Intermediate-Mass Black Hole Feedback in Dwarf Galaxies at High Redshifts

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ABSTRACT

Intermediate-mass black holes (IMBHs: masses between $100 - 10^6 M_\odot$) historically comprise of an elusive population compared to stellar-mass and supermassive BHs. Recently IMBHs have started to be observed at the centers of low-mass galaxies. Using a modified version of the SPH code GADGET-3, we perform cosmological hydrodynamical simulations of $(2h^{-1} \text{ Mpc})^3$ comoving boxes, and investigate the growth and feedback of central IMBHs in dwarf galaxies (DGs). Black Holes of mass $(10^2 - 10^4) M_\odot$ are seeded at the centers of halos with $(10^6 - 5 \times 10^7) M_\odot$. The earliest BHs appear at $z \sim 18 - 25$, and grow thereafter by accreting surrounding gas and by merger with other BHs. Starting from highly sub-Eddington rates (Eddington ratio $< 0.001$), the accretion rate of the BHs increase with time, and reaches $\dot{M}_{BH} = (0.2 - 0.8) \dot{M}_{Edd}$ for the massive IMBHs by $z = 4$. We find that it is possible to build up IMBHs of a few $\times 10^5 - 10^6 M_\odot$ by $z = 5$, when the BHs are seeded in halos less massive than $4 \times 10^7 M_\odot$. The star formation rate density evolution of the DGs (stellar mass $\sim 10^6 M_\odot$) has a peak plateau between $z = 4 - 6$. Star formation is quenched between $z = 9 - 4$ by BH accretion and feedback. The star formation rate density (SFRD) is reduced by factors up to 3, when the BHs have grown to a few times $10^5 M_\odot$. However these IMBHs in DGs are already more massive (at $z \sim 6$) compared to the local $[M_{BH} - M_*]$ correlation and that of high-$z$ quasars. Our conclusions, based on numerical simulation results, support the scenario that early feedback from IMBHs in gas-rich DGs at $z = 5 - 8$ can potentially solve several anomalies in the DG mass range within the concordance $\Lambda$CDM cosmological scenario of galaxy formation (Silk 2017). Our results suggest that IMBHs at DG centers grow faster than their host galaxies in the early Universe, and the resulting BH feedback turns the DGs and the BHs dormant.

1 INTRODUCTION

Black holes (BHs) are usually observed to be of stellar-mass ($M_{BH} \sim 1 - 100 M_\odot$), or supermassive ($M_{BH} \sim 10^6 - 10^9 M_\odot$). Stellar-mass BHs have been historically observed in X-ray binaries existing in our Milky Way and other galaxies (e.g., Bolton 1974; Cowley et al. 1983; Orosz et al. 2003; Corral-Santana et al. 2016), and more recently in globular clusters (e.g., Macarone et al. 2005; Giesers et al. 2018). Supermassive BHs (SMBHs) are believed to exist at the centers of active galactic nuclei (AGN), which liberate enormous amounts of feedback energy powered by the accretion of matter (e.g., Rees 1984; Ferrarese & Ford 2005). AGN are widely observed through their multi-wavelength emission at all cosmic epochs, $z = 0 - 7$, starting from the local Universe up to 13 Gyr ago (e.g., Urry & Padovan 1995; Goulding & Alexander 2009; Mortlock et al. 2011).

By natural extension, there should be a population of intermediate-mass black holes (IMBHs) of masses between $100 - 10^6 M_\odot$ (e.g., van der Marel 2004), which are however not as widely observed. Some studies argue that the accreting BHs in ultra-luminous X-ray sources could be IMBHs (e.g., Miller et al. 2003; Sutton et al. 2012; Caballero-Garcia et al. 2018), based on the calculation of the BH mass from a cold thermal disc accreting at sub-Eddington rates.

We do not know how the SMBHs in AGN grew to billions of solar masses. IMBHs are a possible explanation for the origin of SMBHs. The discovery of an universal population of IMBHs can be the key to understanding whether SMBHs can grow from stellar-mass BHs, or whether a more exotic process accelerated their growth soon after the Big Bang. A recent study by Kovetz et al. (2018) suggest that gravitational wave measurements using the advanced LIGO over six years can be used to limit the formation mechanism of IMBHs by the runaway merger of stellar-mass BHs in globular clusters.

Relatively recently, massive BHs have started to be
observed hosted in Dwarf Galaxies (DGs). Dynamical BH mass limits detected in nearby dwarfs include several examples such as: $M_{\text{BH}} \sim 3 \times 10^5 M_\odot$ in the dwarf elliptical galaxy M32 (van der Marel et al. 1998); $M_{\text{BH}} \sim 10^6 M_\odot$ in the dwarf lenticular field galaxy NGC 404 (Seth et al. 2010); $M_{\text{BH}} < 2 \times 10^5 M_\odot$ in the dwarf elliptical galaxy NGC 205 (Valluri et al. 2003); and $M_{\text{BH}} < 10^5 M_\odot$ in the dwarf spheroidal galaxy Ursa Minor (Demers et al. 1993).

