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Effects of coupled dark energy on the Milky Way and its satellites

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ABSTRACT
We present the first numerical simulations in coupled dark energy cosmologies with high enough resolution to investigate the effects of the coupling on galactic and subgalactic scales. We choose two constant couplings and a time-varying coupling function and we run simulations of three Milky Way-sized haloes (∼10^{12} M⊙), a lower mass halo (6 × 10^{11} M⊙) and a dwarf galaxy halo (5 × 10^{10} M⊙). We resolve each halo with several million dark matter particles. On all scales, the coupling causes lower halo concentrations and a reduced number of substructures with respect to Λ cold dark matter (ΛCDM). We show that the reduced concentrations are not due to different formation times. We ascribe them to the extra terms that appear in the equations describing the gravitational dynamics. On the scale of the Milky Way satellites, we show that the lower concentrations can help in reconciling observed and simulated rotation curves, but the coupling values necessary to have a significant difference from ΛCDM are outside the current observational constraints. On the other hand, if other modifications to the standard model allowing a higher coupling (e.g. massive neutrinos) are considered, coupled dark energy can become an interesting scenario to alleviate the small-scale issues of the ΛCDM model.

Key words: methods; numerical – galaxies: evolution – galaxies: formation – galaxies: haloes – dark energy – dark matter.

1 INTRODUCTION
Since the discovery of the accelerated expansion of the universe (Riess et al. 1998; Perlmutter et al. 1999), a cosmological constant Λ has been the most widely accepted explanation for the required negative pressure. Together with cold dark matter, today the dark sector is accounting for about 95 per cent of the total energy density (Planck Collaboration XIII 2015) and builds the foundations for the so-called Λ cold dark matter (ΛCDM) model.

Despite the highly successful inflationary ΛCDM paradigm, the fundamental problems associated with the introduction of a cosmological constant, namely fine-tuning and coincidence problems (Weinberg 1989), have served as motivations for alternative descriptions of the dark sector. Introducing a time evolving scalar field (dark energy) responsible for the negative pressure is the approach of quintessence models (Peebles & Ratra 1988; Wetterich 1988) and has been one of the most popular generalizations for the cosmological constant in the last decade. Furthermore, given the currently still unknown nature of the dark sector, the possibility of a non-null coupling between dark matter and dark energy has been considered (Wetterich 1995; Anderson & Carroll 1998; Amendola 2000; Billiard & Coley 2000; Amendola & Tocchini-Valentini 2001; Zimdahl, Pavón & Chimento 2001; Farrar & Peebles 2004; Gromov, Baryshev & Teerikorpi 2004). Given that in these models dark matter and dark energy density evolutions are strongly coupled, this would in turn alleviate the coincidence problem (Mangano, Miele & Pettorino 2003; Matarrese, Pietroni & Schimd 2003). The effects of such interaction might be seen on the cosmic microwave background (CMB), on supernovae and on the growth of structures, as pointed out by Matarrese et al. (2003), Amendola (2004), Amendola, Gasperini & Piazza (2004), Koivisto (2005), Guo, Ohta & Tsujikawa (2007) and many others. Structure formation has also been investigated via numerical simulations

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by Macciò et al. (2004), Baldi et al. (2010), Li & Barrow (2011), Carlesi et al. (2014) and their follow up works, where the statistical distribution of structures has been studied. Both Baldi et al. (2010) and Carlesi et al. (2014) found that, when introducing a coupling between dark energy and dark matter, halo concentrations decrease.

In this work, we run the first high-resolution simulations on galactic scales in coupled dark energy cosmologies. Our aim is to obtain high enough resolutions to investigate the properties of the dark matter distribution at subgalactic scales, mass scales at which the effects of the coupling have not yet been studied. The subhaloes that we are interested in will in turn be the hosts of dwarf galaxies and their properties can be compared with observations of satellite dwarf galaxies of both Milky Way and Andromeda. In fact, despite ΛCDM predictions on large scales being in very good agreement with galaxy clustering surveys (Jones et al. 2009; Alam et al. 2015), on galactic scales challenges between ΛCDM predictions and observations have appeared.

