Gravitational-wave astronomy with LIGO-Virgo-KAGRA

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University of Wisconsin-Milwaukee

Yukawa International Seminar 2022a
14-18 February 2022

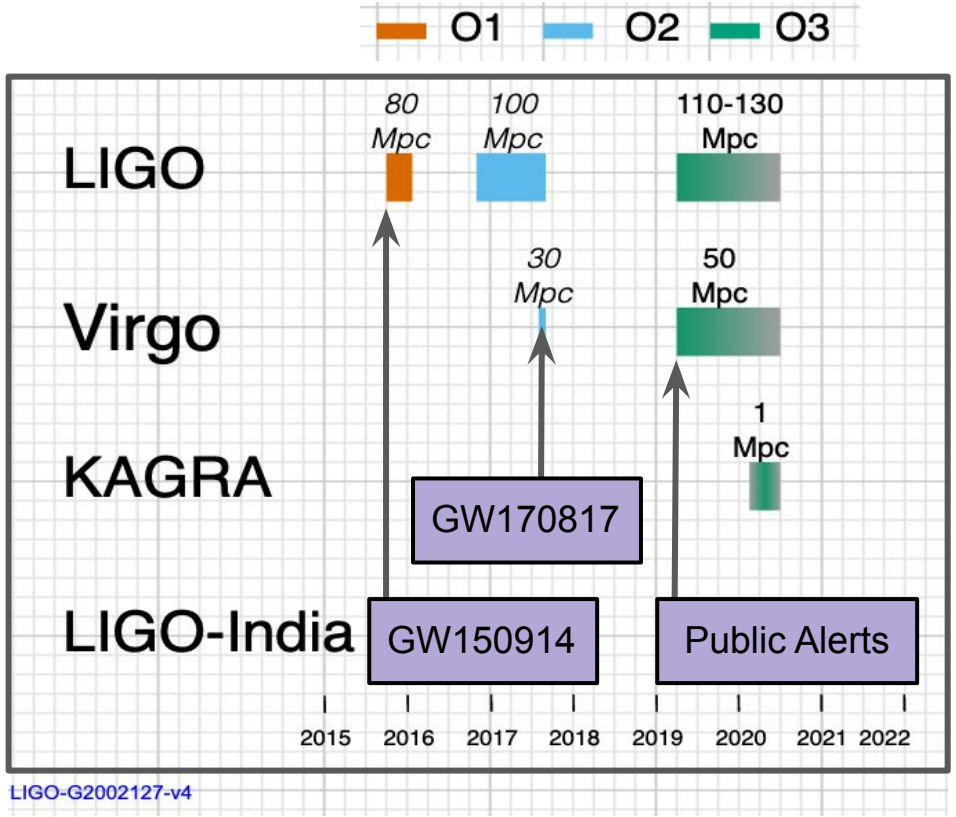
International Gravitational-Wave Observatory Network (IGWN)

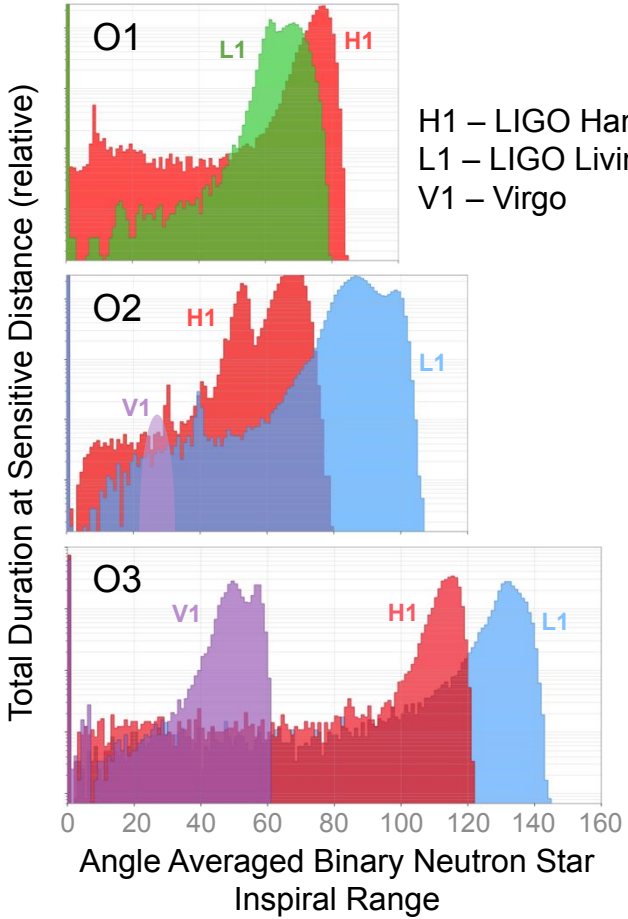
- The LIGO-Virgo-KAGRA Collaboration is an international team of more than 2000 scientists who work together to design, build and operate the international gravitational-wave observatory network.

