

[i]Dipartimento di Fisica "E. Fermi", Università di Pisa, I-56127 Pisa, Italy

Cosmology in the dark: How compact binaries formation impact the gravitational-waves cosmological measurements

**S. Mastrogiovanni,^{a,*} K. Leyde,^a C. Karathanasis,^b E. Chassande-Mottin,^a
D. A. Steer,^a J. Gair,^c A. Ghosh,^d R. Gray,^e S. Mukherjee^{f,g,h} and S. Rinaldi^{i,j}**

^aUniversité de Paris, CNRS, AstroParticule et Cosmologie (APC), F-75013 Paris, France

^bInstitut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain

^cMax Planck Institute for Gravitational Physics (Albert Einstein Institute), Am Mühlenberg 1, Potsdam 14476, Germany

^dGhent University, Proeftuinstraat 86, 9000 Gent, Belgium

^eSUPA, University of Glasgow, Glasgow G12 8QQ, United Kingdom

^fGravitation Astroparticle Physics Amsterdam (GRAPPA), Anton Pannekoek Institute for Astronomy and Institute for Physics, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, The Netherlands

^gInstitute Lorentz, Leiden University, PO Box 9506, Leiden 2300 RA, The Netherlands

^hDelta Institute for Theoretical Physics, Science Park 904, 1090 GL Amsterdam, The Netherlands

^jINFN, Sezione di Pisa, I-56127 Pisa, Italy

E-mail: mastrosi@apc.in2p3.fr

Information about the mass spectrum of compact stars can be used to infer cosmological parameters from gravitational waves (GW) in the absence of redshift measurements obtained from electromagnetic (EM) observations. This method will be fundamental in measuring and testing cosmology with GWs for current and future ground-based GW detectors where the majority part of sources are detected without an associated EM counterpart. In this proceeding, we will discuss the prospects and limitations of this approach for studying cosmology. We will show that, even when assuming GW detectors with current sensitivities, the determination of the Hubble constant is strongly degenerate with the maximum mass for black hole production. We will discuss how assuming wrong models for the underlying population of black hole events can bias the Hubble constant estimate up to 40%.

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*Speaker

1. Introduction

The detection first detection of gravitational waves (GWs) [1, 2] set a new milestone for cosmology as GWs signals from compact binary coalescence directly provide a measure of the source luminosity distance. If this measure, is supplemented with an evaluation of the source redshift, GW signals can be used to probe the cosmic expansion history [3, 4]. This is of great interest given the current tension in the estimation of the Hubble constant H_0 today [5–8].

The binary neutron star merger GW170817, and its electromagnetic (EM), was the first event considered for cosmological studies [9] and provided a measurement of $H_0 = 70_{-8}^{+19}$ km s⁻¹ Mpc⁻¹ [10] (68.3% maximum posterior and highest density intervals). In this case, the redshift of the source was obtained from the observation of the GWs in association to a short gamma-ray burst with the subsequent kilonova and identification of host galaxy [11, 12].

For this motivation, several method that does not rely on a direct EM counterpart have been proposed. The first approach proposed in [4, 13] was to employ galaxy catalogs in correlation with the GWs localization volume to obtain a redshift estimation. This techniques provides a less accurate redshift estimation than a direct detection of the EM counterpart, but it can be applied to all the GWs sources, even binary black holes (BBHs) for which an EM counterpart is not expected. For instance, this technique was applied as case study to GW170817, obtaining $H_0 = 77_{-18}^{+37}$ km s⁻¹ Mpc⁻¹ [14], but also on BBHs and neutron star black hole (NSBH) [15] detected during first three runs of the LIGO and Virgo detectors, see [2, 16–18] for the different H_0 measures. However, even this method suffers from the limitation that (i) galaxy catalogs only covers a limited fraction of the GWs sky localization and (ii) galaxy catalogs rapidly becomes *incomplete* in redshift [17].

Here, we consider a different method, relying only on the GWs signal. The idea is to exploit the fact that as a consequence of the Universe expansion, the inferred binary masses are redshifted, i.e. $M_z = (1+z)M$, where z is the redshift, M is the mass the source and M_z is the mass estimated at the detector. Hence, a redshift evaluation could be implicitly inferred from the knowledge, or using some assumptions on the source masses. This method was originally proposed in [19, 20] for BNSs and extendend in more details in [21] for the mass spectrum of BBHs with Advanced LIGO and Virgo.

