MNRAS **469,** 2845–2854 (2017)
Advance Access publication 2017 May 3
doi:10.1093/mnras/stx1043

A rumble in the dark: signatures of self-interacting dark matter in supermassive black hole dynamics and galaxy density profiles

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Accepted 2017 April 27. Received 2017 April 26; in original form 2017 January 13

ABSTRACT

We explore for the first time the effect of self-interacting dark matter (SIDM) on the dark matter (DM) and baryonic distribution in massive galaxies formed in hydrodynamical cosmological simulations, including explicit baryonic physics treatment. A novel implementation of supermassive black hole (SMBH) formation and evolution is used, as in Tremmel et al., allowing us to explicitly follow the SMBH dynamics at the centre of galaxies. A high SIDM constant cross-section is chosen, $\sigma = 10\ \mathrm{cm^2 gr^{-1}}$, to amplify differences from CDM models. Milky Way-like galaxies form a shallower DM density profile in SIDM than they do in cold dark matter (CDM), with differences already at 20 kpc scales. This demonstrates that even for the most massive spirals, the effect of SIDM dominates over the adiabatic contraction due to baryons. Strikingly, the dynamics of SMBHs differs in the SIDM and reference CDM case. SMBHs in massive spirals have sunk to the centre of their host galaxy in both the SIDM and CDM run, while in less massive galaxies about 80 per cent of the SMBH population is off-centred in the SIDM case, as opposed to the CDM case in which ∼90 per cent of SMBHs have reached their host's centre. SMBHs are found as far as ∼9 kpc away from the centre of their host SIDM galaxy. This difference is due to the increased dynamical friction time-scale caused by the lower DM density in SIDM galaxies compared to CDM, resulting in *core stalling*. This pilot work highlights the importance of simulating in a full hydrodynamical context different DM models combined to the SMBH physics to study their influence on galaxy formation.

Key words: galaxies: evolution – cosmology: theory – dark matter.

1 INTRODUCTION

Self-interacting dark matter (SIDM), originally introduced over a decade ago by Spergel & Steinhardt (2000) as a heuristic model to solve the problem of observed shallow dark matter (DM) profiles in galaxies, is also the simplest case of non-standard DM structure formation models with 'dark sector' interactions. SIDM has recently captured an increasing interest within the community. The collisional, self-scattering particles can create cores of DM within galaxies by transferring mass from the dense central regions of the DM haloes, where the probability of collisions is higher towards the halo outskirts (Balberg, Shapiro & Inagaki 2002; Colín et al. 2002; Koda & Shapiro 2011). This process represents a viable solution to the so-called *core-cusp* problem (Moore 1994; Oh et al. 2008; Walker & Peñarrubia 2011; Adams et al. 2014).

The rate of collisions, determined by the cross-section per unit mass σ/m (from now on simply σ) is constrained from several astrophysical observations, such as the necessity of forming cores in very faint galaxies without evaporating the satellites of Milky Way (MW)-sized haloes or the galaxies in clusters, maintaining the ellipsoidal shape of haloes and clusters and avoiding the gravothermal catastrophe (Firmani et al. 2001; Gnedin & Ostriker 2001; Peter et al. 2013; Robertson, Massey & Eke 2017). Several authors have

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successfully run the SIDM simulations placing further constraints on cross-sections that are constant across all interaction velocities, and found that the relevant range to impact galaxy evolution and avoid upper limits lies between $0.1 < \sigma/(\mathrm{cm^2 gr^{-1}}) < 1$ (Vogelsberger, Zavala & Loeb 2012; Peter et al. 2013; Rocha et al. 2013; Vogelsberger & Zavala 2013; Zavala, Vogelsberger & Walker 2013; Cyr-Racine et al. 2016; Vogelsberger et al. 2016). A velocity-dependent cross-section could, however, ease the constraints on σ by allowing the DM to behave as a collisional fluid in dwarfs, and as a collisionless one at clusters scales (Yoshida et al. 2000; Colín et al. 2002; Elbert et al. 2016). These simple predictions need, however, to be evaluated in the presence of baryonic processes such as supernovae (SN) driven outflows. The SN-driven winds remove the excess of low angular momentum gas and explain the formation of bulgeless galaxies (Governato et al. 2010), which no alternative DM model solves. Outflows also predict, in agreement with observations, the formation of shallow DM profiles at the centre of galaxies (e.g. Governato et al. 2012; Pontzen & Governato 2012; Brooks & Zolotov 2014; Di Cintio et al. 2014a,b; Pontzen & Governato 2014; Oñorbe et al. 2015; Tollet et al. 2016).

Comparing the predictions of SIDM and cold dark matter (CDM) models once coupled to baryon physics has been recently explored in low mass galaxies (Vogelsberger et al. 2014; Fry et al. 2015). Vogelsberger et al. (2014) show that the stellar core in simulated SIDM dwarfs is closely related to the DM core radius generated by self-interactions. In Fry et al. (2015) by choosing a relatively large cross-section of $2\ \mathrm{cm^2\ gr^{-1}}$ and by including the mechanisms able to create a core through the SN feedback and bursty star formation (SF) (Pontzen & Governato 2014), the authors showed that the DM profiles and star formation histories (SFHs) of dwarf galaxies in SIDM simulations do not essentially differ from CDM ones, both being in agreement with observational results.

Attempts to calculate analytically the response of the SIDM particles in the presence of baryons have been made by Kaplinghat et al. (2014): following the scaling relation for SIDM presented in Rocha et al. (2013), they initially showed that by using a cross-section of $\sigma = 0.56\ \mathrm{cm^2 gr^{-1}}$ the deviations in density profile of a Milky Way halo, due to self-interactions, are expected at radii $\lesssim$10 kpc. Kaplinghat et al. (2014) claimed, however, that such analytic prediction holds for the SIDM-only simulations, since the presence of baryons changes the SIDM density profile by decreasing the core radius and increasing the core density: the expected core size in a Milky Way galaxy, for $\sigma = 0.56\ \mathrm{cm^2 gr^{-1}}$ and accounting for the gravitational potential of both baryons and DM, would be around 0.3 kpc, more than an order of magnitude smaller than the core size from the SIDM-only simulations. Such analytic treatment has been shown to be in agreement with results from idealized simulations of SIDM with baryons by Elbert et al. (2016). If proven correct, this would imply that the adiabatic contraction effect due to baryons may loosen the constraints on SIDM cross-sections.

This prediction deserves however further investigation, since it heavily relies on analytic models and idealized simulations, ignoring the complexity of galaxy formation processes such as violent relaxation caused by mergers and outflows created by both SN and supermassive black holes (SMBHs) that regulate SF efficiency in galaxies.

In this paper, we explore for the first time the effect, on galaxies of different masses, of a large constant cross-section in the SIDM simulations, including baryonic physics and SMBHs, and we compare the results against a standard CDM+baryons run. We further study and highlight the differences in the SMBH dynamics in the two cosmologies, by explicitly following the SMBH orbital decay: this is a unique capability of our runs and represents a step forwards compared to previous work in the field. We run a box of 8 Mpc in side up to $z = 0.5$, with the most massive galaxy being a Milky Way analogue. Both runs include a novel parametrization of the SMBH physics following Tremmel et al. (2015, 2016), in which SMBHs are allowed to form in dense pristine gas regions and their orbits can be followed as they sink towards the galaxy centre due to dynamical friction forces (Chandrasekhar 1943; Binney & Tremaine 2008). This approach is a significant improvement over previous 'advection' schemes that force SMBHs at the galaxy centre during merger events or satellite accretion (Di Matteo, Springel & Hernquist 2005; Sijacki et al. 2007), resulting in unrealistic time-scales for SMBH orbital decays. In order to highlight differences between CDM and SIDM, we used a cross-section of $\sigma = 10\ \mathrm{cm^2 gr^{-1}}$, which is allowed at the scale of the Milky Way, and it is in agreement with the upper limits derived by Kaplinghat et al. (2016) using rotation curves of low surface brightness galaxies.

