Cosmology with standard sirens
What's the state of play?

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Overview

1. Why do cosmology with gravitational waves?
2. What is a standard siren?
3. What we learned from the third observing run
4. Combining population and cosmological inference
5. What comes next?
6. Cosmology with the next generation of gravitational wave detectors

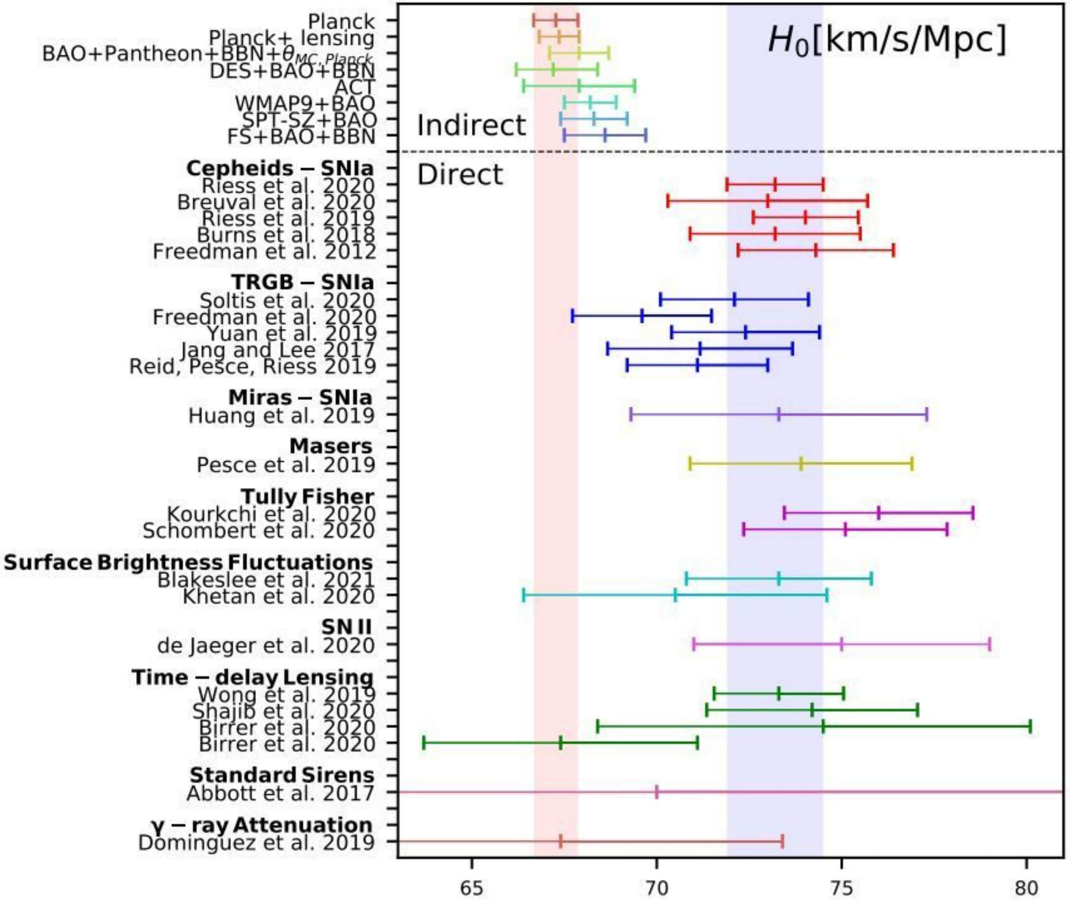
The Hubble tension

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

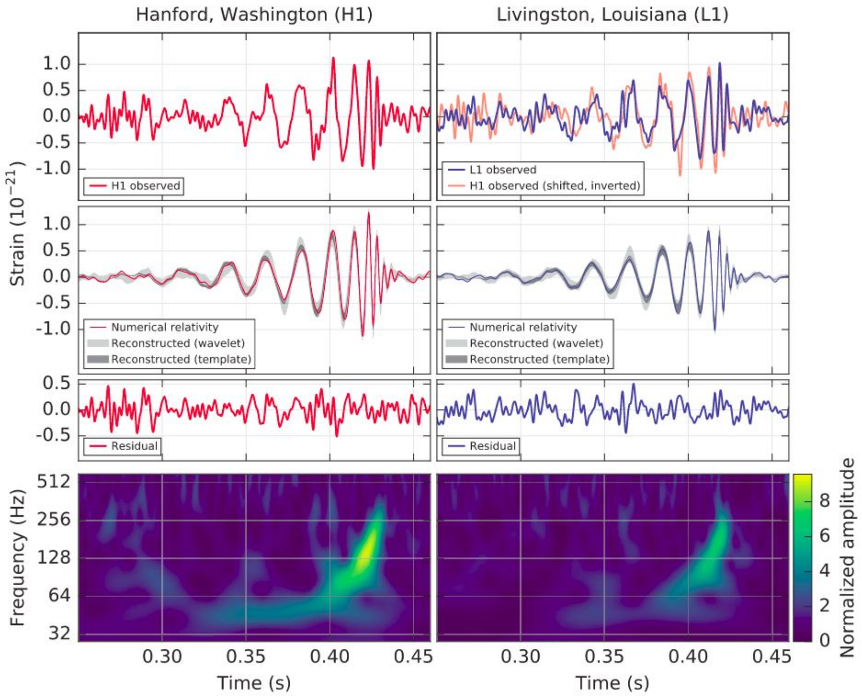
Gravitational waves as standard sirens

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:

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



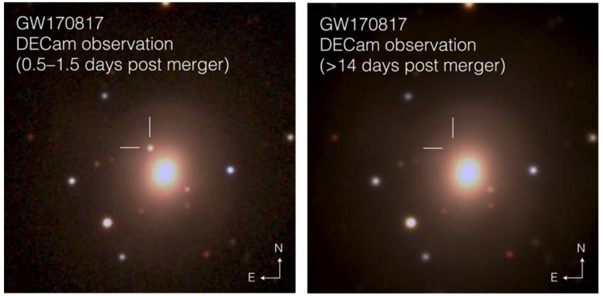
The LIGO Scientific Collaboration and Virgo Collaboration,
Phys. Rev. Lett. **116**, 061102 – Published 11 February 2016

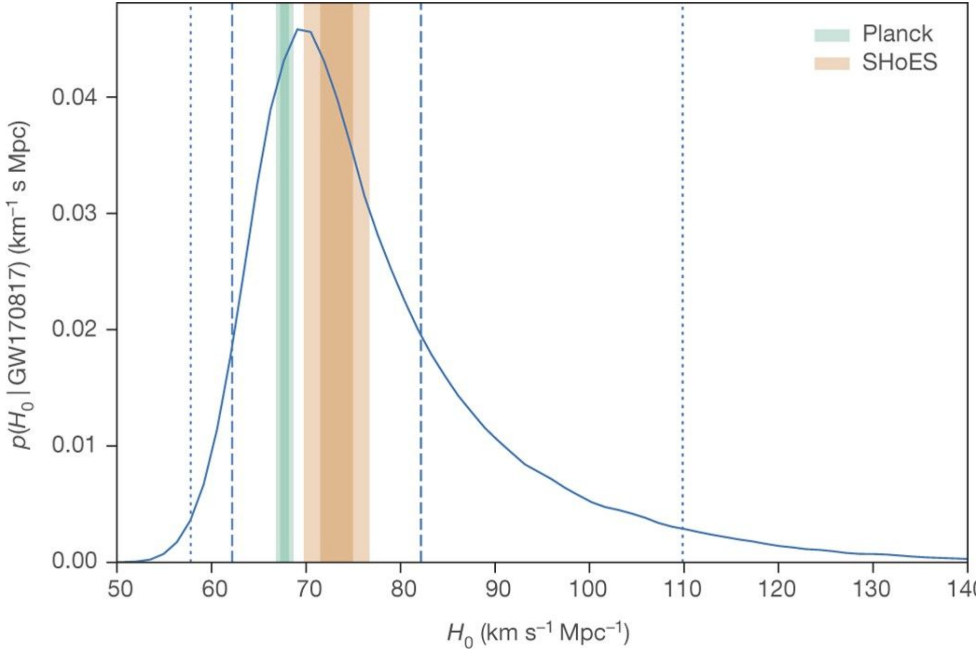
Bright Sirens

Any GW standard siren with an electromagnetic counterpart.

