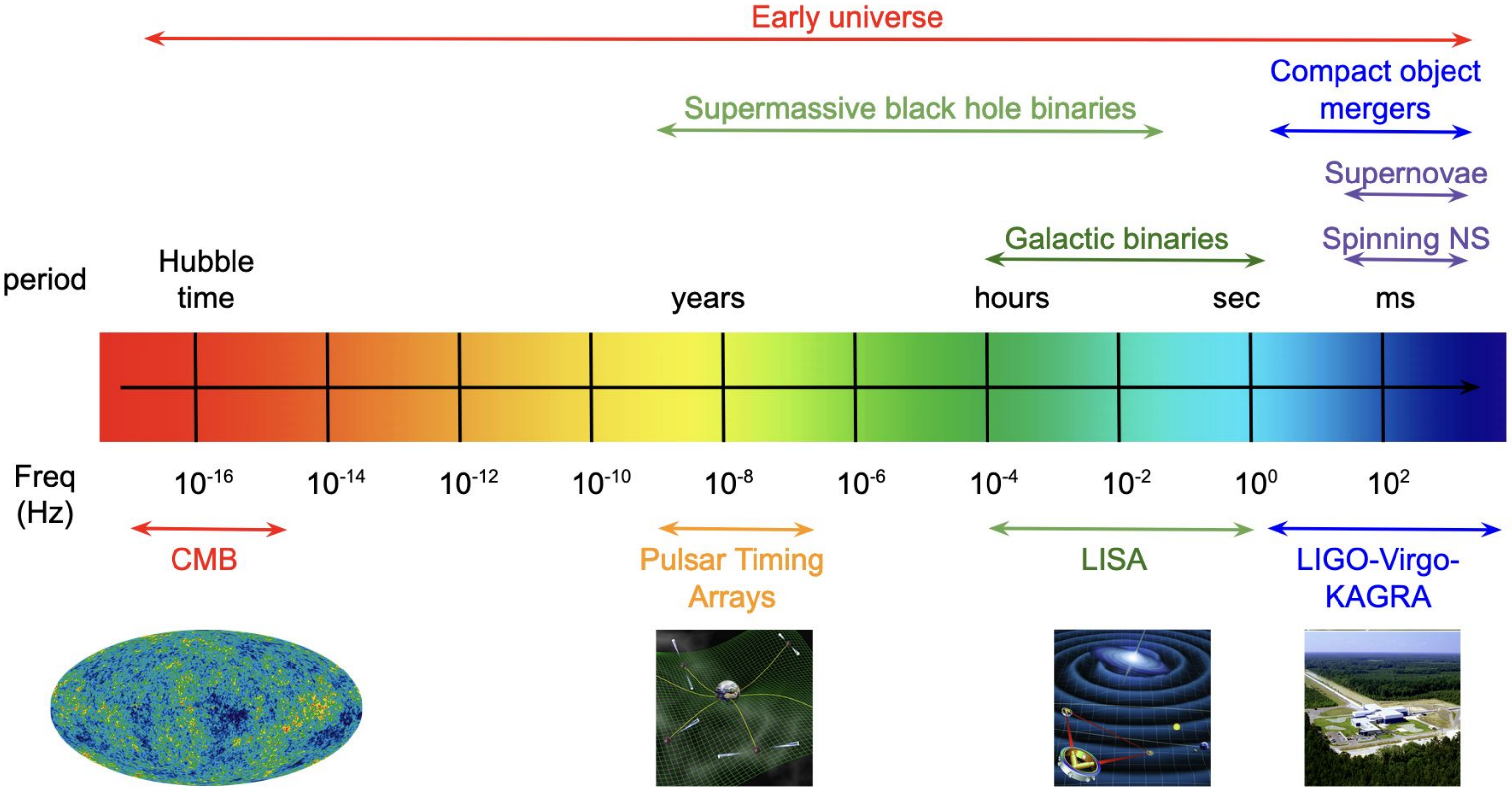
Gravitational-wave astronomy with LIGO-Virgo-KAGRA

Patrick Brady,
University of Wisconsin-Milwaukee

QMUL GWI Inaugural Meeting
18 April 2024

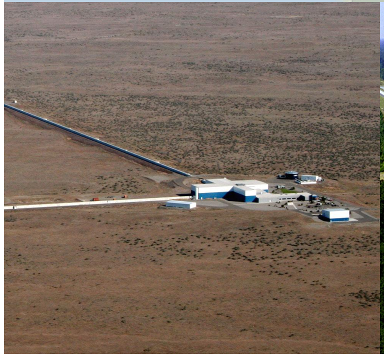
https://dcc.ligo.org/G2400954

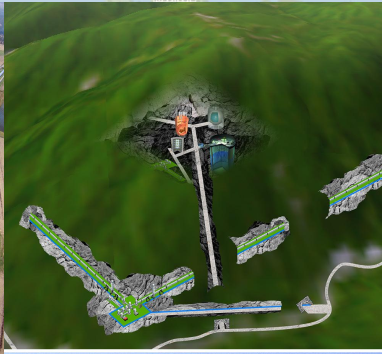
Gravitational-wave spectrum



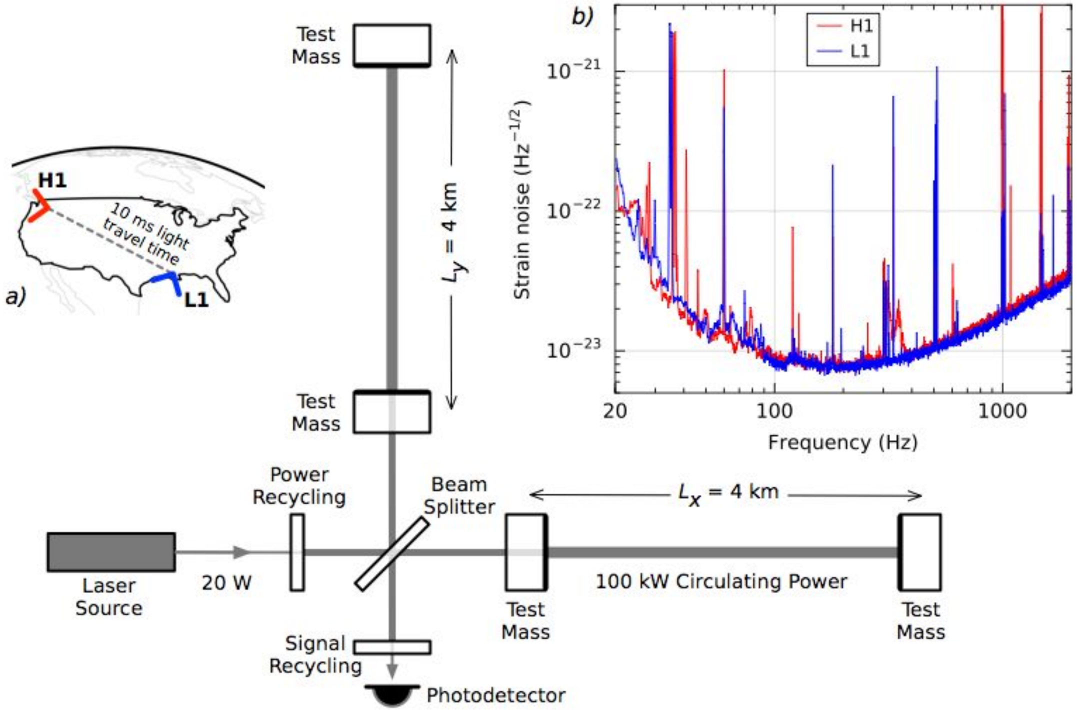
Adapted from: Romano, J.D., Cornish, N.J.
Living Rev Relativ 20, 2 (2017).
https://doi.org/10.1007/s41114-017-0004-1

International Gravitational-Wave Observatory Network (IGWN)





Laser Interferometer Gravitational-wave Observatory (LIGO)

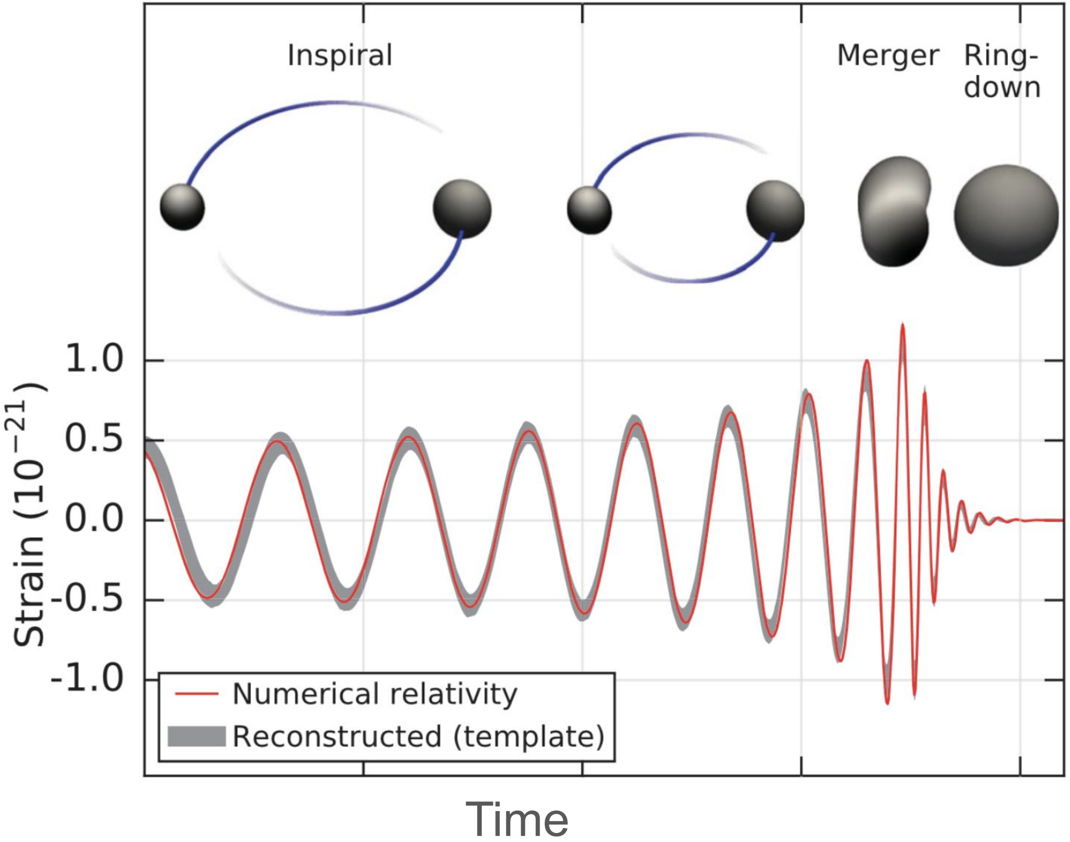


First proposed by Ron Drever, Kip Thorne, and Rai Weiss in 80's.
First funding in 1992; civil construction ended 2000; Initial LIGO 2002-2010

