Studying the impact of the binary black hole formation channels on gravitational-wave cosmology

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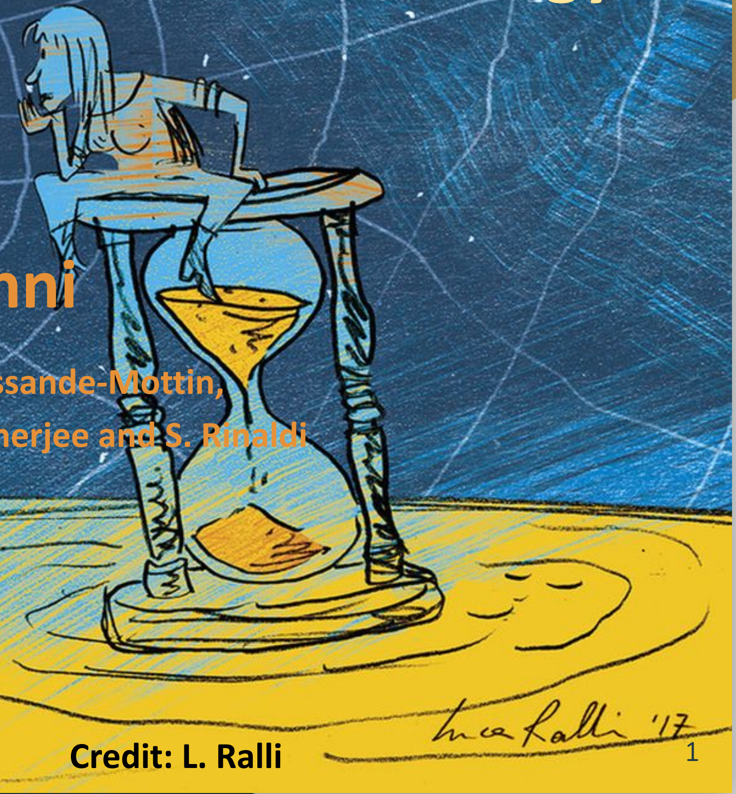
arXiv: 2103.14663

Paris Centre for Cosmological Physics

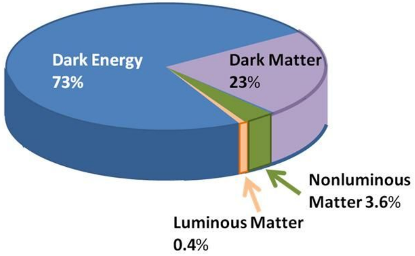


Credit: L. Ralli

The standard cosmological model

According to General Relativity, and confirmed by many observations, the Universe is expanding with a rate described by

W. Freedman, Nature Astronomy, 1, 0169 (2017)



$$\frac{H(z)}{H_0} = \sqrt{\Omega_{m,0}(1+z)^3 + \Omega_\Lambda + \Omega_r(1+z)^4 + \Omega_k(1+z)^2}$$

Hubble constant **Dark matter** **Dark energy** **Radiation** **Curvature**

Despite its success in the standard cosmological model suffers:

- ➢ **Theoretical problems:** What is the nature of Dark Energy?
- ➢ **Observational problems:** Why the measure of the Hubble constant does not agree at the level of the CMB and today? (There is a 4.6 sigma discrepancy)

$$d_L(z) = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

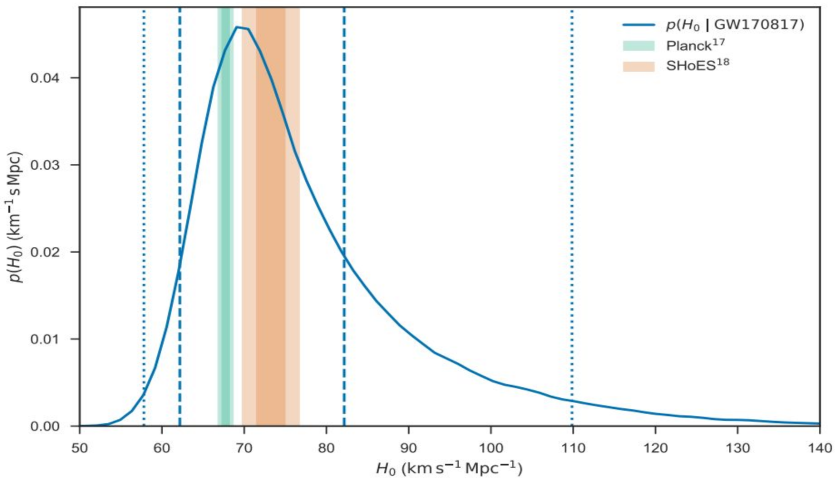
Luminosity distance + redhshit = Fit of cosmology

