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

Rachel Gray

University of Glasgow

Understanding Cosmological Observations

Benasque, Spain, 25th July 2023

Outline

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

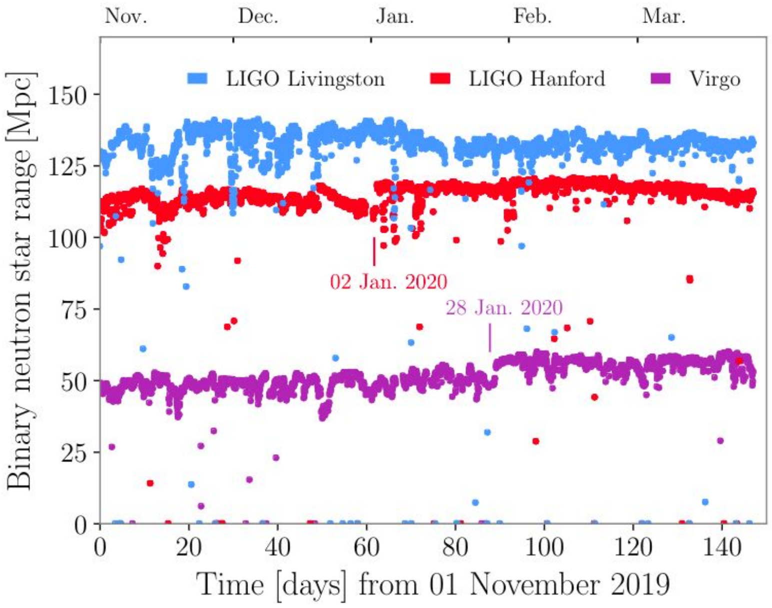
Aerial view of Virgo. Credit: The Virgo Collaboration

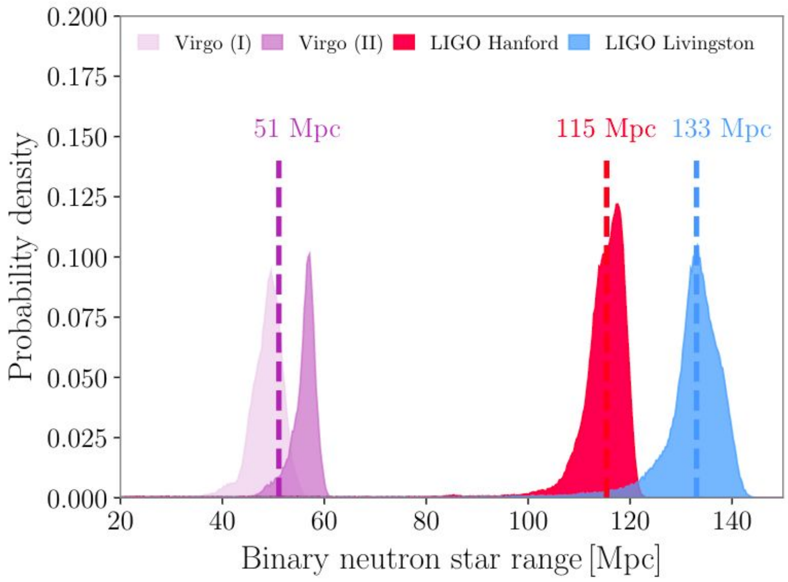
KAGRA. Credit: ICRR, Univ. of Tokyo

LIGO Livingston. Credit: Caltech/MIT/LIGO Lab

LIGO Hanford. Credit: LIGO

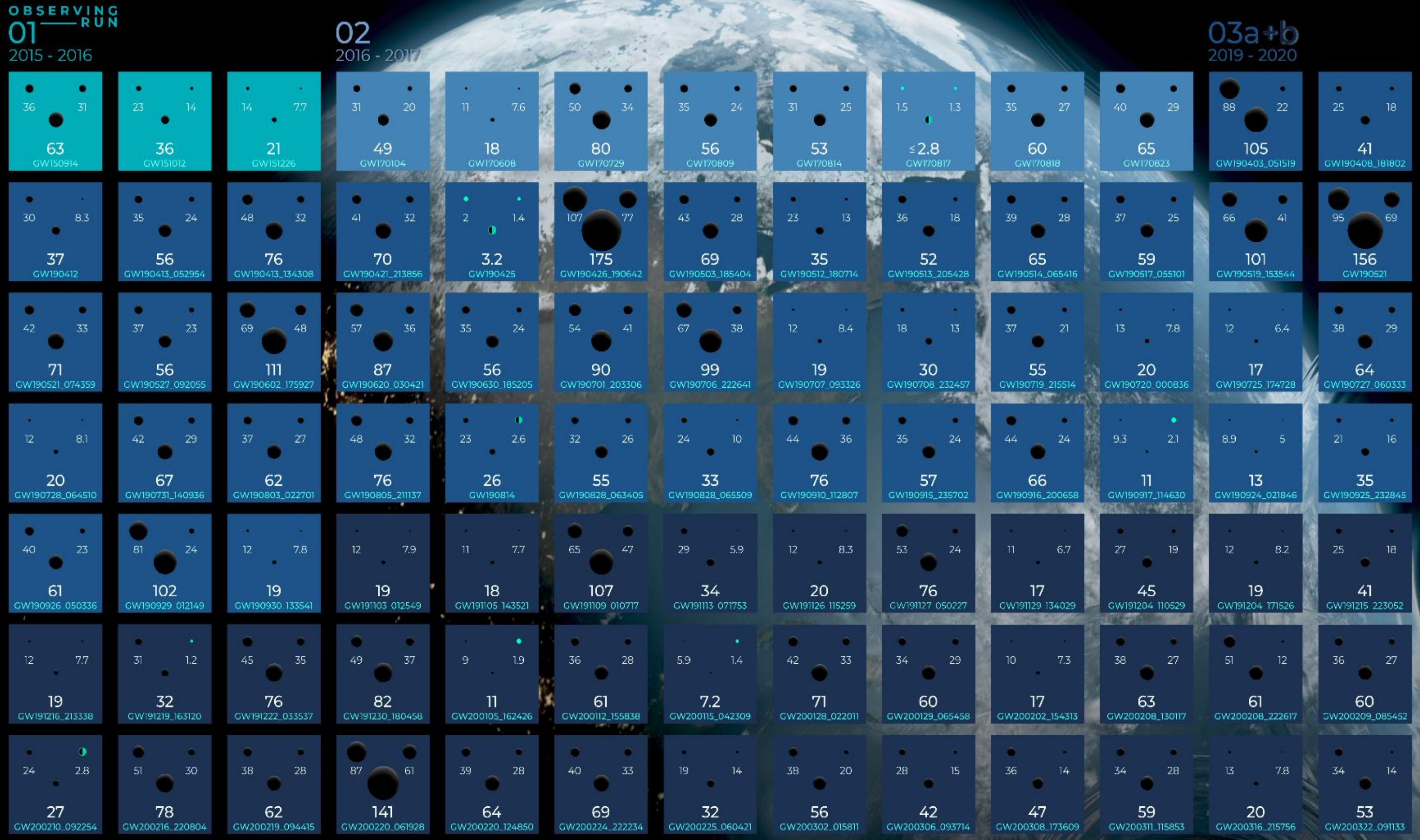
Detector sensitivity





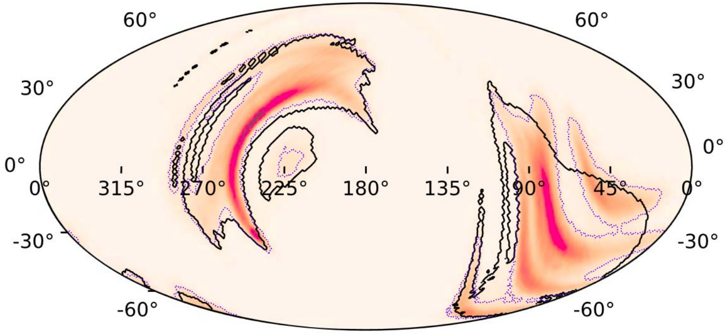
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, Nov 2021, *arXiv:2111.03606*

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

The Hubble tension

Currently there is a tension between early (model-dependent) and late-time (local) measurements of H_0.

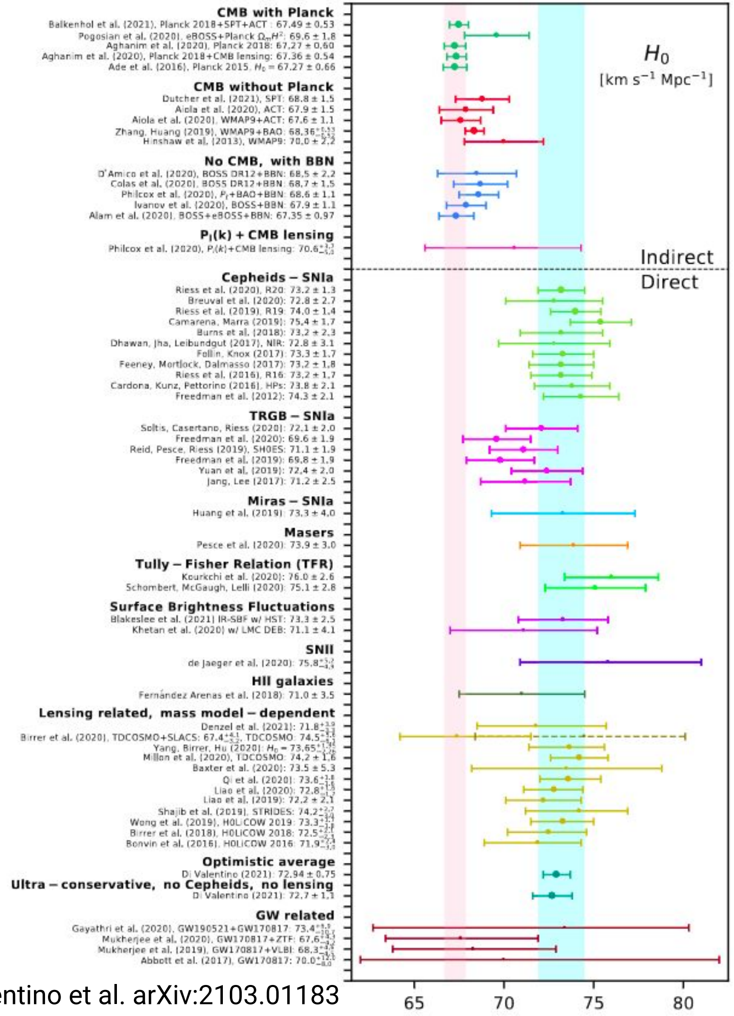
Possible causes:

1. Systematics?
2. New, unknown physics?

Tension lies at 4 - 6σ.

