*Black Hole Winds at All Scales*
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# Intermediate mass black hole feedback in dwarf galaxy simulations with a resolved ISM and accurate nuclear stellar dynamics

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**Abstract.** Recent observations have established that dwarf galaxies can host black holes of intermediate mass (IMBH, $100\,\mathrm{M}_\odot < M_\mathrm{IMBH} \lesssim 10^5\,\mathrm{M}_\odot$). With modern numerical models, we can test the growth of IMBHs as well as their evolutionary impact on the host galaxy. Our novel subsolar-mass (0.8 solar mass) resolution simulations of dwarf galaxies ($M_* = 2\times10^7\,\mathrm{M}_\odot$) have a resolved three-phase interstellar medium and account for non-equilibrium heating, cooling, and chemistry processes. The stellar initial mass function is fully sampled between 0.08–150 $\mathrm{M}_\odot$ while massive stars can form HII regions and explode as resolved supernovae. The stellar dynamics around the IMBH is integrated accurately with a regularization scheme. We present a viscous accretion disk model for the IMBH with momentum, energy, and mass conserving wind feedback. We demonstrate how the IMBH can grow from accretion of the cold and warm gas phase and how the presence of the IMBH and its feedback impacts the gas phase structure.

**Keywords.** intermediate mass black holes, dwarf galaxy evolution, active galactic nuclei

## 1. Introduction

It is now established that also dwarf galaxies host massive black holes (BHs, e.g. Mezcua & Sánchez 2020). While a few supermassive BHs ($M_\mathrm{BH} \gtrsim 10^5\,\mathrm{M}_\odot$) have been detected in dwarf galaxies, the majority of BHs are expected to fall into the intermediate mass (IMBH) regime ($100\,\mathrm{M}_\odot < M_\mathrm{IMBH} \lesssim 10^5\,\mathrm{M}_\odot$, see e.g. Greene *et al.* 2020 for a review). Since gas densities in dwarfs ($M_* < 10^9\,\mathrm{M}_\odot$) are low, the potential wells shallow and the expected BH masses small, these BHs typically have low luminosities and are not necessarily found in the center of the galaxy (e.g. Sharma *et al.* 2020). As a consequence, the vast majority of IMBHs in dwarfs are expected to be unobserved and our understanding of BH occupation fractions and mass functions in this regime is still very incomplete. Furthermore, the scatter of the BH mass - stellar mass relation is significantly larger at the low mass end (e.g. Mezcua *et al.* 2023, Zaw *et al.* 2023).

Because the growth of BHs in low density environments is expected to be very limited, dwarf galaxies might give us a relatively unbiased census of the BH population in the

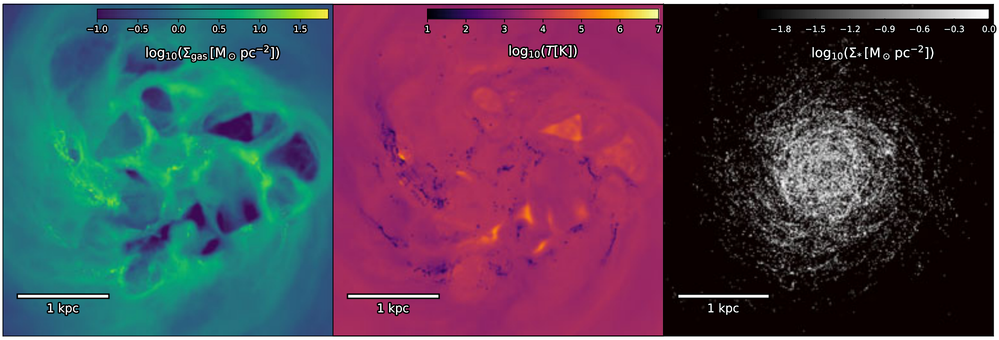

**Figure 1.** Face on view of the dwarf galaxy after 400 Myr of isolated evolution. The stellar feedback drives turbulence in the ISM and significantly limits the available cold gas for the BH by heating and pushing the gas out of the galactic center.

early Universe. Hence, they are well suited to explore the physics of the first BH seeds and to discriminate between proposed seeding scenarios such as direct collapse, Population III stars or gravitational runaway (Greene *et al.* 2020). In this work, we present simulations of BHs in isolated dwarf galaxies to determine typical accretion rates, cycles of activity and observational signatures of IMBHs. We focus on understanding the interplay of star formation, stellar feedback and BH physics.