Some of the central IMBHs in DGs show signatures of activity in the form of low-luminosity AGN. NGC 4395 is a bulgeless dwarf galaxy with an extremely faint Seyfert 1 nucleus (Filippenko & Sargent 1989), and an estimated central BH mass $M_{\text{BH}} \sim 3 \times 10^4 M_\odot$ (Peterson et al. 2003). Pox 52 (G 1200-2038) is a dwarf galaxy with Seyfert characteristics (Kunth, Sargent & Bothun 1987), having a central BH of $M_{\text{BH}} \sim (2-4) \times 10^4 M_\odot$ (Thornton et al. 2008). The dwarf starburst galaxy Henize 2-10 (Reines et al. 2011) has an actively accreting massive BH with an order-of-magnitude mass $M_{\text{BH}} \sim 10^6 M_\odot$.

The population of DGs with observed AGN signatures has been increasing (e.g., Chilingarian et al. 2018). Izotov & Thuan (2008) presented the spectra of 4 low-metallicity DGs with very-high broad Hα luminosities, most likely coming from accretion disks around IMBDS (5 $\times$ 10$^5 \lesssim M_{\text{BH}} \lesssim 3 \times 10^6 M_\odot$). Performing a systematic search for AGN in DGs using optical spectroscopy from the SDSS, Reines, Greene & Geha (2013) found 136 DGs, with stellar mass between $10^5 - 5 \times 10^5 M_\odot$ at $z < 0.055$, hosting active massive BHs with virial BH masses in the range $10^5 < M_{\text{BH}} < 10^6 M_\odot$. Using SDSS DR7, Moran et al. (2014) identified 28 nearby low-mass, low-luminosity DGs containing accreting IMBHs ($10^5 \lesssim M_{\text{BH}} \lesssim 10^6 M_\odot$) at their centers, and derived a lower limit of a few percent on the fraction of DGs containing AGN.

The stellar mass versus BH mass relationship of IMBHs in DGs is found to be more-or-less consistent with the existing local relation extending linearly (in log-log space) into the lower galaxy mass regime, albeit with a large scatter. IMBH candidates detected using deep X-ray observations (e.g., Schramm et al. 2013; Secrest et al. 2014; Lemos et al. 2013) show that low-mass galaxies with $M_\star < 3 \times 10^9 M_\odot$ have BHs of $M_{\text{BH}} \sim 2 \times 10^5 M_\odot$. The most-massive ultracompact dwarf galaxy M59-UCD3 with $M_\star \sim 2 \times 10^8 M_\odot$ has a massive central BH of $M_{\text{BH}} \sim 4 \times 10^6 M_\odot$ (Ahn et al. 2018). The Fornax UCD3 hosting a central $M_{\text{BH}} \sim 3.3 \times 10^8 M_\odot$ corresponds to 4% of the galaxy stellar mass (Afanasiev et al. 2018). Investigating the presence of AGN in nearby dwarf galaxies using mid-infrared emission, Marleau et al. (2017) identified 303 candidates, of which 91% were subsequently confirmed as AGN by other methods. The stellar masses of these galaxies are estimated to be between $10^6 - 10^8 M_\odot$; and the black hole masses in the range $10^5 - 10^6 M_\odot$.

Recently the highest-redshift discovery of AGN in DGs has been made by Mezcua et al. (2015). They present a sample of 40 AGN at $z \sim 2.4$ with luminosities in the range $L_{\text{IR}} \sim 10^{40} - 10^{44}$ erg/s. The hosts are DGs with stellar masses between $10^7 - 3 \times 10^9 M_\odot$, selected from the Chandra COSMOS-Legacy survey. All these AGN are of type 2 and consistent with hosting IMBHs with masses $\sim 10^4 - 10^5 M_\odot$, and typical Eddington ratios > 1%. According to the authors, the observational trends suggest that AGN in DGs evolve differently than those in more-massive galaxies.

AGN influence the formation and evolution of galaxies in the form of feedback, affecting the environment from pc to Mpc scales (e.g., Silk & Rees 1998; Barai 2008; Fabian 2012). Supermassive BHs and host galaxies are argued to co-evolve, generating observational trends such as the central BH mass - host galaxy stellar bulge mass correlations (e.g., Magorrian et al. 1998; Gebhardt et al. 2000). The SMBH energy output is often observed as AGN outflows in a wide variety of forms (e.g., Crenshaw, Kraemer & George 2003; Cicone et al. 2014; Melioli & de Gouveia Dal Pino 2014; Tombesi et al. 2015; Barai et al. 2018).

Analogous to SMBHs producing AGN feedback, the IMBHs are also expected to have feedback; the energy radiated by IMBHs should affect their host galaxies, possibly driving galactic outflows. BH or AGN feedback mechanism has recently started to be observed in low-mass galaxies. Penny et al. (2017) presented observational evidence for AGN feedback in a sample of 69 quenched low-mass galaxies ($M_\star < 4 \times 10^5 M_\odot$): including 6 galaxies showing signatures of an active AGN preventing ongoing star-formation.

AGN feedback operates mostly in the negative form which quenches star formation as seen in simulations (e.g., Scannapieco, Silk & Bouwens 2003; Barai et al. 2014), and supported by some observations (e.g., Schawinski et al. 2008; Lanz et al. 2018). At the same time, AGN feedback can be positive occasionally, where AGN outflows are found to compress clumpy gas clouds and trigger starbursts, in numerical studies (e.g., De Young 1989; Zubovas et al. 2013), and observed in jet-induced star formation (e.g., Chambers, Miley & van Breugel 1987; Zinn et al. 2013). In this work we focus on negative BH feedback effects where star-formation is quenched.

