Gravitational-wave science from the 3rd observing run of Advanced LIGO, Virgo and KAGRA

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Progress on Old and New Themes in Cosmology
2nd May 2023

Outline

- The third observing run
- What did we see in O3?
- The population of compact binaries
- Cosmological analyses with standard sirens
- What's next?

The third observing run

The third LVK observing run

The third observing run from April 2019 to March 2020 with a 1 month break for commissioning.

Total number of gravitational waves observed to date (with probability of astrophysical origin > 0.5): 90

GWTC-3 catalogue: arXiv:2111.03606

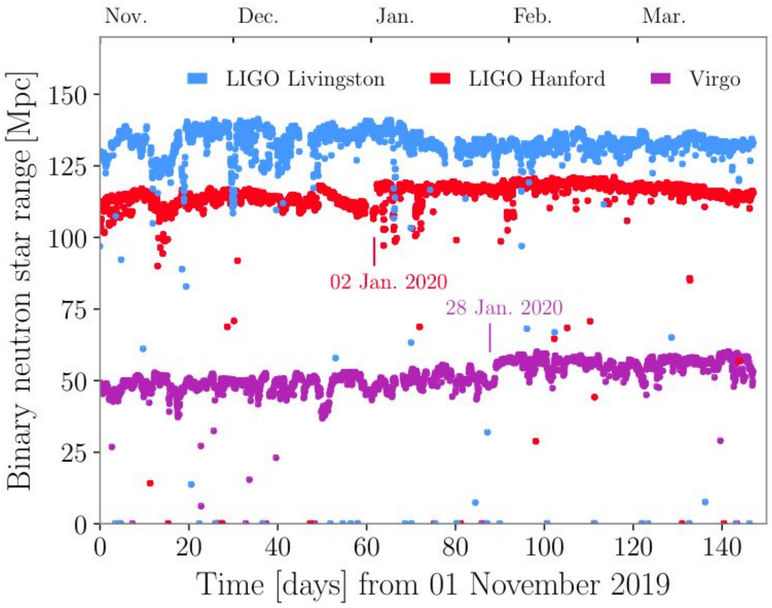

Aerial view of Virgo. Credit: The Virgo Collaboration

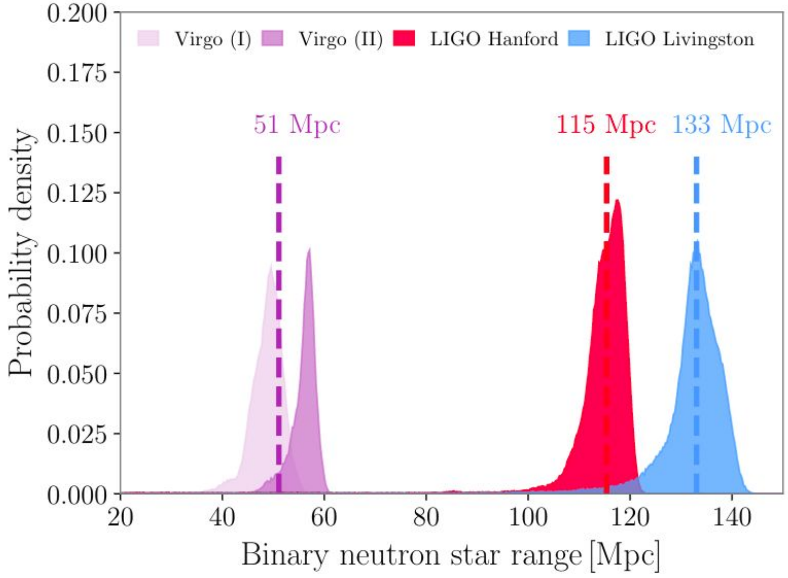

KAGRA. Credit: ICRR, Univ. of Tokyo


LIGO Livingston. Credit: Caltech/MIT/LIGO Lab


LIGO Hanford. Credit: LIGO

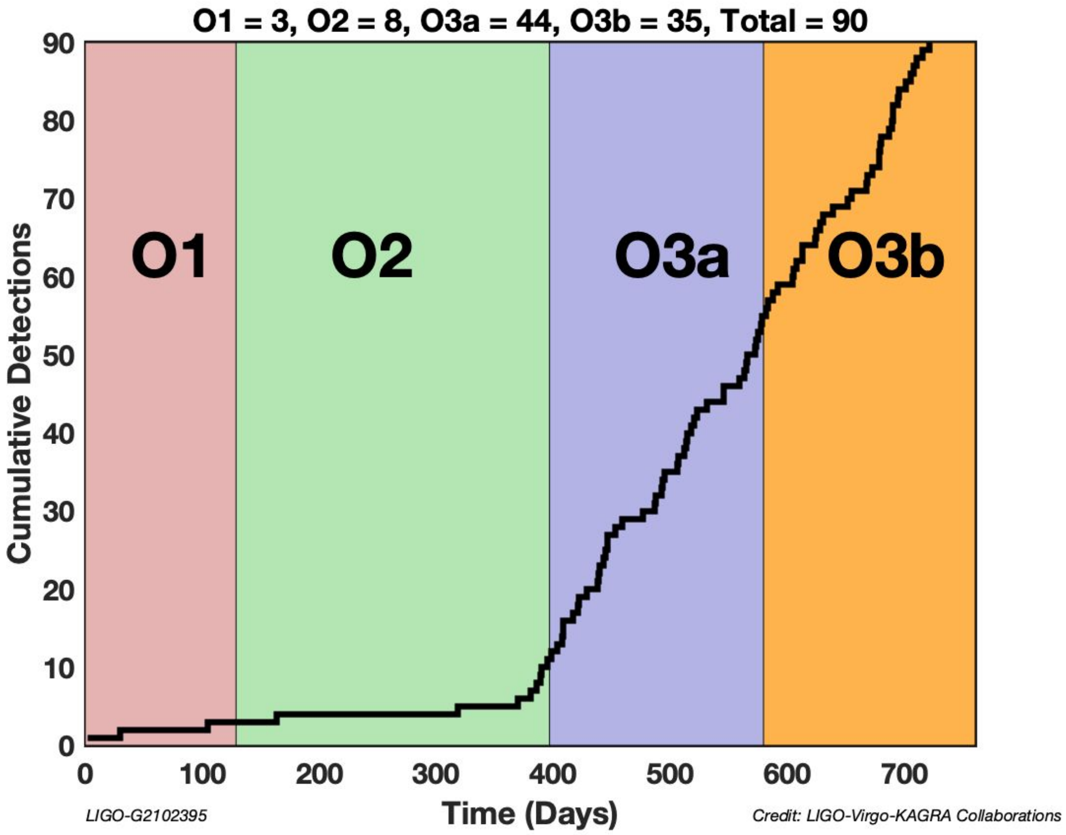
Detector sensitivity



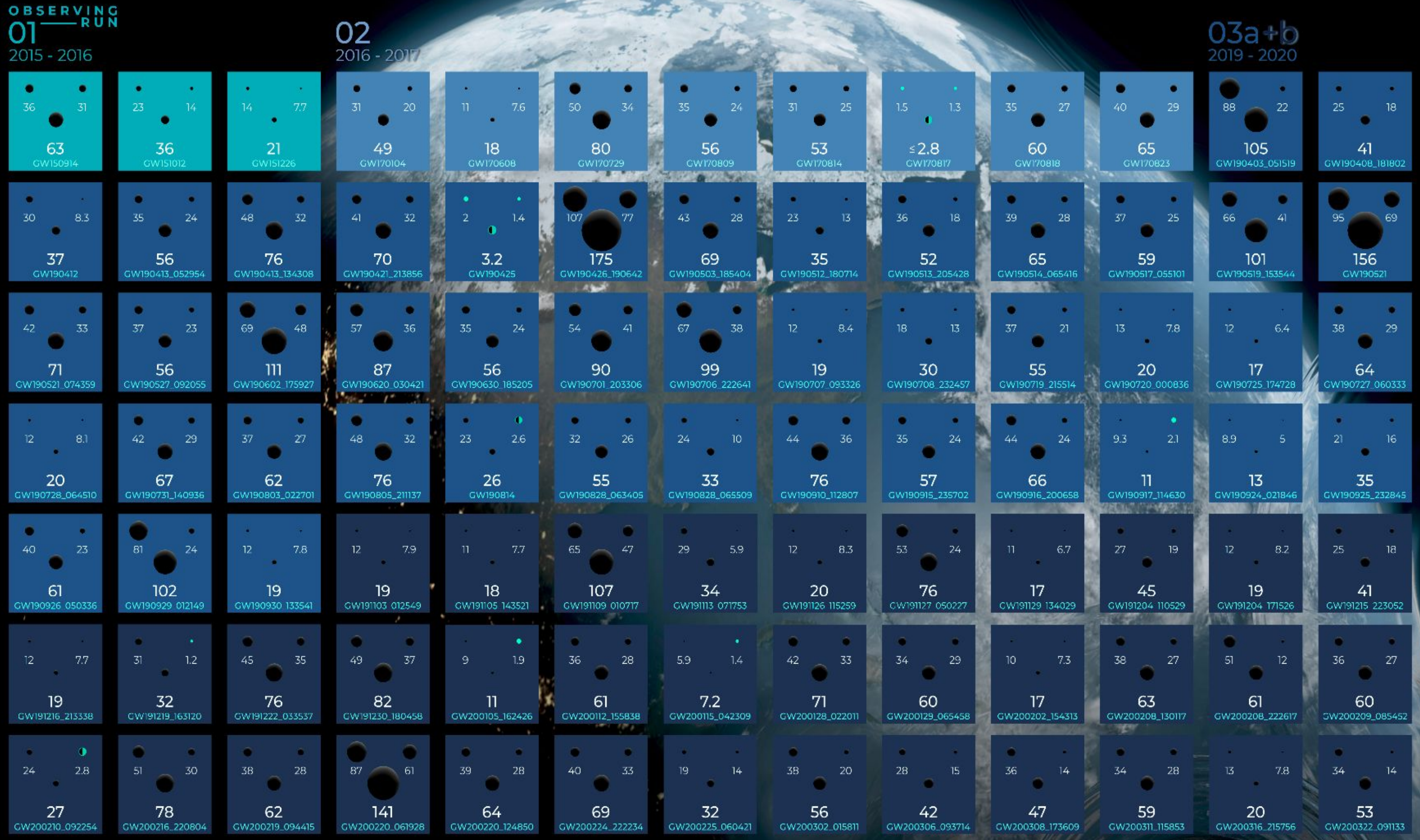


The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, Nov 2021, *arXiv:2111.03606*

