Ground-based gravitational-wave astronomy

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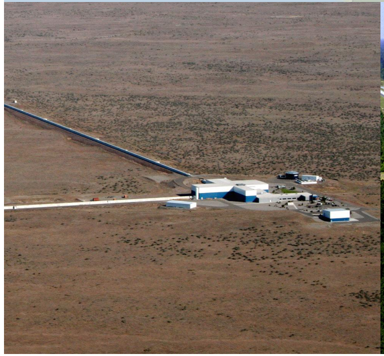
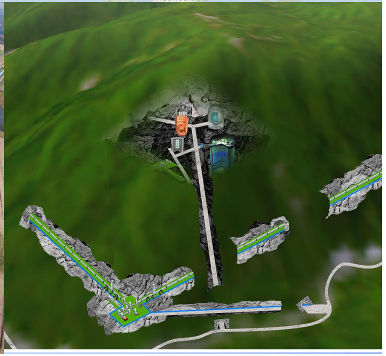
for the LIGO-Virgo-KAGRA Collaboration
28 February 2024

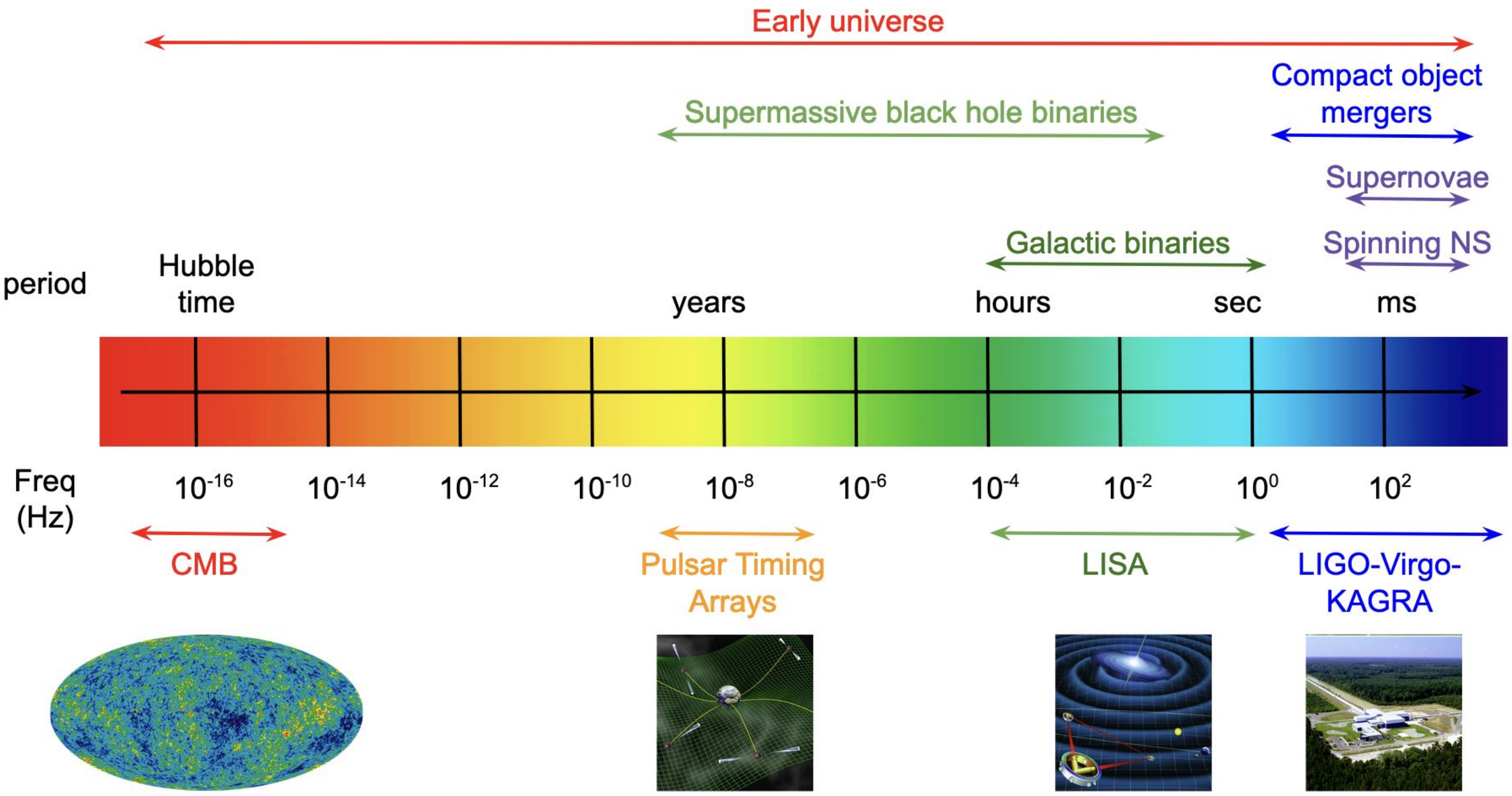
https://dcc.ligo.org/G2400437

International Gravitational-Wave Observatory Network (IGWN)





Gravitational-wave spectrum

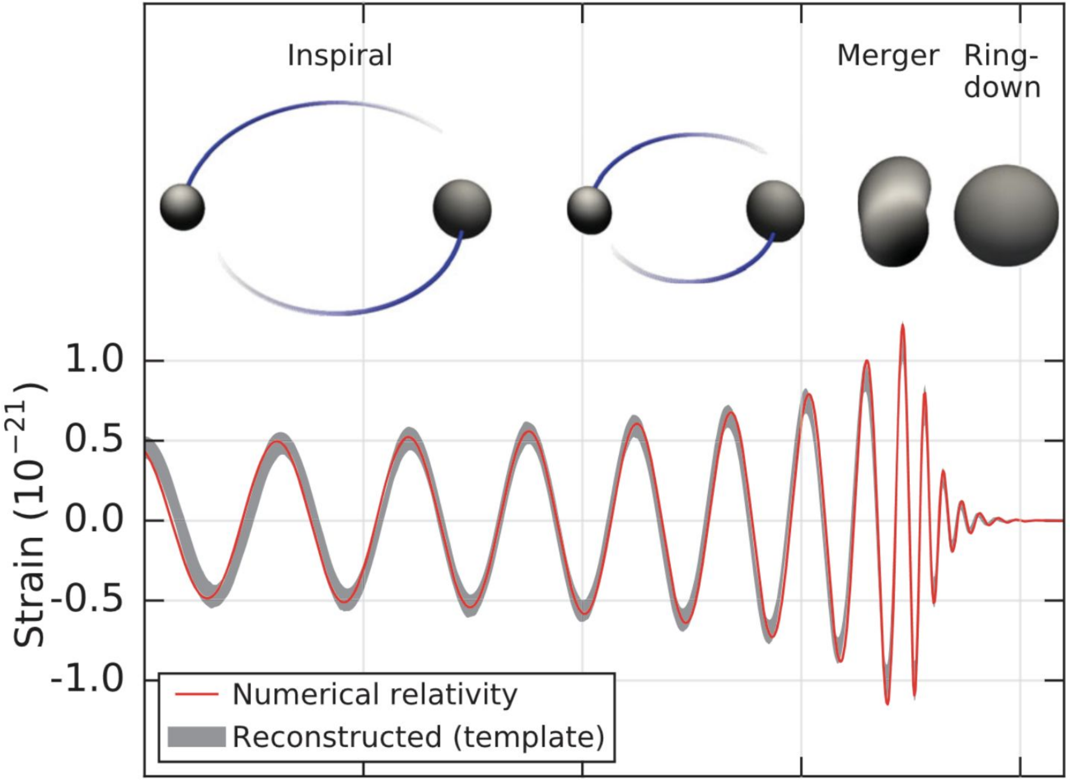


Adapted from: Romano, J.D., Cornish, N.J. Living Rev Relativ 20, 2 (2017). https://doi.org/10.1007/s41114-017-0004-1

