



Signatures of Mass Ratio Reversal in Gravitational Waves from Merging Binary Black Holes

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Abstract

The spins of merging binary black holes offer insights into their formation history. Recently it has been argued that in the isolated binary evolution of two massive stars the firstborn black hole is slowly rotating, while the progenitor of the second-born black hole can be tidally spun up if the binary is tight enough. Naively, one might therefore expect that only the less massive black hole in merging binaries exhibits nonnegligible spin. However, if the mass ratio of the binary is “reversed” (typically during the first mass transfer episode), it is possible for the tidally spun up second-born to become the more massive black hole. We study the properties of such mass ratio reversed binary black hole mergers using a large set of 560 population synthesis models. We find that the more massive black hole is formed second in $\gtrsim 70\%$ of binary black holes observable by LIGO, Virgo, and KAGRA for most model variations we consider, with typical total masses $\gtrsim 20 M_{\odot}$ and mass ratios $q = m_2/m_1 \sim 0.7$ (where $m_1 > m_2$). The formation history of these systems typically involves only stable mass transfer episodes. The second-born black hole has nonnegligible spin ($\chi > 0.05$) in up to 25% of binary black holes, with among those the more (less) massive black hole is spinning in 0%–80% (20%–100%) of the cases, varying greatly in our models. We discuss our models in the context of several observed gravitational-wave events and the observed mass ratio—effective spin correlation.

Unified Astronomy Thesaurus concepts: [Gravitational wave sources \(677\)](#); [Gravitational waves \(678\)](#); [Astrophysical black holes \(98\)](#)

1. Introduction

The population of binary black hole mergers observed by Advanced LIGO (Aasi et al. 2015), Virgo (Acernese et al. 2015), and KAGRA (Akutsu et al. 2019) is rapidly increasing. The inferred merger rates of binary black holes, and their observed mass and spin distributions offer insights into their formation history (e.g., Stevenson et al. 2015; Rodriguez et al. 2016; Vitale et al. 2017b; Farr et al. 2017; Stevenson et al. 2017; Talbot & Thrane 2017). By comparing the data with theoretically synthesized populations, we can learn about their massive-star progenitors.

The birth spins of black holes are uncertain. Recently, several authors have argued that angular momentum transport within massive stars is efficient (Spruit 2002; Fuller et al. 2019), as also supported by observations from astroseismology (Deheuvels et al. 2014; Kurtz et al. 2014; Gehan et al. 2018) and gravitational waves (Belczynski et al. 2020; Zevin et al. 2020). Under this assumption, and the assumption of Eddington-limited accretion, we expect the firstborn black hole to be almost nonrotating (with dimensionless spin $\chi \lesssim 0.01$; Qin et al. 2018; Fuller & Ma 2019) as the majority of the progenitors’ angular momentum will have been transported from its core to its envelope, and subsequently removed through mass transfer and stellar winds.

The same may not be true for the second-born black hole, however. Immediately prior to the formation of the second

black hole, the binary consists of a black hole and a helium (Wolf–Rayet) star with a relatively short orbital period. Tides exerted on the helium star by the black hole can synchronize the rotation of the helium star with the orbital period, leading to a rapidly rotating helium star that may subsequently collapse to form a rapidly rotating black hole (Kushnir et al. 2016; Hotokezaka & Piran 2017; Zaldarriaga et al. 2018; Qin et al. 2018; Bavera et al. 2020; Belczynski et al. 2020).

Naively, if only the second-born black hole can be rapidly rotating, one might expect the more massive black hole (with mass m_1) to be formed first with no spin ($\chi_1 \sim 0$).⁶ This intuition originates from a naive picture of massive binary evolution in which two massive stars never interact: first, the more massive star forms the more massive black hole, since the relation between the initial mass of a star and the black hole mass is believed to be monotonic over a wide range of initial masses (e.g., Belczynski et al. 2010; Team COMPAS et al. 2022). Second, the more massive black hole forms first, since the initially more massive star has the shorter lifetime (e.g., Agrawal et al. 2020; Team COMPAS et al. 2022).

However, binary evolution complicates this picture. Mass transfer from the initially more massive star⁷ to its companion can lead to the mass ratio of the binary being reversed, potentially leading to the initially lower mass star becoming

⁶ We use the notation χ_1 (χ_2) for the spin of the more (less) massive binary black hole. See Biscoveanu et al. (2021) for an alternative parameterization.

⁷ Stellar theorists typically refer to the initially more massive star as the “primary” and the less massive star as the “secondary”. We avoid this jargon since gravitational-wave astronomers refer to the more massive black hole as the “primary”. This leads to confusion when the initially more massive star produces the less massive black hole.



more massive than the primary ever was. For binaries that go on to form merging binary black holes, this can ultimately result in the second black hole that forms in the binary being more massive than the first (e.g., Gerosa et al. 2013; Stevenson et al. 2017; Zevin & Bavera 2022).⁸ This mass ratio reversal (MRR) can have important implications for the spins of the black holes in the binary. If the binary has undergone MRR, this leads to the intriguing possibility that the (progenitor of the) more massive black hole is the one that may be tidally spun up, leading to $\chi_1 \geq 0$.

In this paper, we investigate the frequency and properties of MRR systems in the population of merging binary black holes formed through isolated binary evolution with the goal of making testable predictions for gravitational-wave astronomers. We use a large set of models to test how robust our predictions are to uncertainties in both our treatment of massive binary evolution, and of the cosmic star formation history. We begin by introducing our methodology in Section 2, where we also describe the typical formation history of a merging binary black hole that has undergone MRR. In Section 3, we show that the majority of observable binary black holes undergo MRR in most of our models. We describe the properties of MRR versus non-MRR systems. In Section 4, we illustrate that, within the subset of binary black hole mergers with nonnegligible spin, MRR (non-MRR) systems are identifiable by having non-negligible χ_1 (χ_2). We describe the chirp mass and mass ratio properties of these subpopulations. We end with a discussion in Section 5 and conclude in Section 6.

2. Method

2.1. Population Synthesis Simulations

We study merging binary black holes formed from the evolution of isolated massive binary stars (the “isolated binary evolution” channel) using the publicly available simulations presented by Broekgaarden et al. (2021, 2022). These simulations were performed using the rapid binary population synthesis suite COMPAS⁹ (Stevenson et al. 2017; Vigna-Gómez et al. 2018; Broekgaarden et al. 2019; Team COMPAS et al. 2022), which employs simple parameterized models of single (Hurley et al. 2000) and binary stellar evolution (Hurley et al. 2002) in order to evolve large populations of binaries rapidly.

The simulations from Broekgaarden et al. (2021, 2022) present 560 model realizations, exploring a large range of uncertainties underlying population synthesis models. This includes 20 variations in assumptions related to uncertain stages of massive (binary) star evolution such as mass transfer, supernovae kicks, common-envelope evolution, and Wolf-Rayet winds (see details and Table 1 in Broekgaarden et al. 2022). Each stellar evolution variation is combined with 28 different assumptions about the metallicity-dependent star formation rate density $\mathcal{S}(Z, z)$, which is a function of metallicity (Z) and redshift (z) and describes the amount of star formation and the

distribution of the birth metallicities as a function of cosmic time. Both the stellar evolution and $\mathcal{S}(Z, z)$ uncertainties have been shown by a number of authors to be an important ingredient in predicting populations of merging binary black holes (e.g., Neijssel et al. 2019; Santoliquido et al. 2020; Tang et al. 2020; Briel et al. 2022; Broekgaarden et al. 2022).

To make a meaningful comparison with gravitational-wave data we convert the COMPAS population into an *astrophysical* population of all local (redshift $z \approx 0$) sources and a *detectable* population. We do this using the weights based on Equations (2) and (5) from Broekgaarden et al. (2022). For simplicity, we assume for the detectable population a detector network consisting of LIGO, Virgo, and KAGRA at design sensitivity (from hereon “LVK”), which can see more distant merger events than the current network. For the remainder of this paper we refer to these weighted rates when we discuss the astrophysical or detectable populations. We refer the readers to Broekgaarden et al. (2021, 2022) for more details.

2.2. Selecting MRRs

From the population of binary black hole mergers we obtain the subset of MRRs by selecting the systems for which the black hole that formed second from the initially less massive star (B) is more massive than the black hole that formed first from the initially more massive star (A). In other words, we define MRR as systems that satisfy the condition $m_B > m_A$ at the moment of binary black hole formation such that the binary system has “reversed” its mass ratio between its formation as a binary system and its merger as a binary black hole.¹⁰

2.3. Modeling Black Hole Spin

We model the formation of black hole spin following the methodology of Bavera et al. (2020, 2021). We assume that the firstborn black hole in the binary system always has zero spin, corresponding to efficient angular momentum transport in the star (Qin et al. 2018). For the second-born black hole, we assume that it can be formed spinning if its progenitor helium star has been tidally spun up. This requires the binary to go through a black hole–Wolf Rayet phase with an orbital period of less than 1 day. For these systems we use the prescription for the second-born black hole spin given by Equations (1) and (2) in Bavera et al. (2021), which they based on detailed MESA simulations. This prescription assigns a black hole spin based on the orbital separation and the Wolf-Rayet stellar mass.

To implement this approximation within our simulations, we use the coefficients given for Wolf-Rayet stars at helium depletion. In addition, a few of our binary systems have properties at helium depletion that fall outside of the ranges of Wolf-Rayet star periods and masses given in Bavera et al. (2021). In these cases we assign the spin value using the most similar binary within the allowed range. We further note that although the Bavera et al. (2021) approximation is built for the delayed supernova model prescription from Fryer et al. (2012), we apply it, e.g., to our model (L) that uses the rapid supernova remnant mass prescription. We do not expect this to change our results drastically.

⁸ Algol binaries are a classic example of binaries that have undergone MRR. MRR has also been suggested for binary neutron stars (e.g., Portegies Zwart & Verbunt 1996), neutron star–black hole binaries (e.g., Sipior et al. 2004), and neutron star–white dwarf binaries (e.g., Tauris & Sennels 2000; Toonen et al. 2018) with observational support from young neutron stars in neutron star–white dwarf binaries (e.g., Tauris & Sennels 2000; Kaspi et al. 2000; Ng et al. 2018; Venkatraman Krishnan et al. 2020).

⁹ Compact Object Mergers: Population Astrophysics and Statistics—<https://compas.science>.

¹⁰ There are a negligible number of systems in which significant mass transfer causes m_B to undergo supernova first, in which case we define it to be MRR if $m_B < m_A$, as we are interested in whether the most massive black hole formed second.

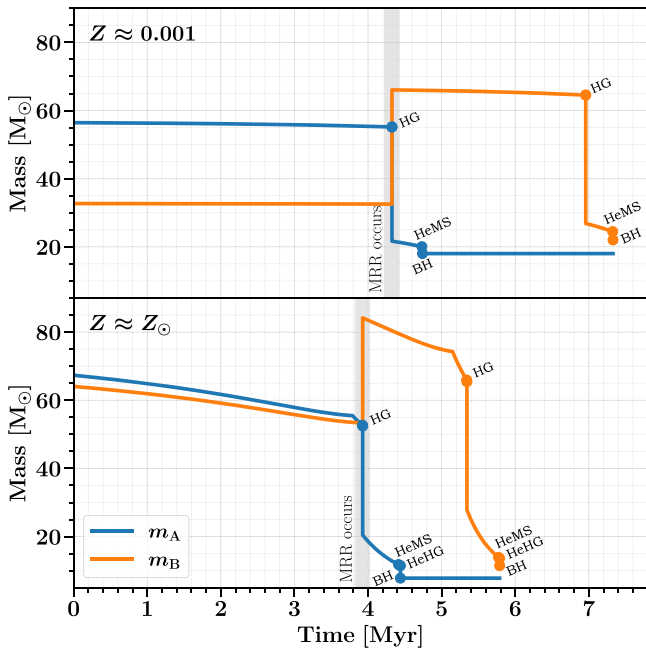


Figure 1. Examples of a binary system in our fiducial model realization that undergoes MRR evolved at low metallicity ($Z \approx 0.001$; top panel) and solar metallicity ($Z \approx 0.0142$; bottom panel). Each panel shows the evolution of the initially more massive (m_A) and less massive (m_B) star as a function of time. Both systems undergo MRR during the first mass transfer episode after approximately 4 Myr into their evolution (as indicated by the gray vertical bar). Transitions to different evolutionary stages are labeled using the acronyms: HG for a Hertzsprung gap star, HeMS for a helium main-sequence star, HeHG for a helium HG star, and BH for a black hole. More examples are provided on GitHub: https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure1_individual_MRR_systems_detailed_evolution/detailedPlots/Figure_1_MRR.pdf https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure1_individual_MRR_systems_detailed_evolution/Individual_System_Evolution_and_MRR_Statistics.ipynb.

