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LIGO/Virgo Sources from Merging Black Holes in Ultradwarf Galaxies

Christopher J. Conselice[1], Rachana Bhatawdekar[1], Antonella Palmese[2], and William G. Hartley[3]
[1] Centre for Astronomy and Particle Theory, University of Nottingham, University Park, Nottingham, NG7 2RD, UK; conselice@nottingham.ac.uk
[2] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA
[3] Department of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT, UK
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Abstract

The origins of the black hole–black hole mergers discovered through gravitational waves with the LIGO/Virgo Collaboration are a mystery. We investigate the idea that some of these black holes originate from the centers of extremely low mass ultradwarf galaxies that have merged together in the distant past at $z > 1$. Extrapolating the central black hole/stellar mass ratio suggests that the black holes in these mergers could arise from galaxies of masses $\sim 10^5$–$10^6\,M_\odot$. We investigate whether these galaxies merge at a rate consistent with the observed black hole rate of $\sim$9.7–101 Gpc^{-3} yr^{-1} using the latest LIGO/Virgo results. We show that in the nearby universe the merger rate and number densities of ultradwarf galaxies are too low, by an order or magnitude, to produce these black hole mergers. However, by considering that the merger fraction, merger timescales, and the number densities of low-mass galaxies all conspire at $z > 1$–1.5 to increase the merger rate for these galaxies at higher redshifts, we argue that it is possible that these observed gravitational wave events could arise from black holes in the centers of low-mass galaxies. The major uncertainty in this calculation is the merger dynamical timescales for black holes in low-mass galaxies. Our results suggest that a very long black hole merger timescale of 4–7 Gyr is needed, consistent with an extended merger history. Further simulations of black hole merger timescales are needed to test this possibility; however, our theory can be tested by searching for host galaxies of gravitational wave events. Results from these searches will put limits on dwarf galaxy mergers and/or the presence and formation mechanisms of black holes through Population III stars in the lowest-mass galaxies.

Unified Astronomy Thesaurus concepts: Gravitational waves (678); Dwarf galaxies (416); Galaxy mergers (608); Intermediate-mass black holes (816); Supermassive black holes (1663); Galaxy evolution (594); LIGO (920)

1. Introduction

The recent discovery of gravitational wave (GW) events with LIGO and Virgo has revolutionized many areas of astronomy. Perhaps the most obvious success of GW detections to date, beyond the detections themselves, is the recovery of neutron star mergers through GW170817 in 2017 August, which resulted in a slew of studies concerning everything from the formation of elements to cosmology, the nature of gravity, and neutron star physics, among others (e.g., Abbott et al. 2017; Palmese et al. 2017; Soares-Santos et al. 2017; Doctor et al. 2019). The event of GW170817 was a landmark one, as it involved the identification of a counterpart in electromagnetic radiation that could be followed up. Among the other GW events to date, there have been no confirmed counterparts or host galaxies, making their discovery interesting mainly because of the fact that GWs were discovered, as well as the inferred existence of black holes (BHs) of several tens of solar masses that merged together. These BH–BH mergers remain a mystery, as it is not yet clear how systems as massive as this can form in the first place and then later merge.

There are several scenarios in which massive BHs such as these can form and then eventually merge together. Both the formation and later merging of binary BHs in star formation events are significant astrophysical problems that are not easy to solve. In stellar evolution, stars that are more massive than $\sim 20\,M_\odot$ will in principle evolve into BHs, although systems that have masses $>100\,M_\odot$ potentially vanish owing to a pair-instability supernova (SN) that destroys the entire star (e.g., Fryer et al. 2012). Furthermore, BHs in X-ray binaries in our Galaxy are known to have masses lower than those of the GW event BHs (e.g., Casares et al. 2017). However, theory shows that it is possible to create such binary BHs (e.g., Belczynski et al. 2016; Stevenson et al. 2017) even though none have yet been detected.

It is also possible that these GW events arise from merging star clusters (e.g., Hong et al. 2018). Another more speculative idea is that these systems are formed from primordial BHs that are produced early in the history of the universe, which may also account for dark matter (e.g., Hawking 1971). It remains most likely, until proven otherwise, that many GW events are produced in (in the likely distant past) star formation sites in galaxies given the close proximity of stars in star-forming regions, allowing for rapid merging and short dynamical friction timescales (e.g., Belczynski et al. 2016). However, other scenarios are worth exploring, as not all GW events with BHs necessarily must have the same origin.

The hypothesis we take in this paper is that some BHs seen in the LIGO/Virgo results are the result of mergers of BHs that existed in the centers of necessarily low-mass dwarf galaxies in the distant past. In more general terms, we calculate the likely number of BH mergers there could be at the low-mass end of the galaxy mass function. To address this question, we use a host of astrophysical information, including the galaxy mass–BH mass relation, the number of lower-mass galaxies at different epochs, and the timescales for how long BH mergers take to merge once their host galaxies have already merged.

Furthermore, the implications for GW events involving BHs at such low masses go far beyond the detection of GWs themselves, possibly also relating to the evolution and formation of galaxies. Some major questions include: how did these BHs form, and how did they get into a position to merge together? Were all of these systems formed in star formation regions near

Table 1
The Full List of GW Events Seen up to the End of 2018 with LIGO/Virgo and Their Derived Properties

Events	z	$m_1/M_\odot$	μ	$M_f/M_\odot$	log $M_{*,1}$
GW150914	$0.09^{+0.03}_{-0.03}$	$35.6^{+4.8}_{-3.0}$	0.86	$63.1^{+3.3}_{-3.0}$	$5.4^{+0.53}_{-0.66}$
GW151012	$0.21^{+0.09}_{-0.09}$	$23.3^{+14.0}_{-5.5}$	0.58	$35.7^{+9.9}_{-3.8}$	$5.2^{+0.55}_{-0.68}$
GW151226	$0.09^{+0.04}_{-0.04}$	$13.7^{+8.8}_{-3.2}$	0.56	$20.5^{+6.4}_{-1.5}$	$5.0^{+0.57}_{-0.70}$
GW170104	$0.19^{+0.07}_{-0.08}$	$31.0^{+7.2}_{-5.6}$	0.65	$49.1^{+5.2}_{-3.9}$	$5.3^{+0.54}_{-0.66}$
GW170608	$0.07^{+0.02}_{-0.02}$	$10.9^{+5.3}_{-1.7}$	0.70	$17.8^{+3.2}_{-0.7}$	$4.9^{+0.57}_{-0.70}$
GW170729	$0.48^{+0.19}_{-0.20}$	$50.6^{+16.6}_{-10.2}$	0.68	$80.3^{+14.6}_{-10.2}$	$5.5^{+0.51}_{-0.64}$
GW170809	$0.20^{+0.05}_{-0.07}$	$35.2^{+8.3}_{-6.0}$	0.68	$56.4^{+5.2}_{-3.7}$	$5.4^{+0.53}_{-0.66}$
GW170814	$0.12^{+0.03}_{-0.04}$	$30.7^{+5.7}_{-3.0}$	0.82	$53.4^{+3.2}_{-2.4}$	$5.3^{+0.54}_{-0.66}$
GW170818	$0.20^{+0.07}_{-0.07}$	$35.5^{+7.5}_{-4.7}$	0.75	$59.8^{+4.8}_{-3.8}$	$5.4^{+0.53}_{-0.64}$
GW170823	$0.34^{+0.13}_{-0.14}$	$39.6^{+10.0}_{-6.6}$	0.74	$65.6^{+9.4}_{-6.6}$	$5.4^{+0.53}_{-0.64}$

