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On the Interpretations of the Massive Binary Black Hole Merger GW190521

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ABSTRACT

On May 21st 2019, the most massive binary black hole (BBH) merger to date was observed with LIGO, having a total mass of nearly 150 $M_\odot$. This is surprising due to the fact that one of the black holes (BHs) within this binary had a mass well within the mass gap determined by stellar astrophysics. The outstanding nature of this merger is further complemented by its large effective spin and its high probability for undergoing significant precession. This had a significant impact on gravitational wave (GW) astrophysics, as this binary is one that could not have formed through stellar evolution alone. In this report, I discuss the interpretations and implications of the properties of the BBH merger GW190521, and explain in detail the situations that could have led to its coalescence. I begin with a preliminary overview of GW astrophysics and what information it can provide. I then briefly explain the process of observing GWs with LIGO, and the measurements they made of GW190521. I then describe various different formation channels for the BBH progenitor system, including hierarchical mergers, eccentric mergers, and dynamical formation channels within star clusters and active galactic nuclei. The validity of each of these formation channels are considered, mainly utilizing Bayesian statistics. Finally, I consider the impacts this observation may have in the future, such as with the new generation of GW observatories.

Keywords: astrophysics, star clusters, AGN, compact objects — black holes, gravitational waves

1. INTRODUCTION

In recent years, the one subfield of astronomy and physics that has amassed a large amount of attention and research interest is that of compact objects. Compact objects are some of the most exotic objects found in the Universe, defining the extremes of astrophysical situations. Black holes have the strongest gravitational influence out of all objects, being able to swallow stars and large amounts of gas on very short timescales. Neutron stars have the densest matter in the Universe, which make them a prime situation for studying the dynamics of matter in very dense and pressurized situations. Seeing as these objects represent two extremes, studying them would be able to tell us a great deal of information about fundamental physics and the laws of nature.

Black holes, due to their extreme gravity, can tell us of the effects of general relativity, by observing what happens to particles that stray too close to them or orbit in their vicinity. Neutron stars can give us insight on the nature of matter in very dense states, and hence how it reacts at very high energies and on very small scales. Studying both of these objects involve the utilization of quantum physics, particle physics, thermodynamics, general relativity, and many more subfields of astronomy and physics. Subsequently, these objects can reveal many aspects of almost all topics in astrophysics.

One of the more recent ways of probing these astrophysical scenarios is through compact object binaries. Seeing as these two objects can tell us information separately, having them in close proximity to each other would be able to reveal even more properties of the Universe. Therefore, we can have three combinations of compact object binaries: binary black holes (BBHs), binary neutron stars (BNSs), and black hole-neutron star binaries (BHNSs). All three of these situations can reveal different aspects of astrophysics (§ 2). They can do so from their progenitor systems, orbital dynamics, and mergers. More recently, mergers have become a key

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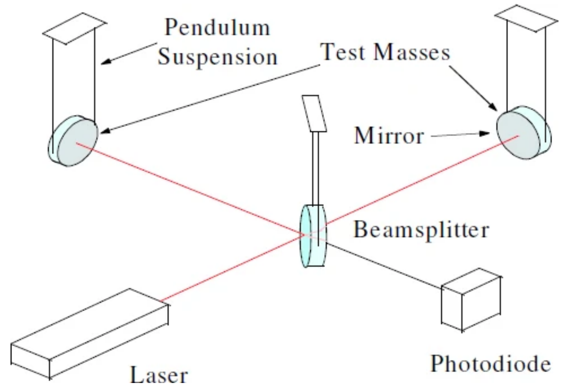

Figure 1. An illustration of the LIGO [15] interferometer. This is based off of a Michelson-Morley interferometer, and functions in almost the same way. The GWs will alter the paths of the interferometer's arms and cause a unique interference pattern on the detector based off of the signal and its orientation. (Pitkin et al. [52])

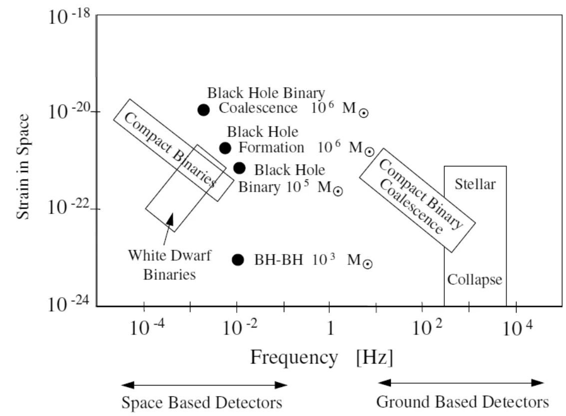

Figure 2. An illustration of the sources that can be measured by GW interferometers, and their locations in frequency-space. It can be seen that current ground-based detectors, such as LIGO [15], can measure compact binary mergers, while space-based interferometers, such as LISA [16], while be able to measure GWs from the creation of the binaries through supernovae from stellar collapse. (Pitkin et al. [52])

way in understanding how these compact object binaries behave, and how the physics predicted to happen within them can be measured. According to Einstein's theory of general relativity, when two masses are accelerated in an asymmetric fashion, they release gravitational radiation, analogous to electromagnetic radiation [52]. However, in most cases, the intensity of this gravitational radiation is not large enough to be measured. The masses need to be very large and the acceleration needs to be very asymmetrical, meaning that these masses exist in a strong gravitational field. One situation which could recreate these conditions is a compact object binary where these two companions are very close together. This happens when the two compact objects slowly decrease in distance from each other and merge. Observing characteristics of this gravitational radiation, including its strain, polarization, wavelength, and change in amplitude, would allow us to characterize the system in which the merger occurred as well as the physics of the individual objects involved in the merger.

The main problem with the detection of gravitational radiation is the accuracy and sensitivity required to do so. After being radiated from an event, gravitational waves (GWs) will gradually lose intensity as they travel across space. As with electromagnetic radiation, the intensity of GWs fall of as d^{-1}, where d is distance from the source. Observing mergers from hundreds to thousands of parsecs away would mean that the incoming GWs would have an amplitude of near 10^{-21} [52]. Furthermore, the detector would also need to be able to discern the characteristics of the GWs on this scale, such as the polarization.

The way in which we detect these GWs is via a modernized Michelson-Morley interferometer, named LIGO [15]. GWs will distort the spacetime they travel through in the direction perpendicular to their propagation. Again, this is analogous to how electromagnetic waves distort the electric and magnetic fields they travel through in the direction perpendicular to their propagation. As the GWs travel, they will contract or lengthen regions of space. This distortion of space can be measured by a simple interferometer. As seen in Figure 1, LIGO's interferometer acts as most interferometers do. A laser is sent into a two-way mirror: the mirror reflects one light ray toward one mirror, and lets one light ray pass through toward another mirror. These light rays will then both come back toward the mirror again, and be reflected toward the detector. LIGO has made very careful consideration so that the mirrors will not be affected by motions of the outside world, as they hang them from pendulums. If the length traveled by one beam of light is different than the other beam of light, there will be an interference pattern recorded by the detector, corresponding to the change in length of the light rays. When GWs pass through the interferometer, either one or both of the perpendicular light beams will have their lengths changed according to the strain the GWs induce in the space they pass through. This can be recorded by the interference pattern overtime, and used to obtain a GW signal. Seeing as the signal will have such a small amplitude, the arms of the LIGO interferometer are very large, as to accentuate the interference patterns made by the GWs.

The GW signal will be different depending on the type of event that caused them. Currently, LIGO has var-

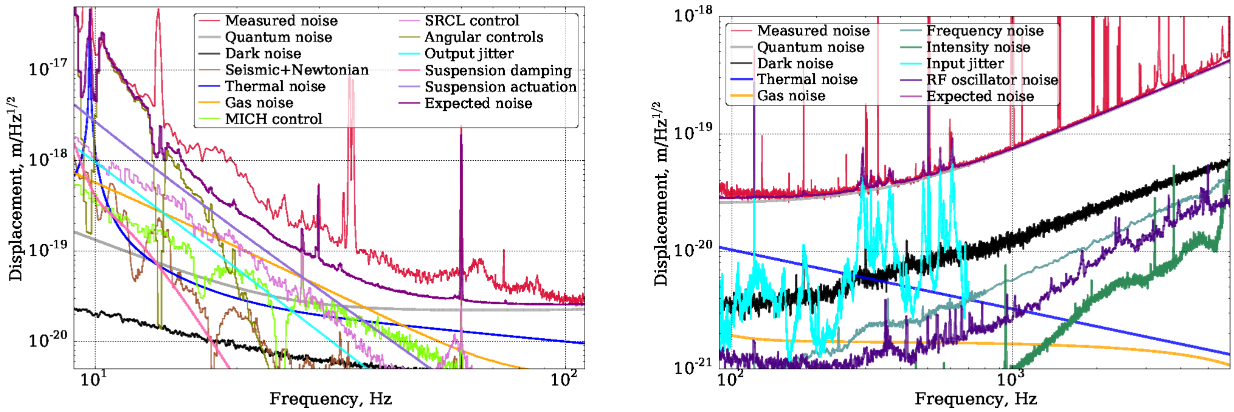

Figure 3. The sensitivities of two of the detectors within the LIGO Collaboration: *Left*: LIGO-Livingston, *Right*: LIGO-Hanford. The noise in both detectors is a combination of environmental, instrumental, and quantum effects. (Martynov et al. [42])

ious templates of GW signals that were created from astrophysical simulations of these compact object mergers under different initial conditions and circumstances. LIGO will compare these templates to the observed signal and extract parameters from the signal using Bayesian inference methods [64]. Therefore, in order to accurately determine what caused these GWs, we first need to simulate a variety of events that could have created them. Then, we can compare the observed signals to our mathematical and physical understanding of the situations to improve our models and theories. We can then begin to further understand the physical processes that occur in these extreme events.

Furthermore, different sensitivities are required to observe different types of events that produce GWs. Ground based detectors, such as LIGO and Virgo, have a maximum sensitivity they can reach before they are limited by noise. This noise is due to a multitude of factors, such as the stochastic gravitational wave background (GWB) [14], or noise from the environment: thermal noise, seismic noise, scattered light, laser noise, beam jitter, etc. Even the quantum noise due to fluctuations in a vacuum are strong enough to affect the observations of the very-low amplitude GWs [42]. Figure 3 displays the noise curves for two detectors within the LIGO consortium. Due to the various sources of noise affecting ground-based observations, LIGO will only be able to measure the most obvious of signals, such as the merger of two compact objects, or even white dwarfs. Figure 2 shows the frequencies of GWs that result from various astrophysical scenarios, and whether ground-based GW detectors can observe them. As we can see, ground-based detectors can observe compact binary mergers very well. They may even be able to observe GWs from highly perturbed or asymmetric core-collapse supernovae [4]. However, only instruments unaffected by many of these different types of noise will be able to measure lower-frequency and lower-strain phenomena, such as BBH mergers with large masses, the dynamics of compact objects binaries, and white dwarf binaries. Such missions as LISA [16] are scheduled to start within the next 20 years, and will be able to measure both these events that require more sensitivity and the GWB.