A black hole is defined to have “nonnegligible spin” if its assigned spin exceeds 0.05. The threshold spin of 0.05 is chosen for this work to represent the resolution of the Bavera et al. (2021) spin prescription, and is additionally motivated by Figure 2 of Galaudage et al. (2021) where a boundary near 0.05 distinguishes the delta peak around spin ~ 0 and the Gaussian distribution of nonnegligible spins. Moreover, Fuller & Ma (2019) show that single stars are expected to typically achieve spins of $\lesssim 0.05$. Other papers have suggested that single star evolution can lead to black hole spins up to $\lesssim 0.1$ (Qin et al. 2018, 2019). We investigate the impact of changing our threshold to 0.1 in Appendix A.3 and find that it does not significantly impact our results.

2.4. Formation Channels

We begin by outlining the formation history of a typical progenitor of a merging binary black hole that is an MRR system. An example is shown in Figure 1 for a binary formed at low ($Z \approx 0.001$) and solar-like ($Z \approx Z_\odot$) metallicity. Two massive stars are born in a wide binary. The examples in Figure 1 start with a binary at $Z \approx 0.001$ ($Z \approx Z_\odot$) metallicity with masses $m_A \approx 56 M_\odot$ ($m_A \approx 67 M_\odot$) and $m_B \approx 33 M_\odot$ ($m_B \approx 64 M_\odot$) and a separation of 70 au (1000 au). The initially more massive star evolves off the main sequence, and fills its Roche lobe while crossing the Hertzsprung gap (HG), which occurs in the example systems after approximately 4 Myr.

If the mass ratio of the binary is not too far from unity (e.g., $m_A/m_B \lesssim 4$; Claeys et al. 2014; Team COMPAS et al. 2022), we find that the mass transfer episode is stable (e.g., Hurley et al. 2002), and the envelope of the initially more massive star is removed, with a large fraction being accreted onto the initially more massive star (Hurley et al. 2002; Schneider et al. 2015; Team COMPAS et al. 2022). This is the evolutionary stage in our COMPAS simulations where MRR typically occurs. After the stable mass transfer phase, the firstborn star has evolved into a stripped helium main-sequence star (HeMS) of $m_A \approx 18 M_\odot$ ($m_A \approx 11 M_\odot$) and the second-born star has evolved to a $m_B \approx 66 M_\odot$ ($m_B \approx 79 M_\odot$) for low (solar) metallicity. The stripped helium core subsequently collapses to form a black hole of $m_A \approx 18 M_\odot$ ($m_A \approx 8 M_\odot$).

Following the formation of the first black hole, the initially less massive star eventually reaches the end of its main sequence and subsequently fills its Roche lobe typically when crossing the HG. Once again, depending on various properties such as the evolutionary stage of the donor star and the binary mass ratio, this phase of mass transfer can either be stable or unstable, resulting in common-envelope evolution (van den Heuvel et al. 2017; Neijssel et al. 2019; Bavera et al. 2021; Gallegos-Garcia et al. 2021; van Son et al. 2022). In the binary portrayed in Figure 1, which is typical of our population synthesis models, we find that this episode of mass transfer is typically stable, as we discuss in more detail in the next section.

The stable mass transfer onto the black hole companion is highly nonconservative (we assume that the maximum mass accretion rate for a compact object is set by the Eddington limit), leading to drastic shrinkage of the binary’s orbit. Eventually the initially less massive also forms a black hole—in the case of $m_B \approx 22 M_\odot$ ($m_B \approx 11 M_\odot$) for low (solar) metallicity, it forms the most massive black hole in the binary black hole system. The subsequent MRR binary black hole system merges in a Hubble time as a potential source for LVK. The main difference at low versus solar metallicity is that, at solar metallicity, the stars lose more mass through line driven stellar winds, leading to smaller black hole masses.

We classify our binary black hole systems into three different categories based on their formation channel (based on, e.g., Neijssel et al. 2019; Bavera et al. 2021; Broekgaarden et al. 2021). Namely, if the binary experiences only stable mass transfer we classify the channel as “only stable mass transfer”. Both binaries in Figure 1 are examples of this channel. On the other hand, if the second, reversed, mass transfer episode is unstable, leading to a common-envelope phase, we classify the channel as a “classic common envelope” channel. We additionally assume for both channels that the first mass transfer phase must occur when the initially more massive star has evolved off the main sequence to exclude the so-called case A mass transfer systems that are typically more poorly modeled in population synthesis simulations. We classify all other systems under “other”. The large majority, $\gtrsim 90\%$, of binary black holes in this channel form through only stable mass transfer phases where the first mass transfer already occurs when the initially more massive star is still on the main sequence (case A mass transfer onto the main-sequence accretor star). We separate these systems from the aforementioned channels because the modeling of case A mass transfer in our simulations, in particular that of the growth of the core, is uncertain (Team COMPAS et al. 2022).

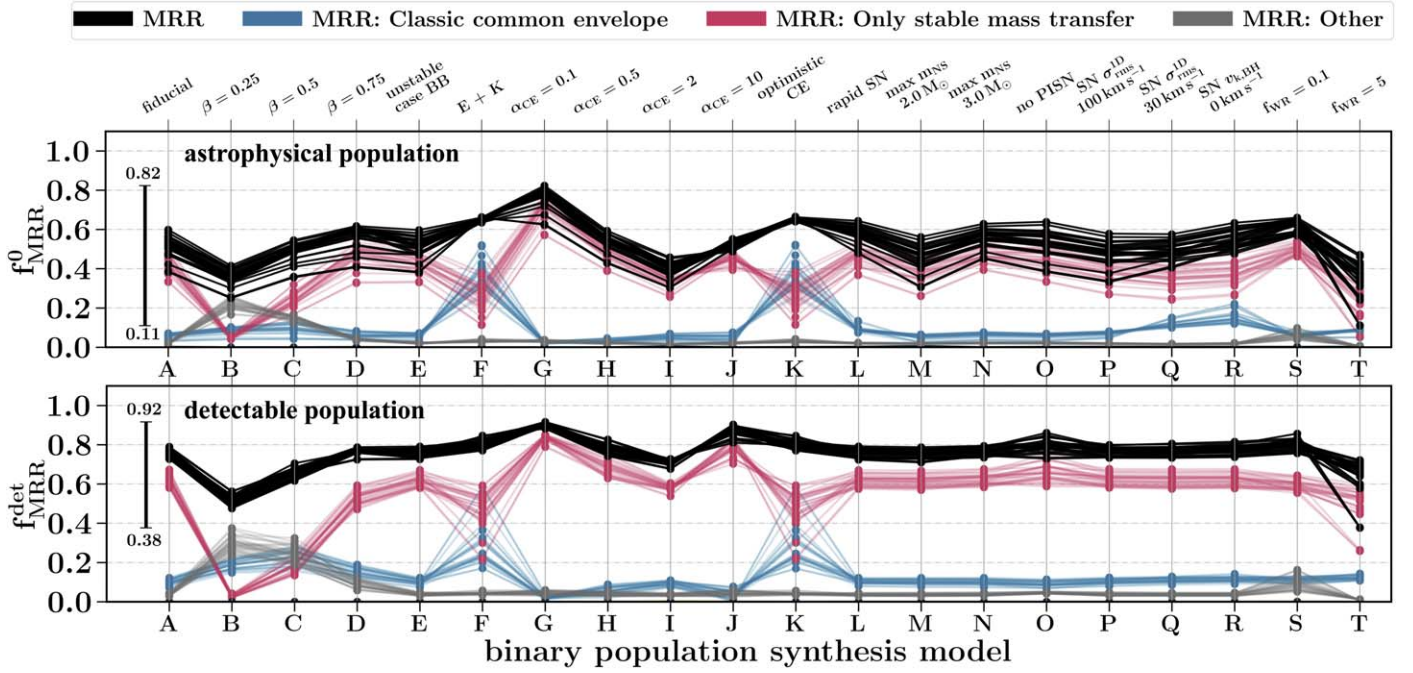


Figure 2. Fraction of MRRs among all binary black hole mergers (black) expected in the astrophysical (redshift 0; top panel) and gravitational-wave detectable (lower panel) populations for our 560 model realizations. The fraction of MRR binary black holes that go through the “classic common envelope” (blue), “only stable mass transfer” (magenta), and “other” (gray) channels are shown (see Section 2.4). We connect models using the same star formation rate density $\mathcal{S}(Z, z)$ with a line for visual purposes only. The vast majority of binaries in the “other” channel in our simulations are systems that experienced a mass transfer phase initiated by a main-sequence donor (case A mass transfer). https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure2_MRR_Rates_For_All_Models/RelativeMRRRates_Combined.pdf https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure2_MRR_Rates_For_All_Models/MRR_Rates_Intrinsic_and_Detectable_summary.ipynb.

3. Results: MRR Rates and Properties

In this section we study the rate (Section 3.1) and properties (Section 3.2) of MRR systems among the population of binary black hole mergers.

3.1. Fraction of MRRs among Merging Binary Black Holes

In Figure 2 we show the fraction of binary black holes in each model realization that have undergone MRR, f_{MRR} , for the astrophysical (top panel) and detectable (bottom panel) populations. The figure also shows the contributions from the different formation channels as defined in Section 2.4. We find several interesting features in the MRR rate results.

First, we find that for the gravitational-wave detectable population, the fraction of MRRs lies between $f_{\text{MRR}}^{\text{det}} \approx 0.38$ – 0.92 (panel 2), indicating that MRR is expected to be a common occurrence in LVK’s observations. Moreover, when excluding a subset of the models with extreme Wolf–Rayet wind factors of $f_{\text{WR}} = 5$ (model T), we find that the fraction of MRRs is always larger than $\gtrsim 0.5$, with most models predicting a contribution of $f_{\text{MRR}}^{\text{det}} \gtrsim 0.7$. In other words, for most models, we expect the more massive black hole to form second for the majority of LVK binary black holes. We discuss the consequences for LVK measurements of black hole spin in Section 4.

Second, we find that for the astrophysical binary black hole population, the fraction of MRRs is lower compared to the detectable population, lying between $f_{\text{MRR}}^0 \approx 0.11$ and 0.82 (panel 2) in all of our models, and $f_{\text{MRR}}^0 \gtrsim 0.3$ when excluding a subset of models T. This fraction is lower compared to the detectable population because, as we will show in Section 3.2,

the binaries that undergo MRR form typically more massive binary black holes compared to the non-MRR systems. These more massive MRR systems are easier to detect with the LVK network, boosting their contribution to the detectable population.

Third, we find that the majority of MRR binary black holes form through the only stable mass transfer sub-channel in most of our models. The exceptions are the models with a mass transfer efficiency parameter of $\beta = 0.25$ (models B) and the stellar evolution models with the “optimistic common envelope” assumption (models F and K), which allows HG donor stars to survive a common-envelope phase (in the default “pessimistic” case these are assumed to not survive the common-envelope phase). In the $\beta = 0.25$ models the MRR fraction is drastically suppressed as the first mass transfer phase is relatively nonconservative, which results in limited mass gain by the initially less massive star. The optimistic common-envelope models allow HG star donors that engage in a common-envelope phase to survive this evolutionary stage (in the default “pessimistic common envelope” assumption we assume these systems merge during this phase). This increases the number of binary black holes, and the (relative) number of MRR forming through the classic common-envelope channel.

Finally, we find that the fraction of MRR binary black holes increases for increasing mass transfer efficiency β (models B, C, and D), decreases for increasing common-envelope efficiencies after $\alpha = 0.1$ (models G, H, and I) but increases again for $\alpha = 10$ (models J), and is not significantly impacted by our variations in supernovae physics (models L–R). We discuss in more detail the outlier models in Appendix A.1.