Hu, J.-P.; Wang, F.-Y. https://doi.org/10.3390/universe9020094

Eleonora Di Valentino et al https://doi.org/10.1088/1361-6382/ac086d



E. Di Valentino et al. arXiv:2103.01183

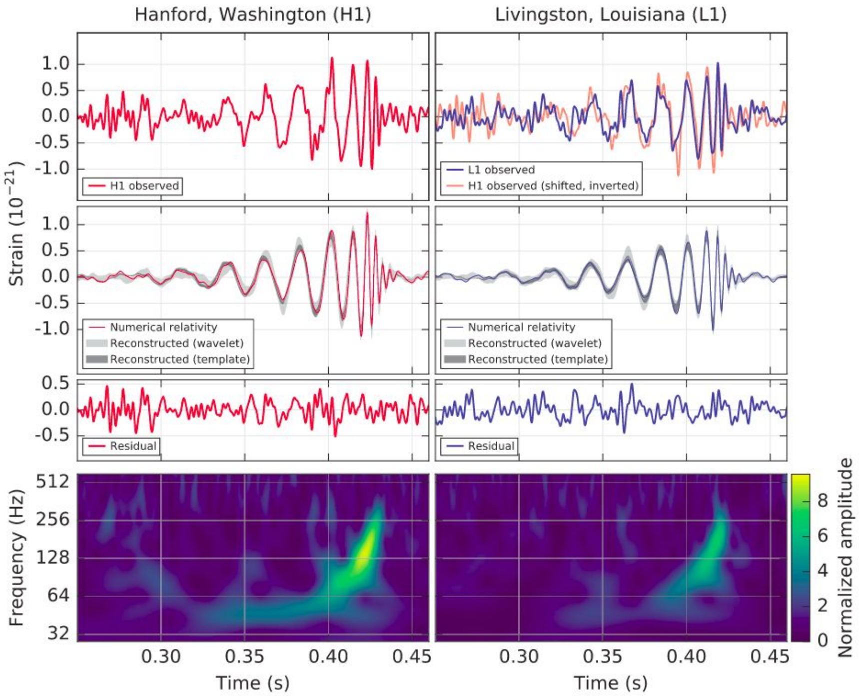
Gravitational waves as standard sirens

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

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

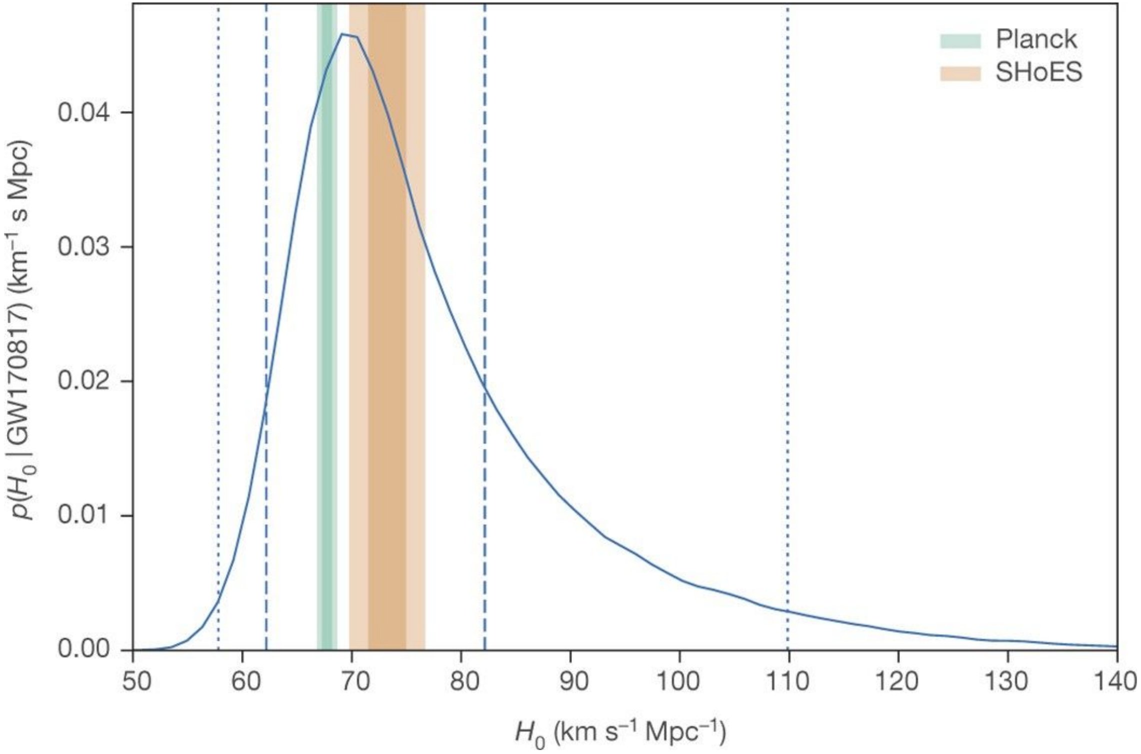
Redshifted chirp mass:

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

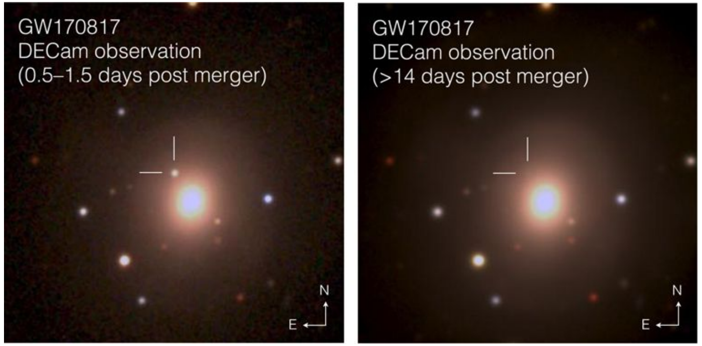


The LIGO Scientific Collaboration and Virgo Collaboration, *Phys. Rev. Lett.* **116**, 061102 – Published 11 February 2016

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

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.

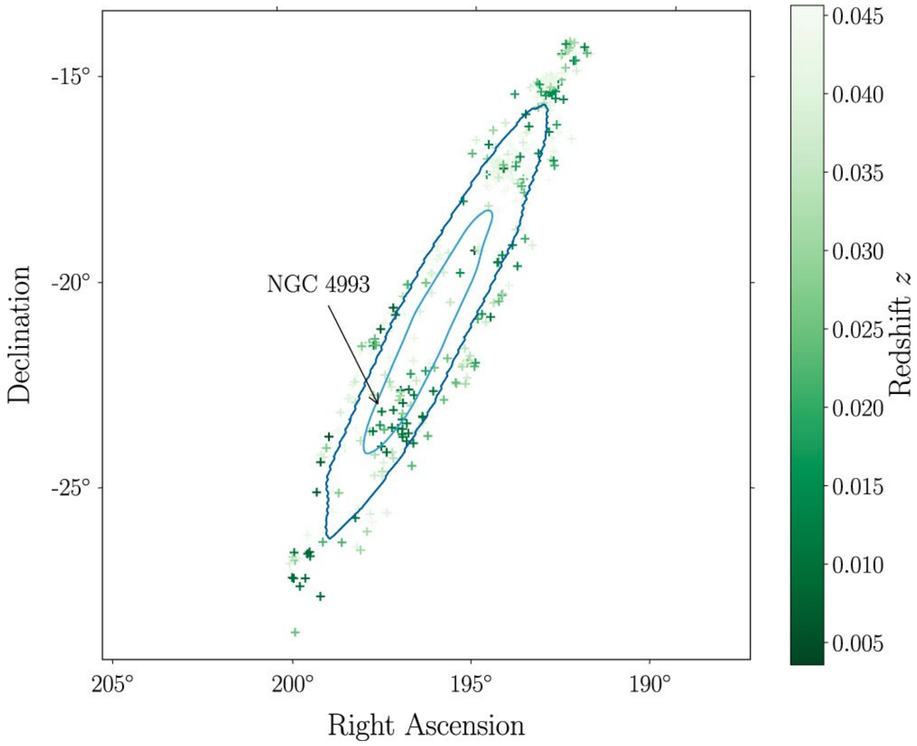
AKA the redshifted masses method

Using galaxy catalogues for cosmological inference

The dark siren + galaxy catalogue method

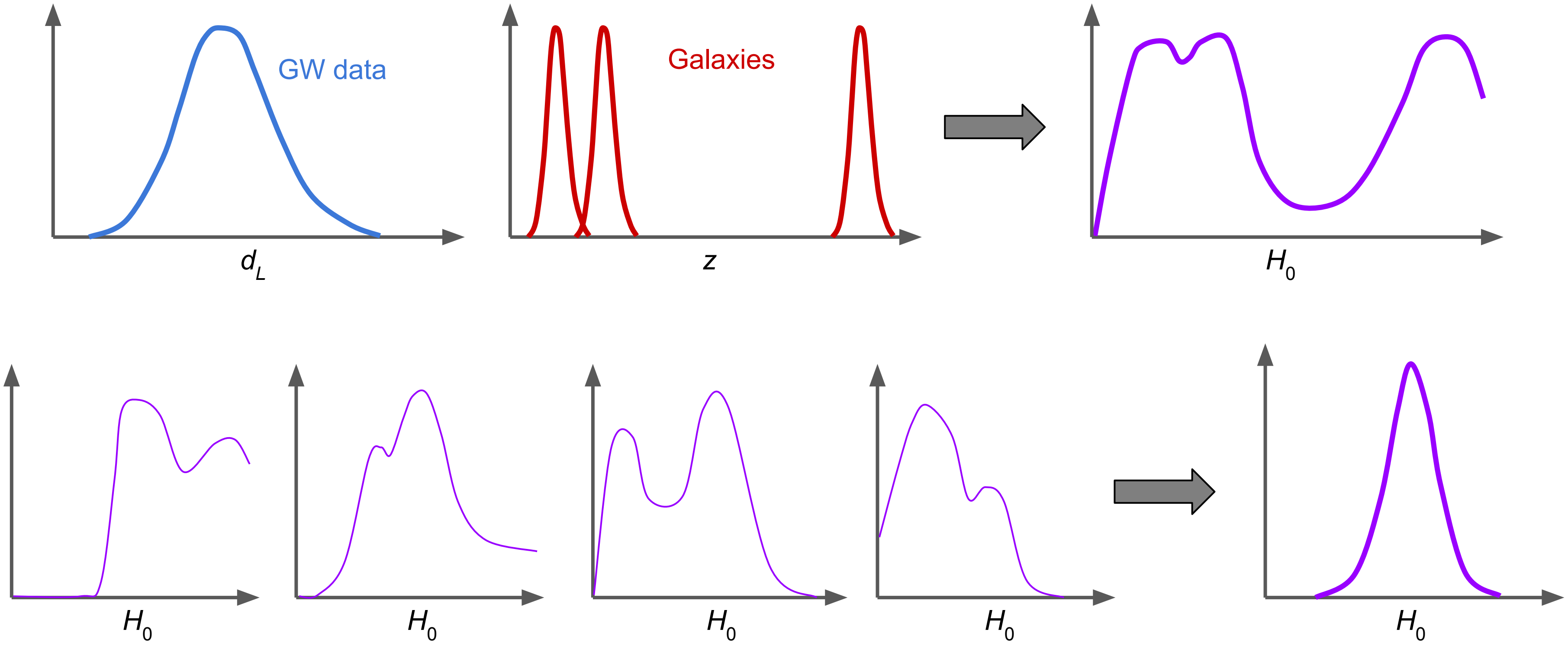
Don't know the true host galaxy, so treat all galaxies in the GW localisation as potential hosts and marginalise over them

(see, e.g. Schutz 1986, Del Pozzo 2012, Chen+ 2018, Soares-Santos+ 2019, Gray+ 2020, Finke+ 2021...)



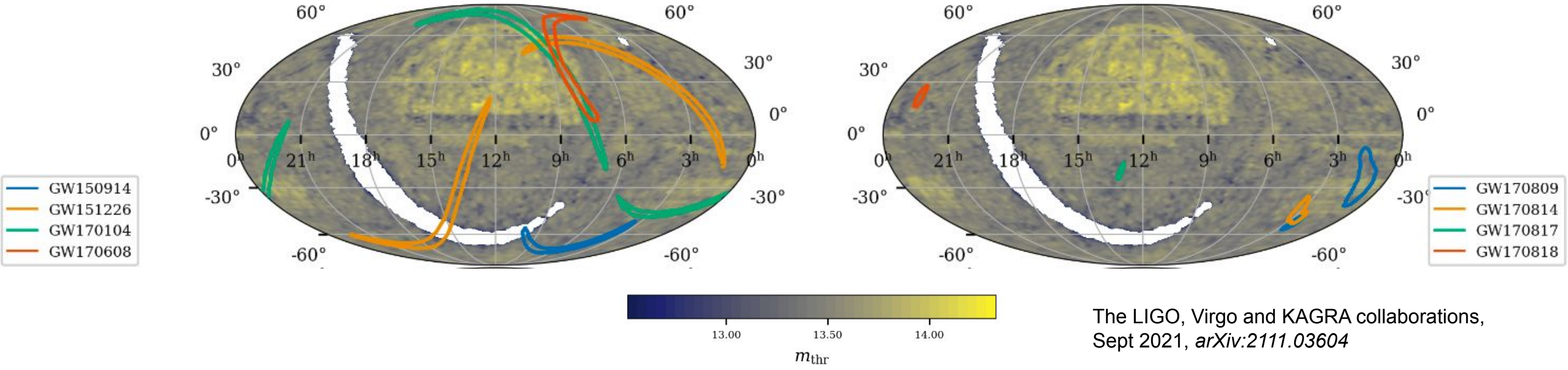
M. Fishbach *et al*. 2019 *ApJL* **871** L13.

The dark siren + galaxy catalogue method



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.



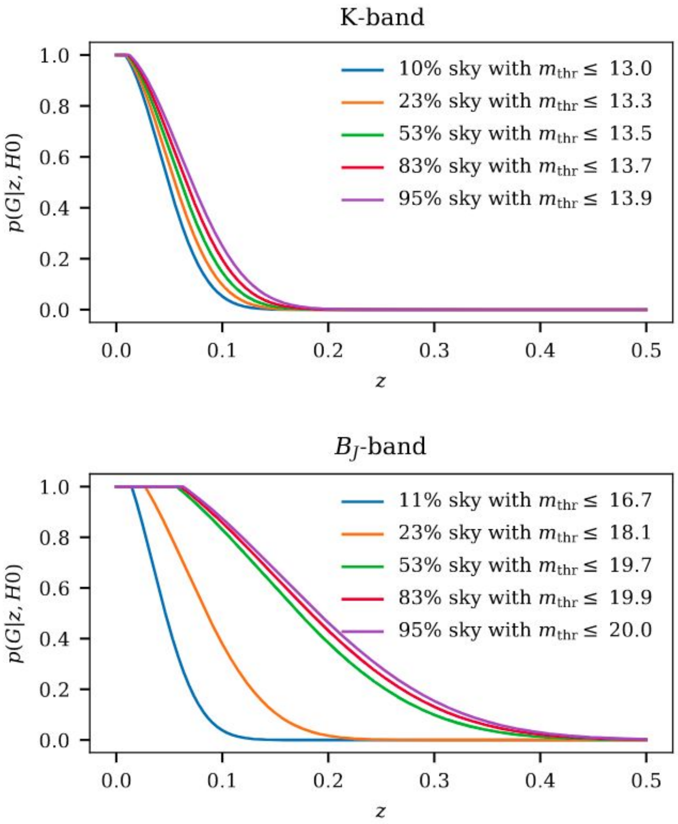
The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

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

Galaxy catalogue incompleteness

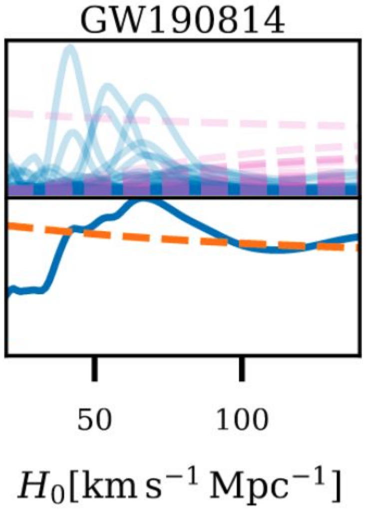
Catalogue completeness is computed on a pixel-by-pixel basis:

