Formation of massive black holes in ultra-compact dwarf galaxies: migration of primordial intermediate-mass black holes in N-body simulation

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ABSTRACT

Recent observational studies of ultra-compact dwarf galaxies (UCDs) have discovered massive black holes (MBHs), with masses of more than $10^6\, M_\odot$, in their central regions. We here consider that these MBHs can be formed through merging of intermediate-mass black holes (IMBHs), with masses of $[10^3 - 10^5]\, M_\odot$, within the stellar nuclei of dwarf galaxies, which are progenitors of UCDs. We numerically investigate this formation process for a wide range of model parameters using N-body simulations. This means that IMBH growth and feedback is neglected in this study. We find that only massive IMBHs of $10^5\, M_\odot$ sink into the central regions of their host dwarf ($\approx 10^{10}\, M_\odot$) to be gravitationally trapped by its stellar nucleus within less than 1 Gyr in most dwarf models. We also find that lighter IMBHs with $[1 - 30]\times 10^3\, M_\odot$ sink into the centre in low-mass dwarfs ($\approx 10^9\, M_\odot$) due to more efficient dynamical friction (DF). Additionally, we show that the IMBHs can form binaries in the centre and, rarely, before they reach the centre, which may lead to the IMBHs merging and thus emitting gravitational waves that could be detected by LISA. Finally, we discuss the required number of IMBHs for the MBH formation in UCDs and the physical roles of stellar nuclei in IMBH binaries and mergers.

Key words: galaxies: dwarf – galaxies: evolution – galaxies: disc – galaxies: kinematics and dynamics – black hole mergers

1 INTRODUCTION

Ultra-compact dwarf galaxies (UCDs) are very compact stellar systems that were discovered in the Fornax cluster of galaxies about two decades ago (e.g. Hilker et al. 1999; Drinkwater et al. 2000). With their typical sizes of 10 - 100 pc and masses between $10^4$ to $10^6\, M_\odot$ (e.g. Drinkwater et al. 2003; Hasegan et al. 2005; Mieske et al. 2008) they link globular clusters (GCs) and dwarf galaxies. However, they were shown to be distinct from both because of their lower surface brightness to core luminosity ratio (Drinkwater et al. 2003). Various physical properties of UCDs, revealed by observation, including internal structural properties, star formation histories, and age-metallicity relation, have shown similarities to both GCs and galaxies for different UCDs (e.g. Evstigneeva et al. 2007; Mieske et al. 2008; Hau et al. 2009; Brodie et al. 2011; Norris et al. 2015). As a consequence, it has been suggested that there might be several UCD subpopulations of different origins (e.g. Norris & Kannappan 2011; Brodie et al. 2011). Although several formation mechanisms have been proposed for UCDs, including tidal stripping of nucleated dwarf galaxies (e.g. Bekki et al. 2001; Mayes 2019), merging of star clusters (e.g. Fellhauer & Kroupa 2002), and starbursts in super-massive molecular clouds (Goodman & Bekki 2018), no theory is yet to explain these observations in a fully self-consistent manner.

The observed mass to luminosity ratio, which in most UCDs is about twice as large as that of galactic GCs (Drinkwater et al. 2003; Brodie et al. 2011), is an important key observed value that needs to be explained by the formation scenarios of UCDs. Different causes like a top-heavy stellar initial mass function (Dabringhausen et al. 2009), dark matter (Baumgardt & Mieske 2008) and central massive black holes (MBHs) (Mieske et al. 2013) have been proposed as an explanation for these enhanced mass to luminosity ratios. The latter is especially interesting as MBHs have
been observed in UCDs recently. Evidence for three MBHs has been found for Virgo Cluster UCDs through dynamic modelling (Seth et al. 2014; Ahn et al. 2017). Similarly, Afanasiev et al. (2018) found evidence for a $3.5 \times 10^6 M_{\odot}$ MBH in the centre of UCD3 in the Fornax cluster. From the mass to luminosity ratio of a sample of 49 UCDs (Mieske et al. 2013) estimated that about half of the UCDs could be expected to host a central black hole (BH) with a noticeable effect on observations.

The obvious question to ask now would be: How did those MBHs get there? Although UCD formation processes have been investigated in previous theoretical models (e.g. Bekki et al. 2003; Pfeffer & Baumgardt 2013; Mieske et al. 2012; Afanasiev et al. 2018), the MBH formation in UCDs is yet to be fully explored. The two main formation channels proposed are: UCDs as the most massive star clusters or nuclei of stripped galaxies (e.g. Mieske et al. 2012; Afanasiev et al. 2018). Mieske et al. (2013) proposed that the MBHs could be inherited from a progenitor galaxy from which the UCDs could have formed. However, there are no theoretical studies about the formation of those MBHs yet. If they are indeed inherited from a progenitor galaxy, we should have a closer look at the properties of BHs in dwarf galaxies.

In the centres of many galaxies evidence for the existence of MBHs was found (e.g. Urry & Padovani 1995; Kormendy & Ho 2013), many of which coexist with nuclear clusters (Graham & Spitler 2009). The formation of these MBHs is yet to be understood and many different formation scenarios have been proposed (Volonteri 2010). One interesting scenario suggested by Ebszuzaki (2003) is that MBHs could have been formed by intermediate-mass black hole (IMBH) mergers. While plenty of evidence for MBHs has been detected, only few promising IMBH candidates have been found (Mezcua 2017).

Similar to the MBH formation there are different hypotheses for the formation of IMBHs. They could have grown from stellar mass BHs due to accretion and mergers (Barai & de Gouveia Dal Pino 2019), however, a collapse of a massive Population III star (Hirano et al. 2014), the direct collapse of a gas cloud (Lodato & Natarajan 2006; Tanaka & Li 2014) or runaway collisions in dense metal-poor clusters (Devecchi & Volonteri 2009; Mapelli 2016) are possible scenarios to form an IMBH. A more detailed overview over different proposed IMBH formation scenarios can be found in Mezcua (2017). Litttle is known about the number of IMBHs in dwarf galaxies. Mapelli (2007) derived an upper limit of one IMBH in the disk and up to 1000 in the halo of the gas rich dwarf galaxy Holmberg II by comparing simulated X-ray sources to observations. It is, however, unknown what the limit of IMBHs in dwarf galaxies is in general.

