Spectral Analysis Using BayesWave for Characterizing Remnant Outcomes in Binary Neutron Star Mergers
First Interim Report

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I. MOTIVATIONS

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 gamma-ray 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 post-merger, 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 high-density 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 long-lived 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 spectrum is dominated by a linear feature f_2 or f_{peak} (quadrupolar oscillations), a quasi-radial symmetric oscillation f_0, a quasi-linear feature of f_{2+0} and f_{2-0} (a coupling between quadrupolar and quasi-radial oscillations) and a fully nonlinear feature for the inspiral $f_{inspiral}$ (a transient spiral deformation). This leads to a classification scheme of the postmerger gravitational wave emission depending on the EoS and binary mass [4]. 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.

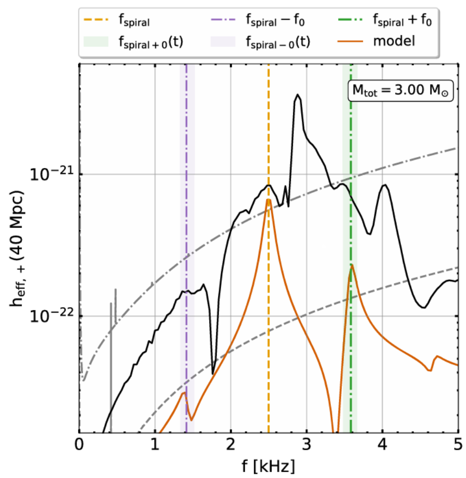

FIG. 1. Frequency modes of the effective spectrum

II. PROJECT

This research project aims to develop a framework using Bayesian inference to distinguish and identify long-lived 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, this project aims to understand the physical distinctions between black hole and neutron star collapse signatures, the significance of spectral frequency "bumps", and the information encoded in the gap between them. This will ultimately allow the refining of current methods for distinguishing remnant types and the fates of BNS mergers based on the spectral features of the signals.

Due to the inherent complexity of the postmerger

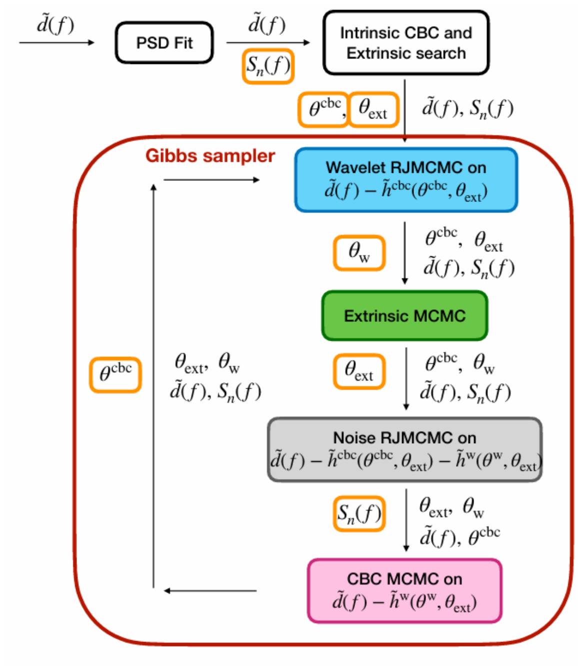

FIG. 2. General BayesWave code workflow

signal, the analysis will be based on the morphology-agnostic data analysis algorithm BayesWave to analyze the frequencies and amplitudes 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 [5].

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 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

$$P(h|d) = \frac{P(d|h) \cdot P(h)}{P(d)} \tag{1}$$

where $P(d|h)$ is the probability of obtaining certain signal parameters such as frequencies and amplitudes of the overlapping modes (h), and the observed gravitational wave data (d). By applying Bayes' theorem, this quantity can be transformed into a computable form.

Figure 2 visually represents the Bayesian inference

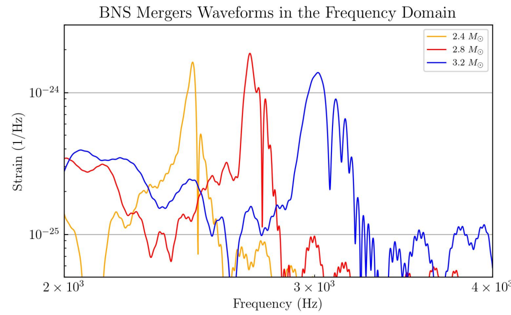

FIG. 3. The plot presents a comparative analysis between three different waveforms for the DD2 EoS across varying total mass values.

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 post-merger phase, enabling a better understanding of the physical processes governing the neutron star remnants of BNS mergers.

III. CURRENT PROGRESS

Thus far I have familiarized myself with the BayesWave software and accessed the LIGO computing cluster. This included performing test runs and injecting simulated gravitational wave signals into the software. In parallel, I developed experience plotting gravitational wave strain data in both the time domain (representing the direct measurement) and the frequency domain (revealing the constituent frequencies). Furthermore, I implemented the computational conversion between these domains through the Fourier transform.

