Gravitational-wave astronomy: Progress & Prospects

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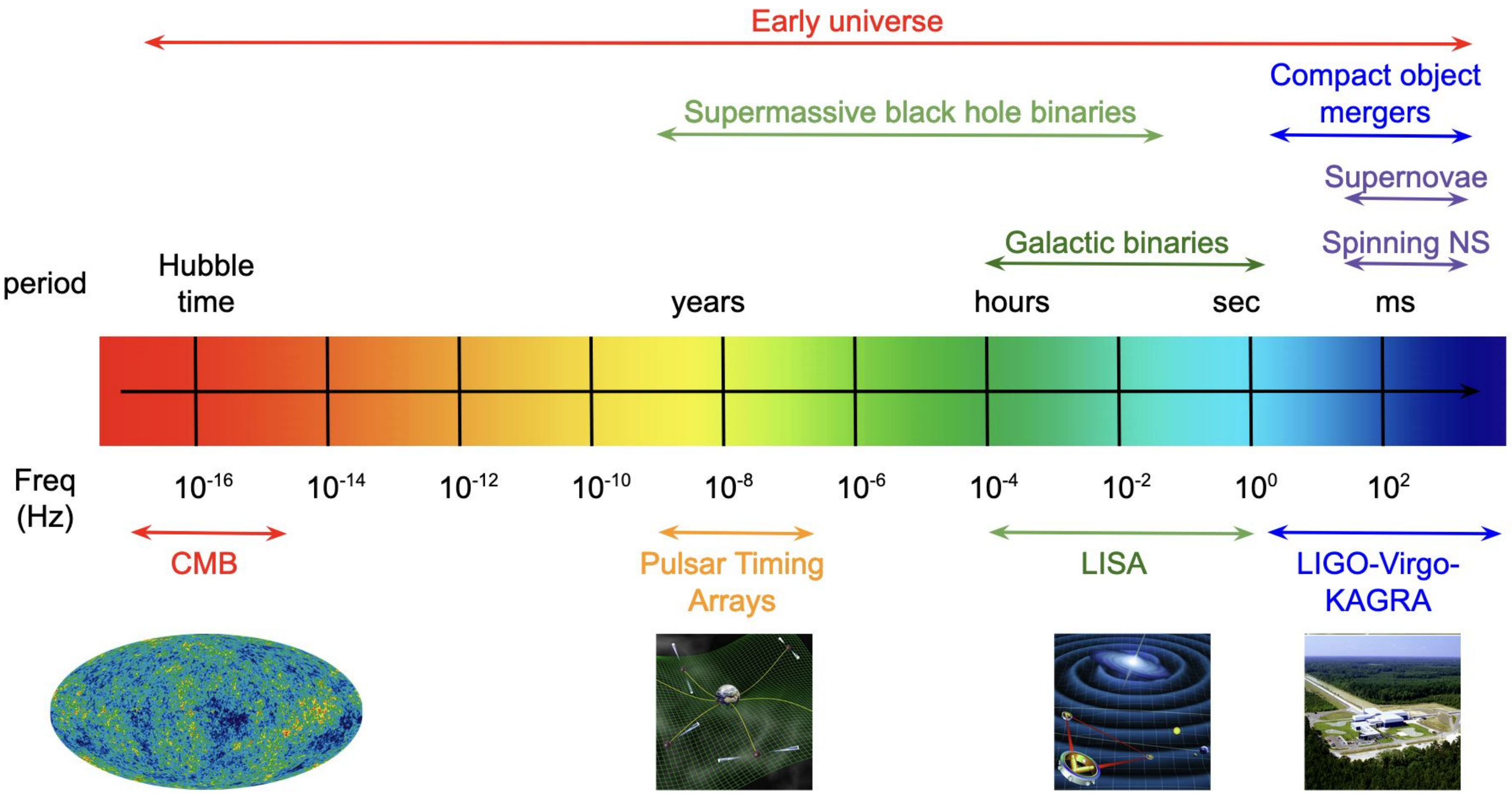
University of Wisconsin-Milwaukee

Symposium on Gravitational Waves
3 June 2024

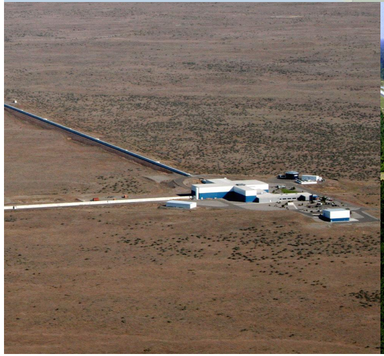
https://dcc.ligo.org/G2401204

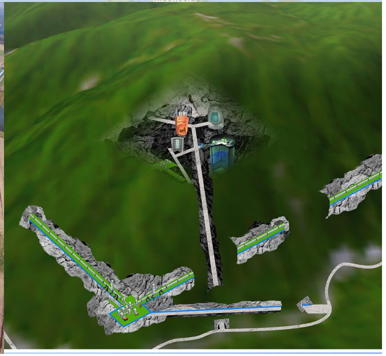
Gravitational-wave spectrum



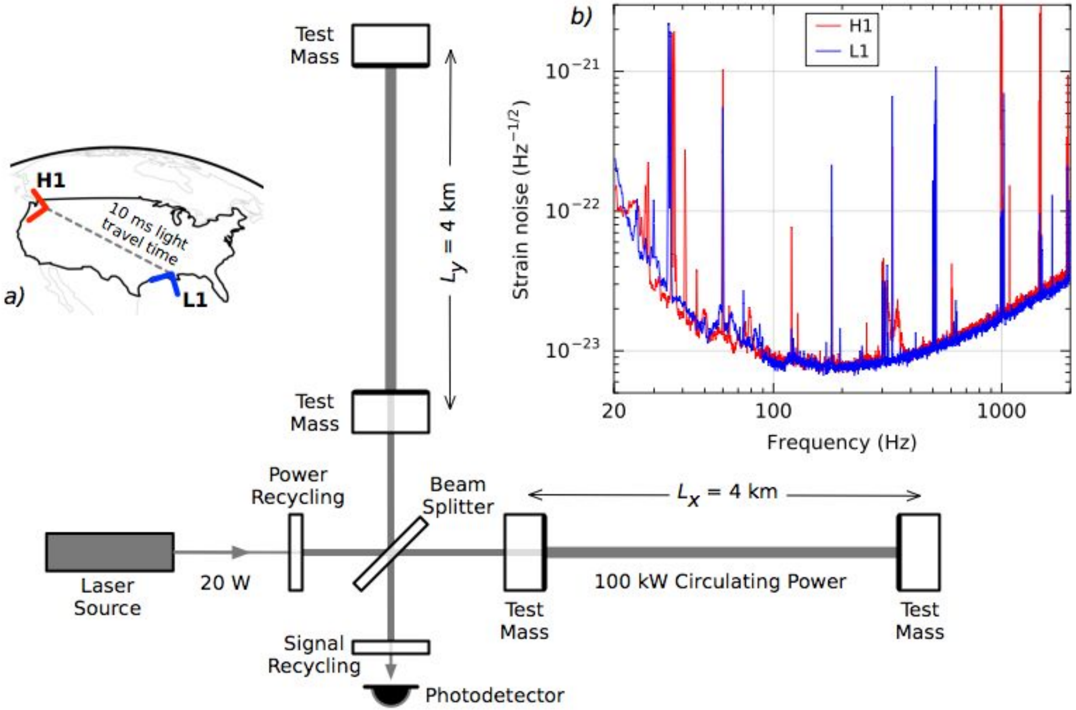
Adapted from: Romano, J.D., Cornish, N.J.
Living Rev Relativ 20, 2 (2017).
https://doi.org/10.1007/s41114-017-0004-1

International Gravitational-Wave Observatory Network (IGWN)





Laser Interferometer Gravitational-wave Observatory (LIGO)

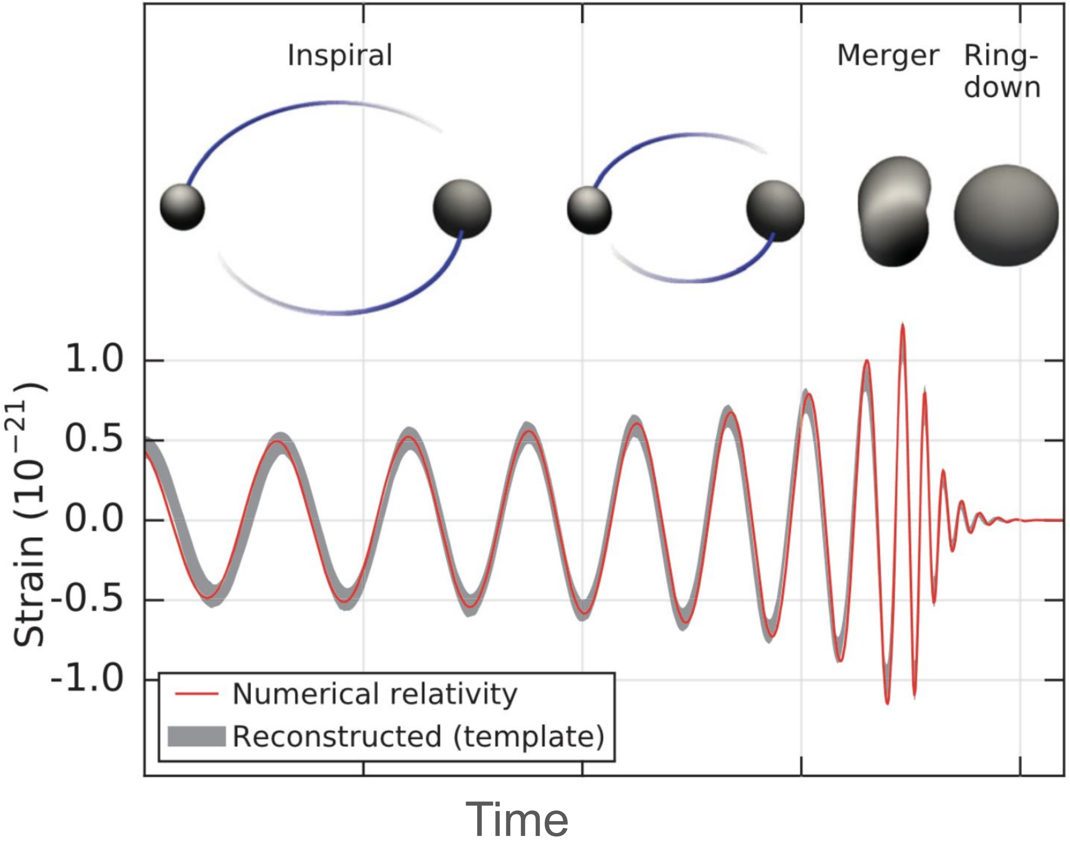


First proposed by Ron Drever, Kip Thorne, and Rai Weiss in 80's.
First funding in 1992; civil construction ended 2000; Initial LIGO 2002-2010

