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Black Holes: The Next Generation – Repeated Mergers in Dense Star Clusters and their Gravitational-Wave Properties

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When two black holes merge in a dense star cluster, they form a new black hole with a well-defined mass and spin. If that “second-generation” black hole remains in the cluster, it will continue to participate in dynamical encounters, form binaries, and potentially merge again. Using a grid of 96 dynamical models of dense star clusters and a cosmological model of cluster formation, we explore the production of binary black hole mergers where at least one component of the binary was forged in a previous merger. We create four hypothetical universes where every black hole born in the collapse of a massive star has a dimensionless Kerr spin parameter, χ_{birth} , of 0.0, 0.1, 0.2, or 0.5. We show that if all stellar-born black holes are non-spinning ($\chi_{\text{birth}} = 0.0$), then more than 10% of merging binary black holes from clusters have components formed from previous mergers, accounting for more than 20% of the mergers from globular clusters detectable by LIGO/Virgo. Furthermore, nearly 7% of detectable mergers would have a component with a mass $\gtrsim 55M_{\odot}$, placing it clearly in the mass “gap” region where black holes cannot form from isolated collapsing stars due to the pulsational-pair instability mechanism. On the other hand, if black holes are born spinning, then the contribution from these second-generation mergers decreases, making up as little as 1% of all detections from globular clusters when $\chi_{\text{birth}} = 0.5$. We make quantitative predictions for the detected masses, mass ratios, and spin properties of first- and second-generation mergers from dense star clusters, and show how these distributions are highly sensitive to the birth spins of black holes.

I. INTRODUCTION

As of 2019, the majority of detected stellar-mass black holes (BHs) have been detected through gravitational waves (GWs). The first two observing runs of LIGO and Virgo (O1 and O2) yielded 10 binary black hole (BBH) mergers [1–6], while the ongoing O3 run has already reported several significant BBH candidates. Before the decade is complete, we will likely have information about the masses, spins, and cosmological redshifts of more than 100 BHs. While there exist many proposed mechanisms for forming double compact object mergers, such as the evolution of massive binary stars [7–12], dynamical formation in dense star clusters [13–26], long-term secular interactions with one (or more) bound companions [27–40], migration and capture in AGN disks [41–44], and even formation from primordial BHs [45], the vast majority of these formation channels source their component BHs from the collapse of massive stars. The outcome of stellar collapse should obey similar physics regardless of the formation channel or merger environment.

When a BBH merges in isolation, the resultant BH is unlikely to interact again with other stars or BHs. But when a merger occurs in a dense stellar environment, such

as a globular cluster (GC) or nuclear star cluster (NSC), the fate of the remnant can be far more interesting. For many years, it was assumed that most BHs produced from the mergers of other BHs would be ejected from their host clusters [46–49], because when the spins of the BBH components are large, the merger products receive large kicks ($\sim 10^3 \text{ km/s}$) due to the asymmetric emission of GWs [50, 51]. However, GW observations have suggested that many of the BBH mergers observed by LIGO/Virgo may have involved BHs with low intrinsic spin, significantly reducing the recoil kicks experienced by the merger products [6, 56].

If the recoil velocity of the merging binary is less than the local escape speed, the newly-formed BH will be retained by the cluster, creating a new generation of BHs. These second-generation (2G) BHs will continue to participate in three- and four-body dynamical encounters, eventually forming new BBHs and potentially merging a second time [58–60]. These mergers have unique masses, mass ratios, and spins which may be difficult or impossible to produce from first-generation (1G) BBHs produced from collapsing stars [61, 62]. In particular, both theoretical modeling of massive stars [63–65] and statistical modeling of the LIGO/Virgo BBH catalog [56, 57, 66] have suggested the existence of a gap in the BH mass

function above $\sim 40M_{\odot}$, arising from pulsational pair instabilities (PPIs) and pair-instability supernovae (PISN). The detection of BHs in this upper-mass gap would be strong evidence for the dynamical processing of BHs prior to their eventual merger.

In this paper, we explore the properties of 1G and 2G BBH mergers created from a realistic collection of GC models. Using a cosmological model for star-cluster formation, we create four hypothetical universes where the birth spins of 1G BHs, χ_{birth} , are uniformly 0.0, 0.1, 0.2, or 0.5. As the birth spin of the BHs is increased, the retention of the BBHs that merge in the cluster decreases, changing the mass and spin distributions of the BBHs detectable by LIGO/Virgo. In Section II, we describe the physics of our GC models, and the weighting scheme we use to reproduce the cosmological formation/evolution of GCs and the detectable population of BBHs. In Section III, we show how the retention of 2G BHs depends on the birth spins. We also describe what fraction of BBH mergers may contain a 2G BH, and what fraction of those sources would lie in the PPI/PISN mass gap. In Section IV, we show the mass, mass ratio, and spin distributions of all 1G and 2G BBHs, and compare them to the current catalog of GW observations. Throughout this paper, we assume a flat Λ CDM cosmology with $h = 0.679$ and $\Omega_M = 0.3065$ [67]. We describe the composition of BBHs by the generation of their components (e.g. a 2G+1G BBH has one 2G component and one 1G component), where 1G BHs are created from collapsing stars, and 2G components are created in a previous BBH mergers.

II. METHODS

We generate 96 models of dense star clusters using the **Cluster Monte Carlo** (CMC) Code, a Hénon-style N -body code for stellar dynamics [68, 69]. Because the Hénon Monte Carlo approach can model the dynamics of individual stars in a cluster, CMC can explicitly follow the formation and evolution of potential GW sources over many Gyr. The stars and binaries in our models are evolved self-consistently from their zero-age main-sequence births using the binary stellar evolution (BSE) package [70–72], with updated prescriptions for the formation of BHs and NSs from massive stars [24, and references therein] and the PPI/PISN physics [59]. These stars and binaries move dynamically through the cluster, where they participate in all the gravitational dynamics — collisional diffusion following the Fokker-Planck approximation [68, 73], binary formation in three-body encounters [74], strong gravitational encounters between stars and binaries [75], tidal stripping by the galactic potential — that can form merging BBHs.

A. Spins, Kicks, and post-Newtonian Dynamics

In [59], we added post-Newtonian (pN) corrections to the orbital dynamics of isolated BBHs and strong gravitational encounters involving BHs using the code developed and tested in [29, 76]. For BBHs that merge inside the cluster, we self-consistently calculate the final mass, spin, and recoil velocity of the BH merger product using detailed fitting formula from numerical relativity simulations [49, 52–55, 77–85]. See [59], Appendix A for a complete description of the equations used. However, in that study we only considered 1G BHs with zero spin (although we extrapolated our results to higher birth spins). Furthermore, we later showed in [86] that naively including the first and second pN corrections to the equations-of-motion can introduce significant biases in the measured eccentricities and binary classifications during strong encounters.

In this paper, we perform the first self-consistent estimates of 2G BBH formation with varying initial BH spins and a realistic model for GC formation. Our GC initial conditions are identical to those presented in [86], and cover a range of initial particle numbers (2×10^5 , 5×10^5 , 10^6 , and 2×10^6), initial virial radii (1pc and 2pc), and galactocentric radii/stellar metallicities (2 kpc/ $0.25Z_{\odot}$, 8 kpc/ $0.05Z_{\odot}$, and 20 kpc/ $0.01Z_{\odot}$). In this study, we expand this grid in a fourth dimension, and consider initial 1G BH spins of 0.0, 0.1, 0.2, and 0.5, for a total of 96 GC models; although the spins of BHs can go as high as 1, we find that a maximum χ_{birth} of 0.5 is already sufficient to eject the vast majority of 1G+1G mergers from the cluster. We do not consider more complicated prescriptions for BH spin based on the stellar mass and metallicity, such as those presented in [87]. However, those results suggest that heavier BHs ($\sim 30M_{\odot}$) may be born with spins in the 0.0-0.2 range, allowing us to extrapolate from the models presented here. The initial positions and velocities of individual particles are drawn from a King profile [88] with a concentration of $w_0 = 5$. The initial stellar masses are chosen from a Kroupa initial mass function (IMF) [89] in a range between $0.08M_{\odot}$ to $150M_{\odot}$. We assume that 10% of objects are initially in binaries, with semi-major axes distributed flatly in log from the point of stellar contact to the local hard/soft boundary. Binary eccentricities are drawn from a thermal distribution, $p(e)de = 2e de$. The primary mass, m_1 , of each binary is taken from the IMF, while the secondary mass is drawn from a flat distribution from 0 to m_1 .

B. GC Population and Detection Weights

In [59], we presented results from a series of GC models with a subset of the initial conditions presented here, but with no differentiation between clusters of different masses, ages, and metallicities. Here, we draw our BBH samples from each GC model according to a cosmologically-motivated model for GC formation [90].

This model was first used to predict the merger rate of BBHs from GCs in [91], and the weighting scheme we use is described in detail in [86]. Briefly, this procedure assigns to each GC model a weight based on how often clusters of that mass and metallicity are formed in the semi-analytic model of [90]. We divide the masses of GCs into 4 logarithmically-spaced bins, with one GC model in the center of each bin. The cluster models are then assigned a weight according to the integral of the cluster initial mass function (CIMF) over the extent of that bin. We assume a CIMF proportional to $1/M_{\text{GC}}^2$; although there is evidence that the CIMF may contain an exponential-like truncation at higher masses [92, and references therein], we find that our results are largely insensitive to such a choice [though the same cannot be said for the overall BBH merger rate; see 91]. We also divide the metallicity of GCs into three bins, and assign each cluster a weight based on the fraction of GCs formed at that metallicity at that redshift (using the median star-formation metallicity in a given halo mass at a given redshift from [93] and the relation between stellar and gas metallicity from [94]). The weight assigned to each GC model is the product of the mass and metallicity weights. For each BBH merger, we convolve the merger time of the BBH with the distribution of formation times for GCs of that metallicity [See 86, Figure 1] by drawing 100 random GC formation times for that BBH, and adding each merger to our sample. In other words, the merger time of a BBH is the cosmic time when that GC formed plus the time taken for the BBH to form and merge in that cluster. BBHs that merge later than the present day are discarded. Each BBH is then assigned the weight associated with its parent cluster, and it is these weights we use to create the results presented here. We note that our cluster formation model encompasses dense stellar clusters beyond the classical GCs observed in the local universe, and also includes low-mass open clusters which have disrupted before the present day, as well as super-star cluster formation in the local universe. However, we refer to this population as GCs for simplicity (and since the majority of BBH production occurs in these massive, old systems).

