GR24 & Amaldi16 @ Glasgow

July 14, 2025

A new chapter of gravitational wave observations with ground-based laser interferometers

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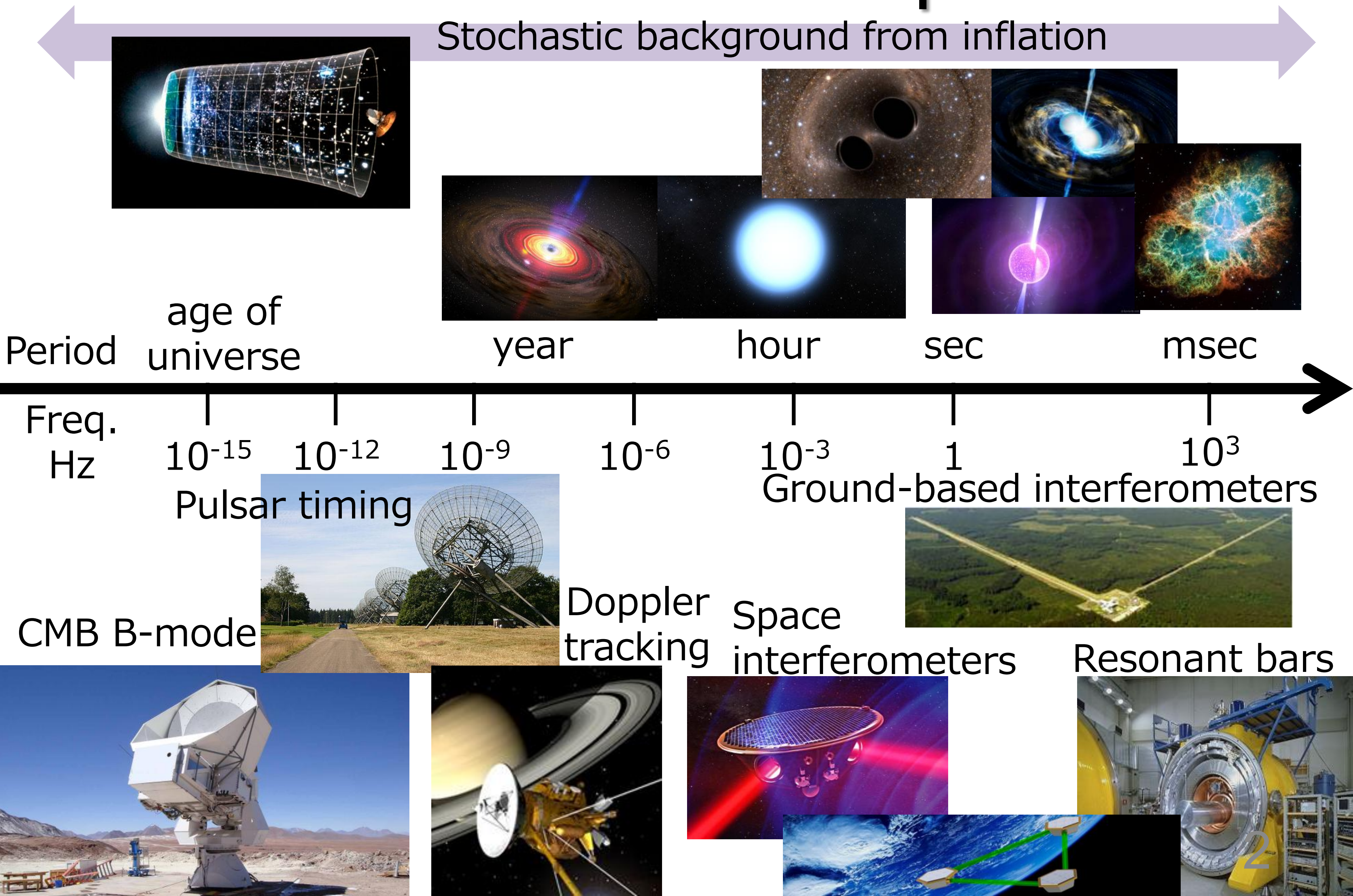
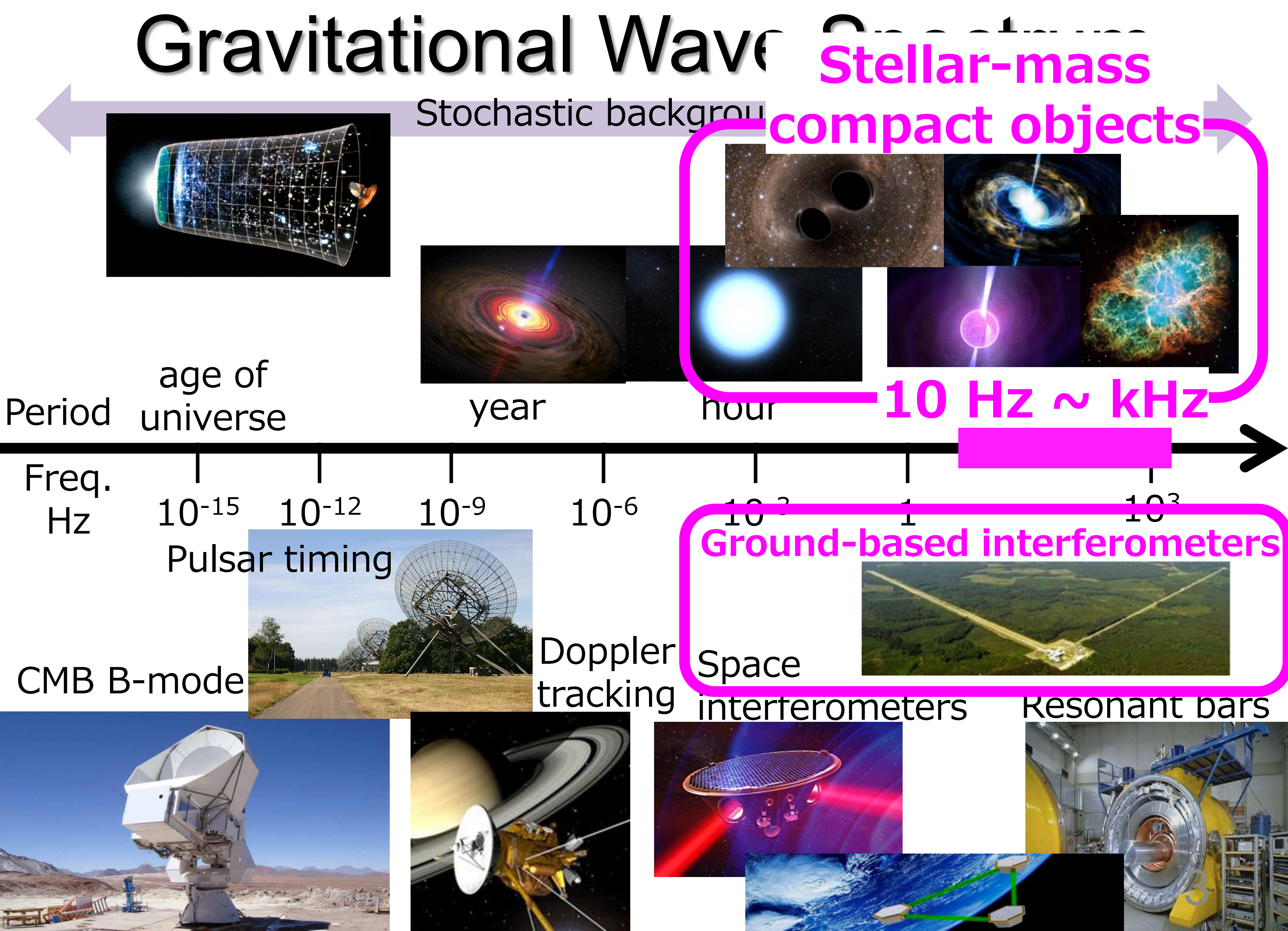
Gravitational Wave Spectrum

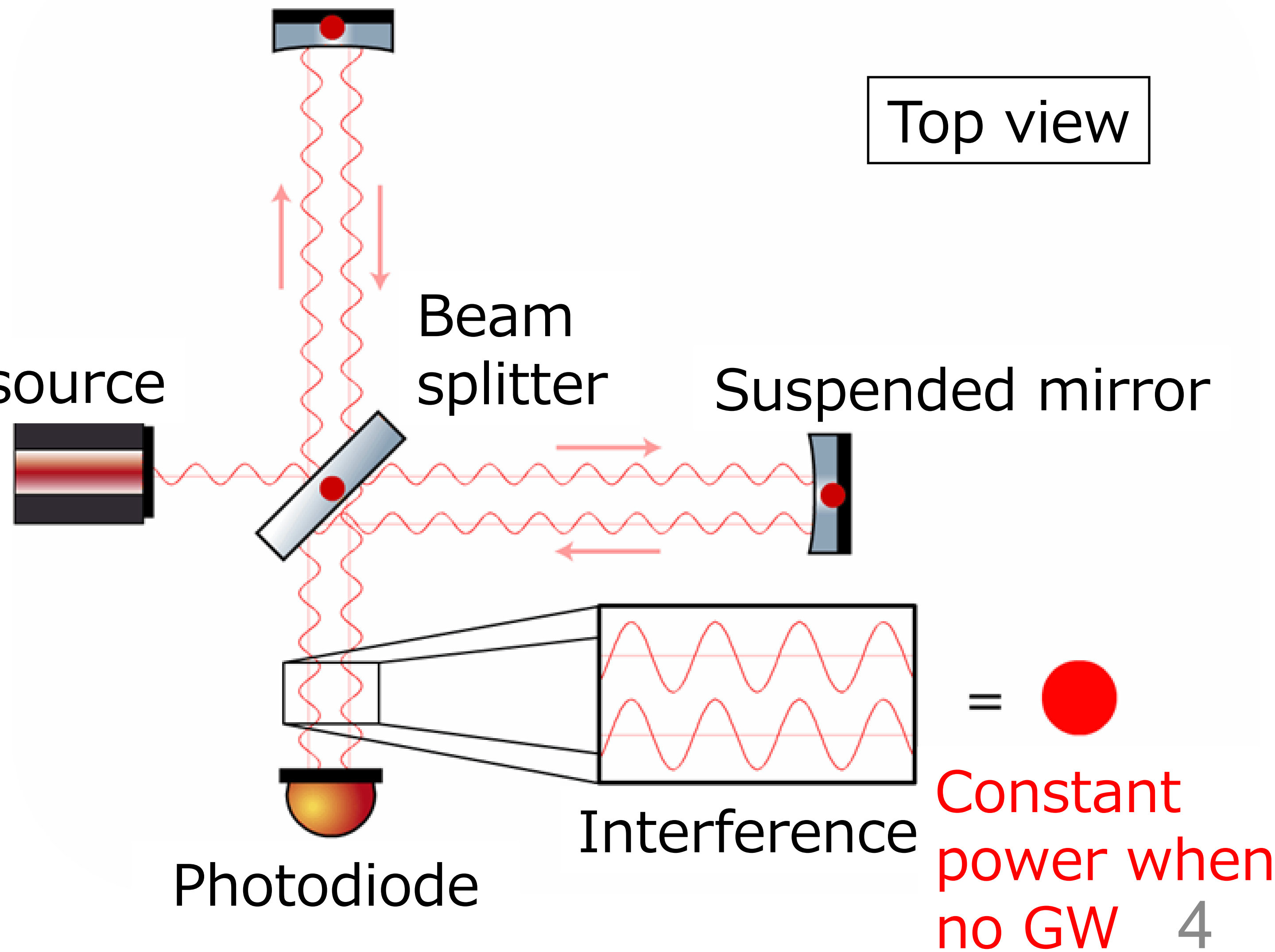




Gravitational Wave
Stellar-mass
compact objects
Stochastic backgrou
age of
universe
Period
year
hour
10 Hz ~ kHz
Freq.
Hz
10-15
10-12
10-9
10-6
10-3
1
103
Ground-based interferometers
Pulsar timing
CMB B-mode
Doppler
tracking
Space
interferometers
Resonant bars
3

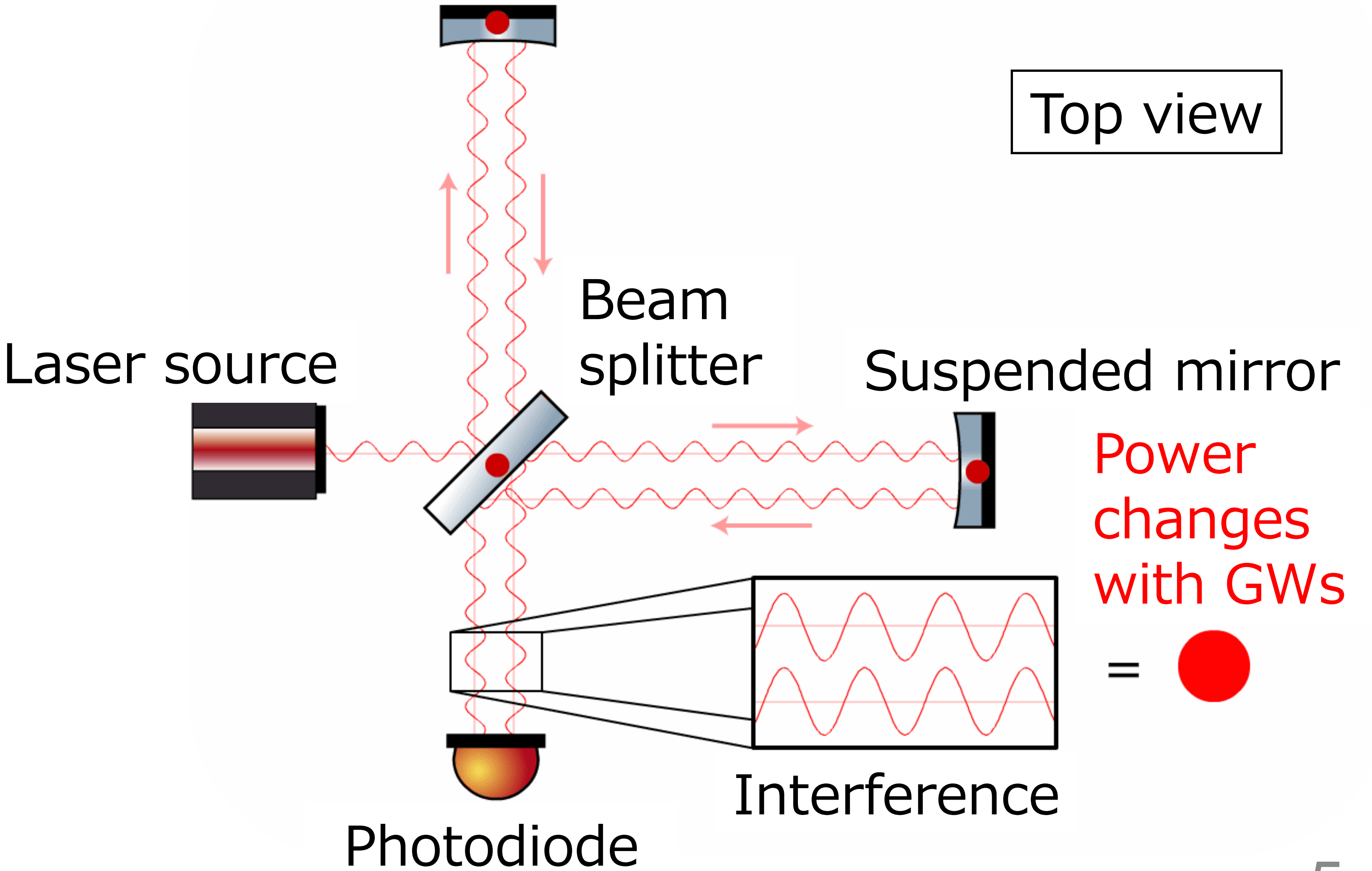
Laser Interferometric GW Detector

- Measures differential arm length change

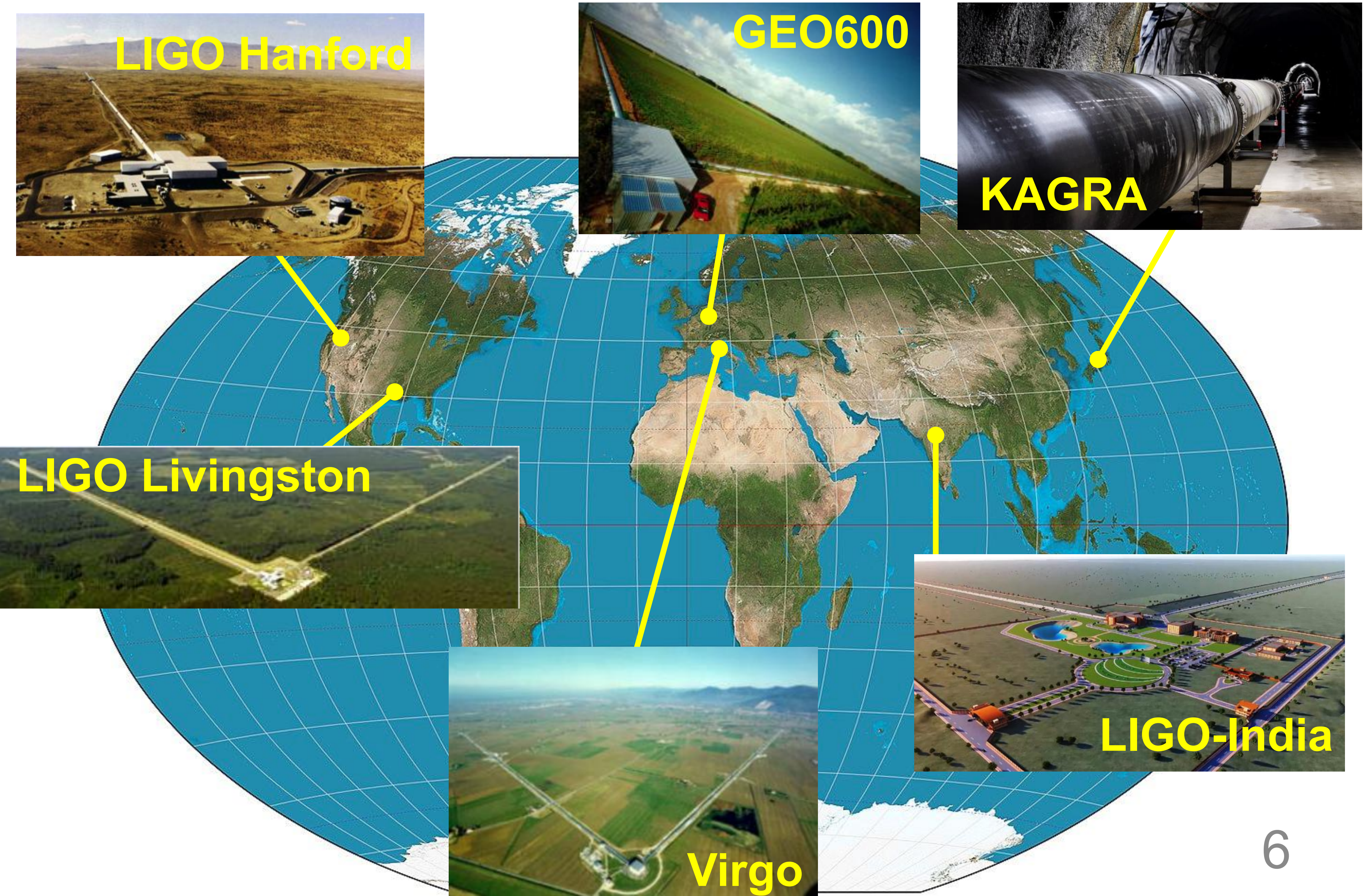


Laser Interferometric GW Detector

- Measures differential arm length change

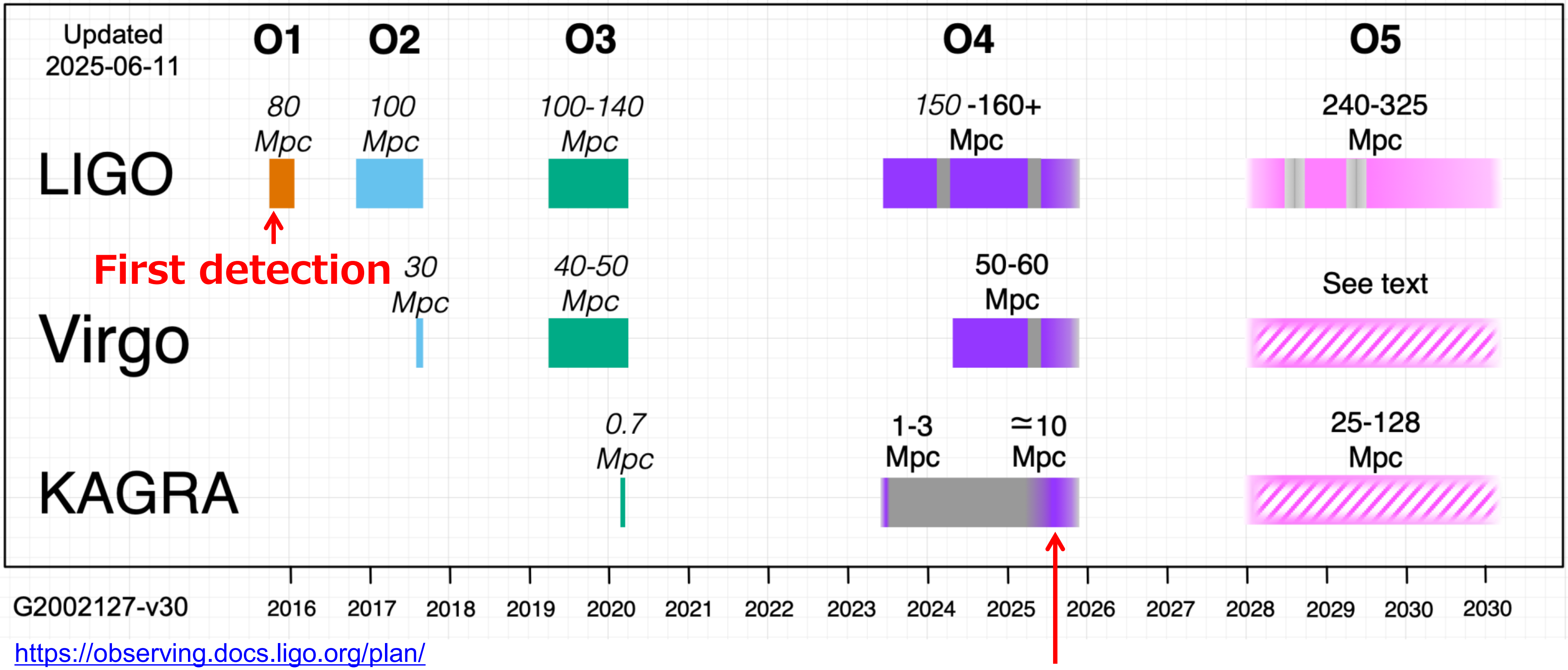


Global Network of GW Detectors



LIGO-Virgo-KAGRA Observations

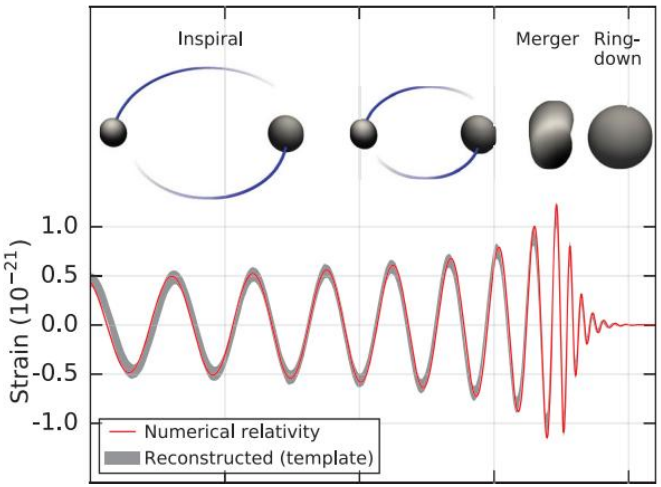
- Coordinated runs to detect GW signals by multiple detectors for better sky localization etc.

