Cosmology with Gravitational-wave Observations

Patrick Brady,
University of Wisconsin-Milwaukee

Lemaitre Conference
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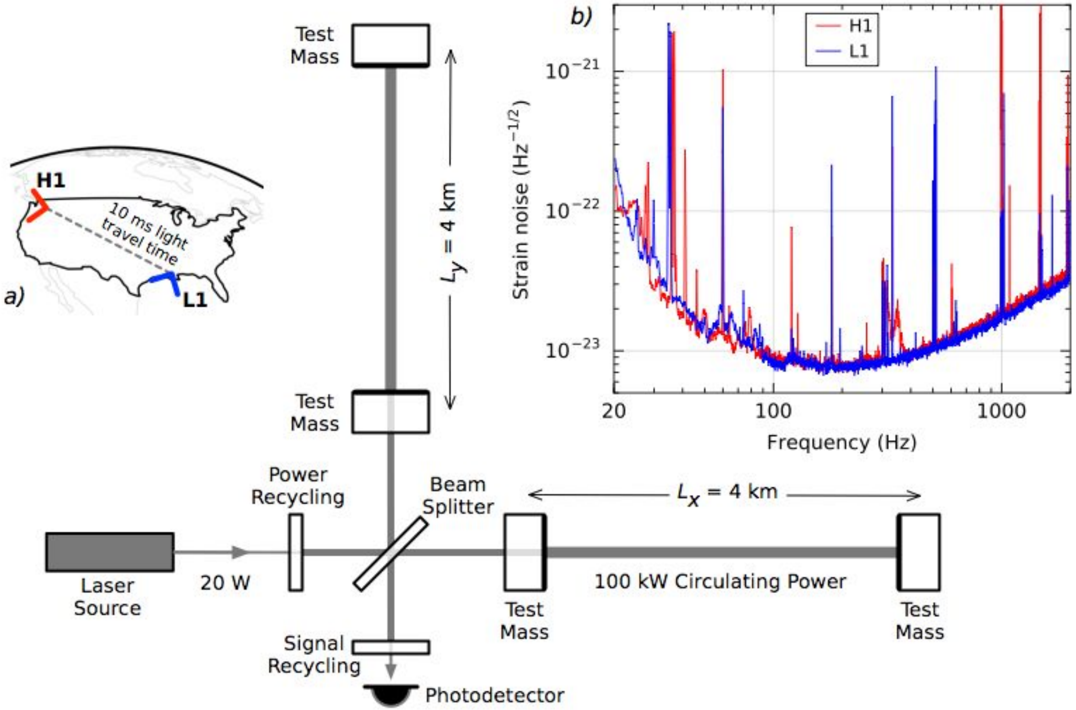
https://dcc.ligo.org/G2401288

International Gravitational-Wave Observatory Network (IGWN)

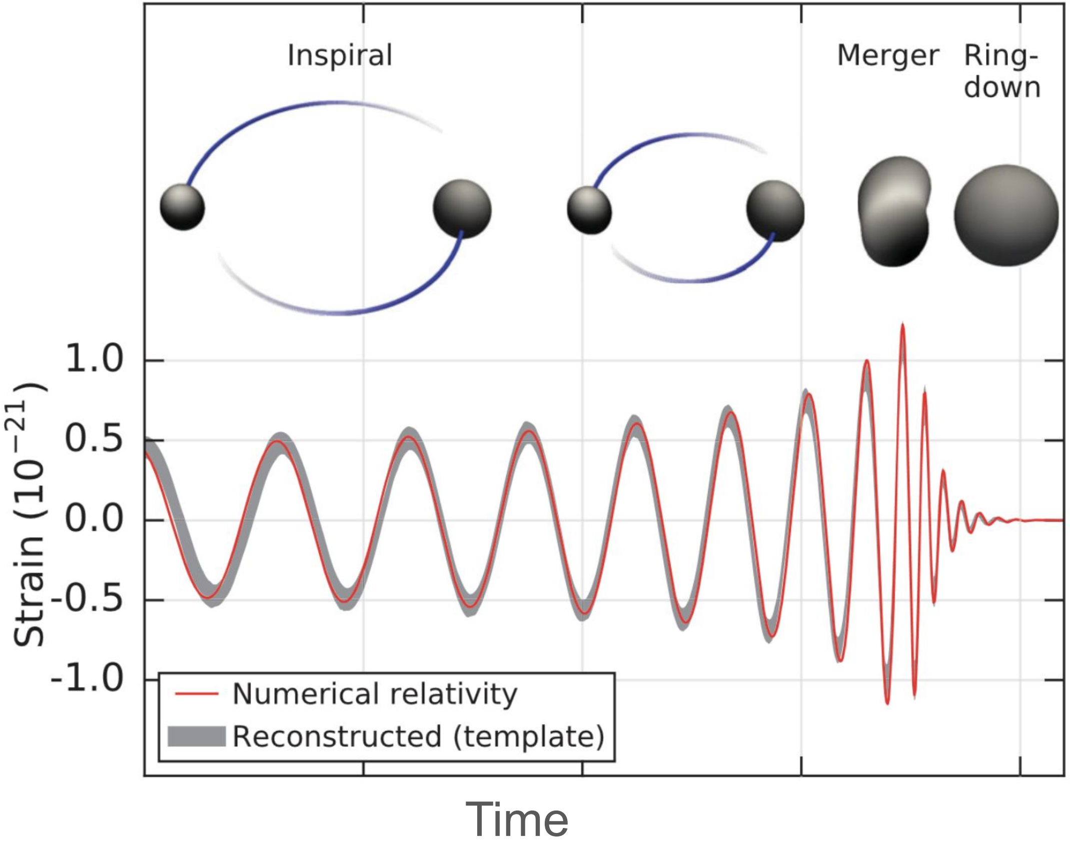
Laser Interferometer Gravitational-wave Observatory (LIGO)



