



Cosmology with Gravitational-wave Observations

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Lemaitre Conference
17 June 2024

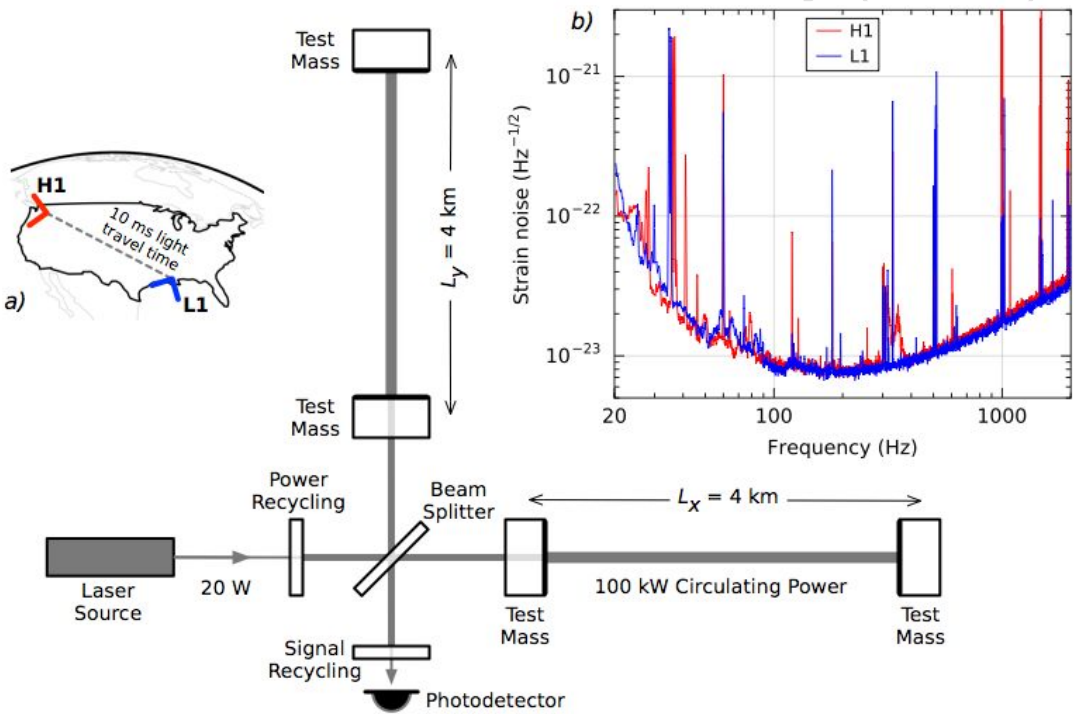
<https://dcc.ligo.org/G2401288>



International Gravitational-Wave Observatory Network (IGWN)



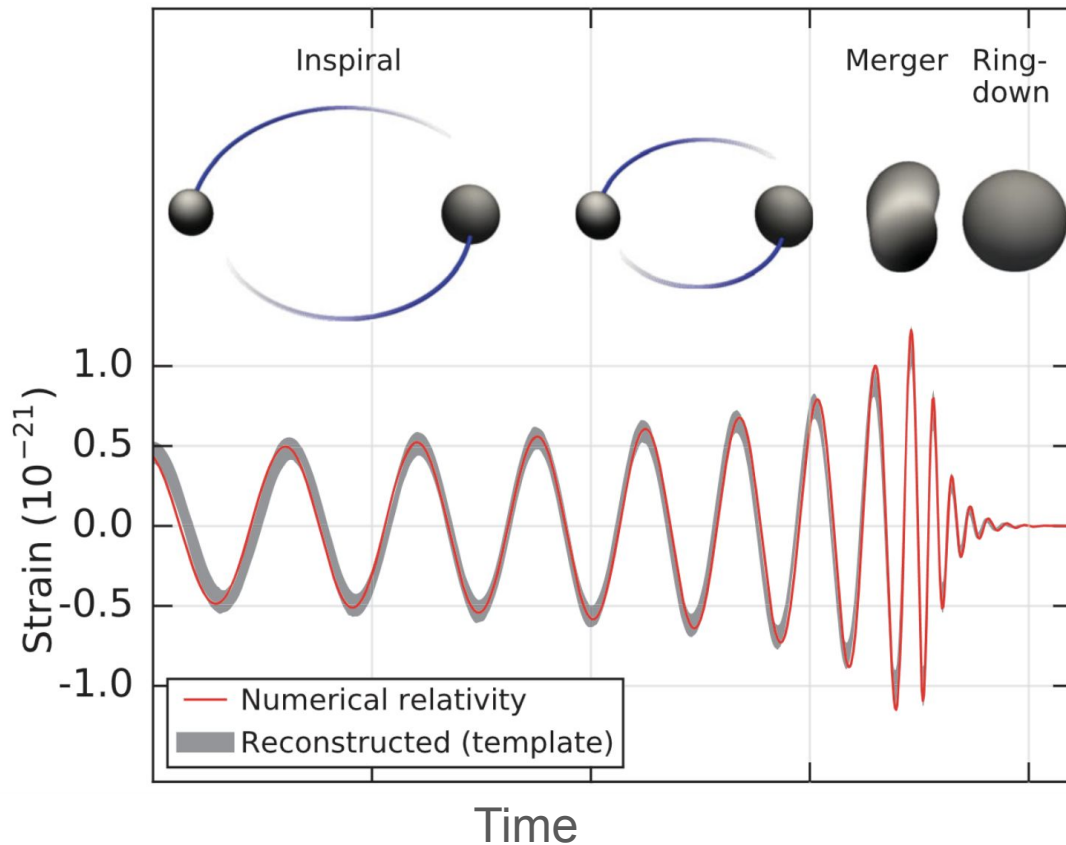
Laser Interferometer Gravitational-wave Observatory (LIGO)