In this proceeding we focus on presenting in more details the impact of the BBHs source mass spectrum assumptions for the estimation. The remainder of the paper is organized as follows. In Sec. 2 we resume the general method and its statistical implementation, in Sec. 3 we highlight and discuss possible systematics in the H_0 and source mass reconstruction for BBHs observed with and without EM counterparts, while in Sec. 4 we draw our conclusions and discuss future perspectives.

2. Basics of the source mass method

The idea is the following: given a set of set of N_{obs} GW detections with their estimations of luminosity distance D_L and detector masses $m_1^{\text{det}}, m_2^{\text{det}}$, one would like to reconstruct, for a given cosmology, the distribution of the binary redshift z and source masses m_1, m_2 . This can be done by defining a *hierarchical likelihood* [22–24] that is used to calculate the probability to of a set of population parameters Λ , that describes the source mass spectrum and redshift distribution of the binaries, together with cosmological parameters such as H_0 . The posterior on the population level

parameters and H_0 can be written as

$$p(\Lambda, H_0 | \{x\}, N_{\text{obs}}) \propto p(H_0, \Lambda) \prod_i^{N_{\text{obs}}} \frac{\int p(x_i | H_0, z, m_1, m_2) p_{\text{pop}}(z, m_1, m_2 | \Lambda) dz dm_1 dm_2}{\int p_{\text{det}}(z, m_1, m_2, H_0) p_{\text{pop}}(z, m_1, m_2 | \Lambda) dz dm_1 dm_2}, \quad (1)$$

where $p(H_0, \Lambda)$ is a prior term and $p(x_i | H_0, z, m_1, m_2)$ is the GW likelihood of the single event which is calculated from the estimated $D_L, m_1^{\text{det}}, m_2^{\text{det}}$ fixing a value of the H_0 . The term $p_{\text{pop}}(z, m_1, m_2 | \Lambda)$ is prior term describing the distribution of binaries in source mass and redshift that depends from the choice of several population parameters Λ . For instance, to describe the redshift distribution of the binaries, usually a powerlaw distribution in $(1+z)$ is implemented [25], while for the source mass spectrum several phenomenological models are available. The denominator of Eq. 1 takes into account selection biases through the evaluation of a detection probability $p_{\text{det}}(z, m_1, m_2, \Lambda)$.

Roughly speaking, a value of H_0 will be preferred, when the collection of reconstructed likelihoods in the source frame $p(x_i | H_0, z, m_1, m_2)$ matches the imposed population prior on $p_{\text{pop}}(z, m_1, m_2 | \Lambda)$. As an example, if the the population prior $p_{\text{pop}}(z, m_1, m_2 | \Lambda)$ excludes masses higher than $50M_\odot$ an event is found with that masses for a value of $H_0 = 30 \text{ km s}^{-1} \text{ Mpc}^{-1}$ but not $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, then the value of $H_0 = 30 \text{ km s}^{-1} \text{ Mpc}^{-1}$ will be automatically excluded as it will return a null hierarchical likelihood.

Of course we do not know a priori the distribution of binaries in source mass and redshift and that is the motivation for which we need to jointly fit for population parameters related to the source mass spectrum and H_0 and other cosmological parameters.

3. Results

In order to quantify how the population assumptions impacts the estimation of H_0 , in [26] perform a simulation of BBHs detected by LIGO and Virgo detectors with sensitivities similar to the ones achieved during the second and third observing runs [27–30].

In particular, we have chosen a uniform in comoving volume merger rate distribution in redshift. The source primary mass spectrum model is a linear combination of a decreasing powerlaw with slope $\alpha = 2$ between minimum mass $m_{\text{min}} = 5M_\odot$ and maximum mass $m_{\text{max}} = 85M_\odot$, and a gaussian component with mean at $\mu_g = 40M_\odot$ and standard deviation of $\sigma_g = 5M_\odot$. We chose the fraction of events born in the gaussian peak to be 10%. For the secondary source mass, we chose a conditional powerlaw model¹, with powerlaw slope $\beta = 0$ (no preference for equal masses). This is a population model compatible with current O2 and O3 BBH events [2, 31]. The cosmology that we fix has $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_{m,0} = 0.308$ [32].

