Constraints on dark matter self-interaction from galactic core size

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Abstract. Self-interaction of particulate dark matter may help thermalising the central region of the galactic halo and driving core formation. The core radius is expectedly sensitive to the self-interaction strength of dark matter (DM). In this paper we study the feasibility of constraining dark matter self-interaction from the distribution of the core radius in isolated haloes. We perform systematic DM only N-body simulations of spherically symmetric isolated galactic haloes in the mass range of $10^{10}$-$10^{15} M_\odot$, incorporating the impact of isotropic DM self-interaction. Comparing the simulated profiles with the observational data, we provide a conservative upper limit on the self-interaction cross-section, $\sigma/m < 9.8 \text{ cm}^2/\text{gm}$ at 95% confidence level. We report significant dependence of the derived bounds on the galactic density distribution models assumed for the analysis.

Keywords: dark matter theory, cosmological simulations, dark matter simulations

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1 Introduction

The standard cosmological framework Lambda Cold Dark Matter (ΛCDM) [1] has proven to be extremely successful in explaining the formation and evolution of large scale structures in our Universe [2–4]. However, at the galactic scales there exists several mismatch between simulations and observations [5]. The core-cusp [6] and missing satellite problem [7] are some of the concerns that have been discussed in this context. Admittedly, these discrepancies may be a reflection of various limitations in the present day N-body simulations. It has been extensively discussed that a more careful consideration of baryonic effects may ease most of the tensions [8–10]. However, these may also be indicative of specific microscopic properties of dark matter (DM) itself. In this paper we adopt this latter paradigm and investigate the correlation of observed galactic core and strength of self-interaction of particulate DM.

Collision-less cold DM (CDM) in the absence of baryonic physics is expected to get gravitationally cooled in the neighborhood of the galactic center during galaxy formation, aiding further collapse and eventually leading to cusp like structures [11]. However, astrophysical observations [12] spanning from dwarf spheroidal galaxies to galaxy clusters indicate that DM haloes are less dense in their central regions as compared to predictions from collision-less CDM N-body simulations [13, 14]. A viable possibility to address this problem is to consider self-interaction within the dark sector [15] that are widely motivated by particle physics models [16–18]. These self-interactions can thermalise the collapsing galactic center thus resisting formation of cusps [19]. In this paper we focus on constraining the DM self-interaction cross-section by comparing the results from DM only N-body simulation of spherically symmetric isolated cores with observations in a wide mass range of astrophysical objects, ranging from galaxies to clusters. This is complementary to the several studies that constrain self-interacting dark matter (SIDM) models using observational evidence from

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### Contents

1 Introduction

2 The SIDM solution to the core cusp problem
   2.1 N-body simulation of isolated SIDM haloes
   2.2 Core radius of the simulated haloes

3 Distribution of core radius in the observed galaxies

4 Constraints on DM self-interaction from the distribution of core size in isolated haloes

5 Conclusion

A Fits to our simulated data

B Fits to the observational data

C Convergence tests

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1 Introduction

The standard cosmological framework Lambda Cold Dark Matter (ΛCDM) [1] has proven to be extremely successful in explaining the formation and evolution of large scale structures in our Universe [2–4]. However, at the galactic scales there exists several mismatch between simulations and observations [5]. The core-cusp [6] and missing satellite problem [7] are some of the concerns that have been discussed in this context. Admittedly, these discrepancies may be a reflection of various limitations in the present day N-body simulations. It has been extensively discussed that a more careful consideration of baryonic effects may ease most of the tensions [8–10]. However, these may also be indicative of specific microscopic properties of dark matter (DM) itself. In this paper we adopt this latter paradigm and investigate the correlation of observed galactic core and strength of self-interaction of particulate DM.

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rotation curves [20–22], stellar kinematics [23] and gravitational lensing [24–27] alongside \( N \)-body simulations.

