Studying the Detectability of High Mass Black Hole Binary Mergers with Future Gravitational Wave Detectors

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Abstract

In this work we will determine the distances to which gravitational waves from Intermediate Mass Black Hole Binary (IMBHB) mergers can be detected by ground based gravitational wave detector network in observing run four (O4), and beyond. Binary black hole mergers between 65 and 150 $M_\odot$ are predicted to be rare as a result of pair instability in the final stages of their progenitor stars, so future observations of IMBHB mergers will help us to understand formation processes. Therefore this study seeks to calculate the detectability of IMBHB mergers for future runs of the detector network. We aim to determine the sensitive luminosity distance of merger events within the IMBH mass range, averaged over other astrophysical parameters. Optimal sensitivity distances will be given for several detector network configurations, including predictions for future detectors. Additionally we will present detection efficiency predictions as a function of red-shift, and distance horizon value for various high mass mergers. We will present the sensitive volume of the detector network, and predict the number of IMBHB merger events we expect to observe in future runs.

Index Terms: distance horizon, intermediate mass black holes, pair pulsational instability, binary black holes, black hole binary mergers, waveform models, gravitational waves.

1. Introduction

1.1. Overview of the Study

This project aims to determine the luminosity distances to which gravitational waves from Intermediate Mass Black Hole Binary (IMBHB) [1] mergers can be detected in observing run four (O4), and beyond, of the Laser Interferometer Gravitational-wave Observatory (LIGO) network. By using waveform approximant models, like the IMRPhenom model family, to simulate gravitational waves (GW) strain (in either the time or frequency domain) produced from the merger of binary black holes (BBHs) we will study the factors that affect sensitivity; specifically those in the intermediate mass range. Considering these simulated strains —averaged over several physical attributes of the merger and external parameters specific to observation —will allow the prediction of the distance sensitivity to be expected for future observing runs.

These simulations use predetermined ratios of fifteen astrophysical parameters [2], that will be sampled over to create a random population. Since IMBHB mergers are expected to be very rare, occurring at a rate density of $0.13^{+0.30}_{-0.11}\ Gpc^{-3}yr^{-1}$ [2], determining the future sensitivity distance relates directly to increased chance of detecting them, since an increase in astronomical distances correspond to cubic increase in spacetime volume (VT). These VTs refer to the co-moving volume, which experience cosmological effects like red shift (on the time domain waveforms/frequency/BBH mass) and time dilation. Strictly speaking this makes the relationship between distance and volume slightly less than cubic. Additional considerations during waveform correction will include detector antenna response from the gravitational wave detector network. The corrected waveforms will be categorized as detectable or not to the network of detectors based on the SNR values calculated for them. Ultimately this will determine the sensitive distance to which GWs from IMBHB mergers will be detectable in upcoming observing runs.

1.2. Gravitational Wave Background

Binary black holes, predicted and later confirmed with the detection of GW150914, are thought to arise from co-evolved binary star systems or dynamical capture in dense stellar environments [3]. Once formed general relativity (GR) predicts that the BHs will orbit each other, losing energy in the form of gravitational radiation and move closer together, until finally merging into a single object [4]. The gravitational waves produced by BBH mergers are a result of the relativistic orbit that ripples space-time [5], emitted at a frequency equivalent to twice of the orbital frequency [6]. Gravitational wave data are consistent with GR so far, so waveform simulations used throughout this study are based on GR simulations.

Although GWs are produced by all moving matter in the universe, only merging events of neutron stars and black holes are loud enough to be visible to the gravitational wave detector network. Loud in terms of Gravitational wave physics meaning a large strain amplitude in the collected frequency data. Even still, not all mergers are visible to the network; for example the detection threshold in O3 required a signal to noise ratio (SNR) of 12 [7] for an event to be distinguishable from noise in the

[1]Explained in depth in section 2.3, Motivation, for the purposes of this study we will refer to black holes between 65 and 150 $M_\odot$ as intermediate mass. This is in order to consider black holes in the pair instability/pulsational pair instability mass gap.

[2]The fifteen parameters include the individual BBH masses, the three spin components for each BH, plane inclination, azimuthal angle, total angular momentum of the system, luminosity distance, time of merger, right ascension and declination. We will assume circular orbits.