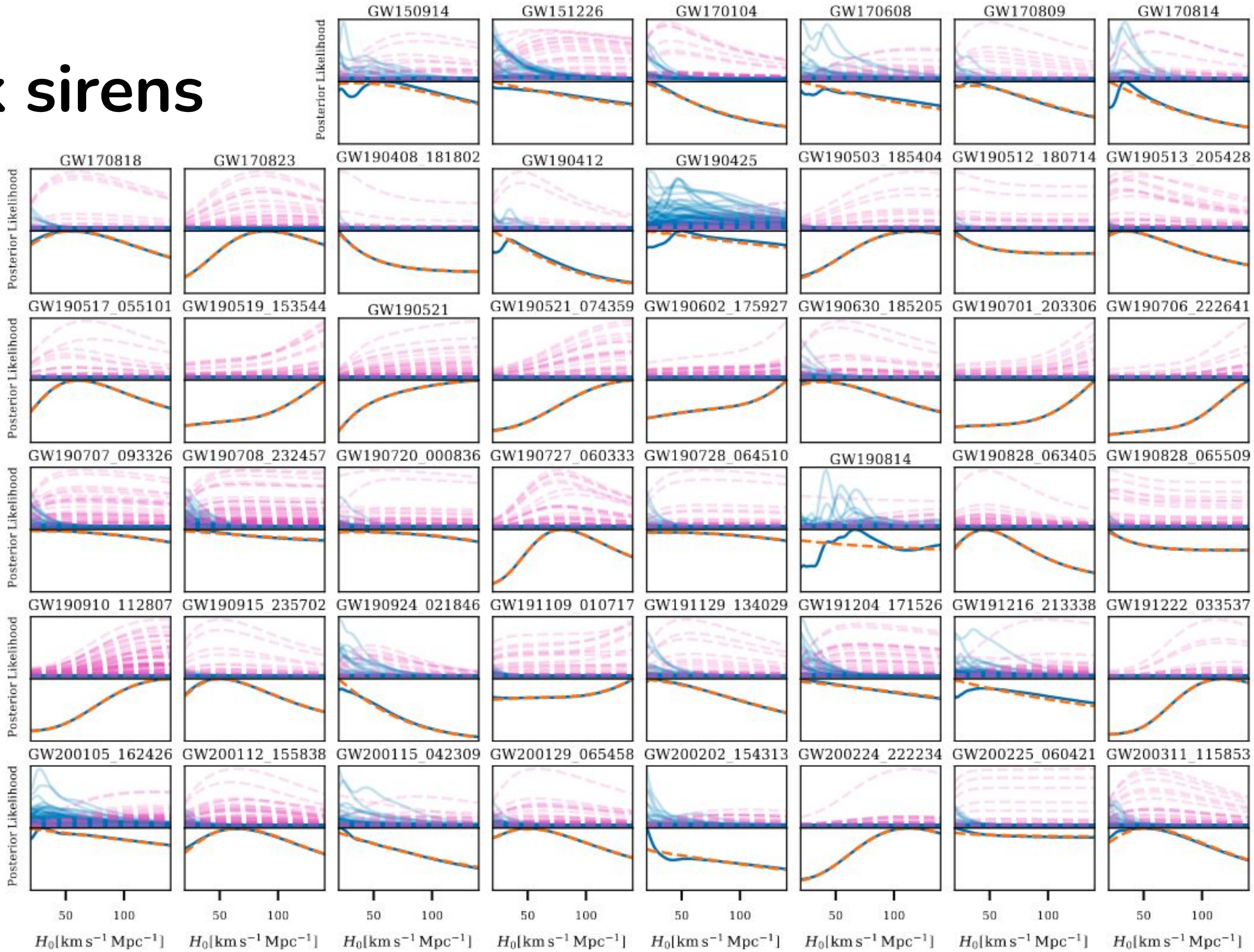
$$P(G|z, H_0) = \frac{\int_{L_{\rm thr}(m_{\rm thr}, z, H_0)}^{L_{\rm max}} \phi(L) L \mathrm{d}L}{\int_{L_{\rm min}}^{L_{\rm max}} \phi(L) L \mathrm{d}L}.$$



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

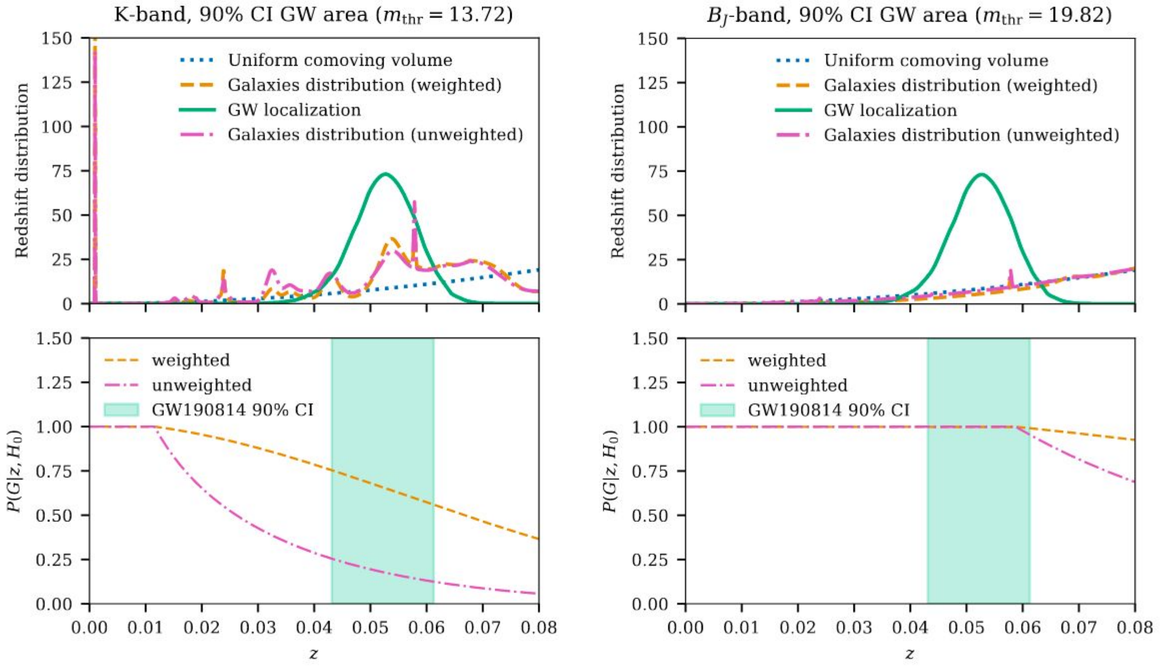
GWTC-3 dark sirens

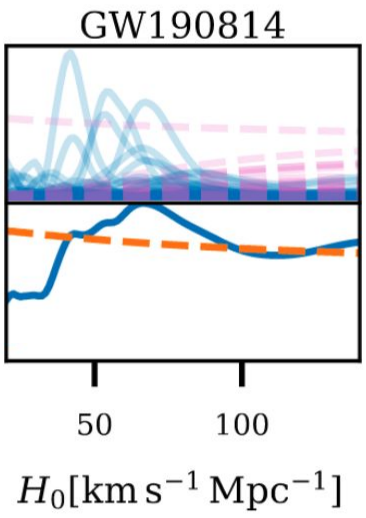




The LIGO, Virgo and KAGRA collaborations, 2023 *ApJ* **949** 76

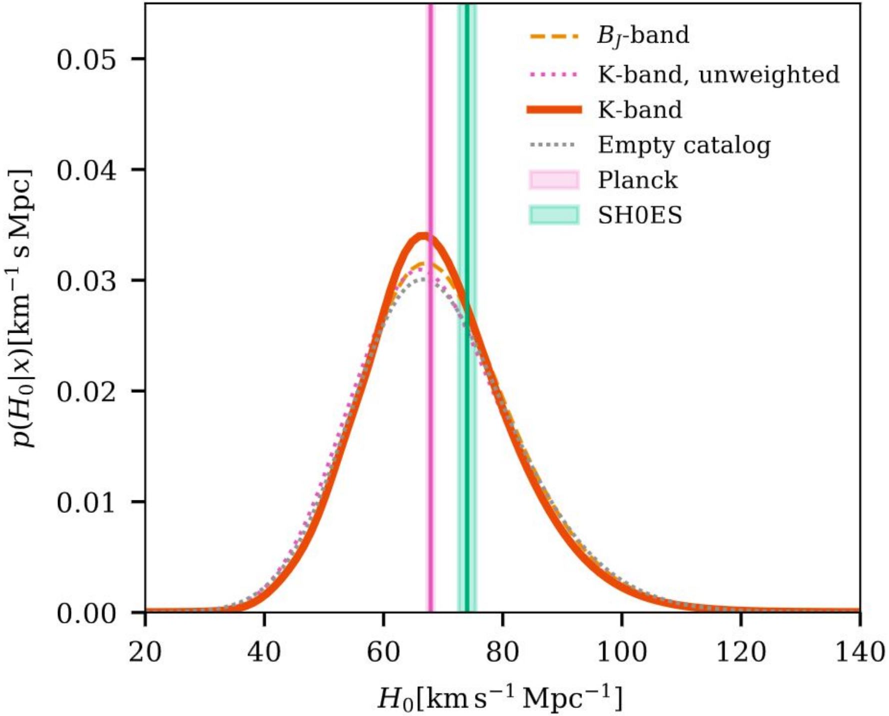
GW190814: the most informative dark siren so far

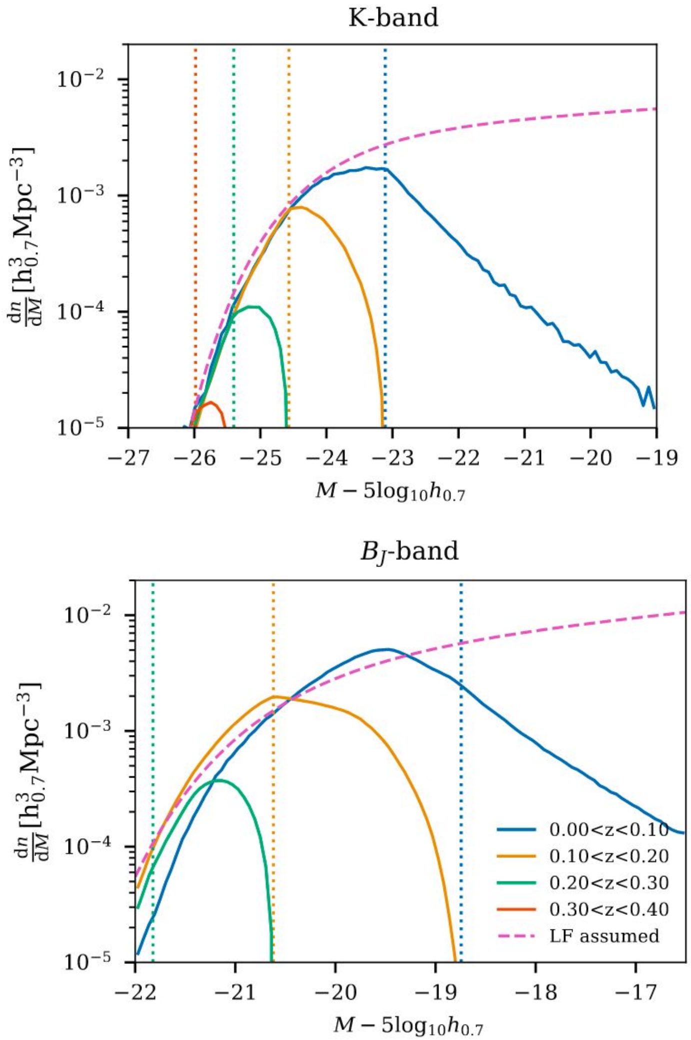




The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

Impact of catalogue assumptions





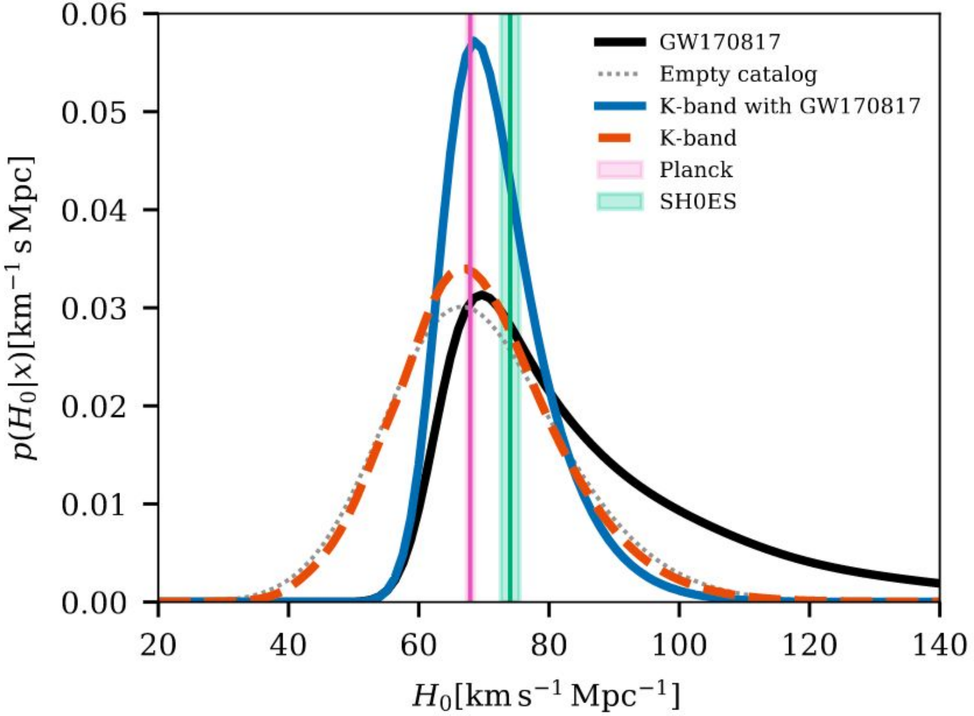
The LIGO, Virgo and KAGRA collaborations,
Sept 2021, *arXiv:2111.03604*

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).