This manuscript is organized as follows: in Section 2, we show the characteristics of the simulated galaxies, including a full description of self-interactions, SMBH and stellar physics implementations; in Section 3, we discuss the main results, focusing on the DM density profiles, SFHs and the SMBH properties in massive (Section 3.1) and intermediate mass galaxies (Section 3.2) and on the global properties of the SMBH population in the SIDM and CDM cosmologies (Sections 3.3 and 3.4); we conclude in Section 4.

2 SIMULATIONS

We run hydrodynamical simulations of the formation of galaxies in a full cosmological context, within a box of 8 Mpc in side, employing cosmological parameters from the latest *Planck* results in a Λ dominated universe ($\Omega_0 = 0.3$, $\Lambda = 0.7$, h = 0.67, $\sigma_8 = 0.83$, Planck Collaboration XVI 2014) and following the evolution of structure formation until $z = 0.5$. We used two underlying models for DM, a CDM and an SIDM one, with the same set of initial conditions. We employ a constant cross-section of $\sigma = 10\ \mathrm{cm^2 gr^{-1}}$ for the SIDM model. The simulations are run using the new *N*-body + SPH code ChaNGa[1] (Menon et al. 2015), which is an improved version of the code Gasoline and includes several standard modules such as a cosmic UV background, SF and blastwave feedback from SN (Wadsley, Stadel & Quinn 2004; Stinson et al. 2006; Wadsley, Veeravalli & Couchman 2008). The SPH implementation also includes thermal diffusion (Shen, Wadsley & Stinson 2010) and eliminates artificial gas surface tension through the use of a geometric mean density in the SPH force expression (Governato et al. 2015; Menon et al. 2015). This update better simulates shearing flows with Kelvin–Helmholtz instabilities.

The simulations are run with a gravitational force spline softening length of 350 pc. The DM is oversampled such that we simulate ~3 times more DM particles than gas particles, resulting in a DM particle mass of $3.4 \times 10^5\ \mathrm{M_\odot}$ and gas particle mass of $2.1 \times 10^5\ \mathrm{M_\odot}$. This methodology decreases numerical noise and improves the SMBH dynamics (Tremmel et al. 2015). The halo masses are defined as the mass of a sphere containing $\Delta_{\rm vir}$ times the critical matter density of the Universe, such that $M_{\rm halo} = 4\pi R_{\rm vir}^3 \Delta_{\rm vir} \rho_{\rm crit}/3$ and $\Delta_{\rm vir}$ depends on the chosen cosmology (Bryan & Norman 1998). For a *Planck* cosmology, $\Delta_{\rm vir} \sim 100$. The haloes are identified using the AHF[2] halo finder (Knollmann & Knebe

[1] www-hpcc.astro.washington.edu/tools/changa.html

[2] http://popia.ft.uam.es/AHF/Download.html

2009) and analysed with the *pynbody*[3] package (Pontzen et al. 2013) and the TANGOS data base (Pontzen et al., in preparation).

Overall, the feedback mechanisms implemented in the simulations are able to create galaxies with the expected stellar mass per each halo mass, despite of the underlying DM model, SIDM or CDM, as shown in Tremmel et al. (2016) and Fry et al. (2015).

2.1 Black hole dynamics and accretion: a new model

The SMBH physics has been implemented following the novel approach of Tremmel et al. (2015, 2016).

The SMBH seed formation is connected to the physical state of the gas in the simulation at high redshift, without any a priori assumptions regarding halo occupation fraction: this allows to naturally populate galaxies of different masses with SMBHs. SMBHs form in the early Universe from dense, pristine low metallicity ($Z < 3 \times 10^{-4}$) gas with densities 15 times higher than the SF threshold ($3m_p/\mathrm{cm}^3$) with temperatures between 9500 and 10 000 K. Seed SMBH formation is then limited to the highest density peaks in the early Universe with high Jeans masses. This technique forms the SMBH seeds within the first billion years of the simulation, allowing us to follow their dynamics throughout the assembly of the host halo, even for small haloes.

An important improvement, which made this study possible for the first time, regards the treatment of dynamical friction. The gravitational wake of a massive body moving in the extended potential of a medium will causes the orbit of SMBHs to decay towards the centre of massive galaxies (Chandrasekhar 1943; Binney & Tremaine 2008). Previous authors have provided analytic expression to compute the dynamical friction time-scales t_{df} of rigid bodies merging at the centre of galaxies (Taffoni et al. 2003; Boylan-Kolchin, Ma & Quataert 2008), showing that it can easily exceed several Gyrs, making previous 'advection' techniques inappropriate to realistically model such a significant time-scale for sinking SMBHs (Di Matteo et al. 2005; Sijacki et al. 2007). Indeed, in 'advection' models the SMBHs are re-positioned and forced at the galaxy centre during merger events or satellite accretion, resulting in unrealistic time-scales for the SMBH orbital decays.

In this work, we instead use a novel prescription first introduced in Tremmel et al. (2015, 2016), which includes a sub-grid approach for modelling unresolved dynamical friction on scales smaller than the gravitational softening length, adding a force correction to the SMBH acceleration. The dynamical friction force is

$$\boldsymbol{F}_{\mathrm{df}} = -4\pi G^2 \ln(\Lambda) M \rho_{\mathrm{host}}(< v_{\mathrm{orb}})/v_{\mathrm{orb}}^2, \quad (1)$$

where M is the mass of the object with orbital velocity v_{orb}, ρ_{host} is the density of host background particles with velocities less than the orbital velocity and Λ is the usual Coulomb logarithm. Such acceleration is added to the SMBHs current acceleration, and integrated in the following time step. The resulting sinking time-scale t_{df} will be therefore dependent on the density of the surrounding galaxy, and on the mass and the velocity of the SMBH itself. This technique has been shown to produce realistically sinking SMBHs (Tremmel et al. 2015). We are consequently able to resolve the dynamics of SMBHs during and after galaxy mergers down to sub-kpc scales, with important implications for the dynamics of SMBHs in galaxies with different underlying densities.

Once formed, the seed mass is set to 10^6 $\mathrm{M}_{\odot}$. SMBHs will then accrete gas according to a modified Bondi–Hoyle formula that accounts for the rotational support of gas (Tremmel et al. 2015, 2016); seeds that exist in unfavourable environments, such as dwarf galaxies, will naturally have limited growth over a Hubble time. The energy from accretion is then isotropically transferred to nearby gas particles with a technique similar to the blastwave SN feedback (Stinson et al. 2006): cooling is turned off for the gas particles immediately surrounding the SMBH, resembling the continuous transfer of energy during each SMBH timestep. The amount of energy coupled to surrounding gas particles is given by $E = \epsilon_r \epsilon_f \dot{M} c^2 \mathrm{d}t$, where $\dot{M}$ is the accretion rate, ϵ_r the radiative efficiency and ϵ_f the efficiency of energy that couples to gas (see Tremmel et al. 2016 for details about the calibration of these parameters). Because SMBH growth depends on the host galaxy mass, the SMBH feedback is able to preferentially limit the growth of massive galaxies, while not quenching the SF in low-mass haloes.