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

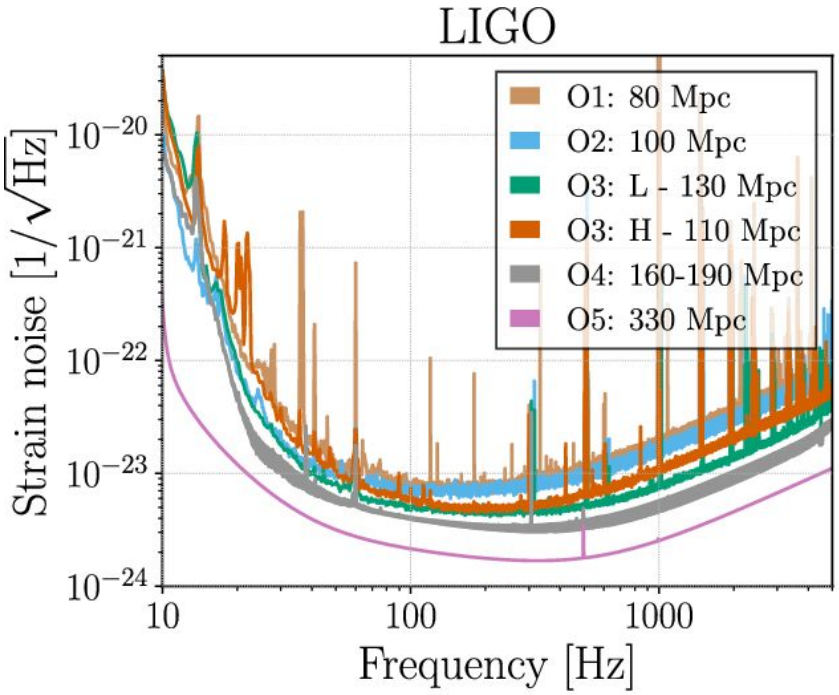
Observing runs

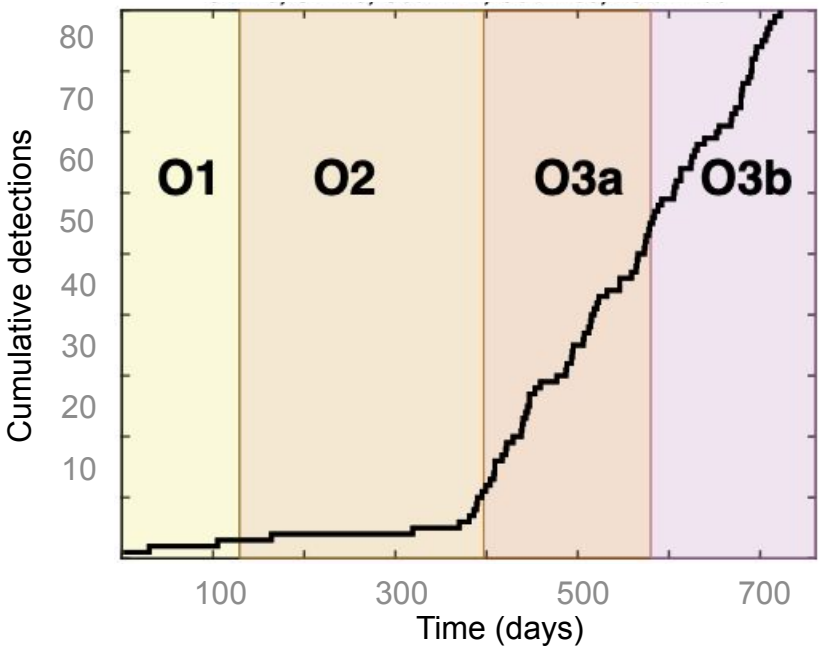




H1 – LIGO Hanford
L1 – LIGO Livingston
V1 – Virgo

Sensitivity & detections



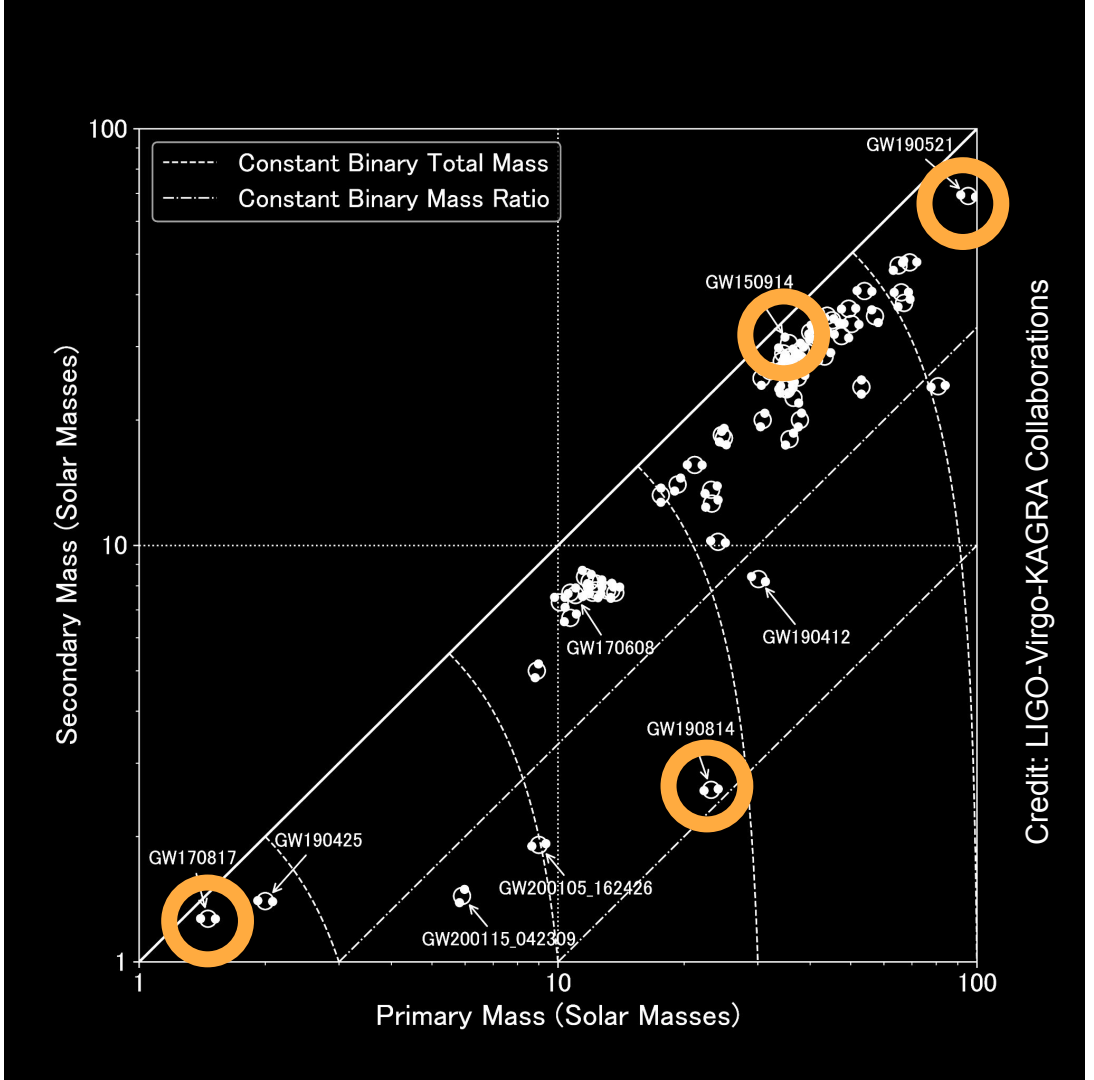


Credit: LIGO-Virgo-KAGRA Collaborations (LIGO-G2102395)

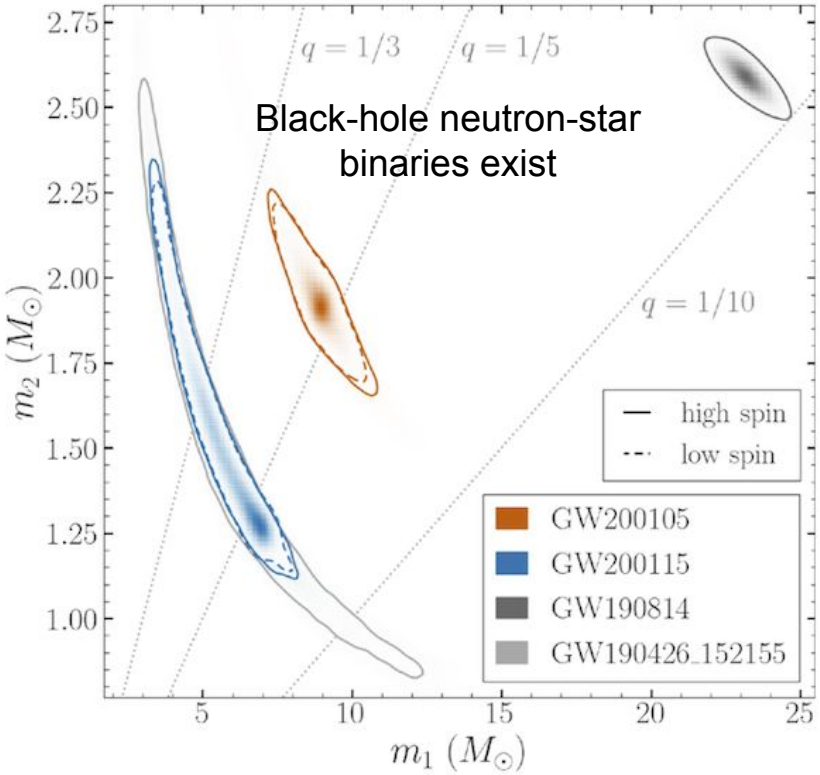
O3 binary detection rate ~ 1 / (5 days)

