Cosmological constraints from the 3rd observing run of Advanced LIGO, Virgo and KAGRA

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10th LISA Cosmology Working Group Workshop

Stavanger, Norway, 6th June 2023

Outline

- The third observing run
- Cosmological analyses with standard sirens
- Using the black hole mass distribution for cosmological inference
- Using galaxy catalogues for cosmological inference
- 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

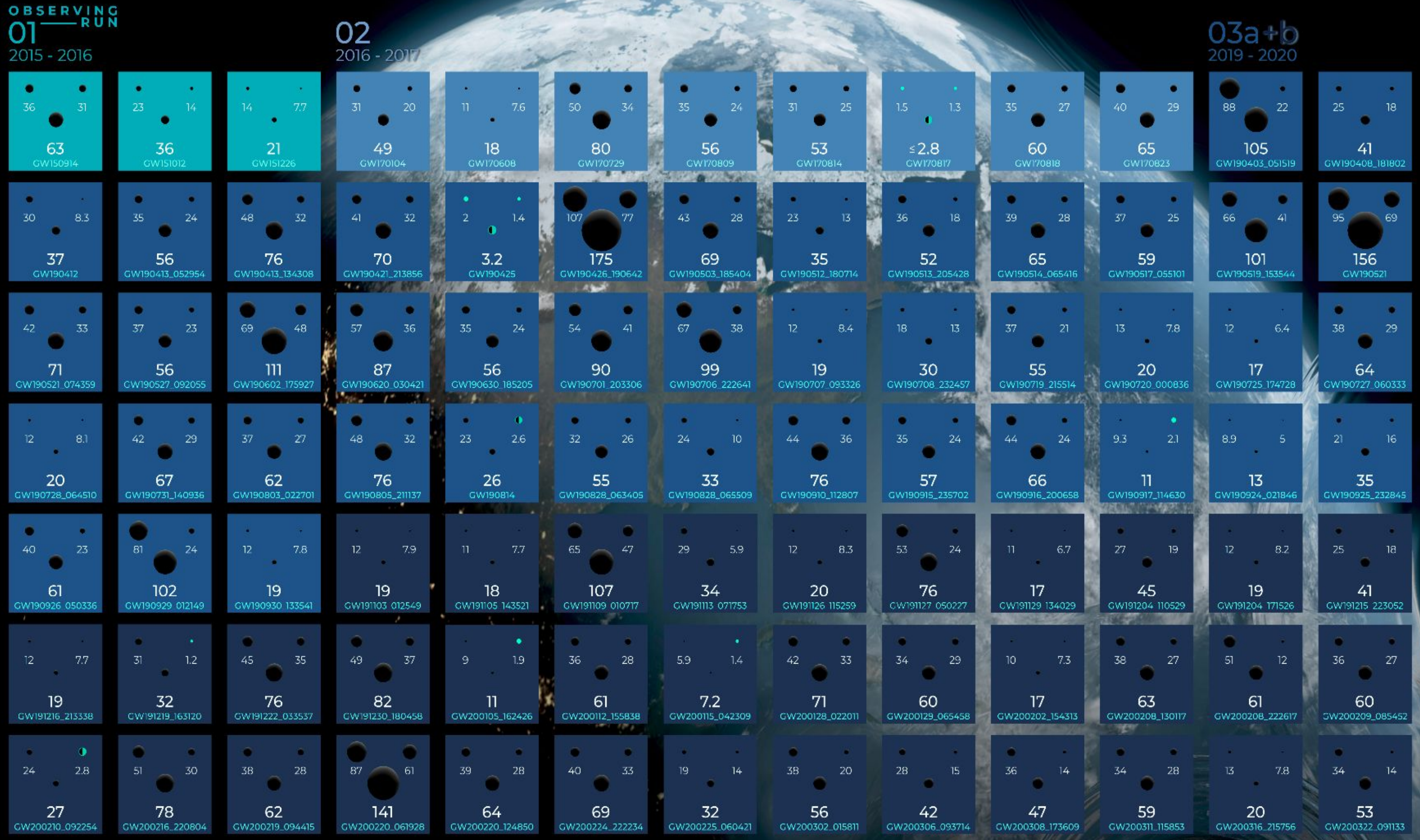

Aerial view of Virgo. Credit: The Virgo Collaboration


KAGRA. Credit: ICRR, Univ. of Tokyo


LIGO Livingston. Credit: Caltech/MIT/LIGO Lab

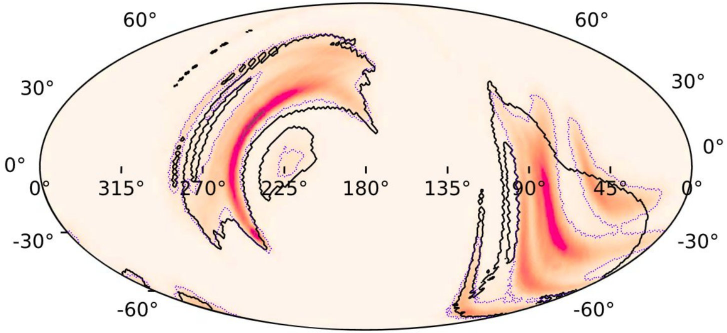

LIGO Hanford. Credit: LIGO

Credit: Carl Knox



A selection of interesting events

- **GW190425**: the second binary neutron star to be detected. Around 160 Mpc away. Detected by L1, V1.
- **GW191219, GW200105, GW200115**: first confident NSBH detections
- **GW190814**: an asymmetric mass compact binary. Only 240 Mpc away, and localised to 18.5 deg^2.