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



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

Strain (quadrupole) at the detector

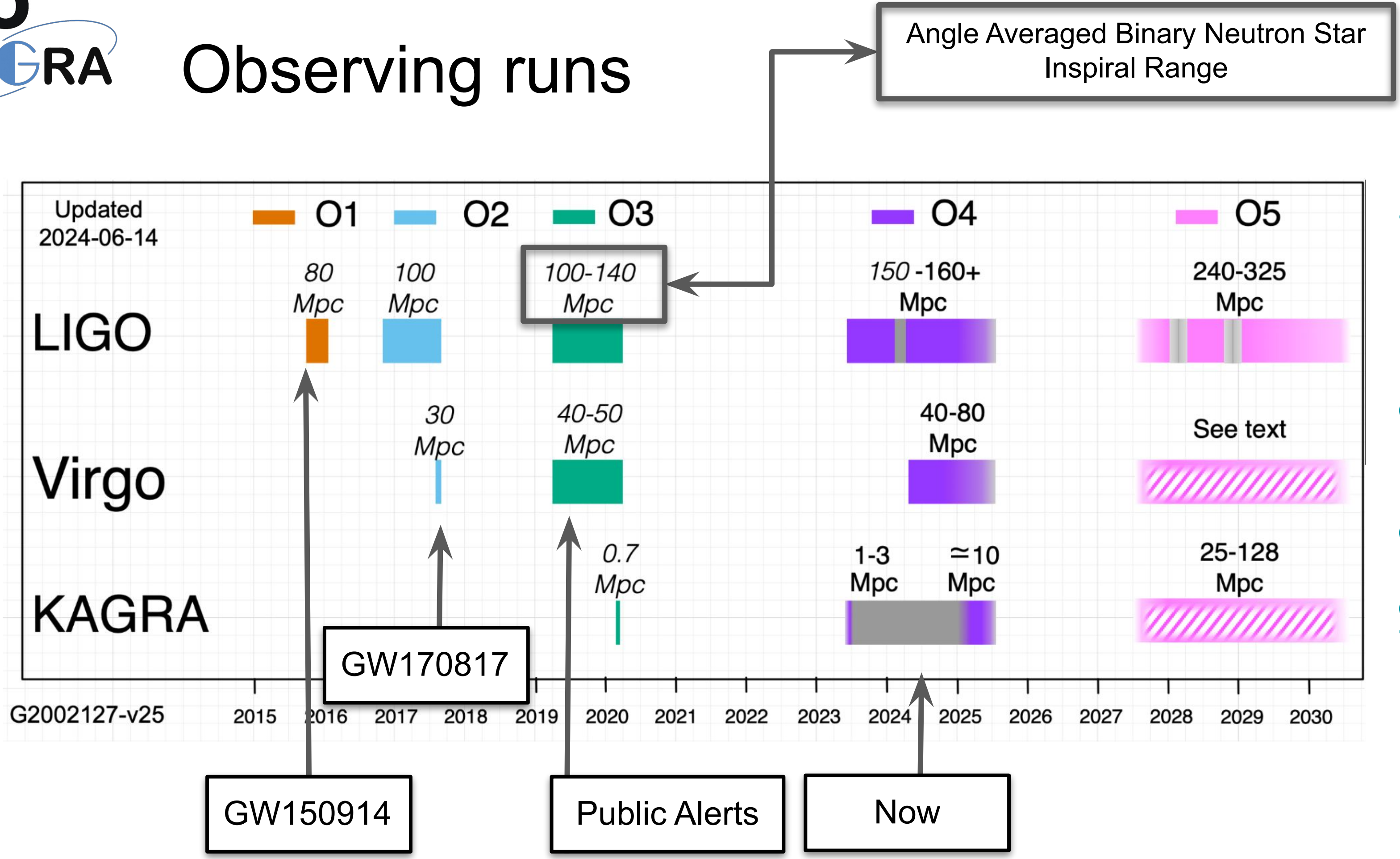
$$h(t) = \frac{\mathcal{M}'\Theta(i,\lambda,\delta,\psi)}{d_L}\left[\pi\mathcal{M}'f(\mathcal{M}',t-t_0)\right]^{2/3}\cos\left[\Phi(t_0-t)+\Psi\right]$$

$$\Phi = -2\left(\frac{t_0-t}{\mathcal{M}'}\right)^{5/8}$$

$$\mathcal{M}' = (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

$$f = \frac{1}{2\pi}\frac{\partial\Phi}{\partial t} = \frac{1}{\pi\mathcal{M}'}\left(\frac{5}{256}\frac{\mathcal{M}'}{t_0-t}\right)^{3/8}$$

