PROCEEDINGS OF SCIENCE

Estimating the redshift dependence of the binary black hole population: combining gravitational-wave detections with limits on the stochastic background

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Utilising data from the direct detections of compact binary coalescences (CBCs) in the first three observing runs of the LIGO-Virgo-KAGRA Collaboration (LVK), we estimate the redshift dependence of the binary black hole (BBH) population. Specifically, we search for signs that the mass distribution of BBHs varies over cosmic history. The detection of such variation would allow us to gain more knowledge about the population itself, but also the formation channels of CBCs throughout the Universe. However, detectable CBCs primarily occur at low to moderate redshift, limiting our ability to constrain the high redshift behaviour of the quantities of interest. Nevertheless, current upper limits on the gravitational-wave background (GWB) from CBCs can be used as an additional source of information to uncover the high redshift behavior of the merger rate and the mass distribution. We implement this joint CBC and GWB analysis in a Bayesian framework, allowing us to construct posteriors for the parameters describing the population of CBCs and their evolution with redshift.

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1. Introduction

Until now, the LIGO-Virgo-KAGRA (LVK) Collaboration has observed $O(100)$ gravitational wave (GW) signals coming from mergers of massive binary objects, events referred to as compact binary coalescences (CBCs) [1]. This allows for studying the population of these objects [2–5]. However, due to the current sensitivities of gravitational-wave detectors, compact binary mergers are primarily observed at low to moderate redshift. Hence, we have little information about mergers happening at high redshift.

But, another source of gravitational waves can gather information at high redshift: the stochastic gravitational-wave background (SGWB). A SGWB is a superposition of unresolved GW signals, such as the mergers of many compact binaries occurring at high redshifts. Although no such background has yet been observed, the *upper limits* on the SGWB nevertheless offer information about the population of CBCs at large redshifts.

We can then combine the direct detections of CBCs together with the upper limits on the SGWB to combine our knowledge at low and moderate with high redshift and see how this influences the underlying population parameters of the CBCs [6]. Specifically in our analysis, we will explore possible redshift dependence of the CBC mass distribution by jointly analyzing CBC data and SGWB upper limits. First, we will discuss the method in Sec. 2. In Sec. 3, we discuss the current results of this ongoing analysis. At the end, in Sec. 4, we give a conclusion and look to the future of this work.

2. Method

We first explore our general model of the merger rate. The total merger rate accounts for the mass distributions of the component masses. We can then write the mass-redshift distribution

$$\frac{dR}{dV_c\, dm_1\, dm_2} = R_{\text{ref}} \frac{f(m_1)}{f(m_{\text{ref}})} \frac{g(z)}{g(z_{\text{ref}})} p(m_2), \tag{1}$$

where R_{ref} is the merger rate per unit volume per unit mass at $m_1 = m_{\text{ref}}$ and $z = z_{\text{ref}}$. The functions $f(m_1)$ and $g(z)$ encode how the merger rate changes with mass and redshift respectively. In particular, $g(z)$ follows a broken power-law shape with a peak redshift z_p and power-law indices α and β at redshift below and above z_p respectively. The function $f(m_1)$ is a mixture between a power-law, with power-law index κ, and a Gaussian peak. Lastly, p_{m_2} is the power-law distribution of the lightest component mass of a binary black hole merger. As a novel part of our analysis, we now let the distribution of the mass be redshift dependent in the inference. We allow the distribution to be variable in redshift. Formulaicly, this gives

$$\frac{dR}{dV_c\, dm_1\, dm_2} = R_{\text{ref}} \frac{f(m_1, z)}{f(m_{\text{ref}}, z_{\text{ref}})} \frac{g(z)}{g(z_{\text{ref}})} p(m_2), \tag{2}$$

where an extra redshift dependence has appeared in the mixture function $f(m_1, z)$. Any part of the power-law plus peak model $f(m_1, z)$ could be varied, e.g. the peak part could be made redshift dependent or the power-law part. For now, let's restrict ourselves to κ. We can then vary that index via $\kappa(z) = \kappa_0 + z * \frac{d\kappa}{dz}$, where in the inference $\frac{d\kappa}{dz}$ will be treated as a parameter next to κ_0. It is

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important to stress again that this variation can be turned on for any parameter, but we chose for this proceeding to focus on κ only. In the eventual paper, more parameters will be discussed.

To constrain the merger rate, we will use two sources as our input. We take N_{obs} direct CBC detections with data $\{d_i\}_{i=1}^{N_{obs}}$ [1] together with the upper limits on the SGWB from the third observing run of the LVK Collaboration [7].

