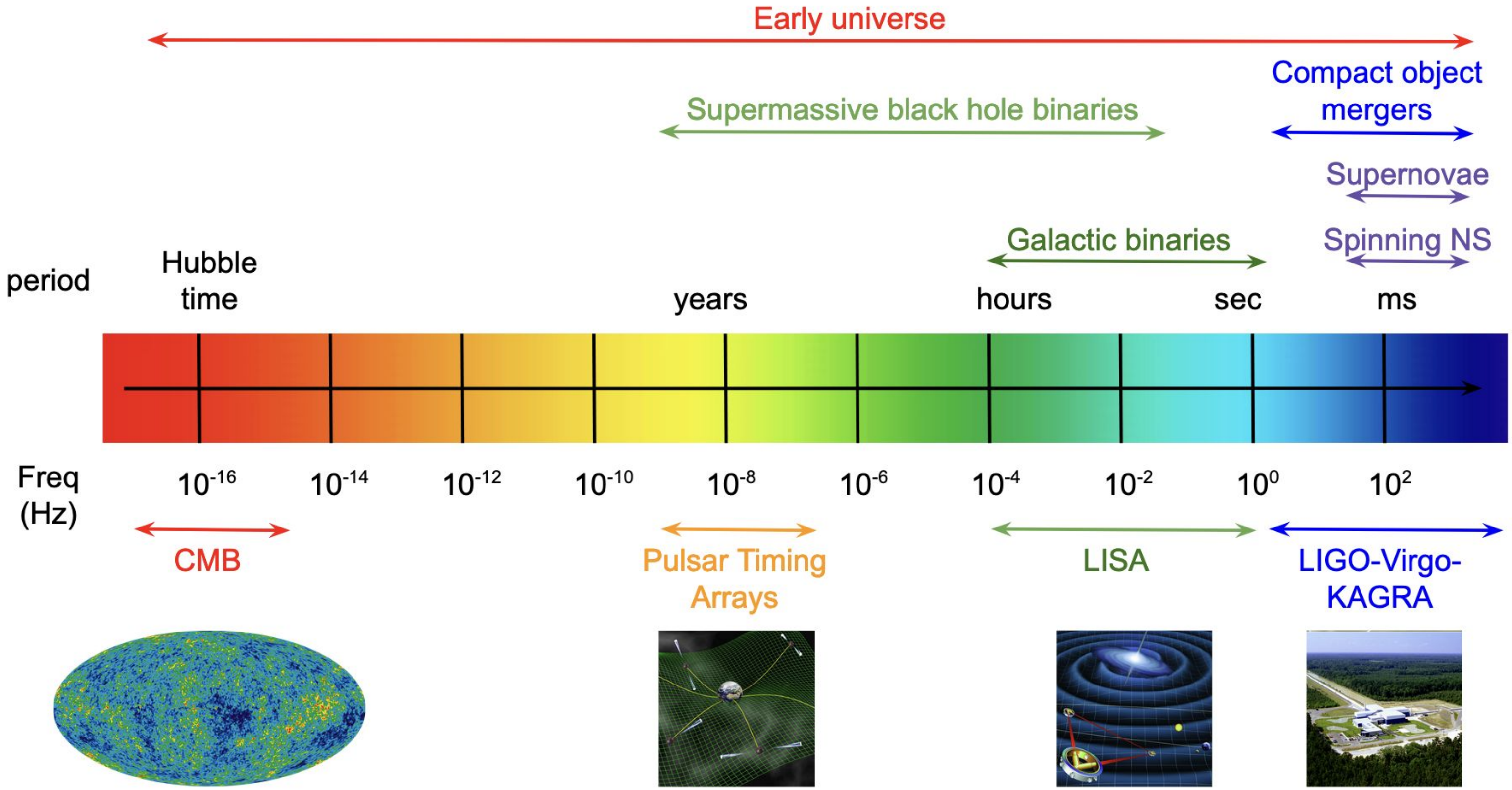
Gravitational-Wave Observational Results and Prospects

Patrick Brady,
University of Wisconsin-Milwaukee

LIGO Science Workshop, ICTS
27 October 2023

https://dcc.ligo.org/G2302128

Gravitational-wave spectrum



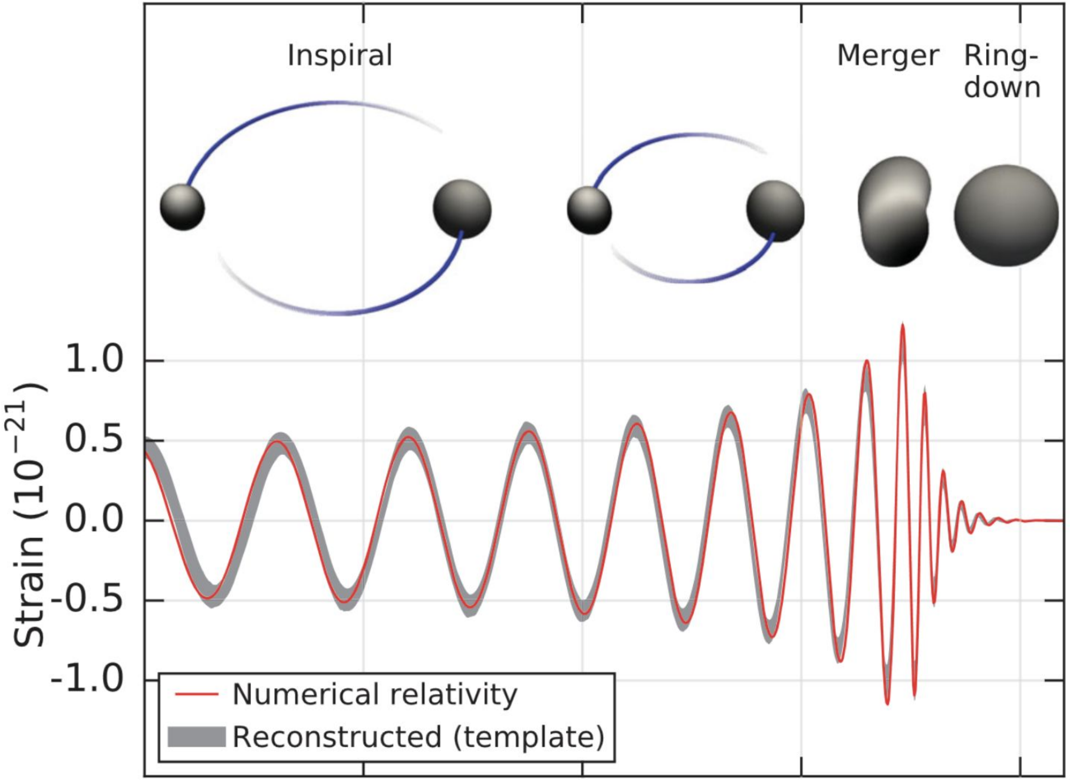
Adapted from: Romano, J.D., Cornish, N.J.
Living Rev Relativ 20, 2 (2017).
https://doi.org/10.1007/s41114-017-0004-1