Gravitational-wave cosmology

GWs provide a direct measurement of the luminosity distance

Bright sirens

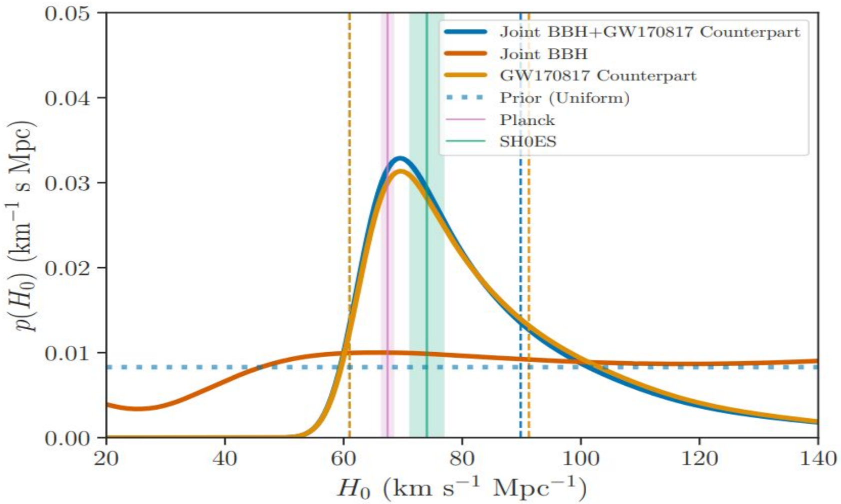
Accurate redshift information from the EM counterpart (GW170817 and GW190521?)



LVC+, Nature volume 551, pages85–88 (2017)