We analyzed $N_{\text{inj}} \leq 1024$ simulated events that passed a network signal-to-noise ration threshold of 12. Below, we briefly discuss two cases from [26], the case in which no EM counterpart is observed and the case in which an EM counterpart is observed for all the events. We estimate jointly sampling from the posterior in Eq. 1 calculated for the cosmological parameters $H_0, \Omega_{m,0}$ and the various population parameters.

¹The condition being $m_2 \leq m_1$.

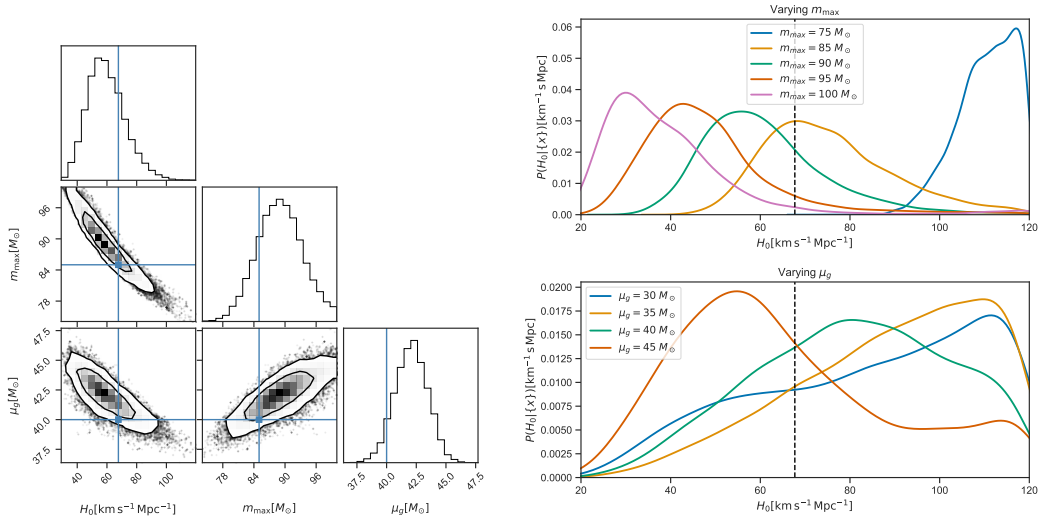


Figure 1: *Left:* Posterior distribution on the H_0 , m_{max} and μ_g for 64 BBH events detected with LIGO and Virgo at current sensitivities. The blue lines show the true parameters. The contours indicate the 1σ and 2σ confidence level intervals. *Right:* Posterior distribution for H_0 obtained by fixing m_{max} and μ_g in a range around their true values $m_{\text{max}} = 85M_\odot$ and $\mu_g = 40M_\odot$. The black dashed line indicates the true value of H_0 . Figure from [26].

3.1 Dark sirens: Impact of the BBHs population assumptions

We discuss in this section our findings when we assume that no EM counterpart is detected with the GW events.

Our first result concerns the impact of $\Omega_{m,0}$ on the determination of H_0 . We perform two runs: in (i) we fix $\Omega_{m,0}$ to its injected value, while in (ii) $\Omega_{m,0}$ is able to vary in the range $[0.1, 0.5]$ with a uniform prior. We find that for detector sensitivities comparable to O2 and O3, $\Omega_{m,0}$ only weakly impacts the determination of H_0 . In fact, while fixing $\Omega_{m,0}$ we find that H_0 could be constrained to the 40% accuracy (90% credible intervals), while if we leave $\Omega_{m,0}$ able to vary, H_0 can be constrained at 50% accuracy. See [26] for more details.

Our second result concerns the interplay between the determination of H_0 and other population parameters, for the simulated population m_{max} and μ_g . In Fig. 1 left panel, we show the joint posterior distribution between H_0 , μ_g and m_{max} for 64 BBHs without EM counterpart.

Indeed, m_{max} and μ_g impact the estimation of the H_0 . Let us take m_{max} as an example: lowering H_0 values move the observed GW source to lower redshifts (remember that what it is estimated is actually D_L), as a consequence, this will push the source masses to higher values (since we measure detector masses). Hence, to “correct” for this increase in source masses, an higher m_{max} is needed and this creates a correlation between the determination of H_0 and m_{max} . A similar discussion is valid for the position of the gaussian peak μ_g .