Cumulative detections to date



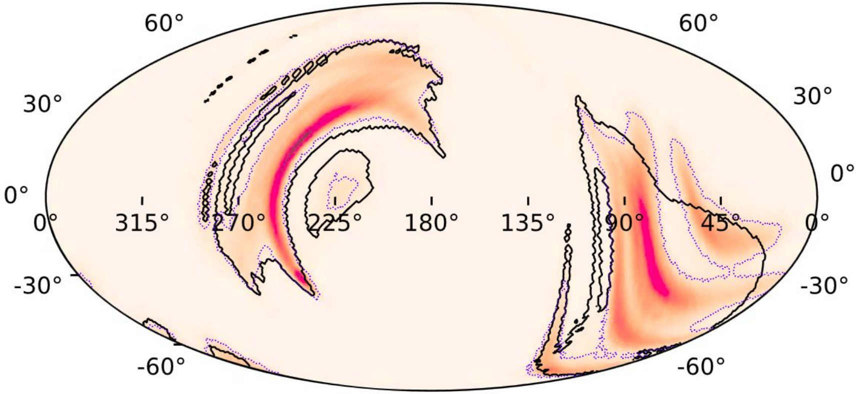
Credit: Carl Knox

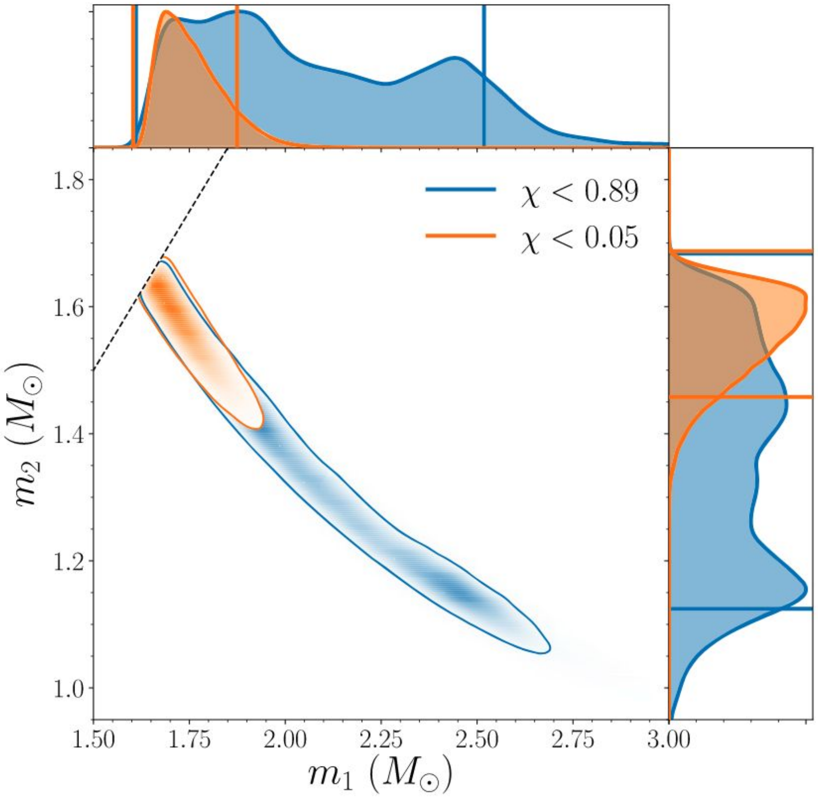


What did we see in O3?

BNS

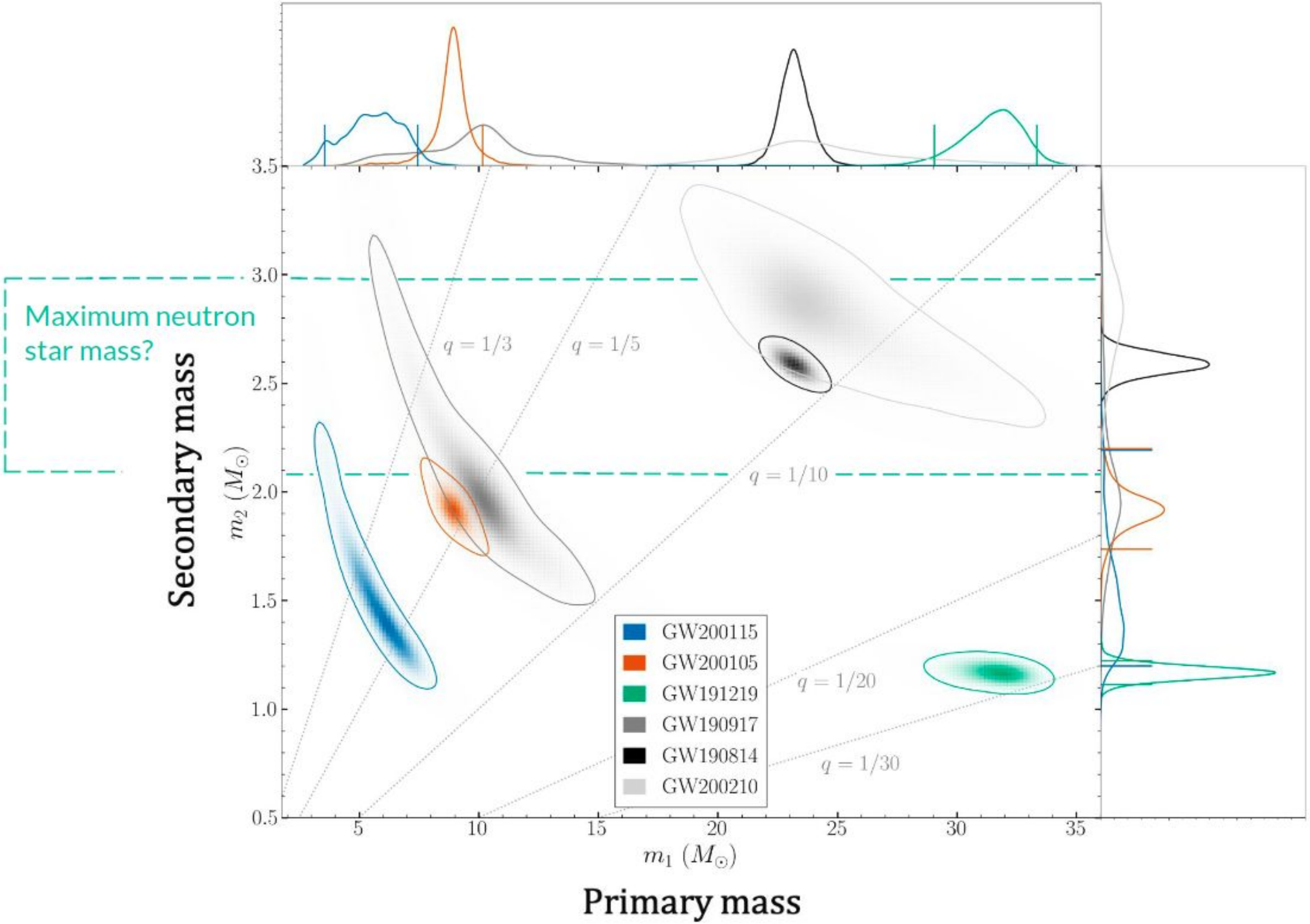
GW190425 is the second binary neutron star to be detected, after GW170817. Around 160 Mpc away.





