ABSTRACT

We examine the evolution of the inner dark matter (DM) and baryonic density profile of a new sample of simulated field galaxies using fully cosmological, $\Lambda$CDM, high resolution SPH + N-Body simulations. These simulations include explicit H$_2$ and metal cooling, star formation (SF) and supernovae (SNe) driven gas outflows. Starting at high redshift, rapid, repeated gas outflows following bursty SF transfer energy to the DM component and significantly flatten the originally 'cuspy' central DM mass profile of galaxies with present day stellar masses in the $10^4.5 - 10^9.8$ $M_\odot$ range. At $z=0$, the central slope of the DM density profile of our galaxies (measured between 0.3 and 0.7 kpc from their centre) is well fitted by $\rho_{\text{DM}} \propto r^{-\alpha}$ with $\alpha \approx -0.5 + 0.35 \log_{10}(M_\star/10^8 M_\odot)$ where $M_\star$ is the stellar mass of the galaxy and $4 < \log M_\star < 9.4$. These values imply DM profiles flatter than those obtained in DM-only simulations and in close agreement with those inferred in galaxies from the THINGS and LITTLE THINGS survey. Only in very small halos, where by $z = 0$ star formation has converted less than $\sim 0.03\%$ of the original baryon abundance into stars, outflows do not flatten the original cuspy DM profile out to radii resolved by our simulations. The mass (DM and baryonic) measured within the inner 500 pc of each simulated galaxy remains nearly constant over four orders of magnitudes in stellar mass for $M_\star < 10^9 M_\odot$. This finding is consistent with estimates for faint Local Group dwarfs and field galaxies.

These results address one of the outstanding problems faced by the CDM model, namely the strong discrepancy between the original predictions of cuspy DM profiles and the shallower central DM distribution observed in galaxies.

Key words: Galaxies: formation – Cosmology – Hydrodynamics.
that their central DM profiles are shallower than the predictions of DM only simulations at scales of 0.1-1 kpc (e.g., Flores & Primack 1994; Moore et al. 1999; Swaters et al. 2003; Simion et al. 2003; de Blok et al. 2008; Donato et al. 2009; Primack 2009; de la Nave et al. 2010; Oh et al. 2014; Elson et al. 2010). In these observational works the measured slopes range between 0 and 1. (Note: in this paper we will identify halos with DM profiles shallower than NFW or Einasto as ‘cored’). These observational results provided a long standing challenge to CDM at scales that cannot be explored by CMB or Lyα experiments (Croft et al. 2002). They also prompted the development of several alternative DM models such as Warm DM (WDM), meta-DM and Self Interacting DM (SIDM). Spergel & Steinhardt (2000), Davé et al. (2001) Knebe et al. (2002), Ahn & Shapiro (2003), Strigari et al. (2007), Colin et al. (2008), Martinez et al. (2009), Abdo et al. (2010), Loeb & Weiner (2011), Lovell et al. (2014), Kodama & Shapiro (2011), Vogelsberger et al. (2012) and alternative gravity theories such as MOND (McGaugh 2000; Gentile et al. 2011).

There is emerging evidence that our poor understanding of the baryonic processes involved in galaxy formation is the source of the inconsistency between the observations of dwarf galaxies and the predictions of CDM. Models of the effect of feedback on the structure of galaxies and the efficiency of SF were originally motivated by the discrepancy between the observed number of dwarf galaxies and the much higher number density of small DM halos predicted by CDM models (Dekel & Silk 1986; Moore et al. 1999; Bower et al. 2006). Without requiring a major change to the ACDM scenario, several models have been presented in the past advocating the evolution of originally cuspy CDM halos into halos with ‘cored’ density profiles through SN feedback or dynamical friction (Navarro et al. 1996a; Dekel et al. 2003b; Mo & Mao 2004; Read & Gilmore 2005; Mashchenko et al. 2006; Goerdt et al. 2006; Toneini et al. 2006; El-Zant et al. 2004; Romano-Díaz et al. 2006; Del Popolo et al. 2008; Lackner & Ostriker 2010; Goerdt et al. 2014; de Souza et al. 2011; Pontzen & Governato 2012). In Governato et al. (2010), hereafter, G10 we presented self-consistent, DM + gas dynamic simulations where shallow DM cores arise naturally in a CDM cosmology (see also Macciò et al. 2012). In these simulations, energy feedback from SNe in star forming regions generate repeated, fast gas outflows. These outflows efficiently remove gas from the inner kpc of protogalaxies (Brook et al. 2011) and, in smaller galaxies, are able to expel a large fraction of gas from the galaxy altogether.

In Pontzen & Governato (2012) we presented a coherent analytical model for core formation that correctly matches results from our simulations. In this model multiple, rapid gas outflows transfer energy to the collisionless DM and create DM cores of about 1 kpc in size in halos of total mass $M = 3 \times 10^{10} M_\odot$. As also described in detail in G10, a crucial ingredient is the spatial distribution of the SF events. If SF is allowed in low density gas $\rho \sim 0.1 - 1$ amu/cm$^3$ (typical in most previous, lower resolution simulations) outflows are weaker and do not generate cores, even if the feedback scheme remains the same. The necessity of simulations to resolve dense gas regions calls for simulations of very high mass and spatial resolution (Mashchenko et al. 2008; Saioh et al. 2008; Ceverino & Klypin 2009). As a key step toward understanding the properties of DM halos at very small masses, many faint Milky Way dwarf satellites have recently been discovered, some with less than one millionth of the Milky Way’s luminosity (e.g., Willman et al. 2005; Belokurov et al. 2007). The first kinematic studies of ‘ultra-faint’ dwarf galaxies have measured mass to light (M/L) ratios as low as 1000 (Simon & Geha 2007; Geha et al. 2009). These results suggest that the smallest cosmic structures where star formation took place might have been identified. It has been argued that the observed population of faint galaxy satellites should be hosted inside cuspy halos, as small, cored halos would easily be destroyed by the Milky Way tidal field (Penarrubia et al. 2010). However, estimates of the mass profiles of ultra-faint dwarfs are uncertain and critically depend on the detailed kinematic of their stars, which are used as dynamical tracers (Walker & Penarrubia 2011). Unlike most field dwarfs, where the evidence for DM cores is robust, current observations have not securely determined if low mass satellites of the MW are hosted inside cored or cuspy DM halos, although Walker & Penarrubia (2011) and Jardel & Gebhardt (2011) reported that the Sculptor and Fornax dwarf galaxies might indeed have cores.

