

WHAT IS THE NATURE OF DARK MATTER'S SELF-INTERACTION, AND COULD IT EXPLAIN THE UNEXPECTED DIVERSITY IN GALAXY ROTATION CURVES ACROSS DIFFERENT MASS SCALES?

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ABSTRACT

The rise in rotational speed of galaxies, despite increasing radii away from the center, hints toward non-luminous, dark matter. The standard CDM model, predicting cuspy density profiles, was proposed to explain the nature of dark matter and, initially, aligned with the observations; however, later observations of dwarf galaxies induced complications, because these systems were found to have shallower, core-like density profiles. This issue, characterized as the 'core-cusp' problem, indicates diversity in galactic rotation curves at large. The Self-interacting Dark Matter (SIDM) model emerged as an alternative explanation for dark matter's nature, where self-interactions between dark matter particles naturally produce cores. The intensity of these self-interactions is judged by the merit of cross-section per unit mass: $\sigma/m_{dm} \sim 1 \text{ cm}^2/\text{g}$. This paper takes into account distinct behaviors of dark matter at three galactic mass scales: dwarf galaxies, mid-sized galaxies, and clusters. Although SIDM simulations were steadily in line with observations at lighter mass scales, it raised the requirement of velocity-dependent self-interaction cross-section in order to remain applicable at heavier mass scales. Not inclining toward SIDM only, this paper scrutinizes other proposed paradigms for explaining dark matter behaviour as well. Finally, it discusses what upcoming observatory missions may entail and proposes future research directions in four domains (observations, simulations, data analysis, and laboratory experiments) to vindicate or disprove SIDM framework.

1 INTRODUCTION TO DARK MATTER AND GALAXY ROTATION CURVE PROBLEM

During the observation of the M31 galaxy's rotational velocity at varying radii, an anomaly diverging from the conventional view emerged. In the inner galaxy, a steep rise in velocity, as expected, was observed; however, at larger radii, specifically beyond 4 kpc, the velocities did not decrease as they should have if the mass were limited to stars and gas (Rubin & Ford, 1970). This finding strongly suggests some sort of gravitational influence beyond the galaxy's center of mass that gives rise to this increased rotational velocity, thereby implying the presence of a substantial amount of non-luminous, or 'dark' matter.

The study of galaxy rotation curves was extended to other samples, and the characteristic of having a cuspy density center remained consistent with the initial finding of M31 (Rubin et al., 1978). Later, based on these findings, the Cold Dark Matter (CDM) model was proposed, and essentially, dark matter halos predicted by this model inevitably led to rotation curves that initially rise rapidly and are approximately flat at larger radii (Navarro et al., 1996).

This generalized postulate, however, failed to account for the relatively new observations of galaxy rotational curves in dwarf and low surface brightness galaxies. These systems revealed

low-density, nearly constant-density cores, contrasting sharply with the dense, cuspy central profiles predicted by the CDM simulations, hinting at a diversity of rotational curves (Spergel & Steinhardt, 2000).

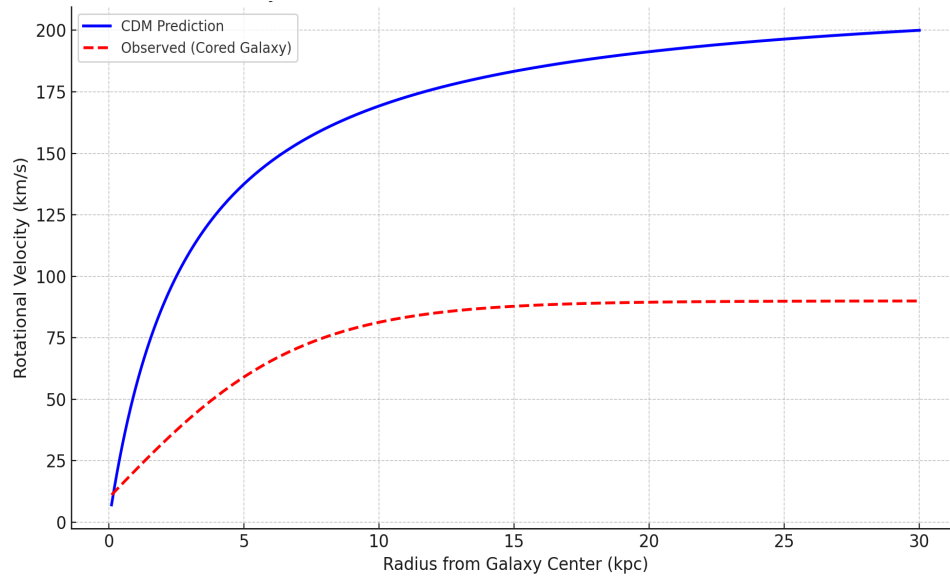


Fig 1: graph of rotational velocity w.r.t distance from the inner galaxy predicted by CDM vs the observed one in dwarf galaxies

Furthermore, according to CDM, a Milky Way-sized halo should host hundreds or thousands of subhalos; however, the observed count of dwarf galaxies in the Milky Way is significantly lower, suggesting a critical issue in the validation of CDM at small scales (Bullock & Boylan-Kolchin, 2017). Given these discrepancies, it can be suggested that the actual nature of dark matter, in specific galaxies like dwarf ones, differs from the CDM assumptions, hence raising a requirement for a paradigm that offers a plausible origin for this diversity in rotational curves. In this regard, can the Self-Interacting Dark Matter (SIDM) model, which can naturally produce smoother, more spherical density cores, account for such inconsistencies?

