Optimal Settings for Fast Low-Latency Skymaps of Neutron Star Binaries
First Interim Report

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The detection of gravitational waves is instrumental to our understanding of astrophysical processes and the fate and evolution of the sources of such waves. One source of gravitational waves is compact binary coalescences (CBC)–binary systems which consist of black holes, neutron stars, or both. Specifically for this project, we will be focusing on neutron star binary systems and how to optimize data intake to improve localization of such systems. Longer signal durations increase typical computing effects but maximize information we can extract from the signals. For analyses where prompt results are essential, such as for multimessenger followup, we aim to study the ideal conditions for accurate analysis.

I. MOTIVATIONS

Since its inception, the Advanced LIGO and Advanced Virgo detectors have discovered a plethora of gravitational waves. Their first gravitational wave transient catalog includes ten binary black hole coalescences and one binary neutron star coalescence. Additionally, an updated second gravitational wave catalog from a third observing period has yielded dozens more events, with signals encompassing even more compact binary coalescences [1].

The binary neutron star merger was detected through GW170817 [2]; the first signal from this low-mass, compact binary inspiral was detected August 17, 2017, and was inferred by astronomers to be located in the NGC 4993 galaxy. Gravitational waves from binary neutron stars exhibit a chirplike time evolution which depends both on the system's component masses, or chirp mass, and its mass ratio and spins. Also unique to neutron star systems is the influence of their internal structure on its waveform; such properties can be inferred from tidal interactions.

The localization of GW170817 to the NGC 4993 galaxy was aided by the skymap that was computed from gravitational wave data. Once the skymap was constructed, astronomers were able to follow up on this data and were able to localize the source within a few hours after initial detection. Figure 1 demonstrates the improved localization of GW170817 from gravitational wave data alone due to improved calibration of Virgo data. Assuming the previously deduced location in NGC 4993, the 90% localization region was reduced from 28 deg^2 to 16 deg^2.

Aiding in this endeavor of gravitational wave detection is BILBY [3], a Bayesian inference library which infers source properties from individual signals of compact binary coalescences. To date, BILBY has produced reliable results for both simulated and real gravitational wave data from compact binary mergers and coalescences. Using these source properties, in upcoming observing runs BILBY will be used to compute skymaps which will then be utilized by astronomers to localize the gravitational wave signal sources, such as in the case of GW170817.

Gravitational wave data allows for localization of the source signal itself, upon which astronomers may then search to identify the exact location of the CBC event. Ideally, this continuous process of intaking gravitational wave data and computing the subsequent skymap should occur in as minimal a timeframe as possible, since an electromagnetic signal from the CBC event could fade rapidly within the span of a few hours or even minutes. The runtime will vary depending on which parameters are sampled but ideally should last from a few minutes up to half an hour.

Ultimately, many inferred source parameters through gravitational wave data of merging binary neutron will be further improved by and electromagnetic detection and identification of the host galaxy. These include specific properties of the binary system itself, such as its mass, spin, and tidal parameters, which may also better equip our general understanding of binary, stellar evolution. Improved localization may also better our understanding of short gamma-ray burst properties and, on a grander scale, the equation of state of neutron-star matter, the nature of gravity, the value of the cosmological constant, and even allow us to test theories of general relativity.

II. PROJECT

We are relying on Bayesian inference for this project. We begin with a posterior probability distribution which is calculated using Bayes' Theorem:

$$p(\theta|d) = \frac{\mathcal{L}(d|\theta)\pi(\theta)}{\mathcal{Z}} \tag{1}$$

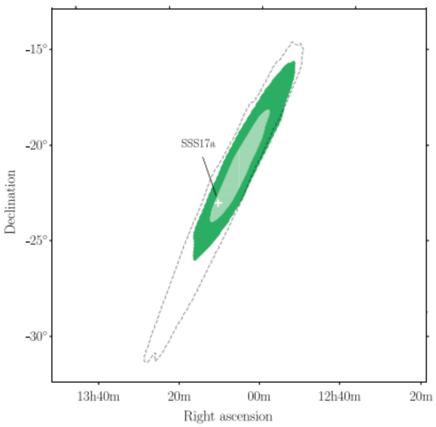

Figure 1. The improved localization of GW170817, with the dotted gray line indicating previous localization of 90% credibility from 2017 and lighter and darker green regions corresponding to increased region credibility of 50% and 90%, respectively, in 2019.

Here θ represents the source parameters, $\mathcal{L}(d|\theta)$ is the likelihood function, or probability of the detectors measuring data d assuming a model hypothesis, $\pi(\theta)$ is the prior distribution, which incorporates any prior knowledge about our parameters, and $\mathcal{Z}$ is the normalization factor, or evidence, which is defined as:

$$\mathcal{Z} = \int \mathcal{L}(d|\theta)\pi(\theta)d\theta \tag{2}$$

This evidence indicates how well the data is modeled by the hypothesis, which is vital for model selection. In this case, the posterior probability distributions are calculated by BILBY, and we apply restricted analysis by focusing on restricted parameters and/or timeframes in order to narrow down the posterior distribution area. Ultimately the parameters that we will primarily be interested in are the sky location and the distance to the source.