2. WHY GRAVITATIONAL WAVES?

As stated in §1, the dynamics of compact objects, and therefore their mergers, can be used to study various topics within astrophysics. All three of the compact object binary types can emit GWs, which can then be analyzed for conditions of their merger and dynamics through Bayesian inference methods [64]. After these signals are analyzed and subsequently released to the public, many inferences can be made about the systems they come from, and the physics of the objects within them. Through GWs, we can uncover highly energetic and gravitationally-influenced phenomena that we would not be able to observe otherwise (except in the case of BNS mergers).

2.1. *Neutron Stars*

Neutron star (NS) mergers can reveal a wealth of information in terms of the dynamics of matter in a very dense state and under large stress due to gravity. Observing GWs from BNS mergers, or even simply through observing NSs themselves, can grant us more knowledge on the very uncertain equation of state (EOS) of matter within them. Different EOSs would in turn generate different model GW waveforms for BNS mergers and different dynamics for the BNS systems. Therefore, comparing simulations using different EOSs to observations of NSs/BNSs would allow us to further constrain the dynamics of highly-dense matter. This could then tell

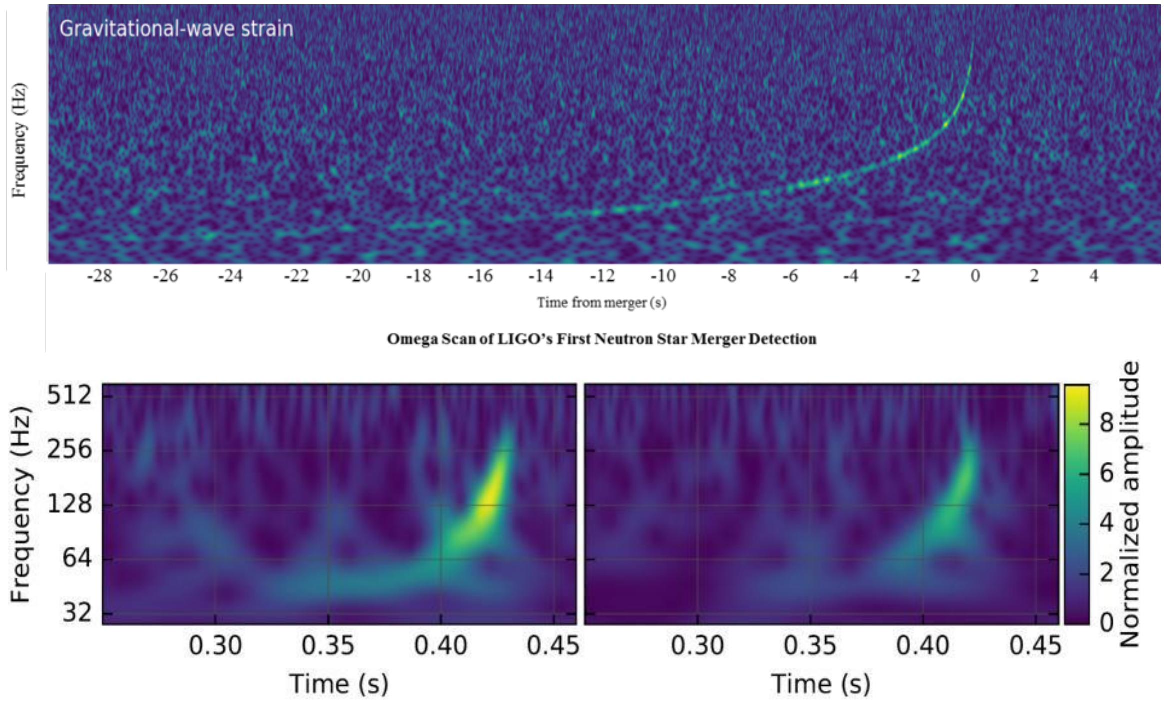

Figure 4. Detection of the BNS merger GW170817. *Top*: The frequency of the incoming GW radiation nearly 30s before merger. The frequency increases as the two NSs grow closer together and eventually coalesce. The colors represent the amplitude of the GW strain on the space that it propagates through. As the merger approaches, the strain becomes more significant. *Bottom*: A similar plot of the frequency of the GW, but showing nearly half a second before the BNS merger. The increase in strain is much clearer in these two plots toward the end of the GW event. (https://www.ligo.caltech.edu/)

us more about particle physics, thermodynamics, and quantum physics.

Currently, there has only been one observed BNS merger: GW170817 [2]. This merger was observed on August 17$^{\text{th}}$ 2017 with the LIGO consortium. There were three coincident detections by three different interferometers within LIGO: LIGO-Hanford, LIGO-Livingston, and Virgo. It is key that multiple detectors confirm a GW signal in a coincident manner, as to increase the validity of its detection, the source of the merger, and the characteristics of the GW signal. Figure 4 shows the increase in frequency as the two NSs in the binary system coalesce. As would be expected, the two objects decrease in radial distance from each other, increasing the frequency at which they accelerate, therefore increasing the frequency at which they produce gravitational radiation. The GWs in turn cause the objects to lose energy, falling in towards each other, until they eventually coalesce, which can be seen when the GW strain reaches its maximum frequency [51]. The time in which this frequency reaches its maximum, the rise of the frequency, and many other characteristics of the strain can be compared to templates of GWs and used to determine characteristics of the system.

Furthermore, GW observations of BNS mergers can be accompanied by electromagnetic observations as well. This comparison of an event with two different mediums of observation has created a new era of "multi-messenger" astronomy. Implications from the electromagnetic observations can be compared to the GW observations to further clarify the cause of these signals. GW170817 also had a short gamma ray burst (sGRB) associated with it, that arrived from the same part of the sky in roughly the same time [2]. In this case, the sGRB suggested that a "kilonova" had occurred after the merger had completed, which is analogous to a supernova of a star. In a kilonova, a large amount of material is ejected from the BNS system after merger. Like in a supernova, a large amount of heavy elements are produced from this merger, though in this situation they are produced in the r-process [36]. These very heavy r-process elements will then undergo β-decay, similar to heavy elements produced in supernovae, and produce a large amount of electromagnetic radiation, characteristic of these r-process elements. Therefore, by studying this kilonova, the sGRB, and the GWs, we will be able to identify the material ejected in the merger, how much of it exists, the conditions of the binary leading up to merger, the remnant that formed after the merger, and so many more characteristics of the system.

There have been many implications of this merger already. Firstly, this presence of an sGRB along with the GWs has given many insights into the remnant of the merger and the EOS of the NSs within the BNS system. Margalit & Metzger [41] have been able to constrain the maximum mass of NSs, and therefore the EOS, through considering the mass of the binary, the tidal deformability of the NSs seen in the GWs, and the implications of the sGRB on the remnant. They conclude different maximum mass limits for different modeled EOSs, meaning that observations in the future of NS masses will be able to rule out certain EOSs. It is also possible to constrain the maximum radius of NSs by considering different collapse scenarios and comparing them to the GW signals [10]. This is done by constraining the threshold mass of a BNS merger remnant, beyond which it will collapse immediately into a black hole. If the mass of the merged BNS remnant is on the order of or lower than this threshold mass, it will be able to survive as a stable "hypermassive" or "supramassive" neutron star for a small amount of time [9]. This can again rule out different EOSs, depending on the maximum radius observed. Comparisons of both the tidal deformability in the GW signal and the sGRB can be used to infer EOSs as well [58].

2.2. *Black Holes*

BBH mergers can also tell us many things about the environment in which these binaries form, how their orbital dynamics evolve, how they merge, and what their remnants are. The first detection of a GW was from a BBH merger: GW150914 [1]. Prior to the observation of GWs, the estimates of black hole (BH) masses came from observations of X-ray binaries (XRBs): binary systems with a black hole and another star. The masses of these black holes were estimated using orbital dynamics and spectral methods. However, there is a large degree of degeneracy when studying the orbital dynamics of these systems, such as due to their inclination angle with respect to our line of sight. Observations of GWs from a BBH merger led to a more accurate estimation of BH masses. Furthermore, the masses inferred from GW150914 were larger than any mass estimated using XRBs. Even from the first BBH merger, knowledge of astrophysical scenarios had improved drastically. Seeing as GWs can only be observed from the events producing largest strain amplitude, we will be more prone to observing large mass BBHs. This makes the effects of gravity and general relativity (GR) more prevalent in these systems, allowing for further tests of GR.

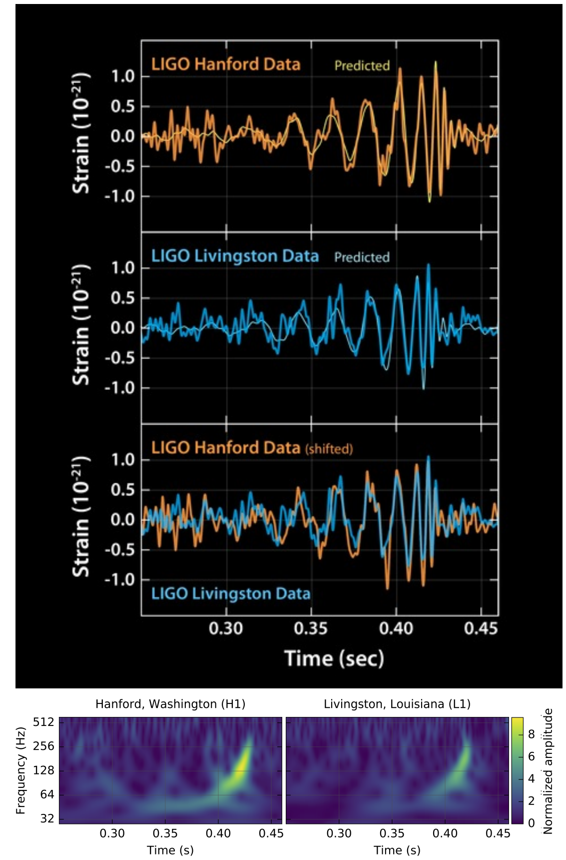

Figure 5. The GW observations made of the BBH merger GW150914. This merger took place on September 14$^{\text{th}}$ 2015 and was detected by two LIGO detectors. *Top*: The strain of the GWs observed from the BBH merger. In both of the detectors' observations, the predicted GW strains are overlayed. We can see that these observations match the predictions fairly well, showing that prior understanding of BBH mergers was justified. *Bottom*: The strain of the GW shown in frequency-space over time, showing nearly half a second before the merger. The left image shows the data from LIGO-Hanford, while the right image shows data from LIGO-Livingston. (https://www.ligo.org/)

Figure 5 shows the strain of the GW for approximately a second before the merger. This merger led to many more accurate predictions on the progenitors of BBH systems, such as hypothesizing that they formed in star clusters [1]. There are also many assumptions made in the initial analysis of this merger that could be explored. Abbott et al. [1] supposed that the eccentricity in the BBH was 0, stating that the eccentricity had dissipated long before the two BHs were measurable. They had also assumed that if the BBH came from an isolated binary, the spins of the BHs would be aligned, as they had formed together. All of these assumptions could be tested in further detail, with the use of numerical simulations to compare observed and simulated waveforms.