International Gravitational-Wave Observatory Network (IGWN)

Compact object mergers

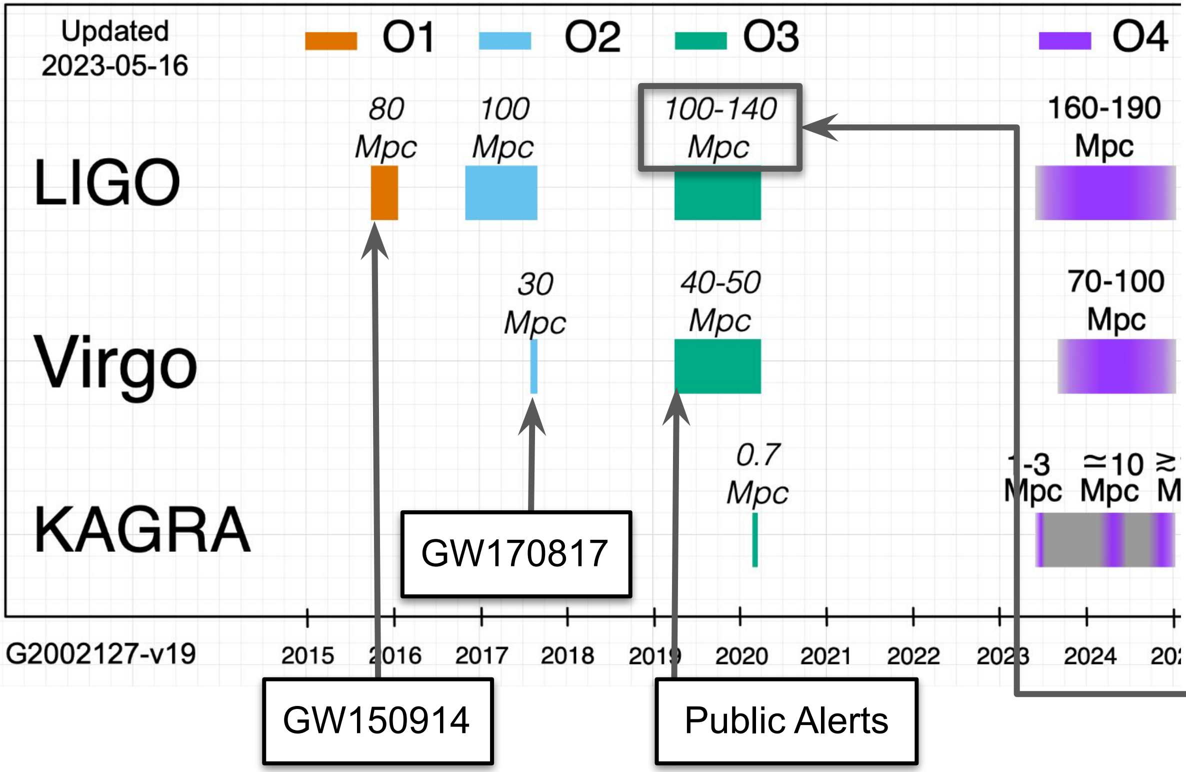
Pairs of stellar-mass black holes, neutron stars, or a stellar-mass black hole and neutron star

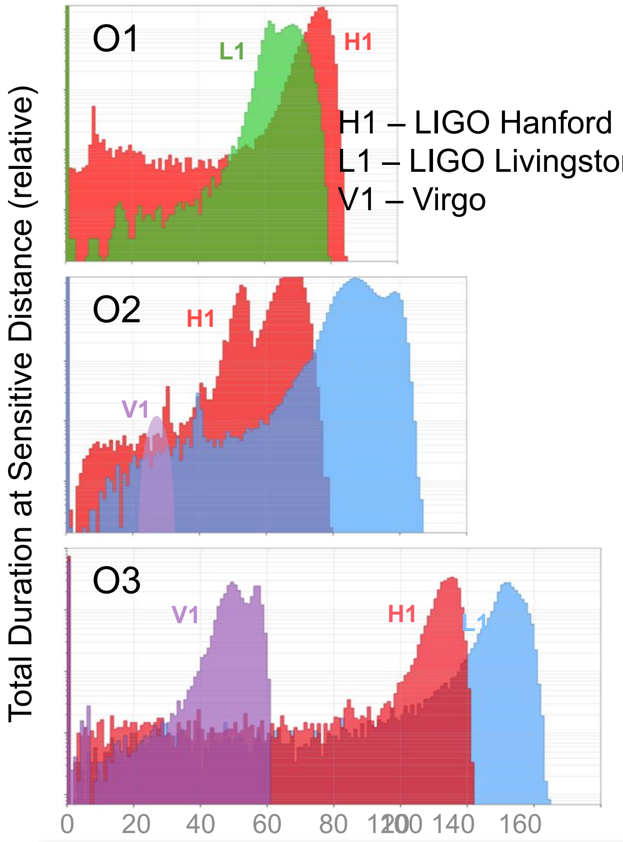
$$h_{ij} \sim \frac{4GM}{c^4}\frac{v^2}{r}$$