## 2. Simulations

*Model of the interstellar medium* We simulate a $M_{\rm baryon} = 6 \times 10^7\,{\rm M}_\odot$ dwarf galaxy with an improved version of the smoothed-particle hydrodynamics (SPH) code Gadget3 introduced in Springel (2005) and Hu *et al.* (2014) at a gas particle resolution of $0.8\,{\rm M}_\odot$. Our model includes non-equilibrium cooling and heating for six chemical species (Hu *et al.* 2016), photo-ionizing feedback from massive stars (Hu *et al.* 2017) as well as resolved supernova explosions (Steinwandel *et al.* 2020). Star formation is based on a Jeans threshold and stars are realized as individual particles down to the Hydrogen burning limit of $0.08\,M_\odot$ as outlined in Lahén *et al.* (2023). An example for a simulated dwarf galaxy is shown in Figure 1, where the turbulent structure of the interstellar medium driven by stellar feedback is clearly visible. For this project, we have added a regularized integrator to resolve the gravitational dynamics of stars in the vicinity of the BH (Rantala *et al.* 2017). Hence, the BH does not need to be fixed to the center of the galaxy and wanders around in the central $\sim 30\,{\rm pc}$ as a result of interactions with gas clouds and close encounters with stars.

*BH accretion and feedback model* The accretion of gas by the BH is modeled with a sink particle prescription based on the angular momentum and Bondi radius of each SPH particle. Accreted mass is transferred to an unresolved accretion disc mass reservoir which feeds the BH on a timescale motivated by the viscous transport inside the unresolved accretion disc. This timescale is a free parameter in our model and we explore various possible parameter choices in a forthcoming paper (Partmann *et al.* in prep). We test two different BH feedback mechanisms: In the thermal feedback model, energy is injected isotropically into the interstellar medium (ISM) based on the mass accretion rate $\dot{M}_{\rm BH}$, the radiative efficiency $\epsilon_{\rm BH}$ and a coupling efficiency to the ISM $\epsilon_{\rm ISM}$

$$\dot{E}_{\rm th} = \epsilon_{\rm ISM}\epsilon_{\rm BH}\dot{M}_{\rm BH}c^2\ . \tag{2.1}$$

As an alternative, we use a kinetic feedback model similar to Ostriker *et al.* (2010), where we assume that the BH launches a collimated wind that thermalizes below the

