Synthetic catalog of black holes in the Milky Way

A. Olejak\textsuperscript{1,2,3} K. Belczynski\textsuperscript{2}, T. Bulik\textsuperscript{1}, and M. Sobolewska\textsuperscript{4}

\textsuperscript{1} Astronomical Observatory, Warsaw University Ujazdowskie 4, 00-478 Warsaw, Poland
\textsuperscript{2} Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotnikow 32/46, 02-668 Warsaw, Poland
\textsuperscript{3} Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00-716 Warsaw, Poland
\textsuperscript{4} Harvard-Smithsonian Center for Astrophysics, 60 Garden St, Cambridge, MA 02138, USA

Received August 23, 2019;

ABSTRACT

Aims. We present an open-access database that includes a synthetic catalog of black holes (BHs) in the Milky Way, divided by the components disk, bulge, and halo.

Methods. To calculate the evolution of single and binary stars, we used the updated population synthesis code StarTrack. We applied a new model of the star formation history and chemical evolution of Galactic disk, bulge, and halo that was synthesized from observational and theoretical data. This model can be easily employed for other studies of population evolution.

Results. We find that at the current Milky Way (disk+bulge+halo) contains about $1.2 \times 10^8$ single BHs with an average mass of about $14 \, M_\odot$, and $9.3 \times 10^5$ BHs in binary systems with an average mass of $19 \, M_\odot$. We present basic statistical properties of the BH population in three Galactic components such as the distributions of BH masses, velocities, or the numbers of BH binary systems in different evolutionary configurations.

Conclusions. The metallicity of a stellar population has a significant effect on the final BH mass through the stellar winds. The most massive single BH in our simulation of $113 \, M_\odot$ originates from a merger of a BH and a helium star in a low-metallicity stellar environment in the Galactic halo. We constrain that only $\sim 0.006 \%$ of the total Galactic halo mass (including dark matter) can be hidden in the form of stellar origin BHs. These BHs cannot be detected by current observational surveys. We calculated the merger rates for current Galactic double compact objects (DCOs) for two considered common-envelope (CE) models: $\sim 3-81 \text{ Myr}^{-1}$ for BH-BH, $\sim 1-9 \text{ Myr}^{-1}$ for BH-neutron star (NS), and $\sim 14-59 \text{ Myr}^{-1}$ for NS-NS systems. We show the evolution of the merger rates of DCOs since the formation of the Milky Way until the current moment with the new star formation model of the Galaxy. Data files are available on our website, https://bhc.syntheticuniverse.org/.

Key words. black hole – Milky Way – population synthesis – binary systems

1. Introduction

The study of the Galactic black hole (BH) population is still a great challenge because BHs themselves do not emit in electromagnetic wavelengths, except for the theoretically predicted Hawking radiation. However, BHs in binary systems can be observed in their interaction with their companion, for example, when a star transfers mass onto the BH (https://stellarcollapse.org/sites/default/files/table.pdf and references within). Binary system with a BH may also be identified by measuring the velocities of the components in wide binary systems (Igoshev & Perets 2019). Recently, after constructing the detector on the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Michelson interferometer Virgo, double compact object (DCO) systems such as BH-BH, BH-NS, and NS-NS could also be detected through the emission of gravitational waves (Abbott et al. 2016a,b,c, 2017a,b,c; The LIGO Scientific Collaboration et al. 2018). Unfortunately, these methods cannot be used in order to detect single BHs, which do not interact with any other massive physical objects. The most promising way to study a single BH population therefore appears to be the gravitational lensing phenomenon (Wyrzykowski et al. 2016a,b). Another possible method that might allow the detection of isolated single and binary BHs is studying the X-ray emission caused by accretion from the dense interstellar medium (ISM) (Tsuna et al. 2018). No BH has been detected with this method so far, however.

On the other hand, with access to cosmological population synthesis simulations and theoretical stellar evolution models, the number of Galactic BHs may be predicted in different configurations. Several attempts of such studies have been made in the past. For example, a total number of Milky Way BHs was estimated by Shapiro & Teukolsky (1983); van den Heuvel (1992); Brown & Bethe (1994) and Timmes et al. (1996) at the level of $10^8 - 10^9$. The population of Galactic BH-BH binaries has been studied using the cosmological simulations by Lamberts et al. (2018). The total number of BH-BH binaries was estimated at $\sim 1.2 \times 10^6$ with the average mass of $28 \, M_\odot$ per system. Massive star and DCO binaries were studied using a galactic evolution code (Vanbeveren & Donder 2010; Mennekens & Vanbeveren 2014). Recently, Wiktorowicz et al. (2019) predicted the number of Galactic BHs that formed from binary star systems assuming one Galactic component (disk) and constant star formation rates (SFR) in the Galaxy.

Almost 20 Galactic stellar BHs in binaries are currently observed (Casares 2007; Casares & Jonker 2014), (https://stellarcollapse.org/sites/default/files/
updated over the years (Belczynski et al. 2002, 2008, 2017).

2.1. Initial conditions

For the initial mass of the single star we adopted three broken power-law initial mass functions (IMF) from Kroupa (1993), but we calibrated the power-law exponent \( \alpha_1 \) to match observations for massive stars as proposed by Kroupa (2002),

\[
\begin{align*}
\alpha_1 &= -1.3 \text{ for } M \in [0.08, 0.5] M_\odot, \\
\alpha_2 &= -2.2 \text{ for } M \in [0.5, 1.0] M_\odot, \\
\alpha_3 &= -2.3 \text{ for } M \in [1.0, 150.0] M_\odot
\end{align*}
\]

We applied the calibrated IMF for single stars and primary (more massive) stars in binary systems. The mass of the secondary (less massive) star of a binary system (\( M_2 \)) is the mass of the more massive star (\( M_1 \)) from the IMF multiplied by the mass ratio factor \( q \) from a uniform distribution in the range \( q \in [0.08/M_1, 1] \).

To generate the initial semimajor axis of a binary system, we used the third Kepler law (relation of semimajor axis to period). We adopted a power-law distribution in log\( (P) \) in the range \( \log (P[\text{days}]) \in [0.15, 5.5] \) with exponent \( \alpha_2 = -0.55 \) and a power-law initial eccentricity distribution with exponent \( \alpha_3 = -0.42 \) in the range \([0,0.9] \). This initial distribution of orbital parameters was taken from Sana et al. (2012), but we adopted the extrapolation of the orbital period distribution proposed by de Mink & Belczynski (2015).

In our simulation we generated single and binary star systems with different metal contents and ages. For each of the 18 stellar populations of the Galactic components (see Sec. 2.5) with a given age and metallicity, we evolved 2.5 \( \times \) 10^6 binary systems (primary component in the mass range 5–150 \( M_\odot \) and secondary in the mass range 0.08–150 \( M_\odot \)) and 5.0 \( \times \) 10^6 single stars (in the mass range 5.0–150 \( M_\odot \)). The total simulated mass of systems generated for each stellar population in the whole IMF mass range 0.08-150 \( M_\odot \) is 3.1 \( \times \) 10^{55} \( M_\odot \) for binaries and 7.6 \( \times \) 10^{55} \( M_\odot \) for single stars. We linearly scaled the number of generated systems to fit the real mass fractions and the binarity of the stellar populations in the Galactic components.

2.2. Physics model

In our simulation we applied the standard updated StarTrack physical model. We used a rapid supernovae (SN) model with explosions driven by instabilities with a rapid growth time of about 10–20 ms (Fryer et al. 2012a). The model includes weak pulsation pair-instability supernovae (PPSN) and pair-instability supernovae (PSN) (Woosley 2017; Belczynski et al. 2016). We applied the moderately weak PPSN model with only up to 50% mass loss by Leung et al. (2019) and approximated the formula for the final post-PPSN remnant mass (\( M_f \)) as a function of He core mass (\( M_{He} \)) in the following way:

\[
M_f = \begin{cases} 
0.83 M_{He} + 6.0 M_\odot & M_{He} \in [40.0, 60.0] M_\odot, \\
55.6 M_\odot & M_{He} \in [60.0, 62.5] M_\odot, \\
-14.3 M_{He} + 938.1 M_\odot & M_{He} \in [62.5, 65.0] M_\odot.
\end{cases}
\]

To obtain remnant natal kicks after SN explosion, we used a Maxwellian velocity distribution with \( \sigma = 265 \) km/s (Hobbs et al. 2006). The BH velocities from the Maxwellian distribution were
multiplied by a fallback factor \( f_{\text{fb}} \in (0, 1) \), which is inversely proportional to the fallback of material after an SN explosion. As a result, we obtain both high and low natal kick velocities for BHs.

