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Structure of dark matter haloes of Milky Way satellite galaxies in SIDM universes

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Abstract. Self-interacting dark matter (SIDM) can create sufficiently large cores in dark matter haloes of dwarf galaxies if the self-interaction cross-section is sufficiently large on scales of dwarf galaxies. Such a large cross-section can be realized without changing the densities and shapes of cluster-size haloes by introducing a velocity dependent cross-section. Lowering the central densities of dwarf-size haloes, however, may change the strength of stellar feedback required to reproduce observed properties of dwarf galaxies such as the luminosity function of the Milky Way's satellite galaxies. We perform simulations of galaxy formation by employing such a velocity dependent self-interaction cross-section to investigate the coupled effect of SIDM and feedback.

Keywords. galaxies: dwarf, galaxies: formation, cosmology: dark matter

1. Introduction

Observations of dark matter dominated systems strongly suggest the presence of dark matter cores, while the cold dark matter model predicts the central cusps. It has also been pointed out that the dark haloes of satellite galaxies (sub-haloes) in simulated Milky Way (MW)-size haloes are too centrally concentrated to be consistent with the kinematics of the MW satellites (Boylan-Kolchin *et al.* 2011).

Although feedback can potentially make the dark matter structure consistent with the observations by modifying the initial cuspy dark matter distribution into a cored one (e.g. Pontzen & Governato 2012), episodic starbursts required to create cores may not consistent with the star formation histories of low surface brightness and dwarf galaxies. Self-interacting dark matter (SIDM) is thus an attractive alternative to CDM to explain the observed properties of dwarf-size haloes. The current constraint on its cross-section is obtained for cluster-size haloes as $\sigma/m_\chi \lesssim 0.1$ cm^2 g^{-1} (Peter *et al.* 2013), where σ is the SIDM cross-section and m_χ is the SIDM particle mass. This cross-section is too small to create sufficiently large cores in dwarf-size haloes (Zavala *et al.* 2013) and makes no difference from CDM simulations when galaxy formation processes are taken into account (Fry *et al.* 2015). Velocity-dependent cross-section proposed by Loeb & Weiner (2011) can overcome this problem by making the SIDM cross-section sufficiently large on the dwarf scale while keeps it small enough on the cluster scale. In Fig. 1, we show the model we adopted in this work, which is the same as the one employed in Zavala *et al.* (2013). The cross-section is large on the dwarf scale ($\lesssim 100$ km s^{-1}), while, on the cluster scale (~ 1000 km s^{-1}), it satisfies the constraint.

2. Simulations

First, we perform pure N-body simulations of two Milky Way-mass haloes assuming both CDM and SIDM. The halo masses are 1.75×10^{12} $M_\odot$ (Halo 1) and 9.01×10^{11} $M_\odot$

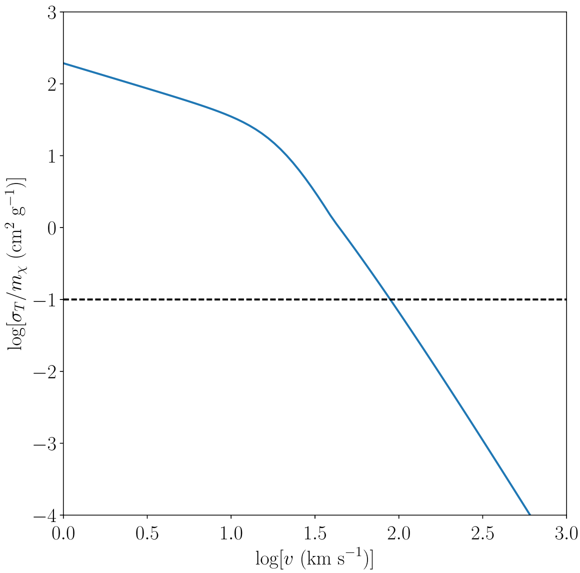

Figure 1. The cross-section per unit mass as a function of the relative velocity. The blue solid line is the one we employed in this work. The constraint obtained for the cluster-size haloes is indicated by the black dashed line.

(Halo 2) at $z = 0$. In low- and high-resolution simulations, the dark matter particle masses are $5.72 \times 10^5\ M_\odot$ and $7.15 \times 10^4\ M_\odot$, respectively. In Fig. 2, we plot the radius at which the circular velocity of a subhalo takes the maximum value, R_{max}, against its maximum circular velocity, V_{max}. We confirm that the CDM subhaloes are too centrally concentrated as claimed by Boylan-Kolchin *et al.* (2011). The SIDM subhaloes are, on the other hand, consistent with the observational estimate.

We show the abundance of the subhaloes as a function of V_{max} in Fig. 3. We find that the number of the low-mass (velocity) subhaloes is substantially reduced. This is because SIDM creates cores in these subhaloes and thus the SIDM low-mass subhaloes are fragile to the tidal disruption. The result of the low-resolution SIDM simulation nicely converges with the high-resolution one since the central density of the subhaloes is already resolved in the low-resolution simulation. In the CDM simulation, on the other hand, the low-mass subhaloes are more abundant in the high-resolution simulation than in the low-resolution one because the central density cusps are better resolved in the high-resolution simulation.