Compact object mergers

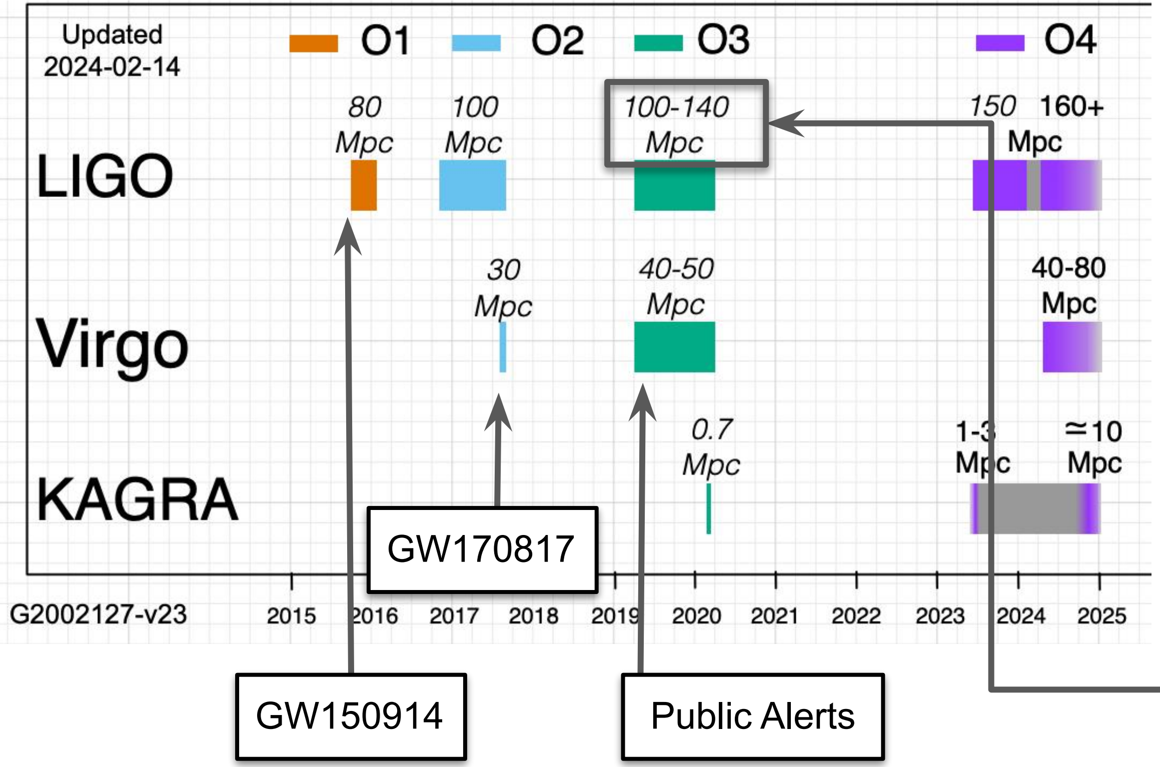
Pairs of stellar-mass black holes, neutron stars, or a stellar-mass black hole and neutron star

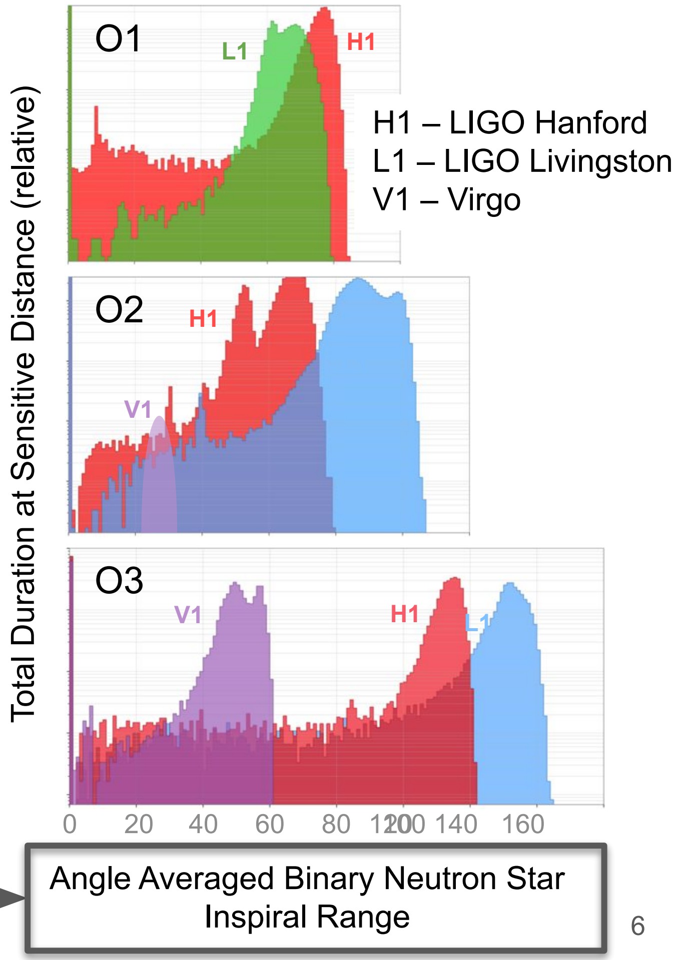
$$h_{ij} \sim \frac{4GM}{c^4}\frac{v^2}{r}$$