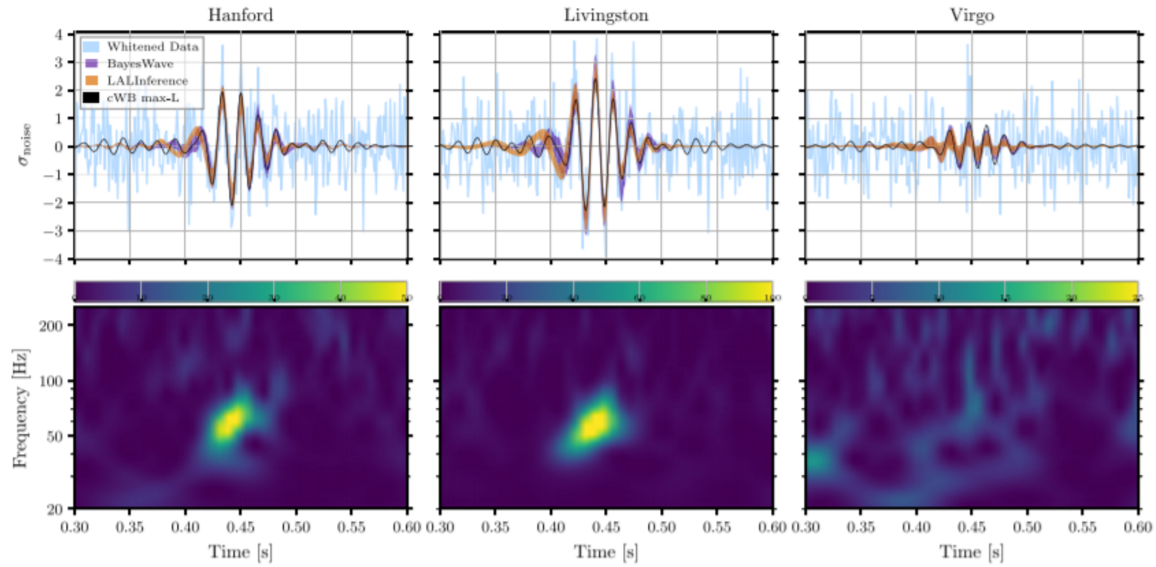

Figure 6. Observation of GW190521 in LIGO-Hanford (*left*), LIGO-Livingston (*middle*), and Virgo (*right*). All three showcase the GW strain ∼.15 seconds before the BBH merger. It can be seen that Virgo obtained the least significant detection due to its lower sensitivity. *Top*: The observed waveform is compared to 3 different waveform templates constructed using the Bayesian modeling of three different programs. *Bottom*: The GW strain as seen in frequency-space, showing the increase in orbital, and therefore GW, frequency of the BBH up to coalescence. (Abbott et al. [3])

We will see throughout §5 that this process of comparing simulated to observed GW waveforms is fruitful in describing unknown astrophysical situations.

3. OBSERVATION OF GW190521

One of the most recent surprising results from GW astronomy is that of the observation of GW190521. This merger was observed as a signal coincident to three of the detectors in the LIGO Consortium: LIGO-Hanford, LIGO-Livingston and Virgo. In initial analysis of GW signals, LIGO will compare to various simulated waveforms of various astrophysical situations, as well as the noise characteristics of the detector on that day to compute the signal's significance. The worst-case scenario granted the signal a signal-to-noise ratio (S/N) of 14.5 and a false-alarm rate of 1 in 8yr. This false-alarm rate translates to the probability that this event is a false-positive detection. Other waveforms granted this detection even stronger confidence. The transient GW signal occurred over approximately .1s and occurred at frequencies much lower than usual [3].

After initial analysis of the data, the GW signal is compiled from all three detections and further scrutinized under various comparisons of noise and simulated waveforms. Firstly, the analysis subtracts any significant narrow spectral lines or noise transients from the time of the signal. Then, the analysis software subtracts models of the noise created from data of the noise near the GW detection. In this situation, there was no noise transients detected near the GW signal, further increasing the confidence of detection. Furthermore, offline analysis and combination of the three detected signals increased the confidence even more. In general, the waveforms that matched the observed GW signal best corresponded to a quasi-circular binary merger. In using Bayesian inferencing methods to determine the characteristics of the system, LIGO found that the total initial mass of the system was $\sim 150 M_\odot$ and the remnant mass was $\sim 142 M_\odot$ [3]. These inferred values are the largest masses of any compact object observed before. The parameters inferred from this signal using waveform analysis from `GstLAL` [13], `Coherent WaveBurst` [63], `PyCBC` [17], and other various software are listed in Table 1.

Normally, in compact binary mergers of black holes, it is assumed that the spins of the black holes are aligned with the angular momentum vector of the system. Black holes have spins aligned with the angular momentum of the system, and therefore each other, when they have formed within the system [27]. When the progenitor of a BBH is a stellar binary, both stars will undergo supernova (SN) in the system and survive. After supernovae, compact remnants of stars will have spins corresponding to their efficiency of angular transport pre-SN. Most stars will develop spins near 0 in these cases, though spin misalignments may occur [23]. The natal kick of these supernovae may also impart an eccentricity into the binary. However, overtime these eccentricities and spin misalignments will be dissipated by the release of

Table 1. Parameters Inferred from GW190521

Parameter	Value
Primary mass (m_1)	85^{+21}_{-14} $M_\odot$
Secondary mass (m_2)	66^{+17}_{-18} $M_\odot$
Primary spin magnitude (χ_1)	$0.69^{+0.27}_{-0.62}$
Secondary spin magnitude (χ_2)	$0.73^{+0.24}_{-0.64}$
Total mass (M_t)	150^{+29}_{-17} $M_\odot$
Mass ratio ($m_2/m_1 \leq 1$)	$0.79^{+0.19}_{-0.29}$
Effective inspiral spin parameter (χ_{eff})	$0.08^{+0.27}_{-0.36}$
Effective precession spin parameter (χ_p)	$0.68^{+0.25}_{-0.37}$
Luminosity Distance (D_L)	$5.3^{+2.4}_{-2.6}$ Gpc
Redshift (z)	$0.82^{+0.28}_{-0.34}$
Final mass (M_f)	142^{+28}_{-16} $M_\odot$
Final spin (χ_f)	$0.72^{+0.09}_{-0.12}$
P ($m_1 < 65M_\odot$)	0.32%
$\log_{10}$ Bayes factor for orbital precession	$1.06^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for nonzero spins	$0.92^{+0.06}_{-0.06}$
$\log_{10}$ Bayes factor for higher harmonics	$-0.38^{+0.06}_{-0.06}$

References— Abbott et al. [3]

GWs [51]. When dealing with very large and asymmetric masses, these facts can not be assumed to be true. These spin misalignments and eccentricities can be perpetuated by the large asymmetry in terms of mass. Therefore, the analysis done by LIGO also tested for the presence of eccentricity. They performed Bayesian inference of parameters related to higher order terms in the BBH evolution, such as higher order multipoles and precession, that could become important when total mass is large. When comparing to these waveforms, they found that the residuals were completely consistent with noise. There was also evidence for non-zero spins of the progenitor BBH system, as well as precession [3].

These characteristics of the system led to a large uncertainty in the dynamics and characterization of the progenitor system. These features extracted from the GWs were unprecedented, as all other BBH GWs were presumed to be from stellar mass black holes. However, the masses of the progenitors ($\sim 85M_\odot$ and $\sim 66M_\odot$) suggest that these are not stellar mass black holes that formed a binary from a progenitor stellar binary system. The two main features that lead to this anomalous behavior are the largely misaligned spin, and the fact that these BH masses lie within the upper mass gap.

4. THE MASS GAP

The mass gap is a theoretical gap in the masses that black holes can take on, predicted by theory and proven by observation. We know of two different types of black holes from observations: stellar mass black holes and supermassive black holes (SMBHs). Stellar mass black holes are known to form from the supernovae of massive stars as they near the end of their life cycle and run out of fuel in their cores. The masses of these remnant BHs of these supernovae explosions are usually only up to $\sim 50M_\odot$ [69]. SMBHs can have masses of $\sim 10^9 M_\odot$, and are found in the centers of galaxies and active galactic nuclei (AGN) in their centers. Thus, we can see that there is a large gap in the mass that BHs can have in general, between the stellar mass BHs and SMBHs. In theory, stellar BHs can form with masses larger than $\sim 150M_\odot$ [69]. Therefore, we can see two unexplained mass gaps within the ranges that BHs can form and have been observed in. The first is due to a lack of observations, which represents the dichotomy between stellar mass BHs and SMBHs, which is a more general gap from $\sim 10^2 - 10^5 M_\odot$. This less constrained mass gap represents a population of intermediate mass BHs (IMBHs), that would suggest the formation mechanism of SMBHs, or the path from stellar mass BHs to SMBHs. The more constrained mass gap, which relates to GW190521, is purely theoretical and due to dynamics within stars and their collapse. This mass gap is also labeled the "upper mass gap" or the "pair instability mass gap", as the process that prevents BHs from forming in this range is pair instability supernova.

As stars in the main sequence progress along their path of stellar evolution, they will eventually run out of Hydrogen fuel in their cores, lacking a stable power source. More massive stars will very quickly move onto burning Helium, and eventually develop Helium cores. For stars with Helium cores of mass greater than $\sim 40 M_\odot$, the contraction of the star will be more accelerated after Helium burning than for stars with less massive cores. In stars with lower mass cores, this contraction would cause an increase in temperature in the center of the star. However, the more accelerated contraction of the star leads to the energy from contraction being used for pair production [66]. Pair production is the nuclear reaction that creates a pair of electrons and positrons from photons. As more pair production occurs within an area of the star, the EOS of that area of the star will also change. It is well-known that when the adiabatic index γ of a certain thin shell of mass within the star exceeds 4/3, it will become unstable. Pair production, when performed in large amounts, can cause γ to exceed 4/3.

