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VIRGO COLLABORATION
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The LSC-Virgo-KAGRA Observational Science White Paper (2025 Edition)

The LSC-Virgo-KAGRA Observational Science Working Groups

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Instructions

This LaTeX template provides a standard framework for documenting the work plans for each division of the Collaboration. Various class, style and macro files are located in the tools subdirectory. In general, any necessary changes to these files should be backported to the template repository so that the modifications can be made available to all of the white paper projects.

There are a number of macros near the top of `WP-template.tex` that will allow you to define the long name of the division, the division acronym, the white paper year, and the document control numbers for LIGO, Virgo and KAGRA.

The Executive Summary provides an overview of the division's work. Each working group should describe the mission of the group and the rationale behind the group's priorities (we strongly recommend keeping this to 2 pages max). The file `ES-template.tex` provides a sample format; each division should decide on a standard format for the working group summaries within their division. The target audience for this section is outside the Collaboration.

Each subsequent section of the white paper documents a set of Collaboration Projects scoped to the working group(s) in the section name, as shown in `AP-template.tex`. A Collaboration Project delivers a product for the Collaboration, e.g. data, software, designs, hardware, publications, services, ... To map this to the language of a work breakdown structure (WBS), as used by some working groups, each project is a level-1 element which is broken down into a complete list of level-2 elements (or **activities**) representing intermediate deliverables of the project. Each level-2 element may be further broken down into a list of level-3 elements (or **tasks**); we strongly recommend including task-level items if a complete list is available at the time of writing.

The file `AP-template.tex` shows how to organize the information about each project. The following LaTeX commands and environments allow standardized information entry for projects:

Command `\WPproject{Name}{yyyy-mm-dd}{yyyy-mm-dd}`: A `WPproject` is a level-1 WBS element. It takes three arguments: the project name, the project start date (in the format yyyy-mm-dd), and the estimated project due date (in the format yyyy-mm-dd). If the dates are not known, please use TBD.

Environment `\begin{WPactivity}[f]{Name}` ...`\end{WPactivity`: A `WPactivity` is a level-2 element of the WBS for the project. It has one optional argument that takes either `t` to indicate the activity is `\InfraOpsTrue` or `f` to indicate the activity `\InfraOpsFalse`. The default is `f`. The first required argument is the name of the activity.

Environment `\begin{WPtask}` ...`\end{WPtask}`: A `WPtask` is a level-3 element of the WBS for the project. Tasks inherit their InfraOps classification from their parent `WPactivity`.

Each `\WPactivity` is automatically added to a list of activities that is included at the end of the white paper. The same is true for each `\WPtask`. A script is provided to parse this information into a csv-file for ingestion into the LSC MOU system.

Required personpower estimates should be added to the central internal spreadsheet

`https://docs.google.com/spreadsheets/d/194HOAAE0-Ps6mC3aMVRq4XtcL_mf5CU7RNjauoRYI3E`

once the projects, activities, and tasks are defined.

Overview and Executive Summary

The Collaboration program committees review and establish the goals of the Collaboration on an annual basis. The LSC Program and the Virgo Collaboration Core Program are documented in LIGO-M2400265 and VIR-0734A-23, respectively. Each Division of the Collaboration identifies the work needed to achieve the Collaboration's goals and documents them in a white paper. This is the white paper for the Observational Science [OBS] Division.

Gravitational wave (GW) searches and astrophysics in the LIGO Scientific Collaboration (LSC), Virgo Collaboration and KAGRA Collaboration are organized into four working groups. The **Compact Binary Coalescence (CBC)** group searches for and studies signals from merging neutron stars and black holes by filtering the data with waveform templates. The **Burst** group searches for generic gravitational wave transients with minimal assumption on the source or signal morphology. The **Continuous Waves (CW)** group targets periodic signatures from rotating neutron stars. The **Stochastic Gravitational-Wave Background (SGWB)** group looks for a gravitational wave background of cosmological or astrophysical origin.

These groups also collaborate with the **Detector Characterization (DetChar)** group, which interfaces with the detector commissioning teams and works to improve GW signal searches by identifying and mitigating noise sources that limit sensitivity to astrophysical signals, as well as with the **Calibration** and **Computing & Software** teams.

The LSC, Virgo Collaboration and KAGRA Collaboration are separate entities but work together closely, especially on data analysis. We often refer to the LSC-Virgo-KAGRA combination as 'LVK'.

This ***LSC-Virgo-KAGRA Observational Science White Paper*** describes the planned activities of the members of the four astrophysical search working groups, including science goals and methods. The subsections in sections 1 through 8 contain "activity plans" with a wide range of themes. Each activity plan is associated with either Section 2 or Section 4 of the LIGO Scientific Collaboration Program (2024 Edition) LIGO-M2400265, as well as with either Section 2 or 4 of the Virgo Collaboration Core Program VIR-0734A-23. Activities that qualify as Infrastructure and Operations activities according to Section 2 of the LIGO Scientific Collaboration Program are indicated by the suffix **INFRAOPS**. All other activities are indicated by the suffix **OTHER**.

The LSC Program Committee and Virgo Core Program Committee set specific goals for collaboration work on an annual basis, using this white paper and other inputs. While this white paper concerns the activities of the four astrophysical search groups, LSC, Virgo and KAGRA activities in the domains of Commissioning, Calibration, Computing, Detector Characterization, LSC Fellows program, and Run Planning can be found in the *LSC-Virgo-KAGRA Operations White Paper* (LIGO-T2400388, VIR-1012A-24, JGW-T2416107). The other white papers are for Education and Public Outreach, LIGO-T2400406, Collaboration Standards and Services, LIGO-M2400297, and LSC Instrument Science, LIGO-T2400407.

Achieving the direct detection of gravitational waves was the result of decades of development of both instrumentation and data analysis methods. Substantial advances were made using data collected by the initial LIGO detectors (2002–2010) and the initial Virgo detector (2007–2011), but no GW signals were detected. The era of GW detection, GW astronomy and astrophysics was enabled by the Advanced LIGO and Advanced Virgo upgrades. The first Advanced LIGO observing run, O1, began in September 2015 and immediately yielded the first detected event, GW150914. The second observing run (O2) took place in from November 2016 to August 2017, starting with just the two Advanced LIGO detectors but with Advanced Virgo joining the run for the final month. The third observing run (O3) took place from April 2019 through March 2020, with both LIGO detectors and the Virgo detector collecting data with better sensitivity than ever before. The KAGRA detector observed jointly with the GEO 600 detector for two weeks in April 2020 as an extension of O3. The fourth observing run (O4) began on 24 May 2024, initially with the two LIGO detectors and KAGRA participating. After one month of operation, KAGRA stopped the observing run and resumed comissioning. The first data taking period (O4a) ended on 16 January 2024, and, following a LIGO commissioning break, the observing run resumed on 10 April 2024 with both LIGO detectors and Virgo participating. At the time of writing this white paper, it is planned that KAGRA will resume operations around spring 2025. It is also planned that O4 will continue up until 9 June 2025.

Epoch	Run Name	Run Duration	Typical Binary Neutron Star (BNS) Range (Mpc) LIGO	Virgo	KAGRA	$E_{\rm GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	
2015–16	O1	4 months	80	–	–	50	–	actual
2016–17	O2	9 months	100	30	–	60	25	actual
2019–20	O3	11 months	110–130	50	1	80–90	35	actual
2023–25	O4a	8 months	130–170	–	1.3	110–120	–	actual
	O4b	15 months	140–190	45–55	3–10	110–120	30–40	actual (to date)
2027–29	O5	TBD	240–325	150–260	25–128	210	100–155	projected

Table 1: Observing schedule, actual and projected sensitivities for the Advanced LIGO, Advanced Virgo and KAGRA detectors. Adapted from *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA* (LIGO-P1200087, VIR-0288C-12, and published in Living Reviews in Relativity), curated by the LVK Joint Run Planning Committee. Projected BNS ranges for O5 are updated by using publicly announced information https://dcc.ligo.org/LIGO-G2002127/public.

Scientific Operations and Observational Results

LSC-Virgo-KAGRA data analysis activities for Observing run 4 (very similar to the activities for O3) are summarized in Table 2, by search group, and prioritized in three categories:

- **Highest priority:** searches most likely to make detections or yield significant astrophysical results.
- **High priority:** promising extensions of the highest priority goals that explore larger regions of parameter space or can further the science potential of LIGO, Virgo and KAGRA.
- **Additional priority:** sources with lower detection probability but high scientific payoff.

Computing needs and resource allocations are derived, in part, from the science priorities presented in this table. Scientific motivations, details on methods and strategies for result validation are provided in the **activity plans** included in the later sections of this white paper.

We note that the LSC and Virgo Collaboration have adopted a *Multiple Pipeline Policy* [LIGO-M1500027], which calls for astrophysical results to be validated with a different analysis, using independent methods and tools when possible. In some cases this may require the same data to be analyzed by more than one pipeline for the same science target.

	LSC-Virgo-KAGRA Observational Science Working Group			
	Burst	CBC (compact binaries)	Continuous Wave	Stochastic Background
Highest priority	Search for short-duration GW bursts (both online and offline)	Responding to exceptional compact binary coalescence detections	Targeted searches for high-interest known pulsars, e.g. Crab, Vela	Searches for an isotropic stochastic GW background
	Search for long-duration GW bursts	Cataloging detections of coalescence of neutron star and black hole binaries and their meaured parameters	Narrow-band searches for high-interest known pulsars	Directional searches for anisotropic stochastic GW backgrounds from point sources
	Responding to exceptional GW burst and multi-messenger detections	Characterizing the astrophysical distribution of compact binaries	Directed searches for high-interest point sources, e.g. Cassiopeia A, Scorpius X-1	Detector characterization, data quality, and correlated noise studies specific to SGWB searches
	Searches without templates from GWs from binary black holes	Testing General Relativity with compact binaries	All-sky searches for unknown sources, either isolated or in binary systems	All-sky search for extended sources using spherical harmonic analysis
	GW burst signal characterization	Low-latency searches to enable multimessenger astronomy	Long-transient searches for emission from nearby post-merger neutron stars	SGWB implications and modeling
	Multimessenger search for GW bursts associated with GRBs	Multimessenger search for CBC-GRB coincidences	Follow-up searches of any promising candidates found by other searches	
		Measuring the properties of extreme matter, e.g. the neutron star equation of state	Detector characterization, data preparation, scientific software maintenance	
		Determination of the Hubble constant		
High priority	Multimessenger searches for GW bursts associated with fast radio bursts, core-collapse supernovae, magnetar flares and high-energy neutrinos.	Improved searches for intermediate mass black hole binaries and intermediate mass-ratio inspirals	Targeted searches for other known pulsars, and non-tensor polarisations	
	Search for BNS post-merger signals	Search for sub-solar mass compact binary coalescences	Targeted searches for CW signals with non-tensor polarizations	Dark matter searches
	All-sky cosmic string search	Search for gravitationally lensed signals from compact binary coalesceces	Directed searches for other point sources of interest	
	Search for domain wall gravitational signatures	Improved waveform models for signals expected during the O4 run	Long-transient searches for emission from distant post-merger neutron stars	
	Optimized algorithms for non-vanilla binary black hole mergers (eccentric, parabolic, or hyperbolic orbits).	Multimessenger searches for binary mergers associated with fast radio bursts and high energy neutrinos		
Additional priority		Optimized search for stochastic background of GWs from CBCs	Searches for long-lived transient emission following a known pulsar glitch	Analysis to separate components of a stochastic GW background
			Continuous GW emission from ultra-light boson clouds around black holes	Search for very long transients ($\sim$ 10 hr $-$ days)
			Direct detection of dark photon dark matter	Search for SGWB-EM sky correlations

Table 2: **Scientific Operations and Observational Results:** Priorities of the LIGO Scientific Collaboration, Virgo Collaboration and KAGRA, for the four astrophysical search working groups. Targets are grouped into three categories (highest priority, high priority, additional priority) based on their detection potential. There is no additional ranking within each category in this table.

Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

Longer term developments which are pursued to advance the scientific frontiers of GW observational science are summarized in Table 3, by search group, and classified in two categories:

- **Essential:** developments considered necessary steps for enhancing the scientific return of future observing runs.
- **Exploratory:** developments which can further the science potential of future observing runs.

Depending on the course of development, these enhancements may be used in the analysis of the O4 data, or may be used farther in the future.

	LSC-Virgo-KAGRA Observational Science Working Group			
	Burst	CBC (compact binaries)	Continuous Wave	Stochastic Background
Essential	Improvement of existing pipelines and methods for GW burst searches	Parameter estimation acceleration	Further improvement and optimization of existing data analysis pipelines	Implement optimal method to search for stochastic background from CBC events
	Plans for the detection of exceptional multi-messenger sources	Essential improvements to waveform models	Development of model-robust/agnostic data analysis methods	
		Improved models of population inference		
		Improvements to statistical measurement of the Hubble constant		
		Essential enhancements to all-sky searches		
Exploratory	Development of new methods for GW burst searches	Research and development in parameter estimation methodology	Development of new and potentially more sensitive data analysis methods	Cross-correlation search for intermittent background
		New tests for exotic black hole physics	Use mock data challenges to compare data analysis pipelines	Component separation using narrowband maps
		Long-term improvements to waveform models		Models for anisotropic backgrounds
		Robust population inference with marginal events		
		Real-time cosmology calculation		
		Exploratory enhancements to all-sky searches		

Table 3: **Enhanced Analysis Methods for Advancing Frontiers**: longer term R&D activities of the LIGO Scientific Collaboration, Virgo Collaboration and KAGRA, for the four astrophysical search groups: Burst, Compact Binary Coalescence (CBC), Continuous Waves (CW), and Stochastic Gravitational-Wave Background (SGWB). The targets are grouped into two categories (essential, exploratory). There is no ranking within each category in this table.

OBS-0.1 Searches for Generic Transients, or Bursts

The mission of the burst group is to detect gravitational-wave transients, or *bursts*, and to gain new information on populations, emission mechanisms, and source physics of the associated astrophysical objects. Central to the burst group philosophy is the assumption of minimal information on the source, so that searches for gravitational-wave bursts typically do not require a well-known or accurate waveform model and are robust against uncertainties in the gravitational-wave signature. Burst searches are, therefore, sensitive to gravitational-wave transients from a wide range of progenitors, ranging from known sources such as binary black hole (BBH) mergers, in particular the most massive and loudest ones, to poorly-modeled signals such as core-collapse supernovae (CCSN) as well as gravitational-wave transients that are currently unknown to science such as cosmic strings, neutron star instabilities, fast radio burst and magnetars. We refer to this as the “eyes wide open" approach.

For example, the complexity of supernovae makes it difficult to reliably map the dynamics of a CCSN into a gravitational-wave signal. The merger of precessing intermediate-mass black holes ($\geq 100\,\mathrm{M}_{\odot}$) produces gravitational-wave transients which appear as short, sub-second bursts in the data. Long gamma-ray bursts (GRBs) could be associated with a gravitational-wave transient lasting more than 10 seconds. Since robust models are not available for many plausible sources, the group employs data analysis methods that are able to detect emission mechanisms that have not been envisioned yet.

The burst group implements a variety of methods to identify instances of statistically significant excess power, localized in the time-frequency domain. To discriminate between gravitational waves and noise fluctuations, each search requires the signal to appear coherently in multiple detectors. The confidence of a candidate event is established by repeating the analysis on many instances of background, obtained by shifting the data from different detectors with non-physical delays.

Although burst search algorithms are designed to detect a wide range of signals, their tuning and interpretation benefit from considering how they perform for plausible astrophysical signals. A variety of targeted searches are designed to increase sensitivity to expected classes of signals. Therefore, the group’s science program involves an active collaboration with the theoretical astrophysics, source modeling, and numerical relativity communities.

Many potential gravitational-wave burst sources should also be observable in other astronomy channels, including γ-ray, X-ray, optical, radio, and neutrino signals. Knowledge of the time and/or sky position of the astrophysical event producing a gravitational-wave burst can be used to increase the sensitivity of a triggered burst search compared to an untriggered, all-sky search, and the association with a known astrophysical event may be critical in establishing our confidence in a gravitational-wave burst detection. Most importantly, joint *multi-messenger* studies of complementary data enable scientific insight that cannot be accessed through gravitational waves or other messengers alone. Therefore, in addition to searches using only the gravitational-wave data, a significant part of the burst group’s science program involves connecting with other observations and working closely with the astronomy and astrophysics communities. An important component of this connection utilizes burst searches running in low- and medium-latency, from minutes to hours, and providing information on transient gravitational-wave candidates to the astronomical community. The first BBH detection, GW150914, and the binary neutron star merger GW170817 illustrated the scientific value of this approach.

Once a confident gravitational-wave transient is identified, characterizing its properties becomes an important goal of the group. This includes producing waveform reconstruction, polarization, and source localization estimates for all observed transients (CBC, CCSN, cosmic strings, etc.) This information can then be used to learn about the nature of the astrophysical source and test different astrophysical scenarios.

OBS-0.1.1 Scientific Operations and O4 Observational Results

The Scientific Operations and O4 Observational Results priorities of the burst group are:

1. **Highest Priority**

    - **Search for short-duration gravitational-wave bursts both online and offline:** The burst group will search for a broad class of short-duration transients. Deliverables include low-latency triggers for electromagnetic follow-up, and papers describing search results. [Section OBS-1.1]

    - **Search for long duration gravitational-wave bursts:** The burst group will search for a broad class of long-duration transients. Deliverables include papers describing the search results. [Section OBS-1.2]

    - **Responding to exceptional gravitational-wave burst and multi-messenger detections (CCSN, BNS, GRB, FRB, Magnetar Flare, Neutrino):** In the event of an exceptional gravitational-wave burst or astrophysical event with a reasonable expectation for detecting gravitational waves, the group will deliver a detection statement (or non-detection statement) in a timely manner, as well as waveform reconstruction and signal interpretation. Examples include a galactic core-collapse supernova, an unusually close binary neutron star merger or gamma-ray burst, or a highly energetic magnetar flare. [Sections OBS-1.5, OBS-5.2, OBS-1.6, OBS-5.4]

    - **Multi-messenger searches from GRB triggers:** Using a known GRB event as a target can increase the sensitivity of a gravitational-wave search. The group will pursue gravitational-wave targeted searches associated to the closest GRB triggers. Deliverables include papers describing the search results. [Section OBS-5.2]

    - **Searches without templates for gravitational waves from binary black holes:** Although most expected BBH mergers will also be detected with CBC searches, burst algorithms are sensitive to a range of features not included in current template banks, including higher order modes, eccentricity, and spin precession. This is important to detect some classes of BBH events. Deliverables include the results of searches targeting both stellar mass and intermediate mass ($M > 100\ M_{\odot}$) black hole systems, with results to be included in papers written jointly with the CBC group. [Sections OBS-1.3, OBS-5.1]

    - **Gravitational-wave burst signal characterization:** For detected transients, a coherent waveform reconstruction, polarization estimates, and source localization enable many potential investigations. Deliverables include producing waveform reconstructions and localizations for all detected transients. [Section OBS-1.4]

    - **Search for gravitational waves associated with GRB:** Using a known astrophysical GRB event as a target can increase the sensitivity of a gravitational-wave search. The group will pursue a triggered search. Deliverables include papers describing the search results. [Sections OBS-5.2]

2. **High Priority**

    - **Multi-messenger searches (CCSN, GRB, Magnetar Flare, Neutrino, Fast Radio Burst):** Using a known astrophysical event as a target can increase the sensitivity of a gravitational-wave search. The group will pursue a number of searches, both triggered and untriggered. This includes some sub-threshold searches. Deliverables include papers describing the search results. [Sections OBS-1.5, OBS-5.2, OBS-1.6, OBS-5.4, OBS-5.3]

- **Search for BNS post-merger signals:** Following a BNS detection, the group will search for a post-merger signal. Finding (or limiting) such a signal provides a powerful equation-of-state measurement. Deliverables include the result of a search for a post-merger signal after each nearby BNS detection. [Section OBS-5.2]

- **All-sky cosmic string search:** The group will search for signals from cosmic strings, and interpret any upper limits as constraints on string parameters. Deliverables include papers describing search results. [Section OBS-6.1]

- **Domain wall search:** The group will search for (non gravitational-wave) signatures from domain walls, and interpret any upper limits as constraints on domain wall coupling parameters. Deliverables include papers describing search results. [Section OBS-1.7]

- **Optimized algorithms for BBH mergers with features well-suited to unmodeled searches.** The group will optimize burst algorithms to search for new populations of non-vanilla BBH mergers, such as systems with high eccentricity, hyperbolic and parabolic encounters. Deliverables include offline searches for these systems and papers describing the search results. [Sections OBS-1.3]

Several of these science targets – including BBH mergers, gamma-ray bursts, and low-latency trigger production – overlap with the CBC group, while others – including long transient and cosmic string searches – overlap with the stochastic group. Joint teams are working together across the multiple groups on these targets.

OBS-0.1.2 Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

The two main levels of longer term R&D activities of the burst group comprise:

1. **Essential**

    - **Improvement of existing pipelines and methods for GW burst searches:** The group will maintain and improve the pipelines employed in GW burst searches and the methods used to produce high-priority results. Deliverables include technical notes and papers describing these improvements.

    - **Plans for the detection of exceptional multi-messenger sources:** In advance of an exceptional astrophysical event, the group will make plans for what types of statements to make in case of a multi-messenger detection, including the quantification of the significance of a candidate multi-messenger detection of cosmic events, and further develop software that will be used to produce the results.

2. **Exploratory**

    - **Development of new methods for GW burst searches:** The group will develop new methods and software to look for GW burst signals. Deliverables include technical notes and papers describing the algorithms and data analysis methods.

OBS-0.2 Searches for Signals from Compact Binary Coalescences

As of this writing, we are in the middle of the O4 run and there have been 60 public alerts for high-significance binary merger events. These are in addition to the 90 binaries that were observed in O1 through O3 with astrophysical probability greater than 0.5.

The O3a and O3b catalog reporting significant events discovered during O3 along with several companion papers are completed. These papers contain significant events, and include more detailed estimation of population distributions of binary masses and spins, more sensitive tests of general relativity using a much larger statistical sample of signals, and improved measurements of the Hubble constant through direct and statistical methods. Furthermore, we reported the discovery of another binary neutron star merger as well as the detection of two coalescing systems comprising likely a neutron star and a black hole.

During O4, we are seeing a compact binary coalescence detection rate approaching a few per week. Projecting the current number of detections made online, we will have ~ 200 high-significance detections by the end of O4. This will pose a significant challenge to the group in analysing the data and producing scientific publications in a timely fashion. But, the scientific payoff will be substantial. The larger population uncovered will help to answer fundamental questions raised by tentative hints seen so far. High-SNR events will yield new insights into the nature of black holes. With additional neutron star mergers, we will be able to make more precise measurements of the neutron star equation of state. The Compact Binary Coalescence (CBC) group aims to discover additional compact binary mergers and to use the gravitational wave signals to advance our understanding of fundamental physics and astrophysics.

The range of scientific activities pursued by the CBC group requires us to prioritize our goals. In the regime of increasing detection frequency over the coming observing runs, we must strike a balance between exploitation of established classes of sources and preparing for detection of new source classes. Achieving these goals requires the group to prioritize the continued research and development of our tools and methods for source detection, estimation of parameters, inference of rates and populations, probing fundamental physics and modeling of waveforms with analytical and numerical relativity. We will continue to develop our search pipelines to improve their sensitivity to quiet sources by improvements in detection statistics, understanding of the noise background and rigorous understanding of data quality. A tremendous human effort is required to develop, deploy, run and interpret the results of low-latency and offline searches in the context of evolving detector sensitivity and data quality. Additionally, the CBC group maintains an active collaboration with a broader community to enhance the impact of our discoveries on theoretical astrophysics and the electromagnetic and astroparticle observing communities.

OBS-0.2.1 Scientific Operations and O4 Observational Results

The Scientific Operations and O4 Observational Results priorities of the CBC group are:

1. **Highest priority**

   - **Responding to exceptional events**.
     We must be prepared to detect and respond to novel sources of extraordinary scientific importance. We define these as sources that yield significant new astrophysics and would warrant a rapid stand-alone publication. These would naturally include new detections of binary neutron stars, intermediate-mass or sub-solar mass binary systems. We also anticipate examples in which measurement of a source's parameters (e.g., masses and spins) could provide significant constraints on its formation channel or our understanding of stellar evolution (e.g., the possible existence of gaps in the black hole mass distribution, minimum or maximum neutron star mass).

Other examples could include sources which are exceptionally loud and allow us to measure the source physics with unprecedented precision, thereby providing exceptional constraints on general relativity, or, for binaries containing a neutron star, improved measurement of the nuclear equation of state. Binaries with observed electromagnetic counterparts can significantly improve our estimate of Hubble constant using the standard-siren distance estimate.

- **Producing a catalogue of detected compact binaries**.

  We will produce a summary of all compact binaries detected during each observing run in order to provide a reference for the astrophysics community with details of the detected source's physical parameters, notable properties, and waveform estimates. This requires a good understanding of systematic errors, including waveform modelling errors. We will continue to reduce our sources of systematic errors by improving our waveform modeling with comparison to numerical relativity simulations. The catalog completeness will be improved by including uncertain signals along with their estimated significance and sky-localization in order to enable subthreshold multimessenger searches.

  Eccentric binary systems are another potential class of source where the searches and waveforms are less mature. Templated searches and unmodeled searches can be combined to allow for more robust searches over a range of eccentricity.

  Along similar lines, the concrete possibility of detection of hyperbolic captures will require the development of models to be used in templated searches to be run in synergy with unmodeled searches.

- **Characterizing the astrophysical distributions of compact objects**.

  As the number of detections increases, we will build a clearer picture of the astrophysical distribution of compact binaries in terms of their masses and spins. This will set novel empirical constraints on the astrophysics of binary evolution. To accurately learn these distributions we need the ability to infer the physical properties of our detected sources and estimate their distribution taking into account the selection effects of our detectors and pipelines.

- **Testing general relativity**.

  The final stages of compact binary coalescence provide a unique window into the behaviour of gravity in the strong-field, high-velocity regime. We will continue to develop the range of tests we are able to perform on our detections, ensuring their robustness through comparison to numerical relativity simulations where possible. We will develop methods of combining multiple detections to place better constraints on the theory, and test specific predictions from general relativity such as the no-hair, area theorems and the general nature of merger remnants, local Lorentz invariance and the mass of the graviton, and the speed of gravitational waves. As more detectors are added to the network we will also be able to make improved tests of the polarization states of gravitational waves.

- **Low-latency and early warning searches to enable multimessenger astronomy**.

  Observations of an electromagnetic or neutrino counterparts to a gravitational wave signal are of huge astrophysical importance to the field, so we will continue to pursue multi-messenger astronomy by searching data in near-real-time and providing public alerts to the astronomical community. This requires the continued development of low-latency pipelines for detection, localization, and estimation of parameters of sources. Early warning pipelines have been deployed in O4 providing pre-merger alerts for binary neutron stars and neutron star black holes in order to capture any prompt emission associated with such events. (The Operations White Paper describes other essential components of this effort, including data quality checks and the infrastructure associated with collating information and distributing alerts.)

- **Multimessenger search for gravitational waves associated with gamma-ray bursts**.

  The coincident detection of a gravitational wave with a gamma-ray burst ranks among the highest impact observations in the compact binary field. We will continue performing a deep coherent search for gravitational waves focused on the sky position of any known gamma-ray bursts, and pursue joint searches for gravitational-wave and GRB signals.

- **Probing the properties of matter in the extremes of physical limits**.

  Binary coalescences involving neutron stars are a unique laboratory for studying the behaviour of matter at super-nuclear densities and pressures. We will refine methods of constraining the neutron star equation of state by measuring its observable effects on the inspiral, merger and post-merger phases of the coalescence signal, and apply these to forthcoming neutron star merger observations.

- **Determination of the Hubble constant**.

  Gravitational waves provide a new way to measure the distance of extra-galactic binary coalescences. When these events are also observed electromagnetically, and the redshift of the host galaxy is measured, an estimate of the Hubble constant can be obtained. As such observations accumulate, this method is expected to provide a competitive and independent method for obtaining the Hubble constant. In addition, statistical approaches such as those involving spatial correlations with a galaxy catalog or those studying the population distribution of binaries can be used for merger events when no identified counterpart is available. With new observations, we will improve our estimate of the Hubble constant.

To enable these highest-priority activities we will engage in research and development in compact binary coalescence search pipelines and parameter estimation, externally-triggered searches, waveform modelling, rate and population inference, tests of general relativity, measurement of cosmological parameters, and measurement of neutron star equation of state.

2. **High priority**

High priority activities are those which are less certain to produce a significant result in the near term, but where the potential payoff would be high.

- **Improved searches for intermediate mass black hole binaries & intermediate mass-ratio inspirals**.

  A goal of the CBC group is to search for intermediate mass black hole binaries. Especially at the highest masses, the success of any search will be sensitive to the effects of higher order modes and precession in the waveforms. An extension of the intermediate mass black hole binaries research is the development of refined searches for intermediate-mass-ratio inspirals and waveforms to describe them.

- **Search for sub-solar mass compact binary coalescences**.

  A speculative source is black hole binaries (or other compact object binaries) having component masses below one solar mass. Primordial black holes could be one channel by which such systems are formed, but there are other possibilities. Such systems might possibly constitute some fraction of the dark matter. A search for sub-solar mass binaries could reveal the existance of a new class of object, or place stronger constraints on the fraction of dark matter explained by sub-solar mass black hole binaries.

- **Search for gravitationally lensed binary coalescences**.

Gravitational lensing of gravitational waves can result in magnification of gravitational wave signals as well as multiple images, which has the effect that the same source is seen as multiple events separated in time. Lensing can also alter the gravitational waveform in ways that could allow us to determine that a signal has been lensed. Detection of a lensed signal would allow us to make inferences about cosmology and population of compact binaries and would allow us to perform improved tests of the number of gravitational wave polarization states.

- **Improved waveform models**.
  The O4 run is likely to produce additional interesting CBC events, possibly with higher signal-to-noise ratio or in new regions of parameter space. Development and validation of improved waveform models may be needed to robustly interpret the detected signal or signals.
- **Multimessenger search for gravitational waves associated with fast radio bursts**.
  It is possible that fast radio bursts are produced during compact binary coalescence. The method for performing deep searches for gravitational waves associated with gamma-ray bursts can be extended to explore periods of time around triggers produced by fast radio bursts. Though the methods are similar, the time window to be explored will need to be reassessed.
- **Multimessenger search for gravitational waves associated with high-energy neutrinos**.
  High-energy neutrinos can be produced during compact binary coalescence. The catalog of compact binary coalescence candidates including the subthreshold trigger list with sky localization information will used to search for joint sources of gravitational waves and high-energy neutrinos around astrophysically motivated time window.

3. **Additional priority**

   Additional priority activities are activities that the Compact Binary Coalescence (CBC) group will undertake if resources are available.

   - **Stochastic background of gravitational waves from compact binary coalescences**.
     The superposition of a large number of weak signals arising from compact binary coalescences in the distant universe will produce a stochastic background of gravitational radiation. Such a background produced by binary black hole mergers is not truly continuous, though, as it originates from discrete signals that are not fully overlapping in time, and an optimized statistical search for such sub-threshold signals will be pursued.

OBS-0.2.2 Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

The two main levels of longer term R&D activities of the CBC group comprise:

1. **Essential**

   - **Parameter Estimation Acceleration and Automation**.
     Parameter estimation engines need to be modernized and optimized to increase their utility, computational performance, and ease of use, in order to handle the future onslaught of events. This will entail management, archiving and interfacing with workflows from other analyses as well as an increase in the level of automation of existing and future pipelines.

- **Essential Improvements to Waveform Models**.
With increasing sensitivity we will become increasingly dependent on highly accurate waveform models. Waveform models that capture sub-dominant modes of emission, improved models of precession, and eccentricity will be developed. In addition, inclusion of additional matter effects, e.g., during the merger and post-merger phases, will be needed for modeling neutron star binary systems. A new and flexible interface for waveform models will be implemented to harvest the power of modern hardware, like GPUs, and software, such as Machine Learning methods. Such interface will help the need improvements in the computational performance of waveform simulations to enable faster parameter estimation on the scale necessary for O4.

- **Improved Models of Population Inference**.
As the census of compact binary coalescences grows, more sophisticated models of the astrophysical population will become possible (e.g., with redshift evolution). New methods of population inference will be introduced to exploit the large number of detections anticipated.

- **Improvements to Statistical Measurement of the Hubble Constant**.
There are a number of potentially biasing systematic effects present in the statistical method of measuring the Hubble constant. These effects will be studied and methods for mitigating them with be implemented in the cosmology code.

- **Essential Enhancements to All-Sky Searches**.
As the network of detectors grows with the addition of KAGRA, and with improvements in the detector sensitivity curves, search pipelines need to be enhanced to make optimal use of the available data. This continued development will improve the search sensitivity of both online and offline pipelines.

2. **Exploratory**

- **Research and Development in Parameter Estimation Methodology**.
Investigation of new algorithms and optimization has the potential to greatly improve the speed of the parameter estimation code and add scalability to allow for increasing number of parameters and more complex signal models.

- **New Tests for Exotic Black Hole Physics**.
Tests for exotic speculative physics such as black hole mimickers or late time gravitational wave echos from black holes will be explored.

- **Long-Term Improvements to Waveform Models**.
In the long term, we seek waveforms containing the full set of possible physics, capable of modeling the inspiral, merger, and post-merger of precessing, eccentric (even hyperbolic), systems including, where applicable, matter effects and disruption.

- **Robust Population Inference with Marginal Events**.
Additional information about the astrophysical population of compact binary coalescences can be gleaned by inclusion of marginal events, whose astrophysical origin is not certain. New methods for including marginal events in population inference will be explored.

- **Real-Time Cosmology Calculation**.
As we move toward larger signal rates and longer stretches of continuous operation, a cosmology

calculation that updates in real time as events occur (with or without a counterpart) will be a boon.

- **Exploratory Enhancements to All-Sky Searches**.
Novel methods can be incorporated into the all-sky search pipelines. For example, searches using templates modelling precessing and sub-dominant emission modes; fully-coherent searches; and the use of machine learning to improve event ranking and detector characterization.

OBS-0.3 Searches for Continuous-Wave Signals

The Continuous Waves (CW) Group aims to measure gravitational wave signals that are long-lived, nearly sinusoidal, and extremely weak. Such signals are believed to be emitted by rapidly rotating neutron stars in our Galaxy. These stars can emit gravitational radiation through a variety of mechanisms, including rotation with elastic deformations, magnetic deformations, unstable r-mode oscillations, and free precession, all of which operate differently in accreting and non-accreting stars. Long-term simultaneous GW and electromagnetic observations of a galactic neutron star would support a rich astrophysical research program. Other possible astrophysical CW sources include boson clouds around black holes and low-mass compact binaries during early inspiral, and CW detection methods can also be used for dark matter directly interacting with interferometric detectors.

There is much astrophysical uncertainty surrounding CW emission mechanisms, in part because (i) electromagnetic astronomers have detected only a small fraction (a few thousand) of the population of neutron stars in the Galaxy (believed to be 10^8–10^9), and (ii) modeling the physics of the interiors of neutron stars, particularly beyond nuclear densities, is extremely difficult. To try to mitigate these uncertainties, the CW group maintains a broad program to search for GW emission from several distinct source categories, as described below. The CW group also encourages active research and development into further improvements to existing search pipelines, as well as formulating ideas for new search methods. In addition, mock data challenges can be useful tools to rigorously compare the performance of data analysis pipelines targeting a particular source category.

For known pulsars with measured spin frequencies, frequency derivatives (also known as *spindowns*) and distances, energy conservation sets an upper limit on GW strain amplitude, known as the *spindown limit*, albeit with significant uncertainties. Searches of LIGO and Virgo data have obtained high-confidence upper limits well below the spindown limits for many pulsars, including the Crab and Vela pulsars; as detector sensitivities improve the number of pulsars for which the spindown limit has been surpassed will continue to increase, primarily at spin frequencies below 100 Hz. For suspected neutron stars with unknown spin frequencies, indirect upper limits based on estimated age or estimated accretion rates can also be derived. Such indirect limits are more optimistic for non-accreting stars, but accreting neutron stars are more likely to be emitting near their limits.

The primary categories of searches pursued by the CW group are ordered below by decreasing prior information known about the sources, which generally leads to decreased sensitivity of the associated searches:

Searches for known pulsars use known ephemerides from radio, X-ray or γ-ray timing measurements, and can achieve strain sensitivities limited only by the intrinsic detector sensitivity and observation time spans. Of high interest are those pulsars with spindown limits within factors of a few of the achievable sensitivities. For these high-interest targets it is desirable to also perform complementary *narrowband* searches which forego a small part of the sensitivity and, relaxing the strict assumption of phase coherence between the GW signal and the measured ephemeris, perform a search in small frequency and spindown bands around their nominal values. It is also of interest to search for evidence of non-tensor polarizations, which if detected would imply a violation of general relativity.

Directed searches use known sky locations of interesting astrophysical point sources but lack prior frequency or spindown information. They are therefore less sensitive than searches for known pulsars due to the computational expense and trials factor associated with searching over several parameters: the GW frequency, and potentially higher-order spindowns; and, if the target astrophysical source has a binary companion, parameters of the binary orbit where unknown. This typically precludes using fully-coherent matched filtering over the year-long time spans of an observing runs. Semi-coherent methods – which partition the data set into shorter segments and incoherently combine the results from these – make the computational problem tractable, but sacrifice additional sensitivity beyond that from the trials factor of exploring a larger parameter space. Important astrophysical sources in this category are: galactic supernova remnants which may contain a young neutron star, e.g. Cassiopeia A; low-mass X-ray binaries (LMXBs) where accretion could over time have built up a detectable non-axisymmetry, e.g. Scorpius X-1; the region of the Galactic center, which may contain a large population of neutron stars not detectable by electromagnetic surveys; and nearby globular clusters (e.g. NGC 6544, Terzan 5, 47 Tuc, NGC5139, Palomar 5, M22, NGC 3201, NGC 6397), where older neutron stars may acquire a detectable non-axisymmetry through debris accretion.

All-sky searches use no astrophysical priors, and instead perform broad surveys for undiscovered neutron stars. The sensitivity achievable with all-sky searches is further limited, with respect to directed searches, by the need to make sky-location-dependent corrections for the Doppler modulation of the detected source frequency due to the Earth's daily rotation and yearly orbit. The number of sky directions that must be searched to maintain accurate demodulation grows rapidly with the time span of the data set being analyzed, and the associated increase in computational cost is typically severe enough to require shorter coherence times than in directed searches. Finally, to be sensitive to neutron stars with a binary companion, the parameters of the binary orbit must also be searched over, further enlarging the search parameter space and computational cost.

In addition to the categories above, the CW group is also interested in searching for GWs from several other sources. Searches for *long-lived transients*, in collaboration with the Burst and Stochastic working groups (Section OBS-1.2), could target emission from e.g. a remnant neutron star formed in a binary neutron star coalescence, or following a pulsar glitch. *Ultra-light boson clouds around black holes* may also produce long-lived CW signals and can be searched for in both directed and all-sky modes. *Compact binaries* can also be CW sources during their early inspiral phase, and for certain mass ranges, such as compact binaries with at least one component being a low-mass primordial black hole, can be covered by CW search methods with the LVK network. A direct detection of *dark matter* with GW detectors, under various models that allow for direct interaction with the interferometers, is also being pursued using CW data analysis methods, and in collaboration with the Stochastic working group (Section OBS-8.2).

OBS-0.3.1 Scientific Operations and O4 Observational Results

The input data to any CW analysis pipeline must be carefully characterized and prepared before use. Improperly calibrated data, or data that is otherwise contaminated with excess noise, must be excised from the input data, otherwise analysis results may be affected by large numbers of spurious outliers. Work on identification and mitigation of spectral noise artifacts (lines or combs) coupling into the calibrated strain channel benefits from a close interaction with the detector characterization working group and the site commissioning staff. A small set of data quality flags, produced by the detector characterization working group, are applied to the calibrated detector data so that the most egregious data are discarded. Frequent, large transient glitches seen beginning in the O3 observing run have motivated the use of data cleaning methods to excise them. The detector response is also validated via "hardware injection" recovery, that is, via the successful reconstruction of signals injected into the interferometer data by radiation pressure actuation on the test masses. A set of such signals are monitored daily, weekly and cumulatively during observing runs, and are essential to validate the detector calibration, data cleaning, and other post-processing steps.

The CW group is undertaking a comprehensive search program using data from the O4 observing run, which is reflected in the following list of priority activities. The prioritization of each activity into different classes is arrived at by considering a number of factors: the prior likelihood of detecting a particular category of source; the sensitivity achievable by searches targeting that source category, which in many cases is restricted by their computational cost; and available human resources needed to produce a vetted observational result.

It is important to note that these factors contain several uncertainties. Prior likelihoods of detection are difficult to quantify and may be re-assessed over time. The sensitivity and computational cost of a particular search is often influenced by the specific data set under consideration, including its spectral noise, which may be hard to predict before the data is examined in detail. The availability of human resources, in particular to bring new analysis methods under development to maturity, may also be uncertain. For those reasons, the prioritization of activities that follows is a best guess at the time of writing, and is subject to change when extrapolated into the future. Finally, note that the ordering of activities within the same priority class in the list below does *not* imply any further prioritization *within* that class.

The categorisation into **key/other** from the 2023 LSC programme[1] is related to the following **highest**, **high** and **additional** priorities in such a way that we call the **highest** and **high** papers **key** and **additional** priorities are categorised as **other**.

1. **Highest priority**
    - Targeted searches (Section OBS-3.1) for all known pulsars for which upper limits within a factor of two of the spindown limit are likely to be achieved, e.g. the Crab and Vela pulsars. These searches will include searching at once and twice the pulsar spin frequency.
    - Narrow-band searches (Section OBS-3.2) for high-interest pulsars, as above, which explore small frequency and spindown bands around the nominal parameters given by the known ephemerides.
    - Directed searches targeting as many high-interest astrophysical point sources as resources allow, in particular Cassiopeia A (Section OBS-3.4), Scorpius X-1 (Section OBS-3.5). and the Galactic center (Section OBS-3.7).
    - All-sky searches for undiscovered neutron stars, either isolated (Section OBS-3.10) or in binary systems (Section OBS-3.11).
    - Long- and short-transient searches for GWs from post-merger neutron stars (Section OBS-3.12) where the estimated distance is similar to or closer than GW170817.
    - Searches for long-lived transient GWs following a pulsar glitch (Section OBS-3.13) where indirect upper limits based on measured glitch parameters are expected to be surpassed.
    - Follow-up searches of any promising CW candidates found by other searches (Section OBS-3.16).
    - Support for CW searches through detector characterization (see the Operations White Paper), data preparation (Section OBS-3.17), and scientific software maintenance (Section OBS-3.18).

2. **High priority**

[1]2023 LSC programme: `https://dcc.ligo.org/M2300188/public`

- Targeted searches (Section OBS-3.1) for known pulsars for which the spindown limit is unlikely to be surpassed, [2] including searches sensitive to non-tensor polarizations.
- Searches for CW emission from r-modes from known pulsars, especially PSR J0537–6910 (Section OBS-3.3).
- Narrow-band searches for CWs from Accreting Millisecond X-ray Pulsars (AMXPs), which are neutron stars in LMXBs with known spin frequency (Section OBS-3.6).
- Searches for a direct detection of dark matter from various models, in collaboration with the Stochastic working group (Section OBS-8.2).

3. **Additional priority**

- More robust, but less sensitive all-sky searches for more generic CW-like signals (Section OBS-3.9).
- Directed searches for other point sources of interest, including but not limited to: additional galactic supernova remnants (Section OBS-3.4), sources in LMXBs (Section OBS-3.5) with unknown spin frequency other than Scorpius X-1, and sources in nearby globular clusters (Section OBS-3.8).
- All-sky and directed searches for CWs from ultra-light boson clouds around black holes (Section OBS-3.14).
- Follow-up of candidates from directional stochastic searches, in collaboration with the Stochastic working group (Section OBS-8.1).
- Long- and short-transient searches for GW from post-merger neutron stars (Section OBS-3.12) at estimated distances larger than GW170817.
- Searches for long-lived transient GWs following a pulsar glitch (Section OBS-3.13) where indirect upper limits are unlikely to be surpassed.
- Searches for transient CW-like emission from low-mass primordial black-hole binaries (Section OBS-3.15).

OBS-0.3.2 Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

The search for CWs is a challenging scientific problem. In particular, when parameters of the sources are unknown and therefore must be searched for over wide parameter spaces, the achievable sensitivity compared to the theoretically-optimal method (e.g. matched filtering) is severely limited by finite computational resources. Sub-optimal but computationally-cheaper algorithms must be utilized. The problem of determining the most sensitive search method, given a fixed computational budget, is not easily solved – yet its solution may prove critical to a first CW detection. Furthermore, many sources may exhibit behaviors which deviate from the usual CW signal model, e.g. spin wandering in LMXBs, or sources with intermittent gravitational emission. Investment in *optimization of existing pipelines*, as well as *development of new, potentially more sensitive and/or robust methods*, is therefore of critical importance.

The CW group aims to support at least two independent search methods/pipelines for each search type; more may be supported as resources allow. This redundancy provides greater robustness against incorrect assumptions in signal modeling and against non-optimal handling of instrumental artifacts.

1. **Essential**

[2] Note that, due to the maturity and insignificant computational cost of the targeted search pipelines, there is virtually no practical benefit to separating the high-interest targets from the others and delivering two separate sets of results.

- Further improvement and optimization of existing data analysis pipelines (Section OBS-3.19).
- Development of model-robust/agnostic data analysis methods (Section OBS-3.20).

2. **Exploratory**

- Development of new and potentially more sensitive data analysis methods (Section OBS-3.21).
- Use mock data challenges to compare data analysis pipelines (Section OBS-3.22).

OBS-0.4 Searches for Stochastic Backgrounds

A stochastic gravitational-wave background (SGWB) is formed from the superposition of many events or processes that are too weak and/or too numerous to be resolved individually. The prime objective of the SGWB group is to measure this background, which can arise from cosmological sources such as inflation, cosmic strings, and phase transition models or from astrophysical sources such as compact binary coalescences, supernovae, and neutron stars. The measured rate of binary black hole (BBH) and binary neutron star (BNS) mergers indicates that, at design sensitivity, Advanced LIGO may detect an astrophysical background. This detection will be of great interest as a probe of the evolution of the Universe since the beginning of stellar activity. Meanwhile, the detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The stochastic searches are built on the cross-correlation infrastructure, which was originally designed to carry out searches for an isotropic stochastic background, but has been adapted to also search for directional stochastic backgrounds and transient GW signals.

Although no SGWB was detected during O1, O2 and O3, results from the isotropic search constrain the energy density of the stochastic background to be $\Omega_0 < 1.7 \times 10^{-8}$ at 95% confidence. When the Advanced detectors reach design sensitivity, we expect to be as low as 6×10^{-10}.

The isotropic search has been extended to include a test of General Relativity (GR) by searching for a background of non-tensor polarizations. This extension provides a tool for model selection between a tensor and non-tensor background signal, as well as an estimate of the background energy density from tensor, vector, and scalar polarizations. It is also important to estimate the individual contributions of distinct sources of the background, which may be described by distinct spectral shapes. Independent methods have been developed to consider all physically allowed spectral shapes using either a mixing matrix deconvolution or Bayesian parameter estimation. Bayesian parameter estimation techniques are also used to estimate or constrain the average chirp mass and merger rate of the binary black hole population. Significant model development will be necessary for understanding and interpretating the observational results. To support the interpretation of the results, mock data challenges with different sources, such as compact binaries and cosmic strings, will be pursued. Additionally, search pipelines targeting popcorn backgrounds are being developed using both the traditional cross-correlation approach as well as the fully Bayesian techniques.

The directional searches provide a method of distinguishing between different stochastic sources using sky maps of gravitational-wave power. The group employs both a radiometer algorithm and a spherical harmonic decomposition to generate sky maps (and strain spectra) that can be used to identify cosmological or local anisotropies as well as point sources. The spherical harmonic decomposition provides an estimate of the energy density of the SGWB from extended sources over the sky. It can also be applied to search for a GW background with parameterized anisotropy, for example anisotropies associated with the compact binary black hole background or cosmic strings. To further study anisotropies in the astrophysical background, GW sky maps can be cross correlated with electromagnetic observables. The broadband radiometer measures the background energy density from point-like sources over the sky, and provides an important tool for GW astronomy when there is significant uncertainty in the phase evolution of a continuous-wave signal. As an application, a narrowband radiometer has been used to search for gravitational waves from Scorpius X-1, the Galactic Center, and SN 1987A. Using a compressed data set folded over a sidereal day, the radiometer can be applied to perform an unmodeled search for persistent sources over all frequencies and sky locations. Directional searches are performed separately for multiple spectral indices in standard LIGO analyses but it may be possible to deconvolve the skymaps to constrain backgrounds of multiple spectral components. Exploration studies are being performed, initially considering two or three power-law spectral indices. We also investigate models of SGWB anisotropies, such as compact binaries and cosmic strings, which we can test against our results. We will test these models with mock data challenges. Continuous-wave (CW) sources with deterministic but unknown phase evolution, such as a neutron star with unknown spin period, may be detectable either via the stochastic radiometer or via methods being developed in the CW group. The Stochastic group continues to develop these searches, in consultation with the CW Group.

It may be possible for neutron stars to emit transient gravitational waves on time scales lasting hours to weeks. Moreover, exotic models allow for the possibility of a seemingly persistent signal to start or stop during an observing run, also leading potentially to very long transient signals. The Stochastic group has developed a cross-correlation pipeline to search for very long-lived gravitational-wave transients on these time scales. Applications of this search include the ability to establish whether an apparently persistent source, e.g., observed in a stochastic background search, exhibits variability in time; and an understanding of the behaviour of detector artefacts on timescales of days to weeks. There is overlap between the very long transient search and searches being carried out in the Burst and Continuous Waves search groups.

The traditional stochastic searches share a common assumption of a Gaussian and stationary background. However, a background from unresolvable binary BH mergers, for example, is likely to be detected first by the Stochastic group even though it will not be stationary and is unlikely to be Gaussian. Non-Gaussian stochastic background signals have been studied using software injections and analyses on mock data. A search for an astrophysical background from unresolved compact binary coalescences is being pursued in conjunction with the CBC group. The joint activity are developing and implementing a Bayesian search strategy that is optimally suited to handle the non-stationarity of the expected background from BBH mergers. We note that collecting information from unresolved binaries at large luminosity distance will also help test the Primordial Black Hole scenario, whose merger rate evolution with redshift is expected to be significantly different from the one of astrophysical black holes.

The Stochastic group is actively involved in detector characterization efforts, with overlap with the Detector Characterization (DetChar) group. For example, the SGWB group relies on magnetic field measurements to estimate and mitigate contamination due to Schumann resonances. There are also plans to study how intermittent signals from (instrumental, environmental, or astrophysical) transients may bias stochastic analyses using software injections. The group has also developed and maintains a stochastic data-quality monitor to track search sensitivity in real time and to identify problematic sources of noise.

OBS-0.4.1 Scientific Operations and O4 Observational Results

The Scientific Operations and O4 Observational Results priorities of the Stochastic group are:

1. **Highest priority**
    - **Search for an isotropic background.** Analyze the O4 data for an isotropic stochastic gravitational-wave background, looking as well for evidence of non-GR polarization modes; constrain relevant astrophysical and cosmological models of isotropic gravitational-wave backgrounds; investigate the effect of correlated magnetic noise on the search.

- **Directional searches for anisotropic backgrounds .** Analyze the O4 data using the radiometer method to generate sky maps for point sources of an anisotropic gravitational-wave background; Produce the O4 data folded to one sidereal day to facilitate applications of more computationally-expensive stochastic searches like the all-sky all-frequency radiometer and searches for parameterized anisotropy; optimize the search sensitivity in terms of angular resolution, regularization bias, and frequency band used in search; perform an unmodeled search for potentially interesting persistent gravitational-wave sources from specific sky locations; perform modelled searches targeting specific anisotropy in the sky, such as in the galactic plane.

- **Data quality and detector characterization studies.** Investigate the effect of non-stationarity and coherent lines in the O4 data on the stochastic searches, and pursue approaches to mitigate these sources of noise.

- **Spherical harmonic analysis for anisotropic background.** Perform all-sky search for extended gravitational wave background sources using spherical harmonic decomposition method applied to O4 data; constrain astrophysical and cosmological models of anisotropic gravitational-wave backgrounds, using angular spectra for both auto-power in gravitational wave background and for the cross-power between the gravitational-wave background and electromagnetic observables.

- **Implications and gravitational-wave background modeling.** Develop more accurate theoretical models of astrophysical and cosmological gravitational-wave backgounds; perform mock data challenges to test the recovery of simulated backgrounds corresponding to different theoretical models, using Bayesian model selection or parameter estimation.

2. **High priority**

   - **Dark matter searches.** Searches for dark photon dark matter in collaboration with Continuous Wave working group.

3. **Additional priority**

   - **Component separation.** Implement frequentist or Bayesian component separation methods to determine the individual spectral contributions to an isotropic gravitational-wave background.

   - **Search for very long transients.** Analyze the O4 data for very-long transient events, thus assessing the temporal distribution of the SGWB. In the case of a BNS or a BHNS detection, the search for a very long duration signal from a merger remnant will be promoted to the rank of highest priority.

   - **GW-EM Correlations.** Develop techniques for measuring possible correlations between GW anisotropy maps and maps of matter structure obtained through electromagnetic approaches (galaxy counts, gravitational lensing and others).

OBS-0.4.2 Enhanced Analysis Methods for Advancing Frontiers of GW Astrophysics, Astronomy and Fundamental Physics

1. **Essential**

- **Stochastic background from compact binary coalescences.** Implement and test an optimal Bayesian search for the nonstationary background produced by individually unresolvable CBC events (e.g., BBH mergers) throughout the universe.

- **Cross-Correlation Based Search for Intermittent Gravitational-wave Backgrounds.** Develop a search for intermittent (i.e., popcorn-like) stochastic GW backgrounds by modifying the standard cross-correlation search for a stationary-Gaussian background to target short intermittent “bursts" of correlated GW signals.

2. **Exploratory**

   - **Component separation using narrowband maps.** Develop and implement component separation methods for anisotropic gravitational-wave backgrounds.

   - **Models for anisotropic backgrounds.** Develop theoretical models of astrophysical backgrounds.

OBS-0.5 Working Group Leadership Roles

Each of the four observational science working groups (CBC, Burst, CW, SGWB) is led by Co-Chairs, with at least one from each collaboration. Because the working groups have many active members and encompass a large scientific scope, the Co-Chair role demands a considerable amount of time and energy.

Some of the working groups have defined formal subgroups devoted to developing and maintaining specific technical capabilities and pursuing various science goals. Several of these subgroups span two or more working groups where the science suggests overlap in sources or methods.

Each paper being prepared has a designated Editorial Team (or Paper Writing Team), formed at the onset of paper preparation, and a paper project manager (or co-manager).

Internal review of science results is led and coordinated by a pair of Review Co-Chairs (one each from the LSC and Virgo) for each of the four astrophysical search groups.

Each collaboration also appoints a Data Analysis (or Observational Science) Coordinator. The Data Analysis Coordinators facilitate the overall process of planning, producing and reviewing scientific analyses and papers, and lead weekly Data Analysis Coordination (DAC) meetings, among other tasks.

OBS-1 Burst Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the CBC and Stochastic groups in sections OBS-5 and OBS-6 respectively.

OBS-1.1 Search for short-duration gravitational-wave bursts

A wide range of highly energetic astrophysical phenomena are expected to be accompanied by emission of gravitational-wave transients lasting from milliseconds to several seconds within the instruments' frequency band. For some transient sources, especially compact binary systems composed of neutron stars and/or black holes, their expected gravitational-wave emission is modeled sufficiently well over most of their parameter space that matched-filter techniques using waveform templates can be used to optimally retrieve astrophysical signals from the interferometer data. However, there exists a range of plausible sources of short-duration gravitational-wave emission for which their signal morphologies are poorly modeled or even unknown, and for which no matched-filter techniques can be effectively employed. Such sources, e.g., core-collapse supernovae, soft gamma repeaters and neutron star glitches. The all-sky search for short-duration bursts targets this wide class of sources. For this reason, the all-sky search invokes general transient-finding methods with minimal assumptions on signal morphology. This also provides the opportunity to identify unanticipated sources and signals.

Since O1, the search for unmodeled transients has benefited from independent implementations of burst analysis pipelines [1, 2, 3]. Each analysis uses a measurement basis (Fourier, wavelet or others) in order to identify coincident or coherent excess power in the data from multiple detectors (e.g. cWB [4], oLIB [5], MLy [6] and BayesWave [7]). These analyses use gravitational-wave strain data from all available detectors to solve the inverse problem for the impinging gravitational-wave signal by using maximum likelihood and Bayesian statistics approaches. Multi-instrument analysis is essential for the robust detection of unmodeled gravitational-wave transients; coincident or fully coherent methods have been shown to perform well at rejecting noise transients while recovering relatively weak signals. We plan to continue using multiple burst pipelines in the foreseeable future. Independent searches for the same science targets present the opportunity for direct comparisons of the analysis, an ability to validate search results, and often leads to search innovation. Multiple, independent searches may also better cover the signal parameter space.

In addition to offline analyses, an all-sky search for transient events is performed in low-latency and successfully produces triggers with as short as a few minutes of time delay to allow for rapid follow-up multi-messenger observations. The ability to quickly identify triggers from generic transient events complements current targeted searches for compact binaries, remaining sensitive to a wider variety of sources.

Gravitational-wave transient searches benefit from data quality information provided by detector experts. That especially includes the findings of the detector characterization groups to identify and understand the origin of the non-stationary noise sources. In particular, data quality vetoes are provided by detector characterization groups to exclude noise outliers and improve the burst search sensitivities.

ACTIVITY OBS-1.1-A-**INFRAOPS**: LOW-LATENCY UN-MODELED GRAVITATIONAL-WAVE SEARCHES

TASK OBS-1.1-A(i)-**INFRAOPS**: ONLINE PIPELINE OPERATION

Prepare, deploy and maintain low-latency pipelines to search for gravitational-wave bursts for O4, using LIGO, Virgo and KAGRA data. This task covers all low-latency pipelines that generate burst alerts (all-sky and BBH). This also includes the source properties inference analyses (skymaps, waveform reconstruction, and unmodelled source properties) performed with low latency.

TASK OBS-1.1-A(ii)-**INFRAOPS**: STRATEGY TO FOLLOW-UP BURST EVENTS DETECTED ONLINE

Decide and implement a strategy to follow-up burst-only candidates found by online pipelines. This procedure includes source identification and parameter estimation using burst waveform models.

TASK OBS-1.1-A(iii)-**INFRAOPS**: BACKGROUND TRIGGERS

Extract background triggers found by online searches. This shall be done on a regular basis during the observing run. This information will guide investigation conducted by detector characterization groups. This will also help search groups to configure offline analyses.

ACTIVITY OBS-1.1-B-**INFRAOPS**: OFFLINE SEARCH FOR SHORT-DURATION BURST SIGNALS IN LIGO, VIRGO, AND KAGRA O4 DATA

TASK OBS-1.1-B(i)-**INFRAOPS**: RUN THE ALL-SKY BURST SEARCHES ON O4 DATA

Configure and run burst pipelines on O4 data and produce search results. Characterize the close-box results and eventually open the boxes. Estimate the significance of the most promising gravitational-wave candidates.

TASK OBS-1.1-B(ii)-**INFRAOPS**: WAVEFORM CATALOG DEVELOPMENT FOR SHORT-DURATION BURST SEARCHES

Continue to enhance the short-duration transient waveform catalogue with astrophysically motivated sources. A selection of the most interesting waveforms will be done for the O4 search results publication.