This weighting procedure provides us with the underlying physical distribution of sources at a given redshift interval per comoving volume, and throughout this paper we present results over all redshifts and in the local universe (defined as $z < 1$). But we are also interested in the distribution of sources that can be detected by LIGO/Virgo, for which we must consider both the increased sensitivity of the detectors to BBHs of higher masses and the larger amount of comoving volume surveyed at higher redshifts. To that end, we also report a detectable distribution of BBH mergers, created by multiplying the astrophysical weights by an additional detectability weight. That weight is calculated with:

$$w_{\text{det}} \equiv f_d(m_1, m_2, \vec{\chi}_1, \vec{\chi}_2, z) \frac{dV_c}{dz} \frac{dt_s}{dt_o}, \quad (1)$$

where $f_d(m_1, m_2, \vec{\chi}_1, \vec{\chi}_2, z)$ is the fraction of sources with masses m_1 and m_2 and spin vectors $\vec{\chi}_1$ and $\vec{\chi}_2$ merging at redshift z that are detectable by LIGO/Virgo, $\frac{dV_c}{dz}$ is the comoving volume at a given redshift, and $\frac{dt_s}{dt_o} = 1/(1+z)$ is the time dilation between clocks at the source and clocks on Earth.

To calculate $f_d(m_1, m_2, \vec{\chi}_1, \vec{\chi}_2, z)$, we first determine $\vec{\chi}_1$ and $\vec{\chi}_2$ by randomly drawing the spin angles isotropically on the sphere. We calculate the optimal matched-filter signal-to-noise ratio (SNR), ρ_{opt} , for each sample using a 3-detector network configuration consisting of the Hanford, Livingston, and Virgo interferometers with projected design sensitivities [95]. Waveforms are generated using the IMRPhenomPv2 approximant [96]. Using an SNR detection threshold of $\rho_{\text{thresh}} = 8.0$, if $\rho_{\text{opt}} < \rho_{\text{thresh}}$, the system is undetectable and $f_d(m_1, m_2, \vec{\chi}_1, \vec{\chi}_2, z) = 0$. Otherwise, we randomly sample the sky location, inclination angle, and polarization angle of each potentially detectable system $N = 10^4$ times and calculate the SNR, ρ_i , for each of these realizations. $f_d(m_1, m_2, \vec{\chi}_1, \vec{\chi}_2, z)$ is the fraction of these systems that exceed ρ_{thresh} :

$$f_d(m_1, m_2, \vec{\chi}_1, \vec{\chi}_2, z) = \frac{1}{N} \sum_i^N \Theta(\rho_i - \rho_{\text{thresh}}), \quad (2)$$

where Θ is the Heaviside step function.

III. SECOND GENERATION BLACK HOLES

A. Birth Spins and Black Hole Retention

The key question in the production of 2G BHs in GCs is whether the BBH mergers that occur in the cluster can be retained by the cluster. In Figure 1, we show the fraction of BBH merger products that are retained in their host clusters as a function of birth spin, χ_{birth} . For the case where the birth spins of 1G BHs are zero, nearly 60% of the merger products are retained in the cluster, since the typical GW kicks are typically limited to $\lesssim 100$ km/s, and depend entirely on the mass ratio of the system. However, in the case where either component has significant spin, either from birth or a previous merger, then the kicks can exceed 1,000 km/s, significantly beyond the typical escape speeds of GCs. In the $\chi_{\text{birth}} = 0.5$ case, less than 3% of merger products are retained. Furthermore, because the merger of two BHs creates a new BH with a spin ~ 0.7 , 1G+2G and 2G+2G BBH merger products are virtually never retained by the cluster, regardless of χ_{birth} . Out of 96 GC models and nearly 10^4 BBH mergers, we only identify one case where a 1G+2G merger is retained by the cluster, owing to the chance alignment of its spins. That merger product forms another binary and is rapidly ejected from the cluster, creating a 3G+1G BBH merger. We also identify one case where a merger takes place during a strong encounter between a single BH and a BBH. The merger product is ejected from the cluster, but it remains bound

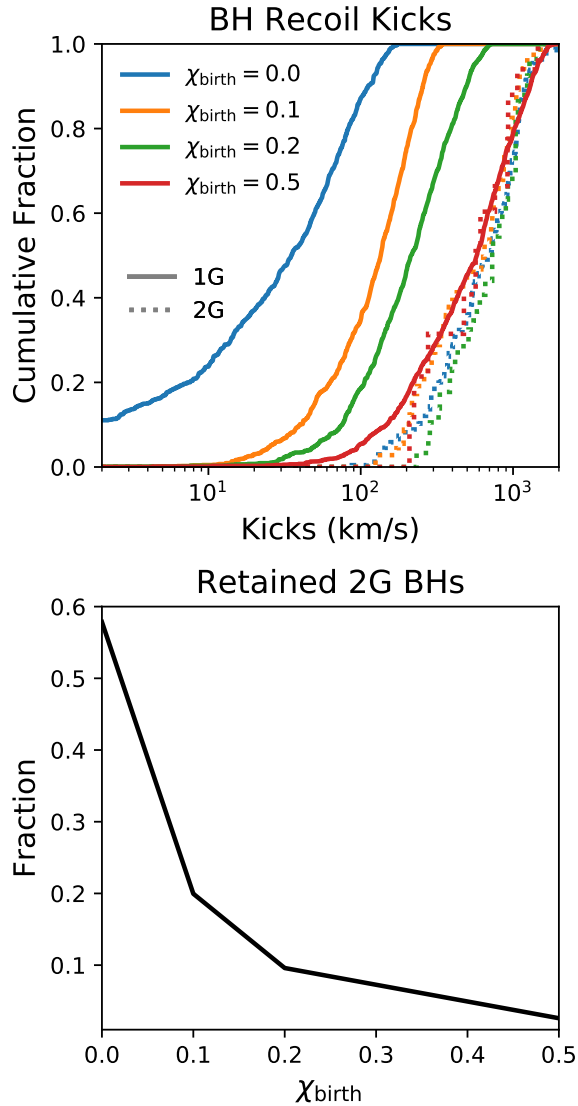


FIG. 1. The effect of initial BH spin on the recoil kicks and retention of BBH merger products. On the top, we show the cumulative distribution of BH kicks for our $\chi_{\text{birth}} = 0.0, 0.1, 0.2$, and 0.5 models in blue, orange, green, and red, respectively. The solid lines show the distribution kicks for binaries comprised of both 1G components, while the dotted lines show the kicks for merging binaries that include at least one 2G BH. On the bottom, we show the fraction of all BBH merger products that are retained in the cluster as a function of the birth spins of BHs.

to the third BH from the triple encounter, merging as a 3G+1G binary in the field [the “double mergers” identified by 100]. For simplicity, we count these systems as 2G+1G BBHs in our results, as their component masses (both $\sim 80M_{\odot} + 30M_{\odot}$) would not distinguish them as a 3G BH. However, we do note that the spin magnitudes of these 3G BHs ($\chi \sim 0.39$ and 0.45) are distinct from the 2G BHs, as is typical for mergers with small mass ratios

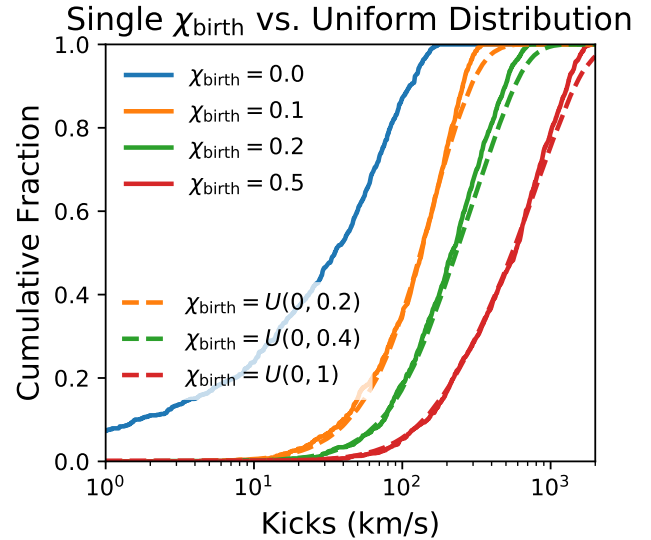


FIG. 2. Same as the top panel of Figure 1, but showing the cumulative kick distribution from the four sets of spin models (solid lines), as well as the kick distributions the BBHs would have experienced if their spin magnitudes had been drawn from uniform distributions (dashed lines). Our $\chi_{\text{birth}} = 0.1, 0.2$, and 0.5 models produce nearly identical kicks to models where the spins were drawn from uniform distributions between 0 and 0.2, 0.4 and 1, respectively.

[e.g., 77].

As noted above, our choice of birth spins for BHs – setting χ_{birth} to discrete values for all BHs regardless of the details of the pre-collapse star – is highly simplistic. In reality, it is entirely possible that the structure of the massive stars that form BHs can determine the final spin of the remnant, since the radial profile of the star will determine the efficiency of angular momentum transport out of the core once the star evolves onto the giant branch. Recent detailed studies massive stars [97, 98], in particular, have suggested that the magnetic Taylor instability may be highly efficient at transporting angular momentum out of the cores of stars prior to collapse, birthing BHs with extremely low ($\chi_{\text{birth}} \sim 0.01$) spins. Unfortunately, to the authors knowledge there exist no published models relating stellar core masses, envelope masses, and metallicities to final BH spins for the range of initial conditions considered here. Studies of the BBH population from LIGO/Virgo [e.g. 56, 99] have similarly been unable to constrain the BH spin magnitude distribution (although the possibility that all BHs are born with near-maximal spins is becoming disfavored).

Our choice of discrete birth spins is different from previous dynamical studies in the literature [e.g., 58], which drew spin magnitudes from a distribution uniform between 0 and 1 (as well as a high-spin model, which is now disfavored). While these choices are both arbitrary, they produce similar results. The distribution of kicks for merging BBHs with spin magnitudes drawn from a

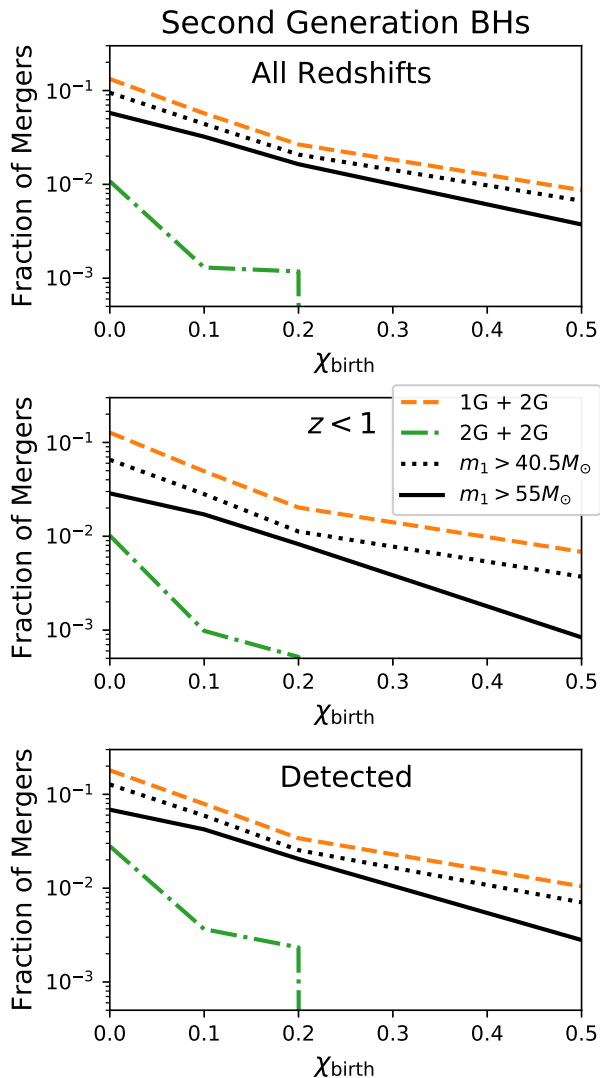


FIG. 3. The fraction of BBH mergers that are comprised of 1G and 2G BHs as a function of the birth spins of 1G BHs. In dashed orange, we show the fraction of BBH mergers that contain one 2G BH, while dotted green shows the fraction of mergers with both 2G components. We also show the fraction of mergers with at least one 2G component that is greater than $40.5M_{\odot}$ in dotted black (the beginning of the PPI/PISN mass gap in our stellar evolution prescriptions), and greater than $55M_{\odot}$ in solid black (our more conservative lower limit for the beginning of the mass gap). The top panel shows the relative fraction of 2G mergers over all redshifts, while the middle panel shows the mergers in the local universe ($z < 1$). The bottom panel indicates the relative fraction of mergers of each type detectable by a three-detector LIGO/Virgo network operating at design sensitivity (see Section II B).