Compact object mergers

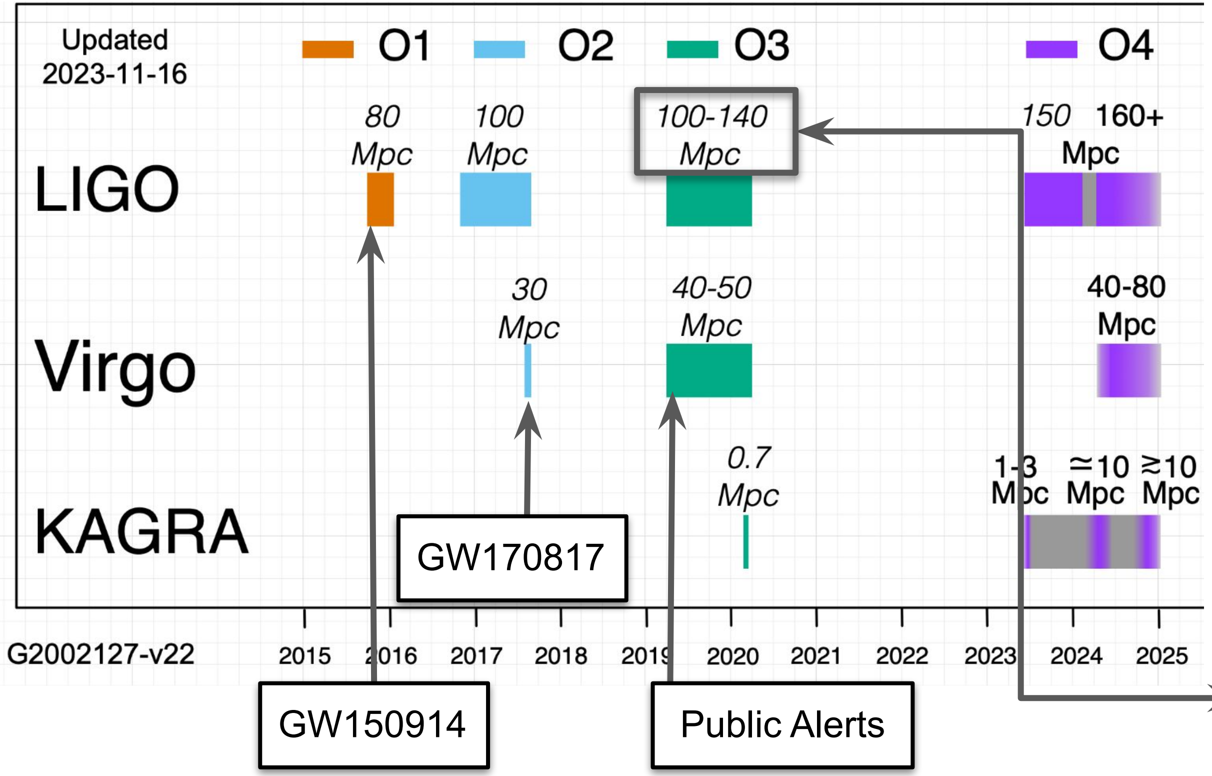
Pairs of stellar-mass black holes, neutron stars, or a stellar-mass black hole and neutron star

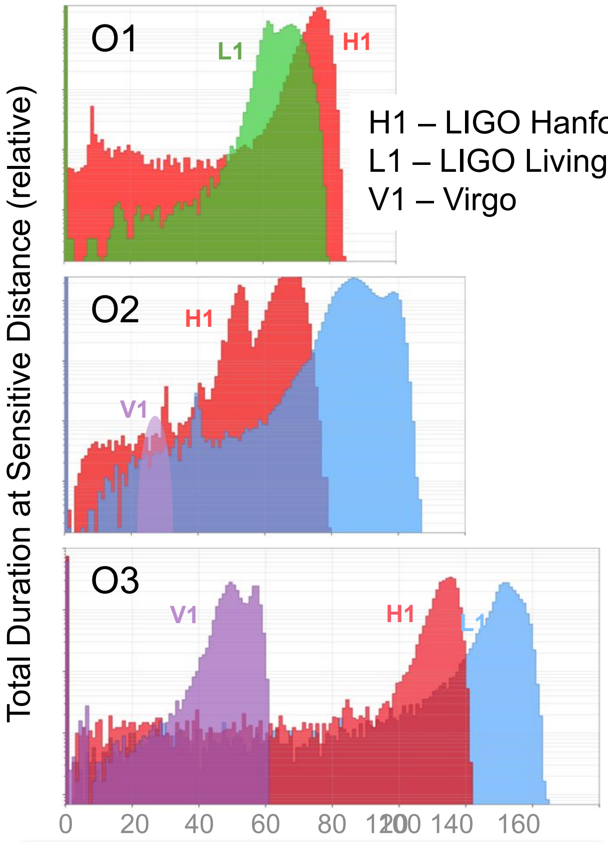
$$h_{ij} \sim \frac{4GM}{c^4}\frac{v^2}{r}$$