B.P. Abbott et al. Phys. Rev. Lett. 116, 061102

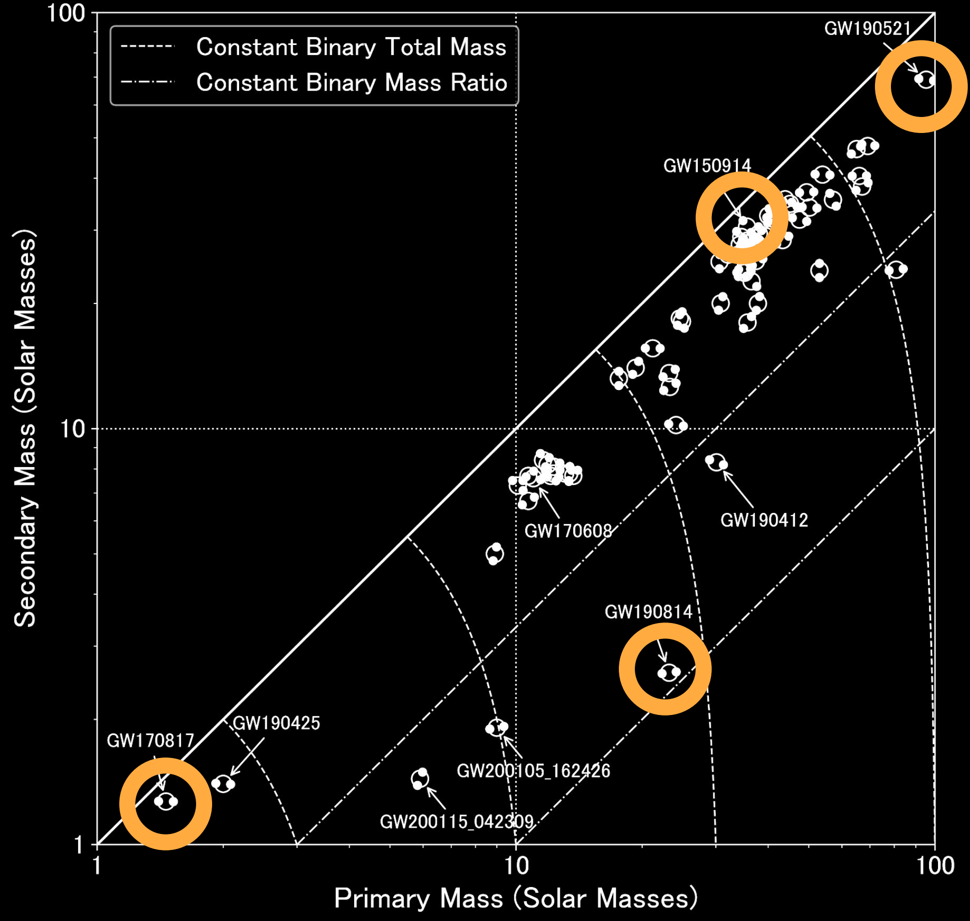
Observing runs





Detections

- 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

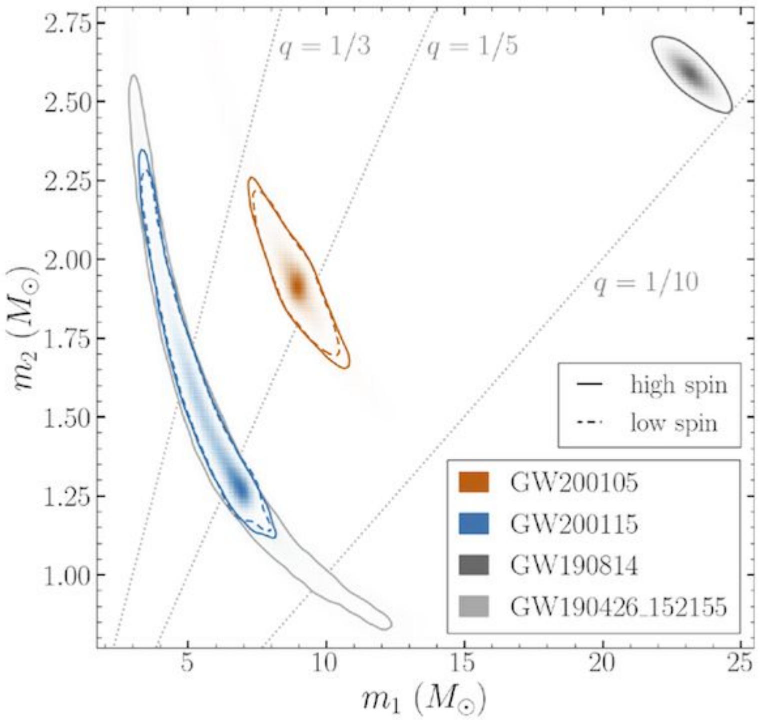


Credit: LIGO-Virgo-KAGRA Collaborations

Mergers involving neutron stars

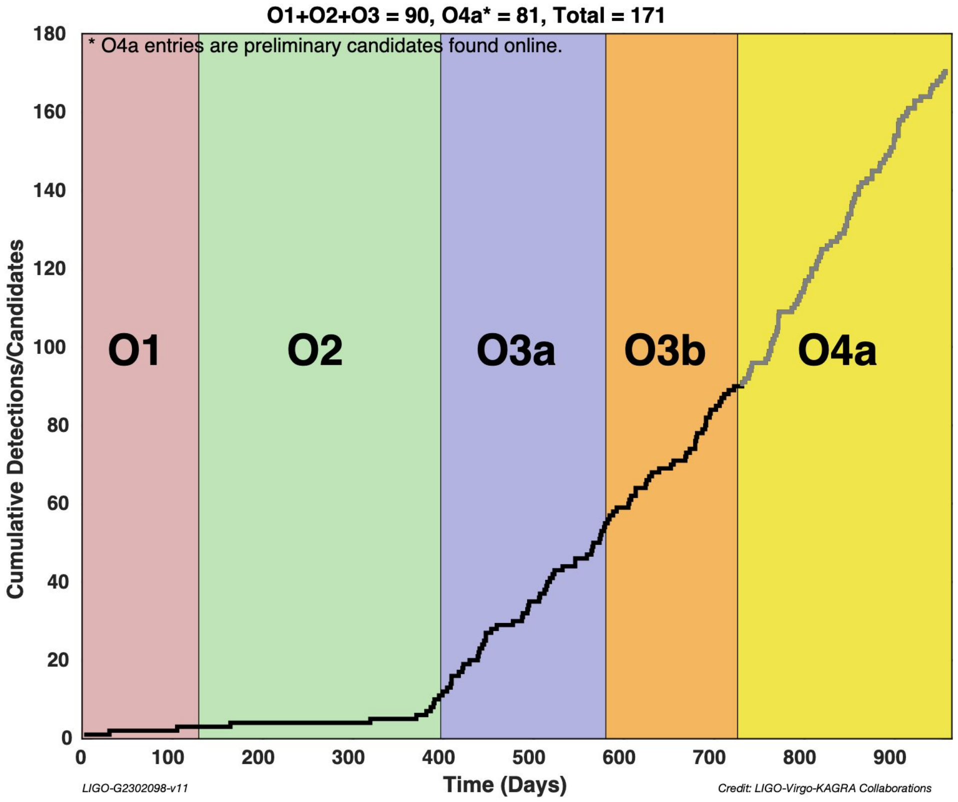
- GW170817 & GW190425
  - Binary neutron star (BNS) merger waves
- GW170817 & GRB 170817A
  - Fractional difference in speed of gravity and the speed of light is between -3×10^{-15} and 7×10^{-16}
- GW170817 & AT 2017gfo
  - Binary neutron star mergers produce kilonova explosions that generate heavy elements

B. P. Abbott et al 2017 ApJL 848 L13

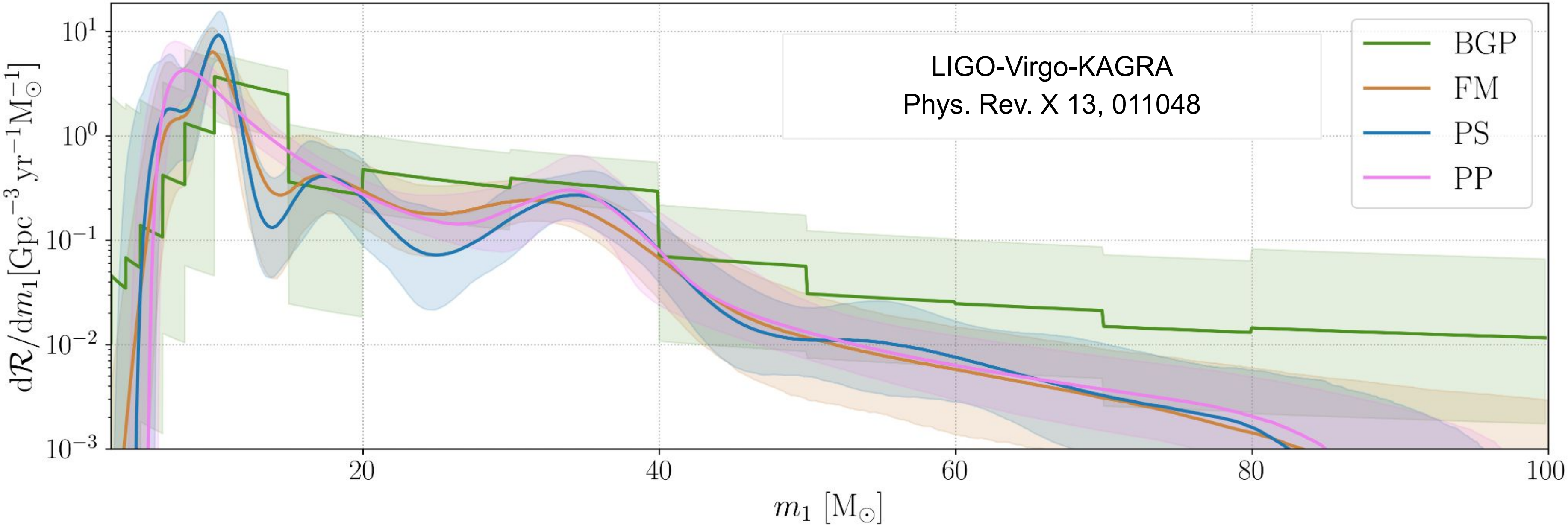


R. Abbott *et al* 2021 *ApJL* **915** L5

Detections versus time observing



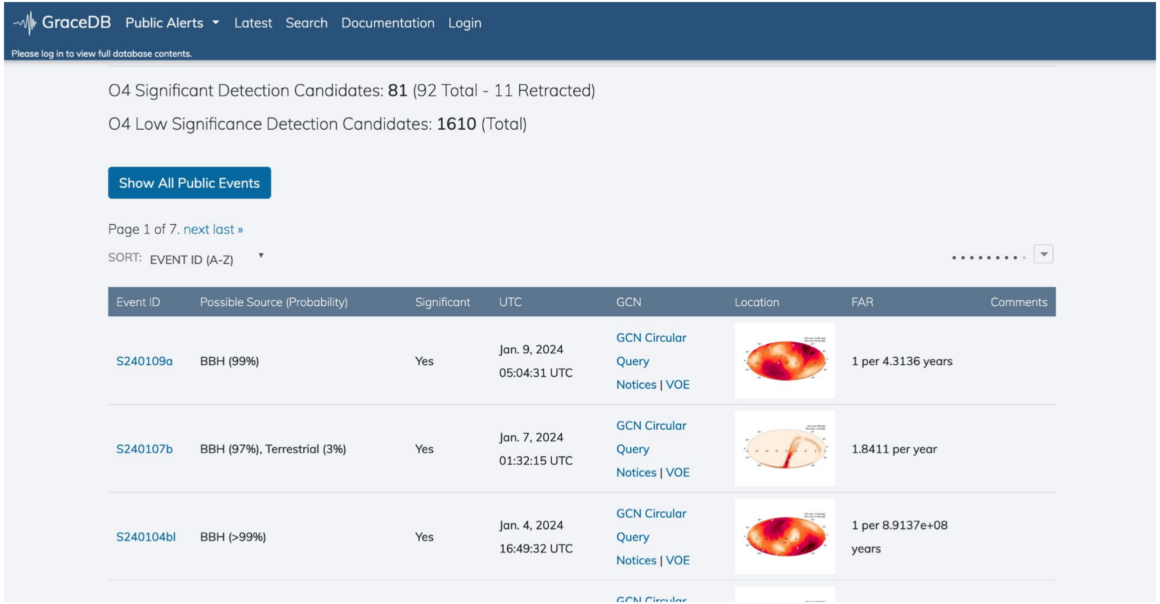
From one to many: measuring populations



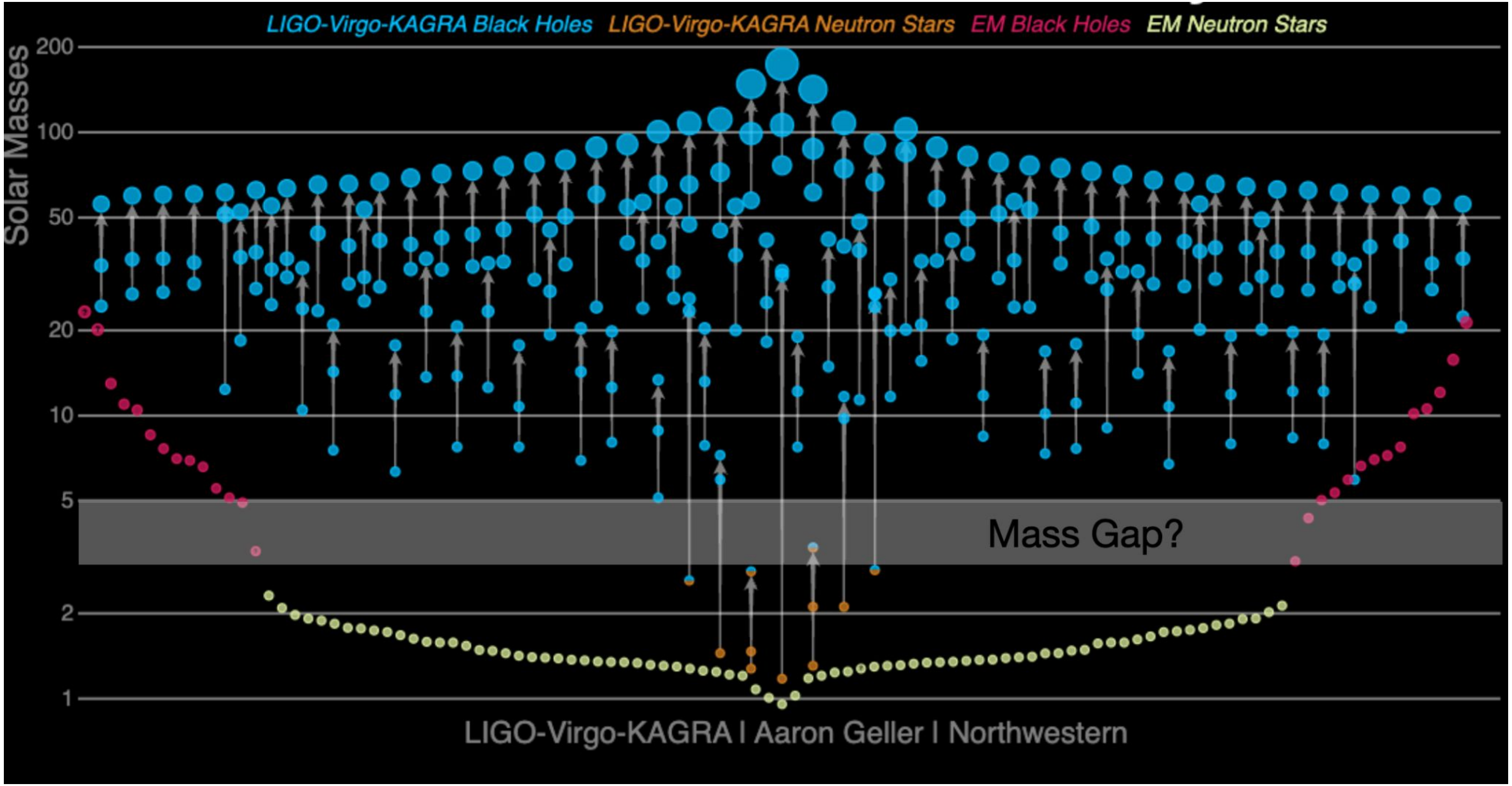
Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

