Gravitational-wave astronomy in the 2020s

Patrick Brady, LSC Spokesperson
University of Wisconsin-Milwaukee

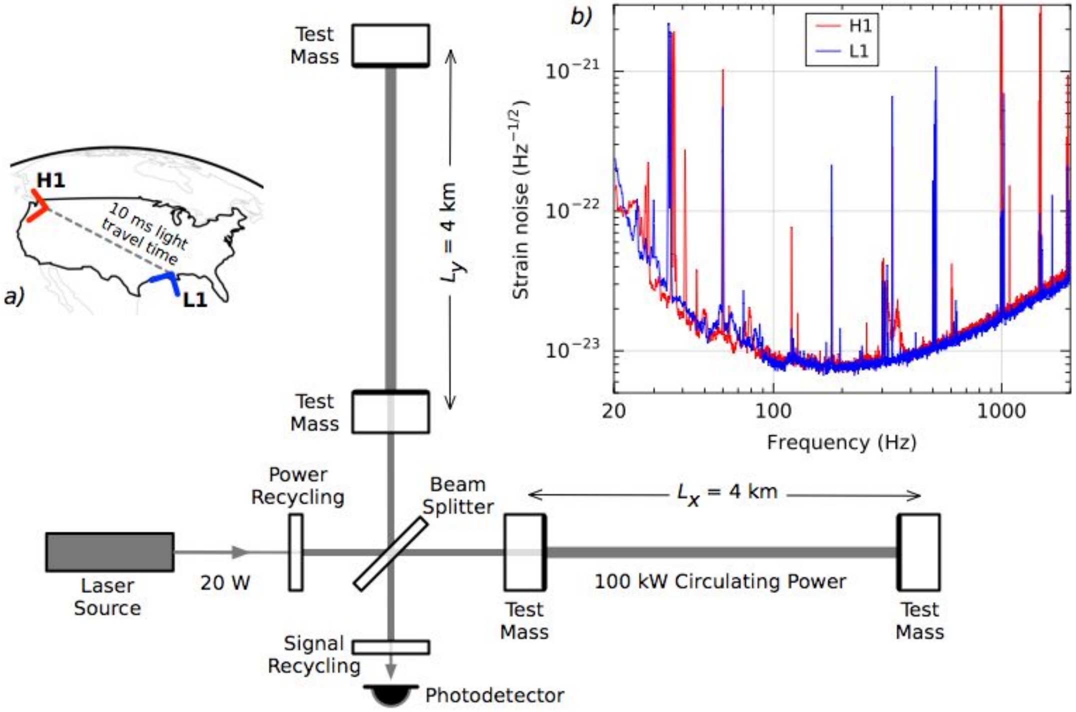
EGO/Virgo
12 May 2022

https://dcc.ligo.org/G2200793

International Gravitational-Wave Observatory Network (IGWN)

- The LIGO-Virgo-KAGRA Collaboration is an international team of more than 2000 scientists who work together to design, build and operate the international gravitational-wave observatory network.

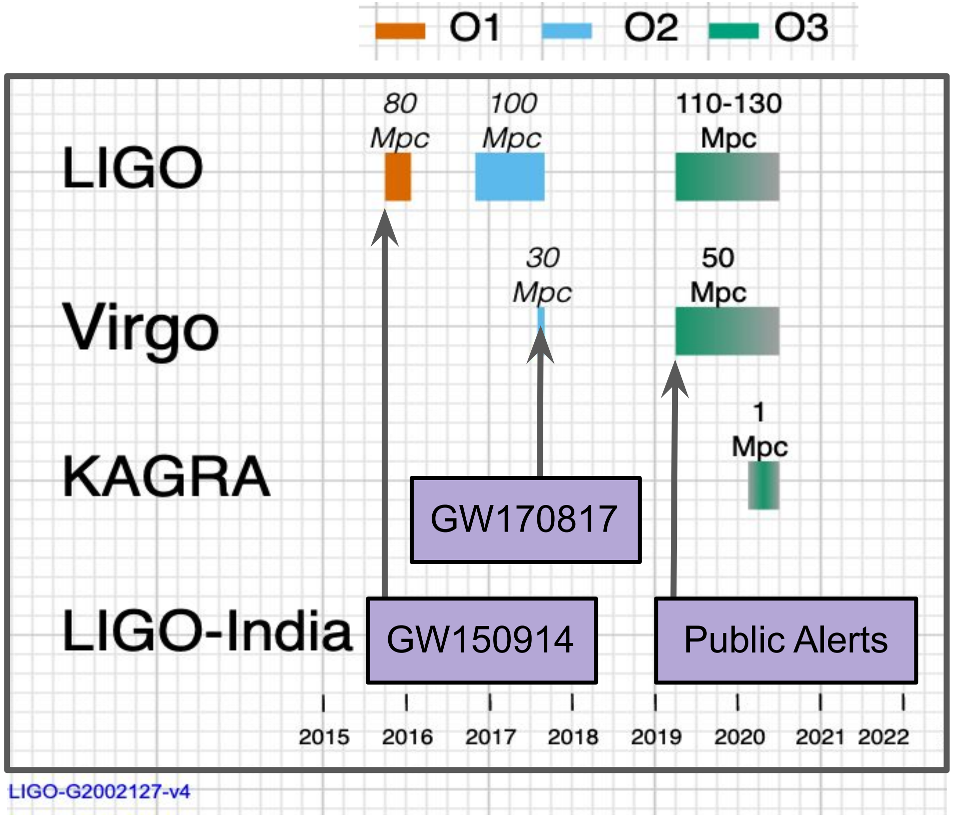
LIGO-Virgo-KAGRA detectors

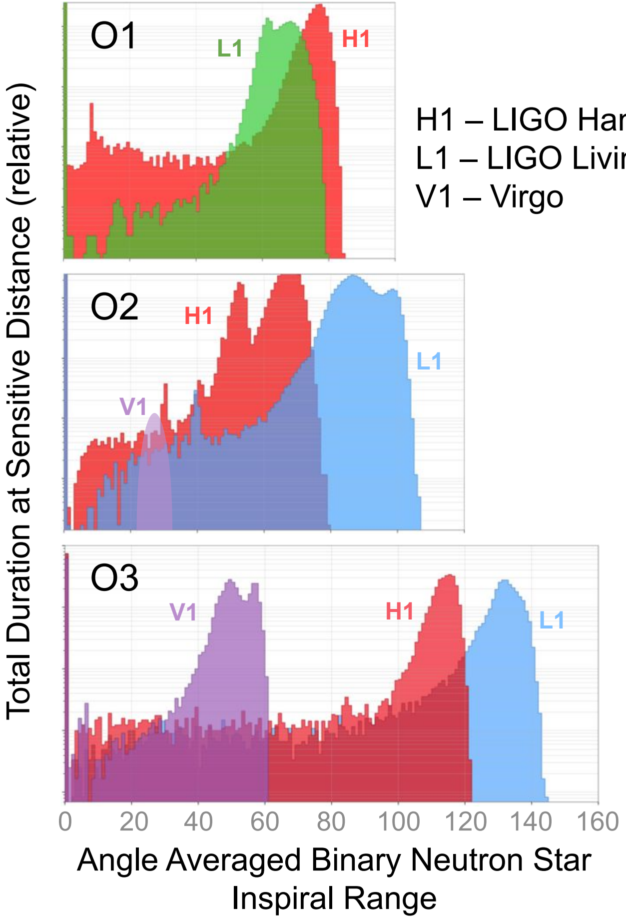


Outline of my talk

- Highlights of gravitational-wave observations 2015-2022
  - Detectors, sensitivity and observing runs
  - Compact binary detections, rates, and unique experiments
  - Searches for other gravitational-wave sources
- The booming 20s
  - 2022-2025
  - 2025-2030
- Next generation facilities
  - Einstein Telescope and Cosmic Explorer

