

Black holes in the low-mass gap: Implications for gravitational-wave observations

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Binary neutron-star mergers will predominantly produce black-hole remnants of mass $\sim 3\text{--}4 M_{\odot}$, thus populating the putative *low-mass gap* between neutron stars and stellar-mass black holes. If these low-mass black holes are in dense astrophysical environments, mass segregation could lead to “second-generation” compact binaries merging within a Hubble time. In this paper, we investigate possible signatures of such low-mass compact binary mergers in gravitational-wave observations. We show that this unique population of objects, if present, will be uncovered by the third-generation gravitational-wave detectors, such as Cosmic Explorer and Einstein Telescope. Future joint measurements of chirp mass \mathcal{M} and effective spin χ_{eff} could clarify the formation scenario of compact objects in the low-mass gap. As a case study, we show that the recent detection of GW190425 (along with GW170817) favors a double Gaussian mass model for neutron stars, under the assumption that the primary in GW190425 is a black hole formed from a previous binary neutron-star merger.

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I. INTRODUCTION

Gravitational-wave (GW) observations over the past 4 years have brought several exciting discoveries. About half of all black holes (BHs) discovered by the LIGO and Virgo detectors during their first and second observing runs had component masses m_i ($i = 1, 2$) larger than $\sim 30 M_{\odot}$, with some of them as massive as $50 M_{\odot}$ [1]. These BH masses are larger than the BH masses of $\lesssim 25 M_{\odot}$ estimated from X-ray observations [2]. Their existence and the fact that they would dominate event rates were predicted well before their discovery [3–7]. Eight out of ten binaries had an

effective spin $\chi_{\text{eff}} = (m_1 \chi_1 \cos \theta_1 + m_2 \chi_2 \cos \theta_2) / (m_1 + m_2)$ (where χ_i denotes the Kerr parameter of each hole and θ_i is the angle between each spin and the orbital angular momentum) consistent with zero within the 90% credible interval [1]. This diversity in the mass and spin parameters of LIGO/Virgo binary BHs hints at a scenario where multiple astrophysical formation channels—including isolated binaries [8] and dynamical interactions [9]—contribute to the observed population. Hundreds or thousands of GW events will be required to assess the relative role of different formation channels (see, e.g., [10–13]) and to probe the BH mass function [14].

Theoretical and observational arguments suggest that stellar evolution may not produce BHs of mass less than $\sim 5 M_{\odot}$ [15–17]. On the other hand, neutron stars (NSs) are expected to have a maximum mass of $\sim 3 M_{\odot}$ [18–22]. The heaviest NS observed to date has a mass of $2.01 \pm 0.04 M_{\odot}$ [23]. There is a recent claim that PSR J0740 + 6620 may

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host a $2.14_{-0.09}^{+0.10} M_{\odot}$ NS, but systematic uncertainties in this measurement are still a matter of debate [24]. The lack of observations of compact object in the range $\sim [2, 5] M_{\odot}$ to date hints at the existence of the so-called *low-mass gap* [15,16,25], in contrast with the “high-mass gap” at $M \gtrsim 50 M_{\odot}$ due to pair-instability supernovae [26].

The general consensus is that the first binary NS merger GW170817 [1,27] produced a hypermassive NS [28,29] that should eventually collapse to a BH in the low-mass gap (but see [30,31] for alternative possibilities). If the NS binary progenitors lived in a dense stellar cluster and the BH remnant is retained in the environment, dynamical interactions and mass segregation could allow it to interact and merge with another compact object. The more recent detection of GW190425 [32] hints toward the existence of an unusual binary system, if both the binary components are believed to be NSs: the total mass of the binary ($3.4_{-0.1}^{+0.3} M_{\odot}$) is significantly larger than the known population of galactic double NS binaries [33,34]. Moreover, due to the lack of any GW190425 electromagnetic counterpart to date, the GW observation alone cannot rule out the possibility of one or both binary components being BHs.

The galactic population of double NSs strongly suggests that a subpopulation of detected binaries could well have been formed in dense clusters (see, e.g., Fig. 1 and Sec. 4 of Ref. [35], where the authors argue that one tenth of the double NS population in our galaxy has globular cluster association). Another subpopulation is likely to have been ejected out of the globular cluster to the galactic field by dynamical interactions. Hence, double NS binaries can exist in dense environments, and a fraction of these could merge producing low-mass BHs. These, in turn, could pair up with other NSs or low-mass BHs and merge within a Hubble time (see [36] for a discussion of the dynamical interactions which can make this possible), contributing an unknown fraction to the compact binary population detectable by second- and third-generation GW detectors.

Recent globular cluster simulations [37] predict that binary NSs dynamically formed in globular clusters should constitute only a tiny fraction ($\sim 10^{-5}$) of the total binary NS mergers, at odds with the observations mentioned above. More studies are necessary to determine this fraction and hence the efficiency of the mechanism studied in this work. Here we take a model-agnostic stand and argue that future GW observations will put this idea to the test, potentially revealing the existence of a new population of compact binary mergers with one or both components in the low-mass gap. In order to account for these large uncertainties, we present our results in terms of “normalized” detection rates and number of detections defined by r/f_{dyn} and $N_{\text{det}}/f_{\text{dyn}}$, respectively, where r and N_{det} are the rate and number of detection of binary NS mergers and f_{dyn} denote the fraction of dynamically formed binary NSs (see Sec. II for details).

In this paper, we construct a model to populate the low-mass gap with BHs resulting from a population of

merging NSs. If binary NSs merge in isolation, the remnant BH that forms in the process will never have the opportunity to form a binary again. Thus, the mass gap (if it exists) remains intact from the point of view of GW observations. Under this assumption, the observation of GW events with BH masses in the range $3 - 5 M_{\odot}$ would imply that stellar evolution can produce BHs in the mass gap. One key point of the present paper is that this conclusion could be erroneous if NSs can form in dense clusters.