The concordance ΛCDM cosmological scenario of galaxy formation presents multiple anomalies in the dwarf galaxy mass range: e.g. core-cusp, number of DGs. Recently Silk (2017) made an exciting theoretical claim that the presence of IMBHs at the centers of essentially all old DGs can potentially solve the problems. Early feedback energy from these IMBHs can affect the host gas-rich dwarf galaxies at $z = 5 - 8$. This early feedback can quench star-formation, reduce the number of DGs, and impact the density profile at DG centers. Dashyan et al. (2017) studied the same problem analytically, and compared AGN versus SN feedback. They find a critical halo mass below which the central AGN can drive gas out of the host halo. This negative feedback effect of AGN is found to be more efficient than SN in the most-massive DGs, where SN is not able to expel the gas.

In this work, we investigate the scenario that IMBHs are present at the centers of dwarf galaxies, by performing cosmological hydrodynamical simulations. Our goals are to (i) test if IMBHs would grow at DG centers in a cosmological environment, and (ii) quantify the impact of feedback from IMBHs on their host DGs, especially the effects on star formation at cosmic epochs $z = 6 - 4$.

This paper is organised as follows: we describe our numerical code and simulation setup in §3 and in §4 we give a summary of our main findings.
2 NUMERICAL METHOD

We use a modified version of the TreePM (particle mesh) - SPH (smoothed particle hydrodynamics) code GADGET-3 (Springel 2005). The sub-resolution physics that we use are described in §2.1 and §2.2. Our different simulation runs are outlined in §2.2.

2.1 Cooling, Star-Formation, SN Feedback

Radiative cooling and heating is implemented by adopting the cooling rates from the tables of Wiersma, Schaye & Smith (2009), which includes metal-line cooling. Eleven element species (H, He, C, Ca, O, N, Ne, Mg, S, Si, Fe) are tracked. Star-formation is implemented following the multiphase effective sub-resolution model by Springel & Hernquist (2003). Stellar evolution and chemical enrichment are computed for the 11 elements (following Tornatore et al. 2007). A fixed stellar initial mass function from Chabrier (2003) is included, in the mass range (0.1 – 100) Msun.

Kinetic feedback from supernovae ejects mass at a rate $\dot{M}_{SN}$ proportional to the SF rate ($\dot{M}_i$) as: $\dot{M}_{SN} = n \dot{M}_i$. The SN wind mass loading factor is taken as $n = 2$ (e.g., Tornatore et al. 2007; Barai et al. 2013; Melioli, de Gouveia Dal Pino & Geraissate 2013), following observations revealing that SN-driven outflow rates are comparable to or larger than SF rates of galaxies (e.g., Martin 1995; Bouche et al. 2012). We adopt a constant-velocity outflow with SN wind velocity $v_{SN} = 350$ km/s (as was done in e.g. Barai et al. 2013; Biffi et al. 2016).

2.2 BH Accretion and Feedback

BHs are collisionless sink particles (of mass $M_{BH}$) in our simulations. A BH (of initial mass $M_{BHseed}$) is seeded at the center of each galaxy more massive than a total mass $M_{gal} = 10^7 M_{\odot}$, which does not contain a BH already. The SN wind mass loading factor is taken as $n = 2$. We test different values of minimum halo mass and seed BH mass in the range: $M_{galMin} = (10^6 – 5 \times 10^7) M_{\odot}$, and $M_{BHseed} = (10^2 – 10^4) M_{\odot}$.

Gas is considered to accrete onto a BH according to the Bondi-Hoyle-Lyttleton accretion rate ($\dot{M}_{Bondi}$; Hoyle & Lyttleton 1939; Bondi 1952), and is limited to the Eddington rate ($\dot{M}_{Edd}$),

$$\dot{M}_{BH} = \min \left( \dot{M}_{Bondi}, \dot{M}_{Edd} \right),$$

$$\dot{M}_{Bondi} = \frac{4\pi G^2 M_{BH} \rho}{c_s^2 + v^2} \Omega,$$

where $G$ is the gravitational constant, $\rho$ is the gas density, $c_s$ is the sound speed, and $v$ is the velocity of the BH relative to the gas. The quantities $\rho$, $c_s$, and $v$ are computed dynamically within the code at every timestep, using the SPH smoothing method for every BH particle (for details see §2.1 of Barai et al. 2014). We set $\Omega = 100$ as a numerical boost factor (as done by e.g., Springel, Di Matteo & Hernquist 2005; Johansson, Naab & Burkert 2009; Dubois et al. 2013). The Eddington luminosity is used to express the Eddington mass accretion rate,

$$L_{Edd} = \frac{4\pi G M_{BH} \rho c}{\sigma_T} = \epsilon_r \dot{M}_{Edd} c^2,$$

where $m_p$ is the mass of a proton, $c$ is the speed of light, and $\sigma_T$ is the Thomson scattering cross-section for an electron. A fraction of the accretion rest-mass energy is coupled to the surrounding gas as feedback energy:

$$E_{feed} = \epsilon_f \dot{M}_{BH} c^2.$$

Here $\epsilon_r$ is the radiative efficiency, and $\epsilon_f$ is the feedback efficiency. We adopt the mean value for radiatively efficient accretion onto a Schwarzschild BH (Shakura & Sunyaev 1973): $\epsilon_r = 0.1$.

The BH feedback energy is distributed in the kinetic form (introduced in Barai et al. 2014, 2016). Surrounding gas is driven outward at a velocity $v_w$ and mass outflow rate $\dot{M}_w$. Given energy conservation,

$$\frac{1}{2} \dot{M}_w v_w^2 = E_{feed},$$

and using Eq. (4), the outflow rate can be expressed in terms of the BH accretion rate,

$$\dot{M}_w = 2\epsilon_f \epsilon_r \dot{M}_{BH} c^2 v_w^2.$$

We use the values: $\epsilon_f = 0.05$, and the range $v_w = 1000, 2000, 5000, 10000$ km/s.

