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LIGO SURF Proposal: Monitoring O3 Gravitational Wave Binary Black Hole Mergers

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ABSTRACT

The LIGO/Virgo Observation Run 3 (O3) began in April 2019 and will continue for a year. Just in the first month, six gravitational wave signals from binary black hole mergers have been detected, as well as potentially one binary neutron star and one neutron star-black hole merger. With each candidate detection, a broad range of information must be extracted. To keep up with the events, this information gathering should be performed as quickly as possible. This includes: a detailed understanding of the state of the two LIGO detectors and the Virgo detector, including any evidence of detector misbehavior that could be responsible for the candidate event or that could corrupt the extraction of astrophysical information from it; a careful evaluation of the event significance by comparing it with instrumental background (candidate events caused by instrumental noise); the extraction of astrophysical parameters from the data; searching for evidence that the event waveform is inconsistent with the expectations from General Relativity or evidence that the calibrated detector response is flawed; inferring the distribution of events as a function of mass, spin, and other parameters; and more. We will perform these tasks throughout the summer and summarize the results at the end of the summer.

Key words: gravitational waves – black holes – general relativity

1 INTRODUCTION

Gravitational waves (GWs) are violent ripples of spacetime caused by catastrophic events such as colliding black holes, supernovae, and merging neutron stars. Predicted by physicist Albert Einstein in his Theory of General Relativity (GR) in 1916, Einstein's field equations showed that such massive accelerating objects would cause distorted waves in the fabric of space-time to travel throughout the universe at the speed of light (Einstein 1916, 1918).

These GWs were not detected for another century, until September 14th, 2015, when the two detectors of the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) both observed the first GW signal, GW150914, at exactly 09:50:45.4 UTC (Abbott et al. 2016). Caused by a binary black hole (BBH) merger, GW150914 was detected during the first observing run (O1) of Advanced LIGO, which ran from September 12th, 2015 to January 19th, 2016 (The LIGO Scientific Collaboration et al. 2018). The second observing run (O2) ran from November 30th, 2016 to August 25th, 2017, and on August 1st, 2017, the Advanced Virgo detector joined O2, allowing for three detectors to simultaneously search for GWs for the first time in history (Acernese et al. 2015).

LIGO is the world's largest, most complex, and most sensitive interferometer, and it is designed purely for the detection of these miniscule oscillations in space-time. The science opportunities afforded by this new era of multi-messenger astronomy are numerous, as GWs carry not just energy and momentum, but crucial information about the structure of their sources (Cai et al. 2017). Therefore, the more detections that are made, the further astrophysicists' understanding of these objects can develop. To that end, a global network of detectors will soon emerge, and detectors have already been built in Japan, Italy, and Germany (Abbott et al. 2009), with a third LIGO detector to be built in India. Furthermore, the third observing run (O3) of Advanced LIGO and Virgo began in April 2019, and is planned to continue throughout the summer of 2019 for one calender year (Turpin et al. 2019).

This is where this project begins: we will monitor these

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detections in real time in order to analyze the data and see what more we can learn about GWs. Observing runs O1 and O2 detected signals from ten BBH mergers and one binary neutron (BNS) signal (The LIGO Scientific Collaboration et al. 2018). Six of these BBH mergers are depicted in Figure 1. However, no neutron star-black hole mergers were observed. Thus, we aim to add to the existing GW data by parsing through the O3 detections, and in particular watching for any GWs caused by new mergers, checking whether the waveforms are consistent with GR, and determining the parameters of the sources. Any new additions to current astrophysical knowledge would be monumental.

2 OBJECTIVES

We aim to achieve a number of goals in our project. First, we will need to monitor detections as they come in, at an expected rate of one or two per week, and immediately analyze them to determine whether the signals are real or are simply instrumental noise fluctuations. This will involve acquiring a detailed understanding of the search pipelines and their output, as well as examining the state of the two LIGO detectors and Virgo detector. In particular, we must search around each candidate event to look for detector misbehavior or impaired data quality that could cause a false signal or impact the extraction of astrophysical information from it. We will also need to take into account the event significance by comparing it the instrumental background, to ensure that a signal has not been faked by instrumental noise.