$U(0, \chi_{\max})$ distribution is nearly identical to the distribution of kicks when $\chi_{\text{birth}} = \chi_{\max}/2$, when marginalizing over all BBH spin orientations and magnitudes. In Figure 2 we show the kick distributions from Figure 1, as well as the distributions of kicks the merging BHs would have received if their spin magnitudes had been drawn

from uniform distributions. The distributions are virtually identical except at large kick velocities (where in both cases the binaries would be ejected from the cluster). This makes our $\chi_{\text{birth}} = 0.1, 0.2$, and 0.5 models equivalent to models where the spin magnitudes are drawn uniformly from 0 to 0.2, 0 to 0.4, and 0 to 1, respectively.

B. Black Holes in the Upper Mass Gap

The easiest identifying feature of 2G BHs is their characteristically large mass. Both theoretical considerations and the first few observed LIGO BBH mergers have suggested the presence of an upper mass gap of stellar-born BHs, where compact objects cannot form due to PPIs/PISNs. In a sufficiently massive, post-carbon burning star with a helium core mass $\gtrsim 30M_{\odot}$, the conversion of photons to electron-positron pairs removes pressure support from the core on a dynamical timescale. In response, the stellar core contracts rapidly, increasing to temperatures sufficient for carbon, oxygen, and silicon burning [e.g. 63]. If this injection of energy is less than the binding energy of the star, as is the case for helium-core masses in the $30M_{\odot} - 64M_{\odot}$ range, then these PPIs will continue to eject mass from the star until the final core mass is between $35M_{\odot}$ and $50M_{\odot}$, and the instability is avoided [64]. For stars with helium-core masses in the $64M_{\odot} - 133M_{\odot}$ range, the first PPI is more energetic than the star's binding energy, and the star is completely destroyed in a PISN. Because of this, it is thought that no star can produce a BH with a mass between $46M_{\odot}$ and $133M_{\odot}$ [65], though we note that stars formed from the mergers of other massive stars may not obey this constraint [e.g., 101]. In our prescription for PPI/PISN, based on that developed in [102], any star with a pre-collapse He-core mass between $45M_{\odot}$ and $65M_{\odot}$ is ground down to $45M_{\odot}$ by PPIs (with the BH mass reduced by a further 10% in the conversion from baryonic to gravitational mass), while any core mass between $65M_{\odot}$ and $135M_{\odot}$ is completely destroyed in a PISN.

At the same time, [62] showed that, because LIGO/Virgo can detect more massive BBHs to higher redshift, the first 6 BBH detections already suggested an upper bound on BH masses of $\sim 40M_{\odot}$. They concluded that the true maximum mass of the population could be identified with less than 40 BBH detections. We argue that the detection of a BBH with a component in the mass gap provide significant evidence of a dynamical formation history for that object. This has been noted previously [59, 61, 62], but without the cosmological model for GC formation or varying initial spin distributions, making this work the first to produce a realistic astrophysical population of 2G BBH mergers. Furthermore, the detection of BBHs in the mass gap would provide information about the total contribution to the BBH merger rate from clusters, since the fraction of mass-gap

BHs to the total number of mergers can be theoretically predicted.

In Figure 3, we show the fraction of all BBH mergers from GCs that are the result of multiple mergers as a function of the initial spin of 1G BHs. If it is assumed that all BHs from stars are born with zero spin, then nearly 13% of BBH mergers from GCs are 1G+2G mergers, while 18% of all detected sources are. Only 1% of mergers are 2G+2G, though this contributes 3% of detected sources. Of the BBH mergers with at least one 2G component, 9% of all mergers (7% at $z < 1$) have one component mass greater than $40.5M_{\odot}$ (representing 13% of the detected population), while 6% (3% at $z < 1$) have a component greater than $55M_{\odot}$ (7% of detected BBHs). Although the largest mass BH that can form from a single star in our simulations is $40.5M_{\odot}$ [59, 102], we assume a threshold of $55M_{\odot}$ as our gold-standard for identifying BHs in the mass gap. This is largely motivated by differences in the various population synthesis approaches to implementing the PPI/PISN physics [e.g., 102–104], though we note that the most recent supernova studies with realistic binary stellar evolution and PPI physics produce a maximum BBH component mass of $46M_{\odot}$ [65].

As we consider models with larger 1G BH birth spins, the fraction of 2G BBH mergers decrease dramatically, as the GW recoils eject significantly more of the 1G BBH merger products from the cluster. Increasing the birth spins of 1G BHs from 0.0 to 0.1 decreases the fraction of BBH mergers with a 2G component by more than a factor of two, while the fraction of detected BBH mergers with a component definitively in the mass gap ($\gtrsim 55M_{\odot}$) decreases from 7% to 4%. If we consider a universe where $\chi_{\text{birth}} = 0.5$ for all 1G BHs, less than 1% of BBH mergers from globular clusters contain 2G BHs, and only 0.3% of detected mergers would be definitively in the mass gap. Of course, if the spin magnitudes of BHs were ~ 0.5 , then the contribution to the BBH merger rate from GCs could be easily identified by spin measurements alone, [e.g. 105–107], regardless of the contribution of 2G BBH mergers.

IV. MASSES AND SPINS

We now explore the mass, mass ratio, and spin distributions of 1G and 2G BBHs from our four cluster populations, and briefly compare them to the current LIGO detections. A full statistical comparison between the distributions presented here and the LIGO/Virgo posterior probability distributions is beyond the scope of this paper, but for reference we show the median and 90% credible intervals for the masses and effective spins of the 10 LIGO/Virgo BBH detections. We also show the BBH catalog released by [108–111], containing a reanalysis of the 10 published LIGO/Virgo events and 7 new BBHs candidates identified on O1 and O2 (though we only show the 7 new BBH candidates that were not identified in the

original LIGO/Virgo catalog). We refer to this as the IAS catalog.

A. Masses

In Figure 4, we show the population of total masses from each of our four GC populations, showing separately the distribution of BBH mergers across all redshifts, in the local universe ($z < 1$), and the distribution detectable by a three-detector LIGO/Virgo network operating at design sensitivity. We divide each population into 1G+1G, 1G+2G, and 2G+2G sub-populations, each normalized to the total BBH merger population. As was obvious in Section III and Figure 3, a significant population of 2G+2G mergers can only be produced from GCs in the case where the birth spins of 1G BHs are zero. As a result, the population of BBHs with total masses $> 120M_{\odot}$ virtually disappears when $\chi_{\text{birth}} > 0$.

The population of 1G+2G BBH mergers is less dependent on the BH birth spins than the 2G+2G mergers, since almost any 2G BH retained in the cluster will be ejected as a binary. As an example, in a cluster with 10^6 initial particles, $r_v = 1\text{pc}$, and $Z = 0.01Z_{\odot}$, 48 2G BHs are produced by in-cluster mergers of 1G+1G binaries, 31 of which are retained by the cluster when $\chi_{\text{birth}} = 0$. Of those 31 BHs, 16 are later ejected from the cluster as binaries while 11 merge again inside the cluster, but only 4 are ejected as single BHs. This is in stark contrast to the 1G BHs, of which nearly 76% are ejected as single BHs, a fraction consistent with previous semi-analytic estimates for the number of single stars ejected by a single hard binary [112, 113]. This difference arises because 2G BHs are typically the most massive BHs in the cluster at any given time, making them more likely to exchange into a less-massive BBH [114]. Additionally, such 2G BHs are less likely to be ejected from the cluster during an encounter with a BBH, since most 2G BHs will be similar in mass to 1G+1G BBHs.

As the birth spin of BHs is increased, the fraction of BBHs with masses greater than $80M_{\odot}$ also decreases significantly in Figure 4. Somewhat surprisingly, there exists a small population of 1G BBHs with total masses $\sim 120M_{\odot}$, even when $\chi_{\text{birth}} = 0.5$. These handful of objects, while rare, are produced very early in the cluster lifetime, either by stable mass transfer onto a $40.5M_{\odot}$ BH, or by stellar mergers which produce massive stars with atypically large hydrogen envelopes and small helium cores [101, 134]. These objects are largely the result of the stellar merger handling in BSE and our adopted PPI/PISN prescriptions, and it is not obvious whether such objects could exist in nature.