Surprisingly, while the Milky Way low luminosity dwarfs span five orders of magnitude in luminosity, dynamical studies estimate that these galaxies contain the same total (baryons+DM) mass in their innermost part, about $10^9 M_\odot$ within the inner 300pc (Strigari et al. 2008). This result provides a useful constraint for all models of galaxy formation and can be interpreted assuming a truncation in the halo mass function as predicted in WDM models (Avila-Reese et al. 2001; Bode et al. 2001; Boylan-Kolchin et al. 2011a; Parry et al. 2011; Schneider et al. 2011) or to the suppression of SF in halos with virial temperature less than the cosmic UV background (Quinn et al. 1996; Benson et al. 2002; Springler et al. 2010). Both processes would set a minimum halo scale for star formation, hence a common mass at a fixed radius. Feedback and gas heating from cosmic sources have been shown (Governato et al. 2007; Font et al. 2011, among many), to alleviate the above mentioned over-abundance of satellites in CDM, while WDM faces already significant observational constraints (Viel et al. 2003; Kuzio de Naray et al. 2010; Lovell et al. 2011) and several works presented evidence that WDM halos would form cores much smaller than observed (Dalcanton & Heggie 2001; Knebe et al. 2002; Strigari et al. 2007), making this model less attractive.

A few models have tried to explain the observed flat stellar mass - central mass relation measured in Strigari et al. (2008), while assuming cuspy DM halo profiles (Rashkov et al. 2011). Some (Li et al. 2009; Macciò et al. 2009) invoke a large scatter in star formation histories (SFH) and halo assembly histories of dwarf galaxies to explain the observed flat luminosity-central mass relation over a large range of halo masses. These results however, are based on DM-only simulations paired to semi analytical models. They therefore neglect important interactions between the baryonic and the DM component of halos, as well as the effect of H$_2$ cooling on SF in dense regions (Gnedin et al. 2000). Ongoing surveys such as ANGST (Dalcanton et al. 2009), THINGS (Walter et al. 2008) and LITTLE THINGS...
(Zhang et al. 2011), Hunter et al. (07) are providing data on the central mass distribution of field galaxies with $V_{\text{peak}} < 60$ km/sec and provide new, strong constraints on the central mass distribution of galaxies (Oh et al. 2011a, hereafter OH11) that need to be properly taken into account. In particular, LITTLE THINGS and THINGS are able to measure DM profiles over a range of galaxy stellar masses and to evaluate the total mass within the central region of galaxies more massive than those in the original 'Strigari relation'.

To summarize, observational measurements of the central mass distribution of galaxies and of the central slope of the underlying DM profile as a function of a galaxy stellar mass, may shed light on the nature of DM and of baryon/DM interactions at scales much smaller than those probed by cosmological test.

In this work we focus on field galaxies and their structural properties, and compare the highest resolution set of simulations of small galaxies to date with measurements of DM slopes obtained from new data from the THINGS and LITTLE THINGS surveys. Focusing on field galaxies allows us to separate the effects of gas outflows from those of tidal interactions (Mayer et al. 2001). The goal of the analysis presented here is to evaluate if galaxies formed in a CDM cosmology have central DM and baryon distributions consistent with observations once the effect of realistic gas outflows is evaluated in a full cosmological context. To achieve this goal we study a new set of high resolution galaxies formed in a full CDM cosmological context. The simulations presented here include a consistent implementation of metal line cooling and $H_2$ physics (Christensen et al. ’11, submitted, CH11 hereafter), essential to correctly model SF in low metallicity gas and in low mass halos (Li et al. 2009, Krumholz & Dekel 2011). The highest resolution simulations in our sample resolve individual SF regions as small as a few $10^5 M_\odot$. The simulations have not been tuned to produce cores, but rather to form a realistic amount of stars and to reproduce the stellar mass/halo mass relation (Conroy et al. 2006, Tollerud et al. 2011, Munshi et al, in prep). As a test of our predictions for the central mass distribution of galaxies, we also show that simulations naturally reproduce an updated flat stellar mass - central mass relation obtained combining MW and field dwarf galaxies. We describe the simulations and the THINGS data in §2, the results on the shape of the DM profiles in §3 and the results on the central mass - stellar mass relation in §4. In §5 we conclude.

2 SIMULATIONS AND OBSERVATIONAL DATA

The simulations used in this work were run with the N-Body + Smoothed Particle Hydrodynamics (SPH) code GASOLINE (Wadsley et al. 2000, Stinson et al. 2006) in a fully cosmological ΛCDM context:

$$\Omega_0 = 0.26, \Lambda = 0.74, h = 0.73, \sigma_8 = 0.77, n = 0.96.$$  

The galaxies were originally selected from two uniform DM-only simulations of 25 and 50 Mpc per side. From these volumes five field-like regions where selected, each centered on a galaxy sized halo of different mass ($3 \times 10^{11}, 2 \times 10^{11}, 3 \times 10^{10}, 2 \times 10^{10}$ and $10^{10} M_\odot$).