Note. The derived properties include, from left to right, redshifts, mass of the more massive BH (m_1), the ratio of the masses of the BHs merging (μ), the final mass of the BH after the merger (M_f), and the derived stellar mass of the more massive of the two merging galaxies that potentially produced the BHs ($M\mathrm{M}_{*,1}$).

each other, or were they formed in separate galaxies? If the latter is the case for some systems, this suggests that these events may reveal information about the merging and formation of galaxies that is otherwise difficult or impossible to infer from other information, as these galaxies cannot be detected beyond the local universe. Likewise, ruling this idea out, which in principle is straightforward, will have important implications for central massive BHs in the lowest-mass dwarf galaxies.

The LIGO detectors have found 11 GW events as of late 2018, 10 of which are BH–BH mergers with the masses of the merging companions on the order of 10–70 $M_\odot$ (Abbott et al. 2019a). This includes LVT 151012, which has a 90% probability of being a real GW event (Abbott et al. 2016). It is important to ask how, or if, these BH mergers fit into our picture of galaxy evolution, or can reveal new light on processes that may produce these BHs to begin with. Understanding this will also give us some clues for how to find the host galaxies of these events that otherwise emit, as far as we know, no electromagnetic radiation.

Finding the host galaxies of GW events likely must be deferred until high-resolution positioning is available using many GW detectors to pinpoint the location of the host galaxies. It thus might be some time before this idea can be fully tested in the absence of afterglow light. However, detailed theoretical work, as well as some observations, can be done to determine whether or not our hypothesis is likely.

The outline of this paper is as follows: in Section 2 we discuss the systems we consider in our paper and the data/results we use to analyze their properties; Section 3 is an outline of our method for deriving the merger rate of central BHs that may exist in the centers of dwarf galaxies; Section 4 is the main calculation, giving the main results; Section 5 is a discussion of our findings, including the implications for discovering the host galaxies of future GW systems; and finally, Section 6 is our summary.

2. Data

The data we use are taken from a combination of different data sets. For the GWs we use the information from the latest LIGO/Virgo survey summary paper, Abbott et al. (2019a). In Table 1 we list the sources considered in this paper, which are the complete set of BH–BH mergers from the LIGO/Virgo results (Abbott et al. 2019a). There are a range of redshifts for these systems, from $z \sim 0.1$ up to $z \sim 0.5$, as well as a range of masses for the more massive systems, from $m_1 = 10.9$ up to 50.6 $M_\odot$ for GW170729, which is also the most distant of the detected systems.

If the mass ratios of these BH mergers reflect the mass ratios of their host galaxies, then these would arise from major galaxy mergers. The criterion for this is that the ratio between the galaxies' stellar masses M_* satisfies $\mu = M_{*,1}/M_{*,2} < 3$. All of our BH mass ratios are <2, which makes these systems nearly equal-mass major mergers.

Many different data sets are used to derive the properties of the possible merging systems. This includes data to determine the likely number densities of galaxies as a function of redshift, as well as the merger fraction of these galaxies. We do not have a firm measurement of either of these for low-mass galaxies at $M_* < 10^6\,M_\odot$ at $z > 0.1$, so they have to be extrapolated from estimates at other mass scales.

For the evolution of the number densities of these galaxies we use the framework presented in Conselice et al. (2016), who carried out a compilation of all stellar mass functions up to $z \sim 6$ to create a modeled method for deriving the most likely galaxy stellar mass functions as a function of redshift. For the merger rates we use the results from Casteels et al. (2014) and Mundy et al. (2017) to derive the likely merger history for these ultradwarf galaxies. We discuss how this is done in more detail in the relevant subsections in Section 3.

3. Method

To infer the likely merger rate of central BHs, we need to consider a few observationally based facts. These include the merger rate of galaxies, the mass of the central BHs in these galaxies, and finally the merger rate of these BHs, or the timescale of their merging, within the galaxy merger remnant. All of these quantities are not currently well constrained. We use a combination of observational results and theoretical modeling to determine what these features are. In some cases we have no direct measurements of these values, and thus we have to make inferences based on the data that we do have, typically using galaxies at higher stellar masses.

We first investigate the BH mass–galaxy mass relation, which allows us to answer the question whether the BHs we see in GW events could possibly arise from BHs that may exist in the centers of low-mass galaxies. We then investigate the merger rate per galaxy of these particular galaxies. We then combine this with the number densities of low-mass galaxies to infer the likely galaxy volume merger rate (in units of mergers per Mpc^{-3}) for the lowest-mass galaxies in the nearby and distant universe up to $z \sim 3$. We later discus the merger timescales of the BHs in these merged systems.

3.1. Black Holes in Ultradwarf Galaxies

3.1.1. Black Holes from Stellar Evolution

The masses of the BHs found by LIGO/Virgo are often several tens of solar masses. The question we address in this section is where these BHs are arising from. The most obvious answer is that they originate from BHs that form in star-forming regions in galaxies. The idea here is that massive stars that form in star formation episodes undergo stellar evolution and explode as SNe, leaving a core remnant of a BH. The question, however, is, what is the likely mass of this remnant BH?

There are several ways to address this. The first is to empirically examine the masses of BHs in our own Milky Way. This is certainly incomplete, but what is found to date within X-ray binaries is that all of the BHs discovered in the Milky Way, besides the central massive one, contain masses that are $<20\,M_\odot$ (e.g., Corral-Santana et al. 2016). These objects cannot be the progenitors of the very massive BHs that LIGO/Virgo have discovered (Table 1).

There is, in fact, a lack of evidence that intermediate BHs with masses $>50\,M_\odot$ exist within our own Galaxy, although likely only 5% or so of X-ray binaries have been found (e.g., Corral-Santana et al. 2016).

While there is very little observational evidence for intermediate BHs, creating these theoretically is also extremely difficult. It is thought that stars form with a maximum mass of $\sim 100\,M_\odot$. At least this is a natural limit for producing a remnant when a star evolves off the main sequence. If stars were more massive than this, they would explode in pair-instability SNe, leaving no BH or any remnant whatsoever. However, when these $<100\,M_\odot$ stars go SN, they do not retain all or even a significant amount of their mass, often only leaving a small fraction to form a BH (e.g., Limongi & Chieffi 2018).