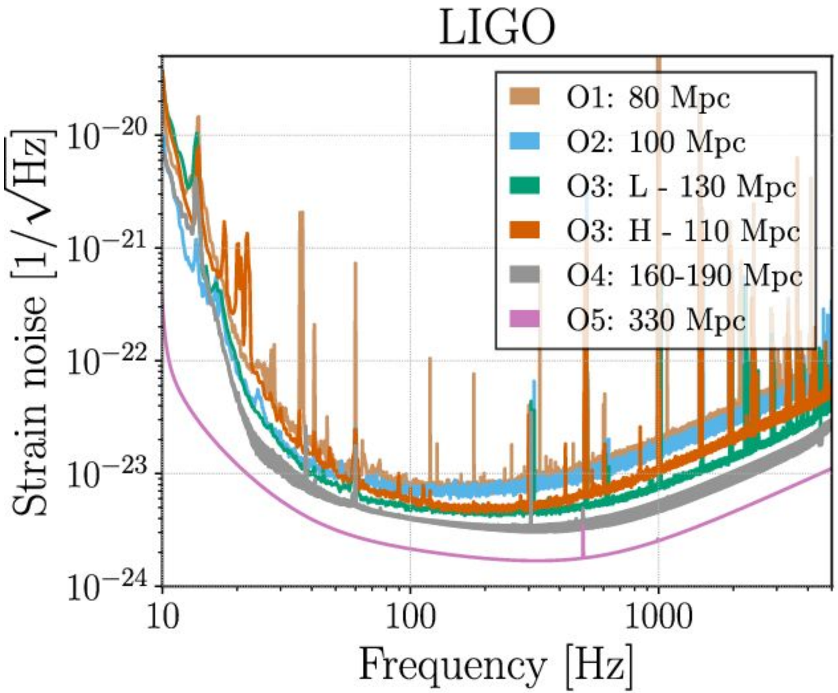
Observing runs

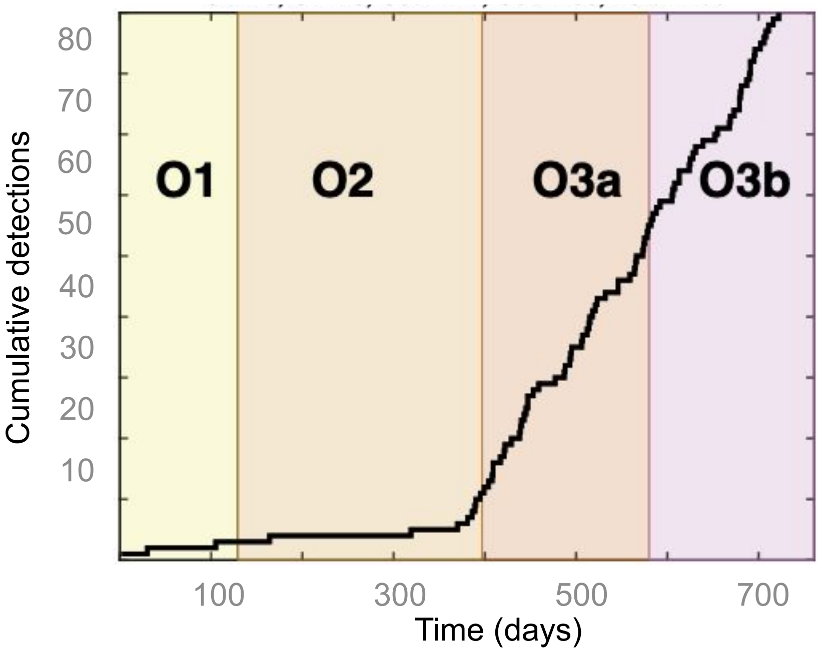




H1 – LIGO Hanford
L1 – LIGO Livingston
V1 – Virgo

Sensitivity & detections



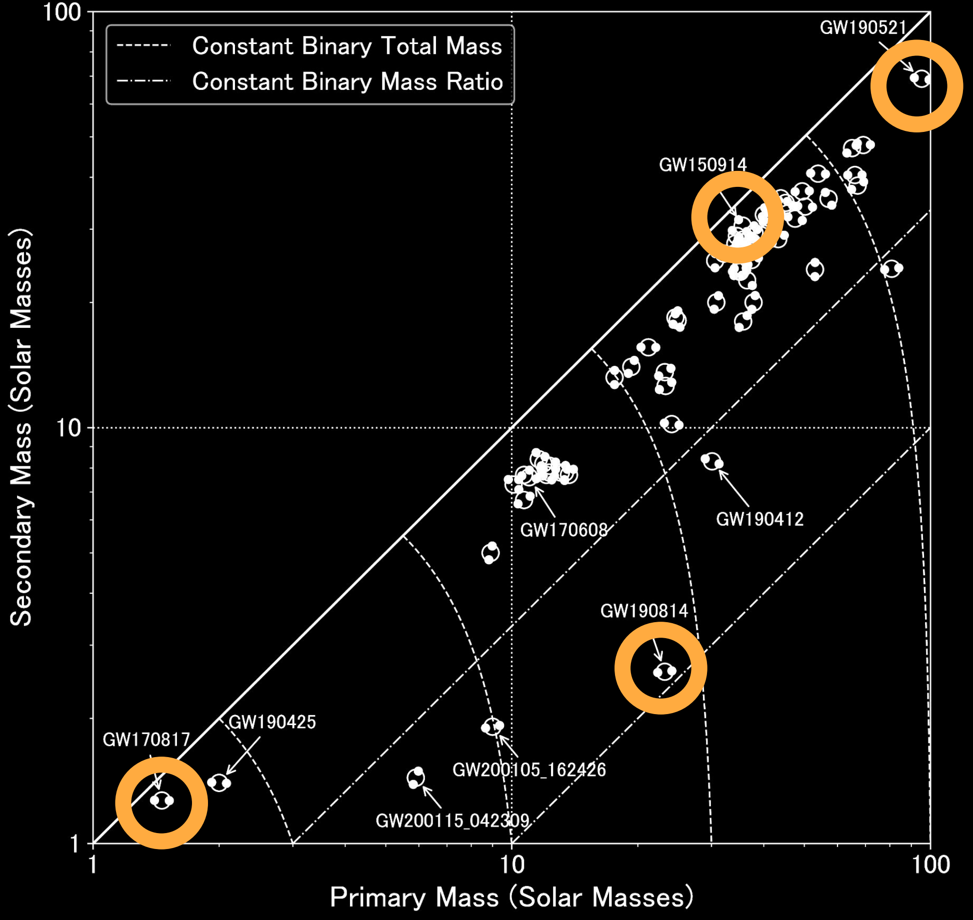


O3 binary detection rate ~ 1 / (5 days)

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

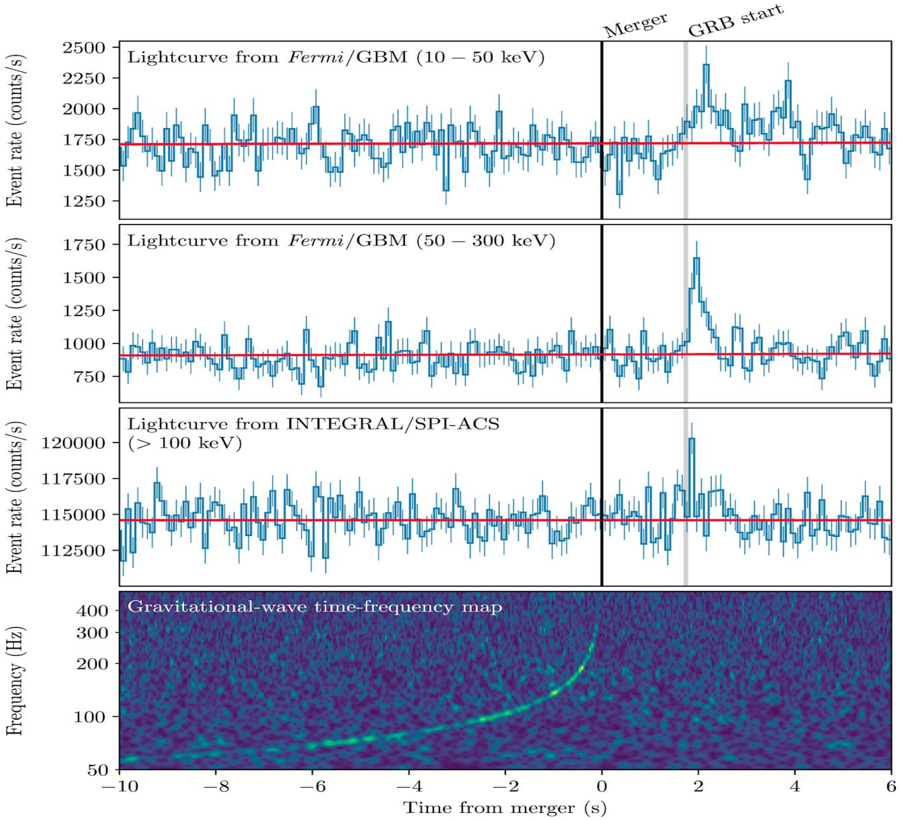
Firsts

- 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



Credit: LIGO-Virgo-KAGRA Collaborations

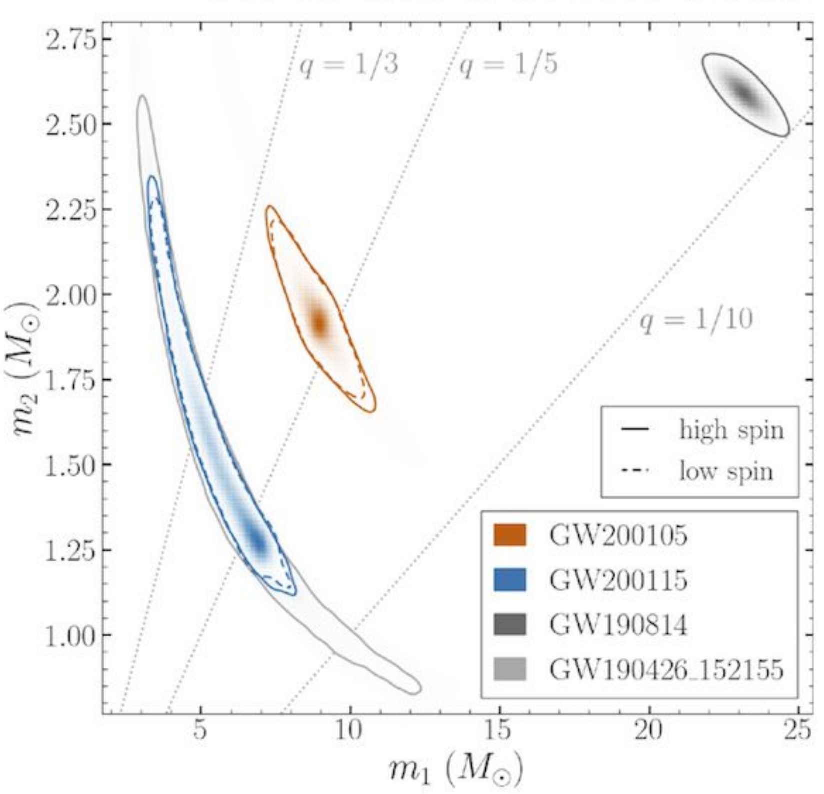
First BNS-GRB association ….



B. P. Abbott et al 2017 ApJL 848 L13

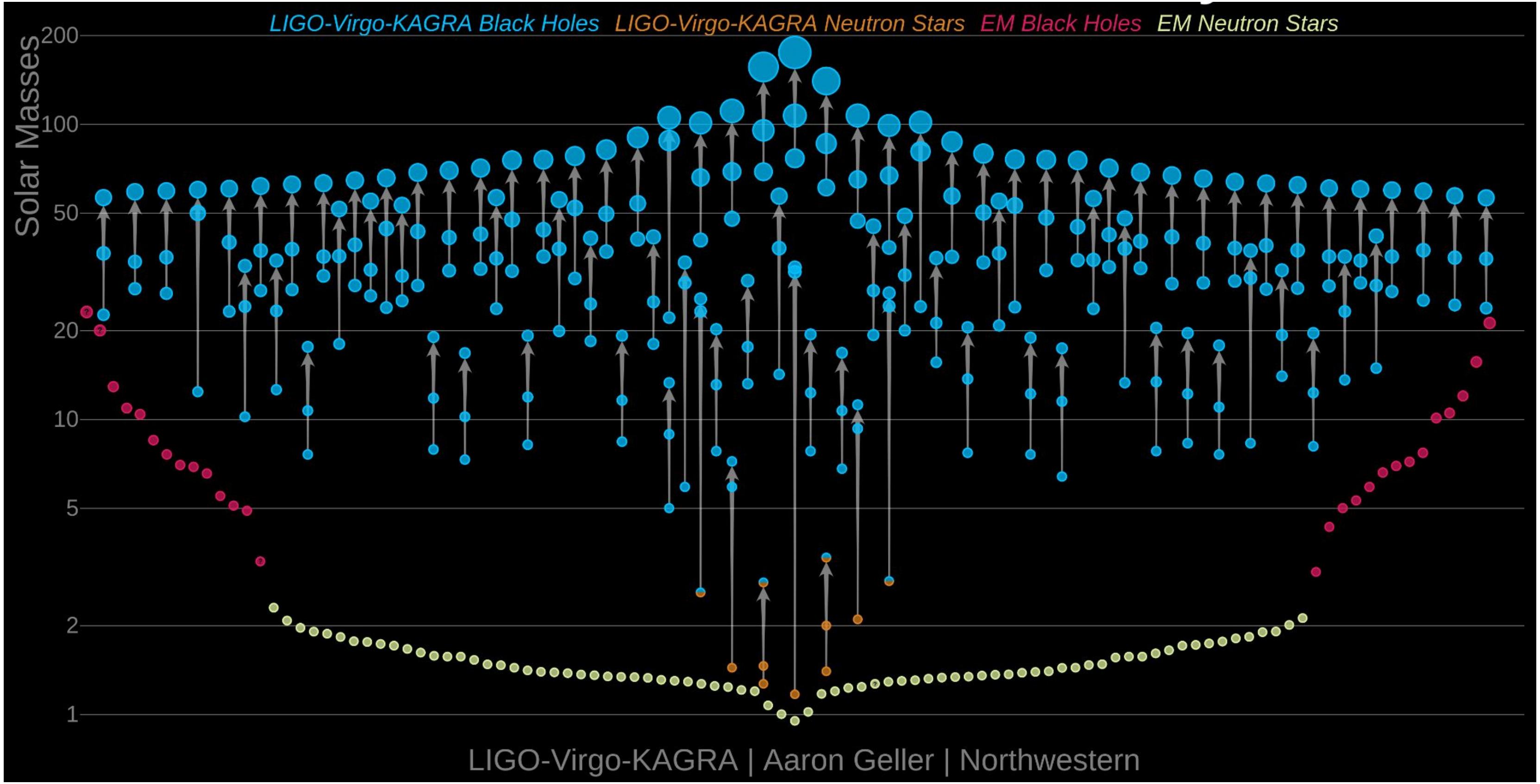
- GW170817 & GRB 170817A
    - Fractional difference in speed of gravity and the speed of light is between -3 x 10^{-15} and 7 x 10^{-16}
- GW170817 & AT 2017gfo
    - Binary neutron star mergers produce kilonova explosions that generate heavy elements