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

Cosmological analyses with standard sirens

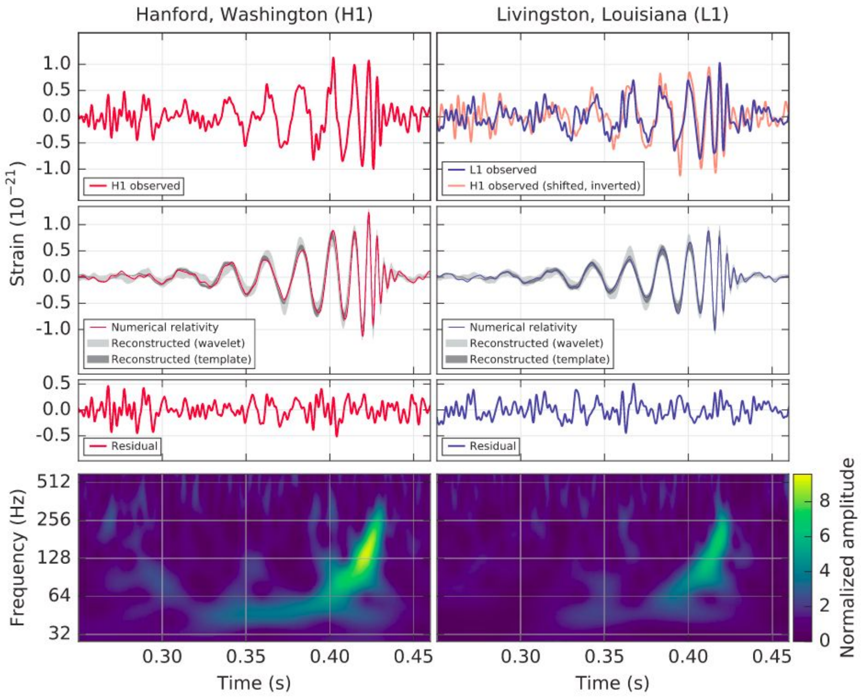
Gravitational waves as standard sirens

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

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

Using the black hole mass distribution for cosmological inference

Cosmological + population inference with $N_{\rm obs}$ GW events

Individual GW event likelihoods

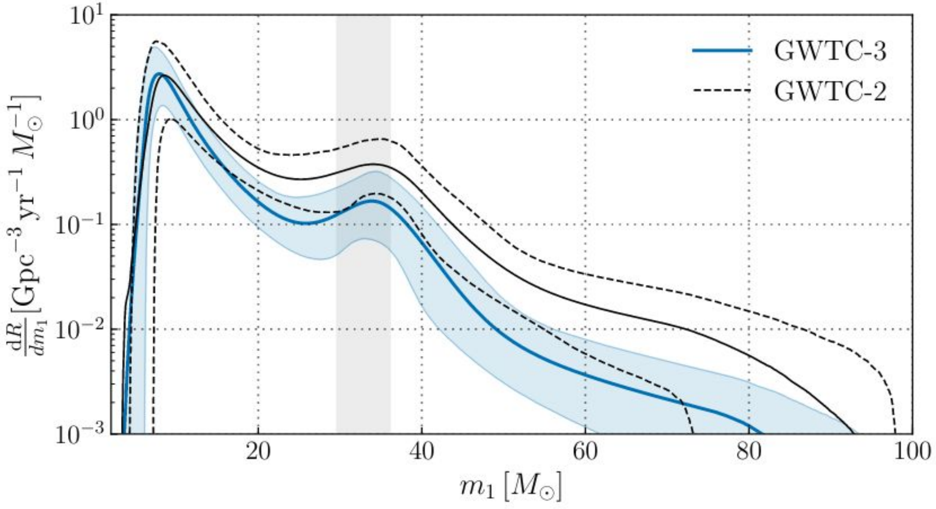
priors

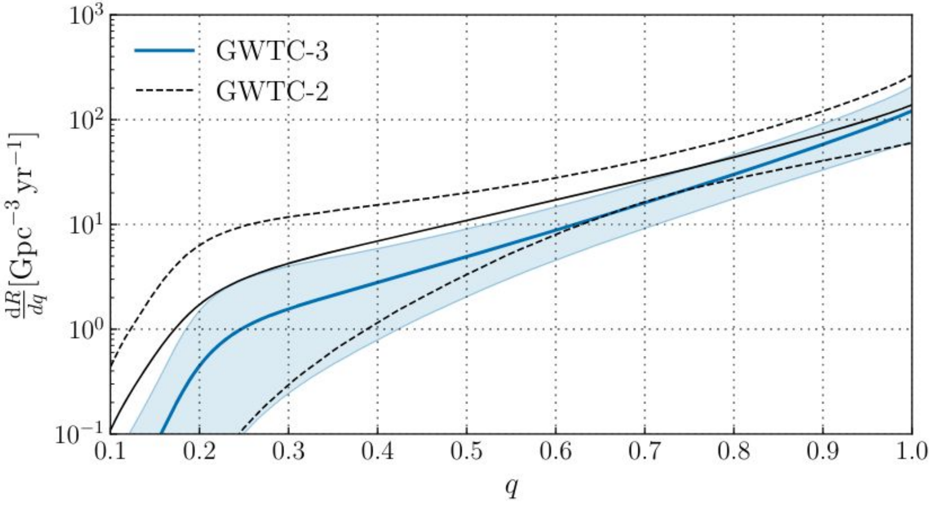
$$p(\Phi|\{x\}, N_{\rm obs}) = p(\Phi) \prod_{i=1}^{N_{\rm obs}} \frac{\int p(x_i|\Phi,\theta)\, p_{\rm pop}(\theta|\Phi) \mathrm{d}\theta}{\int p_{\rm det}(\theta,\Phi)\, p_{\rm pop}(\theta|\Phi) \mathrm{d}\theta},$$

Probability of detecting a GW from the population

$$m_i = \frac{m_i^{\rm det}}{1 + z(D_{\rm L}; H_0, \Omega_{\rm m}, w_0)}.$$

Black hole mass distribution





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

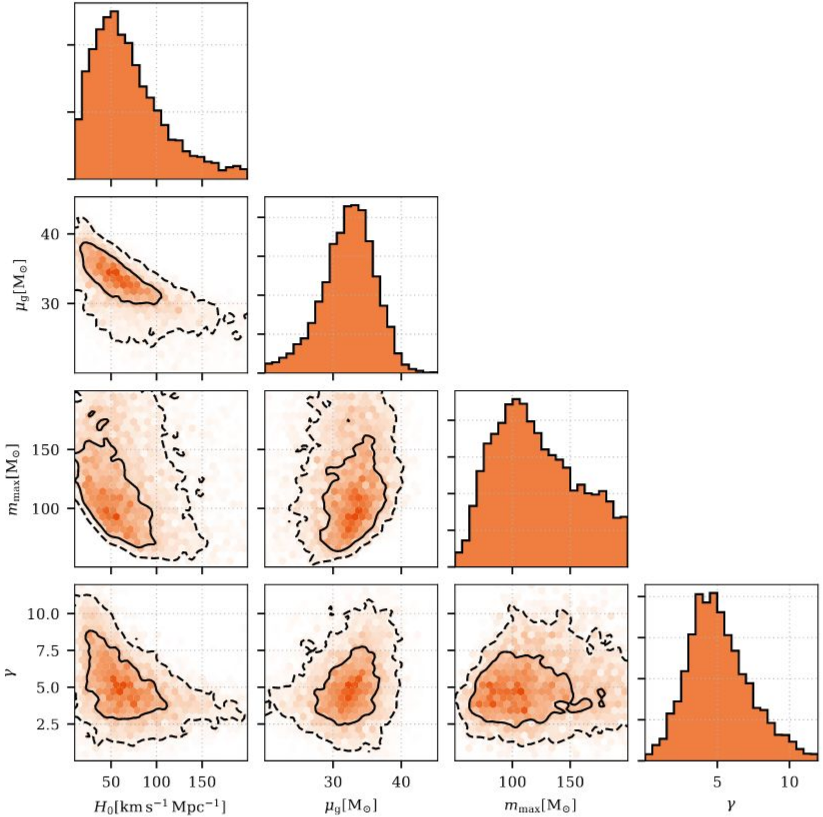
Correlation of cosmological and population parameters

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)

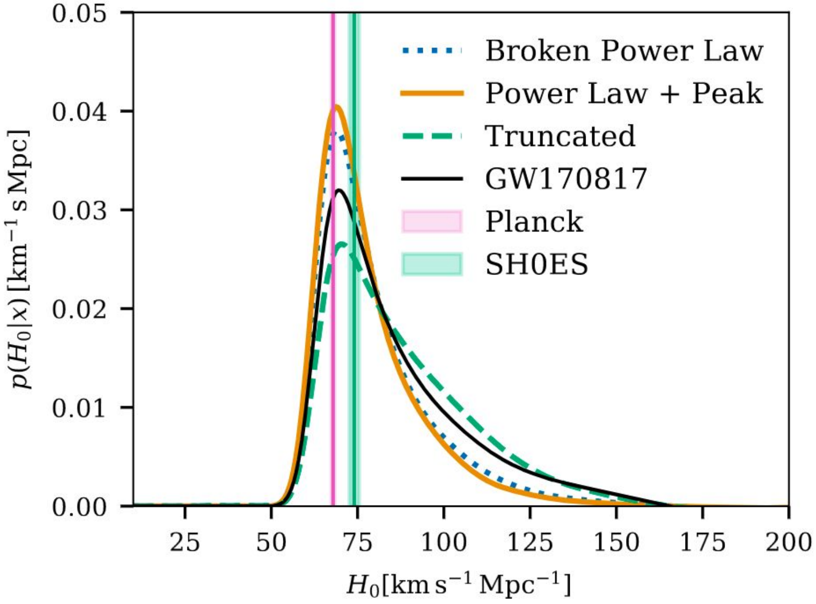


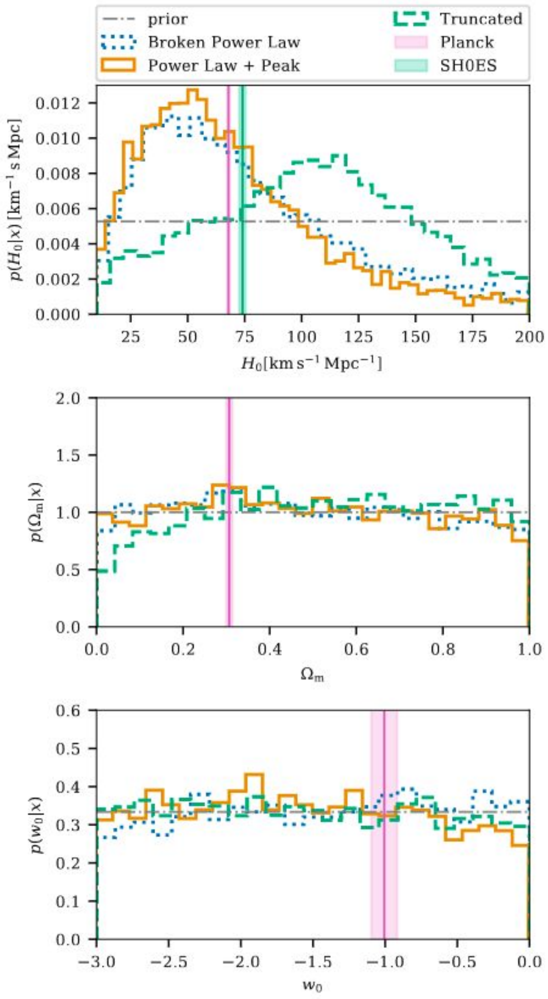
The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

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.

$$H_0 = 68^{+12}_{-8}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$



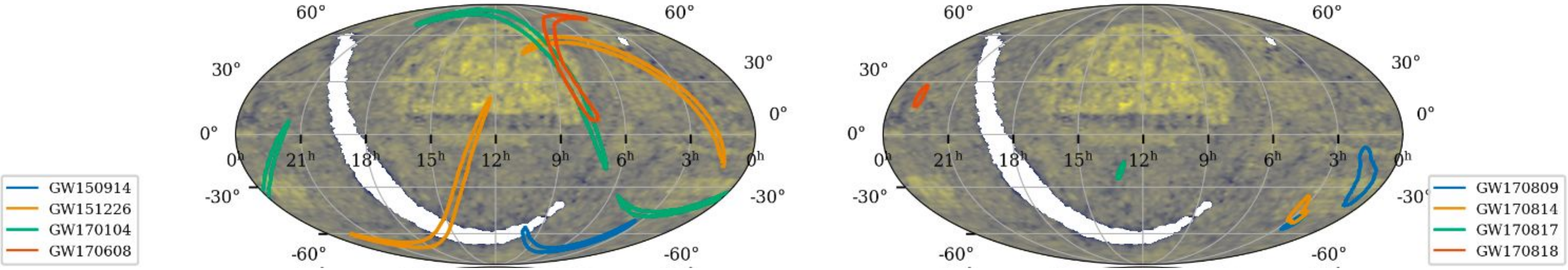


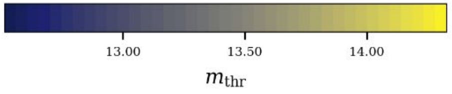
The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

Using galaxy catalogues for cosmological inference

The galaxy catalogue

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.