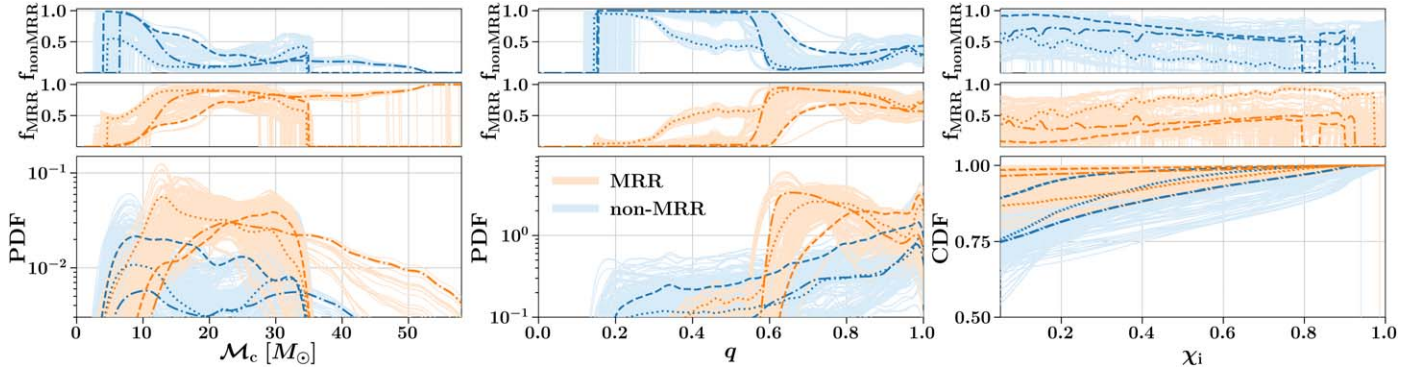


Figure 3. Chirp mass (left panels), mass ratio (middle panels), and dimensionless black hole spin (right panels) for the populations of MRR (orange) and non-MRR (blue) detectable binary black holes for all 560 model realizations. Three realizations, “K123”, “O312”, and “T231” (see [Github](#)) are highlighted with a dotted, dashed-dotted, and dotted curve, respectively. The bottom panels show probability distribution functions (PDFs), except for the black hole spins where we show cumulative distribution functions (CDFs) for visualization purposes. The two top rows show the fraction of expected detectable MRR (f_{MRR}) and non-MRR (f_{nonMRR}) binaries. The PDFs are normalized such that for each model realization the MRR and non-MRR PDFs sum up to one to show the relative normalization. https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure3_and_Figure5_BBH_properties_MRR_and_nonMRR_Distribution_plots/super_MRR_split_panel.pdf https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure3_and_Figure5_BBH_properties_MRR_and_nonMRR_Distribution_plots/Make_Figure_3_and_5_Distribution_Plots.ipynb.

3.2. Observable Properties of MRR Binaries

In the previous section we found that MRR systems can significantly contribute to the detectable binary black hole population. It is, therefore, interesting to consider whether their properties (i.e., chirp mass, mass ratio, and spins) are distinguishable from other binary black hole mergers detected by LVK. In this section, we compare and contrast these properties in the MRR and non-MRR binary black hole populations.

First, we find that the detectable MRR binary black hole mergers are biased to larger chirp masses, $\mathcal{M}_{\text{chirp}}$ (and total mass and individual black hole masses) in all our simulations. As shown in Figure 3, we see that MRR binary black hole systems typically have chirp mass distributions peaking between $\mathcal{M}_{\text{chirp}} \approx 10$ and $35 M_{\odot}$, whereas the non-MRR population peaks around $\mathcal{M}_{\text{chirp}} \approx 5\text{--}20 M_{\odot}$. This is also clear from the top panel, which shows that typically between 50% and 100% of the detected binary black hole mergers with chirp masses of $\mathcal{M}_{\text{chirp}} \gtrsim 10 M_{\odot}$ are expected to be MRRs with a peak around $20 M_{\odot}$ where we expect the large majority to be MRRs. This is because MRR binaries are predominantly formed through the stable mass transfer channel (see Figure 2), whereas non-MRR binaries are typically formed through the classic common-envelope channel. Binary black holes formed through stable mass transfer are more massive than those formed through common-envelope evolution (Neijssel et al. 2019; van Son et al. 2022), leading to this distinction. In the chirp mass plot, one group of models stand out by having a long tail of $\mathcal{M}_{\text{chirp}} \gtrsim 35$. These are our models that do not include pair-instability supernovae (models O), allowing for the formation of black holes with $m_{\text{BH}} \gtrsim 40 M_{\odot}$. The MRR binaries dominate this tail.

Second, MRR binary black holes also have distinct mass ratios (q) compared to the non-MRR systems, as shown in Figure 3. The MRR systems peak, and typically dominate observations, for $q \gtrsim 0.6$, whereas only the non-MRR systems can typically form binary black holes with $q \lesssim 0.6$. This is because for MRR binaries more extreme mass ratios require more extreme mass accretion by the initially less massive star, which is typically challenging and is also disfavored to lead to the successful formation of a binary black hole merger (e.g., it

requires more extreme mass ratios in earlier phases of the binary, which more likely lead to unstable mass transfer phases making the stars merge). More than 50% of binary black holes with $q \sim 0.7$ are MRR in almost all of our model realizations, whereas for mass ratios of $q \sim 0.4$ most models (except the optimistic common-envelope models) predict that less than 10% of the binary black holes are MRR. This preference for mass ratios close to 0.7 in the MRR population comes from the fact that binaries that undergo MRR are born with mass ratios close to unity (see Section A.2).

Let us consider a simplified picture (see discussion in van Son et al. 2022) to explore this, inspired by Figure 1. Consider a binary born with approximately equal mass components $m_{\text{A}}^{\text{ZAMS}} \approx m_{\text{B}}^{\text{ZAMS}} = m^{\text{ZAMS}}$, and let us neglect stellar winds for this simple estimate. Now assume that all of the envelope (which is typically around 50% of the stellar mass, $m^{\text{ZAMS}}/2$) of the initially more massive star is accreted onto the initially less massive star (i.e., assuming fully conservative mass transfer). At this stage, the mass ratio of the binary would be around $m_{\text{B}}/m_{\text{A}} \sim (3m^{\text{ZAMS}}/2)/(m^{\text{ZAMS}}/2) \sim 3$. Again neglecting further mass loss through winds, we take the final mass of the firstborn black hole to be $m_{\text{A}}^{\text{ZAMS}}/2$. The envelope of the initially less massive star is then removed through nonconservative stable mass transfer, leaving it with a final mass of $3m^{\text{ZAMS}}/4$. Hence, the final mass ratio of the binary is around $(3m^{\text{ZAMS}}/2)/(m^{\text{ZAMS}}/2) = 3/2$, or equivalently $q \sim 0.7$.

In general (both MRR and non-MRR), the binary black holes that formed in our models show a preference for close-to-equal masses, with highly asymmetric mass ratios of $q < 0.1$ being so rare as to be essentially nonexistent (Broekgaarden et al. 2022; see Olejak et al. (2020)). There are two sets of models with contributions from the MRR channel to extreme mass ratios around $q \approx 0.5$, which are the models that assume the optimistic common-envelope prescription (models F and K).

Third, we find in Figure 3 that, for both the MRR and non-MRR populations, a significant fraction of the binary black holes contain a black hole with nonnegligible spin ($\chi_i \gtrsim 0.05$). In our models, it is always the second-born black hole that is spinning, as the spin arises from tidal spin up. Hence, for MRR binaries, the more massive black hole is spinning ($\chi_1 > 0$), whereas for non-MRR binaries, it is the less massive black hole that is spinning ($\chi_2 > 0$). The fraction of binary black holes

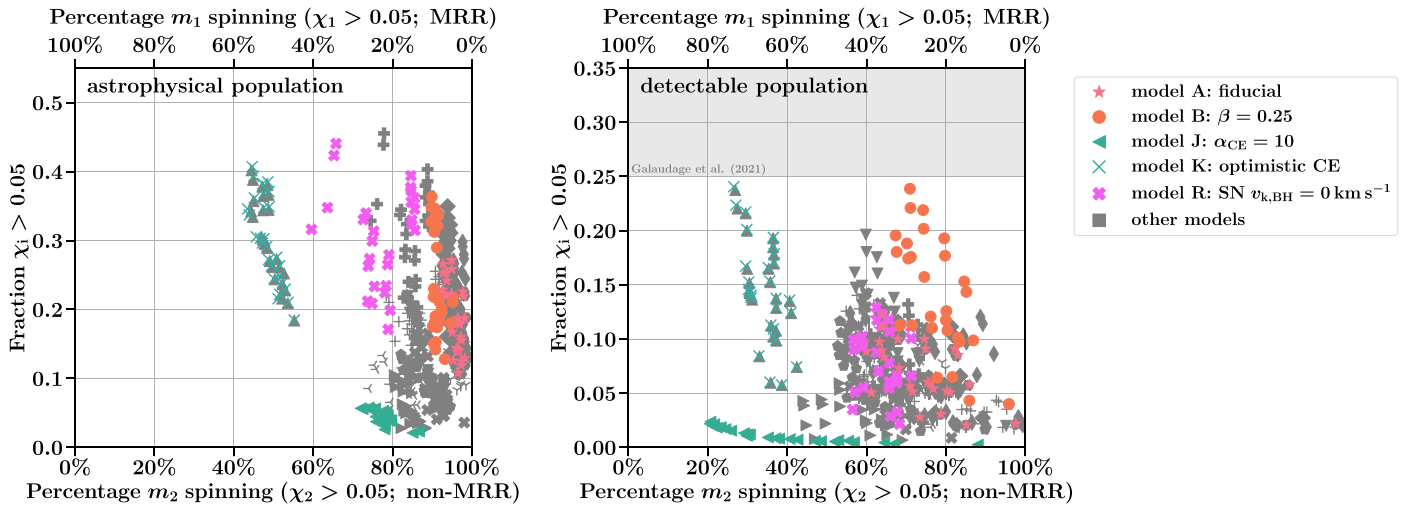


Figure 4. Fraction of the astrophysical (left panel) and detectable (right panel) binary black hole merger population where one of the black holes has a nonnegligible spin magnitude ($\chi_i > 0.05$) plotted against the percentage of systems in which the more massive (m_1) or less massive (m_2) black hole is spinning. Each marker style corresponds to one of our 20 stellar evolution variations for the combination with 28 cosmic star formation history models (see [Github](https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure4_spinning_BBH_Rates/Rate_MRR_spins_panels_spin_threshold_0.05.pdf)). Five stellar evolution variations are highlighted. Part of the 90% credible interval range of 0.25–0.71 for the fraction of binary black hole mergers with nonnegligible spin from Galaudage et al. (2021) is shown with a gray bar. https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure4_spinning_BBH_Rates/Rate_MRR_spins_panels_spin_threshold_0.05.pdf https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure4_spinning_BBH_Rates/Plot_fraction_spinning_BBHs.ipynb.

with no spinning black hole is typically smaller for the non-MRR population ($\gtrsim 60\%$) compared to the MRR population ($\gtrsim 80\%$). This is because non-MRR binary black holes typically go through a common-envelope phase, which shrinks the binary to smaller orbital separations compared to a second stable mass transfer phase. These shorter separations are more likely to allow tidal spin up of the second-born black hole. We discuss the implications of MRR for black hole spins further in the following section.

4. Results: MRR and Black Hole Spin

The population of detectable binary black hole binaries with a nonnegligible black hole spin component (identified in Figure 3) allows for identification of MRR versus non-MRR systems from observations. Namely, for MRR binary black holes, the more massive black hole has a nonnegligible spin of $\chi_1 > 0.05$,¹¹ and the less massive black hole is non-spinning, $\chi_2 = 0$, while for non-MRR binaries $\chi_2 > 0.05$ and $\chi_1 = 0$, as a result of our assumption that only the second-born black hole can spin up through tides. We discuss the implications of this below.

4.1. Fraction of Binary Black Holes with Nonnegligible Spin

Figure 4 shows the fraction of binary black holes with nonnegligible spin ($\chi_i > 0.05$), as well as the fraction among those where the nonnegligible spin is assigned to the more massive black hole ($\chi_1 > 0.05$; MRR) or less massive black hole ($\chi_2 > 0.05$; non-MRR). We find the following.

First, for the astrophysical population we find that the fraction of binary black holes with at least one black hole spinning lies between 0 and 0.5, whereas for the detectable population this becomes 0–0.25. In other words, we expect that at most 25% of the binary black holes detected by LVK will

contain a black hole that has nonnegligible spin, whereas for the astrophysical population this can reach as high as 50%. The fraction is higher for the astrophysical rate because this population contains a higher fraction of non-MRR systems (Figure 2), which have a higher contribution of spinning black holes compared to MRR systems (Figure 3). Recently, Galaudage et al. (2021)¹² inferred that the fraction of observed binary black holes with nonnegligible spins lies around between 0.25 and 0.71 with a median of 0.46, which is significantly higher compared to the fraction of our models. We note that this is a first-order comparison; to compare properly our simulations with observations we need to take into account underlying assumptions such as our threshold spin of 0.05 and the priors used by Galaudage et al. (2021).