The purpose of this paper is to investigate whether the MBHs in the centres of UCDs could have been build initially from IMBHs within the nucleated dwarf galaxies, from which UCDs can originate. Using numerical simulations of nucleated dwarf galaxies with IMBHs, we particularly investigate the dynamical evolution of IMBHs in their host dwarfs. We try to find out whether the effect of dynamical friction (DF) on our IMBHs is strong enough for them to spiral into the nucleus before the galaxy is tidally stripped. We also investigate whether they can be trapped there and form a central cluster in which they could merge to form an MBH. Although previous observational and theoretical studies discussed the physical relationships between stellar galactic nuclei, MBHs, and their host galaxies (e.g. Bekki & Graham 2010; Antonini et al. 2015; Georgiev et al. 2016; Capuzzo-Dolcetta & Tosta e Melo 2017; Arca Sedda et al. 2019), we focus exclusively on the formation of MBHs in UCDs (i.e. stellar nuclei).

The plan of this paper is as follows: In section 2 we will describe the model used. We give a short overview about the code used in section 2.1. The details of the simulated galaxies and IMBHs are explained in section 2.2 and 2.3 respectively and we describe the main parameters used in section 2.4. We show our results in section 3. We discuss the efficiency of DF in section 3.1 what fraction of IMBHs was trapped in the nucleus in section 3.2 and the binaries we found, that potentially could lead to mergers, in section 3.3. We discuss whether IMBH mergers alone are sufficient to explain the formation of MBHs, the potential formation of gravitational waves (GWs) and future work in sections 4.1, 4.2 and 4.3 respectively. Finally we present our conclusions in section 5.

\section{The Model}

\subsection{Simulation code for IMBH evolution}

In order to investigate both (i) the dynamical evolution of dwarf galaxies and (ii) the orbital evolution of IMBHs within their host dwarfs in a self-consistent manner, we adopt our code for direct Nbody simulations used for the evolution of GCs in dwarfs (Bekki & Tsujimoto 2016). Since the details of the code are given in BT16, we here briefly describe the code. The gravitational softening length ($\epsilon$) can be chosen separately for each of the components in a galaxy (e.g., halo, disk, and nucleus) for the adopted numbers of particles of the components. The maximum timestep width

\begin{table}[h]
\centering
\caption{Description of the basic parameter values for the fiducial galaxy model.}
\begin{tabular}{|l|c|}
\hline
\textbf{Physical properties} & \textbf{Values} \\
\hline
DM mass & $1.0 \times 10^6 M_{\odot}$ \\
DM profile & NFW \\
Virial radius & 12.3 kpc \\
$\epsilon$ (DM) & 16 \\
$\epsilon$ (stars) & 5.9 pc \\
$\epsilon$ (nucleus) & 0.5 pc \\
Mass resolution (DM) & $5 \times 10^4 M_{\odot}$ \\
Mass resolution (stars) & 360 $M_{\odot}$ \\
Mass resolution (nucleus) & 180 $M_{\odot}$ \\
Time step width & $1.41 \times 10^5$ yr \\
\hline
\end{tabular}
\end{table}

\textsuperscript{a} $c$ is the $c$-parameter in the NFW dark matter profiles.

\textsuperscript{b} $\epsilon$ is the gravitational softening length for particles.
(\(\delta t\)) is chosen to be rather small ([10^4 - 10^5] yr) in comparison with galaxy-scale simulations, though such narrow \(\delta t\) is not required for the dynamical evolution of dwarf galaxies. We did not include gas dynamics, star formation, chemical evolution, stellar feedback effects, the formation and evolution of dust and molecular gas formation on dust grains in the present study, though our other galaxy-scale simulations included these processes in a self-consistent manner [Bekki 2007, 2013]. This is mainly because because orbital evolution of IMBHs might not be influenced by such baryonic processes. However, if efficient accretion of cold gas onto IMBHs is possible in dwarfs, then the orbital evolution of IMBHs can be significantly influenced by such a process. We will discuss how this IMBH growth via gas accretion can influence MBH formation in our future works.

### 2.2 Host galaxies for IMBHs

We assume that the host galaxy for IMBHs is a dwarf disk galaxy with stellar galactic nucleus embedded in a massive dark matter halo. In this preliminary works, we only investigate the models with no gas, though hydrodynamical processes are not required for the dynamical evolution of dwarf galaxies. In this preliminary works, we only investigate the models with no gas, though hydrodynamical processes are not required for the dynamical evolution of dwarf galaxies.