I plotted waveforms generated for the DD2 EoS presented in [5]. Due to its stiffness, the DD2 EoS predicts a higher pressure for a given density of neutron star matter compared to softer EoS models. As can be seen in Figure 3, studying these waveforms in the frequency domain proves particularly useful. Here, the characteristic features of the signal become more apparent, allowing for a more coherent interpretation of the data. From this, the evolution of a specific pattern with increasing mass can be traced by following its behaviour at higher frequencies.

Notably, the waveforms varied in their total mass parameter while maintaining a constant mass ratio and EoS. This allows investigations of the critical region where the post-merger phase transitions into ringdown (signaling the collapse into a black hole), typically occurring at higher total mass values.

I have conducted a series of post-merger phase

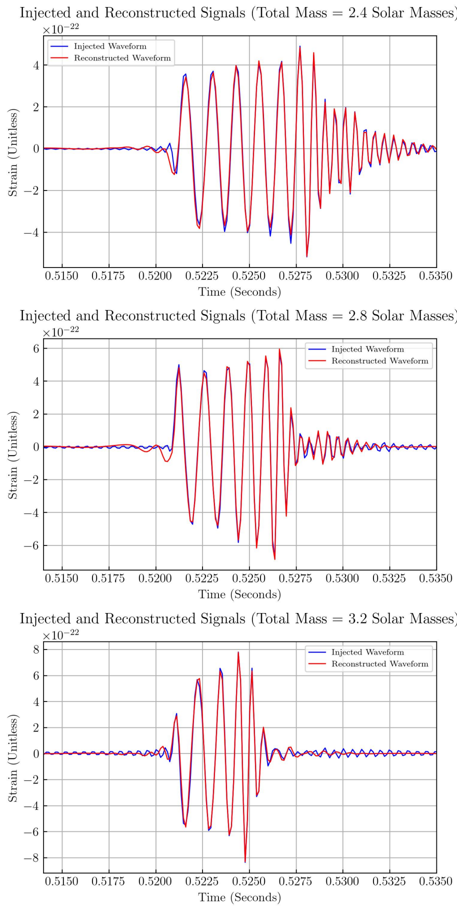

FIG. 4. The plots present a comparative analysis between the injected and reconstructed waveforms through BayesWave for the DD2 EoS across varying total mass values. The plots show the consistency and discrepancy between the signals.

simulation injections to investigate the capabilities of BayesWave for reconstructing post-merger signals from BNS mergers. The injections were designed to incorporate realistic noise characteristics expected in the next-generation Cosmic Explorer observatory which will have longer detector arms (40 km compared to LIGO's 4 km), offering enhanced sensitivity and the potential to detect BNS post-merger events with greater detail.

As illustrated in Figure 4, three different plots show the injections of simulated BNS merger waveforms for the DD2 EoS into BayesWave. The process involved generating data from the provided gravitational wave frame files through BayesWave and running the software to reconstruct the injected signal.

From an initial analysis of the plots, a trend is evident where the amplitude of the post-merger oscillation damps out more rapidly for signals with higher total mass. This observation suggests a faster transition to the ringdown phase, indicative of a more prompt collapse to a black hole in the simulations with higher total mass compared to those with lower total mass. This aligns with theoretical expectations for BNS mergers.

Furthermore, it can be understood that Bayeswave is performing an efficient job in reconstructing the injected signals for the Cosmic Explorer sensitivity. This suggests that the software holds promise for analyzing data from future, next-generation gravitational wave detectors.

IV. CHALLENGES AND FUTURE PROSPECTS

Expanding the scope of the current analysis presents an opportunity to gain deeper insights into the capabilities of BayesWave for reconstructing BNS post-merger signals. While the initial investigation focused on the DD2 EoS which is a stiffer model. I will extend the analysis to encompass a wider EoS landscape incorporating softer EoSs.

Since BayesWave utilizes Markov chain Monte Carlo (MCMC) to sample from a probability distribution, guaranteeing convergence to the target distribution is crucial. Specifically verifying that the outcome of the MCMC runs aligns with a Gaussian distribution that accurately reflects the Cosmic Explorer's PSD to ensure consistency with the expected noise characteristics of the detector.

Moreover, I will generate plots of the reconstructed signals in the frequency domain which is expected to provide valuable insights into the post-merger dynamics. Where frequency oscillation modes present during this phase can be extracted in greater detail.

A challenge lies in interpreting the origin and the physical processes governing the high-frequencies of the waveforms, specifically beyond the well-understood peak frequency and potential secondary peaks. It is anticipated that the characteristics of this high-frequency bump will likely exhibit a dependence on both the total mass of the binary system and the adopted EoS.

V. ACKNOWLEDGEMENT

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