2.1 Likelihood

To perform our analysis, we consider a joint likelihood split into two parts, one for direct detection CBCs and one for the stochastic search given by

$$p(\hat{C}(f), \{d_i\}|\Lambda, \mathcal{R}_{\rm ref}) = p_{\rm BBH}(\{d_i\}|\Lambda, \mathcal{R}_{\rm ref}) p_{\rm stoch}(\hat{C}(f)|\Lambda, \mathcal{R}_{\rm ref}), \quad (3)$$

where we have written upper limits as $\hat{C}(f)$. This likelihood tells us the possibility of detecting $N_{\rm obs}$ direct detections together with those O3 upper limits - or as we will see later the observed magnitude - of the GWB. For further details, see [2, 6].

3. Results and Discussion

Fig. 1a shows our posteriors on a subset of parameters, obtained when analyzing CBC and SGWB data from O3. First, we notice some interesting correlations between different parameters, such as α and the variation in redshift $d\kappa/dz$. We also find that adding upper limits of a SGWB gives not much additional information, perhaps a small difference of variation in redshift.

To extend our analysis and look to to the future, we can consider how these results might change as future detectors improve our sensitivity to the SGWB. Figure 1b illustrates posteriors obtained when analyzing data that contains a simulated observation of the SGWB with a future A+ Advanced LIGO instrument. Comparing to O3 results, we find that observing a background adds information about the variation in redshift, represented by $d\kappa/dz$. Probing higher values of z_p here is also possible, especially compared to the analysis with CBCs only.

4. Conclusion and outlook

Searching for a variation in redshift of the merger rate combining CBC data and upper limits on the SGWB is shown to be promising. Adding the background gives some little amount of additional information, even when not observing a background. Observing such a background in later observing runs could be a vital addition to find redshift dependent merger rates.

In a future paper, we will extend this search to varying other parameters as well. If such a variation is found, it could be due to changing formation channels of these massive binary objects which should be investigated further. Next to that, if the next observing runs give us enough binary neutron star events, we could also extend this analysis to those objects, not only BBHs.

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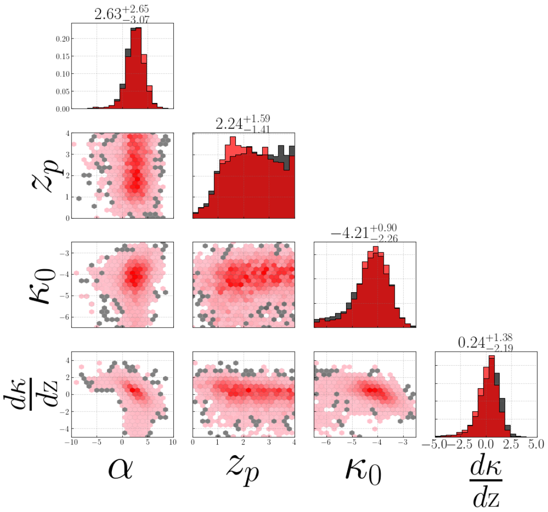
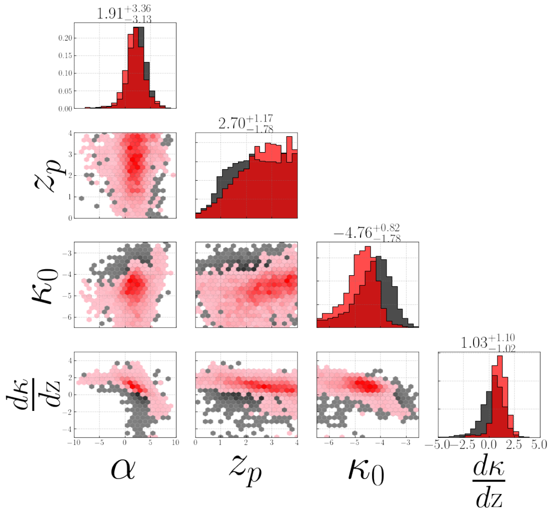


(a) Posteriors corresponding to the O3 run with no observed background.



(b) Posteriors corresponding to the O5 run with an observed background.

Figure 1: In red , we show results for CBC + GWB analysis, in black with CBC only analysis. The parameters shown in the cornerplot are $d\kappa/dz$, which shows the variation in redshift, the power-law index κ_0, the peak redshift of $g(z)$ and the first power-law index α of $g(z)$. The two-dimensional posteriors are shown from highest value red (black) to lowest value pink (gray) for CBC+GWB (CBC only) analysis.

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