Compact object mergers

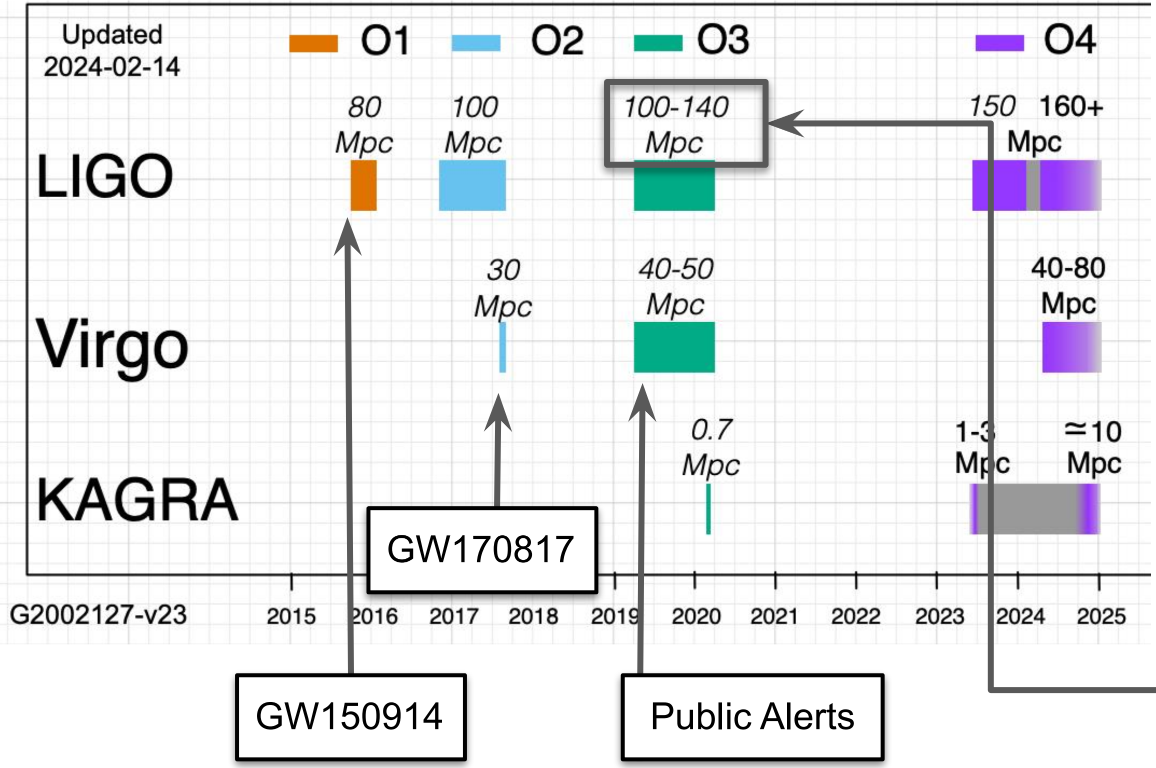
Pairs of stellar-mass black holes, neutron stars, or a stellar-mass black hole and neutron star

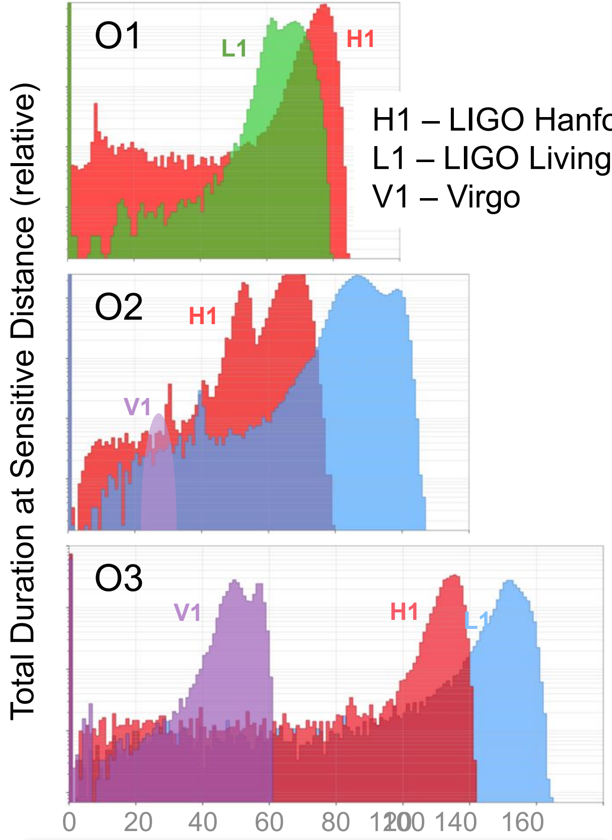
$$h_{ij} \sim \frac{4GM}{c^4}\frac{v^2}{r}$$



