Growing massive black holes in a Local Group environment: the central supermassive, slowly sinking and ejected populations

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Abstract

We explore the growth of $\lesssim 10^7 M_\odot$ black holes that reside at the centres of spiral and field dwarf galaxies in a Local Group type of environment. We use merger trees from a cosmological $N$-body simulation known as Via Lactea 2 (VL-2) as a framework to test two merger-driven semi-analytic recipes for black hole growth that include dynamical friction, tidal stripping and gravitational wave recoil in over 20,000 merger tree realizations. First, we apply a Fundamental Plane limited (FPL) model to the growth of Sgr A*, which drives the central black hole to a maximum mass limited by the black hole Fundamental Plane after every merger. Next, we present a new model that allows for low-level prolonged gas accretion (PGA) during the merger. We find that both models can generate an Sgr A* mass black hole. We predict a population of massive black holes in local field dwarf galaxies – if the VL-2 simulation is representative of the growth of the Local Group, we predict up to 35 massive black holes ($\lesssim 10^6 M_\odot$) in Local Group field dwarfs. We also predict that hundreds of $\lesssim 10^5 M_\odot$ black holes fail to merge, and instead populate the Milky Way halo, with the most massive of them at roughly the virial radius. In addition, we find that there may be hundreds of massive black holes ejected from their hosts into the nearby intergalactic medium due to gravitational wave recoil. We discuss how the black hole population in the Local Group field dwarfs may help to constrain the growth mechanism for Sgr A*.

Key words: black hole physics – Galaxy: centre – galaxies: haloes – galaxies: high-redshift – Local Group.

1 Introduction

Supermassive black holes (SMBHs), with masses of $10^6 \lesssim M \lesssim 10^{10} M_\odot$, are widely believed to dwell at the centres of elliptical galaxies and spiral bulges (e.g. Kormendy & Richstone 1995); the best known example is observed at the centre of the Milky Way, with a mass $M_{\text{SMBH}} = 4.2 \times 10^6 M_\odot$ (Ghez et al. 2008). There is abundant evidence that when a SMBH is in place, it transforms the structure and evolution of the galaxy, from powering active galactic nuclei (AGN) at high redshifts (Greenstein & Matthews 1963; Rees 1984; Alexander et al. 2005; Fan 2005), to regulating star formation throughout the galaxy (Di Matteo, Springel & Hernquist 2005; Croton et al. 2006; Cox et al. 2008), to scouring the galactic nucleus of stars during SMBH mergers (Ebisuzaki, Makino & Okumura 1991; Quinlan 1996; Makino 1997; Milosavljevic & Merritt 2001; Volonteri, Haardt & Madau 2003).

This deep connection between the evolution of SMBHs and galaxies is perhaps best encapsulated in a remarkable correlation between the SMBH mass and the velocity dispersion of the host spheroid (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Marconi & Hunt 2003; Hopkins et al. 2007). The dispersion in the black hole Fundamental Plane (Hopkins et al. 2007) points to an intrinsically tight correlation, at least for a sample of nearby bright spiral and elliptical galaxies with clear dynamical SMBH signatures. However, on a smaller mass scale, in systems that have a mass comparable to the Milky Way mass or smaller, central SMBHS may become less common as bulges become less common (Ferrarese et al. 2006), and in some instances they disappear entirely, such as in the case of M33 (Gebhardt et al. 2001; Merritt, Ferrarese & Joseph 2001) and NGC 205 (Valluri et al. 2005). Many of these bulgeless stellar systems host a nuclear star cluster instead. Nuclear star clusters are found in late-type spirals (Boker et al. 2002) and...
dwarf elliptical galaxies (Cote et al. 2006). This changeover may be the result of a competition between the SMBH and nuclear star cluster for the same gas reservoir. Nayakshin, Wilkinson & King (2009) show that in massive galaxies with a spheroidal velocity dispersion of $\sigma \geq 150 \, \text{km} \, \text{s}^{-1}$, gas accretion on to the black hole dominates and a SMBH forms, while in galaxies with lower velocity dispersions, star formation generates a nuclear cluster. Note that such a star cluster does not exclude presence of an underweight SMBH (Nayakshin et al. 2009).

Several observational and theoretical studies have linked the SMBH mass to the mass of the host dark matter halo (Ferrarese 2002; Baes et al. 2003; Shankar et al. 2006). This relation is a boon to theorists because many of the leading explanations of SMBH birth and growth are driven by hierarchical structure formation (Loeb & Rasio 1994; Haehnelt, Natarajan & Rees 1998; Silk & Rees 1998; Cattaneo, Haehnelt & Rees 1999; Haehnelt & Kauffmann 2000; Monaco, Salucci & Danese 2000; Adams, Graff & Richstone 2001; Granato et al. 2001; Menou, Haiman & Narayanan 2001; Hopkins et al. 2005; Wyithe & Loeb 2005), and are therefore tied to the mass of the dark matter halo.

In the current picture of SMBH assembly, the black hole begins life as a low-mass ‘seed’ black hole at high redshift. It is not clear, though, when exactly these BH seeds emerge or what mass they have at birth. SMBH seeds may have been spawned from the accretion of low angular momentum gas in a dark matter halo (Bromm & Loeb 2003, 2004; Koushiappas, Bullock & Dekel 2004), the coalescence of many seed black holes within a halo (Begelman & Rees 1978; Islam, Taylor & Silk 2004), or from an IMBH formed, perhaps, by runaway stellar collisions (Miller & Colbert 2004; Portegies Zwart et al. 2005; van der Marel 2004) or they could even be primordial (Mack, Ostriker & Ricotti 2007). However, the most likely candidates for SMBH seeds are the remnants that form from the first generation of stars sitting deep within dark matter haloes (Madau & Rees 2001; Heger et al. 2003; Islam, Taylor & Silk 2003; Volonteri et al. 2003; Wise & Abel 2005)—so-called Population III stars. With masses less than roughly $10^3 \, M_\odot$, these relic seeds are predicted to lie near the centres of dark matter haloes at high redshifts (Bromm, Coppi & Larson 1999; Abel, Bryan & Norman 2000, 2002). Structure formation dictates that dark matter haloes form in the early universe and hierarchically merge into larger bound objects, so naturally as dark matter haloes merge, seed black holes sink to the centre through dynamical friction and eventually coalesce.

Gas accretion is thought to play a critical role in fueling the early stages of black hole growth (David, Durisen & Cohn 1987; Kauffmann & Haehnelt 2000; Merloni 2004), and this may explain the tightness of the $M_{\rm BH}$–$\sigma$ relation (Haehnelt & Kauffmann 2000; Burkert & Silk 2001; Di Matteo et al. 2005; Kazantzidis et al. 2005; Robertson et al. 2006). Since high-redshift galaxies are thought to be especially gas rich, each merger brings a fresh supply of gas to the centre of the galaxy, and new fuel to the growing SMBH (Mihos & Hernquist 1994; Di Matteo et al. 2003). From a combination of gas accretion and binary black hole coalescence, it is thought that these Population III-generated seeds may form the SMBHs we observe today (Soltan 1982; Schneider et al. 2002).

During a galaxy merger, each black hole sinks to the centre of the new galaxy potential due to dynamical friction and eventually becomes bound as a binary (Escala et al. 2005; Kazantzidis et al. 2005). Dynamical friction then continues to shrink the orbit until the binary is hard (i.e. the separation between each black hole, $\Delta a_{\text{orb}}$, is such that the system tends to lose energy during stellar encounters; Heggie et al. 2007). Thereafter, further decay is mediated by three-body scattering with the ambient stellar background until the binary becomes so close that the orbit can lose energy via gravitational radiation. In studies of static, spherical potentials, it may be difficult for stellar encounters alone to cause the binary to transition between the three-body scattering phase and the gravitational radiation regime (Milosavljevic & Merritt 2003). However, in gas-rich or non-spherical systems, the binary rapidly hardens and coalesces into one black hole, emitting copious gravitational radiation in the process (Sigurdsson 2003; Kazantzidis et al. 2005; Berczik et al. 2006; Holley-Bockelmann & Sigurdsson 2006; Mayer et al. 2007).

Unless the black hole binaries stall at the final parsec, the longest time-scale governing the coalescence of two black holes occurs when the host galaxies themselves are still merging. Here, the dynamical evolution of two merging galaxies is driven by the combined effect of dynamical friction, which brings the less massive galaxy, or satellite, to the centre of the larger halo, or primary, and tidal interaction which strips mass from the satellite and further delays the merger (e.g. Richstone 1976; Aguilar & White 1986; Holley-Bockelmann & Richstone 1999; Taffoni et al. 2003). If the dynamical friction time-scale is longer than a Hubble time, the black holes carried by their host galaxies will not sink close enough to form a binary.

Sijacki et al. (2007) and Di Matteo et al. (2008) have performed state-of-the-art high-resolution hydrodynamic simulations of cosmological structure formation, following the growth of high-mass SMBHs at the centres of massive elliptical galaxies and clusters of galaxies. Their research was followed by similar semi-analytic work that incorporates a full treatment of dark matter dynamics, radiative gas cooling, star formation and energy feedback processes (Somerville et al. 2008). In this very elegant approach, the SMBH accretes gas through a quasar mode—nearly Eddington rate accretion following a galaxy merger (Croton et al. 2006)—and a radio mode—Bondi–Hoyle accretion associated with relativistic jets (Somerville et al. 2008). Both modes produce feedback that heats the surrounding gas. In this model, the feedback stops the accretion and locks the growth of the SMBHs to the Fundamental Plane. At the same time, the feedback also quenches the star formation, which explains the observed shallow metallicity, stellar density and entropy profiles. However, it has recently been suggested that the implementation and importance of AGN feedback may need to be re-examined (Ostriker et al. 2010). Furthermore, radiation fields and winds produced by massive stars may provide the dominant feedback (Hopkins et al. 2010). In fact, it is worth mentioning that AGN feedback is just one of many feedback processes occurring in galaxy centres; supernovae, star formation and galaxy mergers produce feedback as well (Sinha & Holley-Bockelmann 2010). It is not clear which feedback process contributes the most to the evolution of a given galaxy.