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

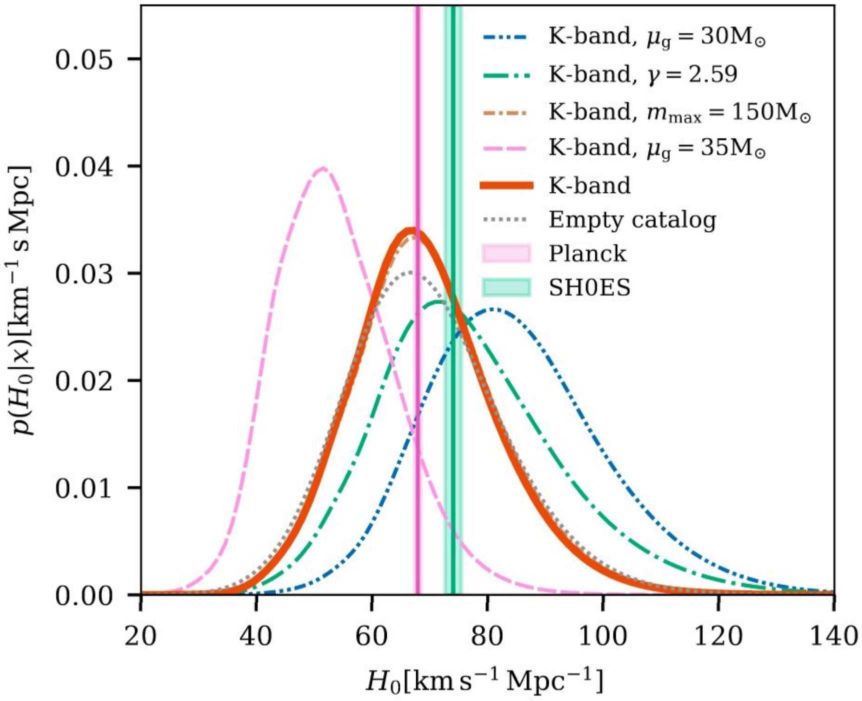


The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

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*

Using the black hole mass distribution for cosmological inference

Cosmological + population inference with N_{obs} GW events

Individual GW event likelihoods

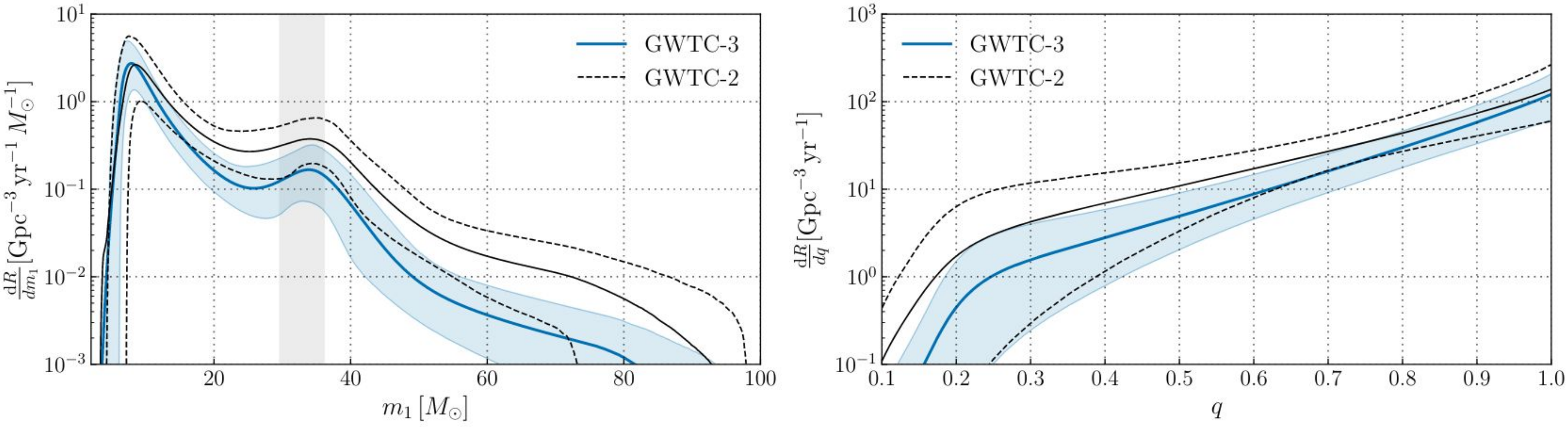
priors

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

Probability of detecting a GW from the population

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

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

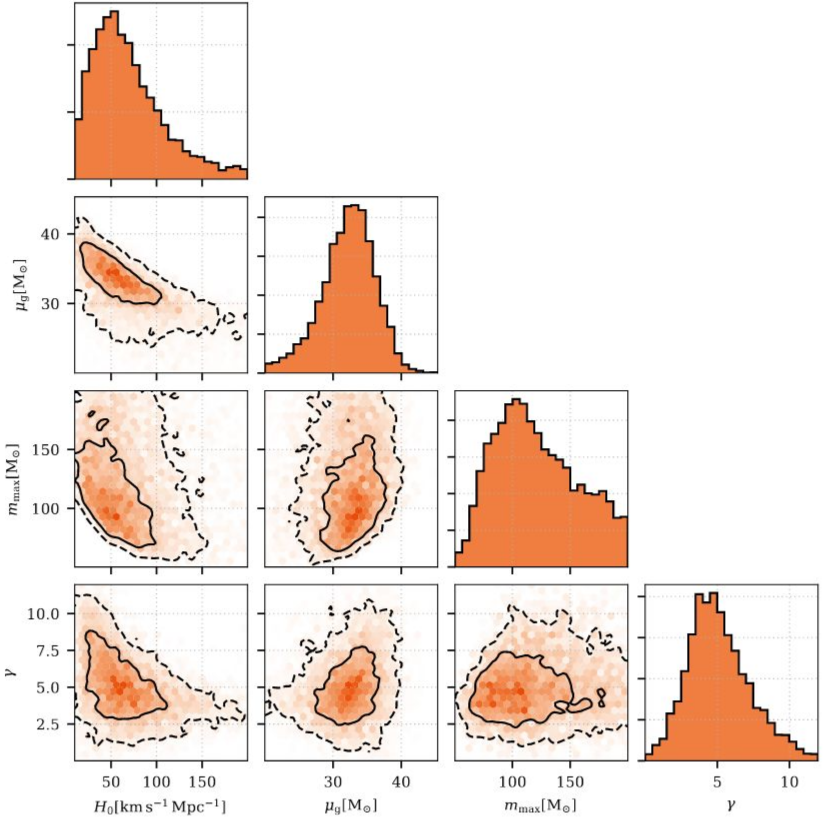
m_{max} (maximum black hole mass)

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

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

Sharp features in the mass distribution are correlated with H0.

(See e.g. Farr+ 2019, Mastrogiovanni+ 2021)

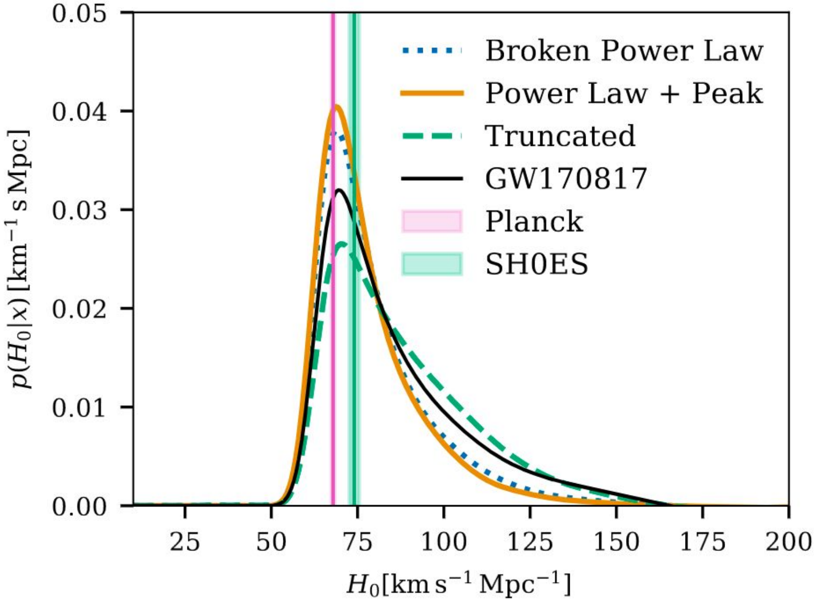


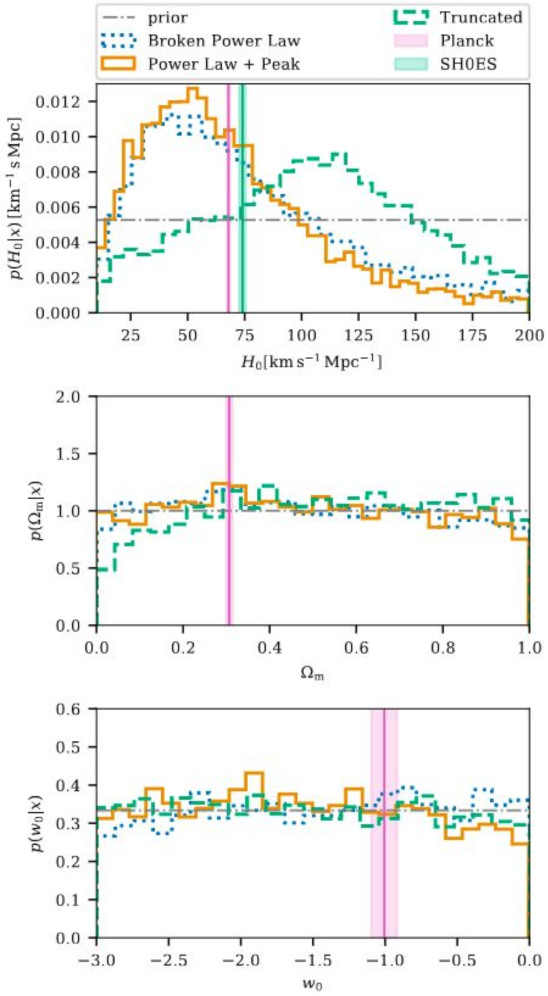
The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

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.

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





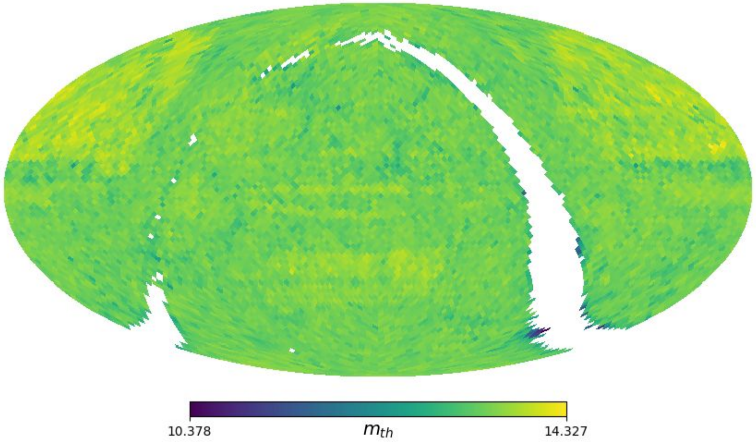
The LIGO, Virgo and KAGRA collaborations, Sept 2021, *arXiv:2111.03604*

A new way forward

Integrating galaxy information to a population analysis

$$p(\Lambda|\{x_{\rm GW}\},\{D_{\rm GW}\},I) \propto p(\Lambda|I)p(N_{\rm det}|\Lambda,I)\left[\iint p(D_{\rm GW}|\theta,\Lambda,I)p(\theta|\Lambda,I)\sum_j^{N_{\rm pix}} p(z|\Omega_j,\Lambda,I)d\theta dz\right]^{-N_{\rm det}}$$

$$\times \prod_i^{N_{\rm det}}\left[\iint \sum_j^{N_{\rm pix}} p(x_{{\rm GW}i}|\Omega_j,\theta,\Lambda,I)p(\theta|\Lambda,I)\underline{p(z|\Omega_j,\Lambda,I)}d\theta dz\right]$$



LOS redshift prior: can pre-compute this to include galaxy catalogue information and the out of catalogue correction.