The interplay, or correlation between the determination of H_0 and population parameters related to the source mass spectrum, can also become a source a bias for the determination of the H_0 . In fact, if an analysis is performed by fixing a erroneous population model for BBHs, then the estimation of H_0 might be systematically biased.

As an example, in Fig. 1 right panel where we show posterior distributions obtained for H_0 when fixing either μ_g or m_{\max} mismatched values with respect to the injected ones. One can see that already with 64 events, the amount of bias due to wrong population assumptions is significant. We therefore argue that population assumptions and cosmological parameters estimation should be taken under control together.

3.2 Bright sirens: Impact of the populations assumptions

We also considered a different situation, namely *What if BBHs are provided with EM counterparts? Will the source mass spectrum assumptions be important?*. This is of course an unrealistic situation but it will give us an idea on the interplay of population assumptions and EM counterparts in this case.

In order to take into account the extra redshift estimation z_{obs} from the EM counterpart, we have to modify Eq. 1. We obtain, with the assumption that the GW likelihood is separable in a term dependent from the luminosity distance $p(x^i|H_0, z_{\text{obs}}^i)$ and in one from the masses $p(x^i|m_1, m_2, z_{\text{obs}})$,

$$p(\Lambda|\{x\}, z_{\text{obs}}) \propto p(\Lambda) \prod_i^{N_{\text{obs}}} \frac{\int p(z_{\text{obs}}^i|\Lambda) p(x^i|H_0, z_{\text{obs}}^i) p(x^i|m_1, m_2, z_{\text{obs}}) p_{\text{pop}}(m_1, m_2|\Lambda) dm_1 dm_2}{\int p_{\text{det,GW}}(m_1, m_2, z, H_0) p_{\text{det,EM}}(m_1, m_2, z, H_0) p_{\text{pop}}(m_1, m_2, z|\Lambda) dm_1 dm_2 dz}. \quad (2)$$

Above, $p_{\text{det,EM}}$ represent the probability of detecting an EM counterpart given a set of binary parameters. It is important to notice that the two last terms depend individually on either the population or cosmological parameters, while $p(z_{\text{obs}}^i|\Lambda)$.

From Eq.2 we can see that if we fix Λ to incorrect values, the evaluation of Eq. (2) will only differ from a normalization constant and H_0 will not be impacted. Of course, the calculation of selection effects in the denominator should be calculated correctly and the population source spectrum assume should include the binary masses in its spectrum.

In Fig. 2 we show an H_0 posterior computed with 64 events of the simulated population and assuming an EM counterpart. One can see that wrong population assumptions are not particularly important.

4. Conclusions

In this paper we have showed the interplay between BBHs population assumptions and the estimation of cosmological parameters with GWs standard sirens. We have shown that parameters that governs features in the source mass spectra of BBHs are likely to introduce strong correlations with the determination of the cosmological parameters, in particular H_0 . On one hand, the source mass spectrum provides a useful channel to investigate cosmology with GWs even in absence of EM counterparts or with incomplete galaxy catalogs. On the other hand, if the source mass spectrum is mismatched, a significant bias on the evaluation of H_0 is introduced.

We have also shown that in presence of an EM counterpart, the dependence of the H_0 estimation from population assumption can be quenched.

In the future, other interesting methods for instance the cross-correlating GW sources with galaxies, see [33–35] can also help leverage the determination of cosmological parameters with GWs.

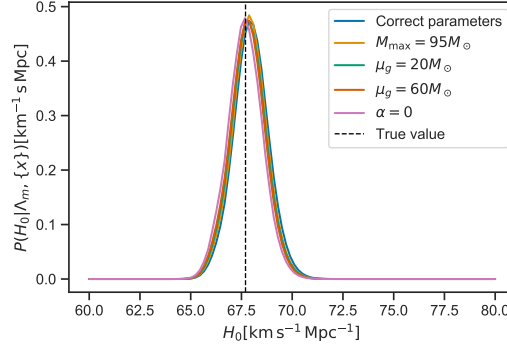


Figure 2: Hubble constant posterior generated from 64 our synthetic population of BBHs fixing different population models and providing the redshift of the GW source (assumed from an EM counterpart). An incorrect choice of one of the population parameters (see legend) does not affect significantly the H_0 estimation. The vertical dashed line indicates the injected value. Note that for this plot the posterior samples are generated taking into account the correlations between masses and luminosity distance (point (ii) above is dropped). Figure from [26]

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