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KAGRA upgrade choices based on sky localization capability

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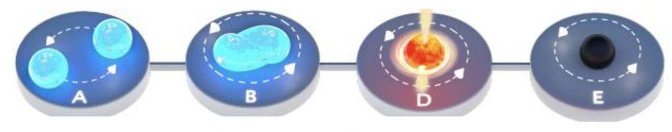
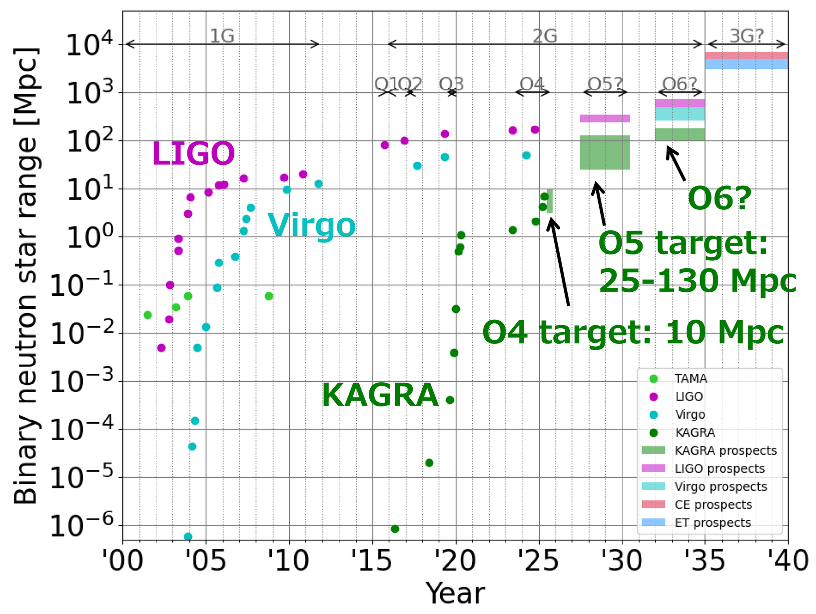
A **high-frequency upgrade of KAGRA is being considered** to probe neutron star physics via binary neutron star (BNS) coalescences. Given the low BNS merger rate, focusing solely on post-merger signals may not be an effective strategy. Even if detected, limited signal-to-noise ratios would make extracting neutron star physics challenging. A key question is whether to prioritize maximizing the BNS range to boost detection rates or enhancing high-frequency sensitivity to improve sky localization and tidal deformability estimation. We estimate the sky localization capability of the LIGO-Virgo-KAGRA network, accounting for detector duty factors. For identical BNS detections, the **high-frequency upgrade improves sky localization by ~20%** over the broadband option. However, in terms of **annual events localized within 1 deg², the broadband upgrade performs better**. Adding KAGRA increases this number by **about 20%**.