In fact, in some metal-rich cases it is impossible to reach the mass limit of the LIGO BH detections from stars that have gone SN. While metal-poor conditions can produce higher-mass remnants, these are rare areas in the nearby universe within massive galaxies. Only a few low rotational velocity stellar models are able to predict BH remnants with the masses detected by LIGO (e.g., Limongi & Chieffi 2018).

It is also the case that for a merger to occur between two BHs, they need to be quite close to each other when they are born. However, the giant phase of stellar evolution means that those stars close enough to merge would become single systems before they were BHs. To relieve this requires that binary stars that become binary BHs would have to have separations that would imply a merger timescale of 100 million Hubble times (e.g., Celoria et al. 2018). Furthermore, a SN explosion, necessary to create BH remnants, could disrupt these binary systems. Some fraction of these systems would survive depending on the mass loss, but others would be disrupted (e.g., Repetto et al. 2012; Pavlovskii et al. 2017.)

This leads us to consider how the typically metal-poor environment of low-mass galaxies may lead to the formation of stellar-mass BHs. We first investigate this by examining the likelihood of there being massive BHs formed in star formation events followed up by a SN that destroyed the star leaving a BH remnant. The question here is whether there would be stars within dwarf galaxies that would become massive BHs with masses $>30\,M_\odot$. If we assume that only massive stars within a Salpeter initial mass function will survive to become BHs with masses that LIGO has identified, we are left with up to 100 or so stellar-mass-sized BHs within galaxies of mass $M_* \sim 10^6$. These BHs, if they exit, could be one route to form mergers as seen in LIGO events. Dwarfs are a likely place for this given that they have lower metallicities, as opposed to higher-mass galaxies, which are often, or even always, much more metal-rich.

3.1.2. Central Massive Black Holes

We next consider the BH galaxy mass relation and whether there is a consistency that the BH masses measured in GW events could arise as merging central BHs in ultradwarf galaxies. For our purposes we define "ultradwarf galaxies" as extremely low mass galaxies with masses $M_* < 10^6\,M_\odot$. These types of systems are very difficult to find in all but the very nearby universe, and examples of these are the ultra-faint dwarfs that have been found in the Local Group (e.g., Walker et al. 2009).

While it is true that central BH masses are often quite high, around $10^6\,M_\odot$ for the highest-mass galaxies, recent results suggest that central BH masses for dwarf or low-mass galaxies are less massive than what would be inferred from the high end of the BH mass–galaxy mass relation (e.g., Reines & Volonteri 2015, hereafter RV15). It is also becoming clear that dwarf galaxies contain central BHs and active galactic nucleus activity (e.g., Reines et al. 2013; Baldassare et al. 2015).

The extent of this is not entirely clear yet at even lower masses, as these systems have hardly been studied; thus, inferences have to be made until better data arrive. Furthermore, as shown in RV15 and other papers, the scatter of the BH mass–galaxy mass relation becomes larger at lower masses, implying that some low-mass systems must have BHs in the range of $<100\,M_\odot$.

The quantitative relation of BH mass to galaxy mass is well calibrated for higher-mass galaxies, but for lower-mass systems it is still not well defined. By examining low-mass dwarf systems, RV15 find a BH galaxy mass relation such that

$$\log(M_{\rm BH}) = \alpha + \beta \log(M_*/10^{11} M_\odot), \qquad (1)$$

in solar units for the masses M_* and $M_{\rm BH}$. The constants fit by RV15 are $\alpha = 7.45 \pm 0.08$ and $\beta = 1.05 \pm 0.11$. This relationship allows us to infer the BH masses measured from the LIGO/Virgo results to the inferred stellar masses of their host galaxies that potentially hosted these BHs. Note that we do this as simply a test to see whether our hypothesis has any validity whatsoever. It is unlikely that the RV15 relation holds exactly at such low masses; however, the trend is such that the relation would only likely get steeper, meaning that it would be in principle possible to find low-mass BHs in ultradwarf galaxies.

Thus, using this relation, and considering the idea that BHs we detect from the LIGO/Virgo results are due to BHs in the centers of galaxies involved in galaxy mergers, we can calculate their original host galaxy mass. The masses of the BHs merging in GW events range from 10.9 to 50.6 $M_\odot$ (e.g,. Mandel & Farmer 2018 Abbott et al. 2019a; Table 1). We show in Figure 1 the inferred relation between the derived stellar mass of a galaxy and the central BH mass, extrapolating to lower masses via the RV15 relation in Table 1. The horizontal lines show the masses of the more massive of the LIGO/Virgo BHs for each merger, and the connecting vertical line shows the stellar mass of the host galaxy derived using the relation above. The uncertainties in this relation are shown by the dashed blue lines. This gives us a range of possible masses for the host galaxies of these sources of $M_* = 10^{4.5}$–$10^6\,M_\odot$.

While these are low-mass galaxies, they are not at a level that is unheard of, and in fact these galaxies probably dominate the universe in terms of numbers (e.g., Conselice et al. 2016). Galaxies with these masses, or lower, are also expected to form in the universe at $z > 10$ (e.g., Tegmark et al. 1997) and are seen in the Local Group. In the following, we use these results to determine the comoving volume number densities of galaxies within this stellar mass range, which in turn is a necessary ingredient to infer the galaxy merger rate.

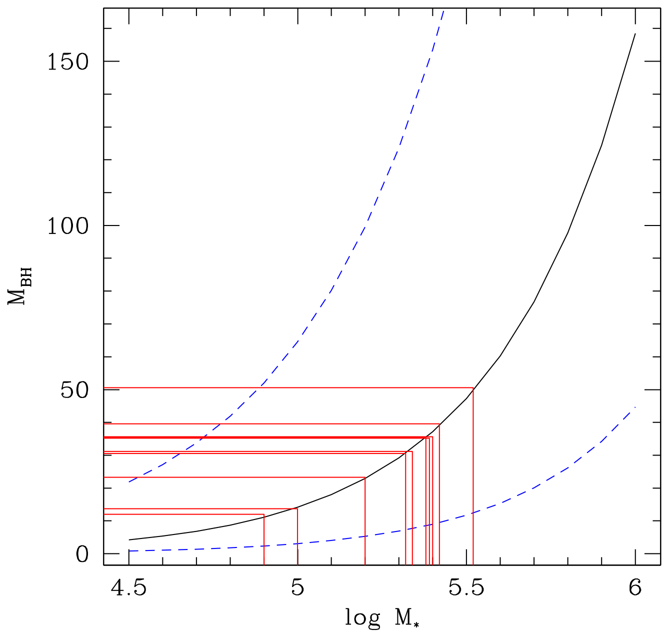

Figure 1. Relation between BH mass and galaxy stellar mass as taken from Reines & Volonteri (2015), extrapolated to lower masses than those used in that study. In general, Reines & Volonteri (2015) find that central BH masses are lower for their given host galaxy mass, compared to high-mass galaxies, at the lower-mass end of their studied relation, finding BH masses down to 10,000 $M_{\odot}$. We show with the red lines the BH masses of the more massive members measured in the LIGO/Virgo detections and the derived mass of the host galaxy for each. The solid black line is the primary relation derived, and the blue dashed lines show the 1σ error on this best fit.

