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# DARK MATTER CORES IN THE FORNAX AND SCULPTOR DWARF GALAXIES: JOINING HALO ASSEMBLY AND DETAILED STAR FORMATION HISTORIES

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## ABSTRACT

We combine the detailed Star Formation Histories (SFHs) of the Fornax and Sculptor dwarf Spheroidals (dSphs) with the mass assembly history of their dark matter halo progenitors to estimate if the energy deposited by Supernova type II (SNeII) is sufficient to create a substantial dark matter core. Assuming the efficiency of energy injection of the SNeII into dark matter particles is  $\epsilon_{gc} = 0.05$ , we find that a *single* early episode,  $z \gtrsim z_{\text{infall}}$ , that combines the energy of all SNeII due to explode over 0.5 Gyr, is sufficient to create a core of several hundred parsecs in both Sculptor and Fornax. Therefore, our results suggest that it is energetically plausible to form cores in Cold Dark Matter (CDM) halos via early episodic gas outflows triggered by SNeII. Furthermore, based on CDM merger rates and phase-space density considerations, we argue that the probability of a subsequent complete regeneration of the cusp is small for a substantial fraction of dwarf-size haloes.

*Subject headings:* galaxies: dwarf — galaxies: evolution — galaxies: formation — galaxies: Local Group — galaxies: individual: Fornax dwarf galaxy, Sculptor dwarf galaxy

## 1. INTRODUCTION

Disagreements at small galactic scales are certainly not a recent surprise for the  $\Lambda$ CDM paradigm, and the so called core-cusp problem is in fact one of the oldest. Flores & Primack (1994) and Moore (1994) first brought the attention on the mismatch between the characteristic  $\rho \sim r^{-1}$  density cusp observed in dark matter (DM) only simulations (Dubinski & Carlberg 1991; Navarro et al. 1996a) and the constant density cores inferred in dwarf disk galaxies. DM cores are now known to be ubiquitous in low surface brightness galaxies (Kuzio de Naray et al. 2008) and nearby dwarf galaxies (de Blok et al. 2008). More recently, the problem has grown starker because of increasing, independent evidence that also several DM dominated dwarf Spheroidals (dSphs) may in fact host DM cores. The large orbits of the Globular Cluster system in Fornax (Goerdts et al. 2006; Sánchez-Salcedo et al. 2006; Cole et al. 2012), the survival of cold kinematical substructures in Ursa Minor and Sextans (Kleyna et al. 2003; Battaglia et al. 2011), and direct dynamical modelling of the stellar population of Fornax and Sculptor (see e.g. Battaglia et al. 2008; Walker & Peñarrubia 2011; Agnello & Evans 2012; Amorisco et al. 2013), all testify against the presence of divergent cusps in dSphs.

An emergent challenge is the so called ‘too big to fail’ problem (TBTf). Boylan-Kolchin et al. (2011, 2012) (BK12) noticed that the observed central densities of the bright dSphs of the Milky Way (MW) are about a factor of a few smaller than those of the most massive satellites

formed in DM-only cosmological simulations of MW-size halos.

There are different means of easing these dwarf-scale controversies. Some of the proposed solutions require changes to the nature of DM as a particle. For example, non-zero thermal velocities imply a suppression of the DM power spectrum at subgalactic scales; however, in order to solve the core-cusp problem, a warm DM particle would be required to be unfeasibly warm (Macciò et al. 2012). DM collisionality, instead, might look like a more promising venue (Vogelsberger et al. 2012; Rocha et al. 2013; Zavala et al. 2013), with self-interacting DM particles – cross section of about  $\sigma/m \gtrsim 0.6 \text{ cm}^2 \text{ g}^{-1}$  – being able to better reproduce the central densities and core-sizes of dwarfs.