| ID | \(M_{\text{dm}}\) (10^{10} M_\odot) | \(M_\odot\) (10^{10} M_\odot) | \(R_\odot\) (kpc) | \(M_{\text{bh}}\) (10^{5} M_\odot) | \(M_{\text{bh}}/m_p\) | \(R_\text{bh}\) (pc) | \(N_\text{bh}\) | Comments |
|----|-----------------|-----------------|----------------|-----------------|-----------------|----------------|----------------|----------|
| M1 | 1.0             | 3.6             | 0.88           | 0.3             | 83.3            | 176            | 10             | fiducial model |
| M2 | 1.0             | 3.6             | 0.88           | 0.1             | 27.8            | 176            | 10             | low-mass model |
| M3 | 1.0             | 3.6             | 0.88           | 1.0             | 277.8           | 176            | 10             | low-mass model |
| M4 | 1.0             | 3.6             | 0.88           | 0.03            | 8.3             | 176            | 10             | no nucleus     |
| M5 | 1.0             | 3.6             | 0.88           | 0.3             | 83.3            | 176            | 10             | no nucleus     |
| M6 | 1.0             | 3.6             | 0.88           | 0.1             | 27.8            | 176            | 10             | no nucleus     |
| M7 | 1.0             | 3.6             | 0.88           | 1.0             | 277.8           | 176            | 10             | no nucleus     |
| M8 | 1.0             | 3.6             | 0.88           | 0.03            | 8.3             | 176            | 10             | no nucleus     |
| M9 | 0.1             | 0.36            | 0.55           | 0.3             | 83.3            | 110            | 10             | low-mass model |
| M10| 0.1             | 0.36            | 0.55           | 0.1             | 277.8           | 110            | 10             | low-mass model |
| M11| 0.1             | 0.36            | 0.55           | 1.0             | 2777.8          | 110            | 10             | low-mass model |
| M12| 0.1             | 0.36            | 0.55           | 0.03            | 83.3            | 110            | 10             | low-mass model |
| M13| 0.1             | 0.36            | 0.55           | 0.3             | 83.3            | 275            | 10             | low-mass model |
| M14| 0.1             | 0.36            | 0.55           | 0.1             | 277.8           | 275            | 10             | low-mass model |
| M15| 0.1             | 0.36            | 0.55           | 1.0             | 2777.8          | 275            | 10             | low-mass model |
| M16| 0.1             | 0.36            | 0.55           | 0.03            | 83.3            | 275            | 10             | low-mass model |
| M17| 1.0             | 3.6             | 0.88           | 0.3             | 83.3            | [44 - 440]     | 10             | distance varies linearly |
| M18| 1.0             | 3.6             | 0.88           | 1.0             | 833.3           | [44 - 440]     | 10             | distance varies linearly |
| M19| 1.0             | 3.6             | 1.75           | 0.3             | 83.3            | 350            | 10             | distance varies linearly |
| M20| 0.3             | 1.3             | 0.48           | 0.1             | 92.6            | 96             | 10             | different \(M_{\text{bh}}\) masses |
| M21| 1.0             | 3.6             | 0.88           | [0.01 - 3]      | [2.8 - 833.3]   | 176            | 6              | different \(M_{\text{bh}}\) masses |
| M22| 1.0             | 3.6             | 0.88           | 0.3             | 83.3            | 176            | 10             | different \(M_{\text{bh}}\) masses |
| M23| 1.0             | 3.6             | 0.88           | [0.01 - 3]      | [2.8 - 833.3]   | 176            | 6              | different \(M_{\text{bh}}\) masses |
| M24| 1.0             | 3.6             | 0.88           | 0.1             | 27.8            | [88 - 880]     | 10             | distance varies linearly |
| M25| 1.0             | 3.6             | 0.88           | 0.3             | 83.3            | [88 - 880]     | 10             | distance varies linearly |
| M26| 1.0             | 3.6             | 0.88           | 1.0             | 277.8           | [88 - 880]     | 10             | distance varies linearly |
| M27| 1.0             | 3.6             | 0.88           | 0.03            | 8.3             | [88 - 880]     | 10             | distance varies linearly |
| M28| 1.0             | 3.6             | 0.88           | 10.0            | 2777.8          | [88 - 528]     | 6              | distance varies linearly |
| M29| 3.0             | 10.8            | 1.52           | 1.0             | 92.6            | 305            | 10             | distance varies linearly |
| M30| 0.03            | 0.1             | 0.15           | 0.1             | 925.9           | 31             | 10             | distance varies linearly |
| M31| 0.03            | 0.1             | 0.15           | 0.01            | 925.9           | 31             | 10             | distance varies linearly |
| M32| 3.0             | 10.8            | 1.52           | 10.0            | 925.9           | 305            | 10             | distance varies linearly |

\(\rho(v) = \frac{\rho_0}{(r/r_\odot)(1 + r/r_\odot)^2}\),

where \(r, \rho_0, \text{ and } r_\odot\) are the spherical radius, the characteristic density of a dark halo, and the scale length of the halo, respectively. The \(c\)-parameter (\(c = r_{\text{vir}}/r_\odot\), where \(r_{\text{vir}}\) is the virial radius of a dark matter halo) and \(r_{\text{vir}}\) are chosen appropriately for a given dark halo mass (\(M_{\text{dm}}\)) by using the \(c = M_{\text{bh}}/R_{\text{vir}}\) relation for \(z = 0\) predicted by recent cosmological simulations [e.g. Neto et al. 2007]. For the adopted mass ranges of \(M_{\text{dm}}\), we consider that \(c = 16\) is a quite reasonable value. In the present study, we mainly investigate dwarf galaxies with \(M_{\text{dm}}\) ranging from \(10^9 \text{ M}_\odot\) to \(10^{10} \text{ M}_\odot\) and \(R_{\text{vir}}\) ranging from 7.7 kpc to 24.5 kpc.

We assume that the stellar disk of a dwarf galaxy can be represented by the so-called exponential profile. Accordingly, the radial (\(R\)) and vertical (\(Z\)) density profiles of the stellar disk are assumed to be proportional to \(\exp(-R/R_\odot)\) with scale length \(R_\odot = 0.2R_\odot\) and to sech\(^2\)((Z/Z_\odot)\), where \(Z_\odot\) is the size of the stellar disk. In addition to the rotational velocity caused by the gravitational field of disk, bulge, and dark halo components, the initial radial and azimuthal velocity dispersions are assigned to the disc component according to the epicyclic theory with Toomre’s parameter \(Q = 1.5\). The vertical velocity dispersion at a given radius is set to be 0.5 times as large as the radial velocity dispersion at that point. The
mass-ratio of the stellar disk to its dark matter halo is assumed to rather small ranging from 0.01 to 0.03, which is consistent with the mass scaling relation between stars and dark matter observed in low-mass galaxies (e.g., Papastergis et al. 2012). It could be possible that small disk galaxies can have small bulges, we do not investigate the models with small bulges in the present study. Small bulges are highly unlikely to influence the orbital evolution of IMBHs.

We assume that an initial stellar nucleus in a dwarf galaxy has a Plummer spherical density profile (e.g., Binney & Tremaine 1987) with a total stellar mass ($M_{\text{nuc}}$) and a size ($R_{\text{nuc}}$). In a Plummer model, the scale length ($a_{\text{nuc}}$) of the system is determined by the formula

$$a_{\text{nuc}} = GM_{\text{nuc}}/6\sigma_{\text{nuc}}^2,$$

where $G$ is the gravitational constant and $\sigma_{\text{nuc}}$ is a central velocity dispersion of the nucleus. In the present study, we do not consider initial angular momentum of the nucleus, because the orbital evolution of IMBHs might not be influenced by the angular momentum. Therefore, the above equation is appropriate for the adopted stellar systems with no initial angular momentum (i.e., dynamically supported only by velocity dispersion). Since observational studies showed that the total masses of stellar galactic nuclei can be proportional to those of the stellar components of their host galaxies (e.g., Cote et al. 2006), we assume that $M_{\text{nuc}}$ is proportional to $M_\text{s}$. We adopt $M_{\text{nuc}} = 1.8 \times 10^7 M_\odot$ and $R_{\text{nuc}} = 44$ pc for $M_{\text{dm}} = 10^{10} M_\odot$ and $M_{\text{nuc}} = 1.8 \times 10^6 M_\odot$ and $R_{\text{nuc}} = 28$ pc for $M_{\text{dm}} = 10^9 M_\odot$.