Each region was then resimulated at higher resolution and with baryons using the ‘zoomed-in’ volume renormalization technique (Katz & White 1993, Brooks et al. 2007, Pontzen et al. 2008), while fully preserving the surrounding large scale structure. This technique allows for significantly higher resolution while capturing the effect of large scale torques that deliver angular momentum to the galaxy (Barnes & Efstathiou 1989). The mass overdensity $\delta\rho/\rho$ for each chosen field ranges from -0.07 to 0.58 when measured on a scale of $4h^{-1}$ Mpc (see table 1).

To simulate even very small halos with million of resolution elements, the mass and spatial resolution of each zoomed region are inversely proportional to the mass of the largest halo in each one of them (see Table 1). The force spline softening ranges between 64 and 170 pc in all runs and is kept fixed at $z < 10$. Star particles are formed with a mass of 400-8000 $M_\odot$. The gas smoothing length is allowed to shrink to 0.1 times the gravitational softening in very dense regions (resulting values around 0.5 are typical) to ensure that hydro forces dominate at very small scales.

The main galaxy in every zoomed region contains several million particles within its virial radius ($R_{\text{vir}}$, defined as the radius at which the average halo density = $100 \times \rho_{\text{crit}}$). Every zoomed region also contains several smaller galaxies with identical mass and spatial resolution, which we include in our analysis. With this approach the total high resolution sample contains 15 field galaxies with between several million to 50000 DM particles within $R_{\text{vir}}$ covering a halo mass range of 3 orders of magnitude. Galaxies and their parent halos were identified using AHF (Knollmann & Knebe 2009). Similar to criteria used in previous works one galaxy undergoing strong interactions at $z=0$ was excluded from the sample. In this work we follow up on G10 and OH11, where we studied the stellar and DM content of halos $M \sim 10^{10} M_\odot$ and extend our predictions on a larger range in halo masses (from a few times $10^8$ to $3 \times 10^{11} M_\odot$), peak velocities $V_{\text{peak}}$ (10 to 100 km/sec) and stellar masses $M_{\text{star}}$ (from $4 \times 10^4$ to almost $10^{10} M_\odot$), spanning a range of halo spin values and accretion histories. In observational terms this range covers faint dwarfs to normal field disk galaxies (Geha et al. 2006). No halos in our sample have been contaminated by particles from the lower resolution volumes and the zoomed in regions are large enough (a few Mpc in each case) to contain all the gas expelled from galaxies by outflows (that can reach as far as several times the virial radius of the parent galaxy). This approach allows us to test for the effects of resolution over a large range in halo masses (i.e. Fig.1 and Fig.2 contain halos of overlapping mass but ran at different resolutions). Given the high resolution of our simulations star forming regions as small as $10^5 M_\odot$ are identified by hundreds of gas and star particles.

As a significant improvement over most cosmological simulations carried to the present time these new simulations include both metal lines and $H_2$ cooling (Shen et al. 2014, CH11). The simulations include a dust dependent description of $H_2$ creation and destruction by Lyman Werner radiation (Gnedin et al. 2009, CH11). Metal lines cooling, the $H_2$ fraction, and self shielding of high density gas from

1 AMIGA’s Halo Finder, available for download at http://popia.ft.uam.es/AMIGA/
local radiation play an important role in determining the structure of the ISM and where SF can occur (Kennicutt 1998; Elmegreen et al. 2008; Krumholz & McKee 2005; Bigiel et al. 2008; Gnedin et al. 2009; Feldmann et al. 2011; Narayanan et al. 2011). With this approach the local SF efficiency is linked directly to the local $H_2$ abundance, as regulated by the gas metallicity and local radiation from young stars. As a result, in our simulations stars naturally form in high density regions around 10-100 amu cm$^{-3}$ without having to resort to simplified approaches based on a fixed local gas density threshold (Governato et al. 2010; Saitoh et al. 2011; Guedes et al. 2011; Kuhlen et al. 2011). A Kroupa (1993) IMF and relative yields are assumed. We include a gas heating spatially uniform, time evolving UV cosmic background following an updated model of Haardt & Madau (1993). Gas heating from UV radiation progressively suppresses star formation in galaxies below $10^{10} M_\odot$, making small DM halos completely void of stars (Benson et al. 2002) and reducing the overabundance of dwarf satellite galaxies (Moore et al. 1998). The smallest galaxies in our sample have some SF occurring before reionization ($z \sim 9$ in our model) likely associated to $H_2$ cooling and then in small, sparse bursts thereafter.

The full details of our physically motivated SN feedback implementation and its applications have been described in several papers and over a range of redshifts: Stinson et al. (2006); Brooks et al. (2007); Governato et al. (2007); Pontzen et al. (2008); Governato et al. (2009); Zolotov et al. (2009); Pontzen et al. (2010); Brook et al. (2011); Brooks et al. (2011); Guedes et al. (2011). As in G10 the SFR in our simulations is set by the local gas density ($\rho_{gas}$)$^{1.5}$ and a SF efficiency parameter, $c_s = 0.1$ to give the correct normalization of the Kennicutt-Schmidt relation (the SF efficiency for each star forming region is much lower than the implied 10%, as only a few star particles are formed before gas is disrupted by SN winds). The maximum temperature for gas to turn into stars is set to 3000K and the efficiency of SF is then further multiplied by the $H_2$ fraction, which effectively drops to zero in warm gas with $T > 10,000$ K. As massive stars evolve into SN, mass, thermal energy and metals are deposited into nearby gas particles. Gas cooling is turned off until the end of the snow plow phase as described by the Sedov-Taylor solution, typically a few million years. The amount of energy deposited amongst those neighbors is $10^{51}$ ergs per SN event. Energy deposition from SN feedback leads to enhanced gas outflows that remove low angular momentum gas from the central regions of galaxies.