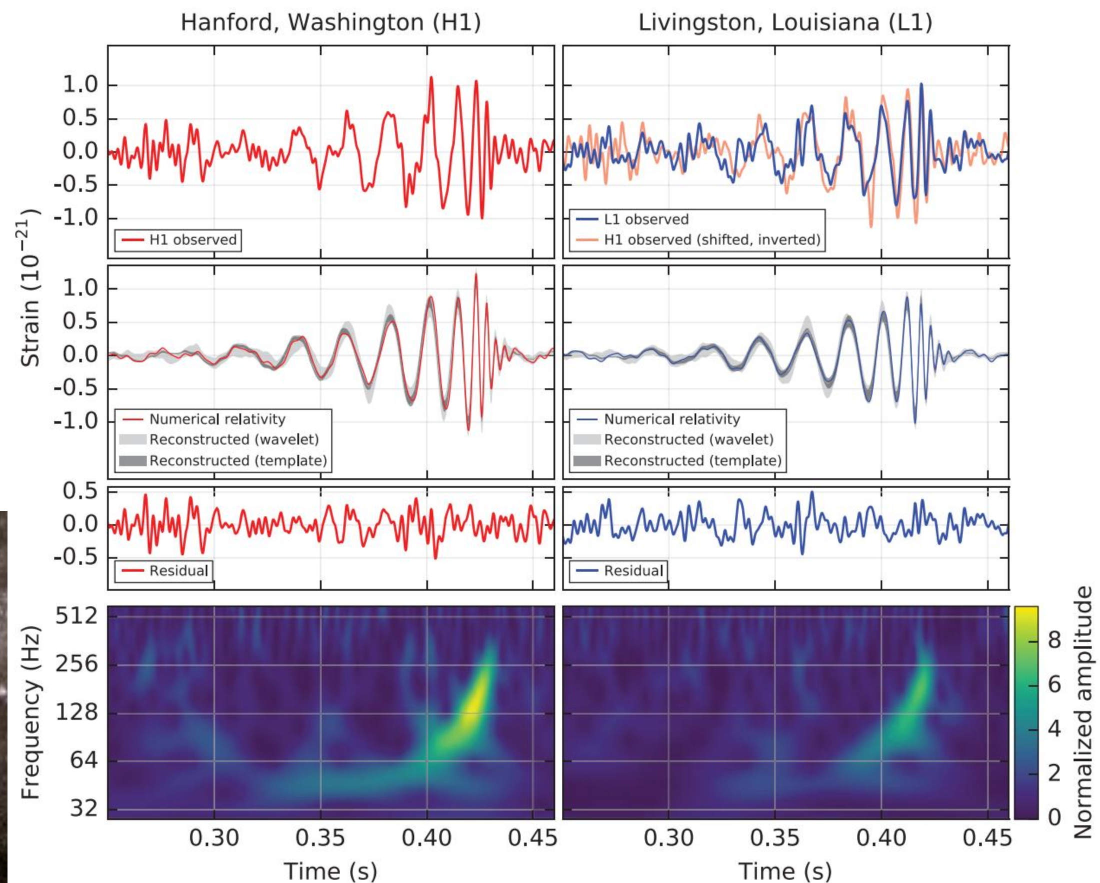


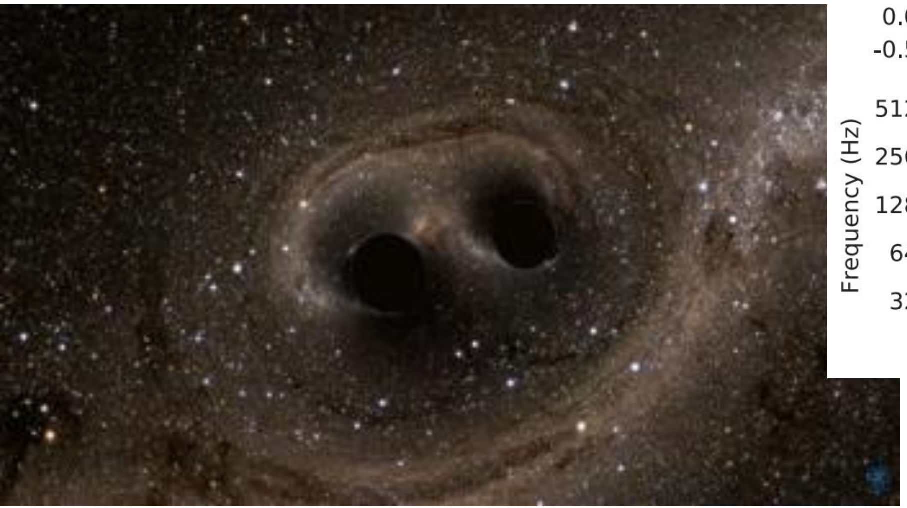
https://observing.docs.ligo.org/plan/

GW150914: The First Event

- Detected by two LIGO detectors
- 10-year anniversary this September!



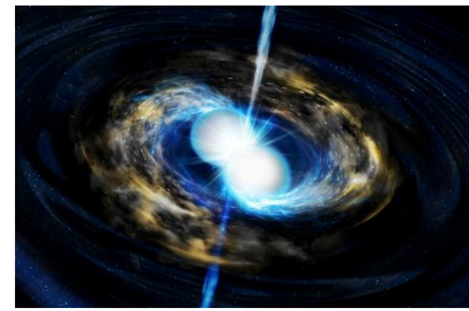




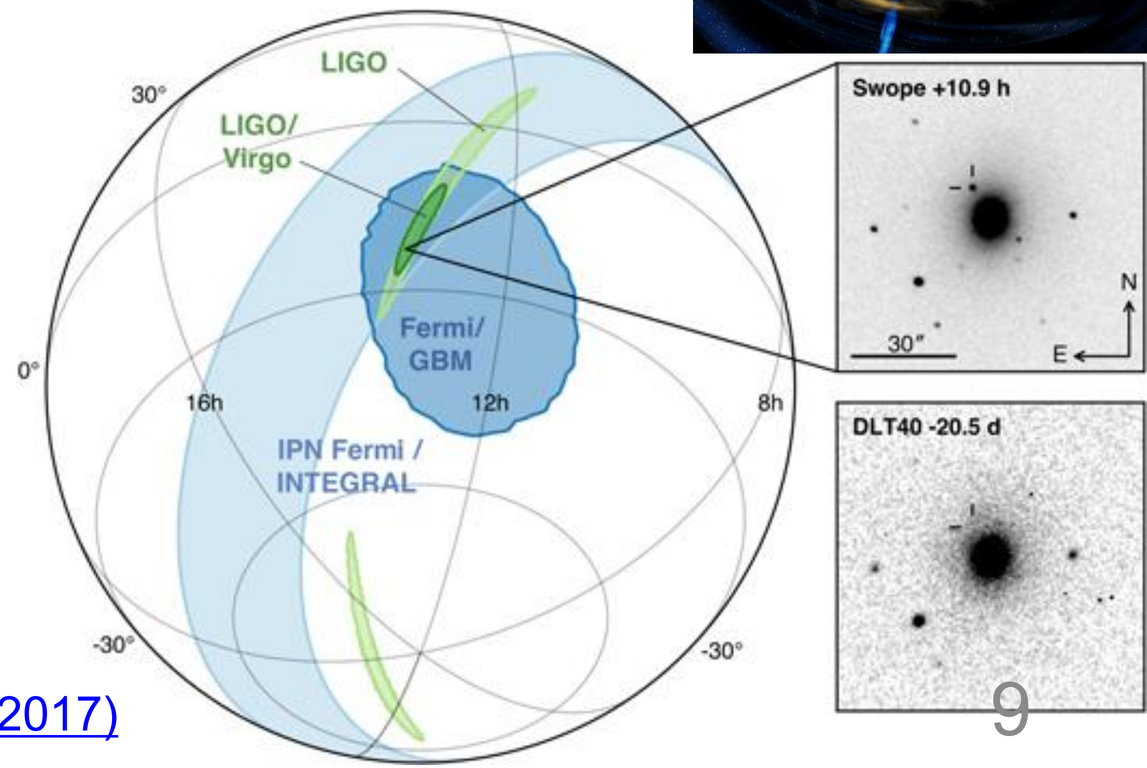
LV, [PRL 116, 061102 (2016)]

GW170817: Multi-Messenger Event

- Detected by two LIGOs & Virgo, localized ~30 deg^2
- Short gamma-ray burst, kilonova detected



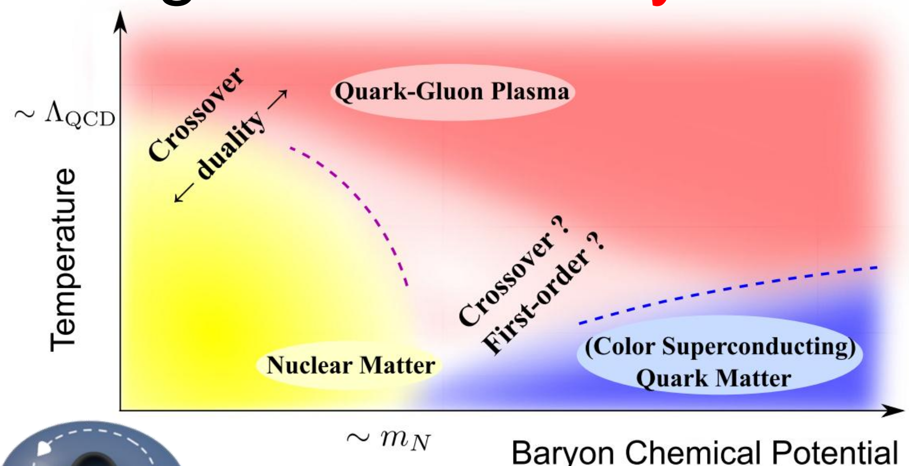
- Speed of gravity
- Hubble constant
- Studies of neutron star equation of state
- Evidence for production of heavy elements



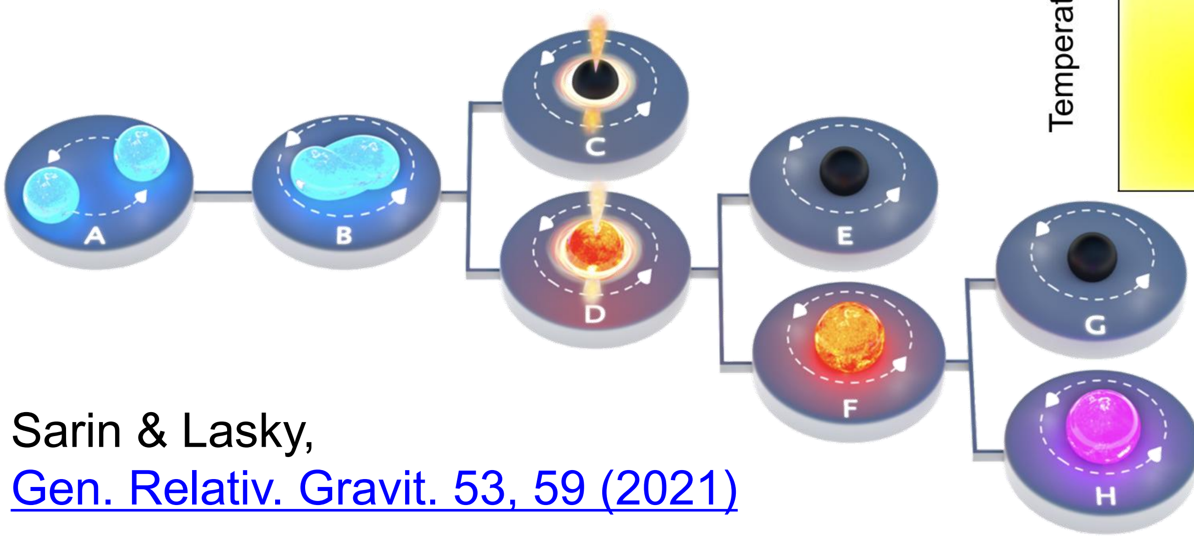
LV and many, [ApJL 848, L12 (2017)]

Neutron Star Open Questions

- What happened after the merger?
- What are the progenitors of GRBs and kilonovae?
  - Short/long GRBs explained by BNS?
  - Diversity of kilonovae? c.f. GRV211211A, GRB2307A
- Can BNS explain all of the origin of the heavy elements?
- QCD phase transition?



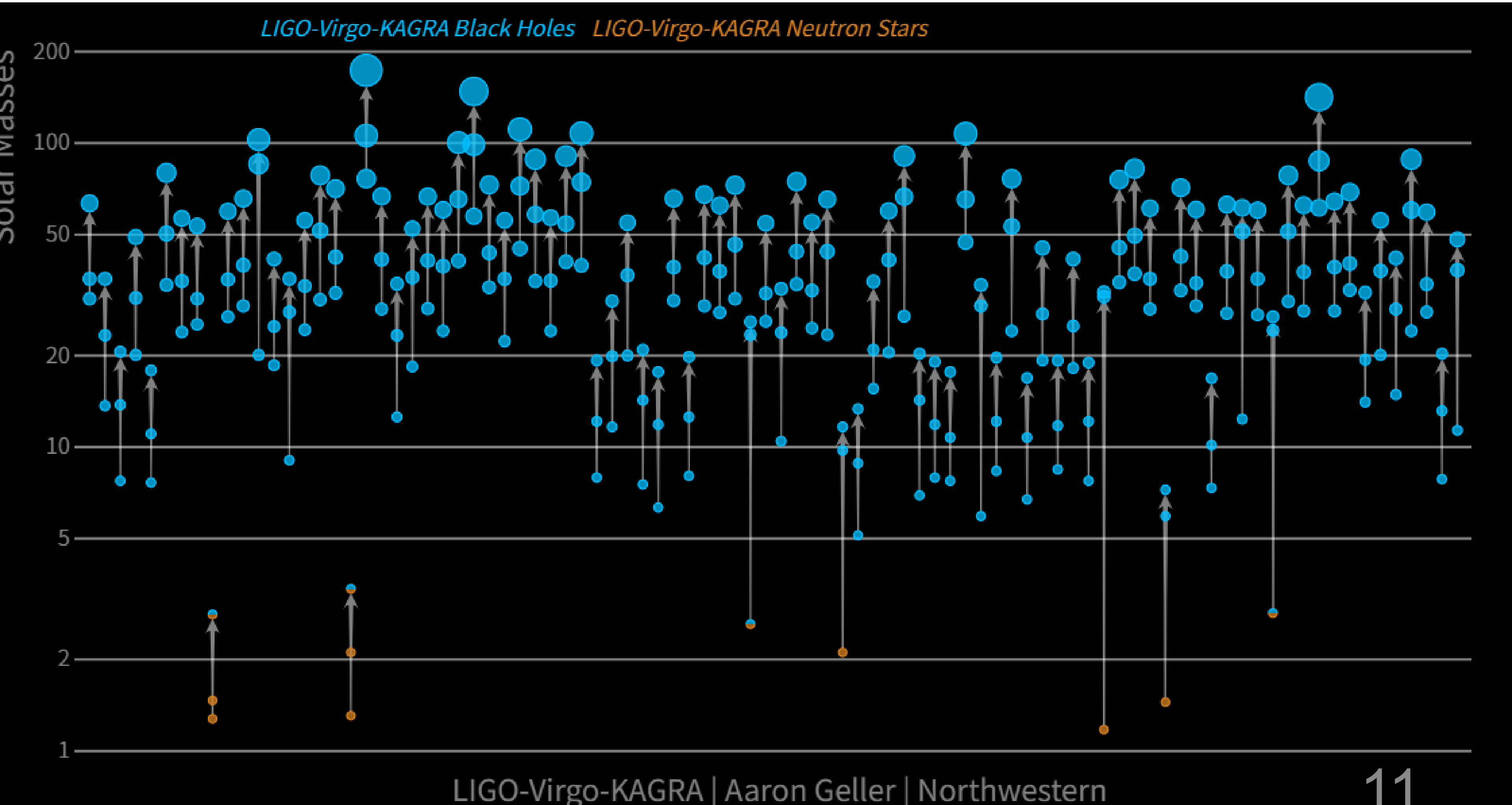
Fujimoto+,
[PRL 130, 091404 (2023)]



Sarin & Lasky,
[Gen. Relativ. Gravit. 53, 59 (2021)]

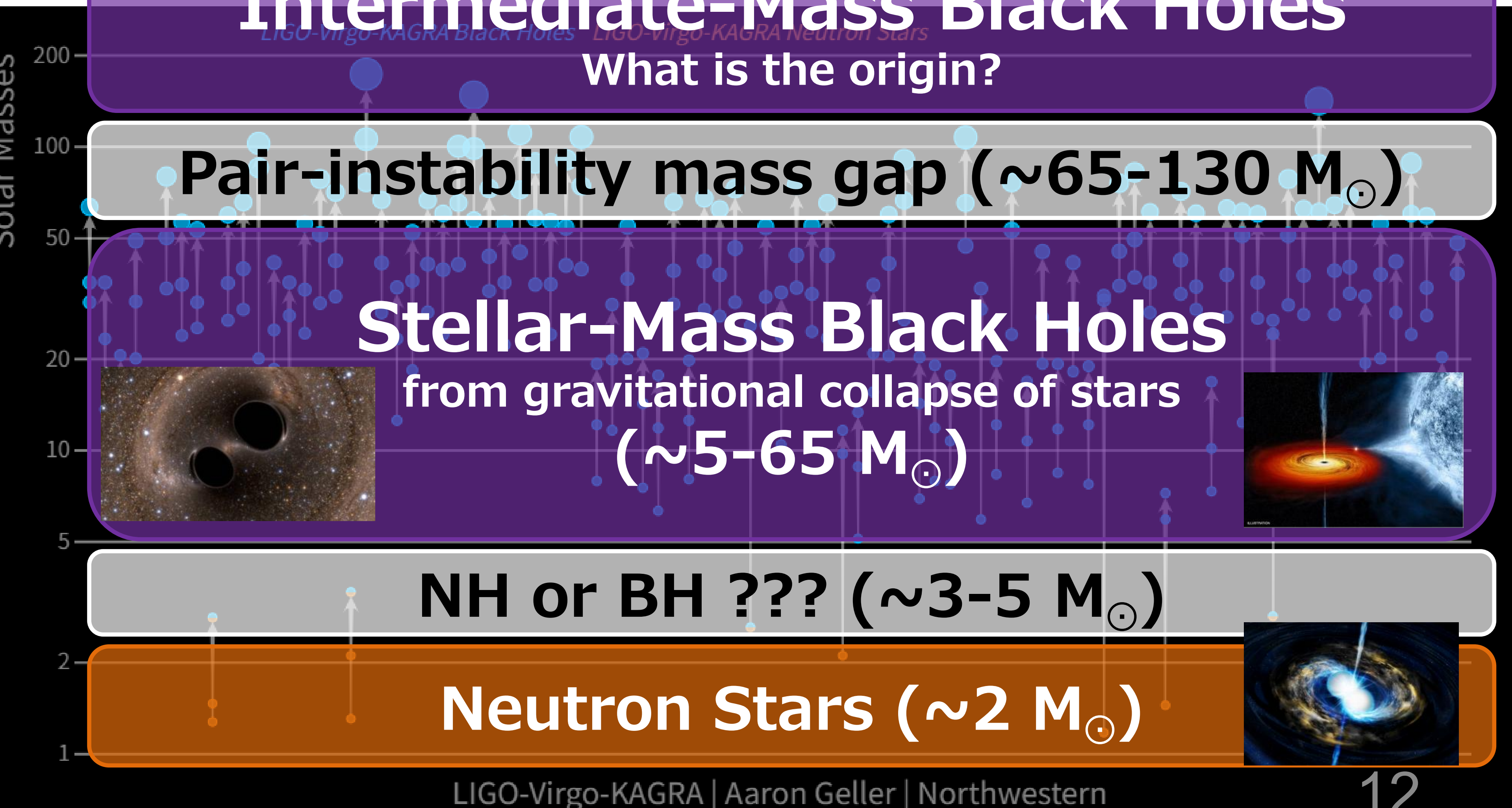
O1-O3 Catalog of Events

- 90 events found during O1-O3 (2015-2020)



Events in the Mass Gaps

- 90 events found during O1-O3 (2015-2020)



Intermediate-Mass Black Holes

What is the origin?

Pair-instability mass gap (~65-130 $M_\odot$)

Stellar-Mass Black Holes

from gravitational collapse of stars

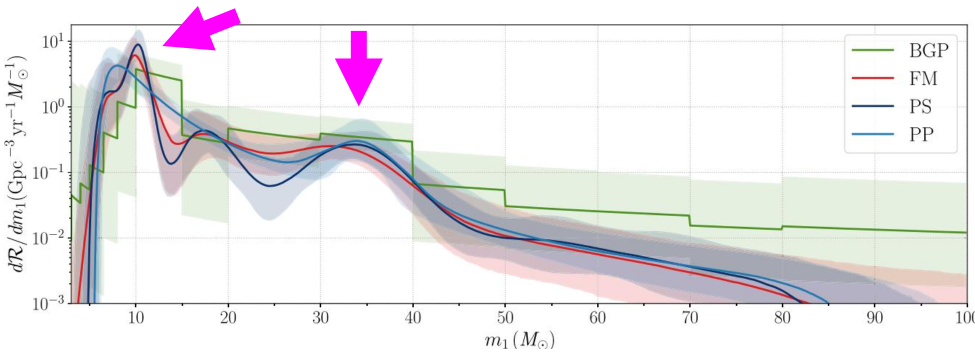
(~5-65 $M_\odot$)

NH or BH ??? (~3-5 $M_\odot$)

Neutron Stars (~2 $M_\odot$)

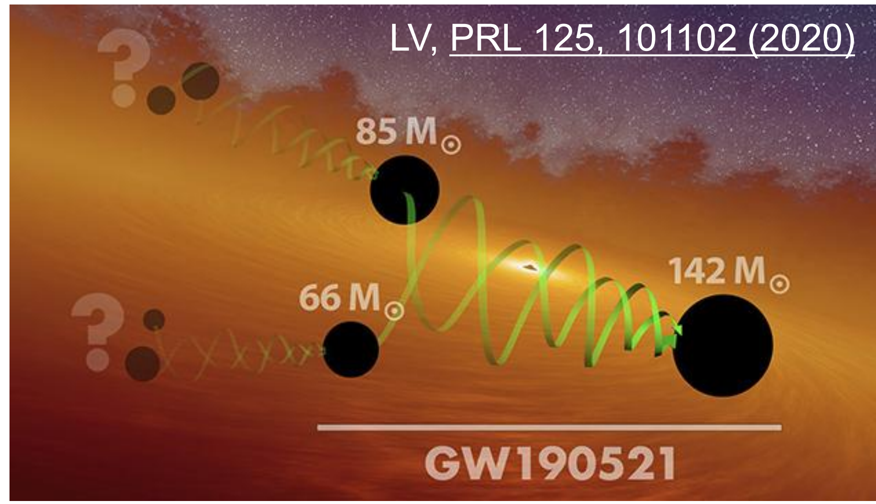
Some of Highlights

Population studies

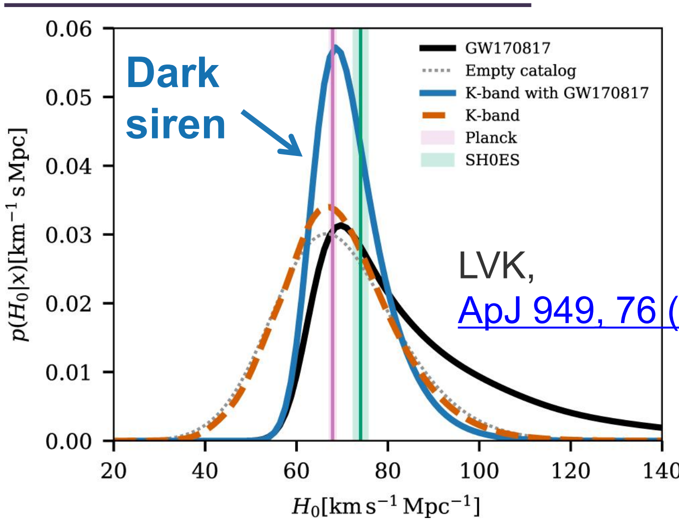


LVK, PRX 13, 011048 (2023)

IMBH events

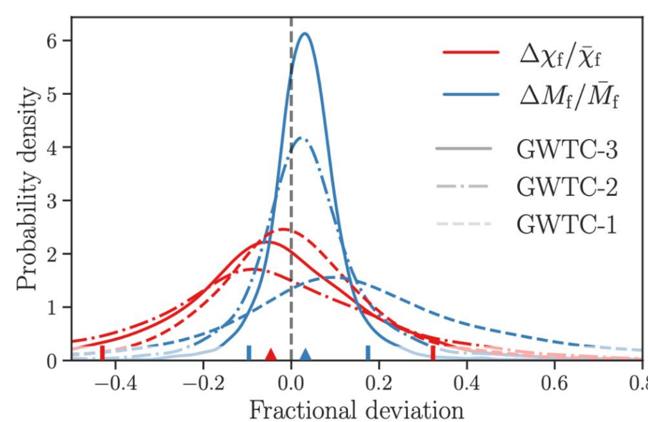


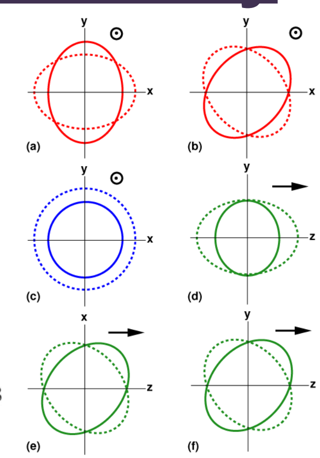
Cosmic expansion measurements



LVK, ApJ 949, 76 (2023)

Tests of General Relativity



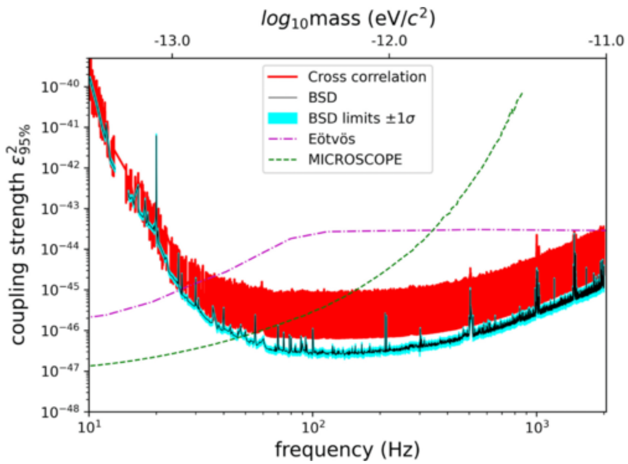


LVK, arXiv:2112.06861

Takeda+, PRD 98, 022008 (2018)

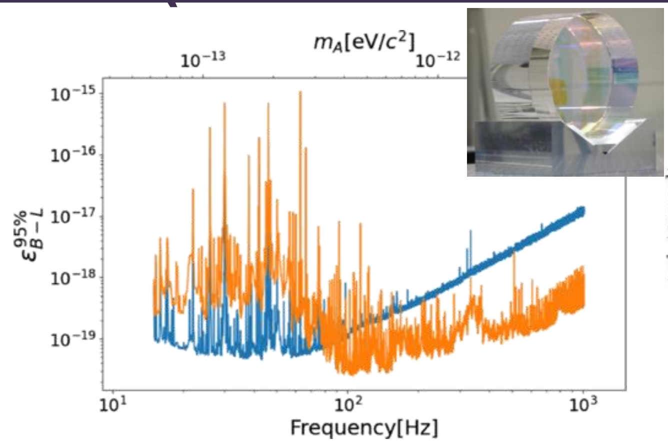
New Physics (Personal Picks!)

