LIGO SURF 2025 Project Plan

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I. INTRODUCTION/BACKGROUND

A. LIGO Background

Laser Interferometer Gravitational-wave Observatory (LIGO) detectors are interferometers with very large (4 km) arms used to detect **gravitational waves** (GWs). These detectors function similarly to Michelson-Morley interferometers, giving an output of complete destructive interference when the arms are the same length. Incoming waves distort spacetime, changing the difference in arm length to produce constructive interference and a measured output light signal. This detector output is the "strain," which is measured as a time series. By performing a Fourier Transform on this data, researchers obtain strain as a function of frequency, and can create a spectrogram of frequency vs. time with strain as a color map. In 2015, the Advanced Laser Interferometer Gravitational Wave Observatory made its first GW detection of a black hole merger, or **compact binary coalescence**[1]. Our project uses simulated waveform models to examine binaries that are both eccentric and precessing, building on existing studies of circular precessing binaries.

B. Basics of Compact Binary Coalescences

A compact binary coalescence (CBC) begins with two black holes orbiting each other, radiating GWs that carry away energy and make the orbital radius decrease in a process known as the radiation reaction. As the radius decreases, the black holes orbit faster and faster and GWs increase in frequency and amplitude. This first stage of a CBC is called the **inspiral**. Eventually, the orbital radius decreases to the point that the two black holes collide and become one, releasing high amplitude GWs in a stage known as the **merger**. The resulting black hole is distorted, and GWs are emitted in the shape of a damped oscillation as the object goes back towards equilibrium in a stage called the **ringdown**. Figure 1 depicts a simulated gravitational wave with each regime of the CBC waveform labelled. On the frequency vs. time spectrogram previously in Section I A, a binary coalescence roughly resembles a

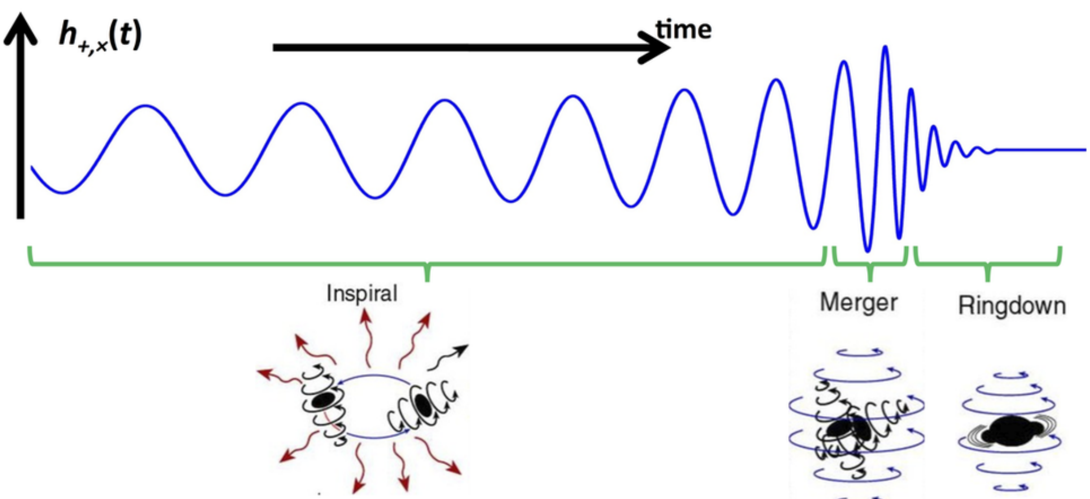

FIG. 1. Labelled diagram of GW showing the three stages of a binary coalescence[2].

checkmark. As time passes, the strain increases in amplitude and the wave increases in frequency due to the radiation reaction, until the two black holes collide and the merger occurs. As time passes and the CBC approaches the merger stage, frequency increases at a progressively faster rate. Figure 2 depicts the spectrogram from the first CBC detection in 2015.