TASK OBS-1.1-B(iii)-**INFRAOPS**: SIGNAL INJECTIONS FOR ALL-SKY BURST SEARCHES

Perform burst signal injections to assess the pipeline detection efficiency following the methodology developed for previous runs.

TASK OBS-1.1-B(iv)-**INFRAOPS**: BACKGROUND TRIGGERS

Extract background triggers found by offline searches. This shall be done on a regular basis during the observing run. This information will guide investigation conducted by detector characterization groups. This will also help search groups to configure offline analyses.

TASK OBS-1.1-B(v)-**INFRAOPS**: FOLLOW-UP DETECTION CANDIDATES FROM ALL-SKY BURST SEARCHES

Use codes designed to evaluate gravitational-wave candidate significance. Employ models to test significance of candidates as astrophysical versus “glitch” (detector artifact) models. As needed, employ techniques to remove glitches from the data near a gravitational-wave candidate – to be used by parameter estimation or other follow-up analyses. Test all existing burst waveform models to match the data and assess the astrophysical origin of the event.

TASK OBS-1.1-B(vi)-**INFRAOPS**: REPORT RESULTS AND REVIEW

Report intermediate results in a timely manner as data becomes available during the observing run (O4 milestones). Periodically report results to the All-Sky Short-Duration group and to the burst group.

TASK OBS-1.1-B(vii)-**INFRAOPS**: REVIEW ANALYSES

Review the Burst all-sky pipelines, the pipeline configurations, as well as the results produced by the pipelines (search results, injection studies, astrophysical upper limits, etc). See also OBS-9.2-E and OBS-9.2-F.

TASK OBS-1.1-B(viii)-**INFRAOPS**: PUBLISH RESULTS FROM ALL-SKY BURST SEARCHES IN O4A

Publish a collaboration paper reporting any signals found by the short-duration searches in the O4a data, and place limits on some classes of sources. See also OBS-9.2-G.

TASK OBS-1.1-B(ix)-**INFRAOPS**: BENCHMARK FOR BURST ALL-SKY SHORT-DURATION SEARCH PIPELINES

Produce the Benchmark Mock Data Challenge set. Measure the pipeline sensitivity to short-duration gravitational-wave bursts using a common set of simulated waveforms. Characterize how the different search pipelines complement each other in terms of sensitivity and parameter-space coverage. Use these results to select search pipelines and to evaluate the trial factor.

ACTIVITY OBS-1.1-C-**INFRAOPS**: UNUSED

TASK OBS-1.1-C(i)-**INFRAOPS**: UNUSED

ACTIVITY OBS-1.1-D-**OTHER**: MULTIPLE PIPELINES STUDIES

TASK OBS-1.1-D(i)-**OTHER**: COMBINE MULTIPLE BURST SEARCH PIPELINES

Develop methods to combine multiple search pipelines, possibly via introducing a unifying statistic, addressing the trials factor open question and enabling improved search results.

ACTIVITY OBS-1.1-E-**OTHER**: TEST ALTERNATIVE MODELS TO GENERAL RELATIVITY USING BURST METHODS

In addition to searching for generic transient gravitational-wave events, we also plan to search for gravitational-wave bursts with alternative polarizations. While Einstein's general theory of relativity (GR) predicts that gravitational waves will have a tensor polarization, some alternative theories of gravity predict gravitational waves with other polarizations (namely scalar and vector polarizations). Using data from LIGO, Virgo and KAGRA detectors makes it possible to distinguish between polarizations of a gravitational-wave signal and to search for these alternative polarizations. We plan to use one or more burst pipeline to search for gravitational-wave signals with non-GR polarizations, and to quantify the consistency between recovered signals and GR polarizations.

TASK OBS-1.1-E(i)-**OTHER**: INVESTIGATE ALTERNATIVES TO GR USING SHORT-DURATION BURST SEARCHES

Model-independent reconstructions of CBC waveforms can be compared with model-dependent reconstructions to search for discrepancies that may highlight deviations from GR.

TASK OBS-1.1-E(ii)-**OTHER**: SEARCH FOR POSTMERGER FEATURES THAT MAY INDICATE DEVIATIONS FROM GR USING BURST TECHNIQUES.

Postmerger features in CBCs can be predicted from a knowledge of the inspiral phase, and any unexpected deviation can signal a deviation from GR. Among the postmerger features we count echoes, which are predicted by some extensions of GR. Echoes are not modeled by conventional CBC models, they are expected to be very short transients, and their detection - which would mark a significant deviation from GR - would be a genuine burst result.

ACTIVITY OBS-1.1-F-**OTHER**: BURST ALL-SKY SHORT-DURATION PIPELINE IMPROVEMENTS

TASK OBS-1.1-F(i)-**OTHER**: INVESTIGATE PIPELINE IMPROVEMENTS FOR SHORT-DURATION BURST SEARCHES

Continue to investigate improvements to pipelines to increase the sensitivity to gravitational-wave bursts. For example, machine learning tools can be used at the post-processing stage to overcome the issue of non-Gaussian transients hampering the searches.

OBS-1.2 Search for long-duration gravitational-wave bursts

Unmodeled long-lived gravitational-wave transients (lasting from $\gtrsim 10\,\mathrm{s}$ to $1000\,\mathrm{s}$) are an exciting class of signals for advanced detectors. Such long-lived transients have been predicted to originate at the death of massive stars. In one class of models, gravitational waves are emitted by a rapidly spinning protoneutron star, which may be spun up through fallback accretion. In another class of models, the signal comes from the motion of clumps in an accretion disk. In either case, the signals are long-lived, narrowband, and may occur with a sufficiently high rate so as to be observed with advanced detectors. Other possible scenarios for long-lived gravitational-wave emission include protoneutron star convection, rotational instabilities in merger remnants, r-mode instabilities associated with glitching pulsars, type I bursts from accreting pulsars, and eccentric binary systems. Searches [8, 9, 10] for these sources use minimal assumptions about the signal waveform, so unexpected sources are detectable as well.

ACTIVITY OBS-1.2-A-**INFRAOPS**: SEARCH FOR LONG-DURATION BURST SIGNALS IN LIGO, VIRGO, AND KAGRA O4 DATA

TASK OBS-1.2-A(i)-**INFRAOPS**: RUN THE ALL-SKY BURST SEARCHES ON O4 DATA

Configure and run burst pipelines on O4 data and produce search results. Characterize the close-box results and eventually open the boxes. Estimate the significance of the most promising gravitational-wave candidates.

TASK OBS-1.2-A(ii)-**INFRAOPS**: WAVEFORM CATALOG DEVELOPMENT FOR LONG-DURATION BURST SEARCHES

Continue to enhance the long-duration transient waveform catalogue with astrophysically motivated sources. A selection of the most interesting waveforms will be done for the O4 search results publication.

TASK OBS-1.2-A(iii)-**INFRAOPS**: SIGNAL INJECTIONS FOR ALL-SKY BURST SEARCHES

Perform burst signal injections to assess the pipeline detection efficiency following the methodology developed for previous runs.

TASK OBS-1.2-A(iv)-**INFRAOPS**: BACKGROUND TRIGGERS

Extract background triggers found by offline searches. This shall be done on a regular basis during the observing run. This information will guide investigation conducted by detector characterization groups. This will also help search groups to configure offline analyses.

TASK OBS-1.2-A(v)-**INFRAOPS**: FOLLOW-UP DETECTION CANDIDATES FROM ALL-SKY BURST SEARCHES

Use codes designed to evaluate gravitational-wave candidate significance. Employ models to test significance of candidates as astrophysical versus "glitch" (detector artifact) models. As needed, employ techniques to remove glitches from the data near a gravitational-wave candidate – to be used by parameter estimation or other follow-up analyses. Test all existing burst waveform models to match the data and assess the astrophysical origin of the event.

TASK OBS-1.2-A(vi)-**INFRAOPS**: REPORT RESULTS

Report intermediate results in a timely manner as data becomes available during the observing run (O4 milestones). Periodically report results to the All-Sky Long-Duration subgroup and to the burst group.

TASK OBS-1.2-A(vii)-**INFRAOPS**: REVIEW ANALYSES

Review the Burst all-sky pipelines, the pipeline configurations, as well as the results produced by the pipelines (search results, injection studies, astrophysical upper limits, etc). See also OBS-9.2-E and OBS-9.2-E.

TASK OBS-1.2-A(viii)-**INFRAOPS**: PUBLISH RESULTS FROM ALL-SKY BURST SEARCHES IN O4A

Publish a collaboration paper reporting any signals found by the long-duration searches in the O4a data, and place limits on some classes of sources. See also OBS-9.2-G.

TASK OBS-1.2-A(ix)-**INFRAOPS**: BENCHMARK ALL-SKY LONG-DURATION SEARCH PIPELINES

Produce the Benchmark Mock Data Challenge set. Measure the pipeline sensitivity to long-duration gravitational-wave bursts using a common set of simulated waveforms. Characterize how the different search pipelines complement each other in terms of sensitivity and parameter-space coverage. Use these results to select search pipelines and to evaluate the trial factor.

ACTIVITY OBS-1.2-B-**INFRAOPS**: UNUSED

TASK OBS-1.2-B(i)-**INFRAOPS**: UNUSED

ACTIVITY OBS-1.2-C-**INFRAOPS**: UNUSED

TASK OBS-1.2-C(i)-**INFRAOPS**: UNUSED

Unused

ACTIVITY OBS-1.2-D-**OTHER**: BURST ALL-SKY LONG-DURATION PIPELINE IMPROVEMENTS

Continue to investigate improvements to pipelines to increase the sensitivity to gravitational-wave bursts. For example, machine learning tools can be used at the post-processing stage to overcome the issue of non-Gaussian transients hampering the searches.

TASK OBS-1.2-D(i)-**OTHER**: INVESTIGATE PIPELINE IMPROVEMENTS FOR LONG-DURATION BURST SEARCHES

ACTIVITY OBS-1.2-E-**OTHER**: BURST ALL-SKY LONG-DURATION PARAMETER ESTIMATION

TASK OBS-1.2-E(i)-**OTHER**: SOURCE RECONSTRUCTION FOR ALL-SKY LONG-DURATION BURST EVENTS

Investigate modeled and unmodeled source reconstruction methods for long transients. It includes to adapt and test the Bayesian parameter estimation code for long-duration signals with the different models of long-duration GW transient sources.

ACTIVITY OBS-1.2-F-**OTHER**: LOW-LATENCY ALL-SKY LONG-DURATION GRAVITATIONAL-WAVE SEARCHES

TASK OBS-1.2-F(i)-**OTHER**: DEVELOP AND TEST A LOW-LATENCY SEARCH PIPELINE FOR LONG-DURATION GRAVITATIONAL WAVES

OBS-1.3 Search without templates for gravitational waves from binary black holes

The binary black hole (BBH) systems in the normal stellar mass range (total mass less than about $100\,\mathrm{M}_\odot$) have been efficiently detected in observing runs O1, O2, and O3 with the matched filter searches using quasi-circular CBC templates, as described in the CBC section. However, other types of potential of CBC systems covering a larger range of component masses, spins and eccentricities should also be considered. Detection of such systems would provide information regarding the viability of several proposed binary formation mechanisms and would help discriminate among different formation models. Targeting this wider parameter space of CBC sources with a burst analysis method, which does not rely on templates, creates a search which is robust to a variety of features including high mass ratios, higher order modes, misaligned spins, eccentric orbits, or deviations from general relativity. These may create mismatch between the observed signal and CBC matched-filter search templates.

There are foreseen two major types of BBH systems for which the Burst searches are especially informative, IMBH and non-circular BBHs. We briefly discuss these two cases below.

High-mass BBH systems

The GW190521 discovery [11] in O3a, representing the first black hole with mass in the pair instability mass gap and the first definitive IMBH, promises to revolutionize this topic. Previously, stellar-mass black holes, originating from core collapse of massive stars, have been observed in the mass range up to $\sim\,65\,\mathrm{M}_\odot$. Due to the pair instability, it is expected that normal stellar evolution will not result in black holes with mass roughly in the range 65 to 100 $\mathrm{M}_\odot$. Meanwhile, massive black holes, exceeding $10^5\,\mathrm{M}_\odot$, appear to be generic in galactic centers. Intermediate-mass black holes (IMBHs) occupy the mass range between these two. IMBHs exceeding the $65\,\mathrm{M}_\odot$ mass limit of stellar-mass black holes may form in dense stellar environments upon the merger of multiple stellar-mass black holes [12, 13, 14]. These IMBHs may then form binaries and merge with stellar-mass black holes in dense environments. Several channels for IMBH formation were explored in the GW190521 "implications" paper [15].

IMBHs with a mass of a few hundred solar masses may generically exist in globular clusters [16, 17]. These IMBHs may form binaries, either when two or more IMBHs are formed in the same cluster [18], or as a result of a merger of two clusters each of which contains an IMBH in the suitable mass range [19]. A large number of IMBH mergers may be a generic feature of some mechanisms of structure formation, although these are likely to occur at high redshifts [20]. Binaries including two IMBHs could also form as a result of evolution of isolated binaries with very high initial stellar masses [21]. Hence, detections of additional

IMBH systems may serve as probes of globular cluster dynamics, and, potentially, as probes of structure formation and growth of super-massive black holes.

The searches are carried out both with matched filter algorithms using CBC templates and Burst algorithms, which do not rely on templates. The matched filter technique yields the optimal detection efficiency for signals of known form in stationary, Gaussian noise and thus requires a sufficiently accurate signal waveform model for use as a template. The IMBH Burst search is robust to a variety of features that may create mismatch between the observed signal and BBH template banks, including high mass ratios, mis-aligned spins, eccentricity, precession, deviations from general relativity, or detector noise artifacts. Therefore, the IMBH search benefits from the combination of the two complementary analysis techniques.

Non-circular BBH systems

The all-sky Burst searches represent a viable detection method for BBH systems over a wide range of their potential parameter space. A particularly interesting case is that of eccentric (eBBH) systems. Theoretical work has suggested that galactic nuclei and globular clusters may be promising settings for the formation of dynamical capture binaries. Since these systems can form with large eccentricities and very small initial separations, there is good reason to expect that significant eccentricity will persist when the binaries evolve into the LIGO/Virgo detection band. Current CBC searches using quasi-circular waveforms from stellar-mass binaries will not efficiently detect these systems for eccentricities of $e \approx 0.05$ or more[22], therefore dedicated burst searches for these potential sources represent a viable alternative [23]. In practice, the eccentric BBH (eBBH) analysis uses a variation of the generic binary stellar mass black hole search carried out with the cWB pipeline [4] which is optimized for such systems. Finally, it is expected that for O4 there will sufficient coverage of eBBH waveforms available to allow application of standard parameter estimation techniques for eBBH candidates.

Other potential non-quasi-circular BBH systems include close hyperbolic encounters (CHE) or BBH captures. Numerical relativity waveforms are starting to become available for such systems, which allows the evaluation of detection efficiencies for Burst searches. Because these waveforms morphologically resemble the class of instrumental artifacts known as “blip glitches," it will be important to evaluate these searches in the presence of real detector noise.

In recent years, the proposal that there is a large population of black holes living in dense clusters has been gaining popularity, both in the context of primordial black hole (PBH) clusters [24] and dense globular clusters with a large amount of stellar remnants [25]. One natural consequence of these dense clusters is that the black holes inside them will gravitationally scatter off each other in hyperbolic encounters [26], and if they get close enough, they will emit bremsstrahlung gravitational waves that can be detected by the LVK interferometers [27]. To date, no systematic search looking for CHE has been published, which if detected could give information about the dynamics of the clusters in which black holes live.

BBH captures are characterised by a close encounter between 2 objects, which become bound at high eccentricities if a critical amount of angular momentum and energy loss occur. Under such conditions there is not enough time for the binary to circularise, and hence BHs merge with high eccentricity. Various scenarios can lead to capture, such as single-single interactions in galactic nuclei, in regions around supermassive BHs [28], and single-single [29], binary-single [30] and binary-binary interactions [31] in globular clusters. Work by [32, 28] suggests that single-single interactions in galactic nuclei produce the highest rate of eccentric stellar mass BH capture events, with most encounters being parabolic and forming within the LIGO/Virgo band. Binary-single capture events are most common in globular clusters, possibly accounting for $\sim 10\%$ of all BBH mergers formed in these environments [30]. Recent simulations have shown that these waveforms are similar to signals detectable by burst search [33], thus it is important for us to characterize the sensitivity of burst searches to such sources.

Given the complementary nature of Burst and CBC searches for BBH systems, a joint Burst-CBC all-sky effort has been organized and is briefly discussed in Section OBS-5.1.

ACTIVITY OBS-1.3-A-**INFRAOPS**: SEARCH FOR GRAVITATIONAL WAVES FROM BBHS WITH BURST METHODS

TASK OBS-1.3-A(i)-**INFRAOPS**: OFFLINE SEARCH

Prepare and run the O4 search pipelines. Report results in a timely manner. Provide feedback on data quality issues to detector characterization.

TASK OBS-1.3-A(ii)-**INFRAOPS**: FOLLOWING-UP DETECTION CANDIDATES

Prepare and use codes designed to evaluate GW candidate significances. Employ models to test significance of candidates as astrophysical versus "glitch" (detector artifact) models. As needed, employ techniques to remove glitches from the data near a GW candidate – to be used by parameter estimation or other follow-up analyses.

TASK OBS-1.3-A(iii)-**INFRAOPS**: EVALUATION OF SENSITIVE PARAMETER SPACE

Use injections to evaluate the sensitivity of the search for ranges of BBH system parameters, including mass ratio, spin, precession, higher-order modes, etc. Compare with the CBC templated searches.

TASK OBS-1.3-A(iv)-**INFRAOPS**: REPORT RESULTS AND REVIEW

Report intermediate results in a timely manner as data becomes available during engineering runs and in the O4 observing run. Reporting should be made within the Burst-BBH group, the joint Burst-CBC group, and periodically to the Burst group.

TASK OBS-1.3-A(v)-**INFRAOPS**: CONTRIBUTE TO GW TRANSIENT CATALOG AND RELATED PAPERS

The all-sky team should work with the catalog team to agree on thresholds for GW detection candidates. They should oversee any necessary follow-up studies for evaluating candidates.

TASK OBS-1.3-A(vi)-**INFRAOPS**: REVIEW ANALYSES

Review the Burst BBH pipelines, the pipeline configurations, as well as the results produced by the pipelines (search results, injection studies, astrophysical upper limits, etc). See also OBS-9.2-E and OBS-9.2-F.

ACTIVITY OBS-1.3-B-**INFRAOPS**: SEARCH FOR GRAVITATIONAL WAVES FROM ECCENTRIC BBHS (EBBH) WITH BURST METHODS

The following tasks for O4 apply specifically to eccentric BBH systems, as well as hyperbolic BBH encounters or BBH captures.

TASK OBS-1.3-B(i)-**INFRAOPS**: SEARCH OPTIMIZATION

Optimize the eBBH search for O4.

TASK OBS-1.3-B(ii)-**INFRAOPS**: RUN THE SEARCH AND CHARACTERIZE SIGNIFICANT CANDIDATES

Search for eBBH signals in O4 data. Evaluate the significance of eBBH candidates. Characterize and follow up the most signifcant candidates.

TASK OBS-1.3-B(iii)-**INFRAOPS**: ECCENTRIC WAVEFORMS

Evaluate eccentric BBH waveforms or hyperbolic BBH encounter waveforms for use in O4 analyses. This includes waveform sensitivity tests and implementation in the analysis.

TASK OBS-1.3-B(iv)-**INFRAOPS**: REPORT RESULTS AND REVIEW

Report intermediate results in a timely manner as data becomes available during engineering runs and in the O4 observing run. Reporting should be made within working groups and periodically to the Burst group. A significant eBBH detection will result in an exceptional event paper.

TASK OBS-1.3-B(v)-**INFRAOPS**: REVIEW ANALYSES

Review the Burst eccentric BBH pipelines, the pipeline configurations, as well as the results produced by the pipelines (search results, injection studies, astrophysical upper limits, etc). See also OBS-9.2-E and OBS-9.2-F.

TASK OBS-1.3-B(vi)-**INFRAOPS**: PUBLISH RESULTS

Publish an exceptional-event paper if the eccentricity of a confidently detected binary merger will have a reconstructed eccentricity that is inconsistent with e=0 at 90% confidence level or higher or if a close hyperbolic encounter event is confidently detected. See also OBS-9.2-G.

ACTIVITY OBS-1.3-C-**INFRAOPS**: UNUSED

TASK OBS-1.3-C(i)-**INFRAOPS**: UNUSED

ACTIVITY OBS-1.3-D-**OTHER**: DEVELOPMENT OF ECCENTRIC WAVEFORMS FOR O4 BURST SEARCHES

TASK OBS-1.3-D(i)-**OTHER**: WAVEFORM DEVELOPMENT

Continue to monitor the development of waveform models for IMBH, eBBH systems, hyperbolic BBH encounters, or BBH captures. Test and evaluate their impact.

ACTIVITY OBS-1.3-E-**OTHER**: IMPROVEMENT OF SEARCH SENSITIVITY TO BBH SIGNALS BEYOND O4

TASK OBS-1.3-E(i)-**OTHER**: OPTIMIZING THE BBH SEARCH

Optimize the non-templated all-sky searches for any BBH system beyond O4.

TASK OBS-1.3-E(ii)-**OTHER**: METHODS FOR IMPROVING THE NON-CIRCULAR BBH SEARCH SENSITIVITY

Investigate options to improve the burst search sensitivity to eccentric black hole signals by using different clustering algorithms and time-frequency graphs obtained from relevant signal models. Same for hyperbolic encounters or BBH captures.

TASK OBS-1.3-E(iii)-**OTHER**: METHODS FOR LOW-MASS CHIRP SYSTEMS.

Investigate methods for improving the Burst BBH search sensitivity for systems with chirp mass less than 10 $M_{\odot}$.

TASK OBS-1.3-E(iv)-**OTHER**: ECCENTRICITY RECONSTRUCTION

Investigate methods for reconstructing the eccentricity of BBH mergers for any eccentricity.

OBS-1.4 Gravitational-wave burst signal characterization

One of the exciting features of gravitational-wave astrophysics is the observation of signals directly tied to the flow of energy and momentum within a source [34]. This signal can be extremely rich in the information it contains. For compact object mergers, it encodes the source masses, spins, distance, and orientation. An observed gravitational-wave signature from a galactic supernova would probe the stellar core, and would give valuable clues to the supernova explosion mechanism, angular momentum, and other dynamic variables. The gravitational waveform from an oscillating neutron star would constrain the neutron star equation of state. For new classes of signals, the waveform will provide a unique path towards understanding the astrophysical source. Even without an astrophysical model, it may be possible to constrain some source parameters based on time-scale and energy arguments.

Reconstructing the waveform of a detected CBC or burst signal with minimal assumptions is a non-trivial process, involving data from multiple detectors, knowledge of detector positions and responses, and a statistical framework for evaluating a best-fit waveform and properties of the detector noise [7, 35, 36]. Quantifying the uncertainty on reconstructed CBC or burst waveforms is also critical to allow comparisons between measured signals and proposed source models, as well as test different astrophysical scenarios such as core-collapse supernovae, neutron star equation of state, and cosmic strings models.

During O1, O2 and O3, reconstructed waveforms were seen to agree with models for expected signals from binary compact objects coalescences [37]. In addition, burst searches provide a measurement of the polarization state for detected gravitational-wave events [36]. Meaningful polarization measurements are possible with three or more detectors in the network.

Closely related to the best-fit waveform is an estimate of the source's direction [38, 39, 40]. The angular position reconstruction of a gravitational wave source, or "skymap", enables searches for coincident emission by a wide range of electromagnetic and particle observatories. This includes both searches of archival data from all-sky instruments or serendipitous observations, and attempts to rapidly respond to low-latency GW triggers by slewing radio, optical, and X-ray instruments.

ACTIVITY OBS-1.4-A-**INFRAOPS**: PARAMETER ESTIMATION OF BURST EVENTS

TASK OBS-1.4-A(i)-**INFRAOPS**: WAVEFORM RECONSTRUCTION

Deliver reconstructed waveforms, with uncertainty, for all detected sources during O4. Compare reconstructed waveforms with the best templates used in CBC match-filtered searches.

TASK OBS-1.4-A(ii)-**INFRAOPS**: SKYMAP RECONSTRUCTION

Deliver reconstructed skymaps for all detected sources during O4.

TASK OBS-1.4-A(iii)-**INFRAOPS**: WAVEFORM MODELS AND SOURCE IDENTIFICATION

Test available burst waveform models against the data. Examples include core-collapse supernovae OBS-1.5, cosmic strings OBS-6.1, pulsar glitches, close hyperbolic encounters of two black holes, etc. For a given gravitational-wave event, this analysis shall be able to prefer one waveform model against another.

TASK OBS-1.4-A(iv)-**INFRAOPS**: O4 CATALOGS AND PAPERS

Deliver reconstructed waveforms, waveform matching results and reconstructed skymaps to the O4 GWTC, and to the corresponding companion papers. Maintain a close working relationship with the catalog paper writing/editorial team.

TASK OBS-1.4-A(v)-**INFRAOPS**: RESULTS AND REVIEW

Report progress and results in a timely manner as data becomes available during the observing run. Reporting should be made within working groups and periodically to the burst group.

ACTIVITY OBS-1.4-B-**OTHER**: DEVELOPMENT OF NEW AND IMPROVED METHODS TO ESTIMATE PARAMETERS OF BURST EVENTS

TASK OBS-1.4-B(i)-**OTHER**: IMPROVE WAVEFORM AND SKY LOCALIZATION RECONSTRUCTION

Continue the development of improved methods for waveform reconstruction, waveform comparisons, and sky localization.

TASK OBS-1.4-B(ii)-**OTHER**: TOOLS FOR SOURCE IDENTIFICATION

Develop methods and analysis tools to identify Burst sources given the reconstructed waveform.

TASK OBS-1.4-B(iii)-**OTHER**: POLARIZATION STUDIES

Provide measurement and interpretation of the polarization patterns for gravitational-wave events detected with the LIGO-Virgo-KAGRA network.

ACTIVITY OBS-1.4-C-**OTHER**: IMPACT OF CALIBRATION ERRORS ON BURST SEARCHES

TASK OBS-1.4-C(i)-**OTHER**: IMPACT OF CALIBRATION ERRORS ON SKY LOCALIZATION AND WAVEFORM RECONSTRUCTION OF BURST SOURCES

Development of methods to quantify the impact of calibration error on burst searches. For example, how the relative calibration error between the detectors impacts the sky localization of the sources.

OBS-1.5 Search for gravitational waves from core-collapse supernova

Start date: 2024-01-01
Estimated due date: 2024-12-31

Once a star with mass $M \gtrsim 10M_{\odot}$ exhausts its fuel, its core collapses to a hot proto-neutron star. The proto-neutron star cools by emitting neutrinos. A shock wave is promptly formed from the proto-neutron star and plows through the stellar mantle. If it breaks out of the star's surface, it lights up the star in a supernova explosion. The neutrinos and/or EM radiation herald a core-collapse supernova, and can be used to trigger a search for GW bursts. GWs are produced by bulk aspherical accelerated motion of matter; in the CCSN context they are a direct probe of the uncertain degree of asymmetry of the supernova engine.

GW signals from CCSN are typically much weaker than signals from binary mergers. Numerical simulations have shown that CCSN signals can span frequencies up to few kHz and durations up to a few seconds, making them hard to detect because their energy is spread over a large area in the time-frequency domain. The current burst searches are not designed to detect such signals and can miss a Galactic CCSN with signal-to-noise ratio below 30. Thus pipeline developments are needed to improve the detection efficiency of CCSN searches.

The strategies for these searches can vary according to detection of different messengers. It may happen that GWs are produced while no electromagnetic or neutrino counterpart is detected, in which case a CCSN-specific all-sky burst search would be the best search strategy. In case we observe only light from a nearby supernova an optically-triggered search is performed, as was performed for O1-O2 [41]. In case we observe low-significance neutrinos, then a sub-threshold neutrino search may be performed. But special attention is placed when an SNEWS alert reports the detection by neutrinos of a galactic or nearby extragalactic supernova, like supernova SN1987A. See also OBS-5.4 for gravitational-wave and neutrino joint analyses.

ACTIVITY OBS-1.5-A-**INFRAOPS**: SEARCH FOR GRAVITATIONAL WAVES FROM CORE-COLLAPSE SUPERNOVA

TASK OBS-1.5-A(i)-**INFRAOPS**: COLLECT TRIGGERS

Review the identification of candidate CCSNe within roughly 20 Mpc from electromagnetic observations. Determine from the electromagnetic observations the best estimates for the time of core collapse and nature of the progenitor.

TASK OBS-1.5-A(ii)-**INFRAOPS**: RUN A TARGETED GRAVITATIONAL-WAVE SEARCH ON O4 DATA

Run a targeted search for CCSN within roughly 20 Mpc with the CCSN time and sky position using dedicated pipelines. In case of non-detection, provide an estimate of the upper limits found by the search.

TASK OBS-1.5-A(iii)-**INFRAOPS**: RUN A CCSN-SPECIFIC ALL-SKY GRAVITATIONAL-WAVE SEARCH ON O4 DATA

Run an all-sky search specifically targeted at CCSN waveforms. Evaluate GW candidate significances and follow-up astrophysical candidates. In case of non-detection, provide upper limits for various CCSN models.

TASK OBS-1.5-A(iv)-**INFRAOPS**: REPORTING RESULTS AND REVIEW

Report progress and the final results of these searches in a timely manner. Reporting should be made within the Supernova group and to the Burst group.

TASK OBS-1.5-A(v)-**INFRAOPS**: REVIEW ANALYSES

Review the supernova search analyses, the search configurations, as well as the results produced by the searches (search results, injection studies, astrophysical upper limits, etc). See also OBS-9.2-E and OBS-9.2-F.

ACTIVITY OBS-1.5-B-**INFRAOPS**: CORE-COLLAPSE SUPERNOVA EXTRAORDINARY EVENTS

TASK OBS-1.5-B(i)-**INFRAOPS**: FORMULATE AND IMPLEMENT A PLAN FOR AN EXTRAORDINARY DETECTION

Formulate and implement a plan to respond to a near-galactic CCSN in O4, including searches triggered by neutrino and/or electromagnetic observations.

TASK OBS-1.5-B(ii)-**INFRAOPS**: RUN THE SEARCH

Run all search pipelines (including the pipelines described in OBS-1.5-A(ii) and OBS-1.5-A(iii)) associated to the external trigger and determine its significance.

TASK OBS-1.5-B(iii)-**INFRAOPS**: PARAMETER ESTIMATION

Employ parameter estimation methods to determine the CCSN parameters and possible explosion mechanism.

TASK OBS-1.5-B(iv)-**INFRAOPS**: REPORT RESULTS AND REVIEW

Report progress and the results of the search in a timely manner. Report final results. Reporting should be made within the Supernova group and to the Burst group.

TASK OBS-1.5-B(v)-**INFRAOPS**: PUBLISH RESULTS

Publish a collaboration paper reporting any significant signals found by the search. Publish a collaboration paper for closeby supernova triggers, for which the previous (O3) upper limits are significantly improved. See also OBS-9.2-G.

ACTIVITY OBS-1.5-C-**INFRAOPS**: SUPERNOVA SUBGROUP ADMINISTRATION

TASK OBS-1.5-C(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with Supernova subgroup leadership. See also OBS-9.2-B.

ACTIVITY OBS-1.5-D-**OTHER**: DEVELOPMENT ACTIVITIES FOR SUPERNOVA ANALYSES

TASK OBS-1.5-D(i)-**OTHER**: PIPELINE DEVELOPMENT AND OPTIMIZATION

Continue to develop and optimize current pipelines for CCSN targeted or all-sky searches. Evaluate improved pipeline sensitivities.

TASK OBS-1.5-D(ii)-**OTHER**: CCSN WAVEFORM DEVELOPMENT

Continue to procure and catalog CCSN waveforms and use them to develop waveform reconstruction and parameter estimation techniques for use in targeted or all-sky CCSN searches.

TASK OBS-1.5-D(iii)-**OTHER**: WAVEFORM RECONSTRUCTION AND PARAMETER ESTIMATION

Develop techniques to distinguish CCSN models in search data and infer the properties of the supernova dynamics, for example parameters of the proto-neutron star.

TASK OBS-1.5-D(iv)-**OTHER**: SUB-THRESHOLD NEUTRINO-GW COINCIDENT SEARCH

Develop a joint sub-threshold neutrino/GW search.

TASK OBS-1.5-D(v)-**OTHER**: STATISTICAL SIGNIFICANCE OF CCSN SEARCH TRIGGERS

Develop methods to separate CCSN signals from non-astrophysical detector noise artifacts and assess the statistical significance of astrophysical candidates. Develop noise reduction techniques to increase the significance of astrophysical triggers, e.g., with signal processing or machine learning algorithms.

TASK OBS-1.5-D(vi)-**OTHER**: SINGLE-INTERFEROMETER DETECTION

Develop methods for detecting CCSN with data from a single GW detector.

OBS-1.6 Search for gravitational-wave transients from magnetar flares and neutron star glitches

Violent phenomena associated with neutron stars, such as flaring activity in magnetars [42, 43, 44] and pulsar glitches, may result in the excitation of various oscillatory modes which leads to transient gravitational wave emission.

The energetics involved with phenomena such as magnetar flares or pulsar glitches place an associated gravitational wave burst near or below the sensitivity of current detectors. If a coincident detection were made, however, this would provide a wealth of knowedge about the progenitors of these events. The detection and characterization of gravitational waves associated with neutron star oscillations holds the potential for gravitational-wave neutron star asteroseismology, while neutron star oscillation mode identification and characterization leads to constraints on the equation of state of the interior of neutron stars.

In O3, two exceptional magnetar-related phenomena lead to a collaboration O3 paper [45]. The first was the observation of a fast radio burst (FRB) associated with the galactic magnetar SGR 1935+2154 (see Section OBS-5.3). While the FRB occurred just after the end of O3, this magnetar was active in x-ray flares earlier during O3. The second was the discovery of a young galactic magnetar J1818 in March 2020, during O3 observations.

Neutron star f-modes may be excited by pulsar glitches and are expected to emit GWs in the frequency range 2-3 kHz. A search for short transient and high-frequency GW emission associated with oscillations of the fundamental quadrupole mode excited by a pulsar timing glitch will be conducted by the Burst group for promising nearby pulsars. This search will be coordinated by the CW group: see section OBS-3.13.

Our goals for science deliverables are focused on the improvement on O3 gravitational-wave emission upper limits [45], development of novel searches and techniques, and the deployment of morphology-independent searches, waveform reconstructions, and parameter estimation follow-ups to *extraordinary* events. Past searches targeting such events include [46, 47, 48, 49, 50]. The methods employed overlap with the long-duration burst searches (Section OBS-1.2) and the Multimessenger Transient Searches group (Section OBS-5.2).

ACTIVITY OBS-1.6-A-**INFRAOPS**: PREPARE FOR A POTENTIAL EXCEPTIONAL O4 MAGNETAR FLARE SEARCH

An exceptional magnetar flare, providing for a possible gravitational-wave detection or an astrophysically interesting limit, would provide motivation for a collaboration paper.

TASK OBS-1.6-A(i)-**INFRAOPS**: MONITOR FLARES DATA

Monitor the reported x-ray flare activity reported by external groups such as Swift or Fermi.

TASK OBS-1.6-A(ii)-**INFRAOPS**: TEST TRIGGERED PIPELINES

Run pipelines similar to those used in O3 in early O4 data to check for sensitivity and any important data quality issues to prepare for the case of any exceptional events.

ACTIVITY OBS-1.6-B-**INFRAOPS**: O4 MAGNETAR FLARE BURST SEARCH

TASK OBS-1.6-B(i)-**INFRAOPS**: CARRY OUT THE O4 ANALYSIS

Carry out the triggered gravitational-wave burst analyses associated with O4 x-ray magnetar flares. This is to include searches for both short- and long-duration gravitational-wave bursts. This will include development of appropriate on-source and off-source windows and a new stacking analysis, analogous to that developed previously [47], that combines data from repeated events from the same progenitor.

TASK OBS-1.6-B(ii)-**INFRAOPS**: REPORTING RESULTS AND REVIEW

Report progress and the results of these searches in a timely manner during the observing run. Report final results. Reporting should be made within the Multimessenger Transient Searches group and periodically to the Burst group.

TASK OBS-1.6-B(iii)-**INFRAOPS**: PUBLISHING RESULTS

If there is an extraordinary event(s) – e.g. a giant galactic flare, an associated FRB, or a very nearby ($\sim$ 1 kpc) normal flare – or a significant improvement in upper limits compared to O3 from the search over all events, publish a collaboration paper reporting the search results. See also OBS-9.2-G.

ACTIVITY OBS-1.6-C-**INFRAOPS**: PREPARE FOR A POTENTIAL EXCEPTIONAL O4 PULSAR GLITCH BURST SEARCH

An exceptional pulsar glitch, providing for a possible gravitational-wave detection or an astrophysically interesting limit, would provide motivation to run a dedicated Burst search, in coordination with the effort conducted in the CW group: see section OBS-3.13.

TASK OBS-1.6-C(i)-**INFRAOPS**: TEST TRIGGERED PIPELINES

Run targeted search pipelines to check for sensitivity and any important data quality issues to prepare for the case of any exceptional events.

ACTIVITY OBS-1.6-D-**OTHER**: DEVELOP NEW AND IMPROVED METHODS TO SEARCH FOR GRAVITATIONAL WAVES ASSOCIATED TO MAGNETARS

TASK OBS-1.6-D(i)-**OTHER**: METHODS AND MODELING STUDIES

Continue to develop improved search and analysis methods. Anticipating the possibility of a gravitational-wave detection from the magnetar searches, methods are being developed to characterize an observed signal in astrophysical terms. One consideration will be whether a candidate gravitational-wave signal is consistent with f-mode excitations from a realistic neutron star at the location provided by the x-ray flares.

OBS-1.7 Search for domain-wall signatures in LIGO-Virgo data

Start date: 2024-01-01
Estimated due date: 2024-12-31

Domain walls are hypothetical two-dimensional topological defects that have been proposed as a possible form of dark matter [51, 52]. Physically they would correspond to the boundary region between disjoint vacuum states of an as-yet undetected scalar field. Depending on the coupling between the scalar field and ordinary matter, the passage of a domain wall through an interferometer could produce an impulsive signal with duration of order 10 ms, with time-of-flight delays of order 10 s between the LIGO, Virgo, and KAGRA detectors [53, 54, 55]. Preliminary analyses with a modified burst search pipeline indicate that the LIGO-Virgo-KAGRA network is 4-6 orders of magnitude more sensitive in terms of the scalar-field coupling energy scale than ground-based and GPS clock detection networks for walls with thicknesses in the 1 m - 10 km range [56].

ACTIVITY OBS-1.7-A-**INFRAOPS**: PREPARE THE O4 DOMAIN-WALL SEARCH

TASK OBS-1.7-A(i)-**INFRAOPS**: DEVELOP A SEARCH PIPELINE

Develop an analysis pipeline to detect the effect of domain walls on the mirrors of gravitational-wave detectors. Estimate the event significance and compare with an estimate of the background.

TASK OBS-1.7-A(ii)-**INFRAOPS**: DEVELOP ANALYSIS TOOLS TO DERIVE UPPER LIMITS

Develop analysis tools to derive upper limits on the energy scale of domain walls.

TASK OBS-1.7-A(iii)-**INFRAOPS**: RUN THE SEARCH ON O4 DATA

Test the newly developed search as data becomes available during the O4 run.

TASK OBS-1.7-A(iv)-**INFRAOPS**: REVIEW ANALYSIS TOOLS

Review the analysis tools developed to search for a domain wall signature in LIGO-Virgo data and to derive upper limits on domain-wall models. See also OBS-9.2-E.

TASK OBS-1.7-A(v)-**INFRAOPS**: REPORT RESULTS AND REVIEW

Periodically report results to the Cosmological Sources subgroup and to the burst group. Review the results before publication. See also OBS-9.2-F.

OBS-2 CBC Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Burst and Stochastic groups in sections OBS-5 and OBS-7.

OBS-2.1 CBC Parameter Estimation R&D (Short Term)

Development of tools for characterizing CBC sources in terms of their parameters (short term).

Motivation and methods

The Parameter Estimation (PE) group aims to develop, improve, and maintain techniques and tools for characterizing compact binaries. For each detected event, the PE group provides posterior estimates for the binary's physical characteristics, both in low latency and for catalog data releases, using sophisticated signal and noise models. The group focuses on developing tools to leverage new signal models with added physical effects (e.g., eccentricity, matter effects) and maintains infrastructure for broader Bayesian inference activities focused on compact binary coalescence, such as tests of general relativity and investigations into lensing. Improved noise models are also being developed to better accommodate non-stationary detector noise, and the group guides future model developments, instrumental designs, and GW science cases.

Major aspects and methods for this activity

ACTIVITY OBS-2.1-A-**INFRAOPS**: DEVELOPMENT OF PARAMETER ESTIMATION CODE

Incremental improvements of the parameter estimation code will be made in preparation for O4, to improve parameter estimation accuracy and performance.

TASK OBS-2.1-A(i)-**INFRAOPS**: FASTER CONVERGENCE WITH IMPROVED SAMPLING ALGORITHMS AND PARALLELIZATION

Working closely with the CBC waveform models R&D group (Sec. OBS-2.7), accelerate sampling-based PE algorithms using a variety of methods, including reduced-order-quadrature (ROQ) techniques, heterodyning, multibanding, improvements to sampling algorithms , and through the implementation and maintenance of CPU- and GPU-parallelized algorithms. This includes ongoing testing and review for low-latency PE in O4 for new source classes, e.g., SSM.

TASK OBS-2.1-A(ii)-**INFRAOPS**: TESTING AND REVIEWING ALTERNATIVE METHODS FOR FASTER PARAMETER ESIMATION (UP TO LOW LATENCY)

We will continue to test and review new PE algorithms for collaboration use, including for online inference. This will include coordinating with the low-latency group when applicable.

ACTIVITY OBS-2.1-B-**INFRAOPS**: EVALUATION OF PARAMETER ESTIMATION METHODS

The PE methods will be evaluated to understand potential biases.

TASK OBS-2.1-B(i)-**INFRAOPS**: USING AND ASSESSING MORE ACCURATE WAVEFORMS

As more faithful waveform models and more numerical relativity simulations become available (see Sec. OBS-2.7) which include and explore more physical effects (e.g., multi-modal effects, amplitude corrections, eccentricity), studies will be required to determine the impacts of the inclusion of such physical effects on PE. Studies will also be required to assess the potential for these waveform models to enable new discoveries and to achieve the scientific goals of the collaboration.

TASK OBS-2.1-B(ii)-**INFRAOPS**: BETTER MEASUREMENT OF WAVEFORM SYSTEMATIC ERRORS

Coordinating closely with waveform group efforts to quantify systematic errors in the waveform models to be developed for and used in O4, the PE group will continue to investigate and quantify the impact of waveform systematics on parameter estimation, especially for exceptional source classes which may be detected in O4.

TASK OBS-2.1-B(iii)-**INFRAOPS**: STUDY THE BIASES TO PE CAUSED BY NON-STATIONARY NOISE

Current PE analyses assume the detector noise to be stationary over intermediate timescales, 1 to 100's times the length of a detected signal. We know the noise is not always stationary on these timescales, thus we must characterize the biases introduced in parameter estimates due to this false assumption.

TASK OBS-2.1-B(iv)-**INFRAOPS**: REQUIREMENTS AND CONSTRAINTS FROM CALIBRATION UNCERTAINTY

The use of marginalisation over uncertanties in the data calibration connects the astrophysical and instrumental inference. Therefore, investigating what requirements on the calibration uncertanties are, for both low- and high-latency analyses, in order to ensure unbiased astrophysical PE results. This also includes accounting for potential systematic errors in the calibration. The work is to be done in coordination with the calibration groups in LIGO, Virgo and KAGRA.

ACTIVITY OBS-2.1-C-**INFRAOPS**: DEPLOYMENT AND MAINTENANCE OF PARAMETER ESTIMATION CODE

Parameter estimation libraries and their dependencies will be deployed and maintained for both online and offline usage during O4.

TASK OBS-2.1-C(i)-**INFRAOPS**: DEPLOYMENT AND MAINTENANCE OF ONLINE PARAMETER ESTIMATION CODE

The parameter estimation pipeline and configuration (including dependencies such as BayesWave) will continue to be deployed and integrated into the low-latency infrastructure during O4.

TASK OBS-2.1-C(ii)-**INFRAOPS**: DEPLOYMENT AND MAINTENANCE OF OFFLINE PARAMETER ESTIMATION CODE

The parameter estimation libraries (including dependencies such as BayesWave) will continue to be maintained and deployed on collaboration computational clusters for use during O4.

TASK OBS-2.1-C(iii)-**INFRAOPS**: MAINTENANCE OF LIBRARY INFRASTRUCTURE

To better facilitate the goals outlined above, we will continue to improve and maintain the code bases used by the PE group. This includes the continued migration of various libraries and functionalities from C to Python to become more development-friendly, and tighter integration of the various code bases, including post-processing routines.

ACTIVITY OBS-2.1-D-**INFRAOPS**: PARAMETER ESTIMATION ANALYSIS, INTEGRATION AND AUTOMATION

As the number of GW event candidates increase, a greater focus on automation and standardization of the PE analysis is required.

TASK OBS-2.1-D(i)-**INFRAOPS**: AUTOMATION OF GENERATING PE CONFIGURATION FILES

We will continue to develop automated methods for generating a configuration file for offline PE using inputs from searches and low-latency PE.

TASK OBS-2.1-D(ii)-**INFRAOPS**: AUTOMATION OF COLLATION OF INPUT DATA TO PE ANALYSES

We will continue to ensure that the collation of additional inputs to parameter estimation is done in an automated and integrated fashion. These include PSDs, calibration uncertainty envelopes, and the appropriate frame files.

TASK OBS-2.1-D(iii)-**INFRAOPS**: AUTOMATION OF INITIALIZATION AND MONITORING OF PE ANALYSES

The PE group will continue to develop and maintain methods for automatically initializing and monitoring PE analyses. This includes further development and maintenance of overview boards where ongoing analyses can be monitored.

TASK OBS-2.1-D(iv)-**INFRAOPS**: AUTOMATION OF POSTPROCESSING OF PE ANALYSES

For a completed PE analysis, the group will continue to archive the finalized results in an automated, centralized, and version controlled way. The group will continue to develop and improve these procedures, and strive to make results easily accessible to all groups within the collaborations. This task also includes generation of comparisons and diagnostics of the analyses to ensure convergence of the samples, and also to avoid problematic railing against prior bounds. This is also a requirement for improvements to the overall PE review process.

ACTIVITY OBS-2.1-E-**INFRAOPS**: PE WITH MATTER EFFECTS

LIGO/Virgo made the first detection of a binary neutron star (BNS) merger in 2017, with one more certain BNS detection in O3 together with two neutron star-black hole (NSBH) candidates. The detected GWs allow for novel measurements of matter effects in the binary mergers, including the neutron star equation of state. Developing good techniques for measuring these effects is an active area of research, and the most recent developments of this work need to be implemented in LIGO's Parameter Estimation code libraries. All of these activities will be carried out in close coordination with the Extreme Matter and Rates & Populations subgroups.

TASK OBS-2.1-E(i)-**INFRAOPS**: PARAMETERIZED EQUATION OF STATE ESTIMATION

Implement new matter equation of state parameterizations, for example, spectral parameterizations, and incorporate them into the parameter estimation engines.

TASK OBS-2.1-E(ii)-**INFRAOPS**: NON-PARAMETRIC EQUATION OF STATE ESTIMATION

Implement non-parametric methods for equation of state estimation into the parameter estimation engines.

TASK OBS-2.1-E(iii)-**INFRAOPS**: PARAMETER ESTIMATION ON MULTIPLE EVENTS

Since the equation of state is believed to be universal, it can be better constrained by analyzing multiple events together. Coordinating closely with the Rates & Populations subgroup, implement and improve methods to do a multiple event equation of state estimation.

ACTIVITY OBS-2.1-F-**INFRAOPS**: PARAMETER ESTIMATION REVIEW

Review of changes to parameter estimation code and deployment configuration.

TASK OBS-2.1-F(i)-**INFRAOPS**: PARAMETER ESTIMATION CODE REVIEW

Review modifications to parameter estimation code.

TASK OBS-2.1-F(ii)-**INFRAOPS**: PARAMETER ESTIMATION ONLINE PIPELINE REVIEW

Review of deployment, configuration, and integration of the online parameter estimation engine.

TASK OBS-2.1-F(iii)-**INFRAOPS**: PARAMETER ESTIMATION AUTOMATION REVIEW

Review of pipelines which perform automated parameter estimation and postprocessing of results.

ACTIVITY OBS-2.1-G-**INFRAOPS**: PARAMETER ESTIMATION SUBGROUP ADMINISTRATION

Management of the Parameter Estimation subgroup.

TASK OBS-2.1-G(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

OBS-2.2 CBC Parameter Estimation R&D (Long Term)

Development of tools for characterizing CBC sources in terms of their parameters (long term).

Major aspects and methods for this activity

ACTIVITY OBS-2.2-A-**OTHER**: FASTER PARAMETER ESTIMATION (UP TO LOW-LATENCY)

Results from stochastic samplers can often take hours to days to obtain, with the lowest-latency analyses making simplifying assumptions (e.g., spins aligned with the orbital angular momentum). We aim to reduce latency, particularly for the more physically accurate and computationally expensive waveform models (e.g., including precession effects). Development along multiple avenues for accelerating PE will continue, including improvement of parallelized sampling algorithms, ROQs, heterodyning, multibanding, improvements to traditional sampling algorithms, and machine learning approaches.

TASK OBS-2.2-A(i)-**OTHER**: INVESTIGATE FASTER PE

ACTIVITY OBS-2.2-B-**OTHER**: MARGINALIZATION OVER CALIBRATION UNCERTAINTIES

During O1, O2 and O3 frequency-dependent but instrument-agnostic models for calibration errors were used for the purposes of marginalization, and estimates of the noise PSD computed from on-source data were used for each analysis. We plan to move toward physically motivated models for calibration errors, and to marginalize over uncertainties in the estimated noise PSDs.

TASK OBS-2.2-B(i)-**OTHER**: MARGINALIZATION OVER FREQUENCY-DEPENDENT DETECTOR CALIBRATION ERRORS AND PSD UNCERTAINTIES

ACTIVITY OBS-2.2-C-**OTHER**: INVESTIGATIONS OF WAVEFORM SYSTEMATICS ON PARAMETER ESTIMATION

Coordinating closely with waveform group efforts to quantify systematic errors in the waveform models, the PE group will continue to investigate and quantify the impact of waveform systematics on parameter estimation, especially in challenging regions of parameter space

TASK OBS-2.2-C(i)-**OTHER**: INVESTIGATE WAVEFORM SYSTEMATICS ON PE

ACTIVITY OBS-2.2-D-**OTHER**: MARGINALISATION OVER WAVEFORM UNCERTAINTY

The systematic differences between waveform models can be incorporated in a statistical model that allows for uncertainty in the waveforms as well as in the parameter of the signal itself. This will allow us to mitigate the effect of waveform systematic errors in the estimation of source properties. This is particularly important for regions of parameter space where numerical simulations are sparse, and there is less data to calibrate waveform models.

TASK OBS-2.2-D(i)-**OTHER**: MARGINALISATION OVER WAVEFORM UNCERTAINTY

ACTIVITY OBS-2.2-E-**OTHER**: PARAMETER ESTIMATION ANALYSES OF BACKGROUND EVENTS

Though not an official task of the PE group, as the most rigorous stage of signal characterization, PE is often looked to for verification of a trigger's status as signal vs. noise. To better inform the collaboration on such matters, we must conduct complete studies of PE analyses of background events to better understand the behavior of posteriors and detection-related statistics (e.g., coherent vs. incoherent Bayes factor) on foreground and background. This work is coordinated with the CBC detection and search R&D group (Sec. OBS-2.13).

TASK OBS-2.2-E(i)-**OTHER**: PE ANALYSES OF BACKGROUND EVENTS

ACTIVITY OBS-2.2-F-**OTHER**: DEVELOPING FULLY BAYESIAN SEARCHES (PE ANGLE)

For many sources of GWs we expect a stochastic background, which need not be persistent or Gaussian. The use of Bayesian inference to detect a population of sub-threshold events could lead to the detection of such a stochastic background. This work is coordinated with the binary coalescence Rates and Population R&D group (Sec. OBS-2.9) and the Stochastic group (Sec. OBS-7).

TASK OBS-2.2-F(i)-**OTHER**: DEVELOPING FULLY BAYESIAN SEARCHES: PE ANGLE

ACTIVITY OBS-2.2-G-**OTHER**: USE OF BAYES FACTORS IN LOW LATENCY TO HELP INFORM DETECTIONS

The production of Bayes factors, which can be useful as detection statistics, currently takes too long to be useful for decisions made in low latency. The fact that such analyses can include physical effects not accounted for in searches (e.g., precession) means that obtaining such statistics on shorter timescales could allow PE to provide crucial new information at the time of detection. This work is coordinated with the CBC detection and search R&D group (Sec. OBS-2.13).

TASK OBS-2.2-G(i)-**OTHER**: USE OF BAYES FACTORS IN LOW LATENCY

ACTIVITY OBS-2.2-H-**OTHER**: RESEARCH AND DEVELOPMENT OF NEW PARAMETER ESTIMATION TECHNIQUES

We will continue to investigate the use of new algorithms or hardware-specific optimization (e.g., GPUs and/or machine learning techniques) for CBC parameter estimation, to support the desire to lower overall latency until final results are obtained, but also to allow codes to scale to increasing numbers of parameters and/or complex signal models.

TASK OBS-2.2-H(i)-**OTHER**: RESEARCH AND DEVELOPMENT OF NEW PE TECHNIQUES

OBS-2.3 Tests of General Relativity R&D (Short Term)

Short-term research and development on tests of general relativity using compact binary coalescences.

Motivation and methods

The Testing General Relativity group is primarily responsible for testing the consistency of the GW signals observed by LIGO, Virgo, and KAGRA with predictions of GR and for developing the associated data analysis infrastructure. Due to the lack of reliable waveform models in alternative theories, so far the group's primary focus has been on "null" tests, which aim to put constraints on deviations from GR predictions without assuming specific alternative theories. Several other aspects of strong gravity, such as the true nature of black holes, the possible existence of exotic compact objects are also explored within the group. Whenever possible, interpretations of our results will be given, by mapping any observational constraints derived from our analyses onto bounds on alternative models.

Major aspects and methods for this activity

ACTIVITY OBS-2.3-A-**INFRAOPS**: DEVELOPING METHODS FOR TESTING GRAVITATIONAL-WAVE PROPERTIES

TASK OBS-2.3-A(i)-**INFRAOPS**: TESTING THE MULTIPOLAR STRUCTURE OF GRAVITATIONAL WAVES

Further develop and improve methods that test the consistency of the amplitudes of different GW multipoles beyond the (l=2,m=2) mode with the predictions of general relativity for compact binaries.

TASK OBS-2.3-A(ii)-**INFRAOPS**: SEARCHES FOR NON-STANDARD POLARIZATIONS

Further develop and improve model agnostic and theory-specific analyses for non-tensorial polarizations.

TASK OBS-2.3-A(iii)-**INFRAOPS**: TESTING GRAVITATIONAL WAVE PROPAGATION FOR SPACETIME SYMMETRY BREAKING

Improve methods to search for signs of modified GW propagation, like dispersion or birefringence related to spacetime symmetry breaking mechanisms.

TASK OBS-2.3-A(iv)-**INFRAOPS**: EXPLORING ACCELERATION EFFECTS ON GRAVITATIONAL WAVEFORM

Develop analysis to look for signs of line-of-sight acceleration that a binary may undergo when coalescing in the vicinity of a massive object.

TASK OBS-2.3-A(v)-**INFRAOPS**: PRINCIPAL COMPONENT ANALYSIS OF MULTIPLE POST-NEWTONIAN COEFFICIENTS

Develop analysis to constrain deviations in multiple post-Newtonian coefficients simultaneously using principal component analysis.

ACTIVITY OBS-2.3-B-**INFRAOPS**: TESTING MERGER REMNANT PROPERTIES AND NEAR-HORIZON DYNAMICS

Sufficiently loud signals from massive compact objects will allow us to test their immediate environments. These tests can be either 1. agnostic with respect to the progenitor, 2. inspiral-informed with respect to progenitor parameters for sampling the prior of remnant parameters, or 3. inspiral-informed with respect to the progenitor with a joint likelihood computation.

TASK OBS-2.3-B(i)-**INFRAOPS**: TESTS OF THE NATURE OF THE MERGER REMNANT

Develop and improve tests of the nature of merger remnants through measurements of parametrized deviations from GR predictions on complex frequencies and cross-comparison of various modes.

TASK OBS-2.3-B(ii)-**INFRAOPS**: PROBING THE NEAR-HORIZON STRUCTURE

Develop and improve searches for echoes and other features that probe the near-horizon structure of the merger remnant or BHs of the progenitor, using template-based and model-agnostic approaches.

Activity OBS-2.3-C-**InfraOps**: Constraining the Parameter Space of Various Black Hole Mimickers

There are theoretical proposals of exotic alternatives to black holes, which can be massive and compact enough to be confused with black holes. Several distinct signatures in the emission of gravitational waves can help distinguish between these objects and black holes, such as finite-size effects on the phase evolution, resonant excitations, etc.

Task OBS-2.3-C(i)-**InfraOps**: Constraining Finite-Size Effects of Black Hole Mimickers

We will be able to constrain the parameter space of some models of black hole mimickers based on measurements of the tidal deformability and spin-induced quadrupole moment, and aim to extend this analysis to include other finite-size effects.

Activity OBS-2.3-D-**InfraOps**: Interpretation of TGR Analyses Results and Implications for Theory

Task OBS-2.3-D(i)-**InfraOps**: Mapping Constraints to Parameter Spaces of Selected Theories

Identify alternative theory frameworks for which a mapping can be drawn between our observational constraints on measured parameters and the theory parameter space. Investigate the regime of validity for such mappings and combine with other observational or theoretical constraints.

Activity OBS-2.3-E-**InfraOps**: Testing GR Infrastructure Maintenance and Improvement

Working in close coordination with the PE and Waveforms R&D groups, we will improve our data analysis code libraries for testing GR and perform incremental upgrades to meet the state-of-the-art in performance, robustness, and automation.

Task OBS-2.3-E(i)-**InfraOps**: Improvements to Library Infrastructure

Improve the base code for testing-GR data analysis pipelines and bring them up to speed with PE standards. This includes integration with Python libraries, inclusion of the most sophisticated waveform models, in coordination with the Waveforms R&D group, and integration with the central CBC data management system.

Task OBS-2.3-E(ii)-**InfraOps**: Packaging and Maintenance of TGR Pipeline Codes

Collect TGR libraries as plugins to standard packages like Bilby, PESummary, and BayesWave, when applicable. Package and ensure streamlined installation on computing clusters, centrally managed via IGWN.

Task OBS-2.3-E(iii)-**InfraOps**: Pipeline Automation

In anticipation of a much higher rate of GW detections in O4 and beyond, develop a framework to automate the processes of job submission and resubmission, monitoring, post-processing, and review for each testing-GR pipeline. This will be done in line with the best practices adopted by the PE R&D group and the CBC group at large.

ACTIVITY OBS-2.3-F-**INFRAOPS**: TESTING GR MOCK DATA CHALLENGES AND ANALYSIS READINESS FOR O4

TASK OBS-2.3-F(i)-**INFRAOPS**: GLITCH MOCK DATA CHALLENGE

Set up and run campaigns on sets of simulated signals overlapping with different types of glitches. Examine the different TGR pipelines' ability to distinguish between the presence of a glitch or a violation of GR in the data and their response to different types of glitches and glitch-removal/data-cleaning processes.