At first glance, it appears that the lack of GW sources with total masses $\gtrsim 100M_{\odot}$ would suggest against a universe where $\chi_{\text{birth}} = 0$ for all 1G BHs. However, we stress that, with 10 BBH detections from LIGO/Virgo (and 17 candidates from the IAS), the lack of such super-heavy BBHs is still consistent with the statistics quoted here,

Total Source-Frame Masses

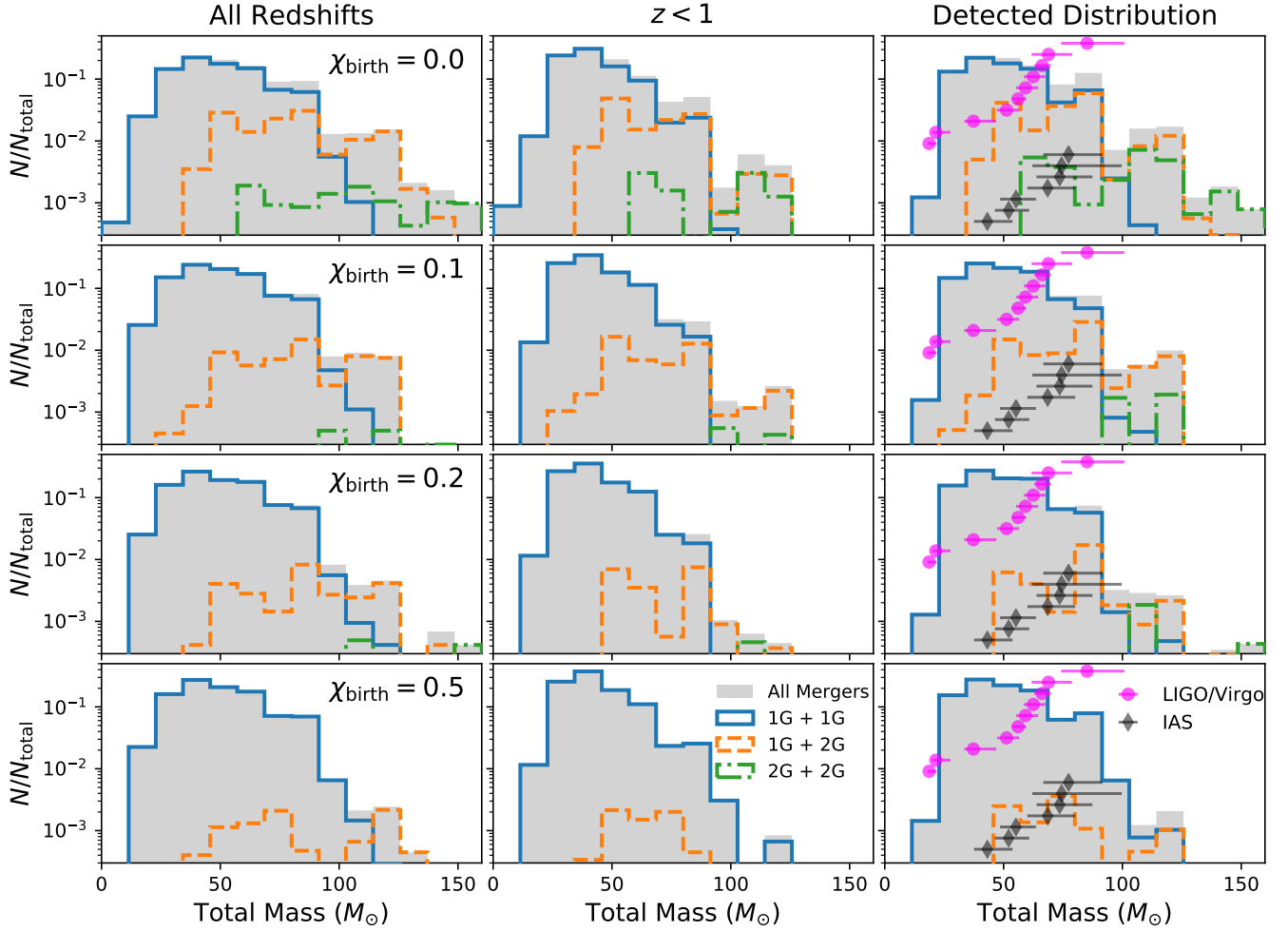


FIG. 4. The distribution of total BBH masses for the mergers from our four GC populations with different birth spins for 1G BHs. The $\chi_{\text{birth}} = 0.0, 0.1, 0.2$, and 0.5 distributions are shown in each row from top to bottom. The left hand column shows all mergers over all redshifts, while the middle column shows mergers occurring in the local universe ($z < 1$). The right hand column shows the distribution of BBHs detectable by a three-detector LIGO/Virgo operating at design sensitivity. The filled grey histogram shows the distribution of all BBH mergers, while the solid blue, dashed orange, and dot-dashed green lines show the contribution from 1G+1G, 1G+2G, and 2G+2G mergers, normalized to the total number of BBH mergers from all generations. In the detectable column, the fuchsia and turquoise ticks show the the total masses from the LIGO/Virgo and IAS catalogs from O1 and O2.

since only 9% of detected BBHs have total source-frame masses greater than the most massive BBH identified to date [GW170729, at $85M_{\odot}$, 6], and only 4% of detected BBHs have total masses greater than $100M_{\odot}$, even when $\chi_{\text{birth}} = 0.0$. These fractions decrease to 2% above $85M_{\odot}$ and 0.5% above $100M_{\odot}$, respectively, when $\chi_{\text{birth}} = 0.5$. However, as the size of the LIGO/Virgo BBH catalog continues to grow, it will become easier to either identify (or rule out the existence of) such massive BBHs in the universe.

In Figure 5, we break down the events presented in Figure 4 into their individual components. Instead of showing full 2D histograms, for simplicity we only show

where 50%, 90%, and 99% of all sources lie in the m_1 - m_2 plane. We also show which bins are dominated by 1G+2G and 2G+2G mergers. There it becomes obvious that any significant number of detections, certainly within the 90th percentile, cannot be produced with component masses above $40M_{\odot}$ when the birth spins of BHs are large. We also note that GW170729 can be easily formed in the $\chi_{\text{birth}} = 0.0$ models, where it lies in the region and mass bin that is dominated (more than 50% of mergers) by 2G BHs, although many of the BBHs in that region are also composed of 1G BHs. This is consistent with statistical studies of GW170729 [115, 116], suggesting that while the event is consistent with a 2G BBH

Component Masses ($m_1 > m_2$)

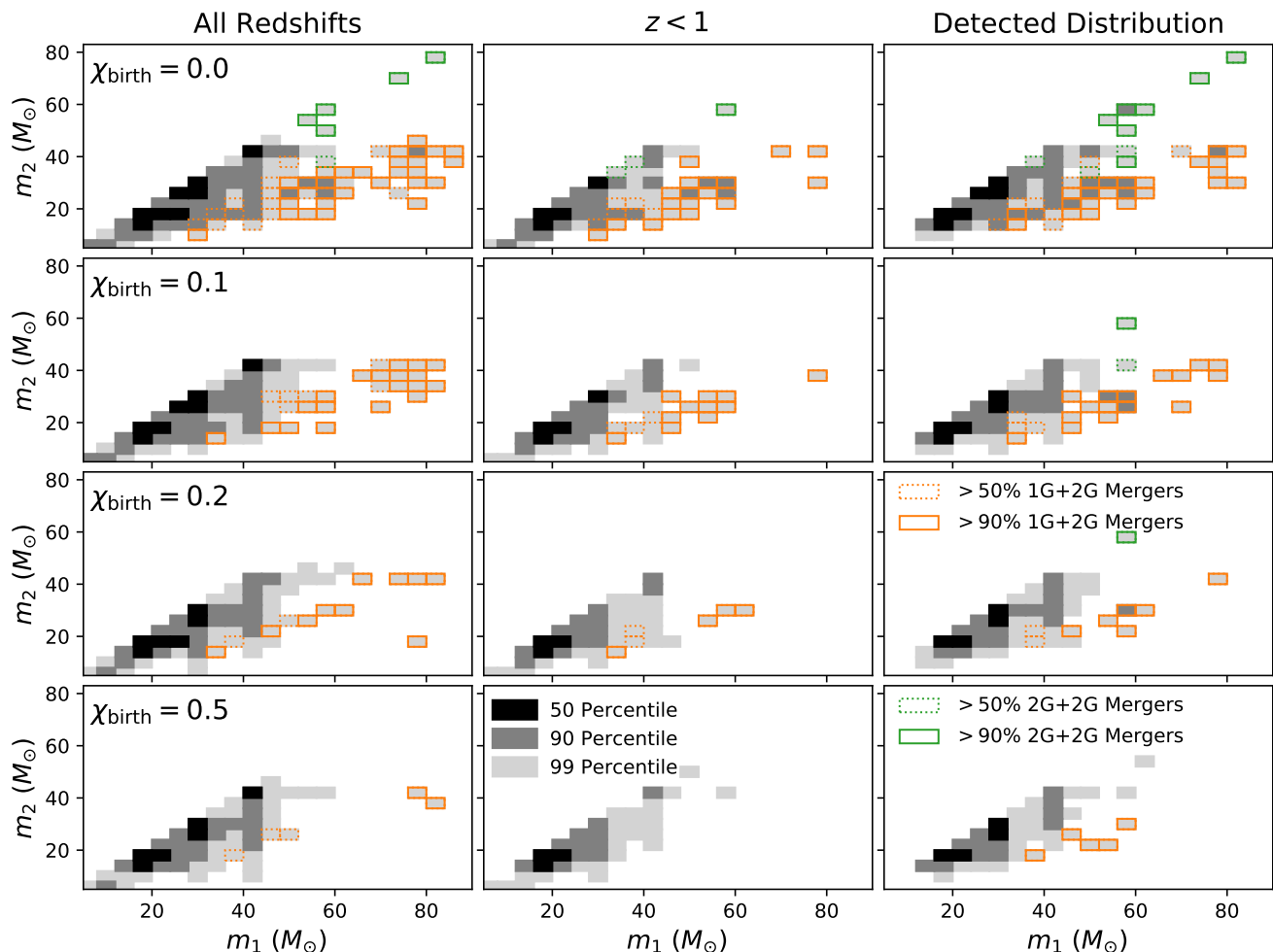


FIG. 5. Similar to Figure 4, but showing the joint component mass distributions from our four GC populations with different birth spins divided into square bins of $4M_\odot$. The contours containing 50, 90, and 99 percent of all sources are shown in black, gray, and light gray, respectively. Each bin is highlighted in dotted (solid) orange if more than 50% (90%) of the mergers in that bin are 1G+2G BBHs. A similar scheme (in green) is used to indicate 2G+2G BBHs.

merger, there is insufficient evidence to say definitively.

Finally, we note that the two lowest mass BBHs in Figures 4 and 5 also appear to be just outside the 99 percentile regions for the masses from GCs. This is because we have restricted ourselves to classical GCs with large virial radii and low metallicities. However, by considering systems with $Z \sim Z_\odot$, such as super-star clusters or open clusters [e.g., 118], dynamics can easily produce such low-mass BBHs [117]. Furthermore, the current collection of GC models do not form low-mass BBHs because any $5\text{--}10M_\odot$ BHs that remain in the cluster are not participating in dynamical encounters at the present day. BBH-forming encounters are dominated by the most massive remaining BHs in the clusters [122], which with our assumed initial conditions are typically in the $10\text{--}15M_\odot$ range. However, if GCs are born with significantly smaller initial virial radii ($\sim 0.5\text{pc}$), then all BHs, includ-

ing the low-mass BHs, will be processed into binaries and ejected from the cluster by the present day. Such ultra-compact clusters are not considered here, but are necessary to explain the observation of core-collapsed GCs in the Milky Way and other galaxies [119, 120].