2 WHAT IS SELF-INTERACTING DARK MATTER?

Self-Interacting Dark Matter (SIDM) refers to a class of dark matter models in which the particles possess significant non-gravitational interactions among themselves. Unlike the standard CDM paradigm, which assumes weakly interacting or collisionless particles, SIDM posits that the dark matter particles can undergo elastic collisions with each other, resulting in scattering (Arrenberg et al., 2013).

The merit of cross section per unit mass — σ/m_{dm} , where dm refers to a dark matter particle — is central in understanding the intensity of these self-interactions.

$$\sigma/m_{dm} \sim 1 \text{ cm}^2/\text{g}$$

The magnitude of this ratio, at large, determines the frequency and the impact of dark matter self-interactions within astrophysical systems (Arrenberg et al., 2013).

The process of self-interaction is analogous to the process of thermal exchange between the particles of a conventional gas, where higher-energy molecules tend to collide with the molecules possessing lower energies. This causes a transfer of energy and eventually leads to a thermal equilibrium in the overall system. In the context of SIDM, the collision of DM particles and the subsequent exchange of kinetic energies redistributes energy spatially within the inner halo. In other words, transfer of energy from regions of higher velocity dispersion to regions of lower velocity dispersion is the product of these self-scattering events, eventually resulting in an isothermal, equilibrium-like state. Altogether, this redistribution of kinetic energies, in turn, affects the gravitational potential profile (Kamada et al., 2016).

With the above taken into account, velocity dispersions, caused by self-interactions, of central particles could reduce the central gravitational binding and cause the innermost particles to migrate outwards. This redistribution, if reasonably inferred, could strongly lead to a shallow central density profile, deviating away from the cuspy central profile predicted by the CDM. Reiterating the earlier point, the effectiveness of this core formation can be suggested to be sensitive to the scattering cross section per unit mass (σ/m_{dm}), as a larger cross section increases the likelihood of collisions, thereby intensifying the thermalisation effects, and vice versa. If sufficiently large, these interactions can be capable of producing the observed cored density profiles across different mass scales.

3 OBSERVATIONS: ROTATION CURVES IN DIFFERENT GALAXIES

Before continuing, it's imperative to understand how rotation curves are measured. One primary approach to measure the rotation curves is using H I 21-cm line observations, taking advantage of the fact that H I gas is distributed extensively in a galaxy disk. Initially, data cubes are obtained by radio interferometers such as the Very Large Array (VLA). These data cubes include spectral information as a function of spatial position, which allows the construction of velocity fields by identifying the Doppler shifts. Next, to interpret these velocity fields in terms of circular motion, the 2D tilted-ring modelling technique is used, involving fitting a series of concentric ellipses to the observed velocity fields. Each ring is parameterised by geometric and kinematic parameters: center position, position angle, rotational velocity, systemic velocity, and inclination. The velocities are then corrected for projection effects dependent on the inclination of the galaxy, yielding the metric of rotational velocity for each radius. This method has been widely adopted (Rogstad et al., 1974; de Blok et al., 2008).

In CDM simulations, DM halos develop steep central density profiles, or otherwise known as 'cusps'. On the contrary, observations of many galactic structures have shown inner density

profiles where DM halo flattens toward the center, deviating away from ‘cusps’ and forming, commonly known, ‘cores’. The problem of core vs. cusp density profiles has continued to portray the distinction of rotation curves that exists in different galaxies.

The sample of 26 galaxies observed in LITTLE THINGS exhibited rotation curves that rose linearly in their central parts (Oh et al., 2015). To be exact, measured logarithmic inner slopes (α) of dark matter density profiles consistently showed values flatter than -0.5, making them shallower than CDM cusp predictions ($\alpha \approx -1$). Furthermore, analysis of 16 dwarf galaxies revealed diverse cores. While some DM cores remained consistent with the NFW profiles predicted by pure CDM simulations, others matched well with predictions of the CORENFW model, portraying core density profiles, in essence (Read et al., 2019). Extending observations to a wider sample of galaxies, findings from the study of 175 galaxies from the SPARC database leaned towards cored halo profiles rather than NFW or the standard CDM model (Li et al., 2020). To be specific, observed rotation curves were fitted with theoretical DM halo models to assess how well those models reproduce the actual kinematic data. Cored halo profiles—Burket, DC14, coreNFW, pISO, and Einasto—systematically provided better fits. Application of the NFW cuspy profile, conversely, reduced the statistical quality of rotation curve fits.

It is important to note that this trend—deviation from cuspy prediction—was not confined to dwarf galaxies, as 175 galaxies from the SPARC sample spanned a wide range of galaxies, including large spiral galaxies (Li et al., 2020). With persistence of core-based profiles in these systems, despite their baryon-dominated centers, it can be concluded that the diversity in inner density profiles extends to systems of varying sizes as well.