As well developed as the current effort to understand SMBH growth is, most work has focused on growing the most massive SMBHs, found predominantly in dense environments. In a Local Group environment though, the galaxy morphology, dynamics and star formation history are all dramatically different. Smaller stellar systems such as disc and dwarf galaxies have SMBHs with lower masses ($\lesssim 10^6 \, M_\odot$) or no SMBHs at all for bulgeless galaxies like M33. In cosmological simulations, AGN feedback models create significant uncertainties for black hole growth in these lower mass haloes (Booth & Schaye 2009). In addition, SMBHs in the Local Group are currently subluminous, implying a different relationship with gas consumption, at least in the present epoch, than the more massive end of the SMBH mass spectrum. None the less, mergers are still expected to provide a key mechanism to channel gas to the galactic centre. While ‘cold mode’ gas accretion (Keres et al. 2005;
Dekel et al. (2009) can channel large amounts of cold gas ($<10^4$ K) to the galactic disc, this gas may not fuel the SMBH. Indeed, high-resolution N-body–SPH simulations of Milky Way formation show that most of the gas that is accreted originates from major mergers; even during the ‘radio mode’, where the gas is accreted by a Bondi–Hoyle mechanism, the gas reservoir is stocked not from the cold mode, but from the major mergers the Milky Way finished billions of years ago (Bellovary, private communication). Hence, galaxy mergers appear to drive SMBH growth in a wide range of masses.

One problem that can preferentially plague low-mass galaxies is gravitational wave recoil. Recent calculations of binary black hole mergers indicate that gravitational wave recoil can kick a newly merged black hole with a speed as large as $\sim$4000 km $s^{-1}$ (Campanelli et al. 2007; Gonzalez et al. 2007a,b; Herrmann et al. 2007; Koppitz et al. 2007; Schnittman & Buonanno 2007). The magnitude of the gravitational wave recoil imparted during any given merger depends on the mass ratio of each black hole, the spin magnitude and orientation with respect to the binary orbital plane, as well as the eccentricity of the orbit (Baker et al. 2007; Campanelli et al. 2007; Schnittman & Buonanno 2007). While certain spin alignment mechanisms (Bogdanovic, Reynolds & Miller 2007; Dotti et al. 2010) could allow massive galaxies to retain their SMBHs, even moderate kicks can eject a growing SMBH from dwarf or high-redshift galaxies (Merritt et al. 2004; Micic, Abel & Sigurdsson 2006; Schnittman 2007; Sesana 2007; Volonteri 2007; Volonteri, Gultekin & Dotti 2010). There are tentative observations that suggest that gravitational wave recoil can indeed eject a SMBH from its host (Komossa, Zhou & Lu 2008). Given the greater vulnerability to recoil, the questionable importance of AGN feedback, and lack of SMBH in some galaxies, one can argue that SMBH growth may be substantially different for these lightest SMBHs in Local Group type of environments.

In this paper we use Via Lactea 2 (VL-2) evolutionary tracks to begin with an N-body merger tree that mimics the assembly of the Milky Way halo (Diemand, Kuhlen & Madau 2007; Diemand et al. 2008). Upon this numerical merger tree we paint semi-analytic recipes for the galaxy and black hole growth. We follow two different merger driven recipes. The first approach is inspired by recent semi-analytic and numerical work on black hole growth (Hopkins et al. 2005, 2007; Croton et al. 2006; Somerville et al. 2008). Here, SMBHs grow slowly through low-level Bondi–Hoyle gas accretion tempered by AGN feedback – the radio mode; this growth is punctuated by rapid Eddington gas accretion triggered by a major merger – the quasar mode. This approach has been used to explain SMBH growth in massive stellar systems but not the growth of massive black holes in the Local Group. Here, SMBH growth is limited by the black hole Fundamental Plane. Hence, hereafter we call this approach Fundamental Plane limited (FPL). In the second recipe, we introduce a model for prolonged black hole gas accretion physically motivated by galaxy dynamics. In this model, the subgrid physics (stellar and AGN feedback, as well as accretion disc microphysics) is bundled into one parameter for gas accretion efficiency that can be constrained by future small-scale, fully general relativistic magnetohydrodynamic AGN simulations. With this approach, gas accretion on to the black hole is based on the dynamics of the galaxy merger – fast at high rate for major mergers and prolonged at low rate for more minor mergers. This model does not use the black hole Fundamental Plane or the $M-\sigma$ relation to limit black hole growth. During a minor merger, the accretion time-scale is longer, but the accretion rate is lower, since less gas is driven toward the BH by a smaller global perturbation. For major mergers, the accretion rate increases, though in practice it never reaches the Eddington rate. We call this approach prolonged gas accretion (PGA). In addition to gas accretion, black holes grow through mergers with other black holes too. In both recipes, we model SMBH growth from direct mergers including gravitational recoil. Since the recoil velocity is highly dependent on BH spin and orientation, we create ~20,000 merger trees to examine the combination of BH spin parameters that favours the $M-\sigma$ relation at redshift zero.

The key difference between FPL and PGA models is in the implementation of AGN feedback. In FPL, the black hole Fundamental Plane is used to calibrate AGN feedback. In PGA, we use AGN feedback to suppress the efficiency of gas accretion, while calibration parameters come from detailed small-scale simulations of galaxy merger remnants.

We describe our method in Section 2 and introduce our black hole growth prescriptions. In Section 3, we present results, focusing on the evolution of our Sgr A* analogue in the FPL and PGA models. In Section 4, we present predictions for the local population of massive black holes, rogue black holes in the Milky Way and ejected black holes into the nearby intergalactic medium. We discuss the implications of our results and future work in Section 5.

2 METHOD

2.1 VL-2 dark matter halo merger tree

In this paper, we use publicly available VL-2 evolutionary tracks (Diemand et al. 2007, 2008). VL-2 is the highest resolution cosmological N-body simulation of Milky Way formation and evolution, and evolves a $\Lambda$ cold dark matter ($\Lambda$CDM) universe with 3-yr Wilkinson Microwave Anisotropy Probe (WMAP3) parameters ($\Omega_M = 0.238$, $\Omega_\Lambda = 0.762$, $\sigma_8 = 0.74$ and $h = 0.7$). The high-resolution region of VL-2 is embedded within a periodic box with a comoving length of 40 Mpc. The evolutionary tracks consist of the time evolution from $z = 27.54$ to 0 of ~20,000 dark matter haloes identified at redshift $z = 4.56$. Haloes have masses as small as $\sim 10^3 M_\odot$.

In our hybrid method, we combine dark matter halo merger trees obtained from VL-2 evolutionary tracks with an analytical treatment of the physical processes that arise in the dynamics of galaxy and black hole mergers. Our N-body approach stops with the creation of the halo merger tree. We seed dark matter haloes with Population III black holes until $z = 5$, following the work of Trenti & Stiavelli (2009) (fig. 1 in Trenti, Stiavelli & Michael 2009), and follow their merger history from redshift $z = 27.54$ to 0 by constructing numerical merger trees interpolating between the snapshots at $z \leq 15$. To define the structure of each dark matter halo within the N-body generated merger tree, we assume a Navarro, Frenk and White (hereafter NFW) density profile (Navarro, Frenk & White 1996). We set the parameters of a given NFW halo using the approach presented in Bullock et al. (2001), assuming the typical virial mass of a dark matter halo to be $M_{v}$ $\sim 1.5 \times 10^{12} M_\odot$ at redshift zero. Note that only haloes that are seeded with black holes or merging with other haloes are retained in our merger tree. For each merger, we tag the more massive halo as the primary, with mass $M_p$, and the less massive halo as the secondary or satellite halo with mass $M_s$. Note that the properties of low-mass dark matter haloes in the mass range of VL-2 ($10^5 \leq M \leq 2 \times 10^{12} M_\odot$) have not been studied in detail at $z \geq 3$.

Note that VL-2 evolutionary tracks do not include any haloes or subhaloes that were not present at $z = 4.56$. Some haloes are completely disrupted in mergers prior to that time (no subhalo counterpart at $z = 4.56$), and some haloes form after $z = 4.56$. These
haloes are small in mass and would have been cut out of the merger tree anyway since they are either too small to host the black hole seed or too small to have relevant amounts of cold gas for either black hole accretion or star formation. Note that VL-2 does not necessarily represent the actual merger histories of Milky Way or Local Group.

2.2 SMBH growth prescriptions

We test two fundamentally different models for SMBH growth: FPL and PGA. In FPL, gas accretion on to the black hole is controlled by AGN feedback in such way that the SMBH mass does not grow above the black hole Fundamental Plane at any time. In PGA, we bundle star formation and AGN feedback, as well as accretion disc microphysics together into gas accretion efficiency parameter; the mass is not restricted to lie on the black hole Fundamental Plane.