Following previous work [10], we refer to compact objects born from stellar collapse as “first generation” (1g), while “second-generation” (2g) compact objects are born from previous mergers. We will show that 1g + 1g, 1g + 2g, and 2g + 2g merger events in the low-mass gap should have rather different chirp mass and effective spin distributions, that can potentially be distinguished with third-generation detectors such as Cosmic Explorer [38] and Einstein Telescope [39]. Similar ideas had previously been proposed to understand the origin of BHs in the high mass gap, if they exist in nature [10,40–42].

The rest of the paper is organized as follows. In Sec. II, we state our assumptions to model the expected populations of BHs and NSs. In Sec. III, we estimate the observational signatures of binaries containing BHs formed from the merger of binary NSs. In Sec. IV, we discuss the implications of GW190425, if indeed the primary component originated from a 2g merger. In Sec. V, we conclude the paper and provide directions for future work.

II. BUILDING THE POPULATION

The mass distribution of NSs is an active research topic [21,22,34,43,44]. To bracket uncertainties, we consider the following three possibilities [33,43]:

- (i) A single Gaussian distribution with mean $\mu = 1.33 M_{\odot}$ and standard deviation $\sigma = 0.09 M_{\odot}$.
- (ii) A superposition of two Gaussian distributions with means $\mu_i = 1.34 M_{\odot}, 1.47 M_{\odot}$, standard deviations $\sigma_i = 0.02 M_{\odot}, 0.15 M_{\odot}$, and weights $\omega_i = 0.68, 0.32$ ($i = 1, 2$), respectively.
- (iii) A uniform distribution in the range $[0.9, 2.0] M_{\odot}$.

We note that model (ii) above is meant to reproduce the mass distribution of recycled NSs in double NS binaries [33], but Ref. [33] also reported a uniform distribution in the range $[1.14, 1.46] M_{\odot}$ for nonrecycled (slowly rotating) NSs. Model (iii) in this paper is a more generic uniform distribution extending over a broader range. The resulting mass distributions are shown in Fig. 1 (black histograms on the left of the three panels). We will refer to the population of NSs drawn from each of these distributions as the 1g of compact objects.

Electromagnetic observations indicate that the fastest-spinning isolated NS has a dimensionless spin magnitude $\chi \lesssim 0.4$ [45], while NSs in binaries are expected to have even smaller spins $\chi \lesssim 0.04$ [46,47]. Therefore, for

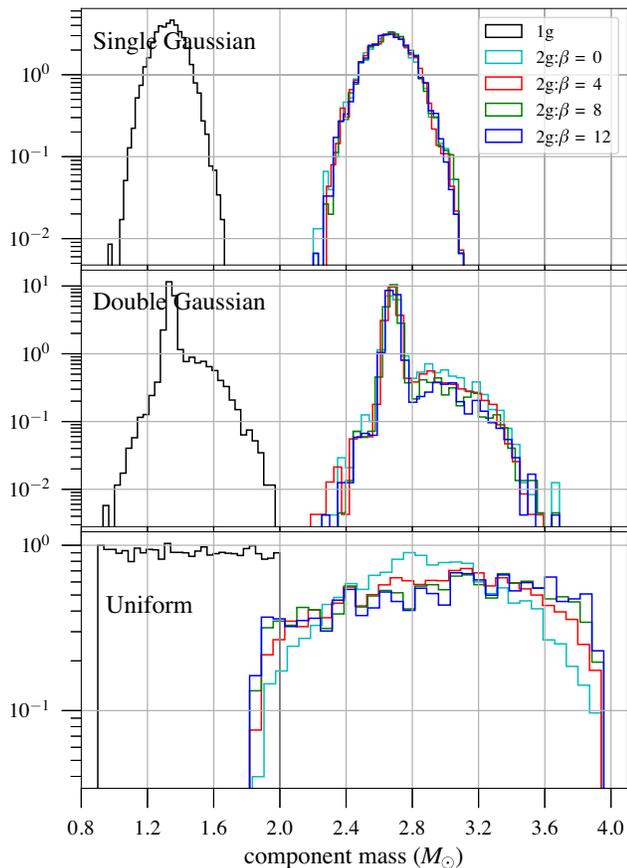


FIG. 1. Mass distribution of 1g NSs (black) and 2g BHs (cyan, red, green, blue) for the three mass distributions used in this work and various choices of the pairing-probability spectral index β .

simplicity, we will assume our 1g NS population to be nonspinning.

If formed in dense stellar environments, 1g NSs might interact with each other, form binaries, and merge. We select binaries according to the pairing probability $p_{\text{pair}}(m_1, m_2) \propto (m_2/m_1)^\beta$, where $m_2 \leq m_1$. To capture a broad phenomenology, we vary the spectral index in the range $0 \leq \beta \leq 12$. This pairing probability is independent of the mass ratio for $\beta = 0$ and favors the formation of comparable-mass binaries for $\beta > 0$. For the case of binary BHs, Refs. [48,49] fitted the observed GW events with $p(m_2|m_1) \propto (m_2/m_1)^\beta$ and measured $\beta \simeq 7$.

For a given 1g NS binary characterized by $m_1^{(1g)}, m_2^{(1g)}$ and selected according to $p_{\text{pair}}(m_1^{(1g)}, m_2^{(1g)})$, we then consider their merger product: a 2g BH. Numerical-relativity simulations suggest that the mass ejected in binary NS mergers is a very small fraction of the total mass of the system, ranging between $10^{-3} M_\odot$ and $10^{-2} M_\odot$ [50]. For simplicity, we neglect the mass loss and simply estimate the masses of 2g BHs as $m^{(2g)} = m_1^{(1g)} + m_2^{(1g)}$. The outcome of this procedure is shown in Fig. 1: 2g BHs resulting from the merger of NSs have masses between $\sim 2 M_\odot$ and

$\sim 4 M_\odot$ and populate the low-mass gap. High (low) values of β preferentially select 1g NSs with comparable (unequal) masses. Their remnants populate the edges (center) of the 2g mass spectrum.