Another comprehensive statistical investigation showed varying DM halo profiles. Observed rotation curves of 304 dwarf and intermediate-mass galaxies, plus an additional 189 massive galaxies, were compared with the latest CDM cosmology-based simulations: EAGLE and LOCAL GROUPS simulation projects (Oman et al., 2015). Some simulated galaxies did match observed rotation curves very well, even for dwarfs; however, the variety of data obtained indicated significant departure from the CDM simulations.

Altogether, the statistical studies mentioned above suggest that while the CDM paradigm is successful in some galactic structures, the notion that it is universal should be discredited. In particular, the discrepancies observed in the studies above manifest as the ‘core-cusp’ problem, reinforcing the rotation curve diversity across galaxies.

4 CASE STUDY: DWARF GALAXIES

Dwarf galaxies serve as critical samples for testing the predictions of dark matter models due to their high DM fractions and relatively simpler baryonic structures. Unlike massive galaxies, where baryonic processes such as star formation and feedback are potent in reshaping the DM

distribution, dwarf galaxies are known to possess weaker baryonic influence, resulting in their internal dynamics being governed mostly by the gravitational potential of dark matter. In the CDM framework, as stated multiple times, simulations of central kinematic profiles predict cusp density profiles. However, observational studies often reveal core-like DM distributions in dwarf galaxies (Read et al., 2019). Considering the limited baryonic impact and such deviations from CDM predictions in these systems, it is only reasonable to speculate that such behaviour cannot be easily attributed to complex baryonic processes alone.

Dwarf galaxies, specifically those that are pressure supported and lack significant gas content, are ideal for such analysis because their stellar kinematics can be utilized to trace the underlying gravitational potential with minimal contamination from baryonic influence. One study in this context analysed the inner dynamics of the Fornax and Sculptor dwarf spheroidal galaxies (Walker & Peñarrubia, 2011). Due to the presence of multiple stellar populations with distinguishable spatial and kinematic properties in each galaxy, the study was able to separate overlapping effects in the data obtained and isolate the accurate mass structure, rather than relying on assumptions about orbital anisotropy that limit the accuracy. The results indicated preference for core DM density profiles in both galaxies. It is imperative to understand that the findings do not rely on gas dynamics or uncertain feedback models, but rather on the dynamical modeling of stars in systems where baryonic effects are minimal, signifying the notion that the behaviour causing flatter density profiles in inner halos is not strongly correlated to baryonic influence.

In certain cases, the structural evolution of dwarf galaxies can be influenced by their environment, specifically their proximity to massive host galaxies such as the Milky Way. Satellite dwarfs, as such systems are commonly referred to, are subject to tidal forces, which can induce stripping and heating of their DM halos, potentially altering their central density profiles. This possibility raises the question of whether the observed core profiles in satellites are intrinsic or the result of external factors. To address this inquiry, therefore, comparisons with isolated dwarf galaxies, which evolve outside the influence of a host, are essential. In this regard, a study utilised simulations of ultra diffuse galaxies (UDGs), galactic structures that mimic regular dwarf elliptical but are much larger and more diffuse (Carleton et al., 2019). The model used successfully reproduced the abundance and size distributions of UDGs when cored halo based simulations were utilised. On the contrary, cuspy haloes produced insubstantial UDG properties (stellar mass, size) that remained incongruent with the actual observations. The presence of core density profiles in environments free from tidal interactions, thus, suggests that core formation can occur independently of environmental processes.

In light of the discussion above, the paper will now establish that the SIDM framework leads to cored halos in small galactic structures. By introducing particle level interactions, dark matter based on the SIDM paradigm can undergo energy distribution and thermalisation in the central halo regions. Finally, these processes, intuitively, result in a flat, cored profile. Findings from

simulations that used the FIRE 2 galaxy framework support this mechanism posited above (Robles et al., 2017). Exploiting SIDM physics, the simulations accurately formed realistic dwarf galaxies with cored DM profiles, closely matching with the real life observations in other studies (Read et al., 2019; Oman et al., 2015; Li et al., 2020). And notably, these cores emerged without the requirement of strong baryonic feedback processes. Altogether, the feature of SIDM paradigm to naturally give rise to cored profiles across a range of environments, without invoking complex baryonic effects, positions it as a compelling alternative to standard CDM for dwarf galaxies.

5 CASE STUDY: MID-SIZED GALAXIES

In mid-sized galaxies, including those with masses comparable to the Milky Way, the shape of the rotation curve offers conclusions on the inner slope of the DM halo profile, and, as will be discussed further, these systems tend to exhibit diverse rotation curves. A high resolution study examined a sample of 34 galaxies, which included the Milky Way sized structures (De Blok et al., 2008). While a fraction of these systems leaned towards cuspy halos predicted by the CDM, the rotation curves of others notably fit the cored halo models well, hence no strong preference for density profile was revealed. In another complementary analysis, the findings demonstrated that a wide range of spiral galaxies, including those with masses comparable to the Milky Way, share a common core like DM distribution (Salucci & Burkert, 2000). While dwarf galaxies, unsurprisingly, showed such behaviour, mid-sized spirals too revealed large constant density cores. Taken together, these studies imply that the standard CDM model does not adequately capture the dark matter structure for the galaxies of this mass scale.

