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GW190521 from the Merger of Ultradwarf Galaxies

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We present an alternative formation scenario for the gravitational wave event GW190521 that can be explained as the merger of central black holes (BHs) from two ultradwarf galaxies of stellar mass $\sim 10^5$–$10^6\ M_\odot$, which had themselves previously undergone a merger. The GW190521 components' masses of $85^{+21}_{-14}\ M_\odot$ and $66^{+17}_{-18}\ M_\odot$ challenge standard stellar evolution models, as they fall in the so-called mass gap. We demonstrate that the merger history of ultradwarf galaxies at high redshifts ($1 \lesssim z \lesssim 2$) matches well the LIGO-Virgo inferred merger rate for BHs within the mass range of the GW190521 components, resulting in a likely time delay of $\lesssim 4$ Gyr considering the redshift of this event. We further demonstrate that the predicted timescales are consistent with expectations for central BH mergers, although with large uncertainties due to the lack of high-resolution simulations in low-mass dwarf galaxies. Our findings show that this BH production and merging channel is viable and extremely interesting as a new way to explore galaxies' BH seeds and galaxy formation. We recommend this scenario be investigated in detail with simulations and observations.

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Introduction.—Since the discovery of gravitational wave (GW) events produced by black holes (BHs) [1], the origin of these massive stellar BHs has been unclear. While BHs of a few tens of solar masses had not been observed before, it is possible that these systems could have been formed from massive stars in metal-poor star formation events [2–4]. On May 21, 2019, the LIGO-Virgo Collaboration detected a GW event from the coalescence of two BHs with masses of $85^{+21}_{-14}\ M_\odot$ and $66^{+17}_{-18}\ M_\odot$ [90% credible interval (CI)] [5,6], further challenging stellar evolution theories to explain the origin of these BHs. The mass of at least one of the BHs falls in the high "mass gap," corresponding to the range between ~ 50 and $135\ M_\odot$. The expectation of stellar evolutionary models is that pulsational pair instability (PPI) and pair instability supernova (PISN) prevent the formation of remnant BHs above $\sim 50\ M_\odot$ from stars with helium cores of mass ~ 32–$64\ M_\odot$ and ~ 64–$135\ M_\odot$, while stars with a higher mass ($\gtrsim 200\ M_\odot$) produced in low-metallicity environments can form BHs with $\gtrsim 135\ M_\odot$ through direct collapse [7–9].

While works have shown that it is possible to form BHs such as those in GW190521 through stellar evolution [10,11], alternative theories have proposed that the LIGO-Virgo compact objects could be explained with primordial BHs (PBH, [12–15]). Another interesting scenario for the formation of these binaries is through dynamical interactions in dense stellar environments [16–19] and through assisted inspiral in active galactic nuclei (AGN) disks [20,21]. Given the properties of the binary and the inferred rate of GW190521-like events, Abbott *et al.* [6] do not find strong evidence for any of these scenarios to be favored. Another possible scenario consists in gas accretion of Pop III stars [22].

Another possibility, first proposed in [23], is that the BHs detected by LIGO-Virgo are produced at the centers of ultradwarf galaxies, low-mass galaxies that are potential analogs of the faint dwarfs studied in the Local Group. The argument consists in an extrapolation of the well-known central BH mass–galaxy mass relation that has been measured for galaxies down to stellar masses of $M_\star \sim 10^8\ \mathrm{M}_\odot$. While we do not have observations of central BHs in lower mass galaxies, there is an increasingly large amount of evidence that they do contain central BHs (e.g., [24–27]), suggesting that ultradwarf galaxies with masses $10^{5\text{–}6}\ \mathrm{M}_\odot$, which dominate the number density of galaxies in the Universe (e.g., [28]), could also harbor such central BHs in the mass range of the GW190521 components.

