Dynamics of black hole – neutron star binaries in young star clusters

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ABSTRACT

Young star clusters are likely the most common birthplace of massive stars across cosmic time and influence the formation of compact binaries in several ways. Here, we simulate the formation of black hole – neutron star binaries (BHNSs) in young star clusters, by means of the binary population synthesis code MOBSE interfaced with the $N$-body code NBODY6++GPU. BHNSs formed in young star clusters (dynamical BHNSs) are significantly more massive than BHNSs formed from isolated binaries (isolated BHNSs): $\sim$ 34\% of the dynamical BHNS mergers have total mass $> 15\ M_{\odot}$, while only $\sim$ 0.01\% of the isolated BHNS mergers have mass in excess of this value. More than 90\% of the dynamical BHNSs are ejected from their parent star cluster before they reach coalescence. Hence, a significant fraction of BHNS mergers occurring in the field might have originated in a young star cluster. The mass spectrum of BHNS mergers from gravitational-wave detections will provide a clue to differentiate between dynamical and isolated formation of BHNSs.

Key words: stars: black holes – stars: neutron – black hole physics – Galaxy: open clusters and associations: general – stars: kinematics and dynamics – gravitational waves

1 INTRODUCTION

The LIGO-Virgo collaboration (LVC) has detected three binary black hole (BBH) mergers during the first observing run (O1, Abbott et al. 2016a; Abbott et al. 2016b; Abbott et al. 2016c) and eight additional gravitational-wave (GW) events during the second observing run (O2), seven of them interpreted as BBHs and one associated with a binary neutron star (BNS, Abbott et al. 2017a,c,b; Abbott et al. 2019). The third observing run (O3) is ongoing and already led to the publication of one event, GW190425 (Abbott et al. 2020), a compact binary coalescence with total mass $\sim 3.4\ M_{\odot}$. This is likely the second observed BNS merger, but has component masses significantly larger than the known Galactic BNSs ("Ozel & Freire 2016). No black hole–neutron star (BHNS) mergers were observed in O1 and O2 (Abbott et al. 2019; Wei & Feng 2019), and we do not know any black hole (BH) – pulsar binary from radio observations.

BHNSs have attracted considerable interest. The observation of a tight black hole (BH) – pulsar binary would be a holy grail of gravity, and is one of the main scientific goals of the Square Kilometer Array (SKA)\footnote{https://www.skatelescope.org/}. The lack of observations of BH–pulsar binaries with current radio facilities is not surprising: Pfahl et al. (2005) estimate that there are no more than one BH – recycled pulsar binary in the Milky Way for every 100 – 1000 BNSs, of which 15 are currently known (Tauris et al. 2017; Farrow et al. 2019).

Similar to BNSs, BHNS mergers might lead to the emission of short gamma-ray bursts under some circumstances (Blinnikov et al. 1984; Eichler et al. 1989; Paczynski 1991; Narayan et al. 1991; Mao et al. 1994; Fryer et al. 1999; Bethe & Brown 1998, 1999; Popham et al. 1999; Ruffert & Janka 1999; Zappa et al. 2019). The properties of possible optical/near-infrared counterparts to BHNSs are still matter of debate (e.g. Fernández et al. 2017; Andreoni et al. 2019; Barbieri et al. 2019).

From the non-detection of BHNS mergers in O1 and
O2, the LVC inferred an upper limit of \( \sim 610 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \) for the local merger rate density of BHNSs (Abbott et al. 2019). Theoretical predictions for the BHNS local merger rate density \( \dot{N}_{\text{BHNS}} \) come mostly from the isolated binary scenario: Dominik et al. (2015) predict \( \dot{N}_{\text{BHNS}} \sim 0.04 - 20 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \), consistent with earlier theoretical predictions (Sipior & Sigurdsson 2002; Pfahl et al. 2005; Belczynski et al. 2007, 2010; O'Shaughnessy et al. 2010). Based on the coupling between population-synthesis simulations and cosmological simulations, Mapelli & Giacobbo (2018) find \( \dot{N}_{\text{BHNS}} \sim 10 - 100 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \), consistent with Artale et al. (2019) (\( \dot{N}_{\text{BHNS}} \sim 60 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \)). Finally, recent population-synthesis models combined with a data-driven approach yield \( \dot{N}_{\text{BHNS}} \sim 4 - 350 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \) (Baibhav et al. 2019; Giacobbo & Mapelli 2019b; Tang et al. 2020).