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Simulation & Galaxies stellar masses $M_\odot$ & DM part. mass $M_\odot$ & Star part. mass $(M_\odot)$ & Softening (pc) & Overdensity & Particles within $R_{vir}$ & $V_{peak}$ km s$^{-1}$ \\
\hline
Fields 1 & 2 & $10^{10}$-$10^8$ & 1.6$\times$10$^5$ & $8 \times 10^3$ & 170 & 0.38 - 0.03 & 3.4-0.05$\times10^6$ & 100-40 \\
Field 3 & 4 & $3 \times 10^9$-$10^7$ & $2 \times 10^4$ & $10^3$ & 85 & 0.58 - 0.07 & 2-0.05$\times10^6$ & 55-30 \\
Field 5 & $10^8$-$10^{3.5}$ & $6 \times 10^3$ & $4.2 \times 10^2$ & 64 & 0.01 & 2-0.05$\times10^6$ & 35-10 \\
\hline
\end{tabular}
\caption{Properties of the simulated galaxies. All masses in $M_\odot$. Column (2) lists the total stellar mass range for each galaxy in the subsample at $z=0$. Columns (3) and (4) list the mass of individual dark matter and star particles, respectively. Column (5) shows $c_s$, the spline gravitational force softening, in pc. Column (6) shows the overdensity in units of the average density around the most massive halo in that zoomed-in region measured on a scale of 4$h^{-1}$ Mpc. (7) lists the range in total number of particles (gas, stars and DM) within the virial radius of the halo at $z=0$. (8) gives the peak velocity at $z=0$. All simulations but Field 4 have also been run as DM-only (See Fig.2).}
\end{table}

![Figure 1. The slope of the dark matter density profile $\alpha$ vs stellar mass measured at 500 pc and $z=0$ for all the resolved halos in our sample. The Solid 'DM-only' line is the slope predicted for the same CDM cosmological model assuming i) the NFW concentration parameter trend given by Macciò et al. (2007) and ii) the same stellar mass vs halo mass relation as measured in our simulations to convert from halo masses. Large Crosses: haloes resolved with more than $0.5 \times 10^6$DM particles within $R_{vir}$. Small crosses: more than $5 \times 10^4$ DM particles. The small squares represent 22 observational data points measured from galaxies from the THINGS and LITTLE THINGS surveys.](image)
tors. Bursty phases typically last 10–100 Myrs with SFR variations on shorter timescales and SF enhanced by a factor of $\sim 4$–20, similar to what measured in Local Group dwarfs (McQuinn et al. 2010). As discussed in Pontzen & Governato (2011) a bursty SF is necessary to create the fast outflows able to transfer energy to the DM component. Outflows also decrease the SF efficiency in halos with total mass smaller than a few $10^{10}$ $M_\odot$. In our set of simulations outflows are predominant at high-$z$ when SF peaks and galaxy interactions are common. These outflows affect the halos that will subsequently merge to form the central regions of the final, present day galaxies.

In the mass range explored by our simulation (up to halos with $M_{\text{vir}} = 3 \times 10^{11}$) the ratio of stellar mass/halo mass (the SF efficiency) is a strong function of halo mass, roughly scaling as $M_{\text{stars}} \propto M_{\text{vir}}^{-2}$. In this halo range SF becomes substantially less efficient in smaller galaxies. In halos with total mass smaller than $10^{9}$ $M_\odot$ (also equivalent to a virial temperature $T_{\text{vir}} < 10^4$K) SN feedback and the cosmic UV background strongly suppress SF. Furthermore, in halos this small, stars only form when H$_2$ cooling is introduced, as gas can cool below $T_{\text{vir}}$. As a result, in the smallest halos only a very small fraction of baryons is then turned into stars. The more massive galaxies in our sample turn only $\sim 10\%$ of their primordial baryon content into stars, after having expelled about $30\%$ of their gas outside $R_{\text{vir}}$. Typical dwarfs in our sample turn a few per cent of their primordial gas fraction into stars, and the smallest galaxies $\sim 0.01\%$. In OH11 (see their Fig.5) we verified that galaxies with $V_{\text{peak}} < 60$ km s$^{-1}$ form the correct amount of stars when compared with a local sample with resolved photometric and kinematic data. In a future paper we will show how our sample closely matches the stellar mass/halo mass relation inferred using halo occupation methods (Moster et al. 2014, Munshi et al. in prep). As a reference and a resolution test of the simulations, most of the above runs have been repeated including only the collisionless CDM component.