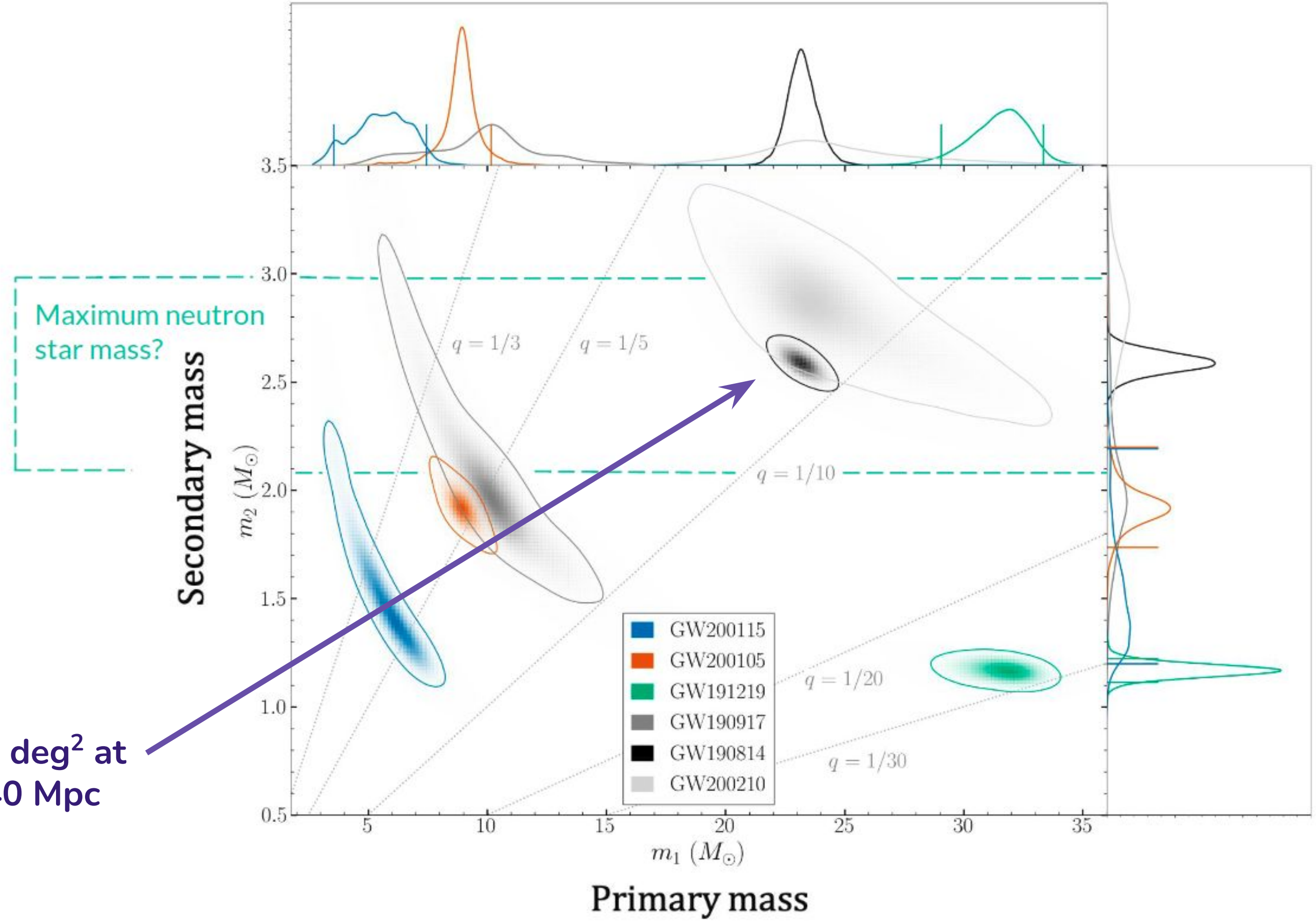
The LIGO Scientific Collaboration and the Virgo Collaboration, Astrophysical Journal Letters 892 (2020) L3

NSBHs



The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, GWTC-3 webinar

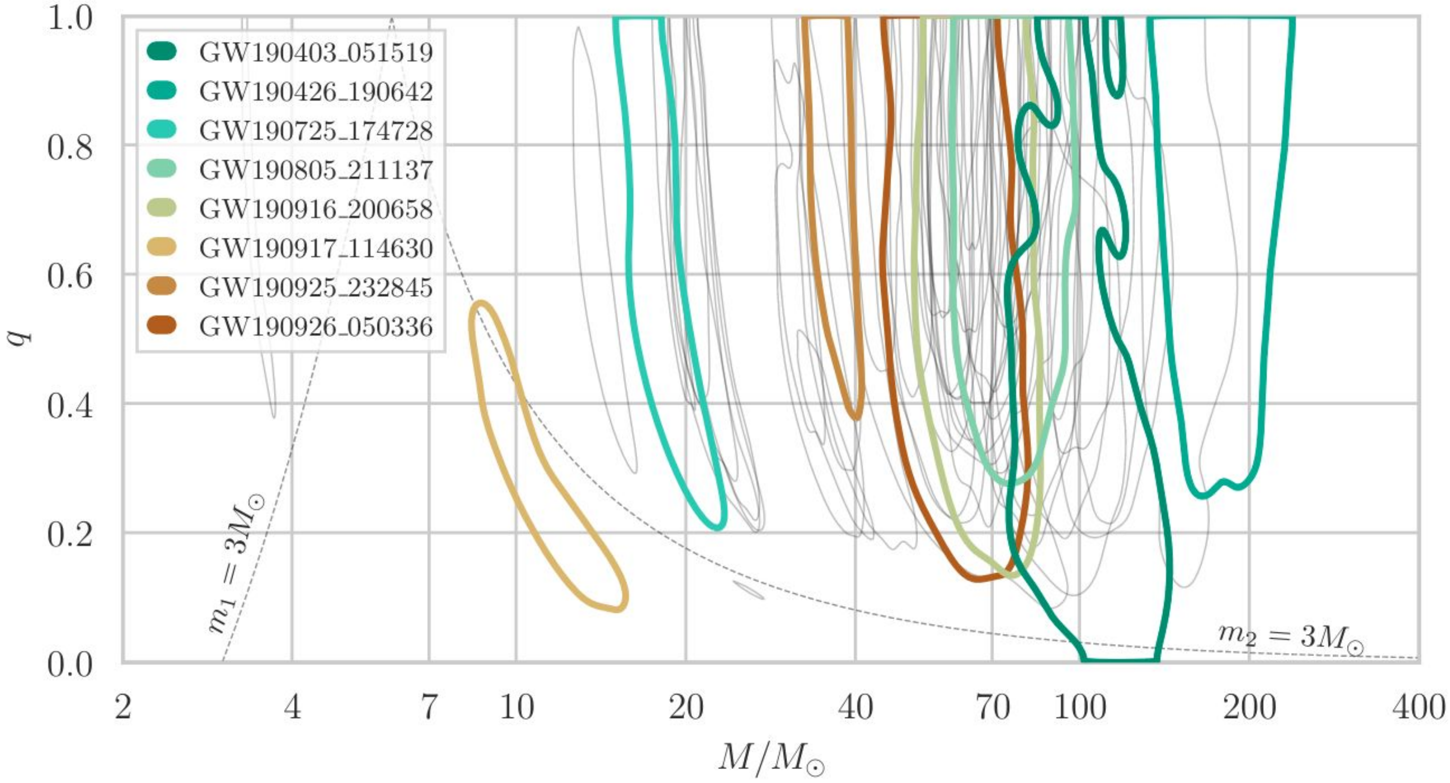
NSBHs



GW190814:
Localised to 18.5 deg^2 at a distance of ~240 Mpc

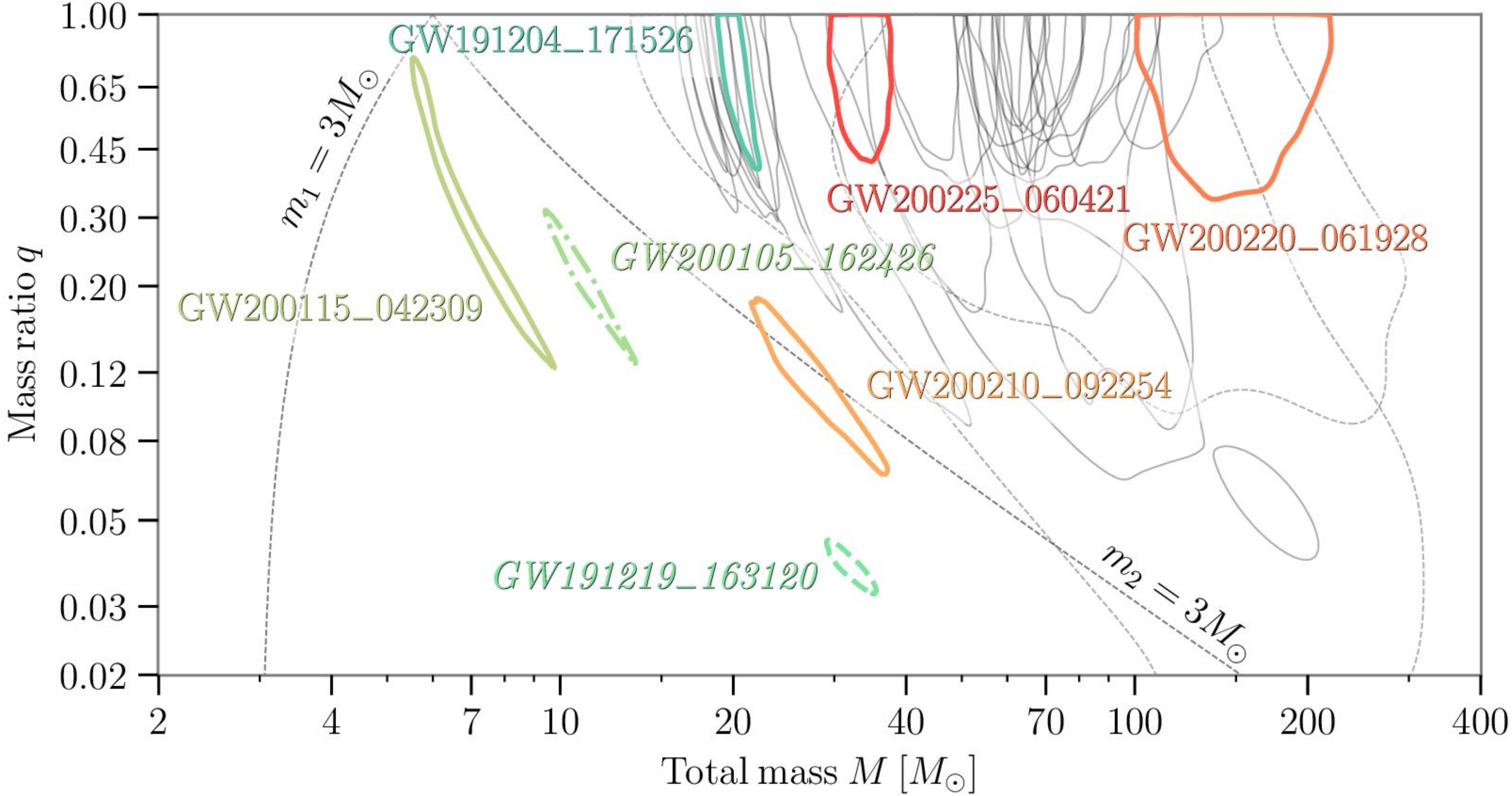
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, GWTC-3 webinar