The question persists, whether Milky Way-mass galaxies possess cored or cuspy DM profile? Observational evidence in this regard leads to a more complex picture. Probing massive, star-forming galaxies at redshifts around $z \sim 2$, when the universe was approximately three billion years old, a study found that many of these systems have compact central structures with steep inner mass profiles (Genzel et al., 2017). These cuspy distributions imply that early galaxies began with centrally concentrated DM and baryonic components and over time, processes such as stellar feedback, gas outflows, or perhaps self interactions may have led to redistribution of mass and therefore, flattening of cusps into cores. To conclude with, this unconventional insight suggests that a core or a cusp behaviour in mid-sized galaxies is not fixed, but rather subject to internal and environmental processes that occur over time, shaping the final DM structure.

Furthermore, the application of SIDM to mid-sized galaxies requires careful consideration of the cross-section metric. Though constant cross-section SIDM models effectively match with observed cores in dwarf galaxies, utilising the same approach generates overly large cores in more massive galaxies, inconsistent with the observed kinematics (Mastromarino et al., 2023). To remain viable for mid-sized galaxies, SIDM has been suggested to be modified by

considering *velocity-dependent self-interaction cross-section*, where scattering strength decreases with increasing relative velocity. (Nadler et al., 2020).

On the other hand, failing to consider relatively abundant baryonic mass present inside mid-sized galaxies also produces overly large cores in simulations. Increased baryonic mass, therefore, may influence how SIDM thermalises the halo, which, consequently, may cause a change in density profiles produced, avoiding extremely large cores. Detailed simulations were used to compare *SIDM only* and *SIDM with baryonic effects* with observed density profiles of galaxies (Creasey et al., 2017). Findings revealed that the inclusion of baryonic influence in SIDM brought the model into close agreement with the observational data, as opposed to the exclusion of baryonic effects which produced extremely large cores, as stated earlier.

To conclude with, it is established that while some mid-sized galaxies are well-fit by cored density profiles, others show steep inner velocity rises that are more consistent with cuspy halos. Variations in stellar feedback history may account for these differences, indicating that baryonic processes significantly modulate the central structure. Alternatively, from the perspective of SIDM, the diversity observed across surveys may be explained if the SIDM paradigm is modified: when applied to mid-sized galaxies, in the absence of velocity dependence and baryon-driven moderation, SIDM weakly matches observed data. On the contrary, SIDM with baryonic effects does entail the ability to reproduce the observed variety of galactic structure at this mass scale, given that its scattering behavior, by velocity-dependent cross section, varies.

6 CASE STUDY: GALAXY CLUSTERS

Galaxy clusters, with total mass exceeding $10^{14} M_{\odot}$, are the largest gravitationally bound structures in the universe. They are composed primarily of dark matter, but also include hot intracluster gas and a smaller fraction of luminous galaxies. Furthermore, their immense scale and deep gravitational wells insulate them from complex baryonic processes that influence the internal dynamics of smaller systems, dwarfs and mid-sized galaxies. Certain processes such as supernova winds or stellar feedback are known to alter DM distributions in galactic structures; however, at this scale, their impact becomes negligible. Given all this, clusters become, so far, cleaner samples for studying DM properties and testing out different models, including SIDM.

The internal structure of galaxy clusters is inferred through complementary observational methods that entail the ability to isolate different mass components for better findings. X-ray imaging and gravitational lensing are effective when exploited together and applied on merging clusters. In merging clusters, because hot gas interacts through pressure and drag while DM and galaxies behave as collisionless components, spatial offsets between these constituents often arise during collisions. This offset has been observed in the merger of the Bullet Cluster,

where it was clearly demonstrated that DM moves separately from regular matter during cluster collisions (Markevitch et al., 2004)

X-ray observations trace the hot intracluster gas, which constitutes the baryonic component in clusters. This extremely heated gas emits X-rays mostly via thermal bremsstrahlung. Observed X-ray brightness and temperature distributions show the spatial arrangement and thermodynamic state of the gas. Gravitational lensing, on the other hand, accentuates the total gravitational potential of the cluster. To be specific, by measuring distortions in the images of background galaxies, lensing allows for reconstruction of the projected mass distribution, which is dominated by DM. Therefore, following the comparison of X-ray and lensing data, studies can disentangle the distribution of the baryonic gas, the luminous galaxies, and the underlying DM.

The spatial separation, observed in the Bullet Cluster, between X-ray emitting gas and the lensing inferred mass peaks (where DM lies) implies low self-interaction cross section at this scale. If DM collided frequently similar to the gas particles, their distribution would have lagged behind, which was not observed (Markevitch et al., 2004). From systems such as this, therefore, upper bounds on the DM self-interaction cross section can be derived: $\sigma/m_{dm} \lesssim 1 \text{ cm}^2/g$ in the case of the Bullet Cluster. Similar to this study, a sample of 72 merging clusters was analysed to determine a more accurate upper limit by utilising Chandra and Hubble Space Telescopes (Harvey et al., 2015). Once again, no lag of DM was detected, indicating little deceleration from self-interactions, and comparisons of positions of galaxies, gas, and DM across the sample derived a more stringent upper bound: $\sigma/m_{dm} < 47 \text{ cm}^2/g$.