Binaries containing second-generation BHs are expected to assemble following a sequence of dynamical interactions; therefore, the BH spins in such binaries are expected to be distributed isotropically. We compute the spin of 2g BHs using fits to numerical-relativity simulations of BH binaries [51].¹

These 2g BHs might interact with the rest of the 1g NSs in the population or with other 2g BHs, form binaries, and possibly produce GW events. If BHs heavier than $5 M_\odot$ formed by stellar evolution reside in the same cluster, they too could pair up with 2g BHs, and produce merger events with a more extreme mass ratio. In fact, due to the higher rate of BH mergers compared to NS mergers in dense stellar environments [37,54], it is likely that most low-mass gap binaries will come from the merger of 2g BHs with massive BHs outside the gap ($\gtrsim 5 M_\odot$). However, we do not consider this possibility in the present work. In our model, the initial population is that of NS binaries and they are the ones that produce BHs in the mass gap. The existence of heavier BHs in the same environment could alter the distribution of BH masses and spins to be discussed below, and we plan to investigate this problem in the future.

Let us make a rough estimate of the abundance of 2g BHs by assuming that they are produced continuously since the formation of the first galaxies. The Milky Way has $\sim 10^8$ NSs [55]. The detection of GW170817 and GW190425 has established the rate of binary NS mergers to be $\sim 10^3 \text{ Gpc}^{-3} \text{ yr}^{-1}$, which translates to a merger rate in a Milky Way equivalent galaxy of 10^{-4} yr^{-1} [56]. Within the age of the Universe $\sim 10 \text{ Gyr}$, we expect that such a galaxy would have witnessed as many as 10^6 binary NS mergers, leading to the same number of 2g BHs. Thus, the abundance ratio of 2g BHs to NSs in the Universe could be assumed to be $\kappa = 0.01$.

This yields a mixture population

$$p(m) = (1 - \kappa)p(m^{(1g)}) + \kappa p(m^{(2g)}). \quad (1)$$

From this distribution, we extract two masses m_1 and m_2 according to p_{pair} and consider their GW emission. This constructs the probability distribution $p(m_1, m_2)$ and leads to three populations: 1g + 1g (where both companions are NSs), 2g + 2g (where both companions are BHs), and 1g + 2g (where an NS pairs with a BH).

¹The final spin resulting from an NS binary could in principle be quite different from that of a BH binary due to different dependence on mass-ratio, finite-size effects, and nonlinear hydrodynamics contributions. However, numerical-relativity simulations suggest that the final spin of NS binary mergers could be as high as ~ 0.8 [52,53], similar to values predicted from BH mergers. In any case, the use of BH binary fits for NS binaries does not have a dramatic impact on our main results.

We distribute merger redshifts uniformly in comoving volume V_c and source-frame time, i.e., $p(z) \propto (dV_c/dz)/(1+z)$, up to some horizon redshift z_H . We estimate GW detectability using a standard single-detector semianalytic approximation [7,57] with a signal-to-noise ratio (SNR) threshold of 8 and the waveform model of [58]. This defines a detection probability $p_{\text{det}}(m_1, m_2, z)$ averaged over polarization, inclination, and sky location. We neglect spins, because they have a small effect on the detection rate [59]. We consider noise curves for advanced LIGO at design sensitivity [60] and Cosmic Explorer in the wide-band configuration [61]. The horizon redshift z_H is chosen such that $p_{\text{det}} = 0$ for $z > z_H$. In particular, we set $z_H = 0.3$ (4) for LIGO (Cosmic Explorer).

The expected merger rate is given by

$$r = \int p(m_1, m_2) \mathcal{R}(z) \frac{dV_c}{dz} \frac{1}{1+z} p_{\text{det}}(m_1, m_2, z) dm_1 dm_2 dz, \quad (2)$$

where $\mathcal{R}(z)$ is the intrinsic merger rate. If \mathcal{R}_{NS} is the total NS-NS merger rate, only the fraction f_{dyn} coming from

dynamical channels is relevant to the formation of 2g BHs, i.e., $\mathcal{R} = f_{\text{dyn}} \mathcal{R}_{\text{NS}}$. At present, there is no clear consensus on the value of f_{dyn} ; see, e.g., [35] and [37]. Therefore, we quote normalized merger rates r/f_{dyn} , and we assume \mathcal{R}_{NS} to be $1000 \text{ Gpc}^{-3} \text{ yr}^{-1}$ [32]. Our results can be easily rescaled when future events will better constrain these values. In practice, we approximate Eq. (2) with a Monte-Carlo sum,

$$\frac{r}{f_{\text{dyn}}} \approx \mathcal{R}_{\text{NS}} \left(\int_0^{z_H} \frac{dV_c}{dz} \frac{1}{1+z} dz \right) \frac{1}{N} \sum_{i=1}^N p_{\text{det}}(m_1^i, m_2^i, z^i), \quad (3)$$

where N is the total number of simulated binaries. The total number of observations, scaled with f_{dyn} , is then given by $N_{\text{det}}/f_{\text{dyn}} = (r/f_{\text{dyn}}) \times T_{\text{obs}}$, where T_{obs} is the duration of the observing run(s).

III. FILLING THE MASS GAP

Figure 2 shows histograms of the detection rate as a function of the chirp mass $\mathcal{M} = (m_1 m_2)^{3/5} / (m_1 + m_2)^{1/5}$.