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

Observing runs



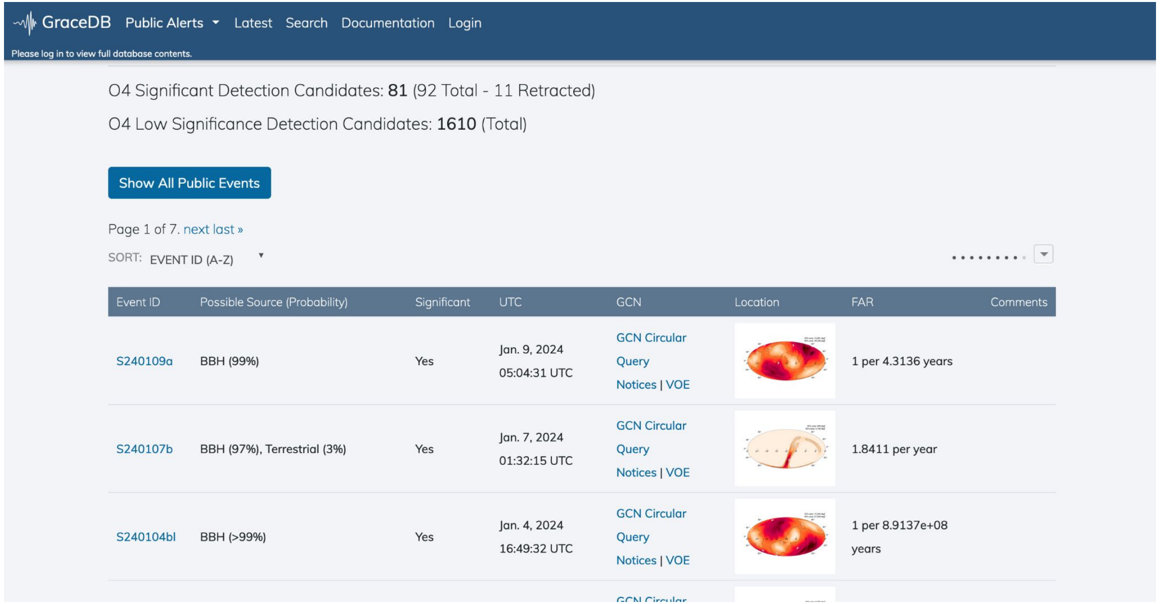


H1 – LIGO Hanford
L1 – LIGO Livingston
V1 – Virgo

Angle Averaged Binary Neutron Star Inspiral Range

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

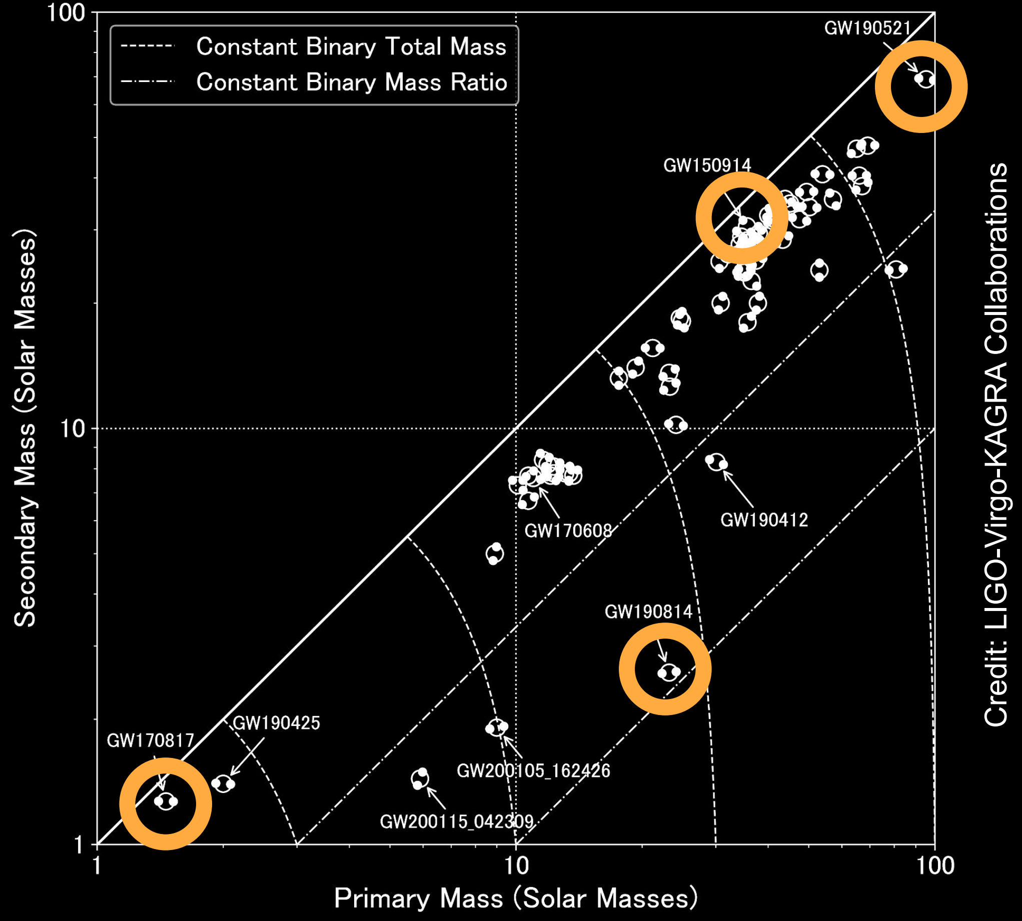
Page 1 of 7. next last »

SORT: EVENT ID (A-Z)

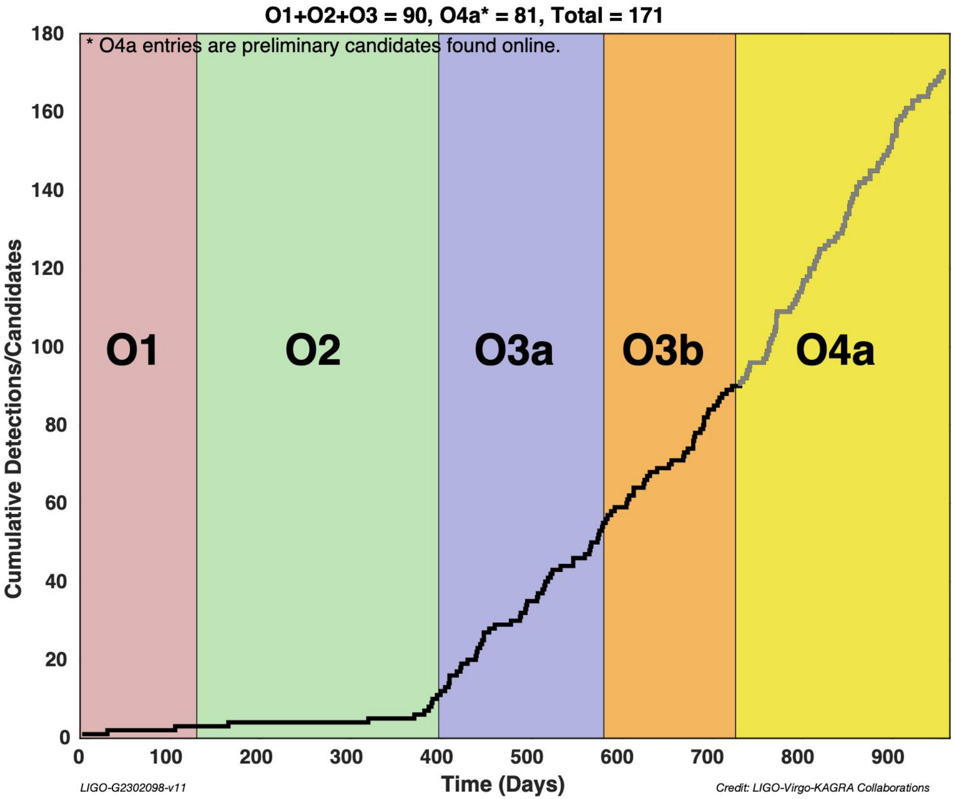
Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S240109a	BBH (99%)	Yes	Jan. 9, 2024 05:04:31 UTC	GCN Circular Query Notices | VOE		1 per 4.3136 years	
S240107b	BBH (97%), Terrestrial (3%)	Yes	Jan. 7, 2024 01:32:15 UTC	GCN Circular Query Notices | VOE		1.8411 per year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