The fourth observing run (O4)

- O4a: 24 May 2023 – 16 Jan 2024, LIGO and KAGRA for 1 month
- O4b: 10 April 2024 – Feb 2025, LIGO and Virgo
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / (2.8 days)
- Improved public alerts
  - Localization
  - Classification
  - Latency
  - Early-warning
  - Low-significance
- Improved sensitivity
  - > 150Mpc BNS range



Masses in the stellar graveyard



FILLING THE MASS ⟷ GAP

with observations of compact binaries from gravitational waves

Includes components of compact binary mergers detected with a False Alarm Rate (FAR) of less than 0.25 per year

Figure credit: Shanika Galaudage / Observatoire de la Côte d'Azur

FILLING THE MASS ⟷ GAP

with observations of compact binaries from gravitational waves

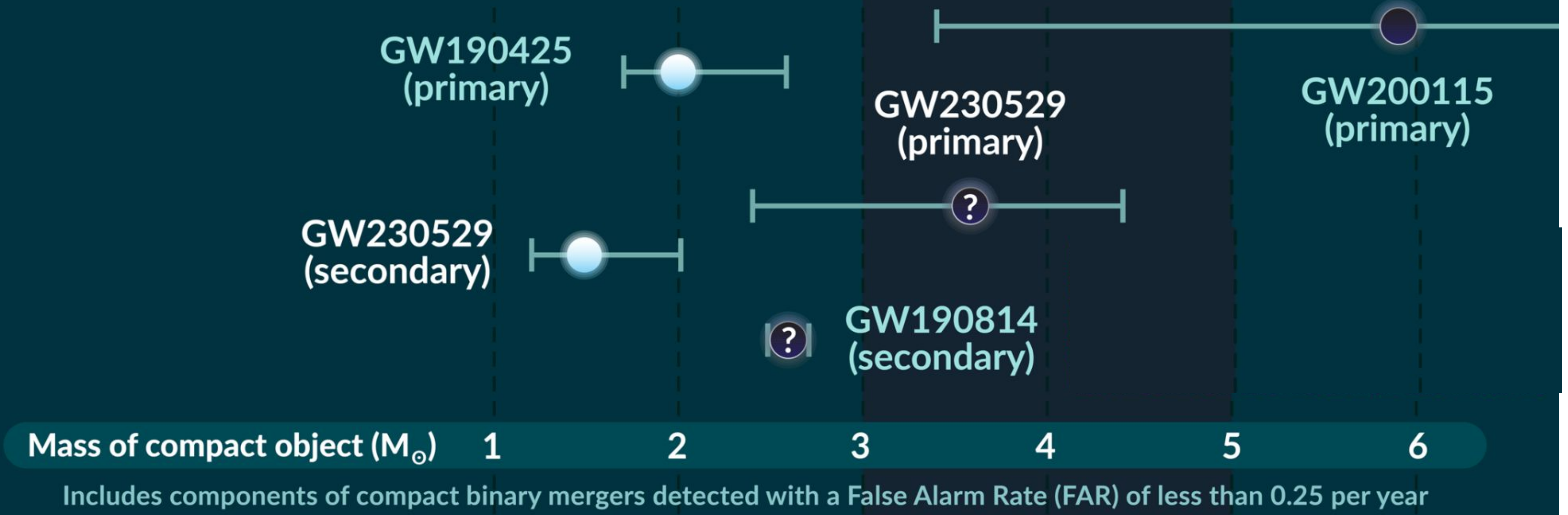
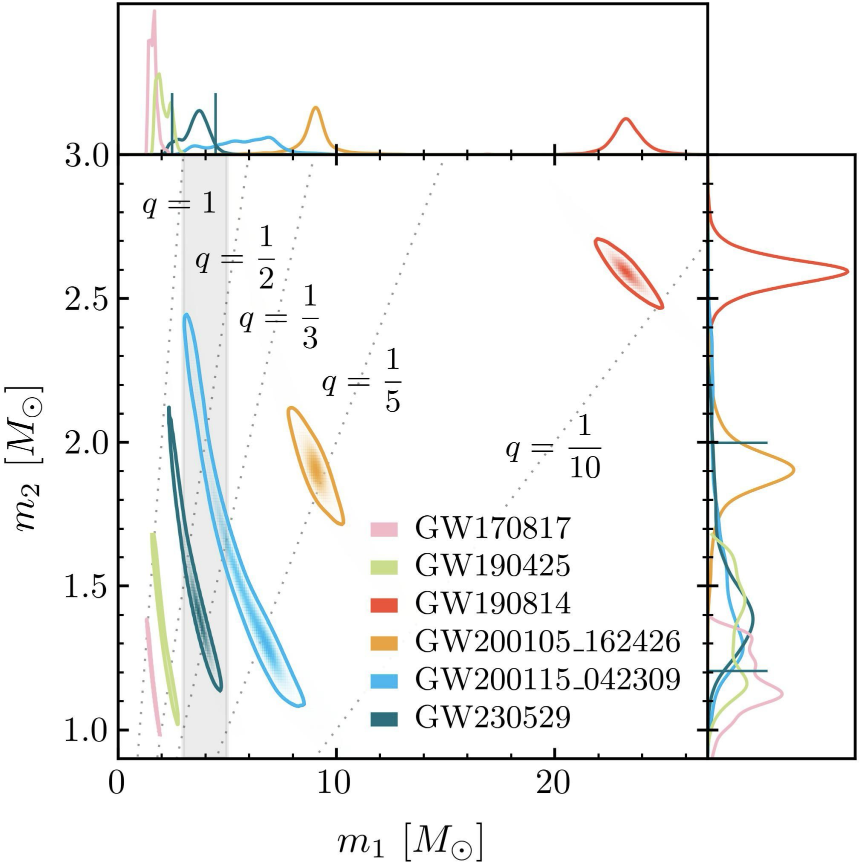


Figure credit: Shanika Galaudage / Observatoire de la Côte d'Azur

GW230529 - Properties



Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter $\chi_{\rm eff}$	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter $\chi_{\rm p}$	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$

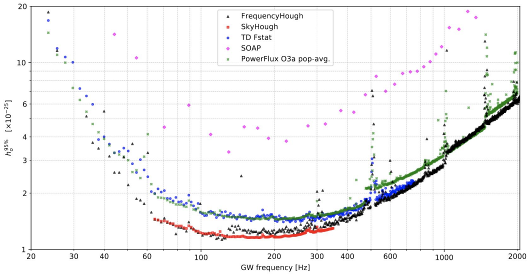
LIGO-Virgo-KAGRA COllaboration
https://arxiv.org/abs/2404.04248

Binary neutron star mergers

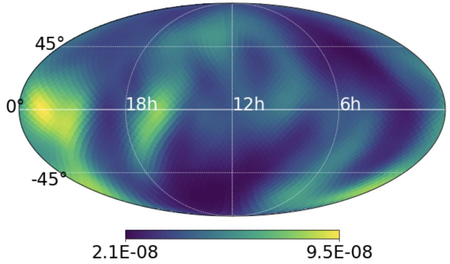
- GW170817 & GW190425
  - Binary neutron star (BNS) merger waves
- O4a
  - Doubled spacetime volume searched, no new BNS events.
  - Based on O1+O2+O3 rates, expected ~ 0.4 - 7 new events.
- O4b (using public information)
  - Using naive O123+O4a rates, expect 0.2 - 3.5 new events in O4b.

Many other observational results

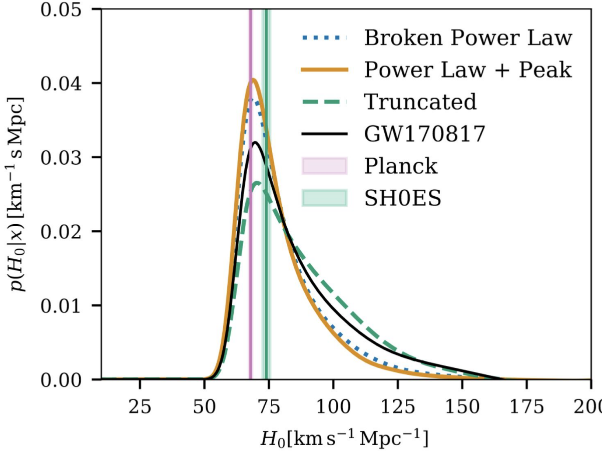
Limits on waves from pulsars
Phys. Rev. D 106, 102008 (2022)



Stochastic background limits
Phys. Rev. D 105, 122002 (2022)



Hubble constant measurements
Astrophys. J. 949, 76 (2023)

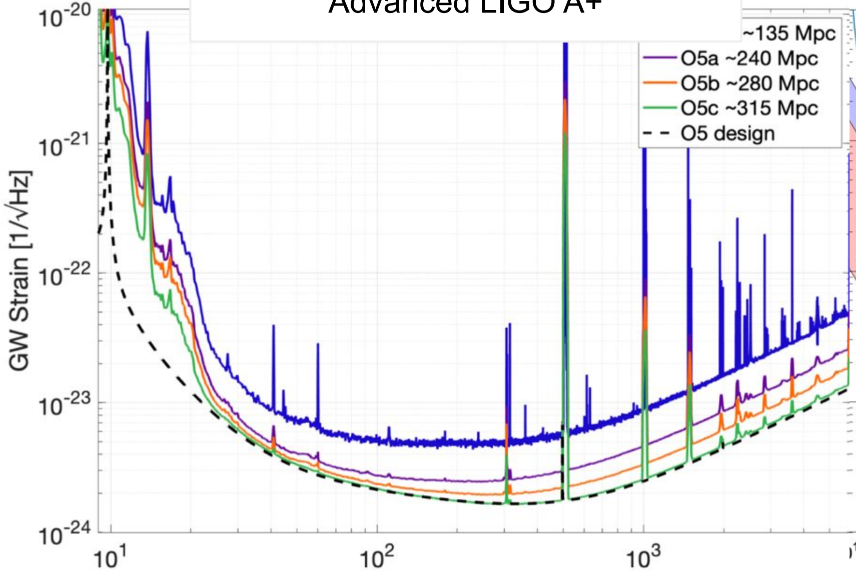


And much more!