The paper is organized as follows. In section 2 we review the rationale for SIDM as a possible solution to the core-cusp problem before we discuss the \( N \)-body simulations performed using the SIDM framework for isolated haloes. In section 3 we discuss the observational data which is used to compare the results of our \( N \)-body simulations. In section 4 we present the obtained bounds on the self-interaction cross-section of DM from galactic core radius before concluding in section 5.

2 The SIDM solution to the core cusp problem

\( N \)-body simulations, based on the collision-less CDM framework usually lead to an over-dense central region inside the DM haloes. Gravitational collapse of galaxies into the central potential of the halo causes thermal cooling in the core region. This reduces the thermal pressure that can resist the collapse, eventually leading to a cusp like galactic center. However, observations reveal a somewhat different and more nuanced picture. The rotation curves of low surface brightness galaxies and late-type disk like, gas-rich dwarf galaxies that are majorly DM dominated [28], indicate the presence of a constant-density or mild cusp-like galactic center with a logarithmic slope of \( \sim 0.2 \). Cored DM profiles have also been inferred for the more luminous spiral galaxies [29]. Previous works like [30] have also advocated the presence of weak density cusps with a logarithmic slope \( \sim 0.5 \) in large elliptical galaxies, motivated from the results of HST observations. Isolating the DM from the stellar components indicate an inner logarithmic density slope \( \sim 0.5 \pm 0.13 \) for clusters having weak cores [31]. Alternately many recent works in literature tend to resolve the dichotomy of DM density inside the galactic center by rigorous stellar modeling [32], studying the dynamics of dwarf galaxies [33], using stellar kinematics and HI rotation curves [34], cosmological hydrodynamic simulations [35] etc. The core-cusp problem is the accepted moniker for this discrepancy in literature [13].

Self-interaction of DM may be instrumental in thermalising the core by aiding transport of heat from the outer edges of the galaxies to the dense central region. This thermalisation of the central region of the DM halo causes the matter to get uniformly distributed within the region [36]. As we move away from the core the density falls off, reducing the self-interaction rate and ultimately behaves like an effective collision less CDM towards the less dense outer edges of the isolated haloes. A typical estimate for the core size may be obtained by requiring at least one self-interaction event per particle within the core, during the lifetime history of the galactic evolution [37],

\[
\frac{\langle \sigma v \rangle_{\text{self}}}{m} \rho(r_c) t_{\text{age}} \approx 1,
\]

where \( \langle \sigma v \rangle_{\text{self}} \) denotes the velocity weighted self-interaction cross section, \( m \) is the DM particle mass, \( \rho(r) \) is the DM density profile, \( t_{\text{age}} \) is the time for evolution of the virialized object and \( r_c \) is the estimated core radius. As evident from this estimate, the core size being a quantifying parameter of the galactic halo, can be directly related to the self-interaction strength of the DM. The possibility of constraining DM self-interaction from the core radius has been previously presented in [38]. It has been pointed out that the surface density of the DM haloes [39] and the velocity dispersion in the central regions can be used to constrain the DM self-interaction [25, 40].

Thus the observed distribution of core radius in various isolated haloes can translate to a limit on the DM self-interaction. As a proof of principle in this paper we perform \( N \)-body
simulations of isolated haloes using a modified GADGET [41–43] simulation tool, taking into account the leading effect of DM self-interaction. We consider a simplified phenomenological SIDM framework where velocity independent elastic $2 \rightarrow 2$ DM scatter process dominate the DM self-interactions. By comparing the distribution of core radius as function of the galaxy mass in simulated results and observed data, we determine a conservative upper-limit on the DM self-interactions.

2.1 N-body simulation of isolated SIDM haloes

A few comments about the N-body simulations carried out in this work is now in order. To simulate the isolated haloes by incorporating the effects of the DM self-interaction, we utilize a modification of the existing gravitational N-body code GADGET [41, 42]. The algorithm follows a basic assumption that whenever a particle (say $j$) is considered to be the nearest neighbour of another particle (say $i$), there exists a finite probability of scattering or interaction. If and when the two particles collide in this sense, the phase space of the scattered DM particles is obtained from the differential scattering cross section $\frac{d\sigma}{d\Omega}$. The positions and velocities are updated at each time-step following the usual Kick-Drift-Kick Leap-frog method.