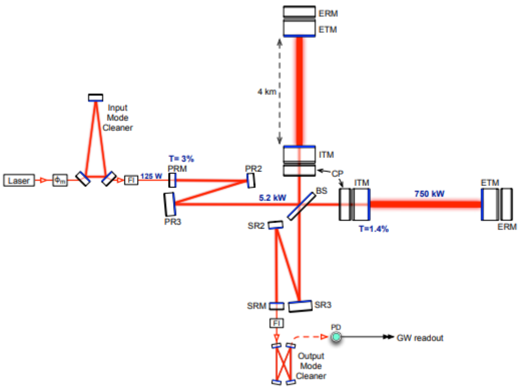

Figure 1: *Advanced LIGO schematics [[11], fig.2]*

data, and the recorded data had to be within the LIGO frequency band, between 24Hz to 2048Hz [8], to be detected. These basic conditions dictate what can be detected by the gravitational wave detector network, but there are multiple intrinsic and external variables that can affect whether the data collected from a merger will meet this criteria.

The gravitational wave detector network uses Michelson Interferometers to measure the GWs, in which the mirrors of the detector are free to be moved by passing GWs. The interferometer bounces lasers between these mirrors, allowing the motion to be quantified as strain of the laser cavities, calculated from the phase difference of the lasers [9]. The gravitational waves arriving at the detectors are measured from their distortion of space in this manner, which is collected as strain data characterized by the following relation [10]:

$$h = h_+ F_+ + h_\times F_\times . \tag{1}$$

Where h is the strain, plus and cross represent the polarizations, and F represents the detector antenna response to each polarization. Each polarization's strain is dependent on the intrinsic properties of the merger event, whereas the detector antenna response is dependent on the detector's antenna response to varying sky location/orientation.

This strain, h, is seen by the gravitational wave detector network only if it both is above the SNR detection threshold and within the LIGO frequency band. The SNR of a merger event can be calculated with the following [12]:

$$\langle a(\theta, f) | b(\theta, f) \rangle = 2 \int_{f_{low}}^{f_{high}} \frac{a(\theta, f) b(\theta, f)^* + c.c}{S_n(f)} df. \tag{2}$$

Where $a(\theta, f)$ is the strain in the frequency domain, $b(\theta, f)$ is the template, and $S_n(f)$ is the power spectral density of the noise. This optimal SNR relationship is also applicable to simulated strains, which will enable predictions of the BBH mergers visible in observation run 4 and beyond.

1.3. Astrophysical Motivation for Finding Distance Sensitivity of High Mass Binaries

Astrophysicists predict a deficit of black holes whose progenitor stars are between the masses of about 95 $M_\odot$ and 130 $M_\odot$ [13] attributed to the pulsational pair instability mass gap. Stars that begin hydrogen fusion at this mass may undergo a pulsational pair instability supernova near the ends of their lives due to the internal thermal conditions. Stars outside of this mass range, conversely, may transition to their final states more immediately, be that a black holes, neutron stars, white dwarf, or other. The stars in the pair instability mass range finish their hydrogen fusion and begin to form heavier cores, containing helium and other heavy elements up until the typical lead barrier. The pressure, and thermal energy, within these heavy cores will build through each burning stage until the heat reaches a critical temperature, exceeding $10^9 K$ [13], at which point the environment creates electron-positron pairs from photons. While the photons provided thermal pressure to support the star's radius, the pair instability electrons and positrons contribute significantly less outward pressure, which leads to disruption of the star's hydro-static equilibrium. The electron-positron pairs are created with a cascading effect, so large quantities of thermal energy go into creating these particle pairs which do little to support the stars radius, eventually leading to overall contraction of the star due to lack of pressure. A chain effect soon follows; the sudden contraction, and therefore increased temperature, creates a period of explosive element burning, providing more fusion pressure within the star, which in turn causes an increase in radius that may be fast enough and ejects many solar masses worth of material from the star. Pair instability stars may be completely decimated from this collapse, but pulsational pair instability stars may go through this cycle many times over, losing layers of mass each time. After the ejection the pulsational stars will contract again, releasing both light and neutrinos, and encounter another instability; a process that repeats until it reaches a stable mass around 65 $M_\odot$, with a heavy core of 40 $M_\odot$ [13]. The succeeding pulses will eject less material, but have higher energy, and can collide with the initial material becoming extremely luminous [13].