Our only guideline is the mass of Sgr A* observed today. Since the mass of the SMBH at the centre of the Milky Way is well constrained, we can identify which physical processes during the growth are most important for the final black hole mass and test their parameter space. The first of these parameters applies to both models: the black hole seed’s initial mass function (BHMF). We test various BHMFs and various values for the minimum and maximum black hole seed mass. A second effect that is present in both models is gravitational wave recoil (see Section 2.4). The third parameter is unique in each model. In the FPL model, the third parameter is the mass accreted during the ‘radio’ or quiescent mode of the AGN duty cycle. The SMBH growth during this phase is usually approximated by Bondi–Hoyle gas accretion, though this is not strictly necessary. We test various values for average mass accretion rate during this radio mode. Since the Bondi–Hoyle mechanism is commonly used, we may occasionally address this quiescent part of SMBH growth as the Bondi–Hoyle phase, but our approach does not depend on the actual growth mechanism here. In the PGA model, the third parameter is the gas accretion efficiency. In our implementation this parameter contains information on how the microphysics acts to suppress accretion on to the black hole, such as supernovae feedback, accretion disc physics etc. We treat all of these processes as free parameters to study the observable consequences at z = 0.

In all models, we adopt Gnedin (2000) and Kravtsov, Gnedin & Klypin (2004) initial cold gas fractions (\(f_{\text{gas}} \sim 10^{-2}\)) for \(M_{\text{halo}} \sim 3 \times 10^{10}\) \(M_{\odot}\); \(f_{\text{gas}} \sim 10^{-3}\) for \(M_{\text{halo}} \sim 4 \times 10^{10}\) \(M_{\odot}\); \(f_{\text{gas}} \sim 0.13\) for \(M_{\text{halo}} \gtrsim 1 \times 10^{11}\) \(M_{\odot}\) in high-redshift galaxies for a reionization range of \(10 \leq z \leq 11\). In this manner we follow the approach of Somerville et al. (2008) for creating the gas reservoirs used for star formation and gas accretion on to the black holes. We do not include further multimode accretion in the merger tree (i.e. Keres et al. 2005).

2.2.1 Fundamental Plane limited model

In the first model, FPL, we use the approach adopted by Somerville et al. (2008), but focus only on those aspects that are important for SMBH growth. In FPL, the SMBH grows through mergers and gas accretion. Gas accretion is controlled by two modes of AGN feedback. The quasar or ‘bright’ mode occurs after the host galaxy goes through a major merger; this causes the central black hole to accrete gas exponentially until it reaches the Eddington limit, and it continues accreting at Eddington limit until it reaches a mass specified by the black hole Fundamental Plane. By design, the black hole mass at the end of each merger is proportional to the stellar mass of the spheroid \(M_{\text{sp}}\) in the model:

\[
\log(M_{\text{BH}}/M_{\text{sp}}) = -3.27 + 0.36 \text{erf}[f_{\text{gas}} - 0.4]/0.28, \tag{1}
\]

where \(f_{\text{gas}}\) is the amount of cold gas available for accretion (Somerville et al. 2008). The quasar mode is replaced by a radio mode until the next major merger. During the radio mode, the black hole accretes gas at lower rates associated with radiatively inefficient Bondi–Hoyle accretion, such as what occurs in an advection-dominated accretion flow model (Fender, Belloni & Gallo 2004). The Bondi–Hoyle accretion rate controls the black hole mass during the longer quiescent phase between galaxy mergers. In the Milky Way today, the SMBH mass is \(4.2 \times 10^6\) \(M_{\odot}\) (Ghez et al. 2008), and the Bondi–Hoyle rate is \(\sim 5 \times 10^{-5}\) \(M_{\odot}\) yr\(^{-1}\) (Quataert & Gruzinov 2000; Melia & Falcke 2001). Since we know the current Sgr A* mass and the accretion rate observed today, we can determine how well the FPL model can match observations. To simplify our investigation we adopted an average Bondi–Hoyle accretion rate during the radio mode over a Hubble time. The Bondi–Hoyle accretion rate in our model is averaged over all radio mode phases the galaxy goes through and since it explicitly excludes AGN feedback which would blow away the gas, the Bondi–Hoyle accretion rate we use is a lower constraint. If we model AGN feedback, the derived accretion rates would be higher.

2.2.2 Prolonged gas accretion model

The SMBH in our PGA model grows through a combination of black hole mergers and gas accretion, inspired by Micic et al. (2007). To review the approach, we assumed that major galaxy mergers would funnel gas to the black hole in each of the progenitors and activate an Eddington-limited growth phase for a Salpeter time. The black hole mass in Micic et al. (2007) grew as \(M_{\text{BH}}(t) = M_{\text{BH},0} \exp(\Delta t/t_{\text{sal}})\), where \(\Delta t = t - t_0\), \(t_{\text{sal}} \equiv c M_{\text{BH}}^2 / [(1 - \epsilon)L]\), \(\epsilon\) is the radiative efficiency, \(L\) is the luminosity and \(c\) is the speed of light; in this picture the black hole mass would roughly double in 40 Myr (Hu et al. 2006). We distinguished two cases depending on the mass ratio of merging dark matter haloes. The first is a more conservative criterion that allows black holes to accrete gas if the mass ratio of the host dark matter halo is less than 4:1 – a major merger. The second case sets an upper constraint on the final black hole mass by allowing gas accretion as long as the merging dark matter haloes have a mass ratio less than 10:1 – on the cusp of what is considered a minor merger. Since our black holes merged promptly after the haloes merged, the accretion time-scale and efficiency for major mergers was the same regardless of the mass ratio or redshift.

In this paper, we continue to model the black hole growth as one of extended gas accretion excited by major mergers. At high redshift, this is likely a good assumption, though note that at low redshift when mergers are infrequent, secular evolution such as bar instabilities may dominate the gas (and therefore black hole) accretion. Integrated over the whole of a black hole lifetime, though, this major merger-driven gas accretion is likely to be the dominant source of gas inflow. Since the black hole growth is so strongly dependent on what fuel is driven to the centre during galaxy mergers, it is important to characterize this merger-driven mass growth, including the critical gas physics that may inhibit or strengthen this nuclear supply. We are motivated by numerical simulations that include radiative gas cooling, star formation and stellar feedback to study the starburst efficiency for unequal mass ratio galaxy mergers (Cox et al. 2008), which finds that the gas inflow depends strongly on the mass ratio of the galaxy (see also e.g. Hernquist 1989; Mihos et al. 2005).
& Hernquist 1994). This study parametrizes the efficiency of nuclear star formation (i.e. gas supply and inflow), \( \alpha \), as a function of galaxy mass ratio. In a broader sense, this study shows how much gas is available for either star formation or gas accretion on to the central black hole. These two processes compete for the same gas and the outcome (nuclear cluster versus SMBH) depends on the mass of the host spheroid (Nayakshin et al. 2009). The efficiency of gas inflow is described by

\[
\alpha = \alpha_{\text{slope}} \left( \frac{M_s}{M_p} - \alpha_0 \right)^{0.5},
\]

where \( \alpha_0 \) defines the mass ratio below which there is no enhancement of nuclear star formation (i.e. gas inflow), and \( \alpha_{\text{slope}} \) is the fitted slope of the solid line in Cox et al. (2008), fig. 15. Here, the gas accretion efficiency has a maximum of 0.56 for 1:1 halo mergers with \( \alpha_{\text{slope}} = 0.6 \), and falls to zero at \( \alpha_0 \). This parametrization is insensitive to the stellar feedback prescription. We use \( \alpha \) to define how efficiently the merger funnels the galaxy’s gas to the black hole accretion disc. In general, all feedback processes (stellar or black hole) can be contained in \( \alpha_{\text{slope}} \). Only small-scale numerical simulations of gas accretion in AGNs with fully implemented and resolved gas physics can relate \( \alpha_{\text{slope}} \) to the mass ratio of merging galaxies. In Cox et al. (2008), the fitted \( \alpha_0 \) parameter suggests gas inflow is sharply curtailed for mass ratios larger than 9. We set the cut-off mass ratio to \( M_p/M_s = 10 \) in order to compare with our previous black hole growth prescription (Micic et al. 2007). We adopt \( \alpha_{\text{slope}} = 0.6 \) as in Cox et al. (2008).

Now that we have implemented a realistic description of the merger time for each black hole within a halo (see next section), we allow them to grow for a physically motivated accretion time-scale. The accretion of gas on to both the incoming and central black hole starts when the two black holes are still widely separated, at the moment of the first pericentre passage, and continues until the black holes merge (cf. Di Matteo et al. 2005; Colpi et al. 2007). This sets the accretion time-scale, \( t_{\text{acc}} \), as follows: \( t_{\text{acc}} = t_f \left( r = r_{\text{acc}} \right) - t_{\text{dyn}} \left( r = r_{\text{vir}} \right) \), where \( t_f \left( r = r_{\text{acc}} \right) \) is the merger time-scale including dynamical friction, and \( t_{\text{dyn}} \left( r = r_{\text{vir}} \right) \) is dynamical time at virial radius \( r_{\text{vir}} \), which marks the first pericentre pass of the black hole. By stopping the accretion as the black holes merge, we roughly model the effect of black hole feedback in stopping further accretion.

Putting these pieces together, the mass accreted by a black hole during \( t_{\text{acc}} \left( r = r_{\text{vir}} \right) \) is

\[
M_{\text{acc}} = M_{BH,0} \left( e^{\left( \frac{\omega_{\text{acc}}}{\omega_{\text{vir}}} \right)} - 1 \right),
\]

where \( M_{BH,0} \) is the initial black hole mass, \( \omega \) is the starburst efficiency (Cox et al. 2008) and \( \omega_{\text{vir}} \) is defined above. After \( t_{\text{acc}} \), the incoming black hole merges with the SMBH at the centre and a new SMBH is formed after having accreted gas for \( t_{\text{dyn}} \). The accretion time and efficiency both implicitly encode the large-scale dynamics of the merger and the bulk gas accretion into the nuclear region, while \( t_{\text{acc}} \) describes the accretion disc physics. As before, we set the Salpeter accretion efficiency to 0.1 (Shakura & Syunyaev 1973).