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

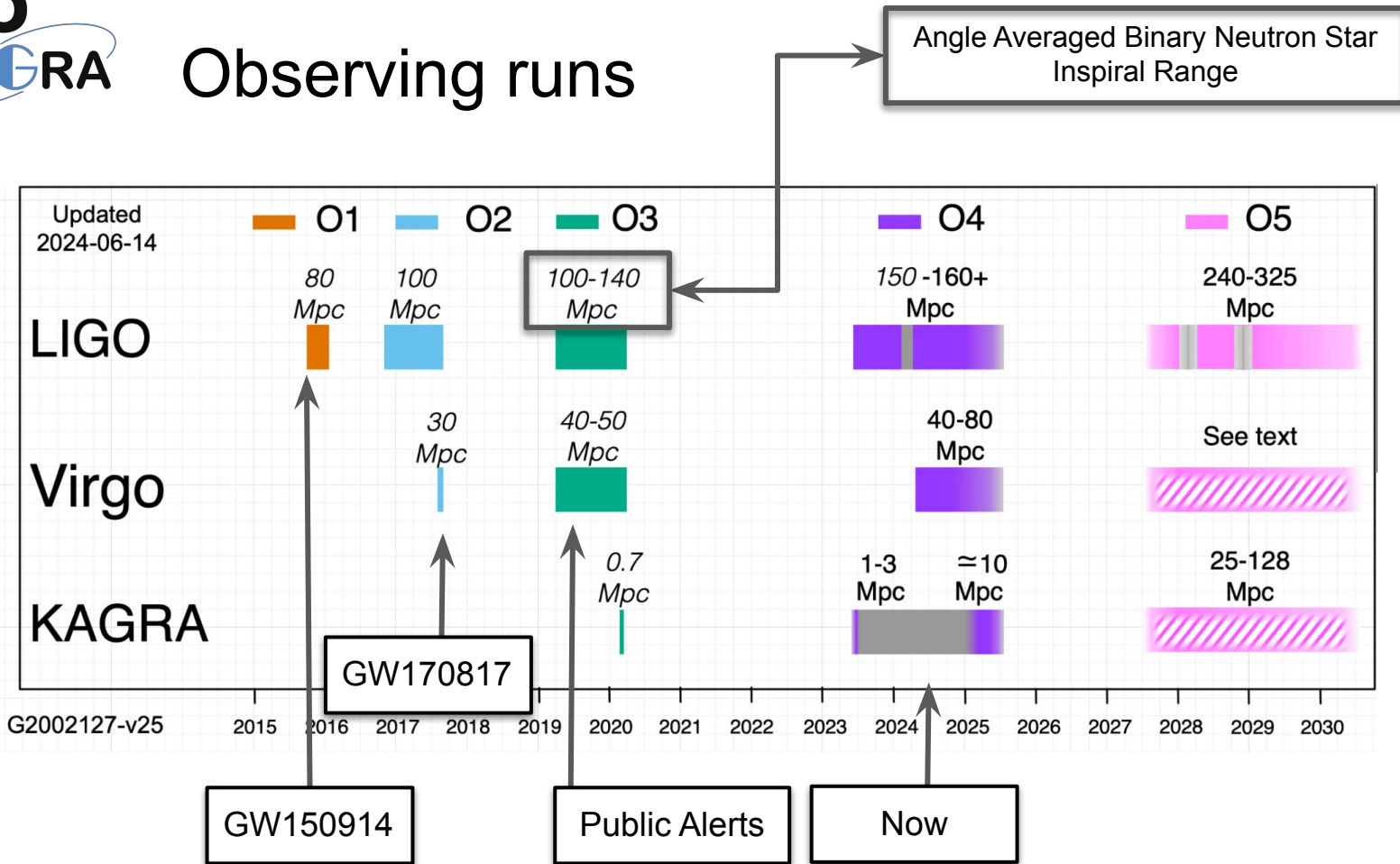
Strain (quadrupole) at the detector

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

$$\Phi = -2 \left(\frac{t_0 - t}{\mathcal{M}'} \right)^{5/8} \quad \mathcal{M}' = (1 + z) \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