Events from O3a



The LIGO Scientific Collaboration and Virgo Collaboration, *arXiv:2108.01045*

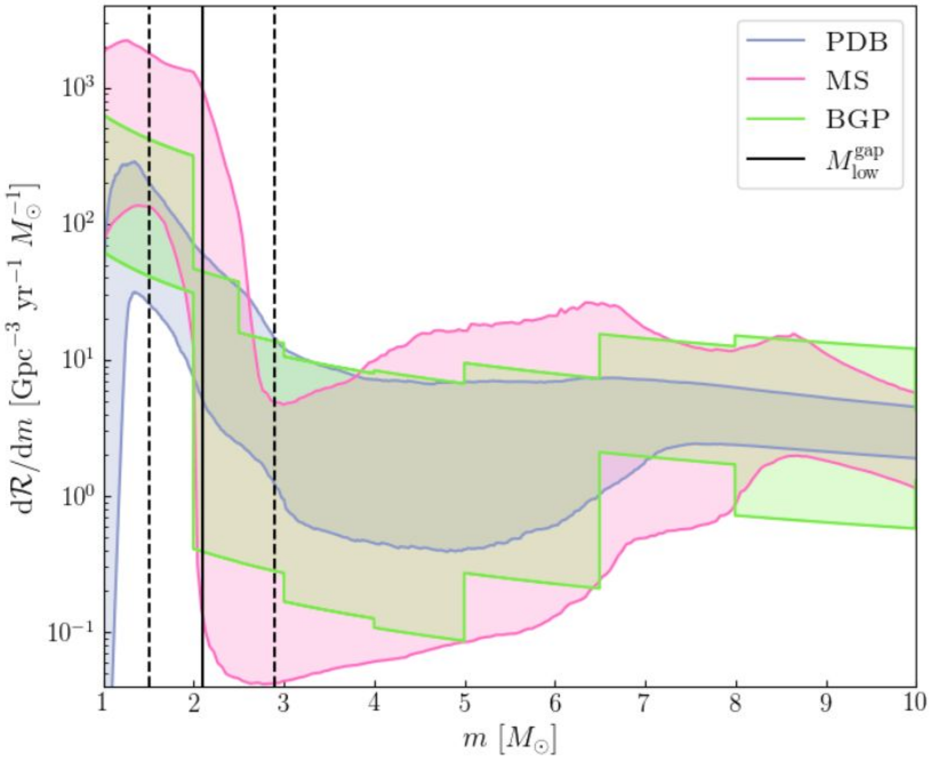
Events from O3b



The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, Nov 2021, *arXiv:2111.03606*

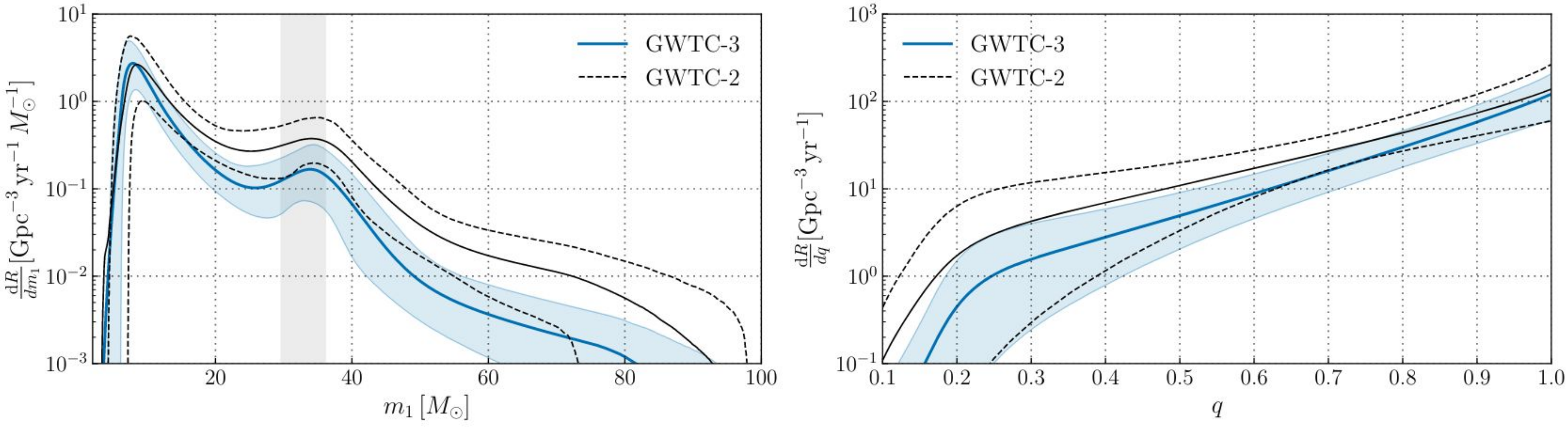
The population of compact binaries

Lower mass gap



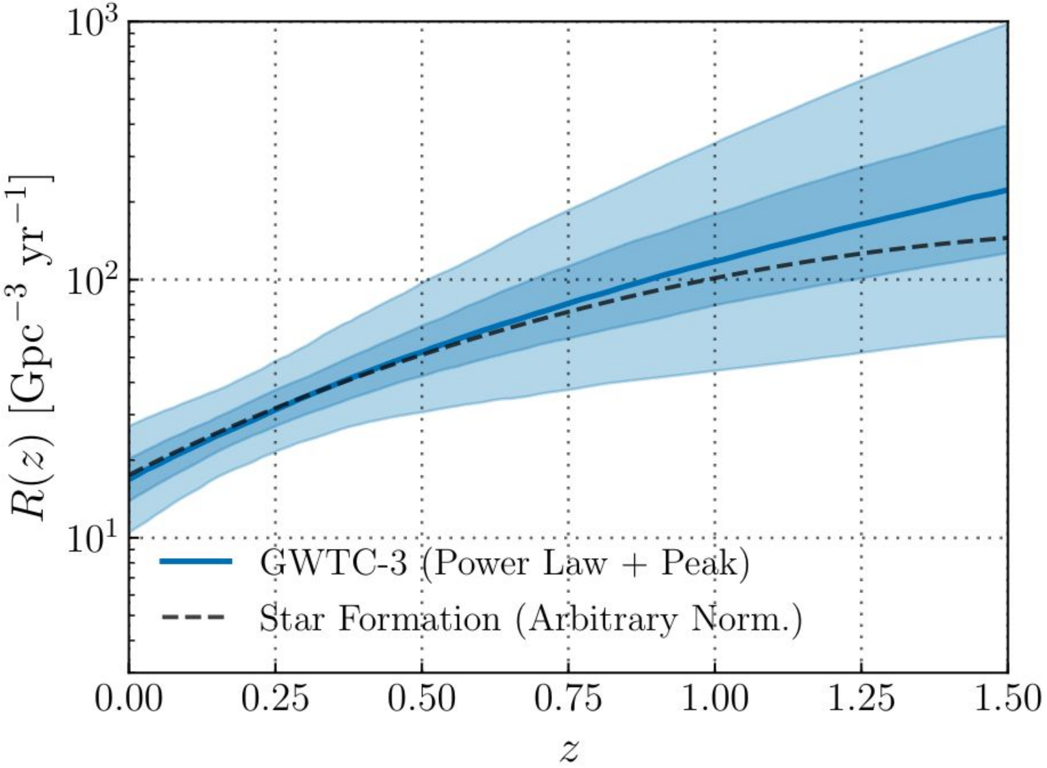
The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, Phys. Rev. X **13**, 011048, March 2023

Black hole mass distribution



The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration,
Phys. Rev. X **13**, 011048, March 2023

Evolution of merger rate with redshift



The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, Phys. Rev. X **13**, 011048, March 2023