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

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.

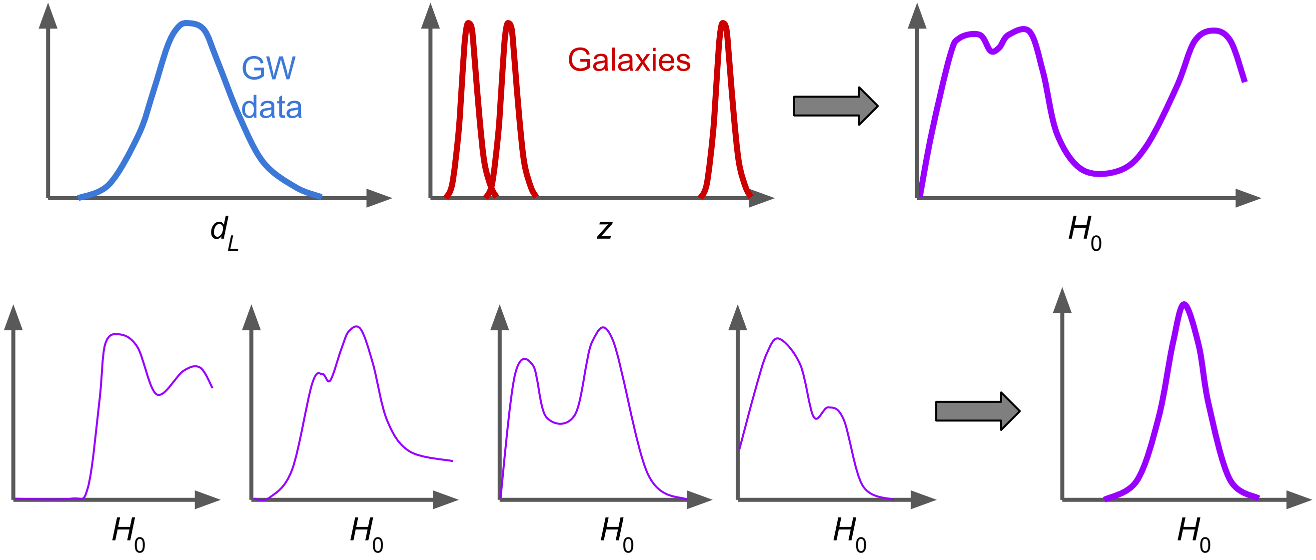
Also dark!

AKA the redshifted masses method

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, Palmese+ 2020, Finke+ 2021…)

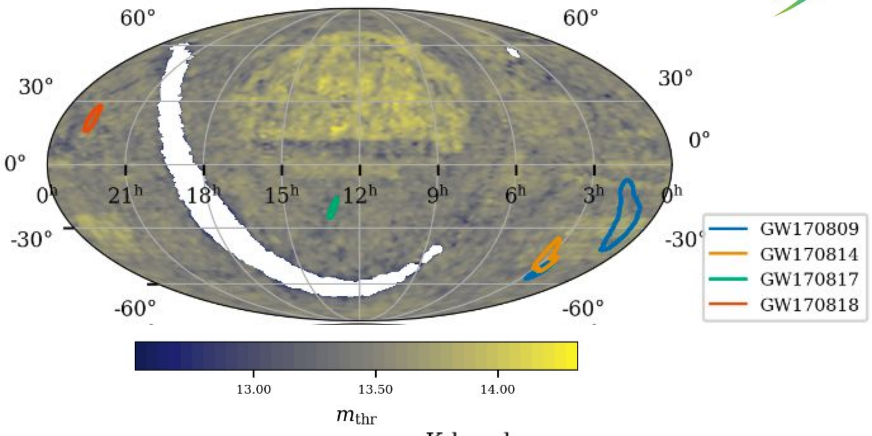


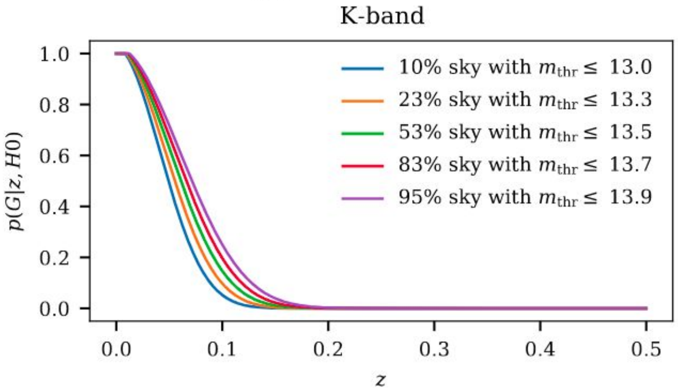
The galaxy catalogue - incompleteness issues?

The O3 LVK cosmology paper made use of the GLADE+ galaxy catalogue (Dalya+ 2022).

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

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





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

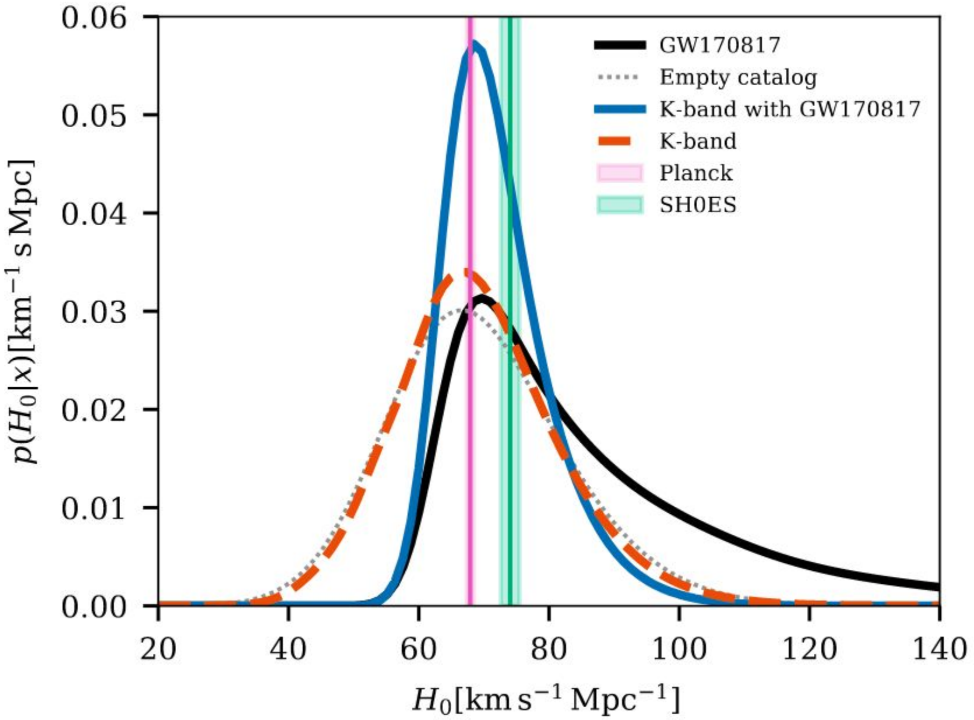
LVK dark siren + galaxy catalogue result

Results using *gwcosmo*.