First neutron-star black hole mergers

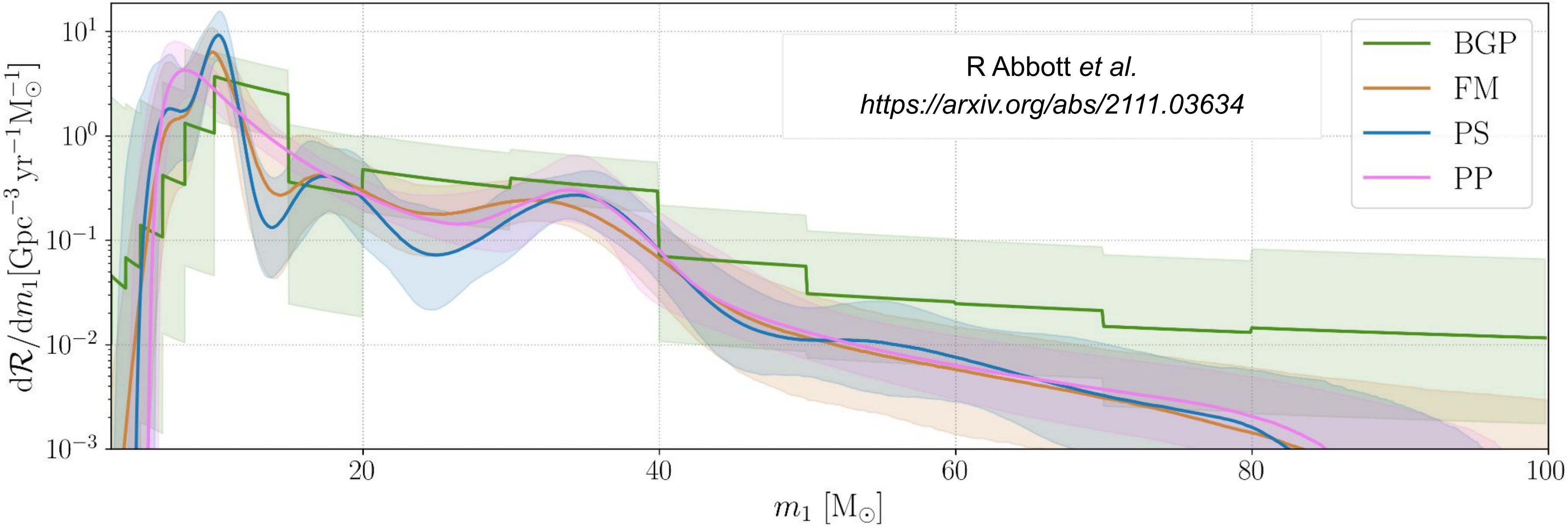


R. Abbott *et al* 2021 *ApJL* **915** L5

Masses in the stellar graveyard



From one to many: measuring populations



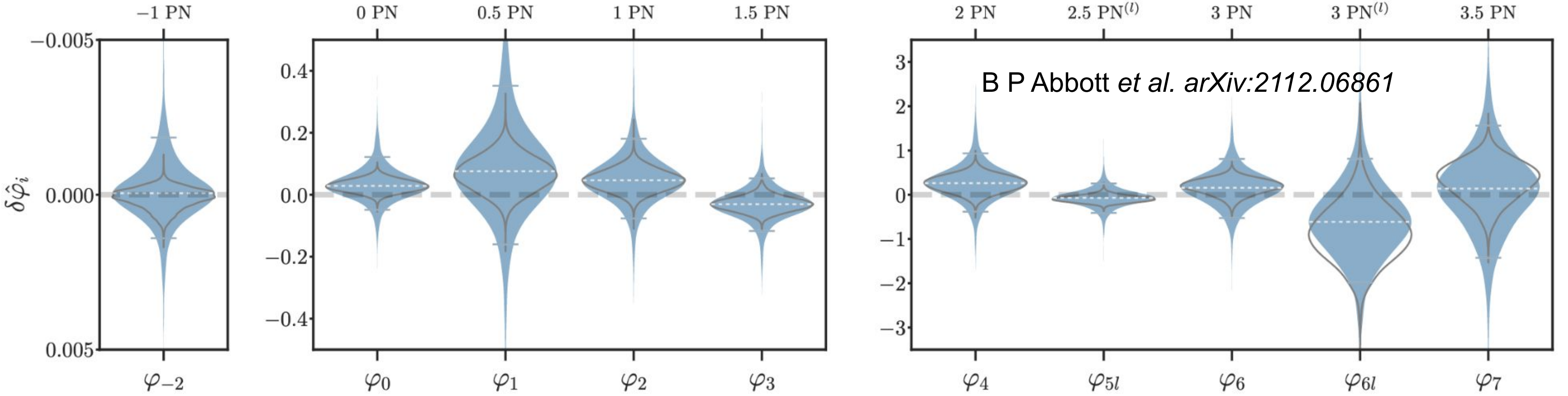
R Abbott *et al.*
https://arxiv.org/abs/2111.03634

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:

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



B P Abbott *et al. arXiv:2112.06861*

Testing modified dispersion

- Gravitational waves in GR propagate non-dispersively at the speed of light.
  - Some modified theories (massive graviton theories, Lorentz-violating theories) predict dispersion of GWs.
- Dispersion => different frequency components of the wave travel at different speeds leading to an effective dephasing of the GW signal which can be measured

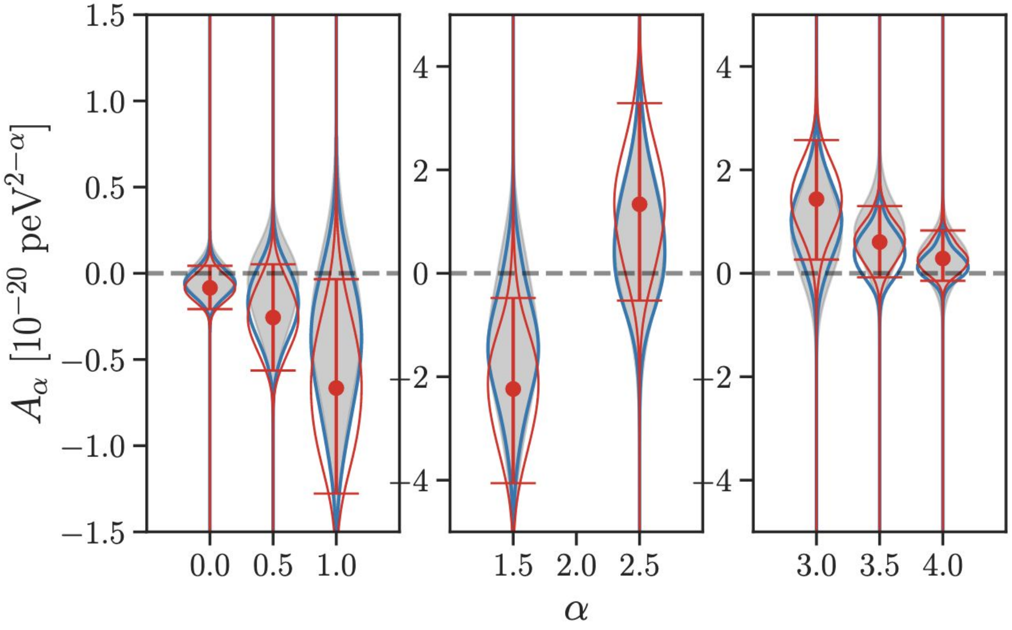
$$E^2 = p^2c^2 + A_j p^j c^j$$

Mirshekari et al. PRD 85, 024041, 2012,
Clifford. M. Will PRD 57, 2061, 1998

- Bound on A_0 is equivalent to bound on the mass of the graviton.

Testing modified dispersion

- Red violin plots show the combined posteriors of the parameter Aα calculated from the GWTC-3 events
- Error bars denote 90% credible intervals.
- The gray shaded area are the combined posteriors corresponding to GWTC-2



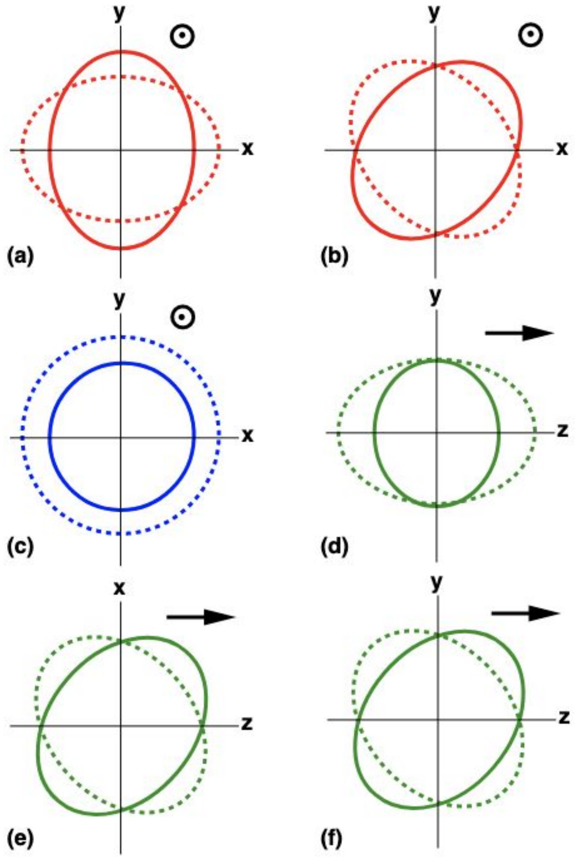
B P Abbott *et al. arXiv:2112.06861*

Other tests

- Polarization: general metric theory allows 6 polarization modes; each detector gives one additional mode; search null-stream for residuals.
    - No evidence in favour of non-GR polarization hypotheses
- Spin induced quadrupole: self spinning effects of compact objects lead to spin-induced deformations that imprint on the GW as 2 PN effects; search for deviations for GR for BBH
    - Found to be consistent with Kerr black holes for BBH candidates

