Self-interacting dark matter on small and large scales

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Abstract

In the self-interacting dark matter paradigm (hereafter SIDM), dark matter (DM) is assumed to have non-gravitational interactions with itself. SIDM has been constrained by observations of galaxy clusters. More recently, measurements of large DM densities at the center of the Milky Way's galaxy satellites are indicating that DM-DM interactions can potentially induce gravothermal core collapse. In this proceeding an overview of the combined measurements of cluster-size galaxies and kinematics of local satellite galaxies is used to argue that DM interactions should depend on the relative velocity of the DM particles.

1 Introduction

The long-held cosmological paradigm of Λ collisionless cold dark matter (ΛCDM) accurately predicts the large-scale structure of the Universe ([1, 2]), however, significant discrepancies on galactic and sub-galactic scales are constantly challenging it.

Of these discrepancies, one of the most challenging is the diversity of the inner dark-matter content in dwarf galaxies (see [3] for a recent review). DM-only simulations predict that dwarf galaxies are embedded in DM haloes that have a steep density profile with a 'cusp' shape ([4]). However, CDM simulations with baryonic feedback processes from star formation and supernova explosions produce gravitational fluctuations, that allow the redistribution of DM, and the formation of flat density cores ([5]). But this appears to be very model-dependent (e.g. [6, 7]). An additional challenge is that baryons can only explain the formation of DM cores or cusp in gas-rich systems, but fail to do so in gas-poor systems. There is substantial evidence for the existence of a diversity in the DM density of gas-poor systems, such as the dwarf spheroidals and ultra-faint satellites of the Milky Way ([8–12]).

This motivates to question the nature of DM and to explore DM physics beyond standard models. A promising alternative is self-interacting dark matter ([13]), which considers that DM particles experience collisions with each other. DM particles collisions transfer heat towards the colder central regions of DM haloes, lowering central densities and creating constant density cores (e.g. [14–20]).

The goal of this proceeding is to review the latest observations that place constraints on the SIDM paradigm, with the aim of understanding whether the DM particles interactions should depend on the particles' relative velocities.

2 SIDM Observational Constraints

The cross section per unit mass, σ/m_χ, is the main parameter that controls the rate of DM particles interactions. A low cross section ($\sigma/m_\chi < 1$ cm^2/g) produces low DM collisions rates, allowing DM haloes to keep cuspy density profiles. Alternatively, high cross sections ($\sigma/m_\chi > 1$ cm^2/g) lead to very frequent DM collisions that are able to produce central density cores (e.g. [17, 21]).

SIDM has been motivated by observations of galaxy clusters colliding, where the mismatch between the DM centre and the galaxy centre can be produced by DM-DM interactions, that induce a drag-like force after the collision ([22–25]). Studies on galaxy clusters-scales investigating the DM-galaxy mismatch, clusters' ellipticity and core-size have set robust upper limits on the SIDM cross section of $\sigma/m_\chi < 1.25$ cm^2/g (e.g. [26–29]). Fig. 1 shows σ/m_χ as a function of the relative velocities between DM particles. In the top x-axis of the figure, the typical mass-scale of haloes within which DM particles are embedded is highlighted. In the large-velocity regime, the latest upper limits and measurements of σ/m_χ are shown along side with the respective references.

For Milky Way-mass haloes, there are not robust constraints. Instead, an upper limit of 10 cm^2/g has been highlighted in Fig. 1 to indicate that a larger σ/m_χ at these scales leads to excessive satellite destruction, which in turn does not produce a realistic Milky Way system of satellites. This is because the excessive interactions between the DM particles from satellites and the host enhance the mass loss of satellites ([30, 31]).

In the dwarf galaxies regime current constraints of σ/m_χ rely on predicting the DM density profile of galaxies following the isothermal Jeans modelling. In this manner, Ref. [8] analysed the density profile of Draco, a cuspy MW dwarf spheroidal galaxy, and concluded that its high central density gives an upper bound on the SIDM cross section of $\sigma/m_\chi < 0.57$ cm^2/g (see also [32, 33]). Others (e.g. [10, 11]) analysed the cuspy profiles of some dwarfs and ultra-faint dwarfs, and concluded that zero self-interactions are favoured. The yellow region in Fig. 1 highlights the regime where $\sigma/m_\chi < 1$ cm^2/g. This regime is not ruled out by any upper limit from the large and small scales, and it indicates that σ/m_χ can be constant.