Ultralight dark matter (10^{-13}~10^{-11} eV range)



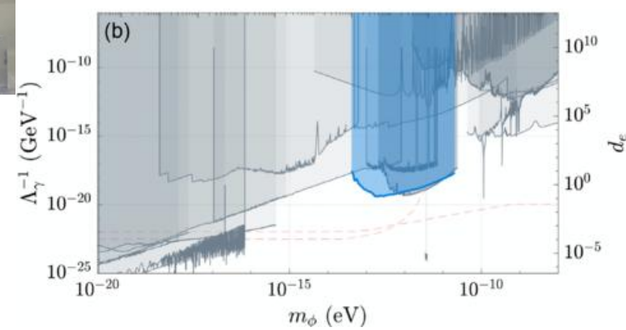
Vector DM from LV

LVK, PRD 105, 063030 (2022)



Vector DM from KAGRA

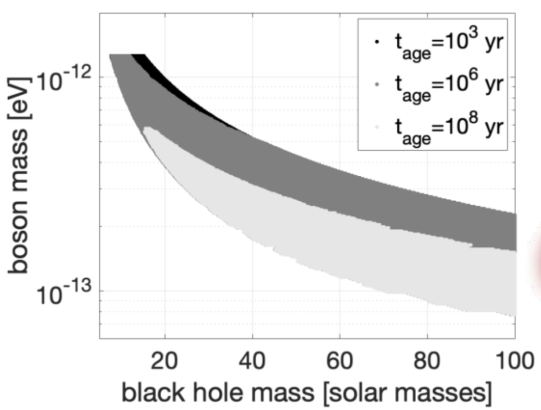
LVK, PRD 110, 042001 (2024)

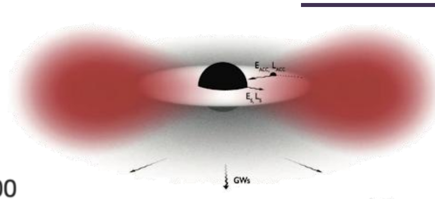


Scalar DM from LIGO/GEO

Göttel+, PRL 133, 101001 (2024)

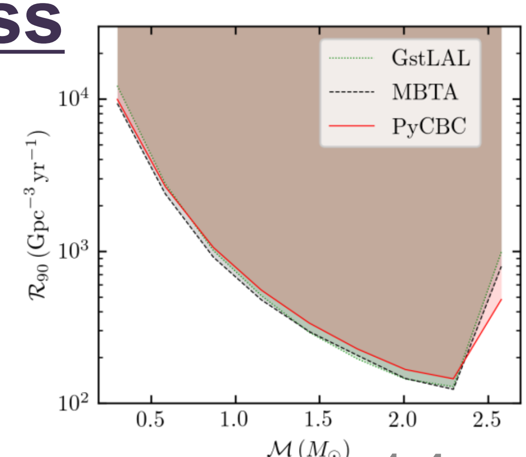
Scalar boson clouds





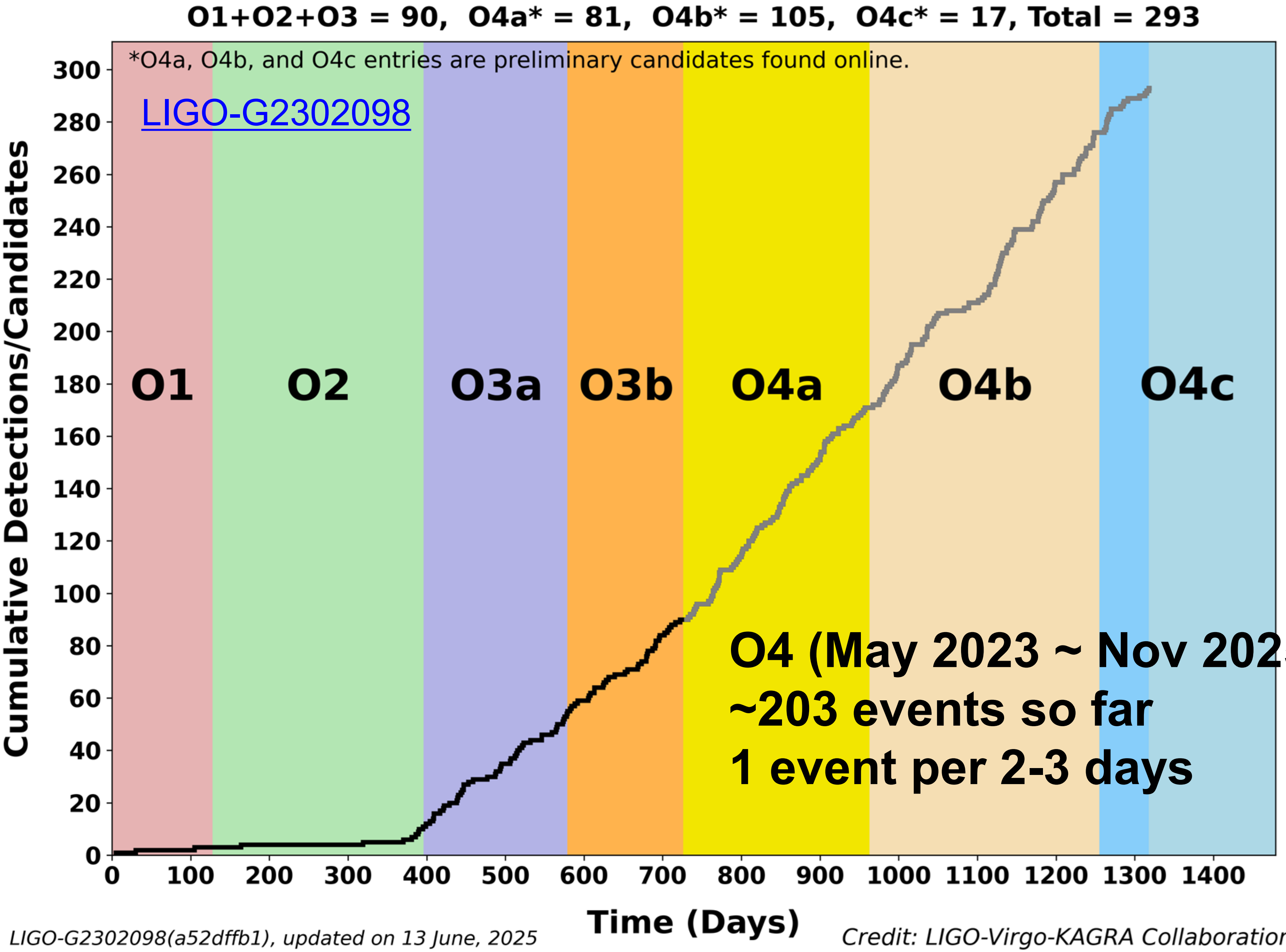
LVK, PRD 105, 102001 (2022)

Sub-solar-mass primordial black holes



LVK, MNRAS 524, 5984 (2023)

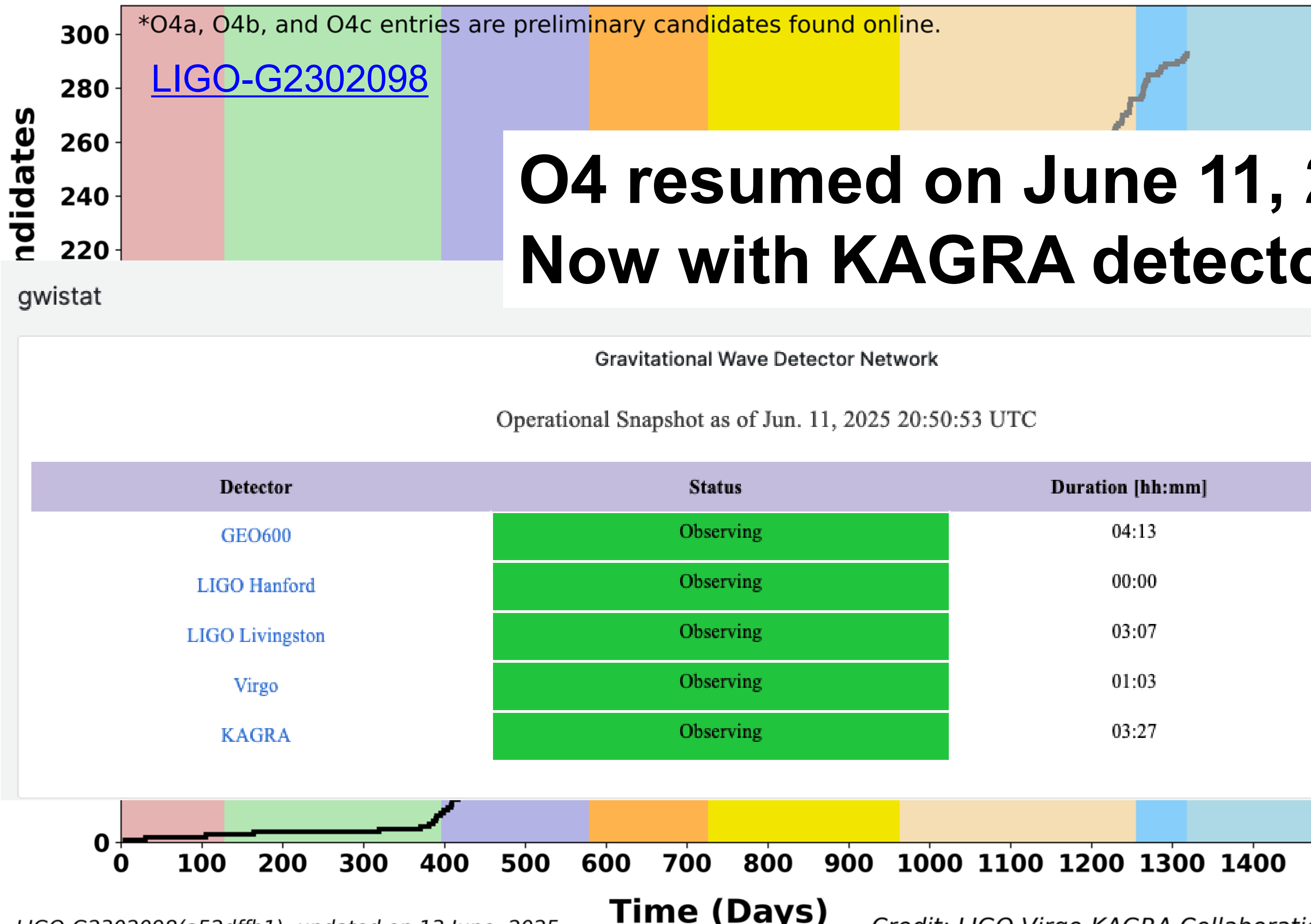
Much More Events in O4



O4 (May 2023 ~ Nov 2025)
~203 events so far
1 event per 2-3 days

Much More Events in O4

O1+O2+O3 = 90, O4a* = 81, O4b* = 105, O4c* = 17, Total = 293



O4 resumed on June 11, 2025
Now with KAGRA detector!

gwistat

Gravitational Wave Detector Network

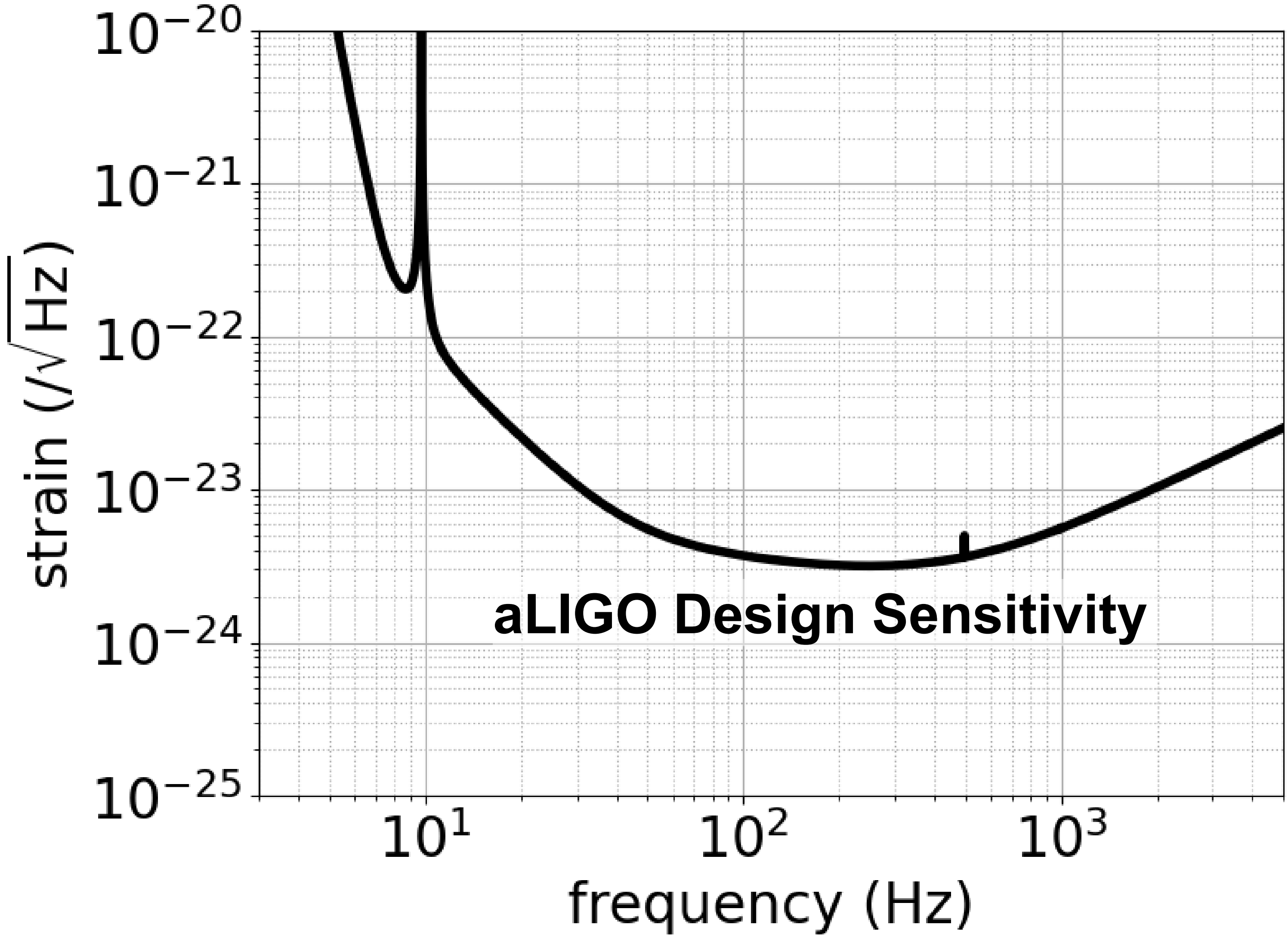
Operational Snapshot as of Jun. 11, 2025 20:50:53 UTC

Detector	Status	Duration [hh:mm]	Latency [s]
GEO600	Observing	04:13	34
LIGO Hanford	Observing	00:00	59
LIGO Livingston	Observing	03:07	45
Virgo	Observing	01:03	52
KAGRA	Observing	03:27	21

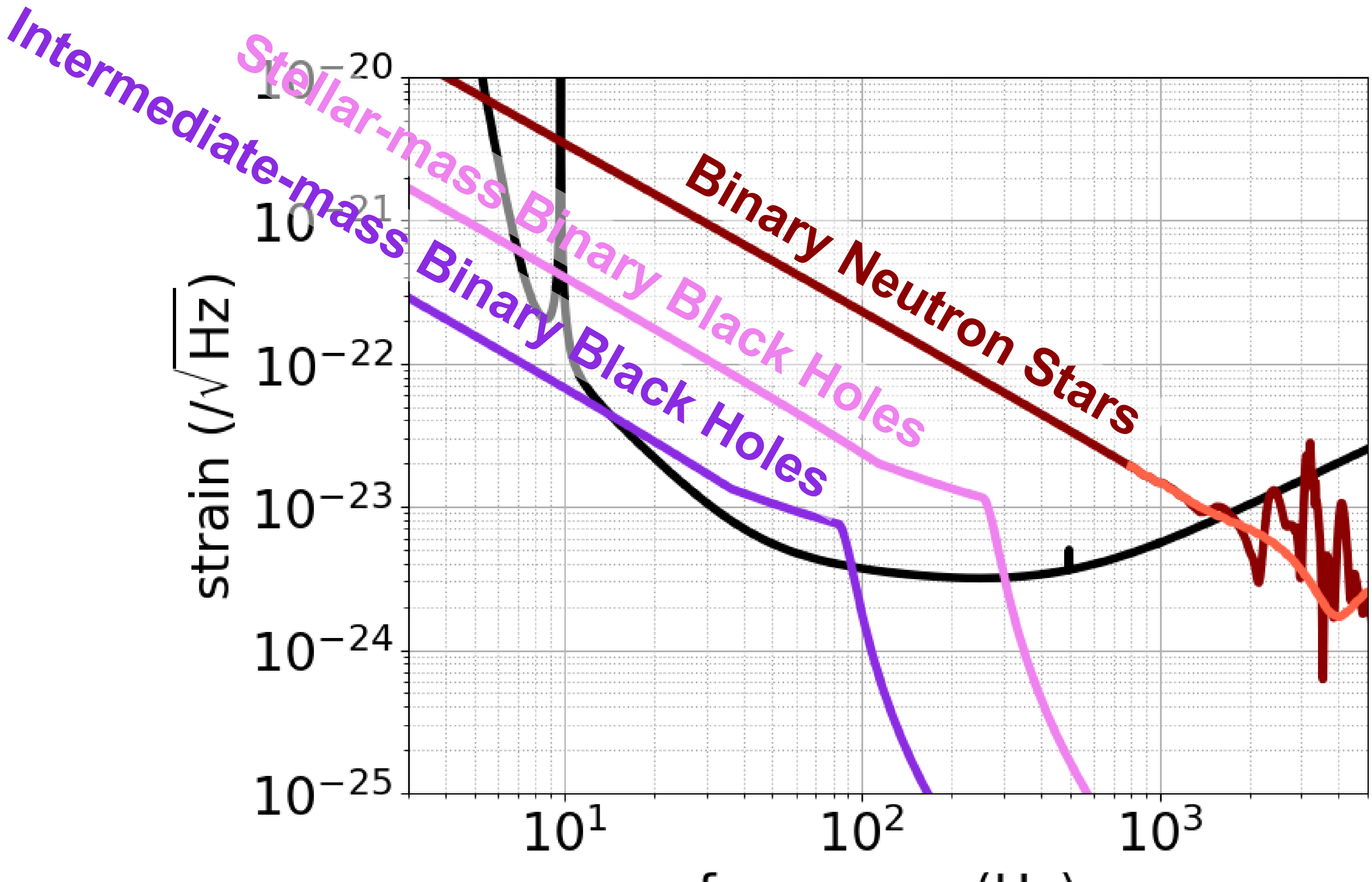
LIGO-G2302098(a52dffb1), updated on 13 June, 2025