On the other hand, it might not be necessary to abandon the realm of CDM to solve the core-cusp problem. In fact, the first attempts at *transforming* a dwarf galaxy’s cusp into a core date back to Navarro et al. (1996b). Through gravitational coupling, baryonic processes such as supernova (SN) momentum feedback could potentially be responsible for the cusp-core transformation. By displacing the gas in essentially impulsive blow-outs, bursts of SN explosions may be able to dynamically heat the central cusp, expanding the orbits of DM particles. Recent numerical experiments have observed such transformations in both cosmological hydrodynamical runs (Mashchenko et al. 2008; Governato et al. 2010, 2012; Zolotov et al. 2012) and idealized controlled simulations (Teyssier et al. 2013).

Apart from more technical reasons connected with numerical resolution and/or with the different implementations of the necessary sub-grid physics, some doubts still remain on the applicability of this scenario to the specific dSphs for which a core has been detected, e.g., Fornax and Sculptor. For instance, the baryonic fraction is a crucial ingredient in this mechanism: it weights the amount of potentially available energy in stellar feedback against the bound halo mass, the growth of which makes any cusp transformation more energetically challenging. For example, BK12, Peñarrubia et al. (2012) and Garrison-Kimmel et al. (2013) have warned that the energy necessary to reduce the central density of a typical TBTF  $\Lambda$ CDM subhalo, with  $V_{max} \approx 35 \text{ km s}^{-1}$ , to a level that is compatible with the bright MW satellites is in fact too large to be provided by stellar feedback.

However, most of these calculations thus far have not taken into account the mass assembly histories of such subhalos, whose bound mass has, on average, grown monotonically with redshift until accretion onto the MW. Additionally, in order to tailor such calculations to a specific dwarf, one should also take into account its particular Star Formation History (SFH): feedback was most effective at specific moments of its assembly history, so that different dwarfs will be impacted in diverse ways.

In this *Letter* we investigate in detail the specific cases of the Fornax and Sculptor dSphs, in order to ascertain whether the observed cores in their DM density distributions can be the result of mechanical feedback from SN explosions. We quantify the available energy by making use of their detailed SHFs (de Boer et al. 2012a,b). Hence, we explore the potential of such energy release on the likely progenitors at different redshifts, finding that large cores can be formed, especially at intermediate redshifts ( $z \gtrsim 4$ ). Finally, by investigating the effect of a similar energy release in more massive halos, we comment on the TBTF problem.

## 2. QUANTIFYING SN RATES THROUGH DETAILED STAR FORMATION HISTORIES

By using both deep multicolor photometry and large spectroscopic samples, de Boer et al. (2012a,b) have recently reconstructed the SFHs of the Fornax and Sculptor dSphs. They find these to be essentially different systems: while Fornax experienced a complex SFH extending to less than only a few hundreds Myr ago, Sculptor had already completed its stellar build-up around 8 Gyr ago. By integrating the star formation rate in time, we estimate that the total stellar mass of the Fornax dSph is  $M_* = (3.12 \pm 0.35) \times 10^7 M_\odot$ , while we obtain  $M_* = (8.0 \pm 0.7) \times 10^6 M_\odot$  for the Sculptor dSph.

We profit from the increased age resolution reached by de Boer et al. (2012a,b) and quantify the number of SN explosions at different moments in time. For simplicity, we only consider the explosion of SN type II (SNeII), whose energetic feedback dominates over that of SNeIa. Figure 1 displays the total number of SNeII explosions which occurred in each age bin of the SFH histogram. These are obtained by following the technique outlined in Matteucci (2012). We isolate the fraction of the stars with mass in the interval  $8 < M/M_\odot < 16$  that explode as SNeII – rather than as type Ia – and subsequently add the massive stars in the interval  $16 < M/M_\odot < 40$ . For a Kroupa IMF, this corresponds to about one SNeII