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

Observing runs



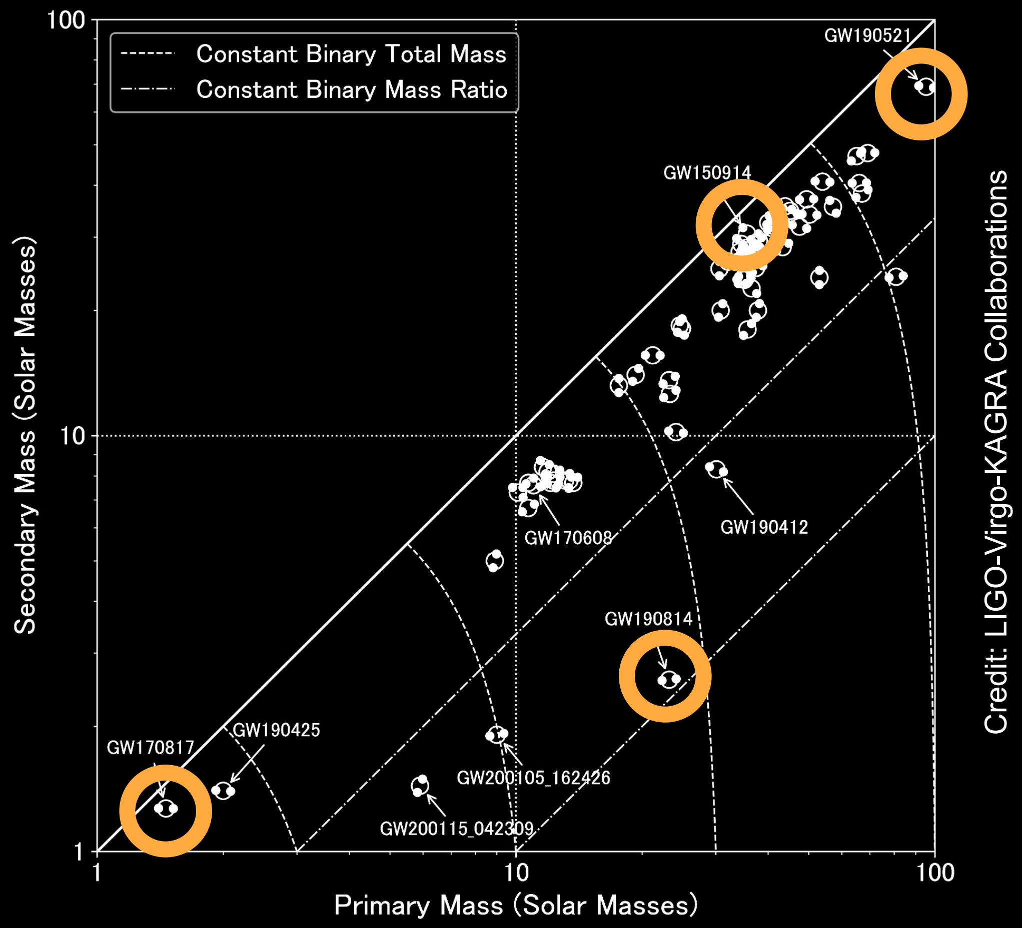


H1 – LIGO Hanford
L1 – LIGO Livingston
V1 – Virgo

Angle Averaged Binary Neutron Star Inspiral Range

Detections

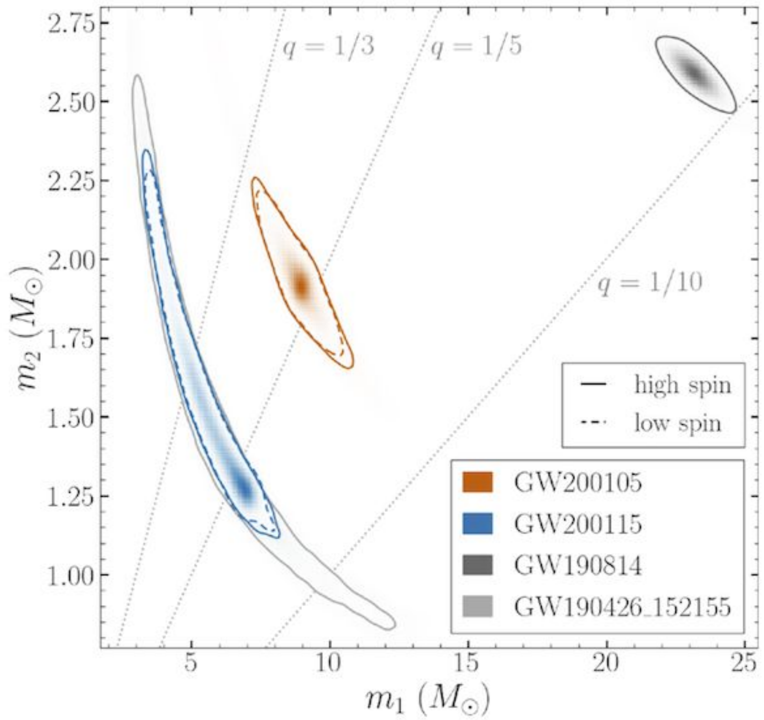
- GW150914
  - First astrophysical source
  - Binary black holes exist
- GW170817
  - Binary neutron star mergers are gamma-ray burst progenitors
- GW190521
  - Black holes exist in pair instability mass gap
- GW190814
  - Compact objects exist with masses between 2-5 Msun



Mergers involving neutron stars

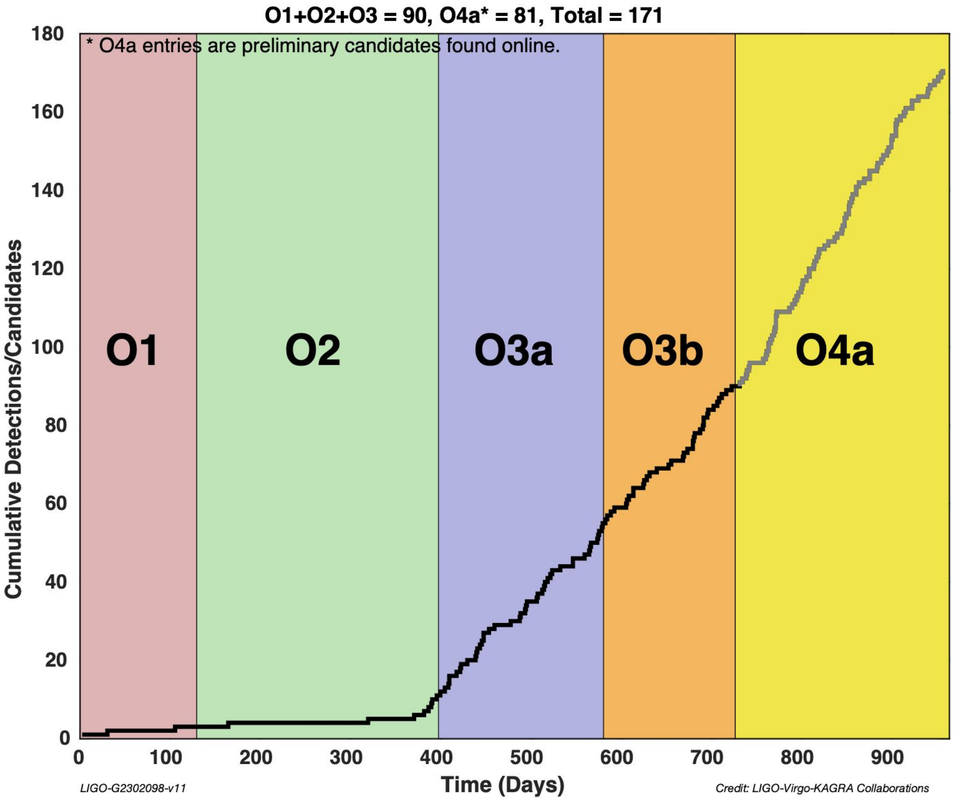
- GW170817 & GW190425
  - Binary neutron star (BNS) merger waves
- GW170817 & GRB 170817A
  - Fractional difference in speed of gravity and the speed of light is between -3×10^{-15} and 7×10^{-16}
- GW170817 & AT 2017gfo
  - Binary neutron star mergers produce kilonova explosions that generate heavy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

B. P. Abbott et al 2017 ApJL 848 L13

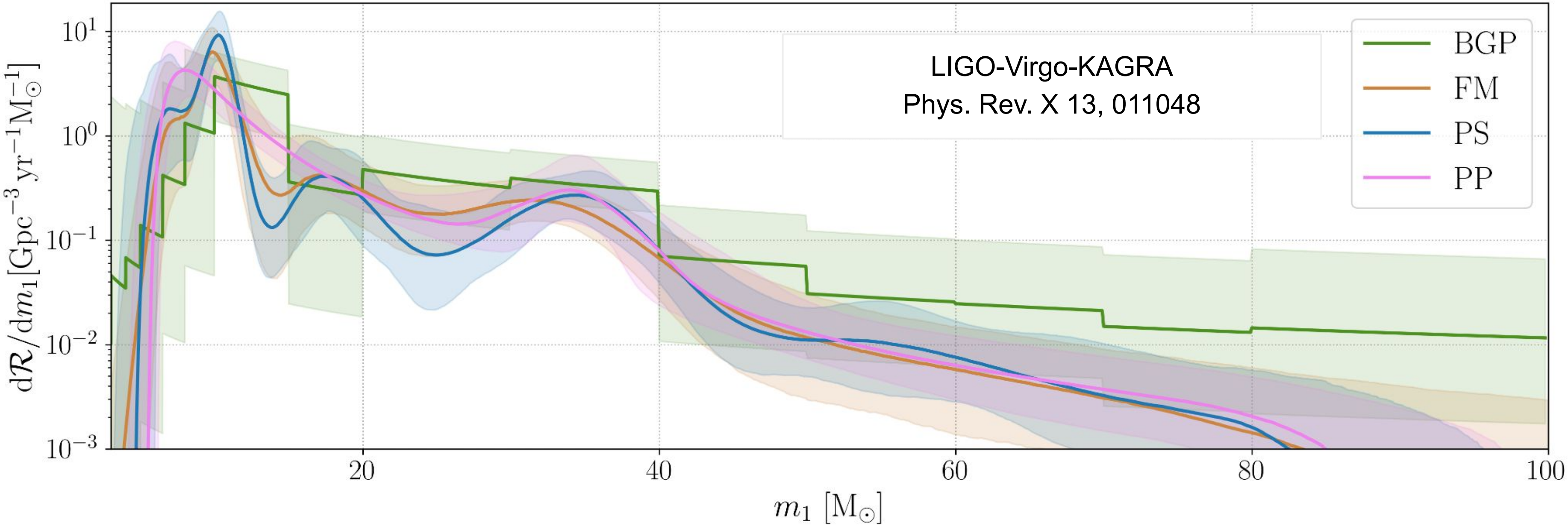


R. Abbott *et al* 2021 *ApJL* **915** L5

Detections versus time observing



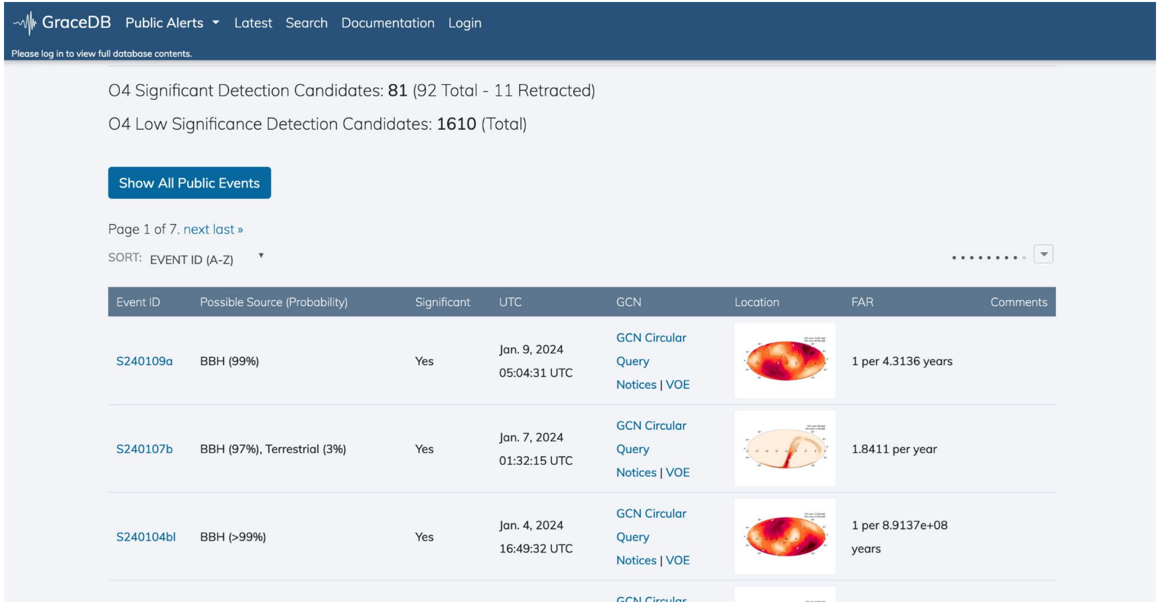
From one to many: measuring populations



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)