Once two ultradwarf galaxies merge, it is possible that also the respective central BHs will merge after some time. This mechanism could be the way supermassive BHs (SMBHs) grow early on in the Universe through hierarchical assembly [29]. The question is whether there are enough of these galaxies close to the redshift of the events under consideration, and whether they merge frequently enough, to recover the inferred LIGO-Virgo merger rate for systems such as GW1905121, which is estimated to be $0.13^{+0.30}_{-0.11}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ [6].

We explore this question in this Letter. First, we calculate the merger rate for galaxies that could produce

GW190521-like events, then we present a discussion of the implications for the proposed formation channel, and finally we provide conclusions.

Method.—To investigate whether GW190521 could be produced through the mergers of central BHs in galaxies we consider the following: the masses of BHs in low-mass galaxies, the merger rate of these galaxies, and the timescales for the BH mergers to occur after their host galaxies have merged. We update the analysis presented in [23], where we considered all of the LIGO-Virgo mergers from the first two observing runs, to specifically explain GW190521-like events. To do this, we first take into account the BH mass–galaxy mass relation from [30]:

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

where solar mass units are used for the galaxies' stellar mass $M_\star$ and the central BH mass $\mathrm{M_{BH}}$. The values of α and β are $\alpha = 7.45 \pm 0.08$ and $\beta = 1.05 \pm 0.11$.

Once the mass range of interest is identified based on the masses of the BHs merging, we calculate the merger rate of galaxies in this mass range following [31] and describe the volumetric rate $\Gamma_{\rm GM}$ per Mpc^3 per Gyr as a function of redshift z as

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

where f is the fraction of galaxies that merge as a function of redshift; $\phi(z)$ is the number density evolution of the galaxies under consideration; and $\tau(z)$ is the timescale for galaxy merging, that is, how many times major mergers occur for the population being studied per Gyr.

The best measured major galaxy merger rate as of today is estimated to be close to 0.02 mergers Gyr^{-1}, based on merger timescales from [32]. However, it is well known that galaxy merging intensifies with lookback time. The redshift evolution of galaxy mergers is well described by

$$f(z) = f_0 \times (1+z)^m, \tag{3}$$

where m is the power-law index and f_0 is the local or $z = 0$ merger fraction for the low-mass galaxies under consideration. Note that this fraction is defined as the number of mergers per galaxy, not the fraction of galaxies merging, which is approximately double the former. Following the findings of [33], we fix $m = 1.82^{+0.37}_{-0.34}$ and $f_0 = 0.01^{+0.002}_{-0.002}$ for major mergers of galaxies with similar mass ratios.

To calculate the number densities of dwarf galaxies we use the results of Conselice *et al.* [28], who carried out a compilation of stellar mass functions up to $z \sim 6$ using several observational datasets and created a model for deriving galaxy stellar mass functions as a function of redshift.

The number density evolution can be represented by a power law of the form

$$\phi(z) = \phi_0 \times (1+z)^q, \tag{4}$$

where ϕ_0 is the local or $z = 0$ number density of galaxies in the mass range of interest. The values we find are $q = 2.47 \pm 0.02$ and $\phi_0 = 0.086 \pm 0.003$ for low-mass galaxies, as explained in [34]. We renormalize this for the number density of galaxies that map onto the GW190521 system.

At last, the galaxy merging timescale is assumed to follow the relation found by Snyder *et al.* [32]: $\tau(z) \propto (1+z)^{-2}$, but with slightly different fits given by a reanalysis of these values presented in [34], such that the timescale changes with redshift as $\tau(z) = \tau_0 \times (1+z)^u$. The fits are performed using the Illustris simulation. By examining how close pairs of galaxies appear and vanish after a merger, and how that changes with time, we are able to determine how the timescale for these mergers evolves with redshifts. The galaxy merger rate is then given by

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

Results and discussion.—The rate of mergers for systems with masses such as GW190521 is inferred to be $0.13^{+0.30}_{-0.11}\ \mathrm{Gpc^{-3}\ yr^{-1}}$ in [6]. In this section, we compare this value to the expected merger rate of galaxies that could host central BHs with masses similar to those measured for the merging components of GW190521.