### 2.3 Dynamical friction

Dynamical friction allows massive black hole binaries to form at the centre of a galaxy in two ways. First, dynamical friction expedites the merger of two dark matter haloes and later the merger of the galaxies they host. In this manner, merging galaxies can efficiently shepherd massive black holes to the centre of the new system, roughly to the inner kiloparsec (see Colpi et al. 2007 for a review). Second, dynamical friction from the gas in the disc carries black holes deeper toward the galactic centre, where they form binary and eventually merge (e.g. Begelman, Blandford & Rees 1980; Escala et al. 2005; Kazantzidis et al. 2005; Dotti et al. 2007). We model both effects as follows.

The time for a satellite to sink to the centre of a primary can be approximated using Chandrasekhar dynamical friction (Binney & Tremaine 1987):

\[
t_{\text{chandra}} = \frac{1.17 r_{\text{vir}} v_c e^a}{\ln \Lambda GM_s},
\]

where \( \ln \Lambda \) is the Coulomb logarithm, \( \ln \Lambda \approx \ln (1 + M_p/M_s) \). To define the satellite orbit, we adopt values suggested by numerical investigations (Colpi, Mayer & Governato 1999) and used in previous semi-analytical work (Volonteri et al. 2003): the circularity \( e^a = 0.8 \), and the circular velocity \( v_c \) is determined at \( r_{\text{acc}} = 0.6 r_{\text{vir}} \). For a 10\(^{22} \)M\(_\odot\) halo, \( r_{\text{vir}} \sim 300 \)kpc.

Assuming that each merging galaxy carries a massive black hole at its centre, \( t_{\text{f0c}} \) is the merging time for massive black holes when all other processes (three-body scattering, gas dynamical friction, gravitational radiation etc.) involved in the formation and later shrinking of the black hole binary are efficient and fast. Because of tidal stripping and possible resonant interactions, simulations have shown that the Chandrasekhar formula underestimates the merger time, especially in the case of minor mergers (e.g. Weinberg 1989; Holley-Bockelmann & Richstone 1999). If this is true, then semi-analytic studies of black hole merger rates using a Chandrasekhar formalism for the merger time will overestimate the true number of black hole mergers.

In an effort to better parametrize dynamical friction, Boylan-Kolchin, Ma & Quataert (2008) used N-body simulations to study dark matter halo merging time-scales, and confirmed that the Chandrasekhar formalism does underestimate the merger time, by a factor of \( \approx 1.7 \) for \( M_p/M_s \approx 10 \) and a factor of \( \approx 3.3 \) for \( M_p/M_s \approx 100 \). They propose a fitting formula that accurately predicts the time-scale for a satellite to sink from the virial radius to the host halo centre:

\[
\frac{t_{\text{merge}}}{t_{\text{dyn}}} = A \frac{(M_{\text{host}}/M_{\text{sat}})^b}{\ln(1 + M_{\text{host}}/M_{\text{sat}})} \exp \left[ c \frac{j(E)}{j(E)} \right] \left[ \frac{r_c(E)}{r_{\text{vir}}} \right]^d,
\]

where \( b = 1.3, c = 1.9, d = 1, A = 0.216 \), circularity \( j(E)/j(E) = 0.5, r_c(E)/r_{\text{vir}} = 0.65 \), as defined in Boylan-Kolchin et al. (2008). The dynamical time, \( t_{\text{dyn}} \), is given at virial radius as

\[
t_{\text{dyn}} = \frac{r_{\text{vir}}}{v_c(r_{\text{vir}})} = \left( \frac{r_{\text{vir}}^3}{GM_{\text{host}}} \right)^{1/2},
\]

Fig. 1 shows the dark matter halo merger time-scale for each pair of merging haloes for both dynamical friction estimates. We have calculated the dark matter halo merger rate with both the Chandrasekhar dynamical friction formula and the Boylan-Kolchin numerical fit (Escala et al. 2005; Kazantzidis et al. 2005; Dotti et al. 2007). Numerical simulations indicate that two black holes...
will sink from ~1 kpc to form a binary with a separation of less than a parsec in ~10 Myr. We incorporate this physics by calculating the dynamical friction time-scale from the virial radius to the inner kpc, and then assume that the two black holes merge 10 Myr afterward. In practice, the dynamical friction time-scale from equations (1) and (2) from the inner kpc to the bound binary stage is often of order 10 Myr; the power of this gas-rich assumption lies in that it entirely circumvents the so-called ‘final-parsec’ problem thought to exist for low-mass ratio mergers of $10^{6.5} < M_{\text{BH}} < 10^8 \text{M}_\odot$ within static, spherical, gas-poor galaxy models (e.g. Milosavljevic & Merritt 2003). We explicitly assume that the black holes in our simulation do not stall at the final parsec before merger, and instead are ushered efficiently into the gravitational radiation stage where they coalesce; this assumption may hold even in the case of gas-poor galaxy models as long as the model is not spherical or in equilibrium (e.g. Berczik et al. 2006; Holley-Bockelmann & Sigurdsson 2006; Spurzem, private communication). Note that this implies that if we assume that each halo initially carries a black hole at its centre, and that each host galaxy is gas rich, Fig. 1 also estimates the time for a black hole to sink from the virial radius to the centre of the host galaxy, become a bound black hole binary, and inspiral due to gravitational radiation.

In our initial work (Micic et al. 2007), mergers of dark matter haloes trigger the immediate merger of the black holes they are hosting. In this paper, subsequent mergers of the central black holes are delayed to account for dynamical friction of the haloes and the black holes within the galaxy. Black holes will not merge if their merger time is larger than a Hubble time, and in that case, we advance the black hole position within the primary halo at each timestep. Knowing the dynamical friction time-scale for each merger, we postpone the black hole mergers accordingly. For the final kpc, we assume that ambient gas and/or non-sphericity will cause two black holes to coalesce within 10 Myr.

2.4 Gravitational recoil

Binary black holes strongly radiate linear momentum in the form of gravitational waves during the plunge phase of the inspiral – resulting in a ‘kick’ to the new black hole. This, in itself, has long been predicted as a consequence of an asymmetry in the binary orbit or spin configuration. Previous kick velocity estimates, though, were either highly uncertain or suggested that the resulting gravitational wave recoil velocity was relatively small, astrophysically speaking. Now, recent results indicate the recoil can drive a gravitational wave kick velocity as fast as $\sim 4000 \text{ km s}^{-1}$ (Baker et al. 2007; Campanelli et al. 2007; Gonzalez et al. 2007a; Herrmann et al. 2007; Kopitz et al. 2007; Lehner & Moreschi 2007; Schnittman & Buonanno 2007; McWilliams 2008; Lousto & Zlochower 2009). In reality, much smaller values than this maximum may be expected in gas-rich galaxies due to the alignment of the orbital angular momentum and the spins of both black holes (Bogdanovic et al. 2007). Recent studies also hint at a potential purely general relativistic spin alignment mechanism (Kesden, Spierhake & Berti 2010). However, even typical kick velocities ($\sim 200 \text{ km s}^{-1}$) are interestingly large when compared to the escape velocity of most astronomical systems – low-mass galaxies, as an example, have an escape velocity of $\sim 200 \text{ km s}^{-1}$ (e.g. Holley-Bockelmann et al. 2008). The effect of large kicks combined with a low escape velocity from the centres of small dark matter haloes at high redshift may play a major role in suppressing the growth of black hole seeds into SMBHs. Even the most massive dark matter halo at $z \geq 11$ cannot retain a black hole that receives $\geq 150 \text{ km s}^{-1}$ kick (Merritt et al. 2004; Micic et al. 2006). We incorporate the effect of recoil velocity on the growth of the SMBH by assigning a kick to each black hole merger in our merger tree. We follow the approach adopted by Holley-Bockelmann et al. (2008), which uses the parametrized fit of Campanelli et al. (2007) to generalize the recoil velocity as a function of the mass ratio of the merging black holes, each individual black hole’s spin amplitude, and the alignment to the orbital angular momentum. We assume that as black holes form a hard binary, their orbits will be highly circular and the eccentricity is close to zero:

$$v_{\text{kick}} = [(v_m + v_\perp \cos \xi)^2 + (v_\perp \sin \xi)^2 + (v_\|)^2]^{1/2},$$  \hspace{1cm} (7)

where

$$v_m = A q^2 (1 - q) \left[ 1 + B \frac{q}{(1 + q)^2} \right],$$  \hspace{1cm} (8)

$$v_\perp = H \frac{q^2}{(1 + q)^5} \left( a_1^2 - q a_2^2 \right),$$  \hspace{1cm} (9)

and

$$v_\| = K \cos (\Theta - \Theta_0) \frac{q^2}{(1 + q)^5} \left( a_2^2 - q a_1^2 \right).$$  \hspace{1cm} (10)

Here, the fitting constants are $A = 1.2 \times 10^4 \text{ km s}^{-1}$, $B = -0.93$, $H = (7.3 \pm 0.3) \times 10^3 \text{ km s}^{-1}$ and $K \cos (\Theta - \Theta_0) = (6.0 \pm 0.1) \times 10^3$, while the subscripts 1 and 2 refer to the first and second BH, respectively; $\perp$ and $\|$ stands for perpendicular and parallel to the orbital angular momentum; the mass ratio $q = M_2 / M_1$; the reduced spin parameter $a_i = S_i / M_i^2$ where $S_i$ is the spin angular momentum of BH $i$. The orientation of the merger is specified by the following: $\Theta$, the angle between the ‘in-plane’ component of $\delta' \equiv (M_1 + M_2) \sin (\Theta_1 / 2)$ and the initial direction at merger; $\Theta_0$, the angle between $\delta'$ and the initial direction of motion and $\xi$, the angle between the unequal mass and spin contribution to the recoil in the orbital plane.

