Cosmology with gravitational waves

Measuring the Hubble constant with current detections

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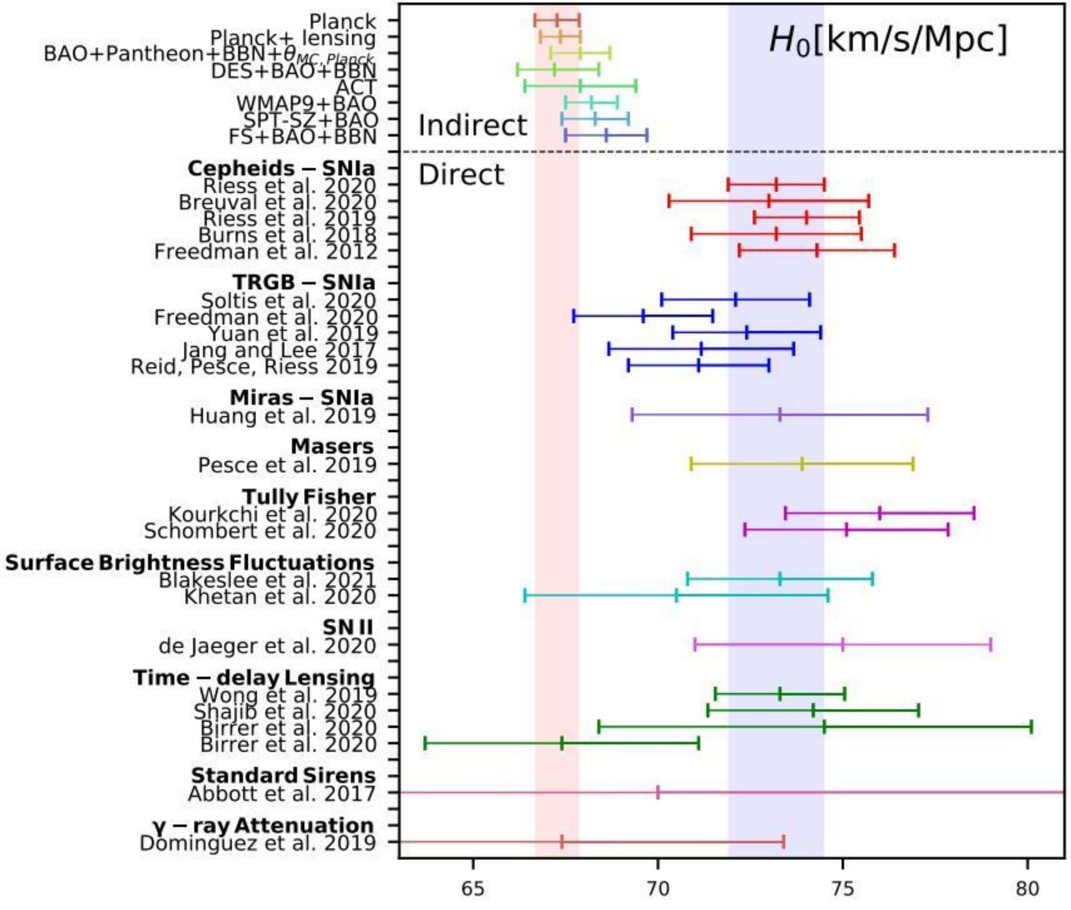
The Hubble tension

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

Tension lies at 4 - 6σ.

Possible causes:

1. Systematics?
2. New, unknown physics?



Eleonora Di Valentino: arXiv:2011.00246

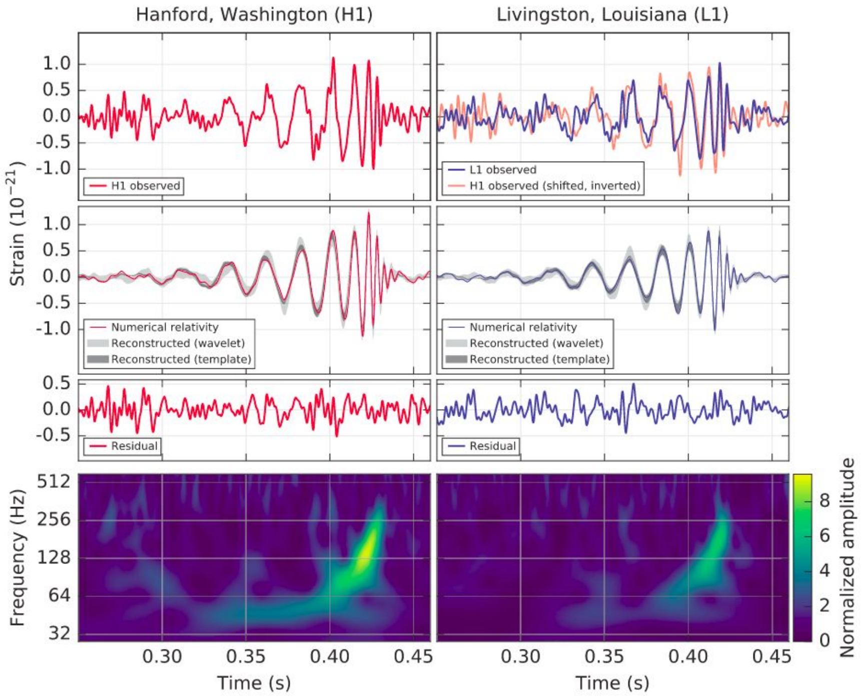
Gravitational waves as standard sirens

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

$$A = \frac{\mathcal{M}_z}{d_L} f(\mathcal{M}_z, t) \qquad \mathcal{M}_z = (1+z)\frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Hubble constant, redshift, luminosity distance relationship:

$$d_L = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{(1+z')^3 \Omega_M + \Omega_\Lambda}}$$



