Searching for Signs of a Galactic Excess of Gravitational Waves

Serena Moseley and Thomas Callister
California Institute of Technology

(Dated: July 9, 2018)

I. INTRODUCTION

A. Gravitational Wave Astronomy

General relativity predicts the existence of gravitational waves, oscillations in the space-time metric that are produced by massive, accelerating objects. Since 2015, gravitational waves have been routinely detected by the Advanced LIGO[1] and Advanced Virgo[2] experiments. Compact binary coalescences (CBCs), namely binary black hole mergers and binary neutron star mergers, have been responsible for all of the gravitational-wave signals detected so far. Signals from CBCs have peak amplitudes at frequencies within the most sensitive band of the Advanced LIGO detectors, between approximately 100 and 1000 Hz[3]. This and the fact that compact binary objects merge at a fairly high rate in the local Universe together make these events the only gravitational-wave sources observed to date.

Besides signals from CBC mergers, the LIGO and Virgo collaborations (LSC/Virgo) also search for a variety of other kinds of signals, including continuous gravitational waves, stochastic gravitational waves, and burst gravitational waves. LSC/Virgo conduct either modeled or unmodeled searches depending on signal of interest. In modeled searches, such as for CBCs, we can predict what the gravitational-wave signal should look like in the data. We can create template waveforms spanning the space of possible CBC signals and search through the data for a match. We perform this matched filter to reduce various noise that can drown out the signal and to boost the signal-to-noise ratio[4]. In contrast, other gravitational-wave signals involve so many unknowns that we cannot know beforehand what it may look like in the data. For this reason, LSC/Virgo also conduct unmodeled searches that don't rely on strong assumptions about the form of the signal. Burst searches are generally unmodeled searches for signals from an unknown transient event. Examples of events that produce gravitational-wave bursts include supernovae and glitching neutron stars[5]. For this project, we will broadly work within the realm of burst searches.

B. Galactic Excess of Gravitational Waves

In nearly every electromagnetic frequency band, the Milky Way stands out as the brightest source in the sky. Given the recent discoveries of gravitational waves, a new "messenger" of astronomical information, we might expect the galaxy to be a similarly bright source of gravitational radiation in the sky. In fact, we already know that such a galactic excess must exist due to the vast quantity of white dwarf binaries that inhabit the Milky Way[6]. These binaries systems, either resolvable or unresolvable, are a significant source of gravitational radiation in the galaxy[5]. However, although we know they exist, we cannot detect them with current ground-based detectors. These systems emit gravitational radiation at frequencies that are several orders of magnitude too small to be detected by either Advanced LIGO or Advanced Virgo, as illustrated in Fig. 1, which graphs the frequency range of the galactic white dwarf population as well as the sensitivity curves of the current ground-based detectors.