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



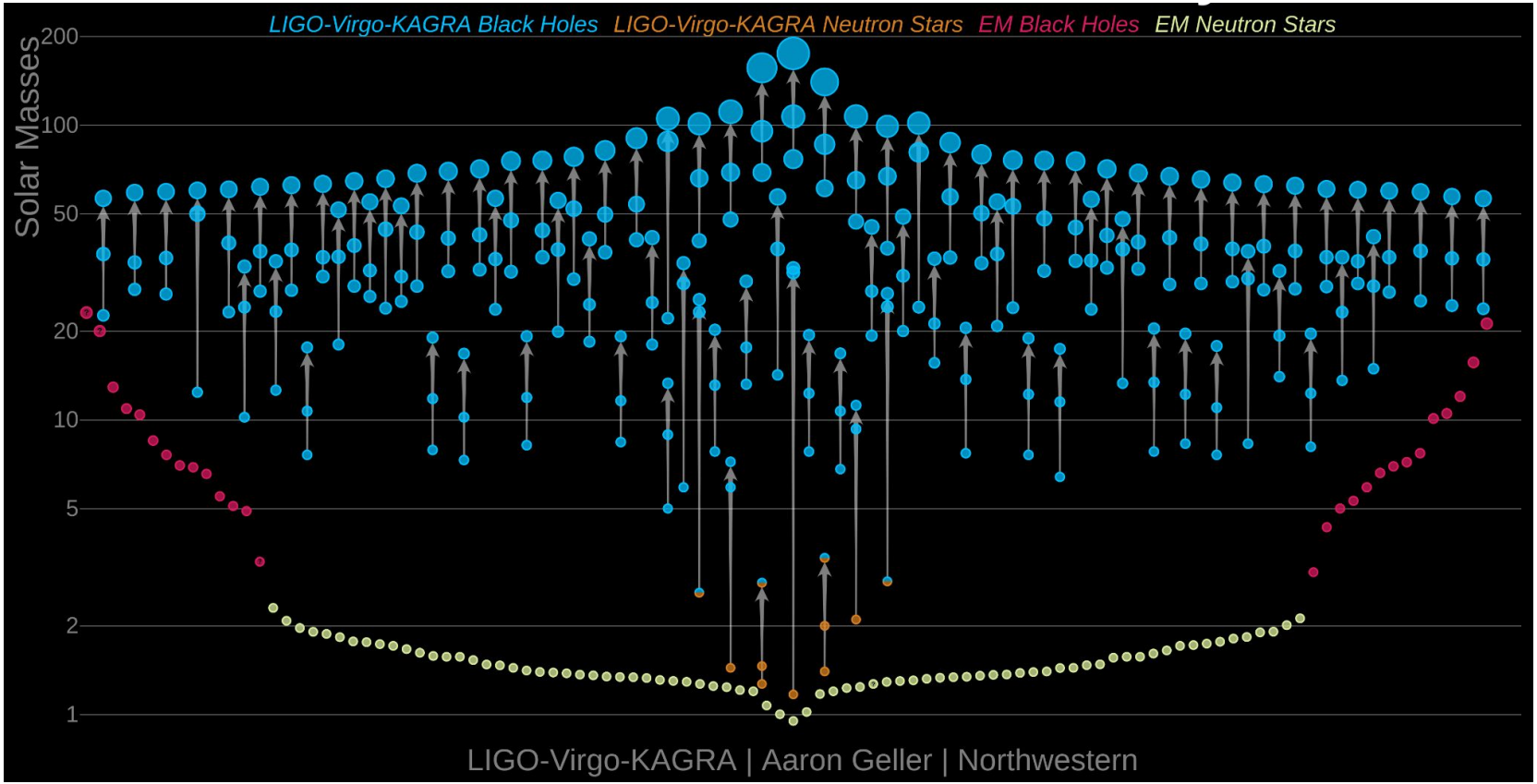
More firsts



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

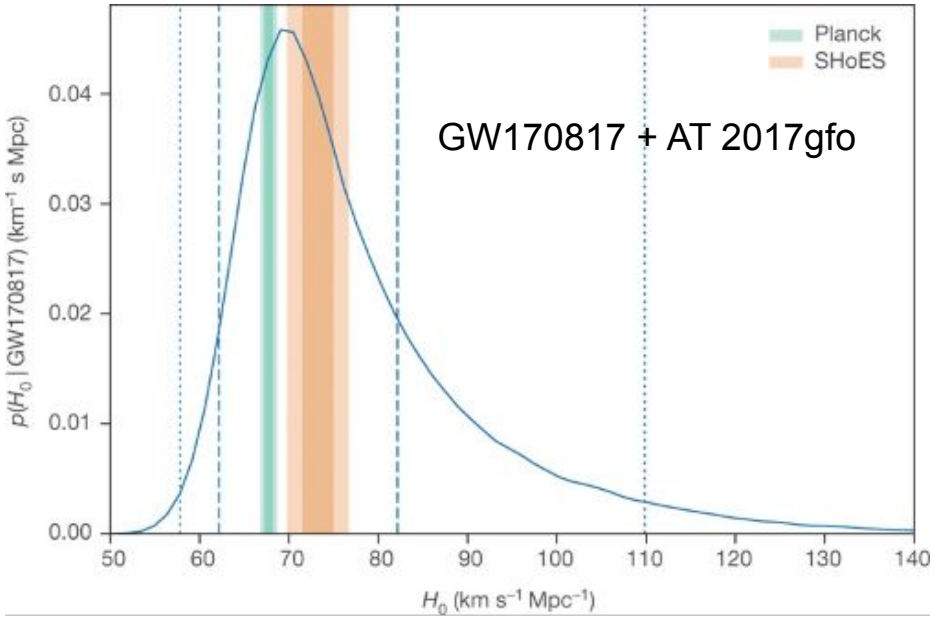
- GW170817 & GRB 170817A
  - Fractional difference in speed of gravity and the speed of light is between -3×10^{-15} and 7×10^{-16}
- GW170817 & AT 2017gfo
  - Binary neutron star mergers produce kilonova explosions that generate heavy elements

Masses in the stellar graveyard

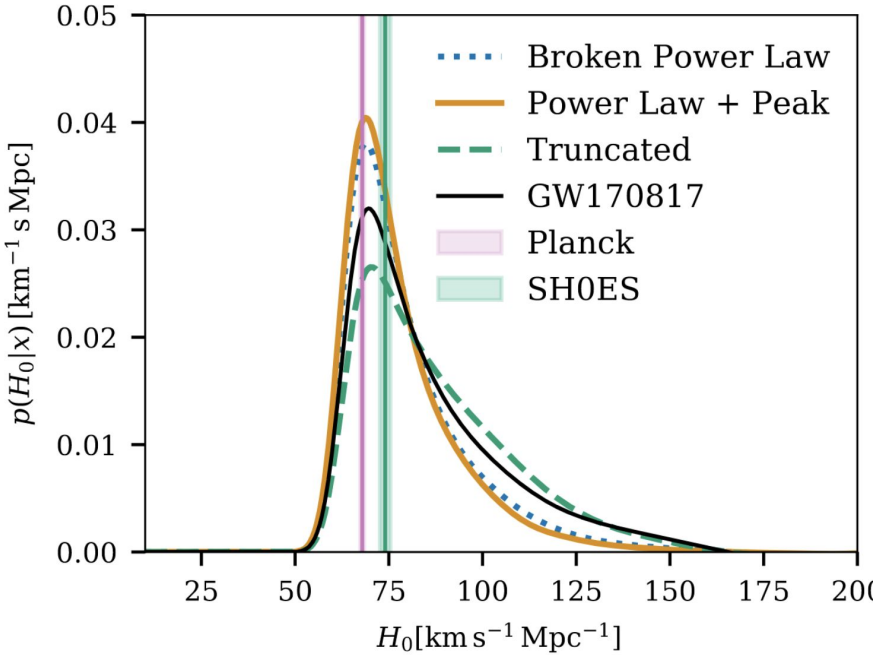


Cosmology with gravitational waves

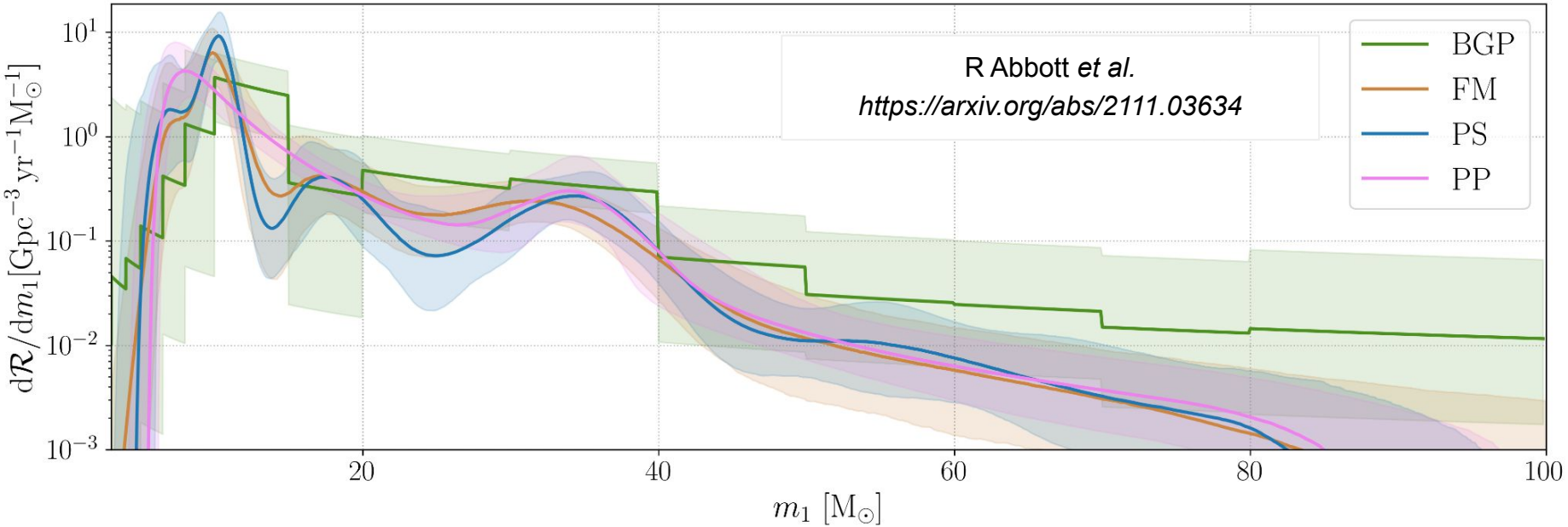
B P Abbott *et al. Nature* **551,** 85–88 (2017) doi:10.1038/nature24471