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

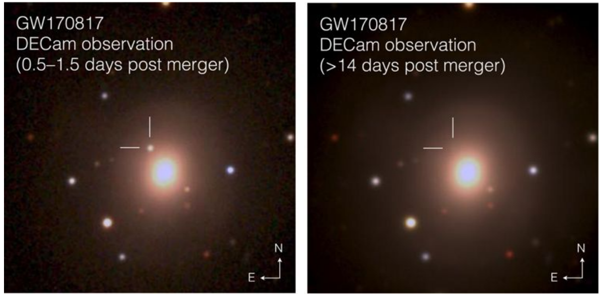
Bright Sirens

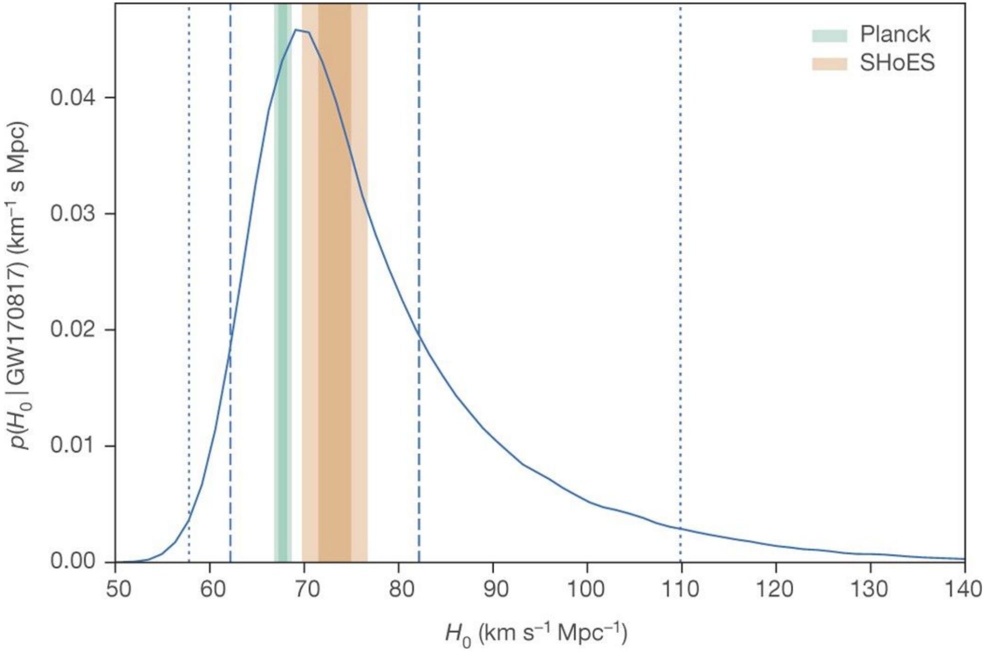
Any GW standard siren with an electromagnetic counterpart.

Observe EM counterpart → identify host galaxy → measure host galaxy's redshift → **measure H_0**

Complicated by galaxy peculiar velocities, poor sky localisation, etc…

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





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).

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

Cosmological analyses with standard sirens

"Bright sirens"

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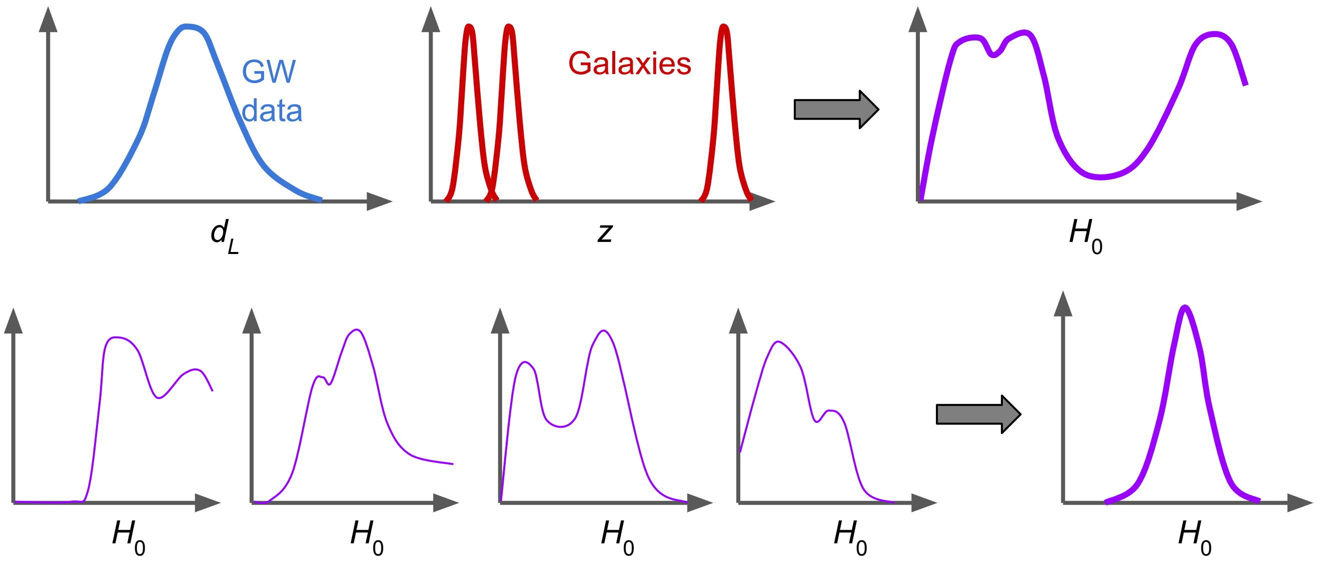
AKA the redshifted masses method