Less attention has been paid to the dynamical formation of BHNSs in dense stellar systems, such as globular clusters or young star clusters (YSCs). We have known for a long time that dynamical exchanges are likely to occur when the mass of the intruder is larger than the mass of one of the two components of the binary system (Hills & Fullerton 1980; Sigurdsson & Hernquist 1993; Sigurdsson & Phinney 1995). Since BHs and their stellar progenitors are among the most massive objects in a star cluster, we expect them to be very efficient in acquiring companions through dynamical exchanges, unless they are ejected earlier from the stellar system. Previous studies have shown that dynamical exchanges significantly contribute to the formation of BBHs in globular clusters (e.g. Portegies Zwart & McMillan 2000; Rodriguez et al. 2015, 2016, 2018, 2019; Fragione & Kocsis 2018; Hong et al. 2018; Samsing 2018; Samsing et al. 2019; Choksi et al. 2019; Kremer et al. 2019; Arca Sedda & Mastrobuono-Battisti 2019), YSCs (e.g. Ziosi et al. 2014; Mapelli & Bressan 2013). This implementation produces a high binary fraction (\( f_{\text{bin}} = 0.4 \)) and fractal initial conditions. We adopted the code NBODY6++GPU (Wang et al. 2015, 2016), coupled with the binary population synthesis code MOBSE (Giacobbo et al. 2018), as described in Di Carlo et al. (2019b).

Simulating YSCs requires challenging N-body simulations, coupled with binary population synthesis calculations. Here, we discuss a new set of 75000 direct N-body simulations of YSCs, including a high binary fraction (\( f_{\text{bin}} = 0.4 \)) and fractal initial conditions. We adopted the code NBODY6++GPU (Wang et al. 2015, 2016), coupled with the binary population synthesis code MOBSE (Giacobbo et al. 2018), as described in Di Carlo et al. (2019b).

2 METHODS

The simulations discussed in this paper were performed with the same code as described in Di Carlo et al. (2019b).

In particular, we use the direct summation N-body code NBODY6++GPU (Wang et al. 2015) coupled with the population synthesis code MOBSE (Mapelli et al. 2017; Giacobbo et al. 2018; Giacobbo & Mapelli 2018). MOBSE is an upgrade of BSE (Hurley et al. 2002), including up-to-date prescriptions for stellar winds, for the outcome of core-collapse supernovae and for pair instability and pulsational pair instability. Mass loss by stellar winds is described as in Fryer et al. (2012). In particular, here we adopt the rapid core-collapse supernova model, which suppresses the formation of compact objects with mass in the 2 - 5 \( M_\odot \) range. According to this model, stars developing a carbon-oxygen core \( m_{\text{CO}} \gtrsim 11 \, M_\odot \) collapse to a BH directly. Finally, pair instability and pulsational pair instability are modelled as described in Spera & Mapelli (2017). This implementation produces a two test cases in which the mass of the BH is 7 \( M_\odot \) and 35 \( M_\odot \), respectively.

Here, we study the formation and evolution of BHNSs in YSCs. YSCs are the nursery of massive stars (which are thought to be the progenitors of BHs and NSs). Thus, it is reasonable to expect that compact objects participate in the dynamics of their parent YSCs, at least for few Myr. Note that the dynamical evolution of globular clusters and YSCs are significantly different. Globular clusters have a two-body relaxation timescale \( t_{\alpha} \) of several hundreds Myr (Spitzer 1987) and a central escape velocity of \( \sim 30 \, \text{km} \, \text{s}^{-1} \), while YSCs have \( t_{\alpha} \sim 10 - 100 \, \text{Myr} \) and a central escape velocity of few km s\(^{-1}\). Hence, while a BH can undergo a longer chain of exchanges in a globular cluster, before being ejected by dynamical or relativistic kicks, usually the time of ejection from a YSC is much shorter (\( \sim \) few Myr). Moreover, the core-collapse timescale in a YSC is \( \sim \) few Myr (Mapelli & Bressan 2013). This implies that most exchanges in globular clusters involve BHs and neutron stars (NSs) that have already formed, while most interactions in YSCs happen when the progenitor stars have not yet collapsed to a BH or NS, with significant differences in the binary compact object populations (Kumamoto et al. 2019; Di Carlo et al. 2019b). Furthermore, while globular clusters formed only in the early epochs (\( \sim 8 \) - 13 Gyr ago), YSCs represent the main formation pathway of massive stars down to the local Universe (Lada & Lada 2003; Portegies Zwart et al. 2010).