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

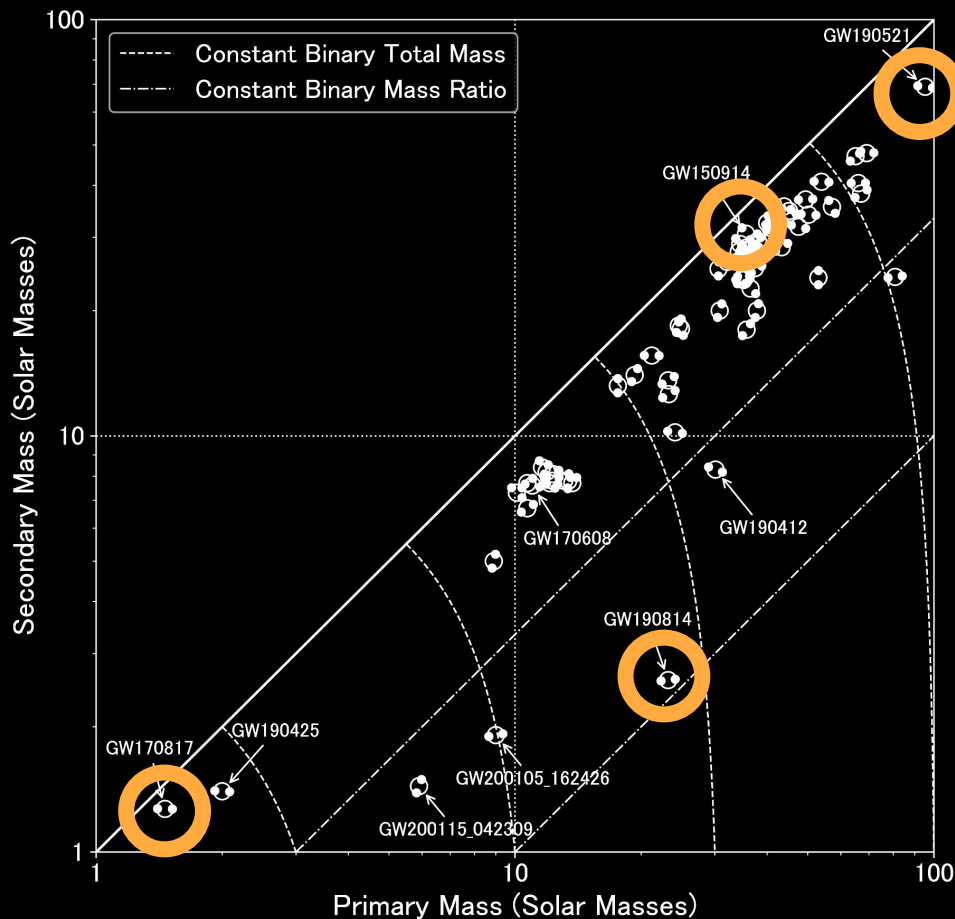
Observing runs



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

Detections

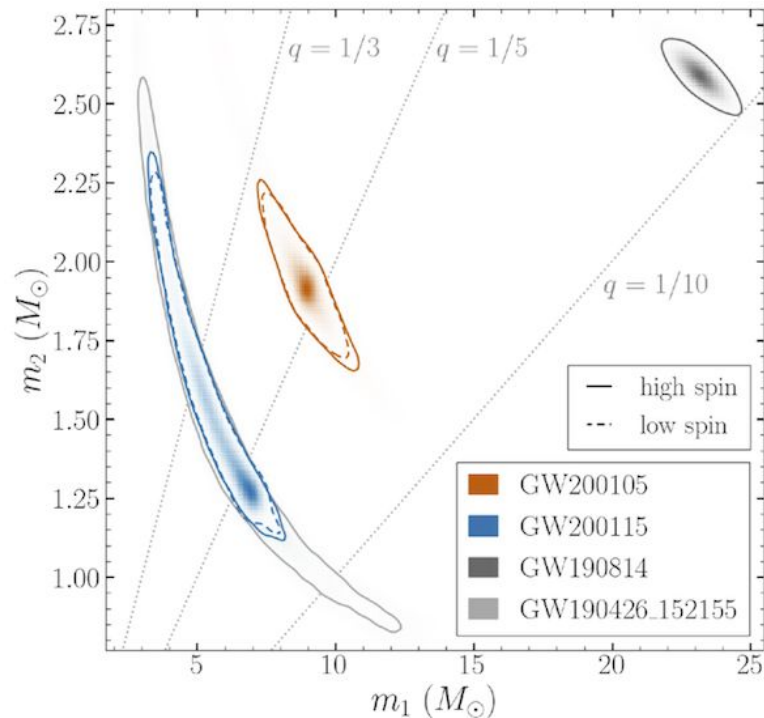
- GW150914
 - First astrophysical source
 - Binary black holes exist
- GW170817
 - Binary neutron star mergers are gamma-ray burst progenitors
- GW190521
 - Black holes exist in pair instability mass gap
- GW190814
 - Compact objects exist with masses between 2-5 Msun