The DM and baryonic mass distribution of the simulated galaxies will be compared with those measured from extensive HI data from a sample of nearby dwarf galaxies from THINGS (Walter et al. 2008) and LITTLE THINGS (Hunter et al. in prep) surveys which focused on field galaxies. The high-resolution HI data ($\sim 6''$ angular; $\lesssim 5.2$ km s$^{-1}$ velocity resolution) combined with Spitzer IRAC 3.6$\mu$m and ancillary optical images significantly reduce various observational systematic effects inherent in lower-resolution data, such as beam smearing, dynamical center offset and non-circular motions, and thus enable us to derive more reliable mass models of the galaxies. For a comparison with our simulations, we select a sample of 22 dwarf galaxies (7 from THINGS and 15 from LITTLE THINGS) that show a clear rotation pattern in their velocity fields. These high-quality multi-wavelength data allow us to measure the enclosed amount of mass and the inner slope of the DM density profile at 500 pc of the galaxies with good accuracy.

![Figure 2. The slope of the dark matter density profile $\alpha$ measured at 500 pc vs virial mass and at $z=0$ for the same galaxies shown in Figure 1. Crosses mark haloes from the DM-only simulations. Open circles are from the haloes that have been re-run in DM-only simulations. Size of symbols is the same as in Figure 1. The solid line is the average slope predicted in Macciò et al. (2007) for haloes in the same ΛCDM cosmology.](http://youtu.be/FbcgEovabDI?hd=1)

### 3 THE EVOLUTION OF DM CORES AS A FUNCTION OF HALO MASS AND REDSHIFT

With the goal of measuring when and how much gas outflows affect the underlying DM profiles in ΛCDM galaxies, in this section we focus on how the central DM density profiles differs from the simple predictions of DM-only runs once cooling, SF processes and gas outflows are introduced. To do this we measure the slope $\alpha$ of the DM density profile at 500pc for all the well resolved galaxies formed in our hydrodynamical simulations, and then compare them with observational data as well as predictions from DM-only simulations.

The $\alpha$ value of the central DM density profile is obtained by spherically averaging the density and fitting the density profile with $\rho_{\text{DM}} \propto r^{-\alpha}$ between 300pc and 700pc. $\alpha$ is then formally defined at 500pc. In this section we exclusively study field galaxies to avoid the effects that satellite – main halo interactions might have on the density profiles (Mayer et al. 2001; Stoehr et al. 2002; Kazantzidis et al. 2004).

Fig. 1 and Fig. 2 show the value of $\alpha$ as a function of galaxy stellar mass and virial mass. The zoomed-in runs approach allows us to cover a large range of galaxy stellar masses, almost 6 orders of magnitude. Both figures clearly show a trend with increasing galaxy stellar (or total) mass showing a central DM profile significantly flatter than the one predicted by CDM simulations that only included a DM component (solid line, showing results from Macciò et al. 2007). In Fig.1 the DM-only predictions are mapped onto the x axis by assuming the same stellar mass - halo mass rela-

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2 http://youtu.be/FbcgEovabDI?hd=1
Figure 3. The dark matter density profile of a dwarf galaxy in our sample, at $z=4,3,1,0$. The prolonged process of cusp flattening due to many separate outflows results in a shallow inner profile at $z=0$. For comparison, the density profile of the same galaxy, but simulated with DM only, is shown in the black dash-dot line. In the DM only simulation the DM maintains its cuspy density profile at all redshifts.

The α trend in the DM-only halos in Fig. 1 and 2, with less negative (flatter) values for increasing stellar and halo masses is partly driven by the constant radius used to compare with observations over a large range in galaxy masses, as in DM Einasto-like density profiles α gets steeper in their outer parts (i.e. for larger $R/R_{vir}$ values), with α rolling from $\sim -1$ close to the centre to $\sim -3$ at $R_{vir}$. For larger halos 500pc represents a smaller fraction of the virial radius, hence the DM profile is flatter (less negative α values) than for smaller halos, where at 500 pc we are instead starting to measure the outer part of the DM profile. This effect is present also in the runs with SF induced outflows, but with a significant shift to flatter profiles and less negative α values over a large range in stellar masses. As a result central DM profiles in runs with outflows become rapidly flatter at halo masses larger than $10^9 M_\odot$ (circles in Fig.2, see also Fig.3). The DM-only runs in our sample follow closely the results from a set of high resolution halos presented by Macciò et al. (2007). Scatter at a similar mass is small and there is no trend with resolution (small vs large crosses). However, in the lowest mass dwarfs in our sample, when star formation converts less than $\approx 10^5 M_\odot$ of baryons per $5 \times 10^9 M_\odot$ of DM (corresponding to $M_{vir} < 5 \times 10^9$, or also $V_{peak} < 20 \kms$) outflows are too weak to remove sufficient amount gas and cause DM heating through energy transfer. These halos maintain their original cuspy DM profile. Note that halos formed in simulations that include outflows accrete slightly less mass over a Hubble time compared to DM-only runs (Fig.2).

In Pontzen & Governato (2012) we presented an analytical model of the cusp flattening process. In the galaxies in our sample this process commonly starts at high redshift ($z \sim 4$) and continues down to $z \sim 1$, when the SFR declines. Fig. 3 shows the DM (spherically averaged) density profile as a function of radius and redshift for a dwarf with final total mass $\sim 10^{10} M_\odot$, showing a rapid flattening at high $z$. Around $z=3$, as the SFR peaks, the galaxy is undergoing several starbursts associated with a rapid accretion and mergers. The DM density profile flattens and reaches a relatively stable profile by $z=1$, when the SFR declines. The last small starbursts have a relatively small effect. By $z=0$ the DM profile shows a flattened profile within the central 1 kpc and its central density is almost an order of magnitude lower than in the DM only case.