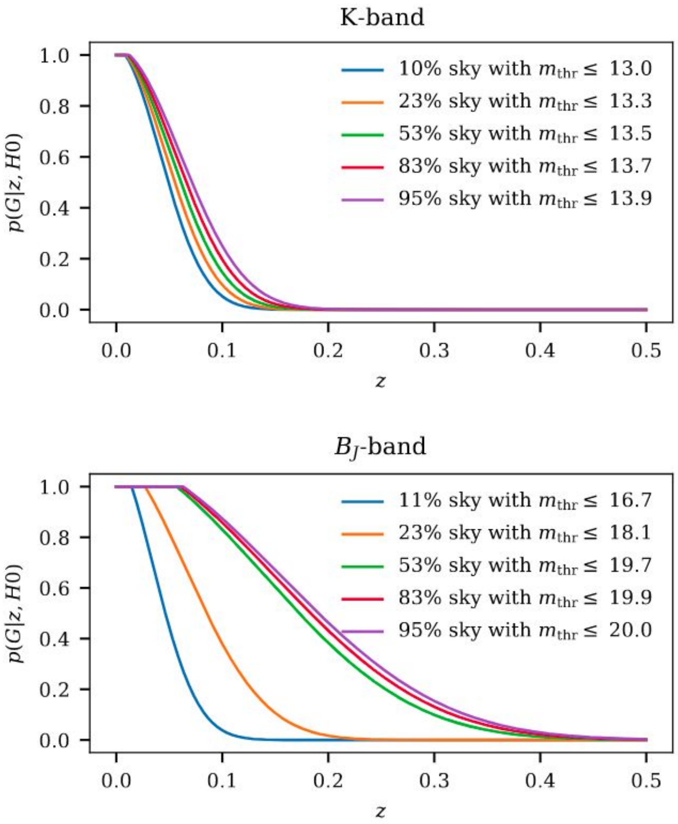
The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

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

Galaxy catalogue incompleteness

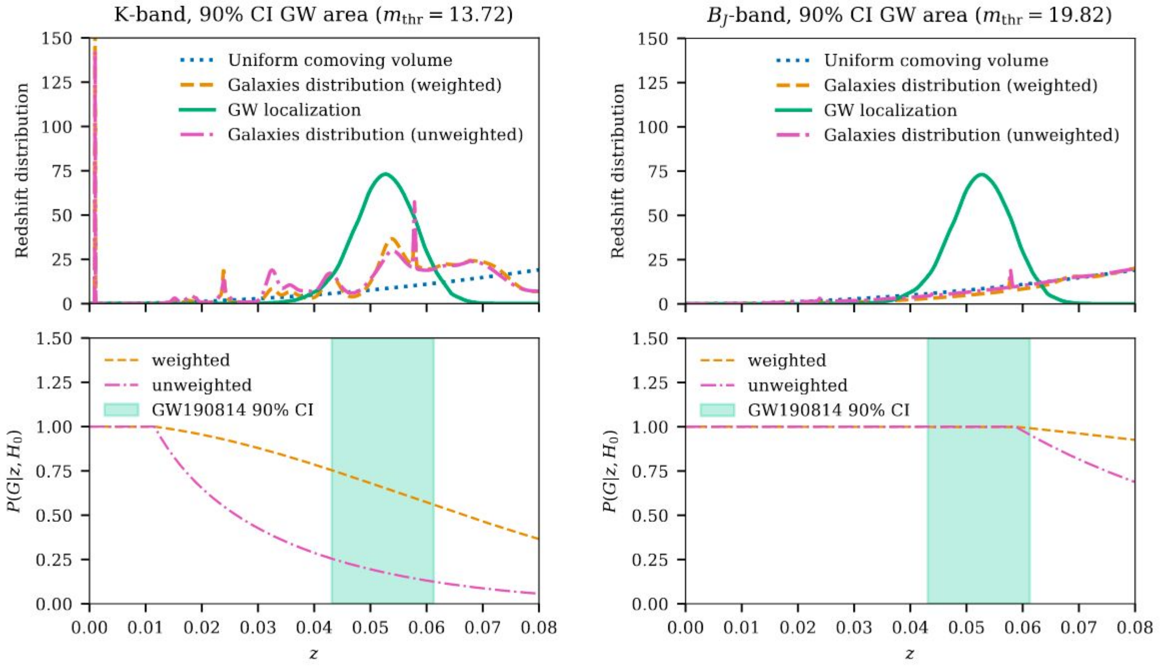
Catalogue completeness is computed on a pixel-by-pixel basis:

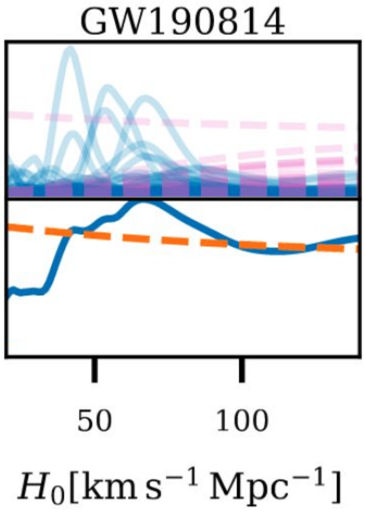
$$P(G|z, H_0) = \frac{\int_{L_{\rm thr}(m_{\rm thr}, z, H_0)}^{L_{\max}} \phi(L) L \mathrm{d}L}{\int_{L_{\min}}^{L_{\max}} \phi(L) L \mathrm{d}L}.$$



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

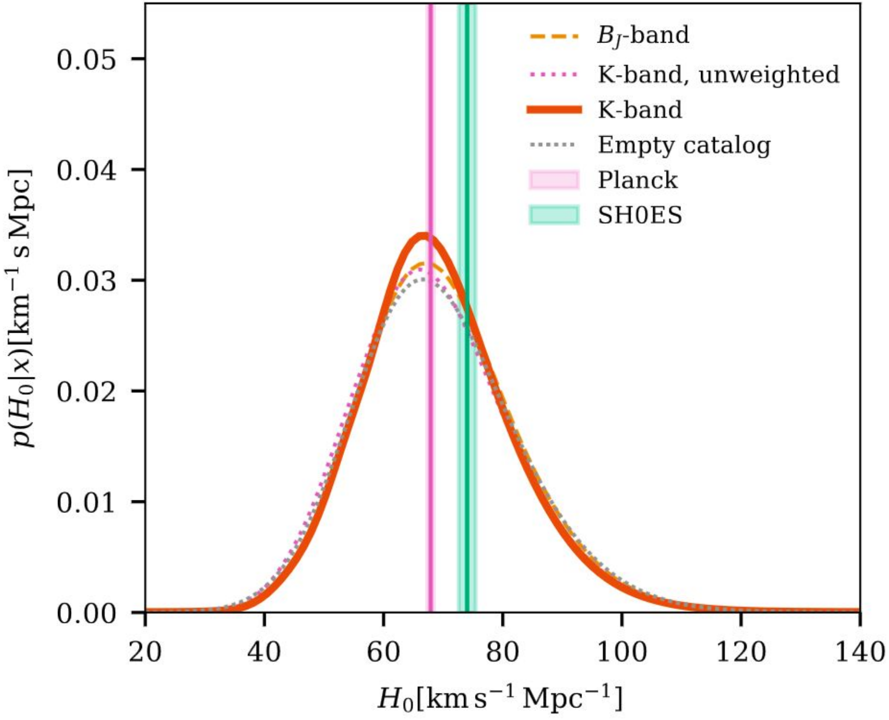
GW190814: the most informative dark siren so far