Another cluster merger, Abell 3827, initially drew attention due to a previously reported separation between DM and galaxies, indicating that DM lagged behind, which in turn implies strong self-interactions at this scale. Later, the system was re-examined using updated mass reconstruction techniques, where revised analysis discovered low lag of DM (Massey et al., 2018). This finding was contrary to what was initially discovered, with the discrepancy arising due to measurement uncertainties and projection errors. Thus, the notion of weak self-interactions at the cluster scale remains consistent. More broadly, constraints on SIDM models have continued to improve through simulation informed lensing analyses. A study combined high-resolution hydrodynamical simulations of cluster mergers with gravitational lensing data (Andrade et al., 2021). The findings reinforced that, in the high velocity environments typical of galaxy clusters, the allowed cross section must be below $\sim 1 \text{ cm}^2/g$, in line with the previous upper bounds.

Altogether, while SIDM remains a viable framework on small scales, its application to massive systems like galaxy clusters requires stringent limits on the interaction strength, as discussed above. Furthermore, it is important to note that the earlier discussed possibility of velocity dependent scattering is invoked at this scale, where high velocity characteristic of merging

clusters ($\gtrsim 1000$ km/s) can be implied to decrease the self-interaction strength of DM, as is supported by the respective findings discussed above.

7 DARK MATTER SIMULATIONS AND PREDICTIONS

Cosmological simulations are important tools for testing DM models, as they allow the tracking of structure formation from early universe initial conditions to the present day. Such simulations begin with a specified matter power spectrum and evolve under gravity using N body or hydrodynamical codes. Additionally, simulations can be further modified to account for baryonic physics. Central to these simulations is the treatment of DM, either as purely collisionless, as in the standard CDM paradigm, or with a prescribed self interaction cross section, as in the SIDM framework. Achieving high resolution in both large scale structure and small scale galaxy formation presents computational challenges, as simulations must resolve the internal kinematics of the individual haloes while simultaneously accounting for cosmological volume. To improve computational efficiency of DM modeling, advancements have over time been presented. For instance, a framework was introduced that reduces the cost of simulating self interacting particles by approximating scattering events, doing so in a way that preserves halo level accuracy without requiring full particle particle interactions (Correa, 2021). This, as a result, allows SIDM simulations to scale more effectively to large volumes while maintaining reliable predictions for halo structure.

Early large-scale SIDM cosmological simulations demonstrated that self interactions lead to core formation in DM halos and alter subhalo density profiles without disrupting largescale matter distribution (Rocha et al., 2013). Further comparative simulations of CDM and SIDM have revealed deviating physical properties, notably the density profiles (Vogelsberger et al., 2014). In CDM simulations, DM is modelled as a collisionless fluid, and halos typically form steep inner density profiles, whereas SIDM simulations, by introducing elastic scattering between DM particles, result in constant density profiles due to thermalisation and energy redistribution in halo centers. In these early comparative simulations, particular SIDM models matched small scale observations more accurately, therefore establishing credibility of SIDM simulations for further studies (Vogelsberger et al., 2014).

To conclude with, SIDM simulations make distinct predictions that can be evaluated using astrophysical observations. To be precise, SIDM predicts flat central density cores, increased tidal stripping and stellar distribution expansion due to core formation, resulting in more tidal debris and lower central densities, and greater diversity in rotation curve shapes among galaxies of similar mass. The outcomes are reported in simulations of various studies (Vogelsberger et al., 2014; Sameie et al., 2020; Rocha et al., 2013). These predictions are directly testable using observed rotation curve shapes, stellar kinematics, gravitational lensing, and satellite mapping across various galactic environments. Where SIDM matches these observables more accurately than CDM, it gains empirical support.

8 WHY THE INTERACTIONS MIGHT DEPEND ON SPEED

A notable shortcoming in the generalisation of the SIDM paradigm is the observed variety of DM halos across different mass galactic structures. Dwarf galaxies, with lower internal velocities ($\gtrsim 30$ km/s), reveal the presence of large central cores, hinting towards strong interactions within such systems. At the other end of the mass scale, however, galaxy clusters show high velocity dispersions ($\gtrsim 1000$ km/s), and their gravitational lensing and dynamical structure constrain the self-interaction cross section to be extremely small. Therefore, a constant, velocity-independent cross-section cannot satisfy both extremes without producing discrepancies in one regime.

Addressing this tension, a framework was introduced, proposing interaction strength to decrease with increasing relative velocity of DM particles (Loeb and Weiner, 2011). In this framework, interactions are strong in systems with low-velocity dispersions—dwarf galaxies—but become suppressed in high-velocity environments similar to galaxy clusters. Low-constant, high-constant, and velocity-dependent cross-section SIDM models were applied to simulations of Milky Way–mass systems and their satellite populations (Zavala et al., 2013).