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mass gap in the BH mass spectrum between \( m_{\text{BH1}} \sim 65 \, M_\odot \) and \( m_{\text{BH2}} \sim 120 \, M_\odot \).

We model YSCs with three different metallicities: \( Z = 0.02, 0.002 \) and 0.0002. We ran 25000 \( N \)-body simulations per each metallicity for a total of 750000 simulations.

YSC masses are sampled in the range \( 300 < M < 1000 \, M_\odot \) from a distribution \( dN/dM_{\text{SC}} \propto M_{\text{SC}}^{-3} \), reminiscent of the distribution of YSCs in the Milky Way (Lada & Lada 2003). Hence, in this work we focus on the smallest star clusters. We will consider more massive star clusters in a follow-up work. We choose the initial star cluster half mass radius \( R_h \) according to the Marks & Kroupa relation (Marks et al. 2012), which relates the total mass \( M_{\text{SC}} \) of a SC at birth with its initial half mass radius \( R_h \):

\[
R_h = 0.10^{0.07}_{-0.04} \times (\frac{M_{\text{SC}}}{M_\odot})^{0.13\pm0.04} \, \text{pc}.
\]  

We generate models of star clusters that are characterized by fractal substructures (as described in Goodwin & Whitworth 2004), by using the software MCLUSTER (Küpper et al. 2011a). The fractal dimension \( D \) is set to be 1.6. We choose fractal initial conditions, because observations (Sánchez & Alfaro 2009; Küpper et al. 2011b; Kuhn et al. 2019) and hydrodynamical simulations (Ballone et al. 2020) indicate that embedded star clusters have a small fractal dimension. The YSCs are initialised in virial equilibrium.

Star masses are extracted from a Kroupa (Kroupa 2001) initial mass function (IMF) with \( 0.1 < M < 150 \, M_\odot \). The orbital parameters of binary systems (semi-major axis and eccentricity) are generated following Sanà et al. (2012). We assume an initial total binary fraction \( f_{\text{bin}} = 0.4 \). MCLUSTER assigns the companion stars based on mass: stars are randomly paired by enforcing a distribution \( P(q) \propto q^{-0.1} \), where \( q = m_2/m_1 \) is the ratio of the mass of the secondary to the mass of the primary star and spans the range \( 0.1-1.0 \), consistent with Sanà et al. (2012). All the stars more massive than \( 5 \, M_\odot \) are forced to be members of binary systems, while stars with mass \( < 5 \, M_\odot \) are randomly paired only till we reach a total binary fraction \( f_{\text{bin}} = 0.4 \). The result of this procedure is that the most massive stars (down to \( 5 \, M_\odot \)) in our case are all members of a binary system, while the binary fraction drops to lower values for lower star masses. This is consistent with observational results (e.g. Moe & Di Stefano 2017).

The force integration in NBODY6++GPU includes a solar neighbourhood-like static external tidal field. In particular, the potential is point-like and the simulated star clusters are assumed to be on a circular orbit around the centre of the Milky Way with a semi-major axis of \( 8 \, \text{kpc} \) (Wang et al. 2016). We integrate each YSC until its dissolution or for a maximum time \( t = 100 \, \text{Myr} \). At time \( t > 100 \, \text{Myr} \), the BHNSs escaped from the parent cluster evolve only due to the emission of gravitational radiation. We estimate the coalescence timescale of these binaries with the formalism described in Peters (1964). A summary of the initial conditions of the simulations is reported in Table 1.

