# Studying Gravitational Waves from Exceptional Binary Black Hole Merger Events

## LIGO SURF 2020 Project Proposal

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Advanced LIGO and Advanced Virgo have detected 66 candidate gravitational wave signals. Each detection contains encoded information about the physical properties of the binary system. As the detectors continue to improve their sensitivity, these developments will allow us to detect rarer systems and introduce more confident statements regarding their source properties. In order to fully characterize the gravitational wave observations, we rely on numerical and analytical models that approximate the signal waveforms from the emitted source as specified by the source parameters (masses, spins, sky location, etc). It has been shown that gravitational waves oscillate at a dominant emission frequency; however, the event GW190412 has demonstrated subdominant higher order harmonic contributions. We will be exploring this phenomena in more detail both in simulation and in recently detected events. The primary focus of this summer project will be to explore higher order modes in gravitational wave signals with newly improved signal models.

## I. INTRODUCTION

In 2015, the Laser Interferometer Gravitational Wave Observatory (LIGO) detected distortions in spacetime that were produced by the gravitational waves of two colliding black holes nearly 1.3 billion light years away. This event revolutionized the way we observe our universe and will be recorded as one of our greatest scientific advancements.

Black hole binaries, along with other compact binaries, are responsible for the gravitational waves that have been detected by the LIGO Scientific Collaboration and Virgo. Since 2015, the year in which the first gravitational wave was detected, there have been nine additionally confirmed gravitational waves from binary black hole mergers, 56 candidate detections of gravitational wave signals, and one confirmed detection from a binary neutron star merger [1]. The current operational detectors are only able to observe the closest and loudest sources that exist in the local universe. Now that gravitational waves can be detected and analyzed, this is only the beginning for gravitational wave science.

The Advanced LIGO and Advanced Virgo detectors had acquired improvements before their third observing run (April 2019-March 2020), also referred to as O3, which increased their sensitivity. With these new implementations, all three detectors (both LIGO detectors and the Virgo detector), have been able to expand their range in the quest to detect gravitational wave signals and have successfully accumulated various new detections. With the observations of 56 new gravitational wave signals, the need for models of the emitted sources is essential [2]. It is expected that with the new data run, unique sources (compact binary coalescences) that include unequal masses or misaligned spins will be well within the astrophysical reach of the observatories. Earlier parameter waveform families were not sufficiently sophisticated to include higher order modes; however, by detecting exceptional events, these models of the gravitational radiation now include more accurate means of measurements. Not only will these models provide us with information regarding the inspiral, merger, and ringdown of the source, but by using the underlying theory of general relativity, we can test its validity more deeply [3].

In particular, in this report, we will be discussing the properties of the event called GW190412, which was observed on April 12, 2019 at 05:30:44 UTC by the Advanced Virgo detector and both Advanced LIGO detectors [3]. Historically, we have detected binaries that all had mass ratios $q = m_1/m_2 \approx 1$ where $m_1 \geq m_2$ [3]. However, GW190412 is the first binary observed to have significantly asymmetric masses with $q = 0.28^{+0.13}_{-0.06}$ [3]. Its signal waveform included its signature dominant quadrupole radiation; however, it contained *detectable* higher harmonics which will provide us with a greater insight to the dynamics of coalescing binary black holes. Therefore, the focus of this study this summer will be on events like GW190412 both in simulation and in recent signal detections.

## II. METHODS

### A. Source Properties

The source properties we have been studying prior to O3 included: masses ($m_1$ and $m_2$), spins of the black holes in the binary ($\vec{S_1}$ and $\vec{S_2}$), the sky location, luminosity distance ($D_L$), binary orbital orientation, time ($t_c$) and phase ($\phi_c$) of coalescence. All of these properties comprise to a total of 15 parameters [3]. Specifying these parameters allows one to predict the signal waveform that may be present in the detector network data.

Gravitational waves are transverse waves that have two independent polarization states denoted as $h_+$ and $h_\times$, where $h_\times$ has its principle axis rotated 45° with respect to $h_+$ [4]. With these two polarizations at hand, we can write the strain of the gravitational wave as the complex quantity $h = h_+ - ih_\times$ [5]. According to the works of pioneering scientists, another fundamental property of gravitational waves from compact binaries is that they are quadrupolar. While gravitational radiation often includes the lowest order radiation term, the quadrupole radiation, there are predictions that include higher multipoles [6]. However, higher multipoles, which are terms above the dominant, quadrupolar term, are particularly complex to infer from a gravitational wave signal produced by near equal mass binaries [3].