Cosmological analyses with standard sirens

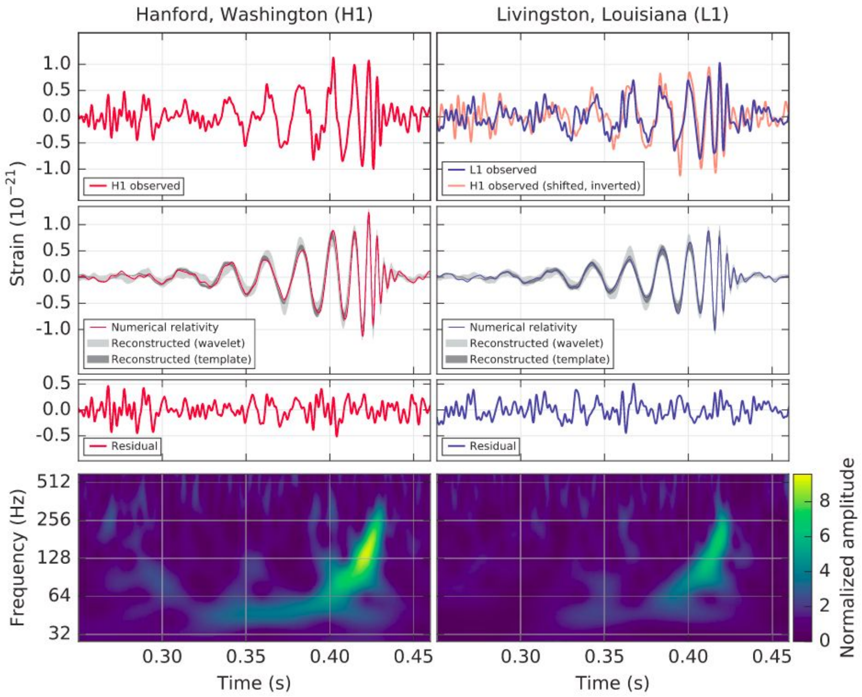
Gravitational waves as standard sirens

Signal amplitude is (inversely) proportional to luminosity distance to source, and independent of the cosmic distance ladder:

$$A = \frac{\mathcal{M}_z}{d_L} f(\mathcal{M}_z, t)$$

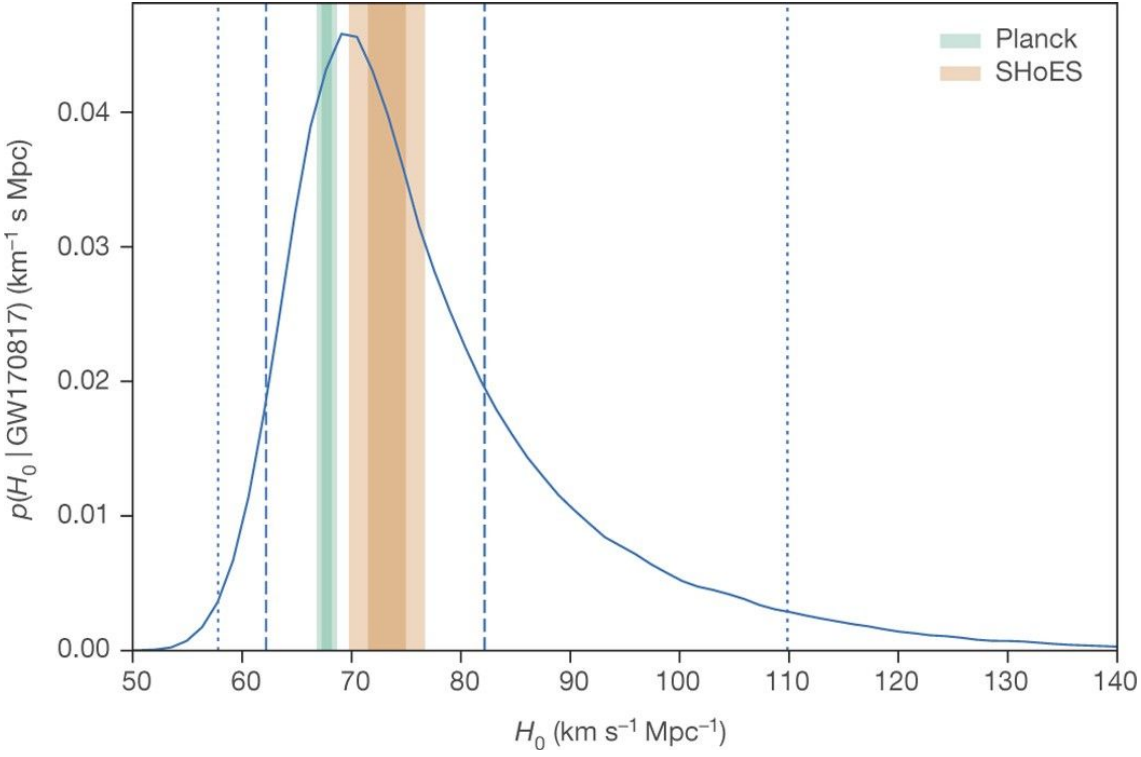
Redshifted chirp mass:

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

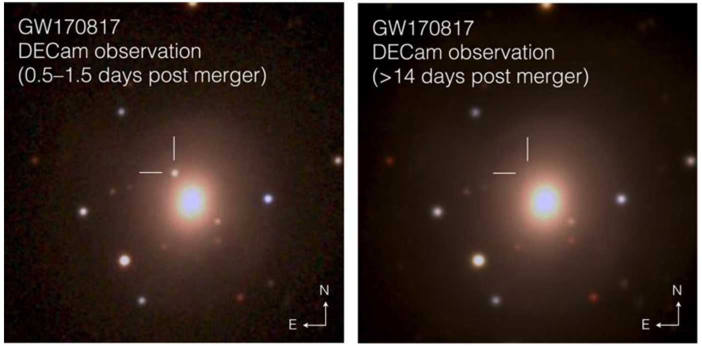


The LIGO Scientific Collaboration and Virgo Collaboration, *Phys. Rev. Lett.* **116**, 061102 – Published 11 February 2016

GW170817



The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration *et al.* *Nature* **551,** 85–88 (2017).



M. Soares-Santos *et al.* 2017
ApJL **848** L16

Cosmological analyses with standard sirens

"Bright sirens"

An **EM counterpart** is observed and used to obtain the host galaxy redshift.

AKA the EM counterpart method

"Dark sirens"

No EM counterpart observed. **Galaxy surveys** are used to provide redshift estimates for potential host galaxies.

AKA the galaxy catalogue method

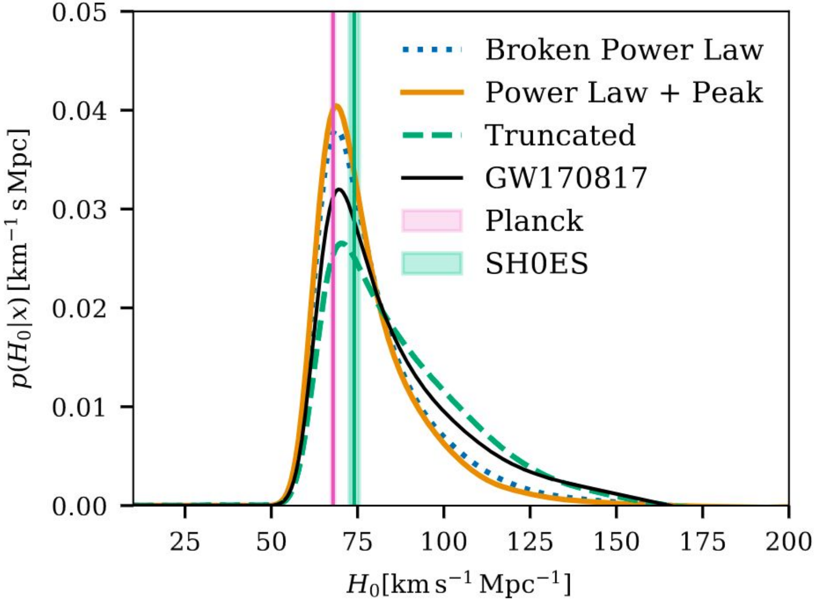
"Spectral sirens"

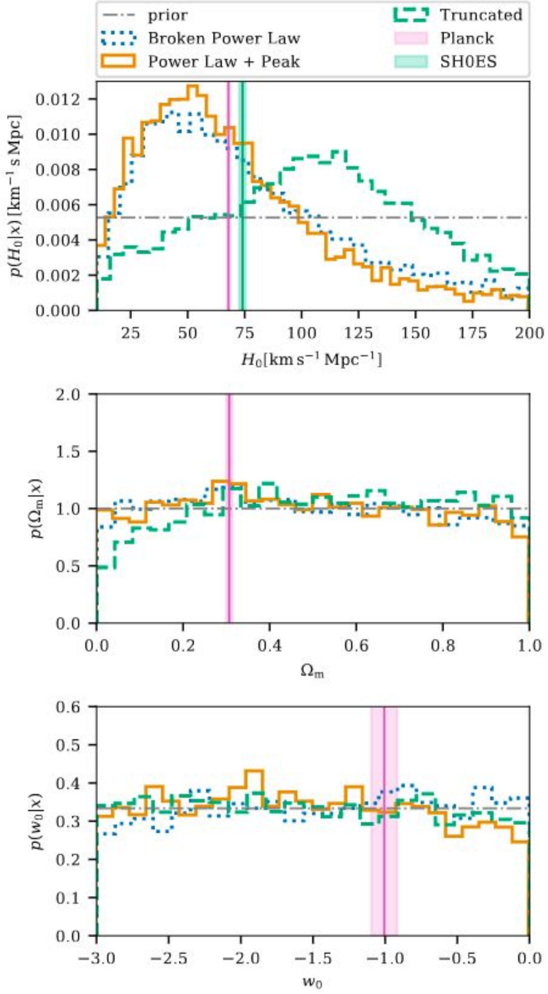
No EM counterpart or galaxy survey is used. Features in the **mass distribution** of the GW population break the mass-redshift degeneracy.

