



# Binary Black Hole Mergers: Formation and Populations

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We review the main physical processes that lead to the formation of stellar binary black holes (BBHs) and to their merger. BBHs can form from the isolated evolution of massive binary stars. The physics of core-collapse supernovae and the process of common envelope are two of the main sources of uncertainty about this formation channel. Alternatively, two black holes can form a binary by dynamical encounters in a dense star cluster. The dynamical formation channel leaves several imprints on the mass, spin and orbital properties of BBHs.

**Keywords:** stars: black holes, black hole physics, Galaxy: open clusters and associations: general, stars: kinematics and dynamics, gravitational waves

## 1. BLACK HOLE FORMATION FROM SINGLE STARS: WHERE WE STAND NOW

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About 4 years ago, the LIGO detectors obtained the first direct detection of gravitational waves, GW150914 (Abbott et al., 2016; Abbott et al., 2016a,b), associated with the merger of two black holes (BHs). This event marks the dawn of gravitational wave astronomy: we now know that binary black holes (BBHs) exist, can reach coalescence by gravitational wave emission, and are composed of BHs with mass ranging from few solar masses to  $\sim 50 M_{\odot}$ . Here, we review the main physical processes that lead to the formation of BBHs and to their merger. We restrict our attention to stellar-born BHs. As to primordial BHs, which might form from gravitational instabilities in the early Universe, we refer the reader to Carr et al. (2016) and Belotsky et al. (2019), and references therein. Before we start discussing binaries, we must briefly summarize the state-of-the-art knowledge about stellar-origin BHs: this is a necessary step to understand their pairing mechanisms.

Stellar-mass BHs are thought to be the final outcome of the evolution of a massive star (zero-age main sequence mass  $m_{ZAMS} \gtrsim 20 M_{\odot}$ ). Hence the mass of the BH should be affected by the two main processes that influence the evolution of a single star: (i) mass loss by stellar winds and (ii) the final collapse.

### 1.1. Stellar Winds

Hot ( $> 10^4$  K) massive stars ( $m_{ZAMS} \gtrsim 30 M_{\odot}$ ) lose a non-negligible fraction of their mass by line-driven winds. This process depends on metallicity ( $Z$ ): the mass-loss rate by stellar winds can be described as  $\dot{m} \propto Z^{\beta}$ , where  $Z$  is the absolute metallicity (see e.g., Vink et al., 2001 and references therein). The most recent models suggest that  $\beta$  is not constant, but depends at least on the luminosity of the star (Gräfener and Hamann, 2008; Vink et al., 2011; Chen et al., 2015): the closer the luminosity  $L_*$  is to the Eddington value  $L_{Edd}$ , the higher the mass loss, basically canceling the dependence on metallicity when  $L_* \gtrsim L_{Edd}$ .

In single stars, stellar winds uniquely determine the final mass of the star at the onset of collapse. If we consider a star with  $m_{ZAMS} = 90 M_{\odot}$  and metallicity  $Z = 0.02$  (i.e., approximately solar), its final mass will be only  $m_{fin} \sim 30 M_{\odot}$ ; while the same star with  $Z < 0.0002$  has  $m_{fin} \gtrsim 0.8 m_{ZAMS}$ . The final mass of a star  $m_{fin}$  is the strongest upper limit to the mass of the BH.

## 1.2. Core-Collapse Supernovae

For example, Fryer (1999) and Fryer and Kalogera (2001) suggest that if the final mass of the star is  $m_{\text{fin}} \gtrsim 40 M_{\odot}$ , the fate of the star is to collapse to a BH directly, without supernova, because the binding energy of the outer stellar layers is too big to be overcome by the explosion. Fryer et al. (2012) elaborate on these early results proposing that the mass of the compact object depends not only on  $m_{\text{fin}}$  but also on the final mass of the carbon-oxygen core. Alternatively, O'Connor and Ott (2011) proposed the role of the compactness parameter  $\xi_M = \frac{M/M_{\odot}}{R(<M)/1000 \text{ km}}$ : if the compactness is small (e.g.,  $\xi_{2.5} \leq 0.2 - 0.4$ ), the SN explosion is successful, otherwise we expect the star to collapse directly. All of these simplified models as well as more sophisticated ones (e.g., Ertl et al., 2016) point toward a similar direction: if the star ends its life with a large final mass, its carbon-oxygen core grows larger, its compactness is generally higher, and so on. Hence, we expect that metal-poor stars, which retain a larger fraction of their mass to the very end and develop larger cores, are more likely to collapse to BHs directly, producing larger BHs (e.g., Mapelli et al., 2009, 2010; Zampieri and Roberts, 2009; Belczynski et al., 2010). This simplified picture seems to agree with observations, but must be taken with several grains of salt: we need a vigorous step forward in core-collapse SN simulations and theoretical models, before we can draw robust conclusions (e.g., Burrows et al., 2018).

