LIGO & Future Gravitational-Wave Detectors

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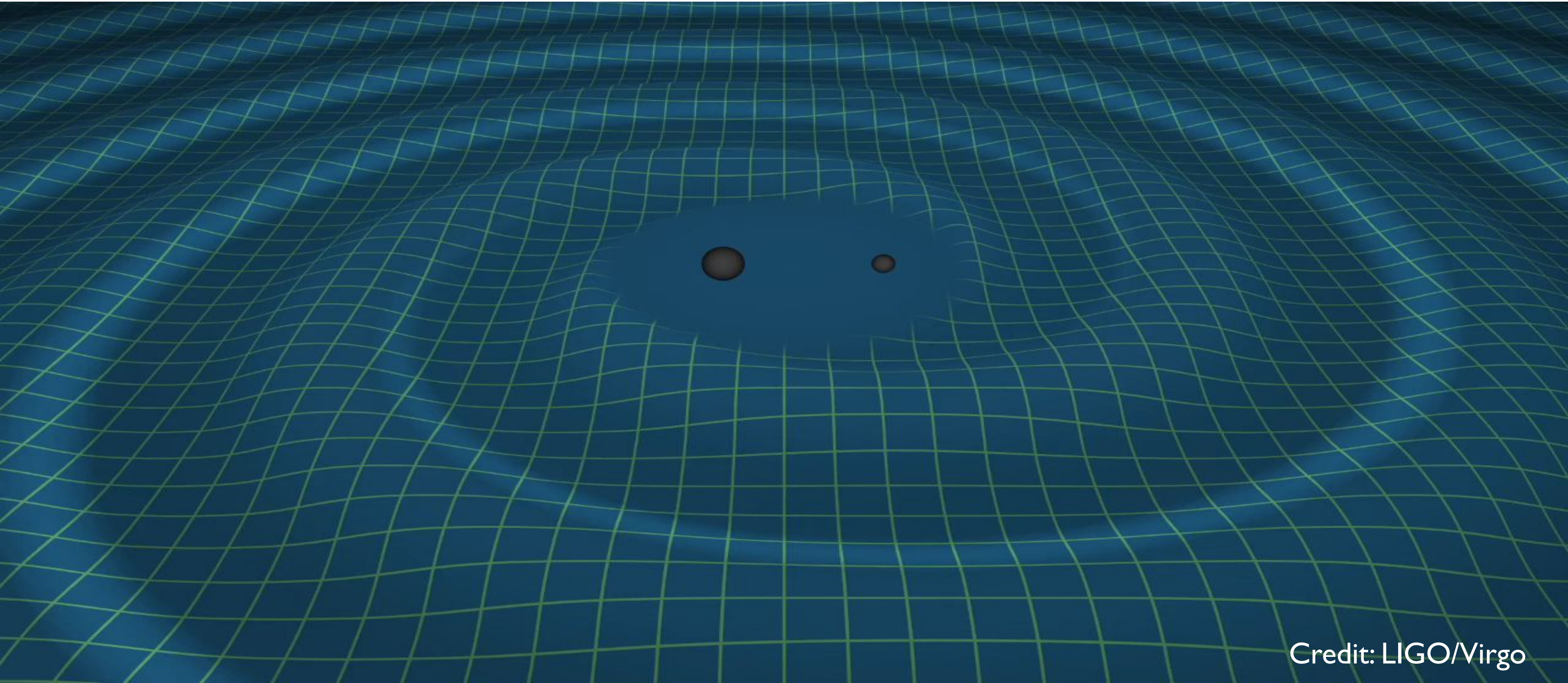
University of Wisconsin-Milwaukee

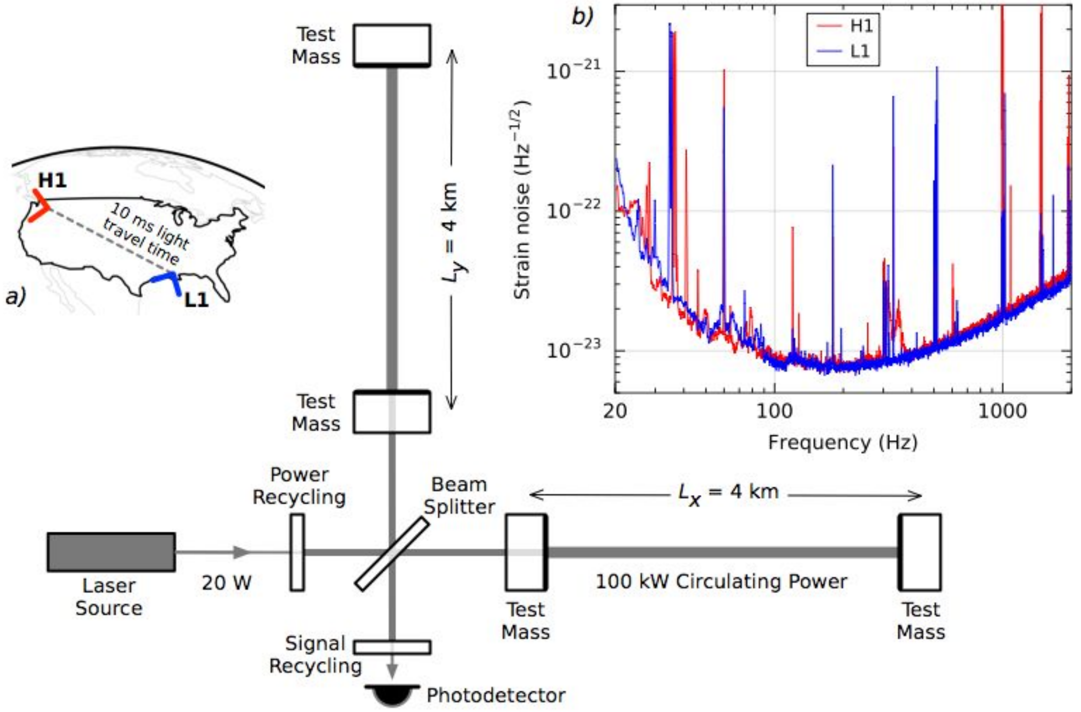
EDSU 2022
7 November 2022

https://dcc.ligo.org/G2202000

Einstein 1916



Laser Interferometer Gravitational-wave Observatory (LIGO)

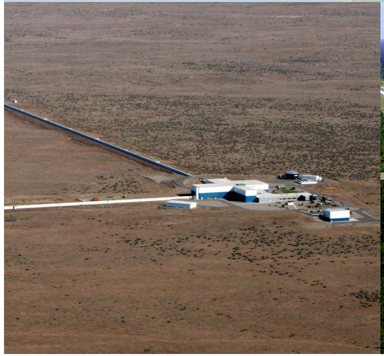


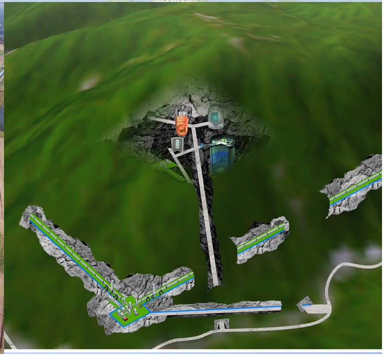
First proposed by Ron Drever, Kip Thorne, and Rai Weiss in 80’s.
First funding in 1992; civil construction ended 2000; Initial LIGO 2002-2010

Advanced LIGO

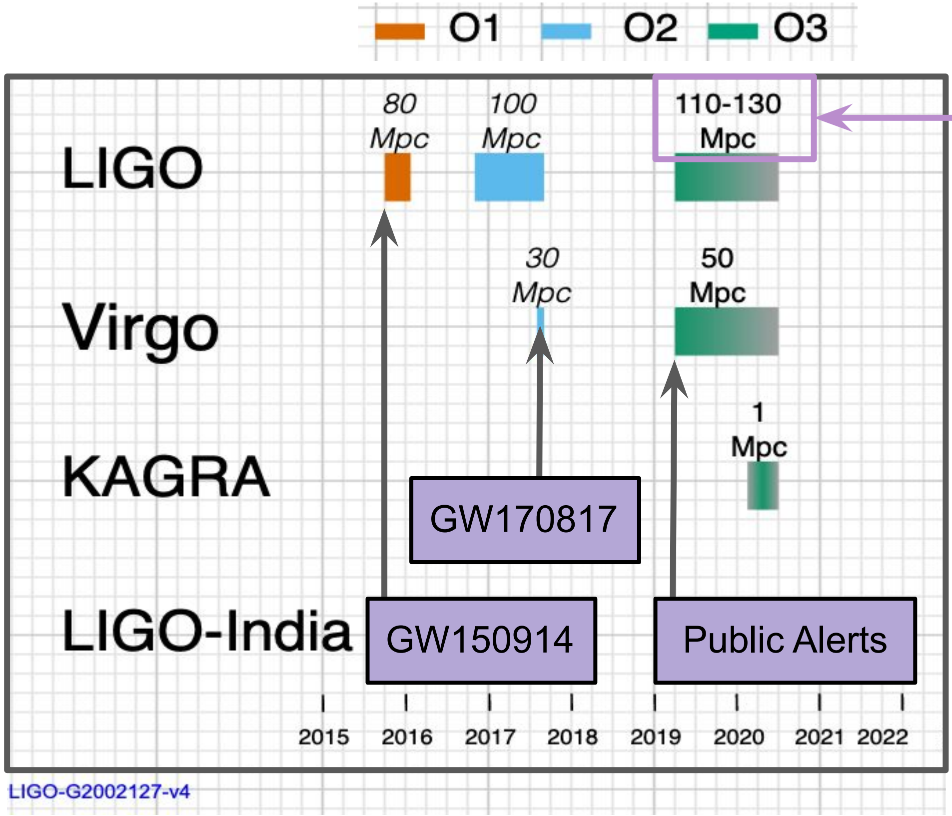
- From the beginning, facilities were planned to house multiple generations of detectors
- Initial LIGO: a necessary step to move to kilometer scale. Detection possible, not likely
- **Advanced LIGO**: detection probable for compact binaries, possible for other sources
    - Funding started in 2008; Livingston completed in mid 2014; Hanford completed at end of 2014
    - Plan to interleave observing with commissioning activities starting in 2015
- First detection of gravitational waves on 14 September 2015!