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

Observing runs



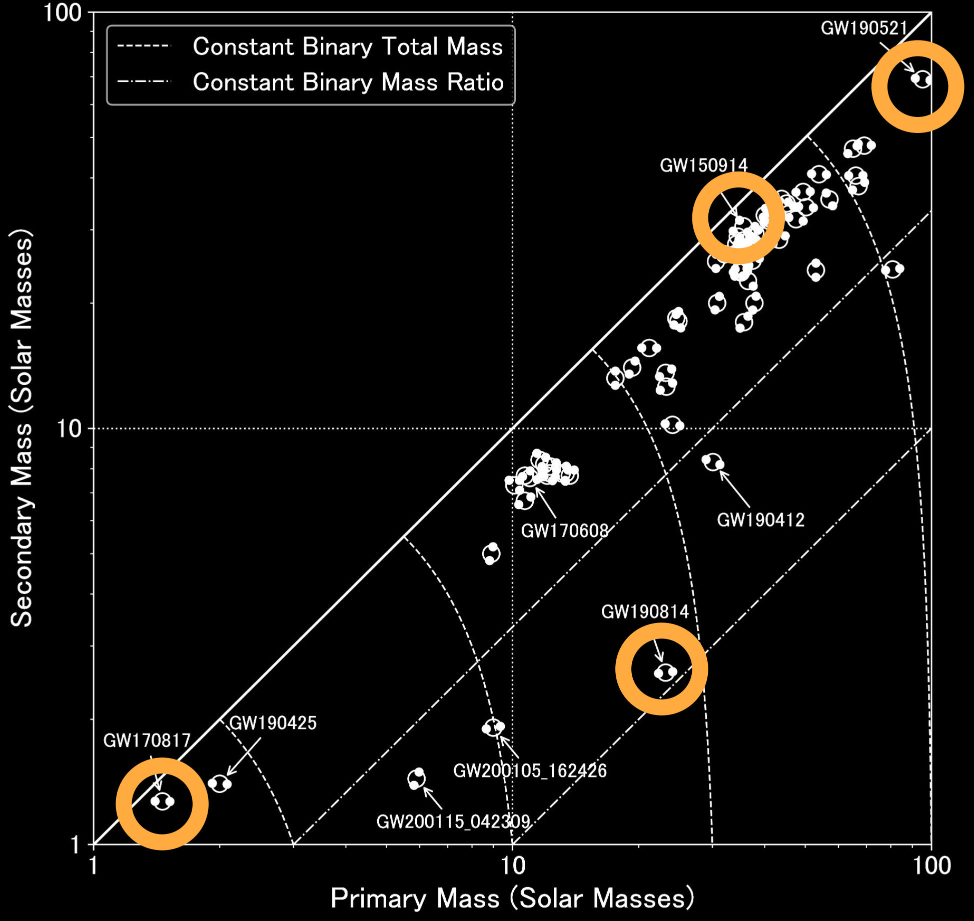


H1 – LIGO Hanford
L1 – LIGO Livingston
V1 – Virgo

Angle Averaged Binary Neutron Star Inspiral Range

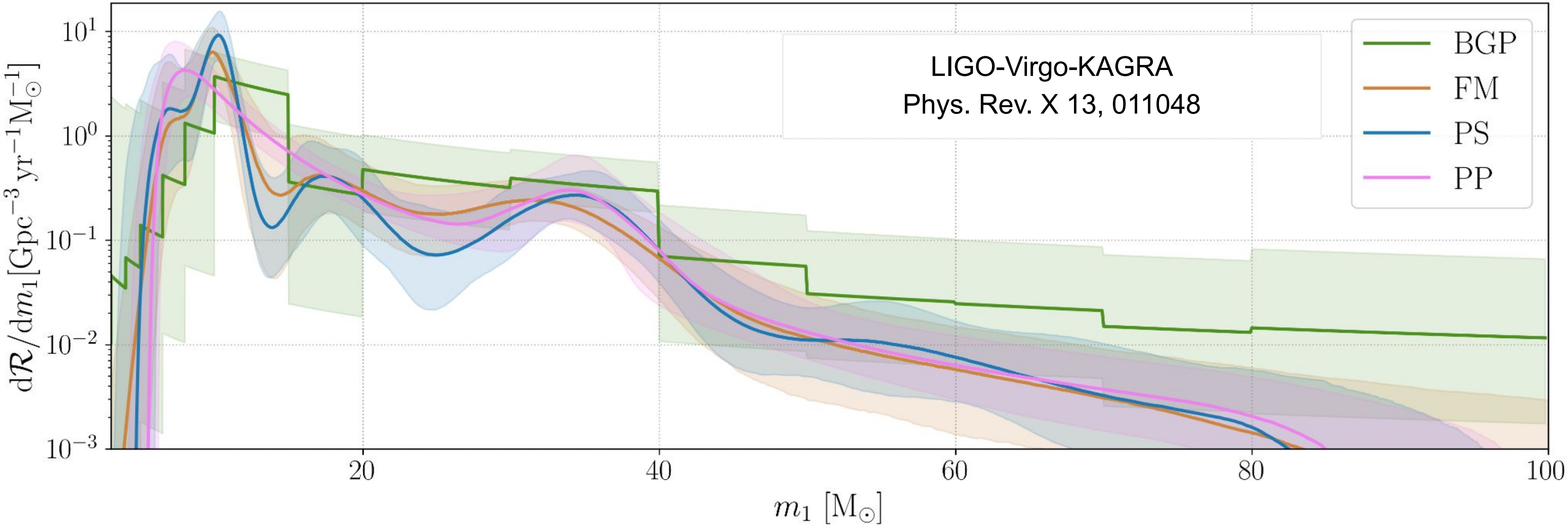
Detections

- 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



Credit: LIGO-Virgo-KAGRA Collaborations

From one to many: measuring populations

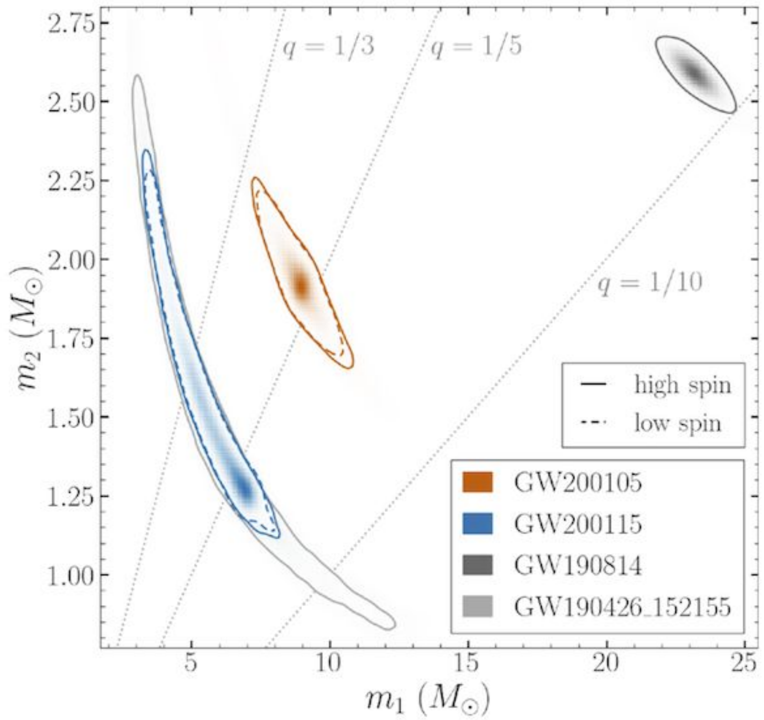


Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

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 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

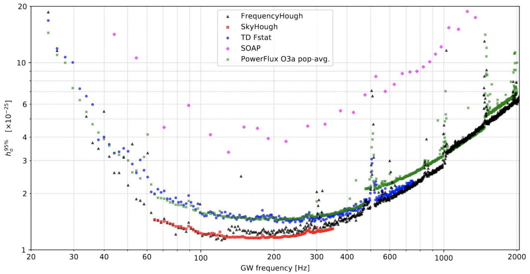


R. Abbott *et al* 2021 *ApJL* **915** L5

Many other observational results

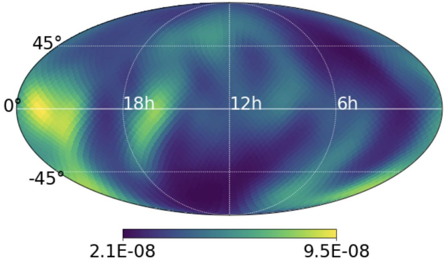
Limits on waves from pulsars

Phys. Rev. D 106, 102008 (2022)