Next, we perform galaxy formation simulations for three isolated dwarf haloes. The virial mass of these haloes in dark matter only CDM simulations at $z = 0$ are $1.86 \times 10^{10}\ M_\odot$ (DW 1), $9.71 \times 10^9\ M_\odot$ (DW 2), and $6.17 \times 10^9\ M_\odot$ (DW 3). We have implemented metallicity dependent gas cooling/heating with a time-evolving ultra-violet background (Haardt & Madau 2012) and metal yields from core-collapse supernovae (SNe), type Ia SNe, and AGB stars (see Okamoto *et al.* 2017). SN feedback is implemented as Hopkins *et al.* 2018. The density profiles at $z = 0$ are shown in Figure 4. We find that the central densities of the SIDM haloes are lower than those of the CDM haloes in the dark matter only simulations. The SIDM effect is, however, marginal on this mass scale ($\sigma/m_\chi \sim 0.1$ cm g^{-1}). We also find that the central dark matter densities are significantly lowered by the baryonic effect. For these haloes, this effect is much stronger than the SIDM effect and therefore SIDM cannot make a significant difference from CDM.

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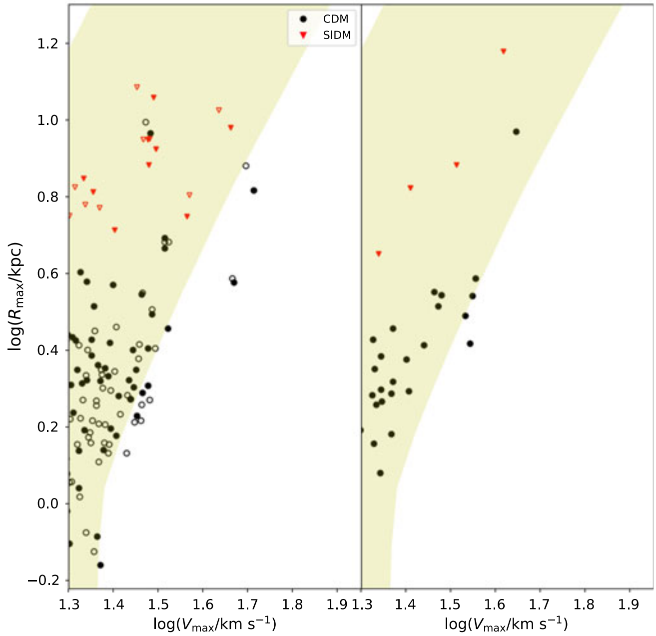

Figure 2. The radius at which the circular velocity takes the maximum value, $R_{\max}$, against the maximum circular velocity, $V_{\max}$, for subhaloes in two MW-mass haloes. The subhaloes in Halo 1 and 2 are shown in the left and right panels, respectively. The CDM and SIDM subhaloes are indicated by the circles and triangles, respectively. In the left panel, the results from the high-resolution simulations are shown by filled symbols. The shaded regions are s the 2σ confidence intervals for possible hosts of the bright MW dwarf spheroidals calculated by Boylan-Kolchin *et al.* (2011).

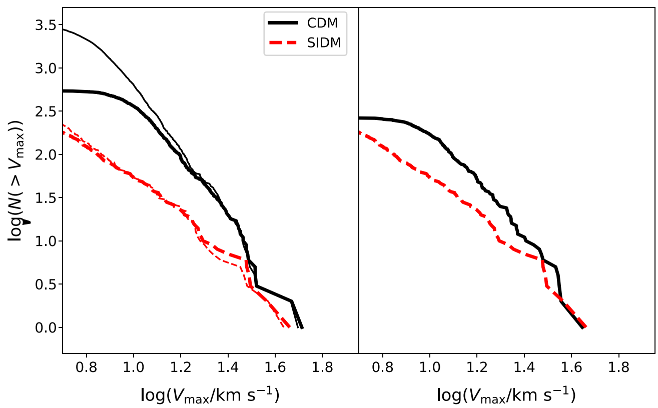

Figure 3. The cumulative velocity function of the subhaloes in Halo 1 (left) and Halo 2 (right). The solid black line indicates the CDM subhaloes and the red dashed line indicates the SIDM ones. In the left panel, the high-resolution simulations are shown by thin lines.

3. Discussion

We have implemented galaxy formation processes and SIDM into GIZMO. With the velocity-dependent cross-section, the abundance of SIDM subhalos is significantly reduced compared with CDM subhalos. When we want to reproduce the observed properties of satellites, we thus have to reduce the strength of feedback in SIDM, which likely

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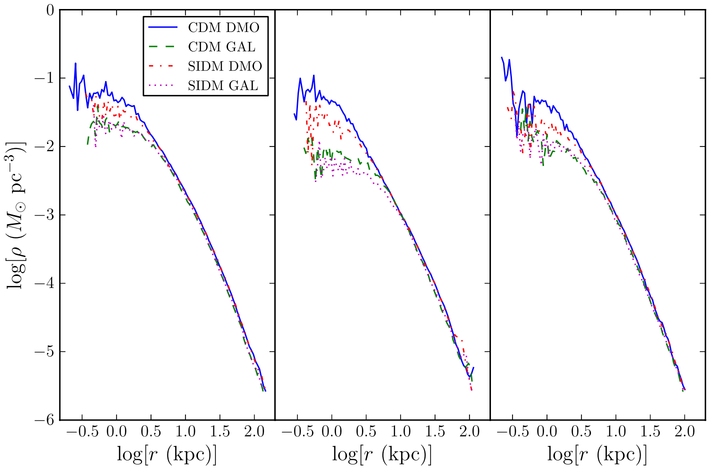

Figure 4. Density profiles of the dark matter halos of DW 1, 2, and 3, from left to right. The solid and dot-dashed lines represent the dark matter only simulations for CDM and SIDM, respectively. The dashed and dotted lines indicate the simulations with galaxy formation processes for CDM and SIDM, respectively.

to affect the structure of subhalos. The next step is therefore high resolution simulations of MW-mass halos with baryons.

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