We generate the initial phase-space of DM particles with a NFW matter distribution. For this purpose we use the publicly available code HALOGEN [44] which sets up spherically symmetric distributions for N-body simulations with a multi-mass technique. We follow an approach based on [43] which is similar to that prescribed in [45–49]. Here the distribution ideally goes to zero at infinity. However, considering the finite extent of a halo, an exponential cut-off is introduced, $r_{\text{cut}}$. The $r_{\text{cut}}$ is identified as the maximum extension of the DM halo, which we have considered to be the virial radius. Following the prescription in reference [43, 50], we set the simulation parameters including the softening lengths $\epsilon$, force resolutions and the characteristic lengths $r_{\text{so}}$ of the initial matter distribution. These parameters determine the characteristics of the individual simulated haloes. We list the values of these parameters in table 1, for the NFW initial distribution. Relevant tests for this implementation are provided in [43] and we ensure that the code is able to reproduce them by optimizing the internal parameters like the scattering probability factor and accuracy of time integration to ascertain the qualitative and quantitative validity of our simulations. All the cosmological parameters are set from the estimations of the PLANCK Collaboration data [51]. We have simulated haloes with six different masses in the range from $10^{10}M_{\odot}$ to $10^{15}M_{\odot}$ for both the CDM scenario and the SIDM scenario with various scattering cross-sections using $10^6$ particles. The final density distribution is obtained after evolving the initial distribution of particles for 10 Gyrs [37, 52, 53]. Admittedly, the resolution of our N-body simulation worsens as we move towards massive haloes. We therefore perform extensive convergence tests to demonstrate the stability of our simulations as sketched in appendix C. We find that the fractional change in the matter density at the central region is less than 20% for an order of magnitude change in the particle numbers. The results presented here should be interpreted modulo this resolution limit of the simulations. Each halo with the aforementioned masses have been simulated with self-interactions for eight different scattering cross-section per unit mass, set at $\sigma/m = (0.1, 0.2, 0.5, 2, 4, 6, 8, 10) \text{ cm}^2/\text{gm}$. As we are simulating haloes with scattering cross-section per unit mass as large as $10 \text{ cm}^2/\text{gm}$, we have kept the evolution timestep to be considerably small by taking the scattering probability to be less than 0.1, such that each particle can have at most one scattering per timestep [43, 54]. For comparison, we have additionally evolved all the haloes without self-interaction, which corresponds to the standard CDM scenario with larger values of $\sigma/m$ disfavored from [19, 55, 56]. For both the CDM and
Table 1. Parameters used for simulating the initial NFW particle distribution of the isolated haloes. [43].

| $M_{\text{halo}} (10^{10} M_\odot)$ | $r_{\text{cut}}$ (kpc) | $r_{\text{so}}$ (kpc) | $\epsilon$ (kpc) |
|---------------------------------|---------------------|------------------|---------------|
| 1                              | 43.7                | 0.43             | 0.02          |
| 10                             | 93.4                | 0.94             | 0.03          |
| $10^2$                         | 199                 | 1.99             | 0.06          |
| $10^3$                         | 427                 | 4.27             | 0.13          |
| $10^4$                         | 913                 | 9.13             | 0.28          |
| $10^5$                         | 1952                | 19.52            | 0.58          |

The implications of DM self-interaction on the thermalisation of the core becomes apparent from the velocity dispersion profile given in figure 1a. We find that the velocity dispersion increases rapidly from the center towards the periphery for the CDM haloes, whereas the corresponding increment is comparatively softer for the SIDM haloes and remain almost constant at the center. This depicts the expected scenario where the interior of the CDM haloes are gravitationally cooled, whereas DM self-interactions in the SIDM haloes thermalises the central region through the transfer of heat from the periphery leading to the formation of density cores inside the haloes. Our numerical estimates qualitatively agree with the results obtained in [27, 50] which considers high resolution cosmological simulations. As a sanity check to our implementation of self-interactions between DM, we find that the variation in density with radius shown in figure 1b, gradually decreases at the central region as the strength of self-scattering increases. This is also in accordance to the studies existing in literature [27, 50].