3.2. Merger Rates of Low-mass Galaxies

To investigate the potential merger rate of BHs in lower-mass galaxies, we consider the merger rate of their potential host galaxies. As mentioned earlier, if these massive BHs were formed in the central portions of galaxies, then based on the galaxy mass–BH mass relation given in Equation (1), we would expect the hosts of these lower-mass central BHs to be low-mass galaxies. We next derive the merger rates for these systems, as this will ultimately be a major clue toward understanding if mergers of lower-mass galaxies can produce some of the GW events found to date with LIGO/Virgo and potentially future events with other detectors. Overall, the galaxy merger rate (number of merging events per Gyr per comoving Mpc^3; Conselice 2014) can be written as

$$\Gamma_{\rm GM}(z) = \frac{f(z)}{\tau(z)}\phi(z), \quad (2)$$

where we have a mixture of observationally and theoretically derived quantities. The function $f(z)$ is the redshift-dependent galaxy merger fraction, while $\phi(z)$ is the volume number density of these systems as a function of redshift. Finally, the timescale for galaxy merging, $\tau(z)$, is a quantity that must be derived from theory (e.g., Mundy et al. 2017). Note that our merger fraction is defined to be the number of mergers per galaxy (not the fraction of galaxies merging, which is different by a factor of ~2). This is done to mimic the LIGO/Virgo rates, which are merger events, not the number of BHs merging.

First, we examine the likely merger fraction of these galaxies, as this will reveal whether there are enough to account for the GW events. The merger fraction and rates for galaxies at such low masses have not been measured, as these systems are not yet studied outside the Local Group. The galaxy merger fraction and rates we use to infer the rates for the lowest-mass galaxies are taken from a number of sources. The lowest-mass galaxies for which the merger rate has been measured are from Casteels et al. (2014); however, we also consider the results of low-mass galaxy mergers from the GAMA survey as described in Mundy et al. (2017).

The nearby galaxy merger rate at the lowest masses ($\sim 10^8\,M_{\odot}$) is measured as ~0.02 mergers Gyr^{-1}. This is based on merger timescales from Lotz et al. (2010), who determine merger rates based on numerical N-body models that include star formation and feedback physics (Casteels et al. 2014). We will thus make the assumption that the merger rate for lower-mass galaxies is at the same level. Galaxies at these low masses cluster at the same scale, or possibly even more strongly, for example, they are often found in rich clusters of galaxies (e.g., Penny et al. 2015). Therefore, it would appear that this assumption is likely valid. Our assumption also follows in general what is predicted in theory for the merger rate of low-mass galaxies (e.g., Snyder et al. 2017).

Furthermore, the merger fraction $f(z)$ increases with look-back time. This is necessary to consider as the timescales for BH mergers, after their host galaxies have merged, can be several gigayears long (e.g., Mapelli et al. 2019); thus, this is not a process that starts and completes within the local universe. The typical way in which this is represented is through a power-law increase of $(1+z)^m$; thus, we represent the galaxy merger fraction evolution as

$$f(z) = f_0 \times (1+z)^m, \quad (3)$$

where m is the power-law index and f_0 is the local or $z = 0$ merger fraction for our low-mass galaxies.

We also need to understand how the timescale for mergers, or the merger rate for galaxies, changes at higher redshifts. This is because if the timescales for mergers were faster in the past, then there would have been many more mergers, at a given merger fraction, compared with lower redshifts. As shown by Snyder et al. (2017), the timescales for mergers decline as $\tau(z) \sim (1+z)^{-2}$ when probing higher redshifts. We thus implement this evolution in the merger timescale, which does a good job of matching the observed and predicted merger rates at high redshifts (e.g., Duncan et al. 2019).

Next, we need to consider the evolution of the number densities, $\phi(z)$, of these lower-mass galaxies, which can potentially host the BHs producing the LIGO/Virgo GW events from BH mergers. We know that the slope α of the power-law or Schechter function fit of the mass function becomes steeper as we go to higher redshifts (e.g., Duncan et al. 2014; Mortlock et al. 2015; Conselice et al. 2016; Bhatawdekar et al. 2019). This means that there are more ultradwarf galaxies, compared to the massive systems, earlier in the universe than today.

The number density evolution, as discussed later in Section 3.4, can thus be represented by a power-law fit of the form

$$\phi(z) = \phi_0 \times (1+z)^q, \quad (4)$$

where q is the power-law index for the increase in the number densities of lower-mass galaxies that we probe at higher redshifts. Putting this all together, we find that the galaxy

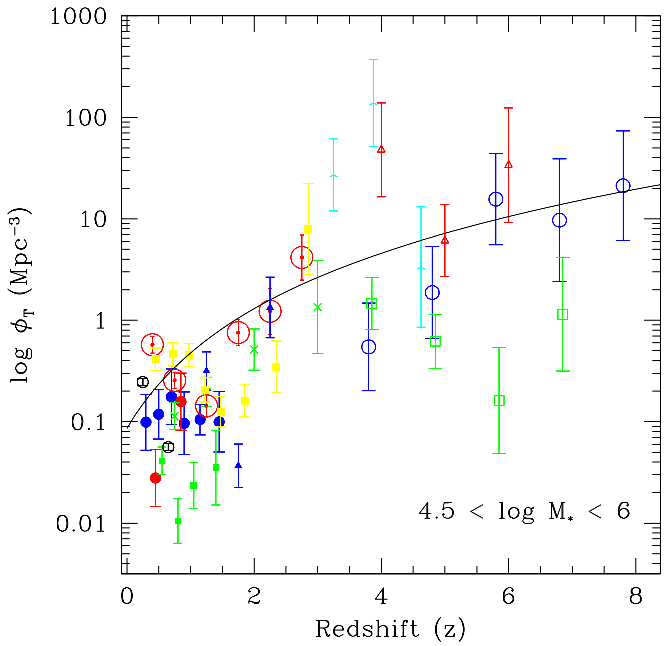

Figure 2. Number density evolution of galaxies with stellar masses between log $M_* = 4.5$ and 6. These are taken from the stellar mass function computation by Conselice et al. (2016). The solid line is the fit to this relation as discussed in Section 3.4. For the most part, particularly at higher redshifts, this is an extrapolation from the lowest limits in which these mass functions are directly measured (see Conselice et al. 2016, for details and for the symbol type definition).