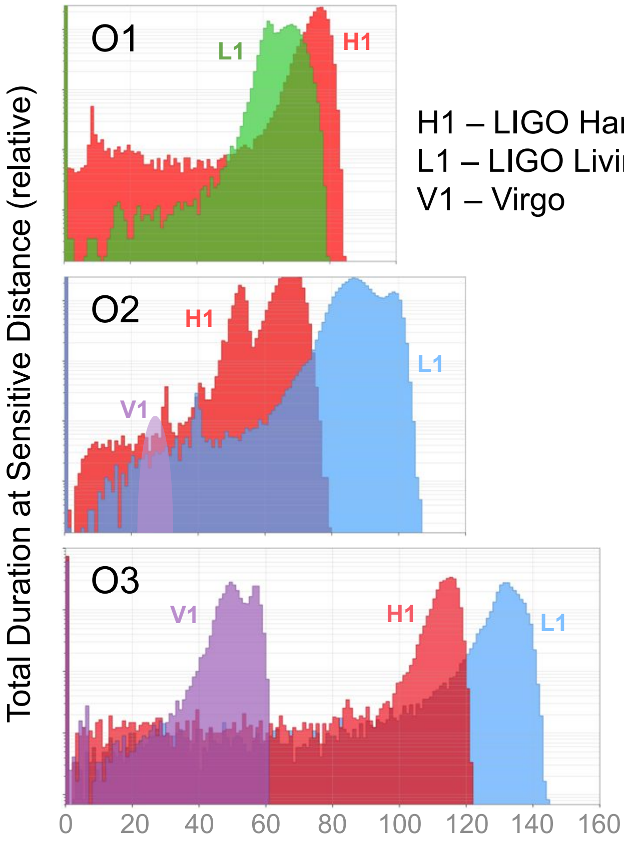
International Gravitational-Wave Observatory Network (IGWN)





Observing runs

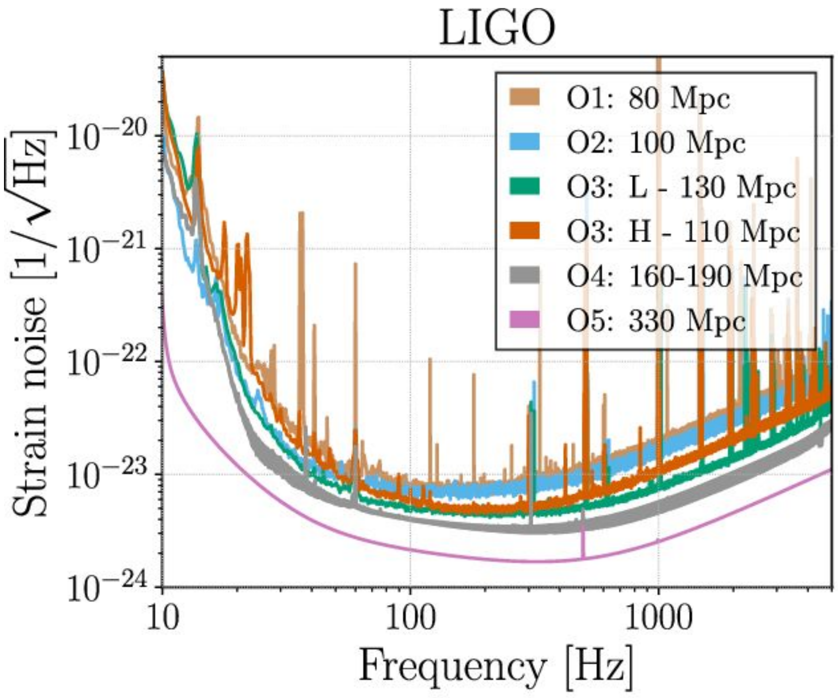


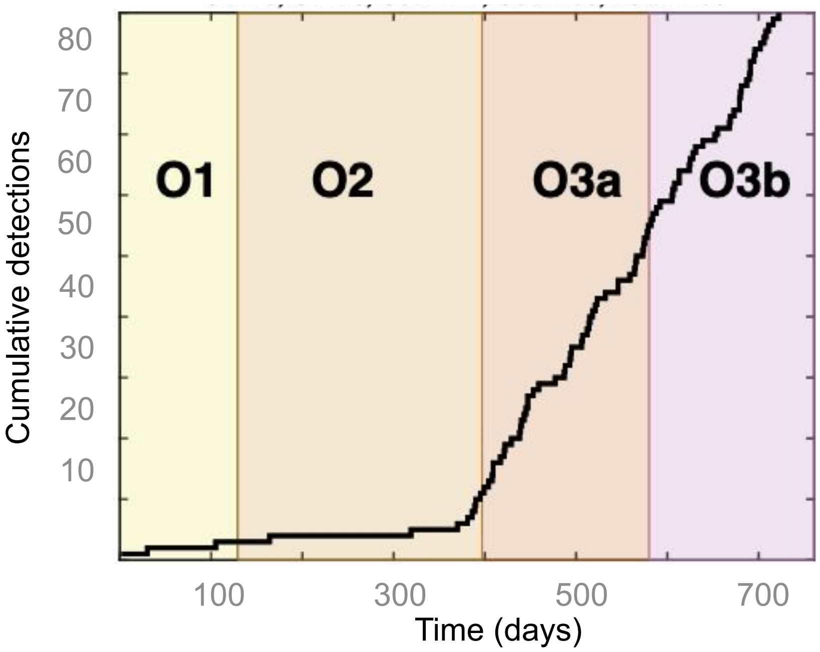


H1 – LIGO Hanford
L1 – LIGO Livingston
V1 – Virgo

Angle Averaged Binary Neutron Star Inspiral Range

Sensitivity & detections



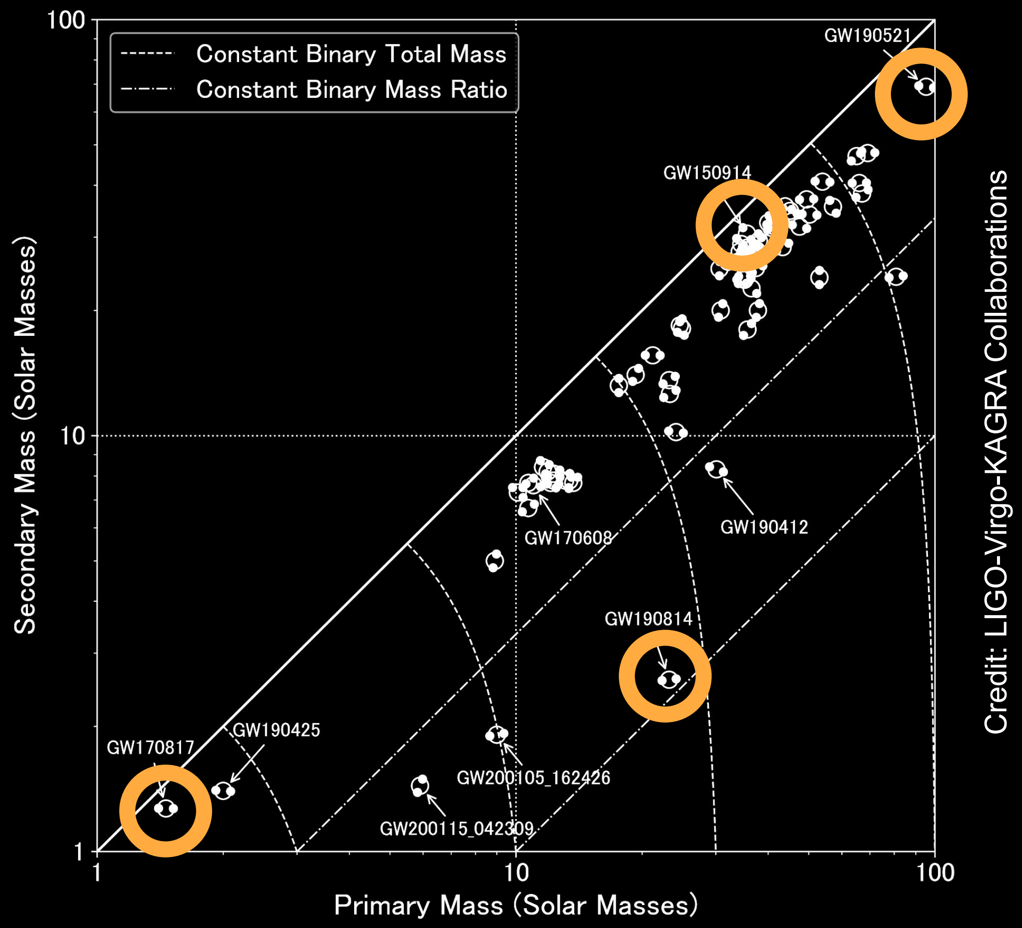


O3 binary detection rate ~ 1 / (5 days)