TASK OBS-2.3-F(ii)-**INFRAOPS**: WAVEFORM SYSTEMATICS MOCK DATA CHALLENGE

Set up and run campaigns on sets of simulated signals generated using waveform models that incorporate different physics (precession, higher harmonics) and assess the response of TGR analyses.

TASK OBS-2.3-F(iii)-**INFRAOPS**: MOCK DATA CHALLENGE ON GR-VIOLATING SIGNALS

Set up and run campaigns of analyses on a diverse, selected set of simulated GR-violating signals. Examine impact on detectability by search pipelines.

TASK OBS-2.3-F(iv)-**INFRAOPS**: REVIEW OF NEW PIPELINES

Participate in the review of the implementation of TGR pipelines destined to run in O4.

ACTIVITY OBS-2.3-G-**INFRAOPS**: TESTING GR: COMBINING CONSTRAINTS FROM MULTIPLE EVENTS

Several of the tests described in this section can benefit from the combination of the observed data coming from different GW events and electromagnetic counterparts, thus leading to stronger constraints. In most cases however, there is not a single statistically robust way of doing so. We will explore Bayesian methods such as hierarchical or nonparametric models to establish the optimal way of combining information for each test of GR.

TASK OBS-2.3-G(i)-**INFRAOPS**: COMBINING TGR CONSTRAINTS FROM MULTIPLE EVENTS

ACTIVITY OBS-2.3-H-**INFRAOPS**: TESTING GR SUBGROUP ADMINISTRATION

Management of the Testing General Relativity subgroup.

TASK OBS-2.3-H(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

ACTIVITY OBS-2.3-I-**INFRAOPS**: ANALYSIS ON RESIDUALS FOR TESTING GR

TASK OBS-2.3-I(i)-**INFRAOPS**: IDENTIFYING DEVIATIONS FROM GR BY CORRELATING RESIDUALS

Implement and test a method for detecting and characterizing deviations from GR (or systematic effects) by projecting cross-correlated residuals onto templates.

ACTIVITY OBS-2.3-J-**INFRAOPS**: RESPONSE TO AN APPARENT VIOLATION OF GR

Develop a comprehensive strategy for the collaboration's response to observational evidence from one or more CBC events that supports a violation of GR. Produce a checklist of studies that the collaboration will carry out to determine if the evidence is significant and robust enough to claim a violation of GR in a publication.

TASK OBS-2.3-J(i)-**INFRAOPS**: PLANNING FOLLOW-UP INVESTIGATIONS

Organize investigations and put together a checklist of follow-up tests, aiming to pin down the nature of the apparent deviation, and to distinguish between violations of GR and other physical or data-related effects.

TASK OBS-2.3-J(ii)-**INFRAOPS**: INJECTION STUDIES

Set up and perform injection campaigns, to build evidence towards supporting or rejecting specific hypotheses.

TASK OBS-2.3-J(iii)-**INFRAOPS**: SEARCH PIPELINES AND DETECTION STATISTICS

Investigations related to search pipeline efficiency and estimates of detection statistics.

TASK OBS-2.3-J(iv)-**INFRAOPS**: WAVEFORM UNCERTAINTIES AND SYSTEMATICS

Investigations related to uncertainties or systematic biases inherent to our waveform models, including incomplete modelling due to missing physics.

TASK OBS-2.3-J(v)-**INFRAOPS**: DATA QUALITY

Investigations related to data quality, DetChar and calibration.

TASK OBS-2.3-J(vi)-**INFRAOPS**: INFERENCE METHODS

Investigations related to the quality of our Bayesian inference methods, the samplers used and the data products produced by them.

TASK OBS-2.3-J(vii)-**INFRAOPS**: EXTREME MATTER

Investigations related to uncertainties or biases that may be due to the presence of matter.

OBS-2.4 Tests of General Relativity R&D (Long Term)

Long-term research and development on tests of general relativity using compact binary coalescences.

Major aspects and methods for this activity

We will develop methods to perform the following tests of general relativity and assessment of systematics.

ACTIVITY OBS-2.4-A-**OTHER**: CHARACTERIZATION OF WAVEFORM SYSTEMATICS FOR TESTING GR

Missing physics, including eccentricity, higher-order modes, spin precession, black-hole charge, and non-vacuum environments, have the ability to mimic deviations of GR. A systematic exploration of the impact of inaccuracies and missing physics in waveform templates on various tests of GR will be conducted.

TASK OBS-2.4-A(i)-**OTHER**: CHARACTERIZATION OF WAVEFORM SYSTEMATICS FOR TGR

Activity OBS-2.4-B-**Other**: Improvements of analysis on residuals for testing GR

Task OBS-2.4-B(i)-**Other**: Identifying deviations from GR by correlating residuals

Develop a method for detecting and characterizing deviations from GR (or systematic effects) by projecting cross-correlated residuals onto templates.

Activity OBS-2.4-C-**Other**: Improvement of Testing-GR Analysis Pipelines and their Performance

Task OBS-2.4-C(i)-**Other**: Speed-up using reduced-order-quadrature methods

Task OBS-2.4-C(ii)-**Other**: Speed-up using multibanding methods

Task OBS-2.4-C(iii)-**Other**: Speed-up using machine-learning techniques

Task OBS-2.4-C(iv)-**Other**: Pipeline improvement using other techniques

Task OBS-2.4-C(v)-**Other**: Speed-up using heterodyning

Activity OBS-2.4-D-**Other**: Beyond-GR effects on the GW waveform and tests of GR

Effects beyond GR will manifest themselves in all stages of the gravitational waveform, including the inspiral, merger, ringdown, and possible echoes. Different tests of GR will respond differently to different classes of effects. We will explore models of beyond-GR effects on the GW waveform and tests of GR, including those motivated by general classes of modified theories (e.g. described by an effective-field-theory framework), as well as classes of exotic compact objects within GR. We will improve existing tests of GR and create new ones, guided by the results of studies using the non-GR waveforms.

Task OBS-2.4-D(i)-**Other**: Effects of alternative theories of gravity on GW waveform and tests of GR

Systematically collect results from theoretical and numerical work towards producing realistic inspiral-merger-ringdown waveforms in alternative theories of gravity. Perform injection studies with these waveforms, to assess the response of current search pipelines and testing-GR pipelines in these scenarios.

Task OBS-2.4-D(ii)-**Other**: Effects of exotic compact objects on GW waveforms and tests of GR

Systematically collect results from theoretical and numerical work towards producing realistic inspiral-merger-ringdown waveforms from the binary coalescence of exotic compact objects in GR, including beyond-standard-model physics. Perform injection studies with these waveforms, to assess the response of current search pipelines and testing-GR pipelines in these scenarios.

Task OBS-2.4-D(iii)-**Other**: New or improved tests of GR

Develop new or improved methods to constrain deviations from GR using CBC signals. For instance, develop an analysis that can infer the true deviations in post-Newtonian coefficients from non-GR signals.

ACTIVITY OBS-2.4-E-**OTHER**: TESTING GR: INTERACTION WITH ADJACENT WORKING GROUPS

TASK OBS-2.4-E(i)-**OTHER**: WAVEFORMS

Continuously liaise with the Waveforms group to keep the TGR pipelines up to date with the most state-of-the-art waveform models available in terms of accuracy and features.

TASK OBS-2.4-E(ii)-**OTHER**: CONTINUOUS WAVES

Explore potential for collaborations on tests of GR, such as searches for non-tensorial polarizations.

TASK OBS-2.4-E(iii)-**OTHER**: STOCHASTIC

Explore potential for collaborations on tests of GR, such as searches for non-tensorial polarizations.

TASK OBS-2.4-E(iv)-**OTHER**: COSMOLOGY

Collaborate on analyses for which there is common scope and expertise, such as modified propagation at cosmological distances (e.g., cases where there is both dispersion and a modification to the luminosity distance) and tests of ΛCDM cosmology with bright or dark sirens.

TASK OBS-2.4-E(v)-**OTHER**: GRAVITATIONAL LENSING

Develop model agnostic and theory-specific analyses to test for the gravitational-wave polarization and massive gravity with strongly lensed gravitational waves.

TASK OBS-2.4-E(vi)-**OTHER**: RATES AND POPULATIONS

Transfer of knowledge regarding expected event rates, detection rates, and impact of GR-violating features on the latter. Set-up of realistic injection datasets for MDCs that will inform our decisions on setting our selection criteria for TGR pipelines.

TASK OBS-2.4-E(vii)-**OTHER**: PARAMETER ESTIMATION

Transfer of knowledge regarding developments in parameter estimation, in particular improvements in efficiency and appropriate settings for various samplers.

OBS-2.5 Studies of Extreme Matter R&D (Short Term)

Develop methods to uncover the nature of ultra dense matter in neutron stars inferred from observed BNS and NSBH signals, from tidal and post-merger signatures.

Motivation and goals

An outstanding issue in nuclear physics is the unknown equation of state (EOS) of neutron-star matter. This has two impacts on gravitational-wave science: First, we must understand (and address) any impact the presence of matter may have on statements from CBC searches and parameter estimation. Second, using both CBC and Burst methods, we hope to learn about the equation of state of matter at extreme densities from LIGO/Virgo detections.

The detection and parameter estimation of binary neutron star (BNS)/neutron star black hole binary (NSBH) systems employ templates that include the late stages of inspiral, where neutron stars will be tidally deformed and possibly even tidally disrupted. The extent of this deformation is highly dependent on the mass of the star and the EOS of the nuclear matter inside the neutron star, so measuring the tidal parameters of the merging binary will constrain the EOS. In certain BNS scenarios—such as extremely large-radius stars or nonlinear couplings—these tidal interactions may also lead to the loss of signals if they are not incorporated into CBC searches.

Measurement of tidal parameters is immediately possible with post-Newtonian waveforms, however systematic errors are large and will limit the strength of the statements LIGO/Virgo can make. The ability to measure matter effects is constrained by the accuracy and speed of inspiral waveforms. Avenues for improvement include improved waveform models and high-frequency follow-up parameter estimation with numerical simulations. Improvements in EOS constraint may also result from optimally combining information from multiple detections, or from constraining equation-of-state parameters directly.

Astrophysical gravitational waves will also include the merger and high-frequency post-merger, which will be challenging for current-generation detectors to measure but carry additional information about neutron-star matter. Burst follow-up of CBC detections is needed to confirm or constrain the presence or absence of these post-merger signals and measure their properties. Data analysis methods that span the inspiral to post-merger stage of BNS events would strengthen overall statements about the EOS.

Multiple BNS/BHNS detections, giving a distribution of measured masses and/or coincident gravitational-wave and electromagnetic counterpart detections, are in themselves relevant for equation of state constraints. In particular, large measured NS masses could constrain more exotic forms of nuclear matter. Any signature of matter in an observed compact binary merger could also confirm whether one component object is a neutron star instead of a black hole. Therefore, tidal parameter measurement within CBC, identification of electromagnetic counterparts, and burst follow-up results can inform rates and population statements about the categories of observed mergers.

Major aspects and methods for this activity

ACTIVITY OBS-2.5-A-**INFRAOPS**: EXTREME MATTER SUBGROUP ADMINISTRATION

Management of the Extreme Matter subgroup.

TASK OBS-2.5-A(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

TASK OBS-2.5-A(ii)-**INFRAOPS**: EDITORIAL TEAM LEADERSHIP AND PAPER MANAGEMENT

Administrative and managerial tasks associated with collaboration papers led by the Extreme Matter subgroup.

ACTIVITY OBS-2.5-B-**INFRAOPS**: CODE DEVELOPMENT AND DEPLOYMENT FOR O4 MATTER ANALYSES

Extension, maintenance and implementation of the infrastructure for matter-related studies during O4.

TASK OBS-2.5-B(i)-**INFRAOPS**: MATTER-RELATED PARAMETER ESTIMATION

With the transition from LALInference to bilby, it is essential to ensure the availability of matter-related pipelines for O4. Maintenance and modernization of infrastructure, algorithms, and code are continuously required as short-term goals. Necessary studies include among others: the usability of accurate TOV solvers for astrophysical results, methods for tidal parameter estimation, a working infrastructure for spectral and piecewise-polytropic EOS inference, the inference of non-linear tidal effects, and rapid inferencing infrastructure for combining multiple events with and without multi-messenger observations to constrain the equation of state.

TASK OBS-2.5-B(ii)-**INFRAOPS**: EOS INFRASTRUCTURE

Extension of the available EOS infrastructure and table database. Revisiting the accuracy of existing EOS tables. Updating and maintaining the EOS constraint information derived from GW and external observations for use across LVK subgroups.

TASK OBS-2.5-B(iii)-**INFRAOPS**: CONSTRAINTS ON RADII, EOS AND REMNANT PROPERTIES

Development, maintenance and deployment of infrastructure for matter analyses that are downstream from parameter estimation. Critical analyses include among others: generation of radius constraints, a working infrastructure for non-parametric EOS inference, inferences of ejecta and the fate of the remnant.

TASK OBS-2.5-B(iv)-**INFRAOPS**: PAPER WRITING AND CURATION OF DATA PRODUCTS

Contributions to the writing of collaboration papers with Extreme Matter subgroup involvement. Development and implementation of standardized formats for Extreme Matter data releases. Curation of data products to ensure they are easily accessible and usable for public release.

ACTIVITY OBS-2.5-C-**INFRAOPS**: EXTREME MATTER: INTEGRATION AND FEEDBACK WITH OTHER R&D GROUPS

The tools and results produced by the extreme matter group depend on and can influence the research direction of other groups and projects.

TASK OBS-2.5-C(i)-**INFRAOPS**: IMPACT OF EOS ON ALERTS

Coordinating with the low-latency subgroup to inform rapid classification and EM bright statements with up-to-date information about neutron star properties.

TASK OBS-2.5-C(ii)-**INFRAOPS**: IMPACT OF WAVEFORM SYSTEMATICS ON INFERENCE

Coordinating with the waveform and parameter estimation groups to quantify the impact of model systematics on EOS constraints.

TASK OBS-2.5-C(iii)-**INFRAOPS**: EOS MEASUREMENTS IN POPULATIONS OF NEUTRON STARS

Coordinating with the parameter estimation and rates and population groups for source classification, prior assumptions, and joint EOS and population inferences (see also Task OBS-2.9-E(iv)). EOS inference is influenced by population assumptions, in particular when multiple signals are considered.

TASK OBS-2.5-C(iv)-**INFRAOPS**: EOS DEGENERACY WITH TESTS OF GR

Providing knowledge about EOS information to quantify degeneracies between modifications to GR and uncertain neutron star EOS properties.

TASK OBS-2.5-C(v)-**INFRAOPS**: IMPACT OF EOS ON MULTI-MESSENGER TRANSIENT SEARCHES

Providing knowledge about EOS information to help to estimate possible multi-messenger counterparts.

OBS-2.6 Studies of Extreme Matter R&D (Long Term)

Develop methods to uncover the nature of ultra dense matter in neutron stars inferred from observed BNS and NSBH signals, from tidal and post-merger signatures (long term).

Major aspects and methods for this activity

ACTIVITY OBS-2.6-A-**OTHER**: SYSTEMATIC ERROR ASSESSMENT FOR EXTREME MATTER ANALYSES

Statements about tidal parameters are limited by uncertainties in the waveform evolution. Waveform injection and parameter estimation studies will be performed to assess the systematic errors in the measured tidal parameters. These studies will explore the impact of differences in waveform model, spin priors, and calibration errors.

TASK OBS-2.6-A(i)-**OTHER**: SYSTEMATIC ERROR ASSESSMENT FOR EXTREME MATTER

ACTIVITY OBS-2.6-B-**OTHER**: WAVEFORM DEVELOPMENT AND COMPARISON

The ability to measure tidal parameters is limited by uncertainties in both point-particle and matter-dependent contributions to the waveform evolution. A detailed analysis of the differences between state-of-the-art waveforms for systems with tides, as well as differences with numerical simulations, is required to inform the waveform development outlined in OBS-2.7.

Inspiral waveforms for compact binary coalescences involving beyond-standard-model matter effects (e.g. massive scalar fields, axions) or exotic compact objects (e.g. boson stars) will be developed to constrain dark matter candidates and non-GR matter interactions.

TASK OBS-2.6-B(i)-**OTHER**: WAVEFORM DEVELOPMENT AND COMPARISON FOR EXTREME MATTER

ACTIVITY OBS-2.6-C-**OTHER**: RAPID ANALYSIS METHODS FOR EXTREME MATTER

Parameter estimation for systems containing neutron stars is not possible for some of the currently implemented tidal effective one body models due to their long evaluation time. Improvements such as surrogate waveform models for the aligned spin waveforms with tidal interactions will be produced.

TASK OBS-2.6-C(i)-**OTHER**: RAPID ANALYSIS METHODS FOR EXTREME MATTER

ACTIVITY OBS-2.6-D-**OTHER**: BNS POST-MERGER REMNANT AND SIGNAL PROPERTIES

A number of modeled and unmodeled data analysis techniques for constraining the energetics and spectral content of BNS postmerger signals have been proposed and some applied to GW170817. The efficacy and optimization of such methods will be studied further using numerical simulations of BNS mergers. Techniques to combine information from pre- and post-merger observations, as well as combining measurements from multiple events (i.e., “stacking”) will be developed. Further detector characterization studies will be pursued in an effort to improve high frequency instrumental sensitivity and to refine and optimize analyses of high frequency data.

Studies will be performed to investigate whether the post-merger waveform associated with the NS resulting from the merger event in the presence of massive scalar fields can provide further constraints on both the axion field and the nuclear equation of state.

Development of waveform models for the post-merger can also be used to complement the inspiral, working towards obtaining a unified inspiral-merger-postmerger model.

TASK OBS-2.6-D(i)-**OTHER**: BNS POST-MERGER REMNANT AND SIGNAL PROPERTIES

ACTIVITY OBS-2.6-E-**OTHER**: RESONANT MODE IMPLICATIONS FOR NEUTRON STAR COALESCENCES

Various mode excitations through the inspiral to merger of neutron stars provide useful modeling frameworks and astrophysical implications. This include p-g mode instabilities in inspiral, resonant r-mode excitations, and approach to f-mode in the final stages of merger. Methods for identifying the presence and significance of such energy transfers will be developed.

TASK OBS-2.6-E(i)-**OTHER**: RESONANT MODE IMPLICATIONS FOR NS COALESCENCES

ACTIVITY OBS-2.6-F-**OTHER**: MULTI-SIGNAL UNDERSTANDING OF COMMON CHARACTERISTICS FOR EXTREME MATTER ANALYSES

As a population of neutron-star signals is revealed, methods for usefully combining the information from a full catalog to learn about the underlying physics of dense matter will be developed and implemented.

Methods for identifying effective EOS variability in the population, e.g. due to accumulation of particle dark matter or a subpopulation of exotic compact objects, will be developed.

TASK OBS-2.6-F(i)-**OTHER**: MULTI-SIGNAL UNDERSTANDING OF CHARACTERISTICS OF DENSE MATTER

ACTIVITY OBS-2.6-G-**OTHER**: CONNECTIONS WITH NUCLEAR PHYSICS AND HIGH-ENERGY ASTROPHYSICS

Extreme matter constraints also stem from investigations of terrestrial nuclear physics experiments, nuclear and QCD theory, and other astronomical observations of neutron stars. LIGO/Virgo analyses will continually need updating to incorporate state-of-the-art methods and models from these fields; for example new equation of state models and constraints and observations of neutron stars used to set our priors.

In addition, extreme matter information about the EOS can also play a role as a prior choice for down-stream analyses, e.g., cosmology or lensing.

TASK OBS-2.6-G(i)-**OTHER**: CONNECTIONS WITH NUCLEAR PHYSICS AND HIGH-ENERGY ASTROPHYSICS

TASK OBS-2.6-G(ii)-**OTHER**: DERIVING EOS INFORMATION (WITH QUANTIFIED UNCERTAINTIES) AS INPUT FOR OTHER ANALYSES

OBS-2.7 CBC Waveform Models R&D (Short Term)

Development of waveforms to faithfully model physics in binary coalescence for searches, parameter estimation and tests of General Relativity (short term).

Motivation and methods

The waveforms group aims to provide the collaboration with waveform models for template-based analyses of gravitational wave events, most importantly for compact binary coalescence events. Our long-term vision foresees waveform models which include all physical effects that may influence our GW analyses, and which can be evaluated sufficiently quickly for all GW-analysis purposes. Furthermore, we strive to quantify errors that arise from model approximations and from neglected physical effects. These goals require a combination of analytical and numerical modeling of CBC waveforms, as well as acceleration techniques to speed up evaluation of waveform models.

Major aspects and methods for this activity

The following activities are critical for generating O4 results.

ACTIVITY OBS-2.7-A-**INFRAOPS**: NEW CBC WAVEFORM MODELS

Improve / add waveform models expanding parameter ranges or introducing new physics.

TASK OBS-2.7-A(i)-**INFRAOPS**: IMPROVE BH-BH WAVEFORM MODELS

Waveform models for BBH systems that include the effects of precession and sub-dominant multipoles have been developed, implemented and reviewed in collaboration code. We aim to further develop BBH models, delivering improvements in terms of accuracy, physical content and computational efficiency. This may include the development of new models as well as the refinement of existing models, e.g., through a re-calibration of IMR waveforms to larger NR data sets. A particular focus will be the parameter space of high mass ratios.

TASK OBS-2.7-A(ii)-**INFRAOPS**: IMPROVE NS-NS WAVEFORM MODELS

This includes improved modelling of BNS tidal and spin effects by comparison to numerical relativity simulations or improved analytical understanding, as well as modelling sub-dominant multipoles. We aim to develop models that include as many of these effects as possible.

TASK OBS-2.7-A(iii)-**INFRAOPS**: IMPROVE BH-NS WAVEFORM MODELS

This includes improved modelling on NS tidal and spin effects, improved modelling of sub-dominant multipoles and the accurate modelling of the merger/disruption of the NS. We aim to develop models that include as many of these effects as possible.

TASK OBS-2.7-A(iv)-**INFRAOPS**: INCLUDE ECCENTRICITY IN BH-BH WAVEFORM MODELS

Eccentric waveform models are required to quantify search sensitivity, and to estimate or bound the eccentricity of observed CBC events. We aim to have an IMR model for BH-BH systems with moderate eccentricity and aligned spins implemented in LAL and reviewed by O4. Further work will address effects of spin precession and subdominant modes on eccentric IMR waveforms.

TASK OBS-2.7-A(v)-**INFRAOPS**: IMPROVED NR-CALIBRATED FITS FOR SPECIFIC BH-BH, BH-NS AND NS-NS PROPERTIES

In addition to full waveform models, there is continued need in parameter estimation and testing-GR applications for more accurate and general NR-calibrated fits for BBH properties such as final mass, final spin, radiated energy, kicks, peak luminosity and frequency. New developments can include both conventional fits and surrogate models, with a particular focus on the full precessing parameter space.

We also aim to implement in LAL accurate NR-calibrated fits for tidally interacting binaries that include the remnant black hole mass and spin, radiated energy, peak luminosity and postmerger frequencies fits.

TASK OBS-2.7-A(vi)-**INFRAOPS**: EXPAND THE NR WAVEFORM CATALOG AS BASELINE DATA FOR A VARIETY OF WAVEFORM/PE/TESTINGGR/BURST PROJECTS

For BBH: Convert to LVC-NR format and add to the LVC-NR repository additional BBH waveforms. Of particular priority are NR waveforms with validated sub-dominant modes of sufficient accuracy even at high SNR; eccentric simulations; simulations at sparsely explored regions of high mass-ratio, high spin or both; long simulations to validate transition to analytical inspiral waveforms; and detailed coverage of merger/ringdown for high-mass systems. We also plan to expand simulation coverage supporting comparisons of GW measurements directly to the NR waveform catalog, without the need for an intermediary model.

For BH-NS, NS-NS systems: Convert to LVC-NR format and add to the LVC-NR repository waveforms for BH-NS and NS-NS systems which are either publicly available, or contributed by NR groups.

ACTIVITY OBS-2.7-B-**INFRAOPS**: EVALUATION OF CBC WAVEFORM MODELS

TASK OBS-2.7-B(i)-**INFRAOPS**: IMPROVE UNDERSTANDING OF WAVEFORM MODEL ERRORS AND ATTENDANT SYSTEMATICS

Improve understanding of waveform model errors and attendant systematics by cross-comparisons between different waveform models and numerical relativity simulations. In particular at significantly unequal mass-ratios and/or high spins, and also paying attention to sub-dominant modes.

ACTIVITY OBS-2.7-C-**INFRAOPS**: ALGORITHMIC AND COMPUTATIONAL IMPROVEMENTS TO CBC WAVEFORM MODELS

TASK OBS-2.7-C(i)-**INFRAOPS**: OPTIMIZATIONS OF IMPORTANT WAVEFORM MODELS

The evaluation time of waveform models needs to be low enough to i) be used in parameter estimation of long signals, ii) be run multiple times on the same event to study the impact of analysis hyperparameters, and finally iii) to cope with the large number of events expected.

We will pursue methods to speed up existing waveform models, e.g., through the use of surrogate/reduced-order-modelling or the reduced-order-quadrature method.

ACTIVITY OBS-2.7-D-**INFRAOPS**: CBC WAVEFORM REVIEW

TASK OBS-2.7-D(i)-**INFRAOPS**: REVIEWS OF WAVEFORM CODE

Review of implementation of waveform models, including code review, correctness of results across domain of applicability, and conformance to waveform conventions.

ACTIVITY OBS-2.7-E-**INFRAOPS**: CODE MAINTENANCE AND INFRASTRUCTURE IMPROVEMENT FOR CBC WAVEFORMS

TASK OBS-2.7-E(i)-**INFRAOPS**: LALSIMULATION CODE MAINTENANCE

Rapid response to LALSimulation bug fixes, code changes and feature requests that are required to carry out the Collaboration's science tasks. Maintenance of LALSimulation code interfaces with common file formats. Maintenance and development of spin evolution codes, including both PN and EOB evolutions.

TASK OBS-2.7-E(ii)-**INFRAOPS**: IMPROVEMENT OF COMMON INFRASTRUCTURE

Examples: Development of common waveform tools, e.g., to aid in waveform reviews. Standardized waveform conventions across models. Increase support for eccentric waveforms, e.g., in the numerical relativity injection infrastructure.

TASK OBS-2.7-E(iii)-**INFRAOPS**: SUPPORT FOR EXTERNAL CODES AND PYTHON INFRASTRUCTURE

Draft, implement and review new waveforms interface that will help integrate Python-based model development for O4. Strengthen support for existing external codes (e.g., gwsurrogate).

ACTIVITY OBS-2.7-F-**INFRAOPS**: CBC WAVEFORMS: INTEGRATION AND FEEDBACK WITH OTHER R&D GROUPS

The Waveforms group is often required to produce recommendations for preferred waveform models or to produce statements regarding waveform systematics. We list projects within the scope of the Waveforms group that have impact on and overlap with other R&D groups.

TASK OBS-2.7-F(i)-**INFRAOPS**: IMPACT OF WAVEFORM SYSTEMATICS ON INFERENCE AND POPULATION STUDIES

Coordinating with both the Parameter Estimation and R&P groups to assess impact of waveform systematics on parameter estimation and population inference. This task includes event specific systematics studies, recommendations for preferred waveform models and studies in support of catalog and exceptional event papers.

ACTIVITY OBS-2.7-G-**INFRAOPS**: CBC WAVEFORMS SUBGROUP ADMINISTRATION

Management of the Waveforms subgroup.

TASK OBS-2.7-G(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

OBS-2.8 CBC Waveform Models R&D (Long Term)

Development of waveforms to faithfully model physics in binary coalescence for searches, parameter estimation and tests of General Relativity (long term).

Motivation and methods

Our ultimate goal is a plurality of waveform models for systems which may include precession, eccentricity and matter effects all together. Specific aspects toward this ultimate goal are articulated in the major aspects for this activity (below).

Major aspects and methods for this activity

ACTIVITY OBS-2.8-A-**OTHER**: ECCENTRIC WAVEFORM MODELS FOR CBC SYSTEMS: PRECESSION, SUB-DOMINANT MODES, TIDAL EFFECTS, OPTIMIZATION, SPIN EVOLUTION

Include effects of spin-precession, sub-dominant modes and matter in the development of signal models for binary coalescence with orbital eccentricity (BH-BH, NS-NS and NS-BH systems). Improve evaluation speed of eccentric waveform models. Incorporate eccentricity into spin evolution codes.

TASK OBS-2.8-A(i)-**OTHER**: ECCENTRIC WAVEFORM MODELS FOR CBC SYSTEMS

ACTIVITY OBS-2.8-B-**OTHER**: WAVEFORM MODELS FOR BINARIES ON UNBOUND ORBITS

Develop waveform models for hyperbolic and parabolic encounters.

TASK OBS-2.8-B(i)-**OTHER**: WAVEFORM MODELS FOR BINARIES ON UNBOUND ORBITS

ACTIVITY OBS-2.8-C-**OTHER**: ACCURATE AND LONG NUMERICAL RELATIVITY SIMULATIONS FOR CBC

Perform numerical relativity simulations for all types of CBC systems with sufficient accuracy and length to quantify waveform modeling errors at sensitivities of future GW detectors.

TASK OBS-2.8-C(i)-**OTHER**: PERFORM ACCURATE AND LONG NR SIMULATIONS

ACTIVITY OBS-2.8-D-**OTHER**: INVESTIGATE APPLICATION OF NEW MATHEMATICAL TOOLS TO CBC WAVEFORM MODELING

Exploration of novel methods that may lead to the development of models that include more physical effects, or that may significantly speed up existing waveform models, but do not necessarily lead to deliverable waveforms in the short term.

TASK OBS-2.8-D(i)-**OTHER**: INVESTIGATE NEW MATHEMATICAL TOOLS FOR WAVEFORM MODELING

ACTIVITY OBS-2.8-E-**OTHER**: CROSS-VALIDATION BETWEEN DIFFERENT NR CODES FOR CBC SYSTEMS

Cross-validation between different NR codes for BH-BH, NS-NS and BH-NS systems to assess the accuracy and reliability of NR waveforms to confirm NR waveforms are of sufficient quality for their use in studies as varied as search-efficiency, parameter recovery bias, and waveform model development.

TASK OBS-2.8-E(i)-**OTHER**: CROSS-VALIDATION BETWEEN DIFFERENT NR CODES FOR CBC SYSTEMS

ACTIVITY OBS-2.8-F-**OTHER**: CONTINUE PER-EVENT NR FOLLOW-UP AS NEEDED

Improve the accuracy of observational statements and/or test systematic biases using NR simulations in response to suitable detection candidates. Develop and improve NR follow-up methods.

TASK OBS-2.8-F(i)-**OTHER**: PER-EVENT NR FOLLOW-UP TO DETECTION CANDIDATES

ACTIVITY OBS-2.8-G-**OTHER**: CBC WAVEFORM MODELS FOR BEYOND-GR TESTS

Expand the repertoire of waveform models that include parameterized departures from GR to better faciliate tests of GR. Examples include, but are not limited to, the development of physically motivated modifications of phase and amplitude evolution to model the effects of non-GR polarization states; the incorporation of physically motivated parameter constraints derived from selected theories.

TASK OBS-2.8-G(i)-**OTHER**: WAVEFORM MODELS FOR BEYOND-GR TESTS

OBS-2.9 Binary Coalescence Rates and Population R&D (Short Term)

Estimate the astrophysical rates of various classes of compact binary coalescences, characterize their population properties via both parameterized models and unmodeled methods, with the objective to uncover features of their astrophysical formation and evolution.

Motivation and methods

The objective of Rates and Population analysis is to infer the astrophysical merger rate (mergers per time per comoving volume) of compact binary systems and their population distribution using the outputs of all-sky searches and individual event parameter estimation analyses. Populations are presently defined over the spaces of binary masses, spin geometry, and redshifts. Inference of the compact binary population is performed by defining models of the underlying population, and then measuring the parameters of these models via comparison against the outputs of CBC and Burst Group searches and parameter estimation.

Binary merger events can be astrophysically classified as binary black hole (BBH), BNS, and NSBH, each of which are currently observed with a non-zero event rate. The limits or boundaries between these categories are not precisely defined a priori, and may be adjusted based on future observations. These categories are furthermore not exhaustive; additional theorized classes include intermediate mass black hole (IMBH) and sub-solar-mass binaries. No sub-solar-mass candidates have been identified to date, however, and although the source of GW190521 could include an IMBH component, this event appears consistent with the bulk BBH population.

The rates and ensemble properties within each category offer information about the range of astrophysical processes governing compact binary evolution. As the binary merger census expands in number and cosmological reach, an increasing number of population features are becoming observationally accessible, in turn offering more powerful observational constraints on astrophysical binary evolution. With several hundred events, we may aim to resolve distinct compact binary sub-populations, probe correlations between binary masses, spins, and redshifts, and determine details concerning the origin of compact binary progenitors.

In addition to the interfacing with CBC and Burst searches and parameter estimation, and with other subgroups studying individual binary mergers (CBC Waveforms, CBC Extreme Matter), we also expect Rates and Population activities to influence the structure of future search catalogs and associated data products, both as downstream users of these data products as inputs to population analyses and as a provider of upstream astrophysical information (such as refined definitions of source categorizations). Rates and Populations work will further interface with other science groups leveraging the ensemble properties of compact binaries. The Stochastic Group, for example, uses the output of Rates and Populations analyses to estimate the unresolved gravitational-wave background; stochastic searches can also provide independent constraints on the rate of high-redshift binary mergers.

Major aspects and methods for this activity

ACTIVITY OBS-2.9-A-**INFRAOPS**: MEASUREMENT OF SEARCH SENSITIVITY TO BINARY POPULATIONS

Develop and maintain methods to efficiently measure the sensitivity of searches over the network of interferometers to a broad range of possible CBC populations, delineated by source parameters, redshift, and/or non-GR modifications; integrate such estimates with population inference codes, and ensure they achieve the accuracy required for science goals; publish associated data products for both internal LVK and external consumers. The main estimation methods are Monte Carlo via direct injection of simulated signals into real data, to be searched with all-sky pipelines, which fully accounts for non-ideal features in the data and in search methods; or, 'semi-analytic' via synthetic injections, with expected SNR used as a proxy for detection probability.

TASK OBS-2.9-A(i)-**INFRAOPS**: SIMULATED SIGNAL CAMPAIGNS

Decide on distributions of simulated CBCs to cover the relevant binary parameter spaces and create simulation sets, specifying sufficiently accurate waveforms to measure selection effects with accuracy comparable to (or better than) other statistical and systematic errors affecting population analysis. Targeted parameter spaces include mass ranges spanning conventional BNS, NSBH, and BBH binaries, as well as binary coalescences including at least one sub-solar-mass compact object. Create and curate data products resulting from analyzing simulations with search pipelines.

TASK OBS-2.9-A(ii)-**INFRAOPS**: LOW-LATENCY SIMULATED SIGNAL CAMPAIGNS

Investigate production of simulated signal campaigns for low-latency searches. The distributions should closely mimic the distributions produced for the final population analyses. The injections sets should be available before the data taking so they can be analyzed in real time.

TASK OBS-2.9-A(iii)-**INFRAOPS**: ONLINE & SEMI-ANALYTIC SENSITIVITY ESTIMATION

For preliminary investigation of population features and checks on intrinsic rates, a rolling estimate of current integrated sensitivity over the O4 run, accounting for the variability of detector and network sensitivity over time, is desirable. Implement and test such a low/medium latency estimate, likely based on semi-analytic synthetic injections. Quantify and correct for the biases of semi-analytic estimates by calibrating/regressing against the outputs of full large-scale injection runs from the previous task.

TASK OBS-2.9-A(iv)-**INFRAOPS**: INTERFACE WITH POPULATION INFERENCE

Any method designed to measure sensitivity to specific populations must be integrated into analyses which require selection function estimates over binary source parameters and/or population hyperparameters. This interface may require additional fitting, resampling or reweighting steps which must be computationally efficient without introducing unwanted biases. Various machine learning methods may be applicable.

ACTIVITY OBS-2.9-B-**INFRAOPS**: PARAMETRIC AND NON-PARAMETRIC MERGER RATE ESTIMATION

TASK OBS-2.9-B(i)-**INFRAOPS**: SIGNIFICANCE ESTIMATION USING MODELLED BINARY POPULATIONS

For known (fixed) source populations, astrophysically-informed significance estimates of signal candidates may be derived directly from the outputs of search pipelines via a signal-noise mixture model [57], using the results of injection campaigns (reweighted if appropriate) to estimate the signal distribution and the search sensitivity. For classes of event with no clear detections, rate upper limits for given populations may be set via a simpler method [58]. Maintain and update such methods to account for refinements in search pipelines and target populations, including intermediate mass and sub-solar mass black hole populations. The impact of population uncertainty on rate may be partly incorporated by evaluating the effect on search sensitivity, however see Task OBS-2.9-D(v) for a more complete treatment.

TASK OBS-2.9-B(ii)-**INFRAOPS**: NON-PARAMETRIC RATE ESTIMATES

For source classes with a small number of detected events, typically up to 3, non-parametric methods based on the measured parameters of the events [59] are used to provide alternative data-driven rate estimates. Implementation requires targeted evaluation of the search sensitivity using event parameter samples, plus calibration to large-scale injection campaigns. Application to intermediate-mass and sub-solar mass black hole binaries if appropriate.

ACTIVITY OBS-2.9-C-**INFRAOPS**: COMPACT BINARY POPULATION ASTROPHYSICS (SHORT TERM)

As compact binary catalogs grow in size and scope, we will perform increasingly detailed studies targeting finer phenomenological details of the compact binary population, and/or linking these details to underlying astrophysical phenomena and evolutionary mechanisms.

TASK OBS-2.9-C(i)-**INFRAOPS**: MASS DISTRIBUTION MODELS

Develop and refine models describing the masses of merging binaries, either descriptive or connected to various possible formation channels. Continue to extend existing single-component modeling of BBH to multiple components / mixtures, with inclusion of more physical content in models as appropriate. Extend the modelling framework to include possible intermediate-mass and sub-solar mass black hole components, as well as primordial black hole components with cosmologically motivated distributions.

TASK OBS-2.9-C(ii)-**INFRAOPS**: SPIN DISTRIBUTION MODELS

Develop and refine models describing the spin geometry of merging binaries (targeting either component spins or phenomenological effective spin parameters) and apply results of model inference to distinguish formation scenarios.

TASK OBS-2.9-C(iii)-**INFRAOPS**: REDSHIFT EVOLUTION AND SPATIAL DEPENDENCE OF MERGER POPULATION

Develop and refine models to infer the dependence of the binary merger rate and ensemble properties (e.g. masses and spins) on redshift. Implement methods to measure or place limits on potential anisotropies in the merger distribution.

TASK OBS-2.9-C(iv)-**INFRAOPS**: INFERENCE ON ASTROPHYSICALLY MOTIVATED POPULATION PROPERTIES

Identify features in mass / spin / redshift-dependent event distributions which arise from astrophysical processes. Interpretation and inference on these within the framework of phenomenological and physically motivated models in the literature.

Activity OBS-2.9-D-**InfraOps**: CBC Rates and Population: Common Code and Data Product Platform Development (short term)

To support the ongoing and future activities of the R&P group, we will continue to develop a common set of codes and data product formats. Several of these codes will also benefit from a single source of information needed by inference codes, such as event sample ingestion and computation of detection selection effects and surveyed volume. In the longer term we may benefit from integration of codebases using similar methods (notably, hierarchical population inference) into a single pipeline.

Task OBS-2.9-D(i)-**InfraOps**: Hierarchical Inference for Parameterized Models

Maintain and optimize codebases for Bayesian hierarchical inference on population model hyperparameters using MCMC or other sampling methods. Extend the inference framework to include mixture models and address resulting issues of priors and sampling.

Task OBS-2.9-D(ii)-**InfraOps**: Inference on Non-Parametric Models

Maintain and extend methods for non-parametric models to explore features of the binary merger population without imposing physically motivated functional forms (e.g. binned mass/spin models, spline/KDE, Gaussian mixture).

Task OBS-2.9-D(iii)-**InfraOps**: Model Checking and Outlier Identification

Maintain and refine methods for checking consistency of modeled populations with actual recovered detection sets (e.g. posterior population checks, cumulative distribution tests) and for detecting possible population outliers, i.e. events apparently inconsistent with current models.

Task OBS-2.9-D(iv)-**InfraOps**: Mid-latency Population Updates

In order to identify exceptional events at/beyond the boundaries of known populations, spot significant emerging population features and enable preliminary exploration of astrophysical implications, we will periodically update inferences during observing runs using current population models. Maintain infrastructure to collect preliminary search sensitivity and parameter estimation outputs on a few-week cadence, and to update population inferences for masses, spins, rates and redshift evolution.

Task OBS-2.9-D(v)-**InfraOps**: Inclusion of Marginal Events in Rate/Population Inference

Implement and refine methods to quantify and account for noise event contamination in population inferences by leveraging search pipeline estimates of background event distributions. For rate estimation this corresponds to existing two- or more-component Poisson mixture methods.

Task OBS-2.9-D(vi)-**InfraOps**: Curation of Data Products

Develop and implement standardized formats for R&P analyses. This includes infrastructure for ingesting standardized data produced by parameter estimation (see Task OBS-2.1-D(iv)), as well as the production and curation of standardized output files containing the results of population analyses. Ensure that data products are easily accessible and usable for public release.

Activity OBS-2.9-E-**InfraOps**: CBC Rates and Population: Integration and Feedback with Other R&D Groups

The tools and results produced by the R&P group are dependent on, and can influence the development of other groups and projects. We list tasks carried out primarily by other groups where R&P input is required either for science motivation or technical requirements and support.

TASK OBS-2.9-E(i)-**INFRAOPS**: RATE/POPULATION INPUTS TO CLASSIFICATION OF SEARCH EVENTS

All-sky search pipelines will produce estimates of terrestrial origin and astrophysical source origin, for candidates seen both in low latency and in searches of archival data for catalog publication. These estimates may be based on specific assumed models of CBC merger rates and source distributions. The R&P group will liaise and advise on such assumptions. Such 'population prior' models may also be incorporated into search ranking statistics and significance estimates, where the CBC All Sky Search group is responsible for detailed implementation.

TASK OBS-2.9-E(ii)-**INFRAOPS**: LIAISON ON SIMULATION CAMPAIGNS

Carrying out large-scale injection campaigns requires consultation with the CBC Waveforms and All Sky Search groups, as well as with project (paper writing) teams, to determine technical requirements and limitations bearing on the accuracy and deployment of the injections.

TASK OBS-2.9-E(iii)-**INFRAOPS**: ROLE OF WAVEFORM SYSTEMATICS IN RATE/POPULATION INFERENCE

Coordinating with the CBC Waveform and Parameter Estimation groups to assess the impact of model systematics on population inference. A handle on such systematics is available by repeating population analysis with parameter estimates arising from different waveform models. This requires multiple reviewed catalogs of event parameters: the CBC Parameter Estimation group is primarily responsible for implementation.

TASK OBS-2.9-E(iv)-**INFRAOPS**: EOS MEASUREMENTS IN POPULATIONS OF NEUTRON STARS

Coordinating with the CBC Parameter Estimation and Extreme Matter groups, population studies with neutron star components will incorporate and contribute to understanding of the equation of state of neutron star matter. See also Task OBS-2.5-C(iii).

TASK OBS-2.9-E(v)-**INFRAOPS**: REEXAMINING EVENTS WITH POPULATION PRIORS

Coordinating with the Parameter Estimation and Extreme Matter groups, individual events should be reexamined with priors corresponding to constraints implied by the current knowledge of the population (e.g. mass and spin reweighting). This will impact our understanding of their properties in the context of the population.

TASK OBS-2.9-E(vi)-**INFRAOPS**: POPULATION IMPACTS ON COSMOLOGY AND LENSING

'Standard siren' methods for measuring the expansion history of the Universe require accurate accounting for selection effects, and thus modeling of relevant populations over mass, spin and redshift. Thus, the current best knowledge of the binary merger population should be applied. Similar considerations apply to studies of strongly lensed GW events. The Cosmology and Lensing groups are responsible for implementation, however a R&P liaison may be required.

TASK OBS-2.9-E(vii)-**INFRAOPS**: POPULATION INFORMATION FOR STOCHASTIC BACKGROUND SEARCH

Estimates of the stochastic background from CBC sources (see Section OBS-4.1) require information on merger rate and population distributions. The Stochastic group is primarily responsible for implementation, however a liaison from R&P may be required.

TASK OBS-2.9-E(viii)-**INFRAOPS**: POPULATION INFORMATION FOR TESTS OF GENERAL RELATIVITY

Tests of General Relativity based on the combination of data from multiple events may rely upon methods and data products developed in the Rates and Populations group. This may include hierarchical inference frameworks as well as injection-based sensitivity estimates. While the Testing General Relativity group is responsible for coordinating and performing these analysis, a liaison from the R&P group may be required.

ACTIVITY OBS-2.9-F-**INFRAOPS**: RATES AND POPULATIONS METHODS AND CODE REVIEW

TASK OBS-2.9-F(i)-**INFRAOPS**: REVIEW OF PARTICULAR METHOD

Integrated method and code review for particular methods used in LVC publications.

ACTIVITY OBS-2.9-G-**INFRAOPS**: CBC RATES AND POPULATION SUBGROUP ADMINISTRATION

Management of the Rates and Populations subgroup.

TASK OBS-2.9-G(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

OBS-2.10 Binary Coalescence Rates and Population R&D (Long Term)

This section highlights developments that may *optionally* be deployed during the O4 run, or further in future, and thus are not required to be tested before O4 data taking.

Major aspects and methods for this activity

ACTIVITY OBS-2.10-A-**OTHER**: METHODS TO MEASURE SEARCH SENSITIVITY TO BINARY POPULATIONS

Extend Monte Carlo or similar methods to estimate selection effects to so far neglected effects on binary signals and regions of parameter space.

TASK OBS-2.10-A(i)-**OTHER**: SIMULATED SIGNAL CAMPAIGNS FOR ECCENTRIC BINARIES

Create and perform simulation campaigns for binary coalescences including significant non-zero orbital eccentricity. This relies on the existence of sufficiently accurate waveform models, which are largely not available at present: see OBS-2.7.

TASK OBS-2.10-A(ii)-**OTHER**: ALTERNATE METHODS FOR SELECTION FUNCTION EVALUATION

Explore alternate strategies for representing and evaluating the compact binary selection function, beyond the standard Monte Carlo integration of pipeline injections (see OBS-2.9-A). Such methods may include analytic models of search horizons, machine learning models, and/or parameter-dependent ranking statistic thresholds, among others.

ACTIVITY OBS-2.10-B-**OTHER**: CBC RATES AND POPULATION: COMMON CODE AND DATA PRODUCT DEVELOPMENT (LONG TERM)

TASK OBS-2.10-B(i)-**OTHER**: MIXTURE MODEL FOR SIGNAL AND NOISE POPULATIONS

Implement a fully self-consistent mixture model analysis that can simultaneously infer the population and rate of both foreground (astrophysical) and background (noise) events, using data from binary merger searches, DetChar and parameter estimation. This will allow for distinguishing terrestrial noise events without biasing our inferences by assuming all candidate events above an arbitrary threshold to be real.

TASK OBS-2.10-B(ii)-**OTHER**: COMMON TOOLKIT AND COMMUNITY CODE DEVELOPMENT

Continued development of other open codes or tools for use by the Rates and Populations community.

ACTIVITY OBS-2.10-C-**OTHER**: COMPACT BINARY POPULATION ASTROPHYSICS (LONG TERM)

TASK OBS-2.10-C(i)-**OTHER**: IDENTIFICATION AND EXPLOITATION OF BBH MASS SCALES FOR COSMOLOGY

Identify and calibrate mass scales in the BBH mass distribution as an independent measure of merger redshifts and explore cosmological constraints that can be obtained from the BBH population.

TASK OBS-2.10-C(ii)-**OTHER**: BAYESIAN MODEL SELECTION WITH PRIMORDIAL BLACK HOLE MERGERS

Develop Bayesian model selection analyses for models including PBH components (versus astrophysical scenarios without such components) based on the merger rate and mass distribution.

OBS-2.11 CBC Cosmology R&D (Short Term)

Develop methods to estimate cosmological parameters using GW observations, and explore other aspects of CBCs as standard distance indicators (short term).

Motivation and methods

The cosmology group is responsible for obtaining estimates of cosmological parameters such as the Hubble constant H_0, matter density of the Universe, dark energy equation of state, as well as testing alternative theories of gravity from GW signals detected by LIGO-Virgo-KAGRA. The methods involved include identification of a set of possible hosts using an observed EM counterpart, statistical redshift association using galaxy catalogs and exploitation of the features present in the source frame mass spectrum. Since a precise estimate requires combining information from multiple events, correcting for any systematic bias that is expected to accumulate over observations is crucial. Selection effects are known to play an important role even with only a few observations. Redshift uncertainties and other effects coming from the EM sector will become increasingly significant. Smaller effects like GW waveform and calibration uncertainties may eventually also become important. A large part of the research and development involves developing methods to understand and account for such effects.

Major aspects and methods for this activity

ACTIVITY OBS-2.11-A-**INFRAOPS**: COSMOLOGY PIPELINES

A precise measurement of cosmological parameters, such as the Hubble constant, requires combining information from multiple GW observations, with or without transient electromagnetic counterparts. The fact that gravitational wave interferometers have a finite detection threshold introduces a systematic selection bias. Additionally, for the statistical analysis with galaxy catalogues, the incompleteness of the catalogue is expected to introduce further biases. Near future cosmological measurements will be limited by assumptions about the underlying astrophysical source population and so it is necessary to work toward simultaneous fitting of cosmological and astrophysical parameters. Further development in this direction will require methodological studies and close links with other groups, in particular Rates and Populations.

The cosmology group develops and maintains two pipelines for the estimation of cosmological parameters from multiple GW observations, taking into account selection effects. These are GWCOSMO and ICAROGW. Both pipelines makes use of galaxy catalogs and can carry out simultaneous fitting of astrophysical population parameters. Future development effort will focus on improving robustness to systematics by marginalising over additional uncertainties.

TASK OBS-2.11-A(i)-**INFRAOPS**: IMPROVE CODE PERFORMANCE

Improve the current pipelines' speed and computational efficiency to allow for easier extensions into inference for a higher number of parameters.

TASK OBS-2.11-A(ii)-**INFRAOPS**: IMPROVE COMBINED COSMOLOGICAL AND POPULATION INFERENCE INCLUDING GALAXY CATALOG INFORMATION

Improvements to the joint cosmological and population inference with galaxy catalogs method.

TASK OBS-2.11-A(iii)-**INFRAOPS**: EXTENDED GW POPULATION MODELS

Extend the treatment of GW population models by including more complex mass and rate evolution models, spin models, etc.

TASK OBS-2.11-A(iv)-**INFRAOPS**: IMPROVEMENTS TO THE EM COUNTERPART METHOD

Improved EM counterpart analysis by including optional EM information (eg inclination angle from jet and peculiar velocity information).

TASK OBS-2.11-A(v)-**INFRAOPS**: EXTENSION BEYOND ΛCDM

Develop extended versions of the cosmological pipelines to produce inference of beyond-ΛCDM and beyond-GR cosmological models by exploiting possible GW propagation effects.

TASK OBS-2.11-A(vi)-**INFRAOPS**: COMBINED BRIGHT AND DARK SIREN ANALYSIS

Development and implementation of a combined bright and dark siren analysis, to allow use of the broadest range of GW events with the most informative EM information available and simultaneously take into account population properties.

TASK OBS-2.11-A(vii)-**INFRAOPS**: DEVELOPMENT OF RESOURCES FOR COSMOLOGICAL PIPELINE USERS

Development and improvement of pipeline documentation, examples, and the creation and running of workshop material for training new users of the current cosmological pipelines.

ACTIVITY OBS-2.11-B-**INFRAOPS**: GALAXY CATALOGS FOR USE WITH COSMOLOGICAL PIPELINES

The GLADE catalogue (hereafter intended at large as any possible version of it) is used as the default galaxy catalogue for dark siren analyses by the LVK. This activity is dedicated to the development and maintenance of the GLADE catalogue for use in current and upcoming cosmological analyses.

TASK OBS-2.11-B(i)-**INFRAOPS**: IMPROVING CURRENT GALAXY CATALOGS FOR USE WITH COSMOLOGICAL PIPELINES

Extending current galaxy catalogs used by the cosmological pipelines to include data from various publicly available wide-angle spectroscopic and photometric surveys. Verify the fidelity of the input galaxy catalogs, especially photometric redshift catalogs, which can increase the completeness of the catalog..

TASK OBS-2.11-B(ii)-**INFRAOPS**: ASSESSMENT OF GALAXY CATALOG FIDELITY

Establish the limiting magnitude of such catalogs over the sky, compute the luminosity functions of the galaxies which are deemed to be reliable, and make them usable as reliable inputs for the cosmological pipelines. Assess the reliability of photometric redshifts and K corrections within the catalogue, and identify the areas of parameter space in which they can be reliably used, and communicate this as recommended ranges for the cosmological pipelines to use.

TASK OBS-2.11-B(iii)-**INFRAOPS**: GENERATION OF LINE-OF-SIGHT REDSHIFT PRIORS

Generate line-of-sight redshift priors with a variety of different settings (magnitude band, lower luminosity limit, resolution, luminosity weighting assumption, magnitude threshold) for use in LVK cosmological results and systematics studies.

TASK OBS-2.11-B(iv)-**INFRAOPS**: CREATION AND MAINTENANCE OF THE GLADE DATABASE

Set up and maintain a database for the GLADE catalogue, such that the data can be easily read and utilised by the cosmological pipelines.

ACTIVITY OBS-2.11-C-**INFRAOPS**: IDENTIFICATION/MITIGATION OF SYSTEMATIC EFFECTS IN MEASUREMENT OF COSMOLOGICAL PARAMETERS

Since a precise estimate of cosmological parameters requires combining information from multiple events, even small systematic effects can lead to biases in measurements. In addition to the impact of selection effects already discussed above, systematic biases can be present in redshift estimates in galaxy catalogues, which can be significant if photometric catalogues are being used. Incorrect assumptions about the astrophysical population of sirens (both bright and dark sirens) and the evolution of the merger rate and the mass distribution, with redshift which can also lead to biases in the measured cosmological parameters. Moreover GW calibration effects and GW waveform uncertainties are also expected to become important as the precision of measurement becomes tighter with an increasing number of observations. Other effects such as galaxy clustering or correlations between BNS mergers and the properties of their host galaxies might also lead to systematic biases if ignored, but could also be exploited to improve the power of the statistical method. We plan to investigate and attempt to understand these effects thoroughly and compute the requirements (on both statistical uncertainties and systematic biases) necessary to achieve any given specified accuracy in the estimation of cosmological parameters.

TASK OBS-2.11-C(i)-**INFRAOPS**: IDENTIFYING AND MITIGATING KEY GALAXY CATALOG SYSTEMATICS

Identifying key systematics arising from, e.g., photometric redshift uncertainties, K corrections, luminosity function fits, luminosity weighting choices, incompleteness, and data compression (pixelation). Development of mitigation/marginalization strategies in analysis pipelines for these systematic effects.

TASK OBS-2.11-C(ii)-**INFRAOPS**: IDENTIFYING AND MITIGATING KEY GW POPULATION SYSTEMATICS

Identifying key systematics arising from redshift dependence of the mass, spin and merger rate of the GW sources. Development of mitigation/marginalization strategies in analysis pipelines for these systematic effects.

TASK OBS-2.11-C(iii)-**INFRAOPS**: IDENTIFYING AND MITIGATING KEY EM COUNTERPART SYSTEMATICS

Identifying key sources of systematics related to EM counterparts for cosmological analysis, including the impact of EM counterpart inclination angle, and selection effects. Development of mitigation/marginalization strategies in analysis pipelines for these systematic effects.

ACTIVITY OBS-2.11-D-**INFRAOPS**: COSMOLOGY MOCK DATA CHALLENGE

Validation of current and future versions of the cosmology pipeline on an O4-like scenario via a mock data challenge.

TASK OBS-2.11-D(i)-**INFRAOPS**: MOCK DATA CHALLENGE: CONSTRUCTION OF MOCK DATA SET

One or more datasets (complete galaxy catalog, incomplete galaxy catalog, observed events) will be generated that include additional physical population features. The datasets will be tailored on the O4 observational scenarios. One dataset will explore the impact of a GW mass distribution which evolves with redshift. One dataset will use the MICECAT catalogue to produce a realistic galaxy catalogue and investigate the impact of incompleteness and other potential sources of bias related to the galaxy catalogue on the cosmological result.

TASK OBS-2.11-D(ii)-**INFRAOPS**: MOCK DATA CHALLENGE: VALIDATION OF COSMOLOGY PIPELINE

Official LVK cosmology pipelines will be validated by running on the previously mentioned mock datasets. The validation of the pipelines will be performed before the first O4 data release in order to demonstrate the reliability of the LVK cosmological results and highlight potential sources of systematics.

ACTIVITY OBS-2.11-E-**INFRAOPS**: REVIEW OF COSMOLOGY PIPELINE

Continuing method and code review of the cosmology pipeline.

TASK OBS-2.11-E(i)-**INFRAOPS**: REVIEW OF COSMOLOGY PIPELINE

All code review activities, including review of new statistical methods or features adopted in the cosmology pipeline; review of the implementation of new statistical methods/features in the cosmology code; and review of the performance of the cosmology code on the mock data challenge.

ACTIVITY OBS-2.11-F-**INFRAOPS**: H_0 PUBLIC WEBSITE CALCULATOR

Produce a low-latency measurement of H0 in the event of an EM counterpart, using only publicly available data, to be displayed on a public website in order to promote the LVK's cosmological work, as well as raising awareness of the nuances that go into a rigorous estimate of H0 in the EM counterpart case.

TASK OBS-2.11-F(i)-**INFRAOPS**: H_0 WEBSITE

Develop and maintain the public website presenting the latest H0 posteriors calculated with publicly available GW and EM counterpart data. The H_0 results on the website will be updated as soon as possible after any unambiguous EM counterpart has been spotted and its redshift measured. The website will also contain descriptions and general information to educate both the scientific community and the larger public on the details of cosmological GW measurements (in collaboration with the LVK EPO group).

ACTIVITY OBS-2.11-G-**INFRAOPS**: COSMOLOGY SUBGROUP ADMINISTRATION

Management of the Cosmology subgroup.

TASK OBS-2.11-G(i)-**INFRAOPS**: COSMOLOGY SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

TASK OBS-2.11-G(ii)-**INFRAOPS**: LEADERSHIP OF SUBGROUPS AND PROJECTS WITHIN THE COSMOLOGY WORKING GROUP

Administrative and managerial tasks associated with the Cosmological Pipelines Subgroup, Galaxy Catalogues Subgroup, Beyond Lambda-CDM Subgroup, and other ongoing group-wide projects that are not covered elsewhere.

OBS-2.12 CBC Cosmology R&D (Long Term)

Develop methods to estimate cosmological parameters using GW observations, and explore other aspects of CBCs as standard distance indicators (long term).

Motivation and methods

With a large number of events, precision cosmology will be possible using gravitational wave observations of CBCs, combining those with optical counterparts with those without. As the precision of the measurement increases, it will become necessary to fully understand potential systematic sources of error.

Major aspects and methods for this activity

ACTIVITY OBS-2.12-A-**OTHER**: DEVELOP A COMPLETE UNDERSTANDING OF SYSTEMATIC EFFECTS IN MEASUREMENT OF COSMOLOGICAL PARAMETERS

Investigations of the importance of all systematic effects, including those not mentioned explicitly in the ShortTerm section.

TASK OBS-2.12-A(i)-**OTHER**: ASSESSING GALAXY CATALOG SYSTEMATICS

Exploring sources of systematics related to the use of galaxy catalogues in dark siren analyses which are expected to be impactful in the long term.

TASK OBS-2.12-A(ii)-**OTHER**: ASSESSING GW POPULATION SYSTEMATICS

Understanding the impact of redshift dependence of the mass, spin and merger rate of the GW sources. Exploring presence of underlying astrophysical correlation between these parameters that can cause any selection bias.