In the simulations we adopted the following mass-transfer settings: 50% nonconservative Roche-lobe overflow (RLOF) and 5% Bondi-Hoyle rate accretion onto the NS-BH in the common-envelope (CE) phase. We did not consider effects of rotation on stellar evolution.

In our simulation we assumed a stellar binary fraction of 50% so that two-thirds of the stars in all Galactic components are formed in binary systems and one-third of them are single stars, as indicated by observational data (Gao et al. 2014; Kobulnicky et al. 2014). The chosen value is a conservative lower limit on the massive stellar binary (Sana et al. 2014). We assumed that solar metallicity is \( Z_0 = 0.014 \) (Asplund et al. 2009).

2.3. Hertzsprung gap stars in the CE phase

We calculated two CE models (called A and B) that represent different scenarios for a binary system with a Hertzsprung gap (HG) star as a donor in the CE phase. In model B we assumed that all of these binary systems merge during the CE phase and possibly create a single BH. In model A we let this system survive the CE phase in the energy balance calculations (Webbink 1984). It is currently not well known which scenario prevails (Ivanova & Taam 2004).

2.4. Mergers

A significant part of Galactic BHs may have formed in mergers of binary systems (Kochanek et al. 2014). The final mass of a BH that formed in stellar mergers depends on the masses of the components and on evolutionary type of the merging objects. The amount of mass ejected from the system after its coalescence is most likely lower for DCOs than for radially extended giant stars. However, stellar collisions are not well studied yet and the final products of different merger types are not fully understood. Observations as well as simulations of stellar coalescence are made only for a limited number of object types, usually for low-mass stars, which are not BH progenitors (J. C. Lombardi et al. 2002; Tylenda & Kamiński 2016), or they refer to dynamical collisions in stellar clusters (Glebbeek et al. 2013). The literature indicates rather low mass-loss during stellar mergers, however: it is up to \( \sim 10 \% \) of the system mass (J. C. Lombardi et al. 2002; Lombardi et al. 2006; Glebbeek et al. 2013). Additionally, the further evolution of the coalescence products is not well understood. We therefore adopted a simple model to estimate evolutionary types and masses of merger products. To specify a type and the structure of the objects that originated from different merger types, we used Table 13 (based on Table 2 from Hurley et al. (2002)). The exceptions from the types listed in the table are two cases: in the first case, when the merger product is defined as 13 (NS), we classified whether a given object is an NS or a BH based on its mass. Current observations indicate that a NS mass may be as high as \( 2.27^{+0.17}_{-0.15} M_\odot \) (Linares et al. 2018). Theoretical models result in a wide range of maximum NS masses: \( M_{\text{NS,max}} = 2.2 - 2.9 M_\odot \) (Kalogera & Baym 1996). In our simulations we adopted a maximum NS mass of \( M_{\text{NS,max}} = 2.5M_\odot \). The second exception are the mergers with white dwarfs (WDs), which may lead to an SN Ia explosion that leaves no remnant behind. Our criterion for SN Ia explosion is in accordance with the procedure in Belczynski et al. (2008).

In order to estimate the total mass of an object created after coalescence, we divided the stars into four main categories: main-sequence (MS) stars, giant (G) stars, helium (He) stars, and compact objects (COs). Within G stars we include types: Hertzsprung gap star, first giant branch star, core He burning star, early asymptotic giant branch star and thermally pulsing asymptotic giant branch star. The total mass of the object formed in a merger (\( M_{\text{imp}} \)) was then calculated according to the procedure below:

- **MS-MS**
  We took the sum of the more massive star and the fraction of mass (\( f_{MS} = 0.8 \)) of the less massive star if (\( M_{MS_1} > M_{MS_2} \)):
  \[ M_{\text{imp}} = M_{MS_1} + f_{MS} \cdot M_{MS_2} \]

- **He-He**
  We took the sum of the more massive star and the fraction of mass (\( f_{He} = 0.8 \)) of the less massive star if (\( M_{He_1} > M_{He_2} \)):
  \[ M_{\text{imp}} = M_{He_1} + f_{He} \cdot M_{He_2} \]

- **G-G**
  We took the sum of the more massive star and the fraction of mass (\( f_G = 0.5 \)) of the less massive star if (\( M_{G_1} > M_{G_2} \)):
  \[ M_{\text{imp}} = M_{G_1} + f_G \cdot M_{G_2} \]

- **CO-CO**
  We took the sum of the masses of the COs,
  \[ M_{\text{imp}} = M_{CO_1} + M_{CO_2} \]

- **MS-He**
  We took the sum of the mass of the He star and the fraction of mass (\( f_{MS} = 0.8 \)) of the MS star,
  \[ M_{\text{imp}} = M_{He} + f_{MS} \cdot M_{MS} \]

- **MS-G**
  We took the sum of the mass of the MS star and the fraction of mass (\( f_G = 0.5 \)) of the G star,
  \[ M_{\text{imp}} = M_{MS} + f_G \cdot M_{G} \]

- **MS-CO**
  We took the sum of the CO mass and the fraction of mass (\( f_{MS} = 0.8 \)) of the MS star,
  \[ M_{\text{imp}} = M_{CO} + f_{MS} \cdot M_{MS} \]

- **He-G**
  We took the sum of the He star mass and the fraction of mass (\( f_G = 0.5 \)) of the G star,
  \[ M_{\text{imp}} = M_{He} + f_G \cdot M_{G} \]

- **He-CO**
  We took the sum of the CO mass and the fraction of mass (\( f_{He} = 0.8 \)) of the He star,
  \[ M_{\text{imp}} = M_{CO} + f_{He} \cdot M_{He} \]

- **CO-G**
  We took the sum of the CO mass and the fraction of mass (\( f_G = 0.5 \)) of the G star,
  \[ M_{\text{imp}} = M_{CO} + f_G \cdot M_{G} \]

Next, after determining the type and mass of the object formed in merging using the scheme above, we still evolved it as a single star of a given type and mass with the code StarTrack even when the object was not compact (WD, NS, or BH). We set the formed star at the beginning of its given evolutionary step. Then the stellar structure (the core and the envelope mass) was calculated with the procedures given by Hurley et al. (2000); Hurley et al. (2002) and Belczynski et al. (2008).
2.5. Star formation history of the Milky Way

We created a new model of SFR and metallicity distribution of stellar populations in the Milky Way. The previously used model was not realistic because it typically considered only one Galactic component (disk) with a constant SFR and the same metallicity for all stars, usually equal to $Z=0.02$ (e.g., in Abadie et al. (2010); Belczynski et al. (2018)). These assumptions are inconsistent with our current knowledge about the Milky Way. The SFR is important for many reasons. For example, the number of Galactic COs (BHs, NSs, and WDs) scales linearly with the assumed stellar mass. The formation time of the considered stellar population may significantly affect the merger rates of DCOs because it determines the fraction of binaries that has already merged.

The metallicity of stellar populations is extremely important for BHs because their formation and mass depend critically on stellar winds, which in turn are a sensitive function of the chemical composition of the progenitor stars (e.g., Belczynski et al. (2010); Mennekens & Vanbeveren (2014); Klenczki et al. (2018)). We have prepared a new model of SFR and the metallicity evolution of three Galactic components: the disk (thin and thick), the bulge, and the halo, based on information in the recent literature. Our overall model for Milky Way star formation is shown in Figure 1, and details are described in the following sections: for the bulge, see Sec. 2.5.1; for the disk, see Sec. 2.5.2; and for the halo, see Sec. 2.5.3.