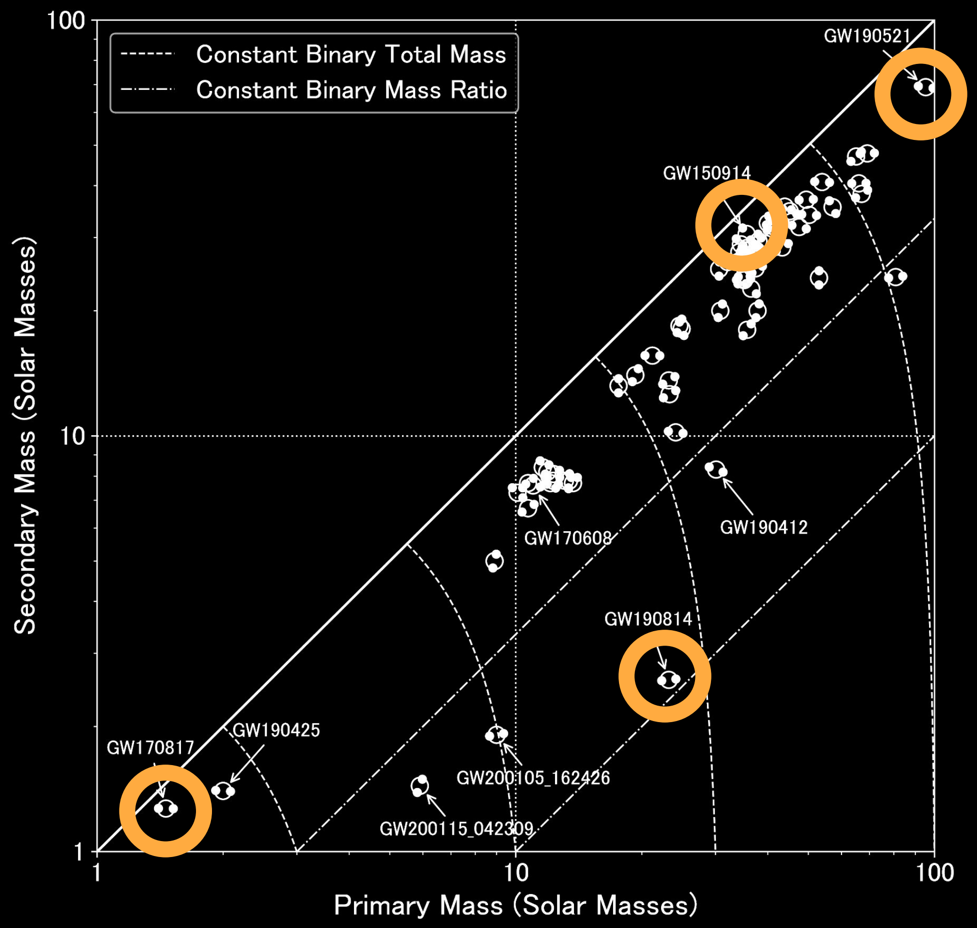
Observing runs



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

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

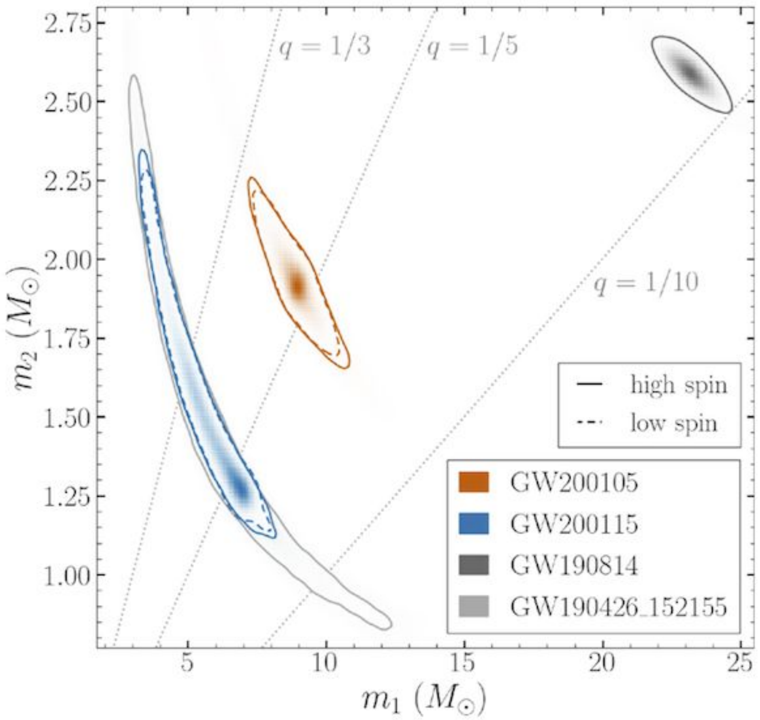


Credit: LIGO-Virgo-KAGRA Collaborations

Mergers involving neutron stars

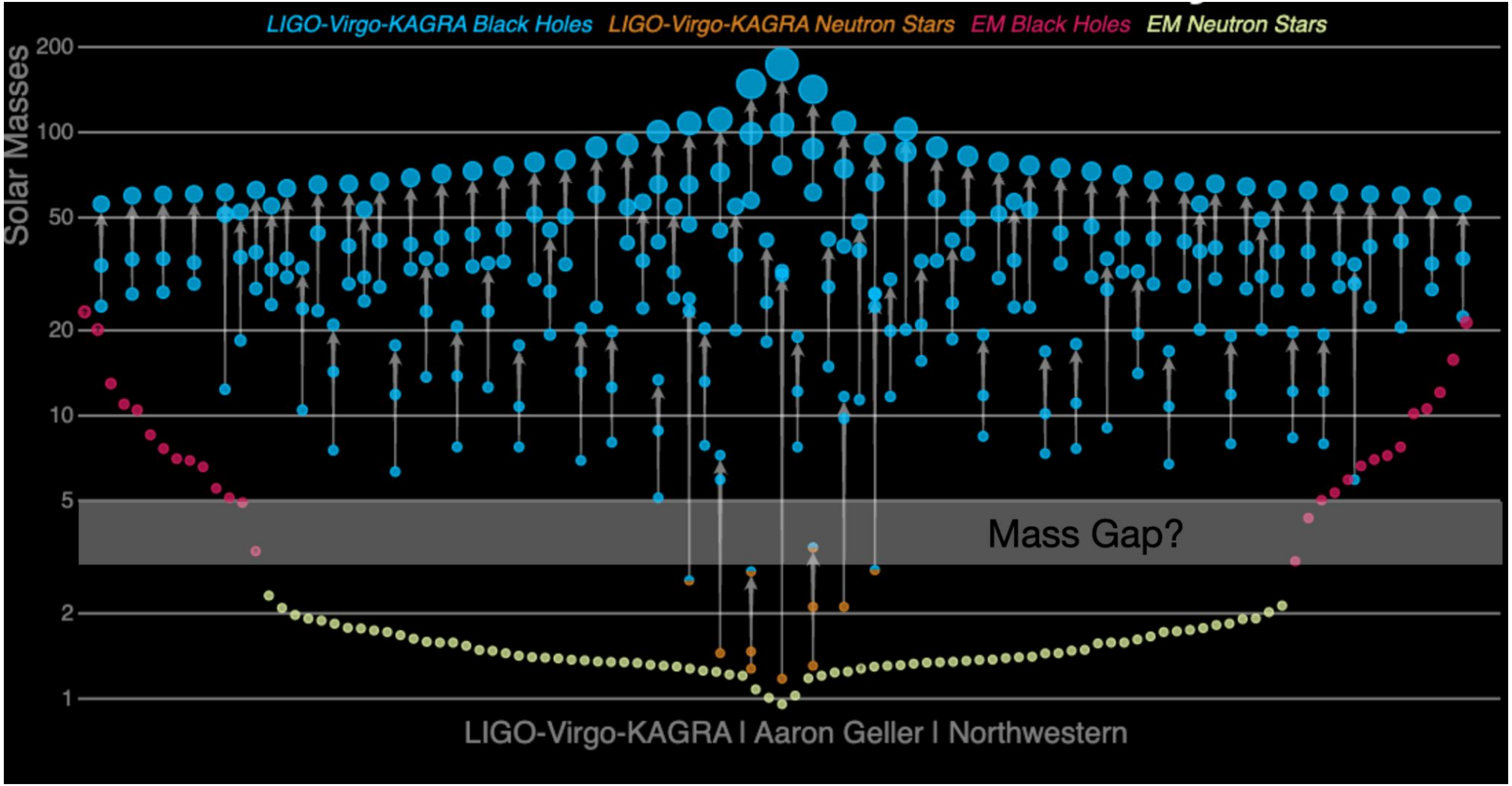
- GW170817 & GW190425
  - Binary neutron star (BNS) merger waves
- GW170817 & GRB 170817A
  - Fractional difference in speed of gravity and the speed of light is between -3 x 10^{-15} and 7 x 10^{-16}
- GW170817 & AT 2017gfo
  - Binary neutron star mergers produce kilonova explosions that generate heavy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