2.2 SF recipes

The parameters associated with stellar physics have been tuned to result in the most realistic galaxies possible at $z = 0$, within the implementation of our sub-grid model (Tremmel et al. 2016). SF in ChaNGa is regulated through a series of sub-grid prescriptions that parametrize unresolved physics into several free parameters. Stars are formed stochastically in cold ($T < 10^4$ K) gas that exceeds a density of $n_{\mathrm{th}} = 0.2m_p/\mathrm{cm}^3$. Supernova feedback is implemented using the Stinson et al. (2006) blastwave formalism, depositing $E_{\mathrm{SN}} = 10^{51}$ erg into the surrounding interstellar medium at the end of the lifetime of stars more massive than 8 $\mathrm{M}_{\odot}$. A Kroupa IMF (Kroupa 2002) is employed to compute the number of stars that will end as SN. Due to the relatively low resolution of the simulations, we do not expect significant core formation from baryonic feedback, which needs an n_{th} of at least $10m_p/\mathrm{cm}^3$ to effectively transfer energy to the DM (see Governato et al. 2010; Pontzen & Governato 2012 for details). In this work, we are focusing on a set-up that does not foreseen the SN-driven DM core formation to avoid, for now, a more complicated scenario.

2.3 Self-interactions implementation

The SIDM model is implemented in a similar way as in Fry et al. (2015), and we refer to their work for a comprehensive explanation of the methodology and further details. In this work, we employ a high constant cross-section of $\sigma = 10\ \mathrm{cm}^2\mathrm{gr}^{-1}$, which is allowed at scales of the Milky Way (Kaplinghat et al. 2016), in order to maximize the effects of self-interactions on DM haloes at every mass. The SIDM interactions are modelled assuming that each simulated DM particle represents a phase-space density patch and the probability of collisions is derived from the collision term in the Boltzmann equation. When a particle collision is detected, the particles are isotropically and elastically scattered, explicitly conserving energy. These interactions are more common in the inner region of the halo where the density is higher. The collisions between dark matter particles will then result in a net transfer of mass outwards from the dense central regions of the DM haloes, over cosmic time-scales, in a process that creates large cores and more spherical haloes with respect to the CDM case (Burkert 2000; Spergel & Steinhardt 2000).

Following the analytic model of Rocha et al. (2013) and Fry et al. (2015) (see also Dooley et al. 2016 for an updated model), we can separate the DM halo into two regions, delimited by a characteristic radius r, imposing that at such radius the average

[3] https://pynbody.github.io/pynbody/installation.html

number of scattering per particles, Γ, for the entire life of a galaxy, t, is unity:

$$\Gamma \approx 1 \approx t \times \rho(r) \times v(r) \times \sigma, \quad (2)$$

where $v(r)$ is the velocity dispersion of DM at radius r and $\rho(r)$ is the DM density at the same radius and $t \sim$10 Gyr for a Milky Way galaxy.

At radii larger than the characteristic radius, the scattering occurs less than once per particle, on average, and we expect the DM density profile to be unaffected by the collisions, maintaining the prediction typical of collisionless CDM haloes, i.e. the Navarro, Frenk & White (1996) (NFW) profile. Within the characteristic radius, instead, scattering from self-interactions happens more than once per particle during a time interval of t: here is where we expect the DM particles to modify the inner DM profile.

We can use equation (2) and the scaling of $\rho v \approx (t\sigma)^{-1}$ as a function of r/r_s, as in fig. 7 of Rocha et al. (2013), where r_s denotes the scale radius of an initial NFW halo, to estimate the radius within which collisions are important, as a function of cross-section. Note that the core radius due to self-interactions will then be a fraction of this special radius. With our value of σ = 10 cm^{2}gr^{-1}, and over a time-scale of 10 Gyr, we expect modifications in the density profile of a Milky Way like halo to happen already at a radius $r/r_s \sim 2$ that, for a typical r_s = 20 kpc, leads to physical radii of 30–40 kpc.

As pointed out in Fry et al. (2015) at the lowest, dwarf scales, not every SIDM model will necessarily form significant DM cores: this is because, according to equation (2), low halo velocities and low central densities may result in a time-scale for collisions comparable to or longer than the lifetime of the halo itself, which will thus maintain the DM cusp. In Zavala et al. (2013), for example, it has been shown that a cross-section of σ = 0.1 cm^{2}gr^{-1} will still produce a populations of satellites with higher-than-observed densities compared to the MW dwarf spheroidals and that a $\sigma \geqslant$ 1 cm^{2}gr^{-1} is needed to solve the discrepancy. With our choice of σ = 10 cm^{2}gr^{-1} and for a time-scale of 10 Gyr, we should expect cores of the order of the scale radius even for galaxies with $M_{\rm halo} \sim 10^{10.0-10.5}$ M$_\odot$.

3 RESULTS

We study the DM density profiles, SFHs and the SMBH dynamics in galaxies of different masses within the SIDM and CDM cosmology. We focus on haloes more massive than $M_{\rm halo} = 10^{10}$ M$_\odot$ since galaxies of lower halo masses in both SIDM and CDM have extensively been studied elsewhere (Vogelsberger et al. 2012, 2014; Rocha et al. 2013; Zavala et al. 2013; Fry et al. 2015).

SMBHs release energy in the surrounding medium, having an effect on both SFH (Tremmel et al. 2016) and possibly on the DM distribution within galaxies. Self-interactions will cause the inner haloes to have a hot core, indicative of heat transport from the outskirts inwards (Balberg et al. 2002; Colín et al. 2002; Koda & Shapiro 2011): with a cross-section of σ = 10 cm^{2}gr^{-1}, we expect to maximize the effect of core formation even in small, $M_{\rm halo} \sim 10^{10}$ M$_\odot$ galaxies. Moreover, the effect of gas inflows during the process of galaxy formation is to slowly drag DM towards the galaxy centre, in a process known as adiabatic contraction (Blumenthal et al. 1986; Gnedin et al. 2011), which renders the centre of the DM haloes more concentrated than what is found in N-body only simulations. The adiabatic contraction process is particularly important in massive galaxies, where the efficiency of SF is the highest. Finally, note that due to limited resolution core formation from baryons (Pontzen & Governato 2012) will be a lower limit, i.e. larger cores are expected in higher resolution runs, which we plan to address in future work.

The goal of this section is to probe the respective contribution of the several above-mentioned competing effects, which may modify the DM distribution within galaxies as well as affect their SFHs and SMBH dynamics.

3.1 Massive, $L_\star$ galaxies

In Fig. 1, we show the DM density profiles of the two most massive, Milky Way-sized haloes within the simulated volume. The SIDM results are shown in blue and CDM ones in red. In both cosmologies, the most massive galaxy (left-hand panel) has a mass of $M_{\rm halo} \sim 10^{12.3}$ M$_\odot$ while the second most massive one (right-hand panel) has $M_{\rm halo} \sim 10^{11.8}$ M$_\odot$, both values being within current