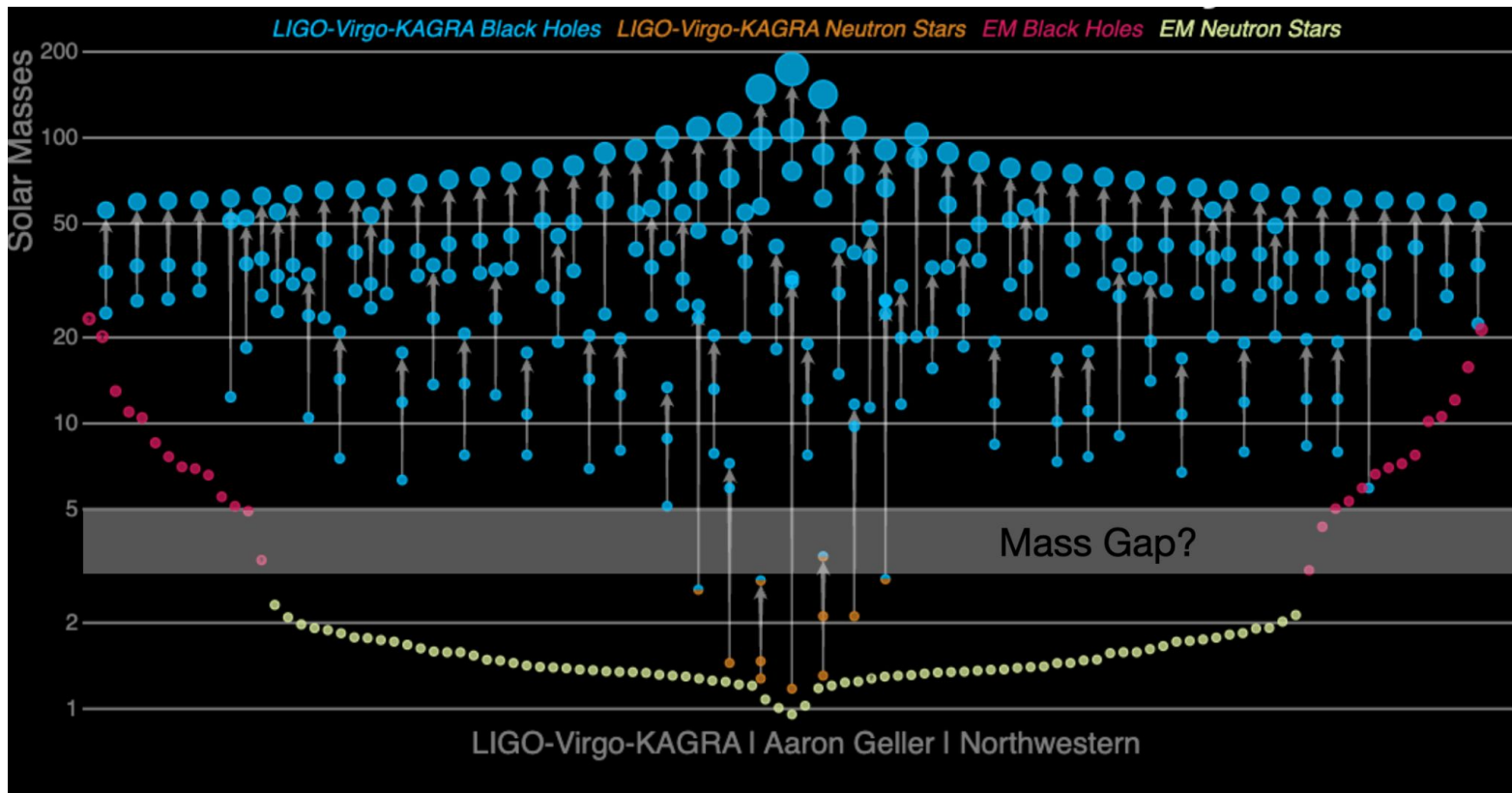
Mergers involving neutron stars

- 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



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

GraceDB Public Alerts ▾ Latest Search Documentation Login

Please log in to view full database contents.




O4 Significant Detection Candidates: **81** (92 Total - 11 Retracted)

O4 Low Significance Detection Candidates: **1610** (Total)

[Show All Public Events](#)