B. P. Abbott et al 2017 ApJL 848 L13



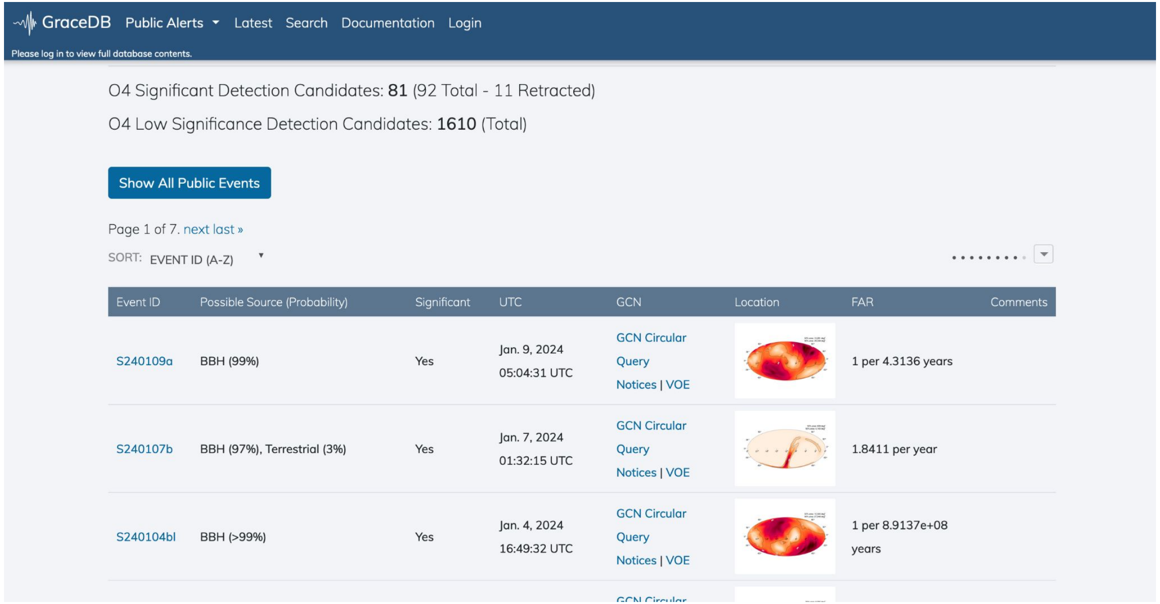
R. Abbott *et al* 2021 *ApJL* **915** L5

Masses in the stellar graveyard



The fourth observing run (O4)

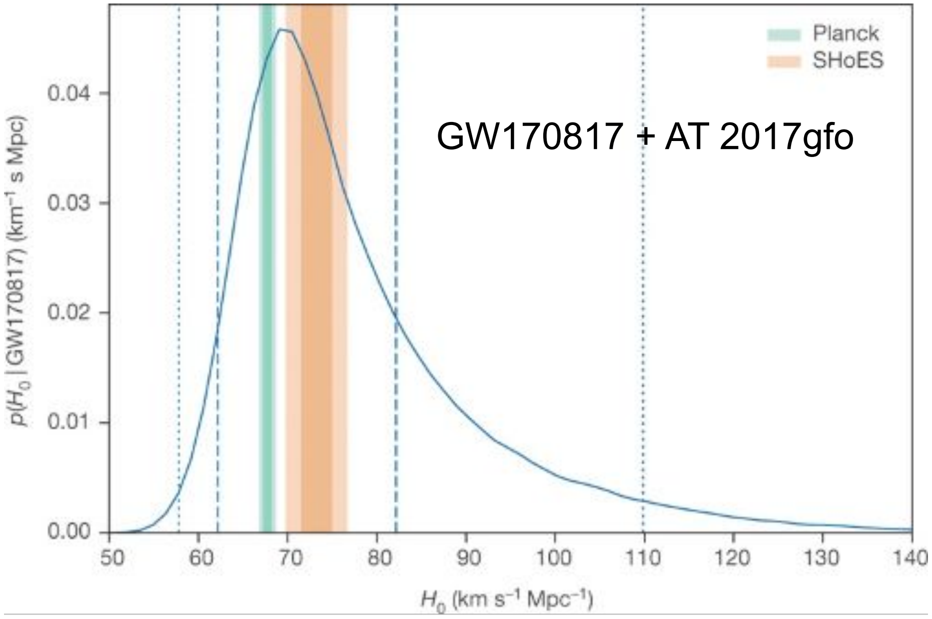
- O4a: 24 May 2023 – 16 Jan 2024, LIGO and KAGRA for 1 month
- O4b: 10 April 2024 – Jun 2025, LIGO and Virgo
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / (2.8 days)
  - O5 ~ 3 / day
- Improved public alerts
  - Localization
  - Classification
  - Latency
  - Early-warning
  - Low-significance



Cosmology with gravitational waves

- Gravitational waves from binaries are standard sirens
  - Measure the luminosity distance to the source and redshifted chirp mass
- 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 [Taylor, Gair & Mandel, Phys. Rev. D 85, 023535 (2012); Farr et al (2019) ApJL 883 L42]