An interesting result of this work is that massive blowouts, that could potentially disrupt the formation of gaseous and stellar disks observed in field dwarfs are not required for the formation of cores. Each outflow typically removes gas only from a small area (typically < 1kpc) around the galaxy center and disks remain fairly thin (Sánchez-Janssen et al. 2010). This model is similar to that proposed in Read & Gilmore (2005), where the need for repeated outflows was stressed, and Mashchenko et al. (2008), where ongoing SF was associated with cusp-flatting. In fact, some studies were not able to create cores using single, massive blowouts (Gnedin & Zhao 2002, Boylan-Kolchin et al. 2011a). Our results suggest that those models fail as the amount of baryons removed from the central kpc is small over a single outflow event, irrespective of the fact that the whole galaxy gas reservoir can be blown away. Consequently, the energy transfer to the central DM over a single outflow event is small compared to the binding energy of the DM cusp and multiple events become necessary.

In the scenario proposed in this work, only very small galaxies ($V_{peak} < 20$), where SF is extremely inefficient, retain the cuspy CDM profile that was originally predicted by DM–only simulations. In very small objects star formation rates are too low to generate sufficient energy to modify the CDM cusp. This sets an interesting scale (Willman et al. 2003, Tollerud et al. 2008) where primordial cuspy profiles would still be observable. These observations would be able to discriminate between CDM and alternative DM models, where cores are generated by primordial effects and would then be present even in the lowest stellar mass objects.

The comparison with the THINGS and LITTLE THINGS dataset shown in Fig.1 (more details in Oh et al, in prep) shows an extremely good agreement between the simulations and the real galaxies. The observational data set includes 22 galaxies. The simulations reproduce both the absolute values of α and the trend with stellar mass.

Using the following formula (de Blok et al. 2001), we...
Figure 4. The total mass (baryons and DM) within the central 500pc as a function of stellar mass: Large and small crosses: simulations. Open squares: galaxies from THINGS (Oh et al. in prep). Stars: dSph from Walker (priv. comm.). Theoretical predictions reproduce the observed flat trend from \(10^5\) to \(10^9\) M\(_\odot\). This is largely due to the large drop in SF efficiency at small halo masses, that stretches the range of galaxy luminosities over a relatively smaller halo mass range. The solid and dashed lines assume different stellar mass - total halo mass relations. A close fit to the simulations as \(M_\star \propto M_{\text{Vir}}^2\) (solid) and one showing \(M_\star \propto M_{\text{Vir}}\) (dashed). Only when the star formation efficiency is a steep function of halo mass it is possible to reproduce the observed trend, as discussed in §4. More massive galaxies above the solid line have a small bulge component.

first converted the dark matter rotation curves derived subtracting the baryons from the total kinematics of the 22 dwarf galaxies to the dark matter density profiles (see Oh et al. 2011a,b for more details),

\[
\rho(R) = \frac{1}{4\pi G} \left[ 2 \frac{V}{R} \frac{\partial V}{\partial R} + \left( \frac{V}{R} \right)^2 \right],
\]

where \(V\) is the rotation velocity observed at radius \(R\), and \(G\) is the gravitational constant. We then measured the logarithmic inner slopes \(\alpha\) of the derived dark matter density profiles assuming a power law (\(\rho \sim r^{-\alpha}\)). After determining a break-radius (< 1 kpc) where the slope changes most rapidly, we measured the inner slope by performing a least squares fit to the data points of a given profile within the break-radius. A similar analysis had been performed by OH11 on two simulated dwarfs that were compared to galaxies from the THINGS survey. Their analysis compared estimates of \(\alpha\) obtained from the observed mass distributions and from artificial observations (HI datacubes paired with artificial photometric images) of the simulations. The two methods showed good agreement. Relevant to the results presented here, OH11 also showed that observations can correctly recover the DM profile of galaxies with no significant biases. Those tests support the analysis and the results presented here. In a future work (Oh et al in prep) the observational dataset will be presented in more detail and it will be compared with results obtained by artificial observations of the new simulations.

We have verified that our results are robust versus unwanted numerical effects. In particular we find that the graininess of the DM potential (due to a finite number of particles) does not substantially affect its response to gas outflows. To this aim we increased the number of DM particles by a factor of eight for all the halos in in Field 3, finding that the measured DM slopes remain substantially unchanged. In G10 we verified that gas resolution effects dominate over pure DM resolution effects as poorer resolution creates more cuspy cores, likely as outflows become poorly resolved and artificial viscosity brings more gas to a galaxy centre. As most halos were re–run including only the DM component we also verified that the central DM profiles in the absence of baryons were as cuspy as those in the literature (Reed et al. 2007, Macciò et al. 2007, e.g.). Fig.2 shows good agreement between the slopes measured from our simulations and the predictions inferred from Macciò et al. (2007) over the whole sample range in mass and resolution. This test, combined with the existing data points in the halo range \(10^{10}-10^{11}\) that span a range in mass and force resolution (Table 1), show that core formation and sizes are stable quantities over the resolution range explored in this work.

The analytical model of core formation presented in Pontzen & Governato (2012) shows that the creation of DM cores should be a generic property of fast, repeated gas (out)flows. Core creation should then be a common outcome of any feedback scheme that can create such flows (Springel et al. 2004, Keres et al. 2008, Oppenheimer et al. 2010, Choi & Nagamine 2011, Hopkins et al. 2011) as long as sufficient spatial resolution and high SF surface densi-
ties are achieved. However, as some traditional SPH implementations provide a poor description of Rayleigh-Taylor and Kelvin-Helmholtz gas instabilities [Agertz et al. 2007] it will be important to evaluate how potential improvements recently introduced by different gasdynamical treatments (Read & Hayfield 2011; Bauer & Springel 2011; Keres et al. 2011) affect the outcome of baryon energy injection from different astrophysical processes. Encouragingly, results showing the formation of DM cores due to repeated energy injection (from super massive black holes) into the gas component were also recently obtained using an AMR code (Marlizzi et al. 2011).

