KAGRA upgrade choices based on sky localization capability

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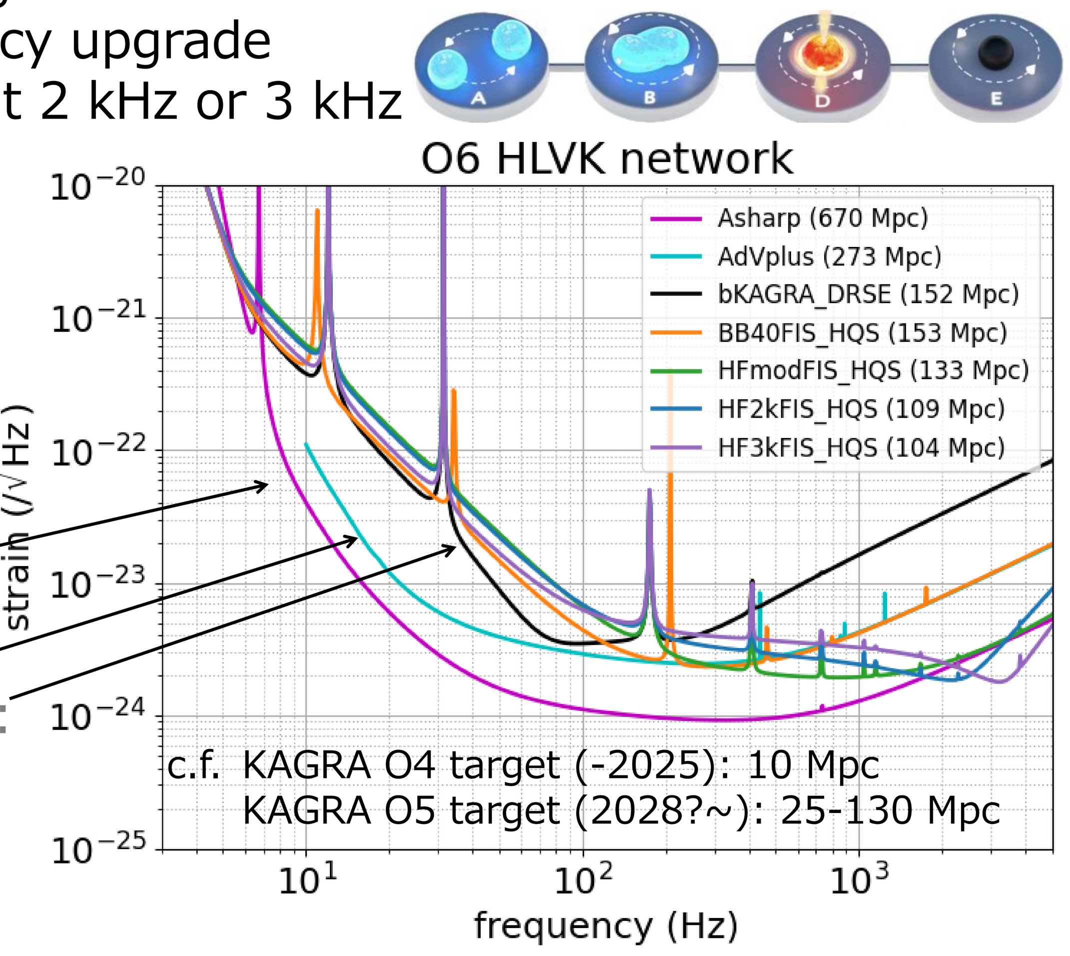
A **high-frequency upgrade of KAGRA is under consideration**, aiming to target post-merger signals of binary neutron star (BNS) coalescences. However, given the **low BNS merger rate**, focusing solely on post-merger signal detection may not be an effective strategy. Even if a post-merger signal is detected, extracting neutron star physics would be challenging due to limited signal-to-noise ratio. An important question is whether to prioritize maximizing the BNS range to increase the detection rate, or to enhance high-frequency sensitivity to improve sky localization and tidal deformability. In this study, we estimate the sky localization capability of the LIGO-Virgo-KAGRA network, incorporating the detectors' duty factors. We find that, for the same BNS detections, the **high-frequency upgrade yields approximately 20% better sky localization** than the broadband option. However, **in terms of the number of events per year localized to within 1 deg², the broadband upgrade performs better**. Notably, with the addition of KAGRA to the network, this number increases by a factor of about **1.5**.