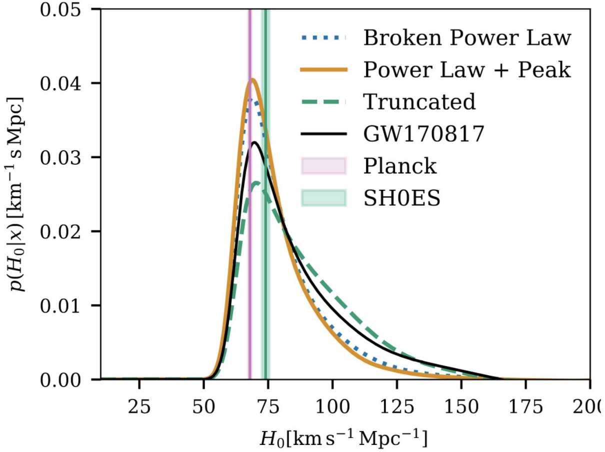
Stochastic background limits

Phys. Rev. D 105, 122002 (2022)



Hubble constant measurements

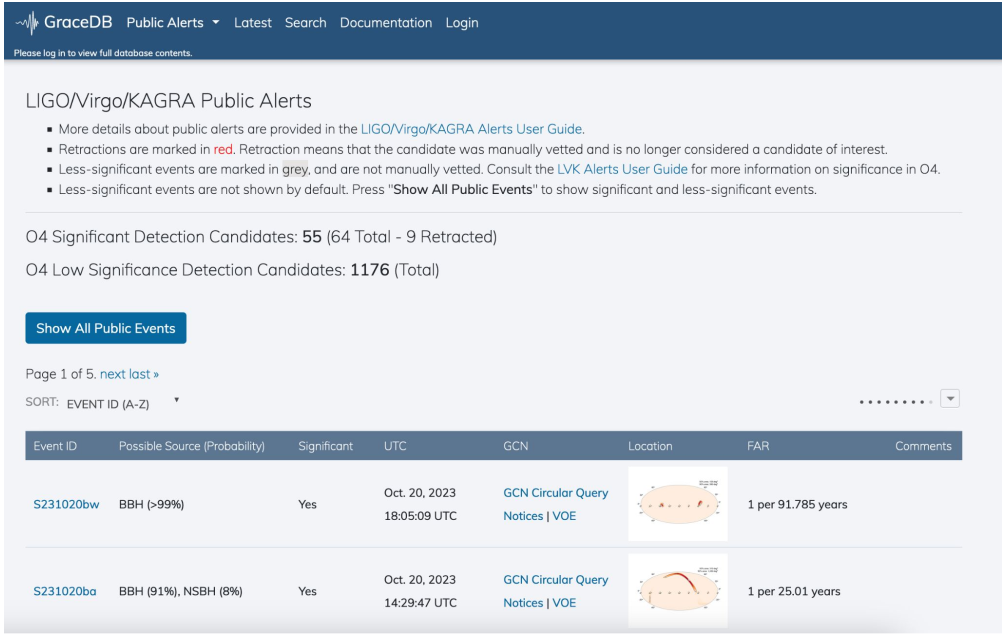
Astrophys. J. 949, 76 (2023)



And much more!

Back to observing!

- 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
    - Stay tuned for new results!


GraceDB Public Alerts Latest Search Documentation Login

Please log in to view full database contents.

LIGO/Virgo/KAGRA Public Alerts

- More details about public alerts are provided in the LIGO/Virgo/KAGRA Alerts User Guide.
- Retractions are marked in red. Retraction means that the candidate was manually vetted and is no longer considered a candidate of interest.
- Less-significant events are marked in grey, and are not manually vetted. Consult the LVK Alerts User Guide for more information on significance in O4.
- Less-significant events are not shown by default. Press "**Show All Public Events**" to show significant and less-significant events.

O4 Significant Detection Candidates: **55** (64 Total - 9 Retracted)

O4 Low Significance Detection Candidates: **1176** (Total)

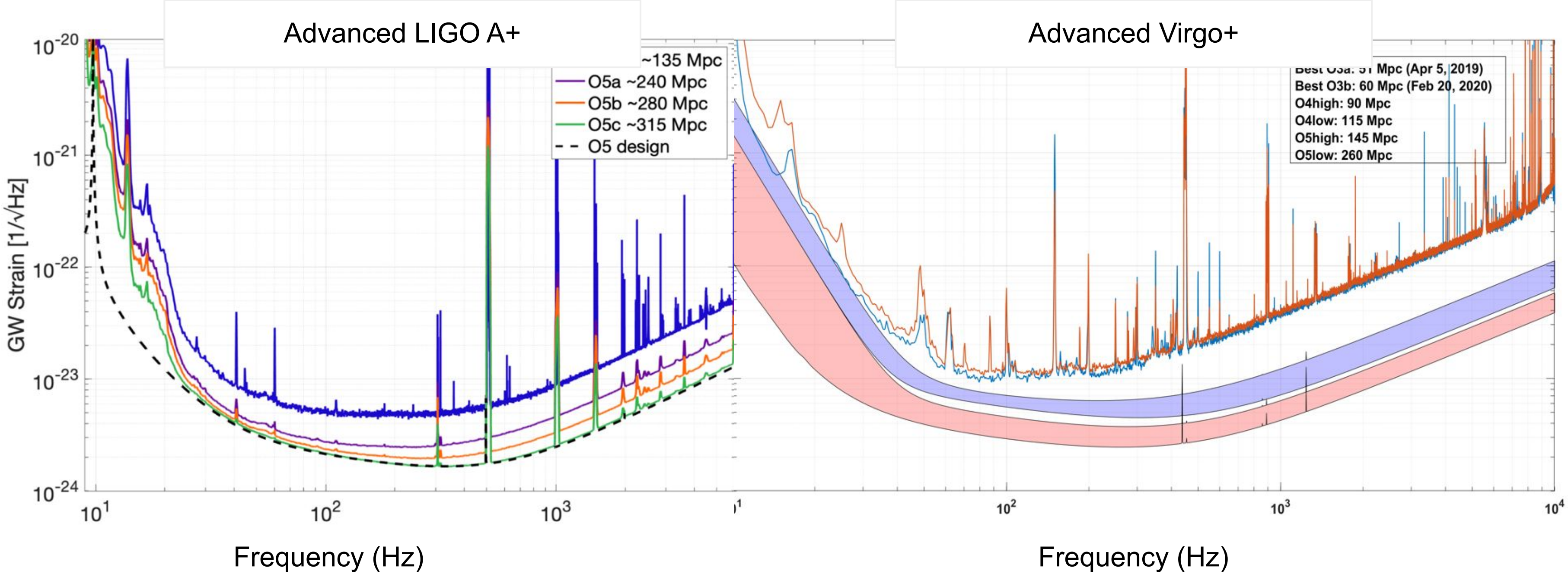
Show All Public Events

Page 1 of 5. next last »