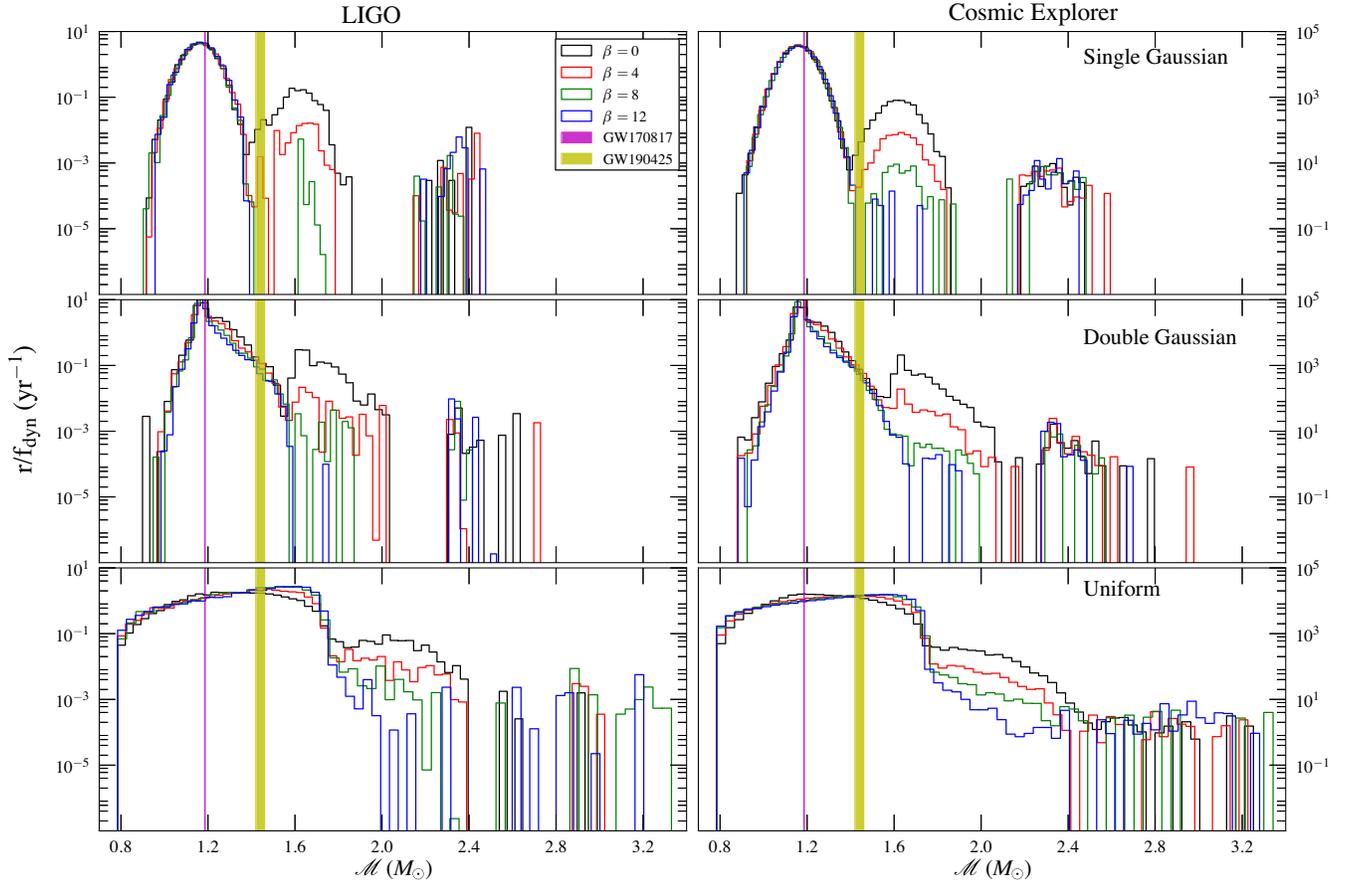


FIG. 2. Detection rate (r/f_{dyn}) per chirp mass bins for 1g + 1g, 1g + 2g, and 2g + 2g mergers as observed by LIGO (left) and Cosmic Explorer (right). Different colors correspond to different pairing probabilities $p_{\text{pair}} \propto (m_2/m_1)^\beta$. Upper, middle, and lower panels show results from the three different mass distributions for 1g NSs: single-Gaussian, double-Gaussian, and uniform, respectively. Also shown are the 90% credible bounds on the chirp mass of GW170817 (magenta) and GW190425 (yellow).

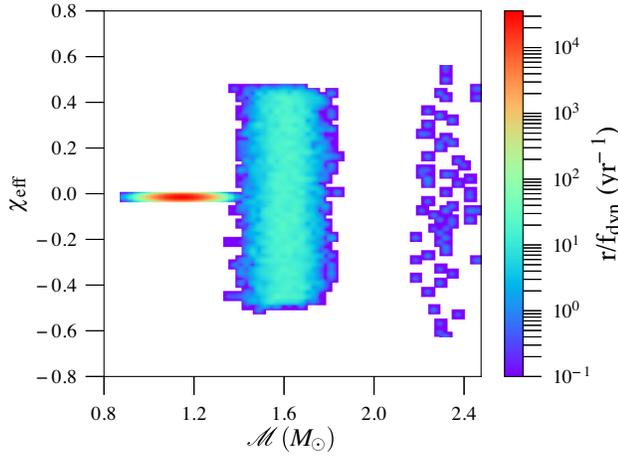


FIG. 3. Joint chirp-mass effective-spin distribution as observed by Cosmic Explorer. The 1g NS mass distribution is modeled by a single Gaussian and we assume $\beta = 0$. The color bar indicates the detection rate (r/f_{dyn}) per bin.

The predicted distribution presents three distinct peaks at low, moderate, and high values of \mathcal{M} : in these regimes, the merger rate is dominated by 1g + 1g, 1g + 2g, and 2g + 2g mergers, respectively. The ratio between the height of the

peaks is $\sim\kappa$ and $\sim\kappa^2$, as a consequence of the rate argument presented above. Among the three populations, hybrid (1g + 2g) mergers present the strongest dependence on β . These mergers are characterized by mass ratios ~ 0.5 , which are suppressed for steep pairing probability functions.