The main differences of our simulations with respect to the ones of Di Carlo et al. (2019b) are i) the mass range of star clusters (we simulate star clusters from 300 to 1000 \( M_\odot \)), while the mass range in Di Carlo et al. 2019b is \( 1-3 \times 10^4 \, M_\odot \)), ii) the metallicity range (Di Carlo et al. 2019b consider only \( Z = 0.002 \), while we simulate also \( Z = 0.0002 \) and 0.02), iii) the treatment of common envelope (whose parameter \( \alpha \) was set to 3 by Di Carlo et al. 2019b, while here we adopt \( \alpha = 5 \), consistent with Fragos et al. 2019), iv) the choice of the prescription for core-collapse supernovae (here we choose the rapid model by Fryer et al. 2012, while Di Carlo et al. 2019b assumed the delayed model and have BHs with mass down to \( \sim 3 \, M_\odot \)) and v) the supernova kick model (in Di Carlo et al. 2019b we assumed the same model as Fryer et al. 2012, while here we use the same prescriptions as run CC15o5 in Giacobbo & Mapelli 2018, i.e. NSs form with a Maxwellian natal kick described with a one-dimensional root-mean square \( \sigma = 15 \, \text{km s}^{-1} \).

In addition, we simulate a comparison sample of isolated binaries with the stand-alone version of MOBSE. The isolated binary sample is composed of \( 3 \times 10^7 \) binary systems (\( 10^7 \) for each metallicity). The isolated sample is the same as run CC15o5 in Giacobbo & Mapelli (2018).

3 RESULTS

3.1 Population of BHNSs formed in YSCs

Figure 1 shows the population of BHNSs formed in our \( N \)-body simulations at \( t = 100 \, \text{Myr} \). This sample includes both systems that merge within a Hubble time and systems with larger orbital separation.

The BHNSs that form from the same binary star (i.e. the stellar progenitors of the BH and the NS were already bound in the initial conditions) are labelled as “original BHNSs”. The BHNSs that form through dynamical exchanges are labelled as “exchanged BHNSs”. We also consider a comparison sample of “isolated BHNSs”, which form in the field from isolated binary evolution. It is important to note that dynamics affects not only exchanged binaries (which, indeed, form by dynamical encounters), but even original binaries: close dynamical encounters shrink (or widen) the semi-major axis of a binary star, change its orbital eccentricity and can even unbind the binary. In particular, lighter and wider binaries (soft binaries) tend to be widened/ionized, while massive and tight binaries (hard binaries) tend to increase their binding energy and shrink (Heggie 1975).

Figure 1 shows that the percentage of exchanged binaries increases with the total mass of the star cluster, at all considered metallicities. The percentage of exchanged binaries is higher in metal-poor star clusters (from \( \sim 50 \% \) to \( \sim 70 \% \) at \( Z = 0.0002 \) to 0.002, depending on the mass of the cluster) than in metal-rich ones (from \( \sim 30 \% \) to \( \sim 50 \% \) at solar metallicity, also depending on the mass of the cluster).

These findings can be interpreted as a result of the interplay between stellar evolution and dynamics. According to our assumptions (in particular, to the Marks et al. 2012 relation), our more massive star clusters are denser than the smaller ones, hence dynamical encounters and exchanges are more common in the former than in the latter. Moreover, BHs are generally more massive in metal-poor clusters, hence BHs born in metal-poor star clusters are more efficient in acquiring companions through exchanges than BHs in metal-rich clusters.

From Fig. 1 we also note that exchanged binaries are generally more massive than original BHNSs. Dynamics
leads to the formation of more massive binaries because it allows the formation of very massive BHs through multiple stellar collisions and dynamical exchanges allow such massive BHs to pair with other compact objects.

Moreover, we find no evidence of correlation between the mass of the parent YSC and the mass of the BHNS. This is true for both original and exchanged binaries. Each of the four bins of cluster mass shows very similar BHNS mass distributions.

3.2 YSCs versus isolated binaries

Figure 2 compares the mass distribution of BHNSs formed in YSCs with that of BHNSs formed in isolation. The maximum mass of a BHNS, $m_{\text{BHNS, max}}$, is similar in original and isolated BHNSs. Its value is $\sim 64, ~63$ and $\sim 21 ~M_\odot$ at $Z = 0.0002, ~0.002$ and 0.02, respectively. In contrast, the maximum BHNS mass is significantly larger in the case of exchanged BHNSs: $\sim 118, ~130$ and $\sim 38 ~M_\odot$ at $Z = 0.0002, ~0.002$ and 0.02, respectively.