AKA the redshifted masses method

Results from redshifted masses

Marginal posteriors on H_0, Ω_m and w_0 using 42 binary black holes with SNR > 11, for 3 different mass models. $H_0 = 68^{+12}_{-8}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$





The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

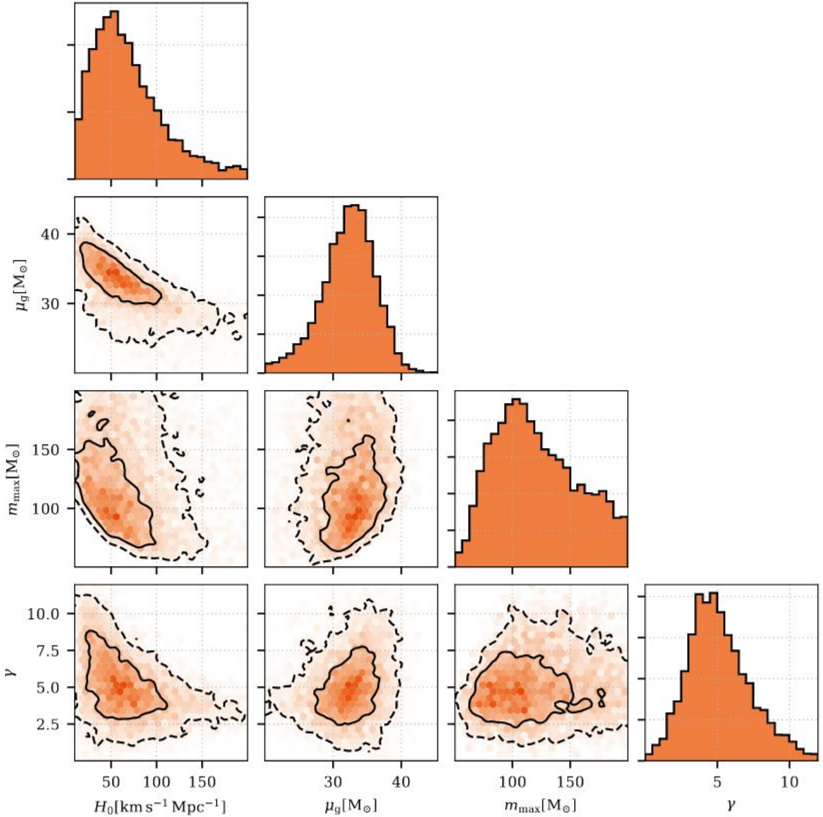
Correlation of cosmological and population parameters

Preferred model: powerlaw + peak

m_{max} (maximum black hole mass)

μ_g (position of the peak in the primary mass distribution)

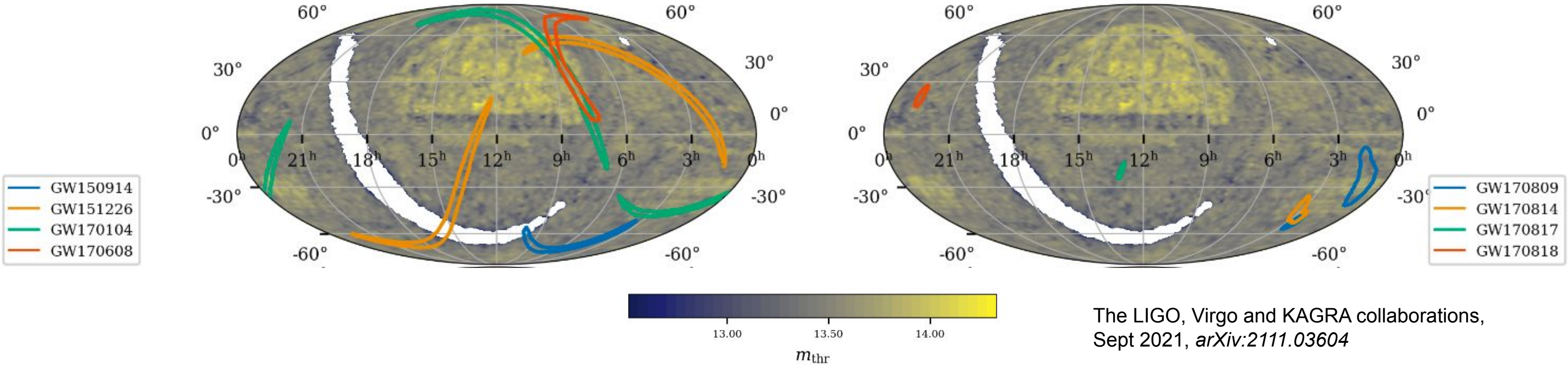
γ (low-z power-law slope of a Madau-Dickinson-like merger rate)



The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

Galaxy catalogues

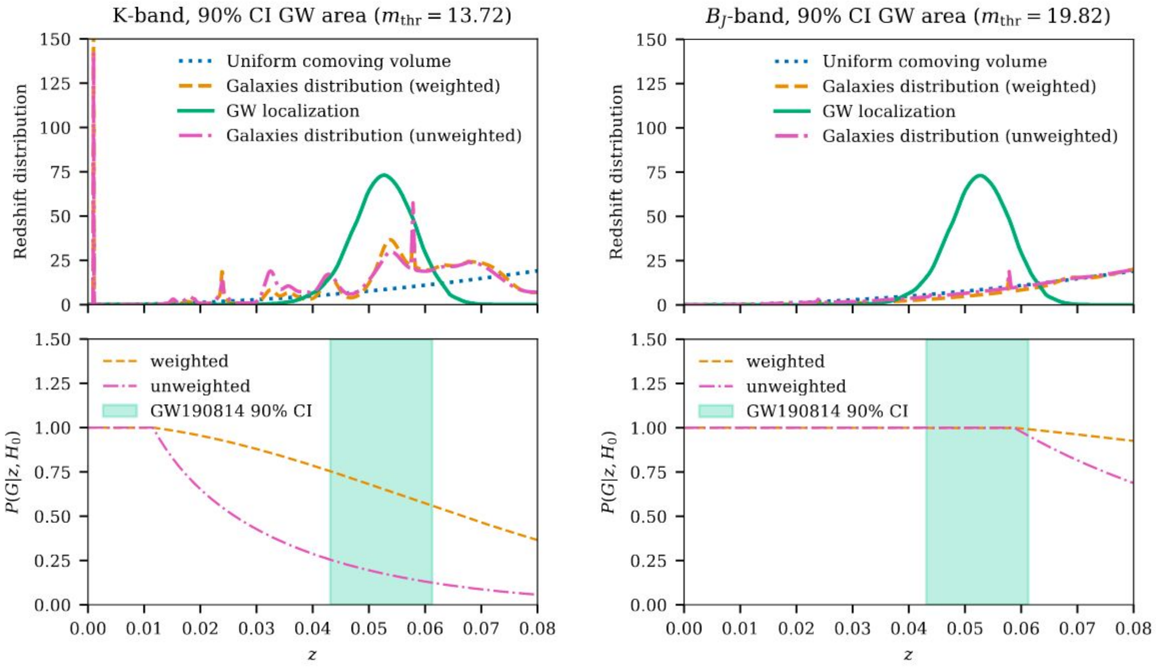
The galaxy catalogue analysis made use of the GLADE+ galaxy catalogue [1], constructed from the GWGC, 2MPZ, 2MASS XSC, HyperLEDA, and WISExSCOSPZ galaxy catalogues, and the SDSS-DR16Q quasar catalogue.