SORT: EVENT ID (A-Z)

Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR	Comments
S231020bw	BBH (>99%)	Yes	Oct. 20, 2023 18:05:09 UTC	GCN Circular Query Notices | VOE		1 per 91.785 years	
S231020ba	BBH (91%), NSBH (8%)	Yes	Oct. 20, 2023 14:29:47 UTC	GCN Circular Query Notices | VOE		1 per 25.01 years	

Working toward O5 sensitivity

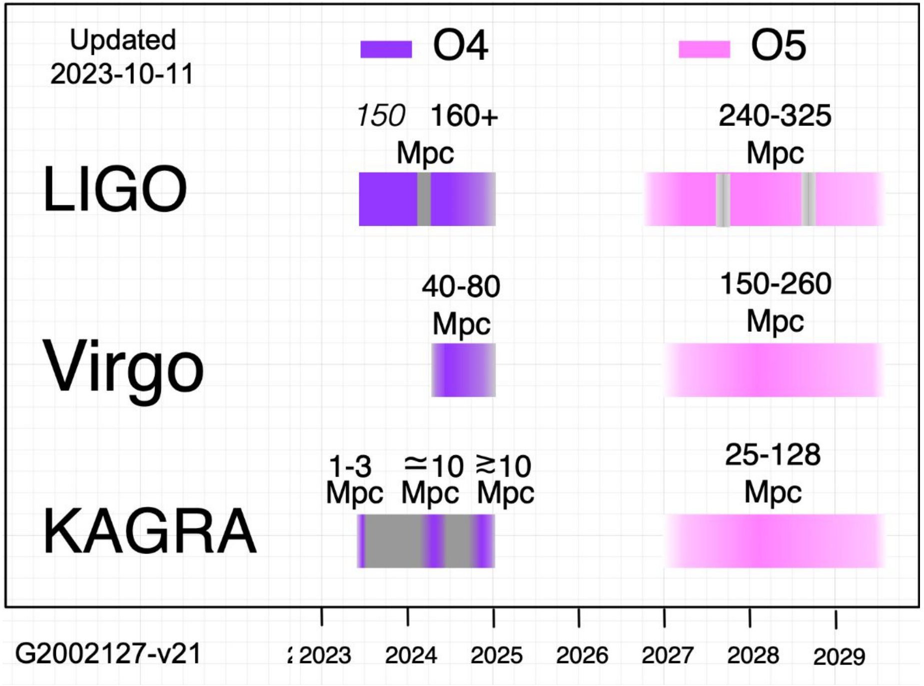


Full Power in the arm cavities: 750 kW
Frequency-dependent Squeezing* level of 6 dB
Test Masses with 2x lower coating thermal noise*

KAGRA will continue to work towards 130Mpc goal in O5

O5 Observing Run

- Current thinking
  - Start is paced by upgrades after O4: 1.5-2 years gap.
  - Intersperse commissioning and observations
- Binary detection rates
  - O3 ~ 1 / 5 days
  - O4 ~ 1 / (2-3) 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.

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}

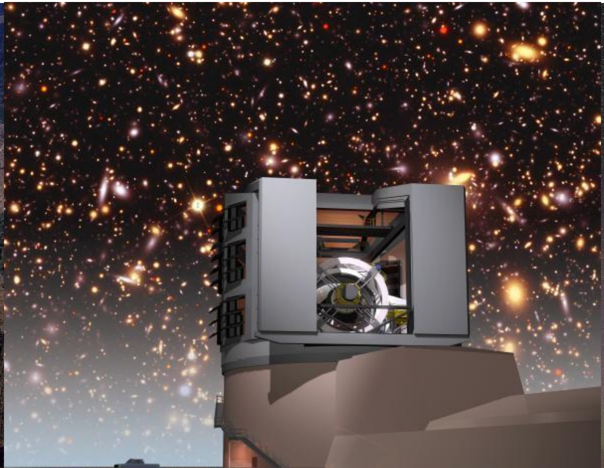
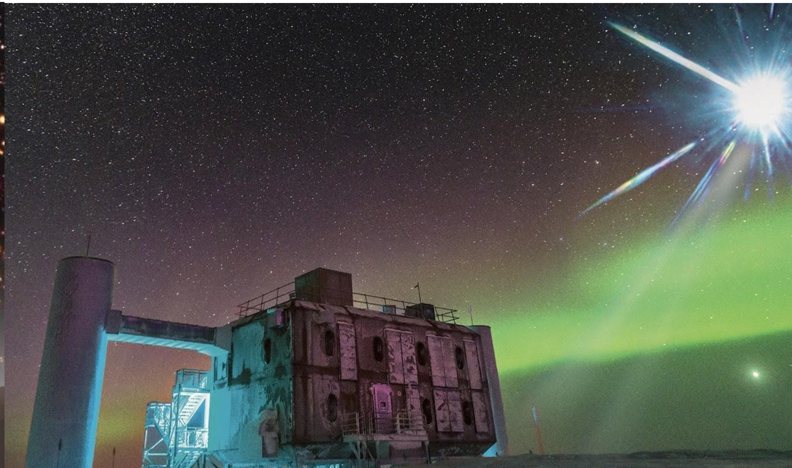
See Fritschel et al, https://dcc.ligo.org/LIGO-T2200287/public

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 + $1A^\sharp$	$1.4^{+2.1}_{-1.0} \times 10^4$	$3.4^{+5.3}_{-2.6} \times 10^3$	$9.7^{+15.7}_{-7.7} \times 10^1$

