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

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(Dated: August 2024)

Neutron stars provide critical insights into the extreme physics of stellar structures. The detection of GW170817 initiated multimessenger astronomy by revealing both gravitational and electromagnetic signals. However, the sensitivities of current gravitational wave detectors limit the detection of the postmerger, which contains crucial information about the remnant's characteristics and the equation of state (EoS) of the neutron star's dense matter. This research project addresses this gap by analyzing postmerger frequency modes and their implications for different EoS by using simulated waveforms from numerical relativity. Employing BayesWave with Sine-Gaussian wavelets, gravitational wave signals are reconstructed to the sensitivity level of future detectors, such as Cosmic Explorer. Results show that BayesWave is effectively reconstructing the signals and is capturing peak and secondary frequency modes. This motivates further understanding of remnant evolution and the transition from a neutron star remnant to a ringdown indicating the formation of a black hole remnant. By exploring these modes across various simulations with varying total mass, including short-lived and long-lived neutron stars and simulations undergoing delayed collapse, this study aims to deepen our understanding of binary neutron star mergers.

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 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 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.

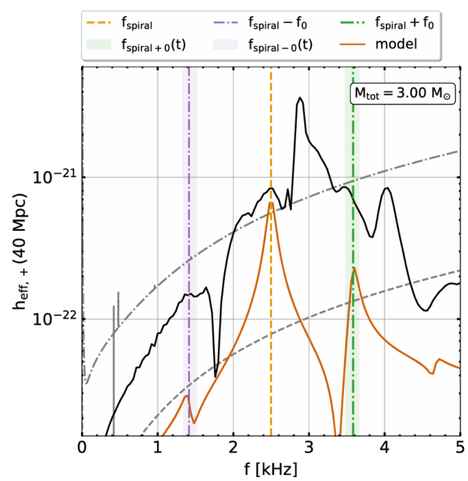

FIG. 1. Frequency modes of the effective spectrum

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.

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 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 workflow implemented in BayesWave, showcasing the way that the algorithm iteratively updates parameters

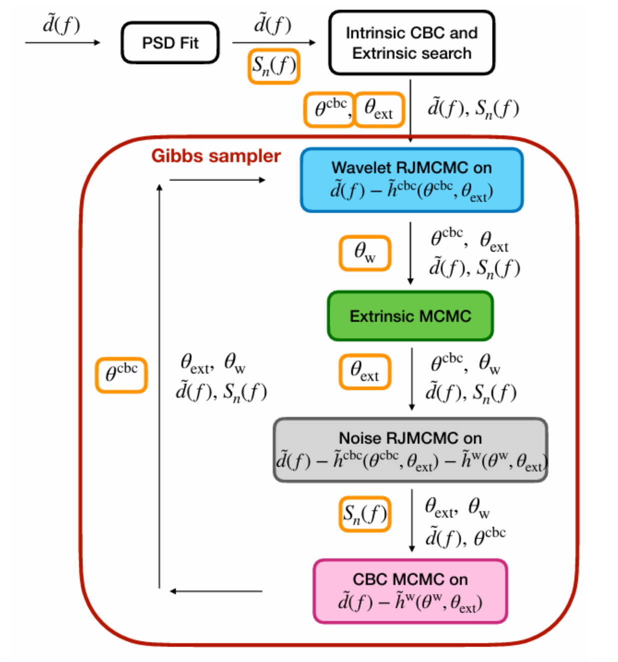

FIG. 2. General BayesWave code workflow

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 done further injections into BayesWave to get the signal reconstructions at the Cosmic Explorer sensitivity level. All of the simulations injected were inferred by numerical relativity (NR).

A. Exponentially Decaying Sinusoids Analytic Model

I started with the DD2 EoS, which is a stiff EoS that predicts higher outward pressure for a given density of the dense matter in neutron stars. The simulations of this particular equation all show a delayed collapse behaviour where no prompt collapses occur in the simulation time. Therefore, a good analytic model for demonstrating such behaviour is the exponentially decaying sinusoids model where the peak frequency f_{peak} is changing while assuming all other frequencies of the model to be constant in

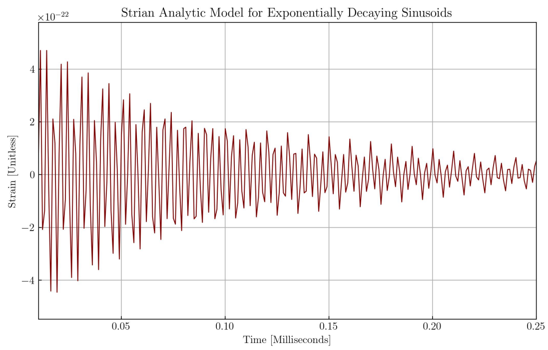

FIG. 3. An analytic model for exponentially decaying sinusoids that is well fit for demonstrating EoSs with a delayed collapse such as DD2