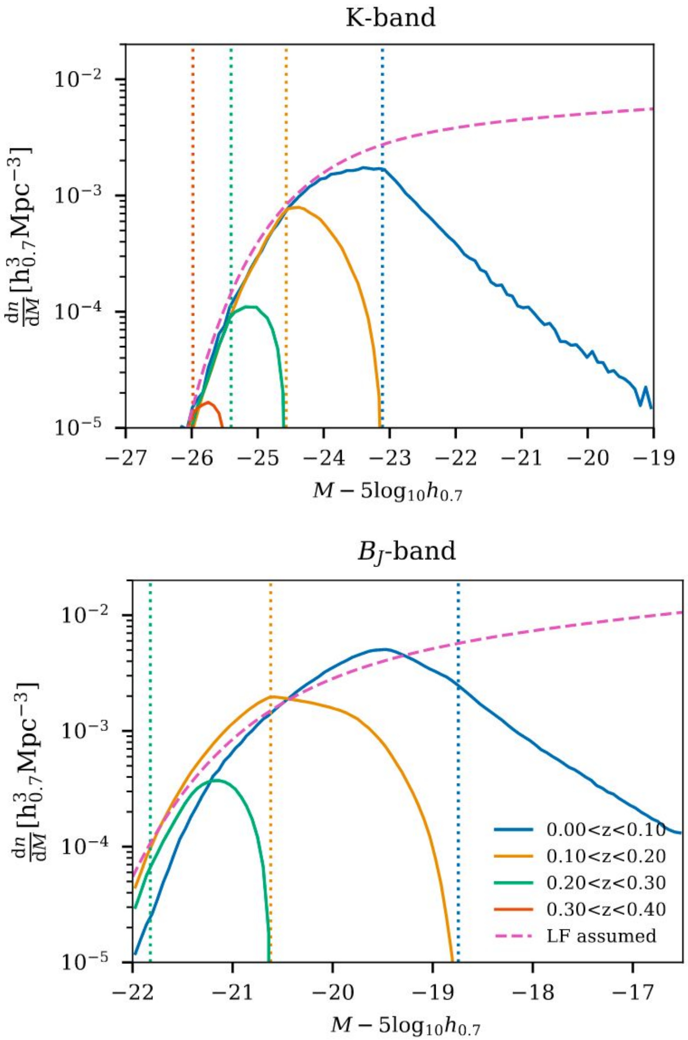




The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

Impact of catalogue assumptions



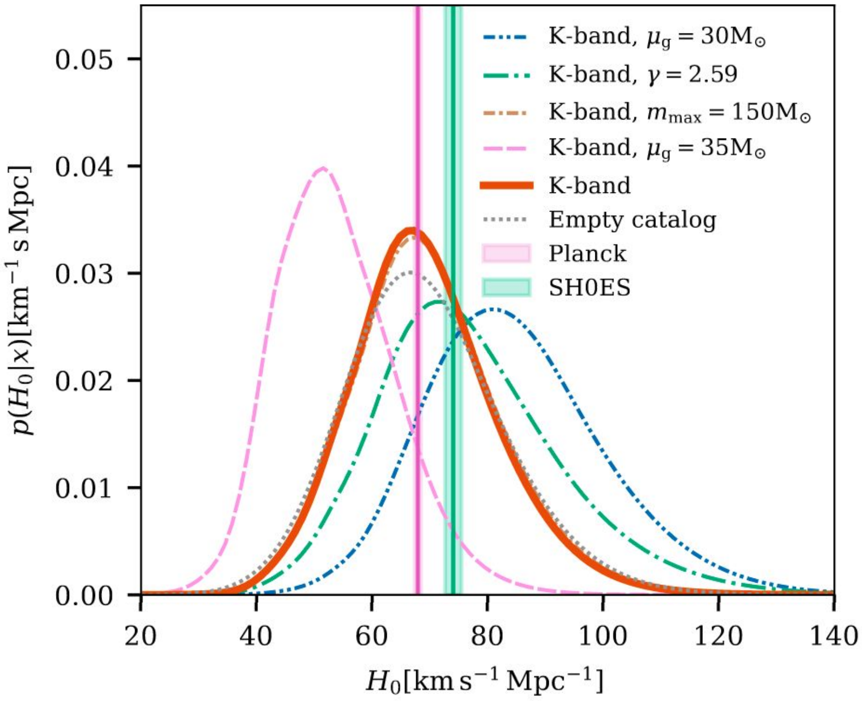


The LIGO, Virgo and KAGRA collaborations,
Sept 2021, *arXiv:2111.03604*

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.



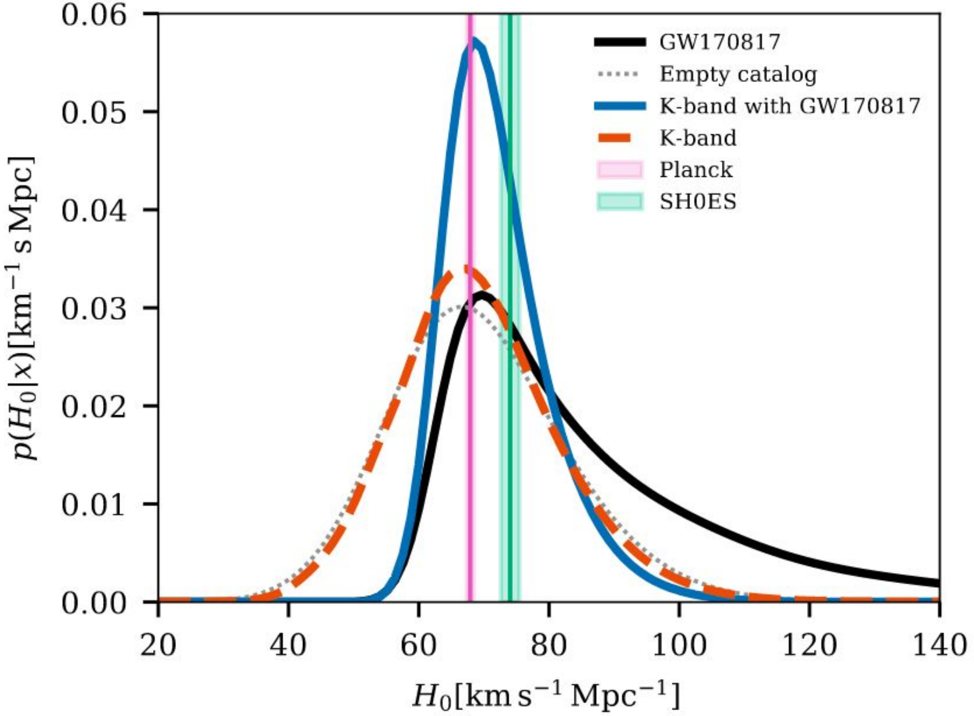
The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

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).

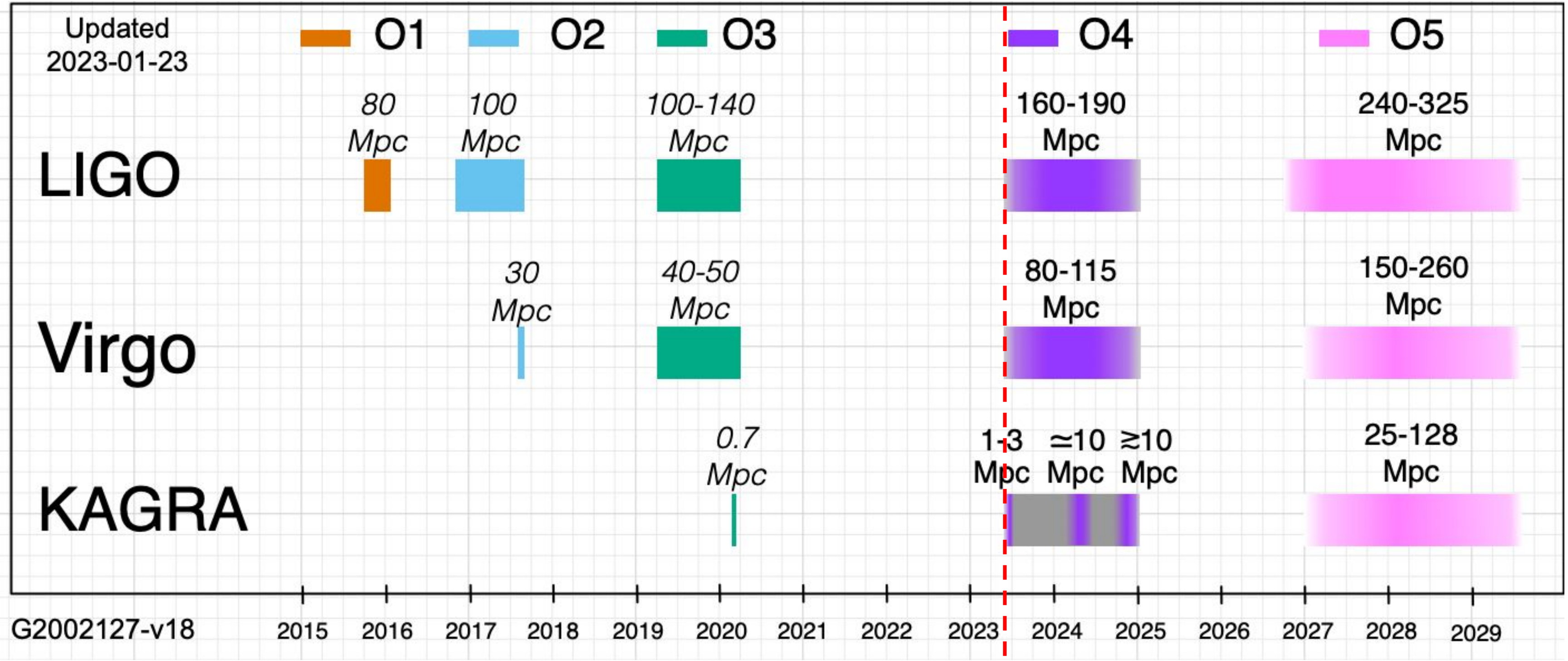
$$H_0 = 68^{+8}_{-6}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$



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

What’s next?