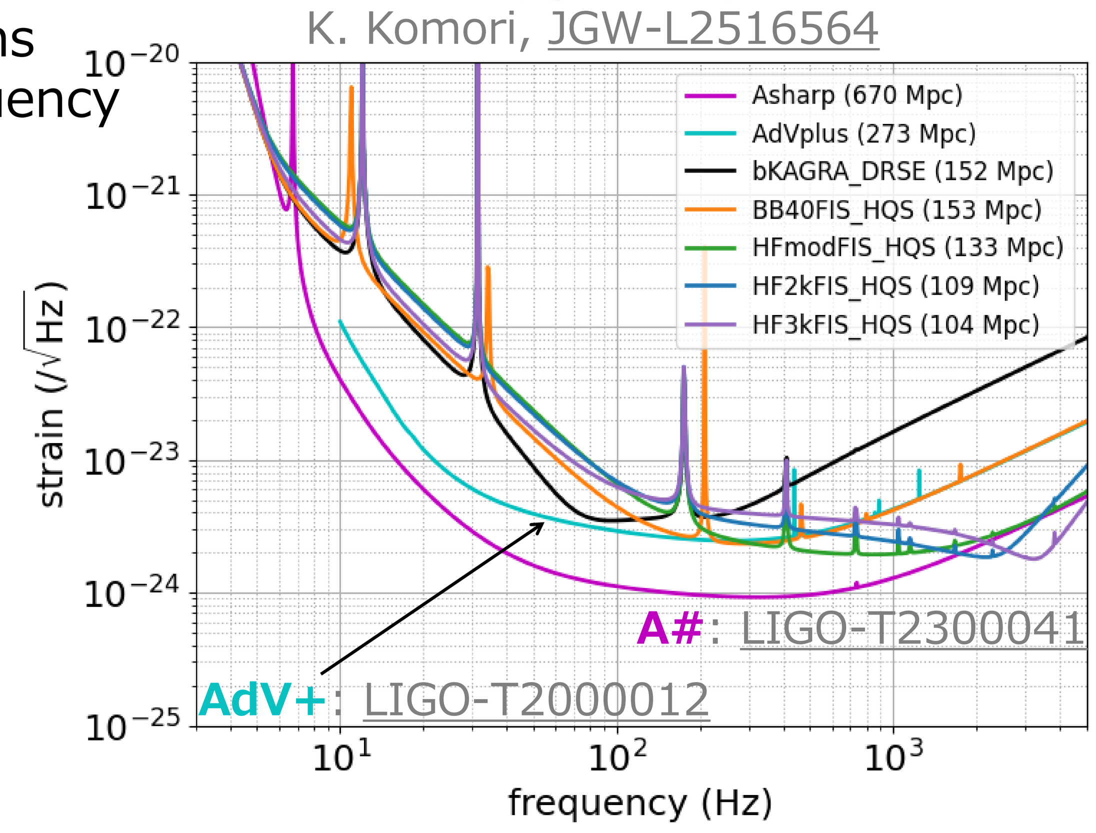
KAGRA upgrade options in 2030s

- KAGRA 10yr Task Force considers 15 upgrade options for 2030s
- Here we consider 4 options out of them
  - **bKAGRA DRSE**: original design sensitivity as a reference
  - **BB40**: broadband upgrade