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

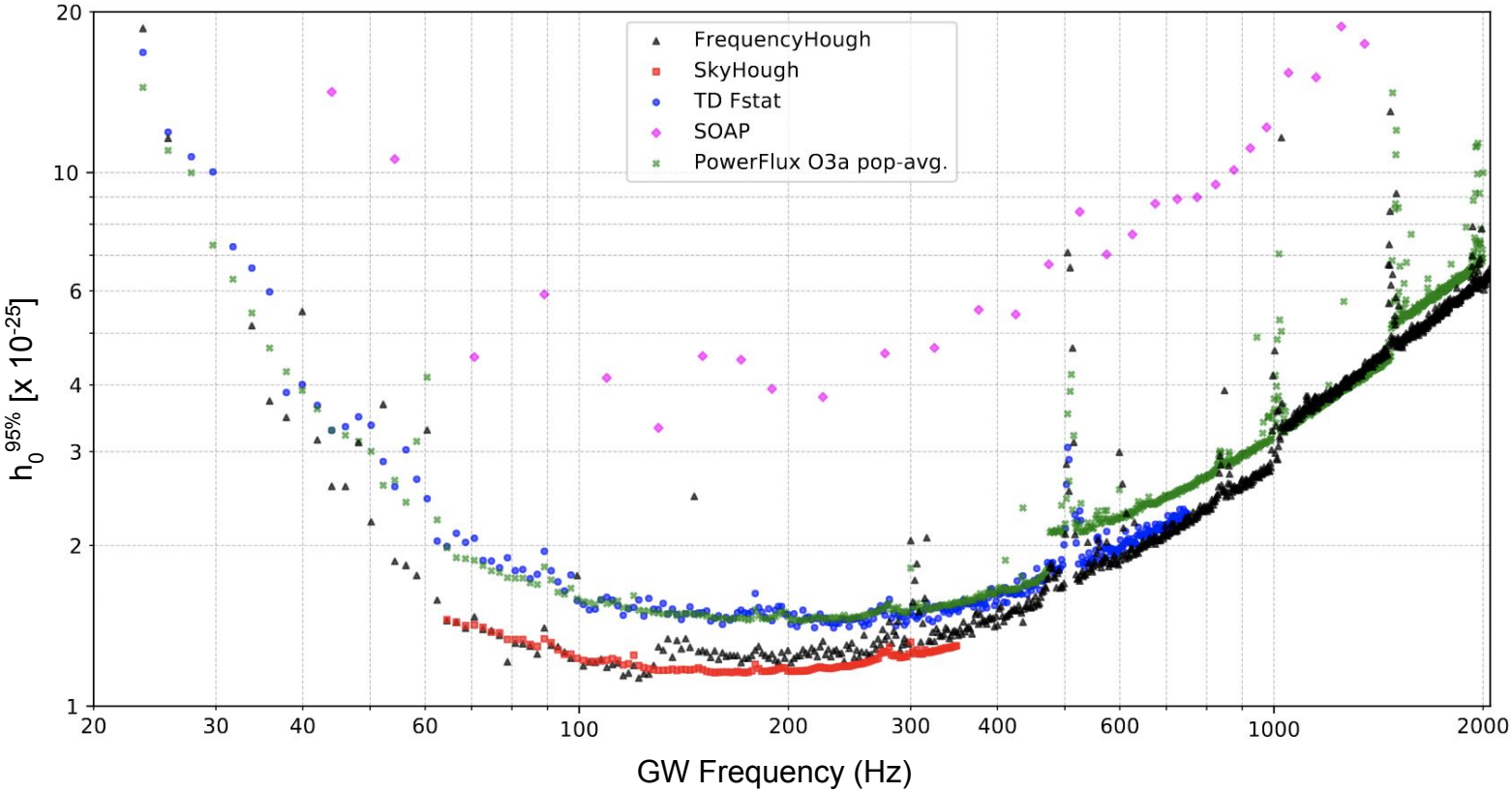


From one to many: measuring populations



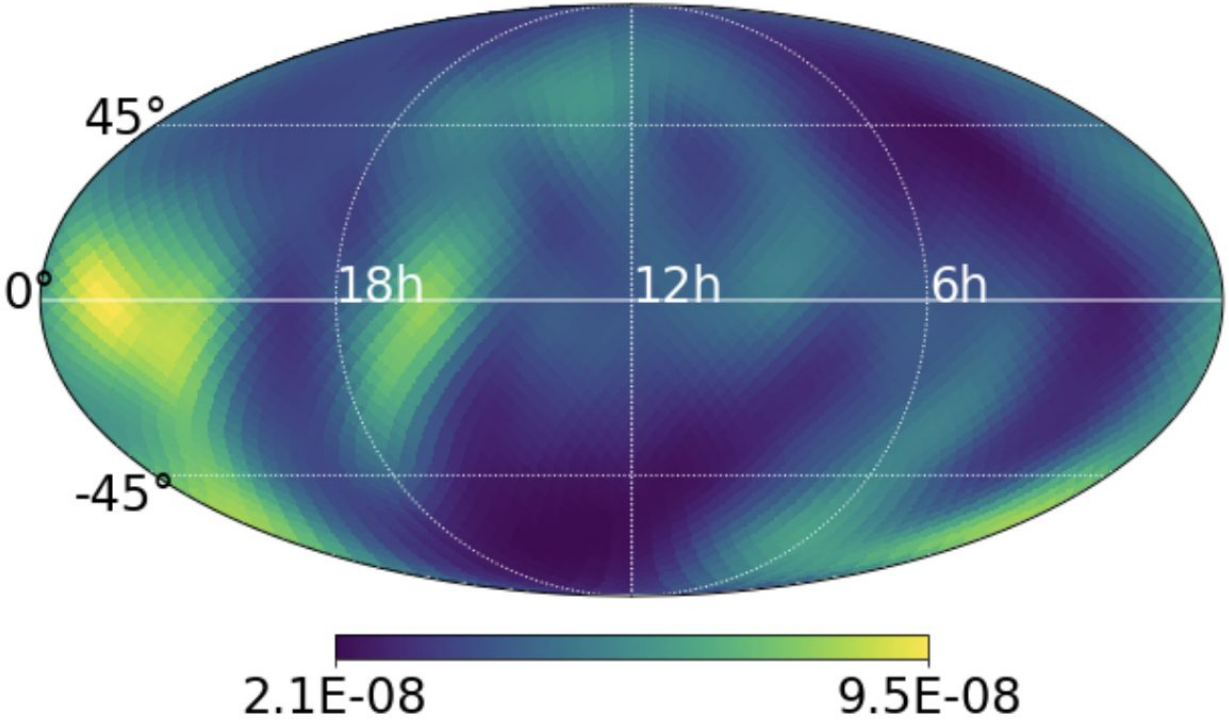
Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

Continuous wave searches



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

Stochastic background searches



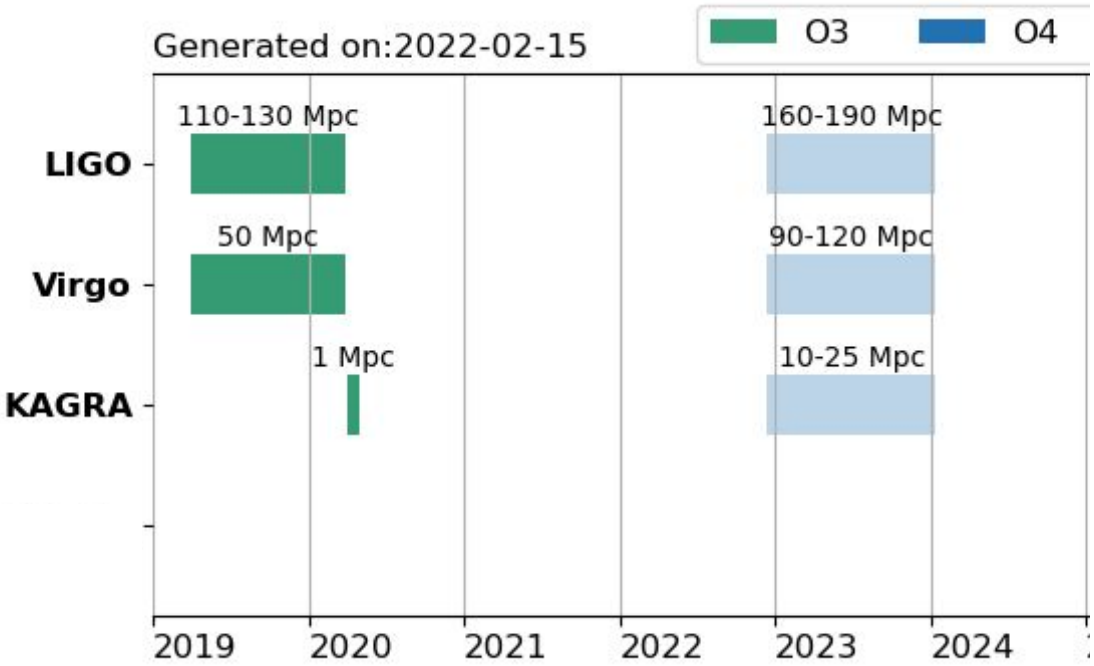
R Abbott *et al. arXiv:2110.09834 (2021)*