R. Gray et al 2023 (in prep), see also Mastrogiovanni et al 2023

The line-of-sight redshift prior

Galaxy catalogue contribution

$$p(z|\Omega_i,\Lambda,s,I)=\frac{p(s|z,\Lambda_{\rm rate},I)}{p(s|\Omega_i,\Lambda,I)}\Bigg[p(G|\Omega_i,\Lambda,I)\frac{1}{N_{\rm gal}(\Omega_i)}\sum_k^{N_{\rm gal}(\Omega_i)}p(z|\hat{z}_k)p(s|M(z,\hat{m}_k,\Lambda_{\rm cosmo}),I)$$

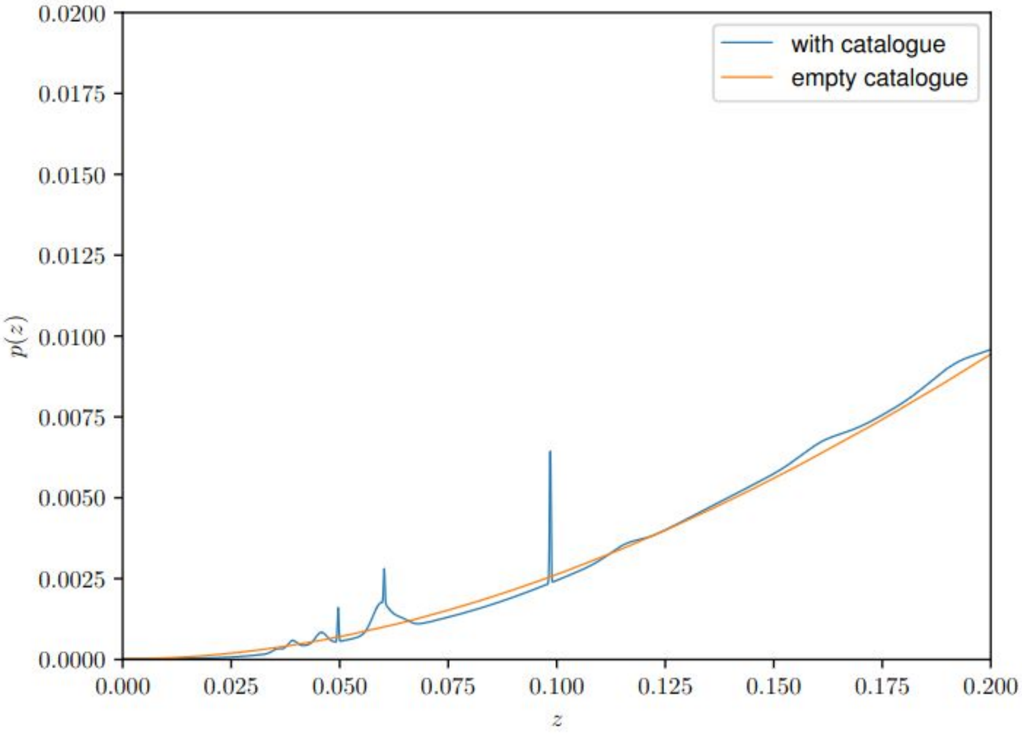
$$+p(z|\Lambda_{\rm cosmo},I)\Bigg(\Theta[z_{\rm cut}-z]\int_{M(z,m_{\rm th}(\Omega_i),\Lambda_{\rm cosmo})}^{M_{\rm max}(H_0)}p(M|z,\Lambda_{\rm cosmo},I)p(s|M,I)\,dM$$

$$+\Theta[z-z_{\rm cut}]\int_{M_{\rm min}(H_0)}^{M_{\rm max}(H_0)}p(M|z,\Lambda_{\rm cosmo},I)p(s|M,I)\,dM\Bigg)\Bigg].$$

Out of catalogue contribution

R. Gray et al 2023 (in prep)

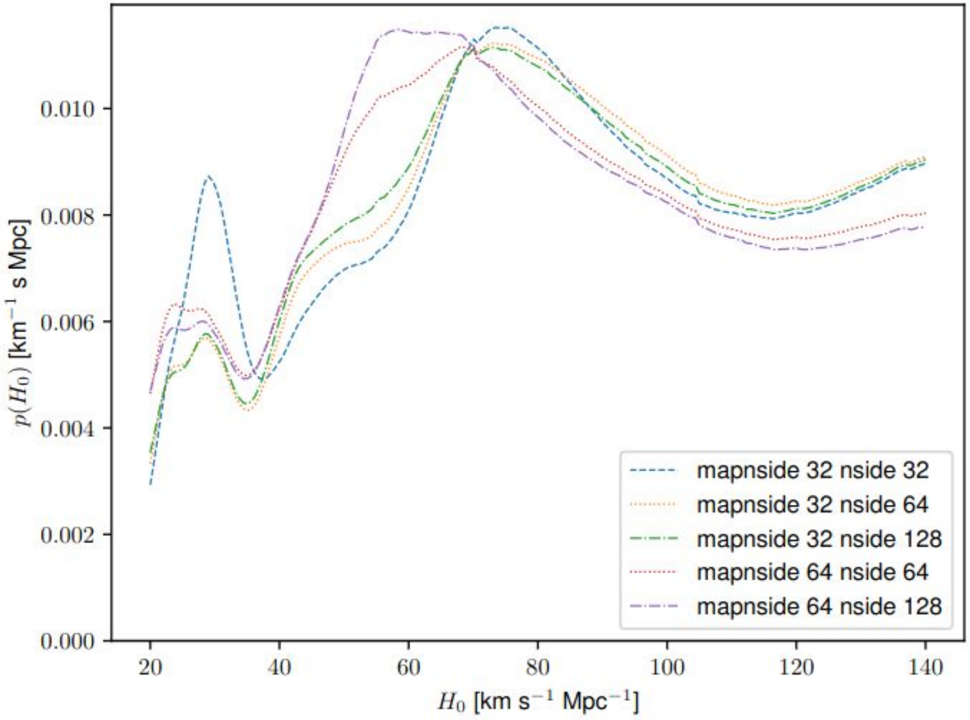
LOS redshift prior (example pixel)



R. Gray et al 2023 (in prep)

Case study of GW190814

Impact of resolution choices on the posterior for GW190814.



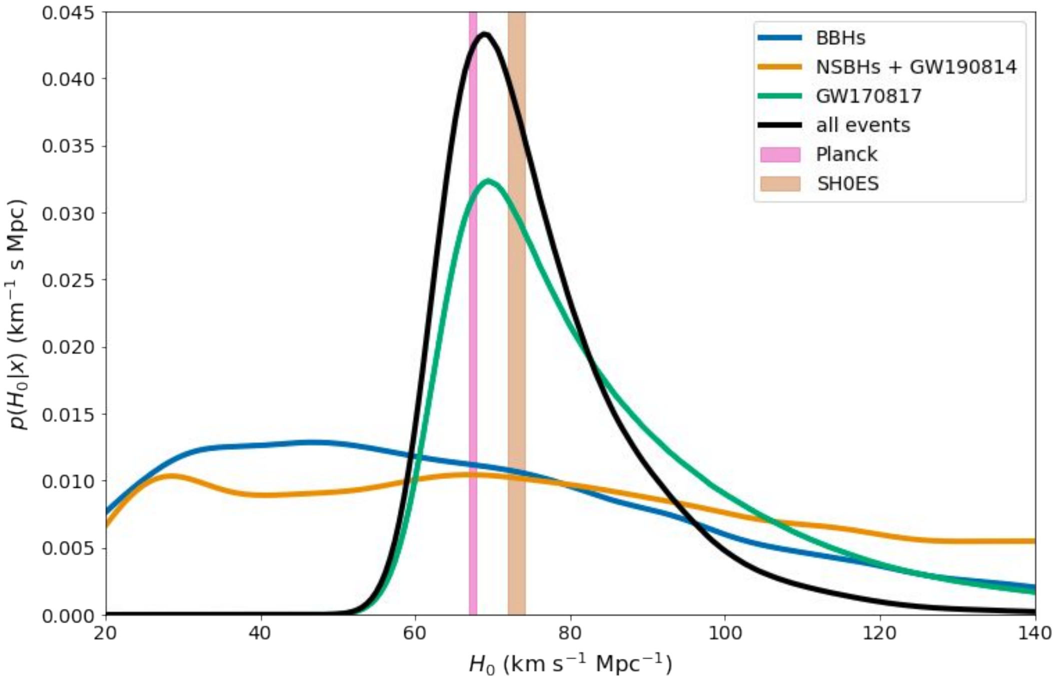
R. Gray et al 2023 (in prep)

A new result

42 BBHs, 2 NSBHs, GW190814, GW190425 analysed with GLADE+, and GW170817+counterpart.

Full population+cosmological inference, then marginalisation over population params.

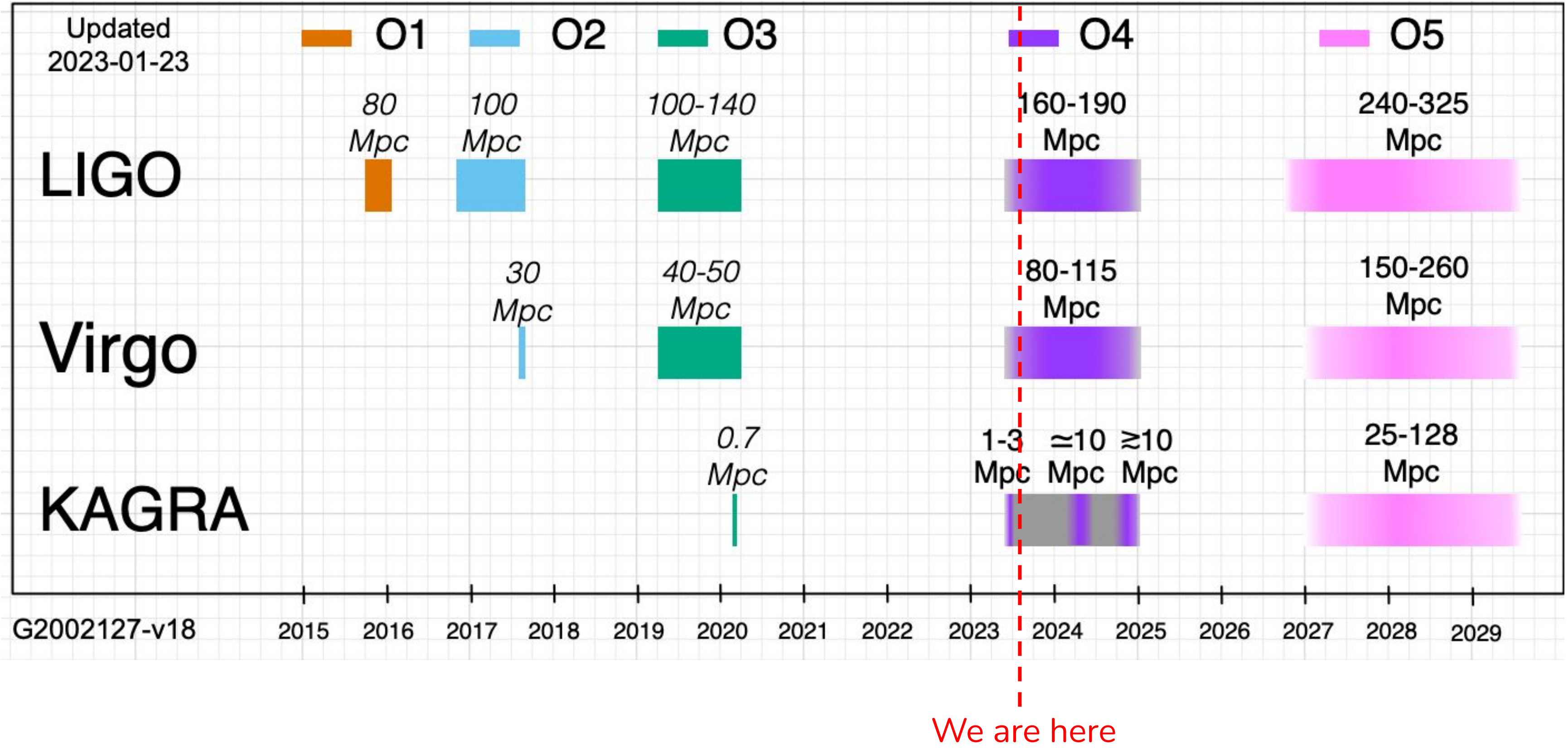
H0 = 69 +13 -7 km s-1 Mpc-1



R. Gray et al 2023 (in prep)

What’s next?

The gravitational wave data side



The galaxy survey side

So far have used GLADE+ because it covers majority of the sky, and it's **incompleteness** in K band is well understood.

In the coming years we need to make use of current surveys with **large sky areas** which go to **higher redshifts** (e.g. the DESI Legacy surveys, DES, etc. (see e.g. Palmese et al 2023)), as well as prepare for upcoming surveys such as LSST.

Ideally we need

- Reliable redshift estimates
- Source-frame luminosity information

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.