KAGRA upgrade options in 2030s

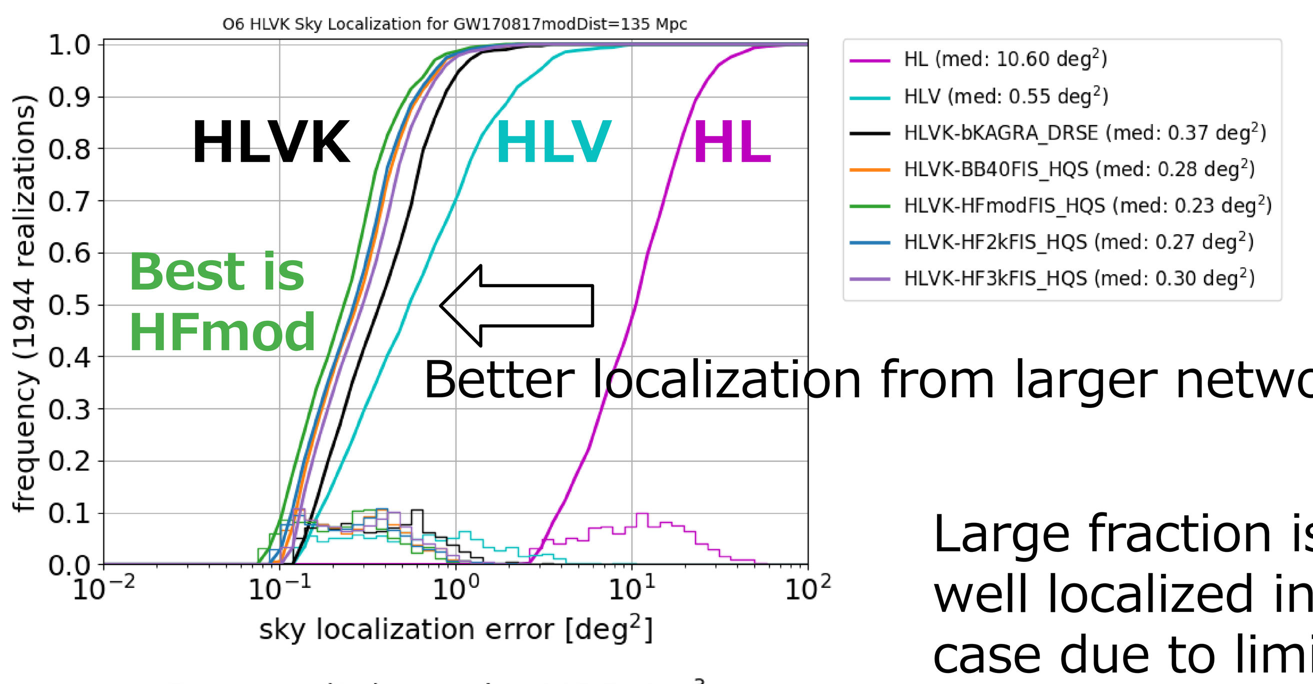
- KAGRA 10yr Task Force considers 15 upgrade options for 2030s
- Here we consider 4 options out of them
  - **bKAGRA DRSE**: original design sensitivity as a reference
  - **BB40**: broadband upgrade
  - **HFmod**: high frequency upgrade
  - **HF2k** or **HF3k**: dips at 2 kHz or 3 kHz
- All assume high-Q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