Second, we find that the percentage among the systems with $\chi_i > 0.05$ for which the more (less) massive black hole among the pair is spinning, i.e., $\chi_1 > 0.05$ ($\chi_2 > 0.05$), varies greatly in our models. For the more (less) massive black hole, these ranges span 0%–60% (40%–100%) and 0%–80% (20%–100%) for the astrophysical and detectable populations, respectively. The largest fraction of binary black holes with $\chi_1 > 0.05$ are presented in the models with the optimistic common-envelope assumption (models F and K), where a significant fraction of the MRR binaries form through the classic common-envelope channel (Figure 2). This produces a relative large fraction of binary black holes with $\chi_i > 0.05$ as common-envelope evolution typically shrinks the binary to shorter orbital periods compared to stable mass transfer, allowing for more efficient tidal spin up. Another model assumption leading to a large fraction of systems having $\chi_1 > 0.05$ is model J which assumes an extremely high common-envelope efficiency ($\alpha = 10$), which also results in tighter binaries.

Third, we notice that both the stellar evolution and $\mathcal{S}(Z, z)$ variations can significantly impact the expected fraction of binary black holes with $\chi_i > 0.05$ as well as the fraction of systems with $\chi_1 > 0.05$ or $\chi_2 > 0.05$. For example, within the stellar evolution model with the optimistic common-envelope

¹¹ Where we define in our study “nonnegligible spin” as systems with $\chi_i > 0.05$ to exclude systems with extremely small spin (Section 2.3). Changing this to, e.g., 0.01 or 0.1, did not significantly impact our results (Appendix A.3).

¹² We use the updated fractions quoted in their [erratum](#).

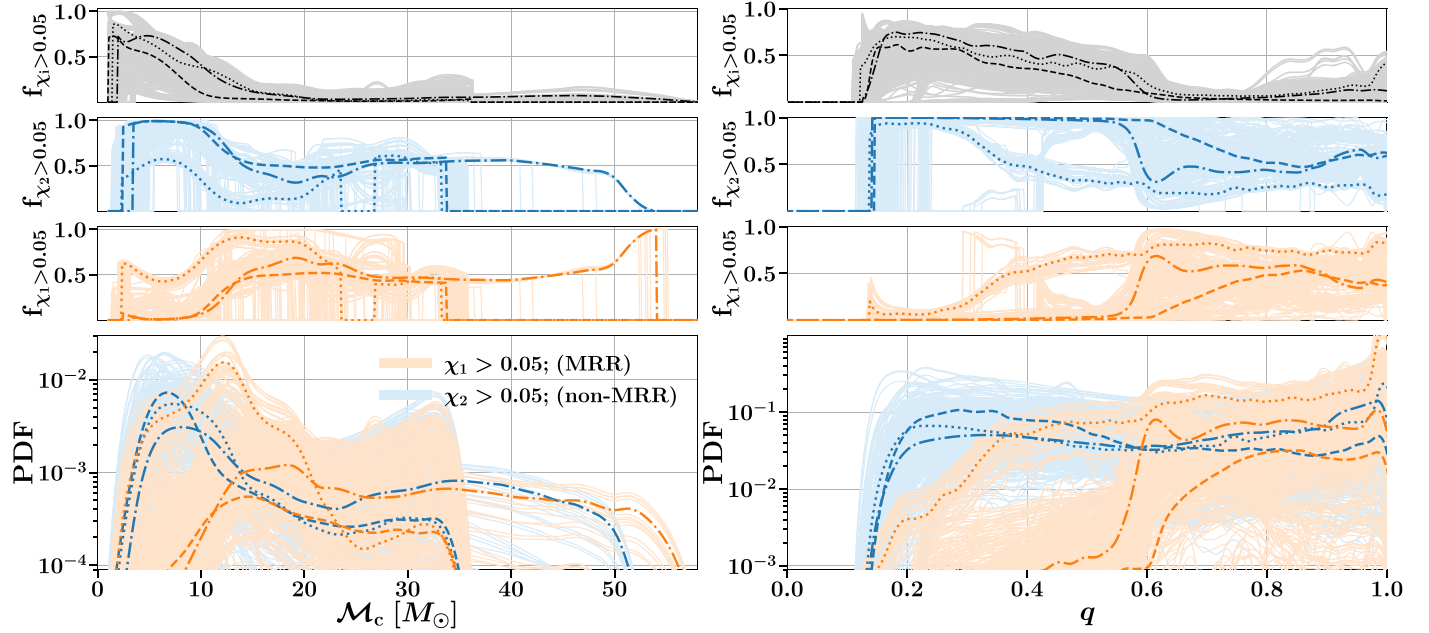


Figure 5. Chirp mass (left panels) and mass ratio (right panels) distributions split up in the subset of systems where the more massive black hole has nonnegligible spin ($\chi_1 > 0.05$; MRR) vs. where the less massive black hole has nonnegligible spin ($\chi_2 > 0.05$; non-MRR). The panels and labels are the same as in Figure 3, but a top panel is added showing the overall fraction of binary black holes with one spinning component ($\chi_i > 0.05$). https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure3_and_Figure5_BBH_properties_MRR_and_nonMRR_Distribution_plots/super_spins_split_2.pdf https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure3_and_Figure5_BBH_properties_MRR_and_nonMRR_Distribution_plots/Make_Figure_3_and_5_Distribution_Plots.ipynb.

assumption (K) the fraction of systems with $\chi_i > 0.05$ varies from 0.2 to 0.4 and 0.05 to 0.25 depending on the chosen $\mathcal{S}(Z, z)$ model for the astrophysical and detectable populations, respectively. The sensitivity of our model realizations to the spin fraction, as well as which black hole is spinning, indicates that improved measurements of spin fractions inferred from future observations could aid in constraining parameters in the stellar and cosmic evolution assumptions within the isolated binary evolution channel.

4.2. Properties of Spinning Binary Black Holes

In the previous section we showed that both the MRR and non-MRR channels can significantly contribute to a subpopulation of binary black holes with nonnegligible spin and that they are identifiable from observations by having nonnegligible χ_1 and χ_2 , respectively. To investigate further the properties of these populations we show the chirp mass and mass ratio distributions for the subset of binary black holes with nonnegligible spin ($\chi_i > 0.05$) for both the subsets for which the spinning black hole is the more massive black hole ($\chi_1 > 0.05$) or the less massive black hole ($\chi_2 > 0.05$) in Figure 5. Overall, we find that as a function of the black hole properties our models allow a wide range of contributions from both channels, see Figure 4. We mention several visible features in the following.

First, as can be seen from the top row panels in Figure 5, our models allow the majority of binary black holes to have nonnegligible spin for systems with $\mathcal{M}_{\text{chirp}} \lesssim 10 M_\odot$ and $q \lesssim 0.4$. For binary black holes with $\mathcal{M}_{\text{chirp}} \gtrsim 10 M_\odot$ or $q \gtrsim 0.4$, on the other hand, the fraction of binary black hole mergers that contain a black hole with spin $\chi_i > 0.05$ rapidly declines. This is because these higher chirp mass or more equal mass ratio systems contain more massive second-born black holes. These more massive second-born black holes form from

a black hole–Wolf Rayet binary with a more massive Wolf–Rayet star and a wider orbit, which disfavor tidal spin up in our model from Bavera et al. (2021), see Section 2.3.

Second, the panels in the second and third row in Figure 5 show the fraction of binary black holes with $\chi_i > 0.05$ where we expect the less massive and more massive black hole to be spinning, respectively. The left panels indicate that we expect for systems with a chirp mass of $\mathcal{M}_{\text{chirp}} \lesssim 10 M_\odot$ in most models $\gtrsim 50\%$ ($\lesssim 50\%$) of the binary black holes with nonnegligible spin to have the less (more) massive black hole m_2 (m_1) spinning, i.e., $\chi_2 > 0.05$ ($\chi_1 > 0.05$). On the other hand, this contribution varies between 0% and 50% (50% and 100%) for systems with a chirp mass $\gtrsim 10 M_\odot$. In all models, except our models that do not allow pair-instability supernovae to occur (O), we do not create binary black holes with $\mathcal{M}_{\text{chirp}} \gtrsim 35 M_\odot$, which creates the steep decline in Figure 5 around this value. In models L we find that for the spinning binary black holes with $\mathcal{M}_{\text{chirp}} \gtrsim 35$ we expect approximately equally that the more or less massive black hole is spinning. For the mass ratio (right panels) we find that only the models with the optimistic common-envelope assumption (F and K) allow a large fraction of MRR binary black holes with nonnegligible spin to contribute significantly at $q \lesssim 0.4$, though these systems remain rare in the overall population (Figure 3). For $q \gtrsim 0.4$ we find that both MRR and non-MRR binaries can significantly contribute to the binary black hole population with a spinning black hole, indicating that we expect to find both systems with $\chi_1 > 0.05$ and $\chi_2 > 0.05$, where the relative contributions depend on the model realization.

Finally, the bottom panels in Figure 5 show the normalized distribution functions of the chirp mass and mass ratio for the subset of binary black holes with a nonnegligible spinning black hole. We find that the chirp mass distribution roughly follows the shape in Figure 3, except that the contribution of

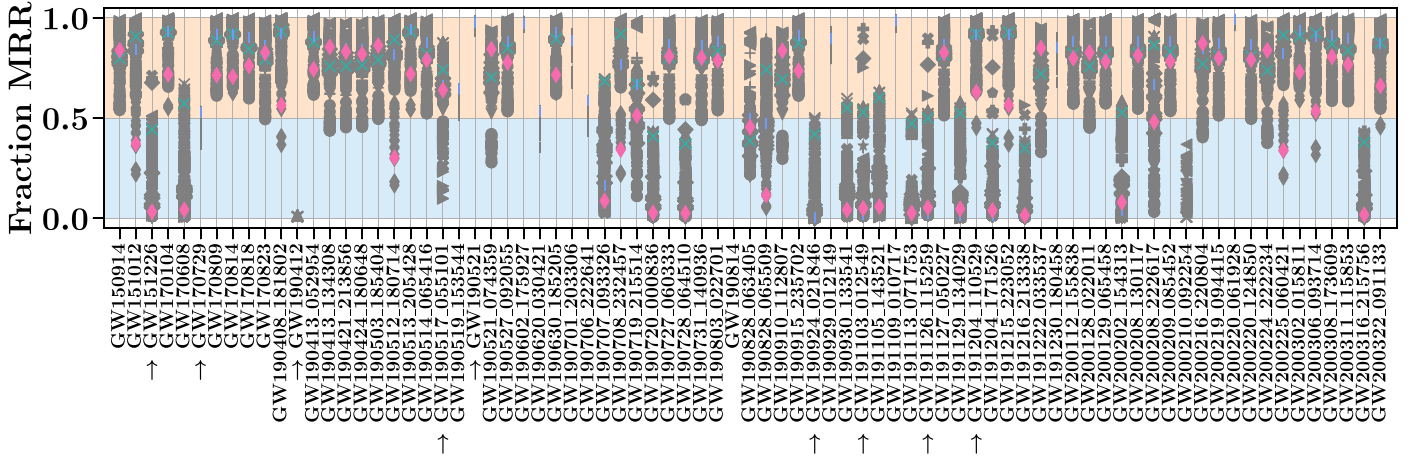


Figure 6. Fraction of binary black hole systems that match the inferred 90% credible contours that are MRR (vs. non-MRR) for the gravitational-wave events from GWTC-1, GWTC-2, and GWTC-3. Arrows indicate the observations that are discussed in the text. Three realizations, “K123”, “O312”, and “T231” (see [Github](https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure6_GW_Ratio_MRR_vs_non_MRR/Rate_allGWs_MRR.pdf)) are highlighted with a cross, vertical line, and diamond marker, respectively. https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure6_GW_Ratio_MRR_vs_non_MRR/Rate_allGWs_MRR.pdf https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure6_GW_Ratio_MRR_vs_non_MRR/fraction_MRR_for_GW_CL.ipynb.

non-MRR binaries are much higher in Figure 5 as a result from the bias toward non-MRR systems for binary black holes with a nonnegligible spin. For the mass ratios we find a much flatter distribution in Figure 5 (compared to Figure 3) as a result that second-born black holes with lower masses are more likely to be spinning, leading to a boost of more extreme mass ratio systems for the non-MRR channel and an overall decrease of the contribution of $q \sim 1$ systems to the spinning population.

5. Discussion

In this section we discuss some of the implications of our models for interpreting gravitational-wave observations.

5.1. Comparison with Observations

The motivation for this work is to explain how MRR affects our interpretation of gravitational-wave signals and to make testable predictions about MRR for gravitational-wave astronomy. We noted in Section 4.2 that among the binary black hole population with nonnegligible spin, for MRR systems χ_1 is spinning (and χ_2 is zero) whereas for non-MRR χ_2 is spinning (and χ_1 is zero). We also found that among the nonnegligible spin population non-MRR binaries are more common (Figure 4), despite MRR binary black holes being more numerous in the overall population (Figure 2). It is possible to measure the magnitudes and directions of black hole spins from their imprint on the observed gravitational waveform. In most cases, the individual spin components are not well constrained, and often a mass-weighted combination of the spins known as the effective inspiral spin parameter χ_{eff} is the best constrained spin parameter.