![Fig. 1. SFR of all Galactic components as a function of lookback time. The current time is 0. The old SFR model (blue dotted line) is plotted for comparison.](image)

2.5.1. Galactic bulge

The Galactic bulge is the central part of the Galaxy with a corotation radius of $\sim 4$ kpc (Gerhard 2001). In our calculation we assumed that the total stellar mass of the Galactic bulge is $0.91\pm0.07\times10^{10}M_\odot$ (Licquia & Newman (2015)). Stellar metallicity and age distribution cover a wide range of values, as is shown both by observations (e.g., Bensby et al. (2018)) and cosmological simulations (e.g., Kobayashi & Nakasato (2011)). To reconstruct the properties of the stellar populations in the bulge, we used the figures from Kobayashi & Nakasato (2011). For the stellar age distribution, we used Fig. 6, and for the stellar age-metallicity relation, we used Fig. 8.

We approximated the metallicity and age relations in the following way: half of the stars in the bulge formed 10-12 Gyr ago (a formation peak, SFR=$\sim2.3M_\odot$ yr$^{-1}$) and the other half of the stars formed from 10 Gyr ago to the current time, with a constant SFR of $\sim0.5M_\odot$ yr$^{-1}$. Star systems that are older than 10 Gyr were divided into four groups equal in mass, of metallicities $0.1Z_\odot$, $0.3Z_\odot$, $0.6Z_\odot$, and $1.0Z_\odot$. A stellar population younger than 10 Gyr has a high metal content, equal to $1.5Z_\odot$. Our model of the star formation and metallicity for the bulge is shown in Figure 2.

![Fig. 2. SFR and metallicity in the Galactic bulge as a function of lookback time. The current time is 0. Vertical dashed lines separate stellar populations with different metallicities.](image)

2.5.2. Galactic disk

In our calculations we used the total mass of the Galactic disk, $5.17\pm1.11\times10^{10}M_\odot$, estimated by Licquia & Newman (2015). We assumed that disk is divided into two main components, the thick and the thin disk. They had different star formation histories. The stellar populations in the disk have different metal contents and ages. The thin disk is dominant in mass; it contains about 90% of all disk stars (Cignoni et al. (2006)). In our model 90% of the total disk stellar mass is therefore contained in the thin disk, and the remaining 10% of mass is in the thick disk.

The thick disk formed first, and its average age has been estimated to be $9.6$ Gyr $\pm 0.3$ by Soubiran & Girard (2005). The contribution of stars younger than 9 Gyr to the thick disk is very low, as was shown by Cignoni et al. (2006). In our model the stellar population in the thick disk formed with an SFR $\sim2.5M_\odot$ during the period from 11 to 9 Gyr ago and has a metal content equal to $0.25Z_\odot$, see Fig. 6 (Liu et al. (2018)).

The SFR of the thin disk was estimated based on the age distribution of observed stars shown in Fig. 13 in Casagrande et al. (2011) and on the results of Kobayashi & Nakasato (2011). We approximated figures by ten star formation episodes, which started 10 Gyr ago and lasted until the present moment. New episodes occurred every 1 Gyr and lasted for $\Delta t = 1$ Gyr, with the constant SFR equal to $5M_\odot$ yr$^{-1}$. Based on the metallicity-age relation presented in Haywood et al. (2013) and Haywood et al. (2015), in the next formation episodes, the metal content of the stellar populations increased and changed from $0.1Z_\odot$ to $Z_\odot$ with...
a rate of $\Delta Z = 0.1 Z_\odot \text{Gyr}^{-1}$. Our SFR and metallicity distribution model of the disk as a function of time is shown in Fig. 3.

![Fig. 3. SFR and metallicity of the Galactic disk as a function of look-back time. The current time is 0. Vertical dashed lines separate stellar populations with different metallicities.](image)

2.5.3. Galactic halo

The Galactic halo is the most massive Galactic component. The total mass of the halo is estimated as $\sim 10^{10} M_\odot$ (Wang et al. 2015; Grand et al. 2019), but most of it is dark matter, which does not reflect or emit electromagnetic radiation. In our simulation we considered only the stellar mass in the Galactic halo, which is a small fraction of the total halo mass, estimated to be about $2 \times 10^8 M_\odot$ (Morrison et al. 2000; Chiba & Beers 2000; Yanny et al. 2000; Siegel et al. 2002; Bullock & Johnston 2005). To reconstruct the age and metallicity of stars in the halo, we used the results of the cosmological simulations by Kobayashi & Nakasato (2011). We show in Fig. 6 the distribution of stellar ages for the halo and in Fig. 8 the relation of stellar age to metallicity. We simplified the relation by dividing the halo into two components equal in mass that formed 11-12 Gyr and 10-11 Gyr ago with metallicities of 0.01Z_⊙ and 0.02Z_⊙, respectively, and a SFR of $\sim 0.5 M_\odot \text{yr}^{-1}$. The model of the SFR and metallicity in the halo is shown in Fig. 4.

![Fig. 4. SFR and metallicity of the Galactic halo as a function of look-back time. The current time is 0. The vertical dashed line separates stellar populations with different metallicities.](image)

2.6. Velocities and coordinates of Galactic BHs

In our online database (https://bhc.syntheticuniverse.org/) we list simple estimates of Galactic coordinates and BH velocities. The coordinates of the BHs were randomly selected using formulas for stellar mass distributions in Galactic components. For the bulge and halo, we used the formulas given by Korol et al. (2018). For the bulge we drew the distances to the Galactic center from the range [0-4] kpc, setting the parameter $r_b = 1.0$ kpc (the characteristic radius of the bulge), while for halo, the possible distance range is [15-30] kpc. We assumed that both bulge and halo are spherical. For BHs in the Galactic disk we used the expression from Li (2016). We drew distances from the range of [2-15] kpc in order to obtain x and y coordinates, while the z coordinate was taken from the uniform distribution in range [-0.15,0.15] kpc because we assumed an average disk height of 0.3 kpc (Rix & Bovy 2013). Here we set the parameter $r_b = 2.0$ kpc (the radius of the central bulge) for continuity between the disk and bulge components.

The total velocity of a Galactic BH is the sum of the motion in the Milky Way gravitational potential and the velocity obtained during isolated or binary evolution. In our estimation of the BH speed, we considered the rotation velocities around the Galactic center and additional BH velocities from physical processes such as SN explosions. Single and binary BHs might obtain a significant portion of kinetic energy after SN or core-collapse formation through a flux release of asymmetric neutrinos (Fryer et al. 2012b; Janka 2017). If the BH is in a binary system, the whole system changes its velocity after the first and second NS or BH formation (Kalogera 1996). If the velocity is high enough, the binary system disrupts. The disruption of a binary system may occur not only in asymmetric SN explosions. A disruption may also be the result of a Blaauw kick (Blauuw 1961) associated with symmetric mass loss, which leads to a change in the mass ratio and in the orbital elements of the system.

We calculated the velocities of single and binary BHs after their formation in three spatial dimensions, $V_s = [V_{s,x}, V_{s,y}, V_{s,z}]$. To estimate the motion of BHs in the Milky Way potential, we used an approximated form of the Galactic rotational curve ($V_r$) that has been applied in other Galactic simulations (e.g., Abramowicz et al. (2018)). The simplified rotational curve has the form $V_r = \begin{cases} 220 \text{ km/s} & \text{for the disk and halo} \\ 220 \text{ km/s} \times r/R_0 & \text{for the bulge.} \end{cases}$

In our estimates, $R_0$ is the radius of bulge, equal to 4 kpc (Gerhard 2001), and $r$ is the distance from the BH to the Galactic center generated from the bulge mass distribution (Korol et al. 2018), as described above.