2.2 Core radius of the simulated haloes

In order to estimate the core radius we fit the simulated haloes with density profiles that incorporate a non-trivial core radius. Our analysis is based on the following two density profiles,

1. Semi-analytic distribution: the semi-analytic distribution profile, also known as the Jeans model which was recently introduced in [37, 57], has been argued to provide a better resemblance to $N$-body simulations with self-interaction [58]. The model considers a pseudo-isothermal profile within a characteristic radius ($r_1$) where self-interaction thermalises the core and beyond $r_1$ it follows the typical NFW distribution [59] indicative of the collision-less nature at the low density periphery,

$$
\rho(r) = \begin{cases} 
\rho_{\text{so}}(r) = \rho_s e^{-h(r/r_o)} & r \leq r_1 \\
\rho_{\text{NFW}}(r) = \frac{\rho_s}{\frac{r}{r_s} \left[1 + \frac{r}{r_s}\right]} & r > r_1.
\end{cases}
$$

(2.1)

The Jeans profile can be defined in terms of three independent parameters namely $r_o$, $r_s$ and $r_1$, using appropriate boundary conditions [60]. Here the functional dependence
of $h(r/r_0)$ on $r/r_0$ has been adopted from [60]. From definition the transition radius gives the estimate for the core size of a Jeans model involving self-interaction of DM.

2. Cored NFW distribution: a convenient parametrisation of a cored halo profile can be done in terms of a slightly modified version of the widely used NFW [61–63] density distribution, by introducing an additional free parameter $r_c$ [64] which estimates the core radius. The distribution is given as

$$\rho_{\text{cNFW}}(r) = \frac{r_s \rho_s}{r_c [1 + \frac{r}{r_s}]^2 [1 + \frac{r}{r_c}]},$$

(2.2)

where the symbols have their usual meanings. The profile implies a constant density core at $r < r_c$, while retaining the usual NFW logarithmic slope of $-3$ at $r \gg r_c$. A similar parametrisation of the core radius as modification of the NFW distribution can be found in [65]

We fit our simulated halo profiles with these models to extract the model dependent core radius. The goodness-of-fit for these density profiles with the simulated isolated haloes can be quantified in terms of $\delta_{\text{rms}}$ given by

$$\delta_{\text{rms}}^2 \equiv \frac{1}{N_{\text{bin}}} \sum_{i=1}^{N_{\text{bin}}} \left[ \log_{10} \frac{\rho_{\text{data}}(r_i)}{\rho_{\text{mod}}(r_i)} \right]^2,$$

(2.3)

which denotes the rms fluctuations of the obtained fits, with respect to the simulated data [58]. Here $N_{\text{bin}}$ denotes the total number of radial bins in which the data is distributed, $\rho_{\text{data}}$ is the average matter distribution corresponding to a particular bin obtained from the $N$-body simulation and $\rho_{\text{mod}}$ is the corresponding density fit for a particular distribution model. We have additionally considered the Burkert distribution [14, 66], the Einasto distribution [66, 67] and the core-modified Isothermal distribution [66, 68]. However we limit our analysis only to the semi-analytic distribution and the cored NFW distributions, as they provide overall better fits to the observed and simulated DM density distributions, quantified through the
goodness-of-fit estimates given by equation (2.3). As can be seen from figure 2, the fits are better for smaller galaxies that are observationally known to have larger relative core size. Representative fits are shown in appendix A. The core radius obtained from our simulated set of isolated haloes have been shown by the orange, red and brown curves in figure 3, for three sets of scattering cross-section i.e. CDM (i.e. $\sigma/m = 0$), 2 cm²/gm and 6 cm²/gm respectively.

