The impact of cored density profiles on the observable quantities of dwarf spheroidal galaxies

David Harvey¹*, Yves Revaz¹, Andrew Robertson² and Loic Hausammann¹

¹Laboratoire d’Astronomie, EPFL, Observatoire de Sauverny, 1290 Versoix, Switzerland
²Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK

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ABSTRACT
We modify the chemo-dynamical code GEAR to simulate the impact of self-interacting dark matter on the observable quantities of 19 low mass dwarf galaxies with a variety star forming properties. We employ a relatively high, velocity independent cross-section of $\sigma/m = 10$ cm$^2$/g and extract, in addition to integrated quantities, the total mass density profile, the luminosity profile, the line-of-sight velocities, the chemical abundance and the star formation history. We find that despite the creation of large cores at the centre of the dark matter haloes, the impact of SIDM on the observable quantities of quenched galaxies is indiscernible, dominated mostly by the stochastic build up of the stellar matter. As such we conclude that it is impossible to make global statements on the density profile of dwarf galaxies from single or small samples. Although based mostly on quenched galaxies, this finding supports other recent work putting into question the reliability of inferred cored density profiles that are derived from observed line-of-sight velocities.

Key words: Galaxies: dwarf — Galaxies: evolution — Local Group — Cosmology — dark matter

1 INTRODUCTION

For the last twenty years it has been argued two major observations have caused a "small-scale crisis" in cosmology. The first is that the central regions of observed dwarf spheroidals have flat density profiles (a core), where CDM predicts centrally-rising profiles (a cusp) (Dubinski & Carlberg 1991; Navarro et al. 1996, 1997) and the second is that there appears to be insufficient dark matter in the most massive sub-haloes (Klypin et al. 1999; Moore et al. 1999; Boylan-Kolchin et al. 2011). However, more recently it has been noted that these structures are very sensitive to baryonic physics and environmental processes, altering the total density profile changing a cusp to a core (Pontzen & Governato 2014) and tidal stripping and ram pressure can disrupt halos bringing the expected number of observed small halos down considerably (Sawala et al. 2016; Wetzel et al. 2016). On the other-hand, even taking into account the unknown effects of baryons, some studies of dwarf galaxies have argued that discrepancies may possibly persist (Schneider et al. 2017) and these inconsistencies can be attributed to an incomplete description of dark matter (Springel & Steinhardt 2000; Lovel et al. 2012; Zavala et al. 2013; Rocha et al. 2013). As a result, it remains unclear whether there exists such a “crisis” or whether observations have been misinterpreted (Verbeke et al. 2017).

In this letter we modify a suite of dwarf spheroidal galaxy simulations to simulate the impact of self-interacting dark matter (SIDM) on their observable quantities and quantify exactly how well these objects can be used to understand the nature of dark matter.

SIDM in recent times has been of increased interest both theoretically and observationally. Theoretically it can thermalise halos, creating cores, and also potentially reduce the amount of substructure (Rocha et al. 2013; Peter et al. 2013; Buckley et al. 2014; Vogelsberger et al. 2016), and hence ease the apparent tensions. Observationally, high-resolution space-based imaging of large samples of galaxy clusters has meant that now we can probe this fundamental property down to $\sigma/m \sim 1$ cm$^2$/g (e.g. Harvey et al. 2015; Robertson et al. 2017; Markevitch et al. 2004; Massey et al. 2017), however, tight constraints from low mass halos remain sparse.

Given the nature of Dwarf Spheroidals and the peak in interest in SIDM, the number of studies looking at simulations of SIDM at the dwarf galaxy scale has naturally grown. Vogelsberger et al. (2014) originally studied two dwarf galaxies with both a constant and velocity dependent cross-section. Studying relatively large dwarf galaxies ($M_{\text{halo}} \sim 10^{10} M_\odot$, $M_* \sim 10^8 M_\odot$) they found that self-interactions had minimal impact on the global properties.

* e-mail: david.harvey@epfl.ch

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of the dwarf galaxies. However they did find that the metallicity in the centre rose by 15% and the stellar distribution traced that of the cored dark matter. Following this, the Feedback In Realistic Environments (FIRE) simulations reproduced the distribution of dwarf galaxies from a variety of formation histories. Secondly these studies did not calculate the impact on the direct observables, including the line-of-sight (LOS) velocities of stars within the halos and verify that the metallicity abundances were consistent with observations. Secondly these studies did not calculate the impact on the direct observables, including the line-of-sight (LOS) velocities of stars within the halos and verify that the metallicity abundances were consistent with observations.