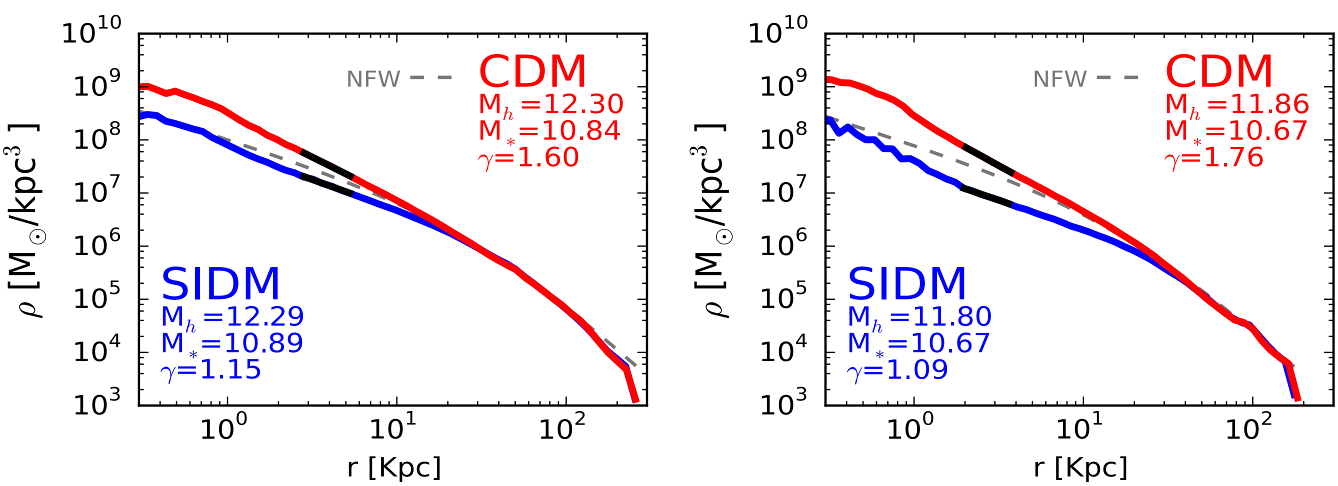

Figure 1 The DMhaloes density profiles for the two most massive, Milky Way-sized galaxies in our simulations. The SIDM results are plotted in blue and the CDM ones in red. The halo and stellar mass in the SIDM and CDM run are indicated, together with the DM inner slope γ computed between 1–2 per cent $R_{\rm vir}$. An unmodified NFW profile of similar halo mass is shown as dashed grey line in each panel. The effect of self-interactions is dominant over the one of adiabatic contraction even in such large, baryon-dominated galaxies, as it can be appreciated in the lower density of the SIDM haloes compared to the CDM ones.

constraints for the MW mass (e.g. Xue et al. 2008; Cautun et al. 2014). The halo and stellar mass are indicated for each galaxy, together with the DM logarithmic density slope γ measured at 1–2 per cent $R_{\rm vir}$. A reference NFW halo of the same mass is shown as dashed grey line.

The highest masses, Milky Way-like galaxies, form a shallower DM density profile in SIDM than they do in CDM. The shallower density profile of DM in the SIDM galaxies can be entirely attributed to the effect of self-interactions that, by transferring heat from the outskirts towards inside, are able to generate a lower density already at scales of 20–30 kpc. We stress here that we do not find a DM core with zero slope out to 20–30 kpc, but rather observe a decreasing of the DM density out to this radius. The density profile of the two most massive CDM galaxies, instead, is contracted with respect to expectations from a CDM-only NFW halo, with a logarithmic inner slope measured at 1–2 per cent $R_{\rm vir}$ of γ = 1.6–1.8: in absence of self-interactions, the contribution of adiabatic contraction is thus dominant in the CDM run.

Our study shows that self-interactions dominate over adiabatic contraction in massive galaxies. Using equation (2) and for a cross-section of σ = 10 cm^{2}gr^{-1}, the self-interactions are expected to modify and lower the DM density profile of MW objects already at radii ~30 kpc. In the hydrodynamical SIDM run, we observe indeed a lowering of the SIDM profile at a similar radius as we would expect in the SIDM-only case, rather than at a much smaller radii as suggested by Kaplinghat et al. (2014) and Elbert et al. (2016). Kaplinghat et al. (2014) predicted that the DM core sizes in baryon dominated galaxies will be negligible, with the core size of MW galaxies expected to be more than an order of magnitude smaller than the core size from SIDM-only simulations, for a cross-section of $\sigma = 0.56$ cm^{2}gr^{-1}. Similarly, a recent study by Elbert et al. (2016) indicated that when the stellar gravitational potential dominates the centre of galaxies, SIDM haloes can be as dense as CDM ones. Our results differ from the results of Kaplinghat et al. (2014) and Elbert et al. (2016) for two reasons: on one side, they used a much smaller cross-section than we do ($\sigma = 0.56$ cm^{2}gr^{-1}), and on another side, their work relied on analytic equilibrium models and idealized simulations, respectively, rather than on detailed hydrodynamical cosmological simulations able to capture the complexity of galaxy formation, as in our case.

In Elbert et al. (2016), the authors used *N*-body simulations and analytic galaxy potentials designed to grow linearly in time, with different scalelengths, in order to explore the halo back-reaction to the growth of DM and disc component, while the Kaplinghat et al. (2014) model is devoted to treat contraction in SIDM haloes due to baryonic potential in an analytic manner. The main problem with these approaches is that they ignore the effect of feedback on the DM haloes, which is very relevant especially when combined with the one of self-interactions: while it is true that stellar feedback alone has not been found to affect the final DM distribution in massive, MW-like galaxies (see Di Cintio et al. 2014a and references therein), no simulations has explored so far the effect of stellar and BH feedback acting on initially different DM profiles, such as the SIDM one studied in this work. Feedback can affect the central distribution of galaxies by powering massive outflows of gas in the interstellar medium on time-scale comparable to the crossing time of DM particles, which creates a way for transferring energy from gas to DM. In particular, the effects of BH and stellar feedback may be different when the underlying density and gravitational potential are lower than the reference CDM scenario, as in the case of self-interacting galaxies. There are indeed evidences that, in the presence of self-interactions, outflows have the ability to extend

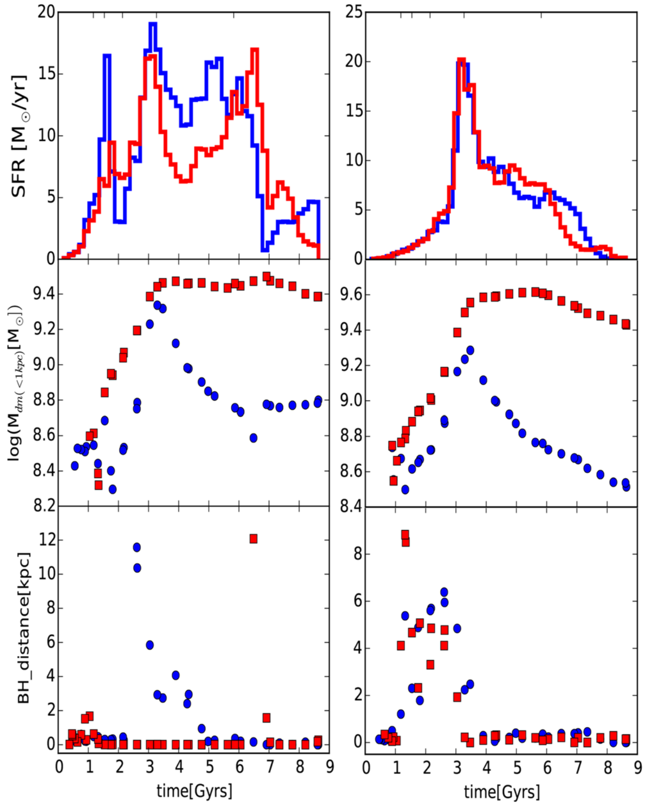

Figure 2. From top to bottom: SFHs, evolution of central DM mass and evolution of SMBH distance from the galaxy centre, for the same galaxies shown in Fig. 1. The SIDM results are indicated as blue lines and circles, while the CDM ones as red lines and squares. Only the most massive SMBH within each galaxy is followed back in time. See the text for details.

further out in the galaxy, and therefore to have a stronger impact on the DM distribution (Vogelsberger et al. 2014). Given the non-adiabatic nature of such processes, it is important to study them with hydrodynamical simulations.

Further, we verified in our runs that the baryonic potential dominates the centre of the massive galaxies shown in Fig. 1 and yet the SIDM halo shows a lower DM density than the CDM case. Specifically, we found the same amount of baryonic mass (~2.2–2.5 × 10^{10} M$_\odot$) within the inner 1 kpc of the SIDM and CDM galaxies, but a much lower content in DM in the SIDM case. The baryonic disc dominates the matter content out to radii as large as 8–9 kpc for the CDM case, and even larger for the SIDM galaxies, given the reduced contribution from the DM component. This means that even when the central potential of massive galaxies is dominated by baryons, in a similar way in the CDM and SIDM galaxies, their final DM density profile does not necessarily follow such potential and it can be strongly modified by the combined effect of self-interactions, stellar and BH feedback, highlighting the importance of simulating galaxies with full hydrodynamics.