TASK OBS-2.12-A(iii)-**OTHER**: ASSESSING EM COUNTERPART SYSTEMATICS

Understanding key sources of systematics related to EM counterparts for cosmological analysis, including the impact of EM counterpart inclination angle, and selection effects. For example investigating thoroughly the potential impact of systematic errors in the peculiar velocity correction for nearby sources.

TASK OBS-2.12-A(iv)-**OTHER**: STUDY OTHER SYSTEMATIC EFFECTS IN MEASUREMENT OF COSMOLOGICAL PARAMETERS

Investigation of all possible systematic effects affecting the inference of cosmological parameters, for example waveform, calibration, population model systematics.

ACTIVITY OBS-2.12-B-**OTHER**: DEVELOPMENT OF CROSS-CORRELATION TECHNIQUE FOR COSMOLOGY MEASUREMENTS

GW sources are expected to follow the underlying matter distribution and should exhibit spatial clustering with other tracers of large-scale structures such as galaxies. The exploration of the spatial clustering between GW sources and spectroscopic/photometric galaxy samples will make it possible to infer the redshift of the GW sources. This kind of redshift estimation can be referred to as 'clustering redshift' estimation. One of the key quantities of spatial clustering is the GW bias parameter which takes into account the population of GW sources and the connection of GW sources with the dark matter distribution. We will set up a Bayesian framework that will use cross-correlation between GW sources and galaxies and will give a joint estimation on cosmological parameters such as H_0, the matter fraction the matter fraction Ω_m, the dark energy equation-of-state parameters w_o, w_a, along with the GW bias parameters and its redshift evolution.

TASK OBS-2.12-B(i)-**OTHER**: DEVELOP CROSS-CORRELATION TECHNIQUE FOR COSMOLOGY MEASUREMENTS

Develop pipelines for cross-correlating GW sources with large scale structure surveys on simulated galaxy catalog and real galaxy catalog.

ACTIVITY OBS-2.12-C-**OTHER**: SYNERGIES WITH OTHER COSMOLOGICAL PROBES

Gravitational wave constraints on cosmological parameters are just one of many methods for understanding the large scale structure and evolution of the Universe. It has been frequently demonstrated that different probes can provide orthogonal constraints which, when combined, are much stronger than any one probe in isolation. As gravitational wave constraints improve, the impact on cosmological inference will be greatest when combined with other data sets. The purpose of this project is to understand how GW observations fit into this wider context. We will identify which other types of data are most complementary to the information coming from the GW observations and how constraints can be improved by combining data sets. Other data sets that we will consider will include type Ia supernovae, Baryon Acoustic Oscillations, strong lensing (e.g., HOLICow), surface brightness fluctuation measurements and others.

Another aspect of this project will be to explore how these combined analyses can improve our understanding of other cosmological probes. An example of this is to use GW measurements to improve calibration of type IA supernovae.

TASK OBS-2.12-C(i)-**OTHER**: CATALOGUE CONSTRUCTION FOR SUPERNOVAE CALIBRATION

A binary neutron star coalescence event could be used to validate the distance to a galaxy or a cluster in which a supernova is known to have occurred and hence provide an independent calibration of the supernova luminosity. The GW measurement would be better than other distance estimators if the event was within 100 Mpc. We will explore how such measurements might influence measurements of H0 using supernovae. Using the population of standard sirens, it may also be possible to cross-calibrate other methods such as Type Ia SNe or BAO. This will be particularly useful as a way to look for systematic errors. Assemble a catalogue of all nearby (< 1 Gpc) supernovae, focussing especially on clusters and SNe type Ia.

TASK OBS-2.12-C(ii)-**OTHER**: MOCK DATA CHALLENGE FOR SUPERNOVA CALIBRATION

Set up a mock data challenge for coincident observation of a binary neutron star event and a SNe Ia.

TASK OBS-2.12-C(iii)-**OTHER**: COMPARISON OF STANDARD SIREN CONSTRAINTS WITH OTHER METHODS

Situate standard siren constraints within the landscape of cosmological constraints, focusing especially on Type Ia supernovae and strong lensing time delay constraints.

ACTIVITY OBS-2.12-D-**OTHER**: TESTS OF ΛCDM

The propagation of GWs over cosmological distances may be affected by deviations from ΛCDM, in particular if gravity is no longer well described by GR at large scales as predicted by some modified gravity models of dark energy. Standard sirens, with or without an EM counterpart, can be used to test these deviations and thus to place constraints on beyond-ΛCDM theories. The scope of this activity is to develop model-independent pipelines to test deviations from ΛCDM, and in particular from GR, in the propagation of GWs.

TASK OBS-2.12-D(i)-**OTHER**: TESTING DEVIATIONS FROM ΛCDM FROM GW PROPAGATION

Expand cosmological pipelines to test phenomenological deviations in the standard ΛCDM propagation of GWs at cosmological distances, including e.g. the frictional term and its redshift evolution, from GW sources with/without EM counterparts.

ACTIVITY OBS-2.12-E-**OTHER**: BUILDING IMPROVED GALAXY CATALOGUES FOR USE WITH COSMOLOGICAL PIPELINES

Undertake investigations to improve the galaxy catalogues used by cosmological pipelines by utilizing the latest EM surveys and assessing the potential sources of systematics from them.

TASK OBS-2.12-E(i)-**OTHER**: ASSESSING THE VIABILITY OF CURRENT AND FUTURE PLANNED EM SURVEYS FOR LVK DARK SIREN COSMOLOGY

Exploring the use of current and upcoming (already planned) galaxy surveys (such as Euclid, LSST, 4MOST, DESI, SPHEREx, Roman) which will be available on timescales of O5 to A#. Assess the viability of using these catalogues, and potential limitations, with the aim of informing future LVK Cosmological analyses.

TASK OBS-2.12-E(ii)-**OTHER**: INVESTIGATING THE USE OF DEDICATED EM SURVEYS FOR LVK DARK SIREN COSMOLOGY

Carry out studies on the potential improvement to cosmological inference that could be obtained through the use of EM surveys which are dedicated to GW cosmology. This includes both targeted follow-up of dark sirens, and larger-scale surveys designed to obtain galaxy information specifically for use in dark siren cosmological analyses.

TASK OBS-2.12-E(iii)-**OTHER**: ALTERNATIVE TRACERS FOR LVK GW COSMOLOGY

Explore the use of alternative EM tracers for use in future LVK dark siren cosmology, such as galaxy cluster catalogues, HI intensity mapping, LRGs, or other galaxy subsets. Assess the use of these tracers for reconstructing $n(z)$, including incompleteness corrections and bias.

ACTIVITY OBS-2.12-F-**OTHER**: PRIMORDIAL BLACK HOLES AND DARK MATTER

Develop methods for constraints and model selection of primordial black hole (PBHs) based on CBC observations. Develop or extend techniques and methods to constrain particle dark matter models from CBC observations in combination with continuous waves and stochastic GW limits.

Gravitational-wave observations provide a novel way to probe the nature and origin of dark matter in cosmology as well as primordial black holes (PBHs) expected to be formed due to inhomogeneities in the early universe. The methods involved in PBH searches and constraints include the computation of the GW signatures (e.g. mass function, rates in different binary formation channels, spin distributions) in different PBH scenarios. Additionally, statistical methods for model selection (PBH versus astrophysical models) would constrain the theoretical PBH models. In several models of dark matter, new particles or fields can leave imprints in the GW signals from CBCs or produce continuous waves or stochastic GW backgrounds.

TASK OBS-2.12-F(i)-**OTHER**: MODEL SELECTION OF PBH VS ASTROPHYSICAL SCENARIOS, BASED ON THE CBC MASS AND SPIN DISTRIBUTIONS

Development or extension of statistical methods for the Bayesian selection of PBH models versus astrophysical scenarios, based on the rate, mass and spin distributions of CBC observations. Improvement of the merger rate prescriptions for PBHs in the case of extended mass distributions. Computation of improved constraints on viable PBH models. Develop tools for Bayesian model selection of PBH models versus astrophysical scenarios based on the inferred rate and mass distributions.

TASK OBS-2.12-F(ii)-**OTHER**: POSSIBLE PBH INTERPRETATION OF EXCEPTIONAL OR SPECIAL EVENTS

For exceptional CBC events, the component masses and spins as well as the inferred merger rates could hint to a primordial origin rather than an astrophysical one. Assuming a primordial origin, the implications of these events for PBH scenarios could be investigated. Methods would include

CBC parameter estimations and merger rate inference based on PBH-inspired mass functions instead of ones expected for neutron stars or astrophysical black holes. Develop tools that can be used to identify an exceptional event as a PBH candidate.

TASK OBS-2.12-F(iii)-**OTHER**: SYNERGIES BETWEEN CBC OBSERVATIONS AND LIMITS ON CWS AND THE SGWB

The PBH scenarios able to explain CBC observations can be further tested against the limits on continuous GWs from inspiralling light PBH binaries, set by all-sky or targetted searches, and on the stochastic GW background from PBH binaries (primordial or in PBH clusters), close encounters and formation in the early universe. Moreover, the synergy between CBC observations and continuous waves and/or the stochastic background leads the way to other aspects of dark matter science. GW backgrounds from PBHs could be distinguished from cosmological and astrophysical backgrounds by distinguishing the shot-noise, pop-corn and continuous regimes and by calculating the duty cycle. A combination of CBC SSM searches with GW background limits could also provide new limits on the abundance of PBHs and on possible PBH mass distributions. Superradiance from (scalar, vector or tensor) ultra-light boson clouds has an effect on the black hole spins. It is therefore possible to set limits on models with ultra-light bosons from spin measurements in black hole mergers. Limits on CW signals from all-sky or directed searches (towards galactic center, known X-ray binaries, or dwarf galaxies) is another way to constrain these models. Stochastic and continuous wave techniques can further be used to constrain the dark photon – the dark photon is expected to couple to the baryons in the detector mirrors, inducing a quantum-mechanical force that can be interpreted as a GW strain. Develop methods for joint inference using CBC, CW, and SGWB search results.

ACTIVITY OBS-2.12-G-**OTHER**: DEVELOPMENT FOR DARK SIREN METHOD WITH SINGLE HOST

BBH sources which are well localised in the plane of the sky can be used to measure the Hubble constant. Such sources may contain a single galaxy in the field of view. A targeted search in the localisation region can identify the host galaxy. Subsequent EM measurements can be undertaken to measure the redshift of the host. This will yield a measurement of the Hubble constant.

TASK OBS-2.12-G(i)-**OTHER**: DEVELOP SINGLE-HOST DARK SIREN METHOD FOR H_0 MEASUREMENT

Develop methods to marginalise H_0 over sub-luminous galaxies. Evaluate the accuracy with which H_0 can be inferred in the presence of higher order modes and spin precession. Develop methods to identify host galaxy.

ACTIVITY OBS-2.12-H-**OTHER**: DESIGNING COSMOLOGICAL PIPELINES FOR THE FUTURE

As GW astronomy moves towards the era of big data, new methods of computation and data compression need to be investigated in order to scale up analyses to handle the number of GW detections expected in O5 and beyond. It is not only the increasing number of GW detections which fuels this need. Large scale galaxy surveys will require new data handling techniques. Ever more complex parameter spaces and distributions will require more efficient sampling techniques. This activity includes development to current and future cosmological pipelines which aim to address these challenges.

TASK OBS-2.12-H(i)-**OTHER**: DEVELOP METHODS FOR HANDLING LARGE-SCALE ANALYSES

Develop methods for handling large-scale data cosmological analyses, including use of machine learning techniques, GPUs, and data compression techniques.

OBS-2.13 CBC All Sky Search ShortTerm R&D

Short term development and tuning of search pipelines for online/offline running; generate template banks; assess data quality issues relevant to CBC detection. Requirements for going into O4 operations.

Motivation and methods

The online and offline detection and search technical development groups work to develop sensitive and computationally efficient pipelines to identify compact binary merger signals in strain data, and manage the generation of search results via running the pipelines on LIGO-Virgo-KAGRA data. These pipelines generally operate in "all-sky" mode, i.e., searching all available data after non-analyzable times have been identified and removed, as distinct from "externally triggered" searches for GWs from reported astrophysical events such as GRBs.

Offline searches run with a latency of order a few days to weeks on a stable and carefully selected data set, to provide reproducible results for publication including precise evaluation of the significance and p-astro classification of candidate events and the sensitivity of the search to populations of realistic binary merger signals. Online / low-latency searches run primarily to generate triggers for follow-up including initial evaluation of trigger significance, mass and spin values and extrinsic parameters relevant to sky localization and p-astro classification. Development of methods for low latency data selection and estimation of search sensitivity is motivated by the desirability of convergence of results between online and offline searches if possible.

Major aspects and methods for this activity

ACTIVITY OBS-2.13-A-**INFRAOPS**: CBC O4 SEARCH PIPELINE DEVELOPMENT

With the evolution of the number of detectors, their sensitivity, the quality of their data, and as we improve our knowledge of the astrophysical population of compact binary mergers, it is often necessary to update aspects of the search pipelines to optimize their efficiency.

Changes to template banks are occasionally needed in order to respond to changes in detector sensitivity curves, as well as changes to the parameter space of signals being targeted.

While previous observing runs of the advanced detector era saw a maximum of 3 detectors taking data simultaneously, O4 might be the first 4-detector run, depending on the progress of KAGRA's sensitivity. Pipelines must be ready to handle this multi-detector data in O4.

In addition, a number of the most important observations have been made with data from only a single detector. Reliably estimating event significance in single-detector data is more challenging than it is with multiple-detector data, and pipelines are working to improve this.

TASK OBS-2.13-A(i)-**INFRAOPS**: CONSTRUCTION OF A TEMPLATE BANK FOR GSTLAL

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes. Tune and test the template bank's performance in simulations and real data.

TASK OBS-2.13-A(ii)-**INFRAOPS**: DEVELOPMENT OF A 4-DETECTOR SEARCH FOR GSTLAL

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK OBS-2.13-A(iii)-**INFRAOPS**: CONTINUE OPTIMIZING THE GSTLAL SEARCH SENSITIVITY FOR O4

Incremental improvements to the GstLAL pipeline's search sensitivity following the evolution of the O4 run.

TASK OBS-2.13-A(iv)-**INFRAOPS**: CONTINUE OPTIMIZING THE GSTLAL P-ASTRO CALCULATION FOR O4

Improvements to the GstLAL pipeline's p-astro computation following the evolution of the O4 run.

TASK OBS-2.13-A(v)-**INFRAOPS**: CONTINUE OPTIMIZING THE GSTLAL COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the GstLAL pipeline's computational performance following the evolution of the O4 run.

TASK OBS-2.13-A(vi)-**INFRAOPS**: CONTINUE OPTIMIZING THE GSTLAL ONLINE LATENCY

Improvements to GstLAL online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

TASK OBS-2.13-A(vii)-**INFRAOPS**: GSTLAL DEVELOPMENT OR OPTIMIZATION WORK SPECIFIC FOR SUB-SOLAR MASS SEARCHES

Any development or optimisation effort needed specifically for the SSM search.

TASK OBS-2.13-A(viii)-**INFRAOPS**: CONSTRUCTION OF A TEMPLATE BANK FOR MBTA

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK OBS-2.13-A(ix)-**INFRAOPS**: DEVELOPMENT OF A 4-DETECTOR SEARCH FOR MBTA

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK OBS-2.13-A(x)-**INFRAOPS**: CONTINUE OPTIMIZING THE MBTA SEARCH SENSITIVITY FOR O4

Incremental improvements to the MBTA pipeline's search sensitivity following the evolution of the O4 run.

TASK OBS-2.13-A(xi)-**INFRAOPS**: CONTINUE OPTIMIZING THE MBTA P-ASTRO CALCULATION FOR O4

Improvements to the MBTA pipeline's p-astro computation following the evolution of the O4 run.

TASK OBS-2.13-A(xii)-**INFRAOPS**: CONTINUE OPTIMIZING THE MBTA COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the MBTA pipeline's computational performance following the evolution of the O4 run.

TASK OBS-2.13-A(xiii)-**INFRAOPS**: CONTINUE OPTIMIZING THE MBTA ONLINE LATENCY

Improvements to MBTA online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

TASK OBS-2.13-A(xiv)-**INFRAOPS**: MBTA DEVELOPMENT OR OPTIMIZATION WORK SPECIFIC FOR SUB-SOLAR MASS SEARCHES

Any development or optimisation effort needed specifically for the SSM search.

TASK OBS-2.13-A(xv)-**INFRAOPS**: CONSTRUCTION OF A TEMPLATE BANK FOR PYCBC

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK OBS-2.13-A(xvi)-**INFRAOPS**: DEVELOPMENT OF A 4-DETECTOR SEARCH FOR PYCBC

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK OBS-2.13-A(xvii)-**INFRAOPS**: CONTINUE OPTIMIZING THE PYCBC SEARCH SENSITIVITY FOR O4

Incremental improvements to the PyCBC pipeline's search sensitivity following the evolution of the O4 run.

TASK OBS-2.13-A(xviii)-**INFRAOPS**: CONTINUE OPTIMIZING THE PYCBC P-ASTRO CALCULATION FOR O4

Improvements to the PyCBC pipeline's p-astro computation following the evolution of the O4 run.

TASK OBS-2.13-A(xix)-**INFRAOPS**: CONTINUE OPTIMIZING THE PYCBC COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the PyCBC pipeline's computational performance for the O4 run.

TASK OBS-2.13-A(xx)-**INFRAOPS**: CONTINUE OPTIMIZING THE PYCBC ONLINE LATENCY

Improvements to PyCBC online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

TASK OBS-2.13-A(xxi)-**INFRAOPS**: PYCBC DEVELOPMENT OR OPTIMIZATION WORK SPECIFIC FOR SUB-SOLAR MASS SEARCHES

Any development or optimisation effort needed specifically for the SSM search.

TASK OBS-2.13-A(xxii)-**INFRAOPS**: CONSTRUCTION OF A TEMPLATE BANK FOR SPIIR

Construct a template bank that covers the parameter space spanning binary neutron stars, neutron star + black holes, stellar-mass binary black holes, and intermediate-mass binary black holes.

TASK OBS-2.13-A(xxiii)-**INFRAOPS**: DEVELOPMENT OF A 4-DETECTOR SEARCH FOR SPIIR

Develop a search capable of analyzing data from LIGO, Virgo, and KAGRA.

TASK OBS-2.13-A(xxiv)-**INFRAOPS**: CONTINUE OPTIMIZING THE SPIIR SEARCH SENSITIVITY FOR O4

Incremental improvements to the SPIIR pipeline's search sensitivity following the evolution of the O4 run.

TASK OBS-2.13-A(xxv)-**INFRAOPS**: CONTINUE OPTIMIZING THE SPIIR P-ASTRO CALCULATION FOR O4

Improvements to the SPIIR pipeline's p-astro computation following the evolution of the O4 run.

TASK OBS-2.13-A(xxvi)-**INFRAOPS**: CONTINUE OPTIMIZING THE SPIIR COMPUTATIONAL PERFORMANCE FOR O4

Incremental improvements to the SPIIR pipeline's computational performance for the O4 run.

TASK OBS-2.13-A(xxvii)-**INFRAOPS**: CONTINUE OPTIMIZING THE SPIIR ONLINE LATENCY

Improvements to SPIIR online analysis that reduce latency of alerts and allow for BNS alerts ~ 30 seconds before merger.

ACTIVITY OBS-2.13-B-**INFRAOPS**: CBC O4 SEARCH PIPELINE DEPLOYMENT

Search pipelines must be deployed, maintained and monitored on collaboration computer clusters for O4 online and offline analyses.

TASK OBS-2.13-B(i)-**INFRAOPS**: DEPLOYMENT OF GSTLAL PIPELINE FOR ONLINE RUNNING

Deploy, monitor, and maintain the GstLAL online pipeline for low-latency trigger generation, including SSM search.

TASK OBS-2.13-B(ii)-**INFRAOPS**: DEPLOYMENT OF GSTLAL PIPELINE FOR OFFLINE RUNNING

Deploy and maintain the GstLAL pipeline for deeper offline searches.

TASK OBS-2.13-B(iii)-**INFRAOPS**: DEPLOYMENT OF MBTA PIPELINE FOR ONLINE RUNNING

Deploy, monitor, and maintain the MBTA online pipeline for low-latency trigger generation, including SSM search.

TASK OBS-2.13-B(iv)-**INFRAOPS**: DEPLOYMENT OF MBTA PIPELINE FOR OFFLINE RUNNING

Deploy and maintain the MBTA pipeline for deeper offline searches.

TASK OBS-2.13-B(v)-**INFRAOPS**: DEPLOYMENT OF PYCBC PIPELINE FOR ONLINE RUNNING

Deploy, monitor, and maintain the PyCBC online pipeline for low-latency trigger generation.

TASK OBS-2.13-B(vi)-**INFRAOPS**: DEPLOYMENT OF PYCBC PIPELINE FOR OFFLINE RUNNING

Deploy and maintain the PyCBC pipeline for deeper offline searches.

TASK OBS-2.13-B(vii)-**INFRAOPS**: DEPLOYMENT OF SPIIR PIPELINE FOR ONLINE RUNNING

Deploy, monitor, and maintain the SPIIR online pipeline for low-latency trigger generation.

TASK OBS-2.13-B(viii)-**INFRAOPS**: DEPLOYMENT OF SPIIR PIPELINE FOR OFFLINE RUNNING

Deploy and maintain the SPIIR pipeline for deeper offline searches.

ACTIVITY OBS-2.13-C-**INFRAOPS**: CBC O4 EARLY WARNING PIPELINE DEPLOYMENT

Early-warning pipelines will be deployed and maintained on collaboration computer clusters for O4 online analyses.

TASK OBS-2.13-C(i)-**INFRAOPS**: DEPLOYMENT OF GSTLAL EARLY-WARNING PIPELINE

Deploy, monitor, and maintain the GstLAL early-warning pipeline for pre-merger trigger generation.

TASK OBS-2.13-C(ii)-**INFRAOPS**: DEPLOYMENT OF MBTA EARLY-WARNING PIPELINE

Deploy, monitor, and maintain the MBTA early-warning pipeline for pre-merger trigger generation.

TASK OBS-2.13-C(iii)-**INFRAOPS**: DEPLOYMENT OF PYCBC EARLY-WARNING PIPELINE

Deploy, monitor, and maintain the PyCBC early-warning pipeline for pre-merger trigger generation.

TASK OBS-2.13-C(iv)-**INFRAOPS**: DEPLOYMENT OF SPIIR EARLY-WARNING PIPELINE

Deploy, monitor, and maintain the SPIIR early-warning pipeline for pre-merger trigger generation.

O4 Early-Warning Pipeline Deployment

ACTIVITY OBS-2.13-D-**INFRAOPS**: CBC O4 SEARCH PIPELINE REVIEW

Review of search pipelines used for O4 results.

TASK OBS-2.13-D(i)-**INFRAOPS**: REVIEW OF GSTLAL PIPELINE

Review of changes to the GstLAL offline pipeline. Both changes to code and to configurations will be reviewed.

TASK OBS-2.13-D(ii)-**INFRAOPS**: REVIEW OF MBTA PIPELINE

Review of changes to the MBTA offline pipeline. Both changes to code and to configurations will be reviewed.

TASK OBS-2.13-D(iii)-**INFRAOPS**: REVIEW OF PYCBC PIPELINE

Review of changes to the PyCBC offline pipeline. Both changes to code and to configurations will be reviewed.

TASK OBS-2.13-D(iv)-**INFRAOPS**: REVIEW OF SPIIR PIPELINE

Review of changes to the SPIIR offline pipeline. Both changes to code and to configurations will be reviewed.

ACTIVITY OBS-2.13-E-**INFRAOPS**: CBC-RELATED DETECTOR CHARACTERIZATION TASKS

Development and maintenance of tools to characterize the impact of detector state on CBC searches and identify possible veto times was ongoing since O3 and will continue through O4 to adapt to new detector characterization challenges encountered.

TASK OBS-2.13-E(i)-**INFRAOPS**: DETCHAR FOLLOWUP OF GSTLAL TRIGGERS

Investigate GstLAL single-detector events produced from offline/online runs to identify things that are harming the search sensitivity and feed this onto instrumentalists to fix the underlying cause and/or include vetoes where appropriate and fair.

TASK OBS-2.13-E(ii)-**INFRAOPS**: DETCHAR FOLLOWUP OF MBTA TRIGGERS

Investigate MBTA single-detector events produced from offline/online runs to identify things that are harming the search sensitivity and feed this onto instrumentalists to fix the underlying cause and/or include vetoes where appropriate and fair.

TASK OBS-2.13-E(iii)-**INFRAOPS**: DETCHAR FOLLOWUP OF PYCBC TRIGGERS

Investigate PyCBC single-detector events produced from offline/online runs to identify things that are harming the search sensitivity and feed this onto instrumentalists to fix the underlying cause and/or include vetoes where appropriate and fair.

ACTIVITY OBS-2.13-F-**INFRAOPS**: CBC ALL-SKY SEARCHES SUBGROUP ADMINISTRATION

Management of the all-sky pipelines subgroup.

TASK OBS-2.13-F(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

OBS-2.14 CBC All Sky Search R&D (Long Term)

Long term development and tuning of search pipelines for online/offline running.

Motivation and methods

As well as continuing to run online and offline searches in O4, we must start to consider the problems that future improvements to the detector, and the inclusion of additional detectors, will bring (All with next to no personpower). We specifically want to consider expanding the search parameter space to include "exotic" sources, which our current searches are not sensitive to. We want to consider how to efficiently search using a network of detectors, and we want to start to consider how we will address the computational challenges that 3G-networks will pose.

Major aspects and methods for this activity

ACTIVITY OBS-2.14-A-**OTHER**: OFFLINE SEARCH FOR CBC INVOLVING AT LEAST ONE SUB-SOLAR-MASS COMPACT OBJECT

TASK OBS-2.14-A(i)-**OTHER**: CONSTRUCTION OF A TEMPLATE BANK FOR GSTLAL SSM SEARCH

Construct a template bank that covers the sub-solar-mass search parameter space.

TASK OBS-2.14-A(ii)-**OTHER**: CONSTRUCTION OF A TEMPLATE BANK FOR MBTA SSM SEARCH

Construct a template bank that covers the sub-solar-mass search parameter space.

TASK OBS-2.14-A(iii)-**OTHER**: CONSTRUCTION OF A TEMPLATE BANK FOR PYCBC SSM SEARCH

Construct a template bank that covers the sub-solar-mass search parameter space.

TASK OBS-2.14-A(iv)-**OTHER**: DEPLOYMENT OF GSTLAL PIPELINE FOR THE SSM SEARCH OFFLINE RUNNING

Deploy and maintain the GstLAL pipeline for offline sub-solar-mass searches, including DetChar followup of eventual candidates.

TASK OBS-2.14-A(v)-**OTHER**: DEPLOYMENT OF MBTA PIPELINE FOR THE SSM SEARCH OFFLINE RUNNING

Deploy and maintain the MBTA pipeline for offline sub-solar-mass searches, including DetChar followup of eventual candidates.

TASK OBS-2.14-A(vi)-**OTHER**: DEPLOYMENT OF PYCBC PIPELINE FOR THE SSM SEARCH OFFLINE RUNNING

Deploy and maintain the PyCBC pipeline for offline sub-solar-mass searches, including DetChar followup of eventual candidates.

ACTIVITY OBS-2.14-B-**OTHER**: SEARCHING FOR NOVEL OR "EXOTIC" CBC SOURCE TYPES

Current search techniques necessarily make assumptions about the signal model to reduce the computational cost. These assumptions lead to certain types of rare, but astrophysically very rewarding, systems potentially being missed. This includes systems exhibiting strong precessional dynamics, systems where subdominant modes have a significant contribution, systems on significantly eccentric orbits, systems containing neutron stars and involving strong matter effects, and signals emitted from compact objects whose behaviour significantly deviates from GR predictions. New methods have been proposed to search for some of these sources, but significant work on implementation and tuning of a search will be required to obtain results. Hopefully some of these features could be searched for already in O4.

TASK OBS-2.14-B(i)-**OTHER**: SEARCH FOR NOVEL OR EXOTIC CBC SOURCE TYPES

ACTIVITY OBS-2.14-C-**OTHER**: CBC COHERENT ALL-SKY SEARCH WITH 3+ DETECTORS

CBC searches currently look for coincident triggers, with the exception of the coherent GRB analysis. In the long term, a network of 3+ detectors of comparable sensitivity will motivate the development of fully coherent search algorithms. Considerable work remains to be done in optimisation to extend the methods pioneered in the coherent GRB analysis to cover the all-sky, all-time parameter space in a computationally efficient manner. This research will continue throughout the O4 timeframe, with the aim of reaching maturity in time for design sensitivity detector networks.

TASK OBS-2.14-C(i)-**OTHER**: COHERENT ALL-SKY CBC SEARCH WITH 3+ DETECTORS

ACTIVITY OBS-2.14-D-**OTHER**: CBC NOVEL SEARCH OPTIMIZATION TECHNIQUES

To address the computational challenge that the 3G era, and to a lesser extent, a 5-detector 2G network at design sensitivity, will pose, we must consider how to reduce the computational cost of our searches. A number of methods have been proposed for this, including reducing the template count by using a reduced basis, using multi-banding to achieve a similar effect and computational optimization of existing codes. Additionally it has been proposed that convolutional neural networks might achieve similar sensitivity to traditional matched-filtering searches, at least in some regions of the search parameter space. Given the wide range of methods and requirements, this activity is expected to be an area of research for some time to come, with the implementation and review of practical methods likely to be during O4 or beyond.

TASK OBS-2.14-D(i)-**OTHER**: NOVEL OPTIMIZATION TECHNIQUES FOR CBC SEARCHES

ACTIVITY OBS-2.14-E-**OTHER**: CBC NOVEL SEARCH SENSITIVITY IMPROVEMENTS

As we learn more about the search parameter space, we should continue to think about how we can most effectively find the compact binary merger signals buried in our data. This broad item covers a number of techniques that might be considered to improve search sensitivity. This ranges from using improved signal-based classifiers to better separate noise from signal, using better glitch identification techniques to remove non-Gaussianities from the data that can particularly harm the search to including better knowledge of the types of compact binary in the Universe to better identify “sub-threshold” events.

TASK OBS-2.14-E(i)-**OTHER**: NOVEL SENSITIVITY IMPROVEMENTS FOR CBC SEARCHES

ACTIVITY OBS-2.14-F-**INFRAOPS**: CBC SEARCH PIPELINE COMBINATION

With multiple pipelines analyzing the same data, the opportunity arises to combine them together to produce a single unified detection statement. There are two distinct motivations to do this. First, if optimally combined, we can leverage their strengths to increase the overall detection efficieny. Second, combining pipelines can simplify the information for downstream analysts providing a single unified statement.

TASK OBS-2.14-F(i)-**INFRAOPS**: DEVELOPMENT OF A COMBINATION META-PIPELINE FOR CBC SEARCHES

We will look to develop a meta-pipeline that combines the outputs from individual pipelines to optimize sensitivity. This will provide users with a single measure of significance folding in our understanding of the relative performance of pipelines. A range of methodologies will be explored, compared and validated using large-scale simulated and or augmented data. The meta-pipeline will be applied to both online and offline searches.

OBS-2.15 Lensing R&D (Short Term)

Research and development on searches for lensing of gravitational waves.

Motivation and methods

The Lensing group is primarily responsible for searching for signatures of gravitational lensing of gravitational waves in the LIGO–Virgo–KAGRA data, and for developing the associated data analysis infrastructure. Depending of the type of lens, gravitational lensing offers a rich phenomenology. Within the Lensing group we search this broad spectrum: from multiple images produced in gravitational waves strongly lensed by a galaxy or galaxy cluster, to interference and wave effects when the lenses sizes are comparable to the wavelengths of the gravitational waves. Other searches for lensing include search for highly magnified events, signatures in the stochastic background, as well as modeling of the gravitational lenses and their population, and constraints on the population of sources. In addition to perform the mentioned searches, we will improve the analysis techniques and develop methods to assess the systematics and detection thresholds. The LVK Collaborations want to be ready for gravitationally lensed detections. Thus, the short-term lensing R&D development develops critical infrastructure to detect gravitational-wave lensing.

Major aspects and methods for this activity

ACTIVITY OBS-2.15-A-**INFRAOPS**: LENSING SEARCHES FOR MULTIPLE IMAGES

TASK OBS-2.15-A(i)-**INFRAOPS**: MACHINE LEARNING MULTI-IMAGE SEARCH PIPELINES

Infrastructure development to improve machine learning algorithms targeting lensed multiple images. Particularly the accuracy of the machine learning pipelines will require further improvements in order to confidently detect strong lensing.

TASK OBS-2.15-A(ii)-**INFRAOPS**: POSTERIOR-BASED SEARCH PIPELINES FOR STRONG LENSING

Infrastructure development to analyse strong lensing candidates with a postprocessing step. Particularly the efficiency of the pipelines, phase consistency calculation and the KDE reconstruction will require further development.

TASK OBS-2.15-A(iii)-**INFRAOPS**: FACTORIZED JOINT PARAMETER ESTIMATION PIPELINES

Infrastructure development for factorized joint parameter estimation using importance sampling and pre-computed look-up tables to perform "factorized" joint parameter estimation. Particularly the mapping from image properties to lens properties, inclusion of better population models, and inclusion of posterior Odd computations, are crucial to strong lensing detections.

TASK OBS-2.15-A(iv)-**INFRAOPS**: JOINT PARAMETER ESTIMATION PIPELINES

Infrastructure development towards joint parameter estimation searches using template-based approaches. Particularly improving the efficiency of the pipeline as well as including more advanced lensing statistical models will be crucial.

TASK OBS-2.15-A(v)-**INFRAOPS**: SUB-THRESHOLD SEARCH PIPELINES

Infrastructure development towards searches for weak multiple-image counterparts to strong lensing candidates. Better identification procedures through the inclusion of sky maps as well as strong lensing time delays will be crucial to correctly identify candidates below the noise threshold.

TASK OBS-2.15-A(vi)-**INFRAOPS**: STRAIN-BASED CROSS-CORRELATION SEARCH PIPELINES

Infrastructure development towards searches for strongly lensed multiple-image using strain-based cross-correlation methods. Particularly improvements on the efficiency and accuracy of the technique are required for a robust detection of lensed gravitational wave signals.

ACTIVITY OBS-2.15-B-**INFRAOPS**: LENSING SEARCH FOR INTERFERENCE AND WAVE EFFECTS

TASK OBS-2.15-B(i)-**INFRAOPS**: MICROLENSING SEARCH PIPELINES

Infrastructure development to target microlensed events and to combine strong lensing analyses with microlensing analyses for both isolated and population of microlenses. Particularly the inclusion of more advanced microlens models going beyond isolated microlenses is crucial for microlensing detections and follow-up analysis of strong lensing candidates. Microlensing searches include traditional Bayesian inference, residual tests and machine learning techniques.

TASK OBS-2.15-B(ii)-**INFRAOPS**: MILLILENSING SEARCH PIPELINES

Infrastructure development towards a new model-independent inference for millilensing based on geometrical optics approximation. A model-independent approach will allow for a follow-up analysis of the strong lensing candidates. Full development of the model-independent search PE framework as well as a mapping from image parameters to millilensing parameters will be crucial to millilens identification and follow-up analysis.

ACTIVITY OBS-2.15-C-**INFRAOPS**: WAVEFORM SYSTEMATICS STUDIES FOR LENSING ANALYSES

Study the impact of using waveforms from different modelling approaches and with different physics content (e.g. precession, higher modes) in the searches, parameter estimation and model selection methods used for identifying lensing signatures of all types. Understanding waveform systematics is critical to distinguish lensed detections from mimickers.

TASK OBS-2.15-C(i)-**INFRAOPS**: PERFORM WAVEFORM SYSTEMATICS STUDIES

ACTIVITY OBS-2.15-D-**INFRAOPS**: LENS MODEL SELECTION EFFECTS

TASK OBS-2.15-D(i)-**INFRAOPS**: SELECTION EFFECTS FOR STRONG-, MILLI- AND MICRO-LENS POPULATION

Development for connecting strong-, milli- and micro-lens detections with lens modelling and their selection effects given the lens and source populations.

TASK OBS-2.15-D(ii)-**INFRAOPS**: SELECTION EFFECTS FROM LENS POPULATION OF COMPACT OBJECTS

Development of improved selection effects when the lenses are compact objects as dark matter. Particularly the inclusion of more advanced primordial black hole models as well as a better connection between the parameter inference pipelines and the follow-up compact object analyses is critical to new dark matter constraints.

TASK OBS-2.15-D(iii)-**INFRAOPS**: MODELING OF LENS POPULATIONS

Development for lens models to be used in the assesment of the evidence of gravitational-wave lensing.

ACTIVITY OBS-2.15-E-**INFRAOPS**: BUILDING COMMON INFRASTRUCTURE FOR LENSING FIRST DETECTION

Develop and review infrastructure in preparation for upcoming runs.

TASK OBS-2.15-E(i)-**INFRAOPS**: DEVELOPMENT OF AUTOMATED LENSING WORKFLOW

Development of automated framework 'LensingFlow' which will be used to automate deployment of the other lensing pipelines.

TASK OBS-2.15-E(ii)-**INFRAOPS**: MOCK DATA CHALLENGE

Creation and analysis of mock data to test the effiency and accuracy of the lensing pipelines and the automated workflow.

TASK OBS-2.15-E(iii)-**INFRAOPS**: BACKGROUND ANALYSIS

Creation and analysis of an unlensed background of events in order to calibrate statistical output from lensing pipelines.

ACTIVITY OBS-2.15-F-**INFRAOPS**: SEARCHING FOR EXCEPTIONAL LENSED CANDIDATES AT LOW AND MEDIUM LATENCIES

TASK OBS-2.15-F(i)-**INFRAOPS**: DEPLOY POSTERIOR-BASED SEARCH PIPELINE

The posterior-based multiple image search pipelines will provide a computationally efficient low-latency way to identify strongly lensed candidate pairs in the data.

TASK OBS-2.15-F(ii)-**INFRAOPS**: DEPLOY THE MACHINE LEARNING PIPELINES

The Machine Learning pipelines will provide a computationally efficient low-latency way to identify strongly lensed candidate pairs in the data that is not based on their posterior samples.

TASK OBS-2.15-F(iii)-**INFRAOPS**: DEPLOY THE SUB-THRESHOLD LENSING PIPELINES

The Sub-threshold pipelines will provide a computationally efficient medium-latency way to identify strongly lensed pairs with one event being sub-threhold.

TASK OBS-2.15-F(iv)-**INFRAOPS**: DEPLOY THE TYPE II IMAGE LENSING PIPELINES

The Type II image pipelines will provide a computationally efficient medium-latency way to identify strongly lensed type II images by their waveform distortions.

TASK OBS-2.15-F(v)-**INFRAOPS**: DEPLOY THE MICROLENSING PIPELINES

The Microlensing pipelines will provide a computationally efficient medium-latency way to identify wave effects due to lensing by compact lenses.

TASK OBS-2.15-F(vi)-**INFRAOPS**: DEPLOY THE MILLILENSING PIPELINES

The Millilensing pipelines will provide a computationally efficient medium-latency way to identify interference effects due to lensing by compact lenses.

TASK OBS-2.15-F(vii)-**INFRAOPS**: FOLLOW-UP ANALYSIS OF INTERESTING CANDIDATES

For any interesting candidate, we will perform a focus study to investigate its potential for being a lensed candidate.

TASK OBS-2.15-F(viii)-**INFRAOPS**: DEPLOYMENT OF AUTOMATED WORKFLOW

The automated lensing workflow 'LensingFlow' will manage the deployment of lensing pipelines to ensure that data is analysed and passed between pipelines efficiently. It will also perform ongoing prioritisation to ensure that more interesting candidates are analysed more quickly whilst ensuring complete analysis in the longer term.

TASK OBS-2.15-F(ix)-**INFRAOPS**: DEPLOY THE STRAIN-BASED CROSS-CORRELATION SEARCH PIPELINES

The strain-based cross-correlation methods will provide a computationally efficient low-latency way to identify strongly lensed candidate pairs in the data that is based on direct analysis of the strain data.

ACTIVITY OBS-2.15-G-**INFRAOPS**: LENSING SUBGROUP ADMINISTRATION

Management of the Lensing subgroup.

TASK OBS-2.15-G(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership.

OBS-2.16 Lensing R&D (Long Term)

Long-term research and development on searches for lensing of gravitational waves.

Major aspects and methods for this activity

ACTIVITY OBS-2.16-A-**OTHER**: STUDY LENSING DETECTION THRESHOLDS AND FALSE ALARM PROBABILITIES

The goal is to determine solid thresholds for the first identification of lensing of gravitational waves in its different regimes. This includes among other things performing background studies, mock data challenges.

TASK OBS-2.16-A(i)-**OTHER**: DETECTION THRESHOLDS AND FALSE ALARMS

ACTIVITY OBS-2.16-B-**OTHER**: MODELING OF LENS POPULATIONS

Improve the modeling of lens populations and lensing rates and investigate the use of improved lens models in data analysis pipelines.

TASK OBS-2.16-B(i)-**OTHER**: MODELING LENS POPULATION

ACTIVITY OBS-2.16-C-**OTHER**: INFERENCE TOOLS FOR LENSING SIGNATURES

Improve the inference tools to detect and characterize lensing signatures from existing detections, including the investigation of microlensing/millilensing effects and multiple images, prior choices, and selection effects.

TASK OBS-2.16-C(i)-**OTHER**: INFERENCE TOOLS

ACTIVITY OBS-2.16-D-**OTHER**: INFERENCE OF THE LENS AND SOURCE POPULATION

Develop methods to make astrophysical inference (e.g., nature of dark matter) from lensing signatures in gravitational-wave signals, as well as develop methods to infer properties of the source population from detections of lensed gravitational-wave signals as well as the stochastic background.

TASK OBS-2.16-D(i)-**OTHER**: INFERENCE SOURCE POPULATION

ACTIVITY OBS-2.16-E-**OTHER**: SUBTHRESHOLD LENSING SEARCHES

Improve sub-threshold search pipelines to detect lensed counterparts of transient gravitational-wave signals.

TASK OBS-2.16-E(i)-**OTHER**: SUB-THRESHOLD

ACTIVITY OBS-2.16-F-**OTHER**: MULTI-MESSENGER SIGNALS OF LENSING

Study the enhancement in the identification of strongly lensed gravitational wave using electromagnetic observations via searching for lensed counterparts or background objects lensed by the same lens. This also includes predicting the time delay from images of host galaxies of CBCs as a means to enhance early-warning and using catalogs of lensed galaxies to help identify lensed CBCs

TASK OBS-2.16-F(i)-**OTHER**: MULTI-MESSENGER LENSING

TASK OBS-2.16-F(ii)-**OTHER**: STRONG LENSING IDENTIFICATION WITH CROSS-MATCHING WITH EM CATALOGS

Leverage the EM imaging and catalogs to extract corresponding image properties such as time-delays, to enhance GW early-warning, and improve significance and inference of the candidate lensed GW event pairs.

ACTIVITY OBS-2.16-G-**OTHER**: LENSING PROBES ON FUNDAMENTAL PHYSICS AND COSMOLOGY

TASK OBS-2.16-G(i)-**OTHER**: TESTING GENERAL RELATIVITY WITH GRAVITATIONAL LENSING

Develop model agnostic and theory-specific analyses to test for the gravitational-wave polarization and massive gravity with strongly lensed gravitational waves.

TASK OBS-2.16-G(ii)-**OTHER**: COSMOLOGICAL INFERENCE

Explore the cosmological inference using gravitational wave lensing and the impact of weak lensing in standard siren methods. This task is to be undertaken in collaboration with the TGR/Cosmology CBC sub-group

TASK OBS-2.16-G(iii)-**OTHER**: MICROLENSING MIMICKERS

To study whether the non-inclusion of certain physical effects in the waveform model can mimic microlensing

TASK OBS-2.16-G(iv)-**OTHER**: GR VIOLATIONS

Explore the possibility that lensed waveforms can show biases in various tests of General Relativity

TASK OBS-2.16-G(v)-**OTHER**: SEARCH FOR COSMIC STRINGS

Modeling gravitational lensing on cosmic strings–topological defects in spacetime. Progressing towards cosmic-string searches using templates.

OBS-2.17 CBC Service Roles

NOTE: these activities are now moved to OBS-9.

These tasks represent critical CBC service roles that are transient in nature and may be appointed positions.

Motivation and methods

Management of the CBC group requires teamwork between appointed and elected leaders along with a host of volunteers who contribute to the review and dissemination of scientific results. Here we capture a few broad classes of these types of service roles.

Major aspects and methods for this activity

ACTIVITY OBS-2.17-A-**INFRAOPS**: SERVING AS CBC CO-CHAIR

Future co-chairs are elected by the working group in the LSC and appointed in Virgo and KAGRA. These people are responsible for management of the CBC working group.

TASK OBS-2.17-A(i)-**INFRAOPS**: STANDING FOR ELECTION AS CBC CO-CHAIR

ACTIVITY OBS-2.17-B-**INFRAOPS**: SERVING AS CBC SUBGROUP LEAD

Subgroup leads are appointed by CBC co-chairs to lead R&D groups.

TASK OBS-2.17-B(i)-**INFRAOPS**: ACCEPTING CBC SUBGROUP LEAD APPOINTMENT

ACTIVITY OBS-2.17-C-**INFRAOPS**: SERVING AS CBC TECHNICAL REVIEWER

Technical reviewers agree to review code or techniques for scientific soundness.

TASK OBS-2.17-C(i)-**INFRAOPS**: ACCEPTING A CBC TECHNICAL REVIEWER APPOINTMENT OR VOLUNTEERING FOR TECHNICAL REVIEW TASKS IF CALLED UPON

ACTIVITY OBS-2.17-D-**INFRAOPS**: SERVING AS CBC PAPER REVIEWER

Paper reviewers agree to review papers for correctness, e.g., checking numbers and the validity of basic statements which interpret the results of the technical analysis.

TASK OBS-2.17-D(i)-**INFRAOPS**: ACCEPTING A CBC PAPER REVIEWER APPOINTMENT OR VOLUNTEERING FOR PAPER REVIEW TASKS IF CALLED UPON

ACTIVITY OBS-2.17-E-**INFRAOPS**: SERVING ON A CBC "KEY PAPER" TEAM

CBC paper team members write or manage CBC papers.

TASK OBS-2.17-E(i)-**INFRAOPS**: ACCEPTING A CBC PAPER TEAM APPOINTMENT OR VOLUNTEERING FOR PAPER TASKS IF CALLED UPON

ACTIVITY OBS-2.17-F-**OTHER**: SERVING ON A CBC "OTHER PAPER" TEAM

CBC paper team members write or manage CBC papers.

TASK OBS-2.17-F(i)-**OTHER**: ACCEPTING A CBC PAPER TEAM APPOINTMENT OR VOLUNTEERING FOR PAPER TASKS IF CALLED UPON

OBS-2.18 O4a and O4b gravitational-wave transient catalog

Produce a catalog of compact binary coalescence candidate signals observed during O4a and O4b (separately) along with parameter estimates and rate estimates. The catalog consists of the data products; see OBS-2.19 for activities and tasks associated with the creation of the associated publication. The catalog would include a union of binary mergers found by templated and/ or burst searches, with template-based parameter estimation.

Motivation and goals

The Catalog represents the list of definitive and marginal compact binary coalescences identified by the LIGO/Virgo/KAGRA Collaborations along with search results, data quality statements, source classification, and parameter estimation results.

Major aspects and methods for this activity

In O4 data we will conduct a deep search for compact objects from $1\,M_{\odot}$ to a maximum mass dictated by the instrument sensitivity (likely not to exceed $\sim 1000\,M_{\odot}$). For detection, spins aligned with the orbital angular momentum will be considered. For components below $2\,M_{\odot}$, spin magnitudes up to 0.04 will be searched for. Otherwise, up to maximal spins of 1 will be considered. Three independent search codes, gstlal, pycbc, and MBTA, will be run on the data. In addition, the cWB burst search will be run, which is capable of detecting higher-mass binary black hole systems.

For all signals above a pre-determined threshold, we will provide estimates of the physical parameters of the source using the best available waveform models, including the statistical errors. We will also provide an estimate of the systematic error by comparing parameter estimation using different waveform families, through comparison to numerical relativity simulations, or by other means. This information is an input to the study of astrophysical rates and distributions.

These data products will constitute the leading high-quality catalog of signals (and sub-threshold triggers) during O4 using the latest versions of data quality and calibration at the time of the analysis. In coordination with the Gravitational Wave Open Science Center we publish the results as an electronic data base and provide a companion usage guide.

ACTIVITY OBS-2.18-A-**INFRAOPS**: OFFLINE CBC SEARCHES FOR O4 CATALOG

Perform searches of gravitational wave data for compact binary coalescences using multiple search pipelines.

Note: requires calibrated data and detector characterization.

TASK OBS-2.18-A(i)-**INFRAOPS**: GSTLAL PIPELINE OPERATION

Offline running of the GstLAL search over the remaining O4 data chunks.

TASK OBS-2.18-A(ii)-**INFRAOPS**: PYCBC PIPELINE OPERATION

Offline running of the PyCBC search over the remaining O4 data chunks.

TASK OBS-2.18-A(iii)-**INFRAOPS**: MBTA PIPELINE OPERATION

Offline running of the MBTA search over the remaining O4 data chunks.

TASK OBS-2.18-A(iv)-**INFRAOPS**: SPIIR PIPELINE OPERATION

Offline running of the SPIIR search over the remaining O4 data chunks.

TASK OBS-2.18-A(v)-**INFRAOPS**: CWB PIPELINE OPERATION

Offline running of the cWB search over the remaining O4 data chunks.

TASK OBS-2.18-A(vi)-**INFRAOPS**: UNIFIED SIGNIFICANCE ESTIMATES

Use the meta-pipeline combination software to combine triggers from search pipeline and provide unified significance statistics for all the triggers.

ACTIVITY OBS-2.18-B-**INFRAOPS**: DATA QUALITY FOR O4 CATALOG

Obtain data quality statements for each detection candidate identified by the offline searches.

TASK OBS-2.18-B(i)-**INFRAOPS**: DETECTOR CHARACTERIZATION ROTA

Produce a data quality report for each candidate event. This task is identical to task O.C.2.1 in the LSC-Virgo Operations White Paper.

ACTIVITY OBS-2.18-C-**INFRAOPS**: OFFLINE PARAMETER ESTIMATION FOR O4 CATALOG

Perform parameter estimation on significant detection candidates identified by the offline searches, with the goal of using at least two waveform models where possible.

Note: requires calibrated data at times of events.

TASK OBS-2.18-C(i)-**INFRAOPS**: PRODUCTION PARAMETER ESTIMATION ANALYSIS

Produce final posteriors on events that are part of the GWTC for release and secondary analysis. This analysis will take initial parameter estimation from the rota as an input, along with other input such as BayesWave PSDs. Analyses will be initialized, monitored, and curated using automated software systems with expert input. This work may also include the re-analysis of past events.

TASK OBS-2.18-C(ii)-**INFRAOPS**: PARAMETER ESTIMATION EVENT ROTA

As required, follow up on automated low-latency parameter estimation analysis with further initial runs. The rota will produce preliminary results and analysis settings for production parameter estimation.

TASK OBS-2.18-C(iii)-**INFRAOPS**: PARAMETER ESTIMATION EXPERT ROTA

Supervise parameter estimation event rota effort, organize regular meetings to monitor rota analysis during assigned period, and certify preliminary results.

TASK OBS-2.18-C(iv)-**INFRAOPS**: PARAMETER ESTIMATION RESULTS CURATION

Collect the output of parameter estimation, including preferred posterior samples, configuration files, PSDs, calibration envelopes, etc. from required runs for each candidate event. If necessary, produce additional runs and catalog the results in an accessible way for downstream analysis.

TASK OBS-2.18-C(v)-**INFRAOPS**: WAVEFORM RECONSTRUCTION

Perform waveform reconstruction to enable consistency/residual tests.

ACTIVITY OBS-2.18-D-**INFRAOPS**: SENSITIVITY ESTIMATION FOR O4 CATALOG

Provide high-level sensitivity statements for various source categories (BNS, NSBH, BBH, etc.) using common injection sets analyzed by all search pipelines, and applying consistent thresholds on significance (either false alarm rate or astrophysical probability).

TASK OBS-2.18-D(i)-**INFRAOPS**: ESTIMATE SPACETIME VOLUME SENSITIVITY FOR GSTLAL

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold.

TASK OBS-2.18-D(ii)-**INFRAOPS**: ESTIMATE SPACETIME VOLUME SENSITIVITY FOR PYCBC

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold.

TASK OBS-2.18-D(iii)-**INFRAOPS**: ESTIMATE SPACETIME VOLUME SENSITIVITY FOR MBTA

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold.

TASK OBS-2.18-D(iv)-**INFRAOPS**: ESTIMATE SPACETIME VOLUME SENSITIVITY FOR SPIIR

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold.

TASK OBS-2.18-D(v)-**INFRAOPS**: ESTIMATE SPACETIME VOLUME SENSITIVITY FOR CWB

Analyze the common injection sets to estimate sensitive spacetime volume(s) at a fiducial significance threshold.

TASK OBS-2.18-D(vi)-**INFRAOPS**: SENSITIVITY CURATION

Collect the results from all search pipelines into a standardised format for further analsysis.

ACTIVITY OBS-2.18-E-**INFRAOPS**: O4 CATALOG PROJECT TEAM

Catalog project management

TASK OBS-2.18-E(i)-**INFRAOPS**: PROJECT MANAGEMENT

Project management and coordination (split between two roles)

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK OBS-2.18-E(ii)-**INFRAOPS**: ALL-SKY SEARCH LEAD

- Coordinate delivery of the CBC search results
- Coordinate with reviewers.

TASK OBS-2.18-E(iii)-**INFRAOPS**: BURST LEAD

- Coordinate delivery of the burst search results
- Coordinate with reviewers.

TASK OBS-2.18-E(iv)-**INFRAOPS**: PARAMETER ESTIMATION LEAD

- Coordinate delivery of the parameter estimation results
- Coordinate with reviewers.

TASK OBS-2.18-E(v)-**INFRAOPS**: DETECTOR CHARACTERISATION LEAD

- Coordinate delivery of the detector characterisation results
- Coordinate with reviewers.

TASK OBS-2.18-E(vi)-**INFRAOPS**: CALIBRATION LEAD

- Coordinate delivery of the calibration results
- Coordinate with reviewers.

TASK OBS-2.18-E(vii)-**INFRAOPS**: CATALOG AND INFRASTRUCTURE LEAD

- Lead development and delivery of the project infrastructure
- Coordinate with reviewers.

TASK OBS-2.18-E(viii)-**INFRAOPS**: WAVEFORM LEAD

- Input into the delivery of all results providing a liason to the waveform group
- Coordinate with reviewers.

TASK OBS-2.18-E(ix)-**INFRAOPS**: DATA RELEASE

- Prepare data for GWOSC and for release on public DCC.

TASK OBS-2.18-E(x)-**INFRAOPS**: SCIENCE SUMMARY

- Write science summary.

ACTIVITY OBS-2.18-F-**INFRAOPS**: O4 CATALOG DATA RELEASE REVIEW

TASK OBS-2.18-F(i)-**INFRAOPS**: REVIEW OF THE CATALOG DATA RELEASE
Review of all data products in the catalog.

ACTIVITY OBS-2.18-G-**INFRAOPS**: O4 CATALOG TECHNICAL REVIEW

TASK OBS-2.18-G(i)-**INFRAOPS**: TECHNICAL REVIEW COORDINATION
Coordinate technical review activities.

TASK OBS-2.18-G(ii)-**INFRAOPS**: REVIEW OF GSTLAL PIPELINE SEARCH RESULTS
Review of GstLAL search results: candidate lists, background estimation, sensitivity.

TASK OBS-2.18-G(iii)-**INFRAOPS**: REVIEW OF PYCBC PIPELINE SEARCH RESULTS
Review of PyCBC search results: candidate lists, background estimation, sensitivity.

TASK OBS-2.18-G(iv)-**INFRAOPS**: REVIEW OF MBTA PIPELINE SEARCH RESULTS
Review of MBTA search results: candidate lists, background estimation, sensitivity.

TASK OBS-2.18-G(v)-**INFRAOPS**: REVIEW OF SPIIR PIPELINE SEARCH RESULTS
Review of SPIIR search results: candidate lists, background estimation, sensitivity.

TASK OBS-2.18-G(vi)-**INFRAOPS**: REVIEW OF CWB PIPELINE SEARCH RESULTS
Review of cWB search results: candidate lists, background estimation, sensitivity.

TASK OBS-2.18-G(vii)-**INFRAOPS**: REVIEW OF PARAMETER ESTIMATION RESULTS
Review of Parameter Estimation results, including posterior samples.

TASK OBS-2.18-G(viii)-**INFRAOPS**: REVIEW OF WAVEFORM RECONSTRUCTION AND CONSISTENCY CHECKS

Review of Waveform Reconstruction results.

ACTIVITY OBS-2.18-H-**INFRAOPS**: DATA FLOW COORDINATION FOR O4 CATALOG

TASK OBS-2.18-H(i)-**INFRAOPS**: DEVELOPMENT

Develop methods to coordinate the handling of data products between different analysts

TASK OBS-2.18-H(ii)-**INFRAOPS**: OPERATION

Operate the data flow coordination tool during the catalogue preparation

Expected products and/or outcomes

- Catalog publication of events in O4a and O4b.
- Strain data release surrounding catalog events in O4a and O4b.
- Posterior samples for catalog events in O4a and O4b.
- Any relevant detector characterisation and calibration uncertainty data required
- Curated summary of injection analysis results

OBS-2.19 O4a and O4b paper describing the results and methods for the gravitational-wave transient catalog

Produce one or more publications describing the methodology and overview results obtained from the gravitational-wave transient catalog

Motivation and goals

The publication will highlight new astrophysical insights learned from the associated gravitational-wave transient catalog. It will also be the definitive place to state changes to methodology and include summary statements on tests of general relativity, equation of state inference, and rates and population inference.

Major aspects and methods for this activity

Providing a comprehensive summary of the detected systems will be one of the main publication goals of the CBC group. To this end, we will describe the catalogue of detections made during O4 and release a detailed description of all detected systems, covering their detection and physical parameters, inferred using the best available waveform models.

ACTIVITY OBS-2.19-A-**INFRAOPS**: O4 CATALOG PAPER EDITORIAL TEAM

Paper project management and writing.

Task OBS-2.19-A(i)-**InfraOps**: Planning and implementation of scoping team suggestions

See https://dcc.ligo.org/LIGO-T2300258

- Investigate potential future changes to the catalog paper
- Coordinate with the CBC group on implementation of changes

Task OBS-2.19-A(ii)-**InfraOps**: Project Management

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

Task OBS-2.19-A(iii)-**InfraOps**: Paper Writing Coordination

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

Task OBS-2.19-A(iv)-**InfraOps**: Figure Preparation

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

Task OBS-2.19-A(v)-**InfraOps**: Table Preparation

- Prepare production-quality tables.
- Prepare data-behind-tables for public dissemination.

Task OBS-2.19-A(vi)-**InfraOps**: Science Summary

- Write science summary.

Activity OBS-2.19-B-**InfraOps**: O4 Catalog Paper Review

Task OBS-2.19-B(i)-**InfraOps**: Review of Paper Scientific Content

Publications & Presentations review of scientific content in Catalog paper.

Task OBS-2.19-B(ii)-**InfraOps**: Editing

Editorial Board review of paper quality in Catalog paper.

Expected products and/or outcomes

- Publication of the catalog of events in O4a and O4b.
- Science summary

OBS-2.20 O4a, O4b, and O4c Astrophysical Distribution of Compact Binaries

Determine the astrophysical mass and spin distributions of compact binary systems, and rate estimates for observations up to and including O4c.

