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Preparing KAGRA for the Era of Multi-Messenger Astronomy

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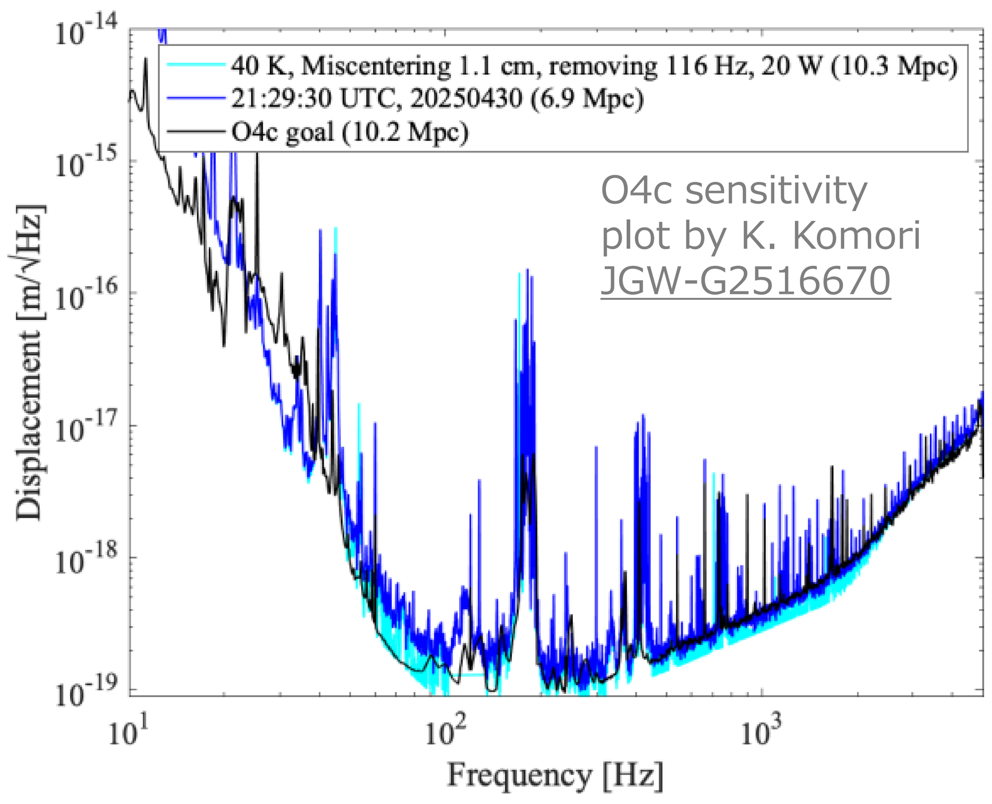
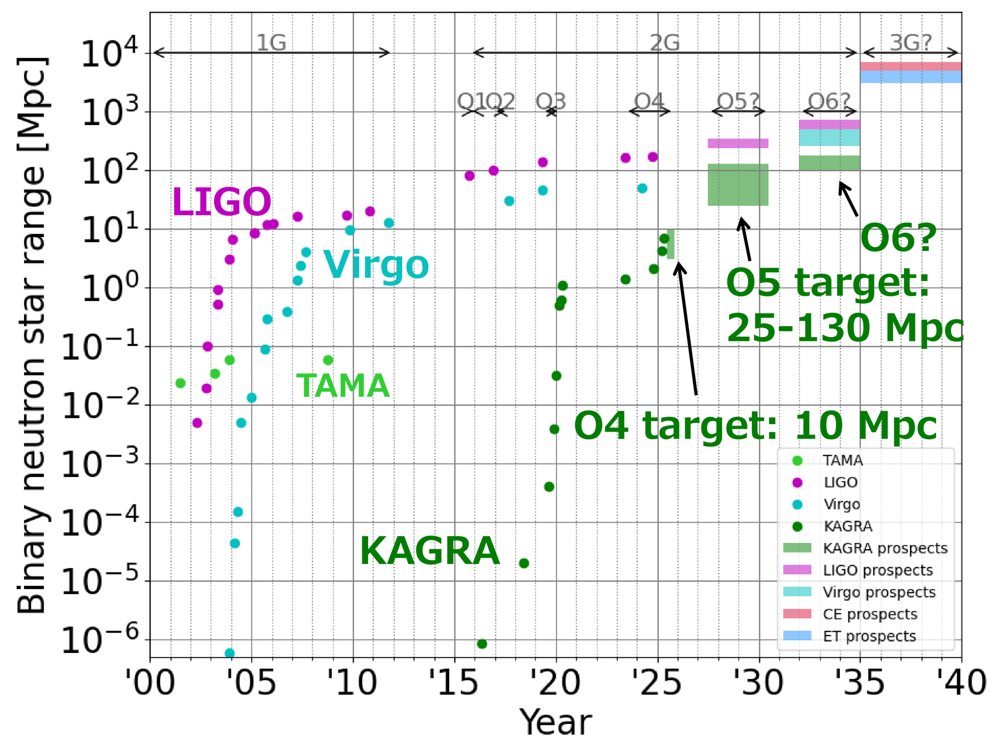
The LIGO-Virgo-KAGRA collaboration has detected over 300 events so far, but multi-messenger observations have only been realized once, with GW170817. GW190425, which is believed to have originated from a binary neutron star (BNS) merger, had poor sky localization, and there have also been events, such as GRB211211A and GRB230307A, that were missed because gravitational wave detectors were not operational at the time. In this context, **improving sky localization and increasing the duty cycle of multiple detectors through KAGRA's operation and upgrades is becoming increasingly important**. This will be essential for capturing the rare BNS merger events and achieving the sky localization precision required for electromagnetic follow-up observations.

