Cosmological and population implications from GW sources

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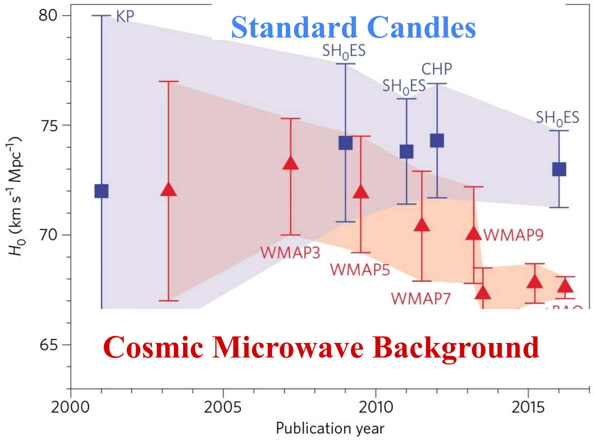
Cosmological tensions

- **The Hubble constant tension:** Do we really know all the engines driving the Universe expansion? [Hill et al., PRD 105 (2022)].

- **The nature of Dark Energy**: How does it behave? What is its Equation of state?

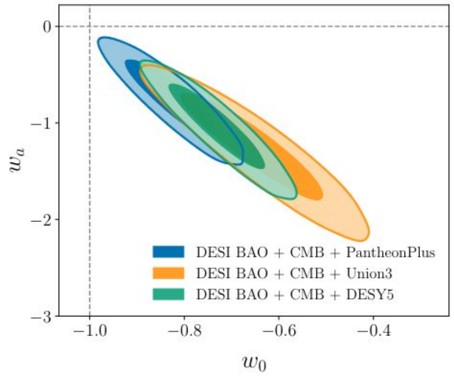


Limitations for current cosmic probes

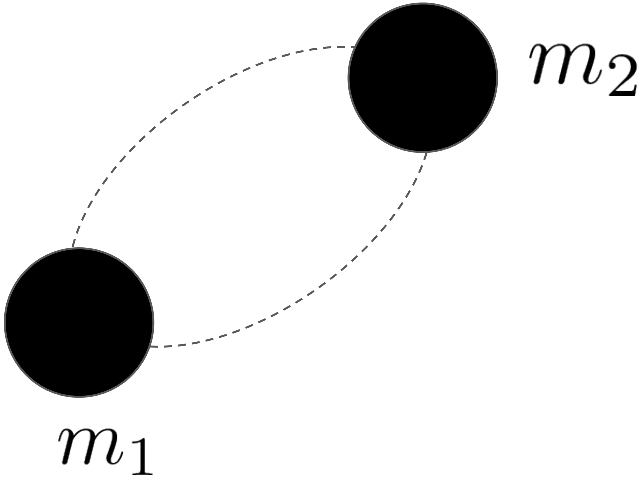
- **Standard Candles:** Only local Universe and require calibration.

- **Cosmic Microwave Background:** Only one, most of information already extracted.

DESI collaboration, arXiv 2404.03002 (2024)



Autopsy of a Binary



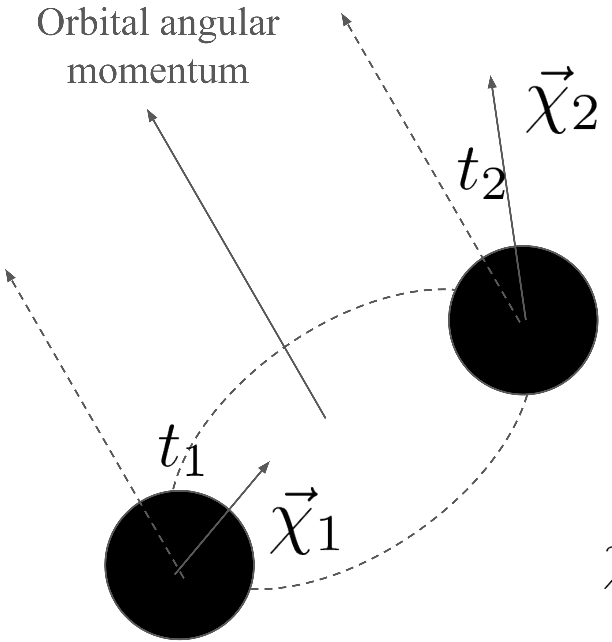
$$q = \frac{m_2}{m_1}$$

Mass ratio

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

Chirp Mass

Autopsy of a Binary



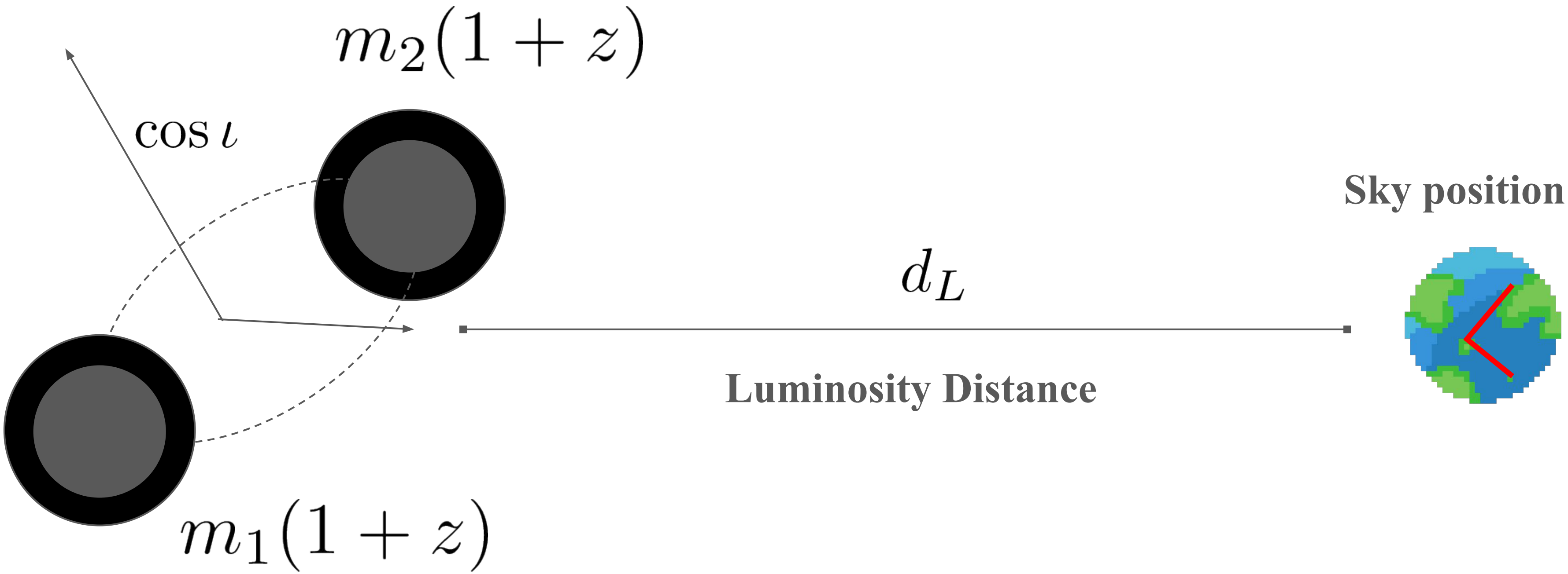
$$\chi_{\rm eff} = \frac{\chi_1 \cos t_1 + q\chi_2 \cos t_2}{1+q}$$