The implementation in the GADGET-3 code involves computing physical quantities by kernel-weighted smoothing over gas particles neighboring each BH. The kernel size, or the BH smoothing length $h_{BH}$, is determined at each timestep by implicit solution of the equation,

$$\frac{4}{3} \pi h_{BH}^3 \dot{M}_{gas} = \rho_{BH},$$

where $\rho_{BH}$ is the kernel estimate of the gas density at the position of the BH, and $\rho_{gas}$ is the mass of 200 neighboring gas particles.

In particular, the kinetic feedback energy from a BH is distributed to the surrounding gas lying inside a bi-cone volume. The slant height of each cone is $h_{BH}$, and the half-opening angle is 45°. The cone-axis direction is considered as fixed for each BH, which is randomly assigned during a BH seeding. Gas particles lying within the bi-cone are tracked, and their total mass $M_{gas}$ is computed. The probability for $i$th gas particle within the bi-cone to be kicked is calculated:

$$p_i = \frac{M_w \Delta t}{M_{gas} \epsilon_f},$$

where $\Delta t$ is the timestep, and $M_w$ is the mass outflow rate obtained from Eq. (6). A random number $x_i$, uniformly distributed in the interval [0, 1], is drawn and compared with $p_i$. For $x_i < p_i$, the gas particle is given an AGN wind kick, such that its new velocity becomes:

$$v_{new} = v_{new} + \dot{M}_w \Delta t v_w^2,$$

where $v_{new}$ is the gas particle’s new velocity.

We notice that, although most of the adopted values of the AGN wind velocity in our models are smaller than those inferred from observations of AGN ultra-fast outflows (e.g., Melioli & de Gouveia Dal Pino 2013; Kraemer, Tombesi & Bottorff 2018 and references therein), the few tests we performed with more compatible values around 10000 km/s did not reveal significant differences in the results (for more details see ).
v_{\text{kick}} = \vec{v}_{\text{dd}} + v_w \hat{n}.

(9)

The kick direction $\hat{n}$ is set radially outward from the BH.

We incorporate a scheme for BH pinning, or BH advection algorithm (also done in e.g., Springel, Di Matteo & Hernquist 2005; Wurster & Thacker 2013; Schaye et al. 2013). Each BH is repositioned manually at each time-step to the center (minimum gravitational potential location) of its host galaxy. This is done in SPH simulations to correct for dynamical movements of BH particles wandering away from galaxy centers by numerical effects.

We consider that central BHs merge when their host galaxies merge during hierarchical structure formation. When two BH particles come near such that the distance between them is smaller than the smoothing length of either one, and their relative velocity is below the local sound speed, they are allowed to merge to form a single BH (e.g., Sijacki et al. 2007; Di Matteo et al. 2012).

### 2.3 Simulations

We perform cosmological hydrodynamical simulations of small-sized boxes to probe dwarf galaxies at high redshifts. The initial condition at $z = 100$ is generated using the MUSiC software (Hahn & Abel 2011). A concordance flat $\Lambda$CDM model is used, with the cosmological parameters (Planck Collaboration 2015, results XIII): $\Omega_{M,0} = 0.3089, \Omega_{\Lambda,0} = 0.6911, \Omega_{B,0} = 0.0486, H_0 = 67.74$ km s$^{-1}$ Mpc$^{-1}$.

The size of the cubic cosmological volume is $(2h^{-1}\text{Mpc})^3$ comoving. We use 256$^3$ dark matter and 256$^3$ gas particles in the initial condition. The dark matter particle mass is $m_{\text{DM}} = 3.44 \times 10^3 h^{-1} M_\odot$, and the gas particle mass is $m_{\text{gas}} = 6.43 \times 10^4 h^{-1} M_\odot$. The gravitational softening length is set as $L_{\text{soft}} = 0.1 h^{-1}$ kpc comoving. Starting from $z = 100$, the box is subsequently evolved up to $z = 4$, with periodic boundary conditions.

### 3 RESULTS AND DISCUSSION

#### 3.1 Large Scale Environment

The gas morphology in our simulation box, or the large scale structures, is plotted in Fig. 1. It displays the projected...
Intermediate-mass black holes

Figure 1. Projected gas kinematics in the whole (2000 h^{-1} kpc)^3 simulation box at z = 4. The three rows present the following gas properties: overdensity (first row – top), temperature (second), and SFR (third – bottom). The two columns are for different simulations: SN (left) and BHs3h4e7v2 (right). The red circles in the top row depict the virial radius \( R_{200} \) of galaxies in the mass range \( M_{\text{halo}} > 10^9 M_\odot \), while the black circles show the \( R_{200} \) of \( 10^8 < M_{\text{halo}} < 10^9 M_\odot \) galaxies. The positions of BHs in run BHs3h4e7v2 are indicated by the magenta cross-points in the top-right panel.
gas kinematics in the whole \((2000 h^{-1} \text{ kpc})^3\) comoving volume at \(z = 4\), for two simulations: SN (left column) and BHs3h4e7v2 (right column). The overdensity (i.e., the ratio between the gas density and the cosmological mean baryon density in the Universe), temperature, and star-formation rate (SFR) of the gas are plotted in the three rows from the top. The black circles in the top row depict the virial radius \(R_{200}\) (defined in Eq. 11) of dwarf galaxies with halo masses in the range \(10^7 \leq M_{\text{halo}} \leq 10^9 M_\odot\). The red circles show the \(R_{200}\) of relatively massive galaxies, those having higher halo masses \(M_{\text{halo}} > 10^9 M_\odot\).