\footnote{However, recent observations (Komossa et al. 2008) may show evidence for large kick velocities $\sim 2500 \text{ km s}^{-1}$.}
Local massive black holes

We assume that the orbit is circular, and we take the mass ratio of merging black holes directly from our merger tree. We have the following free parameters: the spin amplitude and orientation of each black hole, and the orientation of the merger. We explore two spin distributions. The K1 model chooses the spin parameters from a uniform distribution, while the K2 model assumes the black hole spins are aligned with the orbital angular momentum (Bogdanovic et al. 2007). Fig. 2 shows the distribution of kick velocities for both models. We apply both kick velocity distributions to the mergers in our merger tree using 1000 realizations each. This yields 2000 Milky Way merger trees for the PGA model and 2000 for the FPL model.

For each black hole merger, we calculate the kick velocity and compare it to the escape velocity of the host halo at the time of merger. If the kick is larger than the escape velocity, the resulting black hole is removed from the centre of the host halo and from the merger tree. As the result, the host halo will not have a central black hole for a period of time. Subsequently, when the next black hole sinks to the centre, it will simply take place of the central black hole. Depending on how often the central black hole is ejected, the final SMBH mass may be substantially smaller. The sequence and number of kicks in one merger tree realization depends on our kick distribution. Over many realizations, we can produce a probability function for the final black hole mass for each model.

3 RESULTS

Black hole mergers postponed for longer than a Hubble time will not occur, which reduces the merger rate over all redshifts. Those mergers that are postponed but have a merging time-scale less than a Hubble time will merge at lower redshifts. This is made explicit in Fig. 3, which plots the average change in redshift for a merger as a function of redshift if one includes dynamical friction. Black hole mergers at redshift 10 are, on average, pushed to redshift 7, for example. This results in an increase in the black hole merger rate at low redshifts. Since each merger occurs at a lower redshift, it will certainly be a louder gravitational wave source, and any associated electromagnetic signature will be brighter, as well (Holley-Bockelmann et al. 2010).

Interestingly, including dynamical friction from gas at distances smaller than 1 kpc does not make difference in our merger timescales. Those black holes that reach 1 kpc from the galactic centre will reach a parsec even without the gas – gas is simply invoked to ensure that the black holes pass through the three-body scattering stage efficiently. For the rest of this paper, we adopt the Boylan-Kolchin dynamical friction fit as a realistic treatment of the black hole merger time-scale.

3.1 Realizations of supermassive black hole growth

Fig. 4 shows the merger rates in our volume for those dark matter haloes that merge in less than a Hubble time within the mass range

Figure 2. Distribution of gravitational recoil as a function of the mass ratio of merging black holes on circular orbits. The black lines represent random spin orientations and amplitudes – the K1 distribution. In red is the kick range when the spin orientation of the binary black holes aligns with the orbital momentum of the binary – the K2 distribution. If the kick is larger than the escape velocity, the black hole is ejected from the halo.

Figure 3. Thick black – the average change in the merger redshift when dynamical friction is applied as a function of merger redshift (excluding dynamical friction). Red lines represent the minimum and maximum shift in the black hole merger redshift. Dynamical friction postpones black hole mergers toward lower redshifts, making them louder Laser Interferometer Space Antenna (LISA) sources and increasing the local rate as well.

Figure 4. Dark matter halo merger rates as a function of redshift for all haloes that finish merging by redshift zero. Three panels show various ranges for the halo mass ratio and the total combined halo mass. $M_p$ is the primary halo mass, $M_s$ is the satellite halo mass and the total mass is defined by $\rho = \log (M_p + M_s)$. The panel with $M_p/M_s \leq 10$ shows merger rates for major mergers that activate gas accretion on to their black holes.
$10^7 \leq M_{\text{DMH}} \leq 10^{13} \, M_\odot$, for various mass ratios and combined masses of merging dark matter haloes. In our volume, all the mergers that occur at redshifts $z \lesssim 1.5$ will not finish in less than a Hubble time, as these mergers are all high mass ratio. We remind the reader, though, that these halo merger rates are calculated for VL-2 40 Mpc$^3$ simulation box. This model, by design, has no Galaxy clusters, or even rich local groups, and it is for sparse local groups. The VL-2 host halo was specifically chosen ‘not’ to have undergone a major merger more recently than about $z \sim 1$. Almost all the low-redshift mergers for this mass range SMBH are in richer, denser environments, which are just not covered in this model. A better global rate for these low-mass haloes will be achieved with more of these volumes.

Since in PGA the merger time-scale is larger for higher mass ratio haloes, the black hole gas accretion time-scale is longer as well. Fig. 5 shows this time-scale for black holes hosted by dark matter haloes that merge with mass ratio $M_p/M_s$ and combined mass $p = \log (M_p + M_s)$. Notice that gas accretion is activated only for a small range of halo mass ratios $M_p/M_s \leq 10$ (Fig. 5, dashed line). For these mergers, the black holes do not accrete for longer than $\sim 1000$ Myr, and the accretion efficiency is strongly damped as the halo mass ratio tends toward 10:1 – in no case does the system reach the Eddington limit.

Fig. 5 offers valuable information about the FPL model as well. Panels (e) and (f) show that there are no mergers with mass ratios 10:1 or less for haloes above $10^{11} M_\odot$. In fact, the halo that VL-2 marks as the Milky Way halo does not go through any major mergers at low redshift. In the context of FPL, the quasar mode of rapid gas accretion occurs in Milky Way progenitors at high redshifts while the radio mode dominates most of the Sgr A* growth at low redshifts. We should also point out that VL-2 merger history of Milky Way is just one of the possible merger histories, and perhaps not the true one.

3.1.1 The initial mass function of black hole seeds

Galaxies in the mass range of the VL-2 simulation have values for escape velocities comparable to the amplitudes of gravitational wave recoil for black hole mergers with mass ratios $q \geq 0.1$, even in the case of the lower K2 kick distribution. If we are to seed these galaxies with their first black holes, the choice of the BHMF will determine the mass ratio of merging black holes. We examine the influence of the choice of BHMF on VL-2 merger trees in 1000 kick realizations for BHMFs with constant values of 100, 1000 and 5000 $M_\odot$ seeds; and also for random values in the mass ranges 10–200, 10–500 and 10–1000 $M_\odot$. We find that having a constant BHMF or one in a narrow mass interval leads to close-to-equal mass ratio black hole mergers. These mergers have the highest gravitational wave recoil and ejects of black holes in high-redshift dwarf galaxies, which suppresses SMBH growth. Because of the uncertainty in the formation channel for seed black holes, as well as the lack of theoretical constraints on primordial gas fragmentation during Population III star formation (Glover 2010), 10–1000 $M_\odot$ is the least biased of our BHMFs. We adopt this flat BHMF hereafter for the seeds in our merger trees in both the FPL and PGA models. Note that the seed mass in the FPL model is much less relevant than in the PGA model, because the black hole cannot grow more massive than what is dictated by the black hole Fundamental Plane, regardless of the initial seed mass.

3.1.2 Massive black hole accretion properties

With the adopted flat BHMF, the only constraints in the FPL model are the time-average Bondi–Hoyle accretion rate during the radio mode and the strength of gravitational wave recoil. We start by running Milky Way merger trees for various values of the accretion rate and recoil distribution, looking for the values which,
Local massive black holes

Figure 6. Accretion rates and luminosities during the quasar and radio modes for the FPL model (recoil excluded). The upper panel shows gas accretion rates and luminosities for all black holes during a random short time interval ($\delta t = t_f - t_i$). Points represent the quasar mode, while the brown horizontal line represents the radio mode. The black hole mass in the quasar mode increases at lower redshifts, with the final accretion episode between $z = 3$ and 2. Bondi–Hoyle accretion is the dominant growth mechanism at redshift $z \leq 2$. The bottom panel shows the gas accretion rate at short time intervals compared to the Eddington rate (quasar and radio modes combined). Most black holes accrete at the Eddington rate by design.

in combination with the accretion during quasar mode, produce a $\sim 4.2 \times 10^6 M_\odot$ black hole at $z = 0$ in the majority of merger tree realizations. This condition is satisfied for the merger trees with $m_{\text{bondi}} = 7 \times 10^{-4} M_\odot$ yr$^{-1}$ (Fig. 6, brown horizontal line), consistent with the observations of accretion rates in low-mass AGNs in the local Universe. It has been suggested that the Milky Way has evolved from a similar low-mass AGN, which explains the fact that the observed value for accretion in Sgr A* today is an order of magnitude smaller than this best-fitting accretion rate. Outside of the Sgr A* analogue, there are also 35 field dwarf galaxies at $z = 0$ with central black holes (see Section 4.1). Fig. 6 shows black hole accretion properties during the quasar and radio mode for the merger tree that excludes recoil, which corresponds to the maximum accretion. In this model, Milky Way progenitors go through their last quasar mode between $z = 2$ and 3 (Fig. 6, upper panel), after which Bondi–Hoyle accretion becomes the dominant mechanism of Sgr A* growth (Fig. 6, horizontal line in upper panel). In the bottom panel of Fig. 6, the same accretion rate is compared to the Eddington rate. Most of the accretion occurs at the Eddington rate – this is expected since the assumption is built in that the black holes reach the Eddington rate very quickly. In many cases, however, accretion is not activated at all because the host galaxy is small and the spheroid mass prevents the growth of central black hole to match the black hole Fundamental Plane.