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

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

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

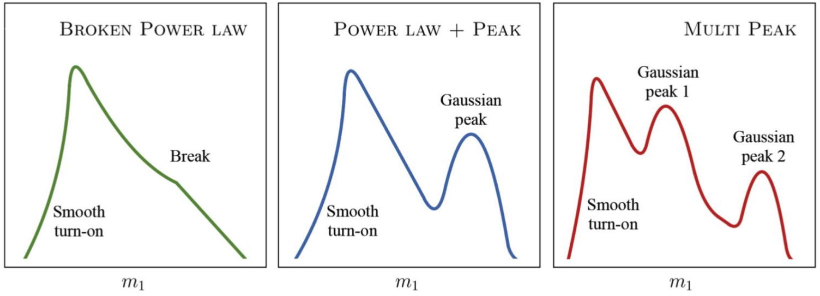


The LIGO, Virgo and KAGRA collaborations, 2023 *ApJ* **949** 76

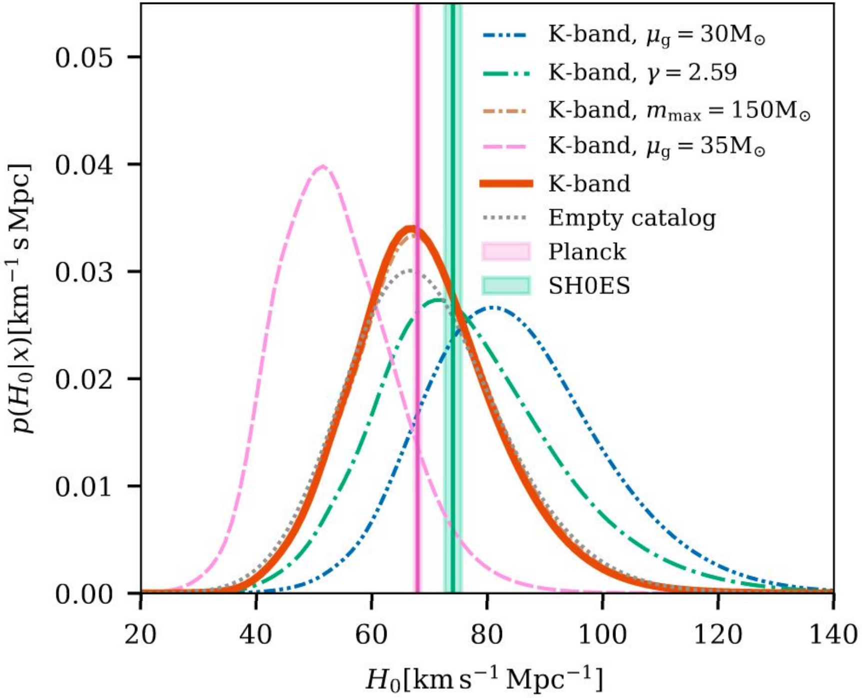
The impact of population assumptions

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.

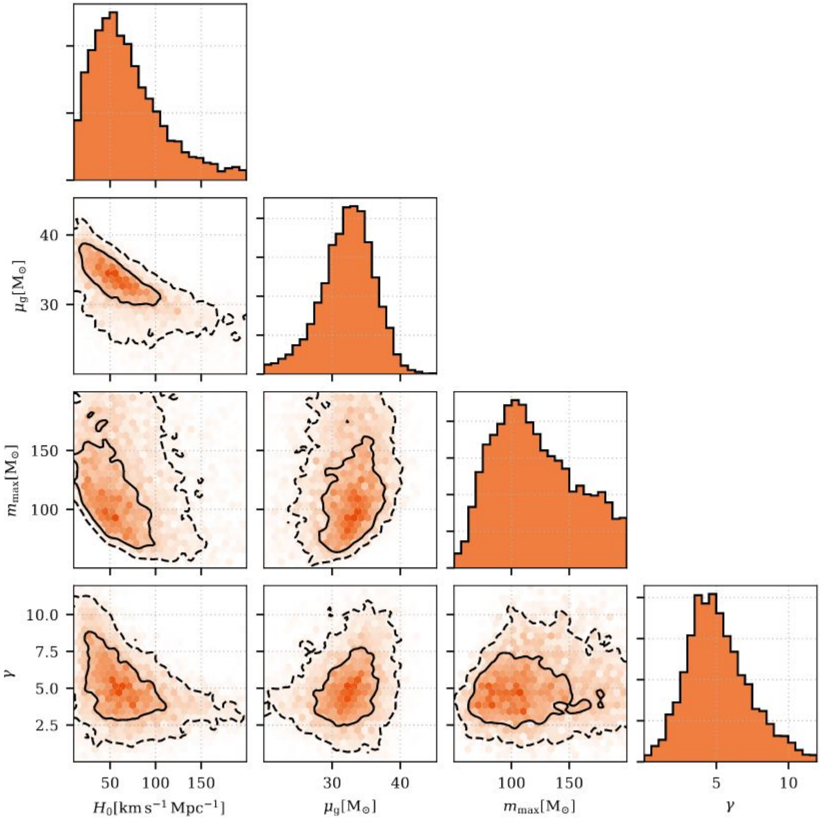


The LIGO, Virgo and KAGRA collaborations, 2023 *ApJ* **949** 76

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)

