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

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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. INTRODUCTION

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 signals 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.

II. OBJECTIVES

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.

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.

III. METHODS

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

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

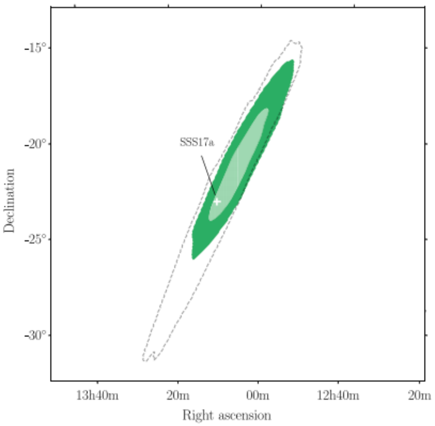

Figure 1. The improved localization of GW170817, with the dotted gray line indicating previous localization of 90% credibility from 2017 and lighter and darker green regions corresponding to increased region credibility of 50% and 90%, respectively, in 2019.

Here θ represents the source parameters, $\mathcal{L}(d|\theta)$ is the likelihood function, $\pi(\theta)$ is the prior distribution, 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. The parameters that we are primarily interested in for this project 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 strive to explore what settings could be used in terms of signal duration and bandwidth, such as pertaining to frequencies, in order to achieve reliable sky localization in a minimal timeframe.

IV. PROJECT SCHEDULE

I will begin by familiarizing myself with the BILBY software and runs on both real and simulated gravitational wave data. By the week three, we will analyze data from GW170817, the first binary neutron star detection, by investigating different settings for the signal duration and bandwidth; this should last around two weeks. For week five, we will explore the effects of neutron star spins on their inferred sky localization, addressing the query of whether we may completely ignore spin with our calculations. We will then turn our attention to simulating signals which that originate from various sky locations and analyze the obtained data, which will occur during weeks six and seven. For our last three weeks, we aim to estimate how well the sky localization can be inferred for different combinations of signal duration and bandwidth. We will compare this with the computational time endured to make those estimates, and compile our results into a final report and presentation.

V. CONCLUSION

The ultimate goal of this project is to recommend the optimal settings to be used for prompt and reliable skymap estimation. Using these optimal settings which produce fast but reliable results will allow for localization of gravitational wave signals, improving our understanding of the nature of neutron binary star systems, a source of such signals.

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[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.