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

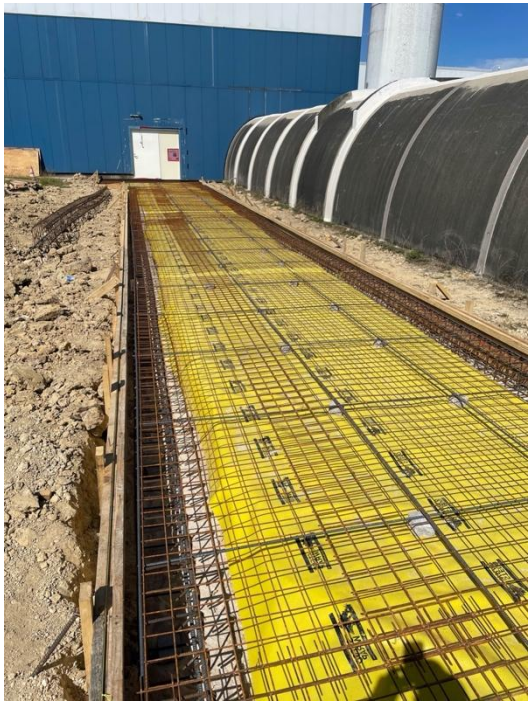


Planned instrumental upgrades for O4

- See talks by Jo van den Brand and Masaki Ando for more information about Virgo and KAGRA upgrade and commissioning plans
- 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