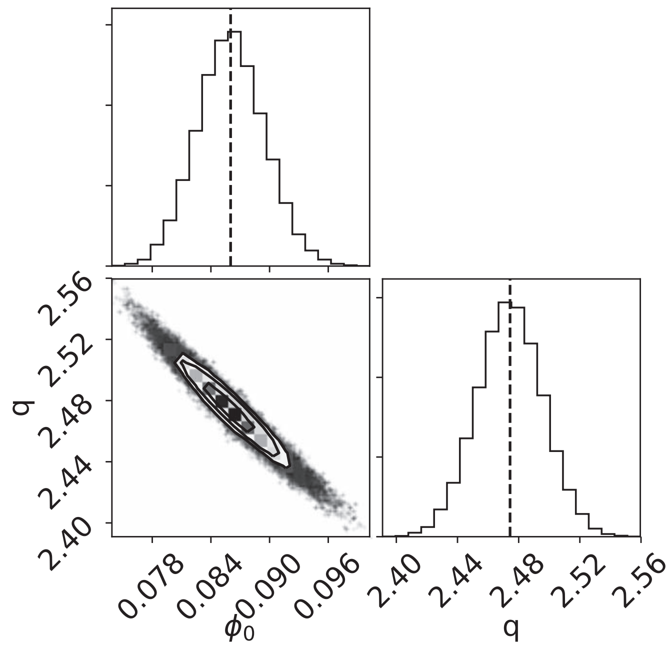

Figure 3. Plot of the contours and distributions of posteriors for the MCMC fit of the evolution in number densities using the data in Figure 2. As can be seen, we find a fairly stable fit for both the central density for low-mass galaxies, ϕ_0, and the power-law exponent for the increase in density, q.

merger rate Γ can be represented by

$$\Gamma_{\rm GM}(z) = \frac{f_0\,\phi_0}{\tau_0}(1+z)^{(2+m+q)}. \quad (5)$$

There are thus five unknowns in this equation that can be derived or inferred based on observational estimates.

3.3. Parameterizing the Galaxy Merger History (m)

The merger history for low-mass galaxies, such as the ones that may produce the GW BH mergers, is unknown. However, what has been shown is that for all galaxy types there is an increase in the merger fraction, such that the exponential on the power law varies between $m = 2$ and 3 (e.g., Mundy et al. 2017). We thus use the best-fitting values for the increase in the pair and merger fraction from Mundy et al. (2017), using a value of $m = 2.68^{+0.59}_{-0.59}$ from the best fit for all samples at high redshift up to $z \sim 3$. See Mundy et al. (2017) for details on how this is calculated and computed using data from the three deepest wide-area extragalactic near-infrared fields.

When we examine the merger history in simulations, such as from the Illustris simulation (e.g., Rodriguez-Gomez et al. 2015), we find similar results to the data. We therefore use this exponent and its error range to determine the number of mergers our low-mass galaxies undergo that potentially host the BHs that merge to produce GW events.

3.4. Number Density Evolution (q)

We also extrapolate the number densities of these low-mass galaxies and how they evolve at higher redshifts. This can be done through the same formalism that we used to determine the total number densities of all galaxies at high redshifts in Conselice et al. (2016). When integrating the number densities between log $(M_*/M_\odot) = 4.5$ and 6, we get the result shown in Figure 2 using data from various surveys at all redshifts. To fit the evolution of $\phi(z)$, we carry out a Markov Chain Monte Carlo (MCMC) analysis using a pure-Python implementation of Goodman & Weare's Affine Invariant MCMC ensemble sampler (Goodman & Weare 2010; Foreman-Mackey et al. 2013). We carry out this analysis to determine the evolution of the number density with redshift using Equation (4) and to fit for the parameters in that equation.

We have inferred the best-fit values for q and ϕ_0 using 10^2 MCMC chains of 10^4 steps each. The posterior values for this fit are shown in Figure 3 and have a slope of $q = 2.47 \pm 0.02$ and $\phi_0 = 0.086 \pm 0.003$. This shows that the number density, ϕ, of these low-mass galaxies increases significantly as we go to higher redshifts. It also implies that there were more low-mass galaxies at early times that must have merged together to form the ultimate BH mergers that could produce the observed GW events.

4. Calculation Result

4.1. The Evolution of Low-mass Galaxy Mergers

The final result of our calculation of the merger rates for low-mass galaxies, plotted in terms of events per Gpc^3 per year, is shown in Figure 4. There are two ways in which we show this relation between the number of merger events and redshift. The first is the solid line, which shows the number of expected merger events if we use the local values of the merger history of galaxies and make the assumption that the merger timescale declines at higher redshifts and the number densities of galaxies at this mass range remain the same. The dashed line shows the relation between the number of merger events and redshift when we evolve the number densities using the relations discussed in Section 3.2.

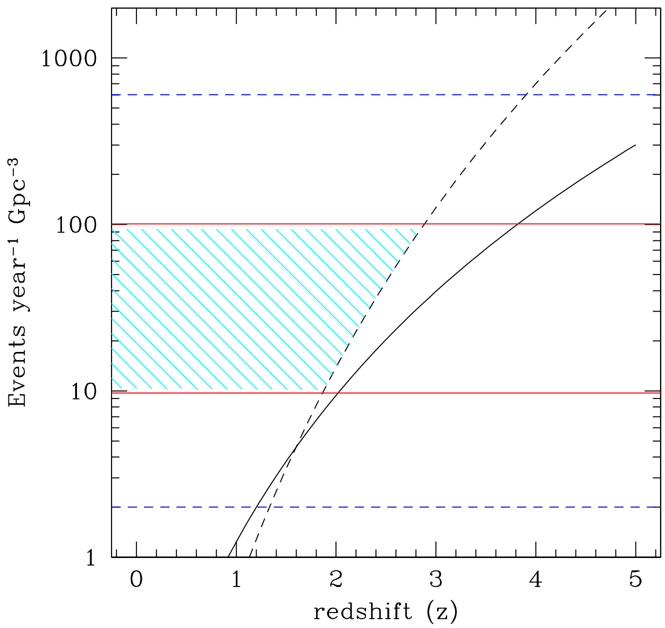

Figure 4. Rate of merging events (dashed and solid lines) as a function of redshift in units of events Gpc^{-3} Gyr^{-1}. the blue dashed horizontal lines show the limits of the LIGO/Virgo event rates from Abbott et al. (2016), while the red solid lines show the updated constraints from Abbott et al. (2019a). The hatched area gives the possible range where the galaxy merger rates are similar to the LIGO/Virgo rates. The solid line shows the evolution of the merger rate if we assume that merger timescales decline with redshift but that the number densities of galaxies at high redshift are similar to those today. The dashed line shows this same relation when we derive the likely number densities of these galaxies using the relations described in Section 3.4.

We also show the range of LIGO/Virgo event rates by the dashed blue horizontal lines going from a few events per year per Gpc^3 to almost 1000 (e.g., Abbott et al. 2016). More recently this rate has been updated to 9.7–101 Gpc^{-3} yr^{-1} (Abbott et al. 2019a), which we plot as the solid red lines.