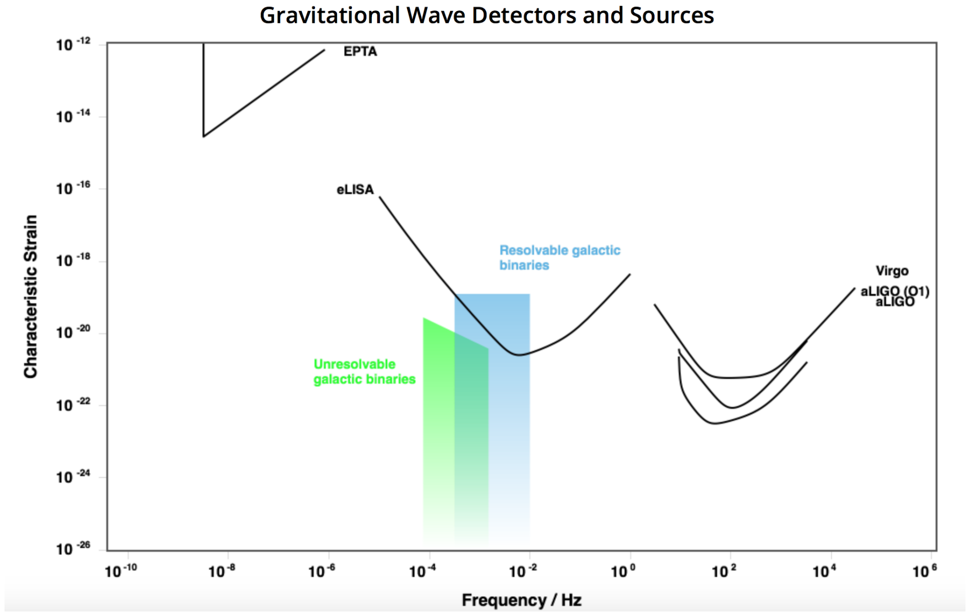

FIG. 1: A plot of the frequency band for unresolvable and resolvable galactic binaries, as well as the sensitivity of Advanced LIGO[7]. The frequency band of the galactic binaries is out of range of the Advanced LIGO sensitivity curve.

While we have yet to identify any galactic excess of gravitational waves in the detectors' output, it may be the case that an unknown galactic source is emitting radiation at the right frequency to be detected by Advanced LIGO and Advanced Virgo. If such sources do exist, they are likely weak as no associated signals have been clearly detected so far. Even if each burst is too weak to detect individually, we can try to detect their combined population by examining the sky distribution of burst triggers. If a real galactic population exists, we can expect the apparent sky direction of the triggers to align with the galaxy. Otherwise, an isotropic distribution in which the sky direction appears random implies the galactic population does not exist. Separately, it is likely that the detectors will one day discover some previously unknown source. Once this happens, we will need to be able to identify the source and knowing where the source likely comes from on the sky will help to characterize it. Thus we seek to develop a method of mapping the sky distribution of unmodeled gravitational-wave bursts to determine whether there exists a galactic excess of gravitational waves in the LIGO-Virgo frequency band.

II. MAPPING WITH BAYESWAVE

A. Skymaps

The localization of a gravitational-wave source depends primarily on two measurements: the difference in arrival times of the signal at the two detectors, and the relative amplitudes measured by each detector. We can use skymaps to map the posterior probability of a signal originating from multiple locations on the sky. Skymaps tend to be two-dimensional projections of the entire sky with colored regions to demonstrate the probability distribution of origin locations for the mapped signal. These regions tend to be rings for gravitational waves to due the nature of their detection.

When a gravitational wave passes through the Earth and is detected by Advanced LIGO, it either passes through one detector before the other, or passes through both at the same time. The time difference between its arrival at the two detectors reveals information about the source location of the signal. For example, if the gravitational-wave signal arrives at both detectors at the same exact time, then the gravitational wave must have traveled along a path perpendicular to the line connecting the two detectors. This constrains the possible source directions to a single circle on the sky.

We can partially break the remaining degeneracy by taking the orientations of the two detectors into account. The two Advanced LIGO detectors are oriented slightly different to each other due to the curvature of Earth's surface. These different orientations mean that the detectors are more sensitive to different regions in the sky. If a signal appears louder in one detector than it does in the other, we can say that the signal is more likely to have come from the region it is more sensitive to on the sky.

Skymaps can be created using a mollweide projection, which is a systematic transformation of latitudes and longitudes onto a two dimensional ellipse. This projection is such that the latitude lines are straight and the longitude lines curve as they deviate east or west of the central meridian. This ellipse is divided up into equal-area grid, as seen in Fig. 2.

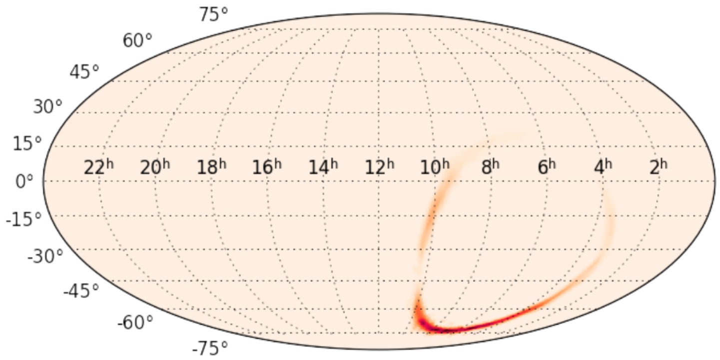

FIG. 2: A mollweide projection skymap, produced by the megasky.py script.