O4c Target: 10 Mpc

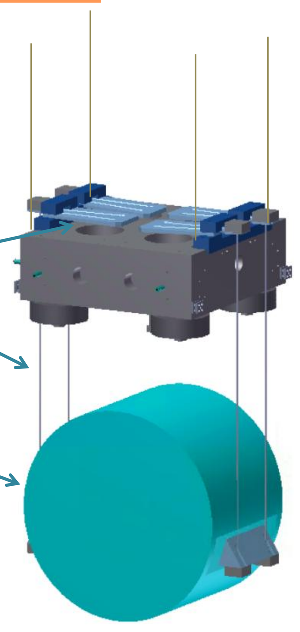
- BNS range of 6.9 Mpc achieved with 90 K, 10 W input
- 10 Mpc target can be achieved by 40 K, 20 W input, removing 116 Hz peak

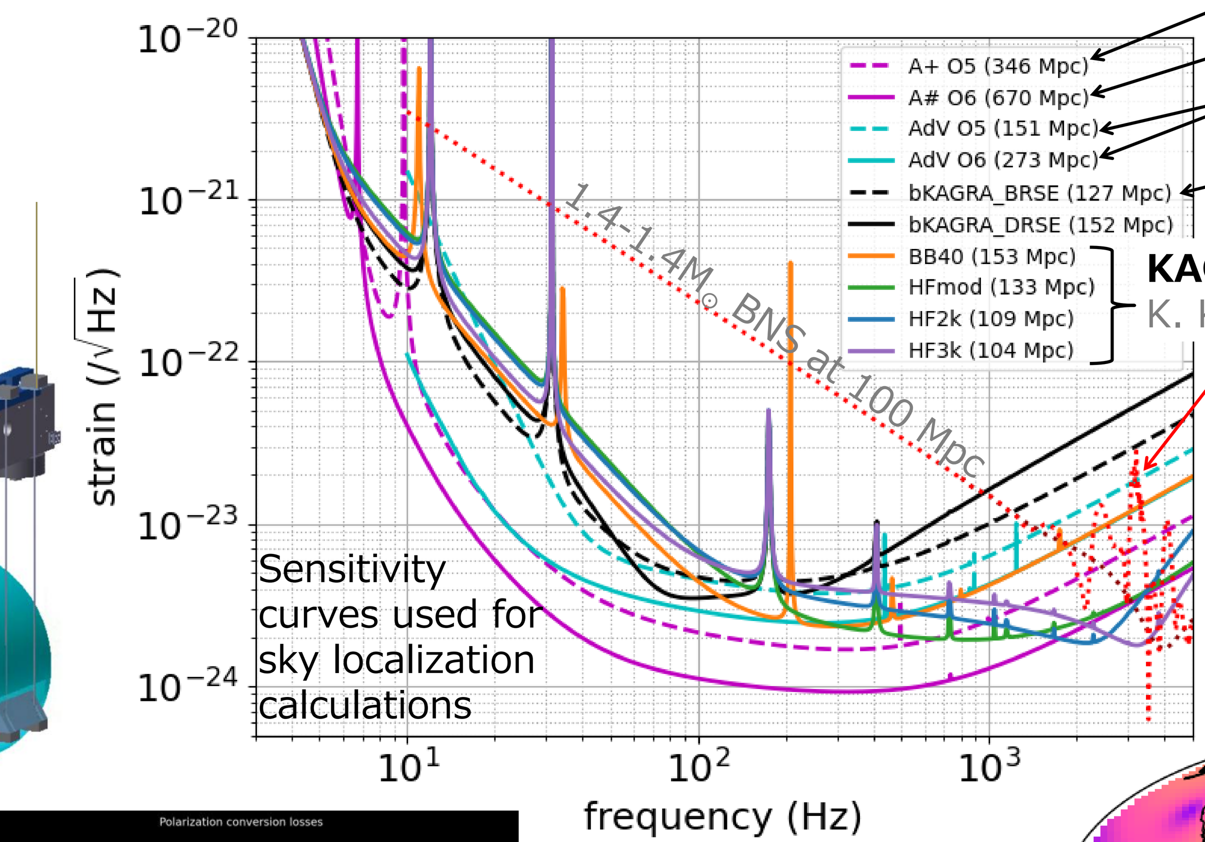




O5 Target: 25-130 Mpc

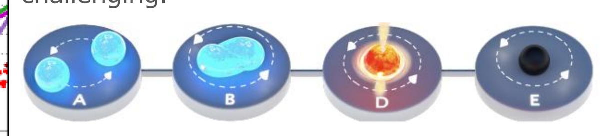
- Less birefringent ITMs under final polishing
- Better OMC vibration isolation and in-vac PD/QPDs under development
- Higher Q suspensions and mirrors required for 50+ Mpc