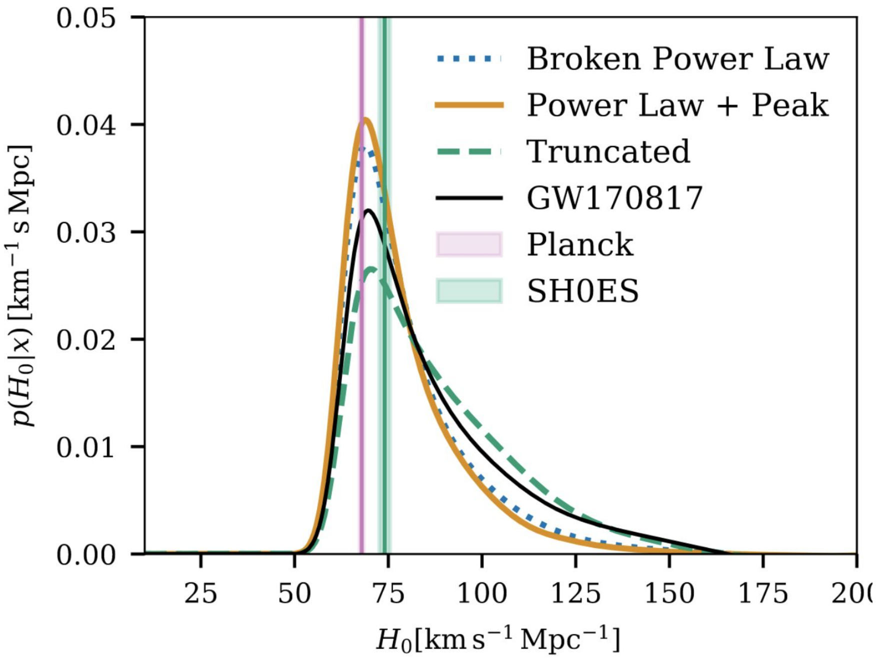
B P Abbott *et al.* *Nature* **551,** 85–88 (2017) doi:10.1038/nature24471



Challenges for cosmology with GW

- **Bright sirens**: Binaries with detectable EM counterparts are rare
  - With ~0-3 BNS mergers detectable in O4, expect ~0 detectable kilonova. GRBs may be more powerful in the future.
- **Dark sirens**: completeness of galaxy catalogs decreases rapidly with redshift making percent accuracy difficult.