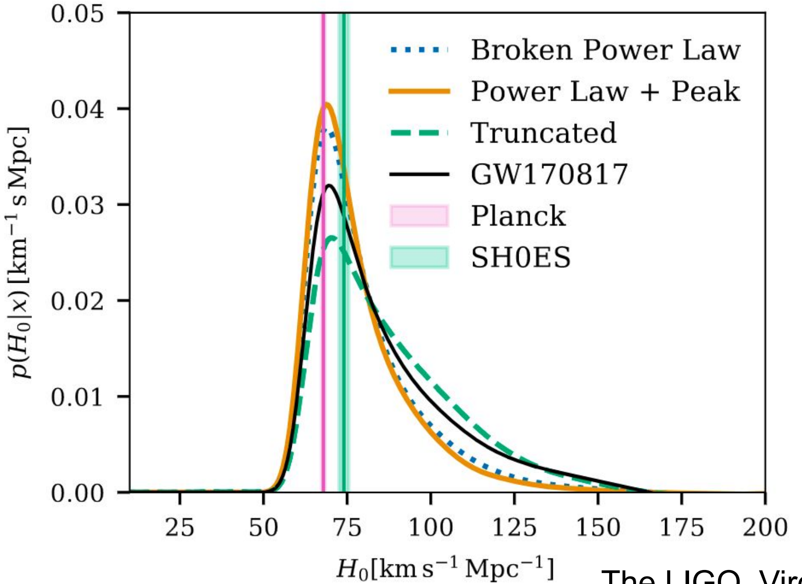


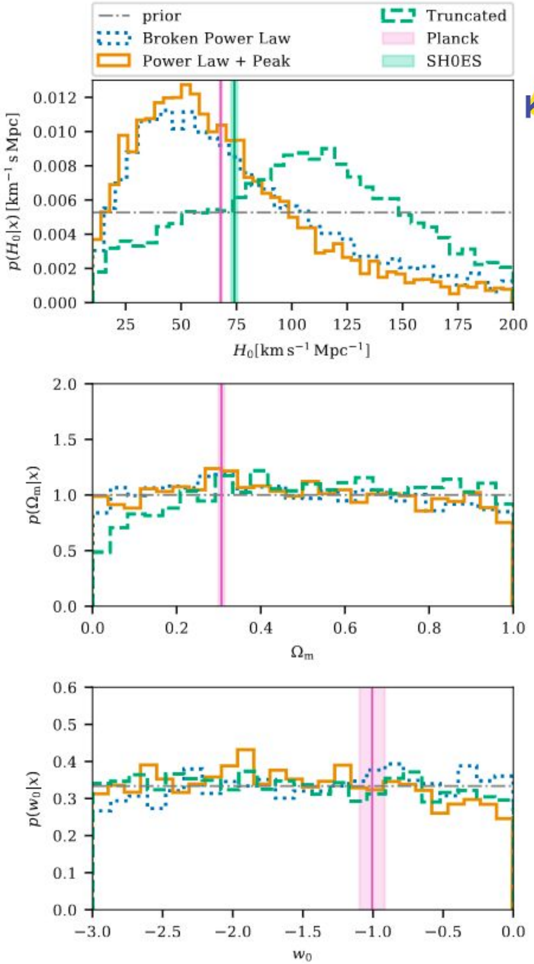
The LIGO, Virgo and KAGRA collaboration, 2023 *ApJ* **949** 76