3 Distribution of core radius in the observed galaxies

To compare the distribution of core radius from the simulated SIDM haloes with those derived from observations, we identify twelve haloes ranging from dwarfs to clusters with virial masses in the order of $10^9 M_\odot$ to $10^{15} M_\odot$. These include three dwarf spheroidal galaxies [DD0-154, NGC-2366, IC-2754], six low surface brightness galaxies (LSB) [F-568-3, F563-V2, F563-1, NGC-3726, NGC3992, Malin-1] and three clusters [MS2137, A611, A2537]. The details of the identified galaxies included in this study are given in table 2. From the observed rotation curve data of the chosen haloes we identify the DM contribution to the circular velocity using the following relation [34].

$$V_{tot}^2(r) = v_{DM}^2(r) + v_{gas}^2(r) + v_\ast^2(r).$$

Here $V_{tot}$ is the total galactic rotation curve, whereas $v_{DM}$, $v_{gas}$ and $v_\ast$ are the individual contribution of DM, gas and stellar contributions respectively. We consider a minimal disc setup for modeling the baryonic contribution of stars and galaxies from the corresponding references in table 2. The dwarf galaxies identified are not satellites and they have mostly weak interactions with larger systems. This allows us to make systematic comparisons between the isolated halo simulations and observations. We extract the DM contribution to the rotation curves from the results of the THINGS survey [69, 70], that also report the contribution of the gas and baryons to the rotation curves supplemented by the Spitzer Infrared Nearby Galaxies Survey (SINGS) [71] using equation (3.1).
| Galaxy Type       | Galaxy Name | Halo mass \((10^{10} M_{\odot})\) | Properties                                | Reference |
|------------------|-------------|---------------------------------|------------------------------------------|-----------|
| Dwarf Spheroidal | NGC-2366    | 0.43                            | Using HI rotation curves (RC)            | [69, 72]  |
|                  | DD0-154     | 0.54                            |                                          | [69, 72]  |
|                  | IC-2754     | 1.46                            |                                          | [69, 72]  |
|                  | F-568-3     | 2.54                            | Observed from Hα rotation curves         | [73, 74]  |
|                  | F563-V2     | 1.65                            |                                          | [73, 74]  |
|                  | F563-1      | 2.8                             |                                          | [73, 74]  |
|                  | NGC-3726    | 20.7                            | Rotation curves of HI distribution       | [76, 77]  |
|                  | NGC-3992    | 37.2                            |                                          | [76, 77]  |
|                  | Malin-1     | 82                              | Giant LSB, RCs of HI and Hα observations| [78, 79]  |
| L.S.B            | F563-1      | 20.7                            |                                          | [76, 77]  |
|                  | NGC-3992    | 37.2                            |                                          | [76, 77]  |
|                  | MS-2137     | 36307                           | Observed lensing (Strong and Weak)       | [31, 64]  |
|                  | A-611       | 83176                           |                                          | [31, 64]  |
|                  | A-2537      | 218776                          |                                          | [31, 64]  |

**Table 2.** Properties of the observed galaxies and clusters used in this study. Other relevant details can be obtained from [80].

We infer the DM density profiles from the DM only rotation curves assuming a spherical DM distribution, using the following relation [72]

\[
\rho(r) = \frac{1}{4\pi G} \left[ 2 \frac{V_c}{r} \frac{\partial V_c}{\partial r} + \left( \frac{V_c}{r} \right)^2 \right]. \quad (3.2)
\]