Based on the central BH–stellar mass relation in Eq. (1), we extrapolate the range of possible stellar masses of the galaxies hosting central BHs with masses consistent with the components of GW190521. As can be seen in Fig. 1, these correspond to stellar masses in the range

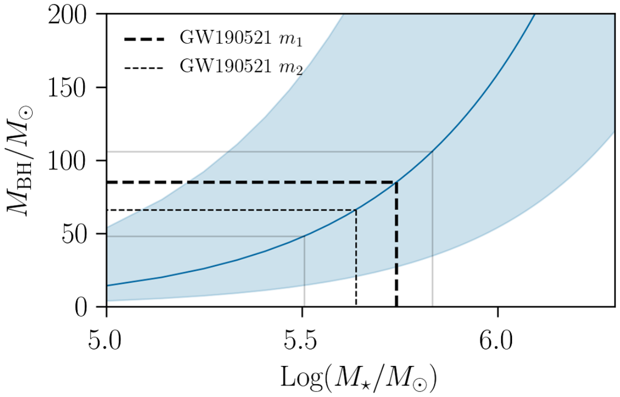

FIG. 1. Extrapolation to low masses of the relation between the central BH mass and galaxy stellar mass from [30] in blue (the shaded region represents the 1σ uncertainty on the relation), with the masses of the GW190521 components from LIGO-Virgo (dashed lines) and the 90% CI for both components (gray lines).

10^5–$10^{6.5}$ $M_\odot$. Galaxies in this mass range have been observed in the local Universe [35,36], even down to $\sim 10^3$ $M_\odot$ [37], and have been studied in simulations [38] that show that they are very abundant.

We then use this mass range to estimate the two parameters entering Eq. (4), ϕ_0 and q, by restricting the galaxies from [28] to the stellar mass range of interest. We examine the number density of nearby galaxies at the mass range of interest by integrating the stellar mass function [39] at $z = 0$ between our mass limits.

The final merger rate evolution for the possible host galaxies of GW190521-like BHs is shown in Fig. 2. The dashed and solid lines show the result using our fit for the number density evolution parameters and using a constant number density, respectively. In both cases, it is clear that the LIGO-Virgo rate for GW190521-like systems (red lines) can be recovered around $1 \lesssim z \lesssim 2$. For the case of GW190521, which is at $z = 0.82^{+0.28}_{-0.34}$, this implies that the likely time delay (i.e., in this case the time between the galaxy merger and the binary merger) is of the order of $\lesssim$4 Gyr.

The validity of the central BH–stellar mass relation used at the masses considered here cannot currently be proven, as there are no measurements of central BH masses in such low-mass galaxies. Deviations from the relation at the low-mass end have been suggested for the specific case of ultracompact dwarfs in order to explain their extreme dynamical mass to light ratios [40]. However, we have considered different scaling relations from [41], and they do not change our conclusions, meaning that reasonable variations to [30] still leave our scenario possible. In the future, possible observations of central BHs in nearby galaxies and clusters [42,43] will enable more precise expectations for our scenario. GW observations may be the most promising route to probe the validity of the scaling relation at the low-mass end. Identification of an electromagnetic counterpart for a nearby event in a dwarf galaxy, or the detection of a "golden" GW event (a merger so well localized to contain only one galaxy) would be a way of probing this relation with current generation GW detectors. Optical studies of dwarf AGN variability will also probe the scaling relation closer to the mass range of interest here in the near future. Deep optical observations by the Dark Energy Survey have already identified AGN candidates for $\sim 10^7$ $M_\odot$ galaxies [44], and the Rubin Observatory will provide even deeper observations to further explore this regime to lower-mass dwarfs [45]. We expect ongoing and future time domain sky surveys to extend the BH-galaxy mass scaling relations down by a few orders of magnitude in the upcoming decade [41].