Recently, signal waveform families have been extended to include higher order modes. The dominant mode is $(l, m) = (2, 2)$ described by a spin-weighted spherical harmonic, ${}_{-2}Y_{lm}(\theta, \phi)$, where $\theta$ and $\phi$ are the emission angles toward the observer relative to the orbital angular momentum, $\ell$. We can describe the multipolar decomposition as:

$$h_+ - ih_x = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} \frac{h(t, \lambda)}{D_L} {}_{-2}Y_{\ell m}(\theta, \phi) \qquad (1)$$

where $t$ denotes the time, $\lambda$ represents the intrinsic parameters such as the black hole's masses and spins, and $D_L$ represents the luminosity distance from the observer [3]. Lastly, we recognize that, $h = h_+ - ih_\times$ is in the form of a complex sinusoidal, $cos(\omega t) - isin(\omega t)$ or similarly $e^{-i\omega t}$.

The event's mass ratio, $q$, is an important factor to consider since it affects the geometry of the source. General relativity predicts that as asymmetric systems increase, so does the importance of higher multipoles.

Another contributor to higher multipoles is the orientation of the source. Higher order multipoles are more prominent when $\theta$ is divergent from 0 or $\pi$, also said to be "face on." As a result to the degeneracy between $\theta$ and $D_L$, higher multipoles allow us to break this degeneracy which allows us to tighten constraints on the two [3].

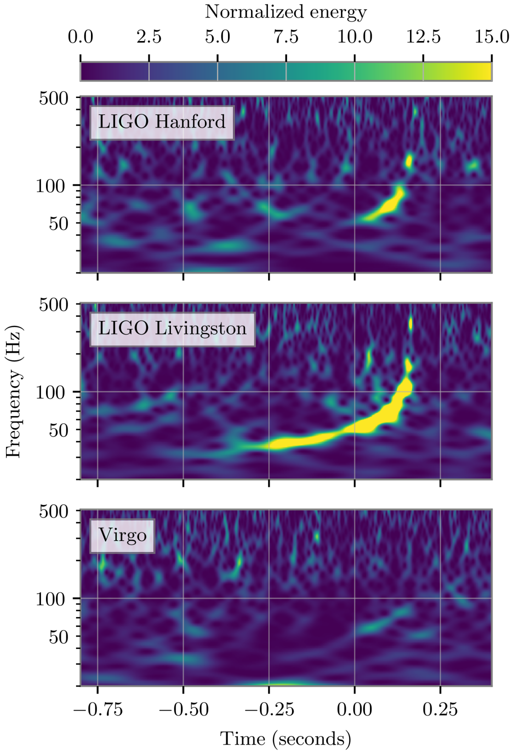

FIG. 1. Spectrogram of GW190412 in LIGO Hanford (top), LIGO Liv- ingston (middle), and Virgo (bottom). The x-axis represents time while the y-axis represents the frequency of the gravitational wave signal. In this time-frequency representation, we show the energy given a specific frequency at a specific time. The increase in frequency and energy over time is a product of the inspiraling black holes followed by their merger.

## B. Signal Models

The models that participate in the analysis for binary black hole mergers are improved from a variety of previous gravitational wave signal models. Specifically, the newest model, NRSur7dq4, which is derived more directly from numerical relativity through interpolation of

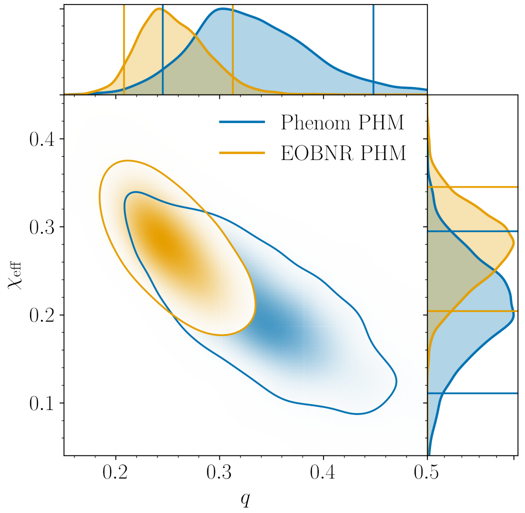

FIG. 2. The x-axis represents the mass ratio, $q$, and the y-axis represents the effective spin, $\chi_{eff}$ of GW190412. The orange and blue contours are produced from two different gravitational wave signal models that incorporate precessing spins and higher multipoles.

the waveforms across parameter space using *surgate modeling* [7]. The effective-one-body (EOB) family is a model that consists of a post-Newtonian waveform that includes the inspiral, merger, and ringdown stitched together with a numerical relativity waveform that contains black hole perturbation theory [3]. In contrast, the phenomenological family is a hybridized model of the EOB-inspiral and a numerical relativity merger [3].The improved models branch from the precessing models of the EOBNR family and the phenomenological family which include effects of higher multipoles.