Once we are sure that a signal is astrophysical, we plan to extract the event parameters, such as the mass, spin and location of the mergers. We also aim to test for consistency of the data with waveforms derived from GR, paying particular attention to events that are different from what has been observed before. This includes sources with unusually large or low masses, large spins, higher order modes, or eccentricity. Lastly, we will update the existing catalogue of GW events and possibly create the signal population models. We will also need to follow the electromagnetic telescope follow-up efforts and activities, identify new discoveries, and automate data checks.

3 APPROACH

The characteristic dimensionless gravitational wave amplitude for a source of mass M located at a distance r away can be described by Equation 1, where Q is the quadrupole moment of the source, ω is its angular frequency of oscillation, a is the separation between the two source frame component masses m_1 and m_2, and M is the total mass (Centrella 2003):

$$h \quad \frac{G}{c^4}\frac{1}{r}\frac{d^2Q}{dt^2}, \quad Q = \quad \omega^2\mu a^2, \quad \mu = \frac{m_1 m_2}{M} = \frac{m_1 m_2}{m_1 + m_2} \tag{1}$$

The angular frequency ω can be rewritten in terms of the orbital period, using Kepler's third law in Equation 2:

$$\omega = 2\pi f_{\rm orb} = \frac{2\pi}{\tau_{\rm orb}}, \quad \tau_{\rm orb}{}^2 = \frac{4\pi^2}{G^1 m_1 + m_2{}^{\rm o}} a^3 = \frac{4\pi^2}{GM} a^3 \tag{2}$$

Here, $f_{\rm GW} = 2 f_{\rm orb}$, where $f_{\rm GW}$ refers to the frequency of the gravitational wave and $f_{\rm orb}$ is the orbital frequency. Equation 1 can thus be rewritten as Equation 3, where $R_{\rm Schw}$ is the Schwarzschild radius of the source:

$$h \quad \frac{GM}{c^2 r}\frac{GM}{c^2 a} \quad \frac{R_{\rm Schw}{}^2}{4ra}, \quad R_{\rm Schw} = \frac{2GM}{c^2} \tag{3}$$

GWs can thus inform us on many features of the source event. We will extract these source parameters from newly detected GWs using Bayesian parameter estimation, a method of mathematical modeling which is used to model real phenomena. In contrast to the classical frequentist approach, which chooses a value for some input parameter θ that maximizes the likelihood of the observed data, Bayesian parameter estimation holds the observed evidence as fixed and instead assumes possible values for θ (Eshky 2009). Bayesian inference is a crucial tool in all of modern science, but is particularly useful in gravitational wave astronomy: a black hole can be completely characterized by its mass and spin vector, and the gravitational waveform from a BBH by a total of fifteen parameters (Thrane & Talbot 2019).

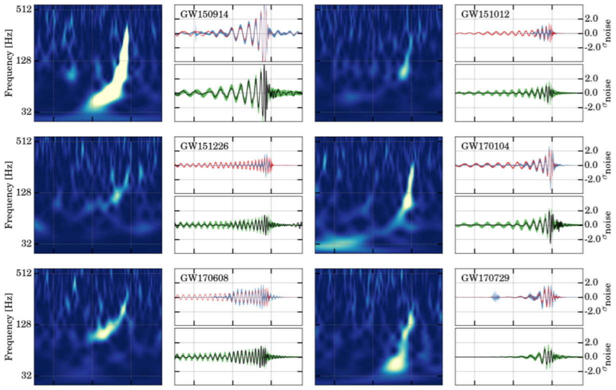

Figure 1. The time-frequency maps and reconstructed signal waveforms for six BBH events detected during O1 and O2. The first panel of each event shows a normalized time-frequency power map of the GW strain. The last two panels show time domain reconstructions of the whitened signal in units of standard deviation of the noise (The LIGO Scientific Collaboration et al. 2018).

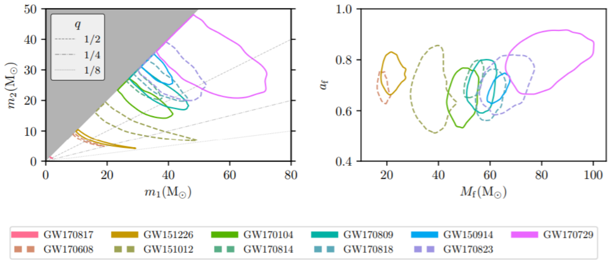

Figure 2. The first of the parameter estimation summary plots, depicting the posterior probability densities of the masses, spins, and SNR of the GW events. Left panel: source frame component masses m_1 and m_2, using the convention that $m_1 \quad m_2$. Right panel: the mass M_f and dimensionless spin magnitude a_f of the final black holes (The LIGO Scientific Collaboration et al. 2018).