The spatial locations of the BHs within our BHs3h4e7v2 simulation box can be visualized in the top-right panel of Fig. 1. Here the magenta cross-points designate BH positions, overplotted with the gas overdensity. In this run, BHs are seeded at the centres of galaxies with \(M_{\text{HaloMin}} = 4 \times 10^9 M_\odot\). Therefore all the red circles \((M_{\text{halo}} > 10^9 M_\odot)\) and most of the black circles \((M_{\text{halo}} = 10^8 - 10^9 M_\odot)\) contain BHs at their centres.

The cosmological large-scale-structure filaments are visible in all the panels of both the runs. There are three Mpc-scale filaments: extending from east to north, from west to north, and from west to south. In addition, there is an overdense region running from the center of the box to the south-west. The filaments consist of dense (yellow and white regions in the top panels), and star-forming (lightgreen, yellow, red and white regions in the bottom panels) gas. The massive galaxies (red circles) lie in the high-density intersections of the filaments, or in the filaments.

In terms of temperature, the immediate vicinity of the dense filaments consists of hotter gas \((T \sim 10^6 \text{ K})\), red regions in the middle panels of Fig. 1, as compared to that in the low-density intergalactic medium and voids (yellow and blue regions). Several mechanisms play together to heat the gas to higher temperatures in the filament vicinity. There are global environmental processes like shock heating during galaxy mergers, and large-scale-structure formation, which are present in both the SN and BHs3h4e7v2 runsт. Acting together there are local galactic processes like feedback driven by SN (present in both the columns), and BHs (present in the right column only), which heats the gas, and also often generate outflows.

As they accrete and grow, the BHs provide feedback energy (according to the prescription described in 2.2), which may drive gas outflows. High-velocity gas ejected by central BH feedback propagates radially outward, and shocks with the surrounding slower-moving gas, creating bubble-like gas outflows. Our simulation BHs3h4e7v2 shows the formation of BH feedback-induced outflows, as can be seen in Fig. 1 in the top-right half of the right column panels, around the most-massive BH. The outflows are extended bipolar oval-shaped regions along the north-east to south-west direction, propagating to about \(10 \times R_{200}\). The outflows consist of hot \((T > 10^6 \text{ K})\) - visible as red areas in the temperature map (middle-right panel), and low-density gas (top-right panel).

### 3.2 Black Hole Accretion and Growth

Fig. 2 presents the BH mass growth with redshift of the most-massive BH for eleven simulations of Table 1. The first BHs are seeded at \(z \sim 18 - 25\) in our simulations, when the first halos reach the corresponding lower limit \(M_{\text{HaloMin}} = (10^6 - 5 \times 10^7) M_\odot\). In some of the runs, one of these first seeds grow to become the most-massive BH. However, in runs BHs3h4e7v2 (light-red curve) and BHs4h4e7v2 (yellow curve), the BH which becomes most-massive is seeded at later epochs \(z \sim 7.5 - 12\). This variance in the seed epochs is because of the different growth modes, as described next.

Each BH starts as an initial seed of \(M_{\text{BHseed}} = (10^2, 10^3) M_\odot\). The subsequent growth is due to merger with other BHs and gas accretion. When two galaxies containing BHs merge during hierarchical structure formation, their central BHs merge as well (according to the prescription in 2.2) to form a single larger BH. In addition, BHs grow in mass by accreting dense gas from their surroundings, as galaxies evolve and gas inflows to their centres.

We find that in general, when seeded in larger halos, BHs start to grow later and have an overall smaller growth at the same redshift (comparing indigo and magenta curves, for instance). Furthermore, larger seed BHs grow more massive earlier than smaller seeds (comparing yellow and light-red curves), as naively expected. We also find that varying the \(M_{\text{HaloMin}}\) and \(M_{\text{BHseed}}\) together has a competing effect on the BH mass growth, which might cancel each other. A BH can grow similarly when seeded in smaller halos with a smaller seed mass (red curve), as in larger halos with a higher seed mass (indigo curve).

Fig. 3 displays the accretion rate evolution with redshift, of the most-massive BH in each run: BH mass accretion rate \((\dot{M}_{\text{BH}})\) in the left panel, and Eddington ratio \(\dot{M}_{\text{BH}}/\dot{E}_{\text{edd}}\) at the right. There is variability of the \(\dot{M}_{\text{BH}}\), whereby it fluctuates by a factor of up to 100. In the beginning, when the BHs are just seeded, they are accreting at highly sub-Eddington rates with Eddington ratio \(<0.0001\). The accretion rate grows with time as the BHs grow in mass, and the gas density in the BH vicinity increases by cosmic gas inflow to galaxy centers. However the gas accretion rate remains sub-Eddington always, with Eddington ratio \(<1\).