Detections

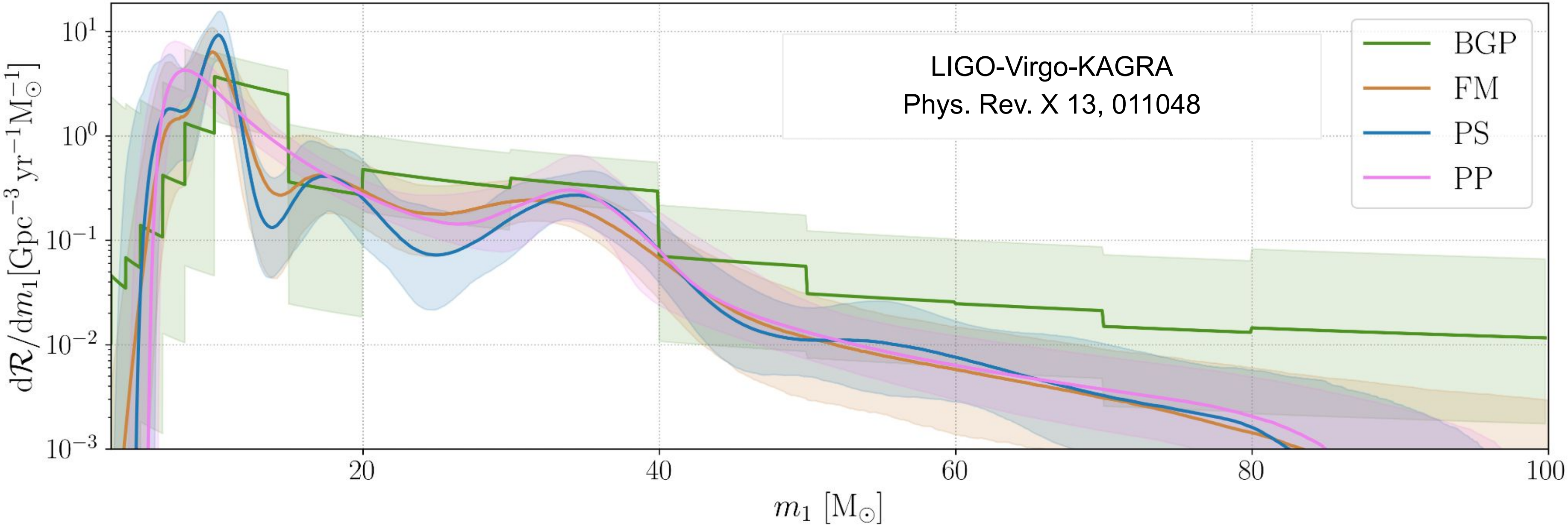
- GW150914
  - First astrophysical source
  - Binary black holes exist
- GW170817
  - Binary neutron star mergers are gamma-ray burst progenitors
- GW190521
  - Black holes exist in pair instability mass gap
- GW190814
  - Compact objects exist with masses between 2-5 Msun



Detections versus time observing



From one to many: measuring populations

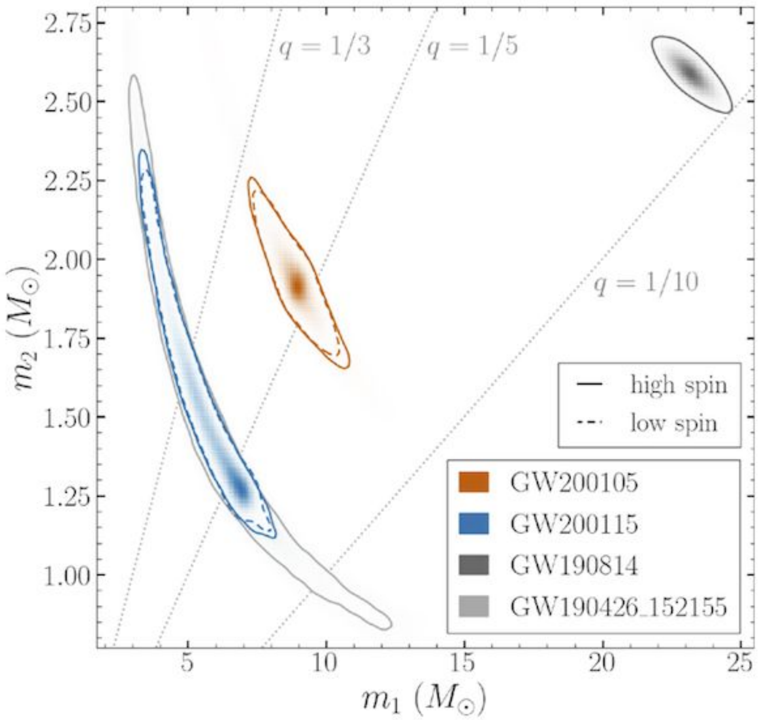


Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

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

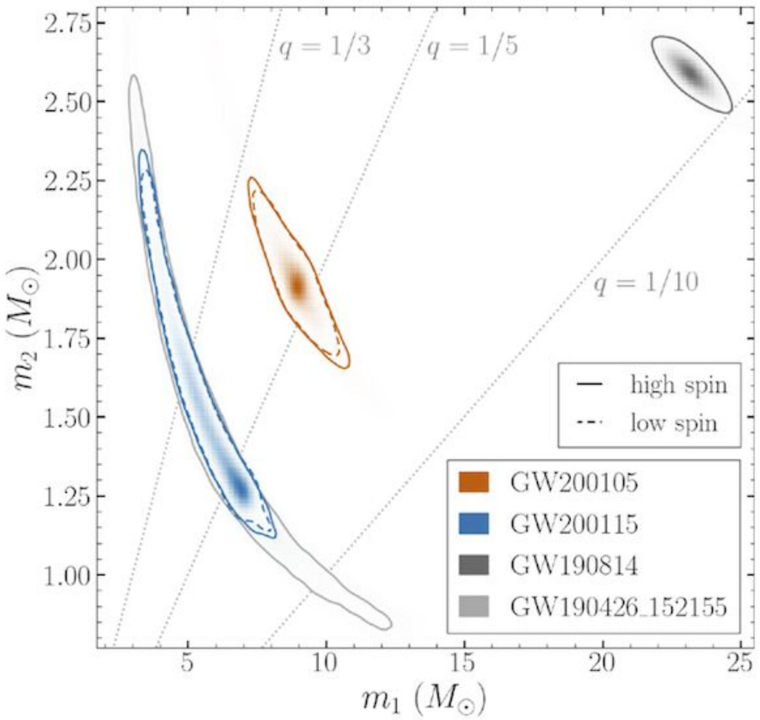
B. P. Abbott et al 2017 ApJL 848 L13



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

Mergers involving neutron stars

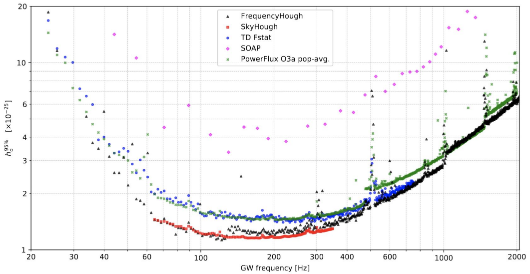
- GW170817 & GW190425
  - Binary neutron star (BNS) merger waves
- O4a
  - Doubled the spacetime volume searched with no new events.
  - Based on O1+O2+O3 rates, expected ~ 0.4 - 7 new events.
- O4b
  - Using naive O123+O4a rates based on public information, expect 0.2 - 3.5 new events in O4b.