Credit: LIGO-Virgo-KAGRA Collaboration

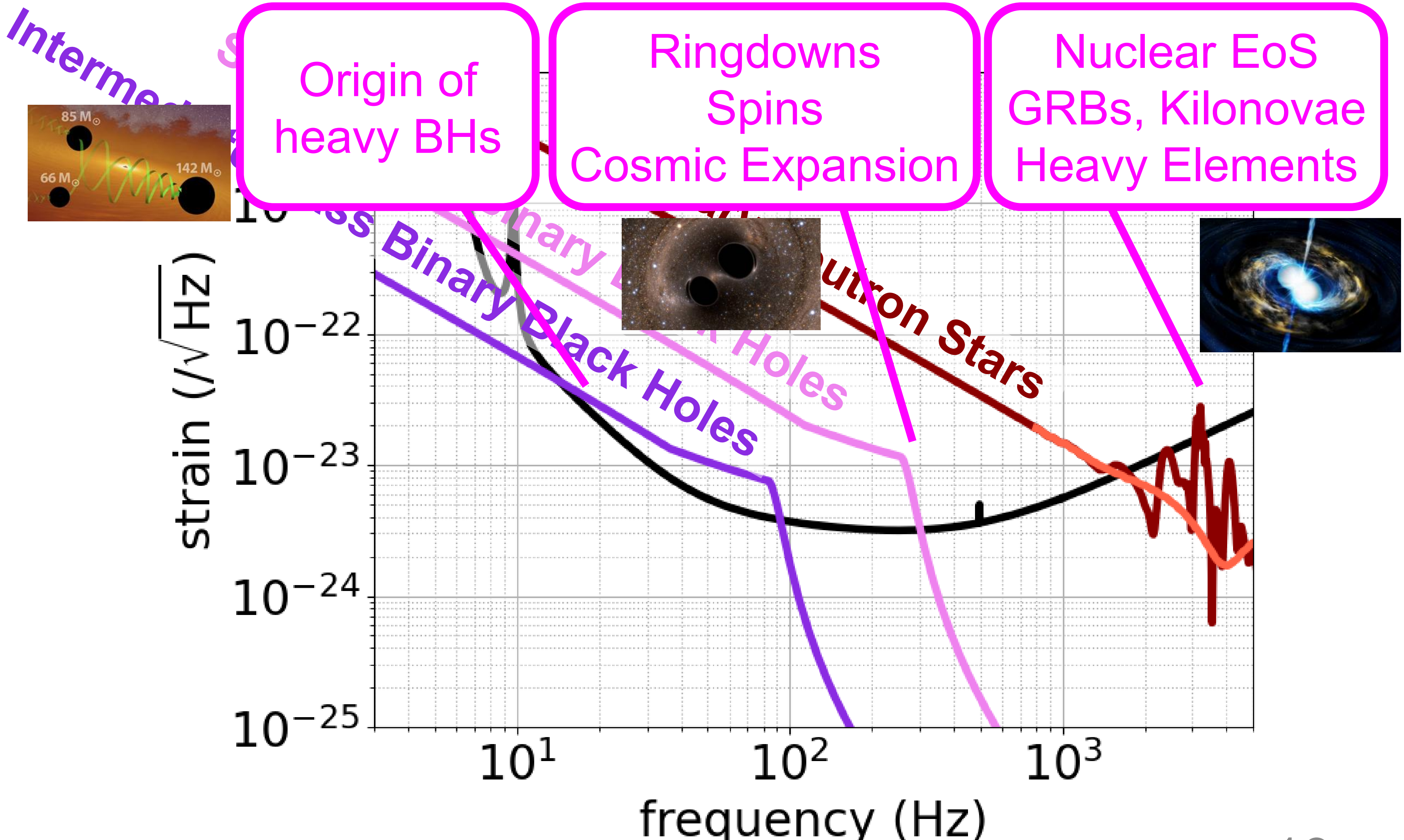
Sensitivity Band



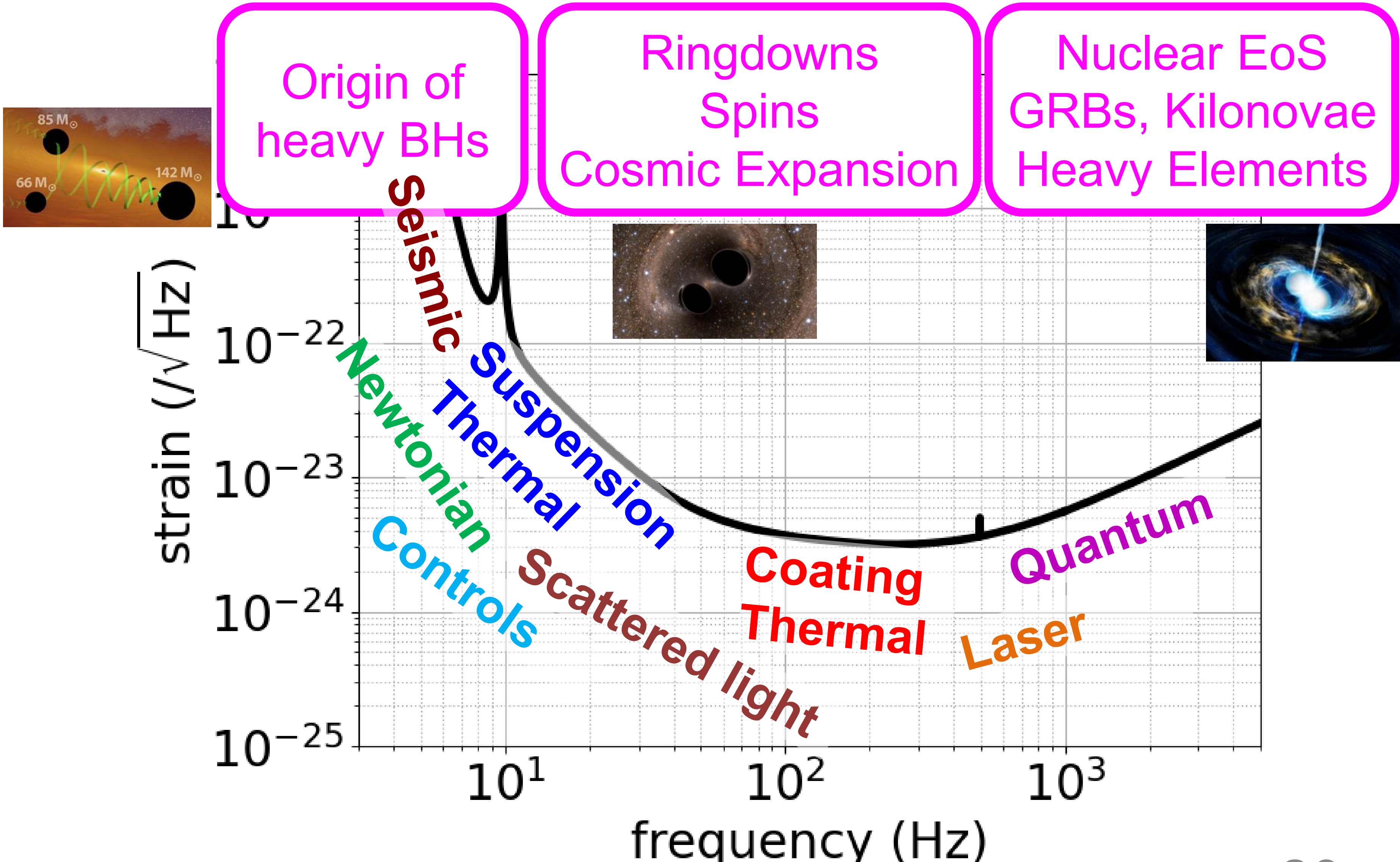
Sensitivity Band and Science



Sensitivity Band and Science



Limiting Noises

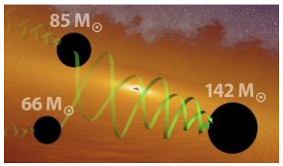


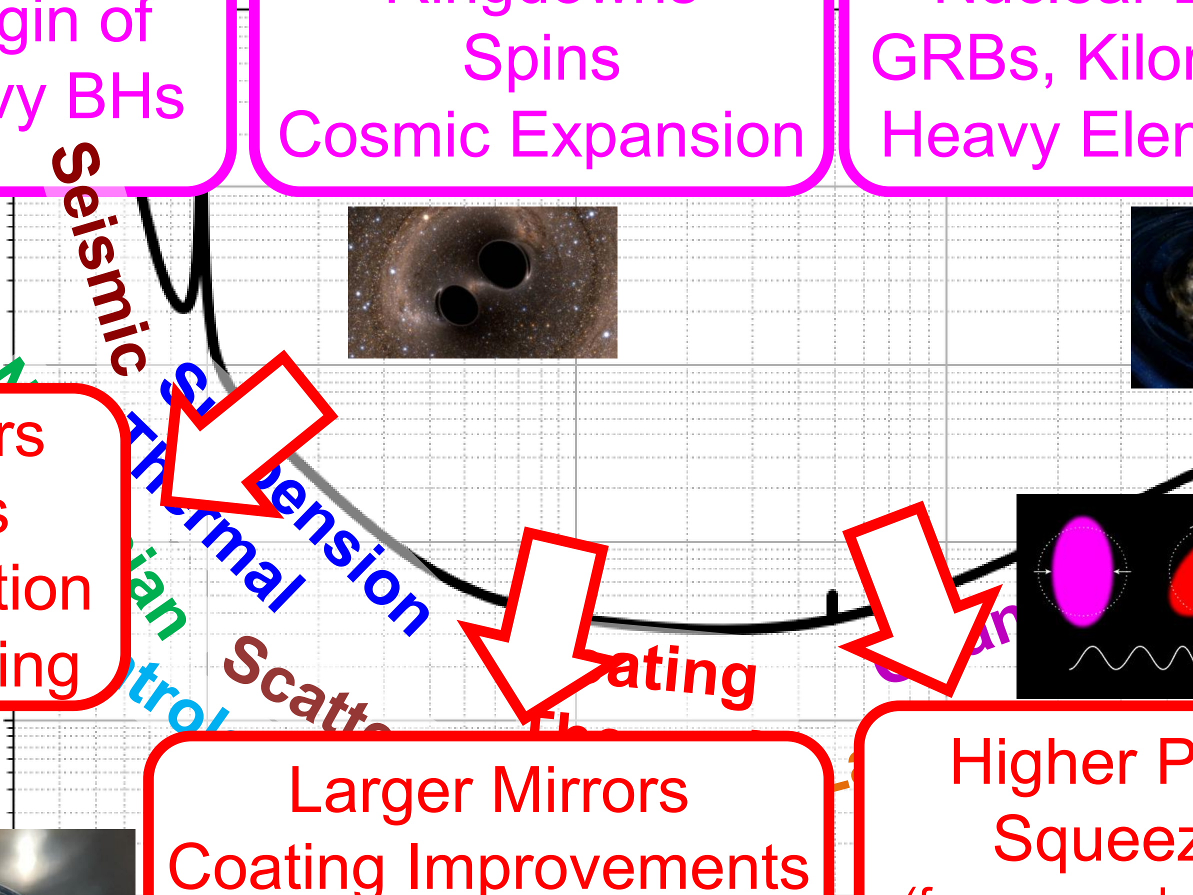
Noise Reducing Techniques

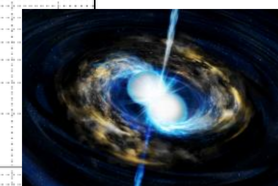
Origin of heavy BHs

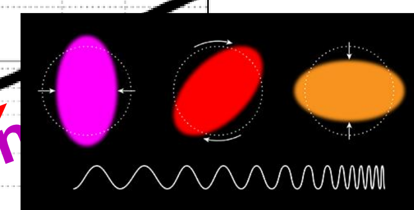
Ringdowns
Spins
Cosmic Expansion

Nuclear EoS
GRBs, Kilonovae
Heavy Elements





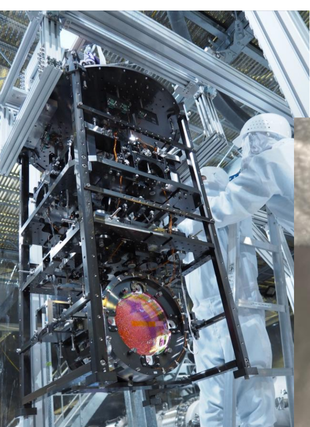


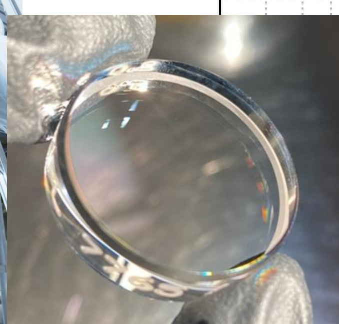


Heavier Mirrors
Suspensions
Noise Cancellation
Machine Learning

Larger Mirrors
Coating Improvements
Cryogenics

Higher Power
Squeezing
(frequency dependent)

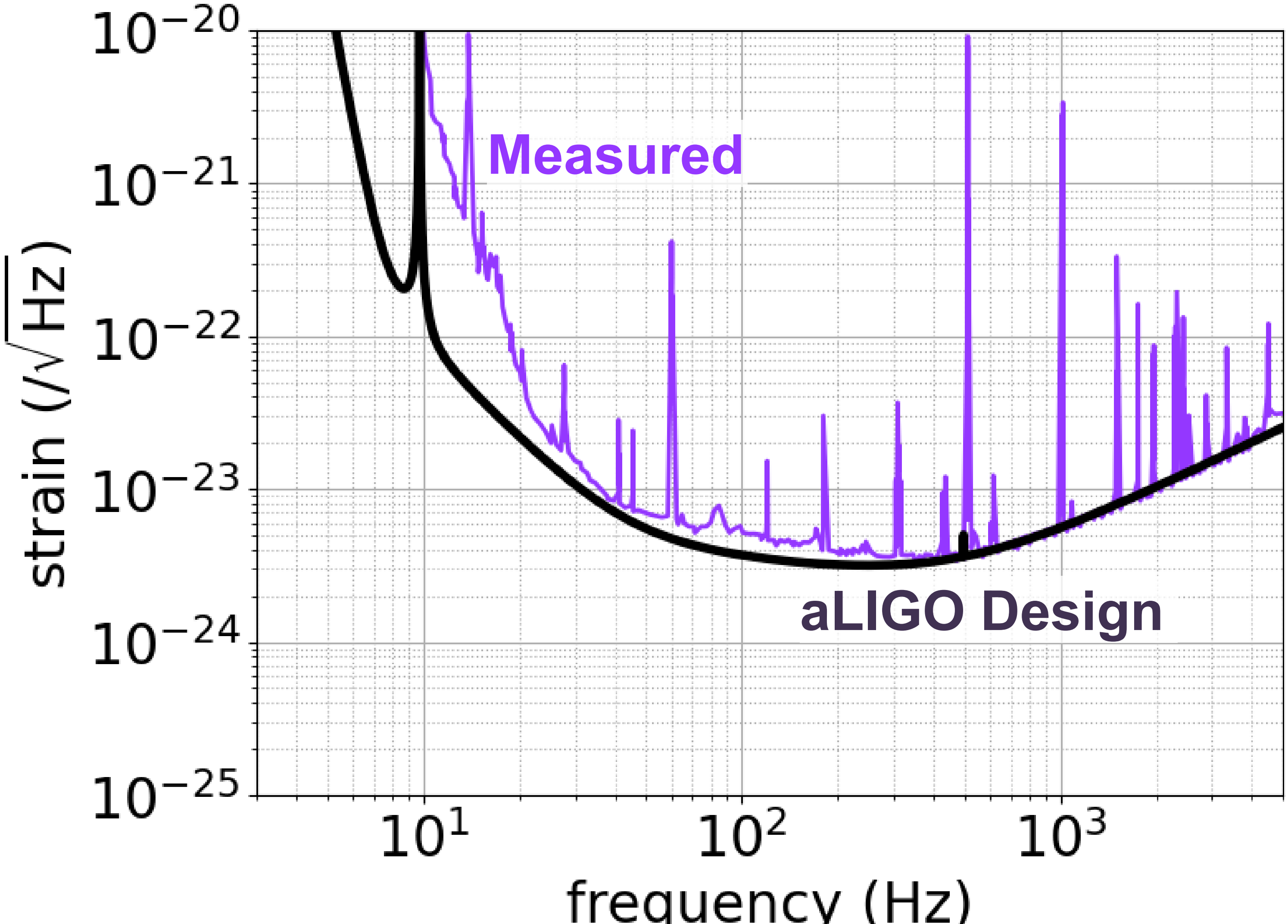




LIGO-G2200805

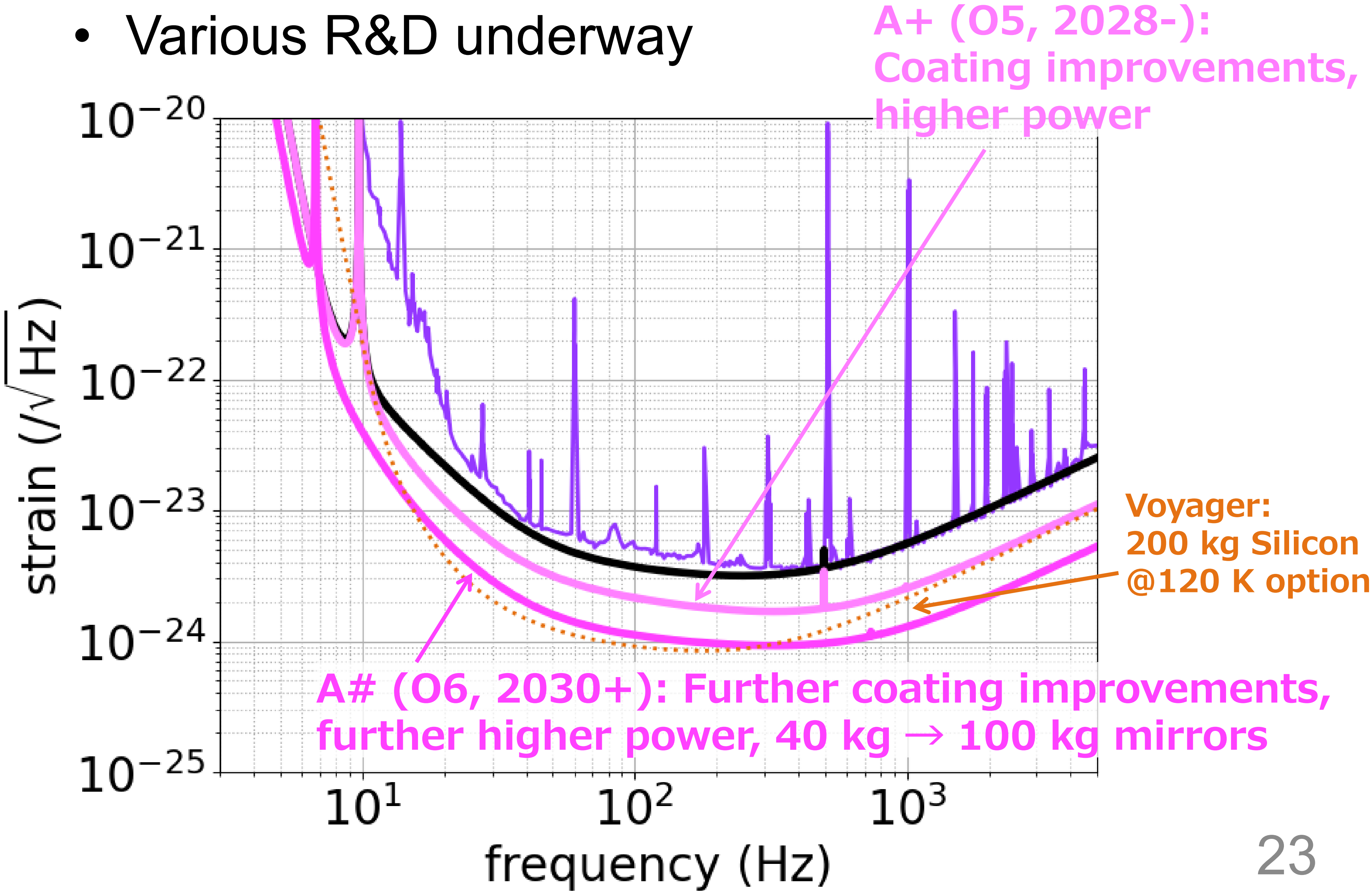
LIGO (US, 4 km, Room Temp.)

- Hanford & Livingston operating at ~150 Mpc



LIGO (US, 4 km, Room Temp.)

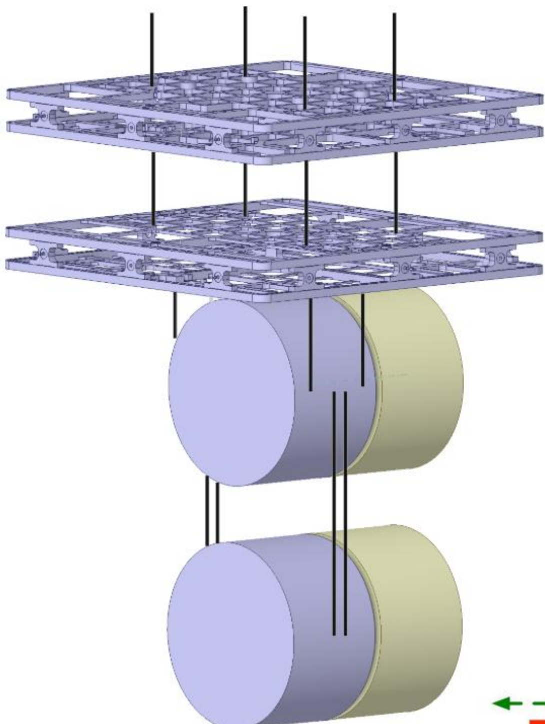
- Various R&D underway

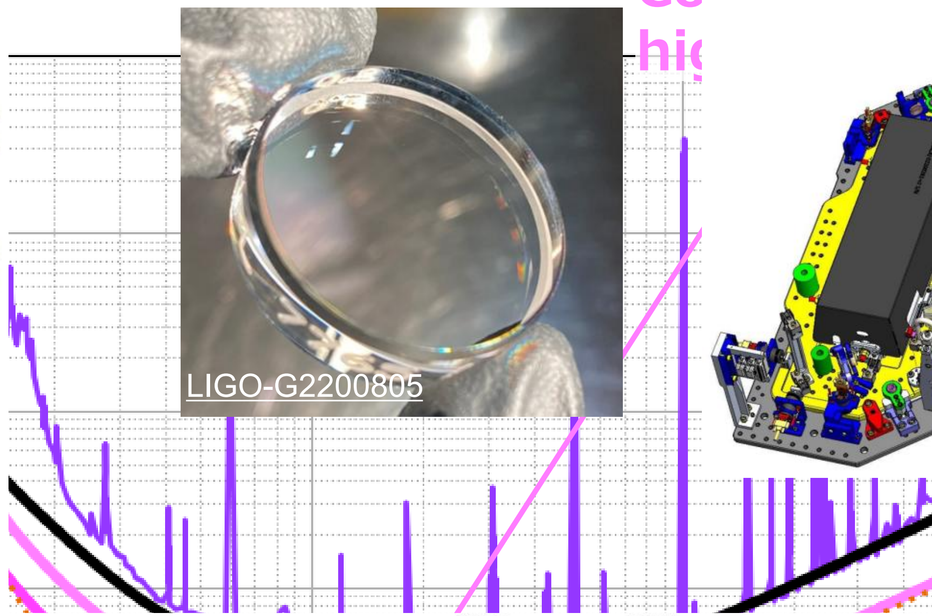


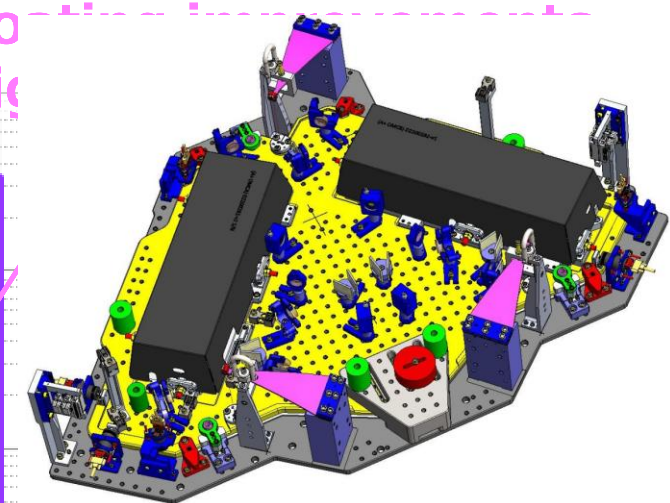
LIGO (US, 4 km, Room Temp.)

- Various R&D underway

A+ (O5, 2028-):
Co
hi



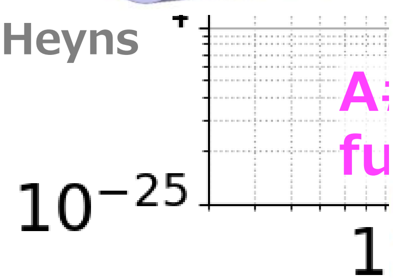




LIGO-T2100318

Voyager:
kg Silicon
0 K option

JD Heyns



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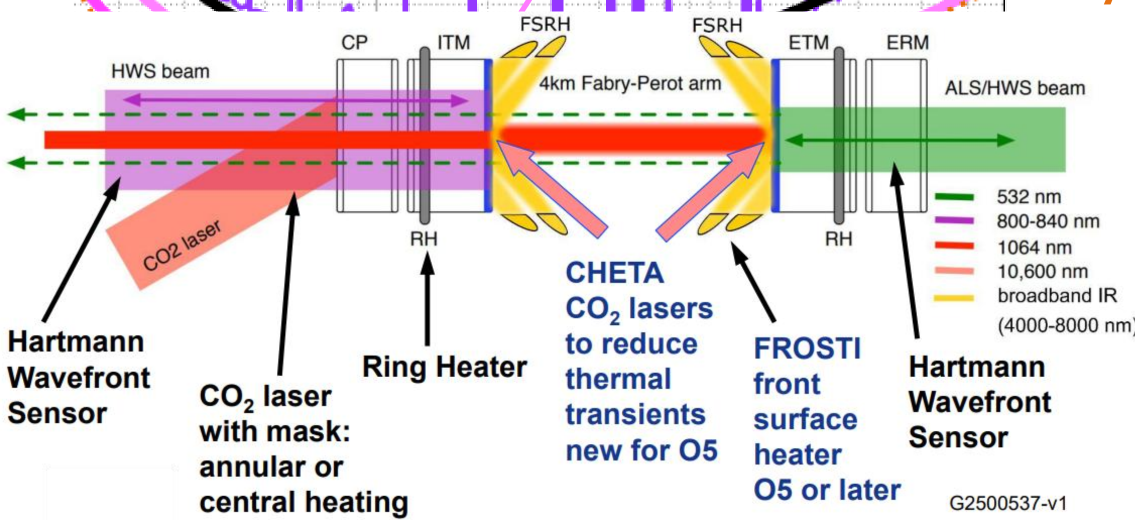
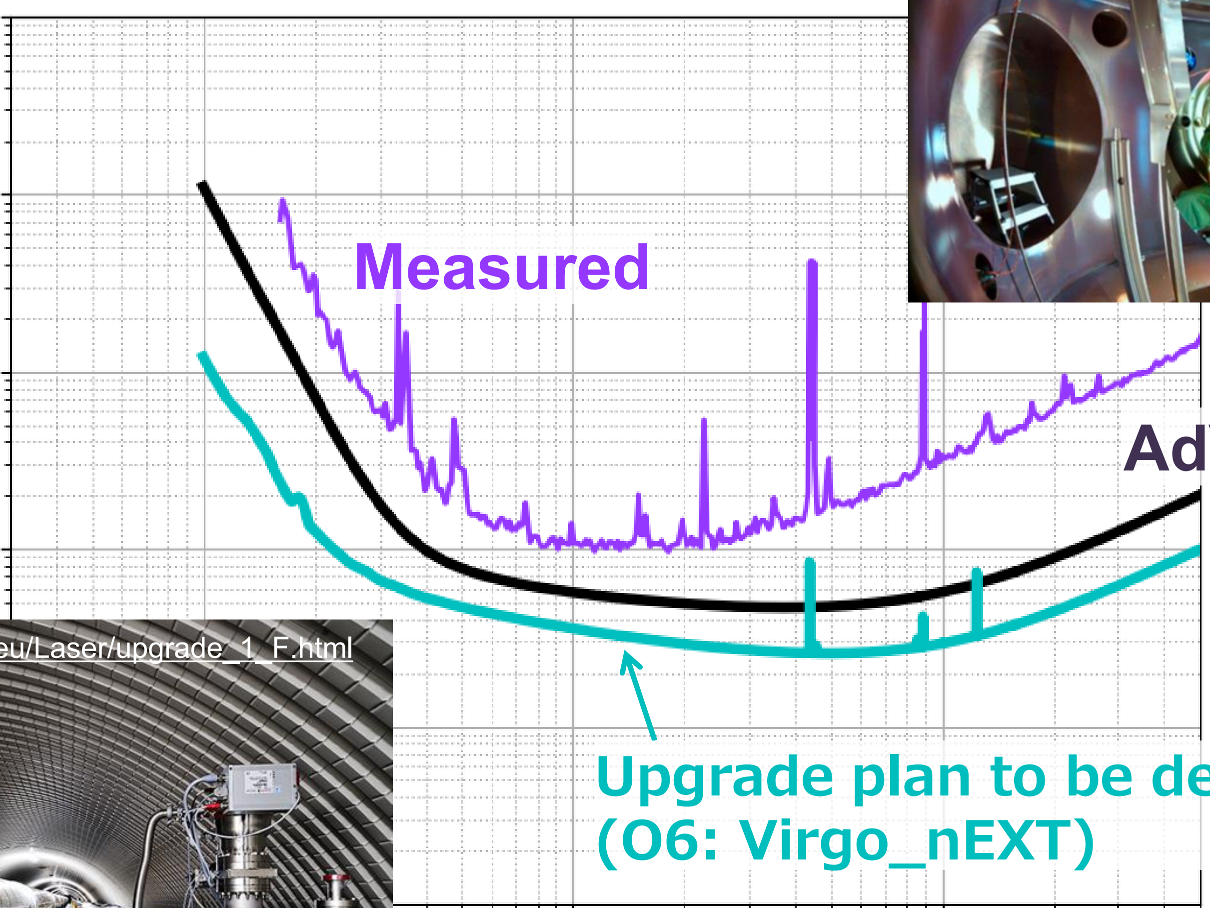
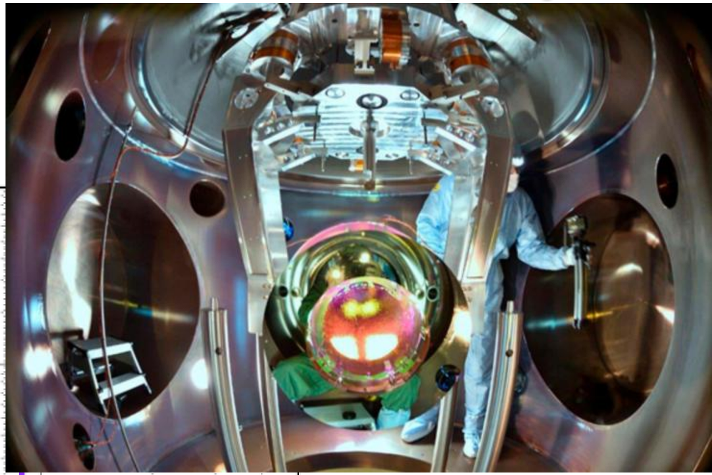


Virgo (Italy, 3 km, Room Temp.)