This figure shows that we are able to match the GW event rate at about $z \sim 1.5$ for the best-case scenario. If the higher limit is used, then the merger rate only matches at $z \sim 2.5$. This higher merger rate is largely due to the increase in number densities of these lower-mass galaxies at higher redshifts, as well as the decline in the merger timescale. It now remains to be seen, and to show, that it is possible for the delay between the merger of two galaxies and the later merger of their central BHs to be similar to the time between the galaxy merger event at $z \sim 1.5$, or higher, and when the GW is observed. Since these GW events are between $\sim$300 and 2200 Mpc in luminosity distance, this means that the GW wave was produced between 1 and 5 Gyr ago. Below we carry out a likelihood calculation for what is the timescale for the merging of the central BHs in these merging systems.

4.2. The BH–BH Merger Timescale

4.2.1. Black Hole Merger Timescale Calculation

The GW events we see from LIGO/Virgo occurred a few billion years ago. The question is, when were the BHs that produced these events created, and how long did it take for them to merge?

There are not many calculations or simulations of the likely time it takes for two central BHs to merge in low-mass galaxies, yet there are some ideas and calculations we can use to create a simple model. There are two scenarios that we investigate in this paper. The first is the relaxation time for a BH within a new system such as a merged ultradwarf galaxy by interacting with similar-mass BHs that may exist from past SNe. The second is the dynamical friction between the existing BHs and stars within the ultradwarf galaxies and the new central BH that has entered the system after the host galaxies merged.

Through various arguments from, e.g., Binney & Tremaine (1987) it can be shown that the two-body relaxation timescale for a system with mass M, size R, and N number of particles goes as

$$t_{\rm relax} = 10^8\ {\rm yr}\left(\frac{1}{\log N}\right)\left(\frac{M}{10^5 M_\odot}\right)\left(\frac{R}{1\ {\rm pc}}\right)^{3/2}\left(\frac{1 M_\odot}{m}\right), \qquad (6)$$

where m is the mass of the BH of interest (e.g., Celoria et al. 2018), in our case $\sim$50–70 $M_\odot$. Ultradwarf galaxies have been discovered in the Local Group such as Segue 2, Ursa Major II, Leo IV, and Leo V. These galaxies have low metallicities [Fe/H] $\sim$–2.5, absolute magnitude and masses similar to the level at which we are examining mergers in this paper, with absolute magnitudes $M \sim -5$ and brighter, velocity dispersions from 30 to 100 km s^{-1}, and sizes that are $\sim$100 pc (e.g., Walker et al. 2009).

Using the values for known ultradwarf galaxies, we calculate that the relaxation timescale is on the order of a few gigayears, certainly less than a Hubble time. This is opposed to high-mass galaxies such as those expected to host supermassive BHs whereby the relaxation time is up to 10,000 times the Hubble time. Ultradwarf galaxies thus provide a unique environment for $\sim$50 $M_\odot$ BHs to become dynamically relaxed by the $\sim$100 similar-mass BHs already present within the ultradwarf.

Second, simple dynamical friction timescales in shallow profiles suggest that the time for two BHs in a dwarf galaxy to merge is between 10 and 100 Gyr (e.g., Binney & Tremaine 1987), depending on orbital eccentricity. This is certainly too long to be a viable path for GW events. We investigate this in more detail below. The dynamical friction timescale can be given by

$$t_f = \frac{1.17}{\ln\Lambda}{\rm Gyr}\left(\frac{r_i}{5\ {\rm kpc}}\right)^2\left(\frac{\sigma}{200\ {\rm km\ s^{-1}}}\right)\left(\frac{10^8 M_\odot}{M}\right), \qquad (7)$$

where r_i is the initial distance, σ is the velocity dispersion of the galaxy of interest, and M is the mass of the BH. Using typical values for ultradwarf galaxies in the nearby universe, we use values of $r_i \sim 100$ pc and $\sigma \sim 300$–100 km s^{-1}. By using a value of $M \sim 50\,M_\odot$ for the largest LIGO/Virgo BH, we indeed find a time for dynamical friction of $t_f \sim 100$ Gyr, obviously far too long to produce a merger.

A simple application of dynamical friction is, however, not necessarily applicable in our situation, as dwarf and low-mass systems can, and do, differ from more massive galaxies. The lowest-mass dwarfs are very dark matter dominated and very small, so simple scaling may not directly apply. Simulations show that mergers for low-mass dwarf galaxies take longer to occur than higher-mass BHs. However, this timescale increase does not scale as steeply as simple dynamical friction calculations would suggest, and thus it seems possible that lower-mass dwarfs would also have timescales on the order of a Hubble time or less.

There is also the fact that many of these central BHs will likely be embedded in central star clusters (e.g., Seth et al. 2010). These star clusters are such that their extra mass would provide a possible conduit to allow faster dynamical friction to occur, thereby leading to more rapid merging of low-mass BHs in the centers of ultra-low-mass dwarfs. This envelope and extra mass would guide the BH and protect it until it reached the center of the merging system, whereby it will merge with the second BH. In fact, recent simulations suggest that this is not only a sufficient but also a necessary method for producing BH mergers (e.g., Antonini & Rasio 2016; Pfister et al. 2019).

Using the above equation with a mass of 1000 $M_{\odot}$, we obtain a dynamical friction timescale of <10 Gyr. If a star cluster of this mass surrounded the central BHs in these merging systems it would be sufficient to facilitate the mergers of these BHs. This is only 10 times the mass of the most massive BHs seen in the LIGO/Virgo events. In fact, because these BHs are low mass, they will more readily reach a smaller separation at subparsec scales before they begin to "see" each other during a merger, thus facilitating a rapid subparsec merger. This requires less hardening with regard to the stellar background and thus naturally leads to a decline and merger at subparsec scales owing to GW radiation.

Furthermore, BH mergers in dwarf galaxy simulations, for systems several orders of magnitude larger than what we consider, show that the timescale for these mergers is on the order of ~6–8 Gyr (Tamfal et al. 2018), similar to what we need in our scenario. Furthermore, some calculations show that the epoch when the BHs that produce GW events occurred should be at high redshift if they originate in star formation events (e.g., Emami & Loeb 2018). As Tamfal et al. (2018) show, the profile of the dark matter is critical for determining the timescale of merging BHs in merging dwarf galaxies. The general dark matter halo profile can be described by an exponent on the density given by γ (e.g., Łokas 2002; Tamfal et al. 2018). Tamfal et al. (2018) investigate the timescales for mergers when $\gamma = 1$, 0.6, and 0.2. $\gamma = 1$ is a Navarro–Frenk–White (Navarro et al. 1997) profile, while $\gamma < 1$ is more commonly seen in lower-mass galaxies (e.g., Oh et al. 2015). Note that Tamfal et al. (2018) consider intermediate-mass BHs (IMBHs; $\sim 10^5\, M_{\odot}$), as central BHs of merging dwarf galaxies that are typically more massive than what is considered in our analysis. As such, we only consider their results a rough timescale for our case, which does not currently have appropriate simulations available. Future work simulating merging BHs in the lowest-mass galaxies would be very revealing and help shed light on this issue.

