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Inferring astrophysics and cosmology with individual compact binary coalescences and their gravitational-wave stochastic background

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Abstract. Gravitational wave (GW) observations from compact binary coalescences (CBCs) enable measurements of the Hubble constant H_0 and other cosmological parameters through the standard siren approach. While resolved binary black hole (BBH) mergers provide direct constraints on luminosity distance, redshift information can be inferred statistically using the redshifted masses. The stochastic gravitational-wave background (SGWB), produced by unresolved CBCs, can constrain additional population properties of the CBCs, thus potentially improving the measurement precision of the cosmic expansion parameters. We develop a hierarchical Bayesian framework to jointly analyze resolved GW events and the SGWB, applying it to LIGO-Virgo-Kagra simulated O5-designed sensitivity data and the real GWTC-3 catalog. We find that the resolved sources provide most of the H_0 precision, while the SGWB helps to exclude low H_0 and low dark matter energy fraction Ω_m values and constrains the peak of the merger rate at higher redshifts. For current detector sensitivities, the cosmological and population results are not impacted by the inclusion of the SGWB.

1 Introduction

Gravitational waves (GWs) from compact binary coalescences (CBCs) are powerful probes of cosmic expansion and current cosmological tensions [1]. Unlike electromagnetic (EM) observations, GWs directly encode information about luminosity distances without relying on a specific cosmological model, positioning them as "standard sirens" [2, 3]. Combined with redshift information, they constrain parameters such as the Hubble constant H_0. However, one of the primary challenges is the lack of redshift information in GW signals. Most often, detections involve dark sirens, such as binary black hole (BBH) mergers, with no EM counterparts. To address the lack of a redshift measure, the spectral siren approach estimates the redshift using the intrinsic relationship between the redshift and the masses in the detector and source frames [4, 5, 6, 7].

In addition to resolved sources, we expect to detect a stochastic gravitational-wave background (SGWB) from unresolved sources [8, 9]. The SGWB depends on the properties of the population and the underlying distribution of CBCs [10]. Studying the interplay between GW signals from CBCs and the SGWB offers an exciting opportunity to improve our understanding of fundamental cosmological and astrophysical parameters [11, 12, 13, 14, 15, 16]. By synthesizing LIGO-Virgo-Kagra (LVK) [17] data from individual CBC events with SGWB measurements, we analyze simulated data for future detectors and reanalyze real data from the third observing run (GWTC-3) [18]. Our goal is to determine to what extent the SGWB can improve constraints on cosmological and population-level parameters.

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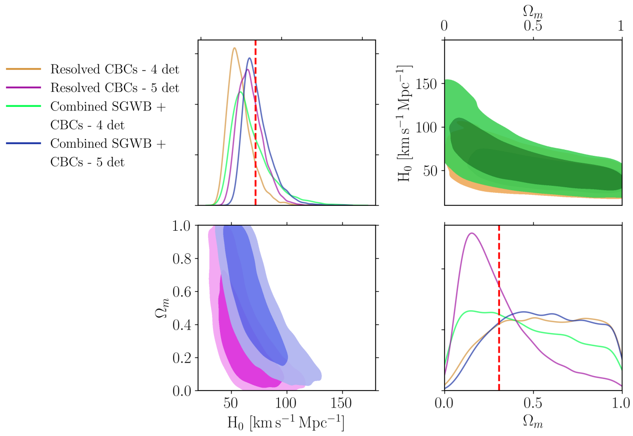

Figure 1: Posterior distributions of the cosmological parameters are shown for the resolved CBC dataset with four detectors (orange) and five detectors (purple), as well as for the combined dataset including both SGWB and CBCs with four detectors (green) and five detectors (blue). In the diagonal panels, the dashed red lines mark the injected (true) parameter values. Figure adapted from [16].

2 Analysis method and simulated data

We constructed a joint likelihood for both resolved CBC signals and SGWB as described in [11, 12] and used in our previous work [16]:

$$\mathcal{L}(\{x\}, \hat{C}|\Phi) = \mathcal{L}_{\rm CBC}(\{x\}|\Phi)\mathcal{L}_{\rm SGWB}(\hat{C}|\Phi), \tag{1}$$

where $\mathcal{L}_{\rm CBC}$ represents the likelihood associated with the detection of resolved sources, which follows an inhomogeneous Poisson distribution [19, 20]. The likelihood $\mathcal{L}_{\rm SGWB}$ denotes the stochastic likelihood modeled as a Gaussian process [8].

The SGWB energy density $\Omega_{\rm GW}$ modeled from the CBC population is given by [21]:

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_{\rm c}} \int_0^{+\infty} dz \, \frac{R(z)}{H(z)(1+z)} \left\langle \frac{dE_{\rm s}}{df_{\rm s}}\bigg|_{f(1+z)} \right\rangle . \tag{2}$$

Here $R(z)$ is the rate of events per unit of comoving volume and per unit of time at redshift z, and $H(z)$ is the Hubble parameter that under the assumption of ΛCDM is defined as $H(z) = H_0\sqrt{\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda}$ [22]. The final term describes the energy spectrum radiated by the CBC population, averaged over the source population at a given redshift. As recognized in [13], the SGWB scales as H_0^{-3}, this scaling arises from the comoving volume density term ($\propto H_0^{-3}$).