In Fig. 2, we show, from top to bottom, the SFHs, temporal evolution of DM mass within 1 kpc and time evolution of the distance of the most massive SMBH from the galactic centre, for the two Milky Way-sized haloes of Fig. 1. The SIDM results are shown in blue and circled points, while CDM ones are shown in red and squares symbols. As shown already in Tremmel et al. (2016), their fig. 9, the role of SMBH is fundamental in order to achieve a decreasing SFH with redshift as expected in spirals of this mass (Papovich et al. 2015): with feedback from stars alone, and without the contribution of SMBHs at heating the surrounding gas, such galaxies would fail at turning off their SF at late times. With the inclusion of the SMBH accretion and feedback, instead, the most massive galaxies are able to attain both a realistic stellar mass and have SF quenched before $z = 0.5$. We notice that the SMBH feedback efficiently suppresses SF over time in a similar fashion within the two cosmologies, SIDM and CDM: the SMBHs in these galaxies have indeed similar high masses, $M_{\rm SMBH} > 10^{7.7}$ M$_\odot$.

In the central panels of Fig. 2, we show the evolution of the DM mass within 1 kpc of the galaxy centre as a function of time. The relative contribution of adiabatic contraction and self-interactions is visible here. In the first 3 Gyr of the galaxy life, during the rapid halo growth phase, the central DM mass increases both in the CDM and SIDM run: this phase also coincides with the first peak of SF. Soon after the initial SF episode ends, the CDM galaxy will keep forming stars and maintaining a similar DM mass within its central region, all the way until $z = 0.5$. On the contrary, the SIDM galaxy will undergo through a radical decrease in central DM mass, as a response to the effect of self-interactions. By $z = 0.5$, the most massive galaxies will only keep about 30 per cent (left-hand panel) and 20 per cent (right-hand panel) of the peak inner DM mass they had at 3 Gyr. This corroborates the finding that the DM halo of large spiral galaxies does not follow the baryonic potential, but it is rather influenced by self-interactions for a cross-section of $\sigma = 10$ cm^{2}gr^{-1}, combined with the effect of stellar and BH feedback. Given the complexity of the physics involved, this knowledge could be only achieved by performing accurate hydrodynamical simulations.

Finally, in the bottom panels, we show the evolution of the distance of the most massive SMBH from the centre of its host galaxy, by selecting the most massive SMBH within each galaxy at $z =$ 0.5 and following it backwards in time. Indeed, thanks to the novel implementation of Tremmel et al. (2015), we are able to accurately follow the orbit of SMBHs through the lifetime of the galaxy and evaluate the effects of dynamical friction on the SMBH decay time. For the most massive galaxy, left-hand panel, we observe that in the CDM run the galaxy undergoes a merger at $t = 6.5$ Gyr that carries in the most massive SMBH. This object quickly merges with the previously existing SMBH, in a time-scale of less than 0.5 Gyr. In the SIDM run, instead, the merger that carries in the most massive SMBH happens at $t = 2.5$ Gyr, and it takes 2.5 Gyr more before the SMBH can actually sink to the centre of the galaxy. For the second most massive galaxy, the SMBH goes to the centre of the host by $t = 3$–4 Gyr, although with a longer time-scale in SIDM than CDM. For such massive spirals, in both cosmologies the most massive SMBH has reached the centre of its host galaxy.

3.2 Intermediate-mass galaxies

We proceed at analysing the effect of self-interactions on the haloes of two medium-mass galaxies with $M_{\rm halo}$~$10^{10.5-10.9}$ M$_\odot$, representative of galaxies in this mass range. The resulting DM profiles are shown in Fig. 3, in blue for the SIDM case and red for the CDM one. We further show an unmodified NFW profile of same halo mass as a dashed grey line. The halo of such medium mass galaxies shows a clear DM core with core radius of 2–5 per cent $R_{\rm vir}$ in the SIDM case, attributable to the effect of self-interactions. In the CDM run, instead, the galaxy retains the original cuspy NFW profile, with no further adiabatic contraction at work. As expected, the effect of adiabatic contraction at these masses is minimal, and therefore, the core formation due to self-interactions is the only relevant process that modifies DM haloes in SIDM galaxies. In Fig. 4, we show, from top to bottom, the SFHs, temporal evolution of DM mass within 1 kpc and time evolution of the distance of the most massive SMBH from the galactic centre, for the same two galaxies of Fig. 3. The SIDM results are shown in blue and circled points, while CDM ones are shown in red and squares. The SFHs of the two galaxies are quite similar in the two runs, with slightly more stars formed in the SIDM case for the most massive galaxy. The inner DM mass constantly decreases through the lifetime of the SIDM galaxies, without following the stellar potential, while it is constant in the CDM galaxies.

An interesting finding concerns the location of SMBHs within these galaxies. As seen in the bottom panels of Fig. 4, the SMBH never sinks to the centre of its host galaxy in the SIDM case, while it is found within a distance smaller than 0.1 kpc in most of the time-snapshots in CDM. The most massive SMBHs within the galaxies in the left-hand panel have a mass of $M_{\rm SMBH} = 10^{6.7}$ and $10^{6.8}$ M$_\odot$ in the CDM and SIDM case, respectively, and they are found at 0.13 and 2.12 kpc from the centre of their host galaxy. Similarly, the most massive SMBHs within the right-hand panel galaxy have $M_{\rm SMBH} = 10^{6.3}$ and $10^{6.6}$ M$_\odot$ and lie at 0.09 and 0.9 kpc from the galaxy centre, in CDM and SIDM, respectively.

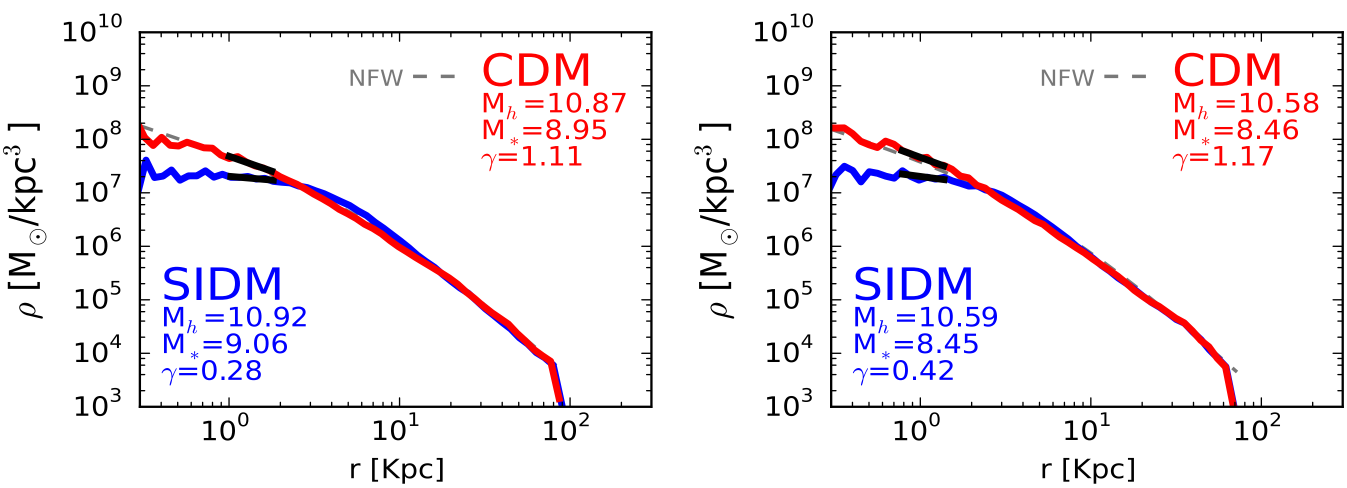

Figure 3. The DM density profiles for two representative medium-mass galaxies within the simulated SIDM and CDM volumes. The SIDM results are indicated as blue lines, CDM ones as red lines and an unmodified NFW halo of similar mass as dashed grey line. The effect of self-interaction is evident in the large DM core formed within the SIDM galaxies, as opposed to the CDM ones that retain an initial NFW profile.