## 1.3. Pair Instability

Core-collapse SNe are not the only mechanism that can end the life of a massive star. When the helium core of a star grows to  $\geq 60 M_{\odot}$  and the central temperature reaches  $\sim 10^9$  K, electron and positron pairs are produced at an efficient rate, leading to a softening of the equation of state. The star undergoes pair instability (PI, Ober et al., 1983; Bond et al., 1984; Heger et al., 2003; Woosley et al., 2007): oxygen, neon, and silicon are burned explosively and the entire star is disrupted leaving no remnant, unless its helium core is  $\geq 130 M_{\odot}$ . In the latter case, the gravity of the outer layers is so big that the star collapses to a massive BH directly as an effect of PI (Heger et al., 2003). Smaller helium cores ( $\sim 30 - 60 M_{\odot}$ ) are associated with a less dramatic manifestation of PI: the softened equation of state drives oscillations of the core (pulsational PI, Barkat et al., 1967; Woosley et al., 2007; Chen et al., 2014; Yoshida et al., 2016); during each oscillation the star sheds some mass till it finds a new equilibrium to a lower core mass, but leaves a BH smaller than expected without pulsational PI (Belczynski et al., 2016a; Spera and Mapelli, 2017; Woosley, 2017, 2019; Marchant et al., 2019; Stevenson et al., 2019; Renzo et al., 2020).

From the combination of PI, core-collapse SNe and stellar-wind mass loss prescriptions, we expect the mass spectrum of BHs to behave roughly as shown in **Figure 1**. In particular, PI is expected to carve a gap in the mass spectrum of BHs between  $\sim 50(-10, +20) M_{\odot}$  and  $\approx 120 - 130 M_{\odot}$ . The uncertainty on this mass gap is mainly connected with uncertainties nuclear reaction rates (Farmer et al., 2019), on the collapse of the residual hydrogen envelope and on the role of stellar rotation (Mapelli et al., 2020). Within this framework, we predict a reasonable mass range for stellar-origin BHs to be  $\sim 3 - 65 M_{\odot}$  (assuming

the most conservative value for the lower edge of pair-instability mass gap). If exotic metal-poor stars exist with mass  $m_{\text{ZAMS}} > 250 M_{\odot}$ , these might directly collapse to intermediate-mass BHs (IMBHs) with mass  $> 100 M_{\odot}$ .