The problem with having $\sigma/m_\chi < 1$ cm^2/g is that such low rate of DM interactions fails to produce central density cores in haloes. In this manner SIDM is unable to solve the diversity problem of CDM, which cannot explain core in gas-poor dwarf galaxies, nor it can account for the full diversity in gas-rich systems ([34]). Several works have concluded that for SIDM being able to produce central density cores in haloes, the cross section needs to be $\sigma/m_\chi > 1$ cm^2/g, with numerical studies finding that $\sigma/m_\chi = 0.5 - 10$ cm^2/g produced DM cores in dwarf galaxies with sizes ~0.3-1.5 kpc (e.g. [21, 35, 36]). This minimum cross section of 1 cm^2/g, needed to solve the cusp-core problem of dwarf galaxies is highlighted in Fig. 2.

In the regime of large cross sections (e.g. $\sigma/m_\chi > 10$ cm^2/g), DM particle interactions are so frequent that they are able to rapidly heat the central DM halo core, causing it to contract and raise in density. In this regime, known as gravothermal core collapse ([37]), DM haloes form a density core early on, which changes to a cuspy profile at later times ([38–40]). Ref. [41] recently demonstrated that the high DM central densities of the satellite dwarf galaxies orbiting the Milky Way can be explained by SIDM, where the classical dwarf satellites are in gravothermal core collapse. Ref. [41] estimated that σ/m_χ should be larger than 10 cm^2/g on dwarf galaxy scales, with σ/m_χ depending on the relative velocity of DM particles, in such a way that DM behaves almost collisionless over cluster scales but as a collisional fluid on dwarf galaxy scales. The large cross sections from Ref. [41] are included in the top-left corner of Fig. 2.

Particle physics models favour such velocity-dependent framework for the DM particle (e.g. [42, 43]), arguing that DM exists in a 'hidden sector', where forces between DM particles

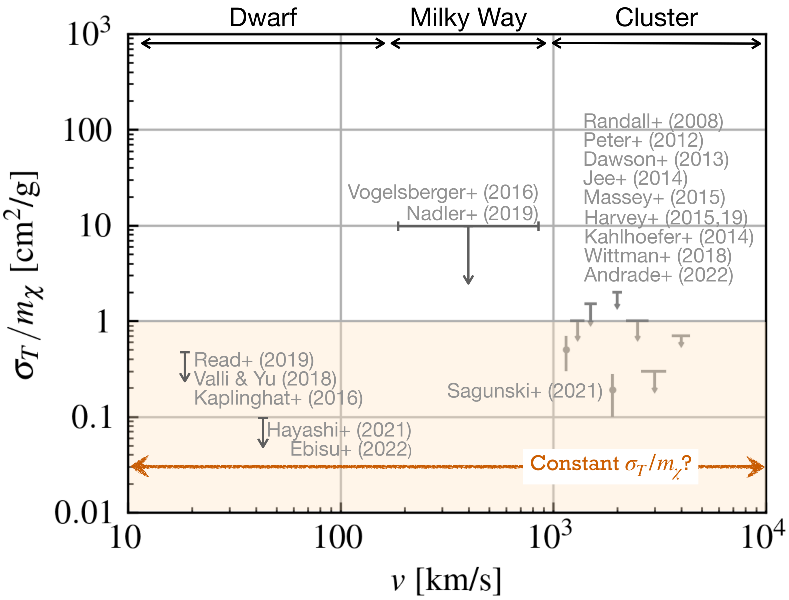

Figure 1: Cross section as a function of the relative DM particles velocities. The top x-axis indicates the typical halo mass that hosts orbits of such velocities. The figure shows upper limits derived from the DM-galaxy mismatch in galaxy clusters colliding, as well as from clusters' ellipticity and core-size. It is also shown a 10 cm^2/g upper limit motivated by the excessive satellite destruction in Milky Way-mass systems, and the recent $\sigma/m_\chi < 1$ cm^2/g upper limits in dwarf-mass scales derived from the cuspy profiles of some dwarfs and ultra-faint dwarfs. In the figure, the yellow region highlights the regime where $\sigma/m_\chi < 1$ cm^2/g. This regime is not ruled out by any upper limit from the large and small scales, and it indicates that σ/m_χ can be constant.

are mediated by analogues to electroweak or strong forces (e.g. [42–47]). The yellow region in Fig. 2 highlights a velocity-dependent σ/m_χ model, which is not ruled out by upper limits from the Milky Way satellite system and galaxy-clusters.