From a more physical perspective, as the contraction within a star accelerates, the energy of the photons within the star will then be greater then the combined rest mass energy of both a positron and an electron [69]. This means that the pair production reaction will be favored in the star, over other reactions that could take place. The increase in pair production will lower the total pressure support within the star [69], as it removes photons from the interior of the star, reducing the pressure from radiation holding back the pressure of the outside layers of the star due to gravity. If pair production is frequent enough, this pressure drop is significant enough to cause instability within the star. This instability is known as pair instability.

Therefore, massive stars will initiate collapse of spherical shells in their interiors if they have massive Helium (He) cores. This runaway hydrodynamical collapse of thin shells only increases the temperature within the star, thus causing more pair production to occur. This leads to further instability and more runaway collapse, accelerating the implosion of the star [66, 69]. At this point, the only nuclear reaction that can produce enough pressure to halt the runaway collapse is Oxygen burning. If Oxygen burning is strong enough, this can lead to large amplitude pulsations in the star. Otherwise, the collapse throughout the star becomes dynamic, and the star's temperature and density profiles are much higher than those that would allow for hydrodynamic equilibrium [66]. At this point, the outer layers of the star fall inwards toward the center of the star, and bounce off of the center, turning it from an implosion to an explosion.

This can lead to many types of supernova depending on the mass of the He core and the star in general. The more massive the He core, the "deeper" the bounce from the implosion will be in the center of the star. Overall, for stars to undergo supernova with an He core of mass $\gtrsim 40 M_\odot$, the total mass of the star must be $\gtrsim 100 M_\odot$. For stars with He cores of $40 - 65 M_\odot$ and total masses of $100 - 140 M_\odot$, the pair instability will lead to violent pulsations within the star. These pulsations will violently eject mass amounts of material from the star, being known as pulsational pair instability supernova (PPISN). For stars with an He core mass $65 - 135 M_\odot$, the pair instability is strong enough to destabilize the star [66]. Pair instability will affect large sections of the core of the star, including the center, meaning that the star's core is unstable. This leads to an explosion large enough to completely disrupt the core, making the particles within the star have a velocity greater than the star's escape velocity [69]. Therefore, there will be no BH remnant after this pair instability supernova (PISN). Stars with He cores of mass $\gtrsim 135 M_\odot$ will collapse immediately to a BH, not undergoing any of the pair instability of lower-mass stars [66]. From observations and theoretical stellar physics, we know that massive stars with He cores $\lesssim 40 M_\odot$ will undergo core-collapse supernova (CCSN) as usual.

From this information, we expect that there should not be any stars that collapse into BHs which have He cores in the mass range $65 - 135 M_\odot$. This suggests that there will be no BHs within the mass range $\sim 50 - 140 M_\odot$. Thus, we see that the merger observed in GW190521 seems to contradict the theoretical stellar physics behind PISNs preventing BHs from forming. However, there are a variety of explanations given to explain the progenitor system of this BBH merger. The main assumption used in discussing these types of progenitor supernovae is that the BBH system involved with GW190521 was born from a stellar binary. In this assumed system, two stars would have undergone supernova and adjusted to them in their orbits overtime. These BHs would eventually dissipate all eccentricity in

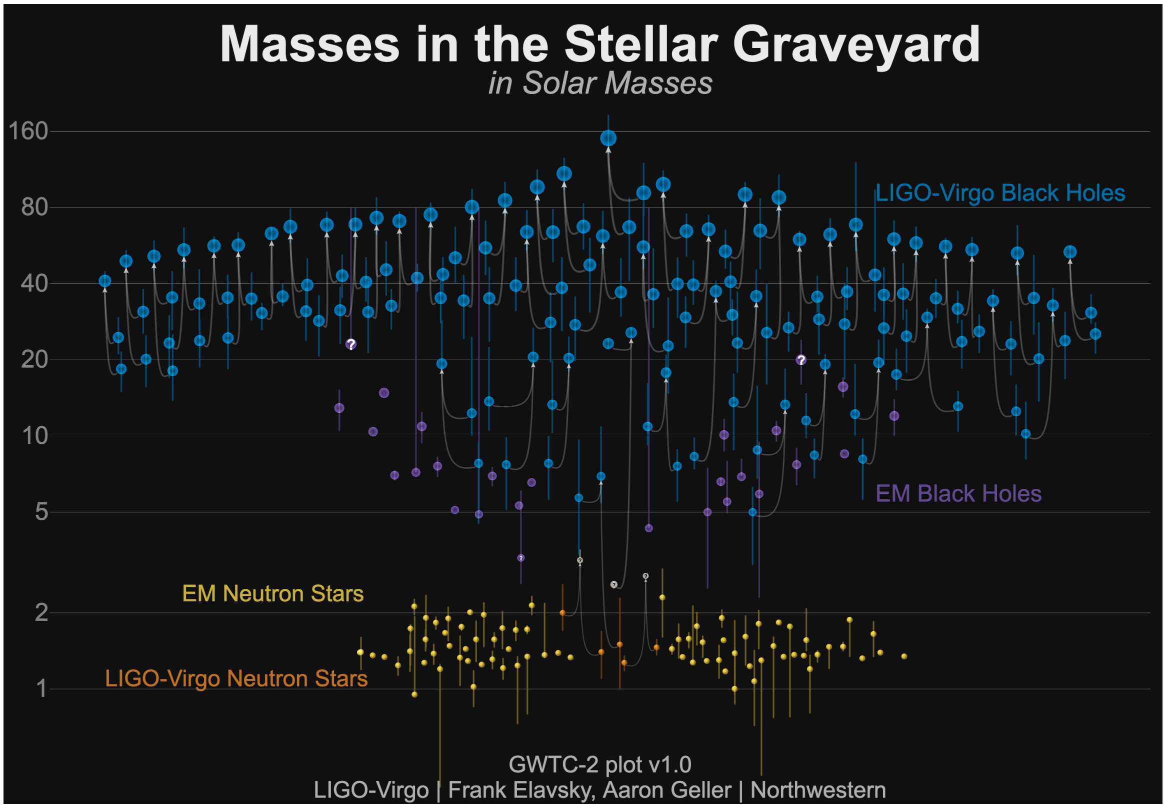

Figure 7. An image presenting the masses of compact objects observed with and without LIGO. We can see that a majority of the BHs observed lie below the upper mass gap of $\sim 65 - 135 M_{\odot}$, though many observed GW events have inferred masses within this PISN upper mass gap. On this graph, GW190521 is seen as the most massive merger remnant in the center at the top of the plot. There is also a lower mass gap, predicted from the maximum mass of NSs, discussed in §2.1. All of the BHs observed from electromagnetic observations are well below the PISN mass gap, while all of the observed NSs are near the predicted NS maximum mass $\sim 2M_{\odot}$. (https://media.ligo.northwestern.edu/)

their system and off-axis angular momenta through the radiation of GWs and tidal effects of gravity. However, if we assume that this BBH system was not formed from a stellar binary, there are many more types of progenitor systems that could explain the masses of the BHs and remnant BH.

5. IMPLICATIONS

In the following sections, we discuss the various scenarios that explain the initial and remnants BH masses measured from GW190521. We also discuss the implications of such events using the parameters inferred from the LIGO observation, seen in Table 1. In addition to these implications and analysis, we also discuss preliminary material used to understand these differing astrophysical situations as background. We then grant the validity of each situation, based on the overall likelihoods presented in data in the literature for each channel of formation.

5.1. *BBH Mergers and Hierarchical Mergers*

From §4, we have learned that we cannot assume that GW190521 formed as an isolated binary system. PISN physics prevents the total mass of the remnant and individual BH masses from existing in BH mergers with stellar binary progenitors. Therefore, we must assume that the two BHs in the BBH system formed separately and came into a binary overtime.

Normally, we assume that BBHs that form from progenitor stellar binaries can be located in any location, as long as stars are able to form there. However, when dealing with these "dynamically formed" BBHs, we have to consider specific locations where this could occur. BBHs formed in this way need to have formed using dynamical friction instead of already being in a binary. Initially, we start with two BHs in a dense environment, say somewhere like a star cluster or in the middle of a galaxy. These BHs will grow closer by having interactions with stars around them and with each other. This turns into a classical 3-body problem eventually, with the two BHs as the inner binary, and a small star as the object far away from the binary. These BHs will accordingly move closer and closer together from the influence of each other and the angular momentum and energy loss from these interactions with stars. This binary will then further harden (decrease in separation) through more interactions with other stars. Eventually, the binary will then impart some of its angular momentum and kinetic energy to stars within its immediate vicinity, hardening further [53, 22]. Eventually, once close enough, these BHs will merge after releasing gravitational radiation. It can be shown that the release of GWs always results in a net loss in energy of the system, meaning the binary will draw closer and eventually merge [51].

However, there are a variety of problems with this very simplistic picture. The first of which is that after a merger or the creation of a BH from a supernova, kicks can eject the remnant from a system. This can also happen in clusters and galaxies from 3-body interactions, where the energy imparted into the BBH from stars surrounding it can kick the binary from the system [45]. Furthermore, creation of BBHs through this dynamical channel of formation can serve to increase the eccentricity of the binary by a large amount [22]. This large eccentricity would make the BBH very unstable, and could lead to the disbanding of the binary if slight perturbations are felt by it.

Many of these problems can be solved by selecting specific locations for the BHs to be in, and introducing certain properties of 3-body problems. It is true that BBH mergers and 3-body interactions can impart kicks onto systems and remnants that could eject them from their environments. Therefore, we need to deal with dense enough environments, where imparting large kicks into the system would not eject them. Or, we would need to deal with environments dense enough that a decent fraction of all BHs or BBHs are not ejected [20]. Even if they are ejected, they would need to be hard enough to merge. The environments first conceived for the creation and merger of these BHs are dense stellar clusters, such as nuclear clusters [7] and globular clusters [49, 70]. For example, nuclear clusters are so dense that they retain most of their BHs [7].