- O4 started 24 May 2023: 20 months with up to 2 months commissioning
    - Virgo delayed due to damage to optics; KAGRA renewed commissioning after 1 month.
- Binary detection rates
    - O3 ~ 1 / 5 days
    - O4 ~ 1 / (2.8 days)
- Improved public alerts
    - Localization
    - Classification
    - Latency
    - Early-warning alerts
    - Low-significance alerts
- Improved sensitivity
    - > 150Mpc BNS range


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)

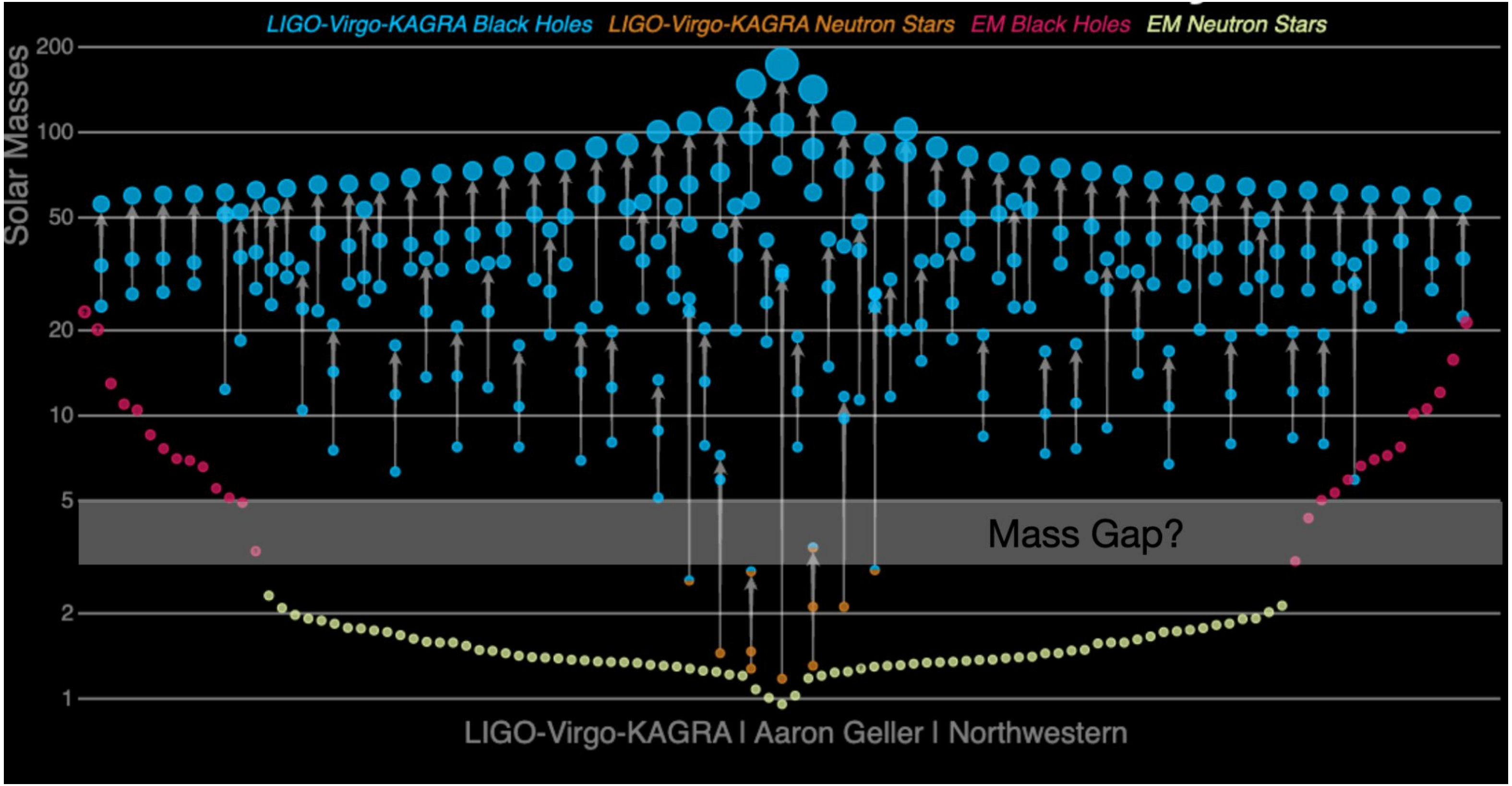
Show All Public Events

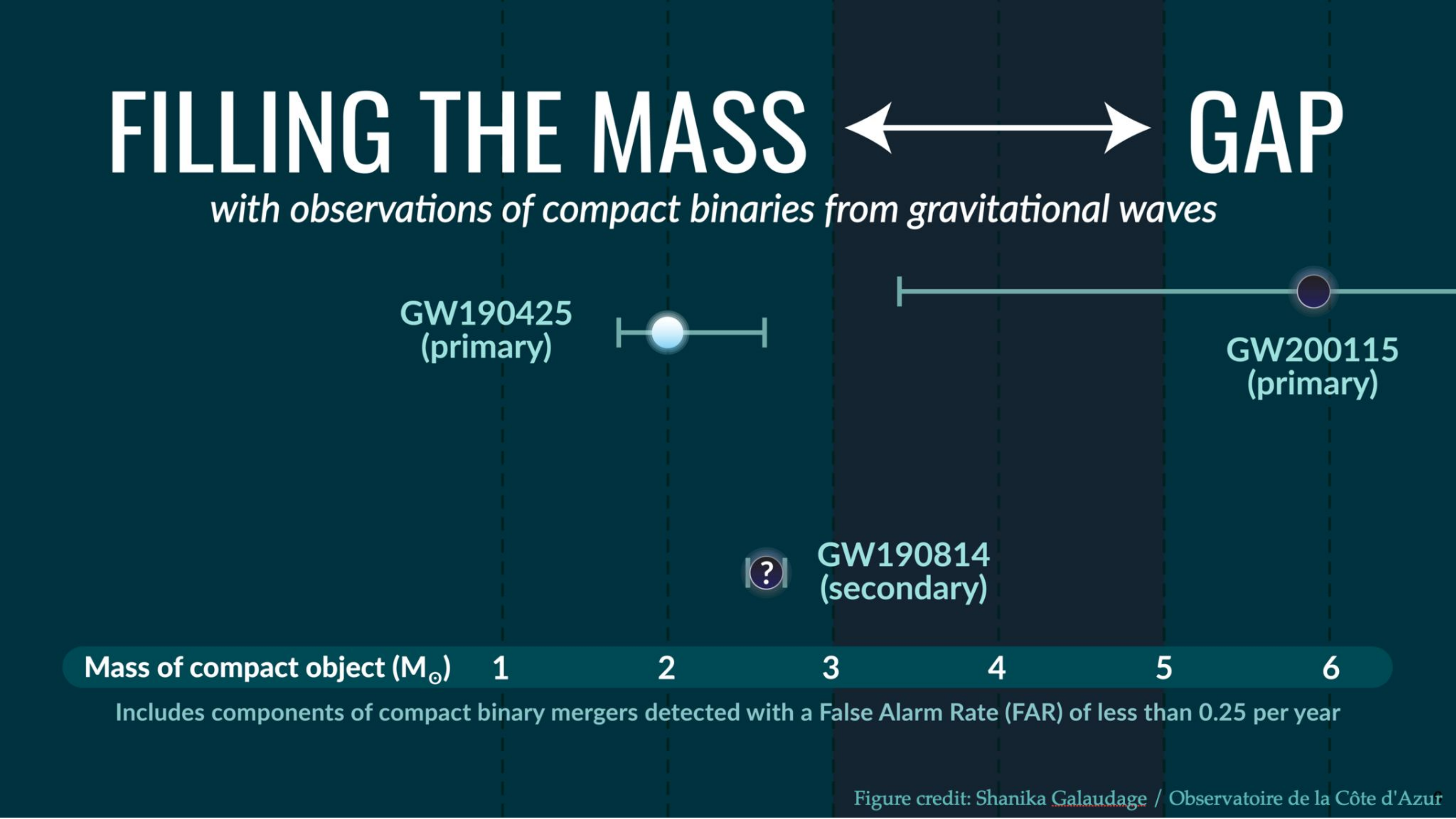
Page 1 of 7. next last »