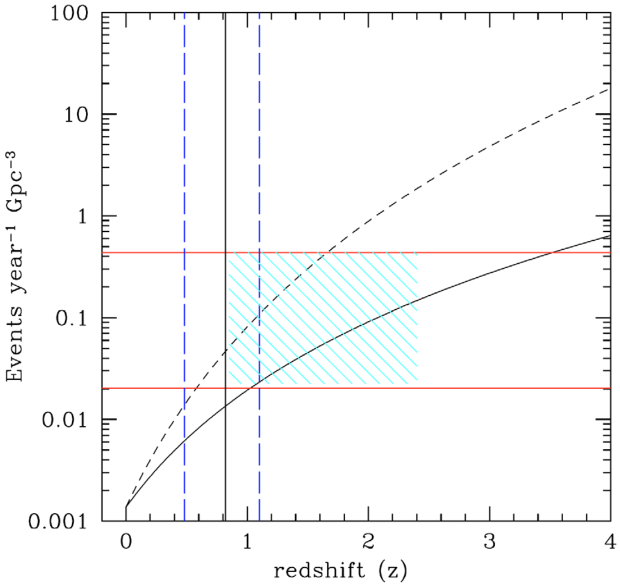

FIG. 2. Rate of merging ultradwarf galaxies in the mass range of interest for GW190521 as a function of redshift. The dashed line is the result using our fit for the number density evolution parameters; the solid line is the result assuming that the galaxy density is constant with redshift and equal to the one measured at $z = 0$. The red lines represent the 90% CI from the rate estimate of events similar to GW190521 from [5]. The blue dashed parallel lines show the range of 90% CI redshift for GW190521. The shaded region shows the time period of 4 Gyr preceding the central redshift.

For this scenario to be viable we need to understand if timescales of the order of $\sim$4 Gyr are reasonable for the BH mergers after the two galaxies have merged. Even within the highest resolution simulations, it is currently not possible to resolve the full dynamics of BHs within merging galaxies [46]. Analytical arguments are therefore required to estimate the time that needs to elapse between the galaxy merger and the BH merger. Using simulations of merging galaxies, Tamfal *et al.* [47] find that the central BHs of dwarf galaxies can merge within a Hubble time or stall, depending on the shape of the dark matter profile. BHs in Navarro-Frenk-White dark matter profiles are, however, likely to merge. To the best of our knowledge, the simulation in [47] is the high-resolution simulation closest to our case in terms of the masses of galaxies and BHs ($\sim 10^8$ $M_\odot$ and ~ 10 $M_\odot$, respectively, so still larger than the GW190521 case). It is therefore reasonable to consider that the central BHs could also merge in our case if the galaxies have a cuspy dark matter profile.

Let us assume that the two central BHs sit at the bottom of the host galaxy's gravitational potential well when the two galaxies merge. When the galaxy merger produces a final remnant with a unique core, the central BHs will tend to sink toward the center. If we assume that the BH separation after the remnant is formed is close to $r \sim 80$ pc (note that the typical half-light radius of low-mass dwarfs is $\sim$100–400 pc [35,48]), then the dynamical friction timescale that will drag the BHs close to the center of the remnant is [49]

