Inferring the variation in redshift of the binary black hole merger rate using multiple gravitational wave searches

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Goals & Motivation

Goals:

- **Combine direct detections** of binary black hole (BBH) mergers and **stochastic gravitational-wave background (SGWB) upper limits** from LIGO-Virgo-KAGRA.
- Investigate and estimate the **redshift evolution in the binary black hole mass distribution** using a Bayesian framework.
- Explore the effect of detecting the SGWB on constraining the BBH distribution, for example its effect on the power-law index κ of the BBH mass distribution.

Motivation:

- Improving our knowledge of the binary black hole mass distribution.
- Finding redshift variation of the mass distributions can point to a **changing mixture of binary black hole formation channels** across cosmic history.
- SGWB upper limits might provide additional information at high redshift compared to BBH mergers which are observed at low to moderate redshifts.

Methodology

We split the merger rate $\mathcal{R}(z)$ into three components, two representing the BH mass distributions and one the redshift distribution [3]: $\mathcal{R}(z) \sim p_{m_1} \cdot p_{m_2} \cdot p_z$

Power-law + Peak

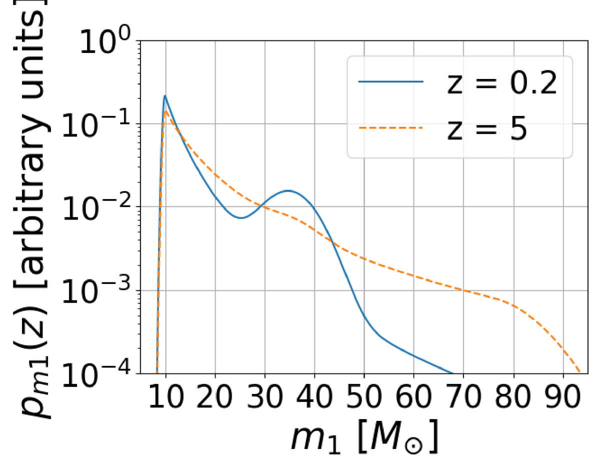

Fig. 3: Example of $p_{m_1}(\kappa(z))$ for fixed κ and $d\kappa/dz$

Power-law
In our analysis, this is a second order effect, given $m_1 > m_2$

Broken power-law

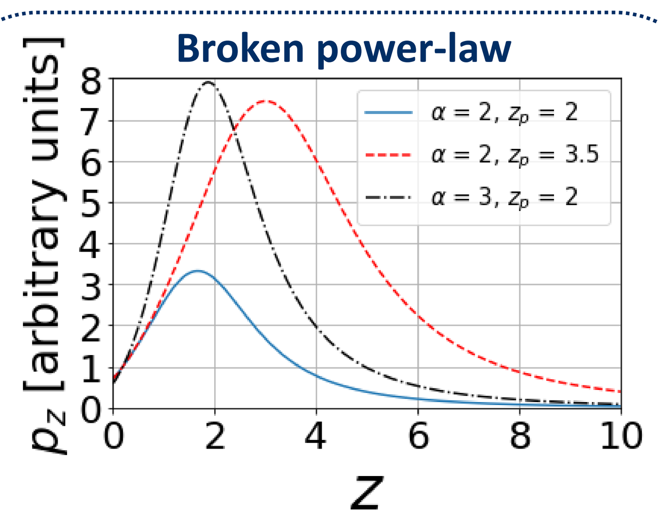

Fig. 4: Example for p_z using different values for parameters α and z_p with others fixed

Novelty: $p_{m_1}(\kappa_0) \to p_{m_1}(\kappa(z))$

We make the mass distribution redshift dependent by varying the power-law index:

$$\kappa(z) = \kappa_0 + z\mathrm{d}\kappa(z)/\mathrm{d}z$$

For Bayesian inference, we factorize the likelihood into two parts:

$$p(\hat{C}, \{d_i\}|\Lambda, \mathcal{R}_0) = p_{\mathrm{BBH}}(\{d_i\}|\Lambda, \mathcal{R}_0)p_{\mathrm{stoch}}(\hat{C}|\Lambda, \mathcal{R}_0)$$