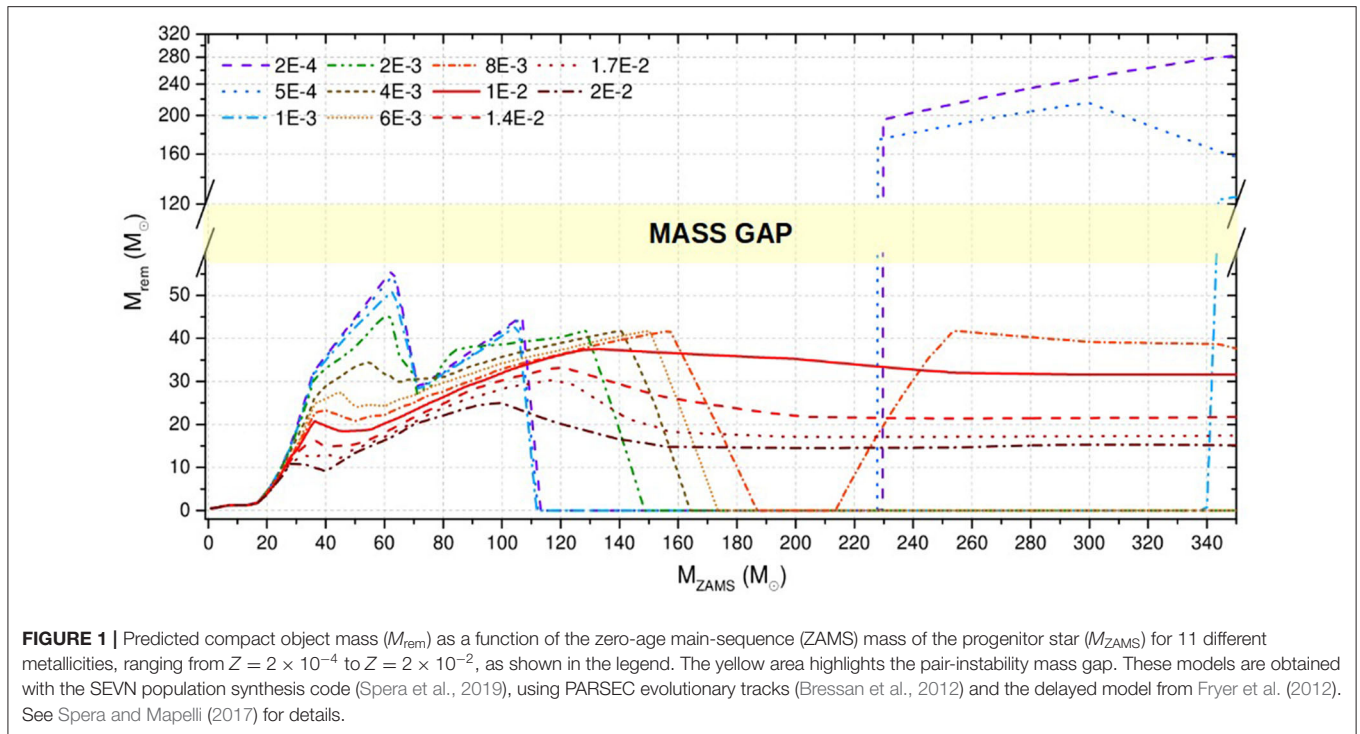
## 2. BINARY BH FORMATION IN ISOLATION

The scenario highlighted in the previous section assumes that the progenitor star is single. But gravitational waves have shown the existence of BBHs with a very short orbital separation: the initial separation of a BBH must be of the order of few ten solar radii for the BBH to merge within a Hubble time by gravitational-wave emission. This challenges our understanding of binary star evolution. A close binary star undergoes several physical processes during its life, which can completely change its final fate (see e.g., Eggleton, 2006). The most important processes include mass transfer and common envelope, tides and natal kicks (Hurley et al., 2002).

Mass transfer and common envelope are crucial in this regard. After main sequence, a massive star can develop a stellar radius as large as several thousand solar radii. Hence, if this star is member of a binary system and its orbital separation is of few hundred to few thousand solar radii, the binary system undergoes Roche lobe overflow and possibly common envelope (Ivanova et al., 2013). If common envelope occurs between a BH and a giant companion star, the BH and the core of the giant star orbit about each other surrounded by the giant's envelope: they feel a strong gas drag from the envelope and lose kinetic energy, inspiralling about each other. This transfers thermal energy to the envelope, which might trigger the ejection of the envelope. If the envelope is not ejected, the binary system merges prematurely giving birth to a single BH. In contrast, if the envelope is ejected, the final binary system is composed of the BH and the core of the giant. Because of the spiral-in, the final semi-major axis of the binary is just few solar radii, much smaller than the initial one. If the naked core collapses to a BH without receiving a strong natal kick, the system becomes a BBH with a short orbital period, able to merge within a Hubble time. Unfortunately, our understanding of common envelope is still poor (see Fragos et al., 2019 for a recent simulation) and this uncertainty heavily affects our knowledge of BBH demography. The left-hand panel of **Figure 2** is a schematic view of the isolated binary evolution channel through common envelope.

Several alternative scenarios to common envelope have been proposed (de Mink and Mandel, 2016; Mandel and de Mink, 2016; Marchant et al., 2016). For example, in the over-contact binary evolution, Marchant et al. (2016) show that, when two massive stars in a tight binary are fast rotators, they remain fully mixed as a result of their tidally induced high spin; in this case, the binary avoids premature merger even if it is overfilling its Roche lobe and might evolve into a tight BBH.

The isolated binary evolution scenario has several characteristic signatures. In the *common envelope* isolated binary evolution scenario, the *masses* of the two BHs span from  $\sim 3 M_{\odot}$  up to  $\sim 45 M_{\odot}$  (see e.g., Giacobbo and Mapelli, 2018) and the *mass ratios* are preferentially close to 1 (although all