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

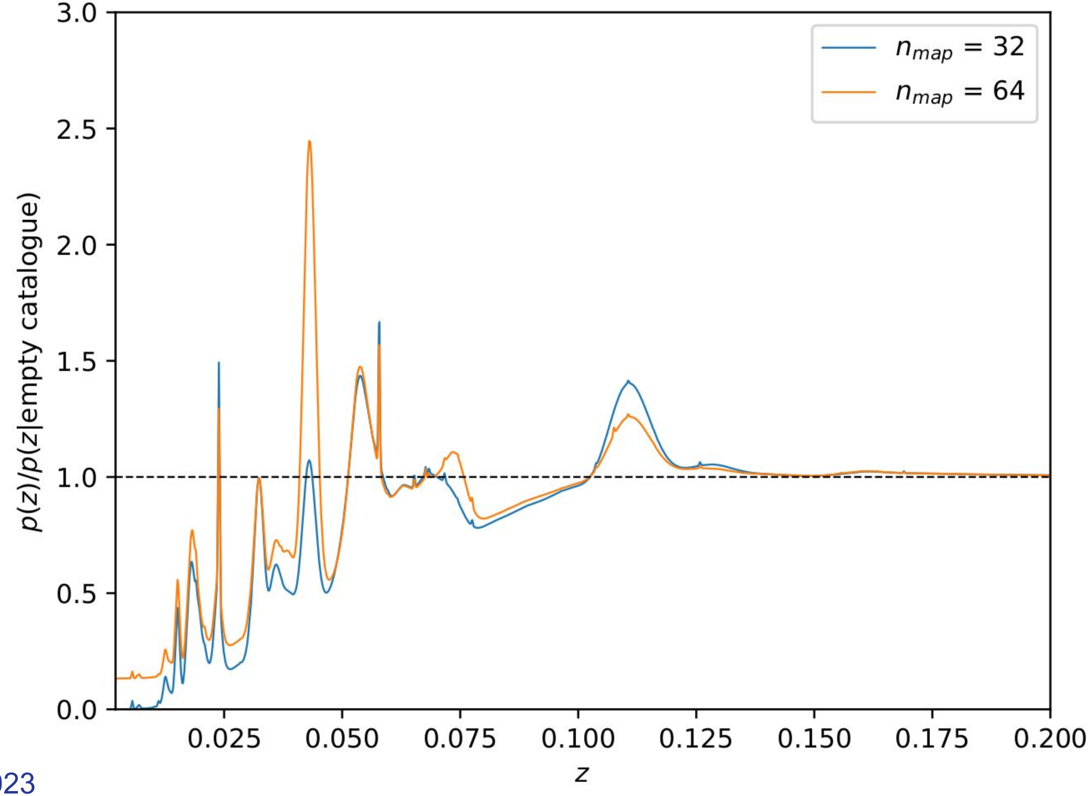
Incorporating a galaxy catalogue

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

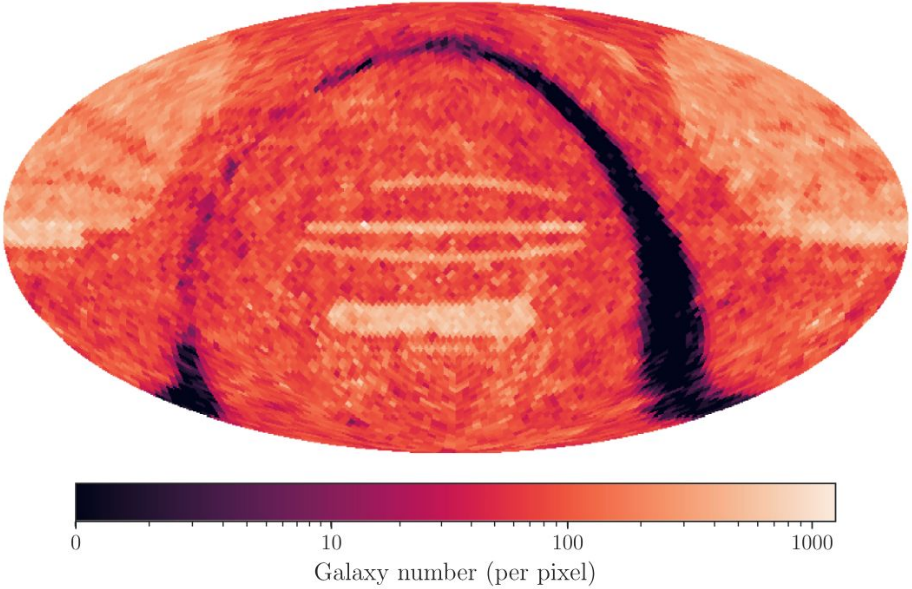


R. Gray *et al* JCAP12(2023)023

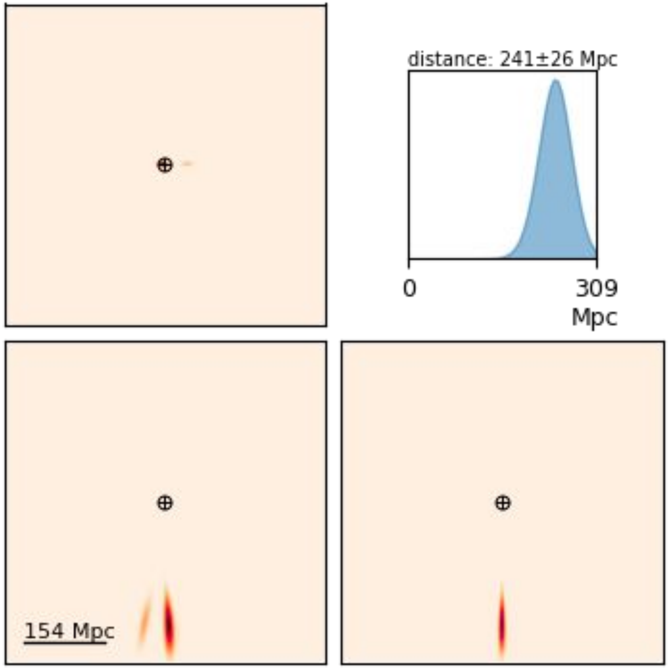
The line-of-sight redshift prior

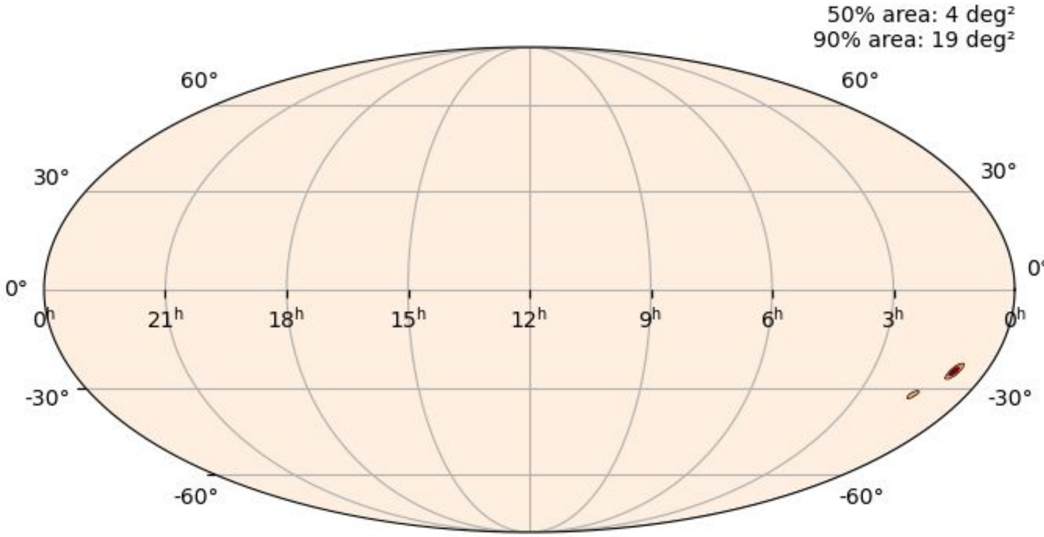
Constructed for every pixel on the sky, the LOS redshift prior contains:

- A sum of the galaxies in each pixel
- Choice of host-galaxy weighting
- Information about the galaxy catalogue completeness
- Assumptions about the universal galaxy distribution



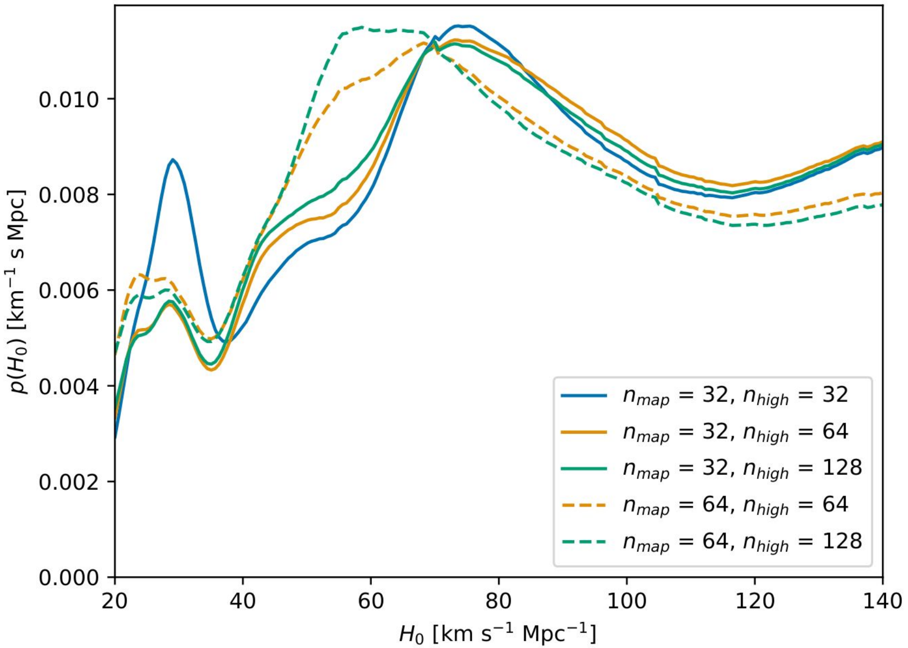
GW190814: the most informative dark siren so far

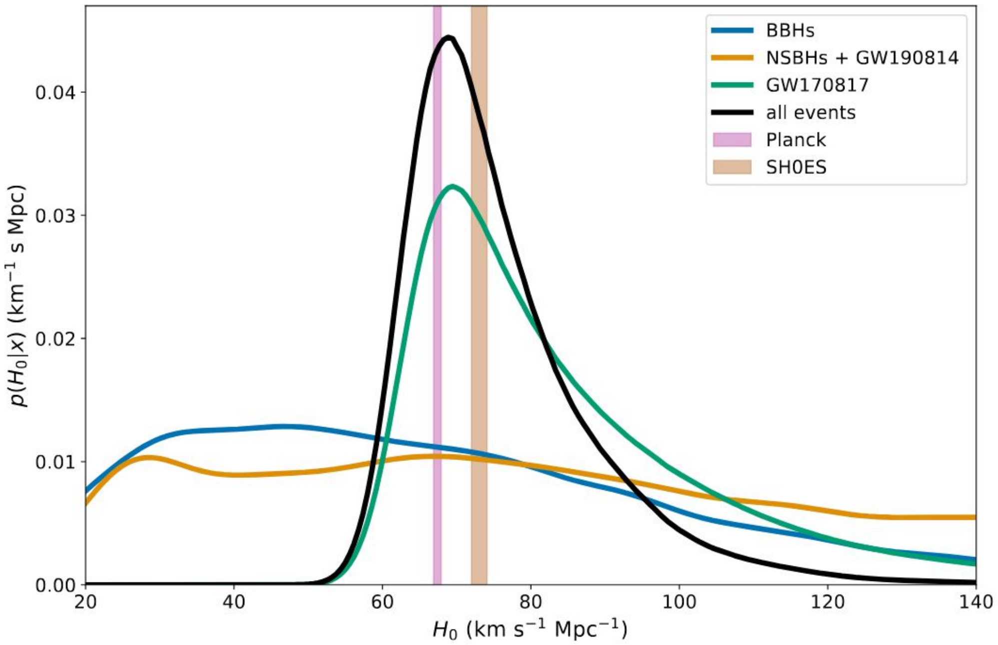




https://gracedb.ligo.org/superevents/S190814bv/

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: photometric redshifts, host weighting choices...

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.

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

Cosmology with 3rd generation GW detectors

The third generation of GW detectors opens up the possibility of constraining cosmological parameters beyond H_0.

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M (1+z')^3 + \frac{\rho_{\mathrm{DE}}(z')}{\rho_0}}}$$

Einstein Telescope and Cosmic Explorer will detect BNSs and BBHs at high enough redshifts to be sensitive to the effect of the dark energy density.