By excluding kicks, Fig. 7 shows the upper constraint on black hole accretion properties for all black holes in the PGA merger tree. Recall that the BHMF is flat and the accretion efficiency is set by simulations. With the choice of BHMF and gas inflow efficiency fixed in this model, kicks are the only free parameter. Black holes in the PGA model can grow beyond the limit specified by the black hole Fundamental Plane. Instead of invoking AGN feedback in the form of an upper limit on the black hole mass, we incorporate it into the gas accretion efficiency. These feedback mechanisms suppress the accretion efficiency, leading to accretion rates that are 0.01–0.8 of Eddington (Fig. 7, bottom panel). These lower accretion efficiencies also result in lower luminosities in the PGA model. While for $\sim 10^6 M_\odot$ black holes, the maximum luminosities is $\sim 10^{45} L_\odot$ in the FPL model (Fig. 6, upper panel), these black holes have an order of magnitude lower luminosity in the PGA model (Fig. 7, upper panel).

Figure 7. Accretion in the PGA model. Left-hand panels show black holes with mass less than $10^4 M_\odot$, and right-hand panels show more massive black holes. Upper panels: gas accretion rates and luminosities for all accreting black holes during a random short time interval ($\delta t = t_f - t_i$). Bottom panels: gas accretion rates at short time intervals as a fraction of the Eddington rate for all accreting black holes. Unlike the FPL model, here most black holes accrete well below the Eddington rate. There are more ($\leq 10^4 M_\odot$) accreting black holes in the PGA model because their growth is not limited by the black hole Fundamental Plane.

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3.1.3 Black hole growth with gravitational wave recoil

We include gravitational wave recoil from the uniform K1 and lower recoil K2 distributions and reproduce 1000 merger trees for each kick distribution in both the FPL and PGA models. This results in 4000 merger trees presented in Figs 8–11.

Fig. 8 shows results for the K1 distribution in the FPL model. When kicks are excluded, the final black hole mass is $5 \times 10^6 M_\odot$. The largest and smallest black holes at the centre of the Milky Way analogue are $4.3 \times 10^6$ and $2.0 \times 10^6 M_\odot$, respectively, while the most common black hole mass is $3.9 \times 10^6 M_\odot$. Fig. 8 also shows the $1\sigma$ spread around the most common value for redshifts $z = 1.5, 1.0, 0.5$ and 0.0, further showing that the typical mass remains near the mass of Sgr A*. In the realization that favours the smallest SMBH mass, the kicks are so large that the black hole is ejected from the centre of the Milky Way in two occasions. The reason the FPL model produces a final SMBH mass that so closely matches Sgr A* is quite trivial: it is built into the model that any major merger will grow the SMBH up to the mass dictated by the black hole Fundamental Plane. Even when the central black hole in the Milky Way analogue is only $\sim 100 M_\odot$ at $z = 1.1$, there is plenty of time to grow the black hole back to the supermassive range.

This also acts to shift the typical black hole mass toward the merger tree realization with largest final black hole mass. In the case of lower amplitude K2 distribution (with black hole spin axes aligned) this effect is even more pronounced (Fig. 9). In Fig. 9, we show the $z \leq 2$ part of the merger tree for the case that excludes kicks, as well as the extrema in final black hole masses, all of which are close to the observed Sgr A* mass.

Gravitational wave recoil matters much more in the PGA model, as can be seen in Fig. 10 which shows the central SMBH mass of the Milky Way analogue as a function of redshift. Although the final black hole mass lies in a much wider range of masses, these outliers in mass are rare. Fig. 11 shows the black hole mass with the largest probability at redshifts $z = 3.0$ (blue), 1.5 (red) and 0.0 (black) for PGA models. The black line shows that for the lower recoil velocities, K2 case at $z = 0$, the typical black hole mass is in the Sgr A* range 90 per cent of the time. Note that since it is thought that the black hole spin vectors may align with one another before coalescence (Bogdanovic et al. 2007; Sperhake 2009; Kesden et al. 2010), we consider this our best and most realistic model. If SMBH grows according to the PGA model then kicks must be in the lower range described by K2 distribution. However, this does imply a scatter in the $M-\sigma$ relation at the low-mass end.

Figure 8. The evolution of Sgr A* in the FPL model for 1000 K1 kick realizations. The black solid line shows the black hole growth when kicks are excluded. Solid and dashed red lines show the black hole growth that produces the largest ($4.3 \times 10^6 M_\odot$) and smallest ($2.0 \times 10^6 M_\odot$) final black hole. The most common black hole mass is $3.9 \times 10^6 M_\odot$ (blue). Also in blue: the $1\sigma$ spread around the most common value for redshifts $z = 1.5, 1.0, 0.5$ and 0.0, further showing that the most common mass is near the mass of Sgr A*.

Figure 9. Sgr A* evolution in the FPL model for 1000 K2 kick realizations (lower recoil). Black: the $z \leq 2$ part of the merger tree when kicks are excluded. Solid red: kick realization favouring the largest black hole at the centre of Milky Way analogue. Dashed red: the kick realization favouring the smallest final black hole. Both the smallest and largest values are close to the observed Sgr A* mass.

Figure 10. Sgr A* evolution in the PGA model for 1000 K1 and K2 (lower recoil) kick realizations. Black solid line: Sgr A* when kicks are excluded. The red thick and thin lines show the K1 and K2 realizations favouring the largest black holes. The blue thick and thin lines show the K1 and K2 realizations favouring the smallest black holes. Here, the scatter is much larger than in the FPL model, particularly for the higher K1 recoil distribution.
Figure 11. Upper panel: number of lower recoil K2 realizations in the PGA model where Sgr A* reaches a certain mass at a certain redshift. Bottom panel: number of K1 realizations in the PGA model where Sgr A* reaches a certain mass at a certain redshift. Histograms are at $z = 3.0$ (blue dashed), $z = 1.5$ (red thin) and $z = 0$ (thick black). In the lower recoil K2 case, Sgr A* reaches the observed value at $z = 0$ in more than 90 per cent of kick realizations.

4 OTHER POPULATIONS OF MASSIVE BLACK HOLES

We distinguish three different massive black hole populations in our merger trees: black holes at the centres of local field dwarf galaxies (other haloes in VL-2 outside of the Milky Way halo); rogue black holes scattered through the Milky Way halo (remnants of satellites which merge with Milky Way but do not reach the centre in less than Hubble time; Micic et al. 2007; Bellovary et al. 2010) and black holes ejected from their host haloes to occupy the intergalactic medium (if the satellite does reach the centre of Milky Way, the following black hole merger might lead to the black hole ejection).

4.1 Massive black holes in the local dwarfs

For dark matter halo masses above roughly $5 \times 10^{11} \text{M}_\odot$, the dark matter halo mass correlates well with the mass of the SMBH (Ferrarese 2002):

$$\frac{M_{\text{BH}}}{10^8 \text{M}_\odot} \sim A \left( \frac{M_{\text{DMH}}}{10^{12} \text{M}_\odot} \right)^m,$$

(11)

where $M_{\text{DMH}}$ is the dark matter halo mass, $A = 0.1$ and $m = 1.65$ defines the slope in the relation. Below this mass, there is tentative evidence that haloes are less effective at forming massive black holes, and may even be unable to form them (Ferrarese 2002). To be fair, though, if this relation does hold down to a $10^{11} \text{M}_\odot$ halo, the expected $2 \times 10^4 \text{M}_\odot$ black hole would be difficult to detect, observationally.

Outside of the Milky Way, there are 35 local field dwarf galaxies in VL-2 identified at $z = 0$ in the mass range $10^7$–$10^{11} \text{M}_\odot$. Fig. 12 shows the black hole mass at the centres of these field dwarfs as a function of dark matter halo mass in the FPL (left) and PGA (right) models. Thick black vertical lines represent minimum and maximum values for the black hole mass in 1000 kick realizations. The red pluses corresponding to the vertical black lines represent the most common mass between minimum and maximum. If a red plus is absent, the most common black hole mass for that halo is zero. Linear fits to the most common masses are presented by red lines.

Figure 12. Black hole demography for the FPL K1 model – upper left; FPL lower recoil K2 model – bottom left; PGA K1 – upper right and PGA lower recoil K2 – bottom right. The dashed line in every panel represents the Ferrarese relation with a slope = 1.65. Red pluses: the most common central black hole mass. For the rest of 35 field dwarf galaxies most common outcome is absence of central massive black hole. Red line: linear fit to the most common black hole masses. Black vertical bars: the scatter in final black hole mass produced by kicks. This would reflect the scatter in relations that connect the central black hole mass with the properties of field dwarf galaxies.
Figure 13. Number of rogue black holes spread through the Milky Way halo as a function of mass for the FPL (left-hand panel) and PGA (right-hand panel) models. Red histograms – the merger tree that excludes black hole kicks. Blue histogram – the most common merger tree in the K1 kick distribution. Green histogram – the most common merger tree for the lower recoil K2 case. These black holes originate from the centres of satellites that merged with the Milky Way analogue but had merger time-scales larger than a Hubble time. As the black holes fail to reach the Milky Way centre, they orbit in the Milky Way halo. These models predict hundreds of rogue black holes with masses reaching up to \( \sim 200,000 M_\odot \).

Note that for our linear fits, we exclude those field dwarfs that have ejected their central black holes entirely in more than 50 per cent of kick realizations.

The FPL model predicts an \( M_{\text{BH}} - M_{\text{DMH}} \) for field dwarf galaxies in K1 and lower recoil velocities K2 cases as follows.