B P Abbott *et al. arXiv:2112.06861*

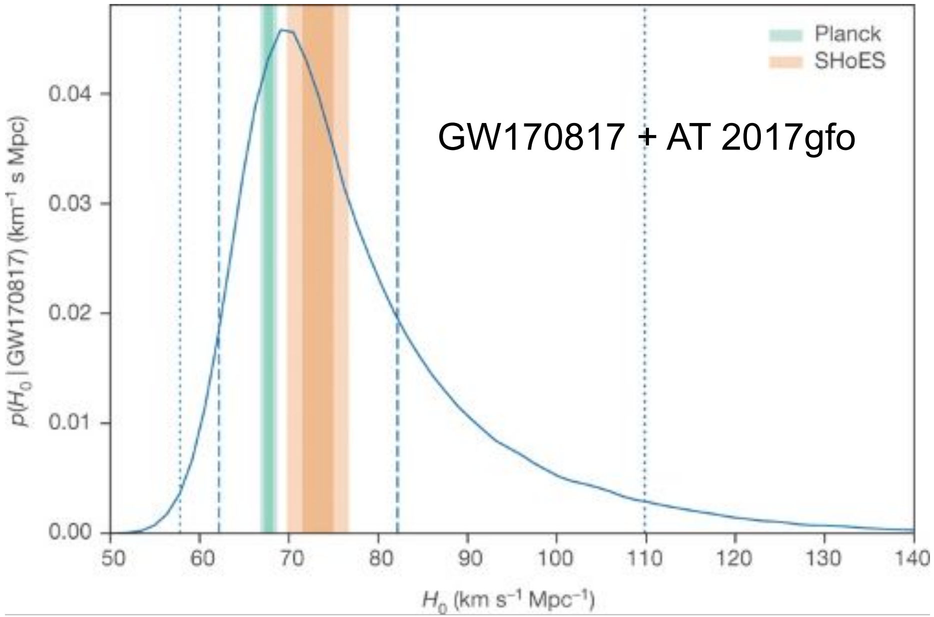
Gravitational–Wave Polarization



C. M. Will, Living Rev. Relativity 17, 2014

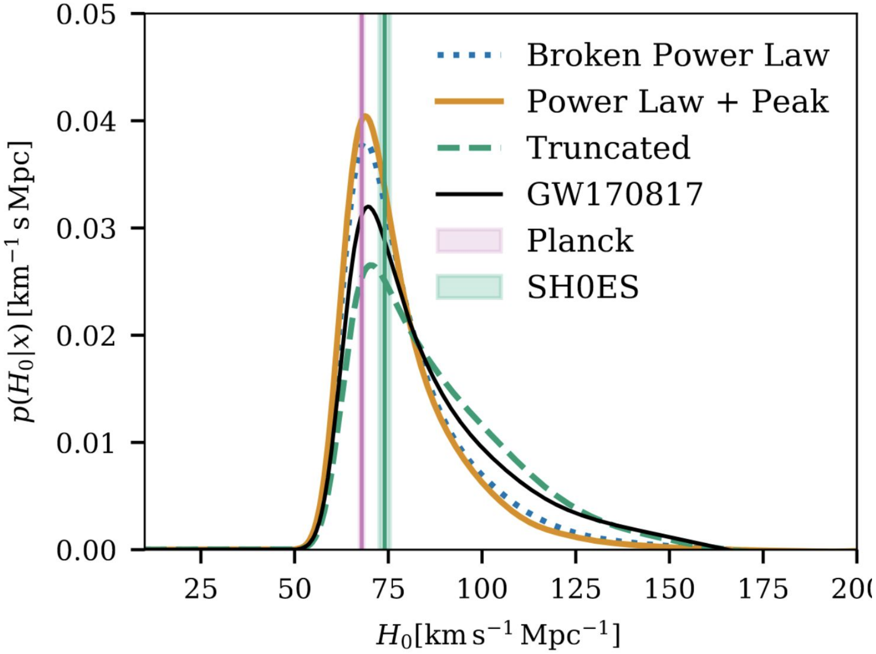
Cosmology with gravitational waves

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



GW170817 + AT 2017gfo

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

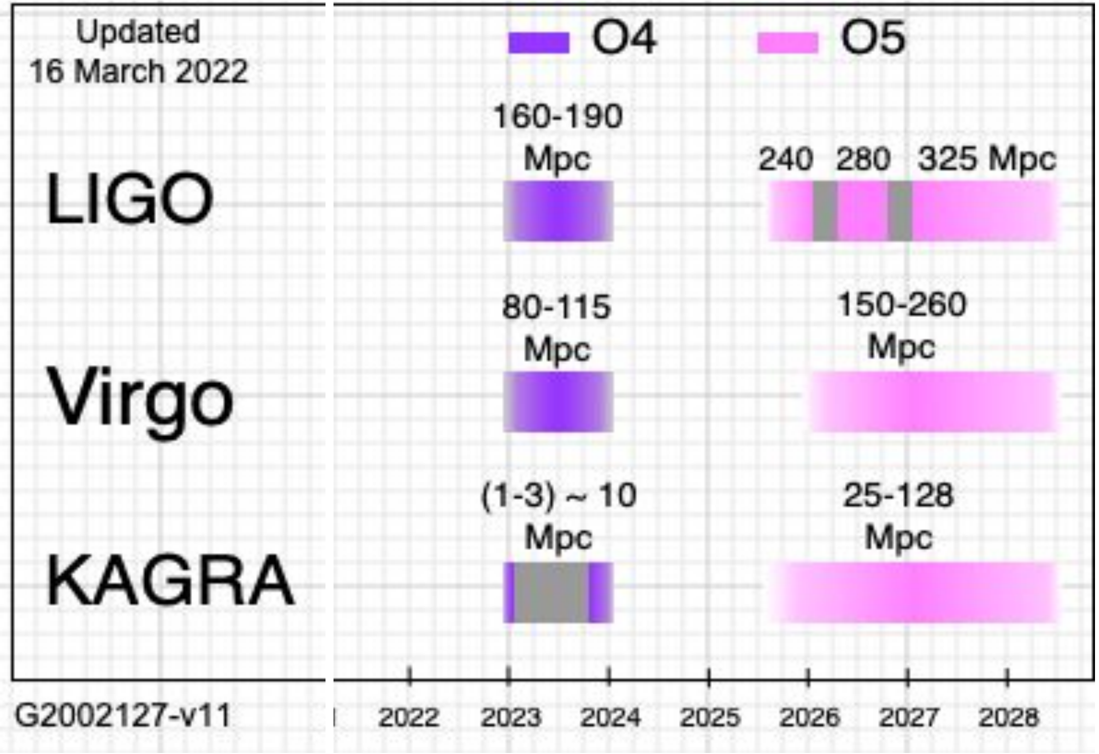


GWOSC - https://www.gw-openscience.org

- Event Portal Query Page
  - https://www.gw-openscience.org/eventapi/html/query/
- Bulk strain data releases (18 months after each 6 month observation period)
  - https://www.gw-openscience.org/{O3,O2,O1}
- GWOSC Office Hours
  - https://www.eventbrite.com/e/gwosc-office-hours-tickets-147886956869
- Open Data Workshops
  - 2021 hosted by Max Razzano at INFN, Pisa
  - Now an online course, w/ 800 students enrolled: https://gw-odw.thinkific.com
- Vibrant community using these data
  - See for example *3-OGC: Catalog of gravitational waves from compact-binary mergers* by Nitz et al [arXiv:2105.09151]

Looking forward to O4

- O4 expected to start 15 Dec 2022
    - ~11 months later than expected
    - COVID caused delays due to site closures & supply chain issues
    - Weather & unanticipated problems caused further delays
- Duration of O4 is under consideration
    - Baseline is 1 year with 1 month commissioning break
    - Could extend the run if scheduling makes that viable

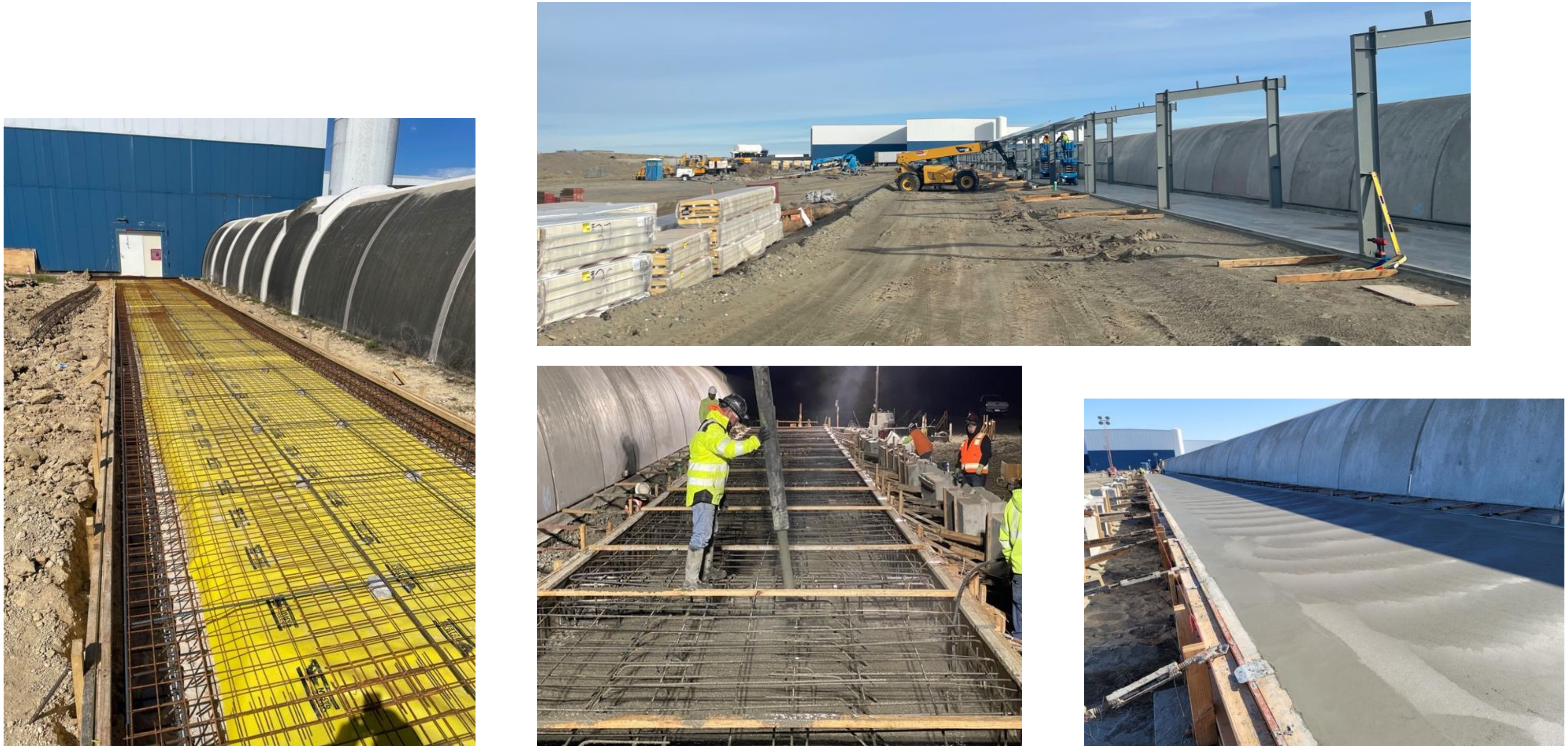


Planned instrumental upgrades for O4

- LIGO, Virgo and KAGRA have been doing major work
  - Here, I summarize the LIGO activities.
  - See https://youtu.be/Ut7Ef5AiA_M for more details about all of the detectors.
- 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
  - Backup plan, if necessary, is to descope FDS with target 165Mpc BNS range