Effective spin parameter

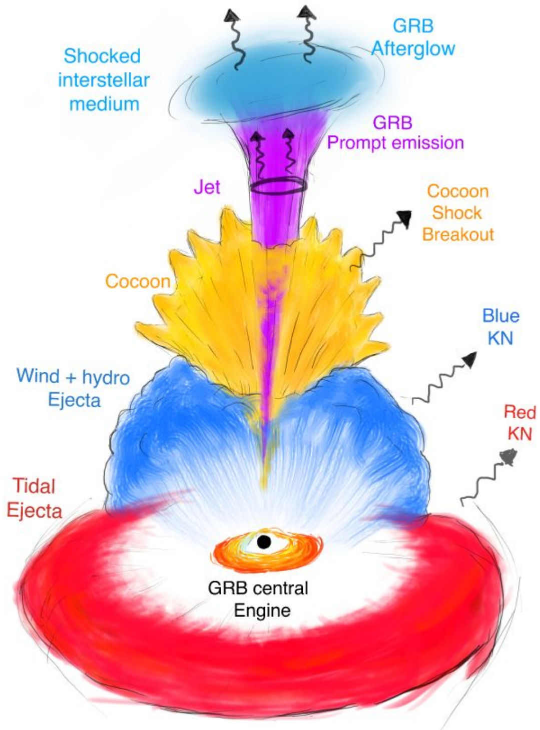
$$\chi_{\rm p} = \max\left[\chi_1 \sin t_1 ; \left(\frac{4q+3}{3q+4}\right) q\chi_2 \sin \ t_2\right]$$

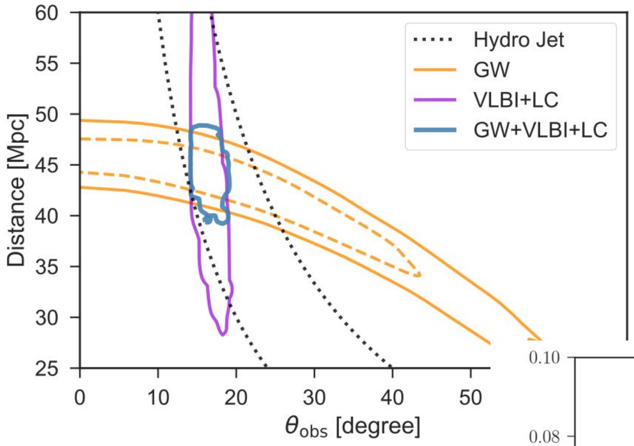
Precessing spin parameter

Autopsy of a Binary



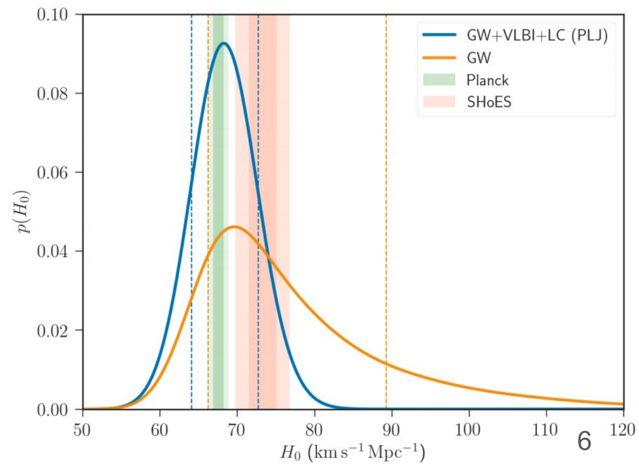
GW19052: AGN flare?



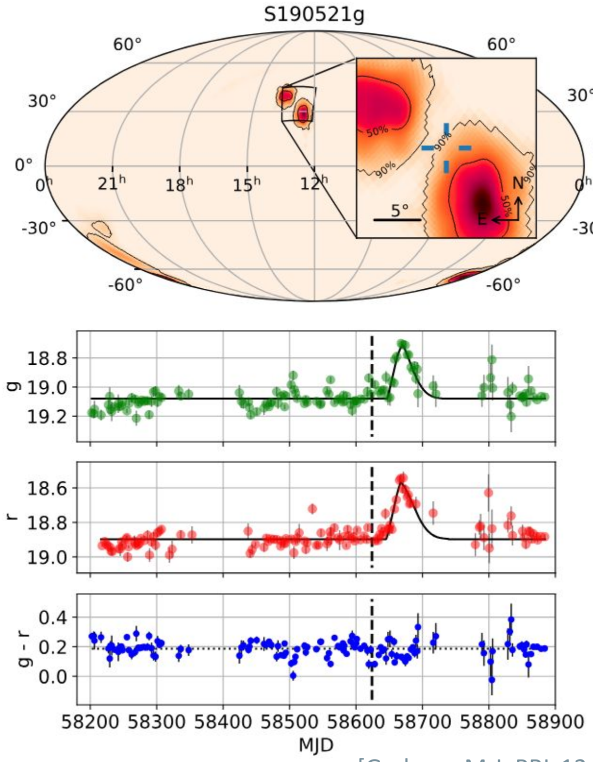


[K. Hotokezaka, Nature Astronomy, 3(2019)]

Afterglow informed cosmology

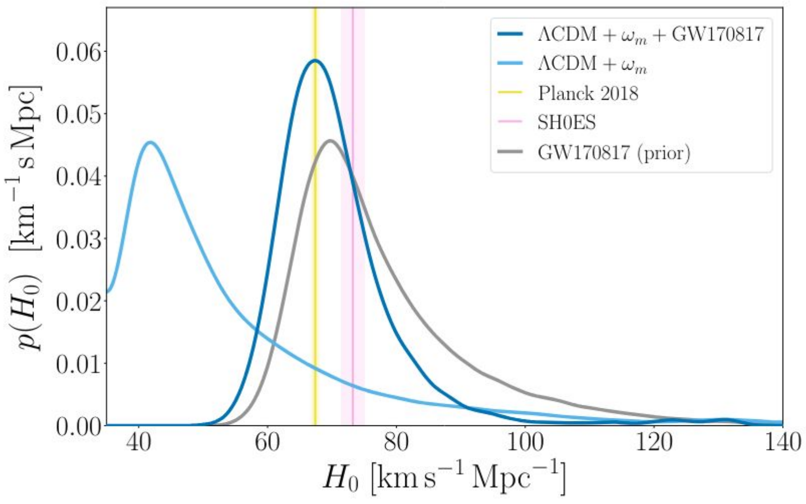


GW19052: AGN flare?



[Graham, M.J. PRL 124 (2020)]

[Chen, H. MNRAS 513 (2022)]