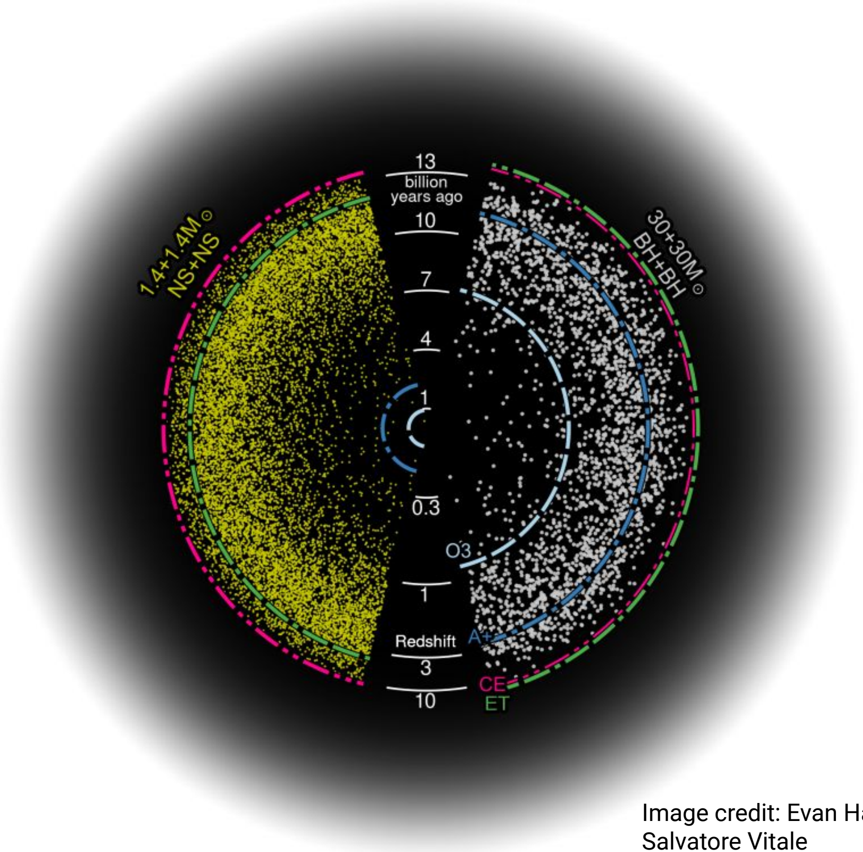
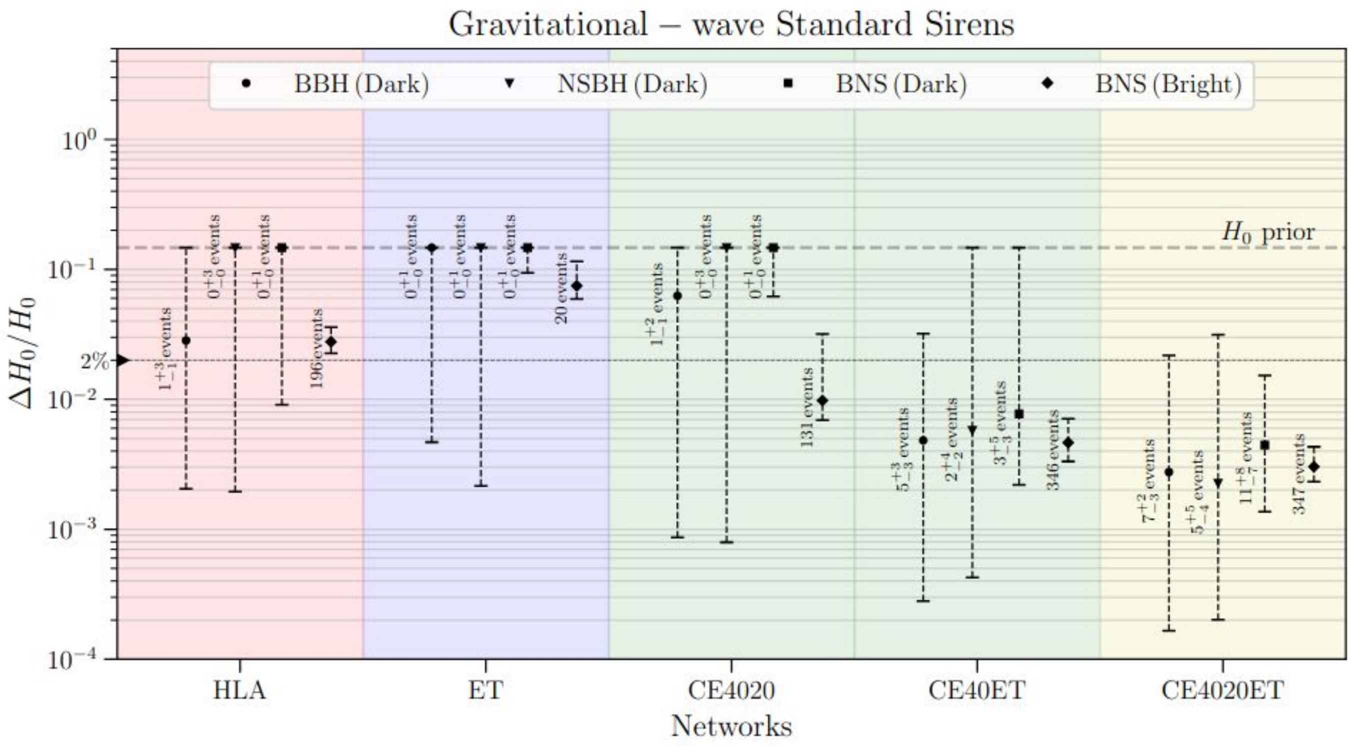


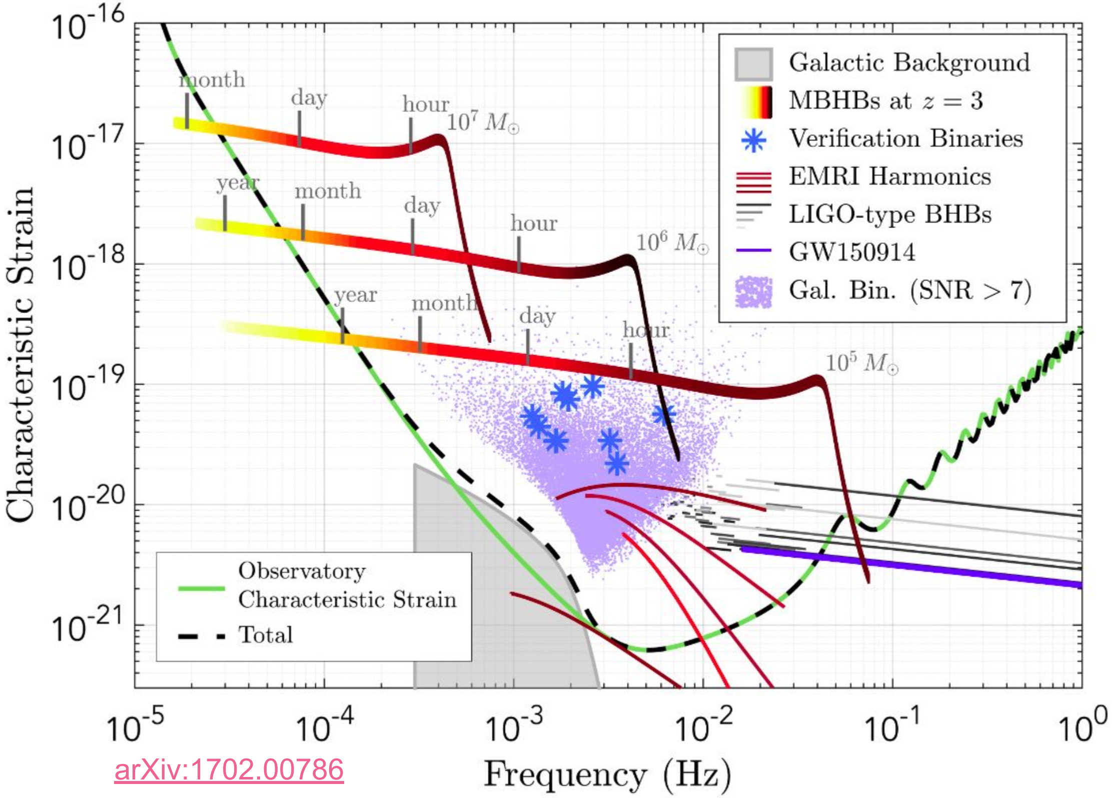
Image credit: Evan Hall, Salvatore Vitale