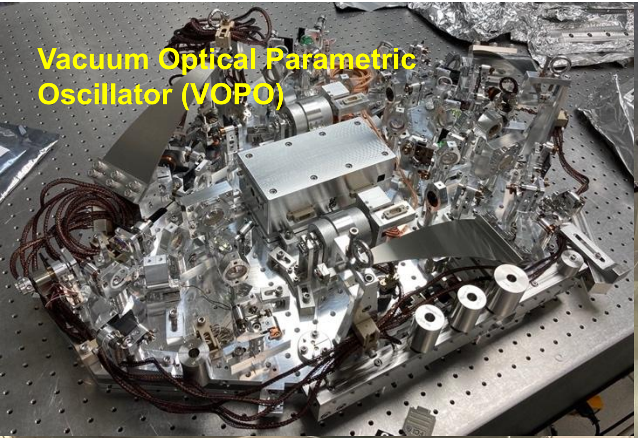
Thanks to Dave Reitze, LIGO Lab

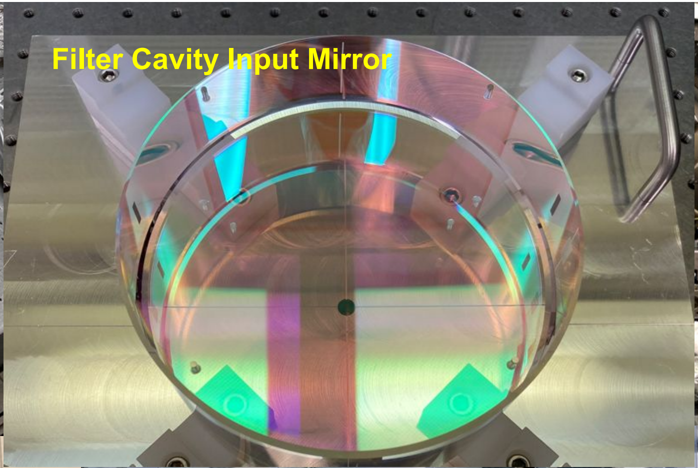
Construction for the filter cavity



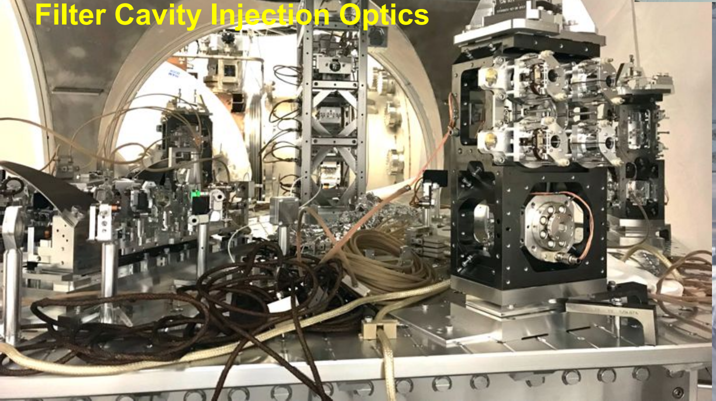
Thanks to Dave Reitze, LIGO Lab

O4 LIGO detector upgrades


Vacuum Optical Parametric Oscillator (VOPO)


Filter Cavity Input Mirror


VOPO Installation at Hanford


Filter Cavity Injection Optics

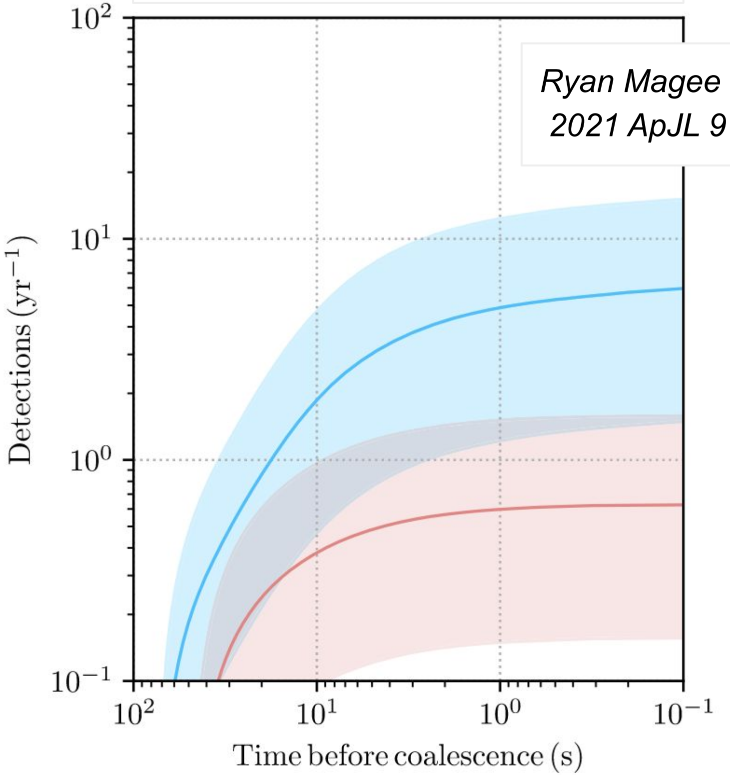

Suspension Installation at Hanford


Low Loss Faraday Isolator

Impact of LVK upgrades on observations

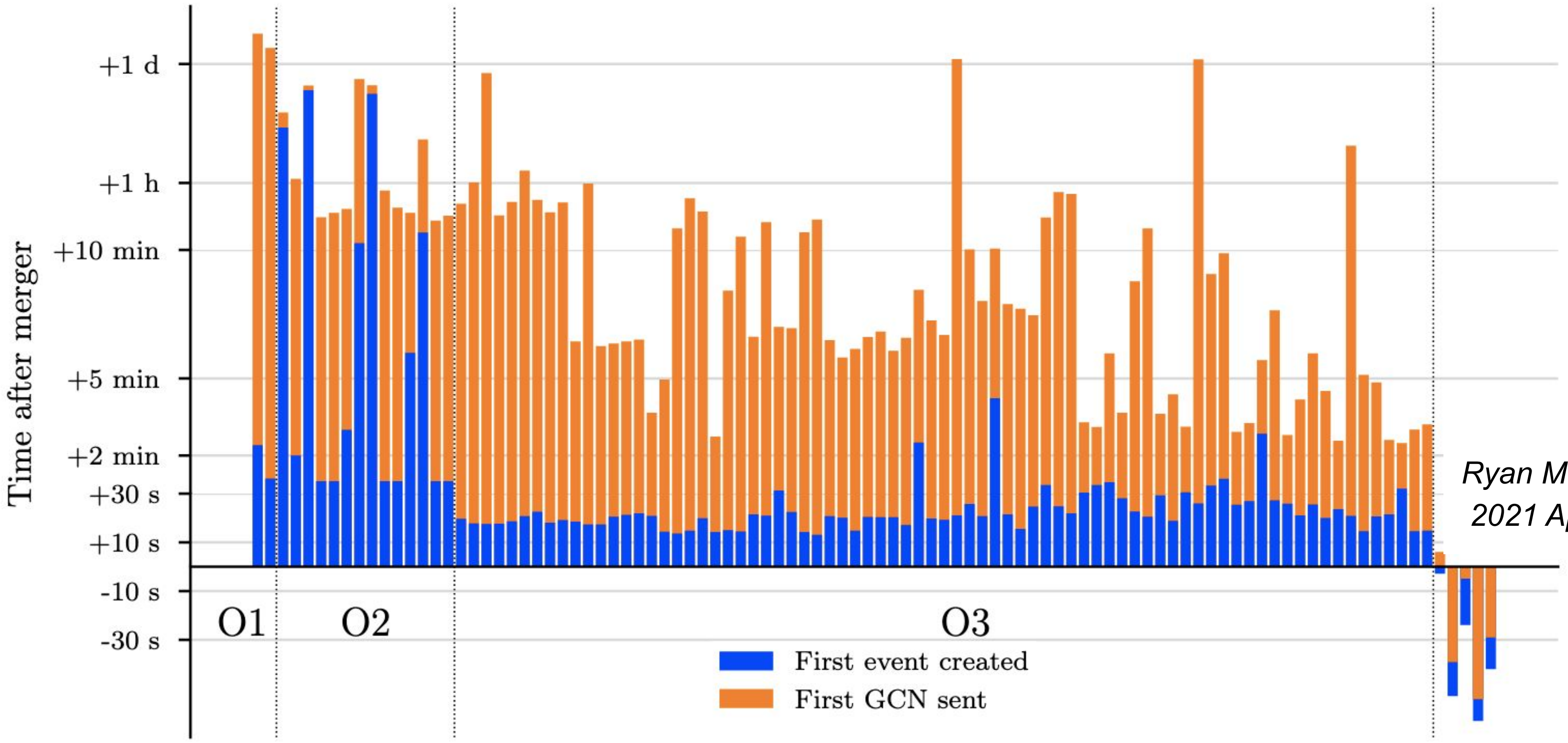
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / 2 days
- Improved public alerts
  - Localization
  - Classification
  - Latency
- Other science
  - Improved SNR
- Discovery space
  - New sources?