In order to calculate the sum of the two velocities ($V_s, V_r$), we generated components of vector $V_s$ in three spatial dimensions for the bulge and halo (spherical motion) and in two dimensions for the disk (motion in plane). The total BH velocity in our results is the norm of the sum of the two velocities $V_s$ and $V_r$ in three dimensions.
3. Results

We present the results of our simulations for the Galactic components in Section 3.1 for the bulge, Section 3.2 for the disk (thin and thick), and in Section 3.3 for the halo. In each of the subsections we provide tables for single and binary BHs. The tables contain basic statistical information such as estimated number of BHs in different configurations, formation channels, and average masses of BHs and their companions (for binary BHs). The tables list two values that refer to the two evolution models A and B (see Sec. 2.3), given in the order A/(B).

In the table with single BHs we include single stars, mergers, and disrupted binaries. These sections refer to the BH formation channel. The section single stars contains BHs that are remnants of the massive single star evolution. The merger section includes single BHs created through coalescence of a binary system, and it is divided into several rows corresponding to the types of objects that have merged. The third section contains BHs from disrupted binary systems. In the merger section, the entries in the row with BH-BH systems refer to the number of single BHs that formed in the merger of two BHs, while in the section for disrupted systems, the number in the row BH-BH is the total number of single BHs after system disruption (i.e., twice the number of disrupted BH-BH binaries).

The table with binary system BHs contains two sections: one with DCO systems (BH-BH, BH-NS, and BH-WD), and one with other binary systems in which the BH companion is an unevolved star. The table contains information about the types of the BH companion objects, the estimated number of BHs in a given Galactic component, and their average masses. In Section 3.4 we constrain the amount of dark matter that might be hidden in the Galactic halo in the form of stellar origin BHs, which cannot be detected by current observation surveys. In Section 3.10 we calculate the change in Galactic CO merger rates from the Milky Way formation until the present time. In Table 11 we present the current Galactic merger rates for BH-BH, BH-NS, and NS-NS binary systems. In Section 3.5 we present and discuss the distribution of single and binary BH mass in the Galactic bulge, disk, and halo. In Section 3.7 we show and discuss the velocity distribution of single and binary BHs in the Galactic components. In Table 10 we list the average speeds of BHs in the bulge, disk, and halo. We constrain the fraction of BHs with speeds high enough to escape from the Galaxy. In Figure 5 we show the change in the total numbers of single BHs and BHs in binary systems in the Milky Way from the Milky Way formation until the present time for the two evolutionary models A and B (Sec. 2.3).

3.1. Galactic bulge

We find that the Galactic bulge hosts about $1.7 \times 10^7$ single BHs and about $1 \times 10^6$ BHs in different types of binary systems. The average mass of a single BH is $11.7/(11.3) M_\odot$, and the average mass of a BH in a binary system is $15.6/(15.8) M_\odot$. The most massive BHs in the bulge are formed by coalescence of a massive binary system (BH and a massive star or binary BH system), and they can reach $\sim 100 M_\odot$.

A significant number of single BHs in the bulge (nearly 50%) are remains of the evolution of single massive stars. The average mass of such a BH is $\sim 11.7 M_\odot$. The second important origin of single BHs is a merger of a binary system, especially MS-MS and MS-He. Almost 30% of the single BHs in the bulge are formed in mergers, and their remaining masses cover a wide range of values. The least massive single BHs originates from mergers of low-mass binaries such as WD-MS or WD-He. The formed masses often fill the first observational mass gap between 3-5 $M_\odot$ (Demorest et al. (2010); Antoniadis et al. (2013); Swihart et al. (2017); Wyrzykowski & Mandel (2019)). The third main formation channel of single BHs is the disruption of binary systems after formation of a BH or NS. These BHs are about 20% of all single BHs in the bulge, and their average mass is $\sim 10 M_\odot$.

The average BH mass in a binary system is $\sim 17 M_\odot$. Most binary systems with a BH in the bulge are BH-BH systems (80% of the binary BHs). The BHs in binary systems with a non-compact companion make up about 3% of all binary BHs in the bulge.

3.2. Galactic disk

About 80% of Galactic BHs are in the disk because in our simulation, this is the most massive component (see Sec. 2.5). In the two disk components, the thin and thick disk, there are in total $\sim 1.0 \times 10^8$ single BHs with an average mass of $\sim 14 M_\odot$, and about $8 \times 10^6$ BHs in binary systems with an average mass of BH $\sim 19 M_\odot$. The most massive BHs in the Galactic disk have a mass of $\sim 100 M_\odot$, and they are formed by coalescence of a BH and a massive star (MS or He).

There are three main formation channels of single BHs in the Galactic disk. About 45% of the single BHs in the thin disk and in thick disk are final remnants of the evolution of massive single stars. The second important channel is the merger of binary systems, which leads to the formation of 25-30% of single BHs in the disk. The BHs from disrupted binaries make up about 20% of all single BHs in the disk, and their average mass is $\sim 12 M_\odot$.

Most binary BHs in the disk ($\sim 80\%$ of BHs in binaries) are in a BH-BH configuration. The average mass of a BH in a binary system is about $\sim 19 M_\odot$. The fraction of BHs with an unevolved companion is small, lower than 2% of all binary BHs in the disk.
Table 1. Single BHs in the bulge

| Object type | Number   | \(\dot{M}_{BH}[M_\odot]\) |
|-------------|----------|--------------------------|
| **Single stars** |         |                          |
| Single star  | \(8.5 \times 10^6\) / (8.5 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 11.7 / (11.7) |
| **Mergers** |         |                          |
| BH - BH     | \(2.0 \times 10^6\) / (2.1 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 28.4 / (24.8) |
| BH - NS     | \(1.6 \times 10^6\) / (2.5 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 10.7 / (12.0) |
| NS - NS     | \(5.0 \times 10^5\) / (4.9 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 2.8 / (2.6) |
| MS - MS     | \(3.1 \times 10^5\) / (3.1 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 12.0 / (12.0) |
| MS - He     | \(2.3 \times 10^5\) / (6.6 \times 10^4) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 19.0 / (20.4) |
| MS - G      | \(1.3 \times 10^4\) / (1.2 \times 10^4) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 11.2 / (11.2) |
| He - He     | \(1.2 \times 10^3\) / (3.2 \times 10^3) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 10.4 / (8.7) |
| CO - MS     | \(1.3 \times 10^3\) / (1.2 \times 10^3) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 14.2 / (14.4) |
| CO - G      | \(2.4 \times 10^3\) / (2.4 \times 10^3) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 5.0 / (4.9) |
| CO - He     | \(8.0 \times 10^2\) / (2.1 \times 10^2) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 17.0 / (5.9) |
| **Disrupted systems** |         |                          |
| BH - BH     | \(1.0 \times 10^6\) / (1.0 \times 10^6) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 10.1 / (10.1) |
| BH - NS     | \(2.9 \times 10^6\) / (2.8 \times 10^6) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 9.8 / (9.7) |
| BH - WD     | \(1.3 \times 10^5\) / (1.3 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 8.6 / (8.6) |
| BH - MS     | \(2.1 \times 10^5\) / (2.1 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 8.4 / (8.4) |
| **Total**   | \(1.7 \times 10^7\) / (1.6 \times 10^6) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 11.7 / (11.3) |

Values for models A and B given in the order A/B. In the section with compact mergers in row BH-BH, the number refers to the number of single BHs that where created. In the section with disrupted systems, the number in row BH-BH represents the total number of single BHs after disruption (not the number of systems).

