

Cosmology with standard sirens

Bernardo Porto Veronese*

PPG COSMO, UFES

(Dated: October 24, 2023)

An article usually includes an abstract, a concise summary of the work covered at length in the main body of the article.

Usage: Secondary publications and information retrieval purposes.

Structure: You may use the `description` environment to structure your abstract; use the optional argument of the `\item` command to give the category of each item.

I. INTRODUCTION

The idea of using gravitational waves (GWs) from compact binary mergers to measure cosmological parameters was first introduced by Bernard Schutz in 1986 [1]. These signals directly provide a measurement of the luminosity distance measurement to the source, which is therefore independent of the cosmic distance ladder. With the addition of redshift information, measurements can therefore be made of those cosmological parameters which impact the expansion history of the Universe, such as the Hubble constant (H_0). This approach is independent of all other local measurements to date.

The standard siren method probes the expansion history of the universe with the distance-redshift relation, with which one can infer the cosmological parameters such as H_0 and the dark energy equation of state parameter w : [2]

$$D_l(z) = (1+z) \frac{c}{H_0 \sqrt{\Omega_K}} \sinh \left[\sqrt{\Omega_K} \int_0^z \frac{H_0}{H(z') dz'} \right] \quad (1)$$

$$\frac{H(z)}{H_0} = \sqrt{\Omega_m(1+z)^3 + \Omega_K(1+z)^2 + \Omega_{de}(1+z)^{3(1+w)}}.$$

To lighten notation, we have omitted the 0-subscript next to the Ω_i 's, although they correspond to the present day values in the above equation. Note that using (1) requires specifying a cosmological model.

A. Gravitational-wave distances

The accuracy of the GW luminosity distance measurement is typically of the order of 10%. The main source of uncertainty comes from the degeneracy between the distance and inclination angle of the source. The latter is defined as the angle between the line-of-sight vector from the source to the detector and the orbital-angular momentum of the binary system.

B. Assigning redshifts to GW sources

From the GW data, it is possible to infer the luminosity distance to the binary source, but not the redshift, as the latter comes degenerate with the chirp mass in the GW waveform modelling. It is therefore necessary to complement it with another source of information that provides the redshift measurement. Multi-messenger observations, such as neutron star mergers with electromagnetic counterparts like short gamma-ray bursts or kilonovae, provide the most straight-forward measurement [3, 4]. An electromagnetic counterpart like a kilonova can typically be pinpointed to a specific galaxy, thereby identifying the host galaxy of the GW merger. The GW signal provides the distance to the host galaxy, while its electromagnetic spectrum provides the redshift. These sources are typically referred to as bright sirens. So far, the only confirmed such event has been the binary neutron star detection GW170817, which occurred so exceptionally close to our galaxy - at $d \sim 40$ Mpc - that a direct, model-independent estimation of H_0 with Hubble's law,

$$v_H = H_0 d, \quad (2)$$

could be made by measuring the Hubble flow velocity v_H , resulting in $H_0 = 70.0_{-8.0}^{+12.0}$ km s⁻¹ Mpc⁻¹ [5].

As stated above, almost all GW events have been detected without an EM counterpart. These *dark sirens* can be used to probe the expansion of the universe provided that they are complemented with an external redshift measurement. In his original paper, Schutz suggested that this information could be inferred from galaxy catalogs: each galaxy contributes to a hypothetical measurement of H_0 , such that the galaxy structure within a GW event's localisation volume is reflected in the H_0 posterior it produces. How informative the individual events are will depend strongly on their localisation volumes. By combining the contributions of many events, the true value of H_0 will be measured as other values will statistically average out. Such analyses have been carried out in the literature, see [6–11].

* bernardo.veronese@edu.ufes.br

II. STATISTICAL FRAMEWORK

In gravitational-wave astronomy, one subject of interest is extracting the distributional properties of a population of sources based on a set of observations which are drawn from that distribution. Any methodology that leads to unbiased estimates of the population parameters

must simultaneously account for measurement uncertainties and selection effects. One way with which the latter affects the observed population is a Mamquist bias: the loudest or brightest sources are more likely to be detected. The standard formalism for extracting the true source population parameters by incorporating these biases in the analysis is frequently labeled as Hierarchical Bayesian inference, see [12–14].

-
- [1] B. F. Schutz, Determining the Hubble Constant from Gravitational Wave Observations, *Nature* **323**, 310 (1986).
 - [2] D. W. Hogg, Distance measures in cosmology, (1999), arXiv:astro-ph/9905116.
 - [3] D. E. Holz and S. A. Hughes, Using gravitational-wave standard sirens, *Astrophys. J.* **629**, 15 (2005), arXiv:astro-ph/0504616.
 - [4] N. Dalal, D. E. Holz, S. A. Hughes, and B. Jain, Short grb and binary black hole standard sirens as a probe of dark energy, *Phys. Rev. D* **74**, 063006 (2006), arXiv:astro-ph/0601275.
 - [5] B. P. Abbott *et al.* (LIGO Scientific, Virgo, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres Observatory, VINROUGE, MASTER), A gravitational-wave standard siren measurement of the Hubble constant, *Nature* **551**, 85 (2017), arXiv:1710.05835 [astro-ph.CO].
 - [6] W. Del Pozzo, Inference of the cosmological parameters from gravitational waves: application to second generation interferometers, *Phys. Rev. D* **86**, 043011 (2012), arXiv:1108.1317 [astro-ph.CO].
 - [7] H.-Y. Chen, M. Fishbach, and D. E. Holz, A two per cent Hubble constant measurement from standard sirens within five years, *Nature* **562**, 545 (2018), arXiv:1712.06531 [astro-ph.CO].
 - [8] M. Fishbach *et al.* (LIGO Scientific, Virgo), A Standard Siren Measurement of the Hubble Constant from GW170817 without the Electromagnetic Counterpart, *Astrophys. J. Lett.* **871**, L13 (2019), arXiv:1807.05667 [astro-ph.CO].
 - [9] R. Gray *et al.*, Cosmological inference using gravitational wave standard sirens: A mock data analysis, *Phys. Rev. D* **101**, 122001 (2020), arXiv:1908.06050 [gr-qc].
 - [10] M. Soares-Santos *et al.* (DES, LIGO Scientific, Virgo), First Measurement of the Hubble Constant from a Dark Standard Siren using the Dark Energy Survey Galaxies and the LIGO/Virgo Binary–Black-hole Merger GW170814, *Astrophys. J. Lett.* **876**, L7 (2019), arXiv:1901.01540 [astro-ph.CO].
 - [11] A. Palmese *et al.* (DES), A statistical standard siren measurement of the Hubble constant from the LIGO/Virgo gravitational wave compact object merger GW190814 and Dark Energy Survey galaxies, *Astrophys. J. Lett.* **900**, L33 (2020), arXiv:2006.14961 [astro-ph.CO].
 - [12] T. J. Loredo, Accounting for source uncertainties in analyses of astronomical survey data, *AIP Conf. Proc.* **735**, 195 (2004), arXiv:astro-ph/0409387.
 - [13] I. Mandel, W. M. Farr, and J. R. Gair, Extracting distribution parameters from multiple uncertain observations with selection biases, *Mon. Not. Roy. Astron. Soc.* **486**, 1086 (2019), arXiv:1809.02063 [physics.data-an].
 - [14] S. Vitale, D. Gerosa, W. M. Farr, and S. R. Taylor, Inferring the properties of a population of compact binaries in presence of selection effects 10.1007/978-981-15-4702-7_45 – 1(2020), *arXiv* : 2007.05579[astro – ph.IM].