To solve the problem of eccentricity, we introduce the concept of Lidov-Kozai resonances [38, 34]. These resonances occur in 3-body systems, for lower-mass BHs, where there is a misalignment between the axis of the inner binary and that of the outer object orbiting the binary. This relative inclination between the two orbits will trade-off with the eccentricity of the inner binary overtime. In a more physical way, the "settling" of the system by reducing the angular momentum of the outer object to align with the inner object will grant more angular momentum to the inner binary, increasing its eccentricity [45]. From the derivation of GWs, we see that the time of collapse of a BBH due to release of gravitational radiation rapidly decreases as the initial eccentricity of the system grows large [51]. Therefore, this will cause BBHs to merge faster if they have high eccentricities, as all dynamically formed BBHs will have. This will prevent strong recoil kicks from happening, as the time to merge from GW release is very small [45].

Using these arguments, we see that dynamically-formed BBHs form in high-density environments through 3-body interactions, and normally have high eccentricities due to them. In many simulations of populations of BBHs and BH merger remnants, it is seen that high eccentricities are overrepresented [70]. It has also been shown that only nearly 8% of all BHs within a typical cluster will not be ejected from these 3-body interactions [70]. There are also other indicators of dynamically formed BBHs. As stated previously, BBHs formed in isolated stellar binaries will have aligned spins, as their spin misalignments are decreased overtime as the binary evolves. However, BHs that form separately can have any direction of spin and angular momentum. There is no constraint on the direction of spin for BHs formed on their own. Therefore, we expect the spin of dynamically formed BBHs to be misaligned, as the individual BH spins are random [65]. When simulating mergers of BBHs formed dynamically, it is typical to choose a constant distribution of spin alignments for the BBH, as the spins of the BHs would be isotropically distributed about a sphere for a population of BHs [20].

Now that we have discussed how dynamically formed BBHs are created and their properties, we can discuss hierarchical mergers. In these dense systems, such as globular clusters and centers of galaxies, it is possible to have multiple mergers for one BH. For example, say two BHs merge dynamically into a larger, more massive BH. This BH also has a randomly oriented spin, but will be higher mass than stellar BHs in the same environment. This "second generation" (2G) BH can then merge with another BH through dynamical friction. Note that it does not matter what generation this second BH is. This merger of a 2G and another BH will then produce a 3G BH. This process can continue for arbitrarily large generations of BHs [20]. As all of these BHs formed through dynamical friction, they will all have the same properties of dynamically formed BBH remnants. The only difference that can be observed is the mass of the remnant and the masses of the individual merging BHs. Seeing as the merging BHs can be different generations, the mass ratio of the two BHs can be very small. Therefore, hierarchical merging will be expected if the mass of the system is large, the binary

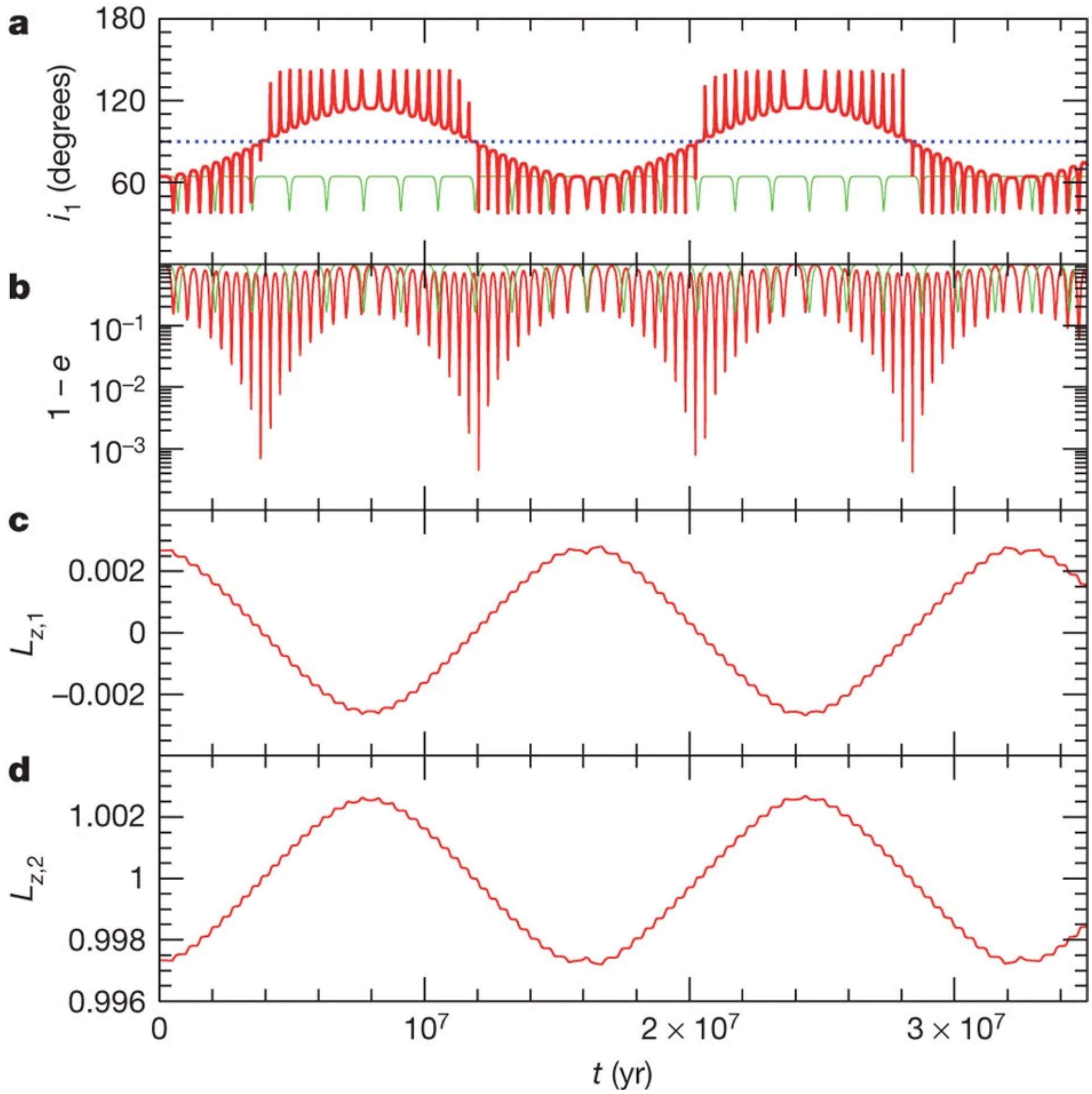

Figure 8. A representation of Lidov-Kozai resonance [38, 34] occurring between a star and a gas giant with small orbital separation. In this situation, the orbit of the inner binary, in this case the star with the gas giant, will have an inclination with respect to the orbit of an asteroid around the inner binary. We can see that overtime, the inclination between the two orbits will trade off with the eccentricity and the angular momenta of the two objects in the inner binary. The eccentricity will reach maxima as the relative inclinations reach minima. This situation is comparable to a BBH, but in a merger, these resonances will be stronger, causing the eccentricity to fluctuate to higher amounts. (Naoz et al. [47])

is eccentric, and the spins are misaligned. Two of these indicators can be seen in the case of GW190521. We see that the total mass of the system is large, the spins are misaligned ($\chi_{eff} \neq 0$), and there is a decent probability for nonzero spins on the individual BHs.

There are various studies that have been conducted to test the validity of GW190521 being a hierarchical merger. The first of these studies simply discusses the probability of GW190521 being the product of a hierarchical merger. Kimball et al. [33] have used BH population analysis on simulations of metal-poor globular clusters to measure the mass distributions and characteristics of each generation of BHs, using Bayesian inference techniques. They also computed the probability of any of the BBH GWs observed in the second run of LIGO to be a hierarchical merger. They found that the probability of at least one of the BHs involved in any of these observations is $\sim 96\%$. One of the two most probable observations of a hierarchical merger was GW190521, with a 50% probability to be a 1G+1G merger and a 50% probability to be a 2G+1G merger. Furthermore, they computed a Bayes factor of 7 when testing if it was more

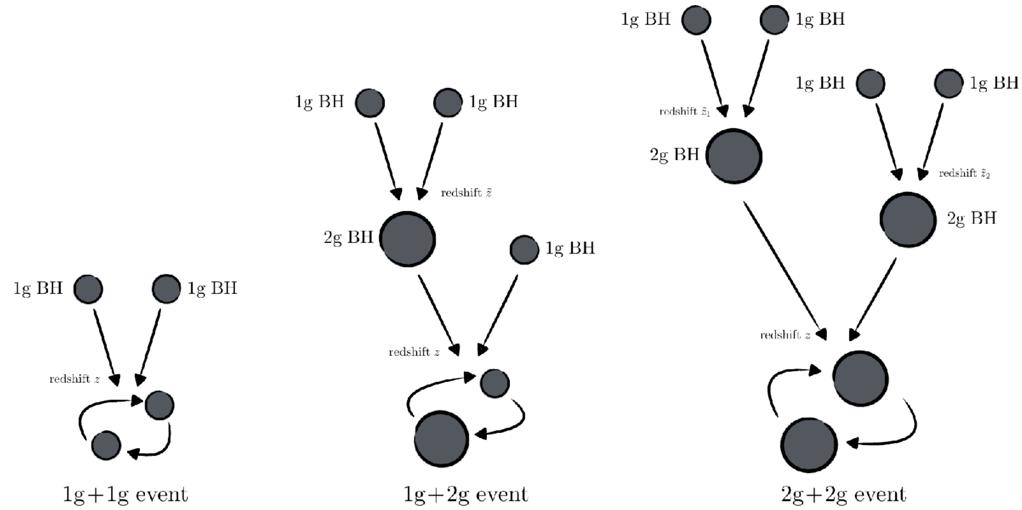

Figure 9. An illustration of various hierarchical mergers of various generations of BHs. We can see that in the 1G+1G merger, two BHs that formed from stellar collapse merger to form a second generation (2G) merger. These hierarchical mergers can occur in various combinations of generations of BHs, as there can be 1G+2G and 2G+2G mergers. These mergers can be distinguished by the information encoded in the GWs we observe. Using Bayesian inference, we can recover the parameters from the merger and determine the properties of the BHs within the merger. (Gerosa & Berti [26])

accurate to allow for hierarchical mergers in the modeling of this population [33]. This shows that GW190521 has a likely chance to be a hierarchical merger of at least two 1G BHs.

Anagnostou et al. [5] took a similar approach in modeling BBHs in globular clusters. However, the goal they were striving to investigate was if BBH mergers in a globular cluster using a certain kind of hierarchical merging could produce an IMBH. This "snowball" merger involves 7 hierarchical mergers within it. There will first be a 1G BH somewhere within the cluster. This will then form a binary through dynamical friction with another BH. This BH will then continue to merge with other BHs, sinking to the center of the cluster along the way. They stop the merging process after 7 mergers, giving this snowball merger a length of 7. Comparing to GW190521, they state that it is likely that GW190521 formed from a merger of BHs of higher generations in a snowball merger with a similar length. Additionally, Fishbach et al. [20] state that BHs of higher generations have spin distributions that peak $\sim .7$ for a variety of combinations of BBH orbital separations and mass ratios, which is close to χ_{eff} and the spins of the individual BHs in GW190521.