mass ratios  $q = m_2/m_1 \gtrsim 0.1$  are possible, see e.g., Giacobbo and Mapelli, 2018). Most processes in binary evolution tend to produce aligned *spins* (e.g., Rodriguez et al., 2016), while the magnitude of the spin is basically unconstrained (but see Qin et al., 2018, 2019; Fuller and Ma, 2019 for some recent attempts to quantify spins). Mass transfer episodes and gravitational-wave decay are expected to efficiently damp *eccentricity*, so that almost all isolated binaries have near zero eccentricity in the LIGO-Virgo band. Finally, local merger rate densities span from a few to few thousand events  $\text{Gpc}^{-3} \text{yr}^{-1}$ , depending on the details of common envelope and natal kicks (e.g., Dominik et al., 2013; Belczynski et al., 2016b; Mapelli et al., 2017; Giacobbo and Mapelli, 2018, 2020; Mapelli and Giacobbo, 2018; Neijssel et al., 2019; Santoliquido et al., 2020; Tang et al., 2020). The scenarios which include alternatives to common envelope predict an even stronger prevalence of systems with  $q \sim 1$ , a preferred mass range  $\sim 25 - 60 M_{\odot}$  (Marchant et al., 2016), high and aligned spins, zero eccentricity in the LIGO-Virgo band, and long delay times ( $\gtrsim 3$  Gyr, de Mink and Mandel, 2016). Local merger rate densities are expected to be  $\sim 10 \text{Gpc}^{-3} \text{yr}^{-1}$  (Mandel and de Mink, 2016), with large uncertainties.

### 3. BINARY BH FORMATION IN STAR CLUSTERS

Star clusters are among the densest places in the Universe. There is a plethora of star clusters, with their distinguishing features: (i) globular clusters (Gratton et al., 2019) are old ( $\sim 12$  Gyr) and massive systems ( $\sim 10^{4-6} M_{\odot}$ ), (ii) nuclear star clusters can be even more massive ( $\sim 10^7 M_{\odot}$ ) and lie at the center of

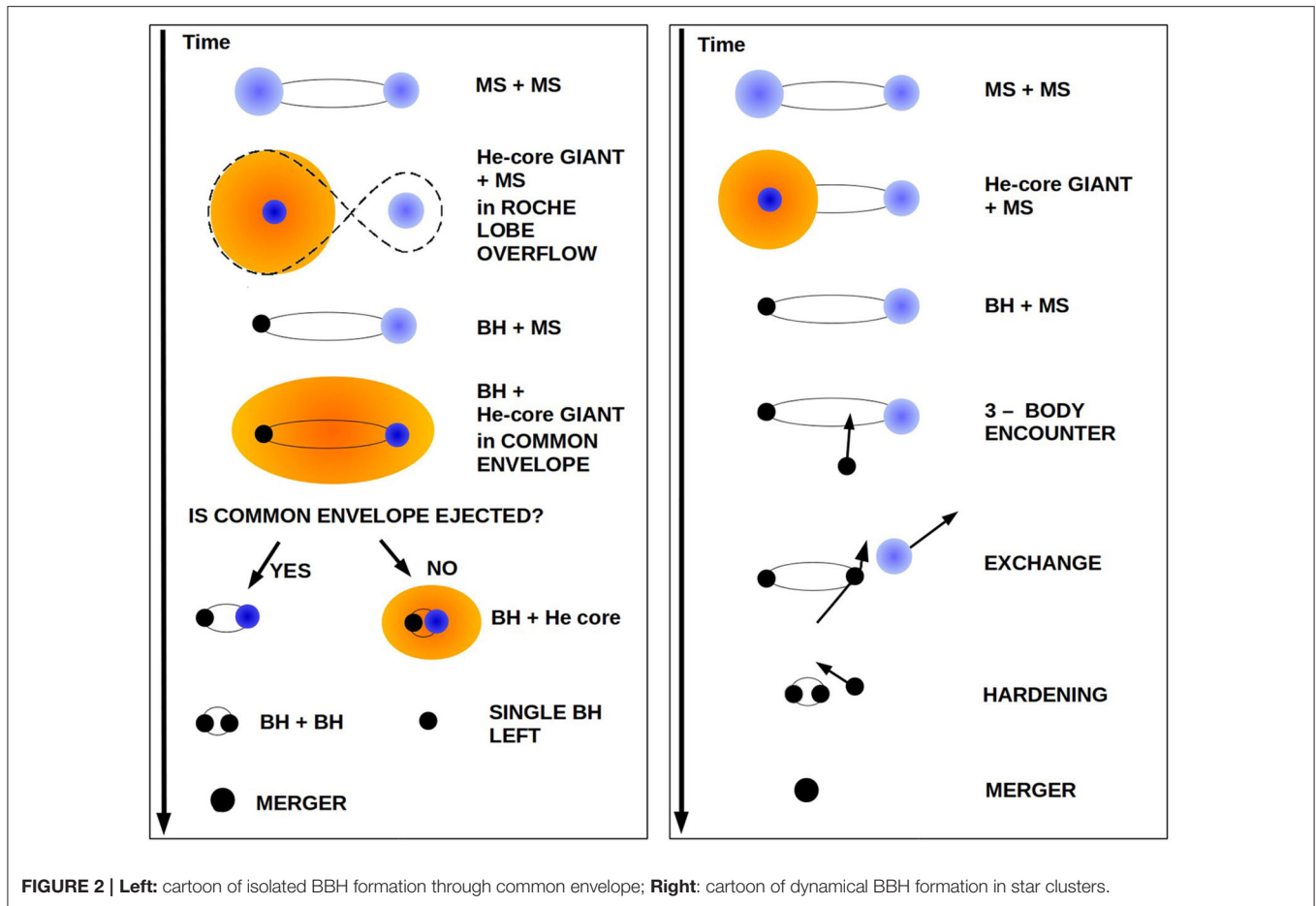
many galaxies, in some cases coexisting with the supermassive BH (Neumayer et al., 2020), (iii) open clusters and young star clusters (Portegies Zwart et al., 2010) are generally less massive (up to  $\sim 10^5 M_{\odot}$ ) and short lived (less than a few Gyr), but are the main birthplace of massive stars in the local Universe (Lada and Lada, 2003).

