# [1] The formation and evolution of binary black holes

**Publication**: *Merging black hole binaries with the SEVN code*, Spera, M. et al. (https://arxiv.org/abs/1809.04605)

The first confirmation of the existence of merging stellar-mass black holes (BHs) came on September 14 2015, when the LIGO interferometers observed the gravitational-wave signal from two BHs with mass larger than 25 Msun (GW150914). Since then, four additional BH mergers were observed, and two of them have BHs with mass larger than 30 Msun. From the theoretical point of view, the models that predict the formation and evolution of binary BHs are still uncertain.

**The main aim of my research project was to study the formation and evolution of merging binary black holes, in different stellar environments. The final goal was to interpret present and forthcoming gravitational-wave detections.**

The results of this research have been already published in the following paper (resubmitted to MNRAS after implementing minor comments from the referee): **Merging black hole binaries with the SEVN code, Spera, M. et al. (https://arxiv.org/abs/1809.04605).**

In this paper, we used our up-to-date population synthesis code (SEVN, Spera, M.+ 2015, http://adsabs.harvard.edu/abs/2015MNRAS.451.4086S ) to evolve a large sample of $1.5 \times 10^8$ binary systems, with metallicity in the range $10^{-4}$ to $4 \times 10^{-2}$. From our simulations, we found that:

1. the mass distribution of black holes BHs in double compact-object binaries is remarkably similar to the one obtained considering only single stellar evolution prescriptions (see Fig. 1, dashed red line compared to the grey area);

2. the maximum BH mass we form is $\sim$ 30, 45 and 55 $M_{\odot}$ at metallicity $Z = 2 \times 10^{-2}, 6 \times 10^{-3}$ and $10^{-4}$, respectively (see Fig. 2, top-row panels).

3. a few massive single BHs may also form ( $<\sim$ 0.1% of the total number of BHs), with mass up to $\sim$ 65, 90 and 145 $M_{\odot}$ at metallicity $Z = 2 \times 10^{-2}, 6 \times 10^{-3}$ and $10^{-4}$, respectively (see Fig. 1, solid black line). These BHs fall in the mass gap predicted from pair-instability supernovae (Spera, M. +, 2017 https://arxiv.org/abs/1706.06109).

4. the most massive BHBs are unlikely to merge within a Hubble time. In our simulations, merging BHs like GW151226 and GW170608 form at all metallicities, whereas the high-mass systems (like GW150914, GW170814 and GW170104) originate from metal poor ($Z <\sim 6 \times 10{-3}$ ) progenitors (see Fig. 2, bottom-row panels) .

5. the BHB merger rate in the local Universe obtained from our simulations is ~ $90\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ , consistent with the rate inferred from LIGO-Virgo data ($12 - 213\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ ).