For FPL K1:

\[
M_{\text{BH}} / 10^8 M_\odot \sim 0.08 \left( M_{\text{DMH}} / 10^{12} M_\odot \right)^{1.14 \pm 0.50}.
\]  

while FPL lower recoil K2 has a slightly shallower slope:

\[
M_{\text{BH}} / 10^8 M_\odot \sim 0.05 \left( M_{\text{DMH}} / 10^{12} M_\odot \right)^{1.06 \pm 0.41}.
\]

The PGA K1 model, on the other hand, predicts

\[
M_{\text{BH}} / 10^8 M_\odot \sim 0.002 \left( M_{\text{DMH}} / 10^{12} M_\odot \right)^{0.64 \pm 0.36}
\]

and finally, the PGA lower recoil K2 model has the following relation:

\[
M_{\text{BH}} / 10^8 M_\odot \sim 0.005 \left( M_{\text{DMH}} / 10^{12} M_\odot \right)^{0.80 \pm 0.36}.
\]

A generic prediction of each model is that the slope is shallower than the Ferrarese relation presented by dashed lines in Fig. 12. For FPL K1 and lower recoil K2 models, the slope \( m \) is 1.14 and 1.06, close to \( M_{\text{DMH}}/M_{\text{BH}} = 10^7 \). PGA models predict an even shallower slope of 0.64 in K1 and 0.80 in the case of lower recoil velocities K2. This tests the PGA model by predicting a substantially flatter mass function for lower mass SMBH. We do point that these differences between FPL and PGA models might be insignificant, considering that scatter around the linear fits is substantial.

4.2 Rogue massive black holes in the Milky Way

Rogue black holes are carried into the Milky Way halo by their host satellites, but have halo merger time-scales longer than a Hubble time. Over the span of the simulation, the Milky Way accretes 669 satellite haloes which host a black hole, and 249 have orbital decay times that are longer than a Hubble time (see Figs 1 and 4 for the merger time-scale, merger rate and mass ratios of these haloes). By redshift zero, then, these haloes are still orbiting at significant distances from the centre of Milky Way – and although the haloes themselves have been stripped by the primary potential, they still host massive black holes. Fig. 13 shows the number of rogue black holes as a function of mass for the FPL (left) and PGA (right) models. As before, the upper limit for black hole mass excludes kicks and is presented in red in both panels. For each kick model, we also present the number of rogue black holes with the typical mass over the realizations. The PGA model predicts that there should be at least one massive rogue black hole in the Milky way halo with mass in range \( 10^5-10^6 M_\odot \).

The distance from the Milky Way centre in all models is correlated with the redshift at which galaxies merge (Fig. 14). If the merger
occurred early at high redshift, the black hole had more time to sink to the centre, and for mergers close to \( z = 0 \), the black hole has just entered Milky Way halo. The redshift at which the halo merges with the Milky Way also marks the end of the rogue black hole growth. Hence, rogue black holes that enter the Milky Way at later times have had more time to grow, and will be more massive than those accreted through early mergers. Figs 15 and 16 show how rogue black hole mass, satellite merger redshift and distance from the Milky Way are correlated. Fig. 15 represents the FPL model, and Fig. 16 represents the PGA model. K1 realizations are shown in the left-hand panels, and lower recoil K2 realizations in the right.

Unfortunately, both figures clearly show that the most massive rogue black holes are furthest away and may be very difficult to observe. We estimate the Bondi accretion on to these black holes to determine how observable they may be and we describe the process below.

There is sufficient evidence that the haloes of galaxies, from massive ellipticals to isolated spirals, can host diffuse hot halo gas (O'Sullivan, Forbes & Pnman 2001; Matthews & Brighenti 2003; Pedersen et al. 2006). As these black holes orbit within the primary halo, they can accrete from this ambient hot gas via Bondi–Hoyle accretion. Here, the mass accretion rate can then be described by

\[
M_{\text{BH}} = \frac{4\pi G^2 M_{\text{BH}} \rho_{\text{ISM}}}{(c_s^2 + \nu^2)^{3/2}},
\]

where \( \rho_{\text{ISM}} \) is the density of the halo gas, \( c_s \) is the gas sound speed and \( \nu \) is the velocity of the black hole. For these rogue black holes, we add this more quiescent form of accretion from the time the black hole has entered the virial radius of the halo in order to determine whether any may be visible today. To model the hot halo gas, we use a technique outlined in Sinha & Holley-Bockelmann (2010). In short, we assume it has an isothermal density profile consistent with X-ray observations of halo gas in ellipticals (Matthews & Brighenti 2003), and that the ideal gas is in hydrostatic equilibrium with the gravitational potential of the halo. We assume a gas core radius of 0.3\( R_c \), where \( R_c \) is the scale radius of the NFW halo, and that the gas temperature is the virial temperature at the virial radius. This yields a central gas temperature of \( \sim 2 \times 10^6 \) K for a dark matter halo of mass \( 2 \times 10^{12} \, M_\odot \), which is also consistent with observations (Pedersen et al. 2006). At redshift zero, we assume the black holes are on bound elliptical orbits of eccentricity 0.8 to match simulation predictions for satellite mergers (e.g. Ghigna et al. 1998; Sales et al. 2007).

By redshift zero, these black holes will have grown to a new mass, \( M_{\text{rogue}} \), and will have a new accretion rate from equation (16). The radiated luminosity from this process can be determined from

\[
L_{\text{rogue}} = \eta M_{\text{BH}} c^2,
\]

where \( \eta \) describes how efficiently mass is converted to energy; the standard assumption for an accretion disc around a spinning black hole sets \( \eta \sim 0.1 \) (Shakura & Syunyaev 1973). We find that our most massive rogue black hole \( M_{\text{rogue}} = 227,643 \, M_\odot \), residing at 225 kpc from the Galactic Centre, can radiate at 3834 \( L_\odot \) (Fig. 17, PGA panels on the right), making it somewhat fainter than the brightest ULXs; the fact that the hot halo gas is so tenuous at these radii is what accounts for the relatively low luminosity.

However, if these rogue black holes are common, they will be observable in the outskirts of the Milky Way halo with Chandra, and the most luminous can have sufficient signal-to-noise ratio for spectral characterization. Note, though, that a significant fraction of these may have advection-dominated accretion flows, rather than thin accretion discs, and hence \( \eta \) may be much less than 0.1; this would naturally make the black hole less luminous, but with a harder spectral signature. It has also been suggested...
Figure 16. Rogue black hole mass as a function of Galactic distance and progenitor halo redshift for the PGA model. Left-hand panels: the K1 distribution. Right-hand panels: the lower recoil K2 case. The blue squares represent the most massive rogue black holes, red circles represent the typical black hole mass and black dots represent the lightest. The most common rogue black hole mass remains at the initial black hole seed mass, but a number of massive rogue black holes are greater than $10,000 M_\odot$. The most massive is $M_{\text{rogue}} \sim 230,000 M_\odot$ at 225 kpc from the Galactic Centre (0.8–0.9 of virial radius).

Figure 17. Bolometric luminosity of rogue black holes as a function of distance from the primary halo centre for the FPL (left) and PGA (right) models. The K1 case is on the upper panels and the lower recoil K2 case on the bottom. Blue squares represent the most massive rogue black holes, red circles represent the typical black hole mass and black dots represent the lightest. Black holes are assumed to accrete via a Bondi–Hoyle mechanism from the ambient gas in the Milky Way. Most rogue black holes are well below solar luminosity, but a few are expected to be luminous X-ray sources (just under the ULX cut-off) that reside in the outskirts of the Milky Way halo. The most massive of them is in PGA model and has a luminosity of $4000 L_\odot$. 

that rogue black holes in the molecular or cold neutral part of the ISM should be more easily detected in the radio than in X-rays (Maccarone 2004; Maccarone, Fender & Tzioumis 2005). Maccarone (2005), for example, calculates that a $2600 M_\odot$ black hole should be observable with Low Frequency Array (LOFAR; above $30 \mu Jy$) in the radio out to about 15 kpc – much closer than the most massive rogue black hole in our model. Assuming larger black hole velocities and a more efficient Bondi accretion rate, rogue black
4.3 Ejected massive black holes

As the SMBH grows, incoming black holes are kicked from the centre of the host halo, forming a population of ‘ejected’ black holes. Fig. 18 shows the cumulative number of black holes lost from the merger tree due to kicks larger than the escape velocity in the top panels, and the ejected black hole mass as a function of redshift on the bottom panels. Again, we show the FPL model on the left and our PGA model on the right. The redshift of the last SMBH ejection is between $z = 2$ and 3 for the PGA model, and between $z = 3$ and 4 for the FPL model. When we compare the difference in total numbers of ejected BHs between K1 and lower recoil K2 realizations (Fig. 18, upper panels), both the FPL and PGA model predict the K1 case ejects up to 50 per cent more black holes. The average masses of ejected black holes are similar in the FPL and PGA models (Fig. 18, bottom panels) with the most common ejected black hole of 100–1000 $M_{\odot}$.

The mass ratio of merging black holes sets the kick amplitude, with large differences between the incoming black hole mass creating a small kick. The typical number of ejected black holes per realization as a function of mass ratio is presented in Fig. 19. The FPL and PGA distributions are again very similar regardless of the kick distribution. The main difference is that higher mass ratio encounters are more common in the PGA K1 model. Since the growth of black holes in the FPL model is very efficient – at Eddington rate – the incoming black holes grow faster and this decreases the mass ratio when the merger occurs. Hence, there are more mergers at $q \leq 0.3$ in FPL K1 and more mergers at $q \geq 0.3$ in PGA K1.

Some of the ejected massive black holes might contribute to the rogue black hole population. Micic et al. (2006) have shown that high-redshift ejections of black holes from their host haloes in the Local Group type environment could lead to their capture by Milky Way potential. Tracking these black holes is beyond the scope of this paper and will be addressed in future work.