Dark sirens

Redshift information taken from galaxy catalogs

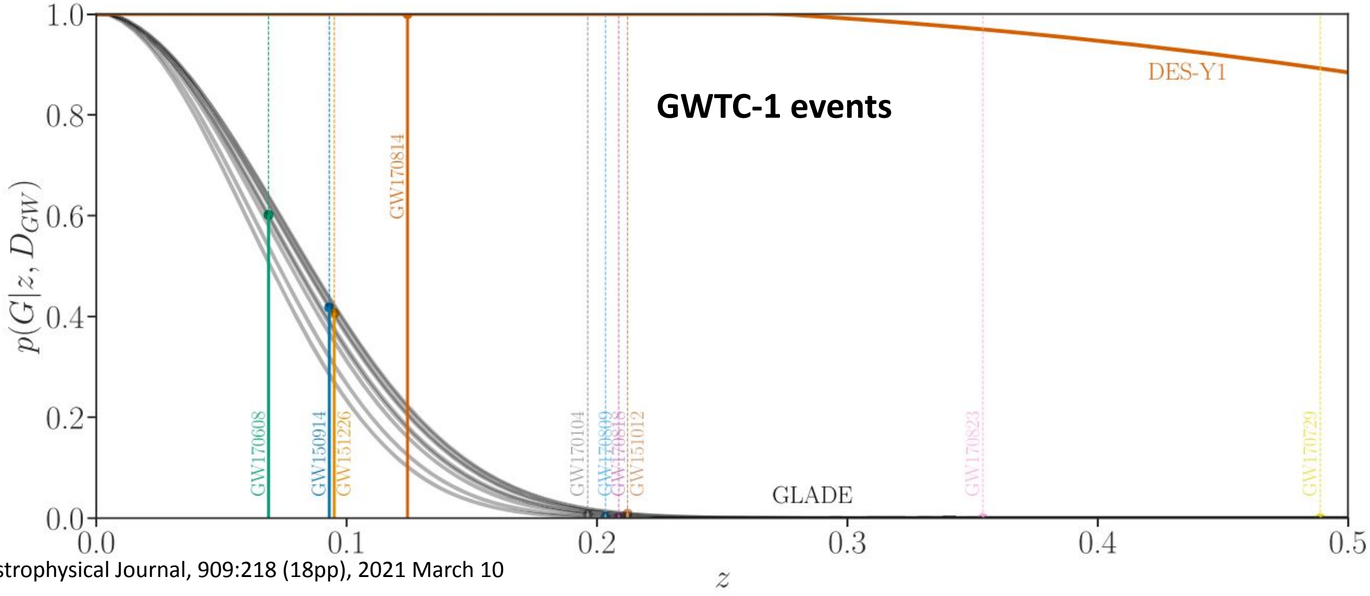


LVC+, The Astrophysical Journal, 909:218 (18pp), 2021 March 10

Gravitational-wave cosmology difficulties

- **Bright sirens:** Few sources, detecting an EM counterpart is extremely rare and it is possible only for close-by events.

- **Dark sirens:** Many sources but Galaxy catalogs completeness rapidly decrease with redshift, moreover the 3D sky localization volume often includes a thousands of galaxies.



LVC+, The Astrophysical Journal, 909:218 (18pp), 2021 March 10

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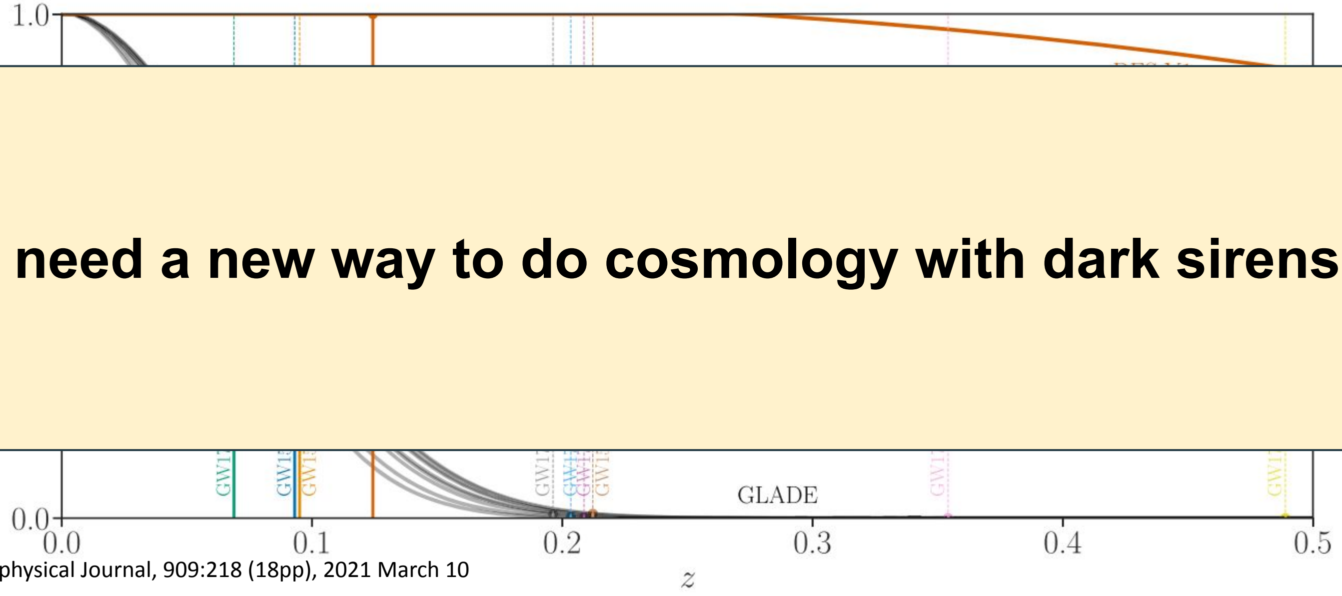


