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Bounds on self-interacting dark matter from galactic cores

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Self-interactions between dark matter particles can induce core formation in galaxies and lead to thermalization of their central regions. The strength of self-interactions between dark matter particles is correlated to the size of the thermalized regions. The possibility of placing a conservative limit on the self-interaction cross-section by analyzing the distribution of core radius in isolated galactic haloes is explored in this work. We systematically use dark matter only N-body simulations of spherically symmetric isolated haloes incorporating isotropic self-scattering. We report a conservative upper limit on the self-interaction cross-section, $\sigma/m < 9.8$ cm^2/gm at 95% confidence level by comparing the generated distributions with the observed data.

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1. Introduction

Although immensely helpful for comprehending the birth and development of massive-scale structures, the Lamda Cold Dark Matter (ΛCDM) cosmology has drawbacks. It is at the galactic scales where it faces specific challenges while comparing its predictions from simulations with astrophysical observations. The core-cusp is one of the major concerns in this domain. While it may be argued to be an artifact of the limitations in present-day N-body techniques, they may very well indicate specific microscopic properties of DM. We study the effect of the observable galactic core on the self-interaction of DM particles using this latter paradigm. Self-interactions can thermalize the collapsing galactic interior, preventing the formation of cusps. We intend to constrain the DM self-scattering cross-section for a wide range of astrophysical objects, from galaxies to clusters, by comparing the results of our N-body simulation with galaxy observations from HI rotation curves, lensing data, and X-ray spectroscopy[1]. As a result of thermalization, the matter in the core of a halo gets dispersed evenly. The matter density of a halo decreases outward from its center. Consequently, the rate at which DM interacts with itself diminishes, and the particles within a halo eventually behave as collision-free CDM outside the cores.

2. Simulating isolated self-interacting DM haloes

Utilizing a modified version of the existing gravitational N-body code `GADGET` [2] and an initial phase-space generator code `HALOGEN` [3], we obtain the phase space of the scattered DM particles obtained from the differential scattering cross-section $\frac{d\sigma}{d\Omega}$, evolved over a period of 10 Gyrs [4]. We have simulated haloes with six different masses in the range of $10^{10} M_\odot$ to $10^{15} M_\odot$ for the CDM and SIDM scenarios with various scattering cross-sections, using 10^6 particles. Each halo containing the aforementioned masses has been simulated with eight different self-interaction cross-sections per unit mass, namely $\sigma/m = (0.1\,, 0.2\,, 0.5\,, 2\,, 4\,, 6\,, 8\,, 10)\ \mathrm{cm}^2/\mathrm{gm}$. As we approach larger halos, the resolution of our N-body simulation drops significantly. For an order of magnitude shift in particle number, we find the fractional change in matter density within the central region to be less than 20%. For this reason, the reported results should be interpreted taking into account the resolution limit of the simulations.

3. Cored halo profiles

In order to quantify the core radius from our study, we need to make a prior assumption about the distribution of DM particles inside the halo. Our analysis is therefore carried with the following two density profiles,

1. **Semi-analytic distribution:** The model considers a pseudo-isothermal profile within a characteristic radius (r_1), inside which self-interactions thermalises the central region and beyond r_1 it follows the usual NFW distribution of collision-less cold DM. This distribution is given by,

$$\rho(r) = \begin{cases} \rho_{\rm iso}(r) \;=\; \rho_0 e^{-h(r/r_0)} & r \le r_1 \\ \rho_{\rm NFW}(r) = \dfrac{\rho_s}{\frac{r}{r_s}\left[1+\frac{r}{r_s}\right]^2} & r > r_1\,. \end{cases} \tag{1}$$

The profile can be defined in terms of three independent parameters, namely r_o, r_s and r_1, using appropriate boundary conditions.

2. **Cored NFW distribution:** In terms of a slightly modified version of the extensively used NFW density distribution, a cored halo profile can be parameterized by introducing a free parameter r_c, which estimates the core radius. The distribution is given as

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

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 $r \gg r_c$.