## III. HIGHER MULTIPOLES

It is critical that both experimental and theoretical models of a gravitational wave signal agree with the measurements made from Advanced LIGO and Virgo. Typically, these models include the dominant $(l, m) = (2, 2)$ mode, however this is not always the case. When the sources have a mass ratio close to one, these models are sufficient to analyze the source parameters of the system, such as distance and inclination. However, when the black hole binary contains an unequal mass ratio, subdominant multipole models may be remarkably more accurate.

Shown in Figure 1, we can see the strain data, the fractional change in displacement between two nearby masses due to the gravitational wave, taken by the three detectors. The time-frequency representation of GW190412 shows the loudness of the event in each detector. Despite the fact that each detector is thousands of kilometers away from one another, we can definitively see that the signal is present in all three which implies that the source has an astrophysical origin rather than local detector noise [3].

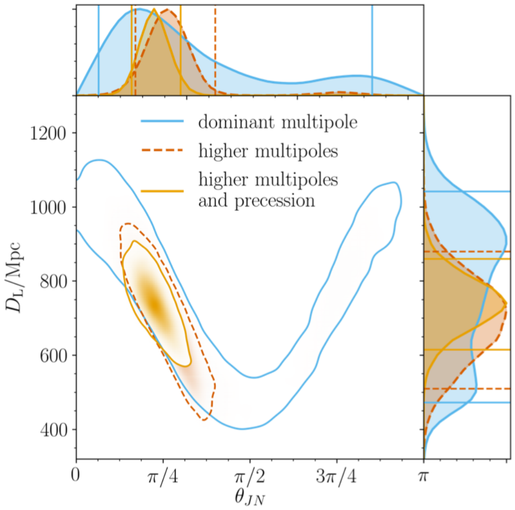

FIG. 3. Posterior distribution of GW190412 luminosity dsitance $(D_L)$ and inclinatoin $(\theta)$. We see that by using models that include the dominant multipole, higher mulitpoles, and higher multipoles and precession, we are able to constrain $D_L$ and $\theta$. Degeneracy breaks when higher order modes are included which allows us to improve our accuracy.

What makes this event so unique is the notable asymmetry of the black hole masses, that is – one of the black hole's mass is roughly three times heavier than the other. This makes GW190412 a favorable system for identifying the presence of higher order modes. Previously, nearly all detected binary systems were consistent with having net aligned spin; however we found that GW190412 has significant net positive aligned spin $\chi_{eff}$ (Figure 2). On account of the unequal mass ratio, we can apply a constraint on the spin of the larger black hole. The mass ratio $(q)$ and effective align spin $(\chi_{eff})$ for GW190412 is illustrated in Figure 2. Making use of higher order modes in the model waveforms will allow us to make more precise measurements of all the parameters including the distance and inclination of the system, also shown in Figure 3. General relativity predictions are precise predictions for the content and strength of higher order multipoles. This summer, I will be investigating the degree to which the constraint predictions do not accurately describe the data.

This is the first time that waveform models incorporating higher order modes from numerical relativity have been applied to an observed gravitational wave signal [3]. This summer, I will be applying these improved signal models to other events observed in O3.

## IV. CONCLUSION

Using numerical relativity and analytical models from coalescing binaries has proven to be essential for current and future gravitational wave analysis. This summer, I will be using Bilby, a Bayesian inference library for gravitational-wave astronomy, to infer the significance of exceptional compact binary coalescences from a signal model that includes higher-order multipoles [8]. By using these gravitational wave signal models, it has been found that GW190412 has the strongest constraint on one of the black holes' spin magnitude thus far [3]. Through the analysis of this binary black hole coalescence, we have found that the $(l, m = (3, 3))$ mode is the second most important multipole while the first remains to be the dominant $(l, m) = (2, 2)$ mode. With this information at hand, we can apply tighter constraints which will ultimately allow us to provide more accurate source parameters.

### A. Work Plan

Before the summer project begins, this proposal outlining the research topic will be submitted. Upon completion, I will continue to do background reading focusing on higher order multipoles as well as exceptional binary black hole merger events. As questions arise from the reading, I will be contacting my mentor as well as co-mentors for clarification. The ultimate goal is to use Bilby to infer the astrophysical source properties of compact binary black hole coalescence. However, before starting simulations using Bilby, I will be going through the user tutorials. I will write and submit status reports in the third and seventh week of the internship which will include discussion of specific progress results and problems obtained thus far. Finally, toward the end of the internship, I will write and present the final presentation and report. All submitted work will be reviewed by my mentor and co-mentors.

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