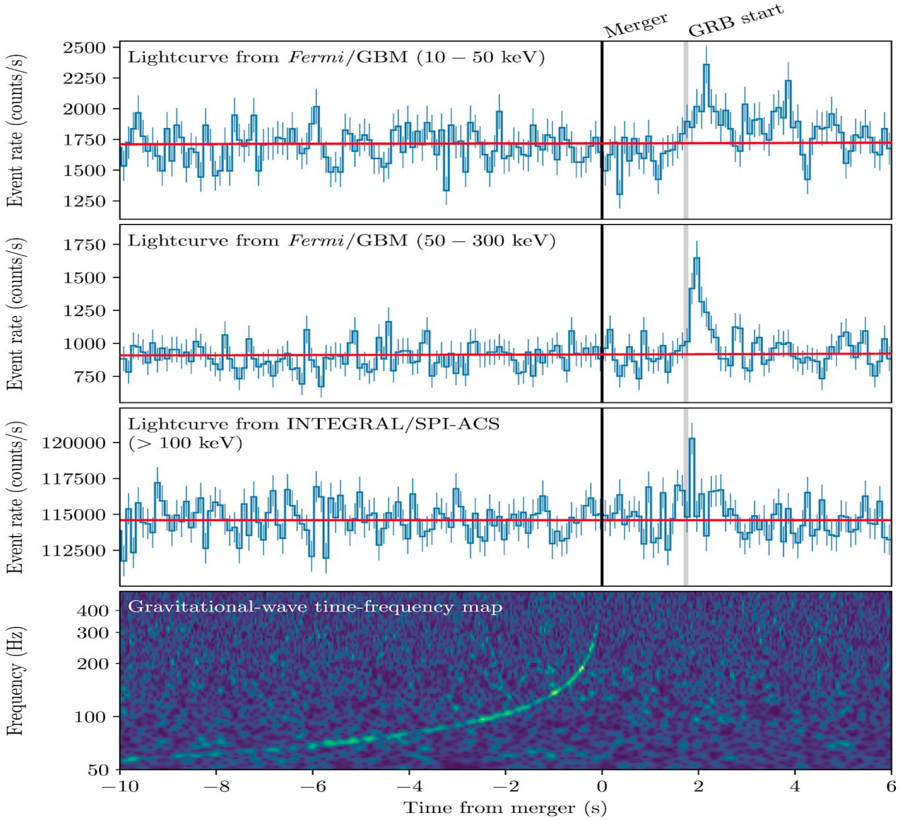
Credit: LIGO-Virgo-KAGRA Collaborations (LIGO-G2102395)

Mergers

- GW150914
  - First astrophysical source
  - Binary black holes exist
- GW170817
  - Binary neutron star mergers are gamma-ray burst progenitors
- GW190521
  - Black holes exist in pair instability mass gap
- GW190814
  - Compact objects exist with masses between 2-5 Msun



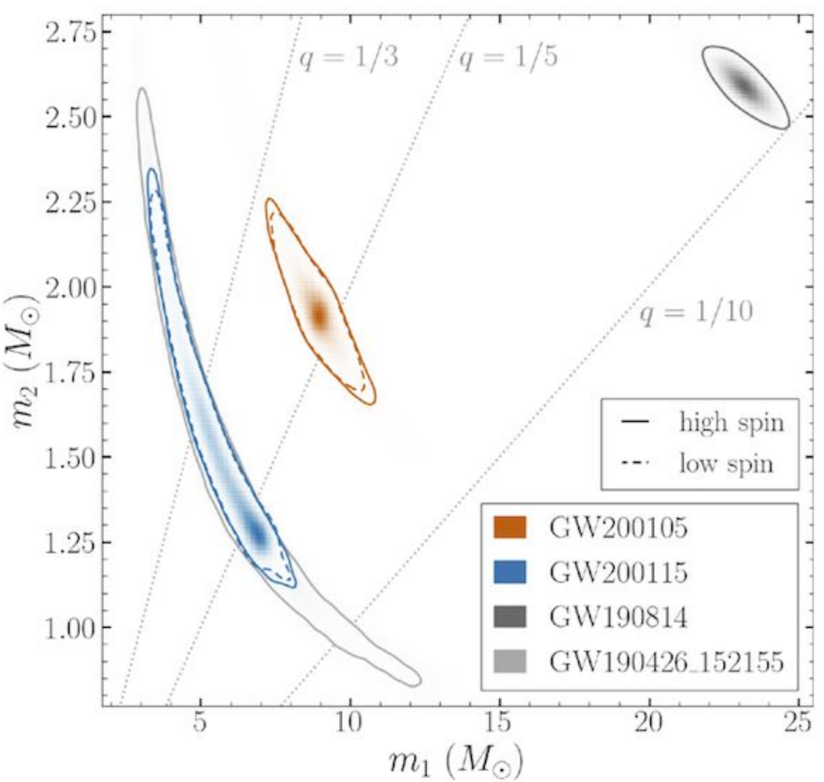
First BNS-GRB association ….



B. P. Abbott et al 2017 ApJL 848 L13

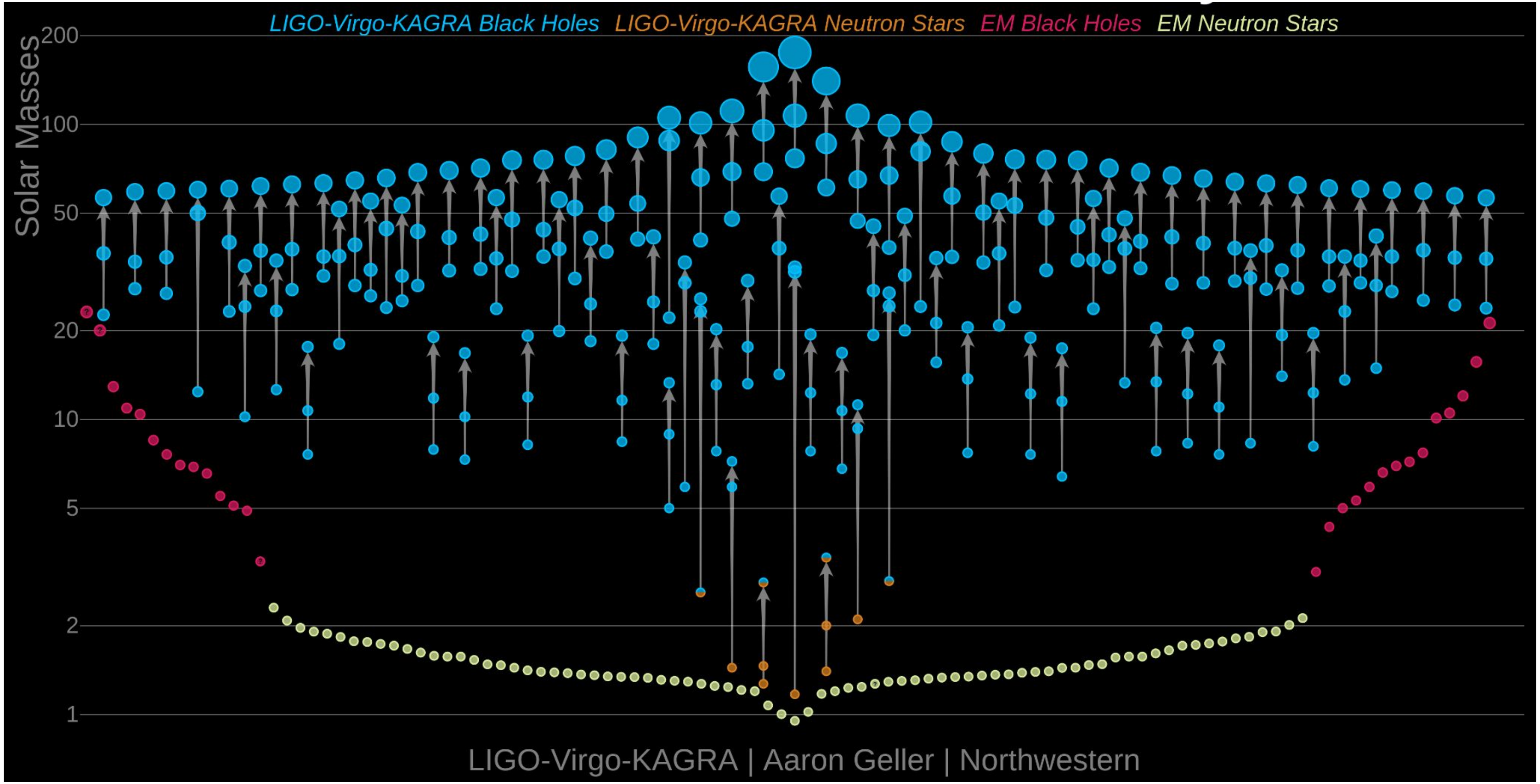
- GW170817
  - Binary neutron star (BNS) merger waves
- GW170817 & GRB 170817A
  - Fractional difference in speed of gravity and the speed of light is between -3×10^{-15} and 7×10^{-16}
- GW170817 & AT 2017gfo
  - Binary neutron star mergers produce kilonova explosions that generate heavy elements