4.2.2. Derived Black Hole Merger Rates

As we have discussed, simulations of merging dwarf galaxies with BHs find that the merger timescale is long owing to less effective dynamical friction. This time for merging is >7 Gyr in this simulation. It is also well known that BH mergers often stall at a few parsecs, and this can lead to quite long merger times of up to 10 Gyr even within dense and massive galaxies (e.g., Volonteri et al. 2015). As Tamfal et al. (2018) further show, if the dark matter profiles of these galaxies are steep, then this leads to a more effective merger and shorter timescale. If these simulations can be extended down to even lower masses, then it is entirely possible that merging dwarf galaxies can produce the GW events seen with LIGO/Virgo in principle, especially if embedded star clusters are considered.

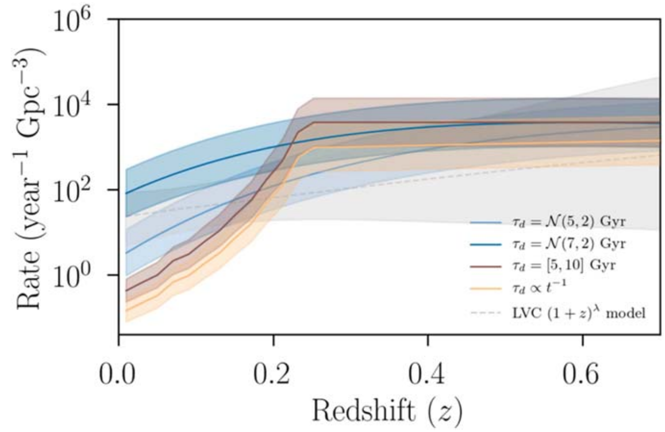

Figure 5. Rate of binary–BH mergers produced by dwarf galaxy mergers as a function of redshift (z), for different time delay distributions. Here we have used a Gaussian distribution around 5 and 7 Gyr with a standard deviation of 2 Gyr (cyan and blue, respectively), a top-hat function between 5 and 10 Gyr (purple), and a distribution that declines as t^{-1} (orange). We also show a LIGO Scientific Collaboration and Virgo Collaboration model from Abbott et al. (2019a) as the dashed line.

We use the delay timescales discussed as a guide to infer the rate of binary–BH mergers at cosmic time t produced by galaxy mergers given some time delay distribution $p(\tau)$ between the galaxy merger and the BH merger. The BH merger rate $\Gamma_{\rm BHM}$ will follow the relation

$$\Gamma_{\rm BHM}(t) = \int_0^t \mathrm{d}\tau \Gamma_{\rm GM}(t - \tau)\, p(\tau), \qquad (8)$$

where $\Gamma_{\rm GM}$ corresponds to the galaxy merger rate in Equation (5). The BH merger rate evolution with redshift will depend on the model chosen for the time delay. Antonini et al. (2015) and Tamfal et al. (2018) show that the typical timescales for merging of central BHs, when a negligible amount of gas is present in the merging galaxies, is ~5 and 7 Gyr, respectively.

We test different time delay distributions: a Gaussian $\mathcal{N}(\tau;\, \mu_\tau,\, \sigma_\tau)$ around these values with a standard deviation of 2 Gyr, a top-hat function between [5, 10] Gyr, and a t^{-1} distribution between [1, 10] Gyr. Figure 5 shows the rates for these distributions, which can be compared to Figure 4.

While sophisticated simulations tailored for the particular galaxy and BH mass range studied here are needed to identify more realistic time delay distributions, it is clear from Figure 5 that this BH merger scenario predicts a rate of BH mergers that evolves with redshift. In particular, the rate is expected to rise with redshift, as a result of the increasing galaxy merger rate with redshift. Such a trend is currently consistent with what is found for the first two LIGO/Virgo observing seasons (Abbott et al. 2019b, their Figure 5).

5. Discussion

We have shown that it is possible in principle that merging ultra-low-mass dwarf galaxies have merger rates that are high enough to produce the GW events seen by LIGO/Virgo. This assumes that BHs exist in these galaxies that were formed in star formation events, or there exist central BHs that then merge together in the remnant galaxy. However, to match the GW event rate requires that the galaxy merging events occur at $z > 1$. Since the GW events are observed at lower redshift, this implies a time delay between these galaxy mergers and the BH mergers of between 6 and 8 Gyr. This timescale and whether BH mergers in dwarfs can occur within this time are likely the biggest uncertainties in making this a viable channel for GW production. There are a couple of implications for these results, which we briefly discuss here.

First, as described earlier in the paper, the BH merger ratio is quite close to 1:1, and never less than 1:2. Major galaxy mergers with which we compare rates have merger ratios that range from 1:4 to 1:1. It is likely that the reason we are seeing only similar-mass BH mergers is that these produce the types of signals that LIGO/Virgo are most likely able to detect. This, however, implies that the merger rate for these systems would be higher if we could detect more "minor" BH mergers. However, for galaxies, most of the major mergers are also between galaxies of similar mass, not quite close to 1:1, but within a factor of two. This suggests that the LIGO/Virgo events cannot all be produced in BH mergers from low-mass galaxies, or else the nearly 1:1 ratio for galaxies would be slightly lower. However, this does not discount that a significant fraction of GW events could arise from these types of mergers, but it is unlikely to account for all of them. It is possible that these GW sources originate from a mixture of star formation events and from origins including primordial BHs and other exotic events. Mergers of central BHs in ultradwarf galaxies, however, might be a significant fraction of these sources.

5.1. Implications for Host Galaxies of GW Events

The scenario presented here also has implications for finding hosts of the GW events. One of the major goals of GW studies is to find the host galaxies in which these BH mergers occur, and ultimately in what regions within galaxies these events arise. Our results suggest that in the absence of an electromagnetic counterpart (e.g., Loeb 2016) the best way to find the sources of these mergers is through the properties of their inferred host galaxies if they form from mergers of central BHs in low-mass galaxies. As such, searches for host galaxies even at modest redshifts will have to probe very deep to find these faint dwarf systems, and it is possible that any "afterglow" would appear as an "orphan" without any obvious host galaxy even in deep imaging. This is due to the resulting host galaxy being low-mass systems with masses of $\sim 10^5$–$10^6\,M_\odot$. However, these host galaxies would likely retain no galaxy–galaxy merger signatures in their central parts given the long multigigayear timescale, which is ample enough for the merged host galaxy to morphologically relax.

An issue with this, however, is that the host galaxy magnitude will be extremely faint with apparent magnitudes of $B \sim 31$–33 for $M_* \sim 10^6\,M_\odot$ galaxies at $z \sim 0.3$, given a reasonable mass-to-light ratio for these galaxies. This assumes that these systems do not further merge later with other galaxies. The remnant of this system would be in a galaxy that is fainter than the limit that we can probe even with the deepest *Hubble Space Telescope* imaging (e.g., Conselice et al. 2011). Thus, in this scenario only the nearest GW source host galaxies would have a realistic chance to be seen before the *James Webb Space Telescope* (*JWST*). The large area in which sources can be localized by using LIGO/Virgo is at least of the order of $10\,\deg^2$. This presents another problem, as finding these faint sources is like finding a microscopic needle in a cosmic haystack. This might, however, be easier if these sources are being gravitationally lensed, magnifying the host galaxy of the gravitational source (e.g., Smith et al. 2018).