### 2.3 IMBH models

Each IMBH in a dwarf galaxy is represented by a point-mass particle with a mass ($M_{\text{bh}}$), and it is initially in the host galaxy’s disk: IMBHs initially in the dark matter halo are not considered in the present study, though they can possibly sink into the central region due to DF against the dark matter particles. Each IMBH is assumed to have a circular velocity at its initial position (i.e., no radial motion initially) and different IMBHs have different initial positions within their dwarf galaxy. Although recent cosmological simulations have investigated the evolution of 3D positions of primordial IMBHs (e.g., Barni & de Gouveia Dal Pino 2019), there are no robust predictions provided for the 3D positions of IMBHs within their host dwarf galaxies. We thus investigate a larger number of models with different IMBH positions in the present study. We assume that each dwarf galaxy can contain 10 IMBHs within its disk, though it is not theoretically and observationally clear how many IMBHs can possibly exist in a dwarf galaxy.

We consider that the following parameter, $R_m$, is quite important in the orbital evolution of IMBHs due to DF in dwarfs:

$$R_m = \frac{m_p}{M_{\text{bh}}},$$

where $m_p$ is the mass of a particle. If this mass-ratio $R_m$ is quite small, then dynamical friction of IMBHs can be properly investigated. For example, $R_m$ for disk star particles is $<0.1$ in the models with $M_{\text{bh}} \geq 3 \times 10^4 M_\odot$. Therefore, we can properly investigate the DF of IMBHs against disk field stars in dwarfs. However, $R_m$ for dark matter particles can be larger than 1 in the models with low-mass IMBHs. Accordingly, we cannot investigate the dynamical friction of IMBHs against dark matter in the present study.

### 2.4 Parameter study

We consider that the model M1 is the fiducial model in which 10 IMBHs are assumed to be moving within a dwarf galaxy with $M_{\text{dm}} = 10^{10} M_\odot$, $M_\text{s} = 3.6 \times 10^6 M_\odot$ and $R_\text{s} = 875$ pc, because this model and those with different IMBH masses shows interesting behaviours of orbital evolution of IMBHs. The total number of particles in the fiducial model is 200000, 1000000, and 100000 for dark matter, stellar disk, and stellar nucleus, which leads to particle masses of 50000, 360 and 180 $M_\odot$ respectively. These large particle masses are required to keep the computational cost reasonably low, however, as we can see in Table 2 the ratios between the IMBH masses and the stellar masses are still large enough to realistically simulate the effect dynamical friction would have on the IMBHs. Different softening lengths are allocated for different components of a dwarf (dark matter, stellar disk, and nucleus) so that the evolution of IMBHs within the stellar disk and its nucleus can be both investigated self-consistently. The mass and size resolution in the model are 360 $M_\odot$ and 5.9 pc, respectively, for the stellar disk. The IMBHs are treated as massive disk particles and therefore have the same softening length as the disk stars (5.9 pc). The parameters of the fiducial model are summarized in Table 1. We mainly investigate 27 models with different model parameters and the parameter values and ranges are summarized in Table 2.

To determine whether a central MBH can form via merging of several IMBHs or not we have to investigate three questions, which we will answer in the next sections:

1. Can IMBHs spiral into the galaxies centre due to DF before the nucleus is stripped by tidal forces?
2. Are enough IMBHs trapped in the nucleus to form a central cluster of IMBHs?
3. Do enough IMBHs merge to form a central MBH?

Regarding the first question, the IMBHs need to spiral into the central regions of stellar nuclei due to dynamical friction in dwarfs before the disintegration of dwarfs through tidal interaction of the dwarfs with their environments (e.g., luminous galaxies, groups, and clusters). Therefore, the dynamical friction time scale ($t_{\text{df}}$) should be shorter than the disintegration time scale ($t_{\text{dis}}$):

$$t_{\text{df}} < t_{\text{dis}}.$$  \hspace{1cm} (4)

Previous numerical simulations of UCD formation through galaxy threshing demonstrated that $t_{\text{dis}}$ should be at least a few Gyr (e.g., Bekki et al. 2003). Therefore, we consider that $t_{\text{df}}$ should be as short as 1 Gyr for MBH formation via IMBH migration into stellar nuclei (before host disintegration) in the present study. Since $t_{\text{dis}}$ can be quite different depending on the orbits of dwarfs within their host environments, the adopted $t_{\text{df}} \approx$ 1 Gyr can be a bit too short.
3 RESULTS

3.1 DF depending on the model parameters

We start by investigating whether and how IMBHs can spiral into the nucleus due to dynamical friction within 1 Gyr. Examples of orbits from our simulations in the fiducial model can be seen in Fig. 1. It is clear that the effect of DF against the field stars gets stronger with the mass of the IMBH until the IMBH ends up near the centre of mass (COM) of the galaxy, as can be seen in the bottom right panel. According to theoretical calculations by Chandrasekhar (1943), the time scale of DF is inversely proportional to the IMBH mass: our results are consistent with these analytical predictions. As we will see below, there could be a threshold mass for the IMBHs to be sunk into the nucleus within 1 Gyr within dwarf disk galaxies.