Timeline of observing runs



We are here

Summary

No confirmed EM counterparts during O3, so two methods were used for cosmological inference on the detected events:

- **Black hole mass distribution**
- **Galaxy catalogue**

Cosmological results provide interesting hints of what is to come, but are not yet competitive with non-GW measurements.

O4 has started and will last for 18 months, which will greatly expand the catalogue of GW detections.

Estimates which combine mass distribution and galaxy catalogue information (plus use of more complete catalogues) will maximise the cosmological information gained.

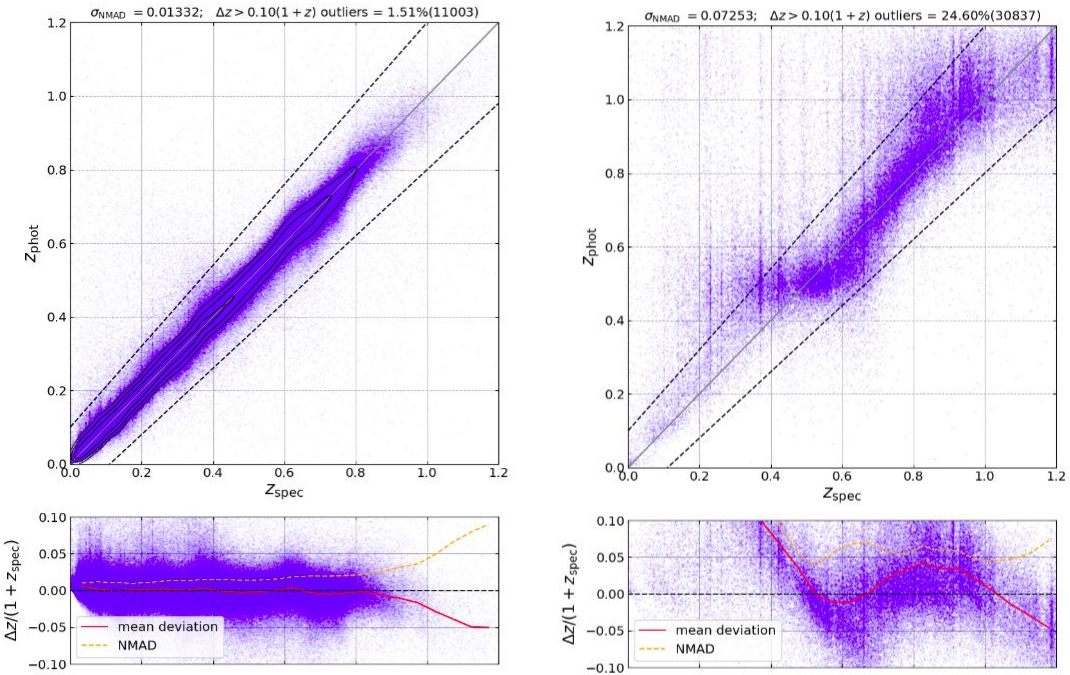
This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Extra slides

Photometric redshifts

Spectroscopic redshifts are costly/time-consuming, so most galaxy surveys provide photometric redshifts.

These are much cheaper, but come with larger uncertainties and can be unreliable at faint magnitudes/high redshifts.



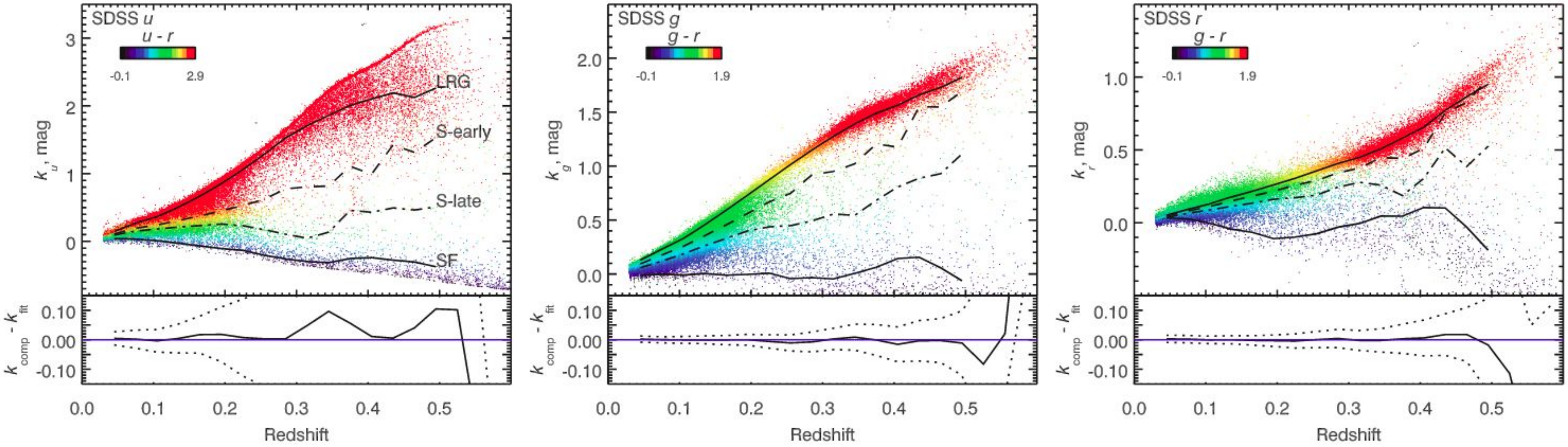
Zhou *et al. MNRAS*, Volume 501, Issue 3, March 2021, Pages 3309–3331

Redshifting of galaxy luminosities

Galaxies don't emit uniformly in all bands. We observe in some band *b*, but the light detected has been redshifted.