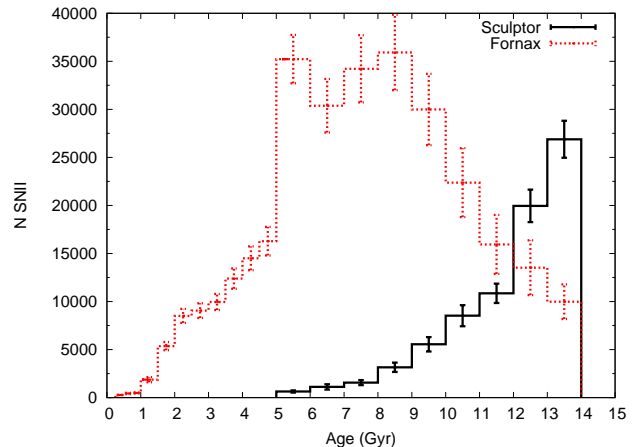


FIG. 1.— The number of SNeII (per age bin) occurring in Sculptor (black, solid) and Fornax (red, dashed), according to the SFH as presented in de Boer et al. (2012a,b).

explosion for each  $100 M_\odot$ . For Fornax, this implies that a total of  $N_{SNeII} \approx 3 \times 10^5$  SNeII explosions occurred to the present day, while a total of  $N_{SNeII} \approx 8 \times 10^4$  exploded in Sculptor over its history.

The DM halo only absorbs a small fraction of the total energy that is actually released in a burst of SNe. Part of the energy is first transferred to the gas, the rapid displacement of which heats the DM particles with a final *gravitational coupling* efficiency  $\epsilon_{gc}$ . Recent estimates place this value between  $\epsilon_{gc} \approx 0.05$  (Kirby et al. 2011) and the more generous  $\epsilon_{gc} \approx 0.4$  adopted in Governato et al. (2010). Also, despite great improvement in the determination of SFHs, resolving in age an old burst of star formation is not yet possible. Henceforth, in order to translate the smooth rate of SNeII explosions  $E'_{SN}$  (see lower panels in Fig. 2) into the actual strength of a particular burst  $E_b$ , we need to introduce a parameter for the ‘burstiness’ of the SFH. We assume that the burst  $E_b(t) = \int_t^{t+\tau} E'_{SN} dt$  collects the energy of SNe exploding over the timescale  $\tau$ . In conclusion, the energy that is actually *injected* in the DM halo after one specific burst is

$$E_{inj} = \epsilon_{gc} \cdot E_b \approx \epsilon_{gc} \cdot \tau E'_{SN} . \quad (1)$$

## 3. HALO ASSEMBLY HISTORIES AND CORE FORMATION

Recently, Peñarrubia et al. (2012) presented a simple and efficient method to quantify the energetics of the cusp-core transformation. Given an initial density profile, they used the virial theorem to estimate the minimum amount of energy that must be absorbed by the DM halo so that its particles can redistribute into a new equilibrium state:

$$E_{inj} = (W_2 - W_1)/2 , \quad (2)$$

where  $W$  is the total gravitational binding energy. We assume that our initial states are cosmologically motivated cuspy NFW profiles (Navarro et al. 1996a), later to be replaced by a cored profile as a result of the energy injection:

$$\rho_2 = \frac{\rho_{s,c} r_s^3}{(r + r_c)(r + r_s)^2} , \quad (3)$$

where  $r_c$  is the core radius and  $\rho_{s,c}$  is such that the virial mass  $M_{200}$  (defined as the mass enclosed in a sphere with

mean density 200 times the critical value) is conserved.

The mass assembly and structural evolution of  $\Lambda$ CDM halos has been followed closely by countless numerical studies. We are interested in the growth of dwarf-size halos that, if they were to grow in isolation up to  $z = 0$ , would now be characterized by  $9 \lesssim \log_{10}(M_{200}^{z=0}/M_{\odot}) \lesssim 10.5$ . Sawala et al. (2010, 2011) and BK12 show that, for redshifts  $z \gtrsim 10$ , the median of the bound mass is essentially exponential with redshift,