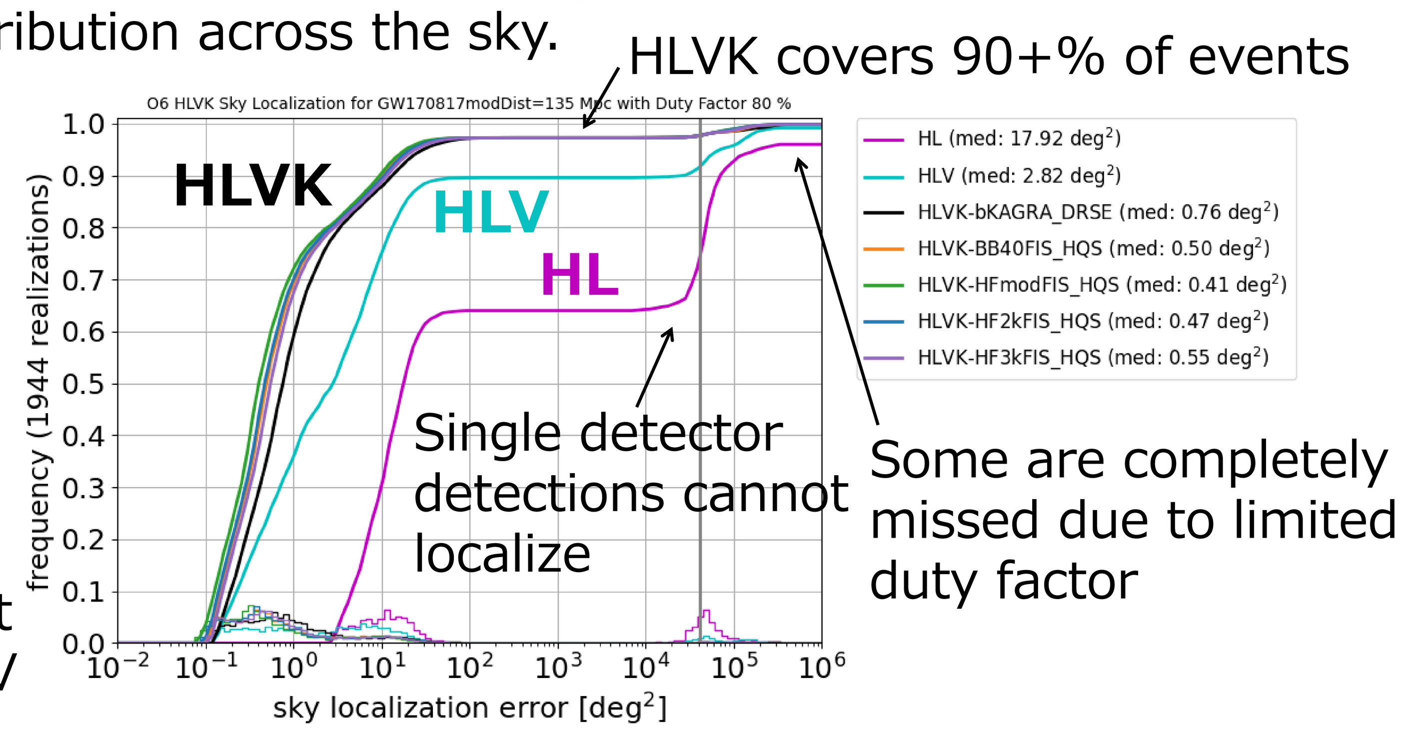
A#: LIGO-T2300041
AdV+: LIGO-T2000012
KAGRA upgrade options: K. Komori, JGW-L2516564