Page 1 of 7, [next](#) [last](#) ▸

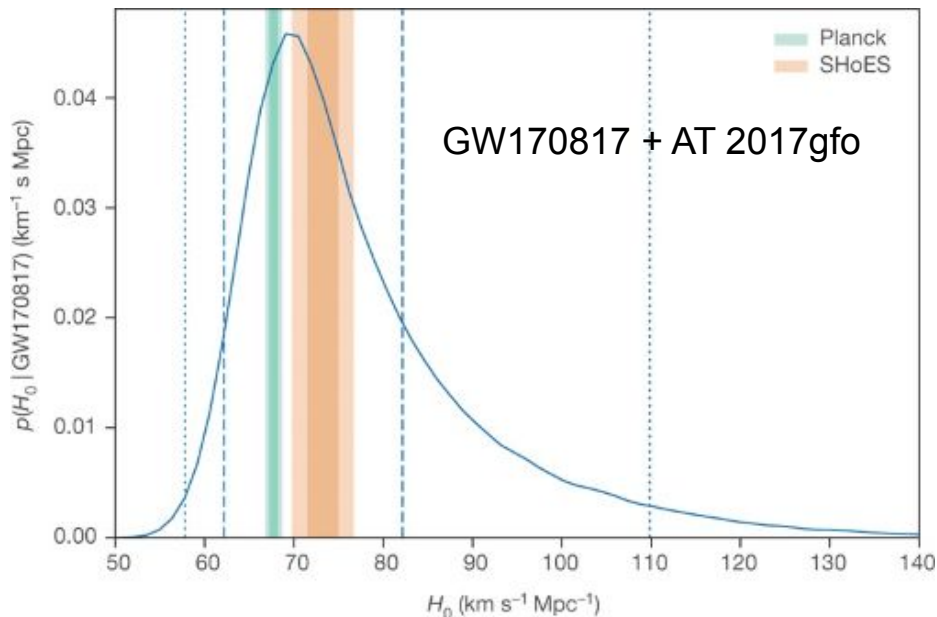
SORT: EVENT ID (A-Z) ▾

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240109a	BBH (99%)	Yes	Jan. 9, 2024 05:04:31 UTC	GCN Circular Query Notices VOE		1 per 4.3136 years	
S240107b	BBH (97%), Terrestrial (3%)	Yes	Jan. 7, 2024 01:32:15 UTC	GCN Circular Query Notices VOE		1.8411 per year	
S240104bl	BBH (>99%)	Yes	Jan. 4, 2024 16:49:32 UTC	GCN Circular Query Notices VOE		1 per 8.9137e+08 years	

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]

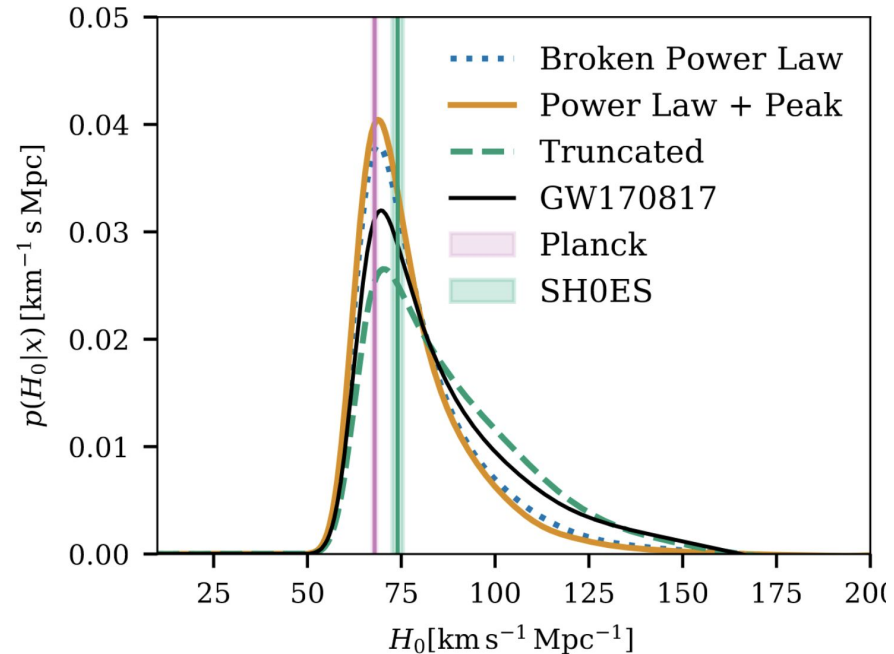
B P Abbott *et al.* *Nature* **551**, 85–88 (2017) doi:10.1038/nature24471



Challenges for cosmology with GW

- **Bright sirens:** Binaries with detectable EM counterparts are rare
 - With $\sim 0-3$ 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 $\sim 3\%$ 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.