Clearly, if NS masses are distributed with a single-peak Gaussian (which could be confirmed with future observations), then even 1g + 2g and 2g + 2g mergers continue to leave a gap in chirp mass between $\sim 1.8 M_{\odot}$ and $\sim 2.2 M_{\odot}$. This would be absent if massive stars are able to leave a remnant in the mass gap. Since we will be able to measure the NS mass distribution very accurately with future detections, this is a firm prediction about the existence of the mass gap that could be tested with third-generation GW detectors.

Figure 3 shows the joint distribution of chirp mass and effective spin observed by Cosmic Explorer assuming the single Gaussian mass distribution and $\beta = 0$; results are qualitatively similar under other assumptions.

Again, events separate into three distinct regions, corresponding to 1g + 1g, 1g + 2g, and 2g + 2g. At low chirp masses, the event rate is dominated by 1g + 1g NS mergers, which are slowly rotating. The effective spin is thus expected to be very small (exactly zero in our

TABLE I. Expected number of detections $N_{\text{obs}}/f_{\text{dyn}}$ from 1 year of observation of LIGO at design sensitivity and Cosmic Explorer.

β	LIGO			Cosmic explorer		
	1g + 1g	1g + 2g	2g + 2g	1g + 1g	1g + 2g	2g + 2g
Single-peak Gaussian mass distribution						
0	24	1.06	0.01	1.9×10^5	5443	45
2	24	0.30	0.02	1.9×10^5	1695	39
4	25	0.10	0.01	1.9×10^5	516	43
6	25	0.02	0.02	1.9×10^5	149	49
8	25	5×10^{-3}	2×10^{-3}	1.9×10^5	47	43
10	25	4×10^{-3}	0.04	1.9×10^5	21	39
12	25	0	0.01	2.0×10^5	3	50
Double-peak Gaussian mass distribution						
0	26	1.19	0.01	2.0×10^5	5804	43
2	26	0.42	8×10^{-3}	2.1×10^5	1675	38
4	26	0.08	5×10^{-3}	2.1×10^5	522	49
6	26	0.04	0.02	2.1×10^5	153	51
8	26	0.01	9×10^{-3}	2.0×10^5	41	32
10	26	3×10^{-3}	0.01	2.0×10^5	15	47
12	26	9.9×10^{-5}	0.02	2.0×10^5	8	54
Uniform mass distribution						
0	29	1.32	0.01	2.1×10^5	6042	39
2	30	0.64	0.03	2.2×10^5	2748	52
4	31	0.31	6.9×10^{-3}	2.2×10^5	1482	35
6	32	0.19	4×10^{-3}	2.2×10^5	959	40
8	32	0.15	0.02	2.2×10^5	673	52
10	33	0.17	0.03	2.2×10^5	625	48
12	33	0.13	0.01	2.2×10^5	576	51

simplified model). At moderate chirp masses, the rate is dominated by $1g + 2g$ mergers. In these BH/NS mergers, the BH is the result of a nonspinning comparable-mass merger and therefore has $\chi_1 \sim 0.7$ [62]. The NS, on the other hand, has $\chi_2 \sim 0$. Since we neglect mass loss and NSs have a relatively narrow mass distribution, these events have $m_1 \sim 2m_2$. The largest (smallest) effective spins these events can have correspond to $\theta_1 = 0$ (π), which implies $|\chi_{\text{eff}}| \gtrsim 2 \times 0.7 / (1 + 2) \sim 0.45$, as shown in Fig. 3. Events with $\mathcal{M} \gtrsim 2 M_\odot$ are $2g + 2g$ BH mergers. In this case, $\chi_1 \sim \chi_2 \sim 0.7$ and $m_1 \sim m_2$. The effective spin is bound by $|\chi_{\text{eff}}| \lesssim 0.7$.

Table I shows the expected number of observations, assuming 1 year of data from either advanced LIGO at design sensitivity or Cosmic Explorer. With second-generation interferometers, the expected number of observations for this population of BHs in the low-mass gap is extremely small. Third-generation detectors will be necessary to unveil these systems, thus adding yet another item to their already vast science case [38,39]. In a few years of operation, Cosmic Explorer might deliver between ~ 1 and ~ 100 BHs in the low-mass gap if $f_{\text{dyn}} \sim 0.01$. A few events should still be visible even if the dynamical contribution to the NS merger rate is smaller than 0.01.

IV. GW190425: A CASE STUDY

LIGO and Virgo have announced the detection of a new NS binary, GW190425 [32], during their third observing run. This is the second event, after GW170817, that is believed to contain at least one NS component (or possibly two). This inference is based entirely on the measured masses of the binary components, $m_1 \in [1.61, 2.52]$ and $m_2 \in [1.12, 1.68]$. As acknowledged in [32], GW observation alone cannot rule out the possibility that this is an NS-BH or a BH-BH binary. A nonzero value for the tidal deformability $\tilde{\Lambda}$ would be a signature of the presence of at least one NS in the system, while $\tilde{\Lambda}$ consistent with zero would imply that the system could be a BH binary. The SNR for GW190425 is not large enough to infer that $\tilde{\Lambda}$ is nonzero, thus not ruling out the possibility that one (or both) of the components in GW190425 is a BH.

What are the astrophysical implications if the primary component is a BH? In particular, can we say anything about the merger rate of such a BH with NSs? As discussed before, it is likely that no compact objects are produced by stellar evolution in the mass range $[2.2, 5]M_\odot$, but NS mergers would definitely produce BHs in the mass gap. Furthermore, if binary NS mergers occur in globular clusters, then the resulting BHs could merge with other NSs in the cluster. Under the assumption that GW190425 is the result of such a merger, we can estimate the rate of these second-generation mergers relative to the binary NS merger rate.