It's actually more complicated than that!

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.

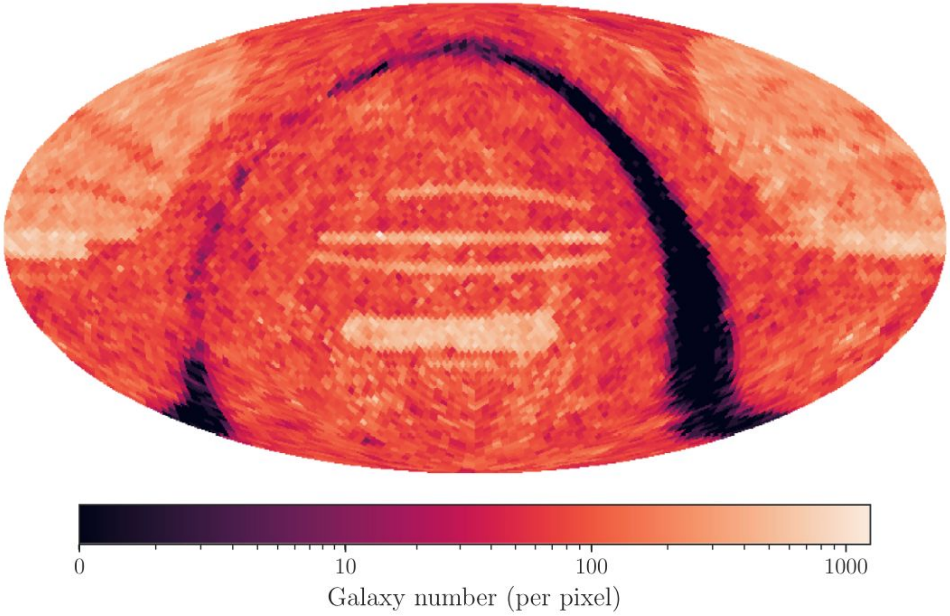
(see, e.g. Schutz 1986, Del Pozzo 2012, Chen+ 2018, Soares-Santos+ 2019, Gray+ 2020, Finke+ 2021…)



The galaxy catalogue - incompleteness issues?

Catalogues are incomplete. Two options:

- Apply cuts to the data so it becomes "effectively complete" (e.g. Soares-Santos+ 2019, Palmese+ 2020)
- Apply an incompleteness correction (e.g. Gray+ 2020)



Catalogue completeness can be computed on a pixel-by-pixel basis, (Gray+ 2022).

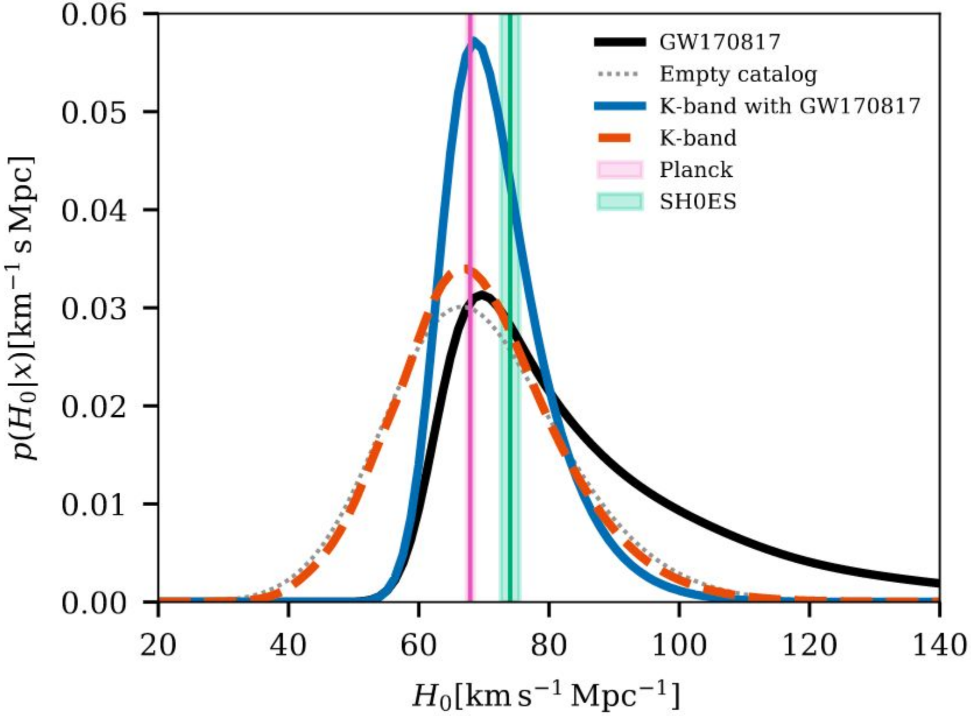
LVK dark siren + galaxy catalogue result

Results using *gwcosmo*.