time, the model is as follows

$$
\begin{aligned}
h_+(t) = {} & A_{\text{peak}} \cdot e^{\left(-\frac{t}{\tau_{\text{peak}}}\right)} \cdot \sin(\phi_{\text{peak}}(t)) \\
& + A_{\text{spiral}} \cdot e^{\left(-\frac{t}{\tau_{\text{spiral}}}\right)} \cdot \sin\left(2\pi f_{\text{spiral}} \cdot t + \phi_{\text{spiral}}\right) \\
& + A_{2-0} \cdot e^{\left(-\frac{t}{\tau_{2-0}}\right)} \cdot \sin\left(2\pi f_{2-0} \cdot t + \phi_{2-0}\right) \\
& + A_{2+0} \cdot e^{\left(-\frac{t}{\tau_{2+0}}\right)} \cdot \sin\left(2\pi f_{2+0} \cdot t + \phi_{2+0}\right)
\end{aligned} \tag{2}
$$

where the f_{peak} component's phase $\phi_{\text{peak}}(t)$ is

$$
\phi_{\text{peak}}(t) = \begin{cases} 2\pi\left(f_{\text{peak},0} + \frac{\zeta_{\text{drift}}}{2}t\right)t + \phi_{\text{peak}}, & \text{for } t \le t_* \\ 2\pi f_{\text{peak}}(t_*)(t - t_*) + \phi_{\text{peak}}(t_*). & \text{for } t > t_* \end{cases} \tag{3}
$$

where ζ_{drift} is the rate at which f_{peak} of the gravitational wave signal changes as the remnant evolves, and t_* is the time at which the change of f_{peak} becomes constant. Based on the previous analytic model, Figure 3 has been generated to show the change in the strain as a function of time showcasing the spectra of a neutron star remnant, where $t_* = 0.2$ ms, $\zeta_{\text{drift}} = 0.5$ for a positively increasing rate of change of f_{peak}, and the $\phi_{\text{peak}}(t)$ is assumed to be equal to zero for the sake of simplification.

B. Windowing the Premerger

Studying postmerger waveforms in the frequency domain allows for the characteristic features of the signal such as the peak and secondary frequency modes to become more apparent. This permits a more coherent interpretation of the data. When signals get converted from the time domain to the frequency domain through the Fourier transform, an appropriate windowing function has to be employed. Here, employing a windowing function that removes the premerger contribution in the

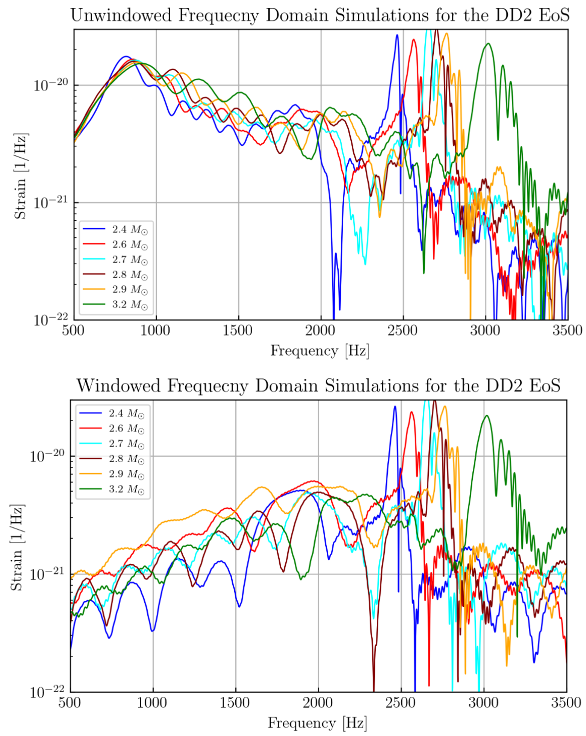

FIG. 4. The effect of a windowing function that terminates the premerger contribution in simulated signals of varying total mass for the DD2 EoS.

signal is crucial. Thus the characteristics and the evolution of the frequency modes would solely be present and more true for the postmerger part of the simulated signal as shown in Figure 4.

So far, multiple things can be understood about the peak and secondary frequency modes by looking at the varying behaviour of the modes as the mass increases for the DD2 EoS simulations. The first is that the higher the total mass, the harder it becomes to identify f_{peak} as other secondary frequency modes become more excited. Second, since all of the DD2 runs showcase a delayed collapse, the decay time of the secondary modes takes approximately 5-6 milliseconds.