Due to the Pulsational Pair Instability (PPI), and Pair Instability (PI), processes there is an observed gap in the 50 to 135 $M_\odot$ range [14]. However with the discovery of GW190521, a high mass BBH merger, during observing run 3 of the LIGO and Virgo detector network, researchers were able to confirm one of the constituent black holes was in the IMBH range. The GWs originated from a BBH merger with constituent masses of 66 $M_\odot$ and 85 $M_\odot$, leaving behind a remnant of 142 $M_\odot$ [2]. There are contending theories on the production of IMBHs, like hierarchical merging of many smaller black holes [15], or primordial origins allowing for masses in this range [16]. Theory and observation aim to elucidate the formation mechanism for super massive black holes in galactic centers, which IMBH formation could provide a clue to. Thus detecting more IMBHB is crucial to develop our understanding, yet these events are few and far between with such a low production rate of $0.13 Gpc^{-3} yr^{-1}$ [2]. Therefore this project aims to determine the sensitive volume for detection of GWs from BBH mergers containing high mass black holes, with data from current and future ground-based detector networks.

Determining the distance sensitivity of the detector network has been important in past observing runs as well. In observing runs one and two (O1 and O2) the sensitivity distance was calculated for differing constituent masses of IMBHB mergers, as shown below [17]. The maximum distance calculated by this previous study is around 1.8 Gpc [17] for optimal conditions of a 100 on 100 $M_\odot$ black hole, aligned-spin source. This project expects to see improved sensitivity distances due to better detector sensitivity in run 4, O4, and more advanced modeling.

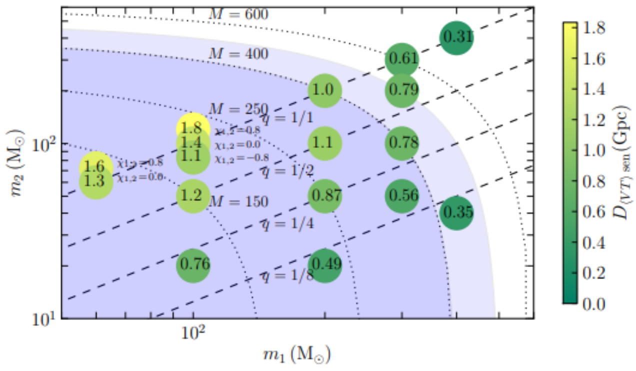

Figure 2: *Distance sensitivity, in Gpc, of IMBHB merger events with varying constituent masses [[17], fig.1].*

2. Methodology

2.1. Gravitational Wave Simulation Tools

To calculate future sensitive volume this project will simulate merging events of BBHs with different models with pycbc waveform model families. These models contain a wide variety of waveform templates, created by combining post-newtonian approximations of the early inspiral with numerical relativity solutions for the merger and ring-down portions of the event. These methods are used to reduce the super computer time needed to produce the templates; post-newtonian approximations are faster than numerical relativity, and numerical relativity reduces the run time of general relativity simulations from a few months, typical of Spectral Einstein Code, to a few seconds [18]. The pycbc waveform package takes advantage of these methods, giving us access to a wide variety of templates under varying parameters. Although this method comes with some inherent limitations, like preset mass ratios, there is little error, comparable to the estimated numerical error of generated waveforms, associated with numerical relativity based simulations [18].

A decision between the waveform models offered by pycbc must be considered for their potential impact on this study. After comparing several waveform model families we have determined that each model has correlation significant enough to be negligible, and have chosen to utilize the IMRPhenomXP model to simulate waveforms. The IMRPhenom waveform family excels at simulating the early inspiral, which other families sometimes neglect to model. Due to the specific focus on distance sensitivity, longer waveforms may be helpful in recovering the most SNR during match filtering. Additionally the IMRPhenom waveform IMRPhenomXP is chosen over it's aligned spin counterpart, IMRPhenomXAS, in order to consider spin to the component BHs.