First, the missing satellites problem, i.e. overabundance of substructures in ΛCDM Milky Way-sized halo simulations when compared to observations of the Milky Way dwarf galaxies (Klypin et al. 1999; Moore et al. 1999). On the other hand, as showed in Madau, Diemand & Kuhlen (2008) and Macciò et al. (2010), accounting for the baryonic physics drastically reduces the number of visible satellites. Secondly, the core/cusp problem, namely the inconsistency between the constant density cores estimated from observations and the cuspy inner density profiles found in ΛCDM simulations. See Flores & Primack (1994), Moore (1994), Diemand et al. (2005), Gentile et al. (2009), Walker & Peña-Garrido (2011), Agnello & Evans (2012) and Salucci et al. (2012), but also van den Bosch & Swaters (2001), Swaters et al. (2003) and Simon et al. (2005). While this inconsistency can be attributed to baryonic feedback processes (e.g. Governato et al. 2012; Di Cintio et al. 2014; Oñorbe et al. 2015), for the case of Milky Way satellites the baryonic explanation is not straightforward since these objects can be almost completely dark matter dominated. Baldi et al. (2010) and Carlesi et al. (2014) showed that for haloes with $M \gtrsim 10^{13} \, M_\odot$, the coupling between dark matter and dark energy produces density profiles that are less cuspy in the inner density regions, which can help alleviating the core/cusp problem. The aim of this work is to investigate whether this effect persists at much lower masses. Moreover, concentrations of the most massive subhaloes orbiting around a ΛCDM Milky Way-sized halo seem to be too high to be hosting the brightest dwarf galaxies observed. This translates into a prediction from ΛCDM numerical simulations for the existence of massive dark matter subhaloes that seem to have failed at forming stars, and is known as the too big to fail problem (Boylan-Kolchin, Bullock & Kaplinghat 2011; Lovell et al. 2012; Rashkov et al. 2012; Tollerud et al. 2012).

Whether these issues bring serious challenges for the ΛCDM model or whether they can entirely be treated by invoking baryonic physics is currently under debate. With this work, we aim at studying the properties of haloes and their substructures to determine whether coupled dark energy cosmologies can alleviate the aforementioned issues. In Section 2, we summarize the theoretical model behind coupled dark energy and we specify our choices of coupling functions. In Section 3, we described the numerical methods used to produce initial conditions and the N-body codes to run the simulations. In Section 4 we show our simulations results, for both haloes and subhaloes. Finally, in Section 5 we present our conclusions.

2 COSMOLOGICAL MODELS

We present a study focused on understanding the non-linear effects of coupled dark energy models on galactic scales. The models that we consider allow for an interaction between dark matter and dark energy (Amendola 2000; Billyard & Coley 2000; Zimdahl et al. 2001; Gromov et al. 2004; Macciò et al. 2004; Baldi et al. 2010) and obey the following lagrangian density:

$$L = R - \frac{1}{2} \partial^{\mu} \partial_{\nu} \phi - V(\phi) - m(\phi) \psi \psi + \mathcal{L}_{\text{kin}}[\psi],$$

where $\mathcal{L}_{\text{kin}}[\psi]$ term includes the kinetic part of the dark matter lagrangian density, and we use units in which the reduced Planck mass is assumed to be unity, $M_\text{pl} \equiv 1/\sqrt{8\pi G} = 1$. The choice of $m(\phi)$ specifies the coupling and in our work we use $m(\phi) = m_0 e^{-\beta \phi}$,

$$\frac{\rho_0 + 3H \rho_c}{\rho_0} = -\beta(\phi) \psi \psi,$$

where $\rho_0$ is the cold dark matter density and $\rho_c$ is the dark energy density, which is $\rho_c \equiv \frac{1}{8\pi G} V(\phi)$. $H \equiv \dot{a}/a$ is the Hubble parameter and dots indicate time derivatives. Our choice for the self-interacting dark energy potential is $V(\phi) \propto e^{-\alpha \phi}$, with $\alpha = 0.08$.

The evolution of cold dark matter density perturbations $\delta_c$ is regulated by the following equation:

$$\delta_c + (2H - \beta \phi) \delta_c - \frac{3}{2} H^2 \left[ (1 + 2\beta^2) \Omega_\phi \delta_c + \Omega_\Omega \delta_\Omega \right] = 0,$$

where $\delta_c$ are the baryonic matter density perturbations, $\Omega_\phi$ and $\Omega_\Omega$ are, respectively, the density parameters $\Omega_\phi \equiv \rho_\phi/\rho_{\text{crit}}$ for cold dark matter and baryons, with critical density $\rho_{\text{crit}} = 3H^2/8\pi G$ and $G$ Newton’s constant. Two extra terms appear in equation (4) compared to the ΛCDM case: a friction term $-\beta \delta_c$, and the factor $(1 + 2\beta^2)$ responsible for the enhancement of the gravitational force acting on cold dark matter particles, which is known as ‘fifth force’. As pointed out in Baldi (2011b), in the linear regime both these extra terms produce an acceleration of growth of cold dark matter density perturbations. On the other hand, when considering the non-linear effects, the friction term is responsible for lowering the concentration of dark matter haloes.