C. Signal Reconstructions Using BayesWave

I have conducted a series of post-merger phase simulation injections to investigate the capabilities of BayesWave for reconstructing post-merger signals from BNS mergers. The injections were designed to incorporate a prior of 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. Moreover, other priors were fed into BayesWave which included an event distance of 40 Mpc and a maxi-

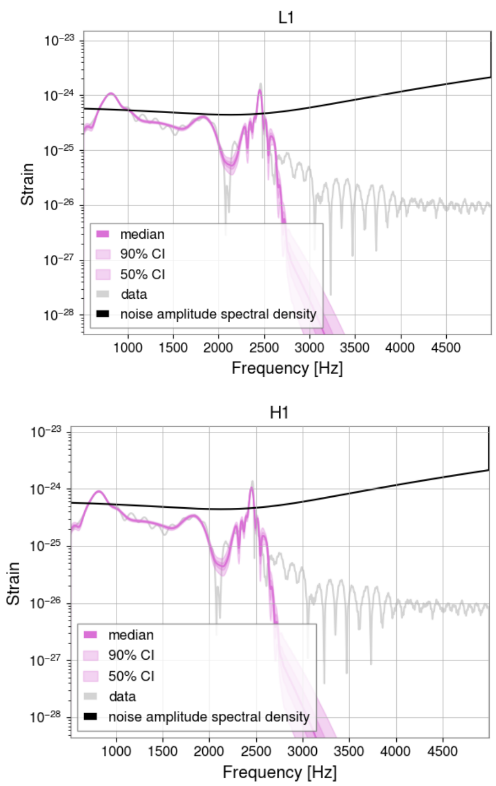

FIG. 5. The signal injections and reconstructions for the DD2 EoS, a delayed collapse simulation with a total mass of 2.4 $M_{\odot}$.

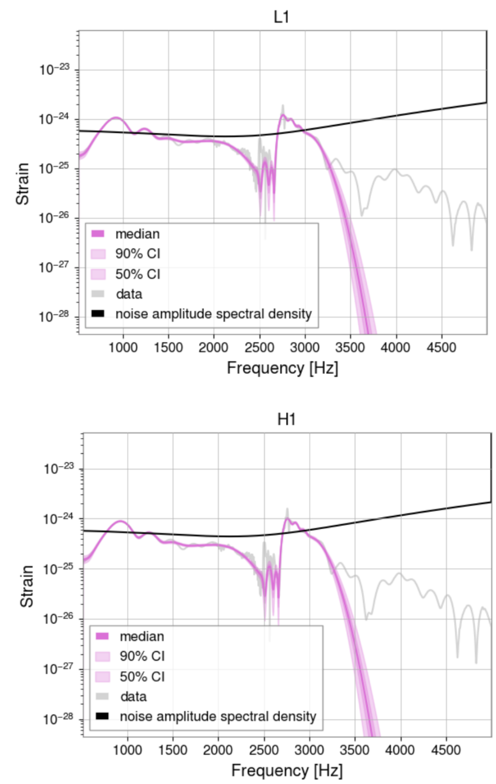

FIG. 6. The signal injections and reconstructions for the MPA1 EoS, a simulation reaching prompt collapse with a total mass of 2.8 $M_{\odot}$.

mum frequency of 4000 Hz. For the likelihood, it depends on the physics of the event and the detector.

To reconstruct signals, first BayesWave has to create the data for the injected signal. Then, run BayesWave main where Markov chain Monte Carlo (MCMC) sampling is running to construct the posterior which represents the reconstructed signal. BayesWave post is then executed to generate plots for the injections in comparison with the reconstructions. I conducted reconstructions for multiple EoSs that include DD2, MPA1, and other varying EoSs that have a constant mass.

For the DD2 and MPA1 runs, to achieve a systematic approach of comparing the outcomes of the runs, the mass ratio was constant, while varying the total mass as it is the variable that states whether a particular configuration will collapse into a black hole or not. The DD2 and the MPA1 EoS reconstructions in the frequency domain are shown in Figures 5 and 6, where it can be seen 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 MPA1 simulations. Although it is a stiffer EoS, in comparison to DD2, it has a prompt collapse transition into a black hole ringdown right after a total mass value of 3.14 $M_{\odot}$, as shown in Figure 7. For total masses higher than that, an analytic model for exponentially decaying sinusoids would no longer be a fit, therefore, I will be looking closely at the ringing modes of black hole remnants from the MPA1 simulations to identify a better model for the evolution of the strain. Moreover, build an understanding on the occurrence of such transitions at a specific configuration.

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.

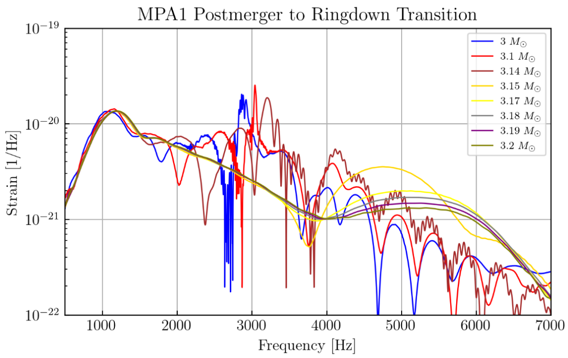

FIG. 7. Simulations of the windowed MPA1 EoS showcasing a transition of postmerger to black hole ringdown as the total mass increases.

V. ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my mentors, Isaac Legred and Katerina Chatziioannou, for their invaluable guidance and support throughout this project.

This work was supported by the National Science Foundation Research Experience for Undergraduates (NSF REU) program, the LIGO Laboratory Summer Undergraduate Research Fellowship program (NSF LIGO), and the California Institute of Technology Student-Faculty Programs.

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