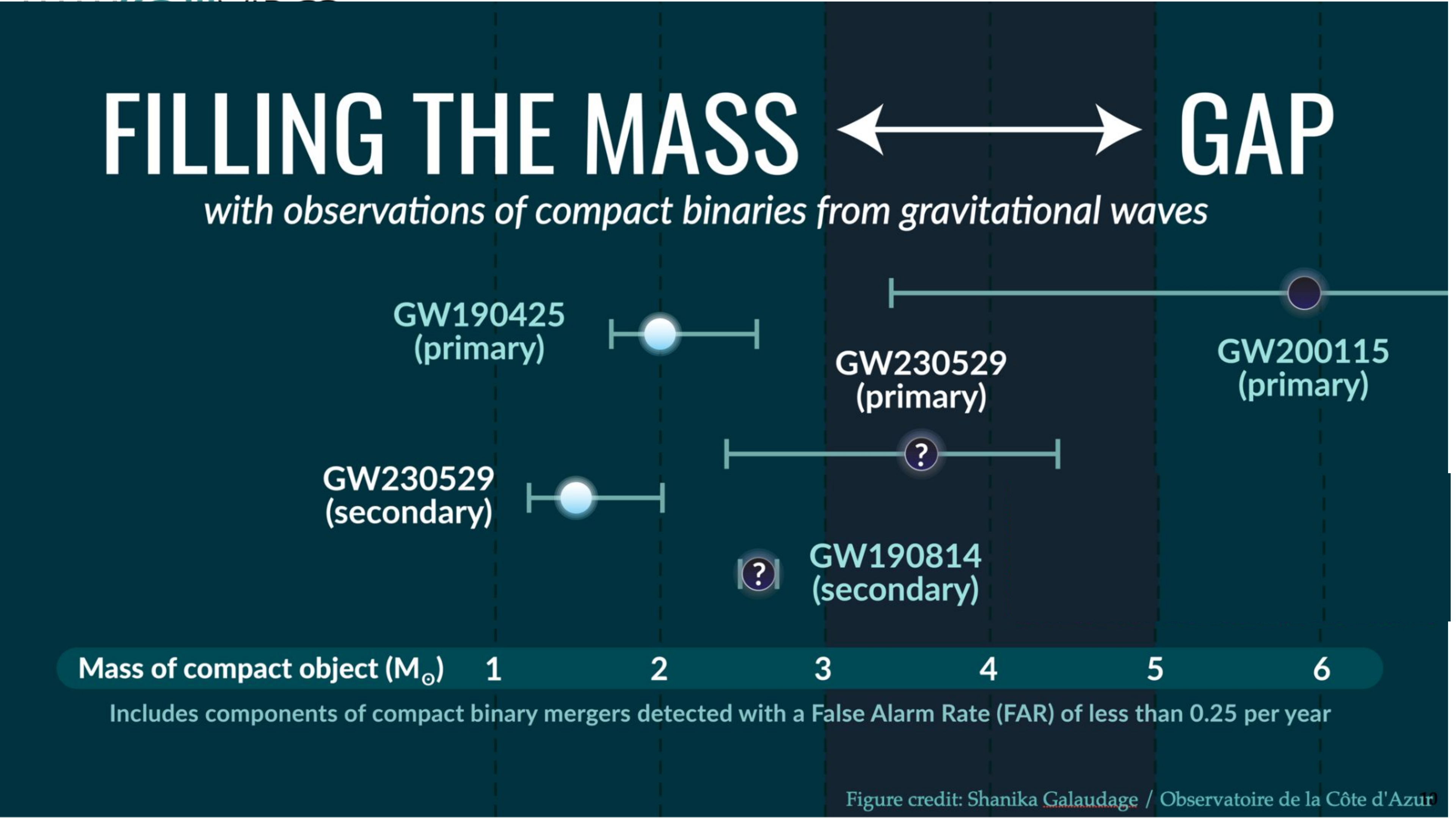
SORT: EVENT ID (A-Z)

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	

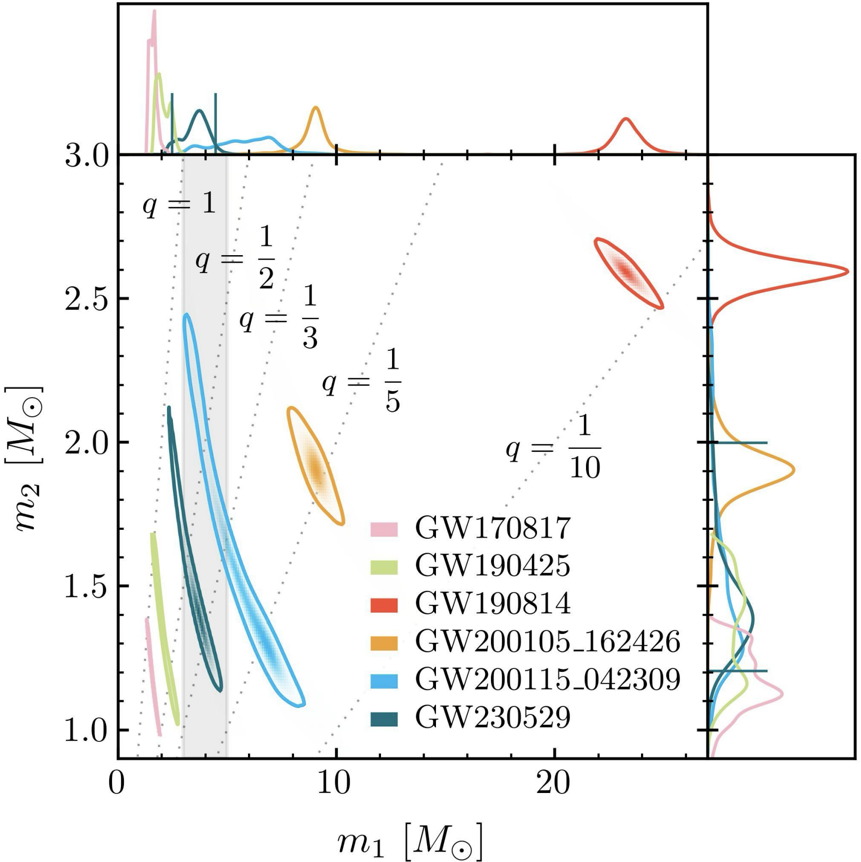
Masses in the stellar graveyard




FILLING THE MASS GAP
with observations of compact binaries from gravitational waves
GW190425 (primary)
GW200115 (primary)
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


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

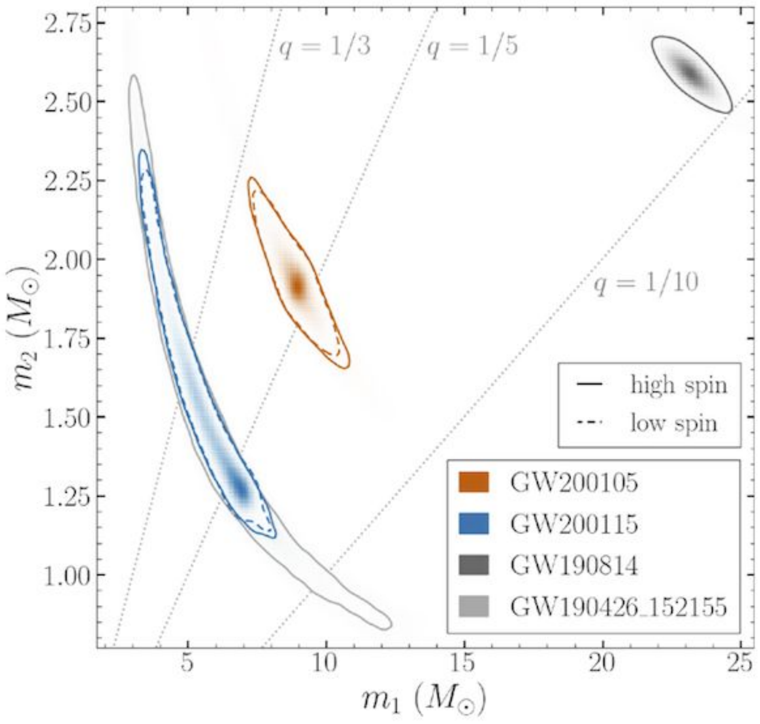


Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$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

Mergers involving neutron stars

- 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 naive O123+O4a rates based on public information, expect 0.2 - 3.5 new events in O4b.

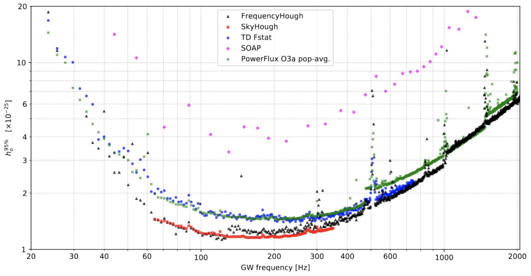


R. Abbott *et al* 2021 *ApJL* **915** L5

Many other observational results

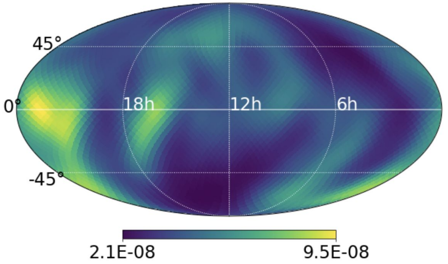
Limits on waves from pulsars

Phys. Rev. D 106, 102008 (2022)



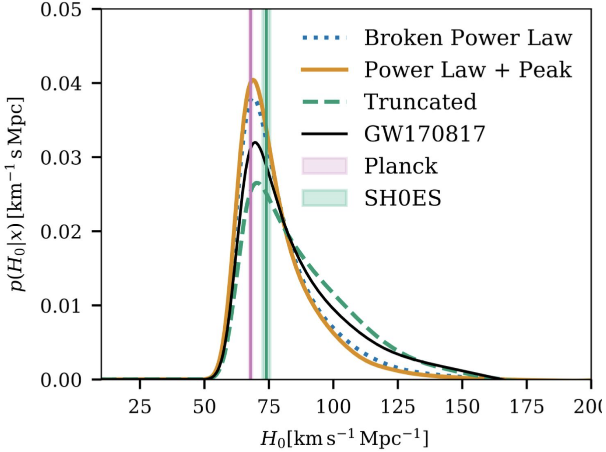
Stochastic background limits

Phys. Rev. D 105, 122002 (2022)



Hubble constant measurements

Astrophys. J. 949, 76 (2023)

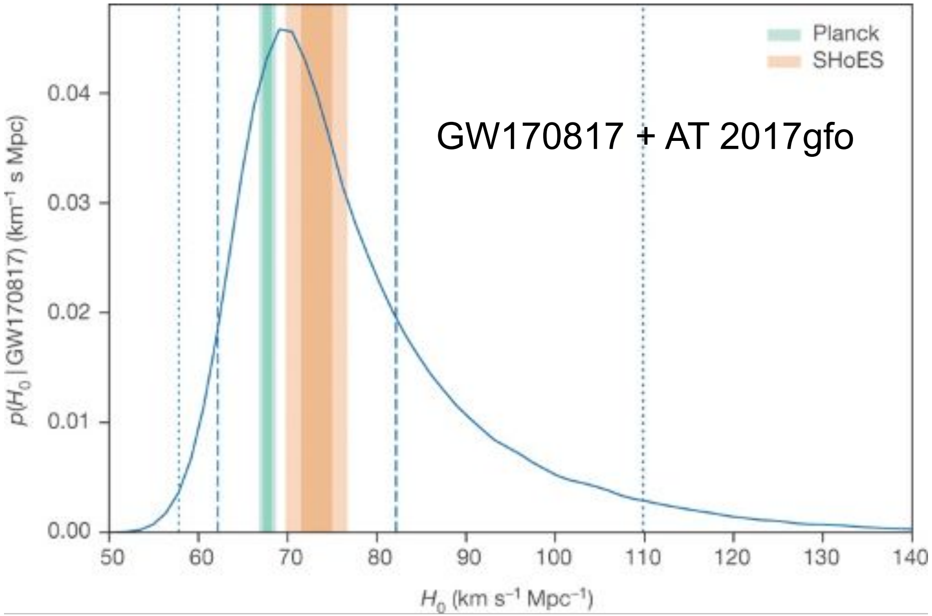


And much more!