  - **HFmod**: high frequency upgrade
  - **HF2k** or **HF3k**: dips at 2 kHz or 3 kHz
- All assume high-Q suspensions as planned, 10 dB input frequency independent squeezing



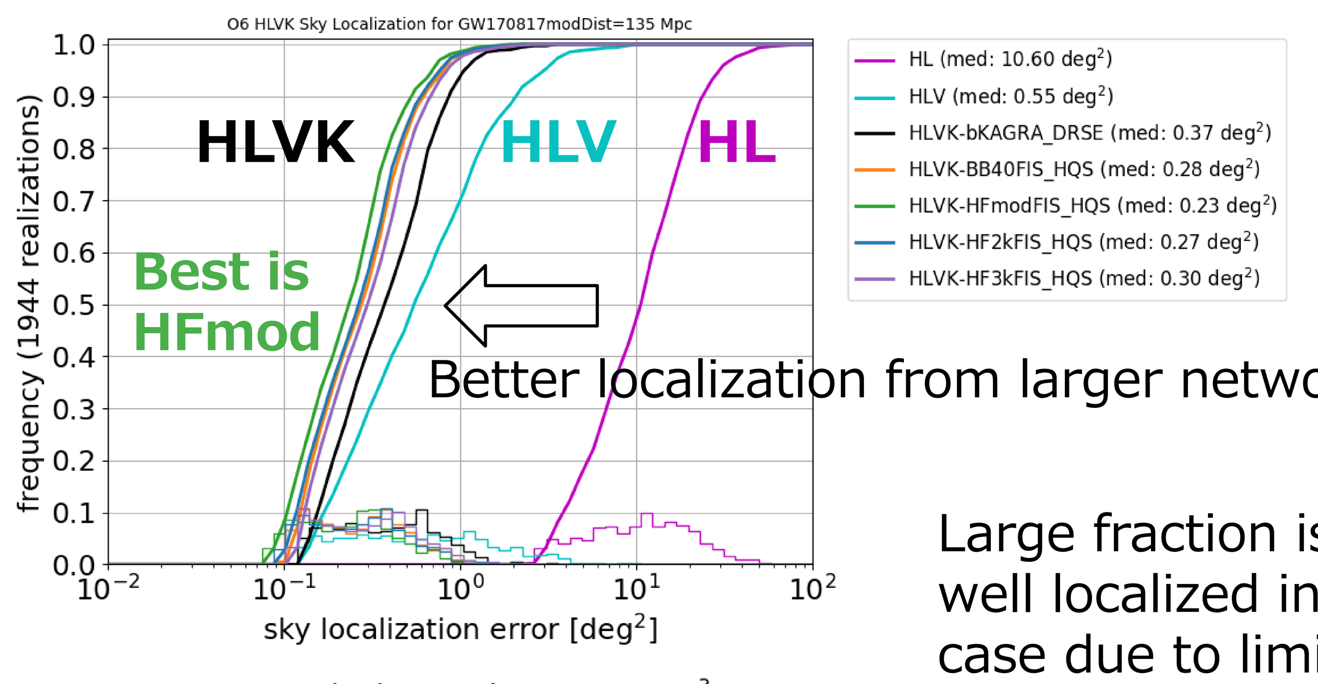
KAGRA upgrade options: K. Komori, JGW-L2516564