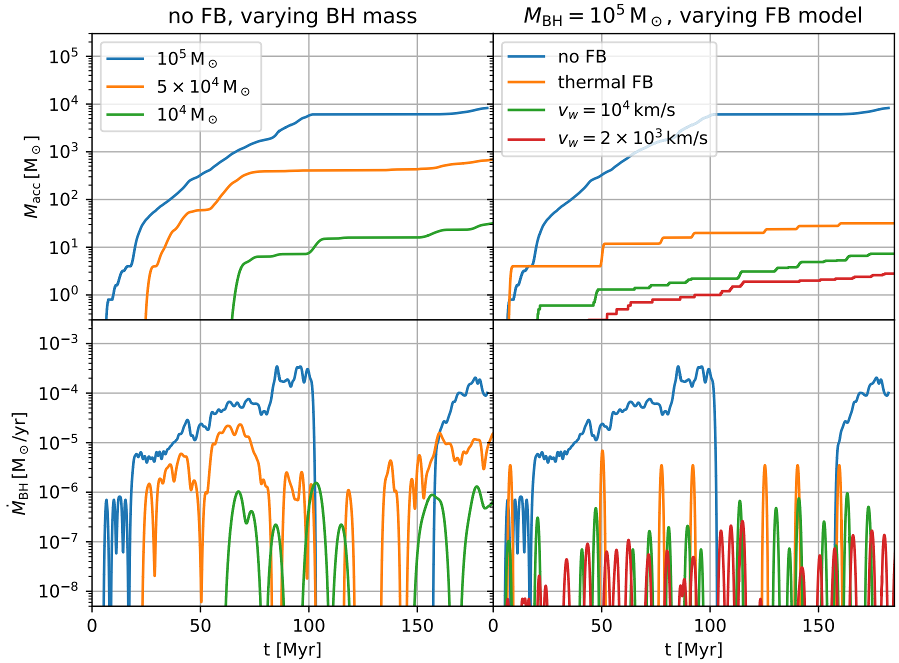

**Figure 2.** Accreted mass and accretion rates for varying BH masses (left) and varying feedback (FB) models (right). The BH growth is very bursty with generally low accretion rates. Stellar feedback can shut down accretion episodically even in the absence of BH feedback. The inclusion of BH feedback prohibits the growth of a BH by reducing the accretion rates by several orders of magnitude.

resolution scale of our simulation ($\sim 0.1\,\mathrm{pc}$). Due to the energy and momentum conservation, the majority of accreted mass is re-ejected as a wind. As a result, the growth rate of the BH is smaller than the inflow of mass by a factor that depends on the assumed wind speed $v_\mathrm{wind}$

$$\eta = \frac{\dot M_\mathrm{outflow}}{\dot M_\mathrm{accreted}} = \frac{2\epsilon_\mathrm{ism}\epsilon_\mathrm{BH}c^2}{v_\mathrm{wind}^2}\,. \tag{2.2}$$

## 3. Results

*BH growth without AGN feedback* For a galaxy of stellar mass $2\times10^7\,\mathrm{M}_\odot$, the extrapolated scaling relations would suggest an IMBH of mass $M_\mathrm{BH} \lesssim 10^5\,\mathrm{M}_\odot$ (Greene *et al.* 2020). In the left column of Figure 2, we show the growth and accretion rates of three BHs with initial masses of $10^4, 5\times10^4$ and $10^5\,\mathrm{M}_\odot$ in simulations without BH feedback. The accretion rates are generally low and typically do not exceed Eddington ratios of 0.1. The growth history is bursty due to the accretion of cold clouds and the strong effect of stellar feedback, that can evacuate the dwarf galaxy center episodically or heat the gas to high temperatures where accretion is inefficient. While our heaviest tested BH can grow by $\sim 5\%$ during the simulation time, the $M_\mathrm{BH} = 10^4\,M_\odot$ BH shows almost no growth.

*BH growth with AGN feedback* Simulations without BH feedback are relevant to derive the amount of cold gas that can in principle feed the BH. However, they neglect the effect of the BH on its environment and the self-regulating nature of the AGN feedback. These effects are known to be important even in dwarf galaxies (see e.g. Schutte *et al.* 2022, Koudmani *et al.* 2022, Silk 2017). Using the $M_\mathrm{BH} = 10^5\,\mathrm{M}_\odot$ BH as a test case, we find that any type of feedback shuts down BH growth almost completely. While the thermal feedback model limits accretion by efficiently heating the ISM around the BH, the kinetic feedback models (shown for wind speeds of $v_w = 10^4$ km/s and $2 \times 10^3$ km/s) lead to even lower accretion rates, because most mass is directly ejected as a wind instead of being accreted onto the BH. We observe only a small impact on the star formation rates in the center of the dwarf galaxy.

## 4. Discussion

Our simulations show that the growth of an IMBH in a $M_* = 2 \times 10^7$ $\mathrm{M}_\odot$, actively star forming ($\sim 10^{-3}$ $\mathrm{M}_\odot$/yr) dwarf galaxy is very limited. Stellar feedback can quench the accretion for extended periods of time by heating and pushing gas out of the galactic center. In addition, the BH feedback makes BH growth even more inefficient. The resulting X-ray luminosities are very low ($\lesssim 10^{40}$ergs/s), slightly below the likely incomplete observations of local dwarfs as e.g. presented in Birchall *et al.* (2020). We conclude that more extreme environments (e.g. galaxy mergers) or less efficient feedback channels are required to grow IMBHs in dwarf galaxies. In a forthcoming paper (Partmann *et al.* in prep), we present a new set of simulations that we use to explore the effect of the parameter choices of our feedback model in more detail as well as the stellar dynamics in the vicinity of the BH.

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