LVC+, The Astrophysical Journal, 909:218 (18pp), 2021 March 10

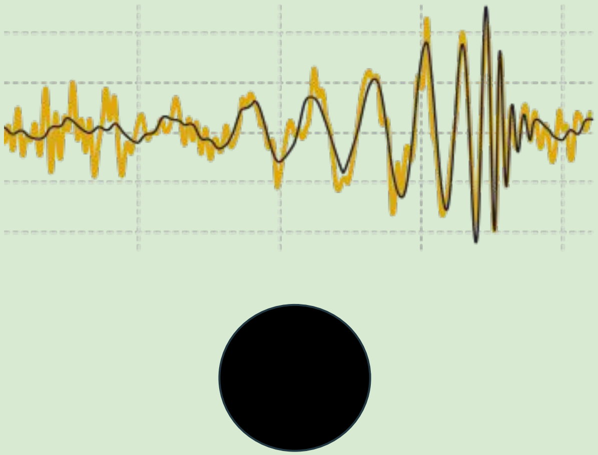
We need a new way to do cosmology with dark sirens

Cosmology with Dark sirens: the source-frame mass

The idea is to exploit the relation between source-frame mass and detector-frame mass.

Taylor+, PRD, 023535 (2012) *Farr+, APJL, 883(2019)*
Taylor+, PRD, 023502 (2012)