To give the reader an intuitive feeling for which of the gravitational-wave detections are MRR or non-MRR candidates, we show in Figure 6 the MRR probability for each of the 79 binary black hole sources from the GWTC-1, GWTC-2, and GWTC-3 catalogs (Abbott et al. 2019b, 2021a, 2021b). To do this we first select for each gravitational-wave detection all binary black hole samples in our model realizations that have a total mass, chirp mass, mass ratio, individual masses, and effective spins that fall inside the inferred 90% credible intervals from LVK. We then determine the ratio of the weight of the MRR versus non-MRR samples that match each

gravitational-wave credible interval.¹³ In addition, in Figures 7 and 8 we show two-dimensional slices of the MRR and non-MRR binary black hole properties overlaid with the credible contours of several gravitational-wave observations. We discuss our results in light of some of the most relevant events below.

Overall, we find that the likelihood that a gravitational-wave source is MRR is strongly model dependent, as can be seen by the large variation per event in Figure 6. This results from the overlap in binary black hole properties between MRR and non-MRR in our simulations (as shown in Figures 7 and 8), the broad variety in MRR contributions to the detectable population already shown in Figures 2 and 4, as well as the large uncertainties in many of the inferred credible intervals. GW191204_110529 is an example of a system with one of the highest MRR fractions ($\gtrsim 0.5$) in Figure 6 for all model realizations, making it a likely MRR candidate due to its total mass around $m_{\text{tot}} \sim 50 M_{\odot}$. On the other hand, GW190924_021846 is a system with one of the lowest MRR fractions ($\lesssim 0.5$) making it a likely non-MRR candidate due to its lower total mass $m_{\text{tot}} \sim 14 M_{\odot}$ (see Figure 7).

The earliest example of a binary black hole showing evidence for a highly spinning component was GW151226 (Abbott et al. 2016), the second binary black hole merger to be observed. Abbott et al. (2016) found that GW151226 originated from a binary black hole merger with a total mass of around $22 M_{\odot}$, and at least one of the component black holes had a spin greater than 0.2. Abbott et al. (2019a) find GW151226 to have a mass of the more massive black hole of $m_1 = 13.7^{+8.8}_{-3.2} M_{\odot}$, a mass of the less massive black hole of $m_2 = 7.7^{+2.2}_{-2.5} M_{\odot}$, and an effective spin of $\chi_{\text{eff}} = 0.18^{+0.20}_{-0.12}$. Its individual spin components are less well constrained to $\chi_1 = 0.69^{+0.28}_{-0.55}$ and $\chi_2 = 0.50^{+0.28}_{-0.45}$ (see also Biscoveanu et al. 2021). Subsequent reanalyses have utilized gravitational

¹³ We note that this method of calculating the ratio between MRR and non-MRR is adhoc and does not take into account the more complex weighting of the posterior distributions (or likelihoods) for the gravitational-wave events detected by LVK. We do this to get a rough feeling of whether MRR or non-MRR binaries dominate in a box in the parameter space around the gravitational-wave events. A more detailed study is outside of the scope of this work. We did test that our choice of 90% credible intervals (i.e., which parameters we choose to mask in) did not significantly impact our results.

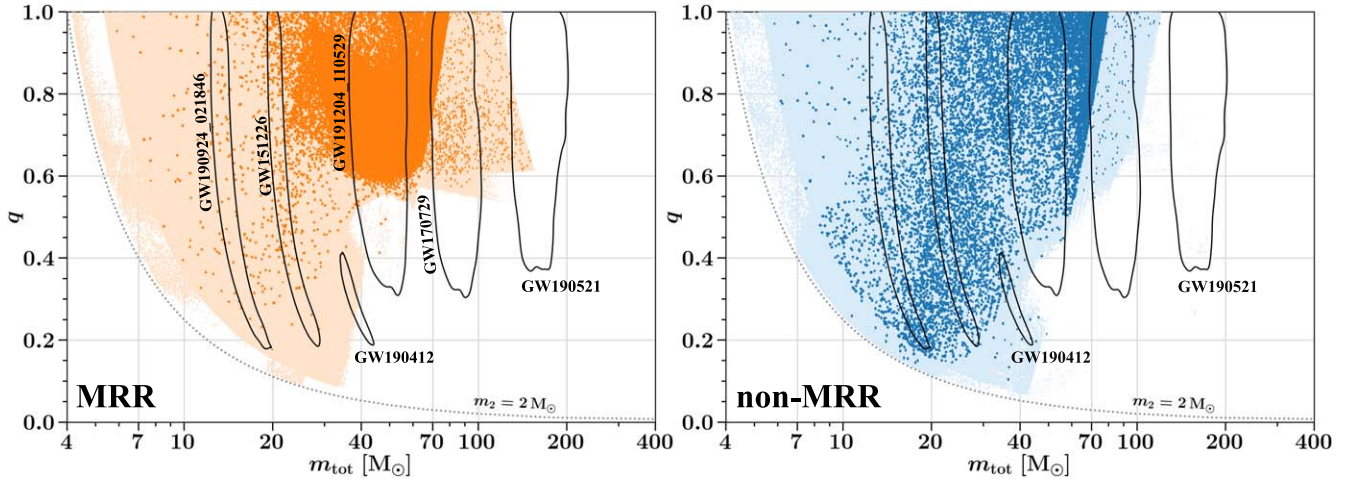


Figure 7. Total mass and mass ratio for MRR (left panel) and non-MRR (right panel) binary black holes in all our combined 560 model realizations. We draw from each model realization 100 binary black holes between the combined MRR and non-MRR populations and show these with a darker hue to visualize the density of points. The 90% credible contours for six gravitational-wave events that are discussed in the text are also shown. https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_7_and_8_and_9_and_10_Discussion_2D_slices/Mtot_vs_q_all_models_all_pointsallNonMRR.png https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_7_and_8_and_9_and_10_Discussion_2D_slices/Make_2D_scatter_Distributions.ipynb.

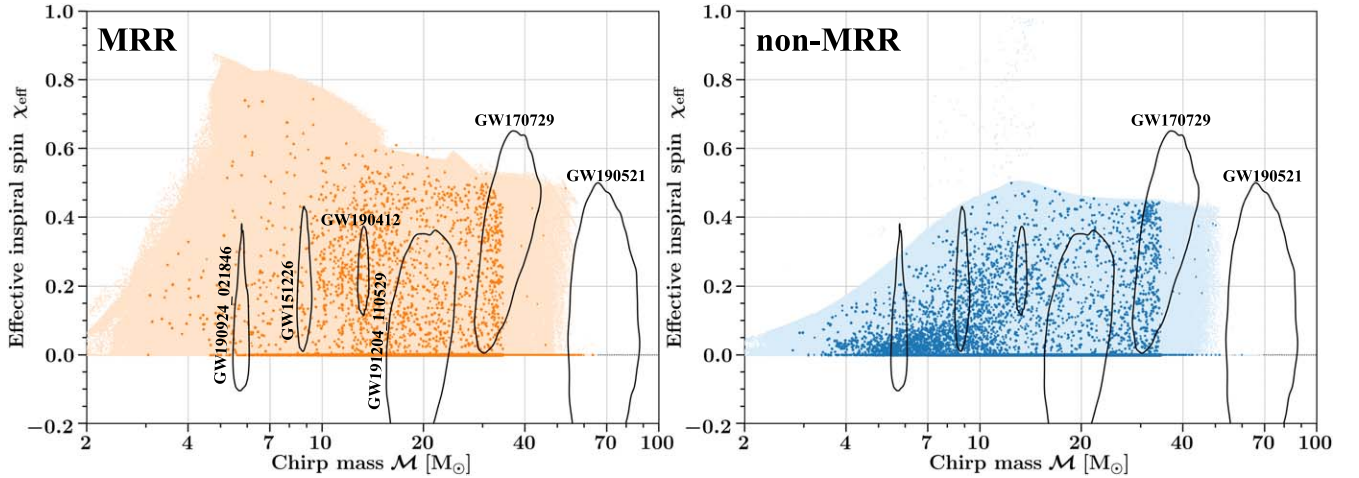


Figure 8. Same as Figure 7 but for the chirp mass and effective spin. https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_7_and_8_and_9_and_10_Discussion_2D_slices/ChiEff_vs_q_all_models_all_pointsallNonMRR.png https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_7_and_8_and_9_and_10_Discussion_2D_slices/Make_2D_scatter_Distributions.ipynb.

waveforms including the contributions of higher-order modes (Chia et al. 2022; Nitz et al. 2021). These analyses found evidence that GW151226 may have had more asymmetric masses than previously thought. However, Mateu-Lucena et al. (2021) argue that these results arise primarily from issues with the sampling of the posterior distribution, though Vajpeyi et al. (2022) deliver a mixed verdict, finding roughly equal support for the low- q and high- q hypotheses. In addition to the technical challenge of sampling the posterior distribution, constraints on black hole spins can also vary significantly depending on the choice of prior assumptions (Vitale et al. 2017a; Zevin et al. 2020). In the full sample of observed binary black holes, there are now several examples of binaries with similar parameters to GW151226, such as the just marginal events GW191103_012549 and GW191126_115259 (Abbott et al. 2021b). The relatively high spins and low masses of GW151226-like events are broadly consistent with our models and can be explained by both an MRR and non-MRR formation, with the non-MRR being (strongly) favored with an MRR fraction of $\lesssim 0.5$ for most of our model

realizations in Figure 6 for GW151226, GW191103_012549, and GW191126_115259, as can also be seen from the location of the GW151226 contour in Figures 7 and 8.

There also appears to be a class of more massive binary black holes with large positive effective spins. This includes the event GW170729 from GWTC-1 (Abbott et al. 2019a). The mass properties of these events are only consistent with systems in our simulations in the models that do not assume a pair-instability mass gap (models O), as can be seen from Figure 3. A particularly intriguing event from GWTC-2 is GW190517_055101 (Abbott et al. 2021a), which has a total mass of $63.5^{+9.6}_{-9.6} M_{\odot}$ and an effective spin of $\chi_{\text{eff}} = 0.52^{+0.19}_{-0.19}$. This matches events for both MRR and non-MRR systems in our simulations.

In binary black holes with a mass ratio that can be confidently measured away from unity, the dominant contribution to the effective spin comes from the spin of the more massive black hole, χ_1 , allowing it to be precisely constrained. One such event is GW190412 (Abbott et al. 2020a), inferred to

be from a binary black hole merger with component masses of $m_1 = 30.1^{+4.6}_{-5.3} M_\odot$ and $m_2 = 8.3^{+1.6}_{-0.9} M_\odot$, constraining the mass ratio to $q = m_2/m_1 = 0.28^{+0.12}_{-0.07}$ (all values quoted at 90% confidence), confidently excluding an equal mass binary. For GW190412, the effective inspiral spin was measured to be $\chi_{\text{eff}} = 0.25^{+0.08}_{-0.11}$, constraining the spin of the more massive black hole to $\chi_1 = 0.44^{+0.16}_{-0.22}$, suggesting the presence of a rapidly rotating more massive black hole.

Mandel & Fragos (2020) argued for an alternative interpretation in which the more massive black hole in GW190412 was non-spinning, but the less massive black hole was rapidly spinning. This was motivated by models of isolated binary evolution in which the second-born black hole can be tidally spun up in a tight binary, as described above.

Zevin et al. (2020) later challenged the interpretation of Mandel & Fragos (2020). They systematically analyzed the gravitational-wave data for GW190412 under an array of different prior assumptions regarding the black hole spins. They examined which spin priors were preferred by the data by calculating the Bayesian evidence under each prior. They showed that a binary configuration allowing for a spinning more massive black hole was mildly preferred over the case in which the more massive black hole was non-spinning, in agreement with Abbott et al. (2020a), and disfavoring the prior preferred by Mandel & Fragos (2020).

In terms of the chirp mass, for binary black holes with chirp masses similar to that of GW190412 ($\sim 13 M_\odot$) MRR is common ($f_{\text{MRR}} \gtrsim 30\%$, Figure 3). However, in our models, merging binary black holes with mass ratios of $q < 0.5$ are uncommon at any chirp mass (see Figure 3), implying that an isolated binary evolution origin for GW190412 is unlikely (though see Olejak et al. 2020, who find that $\sim 10\%$ of merging binary black holes have a mass ratio of $q < 0.4$ in their model). Indeed, only in our simulations that assume the optimistic common-envelope prescription (models F and K) do we find systems matching GW190412. If GW190412 was formed through isolated binary evolution, our models suggest that MRR is unlikely ($f_{\text{MRR}} \lesssim 10^{-2}$) for binary black holes with such asymmetric masses (Figure 3). This supports the arguments of Mandel & Fragos (2020), and makes the findings of a highly spinning more massive black hole (Abbott et al. 2020a; Zevin et al. 2020) difficult to understand through this channel. Several alternate explanations for the origin of GW190412 have been proposed, such as dynamical formation in a dense star cluster (Di Carlo et al. 2020) including the possibility that the more massive black hole is the product of a previous black hole merger (Gerosa et al. 2020; Rodriguez et al. 2020; Liu & Lai 2021).

