Spectral Analysis Using Bayesian Inference for Characterizing Remnant Outcomes in Binary Neutron Star Mergers

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I. INTRODUCTION

Neutron stars offer a unique window into understanding the extreme physics of stellar structures. They serve as the densest mediums that can be directly observed across the sky unlike black holes, which due to their immense gravity, harbour no observable matter, hindering direct investigation of their medium properties. Neutron stars come in binaries where measurements of their mass can be made precisely, offering crucial data for understanding their properties [1].

On August 17, 2017, the LIGO-Virgo collaboration observed a gravitational wave signal, GW170817, from the inspiral of two low-mass compact objects consistent with a binary neutron star (BNS) merger. This marked the first multimessenger detection of a gravitational wave signal accompanied by electromagnetic radiation, as numerous electromagnetic telescopes detected a short gammaray burst and a kilonova emanating from the remnant [2].

The GW170817 detection, while advancing our understanding of BNS mergers, did not possess sensitivities high enough to detect the ringdown phase of the postmerger, which is a characteristic ringing frequency in the spectra of the signal that encodes information about the newly formed remnant as it settles into a stable configuration. Thus, further analyses of this phase are required as they can provide key insights into the remnant's characteristics and the equation of state (EoS) of the highdensity matter.

Through [1], the outcomes of BNS mergers have been contrasted into three cases. A short-lived neutron star indicates a rapid collapse into a black hole with an immediate transition to frequencies associated with its formation. A long-lived neutron star exhibits characteristics that align with the sustained presence of a neutron star, and a delayed Collapse, which exhibits a combination of spectral features from both short-lived and longlived neutron stars, indicating a transitional phase towards eventual collapse that typically occurs 10-100 ms post-merger.

Based on Figure 1, the effective spectrum of BNS mergers demonstrated a dominant peak frequency that when changed over time can indicate the remnant's evolution. While the dominant peak is an oscillation mode, it is crucial to distinguish it from other potential contributors such as pressure modes and gravitational waves that are driven by different restoring forces [3]. The relationship between the peak frequency and secondary frequencies, as well as the features observed in the spectrum between them, can offer insights into the remnant's lifespan and its potential evolution towards black hole formation.

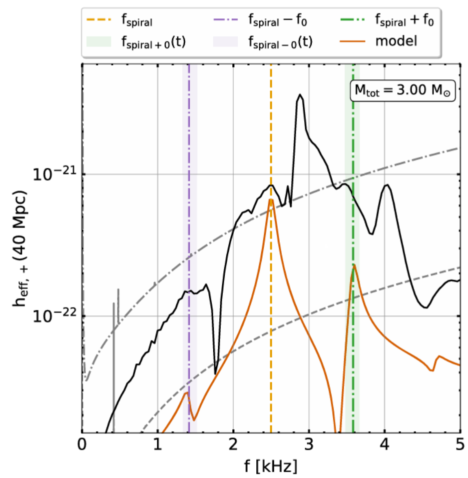

FIG. 1. Frequency modes of the effective spectrum

II. OBJECTIVES

This research project aims to develop a framework using Bayesian inference to distinguish and identify longlived neutron stars, short-lived neutron stars, and neutron stars undergoing delayed collapse into black holes. Furthermore, by analyzing the underlying physics of the ringdown phase, we aim to understand the physical distinctions between black hole and neutron star collapse signatures, the significance of spectral frequency "pumps", and the information encoded in the gap between them. This will ultimately allow us to refine current methods for distinguishing remnant types and the fates of BNS mergers based on the spectral features of the signals.

III. METHODS

The BNS postmerger gravitational wave signal detected by the interferometers of the LIGO-Virgo collaboration resembles an oscillator with multiple overlapping modes. Within the formed remnant, each mode represents distinct physical processes. Due to the inherent complexity of the postmerger signal, we will base our analysis on the morphology-agnostic data analysis algorithm BayesWave to analyze the frequencies and ampli-