For every signal analysis, there exists a trade-off between accuracy and computational efficiency. A typical signal may last for a span of around two minutes with a frequency ranging from 20 Hz to 2000 Hz. Conversely, the duration to compute the associated skymaps may range from a few hours to even months, depending on various factors including models and tools for analyses. This proves problematic when we consider that the electromagnetic signal from the CBC event may last only up to a few hours at most and a skymap must be computed and distributed for astronomical follow-up as soon as possible. As such, we will explore how settings such as time duration and sampling rate may be optimized in order to achieve reliable sky localization in a minimal timeframe. We will also explore whether spin may be completely ignored in our calculations and at which frequencies tidal parameters may be measured. We aim to analyze both binary neutron star injections and real data from GW170817.

III. PROGRESS

Thus far I have familiarized myself with gravitational wave strain data and their various adaptations, including amplitude and power spectral densities and spectrograms. As shown in Figure 2, a spectrogram can show the track of a binary black hole or neutron star merger on a time-frequency plane. Different times and corresponding frequencies along the track allow us to infer various source parameters, with more basic parameters such as mass at lower frequencies and complex parameters such as tides at higher frequencies. I am also learning how to utilize BILBY to perform simple parameter estimations on compact binary mergers by varying basic parameters such as the masses, phase, time, and distance while using delta functions, or keeping the remaining parameters fixed. I was able to generate both one-dimensional and two-dimensional posterior distributions, such as that shown in Figure 3.

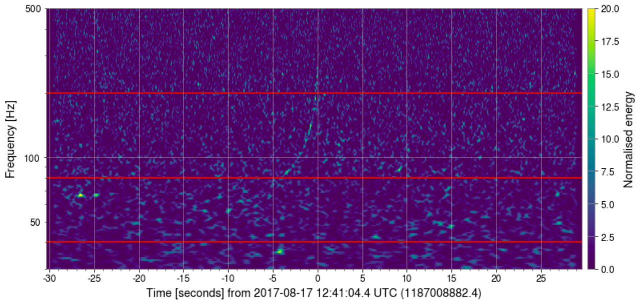

Figure 2. Spectrogram of GW170817 from the LIGO Hanford detector with the merger placed at the 0 second time mark. Horizontal lines denote frequencies of 40, 80, and 200 Hz, respectively, which correspond to various times that different parameters may be inferred.

At the moment I am experimenting with a binary black hole injection, which provides simulated data in order to calculate the posterior distributions given fifteen extrinsic and intrinsic parameters. This injection serves as a precursor to working with binary neutron star injections since there are less parameters to vary, as well as a smaller time duration and sampling rate which results in a shorter runtime.

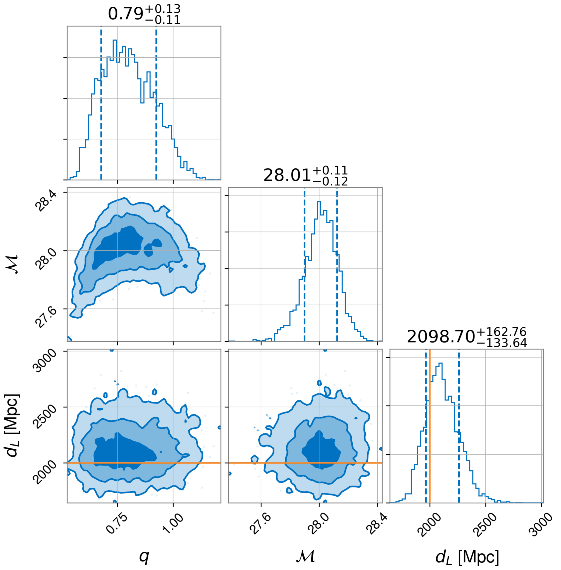

Figure 3. Posterior probability distributions of the chirp mass, mass ratio, and distance of a binary black hole injection in which the mass and distance parameters are sampled over; calculated using BILBY.

IV. CHALLENGES AND FUTURE PROSPECTS

An initial challenge in running the binary black hole injection was the unexpectedly long runtime. Originally we attempted to run it directly on the Jupyter server, but every run took at least an hour, even when the only parameter sampled over was the mass. After running the BBH injection directly on the cluster, the runtime was drastically reduced. Even so, the challenge of a potentially long runtime will pervade future experimentation, especially considering that the project itself involves determining how to reduce runtime. Once I have sufficiently experimented with the binary black hole injection, I will move on to binary neutron star injections which will be computationally more expensive due to the longer time duration and addition of tidal parameters.

[1] B. Abbott *et al.*, Gwtc-1: A gravitational-wave transient catalog of compact binary mergers observed by Ligo and Virgo during the first and second observing runs, (2019), arXiv:1811.12907.

[2] B. Abbott *et al.*, Properties of the binary neutron star merger GW170817, (2019), arXiv:1805.11579.

[3] I. Romero-Shaw *et al.*, Bayesian inference for compact binary coalescences with BILBY: Validation and application to the first LIGO–Virgo gravitational-wave transient catalogue, (2020), arXiv:2006.00714.