Projections for XG



Chen et al (2024)

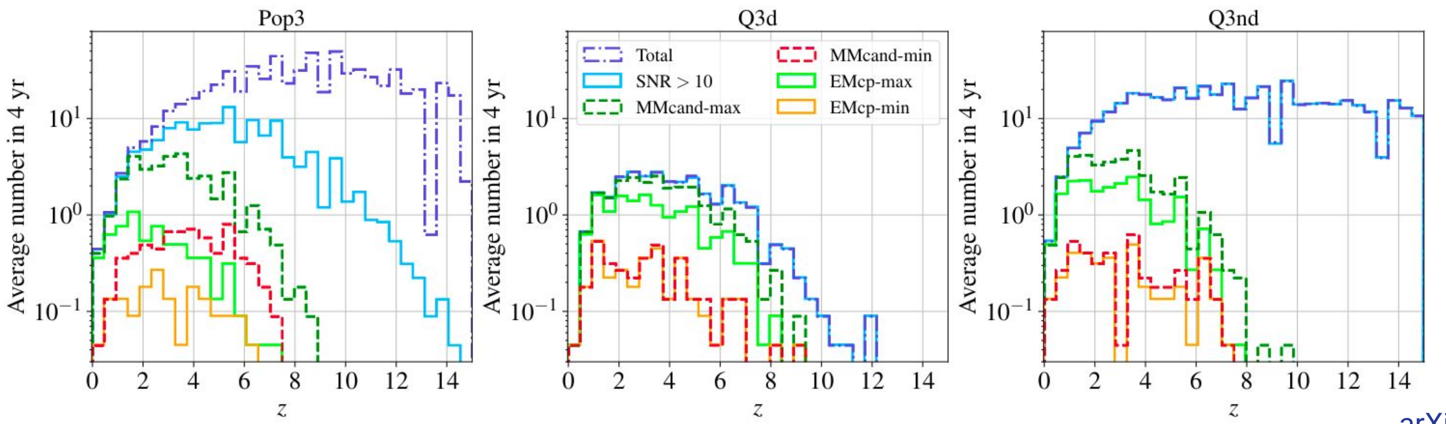
Cosmology with LISA



arXiv:1702.00786

Massive Black Hole Binaries

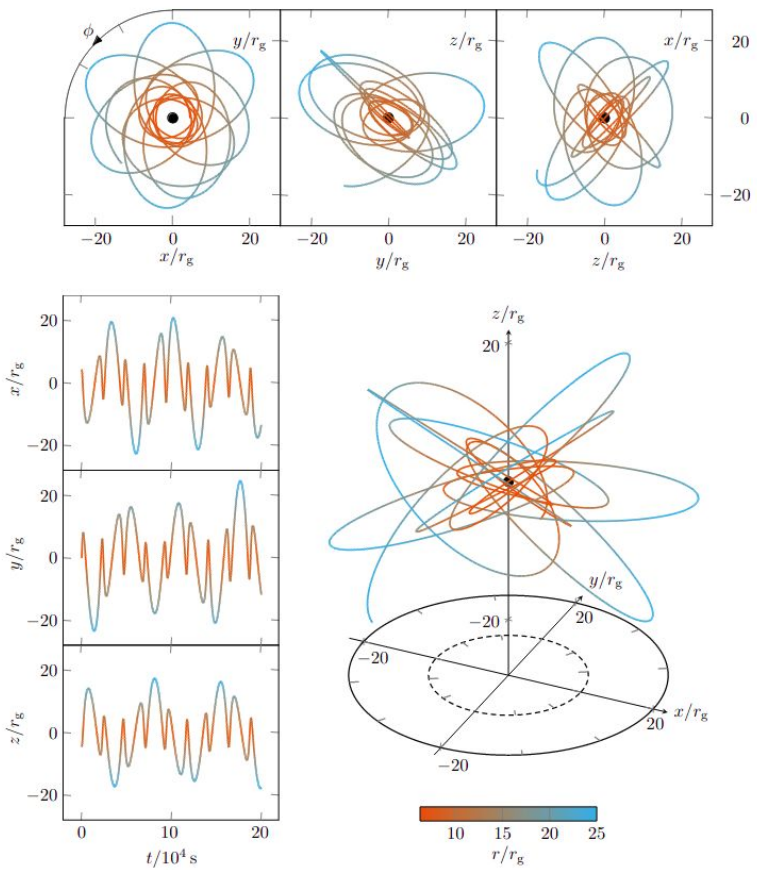
- Rates are uncertain (several to 100s per year)
- High SNR, well localised ($\Delta\Omega$ ~10 deg^2, $\Delta d_L/d_L \lesssim 10\%$)
- Merging in a gas rich environment → EM counterparts?
- Detectable up to z~10
- (see, e.g. Mangiagli+ 2022)



arXiv:2207.10678

Extreme Mass Ratio Inspirals

- Rates are uncertain (10s to 1000s per year)
- Well measured system parameters, ($\Delta\Omega \lesssim 10$ deg^2, $\Delta d_L/d_L \lesssim 10\%$)
- No anticipated EM counterpart
- Effective dark sirens (detectable to redshift ~3)
- (see, e.g. Berry+ 2019, Laghi+ 2021)



arXiv:1903.03686

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 promise of more GW data in **O5 and beyond** guarantee interesting updates in the next ~5 years.

Extra slides

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)

Probability of detecting a GW event

Product over N_{det} GW likelihoods

$p(m_1, m_2)\ p(z)\ p(\Omega)$...

The line-of-sight redshift prior

Probability a galaxy in pixel *i* is inside the galaxy catalogue (depends on assumptions of galaxy luminosity and redshift distributions, and the limiting apparent magnitude of this pixel, m_{th})

Sum over galaxies inside pixel *i*

$$p(z|\Omega_i, \Lambda, s, I) \propto \Bigg[p(G|\Omega_i, \Lambda, I) \frac{1}{N_{\rm gal}(\Omega_i)} \sum_k^{N_{\rm gal}(\Omega_i)} p(z|\hat{z}_k) p(s|M(z, \hat{m}_k, \Lambda_{\rm cosmo}), I) + p(z|\Lambda_{\rm cosmo}, I) \int_{M(z, m_{\rm th}(\Omega_i), \Lambda_{\rm cosmo})}^{M_{\rm max}(H_0)} p(M|z, \Lambda_{\rm cosmo}, I) p(s|M, I)\, dM \Bigg]$$