While the model having low-constant cross-section ($\sigma \sim 0.1 \text{ cm}^2/\text{g}$) produced subhalo population similar to the real-life observations, it failed to produce density profiles that align with observed core profiles of dwarf galaxies. Next, the model having high-constant cross-section ($\sigma \sim 1 \text{ cm}^2/\text{g}$) was able to produce core profiles that agreed with the observed profiles of dwarf galaxies; however, if the same high cross-section were to be applied on galaxy clusters, shapes and densities inconsistent with the actual observations would be produced, something that is discussed in detail earlier in the case study of galaxy clusters. Finally, only velocity-dependent cross-section, with higher interactions in low-velocity environments and lower interactions in high-velocity environments, can simultaneously match dwarfs' density profiles and observed cluster constraints.

An explanation of why velocity-dependent self-interactions arise in the first place is the theorized presence of a light mediator particle that creates an attractive force between DM particles, eventually leading to scattering (Buckley & Fox, 2010). Intuitively, the scattering cross section is intensified at low velocities due to increased interaction time, thus increasing the effect of mediator-induced potential. Conversely, at higher velocities, the interaction time between DM particles becomes shorter, hence weakening the effect of the mediator-induced potential and reducing the scattering cross section. The enhancement of scattering cross section manifests as an inverse power-law scaling with velocity:

$$\sigma \propto \frac{1}{v^n}$$

where n is typically 1 or 2

In summary, velocity dependence enables SIDM to transition smoothly between different regimes. This cross-scale compatibility is essential for reconciling the diverse observational landscape and is supported by experts (Tulin & Yu, 2018). Thus, with this minimal yet effective extension to the standard SIDM, coherent explanations for varying behaviours observed across galactic mass scales can be perfectly established.

9 OTHER THEORIES BESIDES SIDM

Supernova-driven feedback is one of the proposed alternatives for the nature of DM. Repeated outflows of gas caused by star formation inject energy into the surrounding mediums. If sufficient, such energy outflows may induce fluctuations in the gravitational potential, eventually transferring energy to DM particles and flattening cusps into cores. Hydrodynamical simulations revealed this mechanism operates efficiently in gas-abundant dwarf galaxies with bursty star formation histories (Pontzen & Governato, 2012). Cumulative effects of various supernova episodes displaced DM particles from the center, resulting in cored density profiles.

However, several shortcomings of this method remain: in galaxies with low star formation rates—ultra-diffuse galaxies—energy input can be insignificant to drive cored profiles. Furthermore, the timing and haphazard nature of this baryonic process makes it difficult to predict core properties precisely across a broad range of galaxy types. In conclusion, though simulations can produce cores with purely baryonic physics, sensitivity to details of star formation hinders its generalisation.

Instead of considering DM in the first place, some theories propose that gravity itself behaves differently on galactic scales. The theory of Milgromian Dynamics (MOND) was proposed to explain galaxy rotation curves without non-baryonic DM. A distinctive feature of MOND is the External Field Effect (EFE): unlike general relativity, MOND predicts that the internal dynamics of a galaxy depend on the strength of an external gravitational field, renouncing the Strong Equivalence Principle. Observed rotation curves of 153 galaxies in the SPARC database were compared with MOND predictions (Chae et al., 2021). Observations of galaxies experiencing strong external gravitational fields were consistent with MOND predictions with EFE, thus providing an alternative explanation for the counterintuitive rise in rotational velocity with increasing radii of galaxies. Furthermore, MOND predicted, as a result of EFE, a gradual decline in rotational velocity at large radii. Notably, this aligned with SPARC observations. CDM, lacking such an environmental dependence, does not naturally explain this trend.

While such studies establish the need for modification in gravitational laws, MOND nevertheless faces intrinsic limitations that hinder its generalization as an alternative to the existence of DM. Implementing the EFE requires extra information about a galaxy's environment to determine the magnitude of the external field, introducing additional modeling complexity and uncertainty. Furthermore, MOND struggles to consistently describe systems beyond rotationally supported galaxies, such as galaxy clusters and certain pressure supported systems, where discrepancies

persist without considering additional unseen mass. Together, these downsides indicate that this paradigm is not yet sufficiently general or fundamental to fully replace DM.

Fuzzy Dark Matter (FDM) is another alternative candidate to SIDM. This paradigm consists of ultra-light bosons with mass $\sim 10^{-22}$ eV, leading to de Broglie wavelengths comparable to kiloparsec scales. This gives rise to quantum pressure, based on the uncertainty principle, that smooths out the density fluctuations below a critical scale, resulting in halos with suppressed central densities or cores (Hu et al., 2000). Furthermore, FDM predicts that core surface density should scale deeply with core radius; however, observations show no such correspondence. Instead, core surface density is nearly constant over a wide range of core radii (Burkert, 2020). FDM core predictions, nevertheless, are still derived from a limited number of cosmological simulations, raising a requirement for higher resolution simulations. One more challenge in the advancement of this paradigm remains the detection of FDM in the first place: since its interaction cross section with normal matter is very low, FDM is hard to detect.