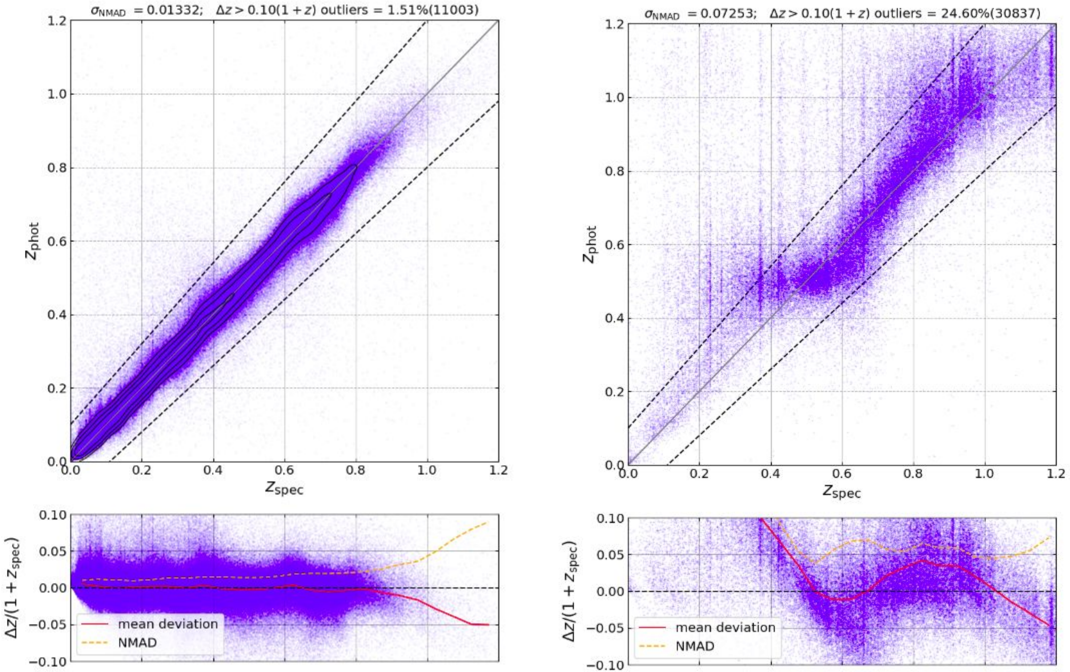
This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

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.



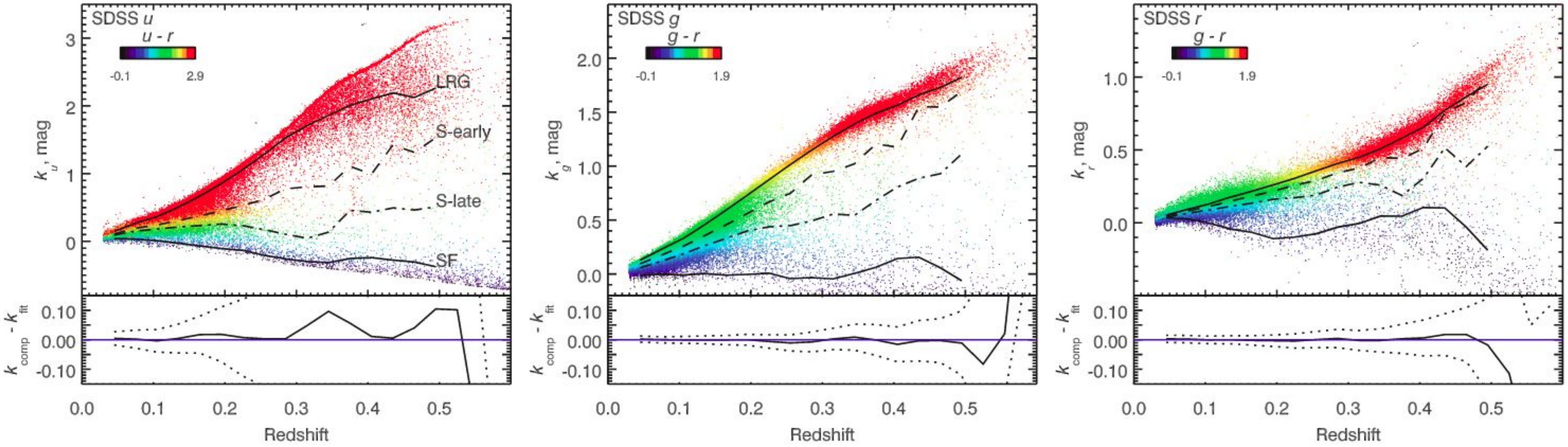
Zhou *et al.* *MNRAS*, Volume 501, Issue 3, March 2021, Pages 3309–3331

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.

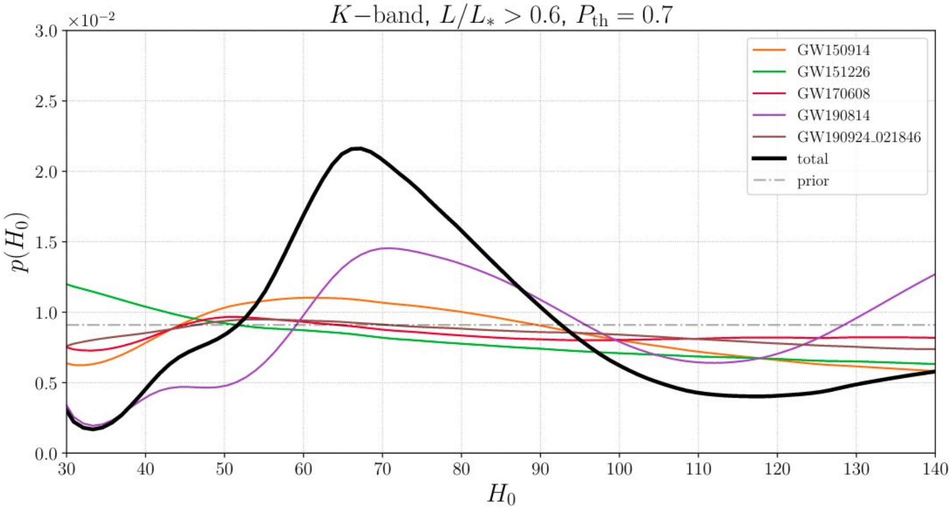
Solution? K corrections

$$M_a = m_b - DM - K$$

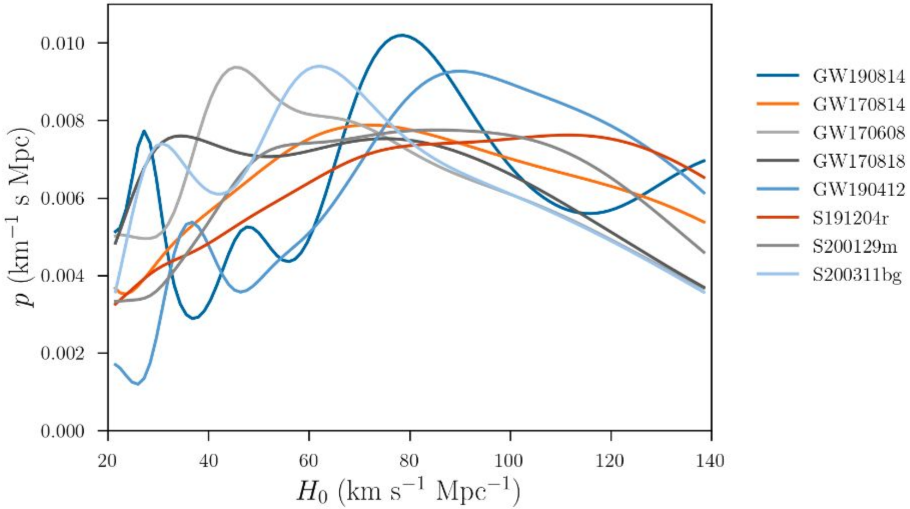


Chilingarian *et al. MNRAS*, Volume 405, Issue 3, July 2010, Pages 1409–1420

More dark siren measurements

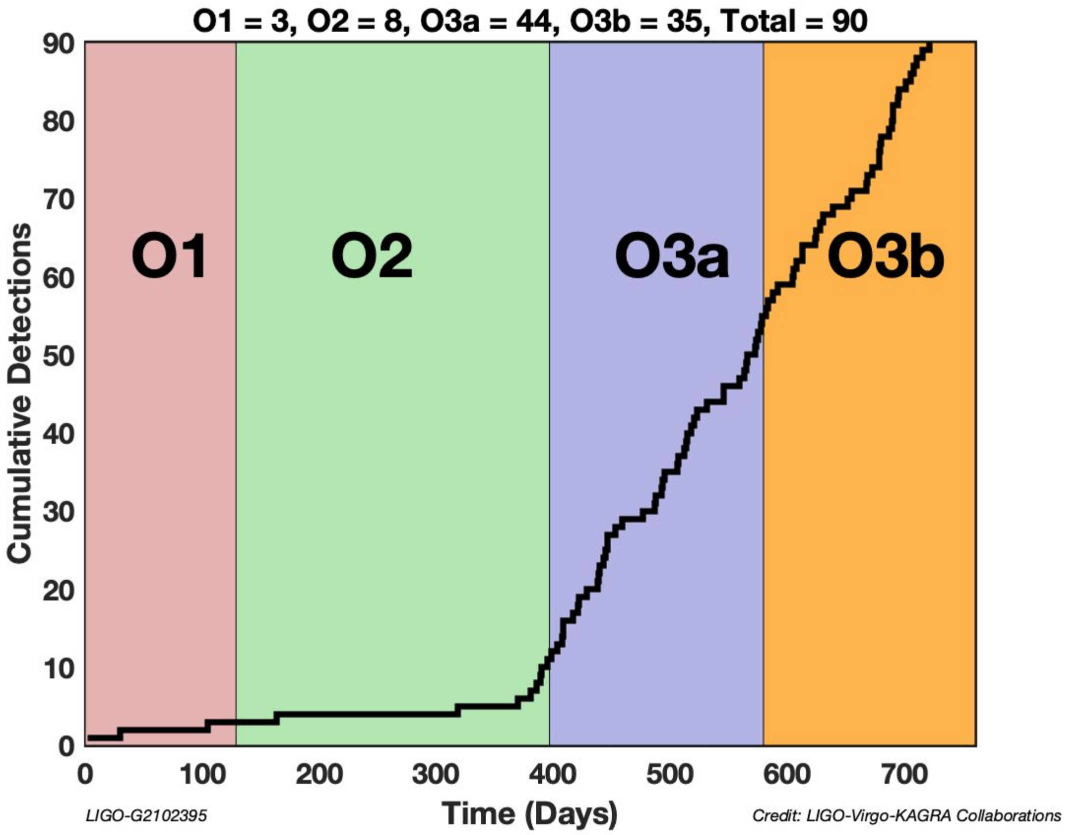


A. Finke *et al, JCAP* 08 (2021) 026



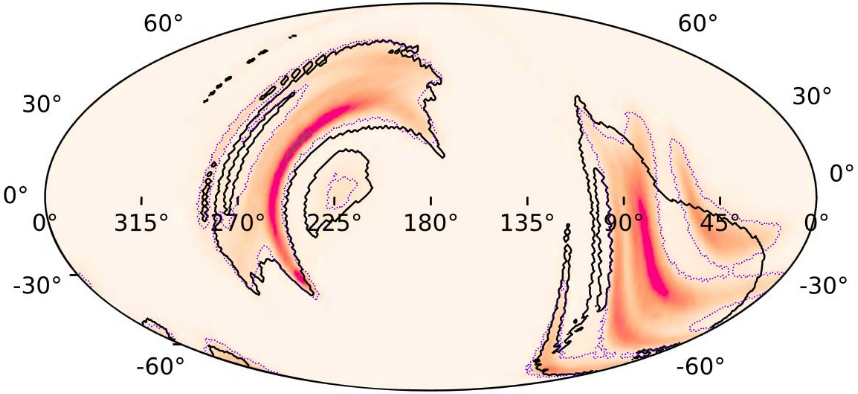
A. Palmese *et al* 2023 *ApJ* **943** 56