The main reason of this striking difference between exchanged binaries and the other systems is that BHs in YSCs can form from the merger of two (or more) stars (Portegies Zwart et al. 2004). In this case, the mass of the BH can be significantly higher than the mass of a BH formed from a single star and can even be in the pair-instability mass gap (see e.g. Di Carlo et al. 2019a for details). Such massive BHs are alone at birth, but they can acquire a companion through dynamical exchanges if they are members of a star cluster.

Another crucial difference between isolated BHNSs and dynamical BHNSs is the number of light systems ($m_{\text{BHNS}} \lesssim 15 ~M_\odot$) and (as a consequence) the slope of the entire mass function. Light BHs are the most common ones in isolated BHNSs, while their contribution is significantly smaller in dynamical (both exchanged and original) BHNSs especially at low $Z$. This is an effect of dynamics, because dynamical exchanges tend to suppress the lightest binaries.

We note that 97% of all the BHNSs formed in YSCs have been ejected from the stellar system by the end of the simulations. As the metallicity of the systems increases, the percentage of retained BHNSs decreases: 5% at $Z = 0.0002$, 3% at $Z = 0.002$ and $< 1$% at $Z = 0.02$. This difference is expected, because BHNSs are generally more massive at low metallicity and thus can be more easily retained inside the YSC.

3.3 Coalescence of BHNSs from YSCs and from isolated binaries

In this Section, we focus on BHNSs that reach coalescence within a Hubble time by emission of GWs. In our dynamical simulations, we find 53 BHNS mergers, of which 24, 27 and 2 are at metallicity $Z = 0.0002, ~0.002$ and 0.02, respectively. Figure 3 shows the mass of the NS ($m_{\text{NS}}$) versus the mass of the BH ($m_{\text{BH}}$) of BHNS mergers. The majority of coalescing BHNSs from YSCs are original binaries (80%), while the remaining (20%) are exchanged binaries. The three most massive BHs ($m_{\text{BH}} > 60 ~M_\odot$) in coalescing BHNSs are exchanged systems, but even original BHNSs can host significantly massive BHs. We estimate that 34% of the BHNS mergers have BH component with mass $m_{\text{BH}} > 15 ~M_\odot$. 54% of such massive merging BHNSs are exchanged while 28% are original binaries. 45% of massive merging BHNSs are found at $Z = 0.0002$ and 55% at $Z = 0.002$. No massive BHNS mergers are found at solar metallicity.

The mass of the NS component of BHNS mergers is always in the range $1.1 \lesssim m_{\text{NS}}/M_\odot \lesssim 2$, but this is a consequence of the assumed prescription for core-collapse supernovae: no compact objects can form with mass $2 - 5 ~M_\odot$ according to the rapid core-collapse supernova model by Fryer et al. (2012). If we had used the delayed core-collapse supernova model by the same authors, we would likely have found compact-object masses in the $2 - 5 ~M_\odot$ range.

Figure 4 shows the cumulative distribution of total mass, chirp mass $M$ and mass ratio $q = m_{\text{NS}}/m_{\text{BH}}$ of BHNS mergers. The mass ratios are always $< 0.4$, consistent with previous results (e.g. Giacobbo & Mapelli 2018). Dynamical and isolated BHNS mergers have a similar minimum mass ratio $q_{\text{min}} \sim 0.02$, but small mass ratios ($q < 0.15$) are significantly more common in dynamical BHNSs than in isolated BHNSs.

The chirp masses of dynamical BHNS mergers have a much broader range of values than the isolated systems: the former extend from $M \sim 1.7 ~M_\odot$ to $M \sim 5.4 ~M_\odot$ (with negligible differences between original and exchanged BHNSs), while the latter are more concentrated in the $2 \lesssim M/M_\odot \lesssim 4$ range with a tail at higher chirp mass.