Table 2. Binary systems with BHs in the bulge

| Object type | Number   | \(\dot{M}_{BH}[M_\odot]\) | \(\dot{M}_{Comp}[M_\odot]\) |
|-------------|----------|--------------------------|--------------------------|
| **DCO system** |         |                          |                          |
| BH - BH     | \(7.6 \times 10^6\) / (7.0 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 17.1 / (17.4) | – |
| BH - NS     | \(3.1 \times 10^6\) / (2.5 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 11.8 / (12.2) | 1.3 / (1.3) |
| BH - WD     | \(2.3 \times 10^5\) / (2.1 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 11.7 / (11.8) | 1.0 / (1.0) |
| **Other binary system** |         |                          |                          |
| BH - MS     | \(3.2 \times 10^5\) / (3.2 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 11.0 / (11.0) | 0.7 / (0.7) |
| BH - G      | \(1.5 \times 10^5\) / (1.5 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 8.8 / (8.8) | 1.3 / (1.3) |
| **Total**   | \(1.0 \times 10^6\) / (9.6 \times 10^5) \(\bar{\dot{M}}_{BH}[M_\odot]\) | 15.7 / (15.9) | 1.0 / (1.0) |

Values for models A and B given in the order A/B. The number in the row with BH-BH systems refers to the total number of BHs (not systems).

3.3. Galactic halo

The Galactic halo is the least massive component in our simulation because we considered only its stellar mass (Sec. 2.5). Most of the halo mass is not in stars, therefore we did not consider this mass in the stellar origin BH formation. The total number of BHs in the halo is only 4 % of the entire Galactic BH population, it contains \(4 \times 10^7\) single BHs with an average mass \(\sim 20 M_\odot\) and about \(5 \times 10^7\) BHs in binary systems with an average BH mass \(\sim 24 M_\odot\).

Because the metallicity of the stellar populations is low, the most massive BH in the simulations, with a mass of 113 \(M_\odot\), is formed in halo. It originates from a merger of a BH and a He star. The formation channels of single BHs in the halo are the same as in the disk and bulge. Over 50% of single BHs are remnants of the evolution of single massive star, and 20-25% formed in binary system mergers (mainly MS+MS, MS+He, and WD+He). The BHs from disrupted binary systems make up \(\sim 15\%\) of the single BHs in the halo, and have an average mass of about 17 \(M_\odot\).

The binary BHs in the halo are also mainly in BH-BH binaries (\(\sim 80\%\) of the binary BHs). The fraction of BHs with a noncompact companion in the halo is \(\sim 1.5\%\).

3.4. Dark matter in BHs of stellar origin

Several microlensing surveys have been made towards the halo in order to search for and constrain the number of massive compact halo objects (MACHOs) that may constitute part of the dark matter (Alcock et al. 2001). MACHOs with masses over 20 \(M_\odot\) cannot be excluded by observations (Tisserand et al. 2007; Wyrzykowski et al. 2011) because current microlensing surveys do not cover timescale that are long enough to detect such massive objects. On the other hand, the existence of wide binary systems in the halo indicates the absence of MACHOs with masses higher than \(\sim 100 M_\odot\). The observed binaries would likely disrupt in interaction with objects with such a high mass (Yoo et al. 2004; Monroy-Rodriguez & Allen 2014). These two restrictions
Table 4. Single BHs in the thick disk

| Object type | Number | $\bar{M}_{BH}[M_\odot]$ |
|-------------|--------|--------------------------|
| **Single stars** | | |
| Single star | $4.3 \times 10^6/(4.3 \times 10^5)$ | 17.0/(17.0) |
| **Merger** | | |
| BH - BH | $2.5 \times 10^5/(2.9 \times 10^4)$ | 30.2/(17.8) |
| BH - NS | $1.7 \times 10^6/(3.9 \times 10^5)$ | 11.8/(12.3) |
| NS - NS | $8.3 \times 10^5/(3.8 \times 10^4)$ | 2.7/(2.6) |
| MS - MS | $1.5 \times 10^6/(1.5 \times 10^5)$ | 18.9/(18.9) |
| MS - G | $4.4 \times 10^5/(3.9 \times 10^4)$ | 17.7/(18.2) |
| He - He | $1.3 \times 10^5/(4.0 \times 10^4)$ | 10.0/(8.5) |
| CO - MS | $1.0 \times 10^5/(1.0 \times 10^4)$ | 17.6/(19.7) |
| CO - G | $2.0 \times 10^5/(2.2 \times 10^4)$ | 4.7/(5.4) |
| CO - He | $7.4 \times 10^5/(2.3 \times 10^4)$ | 19.1/(6.1) |

**Disrupted systems**

| BH - BH | $8.3 \times 10^5/(8.3 \times 10^4)$ | 12.8/(12.8) |
| BH - NS | $1.3 \times 10^6/(1.3 \times 10^5)$ | 13.8/(13.8) |
| BH - WD | $8.8 \times 10^5/(8.8 \times 10^4)$ | 10.3/(10.3) |
| BH - MS | $9.0 \times 10^5/(9.0 \times 10^4)$ | 10.3/(10.3) |

**Total:** $9.5 \times 10^5/(8.5 \times 10^4)$ 17.0/(16.3)

Values for models A and B given in the order A/B. In the section with compact mergers in row BH-BH, the number refers to the number of single BHs that where created. In the section with disrupted systems, the number in row BH-BH represents the total number of single BHs after disruption (not the number of systems).

Table 5. Binary systems with BHs in the thin disk

| Object type | Number | $\bar{M}_{BH}[M_\odot]$ | $M_{comp}[M_\odot]$ |
|-------------|--------|--------------------------|---------------------|
| **DCO system** | | | |
| BH - BH | $5.5 \times 10^5/(4.6 \times 10^4)$ | 19.6/(20.9) | - |
| BH - NS | $2.1 \times 10^5/(1.2 \times 10^4)$ | 12.8/(15.0) | 1.3/(1.3) |
| BH - WD | $1.2 \times 10^6/(1.0 \times 10^5)$ | 14.3/(14.8) | 1.0/(0.9) |
| **Other binary system** | | | |
| BH - MS | $1.2 \times 10^5/(1.2 \times 10^4)$ | 16.4/(16.4) | 0.6/(0.6) |
| BH - G | $6.6 \times 10^5/(6.6 \times 10^4)$ | 14.2/(14.2) | 0.9/(0.9) |
| BH - HG | $1.6 \times 10^5/(1.6 \times 10^4)$ | 15.4/(15.4) | 1.3/(1.3) |

**Total:** $7.0 \times 10^5/(5.9 \times 10^4)$ 18.5/(19.6) 1.0/(0.9)

Values for models A and B given in the order A/B. The number in the row with BH-BH systems refers to the total number of BHs (not systems).

give us the most recent upper and lower limit on the MACHO mass range (Bird et al. 2016).

We calculated the fraction of mass in the Galactic halo that is hidden in the form of stellar origin BHs in the mass range of 20-100 $M_\odot$. The total mass of such BHs is $\sim 6.2 \times 10^6 M_\odot$, which could constitute only $\sim 0.006$% of the total Galactic dark matter mass, which is $\sim 10^{12} M_\odot$ (Wang et al. 2015; Monari et al. 2018; Grand et al. 2019).

Table 6. Binary systems with BHs in the thick disk

| Object type | Number | $\bar{M}_{BH}[M_\odot]$ | $M_{comp}[M_\odot]$ |
|-------------|--------|--------------------------|---------------------|
| **DCO systems** | | | |
| BH - BH | $6.5 \times 10^5/(3.3 \times 10^4)$ | 21.7/(23.1) | - |
| BH - NS | $2.0 \times 10^5/(1.4 \times 10^4)$ | 15.2/(15.9) | 1.3/(1.3) |
| BH - WD | $1.6 \times 10^5/(1.4 \times 10^4)$ | 14.7/(15.2) | 0.9/(0.9) |
| **Other binary systems** | | | |
| BH - MS | $1.2 \times 10^5/(1.2 \times 10^4)$ | 18.1/(18.1) | 0.5/(0.5) |
| BH - G | $2.9 \times 10^5/(2.9 \times 10^4)$ | 17.9/(17.9) | 0.6/(0.6) |
| **Total:** | $8.3 \times 10^5/(6.9 \times 10^4)$ | 20.2/(21.2) | 0.9/(0.9) |

Values for models A and B given in the order A/B. The number in the row with BH-BH systems refers to the total number of BHs (not systems).