Predicted O4 BNS Detections



Ryan Magee et al
2021 ApJL 910 L21

Improvements in cyberinfrastructure

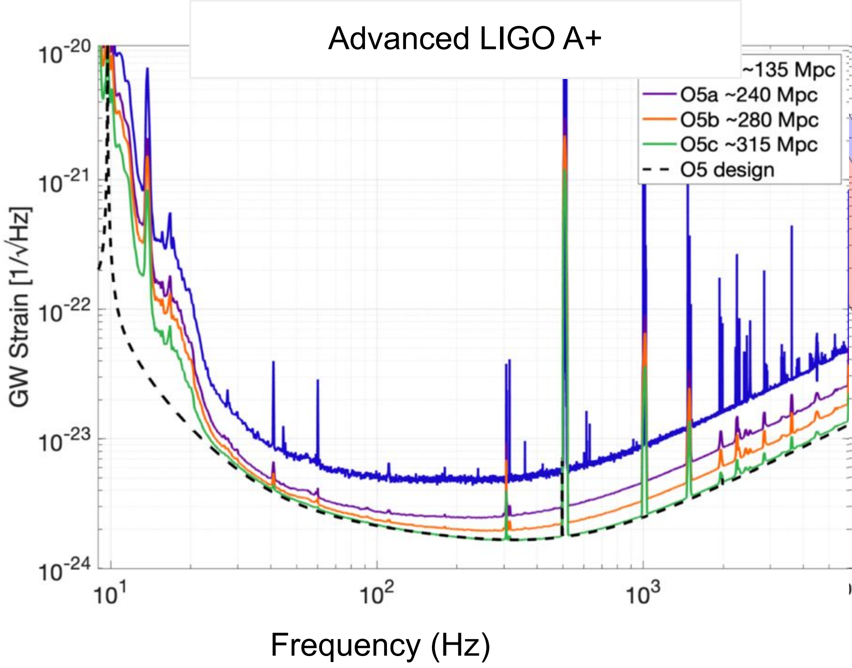


Ryan Magee et al 2021 ApJL 910 L21

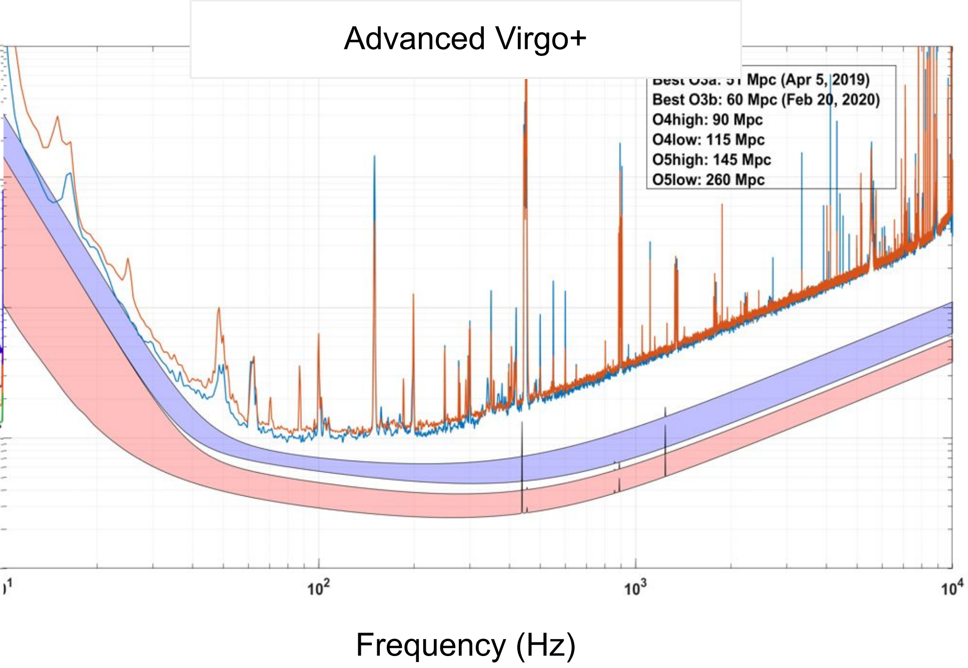
Thanks to Dave Reitze & Giovanni Losurdo

Working toward O5 sensitivity

Advanced LIGO A+



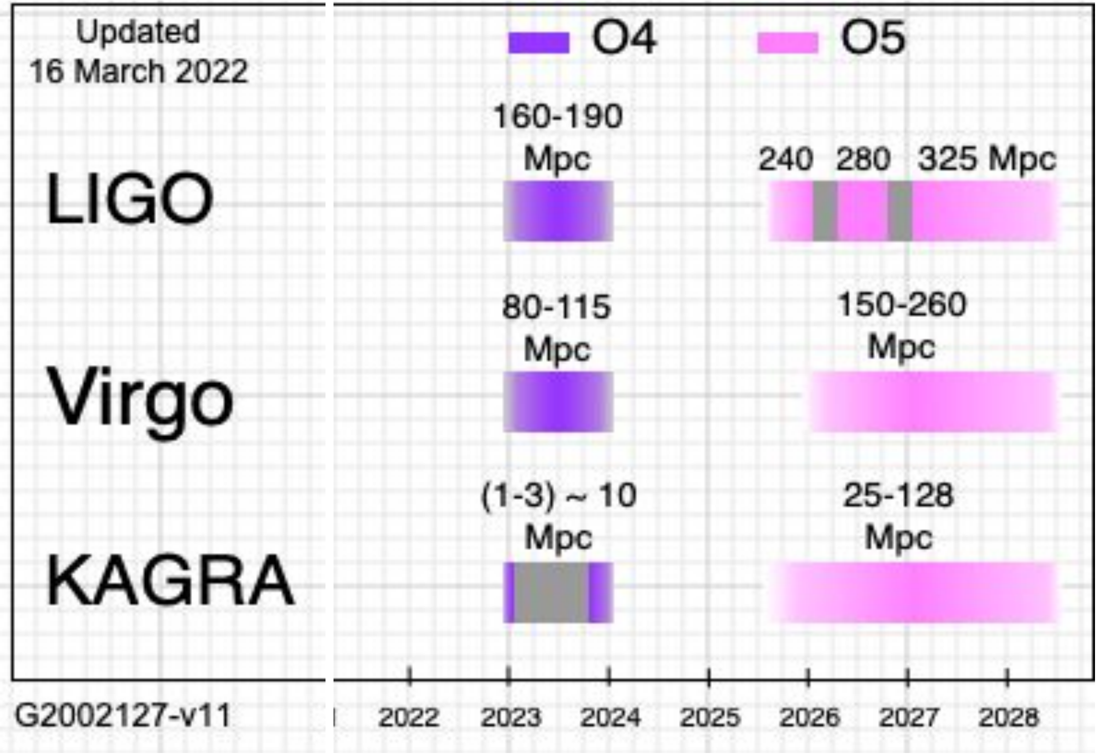
Advanced Virgo+



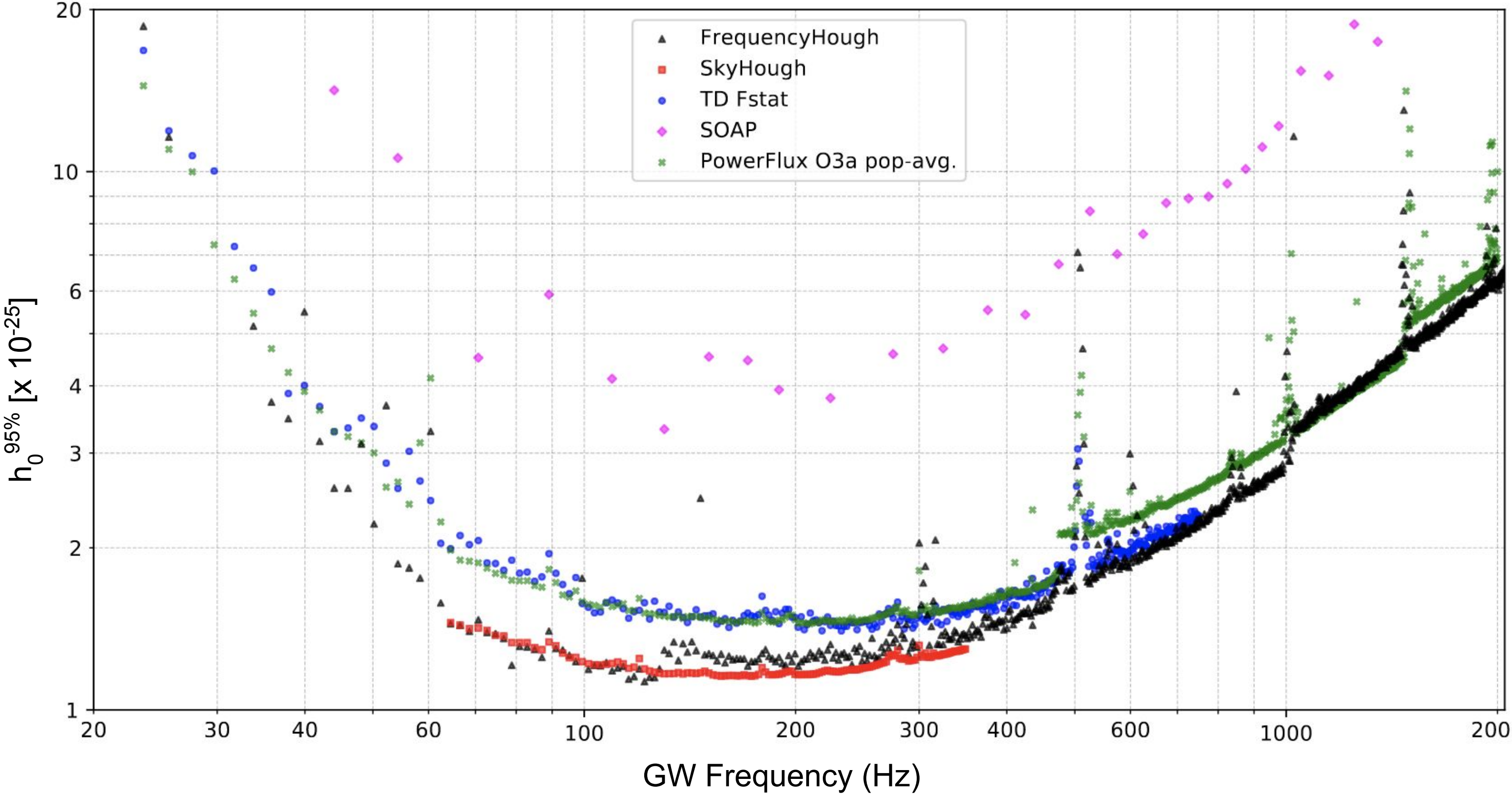
KAGRA will continue to work towards
130Mpc goal in O5