In summary, massive BH components ($m_{\text{BH}} > 15 ~M_\odot$) are significantly more common in dynamical BHNS mergers than in isolated BHNS mergers. Massive BHs are very common not only in exchanged BHNSs, but even in original BHNSs. This result is easy to understand in the case of exchanged BHNSs (these can host more massive BHs born from single star evolution or from previous stellar mergers), but is trickier to grasp for original BHNSs. The higher fraction of massive BHs in original BHNSs with respect to iso-

Table 1. Initial conditions.

| Set  | Run number | $M_{\text{SC}}$ [M$_\odot$] | $r_h$ [pc] | $Z$ | $f_{\text{BH}}$ | $D$ | IMF | $m_{\text{min}}$ [M$_\odot$] | $m_{\text{max}}$ [M$_\odot$] |
|------|------------|-----------------|---------|-----|-------------|-----|-----|---------------------|---------------------|
| Z0002 | 25000      | $3 \times 10^2 - 10^3$ | $0.1 \times (M_{\text{SC}}/M_\odot)^{0.13}$ | $0.0002$ | 0.4 | 1.6 | Kroupa (2001) | 0.1 | 150 |
| Z002  | 25000      | $3 \times 10^2 - 10^3$ | $0.1 \times (M_{\text{SC}}/M_\odot)^{0.13}$ | $0.002$ | 0.4 | 1.6 | Kroupa (2001) | 0.1 | 150 |
| Z02   | 25000      | $3 \times 10^2 - 10^3$ | $0.1 \times (M_{\text{SC}}/M_\odot)^{0.13}$ | $0.02$ | 0.4 | 1.6 | Kroupa (2001) | 0.1 | 150 |
lated BHNSs comes from an interplay between binary evolution and dynamics. As we have already discussed in Giaacobbo & Mapelli (2018), the most massive BHs in our models come from metal-poor stars with mass \( \sim 60 - 80 \ M_\odot \). These stars develop very large radii (hundreds to thousands of solar radii, Spera et al. 2019) during their giant phase. If the initial orbital separation of the binary star was smaller than these large radii, the binary star merges before giving birth to a BHNS. For larger orbital separation, the binary star undergoes Roche lobe overflow, which tends to equalize the final mass of the two compact objects: the final BHNS might merge by GW emission, but the mass of the BH is significantly smaller than expected from single star evolution because of mass transfer and envelope removal. Finally, if the binary is too large to undergo Roche lobe overflow (orbital separation \( a \gtrsim 10^3 \ R_\odot \), Spera et al. 2019), the mass of the BH in the final BHNS is the same as expected from a single star evolution (i.e. \( 50 - 65 \ M_\odot \)) for a metal-poor progenitor with zero-age main-sequence mass \( \sim 60 - 80 \ M_\odot \), but, if the binary is isolated, the final orbital separation is too large to lead to coalescence by GW emission. In a dynamical environment such as an YSC, such original BHNSs with a massive BH component can shrink by dynamical encounters and might be able to merge by GW emission.

Figure 1. Distribution of BHNS total mass versus YSC mass for \( Z = 0.0002, 0.002 \) and 0.02 (top, middle and bottom panel respectively) at \( t = 100 \ \text{Myr} \). Black circles: original BHNSs; blue circles: exchanged BHNSs. Each scatter plot is divided into four bins of cluster mass in the range: \( 250 < M_{SC}/M_\odot < 450 \), \( 450 < M_{SC}/M_\odot < 650 \), \( 650 < M_{SC}/M_\odot < 850 \), and \( 850 < M_{SC}/M_\odot < 1050 \). The percentage of exchanged (E) and original (O) BHNSs in each mass range is indicated in the bottom part of each bin.

Figure 2. Mass of BHNSs (\( m_{BHNS} \)) formed in YSCs and in isolation. The panels from top to bottom refer to \( Z = 0.0002 \) (blue), 0.002 (green) and 0.02 (red), respectively. The filled gray histograms refer to isolated binaries. Solid lines: exchanged BHNSs; dashed lines: original BHNSs.