Table 1. A direct comparison between 19 simulated dwarf galaxies with CDM and the corresponding halo with SIDM (i.e. CDM / SIDM). From left to right the columns give the halo ID, the total mass within $R_{200}$, the total stellar mass within $R_{200}$, the total gas mass within $R_{200}$, $R_{200}$ (the radius at which the mean enclosed density is 200 times the critical density), the mean line of sight velocity and the metallicity. The final column gives the classification of star formation whether it is sustained, extended or quenched.

| Model ID | $L_V$ [$10^6 L_\odot$] | $M_\star$ [$10^6 M_\odot$] | $M_{200}$ [$10^6 M_\odot$] | $R_{200}$ [kpc] | $\sigma_{LOS}$ [km/s] | [Fe/H] | SF Class |
|----------|--------------------------|-----------------------------|-----------------------------|------------------|-------------------|--------|----------|
| h019     | 291/283                  | 434/404                     | 9.5/9.4                     | 280/315          | 50.7/50.5         | 30.5/28.8 | -0.6/-0.5 | Sustained |
| h050     | 4.2/7.1                  | 9.6/13.7                    | 2.6/2.7                     | 15.1/20.2        | 33.0/33.2         | 10.4/10.8 | -1.3/-1.3 | Extended |
| h070     | 2.0/2.0                  | 5.8/5.9                     | 1.8/1.8                     | 0.0/1.5          | 29.2/29.3         | 10.8/10.3 | -1.5/-1.4 | Extended |
| h132     | 0.7/0.7                  | 2.1/2.1                     | 0.9/0.9                     | 0.5/0.6          | 23.1/23.0         | 9.3/9.0  | -2.1/-2.0 | Quenched |
| h074     | 0.5/0.5                  | 1.3/1.2                     | 0.7/0.7                     | 0.4/0.5          | 21.2/21.1         | 9.1/8.5  | -2.1/-2.2 | Quenched |
| h159     | 0.4/0.4                  | 1.1/1.0                     | 0.7/0.7                     | 0.0/0.0          | 21.0/21.0         | 8.9/9.5  | -2.3/-2.3 | Quenched |
| h064     | 0.4/0.4                  | 1.1/1.1                     | 1.9/1.8                     | 5.2/5.0          | 29.5/29.3         | 9.7/8.7  | -1.9/-1.9 | Quenched |
| h059     | 0.3/0.2                  | 0.7/0.6                     | 2.1/2.1                     | 4.2/4.3          | 30.5/30.5         | 9.3/8.9  | -2.4/-2.2 | Quenched |
| h141     | 0.2/0.2                  | 0.6/0.6                     | 0.8/0.8                     | 0.3/0.3          | 21.8/21.9         | 8.3/8.1  | -2.2/-2.4 | Quenched |
| h061     | 0.2/0.2                  | 0.5/0.6                     | 1.9/2.0                     | 3.4/3.6          | 29.8/30.0         | 9.1/9.6  | -2.1/-2.1 | Quenched |
| h111     | 0.2/0.2                  | 0.5/0.4                     | 1.1/1.1                     | 0.1/0.3          | 24.6/24.6         | 10.4/10.5 | -2.4/-2.4 | Quenched |
| h177     | 0.2/0.2                  | 0.5/0.5                     | 0.5/0.5                     | 0.0/0.0          | 19.4/19.4         | 7.7/7.9  | -2.6/-2.3 | Quenched |
| h091     | 0.2/0.2                  | 0.4/0.4                     | 1.4/1.3                     | 0.8/0.7          | 26.5/26.3         | 10.1/8.2 | -1.9/-2.5 | Quenched |
| h106     | 0.2/0.1                  | 0.4/0.3                     | 1.1/1.1                     | 0.1/0.1          | 24.6/24.5         | 9.9/8.3  | -2.8/-2.3 | Quenched |
| h122     | 0.1/0.1                  | 0.4/0.3                     | 1.0/1.0                     | 0.0/0.0          | 23.7/23.7         | 9.1/9.2  | -2.4/-2.5 | Quenched |
| h104     | 0.1/0.1                  | 0.3/0.4                     | 0.9/0.9                     | 0.3/0.1          | 23.3/23.0         | 9.0/8.5  | -2.3/-2.4 | Quenched |
| h123     | 0.1/0.2                  | 0.3/0.4                     | 0.9/0.9                     | 0.1/0.0          | 23.2/23.1         | 7.6/7.6  | -2.2/-2.3 | Quenched |
| h180     | 0.1/0.1                  | 0.3/0.3                     | 0.3/0.3                     | 0.0/0.0          | 15.9/15.7         | 6.9/6.9  | -2.4/-2.3 | Quenched |
| h168     | 0.1/0.1                  | 0.3/0.3                     | 0.6/0.6                     | 0.0/0.1          | 19.7/19.6         | 8.3/9.0  | -2.6/-2.5 | Quenched |