2.2. Averaged Parameters and Sampled Parameters for Waveform Production

This study looks to provide average sensitivity estimates to IMBHB mergers over the whole sky, necessitating averaging over two main variable groups. In order to average we provide random values for each parameter and produce an array of samples to gauge the overall sensitivity. First, all sky location variables are averaged to provide the overall sensitivity. The antenna patterns of the detectors are accounted for before averaging, but the final sensitivity prediction is not location specific. Second being the presence of non-aligned spin of the component BHs, for which we consider two cases of sensitivity, with component spin and without. Spin is not expected to significantly affect the GW strain amplitude so these effects are also averaged over to provide an overall sensitivity.

Conversely we sample over other variables to observe their effect on sensitivity to each detector network. We calculate the sensitivity as a function of component mass and red-shift, which calls for even sampling of these two parameters. The combination of methods for choosing variables provides an overall sensitivity.

Figure 3 is an example waveform with randomly assigned parameters, and the strain that would be detected by LIGO Livingston, LIGO Hanford, and Virgo. This is one of the waveforms that will be included in the averaging process for in these particular mass and red-shift bins[3]. The feautures of this waveform that are important to note includes the spin-induced amplitude modulation and the varying detector responses. The goal of averaging over these parameters is to eliminate dependencies on everything but the mass and distance of the merger event in the final sensitivity measurement.

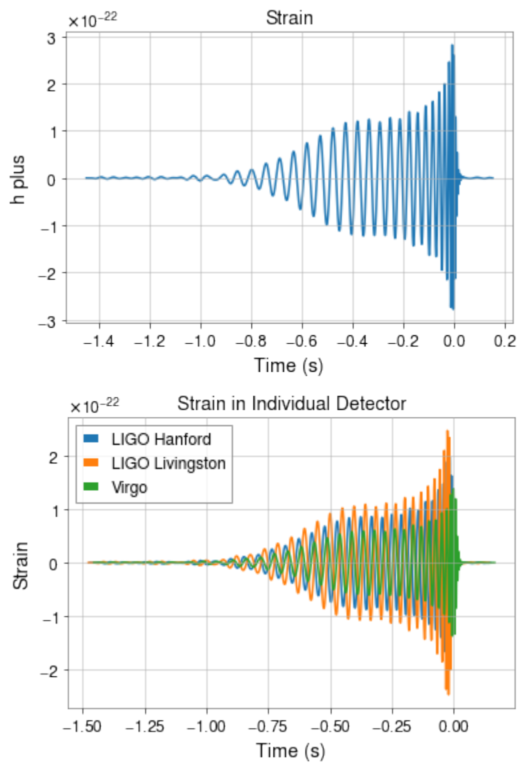

Figure 3: *An example of a simulated merging event using random parameter selection. The waveform was produced with the IMRPhenomXP waveform approximant from pycbc for two black holes of 75 $M_\odot$ and 25 $M_\odot$ at 3000Mpc. A slight spin-induced amplitude modulation is visible due to non-aligned component spins. The top graph is the strain of the GW plus polarization. The bottom graph is the strain each detector in the network would detect based on the mergers sky position.*

[3] All waveforms are produced under the assumption of the flat lambda-CDM model when accounting for cosmological effects.

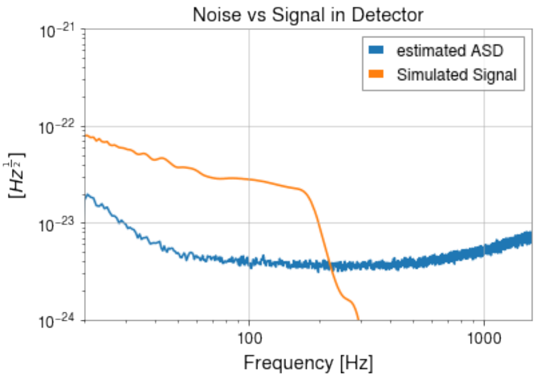

Figure 4: *The above is the frequency domain data corresponding to the event from figure 3. The blue line represents the estimated amplitude spectral density of the noise in the detector, while the orange line is that of the signal.*

Figure 4 is the corresponding frequency domain data for the same simulated signal, in comparison to the LIGO Livingston noise amplitude spectral density (ASD). The small oscillations from 30-50Hz are a visible result of the same amplitude modulation seen in the time domain graph. This particular merger event falls well within the LIGO band, spending more time at lower frequencies, and we predict would be visible to the the network, with an SNR of

2.3. Assumed Initial Conditions

In order to produce predictions for future observing runs, we must use assumptions for what future conditions will look like. Our calculations for O3 utilizes real data, in particular the real noise power spectral density (PSD), to determine the SNR of any given event. However we can not know the noise PSDs for the future, and therefore rely on the pycbc detector PSDs for this study. These are most likely overly-optimistic, and will lead to slightly higher SNR values than would be realistically expected. In particular the low frequencies are expected to have higher noise than the PSDs we use in this study, so we predict higher sensitivity to both high mass and high systems.