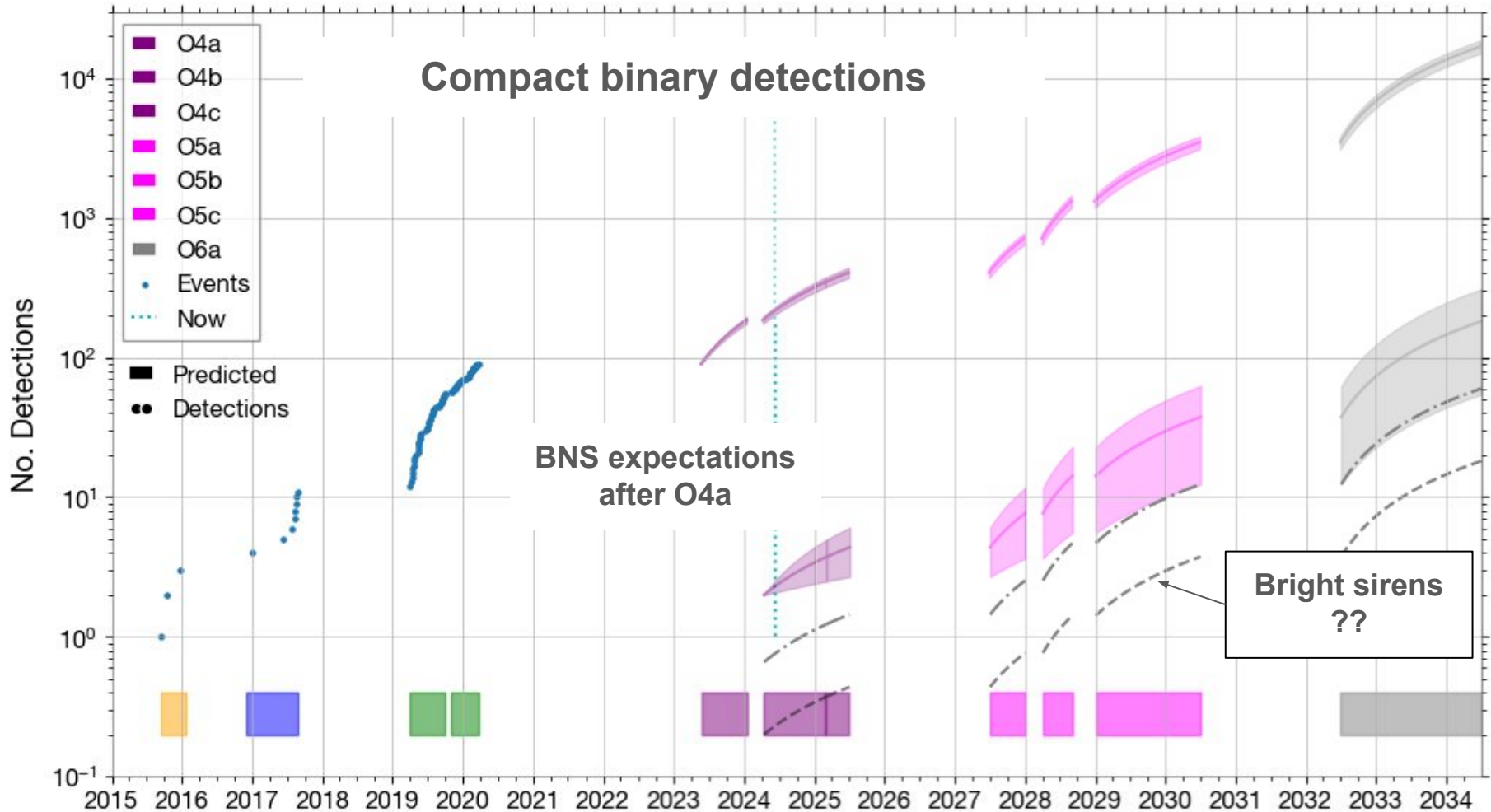
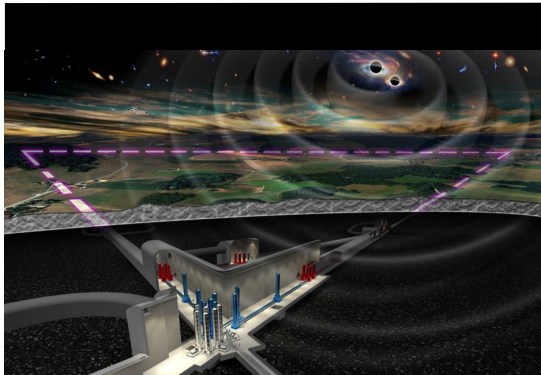
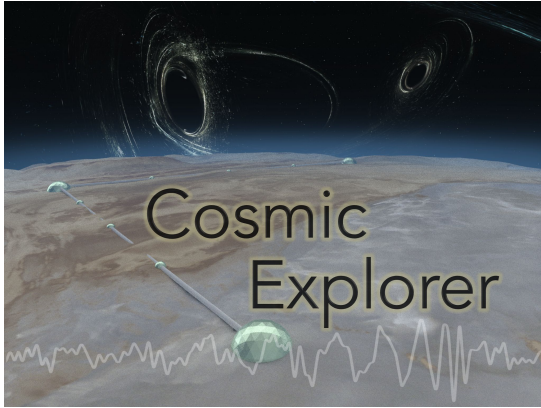