1 For those bright galaxies that continuously form stars, owing to the large sound speed of the feedback-heated dense gas, the time step may drop below 1000 years.
Results

Table 1 gives an overview of the results. For each column we show the CDM value followed by the SIDM value for the same halo. Throughout we split our sample into three star forming classes: sustained, extended and quenched as shown in the final column of this table.

In Figure 1 we show the radial dependence of four different properties for the three samples of dwarf galaxies at $z = 0$. The left hand column gives the sustained star forming galaxy, the middle column gives the two extended star forming galaxies and the final column gives the distribution of the 16 quenched galaxies, giving the region in which 68% of these galaxies lie. We also delineate the 2.8 times Plummer-equivalent gravitational softening length for the dark matter particles in the simulation, value beyond which the gravitational forces are Newtonian.

The top row shows the total matter density profile. In all but the sustained star forming galaxy we find that SIDM leads to cored density profiles, while CDM has larger central densities, also shown in the dark matter only profiles. Interestingly the core is unobservable in the total matter profile of h019 suggesting that the additional stellar component dominates in these galaxies and is also cored.

Investigating h019 further, we find that the mass within 300pc doubles in the final 2 Gyrs. This effect could be due to core collapse from a very high cross-section (Elbert et al. 2018). However, h019 is complicated, experiencing a major merger and as such particularly difficult to interpret.

Despite the dramatic difference between CDM and SIDM, we find that the projected luminosity profiles do not differ noticeably as shown in the third row. Interestingly, we find that SIDM in h050 has the opposite effect to what is expected. The SIDM increases the luminosity of this galaxy despite having a cored dark matter density, demonstrating the stochasticity during the formation of stars and how their dynamics are only weakly coupled to the dark matter. Finally, the quenched galaxies exhibit overlapping distributions, meaning that it would be impossible to differentiate between SIDM and CDM in these small, low mass haloes.

The final row shows the LOS velocity profiles. We find that the sustained star forming galaxy is slightly lower for

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the SIDM than the CDM. Although the total mass is the same, this difference might be the result of late time formation of stars within a cored halo resulting in this lower velocity. The middle column presents a somewhat unclear conclusion. Although h070 reacts to the drop in total density by exhibiting a lower velocity profile, halo h050 clearly has an indistinguishable velocity profile, despite also having reduced total and dark matter densities. We postulate that although these galaxies can have very different density profiles, stochastic build up of the stellar matter at early times in the central regions can cause CDM to mimic the observables of cored profiles in SIDM. The final column shows overlapping distributions, suggesting that it is common for dwarfs to have similar velocity profiles despite harbouring a factor of ~5 difference in total density.

3.1 Time evolution of the line-of-sight velocities
It is striking from Fig. [1] that although the total mass within the central region changes significantly with SIDM, we find little change in the stellar LOS velocities. We postulate this is because the observable quantities of the stars are defined by the potential in which they are formed, when the halo harbours a cusp. To examine this further we study the time evolution of the mass within 300 pc of three dwarf galaxies and the stellar LOS velocity at the same radii. Figure [3] shows the results. Each panel presents the results from a single dwarf galaxy with the CDM (SIDM) results in red (blue). The shaded region shows the evolution of the LOS velocities over cosmic time with the 1σ error and the solid lines shows the total mass within a 3D radius of 300 pc. We clearly see the core developing, with the SIDM mass departing from the CDM mass over time. However, the LOS velocity remains unchanged from its initial values, only mildly evolving with time. We conclude that the impact on the LOS velocity due to a redistribution of the central dark matter is imperceptible. This conclusion is confirmed by a Jeans prediction of the velocity dispersion of our simulated dwarfs.