In the absence of any other process (e.g., stellar evolution or primordial BHs) contributing to the BH population in

the mass gap, an observed merger belongs to one of two classes: (a) an NS-NS merger, that we call a class $1g$ merger, or (b) an NS-BH merger (let us call it a ‘‘class $1.5g$ ’’ merger) where the BH is the result of a previous NS-NS merger. If α denotes the rate of $1.5g$ mergers relative to $1g$ mergers, then $R_{1.5} = \alpha R_1$. Assuming that the sensitive volumes for the two mergers are V_1 and $V_{1.5}$, respectively, the Poisson likelihood for these detections is [63–65]

$$p(N_1, N_{1.5} | R_1, \alpha) = \alpha^{N_{1.5}} R_1^{N_1 + N_{1.5}} e^{-R_1(V_1 + \alpha V_{1.5})}, \quad (4)$$

where N_1 and $N_{1.5}$ are the number of $1g$ and $1.5g$ mergers, respectively. Integrating out R_1 after applying a prior $p(R_1) \propto R_1^{-\gamma}$ (e.g., $\gamma = 0$ for a flat prior, $\gamma = 1/2$ for Jeffreys prior, $\gamma = 1$ for a flat-in-log prior), we find

$$p(N_1, N_{1.5} | \alpha) \propto \frac{\alpha^{N_{1.5}}}{(V_1 + \alpha V_{1.5})^{N_1 + N_{1.5} - \gamma + 1}}. \quad (5)$$

If we make the approximation that the volumes scale in the usual way with chirp mass, then Eq. (5) becomes

$$p(N_1, N_{1.5} | \alpha) \propto \frac{\alpha^{N_{1.5}}}{\left[1 + \alpha \left(\frac{\mathcal{M}_{1.5}}{\mathcal{M}_1}\right)^{15/6}\right]^{N_1 + N_{1.5} - \gamma + 1}}, \quad (6)$$

where \mathcal{M}_1 and $\mathcal{M}_{1.5}$ are characteristic chirp masses for $1g$ and $1.5g$ populations, respectively.

Based on the chirp mass measurement of GW170817 and GW190425, and referring to Fig. 2, it is likely that $N_1 = 1$ and $N_{1.5} = 1$ for single Gaussian mass model (GW170817 belonging to $1g$ class and GW190425 belonging to $1.5g$ class), and $N_1 = 2$ and $N_{1.5} = 0$ for double Gaussian mass model (both GW170817 and GW190425 belonging to $1g$ class) [33]. Assuming a flat prior on R_1 (i.e., $\gamma = 0$) and taking $\mathcal{M}_{1.5}/\mathcal{M}_1 = 1.5$, we compute the posterior probability for α for the two mass models in Fig. 4.

The posterior probability for α gives a 90% credible interval for α of $[0.08, 0.91]$ for the single Gaussian mass model, whereas $\alpha > 8.2 \times 10^{-5}$ for the double Gaussian

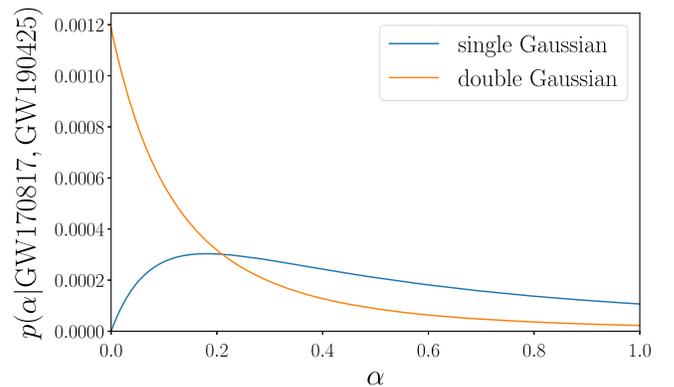


FIG. 4. The posterior probability of α computed using Eq. (6).

models. The current binary evolutionary models predict very small α values [37], consistent with the value inferred above using the double Gaussian mass model. The single Gaussian model, on the other hand, provides relatively large α . This implies that the two binary NS events so far (GW170817 and GW190425) favor a double Gaussian mass model over the single Gaussian mass model, under the assumptions that (i) BHs in the mass gap are formed only via compact binary mergers, and (ii) the primary of GW190425 is a BH formed through an NS-NS merger. Future observations would either strengthen or weaken this claim.

V. CONCLUDING REMARKS AND FUTURE WORK

Astrophysical considerations suggest the possible existence of a mass gap between the heaviest NSs and the lightest stellar-origin BHs [15,16]. The gap could well be just a selection effect [17], so it is important to verify whether BHs populating the mass gap exist in nature. GW observations will present orthogonal selection effects compared to electromagnetic probes, thus offering a promising opportunity to settle this issue. As the number of GW detections increases, we will be able to determine whether the mass gap is populated and to set constraints on the astrophysical mechanisms that populate it [66,67].

Understanding the existence of compact objects in the mass gap has important astrophysical implications. Stellar collapse can only produce BHs with masses $M \lesssim 5 M_{\odot}$ if the explosions are driven by instabilities that develop over timescales $\gtrsim 200$ ms [25]: if these instabilities develop on shorter timescales, the predicted mass spectrum has a gap.

Several arguments indicate that the first binary NS merger GW170817 must have produced a hypermassive NS [28,29], that should eventually collapse to a BH in the low-mass gap. The total mass of the GW190425 binary is significantly larger than the mass of galactic double NS binaries, and we cannot rule out the possibility of one or both binary components being BHs. These two observed events and simple rate estimates suggest that the ratio of NS-NS merger remnants to NSs in a Milky Way equivalent galaxy should be $\kappa \sim 0.01$. This implies the existence of a population of low-mass BHs in merging compact binaries, which can be probed with third-generation GW detectors.

The inverse problem is also intriguing. Measuring the relative abundance of NS mergers and low-mass gap BH mergers will allow us to infer the typical number of NS mergers occurring in a galaxy during its cosmic lifetime.