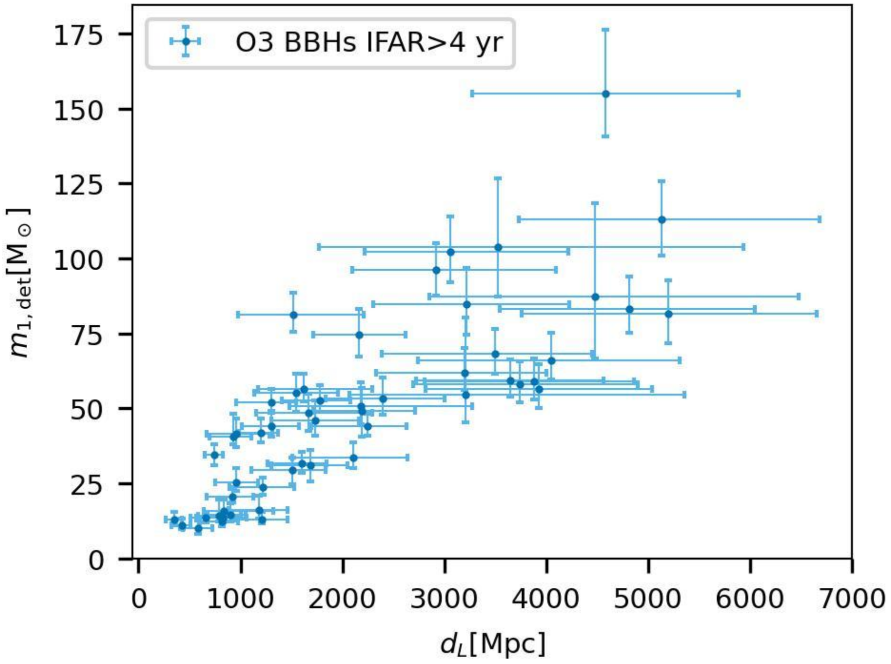


Spectral sirens

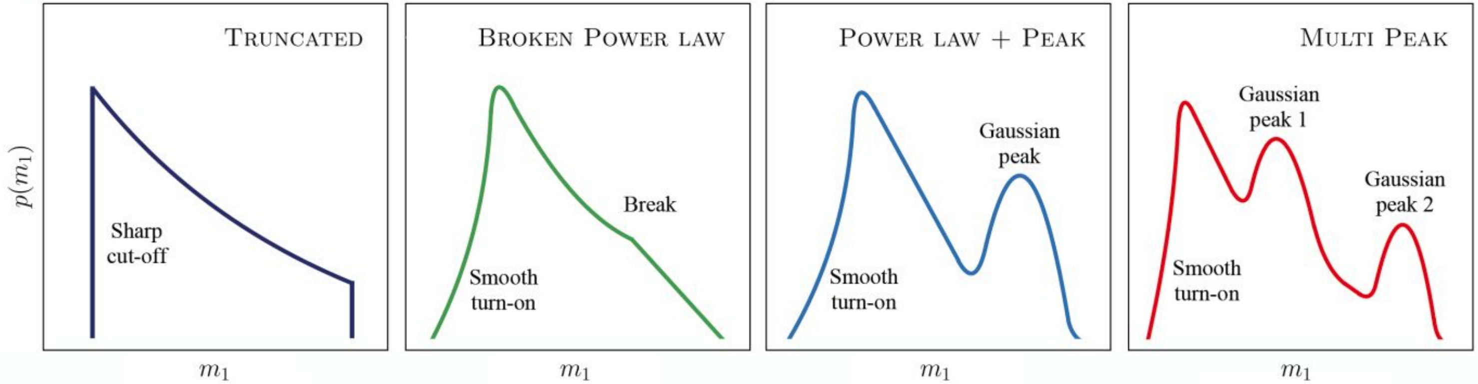
- We detect many dark sirens for which we can estimate the **luminosity distance** and **detector frame masses**.

- We can leverage the detector mass-luminosity distance relation to extract cosmological information *[SM+, PRD 104 (2021)]*.

$$m_{1,\mathrm{det}} = m_{1,\mathrm{s}}(1+z)$$



Spectral sirens



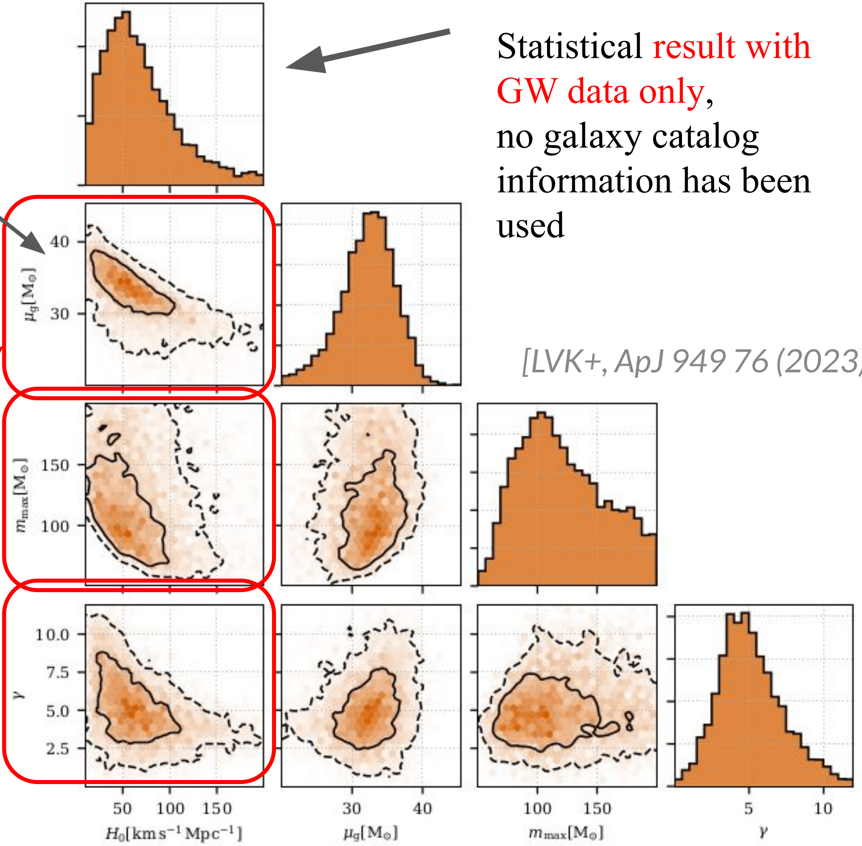
Current analyses use phenomenological parametric models for the source mass to fit **alongside** cosmology *[LVK+ 2021 ApJL 913 L7]*

Spectral sirens: Latest results

The excess of BBHs around 35 solar masses sets a scale for the redshift and provides constraints on H0.

Population parameters that correlate with H0

Posteriors of H_0, mu of the Gaussian peak, maximum mass of the BH and the merger rate evolution.



Statistical result with GW data only, no galaxy catalog information has been used

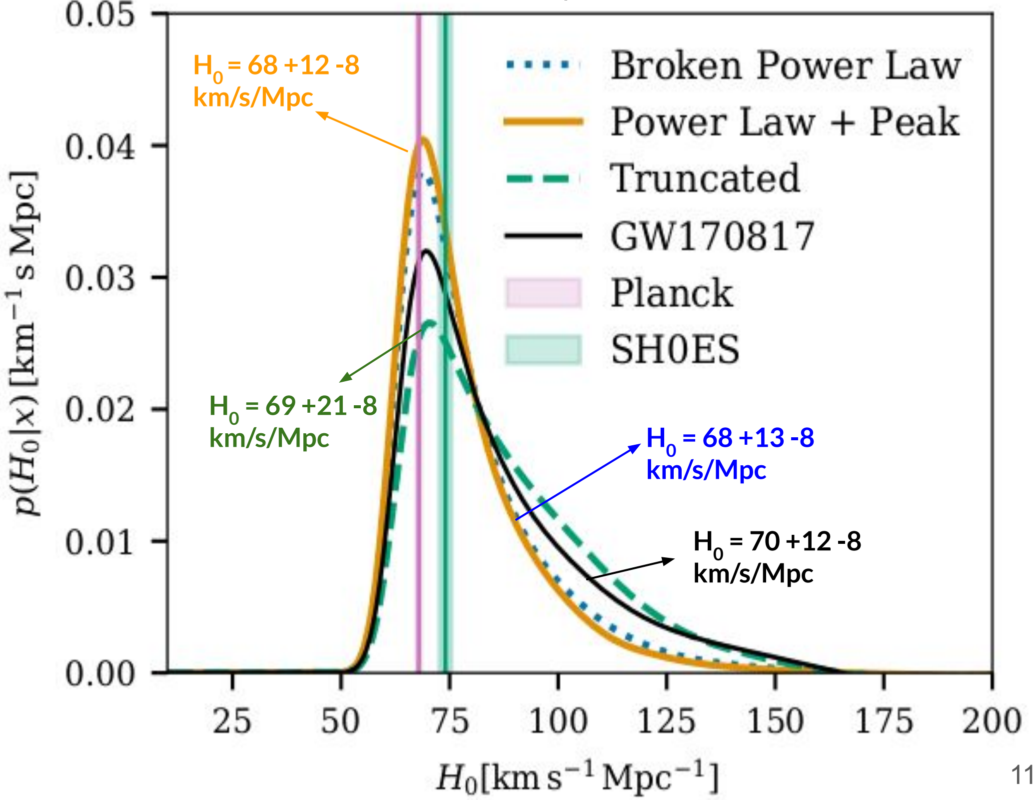
[LVK+, ApJ 949 76 (2023)]

Spectral sirens: Latest results

The only EM information is the counterpart of GW170817

H_0 posterior of the 3 mass models combined with GW170817 posterior

[LVK+, ApJ 949 76 (2023)]