- $\hat{C}$: GWB estimator
- $\{d_i\}$: BBH merger event data
- Λ: Hyperparameters: κ, $d\kappa/dz$ (See Fig. 3); α, z_p (See Fig. 4)
- $\mathcal{R}_0$: Reference merger rate

BBH: detections and SGWB upper limits

We use O(80) direct detections of BBH mergers [1], chirps, and combine them with the SGWB upper limits from the LIGO-Virgo-KAGRA collaboration's third observing run O3 [2].

The SGWB from BBH mergers is the combination of all detected and undetected BBH merger events. It is characterized by the energy density $\Omega_{GW}(f)$. Its shape and amplitude can be predicted using current direct detections from O1-3 as shown in Fig. 2.

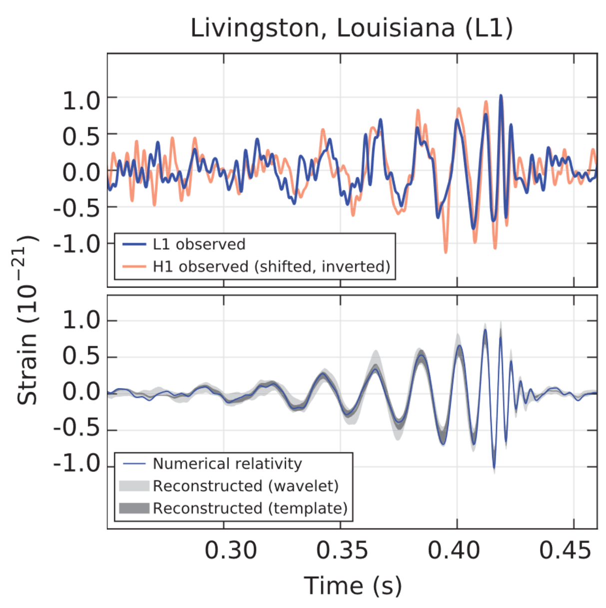

Fig. 1: Example of chirp detection
LIGO and Virgo Collaboration, Phys. Rev. Lett. 116, 061102

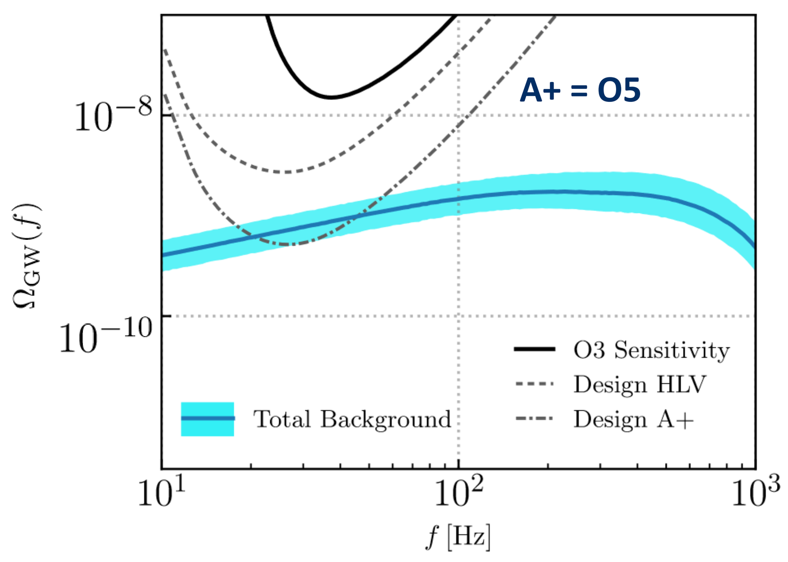

Fig. 2: Showing predicted total background of BBH mergers with O3 and O5 sensitivity
Phys. Rev. X 13, 011048

From now to the future

We compute the energy density of the background $\boldsymbol{\Omega_{GW}(f)}$ for all realized samples of O3. For each sample, we varied the hyperparameters of the model. These densities are shown on Fig. 5 where each sample is represented by a blue line.