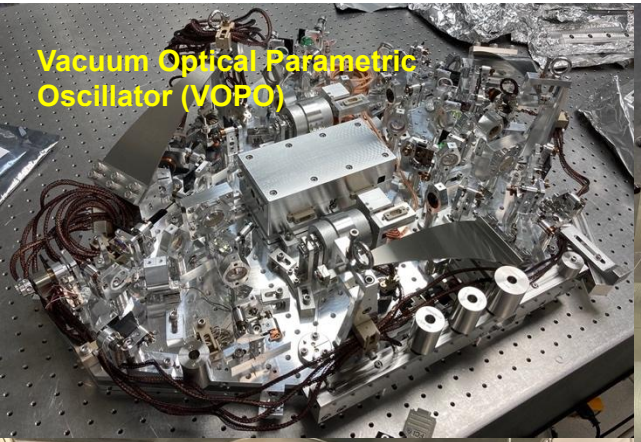
Construction for the filter cavity

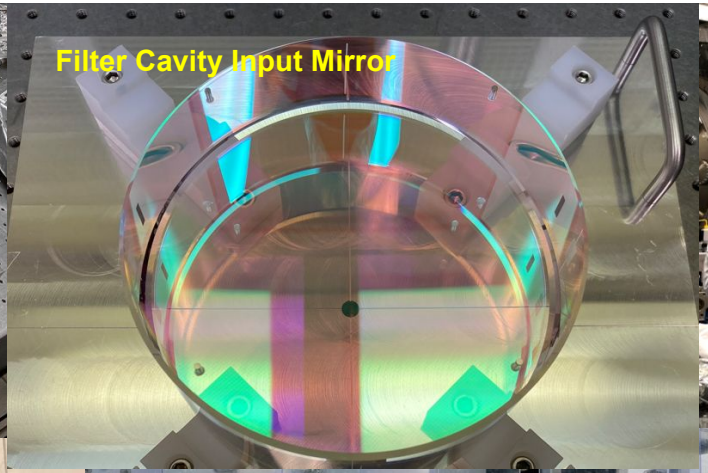


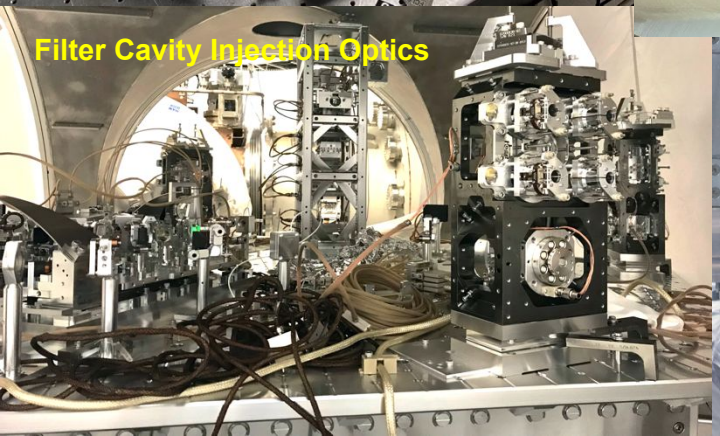
LIGO VIRGO KAGRA

Thanks to Dave Reitze, LIGO Lab

O4 LIGO detector upgrades

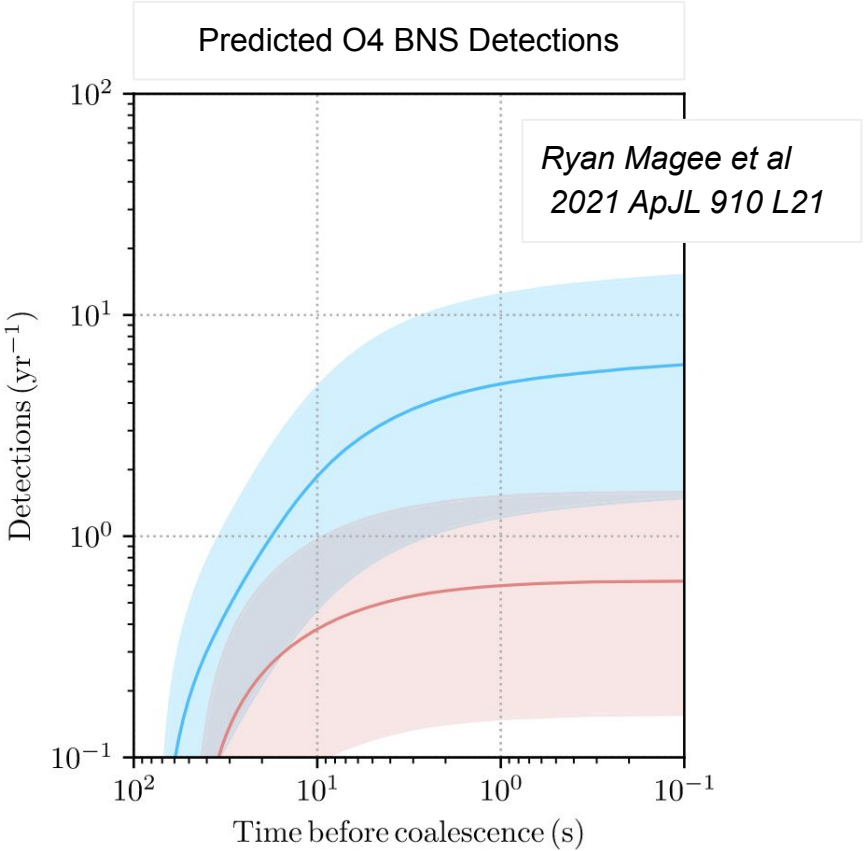




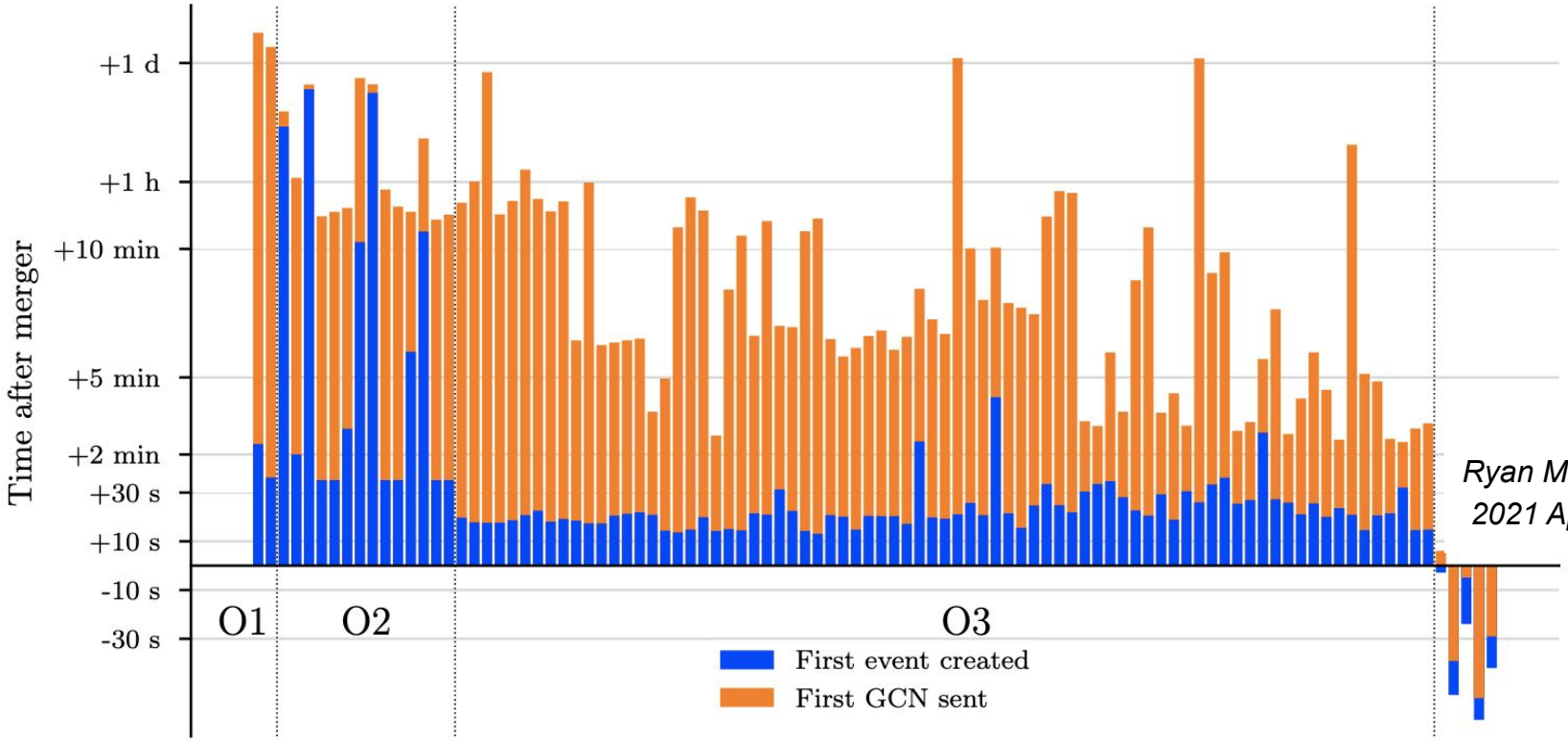


Impact of LVK upgrades on observations

- 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?