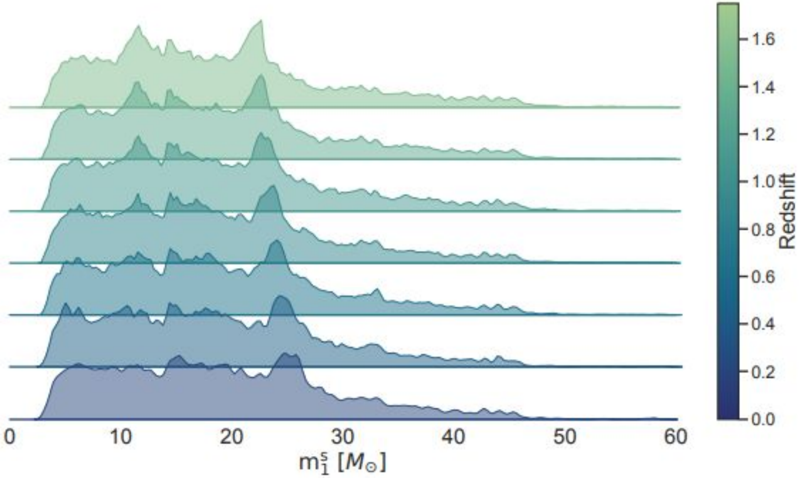


Spectral sirens: Systematic biases

- We use a synthetic BBH catalog containing 4 different formation channels: isolated binaries and hierarchical mergers in young, globular and nuclear star clusters. [M. Mapelli et al MNRAS 511 (2022)]

- The BBH mass spectrum shows a mild evolution in redshift, in particular in the 10-30 solar mass region.

- We simulated 2000 GW detections from the BBH catalog and using simple redshift-independent mass models we inferred the value of H0.

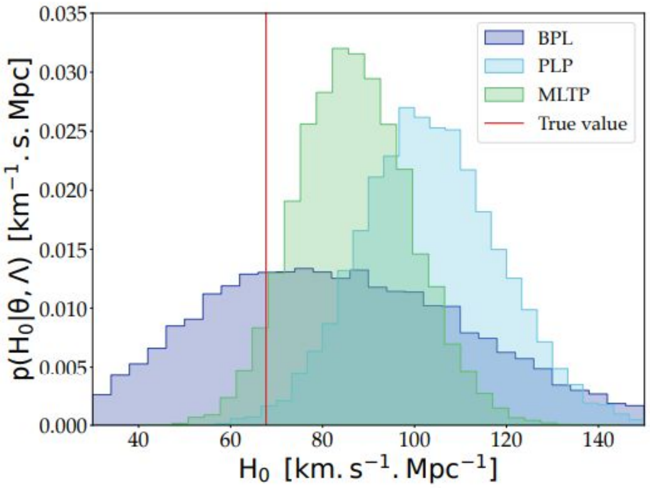


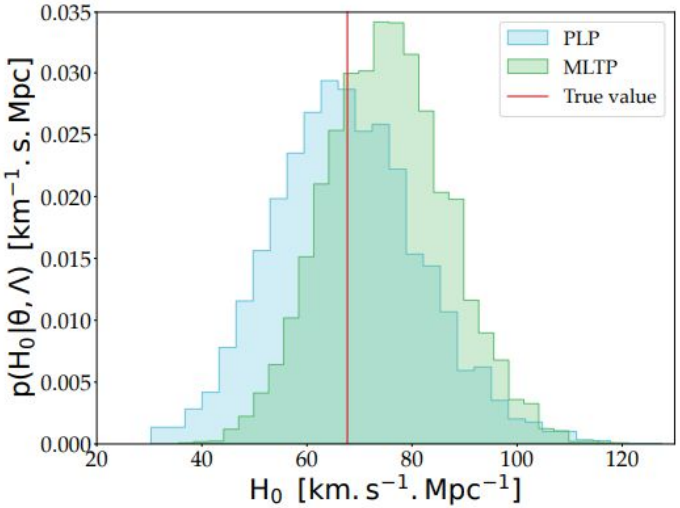
*[G. Pierra, **SM**+, S. Perries, M. Mapelli, PRD 109 (2024)]*

Spectral sirens: Systematic biases

- Redshift-independent mass models with mass features are more prone to systematics when inferring H0

- The bias is removed when removing the mild redshift dependence from the mass spectrum

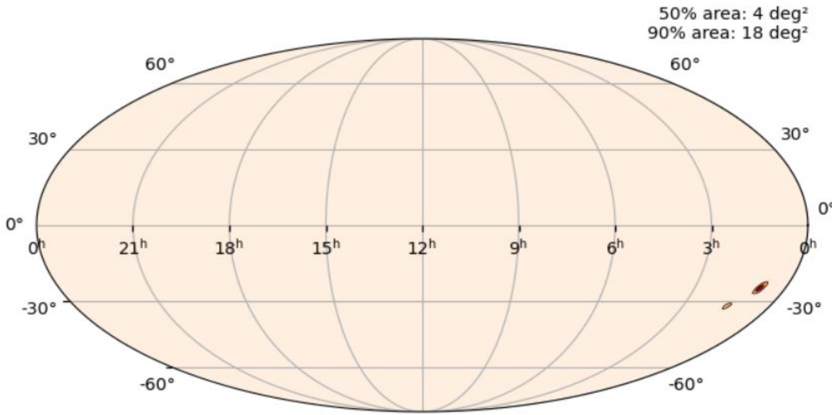


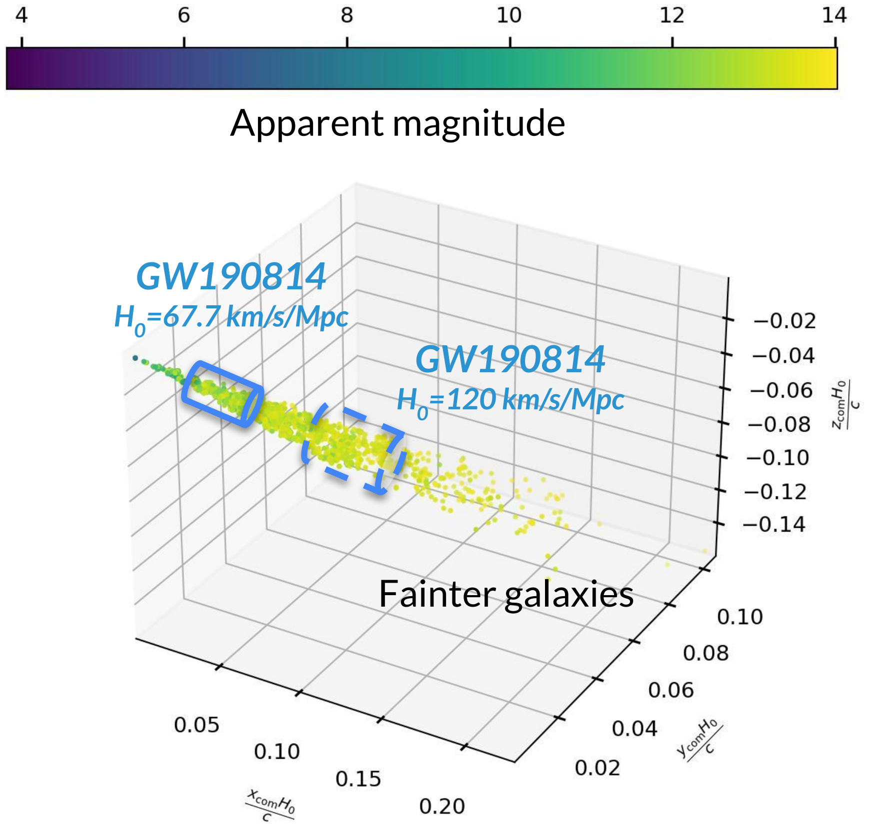


*[G. Pierra, **SM**+, S. Perries, M. Mapelli, PRD 109 (2024)]*

Dark sirens: Galaxy catalogs

- A cosmological model has statistical support when the GW localization matched an *overdensity* of galaxies.
- Galaxy catalogs are not complete at higher redshifts, we need to apply corrections in order to now bias our analyses *[R. Gray+, PRD (2019)].*