B. Mass Ratios

The dynamical formation of BBHs in GCs typically involves the most massive BHs available in the cluster at any given time [e.g., 122]. Even if a BBH were to form with a significantly low mass ratio, repeated binary-single and binary-binary encounters would preferentially exchange BHs into the binary in favor of creating a nearly equal-mass system [114]. The BBHs that merge in the cluster therefore tend to have nearly equal mass compo-

Mass Ratios

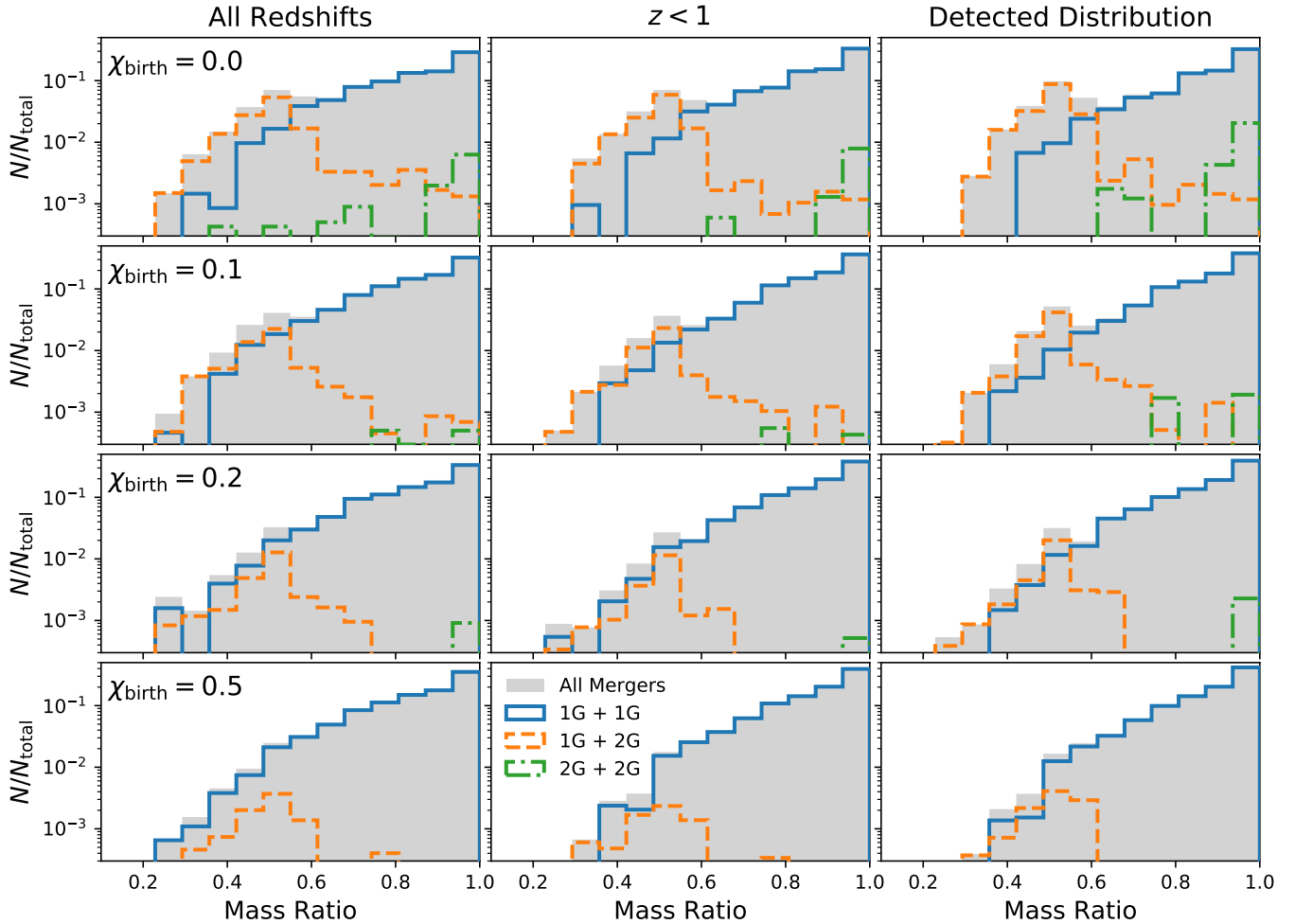


FIG. 6. Similar to Figure 4, but showing instead the distribution of mass ratios, m_2/m_1 (where $m_2 < m_1$) for all BBH mergers from the four GC spin populations. Note that we do not show the posterior distributions for the LIGO/Virgo or IAS events, as the 90% credible regions are very poorly constrained.

nents drawn from the most massive BHs in the cluster. When a BBH merges, its 2G merger product — if it is retained in the cluster — is then nearly twice the mass of the most massive 1G BHs. And because GCs typically only harden ~ 1 BBH at any given time, that 2G BH is most likely to rapidly merge again before the cluster can form another 2G BH. We note that this is not true in NSCs, where the larger escape speeds make it possible to retain mergers of even 2G BBHs, potentially building several successive generations of BBH mergers [58, 121].

In Figure 6, we show the mass ratio distributions for our four χ_{birth} populations of GCs. As expected, the distribution of 1G+1G BBHs piles up strongly at a mass ratio of 1, as seen in previous dynamical studies [25]. However, the 1G+2G BBHs peak at a much lower mass ratio of ~ 0.5 , because the 2G BH in these binaries is typically twice the mass of the most massive 1G BHs in the cluster. The detected distribution of BBHs shows

a significant secondary peak in the mass ratio distribution at $q \sim 0.5$, driven by the more massive 1G+2G and their correspondingly larger detection weights. Finally, the handful of 2G+2G BBHs typically have mass ratios closer to unity. This is consistent with the trend towards equal mass binaries: if a cluster manages to retain two 2G BHs at once, one 2G BH will likely eject any 1G BH bound to its fellow 2G BH, in favor of creating a near-equal mass 2G+2G system.

C. Effective Spins

Even for non-spinning BHs, a BBH merger produces a remnant with $\chi \sim 0.7$ [e.g., 77, 80, 123]. Because of this, we expect BBH mergers with 2G components to have some spin regardless of the χ_{birth} of 1G BHs. Un-

Effective Spins

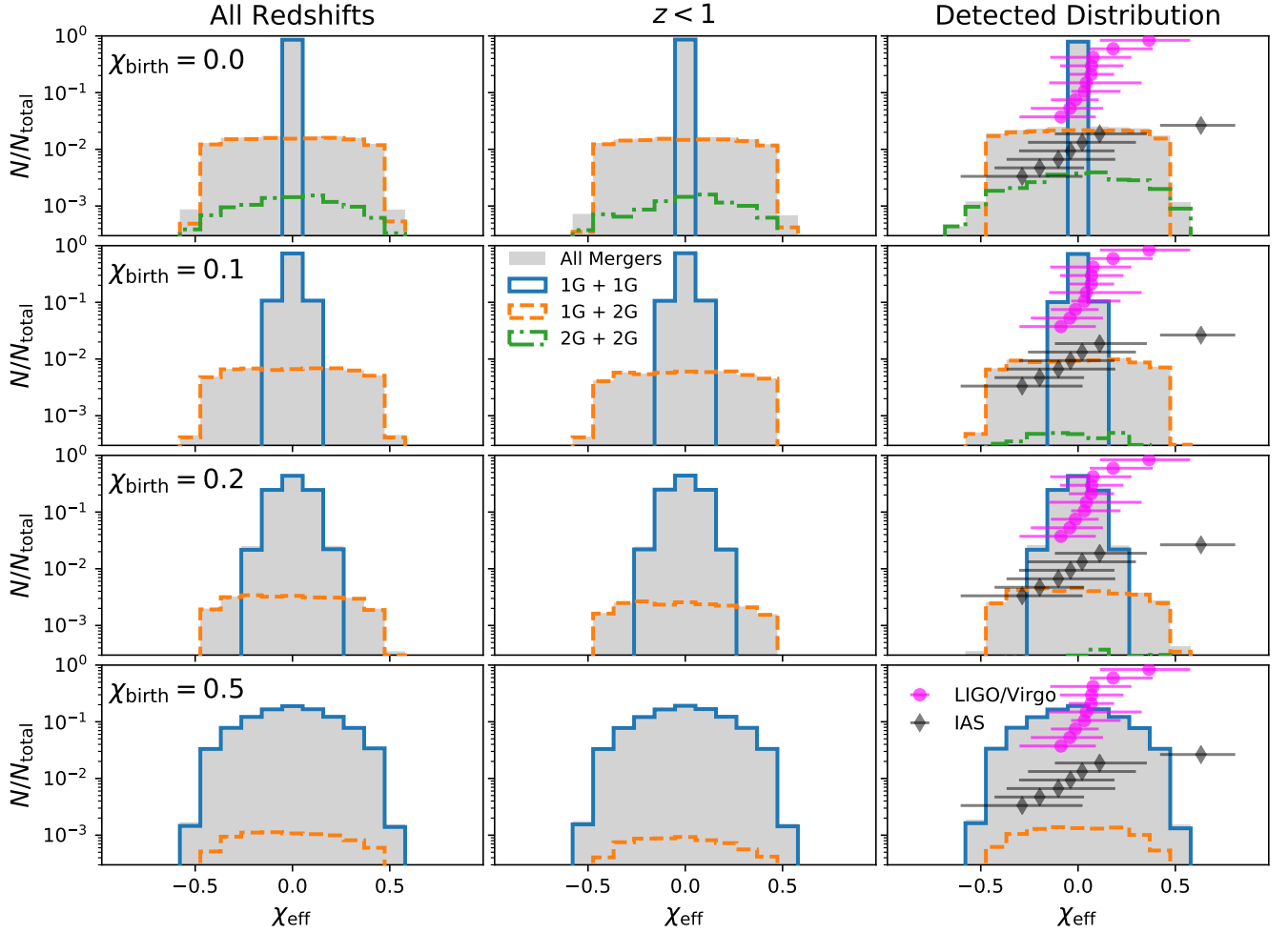


FIG. 7. Similar to Figure 4, but showing instead the distribution of effective spins for all BBH mergers from the four GC spin populations. Note that we have reweighted the posterior distributions from the IAS catalog to use a prior probability distribution with uniform spin magnitudes and isotropic spin orientations.

fortunately, what GW experiments measure best is not the individual spins of the components, but the effective spin of the BBH, χ_{eff} , given by the mass-weighted projection of the spins onto the orbital angular momentum of the binary:

$$\chi_{\text{eff}} = \left[\frac{m_1 \vec{\chi}_1 + m_2 \vec{\chi}_2}{m_1 + m_2} \right] \cdot \hat{L}. \quad (3)$$

For dynamically-assembled BBHs, the angle between the spin and orbital angular momenta is expected to be isotropically distributed [105], suggesting that the distribution of χ_{eff} should be symmetric and centered on zero, with a tail determined by the spins of the components and the mass ratio distribution of the binaries.