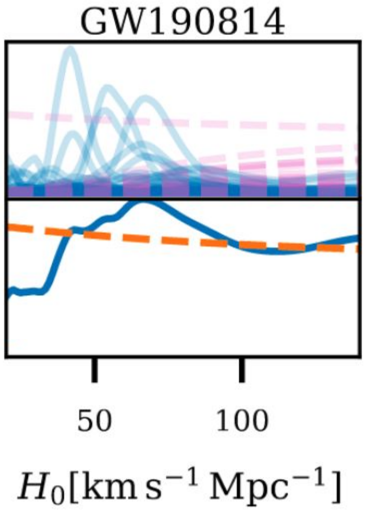


The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

[1] G Dálya *et al*. *MNRAS*, Volume 514, Issue 1, July 2022, Pages 1403–1411

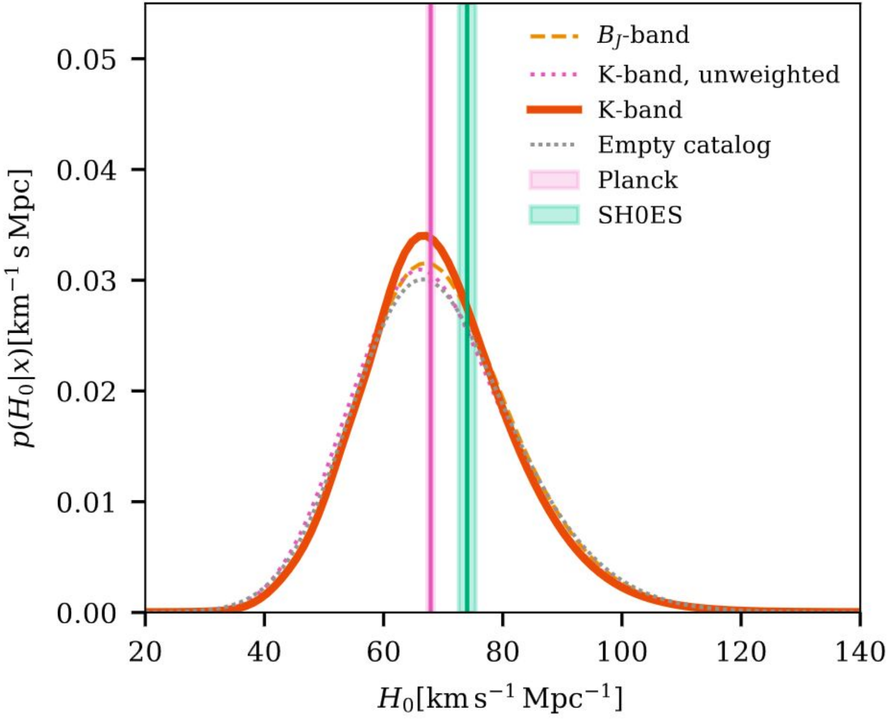
The most informative dark siren so far

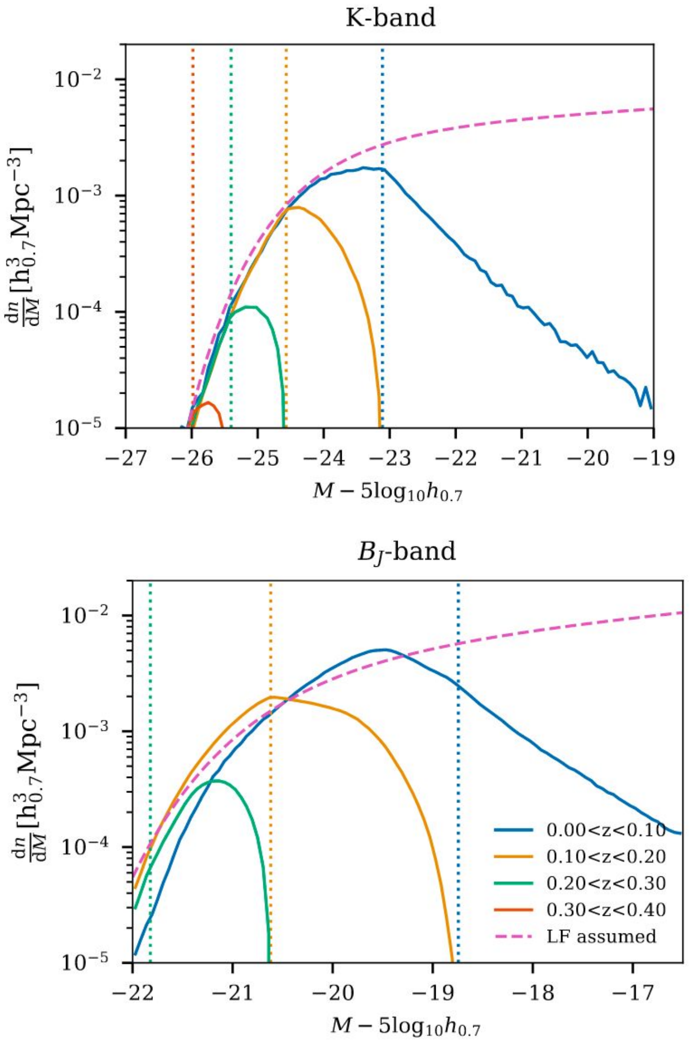




The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

Impact of catalogue assumptions



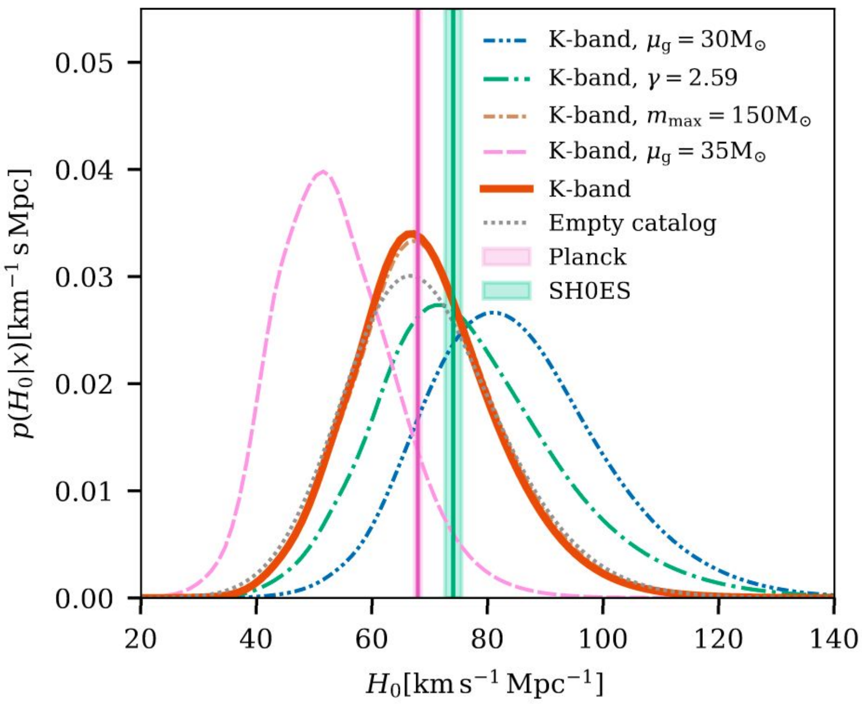


The LIGO, Virgo and KAGRA collaborations,
Sept 2021, *arXiv:2111.03604*

Impact of population assumptions

Changing the population parameters which correlate most strongly with H_0 (m_{max}, μ_g, γ), leads to a significant shift in the posterior.

The galaxy catalogue analysis is not separable from redshifted masses.



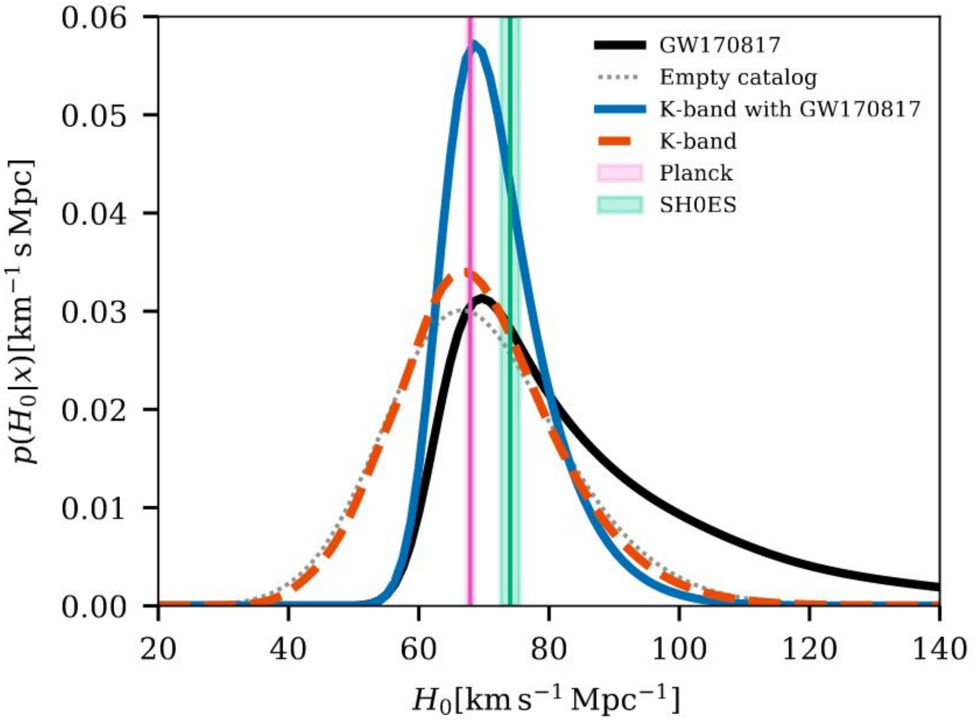
The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

Results from galaxy catalogues

Uses 42 BBH detections, GW190814, two BNS events and two NSBH events.

All are analysed with the GLADE+ galaxy catalogue in the K-band (apart from GW170817).