First neutron-star black hole mergers

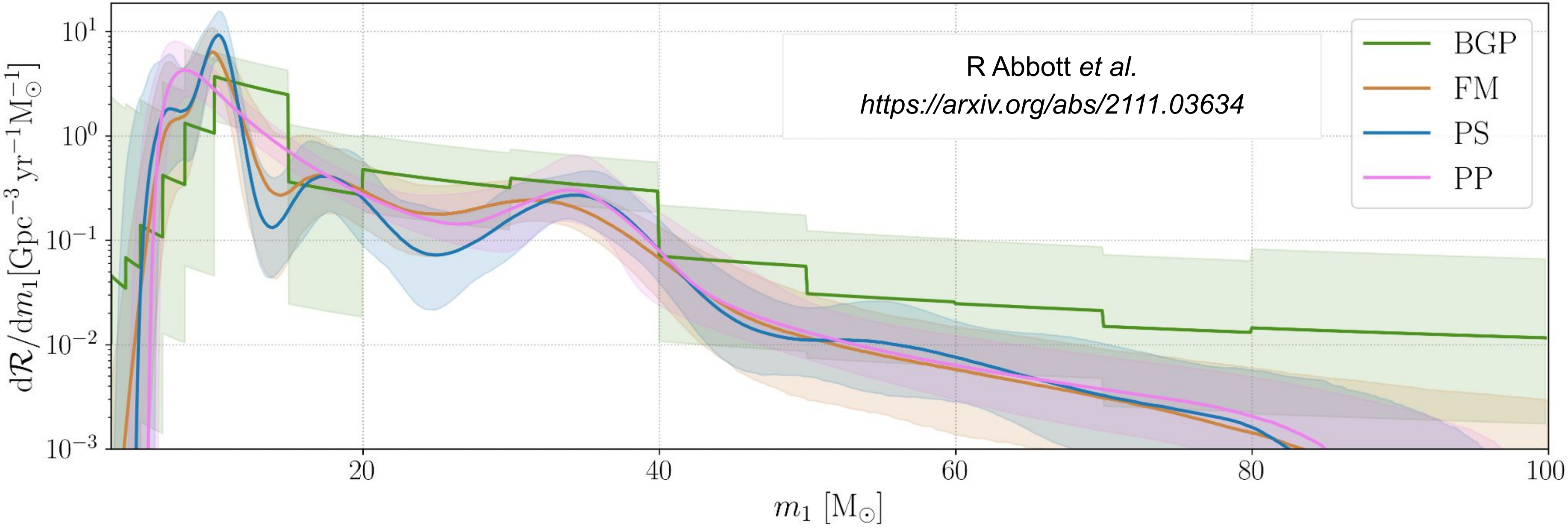


R. Abbott *et al* 2021 *ApJL* **915** L5

Masses in the stellar graveyard



From one to many: measuring populations

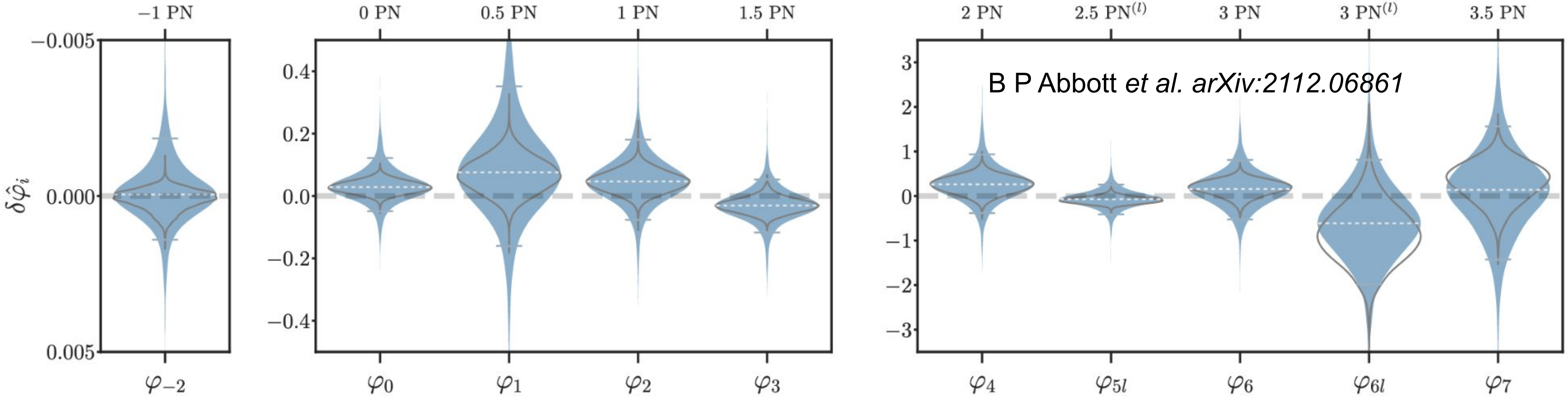


Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

Testing GW generation with BBH

- Look for deviations in the phasing coefficients of a 3.5PN TaylorF2 phase:

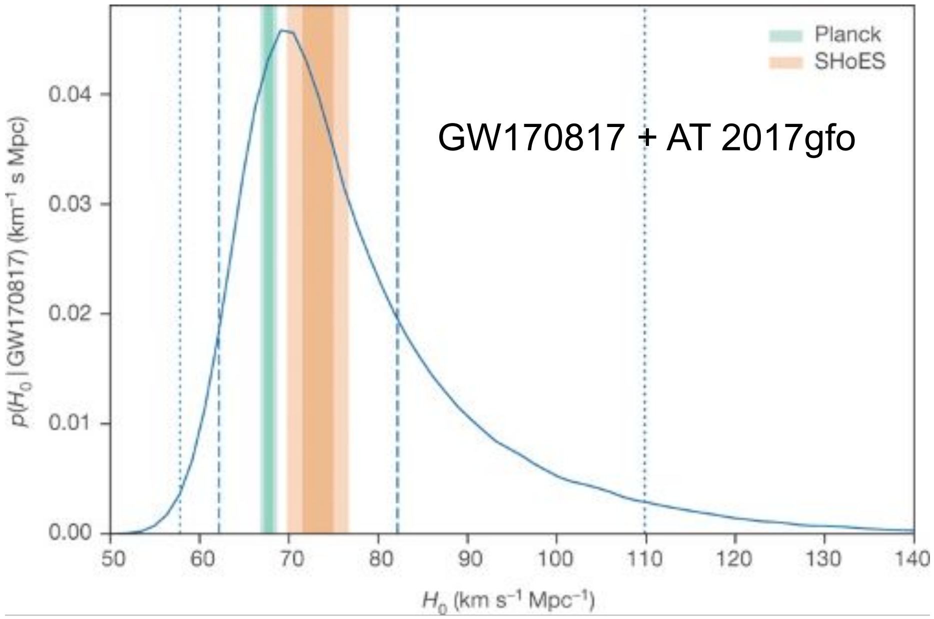
$$\varphi_{\rm PN}(f) = 2\pi f t_c - \varphi_c - \frac{\pi}{4} + \frac{3}{128\eta}\left(\pi\tilde{f}\right)^{-5/3}\sum_{i=0}^{7}\left[\varphi_i + \varphi_{i\,l}\log(\pi\tilde{f})\right]\left(\pi\tilde{f}\right)^{i/3}$$