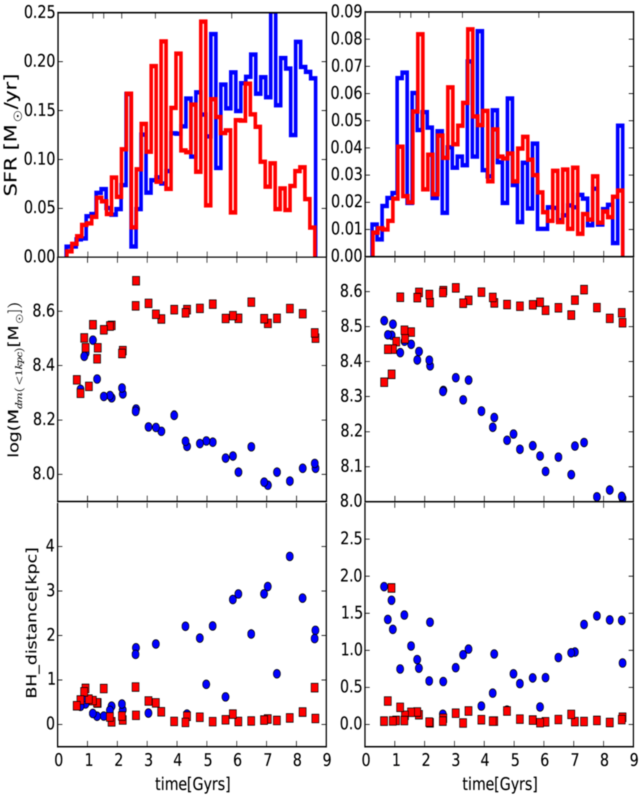

Figure 4. From top to bottom: SFHs, evolution of central DM mass and evolution of SMBH distance from the galaxy centre, for the same two medium mass galaxies shown in Fig. 3. Only the most massive SMBH within each galaxy is followed back in time. The SIDM results are indicated as blue lines and circles, CDM ones as red lines and squares. See the text for details.

The fact that the SMBHs cannot reach the centre of their galaxy in the SIDM case is explained by the lower dynamical friction force that they feel: in the presence of a core, such as the one caused by self-interactions on the DM distribution, the sinking object goes through a 'stalling' phase in which essentially no dynamical friction is experienced. Such behaviour was first reported and analysed by Read et al. (2006) using analytic methods and *N*-body simulations, and we confirm here its validity using hydrodynamical simulations. In the presence of a cored central distribution of mass, such as the one found in SIDM galaxies, we expect SMBHs not to be found at the centre of their host galaxies. Of course, the time-scale over which each SMBH sinks depends further on its mass: this is why, in the case of the massive SMBHs belonging to MW-like galaxies of Fig. 1, we found them at the centre of their hosts both in SIDM and CDM. Moreover, in the most massive galaxies, the inner slope of DM never approaches the zero value, which is the key for having a 'stalling' behaviour.

The 'stalling' of SMBHs in SIDM is clearly visible in both bottom panels of Fig. 4. Intriguingly, in the left-hand panel, we can observe the SIDM SMBH orbit oscillating, and surprisingly drifting away from the galaxy centre as we move towards low redshifts. This rather unexpected behaviour seems to correlate with the SFH of the galaxy. A possible explanation is that the SN-driven gas outflows, launched during the SF episodes, have a different impact on the SIDM galaxy, whose gravitational potential in the inner region has been modified by the self-interacting particles. If this is the case, we should observe a correlation between gas outflows and SMBHs orbits. As a proxy for gas outflows, we verified that the gas mass that gets ejected from the inner 1 kpc of the galaxy centre throughout its lifetime correlates with the SMBHs orbits, such that the SMBHs drift away just after an outflow has occurred. The different extension and impact of SN-driven outflows in the SIDM simulations was also argued in Vogelsberger et al. (2014), simulating dwarfs of $M_{\rm halo}{\sim}10^{10}$ M$_\odot$.

While this finding deserves further investigation, and needs to be verified by means of higher resolution simulations, the picture that emerges is the following: strong outflows of gas are more efficient in the presence of an initial core – like the one formed in SIDM galaxies – and are able to influence further the DM, stellar and SMBH distribution in SIDM galaxies. The SMBH responds to rapid variation in the potential in the same way as DM and stars, by moving and drifting outwards. In the CDM case, instead, the impact of outflows on an initially NFW halo is minimal given the low SF density threshold implemented, such that the small variations in central potential are never able to create a DM core nor to influence the dynamics of SMBHs: subsequent outflows are simply not able to modify neither the DM, nor the stellar distribution, nor the SMBH position.

3.3 Black holes global properties

The properties of the SMBHs population in SIDM and CDM runs are explored in this section. We identified the most massive SMBH associated with each central galaxy in our sample, at the latest simulated redshift $z = 0.5$. Galaxies less massive than $M^{\star}{\sim}10^{7.5}$ M$_\odot$ in SIDM and $M^{\star}{\sim}10^{7.0}$ M$_\odot$ in CDM do not possess any SMBH. We have excluded galaxies with ongoing mergers that are carrying in the main SMBH of a halo, since this would misleadingly provide a large distance of the SMBH from the centre of the galaxy within which it is just falling in. This criterion eliminates two SMBHs in the CDM run and two in the SIDM one. We have instead left in our sample galaxies with recent mergers if their most massive SMBH belongs to the same galaxy before and after the merger itself.

We identified a total of 33 SMBHs in SIDM and 41 in CDM, each of them associated with an individual galaxy in the corresponding simulation. In Fig. 5, we show, from left to right, the SMBH mass-galaxy stellar mass relation (circles for SIDM and squares for CDM) and normalized histograms of luminosities, with corresponding probability density functions (PDFs), for the full SMBH population in SIDM (blue) and CDM (red) runs. Luminosities are computed starting from accretion rates averaged over few Myrs, and taking into account that radiative efficiency is assumed to be 0.1. In the left-hand panel of Fig. 5, same colours refers to the same galaxy within the two runs, and overimposed as a black line is the $M_{\rm SMBH}$–$M^{\star}$ relation of active galactic nuclei obtained with the *Chandra* deep field survey (Schramm & Silverman 2013).

The SMBH physics prescriptions adopted in this work, following Tremmel et al. (2015, 2016), are able to reproduce a realistic relation between the SMBH mass and their host galaxy stellar mass in both SIDM and CDM cosmologies (Häring & Rix 2004; Schramm & Silverman 2013). At low SMBH masses, towards the lower end of the mass function ($M_{\rm SMBH}$ ∼ 10^6 M$_\odot$), the scatter in the relation increases as noticed already in Tremmel et al. (2016). At a fixed stellar mass, several SMBHs in the CDM run tend to be more massive than the SIDM ones, reflecting the fact that SMBHs in a dense CDM halo can grow more than their SIDM counterpart. The two most massive galaxies instead host SMBHs with a similarly high mass of $M_{\rm SMBH} > 10^{7.5}$ M$_\odot$. The overall distribution of SMBH luminosities in the right-hand panel of Fig. 5 shows that the peak of luminosity of CDM-SMBHs happens at higher