- **Spectral sirens**: must measure the mass and cosmology simultaneously.
  - ~1000 events could give ~3% accuracy according to Hernandez and Ray, arXiv:2404.02522; Farah et al arXiv:2404.02210

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



What's next?

- 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.

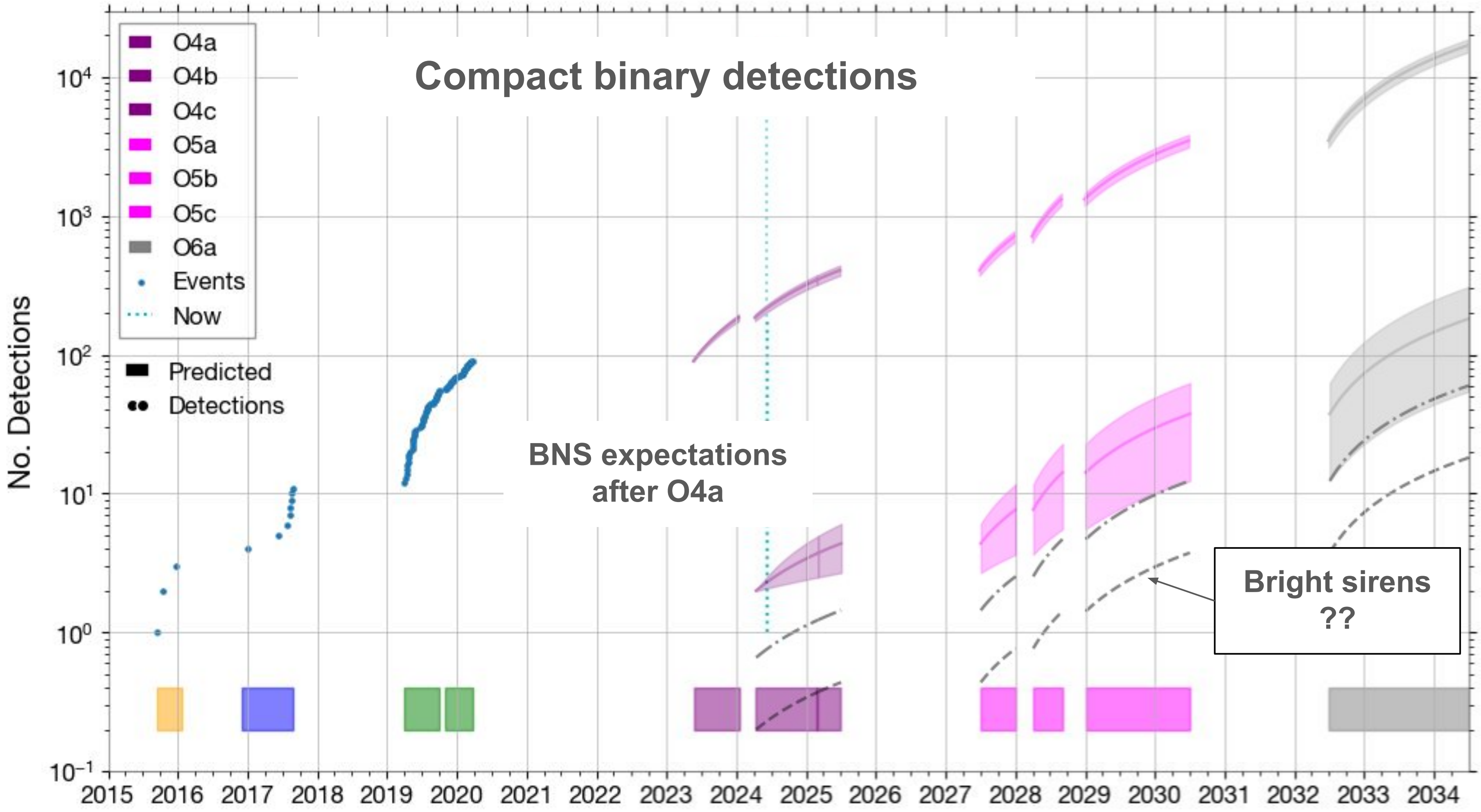
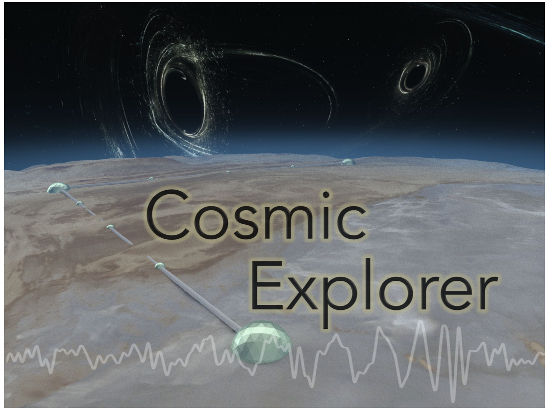
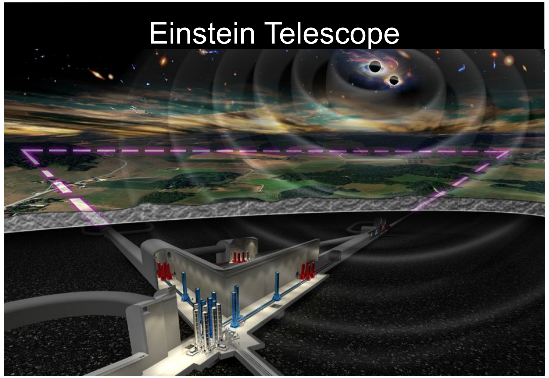
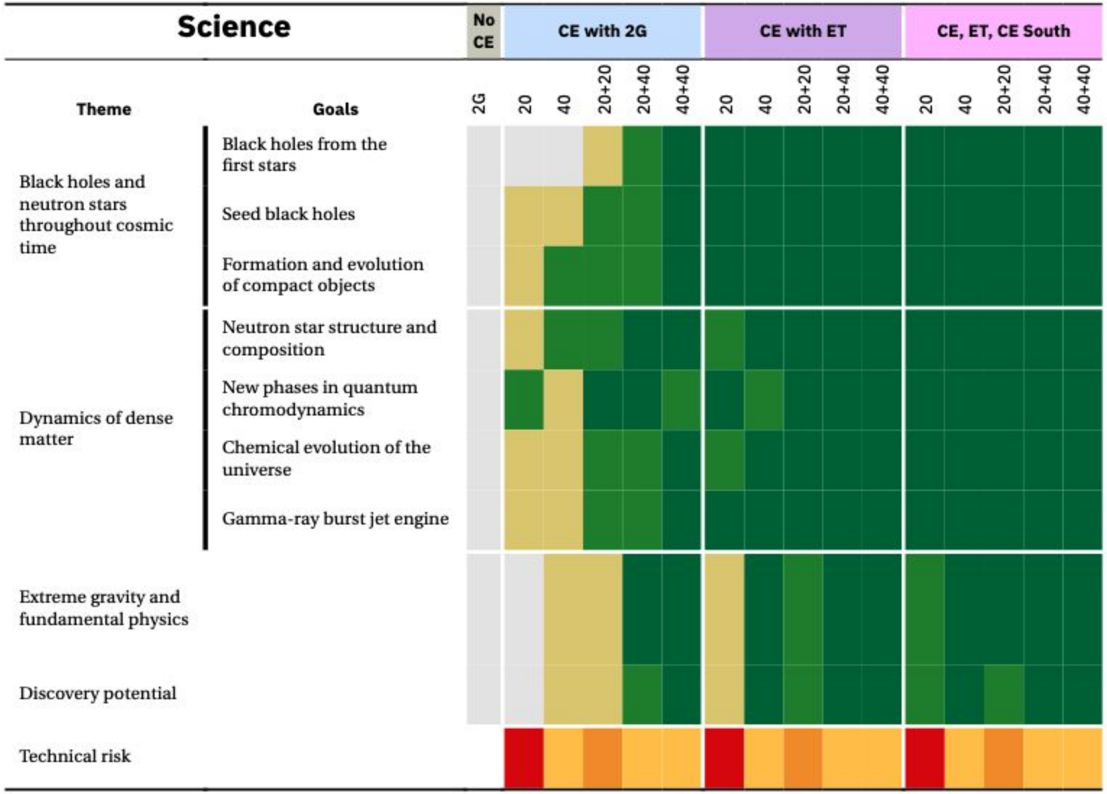