  - Sapphire blade spring loss angle: 3.6×10^{-5} (Design: 7×10^{-7})
  - Sapphire suspension loss angle: 10^{-5} to 10^{-4} at 80 K (Design: 2×10^{-7})
  - Sapphire mirror loss angle: 1×10^{-6} at 80 K (Design: 1×10^{-8})
- Achieving 127 Mpc would allow us to improve BNS sky localization at 135 Mpc from HLV 1.55 deg² to HLVK 0.81 deg² (median)

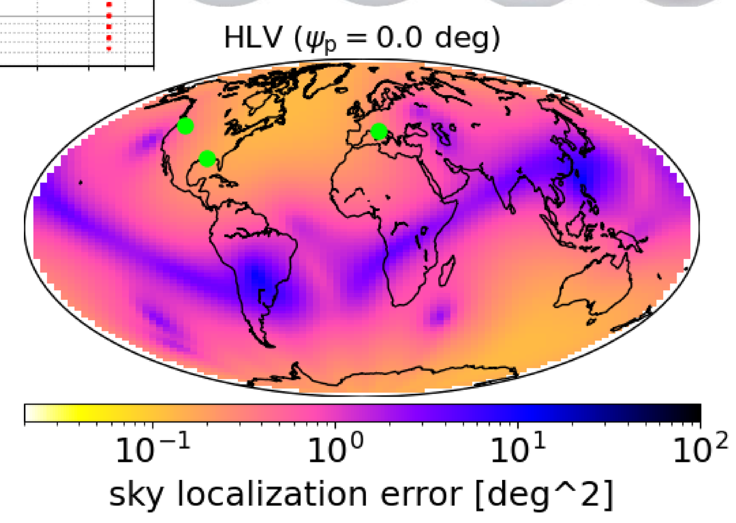




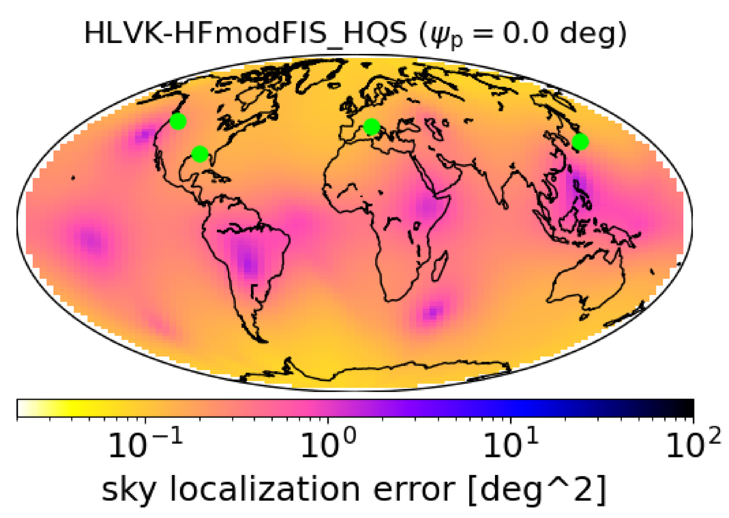
LIGO-T1800042
LIGO-T2300041
LIGO-T2000012
KAGRA O5 High
KAGRA O6 options: K. Komori, JGW-L2516564