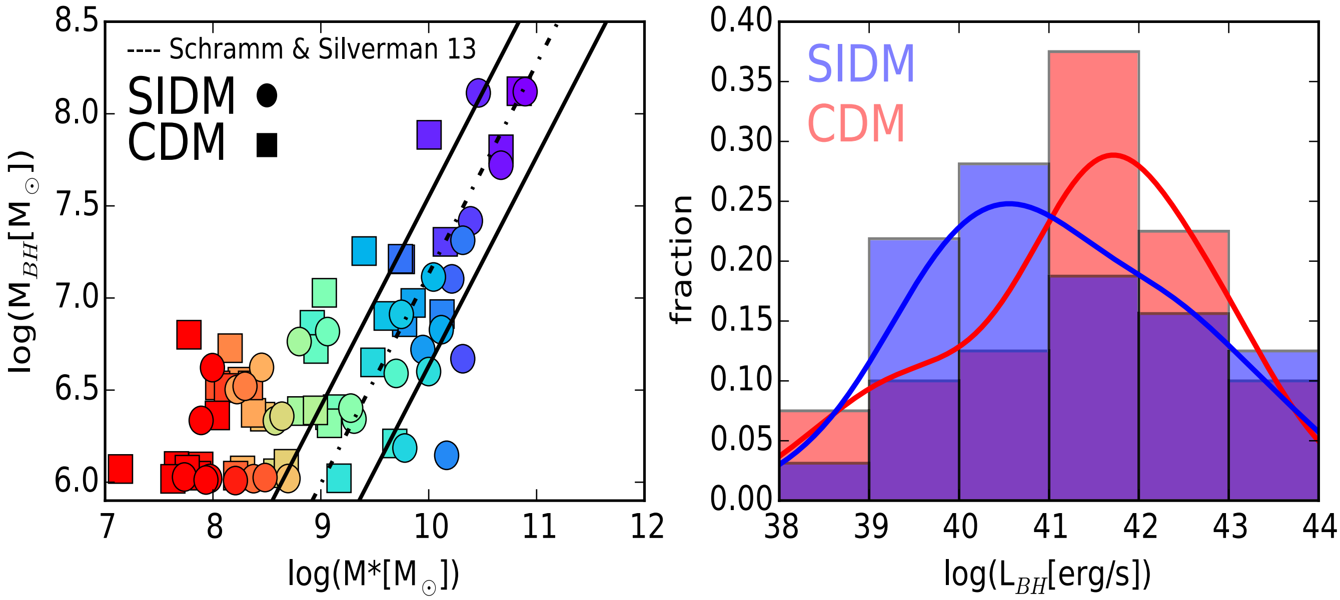

Figure 5. Global properties of the SMBHs population in SIDM and CDM galaxies. Only the most massive SMBH in each galaxy is shown. Left-hand panel: SMBH mass-host stellar mass relation, SMBHs in SIDM galaxies are indicated as circles and corresponding CDM ones as squares. Same colours refer to the same galaxy in the two runs. Right-hand panel: normalized histograms and PDFs of the SMBH luminosities, the SIDM results are shown in blue, CDM ones in red.

luminosities than the corresponding SIDM case: from the PDFs, we estimated a peak at $L_{\rm SMBH} = 10^{41.7}$ erg s^{-1} in the CDM case, and at $L_{\rm SMBH} = 10^{40.5}$ erg s^{-1} in the SIDM case. While, of course, caution should be exercised due to the low number statistic, the reason for this has to be searched in the SMBHs evolution and accretion: SMBHs forming within galaxies with a shallow central profile, like the ones of the SIDM haloes, will accrete less mass and therefore have a lower luminosity than the corresponding CDM case, in which SMBHs accrete in a denser environment with higher average gas supply that can reach into the SMBH.

3.4 Black holes dynamics

Most interestingly, we found that the dynamics of SMBHs is different in the two cosmologies and that, in the SIDM case, it has been affected by the modification to the halo structure due to self-interactions between DM particles. In Fig. 6, we plot the distance of SMBHs from host centre versus host stellar mass, with SIDM results indicated as circles (left-hand panel) and CDM ones as squares (right-hand panel). As in the previous section, only the most massive SMBH within each galaxy is shown, and same colours refer to the same galaxy in the two cosmologies.

It appears that several SMBHs in SIDM galaxies have not yet reached the galaxy centre, being found as far as ∼9 kpc from it, while the vast majority of SMBHs in CDM lie within 1 kpc from the centre of the host galaxy. We observe a striking difference in the behaviour of SMBHs in SIDM and CDM, already anticipated in Section 3.2: SMBHs in the SIDM run are on average further away from the galaxy centre than their CDM counterparts. Only 4 outlier SMBHs lie at or above 1 kpc from the host's centre in CDM galaxies, while in the case of SIDM we found as many as 13 SMBHs above such a distance. In the SIDM case, SMBHs are found as far as ∼9 kpc from the host centre. More specifically, 88 per cent of all the SMBHs identified in the CDM simulation have sunk to the centre of their host galaxy and lie within 350 pc (corresponding to the resolution limit of our simulation, ϵ) from it by $z = 0.5$, while only about 20 per cent of the SMBHs in the SIDM run lie within the same distance from their host galaxy. All the SMBHs that lie within ϵ from the centre of SIDM galaxies are found in galaxies more massive than $M^{\star} = 10^{10}$ M$_{\odot}$, indicating that the mechanism responsible for keeping SMBHs away from the centre is more dramatic in lower mass galaxies. Recall that our SMBH model is able to effectively take into account the dynamical friction forces acting on the SMBHs, which are therefore *not* forced at the centre of the galaxy as in previous prescriptions (Di Matteo et al. 2005; Sijacki et al. 2007), but they are rather allowed to orbit and sink at the centre of their hosts over realistic time-scales.

We can therefore understand the trends shown in Fig. 6 in terms of dynamical friction time-scales (Chandrasekhar 1943; Read et al. 2006; Binney & Tremaine 2008). Because the time-scale is inversely proportional to the density of the surrounding medium, SMBHs sinking within lower density SIDM haloes have not yet reached the centre of their host, and are 'stalling' within the core of SIDM galaxies, in agreement with the analytic model presented in Read et al. (2006) and Petts, Read & Gualandris (2016). The 'stalling' is due to the failing of the Chandrasekar formula in the presence of a central density core, and reflects the situation in which SMBHs effectively do not feel any dynamical friction. In comparison, a much more centrally concentrated CDM halo will have a short enough dynamical friction time-scale for the SMBHs to have sunk all the way to its centre. Moreover, as already investigated in Section 3.2, the increased efficiency of gas outflows in the presence of an underlying cored distribution further contributes to keep the SMBH away from the galactic centre during vigorous SF episodes. Both effects are clearly shown in Fig. 4, by comparing an SIDM and CDM halo of similar masses. The SMBHs found within the highest stellar mass galaxies ($M^{\star} > 10^{10.5}$ M$_{\odot}$) have instead reached the centre of their hosts in both SIDM and CDM, as shown explicitly in Fig. 2: this is because despite of the lower central density of such galaxies in the SIDM run, their associated SMBHs are massive enough to dominate the dynamical friction time-scale, allowing to sink all the way to the host's centre. The dramatic effect of longer dynamical friction