5.2. *Mergers in Star Clusters*

Seeing as star clusters are themselves dense environments, they would be ideal locations for the dynamically formed BBH mergers that have been discussed in §5.1. After most of the BHs have formed in a given star cluster (roughly 40 Myr after the last supernova), the BHs will sink into the center of the cluster. This sinking of BHs overall takes approximately 1 Gyr. After this time, stellar mass loss will have diminished, as the cluster is old and most of its stars have gone supernova. After this stage, the cluster's core will contract, leading to a more concentrated gravitational sink in the center. This will lead to the formation of more BBHs in the cluster overall [70]. Furthermore, BHs throughout the cluster can merge with other BHs as they sink to the center of the cluster [45].

This creation and merger of BBHs is only increased in denser, nuclear clusters. These nuclear clusters are very dense and contain a sizable population of younger stars. These stars act as a source of BHs and BBHs to the cluster over the cluster's lifetime [7]. This population of younger stars will continue to produce BHs through supernovae, which can then form binaries with other BHs in the cluster, sink to the center, and merge. Therefore, we can see that hierarchical and dynamically formed BBH mergers are likely to happen in dense star clusters. However, there is also another method of forming BHs within the PISN upper mass gap.

In very dense environments like star clusters, stars themselves may collide and merge often. In young clusters, this occurs even more frequently, as there is a greater population of stars in general. These stars themselves will then undergo supernovae and collapse into BHs. If the massive star formed through stellar collisions has a high enough mass, it may collapse into a BH within the upper mass gap. This is made possible mainly due to the density of stars within a cluster, and the process of mass segregation.

Overtime massive stars in dense clusters gravitationally segregate, where the most massive stars will fall towards the center of the cluster [49]. This is analogous to the BHs sinking towards the center of the cluster as it ages. It should be noted that these massive stars can also form progenitors of BBHs that form in isolation from stellar binaries. In many observed young massive clusters, however, this segregation takes place over times much less than the cluster's relaxation time. This signals that the massive stars within the cluster would not have had time to segregate. Therefore, there have been theoretical studies investigating primordial mass segregation within young massive clusters. This primordial mass segregation is mainly based on the initial conditions of the region the stars were formed in [35].

Kremer et al. [35] have done a study using simulations of populations of stars within young massive clusters to observe the properties of BHs formed from stars who have undergone stellar collisions. In this work, they perform simulations both with and without primordial mass segregation, to see which type of cluster dynamics supports mass gap BHs. Furthermore, they represent various types of stellar mergers and dynamics for different types of stars involved in the mergers. For example, some collisions may require a "sticky-ball" model, while others require common envelope evolution. They then allow the BHs that have formed from either regular channels or stellar collisions to enter BBHs. In the process of CCSN, they allow PPISN and PISN to occur.

In these simulations, of the 259 BBH mergers, 37% featured at least one component which underwent at least one stellar collision. Furthermore, 6% of the mergers involved a BH in the mass gap. In this study, they also investigated the pairs of BHs that merged throughout the simulations. They found that 3% of the mergers involved a mass gap BH and a BH from a stellar collision, and 4% of the mergers involved a mass gap BH and a 2G BH. We can see that in this model for young massive clusters, mergers involving hierarchical BHs are less frequent than mergers involving BH formed from stellar collisions. This means that BHs within the mass gap may favor forming from BHs created from stellar collisions over forming from hierarchical mergers. To further validate this implication, Kremer et al. [35] calculated the rate of BBH mergers involving a mass gap BH. In doing so, they came to a value of .1 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$, which is very close to the rate of events like GW190521, predicted by LIGO to be $0.13^{+0.30}_{-0.11}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ [3]. Seeing as the rate of BBH mergers with mass gap BHs is very similar to an observation of a merger with a mass gap BH, this implication that there are a large amount of mergers involving stellar collision BHs is somewhat validated. Furthermore, mass gap BH mergers favored the simulations with primordial segregation, as if the masses were already segregated at early times within the cluster, there would be more time for the BHs to merge and stars to collide.

5.3. *GW190521 as an Eccentric Merger*

As stated in §5.1, BBHs formed via dynamical friction will have many parameters that can distinguish them from BBHs that have formed from isolated binaries. From Table 1, we can see that GW190521, representative of a dynamical merger, has a high spin and a large mass. We can also see that the proposed primary mass in the system m_1 has a mass within the PISN mass gap for BHs. From the process of dynamical friction, we also know that BBHs can form with very high eccentricities. In fact, any binary formed from chance encounters like those formed from dynamical friction can have large eccentricities. Therefore, an observational signature of chance encounters is a large eccentricity [24]. We know that BBHs formed from an isolated stellar binary will dissipate their eccentricity through release of GWs. In §4, we saw that the eccentricity of low-mass BBHs can be affected by Lidov-Kozai resonances, which can serve to both increase and decrease the binary's eccentricity. However, it has been shown that the rate of mergers that experience a Lidov-Kozai resonance which significantly changes its eccentricity is relatively low [59]. Therefore, many BBHs within dense environments will not have time to dissipate their eccentricities completely through the emission of GWs. BBHs could form with low orbital separations and high eccentricities, leaving little time to dissipate through gravitational radiation [24].

Therefore, in order to properly model the characteristics of the system a GW has come from, we need to involve the effects of eccentricity and precession in the waveforms we are using to compare to observed GWs. Furthermore, more massive BBHs will be more likely to show effects of eccentricity and precession, as they will form with high eccentricities. We can therefore derive properties of the merger or the binary system from its eccentricity. Studies of populations BBHs in dense star clusters have shown that out of all BBHs merged, $\sim 5\%$ have $e > .1$ [55, 6].

There have been various studies analyzing GW190521, while taking into account eccentricity. One study, done by Romero-Shaw et al. [54], has used Bayesian inference on the observed GW190521 waveform using non-eccentric waveforms, while including effects of eccentricity in their analysis. The parameters they have inferred are located in Table 2. They found that the BBH in GW190521 has an eccentricity greater than .1 . The eccentric BBH model they used was favored over the normal precessing model with a Bayes factor of 100. They also found masses consistent with the data from the LIGO observation, validating their methods.

Gayathri et al. [24] have studied this eccentric BBH situation in more detail, creating a family of waveforms which include a range of high eccentricities and precession. In doing this, they performed 325 numerically relativistic simulations to obtain 325 waveforms. Like LIGO, they then extracted parameters from GW190521 using Bayesian inference using their eccentric waveforms as templates (Table 2). We can see that the inclusion of eccentricity in the waveforms increased the mass of the system, and the individual BHs, and decreased the distance to the system. However, the inclusion of these parameters gave a similar value for the spin parameter for precession. They found that an eccentricity $\sim .7$ gave the highest likelihood, which also supports the results from Romero-Shaw et al. [54]. They also found that their waveforms including eccentricity favored the waveforms used by LIGO with a Bayes factor ≈ 100.

From both of these studies, we see that the eccentric, precessing merger scenario is supported over the non-eccentric, precessing scenario. Unfortunately, this may completely invalidate the parameters obtained by LIGO in using their waveforms. It has been shown that there is a degree of degeneracy in the waveforms including eccentricity and precession. GW signals formed from head-on collisions or those with high eccentricities can be confused with those emitted by precessing, non-eccentric mergers [12]. Therefore, simply from not utilizing eccentric waveforms, the parameter estimates from Bayesian inference can be completely off. However, the inverse may be true, in that results using these eccentric waveforms can be confused with those from non-eccentric ones. Therefore, more information on the system or astrophysics of the situation is needed. However, it seems to be that GW190521 is a highly eccentric merger with eccentricity near .7.

5.4. *Mergers in AGN*

As we have seen, historically, most of the discussion considering BBHs formed from dynamical encounters have been focused on star clusters. These environments represent very dense areas of space containing very high escape velocities, so that even after mergers, remnants will still remain in the system to undergo more mergers. However, there is also an alternative dense environment which has been proposed to have BBHs and BBH mergers: AGN. It a very well-received idea that AGN are SMBHs residing in the centers of galaxies, producing light from interactions within their accretion disks. Seeing as the BHs within these AGN are so massive, they can have gravitational interactions out to very large distances. Furthermore, matter near the core of this SMBH will feel very strong effects of its gravity (hence we call this matter in the strong regime). This combined with the fact that the accretion disk is confined to a plane also implies that the matter near the SMBH is very dense. Additionally, AGN contain the dense nuclear star clusters (NSCs) mentioned in §5.2 around their cores. Therefore, there are a plethora of resources to form BHs and BBHs, and a dense environment to keep them from being ejected from the system.

In fact, there is even more of a reason that BHs and BBHs would be more present in AGN than in other dense environments. One of the first reasons shown why this may occur is the number of BHs within AGN and its accretion disk. When first forming the accretion disk, the SMBH within the AGN will pull gas from its surroundings. In its surroundings, we know that there is an NSC, so if the pull of this SMBH is strong enough, it can pull a number of stars from the NSC into its accretion disk [30, 56]. This "grounding" of stars in the NSC may also ground BHs if the NSC is old enough. Furthermore, it has been shown that conditions within accretion disks of quasars favor the formation of massive and supermassive stars, which would grant a population of BHs within the accretion disk [28]. It has also been shown that AGN disks can harbor tens of thousands of stellar mass BHs and massive stars that will eventually form BHs [46]. The initial mass function (IMF) of stars, which determines the distribution of mass of a certain population of stars, prefers higher masses near the center of AGN [46]. These BHs could be ejected from natal kicks in the SN that form them, but a fraction of BHs born in the AGN disk will remain in the disk [37].