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

All are analysed with the GLADE+ catalogue (Dalya+ 2022) in the K-band (apart from GW170817).

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

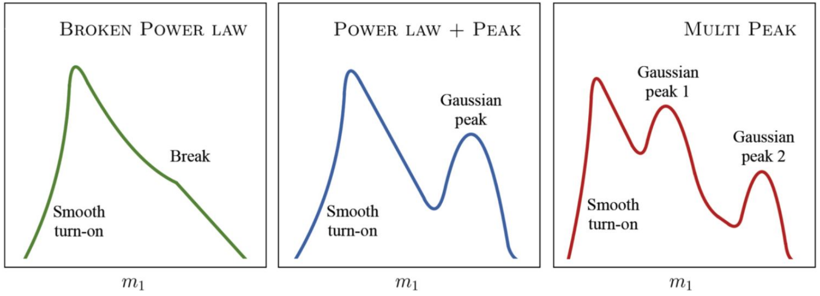


The LIGO, Virgo and KAGRA collaborations, 2023 *ApJ* **949** 76

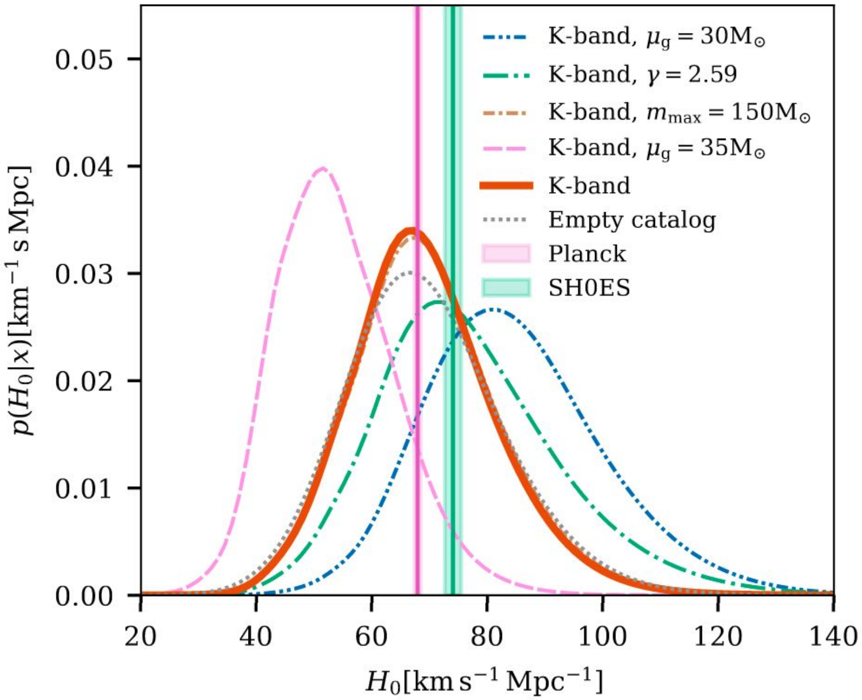
The impact of population assumptions

Population assumptions have a **huge** impact on H_0 inference.

Features in the population's mass distribution break the mass-redshift degeneracy — cosmologically informative.