There is one caveat in our models: we assume that all merger remnants are retained inside the cluster and remain available to form 2g objects. Both natal and merger kicks might decrease the available number of low-mass BHs in clusters. Including this effect in future work might provide a handle to constrain the escape speed of dense stellar clusters with GW data [40].

Some events (e.g., GW151226 and GW170608; [1]) already hint at a non-negligible probability that some BHs may be in the low-mass gap. At the present sensitivity, however, those posterior tails strongly depends on the assumed prior [68]. We plan to explore the astrophysical implications of this population of BH binaries in future work.

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- [1] B. P. Abbott *et al.*, *Phys. Rev. X* **9**, 031040 (2019).
- [2] J. Casares, P. G. Jonker, and G. Israelian, X-Ray binaries, in *Handbook of Supernovae*, edited by A. W. Alsabti and P. Murdin (Springer, Cham, 2017), p. 1499.
- [3] K. Belczynski, T. Bulik, C. L. Fryer, A. Ruiter, F. Valsecchi, J. S. Vink, and J. R. Hurley, *Astrophys. J.* **714**, 1217 (2010).
- [4] K. Belczynski, M. Dominik, T. Bulik, R. O’Shaughnessy, C. Fryer, and D. E. Holz, *Astrophys. J. Lett.* **715**, L138 (2010).
- [5] M. Dominik, K. Belczynski, C. Fryer, D. E. Holz, E. Berti, T. Bulik, I. Mandel, and R. O’Shaughnessy, *Astrophys. J.* **759**, 52 (2012).
- [6] M. Dominik, K. Belczynski, C. Fryer, D. E. Holz, E. Berti, T. Bulik, I. Mandel, and R. O’Shaughnessy, *Astrophys. J.* **779**, 72 (2013).
- [7] M. Dominik, E. Berti, R. O’Shaughnessy, I. Mandel, K. Belczynski, C. Fryer, D. E. Holz, T. Bulik, and F. Pannarale, *Astrophys. J.* **806**, 263 (2015).
- [8] K. A. Postnov and L. R. Yungelson, *Living Rev. Relativity* **17**, 3 (2014).
- [9] M. J. Benacquista and J. M. B. Downing, *Living Rev. Relativity* **16**, 4 (2013).
- [10] D. Gerosa and E. Berti, *Phys. Rev. D* **95**, 124046 (2017).
- [11] M. Zevin, C. Pankow, C. L. Rodriguez, L. Sampson, E. Chase, V. Kalogera, and F. A. Rasio, *Astrophys. J.* **846**, 82 (2017).
- [12] J. Powell, S. Stevenson, I. Mandel, and P. Tino, *Mon. Not. R. Astron. Soc.* **488**, 3810 (2019).
- [13] Y. Bouffanais, M. Mapelli, D. Gerosa, U. N. Di Carlo, N. Giacobbo, E. Berti, and V. Baibhav, *Astrophys. J.* **886**, 25 (2019).
- [14] E. D. Kovetz, I. Cholis, P. C. Breyse, and M. Kamionkowski, *Phys. Rev. D* **95**, 103010 (2017).
- [15] C. D. Bailyn, R. K. Jain, P. Coppi, and J. A. Orosz, *Astrophys. J.* **499**, 367 (1998).
- [16] F. Özel, D. Psaltis, R. Narayan, and J. E. McClintock, *Astrophys. J.* **725**, 1918 (2010).
- [17] W. M. Farr, N. Sravan, A. Cantrell, L. Kreidberg, C. D. Bailyn, I. Mandel, and V. Kalogera, *Astrophys. J.* **741**, 103 (2011).
- [18] C. E. Rhoades and R. Ruffini, *Phys. Rev. Lett.* **32**, 324 (1974).
- [19] F. Özel, D. Psaltis, R. Narayan, and A. S. Villarreal, *Astrophys. J.* **757**, 55 (2012).
- [20] B. Kiziltan, A. Kottas, M. De Yoreo, and S. E. Thorsett, *Astrophys. J.* **778**, 66 (2013).
- [21] J. Antoniadis, T. M. Tauris, F. Özel, E. Barr, D. J. Champion, and P. C. C. Freire, [arXiv:1605.01665](https://arxiv.org/abs/1605.01665).
- [22] J. Alsing, H. O. Silva, and E. Berti, *Mon. Not. R. Astron. Soc.* **478**, 1377 (2018).
- [23] J. Antoniadis *et al.*, *Science* **340**, 1233232 (2013).
- [24] H. T. Cromartie *et al.*, *Nat. Astron.* **4**, 72 (2020).
- [25] K. Belczynski, G. Wiktorowicz, C. L. Fryer, D. E. Holz, and V. Kalogera, *Astrophys. J.* **757**, 91 (2012).
- [26] S. E. Woosley, *Astrophys. J.* **836**, 244 (2017).
- [27] B. P. Abbott *et al.* (LIGO and Virgo Collaborations), *Phys. Rev. Lett.* **119**, 161101 (2017).
- [28] B. Margalit and B. D. Metzger, *Astrophys. J. Lett.* **850**, L19 (2017).
- [29] B. P. Abbott *et al.* (LIGO and Virgo Collaborations), *Classical Quantum Gravity* **37**, 045006 (2020).
- [30] Y.-W. Yu, L.-D. Liu, and Z.-G. Dai, *Astrophys. J.* **861**, 114 (2018).
- [31] L. Piro, E. Troja, B. Zhang, G. Ryan, H. van Eerten, R. Ricci, M. H. Wieringa, A. Tiengo, N. R. Butler, S. B. Cenko, O. D. Fox, H. G. Khandrika, G. Novara, A. Rossi, and T. Sakamoto, *Mon. Not. R. Astron. Soc.* **483**, 1912 (2019).
- [32] B. P. Abbott *et al.* (LIGO and Virgo Collaborations), *Astrophys. J. Lett.* **892**, L3 (2020).
- [33] N. Farrow, X.-J. Zhu, and E. Thrane, *Astrophys. J.* **876**, 18 (2019).
- [34] J. Zhang, Y. Yang, C. Zhang, W. Yang, D. Li, S. Bi, and X. Zhang, *Mon. Not. R. Astron. Soc.* **488**, 5020 (2019).
- [35] J. J. Andrews and I. Mandel, *Astrophys. J. Lett.* **880**, L8 (2019).
- [36] M. Safarzadeh, A. S. Hamers, A. Loeb, and E. Berger, *Astrophys. J. Lett.* **888**, L3 (2020).
- [37] C. S. Ye, W.-f. Fong, K. Kremer, C. L. Rodriguez, S. Chatterjee, G. Fragione, and F. A. Rasio, *Astrophys. J. Lett.* **888**, L10 (2020).
- [38] D. Reitze *et al.*, *Bull. Am. Astron. Soc.* **51**, 35 (2019), https://113qx216in8z1kdeyi404hgfw-engine.netdna-ssl.com/wp-content/uploads/2019/05/141_reitze.pdf.
- [39] M. Punturo *et al.*, *Classical Quantum Gravity* **27**, 194002 (2010).
- [40] D. Gerosa and E. Berti, *Phys. Rev. D* **100**, 041301 (2019).
- [41] M. Fishbach, D. E. Holz, and B. Farr, *Astrophys. J. Lett.* **840**, L24 (2017).
- [42] C. L. Rodriguez, P. Amaro-Seoane, S. Chatterjee, and F. A. Rasio, *Phys. Rev. Lett.* **120**, 151101 (2018).
- [43] F. Özel and P. Freire, *Annu. Rev. Astron. Astrophys.* **54**, 401 (2016).
- [44] D. Keitel, *Mon. Not. R. Astron. Soc.* **485**, 1665 (2019).
- [45] J. W. T. Hessels, S. M. Ransom, I. H. Stairs, P. C. C. Freire, V. M. Kaspi, and F. Camilo, *Science* **311**, 1901 (2006).
- [46] M. Burgay, N. D’Amico, A. Possenti, R. N. Manchester, A. G. Lyne, B. C. Joshi, M. A. McLaughlin, M. Kramer, J. M. Sarkissian, F. Camilo, V. Kalogera, C. Kim, and D. R. Lorimer, *Nature (London)* **426**, 531 (2003).
- [47] K. Stovall *et al.*, *Astrophys. J. Lett.* **854**, L22 (2018).
- [48] B. P. Abbott *et al.* (LIGO and Virgo Collaborations), *Astrophys. J. Lett.* **882**, L24 (2019).
- [49] M. Fishbach and D. E. Holz, *Astrophys. J. Lett.* **891**, L27 (2020).
- [50] M. Shibata and K. Hotokezaka, *Annu. Rev. Nucl. Part. Sci.* **69**, 41 (2019).
- [51] F. Hofmann, E. Barausse, and L. Rezzolla, *Astrophys. J. Lett.* **825**, L19 (2016).
- [52] W. Kastaun, F. Galeazzi, D. Alic, L. Rezzolla, and J. A. Font, *Phys. Rev. D* **88**, 021501 (2013).
- [53] T. Dietrich, M. Ujevic, W. Tichy, S. Bernuzzi, and B. Brügmann, *Phys. Rev. D* **95**, 024029 (2017).
- [54] C. L. Rodriguez, S. Chatterjee, and F. A. Rasio, *Phys. Rev. D* **93**, 084029 (2016).
- [55] D. H. Hartmann, *Astron. Astrophys. Rev.* **6**, 225 (1995).
- [56] J. Abadie *et al.* (LIGO and Virgo Collaborations), *Classical Quantum Gravity* **27**, 173001 (2010).
- [57] L. S. Finn and D. F. Chernoff, *Phys. Rev. D* **47**, 2198 (1993).