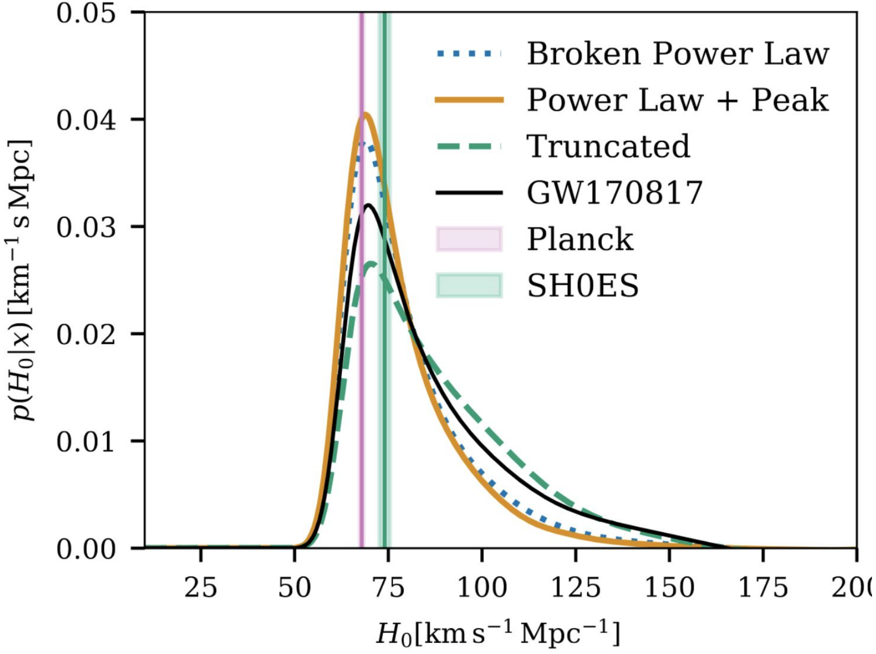
B P Abbott *et al. arXiv:2112.06861*

Cosmology with gravitational waves

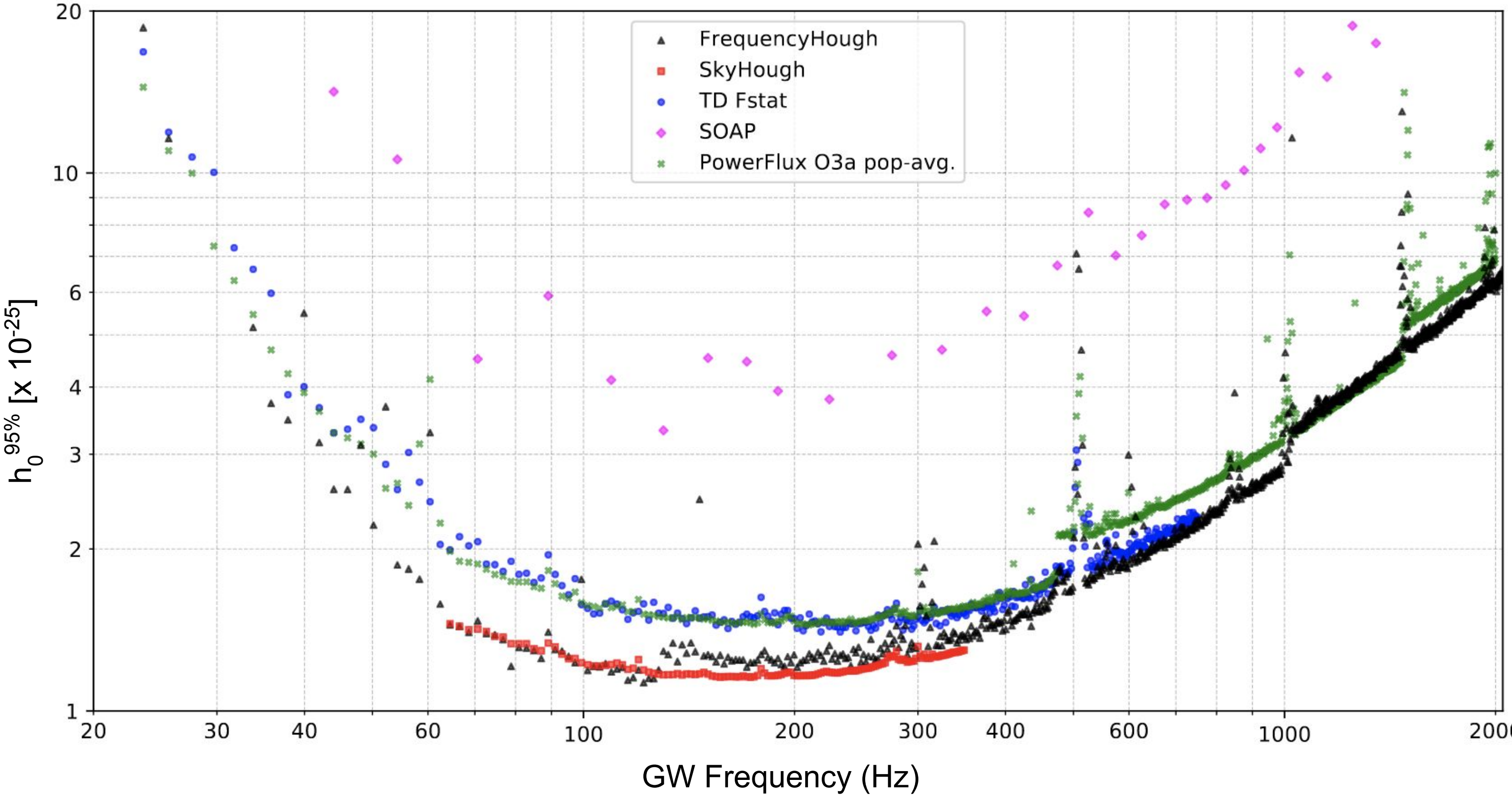
B P Abbott *et al.* *Nature* **551,** 85–88 (2017) doi:10.1038/nature24471



R Abbott *et al.* *arXiv:2111.03604* *(2021)*

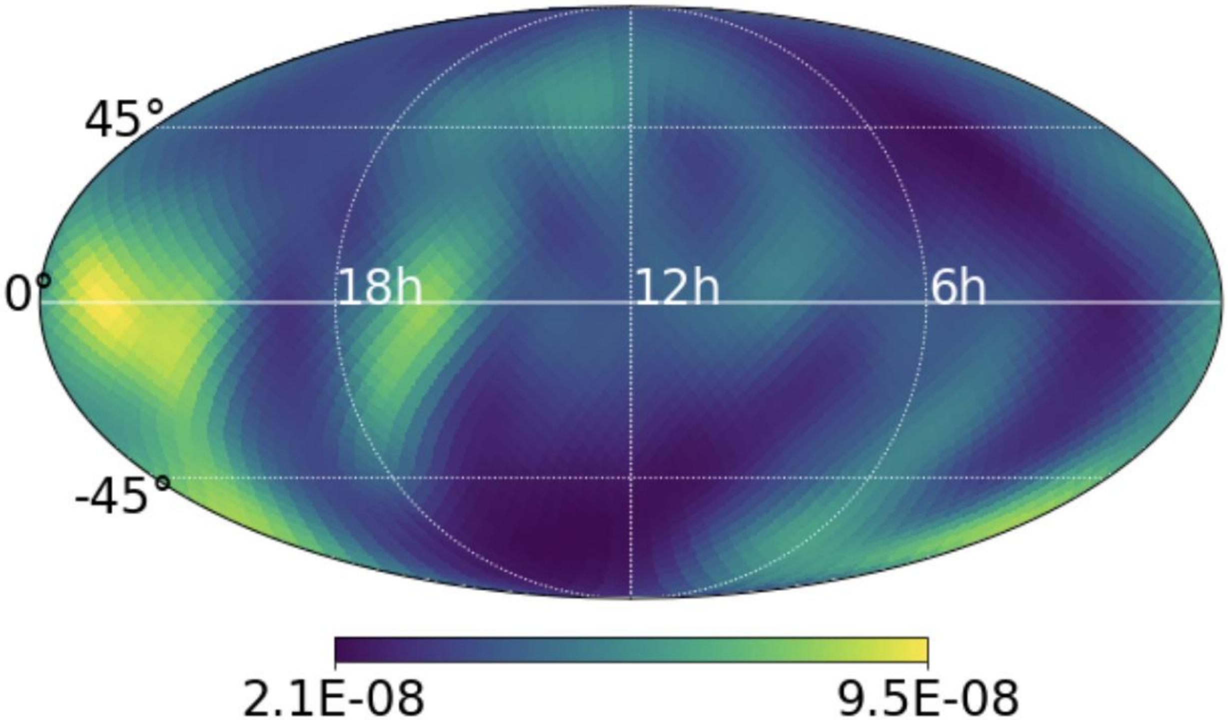


Continuous wave upper limits



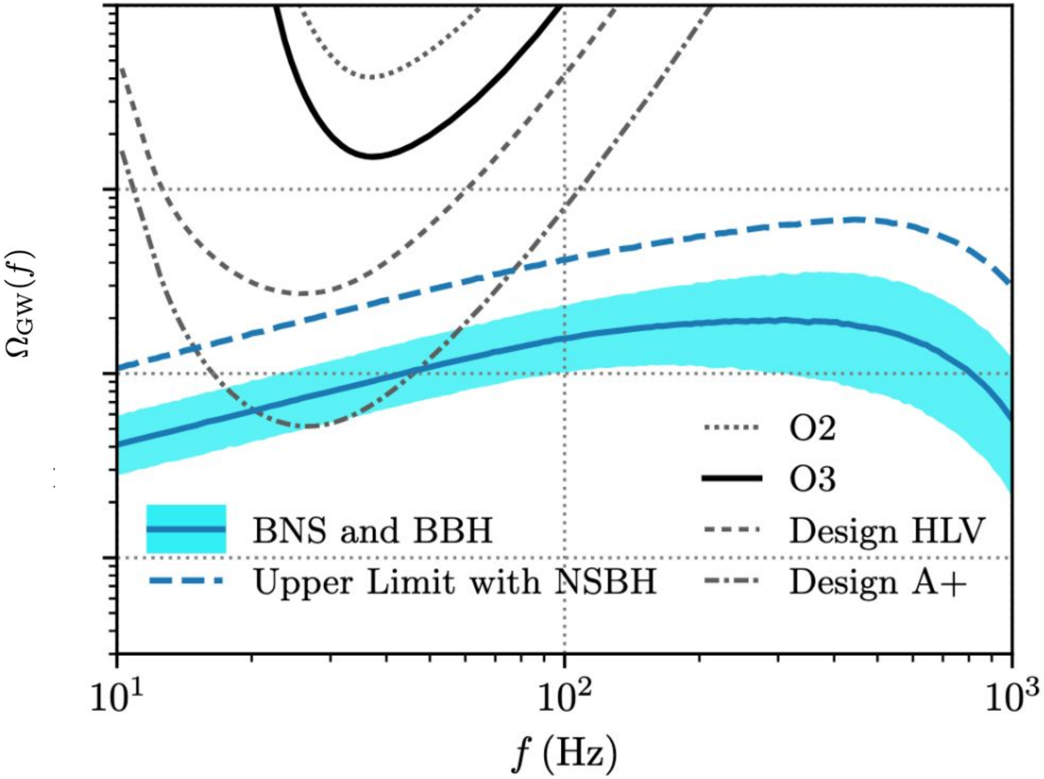
R Abbott *et al.* *arXiv:2201.00697* (2022)