R. Abbott *et al* 2021 *ApJL* **913** L7.

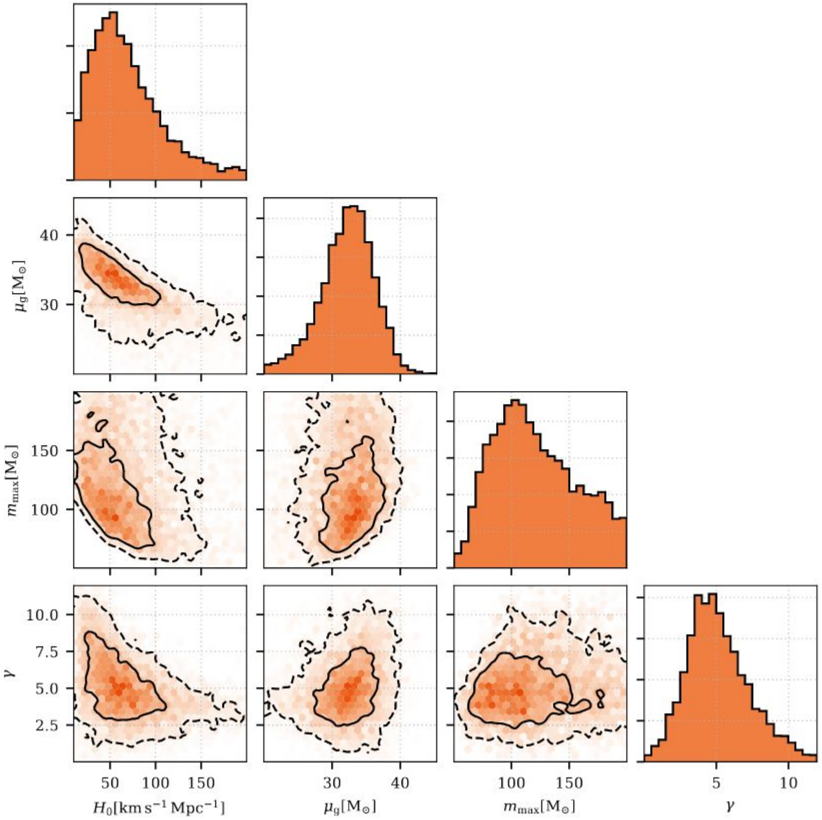


The LIGO, Virgo and KAGRA collaborations, 2023 *ApJ* **949** 76

Spectral sirens: information from the population

Results using *icarogw* from the LVK GWTC-3 cosmology paper.

Sharp features in the mass distribution are correlated with H_0 (e.g. Farr+ 2019, Mastrogiovanni+ 2021)

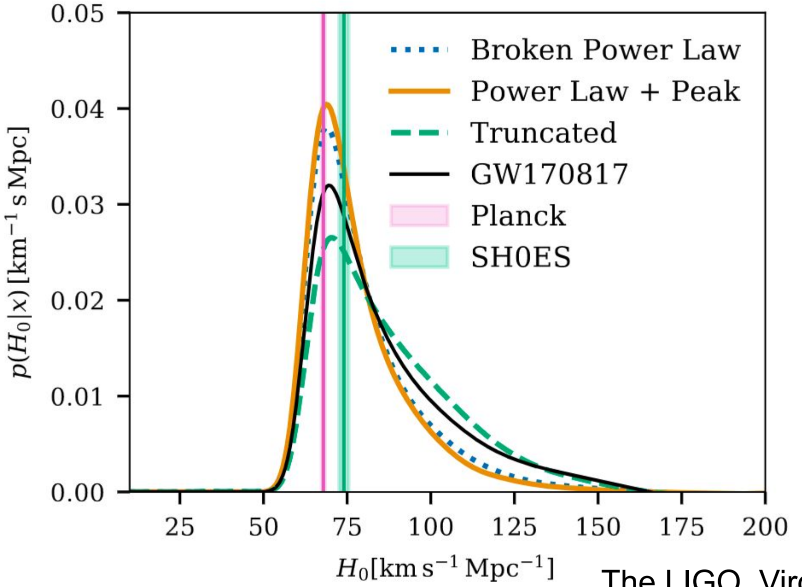


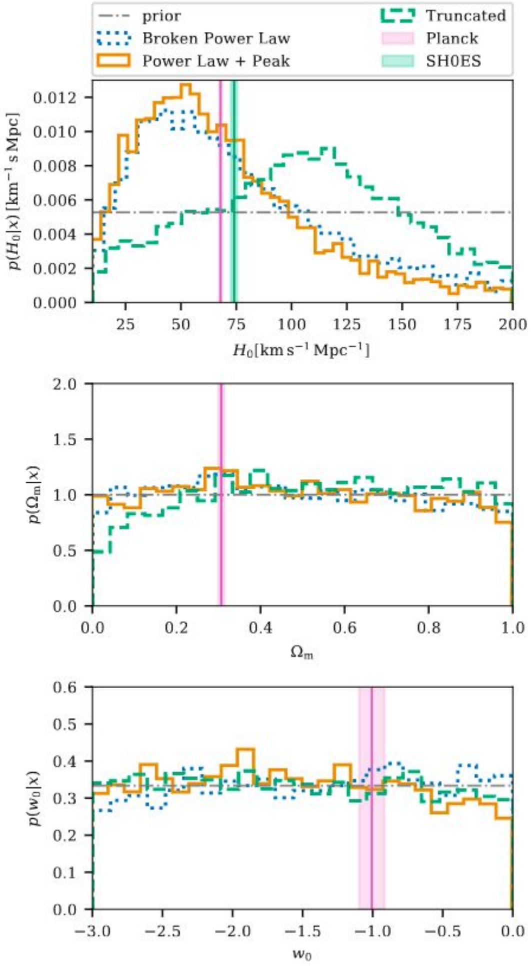
The LIGO, Virgo and KAGRA collaboration, 2023 *ApJ* **949** 76

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, 2023 *ApJ* **949** 76

Incorporating a galaxy catalogue

The galaxy catalogue (along with assumptions which allow us to account for galaxy catalogue incompleteness) is going to become the basis for the new **redshift prior** in the analysis (Gray+ 2023, Mastrogiovanni+ 2023).