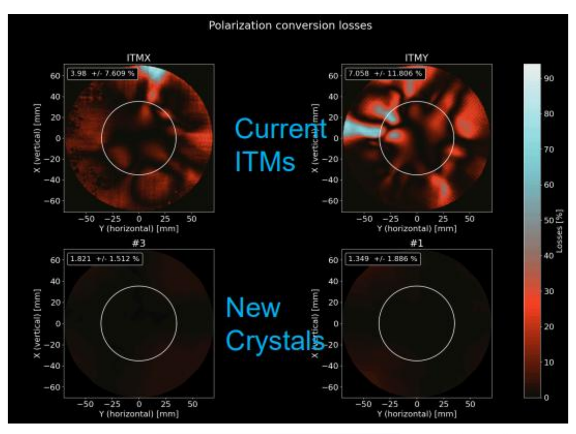
Post-merger signal example
R. Harada+, PRD **110**, 123005 (2024)
Even if detected, limited signal-to-noise ratios would make extracting neutron star physics challenging.



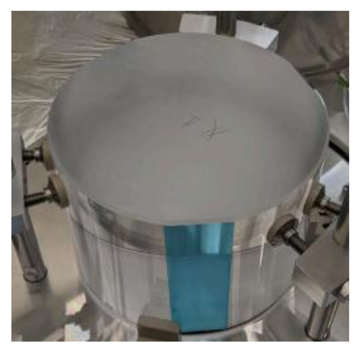


Adding KAGRA O6

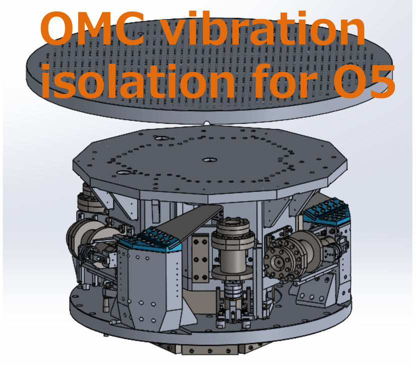


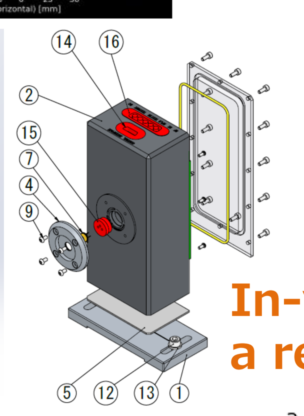


New sapphire crystals for O5



OMC vibration isolation for O5





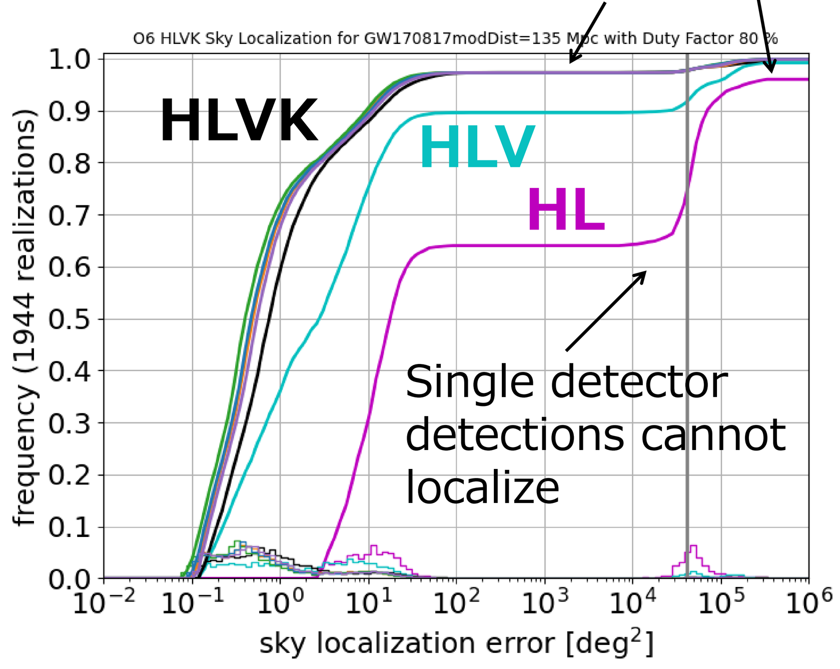
In-vac RF PD with a resealable lid

Comparing upgrade plans for O6

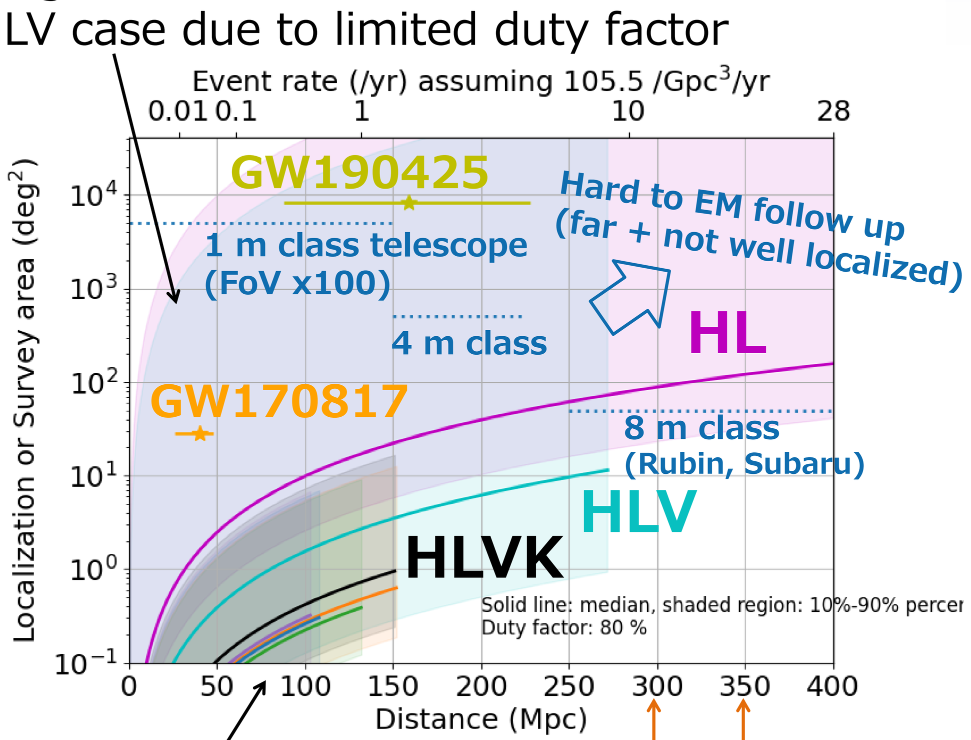
- Considering 4 plans (all having designed Q suspensions and mirrors)
  - **bKAGRA DRSE**: original design sensitivity as a reference
  - **BB40**: broadband upgrade with 40 kg mirror (all others 23 kg)
  - **HFmod**: high frequency upgrade with higher power
  - **HF2k** or **HF3k**: dips at 2 kHz or 3 kHz with T_{SRM}=0.5%
- Frequency dependent squeezing and better coating are not in the baseline plan due to limited resources
- We usually assume a 100% single detector duty factor but reducing it to, e.g., 80% significantly alters the sky localization distribution across the sky.