Source frame



Expansion of the Universe

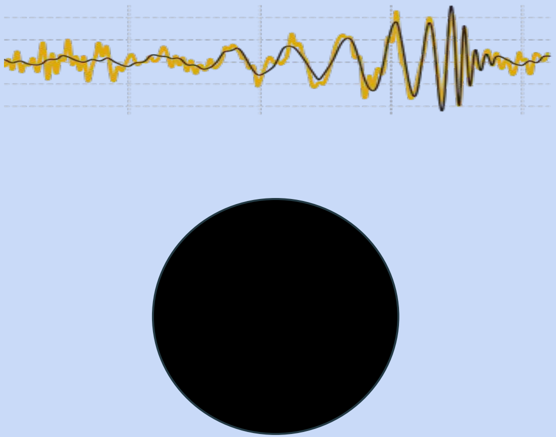
Phase evolution conserved

Just amplitude scaling

Redshifted mass

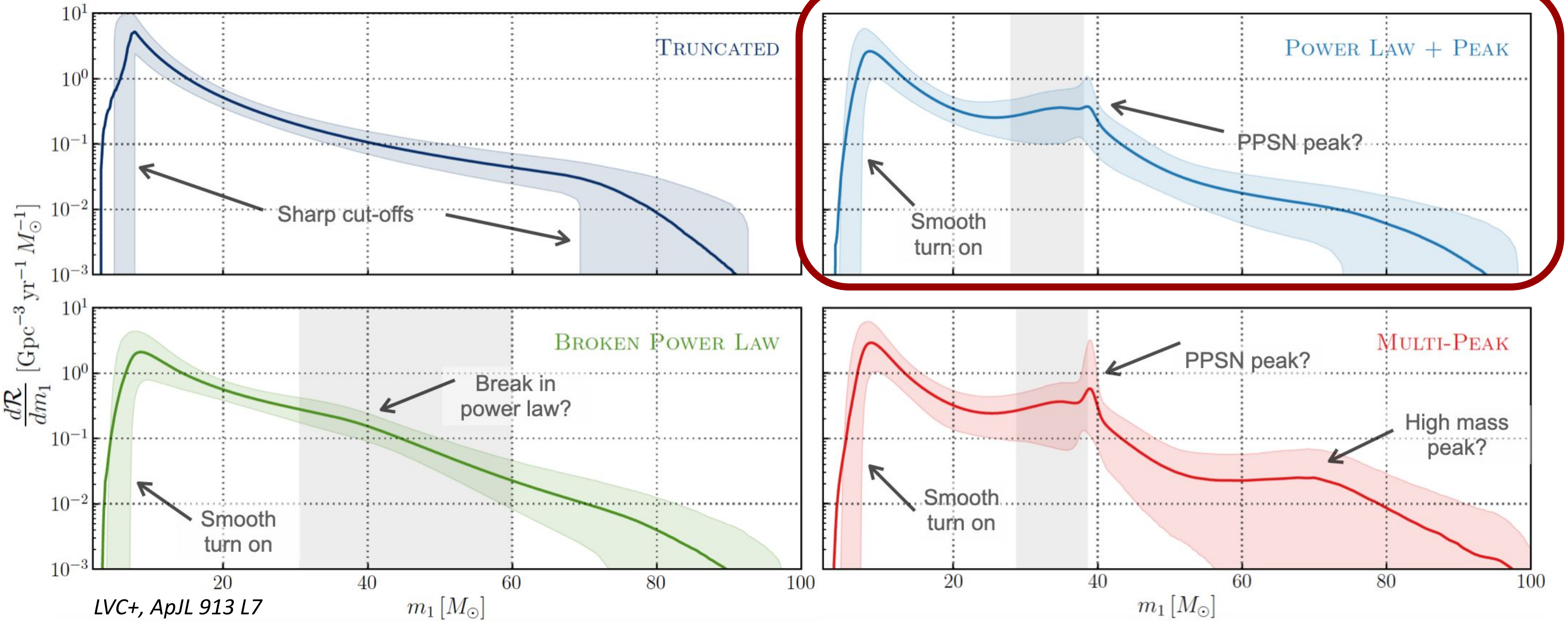
$$m_s = \frac{m_d}{1+z}$$

Detector frame



Cosmology with Dark sirens: the source-frame mass

The idea is to use phenomenological description of the BHs source-frame mass distribution to measure conjointly with cosmology



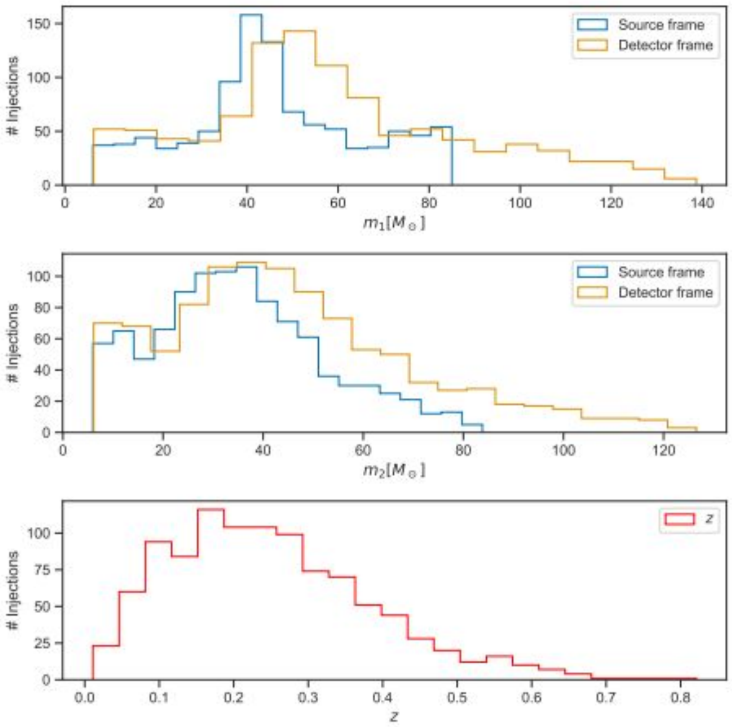
LVC+, ApJL 913 L7

Analysis with 44 confident BBH. Primary mass distribution

Cosmology with Dark sirens: the source-frame mass

- We simulate BBHs sources from a source-frame mass model which is a truncated powerlaw+gaussian component.
- The gaussian component has a peak at 40 solar masses (PISN) and the powerlaw has a hard cut-off at 85 solar masses. The powerlaw decrease with a coefficient of -2.
- We choose a Planck cosmology and detectors with O3-like sensitivities.
- We fit jointly the source-frame mass spectrum and cosmology