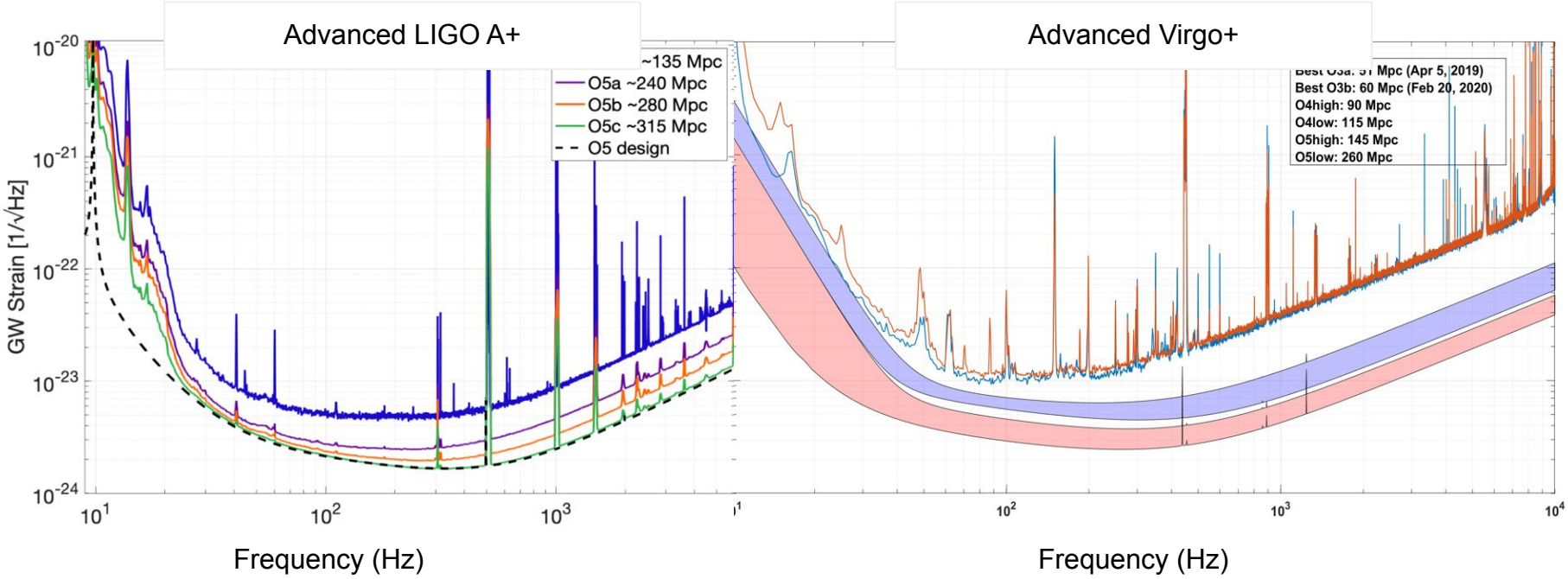
Improvements in cyberinfrastructure



Ryan Magee et al
2021 ApJL 910 L21

Thanks to Dave Reitze & Giovanni Losurdo

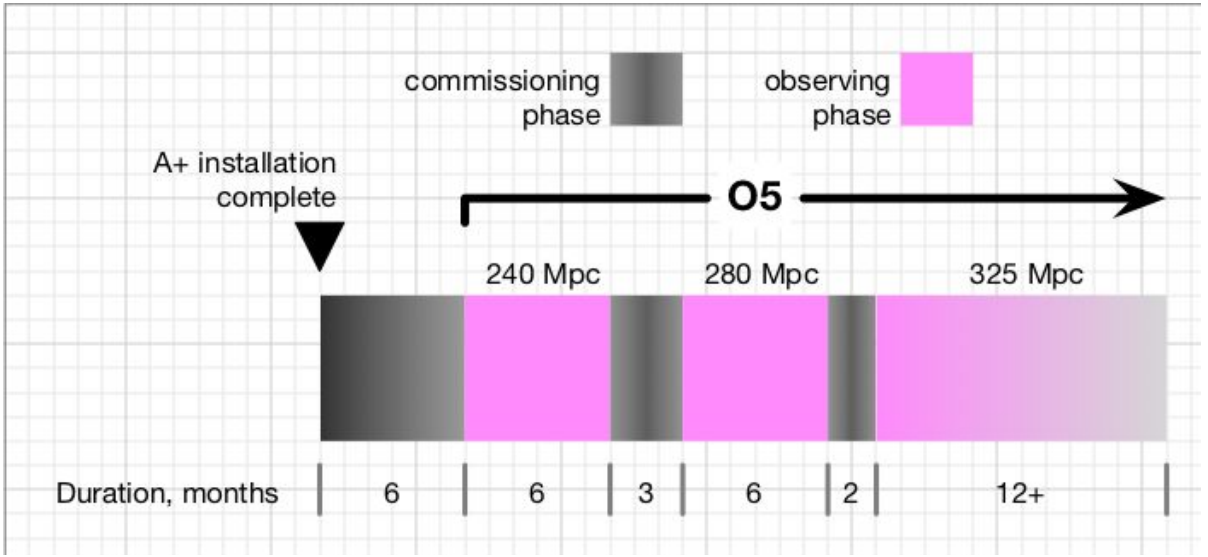
Working toward O5 sensitivity



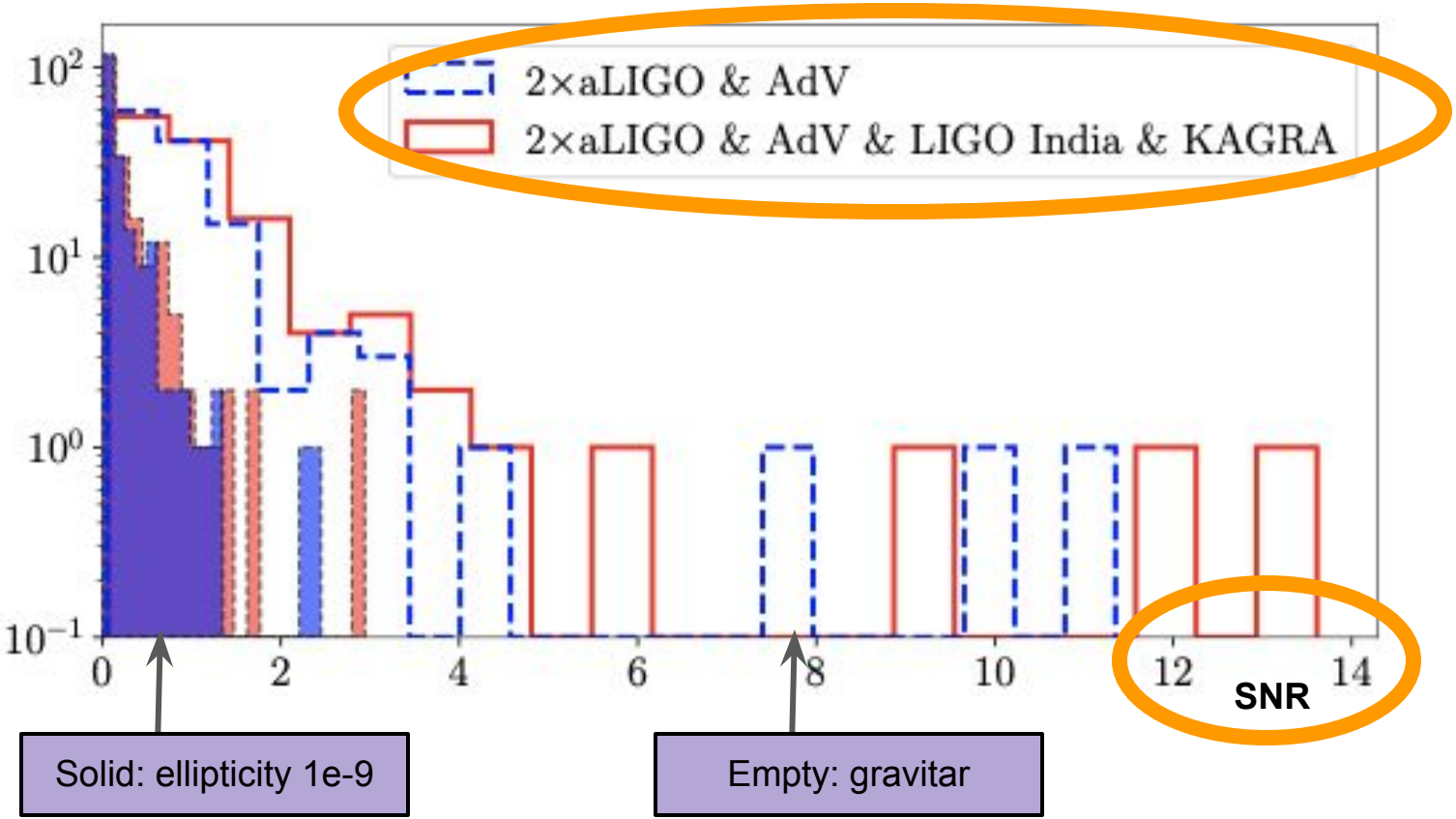
KAGRA will continue to work towards
130Mpc goal in O5

O5 Observing Run

- Current thinking
  - Start is paced by upgrades after O4
  - 1.5-2 years 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?

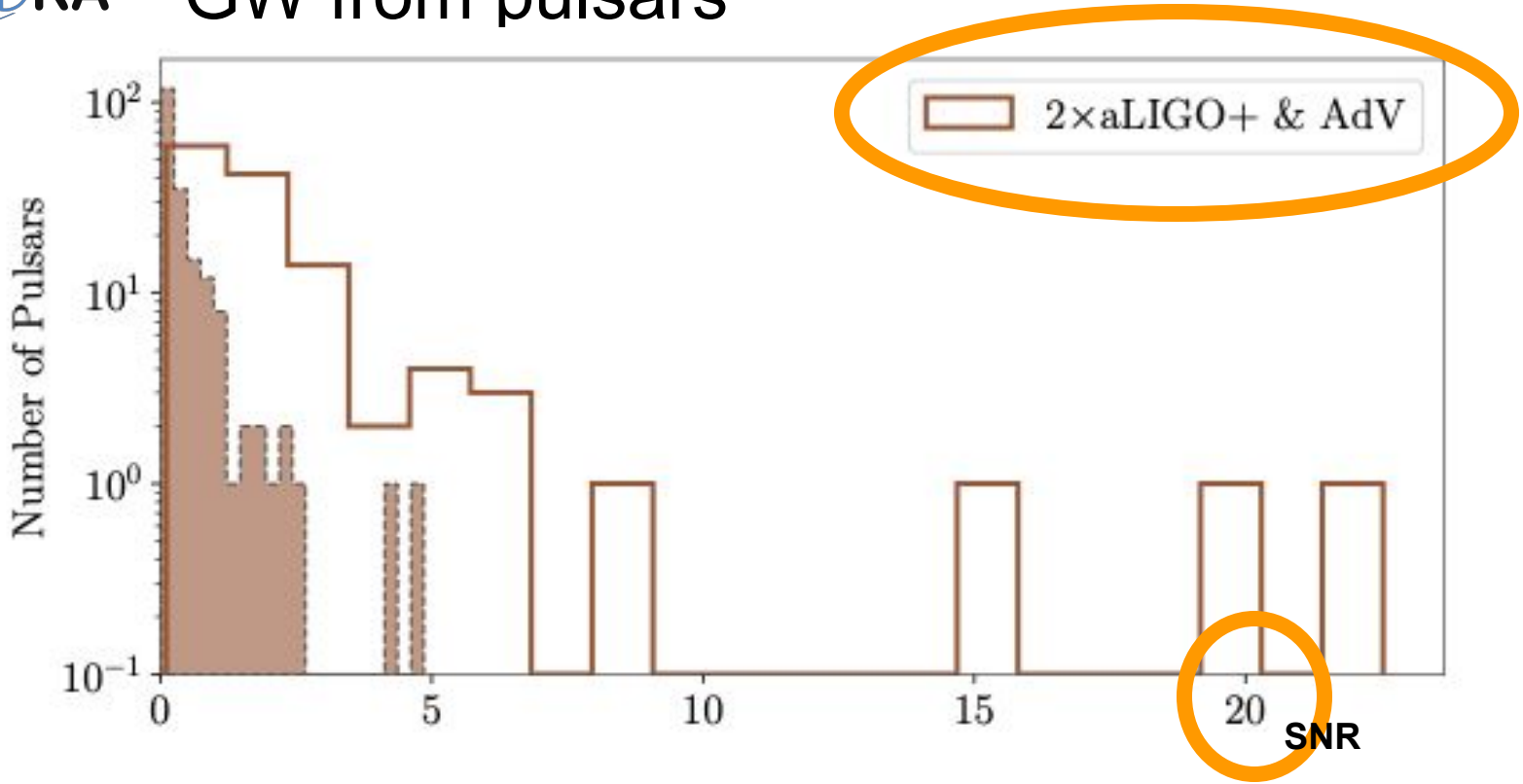


GW from pulsars



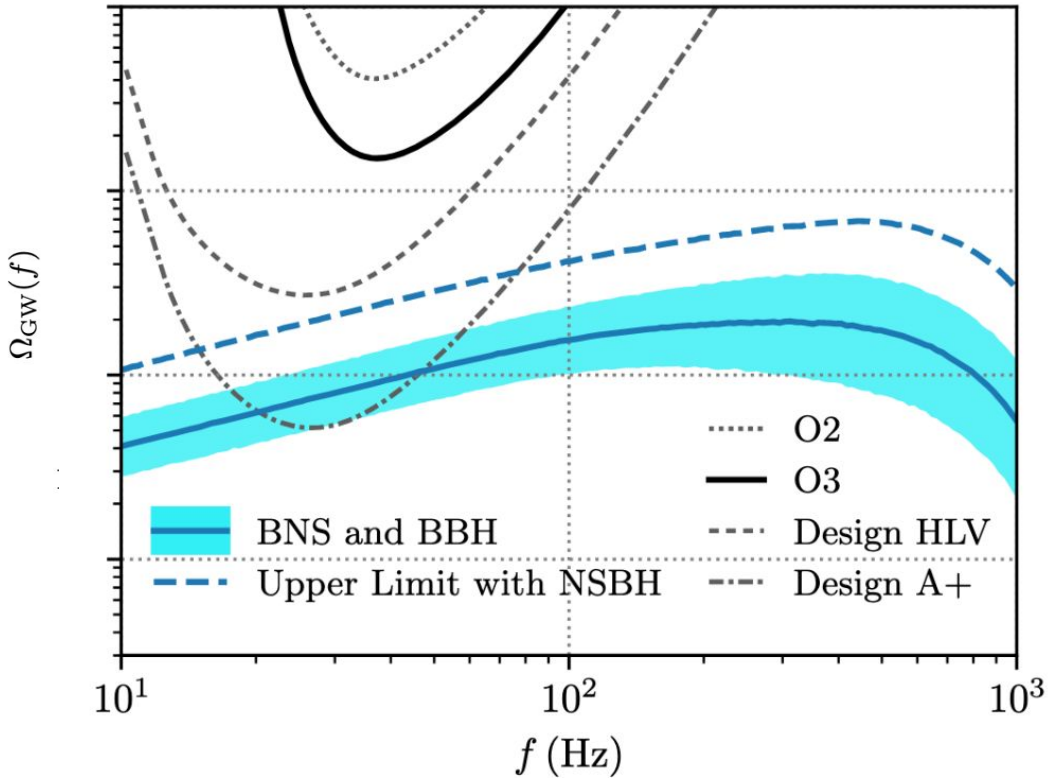
Pitkin et al, Ap. J. Lett 863, 2, L40 (2018)