Other examples of similar binaries may include GW190403_051519 (Abbott et al. 2021c; Qin et al. 2022),¹⁴ a binary black hole with a mass ratio of $q = 0.25^{+0.54}_{-0.11}$ and a more massive black hole spin of $\chi_1 = 0.92^{+0.07}_{-0.22}$. Qin et al. (2022) argued that the observation of such rapidly spinning black holes may indicate that the efficiency of angular momentum transport in massive stars is much weaker than otherwise argued. However, the more massive component of GW190403_051519, with a mass of $m_1 = 88.0^{+28.2}_{-32.9} M_\odot$, lies in the pair-instability mass gap, which is not expected to be

populated in the isolated binary evolution channel (Fowler & Hoyle 1964; Farmer et al. 2019; Stevenson et al. 2019), and which only our model without a pair-instability supernova implemented (model O) produces. This may suggest that a second-generation black hole is a plausible explanation for the more massive black hole in this system. The system GW190521 (Abbott et al. 2020b, 2020c) is very similar and we find that only our model without pair-instability supernovae implemented produces such systems, in which case it is likely an MRR system (Figure 6).

In addition, recently it has been argued that the binary black hole observations by LVK suggest a possible anticorrelation between the mass ratio q and the effective inspiral spin parameter χ_{eff} , such that more extreme mass ratios have higher effective spins (Abbott et al. 2021b; Callister et al. 2021). We find hints of a similar correlation for the MRR binary black holes in most of our model realizations, particularly those that assume the optimistic common-envelope prescription as shown in Figure 9 (though our overall rate of extreme mass ratio events remains low). However, the non-MRR binary black holes in the simulations, which typically dominate the systems with nonnegligible spin, do not show this correlation. This is because the effective spin is a mass-weighted spin parameter such that for extreme mass ratios it is dominated by the spin of the most massive black hole, χ_1 . In the MRR case χ_1 is nonnegligible and χ_2 is zero, which can lead to high effective spins for extreme mass ratios similar to the observed anticorrelation. On the other hand, in non-MRR systems χ_2 is nonnegligible and χ_1 is zero, resulting in lower spins for extreme mass ratios and the opposite correlation.

Lastly, recently several authors have suggested the existence of redshift evolution in the binary black hole (effective) spin distribution, finding at higher redshifts both a larger fraction of binary black holes with nonnegligible spin and a broadening in the black hole spin magnitude distribution (Bavera et al. 2022; Biscoveanu et al. 2022). This positive spin-redshift correlation matches the expected behavior in our model assumptions. In our simulations, black holes dominantly spin up through tides (see Qin et al. 2018; Bavera et al. 2021) such that binaries with smaller separations at the black hole–Wolf Rayet phase are more commonly spun up and have stronger black hole spins. At the same time, the shorter separations also result in significantly smaller delay times between the formation of the binary black hole and its merger (Peters 1964). This leads to binary black hole systems with shorter delay times to also have higher spins, as shown for our simulations in Figure 10 (see Qin et al. 2018). At higher redshifts the binary black hole population has a larger contribution from systems with shorter delay times (which have already merged at lower redshifts and cannot contribute to this population). Together, the above leads to a redshift evolution in the spin distribution of binary black hole systems. To understand the redshift behavior in more detail it is important to also include many other uncertainties in the assumptions of the spins, stellar evolution, and star formation history, which is outside of the scope of this study.

5.2. Comparison with other Formation Channels

Our work studied the isolated binary evolution channel, but other channels to form binary black hole mergers have been proposed in the literature (see Mandel & Farmer 2022 for a recent review). We compare our results to the main alternative formation channels below.

¹⁴ GW190403_051519 is not shown in Figure 6 as it is an event from the GWTC-2.1 catalog with a false alarm rate below 1 yr^{-1} , which we did not include.

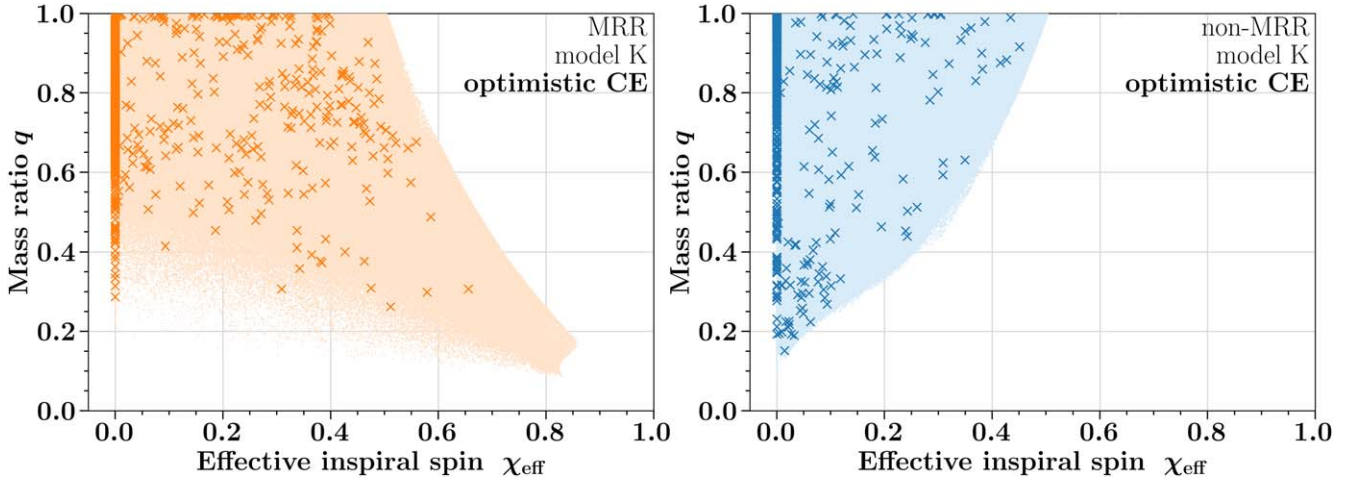


Figure 9. Same as Figure 7 but for the effective spins and mass ratios for our model with the optimistic common-envelope prescription (model K). There is an anticorrelation present in the MRR binaries (left panel), but the opposite behavior is visible in the non-MRR binaries (right panel). For each of the 28 star formation history combinations we draw 1000 samples (combined over MRR and non-MRR) that we highlight with larger markers. The other stellar evolution models are shown on GitHub. https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_7_and_8_and_9_and_10_Discussion_2D_slices/individual_ChiEff_vs_q/ChiEff_vs_q_all_models_all_points_K.png https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_7_and_8_and_9_and_10_Discussion_2D_slices/Make_2D_scatter_Distributions.ipynb.

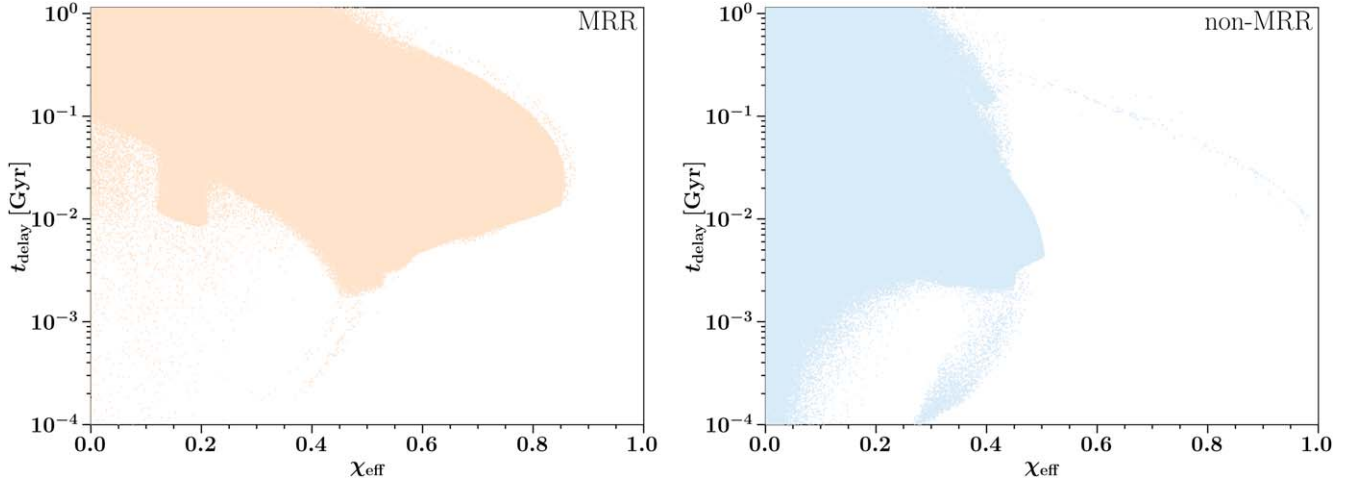


Figure 10. Effective spin and delay time for MRR (left) and non-MRR (right) binary black holes in our 20 stellar evolution simulations. Convolution of the delay times with a metallicity-specific star formation history ($S(Z, z)$) provides the binary black holes as a function of redshift. There is an anticorrelation present where binary black holes with larger effective spins have shorter delay times, which is particularly visible in the MRR panel. We provide the same figure for each model separately at GitHub. https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_7_and_8_and_9_and_10_Discussion_2D_slices/ChiEff_vs_tdelay_2Dplot_priorWeighted_not_drawing.png https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_7_and_8_and_9_and_10_Discussion_2D_slices/Make_2D_scatter_Distributions.ipynb.

First, we did not consider the chemically homogeneous evolution pathway (Mandel & de Mink 2016; Marchant et al. 2016; Riley et al. 2021). Binaries formed through chemically homogeneous evolution are expected to have high black hole masses around $M \gtrsim 20 M_{\odot}$, mass ratios close to unity, and both components may be rapidly spinning (Marchant et al. 2016). Among the population of binary black holes with nonnegligible spin, a system might thus be particularly distinguishable from the systems studied in this paper by having both nonnegligible χ_1 and χ_2 in combination with $q \sim 1$. Typically, the contribution from chemically homogeneous evolution to the binary black hole population is expected to be small (e.g., Mandel & Broekgaarden 2022).

Second, binary black holes may originate from dynamical interactions in dense stellar environments such as globular and open clusters. Binary black holes formed in star clusters are

expected to have an isotropic distribution of spins (e.g., Rodriguez et al. 2016). Black holes born in star clusters likely have small spins ($\chi \sim 0$) for similar reasons to those discussed above, with the exception of a small fraction of black holes formed through previous black hole mergers, which are expected to have high spins, $\chi \sim 0.7$ (e.g., Gerosa & Fishbach 2021). This channel is expected to produce a significant fraction of binary black holes with misaligned spins, which would make such systems distinguishable from the systems expected in our study.

Alternatively, binary black holes assembled in active galactic nuclei have been suggested to have spins with the more massive component spinning as a result from spherical and planar symmetry-breaking effects (e.g., McKernan et al. 2021). They particularly showed that this can result in the mass ratio– $\chi_{\text{effective}}$ correlation that LVK seems to observe, though

the contribution that this channel can have to the overall binary black hole population is still under debate.

5.3. Neutron Star–Black Hole Binaries

In this paper we have focused on predictions for the masses and spins of binary black holes formed through isolated binary evolution involving a phase of MRR. Similar evolutionary scenarios to those shown in Figure 1 can also occur at lower masses and produce neutron star–black hole binaries, where the (more massive) black hole is formed second (Broekgaarden et al. 2021; Chattopadhyay et al. 2021; Hu et al. 2022). In the context of radio astronomy, this can be important for determining if the neutron star can be born first and recycled (Chattopadhyay et al. 2021). Broekgaarden et al. (2021) calculated f_{MRR} for merging black hole–neutron star binaries using the same set of models used here. They found that in most of these models, the neutron star is born first in less than 1% of cases. In model D (high mass transfer efficiency) and H (optimistic CE) this rises to around 10% of cases. The dramatic difference between neutron star–black holes and binary black holes arises due to their different evolutionary pathways (Broekgaarden et al. 2021).

This suggests that the black hole almost always formed first in neutron star–black hole binaries, and thus, by the arguments given earlier, would be expected to be almost nonrotating. This supports the alternative interpretation of the neutron star–black hole binary GW200115 (Abbott et al. 2021d) by Mandel & Smith (2021), in which they argued that the black hole was consistent with being non-spinning.