Table 7. Single BHs in the halo

| Object type | Number | $\bar{M}_{BH}[M_\odot]$ |
|-------------|--------|--------------------------|
| **Single stars** | | |
| Single star | $2.1 \times 10^5/(2.1 \times 10^4)$ | 19.0/(19.0) |
| **Compact mergers** | | |
| MS - MS | $4.7 \times 10^5/(4.7 \times 10^4)$ | 22.9/(22.9) |
| MS - He | $1.3 \times 10^5/(3.7 \times 10^4)$ | 26.6/(30.3) |
| MS - G | $1.2 \times 10^5/(1.3 \times 10^4)$ | 23.2/(23.6) |
| He - He | $2.3 \times 10^5/(1.6 \times 10^4)$ | 13.5/(11.7) |
| CO - MS | $6.9 \times 10^5/(6.9 \times 10^4)$ | 14.6/(14.6) |
| CO - G | $2.2 \times 10^5/(2.0 \times 10^4)$ | 11.3/(13.0) |
| CO - He | $4.2 \times 10^5/(2.0 \times 10^4)$ | 24.8/(11.0) |
| **Disrupted systems** | | |
| BH - BH | $2.9 \times 10^5/(1.2 \times 10^4)$ | 16.8/(15.0) |
| BH - NS | $5.2 \times 10^5/(2.5 \times 10^4)$ | 17.6/(16.0) |
| BH - WD | $3.8 \times 10^5/(1.8 \times 10^4)$ | 13.1/(12.7) |
| BH - MS | $4.7 \times 10^5/(4.7 \times 10^4)$ | 13.5/(13.5) |
| **Total:** | $3.7 \times 10^5/(3.2 \times 10^4)$ | 21.0/(19.9) |

Values for models A and B given in the order A/B. In the section with compact mergers in row BH-BH, the number refers to the number of single BHs that where created. In the section with disrupted systems, the number in row BH-BH represents the total number of single BHs after disruption (not the number of systems).

3.5. Mass distribution

In Figures 8 and 9 we present the distribution of single and binary BHs masses for the two evolutionary models A and B and the three Galactic components bulge, disk, and halo. The mass distribution for single and binary BHs is very different. The average mass of a BH in a binary system $\sim 19 M_\odot$ is higher than
for single BHs with an average mass of ~ 14 M⊙. The difference in average mass of single and binary BHs is mainly due to the distribution of our adopted natal kick: the less massive the remnant (BH or NS), the higher the velocity it obtains. This results in the disruption of many low-mass binaries during the formation of a BH or NS. In all Galactic components, the mean BH mass in a binary BH-BH system is higher than the mass of a BH from disrupted BH-BH systems (see Tables 1-8). Moreover, BHs in a binary system are mainly in BH-BH systems because of the accretion factor f. The total number of single BHs was reduced, the total number of single BHs is lower the smaller the accretion factor f. In the nonaccretion model, objects in the second mass gap are only the products of DCO mergers, and in the other two models, BHs with masses higher than the PPSN limit might have formed, for example, by a BH and MS or BH and HE star coalescence. The average single BH masses for the first mass gap estimate is given in the Table 9. Because accretion of matter during merger is reduced, the total number of single BHs is lower the smaller the accretion factor f. The total number of single BHs was reduced by about 10% compared to the standard model described in Section 2.4.

The range of possible binary BH masses is narrower than for single BHs. The upper limit on binary BHs masses (~ 50-60 M⊙) is similar in all Galactic components, disk, bulge, and halo, and it is the result of two physical processes: stellar winds (Belczynski et al. 2010) and the pair-instability limit (Leung et al. 2019; Woosley 2017). The upper limit is consistent with the second observational mass gap. The first mass gap is also reconstructed for binary BHs in the rapid SN model (Fryer et al. 2012a). However, there is a narrow, isolated peak near a range of 2.5-3 M⊙ (close to the highest NS mass). The peak is made of BHs that formed in accretion of matter on the massive NS from its binary companion. The fraction of BHs with an unevolved companion (e.g., MS or G star) is small, a few percent of all binary BHs. The companion is usually a low-mass star M<1 M⊙. More massive stars are less frequent, especially in older stellar populations, because their evolution time is shorter than most population ages. Even if the NS interacts with the more massive companion, the mass transfer onto the NS or BH during a short-lived CE event
is related to the Bondi-Hoyle accretion, which in our model is rather inefficient (see Sect. 2).

3.6. Separation and eccentricity of BH binary systems

In our database we include orbital parameters (separation and eccentricity) of all binary systems that contain a BH. The distribution of the system separation in the Galactic components for the CE model A (top) and B (bottom) is plotted in Figure 14 (log-log scale) and covers a wide range from a few $R_\odot$ to $10^8 R_\odot$. The average separation is different in the Galactic components: in the bulge, it is $\sim 8.8 \times 10^4 (9.4 \times 10^4) R_\odot$; in the disk, it is $\sim 6.4 \times 10^4 (7.4 \times 10^4) R_\odot$, and in the halo, it is $\sim 3.9 \times 10^6 (3.9 \times 10^6) R_\odot$.

The distribution of the BH system eccentricities in the Galactic components is shown in Figure 15 for model A (top) and model B (bottom). It is dominated by low eccentricities, with a high peak near 0-0.1. The average eccentricity of BH binary systems is similar in all Galactic components and is in the range of $[0.15 - 0.18]$. The components in wide binary systems did not exchange mass during the evolution, and the orbit was only affected by wind mass loss, magnetic braking, or emission from gravitational waves.

3.7. Velocity

In Figures 16 and 17 we plot the distribution of the velocities of a single and a binary BH for the two models A and B (see Sec.2.3) and the three Galactic components. With the red dashed line we mark the velocity equal to 580 km/s, which is the estimated value of the local Galactic escape speed at the position of the Sun (Monari et al. 2018). The escape speed depends on the location in the Milky Way and can take values in the range from $\sim 550$-650 km s$^{-1}$.

The average value for single and binary BHs is similar in a given Galactic component because BHs in general do not reach high speeds as a result of the binary or single evolution. Most BH velocities are close to the values that we adopted from the approximated form of the rotation curve for a given component (2). Very high speeds of single BHs (over 1000 km/s) are rare cases (note the log scale). However, there is a difference in the range of possible speeds of single and binary BHs. Single BHs may achieve speeds from 0 to even $\sim 1700$ km/s in model A and to 1100 km/s$^{-1}$ in model B. The maximum speed of a BH in a binary system is $\sim 700$ km s$^{-1}$. This is a result of the natal kick distribution we assumed (see Sect. 2). An NS and a low-mass BHs receive higher natal kicks, inversely proportional to the remnant mass. These systems are often disrupted. BHs from disrupted binaries may achieve high velocities and are classified as single BHs. BHs in binary systems are often more massive and receive lower natal kicks (remain bound). Sporadic cases of very high speeds in model A are low-mass BHs from close binaries that became disrupted after the formation of the BH or NS that passed CE phase with an HG donor. In the Table 10 we present the average single and binary BH speeds for the two models A and B and the Galactic bulge, disk, and halo.

We calculate that $\sim 5\%$ of the single BHs ($\sim 6 \times 10^6$) and less than 0.0001% of the binary BHs ($\sim 10$) have velocities greater than 550 km/s, the lowest escape velocity from the Milky Way (Monari et al. 2018). This gives us an upper limit on the fraction of BHs that might escape form the Galaxy in our physical model. If we were to adopt a natal kick model with no fallback parameter, the fraction of BHs with very high velocities would increase.

| Table 10. Average values of BH speeds in the Galactic components bulge, disk, and halo. Results for the two models A and B are listed in the order A(B), see Sect. 2.3. |
|---|---|---|---|
| | Bulge [km/s] | Disk [km/s] | Halo [km/s] |
| Single BH | 140(140) | 238(239) | 242(246) |
| Binary BH | 112(111) | 221(221) | 220(220) |

3.8. BH binaries with a noncompact companion

We present the parameters of our synthetic population of Galactic BHs with a nonevolved binary companion, which might be an MS, G, or He star. This fraction of BH systems might be especially interesting for BH hunters because these systems are more likely to be detected because they have a visible companion. However, they appear to make up only a small fraction (less than 1% of all Galactic BHs).