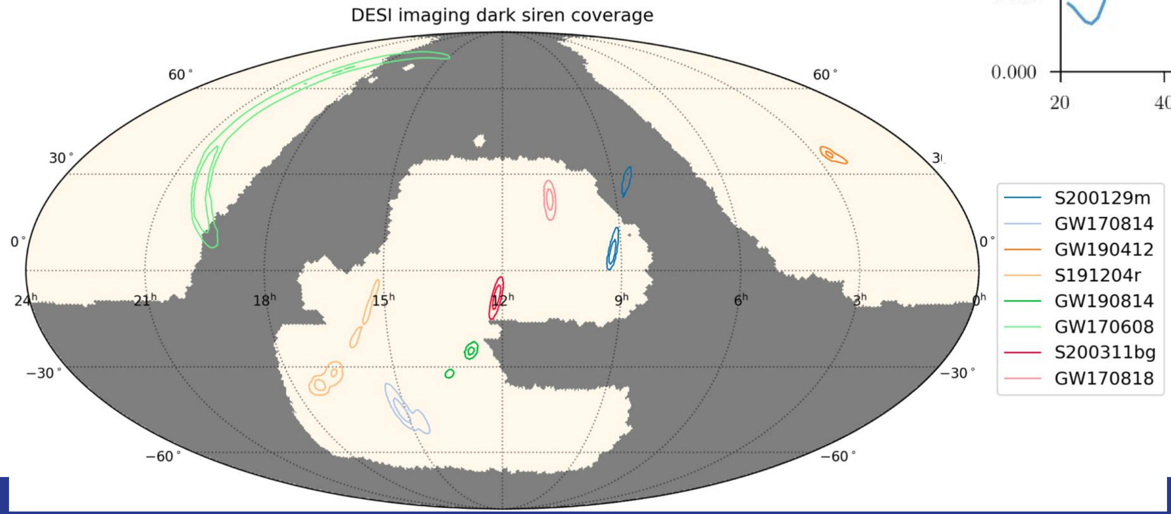
Uniform in comoving volume

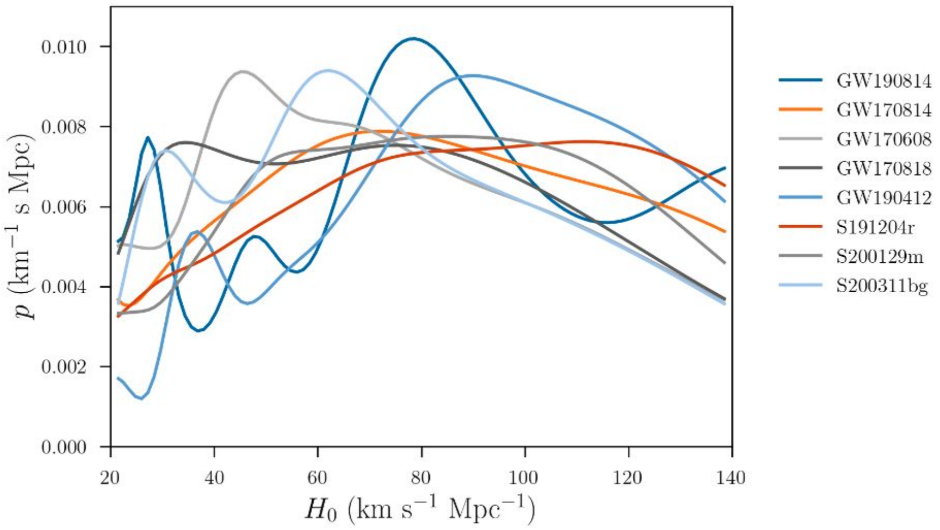
Luminosity function (e.g. Schechter function)

Apparent magnitude threshold for pixel *i*

Host galaxy weighting

The result using DESI Legacy surveys



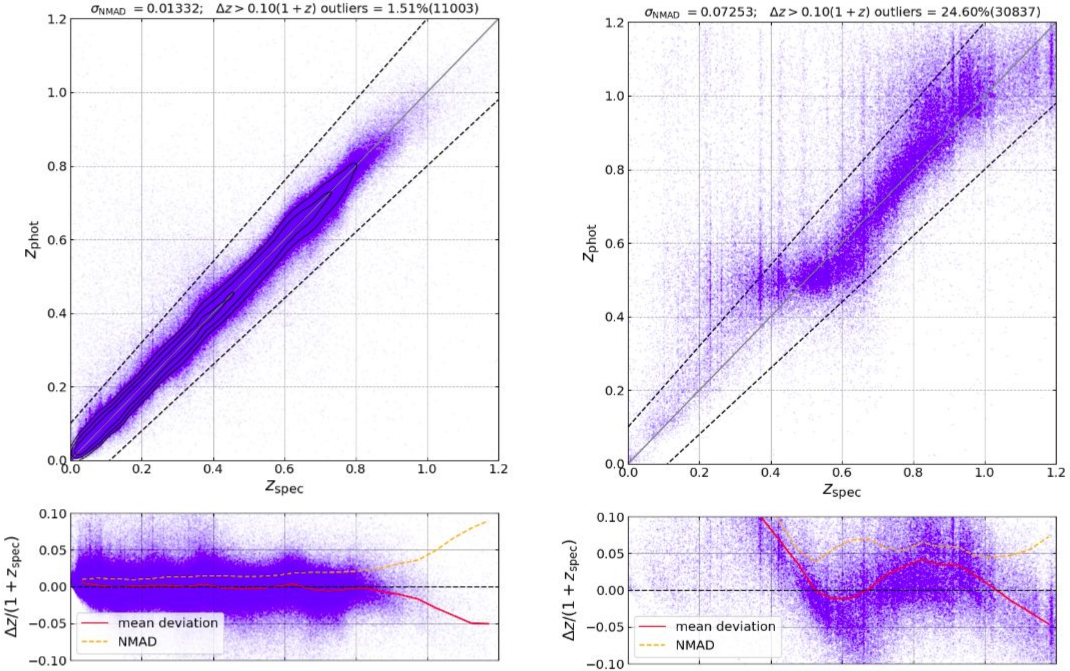


A. Palmese *et al* 2023 *ApJ* **943** 56

Galaxy catalogue complications: 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.



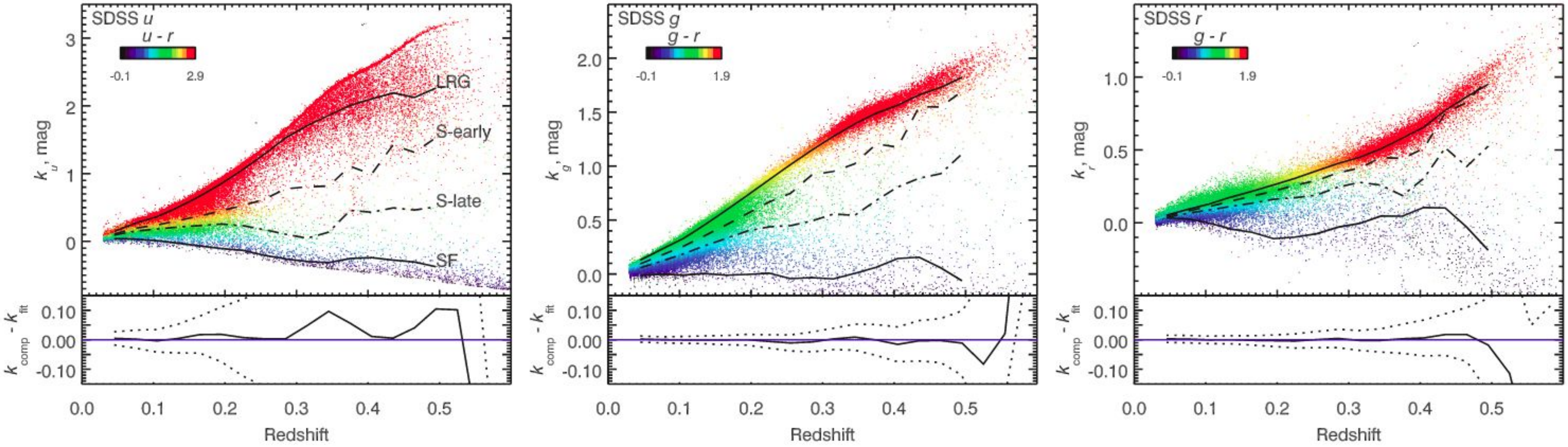
Zhou *et al.* *MNRAS*, Volume 501, Issue 3, March 2021, Pages 3309–3331

Galaxy catalogue complications: Redshifting 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