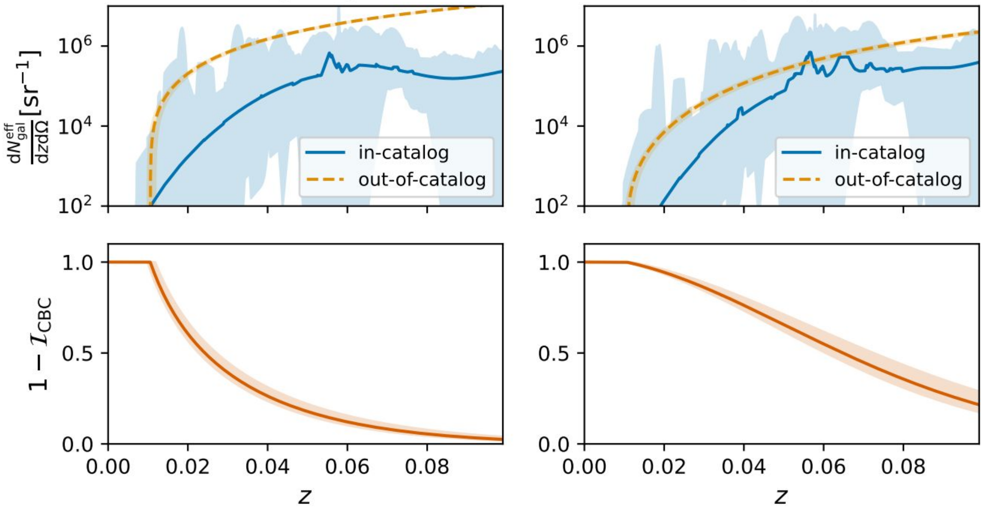


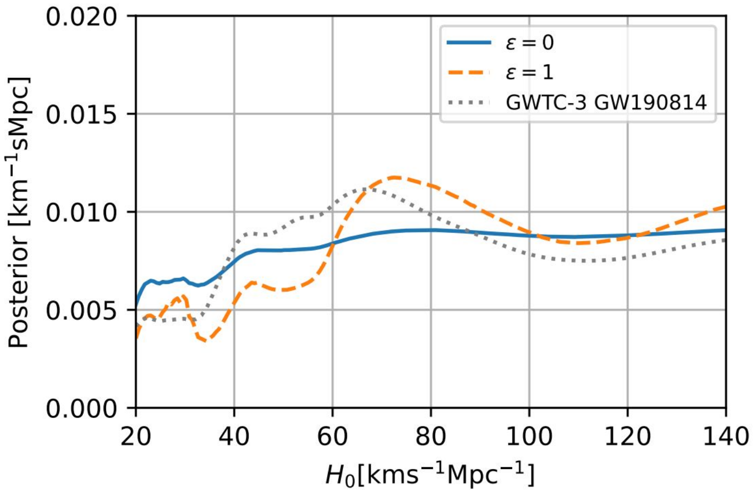


Dark sirens: Galaxy catalogs

Equal host probability

Red-luminous galaxies preferred hosts

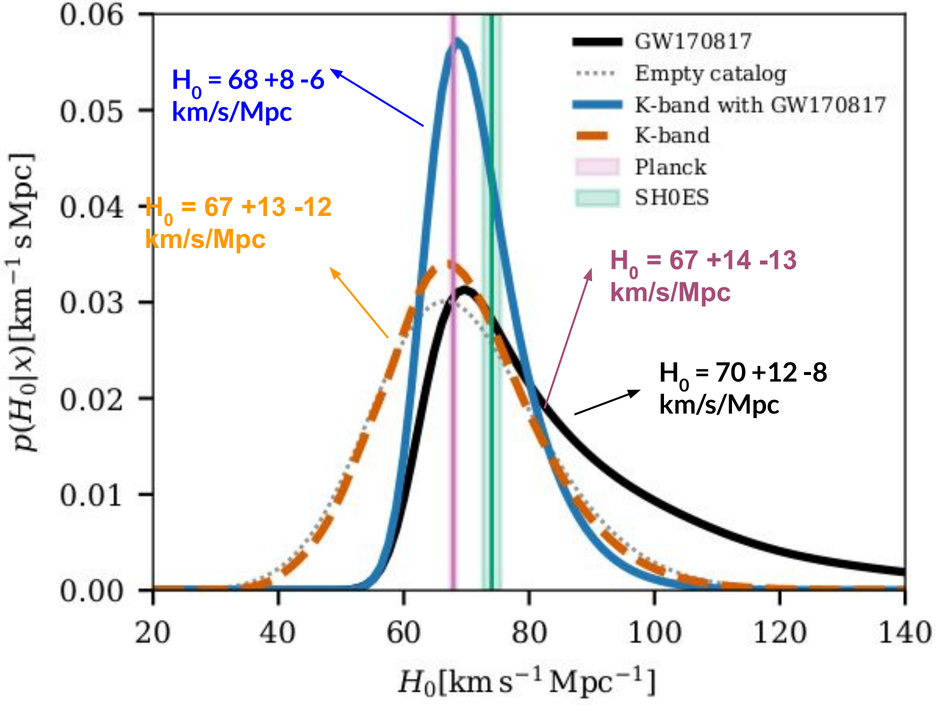




[Mastrogiovanni+, PRD 108 (2023)]

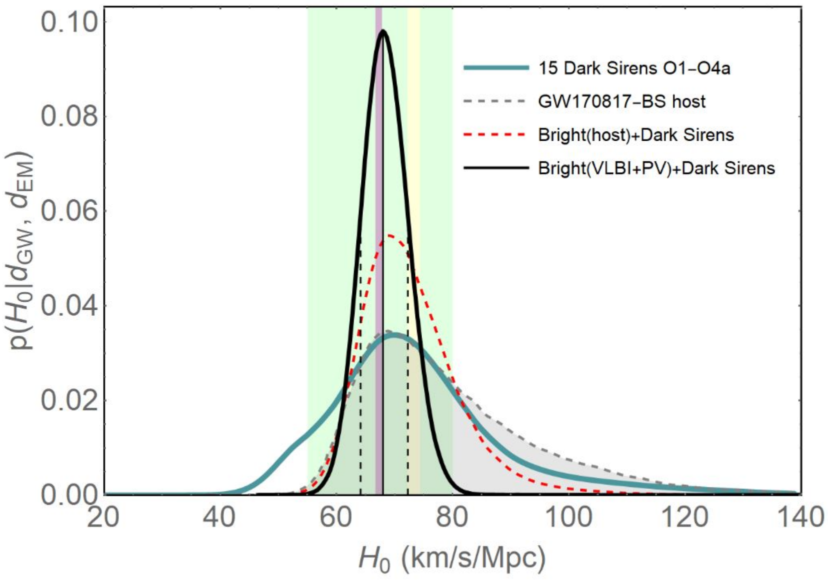
Dark sirens: Galaxy catalogs

[LVK+, ApJ 949 76 (2023)]



GLADE +

[Bom+, 2404.16092]



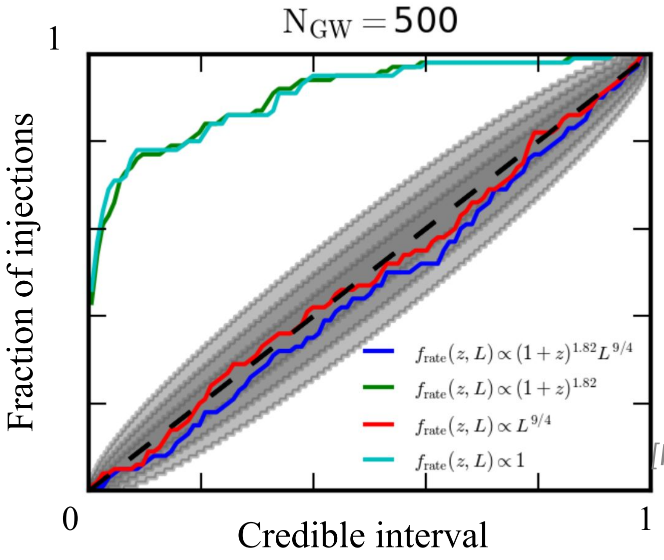
DESI Legacy + Delve

Dark sirens: Biases

For a typical 20% luminosity distance error Galaxy luminosity (K-band) is important only if events come all from the same line-of-sight.