We simulated two observing scenarios using two years of O5-sensitivity data. In the first ("resolved CBCs"), both years target resolved sources; in the second ("combined SGWB and CBCs"), one year measures resolved events and the other the SGWB. Each was tested with a five-detector network (LIGO Livingston, Hanford, India, Virgo, KAGRA) and a four-detector setup excluding LIGO India [23, 24, 25, 26]. Unless noted, results refer to the five-detector configuration.

The CBC population is simulated by assuming a ΛCDM cosmology [22], a power law plus peak BBH mass model [27], and a Madau rate model [28], with detections modeled using a network of five or four detectors. Resolved sources were generated with simplified S/N calculations and posterior sampling, reproducing realistic parameter correlations [29, 30]. The SGWB was simulated through Gaussian cross-correlation measurements over 1 year of observation time, using the same detector networks and O5 sensitivities [31].

3 Results with simulated data

Using the simulated data sets from Sect. 2, as detailed in our previous work [16], we performed three analyses: resolved CBCs, SGWB-only, and their combination.

Figure 1 shows the corner plots for H_0 and $\Omega_{\rm m}$ in each analysis. For the five-detector network, CBCs alone yield $H_0 = 59.7^{+17.1}_{-13.4}$, while adding the SGWB gives $H_0 = 66.2^{+19.3}_{-12.1}$ km s^{-1} Mpc^{-1}, with no notable

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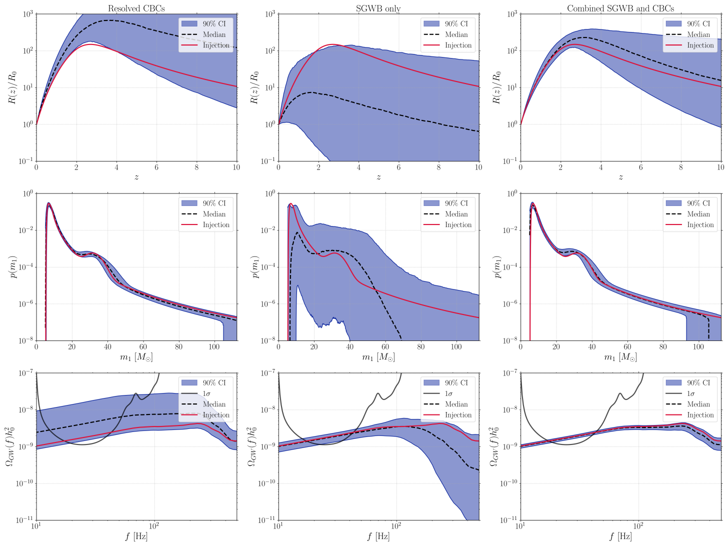

Figure 2: PPCs from the resolved CBC (left), SGWB-only (center), and joint (right) analyses. Blue lines show median and 90% credible intervals; red shows the injected model. Top: merger-rate evolution $R(z)/R_0$. Middle: primary BH mass distribution. Bottom: $\Omega_{\rm GW} h_0^2(f)$. The black line marks the 1σ upper limit defined in Eq. 8 of [16]. Figure adapted from [16]

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increase in precision. This means that most of the H_0 constraint comes from resolved spectral sirens, although the SGWB contribution helps rule out regions of low H_0 and low $\Omega_{\rm m}$. For a four-detector network, the posterior population is completely dominated by resolved sources, and the inclusion of SGWB cannot improve precision in any region of the H_0, Ω_m plane; this holds for the rest of the population parameters. Hence, we focus on the five-detector network for the rest of the paper.

In Fig. 2, we show posterior predictive checks (PPCs) for the reconstructed mass spectrum, binary black hole merger rate, and SGWB as a function of frequency. Using only resolved sources, the redshift distribution is well reconstructed at low z but becomes prior-dominated beyond z_p, since the high-redshift slope k and peak z_p of the merger rate are poorly constrained. With SGWB-only data, degeneracies among R_0, γ, and k further increase prior dependence, though some information on z_p remains. Combining resolved sources and the SGWB yields informative reconstructions up to $z \sim 2$–3, reducing prior dependence and agreeing with previous results [12]. Most mass-spectrum information arises from individual sources, while the SGWB energy-density improvement mainly reflects tighter constraints on γ and z_p from the combined CBC rate parameters.

When applied to O3 data (59 BBH detections), we find that the SGWB does not impact population or cosmological posteriors. This is because the predicted $\Omega_{\rm GW}$ remains below current detection thresholds, in agreement with previous findings that the contribution of SGWB at current LVK sensitivity is not detectable [10].

4 Conclusions

In this work, we have discussed how it is possible to include the SGWB in spectral siren analyses for GW cosmology and enhance our understanding of astrophysical populations and cosmological parameters. Although current sensitivity limits prevent SGWB measurements from meaningfully improving parameter estimation, this will change as detection thresholds decrease. The inclusion of SGWB helps exclude low H_0 and Ω_m values. Beyond cosmology, on an astrophysical population level, the integration of SGWB data slightly improves our understanding of the redshift evolution of CBC rates and helps with the measurements of γ and z_p. The SGWB sensitivity to unresolved sources at higher redshifts allows for tighter constraints on the merger rate distribution at high redshifts. In this exploratory study, we adopted several simplifying assumptions that can be refined in future work. As GW observatories achieve greater sensitivity, the joint use of resolved event analyses and stochastic background measurements will become increasingly important for advancing precision GW cosmology.

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