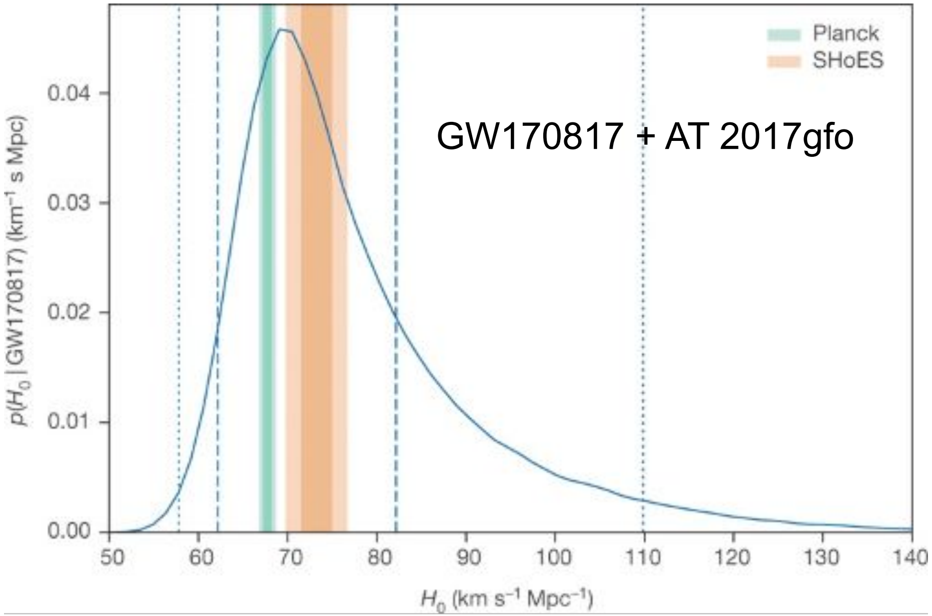
Ish Gupta & B. Sathyaprakash

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]

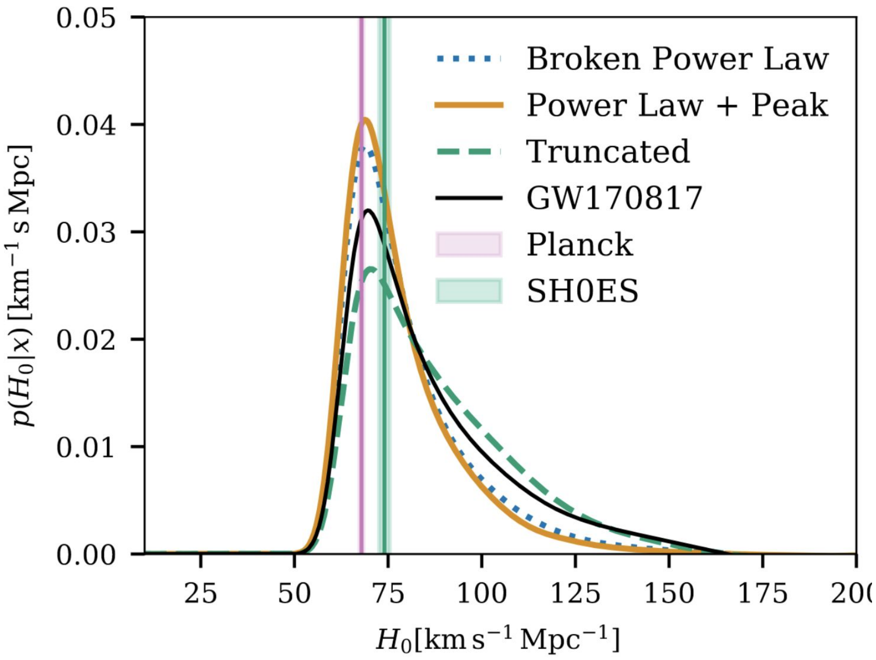
B P Abbott *et al.* *Nature* **551,** 85–88 (2017) doi:10.1038/nature24471



Challenges for cosmology with GW

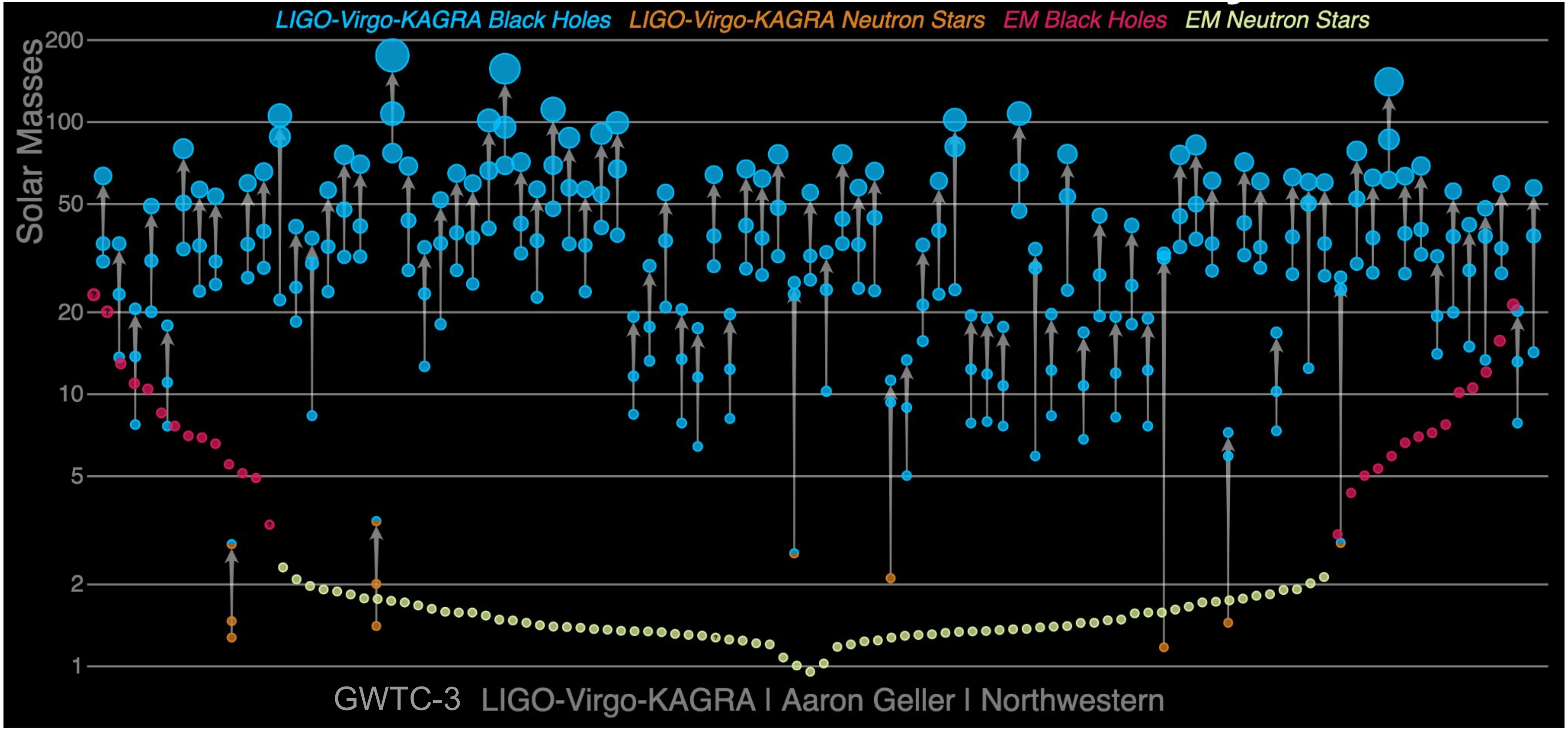
- Binaries with detectable EM counterparts are rare
  - With ~5-10 BNS mergers detectable in O4, expect ~1 detectable kilonova.
  - GRBs further away, but only a fraction beamed to Earth.
- Sub-percent accuracy with many
  - Completeness of galaxy catalogs decreases rapidly with redshift.
  - Mass scales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

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



Thank you!