In Figure 7, we show the χ_{eff} distributions for our four χ_{birth} populations. If we assume that LIGO/Virgo

can confidentially exclude non-zero spins for BBHs with $|\chi_{\text{eff}}| \gtrsim 0.2$ [e.g., 6, 124], then the worst-case scenario for detecting the spin of BBHs from dense star clusters is the case where $\chi_{\text{birth}} = 0.2$. There, only 1% (2%) of the actual (observed) distribution of BBHs will merge with $|\chi_{\text{eff}}| > 0.2$. If 1G BHs are born with no spin, the production of 2G BBH mergers through repeated mergers can produce a population with significant spin, with 8% (11%) of the actual (observed) population of BBHs having $|\chi_{\text{eff}}| > 0.2$. On the other hand, if the spins of 1G BHs are 0.5, then 37% of all BBH mergers (actual and observed) will have $|\chi_{\text{eff}}| > 0.2$. Because we have assumed that all 1G BHs are born with the same spins regardless of their masses, there is no difference between the observed and actual distributions of χ_{eff} for 1G BBH mergers. However, because BBHs with 2G components are characteristically more massive, they are detectable in a larger volume of space.

As with Figure 4, we also show the median and 90% regions of the 1-dimensional marginalized posteriors for χ_{eff} in Figure 7. However, the posterior distributions provided in [111] and [56] were computed using different prior probabilities for the spin distributions. The LIGO/Virgo parameter estimation prior assumes a uniform distribution of component spin magnitudes with the spin orientations isotropically distributed on the sphere. The IAS parameter estimation, on the other hand, uses a uniform prior on χ_{eff} . This flat prior distribution is not peaked at $\chi_{\text{eff}} = 0$ (unlike the LIGO/Virgo prior) and is partially responsible for the large spins — e.g. the median χ_{eff} of 0.81 and -0.7 for GW151216 and GW170403 respectively — reported by the IAS analysis. To present our results self-consistently, we reweight the posterior samples from the IAS using the same prior probability distribution employed by LIGO/Virgo analysis.

Unlike the previous plots, the distribution of measured χ_{eff} shown in Figure 7 is significantly different between the LIGO/Virgo and IAS catalogs. As stated above, the IAS catalog contains a candidate BBH merger — GW151216, with median posterior probability of $\chi_{\text{eff}} = 0.81$ (under the flat χ_{eff} prior) or $\chi_{\text{eff}} = 0.63$ (under the uniform in spin magnitude/isotropic in spin direction prior) — that cannot be easily produced by any of the models presented here [109, 110]. We find no BBH models with $\chi_{\text{eff}} = 0.81$, and even if all 1G BHs were born with maximal spins [an assumption already disfavored by model selection of the 10 LIGO/Virgo BBHs, 56], less than 2% of BBH mergers would have $\chi_{\text{eff}} > 0.81$. If we instead assume a prior with isotropic spin directions and uniform spin magnitudes, we can produce 2G+2G mergers with $\chi_{\text{eff}} = 0.63$, but even then, only 0.2% of detected 2G+2G mergers have sufficiently aligned spins in the $\chi_{\text{birth}} = 0.0$ model. We note that GW151216 is only given a 71% of being of astrophysical origin [111]; however, if further detections reveal these events to be part of a population of highly spinning and aligned BBHs, it would suggest another formation mechanism for BBHs may also operate in the universe, such as the chemically-homogeneous binary evolution channel [126–128].

While cluster dynamics cannot easily produce the most highly spin-aligned BBH candidate, it is a natural explanation for the most spin-anti-aligned event, GW170121. This event from the IAS catalog, which (unlike GW151216) has a $>99\%$ chance of being astrophysical, is also the first BBH event with significant spin anti-alignment. Under both priors, 90% of the posterior support for χ_{eff} is less than zero. Furthermore, the median value of the χ_{eff} posterior (-0.3 when a flat prior is employed, and -0.2 when using an isotropic/uniform spin prior). This configuration is unlikely to arise from isolated binary evolution without significant BH natal kicks [105, 125], but can easily be explained by dynamical processing of BBHs. 6% of all detected BBHs in our $\chi_{\text{birth}} = 0$ models have $\chi_{\text{eff}} \leq -0.2$. As the birth spins are increased, this number decreases to 1% of all mergers when $\chi_{\text{birth}} = 0.2$ (due to the depletion of 2G BHs)

before increasing to more than 18% of detected mergers when $\chi_{\text{birth}} = 0.5$. If we assume that GW170721 originated in a dense stellar environment, then its large, negative effective spin would require either significant birth spins for 1G BHs or significant numbers of 2G BHs (and correspondingly low birth spins). However, models with $\chi_{\text{birth}} = 0.1$ or 0.2 would be less likely to produce such systems, as only 2% and 1% of detected BBHs from those models have $\chi_{\text{eff}} \leq -0.2$.

D. Spin Magnitudes

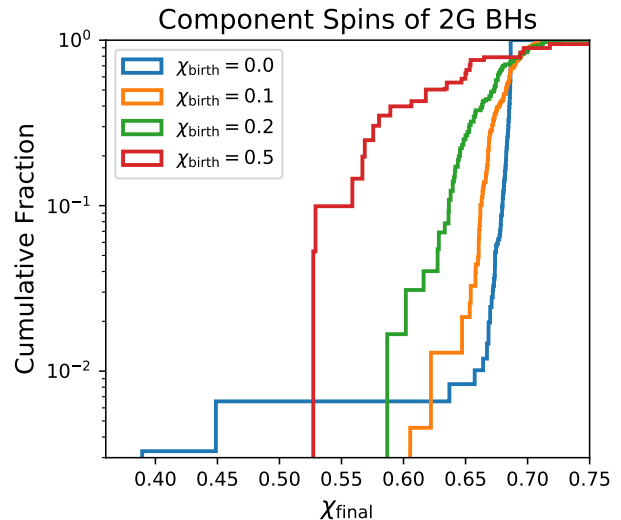


FIG. 8. The cumulative distribution of the component spins for 2G BHs which merge across all redshifts. We show the distributions for our $\chi_{\text{birth}} = 0, 0.1, 0.2$, and 0.5 populations in blue, orange, green, and red, respectively. As the birth spins of BHs are increased, the distribution broadens from being very strongly peaked at $\chi_{\text{final}} \approx 0.69$ when $\chi_{\text{birth}} = 0.0$ to having a median of 0.62 when $\chi_{\text{birth}} = 0.5$. For completeness, we also include the two 3G BHs that form and merge (with lower χ_{final}) in the $\chi_{\text{birth}} = 0.0$ population; see section II A.

The merger of two non-spinning, equal-mass BHs will produce a final BH with a spin of $\chi_{\text{final}} \sim 0.69$. However the final spin of the newly-formed BHs depends strongly on both the mass ratio, with smaller mass ratios preferring lower spins [e.g., 77], and the spin magnitudes and orientations at the point of merger [80–82]. Of course, while this 7-dimensional parameter space (the two BH spin vectors and the mass ratio) determine the final spin of the BH, they are also the parameters responsible for the magnitude of the GW recoil kicks imparted to BBH merger remnants. Because of this, certain regions of final mass and spin parameter space for 2G BBHs are inaccessible in realistic clusters, because the BBH configuration required to produce a given remnant would also result in a GW kick greater than the escape speed of the cluster [e.g., 49].

As an example, in our $\chi_{\text{birth}} = 0.0$ models, the entirety of the GW recoil kick for 1G+1G BBH mergers is driven by the mass ratio of the system: when the components are of equal mass, no kick is given, and the spin of the remnant is $\chi_{\text{final}} \approx 0.69$. As the mass ratio is decreased, the kick increases, to a maximum of $\sim 175 \pm 11 \text{ km/s}$ when the mass ratio is $q \sim 1/3$ [78], while the remnant spin decreases to $\chi_{\text{final}} \approx 0.55$, [c.f. Table 1 of 77]. In Figure 8, we show the spin magnitudes of all the 2G BBHs that merge in our four GC universes, and can clearly see that the distribution of 2G spin magnitudes from $\chi_{\text{birth}} = 0$ universe are strongly concentrated at $\chi_{\text{final}} \approx 0.69$, with 90% of sources lying between 0.67 and 0.69. As the birth spin of BHs is increased, the component spins of the 2G BHs become less concentrated: the distribution of final spins for the $\chi_{\text{birth}} = 0.5$ universe has a median of 0.62, with 90% of sources having final spins between 0.53 and 0.72. This broadening is largely a result of the increasing parameter space of BBH mergers that produce low-kick BBH mergers as we consider systems where the spin vectors of the two BHs are important. We leave a full mapping of the final BH spin and BH retention fraction to future work.

V. CONCLUSIONS

In this paper, we explored the production, merger properties, and detectable populations of 2G BHs: BHs which were forged by previous BBH mergers in the cores of dense star clusters. Using self-consistent dynamical models of GCs with different birth spins for BHs, we showed that if all BHs created from stellar collapse are born with no spin, then more than 10% of all BBH mergers from clusters (and nearly 20% of the detections) should have at least one component created during a previous merger. Of those, $\sim 7\%$ would have at least one component above $55M_{\odot}$, placing it clearly in the upper-mass gap where the formation of BHs from single or binary stars is inhibited by the PPI/PISN mechanism. If the birth spins of 1G BHs is higher, the retention of 2G BHs by the cluster decreases, and the number of 2G BBH mergers drops precipitously. In the largest spin model we consider, where $\chi_{\text{birth}} = 0.5$, less than 3% of 2G BHs are retained by the cluster, and less than 1% of detectable BBH mergers contain 2G BHs.

As previously stated, if all 1G BHs were born with spins of $\chi_{\text{birth}} = 0.5$, then measurements of the spins would themselves be an effective tool to distinguish BBH formation scenarios. As GW parameter estimation can reliably measure χ_{eff} to within a 90% uncertainty of ± 0.2 , we would expect that LIGO/Virgo would already have evidence for or against the dynamical formation scenarios (as $\sim 20\%$ of all BBHs from GCs would have $\chi_{\text{eff}} < -0.2$). In many ways, the worst case scenario for identifying BBHs from the dynamical formation channel would be the case where $\chi_{\text{birth}} \sim 0.2$. In that regime, the birth spins of 1G BHs are too low to be reliably mea-

sured (less than 2% of detected BBH mergers would have $\chi_{\text{eff}} < -0.2$), while $\lesssim 5\%$ of detected mergers would have components in the mass gap. However, the recently identified BBH candidate GW170121 has $\chi_{\text{eff}} < 0$ at 90% confidence, regardless of the assumed prior distribution. If it is assumed that this BBH was created in a dense stellar environment, then it suggests either that all 1G BHs are born with low spins, creating a population of highly spinning, retained 2G BBH mergers, or that the birth spins of 1G BHs are significantly larger than $\chi \sim 0.2$.

Throughout this paper, we have limited ourselves to 2G BHs that were created from the mergers of previous BHs. However, it has been proposed for many years that massive BHs, and even the progenitors of intermediate-mass BHs (IMBHs), could be forged by the repeated mergers of massive stars during the early stages of cluster evolution [101, 129–134]. We identified a handful of these objects in Section IV A, and noted that some merged with components $\gtrsim 55M_{\odot}$, even though they were considered 1G BHs in our simulations. These objects could have important implications for the formation of BHs in the mass gap and for the creation of both IMBHs and the seeds of super-massive BHs. However, significant work remains to be done to better understand the evolution of massive stars that are created from the mergers of other massive stars.