Figure: Amanda Baylor, Cody Messick, PRB

Next Generation Detectors

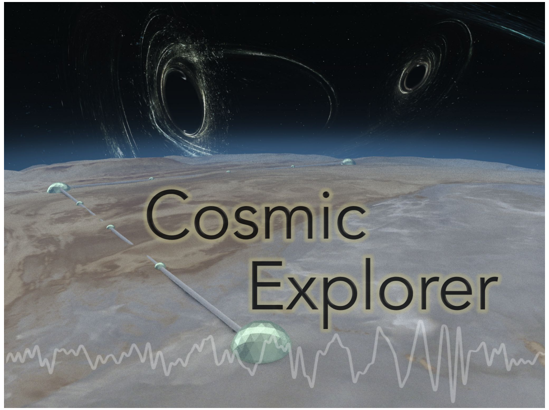






A Horizon Study for Cosmic Explorer
https://arxiv.org/abs/2109.09882

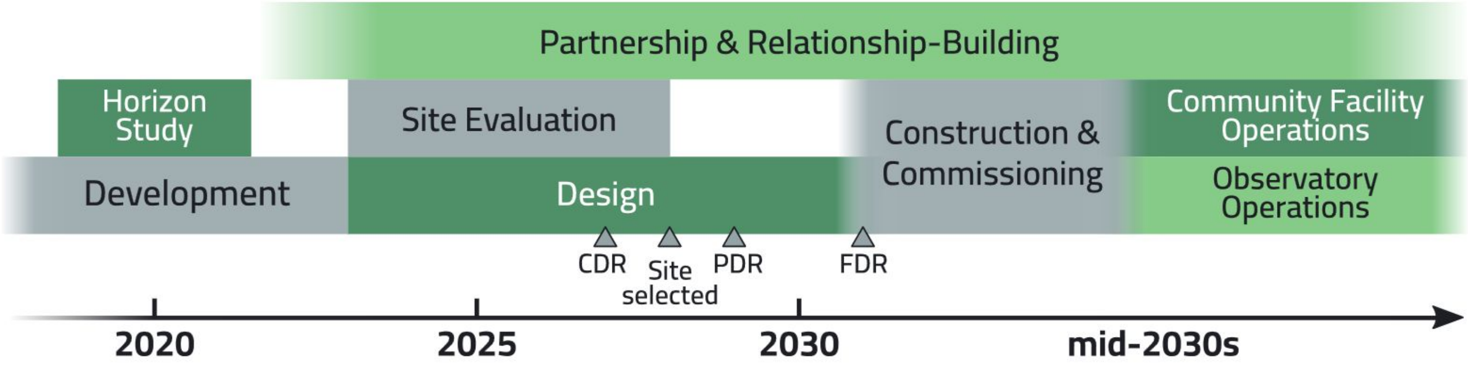
Cosmic Explorer Timeline



A Submission to the NSF MPSAC ngGW Subcommittee

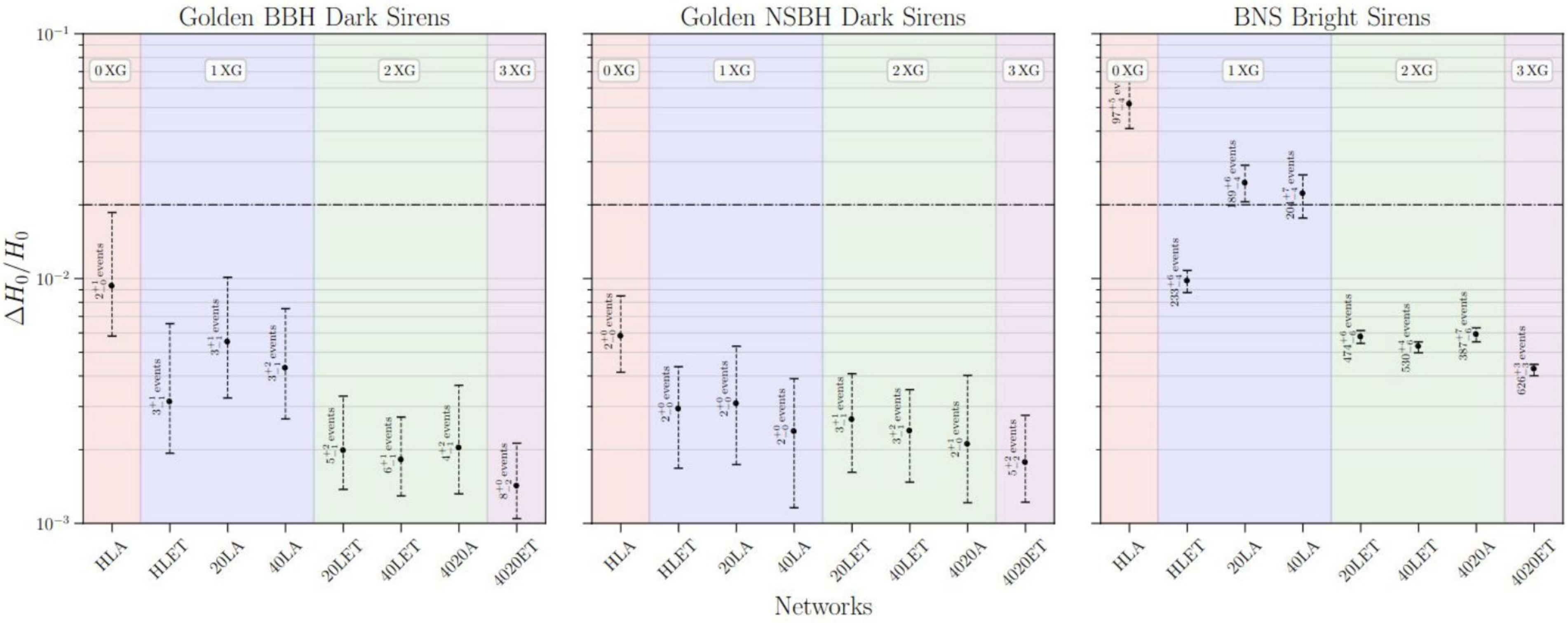
https://dcc.cosmicexplorer.org/CE-P2300018/public

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



Parting thought

Gupta *et al. arXiv:2307.10421 (2023)*



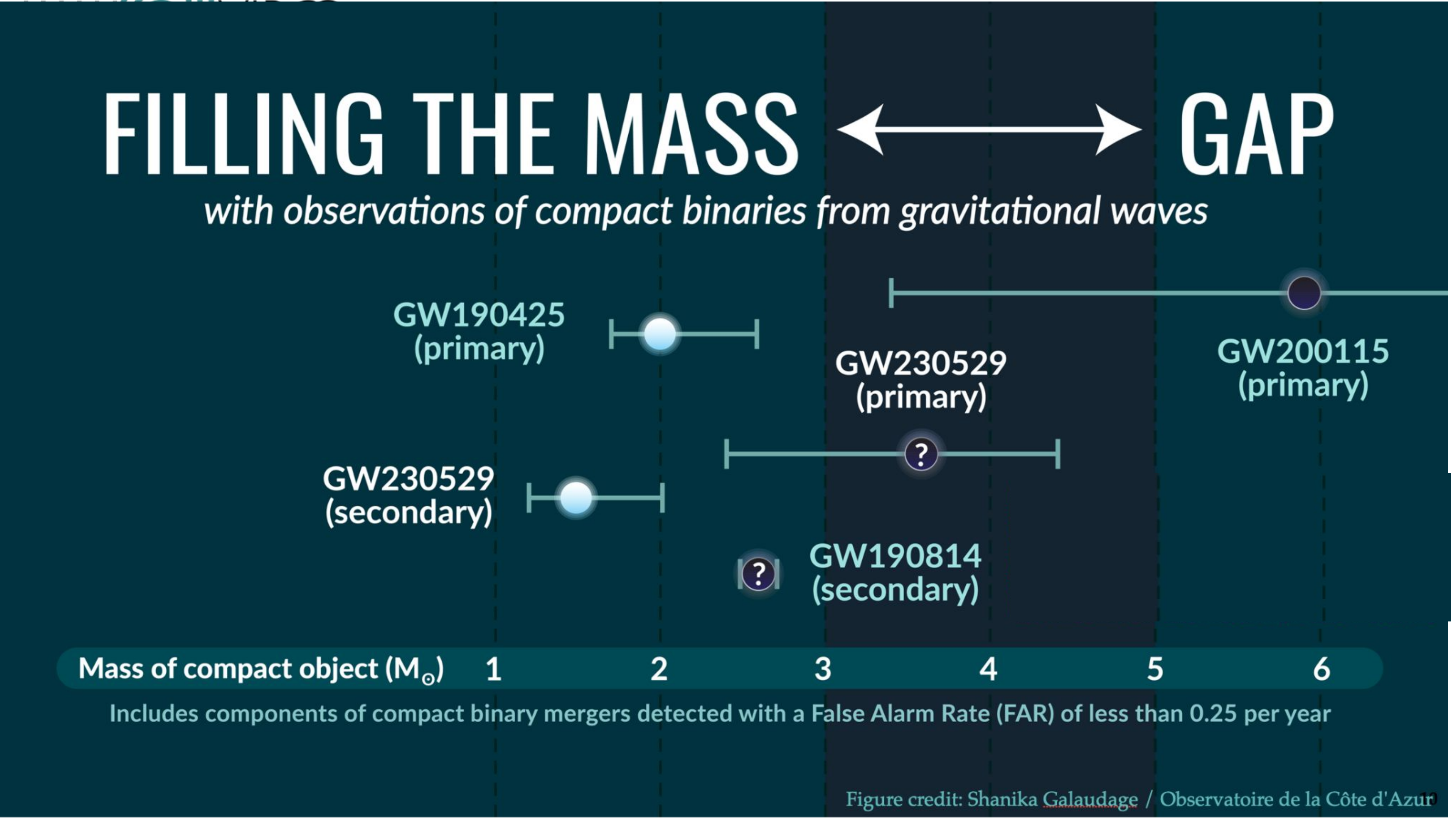
Thanks to all my collaborator especially those in the LIGO-Virgo-KAGRA Collaboration