5.4. Eddington-limited Accretion

We have assumed the spin of the firstborn black hole to be zero. This is justified by our assumption of Eddington-limited accretion onto compact objects, which limits the amount of mass accreted by black holes and therefore the accretion-induced spin up. It is possible that some mechanism exists to overcome the Eddington limit in these systems. Allowing for super-Eddington accretion rates onto black holes could allow for greater amounts of accretion, and thus spin up of firstborn black holes. Super-Eddington accretion is assumed by default in the BPASS models (Eldridge et al. 2017). van Son et al. (2020) investigated super-Eddington accretion using COM-PAS. They found that super-Eddington accretion did not strongly impact the occurrence of MRR, but can significantly increase the masses of the firstborn black holes (see their Figure 1), although in many of these systems, the assumption of conservative mass transfer causes the orbit of the binary to widen significantly, such that these binaries no longer merge within the age of the universe. Bavera et al. (2021) similarly found that allowing for highly super-Eddington accretion almost completely removes the contribution of the stable mass transfer channel, as conservative mass transfer is not as effective at reducing the orbital separation of the binary as the typically highly nonconservative mass transfer that occurs during Eddington-limited accretion. Zevin & Bavera (2022) also consider highly super-Eddington accretion during case A mass transfer onto a black hole and find that it can produce firstborn black holes with significantly higher spins (see also Shao & Li 2022).

5.5. Inferring the Fraction of Binary Black Holes Having Undergone MRR from Observations

The predictions presented here can be used to inform the construction of phenomenological population models that take into account MRR. These phenomenological models can then be used to analyze the observed population of binary black hole mergers (see Abbott et al. 2021e).

Most phenomenological models for the spin distribution of binary black holes currently in use assume that the spins of both components are drawn from the same distribution (Talbot & Thrane 2017; Wysocki et al. 2019; Abbott et al. 2021e; Galadage et al. 2021), a decision motivated by the desire to limit the number of free parameters in the model, though see Biscoveanu et al. (2021) for an example of an analysis that does not make this assumption. A key feature of our model is that in some fractions of systems, the more massive black hole is spinning ($\chi_1 > 0$), while the less massive black hole is non-spinning ($\chi_2 = 0$). Conversely, there is also a subpopulation where the less massive black hole is spinning ($\chi_2 > 0$) and the more massive black hole is non-spinning ($\chi_1 = 0$). In the majority of systems ($\sim 80\%$) both black holes are non-spinning ($\chi_1 = \chi_2 = 0$). Except for special cases, such as binary black holes formed through double core common-envelope phases (Neijssel et al. 2019; Broekgaarden et al. 2021; Olejak & Belczynski 2021) or chemically homogeneous evolution (Marchant et al. 2016), we do not expect both black holes to have significant spins. For the subpopulation of spinning black holes, the distribution is not robustly predicted by our models (see the variation in the right-hand panel of Figure 3). Regardless, one could use this figure to derive a flexible parametric model to describe the distribution of black hole spin magnitudes. Such a phenomenological model should separately model the spin distribution of the more massive (χ_1) and the less massive (χ_2) black holes.

By determining the fraction of observed binary black holes in which the more massive one is spinning ($\chi_1 > 0$), one can place a lower limit on the fraction of binaries that have undergone MRR (f_{MRR}). Similarly, a constraint on the fraction of systems in which the less massive black hole is spinning ($\chi_2 > 0$) allows one to place an upper limit on f_{MRR} , though we expect that in practice this constraint will be weaker, as it is typically difficult to constrain the spin magnitude of the less massive black hole (Abbott et al. 2021b). Unfortunately, it may be difficult to link directly the fraction of observed binary black holes with $\chi_1 > 0$ to the true fraction of binaries that have undergone MRR (f_{MRR}), since we have shown that in many binary black holes formed through MRR, both components are effectively non-spinning. In our models, the former fraction is typically only around 5%, while f_{MRR} is around 70% (see Figure 4). Binary population synthesis models such as those presented in this work may help bridge this gap.

Not only would constraining f_{MRR} observationally provide insight into the order in which the black holes formed, it is also closely linked to the fraction of binary black holes formed through only stable mass transfer, instead of common-envelope evolution (see Figure 2). Hence, a robust measurement of f_{MRR} could also provide insights into the formation pathways of binary black holes formed through massive binary evolution.

5.6. Comparison with Predictions from other Population Synthesis Codes

We now briefly compare and contrast our key results with previous studies of binary black hole formation and MRR. One

of the first population synthesis papers to study MRR in binary black hole mergers was done by Gerosa et al. (2013) who focused on the implications of MRR in binary evolution for the precession of black hole spins in binary black holes using a suite of population synthesis models from Dominik et al. (2012). These models predict f_{MRR} in the range 0.1–0.4, with a strong dependence on metallicity. Compared to Gerosa et al. (2013), we added new models and implement the contributions from different metallicities according to the metallicity-specific star formation history, accounting also for gravitational-wave selection effects.

Gerosa et al. (2018) use an updated version of the models from Gerosa et al. (2013), accounting for gravitational-wave selection effects. For moderate black hole kicks, roughly one third of the binary black holes formed through common-envelope evolution in their models undergo MRR (see their Figure 3 and associated discussion). At least part of the discrepancy between the results of Gerosa et al. (2018) and the present work can be attributed to different assumptions regarding the stability and efficiency of mass transfer (see Belczynski et al. 2022 for further discussion).

Olejak & Belczynski (2021) studied the formation of binary black holes with high effective spin parameters through isolated binary evolution. They show an example of a MRR binary black hole forming through stable mass transfer (see their Figure 1) in which the more massive black hole is rapidly rotating as a result of tidal spin up, and also discuss that a fraction of detectable binary black holes is expected to have (significant) spin. However, Olejak & Belczynski (2021) do not quantify how common MRR is in their models, nor how robust that prediction is under variations of the underlying binary evolution physics; these are the main goals of the present work.

Recently, Zevin & Bavera (2022) also studied MRR in isolated binary evolution; their work complements our own and reinforces our findings. In general, there is fairly good agreement between the two studies, with the largest differences arising due to different choices for the fiducial binary evolution model (e.g., the mass transfer efficiency). Our models explore a wider range of uncertainties in the cosmic star formation history than explored by Zevin & Bavera (2022), while they explore a wider range of accretion efficiencies for compact objects, and explore models where multiple assumptions are varied from the fiducial assumption at once (something we have not done, with the exception of model F). Across their suite of models, Zevin & Bavera (2022) find that more than 40% of binary black holes have undergone MRR for mass transfer accretion efficiencies of $\beta > 0.5$ (with all other parameters at their fiducial values), with this fraction increasing with the assumed efficiency of mass transfer (as we also find in our models B, C, and D; see Figure 2). Our default model translates to a relatively high mass transfer efficiency (as can be seen from Figure 1), and this likely explains why our results are toward the high end of those found by Zevin & Bavera (2022). They also find that in MRR systems, the mass of the more massive black hole is rarely greater than twice the mass of the less massive black hole, again in broad agreement with our findings.

6. Conclusions

In this paper we investigated the occurrence of MRR, where the more massive black hole is second-born, in the population of merging binary black holes originating from isolated

massive binary stars. Using a large set of state-of-the-art population synthesis models from Broekgaarden et al. (2021) we investigate the rate and properties of MRR binary black hole mergers. We discuss that MRR in binary black hole systems can have important observational consequences as the second-born black hole can be tidally spun up if the orbital period of the binary is short enough, while the firstborn black hole is assumed to be non-spinning, which we model following Qin et al. (2018) and Bavera et al. (2020). This introduces the possibility of the more massive black hole in a merging binary black hole system being rapidly rotating. Our main findings are summarized below.

1. We find that typically more than 70% of observed binary black holes have undergone MRR in most of our models (Figure 2). I.e., we expect that for the majority of observed binary black hole mergers the most massive black hole component was born second.
2. We find in Figure 3 that MRR systems particularly dominate the binary black hole detections for larger chirp masses ($\gtrsim 10 M_{\odot}$) and larger mass ratios ($q \gtrsim 0.6$, with a peak of around $q \sim 0.7$). Non-MRR systems, on the other hand, dominate the binary black hole population for $\mathcal{M}_{\text{chirp}} < 10 M_{\odot}$ and $q < 0.6$.
3. We show in Figure 4 that our models predict up to 25% of detectable binary black holes contain a component with nonnegligible spin. Among this nonnegligible spin population, we find that the fraction of systems with nonnegligible spin in which the more (less) massive black hole among the pair is spinning varies greatly in our models. We expect the more (less) massive black hole to be spinning in 0%–80% (20%–100%) of the detectable nonnegligible spin population.
4. For the subset of spinning binary black holes, we investigated which component we expect to be spinning as a function of chirp mass and mass ratio. We found that overall our model realizations allow both the more massive (MRR) as well as the less massive black hole to be spinning (non-MRR) as a function of chirp mass and mass ratio values (Figure 5). For mass ratios below $q \lesssim 0.4$, however, we expect the less massive black hole to dominate the spin population in all models.
5. We discussed our results in the context of the current population of binary black hole mergers in Section 5.1 and found that candidates for MRR systems include GW191204_110529 and similar binaries, whereas we find that binaries such as GW151226 and GW190412 (Abbott et al. 2020a) are unlikely to have undergone MRR based on their total mass and mass ratio properties (Figures 6, 7, and 8).
6. We discussed in Section 5.1 that our MRR binaries do show hints of the observed anticorrelation between mass ratio and effective spin (Figure 9), but that in the overall population the binary black holes with nonnegligible spins are dominated by non-MRR binaries.

Overall, our results highlight that a significant fraction of the observed binary black hole mergers might have undergone MRR such that the more massive black hole in the system formed second. We expect to identify these systems by mergers where the more massive black hole has nonnegligible spin. Future observations will test our findings and help investigate stellar evolution assumptions.

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Data Availability and Software: The authors made use of the binary black hole simulations from (Broekgaarden et al. 2022), which are publicly available at Broekgaarden (2021). All code to reproduce the results and (additional) figures in this paper are publicly available on GitHub at https://github.com/FloorBroekgaarden/MRR_Project https://github.com/FloorBroekgaarden/MRR_Project; a copy of these materials was deposited on Zenodo: doi:10.5281/zenodo.6978990. In addition, a link to the specific Jupyter notebook to recreate a figure is provided in each figure caption.

The authors made use of PYTHON from the Python Software Foundation. Python Language Reference, version 3.6. Available at <http://www.python.org> (van Rossum 1995). In addition the following Python packages were used: MATPLOTLIB (Hunter 2007), NUMPY (Harris et al. 2020), SCIPY (Virtanen et al. 2020), ipython/jupyter (Perez & Granger 2007; Kluyver et al. 2016), PANDAS (McKinney 2010), SEABORN (Waskom & the seaborn development team 2020), ASTROPY (Astropy Collaboration et al. 2018), and HDF5 (Collette 2013).

In addition, we used the posterior samples for the events from the GWTC-1, GWTC-2, and GWTC-3 catalogs provided by the Gravitational Wave Open Science Center (<https://www.gw-openscience.org/>), a service of LIGO Laboratory, the LIGO Scientific Collaboration and the Virgo Collaboration. LIGO Laboratory and Advanced LIGO are funded by the United States National Science Foundation (NSF) as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck-Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. Virgo is funded, through the European Gravitational Observatory (EGO), by the French Centre National de Recherche Scientifique (CNRS), the Italian Istituto Nazionale di Fisica Nucleare (INFN) and the Dutch Nikhef, with contributions by institutions from Belgium, Germany, Greece, Hungary, Ireland, Japan, Monaco, Poland, Portugal, Spain. This research has made use of NASA’s Astrophysics Data System Bibliographic Services.