4 DISCUSSION & CONCLUSIONS
We simulate a suite of 19 dwarf spheroidal galaxies using a modified version of the chemo-dynamical code GEAR to include self-interacting dark matter. We simulate a velocity independent cross-section of σ/m = 10 cm²/g with a three regimes of star formation and extract four observable quantities: the luminosity and the line-of-sight velocity profile, the metallicity abundance and the integrated star formation history. In general we find the change in dark mat-
The time evolution of the LOS velocity of stars at $500\,\text{pc}$ from the centre of the halo and its associated 1\,$\sigma$ error for three dwarf galaxies. The solid line is the time evolution of the integrated mass inside the same radius. The red are the dwarf galaxies with CDM and the blue is the SIDM.

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REFERENCES

Binney, J. & Tremaine, S. 1987, Galactic dynamics
Boylan-Kolchin, M., Bullock, J. S., & Kaplinghat, M. 2011, *MNRAS*, 415, L40
Buckley, M. R., Zavala, J., Cyr-Racine, F.-Y., Sigurdson, K., & Vogelsberger, M. 2014, *Phys. Rev. D*, 90, 043524
Dubinski, J. & Carlberg, R. G. 1991, *ApJ*, 378, 496
Durier, F. & Dalla Vecchia, C. 2012, *MNRAS*, 419, 465
Elbert, O. D., Bullock, J. S., Kaplinghat, M., et al. 2018, *ApJ*, 853, 109
Harvey, D., Massey, R., Kitching, T., Taylor, A., & Tittley, E. 2015, *Science*, 347, 1462
Hernquist, L. 1993, *ApJS*, 86, 389
Hopkins, P. F. 2013, *MNRAS*, 428, 2840
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, *ApJ*, 522, 82
Lovell, M. R., Eke, V., Frenk, C. S., et al. 2012, *MNRAS*, 420, 2318
Markevitch, M., Gonzalez, A. H., Clowe, D., et al. 2004, *ApJ*, 606, 819
Massey, R., Harvey, D., Liesenborgs, J., et al. 2017, ArXiv e-prints
Moore, B., Ghigna, S., Governato, F., et al. 1999, *ApJ*, 524, L19
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, *ApJ*, 462, 563
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, *ApJ*, 490, 493
Peter, A. H. G., Rocha, M., Bullock, J. S., & Kaplinghat, M. 2013, *MNRAS*, 430, 105
Pontzen, A. & Governato, F. 2014, *Nature*, 506, 171
Revaz, Y., Arnaudon, A., Nichols, M., Bonvin, V., & Jablonka, P. 2016, *A&A*, 588, A21
Revaz, Y. & Jablonka, P. 2012, *A&A*, 538, A82
Revaz, Y. & Jablonka, P. 2018, ArXiv e-prints
Robertson, A., Massey, R., & Eke, V. 2017, *MNRAS*, 465, 569
Robles, V. H., Bullock, J. S., Elbert, O. D., et al. 2017, *MNRAS*, 472, 2945
Rocha, M., Peter, A. H. G., Bullock, J. S., et al. 2013, *MNRAS*, 430, 81
Sawala, T., Frenk, C. S., Fattahi, A., et al. 2016, *MNRAS*, 457, 1931
Schneider, A., Trujillo-Gomez, S., Papastergis, E., Reed, D. S., & Lake, G. 2017, *MNRAS*, 470, 1542
Spergel, D. N. & Steinhardt, P. J. 2000, *Physical Review Letters*, 84, 3760
Springel, V. 2005, *MNRAS*, 364, 1105
Strigari, L. E., Frenk, C. S., & White, S. D. M. 2017, *ApJ*, 838, 123
Verbeke, R., Papastergis, E., Ponnamperuma, A. A., Rathi, S., & De Rijcke, S. 2017, *A&A*, 607, A13
Vogelsberger, M., Zavala, J., Cyr-Racine, F.-Y., et al. 2016, *MNRAS*, 460, 1399
Vogelsberger, M., Zavala, J., Simpson, C., & Jenkins, A. 2014, *MNRAS*, 444, 3684
Wetzel, A. R., Hopkins, P. F., Kim, J.-h., et al. 2016, *ApJ*, 827, L23
Zavala, J., Vogelsberger, M., & Walker, M. G. 2013, *MNRAS*, 431, L20