Since dwarfs are often found in dense environments, a good possible location for GW source positions would be in clusters of galaxies or groups with satellite galaxies merging. Mergers between low-mass galaxies would not occur frequently within extreme or low-density environments. Imaging such as with the Dark Energy Survey (e.g., Doctor et al. 2019) would have trouble identifying a host galaxy within this scenario, and finding a counterpart with no host galaxy would give some evidence for this idea. Unfortunately, LSST at a nominal depth of magnitude 27 will also not be able to identify these hosts. The only real possibility will be through deep *JWST* imaging unless these systems are very nearby.

Furthermore, finding BHs in ultradwarf galaxies would be another way to determine whether or not our theory is viable. This could be done in a number of ways, including deep kinematic observations and perhaps X-ray and radio techniques to try to identify active BHs that might be accreting matter in these galaxies. However, since few of these galaxies have gas in them, this might prove difficult. Perhaps the best way to test this idea is to search for star clusters within the centers, or near the centers, of these ultradwarf galaxies that would have masses $>1000\,M_\odot$. This could, in principle, be carried out today with existing facilities. Furthermore, finding and studying these ultradwarf galaxies at higher redshifts, and in environments other than the Local Group, is another way to make progress in testing this theory.

These GW events would also be found in or near the centers of these galaxies if follow-up imaging was deep enough to find the host sources. If GW events are located in massive galaxies, especially outside their centers and within star-forming regions, it would be a difficult observation to reconcile with the idea that these objects formed in low-mass galaxies that later merged. However, if this is the case, then some assumptions about dark matter, BH stellar mass relations, or merging within dwarf galaxies need to be revised.

If it turns out that no sources of GWs are within merging or the remnants of merging low-mass galaxies, then this would imply one of three things: (1) most ultra-low-mass dwarfs do not contain central BHs, (2) the merger timescales for BHs in ultra-low-mass dwarfs are longer than what we find in simulations for more massive dwarfs, or (3) the merger rate of dwarf galaxies is not as high as we think. All of these have implications for our understanding of dark matter and galaxy/BH evolution/formation. If some GW events are formed in mergers of dwarfs, it would be a strong indication that initial BH formation occurs from seed Population III stars that formed early in the history of the universe (e.g., Kinugawa et al. 2014), as opposed to a collapse of gas early in the universe (e.g., van Wassenhove et al. 2010). Some of these early stars are predicted to range from 30 to $1000\,M_\odot$ (e.g., Ohkubo et al. 2009).

Another way to distinguish this scenario from the star formation one is to look at the spin of the BHs that produce these GW events. Binary formation scenarios, such as in star formation episodes, predict that the spins of the merging BHs should be more or less aligned (e.g., Piran & Hotokezaka 2018). However, what is found is that there is an isotropic distribution in spins for the known BH mergers (Piran & Hotokezaka 2018), which would be expected for mergers of BHs originating from the centers of different galaxies. Future observations of BH mergers, especially in the next few years, will help clarify many of these issues.

6. Summary

We investigate in this paper the possible progenitors and formation mechanisms of the merging BHs discovered to date by LIGO/Virgo, and possibly future ones with new detectors. The BHs discovered so far are fairly massive, several tens of solar masses in mass, and were previously in a position to merge. We discuss in this paper the possibility that these massive BHs arise from the mergers of BHs that were in low-mass merging dwarf galaxies. Since no host galaxies for these events have been found to date, due in no small part to it being very difficult or impossible to identify the source of the GW events based on the emission of an afterglow or counterpart, it remains a mystery where these sources arise from. However, even if all LIGO/Virgo sources are in star-forming regions, it is still possible that some future events can occur through alternative channels. LIGO/Virgo will remain an important source for finding possible low-mass galaxy mergers, as opposed to higher-mass galaxy mergers better detected with *LISA* and pulsar timing arrays (e.g., Chen et al. 2018).

Since the source of these events is debated, it is important to address the question whether these GW sources could arise from binary BHs that were once at the centers of two distinct low-mass ultradwarf galaxies that later merged. We addressed this question in this paper by investigating the volume number densities and likely merger history of low-mass galaxies at high redshifts. We find that the merger rate of galaxies goes up significantly with redshift, as do the number densities of low-mass galaxies. In summary, we find the following:

I. Extrapolating the BH mass–galaxy mass relation calibrated for dwarf galaxies to the lower limits of possible galaxies, we determine that it is possible that low-mass galaxies between $M_* = 10^{4.5}$ and $10^6 M_\odot$ could host BHs of tens of solar mass in their centers. This is especially the case if the scatter in this relation becomes larger at lower masses, ensuring that a large fraction of galaxies with these masses host central BHs with masses $<100\,M_\odot$.

II. The merger rate of nearby low-mass galaxies is certainly too low to produce the GW event rate from LIGO/Virgo. Therefore, if these events are produced by the mergers of BHs in low-mass galaxies, the mergers of the galaxies themselves must have occurred in the distant past.

III. We determine the merger rate and number densities of the lowest-mass galaxies in the distant universe. We combine these results to determine the merger rate for low-mass galaxies up to $z \sim 3$. We determine that it is possible to reach the lower limits of the GW event rate by $z \sim 1.5$. This, however, requires the merger timescale for the BHs within merging galaxies to be ~6–8 Gyr. This timescale is indeed found in detailed *N*-body models of BH mergers in merging dwarf galaxies, although the systems studied to date in simulations are all several orders of magnitude larger than the ones we consider here. However, if these BHs are embedded in massive central star clusters, this would be an effective conduit to drive these systems to the center of the merger remnant, where they can merge within <10 Gyr based on dynamical friction and two-body relaxation arguments. This timescale is similar to what we found within IMBHs in slightly more massive galaxies, but detailed simulations tailored for the galaxy and BH mass ranges studies here will be required to confirm whether this is a reasonable time delay. If this is the case, we expect the rate of BH mergers to increase with redshift for a number of delay time distributions.

Future observations of GW rates will either give credence to this idea or rule it out. As the resolution and ability to pinpoint locations of GW events improve, we will one day be able to determine the location of the host galaxies of these events. This paper also suggests that “orphan” afterglows of GW events should be searched for, as the hosts of these events will be fainter than $B \sim 30$. If this scenario is correct, then deeper imaging with *JWST* may be needed to reveal these galaxies even at modest redshifts. In either case, there will be interesting implications for galaxy formation and evolution, and possibly dark matter. More observations of ultradwarf galaxies would be valuable to test this idea, and theoretical modeling should be carried out to predict the merger timescales of the BHs in these systems.

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ORCID iDs

Christopher J. Conselice https://orcid.org/0000-0003-1949-7638
Antonella Palmese https://orcid.org/0000-0002-6011-0530

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