In Figs. 18 and 19 we plot the mass distribution of BHs (top) and their companions (bottom) for the two CE models A and B and the three Galactic components. The mass distribution is similar for models A and B, and the mass distribution for BHs and their companions varies depending on the given Galactic component. The mean masses of the BHs in the Galactic components are $\sim 16 M_\odot$ in the disk, $\sim 11 M_\odot$ in the bulge, and $\sim 21 M_\odot$ in the halo, while the mean masses of the companion stars are $\sim 3.5 M_\odot$ in the disk, $\sim 2.0 M_\odot$ in the bulge, and $\sim 0.5 M_\odot$ in the halo. The differences in BH masses are mainly the effect of the metallicity, which is very low in the halo compared with the disk and bulge. The difference in the companion mass distribution is the result of the age and star formation history of a given component. We assumed that stellar populations in the halo formed 10-12 Gyr ago, which means that only low-mass stars have not yet completed their evolution. On the other hand, we assumed that many young stars are located in the disk and some young populations in the bulge, so that binaries with more massive stars are still possible. We plot the orbital parameters (separation and eccentricity) of the systems. The distribution of the separations is shown in Fig. 20 and the eccentricities in Fig. 21. The distribution of the separations covers a wide range from a few $R_\odot$ to $10^7 R_\odot$ and appears to be approximately uniform on the log-log scale. The eccentricities of the systems are rather low; there is a peak in the number of systems with eccentricities 0-0.1, while the average of all Galactic components is about 0.25. In Figure 22 we plot a diagram that illustrates the relationship between the system separations and eccentricities.

3.9. Massive BHs from MS+He mergers

We found some cases of MS+He star mergers that can produce a star with a He core mass below the pair-instability limit, with a total mass (core + envelope) as high as 60-90 $M_\odot$. We assumed that the naked He star is more compact than a MS star, and therefore the mass of the core after a merger would not increase. This means that the total mass accreted from the MS companion creates the envelope. It has been shown by Woosley (2017) that for ultralow-metallicity and Population III stars the PPSN or PSN instability can be shifted to $\sim 70 M_\odot$ at most because such
stars can keep massive H-rich envelopes. Considering this limit, we removed from our database BHs that formed in an MS+He merger that are more massive than 70 M⊙. However, single BHs with masses above that limit can be still created in BH mergers, for instance, BH+MS or BH+BH mergers. A similar scenario was recently considered by Tanikawa et al. (2019) in the context of LB-1 formation.

3.10. Galactic merger rates

We calculated the change in merger rates of DCO systems (BH-BH, BH-NS, and NS-NS) from the Galactic formation until the present. We present results for the two models A and B (Sec. 2.3). The DCO merger rates have changed along with the star formation and stellar metallicity of the Galactic components (see Fig. 6). In general, the higher the SFR at the given time, the higher the merger rates because the time-delay distribution between the formation of a binary system and its merger is a steep power law (∝ t−1)(Dominik et al. 2012). Furthermore, the metallicity of the stellar population is an important factor that strongly influences the DCO merger rates, especially for BH−BH systems (Dominik et al. 2013; Spera et al. 2015; Dvorkin et al. 2016). The highest BH−BH merger rates in models A and B occurred between 8−11 Gyr ago. The effect was caused by a peak in SFR (Sec. 2.5) because at that time the star formation episode in bulge intensified, the stellar population of the thick disk formed, and the star formation in the thin disk had started. High BH−BH merger rates were also caused by the low metallicity of the stars that formed in this period. In both models the BH−BH merger rates decrease with time, but in model B the rates decrease more dramatically. At higher metallicity, binary systems evolve in a such way that the HG star is more often a donor in the CE phase because of increased mass loss through stellar winds. These systems are then eliminated from a binary system population (see Sec. 2.3).

The merger rates of BH-NS and NS-NS systems did not change so much with Galaxy formation and metallicity as the rates for BH−BH systems. A lower metallicity slightly decreases the NS−NS merger rates, but this effect was compensated for by more intensive SFR episodes at early ages (8−11 Gyr). Because in the standard physical model we assumed natal kicks with high σ=265 km/s (see Sec. 2.2) and a fallback factor inversely proportional to the mass, many low-mass CO binary systems become disrupted by SN explosion or core collapse. These disruptions decreased the CO merger rates, especially for NS−NS systems. Our rates for DCO system mergers can be compared with the results for other implemented physical models for a wide range of natal kick distributions, CE efficiency parameters, or the mass fraction that is ejected during RLOF, which are presented in for example: Tutukov et al. (1992); Abadie et al. (2010); Voss & Tauris (2003); Belczynski et al. (2018).

For comparison, we present the evolution of the merger rates and the current values for an old simplified Galactic SFR and for a chemical evolution model (Fig. 7). The previous model assumed only one Galactic component (disk) with mass 3.5 × 1010 M⊙. The SFR was constant during 10 Gyr (3.5 M⊙/year), and all stars were formed with the same metallicity equal to Z=0.014.

In Table 11 we present the current Galactic merger rates of BH-BH, BH-NS, and NS-NS systems per Myr−1 for the two CE models A and B. For comparison we also calculated the current merger rates for an old SFR and for the metallicity distribution model of the Milky Way (Sec. 2.5). Merger rates for the old model are in general lower than for the new model for all types of DCO systems. The most significant difference is in the case of BH-BH systems, for which current rates (in model B) are one order of magnitude lower for the old model.

We calculated the fractions of current Galactic DCO systems that will merge in one Hubble time (in the next 14 Gyr). The percentage fraction of such systems for the two evolution models is given in the order A/(B), ~6%/1(1%) for BH-BH, ~13%/6(6%) for NS-NS, and ~16%/2(2%) for BH-NS systems. Star formation is still taking place in some parts of the Milky Way, therefore the number of DCO systems will also increase. Numerical data are presented in Table 12.

We do not compare our current Galactic results with LIGO/Virgo estimates because to calculate the cosmic merger rate of a DCO, the entire cosmic SFR(z) and metallicity dist-
Fig. 7. Merger rates of DCO binaries (BH-BH, BH-NS, and NS-NS) as a function of time since the Big Bang. Results are shown for an old Galactic SFR and a chemical evolution model and the two evolutionary models A and B, see Sect. 2.3. Current time is 0.

Table 12. Number of current Galactic double compact systems that will merge in a shorter and longer time than the Hubble time ($T_{\text{Hub}}$). Results are listed for models A and B, see Sect. 2.3, and for the new SFR and metallicity distribution model 2.5

| System type | Merger time $< T_{\text{Hub}}$ | Merger time $> T_{\text{Hub}}$ |
|-------------|-------------------------------|--------------------------------|
| BH-BH       | $1.8 \times 10^3/(1.7 \times 10^3)$ | $3.4 \times 10^6/(2.5 \times 10^6)$ |
| NS-NS       | $6.1 \times 10^3/(2.9 \times 10^3)$ | $4.7 \times 10^5/(3.5 \times 10^5)$ |
| BH-NS       | $3.9 \times 10^3/(2.9 \times 10^3)$ | $2.4 \times 10^5/(1.3 \times 10^5)$ |

4. Conclusions

We presented population synthesis statistical estimates of the current Milky Way BH population properties. We used the most recent version of the code StarTrack with standard physics (Sec. 2) and processed the data with the new SFR and metallicity distribution model of our Galaxy, based on theoretical models and observations. We showed results for two models A and B, which correspond to different scenarios of a CE phase (Sec. 2.3). Our results are listed below.

1) At the present moment, the Milky Way (disk+bulge+halo) contains about $1.2 \times 10^6$ single BHs with an average mass 14 $M_\odot$ and $9.3 \times 10^6$ BHs in binary systems with an average mass 19 $M_\odot$.