The appearance of extra terms becomes clear when calculating the acceleration felt by the $i$th dark matter particle $\mathbf{v}_i$ in a coupled dark energy cosmology for the limit of a light scalar field (see Baldi et al. 2010 for calculation):

$$\ddot{\mathbf{v}} = \beta(\phi) \dot{\mathbf{v}} + G [1 + 2\beta(\phi)^2] \sum_{j \neq i} \frac{m_j |\mathbf{r}_{ij}|}{|\mathbf{r}_{ij}|^3},$$

where $\mathbf{v}_i$ is the velocity of the $i$th dark matter particle, $m_i$ is the mass of the $j$th particle and $r_{ij}$ is the distance between the $i$th and the $j$th dark matter particles. The term $\beta(\phi) \dot{\mathbf{v}}$ accelerates dark matter particles in the direction of their motion and thus lowers halo concentrations.

Based on Baldi et al. (2010); Baldi (2011b), we chose three coupling scenarios. EXP003 and EXP006 have a constant coupling with $\beta = 0.15$, 0.3, while EXP008c3 has a variable coupling $\beta(\phi)$ (see Table 1 for more details). The coupling values for EXP003 and...
EXP008e3 are within the CMB constraints found in Pettorino et al. (2012), while the coupling value for EXP006 represents an extreme case (about 6σ outside observational limits from Pettorino et al. 2012) which is used as a toy model to better investigate the effects of the coupling on non-linear structure formation.

3 NUMERICAL METHODS

3.1 Initial conditions and coupled dark energy

As in Penzo et al. (2014), we used GRAFIC-DE, an extension of the initial condition generator GRAFIC-2 (Bertschinger 2001) such that initial conditions for a generic cosmological model can be produced once the evolution of the cosmological parameters are given as an input. GRAFIC-DE requires transfer functions, evolution of the density parameters $\Omega_i$, linear growth factor $D_+$ and growth rate $f_2 = d\ln D_+ / d\ln a$. As the original code, GRAFIC-DE is able to generate multimass initial conditions from a cosmological box. In Fig. 1, we show the evolution of the linear growth factor $D_+$ for all four cosmological models. The transfer functions for $\Lambda$CDM have been produced using CAMB (Lewis & Bridle 2002), while the transfer functions for the coupled dark energy models $T_{\Lambda\text{DE}}$ have been produced by scaling the $\Lambda$CDM transfer functions $T_\Lambda$ with the $D_+$ of the coupled model, i.e. $T_{\Lambda\text{DE}} = T_\Lambda D_{\Lambda\text{DE}} / D_{\Lambda A}$. All initial conditions were created using the same random seeds, in order to be able to compare structures among the models. We chose to normalize all the cosmological models so that they share the same cosmological parameters at $z = 0$: $\Omega_m = 0.0458$, $\Omega_{DE} = 0.229$, $H_0 = 70.2$ km $s^{-1}$ Mpc$^{-1}$, $\sigma_8 = 0.816$, $n_s = 0.968$, where these parameters are density parameters for baryons and dark matter, Hubble constant, root mean square of the fluctuation amplitudes and primeval spectra index. The reason for this choice is that in this work we are not interested in the cosmological viability of these models per se, but rather on the effects at non-linear scales. With this choice of normalization, we are able to isolate the effects of the coupling on non-linear structure formation from the effects of different cosmological parameters at $z = 0$.

3.2 N-body simulations

We first generate two sets of uniform particle distributions, a 80 Mpc $h^{-1}$ box and a 12 Mpc $h^{-1}$ box, both with 350$^3$ particles.
The initial conditions were evolved with the code GADGET-2 (Springel 2005), which includes the coupled dark energy implementation introduced in Baldi et al. (2010).

We chose four dark matter haloes in the $\Lambda$CDM 80 Mpc $h^{-1}$ box and one dwarf halo in the $\Lambda$CDM 12 Mpc $h^{-1}$ box, and looked for their corresponding realizations in the coupled dark energy simulations. Note that we used the same random seed for all initial conditions to be able to follow the same haloes in all cosmological boxes. Our haloes have been chosen so that no other haloes with comparable masses were found within four times their virial radii. We then re-ran the cosmological boxes with increased resolution in a Lagrangian volume that includes all particles that at $z = 0$ were found in three times virial radii of each selected halo.

Our final sample is composed of three Milky Way-sized haloes (halo$\alpha$, halo$\beta$ and halo$\gamma$), a $6 \times 10^{11} \ M_\odot$ halo (halo$\delta$) and a dwarf halo (halo$\epsilon$). For more details on the haloes properties at $z = 0$, see Table 2. For the halo identification, we used the code Amiga Halo Finder (AHF; Knollmann & Knebe 2009). When using AHF we are not taking into account the change in the gravitational constant (which is instead included in the modified version of GADGET-2 that we used for all our simulations). We believe this does not significantly influence the halo identification process since the effect of the change in the...
gravitational constant is non-significant at non-linear scales; this is shown in the analysis carried out in Baldi (2011b).