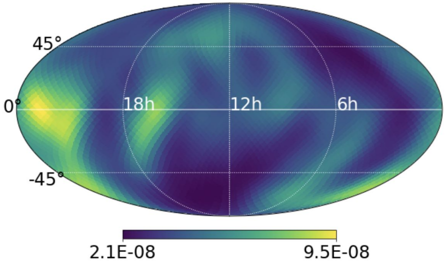
R. Abbott *et al* 2021 *ApJL* **915** L5

Many other observational results

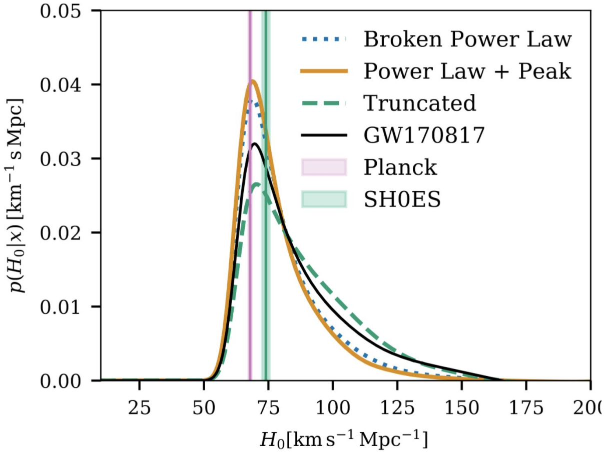
Limits on waves from pulsars
Phys. Rev. D 106, 102008 (2022)



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



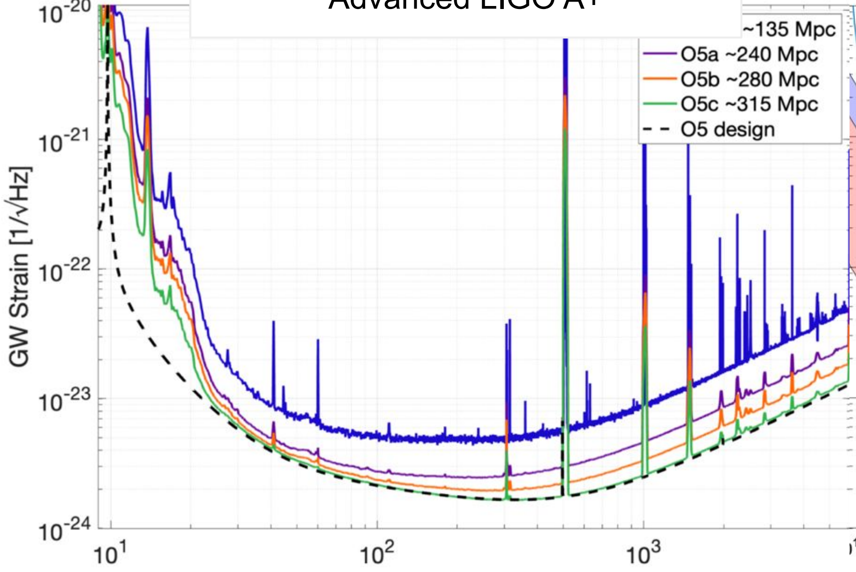
Hubble constant measurements
Astrophys. J. 949, 76 (2023)



And much more!

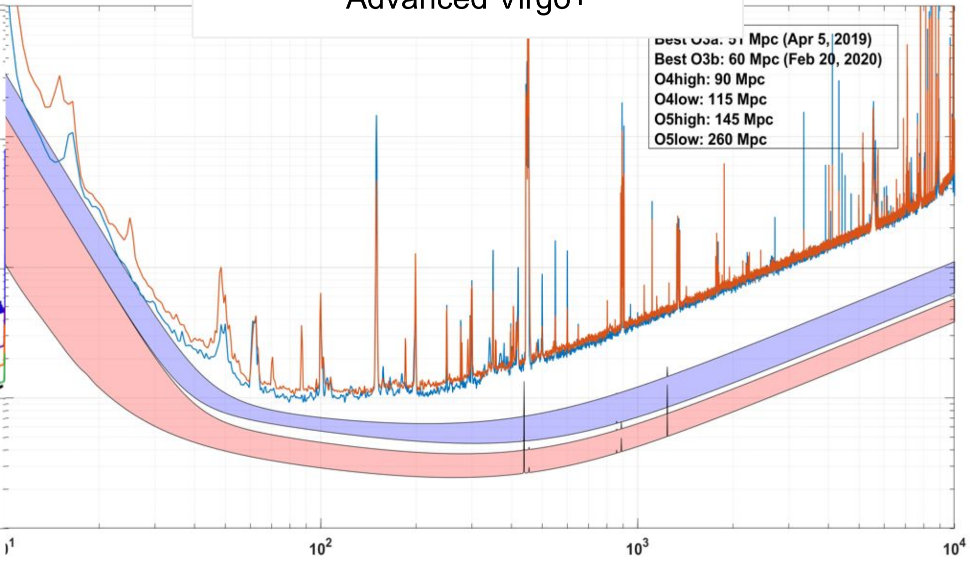
Working toward O5 sensitivity

Advanced LIGO A+



Frequency (Hz)

Advanced Virgo+



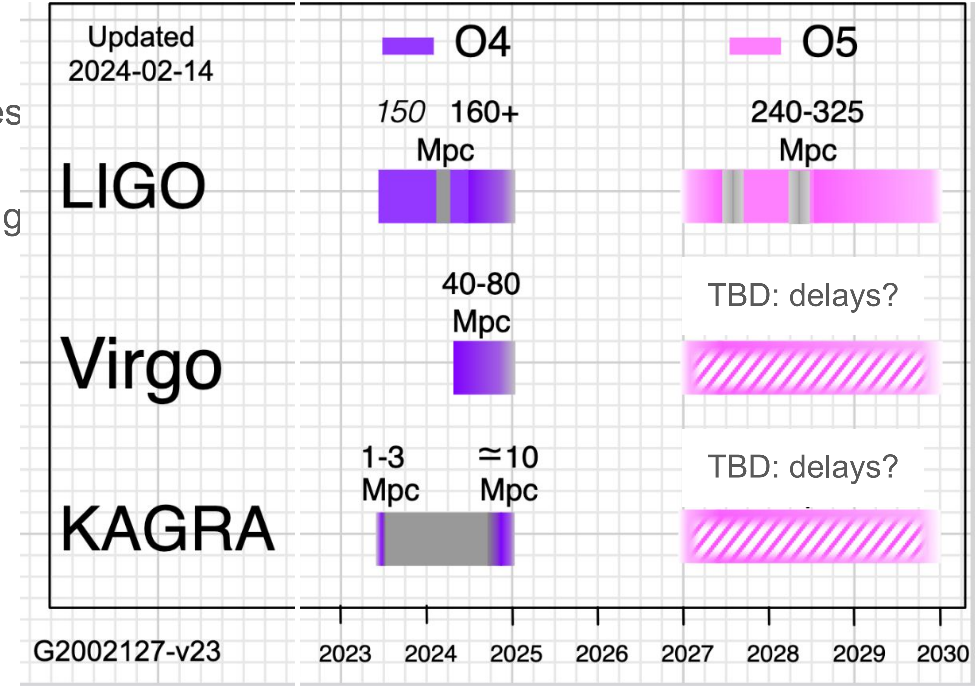
Frequency (Hz)

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

- 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?