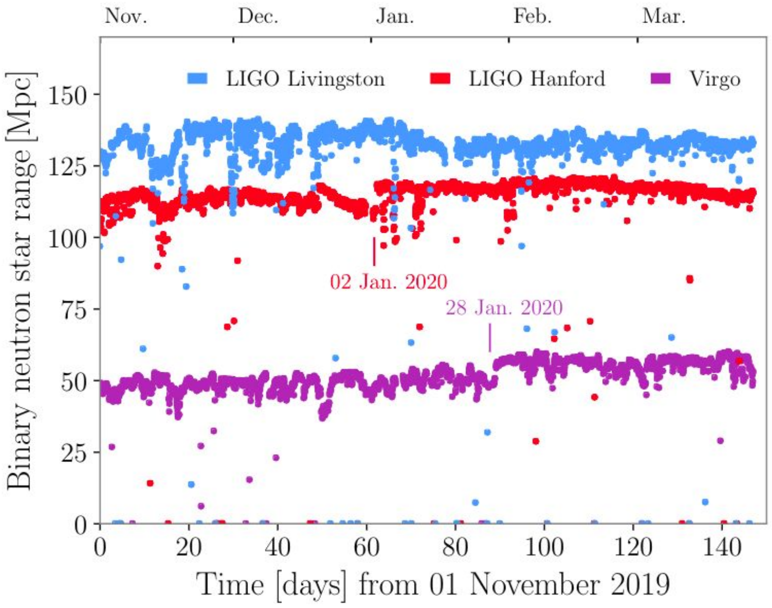
Solution? K corrections

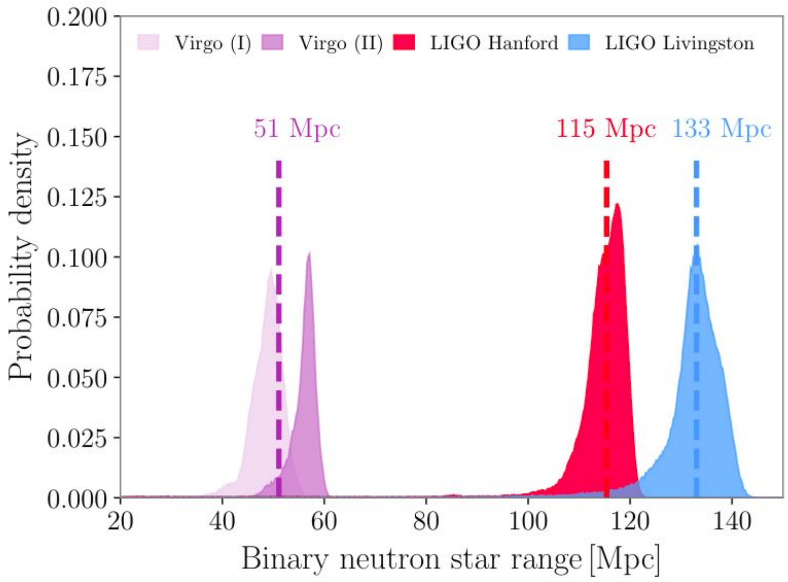
$$M_a = m_b - DM - K$$



Chilingarian *et al. MNRAS*, Volume 405, Issue 3, July 2010, Pages 1409–1420

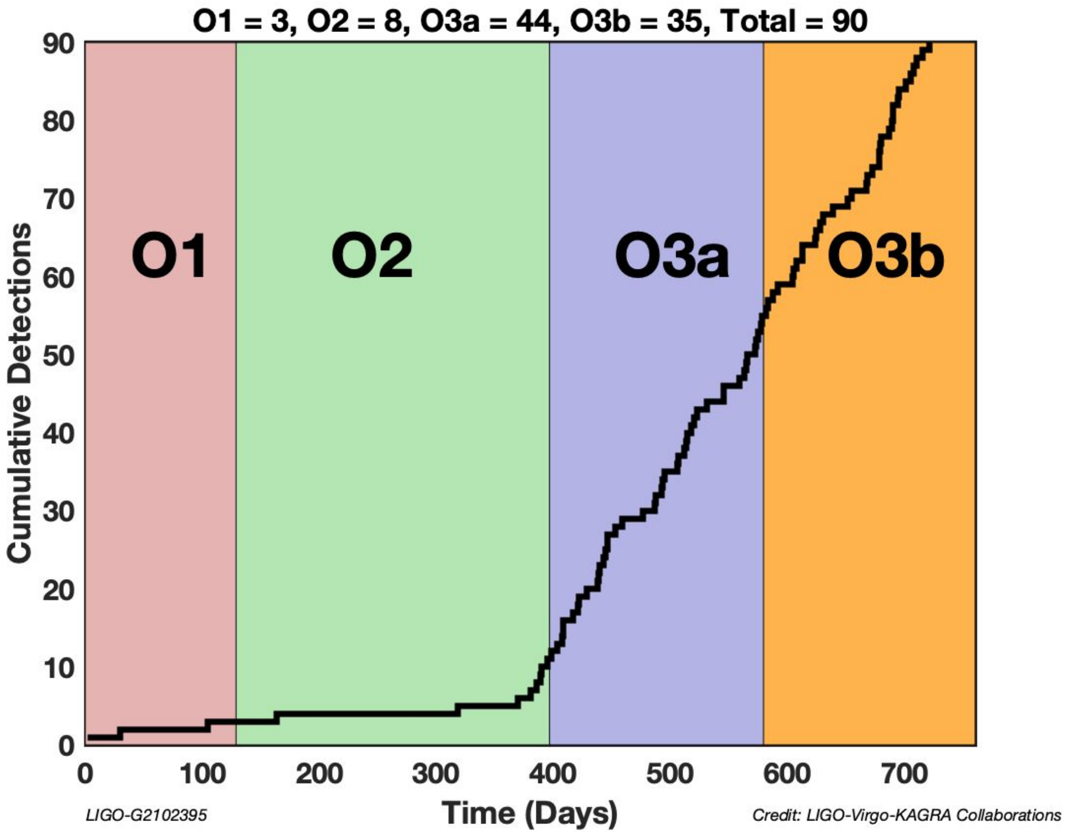
Detector sensitivity



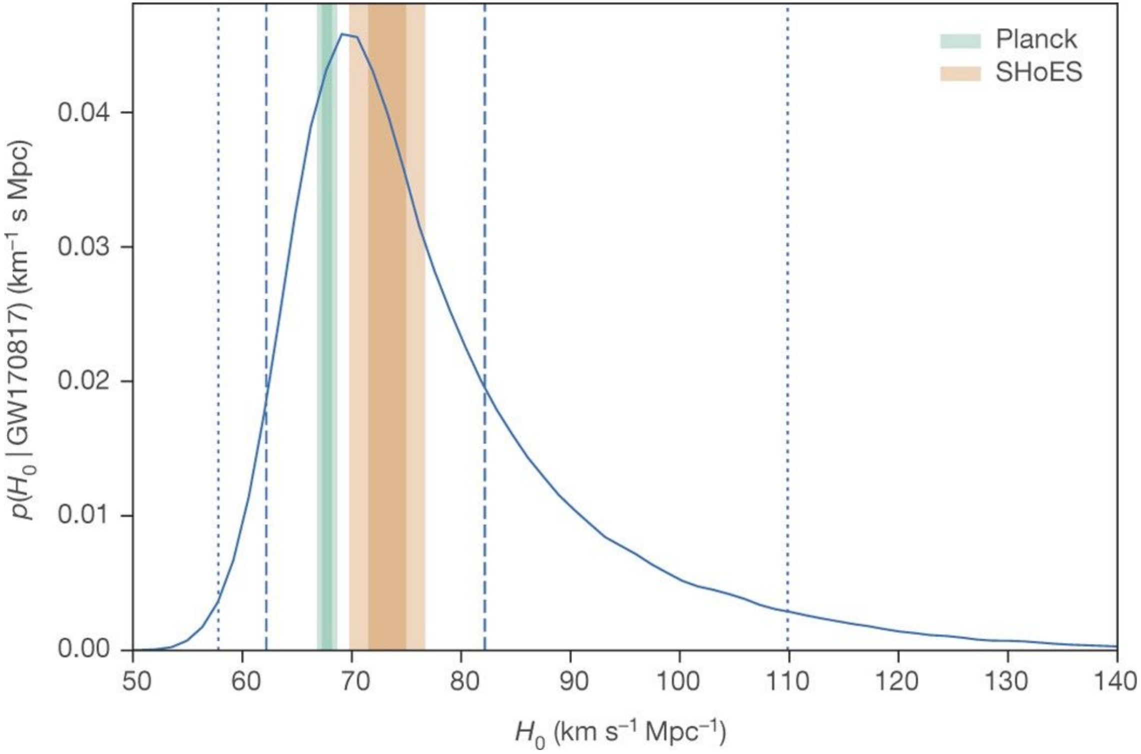


The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, Nov 2021, *arXiv:2111.03606*

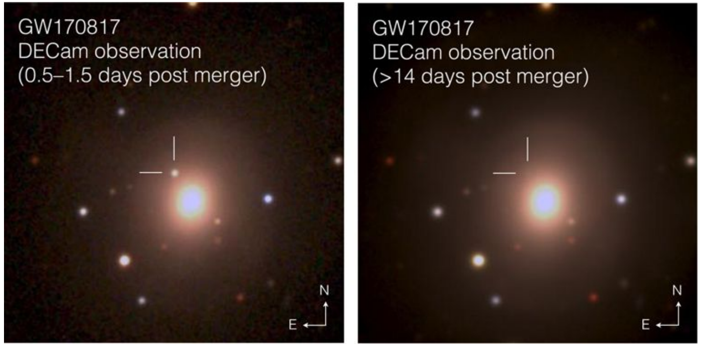
Cumulative detections to date



Bright sirens



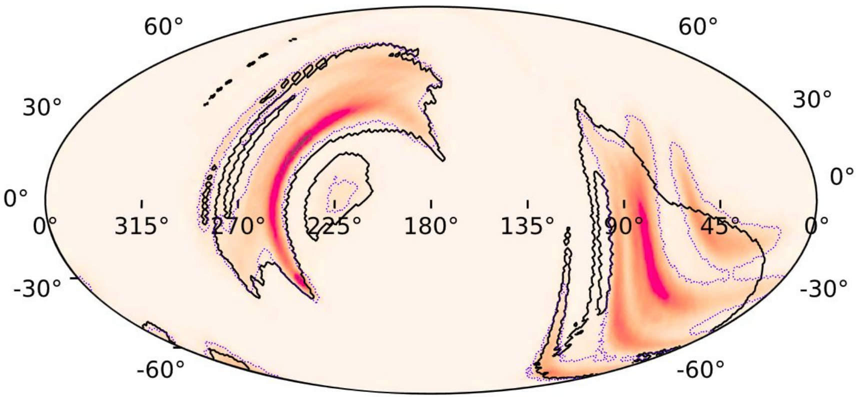
The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration *et al.* *Nature* **551,** 85–88 (2017).