The sensitivity curves of O3 and O5 [4] are represented by the red lines. One sample which can be detected in O5 is chosen and injected into our analysis.

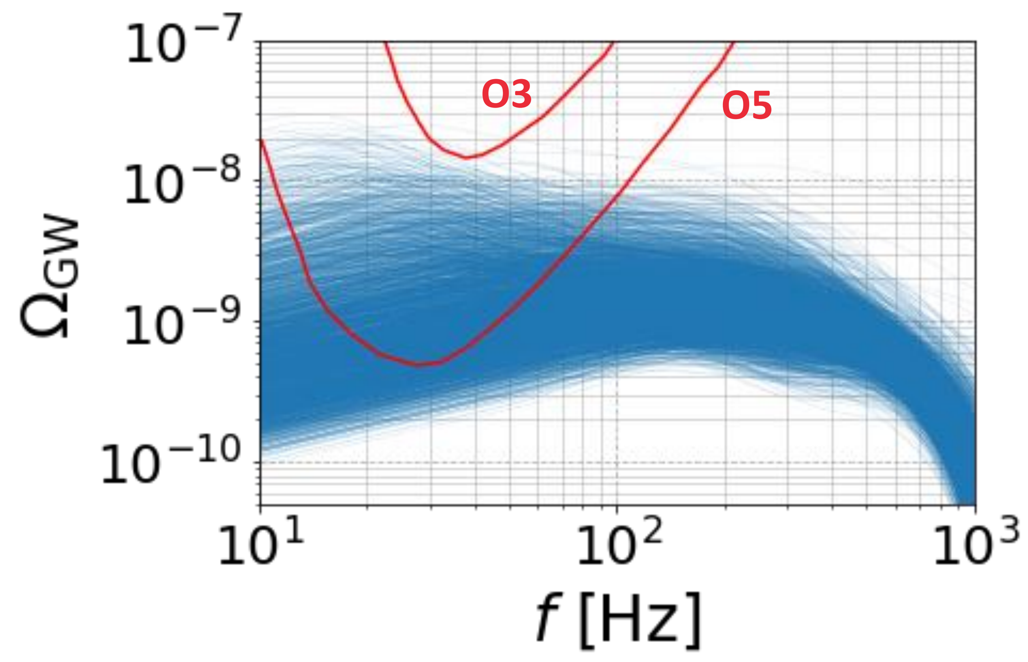

Fig. 5: The energy density of the background is computed for all samples in our analysis using the stochastic upper limits and direct BBH detections from O3.
Two red sensitivity curves for O3 and O5 are shown. Several blue lines are crossing O5 sensitivity, meaning these samples are detectable in O5 and can be used to inject into the analysis.

Results: Parameter Estimation and beyond

BBH only analysis (black) — BBH + GWB analysis (red)