As we produce simulated data and predicted SNR, we must consider the metric for which we claim detection in comparison with search pipelines. In this work we threshold the SNR such that if a given event has SNR above 12, we say it is detected by the detector network. In reality search pipelines use a combination of variables, along with SNR, to tag a candidate event. Without real data in this analysis however, we have determined that it is unnecessary to use the search pipeline methods. Additionally we consider waveforms with both spin distributions and higher order modes (HOMs), factors which search pipelines do not include in their template banks. This work does address spin and HOMs in order to determine what effect they would have on detection ability.

When producing the number of IMBHB mergers expected to be observed in the future we must also consider the assumption that the detector network will have a constant duty cycle, and therefore observe all events. This is not a realistic expectation for future observing periods, so once again it should be expected that actual detections will be less than the value presented here.

2.4. Detector Frame

Once the source frame signal has been produced we must consider the varying detector antenna response. Detector response is the reason for the discrepancy in strain, and time delay, seen in the bottom panel of figure 3. This example waveform would be most favorably oriented with respect to the Livingston detector, based on the random sky location parameters given. At different sky locations the largest amplitude could be from a different detector, which is why to determine the overall sensitivity this study will average over random sky locations and orientations.

In addition to detector sensitivity at any given sky location, the waveforms must be red-shifted. This affects the amplitude, and frequency, of the strain detected, and will affect SNR and estimated parameters. The LIGO detector can record frequencies from 24 Hz up to 2048 Hz [8], at a SNR of about 12 [7]. A distant merger emitting waves can appear outside of the LIGO band for higher mass systems, or into the band for very low mass systems. Therefore the study will have to take into account the source frequency produced by the merger, and determine if the following conditions affect its final detectability: The red-shift on signals can reduce the frequency of the mergers to the region below the LIGO band, in which case they will no longer be visible. The amplitude of the signal is inversely proportional to the radial distance to Earth, so some signals may be diminished below the detectable SNR, presumably not triggering a search pipeline. The orientation of the event being favorable to the detector network (optimal events are directly over a detector and face-on) [19]. After these final considerations we can use the detection efficiencies to determine the expected sensitive volume for each scenario.

2.5. Next Steps

Merging binaries behave like a standard candle, with knowledge of a few intrinsic variables, like mass, spin, etc., we can determine their initial amplitude using general relativity. Similarly with knowledge of radial distance, r_{max}, of the merger it is possible to predict the amplitude the detectors here on Earth will receive. Therefore the waveforms will be generated using waveform models at a distance of $\frac{1}{r_{max}}$ for varying binary masses to maximize the signal. The next steps here will be to be sample waveforms on a large scale, using Monte Carlo sampling, and categorize the efficiencies with which they can be detected based on select variables. Then using Bayesian statistical methods the maximized waveforms will be subtracted from data to construct Gaussian noise likelihoods corresponding to the parameters. From there the SNR can be constructed for the simulations, thereby determining a horizon distance estimate for varying stellar masses in the LIGO detector network.

The quantities that interest us in this study are the SNRs, and detection efficiencies, of BBH mergers depending on mass ratio. Therefore we look to average over secondary parameters, such as spin and sky location, to determine the general sensitivity of the Detector Network. The procedure to obtain these results will be explained in depth in the following sub-sections, and was made to allow for easy parameter variation and SNR thresholding changes. This flexible code can be manipulated to account for new information, such as more detailed parameters for simulation, or future detector details. In order to predict the sensitivity of the future observing runs, we use the assumed power spectral densities (PSDs) provided by the pycbc library. This yields an optimal SNR prediction for the future.

3. References

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