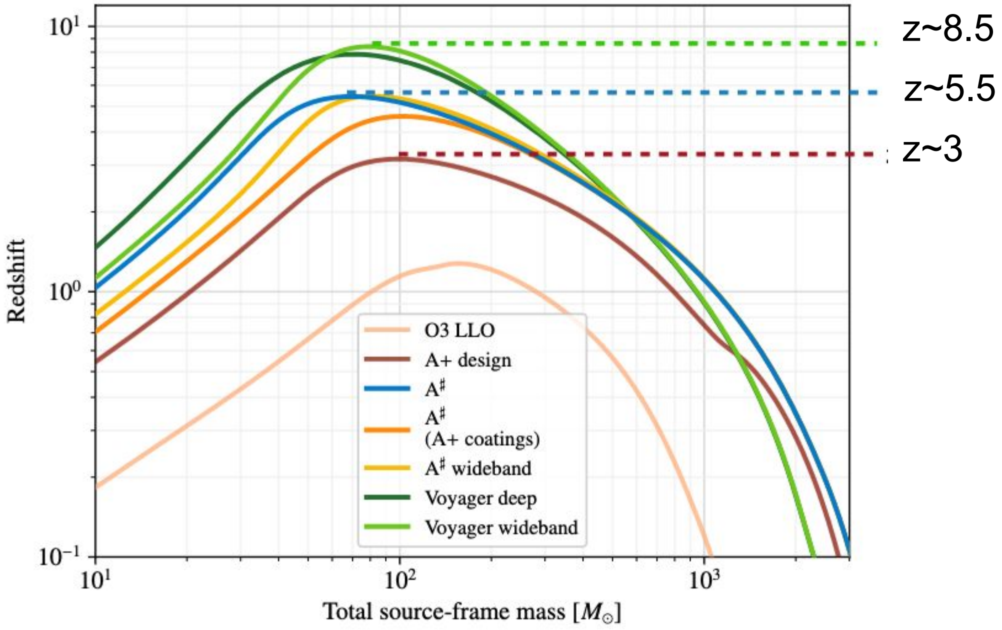
Gravitational-Wave Transient Catalog

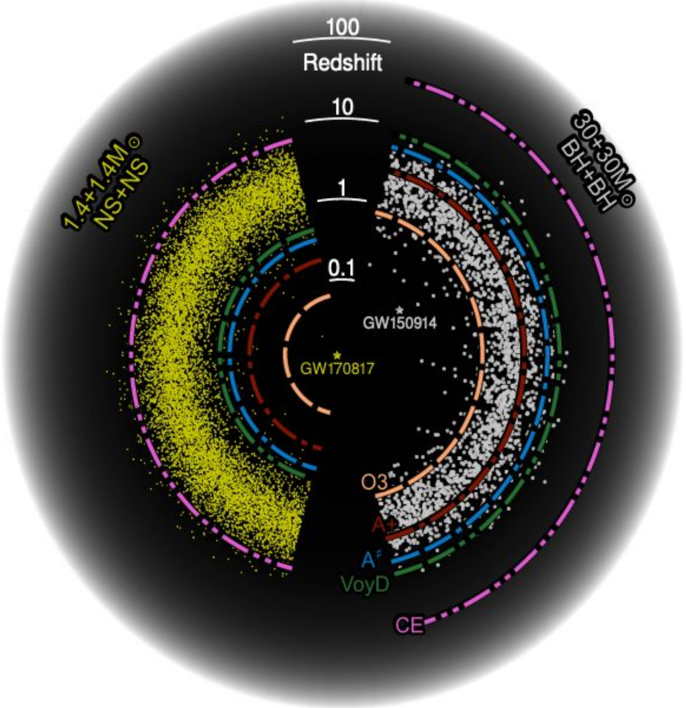


LIGO-Virgo-KAGRA, arXiv:2111.03606 [gr-qc]

Observational Science with A#

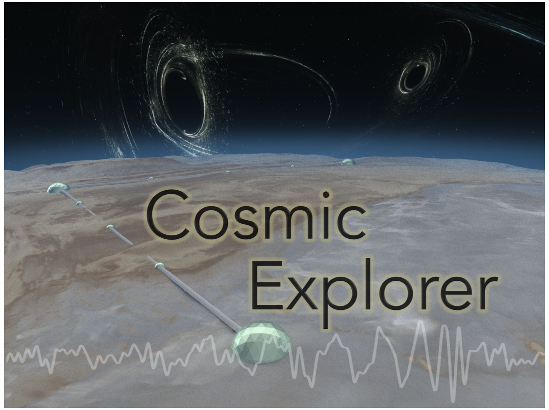
Horizon for optimally oriented and located binary mergers