The softening lengths are chosen to be 1/40 of the intraparticle distance in the low-resolution simulation divided by the refinement factor RF; RF = 15 for halo α, halo β and halo δ. Precisely, the softening lengths are 0.54 kpc for haloα and haloγ, 0.34 kpc for haloβ and haloδ, 0.081 kpc for halo ε. The particle masses at $z = 0$ in the high-resolution volumes are $3.8 \times 10^{10} \, M_\odot$ for halo α, $9.4 \times 10^{10} \, M_\odot$ for halo β and halo γ, and $1.3 \times 10^{10} \, M_\odot$ for halo δ. In Fig. 3, we show the projected density maps of the four most massive haloes for each cosmological model. We will discuss the dwarf halo in Section 4.3. For the density maps and throughout the paper, we chose to calculate halo properties using $R_{200}$, radius at which the density is 200 times the critical density.

4 RESULTS

Fig. 2 shows the ratio between the mass functions for the coupled dark energy cosmologies with the one for ΛCDM for redshifts $z = 2, 1, 0$ for our 80 Mpc $h^{-1}$ boxes. For all redshifts, significant differences on the mass functions are only present in EXP006 (red lines). The higher the coupling the lower the number of haloes at a given mass. This behaviour is what Baldi et al. (2010) found for higher halo masses. In their work, they have a box size of $320 h^{-1}$ Mpc which limits the study to haloes with masses $M \gtrsim 10^{13} \, M_\odot$. For this reason, in our work we focus on testing the effects of the coupling at lower halo masses. In Section 2, we briefly described the coupled dark energy cosmological model and the appearance of extra terms introduced by the coupling. Baldi (2011b) shows that the term affecting structure formation the most is the friction term of equation (5). By accelerating dark matter particles in the direction of their motion, the kinetic energy of the system will increase and the system itself will react by expanding. As a consequence, Baldi (2011b) shows that part of the mass is pushed at greater radii and the halo masses decrease. In the following sections, we will show how the effects of the extra terms is key to explain the differences from ΛCDM for both main haloes and their subhaloes for the case of Milky Way-sized haloes.

4.1 Host haloes properties

In the 80 Mpc $h^{-1}$ boxes at $z = 0$, we choose four haloes, halo α, halo β, halo γ and halo δ, and we resimulated them with much higher resolutions. We checked that all four haloes are relaxed using the criterion from Macciò, Dutton & van den Bosch (2008). In the following sections, we show their concentrations and density profiles, rotation curves, evolution of the scale radius and accretion histories.

4.1.1 Concentrations and density profiles

By introducing a coupling between dark matter and dark energy, halo concentrations decrease. This was shown in Baldi et al. (2010), Li & Barrow (2011), and Carlesi et al. (2014) for haloes with masses $M \gtrsim 10^{13} \, M_\odot$. In this work, we investigate mass scales $M \lesssim 10^{12} \, M_\odot$. Furthermore, the resolution that we are able to reach is higher thanks to the multimass technique. In Table 2, we show the concentration values for each halo, for which we use the definition

$$c \equiv R_{200}/r_s,$$

where $r_s$ is the scale radius in the Navarro–Frenk–White (NFW) profile (Navarro, Frenk & White 1997). We computed $r_s$ via a $\chi^2$ minimization procedure using the Levenberg & Marquart method as in Macciò et al. (2008). In agreement with literature, we find that haloes which live in a coupled dark energy cosmology have lower concentrations. Fig. 4 shows the density profiles for halo α, halo β, halo γ and halo δ. The ordering of the profiles with respect to ΛCDM is maintained for all four haloes, with a significant flattening of the inner part of the profiles only for the extreme coupled cosmology EXP006, while differences are less evident in the EXP003 and EXP008e3 haloes. Interestingly, the EXP006 realization of halo α ($M = 7.6 \times 10^{11} \, M_\odot$) produces a much flatter halo profile, with slope $\alpha = -0.8$, which falls out of NFW parametrization. On the other hand, all other profiles of halo α, halo β, halo γ and halo δ in all cosmologies are well described by the NFW profile. Additionally, in Fig. 5 we show the rotation curves at $z = 0$ for the four haloes. Note that, due to the high resolution of our simulations, the errors $\sqrt{N_p}$ are well below 1 per cent everywhere, with $N_p$ number of particles for each bin. For models within the observational constraints, the rotation curves are not significantly affected. The only case in which we observe a considerable flattening is the extreme model EXP006, for all four cases. This is in agreement with Penzo et al. (2014), where we find that differences in rotation curves among models within observational constraints for dynamical dark energy are not significant in the dark matter only case. On the contrary, in hydrodynamical simulations we find observable differences in rotation curves due to the effects of baryons which enhance the variations in the dark matter accretion. We expect the same enhancement also in coupled dark energy models once hydrodynamics is taken into account. This aspect will be explored in a future work.