Motivation and goals

With the addition of new detections during O4, stronger constraints on the BBH, BNS, and NSBH populations are possible and may lead to new insights on compact binary formation and evolution. Three papers will be produced analyzing the compact binary population in O4. An O4a paper will summarize our knowledge of the binary population after the first half of the fourth observing run, acting as an update to the O3b Astrophysical Distributions Paper. This will be followed by analogous O4b and O4c papers including data from subsequent catalog releases. Should we make a favorably large number of BNS and NSBH detections in O4b and/or O4c, it is possible that the corresponding Astrophysical Distributions papers may be split in two, with a "high mass" paper concerning the distribution of binary black holes and a "low mass" paper studying the population of BNS and NSBH events, although current detection rates leave this possibility unlikely.

The activities below are applicable to both the O4a, O4b, and O4c paper efforts.

Major aspects and methods for this activity

ACTIVITY OBS-2.20-A-**INFRAOPS**: BINARY NEUTRON STAR POPULATION INFERENCE FOR O4 POPULATION PAPERS

Inference on the population of binary neutron stars, including "joint" analyses characterizing the combined population of one or more CBC classes.

TASK OBS-2.20-A(i)-**INFRAOPS**: PARAMETRIC BNS POPULATION INFERENCE

Perform parametric hierarchical inference using PE posteriors and sensitivity estimates for BNS events in the O4a, O4b, and O4c catalogs.

TASK OBS-2.20-A(ii)-**INFRAOPS**: NON-PARAMETRIC BNS POPULATION INFERENCE

Perform non-parametric hierarchical inference using PE posteriors and sensitivity estimates for BNS events in the O4a, O4b, and O4c catalogs.

ACTIVITY OBS-2.20-B-**INFRAOPS**: NEUTRON STAR-BLACK HOLE POPULATION INFERENCE FOR O4 POPULATION PAPERS

Inference on the population of neutron star-black hole mergers, including "joint" analyses characterizing the combined population of one or more CBC classes.

TASK OBS-2.20-B(i)-**INFRAOPS**: PARAMETRIC NS-BH POPULATION INFERENCE

Perform parametric hierarchical inference using PE posteriors and sensitivity estimates for NSBH events in the O4a, O4b, and O4c catalogs.

TASK OBS-2.20-B(ii)-**INFRAOPS**: NON-PARAMETRIC NS-BH POPULATION INFERENCE

Perform non-parametric hierarchical inference using PE posteriors and sensitivity estimates for NSBH events in the O4a, O4b, and O4c catalogs.

ACTIVITY OBS-2.20-C-**INFRAOPS**: BLACK HOLE MASS DISTRIBUTION FOR O4 POPULATION PAPERS

Inference on the mass distribution of binary black holes observed, including "joint" analyses characterizing the combined population of one or more CBC classes.

TASK OBS-2.20-C(i)-**INFRAOPS**: PARAMETRIC INFERENCE OF THE BBH MASS DISTRIBUTION

Perform parametric hierarchical inference using PE posteriors and sensitivity estimates for BBH events in the O4a, O4b, and O4c catalogs, using a variety of phenomenological models to extract different physical features.

TASK OBS-2.20-C(ii)-**INFRAOPS**: NON-PARAMETRIC INFERENCE OF THE BBH MASS DISTRIBUTION

Produce non-parametric estimates of the BBH mass distribution using PE posteriors and sensitivity estimates for BBH events in the O4a, O4b, and O4c catalogs.

ACTIVITY OBS-2.20-D-**INFRAOPS**: REDSHIFT AND SPATIAL DEPENDENCE OF BLACK HOLE POPULATION FOR O4 POPULATION PAPERS

Estimate the merger rate and/or ensemble properties of binary black holes as a function of redshift and test for spatial isotropy of mergers.

TASK OBS-2.20-D(i)-**INFRAOPS**: INFERENCE ON REDSHIFT EVOLUTION OF THE BBH POPULATION

Quantify possible evolution of the BBH merger rate and ensemble properties as a function of redshift

TASK OBS-2.20-D(ii)-**INFRAOPS**: MEASUREMENT AND BOUNDS ON ANISOTROPY

Constrain the spatial (directional) dependence of BBH mergers and quantify any possible anisotropy in spatial distribution or binary orientation.

ACTIVITY OBS-2.20-E-**INFRAOPS**: BLACK HOLE SPIN DISTRIBUTION FOR O4 POPULATION PAPERS

Inference on the spin distributions of binary black hole mergers.

TASK OBS-2.20-E(i)-**INFRAOPS**: PARAMETRIC INFERENCE OF THE BBH SPIN DISTRIBUTION

Parametrically infer the binary black hole spin distribution using PE posteriors and sensitivity estimates for BBH events in the O4a, O4b, and O4c catalogs, using a variety of phenomenological models to extract different physical features.

TASK OBS-2.20-E(ii)-**INFRAOPS**: NON-PARAMETRIC INFERENCE OF THE BBH SPIN DISTRIBUTION

Non-parametrically infer the binary black hole spin distribution using PE posteriors and sensitivity estimates for BBH events in the O4a, O4b, and O4c catalogs.

ACTIVITY OBS-2.20-F-**INFRAOPS**: MODEL CHECKING AND OUTLIER TESTS FOR O4 POPULATION PAPERS

Evaluate the goodness-of-fit of the mass, spin, and redshift distribution models and identify potential outliers in the set of events.

Task OBS-2.20-F(i)-**InfraOps**: Compare posterior predictive distributions to observations

Check the consistency of the parameterized models with the observations and look for potential tensions between the model and the data.

Task OBS-2.20-F(ii)-**InfraOps**: Outlier identification

Identify outliers in the population by various methods including leave-one-out analyses to test the robustness of the population results against the targeted exclusion of individual events.

Activity OBS-2.20-G-**InfraOps**: O4 Population Editorial Team

Paper project management and writing.

Task OBS-2.20-G(i)-**InfraOps**: Project Management

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

Task OBS-2.20-G(ii)-**InfraOps**: Paper Writing Coordination

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

Task OBS-2.20-G(iii)-**InfraOps**: Figure Preparation

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

Task OBS-2.20-G(iv)-**InfraOps**: Science Summary and Data Release

- Write science summary.
- Prepare data public release on Zenodo, DCC, and/or GWOSC

Activity OBS-2.20-H-**InfraOps**: O4 Population Technical Review

Task OBS-2.20-H(i)-**InfraOps**: Technical Review Coordination

Coordinate technical review activities.

Task OBS-2.20-H(ii)-**InfraOps**: Review of Binary Neutron Star Population Inference Results

Review of the parametric and non-parameteric population inference results.

Task OBS-2.20-H(iii)-**InfraOps**: Review of the Neutron Star-Black Hole Population Inference Results

Review of the parametric and non-parameteric population inference results.

TASK OBS-2.20-H(iv)-**INFRAOPS**: REVIEW OF BBH MASS DISTRIBUTION RESULTS
Review of the parametric and non-parameteric mass distribution results.

TASK OBS-2.20-H(v)-**INFRAOPS**: REVIEW OF REDSHIFT AND SPATIAL DEPENDENCE OF BLACK HOLE POPULATION
Review of the non-evolving BBH rate estimation and redshift evolution.

TASK OBS-2.20-H(vi)-**INFRAOPS**: REVIEW OF BLACK HOLE SPIN DISTRIBUTION RESULTS
Review of the parameteric hierarchical inference of spins.

TASK OBS-2.20-H(vii)-**INFRAOPS**: REVIEW OF MODEL CHECKING RESULTS
Review of the posterior predictive checks and outlier analyses, including data behind figures.

ACTIVITY OBS-2.20-I-**INFRAOPS**: O4 POPULATION PAPER REVIEW

TASK OBS-2.20-I(i)-**INFRAOPS**: REVIEW OF PAPER SCIENTIFIC CONTENT
Review of scientific content in Astrophysical Distributions paper.

TASK OBS-2.20-I(ii)-**INFRAOPS**: EDITING
Editorial Board review of paper quality in Astrophysical Distributions paper.

TASK OBS-2.20-I(iii)-**INFRAOPS**: REVIEW OF PUBLIC DATA RELEASE
Review of public data release products, the archival of analysis outputs, figure generation scripts, and/or other supplemental data.

Expected products and/or outcomes

- O4a Astrophysical Distributions companion paper.
- O4b Astrophysical Distributions companion paper.
- O4c Astrophysical Distributions companion paper.
- Public hyperposterior samples produced by hierarchical population analyses
- Data products describing the detector sensitivity that can be used for independent population analyses.
- Data behind the figures appearing in the O4a, O4b, and O4c Astrophysical Distributions papers.

OBS-2.21 Strong-Field Tests of General Relativity with O4a, O4b and O4c data

Subject GR to a battery of tests based on observed CBC signals, ranging from tests of strong field dynamics to tests of the nature of gravitational waves, using events in the O4a, O4b and O4c catalogs.

Motivation and goals

LIGO's initial crop of binary black hole mergers has allowed us, for the first time, to test the predictions of general relativity in the highly relativistic, strong-field regime [60, 61]. Using these events we set limits on the deviation from the post-Newtonian (PN) description of the inspiral phase, mass of the graviton and dispersion relationship for GWs. Moreover, we have shown that the final remnant's mass and spin are mutually consistent, and that the data following the peak are consistent with the least-damped quasi-normal mode of the remnant black hole. With the first detection in O2, we also started constraining dispersive gravitational wave propagation [62]. Additionally, most of these constraints were further improved by combining detections [61, 63].

The first detection of a binary neutron star merger, GW170817 [64], had a long inspiral phase from which we were able to conduct a phenomenological test for dipole radiation and improve the constraints on some other low-order PN coefficients [65]. GW170817 was also detected in conjunction with electromagnetic information, which has given us information beyond what can be measured with just a gravitational-wave signal, such as the redshift of the source and the time difference between the gravitational-wave and electromagnetic signal. These additional pieces of information have allowed us to place tight constraints on the speed of gravity and also constrain some Standard Model Extension coefficients [66]. They have also given us the ability to put constraints on alternative theories of gravity that predict large deviations between the gravitational-wave and electromagnetic signal, and insight into the polarization modes of gravitational waves [65].

In O3, we have also observed events with unequal masses that require descriptions beyond the dominant quadrupole moment [67, 68], allowing us to test additional predictions of GR. We have also made the first NSBH detection and found that it is also consistent with GR. Additionally, we have added additional tests for the consistency of the binary black hole signals with Kerr spin-induced quadrupole moments and of the consistency of the ringdown phase with the predictions for a Kerr black hole, as well as constraints on echoes after the end of the signal, and a more general framework for constraining alternative gravitational wave polarizations [69, 70].

In O4, we expect new detections of BBHs, BNSs, and NSBHs, which will further tighten the existing constraints. There are also a number of new analyses proposed, though we only list the established analyses that have contributed to previous papers below. We also only list single O4a, O4b and O4c testing GR papers for simplicity, but plan to split up each of these into three separate papers to keep them from becoming too large and to allow us to better advertise the individual results.

Due to the lack of waveform models arising from alternative theories of gravity, in the near future our phenomenological tests will continue to follow the "top-down" methodology which will allow us to detect deviations from GR, but not necessarily to identify the underlying alternative theory. However, there are efforts underway to provide benchmarks for, e.g., the tests of post-Newtonian coefficients in terms of specific alternative theories and to reinterpret the modified dispersion results in terms of constraints on dark energy theories. Below we list the priority science results anticipated from GW observations in the O4 observing run.

Major aspects and methods for this activity

ACTIVITY OBS-2.21-A-**INFRAOPS**: TESTING GR CONSISTENCY FOR O4 PAPERS

Look for inconsistency between observed results and GR predictions for the events in the O4a, O4b and O4c Catalogs.

TASK OBS-2.21-A(i)-**INFRAOPS**: RESIDUALS TEST

Subtract best fit waveforms from data surrounding each event and look for excess residuals. Apply this test to all confident detections.

TASK OBS-2.21-A(ii)-**INFRAOPS**: INSPIRAL-MERGER-RINGDOWN CONSISTENCY TEST

Compare predicted final mass and spin of each event, as determined from the inspiral, with the values inferred from the post-inspiral stages, according to GR. Apply this test to all confident high-mass BBH events satisfying the test's selection criteria.

TASK OBS-2.21-A(iii)-**INFRAOPS**: TESTING THE CONSITENCY OF SUBDOMINANT MULTIPOLAR AMPLITUDES

Test the consistency of the amplitudes of different GW multipoles beyond the (l=2,m=2) mode with the predictions of general relativity for compact binaries, based on our most accurate models that include higher harmonic modes.

ACTIVITY OBS-2.21-B-**INFRAOPS**: TESTING GRAVITATIONAL-WAVE PROPERTIES FOR O4 PAPERS

Testing gravitational-wave properties, including generation and propagation, in the O4a, O4b and O4c Catalogs.

TASK OBS-2.21-B(i)-**INFRAOPS**: PARAMETER ESTIMATION INCLUDING NON-GR EFFECTS IN INSPIRAL AND POST-INSPIRAL

Perform parameter estimation for each event while including a parameterized set of deviations from GR in the inspiral, merger and ringdown stages.

TASK OBS-2.21-B(ii)-**INFRAOPS**: TEST FOR MODIFIED DISPERSION RELATION

Perform parameter estimation on all events in the Catalogs while allowing for dephasing potentially caused by a modified dispersion relation.

TASK OBS-2.21-B(iii)-**INFRAOPS**: TEST FOR SPACETIME SYMMETRY BREAKING

Search for signs of modified GW dispersion including birefringence, related to spacetime symmetry breaking mechanisms.

TASK OBS-2.21-B(iv)-**INFRAOPS**: TEST FOR NON-TENSORIAL POLARIZATIONS

Perform model selection between various polarization hypotheses (all combinations of tensor, vector, and scalar) for events observed by at least two detectors.

TASK OBS-2.21-B(v)-**INFRAOPS**: SPEED OF GRAVITY

Constrain the speed of gravity through comparison with the arrival time of a counterpart GRB.

ACTIVITY OBS-2.21-C-**INFRAOPS**: TESTING THE REMNANT PROPERTIES AND NEAR-HORIZON DYNAMICS FOR O4 PAPERS

Probe the immediate environment of remnant compact objects in O4a, O4b and O4c.

TASK OBS-2.21-C(i)-**INFRAOPS**: TESTS OF THE NATURE OF THE MERGER REMNANT

Test the nature of the merger remnant through measurements and cross-comparison of various quasi-normal modes.

TASK OBS-2.21-C(ii)-**INFRAOPS**: PROBING THE NEAR-HORIZON STRUCTURE

Search for near-horizon effects such as late-time echoes using template-based and model-independent approaches.

ACTIVITY OBS-2.21-D-**INFRAOPS**: O4 TESTING GR EDITORIAL TEAM

Paper project management and writing.

TASK OBS-2.21-D(i)-**INFRAOPS**: PROJECT MANAGEMENT

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK OBS-2.21-D(ii)-**INFRAOPS**: PAPER WRITING COORDINATION

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK OBS-2.21-D(iii)-**INFRAOPS**: FIGURE PREPARATION

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK OBS-2.21-D(iv)-**INFRAOPS**: SCIENCE SUMMARY AND DATA RELEASE

- Write a science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY OBS-2.21-E-**INFRAOPS**: O4 TESTING GR TECHNICAL REVIEW

TASK OBS-2.21-E(i)-**INFRAOPS**: TECHNICAL REVIEW COORDINATION

Coordinate technical review activities.

TASK OBS-2.21-E(ii)-**INFRAOPS**: REVIEW OF RESIDUALS TEST

Review of the residuals consistency test results.

TASK OBS-2.21-E(iii)-**INFRAOPS**: REVIEW OF IMR TEST

Review of the IMR consistency test results.

TASK OBS-2.21-E(iv)-**INFRAOPS**: REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE GENERATION

Review of the parameterized test of gravitational wave generation results.

TASK OBS-2.21-E(v)-**INFRAOPS**: REVIEW OF PARAMETERIZED TESTS OF GRAVITATIONAL WAVE PROPAGATION

Review of the modified dispersion relation test results.

TASK OBS-2.21-E(vi)-**INFRAOPS**: REVIEW OF POLARIZATION TEST
Review of the polarization test results.

TASK OBS-2.21-E(vii)-**INFRAOPS**: REVIEW OF SPEED OF GRAVITY
Review of the speed of gravity analysis.

TASK OBS-2.21-E(viii)-**INFRAOPS**: REVIEW OF QUASI-NORMAL MODES TESTS
Review of the quasi-normal modes tests' results.

TASK OBS-2.21-E(ix)-**INFRAOPS**: REVIEW OF SEARCH FOR LATE TIME ECHOES
Review of the search for late time echoes results.

TASK OBS-2.21-E(x)-**INFRAOPS**: REVIEW OF POSTERIOR SAMPLE CHAINS FOR RELEASE
Review of posterior sample chains to be released.

ACTIVITY OBS-2.21-F-**INFRAOPS**: O4 TESTING GR PAPER REVIEW

TASK OBS-2.21-F(i)-**INFRAOPS**: REVIEW OF PAPER SCIENTIFIC CONTENT
Publications & Presentations review of scientific content in O4a, O4b and O4c Testing GR companion papers.

TASK OBS-2.21-F(ii)-**INFRAOPS**: EDITING
Editorial Board review of paper quality in O4a, O4b and O4c Testing GR companion papers.

Expected products and/or outcomes

- O4a Testing GR companion paper.
- Posterior samples from each analysis in O4a Testing GR paper.
- Data behind the figures appearing in O4a Testing GR paper.
- O4b Testing GR companion paper.
- Posterior samples from each analysis in O4b Testing GR paper.
- Data behind the figures appearing in O4b Testing GR paper.
- O4c Testing GR companion paper.
- Posterior samples from each analysis in O4c Testing GR paper.
- Data behind the figures appearing in O4c Testing GR paper.
- Low-latency speed of gravity paper (if there is a high-significance detection with a GRB counterpart)

OBS-2.22 O4a and O4b Inference of Cosmological Parameters with Observational Data

Measure cosmological parameters, in particular the Hubble constant, using both GW events for which a reliable EM counterpart is observed and an associated redshift measurement is obtained, and statistical associations with a galaxy catalog and/or features in the source population mass distribution for events without EM counterparts.

Motivation and goals

Gravitational waves from the binary neutron star merger GW170817 along with its uniquely identified host galaxy led to a first "standard siren" measurement of the Hubble parameter independent of the cosmological distance ladder. The identification of the host galaxy was possible because of the coincident optical counterpart to GW170817. Similar observations in O4 of binaries involving a neutron star with identified electromagnetic counterparts will improve the precision of the measurement. The statistical method of combining gravitational-wave distance estimates with catalogues of potential host galaxies, as well as the population method employing features of the mass distribution of GW sources to infer cosmological constraints, are expected to provide observational results once a significant number of events have been observed in O4 and have been reported in the associated O4(a/b) catalog (i.e., towards the second half of 2023 or later). There may be an exception for particularly well-localised GW events, or events for which an EM counterpart (which cannot be associated with a specific host galaxy) allows the sky localisation of the event to be significantly improved. The main results from the two methods mentioned above, statistical and mass features method, will be used to provide a new update on the constraint of H_0 and, where possible, other cosmological parameters following O4(a/b).

Major aspects and methods for this activity

ACTIVITY OBS-2.22-A-**INFRAOPS**: MEASUREMENT OF COSMOLOGICAL PARAMETERS FOR O4 PAPER

Obtain a combined estimate on cosmological parameters, in particular on H_0, from compact binaries with identified electromagnetic counterparts.

TASK OBS-2.22-A(i)-**INFRAOPS**: COUNTERPART ONLY MEASUREMENT OF COSMOLOGICAL PARAMETERS FROM O4

Analyze events with EM counterparts to obtain a joint measurement on the Hubble constant, and if possible on other cosmological parameters.

TASK OBS-2.22-A(ii)-**INFRAOPS**: STATISTICAL ONLY MEASUREMENT OF H_0 FROM O4

Analyze events without EM counterparts to obtain a joint statistical measurement on the Hubble constant, other cosmological parameters (where possible), and GW population parameters from O4 data.

TASK OBS-2.22-A(iii)-**INFRAOPS**: ASSESSMENT OF SYSTEMATIC UNCERTAINTIES

Investigate the effect of potential systematic uncertainties on statistical measurements of cosmological parameters, by varying parameters such as the luminosity function, the GW mass model, galaxy catalog observation band, etc.

TASK OBS-2.22-A(iv)-**INFRAOPS**: COSMOLOGY ROTA EXPERT

Be an expert on the cosmological pipelines rota, and guide the rota team through rota tasks (detailed below).

TASK OBS-2.22-A(v)-**INFRAOPS**: COSMOLOGY ROTA MEMBER

Take shifts on the Cosmological pipelines rota. During shifts, run the cosmological pipelines on newly detected GW events to assess their level of constraining power on cosmological parameters, and highlight any particularly interesting events to the Cosmology Working Group. In the event of a potentially EM bright event, work with experts in the Cosmology group and EM taskforce to carry out necessary analyses on a short timescale.

ACTIVITY OBS-2.22-B-**INFRAOPS**: O4 COSMOLOGY EDITORIAL TEAM

Paper project management and writing.

TASK OBS-2.22-B(i)-**INFRAOPS**: PROJECT MANAGEMENT

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK OBS-2.22-B(ii)-**INFRAOPS**: PAPER WRITING COORDINATION

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK OBS-2.22-B(iii)-**INFRAOPS**: FIGURE PREPARATION

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK OBS-2.22-B(iv)-**INFRAOPS**: SCIENCE SUMMARY AND DATA RELEASE

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY OBS-2.22-C-**INFRAOPS**: O4 COSMOLOGY TECHNICAL REVIEW

TASK OBS-2.22-C(i)-**INFRAOPS**: TECHNICAL REVIEW COORDINATION

Coordinate technical review activities.

TASK OBS-2.22-C(ii)-**INFRAOPS**: REVIEW OF MEASUREMENTS OF COSMOLOGICAL PARAMETERS

Review of all cosmological measurements, with or without EM counterparts, including review of posterior sample chains and systematic uncertainty studies. In particular review of results of the O4(a/b) cosmology paper and possible O4 EM counterpart papers.

ACTIVITY OBS-2.22-D-**INFRAOPS**: O4 COSMOLOGY PAPER REVIEW

TASK OBS-2.22-D(i)-**INFRAOPS**: REVIEW OF PAPER SCIENTIFIC CONTENT
Publications & Presentations review of scientific content in cosmological papers.

TASK OBS-2.22-D(ii)-**INFRAOPS**: EDITING
Editorial Board review of paper quality in cosmological papers.

Expected products and/or outcomes

- O4(a/b) cosmology companion paper (review and publication).
- Data behind the results and figures appearing in the O4(a/b) cosmology paper.
- Cosmological results for O4 EM counterpart CBC paper(s) + associated data.

OBS-2.23 O4a, O4b and O4c Search for Lensed Gravitational Waves

Search for gravitational-wave lensing signatures following O4a, O4b and O4c

Motivation and goals

Gravitational waves can be gravitationally lensed by intervening galaxies, galaxy clusters, or smaller lenses such as compact objects. Lensing can result in multiple images separated in time, and modifications to the waveform due to microlensing. Here we will look for signatures of lensing in O4 data.

Major aspects and methods for this activity

ACTIVITY OBS-2.23-A-**OTHER**: MULTIPLE IMAGE ANALYSES FOR O4 LENSING PAPER

Search for evidence that two or more gravitational wave observations might have a common lensed source.

TASK OBS-2.23-A(i)-**OTHER**: RAPID IDENTIFICATION WITH MACHINE LEARNING
Use machine learning techniques to rapidly identify lensed candidate pairs.

TASK OBS-2.23-A(ii)-**OTHER**: POSTERIOR-BASED ANALYSES
Analyze all the O4 events to identify lensed multi-image candidate pairs using posterior-based methods assesing the consistency of the base parameters and phases.

TASK OBS-2.23-A(iii)-**OTHER**: FACTORIZED JOINT PARAMETER ESTIMATION
Perform factorized joint parameter estimation on event pairs by replacing the prior in the second event analysis with the posterior of the first event and pre-computing waveforms.

TASK OBS-2.23-A(iv)-**OTHER**: JOINT PARAMETER ESTIMATION ANALYSES
Perform joint parameter estimation on event pairs to compute the Bayes factor of lensed vs. unlensed hypotheses.

TASK OBS-2.23-A(v)-**OTHER**: SUB-THRESHOLD SEARCHES

Search for sub-threshold candidates that could be lensed images associated with other, confidently detected events.

TASK OBS-2.23-A(vi)-**OTHER**: TYPE II IMAGE SEARCHES

Search for waveform distortions induced in type II images

TASK OBS-2.23-A(vii)-**OTHER**: LENS MODEL SELECTION

For any candidate lensed events, utilize model selection to determine the properties of the gravitational lens.

TASK OBS-2.23-A(viii)-**OTHER**: ASSESSMENT OF UNCERTAINTIES

Investigate the systematic uncertainties of the methods targeting multiple images through mock data studies and investigations of waveform systematics.

ACTIVITY OBS-2.23-B-**OTHER**: INTERFERENCE AND WAVE-EFFECTS FOR O4 LENSING PAPER

Search for evidence of frequency-dependent distortion of signals that could arise from lensing either by isolated or a population of small lenses.

TASK OBS-2.23-B(i)-**OTHER**: SEARCH FOR MICROLENSING EFFECTS

Perform parameter estimation and residual tests on events to determine if there is evidence of microlensing distortions.

TASK OBS-2.23-B(ii)-**OTHER**: SEARCH FOR MILLILENSING EFFECTS

Perform parameter estimation on events to determine if there is evidennce of milli-imaging of gravitational waves.

TASK OBS-2.23-B(iii)-**OTHER**: MICROLENSING AND MILLILENSING ANALYSIS OF STRONG LENSING CANDIDATES

For any candidate strongly lensed event, combine the strong lensing images to study microlensing.

TASK OBS-2.23-B(iv)-**OTHER**: ASSESSMENT OF UNCERTAINTIES

Investigate the systematic uncertainties of the methods targeting distorted signals through mock data studies and investigations of waveform systematics.

ACTIVITY OBS-2.23-C-**OTHER**: INFERENCE ON LENS AND SOURCE POPULATIONS FOR O4 LENSING PAPER

The objective is to derive the rate of observable strong gravitational-wave lensing and to derive constraints on the lensed event rates and populations based on the (non-)detection of gravitational-wave lensing.

TASK OBS-2.23-C(i)-**OTHER**: GRAVITATIONAL-WAVE LENSING RATES BASED ON KNOWN MODELS

Estimate the gravitational-wave lensing rate and multi-image time-delays based on current knowledge of the populations of binary black holes and lenses. This will enable us to estimate the prior odds of gravitational-wave lensing, which is useful as input for joint parameter estimation.

TASK OBS-2.23-C(ii)-**OTHER**: DERIVE BOUNDS ON GRAVITATIONAL-WAVE LENSING

Use the (non-)detection of lensed gravitational waves and limits from the stochastic background, to set constraints on the gravitational-wave lensing rate and the population of lensed binaries.

TASK OBS-2.23-C(iii)-**OTHER**: CONSTRAIN COMPACT DARK MATTER

Using the microlensing search results, set constraints on the compact dark matter fraction.

ACTIVITY OBS-2.23-D-**OTHER**: O4 LENSING PAPER EDITORIAL TEAM

Paper project management and writing.

TASK OBS-2.23-D(i)-**OTHER**: PROJECT MANAGEMENT

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK OBS-2.23-D(ii)-**OTHER**: PAPER WRITING COORDINATION

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK OBS-2.23-D(iii)-**OTHER**: FIGURE PREPARATION

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK OBS-2.23-D(iv)-**OTHER**: SCIENCE SUMMARY AND DATA RELEASE

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY OBS-2.23-E-**INFRAOPS**: O4 LENSING PAPER TECHNICAL REVIEW

TASK OBS-2.23-E(i)-**INFRAOPS**: TECHNICAL REVIEW COORDINATION

Coordinate technical review activities.

TASK OBS-2.23-E(ii)-**INFRAOPS**: REVIEW OF POSTERIOR-BASED ANALYSES

Review of the posteror-based analyses of strong lensing.

TASK OBS-2.23-E(iii)-**INFRAOPS**: REVIEW OF MACHINE LEARNING ANALYSES

Review of the machine learning analysis study.

TASK OBS-2.23-E(iv)-**INFRAOPS**: REVIEW OF FACTORIZED JOINT PARAMETER ESTIMATION ANALYSES

Review of the factorized joint parameter estimation analyses.

TASK OBS-2.23-E(v)-**INFRAOPS**: REVIEW OF FACTORIZED JOINT PARAMETER ESTIMATION POSTERIOR SAMPLES

Review of the posterior samples from the factorized joint parameter estimation analyses.

TASK OBS-2.23-E(vi)-**INFRAOPS**: REVIEW OF JOINT PARAMETER ESTIMATION ANALYSES

Review of the joint parameter estimation analyses.

TASK OBS-2.23-E(vii)-**INFRAOPS**: REVIEW OF JOINT PARAMETER ESTIMATION POSTERIOR SAMPLES

Review of the posterior samples from the joint parameter estimation analyses.

TASK OBS-2.23-E(viii)-**INFRAOPS**: REVIEW OF SUB-THRESHOLD SEARCH

Review of the sub-threshold search for lensed images.

TASK OBS-2.23-E(ix)-**INFRAOPS**: REVIEW OF TYPE II IMAGE SEARCHES

Review of the type II image search.

TASK OBS-2.23-E(x)-**INFRAOPS**: REVIEW OF MICROLENSING STUDIES

Review of the search for microlensing effects and associated posterior samples.

TASK OBS-2.23-E(xi)-**INFRAOPS**: REVIEW OF MILLILENSING STUDIES

Review of the search for millilensing effects and associated posterior samples.

TASK OBS-2.23-E(xii)-**INFRAOPS**: REVIEW OF POPULATION INFERENCE STUDIES

Review of the studies of lensing statistics.

TASK OBS-2.23-E(xiii)-**INFRAOPS**: REVIEW OF AUTOMATED WORKFLOW INFRASTRUCTURE

Review of the automated lensing workflow 'LensingFlow' infrastructure.

ACTIVITY OBS-2.23-F-**INFRAOPS**: O4 LENSING PAPER REVIEW

TASK OBS-2.23-F(i)-**INFRAOPS**: REVIEW OF PAPER SCIENTIFIC CONTENT

Publications & Presentations review of scientific content in the lensing paper.

TASK OBS-2.23-F(ii)-**INFRAOPS**: EDITING

Editorial Board review of paper quality in the lensing paper.

ACTIVITY OBS-2.23-G-**OTHER**: COMMON INFRASTRUCTURE MANAGEMENT FOR O4 LENSING PAPER

Management and participation in the running of common frameworks used for conducting lensing analyses.

TASK OBS-2.23-G(i)-**OTHER**: LENSING AUTOMATION FRAMEWORK MONITORING

Monitor the automated lensing workflow 'LensingFlow', ensuring that lensing analyses are successfully being started, completing, and having the automated checks performed. This will be performed in a rota system.

Expected products and/or outcomes

- O4a, O4b and O4c Lensing companion paper.
- Posterior samples from joint parameter estimation analyses.
- Data behind the figures appearing in the O4a, O4b and O4c Lensing paper.

OBS-2.24 O4a and O4b Search for Sub-Solar-Mass Compact Binary Coalescences

Search for compact binary coalescences with a component having mass below a solar mass

Motivation and goals

Compact objects with masses below $\sim 1\ M_\odot$ are not expected to be generated as endpoints of stellar evolution. The lowest mass neutron stars are expected to have masses above the Chandrasekhar mass [71] less the gravitational binding energy. Current models and observations place the minimum neutron star mass near $\sim 1.15\ M_\odot$ [72, 73, 74]. The lightest black holes are constrained by the maximum non-rotating neutron star mass, which is currently believed to be $\sim 2\ M_\odot$ [75].

There are several models that predict the formation of sub-solar mass black holes. One class posits that sub-solar mass primordial black holes could have formed via the prompt collapse of large overdensities in the early universe [76]. The size and abundance of primordial black holes is closely related to the early universe equation of state and the scale of the primoridal perturbations [77, 78, 79, 80]. Another class of models links sub-solar mass black holes to particulate dark matter, either via a complex particle spectrum [81] or nuclear interactions with neutron stars [82, 83, 84, 85, 86, 87, 88].

O4 deliverables

- Carry out a thorough search for sub-solar mass compact binary mergers in O4 data

ACTIVITY OBS-2.24-A-**OTHER**: O4 SEARCH FOR SUB-SOLAR MASS COMPACT BINARY MERGERS

TASK OBS-2.24-A(i)-**OTHER**: DETERMINE SEARCH PARAMETERS
Design, generate, and test coverage of a bank of template waveforms for sub-solar mass compact binaries.

TASK OBS-2.24-A(ii)-**OTHER**: RUN SEARCH PIPELINE
Carry out a matched filter based search using the template bank designed to recover sub-solar mass compact binaries.

ACTIVITY OBS-2.24-B-**OTHER**: INTERPRETATIONS OF O4 SUB-SOLAR MASS SEARCH RESULTS

In the event of a detection, we will perform parameter estimation. For a null result, we will provide rate upper limits and discuss other ways to meaningfully present constraints on the abundance of sub-solar mass compact objects/binaries.

TASK OBS-2.24-B(i)-**OTHER**: RATE ESTIMATION
For a null result, we will provide rate upper limits and discuss other ways to meaningfully present constraints on the abundance of sub-solar mass compact objects/binaries.

TASK OBS-2.24-B(ii)-**OTHER**: PARAMETER ESTIMATION

In the event of a detection, we will perform parameter estimation.

ACTIVITY OBS-2.24-C-**OTHER**: O4 SUB-SOLAR MASS EDITORIAL TEAM

Paper project management and writing.

TASK OBS-2.24-C(i)-**OTHER**: PROJECT MANAGEMENT

- Task management.
- Monitor milestones and deliverables.
- Coordinate with reviewers.
- Address / adjudicate comments.
- Follow publication procedures.

TASK OBS-2.24-C(ii)-**OTHER**: PAPER WRITING COORDINATION

- Prepare / solicit text for sections of paper.
- Text editing.
- Incorporate / address comments.

TASK OBS-2.24-C(iii)-**OTHER**: FIGURE PREPARATION

- Prepare production-quality figures.
- Prepare data-behind-figures for public dissemination.

TASK OBS-2.24-C(iv)-**OTHER**: SCIENCE SUMMARY AND DATA RELEASE

- Write science summary.
- Prepare data for GWOSC and for release on public DCC.

ACTIVITY OBS-2.24-D-**INFRAOPS**: O4 SUB-SOLAR MASS TECHNICAL REVIEW

TASK OBS-2.24-D(i)-**INFRAOPS**: TECHNICAL REVIEW COORDINATION

Coordinate technical review activities.

TASK OBS-2.24-D(ii)-**INFRAOPS**: REVIEW OF SEARCH RESULTS

Review of search results: candidate lists, background estimation, sensitivity.

TASK OBS-2.24-D(iii)-**INFRAOPS**: REVIEW OF PARAMETER ESTIMATION POSTERIOR SAMPLES

Review of Parameter Estimation posterior sample chains.

ACTIVITY OBS-2.24-E-**INFRAOPS**: O4 SUB-SOLAR MASS PAPER REVIEW

TASK OBS-2.24-E(i)-**INFRAOPS**: REVIEW OF PAPER SCIENTIFIC CONTENT

Publications & Presentations review of scientific content in Catalog paper.

TASK OBS-2.24-E(ii)-**INFRAOPS**: EDITING

Editorial Board review of paper quality in Catalog paper.

OBS-2.25 Characterizing exceptional CBC events

Prepare / write a paper to discuss in detail any compact binary coalescence that is deemed to be of particular relevance and meriting its own publication. This complements the catalog concept. (This paper could include Burst content if found by a burst search.)

Motivation and goals

In future observing runs, we expect to detect a broad range of compact object merger scenarios. A fraction of these will be exceptional events in the context of previous observations. Such systems will warrant specific attention to be determined only once confirmed. Further, there is a possibility that the first detection of CBC signals with KAGRA can be achieved during O4 altough it depends on the sensitivity KAGRA can achieve. If that happens, it is a major milestone of KAGRA and the gravitational wave astronomy.

Some examples of exceptional events would be one that yields:

- a binary with a sub-solar-mass component;
- other astrophysically interesting component masses (large mass ratio, large black hole mass, large neutron star mass, etc.);
- clear statement on neutron star equation of state;
- measurement of a high-spin system;
- clear evidence of orbital eccentricity;
- a multi-messenger counterpart (externally-triggered or in electromagnetic/neutrino follow-up searches);
- substantial improvement in the measurement of the Hubble constant;
- clear evidence of deviation from general relativity;
- a gravitationally lensed gravitational wave detection;
- clear indication of a particular formation channel.
- first detection or finding signs of a signal with KAGRA.

Major aspects and methods for this activity

Activities and tasks will come into scope upon the identification of an exceptional event. Here we give a generic placeholder for future accounting purposes.

ACTIVITY OBS-2.25-A-**INFRAOPS**: EXCEPTIONAL CBC EVENT AD HOC ACTIVITY

Placeholder for an ad hoc activity. Activities will be defined upon the occurrence of an exceptional event.

TASK OBS-2.25-A(i)-**INFRAOPS**: AD HOC TASK

Placeholder for an ad hoc task. Tasks will be defined upon the occurrence of an exceptional event.

Expected products and/or outcomes

A detailed analysis of exceptional events with parameter estimation and astrophysical interpretation.

OBS-3 CW Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Stochastic group in section OBS-8. For these activities, some combination of data from LIGO, Virgo and KAGRA will be used as deemed appropriate in each case.

OBS-3.1 Targeted searches for known pulsars

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

Rapidly spinning neutron stars in our Galaxy may emit CWs if they are not perfectly symmetric about their spin axis. Our searches target a subset of sources for which pulses are observed in radio, X-ray, or other electromagnetic radiation bands. Pulsar timing through electromagnetic observations can tell us precise sky positions, frequencies, frequency evolution, and binary orbital parameters (if applicable) of these objects, so that targeted analyses need search only a small parameter space (sometimes only a single phase template) and are not computationally limited. Electromagnetic observations also set an upper limit on the GW strain we could see from a known pulsar, by assuming that all of its observed spin-down is due to GW emission (see Equation 5 of [89]).

The standard searches assume GW emission from a triaxial neutron star, with the electromagnetic and GW components rotating as one unit. This would lead to GW emission at twice the rotation frequency ($2f$) of the star. Detecting such emission would represent the first ever measurement of the difference between the two (equatorial) components of the inertia tensor. This would provide important information on the strength and strain profile of the solid phase of the star (the crust, or possibly a solid core) and/or information on the nature of the internal magnetic field. Emission from other mechanisms is possible and can lead, for example, to a signal at a star's rotation frequency, f [90]. Hence, we also search for signals at either f, or both f and $2f$, whose detection would give further insight into the coupling between the crust and core of a neutron star.

Traditional searches for CWs targeted at known pulsars assume that sources emit the tensorial plus and cross GW polarizations predicted by the general theory of relativity. It is conceivable, however, that due to a departure from general relativity neutron stars may generate scalar and vector polarizations, on top or instead of tensor ones. If so, power in those extra modes would have been largely missed by standard targeted searches. In contrast, a search for non-tensorial continuous signals from known pulsars would be capable of detecting and classifying those alternative modes in a theory-independent way [91, 92, 93].

Generic metric theories of gravity may support up to six gravitational polarizations: two scalar modes (breathing and longitudinal), two vector modes (x and y) and two tensor modes (plus and cross). Because general relativity makes the unambiguous prediction that only the two tensor modes may exist, the presence of any of the tensorial modes, no matter how weak, would be fatal for the theory. Although it is not possible to use the current LIGO–Virgo network to carry out this important test of general relativity with transient signals, this can be done with long-lived CWs.

Methods

Three mature analysis pipelines for targeted searches are the time-domain Bayesian pipeline [94, 95], the 5-vector method [96], and the time-domain $\mathcal{F}/\mathcal{G}$-statistic method [89]. All three pipelines will be used for high-value targets for which the spin-down limit can be, or could nearly be, surpassed. The remaining sources will be searched for with the time-domain Bayesian pipeline. Searches will target emission at both f and $2f$. For calculating realistic values of the spin down limits, using improved intrinsic spin frequency derivative values, work by [97] can be used.

One search for non-tensorial CWs from known pulsars expands the time-domain Bayesian targeted analysis [94] to be sensitive to signals of any polarization content at a given frequency, without assuming any specific theory of gravity or emission mechanism. If a signal is detected, rigorous Bayesian methods will allow us to determine whether there is evidence of a departure from general relativity. Another search for scalar GW radiation predicted by Brans-Dicke theory adapts the $\mathcal{F}$-statistic to search for this particular GW signal.

Activities for O4

ACTIVITY OBS-3.1-A-**INFRAOPS**: EARLY-O4 HIGH-VALUE TARGETED PULSAR SEARCHES

A selection of the most promising targets, consisting of both millisecond and young pulsars, will be targeted using the first eigth months of data from the O4 run. This will lead, for example, to surpassing the spin-down limit for PSR J0737$-$3039A, the mildly recycled pulsar in the famous "double pulsar" system, and producing limits on the ellipticity of a handful of MSPs to levels of just a few $\times 10^{-9}$. We will produce a paper, aimed at a high profile journal, describing a search for signals from these selected targets.

TASK OBS-3.1-A(i)-**INFRAOPS**: OBTAIN PULSAR EPHEMERIDES

Obtain timing ephemerides from electromagnetic observers for the selected pulsars that are coherent over the run.

TASK OBS-3.1-A(ii)-**INFRAOPS**: RUN TIME-DOMAIN BAYESIAN PIPELINE

Run the time-domain Bayesian pipeline on the selected targets, searching at the two harmonics of the pulsar spin frequency: f and $2f$.

TASK OBS-3.1-A(iii)-**INFRAOPS**: RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

Search for GWs from the selected pulsars analyzing data from the network of detectors (LIGO, Virgo and KAGRA). Search at two harmonics of the pulsar spin frequency: f and $2f$.

TASK OBS-3.1-A(iv)-**INFRAOPS**: RUN THE 5-VECTOR PIPELINE

Search for GWs from the selected pulsars. Independent searches at f and $2f$.

TASK OBS-3.1-A(v)-**INFRAOPS**: REVIEW

Review any recent updates to the analysis codes, as well as the analysis results.

TASK OBS-3.1-A(vi)-**INFRAOPS**: WRITE PAPER

Write a paper describing the results of the search, with an emphasis on the astrophysical significance of surpassing the spin-down limit for any pulsars.

ACTIVITY OBS-3.1-B-**INFRAOPS**: FULL-O4 TARGETED PULSAR SEARCHES

As with previous runs (e.g. [98, 93]), we will perform a search for all pulsars with rotation frequencies greater than 10 Hz for which we have a reliable timing ephemeris spanning the run. The search will target emission at either, or both, once and twice the stellar rotation frequency. From the results we will make inferences on the underlying ellipticity distributions of populations of pulsars.

TASK OBS-3.1-B(i)-**INFRAOPS**: OBTAIN PULSAR EPHEMERIDES

Obtain timing ephemerides from electromagnetic observers for pulsars with rotation frequencies greater than 10 Hz that are coherent over the run.

TASK OBS-3.1-B(ii)-**INFRAOPS**: RUN TIME-DOMAIN BAYESIAN PIPELINE

Run the time-domain Bayesian pipeline on all the targets.

TASK OBS-3.1-B(iii)-**INFRAOPS**: RUN THE 5-VECTOR PIPELINE

Search for GWs from all the pulsars for which updated ephemerides will be available. Independent searches at f and $2f$.

TASK OBS-3.1-B(iv)-**INFRAOPS**: RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

Search for GWs from the tens of known pulsars for which the spin-down limit can be surpassed or nearly surpassed. Analyze data from the network of detectors. Search at two harmonics of the pulsar spin frequency.

TASK OBS-3.1-B(v)-**INFRAOPS**: POPULATION INFERENCE CODE DEVELOPMENT AND REVIEW

Review the code to be used to perform the population inference on the pulsar ellipticity distributions.

TASK OBS-3.1-B(vi)-**INFRAOPS**: POPULATION INFERENCE

Perform population inference on the ellipticity distribution of pulsars, splitting the population between "young" and millisecond pulsars.

TASK OBS-3.1-B(vii)-**INFRAOPS**: REVIEW

Review any recent updates to the analysis codes, as well as the analysis results.

TASK OBS-3.1-B(viii)-**INFRAOPS**: WRITE PAPER

Write a paper describing the results of the search.

ACTIVITY OBS-3.1-C-**INFRAOPS**: O4 TARGETED PULSARS NON-TENSORIAL ANALYSIS

We will perform a search for CW signals from a selection of known pulsars in which we allow their polarization state to contain non-tensorial modes. This search will be performed on data using the same set of pulsars as for the standard targeted pulsar search (Section OBS-3.1). It will expand upon the analysis done on previous data by allowing the signals to have emission at both once and twice the source rotation frequency.

TASK OBS-3.1-C(i)-**INFRAOPS**: CODE UPDATE

Update the Bayesian parameter estimation code to allow the inclusion of components of the non-tensorial signal at both f and $2f$.

TASK OBS-3.1-C(ii)-**INFRAOPS**: CODE REVIEW

Review the code updates to confirm they perform as expected.

TASK OBS-3.1-C(iii)-**INFRAOPS**: RUN TIME-DOMAIN BAYESIAN PIPELINE

Run the time-domain Bayesian pipeline on all targets, making use of the pulsar ephemerides and heterodyned data products already obtained for the standard known pulsar search.

TASK OBS-3.1-C(iv)-**INFRAOPS**: RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

For around 30 known pulsars for which the spin down limit can be surpassed or nearly surpassed, search for for scalar radiation predicted by Brans-Dicke theory.

TASK OBS-3.1-C(v)-**INFRAOPS**: REVIEW

Review any recent updates to the analysis codes, as well as the analysis results.

TASK OBS-3.1-C(vi)-**INFRAOPS**: PAPER CONTRIBUTION

Add these results to the full targeted search paper.

OBS-3.2 Narrow-band searches for known pulsars

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

These searches are an extension of targeted searches for known pulsars (Section OBS-3.1) in which the position of the source is assumed to be accurately known while allowing for uncertainties in the rotational parameters [99]. This type of search is generally computationally heavier with respect to targeted searches, but still cheaper than directed or all-sky searches. In general, narrow-band searches allow one to take into account a possible mismatch between the CW signal parameters and the rotation parameters inferred from electromagnetic observations. For instance, the GWs could be emitted by the core of the neutron star which may have a slightly different rotational frequency with respect to the magnetosphere.

Methods

Two pipelines, one based on the 5-vector method [100] used in targeted searches, and one based on the frequency-domain $\mathcal{F}$-statistic [101], can be used for narrow-band searches. The basic idea is to explore a range of frequency and spin-down values around the electromagnetic-derived values by properly applying barycentric and spin-down corrections to the data in such a way that a signal would appear as monochromatic apart from the sidereal modulation. Of the order of 10^7 points in the parameter space are typically explored in a narrow-band search.

Activities for O4

ACTIVITY OBS-3.2-A-**INFRAOPS**: EARLY-O4 NARROW-BAND CW SEARCHES

Using the O4a data, we will search for CWs from known pulsars for which we expect to surpass or approach the spindown limit. If no updated ephemeris will be available, we will use the ones of O3 propagated to an O4 reference time.

TASK OBS-3.2-A(i)-**INFRAOPS**: RUN SEARCHES

Run the search using the 5-vector method and, if enough person power is present, the $\mathcal{F}$-statistic method and produce and check for the presence of interesting outliers.

TASK OBS-3.2-A(ii)-**INFRAOPS**: OUTLIERS FOLLOWUP – TARGETED SEARCHES

Check the nature of the outliers by performing several targeted searches using more and more data for each outlier. A persistent GW signal is expected to be always present. Compare these results with software injections if necessary. Follow-ups with other analysis methods, including those testing for transient properties, should also be performed (see Section OBS-3.16).

TASK OBS-3.2-A(iii)-**INFRAOPS**: SENSITIVITY STUDIES

We will compute upper limits on CW emission from a subset of the pulsars in different frequency bands, in order to check our sensitivity.

TASK OBS-3.2-A(iv)-**INFRAOPS**: REVIEW SEARCH RESULTS

Review of any updated part of the codes and the search results.

TASK OBS-3.2-A(v)-**INFRAOPS**: PUBLISH RESULTS

Results will be either included in the O4a high-value pulsars paper together with targeted search results, or as comparison results in the full-O4 narrow-band paper.

ACTIVITY OBS-3.2-B-**INFRAOPS**: FULL-O4 NARROW-BAND CW SEARCHES

We will search for CWs from $\sim$40 known pulsars for which we expect to surpass or approach the spindown limit using the entire data. If no interesting outliers are present, we will set upper limits on GW strain. We expect to surpass the spindown limit for 4–5 additional pulsars at frequencies lower than 100 Hz and to improve our previous constraints in [102, 103].

TASK OBS-3.2-B(i)-**INFRAOPS**: RUN SEARCHES

Run the search on O4a+b data using the 5-vector method and, contingent on person power, the $\mathcal{F}$-statistic method and produce and check for the presence of interesting outliers.

TASK OBS-3.2-B(ii)-**INFRAOPS**: OUTLIERS FOLLOWUP – TARGETED SEARCHES

Check the nature of the outliers by performing several targeted searches using more and more data for each, with the inclusion of O4c data. A persistent GW signal is expected to be always present. Compare these results with software injections if necessary, and do follow-ups with other analysis methods, including those testing for transient properties (see Section OBS-3.16).

TASK OBS-3.2-B(iii)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, we will put upper limits on GW strain.

TASK OBS-3.2-B(iv)-**INFRAOPS**: REVIEW SEARCH RESULTS

Review of any updated part of the codes and the search results.

TASK OBS-3.2-B(v)-**INFRAOPS**: PUBLICATION

Produce a publication with the results of each pipeline.

OBS-3.3 Searches for r-modes from known pulsars

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

PSR J0537–6910 is a young (1–5 kyrs) energetic X-ray pulsar, rotating at a spin frequency $\nu = 62$ Hz [104], in the Large Magellanic Cloud at a distance of 49.6 kpc [105]. PSR J0537–6910 (hereafter J0537) has been the subject of a number of studies, starting from its first detection with the *Rossi X-ray Timing Explorer* (*RXTE*; [106]) up to recent observations starting in 2017 with the *Neutron Star Interior Composition Explorer* (*NICER*; [107]). J0537 is intriguing for several reasons. Not only is it the fastest spinning young pulsar known, but measurements of its spin evolution also reveal J0537 to be the most prolific glitcher known. J0537 is, however, unique, as it is the only glitching pulsar that shows a strong correlation between the size of a glitch and the waiting time to the next glitch [108, 109, 110, 111], which suggests that a threshold has to be reached to trigger the glitch mechanism (see [112] for a review of pulsar glitch models). One can try to understand the impact of glitches on the spin evolution of J0537 by comparing its long-term spin evolution, i.e., the trend over a number of years and consequently over many glitches, to its short-term spin evolution between glitches. [109] studied the spin evolution over a 13-year span of *RXTE* data (1999–2011) and determined a long-term second frequency derivative $\ddot{\nu} = -7.7 \times 10^{-22}$ Hz s^{-2} (and $\dot{\nu} \approx -1.99 \times 10^{-10}$ Hz s^{-1}), which leads to a braking index $n = \nu\ddot{\nu}/\dot{\nu}^2 = -1.22 \pm 0.04$. Similar estimates were obtained by [110] and more recently by [111] The braking index n is obtained by assuming a power-law spin-down mechanism for the neutron star of the form $\dot{\nu} \propto -\nu^n$, where $n = 3$ if magnetic dipole radiation (at constant magnetic field strength and inclination) is the dominant spin-down mechanism. A negative value of n thus describes an unusual spin evolution, which may be a consequence of the cumulative effect of glitches during the more than 20-year time span of monitoring observations since 1999 (see discussions in [109, 111]). In order to test this hypothesis, it is of interest to study the braking index between glitches. This allows us to understand if, far from a glitch, it is possible to extract an 'intrinsic' braking index that can provide information on the physical spin-down mechanism for J0537. A detailed analysis of post-glitch relaxations shows that, while the inter-glitch braking index is large for days after a glitch, it tends to an asymptotic value of $n \approx 7.4$ for longer times [113]. Similar values of n are also obtained independently by [110] and from analysis of recent *NICER* observations [111, 114]. Such a value may be indicative of the spin evolution of J0537 not being driven by electromagnetic wave emission but by gravitational-wave (GW) emission due to a constant amplitude r-mode oscillation for which $n \approx 7$ [113]. Furthermore previous theoretical analysis of the r-mode instability curve have already singled out J0537 as young enough to be in the region of parameter space where the r-mode is unstable and emitting GWs [115], thus providing additional motivation for the search.

Methods

There are two mature pipelines to perform the r-mode search from pulsar J0537: the 5-vector method and time domain $\mathcal{F}/\mathcal{G}$-statistic method. Both methods involve coherent analysis of the data between the glitches of the pulsar. As the position of J0537 is known very accurately, a directed search is performed and the pipelines search a parameter space of frequency and frequency derivatives. The r-mode GW emission frequency $f_{\rm GW}$ depends on the pulsar spin frequency ν and on the neutron star structure (e.g., [116, 117]). We adopt search parameter ranges in frequency recently updated in [117] and its derivatives following the analysis of [118]. The 5-vector method also involves incoherent addition of the statistic from the coherent analysis of inter-glitch segments, whereas the $\mathcal{F}/\mathcal{G}$-statistic method searches also for the second frequency derivative. Both methods were used in the search for r-mode GW emission from J0537 in O3 data [119] using the timing obtained from the *NICER* mission.

Activities for O4

ACTIVITY OBS-3.3-A-**INFRAOPS**: O4 SEARCH FOR R-MODES FROM PSR J0537−6910

We perform the search for r-mode GW emission from J0537 using the two pipelines and using the ephemeris of J0537 from the *NICER* mission.

TASK OBS-3.3-A(i)-**INFRAOPS**: OBTAIN EPHEMERIS OF J0537

Obtain the ephemeris of J0537 from the *NICER* mission observations covering the whole O4 data span.

TASK OBS-3.3-A(ii)-**INFRAOPS**: RUN THE 5-VECTOR PIPELINE

TASK OBS-3.3-A(iii)-**INFRAOPS**: RUN THE TIME-DOMAIN $\mathcal{F}/\mathcal{G}$-STATISTIC PIPELINE

TASK OBS-3.3-A(iv)-**INFRAOPS**: OUTLIERS FOLLOWUPS

Check the nature of the outliers by performing targeted searches and other pipelines (see Section OBS-3.16). Compare these results with software injections if necessary.

TASK OBS-3.3-A(v)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, we will set upper limits on the GW emission from r-modes, upper limits on the r-mode amplitude and constraints on the mass of pulsar J0537.

TASK OBS-3.3-A(vi)-**INFRAOPS**: REVIEW SEARCH RESULTS

Review of any updated part of the codes and the search results.

TASK OBS-3.3-A(vii)-**INFRAOPS**: PUBLICATION

Produce a joint publication with the results of each pipeline.

OBS-3.4 Directed searches targeting Galactic supernova remnants

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

Young neutron stars may be the strongest isolated radiators of gravitational waves. Supernova kicks indicate that neutron stars are born with some asymmetry, and spin-downs of young pulsars are generally more rapid than those of old pulsars, allowing for more gravitational wave emission as a possible part of that spin-down. Mountains may settle on long timescales with no plate tectonics to revive them, and r-modes (long-lived fluid oscillations) eventually succumb to viscosity as the star cools. Many of the youngest neutron stars in the Galaxy are known not as pulsars, but as non-pulsing X-ray point sources embedded in young supernova remnants, such as the current record holder Cassiopeia A at $\sim$ 300 years old. Small pulsar wind nebulae and extremely young supernova remnants without true point sources, e.g., SNR 1987A, also merit consideration.

For these targets the sky direction is known but there is no timing solution, so the searches cover wide bands of frequency (hundreds of Hz) and frequency derivatives. The parameter space is still small enough compared to all-sky surveys that time spans of order one-to-several weeks can be coherently integrated; and semi-coherent techniques can integrate longer time spans.

Methods

Most previous searches have been based on the $\mathcal{F}$-statistic [120], either as fully coherent [121, 122, 123] or semi-coherent [124] methods. Hidden Markov model techniques can also be used to track the unknown signal frequency in a young supernova remnant as it wanders due to secular spin-down and un-modeled stochastic timing noise [125], and are a computationally cheap supplement to other techniques. An extended application of the hidden Markov model technique allows tracking both once and twice the spin frequency of the star, producing better sensitivities in the case that the signal contains two frequency components [126]. The Single harmonic and the dual harmonic Viterbi pipelines have been applied for the search of young supernova remnants in O3a [127].

Another way of looking for these signals is to use the FrequencyHough transform as already done for all-sky searches. The FrequencyHough algorithm has been implemented in the Band-Sampled-Data framework [128] and adapted to a directed search pipeline use already in O2 for the Galactic center search [129]. The pipeline is a semi-coherent method where the coherent part is covered by the BSD heterodyned data while the incoherent part is performed through the production of "peakmaps" and Frequency Hough maps. This pipeline has been used for the search of young supernova remnants in O3a [127].

The computationally intensive Weave-based search (semi-coherent $\mathcal{F}$-statistic) will focus on a handful of the most promising sources and use multi-day coherence times to dig deep in the noise, assuming a signal model with smooth frequency evolution. Outliers from the initial search stage will be followed up in a multi-stage analysis that requires increasing SNR for increasing coherence time. This pipeline has been already used in O3a for the search of Cas A and Vela Jr [130]

The fully coherent Drill search (also based on the $\mathcal{F}$-statistic) will target a complementary set of the most promising sources, focusing on those where long coherence times are feasible.

Depending on person power, PyStoch [131] will be employed as well. All available source information will be used to define the frequency and frequency derivative(s) ranges for the search, which will require adjusting the bin size in PyStoch. We will then run PyStoch and combine the bins appropriately to check for significant candidates across different runs. Finally, we will follow up on any significant candidates using stroboscopic resampling and, if needed, the Frequency Hough in directed mode.

Activities for O4

For O4, there will be analyses of various targets with several pipelines, and at least two publications (quick-turnaround O4a results and full-O4 results). Which pipeline contributes to which publication and on which subset of targets will be assessed based on run progress, data quality and available resources.

ACTIVITY OBS-3.4-A-**INFRAOPS**: O4 SUPERNOVA REMNANT CW SEARCHES

We will run directed searched for selected supernova remnants using some of the available pipelines, i.e., the two Viterbi (single and dual harmonic), BSD-directed, Weave and/or Drill, as well as PyStoch. This first activity lists the tasks needed for both the O4a and Full-O4 searches, while tasks for running the actual searches are listed separately below.

TASK OBS-3.4-A(i)-**INFRAOPS**: SOURCE SELECTION

Select a list of sources for directed searches. These sources will likely include all of those sought in the O3a searches (Cassiopeia A, Vela Jr, ...) in addition to SNR 1987A and perhaps other new sources of interest.

TASK OBS-3.4-A(ii)-**INFRAOPS**: REVIEW CODES AND SEARCH RESULTS

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section OBS-3.19); for both the O4a and Full-O4 searches.

ACTIVITY OBS-3.4-B-**INFRAOPS**: INTEGRATING DRILL PIPELINE INTO THE LSC

TASK OBS-3.4-B(i)-**INFRAOPS**: REMAINING CODE DEVELOPMENT

Drill works, but a few short term efficiency improvements will be useful.

TASK OBS-3.4-B(ii)-**INFRAOPS**: FIRST LSC REVIEW

Review the code for LSC use.