We compiled the results of simulations with different model parameters in Figs. 2 and 3. In both Figs. the models are sorted by $M_{bh}$ with the lowest mass (3 x $10^4$ $M_\odot$) to the far left and the models with the highest masses (10$^5$ $M_\odot$) to the far right. It is clear that only massive IMBHs can reach the centre within 1 Gyr. The models in Fig. 2 all have the same disc parameters as our fiducial model. As we can see, the majority of the IMBHs move closer to the COM, with a lot of them ending up within 20 per cent of $R_i$, where we can find the largest number of IMBHs. Again we see that the effect of dynamical friction is stronger for heavy IMBHs. No IMBH with a mass of less than 10$^4$ $M_\odot$ is found within 20 per cent of its initial radius while most of the IMBHs with 10$^5$ $M_\odot$ can be found in this bin. As the lighter IMBHs are not affected by dynamical friction as strongly, a second maximum can be seen around the initial distance. This shows that the dynamical friction is very weak for those lighter IMBHs.

In Fig. 4 we can see the number of IMBHs depending on their final distance to the COM of the nucleus (stars for models without a nucleus) over their initial distance. As we can see, the majority of the IMBHs move closer to the COM, with a lot of them ending up within 20 per cent of $R_i$, where we can find the largest number of IMBHs. Again we see that the effect of dynamical friction is stronger for heavy IMBHs. No IMBH with a mass of less than 10$^4$ $M_\odot$ is found within 20 per cent of its initial radius while most of the IMBHs with 10$^5$ $M_\odot$ can be found in this bin. As the lighter IMBHs are not affected by dynamical friction as strongly, a second maximum can be seen around the initial distance. This shows that the dynamical friction is very weak for those lighter IMBHs.

The number of IMBHs depending on the absolute value of their final distance to the COM is shown in Fig. 5. Again we see that only heavy IMBHs move towards the COM. Only IMBHs with masses higher or equal than 3 x $10^4$ $M_\odot$ can be found within 10 pc of the COM; and only IMBHs with masses higher or equal to $10^4$ $M_\odot$ are visible within 20 pc of the COM, where we can find 63 IMBHs (24 per cent of the total IMBHs). Only two of those have a mass of 10$^4$ $M_\odot$, while the masses of the others are at least 3 x $10^4$ $M_\odot$. A maximum can be found between 100 and 158 pc which is close to the initial distances of most of our models (176 pc for our fiducial model, 110 and 225 pc for the low-mass models). No clear trend is visible within the lowest 20 pc. This is the region where the IMBHs form a cluster and therefore influence each other. Because of our model’s limitations (large softening length), we cannot simulate the behaviour of dense IMBH clusters accurately. Future simulations with e.g. NBODY6 will be required to accurately model the behaviour of the IMBHs in this region.

A comparison between the initial and final distances of the IMBHs from the COM can be seen in Fig. 6. The identity is shown as a blue line. The graph shows a lot of dispersion due to the chaotic nature of our model. However, it can be seen that in general the distances are reduced, which is to be expected if the IMBHs are subject to dynamic friction. We also see that the effect is stronger for the models with IMBH masses of 10$^5$ $M_\odot$. While those heavy IMBHs can almost all be found far below the identity, showing that they moved closer to the COM of the galaxy, the distances of most of the light IMBHs did not change significantly.
3.2 Trapping IMBHs in the nucleus

If the IMBHs shall be left over in the UCD after the dwarf galaxy was tidally stripped, they have to be inside the nucleus at that time. Otherwise, they would be removed with the rest of the disk. We found that in our models with heavier IMBHs, some of the IMBHs were indeed trapped in the nucleus. An example of this can be seen in Fig. 7, where we show the eight IMBHs of M3 that were trapped in the nucleus. It is clearly visible, that the IMBHs gather in the central region of the nucleus. However, while those eight IMBHs are within 10 pc of the COM not all IMBHs spiral in. The remaining two IMBHs were at a distance of around

![Figure 2](image_url)

**Figure 2.** Time evolution of the distances between the IMBHs and the galactic centre. The mass of the IMBHs is shown in the upper left. W/ Nucleus and W/O Nucleus means the models with or without stellar nuclei, respectively. The model names are shown in the top right corner. Different colours denote different IMBHs.

![Figure 3](image_url)

**Figure 3.** The same as Fig. 2 but for low-mass models with $M_s = 3.6 \times 10^7 M_\odot$. The IMBHs in the top row start at a distance of 0.2 $R_s$ from the centre and the ones in the bottom row from 0.5 $R_s$. 




Figure 4. The final distances $R_f$ of the IMBH over their initial distances $R_i$ are shown for all models. IMBHs of different mass are shown in different colours as shown in the top right. The extreme models starting from M28 are excluded from this graph.

Figure 5. The same as Fig. 4 but for $R_f$ (logarithmic scale).

Figure 6. The final distances of the IMBHs in relation to their initial distances for all models. Sorted by the masses of the IMBHs. The identity is shown in blue. The extreme models starting from M28 are excluded from this graph.

Figure 7. Distribution of stars (blue dots) and IMBHs (big red dots) projected onto the x-y-plane for the central 30 pc of a dwarf in model M3 after 1 Gyr. The initial distance of these IMBHs was 167 pc. This newly developed IMBH cluster can possibly merge to form a single MBH in the present scenario.

The final distances of the IMBHs to the COM of all models are shown in Table 3. As we can see for models with galaxy parameters similar to our fiducial one, central clusters only form in models with IMBH masses of $10^5 M_\odot$. In our low mass models we have central clusters for models with $3 \times 10^4 M_\odot$ as well. In our models with low IMBH masses however only a single or no IMBH reaches the COM.

The five IMBHs to reach the COM in M3 first are shown 162 and 270 pc respectively with an initial distance of 176 pc for all IMBHs in this model. These large radii would be due to the epicyclic motions of these IMBHs caused by the gravitational potential of their dwarf and interaction with other IMBHs. We can also see that there are still plenty of stars in between the IMBHs. In our simulation the stars belonging to the nucleus have a smaller softening length (0.5 pc) than the IMBHs (5.9 pc). The large softening length prevents the IMBHs from getting closer to each other. From our present simulation we cannot see whether the IMBHs would form an even tighter cluster. We will discuss the possible further evolution of the central “IMBH cluster” in section 4.2.
Figure 8. Orbital evolution of IMBHs in model M3. The orbits are shown between $T = 0.816$ Gyr and $T = 0.832$ Gyr. The IMBH positions at $T = 0.832$ Gyr are marked with black dots.