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]

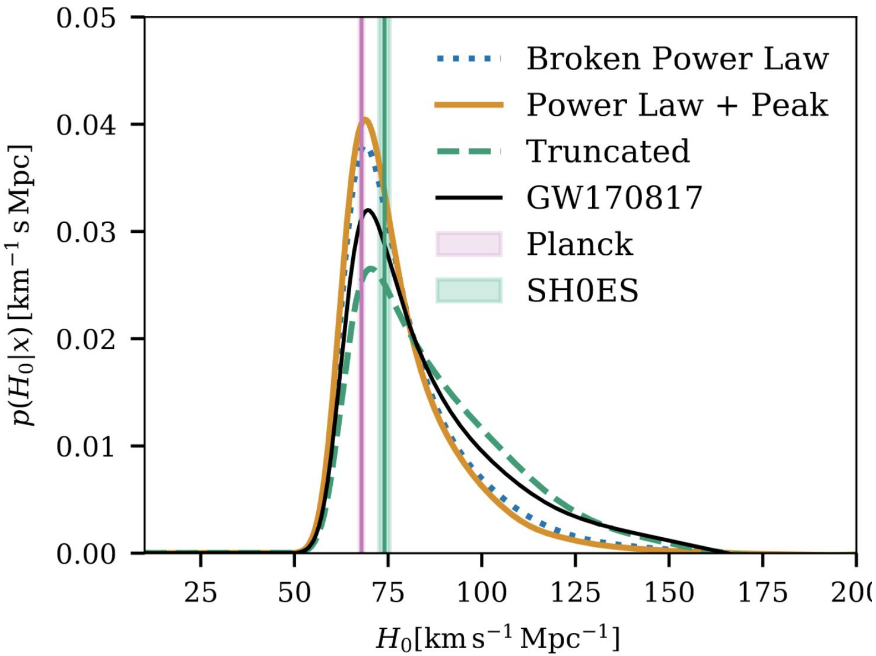
B P Abbott *et al. Nature* **551,** 85–88 (2017) doi:10.1038/nature24471



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.

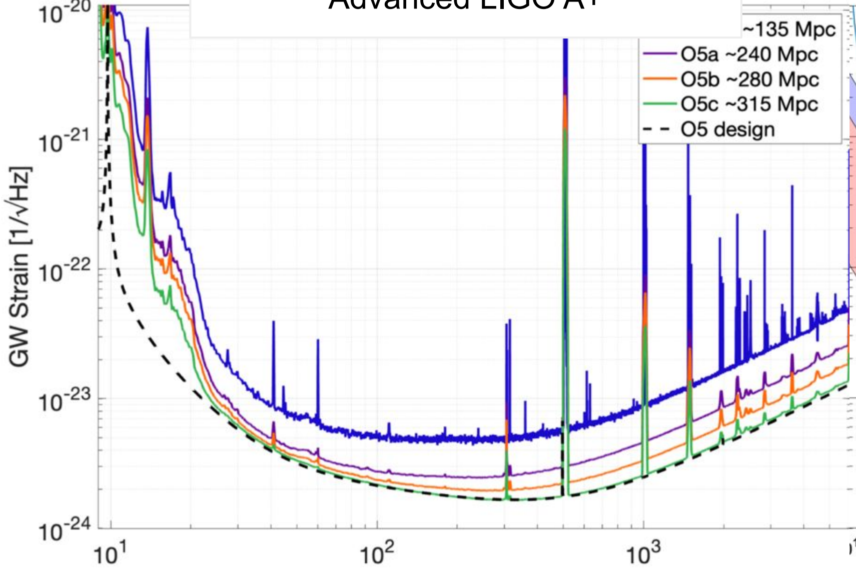
R Abbott *et al. arXiv:2111.03604 (2021)*



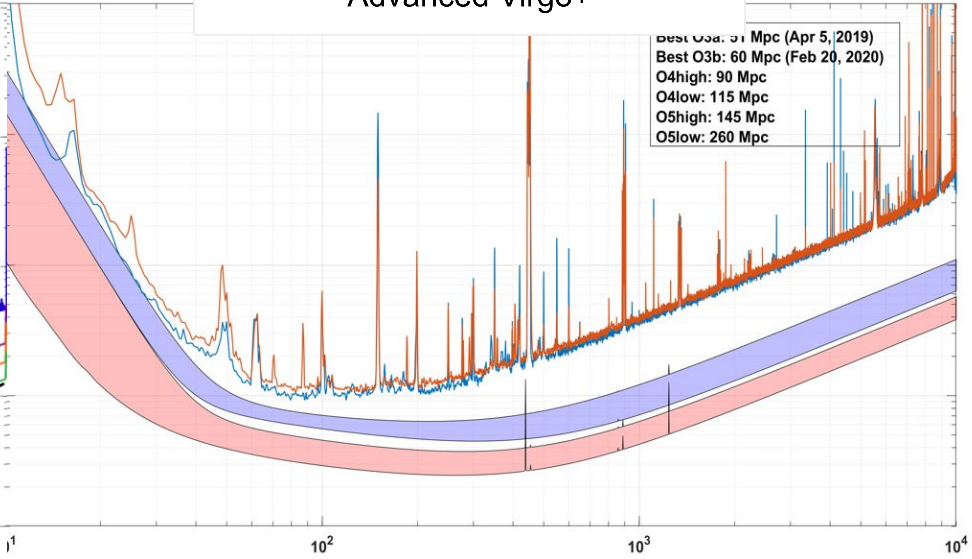
Thanks to Dave Reitze & Giovanni Losurdo

Working toward O5 sensitivity

Advanced LIGO A+



Advanced Virgo+



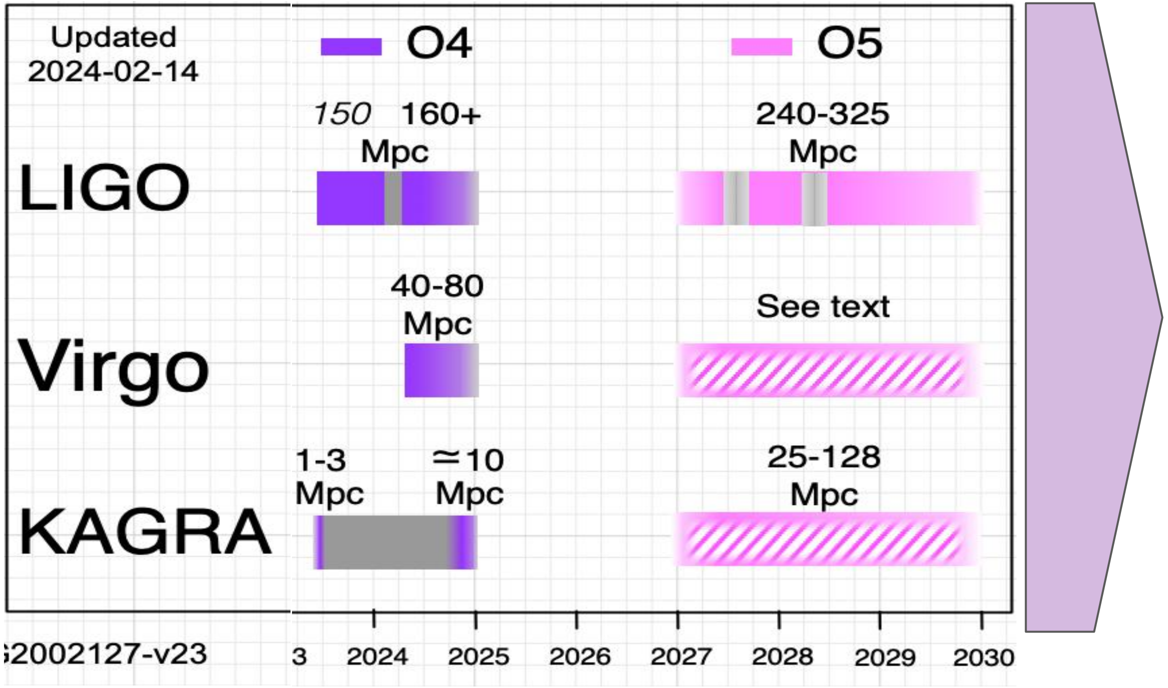
Full Power in the arm cavities: 750 kW
Frequency-dependent Squeezing* level of 6 dB
Test Masses with 2x lower coating thermal noise*