- Operating at ~50 Mpc

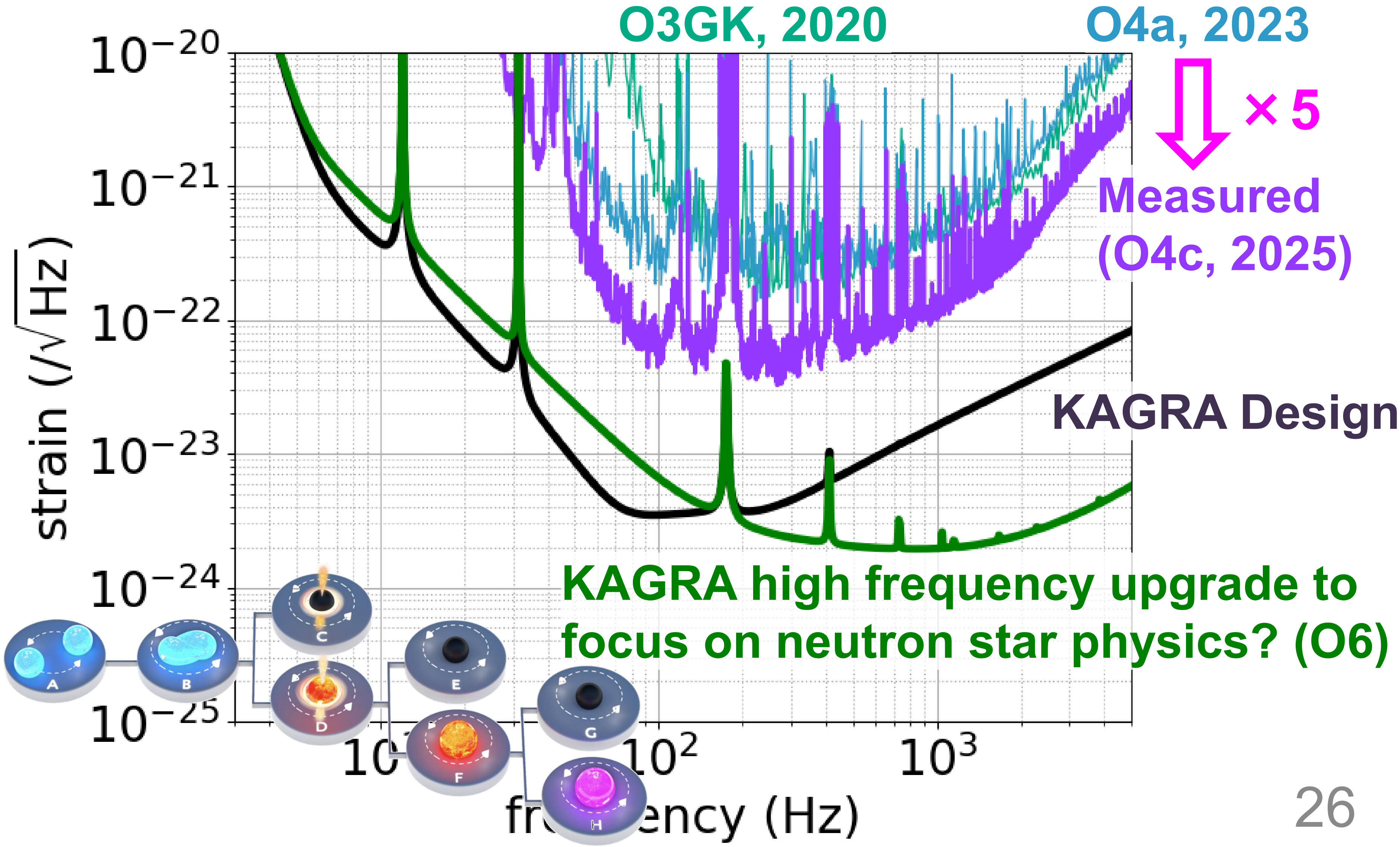




https://www.virgo-gw.eu/Laser/upgrade_1_F.html

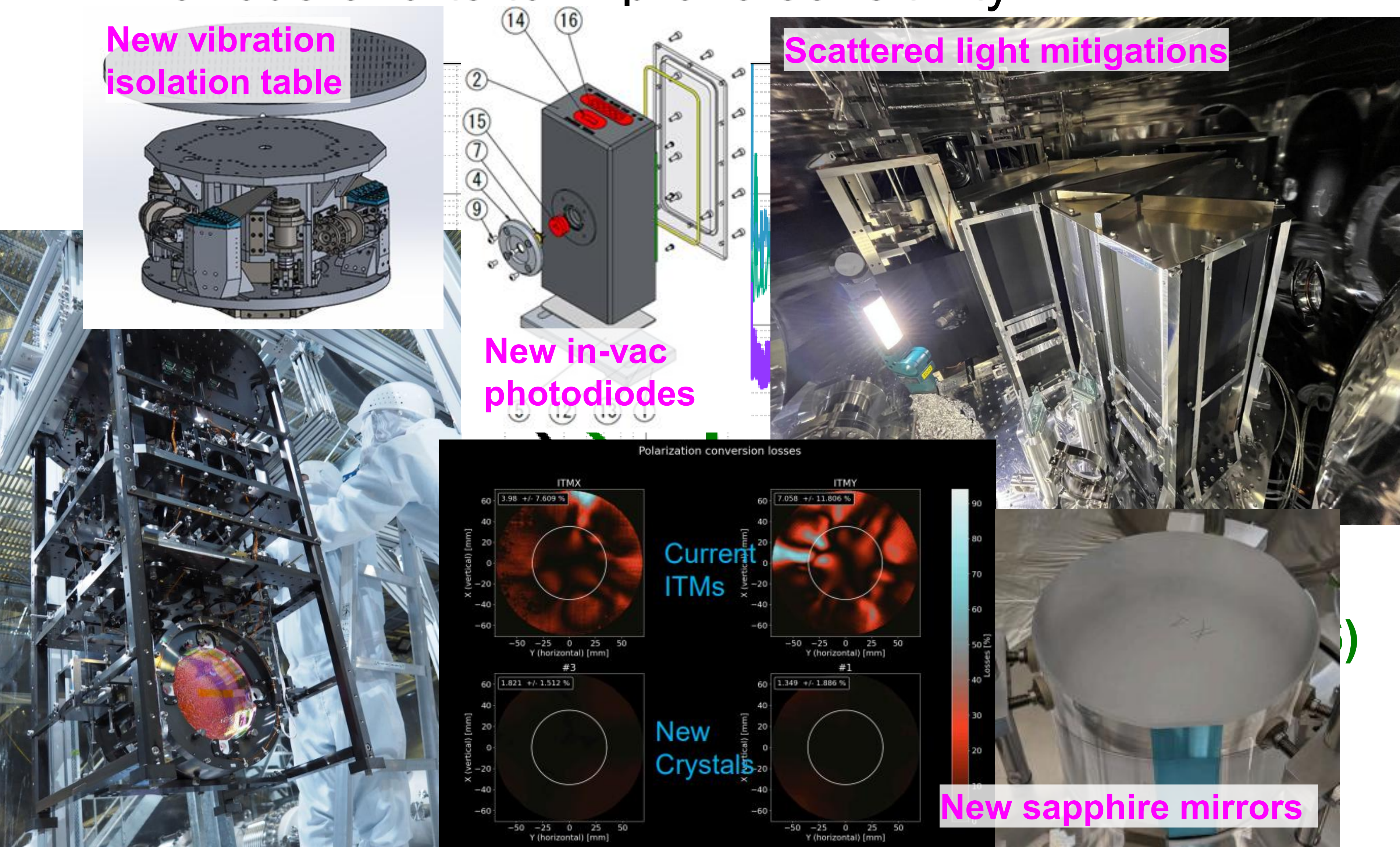
KAGRA (Japan, 3 km, 22 K)

- Operating at ~6 Mpc at ~50 K (IX ~90 K)



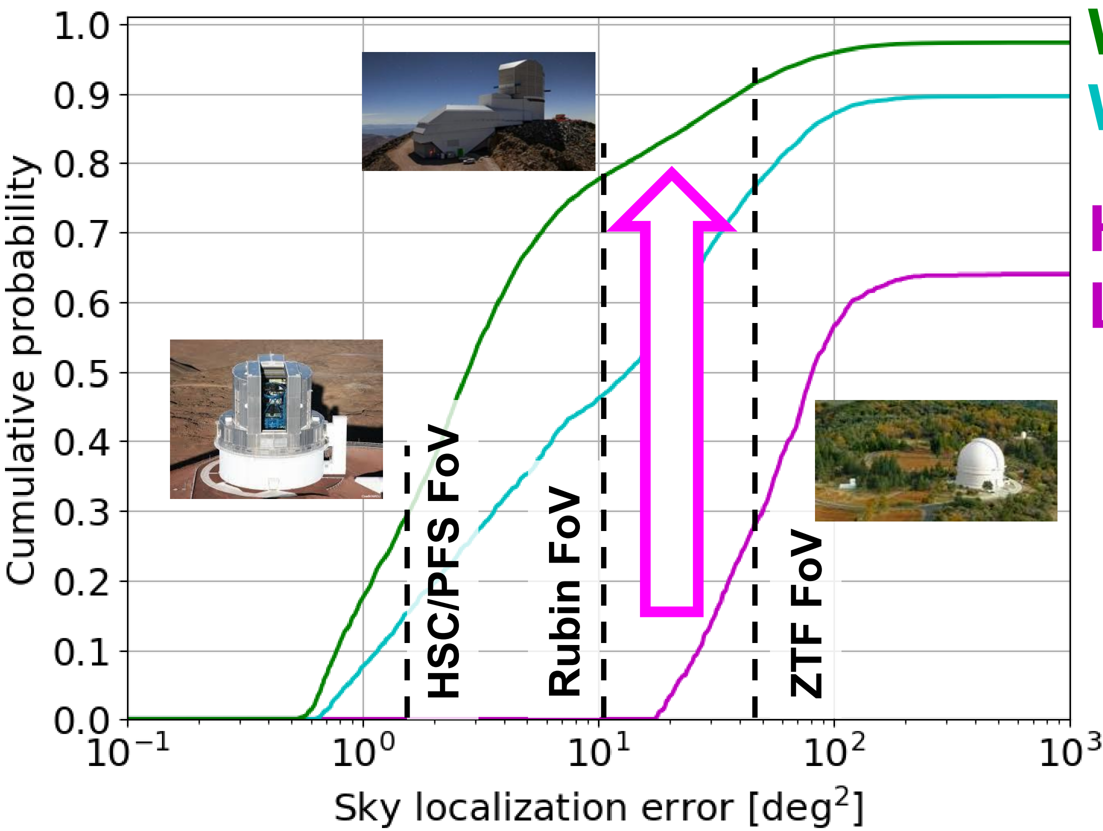
KAGRA (Japan, 3 km, 22 K)

- Various efforts to improve sensitivity



With Addition of KAGRA…

- Better sky coverage and 3+ detector duty factor
- Better sky localization helping multi-messenger
  - 1~5 BNS detections/year localized < 10 deig^2 in O5
  - 5~23 BNS detections/year localized < 10 deig^2 in O6



With KAGRA

With Virgo

Hanford and Livingston

* Fisher analysis for BNS at 100 Mpc
* Single detector duty factor of 80% assumed
* BNS merger rate 90-450 /Gpc^3/yr

See, also:
R. Weizmann Kiendrebeogo+, ApJ 958, 158 (2023)

LIGO-India (4 km, Room Temp.)

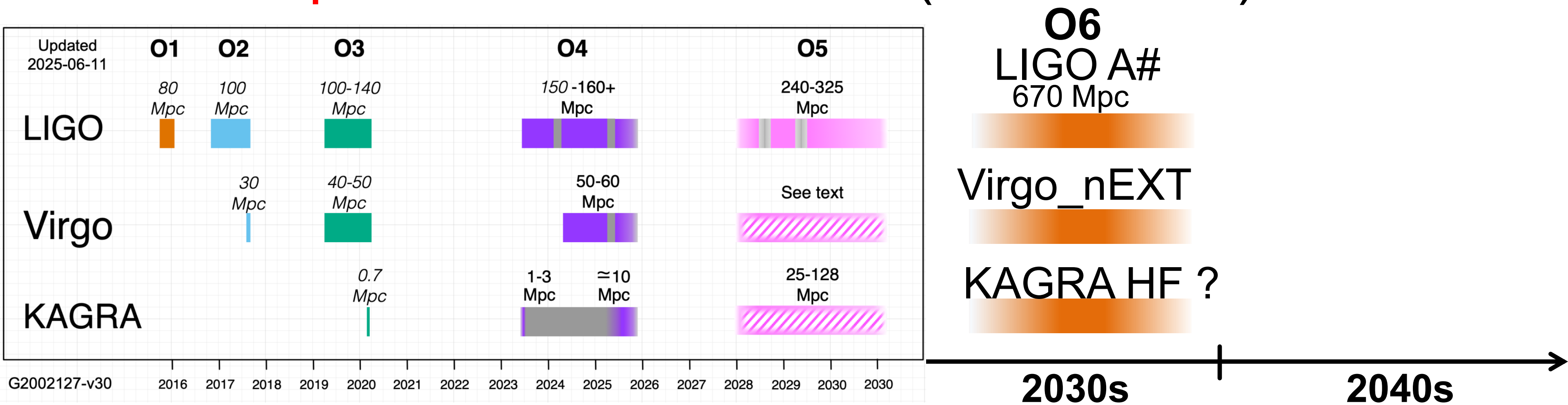
- Aundha site acquired in May 2023
- Being built as the Advanced LIGO configuration
- Aim to be operational in the early 2030s

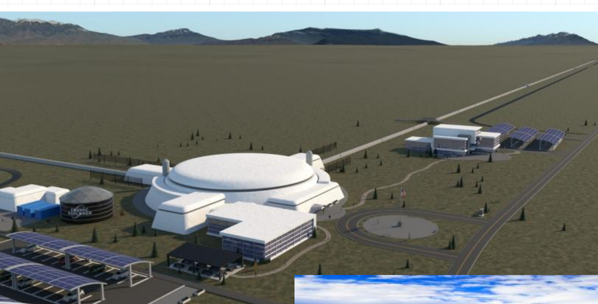
1:1 scale vacuum testing

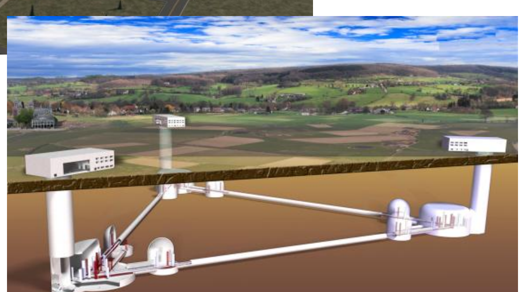
10 m prototype at RRCAT being built for testing and training

Next Generation Detectors

- Next generation detectors coming in late 2030s, with space-based detectors (multi-band!)



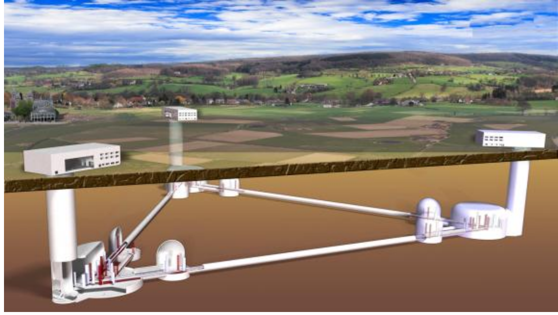




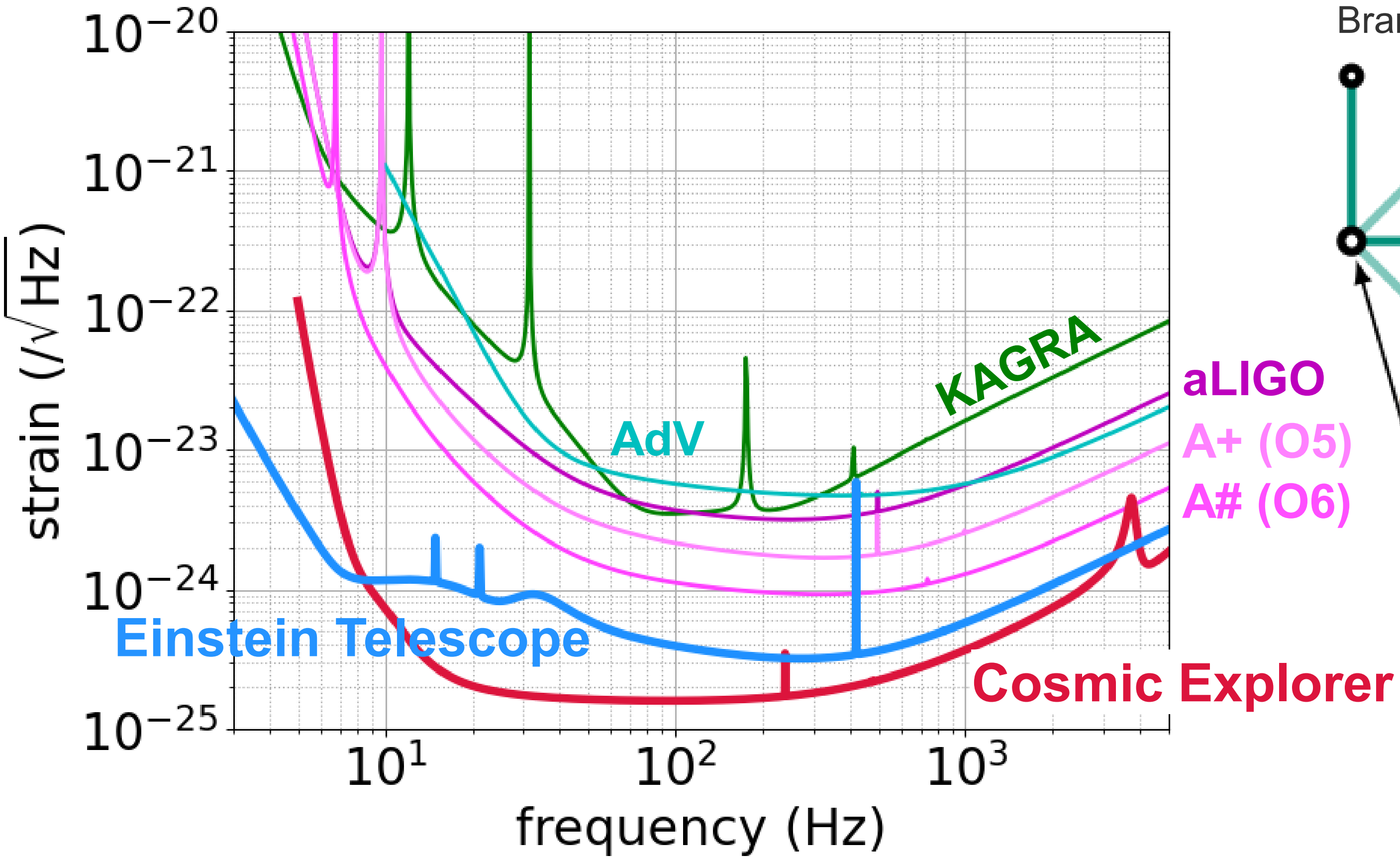
B-DECIGO 

LISA 

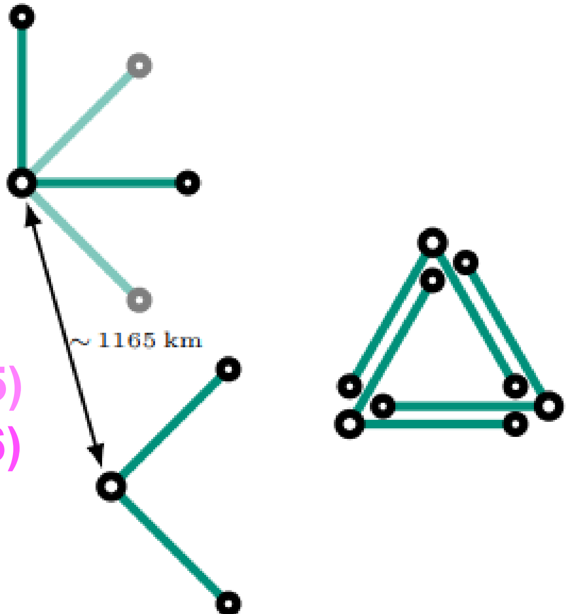
Einstein Telescope

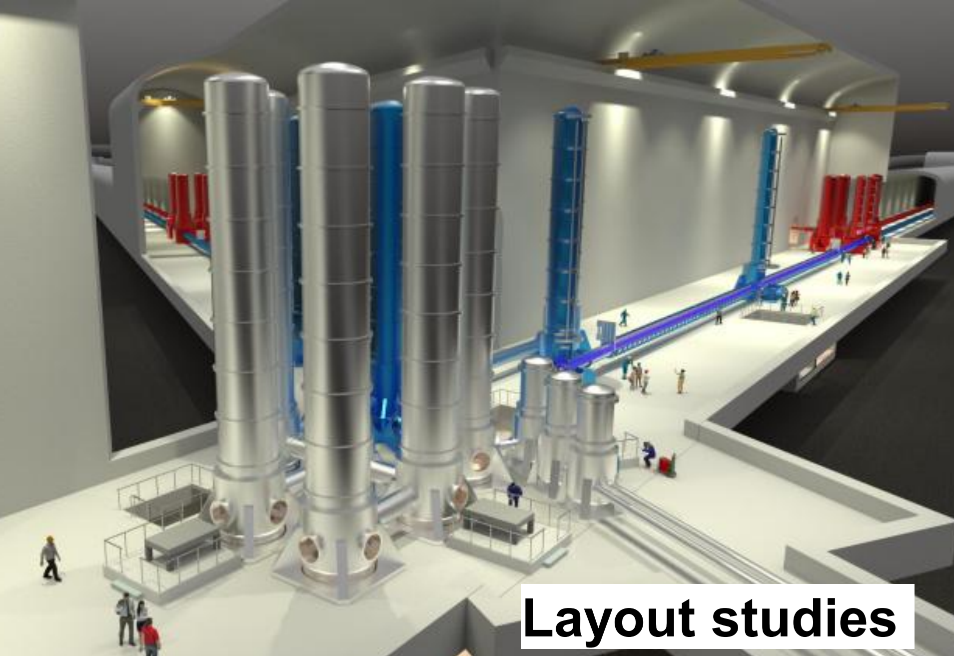


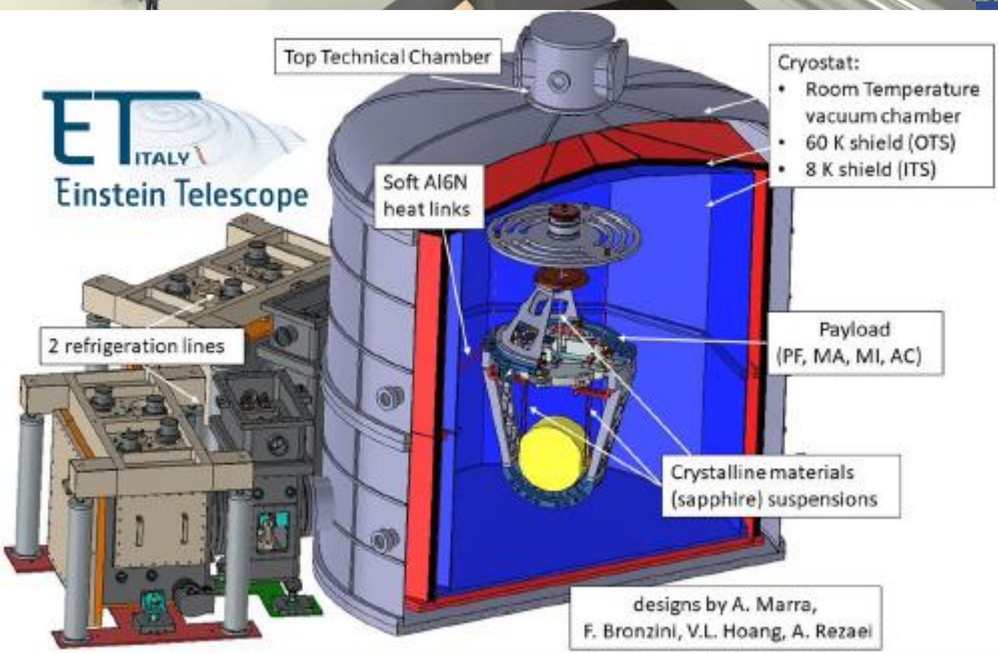
- Xylophone configuration
  - 10 K silicon interferometer for low frequency
  - Room temp. fused silica interferometer for high frequency
- 10 km △ or two 15 km L, underground