Table 3. The number of IMBH that are closer than 20 pc or between 20 and 50 pc to the COM of the nucleus for each model. For the models without a nucleus the COM of the galaxy’s stars is used instead.

| Model ID | $N_{\text{bh}} (R_t < 20 \text{ pc})$ | $N_{\text{bh}} (20 \text{ pc} < R_t < 50 \text{ pc})$ |
|----------|-----------------------------------|--------------------------------------------------|
| M1       | 0                                 | 0                                                |
| M2       | 0                                 | 0                                                |
| M3       | 8                                 | 0                                                |
| M4       | 0                                 | 1                                                |
| M5       | 0                                 | 1                                                |
| M6       | 0                                 | 1                                                |
| M7       | 7                                 | 1                                                |
| M8       | 0                                 | 1                                                |
| M9       | 10                                | 0                                                |
| M10      | 1                                 | 0                                                |
| M11      | 10                                | 0                                                |
| M12      | 0                                 | 0                                                |
| M13      | 6                                 | 3                                                |
| M14      | 0                                 | 0                                                |
| M15      | 10                                | 0                                                |
| M16      | 0                                 | 0                                                |
| M17      | 1                                 | 1                                                |
| M18      | 4                                 | 0                                                |
| M19      | 0                                 | 0                                                |
| M20      | 1                                 | 0                                                |
| M21      | 2                                 | 0                                                |
| M22      | 0                                 | 0                                                |
| M23      | 1                                 | 0                                                |
| M24      | 0                                 | 0                                                |
| M25      | 1                                 | 0                                                |
| M26      | 1                                 | 0                                                |
| M27      | 0                                 | 0                                                |
| M28      | 3                                 | 3                                                |
| M29      | 0                                 | 0                                                |
| M30      | 10                                | 0                                                |
| M31      | 9                                 | 1                                                |
| M32      | 10                                | 0                                                |

Figure 9. Time evolution of distances of different IMBHs in model M13 (shown in different colours) to one specific IMBH in the model. It can clearly be seen that this IMBH forms a binary with another one visible in blue at around $T = 0.4$ Gyr.

in Fig. 8 between $T = 0.816$ and 0.832 Gyr. At this time the formation of the central cluster starts and it can be seen that the orbits of the IMBHs shrink rapidly due to dynamical friction against the stellar nucleus. In the case of the first two IMBH to reach the COM they reach less than 10 pc at 0.832 Gyr. We can also see the other IMBHs spiral in around them. The exact behaviour of the IMBHs after forming a central cluster needs to be investigated in future simulations.

Although $M_{\text{bh}} = 10^6 M_\odot$ is too big for IMBH thus would not be a reasonable in this parameter study, we analysed a model with $M_{\text{bh}} = 10^6 M_\odot$ as an extreme test, to gain a better understanding of the importance of BH masses in the orbital evolution of IMBHs. The dwarf galaxy for this model has the same parameters as the fiducial model. The results are discussed in Appendix A. Furthermore, the results for models with very massive ($M_{\text{dm}} = 3 \times 10^{10} M_\odot$) and very low-mass ($3 \times 10^8 M_\odot$) dark matter halo are described in Appendix B.

3.3 Binary formation

Another important aspect of this study is the formation of IMBH binaries, which may lead to mergers emitting GWs. It should be noted that our code cannot compute mergers or simulate the behaviour of close binaries accurately due to the large size resolution of the models of 5.9 pc and GW physics not being included.

To spot binaries, we first plotted the distances of the IMBHs to each other. An example of this can be seen in Fig. 9 which shows the distances of the IMBHs of M13 to one of the binary forming IMBHs. It can clearly be seen that one of the other IMBHs (visible in blue) stays within 10 pc to it between 0.4 and 0.6 Gyr. The binary dissolves after two close encounters with other IMBH. After we identified the potential binary, we can have a look at its orbits.
not necessarily need to be true in reality, making IMBHs encounters rarer. The binary in Fig. 10 D stays bound for about 0.2 Gyr until other IMBHs join it and form a central cluster. Similarly, the other binaries we found stay bound for a few $10^{-1}$ Gyr until they dissolve, usually due to an encounter with another IMBH. However, the majority of IMBHs reaches the COM of the nucleus without becoming part of a binary prior to reaching the COM.

Because of our large scale length, we cannot say if distinct binaries would form in the central IMBH cluster or not. However, if such binaries form, it is quite likely that those binaries would quickly harden due to encounters with nearby stars. This is especially true in the presence of a nucleus, which would increase amount of stars near the COM. We will discuss the merger process of those IMBHs further in section 4.2.

4 DISCUSSION

4.1 Can IMBH mergers sufficiently explain MBH formation?

In the last section we showed that IMBHs can spiral into the nucleus and then the get trapped there. However, as we saw in section 5, only heavy IMBHs spiral in. For our fiducial model, which has a galaxy mass of $1.036 \times 10^{10} M_{\odot}$, their masses need to be at least around $10^5 M_{\odot}$. The four central BHs we have observed in UCDs so far had masses between $3.5 \times 10^5$ (Afanasiev et al. 2018) and $2.1 \times 10^7 M_{\odot}$ (Seth et al. 2014). Can BHs of this size be built from numerous IMBHs within the central regions of dwarf galaxies?

For this study we neglect the mass lost due to GW radiation so that all of the mass from merging IMBHs adds to the final mass of the central MBH. Therefore, to create a light MBH of $10^6 M_{\odot}$, we need more than 10 of our heaviest IMBHs. For the heaviest MBH observed in an UCD so far, that number rises to over 210. We also want to note that not necessarily all IMBHs reach the COM. For example in M3 only 80 per cent of the IMBHs are trapped in the nucleus. Additionally, Rasskazov et al. (2019) found that IMBHs merging in GCs could experience strong recoil kicks with kick velocities of over $10^3$ km s$^{-1}$ due to symmetric GW emission. This could be strong enough to eject the IMBHs from the nucleus again. Therefore, the required number of IMBHs could be a lot higher than estimated here.