The extremely good agreement between observations and simulations strongly supports that baryon-DM interactions, and specifically repeated baryonic outflows, are able to lower the DM density at the center of galaxies, creating DM ‘cores’. This result resolves one of the outstanding problems faced by the CDM model of galaxy formation, namely the strong discrepancy between the original model predictions and the observed DM distribution in galaxies.

4 THE CENTRAL MASS CONCENTRATION OF GALAXIES: SIMULATIONS VS OBSERVATIONS

In this section we compare the total mass contained in the central regions of our simulated galaxy sample with the existing constraints coming from 12 galaxies in the LITTLE THINGS and THINGS sample and from a sample of local dwarf spheroidals (Walker et al. 2009, dSph). This comparison is necessary to test if the distribution of stars, gas and DM of the simulated galaxies is realistic over a range of galaxy masses, hence making our predictions on the shape of the DM density profiles of galaxy halos robust. With this goal we will focus on a recent observed relation that has placed strong constraints on the CDM model, namely the central mass – luminosity relation (Strigari et al. 2008, S08 hereafter). As our simulations have not been tuned to be a good match to these observational data they will provide a good test of the efficiency of SF as a function of stellar mass and of the relative effect of outflows as a function of halo mass.

Fig. 4 shows the total mass within 500 pc for the simulated field galaxies in our sample, as a function of their total stellar mass. The figure also shows similar estimates from observed galaxies. For the observational sample, stellar masses are obtained assuming a M/L ∼ 2 for the Walker et al sample (Walker, priv.comm.) and from the optical and Spitzer IRAC 3.6μm photometry for the THINGS and LITTLE THINGS samples (Oh et al. in prep.). In particular, for the THINGS and LITTLE THINGS samples, we obtain the 3.6μm mass-to-light ratio values from optical colors based on Bruzual & Charlot stellar population synthesis models (Oh et al. 2008; Bell & de Jong 2003). In addition, assuming a spherical potential, we calculate the total masses (DM + baryons) within 500 pc of the THINGS and LITTLE THINGS samples from their total rotation curves.

Measurements from simulations are in extremely good agreement with the observed estimates, which with the addition of the THINGS and LITTLE THINGS datapoints extend the results in S08 by almost two orders of magnitude to larger galaxy masses. It is also remarkable that the two observational samples agree with each other very well, being one comprised of Milky Way satellites and the other of field, rotationally supported galaxies. Our simulations predict that the flat central mass – stellar mass relation will start an upward trend for galaxies with stellar masses > 10^9 M⊙. At that mass scale our simulated galaxies start having a small bulge component and the total mass within 500 pc starts growing. The flat central mass - stellar mass relation shown by our simulated CDM galaxies, differs from the naive expectations from DM-only runs, which show a clear correlation between halo peak velocity (or halo mass) and the mass within a fixed radius; in those models more massive halos contain more mass (Li et al. 2009) within a fixed radius.

Our analysis, focusing on simulated field halos, also removes the complications introduced by the dynamical interactions with the host galaxy potential as for the satellites of the Milky Way (Stoehr et al. 2012). Fig.5 shows the circular velocity V_c (defined as \sqrt{(M/r)}) for the galaxies in our sample, where M is the total mass within r. This plot supports the finding that the total amount of mass within the central kpc is a weak function of the galaxy peak velocity. These findings suggests that in our simulations a flat central mass – stellar mass relation originates from having a large range in luminosities over a relatively small range in halo masses and is possibly further helped by the flattening of the central DM mass profile in the more massive galaxies. The continuous and dashed lines in Fig.4 show the resulting central mass - stellar mass relation if a different mapping between halo and stellar mass is adopted (normalized at 10^9 M⊙). The continuous line is for M_c ∝ M_V^{1/2} as in our simulations. The dashed line assumes a linear relation M_c ∝ M_V that would be created by having less efficient feedback at smaller masses, resulting in more stars. In this

![Figure 5. The z = 0 rotation curve of a sub-sample of our simulated galaxies measured at z=0 from the simulations that included SF and gas processes. Each line correspond to a different galaxy. The amplitude of the rotation curve measured at ~ 500pc is almost constant over a large range of masses as more massive galaxies tend to have flatter DM cores.](image-url)
second case there is a clear trend between stellar mass and total central mass, as a much larger range in halo masses is mapped over the same range in stellar masses. As a consequence, if simulations had a weaker feedback they would not match the central mass - stellar mass relation.

Note that we only plot the subsample of Strigari’s sample that could be safely extrapolated out to 500pc. As shown in S08, the full sample continues to follow a flat central mass - stellar mass relation down to $\sim 10^8 M_\odot$ (in stars) when measured at 300pc. We decided against extrapolating to 500pc the stellar and total masses of the smallest galaxies in the observed sample. This extrapolation becomes less reliable going to very faint/small galaxies with very small sizes (Walker, private comm.). On the other hand our simulations would become less reliable at smaller radii. We plan to study the mass distribution in ultra-faint dwarfs and in satellites of MW–like systems in future, higher resolution simulations that will allow robust predictions at smaller radii.