Some are completely missed due to limited duty factor

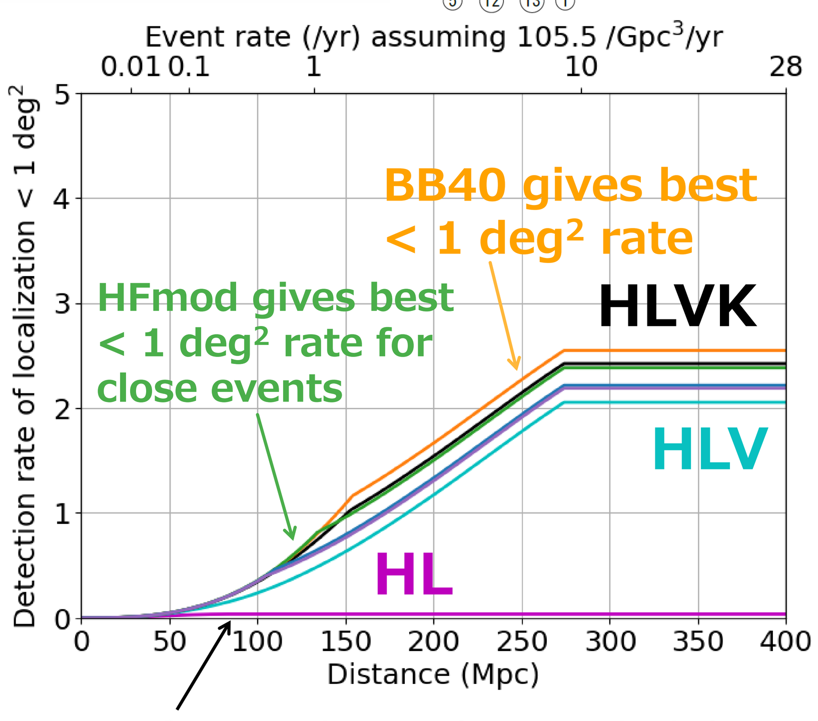
HLVK covers 90+% of events



Large fraction is not well localized in HLV case due to limited duty factor



Mostly covered by HLVK **GRB230307A** **GRB211211A**



Low rate for HL due to low probability of < 1 deg² (saturates at ~80 Mpc)

	HL	HLV	bKAGRA	BB40	HFmod	HF2k	HF3k
BNS range (1.4-1.4 M☉)	670 Mpc	273 Mpc	152 Mpc	153 Mpc	133 Mpc	109 Mpc	104 Mpc
Median localization [1]	10.6 deg²	0.55 deg²	0.37 deg²	0.28 deg²	0.23 deg²	0.27 deg²	0.30 deg²
< 10 deg² rate [2]	1.1 /yr	5.3 /yr	5.5 /yr	5.6 /yr	5.5 /yr	5.4 /yr	5.4 /yr
< 1 deg² rate [2]	0.04 /yr	2.1 /yr	2.4 /yr	2.5 /yr	2.4 /yr	2.2 /yr	2.1 /yr
Post-merger rate [3]				< 10^{-3} /yr	< 0.06 /yr	< 0.1 /yr	< 0.2 /yr
Tidal dimensionless improvement compared with HL case [4]				~25%	~55%	~45%	~30%
Intracavity power per arm			0.34 MW	0.34 MW	0.75 MW	1.3 MW	1.3 MW
ITM Transmission			0.4%	0.4%	0.4%	0.2%	0.4%
SRM Transmission			15% (DRSE)	15%	4%	0.5%	0.5%
Frequency independent squeezing			0 dB	10 dB input	10 dB input	10 dB input	10 dB input

[1] For GW170817-like binary at 135 Mpc
[2] Detection rate for 80% duty factor case
[3] Detection rate with SNR>5. Depend on neutron star equation of state and BNS event rate. See H. Tagoshi & S. Morisaki, JGW-P2416311 for details.
[4] Reduction of estimation error due to addition of KAGRA. See S. Morisaki, JGW-G2516593 for details.

Which KAGRA O6 plan do you like?

Methods and Acknowledgements

- Sky localization estimated via Fisher analysis using the IMRPhenomD waveform for a GW170817-like binary at redshift z = 0.03 (135 Mpc), sampled over 1944 uniformly distributed combinations of source location and polarization angle [see YM+, PRD **102**, 022008 (2018) for details].
- This was repeated for all combinations of detectors, and the resulting sky localization distributions were combined according to the network duty factor to obtain the actual sky localization distribution.
- Sky localization as a function of distance was plotted using $\Delta\Omega \propto (\mathrm{SNR})^{-2} \propto d^2$, up to the BNS range (the sky-averaged distance at which a BNS signal can be detected with SNR = 8).
- Event rate was estimated using O3b estimate of 105.5 /Gpc³/yr, multiplied by volume $4\pi/3 * L^3$, assuming all the BNS are 1.4-1.4M☉ [LVK, PRX **13**, 011048 (2023)]
- Treatment of beyond BNS range and BNS mass distribution is of future work.
- We would like to thank Masaomi Tanaka for his invaluable input on sky localization requirements from the perspective of optical and infrared follow-up observations.