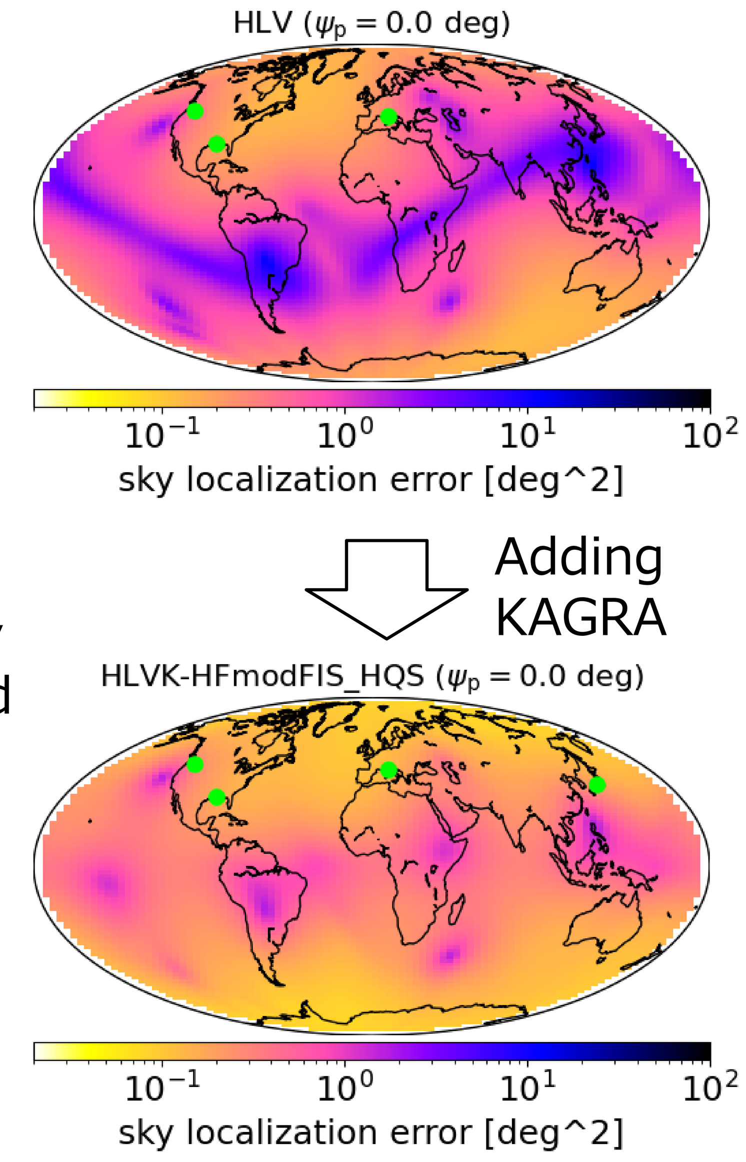


Sky localization capability including duty factor

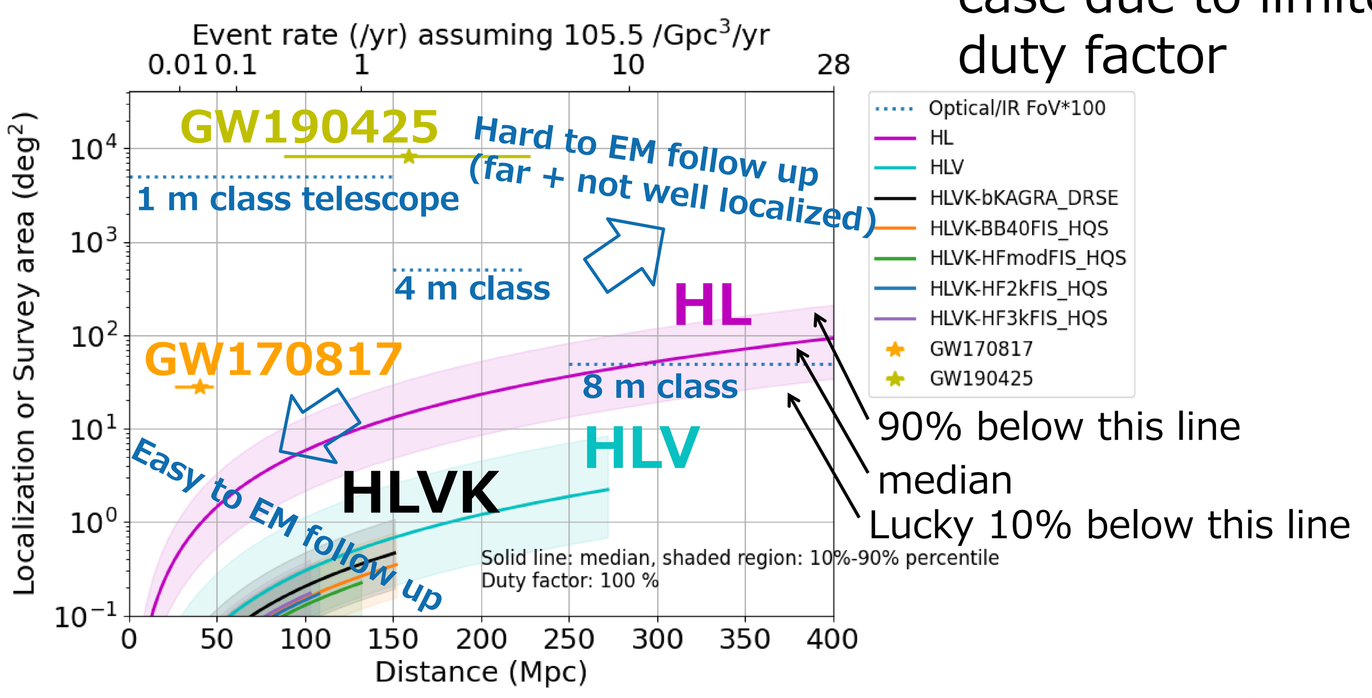
- We usually assume a 100% single detector duty factor (left plots) but reducing it to, e.g., 80% (right plots) significantly alters the sky localization distribution across the sky.