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}

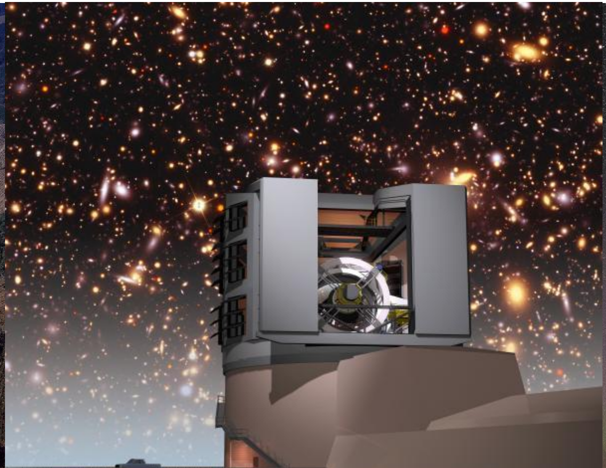
See Fritschel et al, https://dcc.ligo.org/LIGO-T2200287/public

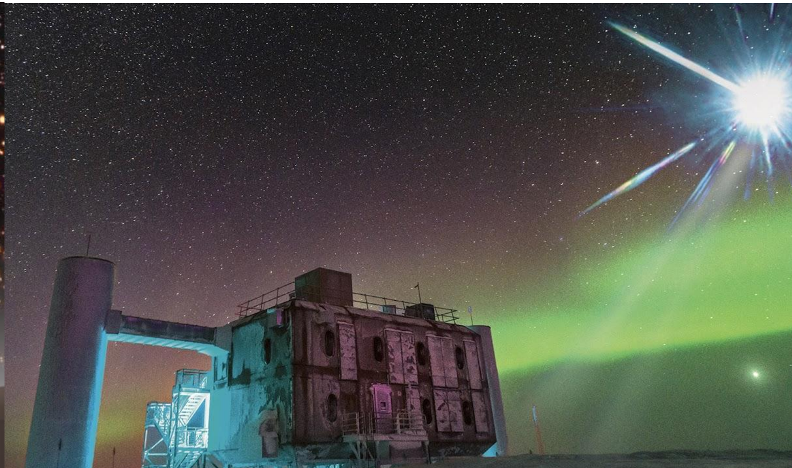
LIGO network is a cornerstone of MMA

- 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

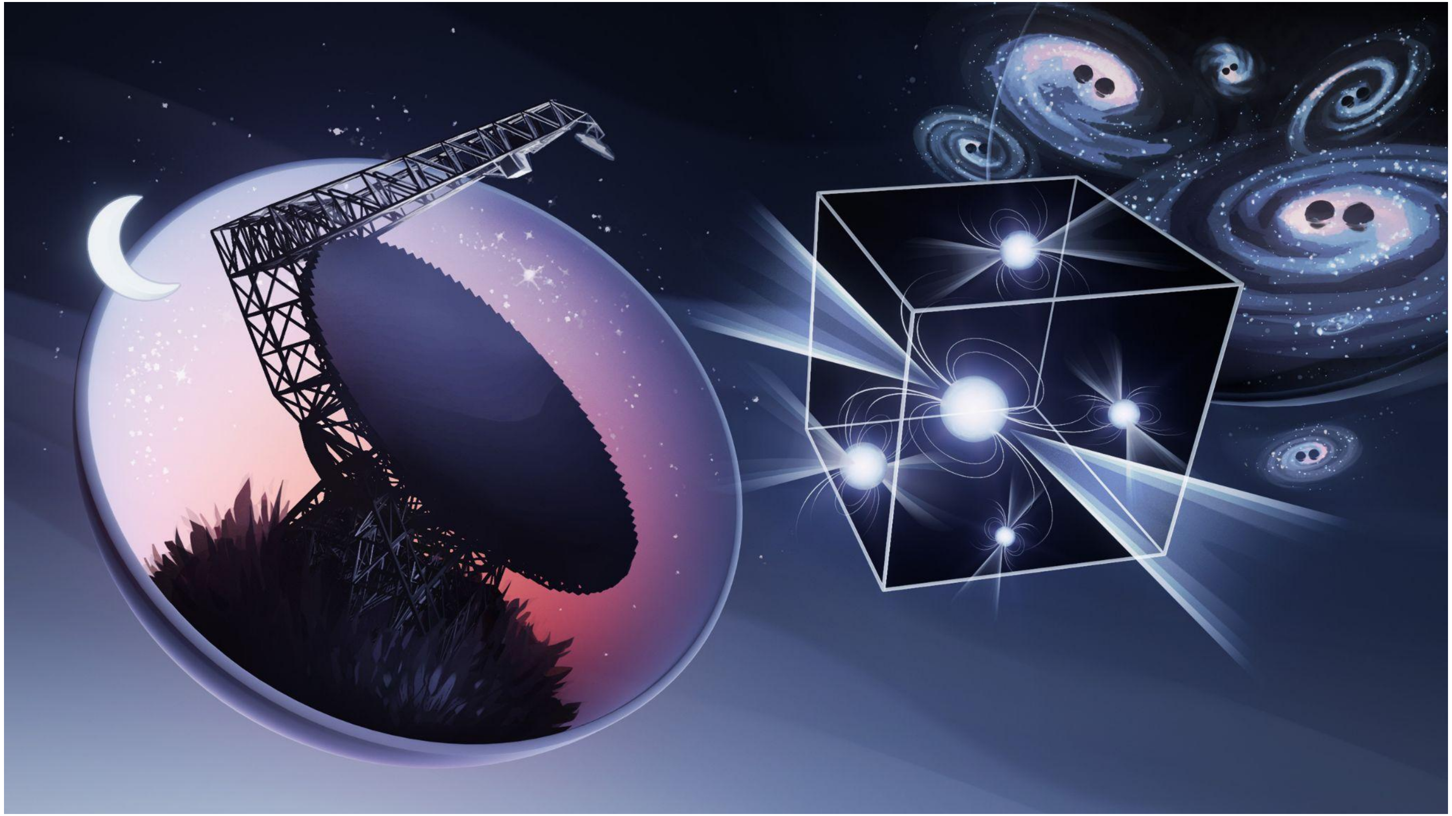
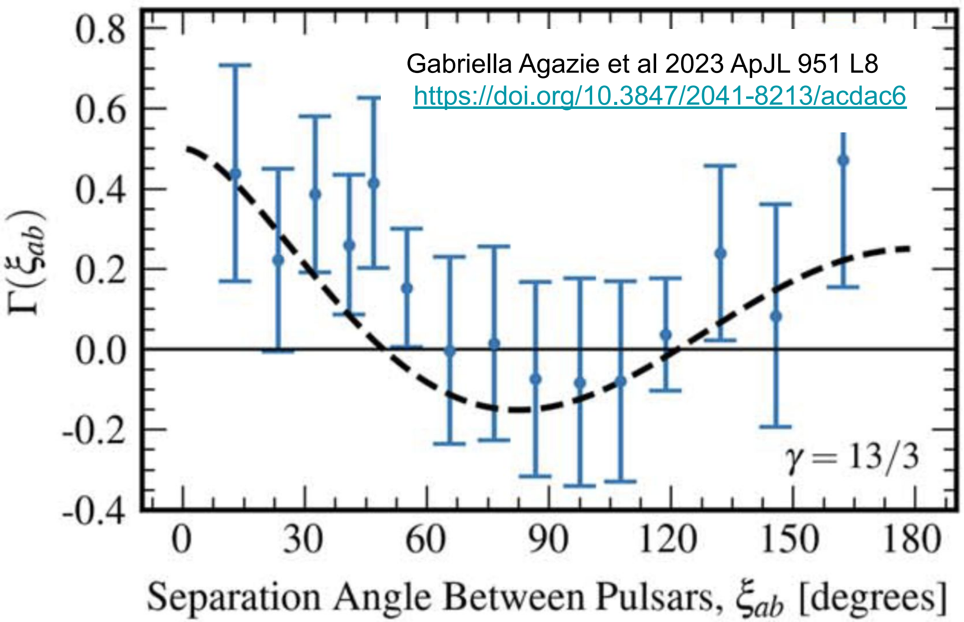