Quantifying the number of IMBHs expected to form in a galactic disk is difficult as IMBHs are hard to detect observationally. As we saw heavy IMBHs, which we would require in our scenario, also spiral in within a relatively short time frame and therefore the window of opportunity to detect them is relatively short. If the hypotheses for IMBH formation we mentioned in the introduction are correct we could try to reduce the required number of IMBHs in a dwarf for the adopted MBH formation scenario. For example, if stellar nuclei are formed from merging GCs initially, then stellar nuclei might have a number of IMBHs already. However, as discussed by previous studies of IMBHs in GCs (e.g. Baumgardt et al. 2019), the masses of IMBHs in massive galactic GCs can be rather small ($< 10^4 M_{\odot}$). So, this idea might not be so promising.

![Figure 10. Four examples of IMBH binaries forming in our simulations. All of them are plotted relative to one of the IMBHs marked with a cross. The position of the IMBHs at the beginning of the time interval given below are shown with a blue square, at its end with a red dot. The model IDs are given at the top left of each panel. Panel A shows a binary forming in M13 between $T = 0.367$ Gyr and $T = 0.430$ Gyr. The orbit of a third IMBH that was interfering with the binary is plotted in grey. It enters from the top at $T = 0.412$ Gyr and leaves towards the bottom at $T = 0.416$ Gyr. Panels B and C show binaries that formed in M15. They are shown between $T = 0.056$ Gyr and $T = 0.080$ Gyr, and between $T = 0.195$ Gyr and $T = 0.207$ Gyr respectively. Finally, we show a binary that formed in M18 in panel D. It formed between $T = 0.550$ Gyr and $T = 0.564$ Gyr. It should be noted here that the binary orbits are quite diverse ranging from almost circular orbits to highly elongated ones.](image)
4.2 GW radiation from binary IMBHs

In our simulation we showed that especially heavy IMBHs spiral into the centre of the nucleus, where they form a cluster with less than 10 pc between individual IMBHs. We also explained that we cannot resolve smaller distances between IMBHs due to our large softening distance. What we would expect to happen after the binary formation would be the hardening of the binary due to the encounters with the surrounding stars. If the binary reaches a certain distance energy loss through GW generation becomes dominant and the binary merges emitting GWs.

When the IMBHs binary encounters stars it will harden by ejecting the lighter stars. This is no problem as long as the IMBH binary is still moving towards the COM. If the IMBHs are already in the centre of the galaxy, a loss cone will form around the binary. The question becomes whether or not this loss cone can be refilled with stars quickly enough for the binary to harden sufficiently to reach the distance where GW emission becomes efficient. If this is not the case the binary evolution stalls at a distance of less than 1 pc. This is known as the final parsec problem (Milosavljević & Merritt 2003). In our model, however, we saw that most IMBHs reach the COM without becoming part of a binary. Therefore, several IMBHs meet at the COM of the dwarf galaxy, so that the interactions of the IMBHs among each other could lead to the quick formation of tight binaries and increase the number of mergers. The same interactions could, on the other hand, also lead to ejections of IMBHs further increasing the required number of IMBHs.

However, could we detect the GWs emitted by our IMBH mergers? LISA’s detection limits are shown in Fig. 2 from Jani et al. (2019). According to this, LISA can detect BHs between $10^3$ and $10^6 M_\odot$ depending on the IMBH binary’s properties and its redshift. The masses required by our model are within those boundaries. Therefore, the mergers leading to a central MBH in a UCD or stellar nucleus should be detectable using LISA given the BHs are at a low enough redshift. It remains to be investigated in the future how many IMBH mergers are possible in UCDs and stellar nuclei of dwarfs for a fixed volume at low redshifts in order to estimate the detection rate of IMBH merging in LISA.

4.3 Future work

One of the questions left open is: How many seed IMBHs can we expect in the disk of a dwarf galaxy and how massive are they? GW detections by LISA might be able to shed some light on this issue by detecting IMBH mergers. However, as LISA can only detect IMBHs mergers and not single individual IMBHs in dwarfs, we need to look other effects like X-ray signals due to the accretion of cold gas on these single IMBH. Additionally, theoretical and numerical work quantifying the expected number of IMBHs in galactic disks is required.

A major part still to be investigated is the final stage of merging the IMBHs. One possible approach would be to investigate only the final stage after the IMBHs were already trapped in the nucleus. In this case the influence of the outer disk stars can be neglected. Using this smaller system we have more resources to use smaller timesteps and a smaller softening length, which would allow us to observe the hardening of our binaries to get a better understanding of the time scales up to the actual merger. In particular, this could tell us whether or not binaries can reach the distance at which GW emission becomes important. However, this distance is very small. Even for very massive BHs ($10^5 M_\odot$) the estimated distance at which GWs become important is at around $10^{-2}$ pc (Vasiliev 2016). To simulate the last bit GW physics would be required which means that we needed a completely different code.

Another question which would be answered in these more detailed simulations is what portion of the IMBHs contributes to the final MBH and how many of them are ejected due to 3-body-interactions and recoil kicks. Hurley et al. (2016) simulated a similar scenario for stellar mass BHs in GCs. They found that the majority of BHs were ejected. If similar results were found for IMBHs in dwarf galaxies this would heavily increase the number of IMBHs required by our model. Additionally, it would be interesting to learn how these effects affect the dynamical evolution of the UCD.

In our current work, we assumed that our system only consists of stars, dark matter and IMBHs. However, for a more realistic model the influence of other components should be investigated as well. Especially the accretion of gas could influence the result significantly. While gas accretion would add some mass to the IMBHs, DF is less efficient for gas than it is for stars due to the collisional nature of gas. Therefore, the complete investigation we did here had to be repeated after adding gas, to investigate the effect on BH dynamics as well.