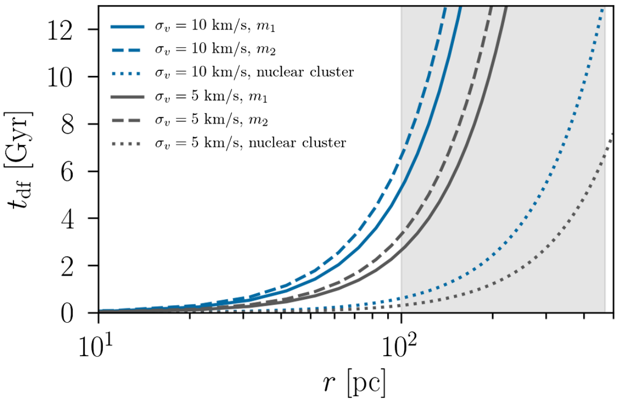

FIG. 3. Dynamical friction timescale for BHs of mass $m_1 = 85\ M_\odot$ and $m_2 = 66\ M_\odot$ at different separations from the center of the galaxy remnant, having stellar mass $M_\star = 10^6\ M_\odot$ formed by the merger of two ultradwarf galaxies. The shaded region represents the typical half-light radius of nearby $M_\star \sim 10^6\ M_\odot$ galaxies, and their velocity dispersion ranges between 5 and 10 km s^{-1}.

$$t_{\rm df} = \frac{0.67}{\Lambda}\,{\rm Gyr}\left(\frac{r}{4\ {\rm kpc}}\right)^2\left(\frac{\sigma}{100\ {\rm km\,s^{-1}}}\right)\left(\frac{10^8\ M_\odot}{M}\right), \quad (6)$$

where σ is the central velocity dispersion of the galaxy, $\Lambda = \ln(1 + M_\star/M)$, M is the mass of the BH (or of the star cluster, as we shall assume later), and $M_\star$ is the stellar mass of the remnant galaxy. Using typical values for dwarf galaxies in the nearby universe, we assume $\sigma \sim 10$ km s^{-1} and find $t_{\rm df} \sim 4$ Gyr for the components of GW190521 at ~80 pc from the center.

Figure 3 shows the dynamical friction timescales for different values of the central velocity dispersion for the different BH masses taken into account. If the velocity dispersion of the galaxy is as low as $\sigma \sim 5$ km s^{-1} (which is a reasonable lower limit for this mass range; [48,50]), dynamical friction can be effective in ~4 Gyr from $\gtrsim$100 pc, thus close to the typical half-light radius of $10^6\ M_\odot$ galaxies (gray lines). Moreover, it is likely that the central BHs are embedded in a nuclear star cluster, for which dynamical friction will be more effective. For a cluster of 1000 $M_\odot$ (dotted lines), we find that dynamical friction can be effective within ~4 Gyr from the edges of the remnant galaxy, at ~200–300 pc.

At shorter separations, once the binary is formed, hardening by stellar encounters and GW radiation will dominate the binary dynamics. Biava *et al.* [51] find that the duration of these latter phases (the "lifetime" of the binary) can take a huge range of values, from a fraction of Gyr to more than the Hubble time, depending on the characteristics of the galaxy profile. This scatter in the binary lifetime is even more prominent at the lower masses, and we therefore do not attempt to model these stages.

Early works on massive BH binaries have hinted to the possibility that those binaries may stall at 0.1–1 pc, due to the so-called "final parsec problem" [52]. Several more recent works using more sophisticated simulations have shown that this problem applies only to spherical and axisymmetric stellar system, while there is no final parsec problem for triaxial galaxies [53–56] even in the absence of gas around the binary, and most elliptical galaxies and bulges of spirals are thought to be triaxial. This is true even in very mildly triaxial systems, so this will apply to galaxies that have recently experienced a merger [54], which is the case we consider here. Moreover, the detection itself of the LIGO-Virgo BBH mergers is evidence against the final parsec problem, or at least that it does not always apply for the mass ranges probed.

It is therefore reasonable that a BH binary could form and merge within a few Gyr of the merger of the host galaxies, if the BHs reach close enough (~80–100 pc) to the bottom of the potential well of the remnant galaxy, or if they are embedded in star clusters, so that dynamical friction is effective, and if the stellar and dark matter distribution satisfy the criteria that have been explored for higher mass galaxies. In the future, it will be interesting to explore binary formation using high-resolution simulations for the mass range of interest here.

We note that the hardening phase of the binary evolution could increase the binary eccentricity through stellar scattering, and eccentricity measurements could provide motivation in favor of this scenario. Remarkably, it has been noted for GW190521 that the binary could have had an eccentric orbit [57,58].