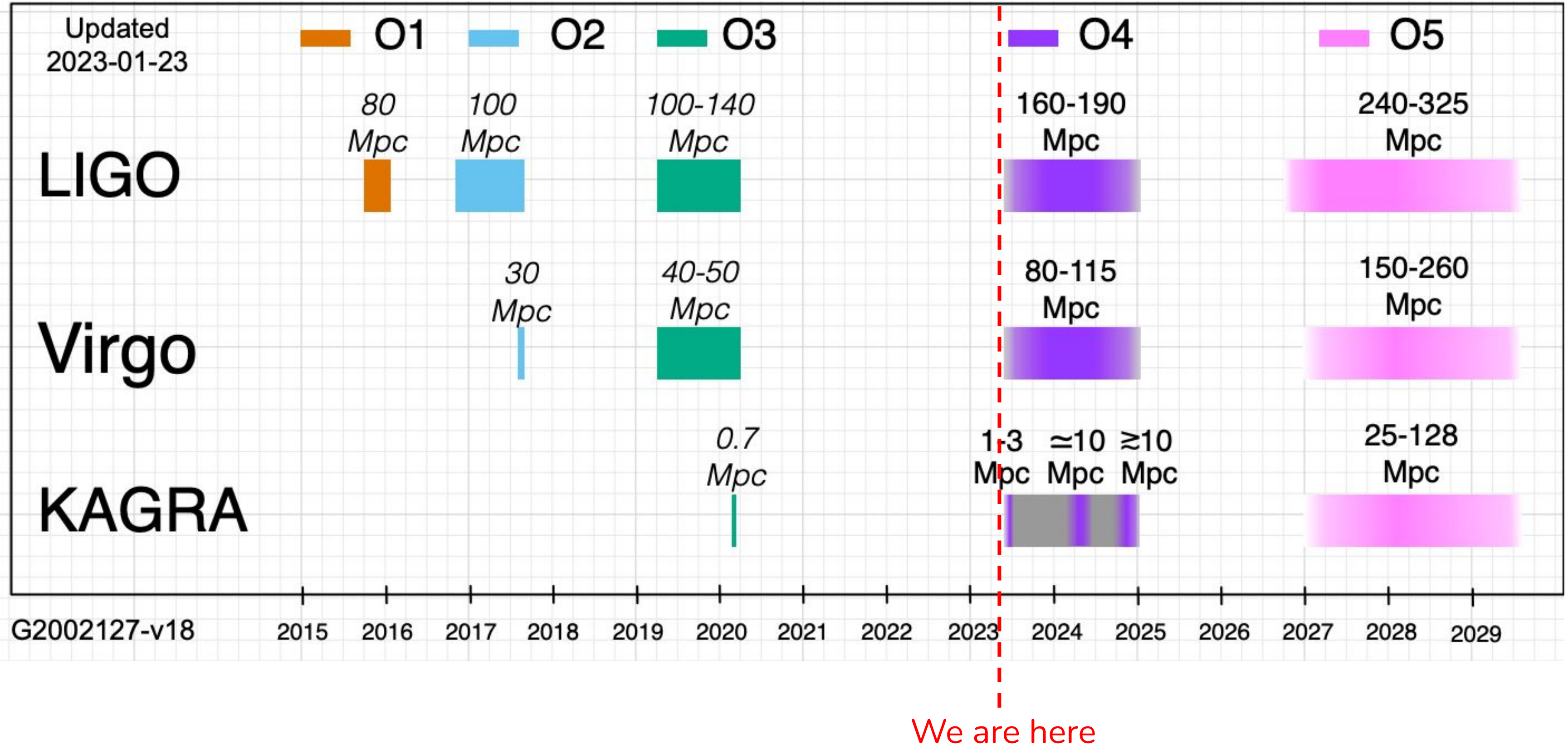
$$H_0 = 68^{+8}_{-6}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$



The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

What’s next?

Timeline of observing runs



Summary

The third observing run had the greatest sensitivity range range to date, leading to an impressive catalogue of detections.

These detections cover a diverse range of masses, and include the first confident detection of a neutron star-black hole merger!

This set of events has allowed us to constrain the astrophysical population of events to the greatest degree of accuracy so far. Cosmological results provide interesting hints of what is to come, but are not yet competitive with non-GW measurements.

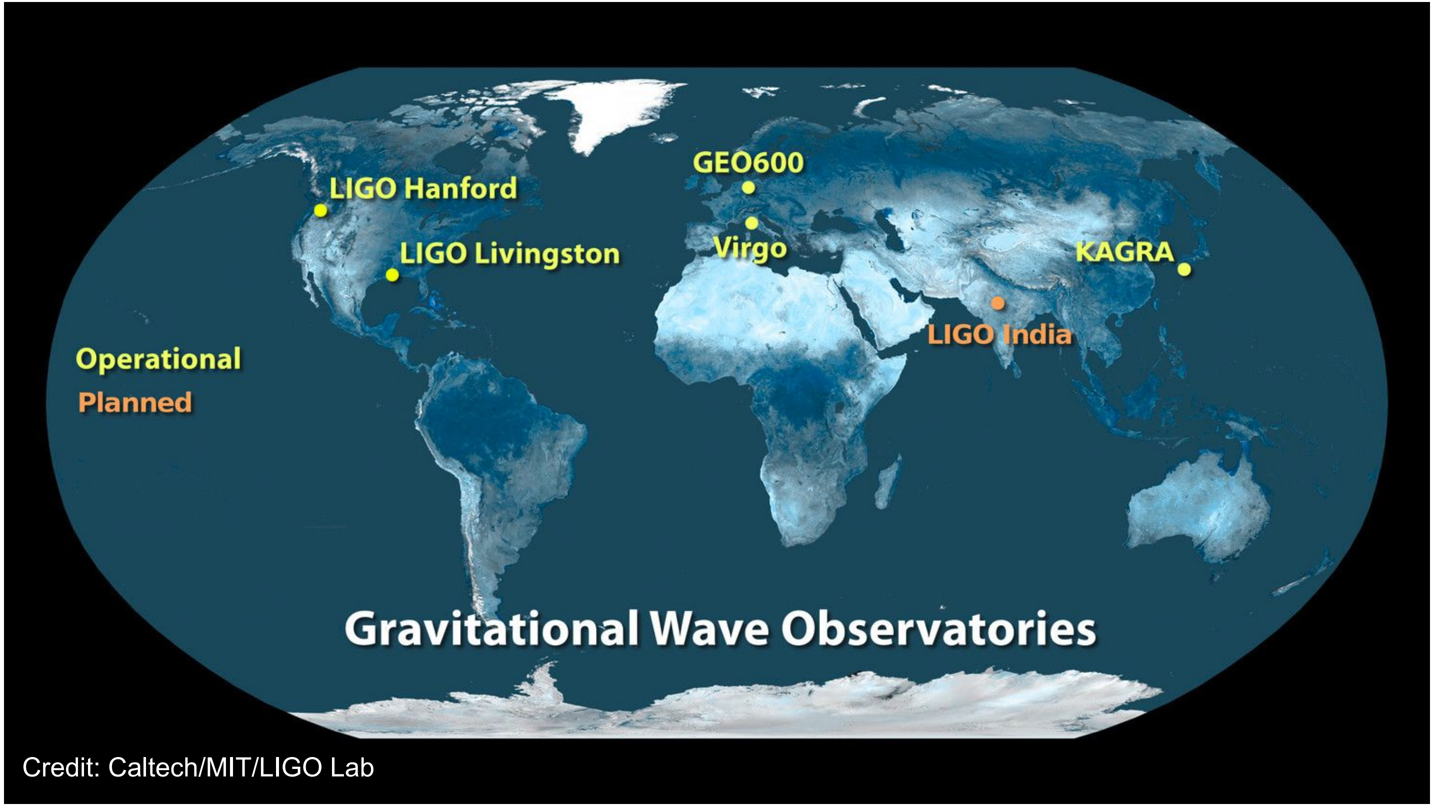
O4 is starting soon (24th May) and will last for 18 months, which will greatly expand the catalogue of GW detections.

Thanks for listening!

This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Extra slides

The gravitational-wave detector network



Rates

Merger rates in Gpc^{-3} yr^{-1} for different mass bins:

	BNS	NSBH	BBH	NS-Gap	BBH-gap	Full
	$m_1 \in [1, 2.5]M_\odot$	$m_1 \in [2.5, 50]M_\odot$	$m_1 \in [2.5, 100]M_\odot$	$m_1 \in [2.5, 5]M_\odot$	$m_1 \in [2.5, 100]M_\odot$	$m_1 \in [1, 100]M_\odot$
	$m_2 \in [1, 2.5]M_\odot$	$m_2 \in [1, 2.5]M_\odot$	$m_2 \in [2.5, 100]M_\odot$	$m_2 \in [1, 2.5]M_\odot$	$m_2 \in [2.5, 5]M_\odot$	$m_2 \in [1, 100]M_\odot$
PDB (pair)	170^{+270}_{-120}	27^{+31}_{-17}	$25^{+10}_{-7.0}$	19^{+28}_{-13}	$9.3^{+15.7}_{-7.2}$	240^{+270}_{-140}
PDB (ind)	44^{+96}_{-34}	73^{+67}_{-37}	$22^{+8.0}_{-6.0}$	$12^{+18}_{-9.0}$	$9.7^{+11.3}_{-7.0}$	150^{+170}_{-71}
MS	660^{+1040}_{-530}	49^{+91}_{-38}	37^{+24}_{-13}	$3.7^{+35.3}_{-3.4}$	$0.12^{+24.88}_{-0.12}$	770^{+1030}_{-530}
BGP	$98.0^{+260.0}_{-85.0}$	$32.0^{+62.0}_{-24.0}$	$33.0^{+16.0}_{-10.0}$	$1.7^{+30.0}_{-1.7}$	$5.2^{+12.0}_{-4.1}$	$180.0^{+270.0}_{-110.0}$
MERGED	$10 - 1700$	$7.8 - 140$	$16 - 61$	$0.02 - 39$	$9.4 \times 10^{-5} - 25$	$72 - 1800$

The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, Phys. Rev. X **13**, 011048, March 2023