2) There are three main formation channels of single BHs: ~ 50% are remnants of massive single star evolution, ~ 30% formed in binary system mergers, and ~ 20% of the single BHs originate in disrupted binary systems during the formation of a BH or neutron star.

3) The most massive BH in the simulation comes from the old low-metal environment of the Galactic halo. It formed by BH-MS system coalescence, and its mass is as high as ~ 113 $M_\odot$.

4) BHs in binary systems constitute ~ 10% of the whole Galactic BH population. Most of the BHs in binary systems are in a BH-BH configuration. The fraction of BH binaries with noncompact companion is small, about 0.3% of all Galactic BHs. We estimated the change in the merger rates of DCO systems (BH-BH, BH-NS, and NS-NS) along with the Galaxy star formation. The current Galactic merger rates depend on the model, and they are estimated at ~ $81/3$ Myr$^{-1}$ for BH-BH, ~ $9/1$ Myr$^{-1}$ for BH-NS, and ~ $59/14$ Myr$^{-1}$ for NS-NS systems.

5) We constrain that only ~ 0.006% of the total Galactic halo mass (including dark matter) could be hidden in the form of BHs with stellar origin, which cannot be detected by current observational surveys.

6) The velocities of only ~ 5% of the single BHs and 0.001% of the binary BHs are high enough to escape from the Galactic potential.

Because of our assumption of the binary fraction Sec. (2.2) and orbital separation (Sec. 2.1), the number of binary systems and system mergers might be slightly underestimated.

Distribution Z(z) as a function of redshift need to be considered. However, this calculation for StarTrack physical models (including those presented in this work) were carried out inBelczynski et al. (2017), Sec. 3.2, noting full agreement with BH-BH, BH-NS, and NS-NS LIGO/Virgo estimates.
Fig. 8. Single (top) and binary (bottom) BHs mass distribution in the three Galactic components for model A. In model A we allowed a binary system to survive the CE phase with an HG donor star. The mass of the objects formed in a merger is estimated as explained in Sect. 2.4.

Fig. 9. Single (top) and binary (bottom) BHs mass distribution in the three Galactic components for model B. In model B we assumed that the CE phase with an HG star donor always leads to a binary system merger. The mass of the objects that formed in a merger is estimated as explained in Sect. 2.4.
Fig. 10. Single BH mass distribution in the three Galactic components for model A. In model A we allowed a binary system to survive the CE phase with an HG donor star. The mass of the objects that formed in a merger is estimated as a lower limit assuming total mass loss from the second merging object (except for two CO mergers).

Fig. 11. Single BH mass distribution in the three Galactic components for model B. In model B we assumed that the CE phase with an HG star donor always leads to a binary system merger. The mass of the objects that formed in merger is estimated as a lower limit assuming total mass loss from the second merging object (except for two CO mergers).

Fig. 12. Single BH mass distribution in the three Galactic components for model A. In model A we allowed a binary system to survive the CE phase with an HG donor star. The mass of the objects that formed in a merger is shown, assuming 50% mass loss from the second merging object (except for two CO mergers).

Fig. 13. Single BH mass distribution in the three Galactic components for model B. In model B we assumed that the CE phase with an HG star donor always leads to a binary system merger. The mass of the objects that formed in a merger is shown, assuming 50% mass loss from the second merging object (except for two CO mergers).
Fig. 14. Distribution of the separation in all Galactic BH binary systems in the three Galactic components and for CE models A (top) and B (bottom).

Fig. 15. Distribution of the eccentricity in all Galactic BH binary systems in the three Galactic components and for CE models A (top) and B (bottom).
Fig. 16. Single (top) and binary (bottom) BHs velocity distribution in the three Galactic components for model A. In model A we allowed a binary system to survive the CE phase with an HG donor star. With the red dashed line we mark the velocity equal to 580 km/s, which is the estimated value of the local Galactic escape speed at the position of the Sun (Monari et al. 2018).

Fig. 17. Single (top) and binary (bottom) BHs velocity distribution in the three Galactic components for model B. In model B we assumed that the CE phase with an HG donor star always leads to a binary system merger. With the red dashed line we mark the velocity equal to 580 km/s, which is the estimated value of the local Galactic escape speed at the position of the Sun (Monari et al. 2018).
Fig. 18. Distribution of a BH (top) and its companion masses (bottom) in Galactic BH binary systems with a nonevolved companion in the three Galactic components for evolution model A.

Fig. 19. Distribution of a BH (top) and its companion masses (bottom) in Galactic BH binary systems with a nonevolved companion in the three Galactic components for evolution model B.
**Fig. 20.** Distribution of the separation in Galactic BH binary systems with a nonevolved companion in the three Galactic components for evolution models A (top) and B (bottom).

**Fig. 21.** Distribution of the eccentricity in Galactic BH binary systems with a nonevolved companion in the three Galactic components for evolutionary models A (top) and B (bottom).
Fig. 22. Diagram with orbital parameters. The separation and eccentricity for BH binary systems with a noncompact companion. Results for the two models A (top) and B (bottom) are shown.
Table 13. Types of objects that originated from different types of stellar mergers based on Table 2 from Hurley et al. (2002).

| First stellar type \( k_1 \) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|-------------------------------|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|
| 0                             | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 4 | 6 | 6 | 3  | 6  | 6  | 13 | 14 |
| 1                             | 1 | 1 | 2 | 3 | 4 | 5 | 6 | 4 | 6 | 6 | 3  | 6  | 6  | 13 | 14 |
| 2                             | 2 | 2 | 3 | 3 | 4 | 4 | 5 | 4 | 4 | 4 | 3  | 5  | 5  | 13 | 14 |
| 3                             | 3 | 3 | 3 | 3 | 4 | 4 | 5 | 4 | 4 | 4 | 3  | 5  | 5  | 13 | 14 |
| 4                             | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4  | 4  | 4  | 13 | 14 |
| 5                             | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4  | 4  | 4  | 13 | 14 |
| 6                             | 6 | 6 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4  | 4  | 4  | 13 | 14 |
| 7                             | 7 | 4 | 4 | 4 | 4 | 4 | 4 | 7 | 8 | 9 | 7  | 9  | 9  | 13 | 14 |
| 8                             | 8 | 6 | 6 | 4 | 4 | 4 | 4 | 6 | 8 | 9 | 7  | 9  | 9  | 13 | 14 |
| 9                             | 9 | 6 | 6 | 4 | 4 | 4 | 4 | 6 | 9 | 9 | 7  | 9  | 9  | 13 | 14 |
| 10                            | 10| 3 | 3 | 3 | 3 | 4 | 4 | 7 | 7 | 7 | 15 | 9  | 9  | 13 | 14 |
| 11                            | 11| 6 | 6 | 5 | 5 | 4 | 4 | 6 | 9 | 9 | 9  | 11 | 12 | 13 | 14 |
| 12                            | 12| 6 | 6 | 5 | 5 | 4 | 4 | 6 | 9 | 9 | 9  | 12 | 12 | 13 | 14 |
| 13                            | 13| 13| 13| 13| 13| 13| 13| 13| 13| 13| 13 | 13 | 13 | 13 | 14 |
| 14                            | 14| 14| 14| 14| 14| 14| 14| 14| 14| 14| 14 | 14 | 14 | 14 | 14 |

The numeric types are consistent with Hurley et al. (2002):
0 – main sequence star with \( M \leq 0.7 \) Msun (deeply or fully convective)
1 – main sequence star with \( M > 0.7 \) Msun
2 – Hertzsprung gap star
3 – first giant branch star
4 – core helium burning star
5 – early asymptotic giant branch star
6 – thermally pulsing asymptotic giant branch star
7 – main sequence naked helium star
8 – Hertzsprung gap naked helium star
9 – giant branch naked helium star
10 – helium white dwarf
11 – carbon or oxygen white dwarf
12 – oxygen or neon white dwarf
13 – neutron star
14 – black hole
15 – massless remnant