O5 Observing Run

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

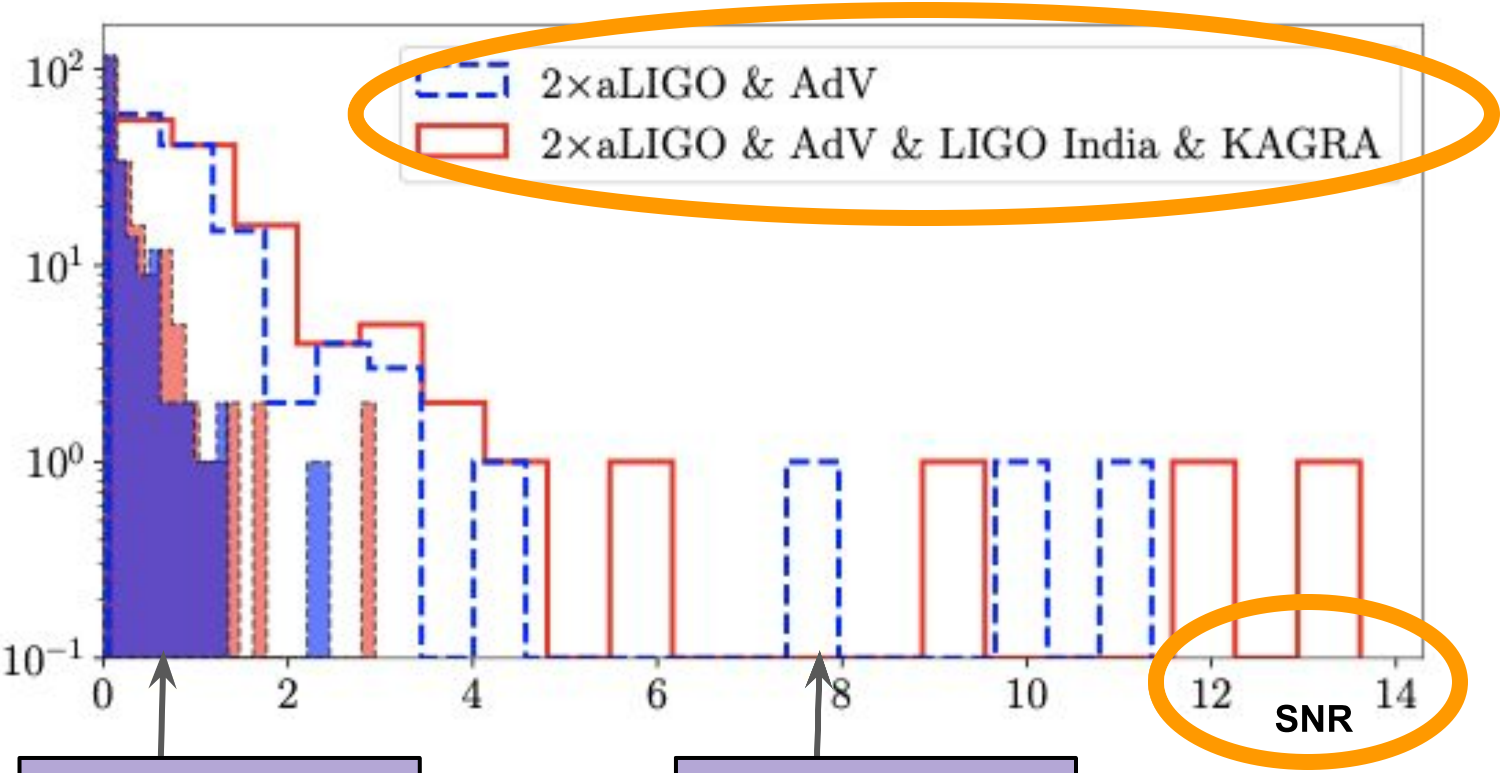


Continuous wave searches



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

GW from pulsars

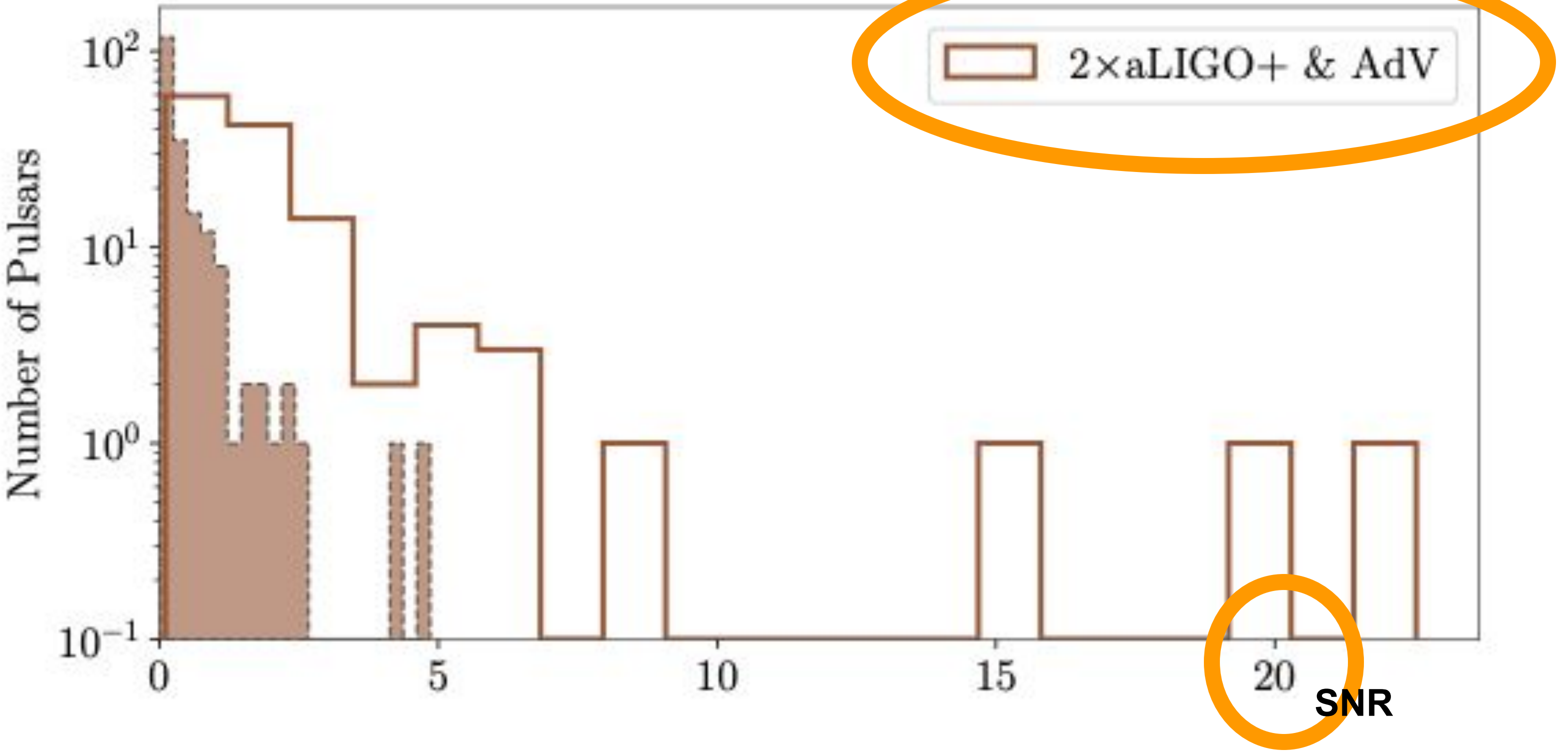


Solid: ellipticity 1e-9

Empty: gravitar

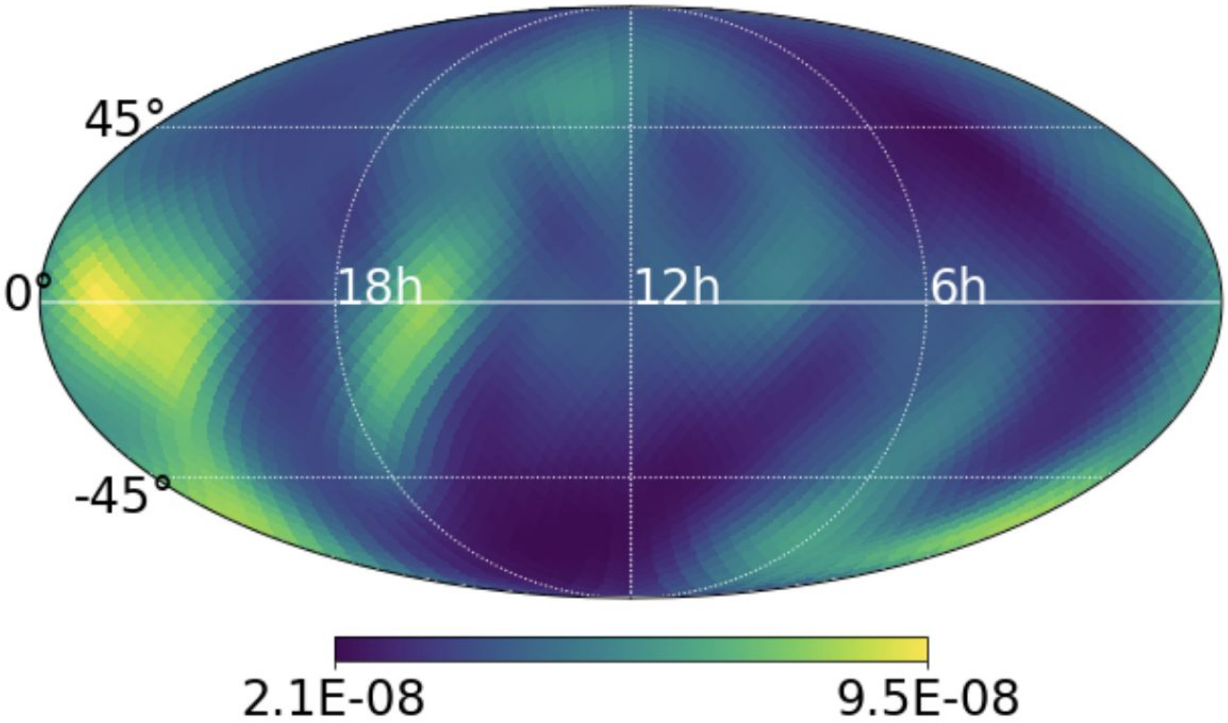
Pitkin et al, Ap. J. Lett 863, 2, L40 (2018)

GW from pulsars



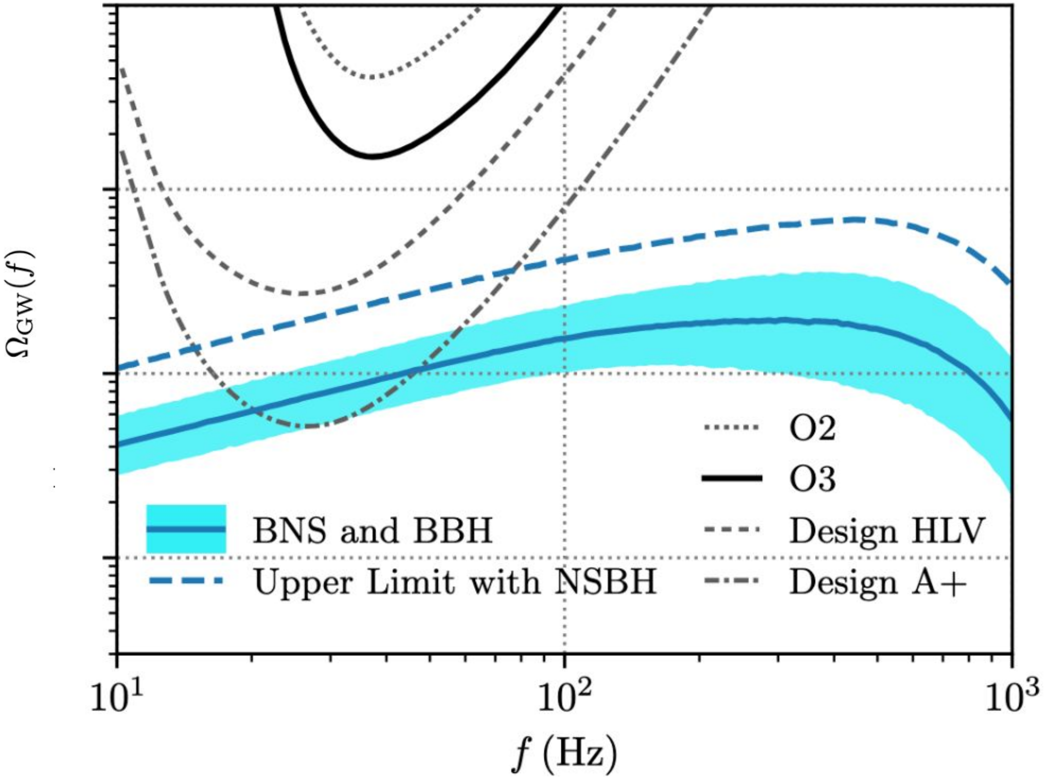
Pitkin et al, Ap. J. Lett 863, 2, L40 (2018)

Stochastic background searches



R Abbott et al. arXiv:2110.09834 (2021)