Here \(V_c(r)\) is the corresponding DM circular velocity at a radial distance \(r\) from the halo center and \(G\) is the universal Gravitational constant. For the dwarf galaxies we use the masses given in [72]. The stellar contribution in these galaxies is low, which reduces errors involving the uncertainty in the stellar mass-to-light ratio \(\gamma_\ast\), giving a more accurate identification of the DM distribution. For the LSB galaxies we use the results of DensePak Integrated Velocity fields [73, 74, 77] to extract the DM contribution to the rotation curves and the galaxy masses. For the galaxy clusters we use a sample of massive, relaxed galaxy clusters with centrally-located brightest cluster galaxies (BCG) at redshifts \(z = 0.2 - 0.3\), derived from observational tools of strong and weak gravitational lensing combined with resolved stellar kinematics within the BCGs. The total radial density profile with both DM and baryons over scales of 3–3000 kpc are presented in [31, 64]. Our estimated core radius for the observed set of galaxies and clusters are represented by the magenta line in figure 3. The corresponding shaded bands denote the region of uncertainty associated with the core estimates from observations. The individual fits to the inferred DM density distribution are shown in appendix B.
We obtain constraints on the DM self-interaction by statistically comparing the core radius distributions extracted from observations with the ones obtained by our simulated SIDM haloes. To obtain the best fit core radius we utilize standard regression tools like the scipy [81] module in python and inbuilt functions in Mathematica. These comparisons and hence the obtained constraints are sensitive to the choice of the DM density profile. The core radius distributions have been presented in figure 3, where the orange, red and brown points give the estimates of core radius from N-body simulations with zero, 2 and 6 cm$^2$/gm interaction strengths respectively as a function of the DM halo mass. The corresponding vertical lines give an estimate of the uncertainties involved in determining $r_c$, that has been obtained by simulating four different realizations of every scenario and extracting the statistical errors in our simulations. The polynomial fits to these points are shown by the corresponding coloured curves. We are now in a position to compare our observed and simulated cores and measure the goodness-of-fit between the two.

The distribution of the core radius provides us with a handle to statistically compare the DM self-interaction to obtain limits on the interaction cross-section. This approach of comparing the core radius distribution rather than comparing the core radius of individual isolated haloes, make the analysis more robust by reducing the simulation errors. The goodness-of-fit for the distribution is done using the standard chi-square $\chi^2$,

$$\chi^2 = \frac{1}{N} \sum_i^N \left[ \frac{(r^s_c)_i - (r^o_c)_i}{\sigma_i} \right]^2,$$

and the reduced chi-square defined by $\Delta \chi^2 = \chi^2 - (\chi^2)_{\text{min}}$, where $N$ corresponds to the total number of points sampled from the best fit curves, $r^s_c$ and $r^o_c$ are the core radius obtained from the simulations and observational data respectively and $\sigma_i$ are the errors associated with
Figure 4. Effective $\chi^2$ as a function of $\sigma/m$. The left and right panels denote the $\Delta \chi^2$ variations for the semi-analytic distribution and the cored NFW distribution respectively. The green and yellow regions denote the 68% and 95% confidence regions respectively with respect to the minimum $\chi^2$. The red, blue and brown dashed vertical lines represent the upper limits at 95% confidence obtained from the Bullet cluster, Abell Cluster and MACSJ0025 (Baby bullet) cluster respectively.

The green and yellow shaded regions in figure 4 represent the 68% and 95% confidence band of our chi-square distribution [82]. We report $\sigma/m$ below 8.6 (9.8) cm$^2$/gm to lie within 95% confidence level and 0.3 (5.4) cm$^2$/gm within 68% confidence level for the Jeans (cored NFW) model. The bounds on SIDM interaction strengths from the Bullet cluster [24, 26, 83], the Abell Cluster [84] and the MACSJ0025 cluster (baby bullet) [85] have been shown by the vertical dashed lines in figure 4. The limits obtained from this analysis are consistent with the aforementioned limits and other studies quoted in the literature [86–89].

These bounds are premised on the assumption that the distribution of DM is spherically symmetric in the isolated haloes and have an isotropic DM self-interaction. Any impact of non-sphericity or triaxiality [35, 90] has been neglected in the results presented here. Inclusion of baryons provides a competing mechanism to thermalise the central region of the haloes driving core formation. Additional effects like supernova feedback, stellar formation, viscosity etc would further aid in the formation of cores. Expectedly the inclusion of these phenomenon would make the bounds in the DM self-interaction more stringent. The limits originating from the DM only simulations can be considered to be more conservative and the results presented here should be interpreted within this context.
5 Conclusion