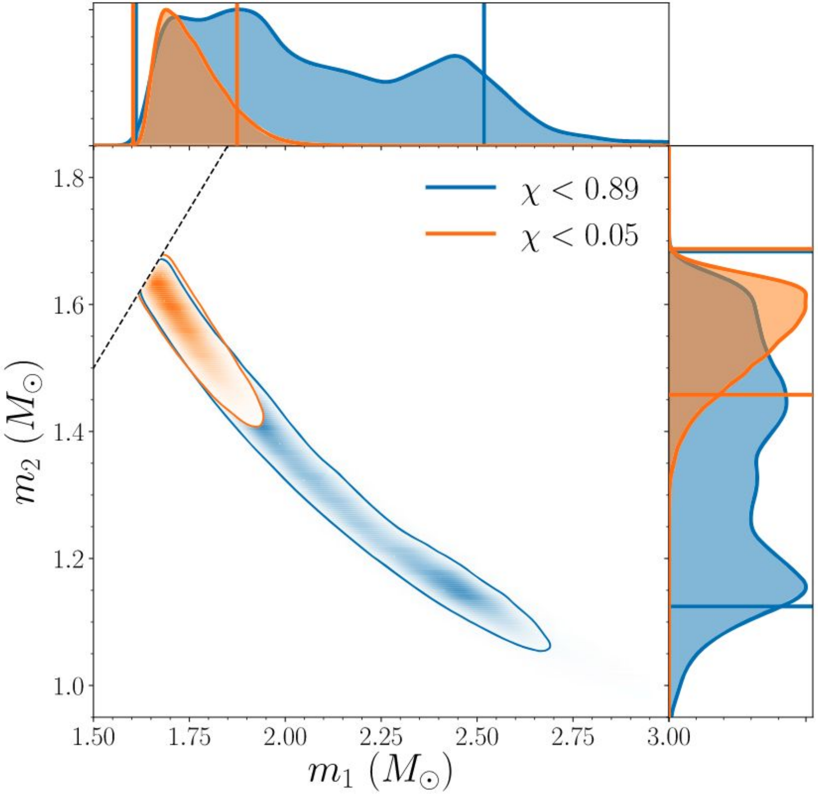


M. Soares-Santos *et al.* 2017
ApJL **848** L16

BNS

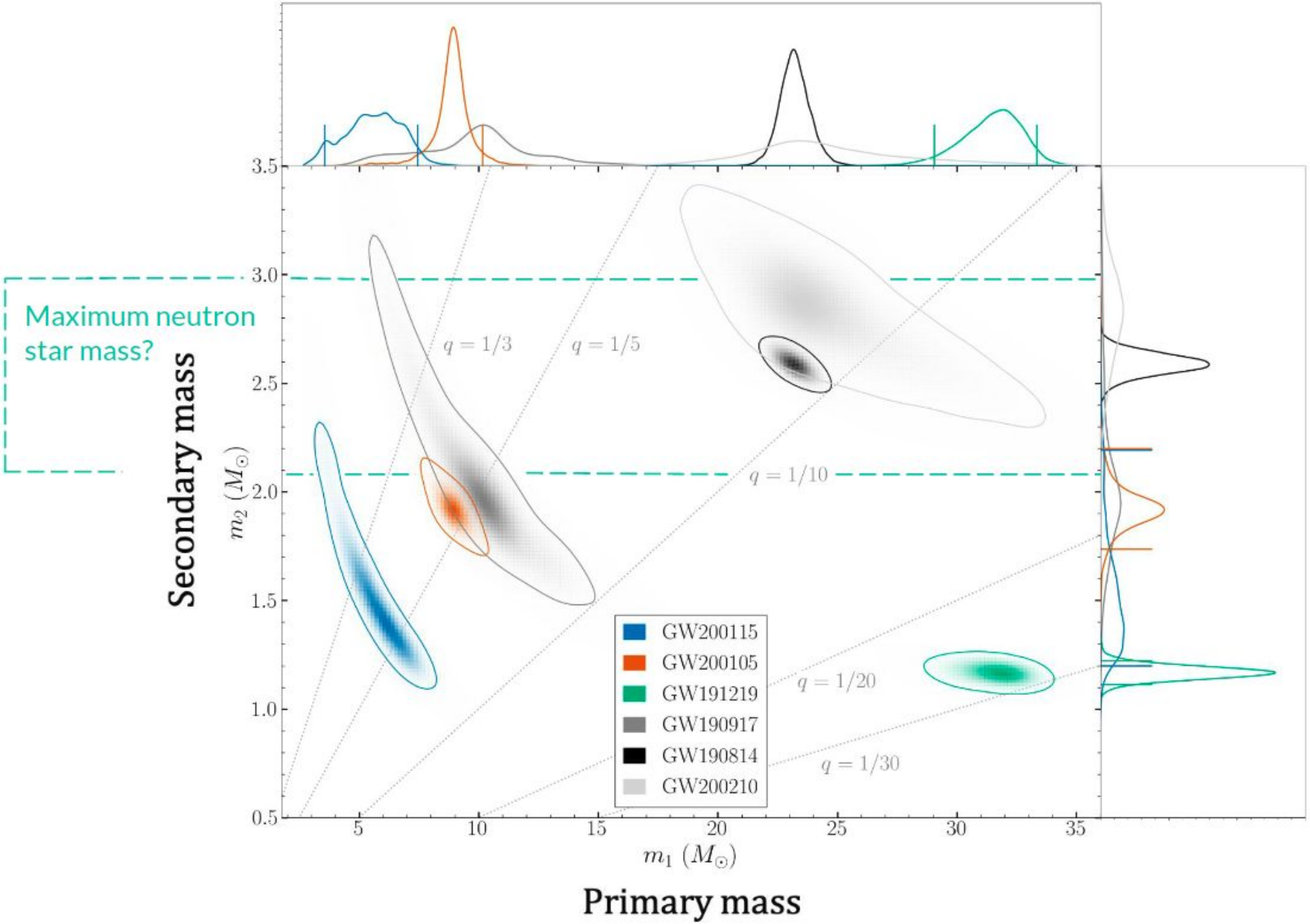
GW190425 is the second binary neutron star to be detected, after GW170817. Around 160 Mpc away.





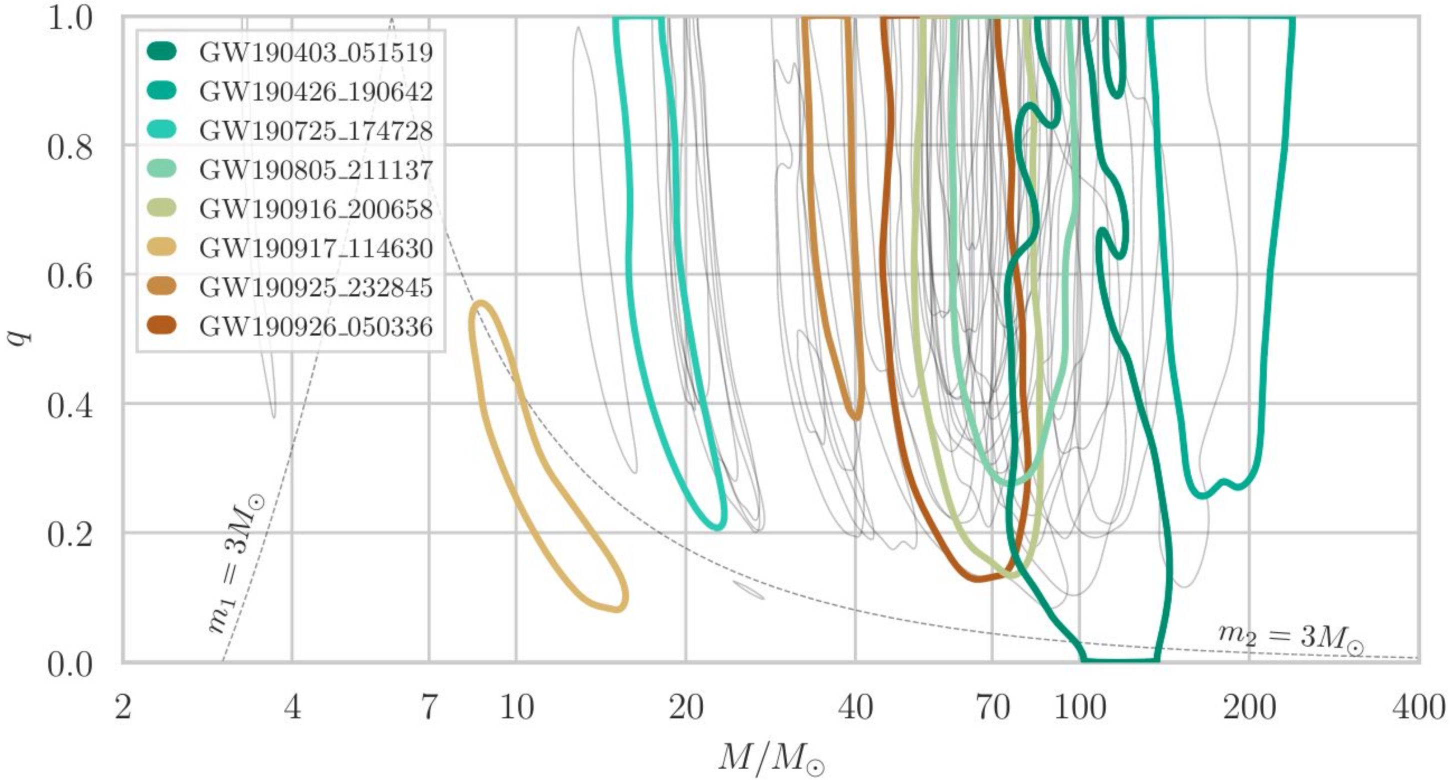
The LIGO Scientific Collaboration and the Virgo Collaboration, Astrophysical Journal Letters 892 (2020) L3