In the analysis carried out in Baldi (2011a,b), lower concentrations (and therefore less steep density profiles and flatter rotation curves) were shown to be linked to the presence of the friction term $-\beta \ddot{\phi}_b$, in the equation for the linear evolution of density perturbations (equation 4), which injects kinetic energy into the halo. The resulting expansion lowers halo concentration by moving matter from inner to outer radii. As a consequence, rotation curves tend to be flatter than in ΛCDM and density profiles less centrally concentrated. We suggest that the same mechanism is in place also for the less massive haloes ($M \lesssim 10^{12} \, M_\odot$) analysed in this work. We are aware that the mass range is different to the one probed by Baldi (2011a,b), and we acknowledge the possibility that other effects could be important at these masses.

4.1.2 NFW scale radius evolution

In the Section 4.1.1, we have showed that haloes that form in a coupled dark energy cosmology with a high value for the coupling constant have concentrations that are significantly lower at $z = 0$. Given that almost all haloes are well described by an NFW density profile, it means that their NFW scale radii $r_s$ are much larger than the scale radii of the corresponding ΛCDM realizations. In Fig. 6, we show the behaviour of the scale radius $r_s$ as a function of redshift for halo δ in all four cosmologies; the other Milky Way-sized haloes have similar behaviours. The fitting is performed with the gnuplot fitting routine and the asymptotic standard error is shown. Compared to the ΛCDM case, haloes which live in coupled dark energy cosmologies show a larger scale radius at all redshifts.

4.1.3 Main haloes accretion histories

In order to better investigate the origin of the different concentrations, in this section we focus on halo formation times. Fig. 7
Coupled dark energy, Milky Way and satellites

Figure 4. Density profiles for halo $\alpha$, halo $\beta$, halo $\gamma$ and halo $\delta$ at $z = 0$, each for $\Lambda$CDM (black), EXP003 (cyan), EXP008e3 (blue) and EXP006 (red). The inner radius is equal to three times the softening length, while the outer radius is four times $R_{200}$ of each halo. The vertical dashed lines mark $R_{200}$ for each halo in each cosmology.

Figure 5. Rotation curves for halo $\alpha$, halo $\beta$, halo $\gamma$ and halo $\delta$ at $z = 0$, each for $\Lambda$CDM, EXP003, EXP008e3 and EXP006. The inner radius is equal to three times the softening length, while the outer radius is four times $R_{200}$ of each halo. The vertical dashed lines mark $R_{200}$ for each halo in each cosmology.

Figure 6. Scale radius obtained by fitting an NFW density profile using the Levenberg & Marquart method for halo $\beta$ as a function of redshift.

shows halo accretion histories, namely the evolution of the mass enclosed in $R_{200}$ as a function of expansion factor $a = 1/(1 + z)$. Haloes growing in $\Lambda$CDM, EXP003 and EXP008e3 cosmologies show similar accretion histories; while haloes forming in the EXP006 cosmology show a lower clustering compared to $\Lambda$CDM starting between $0.4 \lessapprox a \lessapprox 0.6$ and arriving today with a significantly lower halo mass. Among the three haloes, coupled cosmology runs show unexpected drops in the accretion histories. These would be unusual in a $\Lambda$CDM scenario since halo total masses do not decrease unless it is a temporary effect of a merger (see for instance halo $\alpha$ and halo $\beta$ around $a = 0.3$). On the other hand, in coupled cosmologies, by injecting kinetic energy into the system, the friction term in equation (4) moves particles to radii larger than $R_{200}$ and may cause some of them to become gravitationally unbound. These effects of the coupling were previously studied in Baldi (2011a,b).

In order to estimate the time of formation for each halo, we searched for the scale factor at which the halo has gained half of its today’s mass. Table 3 summarizes the formation epochs for all haloes. We find that haloes in the EXP006 cosmology do not have later formation times than in $\Lambda$CDM. Two of our EXP006 haloes show earlier formation times compared to their $\Lambda$CDM halo.
counterparts. This is in agreement with that found in Baldi et al. (2010) and Baldi (2011b) for more massive haloes: coupled dark energy cosmologies statistically show earlier formation times that ΛCDM. On the other hand, as pointed out in Wechsler et al. (2002), Ludlow et al. (2013) and Dutton & Macciò (2014), in a ΛCDM cosmology an early formation epoch leads to higher concentrations. The same happens for dynamical dark energy cosmologies, e.g. Klypin et al. (2003) and Dolag et al. (2004). Interestingly, in coupled dark energy cosmologies this behaviour is not preserved. Despite the fact that a stronger coupling can result in an earlier or comparable halo formation epoch, halo concentrations decrease when the coupling is increased. The friction term in equation (4) is responsible for making the halo expand by altering its virial equilibrium through the injection of kinetic energy in the system, which in turns lowers the concentration. This shows how in coupled cosmologies lower concentrations are not the result of formation histories but rather the effect of modified dynamics.