ACTIVITY OBS-3.4-C-**INFRAOPS**: O4A DIRECTED SUPERNOVA REMNANTS CW PUBLICATION

TASK OBS-3.4-C(i)-**INFRAOPS**: RUN SEARCH AND POST-PROCESSING

Run directed searches using multiple pipelines, identify and follow up candidates.

TASK OBS-3.4-C(ii)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

TASK OBS-3.4-C(iii)-**INFRAOPS**: PUBLICATION

Produce a single publication either presenting the detection of CWs from one or more supernova remnants or comparing upper limits from the search pipelines that were used.

ACTIVITY OBS-3.4-D-**OTHER**: FULL-O4 DIRECTED SUPERNOVA REMNANTS CW PUBLICATION

TASK OBS-3.4-D(i)-**OTHER**: RUN SEARCH AND POST-PROCESSING

Run directed searches using multiple pipelines, identify and follow up candidates.

TASK OBS-3.4-D(ii)-**OTHER**: SET UPPER LIMITS

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

TASK OBS-3.4-D(iii)-**OTHER**: PUBLICATION

Produce a single publication either presenting the detection of CWs from one or more supernova remnants or comparing upper limits from the search pipelines that were used.

OBS-3.5 Directed searches targeting Scorpius X-1 and other low-mass X-ray binaries

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

Accretion in a binary system leads to recycling, where the neutron star spins up to near-kHz frequencies. In the torque balance scenario, the gravitational radiation reaction torque balances the accretion torque, which is proportional to the X-ray flux, in turn implying a limit on the characteristic wave strain proportional to that flux [132]. Torque balance is one possible explanation for the observed fact that the spin frequencies of low-mass X-ray binaries (LMXBs) are systematically lower than predicted. Directed searches for accreting binaries are a high priority because the sources are relatively powerful if they are emitting near the torque balance limit. A CW detection would shed light on several important astrophysical questions: by combining CW and electromagnetic data, one could tie down the emission mechanism, produce equation-of-state information, and probe the physics of the X-ray emission mechanism and of any differential rotation between the interior and crust.

Methods

A number of largely independent algorithms have been developed which can be used to search for LMXBs: cross-correlation [133, 134, 135, 136], doubly-Fourier transformed data (TwoSpect; [137]), hidden Markov models (Viterbi; [138, 139, 140, 141, 142]), coherent summation of matched-filter sidebands (Sideband; [143]), and a resampling procedure, which is a generalization of the 5-vector method [144], and F-statistic based semicoherent procedure with known sky-localization of the source (BinaryWeave; [145, 146]). The central challenge facing these searches is that the spin frequency and orbital parameters are in general unknown. Furthermore the spin frequency is likely to wander stochastically in response to the fluctuating torque [147].

Activities for O4

ACTIVITY OBS-3.5-A-**INFRAOPS**: EARLY-O4 SCORPIUS X-1 SEARCH

We will run a directed search for continuous gravitational waves from Scorpius X-1 at signal frequencies $f \lesssim 200\,\mathrm{Hz}$ in data from O4a using at least the cross-correlation pipeline. We will use the resampling algorithm [135] to allow a longer coherence time, as was done in [148]. In the event of a detection, we will publish results from all pipelines, as well as detailed follow up; otherwise we will set upper limits.

TASK OBS-3.5-A(i)-**INFRAOPS**: OPTIMIZATION OF THE RESAMPLING CROSS-CORRELATION SEARCH PIPELINE

We need to determine the appropriate configuration for the O4a analysis, and correct any issues uncovered in the resampling pipeline.

TASK OBS-3.5-A(ii)-**INFRAOPS**: REVIEW RESAMPLING PIPELINE

As this is the first time the resampling CrossCorr code will be used for an LVK analysis, it will need to be reviewed.

TASK OBS-3.5-A(iii)-**INFRAOPS**: RUN CROSS-CORRELATION SEARCH

Run cross-correlation search, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK OBS-3.5-A(iv)-**INFRAOPS**: FOLLOW UP STATISTICAL OUTLIERS – VETOES

Follow up statistical outliers using line-lists and tests of the efficacy of each candidate source.

TASK OBS-3.5-A(v)-**INFRAOPS**: FOLLOW UP STATISTICAL OUTLIERS – PARAMETER ESTIMATION

Statistical outliers that pass vetoes in the above task should be analyzed with a denser set of matched-filter templates if possible and followed up using more-sensitive, but computationally intensive search methods like that used for the targeted known pulsar search.

TASK OBS-3.5-A(vi)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, each pipeline sets upper limits on gravitational-wave emission from Scorpius X-1.

TASK OBS-3.5-A(vii)-**INFRAOPS**: REVIEW SEARCH RESULTS

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section OBS-3.19).

TASK OBS-3.5-A(viii)-**INFRAOPS**: PUBLICATION

Produce a single publication either presenting the detection of continuous gravitational-waves from Scorpius X-1 or producing improved upper limits.

ACTIVITY OBS-3.5-B-**INFRAOPS**: FULL-O4 SCORPIUS X-1 SEARCHES

We will run a directed search for continuous gravitational waves from Scorpius X-1 using at least the cross-correlation and Viterbi search pipelines. The BinaryWeave pipeline will also be used if it can be implemented and reviewed on an appropriate timescale. In the event of a detection, we will publish results from all pipelines, as well as detailed follow up; otherwise we will set upper limits.

TASK OBS-3.5-B(i)-**INFRAOPS**: RUN INCREMENTAL VITERBI SEARCHES

Run Viterbi search to analyze data as soon as calibrated, cleaned, and gated data becomes available – even if these products are only subsets of the full run – to generate a list of candidates to follow up.

TASK OBS-3.5-B(ii)-**INFRAOPS**: RUN VITERBI SEARCH

Run Viterbi search on GPUs, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK OBS-3.5-B(iii)-**INFRAOPS**: ESSENTIAL OPTIMIZATION OF THE CROSS-CORRELATION SEARCH CODE

Planned improvements over the O3 pipeline to deliver a faster search include use of resampling [135] to speed up the computation at lower frequencies, and re-optimization of the choice of coherence times as a function of frequency and orbital parameters.

TASK OBS-3.5-B(iv)-**INFRAOPS**: RUN CROSS-CORRELATION SEARCH

Run cross-correlation search, post-process results, produce a list of candidate sources in the event of statistical outliers. At low frequencies, this will use the resampling pipeline as detailed above.

TASK OBS-3.5-B(v)-**INFRAOPS**: UPDATE AND PREPARE BINARYWEAVE FOR REAL DATA

Person-power permitting, update the BinaryWeave pipeline for searching real detector data with noise, add/incorporate noise vetos and instrumental line detections.

TASK OBS-3.5-B(vi)-**INFRAOPS**: PERFORM PARAMETER SPACE OPTIMIZATION FOR BINARYWEAVE

Person-power permitting, perform Sco X-1 parameter space optimization for BinaryWeave with updated astrophysical constraints and electromagnetic data to maximize search sensitivity.

TASK OBS-3.5-B(vii)-**INFRAOPS**: RUN BINARYWEAVE SEARCH

Person-power permitting, run a BinaryWeave search, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK OBS-3.5-B(viii)-**INFRAOPS**: FOLLOW UP STATISTICAL OUTLIERS – VETOES

Follow up statistical outliers from each search using line-lists and tests of the efficacy of each candidate source. This may be done collectively or by each individual search.

TASK OBS-3.5-B(ix)-**INFRAOPS**: FOLLOW UP STATISTICAL OUTLIERS – PARAMETER ESTIMATION

Statistical outliers that pass vetoes in the above task should be analyzed with a denser set of matched-filter templates if possible and followed up using more-sensitive, but computationally intensive search methods like that used for the targeted known pulsar search.

TASK OBS-3.5-B(x)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, each pipeline sets upper limits on gravitational-wave emission from Scorpius X-1.

TASK OBS-3.5-B(xi)-**INFRAOPS**: REVIEW CODES AND SEARCH RESULTS

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section OBS-3.19).

TASK OBS-3.5-B(xii)-**INFRAOPS**: PUBLICATION

Produce a single publication either presenting the detection of continuous gravitational-waves from Scorpius X-1 or comparing upper limits from the search pipelines that were used.

ACTIVITY OBS-3.5-C-**OTHER**: O4 SEARCHES FOR OTHER LMXBS

Time and personpower permitting, we may run directed searches for other low mass X-ray binary (LMXB) targets with unknown spin frequency, besides Sco X-1, and as opposed to accreting millisecond X-ray pulsars with known spin frequencies (Section OBS-3.6).

TASK OBS-3.5-C(i)-**OTHER**: IDENTIFY TARGETS AND DETERMINE PARAMETER RANGES

We need to identify a list of promising LMXB targets for each search, and coordinate with electromagnetic astronomers to ensure we have the appropriate parameter ranges from orbital ephemerides.

TASK OBS-3.5-C(ii)-**OTHER**: RUN VITERBI SEARCH

Run Viterbi search on GPUs, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK OBS-3.5-C(iii)-**OTHER**: ADAPT CROSSCORR SEARCH FOR A BROADER TARGET LIST

Since the CrossCorr search has only previously been run on Sco X-1, some work will need to ensure that the infrastructure still works for different parameter space regions.

TASK OBS-3.5-C(iv)-**OTHER**: RUN CROSSCORR SEARCH

Run CrossCorr search, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK OBS-3.5-C(v)-**OTHER**: FOLLOW UP STATISTICAL OUTLIERS – VETOS

We will use the same veto procedure as applied in the Scorpius X-1 search to follow up any statistical outliers.

TASK OBS-3.5-C(vi)-**OTHER**: PUBLICATION

Produce publication presenting the LMXB search results, potentially as part of the Sco X-1 paper.

TASK OBS-3.5-C(vii)-**OTHER**: REVIEW CODES AND SEARCH RESULTS

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section OBS-3.19).

OBS-3.6 Narrowband directed searches targeting accreting millisecond X-ray pulsars

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

Accreting millisecond X-ray pulsars (AMXPs) are accreting neutron stars in which outbursts are observed, providing constraints on the neutron star spin frequency. This allows a deeper and faster search than the all-frequency search for LMXBs such as Sco X-1 (Section OBS-3.5).

Methods

The search for GWs from AMXPs has been conducted [149, 150] using a Hidden Markov Model (Viterbi pipeline) [138, 139].

Activities for O4

ACTIVITY OBS-3.6-A-**INFRAOPS**: O4 SEARCHES FOR AMXPS

We will run a narrowband search for a selection of accreting millisecond X-ray pulsars (AMXPs), which are low mass X-ray binaries (LMXBs) with electromagnetic constraints on the neutron star rotation frequency. We will use the Viterbi search pipeline initially, however other search pipelines could also be used if person and computational resources allow.

TASK OBS-3.6-A(i)-**INFRAOPS**: TARGET LIST

Identify a list of AMXP targets.

TASK OBS-3.6-A(ii)-**INFRAOPS**: RUN VITERBI SEARCH

Run Viterbi search on GPUs, post-process results, produce a list of candidate sources in the event of statistical outliers.

TASK OBS-3.6-A(iii)-**INFRAOPS**: FOLLOW UP STATISTICAL OUTLIERS – VETOS

We will use the same veto procedure as applied in the previous AMXP searches, and the Scorpius X-1 Viterbi search, to follow up any statistical outliers.

TASK OBS-3.6-A(iv)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, we will put upper limits on GW strain, and convert to astrophysical parameters, such as ellipticity and r-mode amplitude.

TASK OBS-3.6-A(v)-**INFRAOPS**: REVIEW CODE AND SEARCH RESULTS

Review of any updated part of the codes and the search results.

TASK OBS-3.6-A(vi)-**INFRAOPS**: PUBLICATION

Produce publication presenting AMXP search results.

OBS-3.7 Directed searches targeting the Galactic center

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

All-sky CW searches are computationally limited because of the rapid increase in computational cost with coherence time of the search. Hence there is a trade-off between searching the largest sky area at reduced sensitivity, or searching a smaller sky region with increased sensitivity. There are regions in the sky that are thought to host high concentrations of the types of objects that might be emitting detectable CWs; the Galactic center and globular clusters are both regions of interest. Several independent lines of evidence suggest the presence of a large number of NSs in the few inner parsecs of the Milky Way and may also explain the EM excess measured by astronomical surveys which are not emitted by resolved sources [151, 152, 153, 154, 155]. Nevertheless, the dark matter interpretation for the origin of this excess cannot be ruled out. In this search three different sources of CW (and CW-like) signals will be searched for: isolated NSs, boson clouds around spinning BHs, and small compact (dark) objects binaries (e.g. primordial black holes) with masses below $10^{-3}\ M_{\odot}$. The results can also be reinterpreted taking into account the possibility that the signals may come from a larger distance behind the galactic center and have been lensed by the supermassive black hole.

Methods

The idea is to explore a wide frequency and spin-down/spin-up parameter space, limiting–where possible– the computational cost of the search. The BSD-directed search pipeline [129], pointing to the sky position of Sgr A*, will be used. The BSDs are complex time series sampled at 0.1 s and divided into frequency bands of 10 Hz [128]. For the search for CW signals the time series is heterodyned, partially removing the Doppler effect. From this time series we build "peakmaps", which consist in a collection of time-frequency peaks selected from the average spectrum. The peakmap will be the input of the FrequencyHough transform which will map the time-frequency peaks into the intrinsic frequency/spin-down values of the source. Selected candidates, if significant enough, will be followed up with methods similar to those used in all-sky searches. The BSD-directed search pipeline will be used for the search of standard isolated NSs. Another pipeline

(BSD-COBI), will be used for the search of small dark compact objects. The BSD-COBI is a more general pipeline for the search of small dark compact objects like primordial black holes and it can be set up for the search of these signals in the galactic center or be tuned for an all-sky search. This pipeline uses heterodyned data and peakmaps. The semi-coherent 5-vector method will be used for the search of boson clouds [156]. This last method will be also applied for the search of boson clouds formed around black holes in globular clusters (see (Section OBS-3.8)).

Activities for O4

ACTIVITY OBS-3.7-A-**INFRAOPS**: O4 GALACTIC CENTER CW SEARCH

We will run a directed search for the Galactic center using the available pipelines reviewed by the time of the start of the search. The BSD-directed for isolated NSs is the same used for the O3 search in [157], no changes are forseen for this pipeline. The semi-coherent 5-vector method [156] for the search of boson clouds is currently under review. The BSD-COBI pipeline for small dark compact objects will start the review soon.

TASK OBS-3.7-A(i)-**INFRAOPS**: RUN SEARCH AND POST-PROCESSING

Run directed search(es), identify and follow up candidates.

TASK OBS-3.7-A(ii)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, set upper limits on signal strain and other astrophysical properties.

TASK OBS-3.7-A(iii)-**INFRAOPS**: REVIEW SEARCH CODE AND RESULTS

Review the search procedure and results, as well as any recent search method improvements and optimizations (Section OBS-3.19).

TASK OBS-3.7-A(iv)-**INFRAOPS**: PUBLICATION

Produce a publication presenting the results.

OBS-3.8 Directed searches targeting globular clusters

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

We plan to perform a deep search for CWs from millisecond pulsars and depleting scalar boson clouds in globular clusters (GCs). GCs are known to host large populations of millisecond pulsars and recent theoretical advances and observations suggest they can also host a significant number of stellar mass black holes (BHs) [158, 159, 160, 161]. Such BHs can develop an ultra-light boson cloud through the superradiance process which, after formation, decays through the emission of CWs. GCs have a small spatial extension, corresponding to one or few sky pixels, depending on the search coherence times. In addition, the range of interesting spin-down/up values for the aforementioned class of sources is small. Indeed, millisecond pulsars are characterized by a spin-down typically smaller than about -10^{-13} Hz/s, and the CW signal from depleting scalar boson clouds has been predicted to have a very small spin-up, up to $+10^{-14}$ Hz/s (at least if boson self-interaction can be neglected). Hence, deep directed searches at a reasonable computing cost can, in priciple, be performed. No other directed searches toward GCs have been done in O3 and planned in O4. Other searches covering GC positions, like all-sky searches, are less sensitive than the search we plan. This search points to nearly monochromatic signals and is complementary to the all-sky boson cloud search (Section OBS-3.14), which aims at covering signals with some frequency wandering [162].

Methods

We plan to run the search using a new semi-coherent method recently developed [156].The method is built on the so-called *5-vector* statistics [96], largely used in targeted searches for known pulsars, which is here adapted to a semi-coherent scheme. For each given sky direction, Doppler and spin-down are corrected with a two-step procedure in which an initial rough correction performed over the full dataset is followed by a refined one over time segments of duration equal to an integer number of sidereal days. This new pipeline allows to make sensitive and computationally cheap searches toward specific sky directions. For a coherence time of about 5 days, one sky pixel is enough to cover the extension of typical GCs.

We additionally plan to explore the possibility of using a hidden Markov model-based method which explicitly accommodates spin wandering [138] as a complementary approach.

Activities for O4

A tentative list of GCs we will target in this search consists of: Terzan 5, 47 Tuc, NGC5139, Palomar 5, M22, NGC 3201, NGC 6397. We will run the search separately for subsets of the O4 run, suitably combining the results. Each search will cover the frequency range [20, 1500] Hz and the spin-down(up) range $[-10^{-11}, 10^{-11}]$ Hz/s. The search results will be described in an observational paper.

ACTIVITY OBS-3.8-A-**OTHER**: O4 GLOBULAR CLUSTERS CW SEARCH

We will run a directed search toward some globular clusters, aiming at CW emission from millisecond pulsars and scalar boson clouds around stellar mass black holes. The search will be based on a semi-coherent method, relying on the combination of five-vector statistics computed over data segments with duration of 3-5 sidereal days. Outliers will be followed-up with the same method, over a restricted volume of the parameter space, increasing the data segment duration to 8-12 sidereal days.

TASK OBS-3.8-A(i)-**OTHER**: RUN SEARCH

Run the search and identify outliers.

TASK OBS-3.8-A(ii)-**OTHER**: OUTLIER FOLLOWUP

Outlier follow-up using the same method.

TASK OBS-3.8-A(iii)-**OTHER**: PUBLICATION

Produce a publication presenting the results.

ACTIVITY OBS-3.8-B-**INFRAOPS**: O4 GLOBULAR CLUSTERS CW SEARCH – REVIEW

TASK OBS-3.8-B(i)-**INFRAOPS**: REVIEW SEARCH CODE AND RESULTS

Review search results (main analysis code review already done).

OBS-3.9 All-sky searches for unknown generic continuous-wave sources

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

CW searches largely focus on signals expected from specific gravitational wave sources or source classes. However, we also need to consider sources that produce quasi-sinusoidal gravitational waves but with a time evolution that does not fit with our expectations. Non- (or low-) parametric search techniques can explore the parameter space beyond the regions covered by semi-coherent methods and with competitively similar sensitivities. With slight modification, these techniques can also be used to identify and distinguish instrumental artefacts.

Methods

SOAP [163] is a non-parametric search pipeline which is computationally cheap, returning results within $\mathcal{O}$(hours) after SFTs are generated. The non-parametric nature of the search makes it sensitive to many different signal types which may not follow the standard CW frequency evolution. The SOAP pipeline is now mature, and recent developments have enabled it to return sky localisation estimates as well as identifying a possible signal. By its nature, SOAP can only set upper limits if a signal model is assumed, so the fully-generic search is purely a detection pipeline. However, when a search sensitivity can be set, on (say) isolated neutron stars with a constant rate of spindown, its sensitivity is comparable to semi-coherent searches with coherence times of 30 minutes.

Activities for O4

ACTIVITY OBS-3.9-A-**OTHER**: O4A GENERIC CW ALL-SKY SEARCH

TASK OBS-3.9-A(i)-**OTHER**: RUN SEARCH
SOAP is computationally cheap, and will be run continuously throughout O4a with an update cadence of one week.

TASK OBS-3.9-A(ii)-**OTHER**: OUTLIERS FOLLOWUP – ASTROPHYSICAL PLAUSIBILITY
We will also check the astrophysical plausibility of the Viterbi track.

TASK OBS-3.9-A(iii)-**OTHER**: PUBLICATION
Produce a publication that includes the results of the pipeline, or contribute to a joint paper with the isolated-NS searches (Section OBS-3.10).

ACTIVITY OBS-3.9-B-**INFRAOPS**: O4A GENERIC CW ALL-SKY SEARCH - CODE REVIEW

TASK OBS-3.9-B(i)-**INFRAOPS**: REVIEW SEARCH CODE AND RESULTS
Review of any updated part of the codes and the search results.

ACTIVITY OBS-3.9-C-**OTHER**: FULL-O4 GENERIC CW ALL-SKY SEARCH

TASK OBS-3.9-C(i)-**OTHER**: RUN SEARCH

SOAP is computationally cheap, and will be run continuously throughout O4 with an update cadence of one week.

TASK OBS-3.9-C(ii)-**OTHER**: OUTLIERS FOLLOWUP – ASTROPHYSICAL PLAUSIBILITY

We will also check the astrophysical plausibility of the Viterbi track.

TASK OBS-3.9-C(iii)-**OTHER**: PUBLICATION

Produce a publication that includes the results of the pipeline, or contribute to a joint paper with the isolated-NS searches (Section OBS-3.10).

ACTIVITY OBS-3.9-D-**INFRAOPS**: FULL-O4 GENERIC CW ALL-SKY SEARCH - CODE REVIEW

TASK OBS-3.9-D(i)-**INFRAOPS**: REVIEW SEARCH CODE AND RESULTS

Review of any updated part of the codes and the search results.

OBS-3.10 All-sky searches for unknown isolated sources

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

While other CW searches explore regions of potentially high interest, e.g. known pulsars and directed search targets, it is prudent to conduct comprehensive searches of the entire parameter space so as not to miss an unexpected source, one for which electromagnetic emission has not yet been detected. Theory suggests that fractional deformations or *ellipticities* of neutron stars as high as 10^{-5} could be sustained by neutron star crusts. On the other hand, there are observed neutron stars with ellipticities smaller than 10^{-8}, and it may well be that still smaller ellipticities are common. As our searches struggle to touch ellipticities of 10^{-7} at the top of the explored frequency range, it is likely that the first discovered source would have an unusually high ellipticity.

Methods

There are several pipelines in the CW group that have been optimized for different search scenarios, data quality and analysis speed. PowerFlux [164] can be used to carry out broad all-sky searches over the entire frequency space with the aim of producing results as promptly as possible. It is the only pipeline that performs direct estimation of GW power. The loosely coherent pipeline [165] is capable of improved sensitivity at greater computational cost. FrequencyHough [166] and SkyHough [167] are based on different implementations of the Hough transform algorithm and inherit its resilience to contaminated data. The time-domain $\mathcal{F}$-statistic pipeline [168] is based on a method with a long coherence time. This makes it resilient to many artifacts affecting pipelines with shorter coherence lengths. All pipelines have experience with processing large numbers of outliers with streamlined follow-up methods and vetoes. The Weave [169] pipeline, based on the $\mathcal{F}$-statistic and optimal lattice template banks, has been used for a deep all-sky search over a narrow frequency band [170]. For the non-parametric SOAP [163] pipeline, see (Section OBS-3.9).

Activities for O4

For O4, there will be several analyses with these pipelines, and at least two publications (quick-turnaround O4a results and full-O4 results). Which pipeline contributes to which publication will be assessed based on run progress, data quality and available resources.

ACTIVITY OBS-3.10-A-**INFRAOPS**: O4 ALL-SKY ISOLATED CW SEARCHES

TASK OBS-3.10-A(i)-**INFRAOPS**: RUN THE SKYHOUGH SEARCH

Run the SkyHough search code on multi-interferometer data, produce a large list of candidate sources, and post-process the results with a number of vetoes and follow-ups.

TASK OBS-3.10-A(ii)-**INFRAOPS**: RUN TIME-DOMAIN $\mathcal{F}$-STATISTIC PIPELINE

Run the time domain F-statistic pipeline for the detector network. Search a broad frequency range divided into time-frequency segments using the two-step procedure. First search the segments coherently using the $\mathcal{F}$-statistic and then search for coincidences among candidates in each narrow ($\sim$1 Hz) frequency band.

TASK OBS-3.10-A(iii)-**INFRAOPS**: RUN THE FREQUENCYHOUGH SEARCH

Run the FrequencyHough search code on data from the LIGO and Virgo detectors to search for significant outliers. If person power is available, we will perform a follow-up based on the standard approach (computation of a set of FrequencyHough maps with higher coherence time), plus – for a subset of them – the new semi-coherent 5-vector method to further increase the coherence time. In any case, O4a outliers will be used for coincidences with outliers from later in the run.

TASK OBS-3.10-A(iv)-**INFRAOPS**: RUN THE POWERFLUX SEARCH

Run the PowerFlux search code on data from the LIGO detectors to set upper limits and search for significant outliers. Run the PowerFlux search code on data from the LIGO detectors to set upper limits and search for significant outliers. Loose coherence will be used to follow up outliers in multiple stages, requiring improved SNR with each stage of increased effective coherence time.

TASK OBS-3.10-A(v)-**INFRAOPS**: RUN THE WEAVE SEARCH (SUBJECT TO PERSONPOWER)

If personpower is available, contribute a search using the Weave pipeline. This may e.g. follow the idea of [170] in performing a deep all-sky search over a narrow range of frequencies.

TASK OBS-3.10-A(vi)-**INFRAOPS**: FOLLOW UP STATISTICAL OUTLIERS

Follow up statistical outliers from each search using longer coherent integration times. This may be done collectively or by each individual search.

TASK OBS-3.10-A(vii)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, each pipeline sets averaged population based upper limits on the gravitational-wave strain amplitude and derives astrophysical implications.

TASK OBS-3.10-A(viii)-**INFRAOPS**: REVIEW

Review search setups and results, as well as any recent search method improvements and optimizations (Section OBS-3.19).

ACTIVITY OBS-3.10-B-**INFRAOPS**: O4A ALL-SKY ISOLATED CW SEARCH PUBLICATION

TASK OBS-3.10-B(i)-**INFRAOPS**: PUBLICATION

Produce a single publication either presenting the detection of CWs from isolated spinning neutron stars or comparing upper limits from the search pipelines that were used.

ACTIVITY OBS-3.10-C-**INFRAOPS**: FULL-O4 ALL-SKY ISOLATED CW SEARCH PUBLICATION

TASK OBS-3.10-C(i)-**INFRAOPS**: PUBLICATION

Produce a single publication either presenting the detection of CWs from isolated spinning neutron stars or comparing upper limits from the search pipelines that were used.

ACTIVITY OBS-3.10-D-**INFRAOPS**: NEW CODE FOR THE SKYHOUGH SEARCH USING THE $\mathcal{F}$-STATISTIC

Development work is undergoing to significantly improve sensitivity of the SkyHough search. The new version of the search pipeline that is planned for delivery in time for the full-O4 analysis will use sparse matrix representations and GPU acceleration to gain the benefits of demodulation (via the $\mathcal{F}$-statistic), increasing the time baseline of the coherent step and, consequently, the depth of the search. An alternative is to use the generic track-based code [171] that is in development for both isolated and binary sources.

TASK OBS-3.10-D(i)-**INFRAOPS**: FINALIZE DEVELOPMENT AND TUNING

TASK OBS-3.10-D(ii)-**INFRAOPS**: INJECTION CAMPAIGN AND SENSITIVITY STUDY

TASK OBS-3.10-D(iii)-**INFRAOPS**: REVIEW OF UPDATED PARTS OF THE CODES

ACTIVITY OBS-3.10-E-**INFRAOPS**: IMPROVEMENTS IN THE CW ALL-SKY TIME-DOMAIN $\mathcal{F}$-STATISTIC PIPELINE

Improvements in the multi-stage pipeline include extending the 2nd-stage coincidences procedure to more general model-agnostic signal types, rewriting the signal injection/upper limits part of the pipeline, and followup of outliers by a ML procedure to study the $\mathcal{F}$-statistic distribution for a given sky position.

TASK OBS-3.10-E(i)-**INFRAOPS**: EXTENSION OF THE COINCIDENCES PROCEDURE

Currently only strictly continous almost-monochromatic signals are being search for. By taking into account signal types with e.g. amplitude variation, the triggers found by the 1st stage of the pipeline may be used in search for transient signals.

TASK OBS-3.10-E(ii)-**INFRAOPS**: SIGNAL INJECTIONS/UPPER LIMITS

We perform signal injections in each time-domain segment and each band to establish coincidences and set search upper limits. This part of the pipeline needs a technical rewrite, and additional improvements e.g., using ML methods to optimally chose injection amplitudes for a given frequency band (relate the ULs as a function of frequency with the sensitivity curve of the detectors).

TASK OBS-3.10-E(iii)-**INFRAOPS**: OUTLIER FOLLOWUP BY STUDYING THE $\mathcal{F}$-STATISTIC DISTRIBUTION IN f-$\dot{f}$ PLANE

For outliers found by first stages of the pipeline, we plan to confirm their astrophysical nature (or instrumental nature) by studying the distribution of $\mathcal{F}$-statistic values on the dense grid in the f-$\dot{f}$ plane (i.e., for a given sky position). This task will be enhanced by ML techniques.

OBS-3.11 All-sky searches for unknown sources in binaries

Start date: 2023-05-24
Estimated due date: 2025-08-23

Motivation

CW emission from neutron stars in binary systems (see also Section OBS-3.5) is of particular interest because of recycling, where a neutron star accretes matter from a companion star, gaining angular momentum and speeding up. Most millisecond pulsars observed in radio, X-rays and/or γ rays reside in or once resided in systems where the accretion has stopped, but where the neutron stars retain a high angular velocity. Accretion can provide a natural mechanism to impart asymmetries in the neutron star moment of inertia, thus causing the star to emit continuous gravitational waves, even after accretion has subsided.

Neutron stars in unknown binary systems present an extreme challenge for CW searches because the unknown orbital characteristics produce unknown modulations of the source frequency in the Solar System Barycenter (SSB), in addition to calculable modulations due to the Earth's motion with respect to the SSB. As is well known, even the calculable modulations for an assumed source frequency make an all-sky search for unknown isolated stars a formidable computational challenge, and adding the unknown binary orbital modulations makes the problem all the more difficult.

Methods

The TwoSpect method [172], which relies on doubly-Fourier transformed data, was the first method applied to LIGO and Virgo data to perform an all-sky search for unknown sources in binaries [173]. TwoSpect allows for a broad parameter space range to be covered while maintaining computational efficiency, but is not currently committed to run on O4 due to person-power constraints.

The BinarySkyHough is a pipeline [174] developed from the SkyHough method, one of the semi-coherent pipelines able to perform all-sky searches for continuous wave signals with a low computational cost. BinarySkyHough is an extension of this method, which allows to search for signals from neutron stars in binary systems, which have an extra Doppler modulation. Due to the highly increased computational cost, BinarySkyHough requires GPUs in order to have a feasible computational cost. This pipeline was previously employed to analyse O2 open data [175] and early O3 data [176].

Another, more generic track-based code [171] is now also available that can cover sources in binaries as well.

Activities for O4

A search will be performed on data from the first part of the run (O4a).

ACTIVITY OBS-3.11-A-**INFRAOPS**: O4A ALL-SKY SEARCH FOR CWS FROM NSS IN BINARIES

Unknown CW sources in binary systems will be searched for in O4 data using GPUs to analyze wide frequency bands in an all-sky search. The results are analyzed using a suite of vetoes and follow-up strategies.

TASK OBS-3.11-A(i)-**INFRAOPS**: ACQUISITION OF COMPUTING RESOURCES

The use of GPUs is crucial to perform the main stage of the search, which uses a highly efficient implementation of the Hough transform to analyze wide parameter-space regions with an increased level of robustness against spectral artifacts [174]. The search will leverage the use of internal computing resources of the collaboration on the LDG with external resources from the OSG and acquired through competitive allocation calls.

TASK OBS-3.11-A(ii)-**INFRAOPS**: RUN THE SEARCH

Run the search code on multi-interferometer data, and produce a large list of candidate sources.

TASK OBS-3.11-A(iii)-**INFRAOPS**: POST-PROCESSING AND VETOES

The main results of the search are toplists containing the most significant parameter-space points for each of the analyzed regions. A number of candidates will be selected for follow-up, optionally including a clustering algorithm [177] that groups together candidates with a common origin.

TASK OBS-3.11-A(iv)-**INFRAOPS**: FOLLOW-UP CANDIDATES

The default follow-up strategy will use an MCMC-based $\mathcal{F}$-statistic search implemented in the PyFstat Python package [178, 179]. The flexibility of this procedure allows for the application of several follow-up strategies, either based on detector-consistency vetoes, as done in [176], or using hierarchical schemes to compare the behaviour of a CW candidate as the coherence time increases [180, 181].

TASK OBS-3.11-A(v)-**INFRAOPS**: REVIEW

This will include code review as well as reviewing search results.

TASK OBS-3.11-A(vi)-**INFRAOPS**: PUBLICATION

A paper on these results will be written and submitted for publication.

ACTIVITY OBS-3.11-B-**INFRAOPS**: FINALIZATION OF NEW TRACK-BASED CODE FOR ALL-SKY BINARY CW SEARCHES

A new search pipeline [171] has been developed, with a simpler structure than BinarySkyHough and improved parallelization of template evaluation on GPUs. Optimization still is required, and then these improvements will positively impact the sensitivity and computational efficiency of the search.

TASK OBS-3.11-B(i)-**INFRAOPS**: FINALIZE OPTIMIZATION OF NEW CODE AND APPLICATION TO BINARIES

OBS-3.12 Searches for transient emission from post-merger neutron stars

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

CW-derived analysis methods can also be used to search for long-duration transient GWs from newborn neutron stars with rapid spindown, including signals from neutron star remnants of nearby binary neutron star (BNS) mergers [182] such as GW170817 [64]. In particular, while shorter remnant signals on the order of milliseconds to hundreds of seconds can also be effectively searched for with methods derived from burst and stochastic searches [183], longer signals associated with the rapid spindown of a supramassive or long-lived young neutron star are well suited for CW-derived methods [184]. These remnant searches can play a crucial role in constraining the nature of the remnant and thus the nuclear physics properties of the involved objects [185, 186].

On the other hand, for a hypermassive NS remnant that collapses to a black hole in less than 1 s, simulations show that the post-merger GW emission is dominated by the quadrupolar f-mode with frequencies in the kHz range. This signal typically lasts a few tens of milliseconds. The post-merger signal is quite complex, but it can be well approximated by a damped sinusoid resembling a ringdown signal [187].

The same methods can also apply to newborn neutron stars from the regular core-collapse supernova channel; see (Section OBS-3.21) for investigations into that case.

Methods

Even for long-duration post-merger signals, the parameter space [188, 189], signal morphology and data quality requirements are quite different from other CW searches. Available methods include adaptations of the hidden-Markov-model Viterbi tracking algorithm [190, 191] and the two semi-coherent Hough algorithms [167, 192, 193, 194] to the rapid-spindown waveform model from [195]. It is also possible to combine some of these methods, with a cheaper, more generic method as a first-stage search and a semi-coherent modelled algorithm as a follow-up stage.

The selection of worthwhile BNS candidates for long-duration post-merger searches depends on the rate of increase in detector sensitivity, on the distances at which such events are found, on the inferred total mass of each binary, and on how well they are localized.

For the shorter f-mode signals, a recently developed pipeline [187] is based on matched filtering for exponentially damped sinusoids, using a likelihood-ratio statistic called the $\mathcal{P}$-statistic, similar to the well-known $\mathcal{F}$-statistic [120]. The grid in the frequency – frequency drift parameter space can be constructed as in CW directed searches [196].

Activities for O4

ACTIVITY OBS-3.12-A-**INFRAOPS**: LONG-DURATION POST-MERGER SEARCHES - ONGOING COORDINATION WITH OTHER WORKING GROUPS

During current and future observing runs, post-merger experts from the CW group will be on standby to coordinate, in the event of an interesting nearby BNS detection, with other working groups and the observatory heads/operators about search plans and required stand-down times in detector interventions to maximize science opportunities.

TASK OBS-3.12-A(i)-**INFRAOPS**: ONGOING COORDINATION WITH OTHER WORKING GROUPS ON POST-MERGER SEARCHES

ACTIVITY OBS-3.12-B-**INFRAOPS**: OPPORTUNISTIC LONG-DURATION POST-MERGER SEARCHES DURING O4 (ON STANDBY)

Pending on person power and event rates, we will run a directed search for long-duration signals from a possible remnant of any sufficiently nearby, low-mass and well-localized BNS merger, using some of the available pipelines: Viterbi [190, 191], Adaptive Transient Hough [192] or updated versions of it, and/or Generalized Frequency Hough [194].

TASK OBS-3.12-B(i)-**INFRAOPS**: CANDIDATE IDENTIFICATION AND LIAISON WITH CBC PARAMETER ESTIMATION

When a promising candidate has been identified based on low-latency CBC parameter estimates (distance, masses and sky localization), CW analysts will liaise with the CBC parameter estimation experts to follow the progress of refined inference runs to obtain the best estimates for informing our decision to run a search and on details of the search setups.

TASK OBS-3.12-B(ii)-**INFRAOPS**: COORDINATION WITH SHORT-DURATION PUBLICATION PLANS

The planning of these searches and the eventual publication will require coordination with members of the CBC, burst and stochastic groups to ensure full exploitation of all post-merger science opportunities, proper folding-in of prior information from the inspiral phase, efficient data quality studies, and a streamlined publication schedule.

TASK OBS-3.12-B(iii)-**INFRAOPS**: SEARCH SETUPS

Optimal search setups need to be determined based on the availability and quality of data around and after the merger, including gaps, nonstationarities, transient line features etc.

TASK OBS-3.12-B(iv)-**INFRAOPS**: RUN SEARCHES

Run different existing search pipelines, post-process results, and in the event of interesting outliers produce a list of candidate signals.

TASK OBS-3.12-B(v)-**INFRAOPS**: VETOES AND CANDIDATE FOLLOW-UP

Follow up candidates from each search, either collectively or by each individual search team.

TASK OBS-3.12-B(vi)-**INFRAOPS**: SET UPPER LIMITS

In the event of no detection, each pipeline sets upper limits through injection of simulated signals.

TASK OBS-3.12-B(vii)-**INFRAOPS**: REVIEW SEARCH RESULTS

This will include code review of any updated parts of the search pipelines, as well as reviewing their search configurations and results.

TASK OBS-3.12-B(viii)-**INFRAOPS**: PUBLICATION

Either produce a single stand-alone publication presenting results of the different search pipelines and/or incorporate the results as a brief summary in a more general paper on the BNS event.

ACTIVITY OBS-3.12-C-**INFRAOPS**: OPPORTUNISTIC SHORT-DURATION POST-MERGER SEARCHES DURING O4 (ON STANDBY)

Using the $\mathcal{P}$-statistic method [187], promising targets along the lines discussed above will also be analyzed for short-duration signals.

TASK OBS-3.12-C(i)-**INFRAOPS**: OBTAIN PARAMETERS OF THE BNS SIGNALS FORM CBC PIPELINES

We shall obtain parameters of each BNS merger signal detected by CBC pipelines. In particular merger times in each detectors, masses, tidal parameters, extrinsic parameters (polarization angles and distance to the source), and positions of the sources in the sky.

TASK OBS-3.12-C(ii)-**INFRAOPS**: RUN THE TIME-DOMAIN $\mathcal{P}$-STATISTIC POST-MERGER PIPELINE

We shall search with our pipeline a few tens of milliseconds of data after each BNS merger reported by CBC pipelines.

TASK OBS-3.12-C(iii)-**INFRAOPS**: DETERMINE SENSITIVITY OF THE SERACH

In the case of no detection, determine sensitivity of the search by injections of numerical-relativity post-merger waveforms from the CoRe database.

TASK OBS-3.12-C(iv)-**INFRAOPS**: REVIEW CODE AND SEARCH RESULTS

Review of the code and the search results.

TASK OBS-3.12-C(v)-**INFRAOPS**: PUBLICATION

Produce a publication with the results of the searches for the whole O4 or incorporate the results as a brief summary in papers on a significant nearby BNS events.

OBS-3.13 Searches for long-transient emission following a pulsar glitch

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

The CW group is primarily focused on searching for truly *continuous* GWs: periodic signals lasting at least as long as an observation run. However, electromagnetic observations of transient neutron star phenomena, such as pulsar glitches, raise the possibility that neutron stars also emit GW signals on time scales of hours–months due to short-lived deformations [197, 198]. The mechanisms behind pulsar glitches are still poorly understood [199] and post-glitch GW observations (including upper limits) could yield valuable insights complementary to radio and other EM observations.

Methods

Many CW search algorithms can be adapted to search for long-duration transients by studying their intermediate, time-dependent data products or running separate analyses on shorter time intervals. For quasi-monochromatic transients during the post-glitch relaxation phase, the transient $\mathcal{F}$-statistic [197, 200] is an efficient method with demonstrated performance on real data [201, 103]. Searches with this method can be cheaply run for several targets, with additional development and/or the use of GPUs [200, 178] allowing for broader searches or covering more targets. Other candidate methods for such signals include the time-domain Bayesian (cwinpy) [95], HHM-Viterbi [138, 190], and FrequencyHough [166] pipelines. For shorter signals with nontrivial frequency evolution, more immediately associated with the glitch event itself, methods similar to those for post-merger searches [190, 191, 192, 194], based on machine learning, or from the burst and stochastic domains [7, 202, 36] could also be employed.

Similar to post-merger searches (Section OBS-3.12), post-glitch searches face unusual data quality and candidate validation challenges. For example, periods of no or degraded data due to environmental effects degrade transient search performance more strongly than for full-run CW searches, and transient instrumental lines that would be too weak to affect a year-long analysis can produce strong spurious candidates in a transient search. Once statistical outliers are found in a search, the standard approach of increasing coherence time is not always helpful for transients, and follow-up must instead rely on data quality studies, varying the time steps used in the analysis, generalizing the signal model, and grid-less MCMC methods [203, 178].

Activities for O4

ACTIVITY OBS-3.13-A-**INFRAOPS**: SEARCHES FOR LONG-DURATION SIGNALS AFTER PULSAR GLITCHES DURING O4

The exact set of pipelines to be used depends on the observed glitches and available person power.

TASK OBS-3.13-A(i)-**INFRAOPS**: MONITOR AND SELECT TARGETS

Data on promising glitches in nearby pulsars needs to be collected and used to prioritise search targets. This will be based on the work of EM observers under the same MoUs as for targeted CW searches (Section OBS-3.1) and public literature and databases. How promising a glitch is as a search target will be estimated based on indirect energy upper limits [197, 204], the precision of available ephemerides, and the duty cycle and data quality around and after the glitch.

TASK OBS-3.13-A(ii)-**INFRAOPS**: DATA PREPARATION AND DATA QUALITY STUDIES

The total time interval covered by each search depends on the pattern of usable science quality data segments. SFTs for these intervals and the relevant frequency bands can normally extracted from the standard broadband SFTs. However, for quick follow-up of high-profile glitches, these searches might actually be the first CW-style analyses to look at new data, and hence the segment selection, time-domain gating and SFT production (as described in Section OBS-3.17) might need to be pushed forward to an accelerated schedule for the time and frequency ranges of interest for such a glitch. Shorter-duration SFTs may also need to be generated for some follow-up studies. Strong transient instrumental lines need to be identified in advance and cleaned from the data.

TASK OBS-3.13-A(iii)-**INFRAOPS**: SEARCH

For each glitch target, a search of several months of data covering a small frequency band (similar to the searches in Section OBS-3.2) must be performed. The detailed search setup can be chosen based on the number of promising targets, the uncertainties in pulsar ephemerides, and the available person-power and computing budget.

TASK OBS-3.13-A(iv)-**INFRAOPS**: CANDIDATE FOLLOW-UP

Any statistical outliers that cannot be attributed to instrumental lines must be followed up with variations in the search setup and through independent pipelines, including MCMC methods [203, 178, 95].

TASK OBS-3.13-A(v)-**INFRAOPS**: SET UPPER LIMITS

If no promising detection candidates survive, upper limits can be set through injections of simulated signals. For large glitches in nearby pulsars, beating the indirect energy upper limit [197, 204] may be possible.

TASK OBS-3.13-A(vi)-**INFRAOPS**: ASTROPHYSICAL INTERPRETATION

Both for detections and for non-detections below the indirect energy limits, interesting constraints on neutron star physics and GW emission scenarios can be placed. In particular, when both CW and burst-style analysis results are available, combined constraints can be obtained.

ACTIVITY OBS-3.13-B-**INFRAOPS**: PUBLICATION(S) ON GLITCHING PULSARS

The case for a separate paper on transients from pulsar glitches depends on the number of such events observed in EM timing of nearby pulsars with frequencies matching the detectors' sensitivity band (assuming the usual factor of 2 for the dominant GW emission frequency) and the predicted chance of surpassing the energy-based indirect upper limits on GW strain (depending on frequency, glitch size and pulsar distance, [197, 204]). A standalone paper will be pursued if at least one large, nearby glitch (e.g. from the Vela pulsar) promises a first surpassing of such limits, while combination with the full-O4 known pulsar or narrowband papers (Sections OBS-3.1, OBS-3.2) is the fallback for less promising targets.

TASK OBS-3.13-B(i)-**INFRAOPS**: COORDINATION WITH OTHER WORKING GROUPS

For large glitches from nearby pulsars (e.g. Vela), and if a sufficient number of detectors were in observing mode close to the glitch, additional short-duration transient searches may be pursued by other working groups (e.g. Section OBS-1.6), and CW group members will coordinate with the analysis leads from those groups to exchange information, coordinate data quality studies, combine astrophysical constraints, and potentially merge paper plans.

TASK OBS-3.13-B(ii)-**INFRAOPS**: CODE REVIEW

The transient $\mathcal{F}$-statistic code in LALSuite is reviewed. Improved and refactored wrapper scripts and minor updates to the PyFstat package [179] will require a limited update review. Any additional analysis codes joining this activity will be based on existing codes reviewed for other applications, but require additional review in their application to the post-glitch case. Newly developed tools to place combined astrophysical constraints from CW- and burst-style searches may require additional review.

TASK OBS-3.13-B(iii)-**INFRAOPS**: REVIEW SEARCH RESULTS

In addition, the target list, search configurations and results will also require review.

TASK OBS-3.13-B(iv)-**INFRAOPS**: PUBLICATION

The paper(s), or contributions to joint CW–transient known pulsar / narrowband papers, will be reviewed following standard editorial board practices. Coordination with short-duration transient searches for the same targets will be beneficial.

OBS-3.14 Searches for continuous emission from ultra-light boson clouds around black holes

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

Ultra-light boson clouds forming around BHs are expected to emit CW-like signals over long times. According to theoretical predictions, which are based on several approximations, the emitted signal is monochromatic with a small spin-up. The actual signal could be more complicated due to matter accretion, presence of a binary companion, unpredicted physics, etc. For this reason it is important to develop robust methods that are able to detect long-lasting signals, with (small) spin-up and a finite unknown coherence time. In the case of vector boson clouds, the signal amplitudes are expected to be higher than scalar boson signals, but the signals have a shorter lifetime with a higher spin-up. While we have in mind BH/ultra-light boson cloud systems as a reference source, similar methods can be used to search for other signals with similar characteristics.

The search for CW signals from boson clouds around spinning BHs is conceptually similar to "standard" searches of CWs from asymmetric spinning neutron stars. Therefore the core data analysis techniques can be shared among them. There are, however, some specificities that we can take into account to improve the boson cloud search. The following points support performing the searches for boson clouds and asymmetrically rotating neutron stars separately.

First, in all-sky searches, the simple idea of working with FFT databases of different length allows us to deal with non-monochromatic signals, potentially providing a significant gain in sensitivity, with respect to the standard choice of a fixed FFT duration, as shown in [205]. The feasibility of this approach for boson cloud searches is guaranteed by the small range of frequency derivative values we need to consider. For standard CW searches for spinning neutron stars, the large spin-down range we need to cover prevents us from using this method, due to computational cost constraints. Second, in all-sky searches, candidates are selected with a "top list" criterion according to which for every frequency band (e.g 0.1 Hz), and every sky position, the two most significant candidates, across the whole spin-down/up range, are chosen. Now, if we should consider the boson cloud search as a particular case of a standard all-sky search, we would select candidates over a spin-down/up range much larger than needed. As a result, there would be a very high probability to select candidates much stronger than those we could choose by running the search only on the restricted spin-up range suitable for boson clouds. This, clearly, implies a net loss in sensitivity: by running a search specifically for bosons we can select weaker candidates, i.e. go "deeper". Finally, for directed searches, the targets are of course different from those of CW searches for spinning neutron stars. Improved semi-coherent search methods are also developed to cover larger spin-up rate in directed searches, especially for vector signals.

Methods

A simple semi-coherent procedure, in which data are analyzed using various collections of FFTs of durations from hundreds to thousands seconds, has been developed [205]. The procedure is computationally cheap (relative to standard all-sky CW searches) and is designed for an all-sky search. In the last search, carried on O3 data, the variable FFT duration has been obtained by applying a moving average, with varying width, to time-frequency maps built with a fixed FFT duration [162]. Another method is a semi-coherent directed search for such systems based on hidden Markov model tracking, which is robust against potentially slow frequency variations of the signals due to the expected intrinsic evolutions and astrophysical interactions [206]. The first observational constraints on the mass of ultra-light scalar bosons have been set in all-sky [207] and directed [208] searches carried out on LIGO O2 data. New all-sky constraints are obtained in O3 [162] and exclusion regions in the black hole-boson mass space are mapped from the upper limits obtained in the O3 directed search for CW signals in the Galactic Center [157]. A new hidden Markov model based method has been developed and will be used in O4 to track more rapidly evolving vector boson signals (e.g., on a timescale of hours to months) [209]. A more accurate, numerically calculated waveform model will be used as theoretical predictions to interpret the O4 results and derive the constraints [210]. We will also continue to improve the accuracy of the superradiance waveform model, and use it as an aid in designing future searches.

Activities for O4

We will run two searches, one all-sky search for scalar boson clouds, and a directed search for vector boson clouds, targeting promising post-merger black holes and potentially a few interesting galactic black holes. A directed search for scalar boson clouds around post-merger black holes will be also carried out, pending person power and identification of interesting targets. These analyses will be collectively described in two observational papers, one for scalar bosons (all-sky search and possibly additional directed searches) and the other for vector bosons (directed searches only).

ACTIVITY OBS-3.14-A-**OTHER**: O4 ALL-SKY AND DIRECTED SEARCHES FOR ULTRA-LIGHT SCALAR BOSON CLOUDS

We will run an all-sky search for scalar boson cloud continuous signals, relying on the semi-coherent all-sky pipeline method described above [205], as well as further developments introduced in [162]. Candidate follow-up will be based on the FrequencyHough [166], the Viterbi tracking [206] and a new semi-coherent method based on 5-vectors [156]. Directed searches for scalar boson clouds in the galactic center will be carried out using the new method in [156] (Section OBS-3.7). A dedicated search for boson clouds in some selected globular clusters will be carried out in a separate search (Section OBS-3.8).

Pending on person power and identification of interesting sources, other opportunistic directed searches for scalar boson clouds around some specific nearby black holes, black holes in other globular clusters not targeted in (Section OBS-3.8), and post-merger black holes may get added, using methods [205, 206, 156].

TASK OBS-3.14-A(i)-**OTHER**: RUN SEARCH

Run the search and identify candidates.

TASK OBS-3.14-A(ii)-**OTHER**: OUTLIER FOLLOWUP – OTHER STUDIES

TASK OBS-3.14-A(iii)-**OTHER**: SET CONSTRAINTS

In the event of no detection, interpret results and set constraints on scalar ultra-light boson mass and other properties.

TASK OBS-3.14-A(iv)-**OTHER**: PUBLICATION

Produce a publication presenting the results.

ACTIVITY OBS-3.14-B-**INFRAOPS**: O4 ALL-SKY AND DIRECTED SEARCHES FOR ULTRA-LIGHT SCALAR BOSON CLOUDS - REVIEW

TASK OBS-3.14-B(i)-**INFRAOPS**: REVIEW SEARCH CODE AND RESULTS

Review some portions of the analysis pipeline and search results. Note that the core analysis code of the FFT-based directed search method is the same as for the all-sky search. The semi-coherent 5-vector method has been lately reviewed. The Viterbi pipeline for scalar bosons has been reviewed in previous CW analyses.

ACTIVITY OBS-3.14-C-**OTHER**: O4 DIRECTED SEARCHES FOR ULTRA-LIGHT VECTOR BOSON CLOUDS

We will run a directed search for vector boson clouds following up nearby and well-localized merger remnants observed in O4, using a newly developed semi-coherent methods based on hidden Markov model tracking [209]. We will use the sky localization and remnant black hole properties inferred from the merger events to guide the choice of parameter space and search configurations. Other suitable methods under development may join the analysis pending on the timeline.

TASK OBS-3.14-C(i)-**OTHER**: RUN SEARCH AND POST-PROCESSING

Run the search, identify and follow up candidates, and veto outliers caused by instrumental artifacts.

TASK OBS-3.14-C(ii)-**OTHER**: SET CONSTRAINTS

In the event of no detection, interpret results and set constraints on vector ultra-light boson mass and other properties.

TASK OBS-3.14-C(iii)-**OTHER**: PUBLICATION

Produce a publication presenting the results.

ACTIVITY OBS-3.14-D-**INFRAOPS**: O4 DIRECTED SEARCHES FOR ULTRA-LIGHT VECTOR BOSON CLOUDS - REVIEW

TASK OBS-3.14-D(i)-**INFRAOPS**: REVIEW SEARCH CODE AND RESULTS

Review some portions of the analysis pipeline and search results. The newly developed Viterbi pipeline for vector boson search [209] is under review right now (expected conclusion within 2-3 months). Note that the core code is similar to other Viterbi versions (reviewed in previous analyses); the configurations and interpretations are the main focus of this review.

OBS-3.15 Searches for light primordial black-hole binaries

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

The rates, progenitor masses and low effective spins of black hole mergers detected by LVK [37, 211] have revived interest in primordial black holes (PBHs) that comprise at least one solar mass [212, 213, 214]. Furthermore, PBHs with masses well below a solar mass, i.e. between $[10^{-7} - 10^{-1}]M_\odot$, remain plausible for certain PBH formation scenarios [215]. For such systems, the signals emitted by PBH binaries slowly inspiraling towards each other resemble (transient) continuous gravitational waves, lasting for $\mathcal{O}(\mathrm{hours}-\mathrm{days})$ at the high-end of the mass range quoted, and $\mathcal{O}(\mathrm{years})$ at the low end. These planetary-mass systems are well-motivated observationally as well as theoretically. There have been recent detections of stellar and quasar microlensing events [216, 217, 218] that suggest compact objects or PBHs with masses $[10^{-6}, 10^{-5}]M_\odot$ could constitute a fraction of dark matter of order $f_{\mathrm{PBH}} \sim 0.01$, which is consistent within the unified scenario for PBH formation presented in [219], but greater than expected for floating planets [220]. It has even been hypothesized that Planet 9 could be a PBH with a mass of $10^{-6}M_\odot$ that was captured by the solar system [221], motivating the development of methods to detect the accretion of small Oort cloud objects [222]. However, astrophysical uncertainties plague these observations, e.g. due to the clustering properties of PBHs [223, 224, 225, 226, 226, 227, 228], underlining the importance of probing these mass regimes using complementary and independent observational methods that could help to distinguish PBHs from other sources.

At the moment, LVK analyses search for sub-solar mass black holes only down to $0.1M_{\odot}$ (Section OBS-2.24), due to computational restrictions intrinsic to matched filtering that prevent the generation of such long waveforms for masses below $0.1M_{\odot}$. It is therefore necessary to devise methods that can search for PBHs below $0.1M_{\odot}$, which can be done by adapting CW methods [167, 166, 229, 194, 190, 192, 184, 230, 191]. These methods must also be robust against noise disturbances and be able to handle gaps in the data, since the signals will be long enough such that the detector noise spectrum will change. Already, constraints on asteroid-mass PBH binaries exist based on the results of all-sky CW searches [231, 232]; however, to obtain stringent constraints in the PBH mass parameter space, dedicated searches need to be performed. The results of such an investment in this kind of science will be the first-ever GW constraints of planetary-mass PBHs, or a potential detection of a very elusive compact object.

Methods

The methods employed to perform these kinds of searches are based on CW methods that look for isolated neutron stars after a supernova or BNS merger. One such method is the Generalized Frequency-Hough [194, 233], that tracks power-law time–frequency evolutions using a particularly efficient implementation of the Hough Transform. This method can handle searches for PBH inspirals between roughly $10^{-6} - 10^{-2}M_{\odot}$, which would correspond to signals spanning hours–days. Furthermore, machine learning methods [229, 230] could also be applied to this problem, as well as particular implementations of matched filtering in restricted portions of the parameter space between $10^{-4} - 10^{-1}M_{\odot}$, and the Viterbi algorithm [234]. The Generalized Frequency Hough method has recently been demonstrated to be applicable for planetary mass PBH searches [235, 236]. Matched filtering could be used to enhance the sensitivity of the Generalized Frequency-Hough to higher masses closer to $10^{-1}M_{\odot}$. Furthermore, we can consider the case of asymmetric mass ratio binaries, which the Generalized Frequency-Hough could directly constrain, assuming circular orbits. However, we plan to improve methods , based on more precise waveform modelling, to search for so-called mini extreme mass ratio inspirals [237], for which the circular orbit approximation will fail. These kinds of methods will also serve as prototypes for searches in future ground-based and space-based detectors, when the signals will last a lot longer even for the canonical sources of GWs.

Activities for O4

ACTIVITY OBS-3.15-A-**INFRAOPS**: DEVELOP SEARCH METHODS FOR LIGHT PRIMORDIAL BLACK-HOLE BINARIES

TASK OBS-3.15-A(i)-**INFRAOPS**: DEVELOP EXTENDED CW SEARCH

Determine constraints on $\dot{f}$, determine if blind injections are needed, and determine required SNR threshold for upper limits.

TASK OBS-3.15-A(ii)-**INFRAOPS**: DEVELOP MATCHED FILTERING SEARCH

Create truncated template bank which looks for partial, high-frequency portion of chirps in mass range $10^{-4} - 10^{-1}M_{\odot}$. The start frequency will determine the range truncation, and will in turn will be determined by maximum template duration limitation from computational resources.

Determine if the same SNR can be used when using a truncated frequency range. Determine how to combine SNR or upper limits for masses whose low-frequency part is being searched by CW methods. Essentially, develop the formalism for a hybrid search pipeline.

TASK OBS-3.15-A(iii)-**INFRAOPS**: DEVELOP ADDITIONAL SEARCH METHODS

Based on implementation progress and person power, new searches will be explored in collaboration with the CBC group OBS-2.11 and OBS-2.24.

ACTIVITY OBS-3.15-B-**OTHER**: O4 SEARCH FOR LIGHT PRIMORDIAL BLACK-HOLE BINARIES

This activity number is no longer in use, see the separate O4a and O4bc sections below.

ACTIVITY OBS-3.15-C-**INFRAOPS**: O4 SEARCH FOR LIGHT PRIMORDIAL BLACK-HOLE BINARIES - REVIEW

TASK OBS-3.15-C(i)-**INFRAOPS**: REVIEW SEARCH CODE AND RESULTS

Review of any updated part of the codes and the search results.

ACTIVITY OBS-3.15-D-**OTHER**: O4A SEARCH FOR LIGHT PRIMORDIAL BLACK-HOLE BINARIES

The initial search and publication will cover the first period, O4a, of the run.

TASK OBS-3.15-D(i)-**OTHER**: RUN FREQUENCYHOUGH AND GENERALIZEDFREQUENCYHOUGH SEARCH

TASK OBS-3.15-D(ii)-**OTHER**: OUTLIER FOLLOWUP – OTHER STUDIES

TASK OBS-3.15-D(iii)-**OTHER**: SET UPPER LIMITS

In the event of no detection, we will put upper limits on the GW emission.

TASK OBS-3.15-D(iv)-**OTHER**: PUBLICATION

Produce a publication with the results of each pipeline.