NSBHs



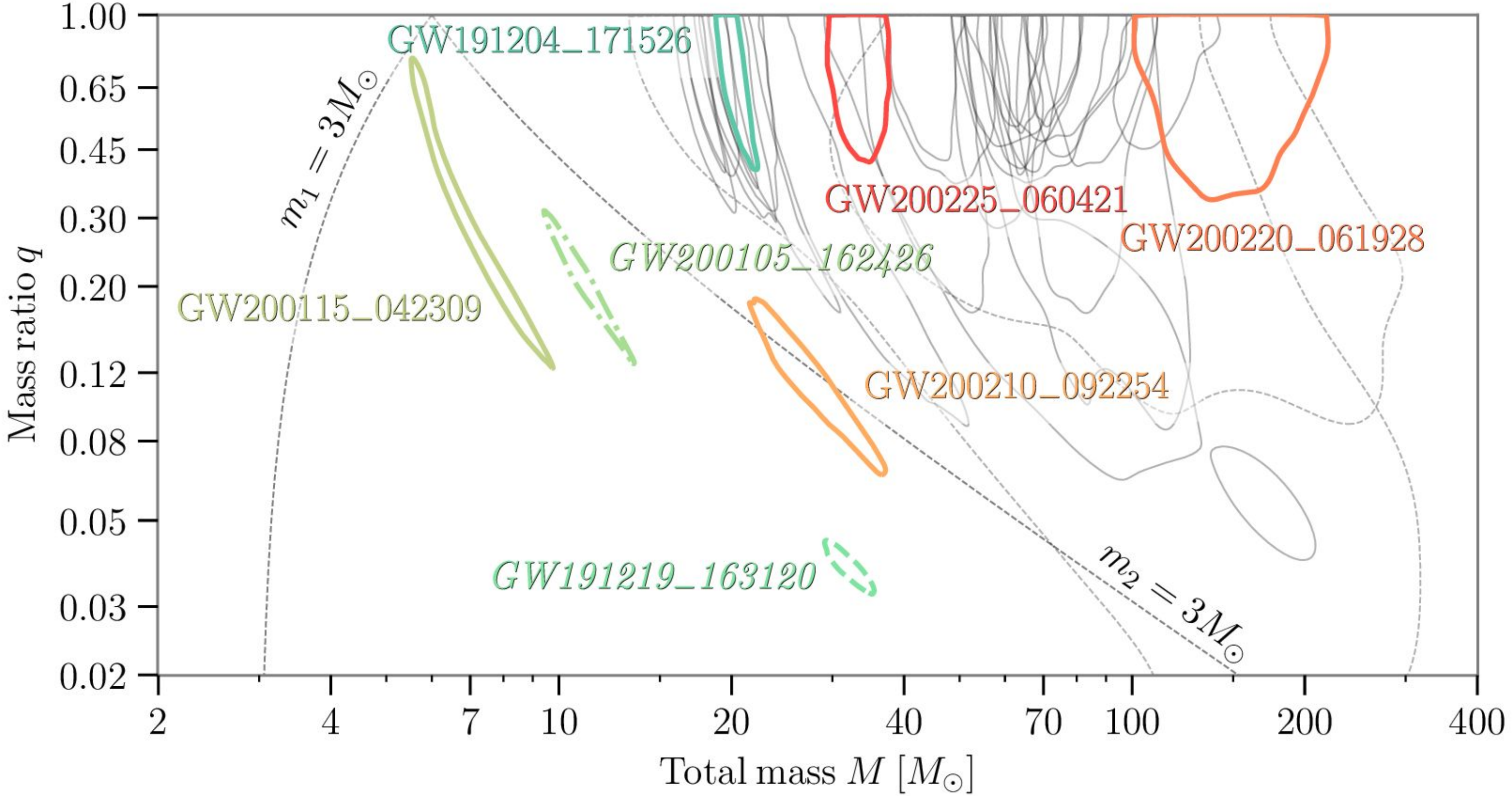
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, GWTC-3 webinar

Events from O3a



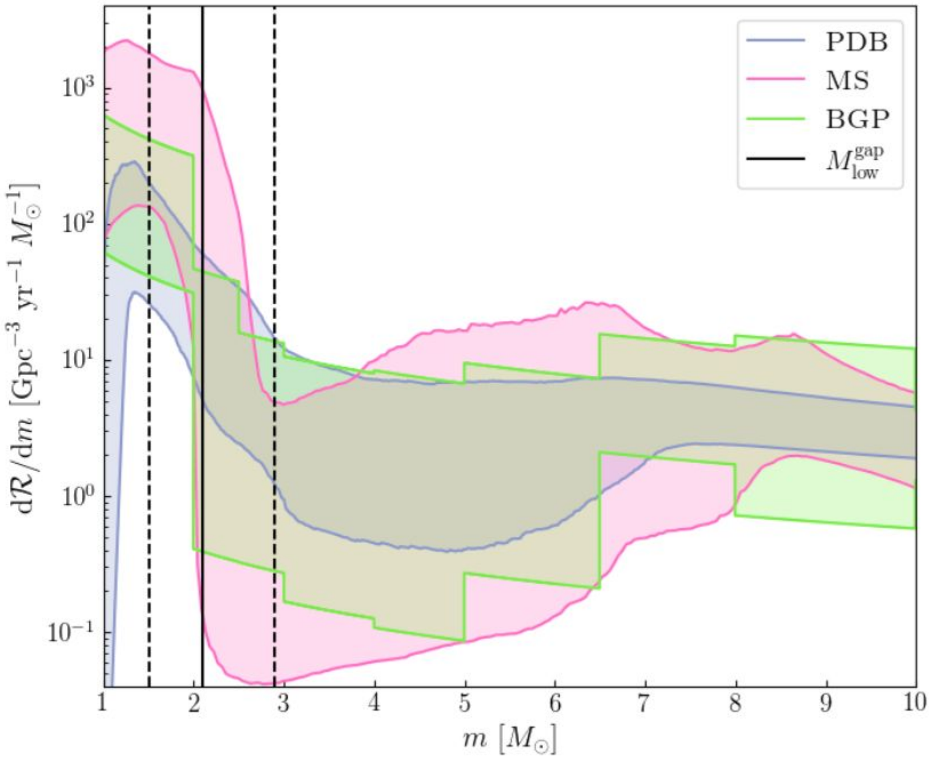
The LIGO Scientific Collaboration and Virgo Collaboration, *arXiv:2108.01045*

Events from O3b



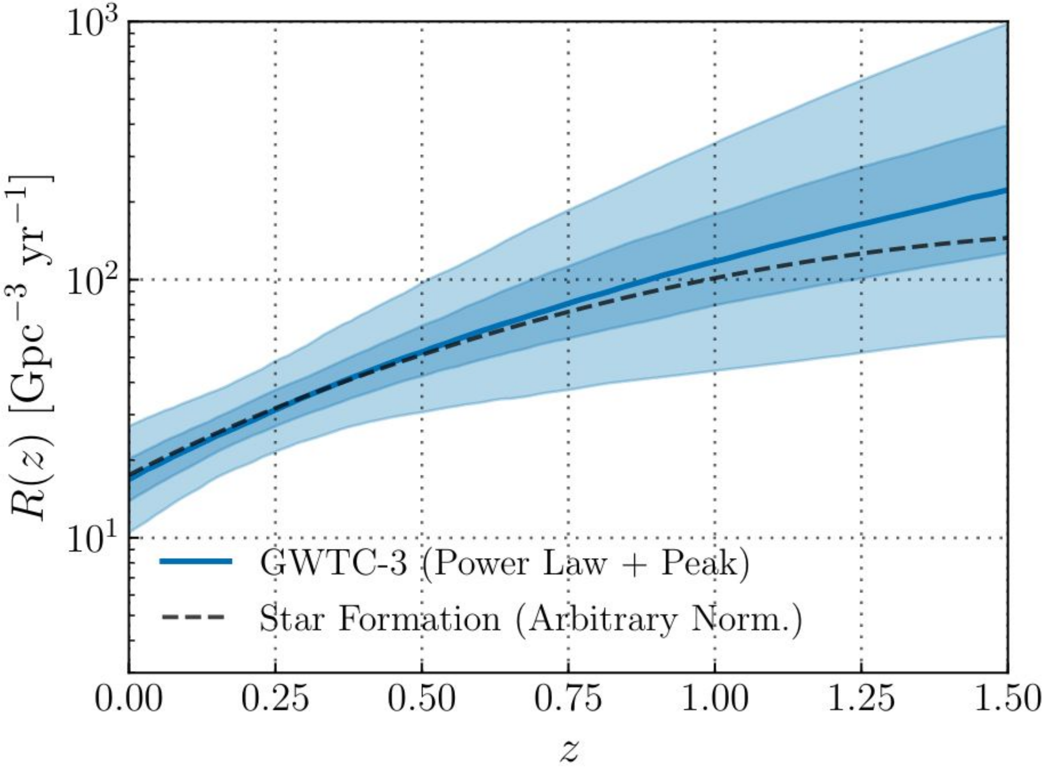
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, Nov 2021, *arXiv:2111.03606*

Lower mass gap



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