Branchesi+, [JCAP 07, 068 (2023)]

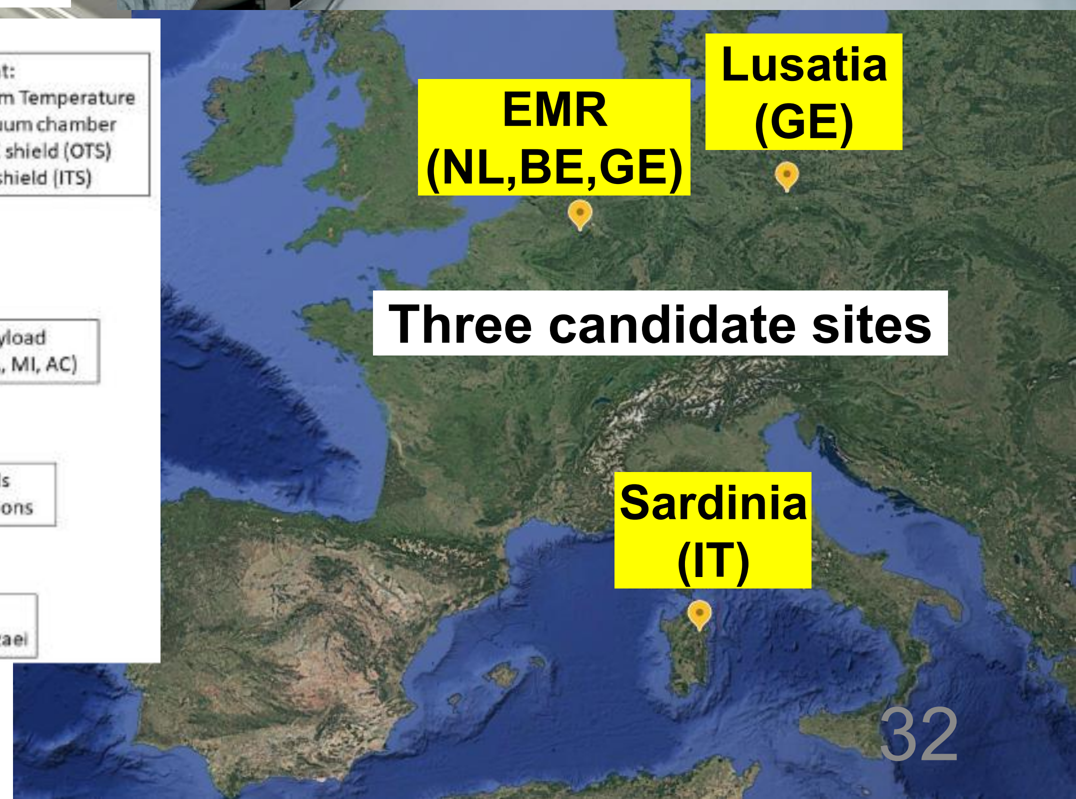






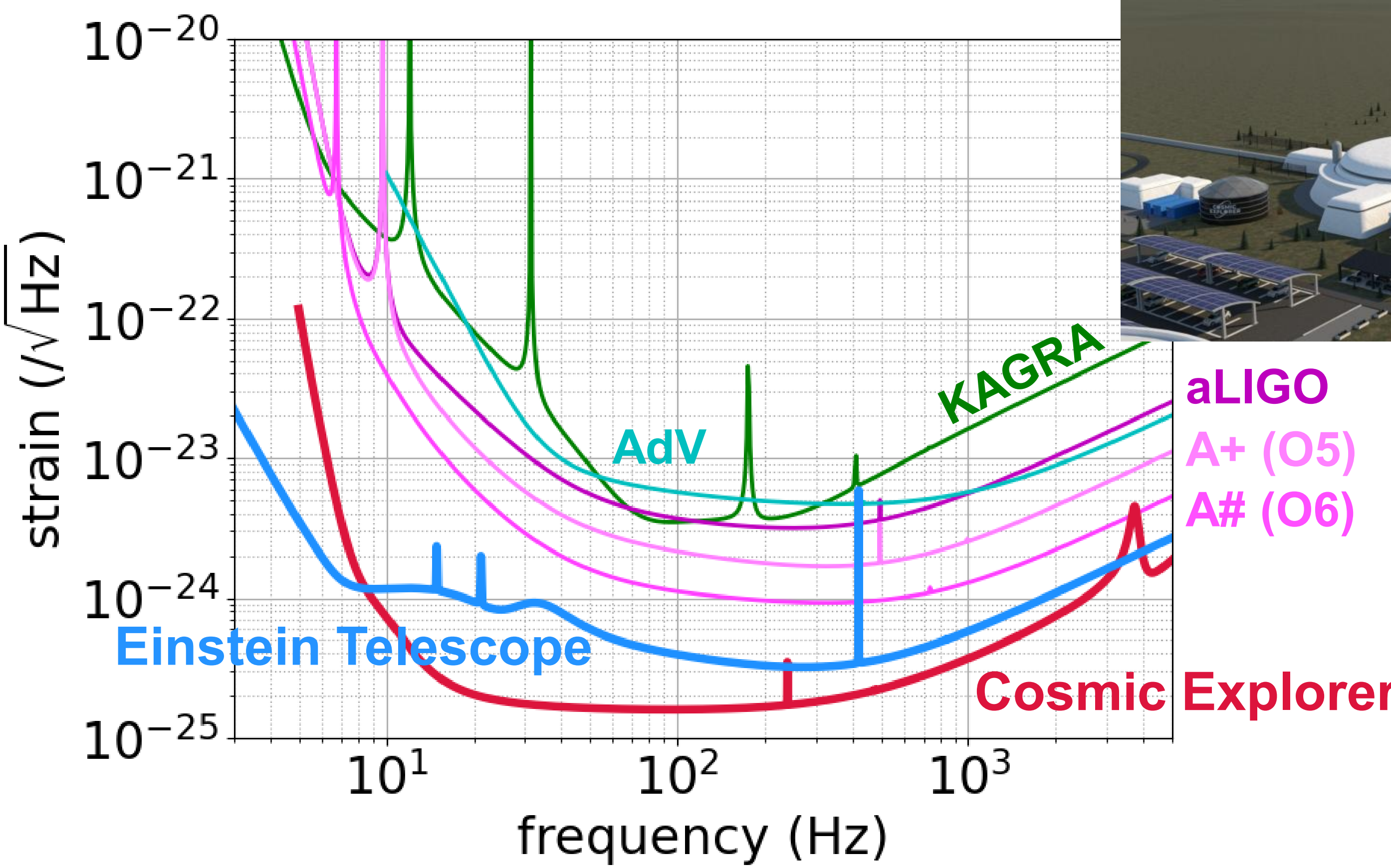
Cryogenic payload in Rome

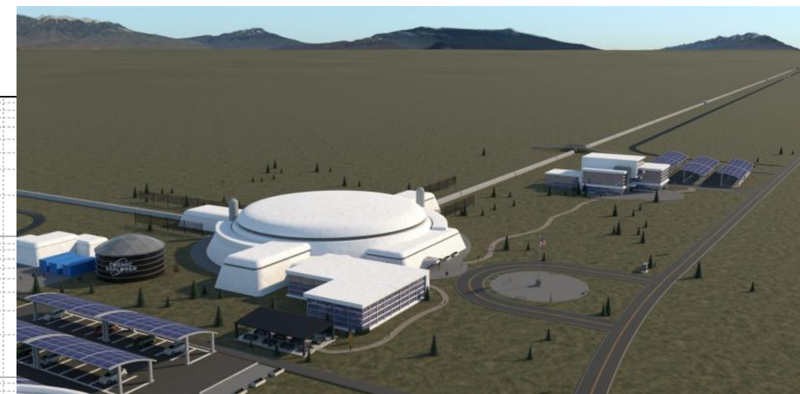
From L. Naticchioni (GWADW2025)

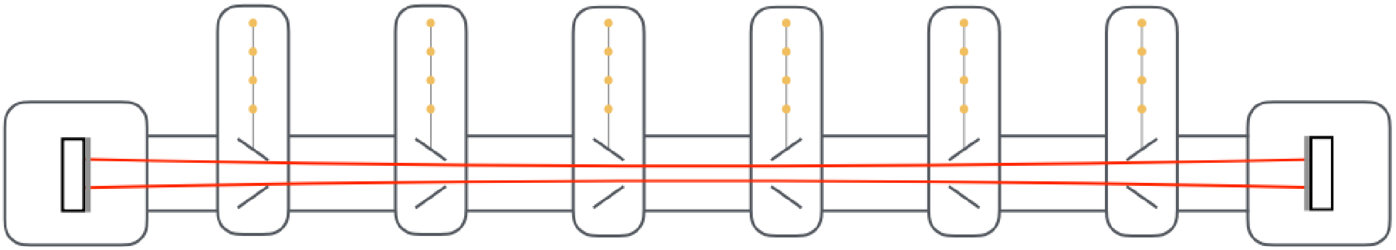


Cosmic Explorer

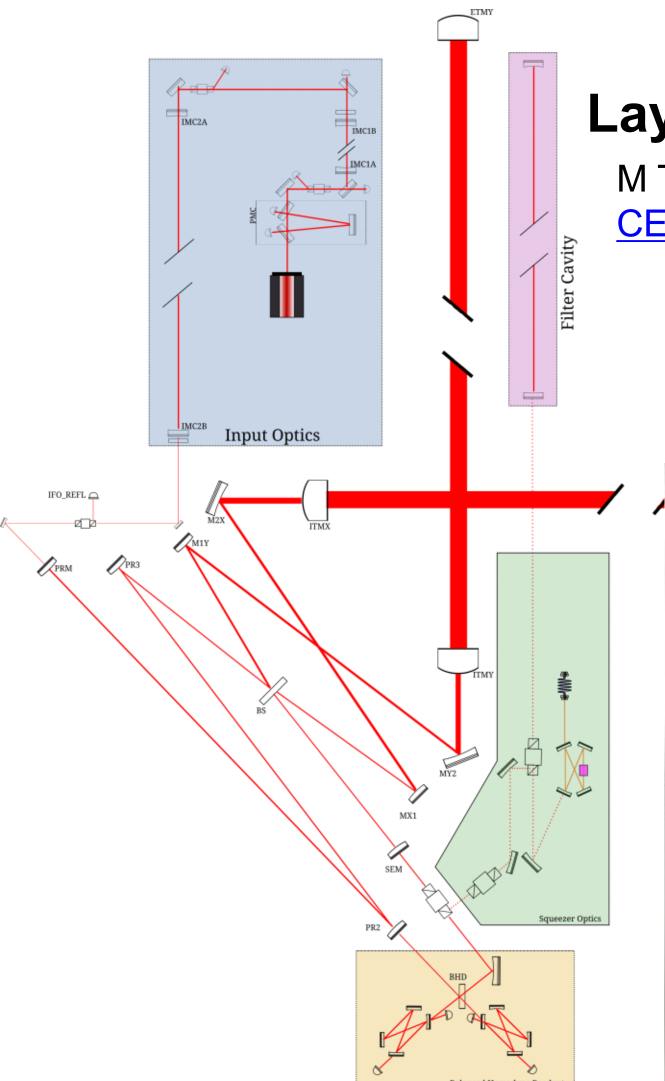
- 40 km and 20 km L-shaped
  - 40 km only if ET in Europe
- Room temp. fused silica (technical overlap with A#)







Stray light mitigation

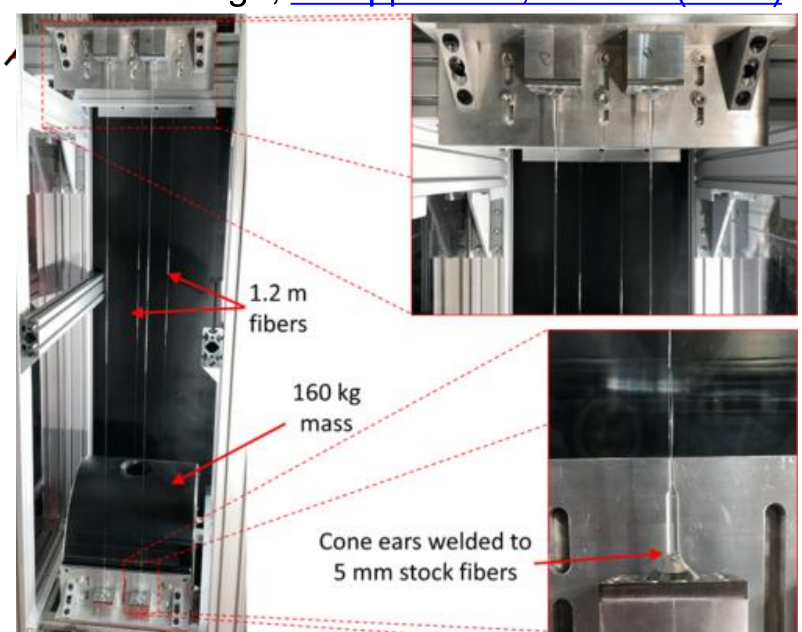


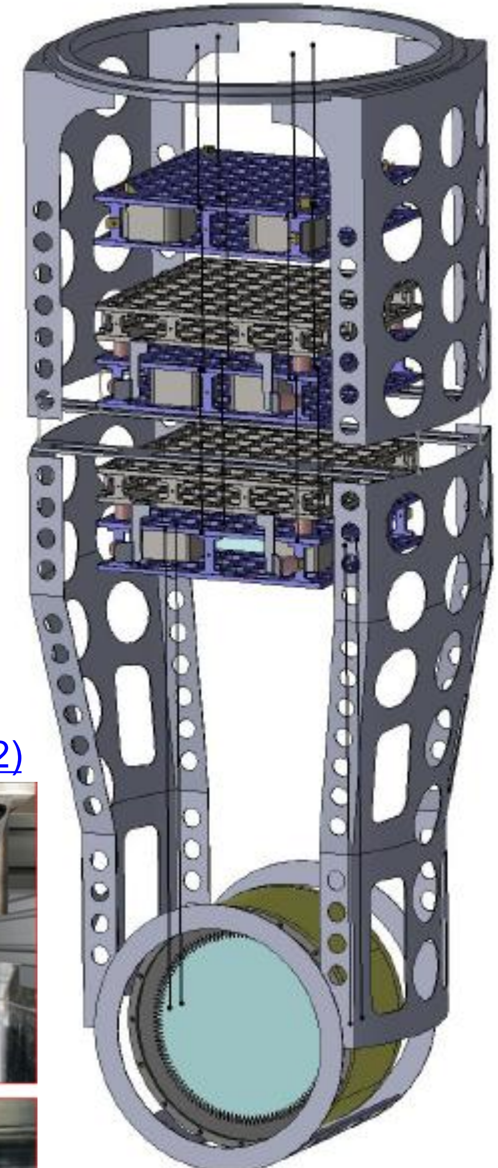
Layout studies

M Todd,
[CE-G2500002]()

Heavy suspension tests

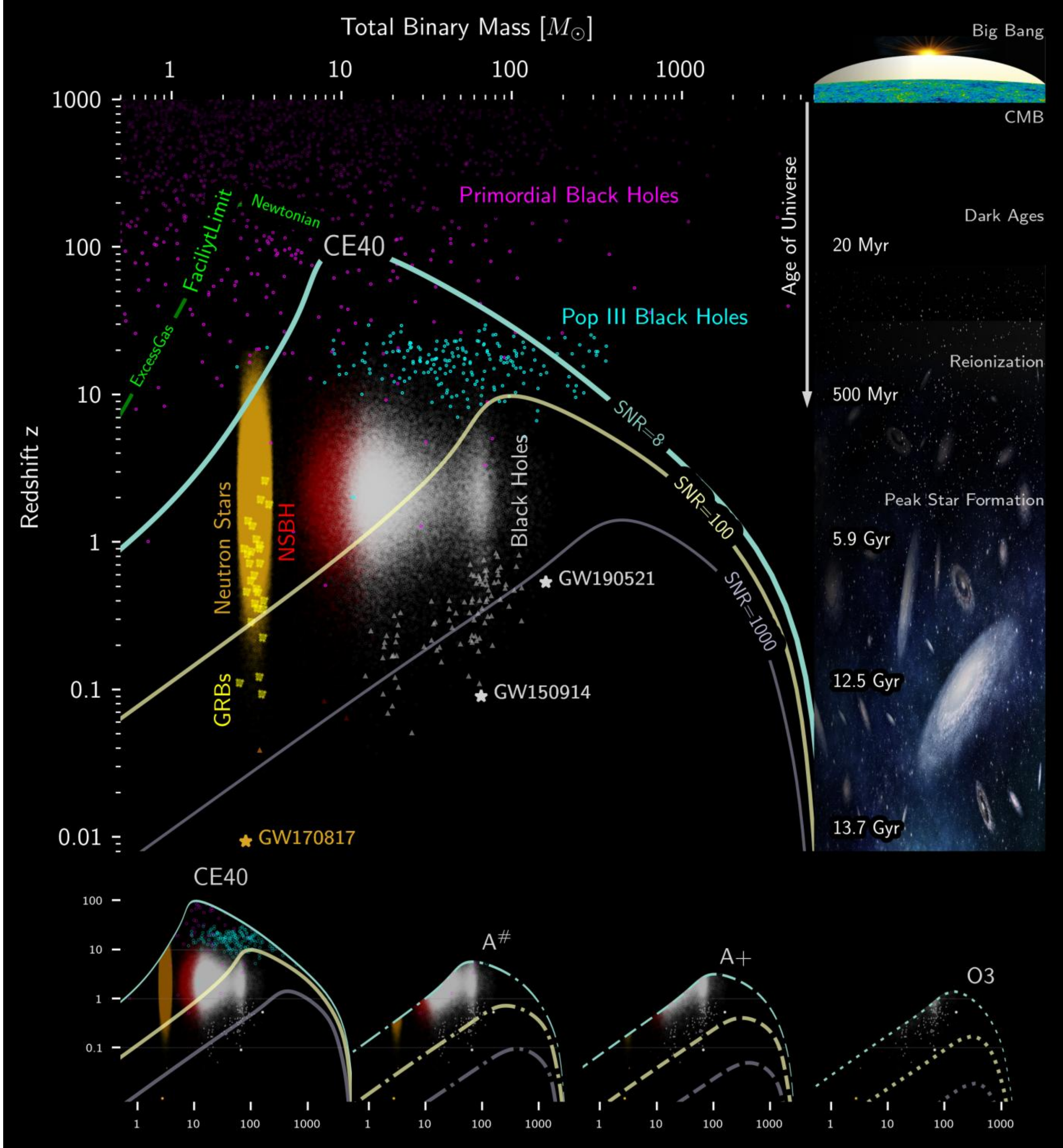
Cumming+, [PRApplied 17, 024044 (2022)]()





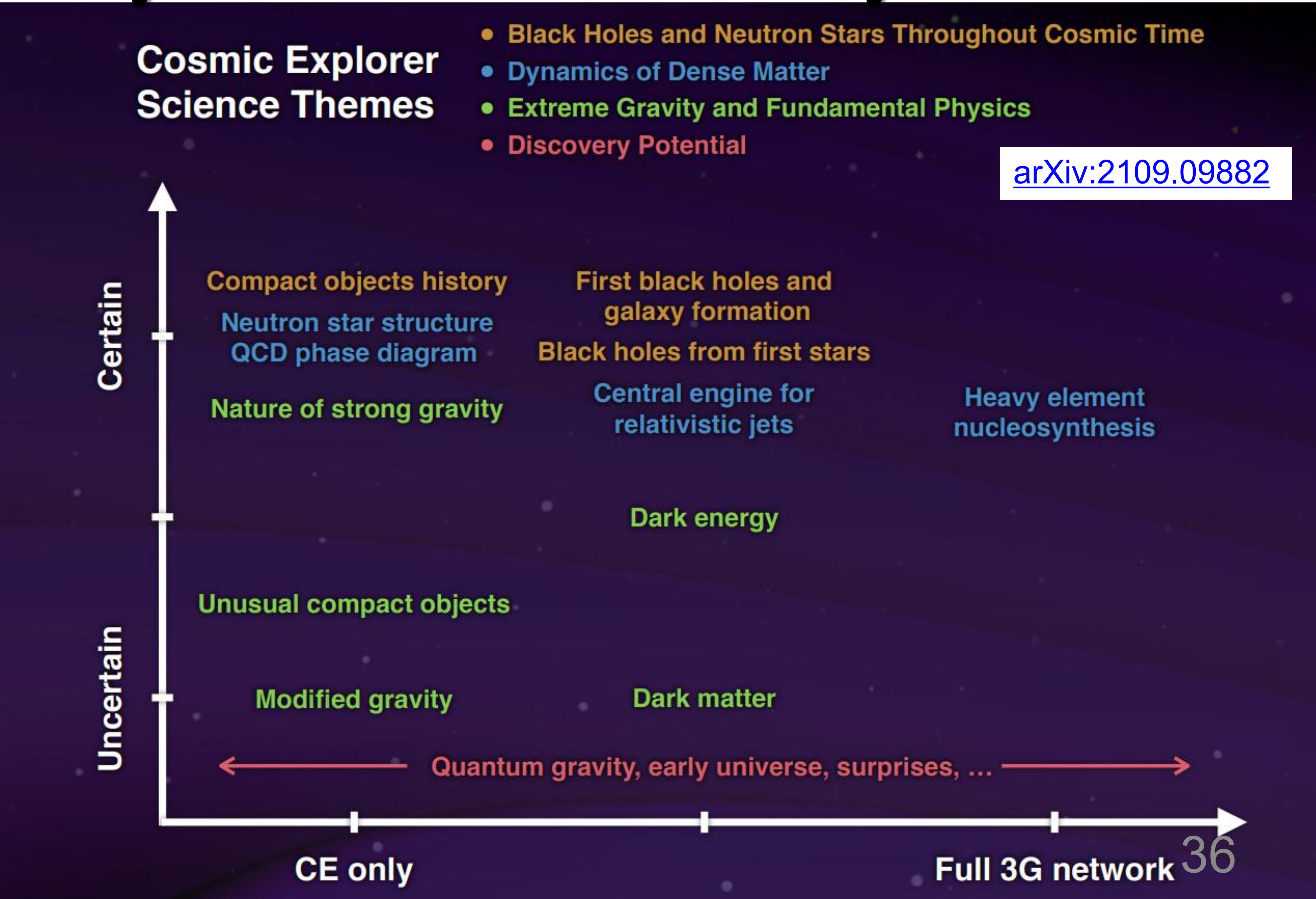
From M. Evans
(GWADW2025)

Next Gen. detectors can observe compact binaries throughout cosmic history

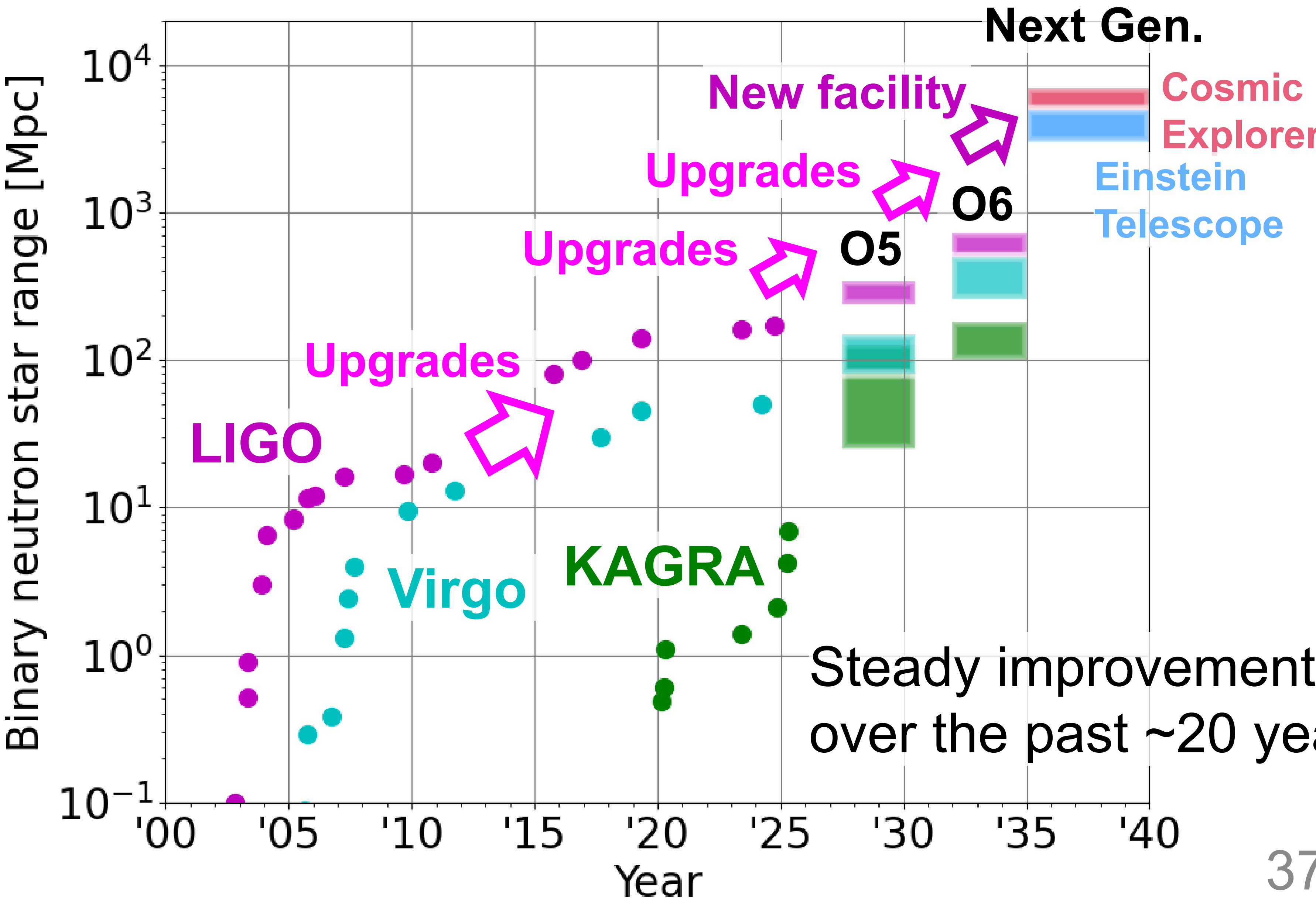


https://gravitationalwaves.syracuse.edu/about/

Key Science Enabled by Next Gen.