We have also only considered GCs that are born with initial binary fractions of 10%. This is a standard choice in stellar dynamics, as it has been shown to reproduce the binary fraction of present-day GCs [72, 135]. However, given the short lifetimes of massive stars, the initial binary fraction of massive stars in young GCs is essentially unconstrained [though observations in the local universe suggest fractions as high as 70%; see 137]. This has been shown to effect the merger rate of BBHs from GCs [117], and would have a significant impact on the production of 2G BBHs in GCs, particularly if the majority of massive stellar binaries produced BBHs that merged early in the cluster lifetime [e.g., 136]. These 2G BHs might have distinct properties from those studied here, most of which were created through dynamical encounters. We leave a proper study of the effects of massive binary stars and their resultant BBH mergers in clusters to future work.

Finally, we note that showing the distributions of the median values from both the LIGO/Virgo and IAS catalogs is a crude way to compare the results from O1 and O2 to the distributions presented here. A more appropriate comparison between different formation channels and the LIGO/Virgo results, such as those presented in [57, 138–143], is beyond the scope of this paper. However the true scientific potential of GW astronomy will depend on doing a proper comparison between the full 15-dimensional posterior distributions for GW events and multiple theoretical distributions, such as the ones presented here. A study comparing the observational and theoretical distributions using Bayesian model selection techniques is currently underway [144].

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- [1] B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, et al., *Phys. Rev. Lett.* **116**, 241103 (2016).
 - [2] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, and V. B. Adya, *Phys. Rev. Lett.* **118**, 221101 (2017).
 - [3] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, and V. B. Adya, *Astrophys. J.* **851**, L35 (2017).
 - [4] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, and V. B. Adya, *Phys. Rev. Lett.* **119**, 1 (2017).
 - [5] B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, et al., *Phys. Rev. Lett.* **116**, 061102 (2016).
 - [6] B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, et al., *arXiv e-prints*, arXiv:1811.12907 (2018).
 - [7] P. Podsiadlowski, S. Rappaport, and Z. Han, *MNRAS* **341**, 385 (2003).
 - [8] M. Dominik, K. Belczynski, C. Fryer, D. E. Holz, E. Berti, T. Bulik, I. Mandel, and R. O’Shaughnessy, *Astrophys. J.* **759**, 52 (2012).
 - [9] 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).
 - [10] M. Dominik, K. Belczynski, C. Fryer, D. E. Holz, E. Berti, T. Bulik, I. Mandel, and R. O’Shaughnessy, *Astrophys. J.* **779**, 72 (2013).
 - [11] K. Belczynski, D. E. Holz, T. Bulik, and R. O’Shaughnessy, *Nature* **534**, 512 (2016).
 - [12] R. Voss and T. M. Tauris, *MNRAS* **342**, 1169 (2003).
 - [13] A. Askar, M. Szkudlarek, D. Gondek-Rosińska, M. Giersz, and T. Bulik, *MNRAS Lett.* **464**, L36 (2016).
 - [14] A. Tanikawa, *MNRAS* **435**, 1358 (2013).
 - [15] J. Hong, E. Vesperini, A. Askar, M. Giersz, M. Szkudlarek, and T. Bulik, *MNRAS* **480**, 5645 (2018).
 - [16] J. M. B. Downing, M. J. Benacquista, M. Giersz, and R. Spurzem, *MNRAS* **416**, 133 (2011).
 - [17] R. M. O’Leary, F. A. Rasio, J. M. Fregeau, N. Ivanova, and R. O’Shaughnessy, *Astrophys. J.* **637**, 937 (2006).
 - [18] K. Moody and S. Sigurdsson, *Astrophys. J.* **690**, 1370 (2009).
 - [19] Y.-B. Bae, C. Kim, and H. M. Lee, *MNRAS* **440**, 2714 (2014).
 - [20] S. F. Portegies Zwart and S. L. W. Mcmillan, *Astrophys. J.* **528**, L17 (2000).
 - [21] N. Choksi, M. Volonteri, M. Colpi, O. Y. Gnedin, and H. Li (2018).
 - [22] S. Chatterjee, C. L. Rodriguez, and F. A. Rasio, *Astrophysical Journal* **834** (2016).
 - [23] J. M. B. Downing, M. J. Benacquista, M. Giersz, and R. Spurzem, *MNRAS* **407**, 1946 (2010).
 - [24] C. L. Rodriguez, S. Chatterjee, and F. A. Rasio, *Phys. Rev. D* **93**, 084029 (2016).
 - [25] C. L. Rodriguez, C.-J. Haster, S. Chatterjee, V. Kalogera, and F. A. Rasio, *Astrophys. J.* **824**, L8 (2016).
 - [26] C. L. Rodriguez, M. Morscher, B. Pattabiraman, S. Chatterjee, C.-J. Haster, and F. A. Rasio, *Phys. Rev. Lett.* **115**, 051101 (2015).
 - [27] B.-M. Hoang, S. Naoz, B. Kocsis, F. A. Rasio, and F. Dosopoulou, *Astrophys. J.* **856**, 140 (2018).
 - [28] S. Prodan, F. Antonini, and H. B. Perets, *Astrophys. J.* **799**, 118 (2015).
 - [29] J. M. Antognini, B. J. Shappee, T. A. Thompson, and P. Amaro-Seoane, *MNRAS* **439**, 1079 (2014).
 - [30] F. Antonini and H. B. Perets, *Astrophys. J.* **757**, 27 (2012).
 - [31] F. Antonini, S. Chatterjee, C. L. Rodriguez, M. Morscher, B. Pattabiraman, V. Kalogera, and F. A. Rasio, *Astrophys. J.* **816**, 65 (2016).
 - [32] F. Antonini, S. Toonen, and A. S. Hamers, *Astrophys. J.* **841**, 77 (2017).
 - [33] K. Silsbee and S. Tremaine, *Astrophys. J.* **836**, 39 (2017).
 - [34] Antonini F., Rodriguez C. L., Petrovich C., Fischer C. L., 2018, *MNRAS*, 480, L58
 - [35] Liu B., Lai D., 2017, *ApJL*, 846, L11
 - [36] Rodriguez C. L., Antonini F., 2018, *ApJ*, 863, 7
 - [37] Stephan A. P., et al., 2019, *ApJ*, 878, 58
 - [38] Liu B., Lai D., Wang Y.-H., 2019, *arXiv*, arXiv:1905.00427
 - [39] Fragione G., Kocsis B., 2019, *MNRAS*, 486, 4781
 - [40] Fragione G., Grishin E., Leigh N. W. C., Perets H. B., Perna R., 2019, *MNRAS*, 488, 47
 - [41] N. C. Stone, B. D. Metzger, and Z. Haiman, *MNRAS* **464**, 946 (2017).
 - [42] I. Bartos, B. Kocsis, Z. Haiman, and S. Márka, pp. *Astrophys. J.* **835**, 165 (2017).
 - [43] B. McKernan, K. E. Saavik Ford, J. Bellovary, N. W. C. Leigh, Z. Haiman, B. Kocsis, W. Lyra, M.-M. Mac Low, B. Metzger, M. O’Dowd, et al., *Astrophys. J.* **866**, 66 (2018).
 - [44] A. Secunda, J. Bellovary, M.-M. Mac Low, K. E. S. Ford, B. McKernan, N. Leigh, and W. Lyra et al., *Astrophys. J.* **878**, 85 (2019).
 - [45] S. Bird, I. Cholis, J. B. Muñoz, Y. Ali-Haïmoud, M. Kamionkowski, E. D. Kovetz, A. Raccanelli, and A. G. Riess, *Phys. Rev. Lett.* **116**, 1 (2016).
 - [46] A. Gualandris and D. Merritt, *Astrophys. J.* **678**, 780 (2008).