4.2 Subhaloes

In this section, we study the subhalo abundance, their radial distribution and circular velocities.

4.2.1 Abundance

The lower number of substructures present in EXP006 haloes compared to ΛCDM can be recognized in Fig. 3. Fig. 8 shows the subhalo mass function, where only subhaloes that lie within $R_{200}$ and that have more than 400 particles are considered. The errors are taken to be $\sqrt{N}$, where $N$ is the number of counts in a given mass bin. The total number of subhaloes in EXP006 realizations is always from 50 to 75 per cent lower than in the respective ΛCDM cases, while differences between EXP003 and EXP008e3 and ΛCDM are much less evident (~10 per cent). Thus, the missing satellites problem (Klypin et al. 1999; Moore et al. 1999) can be progressively alleviated when increasing the coupling. Note that the differences in the subhaloes minimum mass among halo$\alpha$, halo$\beta$, halo$\gamma$ and halo$\delta$ at $z = 0$ are due to the different resolutions used (see Section 3.2).

4.2.2 Radial distribution

Fig. 9 shows the cumulative distribution of subhaloes as a function of the distance from the main halo centre for halo$\alpha$, halo$\beta$, halo$\gamma$ and halo$\delta$ at $z = 0$ for each cosmology.

Table 3. Values for the formation epochs $a_c$ for halo$\alpha$, halo$\beta$, halo$\gamma$ in all four cosmologies.

| Halo   | ΛCDM | EXP003 | EXP008e3 | EXP006 |
|--------|------|--------|----------|--------|
| halo$\alpha$ | 0.310 | 0.304  | 0.308    | 0.313  |
| halo$\beta$  | 0.434 | 0.436  | 0.438    | 0.270  |
| halo$\gamma$ | 0.370 | 0.355  | 0.361    | 0.299  |

Figure 8. Cumulative number of subhaloes with more than 400 particles as function of their mass for halo$\alpha$, halo$\beta$, halo$\gamma$ and halo$\delta$ at $z = 0$ for each cosmology.
of subhaloes in EXP006 haloes compared to their respective ΛCDM cases, while for EXP003 and EXP008e3 cosmologies differences are not so evident.

As pointed out in Section 4.1.3, the extra terms due to the coupling appearing in the equation for the evolution of density perturbations (equation 4) decrease halo concentrations despite the earlier or comparable halo formation epochs. We claim that the decrease of halo concentration can be also responsible for the lower number of subhaloes compared to ΛCDM. Given that also subhaloes have lower concentrations (confirmed by the subhaloes rotation curves shown in Fig. 12), when falling into the main halo potential well, they can be heavily stripped and less subhaloes with more than 400 particles survive. If this claim is correct, we should be able to find a difference in the subhaloes number distribution when we reach distances from the main halo centre that are bigger than the radius from which the gravitational influence of the host halo is felt. In Fig. 11, we show the differential radial distribution of the number of subhaloes out to about three times the virial radius of each halo. For the sake of clarity, we choose to show only ΛCDM and the most extreme case, EXP006, for all four haloes. The dotted lines represent one and two times $R_{200}$ for each halo in each cosmology. What we would like to stress, is that there seem to be a decrease in the number of subhaloes living in EXP006 cosmology compared to their ΛCDM realizations only within the gravitational influence of the main halo. Between 1.5 and $2R_{200}$, this behaviour inverts and haloes living in the strongly coupled cosmology seem to have a larger or at least a comparable number of subhaloes with respect to their ΛCDM cases. Thus, we ascribe the presence of a lower subhaloes number to a massive stripping effect rather than EXP006 producing intrinsically a lower number of subhaloes. On the other hand, we cannot exclude that coupled cosmologies could show a lower number of subhaloes because mergers and accretions could be much slower in EXP006, so that subhaloes form more slowly and in smaller numbers, and only fewer of them might have fallen into the main haloes at $z = 0$. Finally, we would like to stress on the fact that lowering the number of subhaloes can also be achieved by warm dark matter (WDM) cosmologies (e.g. Anderhalden et al. 2013), but the fundamental difference lies on the fact that WDM will have a lower number of (sub)haloes both inside and outside the virial radius, due to the overall suppression of the initial power spectrum. On the contrary, our coupled models have an even larger number of subhaloes compared to ΛCDM outside the virial radius, and this is even true for EXP006. To summarize, subhaloes in WDM cosmologies were never formed, while in coupled dark energy cosmologies subhaloes do form but they could be heavily stripped.