GW from pulsars



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

Isotropic GW Background



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

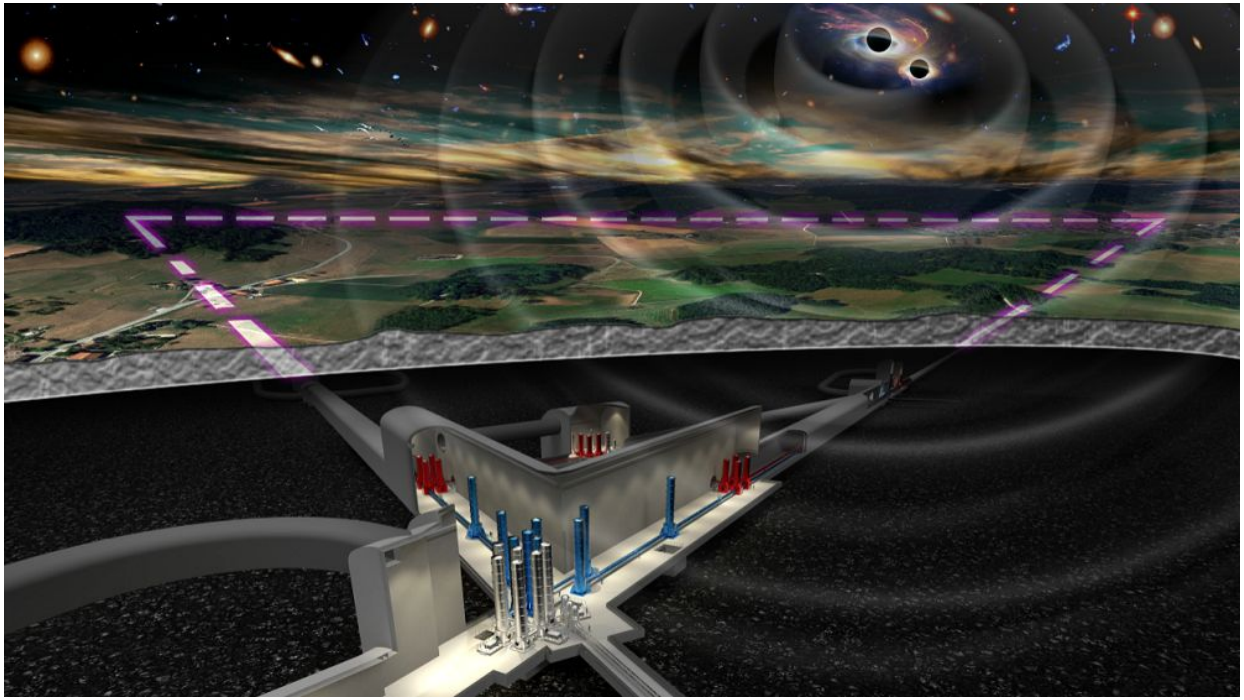
Post-O5 planning

- LIGO and Virgo have charged study groups to explore options for upgrades beyond O5
  - Expected to make recommendations in spring 2022
- 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
- Whatever the outcome of these studies, LIGO, Virgo and KAGRA are looking to observations through the end of the decade and into the next with improving sensitivity.

Next Generation Facilities

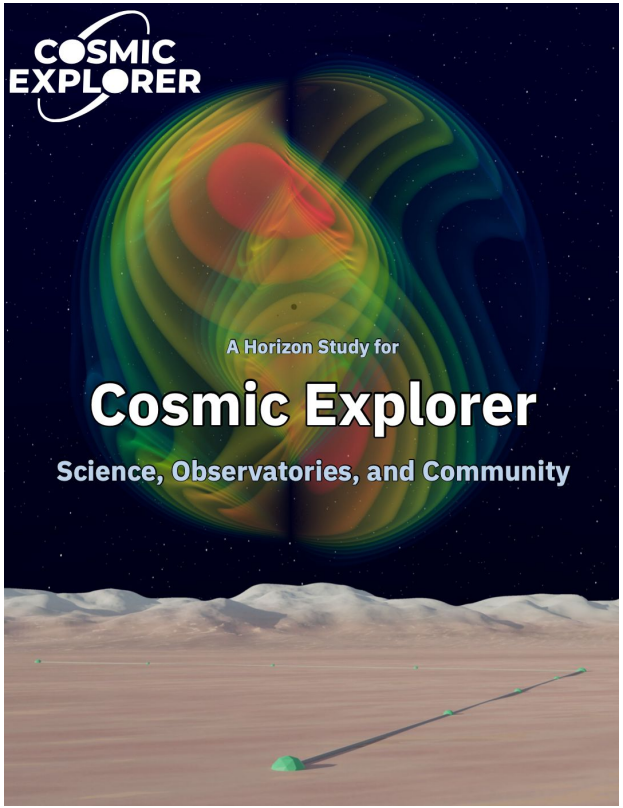
Einstein Telescope

- Proposed underground facility in Europe
- 10km arms, cryogenic optics, triangular configuration
- ET is on the European Strategy Forum on Research Infrastructures (ESFRI) 2021 roadmap
- See Jo van den Brand's talk



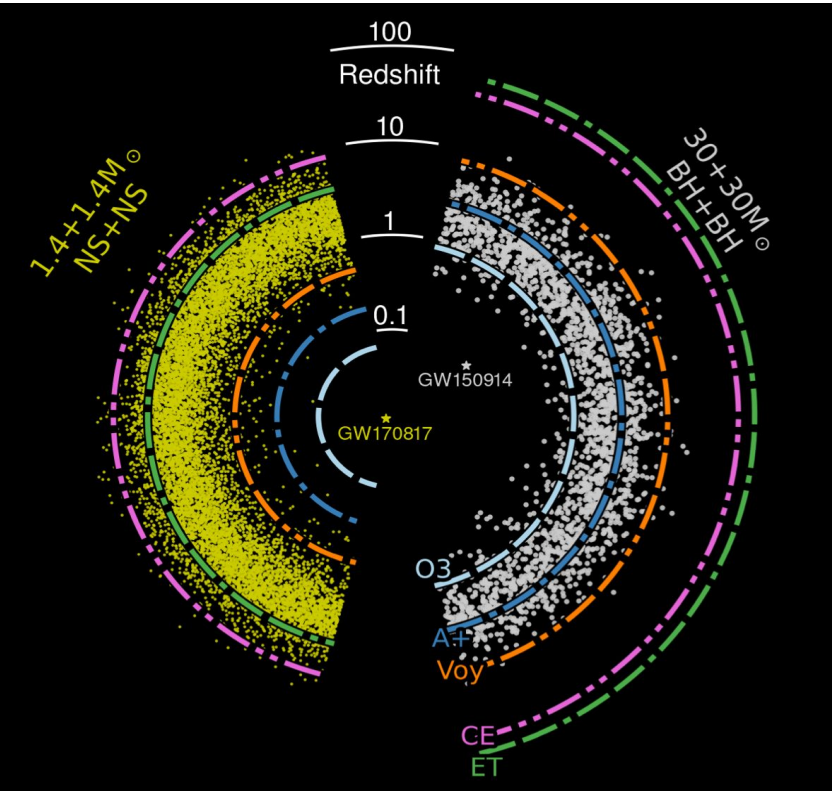
Cosmic Explorer

- 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!