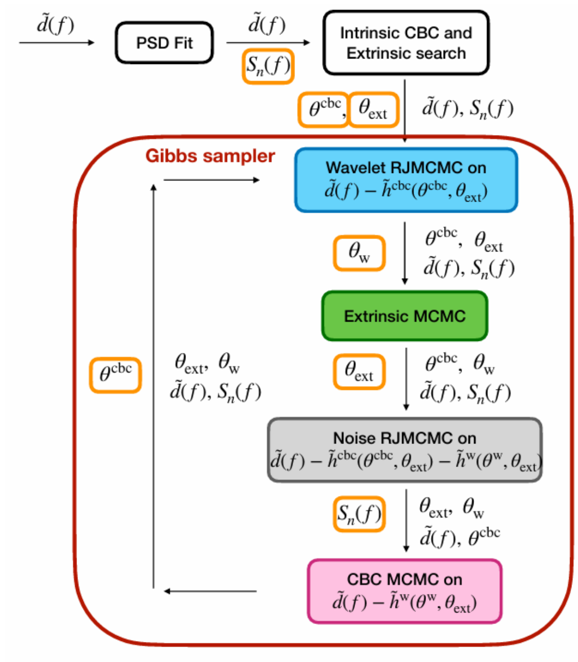

FIG. 2. General BayesWave code workflow

tudes of these modes. BayesWave is a data-driven algorithm where Sine-Gaussian wavelets for the postmerger phase can be employed for signal reconstruction, providing a more realistic assessment for reconstructing the postmerger signal from raw gravitational wave data [4].

In the frequency domain, the peak's width exhibits an inverse relationship with the corresponding mode's duration. Therefore, short-lived modes have broad peaks, potentially leading to challenges in our upcoming analysis for their identification and separation from other components within the spectrum.

Since BNS mergers are rare events presenting consequent limitations in observational data, Bayesian statistics offer a powerful approach to address this limitation. Unlike traditional frequentist methods, Bayesian inference allows us to incorporate prior knowledge about the system. The mathematical framework for this purpose is stated in the Bayes' theorem. It enables us to quantify the targeted probability, which is defined as

$$P(\theta|D) = \frac{P(D|\theta) \cdot P(\theta)}{P(D)} \quad (1)$$

where $P(\theta|D)$ is the probability of obtaining certain signal parameters such as frequencies and amplitudes of the overlapping modes (θ), and the observed gravitational wave data (D). By applying Bayes' theorem, we can transform this quantity into a computable form.

Figure 2 visually represents the Bayesian inference workflow implemented in BayesWave, showcasing the way that the algorithm iteratively updates parameters that are related to wavelet modelling, extrinsic parameters, noise modelling, and Compact Binary Coalescence (CBC), also referred to as BNS merger parameters. Therefore, implementing Sine-Gaussian wavelets through BayesWave for signal reconstruction offers a refined opportunity to delve deeper into the complexities of the postmerger phase, enabling a better understanding of the physical processes governing the neutron star remnants of BNS mergers.

IV. PROJECT SCHEDULE

By the start of the program, 2-3 weeks will be focused on building a strong foundation in the relevant software tools and concepts. Then, 3-4 weeks will be dedicated to core research activities of running the BayesWave algorithm and interpreting results for classifying remnants of BNS mergers. For the finalization stage, 2-3 weeks will be spent drawing conclusions based on the analysis and interpretation, alongside preparing a final presentation summarizing the research methodology, key findings, and their implications.

V. CONCLUSION

Ultimately, this project will contribute to a more comprehensive picture of the outcomes of BNS mergers. By leveraging Bayesian inference and the BayesWave algorithm, we aim to achieve a more robust classification of remnant types. This will be achieved by analyzing the ringdown phase of the gravitational wave signal, focusing on the peak frequency, secondary frequencies, and the spectral gap between them. Furthermore, our findings are expected to shed light on the underlying physics differentiating black hole and neutron star collapse signatures.

[1] Alexander Bauswein, Oliver Dreyer, Hans-Thomas Janka, and Georg G Raffelt. Equation of state effects on the gravitational-wave signal from neutron star mergers. *Physical Review Letters*, 108(16):161101, 2012.

[2] B.P. Abbott, R. Abbott, T.D. Abbott, F. Acernese, K. Ackley, C. Adams, A. Adams, S. Ain, M. Ajello, and

G. Allen. Gw170817: Observation of gravitational waves from a binary neutron star merger. *Physical Review Letters*, 119(16):161101, 2017.

[3] Theodoros Soultanis, Andreas Bauswein, and Nikolaos Stergioulas. Analytic models of the spectral properties of gravitational waves from neutron star merger remnants. *Physical Review D*, 105(4):043020, 2022.

[4] Marcella Wijngaarden, Katerina Chatziioannou, Andreas Bauswein, James A Clark, and Neil J Cornish. Probing neutron stars with the full premerger and postmerger gravitational wave signal from binary coalescences. *Physical Review D*, 105(10):104019, 2022.