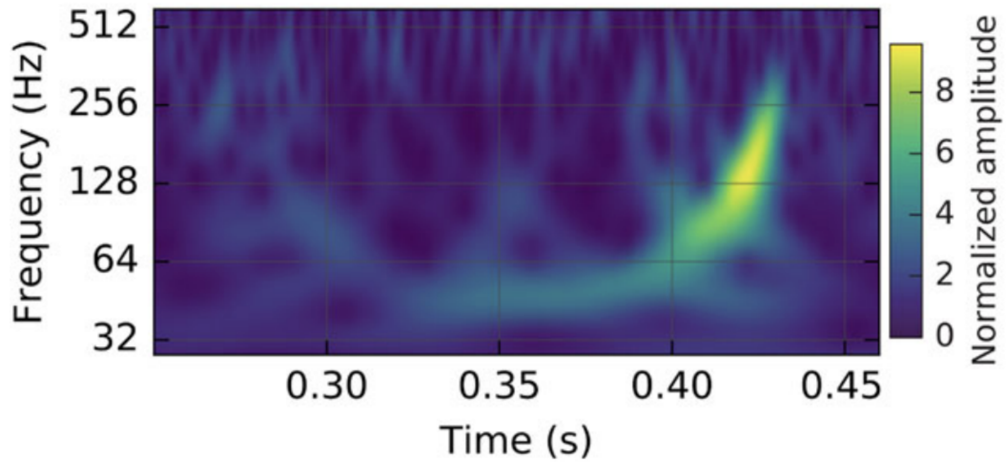

FIG. 2. Spectrogram for the 2015 first observation of a CBC. The crescent-like shape is the GW, and the merger occurs at the brightest spot on the shape[1].

C. Eccentricity

Analysis of current LIGO data assumes that the orbit of a binary black hole system is quasi-circular. However, as detectors become more sophisticated, we are more likely to begin observing eccentricity in detected waveforms. Modelling eccentricity allows researchers to stop making the assumption of quasi-circularity and will ensure that the tools exist to analyze eccentric waveforms when we eventually observe them.

Eccentricity (e) varies from 0 to 1 for bound systems, with e = 0 representing a circular orbit and e = 1 a parabolic orbit. In an elliptical binary, the speed of each black hole varies depending on its location in its orbit. At the point where the two black holes are closest together, known as **periastron**, the black holes travel at their fastest speeds and emit the highest amplitude GWs. Conversely, they travel slowest when farthest away from each other at **apastron**, emitting lower amplitude GWs. These amplitude changes modulate the signal, creating periodic "knocks" at periastron[3]. Some black holes in elliptical binaries will also experience **periastron precession**, an effect predicted by general relativity wherein an object's orbit itself precesses around the focus of its orbital ellipse within the orbital plane. This precession is due to ellipticity, and is not related to the precession discussed in Section I D.

D. Spin and Precession

Taking into account the spins of the black holes in a CBC further complicates the observed GW. General relativity predicts that spinning objects affect the curvature of spacetime by "dragging" the space around them[4]. In a binary black hole system, we call the orbital angular momentum vector $\overrightarrow{L}$. This vector is always perpendicular to the plane of orbit. When the spins of the black holes are in the same axis as $\overrightarrow{L}$, the system has **aligned spins** and both the spins and orbital angular momentum remain fixed in direction[5]. Systems with aligned spins have been well modelled and investigated[6].

However, if the spins are not aligned with $\overrightarrow{L}$, the system is complicated by a precession effect known as **Lense-Thirring Precession**, which has been observed in detector data. Due to general relativity, a spinning black hole will drag the space around it within the plane of orbit, affecting the the GWs it emits. This dragging effect creates spin-orbit and spin-spin couplings, leading both the orbital plane (and thus $\overrightarrow{L}$) and the spins of the black holes themselves to precess[4]. Precession leads to aperiodic modulation of the signal's amplitude and frequency as the alignment of the incoming GW with respect to the detector changes with $\overrightarrow{L}$, an effect that is demonstrated by Figure 3.

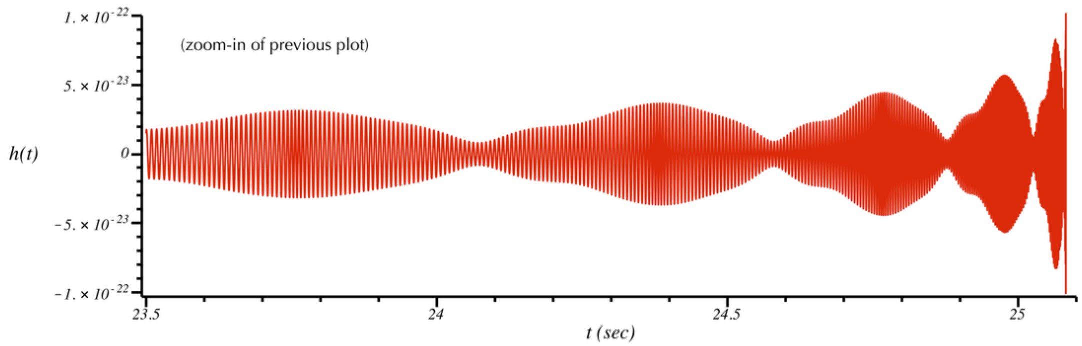

FIG. 3. Waveform for CBC with extreme precession effects visible in the modulation of both amplitude and frequency[5].