FILLING THE MASS ⟷ GAP

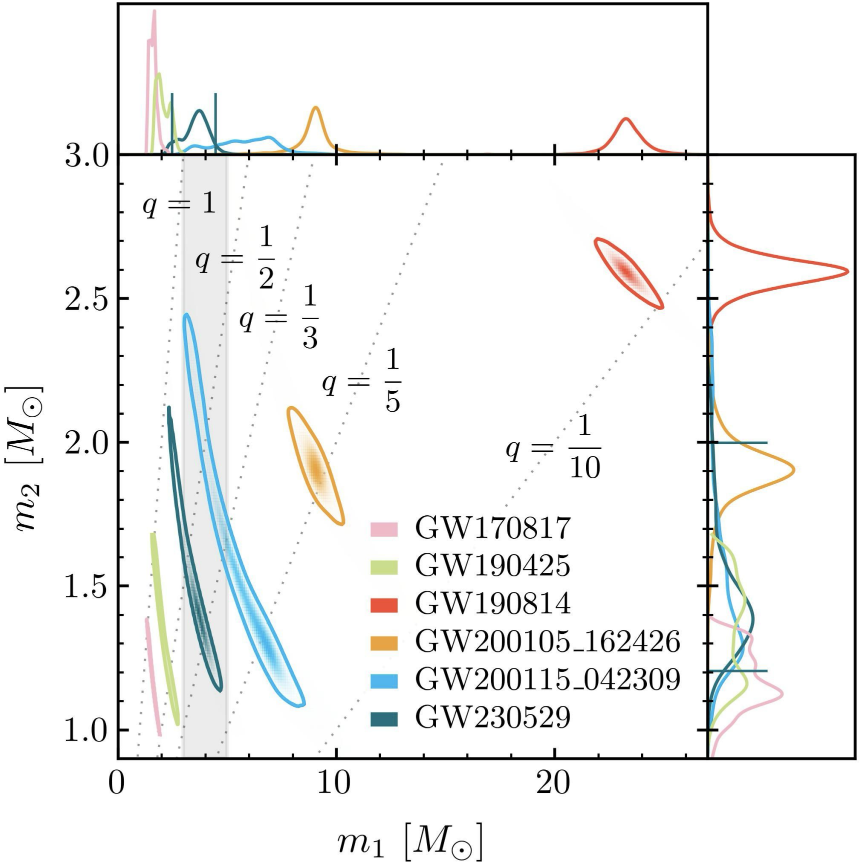
with observations of compact binaries from gravitational waves

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
GW190425 (primary)
GW230529 (primary)
GW200115 (primary)
GW230529 (secondary)
GW190814 (secondary)
Mass of compact object ($M_\odot$) 1 2 3 4 5 6
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

GW230529 - Properties

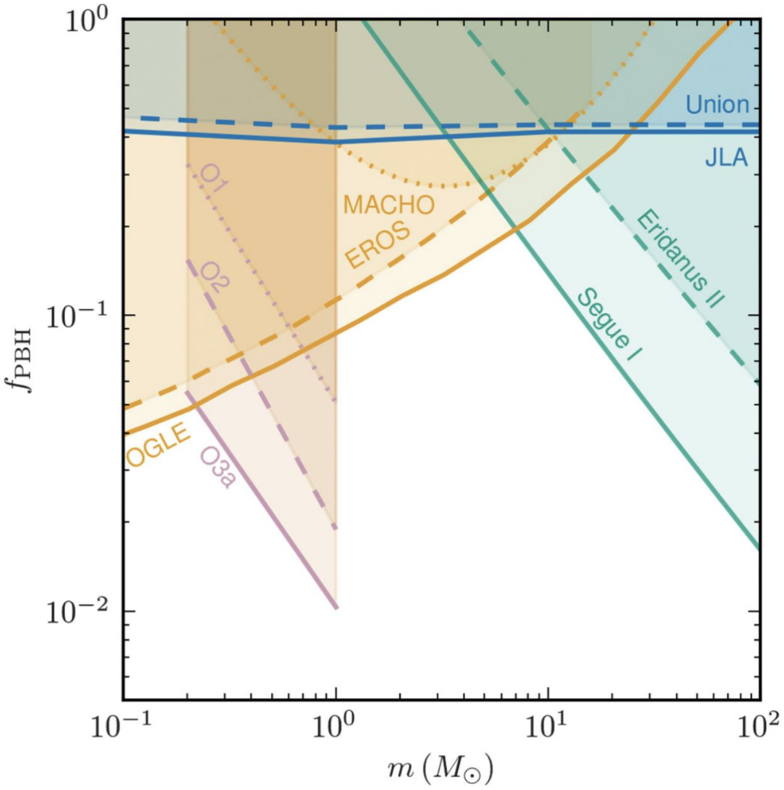


Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
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

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