Figure: Amanda Baylor, Cody Messick, PRB

Next Generation Detectors

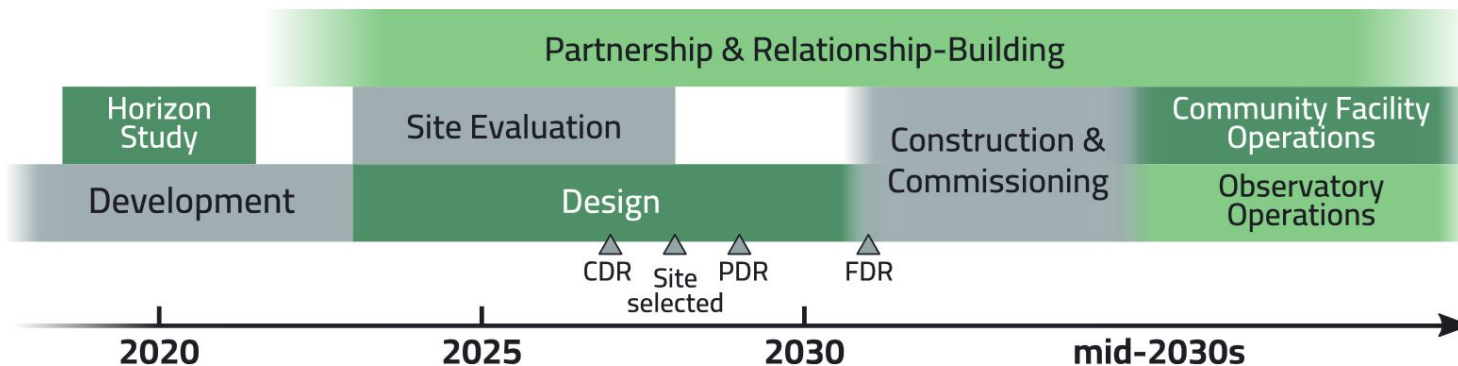
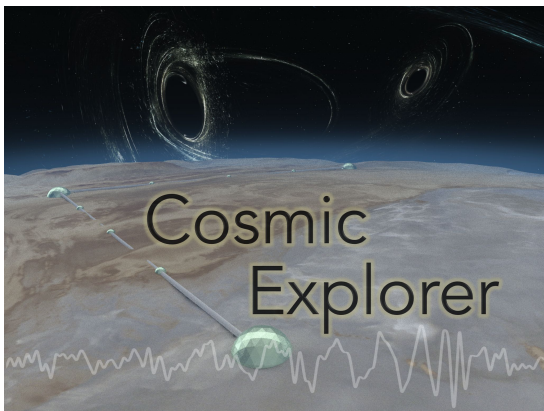


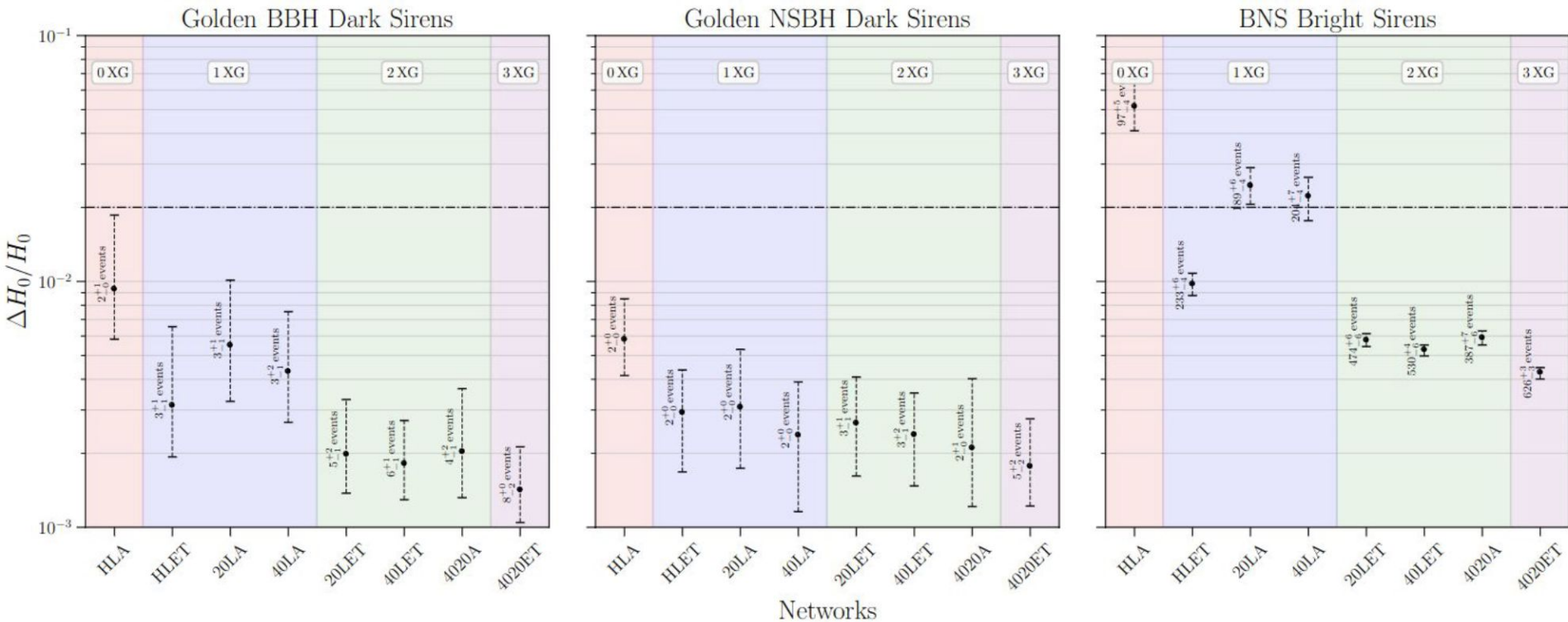
Science		No CE	CE with 2G					CE with ET					CE, ET, CE South				
Theme	Goals	2G	20	40	20+20	20+40	40+40	20	40	20+20	20+40	40+40	20	40	20+20	20+40	40+40
Black holes and neutron stars throughout cosmic time	Black holes from the first stars	Grey	Grey	Yellow	Green	Green	Green	Green	Green	Green	Green	Green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