E. The Co-Precessing Frame

The **co-precessing frame** is the reference frame that rotates with $\overrightarrow{L}$ such that $\overrightarrow{L}$ is always in the +z direction. Using the approximation of the co-precessing frame reduces the complex seven-dimensional parameter space of a precessing system to a two-dimensional space built on waveforms that do not precess. This process characterizes the precessing system by describing $\overrightarrow{L}$'s position with respect to each axis with three time-dependent rotation angles, the most important of which is $\beta(t)$: the angle between $\overrightarrow{L}$ and the +z axis in the lab frame[6]. Shifting into the co-precessing frame forces $\beta(t) = 0$, simplifying the system. For circular binaries, the co-precessing frame successfully counteracts precession effects, leaving a GW similar to one from an aligned or no spin system. Our project will study the "untwisting" effect of transforming into the co-precessing frame for models that are both eccentric and precessing to determine the effectiveness of this approximation for non-circular binaries.

II. OBJECTIVES

Our main objective is to study the effect of shifting to the co-precessing frame on eccentric and precessing waveform models. By doing so, we hope to determine the accuracy of the approximation of the co-precessing frame as removing precession effects from non-circular binaries. We will use simulated waveforms and study them in the co-precessing frame to determine the effects of this transformation. We hope to find that untwisting into the co-precessing frame does successfully remove precession from eccentric systems, which will give us better tools for modelling mergers in the future. If we find problems in this approximation, we will attempt to determine if they are systematic and a pattern can be determined, or if missing physics in the model means the approximation does not hold.

Determining a map from an eccentric and precessing waveform to an eccentric waveform through the co-precessing frame will allow future complicated models that go beyond **post-Newtonian** (PN) approximations to be more easily created. If we find that the co-precessing frame assumptions hold true for eccentric binaries, these future models could begin by building an non-precessing eccentric waveform model, then add in precession through "twisting" away from the co-precessing frame into an more complex eccentric and precessing waveform.

III. APPROACH

To accomplish our objectives we will generate waveforms in one or multiple of the following ways:

1. using pyEFPE [7] to generate eccentic-precessing waveforms from CBC parameters
2. using a PN code package [8] to generate dynamics of a system (such as spin and position over time) in combination with code from Isaiah Tyler's previous SURF project to create the waveforms themselves
3. using Spectral Einstein Code (SpEC) to generate dynamics in combination with Isaiah Tyler's code to create waveforms

We will generate two sets of waveforms: an eccentric-precessing group, and a group that is only eccentric. We will create both sets such that they have the same eccentricity, and differ only in whether or not they precess. We will then un-twist the first set of eccentric-precessing waveforms into the co-precessing frame and compare them to the set of eccentric waveforms. If the two groups look very similar after this transformation, we will have supported the idea that transformation into the co-precessing frame successfully eliminates precession effects for eccentric systems. If there are differences between the sets of waveforms, we will endeavor to find a systematic pattern in those differences so that a map between eccentric and eccentric-precessing waveforms can still be created.

To generate and compare these waveform models we will need access to the Caltech computing cluster. We will also check in with the PN group as we plan our methods to discuss specific mechanics of coding the transformation into the co-precessing frame.

IV. PROJECT SCHEDULE

Dates	Stage	Tasks & Plan
17 - 27 June	Orientation	LIGO Gravitational Wave Open Data Workshop, orientation, and acclimation to the LIGO SURF program and Caltech
30 June - 11 July	Background	Become aquatinted with material and tools that we will be using to complete this project including (but not limited to): eccentricity, precession, Post-Newtonian dynamics, waveforms, and various code packages
14 - 25 July	Code and Model Exploration	Gain familiarity with utilizing pyEFPE [7], PN[8], and SpEC codes and their outputs to generate BBH dynamics and waveforms through a series of tutorial notebooks and writing code
28 July - 8 August	Untwisting Investigation	Study the impact of the coprecessing frame untwisting transformation utilizing the precessing CBC dynamics and waveforms generated by various dynamics and waveform codes, apply this study to eccentric systems and examine those results
11 - 15 August	Comparison and Analysis	Compare the results of untwisting the waveforms and dynamics from the codes used in this study
18 - 22 August	Final Materials	Complete final report and final presentation, practice and give final presentation to LIGO SURF peers

TABLE I. General work plan for the intended project for this summer. This table follows the outline from Sec. III

V. REFERENCES

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