O3

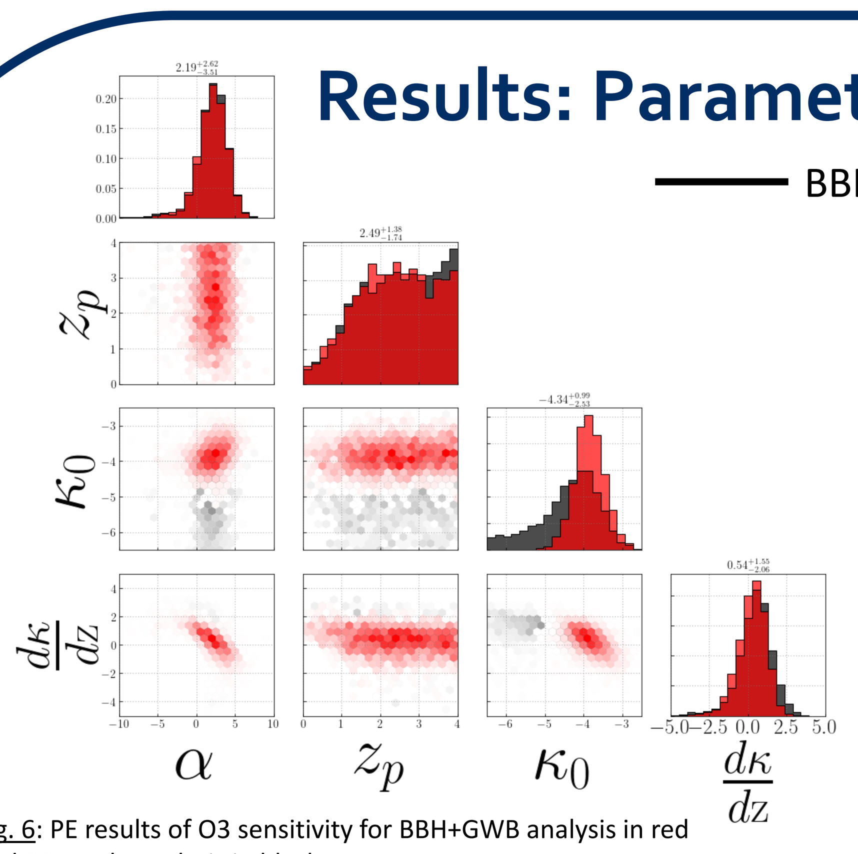

Fig. 6: PE results of O3 sensitivity for BBH+GWB analysis in red and BBH only analysis in black.

O5

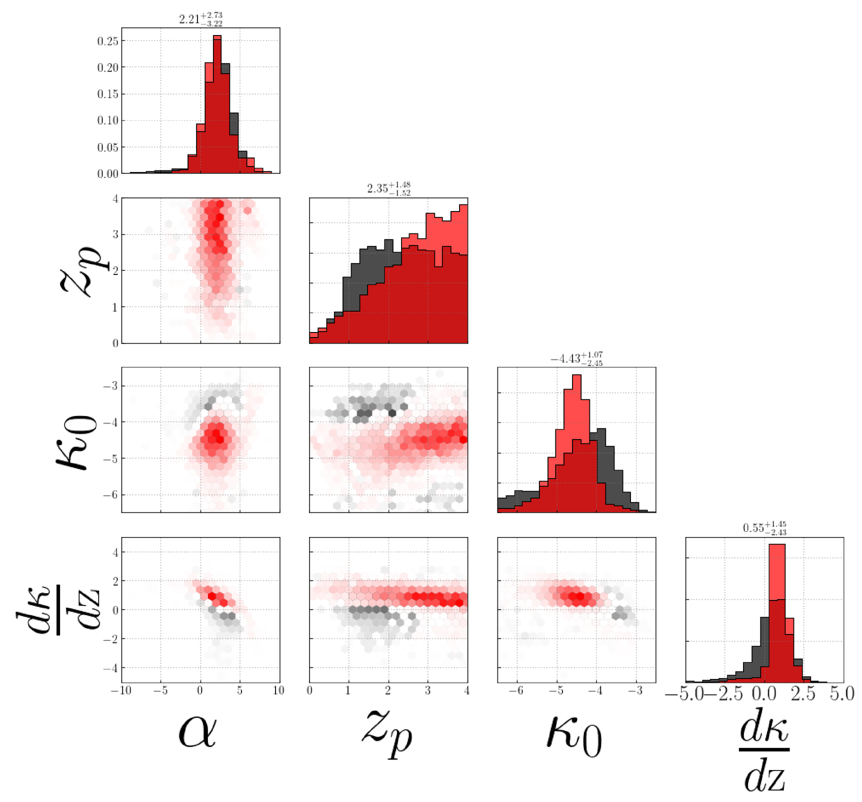

Fig. 7: PE results of O5 sensitivity with a detectable SGWB injected for BBH+GWB analysis in red and BBH only analysis in black.