4.2.3 Circular velocities

Boylan-Kolchin et al. (2011) first showed that $N$-body simulations of a Milky Way-sized halo predict a significant number of subhaloes with circular velocities higher than the circular velocities that we measure for the brightest satellites of the Milky Way, which is surprising since these massive subhaloes should not fail in producing stars.

The discrepancy between ΛCDM prediction and observations can be alleviated in multiple ways, starting from baryonic processes. Brooks & Zolotov (2014) suggest that baryonic feedback processes could be responsible for a dark matter redistribution, with the result of decreasing the central densities of the most massive subhaloes. Rashkov et al. (2012) point out that the possibility of star formation being stochastic below a certain mass would justify the Milky Way having massive dark satellites; furthermore, they highlight the fact that the tension between the Via Lactea II simulation and observations is only a factor of 2 in mass, which suggests that the uncertainty on the Milky Way virial mass could be a viable way out from the tension (Vera-Ciro et al. 2013; Kennedy et al. 2014). Purcell & Zentner (2012) showed that there exists a significant variation in subhalo properties even when the host haloes have the same virial mass.

Last but not least, the discrepancy can be alleviated by appealing to non-ΛCDM cosmologies. The cases for warm, mixed (cold and warm) and self-interacting dark matter are considered in Lovell et al. (2012), Anderhalden et al. (2012, 2013) and Vogelsberger, Zavala & Loeb (2012), respectively. In all cases they find that subhaloes are less concentrated due to their late formation time, suggesting
that alternative cosmologies can contribute to alleviate the tension between predictions and observations.

Fig. 12 shows the rotation curves for the 12 most massive subhaloes at the moment of infall. We used the correlation between orbital energy and subhalo mass-loss found in Anderhalden et al. (2013) to determine the subhaloes ranking. Each row illustrates subhaloes rotation curves for a given main halo in all considered cosmologies. From top down we show halo α, halo β, halo γ, halo δ. In yellow, we show the observed values for $v_{\text{circ}}(r_{1/2})$ for the brightest dwarf galaxies orbiting around the Milky Way. Data are taken from Anderhalden et al. (2013) and references therein. Despite halo α and halo δ having comparable masses, the tension between simulated curves and measured points in the ΛCDM case is more evident in halo δ, supporting the fact that subhalo properties can vary even when host haloes have the same virial mass (Purcell & Zentner 2012). The tension is alleviated in the case of halo γ and even more halo δ, given their lower masses (Vera-Ciro et al. 2013).

Overall, when looking at all haloes in EXP003 and EXP008e3 cosmologies, these do not show significant improvement compared to their ΛCDM realizations in decreasing the inner densities of subhaloes. On the other hand, in the case of EXP006 cosmology, all four haloes show such a dramatic decrease in subhalo rotational velocity peaks that rotation curves become incompatible with measured values. The dramatic decrease was to be expected given the choice of a large coupling parameter for EXP006 cosmology, but none the less it is useful to understand the effects of the coupling.

4.3 Zooming-in on a dwarf halo

To better explore the effects of the coupling at high resolutions, we simulated a dwarf galaxy halo, halo ϵ. We chose an isolated halo (no structures with comparable mass within four of its virial radii) and, given the results of Section 4.2, we only focused on the two most distant cosmological cases, ΛCDM and EXP006 cosmology. The virial masses are $4 \times 10^9$ and $3 \times 10^9 \, M_\odot$ respectively, with a mass resolution of $1.3 \times 10^3 \, M_\odot$. Fig. 13 shows the density maps