- [58] S. Khan, S. Husa, M. Hannam, F. Ohme, M. Pürrer, X. J. Forteza, and A. Bohé, *Phys. Rev. D* **93**, 044007 (2016).
- [59] D. Gerosa, E. Berti, R. O’Shaughnessy, K. Belczynski, M. Kesden, D. Wysocki, and W. Gladysz, *Phys. Rev. D* **98**, 084036 (2018).
- [60] B. P. Abbott *et al.* (LIGO and Virgo Collaborations), *Living Rev. Relativity* **19**, 1 (2016).
- [61] B. P. Abbott *et al.* (LIGO Collaboration), *Classical Quantum Gravity* **34**, 044001 (2017).
- [62] E. Berti, V. Cardoso, J. A. Gonzalez, U. Sperhake, M. Hannam, S. Husa, and B. Brügmann, *Phys. Rev. D* **76**, 064034 (2007).
- [63] W. M. Farr, J. R. Gair, I. Mandel, and C. Cutler, *Phys. Rev. D* **91**, 023005 (2015).
- [64] S. R. Taylor and D. Gerosa, *Phys. Rev. D* **98**, 083017 (2018).
- [65] I. Mandel, W. M. Farr, and J. R. Gair, *Mon. Not. R. Astron. Soc.* **486**, 1086 (2019).
- [66] T. B. Littenberg, B. Farr, S. Coughlin, V. Kalogera, and D. E. Holz, *Astrophys. J. Lett.* **807**, L24 (2015).
- [67] I. Mandel, C.-J. Haster, M. Dominik, and K. Belczynski, *Mon. Not. R. Astron. Soc.* **450**, L85 (2015).
- [68] S. Vitale, D. Gerosa, C.-J. Haster, K. Chatziioannou, and A. Zimmerman, *Phys. Rev. Lett.* **119**, 251103 (2017).
- [69] D. Gerosa, GWDET: Detectability of gravitational-wave signals from compact binary coalescences, <https://github.com/dgerosa/gwdet>, <https://doi.org/10.5281/zenodo.889966>.