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



Cosmic Explorer Timeline







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

GW190425
(primary)



GW190814
(secondary)

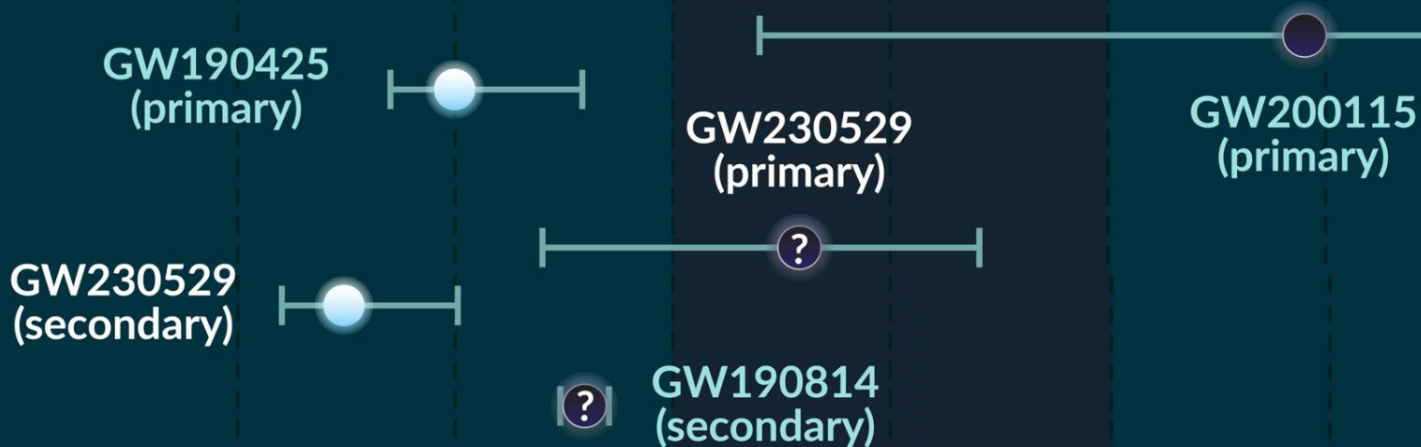
GW200115
(primary)

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

FILLING THE MASS GAP

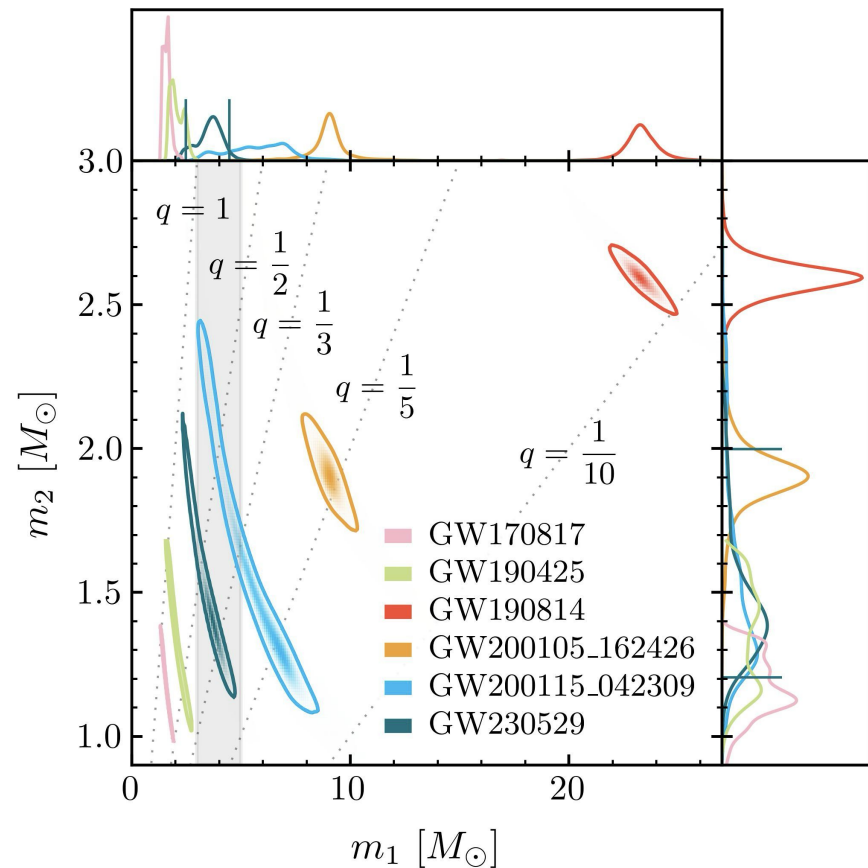
with observations of compact binaries from gravitational waves



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

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 χ_{eff}	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter χ_p	$0.40^{+0.39}_{-0.30}$
Luminosity distance D_L/Mpc	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$

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.