5 CONCLUSIONS

We have investigated whether MBH formation through the merging of IMBHs is possible in dwarf galaxies using Nbody simulations. We have assumed that (i) each IMBH is represented by a point-mass particle, (ii) IMBHs cannot grow through accretion of interstellar medium (ISM) of their host dwarf galaxies, and (iii) IMBHs can gravitationally interact with other IMBHs and stars and dark matter of their hosts (no hydrodynamical interaction with ISM). We have mainly investigated how dynamical friction of field stars of dwarf galaxies can influence the orbits of IMBHs within the dwarfs. The principle results are as follows:

1. Only the most massive IMBHs ($10^5 M_\odot$ for large dwarf galaxies ($\approx 10^{10} M_\odot$) and $3 \times 10^4 M_\odot$ for small ones ($\approx 10^7 M_\odot$)) spiral in due to DF of IMBHs against disk field stars within less than 1 Gyr. There is a positive correlation between dwarf mass and threshold mass for IMBHs being able to spiral into the dwarf’s COM quickly enough. However, in a galaxy with 3 times the mass of our fiducial model the threshold mass exceeds $10^5 M_\odot$, while for a galaxy with a third of our low-mass model even $10^3 M_\odot$ can spiral into the COM within 1 Gyr. The masses of IMBHs and the dwarfs are the main factors that determine whether the IMBHs spiral in or not. DF is stronger for heavier IMBHs and in smaller dwarfs. The initial distance and the presence or absence of a nucleus have only little influence.
2. Binary IMBHs in dwarf galaxies can form both after the IMBHs reach the nucleus and before. However, the latter is quite rare. While we could observe binary formation in our simulations, we could not observe the hardening of the binaries due to the relatively large gravitational softening length used. As most binaries form inside the nucleus, simulating only the nucleus with a smaller softening length could give us further inside in the behaviour of IMBH binaries. Therefore, future simulations using a different code, e.g. NBODY6, are required and for the final merger modelling energy loss due to GWs will be required as well.

3. We expect that merging of massive IMBHs with $M_{bh} \sim 10^5 M_\odot$ can occur mostly in the central regions of dwarfs. Given these high masses, we expect the merger to emit GWs that could be detected by LISA if they are within dwarfs at lower redshifts.

4. At present we cannot say how many IMBHs should be expected in the disk of a dwarf galaxy. Our model requires at least 10 IMBHs for a small MBH ($10^6 M_\odot$) to form. The required number is even larger if we take into account that not all IMBHs necessarily reach the centre and that mass is lost due to GW and possibly ejections. The number of IMBHs required for large MBHs to form is quite large ($>200$ for the heaviest MBH found in an UCD thus far). It is unknown if such a high number of IMBHs can exist in the disk of a dwarf galaxy. Therefore, future simulations should investigate the role of gas accretion in IMBH formation as well.

From the present work, we can conclude that it is possible that the MBHs observed in UCDs formed through IMBH mergers, though a high enough number of IMBHs in the disk of a dwarf galaxy. Additional more detailed investigations of the hardening of IMBH binaries and their mergers are needed. Investigating other processes contributing to BH growth, such as gas accretion, would contribute to completing the picture as well.

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APPENDIX A: SIMULATIONS WITH LARGER BHS

In addition to testing the effects of DF on IMBHs, we tested what happens if we have $10^6 M_{\odot}$ BHs from the start in model M28. The evolution of the MBH orbits can be seen in Fig. A1 in the appendix. The BH in this model reach the galaxy’s COM after less than 0.2 Gyr and, therefore, a lot faster than for example the BHs in M3, which are a factor of 10 lighter, while the galaxy’s parameter stay the same. This is to be expected, because the more massive BHs have a larger sphere of influence, therefore increasing the deceleration the BHs experience. In Table 3 we can see, that only 3 of the six MBH end up within the inner 20 pc of the nucleus. The other 3 are within the central 50 pc. This is due to the highly eccentric orbits the MBHs have due to their interactions with one another. This leads to a total BH mass of $6 \times 10^6 M_{\odot}$ in the central cluster, which is within the range of observed MBHs in UCDs ($3.5 \times 10^6$ to $2.1 \times 10^7 M_{\odot}$). No evidence of binaries forming before the MBHs reach the galaxies COM. Because of our small sample we cannot derive a general conclusion from this. We can, however, conclude from the quick descent of the MBHs into the dwarf’s COM that such an event would be highly improbable as there is only little time for those binaries to form.

Figure A1. The six IMBHs of M28. This models parameter’s are the same as for the fiducial model, which means that the dwarf’s mass is at $1.036 \times 10^{10} M_{\odot}$. However, the IMBH in this model have a mass of $10^6 M_{\odot}$. Different colours denote different BHs.

APPENDIX B: SIMULATIONS WITH DIFFERENT GALAXY MASSES

The results of our models with the heaviest dwarf, M29 and M32, can be seen in Fig. B1. While the distances of the

Figure B1. Two different models for a heavy dwarf. The model ID can be seen in the top right, while the BH mass is shown in the top left of each panel. Different colours denote different IMBHs. With a mass of $3.108 \times 10^{10} M_{\odot}$ this galaxy’s mass is 3 per cent of that of the Milky Way and 3 times that of our fiducial model.

Figure B2. $10^4 M_{\odot}$ IMBHs in a smaller galaxy in model M30. Different colours denote different IMBHs. This galaxy’s mass is $3.1 \times 10^8 M_{\odot}$, less than a third of that of our low-mass models.
IMBHs to the dwarf’s COM fluctuate rapidly in model M29, none of the IMBHs gets to a distance closer than 100 pc. No general trend is visible. This can be explained through the high velocities of the stars that lead to them only having short encounters with the IMBHs and therefore a low DF deceleration. Because of this the threshold mass for BH of $10^5 \, M_\odot$ we found for our fiducial model does not apply here. As we can see looking at model M32 $10^6 \, M_\odot$ BHs do spiral into the dwarf’s COM. This means that the threshold mass is shifted to higher values.

The opposite effect can be seen for models M30 and M31. As a result of their low velocities, DF is very efficient and we can see the IMBHs move towards the dwarf’s COM quickly. An example of this can be seen in Fig. B2 where ten $10^4 \, M_\odot$ IMBHs move to an orbit with less than 20 pc in less than 0.2 Gyr. From Table 3 we can see, that even small $10^3 \, M_\odot$ IMBHs reach the COM in less than one Gyr. This continues the trend we already observed, namely that the threshold mass for IMBHs to be able to reach the COM within 1 Gyr is lower in lighter dwarfs and higher in heavier dwarfs. While there is an initial binary in both M30 and M31, no binaries form during the evolution of any of the four models discussed here before the IMBHs reach the dwarf’s COM.