Thanks to Dave Reitze & Giovanni Losurdo

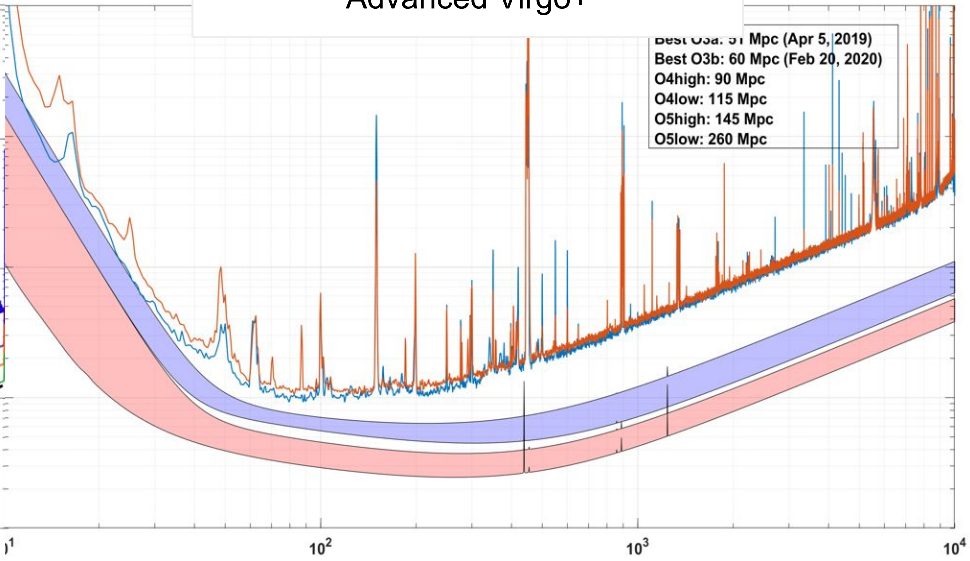
Working toward O5 sensitivity

Advanced LIGO A+



Frequency (Hz)

Advanced Virgo+



Frequency (Hz)

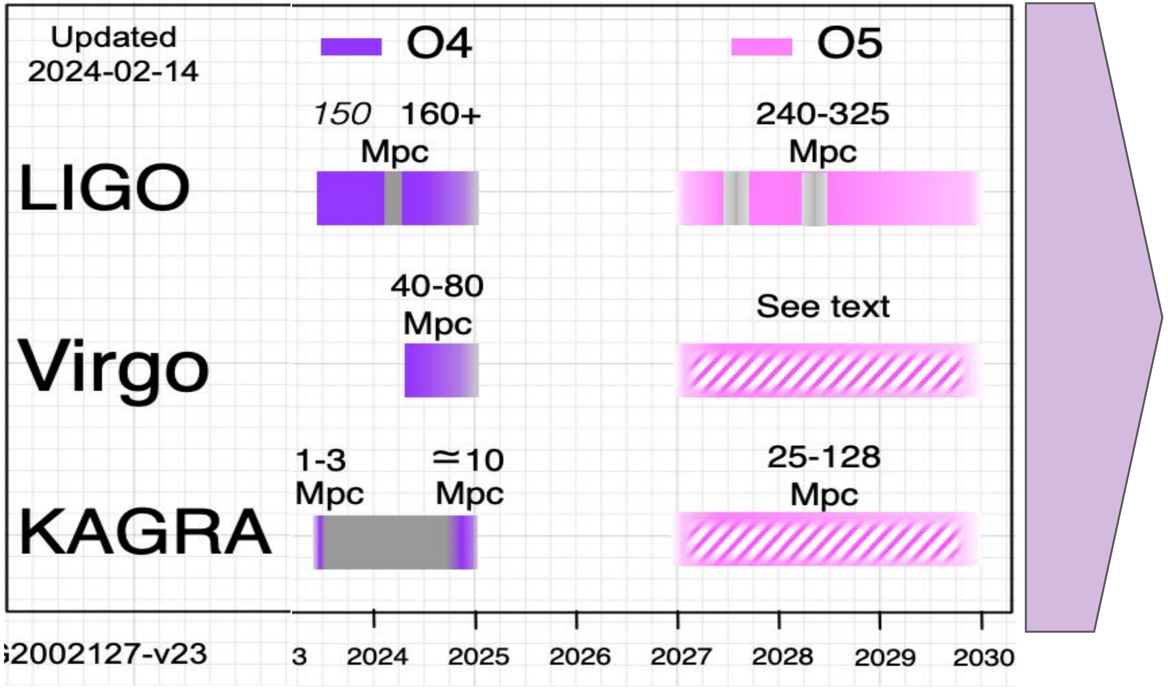
Full Power in the arm cavities: 750 kW
Frequency-dependent Squeezing* level of 6 dB
Test Masses with 2x lower coating thermal noise*

KAGRA will continue to work towards 130Mpc goal in O5

O5 Observing Run

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

- Current thinking
  - Start is paced by upgrades after O4: 2 years gap.
  - Intersperse commissioning and observations
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / (2.8) days
  - O5 ~ 3 / day
- Other science
  - Improved SNR
  - New sources?



https://observing.docs.ligo.org/plan/

Early 2030s

- LIGO Aundha Observatory (LAO) is to be constructed in India and operated as part of the LIGO network in the 2030s.
- $A^{\#}$: targeted improvements to the LIGO detectors
  - Report of LSC post-O5 study group [Fritschel et al, https://dcc.ligo.org/LIGO-T2200287/public]
  - Achieve close to a factor of 2 amplitude sensitivity improvement with larger test masses, better seismic isolation, improved mirror coatings, higher laser power, better squeezing …
  - Begin observing at the end of 2031 and observe for several years.
  - $A^{\#}$ an engine for observational science and a pathfinder for next-generation technologies.
  - A network including LIGO A# detectors would be a cornerstone for multimessenger discovery.
- Virgo has scoped similar improvements, called VirgoNEXT, with similar timetable. KAGRA is focused on reaching its current target.

Observational Science with $A^{\#}$

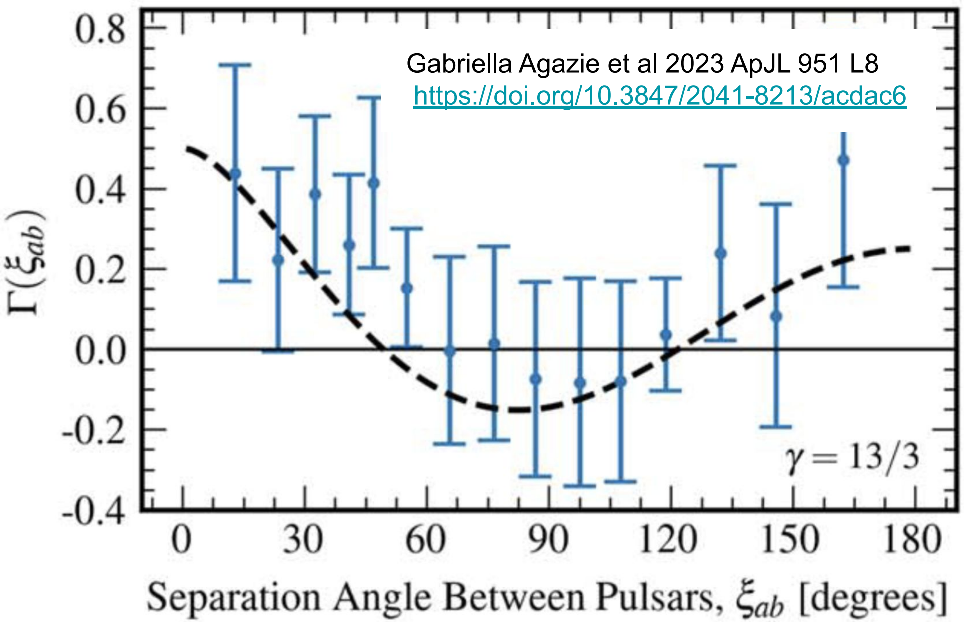
- Probe the compact object binary population with unprecedented precision
  - Masses, spins, sub-populations.
  - Clues about their formation and astrophysical environment.

- Hubble constant measurement to sub-percent levels
- Black hole spectroscopy via sub-dominant modes
- Neutron star radius measurements to sub-km
- Enlarge discovery space: nearby supernova, continuous wave sources, stochastic background

Configuration	Annual Detections		
	BNS	NSBH	BBH
A+	135^{+172}_{-78}	24^{+34}_{-16}	740^{+940}_{-420}
$A^{\sharp}$	630^{+790}_{-350}	100^{+128}_{-58}	2100^{+2600}_{-1100}
$A^{\sharp}$ (A+ coatings)	260^{+320}_{-140}	45^{+60}_{-27}	1150^{+1450}_{-640}
$A^{\sharp}$ Wideband (A+ coatings)	200^{+250}_{-110}	40^{+54}_{-25}	970^{+1220}_{-540}
Voyager Deep	1280^{+1610}_{-710}	190^{+240}_{-110}	3100^{+3900}_{-1700}
Voyager Wideband	730^{+920}_{-410}	129^{+165}_{-74}	2300^{+2900}_{-1300}