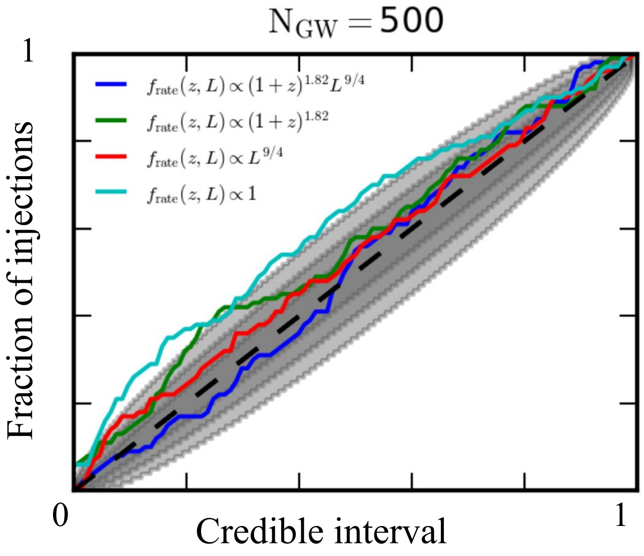
Note: There are many other galactic properties that we should study…

10 square degrees from same line-of-sight



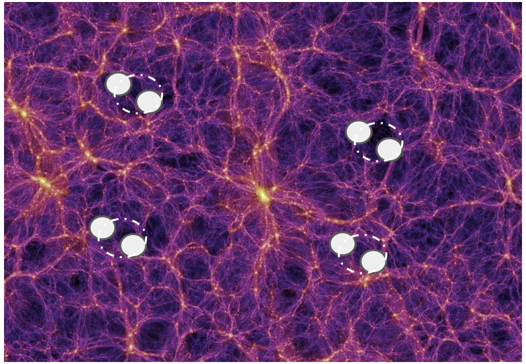
[Perna, **SM**, 2405.07904]

10 square degrees isotropic

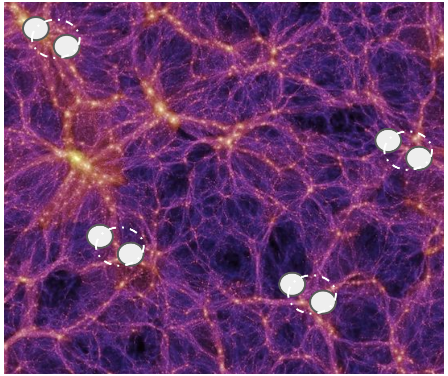


Tracking sirens

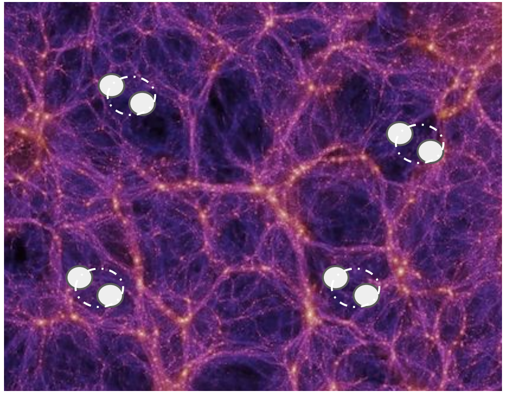
Redshift 0



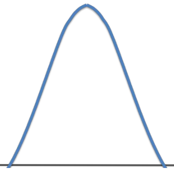
Redshift 1.5



Redshift 2



Possible redshift



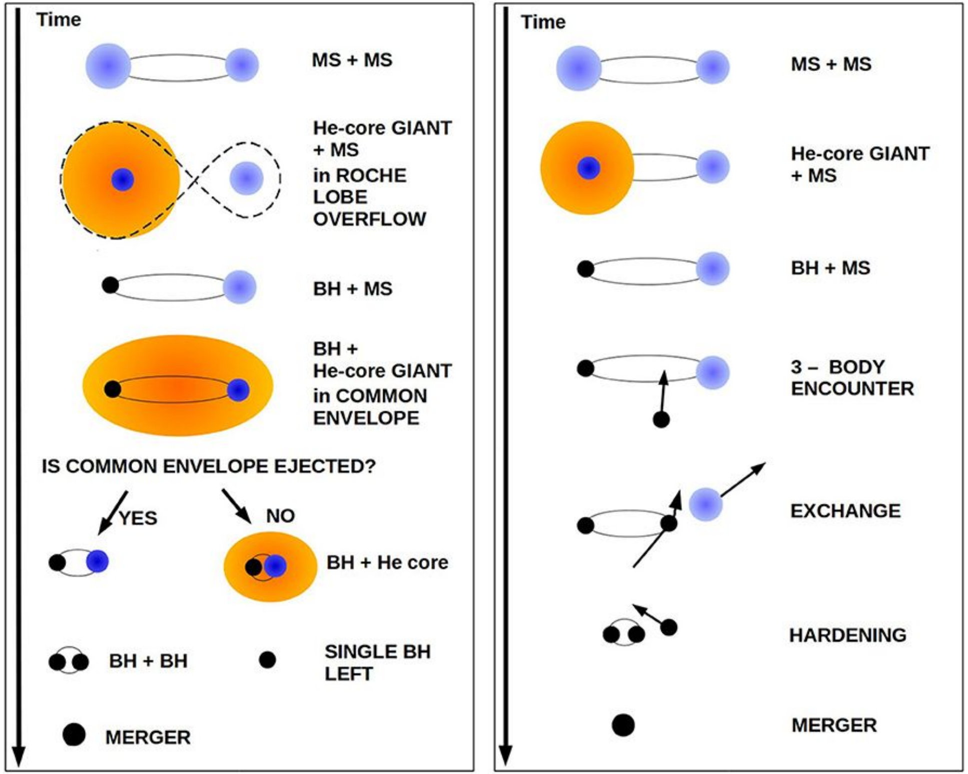
Open question: How does GW track other Large-scale structure tracers? (Mostly galaxy clusters and HI maps)

[S. Libanore et al JCAP02(2021)035]

The spins of Binary Black Holes

Two main formation channels:

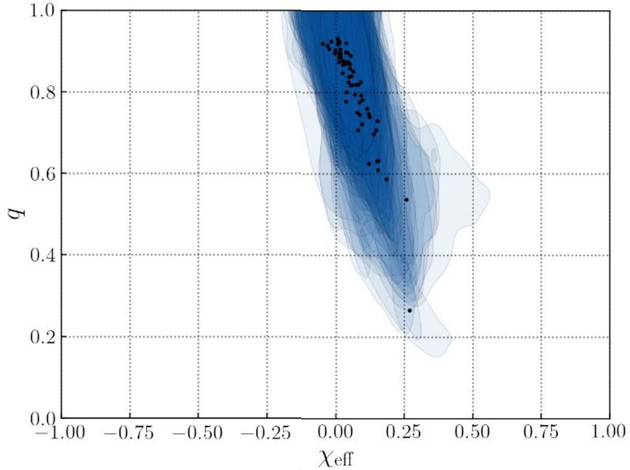
- **Isolated stellar binary evolution:** First generation black holes with spins aligned with the orbital angular momentum.
- **Hierarchical mergers:** Possibly n-th generation black holes (spin~0.7) with isotropic spins.