- [47] Schnittman J. D., 2007, *ApJL*, **667**, L133
- [48] K. HolleyBockelmann, K. Gültekin, D. Shoemaker, and N. Yunes, *Astrophys. J.* **686**, 829 (2008).
- [49] D. Merritt, M. Milosavljević, M. Favata, S. A. Hughes, and D. E. Holz, *Astrophys. J.* **607**, L9 (2004).
- [50] González, J. A., Hannam, M., Sperhake, U., et al. 2007, *Phys. Rev. Lett.*, **98**, 231101
- [51] Campanelli M., Lousto C. O., Zlochower Y., Merritt D., 2007, *PhRvL*, **98**, 231102
- [52] M. Campanelli, C. Lousto, Y. Zlochower, and D. Merritt, *Astrophys. J.* **659**, L5 (2007).
- [53] C. O. Lousto and Y. Zlochower, *Phys. Rev. D* **77**, 044028 (2008).
- [54] C. O. Lousto, Y. Zlochower, M. Dotti, and M. Volonteri, *Phys. Rev. D* **85**, 084015 (2012).
- [55] C. O. Lousto and Y. Zlochower, *Phys. Rev. D* **87**, 084027 (2013).
- [56] B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, et al., *arXiv e-prints*, *arXiv:1811.12940* (2018).
- [57] Talbot, C., & Thrane, E. 2018, *Astrophys. J.*, **856**, 173
- [58] F. Antonini, S. Chatterjee, C. L. Rodriguez, M. Morscher, B. Pattabiraman, V. Kalogera, and F. A. Rasio, *Astrophys. J.* **816**, 65 (2015).
- [59] C. L. Rodriguez, P. Amaro-Seoane, S. Chatterjee, and F. A. Rasio, *Phys. Rev. Lett.* **120**, 151101 (2018).
- [60] F. Antonini, M. Gieles, and A. Gualandris, *MNRAS* **486**, 5008 (2019).
- [61] D. Gerosa and E. Berti, *Phys. Rev. D* **95**, 124046 (2017).
- [62] M. Fishbach, D. E. Holz, and B. Farr, *Astrophys. J.* **840**, L24 (2017).
- [63] S. E. Woosley and A. Heger, *The Deaths of Very Massive Stars*. In: Vink J. (eds) *Very Massive Stars in the Local Universe*. *Astrophysics and Space Science Library*, 199-225, (2015).
- [64] S. E. Woosley, *Astrophys. J.* **836**, 244 (2017).
- [65] S. E. Woosley *arXiv e-prints*, *arXiv:1901.00215* (2019).
- [66] M. Fishbach and D. E. Holz, *Astrophys. J.* **851**, L25 (2017).
- [67] P. A. R. Ade, N. Aghanim, M. Arnaud, M. Ashdown, J. Aumont, C. Baccigalupi, A. J. Banday, R. B. Barreiro, J. G. Bartlett, N. Bartolo, et al., *Astron. & Astrophys.* **594**, A13 (2016).
- [68] K. J. Joshi, F. A. Rasio, and S. Portegies Zwart, *Astrophys. J.* **540**, 969 (2000).
- [69] B. Pattabiraman, S. Umbreit, W.-k. Liao, A. Choudhary, V. Kalogera, G. Memik, and F. A. Rasio, *Astrophys. J. Suppl. Ser.* **204**, 15 (2013).
- [70] J. R. Hurley, O. R. Pols, and C. A. Tout, *MNRAS* **315**, 543 (2000).
- [71] J. R. Hurley, C. A. Tout, and O. R. Pols, *MNRAS* **329**, 897 (2002).
- [72] S. Chatterjee, J. M. Fregeau, S. Umbreit, and F. A. Rasio, *Astrophys. J.* **719**, 915 (2010).
- [73] M. Hénon, *Dynamics of the Solar Systems*, *IAU Symposium* (1975).
- [74] M. Morscher, S. Umbreit, W. M. Farr, and F. A. Rasio, *Astrophys. J.* **763**, L15 (2013).
- [75] J. M. Fregeau and F. A. Rasio, *Astrophys. J.* **658**, 1047 (2007).
- [76] P. Amaro-Seoane and X. Chen, *MNRAS* **458**, 3075 (2016).
- [77] E. Berti, V. Cardoso, J. A. Gonzalez, U. Sperhake, M. Hannam, S. Husa, and B. Brügmann, *Phys. Rev. D* **76**, 064034 (2007).
- [78] J. A. González, U. Sperhake, B. Brügmann, M. Hannam, and S. Husa, *Phys. Rev. Lett.* **98**, 091101 (2007).
- [79] M. Kesden, *Phys. Rev. D* **78**, 084030 (2008).
- [80] W. Tichy and P. Marronetti, *Phys. Rev. D* **78**, 081501 (2008).
- [81] A. Buonanno, L. E. Kidder, and L. Lehner, *Phys. Rev. D* **77**, 026004 (2008).
- [82] L. Rezzolla, E. Barausse, E. N. Dorband, D. Pollney, C. Reisswig, J. Seiler, and S. Husa, *Phys. Rev. D* **78**, 044002 (2008).
- [83] E. Barausse and L. Rezzolla, *Astrophys. J.* **704**, L40 (2009).
- [84] E. Barausse, V. Morozova, and L. Rezzolla, *Astrophys. J.* **758**, 63 (2012).
- [85] C. O. Lousto and Y. Zlochower, *Phys. Rev. D* **89**, 104052 (2014).
- [86] C. L. Rodriguez, P. Amaro-Seoane, S. Chatterjee, K. Kremer, F. A. Rasio, J. Samsing, C. S. Ye, and M. Zevin, *Phys. Rev. D* **98**, 123005 (2018).
- [87] K. Belczynski, J. Klencki, G. Meynet, C. L. Fryer, D. A. Brown, M. Chruslinska, W. Gladysz, R. O'Shaughnessy, T. Bulik, E. Berti, et al., *arXiv e-prints*, *arXiv:1706.07053* (2017).
- [88] I. R. King, *Astron. J.* **71**, 64 (1966).
- [89] P. Kroupa and C. Weidner, *Astrophys. J.* **598**, 1076 (2003).
- [90] K. El-Badry, E. Quataert, D. R. Weisz, N. Choksi, and M. Boylan-Kolchin *MNRAS* **482**, 4528 (2018).
- [91] C. L. Rodriguez and A. Loeb, *Astrophys. J.* **866**, L5 (2018).
- [92] S. F. Portegies Zwart, S. L. McMillan, and M. Gieles, *Annu. Rev. Astron. Astrophys.* **48**, 431 (2010).
- [93] P. S. Behroozi, R. H. Wechsler, and C. Conroy, *Astrophys. J.* **770**, 57 (2013).
- [94] X. Ma, P. F. Hopkins, C. A. Faucher-Giguère, N. Zolman, A. L. Muratov, D. Kereš, and E. Quataert, *MNRAS* **456**, 2140 (2016).
- [95] B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, et al., *Liv. Rev. Relativ.* **21** (2018).
- [96] M. Hannam, P. Schmidt, A. Bohé, L. Haegel, S. Husa, F. Ohme, G. Pratten, and M. Pürrer, *Phys. Rev. Lett.* **113**, 1 (2014).
- [97] Fuller, J., Piro, A. L., & Jermyn, A. S. 2019, *MNRAS*, **485**, 3661
- [98] Fuller, J., & Ma, L. 2019, *Astrophys. J.* (in press), *arXiv e-prints*, *arXiv:1907.03714*
- [99] Wysocki, D., Lange, J., & O'Shaughnessy, R. 2018, *arXiv e-prints*, *arXiv:1805.06442*
- [100] J. Samsing and T. Ilan, *MNRAS* **482**, 30 (2019).
- [101] M. Mapelli, *MNRAS* **459**, 3432 (2016).
- [102] K. Belczynski, A. Heger, W. Gladysz, A. J. Ruiter, S. Woosley, G. Wiktorowicz, H.-Y. Chen, T. Bulik, R. O'Shaughnessy, D. E. Holz, et al., *Astronomy & Astrophysics* **594**, A97 (2016).
- [103] M. Spera and M. Mapelli, *MNRAS* **470**, 4739 (2017).
- [104] Stevenson, S., Sampson, M., Powell, J., et al. 2019, *arXiv e-prints*, *arXiv:1904.02821*
- [105] C. L. Rodriguez, M. Zevin, C. Pankow, V. Kalogera, and F. A. Rasio, *Astrophys. J.* **832**, L2 (2016).
- [106] W. M. Farr, S. Stevenson, M. C. Miller, I. Mandel,

- B. Farr, and A. Vecchio, *Nature* **548**, 426 (2017).
- [107] B. Farr, D. E. Holz, and W. M. Farr, *Astrophys. J.* **854**, L9 (2018).
- [108] J. Roulet, L. Dai, T. Venumadhav, B. Zackay, and M. Zaldarriaga, arXiv e-prints, arXiv:1904.01683 (2018).
- [109] T. Venumadhav, B. Zackay, J. Roulet, L. Dai, and M. Zaldarriaga, arXiv e-prints, arXiv:1904.07214 (2019).
- [110] B. Zackay, T. Venumadhav, L. Dai, J. Roulet, and M. Zaldarriaga, arXiv e-prints, arXiv:1902.10331 (2019).
- [111] T. Venumadhav, B. Zackay, J. Roulet, L. Dai, and M. Zaldarriaga, arXiv e-prints, arXiv:1902.10341 (2018).
- [112] J. Goodman, *Astrophys. J.* **280**, 298 (1984).
- [113] D. Heggie and P. Hut, *The Gravitational Million-Body Problem: A Multidisciplinary Approach to Star Cluster Dynamics*, by Douglas Heggie and Piet Hut. Cambridge University Press, 2003, 372 pp. (2003).
- [114] S. Sigurdsson and E. S. Phinney, *Astrophys. J.* **415**, 631 (1993).
- [115] C. Kimball, C. P. L. Berry, and V. Kalogera, arXiv e-prints, arXiv:1903.07813 (2019).
- [116] K. Chatziioannou, R. Cotesta, S. Ghonge, J. Lange, K. K. Y. Ng, J. C. Bustillo, J. Clark, C.-J. Haster, S. Khan, M. Puerrer, arXiv e-prints, arXiv:1903.06742 (2019).
- [117] S. Chatterjee, C. L. Rodriguez, V. Kalogera, and F. A. Rasio, *Astrophys. J.* **836**, L26 (2017).
- [118] B. M. Ziosi, M. Mapelli, M. Branchesi, and G. Tormen, *MNRAS* **441**, 3703 (2014).
- [119] K. Kremer, C. S. Ye, S. Chatterjee, C. L. Rodriguez, and F. A. Rasio, *Astrophys. J.* **855**, L15 (2018).
- [120] K. Kremer, S. Chatterjee, C. S. Ye, C. L. Rodriguez, and F. A. Rasio, *Astrophys. J.* **871**, 38 (2019).
- [121] Gerosa, D., & Berti, E. 2019, arXiv e-prints, arXiv:1906.05295
- [122] M. Morscher, B. Pattabiraman, C. Rodriguez, F. A. Rasio, and S. Umbreit, *Astrophys. J.* **800**, 9 (2015).
- [123] C. O. Lousto, H. Nakano, Y. Zlochower, and M. Campanelli, *Phys. Rev. D* **81** (2010).
- [124] S. Vitale, R. Lynch, V. Raymond, R. Sturani, J. Veitch, and P. Graff, *Phys. Rev. D* **95**, 064053 (2017).
- [125] Gerosa D., Berti E., O’Shaughnessy R., Belczynski K., Kesden M., Wysocki D., Gladysz W., 2018, *PhRvD*, 98, 084036
- [126] S. E. De Mink and I. Mandel, *MNRAS* **460**, 3545 (2016).
- [127] I. Mandel and S. E. De Mink, *MNRAS* **458**, 2634 (2016).
- [128] P. Marchant, N. Langer, P. Podsiadlowski, T. M. Tauris, and T. J. Moriya, *Astron. & Astrophys.* **588**, A50 (2016).
- [129] S. F. Portegies Zwart, H. Baumgardt, P. Hut, J. Makino, and S. L. W. McMillan, *Nature* **428**, 724 (2004).
- [130] Gürkan, M. A., Freitag, M., & Rasio, F. A. 2004, *Astrophys. J.*, **604**, 632
- [131] Freitag, M., Gürkan, M. A., & Rasio, F. A. 2006, *MNRAS*, **368**, 141
- [132] Gürkan, M. A., Fregeau, J. M., & Rasio, F. A. 2006, *Astrophys. J.*, 640, L39
- [133] S. F. Portegies Zwart and S. L. W. McMillan, *Astrophys. J.* **576**, 899 (2002).
- [134] U. N. Di Carlo, N. Giacobbo, M. Mapelli, M. Pasquato, M. Spera, L. Wang, and F. Haardt, arXiv e-prints, arXiv:1901.00863 (2019).
- [135] J. R. Hurley, S. J. Aarseth, and M. M. Shara, *Astrophys. J.* **665**, 707 (2007).
- [136] J. Morawski, M. Giersz, A. Askar, and K. Belczynski, *MNRAS* **481**, 2168 (2018).
- [137] Chini, R., Hoffmeister, V. H., Nasseri, A., et al. 2012, *MNRAS*, **424**, 1925
- [138] M. Zevin, C. Pankow, C. L. Rodriguez, L. Sampson, E. Chase, V. Kalogera, and F. A. Rasio, *Astrophys. J.* **846**, 82 (2017).
- [139] Talbot C., Thrane E., 2017, *PhRvD*, 96, 023012
- [140] Taylor S. R., Gerosa D., 2018, *PhRvD*, 98, 083017
- [141] Powell J., Stevenson S., Mandel I., Tiño P., 2019, *MNRAS*, 1874
- [142] Bouffanais Y., Mapelli M., Gerosa D., Di Carlo U. N., Giacobbo N., Berti E., Baibhav V., 2019, arXiv, arXiv:1905.11054
- [143] Gaebel S. M., Veitch J., Dent T., Farr W. M., 2019, *MNRAS*, 484, 4008
- [144] M. Zevin, C. Pankow, C. L. Rodriguez, E. Chase, V. Kalogera, and F. A. Rasio, In prep. (2019).