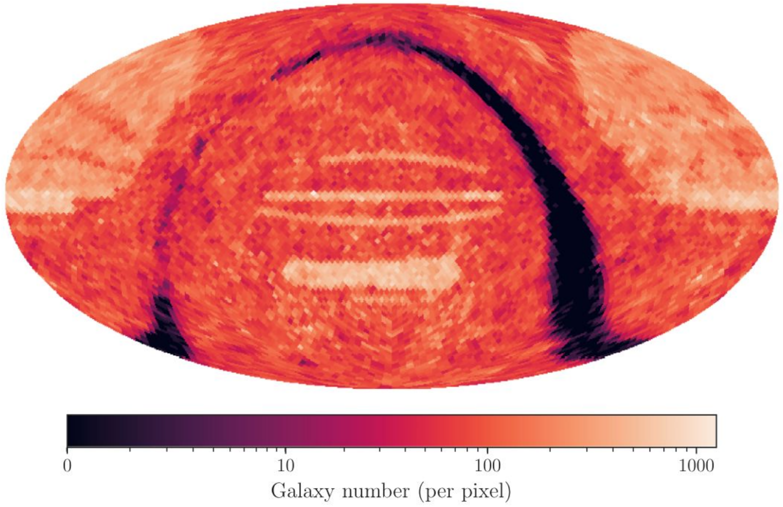
$$p(z|\kappa) \propto \frac{1}{1+z} \frac{dV_c}{dz} \mathcal{R}(z)$$

Uniform in comoving volume distribution replaced by "line-of-sight redshift prior"

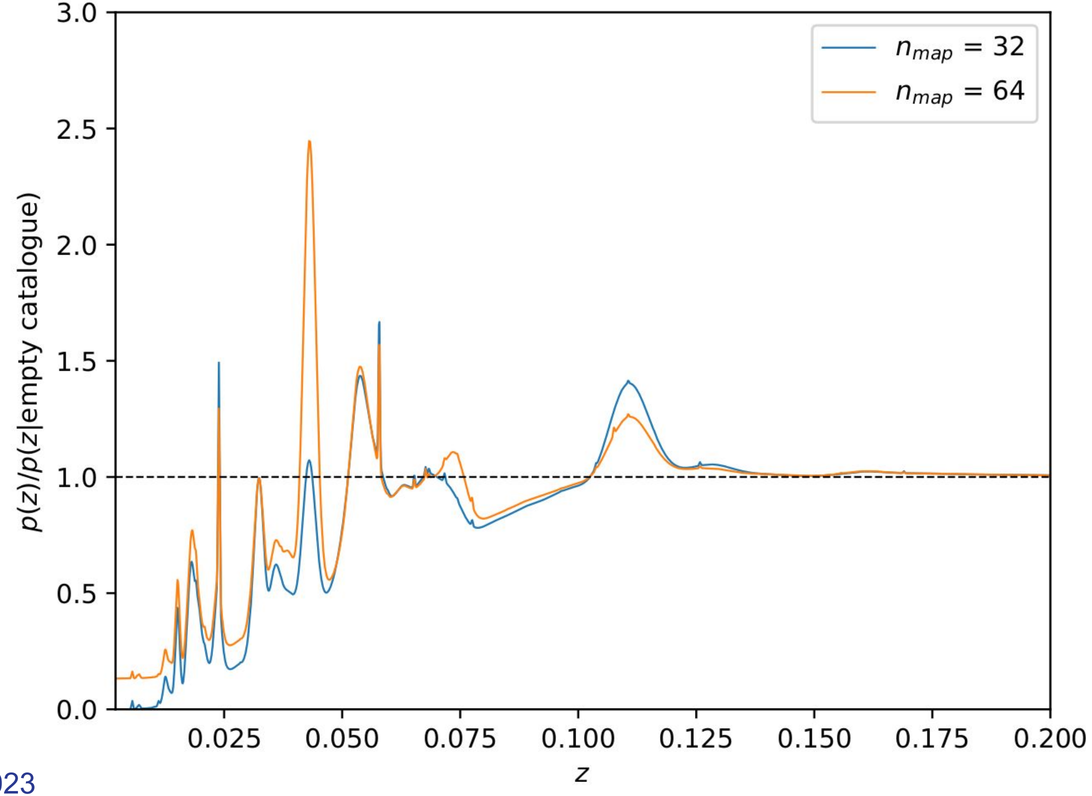
The line-of-sight redshift prior

Constructed for every pixel on the sky, the LOS redshift prior contains:

- A sum of the galaxies in each pixel
- Choice of host-galaxy weighting (luminosity weighted?)
- Information about the EM detection criteria (apparent magnitude threshold?)
- Assumptions about the universal galaxy distribution (uniform in comoving volume, follows a Schechter function?)