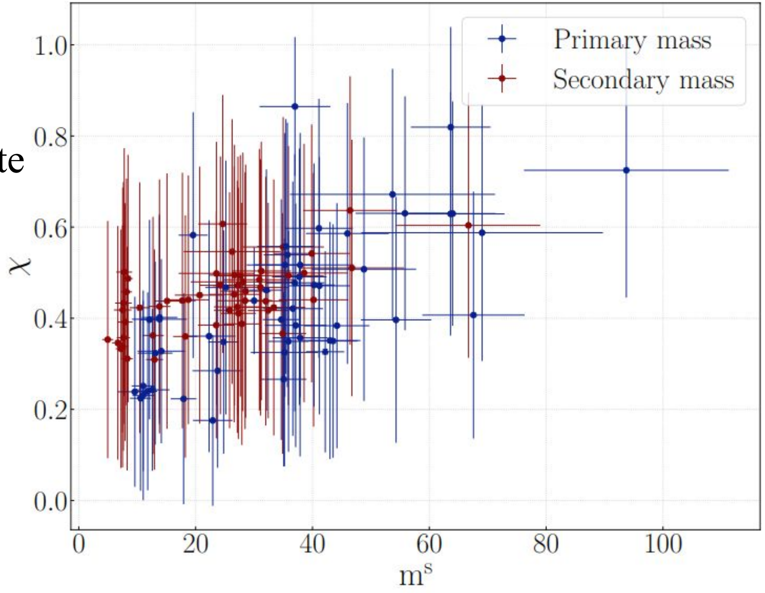
[Mapelli M. Handbook of Gravitational Wave Astronomy]

The spins of Binary Black Holes

- The spin magnitude of Binary Black Holes is a smoking gun to distinguish astrophysical formation channels.
- Effective spin correlates with mass ratio. What about mass?
- There are already some hints that spin parameters might correlate with mass ratio and redshift [Kimball ApJL 915 2021, Biscoveanu S.ApJL 932 2022, Godfrey 2304.01288].



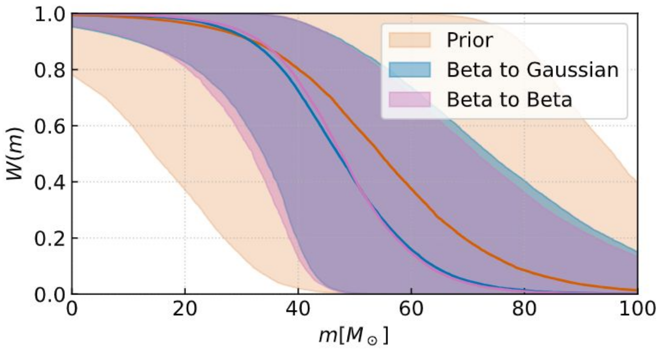
[LVK+ PRX 13 (2023)]



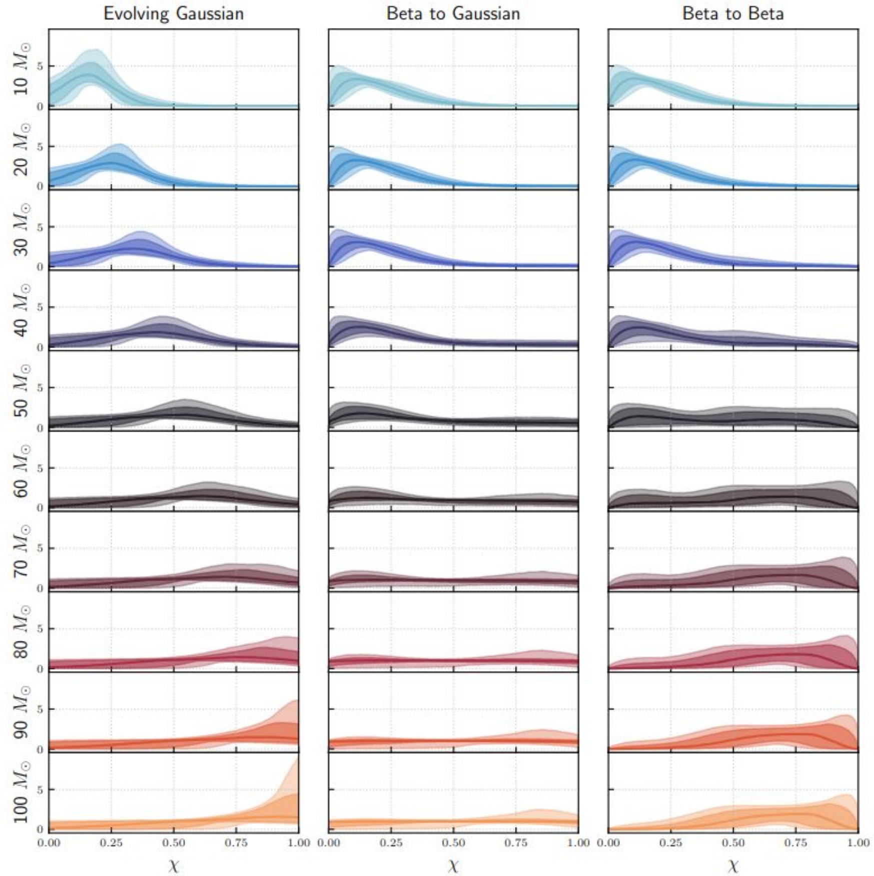
*[Pierra, **SM**, Perries under internal LVK review]*

The spins of Binary Black Holes

- We first try models that transition between two spin populations depending on the source mass.
- We obtain that there is evidence for a transition between two subpopulations of spins magnitude around 40 solar masses.
- Lower masses, lower the spins. Higher masses have different spin distributions.

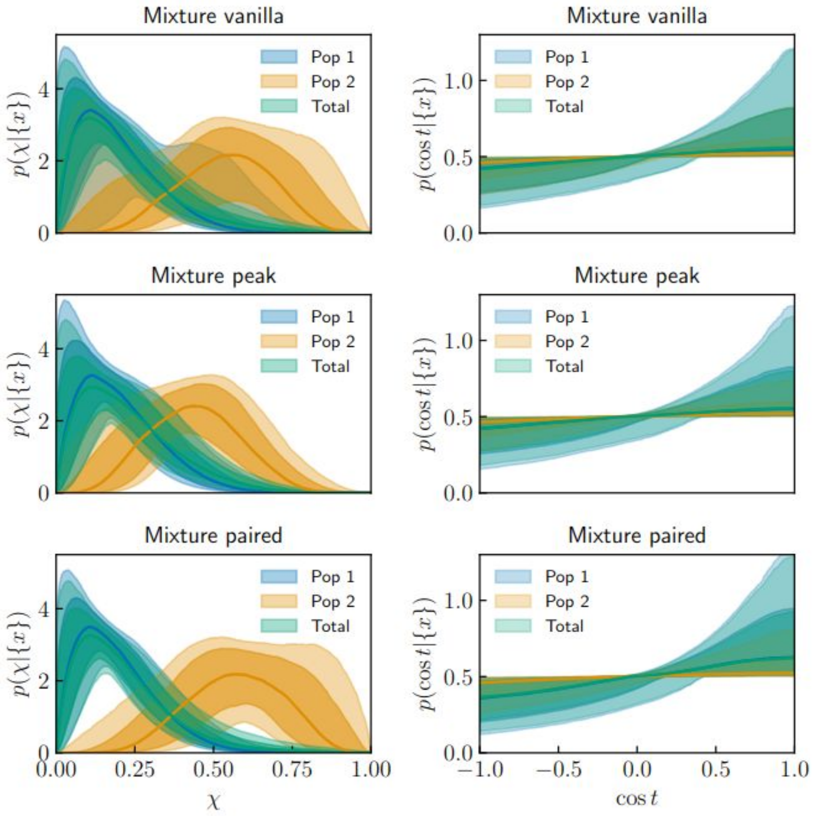


*[Pierra, **SM**, Perries under internal LVK review]*



The spins of Binary Black Holes

- We then try to fit the BBH population as a **mixture** of two independent sub-populations in terms of masses and spins.
- We obtain that 98% of events is formed from a population with **low masses** (up to 40-60 solar masses) with **low spins**.
- We obtain that 2% of the population has masses **above** 40-60 solar masses and spins **supporting** 0.7. There is also a hint for a more isotropic distribution.