One sample is taken and will serve as the representation of the detected SGWB in O5. We inject it our analysis, and perform parameter estimation (PE), see Fig. 6 for O3 and Fig. 7 for O5. Adding the SGWB in the analysis provides additional information.

We can also plot $\mathcal{R}(z)$ at a fixed m_1 to check how detecting the SGWB changes our distribution and to gain intuition.

$\boldsymbol{\mathcal{R}(z)}$ **at** $\boldsymbol{m_1 = 20\ M_\odot}$

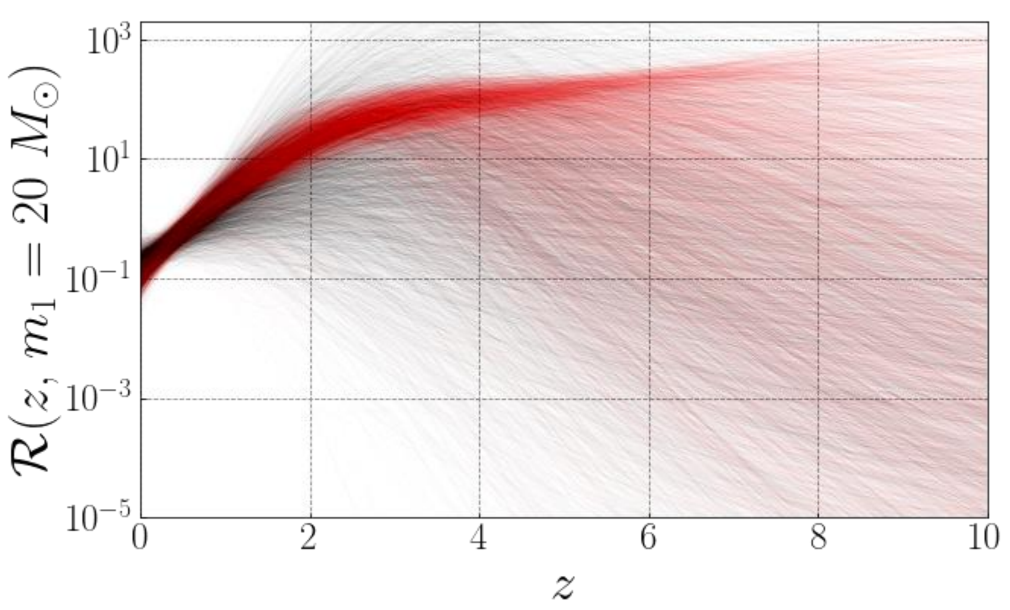

Fig. 8: The computed $\boldsymbol{\mathcal{R}(z)}$ at fixed $m_1 = 20\ M_\odot$ for all samples of the O5 analysis. Once in red for the analysis where the GWB is included and once in black where only the direct BBH detections are considered.

Conclusions and future work

We show that it is possible to **obtain information** about the **variation with redshift of the BBH mass distribution**, even when not observing the SGWB. A possible detection of the SGWB in O5 will give significant information about the variation with redshift and improve constraints on the hyperparameters in our model.

In future:

- **Varying different parameters**, investigating their evolution with redshift and how they might influence the merger rate evolution, e.g., varying peak redshift.
- Investigating the effect of constraints of variation with redshift on possible formation channel of BBHs.
- Extending the analysis to binary neutron star mergers.

Paper(s) in preparation: Lalleman et al., Turbang et al.

References

[1] Abbott R, et al. (2021) GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run. https://arxiv.org/abs/2111.03606
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