See Fritschel et al, https://dcc.ligo.org/LIGO-T2200287/public

Recent Pulsar Timing Observations



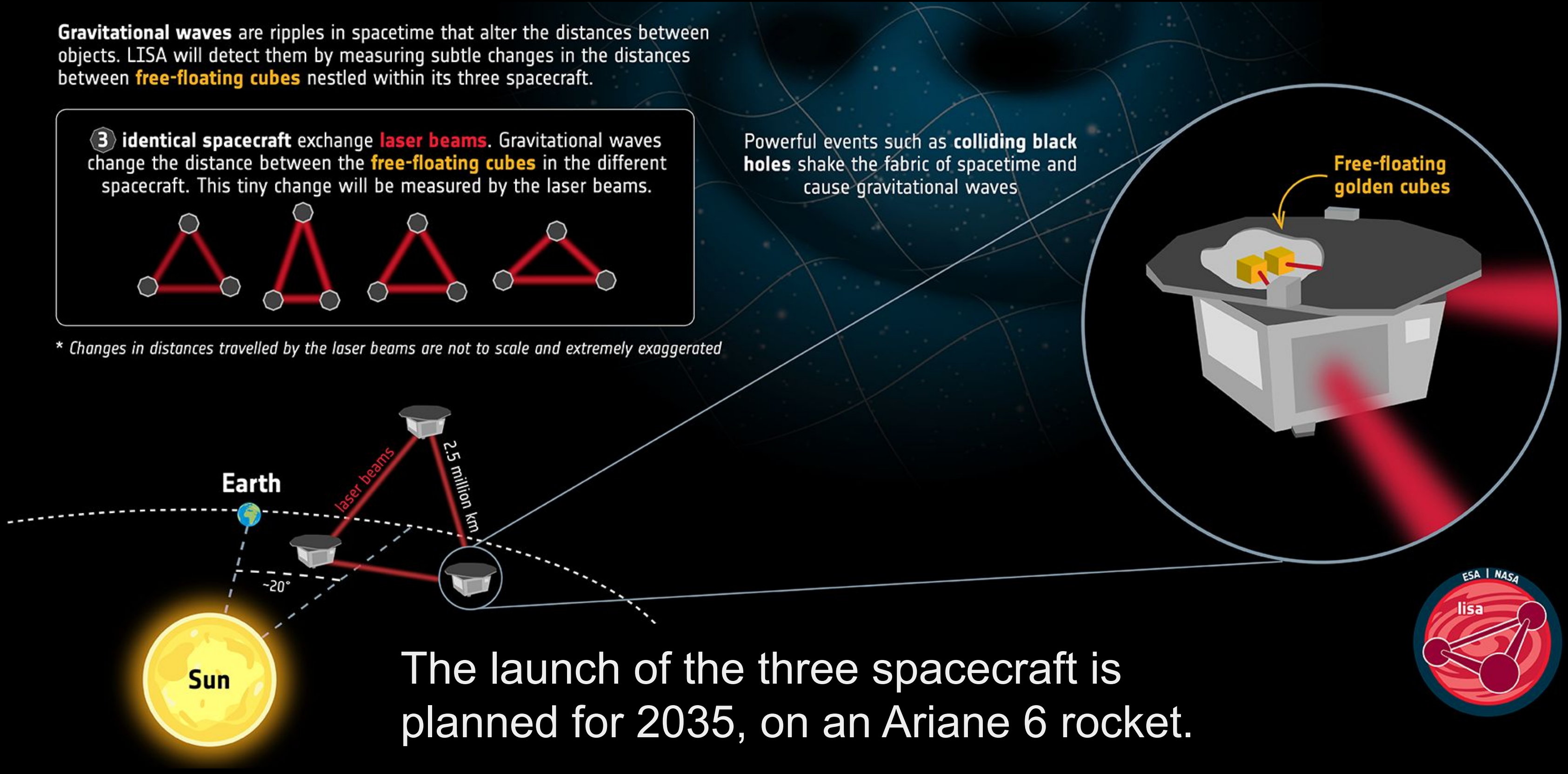
Hellings-Downs interpulsar correlations from a gravitational-wave background.

- Bayesian analysis ~ 3 sigma
- Frequentist analysis ~ 3.5 - 4 sigma

Possibly background from supermassive black hole binaries.

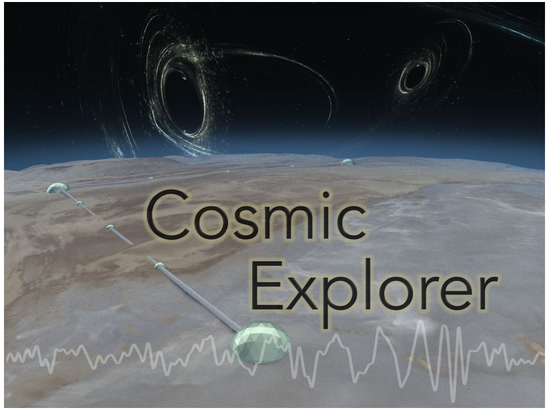
- NANOGrav - G. Agazie et al 2023 ApJL 951 L8
- PPTA - D. J. Reardon et al 2023 ApJL 951 L6
- EPTA and InPTA - J. Antoniadis et al. A&A, to appear
- CPTA - H. Xu et al 2023 Res. Astron. Astrophys. 23 075024

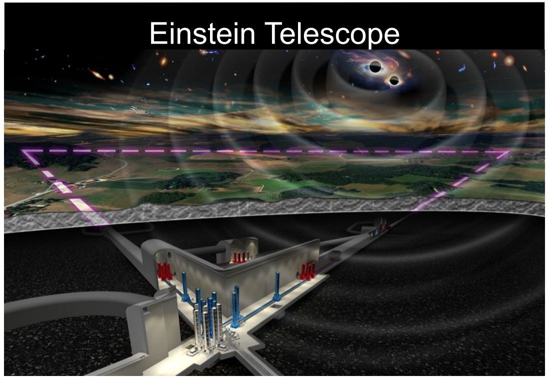
LISA mission

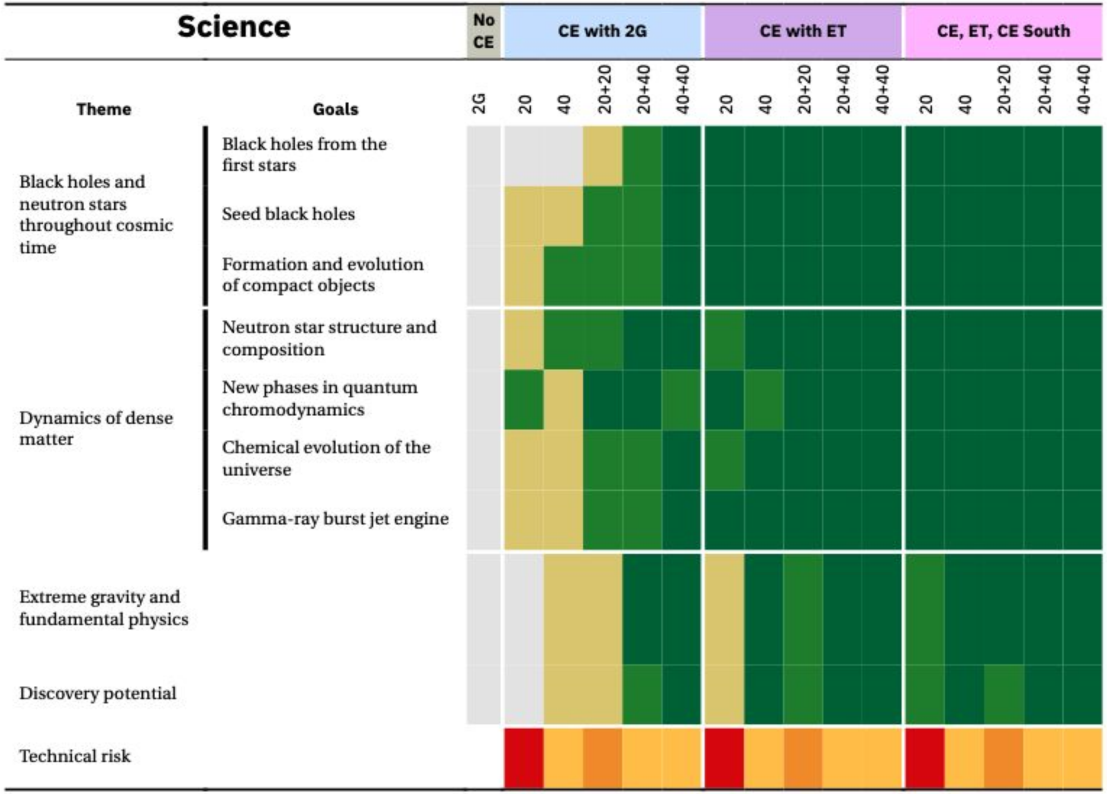


The launch of the three spacecraft is planned for 2035, on an Ariane 6 rocket.

Next Generation Detectors

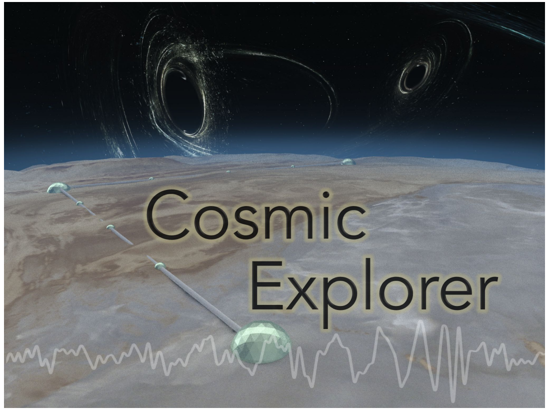






A Horizon Study for Cosmic Explorer
https://arxiv.org/abs/2109.09882

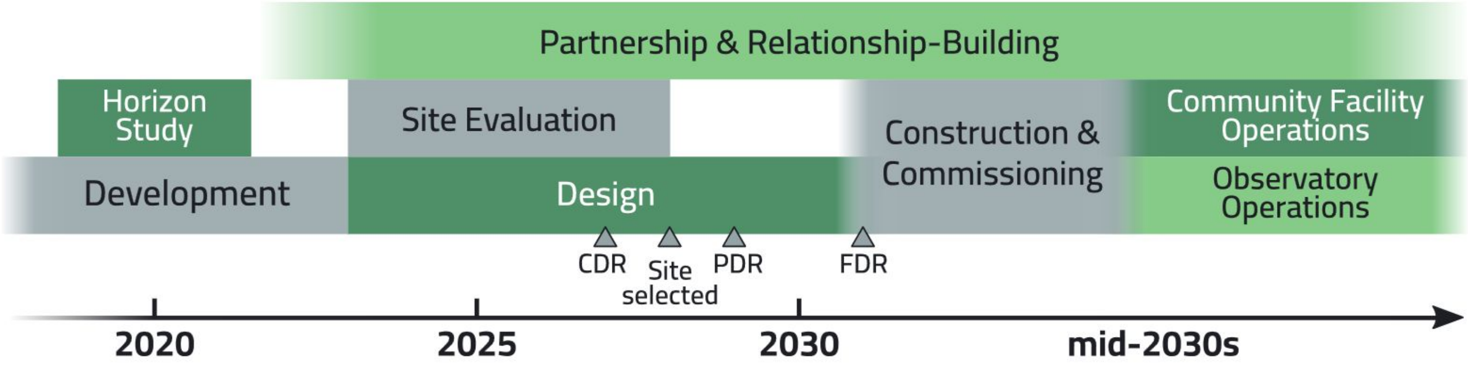
Cosmic Explorer Timeline



A Submission to the NSF MPSAC ngGW Subcommittee

https://dcc.cosmicexplorer.org/CE-P2300018/public

Top-level timeline showing a phased approach to design and construction.