We find that the massive BHs grow to \(M_{\text{BH}} = 10^8 - 10^9 M_\odot\) by \(z = 5\) in most of our simulations (red, lime-green, indigo, magenta, brown, green, light-red, black, blue, and yellow curves). The accretion rate of these massive BHs has grown to \(M_{\text{BH}} = (0.2 - 1) M_{\text{Edd}}\). The exception is the case where BHs of the smallest seed \((10^7 M_\odot)\) are placed in the largest halos \((7 \times 10^7 M_\odot)\) (cyan curve), where the most-massive BH grows up to \(M_{\text{BH}} = 10^9 M_\odot\) only. For this BH, gas accretion is always occurring at low Eddington ratios \((M_{\text{BH}} \approx 0.01 M_{\text{Edd}})\).

The final BH properties reached at \(z = 4\) depend on the simulation. E.g., in run BHs4h4e7v2 (brown curve): \(M_{\text{BH}} = 2 \times 10^9 M_\odot\) and \(M_{\text{BH}} = 0.02 M_\odot/\text{yr}\). In Table 2 we list the final BH mass and the accretion rate of the most-massive BH, together with the final redshift of each simulation run.

### 3.3 Star Formation Rate Density

Stars form in the simulation volume from cold dense gas. Fig. 4 exhibits the global Star Formation Rate Density (SFRD) as a function of redshift, for all the simulations labelled by the different colors. The SFRD (in \(M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}\)) is computed by summing over all the SF occurring
Figure 2. BH mass growth with redshift of the most-massive BH in each run. The different colours discriminate the runs as labelled, which are: BHs2h1e6v2 - red curve, BHs2h1e6v10 - lime-green, BHs2h7e7v2 - cyan, BHs3h1e7v2 - indigo, BHs3h3e7v2 - magenta, BHs3h3e7v1 - brown, BHs3h4e7v1 - green, BHs3h4e7v2 - light-red, BHs3h4e7v10 - black, BHs3h5e7v2 - blue, and BHs4h4e7v2 - yellow.

Figure 3. BH accretion rate (left panel) and Eddington ratio growth with redshift of the most-massive BH in each run.
Table 2. Final black hole mass and accretion rate of the most-massive BH for the different simulation runs.

| Run name          | Final Redshift | BH mass, $M_{\odot}$ | BH accretion rate, $M_{\odot}/yr$ |
|-------------------|----------------|----------------------|-----------------------------------|
| BHs2h1e6v2        | 7.5            | $6 \times 10^7$      | 0.002                             |
| BHs2h1e6v10       | 6.5            | $3 \times 10^6$      | 0.03                              |
| BHs2h4e7v2        | 4.2            | $2 \times 10^4$      | $10^{-5}$                         |
| BHs2h7e7v2        | 4              | $1 \times 10^2$      | $10^{-6}$                         |
| BHs3h1e7v2        | 7.5            | $3 \times 10^5$      | 0.0007                            |
| BHs3h2e7v2        | 6.2            | $3.5 \times 10^4$    | 0.001                             |
| BHs3h3e7v2        | 4.2            | $8 \times 10^3$      | 0.01                              |
| BHs3h3e7v1        | 4.2            | $3 \times 10^6$      | 0.03                              |
| BHs3h4e7v1        | 4              | $4 \times 10^5$      | 0.002                             |
| BHs3h4e7v2        | 4              | $4 \times 10^4$      | 0.004                             |
| BHs3h4e7v5        | 4              | $2 \times 10^6$      | 0.03                              |
| BHs3h4e7v10       | 4.2            | $3 \times 10^6$      | 0.06                              |
| BHs3h5e7v2        | 4              | $3 \times 10^5$      | 0.0002                            |
| BHs4h4e7v2        | 6.5            | $1 \times 10^6$      | 0.008                             |

Figure 4. Total star formation rate density in simulation volume as a function of redshift, with the different models labelled by the colours. For comparison, the dark-brown and orange curves show two models from Barai et al. (2015), which are SFRD results for more-massive galaxy formation/evolution, from larger volume cosmological simulations.
in each simulation box at a time, and dividing it by the
time-step interval and the box volume.

The SFRD rises with time from early epochs \( z \sim 15 \), and all the runs behave similarly up to \( z \sim 9 \). Most of the simulations reach a maximum SFRD in the form of a plateau
between \( z = 4 - 6 \), and the SFRD decreases at \( z > 6 \) and at \( z < 4 \). We consider the SN run (dark blue curve) without BHs as the baseline, and compare other simulations with it to estimate the impact of BH feedback. The SFRD in simulation \( \text{BHs}2h7e7v2 \) (cyan curve) is almost similar to that in the run SN, because the BHs are too small there to generate enough feedback. A similar outcome happens in the other runs at \( z > 9 \), when the BHs are too small.

Star formation mostly occurs over an extended region at galaxy centres, where cosmic large-scale-structure gas inflows and cools. The presence of a central BH quenches star formation, because a fraction of dense gas is accreted onto the BH, and a fraction is ejected out by BH feedback. The processes of BH accretion and feedback suppress SF substantially in most of the runs, from \( z \approx 9 \) onwards, when the BHs have grown massive and generate larger feedback energy. Compared to the SN case (dark blue curve), the SFRD is reduced by a factor of several in most of the other runs at \( z < 9 \).