The central density of star clusters is sufficiently high ( $\gtrsim 10^3$  stars  $\text{pc}^{-3}$ ) and their typical velocity dispersion sufficiently low (from a few to a few tens of  $\text{km s}^{-1}$ , possibly with the exception of nuclear star clusters) that their central two-body relaxation time (Spitzer, 1987) is shorter than their lifetime. This has one fascinating implication: the orbits of stars and binary stars in a star cluster are constantly perturbed by dynamical encounters with other cluster members. This process affects the formation and the evolution of binary BHs in multiple ways (e.g., Portegies Zwart and McMillan, 2000).

#### Dynamical Exchanges

Dynamical exchanges occur when a binary system interacts with a single stellar object and the latter replaces one of the members of the binary. We have known for a long time that massive objects are more likely to acquire companions by dynamical exchanges (Hills and Fullerton, 1980). Since BHs are among the most massive objects in a star cluster, they are very efficient in forming new binaries through exchanges (e.g., Ziosi et al., 2014).

During a three-body encounter, a binary star exchanges a fraction of its internal energy with the third body. If the binary is particularly tight (hard binary), such encounters tend to harden the binary star, i.e., to increase its binding energy by reducing its semi-major axis (*dynamical hardening*). In the case of a BBH,



**FIGURE 2 |** Left: cartoon of isolated BBH formation through common envelope; Right: cartoon of dynamical BBH formation in star clusters.

this hardening might speed up the merger, because it drives the semi-major axis of the BBH in the regime where orbital decay by gravitational waves becomes efficient (see e.g., Figure 10 of Mapelli, 2018). On the other hand, the least massive BBHs can even be *ionized*, i.e., split by strong dynamical encounters with massive intruders.

## Mergers of Massive Stars

Mergers of massive stars are common in dense young star clusters, because of the short dynamical friction timescale (Portegies Zwart et al., 2010). Under some assumptions, these mergers can lead to the formation of massive BHs ( $m_{\text{BH}} > 60 M_{\odot}$ ), with mass in the pair-instability gap (Di Carlo et al., 2019a). In star clusters, such massive BHs can acquire a companion by dynamical exchanges, leading to the formation of BBHs in the mass gap. A fast sequence of stellar mergers in the dense core of a young star cluster (also known as *runaway collision*, Portegies Zwart et al., 2004; Giersz et al., 2015) might even lead to the formation of intermediate-mass BHs (IMBHs), i.e., BHs with mass  $m_{\text{BH}} > 100 M_{\odot}$ , especially at low metallicity (Mapelli, 2016).

The dynamical processes we briefly summarized above (and in the right-hand panel of Figure 2) leave a clear imprint on BBHs. First, dynamically formed BBHs extend to higher

masses than isolated BBHs: they might even be in the pair-instability mass gap or in the IMBH regime (Di Carlo et al., 2019b; Rodriguez et al., 2019). Secondly, dynamical exchanges randomize the spin direction, leading to an isotropic distribution of BH spins. In contrast, isolated BBHs have a preference for aligned spins (Rodriguez et al., 2016; Gerosa et al., 2018). Third, dynamics can trigger the merger of BBHs with non-zero eccentricity even in the LIGO-Virgo band (Samsing et al., 2014; Rodriguez et al., 2018; Samsing, 2018; Zevin et al., 2019). These signatures provide an unique opportunity to differentiate among the isolated and the dynamical formation channel when the number of gravitational-wave detections will be of the order of a few hundreds (e.g., Zevin et al., 2017; Bouffanais et al., 2019).

## AUTHOR CONTRIBUTIONS

MM collected the material and wrote the review.

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**Conflict of Interest:** The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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