We have seen from §5.2 that dynamical interactions serve to form binaries and harden them. In interactions within globular clusters, these dynamical friction interactions occur when an inner binary of BHs exchanges angular momentum with a low-mass star near it, or another BH. This can also happen in AGN, where massive stars and BHs will migrate either inward or towards the SMBH in an AGN by exchanging angular momentum with low-mass stars [46]. When we are dealing with AGN and their accretion disks, we no longer have to rely on these 3-body encounters. In general, when a binary is located within a disk of gas, the binary will harden as its angular momentum is exchanged with the gas [57]. This

Table 2. GW190521 Parameters Assuming an Eccentric Merger

Parameter	Gayathri et al. [24]	Romero-Shaw et al. [54]
Primary mass (m_1)	$102^{+7}_{-11} M_\odot$	$84 M_\odot$
Secondary mass (m_2)	$102^{+7}_{-11} M_\odot$	$62 M_\odot$
Total mass	$204^{+14}_{-33} M_\odot$	146 $M_\odot$
Mass ratio (q)	1	.738
Luminosity distance (D_L)	$1.84^{+1.07}_{-0.054}$ Gpc	5.0 Gpc
Redshift (z)	$0.35^{+0.16}_{-0.09}$	...
Eccentricity (e)	0.67	$> .1$
Effective spin (χ_{eff})	0	...
Precession spin (χ_p)	0.7	...
Right ascension (α)	...	3.3 rad
Declination (δ)	...	0.5 rad
Reference phase (ϕ)	...	6.2 rad
Polarization (ψ)	...	1.6 rad
Inclination (θ_{JN})	...	0.3 rad
Geocent time (t_0)	...	39.368 yr

Note—These are the parameters extracted from the observed GW signal from GW190521. The parameters from Gayathri et al. [24] utilize eccentric precessing waveforms constructed using simulations of eccentric BBH mergers. Romero-Shaw et al. [54] do not use waveforms including eccentricity and precession, but the same waveforms that LIGO had used in inferring their parameters. However, in their analysis, they utilize assumptions of eccentricity and precession to extract information about the BBH. We can see that Gayathri et al. [24] obtain more information about the system dynamics and individual BHs, while Romero-Shaw et al. [54] obtain more information about the orbits within the system.

References— Gayathri et al. [24], Romero-Shaw et al. [54]

can be applied to binaries within the AGN accretion disk, or the orbits of objects around the SMBH within the accretion disk. Therefore, objects located within the accretion disk will migrate inward towards the SMBH overtime [46, 56, 28]. The more massive objects, such as BHs and massive stars, will migrate inwards faster than the lower mass objects, leading to a segregation of mass within the AGN disk [46, 50]. Therefore, there is a large concentration of stellar remnants in the cores of AGN, which serves as a breeding ground for BBHs and mergers [46, 30]. Subsequently, the mass of compact object remnants dominates the central mass of the AGN, totaling near $10^6 M_\odot$ [46].

From the information we have seen so far, there are two ways in which a BBH could form within an AGN disk. Either (i) the BBH forms as two BHs are migrating towards the central SMBH, or (ii) the BBH has formed already prior to large-scale migration. We will deal with the process of forming BBHs through migrations first. If two BHs encounter each other within the accretion disk as they are migrating inward with low relative velocities to each other, then they can form a BBH [57]. However, the motions of the accretion disk can also affect the formation rate of BBHs from migration interactions. When we assume that an accretion disk is isothermal, the migration of objects will always be inward. However, under other conditions, migration within the accretion disk can be outward. Therefore, there are places within the accretion disk where both of these conditions exist and cancel each other out [57]. In these locations, migration is halted and migrating objects stand still [39]. We call these locations ‘migration traps”, which naturally attract migrating objects within AGN. Therefore, BHs within AGN will be attracted towards migration traps, and can form BBHs with other BHs migrating towards the migration trap along the way. These BHs migrating inwards can also accrete mass from the accretion disk and grow more massive [43]. After an extended period of time, there will be a pile-up of BHs in the migration trap, where many BHs will merge [43, 68]. This massive BH within the migration trap can keep attracting BHs and merging with them overtime. It has been shown that more massive bodies migrate towards the migration trap faster [57]. Therefore, there is an increased chance of mergers happening on the way to migration traps, as larger BHs will have a larger gravitational reach, and there is an increased chance of mergers happening in the migration traps, as the BHs within the migration traps will have large masses early on.

If a BBH has already formed in the AGN, or if it has formed from one of the processes discussed previously, then there are a variety of mechanisms that push it to merger. When BBHs form inside of the accretion disk, many times they will have some inclination with respect to the plane of the accretion disk. In their orbits, these BHs within the BBH will cross the accretion disk, each time accreting a certain amount of gas. Overtime, this accretion produces a drag on the BHs within the binary, eventually causing the BBH's angular momentum to align with that of the accretion disk [8]. After the BBH has aligned with the accretion disk, it will harden due to torque and drag from the surrounding gas [32]. The torques from the interaction between the BBH and the gas will create a cavity within the accretion disk around the BBH. At the edge of this cavity, a circumbinary accretion disk is naturally formed. Tidal forces suppress accretion onto the cavity and therefore the binary, meaning that the binary is imparting some of its angular momentum into the circumbinary accretion disk. This release of angular momentum and the torque it imparts on the binary hardens it, making the BHs come closer together [30].

Seeing as so many binaries can be produced with in AGN, and drag and torque from the gas facilitates mergers, there are a lot of mergers taking place within AGN. The density of the environment along with the presence of migration traps also facilitates hierarchical mergers, seen in §5.1 [68, 60]. The efficiency to which the gas can extract angular momentum causes these mergers to be very quick, often times not being able to decrease the eccentricity of the BBH before merger [30, 8, 56]. As if there weren't enough processes facilitating BH mergers in AGN, the SMBH can also produce Lidov-Kozai oscillations within BBHs. These oscillations cause BBHs to merge faster, as well as increase the eccentricity and inclinations of mergers [21, 8]. The rate of mergers due to Lidov-Kozai oscillations depends on the mass of the SMBH, but in general is .17-.52 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ [21]. Therefore, we expect to see a large amount of eccentric and inclined mergers in from AGN. In total, the upper limit to the BBH merger rate in AGN has been proposed as 72 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$, or 13 yr^{-1} observed by LIGO [8, 57].

Assuming only that the accretion disk aligns BBHs with the angular momentum of the disk and hardens them, and that migration traps exist, we can declare that most BBH mergers within AGN are hierarchical. From this, we can observe that higher-mass BHs are overrepresented in BH populations by a factor proportional to the mass of the SMBH [67]. Yang et al. [68] found that $\sim 30\%$ of mergers have BHs with masses within the PISN mass gap, and $\sim 50\%$ of binaries have orbital momentum aligned with the disk. They also found, intuitively, that the mass distributions for higher generations of BHs favor higher masses. They also confirmed that the effective spin of 1G+1G BBH merger remnants peak at $\sim$ .7, which is close to that of GW190521. Furthermore, they found that $(47, 29, 15, 6, 1)\%$ of mergers in AGN are (1,2,3,4,5)G. This makes sense, as there would initially be a lot of 1G BHs, so most of the mergers would be 1G. It would make sense if GW190521 took place in an AGN, as 1G and 2G mergers make up nearly 76% of all mergers.

However, there is another method of forming binaries and forcing them to merge in an eccentric fashion, similar to the dynamical formation of BBHs in star clusters. These 3-body encounters involve a BBH interaction with a single BH, being labeled a binary-single (BS) interaction. These interactions are like those in star clusters, but the outer mass is on the order of the inner masses. In these encounters there are two situations that could occur: (i) the inner binary merges and then its remnant merges with the third BH, (ii) the inner binary merges and is ejected from the 3-body system. These situations are called 3-body and 2-body mergers respectively. In many cases, 2- and 3-body mergers are needed to decrease the BBHs orbital separation enough to merge, through exchange of angular momentum [56]. Samsing et al. [56] performed numerical simulations of these 2- and 3-body mergers to measure statistics of BBHs, while assuming that all interactions were confined to a 2-dimensional (2D) plane. They found that the probability of 2-body mergers was higher than that of 3-body mergers. However, 3-body mergers occurred more often within distances of $\sim$ .1 AU of the SMBH and, produced higher eccentricities, larger than .1. Additionally, they found that eccentric mergers within a disk took place at a rate an order of magnitude higher than eccentric mergers within a 3D space, such as a cluster. This sug-

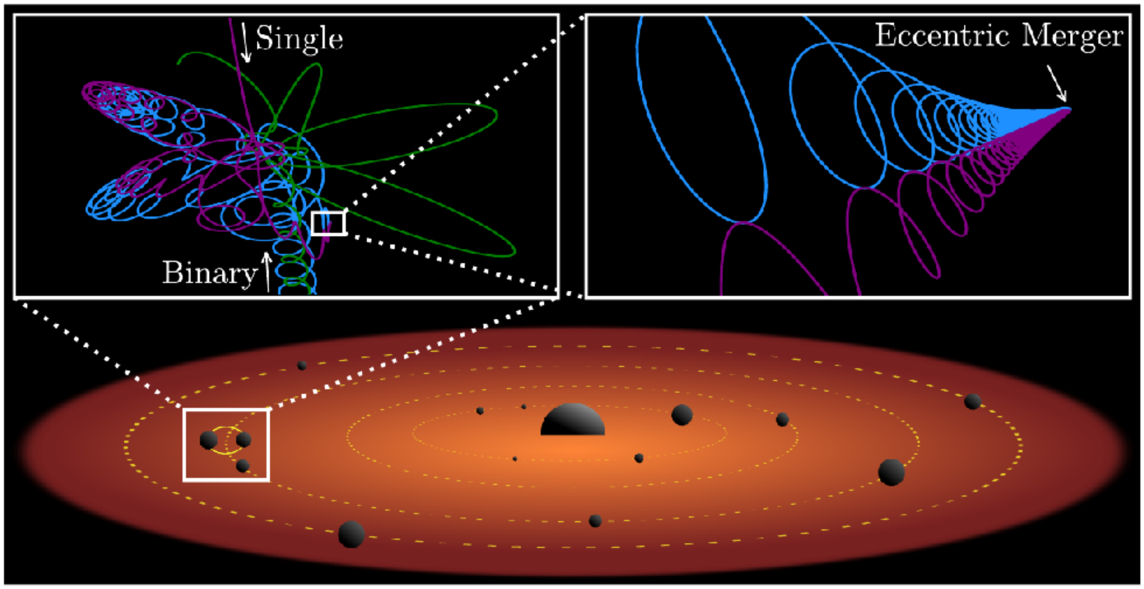

Figure 10. A representation of how a binary-single (BS) interaction would take place within an AGN. The bottom image represents the plane of the AGN accretion disk with various BHs within it, including the SMBH at the center. The top left image displays the 3-body system overtime, with the inner binary trajectories shown in blue and purple. The outer black hole perturbs the inner binary, hardening it and increasing its eccentricity. The image on the top right displays the eccentric BBH merger that takes place after the orbital distance within the BBH becomes small enough for GWs to remove energy from the system. (Samsing et al. [56])

gests that GW190521 is more likely to have taken place within an AGN, seeing as it has been proposed to have high eccentricity.