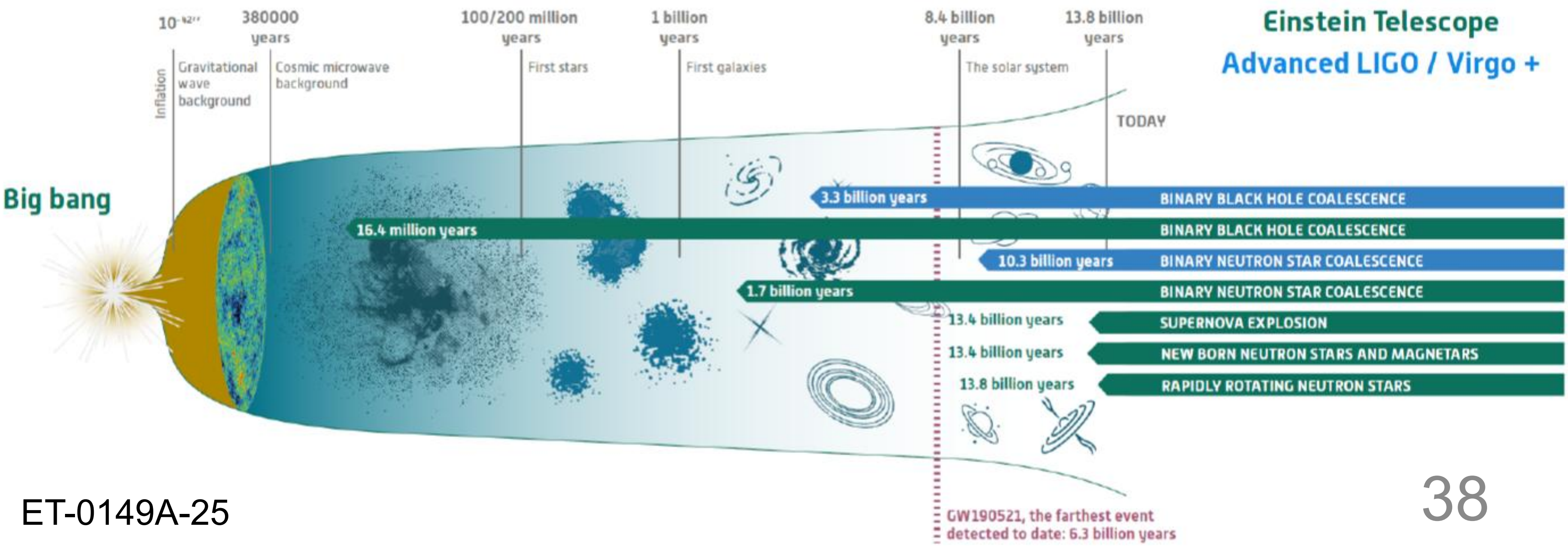
Sensitivity Evolution of LVK



Steady improvements over the past ~20 years

Message: *Future is bright and loud!*

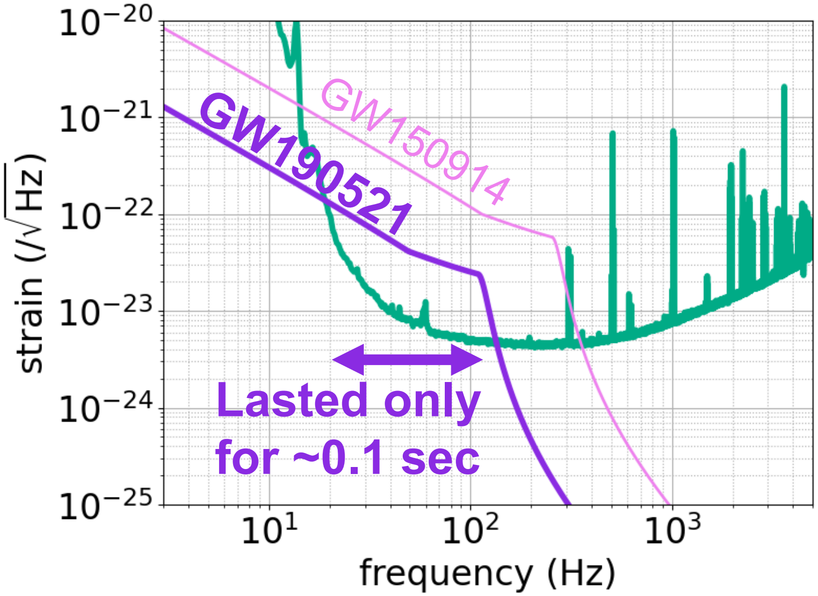
- More events, more multi-messenger events expected in future observing runs, with improved sensitivity and an expanded detector network
- Global efforts are underway to realize next generation detectors capable of observing gravitational waves throughout cosmic history

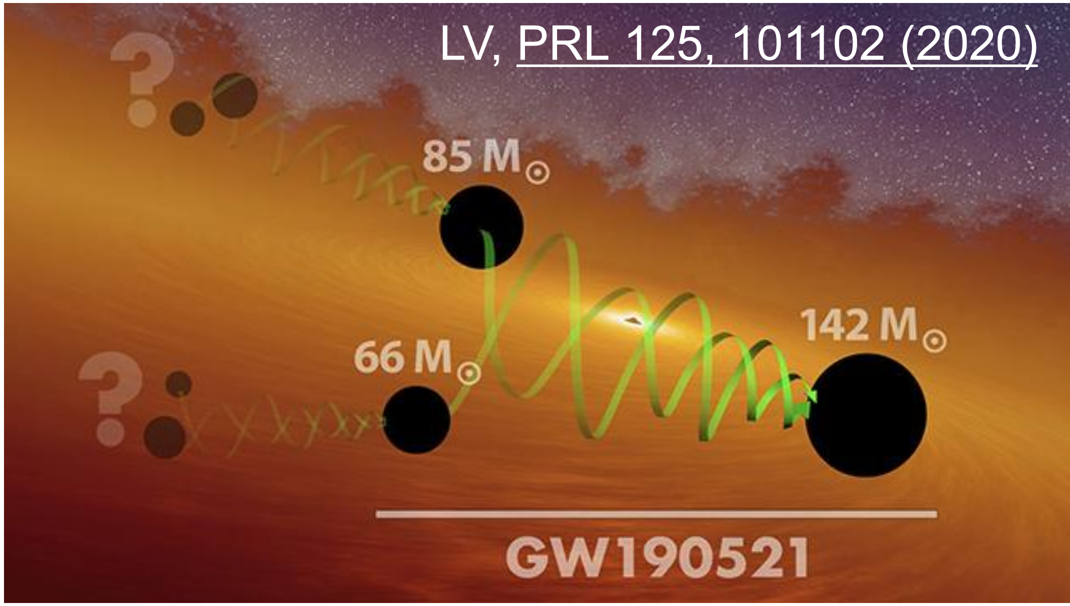


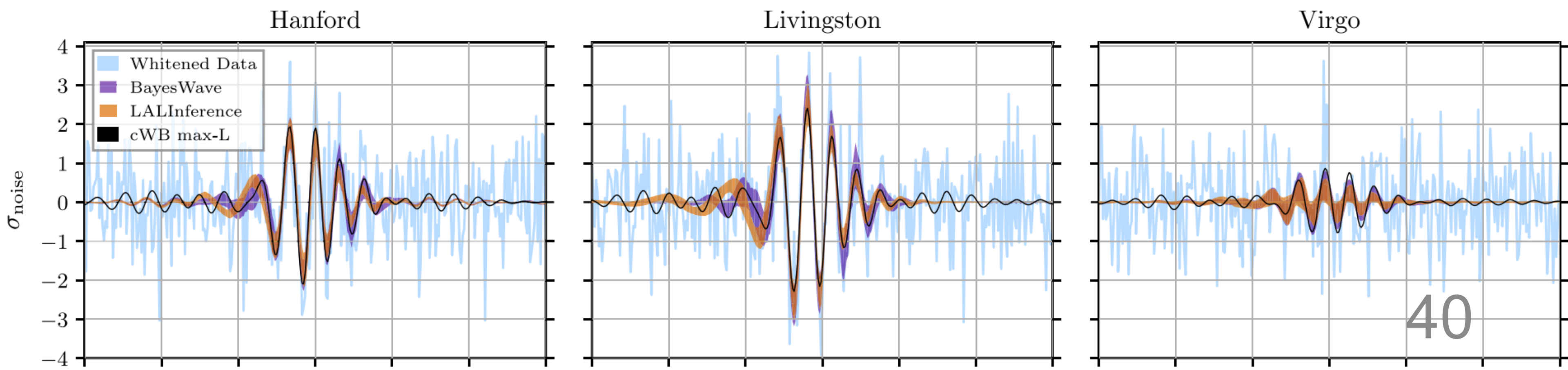
Bonus Slides

GW190521: First IMBH Event

- Low frequency sensitivity need to be improved to see the inspiral, and to detect more of these events

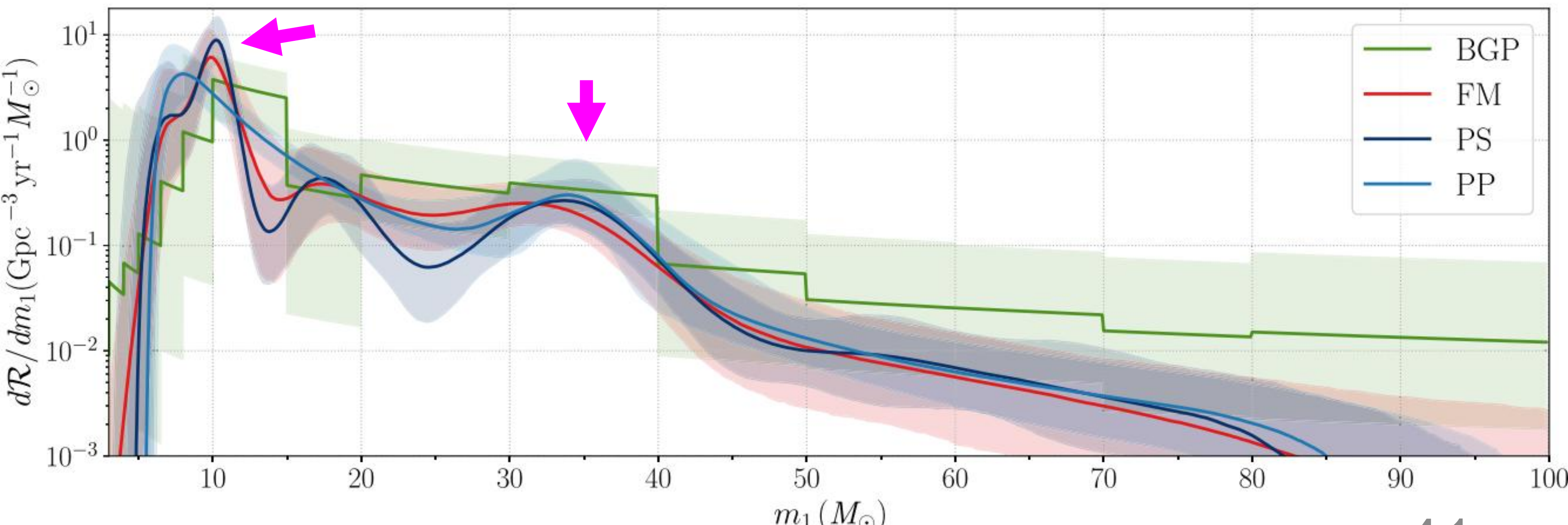






Population Studies

- Peaks at ~10 $M_\odot$ and ~35 $M_\odot$, origin uncertain
- More random spin tilt with respect to orbital axis
  - At least some of them are formed dynamically
- No clear evidence for/against upper mass gap
  - dynamical formation & hierarchical merger?

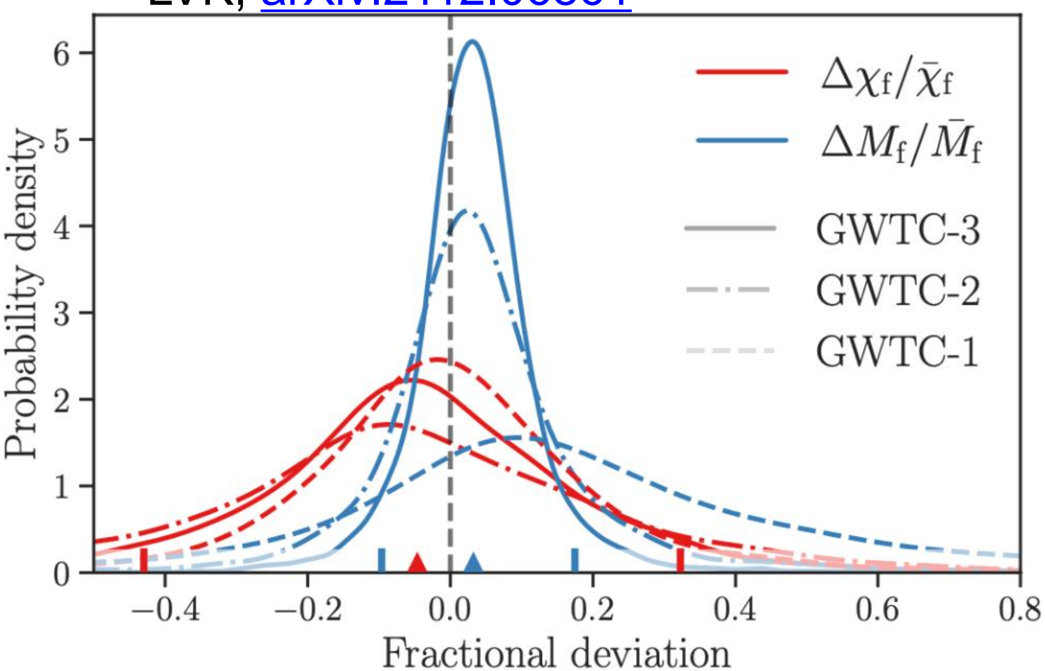


LVK, PRX 13, 011048 (2023)

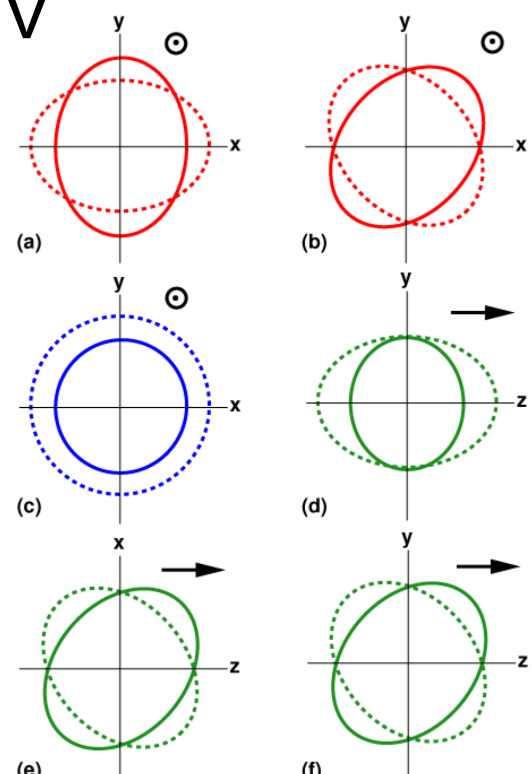
Tests of General Relativity

- Novel tests in strong-field regime
- Inspiral and post-inspiral signals are consistent
- No evidence for beyond-GR polarizations
  - Need for 4+ detectors to distinguish 4+ polarizations
- Graviton mass < 1.3×10^{-23} eV

LVK, arXiv:2112.06861

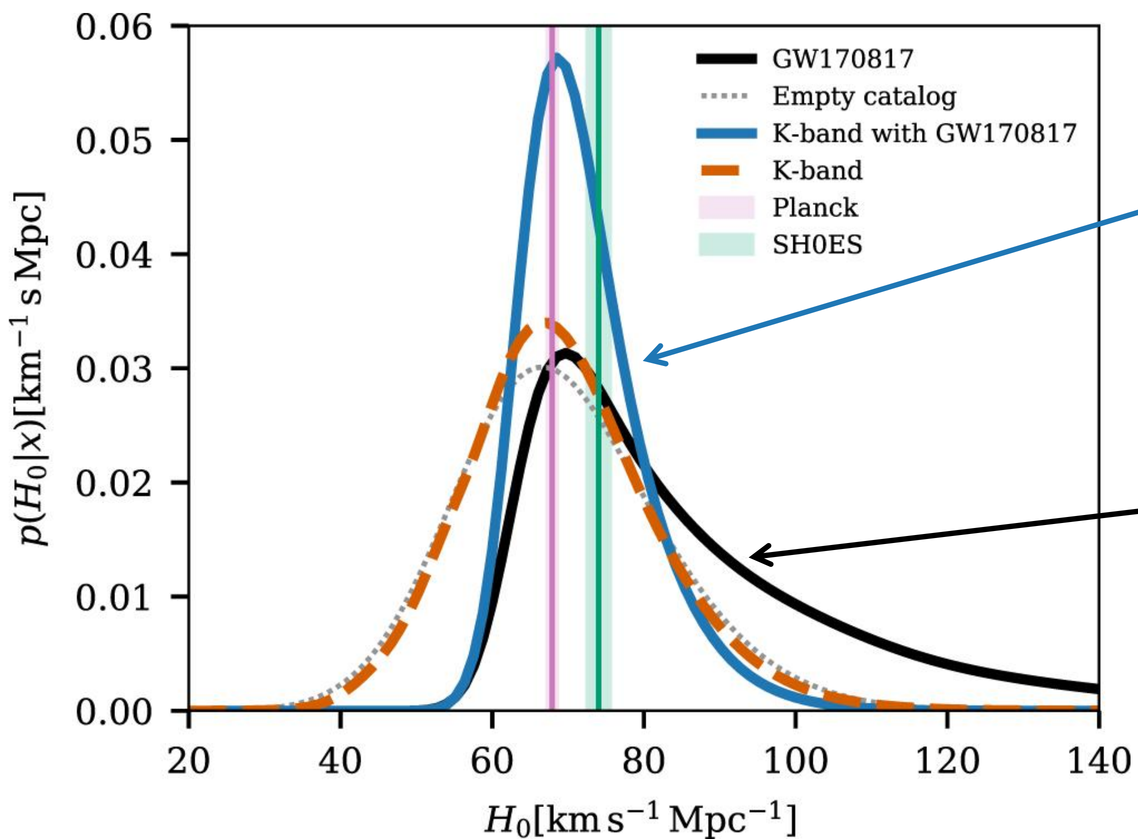


Takeda+, PRD 98, 022008 (2018)



Cosmic Expansion Measurements

- Using luminosity distance measured by GW
- Dark siren also possible by using a galaxy catalog
- Independent test of DESI BAO dynamical dark energy results should be possible in the future e.g. arXiv:2504.04646



With BBH x galaxy catalog

(dependent on assumptions on BBH source mass distribution)

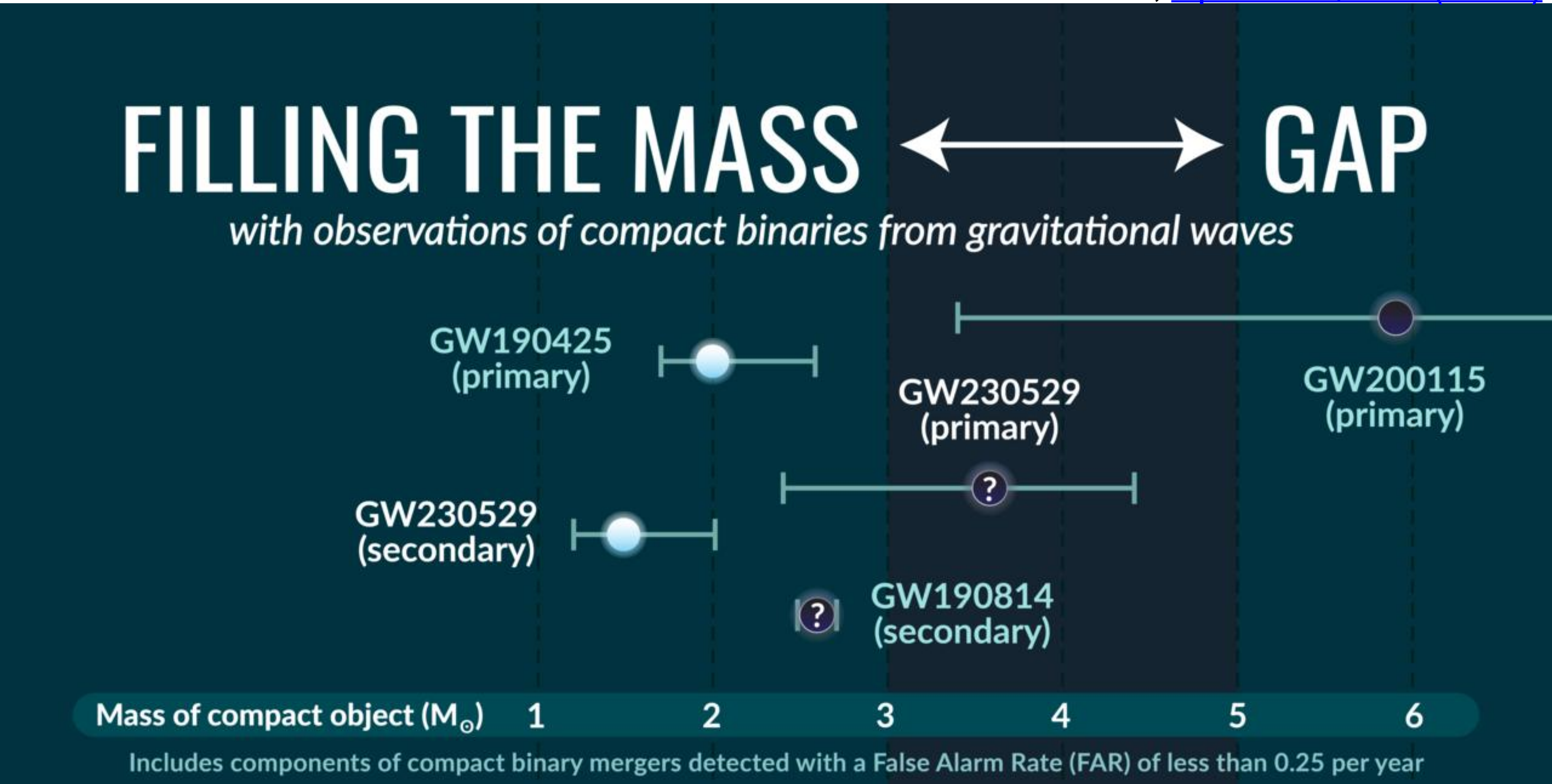
GW170817 only

LVK, ApJ 949, 76 (2023)

GW230529: Lightest NS-BH?