5 DISCUSSION AND CONCLUSIONS

Using a very high resolution small volume cosmological $N$-body simulation (VL-2), we construct the merger history of black holes in low-mass dark matter haloes in a Local Group analogue. We found that the method used to estimate the dynamical friction time-scale makes a large difference in the total rate and redshift distribution of black hole mergers (see also Holley-Bockelmann et al. 2010). In particular, for example, an $N$-body-based dynamical friction estimate (Boylan-Kolchin 2008) yields longer merger time-scales.
than does Chandrasekhar dynamical friction. These larger, more realistic merger time-scales will postpone black hole mergers to lower redshifts. Moreover, if most of the black hole growth is tied to gas accretion that is activated by major mergers, then using Chandrasekhar dynamical friction will overestimate the black hole mass.

We studied the growth and merger rate of black holes from seeds at redshift $\sim 20$ to low-mass SMBHs at redshift zero, analytically incorporating the important subresolution physics to model the black hole dynamics and gas accretion. We find that having a constant mass black hole seeds, or a narrow BHMF leads to nearly equal mass ratio black hole mergers. These mergers have largest gravitational wave recoil velocities, which eject the black holes from their host galaxies and suppress SMBH growth. A wider range BHMF presents far fewer problems in growing SMBHs, even when the black holes spins are large.

Many groups are beginning to explore the formation and evolution of massive SMBHs in large volume cosmological volumes, with a sophisticated and self-consistent treatment of the subgrid physics (e.g. Croton et al. 2006; Sijacki et al. 2007, 2009; di Matteo et al. 2008). With larger simulation volumes, these simulations are capable of forming hundreds of massive SMBHs at the centres of massive elliptical galaxies and clusters of galaxies. In fact, the FPL model we adopt is a semi-analytic model (Somerville et al. 2008) resulting from these techniques. Because of high computational cost, however, the same numerical approach has not been applied in smaller cosmological volumes where the bulk of the halo evolution is non-linear. Here, high-redshift dwarf galaxies merge to form the Local Group galaxies, and massive black holes have masses well below $10^7 M_\odot$.

We use small volume $N$-body simulations and apply two semi-analytic recipes for SMBH growth. One class of models is always limited by the black hole Fundamental Plane (FPL). Here, the growing black hole mass is a function of the total stellar mass in the galaxy bulge. This approach has successfully produced SMBHs in massive galaxies. We show that the FPL model can also be used for black hole growth in small volumes. In particular, black hole mergers combined with (a) gas accretion in a quasar mode and (b) a time averaged Bondi–Hoyle accretion rate of $7 \times 10^{-4} M_\odot$ yr$^{-1}$ in a radio mode, can produce the observed mass of the Sgr A$^\ast$ SMBH. Today, the observed Sgr A$^\ast$ accretion rate is an order of magnitude less efficient than this radio mode accretion rate, but this may not be unreasonable, since the Milky Way is not considered an AGN anymore. Other low-mass AGNs in the local Universe are observed to have $10$–$100$ times more efficient gas accretion. The FPL model, by design, guarantees the formation of a Fundamental Plane black hole. However, in reality, not every galaxy has such a system, due to the competition between black hole growth and nuclear star cluster formation in low-mass spheroids.

We have proposed an alternative method which could provide deeper insight into the formation of the lightest SMBHs ($< 10^7 M_\odot$) by incorporating growth prescriptions calculated in small-scale merger simulations. Gas accretion on to the black hole is always suppressed by stellar or AGN feedback, and depends on the structure of the gas, as well as the microphysics (such as turbulence, fully relativistic magnetohydrodynamics etc.) that is currently physically beyond modelling. Our model provides a framework into which the microphysics can easily be incorporated once simulations and observations reveal the nature of these processes. In contrast, in the FPL model, these effects are irrelevant, since gas accretion occurs in the same manner in all $\leq 10:1$ galaxy mergers. The final outcome is always a Fundamental Plane black hole since feedback rapidly drives the evolution of Fundamental Plane rather than the growth of black holes. In the PGA model, we can incorporate an accretion efficiency parameter into the gas accretion prescription to make black hole growth less efficient for stronger feedback and vice versa. We use a formalism that relates the gas accretion efficiency to galaxy merger ratios; gas accretion is most efficient for major mergers and negligible for minor mergers. In addition, minor mergers will last much longer than equal mass mergers. When these two effects combine, the PGA model produces short bursts of high-rate gas accretion for equal mass mergers, and long, slow gas accretion for $10:1$ mass ratio mergers. As a result, most black holes in the PGA model never reach the Eddington rate.

We also modelled the effect of gravitational wave recoil on assembling the lightest SMBHs. One way to mitigate gravitational wave recoil is to increase the black hole merger symmetry; smooth dense gas, for example, may quickly align the spin vectors of each SMBH before coalescence (Bogdanovic et al. 2007; Dotti et al. 2010). In order to understand how damaging gravitational wave recoil can be, and to pin down the epoch that a growing black hole is most vulnerable to recoil, we do not pre-select the merger configurations with the lowest recoils in $K1$ and select spins aligned to the orbital angular momentum in lower recoil model $K2$. In previous work, when black holes are merging in massive stellar systems, the large gravitational potential creates large escape velocities. Hence, a $K2$ kick distribution with much lower recoil velocities helps retain the central black holes (Volonteri et al. 2010). In our merger tree, most of the dark matter haloes have masses below $10^{10} M_\odot$, and the typical halo mass is $10^2$–$10^6 M_\odot$. Since the escape velocities in these systems are below $100 \text{ km} \text{s}^{-1}$, even the moderate kicks will eject the SMBH. When gravitational recoil is included in the FPL model, the final black hole mass is unaffected in most cases. This is the consequence of the FPL requirement of a very high gas accretion efficiency. Even in the most damaging $K1$ realization where the black hole is ejected twice from the merger tree, the accretion of gas is so efficient that a $\sim 100 M_\odot$ black hole that is ushered to the centre has time to grow to $2 \times 10^6 M_\odot$. When gravitational recoil is included in the PGA model, the final mass of the central black hole in the $K1$ realizations is lower by roughly an order of magnitude than in $K2$ (lower recoil model). 90 per cent of the $K2$ realizations are in the $\text{Sgr A}^\ast$ mass range. PGA model predicts that kicks have to follow lower distribution of gravitational recoil velocities, $K2$.

When we look at the mass of the black holes at the centres of local field dwarf galaxies, none of the models, FPL or PGA, matches the extrapolation of the Ferrarese (2002), relation which relates black hole masses to the masses of host dark matter haloes. Even when we remove gas accretion as a mechanism for black hole growth, their masses will be larger than predicted by Ferrarese relation as the result of seed black hole mergers, despite the fact that the initial black hole seeds were Population III remnants and therefore considered light seeds. It is possible that the black hole Fundamental Plane exists for low-mass SMBHs in field dwarf galaxies, but it may simply have a different slope than for high-mass SMBHs; indeed this was alluded to in the original Ferrarese work. We do find a shallower slope in all models. In FPL, the slope is close linear and tracks the following proportion: $M_{\text{BH}}/M_{\text{DMH}} = 10^{-3}$. The PGA model predicts an even shallower slope – $0.64$–$0.80$ – although the scatter caused by gravitational wave recoil makes it hard to distinguish between FPL and PGA. Note that gas consumption in field dwarf galaxies may favour nuclear star cluster formation rather than a massive black hole. Both FPL and PGA models are consistent with this picture since roughly half the dwarfs contain no central black hole, though the PGA models predict more empty haloes on average than FPL. It is important to note that the black hole demographics

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in the dwarf galaxy regime are critical to distinguish between the FPL and PGA models.

We also identified two massive rogue black hole populations. First, we find ejected black holes, or black holes with kick velocities larger than the host halo escape velocity. We will address the properties of this population with a detailed treatment of their dynamics in the future. The second are rogue black holes from the remnants of satellites that had merger time-scales longer than a Hubble time. We find hundreds of these rogue black holes at distances of \(~\sim 200\) kpc from the galactic centre and with masses from 10 to 10\(^7\) \(M_\odot\) (depending on the model). The most massive of these may be detected in X-ray and are possible mesolensing candidates. These two populations of black holes, which have quite different formation mechanisms, might not be easily disentangled. It is possible that a growing primary halo may recapture black hole ejected by recoil, in which case both populations occupy a similar parameter space (Miczek et al. 2006).

In conclusion, our model successfully reproduces Sgr A\(^*\) without limiting the black hole growth to the black hole Fundamental Plane. It predicts that kicks have to follow lower recoil velocity distribution (K2). It also predicts a substantially flatter mass function (slope = 0.64–0.8) for lower mass SMBH in local field dwarfs. It predicts Milky Way rogue black holes, and a population of ejected black holes. This model provides cosmological framework into which the results of small-scale simulations can easily be incorporated in the future. At this point, the model is limited only by the lack of understanding of how various feedback mechanisms couple with each other and with the gas accretion on to the black hole. There is ample ground to cover in this respect. As one example, Ostriker et al. (2010) claim that all previous studies of SMBH growth may overestimate the final black hole mass by \(~\sim 2\) orders of magnitude by treating only the energy part of AGN feedback, neglecting the importance of momentum and mechanical feedback. Hopefully, this will be resolved in the future.

One issue is how well the VL-2 simulation represents the Milky Way merger history. The reality is that VL-2 represents one out many possible evolutionary histories of the Local Group, and not necessarily the correct one. The fact that only major mergers activate the quasar mode means that the number of major mergers each galaxy goes through has a huge impact on the black hole accretion history. This underlines the importance of approaching the problem of Sgr A\(^*\) growth statistically by simulating hundreds of highly resolved small simulation volumes. To resolve thousands of Milky Way mass haloes with VL-2 resolution, gas physics and black hole dynamics implemented on the fly will be computationally too expensive in the near future.

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