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

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

Early 2030s

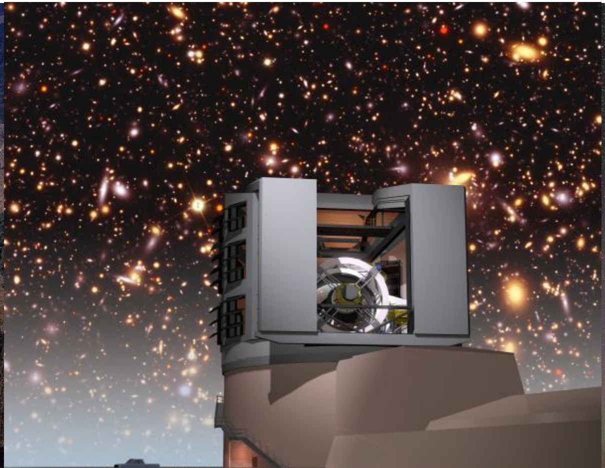
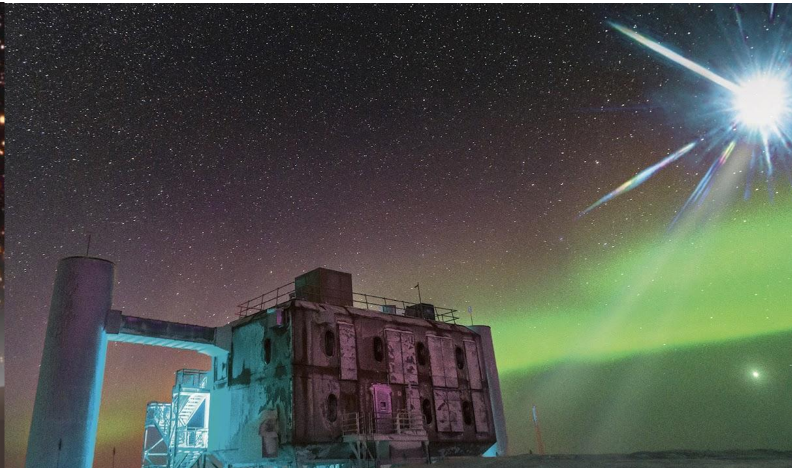
- LIGO Aundha Observatory (LAO) is to be constructed in India and operated as part of the LIGO network in the 2030s.
- $A^{\#}$: targeted improvements to the LIGO detectors
  - Report of LSC post-O5 study group [Fritschel et al, https://dcc.ligo.org/LIGO-T2200287/public]
  - Achieve close to a factor 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.

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

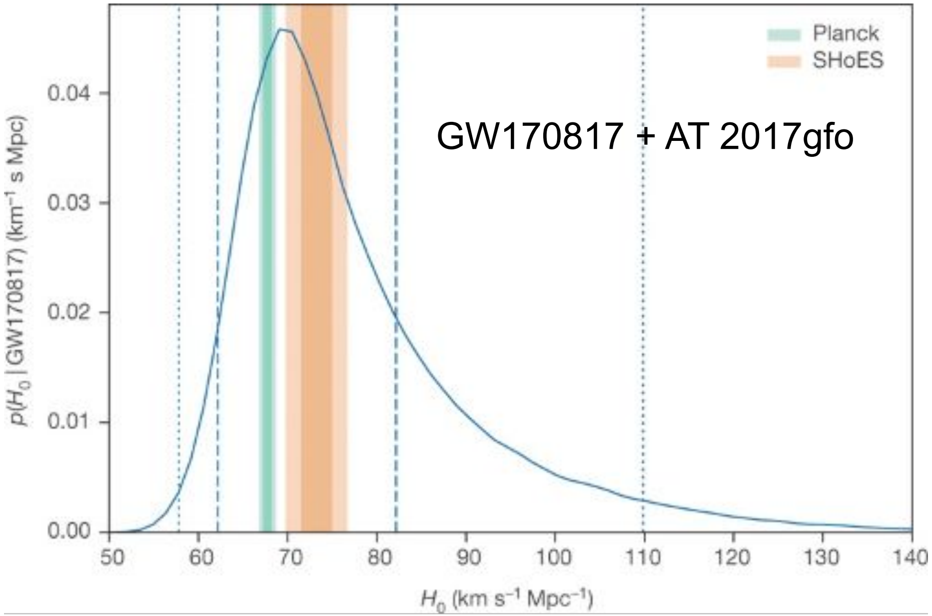
Ish Gupta & B. Sathyaprakash

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]

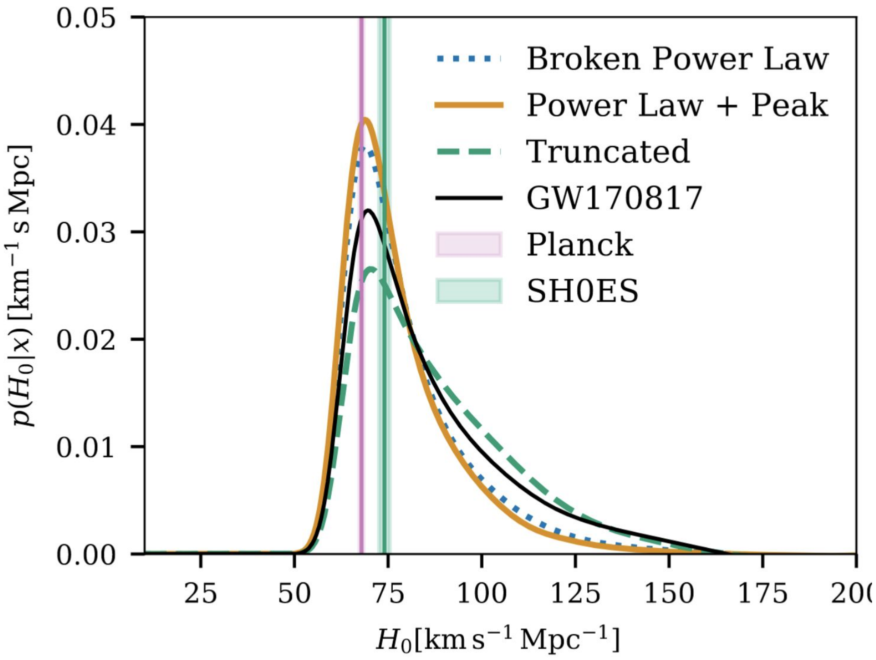
B P Abbott *et al. Nature* **551,** 85–88 (2017) doi:10.1038/nature24471