ACTIVITY OBS-3.15-E-**OTHER**: O4BC SEARCH FOR LIGHT PRIMORDIAL BLACK-HOLE BINARIES

An additional search and publication will cover the remainder of the run: O4b and O4c.

TASK OBS-3.15-E(i)-**OTHER**: RUN SEARCH WITH FREQUENYHOUGH, GENERALIZEDFREQUENCYHOUGH, AND MATCHED FILTERING COMBINED

TASK OBS-3.15-E(ii)-**OTHER**: OUTLIER FOLLOWUP – OTHER STUDIES

TASK OBS-3.15-E(iii)-**OTHER**: SET UPPER LIMITS

In the event of no detection, we will put upper limits on the GW emission.

TASK OBS-3.15-E(iv)-**OTHER**: PUBLICATION

Produce a publication with the results of each pipeline.

OBS-3.16 Support for continuous wave searches: Follow-up of interesting candidates

Start date: 2024-01-01
Estimated due date: 2026-12-16

Motivation

A candidate for the first detection of continuous gravitational waves will need to be vigorously vetted by many different pipelines. Since many wide-parameter-space searches produce very large numbers of candidates, follow-up pipelines which can efficiently deal with a long list of targets will be necessary.

Methods

Naturally, the pipelines used to search for known pulsars (Sections OBS-3.1, OBS-3.2) may also be used for candidate follow-up; particularly via the CWInPy package [95] and the 5-vector method [96]. Follow-up pipelines have also been developed as part of many of the directed (Sections OBS-3.4, OBS-3.5, OBS-3.7, OBS-3.8) and all-sky (Sections OBS-3.10, OBS-3.11) search methods. A highly-optimized semi-coherent $\mathcal{F}$-statistic search code [169] was found to be more effective for candidate follow-up compared to other implementations [238]. A semi-coherent follow-up (and directed search) method [156] using 5-vectors [96] has been recently developed and reviewed, extending a simpler procedure used in BSD-based directed searches [129]. Other methods have been developed more specifically for candidate follow-up. A general-purpose follow-up procedure based on MCMC methods in the PyFstat package [203, 178] has been described in [180, 181]. A long-transient add-on to semi-coherent analyses is also available for intermediate follow-up steps [239].

The follow-up of outliers from CW searches will generally be accompanied by manual data quality investigations to check for any spectral artifacts that may be responsible for the outliers (see the Operations White Paper [240]).

Activities for O4

ACTIVITY OBS-3.16-A-**INFRAOPS**: MAINTENANCE AND UPDATES OF CW FOLLOW-UP METHODS

Follow-up methods are continuously being improved in order to fullfil different trade-offs regarding sensitivity and robustness against instrumental artifacts. At the same time, LALSuite routines evolve in order to fix issues identified during production time of the previous run, meaning specific follow-up implementations need to be maintained in order to be actively used in production for the next time.

TASK OBS-3.16-A(i)-**INFRAOPS**: MAINTENANCE AND IMPROVEMENTS OF PYFSTAT FOLLOW-UP TOOLKIT

PyFstat [178, 179] is a package for $\mathcal{F}$-statistic-based data analysis, aimed mostly at candidate followup for both standard CWs and long-duration transients (Section OBS-3.13), including hierarchical followup schemes [180, 178]. Continued maintenance is required for full LALPulsar interoperability, as well as ongoing improvements to its own utilities.

TASK OBS-3.16-A(ii)-**INFRAOPS**: MAINTENANCE AND IMPROVEMENTS OF OTHER FOLLOW-UP METHODS

TASK OBS-3.16-A(iii)-**INFRAOPS**: REVIEW OF UPDATED PACKAGES

ACTIVITY OBS-3.16-B-**INFRAOPS**: FOLLOW-UP OF INTERESTING CW CANDIDATES

As required/requested, use a range of different analysis methods to follow up any interesting candidates found by frontline continuous wave searches, with the goal to confirm or reject their continuous nature. The use of a broad set of tools may require to re-generate data in different formats in order to suit the technical requirements of different pipelines. This includes, for example, the re-generation of SFT data files using different baseline durations. The interpretation of follow-up results will also form a key part of LVK search results publications.

TASK OBS-3.16-B(i)-**INFRAOPS**: PRODUCE DATA PRODUCTS IN THE REQUIRED FORMAT

TASK OBS-3.16-B(ii)-**INFRAOPS**: FOLLOW-UP OF INTERESTING CW CANDIDATES

TASK OBS-3.16-B(iii)-**INFRAOPS**: REVIEW OF THE FOLLOW-UP RESULTS

TASK OBS-3.16-B(iv)-**INFRAOPS**: CONTRIBUTE TO RESULTS PAPERS

ACTIVITY OBS-3.16-C-**INFRAOPS**: FOLLOW-UP OF INTERESTING LONG-TRANSIENT CW-LIKE CANDIDATES

As required/requested, use a range of different analysis methods to follow up any interesting candidates found by frontline long-transient searches, or to study transient properties of candidates found in CW searches but found in a previous follow-up stage to not follow the expected CW behaviour. In a similar vein to the previous task, this may require to re-generate data in different formats to suit the technical requirements of the different involved pipelines. The interpretation of follow-up results will also form a key part of LVK search results publications.

TASK OBS-3.16-C(i)-**INFRAOPS**: PRODUCE DATA PRODUCTS IN THE REQUIRED FORMAT

TASK OBS-3.16-C(ii)-**INFRAOPS**: FOLLOW-UP OF INTERESTING LONG-TRANSIENT CW CANDIDATES

TASK OBS-3.16-C(iii)-**INFRAOPS**: REVIEW OF THE FOLLOW-UP RESULTS

TASK OBS-3.16-C(iv)-**INFRAOPS**: CONTRIBUTE TO RESULTS PAPERS

OBS-3.17 Support for continuous wave searches: Data preparation

Start date: 2024-01-01
Estimated due date: 2026-12-16

Motivation

Since continuous GWs are nearly monochromatic in the Solar System Barycenter reference frame, it is useful for most CW search pipelines to pre-process the $h(t)$ strain time series into a few common data products ready for analysis by the different pipelines. Common data products include: Short Fourier Transforms (SFTs), Short Fourier Transform Database (SFDB), Band-Sampled Data (BSD), and heterodyned data. Different data products are needed because different analysis pipelines are optimized for knowledge of a putative source (e.g., targeted, directed, or all-sky).

Methods

Data products generated for CW searches generally rely on well known digital data analysis methods, such as the Fast Fourier Transform, heterodyning, or resampling. These algorithms are coded and used within the LALSuite library and the Virgo PSS C code and the Matlab software Snag.

In conjunction with characterising every observing run data set, an appropriate set of data quality flags are used to select time intervals of high-quality $h(t)$ data and used as input for these data products. These are produced by the detector characterization group in the operations division, see activity OPS-8.2-G in the LVK operations white paper [240]. In addition, self-gating of $h(t)$ to deal with very loud glitches (see activity OPS-8.2-L in the LVK operations white paper [240]) has since O3 been found to be essential for a good sensitivity of CW searches, as they contaminate the noise floor across the spectrum when Fourier-transformed. Once appropriate data are selected, they are processed, stored in common locations accessible to multiple clusters, or distributed across clusters using current standard technologies.

The time-domain Bayesian [94] and $\mathcal{F}/\mathcal{G}$-statistic [89] targeted pulsar searches require narrowband time series for each pulsar. The production of these time series makes use of pulsar timing ephemerides that provide a coherent phase solution for each pulsar signal over the course of an observing run. For each pulsar the phase evolution is used to heterodyne the raw $h(t)$, which is subsequently low-pass filtered and downsampled [241]. This gives a complex time series, with a sample rate of one per minute, which can then be used for further analysis.

Most of the other searches based on LALSuite [242] use short Fourier transforms in the SFT format specified in [243]. For O4, this has been updated to v3, which now records the window function (if any) applied to SFTs in their headers and enforces a more prescriptive filename and directory naming convention, so that O4 production SFT filenames will be globally unique to facilitate replication.

Another data format, the short FFT data base (SFDB), is produced using the same software and procedures used for all the past runs. BSD files [128] are produced from SFDB files.

Activities for O4

ACTIVITY OBS-3.17-A-**INFRAOPS**: DETERMINE APPROPRIATE TIME SEGMENTS TO ANALYZE IN CW SEARCHES

Before producing common data products, it is important to identify time segments for which data is reliable. Data quality flags will be chosen in such a way to eliminate truly bad data.

TASK OBS-3.17-A(i)-**INFRAOPS**: DETERMINE APPROPRIATE TIME SEGMENTS FOR CW SEARCHES TO ANALYZE

ACTIVITY OBS-3.17-B-**INFRAOPS**: IMPROVE CW DATA PREPARATION INFRASTRUCTURE AND SOFTWARE

Parts of the data preparation infrastructure and software tools have been in use for a long time. For completing O4 analyses and towards O5, they require continued updates to improve code maintainability, adherence to modern coding standards, and usability. This will also enable the tools to support more flexible requirements from analysis pipelines, and to improve interoparability with modern data storage and distribution solutions.

TASK OBS-3.17-B(i)-**INFRAOPS**: IMPROVE DATA PREPARATION INFRASTRUCTURE FOR CW SEARCHES

Broadband Tukey-windowed SFTs for analysis will be generated daily on the Caltech cluster, along with derived spectral plots (daily and cumulative) and numerical data for detector characterization studies. This infrastructure has been consolidated compared to O3, combining the weekly SFT generation and some of the daily spectral analysis using Fscan products. The same set of O4 SFTs is used for producing daily CW-focused figures of merit for the Detchar Daily Summary pages and for monitoring of CW hardware injections.

TASK OBS-3.17-B(ii)-**INFRAOPS**: IMPROVE DATA HANDLING SOFTWARE FOR CW SEARCHES

Essential LALSuite [242] programs and other software used for data handling, such as lalpulsar_MakeSFTs and lalpulsar_MakeSFTDAG, require constant maintenance and updates to align with changing computing infrastuctures.

ACTIVITY OBS-3.17-C-**INFRAOPS**: PRODUCE FOURIER TRANSFORM FILES FOR CW SEARCHES

TASK OBS-3.17-C(i)-**INFRAOPS**: VET GATED $h(t)$ FRAMES

Vet gated $h(t)$ frames (for their production, see activity OPS-8.2-L in the LVK operations white paper [240]) for any issues before starting SFT/SFDB production.

TASK OBS-3.17-C(ii)-**INFRAOPS**: PRODUCE SFTS

SFT files will be produced for a variety of coherence times and at least two windowing choices (Tukey, Hann). Vet produced SFT files for any issues.

TASK OBS-3.17-C(iii)-**INFRAOPS**: PRODUCE SFDB

SFDB files will be produced at the CNAF computing center with four different coherence times: 8192 s, 4096 s, 2048 s, 1024 s for the frequency bands [10 - 128] Hz, [128 - 512] Hz, [10 - 1024] Hz, [10 - 2048] Hz, respectively. Data are overlapped by half and a window cosine flat (similar to Tukey) is used. Strong glitches in the data, in time domain, are identified and subtracted from the data, before constructing the FFTs. SFDB data can be distributed to different LVK computing centers, if this will be needed. The production of the $h(t)$ channel will be done on a monthly basis, using analysis-ready frames.

TASK OBS-3.17-C(iv)-**INFRAOPS**: DISTRIBUTE DATA PRODUCTS

SFT data products will be distributed to different LSC computing clusters, and SFDBs will be transferred to other Virgo clusters as well as the Caltech LSC cluster.

ACTIVITY OBS-3.17-D-**INFRAOPS**: PRODUCE TIME SERIES FILES FOR CW SEARCHES

TASK OBS-3.17-D(i)-**INFRAOPS**: PRODUCE BSD

BSD files [128] will be produced on a monthly base, from the SFDBs. Each file contains a complex, reduced analytic time series covering a 10 Hz frequency band. Each file contains the auxiliary information needed for the analyses.

TASK OBS-3.17-D(ii)-**INFRAOPS**: PRODUCE NARROWBAND HETERODYNED TIME SERIES

The narrowband heterodyned time series will be produced for a range of pulsars with rotation frequencies $\gtrsim 10\,\mathrm{Hz}$ for which ephemerides can be obtained from electromagnetic observers.

OBS-3.18 Support for continuous wave searches: Scientific software maintenance

Start date: 2024-01-01
Estimated due date: t.b.d.

Motivation

The software used and developed by the CW group are maintained in version-controlled repositories in different locations, including public as well as internal repositories, and generally are managed by the code authors themselves. One exception is the more centralized LALSuite repository [242], which contains important CW core routines and data, such as the antenna patterns as a function of time and sky location and routines to handle Sun and Earth ephemerides. To ensure that this software base is maintained with standard good practice procedures, contributions to the main LALSuite repository [3] are restricted to a merge request model.

Additional software packages, either downstream of LALSuite or entirely independent, that have previously been reviewed for LVK usage, need to be maintained to continue working in an evolving software and hardware ecosystem.

For reproducible scientific results, it is also essential to have our software follow a release and deployment model that allows to track which version was used for each scientific result, and support of best practices in such deployment is an important activity within the group.

Another essential contribution to the long-time health of the CW software stack and to ensure collaborative use within the group is to improve documentation of existing software, also including the preparation of tutorials for new users.

Methods

Best practices in development, maintenance, releases and deployment will aim to follow those developed in the wider scientific software community and defined more specifically by the LVK computing group.

For LALSuite specifically, maintainers from the CW group assist the LALSuite librarian in vetting and approving merge requests to the main repository, to ensure code is well documented and tested, maintains backward compatibility as much as possible, and to reduce the likelihood of introducing new bugs. Issues potentially relevant to the whole group, as well as recently-approved merge requests, are discussed in the weekly teleconferences. Code contributions from external authors (defined as those who are not LVK members) are also supported through an e-mail service desk system.[4]

Activities for O4

ACTIVITY OBS-3.18-A-**INFRAOPS**: MAINTENANCE OF CW SOFTWARE IN LALSUITE

Address issues and approve merge requests to CW software in the LALSuite repository, and keep the CW group informed of any important changes or bugs. Occasionally, larger upgrades to keep CW software modernised, maintainable, and to support new use cases and packaging requirements may be needed.

TASK OBS-3.18-A(i)-**INFRAOPS**: MAINTENANCE OF CW SOFTWARE IN LALSUITE

[3] `https://git.ligo.org/lscsoft/lalsuite`
[4] contact+lscsoft-lalsuite-1438-issue-@support.ligo.org

ACTIVITY OBS-3.18-B-**INFRAOPS**: CW SUPPORT FOR LALSUITE REPOSITORY MANAGEMENT

Work with the LALSuite librarian to ensure the contribution model, code review, continuous integration and other aspects of the repository management continue to evolve and are suitable for the scientific needs of the working group. Work to ensure timely releases of LALSuite, and support CW analysts in using released software versions for improved reproducibility.

TASK OBS-3.18-B(i)-**INFRAOPS**: CW-RELATED SUPPORT FOR LALSUITE REPOSITORY MANAGEMENT

ACTIVITY OBS-3.18-C-**INFRAOPS**: SUPPORT FOR OTHER SHARED CW SOFTWARE TOOLS AND ANALYSIS PACKAGES

Support of other packages outside of LALSuite, but often building on it, whose use is shared across CW analysis pipelines and projects, ensuring their robustness and interoparability. This includes for example data input/output libraries for different formats, interfaces to detector characterization information, and follow-up packages (Section OBS-3.16).

TASK OBS-3.18-C(i)-**INFRAOPS**: SUPPORT FOR DEVELOPMENT AND MAINTENANCE OF SHARED CW-RELATED SOFTWARE TOOLS AND ANALYSIS PACKAGES

TASK OBS-3.18-C(ii)-**INFRAOPS**: IMPROVED DOCUMENTATION OF EXISTING REVIEWED CW SOFTWARE

TASK OBS-3.18-C(iii)-**INFRAOPS**: SUPPORT FOR RELIABLE DEPLOYMENT OF CW SOFTWARE

OBS-3.19 Further improvement and optimization of existing data analysis pipelines

Start date: 2024-01-01
Estimated due date: t.b.d.

Motivation

The most efficient use of limited computing resources is essential to the scientific goals of the CW group. Typically, the codes used by the CW group are highly optimized, due to the demanding computational nature of many searches, but further improvements may still be possible. Time spent on optimization will need to be weighed against the potential reduction in run time of the analysis in question, as well as the time needed to review the new version of the code. Code improvement also includes refactoring to better work with modern hard- and software technologies, adapting to broader or more specific astrophysical source classes and priors, inclusion of data quality information, and other enhancements.

Activities

ACTIVITY OBS-3.19-A-**INFRAOPS**: CW PIPELINE OPTIMIZATION REPORTS AND WORK WITH COMPUTING GROUP

At the request of the IGWN computing chairs, the CW group may periodically produce optimization reports to ensure responsible use of LVK computing resources. When requested, pipelines that are found to be the highest users of computing resources will produce optimization reports and work with the IGWN computing optimization team to reduce the computing load.

TASK OBS-3.19-A(i)-**INFRAOPS**: PREPARE OPTIMIZATION REPORTS (ON REQUEST)

TASK OBS-3.19-A(ii)-**INFRAOPS**: IMPLEMENT OPTIMIZATIONS SUGGESTED BY IGWN COMPUTING TEAM

ACTIVITY OBS-3.19-B-**OTHER**: ASTROPHYSICALLY-INFORMED CW PARAMETER SPACE SELECTION

All-sky searches for unknown CW sources are extremely computationally expensive. It is therefore important to find ways of using the available computational and man-power resources most efficiently. This can be achieved through analysis of existing catalogues of pulsars, supernova remnants and galactic structure, and/or through Monte Carlo-type modelling of the Galactic neutron star population, to build an astrophysically-informed picture of where in parameter space detections are most likely to be made. This knowledge could then be used to make decisions as to how to allocate resources, in terms of sky locations and spin-down parameters.

TASK OBS-3.19-B(i)-**OTHER**: ASTROPHYSICALLY-INFORMED PARAMETER SPACE SELECTION FOR CW SEARCHES

ACTIVITY OBS-3.19-C-**OTHER**: FURTHER IMPROVEMENT AND OPTIMIZATION OF SKYHOUGH AND RELATED CODES

The SkyHough method is one of the semi-coherent pipelines able to perform all-sky searches for continuous wave signals with a low computational cost. SkyHough has been used to analyze O1, O2 and O3 data [244, 245, 246]. Other search codes derived from SkyHough are BinarySkyHough [174] and a newer track-based code [171], which can both be used for all-sky searches of unknown neutron stars in binary systems.

TASK OBS-3.19-C(i)-**OTHER**: FURTHER IMPROVEMENT, OPTIMIZATION AND ALTERNATIVE IMPLEMENTATIONS

This covers work, both on the original SkyHough and derived codes, beyond that needed for direct O4 application as discussed in (Section OBS-3.10).

ACTIVITY OBS-3.19-D-**OTHER**: FURTHER IMPROVEMENT AND OPTIMIZATION OF TRACK-BASED CODE FOR NEWBORN NEUTRON STARS

The AdaptiveTransientHough [192] code for long-duration CW-like signals from newborn neutron stars with rapid spindown was used for GW170817 [184]. A new, generic track-based code [171] can be used, besides standard CW signals, also for this type of long transients [247], but requires further development and optimization.

TASK OBS-3.19-D(i)-**OTHER**: FURTHER IMPROVEMENT AND OPTIMIZATION OF TRACK-BASED CODE FOR NEWBORN NEUTRON STARS

ACTIVITY OBS-3.19-E-**OTHER**: IMPROVEMENT AND OPTIMIZATION OF TRANSIENT $\mathcal{F}$-STATISTIC SEARCHES

The transient $\mathcal{F}$-statistic method [197, 200] is well suited for quasi-monochromatic long transients after pulsar glitches (Section OBS-3.13). It is computationally cheap as long as applied only to narrow frequency bands around twice the pulsar rotation frequency and simple, rectangular transient window functions. However, the search can be made more robust and general with several improvements over the simple type of setup as it was used in [201]. The method itself can easily support generic transient amplitude evolutions [197], e.g. exponential decay, but the LALSuite code [242] is very slow for these. A much faster GPU implementation is available [200, 178, 179] but will require some (limited) amount of additional work to integrate it in the full search pipeline, plus additional review. The easiest way to run a transient $\mathcal{F}$-statistic search is to reuse the standard 1800 s SFTs produced for other CW searches (Section OBS-3.10), but extension of the search space to shorter transients and a detailed follow-up with denser coverage of transient parameters can be achieved with generating and analyzing multiple sets of SFTs with different baselines. Better methods in the time and/or frequency domain to find, clean or mitigate instrumental artifacts will improve the robustness of the search and reduce the effort required for follow-up and review of outliers. Machine-learning methods (Section OBS-3.21) can make the searches faster and more robust to different amplitude and frequency evolutions (e.g. [248]).

TASK OBS-3.19-E(i)-**OTHER**: IMPROVEMENT AND OPTIMIZATION OF TRANSIENT $\mathcal{F}$-STATISTIC SEARCHES

ACTIVITY OBS-3.19-F-**OTHER**: OPTIMIZATION OF THE FREQUENCYHOUGH PIPELINE

The main target is to port the heaviest parts of the code to use GPUs. The core FrequencyHough routine has been already ported and reviewed. The capability of running a full all-sky search on new LIGO-Virgo data will depend on the availability of enough GPU resources. The porting will be based on the TensorFlow framework. Extensive tests and comparisons with old code will be done in order to verify the new code behaves properly. An exploratory analysis, over a reduced parameter space, will be run using O2 data. A paper describing the new implementation and the pilot analysis will be written. New pieces of the code, not previously reviewed, will be subject to a review.

TASK OBS-3.19-F(i)-**OTHER**: OPTIMIZATION OF THE FREQUENCYHOUGH PIPELINE

ACTIVITY OBS-3.19-G-**OTHER**: FURTHER IMPROVEMENT AND OPTIMIZATION OF THE TIME-DOMAIN $\mathcal{F}$-STATISTIC SEARCH

The Time-Domain $\mathcal{F}$-statistic method is one of the semi-coherent pipelines able to perform all-sky searches for CW signals in many-days time-domain segments, as well as sensitivity upper limits calculations via software signal injections, with a moderate computational cost [168]. However, some technical code optimization as well as improvements in the post-processing stages of the pipeline are still possible.

TASK OBS-3.19-G(i)-**OTHER**: OPTIMIZATION TO COINCIDENCES BETWEEN TRIGGERS FOUND IN TIME-DOMAIN SEGMENTS

Technical code optimization of task described in (Section OBS-3.10).

TASK OBS-3.19-G(ii)-**OTHER**: OPTIMIZATION TO SIGNAL INJECTIONS PROCEDURE/UPPER LIMITS CALCULATION

Technical code optimization of task described in (Section OBS-3.10).

ACTIVITY OBS-3.19-H-**OTHER**: FURTHER OPTIMIZATION OF THE CROSS-CORRELATION PIPELINE

CrossCorr is the most sensitive pipeline to search for Sco X-1 (Section OBS-3.5). Since the sensitivity is determined by the coherence time, which is tied to computing cost, the search is computationally limited: any further improvements (beyond those discussed in (Section OBS-3.5)) which allow the code to run faster enable us to run a more sensitive search.

TASK OBS-3.19-H(i)-**OTHER**: IMPROVE FOLLOWUP AND CANDIDATE VETOS FOR CROSS-CORRELATION

The current CrossCorr analysis procedure includes hierarchical stages where followup analyses are done near the parameters of candidates, using longer coherence times as well as searches using data from only one detector at a time. These are used to reject candidates which do not increase their SNR as much as simulated signals when the coherence time is increaded, or which have higher SNR in a single-detector search than a full-date search. There is room for improvement by including additional measures such as accumulation of SNR with observing time. Rather than choosing decision metrics ad hoc, we may employ machine learning algorithms such as multivariate statistical classifiers to distinguish signals from noise.

TASK OBS-3.19-H(ii)-**OTHER**: ENABLE INCREMENTAL ANALYSIS

The CrossCorr pipeline currently needs to run on all the data at once. For O5 and beyond, we expect the observatories to be in continuous observation for several years, with public release of early data before all the data have been taken. We need to develop procedures to include new data in already-run analyses so that the search can be run incrementally.

TASK OBS-3.19-H(iii)-**OTHER**: ADDITIONAL OPTIMIZATION OF THE CROSS-CORRELATION PIPELINE

ACTIVITY OBS-3.19-I-**OTHER**: EXPLORE FURTHER TWOSPECT ANALYSIS IMPROVEMENTS

TwoSpect provides a framework for analysis of CW sources in binary systems, and is especially powerful when the neutron star or binary parameters are unknown. Pending person power, explore new analysis strategies with the goal of improvements in TwoSpect detection capabilities; this would prove very useful for future all-sky searches for unknown neutron stars in binary systems.

TASK OBS-3.19-I(i)-**OTHER**: EXPLORE FURTHER TWOSPECT ANALYSIS IMPROVEMENTS

ACTIVITY OBS-3.19-J-**OTHER**: FURTHER IMPROVEMENTS TO PYFSTAT FOLLOW-UP TOOLKIT

Potential developments of the PyFstat [178, 179] package beyond those discussed above (Section OBS-3.16) include the possible migration of the MCMC-based followup methods [203] to newer sampling backends.

TASK OBS-3.19-J(i)-**OTHER**: IMPROVEMENTS TO PYFSTAT FOLLOW-UP TOOLKIT

ACTIVITY OBS-3.19-K-**OTHER**: IMPACTS OF CALIBRATION SYSTEMATIC ERROR AND UNCERTAINTY ON CW SEARCHES

Improved understanding of calibration systematic error and uncertainty is increasingly important, especially when performing parameter estimation on a source signal. It is also important to understand how time- and frequency- dependent errors impact results from CW search pipelines, especially when systematic error may be poorly quantified. We intend to research the impact of calibration error and uncertainty, as currently understood, in the Viterbi/HMM pipeline. We expect this kind of study could be expanded to include other pipelines. The conclusions of such studies will enable better understanding on usage of different calibration versions and impacts on CW analysis results.

TASK OBS-3.19-K(i)-**OTHER**: IMPACTS OF CALIBRATION SYSTEMATICS AND UNCERTAINTY ON CW SEARCHES

ACTIVITY OBS-3.19-L-**OTHER**: FURTHER DEVELOPMENT OF OTHER CW PIPELINES

Various other pipelines are already reviewed and in active use for the continuous wave analyses described in this white paper. Optimization and other development work analogous to the specific cases mentioned above may be required for long-term scientific goals of the collaboration.

TASK OBS-3.19-L(i)-**OTHER**: OPTIMIZATION OF OTHER EXISTING PIPELINES

TASK OBS-3.19-L(ii)-**OTHER**: IMPROVEMENTS AND NEW FEATURES ADDED TO OTHER EXISTING PIPELINES

ACTIVITY OBS-3.19-M-**INFRAOPS**: REVIEW OF IMPROVED CW PIPELINES

Review of improved pipelines is essential to ensure they can be used for LVK scientific results.

TASK OBS-3.19-M(i)-**INFRAOPS**: REVIEW IMPROVEMENTS TO EXISTING PIPELINES

ACTIVITY OBS-3.19-N-**INFRAOPS**: PREPARATION OF KEY CW PIPELINES FOR THE CONTINUOUS-OBSERVING ERA (O5)

O5 is planned as a multi-year run in an (almost) “continuous observing” mode, with yearly data releases. This requires much faster turnaround times of CW results from start of data taking to final publication, and the possibility to incrementally update results. Many existing pipelines, especially the most computationally expensive, will require significant re-engineering to meet this challenge. Development work on such modifications for pipelines that are already reviewed and contributing to key science goals will be considered infraops despite the long remaining time to O5. Computational efficiency should be a key aspect in any such changes.

TASK OBS-3.19-N(i)-**INFRAOPS**: ADAPT EXISTING KEY PIPELINES TO O5 CHALLENGES

OBS-3.20 Development of model-robust/agnostic data analysis methods

Start date: 2024-01-01
Estimated due date: t.b.d.

Motivation

Given the limited knowledge of neutron star physics, particularly beyond nuclear densities, it is conceivable that the usual continuous quasi-sinusoidal model of a CW signal may not entirely reflect nature, and that not accounting for such deviations could prevent detection. In general, without knowledge of what form such deviations could take, this is a difficult issue to address. Relaxing the assumption of phase lock between gravitational and electromagnetic emission is a key motivation for the narrow-band pulsar searches (Section OBS-3.2). The stochastic wandering of the spin frequency of LMXBs is a key consideration for directed searches (Section OBS-3.5), although the timescale of the wandering is difficult to quantify. The lack of knowledge of the behavior of long-transient signals, such as from a post-merger neutron star remnant (Section OBS-3.12) or a pulsar glitch (Section OBS-3.13) motivates the development of robust pipelines for such sources. Same arguments apply to all-sky searches (Section OBS-3.10), (Section OBS-3.9). Signals which are not truly continuous, but are intermittent on some timescale, present a particular challenge by expanding the parameter space to include the start and end time of any gravitational-wave emission as a subset of an observing run. New methods based on traditional statistics and on machine learning [249] can contribute to solving these challenges.

Activities

ACTIVITY OBS-3.20-A-**OTHER**: POST-MERGER NEUTRON STAR CW SEARCH METHODS WITH IMPROVED SENSITIVITY AND/OR ROBUSTNESS

Post-merger neutron star searches are a relatively new area of activity in the CW group. While a number of pipelines have been successfully developed so far, further improvements in analysis methods may still be possible. For instance, the likely rapid spindown and uncertain signal model for post-merger neutron stars present numerous challenges to obtaining optimal sensitivity, which new methods development could potentially address.

TASK OBS-3.20-A(i)-**OTHER**: POST-MERGER NS CW SEARCH METHOD IMPROVEMENTS

ACTIVITY OBS-3.20-B-**OTHER**: MACHINE LEARNING FOR LESS MODEL-DEPENDENT CW AND TRANSIENT-CW SEARCHES

Many CW and transient CW searches are optimized for very specific signal models, which means that we are bound to find only signals we expect. Machine Learning methods can help to alleviate this problem by training the algorithms on signals following the standard model plus allowing for some variations, and then benefiting from the method's robustness to deviating signals.

TASK OBS-3.20-B(i)-**OTHER**: MACHINE LEARNING FOR LESS-MODEL-DEPENDENT CW AND TRANSIENT-CW SEARCHES

We will investigate the application of ML methods to perform various searches, with the aim of comparable sensitivity and decreased computational cost.

TASK OBS-3.20-B(ii)-**OTHER**: MACHINE LEARNING POST-PROCESSING OF CANDIDATES FOUND BY SEARCH PIPELINES

Complementary to other follow-up methods discussed above (Section OBS-3.16), ML methods may be applied to candidates found in continuous wave searches. For example, in the Time-Domain F-statistic search, ML clustering can be trained on specific (or general) frequency or amplitude evolution of signals in the coherent analysis of time-domain data segments of specific duration. Alternatively, ML methods may be used to veto outliers obtained in the coincidences procedure. This could allow for increased robustness to non-standard signals.

OBS-3.21 Development of new and potentially more sensitive data analysis methods

Start date: 2024-01-01
Estimated due date: t.b.d.

Motivation

The CW group welcomes work on significant improvements to existing methods that open new scientific opportunities, as well as blue-sky research into completely new ideas for search methods which may yield increased sensitivity or new scientific scope with respect to current algorithms. Many ideas used in CW data analysis have been imported from other fields of astronomy which also analyze long time series, such as radio pulsar astronomy, as well as from more general trends in data analysis, e.g., the use of Bayesian inference. Other successful ideas have come from engineering fields, such as the Viterbi algorithm used in digital communications.

Activities

ACTIVITY OBS-3.21-A-**OTHER**: DEVELOPMENT OF ALTERNATIVE AND NEW CW SEARCH METHODS

TASK OBS-3.21-A(i)-**OTHER**: ALTERNATIVE METHODS FOR COMPUTATIONALLY EXPENSIVE CW SEARCHES

The sensitivity of many CW searches, such as directed and all-sky searches, are fundamentally limited by their computational cost, which typically scales steeply with observation time. It is therefore important to pursue "blue skies" research into alternative analysis methods that are fundamentally less computationally expensive and/or scale more shallowly with observation time, thereby permitting more sensitive searches. Outcomes in this area are difficult to predict, nevertheless success could potentially be vital to a first CW detection.

TASK OBS-3.21-A(ii)-**OTHER**: SEARCH PROCEDURES FOR NEW SCIENCE TARGETS WITHIN LSC PROGRAM SCOPE

The LSC program covers a broad range of continuous-wave like science targets, including also more exotic astrophysical sources and new physics such as dark matter direct detection. Any development of new methods that allow to search for science targets under this scope can be considered a useful long-term contribution to the group.

ACTIVITY OBS-3.21-B-**OTHER**: ELLIPTICITY DISTRIBUTION INFERENCE FROM CW SEARCHES

For any individual pulsar targeted by a CW search one can estimate the parameters defining the gravitational-wave signal. The amplitude of the signal, as observed at Earth, is defined by the mass quadrupole of the source and its distance from us. The mass quadrupole can itself be parameterized by the ellipticity of the star under assumptions about the equation of state and moment of inertia. For a population of sources it is interesting to understand the distribution of ellipticities across all pulsars, which may help constrain the underlying physics that gives rise to such a distribution. We will expand on the works in [250] and in [251] to combine results from the targeted pulsar searches to infer the properties of various parameterized ellipticity distributions, and how these might vary for different sub-populations of pulsars, e.g., "young" versus recycled millisecond pulsars.

TASK OBS-3.21-B(i)-**OTHER**: ELLIPTICITY DISTRIBUTION INFERENCE

ACTIVITY OBS-3.21-C-**OTHER**: MACHINE LEARNING FOR EFFICIENT ANALYSIS OF CWS AND TRANSIENT-CWS

In addition to making CW and transient-CW searches less model-dependent (Section OBS-3.20), machine learning can also help to reduce the amount of resources needed to find and study signals. For example, searches using convolutional neural networks take orders of magnitude less time than traditional methods, and can approach their sensitivity both for signals that follow our models and even ones that do not. Moreover, machine learning has the capabilities to estimate the parameters of transient CW signals. Finally, it does not necessarily have to be used to detect signals; rather, it can be used to generate waveforms [252, 253], to veto likely false candidates, etc. We plan to continue efforts to use machine learning to run searches [230, 248], perform parameter estimate [254, 255], and to apply it in new ways. We also plan to continue the work of [256] in order to better understand how machine learning methods respond specifically to noise disturbances, so that we can quote reliable false alarm probabilities, sensitivities in the presence of non-Gaussianities, and actually apply more of them to real searches.

TASK OBS-3.21-C(i)-**OTHER**: MACHINE LEARNING FOR EFFICIENT ANALYSIS OF CWS AND TRANSIENT-CWS

ACTIVITY OBS-3.21-D-**OTHER**: FURTHER IMPROVEMENTS TO BINARYWEAVE PIPELINE

Accreting neutron stars in low-mass X-ray binary systems (LMXB), particularly Sco X-1, are one of the strongest candidates for the future detection of CW signals. A new detection pipeline, namely BinaryWeave, has been developed that is suitable for searching for CW signals from spinning neutron stars in binary systems with known sky position over a wide parameter space. (Section OBS-3.5). Further development and characterization of the pipeline is ongoing.

TASK OBS-3.21-D(i)-**OTHER**: FURTHER IMPROVEMENTS TO BINARYWEAVE PIPELINE

ACTIVITY OBS-3.21-E-**OTHER**: NEW TECHNIQUES FOR FOLLOW-UP AND PARAMETER ESTIMATION OF CW CANDIDATES

There is so far a limited set of methods available to do Bayesian sampling on CW signal candidates, both for follow-up with enhanced coherence times (Section OBS-3.16) and especially for full parameter estimation. But many modern sampling algorithms and software packages have been developed in the wider GW, astrophysics and data science communities. Implementing and characterizing these for CW applications is a crucial step towards the robust identification and scientific exploitation of CW signals from a wide range of searches (from all-sky to targeted).

TASK OBS-3.21-E(i)-**OTHER**: IMPLEMENT AND CHARACTERIZE NEW SAMPLERS FOR CW APPLICATIONS

ACTIVITY OBS-3.21-F-**OTHER**: EXPANDED PARAMETER ESTIMATION AND ASTROPHYSICAL INFERENCE FOR NEWLY-DISCOVERED CW SOURCES

Further work is needed to develop robust and efficient parameter estimation methods for CW detections.

One specific example is that, if a known radio or X-ray pulsar is seen to be a continuously emitting gravitational wave source, its mass quadrupole can be readily estimated from the signal strain and the distance to the pulsar. This distance is usually known reasonably well from dispersion or parallax measurements. If however the source of the gravitational waves is not radio or X-ray loud we need another way to determine its distance if we are to progress further than a simple strain and frequency measurement. For close, bright GW sources we can apply the same annual parallax method used in radio to gravitation observations. The current targeted parameter estimation code [95] can be adapted to include frequency and its derivative, sky position and parallax (or distance) as constrained parameters, returning estimates of the neutron star's mass quadruple and distance. Of course this process is sensitive to the signal-to-noise ratio and will become increasingly important in A+ and beyond.

TASK OBS-3.21-F(i)-**OTHER**: DISTANCE ESTIMATION TO CW SOURCES VIA GW PARALLAX

TASK OBS-3.21-F(ii)-**OTHER**: DEVELOPMENT OF OTHER PARAMETER ESTIMATION TECHNIQUES FOR CW SOURCES

ACTIVITY OBS-3.21-G-**OTHER**: EFFICIENT SEARCHES FOR LONG-DURATION CW-LIKE TRANSIENTS FROM UNKNOWN SOURCES

Search techniques for long-duration CW-like signals, such as post-merger (Section OBS-3.12) and post-glitch (Section OBS-3.13) signals, are so far severely computationally limited and only run on targets with known sky position and approximately known starting time. As for CWs, all-sky searches over broad frequency ranges are even more expensive, though the sky needs to be covered less densely for shorter durations. Searching for arbitrary transients with starting time anywhere within an observing run gives another huge scaling factor. New approaches are needed to meet this computational challenge for "all-sky all-frequency all-time" searches.

TASK OBS-3.21-G(i)-**OTHER**: DEVELOP AND CHARACTERIZE HIGHLY EFFICIENT METHODS FOR FINDING TRANSIENTS FROM UNKNOWN SOURCES

ACTIVITY OBS-3.21-H-**OTHER**: ASTROPHYSICAL IMPLICATIONS AND MULTI-MESSENGER STUDIES OF CW DETECTIONS

The first CW detections will require detailed astrophysical interpretation. At least in the case of our main targets, neutron stars, there is also a rich range of opportunities for multi-messenger combined analysis of electromagnetic and GW data on the same sources. Testing for consistency of GW-inferred source parameters and those known from EM observations has been identified as an important step in CW candidate validation, and optimal Bayesian methods for combined inference can be useful contributions to exploiting LVK detections.

TASK OBS-3.21-H(i)-**OTHER**: DEVELOP METHODS FOR SYSTEMATIC ASTROPHYSICAL INTERPRETATION AND COMBINED ELECTROMAGNETIC AND GW STUDIES OF CW DETECTIONS

ACTIVITY OBS-3.21-I-**OTHER**: STUDYING GRAVITATIONALLY LENSED CWS

Directed searches towards the galactic center can potentially detect CWs that undergo gravitational lensing by the supermassive black hole [257]. Strong lensing will create multiple copies of the signal with a time delay, which will interfere with each other. If the time delay is constant, the interfered signal would be indistinguishable from an unlensed CW. However, if the relative motion between the source and the lens is sufficiently large, the lensing time delay can vary with time. This will result in the modulation of the amplitude and phase of the lensed CW signals, rendering them distinguishable. Observation of lensed CWs could enable unique probes of the properties of the supermassive black hole as well as the astrophysical environment of the galactic center.

TASK OBS-3.21-I(i)-**OTHER**: DEVELOP METHODS TO REINTERPRET STANDARD CW UPPER LIMITS UNDER THE LENSING HYPOTHESIS

TASK OBS-3.21-I(ii)-**OTHER**: DEVELOP DEDICATED SEARCH METHODS FOR LENSED CWS

ACTIVITY OBS-3.21-J-**OTHER**: INVESTIGATE SEARCHES FOR LONG-DURATION TRANSIENT SEARCHES FOR NEWBORN NEUTRON STARS

The methods as discussed in (Section OBS-3.12) for the case of BNS merger remnants can also be applied to newborn neutron stars from the regular core-collapse supernova formation channel. The event rates, parameter space and search setup details need to be investigated before designing practical searches.

TASK OBS-3.21-J(i)-**OTHER**: STUDY THE ASTROPHYSICAL RATES AND PRIORS ON PARAMETER SPACE FOR NEWBORN NEUTRON STARS

TASK OBS-3.21-J(ii)-**OTHER**: IMPLEMENT SEARCH PROCEDURES FOR NEWBORN NEUTRON STARS

ACTIVITY OBS-3.21-K-**OTHER**: IMPROVED MODELLING OF ULTRALIGHT BOSON CLOUD GRAVITATIONAL WAVE SIGNALS

Current models for the gravitational wave signals from ultralight boson clouds that arise from black hole superradiance have limited accuracy, in particular in capturing the frequency evolution in the more relativistic part of parameter space. A better model will allow for a more accurate translation of signal constraints into constraints on physical parameters, and potentially enable more sensitive searches.

TASK OBS-3.21-K(i)-**OTHER**: DEVELOP A MORE ACCURATE ULTRALIGHT BOSON GRAVITATIONAL WAVE MODEL AND STUDY HOW IT CAN BE USED TO IMPROVE SEARCHES

ACTIVITY OBS-3.21-L-**OTHER**: METHODS TO COMBINE CW SIGNIFICANCE ESTIMATES AND OTHER RESULTS FROM MULTIPLE PIPELINES

When independent pipelines (or different configurations of the same pipeline) address the same astrophysical source, methods should be developed, where possible, to combine results from the individual pipelines leading to a single quantitative statement such as the confidence in each candidate or an appropriate upper limit in the event of a non-detection. Follow-up stages also need to be taken into account.

TASK OBS-3.21-L(i)-**OTHER**: DEVELOP METHODS TO COMBINE RESULTS FROM MULTIPLE PIPELINES

ACTIVITY OBS-3.21-M-**OTHER**: DEVELOPMENT OF AN ALL SKY SEARCH USING THE IWAVE METHOD

IWAVE [258] is a phase locked loop algorithm based on adaptive filters developed to lock on to and track pseudo-sinusoidal signals. The method has demonstrated sensitivity to magnetar signals injected into interferometer data at source distances of order 100kPc is highly computationally efficient, and has few input parameters. We are developing a search pipeline around the IWAVE method.

TASK OBS-3.21-M(i)-**OTHER**: DEVELOP THE IWAVE PIPELINE, IDENTIFY A PLAYGROUND DATA SET, PERFORM SIMULATION STUDIES TO ASCERTAIN SENSITIVITY, READY THE PIPELINE FOR REVIEW, AND RUN THE PIPELINE ON INTERFEROMETER DATA.

OBS-3.22 Use mock data challenges to compare data analysis pipelines

Start date: 2024-01-01
Estimated due date: t.b.d.

Motivation

Mock data challenges (MDCs) can be a useful tool for comparing different data analyses pipelines. By subjecting each pipeline to a common set of tests, the benefits and costs of each pipeline can be rigorously assessed. In the past, successful mock data challenges organized within the CW group have compared pipelines for directed searches for Scorpius X-1 [259] and all-sky searches for isolated sources [260]. Since most CW pipelines have been in a mature state for many years, and taking into account constrained human resources, currently no extensive MDCs are planned as essential run preparation, but the CW group still welcomes and supports such efforts as person power and resources allow.

Methods

Commonly, simulated data containing signals of varying strengths whose parameters are unknown to the analysts are prepared by a neutral party, and each pipeline is assessed based on the number of simulated signals it found. This can be done both as fully blind mock data challenges, or as simpler coordinated injection sets shared across different pipelines, which any multi-pipeline analysis project can benefit from.

Activities

ACTIVITY OBS-3.22-A-**OTHER**: SIMULATION INVESTIGATION FOR SCO X-1

Personpower permitting, the performance of CW pipelines to search for Sco X-1 may be tested with simulated signals injected into O3 data. In particular, simulations may be generated with varying amounts of spin wandering to check the practical limitations of CW pipelines. Results and conclusions would be reported in a short-author paper.

TASK OBS-3.22-A(i)-**OTHER**: DESIGN OF A SIMULATION INVESTIGATION FOR SCO X-1

TASK OBS-3.22-A(ii)-**OTHER**: PIPELINE PARTICIPATION IN SIMULATION INVESTIGATION FOR SCO X-1

TASK OBS-3.22-A(iii)-**OTHER**: EVALUATION OF A SIMULATION INVESTIGATION FOR SCO X-1

ACTIVITY OBS-3.22-B-**OTHER**: TARGETED MDCS FOR CW CANDIDATE FOLLOW-UP AND HANDOVER

The seamless handover of CW detection candidates from first-stage searches to independent follow-up pipelines (Section OBS-3.16) has been identified as an important task for validating such candidates. Targeted MDCs (in the sense of covering specific parameter space regions, where interesting candidates are expected or have already been observed) can be a useful tool to exercise and characterise such handover procedures, including the setting of follow-up priors based on search results and their uncertainty estimates, as well as the choice of appropriate false-dismissal / false-alarm operating points for the follow-up pipelines.

TASK OBS-3.22-B(i)-**OTHER**: DESIGN OF TARGETED MDCS FOR CANDIDATE FOLLOW-UP AND HANDOVER

TASK OBS-3.22-B(ii)-**OTHER**: PIPELINE PARTICIPATION IN TARGETED MDCS

TASK OBS-3.22-B(iii)-**OTHER**: EVALUATION OF TARGETED MDCS FOR CANDIDATE FOLLOW-UP AND HANDOVER

ACTIVITY OBS-3.22-C-**OTHER**: OTHER CW MDCS

The CW group supports the design and implementation of any other MDCs that answer a clear question on comparing the sensitivity, robustness or parameter space coverage of several CW analysis methods or pipelines, as long as these clearly contribute to the group deliverables on O4 or to improving CW science in future observing runs. This may also involve public challenges like the recent Kaggle competition on CW detection[5].

TASK OBS-3.22-C(i)-**OTHER**: DESIGN OF MDCS

TASK OBS-3.22-C(ii)-**OTHER**: PIPELINE PARTICIPATION MDCS

TASK OBS-3.22-C(iii)-**OTHER**: EVALUATION OF MDCS

OBS-4 Stochastic Group Activity Plans

In addition to the activities described in this section, see the activities being undertaken jointly with the Burst, CBC, and CW groups in sections OBS-6, OBS-7, and OBS-8, respectively. Activities pursued jointly with the Detector Characterization group are described in the corresponding sections of the *LSC-Virgo-KAGRA Operations White Paper* (LIGO-T2300409.

OBS-4.1 Search for an isotropic stochastic gravitational-wave background (short term)

Start date: 2025-01-01
Estimated due date: 2025-12-31

OBS-4.1.1 Scientific Case

The stochastic isotropic search targets the stochastic gravitational-wave background, which arises from a superposition of a variety of cosmological and astrophysical gravitational-wave sources. Potential cosmological sources include the amplification of vacuum fluctuations following inflation [261], phase transitions in the early universe [262, 263], and cosmic (super)strings [264, 265, 266, 267]. Astrophysical contributions to the stochastic background consist of an incoherent superposition of sources that are unresolved or too weak to be detected individually. The most promising contribution for terrestrial detectors comes from the population of compact binaries such as binary neutron stars [268], binary black holes [269], or black-hole–neutron stars. The detection of a cosmological background would be a landmark discovery of enormous importance to the larger physics and astronomy community. The detection of an astrophysical background would also be of great interest as it would give important constraints on the star formation history and the evolution of the mass distributions with redshift. The implication from Advanced LIGO/Virgo's first and second observing runs is that the stochastic gravitational-wave background from binary black holes and binary neutron stars is consistent with optimistic predictions, and is potentially observable with advanced detectors [269, 268, 270].

General relativity allows only for two gravitational-wave polarizations – the tensor plus and cross modes. Alternative theories, such as scalar-tensor theories [271, 272], $f(R)$ gravity [273, 274], bimetric [275] and massive [276] gravity theories, generically predict up to four additional vector and scalar polarization states.

[5] https://www.kaggle.com/competitions/g2net-detecting-continuous-gravitational-waves

The direct measurement of gravitational-wave polarizations may therefore serve as a powerful phenomenological test of gravity.

OBS-4.1.2 Methodology

The primary goal of the isotropic search is to estimate the energy density of the stochastic background:

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_c}\,\frac{d\rho_{\rm GW}}{d\ln f}\,, \tag{1}$$

where $\rho_{\rm GW}$ is the energy density of gravitational waves, ρ_c is the critical density of the universe, and f is the frequency. This is accomplished through a well-established cross-correlation procedure, documented in [277, 278], which has served as the basis for all previous LIGO/Virgo stochastic searches [279, 280, 281, 282, 283, 284]. The stochastic pipeline estimates $\Omega_{\rm GW}(f)$ given some assumed power law $\Omega_{\rm GW}(f) \propto f^{\alpha}$. Cosmological sources such as inflation and cosmic string backgrounds are predicted to have $\alpha = 0$, while $\alpha = 2/3$ is appropriate for the signal from binaries.

ACTIVITY OBS-4.1-A-**INFRAOPS**: SEARCH FOR AN ISOTROPIC STOCHASTIC BACKGROUND

TASK OBS-4.1-A(i)-**INFRAOPS**: O4 ANALYSIS

(i) Measure (or set upper limits on) the energy density of the isotropic stochastic background for different power laws and non-GR polarizations using the combined O1, O2, O3, and O4 data from Advanced LIGO (LHO and LLO), Advanced Virgo, and KAGRA; (ii) Using these measurements or upper limits, constrain theoretical models for the isotropic stochastic background, e.g., binary black holes, binary neutron stars and neutron star-black hole binaries (see below), (iii) Implement a method to mitigate loud glitches in O4. (iv) Constrain the presence of magnetic noise.

TASK OBS-4.1-A(ii)-**INFRAOPS**: O4 ISOTROPIC ANALYSIS INFRASTRUCTURE

Develop and review infrastructure that will support O4 analyses. This includes: (i) Extending the parameter estimation modules of the new python-based pipeline for isotropic stochastic background search, pygwb, to investigate the implications on new astrophysical and cosmological models; (ii) Identify data quality issues in O4 data for the isotropic searches, and (iii) Performing mock data challenges to verify the detection capabilities of the stochastic search and test the model prediction.

TASK OBS-4.1-A(iii)-**INFRAOPS**: IMPLICATIONS FOR ASTROPHYSICAL MODELS

Our measurements of the energy density of the stochastic gravitational-wave background will allow us to place observational constraints on specific theoretical models of the background. For example, applying the Bayesian parameter estimation techniques outlined in [285, 268, 286], we can estimate or place upper limits on the average chirp mass and merger rate of the binary black hole population. Understanding the observational implications also requires us to develop more accurate astrophysical models of the binary black holes. This work is coordinated with the binary coalescence Rates and Population group (Sec. OBS-2.9). We will develop methods to infer properties of the underlying compact binary population from a detection of an astrophysical stochastic background, such as the merger rate as a function of redshift. Mock data challenges will be used to test the recovery of simulated backgrounds. We expect the implications for astrophysical stochastic background to be included in the O4 isotropic background search papers.

TASK OBS-4.1-A(iv)-**INFRAOPS**: IMPLICATIONS FOR COSMOLOGICAL MODELS

With the measurements or upper limits on the energy density, we can explore the implications of these results for isotropic stochastic background due to cosmological models. We will develop methods and carry out a program to compute implications of our observations for models of interest in cosmology. In particular, we will study first-order phase transitions, cosmic strings, domain walls, parity violation, stiff equation of state, axion inflation, curvature perturbations, particle dark matter candidates, and primordial black holes as dark matter candidates. The implications for cosmological stochastic background models will be explored in a separate isotropic search publication.

OBS-4.2 Search for an isotropic stochastic gravitational-wave background (long term)

Start date: 2025-01-01
Estimated due date: 2025-12-31

In addition to our standard isotropic analysis, there are several additional activities underway to improve the sensitivity of our search.

ACTIVITY OBS-4.2-A-**OTHER**: COMPONENT SEPARATION (ISOTROPIC STOCHASTIC BACKGROUND)

An important extension of the standard isotropic search is to estimate the individual contributions of distinct sources of the background, because the true background is unlikely to be fully described as a single power law. Even if there is one strong (detectable) power law component, the upper limits on the weaker components will be affected by the strong one(s). One should perform a joint analysis considering all the physically allowed spectral shapes together. A “component separation” method was recently developed to put joint upper limits on the amplitudes of multiple spectral shapes [287]. This method uses the results produced by the isotropic search for each spectral shape and estimates the joint upper limit by deconvolving them via a mixing matrix. In addition to the component separation method, we also will implement a related approach using Bayesian parameter estimation to study more general models such as broken power laws. This analysis can be applied in post-processing, using the measured cross-correlation spectrum as the fundamental data product.

TASK OBS-4.2-A(i)-**OTHER**: COMPONENT SEPARATION FOR ISOTROPIC STOCHASTIC SEARCHES

ACTIVITY OBS-4.2-B-**OTHER**: A CROSS-CORRELATION BASED SEARCH FOR INTERMITTENT GRAVITATIONAL-WAVE BACKGROUNDS

To better search for intermittent (i.e., popcorn-like) stochastic GW backgrounds (most-likely produced by astrophysical sources such as stellar-mass binary black hole mergers), efforts are currently underway to modify the standard cross-correlation search for a stationary-Gaussian background to target short intermittent “bursts" of correlated GW signals. The search is based on a mixture-likelihood formalism involving the duty cycle of the signals, analogous to the fully-Bayesian search for BBH mergers. But rather than marginalize over the parameters of deterministic chirp signals, this new method looks for evidence of excess correlated $f^{-7/3}$ GW power, as expected for binary inspiral signals. Although suboptimal compared to the fully-Bayesian search for BBH mergers, the cross-correlation-based search is computationally efficient, using cross-correlation frequency spectra and their variances as sufficient statistics for the analysis. Preliminary testing on simple toy models indicate that the cross-correlation-based search is a promising strategy for intermittent GW signals. Additional testing on more realistic simulated data sets containing injected BBH merger signals and noise transients is needed before this method can be run with confidence on real LIGO-Virgo data. The hope is to complete this testing in time for the search to be ready around the end of O4 observation.

TASK OBS-4.2-B(i)-**OTHER**: CROSS-CORRELATION BASED SEARCH FOR INTERMITTENT GW BACKGROUNDS

OBS-4.3 Directional searches for persistent gravitational waves

Start date: 2025-01-01
Estimated due date: 2025-12-31

OBS-4.3.1 Scientific Case

While most prescriptions of the SGWB predict an isotropic signal, there are mechanisms that could introduce anisotropy [267, 288, 289, 290, 291, 292, 293]. For example, a confusion background may arise from binary mergers [285, 294, 295], core-collapse supernovae [296, 297], neutron-star excitations [298, 299], persistent emission from neutron stars [300, 301], and compact objects around supermassive black holes [302, 303]. Depending on the rate and redshift distribution of these objects, the corresponding SGWB could be isotropic or anisotropic. Such an anisotropic signal may appear with greater statistical significance in the anisotropic search than in the isotropic search.

The directional search provides information on the angular content of the SGWB in the form of a map of the gravitational-wave sky, and is therefore a powerful tool for distinguishing among different possible sources of the SGWB. The stochastic directional search provides a crucial follow-up to characterize anisotropies present in stochastic GW signals detected by the isotropic search; it facilitates the detection of highly anisotropic stochastic sources (e.g., clustered in the Galactic plane) that might be missed by the isotropic search; it provides a robust and sensitive search for narrowband point sources from interesting persistent sources (such as accreting binary systems like Sco X-1, young neutron stars like SN1987A, or unknown neutron stars such as a localised population at the galactic center [304]); and it provides a possibility of cross-correlating the SGWB anisotropies with anisotropies in electromagnetic observations (galaxy counts, gravitational lensing) to extract further information on the origin and composition of the SGWB.

OBS-4.3.2 Methodology

The anisotropic SGWB search estimates the energy density of the stochastic background while keeping the directional information [305]:

$$\Omega_{\rm GW}(f,\Theta) \equiv \frac{1}{\rho_c}\,\frac{d^3\rho_{\rm GW}}{d\ln f\, d^2\Theta} = \frac{2\pi^2 f^3}{3H_0^2}\,H(f)P(\Theta), \quad \Omega_{\rm GW}(f) = \int d\Theta\,\Omega_{\rm GW}(f,\Theta), \tag{2}$$

for Hubble parameter H_0 and sky location Θ. The frequency spectrum is typically assumed to be a power law in the frequency band of GW detectors: $H(f) = (f/f_0)^{\alpha-3}$. For a given value of the power index α (for example, $\alpha = 0$ for inflation and cosmic strings, $\alpha = 2/3$ for compact binaries, and $\alpha = 3$ gives a fiducial value for other astrophysical backgrounds such as supernovae), the objective of the search is to estimate $P(\Theta)$. Two approaches are pursued. In the radiometer algorithm, we assume the signal is characterized by a point source

$$P(\Theta) = \eta(\Theta_0)\delta^2(\Theta,\Theta_0), \tag{3}$$

and in the spherical harmonic decomposition (SHD) algorithm we assume that the signal can be written as a superposition of spherical harmonics

$$P(\Theta) = \sum_{lm} P_{lm} Y_{lm}(\Theta). \tag{4}$$

Likelihood maximization leads to estimators of the angular content of the SGWB for the radiometer ($\hat{\eta}_\Theta$) and spherical harmonic ($\hat{P}_{lm}$) cases:

$$\hat{\eta}_\Theta = (\Gamma_{\Theta\Theta})^{-1} X_\Theta \tag{5}$$

$$\hat{P}_{lm} = \sum_{l'm'} (\Gamma^{-1})_{lm,l'm'} X_{l'm'}. \tag{6}$$

The Fisher matrix $\Gamma(f,t)$ encodes the uncertainty associated with deconvolving the raw cross-correlation measurement for different directions on the sky (see [306, 305, 307] for further description and details on its inversion).

In [308], it was demonstrated that the data compression using sidereal folding [309] significantly improves the computational speed of directional analyses. Hence directional analyses are carried out using folded data.

ACTIVITY OBS-4.3-A-**INFRAOPS**: DIRECTIONAL SEARCH FOR PERSISTENT GRAVITATIONAL WAVES (SHORT TERM)

TASK OBS-4.3-A(i)-**INFRAOPS**: MOCK DATA CHALLENGE

Conduct an extensive Mock Data Challenge (MDC) to: (i) understand the angular resolution of the directional searches for the stochastic background, both in the case of detection and in the case of parameter estimation; (ii) study the Fisher matrix regularization schemes and their bias on the estimates of the angular power spectrum; (iii) determine the optimal choice for the frequency band to be used in directional searches; (iv) explore how all of the above change as a function of the detector network; and (v) perform parameter estimation targeted for modeled skymaps such as kinematic dipole and galactic plane. Results of this MDC will guide the choices to be made in searches for anisotropic stochastic background using O4 data.

TASK OBS-4.3-A(ii)-**INFRAOPS**: CODE DEVELOPMENTS

Develop and review a fully python-based code infrastructure for O4 directional analyses. This will include (i) organizing the exisiting code base of `PyStoch`, (ii) folding data generation using intermediate data products from new python-based isotropic code infrastructure `pyGWB`, (iii) extending `PyStoch` to perform spherical harmonic analysis in python, (iv) python-based post processing codes to calculate significance and upper limits, (v) improving the upper limit calculation using better Bayesian priors, (vi) improving data quality cuts for directional analyses, and (vii) demonstrating the efficiency of detection checklist and readiness for the first detection.