Tagawa et al. [61] expanded upon this, introducing BS interactions in 3D, while also accounting for non-BS mergers, meaning mergers of two singular BHs. They found that when BS interactions are allowed in 3D, $\sim 14\%$ of mergers have an eccentricity significant enough before merger that it is measurable by LIGO. When trying to reproduce BBH waveforms, they found that most of the parameters coincided with those of GW190521. However, the eccentricity of the BBHs in the simulations was not consistent with what was inferred from the observed GW. In general, they found that $\sim 10-70\%$ of mergers in AGN had detectable eccentricities. Therefore, these rates and probabilities provide a decent chance for GW190521 to be a merger in AGN.

Tagawa et al. [60] performed another set of simulations, including 2- and 3-body mergers and hierarchical mergers. Their simulations also supported BNS mergers, as well as mergers within the lower mass gap. These lower mass gap objects were treated as BHs, and then allowed to merge with other BHs. After obtaining statistics of these mergers and binaries, they then compared parameters to that of GW190521. They confirmed that the misalignment between the spins of the BHs and the orbital momentum was isotropically distributed about a sphere and a spin distribution peak at $\sim .7$, which was stated as a property of dynamically formed binaries and hierarchical mergers. They found that BHs like those in GW190521 come from hierarchical mergers involving BHs with generations ≥ 6. This is similar to what we have seen with the snowball merger in §5.1. Furthermore, they found that the rate of GW190521 can be explained by formation within an AGN. They found that the rate of GW190521 and the parameters obtained from it are consistent with both higher generation and 2G+2G mergers. Only some 1G+1G mergers were able to reaches masses as large as GW190521, if they accreted enough mass at a super-Eddington rate from the accretion disk. Therefore, we can see that many of the parameters obtained from GW190521 are consistent with these 3-/2-body and hierarchical mergers in AGN.

In addition to GWs, there are also electromagnetic signals that could come from BBH mergers in AGN, further validating this method of formation. In a BH merger, mass is lost as the BHs merge and after the merger remnant begins its "ringdown" phase. This mass loss carries away angular momentum and energy from the system post-merger, and transfers it to gas that then interacts with gas in the accretion disk. The collision of this ejected mass and the accretion disk gas will release energy that can be seen in electromagnetic radiation [44]. Energy could also be released if the merger imparts a kick on the remnant, which then forms a

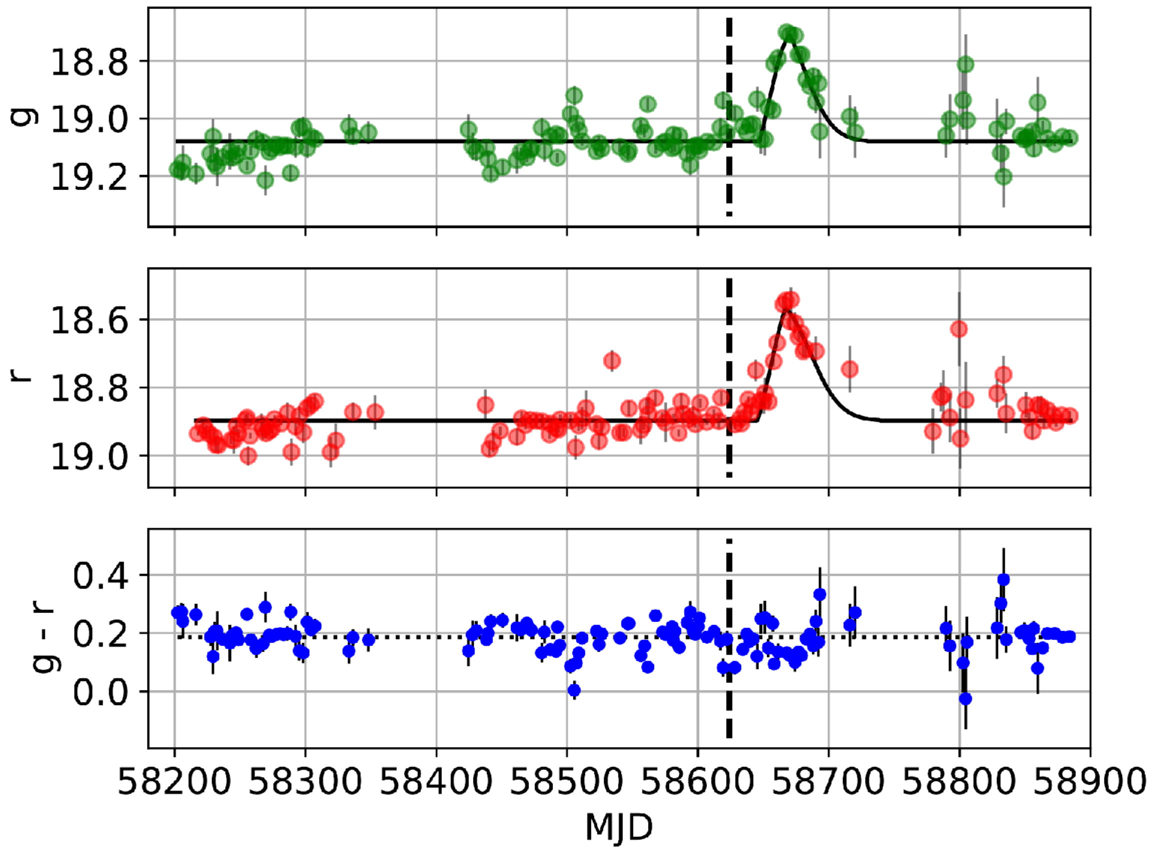

Figure 11. The measured lightcurve for the flare from AGN J1249+3449, labeled ZTF19abanrhr. This curve supposedly corresponds to the BBH merger GW190521 as it is localized in the sane area on the sky and has a suitable delay from the GW event. The two top curves are measured in the g and r bands respectively by the Zwicky Transient Facility, as well as their corresponding fits. The bottom plot is the corresponding g-r color overtime, showing nearly a constant value. The vertical dashed line through all three plots represents the time when the observation was triggered. (Graham et al. [29])

shock as it is propelled through the accretion disk. This shock will produce a certain characteristic radiation, much like shocks seen from asymmetric SN [44]. Additionally, BBHs can release electromagnetic radiation if one of their BHs experiences super-Eddington accretion [8], as seen in the 1G+1G hierarchical mergers in Tagawa et al. [60]. There was an observed electromagnetic counterpart to GW190521 though it has bee contested. This signal was observed from an AGN in the optical by the Zwicky Transient Facility [11], labeled ZTF19abanrhr [29]. Gayathri et al. [25] used a variety of parameters from both GW190521 and ZTF19abanrhr, including D_L, e, z, and the mass of the AGN to determine a measurement of the Hubble constant H_0. Using only GW190521 they found a value $\sim$ 88.6 km s^{-1} Mpc^{-1}. After combining parameters from GW190521 and other GW measurements, they found a value that was in agreement with other measured values. Therefore, assuming GW190521 is a BBH merger in an AGN allowed for measurement of cosmological constants.

6. CONCLUSION

In this report, we have discussed the various interpretations of the BBH merger GW190521, and the implications it has had on various subfields within GW astrophysics. We have seen that GW190521 is the first merger to have displayed a BH component within the upper PISN mass gap, signaling that it is the first observed merger to contain a BH that was not the product of stellar evolution. We saw from the LIGO detection that this merger displayed various qualities that signal an eccentric or hierarchical merger, with a large total mass, asymmetric spin, and large chance for precession. This merger further validated claims of hierarchical mergers taking place within star clusters and active galactic nuclei as well. Before this observation, there was no direct evidence of hierarchical mergers or BHs with masses within the mass gap. GW190521 proved that situations within star clusters and AGN could exist, and various likelihoods of these events were calculated. In §5.2, we saw that BHs could merge in a dynamical fashion through dynamical friction in 3-body interactions. In §5.1, we saw that these dynamically formed BHs could then lead to hierarchical mergers, which could occur over and over to produced n^{th} generation BHs. In star clusters, these BHs sink to the center and then continue to merge with other BHs. In §5.3, we saw that if BBHs merge quick enough, they will not have enough time to dissipate their eccentricity, which will show in their GW waveforms. GW190521 was proposed to have a high eccentricity, which validates the claims seen in §5.4. There were a variety of situations proposed for GW190521 to have taken place within the accretion disk of an AGN. The fact that GW190521 has a large spin, high mass, and traces of an eccentric merger all agree with BBHs within AGN. Furthermore, a flare within an AGN was detected in the area of the sky where the GW was observed, signaling a coincident detection. From all of these different areas of GW astrophysics, we can see that the effects of observing GW190521 are profound.

Additionally, GW190521 was the first direct observation of an IMBH. This lays the groundwork for future investigations into seeds of SMBHs or the link between stellar mass BHs and SMBHs. IMBHs have long been theorized as seeds of SMBHs [19], primordial BHs [31], or even BHs stemming from supernovae of Population III stars [48]. Now that we finally have confirmation of one existing, and the characteristics of one and its possible methods of formation, we will be able to investigate this subject further.

In the future, we will be able to observe even more of these types of mergers, with next generation GW observatories such as LISA [16] or the Einstein Telescope [40]. Toubiana et al. [62] have utilized the data from GW190521 to see how much information we will be able to obtain from these types of systems and mergers with LISA. LISA will be able to measure chirp masses with fractional errors $\sim 10^{-4}$, distances with fractional errors $\sim .4$, sky positions within ~ 1 deg^2, and predict coalescence times of GW events within minutes. With these capabilities, LISA could inform observatories weeks before an electromagnetic counterpart arrives at Earth. Assuming that the observation of ZTF19abanrhr is real, they find that LISA will be able to detect super-Eddington accretion rates from dynamical friction in AGN from the waveforms of BBH mergers like GW190521. Furthermore, they would be able to confirm if GW190521, if it were an AGN merger, took place in a migration trap within the accretion disk. These environmental effects inferred from waveforms can tell us a lot of information about radiative transfer models, accretion, BH physics, and GR. LISA will also be able to measure the Shapiro time delay associated with GW events, as well as lensing of GWs from BBH mergers.

Furthermore, these telescopes will be more accurately be able to distinguish the progenitors of these very uncertain systems by measuring such parameters as eccentricity and precession in finer detail. Such mergers as GW190521 and future observatories will be able to tell us a wealth of information about GW astrophysics, and have implications in many different facets of astronomy and physics altogether, including the Standard Model by constraining nuclear reaction rates [18]. The implications of GW190521 will continue to be seen in the near future, and new developments in technology and theory will continue to be tested by its results.

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