Figure 3. Mass of the BH (\( m_{BH} \)) versus mass of the NS (\( m_{NS} \)) of BHNS mergers. Circles: original BHNSs; stars: exchanged BHNSs. Blue: \( Z = 0.0002 \); green: \( Z = 0.002 \); red: \( Z = 0.02 \). Filled contours (grey colour map) indicate isolated BHNS mergers (Giacobbo et al. 2018) for all the three metallicities.
Finally, 94% of dynamical BHNS mergers happen after the binary was ejected from the YSC. This is a crucial result because it means that the vast majority of BHNSs born in YSCs are field binaries by the time of their merger. The population of BHNS mergers in the field is then the result of a mixture between genuine isolated binaries and dynamical systems previously ejected from their parent star cluster.

### 3.4 Merger efficiency and rate

We estimate the merger efficiency, $\eta(Z)$, defined as the number of mergers $N_{\text{merg}}(Z)$ within a Hubble time, divided by the total initial stellar mass of the YSCs at a given metallicity: $\eta(Z) = N_{\text{merg}}(Z)/M_*(Z)$, where $M_*(Z) = \sum_i M_{\text{SC},i}(Z)$. The merger efficiency is a good proxy for the merger rate, because it does not depend on assumptions on star formation rate, metallicity evolution and delay time (apart from its integrated value). Table 2 shows the merger efficiency for BHNSs from YSCs ($\eta_{\text{YS}}$) and from isolated binaries ($\eta_{\text{IB}}$) at different metallicities. In metal-poor systems ($Z = 0.0002, 0.002$), the merger efficiency of BHNSs from small YSCs is about a factor of 10 lower than the BHNS merger efficiency from isolated binaries. In contrast, at solar metallicity ($Z = 0.02$) the BHNS merger efficiency associated with YSCs is about a factor of 60 higher than the BHNS merger efficiency from isolated binaries.

This result can be interpreted as follows. In metal-poor environments, where very massive BHs can form ($m_{\text{BH}} \geq 50 M_\odot$), exchanges favour the formation of BBHs and suppress the formation of BHNSs, because NSs are much lighter than BHs. In metal-rich environments, where BHs are rather light, dynamics enhances the merger rate of BHNSs.

From the merger efficiency, we can estimate the merger rate density in the local Universe as already described in equation 5 of Giacobbo & Mapelli (2019a):

$$R_{\text{BHNS}}(Z) = \frac{1}{H_0 n_\text{ib}(z=0.1)} \int_{z_{\text{min}}}^{z_{\text{max}}} f_{\text{loc}}(z, Z) SFR(z)(1+z)\mathcal{E}(z) dz,$$

where $SFR(z)$ is the star formation rate density (for which we adopt the fitting formula proposed by Madau & Dickinson 2014); $\mathcal{E}(z) = [\Omega_M(1+z)^3 + \Omega_\Lambda]^{1/2}$; $n_\text{ib}(z=0.1)$ is the look-back time at redshift $z=0.1$, and $f_{\text{loc}}(z, Z)$ is the fraction of merging systems that formed at a given redshift $z$ and merge in the local Universe ($z \leq 0.1$) per unit solar mass. In particular, $f_{\text{loc}}(z, Z) = [N_{\text{loc}}(z,Z)/N_{\text{merg}}(Z)] \eta(Z)$, where $N_{\text{loc}}(z,Z)$ is the number of BHNSs that form at redshift $Z$ with metallicity $Z$ and merge in the local Universe. We assume $z_{\text{max}} = 15$ and $z_{\text{min}} = 0$. Finally, $H_0$, $\Omega_M$, and $\Omega_\Lambda$ are the cosmological parameters for which we take the values from Planck Collaboration et al. (2016). We describe the metallicity evolution of stars in the Universe as detailed in Giacobbo & Mapelli (2019a), based on De Cia et al. (2018).

From equation 2, we obtain a local merger rate density $R_{\text{BHNS}} \sim 50 \text{ Gpc}^{-3} \text{ yr}^{-1}$, by assuming that all the cosmic star formation rate occurs in YSCs like the ones we simulated in this paper.