$$M_{200}(z) \approx M_{200}^{z=0} \exp(-z/z_0). \quad (4)$$

Additionally, comparing the same works we find that the characteristic time scale  $z_0$  of such growth is approximately independent of  $M_{200}^{z=0}$  in the mentioned interval, so that we can univocally fix it ( $z_0 = 0.15$ ). We will not model the effects of tidal stripping and heating, which depend critically on the dwarf's orbit and infall time; both of these effects make the core-cusp transformation more effective after accretion, so that we can conservatively consider the mass assembly of haloes which are isolated to the present time. Mass growth is accompanied by structural evolution, which we can reproduce by evolving with redshift the concentration-mass relation, for example as explicitly prescribed – for isolated haloes – by Gao et al. (2008). In conclusion, once the current mass of a  $\Lambda$ CDM halo  $M_{200}^{z=0}$  has been chosen, we can reconstruct its assembly history and calculate, at any redshift, its detailed DM density profile, and then its binding energy  $W_1$ .

Before addressing the specific cases of Fornax and Sculptor, it is useful to consider the dimensionless ratio  $E_{inj}/W_1$ . In terms of core formation, interesting episodes of stellar feedback are those in which the DM halo absorbs a fraction of its own potential energy:  $0.01 \lesssim E_{inj}/W_1 \lesssim 0.1$ . When the injected energy is smaller, no astrophysically appreciable core is formed; if it is higher, the episode is potentially catastrophic in reshaping the halo, and the qualitative model given by eqn. (2) likely breaks.

The structural properties of  $\Lambda$ CDM halos are such that:

$$W_1(z) \propto \rho_s^2 r_s^5 \sim M_{200}(z)^{1.65} \propto (M_{200}^{z=0})^{1.65}, \quad (5)$$

i.e. there is a simple scaling between the potential energy  $W$  and  $M_{200}^{z=0}$ , the only free parameter in the median mass assembly history. As a consequence, since the SNeII rate  $E'_{SN}$  is fixed by the SFH, the evolution of a given halo will be essentially driven by the global factor:

$$\epsilon_{gc} \cdot \tau / \text{Gyr} \cdot (M_{200}^{z=0}/M_{\odot})^{-1.65} \equiv \epsilon_{tot} \cdot (M_{200}^{z=0}/M_{\odot})^{-1.65}. \quad (6)$$

In other words, given a burst of SN of energy  $E_b(t)$ , it is equivalent to have a 4 times heavier halo or 10 times smaller total efficiency, both changes determine an analogous effect in the ratio  $E_{inj}/W_1$ , which corresponds to a comparable result in terms of core formation.

### 3.1. Fornax and Sculptor

Figure 2 follows the evolution of the Fornax and Sculptor dSphs (left and right panels, respectively), and quantifies the effect of SNeII feedback – obtained from the SFHs – on their likely progenitors. Both plots show the ‘ratio of interest’  $E_{inj}/W_1$  of each possible SN burst

$E_b(t)$ , as a function of redshift. Shaded areas are obtained by assuming that the gravitational coupling efficiency is  $\epsilon_{gc} = 0.05$  and that individual bursts collect the energy of the smooth SNe rate  $E'_{SN}$  over a time  $\tau = 0.5$  Gyr. The color coding shows the core size that any of these bursts would individually form at a given redshift, starting from the corresponding  $\Lambda$ CDM progenitor.

The width of the shaded areas in both panels reflects the uncertainty on the virial masses of Fornax and Sculptor. We assume that their inner regions – namely within their half-light radii – have not been significantly affected by mass depletion due to tidal forces after infall. The mass at approximately the half-light radius  $M^{z=0}(< R_h)$  represents the most robust dynamical constraint allowed by current kinematic data (Walker et al. 2009; Wolf et al. 2010; Amorisco & Evans 2012). We identify the allowed progenitors as those haloes that, at  $z_{inf}$ , were already massive enough to comply with the requirement  $M^{z=z_{inf}}(< R_h) = M^{z=0}(< R_h)$ . According with recent estimates (Rocha et al. 2012), Fornax was accreted between 4 and 9 Gyr ago, while Sculptor between 7 and 9 Gyr ago. We find that higher infall redshifts imply higher virial masses, and then conservatively use, for both dwarfs, the interval  $1 \lesssim z_{inf} \lesssim 2$ . This translates in the mass interval  $9.4 \leq \log_{10}(M_{200}^{z=0}/M_{\odot}) \leq 10$  for Fornax and  $9.3 \leq \log_{10}(M_{200}^{z=0}/M_{\odot}) \leq 9.9$  for Sculptor.