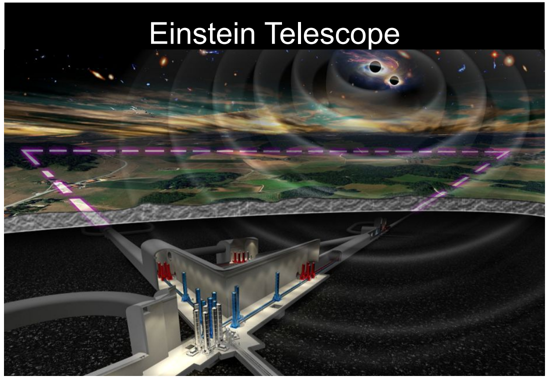


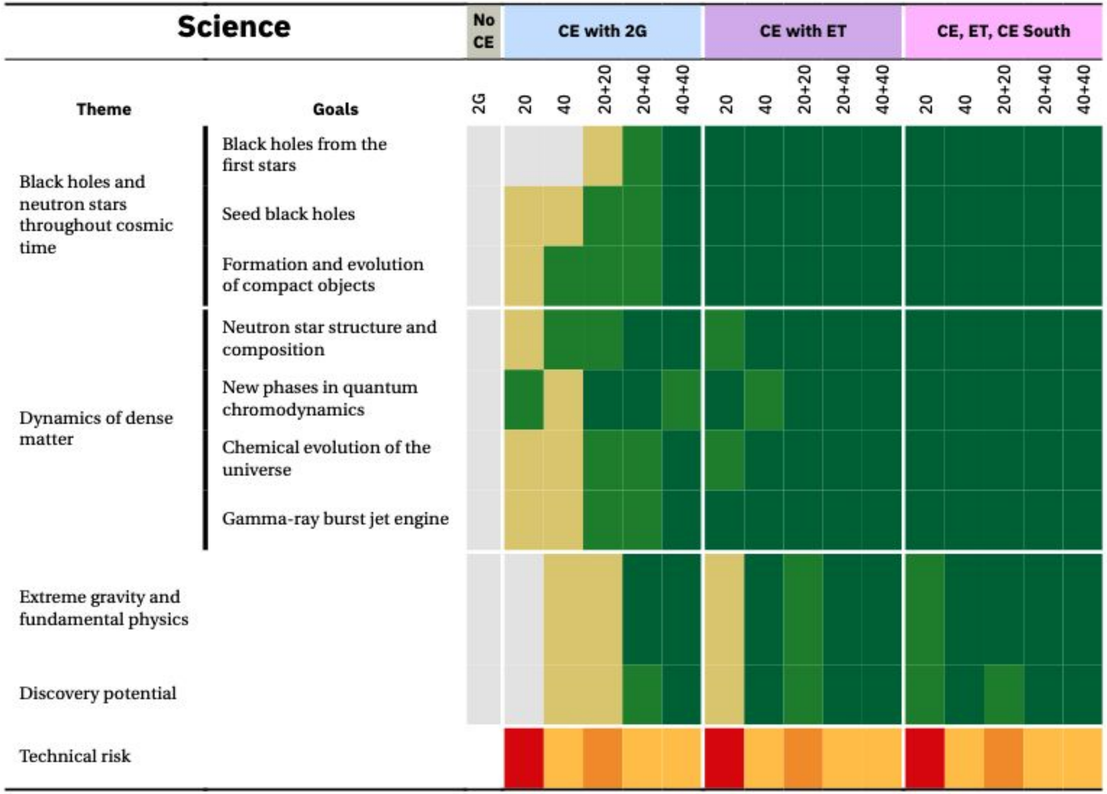


See Fritschel et al, https://dcc.ligo.org/LIGO-T2200287/public

Next Generation Detectors

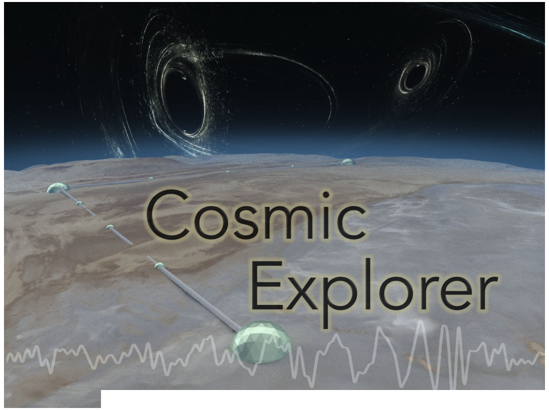






A Horizon Study for Cosmic Explorer
https://arxiv.org/abs/2109.09882

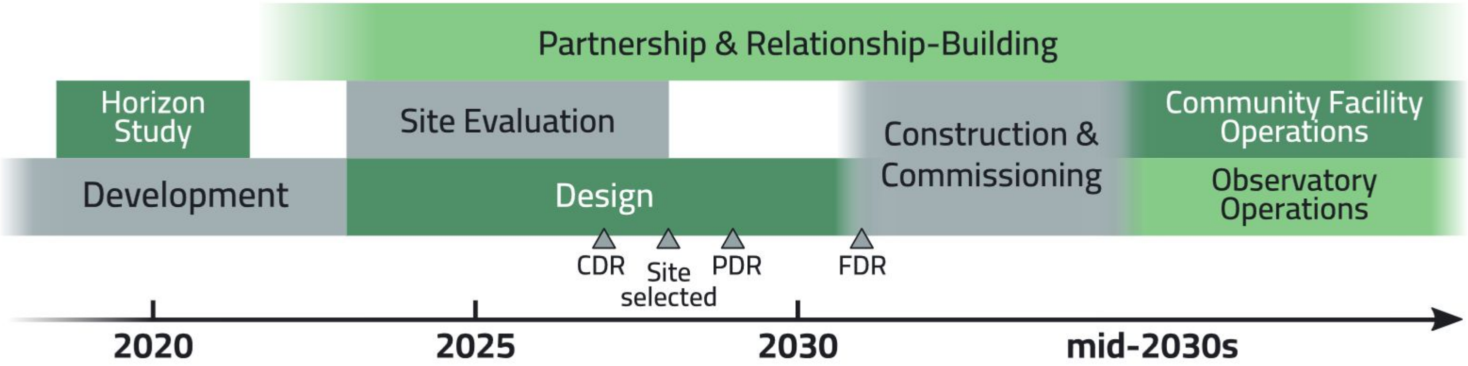
Cosmic Explorer Timeline



A Submission to the NSF MPSAC ngGW Subcommittee

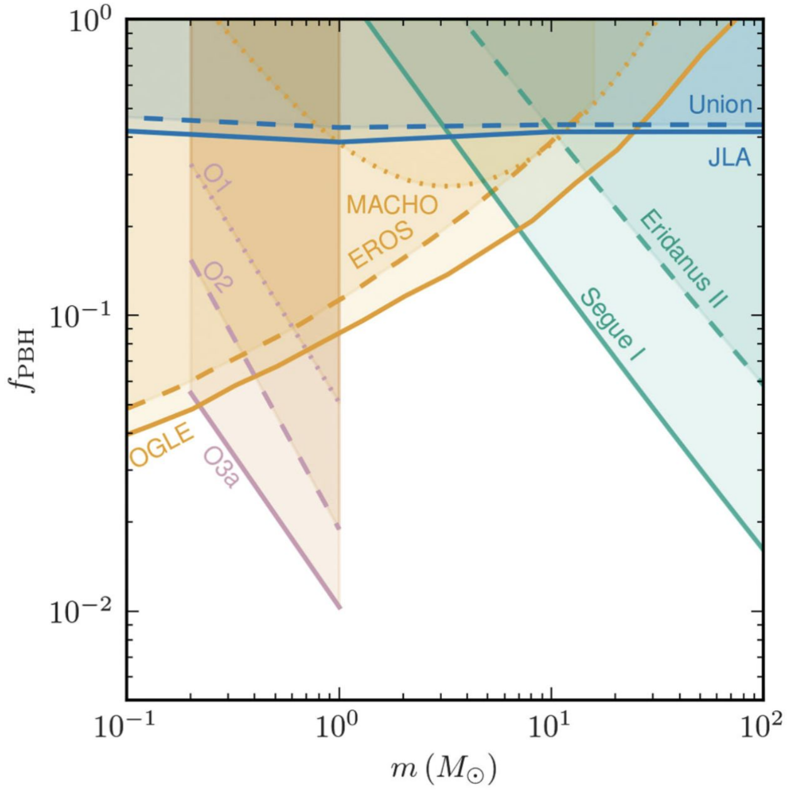
https://dcc.cosmicexplorer.org/CE-P2300018/public

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



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