- Single detector event, no EM counterparts

LVK, [ApJL 970, L34 (2024)]



Credit: S. Galaudage, Observatoire de la Côte d’Azur.

Summary of Open Questions

- What is the origin of heavy black holes?
- What are the compact objects in ~3-5 $M_{\odot}$ range?
- After the merger of binary neutron stars?
- What is the origin of heavy elements?
- Test of no-hair theorem with black hole ringdowns
- Hubble tension, dynamical dark energy …

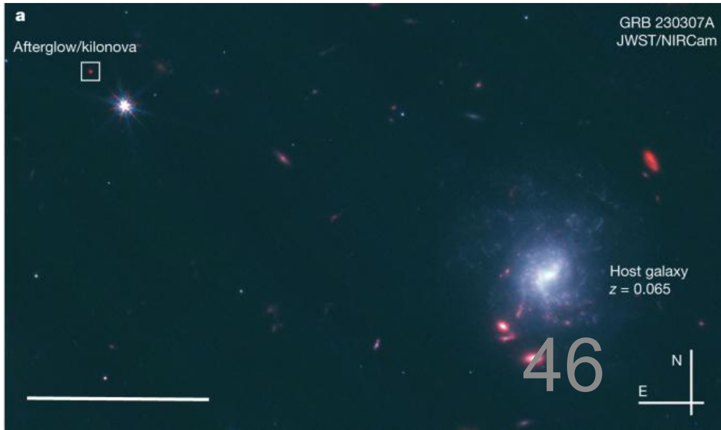
- Continuous waves, bursts from supernovae …

- Clear need for more detectors with better sensitivity
- More multi-messenger detections

Power of Multi-Messenger Obs.

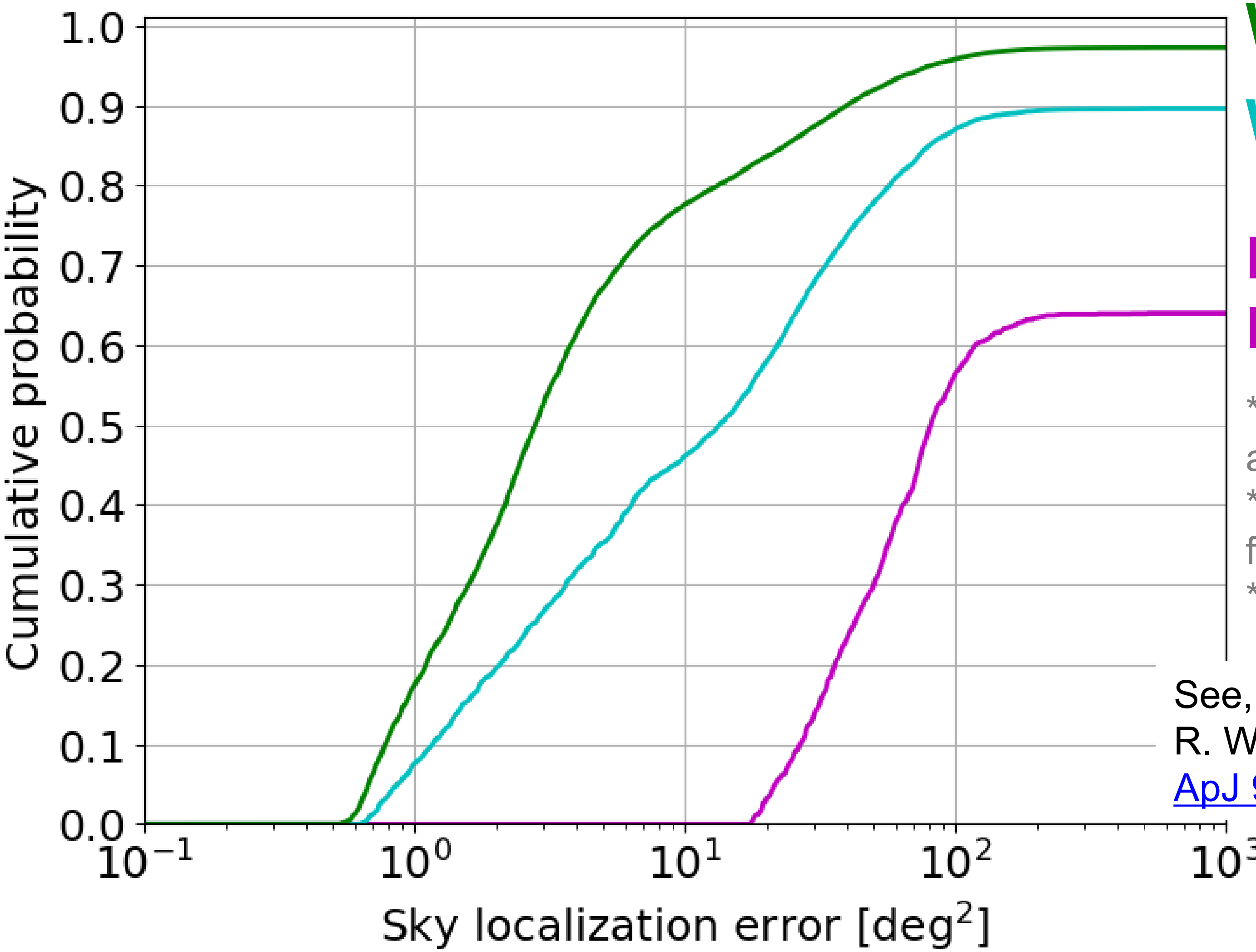
- **GW170817** (**GW** + **EM** event) @ 40 Mpc
  - Localized to 30 deg^2 with Hanford, Livingston, Virgo
  - GW from BNS merger, short GRB, kilonova detected
- **GW190425** (**GW** only event) @ 159 Mpc
  - Localized to ~8000 deg^2 with Livingston, Virgo
  - GW from BNS merger, no EM counterpart
  - Probably prompt collapse to BH??
- **GRB211211A** (**EM** only event) @ ~350 Mpc
- **GRB230307A** (**EM** only event) @ ~300 Mpc
  - GW detectors not operating
  - BNS merger??
  - Long GRB
  - kilonova spectrum different from GW170817 (really BNS??)

Levan+, [Nature 626, 737 (2024)]



Sky Localization in O5 (2028~)

- 1~5 BNS detections per year localized < 10 deg^2

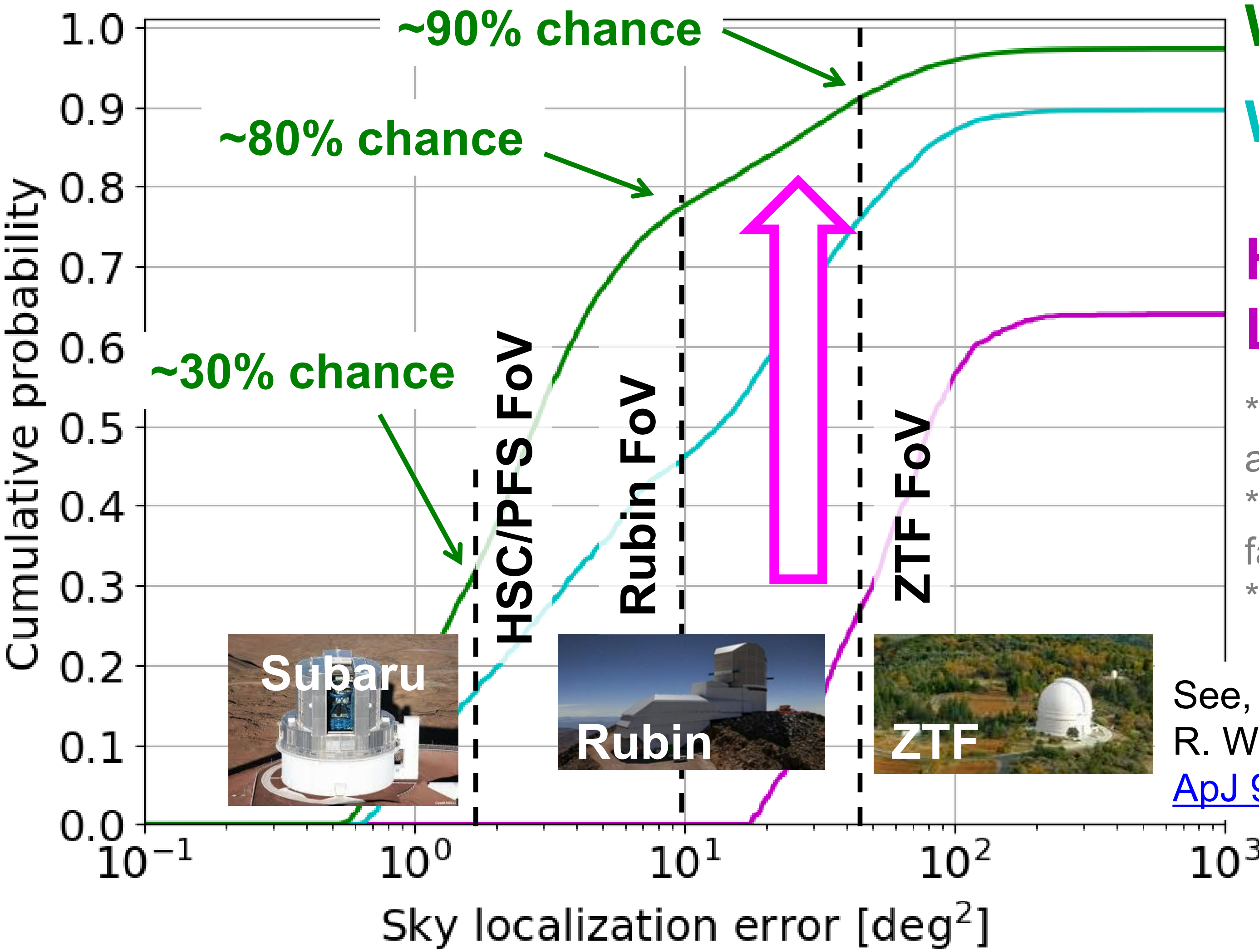


* Fisher analysis for BNS at 100 Mpc
* Single detector duty factor of 80% assumed
* BNS merger rate 90-450 $/Gpc^3/yr$

See, also:
R. Weizmann Kiendrebeogo+, ApJ 958, 158 (2023)

Sky Localization in O5 (2028~)

- 1~5 BNS detections per year localized < 10 deg^2



With KAGRA

With Virgo

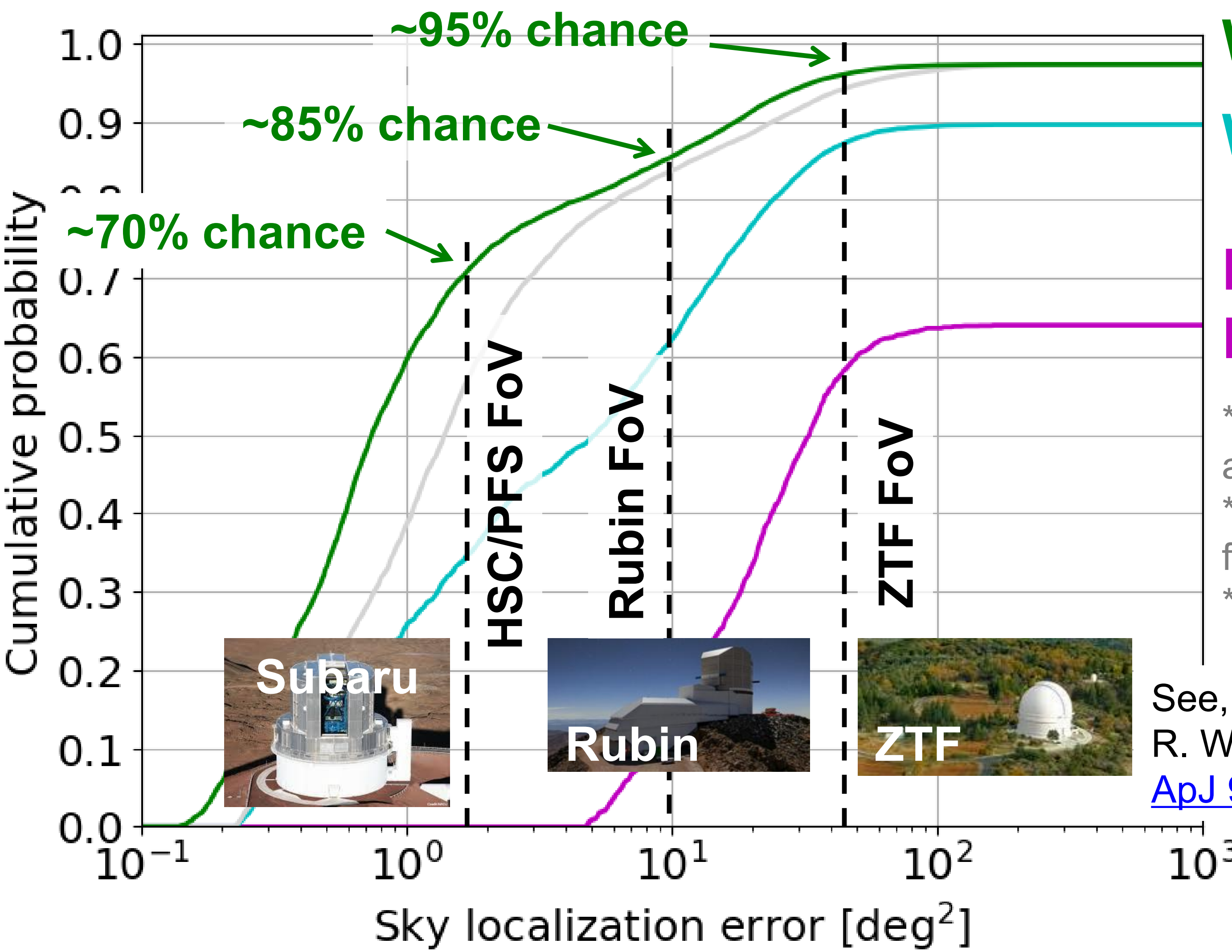
Hanford and Livingston

* Fisher analysis for BNS at 100 Mpc
* Single detector duty factor of 80% assumed
* BNS merger rate 90-450 /Gpc^3/yr

See, also:
R. Weizmann Kiendrebeogo+, [ApJ 958, 158 (2023)]

Sky Localization in O6 (2030+)

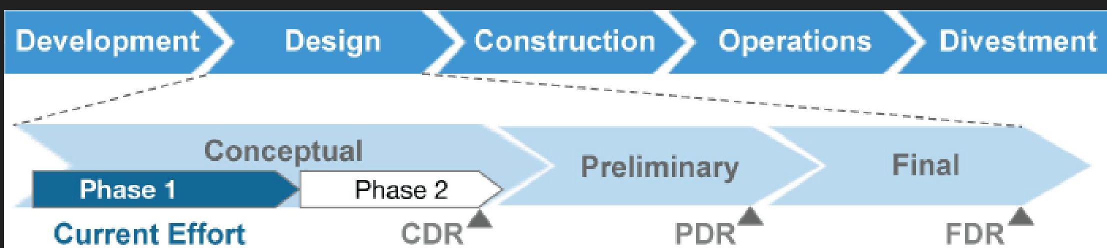
- 5~23 BNS detections per year localized < 10 deg^2



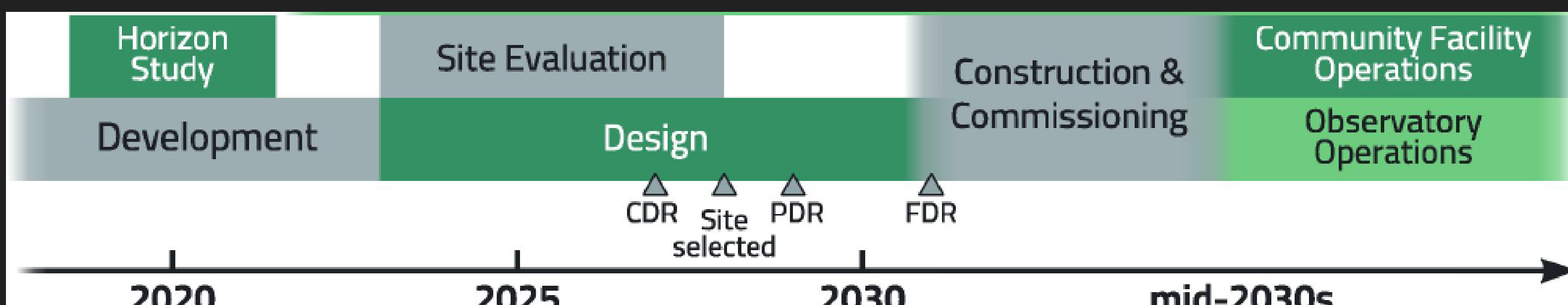
* Fisher analysis for BNS at 100 Mpc
* Single detector duty factor of 80% assumed
* BNS merger rate 90-450 /Gpc^3/yr

See, also:
R. Weizmann Kiendrebeogo+, ApJ 958, 158 (2023)

Cosmic Explorer Timeline



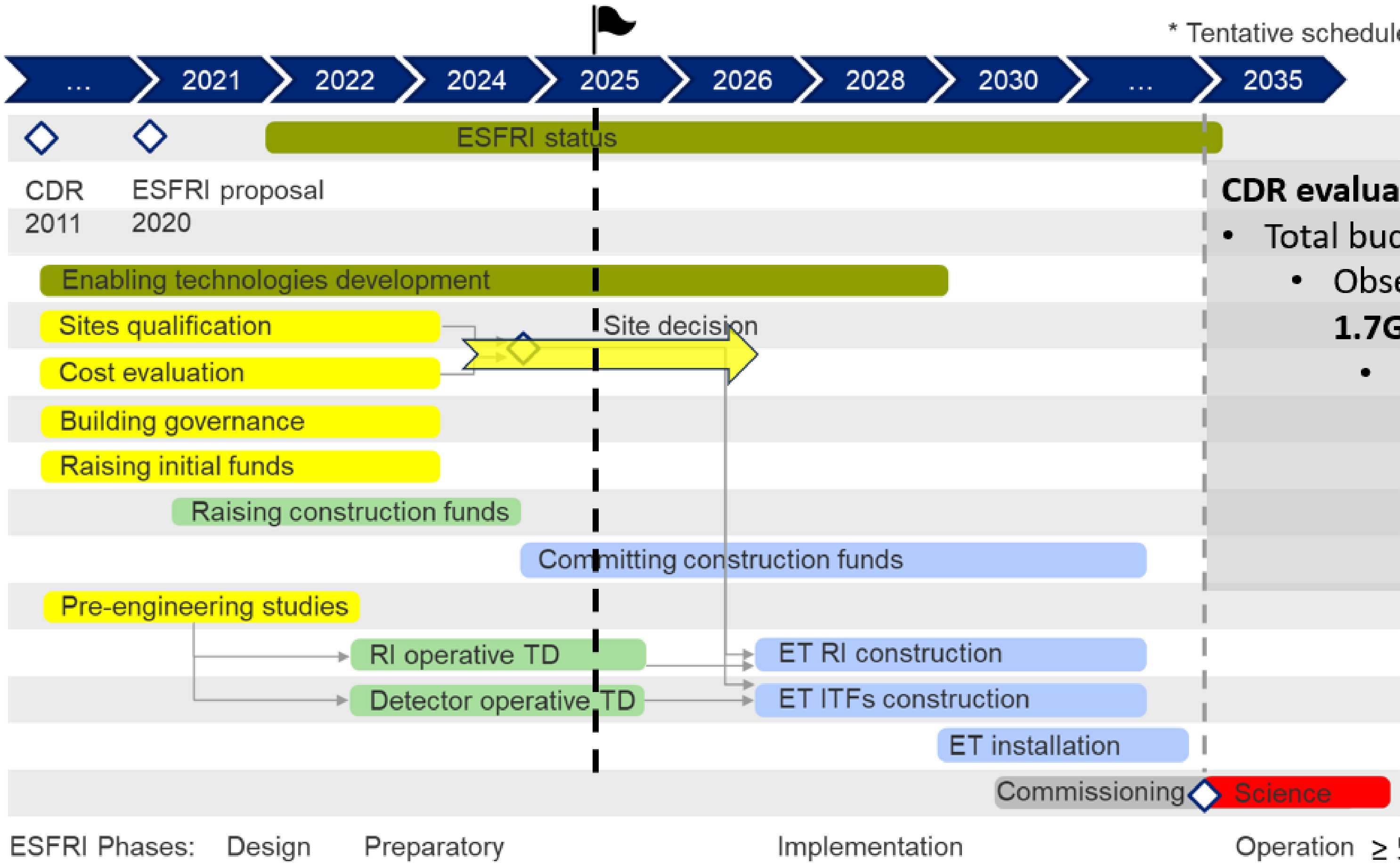
- Project progress
  - Conceptual Design (3+years)
  - Preliminary Design ~$75M (2-3 years)
  - Final Design ~$100M (2 years)
  - Construction ~$1-2B (5 years)
  - Operations ~$60M / year (50 years?)
  - Decommissioning/Divestment



From M. Evans (GWADW2025)

Einstein Telescope Timeline

ET timeline and costs as presented to ESFRI



CDR evaluations:

- Total budget ~ **2G€**
  - Observatory budget ~ **1.7G€**
    - Infrastructure Budget:
      - Civil infrastructure: **~930M€**
      - Vacuum system: **~570M€**

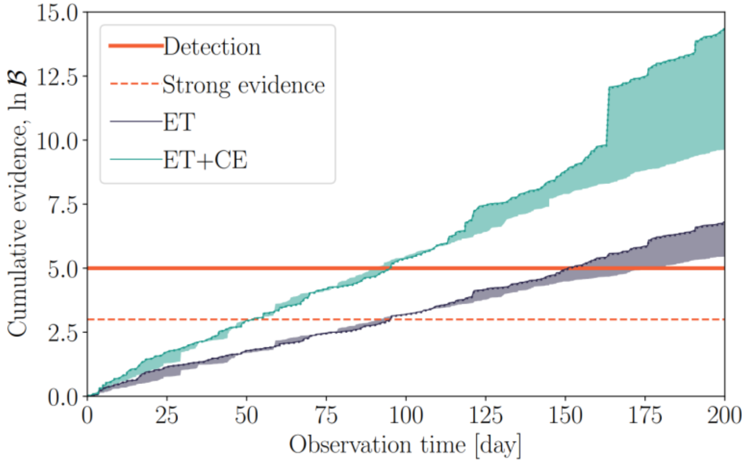
Currently evaluating realistic costs based on engineering feasibility studies at EMR and Sardinia

From L. Naticchioni

The version presented to ESFRI in 2021. Not updated.

Next Gen. Science Personal Picks

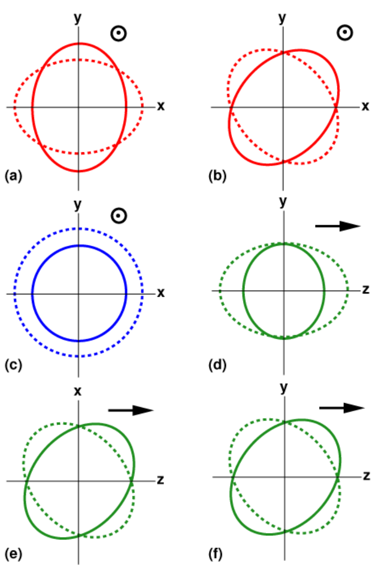
Displacement and Spin Memory



Permanent shift in the displacement and twist of the spacetime could be detected by ET and CE

Goncharov, Donnay, Harms, [PRL 132, 241401 (2024)]

Polarization and Sky Localization



	Parameter	BNS (ET-D—ET-D)	BNS (ET-D—CE)	BNS (CE-CE)
	SNR	75.2	120	151
Model TS1	$\Delta \ln d_L$	0.0520	0.124	0.569
	$\Delta\Omega_s[\mathrm{deg}^2]$	0.346	0.643	3.51
	ΔA_{S1}	0.0797	0.178	0.913

Takeda+, [PRD 100, 042001 (2019)]

More polarization can be resolved & better sky localization with ET and CE due to low frequency sensitivity and Earth rotation