Isotropic GW Background



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

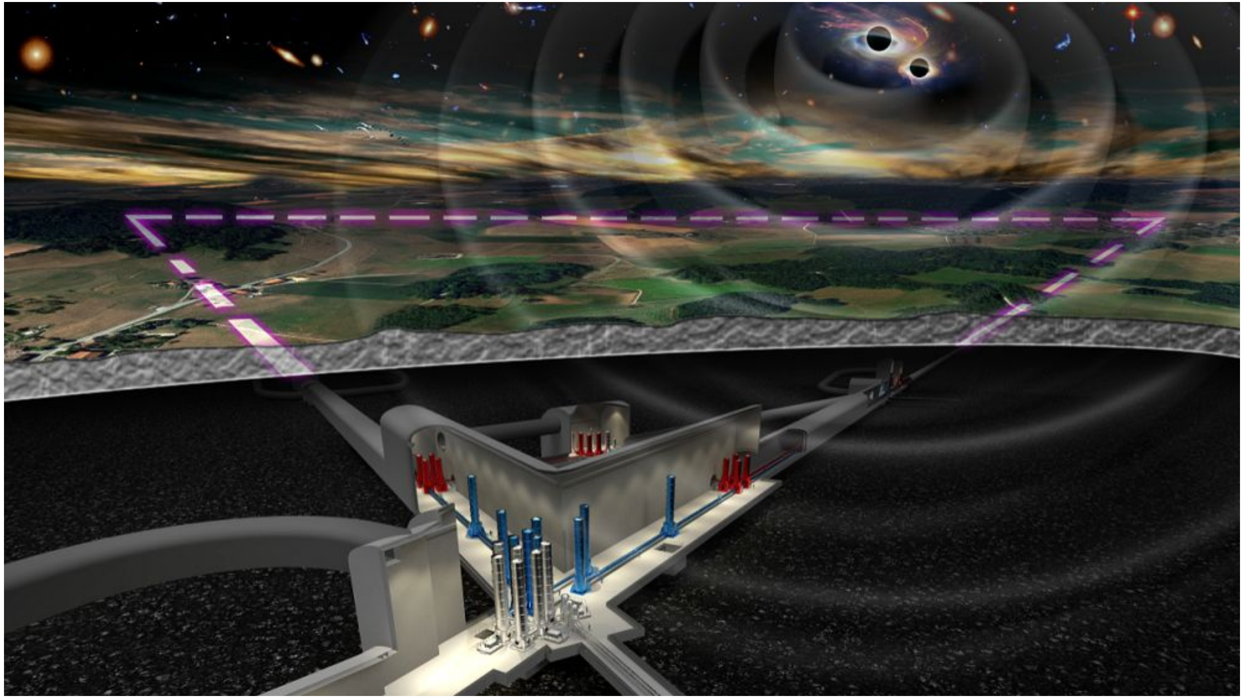
Post-O5 planning

- The LVK is committed to continued observations **beyond 2028** (contingent on continued funding of the observatories).
- Work is underway to scope detector upgrade options and observing strategies for after O5.
  - Plans will be developed and refined, with community input, over the next couple of years.
- LIGO is exploring:
  - LIGO Voyager upgrade to cryogenic detectors with silicon test masses and other modifications.
  - Or a path that makes a series of incremental modifications targeted to deliver specific sensitivity benefits
  - Considerations included readiness/technical risk, cost, impact on observing time and how the program would dovetail with the implementation of Cosmic Explorer

Next Generation Facilities

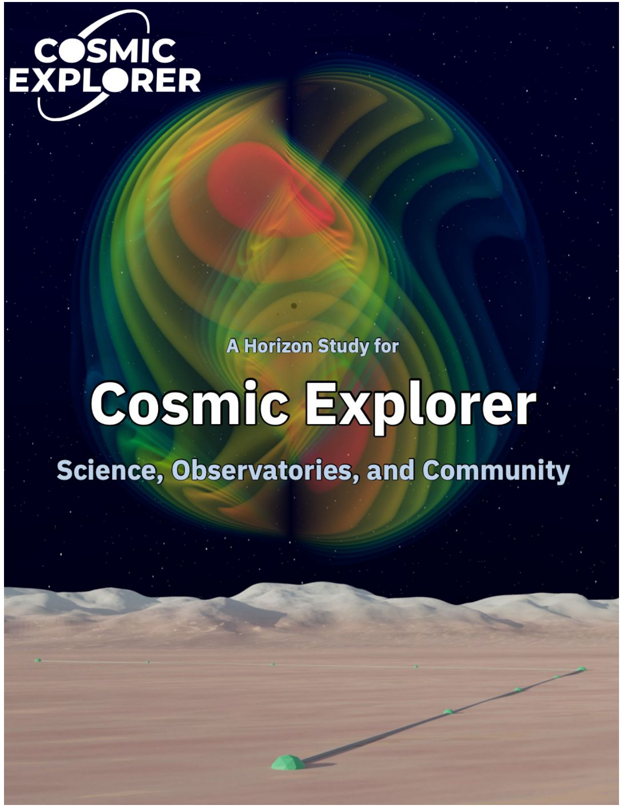
Einstein Telescope

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



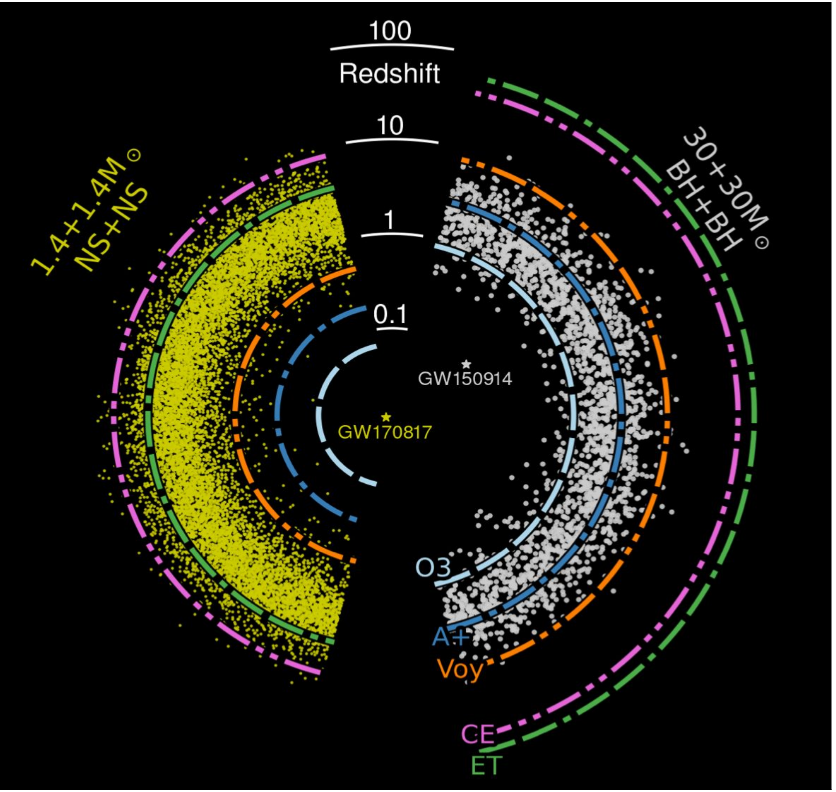
Cosmic Explorer

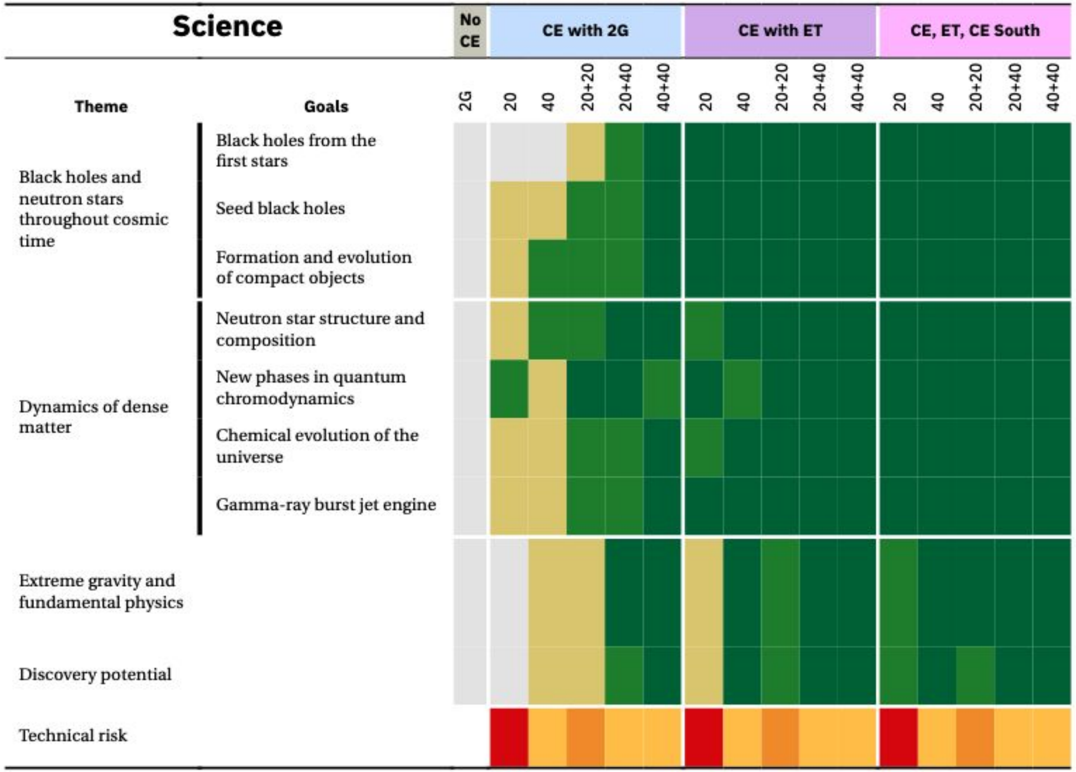
- Proposed above ground facility in the US
- Two 40km orthogonal arms using mature technology from current ground-based detectors
- Cosmic Explorer Horizon Study
    - Released in October 2021
- DAWN VI Workshop
    - “There was a consensus that Cosmic Explorer is a concept that can deliver the promised 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





Science		No CE	CE with 2G					CE with ET					CE, ET, CE South				
Theme	**Goals**	2G	20	40	20+20	20+40	40+40	20	40	20+20	20+40	40+40	20	40	20+20	20+40	40+40
Black holes and neutron stars throughout cosmic time	Black holes from the first stars	⬜	⬜	⬜	🟨	🟩	■	■	■	■	■	■	■	■	■	■	■
	Seed black holes	⬜	🟨	🟨	🟩	🟩	■	■	■	■	■	■	■	■	■	■	■
	Formation and evolution of compact objects	⬜	🟨	🟩	🟩	🟩	■	■	■	■	■	■	■	■	■	■	■
Dynamics of dense matter	Neutron star structure and composition	⬜	🟨	🟩	🟩	■	■	🟩	■	■	■	■	■	■	■	■	■
	New phases in quantum chromodynamics	⬜	🟩	🟨	■	■	🟩	■	🟩	■	■	■	■	■	■	■	■
	Chemical evolution of the universe	⬜	🟨	🟨	🟩	🟩	■	🟩	■	■	■	■	■	■	■	■	■
	Gamma-ray burst jet engine	⬜	🟨	🟨	🟩	🟩	■	■	■	■	■	■	■	■	■	■	■
Extreme gravity and fundamental physics		⬜	⬜	🟨	🟨	■	■	🟨	■	🟩	■	■	🟩	■	■	■	■
Discovery potential		⬜	⬜	🟨	🟨	🟩	■	🟨	■	🟩	■	■	🟩	■	🟩	■	■
Technical risk			🟥	🟠	🟧	🟠	🟠	🟥	🟠	🟧	🟠	🟠	🟥	🟠	🟧	🟠	🟠

A Horizon Study for Cosmic Explorer
https://arxiv.org/abs/2109.09882

Thank you!