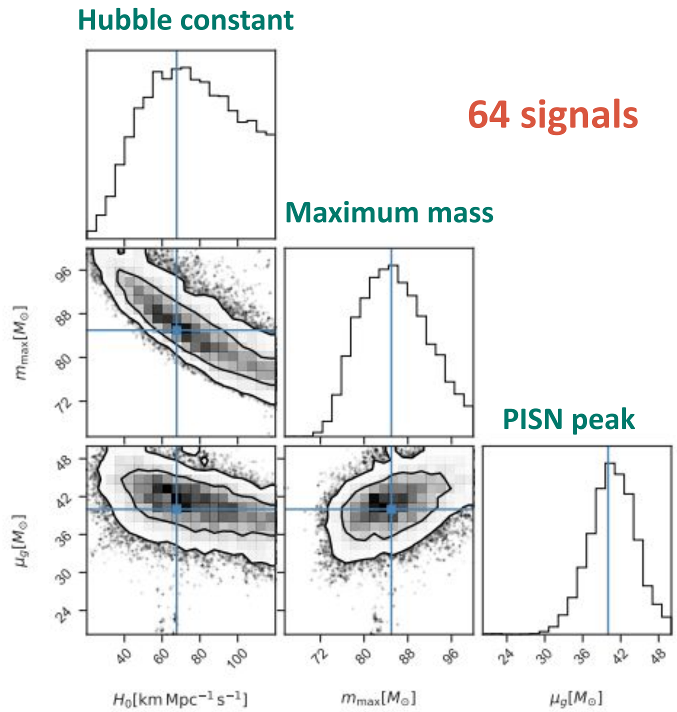
Simulated sources (fixing cosmology)

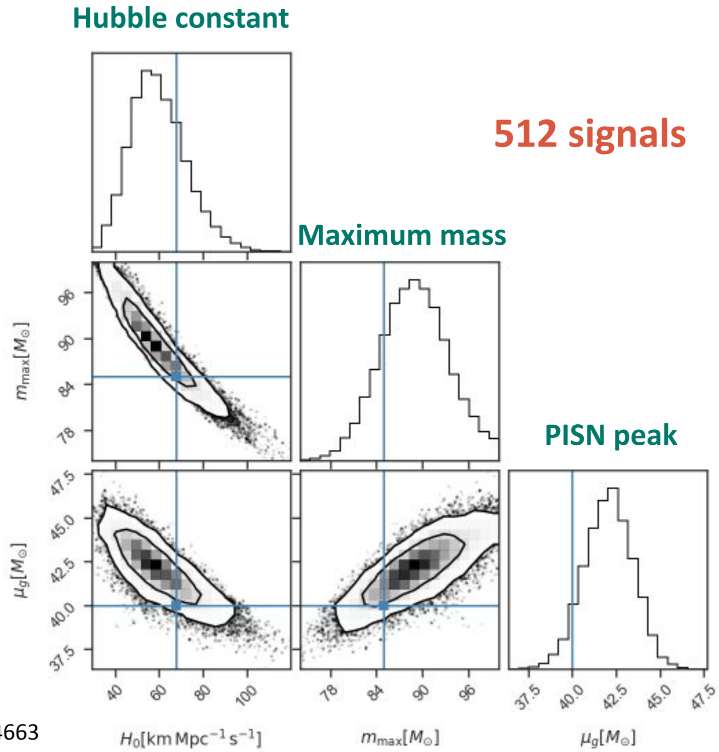


SM+, arXiv: 2103.14663

Cosmology with Dark sirens: the source-frame mass

- There is a tight correlation between the estimation of the source-frame mass spectrum and cosmology