We can compute the gravitational-wave brightness of each pixel on a skymap using HEALPix software. HEALPix minimizes distortion and splits the skymap into equal area pixels of various heights. The heights correspond to the number of events coming from that bin's location on the sky, giving the brightness[8].

B. Bayesian Statistics and Bayeswave

Baye's Theorem states that the probability of some event A given some event B, known as the posterior probability, is as follows (1):

$$P(A \mid B) = \frac{P(B \mid A)\, P(A)}{P(B)}, \tag{1}$$

where $P(B \mid A)$ is the likelihood, $P(A)$ is the prior probability, and $P(B)$ is the evidence[9]. If we consider some parameter θ and we have a prior probability for it, we can use Baye's

Theorem to update the probability of θ given new information. Thus, we can compute the posterior probabilities required for plotting gravitational-wave bursts on skymaps. Rather than compute the probabilities ourselves, we can use Bayeswave to produce posterior samples. Bayeswave is an algorithm that reconstructs gravitational-wave signals using an arbitrary number of Sine-Gaussian wavelets[9]. It generates posterior samples that can be used to estimate model parameters and allows us to reconstruct a gravitational-wave signal without a predicted waveform. In (Fig. 3), we see a Bayeswave-reconstructed strain plot for the gravitational-wave signal from the first binary black hole merger detection, GW150914.

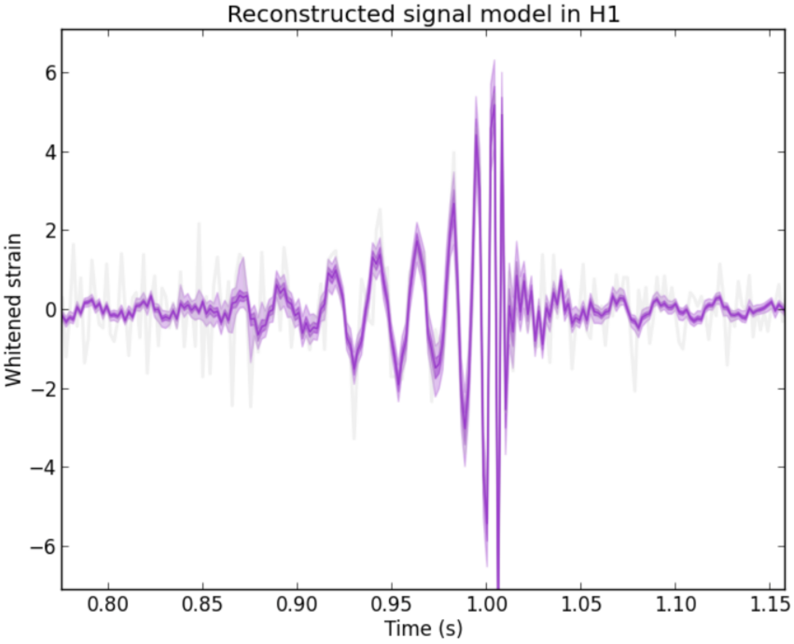

FIG. 3: A reconstructed strain plot for GW150914 generated by the megasky.py script.

III. OBJECTIVES

We will develop a method to search for signs of excess galactic gravitational waves by generating skymaps from data simulating gravitational-wave bursts. We will inject a large number of pure signal and pure noise triggers into Bayeswave to obtain posterior samples. We will then use these posterior samples to generate HEALPix bin heights so that we can generate skymaps for our triggers. We will combine the resultant skymaps for our population of events into a probability distribution of source locations. If a population of galactic gravitational-wave bursts exists within the data, then we would expect to see a galactic disk in this composite probability distribution. If this population does not exist, or if the bursts are isotropic, then we would expect to see a lack of structure within the probability distribution.

IV. PROGRESS ON PROJECT

Our initial proposed timeline was as follows:

Weeks 1-2: Learn how to simulate data and run Bayeswave on it.

Weeks 3-5: Simulate pure signals with no noise and demonstrate that we can recover a map of the galaxy from it.

Weeks 6-7: Simulate pure noise and show that we cannot recover a meaningful map from it.

Weeks 8-10: Put the signals and noise together and recover a galactic plane from it. Do the same with real LIGO data if time allows.