3 Velocity-dependent SIDM

The velocity-dependent cross section illustrated in Fig. 2 has been recently studied in a DM-only cosmological simulation of SIDM ([48]). Ref. [48] modelled the interaction among DM particles with the scattering following a Yukawa potential. Assuming that the scattering potential can be treated as a small perturbation (Born approximation), the differential cross-section used for the DM-DM interactions takes the form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\alpha_\chi^2}{m_\chi^2 (m_\phi^2/m_\chi^2 + v^2 \sin^2(\theta/2))^2}. \tag{1}$$

Assuming the coupling strength to be $\alpha_\chi = 4.96 \times 10^{-6}$, the dark matter mass, $m_\chi = 4.23$ GeV, and the mediator mass, $m_\phi = 0.35$ MeV, the velocity-dependent cross section reaches 100 cm^2/g on dwarf scales, 1 cm^2/g on MW-mass scales and < 1 cm^2/g on cluster-size galaxies. Using this model implemented in a cosmological simulation, Ref. [48] showed that it produces a diversity in the shape of DM density profiles in the DM halo population. The diversity is

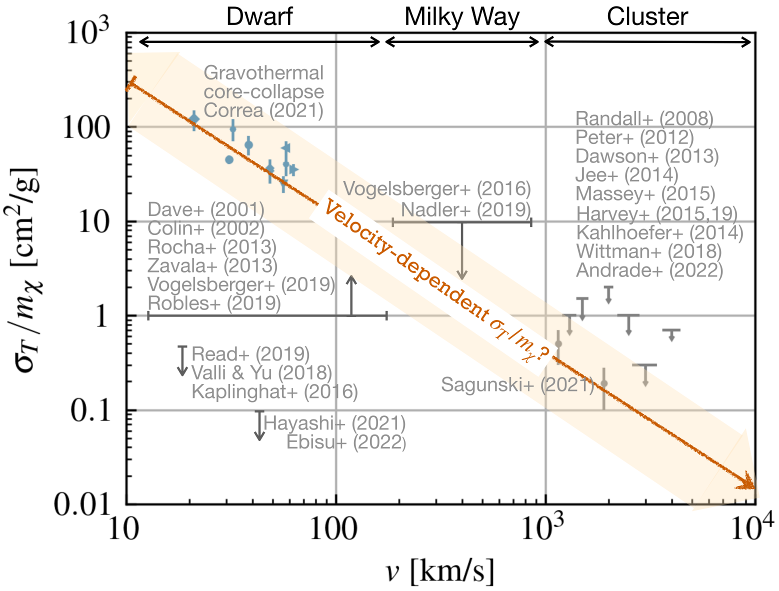

Figure 2: Same as Fig. 1. This figure indicates the lower limit of $\sigma/m_\chi > 1$ cm^2/g needed in dwarf-mass scales for SIDM being able to produce central density cores. Additionally, it shows the values of σ/m_χ derived in Ref. [41] under the condition of gravothermal-core collapse. The yellow region highlights a velocity-dependent σ/m_χ model, which is not ruled out by upper limits from the Milky Way satellite system and galaxy-clusters.

particularly large in satellite haloes.

4 Conclusion

In this proceeding I reviewed the combined measurements of cluster-size galaxies and kinematics of local satellite galaxies, and argued that DM interactions should depend on the relative velocity of DM particles. This conclusion is driven by the strong upper limits of $\sigma/m_\chi < 1$ cm^2/g derived using cluster-size haloes, and the recent result that large σ/m_χ on dwarf galaxy scales explains the diversity of rotational curves of these systems ([48]). The favoured velocity-dependent model considers a cross section that reaches 100 cm^2/g on dwarf scales, 1 cm^2/g on MW-mass scales and < 1 cm^2/g on cluster-size galaxies. This work concludes that a SIDM velocity-dependent model offers a promising explanation that alleviates the discrepancies on galactic and sub-galactic scales currently challenging the ΛCDM paradigm.

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