We find that BH accretion and feedback causes a quenching of the SFRD at cosmic epochs \( z \lesssim 9 \), by factors \( 1.1 - 3 \) times reduction. The precise redshifts and suppression factors are given in the following for the different simulations (with the same BH outflow velocity \( v_w = 2000 \) km/s):

- \( \text{BHs}2h1e6v2 \) (red curve in Fig. 1) at \( z \lesssim 9 \) up to 2 times reduction of SFRD,
- \( \text{BHs}3h1e7v2 \) (indigo curve) at \( z \lesssim 8 \) up to 1.1 times,
- \( \text{BHs}4h4e7v2 \) (yellow curve) at \( z \lesssim 8 \) up to 2 times,
- \( \text{BHs}3h2e7v2 \) at \( z \lesssim 7 \) up to 1.5 times,
- \( \text{BHs}3h3e7v2 \) (magenta curve) at \( z \lesssim 5 \) up to 2 times,
- \( \text{BHs}3h4e7v2 \) (light-red curve) at \( z \lesssim 4.5 \) up to 3 times,
- \( \text{BHs}3h5e7v2 \) (blue curve) at \( z \lesssim 4.2 \) up to 3 times.

Thus, we find that BHs need to grow to a mass \( M_{\text{BH}} \sim \) a few times \( 10^5 M_\odot \), in order to suppress star-formation in dwarf galaxies (of \( M_* = 10^5 - 10^7 M_\odot \)).

A larger BH outflow velocity \( (v_w) \) does not change the results substantially. E.g., comparing the red and lime-green curves in Fig. 2 the BH mass growth remains almost the same with \( v_w = 2000 \) and 10000 km/s. Increasing \( v_w \) decreases the mass outflow rate \( (M_w \text{ in Eqs. (4) and (5)}) \), in the way favoring an increase in the BH accretion rate, as we see in Fig. 3 at late epochs (comparing red and lime-green curves at \( z < 9 \)). Further, the smaller mass outflow rate to the environment delays the suppression of star formation (comparing lime-green and red curves in Fig. 1).

3.4 Black Hole - Galaxy Correlation

The BH - galaxy correlation obtained in our simulations is presented in Fig. 5 as the \( M_{\text{BH}} \) versus \( M_* \) (stellar mass) diagram. It shows all the galaxies within the simulation volume with \( M_* > 10^{15} M_\odot \), at two epochs: \( z = 7.94 \) in the left panel, and \( z = 5.49 \) in the right panel. The plotting colour distinguishes results from different runs. Observational data is overplotted as the black lines indicating the BH mass versus stellar bulge mass relationships at different epochs. Local galaxies \( (z = 0) \) are represented by the black-dashed line: \( M_{\text{BH}}/M_* = 0.002 \) [Marconi & Hunt 2003]. The ratio is observed to be steeper at high-z. Far-IR and CO bright \( z \sim 6 \) quasars lie along the black-solid line: median \( M_{\text{BH}}/M_* = 0.022 \) [Wang et al. 2010].

We find a huge scatter in the \( [M_{\text{BH}} - M_*] \) correlation of the simulated galaxies, especially at low-\( M_* \). In our simulations \( \text{BHs}2h1e6v2 \) (red symbols in Fig. 5) and \( \text{BHs}3h1e7v2 \) (indigo symbols), dwarf galaxies with stellar masses between \( M_* = 10^5 - 10^7 M_\odot \) contain BHs in the range \( M_{\text{BH}} = 10^3 - 10^5 M_\odot \) at \( z = 7.9 \), which are hence already more massive than BHs following the local relation, as well as BHs in \( z \sim 6 \) quasars. These two are also the runs where SF quenching happens the earliest, implying that the suppression occurs due to BH activities.

BHs in the simulation \( \text{BHs}4h4e7v2 \) (yellow symbols in Fig. 5) fall on the observed \( z \sim 6 \) relation of \( [M_{\text{BH}} - M_*] \) already at \( z = 7.9 \). In the run \( \text{BHs}3h2e7v2 \), BHs lie in between the two correlations at \( z = 7.9 \), and have migrated to the \( z \sim 6 \) relation at the later epoch. Central BHs in the runs \( \text{BHs}3h3e7v2 \) (magenta symbols), \( \text{BHs}3h4e7v2 \) (light-red symbols), and \( \text{BHs}3h5e7v2 \) (blue symbols) more or less follow the local \( z = 0 \) correlation at both the epochs plotted; although their scatter increases substantially in the right panel. When BHs do not grow much (run \( \text{BHs}2h7e7v2 \), cyan symbols, most-massive reaching \( M_{\text{BH}} < 10^4 M_\odot \) only), they always lie significantly below both of the \( [M_{\text{BH}} - M_*] \) correlations.

At the same time there are studies (e.g., Volonteri & Natarajan 2009, using semi-analytical models), which find that the existence of the \( [M_{\text{BH}} - M_*] \) correlation is purely a reflection of the merging hierarchy of massive dark matter haloes.

We find that there is a direct connection between early BH growth and the quenching of SF, which is henceforth caused by resulting BH feedback. In addition, our results of fast BH growth at the centers of dwarf galaxies suggest that these BHs grow faster than their host galaxies in the early Universe.

4 SUMMARY AND CONCLUSIONS

Intermediate-Mass Black Holes (with masses between \( 100 - 10^5 M_\odot \)) have historically been an elusive population of BHs, compared to the stellar-mass and supermassive (widely observed at the centers of AGN) BH counterparts. Recently these IMBHs have started to be observed in low-mass galaxies. Our work focuses on the case that IMBHs are formed at the centers of dwarf galaxies. Early feedback from such IMBHs is expected to release energy and affect the host gas-rich dwarf galaxies at \( z = 5 - 8 \), quenching star-formation, reducing the number of DGs, and impacting the density profile at DG centers. This can possibly solve several anomalies in the dwarf galaxy mass range within the concordance ΛCDM cosmological scenario of galaxy formation [Silk 2017].