Stochastic background upper limits



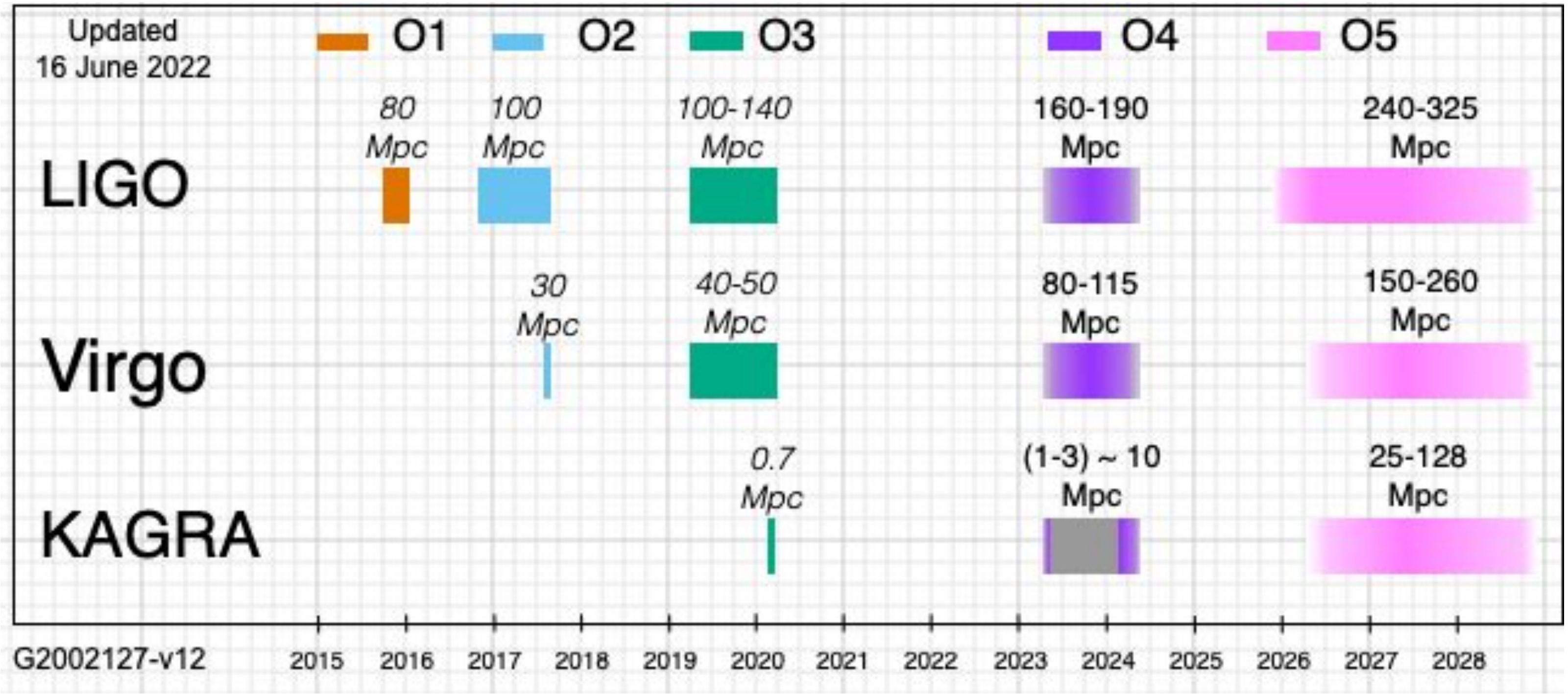
R Abbott *et al.* *arXiv:2110.09834* (2021)

Isotropic GW Background



LVC, Phys. Rev. D 104, 022004 (2021)

Observing plans



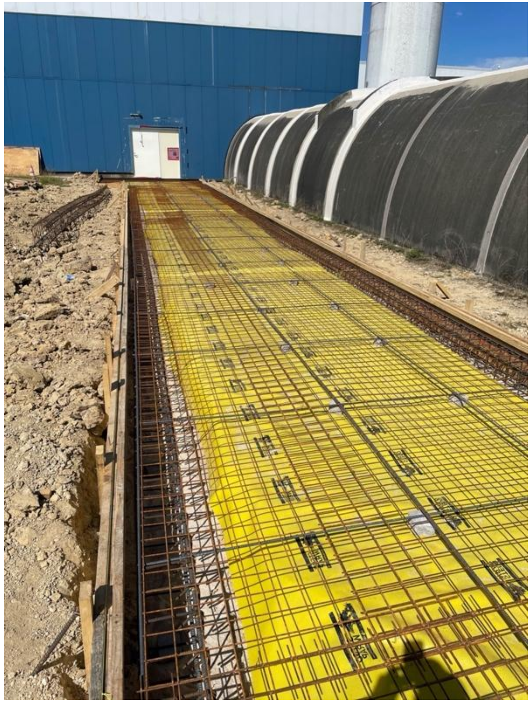
LIGO-Virgo-KAGRA anticipate observing to dovetail with next generation facilities

Observing plans are now being maintained at https://observing.docs.ligo.org/plan/

LIGO instrumental upgrades for O4

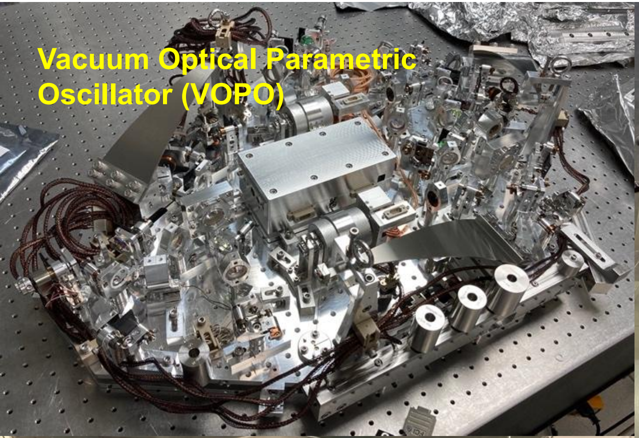
- LIGO, Virgo and KAGRA have been doing major work
    - Here, I summarize the LIGO activities.
    - Talks by Arnaud about Virgo and Ushiba about KAGRA
- LIGO planned major upgrades from O3 to O4:
    - New laser amplifier (improve high-frequency sensitivity)
    - Point absorber free test masses (improve high-frequency sensitivity)
    - Frequency dependent squeezing (FDS) (improve broadband sensitivity)
    - Adaptive mode matching (improve broadband sensitivity)
    - Low-loss faraday isolator (improve broadband sensitivity)
    - Stray light baffles (improve low frequency sensitivity)
- LIGO target for O4: 190Mpc BNS range
    - Requires commissioned FDS; without FDS, target 165Mpc BNS range