TASK OBS-4.3-A(iii)-**INFRAOPS**: O4 DIRECTIONAL ANALYSIS

(i) Identify data quality issues in O4 data specifically relevant for directional analyses; (ii) Generate folded data for directional searches; (iii) Perform all-sky search for measuring (or constraining) the energy flux on the sky from point sources (narrowband and broadband radiometer analysis) for different power-law indices and produce GW sky maps. The maps can be used to identify patches on the sky to follow up with CW searches [See Section OBS-8.1]; (iv) Perform an unmodeled search for potentially interesting persistent GW sources from specific sky locations or from the galactic plane; (v) Constrain published models of anisotropic GW backgrounds, for example due to millisecond pulsars in the Milky Way.

TASK OBS-4.3-A(iv)-**INFRAOPS**: O4 SPH ANALYSIS

(i) Perform all-sky search for extended sources using spherical harmonic decomposition for different power-law spectral indices applied to O4 data. (ii) Identify data quality issues affecting the SpH analysis; (iii) Standardise methods to constrain published models of anisotropic GW backgrounds, for example from cosmic strings or compact binaries, using angular spectra for both auto-power in gravitational wave background and for the cross-power between the gravitational-wave background and electromagnetic observables.

OBS-4.4 Directional searches for persistent gravitational waves (long term)

In addition to our standard directional analysis, there are several extensions planned or already in production.

ACTIVITY OBS-4.4-A-**OTHER**: COMPONENT SEPARATION USING NARROWBAND MAPS (DIRECTIONAL STOCHASTIC SEARCHES)

Like the isotropic search, directional searches are also performed separately for multiple spectral indices in standard analyses. A method is being developed to generate skymaps for multiple spectral components. However, deconvolution of skymaps, even with one index poses serious challenges, which only gets amplified when multiple components are present. Exploration studies are being performed, initially considering two or three power-law spectral indices.

TASK OBS-4.4-A(i)-**OTHER**: COMPONENT SEPARATION FOR DIRECTION SEARCHES USING NARROWBAND MAPS

ACTIVITY OBS-4.4-B-**OTHER**: IMPLICATIONS AND PARAMETER ESTIMATION FOR MODELS OF ANISOTROPIC BACKGROUNDS

Observation of anisotropy in the SGWB could indicate structure between now and the surface of last scattering, the scale of which could be used to inform models of our cosmological history. Recent theoretical developments have established the framework for estimating anisotropies in cosmological and astrophysical SGWB models [289, 291], and have applied the formalism to specific cases of the models due to BBH mergers [290, 292, 293, 310, 311, 312, 312, 313] and due to cosmic string networks [291]. We will develop methods of using the measured SGWB anisotropies to constrain theoretical SGWB models. We will employ a recently developed method for estimating the angular spectrum of anisotropies that gives an unbiased estimate of the true, astrophysical spectrum, removing the offset due to shot noise [310, 313]. We also investigate ways of correlating SGWB anisotropy measurements with electromagnetic proxies for the evolution of structure in the universe (galaxy counts, gravitational lensing, cosmic infrared background) so as to extract information about the evolution and composition of the SGWB. Finally, we plan to use the spherical harmonic search to study parameterized models of anisotropy, for example arising from neutron stars in the galactic plane [288, 314, 315] or in the galactic center [304].

TASK OBS-4.4-B(i)-**OTHER**: PARAMETER ESTIMATION FOR DIRECTIONAL SEARCHES

(i) Search for anisotropic distribution of GW background using pixel-based skymap templates and constrain the amplitude of the background. (ii) Perform Bayesian parameter inference for several skymap models, such as kinematic dipole and galactic plane to place constraints on model parameters, e.g. amplitude, spectral index. (iii) Perform Bayesian parameter inference for angular power spectrum C_ℓ for astrophysical GW background, for example, compact binary coalescence and cosmic strings. (iv) Develop machine-learning inference techniques for estimating the angular power spectrum.

TASK OBS-4.4-B(ii)-**OTHER**: GW-EM CORRELATION

(i) Estimate correlations of anisotropy in the stochastic gravitational wave background and anisotropy in electromagnetic tracers of the structure in the universe (galaxy counts, weak lensing, cosmic microwave background, cosmic infrared background) by measuring angular power spectra between skymaps. (ii) Develop techniques for estimating these correlations in both *clean* and *dirty* space, as well as techniques for minimizing the impact of regularization of the Fisher matrix. (iii) Develop frameworks for parameter estimation in astrophysical models of SGWB-EM correlations. (iv) Include the effect of spatial and temporal shot noise in the above parameter estimation frameworks.

OBS-4.5 Search for very-long transient gravitational-wave signals

Start date: 2025-01-01
Estimated due date: 2025-12-31

OBS-4.5.1 Scientific Case

The long transient search looks for very long-lived transient signals ($\gtrsim 10$ hr, to as long as months) that might be otherwise overlooked or mistaken as an apparent stationary stochastic signal. There are several potential astrophysical sources for gravitational-wave transients on these time scales. For example, in Ref. [316], several scenarios associated with neutron stars are suggested, including non-axisymmetric Ekman flow occuring after a glitch and emission from free precession (with a damping time possibly lasting from weeks to years) [120, 317, 318]. Remnants of BNS mergers are particularly interesting as potential sources of very long transient signals. Futhermore, it is worthwhile to be prepared for a surprise: a very long-lived transient signal from an unexpected source. Recent work studying gravitational-wave emission from gravitationally bound axion clouds [319], potentially starting and stopping on the timescale of a few years, serves to illustrate this possibility. Finally, regardless of the specific source, one or more long-lived transient signals (or coherent long-duration noise) can produce an apparent signal in the isotropic and directional stochastic searches, while simultaneously evading detection in searches for short-duration transients. As a result, a dedicated search is necessary to understand the origin of apparent stochastic signals.

OBS-4.5.2 Methodology

The transient searches will constrain the energy density $\Omega_{\rm gw}$ [277] due to transient phenomena. As a baseline, the transient searches are carried out using the Stochastic Transient Analysis Multi-detector Pipeline (STAMP) [320, 321, 322, 323, 324]. STAMP produces spectrograms of auto- or cross-power for two detectors [320]. Gravitational-wave signals appear as tracks of brighter-than-usual spectrogram pixels. STAMP employs a user-specified clustering algorithm (there are a few options [320, 325, 323, 324, 326]) in order to identify statistically significant clusters of pixels. Highly-parallel seedless clustering algorithms are available [323, 324], taking advantage of GPUs and multi-core CPUs for dramatic speed-ups [324]. Seedless clustering was used in the analysis of the Advanced LIGO O1 data. The results of an all-sky search for long transients using O1, O2, and O3 data are presented in [8, 9, 10].

We will analyze data on timescales of ≈ 10 hr–1 month in order to determine if there are individual long-lived transient signals contributing to the isotropic or directional stochastic measurements. We have run STAMP in all-sky mode on O1/O2/O3 data used in the stochastic search, and we will run the same pipeline on the O4 data. In order to analyze these very long signals, we have added an extra stage of pre-processing in which the data are compressed through time-averaging as described in [327]. As an application of the STAMP very-long-transient pipeline, we will work in collaboration with the Burst group (Section OBS-1.2) and CW group (Section OBS-3.12) to search for post-BNS-merger gravitational-wave signals. Such a search for a long-lived remnant of GW170817 was conducted [184], with the STAMP pipeline being run as a directed unmodeled search, and we plan to repeat similar searches for remnants of promising BNS mergers observed in O4.

The STAMP code package has also produced spin-off technology that has proven useful for detector characterization [328, 329] and follow-up/visualization of CBC triggers [326]. We expect continued development and maintenance of STAMP will be broadly useful for the Stochastic Group activities and the wider LSC/Virgo community.

ACTIVITY OBS-4.5-A-**OTHER**: SEARCH FOR VERY LONG TRANSIENTS

TASK OBS-4.5-A(i)-**OTHER**: VLT CONTRIBUTION TO $\Omega_{\rm gw}$

Measure (or set upper limits on) the energy density of the very long transient signals and their contribution to the overall $\Omega_{\rm gw}$ using O4 data. If a stochastic background is observed, contribute to developing the energy budget of the observed background by estimating the contribution of the very long transients.

TASK OBS-4.5-A(ii)-**OTHER**: STUDY OF BNS MERGER REMNANTS

Apply the search for very long transients to data following mergers of binary neutron stars observed in O4 observing run. Coordinate the search and the publication with similar searches conducted in the burst and CW groups.

TASK OBS-4.5-A(iii)-**OTHER**: MACHINE LEARNING APPROACH TO IDENTIFYING LONG TRANSIENTS

Explore the use of modern Machine Learning algorithms to parse the cross-power spectrograms with the goal of improving the sensitivity and computational efficiency of the search.

OBS-5 Burst+CBC Joint Activity Plans

OBS-5.1 Search for gravitational waves from black hole binaries

Start date: 2024-01-01
Estimated due date: 2024-12-31

Binary black hole (BBH) systems in the normal stellar mass range have been efficiently detected in observing runs O1, O2, and O3 with matched filter searches using quasi-circular CBC templates. However, for high-mass systems in the IMBH range (total mass of about $100\,\mathrm{M}_\odot$ or more), we expect Burst searches, which do not rely on templates, to perform similarly to the CBC searches. Furthermore, if there exist BBH systems not currently well described by quasi-circular waveforms, we would expect the Burst searches to provide good detection capability. The GW190521 discovery [11] in O3a, representing the first IMBH detection, is an example where CBC and Burst searches found the signal with similar significance. On the other hand, for non-circular BBH systems, such as eccentric binaries (with $e > 0.05$) or hyperbolic encounters, templated CBC searches are not currently expected to be competitive with Burst searches, although we do not yet have evidence that such systems exist at a detectable rate within the LIGO-Virgo-KAGRA horizon. Tasks associated to eccentric binary systems are listed in OBS-1.3.

Given the complementarity of the Burst and CBC searches, for O4 we will utilize a more uniform organizational structure for carrying out the all-sky searches for BBH systems. In particular, the CBC all-sky group has been generalized to a combined CBC-Burst group with joint leadership. Results are to be reported in exceptional event papers, if appropriate, but more typically in the GWTC catalogs, astrophysical populations, and testing GR papers.

The methods, targets and goals for the all-sky searches are described separately in the CBC and Burst sections of this White Paper.

ACTIVITY OBS-5.1-A-**INFRAOPS**: BBH SUBGROUP ADMINISTRATION

TASK OBS-5.1-A(i)-**INFRAOPS**: SUBGROUP LEADERSHIP

Administrative and managerial tasks associated with subgroup leadership. See also OBS-9.2-B.

OBS-5.2 Multimessenger search for gravitational waves and gamma-ray bursts

Gamma-ray bursts (GRBs) are extremely energetic bursts of gamma-rays from cosmological sources observed by orbiting satellite detectors at a rate of about one per day. Two phenomenologically recognized categories have traditionally been identified [330]: short-duration (< 2 s) GRBs with generally harder spectra, and long-duration (> 2 s) GRBs with generally softer spectra. Astrophysical evidence had led to the hypothesis that these categories herald the creation of a compact object [a black hole (BH) or a neutron star (NS)] by way of two distinct pathways, both of which involve the emission of transient gravitational waves. Very recent detections of kilonovae (for example, [331, 332]) associated with long-duration GRBs indicate that these categories may not be so well defined and that a sub-population of long-duration GRBs is likely associated with compact binary coalescences.

The NS-NS and NS-BH coalescences have been invoked as a short GRB progenitor candidates for decades [333, 334, 335, 336, 337]. The joint observation of GRB 170817A and GW170817 has confirmed that NS-NS coalescences are the progenitors of at least some short GRBs [66]. Any future coincident observations of GWs and short GRBs would also be a major scientific result, demanding a rapid publication. A possible association should be communicated with low latency to enable follow-up observations of the GRB of interest. Finally, the nature of the post-merger remnant (hypermassive/supramassive NS or BH) can be investigated via searches for post-merger GWs similar to those carried out for the case of GW170817/GRB 170817A [183].

Long GRBs gravitational collapse of massive stars. The wide range of observable properties they display has led to the speculation that there may be sub-classes involving different mechanisms, with astrophysical details far from being fully understood. Any significant GW detection would presumably contribute to our understanding of the underlying astrophysics. Some models predict GW emission associated with the accretion disk itself, or with a post-collapse proto-NS, which would give rise to long-duration ($\lesssim 1$ s) GW emission. The observation of X-ray "plateaus" following the GRB on timescales of tens of minutes to hours after the main burst has suggested that GRB central engines may live longer (~ 1000 s) than previously thought.

To search for gravitational waves associated with GRBs, we use triggered (using GRB time and sky position), coherent algorithms that target either NS-NS and NS-BH binary inspiral signals [338] in the case of short GRBs, or generic GW burst signals [339] for all GRBs. These searches are more sensitive than the corresponding all-sky searches and are run both online (<24 hour latency) and offline. We use an additional algorithm [340, 341] to search online (minutes latency) for coincidences between low-latency, all-sky GW triggers and GRBs. These methods were applied to the full sample of GRBs which occurred during O1 [342], O2 [343], and O3 [344, 345]; the offline, triggered searches were also used to process GRBs which occured during the first joint observation of the KAGRA detector with GEO 600 [346]. We continue to develop methods to utilize sub-threshold GW triggers, sub-threshold GRB triggers, or both. An offline search using sub-threshold all-sky CBC triggers to search for coincident GRBs with Fermi was established with the O1 publication [347].

An offline cross-correlation algorithm[348] targeting long-duration GWs from the remnants of exceptional short or long GRBs, potentially in association with EM plateaus, will be used for opportunistic searches.

ACTIVITY OBS-5.2-A-**INFRAOPS**: TRIGGERED O4 GRB SEARCH AND PUBLICATIONS - OFFLINE

The following tasks are necessary for implementing the standard offline, triggered GRB search and to report results. The main activities will be to prepare and run the O4 searches, with a plan to split the search into searches during the O4a and O4b portions of the run.

TASK OBS-5.2-A(i)-**INFRAOPS**: CATALOG THE GRBS

Collect and catalog the GRBs from Swift and Fermi from early O4 running to be used in the triggered searches. Determine if IPN will be used to provide triggers for O4 and, if so, set up procedures for collecting the IPN information.

TASK OBS-5.2-A(ii)-**INFRAOPS**: PREPARE THE SEARCH PIPELINES FOR O4A AND O4B

Prepare to run the Burst and CBC pipelines on the appropriate GRB triggers, as catalogued above.

TASK OBS-5.2-A(iii)-**INFRAOPS**: RUN THE O4 SEARCHES

Run the O4 offline searches.

TASK OBS-5.2-A(iv)-**INFRAOPS**: COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW

Report results and prepare publications for O4a and O4b. See also OBS-9.2-G.

TASK OBS-5.2-A(v)-**INFRAOPS**: EXCEPTIONAL EVENTS

Follow up any exceptional event candidates identified in O4 in the all-sky Burst or CBC searches, or resulting from the above triggered searches. Follow-up will include consideration of any opportunistic search for long duration GWs from GRB remnants. Make the case for or against a single-event publication.

ACTIVITY OBS-5.2-B-**INFRAOPS**: UNUSED

TASK OBS-5.2-B(i)-**INFRAOPS**: UNUSED

Unused

ACTIVITY OBS-5.2-C-**INFRAOPS**: ONLINE O4B GRB-TRIGGERED SEARCHES

TASK OBS-5.2-C(i)-**INFRAOPS**: PREPARE THE O4B ONLINE SEARCH PIPELINE

Prepare updated infrastructure and configurations required to run the CBC search algorithms in medium latency for O4b. The configurations for the pipeline and search will be adjusted to increase the sensitivity of the search, at the cost of increased computational complexity. The changes will need to be reviewed.

TASK OBS-5.2-C(ii)-**INFRAOPS**: CONDUCT THE MEDIUM LATENCY SEARCH FOR O4B

Maintain and operate the CBC search algorithms in medium latency for O4.

ACTIVITY OBS-5.2-D-**INFRAOPS**: GRB SUB-THRESHOLD SEARCHES - O4

Complete the programs described in the MOUs with the Fermi and Swift collaborations for exploiting potential associations of (sub-threshold) GW triggers with (sub-threshold) Fermi-GBM or Swift triggers. Begin and complete the planned program for O4.

TASK OBS-5.2-D(i)-**INFRAOPS**: TARGETED SEARCHES

Begin and complete the planned program for O4.

TASK OBS-5.2-D(ii)-**INFRAOPS**: UNTARGETED SEARCHES

Begin and complete the planned program for O4.

ACTIVITY OBS-5.2-E-**OTHER**: UNUSED

TASK OBS-5.2-E(i)-**OTHER**: UNUSED

ACTIVITY OBS-5.2-F-**INFRAOPS**: GRB PIPELINE DEVELOPMENT FOR O4

Some pipeline development activities are ongoing and are planned to be used for the offline analyses, particularly for O4b.

TASK OBS-5.2-F(i)-**INFRAOPS**: PIPELINE DEVELOPMENT FOR MODELLED AND UNMODELLED GW SEARCHES

Complete development and review of pipelines designed to followup triggers from astronomical community, including searches for CBC GW signals and unmodelled GW signals.

ACTIVITY OBS-5.2-G-**INFRAOPS**: ESTIMATING SENSITIVITY AND SIGNIFICANCES OF TARGETED GRB SEARCHES

TASK OBS-5.2-G(i)-**INFRAOPS**: TRIALS FACTOR TO FAR ESTIMATION

Assess the relative sensitivty of targeted searches conducted by the group to the all-sky searches in the event of significant triggers found in the searches. This includes accurately estimating the trials factor impact of searching for GWs associated with a population of transients. The statistical significance used by the current searches cannot be directly compared with all-sky searches, as those searches use false-alarm-rate estimates, and thus a method for assessing the estimated false-alarm-rate of the targeted searches needs to be created.

TASK OBS-5.2-G(ii)-**INFRAOPS**: DESIGN SEARCH PLANS FOR FUTURE SEARCHES BASED ON SENSITIVITY

Due to the potential impact of trials factors, planning must be undertaken to determine what number of events should be analyzed for each trigger population. Additionally, a statistically accurate decision needs to made for whether or not different populations may be studied with or without incurring the trials factor of other targeted searches for GW, e.g. when do FRB followup searches effectively impact GRB followup search sensitivity due to trials factors.

ACTIVITY OBS-5.2-H-**INFRAOPS**: UNUSED

TASK OBS-5.2-H(i)-**INFRAOPS**: UNUSED

Unused.

ACTIVITY OBS-5.2-I-**OTHER**: GW-GRB PIPELINE IMPROVEMENTS

Continue to improve the PYGRB and X pipelines for use beyond O4, especially to speed up execution times and to improve sensitivity by background reduction.

TASK OBS-5.2-I(i)-**OTHER**: GW-GRB PIPELINE IMPROVEMENTS

Improve the PYGRB and X pipelines.

ACTIVITY OBS-5.2-J-**OTHER**: MEDIUM LATENCY GRB PIPELINE

Continue development and updating of the infrastructure to run the GRB medium latency pipeline.

TASK OBS-5.2-J(i)-**OTHER**: MEDIUM LATENCY GRB PIPELINE

Develop and update the infrastructure of the GRB medium latency pipeline.

ACTIVITY OBS-5.2-K-**OTHER**: GRB LONG-DURATION SEARCH

For the cross-correlation search, test the feasibility of parameter estimation analyses aimed at ensuring understanding of any parameter correlations, and establishing appropriate probability coverage.

TASK OBS-5.2-K(i)-**OTHER**: GRB LONG-DURATION CROSS-CORRELATION SEARCH

Development work for GRB long-duration cross-correlation search

ACTIVITY OBS-5.2-L-**OTHER**: GRB SUB-THRESHOLD SEARCH IMPROVEMENTS

Continue development of methods to exploit sub-threshold GRBs (from Fermi, Swift) and/or sub-threshold GW triggers.

TASK OBS-5.2-L(i)-**OTHER**: GRB SUB-THRESHOLD SEARCHES

Development work for exploiting sub-threshold GRBs and/or GW triggers.

OBS-5.3 Multimessenger search for gravitational waves and fast radio bursts

Since the publication in summer 2013 of four Fast Radio Bursts (FRBs) identified in Parkes Telescope data [349] there has been considerable scientific interest in these millisecond-scale radio transients which, based on their observed dispersion measures, appear to mostly occur at cosmological distance scales. A multitude of FRBs have been published so far [350], including repeating sources [351], and an increasing number of radio telescopes are becoming involved in FRB identification, most notably the CHIME detector[352].

Since 2020, an MOU agreement between LIGO/Virgo and CHIME has been in place, which has allowed on order 10^2 FRB triggers within a plausible GW horizon distance to become available for the O3 and O4 runs. Results for the FRBs that occured in O3a are published [353], while the O3b analyses are currently (November 2023) ongoing.

Currently, while numerous papers have suggested plausible sources for these radio transients, their origin is unclear. Observations indicate two possible classes – repeaters and non-repeaters – and it may be that there are multiple progenitor types. Not all plausible mechanisms for emission of FRBs are likely to result in simultaneous gravitational wave emission at detectable frequencies. However, compact binary coalescences, neutron star asteroseismology, and cosmic string cusps are all proposed mechanisms for production of both gravitational waves and short duration radio transients in the frequency ranges of interest. See [354] and references therein for descriptions of the relevant models. Identification of a clear coincidence between an FRB and a transient gravitational wave, while challenging at current sensitivities, would be of tremendous scientific value in determining the nature of FRBs in addition to being a major achievement in the field of gravitational-wave astronomy.

Recently, there was potentially an important clue in the FRB story. In April 2020, galactic magnetar SGR 1935+2154 became very active in x-ray emission. And on April 28 an FRB was observed[355] from this source. The observed fluence provided an estimate for the intrinsic FRB energy which was 1 to 6 orders of magnitude less energetic than previously observed (cosmological) FRBs, but otherwise closely resembled previous FRBs. While this provides credence to the magnetar model of FRBs, it is still unclear how many FRB progenitor classes actually exist in nature.

Given the unknown nature of FRBs, it is appropriate to apply both CBC and Burst pipelines in triggered searches, essentially mirroring the externally triggered GRB searches, except for the choice of triggers and on-source windows. The development of future methods and pipelines that will benefit both of these search types is contained in the whitepaper section on GRB followup searches, OBS-5.2, and is not repeated here.

ACTIVITY OBS-5.3-A-**INFRAOPS**: O3B FRB ANALYSES AND PUBLICATIONS

TASK OBS-5.3-A(i)-**INFRAOPS**: COMPLETE THE O3B SEARCH AND PUBLICATION

Finalize the analysis of events that were determined to be repeating FRBs during the processing of the sample and any other events with updated information. Complete the corresponding O3b collaboration paper. See also OBS-9.2-G.

ACTIVITY OBS-5.3-B-**INFRAOPS**: PREPARE THE O4 FRB SEARCH, COMPLETE THE O4 FRB SEARCH AND PUBLICATION

Prepare for an O4 search. The methods are currently assumed to be very similar to those used in O3.

TASK OBS-5.3-B(i)-**INFRAOPS**: COLLECT THE FRB TRIGGERS

Arrange for the collection of FRB triggers. MOU agreements have been established with the CHIME collaboration. Make a selection on the triggers using available dispersion measure methods, if necessary, to select the triggers within the plausible O4 GW horizon.

TASK OBS-5.3-B(ii)-**INFRAOPS**: RECONFIGURE, TEST AND RUN THE SEARCH PIPELINES

Reconfigure (if necessary), test, and run the Burst and CBC pipelines over triggers from early O4 running. Determine if additional changes are needed and react to any new data quality issues.

TASK OBS-5.3-B(iii)-**INFRAOPS**: COLLECT, REPORT, PUBLISH RESULTS, AND REVIEW

Report results and prepare publications for O4.

TASK OBS-5.3-B(iv)-**INFRAOPS**: EXCEPTIONAL EVENTS

In the event of a GW-FRB detection or an astrophysically interesting upper limit, make the case for a single-event publication.

OBS-5.4 Multimessenger search for gravitational waves and high-energy neutrinos

Some dynamical processes with strong gravitational-wave emission, such as compact binary mergers or stellar core-collapse with rapidly rotating cores, can drive relativistic outflows that result in the emission of high-energy neutrinos [356, 357]. Detecting both messengers from a common source would provide the unique opportunity to develop and fine-tune our understanding of the connection between the central engine [358], its surroundings [359], and the nature of relativistic outflows [360, 361]. A joint search also increases the sensitivity compared to gravitational-wave-only or neutrino-only searches, and can be especially interesting for sources that are difficult to detect electromagnetically [362, 363, 364].

In previous runs, we worked closely with the IceCube and ANTARES collaborations to develop and perform sensitive multimessenger analyses to search for neutrinos associated with gravitational-wave candidates, and in particular with GW150914 [365], LVT151012 and GW151226 [366], and GW170817 [367]. No coincident neutrinos were found. The results were used to constrain the neutrino flux from these sources. Additionally, we have looked for coincidences of sub-threshold events in both the neutrino and GW detectors [368, 369], including the coincident subthreshold analysis for the O1 observing period [370]. The LLAMA search method uses temporal and spatial coincidence between the gravitational-wave and high-energy neutrino triggers to identify detection candidates. Additionally, it evaluates the significance of joint candidates by incorporating astrophysical priors through a Bayesian framework [371] while also including LIGO-Virgo as well as neutrino detector characteristics. The Bayesian framework is extendable to include additional messengers [372].

Gravitational-wave searches can also be triggered by high-energy neutrino events. In particular, using the time and space information from the high-energy neutrino event, we can run a targeted gravitational-wave search in the LIGO-Virgo-KAGRA data. These searches may benefit from sharing pipelines and methods with the searches for GW associated with gamma-ray bursts and fast radio bursts, and the development of future methods and pipelines that benefits all of these search types is contained in the whitepaper section on GRB followup searches, OBS-5.2, and is not repeated here.

ACTIVITY OBS-5.4-A-**INFRAOPS**: COMPLETE THE O3 GW-HEN SEARCH

TASK OBS-5.4-A(i)-**INFRAOPS**: PUBLISH RESULTS

Work toward publishing a collaboration paper reporting results of the O3 sub-threshold search. See also OBS-9.2-G.

ACTIVITY OBS-5.4-B-**INFRAOPS**: O4 LOW-LATENCY GW-HEN COINCIDENT SEARCH

Task OBS-5.4-B(i)-**InfraOps**: Online pipeline operation

Determine appropriate pipeline for online coincident search between GW and HEN triggers. Configure pipeline with appropriate time windows and false-alarm rates. Operate and maintain pipeline and configurations.

Task OBS-5.4-B(ii)-**InfraOps**: Report results

Report intermediate results in a timely manner as data becomes available during the observing run. Periodically report results to the Multimessenger Transient Searches subgroup, to the burst group, and to the CBC group.

Activity OBS-5.4-C-**InfraOps**: O4 offline GW-HEN coincident searches

Task OBS-5.4-C(i)-**InfraOps**: Run coincident searches on O4 data

Configure and run the coincident analyses on O4 data using data from IceCube and KM3Net and produce offline search results. Consider Burst and CBC triggers using LIGO and Virgo detectors. Consider the high-energy neutrino triggers provided by the IceCube and KM3NeT collaborations. Characterize the close-box results and eventually open the boxes. Estimate the significance of the most promising coincident triggers.

Task OBS-5.4-C(ii)-**InfraOps**: Report results

Report intermediate results in a timely manner as data becomes available during the observing run. Periodically report results to the Multimessenger Transient Searches subgroup, to the burst group, and to the CBC group.

Task OBS-5.4-C(iii)-**InfraOps**: Publish search results

Work toward publishing a collaboration paper reporting any signals found by the coincident search with the O4 data. See also OBS-9.2-G.

Task OBS-5.4-C(iv)-**InfraOps**: Exceptional events

In the event of a detection or an astrophysically interesting upper limit, make the case for a single-event publication. This would include an extended time window search for neutrinos in the direction of a confirmed electromagnetic counterpart.

Activity OBS-5.4-D-**Other**: GW-HEN pipeline improvements

Task OBS-5.4-D(i)-**Other**: Investigate pipeline improvements for joint searches

Continue to investigate improvements to pipelines to increase the sensitivity of the coincident search to joint events.

Activity OBS-5.4-E-**InfraOps**: Develop a HEN-targeted gravitational-wave search and conduct a targeted HEN-triggered search for O4

Task OBS-5.4-E(i)-**InfraOps**: Use high-energy neutrino events to trigger a gravitational-wave search

Develop methods and analysis tools to perform a targeted gravitational-wave search or searches triggered by high-energy neutrino events. In particular, the time and sky location of the high-energy neutrino event can be used to improve the sensitivity of the gravitational-wave search.

TASK OBS-5.4-E(ii)-**INFRAOPS**: RUN THE TARGETED SEARCH ON O4 DATA

Configure and run the targeted analyses on O4 data and produce offline search results. Consider the high-energy neutrino triggers provided by the IceCube and KM3NeT collaborations. Characterize the close-box results and eventually open the boxes. Estimate the significance of the most promising coincident triggers.

TASK OBS-5.4-E(iii)-**INFRAOPS**: REPORT RESULTS

Report intermediate results in a timely manner as data becomes available during the observing run. Periodically report results to the Multimessenger Transient Searches subgroup, to the burst group, and to the CBC group.

TASK OBS-5.4-E(iv)-**INFRAOPS**: PUBLISH SEARCH RESULTS

Work toward publishing a collaboration paper reporting any signals found by the targeted search with the O4 data. See also OBS-9.2-G.

ACTIVITY OBS-5.4-F-**OTHER**: PREPARE FOR THE POSSIBILITY OF A TRIPLE-MESSENGER GW-EM-HEN SEARCH

TASK OBS-5.4-F(i)-**OTHER**: PREPARE FOR A TRIPLE MESSENGER EVENT

Improve the coincident pipelines to include the statistical treatment of multimessenger events with three (gravitational-wave, neutrino, and electromagnetic) messengers.

OBS-6 Burst+Stochastic Joint Activity Plans

OBS-6.1 Search for gravitational waves from cosmic strings

Start date: 2025-01-01
Estimated due date: 2025-12-31

Cosmic strings [52] are one-dimensional topological defects, formed after a spontaneous symmetry phase transition characterized by a vacuum manifold with non-contractible loops [373]. These objects are expected to be generically formed in the context of Grand Unified Theories [374]. Their obervational consequences offer a tool to probe particle physics beyond the Standard Model at energies far above the ones reached at accelerators. More recently it was realized that strings can also be produced within the framework of string-theory-inspired cosmological models and grow to cosmic scales [375, 376, 377, 378]. Cosmic strings produced in string-theory-motivated models (dubbed "cosmic superstrings") have received much attention since they could provide observational signatures of string theory [379, 380].

A promising way of detecting the presence of cosmic strings and superstrings is the gravitational-wave emission from loops [381, 382] and long strings [383]. When two string segments meet, they may exchange partners. When a string intercommutes with itself, a closed loop breaks off. The loop oscillates, radiates gravitationally, and eventually decays. Special points on the cosmic string loop play an important role: cusps and kinks. Cusps are points along the string with large Lorentz boosts. They are transient and produce a beam along a single direction. Kinks are loop discontinuities that form every time intercommuting occurs. They propagate around the string, beaming over a fanlike range of directions. Since long (super-horizon) strings are not straight due to the existence of kinks, they also emit gravitational radiation [383]. Both cusps and kinks produce powerful bursts of gravitational waves [384]. In addition, left- and right-moving colliding kinks will produce a gravitational-wave spectrum emitted in all directions, this is the dominant mechanism for fairly wiggly strings [385].

Cosmic string gravitational-wave events are searched individually using matched-filtering techniques or as a stochastic background of all signals in the Universe [386, 282]. The two searches are conducted over LIGO-Virgo data and provide complementary results. In particular, observational constraints on cosmic string models are given as bounds on the string tension $G\mu(c = 1)$, where G is Newton's constant and μ the mass per unit length. These bounds are then used to drive further theoretical developments and constrain particle physics beyond the Standard Model as well as early Universe cosmological models.

Activity OBS-6.1-A-**InfraOps**: O4 search for gravitational-wave bursts from cosmic strings

Task OBS-6.1-A(i)-**InfraOps**: Run the search and review results

Run the templated search for gravitational-wave bursts from cosmic strings over O4 data. Test all gravitational-wave production mechanisms: cusp alone, kink alone, or kink-kink collision.

Task OBS-6.1-A(ii)-**InfraOps**: Follow up gravitational-wave candiates

If a gravitational-wave Burst event is significant, estimate the cosmic string parameters considering up-to-date loop distribution models. Interpret cosmologically the results.

Task OBS-6.1-A(iii)-**InfraOps**: Set upper limits on cosmic string models

Constrain cosmic string parameters for specific models/simulations predicting the loop distribution. Derive the expected rate of gravitational-wave events from cosmic strings and compare it with the rate measured with signal injections. If no clear gravitational-wave event is detected, set upper limits on cosmic string parameters.

Task OBS-6.1-A(iv)-**InfraOps**: Develop a strategy to follow-up unmodelled burst candidates

If a short-duration unmodeled burst candidate is detected by the all-sky searches (see Sec OBS-1.1), a procedure shall be in place to assess the astrophysical nature of the event. A cosmic string scenario must be examined and the possibility of this scenario must be quantified.

Activity OBS-6.1-B-**Other**: Develop a new framework to derive cosmic string upper limits from the Burst search results

Task OBS-6.1-B(i)-**Other**: New upper limits from Burst results

The burst search is sensitive to rare bursts from loops that are relatively nearby compared to those probed with the stochastic background. Develop an analysis framework to constrain the number density of such loops given the Burst search results.

Activity OBS-6.1-C-**InfraOps**: O4 Stochastic background search for cosmic strings

Task OBS-6.1-C(i)-**InfraOps**: Determine model paramaters

Consider up-to-date cosmic string loop distribution models supported by numerical simulations for Goto-Nambu strings. Follow also an agnostic approach, interpolating between theoretical models, for example based on [387].

TASK OBS-6.1-C(ii)-**INFRAOPS**: PARAMETER ESTIMATION

For the chosen cosmic string models, perform the parameter estimation using the latest (O4) results of the stochastic searches to compute excluded or preferred regions of the parameter space (string tension and number of kinks).

ACTIVITY OBS-6.1-D-**OTHER**: IMPROVE COSMIC STRING MODELS

TASK OBS-6.1-D(i)-**OTHER**: IMPROVED MODELS FOR COSMIC STRING SEARCHES

It is expected that theoretical developments will continue to provide the impetus towards new types of cosmic string related phenomena and/or to improve cosmic string templates for gravitational-wave burst searches. It is expected that soon we will be able to improve considerably the cosmic string models we are using and include further effects.

OBS-7 Stochastic+CBC Joint Activity Plans

OBS-7.1 Search for the stochastic background from unresolvable binary black hole mergers

Start date: 2025-01-01
Estimated due date: 2025-12-31

OBS-7.1.1 Scientific Case

The recent detections of binary black-hole (BBH) mergers by aLIGO and aVirgo suggest the near-term possibility of detecting the stochastic background of weaker, unresolvable BBH signals out to large redshift. Rate estimates predict one such event every $\sim$2 minutes on average, with each merger lasting $\mathcal{O}(1\text{ second})$. Thus, the duty cycle is $\lesssim 10^{-2}$, implying a “popcorn-like" *highly non-stationary* stochastic signal. Although the standard cross-correlation search can be used to search for such a background, the low duty cycle of the expected signal renders the standard (Gaussian-stationary) search *sub-optimal*, since most of the segments analyzed will consist of only detector noise. Here we propose a joint activity between the stochastic and compact binary coalescence (CBC) groups to develop and implement a Bayesian search strategy (originally proposed by Smith and Thrane [388]), which is optimally-suited to handle the non-stationarity of the expected background from BBH mergers.

OBS-7.1.2 Methodology

The search methodology is based on Smith et al. [388] which applies Bayesian parameter estimation to all available data. The search uses the output of parameter estimation code (e.g., Bilby [389]) to construct a probability density on the *astrophysical duty cycle* which we take to be the fraction of analyzed data segments which contain a CBC signal

$$p(\xi|d) = \prod_{i=1}^{N} \left[\xi \mathcal{Z}_s^i + (1-\xi)\mathcal{Z}_n^i + \text{glitch terms}\right] . \tag{7}$$

The data d are broken up into N segments d_i, each of duration T; ξ denotes the probability that a particular segment contains a signal, which is related to the rate R via $R = \xi/T$; $\mathcal{Z}_s^i$ and $\mathcal{Z}_n^i$ are respectively the signal and noise evidences of the i^{th} data segment and are the outputs of Bilby. For readability, the glitch-model terms have been omitted. The search treats non-Gaussian glitches in the data as uncorrelated CBC-like signals in two or more detectors. These glitch terms are also outputs of Bilby and this particular glitch model was shown in [388] to yield unbiased estimates of the astrophysical duty cycle in O1 background data. Using Bayesian inference, one can then calculate the Bayes factor for the signal+noise to noise-only models, which can be used as a detection statistic, e.g.,

$$B = p(\xi > 0|d)/p(\xi = 0|d) \tag{8}$$

to estimate the rate of BBH events. It is the *mixture* form of the likelihood that allows one to handle the non-stationarity.

Because the search applies Bayesian parameter estimation to compute the signal and noise evidences of the data, we also obtain posterior PDFs of the CBC parameters (such as masses and spins) irrespective of whether the data contains a signal or not. The PDFs from each data segment can, in principle, be combined in a Bayesian way to infer the properties of the whole population of CBC signals.

The proposed search in O4 will focus on searching for "high-mass" BBH systems, which we take to be BBH systems with chirp masses in the range $12M_{\odot} \leq M_c \leq 60M_{\odot}$. This enables us to keep computational costs manageable as it only requires analyzing data segments that are up to 4s in duration.

It was estimated in [388] that the BBH background can be detected using around one day of design sensitivity data. Subsequent work has investigated how the signal from unresolved binaries is distributed in redshift [390]. The same study develops tools to extract the population parameters of unresolved binaries; see also [391]. Meanwhile, in [392] it was shown that it will be necessary to marginalize over uncertainty in the noise power spectral density to avoid bias in the estimate of duty cycle. Further, bias in the duty cycle can be induced by windowing functions applied to time domain data, which cause correlations between frequency bins in the frequency domain. We expect that using O4 data we can make a confident detection using around one week of data. While the computational cost of the search is high (due to the application of Bayesian parameter estimation), we expect to be able to analyze data in real time using a modest fraction of the LIGO Data Grid computing resources.

ACTIVITY OBS-7.1-A-**OTHER**: IMPLEMENTATION AND MOCK DATA CHALLENGE VALIDATION (SEARCH FOR UNRESOLVED BBH)

1. Develop a set of data analysis routines to implement the above search such that it is both computationally feasible and robust against non-Gaussian features in the detector noise.
2. Perform a large-scale mock data challenge (MDC) of the proposed search method on synthetic data and O4 background data, including tests of its efficacy relative to the standard Gaussian-stationary search.
3. Develop the necessary computational tools to be able to search for weak BBH signals at cosmological distances (luminosity distances greater than ~ 15 Gpc).
4. Publish the results of the MDC.

TASK OBS-7.1-A(i)-**OTHER**: THE BAYESIAN SEARCH IMPLEMENTATION AND MDC VALIDATION

Assuming that the above activities are performed successfully, we can then move to applying this search to O4 data.

ACTIVITY OBS-7.1-B-**OTHER**: O4 ANALYSIS (SEARCH FOR UNRESOLVED BBH)

1. Run the search on O4 data. Detect the background of BBH mergers and measure the astrophysical duty cycle.
2. Perform inference on the population properties of the BBH background, such as the mass spectrum, spin and redshift distributions, and distribution across the sky.
3. Prepare full collaboration paper on search results.

   TASK OBS-7.1-B(i)-**OTHER**: THE BAYESIAN SEARCH O4 ANALYSIS

OBS-8 Stochastic+CW Joint Activity Plans

OBS-8.1 Identification and follow-up of outliers in stochastic directional analysis skymaps

Start date: 2024-01-01
Estimated due date: 2026-12-16

Motivation

Performing all-sky searches for continuous gravitational wave sources is an important goal of gravitational wave astronomy. Significant trade-offs between sensitivity against computational costs must be considered. Continuous wave analyses carry out optimal targeted searches for known sources or use a variety of different hierarchical search strategies, depending on the amount of information known for a putative source. Unmodeled, radiometer-style searches reaching maturity in stochastic gravitational wave searches are comparatively computationally inexpensive. A novel technique to aid rapid analysis of detector data is to combine CW and stochastic searches in a hierarchical search. This can be achieved by utilising the sky-maps produced by the stochastic directional analysis [308] on folded data [309].

Methodology

The goal is to perform fast ("quick-look") all-sky analysis for continuous wave signals, even though the expected sensitivity will be less than other, dedicated searches. The directional analysis carried out using `PyStoch` [131] produces a full GW sky- map at every frequency bin. Those regions of parameter space (sky locations and frequencies) that produce interesting outliers could be passed to continuous wave searches for follow up under the assumption that the outlier may be due to a rapidly rotating neutron star or possibly a boson cloud surrounding a black hole.

Recently developed model-agnostic continuous wave searches based on F-statistic and Viterbi/Hidden Markov Model have shown great promise to follow-up the `PyStoch` outliers. This method can be employed to confirm or reject outliers, enabling subsequent, more computationally costly but more sensitve, analyses to further follow up remaining candidates.

ACTIVITY OBS-8.1-A-**INFRAOPS**: IMPLEMENTATION AND MOCK DATA CHALLENGE VALIDATION (STOCHASTIC DIRECTIONAL ANALYSIS FOR CW SOURCES)

TASK OBS-8.1-A(i)-**INFRAOPS**: DETERMINE SCOPE OF MOCK DATA CHALLENGE

In order to assess all aspects of the hierarchical `PyStoch` and follow- up search, a set of simulated waveforms need to be selected and added to data (either simulated Gaussian noise, or real detector data), prior to processing data through the pipeline.

TASK OBS-8.1-A(ii)-**INFRAOPS**: IDENTIFICATION OF OUTLIERS IN STOCHASTIC DIRECTIONAL ANALYSIS

Development of a reliable statistic to identify patches on the sky for follow up and share the coordinates of the patches in a readily usable format. This may depend on the parameters used for the searches. It may be possible make the information more robust by combining results of activities with similar goals.

TASK OBS-8.1-A(iii)-**INFRAOPS**: FOLLOW-UP OF OUTLIERS AND SET UPPER LIMITS

Employ the F-statistic/Viterbi follow up to assess sensitivity of the pipeline, and understand how much parameter space should be explored around each outlier. Explore methods to put more stringent upper limits on physical parameters. Understand the upper limit procedure.

ACTIVITY OBS-8.1-B-**INFRAOPS**: O4 ANALYSIS (STOCHASTIC DIRECTIONAL ANALYSIS FOR CW SOURCES)

TASK OBS-8.1-B(i)-**INFRAOPS**: ANALYZE STOCHASTIC DIRECTIONAL SEARCH FOR OUTLIERS

Using the ranking statistic developed using mock data validation, identify outliers and parameter space to be passed to the CW stage for follow up

TASK OBS-8.1-B(ii)-**INFRAOPS**: FOLLOW UP OUTLIERS USING CW ANALYSES

Process the outliers using the follow up procedures developed using the mock data validation.

TASK OBS-8.1-B(iii)-**INFRAOPS**: DERIVE SENSITIVITY ESTIMATES

Aside from the upper limits set by the stocastic directional search, derive sensitivity estimates for the follow-up, under the assumption that the outliers could be continuous gravitational wave signals. Explore possibility to set upper limits from the combined analysis.

TASK OBS-8.1-B(iv)-**INFRAOPS**: REVIEW

Review search set up, code, scripts, and results.

TASK OBS-8.1-B(v)-**INFRAOPS**: PUBLICATION

Prepare the results for the inclusion into O4 directional paper or other relevant publication.

OBS-8.2 Dark matter direct interaction searches

Start date: 2023-05-24
Estimated due date: 2026-12-16

Motivation

Gravitational wave interferometers can also be used to search for the existence of dark matter that could couple directly to the detector.

Scalar, dilaton DM would cause time-dependent oscillations of the values of fundamental constants, such as the electron mass and fine structure constant[53, 393, 54]. Physically, the Bohr radius would change, causing time-varying changes in the size and index of refraction of the beam splitter [55]. Since the light from each cavity would traverse a slightly different path on the surface of the beam splitter, a differential phase would result whose magnitude is independent of the length of the arms. The phase sensitivity depends on the amount of quantum noise at high frequencies and depends on many other factors overall, including cavity finesse etc. As shown in Ref. [394], the most sensitive detector at high frequencies currently is actually GEO600, since it employs squeezed vacuum light that greatly reduces quantum noise compared to LIGO/Virgo/KAGRA. LIGO/Virgo/KAGRA can provide additional independent constraints above 100 Hz, and competitive constraints below 100 Hz [394]. This same scalar DM will also cause a change in length of the reference cavity which is used for pre-stabilizing the laser in LIGO, in turn resulting in a relative frequency shift between the reference cavity and the IMC-CARM system [394]. This frequency shift can be read out in the auxilliary channel and can provide most competitive limits below 100 Hz [394]. Additionally, axions could couple to the laser light and alter the phase velocities of left- and right-hand circularly polarized light [395]. In this case, the birefringence in the interferometer, i.e. optical path difference between p- and s-polarized lights, has to be measured using some additional optics that would need to be added to the interferometers that do not affect the sensitivity to gravitational waves [395, 396].

Vector dark matter, such as dark photons arising from e.g. the misalignment mechanism [397] or cosmic string network decays [398], would interact with baryons in the input and end mirrors, causing oscillatory forces on them that can be formulated as arising from a "dark electric field", analogously to the ordinary photon [399]. Since the dark matter field sees each of the mirrors in a different location with respect to its propagation direction, each one experiences a slightly different force, leading to different travel times for light down each arm and hence a differential strain [399]. Furthermore, an additional contribution to the differential strain arises due to the finite amount of time light takes to traverse each arm, a "common-mode motion" effect [400]. Tensor dark matter [401], arising as a modification to gravity that could also play the role of DM [402], could also cause a differential strain analogously to GWs by stretching and squeezing the spacetime around the mirrors [403].

All of these types of dark matter would mimic a GW signal in a very narrow frequency band. Because the distance between detectors is much smaller than the coherence length of the dark-matter signal, the LIGO/Virgo/KAGRA detectors experience nearly the same dark matter background; thus their observable signals are highly correlated.

Methodology

A straightforward analysis pipeline was developed and results have been obtained from LIGO O1 data [404]. A semi-coherent method was recently developed within the Band-Sampled Data (BSD) framework [405] that carefully varies the fast Fourier Transform length to account for the expected frequency spread of the signal. This method was applied to the O3 data resulting in stringent upper limits on the dark photon signal, as summarized in [406]. These limits improve upon existing ones from O1 because they account for the contribution to the strain due to the finite light travel time [400]. Furthermore, a search of GEO600 was performed for scalar, dilaton dark matter using the LPSD method that varies, bin by bin, the fast Fourier Transform length, resulting in extremely stringent constraints on the coupling of dilatons to photons and electons [407]. A method to follow-up potential dark matter candidates using the Wiener filter has also been developed, and would allow not just to rule out candidates resulting from spurious detector artifacts, but actually confirm the existence of a dark matter particle and distinguish amongst models for these particles [408].

Two new methods to search for dark matter interacting with other parts of the interferometers have been proposed: one looks for a dilaton signal in the reference cavity and LIGO beam splitters [394], another looks for correlations in multiple non-strain channels in the GW detectors caused by vector bosons [409, 410, 411]. Finally, axions could be searched for jointly with KAGRA and LIGO for "unwanted" polarizations in the interferometers [395], though methods to better estimate calibration errors in the polarization rotation angle are needed. The LPSD pipeline will be run on low-frequency LIGO/Virgo data because it is expected that LIGO/Virgo are more sensitive to dilatons coupling to standard-model particles in the beam splitter than GEO600.

Activities for O4

ACTIVITY OBS-8.2-A-**INFRAOPS**: O4 DARK MATTER DIRECT INTERACTION SEARCH

This activity covers the full-O4 analysis, with a separate O4a only activity listed below for historical reasons (to preserve section numbering).

TASK OBS-8.2-A(i)-**INFRAOPS**: DEVELOP REFCAV PIPELINE

These pipelines will be applied to carry out an analysis of O4 data. The refcav/dilaton pipeline needs significant development - lowering noise in IMC-F, detchar, calibration, and then search.

TASK OBS-8.2-A(ii)-**INFRAOPS**: DEVELOP CALIBRATION METHOD SEARCH

This method to search KAGRA and LIGO data for unwanted polarizations induced by axions needs significant development. Estimation of polarization rotation angle is needed.

TASK OBS-8.2-A(iii)-**INFRAOPS**: DEVELOP EXTENDED CROSS-CORRELATION METHOD

This method refines the previously developed cross-correlation method, such as developing a template based search for the signal, and possibly including other improvements. These may or may not be used in the full O4 paper, depending on the development and review status.

TASK OBS-8.2-A(iv)-**INFRAOPS**: DATA PREPARATION

SFDBs and BSDs will need to be produced up to 2048 Hz, and, if person power is available, up to 4096 Hz. and LIGO SFTs will be employed as well for most methods.

TASK OBS-8.2-A(v)-**INFRAOPS**: RUN SEARCH

Run the various pipelines on the prepared detector data.

TASK OBS-8.2-A(vi)-INFRAOPS: OUTLIER FOLLOWUP AND DATA QUALITY STUDIES

Follow-ups of potentially interesting signals will be performed by varying the FFT length, looking for coincidences in various detectors, and applying the Wiener filter method.

TASK OBS-8.2-A(vii)-INFRAOPS: SET UPPER LIMITS

Realistically, the output of this search will be upper limits on the strength to which dark matter couples to standard model particles – baryons, baryon-lepton, electrons or photons.

TASK OBS-8.2-A(viii)-INFRAOPS: REVIEW SEARCH METHODS AND RESULTS

The BSD excess power pipeline is fully developed and reviewed. The cross correlation method was also previously reviewed. Possible improvements to the cross correlation method need additional review. The follow-up method using the Wiener filter to confirm or deny the presence of dark matter signals, and distinguish between different models, needs review.

The multi-channel method, refcav method, beam splitter search method, and the calibration methods all need review.

TASK OBS-8.2-A(ix)-INFRAOPS: PUBLICATION

Produce a publication with the results of each pipeline.

ACTIVITY OBS-8.2-B-INFRAOPS: O4A DARK MATTER DIRECT INTERACTION SEARCH

A separate analysis and publication on the first part, O4a, of the run will be implemented first.

TASK OBS-8.2-B(i)-INFRAOPS: DATA PREPARATION

SFDBs and BSDs will need to be produced up to 2048 Hz, and, if person power is available, up to 4096 Hz. and LIGO SFTs will be employed as well for most methods.

TASK OBS-8.2-B(ii)-INFRAOPS: RUN SEARCH

Run the various pipelines, except the multi-channel one, on the prepared detector data. Potentially the refcav search could be run in O4a.

TASK OBS-8.2-B(iii)-INFRAOPS: OUTLIER FOLLOWUP AND DATA QUALITY STUDIES

Follow-ups of potentially interesting signals will be performed by varying the FFT length, looking for coincidences in various detectors, and applying the Wiener filter method.

TASK OBS-8.2-B(iv)-INFRAOPS: SET UPPER LIMITS

Realistically, the output of this search will be upper limits on the strength to which dark matter couples to standard model particles – baryons, baryon-lepton, electrons or photons.

TASK OBS-8.2-B(v)-**INFRAOPS**: REVIEW SEARCH METHODS AND RESULTS

The cross correlation and BSD excess power pipelines are fully developed and reviewed. The follow-up method using the Wiener filter to confirm or deny the presence of dark matter signals, and distinguish between different models, needs review. The refcav method will need review.

TASK OBS-8.2-B(vi)-**INFRAOPS**: PUBLICATION

Produce a publication with the results of each pipeline.

OBS-9 Leadership and Service Roles

OBS-9.1 Observational Science Division Leadership

Start date: ongoing
Estimated due date: ongoing

The Observational Science Division is responsible for coordinating, overseeing, and reviewing observational science work.

ACTIVITY OBS-9.1-A-**INFRAOPS**: OBSERVATIONAL SCIENCE DIVISION CHAIR

The Observational Science Division Chair coordinates the activities of the Division.

OBS-9.2 Burst Working Group Leadership and Service Roles

Start date: 2024-01-01
Estimated due date: 2024-12-31

ACTIVITY OBS-9.2-A-**INFRAOPS**: SERVING AS BURST CO-CHAIR

Burst co-chairs are elected by the working group in the LSC and appointed in Virgo and KAGRA. These people are responsible for management of the working group.

ACTIVITY OBS-9.2-B-**INFRAOPS**: SERVING AS BURST SUBGROUP LEAD

The Burst group is sub-divided into search groups: “All-sky short-duration searches”, “All-sky long-duration searches”, “Supernova”, “Multimessenger transient searches”, “Burst BBH”, and “CBC all-sky” (joint with CBC). The subgroup leads shall coordinate the subgroup activities, organize the work to deliver analysis results in a timely manner, and organize regular meetings to discuss progress.

ACTIVITY OBS-9.2-C-**INFRAOPS**: SERVING AS BURST LIAISON

Liaison persons are appointed by the Burst co-chairs to provide a communication channel with Operation groups: Detector Characterization, Calibration, Computing, and Low-Latency Alerts.

ACTIVITY OBS-9.2-D-**INFRAOPS**: SERVING AS BURST REVIEW CO-CHAIR

Burst review co-chairs are in charge of appointing teams to review Burst analyses and results in LVK scientific papers. They shall also maintain a framework to track the progress of on-going reviews (wiki, gitlab, spreadsheets, etc.).

ACTIVITY OBS-9.2-E-**INFRAOPS**: SERVING AS BURST TECHNICAL REVIEWER

Technical reviewers agree to review code or techniques for scientific soundness. They are appointed by the Burst review co-chairs.

ACTIVITY OBS-9.2-F-**INFRAOPS**: SERVING AS BURST PAPER REVIEWER

Paper reviewers agree to review papers for correctness, e.g., checking numbers and the validity of basic statements which interpret the results of the technical analysis. They are appointed by the Burst review co-chairs.

ACTIVITY OBS-9.2-G-**INFRAOPS**: SERVING ON A BURST LVK PAPER

Burst paper team members write or manage Burst papers. They are appointed by the Burst co-chairs.

OBS-9.3 Compact Binary Working Group Leadership

Start date: ongoing
Estimated due date: ongoing

ACTIVITY OBS-9.3-A-**INFRAOPS**: SERVING AS CBC CO-CHAIR

Future co-chairs are elected by the working group in the LSC and appointed in Virgo and KAGRA. These people are responsible for management of the CBC working group.

ACTIVITY OBS-9.3-B-**INFRAOPS**: SERVING AS CBC SUBGROUP LEAD

Subgroup leads are appointed by CBC co-chairs to lead R&D groups.

ACTIVITY OBS-9.3-C-**INFRAOPS**: SERVING AS CBC REVIEW CHAIR

Serving as a CBC Review Chair. CBC Review Chairs are appointed by the DAC.

ACTIVITY OBS-9.3-D-**INFRAOPS**: SERVING AS CBC TECHNICAL REVIEWER

Technical reviewers agree to review code or techniques for scientific soundness.

ACTIVITY OBS-9.3-E-**INFRAOPS**: SERVING AS CBC PAPER REVIEWER

Paper reviewers agree to review papers for correctness, e.g., checking numbers and the validity of basic statements which interpret the results of the technical analysis.

ACTIVITY OBS-9.3-F-**INFRAOPS**: SERVING ON A CBC “KEY PAPER” TEAM

CBC paper team members write or manage CBC papers.

ACTIVITY OBS-9.3-G-**OTHER**: SERVING ON A CBC “OTHER PAPER” TEAM

CBC paper team members write or manage CBC papers.

OBS-9.4 Continuous Waves Working Group Leadership

Start date: ongoing
Estimated due date: ongoing

Activity OBS-9.4-A-InfraOps: Serving as Continuous Waves Co-chair

Future co-chairs are elected by the working group in the LSC and appointed in Virgo and KAGRA. These people are responsible for management of the working group.

Activity OBS-9.4-B-InfraOps: Serving as Continuous Waves Review chair

Reviews of codes, results and papers across the CW group are coordinated by a team of designated review chairs.

Activity OBS-9.4-C-InfraOps: Serving as CW – Calibration liaison

Facilitate discussions between the Continuous Waves Working Group of the OBS division and the Calibration Working Group of the OPS division. Report on relevant calibration issues and news to the CW chairs and at the weekly CW telecons. Report CW requirements and concerns to the computing group. Currently, one liaison is named across the LVK.

Activity OBS-9.4-D-InfraOps: Serving as CW – Computing liaison

Facilitate discussions between the Continuous Waves Working Group of the OBS division and the Computing and Software Working Group of the OPS division. Report on relevant computing issues and news to the CW chairs and at the weekly CW telecons. Report CW requirements and concerns to the calibration group. Currently, one liaison is named across the LVK.

Activity OBS-9.4-E-InfraOps: Serving as CW – Detector Characterization liaison

Facilitate discussions between the Continuous Waves Working Group of the OBS division and the Detector Characterization Working Group of the OPS division. Report on relevant data quality issues and news to the CW chairs and at the weekly CW telecons. Report CW requirements and concerns to the DetChar group. Currently, one liaison is named for LIGO and Virgo respectively, with a KAGRA liaison to be nominated in the future if required.

OBS-9.5 Stochastic Working Group Leadership

Start date: ongoing
Estimated due date: ongoing

Activity OBS-9.5-A-InfraOps: Serving as Stochastic Co-chair

Future co-chairs are elected by the working group in the LSC and appointed in Virgo and KAGRA. These people are responsible for management of the working group.

Activity OBS-9.5-B-InfraOps: Serving as Stochastic Review chair

Reviews of codes, results and papers across the Stochastic group are coordinated by a team of designated review chairs.

ACTIVITY OBS-9.5-C-**INFRAOPS**: SERVING AS A STOCHASTIC SUBGROUP CO-LEAD

Stochastic Working Group currently includes seven subgroups focusing on different aspects of the stochastic background searches: Isotropic Search Subgroup; Anisotropic Search Subgroup;Intermittent Duration Background Subgroup; Mock-Data Challenges Subgroup; Stochastic Detchar Subgroup; Modeling, Implications, and Parameter Estimation Subgroup; and Astrophysical SGWB Modelling and Parameter Estimation Subgroup. Each Subgroup has two co-leads, assigned by the Stochastic Working Group co-chairs. These co-leads are responsible for management and coordination of the work in their respective subgroups.

ACTIVITY OBS-9.5-D-**INFRAOPS**: SERVING AS STOCHASTIC – CALIBRATION LIAISON

Facilitate discussions between the Stochastic Working Group of the OBS division and the Calibration Working Group of the OPS division. Report on relevant calibration issues and news at the Stochastic Group weekly telecons. Report Stochastic Group's requirements and concerns to the calibration group.

ACTIVITY OBS-9.5-E-**INFRAOPS**: SERVING AS STOCHASTIC – COMPUTING LIAISON

Facilitate discussions between the Stochastic Working Group of the OBS division and the Computing and Software Working Group of the OPS division. Report on relevant computing issues and news at the Stochastic Group weekly telecons. Report Stochastic Group's requirements and concerns to the Computing group.

ACTIVITY OBS-9.5-F-**INFRAOPS**: SERVING AS STOCHASTIC – DETECTOR CHARACTERIZATION LIAISON

Facilitate discussions between the Stochastic Working Group of the OBS division and the Detector Characterization Working Group of the OPS division. Report on relevant data quality issues and news at the Stochastic Group weekly telecons. Report Stochastic Group's requirements and concerns to the DetChar group.

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