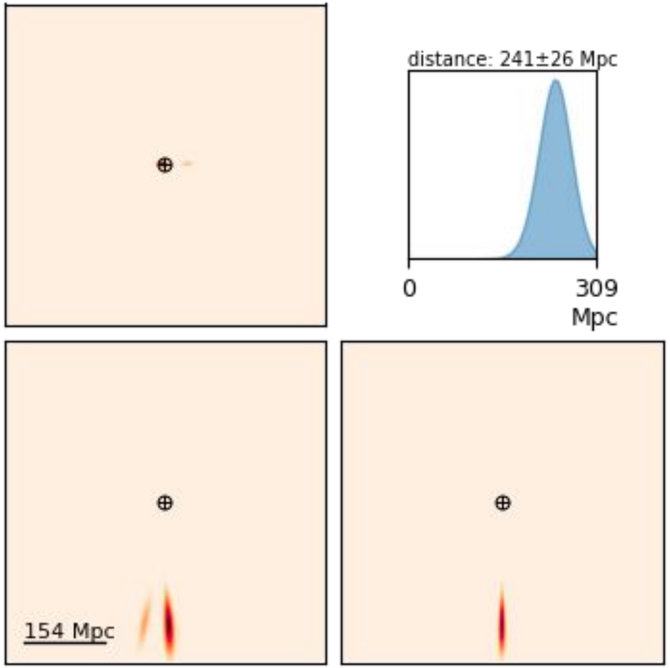


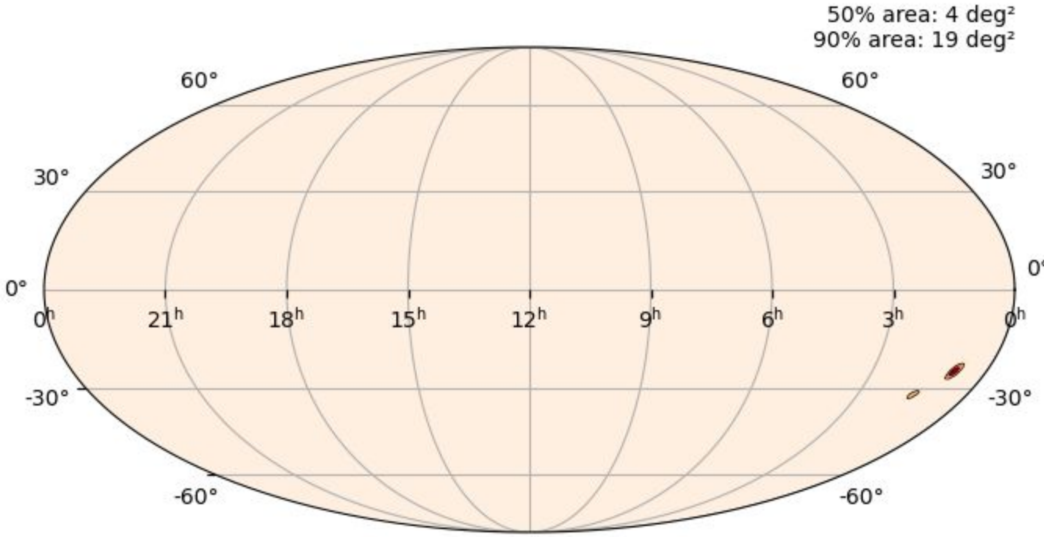
The line-of-sight redshift prior



R. Gray *et al* JCAP12(2023)023

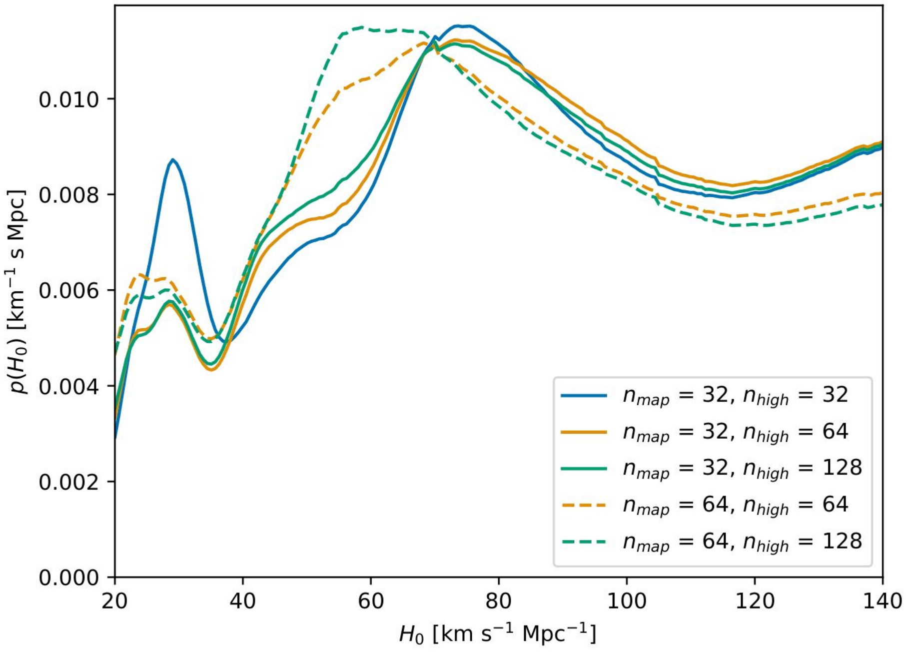
GW190814: the most informative dark siren so far