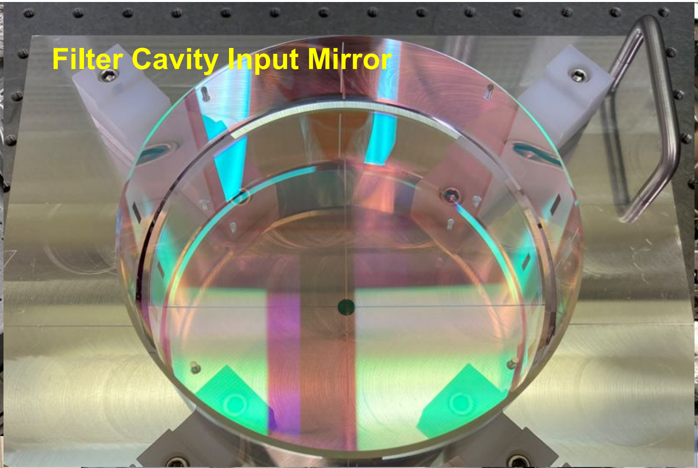
Construction for the filter cavity

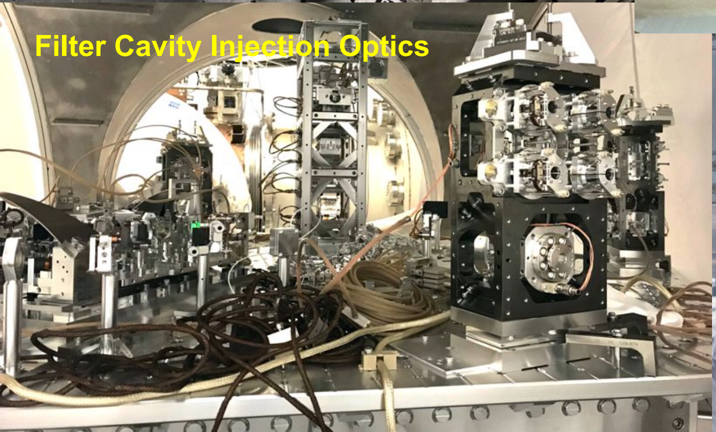


Thanks to Dave Reitze, LIGO Lab

O4 LIGO detector upgrades



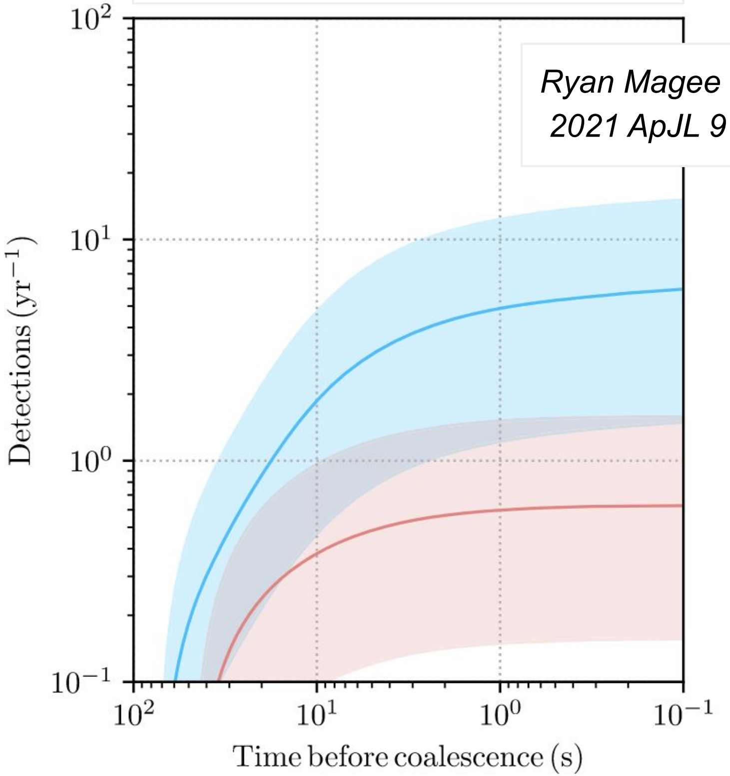




Impact of LVK upgrades on observations

- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / 2 days
- Improved public alerts
  - Localization
  - Classification
  - Latency
- Other science
  - Improved SNR
- Discovery space
  - New sources?

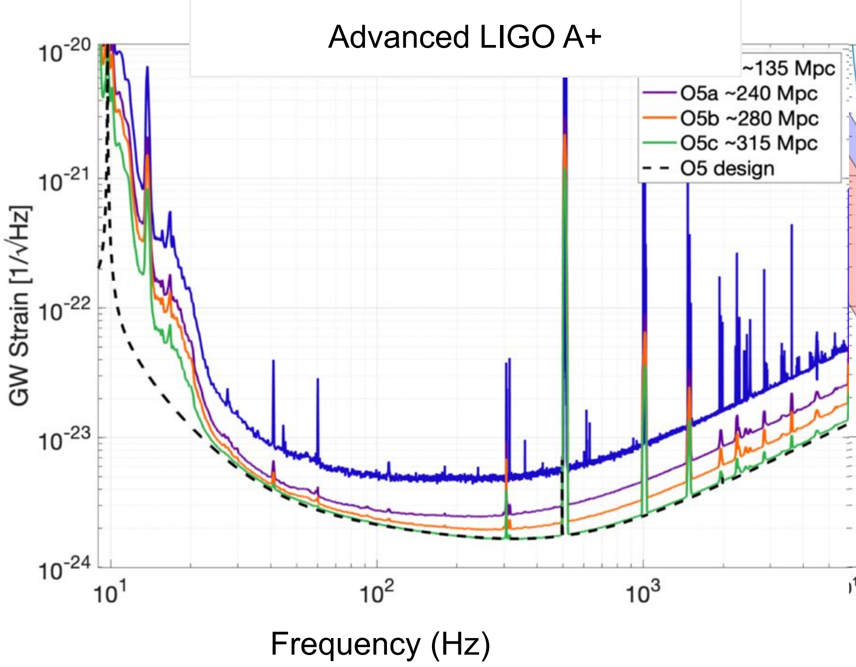
Predicted O4 BNS Detections

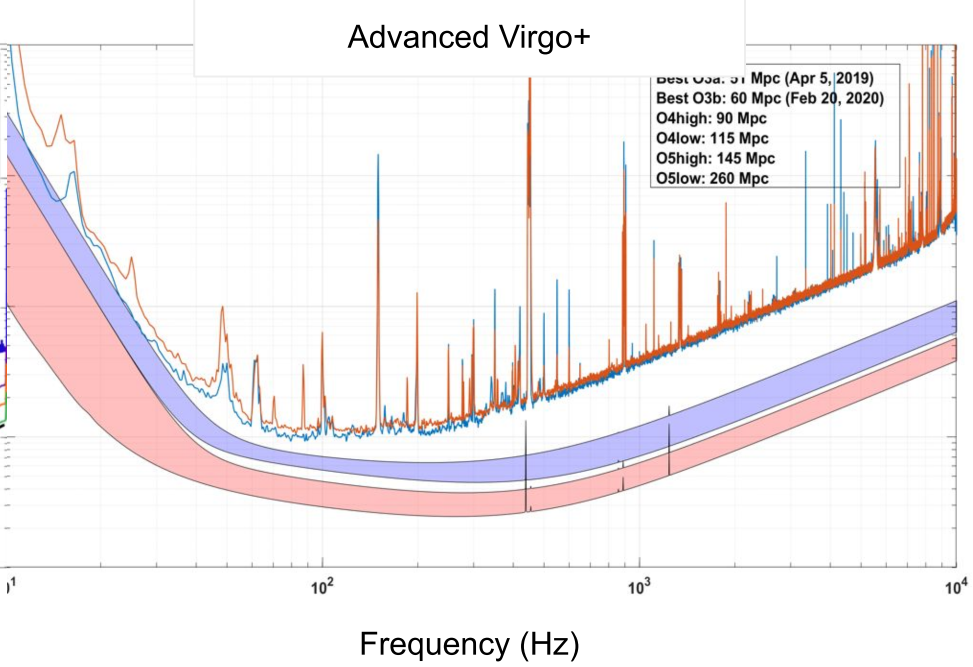


Ryan Magee et al 2021 ApJL 910 L21

Thanks to Dave Reitze & Giovanni Losurdo

Working toward O5 sensitivity

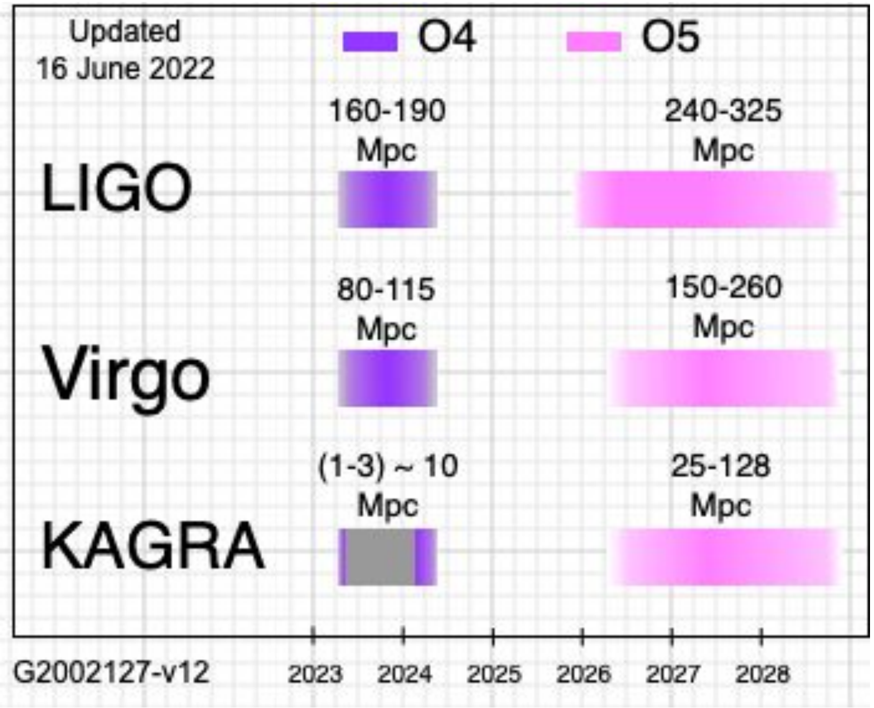




KAGRA will continue to work towards
130Mpc goal in O5

O5 Observing Run

- Current thinking
  - Start is paced by upgrades after O4: 1.5-2 years gap.
  - Intersperse commissioning and observations
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / 2 days
  - O5 ~ 3 / day
- Other science
  - Improved SNR
  - New sources?



LIGO-Virgo-KAGRA anticipate observing to dovetail with next generation facilities

Observing plans are now being maintained at https://observing.docs.ligo.org/plan/