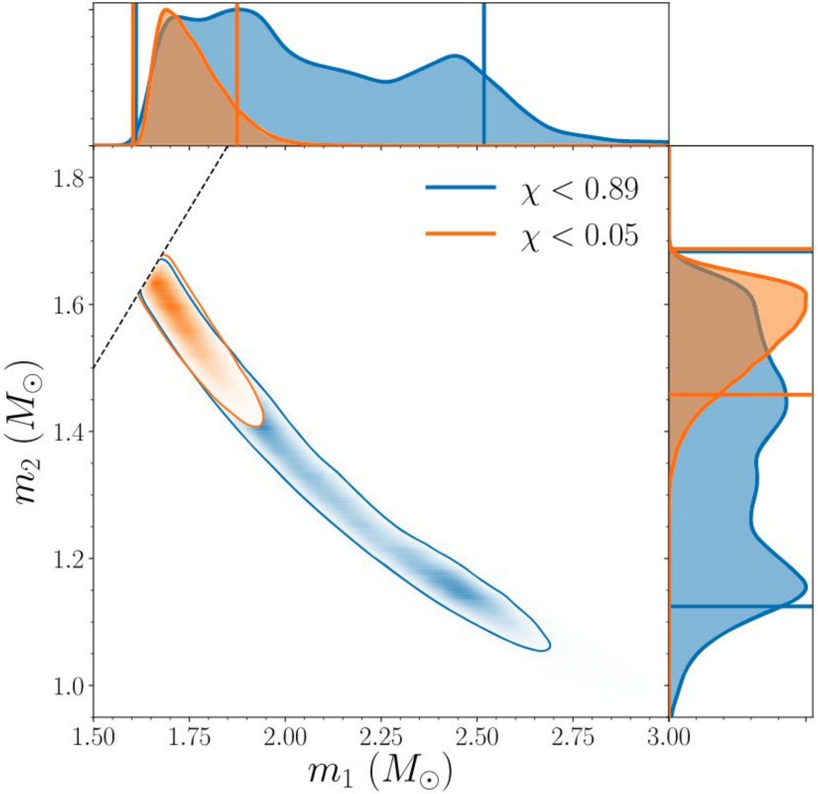
Cumulative detections to date



BNS

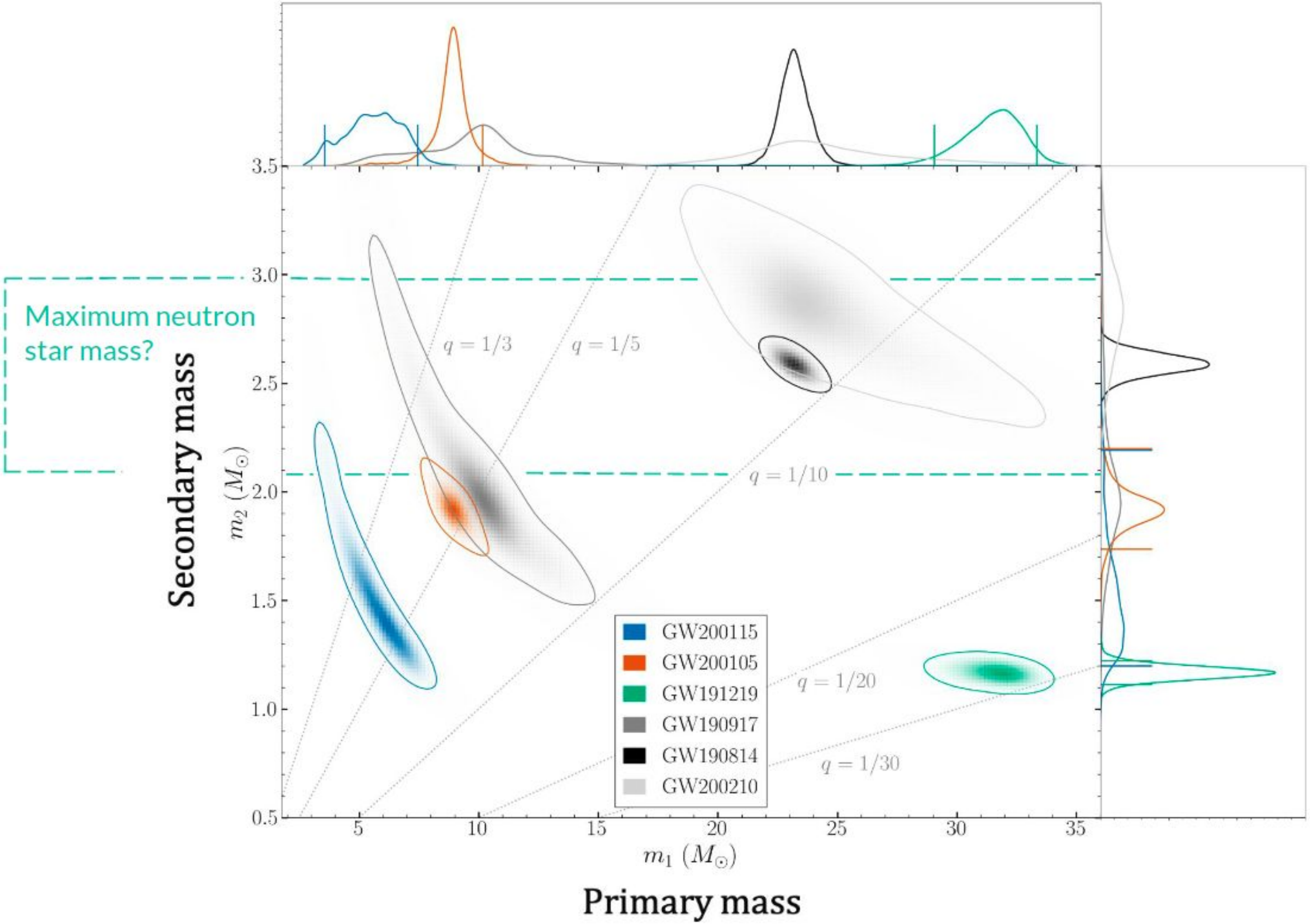
GW190425 is the second binary neutron star to be detected, after GW170817. Around 160 Mpc away.





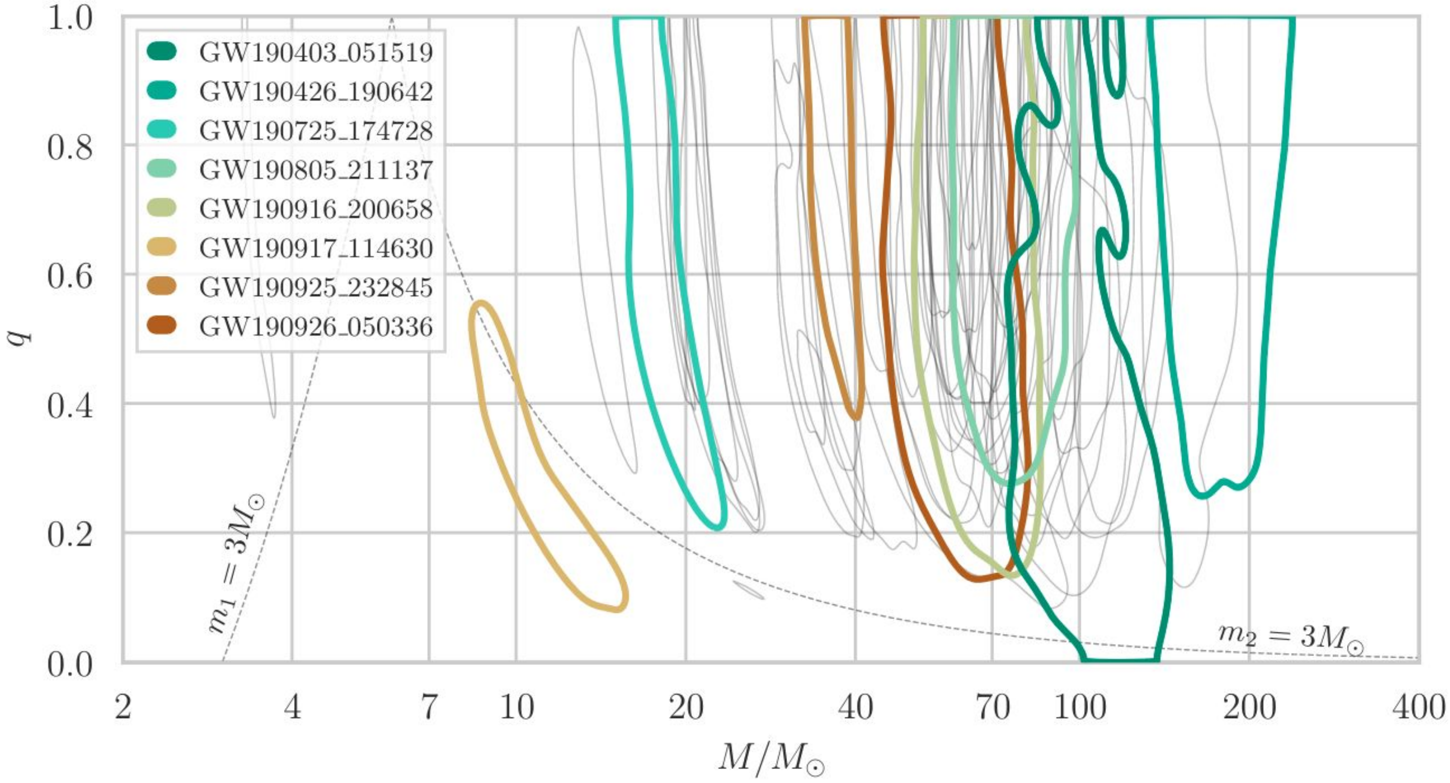
The LIGO Scientific Collaboration and the Virgo Collaboration, Astrophysical Journal Letters 892 (2020) L3

NSBHs



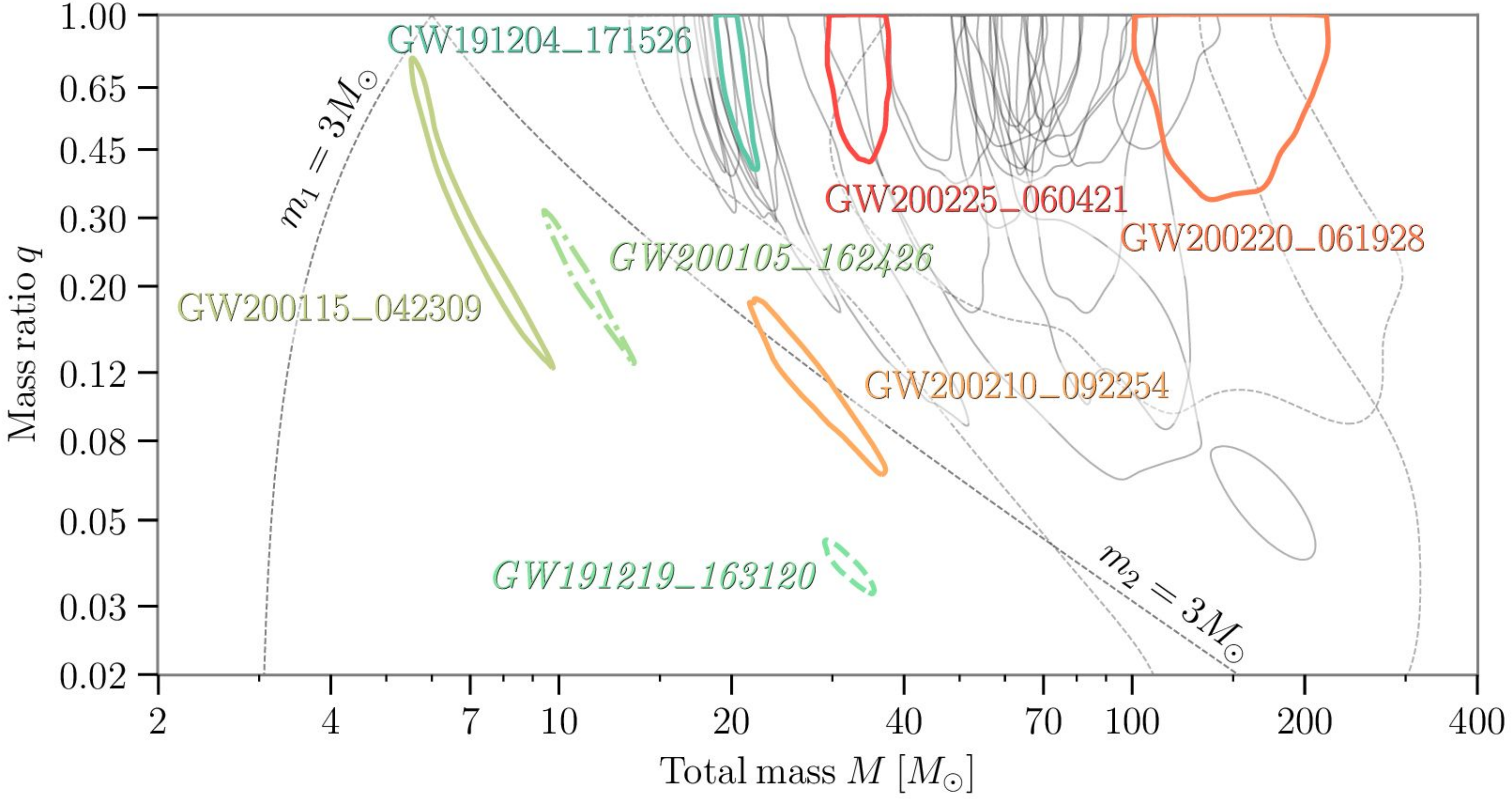
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, GWTC-3 webinar

Events from O3a



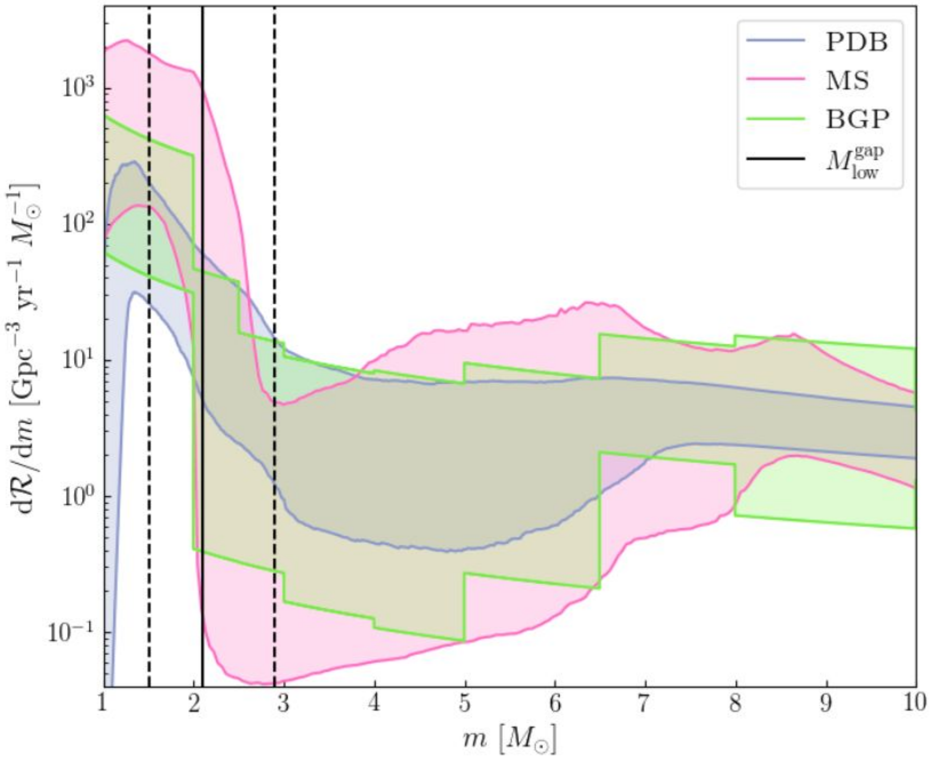
The LIGO Scientific Collaboration and Virgo Collaboration, *arXiv:2108.01045*