As the color coding shows, at redshifts higher than 4 (6), a single burst of SNe with low coupling is indeed able of creating a core of at least 100 pc in Sculptor (Fornax). Lower virial masses in the allowed interval make the effect of feedback considerably more pronounced, with nominal core radii shooting above 1 kpc. The dashed red lines in both panels show the level of caution  $E_{inj}/W_1 = 0.2$ , where any transformation goes probably beyond the simple formation of a core. This might even be used to put upper bounds on the coupling efficiency  $\epsilon_{gr}$  or on the strenght of the burst itself (parameterised by  $\tau$ ).

As prescribed by eqn. (6), the vertical arrows in the right-hand panel of Fig. 2 indicate the magnitude of the effect of intermediate changes in the free parameters of the problem. In particular, given that subhaloes surviving to the present times might have been more concentrated than the average isolated halo with the same virial mass, we have investigated the effect of more concentrated progenitors. An increasing concentration makes the cusp-core transformation more challenging, although we find that the effect is quite limited. A concentration that is two times higher than the concentration-mass relation compiled by Gao et al. (2008) (the 95% percentile implies a concentration that is only 50% higher) results in a change in the core sizes that is equivalent to a vertical shift of  $\approx 0.2$  dex in our Fig. 2, leaving our conclusions unchanged.

Because of tidal effects, Fig. 2 substantially underestimates the effect of any burst at  $z \leq z_{inf}$ . This is especially relevant for Fornax, that has an important stellar population of intermediate age. As the arrows in the right-panel show, at  $z \approx 1$ , for a reduction of only a factor of 4 of the bound mass, a single burst accumulating the energy of all SNe exploding over a 0.5 Gyr period with a low coupling could be capable of forming a core of about 1 kpc.