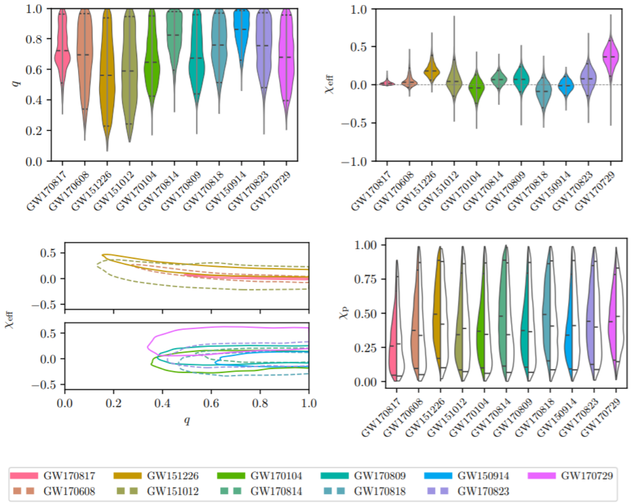

Figure 3. The second of the parameter estimation summary plots. These plots depict the posterior probability densities of the mass ratio ($q = \frac{m_2}{m_1}$), the dimensionless effective spin $\chi_{\rm eff}$ of the GW events, and their dimensionless precessing spin χ_p (The LIGO Scientific Collaboration et al. 2018).

We will therefore use Bilby, a user-friendly Bayesian inference library, to extract these fifteen parameters from the detected GWs (Ashton et al. 2019). These parameters are composed of the following intrinsic parameters:

(1) the source frame component masses m_1 and m_2
(2) the source frame component spin vectors $\vec{\chi}_1$ and $\vec{\chi}_2$,

as well as the following extrinsic parameters:

(3) the luminosity distance d_L
(4) the source's sky localization $\Delta\Omega$, characterized by its right ascension (RA) and right declination (Dec)
(5) the polar angle ι and polarization angle ψ of the orientation of the binary orbit with respect to the line-of-sight of the observer
(6) the coalescence time t_c at which the signal from the merger reaches the center of the Earth
(7) the phase of the signal ϕ_c at the moment of coalescence

We will extract a number of derived parameters from these input parameters, including the final source frame mass M_f, the final spin a_f, the radiated energy $E_{\rm rad}$, the peak luminosity $l_{\rm peak}$, and the redshift z. We also plan to determine the chirp mass $\mathcal{M}$ and the dimensionless effective aligned spin $\chi_{\rm eff}$, described by Equations 4 and 5 respectively, where μ is the reduced mass of the source event, M is its total mass, and $\hat{L}_N$ is its Newtonian angular momentum.

$$\mathcal{M} = M\eta^{3/5}, \quad \eta = \frac{\mu}{M} = \frac{m_1 m_2}{M^2} \tag{4}$$

$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\ \hat{L}_N}{M} \tag{5}$$

An example of this Bayesian parameter estimation as applied to the O1 and O2 data is depicted in Figures 2 and 3. The former shows the source mass frame m_1 and m_2, as well as the mass M_f and dimensionless spin magnitude a_f of the final black holes. The latter shows the mass ratio $q = \frac{m_2}{m_1}$ 1, the dimensionless effective spin $\chi_{\rm eff}$, and the dimensionless precessing spin χ_p. For Kerr black holes, $|\chi_{1,2}|$ 1, so both $\chi_{\rm eff}$ and χ_p lie between 1 and -1.

4 WORK PLAN

The objectives outlined in Section 2 are not intended to be completed by a single person. I will work as part of a team of six to seven researchers, about three or four of whom will be fellow SURF students. The expected work plan for the summer is as follows:

(1) Weeks 1-3: During this period I will come to speed on the background knowledge. This will involve learning to deeply understand the objectives, reading relevant background papers, and learning to use the necessary software tools.
(2) Weeks 4-7: I will begin to analyze the LIGO candidate event detections as soon as they come in. In reaching final conclusions on these candidate detections, I will apply the tools that I learned in previous weeks. Sometime during this period I will go on a trip with the other LIGO SURF students to the LIGO Livingston Observatory in Louisiana.
(3) Weeks 7-10: I will gather all of my results and prepare a final presentation, as well as a final paper.

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