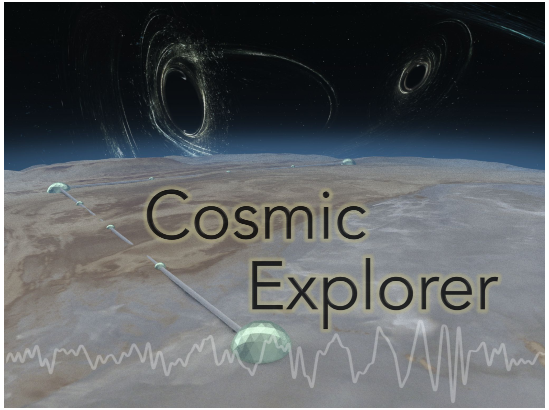
Challenges for cosmology with GW

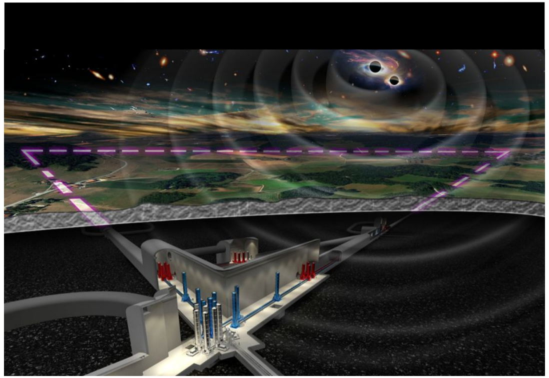
- Binaries with detectable EM counterparts are rare
  - If ~ ~~5-10~~ 3 BNS mergers are detected in O4, expect fewer than ~ 1 detectable kilonova.
  - GRBs further away, but only a fraction beamed to Earth.
- Sub-percent accuracy with many
  - Completeness of galaxy catalogs decreases rapidly with redshift.
  - Mass scales are highly uncertain, e.g. maximum black hole mass from PISN, or must be measured simultaneously.

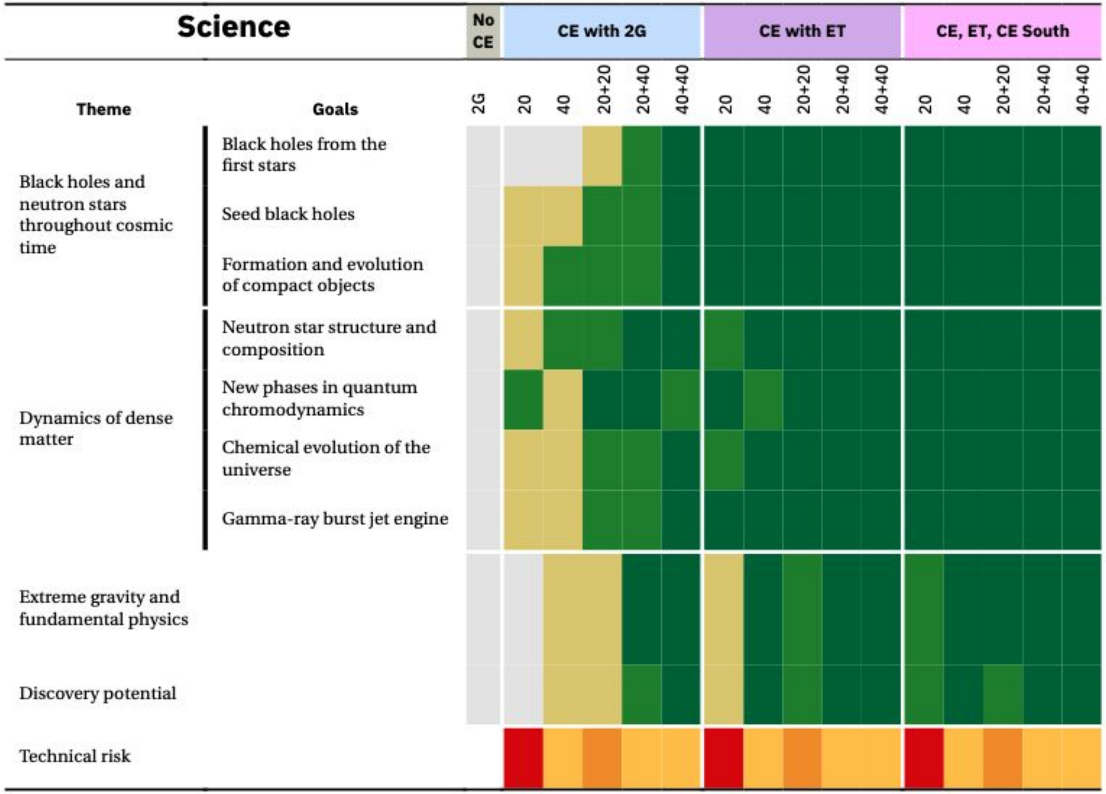
R Abbott *et al. arXiv:2111.03604 (2021)*



Next Generation Detectors







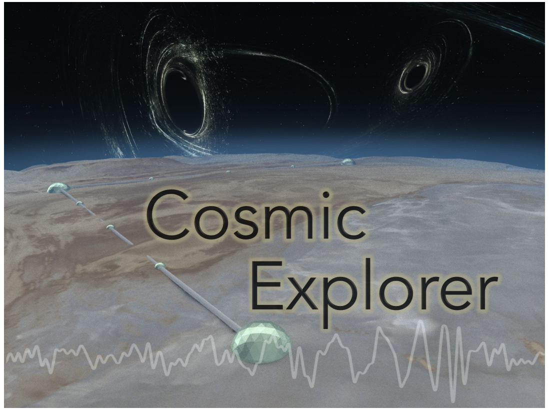
A Horizon Study for Cosmic Explorer
https://arxiv.org/abs/2109.09882

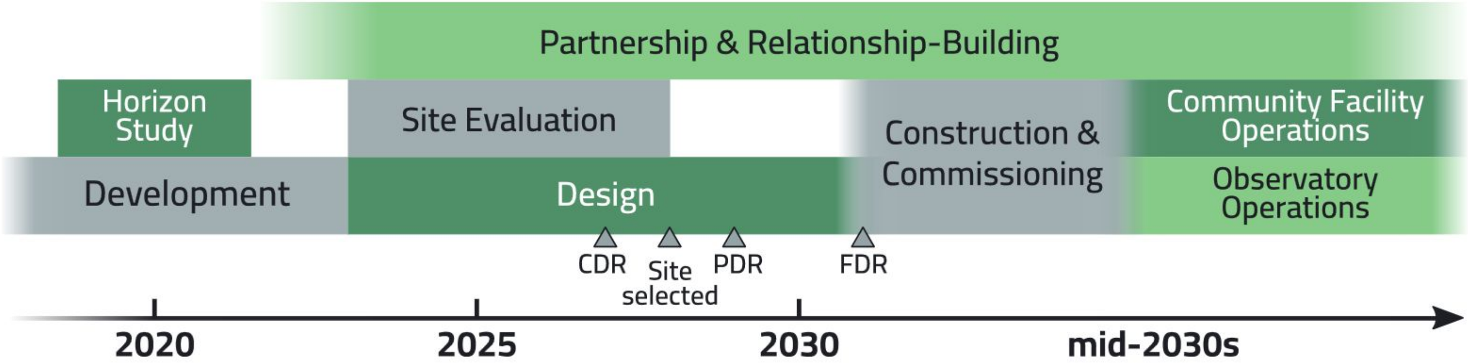
Top-level timeline showing a phased approach to design and construction.