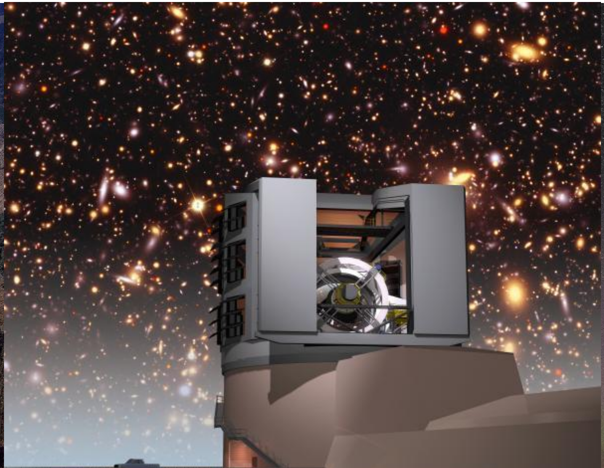
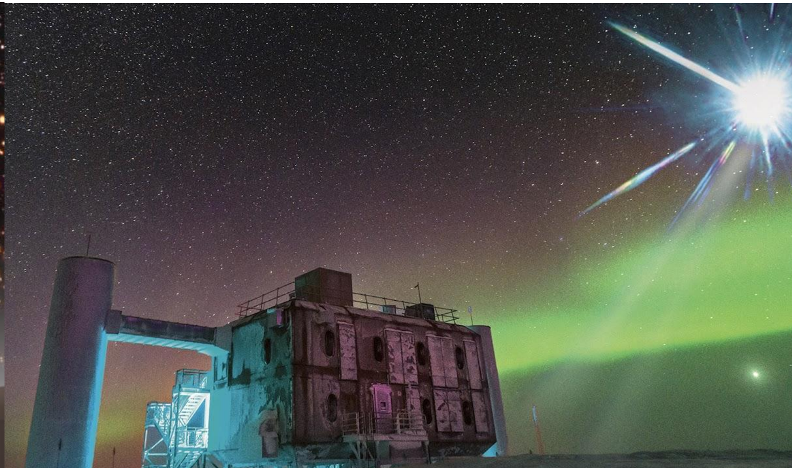
Thank you!

LIGO network is a cornerstone of MMA

- The number of detections per year for four different detector networks for binary neutron stars within z = 0.5

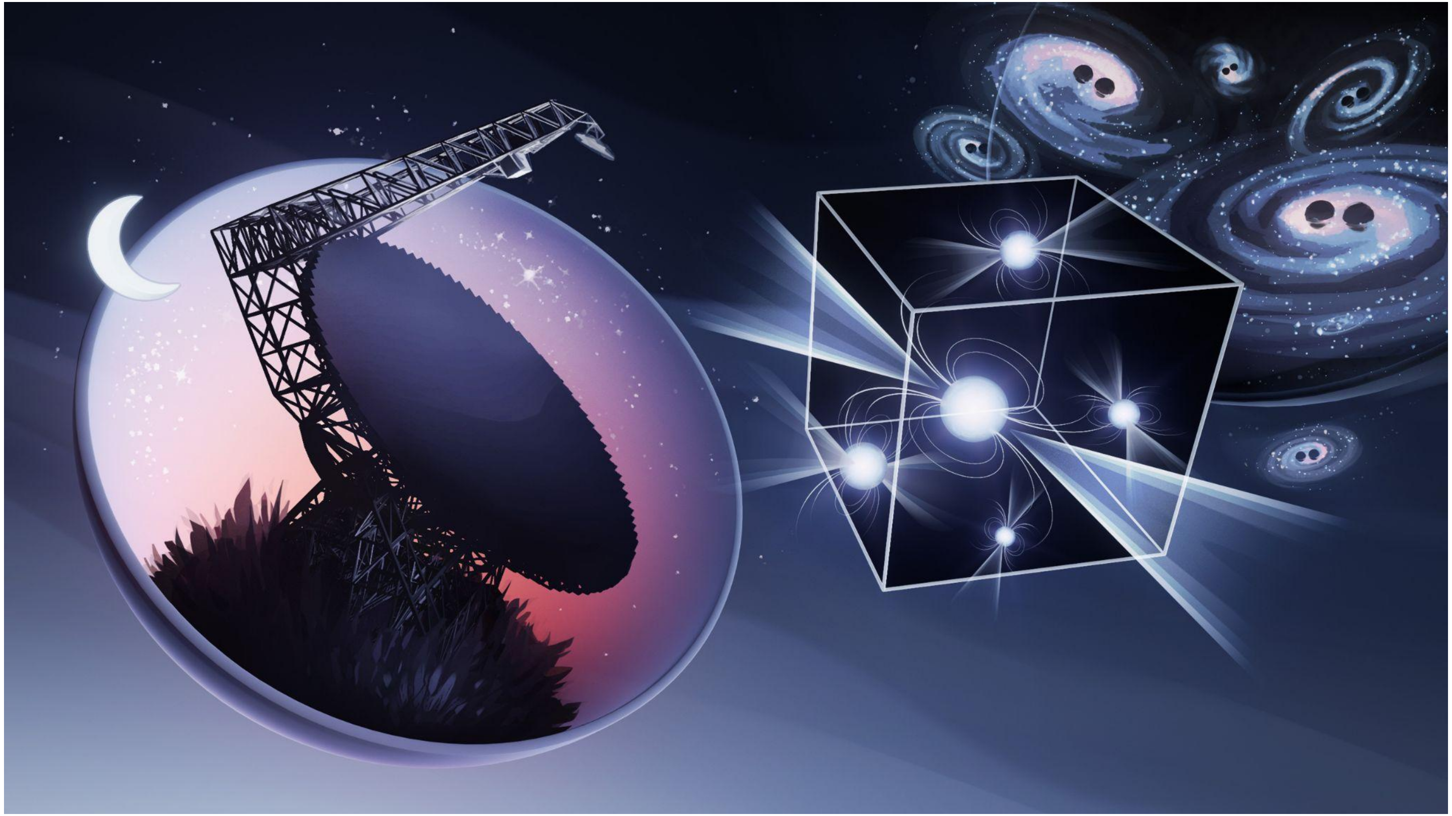
Metric	Ω_{90} (deg)^2		
Quality	≤ 100	≤ 10	≤ 1
3A$^\sharp$	$1.2^{+1.8}_{-0.9} \times 10^3$	$3.2^{+4.7}_{-2.5} \times 10^2$	$5.0^{+11.0}_{-5.0} \times 10^0$
CE20 + 2A$^\sharp$	$8.6^{+13.3}_{-6.4} \times 10^3$	$8.6^{+12.9}_{-6.8} \times 10^2$	$1.7^{+3.3}_{-1.5} \times 10^1$
CE40 + 2A$^\sharp$	$9.8^{+15.1}_{-7.3} \times 10^3$	$9.7^{+14.6}_{-7.6} \times 10^2$	$1.8^{+3.8}_{-1.6} \times 10^1$
CE40 + CE20 + 1A$^\sharp$	$1.4^{+2.1}_{-1.0} \times 10^4$	$3.4^{+5.3}_{-2.6} \times 10^3$	$9.7^{+15.7}_{-7.7} \times 10^1$