### 4 CONCLUSIONS

We have studied the formation of BHNSs in 75000 low mass ($300 - 1000 \ M_\odot$) young star clusters (YSCs) by means of direct N-body simulations coupled with binary population synthesis. We have used a version of NBODY6++GPU (Wang et al. 2015) interfaced with our population-synthesis code MOBSE (Giacobbo et al. 2018), as described in Di Carlo et al. (2019b). Very few studies address the dynamics of BHNSs (Devecchi et al. 2007; Clausen et al. 2013; Ye et al. 2020) and none of them focus on YSCs. YSCs are generally less massive than globular clusters and short-lived, but they form all the time across cosmic history: YSCs are the main nursery of BHNSs from YSCs and from isolated binaries. Column 1: metallicity $Z$; column 2: BHNS merger efficiency for YSCs ($\eta_{\text{YS}}$); column 3: BHNS merger efficiency for isolated binaries ($\eta_{\text{IB}}$), from Giacobbo & Mapelli (2018).

| $Z$     | $\eta_{\text{YS}}$ | $\eta_{\text{IB}}$ |
|---------|---------------------|---------------------|
| 0.0002  | $1.8 \times 10^{-6}$ | $1.7 \times 10^{-7}$ |
| 0.002   | $2.1 \times 10^{-6}$ | $2.4 \times 10^{-5}$ |
| 0.02    | $1.5 \times 10^{-7}$ | $2.6 \times 10^{-9}$ |
stars in the local Universe. Moreover, none of the previous works investigate the impact of star cluster dynamics on the mass of BHNSs.

We find that BHNSs formed in YSCs are significantly more massive than BHNSs formed from isolated binary evolution. At low metallicity, the mass of the BH component in a BHNS can reach \( \sim 120 M_\odot \) in YSCs and \( \sim 65 M_\odot \) in isolated binaries, respectively. If we focus on dynamical BHNSs that merge within a Hubble time by GW emission, the vast majority of BHNSs in isolated binaries (\( > 99 \% \)) have mass \( m_{\text{BHNS}} \leq 15 M_\odot \), while \( \sim 34 \% \) of BHNSs in YSCs have mass \( m_{\text{BHNS}} > 15 M_\odot \). Interestingly, not only the exchanged BHNSs (i.e. BHNS systems formed by dynamical exchanges) but also original BHNSs in YSCs (i.e. BHNS systems that form in a YSC from the evolution of a primordial binary star) are significantly more massive than BHNSs formed in isolation. This indicates that dynamical hardening is important for BHNSs in YSCs.

Our simulations do not include compact object spins, because of the large theoretical uncertainties about their magnitude. On the other hand, we expect that dynamical encounters completely randomize the direction of the spins, at least in the case of exchanged binaries (Bouffanais et al. 2019). This implies that our dynamical BHNSs have non-zero components of the spin in the orbital plane, showing precession. Binaries with non-aligned spins and small mass ratio \( q = m_{\text{NS}}/m_{\text{BH}} \) are not expected to be accompanied by bright electromagnetic counterparts (e.g. Zappa et al. 2019).

The vast majority of BHNSs formed in YSCs (\( > 90 \% \)) merge after they were ejected from their parent star cluster. This implies that a large fraction of BHNS mergers in the field might have formed in YSCs.

In metal-poor YSCs (\( Z = 0.0002, 0.002 \)), the BHNS merger efficiency of YSCs is a factor of 10 lower than that of isolated binaries. In contrast, at solar metallicity (\( Z = 0.02 \)) the BHNS merger efficiency of YSCs is a factor of 60 higher than the BHNS merger efficiency of isolated binaries: dynamics triggers a significant number of BHNS mergers at solar metallicity and reduces the differences between metal-poor and metal-rich environments.

Finally, we estimate a local merger rate density \( \dot{\nu}_{\text{BHNS}} \sim 50 \text{ Gpc}^{-3} \text{yr}^{-1} \) consistent with recent estimates from isolated binary evolution (Mapelli & Giacobbo 2018; Artale et al. 2019; Baibhav et al. 2019; Giacobbo & Mapelli 2019b; Tang et al. 2020) and with the upper limit inferred from the first and the second observing runs of LIGO and Virgo (Abbott et al. 2019). Hence, a large fraction of BHNS mergers occurring in the field might have originated in a YSC. We expect that the mass spectrum of BHNS mergers from GW detections will provide a clue to differentiate between dynamical and isolated formation of BHNSs.

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