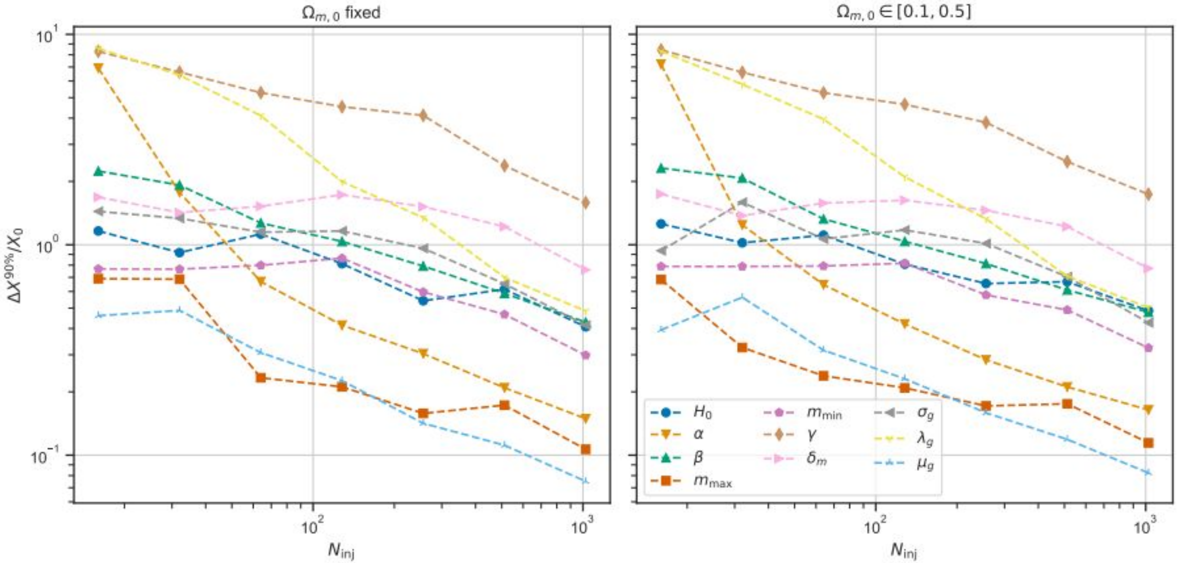


SM+, arXiv: 2103.14663

Cosmology with Dark sirens: the source-frame mass

- ❑ Cosmology and the source-frame mass distribution can be measured jointly.

- ❑ With this simulated population, the Hubble constant can be constrained to ~30% (at 90% CL) level with 1024 events.



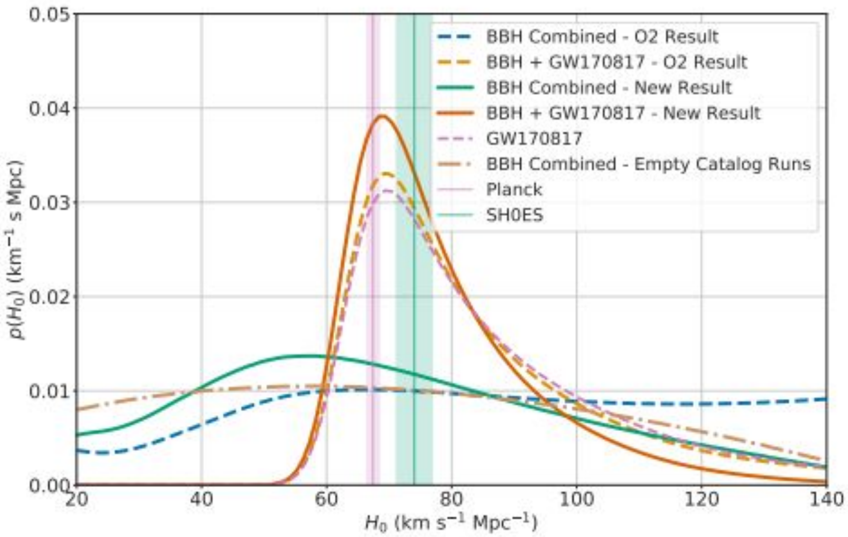
The dark matter fraction will not play a fundamental role with current sensitivities.

SM+, arXiv: 2103.14663

Cosmology with Dark sirens: the source-frame mass

- ❑ Population assumptions on the source-frame mass spectrum will be important even for dark sirens analyses with galaxy surveys.