Events from O3b



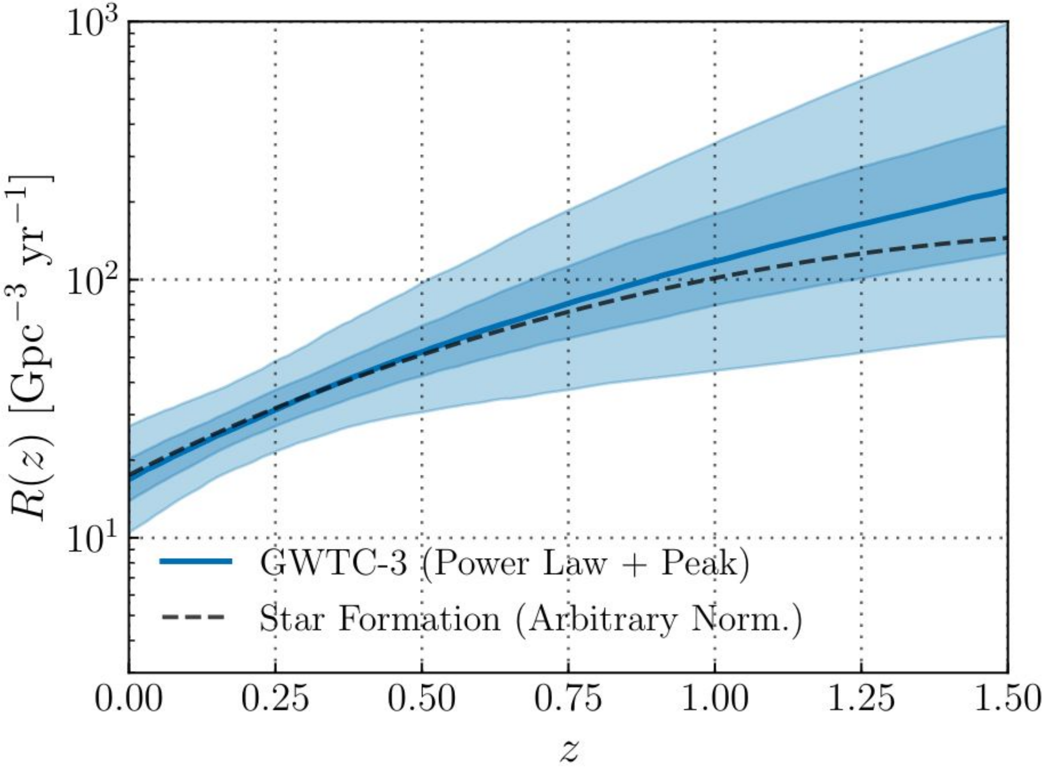
The LIGO Scientific Collaboration, the Virgo Collaboration, the KAGRA Collaboration, Nov 2021, *arXiv:2111.03606*

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

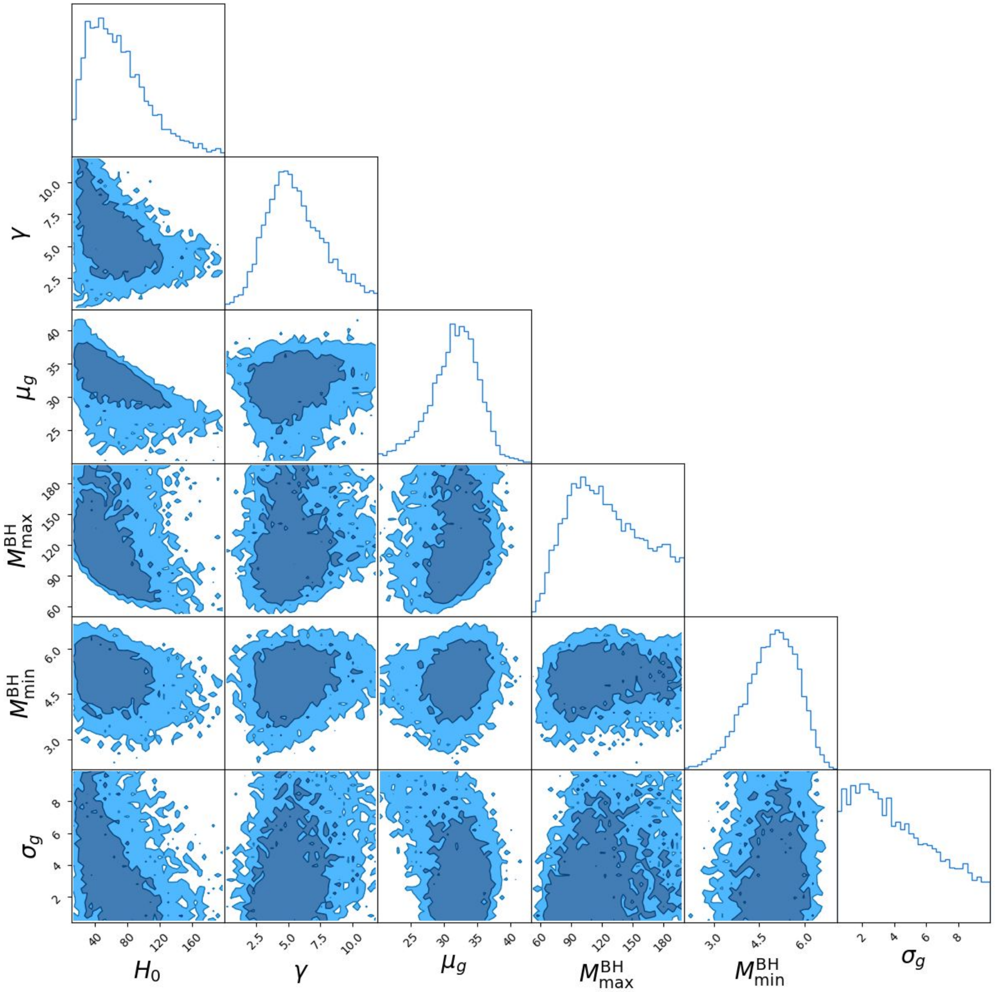


The LIGO Scientific Collaboration, the Virgo Collaboration and the KAGRA Collaboration, Phys. Rev. X **13**, 011048, March 2023

Population only result

42 BBHs with network SNR > 11.

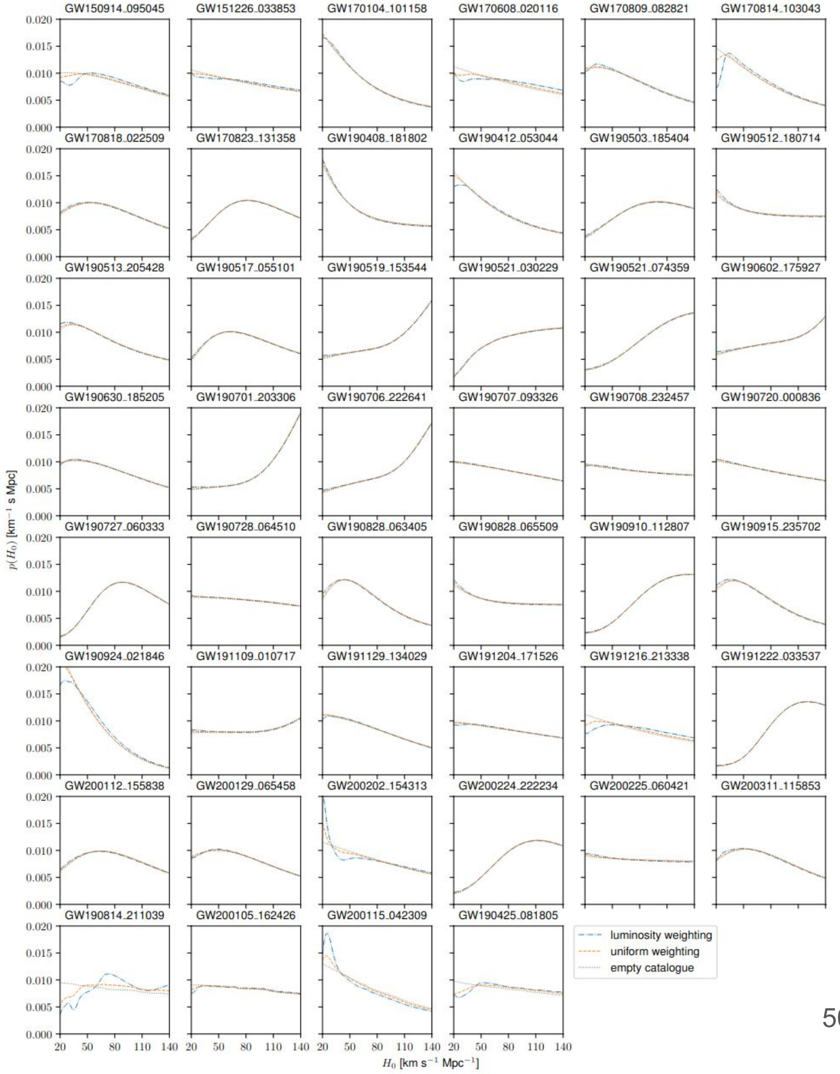
Good agreement with GWTC-3 cosmology paper.



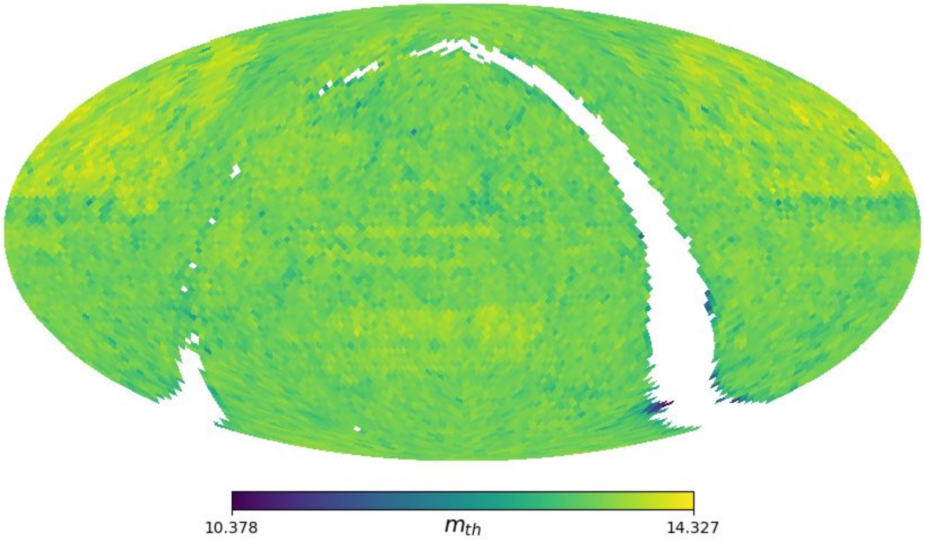
Fixed population results

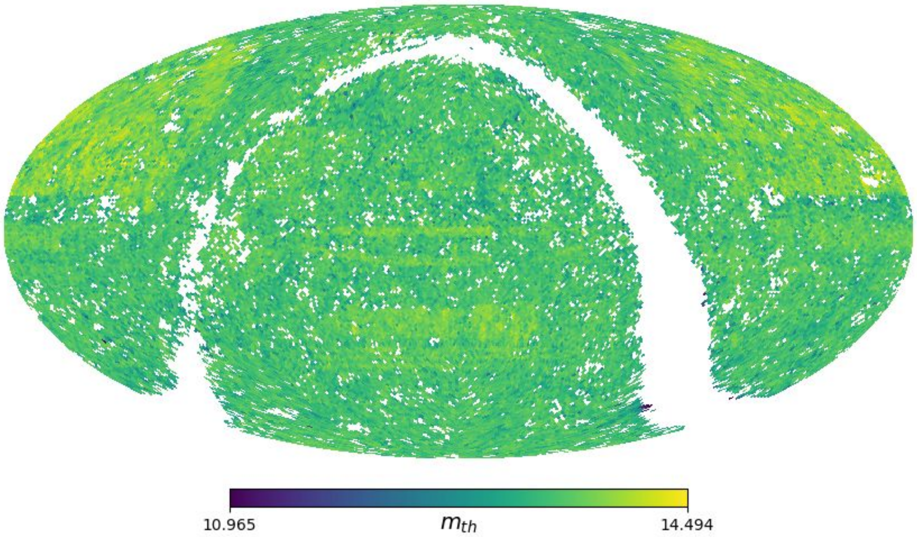
42 BBHs, 2 NSBHs, GW190814, GW190425, analysed with empty catalogue, K band weighted and uniform weighting (GLADE+).

Good agreement with GWTC-3 cosmology paper.



Mth map: nside 32 vs 64





Summary

- This version of gwcosmo is ~1000 times faster than the one used during O3.
- The amount of memory the LOS redshift prior requires is **not** dependent on the number of galaxies in the galaxy catalogue (good for large surveys in the future!)
    - But it does depend on the pixel resolution
    - And also on the redshift resolution required to accurately capture redshift uncertainties
- Can carry out inference on H_0, MG parameters (see Anson's talk) and GW population parameters.
    - Other cosmological parameters (Ω_M, w_0, w_A) remain a as a challenge to be implemented in the future.