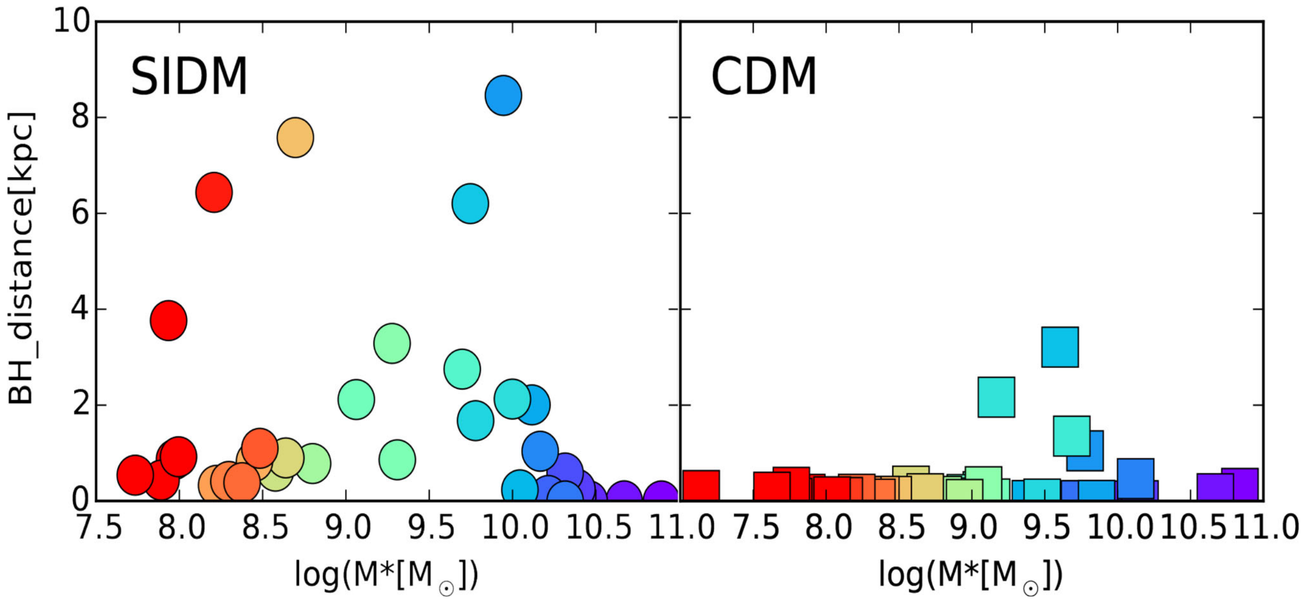

Figure 6. The SMBH distance from the centre of its host galaxy as a function of host stellar mass, in SIDM (left-hand panel, circles) and CDM (right-hand panel, squares), respectively. Same colours refer to the same galaxy in the two runs. Only the most massive SMBH within each galaxy is shown.

time-scales observed in SMBHs within the SIDM simulations, combined with the increased impact of gas outflows on the central potential of the SIDM galaxies, implies that the majority of galaxies with masses below $M^{\star}{\sim}10^{10.5}$ M$_\odot$ are expected to have an SMBH offset from their centre in an SIDM universe.

4 CONCLUSIONS

We investigated the properties of galaxies in hydrodynamical cosmological simulations, run in a 8-Mpc box down to redshift $z = 0.5$, within a CDM as well as an SIDM scenario using same initial conditions. The implementation of SIDM follows the already published work of Fry et al. (2015). We used a constant cross-section of $\sigma = 10$ cm^{2}gr^{-1}, which is close to the upper limit for Milky Way-like galaxies (Kaplinghat et al. 2016), to maximize the effect of self-interactions on the DM profiles. The simulations, run with the *N*-body + SPH code ChaNGA (Menon et al. 2015), include SF, UV background, blast wave feedback from SN, thermal diffusion (Wadsley et al. 2004, 2008; Stinson et al. 2006; Shen et al. 2010) as well as an improved prescription for the SMBH physics as in Tremmel et al. (2015). SMBHs form from dense, low-metallicity gas at early times, accrete gas according to a modified Bondi–Hoyle formula that accounts for the rotational support of gas, and feel a realistic dynamical evolution through dynamical friction prescription (Tremmel et al. 2015, 2016), allowing SMBHs to experience realistic perturbations and sinking time-scales during satellite accretion and galaxy merger events. The prescription for the SMBH growth and feedback has been calibrated, along with SF and feedback processes, to produce galaxies with realistic stellar and SMBH masses (Tremmel et al. 2016). The SF threshold of $0.2\mathrm{m_p/cm^3}$ used in both cosmologies is too low to lead to the creation of central DM cores via outflows (Pontzen & Governato 2012). In contrast, with such a high cross-section σ, DM cores are expected to form in pure SIDM haloes even at the lowest masses considered here, $M_{\rm halo} \sim 10^{10}$ M$_\odot$ (see Rocha et al. 2013 and Fry et al. 2015 for similar discussion). The main results of this work can be summarized as follows:

Density profiles and SFHs:

(i) Massive galaxies, $M_{\rm halo} \sim 10^{12}$ M$_\odot$, show a less dense DM profile in the SIDM case compared to the CDM one, with the SIDM halo density falling below the CDM one already at radii of 20 kpc, being the effect of self-interactions dominant over the adiabatic contraction. This is despite the similarly dominating baryonic potential at the centre of such massive galaxies in both cosmologies. Feedback from the central SMBH is efficient at regulating SF in both the SIDM and CDM runs (Tremmel et al. 2015), and the most massive galaxies show a similarly declining SFH, reminiscent of the one observed in massive spirals.

(ii) Medium mass galaxies, $10^{10} < M_{\rm halo}/$ M$_\odot$ $< 10^{11}$, show a well-defined DM core in the SIDM run, while a usual NFW halo in the CDM one. The effects of both SMBH feedback and adiabatic contraction are not dominant at these scales, and the only modification to the DM profile is due to self-interactions (see also Vogelsberger et al. 2012; Zavala et al. 2013; Fry et al. 2015).

Black hole dynamics:

(i) The CDM run produces more high-luminosity SMBHs with respect to the SIDM case (~70 per cent of CDM SMBHs have $L_{\rm SMBH} > 10^{41}$ erg s^{-1}, while only 45 per cent of the SIDM ones are found above this value), a consequence of the higher accretion rate due to the denser local environment around the SMBHs.

(ii) The dynamics of SMBHs changes in the two runs. In the SIDM case, due to the longer dynamical friction time-scales (Chandrasekhar 1943; Taffoni et al. 2003) caused by the lower density in the central regions of the DM haloes, the SMBHs experience the phenomenon of *core stalling*, in agreement with analytic predictions from Read et al. (2006), and never reach the host galaxy centre. SMBHs are found at a distance of up to 9 kpc from the galaxy centre in SIDM. Only about 20 per cent of the most massive SMBHs associated with the SIDM galaxies have reached a distance from the centre smaller than our resolution limit, 350 pc, while as many as ∼90 per cent of the SMBHs in CDM are found well within this value.

In an SIDM cosmology with a large constant cross-section of $\sigma = 10\ \mathrm{cm^2 gr^{-1}}$, about 83 per cent of the galaxies with masses lower than $M^{\star} \sim 10^{10.5}\ \mathrm{M_{\odot}}$ should have an SMBH offset from their centre due to the effect of longer dynamical friction time-scales caused by shallow density cores. This prediction could lead to a series of potentially observable quantities, such as anomalies in the stellar velocity dispersion at the SMBH location, and further activities connected to gas accretion, such as off-centre bright nuclei and off-centre X and radio sources.

Our study highlights the critical importance of properly modelling baryonic physics processes and SMBH dynamics within different underlying DM models. We plan to extend this work to higher resolution simulations in which baryonic-driven core formation will play a role as well. This will help verifying whether the offset of SMBHs occurs even in galaxies whose cores are generated by stellar feedback, rather than by self-interactions.

ACKNOWLEDGEMENTS

All simulation analysis made use of the *pynbody* (Pontzen et al. 2013) and TANGOS (Pontzen et al., in preparation) suites. ADC is supported by the DARK-Carlsberg and the Karl Schwarzschild independent fellowship programmes. ADC thanks the Mainz Institute for Theoretical Physics (MITP) for its hospitality. MT was partially supported by NSF award AST-1514868. FG acknowledges support from NSF grant AST-0607819 and NASA ATP NNX08AG84G. AMB acknowledges support from NSF grant AST-1411399. MV acknowledges support through an MIT RSC award and the support of the Alfred P. Sloan Foundation.

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