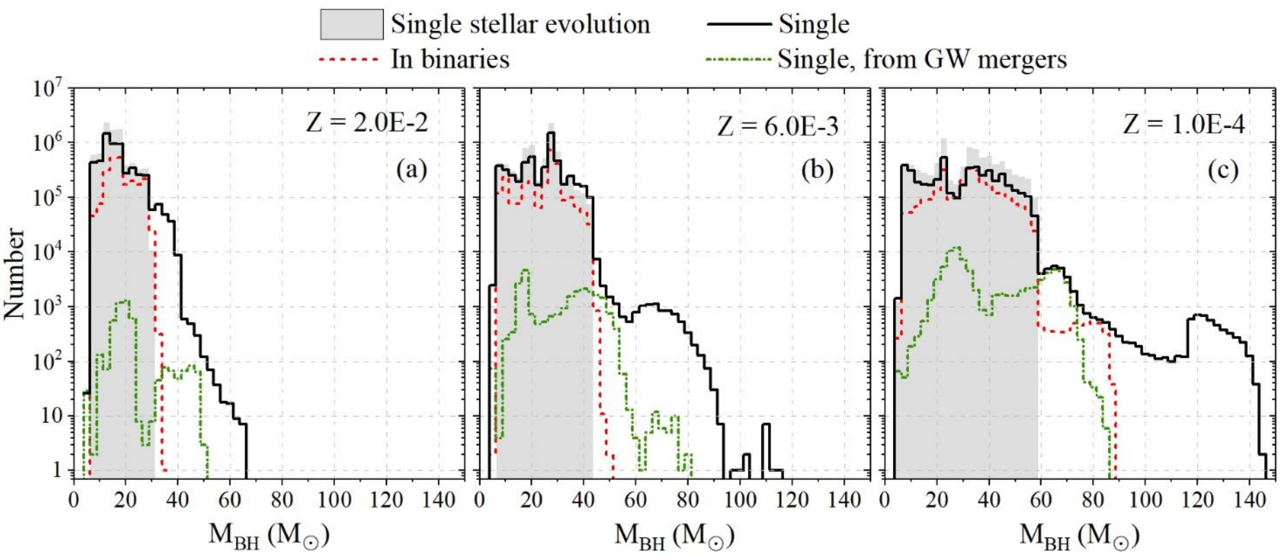


**Fig. 1:** The distribution of the masses of BHs formed in our simulations. Dashed red line: BHs in compact-object binaries; solid black line: single BHs; dash-dotted green line: single BHs that formed from a GW merger. Grey area: BH mass distribution from single star evolution. Left-hand panel (a): $Z = 2 \times 10^{-2}$ ; central panel (b): $Z = 6 \times 10^{-3}$ ; right-hand panel (c): $Z = 10^{-4}$ .

## [2] Intermediate-mass black holes in star clusters

**Publications: 1)** *Effects of a central black hole on the jerks and jounces of pulsars in globular clusters***,** Abbate, F, Spera, M, Colpi, M, (in preparation)

**2)** *Using pulsar jerks to identify IMBHs in star clusters with machine learning***,** Pasquato, M, Spera, M, Abbate, F, (in preparation)

Intermediate-mass black holes (IMBH) are black holes that lie between stellar-mass black holes (with masses $\lesssim 10^2 M_\odot$) and supermassive black holes ($\gtrsim 10^5 M_\odot$). They may play a crucial role in a plethora of astrophysical phenomena: they are possible seeds for the formation of supermassive black holes, they can power some of the brightest X-ray sources, and they can be loud sources of (detectable) gravitational waves.

Still, the existence of intermediate-mass black holes is uncertain and their formation processes are still matter of debate. The dynamical formation scenario for IMBH suggest that globular clusters are ideal hosts for IMBHs but both direct and indirect IMBH searches in star clusters proved inconclusive.

Part of the computing hours of my research project were used to **run a large grid of N-body simulations of star clusters with different initial properties and different IMBH at their centres**. To run the simulations, we used the **HiGPUs-RX code**, whose development was finished thanks to part of the computing hours of my project. The final goal is to **test the effectiveness of new techniques to identify IMBHs in star clusters.** The technique is based on measuring jerks (first time-derivative of acceleration) and snaps (second time-derivative of acceleration) of millisecond pulsars. We show that the effects of a putative IMBH on the jerks and snaps of a pulsar can be measured in pulsar timing campaigns and **may reveal the presence and the mass of the IMBH. We are also exploring a machine learning approach. We trained our machine using jerks and snaps from N-body simulations to check if we were able to identify star clusters that host IMBHs.**

## [3] Development of HiGPUs-RX and SEVN

**Publication:** *Merging black-hole binaries in star clusters: results from a new up-to-date N-body code* Spera, M, (in preparation)

Part of the computing hours were used to finish the development of the HiGPUs-RX and the SEVN codes, both used to perform the population-synthesis and N-body simulations described in this report.

**HiGPUs-RX has been modified to use the new AVX-512 instructions in all its sections and the SEVN code was improved through OpenMP to run multiple binary systems at the same time.**

Both the new versions of the codes were coupled together to study the interplay of stellar dynamics and evolution on the formation of merging black hole binaries in star clusters. Detailed results and applications will be presented in a forthcoming paper.

Part of the simulations that will be used in this paper have been already run to study new techniques to identify IMBH in star clusters (see Section [2]). To complete the simulation set we will need to run additional N-body simulations, therefore my plan is to apply for more computational resources at CINECA.