Illustration Credit
Olena Shmahalo for NANOGrav

Recent Pulsar Timing Observations



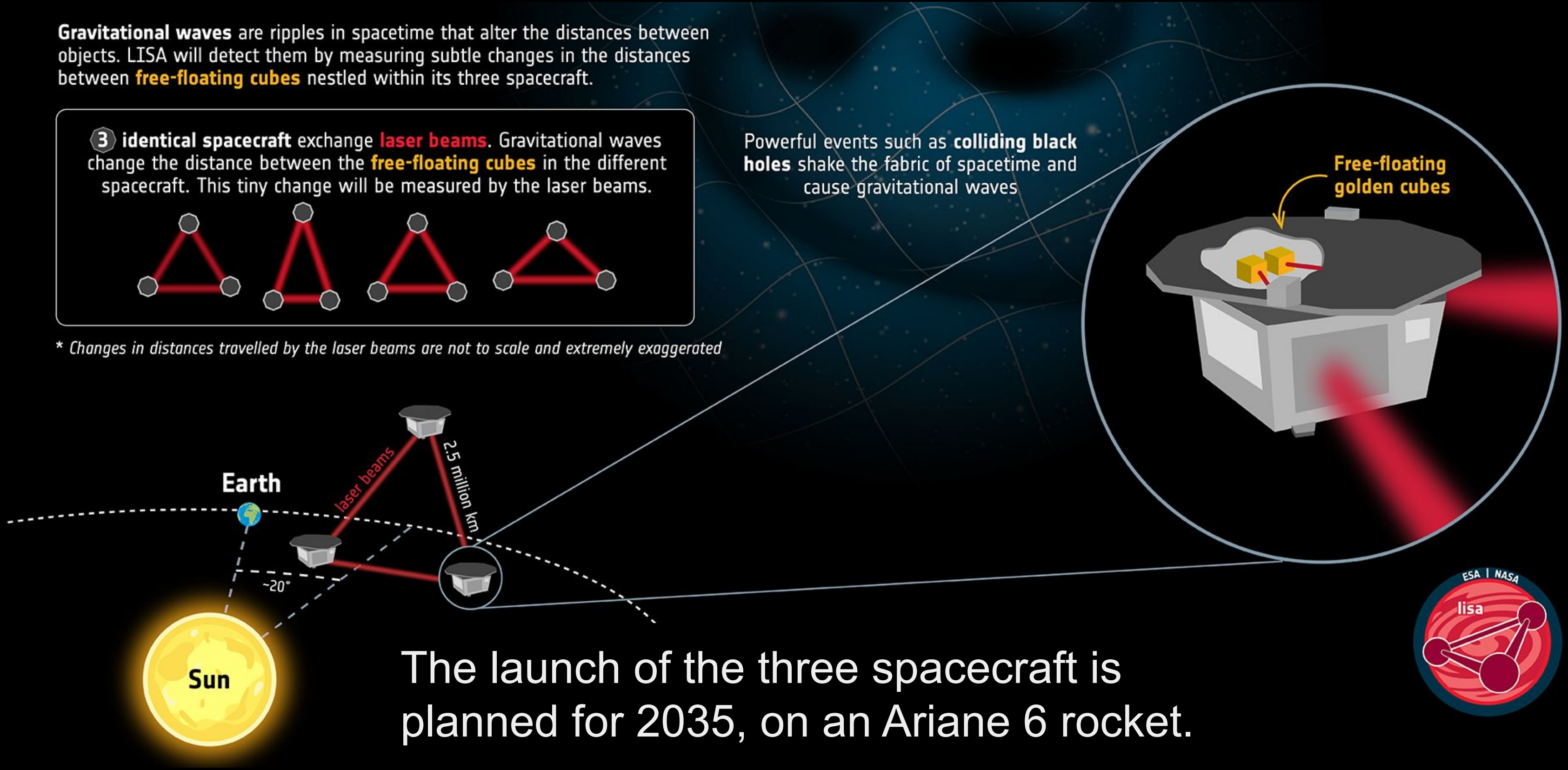
Hellings-Downs interpulsar correlations from a gravitational-wave background.

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

Possibly background from supermassive black hole binaries.

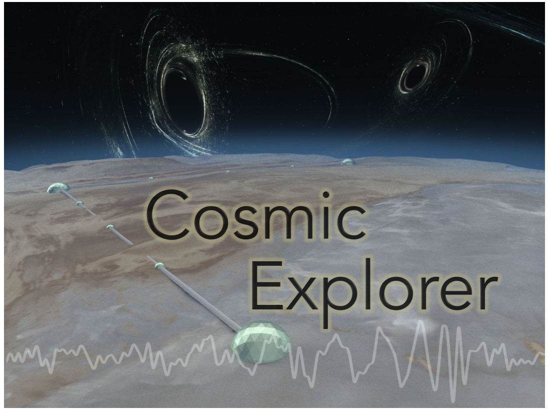
- NANOGrav - G. Agazie et al 2023 ApJL 951 L8
- PPTA - D. J. Reardon et al 2023 ApJL 951 L6
- EPTA and InPTA - J. Antoniadis et al. A&A, to appear
- CPTA - H. Xu et al 2023 Res. Astron. Astrophys. 23 075024

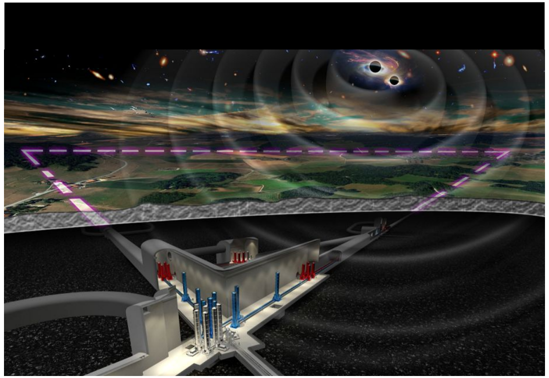
25 Jan: LISA mission approved!

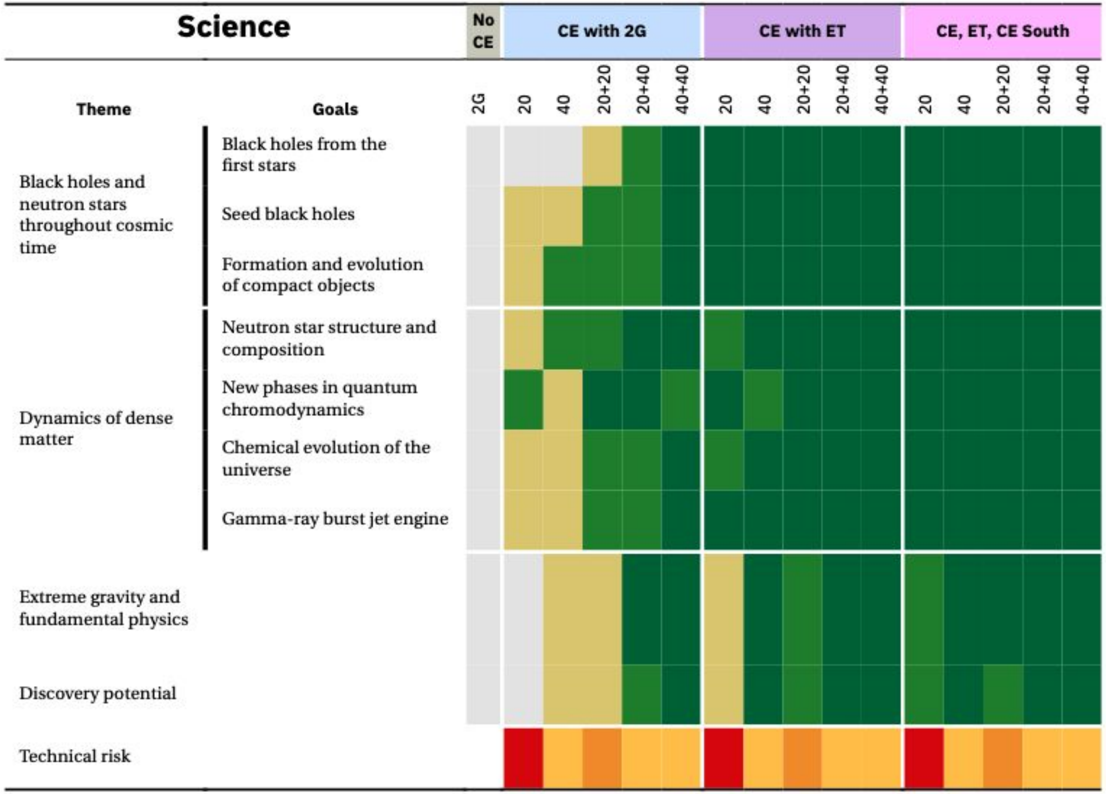


The launch of the three spacecraft is planned for 2035, on an Ariane 6 rocket.

Next Generation Detectors







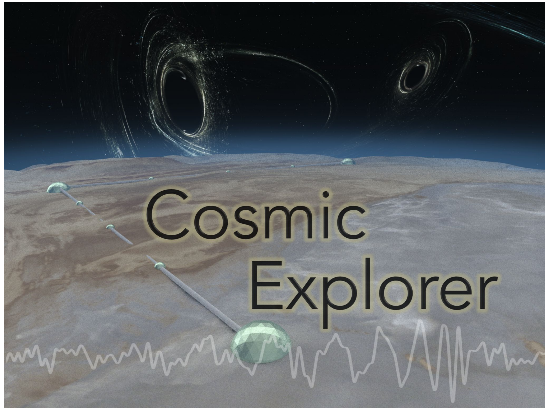
A Horizon Study for Cosmic Explorer
https://arxiv.org/abs/2109.09882

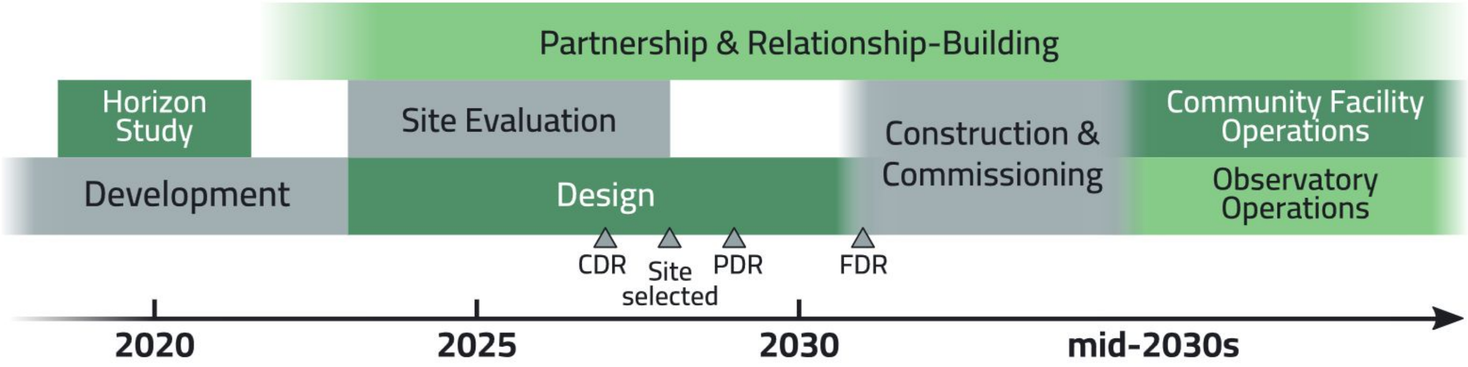
Top-level timeline showing a phased approach to design and construction.

Submitted to the NSF MPSAC GW Subcommittee

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

Cosmic Explorer Timeline





LIGO VIRGO KAGRA

Thank you!