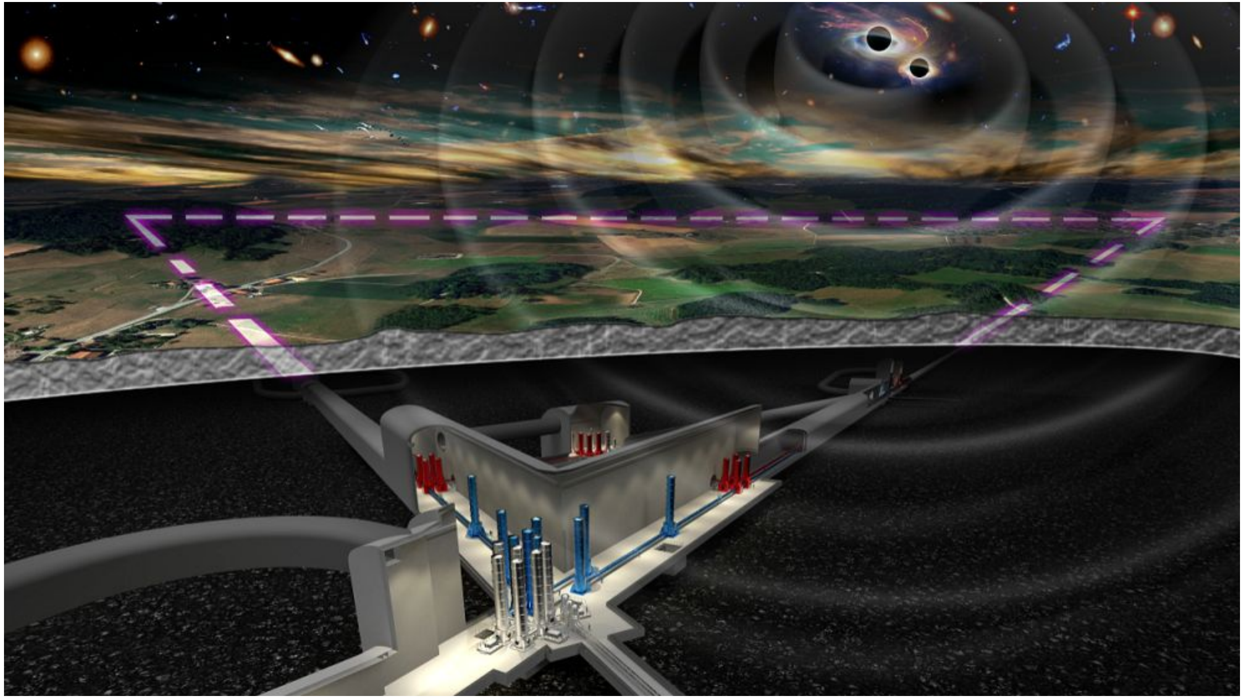
Post-O5 planning

- The LVK is committed to continued observations **beyond 2028** (contingent on continued funding of the observatories).
- Over the past year, we have scoped detector upgrade options for after O5.
  - Targeted improvements have been identified to achieve 1.25-1.7 amplitude sensitivity improvement.
    - Larger test masses, better seismic isolation, subtract newtonian noise…
    - Higher laser power, better squeezing, improved thermal compensation…
  - Other options
    - Crystalline coatings for test masses …
    - Cryogenic detector (Voyager) … very interesting, technologies not mature yet.
- Next steps:
  - Synchronize IGWN plans; instrument design & proposal; observing plan to dovetail with the implementation of Cosmic Explorer and Einstein Telescope.

Next Generation Facilities

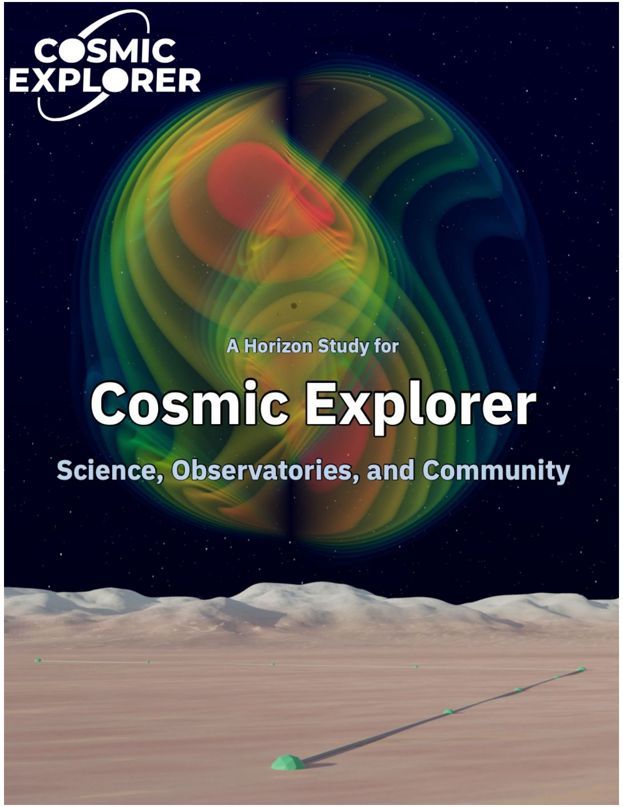
Einstein Telescope

- Proposed underground facility in Europe
- 10km arms, cryogenic optics, triangular configuration
- ET is on the European Strategy Forum on Research Infrastructures (ESFRI) 2021 roadmap



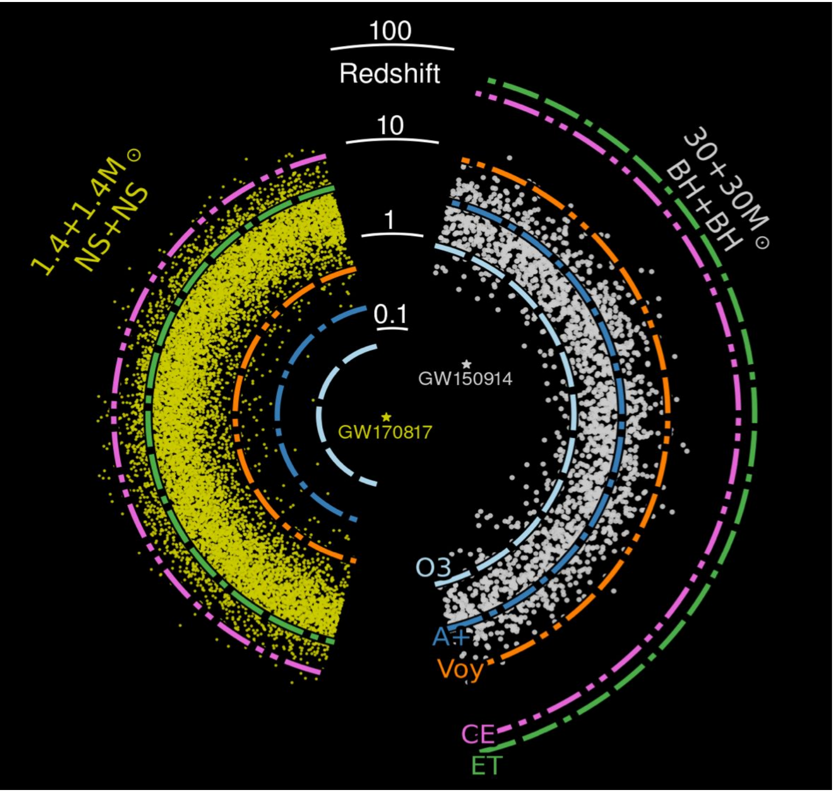
Cosmic Explorer

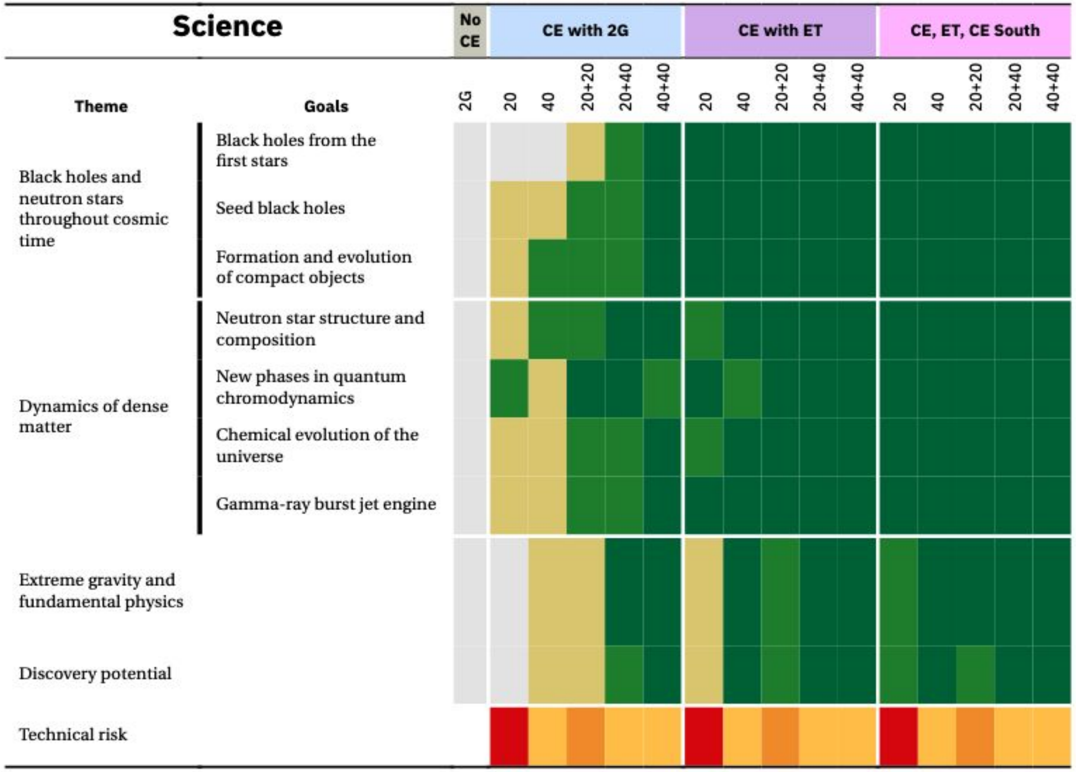
- Proposed above ground facility in the US
- Two 40km orthogonal arms using mature technology from current ground-based detectors
- Cosmic Explorer Horizon Study
  - Released in October 2021
- DAWN VI Workshop
  - “There was a consensus that Cosmic Explorer is a concept that can deliver the promised science. A strong endorsement of Cosmic Explorer, as described in the CE Horizon Study, is a primary outcome of DAWN VI."



https://arxiv.org/abs/2109.09882

Cosmic Explorer Science Reach





A Horizon Study for Cosmic Explorer
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Thank you!