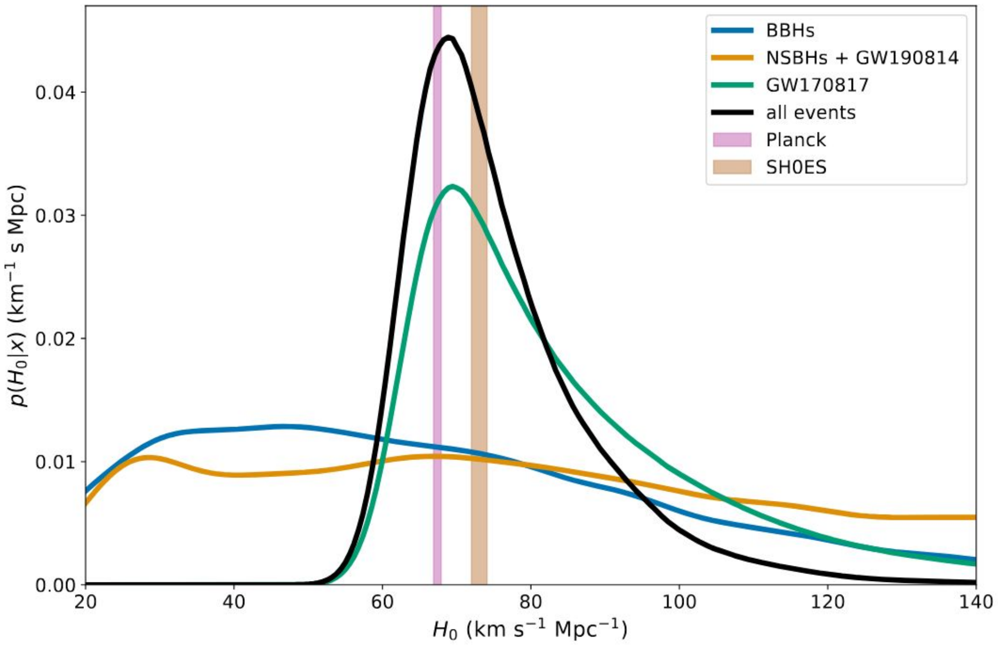




https://gracedb.ligo.org/superevents/S190814bv/

Results





$$H_0 = 69^{+12}_{-7} \text{ km s}^{-1} \text{Mpc}^{-1}$$

R. Gray *et al* JCAP12(2023)023

Next steps

Galaxy Catalogues

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 and Euclid.

Potential complications getting reliable redshift and galaxy luminosities/masses.

Gravitational waves

Number of detections guaranteed to keep increasing across O4, O5 and beyond. Need to keep an eye on **potential sources of systematics** (mass models, evolution with redshift?).

Beyond the Hubble tension

Cosmology with standard sirens isn't limited to the Hubble constant. As we detect events from higher redshifts, we become sensitive to other cosmological parameters.

Can also use standard sirens to test **modified gravity models** (e.g. where the GW luminosity distance differs from EM luminosity distance due to an additional friction term) - see, e.g. Finke+ 2021, Leyde+ 2022, Chen+ 2023.

$$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

Conclusions

- With only one **bright siren** to date, **dark sirens** offer a complementary way of constraining cosmological parameters like H0.
- Current measurements with LVK BBHs have demonstrated the importance of **jointly inferring cosmological and population parameters**.
- Incorporating a **galaxy catalogue** adds additional constraining power. Nearby, well localised events can be very informative!
- So far, the use of a **line-of-sight redshift prior** is the best (only?) way of incorporating incomplete galaxy catalogues into a population-level analysis.
- Upcoming **large-scale galaxy surveys**, and the guarantee of more GW data in **O5 and beyond** makes this an exciting area to watch.

Extra slides

Population inference with N_{det} GW events

$$p(\Lambda|\{x_{\text{GW}}\},\{D_{\text{GW}}\},I) \propto p(\Lambda|I)p(N_{\text{det}}|\Lambda,I)\left[\int p(D_{\text{GW}}|\theta,\Lambda,I)p(\theta|\Lambda,I)d\theta\right]^{-N_{\text{det}}} \times \prod_{i}^{N_{\text{det}}} \int p(x_{\text{GW}i}|\theta,\Lambda,I)p(\theta|\Lambda,I)d\theta,$$

Population inference with N_{det} GW events

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Posterior on population parameters

Population inference with N_{det} GW events

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Posterior on population parameters

Prior on population parameters

Population inference with N_{det} GW events

$$p(\Lambda|\{x_{\rm GW}\},\{D_{\rm GW}\},I) \propto p(\Lambda|I)p(N_{\rm det}|\Lambda,I)\left[\int p(D_{\rm GW}|\theta,\Lambda,I)p(\theta|\Lambda,I)d\theta\right]^{-N_{\rm det}} \times \prod_i^{N_{\rm det}} \int p(x_{{\rm GW}i}|\theta,\Lambda,I)p(\theta|\Lambda,I)d\theta,$$

Posterior on population parameters

Prior on population parameters

Rates term (Poisson distribution)

Population inference with N_{det} GW events

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Posterior on population parameters

Prior on population parameters

Rates term (Poisson distribution)

Probability of detecting a GW event

Population inference with N_{det} GW events

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Posterior on population parameters

Prior on population parameters

Rates term (Poisson distribution)

Probability of detecting a GW event

Product over N_{det} GW likelihoods

Population inference with N_{det} GW events

$$p(\Lambda|\{x_{\text{GW}}\},\{D_{\text{GW}}\},I) \propto p(\Lambda|I)\,p(N_{\text{det}}|\Lambda,I)\left[\int p(D_{\text{GW}}|\theta,\Lambda,I)\,p(\theta|\Lambda,I)\,d\theta\right]^{-N_{\text{det}}}$$

$$\times \prod_{i}^{N_{\text{det}}} \int p(x_{\text{GW}i}|\theta,\Lambda,I)\,p(\theta|\Lambda,I)\,d\theta,$$

Posterior on population parameters

Prior on population parameters

Rates term (Poisson distribution)

Probability of detecting a GW event

Product over N_{det} GW likelihoods

$p(m_1, m_2)\; p(z)\; p(\Omega)\ldots$