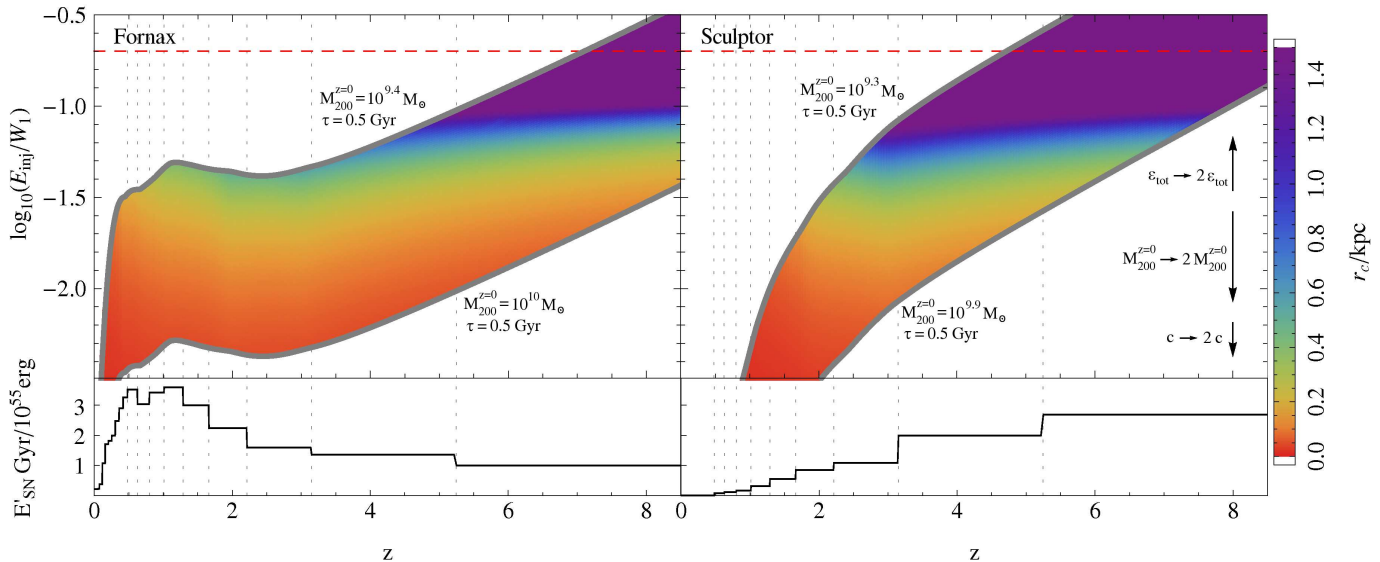


FIG. 2.— The effect of SNeII momentum feedback obtained from the detailed SFHs of the Fornax (left panel) and Sculptor (right panel) dSphs. In both panels the shaded areas display the effect of individual bursts that collect *all* the energy of SNe exploding in a period of half a Gyr, for progenitors in the mass range  $9.4 \leq \log_{10}(M_{200}^{z=0}/M_{\odot}) \leq 10$  for Fornax,  $9.3 \leq \log_{10}(M_{200}^{z=0}/M_{\odot}) \leq 9.9$  for Sculptor. The gravitational coupling of the bursts with the DM halo occurs with an efficiency of  $\epsilon_{gc} = 0.05$ . The lower panels display the history of SN rates according to the SFHs of Fig. 1. The arrows on the right panel indicate the magnitude of the vertical shifts that occur if certain parameters are varied as given in the legends.

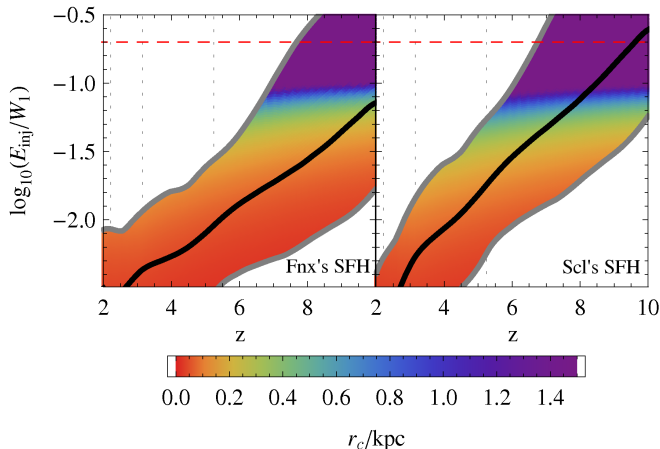


FIG. 3.— The effect of the stellar feedback obtained from the SN rates of Fornax and Sculptor (left and right panels, respectively) during the mass assembly history of a typical ‘too big to fail’ DM subhalo (68% confidence region of the mass assembly history, see BK12). Injected energies are calculated assuming a burst with  $\epsilon_{gc} = 0.05$  and  $\tau = 0.5$  Gyr.

### 3.2. The ‘too big to fail’ problem

If evolved in isolation to the present day, a typical TBTF subhalo would have a virial mass of about  $M_{200}^{z=0} \approx 10.2$ . This is more similar to the mass-range suggested for Fornax and Sculptor by abundance-matching (see Peñarrubia et al. 2012), although somewhat at odds with the kinematical constraints. We investigate the effect of the SFHs of Fornax and Sculptor on  $V_{max} \approx 35 \text{ km s}^{-1}$  DM subhalos by using their average mass assembly history as recorded in Fig. 4 of BK12. For the 68% confidence region in the mass assembly distribution, our Fig. 3 displays the evolution of the ratio of interest  $E_{inj}/W_1$  for the case of bursts with  $\tau = 0.5$  Gyr, and a gravitational coupling efficiency  $\epsilon_{gc} = 0.05$ . Despite the larger binding energies, the SFHs of both Fornax and Sculptor (left and right panels, respectively) prescribe enough SN ex-