In the past three weeks, we have focused more on learning terminal commands and writing code to make our desired plots than begin simulating data for Bayeswave. We have begun writing a script in Python to take input right ascension and declination coordinates for many events generated by Bayeswave and plot them on a HEALPix skymap (Fig. 4).

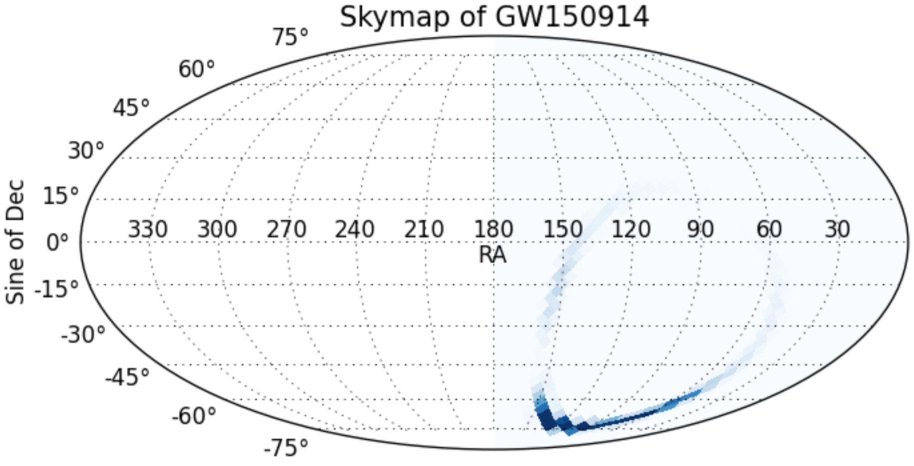

FIG. 4: A HEALPix map generated by our skymap.py script.

A certain number of initial samples from Bayeswave's burn-in stage are incongruent with the rest of the population and therefore need to be discarded. In order to do so, we wrote methods to plot the right ascension and declination coordinates as time series (Fig. 5, 6) to see how many initial samples should be cut out.

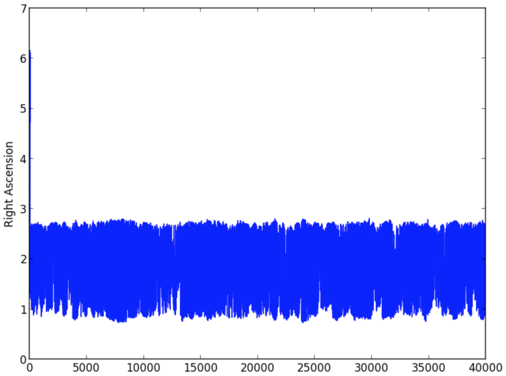

FIG. 5: A plot of the right ascension values for 40,000 samples, created by our skymap.py script. Note the peak in values for the initial samples from the burn-in stage.

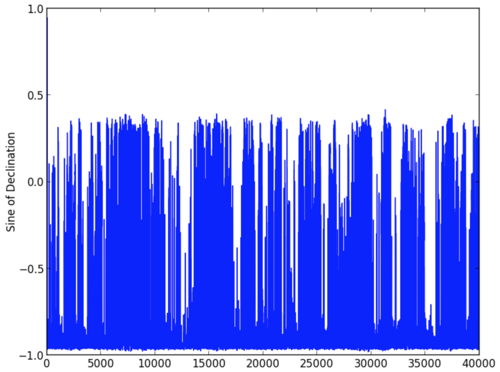

FIG. 6: A plot of the sine of the declination values for 40,000 samples, created by our skymap.py script. Note the peak in values for the initial samples from the burn-in stage.

We originally tried to plot our data as a heatmap but ran into difficulty figuring out how to create such a plot using Python. Given the variety of different ways to visualize posteriors, we decided to us a mollweide projection of a scatter plot instead.

We are currently working to write a method to downsample the population so that we can ensure the samples we use in our skymaps are independent of each other. We will use Acor to compute the correlation length for our right ascension and declination series. The correlation length corresponds to the amount that we will need to downsample by for a given data set. After that, we will begin injecting pure signal and pure noise triggers into Bayeswave.

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[10] Correspondence with Tom Callister