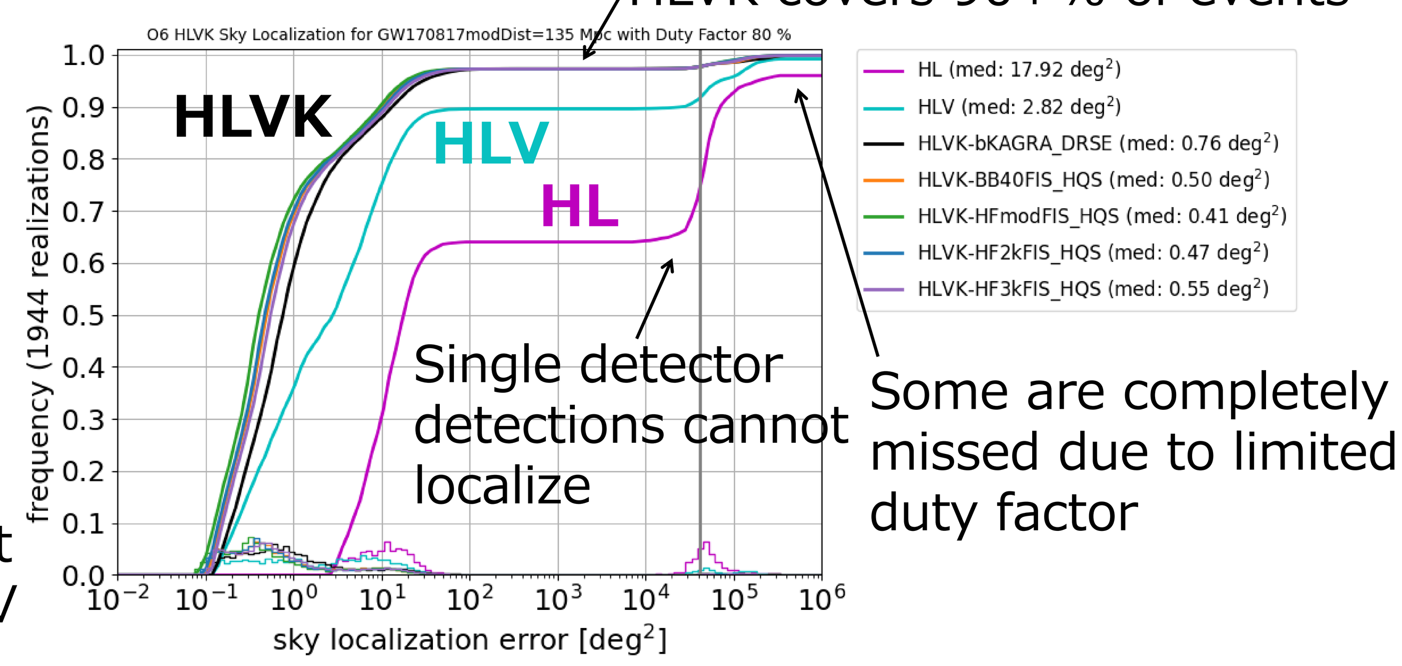


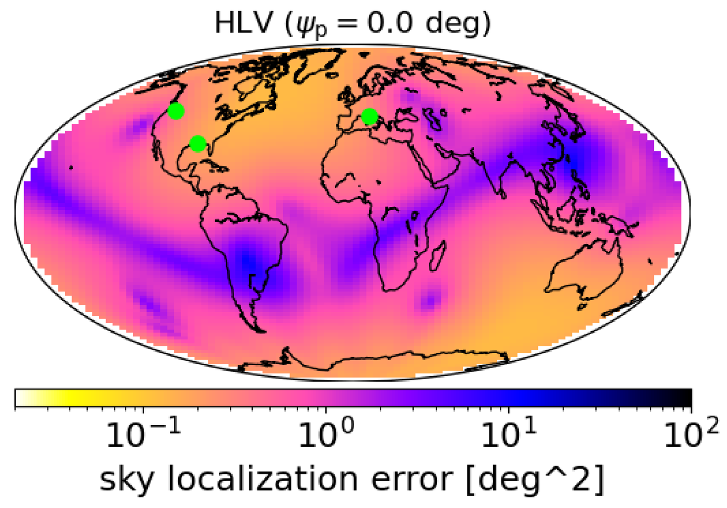


Sky localization capability including duty factor

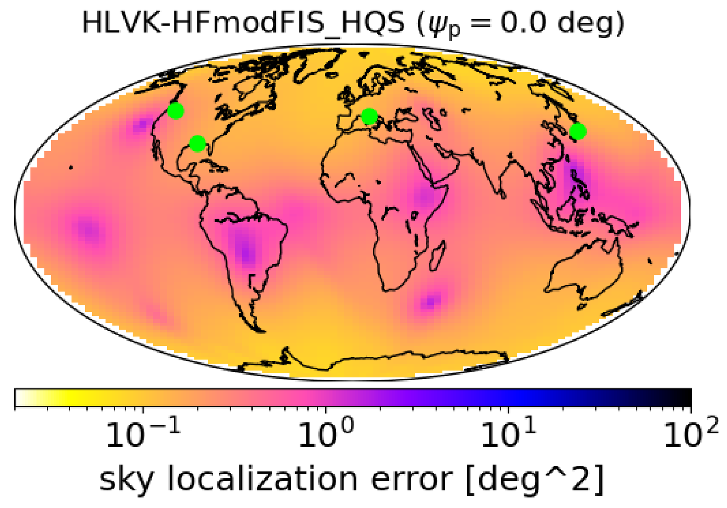
- We usually assume a 100% single detector duty factor (left plots) but reducing it to, e.g., 80% (right plots) significantly alters the sky localization distribution across the sky.