Submitted to the NSF MPSAC ngGW Subcommittee

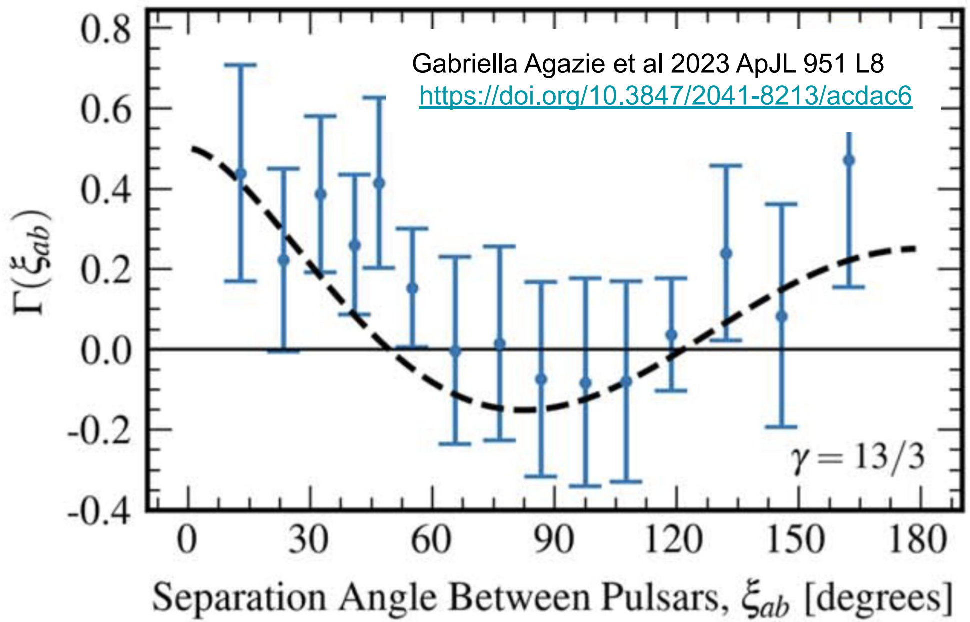
https://dcc.cosmicexplorer.org/CE-P2300018/public

Cosmic Explorer Timeline





Recent Pulsar Timing Observations



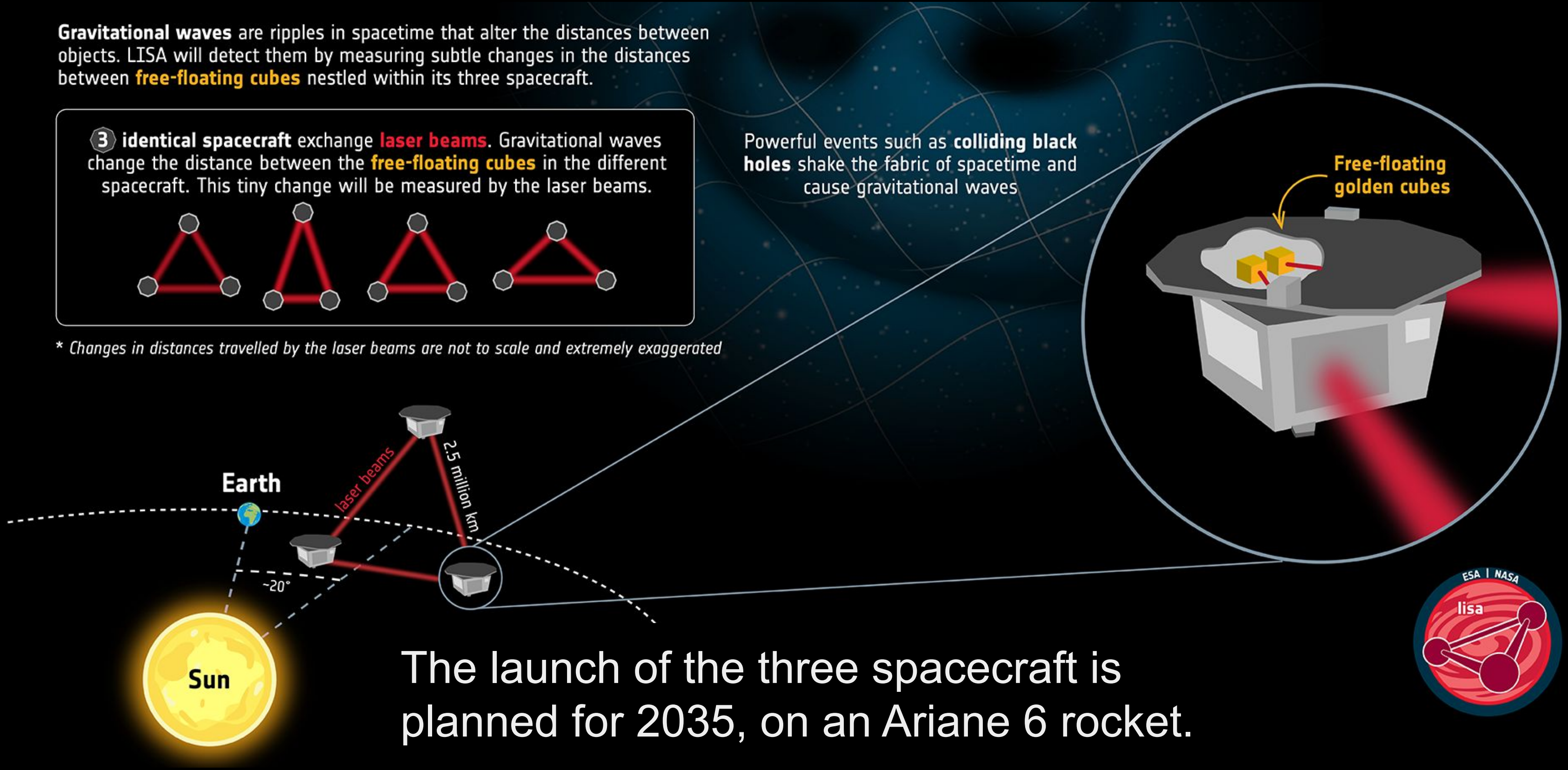
Hellings-Downs interpulsar correlations from a gravitational-wave background.

- 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.

Thank you!