In this work we study the feasibility of using the distribution of core radius in isolated haloes as a mean of constraining DM self-interaction. As a proof of principle we simulate haloes with six different masses in the mass range $10^{10} - 10^{15} M_\odot$ for the CDM as well as the SIDM scenario, having $\sigma/m$ in the range of $(0 - 10) \text{ cm}^2/\text{gm}$. We thereby compare these simulations with observational data for twelve different haloes in the same mass range. The comparison requires us to assume an underlying model for the density profile making the translated limits on the self-interaction cross-section sensitive to these choices. However a model independent definition of the halo core radius would make the study more robust. A possibility is to utilize the discontinuous change in the slope of the rotation curves between the core and the periphery in order to identify the core radius directly from the density profiles. A detailed study on the numerical feasibility and stability of this is beyond the mandate of our present work. For a velocity independent point like interaction we find that for the semi-analytic distribution, the CDM scenario provides an overall best fit to the wide range of halo mass comprising of dwarfs, LSBs and clusters. Whereas the cored NFW model prefers a small but non-zero scattering cross-section. Remaining within the limits of spherical symmetry and employing DM only simulations, we obtain a conservative bound on $\sigma/m$ to be below $9.8 \text{ cm}^2/\text{gm}$ at 95% confidence level. This is comparable to bounds from galaxy cluster mergers available in the literature. However these bounds should be interpreted carefully as they are sensitive to the uncertainties associated with the simulations and observations.

Distribution of core sizes in the isolated haloes may provide a complementary handle to compare and constrain DM self-interaction. Here we demonstrate its utility in the simplest context of velocity independent point like interactions. However, high resolution cosmological simulations from which a large number of isolated haloes may be identified can be employed to compare and distinguish between the strength and velocity dispersion of DM self-interaction. Such dedicated studies are now in order and will be carried out elsewhere.

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A Fits to our simulated data

As discussed in section 2.1, we show here the fits to the individual density distributions obtained for our $N$-body simulations. The density distributions for the CDM scenario and a SIDM scenario with $\sigma/m = 2 \text{ cm}^2/\text{gm}$ are shown in the top and bottom panel of figure 5 respectively. This is shown for three different halo mass namely $10^{10} M_\odot$, $10^{13} M_\odot$ and $10^{15} M_\odot$.
in the left, middle and right panels of the figure respectively. The green solid and red dashed curves represent the best fit curves for the semi-analytic distribution and the cored NFW distribution respectively, the corresponding vertical colored lines denote the extent of its core radius. The simulated data are shown by the gray points.

**B Fits to the observational data**

LSB and dwarf spheroidal galaxies are often considered as ideal targets for DM studies as their mass content of baryons are minimum. Observations indicate that many of these galaxies have a DM core rather than an expected cusp [91]. Here we present the individual fits to the inferred DM density distributions from the observational data for the dwarfs, LSBs and clusters in figure 6, 7 and 8 respectively, that have been discussed in section 3. The top, middle and bottom panels show the fits for the three dwarf spheroidals, six LSB galaxies and three clusters respectively. The green solid and red dashed curves represent the best fits to the inferred density distributions for the semi-analytic distribution and the cored NFW distribution respectively. The corresponding vertical lines denote the extent of the core radius. The DM distribution inferred from observations are shown by the gray points.

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**Figure 5.** Model fits to the DM distributions obtained from the N-body simulations.
Figure 6. Model fits to the DM distributions inferred from dwarf galaxy observations.

Figure 7. Model fits to the DM distributions inferred from LSB observations.

Figure 8. Model fits to the DM distributions inferred from cluster observations.

C Convergence tests

Here we discuss the results of the convergence test for our simulations, with four different sets of particle numbers, $10^4$, $10^5$, $10^6$ and $10^7$ that have been shown in figure 9 by the red,
Figure 9. Variations in the central DM density for four different sets of particle numbers. 

...blue, green and purple curves respectively. We plot the DM density distribution of the halo as a function of the radius from its center for the CDM scenario with a halo mass of $10^{13} M_\odot$ in figure 9. We find a convergence in the central matter density as the particle content increases. The variation is seen to be less than 20%, with an order of magnitude change in particle numbers, which further decreases as the particle content of the simulations increase.

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