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**Figure 12.** Rotation curves of the most massive subhaloes at the moment of infall for each halo in each cosmology. From the top row down we show halo α, halo β, halo γ, halo δ, from left to right we show ΛCDM (black), EXP003 (cyan), EXP008e3 (blue), EXP006 (red). We estimate the subhalo mass ranking at the moment of infall using the correlation between orbital energy and subhalo mass-loss found in Anderhalden et al. (2013). The yellow points are the observed values for $v_{\text{circ}}(r_{1/2})$ for the brightest dwarf galaxies orbiting around the Milky Way. Data are taken from Anderhalden et al. (2013) and references therein. The masses of each main halo realizations is written on each panel.
for halo in both cosmologies, with ΛCDM on the upper panel. It is visible how the number of substructures decreases in the case with coupling. Upper panels of Fig. 14 show density profiles and rotation curves for halo in both cosmologies. The effect of the coupling is very evident in lowering the concentration and flattening the rotation curve. The values for the halo concentrations are $c = 15.2$ and $6.5$ for ΛCDM and EXP006 cosmology, respectively. Although the density profile in the coupled dark energy case is less concentrated, it is still cuspy, showing that in coupled cosmologies, as in ΛCDM, we are not able to produce a dark matter only cored density profile. The inconsistency with observation thus still persists, given the observational evidence that supports cored density profiles for the satellites of the Milky Way (Walker & Peñarrubia 2011; Amorisco & Evans 2012; Amorisco, Agnello & Evans 2013). Interesting to note, by constructing a model in which both warm and cold dark matter are present and only the cold component is coupled to dark energy, a very high value ($\beta_c \sim 10$) for the coupling constant is favoured (Bonometto, Mainini & Macciò 2015) and simulated dark matter only dwarf haloes show a cored density profile (Macciò et al. 2015). The lower panel of Fig. 14 shows the accretion history, $M_{200}$ as function of scale factor. As in Section 4.1.3, we calculated the formation epochs referring to the scale factor at which the halo has gained half of its today’s mass. We find $a_c = 0.331$ (ΛCDM), $a_c = 0.329$ (EXP006). Despite the very significant difference in concentration between these two haloes, their formation times are comparable, confirming that the difference in concentration is not driven by formation times but rather by the modified dynamics, also at dwarf galaxy scales.

5 CONCLUSIONS

We have performed the first study of high-resolution galactic scale simulations in coupled dark energy cosmologies. The aim is to study the effects of the coupling between dark energy and dark matter on these scales, so far neglected in previous studies. We chose to investigate two models with coupling values that are within the observational constraints from Pettorino et al. (2012), one with constant coupling and one with varying coupling with redshift; we also chose a third model where the constant coupling value has been pushed beyond observational constraints to better investigate its effects. We then selected three Milky Way-sized haloes, a $6 \times 10^{11} M_\odot$ halo and a dwarf halo $5 \times 10^9 M_\odot$, and studied their properties in a ΛCDM reference model and in the coupled cosmologies, resolving each halo with $\sim 10^6$ dark matter particles.

We computed concentrations and formation epochs for all haloes and we find that, despite the earlier or comparable formation epochs of the coupled cosmologies haloes, these have lower concentrations. In a ΛCDM or a dynamical dark energy scenario, earlier formation epochs would imply higher concentrations, but in the coupled dark energy case the reason for lower concentrations is not related to formation histories, but rather to the modified dynamics. We ascribe this behaviour to the presence of the friction term $-\beta \dot{\phi} \delta_c$ in the
equation for the linear evolution of density perturbations (equation 4) in coupled cosmologies. This extra term, compared to the $\Lambda$CDM case, redistributes the dark matter particles and lowers the central densities, in spite of the formation times (see Baldi 2011b). Given that the mass range that we investigate is complementary to previous studies, we cannot exclude that also other extra terms appearing with the coupling can be important.

In particular, subhaloes can also be significantly less concentrated. When falling towards their host, they can be more heavily stripped once they start feeling the gravitational influence of the host halo. One possible explanation is that this translates into decreasing the number of subhaloes compared to the $\Lambda$CDM realization and, additionally, subhaloes are themselves less massive and less concentrated. For these reasons, coupled cosmologies can be helpful in alleviating satellite-scales inconsistencies of $\Lambda$CDM. On the other hand, we find that in order to try to solve these issues with the coupling alone, one needs to use an extreme value for the coupling constant that is ruled out by observational constraints. In fact, only in the case with the highest coupling value the number of subhaloes is significantly reduced (up to 75 per cent less subhaloes) than in the respective $\Lambda$CDM cases, while for the viable coupling cosmologies the decrease is much less significant (10 per cent less subhaloes). Moreover, we find that the distribution of the subhaloes inside the main halo virial radius does not vary significantly among cosmologies. Lastly, less concentrated coupled cosmologies subhaloes can in principle be useful to reconcile the inconsistency between the observed properties of the Milky Way dwarf galaxies and $\Lambda$CDM simulations predictions, but once more a high enough value for the coupling must be assumed. Interestingly, allowing the introduction of massive neutrinos does alleviate the constraints on the coupling (see e.g. La Vacca et al. 2009), leaving coupled dark energy models dynamics an interesting option for subgalactic scales.

Overall coupled dark energy models can be as effective as $\Lambda$CDM in reproducing observations on subgalactic scales. Furthermore, by increasing the coupling value, these models may help improve the agreement between predicted and observed properties. Given that higher coupling becomes viable when considering other extensions to the $\Lambda$CDM model, coupled dark energy models present themselves as an interesting alternative to the standard model. These cosmologies would need to be further investigated, possibly taking into account the effects of baryons at subgalactic scales, which, as already shown in dynamical dark energy models (Penzo et al. 2014), are expected to amplify differences observed in the dark matter only case.

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