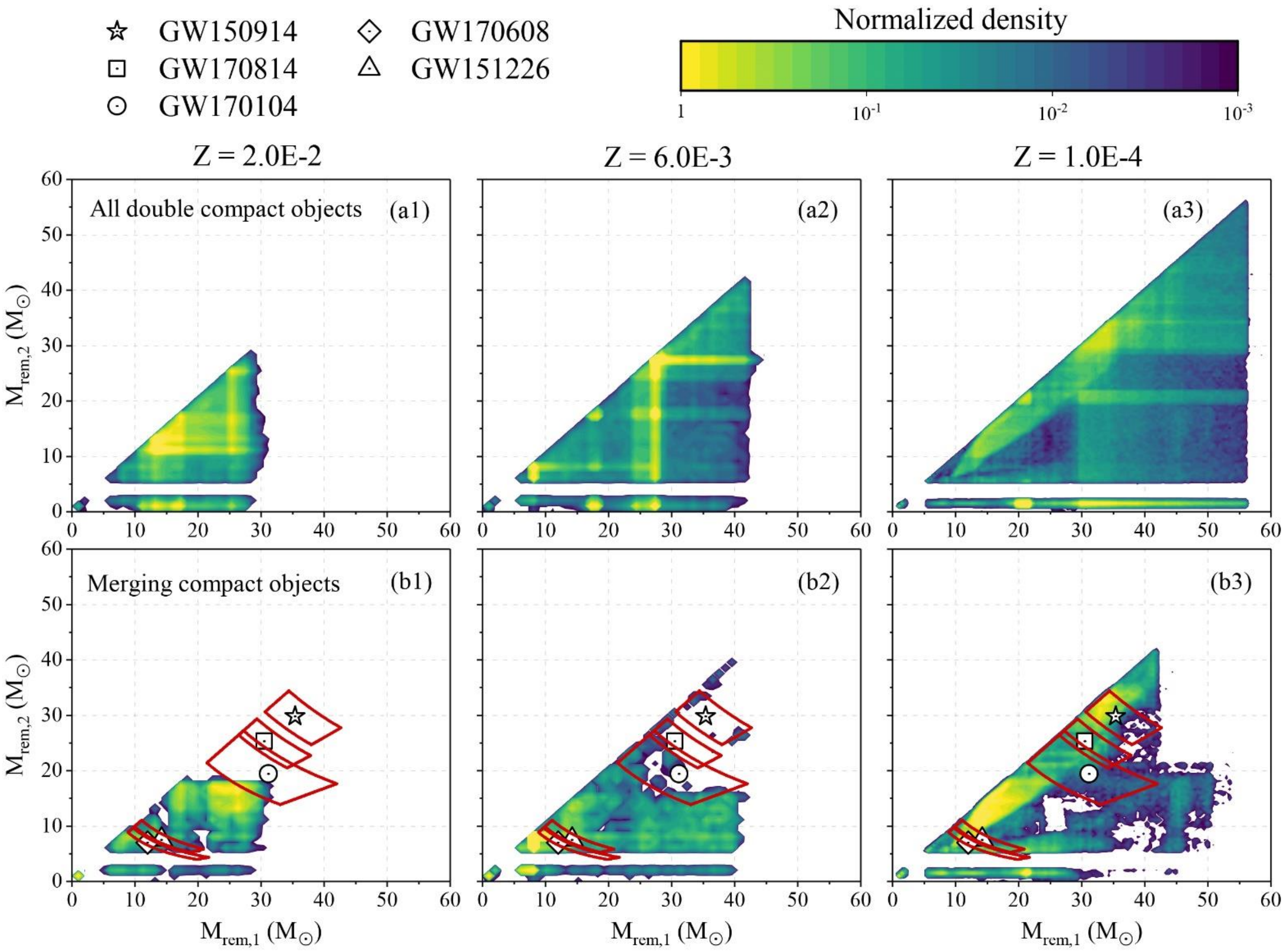


**Fig. 2**: Mass of the less massive remnant (Mrem, 2) as a function of the mass of the more massive remnant (Mrem, 1) in all compact-object binaries (top row), and in the compact-object binaries merging within a Hubble time (bottom row). The logarithmic colour bar represents the number of remnants per cell, normalized to the maximum cell-value of each plot. Each cell is a square with a side of 0.5 M. Left-hand column (labelled as 1): Z = 2 × 10−2; central column (2: Z = 6 × 10−3); right hand column (3): Z = 10−4. The open symbols are the BH mergers detected by LIGO/Virgo in O1 plus the first results of O2. The solid red lines around the open symbols define the 90% credible interval on the chirp mass and the mass ratio of each GW event.