We have investigated the growth and feedback of IMBHs at DG centers, by performing cosmological hydrodynamical simulations. We have employed a modified version of the SPH code GADGET-3. It includes the following
sub-resolution physics: radiative cooling and heating from a photoionizing background, star-formation, stellar evolution, chemical enrichment for 11 elements, supernova feedback, AGN accretion and feedback. We simulated (2h\(^{-1}\) Mpc\(^3\))\(^3\) comoving volumes to probe dwarf galaxies at high redshifts. The mass resolutions are \(3 \times 10^3 h^{-1} M_\odot\) for dark matter particles, and \(6 \times 10^3 h^{-1} M_\odot\) for gas particles. The length resolution is 0.1h\(^{-1}\) kpc comoving which is the gravitational softening length. The cosmological boxes are evolved with periodic boundary conditions, from \(z = 100\) up to \(z = 4\).

We executed a series of simulations; one of them is a control case with SF-only and no BH; the other runs include BHs and explore different parameter variations of the BH sub-resolution models. In particular, we seed BHs of mass: 

\[
M_{\text{BHseed}} = (10^2, 10^3, 10^4) M_\odot
\]

at the centers of massive halos with 

\[
M_{\text{halo}} > M_{\text{HaloMin}} = (10^6 - 5 \times 10^7) M_\odot
\]

In addition to \(M_{\text{HaloMin}}\) and \(M_{\text{BHseed}}\), we also vary the outflow velocity for BH kinetic feedback: \(v_w = (1000 - 10000) \text{ km/s}\).

The earliest BHs appear at \(z \sim 18 - 25\) in our simulations, when the first halos reach the corresponding lower limit \(M_{\text{HaloMin}}\). The BHs are allowed to grow by accreting surrounding gas and by merger with other BHs. As they accrete and grow, the BHs eject out feedback energy, and impact their host DGs. We find the following results for the growth and feedback of IMBHs in our simulations:

- The BHs grow to intermediate masses \(M_{\text{BH}} = 10^5 - 10^7 M_\odot\) by \(z = 5\), when the BHs are seeded in halos with \(M_{\text{HaloMin}} \leq 4 \times 10^7 M_\odot\). The most-massive BH at \(z = 4\) has: \(M_{\text{BH}} = 2 \times 10^6 M_\odot\) and \(M_{\text{BH}} / M_\odot = 0.02\) yr.
- BHs seeded in smaller halos grow faster (considering the same redshift) than those seeded in larger halos. E.g. at \(z = 7\), the most-massive BH in the simulation has grown to \(M_{\text{BH}} = 10^5 M_\odot\) when seeded in \(M_{\text{HaloMin}} = 2 \times 10^7 M_\odot\) halos, while it grows only to \(M_{\text{BH}} = 4 \times 10^4 M_\odot\) when seeded in \(M_{\text{HaloMin}} = 3 \times 10^7 M_\odot\) halos.

- The effect of increasing or decreasing the parameters \(M_{\text{HaloMin}}\) and \(M_{\text{BHseed}}\) together on the BH mass growth can be the same. E.g., a BH can grow similarly when seeded in smaller halos \((M_{\text{HaloMin}} = 10^6 M_\odot)\) with a smaller seed mass \((M_{\text{BHseed}} = 10^2 M_\odot)\), as in larger halos \((M_{\text{HaloMin}} = 10^7 M_\odot)\) with a higher seed mass \((M_{\text{BHseed}} = 10^3 M_\odot)\).

- The variation in the BH outflow velocity has little effect upon the BH growth, although the increase of the outflow velocity delays the suppression of SF.

- Starting from highly sub-Eddington rates \((\text{Eddington ratio} < 0.001)\), the accretion rate of the BHs increases with time, and reaches \(M_{\text{BH}} = (0.2 - 0.8) M_{\text{Edd}}\) for the massive IMBHs by \(z = 4\).

- Our simulations probe dwarf galaxies with a stellar mass between \(M_* = (10^4 - 10^5) M_\odot\). The star formation rate density evolution of these DGs has a wide maximum in the form of a plateau between \(z = 4 - 6\), and the SFRD decreases at \(z > 6\) and at \(z < 4\).

- Star-formation is quenched between \(z = 9 - 4\) by BH accretion and feedback. The SFRD is reduced by factors \(1.1 - 3\), when the BHs have grown to a mass \(M_{\text{BH}} \sim 10^7 M_\odot\).

- There is a huge scatter in the BH - galaxy \([M_{\text{BH}} - M_*]\) correlation of the simulated galaxies, especially at low-\(M_*\).

In our runs where SF quenching happens the earliest, the IMBHs \((M_{\text{BH}} = 10^5 - 10^6 M_\odot)\) in DGs \((M_* = 10^4 - 10^5 M_\odot)\) are already more massive at \(z = 7.9\), as compared to the local \([M_{\text{BH}} - M_*]\) correlation and that of high-\(z\) quasars. Cen-

Figure 5. BH mass versus stellar mass of the galaxies within the simulation volume, at two epochs \(z = 7.94, 5.49\), in the two panels. The plotting colours distinguish results from different runs. The black lines indicate the observed BH mass versus stellar bulge mass relation for: \(z \sim 6\) quasars \(\text{[Wang et al.} 2010]\) as the solid line, and local galaxies \(\text{[Marconi & Hunt} 2003]\) as the dashed line.
Intermediate-mass black holes

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