Another framework is Warm Dark Matter (WDM) that proposes decoupling of DM particles while they were still relativistic in the early universe. Their non-negligible velocities then lead to free streaming, resulting in eradication of primordial fluctuations beyond a certain scale. This, therefore, suppresses the formation of low mass halos. Indeed, when WDM simulations were compared with Milky Way observations, models with DM particle masses of about 1.5 keV produced fewer subhalos, aligning with the observations and addressing the CDM framework's 'too many satellites' shortcoming (Lovell et al., 2014). However, WDM still remains ineffective in addressing the 'core cusp' problem. Respective simulations produced relatively smaller cores than those observed in dwarf galaxies, essentially leaning towards cuspy density profiles.

10 CURRENT OBSERVATIONS AND WHAT MIGHT COME NEXT

Over the past few years, large scale galaxy surveys such as SPARC (Spitzer Photometry & Accurate Rotation Curves) and THINGS (The HI Nearby Galaxy Survey) have become central to our understanding of DM distribution in galaxies. Specifically, these datasets include high resolution photometric and kinematic measurements of galaxies having a wide range of masses. Notably, there are recurring findings in these surveys: flattened density profiles, or cores, in contrast with cuspy central densities predicted by CDM simulations; and wide diversity of rotation curve shapes observed in galaxies, discrediting the universality of the CDM paradigm (Oh et al., 2015; Oman et al., 2015; Read et al., 2019; Li et al., 2020).

Gravitational lensing bypasses the assumption about the relationship between luminous and non luminous matter and traces how mass distorts spacetime regardless of whether it emits light, making it a potent, independent tool. A subdomain of this method, strong lensing, is an emerging effective method to probe DM distributions and reveal novel findings. Recently in 2020, for instance, the first study to constrain the concentration of DM subhalo using strong lensing revealed discrepancies when compared with CDM simulations (Minor et al., 2021). To

be specific, a DM subhalo was detected with an extremely higher density than expected for its mass under CDM, strengthening the notion calling for the requirement of another DM framework. The study, while establishing strong lensing as an effective methodology, further emphasised its use to yield more accurate findings in future surveys such as Euclid and LSST.

Looking ahead, therefore, relatively recent and upcoming surveys such as Legacy Survey of Space and Time (LSST), Euclid and James Webb Space Telescope (JWST) are expected to advance the empirical understanding of DM, with each survey focusing on disparate regimes of scale, resolution, redshift and much more.

The Legacy Survey of Space and Time (LSST), conducted by the recently incepted Vera C. Rubin Observatory, will provide deep time domain imaging of billions of galaxies over a 10-year period. Its immense depth and sky coverage will crucially improve our ability to detect cosmological features—LSB galaxies, tidal features, satellite populations—that are important observational probes of DM structure and halo evolution. For SIDM in particular, LSST will allow mapping of core sizes and halo shapes across environments and redshifts, helping evaluate whether core formation trends are consistent with velocity dependent self interactions. Euclid, launched in 2023 by ESA, is designed to test DM and dark energy through precise measurements of weak gravitational lensing and galaxy clustering. By observing distortions in the shapes of distant galaxies caused by intervening DM, Euclid will construct a statistical map of the large scale matter distribution. Its weak lensing data can be used to complement strong lensing studies, providing necessary constraints for features such as halo concentration mass, where SIDM and other alternatives to CDM make distinct predictions. Lastly, while not focused as a DM mission, the James Webb Space Telescope (JWST) entails the ability to offer indirect constraints through its unprecedented ability to observe the formation and structure of the earliest galaxies. It is unsurprising that high redshift systems observed by JWST are influenced by the initial conditions of DM. If SIDM alters halo assembly histories or suppresses small scale structure at early times, those effects may be imprinted on the morphology, clustering or stellar content of early galaxies. JWST, therefore, can be utilized to extend the reach of DM testing to cosmic epochs previously deemed inaccessible.

Zooming out, while SIDM is primarily tested through astrophysical observations, some of its theoretical realizations predict new particles or mediators that could leave signatures in terrestrial laboratory experiments. In particular, direct detection efforts such as LZ and XENONnT are beginning to probe parts of the SIDM parameter space, especially in models where the self interaction arises from a light mediator that also may influence ordinary matter, albeit weakly. However, detection remains challenging due to the dearth of recoil signals in standard detector regimes. Nonetheless, addressing this challenge, emerging low threshold detectors—SuperCDMS, SENSIE, DAMIC-M—may achieve the sensitivity needed to access these interactions. Collider searches, including at the Large Hadron Collider (LHC), could also offer constraints or indirect evidence. Some SIDM models involve portals linking the dark and

visible sectors, producing missing transverse energy or displaced decay vertices. Although no such events have yet been confirmed, future runs with improved precision and dedicated triggers may begin to test viable SIDM constructions. Finally, fixed target experiments like NA64 and LDMX too offer a route to probe light mediators with very weak couplings. These experiments look for missing momentum or displaced decay signatures resulting from dark photon or scalar production.