Appendix

A.1. Zooming in on Some of the Model Variations

Three sets of stellar evolution models particularly stand out because of their MRR rates presented in Figure 2. First, model B (which assumes a low mass transfer efficiency, β , arbitrarily fixed to $\beta = 0.25$) predicts one of the lowest MRR fractions of $f_{\text{MRR}}^{\text{det}} \approx 0.5$ and $f_{\text{MRR}}^0 \approx 0.4$ in Figure 2. In these models the accreting star can at most accept 25% of the mass from the donating star during a stable mass transfer phase. This mostly affects the first mass transfer phase as typically the second, reversed, mass transfer phase involves a compact

object and is assumed to be Eddington-limited. In our fiducial simulations the accretion efficiency instead is determined by the thermal timescale of the accretor (Team COMPAS et al. 2022), which, for the binary black holes in our simulation, typically leads to almost fully conservative $\beta \approx 1$ mass transfer in the first mass transfer phase in the majority of our binary black hole progenitors (see Figure 1). In model B, the low β significantly reduces the total amount that the initially less massive star accretes in our simulations. As a result the initially less massive star becomes less massive and the chance of MRR is reduced. Indeed, for increasing β (models B, C, and D), we find an increasing fraction of MRR. The low mass transfer efficiency particularly lowers the stable mass transfer channel as this channel produces more of the near equal mass binary black hole mergers that can be MRR in our fiducial model, but does not produce a massive enough secondary in the $\beta = 0.25$ simulations. Instead, there is a visible rise from the “other” channel, which is mostly coming from systems where the more massive initiates the first mass transfer phase on the main sequence, which is a slower mass transfer phase and therefore allows more overall mass accretion. We note also that several studies have argued for the possibility of very nonconservative mass transfer, corresponding to β values below our lowest assumed value of $\beta = 0.25$ (e.g., Petrovic et al. 2005; de Mink et al. 2009; Shao & Li 2016). If this is the case (almost) no mass can be transported to the accretor star and the MRR fraction would drop toward zero (see Zevin & Bavera 2022). Future work should further investigate this. For the interested reader, we provide example plots comparing the impact from the mass transfer efficiency assumption (models A, B, C, and D) on the mass evolution of binary black hole progenitors on our GitHub. Second, a subset of the models with strong Wolf–Rayet wind factors of $f_{\text{WR}} = 5$ (model T) also have low MRR fractions of $f_{\text{MRR}}^{\text{det}} \approx 0.4$ and $f_{\text{MRR}}^0 \approx 0.11$, as shown in Figure 2. The models with $f_{\text{WR}} = 5$ increase the mass loss through stellar winds during the Wolf–Rayet phase by a factor 5 compared to our fiducial model (A). As a result, the more massive star loses more mass during its Wolf–Rayet phase in model T and thus the star has a lower mass when it finally undergoes a supernova. These lower mass stars are expected to produce larger amounts of ejecta during the supernova (or equivalently, have a lower fallback fraction) in the delayed Fryer et al. (2012) supernova prescription implemented in all COMPAS simulations presented here (except for model L). These lower mass stars also receive higher supernova natal kicks as the kicks are scaled down with the fallback fraction in the delayed prescription. This difference in kicks is particularly noticeable for the formation of MRR binary black holes at higher (solar-like) metallicities as at lower metallicities the stars in both the fiducial model and the increased Wolf–Rayet factor model are typically massive enough ($\gtrsim 11 M_{\odot}$; see also Fryer et al. 2012; van Son et al. 2022) to receive (almost) complete fallback. For the higher metallicities case, on the other hand, the majority of binaries that in the fiducial model form a binary black hole, disrupt during the first supernova as a result of the larger kicks in the models with large values of f_{WR} . This drastically reduces the number of MRR systems at high metallicities as the MRR systems typically have primaries with low pre-supernova masses that then receive these higher supernova natal kicks. As a result, particularly the $S(Z, z)$ models that form many stars with high average metallicities have much lower MRR fractions. The same models also have

significantly lower binary black hole merger rates, that fall below the currently observed rate as inferred from the third gravitational-wave catalog as shown earlier by Broekgaarden et al. (2021) (their Figure 2).

Third, the models that assume the so-called “optimistic” common-envelope prescription (models F and K) stand out in Figure 2 as the classic common-envelope channel contributes significantly to the MRR fraction. In this channel HG donor stars that engage in a common-envelope phase are allowed to survive (in the default “pessimistic case” such systems are assumed to undergo a merger). This assumption significantly increases the total amount of binary black hole mergers by adding systems that go through the common-envelope channel. A fraction of these systems undergo MRR (in the first mass transfer), also increasing (decreasing) the relative fraction of MRR from the common-envelope channel (only stable mass transfer) channel.

We provide for the interested reader example plots showing the impact on the mass evolution of several binary black hole progenitors for the majority model variations discussed in this section (models A, B, C, D, and T) on our [GitHub](#). We do not include the optimistic common-envelope models (F and K) as in these simulations binary black hole systems are added rather

than that the evolution pathway is changed (see also Broekgaarden et al. 2021).

A.2. MRR Binary Black Hole Properties at Birth

In Figure 11 we show cumulative distributions of the initial properties of massive binaries that go on to form merging binary black holes. In particular, we show the distributions for the more massive mass, the binary mass ratio, and the orbital separation and split this up for MRR and non-MRR systems. For each parameter, we additionally show the underlying distribution from which all massive binaries were sampled (see Broekgaarden et al. 2022 for further details). We highlight in Figure 11 the initial parameters of the population of merging binary black holes that undergo MRR.

We find that in all our models MRR binary black hole mergers form from binaries with birth properties that are similar to the total binary black hole (including both MRR and non-MRR binaries) population. The most significant difference are that the MRR binary black hole population forms from a population of initial binaries with more equal mass binaries (such that they are closer to MRR initially) and smaller separations (which favors more conservative mass transfer; Schneider et al. 2015).

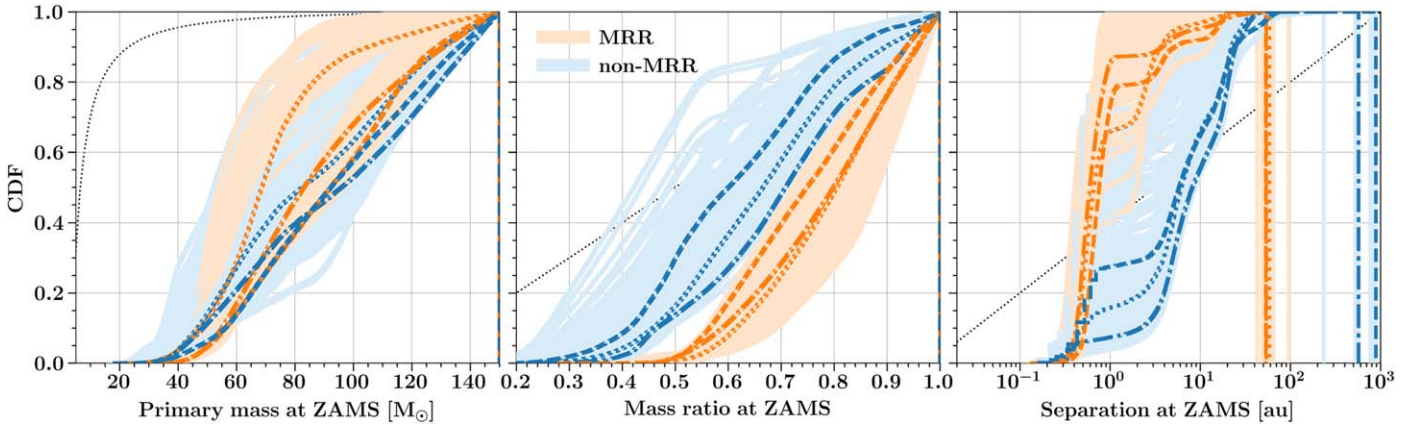


Figure 11. Cumulative distribution function of the zero-age main sequence more massive mass (left panel), mass ratio (center panel), and separation (right panel) for our 560 model realizations. For each panel we show the distribution for MRR (orange) and non-MRR (blue). MRR binaries have more equal mass ratios and shorter separations at zero-age main sequence compared to the overall binary black hole population. In each panel for comparison in gray the birth distribution of all binaries in COMPAS are shown. Three realizations, “K123”, “O312” and “T231” (see [Github](#)) are highlighted with a dotted, dashed–dotted and dotted curve, respectively. https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_Appendix_MRR_Properties_vs_nonMRR_ZAMS_CDFs_Panels/CDF_models_multiPanel_ZAMS.png https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure_Appendix_MRR_Properties_vs_nonMRR_ZAMS_CDFs_Panels/FractionOfDetectable_BBHs.ipynb.

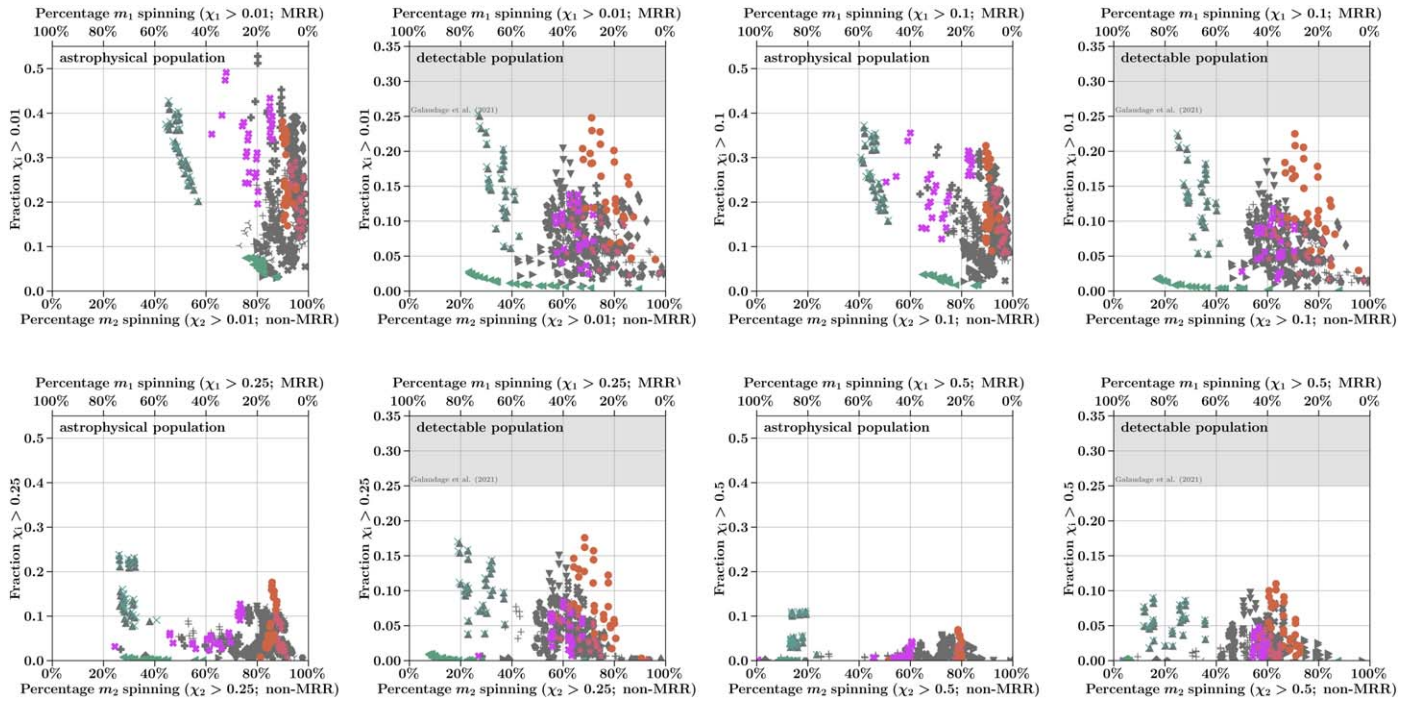


Figure 12. Same as Figure 4 but assuming spin thresholds of 0.01 (top left), 0.1 (top right), 0.25 (bottom left), and 0.5 (bottom right). https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure4_spinning_BBH_Rates/Rate_MRR_spins_panels_spin_threshold_0.05.pdf https://github.com/FloorBroekgaarden/MRR_Project/blob/main/Figure4_spinning_BBH_Rates/Plot_fraction_spinning_BBHs.ipynb

A.3. Impact from Varying the Assumed Spin Threshold

Throughout our work we have defined black holes to have nonnegligible spins if their spins exceeded a threshold value of 0.05 (see Section 2.3). We test whether our results are sensitive to this threshold value by changing the threshold to 0.01, 0.1, 0.25, and 0.5. Figure 12 shows that the fraction of detectable binary black hole mergers with nonnegligible spins is only mildly impacted for spin thresholds of 0.01 or 0.1 by changing to $\lesssim 0.26$ and $\lesssim 0.23$, respectively (compared to $\lesssim 0.25$ for a threshold of 0.05). For the astrophysical population, the decrease in the fraction is slightly more substantial, as a result that this population is more strongly weighted to low mass binary black hole systems, which are the systems that are mapped to the moderate spin values by Bavera et al. (2021). Figure 12 also shows that among the spinning binary black hole population the relative fraction of systems where χ_2 is spinning slightly decreases with an increasing spin threshold. This results from the non-MRR binary black holes contributing a relatively larger fraction of the nonnegligible black hole spin population at small χ_1 values, as shown in Figure 3. Varying the spin threshold did not drastically impact our other results including those presented in Figure 5.

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