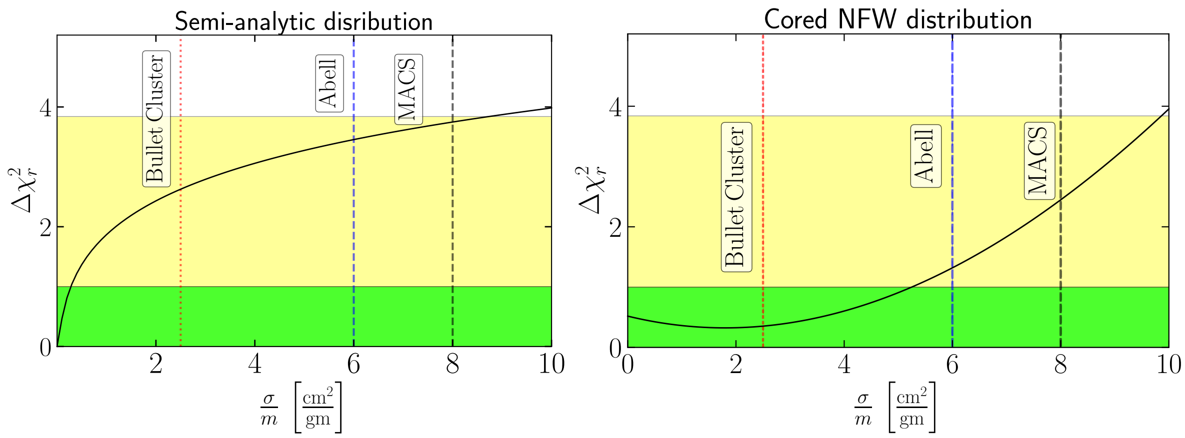
4. Core radius in observed galaxies

Twelve galaxies, ranging in size from dwarfs to clusters and having virial masses between $10^9\,M_\odot$ and $10^{15}\,M_\odot$ are used to compare the distribution of core radius within simulated halos in the presence and absence of self-interactions. 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]. Thereby, we constrain the DM self-interaction by statistically comparing the core radius distributions extracted from observations with the core radius distributions obtained from our simulated haloes. To fit the data with our density distribution profiles, we utilize standard regression tools like the `scipy` module in python and inbuilt functions in Mathematica. In order to check the goodness-of-fit of a distribution corresponding to a particular DM self-scattering strength, we employ a standard chi-square χ_r^2 test. The estimated reduced chi-square $\Delta\chi_r^2$ as a function of the interaction cross-section per unit mass for the two models considered are shown in figure 1. The curves in figure 1 imply that the semi-analytic distribution has a minimum at $\sigma/m = 0$, although the cored NFW favors a small scattering cross-section of $1.7\,\text{cm}^2/\text{gm}$.

In figure 1, the areas highlighted in green and yellow respectively reflect the 68% and 95% confidence bands of our chi-square distributions. This work reports σ/m to remain below $8.6\,(9.8)\,\text{cm}^2/\text{gm}$ at 95% confidence level for the Jeans (cored NFW) model. The vertical dashed lines in figure 1 represent the limits on SIDM interaction strengths derived from the Bullet cluster, the Ablle Cluster, and the MACSJ0025 cluster (baby bullet). The results of this analysis are in agreement with those of the aforementioned studies and other related works. These constraints assume the DM population is isotropic and the matter is distributed spherically symmetric. The presence of baryons offers a supportive mechanism for thermalizing the central region of the halos, which is essential for driving core formation. The formation of cores would be aided further by additional phenomena such as feedback from supernovae, the formation of stars, and viscosity. The incorporation of these factors would therefore make the limitations on DM self-interaction more severe.

5. Conclusion

In this study, we investigate the viability of exploiting the distribution of core radius in isolated halos to constrain DM self-interaction. As a demonstration of the concept, we simulate six distinct



(a) **(b)**

Figure 1: Effective χ^2_r as a function of σ/m. The left and right panels denote the $\Delta\chi^2_r$ 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 χ^2_r. 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.

halo masses with different scattering strengths. Consequently, we compare our simulations with observational data for the twelve haloes in the same mass range. The comparison necessitates the assumption of an underlying model for the density profile, which makes the translated bounds on the self-interaction cross-section sensitive to the choice. Nonetheless, a model-independent description of the halo core radius would strengthen such a study. For velocity-independent point-like interactions, we demonstrate that, for the semi-analytic distribution, the CDM scenario offers the best overall fit to the vast halo mass range, consisting of dwarfs, LSBs, and clusters. In contrast, the cored NFW model favors a small, non-zero, scattering cross-section. Considering spherical symmetry limitations and employing DM-only simulations, we find a conservative bound at 95% confidence level on σ/m to be less than $9.8\text{cm}^2/\text{gm}$. This bound is comparable to the reported limits derived from galaxy cluster mergers. Nonetheless, given their sensitivity to simulation and observational uncertainty, these constraints should be considered cautiously.

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