It is imperative to note that while no definitive laboratory signature of SIDM has been found yet, the complementarity between astrophysical observations and laboratory experiments is a potent, effective path to vindicate the paradigm of self interactions.

11 CAN SIDM REALLY EXPLAIN DIVERSE ROTATION CURVES?

So far, this paper has established SIDM as an alternative to the standard CDM model. Notable success of SIDM lies in naturally produced cored density profiles, a notion reiterated by observations of dwarf galaxies, where baryonic mass is relatively low. Hence, this result can be attributed to elastic scattering due to self interaction rather than strong dependence on any baryonic process. In mid-sized galaxies, SIDM accommodates observed rotation curves by considering velocity dependent interaction cross section, where scattering strength decreases due to higher relative velocity of DM particles. This, in turn, avoids overly large cored profiles, producing moderate cored profiles which closely match the observations. On the other hand, simulations have shown that accounting for SIDM with baryonic effects can also avoid overly large cores produced by SIDM only models. Either of these modifications of SIDM, therefore, remains consistent with the observations. Yet, extrapolating the earlier—velocity dependent cross section—to galaxy clusters turns out to be successful: with even higher DM velocities, the SIDM model with reduced cross section explains the observations at this mass scale. This, in conclusion, strongly implies the compelling theoretical strength of SIDM's ability to unify the structural diversity under a common mechanism.

Velocity dependent cross section, a critical component for universality of SIDM, largely remains theoretical, however. Speculations on why this phenomenon arises point towards a light mediator particle, existence of which remains undetected to date. The absence of direct or indirect evidence for these mediators weakens the empirical foundation of such constructions when applied uniformly across mass scales. Moreover, SIDM does not fully eliminate diversity observed. Such as in dwarf galaxies, some systems with distinct timescales were found to retain cuspy inner profiles (Read et al., 2019). This raises two possibilities: either SIDM requires further environment or formation history dependent modeling, or it lacks true universality in its predictive scope. These issues do not necessarily falsify SIDM, but they highlight that current formulations may not constitute a fully predictive, self contained theory without fine tuning or auxiliary assumptions.

With timescales taken into account, SIDM must not only reproduce the observed density profiles but also do so on timescales consistent with galaxy formation. In dwarf galaxies, simulations find that cores can form within 1 to 5 Gyr, aligning well with the old stellar populations and established dark matter cores in classical dwarfs. However, not all systems evolve uniformly. In late forming or environmentally quenched galaxies, such as satellites subject to tidal effects, the timing of core formation may be altered. Some simulations (e.g., the FIRE SIDM runs) explore how combining SIDM with baryonic feedback can accelerate core formation, but this complicates attribution: are cores forming primarily due to self interactions, feedback, or both?

In summary, SIDM stands out as a better and physically coherent alternative to CDM in explaining inner halo diversity. Its ability to link core formation with halo properties through an interaction mechanism, especially when velocity dependent, gives it strong theoretical appeal. But empirical and theoretical challenges remain, particularly in pinning down its microphysical basis and testing its universality across all systems. Whether SIDM is the correct description of dark matter or simply a successful effective theory in certain regimes remains an open but increasingly tractable question.

12 FUTURE RESEARCH DIRECTIONS

Progress on SIDM requires parallel advances in the domains of simulation, observation, analysis, and laboratory physics, each area offering a unique insight into the framework.

Develop and Use High Resolution Simulations Integrating Baryonic Effects and SIDM

It is imperative to develop next generation hydrodynamic simulations that integrate high resolution, realistic baryonic effects with SIDM physics. Projects like FIRE-2 can help isolate disparate imprints of SIDM on halo structure and galaxy formation. Without such a pathway, disentangling SIDM effects from baryonic processes remains ambiguous.

Achieve Precise Kinematic Mapping Across Mass Scales

Make use of recent and upcoming observatory tools — JWST, Vera C. Observatory — to precisely measure rotation curves and, most importantly, extend rotation curve measurements to ultra faint dwarfs, low surface brightness spirals, and high redshift systems to test SIDM across a broader dynamic range. Furthermore, utilise emerging promising methods like strong lensing to sharpen constraints and, as a result, gain better insights.

Focus On Experimental Searches For Light Mediator Particles

As discussed, if self-interactions arise from light mediators, they should leave signatures in low energy experiments: beam dumps, fixed target setups, etc. Conduct such laboratory experiments while simultaneously advancing detection sensitivity in detectors used, given the relatively faint nature of detection in current detectors.

Exploit AI-Based Analysis

Though not really discussed in the paper, AI is revolutionizing space exploration, given its inherent ability to process cumbersome data and identify patterns. Develop machine learning models to classify core versus cusp profiles. Use AI based processing to uncover hidden correlations across datasets. Furthermore, train AI models with upcoming, more accurate observational data along with data from high resolution simulations to constrain velocity dependent interaction models.

Test SIDM Predictions At Larger Scales

Analyse the influence of SIDM on filament morphology, void properties, halo alignments, etc. If simulations reveal that SIDM changes such large scale structures even slightly, future surveys — LSST, Euclid — might detect it. This can, as a result, separate SIDM from other DM models in a novel way and vindicate the paradigm.

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