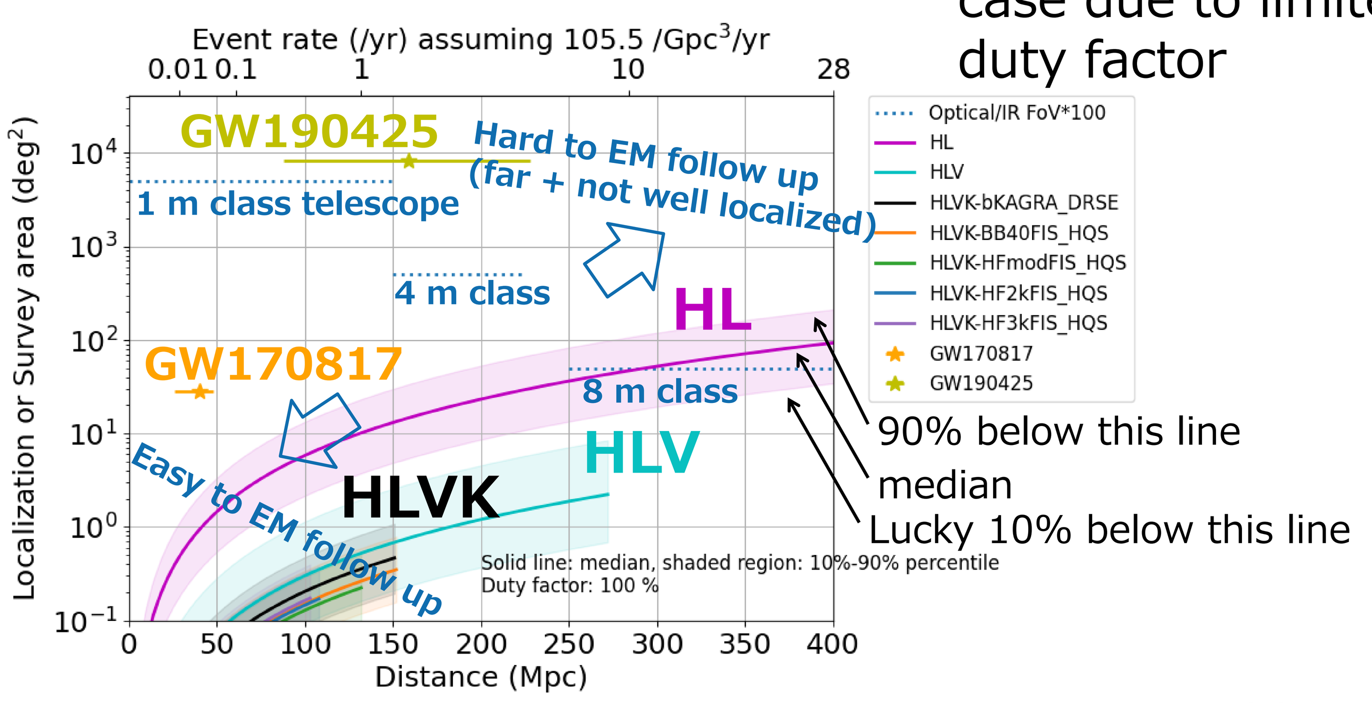


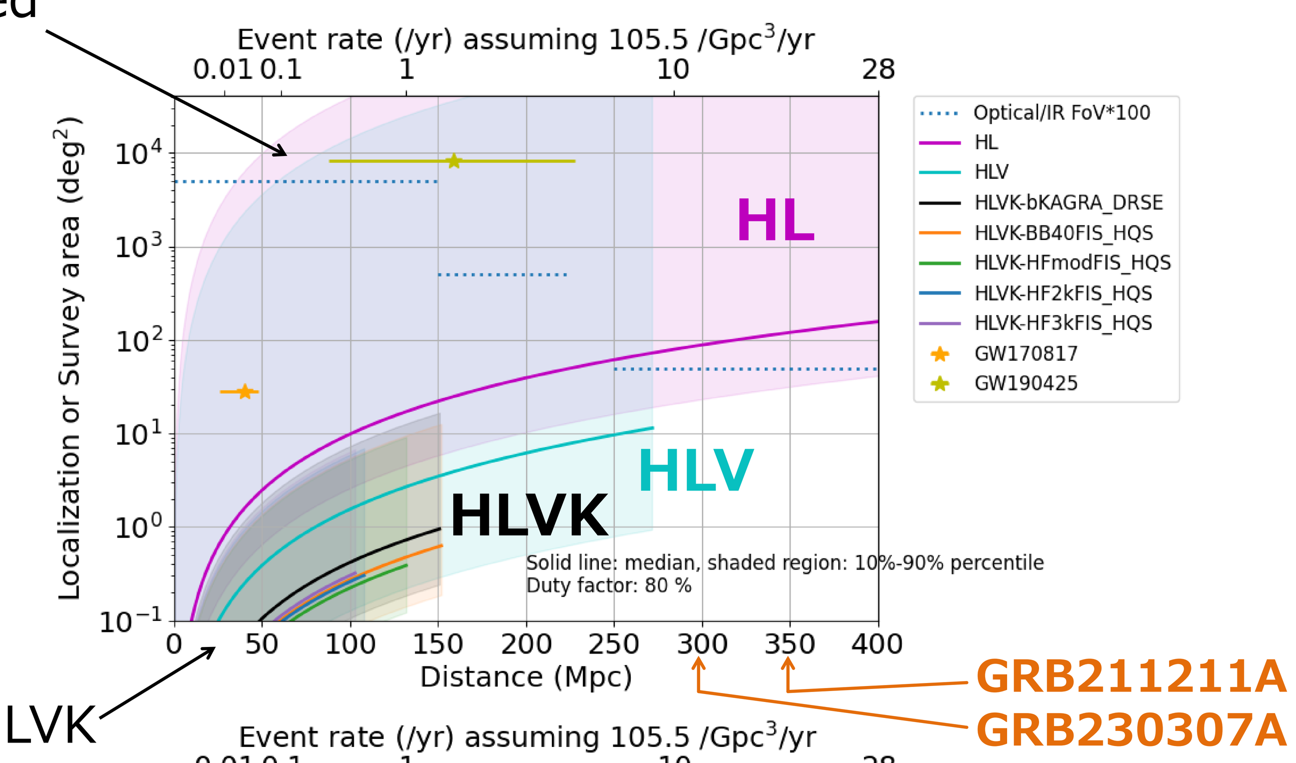


Adding KAGRA

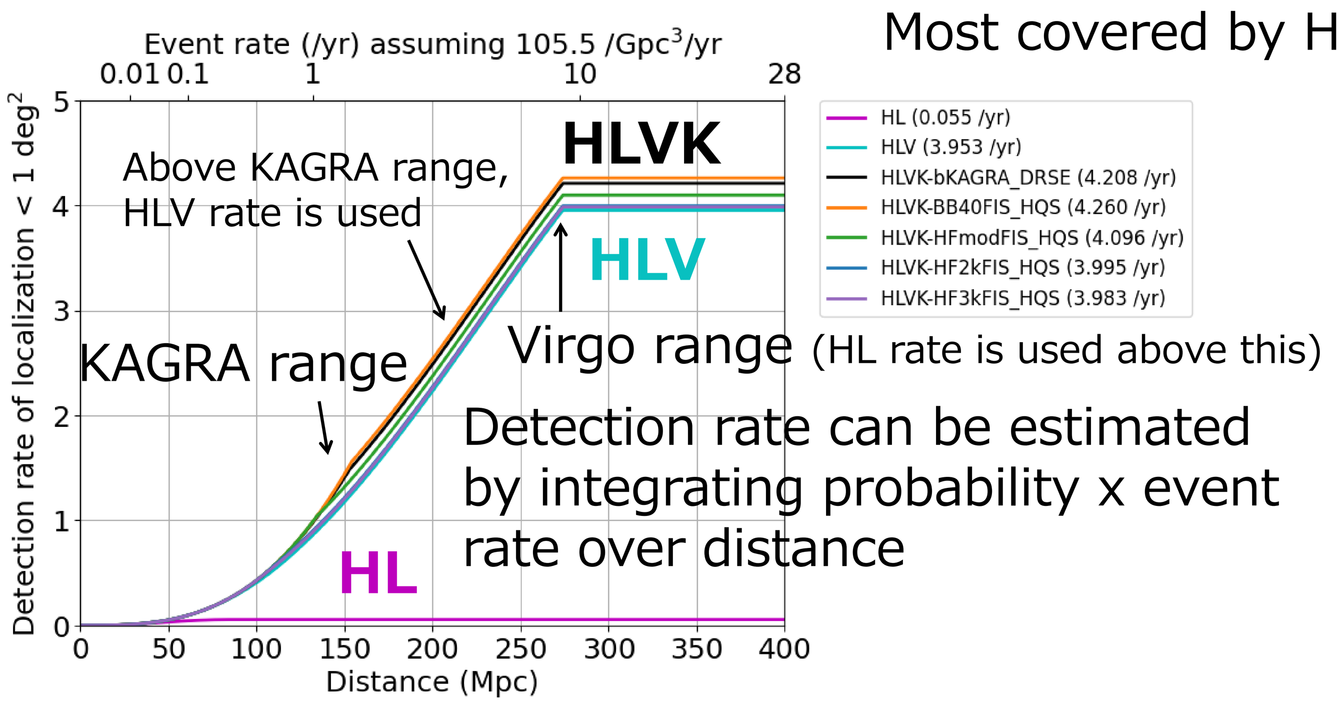


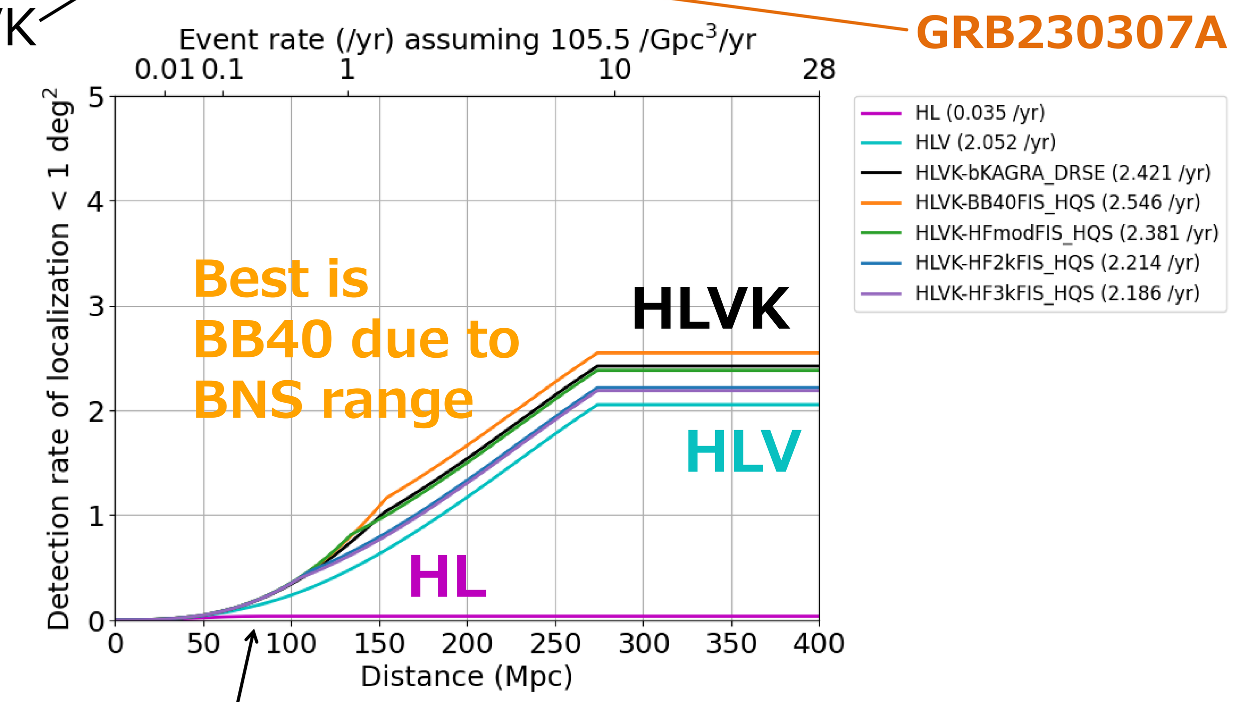
Large fraction is not well localized in HLV case due to limited duty factor





Most covered by HLVK





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

Comparison of upgrades

	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 deformability improvement compared with HL case [4]				~25%	~55%	~45%	~30%

[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 $4\pi/3 \cdot L^3$ [LVK, PRX **13**, 011048 (2023)]
- Treatment of beyond BNS range 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.