- ❑ Since galaxy catalogs are incomplete and GW events not accurately localized, the source-frame mass spectrum will implicitly provide information.



Impact of population on GWTC-1 analyses:

- ❑ Population assumptions already play a fundamental role with ~6 GW events.

- ❑ We use a population model that match well with H0~70 km/Mpc/s to show its impact on O2.

Cosmology with Dark sirens: the source-frame mass

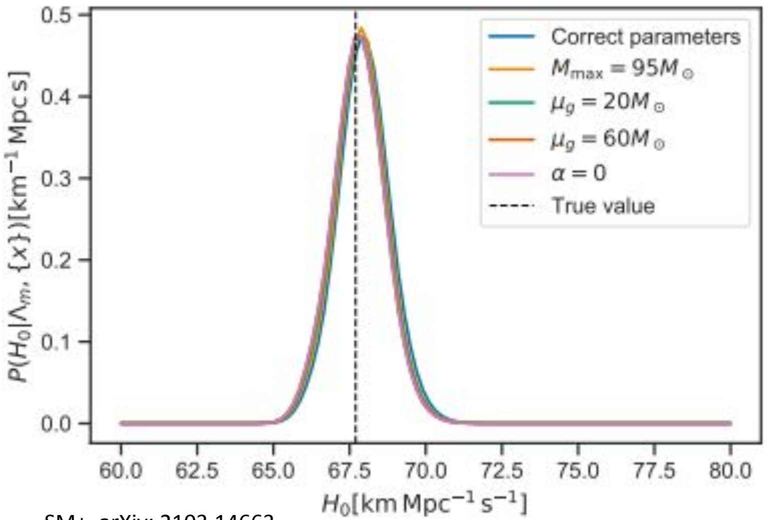
- On the other hand population assumptions will not be important when having an EM counterpart (the redshift is well measured).

- In this case, it is sufficient to choose a population model that includes the masses estimated for the events that we are analyzing.

The likelihood factorizes in a cosmological part + a population part

$$p(\Lambda|\{x\}, z_{\rm obs}) \propto \frac{p(\Lambda)}{[p(\mathscr{D}|\Lambda)]^{N_{\rm obs}}}$$
$$\times \prod_i^{N_{\rm obs}} p(z^i_{\rm obs}|\Lambda_c) p(x^i|d_L(\Lambda_c, z^i_{\rm obs}))$$
$$\times \prod_i^{N_{\rm obs}} I(x^i; \Lambda_m, z^i_{\rm obs}),$$

64 BBHs with EM counterpart



SM+, arXiv: 2103.14663

Conclusions

- Gravitational-wave sources provide a new way to study cosmology.
- The bright siren and dark siren method with galaxy catalogs will become less and less viable as we detect further GW events.
- The knowledge of the source-frame mass distribution of BBHs can help to obtain a redshift estimation.
- It will be possible to measure jointly the source-frame mass distribution and cosmology using thousands of GW sources.
- Population assumptions also play a fundamental role for galaxy catalog-based analyses.
- When the GW have an EM counterpart observed population assumptions will not matter*.

Extra slides

How do we infer the population properties?

We want to describe the population with some parameters population parameters Λ

$$p(\Lambda|\{x\}, N_{\mathrm{obs}}) \propto p(\{x\}, N_{\mathrm{obs}}|\Lambda)p(\Lambda) \Longrightarrow p(\{x\}, N_{\mathrm{obs}}|\Lambda)p(\Lambda) = \boxed{p(N_{\mathrm{obs}}|\Lambda)} \prod_i^{N_{\mathrm{obs}}} p(x_i|N_i, \Lambda)$$

Using the bayes theorem...

$$p(x_i|N_i, \Lambda) = \frac{\boxed{p(N_i|x_i, \Lambda)}\boxed{p(x_i|\Lambda)}}{\boxed{p(N_i|\Lambda)}}$$

- Probability of detecting N_obs events given some population parameters: A Poisson distribution
- Probability of detecting the event, given the current data set and the population parameters (one since we detected the event)
- Probability of detecting an event considering all the possible data sets (realization of the noise)
- Calculated from GW-likelihood