The scatter in accretion histories and SF truncation times of the MW satellites due to ram pressure (Mayer et al. 2007) has often been cited as a possible origin of the central mass - stellar mass relation (Maccio et al. 2008, Li et al. 2004, Parry et al. 2011), as it would cause a large scatter in the amount of formed stars at a given halo mass. This mechanism cannot be responsible for the flat trend in Fig.4, where the THINGS galaxies and all the simulated galaxies are field galaxies with a prolonged, untruncated SFH. We plan a more detailed comparison using a larger ensemble of simulated satellites of MW analogues (Brooks et al, in prep.). These results are very encouraging, as the ability of creating realistic galaxies (see also G10) gives further support to gas outflows as the origin of the flattening of CDM density profiles.

5 CONCLUSIONS

In this work we used fully cosmological hydrodynamical simulations to show that once baryonic processes are correctly taken into account, shallow central DM profiles are a common property of field galaxies formed within the $\Lambda$CDM model. Our predictions are in excellent agreement with observational estimates of the DM distribution in galaxies from the THINGS and LITTLE THINGS data samples and extend results from Governato et al. (2010, 2012). The introduction of gas outflows in high resolution simulations resolves the long standing tension between the observed ‘cored’ DM distribution at the center of small galaxies and the dense cuspy DM distribution predicted in (C)DM–only simulations. SN feedback is shown to be a vital ingredient in galaxy formation models, where the removal of low angular momentum gas creates at the same time galaxies with DM cores and bulgeless dwarfs (Fall 1983, Bullock et al. 2001, van den Bosch et al. 2001, Maschordered et al. 2008, Brook et al. 2011, Pontzen & Governato 2012, G10).

This work highlights the fundamental role that baryon and DM interactions play in shaping galaxy properties as fundamental as their central DM and baryon distribution. Predictions on the detailed properties of galaxies based on DM–only simulations or methods where baryon dynamics are not fully coupled to the DM need to be viewed with some caution.

The simulated galaxies described in this work covered more than 5 orders of magnitude in stellar mass and circular velocities from 10 km s$^{-1}$ to 100 km s$^{-1}$. These simulations were carried to $z=0$, included metal cooling and H$_2$ related processes with the spatial and mass resolution to identify individual star forming regions. In these simulations bursty SF limited to dense, H$_2$ rich regions creates repeated, fast outflows which break the adiabatic approximation. Over several Gyrs, these fast and repeated outflows progressively lower the central DM density of galaxy halos and turn CDM central ‘cuspy’ profiles into much shallower ‘cores’.

With the combination of SN feedback and cosmic UV background adopted in this work, the DM distribution remains cuspy (or at least with cores smaller than our current spatial resolution) only in dwarfs with $M_{star}$ less than $10^5 M_\odot$, where less than 0.03% $M_\odot$ of the original baryon fraction was turned into stars. These findings strongly support the analytical model presented in Pontzen & Governato (2012) and other numerical works on the formation of cores (Governato et al. 2010, Martizzi et al. 2011, Macciò et al. 2012), while making detailed observable predictions.

As an important consistency check of our model of baryon–DM interactions, we compared our simulations to the observed central mass - luminosity relation for dwarf, extended to a sample containing also filed galaxies from the THINGS and LITTLE THINGS surveys (Oh et al, in prep, S08). Our simulations reproduce the almost constant total mass within the central 500pc of dwarf galaxies over a wide range of masses, up to a few times $10^8 M_\odot$. In our framework this result is caused by rapidly decreasing SF efficiency at decreasing halo masses and SN feedback simultaneously lowering the central DM density in more massive galaxies. These two effects cause galaxies over a large range in luminosities to inhabit halos with a relatively small mass range within the central kpc.

The correct modeling of baryon–DM interactions in galaxy formation simulations is still in its early stages and the differences between various feedback schemes are possibly even larger than the discrepancies still existing between different gasdynamical codes (Scannapieco et al. 2011). It is remarkable that feedback processes similar to those commonly observed in galaxies can simultaneously improve on at least three fundamental problems in galaxy formation: i) the substructure overabundance problem by rapidly decreasing SF efficiency at smaller halo masses, ii) the formation of bulgeless galaxies in hierarchical models by the selective removal of low angular momentum gas and iii) the existence of DM cores in CDM cosmologies by allowing energy transfer from baryons to the DM matter. While it is possible that other physical processes are involved in each of the above problems, numerical and analytical models point to the ubiquitous role of energy feedback. Further comparisons with observational data, especially the constraints coming from the Milky Way satellites, will involve understanding in detail how the properties of the mass distribution of faint dwarf galaxies can be inferred from their stellar kinematics (Evans et al. 2011, Koposov et al. 2011, Boylan-Kolchin et al. 2011a, Adams et al. 2012) and how interactions with the main galaxy affect the DM, SFHs and final stellar distribution of galaxy satellites. We expect these comparisons to add further constraints on the effects of SN feedback as a function of halo mass and to guide predictions.
for DM direct detection experiments \cite{Dalal_2002}. In the near future we will also extend our analysis to higher mass systems as \( \sim 10^8 \) galaxies, where the presence of DM cores is still debated \cite{Swaters_2011,Chemin_2011}. Measurements of the mass distribution in very faint galaxies will be able to strongly distinguish between baryon-DM interaction models from those invoking alternative DM models to explain the observed central distribution of galaxies.

ACKNOWLEDGMENTS

FG and TQ were funded by NSF grant AST-0908499. FG acknowledges support from NSF grant AST-0607819 and NASA ATP NNX08AG84G. AZ gratefully acknowledges support from The Grainger Foundation. Some of SHO research was carried out at TACC and NAS. We thank Matthew Walker for sharing his data and Oleg and Nick Gnedin, Avishai Dekel, Piero Madau, Mike Boylan-Kolchin and Jorge Peñarrubia for useful discussions.

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