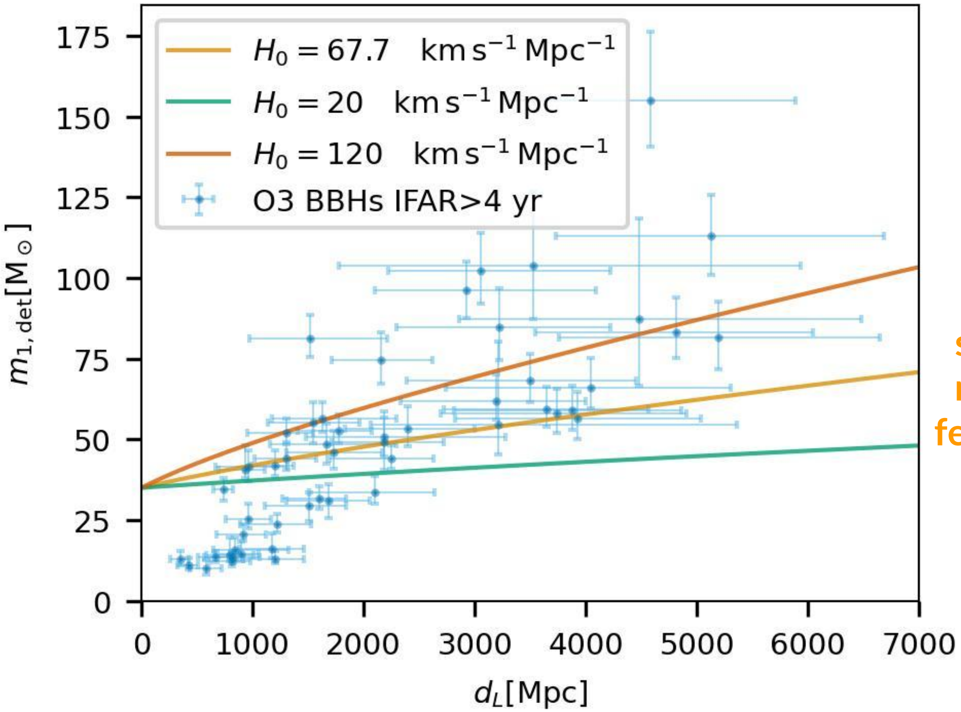
Conclusions

- **Bright sirens** cosmology currently counts 1(2) sources.
- Dark sirens cosmology exploiting the mass spectrum and galaxy surveys is a **promising avenue** for the future.
- Potential biases for dark sirens cosmology can be hidden in how we describe the mass spectrum and the GW host probability.
- We need to develop clustering techniques with Large Scale Structure Tracers.
- Spins could become important for cosmology as they seem to correlate with the source mass.

Extra Slides

Spectral sirens

- Cosmological models and source masses can be recast to the luminosity distance - detector mass plane.
- Cosmological information can be extracted by jointly fitting this plane.



35 solar mass feature

Hierarchical Likelihood

The likelihood for an inhomogeneous Poisson process in presence of selection biases, for a **constant rate in detector time**, is (see Mandel+ 2018 MNRAS, Vitale+ 2020)

Rate

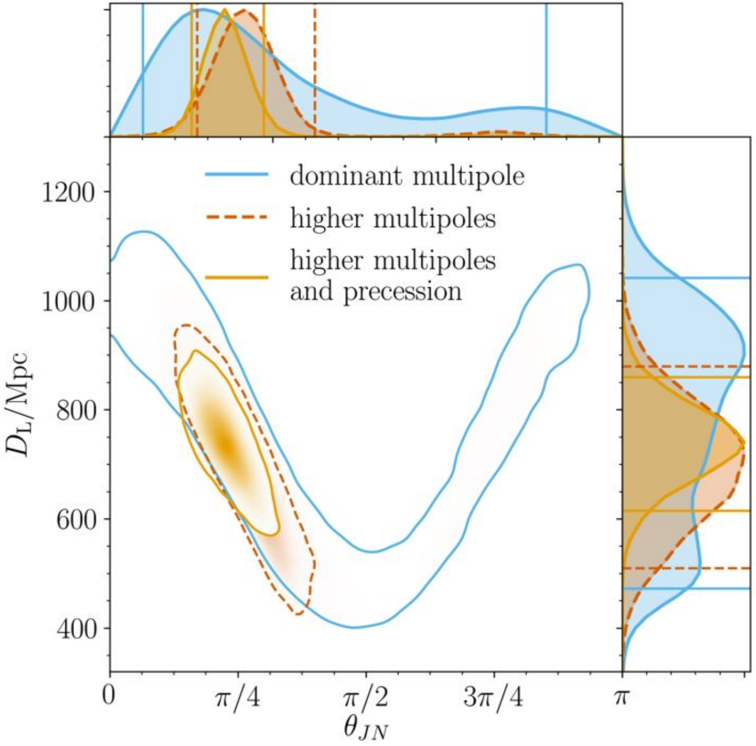
$$\mathcal{L}(x|\Lambda) \propto e^{-N_{\rm exp}} \prod_{i=1}^{N_{\rm obs}} T_{\rm obs} \int \mathcal{L}_n(x|\theta,\Lambda) \frac{dN}{dt d\theta} d\theta$$

Noise process

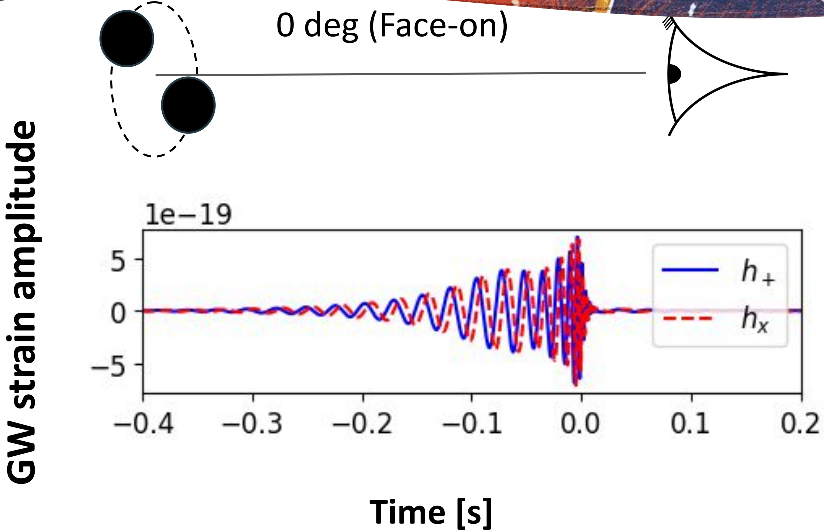
Expected number of detections

$$N_{\rm exp} = T_{\rm obs} \int p_{\rm det}(\theta,\Lambda) \frac{dN}{dt d\theta} d\theta.$$

Inclination angle



[B. P. Abbott, PRD 102, 043015]



There are large uncertainties on the GW estimation of the luminosity distance. The precision can be improved with (i) extra EM information (ii) precession or higher order modes.

Spectral sirens: rates

The CBC likelihood is often parametrized in terms of redshift and **source-frame time**

$$\frac{dN_{\rm CBC}(\Lambda)}{d\vec{m}d\vec{\chi}d\Omega dz dt_s} = R_0$$

Rate of CBC [#mergers Gpc^-3 yr^-1]

$$\psi(z;\Lambda)$$

Rate evolution function, e.g. (1+z)^gamma. Two models available

$$p_{\rm pop}(\vec{m},\vec{\chi}|\Lambda)$$

Probabilities for source-frame masses and spins, 8 models for masses, 2 for spins

$$\frac{dV_c}{dz d\Omega}$$

Comoving volume (depends on cosmology)

Dark sirens: rates

The CBC likelihood is often parametrized in terms of redshift and **source-frame time**

CBC per galaxy per year

$$\frac{dN_{\rm CBC}(\Lambda)}{dz d\vec{m} d\vec{\chi} d\Omega dt_s} = R^*_{\rm gal,0}\psi(z;\Lambda)p_{\rm pop}(\vec{m},\vec{\chi}|\Lambda)\times$$

Term similar to the vanilla rate

$$\left[\frac{dV_c}{dzd\Omega}\phi_*(H_0)\Gamma_{\rm inc}(\alpha+\epsilon+1, x_{\rm max}(M_{\rm thr}), x_{\rm min})+\right.$$

Integral of Schecter function

Number density of galaxies per steradian (completeness correction)

$$\left.\frac{1}{\Delta\Omega}\sum_{j=1}^{N_{\rm gal}(\Omega)} f_L(M(m_j,z);\Lambda)p(z|z^j_{\rm obs},\sigma^j_{\rm z,obs})\right]$$

Number density of galaxies per steradian (catalog)

Luminosity weight

Galaxy localization in redshift

Sky pixel area