plosions in their oldest couple of bins –  $t \gtrsim 12$  Gyr or  $z \gtrsim 3.5$  – that a suitably early burst would be able to enforce the formation of a core of several hundreds of parsecs. In order to lower the central density of a  $\Lambda$ CDM halo with  $M_{200}^{z=0} \approx 10.2$  to the levels of the MW bright dSphs (for example  $V_{circ} \approx 15 \text{ km s}^{-1}$  at  $r = 600 \text{ pc}$ ), a core of about  $r_c \approx 1 \text{ kpc}$  is needed, so that a *single* burst at redshifts  $z_b \gtrsim 10$  is necessary for Fornax, while  $z_b \gtrsim 7$  is likely enough for Sculptor.

## 4. DISCUSSION AND CONCLUSIONS

The detailed SFHs for the Fornax and Sculptor dSphs (de Boer et al. 2012a,b) imply that a significant number of SNeII exploded within their DM progenitors long before infall onto the MW. By coupling these SNe rates with the mass assembly histories of the DM progenitors, as given by recent CDM  $N$ -body simulations, we find that it is energetically plausible to create cores of several hundred parsecs in both dwarfs. Sufficient conditions for this to happen are (i) an energy deposition from the SNe into the DM particles with a coupling efficiency of  $\epsilon_{gc} = 0.05$ , and (ii) a *single* burst occurring before infall that instantaneously collects the energy of all SNe due to explode over a period of about 0.5 Gyr. A higher coupling efficiency, a more violent burst and/or repeated events would create even larger cores.

The earliest time when such a burst could have occurred is limited by photo-heating from the UV background after reionization, which prevents the condensation of gas in the early stages of the progenitor. The questions of how ‘bursty’ the SFH can be, and how ‘early’ the first effective burst can occur, remain open. Current implementations of galaxy formation simulations have not reached a consensus on the treatment of gas outflows driven by feedback, with different treatments seemingly producing realistic galaxy populations (e.g. Vogelsberger et al. 2013; Munshi et al. 2013; Starkenburg et al. 2013; Marinacci et al. 2013).

After the creation of such cores, the growth of the DM progenitors might pose a threat to their survival through slow accretion and mergers. However, complete reinforcement of the cusp seems quite unlikely. In order to do so, slow accretion and minor mergers should deposit a substantial amount of cold material into the central regions, with low specific angular momentum, which is not what is observed in the *inside-out* slow growth of CDM haloes. As for major mergers, because of phase-space density conservation, a dominant cusp can be reinforced only if the merging system is itself cusped (Dehnen 2005) and, at the same time, the mass ratio is sufficiently high. Even assuming the incoming halo had managed to conserve its own cusp, merger rates are mass dependent in CDM, so that only about 50% of dwarf-size haloes like Fornax and Sculptor experience a merger with mass ratio  $\gtrsim 1/3$  between  $z_{inf} \approx 1 \leq z \leq 4$  (Fakhouri et al. 2010).

Our main finding is that the energy requirements for the cusp-core transformation in dSphs do not seem very demanding when compared to their detailed SFHs, if these were indeed bursty. Our results provide an additional motivation to look for observational signatures

that can clearly distinguish a bursty from a quiescent SFH at time scales  $\lesssim 0.1$  Gyr (observational evidence seemingly supporting bursty star formation has been presented e.g. van der Wel et al. 2011). For instance, for those dwarfs in which kinematically cold clumps are present, these can be used to put lower bounds on the age of any useful SN burst, which would otherwise pose a serious threat to the survival of such delicate substructures.

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