Another binary property of interest for various formation scenarios is the spin. Previous measurements of the effective binary spin $\chi_{\rm eff}$ from population studies hinted to a BBH population with randomly aligned spins [59], posing a challenge for the isolated binary formation scenario. In the case of merging dwarf galaxies, the binaries do not necessarily need to have aligned spins although alignment could be facilitated in the case in which the binary forms a circumbinary disk in the presence of gas [60].

An important question is how the BHs in GW190521 could form, even in the case they are the central BHs of galaxies. In this scenario, we believe that the possible mechanisms could be similar to those proposed for the formation of SMBHs. One of the two main channels consists in the formation of very massive, early stars, the Pop III stars [61,62], which could leave behind BH seeds from tens to hundreds of solar masses, which would then grow through hierarchical mergers and accretion [29]. Another modeling scenario is based on gravitational instabilities in self-gravitating gas clouds that form an initial BH of mass $\lesssim$20 $M_\odot$, which can grow through accretion [63]. If the scenario proposed here is confirmed to contribute to the rate of observed BBH mergers, it could open a new observational window into the formation of SMBHs and galaxy formation. On the other hand, if this scenario is ruled out, it would also provide interesting information about the growth of SMBHs through hierarchical assembly.

One way of confirming or ruling out this scenario would be to search for the electromagnetic counterparts in dwarf galaxies, when they occur in the nearby Universe ($z \lesssim 0.1$). Especially in the case of central BHs as dwarf AGNs, an electromagnetic counterpart could be expected, and a binary AGN could be identified through electromagnetic radiation variability [64]. Merging activity of dwarf galaxies containing AGNs is likely to affect the majority of dwarfs hosting AGNs, and binary dwarf AGN candidates have already been identified in the nearby Universe [65]. If a counterpart is found, binary BHs can also enable standard siren measurements of cosmological parameters [66–69] that are more precise than the case without counterparts [70,71]. A candidate counterpart has been reported for this event in AGN J124942.3 + 344929 [72]. While the AGN is much brighter than what we would expect for a low-mass central BH from the proposed scenario, a confident association with the GW event cannot be established [73,74], so that this candidate counterpart can neither confirm nor rule out our scenario.

Another possibility to test the proposed scenario is a comparison to the expected rate evolution, which is likely to grow with redshift as the galaxy merger rate increases, as actually found by LIGO-Virgo [75].

Summary and conclusions.—In this Letter we describe a new, relatively unexplored channel for the production of GW binary BH events. We argue that the binary components of the event GW190521, which produced the most massive BH remnant found in GWs to date, could be the central BHs of merging ultradwarf galaxies. We find that the merger rate of ultradwarf galaxies at $1 < z < 2$ is compatible with the inferred rate for GW190521-like events, making our scenario a viable possibility. The required time delay for the BH merger in the case of GW190521 is likely to be $\lesssim$4 Gyr. We show that typical time delays could be on the order of Gyrs considering dynamical friction arguments, and our findings highlight the necessity of realistic simulations for central BHs in merging dwarf galaxies to provide more stringent constraints on the expected rate of merging BHs.

We also note that the proposed scenario could be interesting for the case in which only one object is a massive stellar mass BH (and potentially the central BH of a dwarf), and the secondary in the binary is a lower mass object, and not a central BH. This could be relevant for events like GW190814 [76] and GW190412 [77]. We also do not exclude the possibility that the secondary of GW190521 could be of stellar origin and below the mass gap, implying that the primary would have a mass of $\sim 113\ M_\odot$ [78], and could then be the central BH of a $\sim 10\ M_\odot$ dwarf.

If confirmed, this scenario would open new avenues in GW follow–up strategies, cosmology, and in particular galaxy formation and evolution. Future observations of binary BH by LIGO-Virgo-KAGRA will build a larger sample of intermediate mass BHs and possibly shed light on this formation channel as population analyses provide interesting constraints on the rate evolution and the mass function of these systems.

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