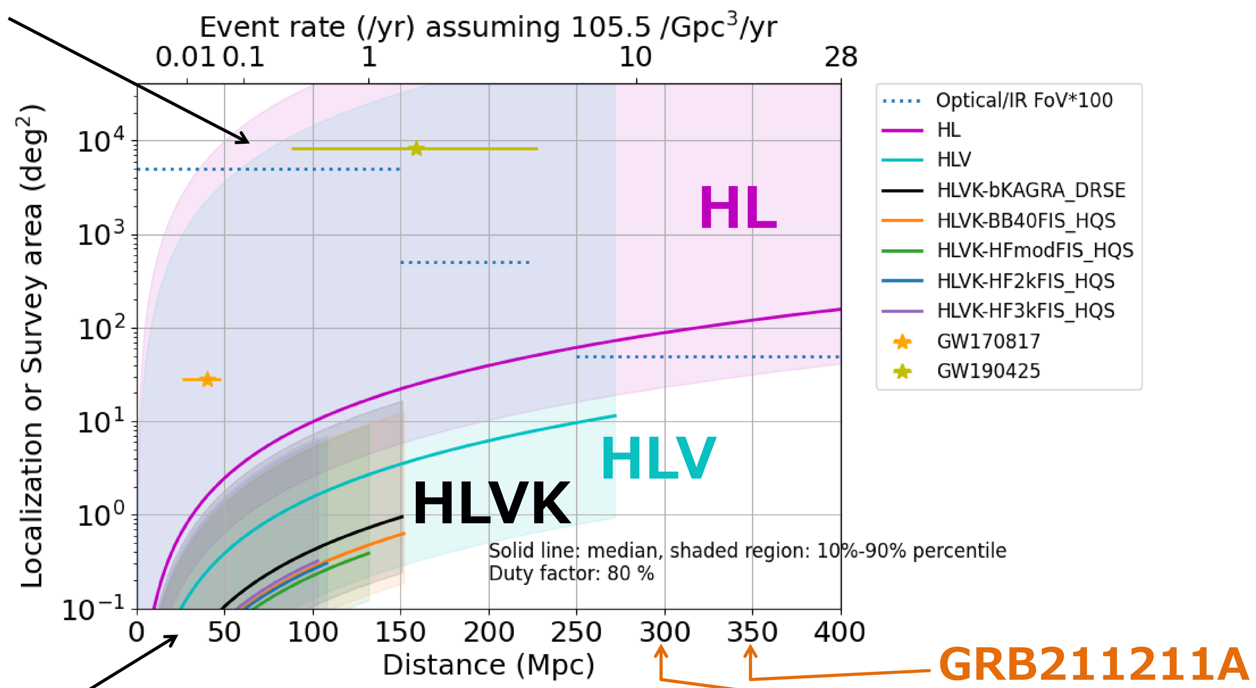




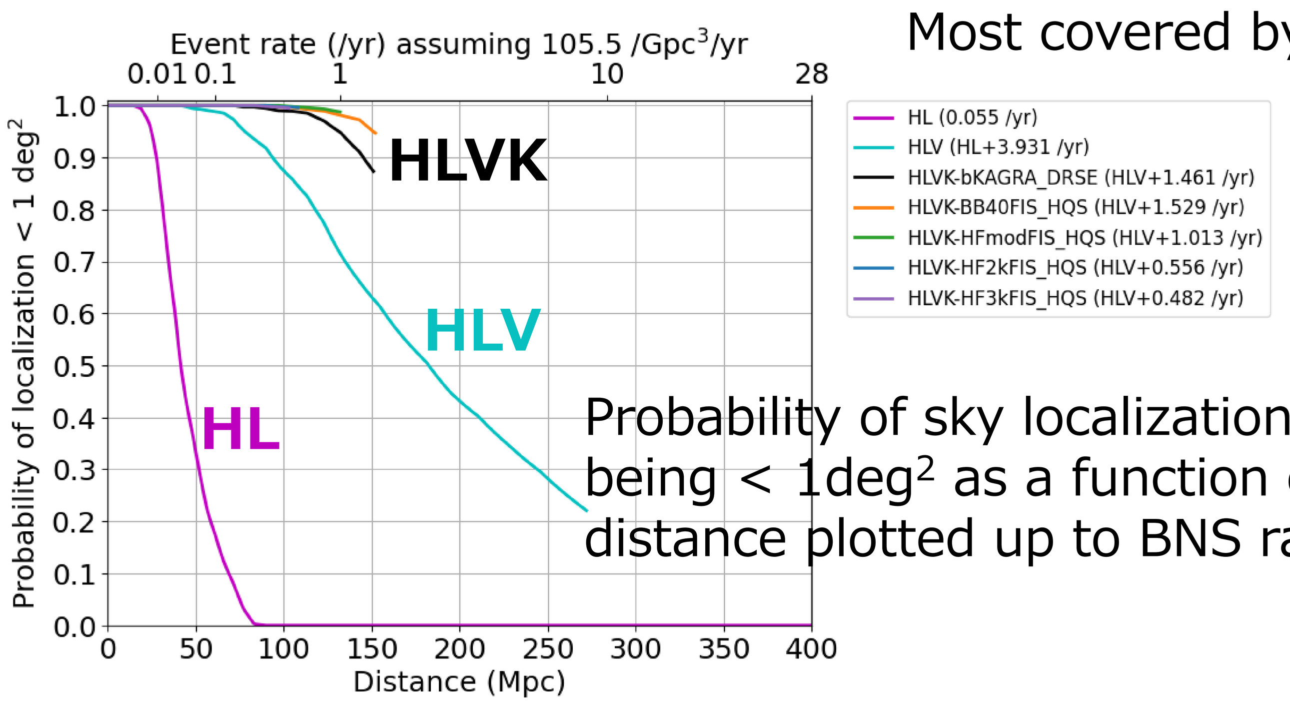


Large fraction is not well localized in HLV case due to limited duty factor

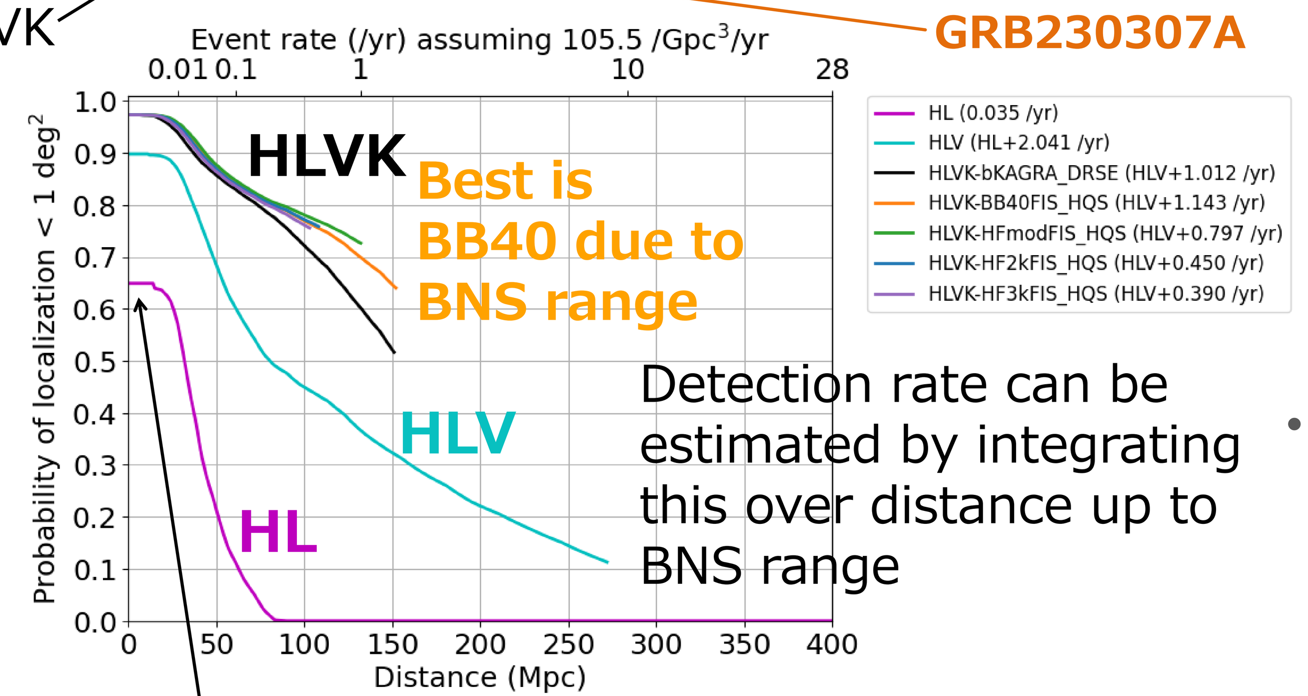




Most covered by HLVK



Probability of sky localization being < 1deg² as a function of distance plotted up to BNS range



Detection rate can be estimated by integrating this over distance up to BNS range

Probability of 2+ detector event

Comparison of upgrades

	HL	HLV	bKAGRA	BB40	HFmod	HF2k	HF3k
BNS range	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	6.4 /yr	7.8 /yr	7.8 /yr	7.4 /yr	6.9 /yr	6.9 /yr
< 1 deg² rate [2]	0.04 /yr	2.1 /yr	3.1 /yr	3.2 /yr	2.9 /yr	2.5 /yr	2.5 /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%

Which KAGRA O6 plan do you like?					

[1] At 135 Mpc, for 100% duty factor case
[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.

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.