Ish Gupta & B. Sathyaprakash

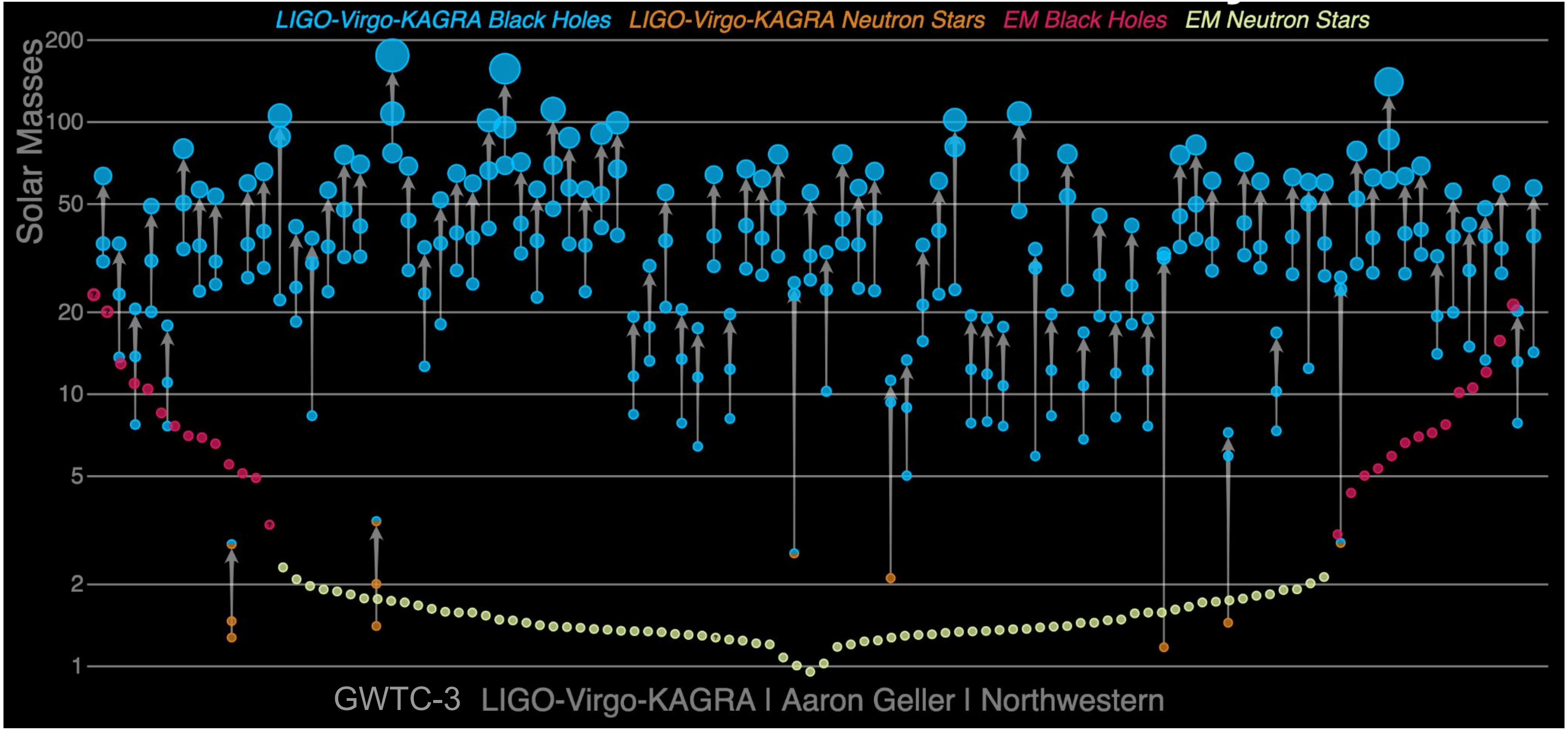




Pulsar Timing Observations

Illustration Credit
Olena Shmahalo for NANOGrav



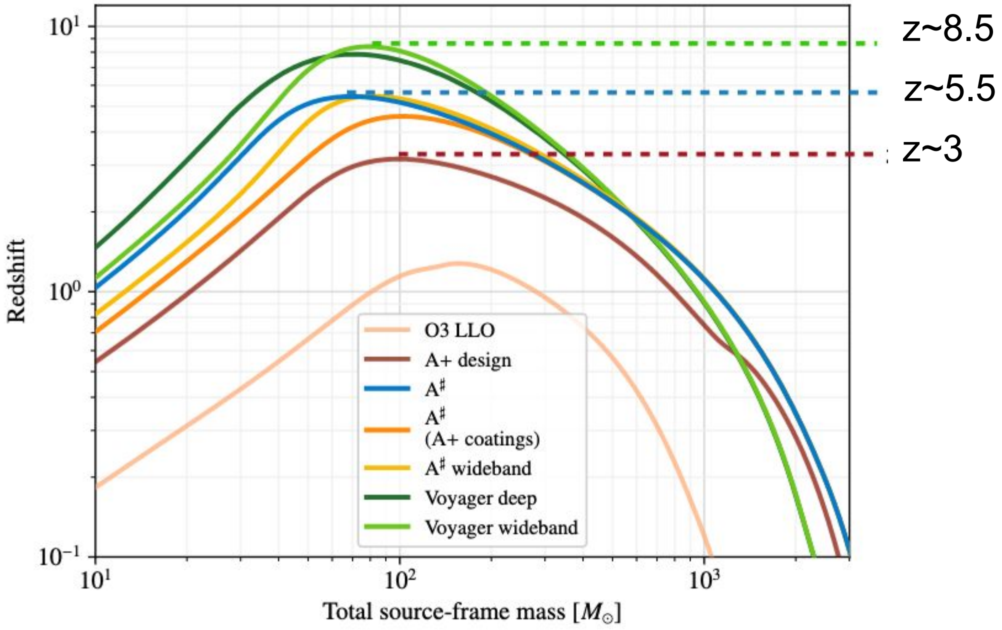
Gravitational-Wave Transient Catalog

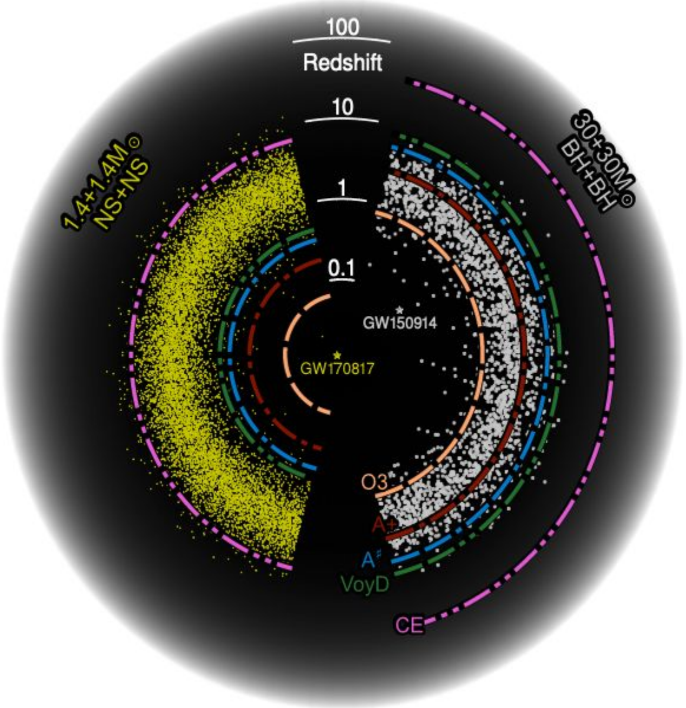


LIGO-Virgo-KAGRA, arXiv:2111.03606 [gr-qc]

Observational Science with A#

Horizon for optimally oriented and located binary mergers

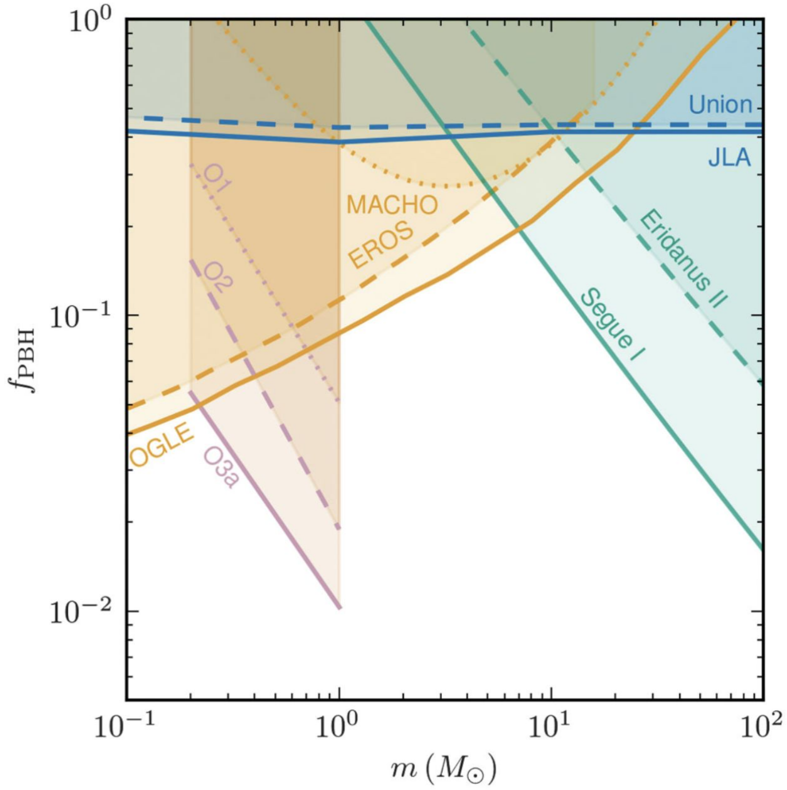




See Fritschel et al, https://dcc.ligo.org/LIGO-T2200287/public

Search for subsolar-mass binaries

- Search for compact binary mergers with at least one object of mass 0.2 - 1 Msun.
- No detections.
- Example constraints on fraction of dark matter in primordial black holes from an isotropic distribution of equal-mass binaries.

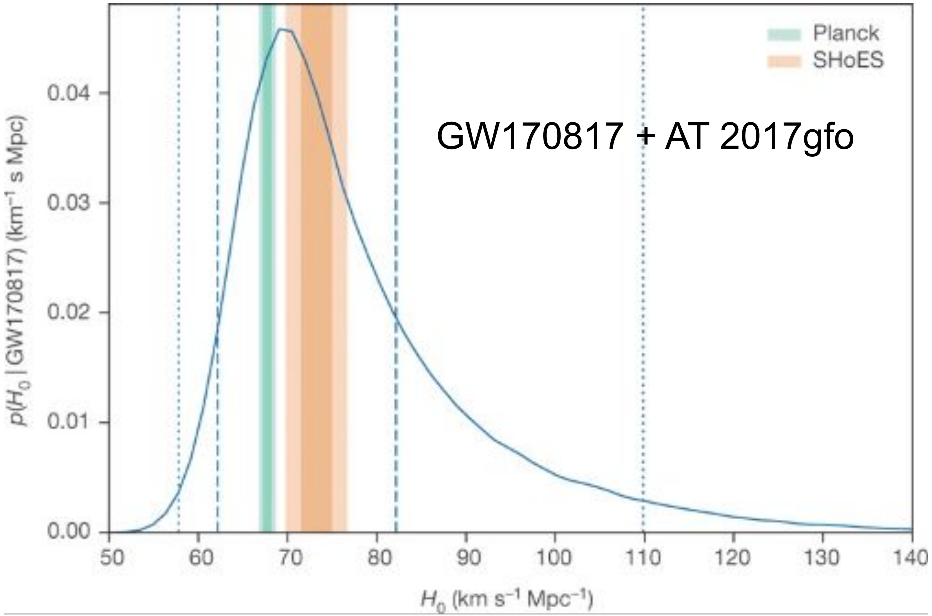


LIGO-Virgo Collaboration
Phys. Rev. Lett. 129, 061104

Cosmology with gravitational waves

- Gravitational waves from binaries are standard sirens
  - Measure the luminosity distance to the source and redshifted masses
  - Cannot measure redshift directly
- Get redshift some other way
  - Electromagnetic counterpart, e.g. GW 170817, GRB 170817A, AT 2017gfo
- Sub-percent accuracy with many
  - Cross correlate with galaxy redshifts [Schutz, Nature **323**, 310 (1986)]
  - Mass scale imprinted on spectrum of detected binary mergers [Will M. Farr et al 2019 ApJL 883 L42]

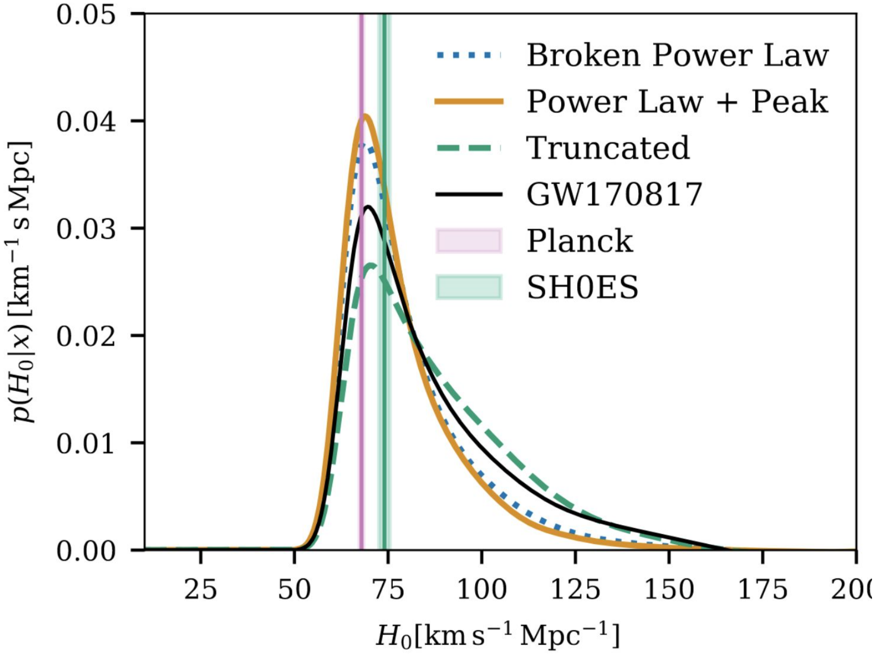
B P Abbott *et al.* *Nature* **551,** 85–88 (2017) doi:10.1038/nature24471



Challenges for cosmology with GW

- Binaries with detectable EM counterparts are rare
    - With ~5-10 BNS mergers detectable in O4, expect ~1 detectable kilonova.
    - GRBs further away, but only a fraction beamed to Earth.
- Sub-percent accuracy with many
    - Completeness of galaxy catalogs decreases rapidly with redshift.
    - Mass scales are highly uncertain, e.g. maximum black hole mass from PISN, or must be measured simultaneously.

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



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!