Snowmass2021 - Letter of Interest

Self-Interacting Dark Matter

Thematic Areas: (check all that apply □/■)

■ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Astro-particle physics and cosmology

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Abstract: (maximum 200 words)

The cold dark matter (CDM) theory works well in explaining the large-scale structure of the Universe, but it has difficulties in fully accommodating observations on galactic scales. This small-scale crisis may indicate that CDM is inaccurate in describing the inner structure of galaxies and a paradigm shift is required. Recent work shows that self-interacting dark matter (SIDM) provides a promising alternative to CDM. With upcoming observational facilities in the next decade, we propose to study predictions of dark matter self-interactions in galactic systems and compare them with astronomical observations. In particular, we suggest focusing on spiral galaxies, satellite dwarfs of the Milky Way, and newly discovered ultra-diffuse galaxies. In these systems, dark matter distributions exhibit a great diversity that challenges CDM most seriously, and hence they may provide a definitive test of the self-interacting nature of dark matter.

In the prevailing dark matter theory, Cold Dark Matter (CDM), dark matter particles are assumed to be cold and collisionless, aside from gravity. This theory works well in explaining the large-scale structure of the universe and overall properties of galaxy formation and evolution, but it has difficulties in explaining observations on small scales[1,2]. For example, rotation curves of spiral galaxies in the field exhibit a great diversity[3,4], which is hard to understand in CDM. Dwarf spheroidal galaxies of the Milky Way are diverse in dark matter content as well,[5,6] and there exists an anti-correlation between their central dark matter density and pericenter distance[7]. The discovery of dark matter-deficient galaxies NGC 1052-DF2[8] and -DF4[9] further challenges CDM[10]. All these discrepancies indicate that CDM may break down on galactic scales and a paradigm shift is needed.

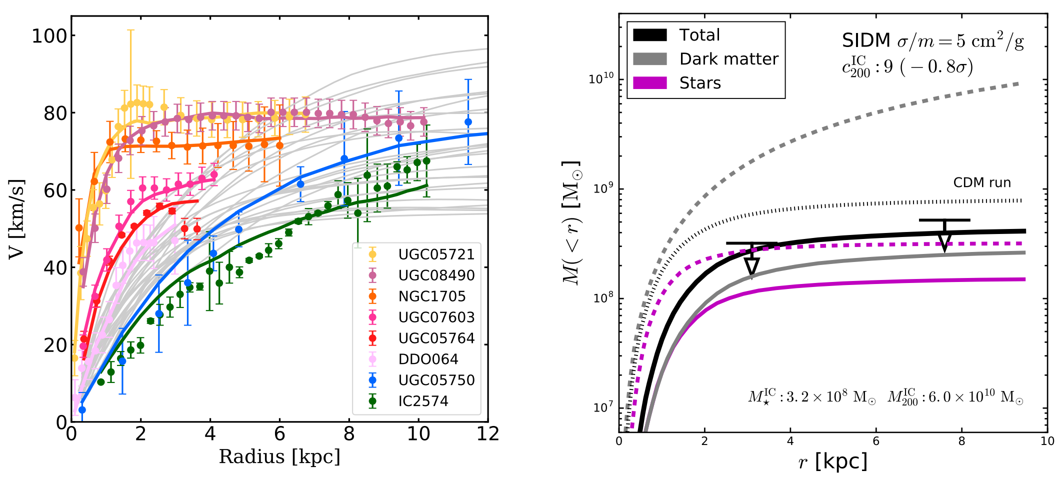

Figure 1: *Left:* SIDM fits (solid-colored) to the rotation curves of eight galaxies in the SPARC sample (colored dots with error bars), spanningthe full range of the diversity, compared with simulated analogs in a similar velocity range from hydrodynamical CDM simulations with strong feedback (gray)[11]. Reprinted from Kaplinghat et al.[12] *Right:* mass profiles profiles before (dashed) and after (solid) tidal evolution for an SIDM model constructed to reproduce observations of dark-matter-deficient galaxies NGC 1052-DF2 and -DF4. The total mass profile of its CDM counterpart is displayed (dotted) for comparison. The black arrows denote the upper limits on the total dynamical mass for NGC 1052-DF2[8]. Reprinted from Yang et al.[10]

Recently, there is exciting progress in addressing the small-scale issues of CDM in the framework of self-interacting dark matter (SIDM)[1], where dark matter particles have a large self-scattering cross section $\sigma/m \gtrsim 1\ \mathrm{cm}^2/\mathrm{g}$, similar to the nuclear interactions. Dark matter self-interactions thermalize the inner halo and change its structure in accord with observations[4,13,14]. Fig. 1 (left) shows excellent SIDM fits to the rotation curves of eight galaxies, chosen to exemplify the full range of the diversity within the same mass scale. SIDM predicts both cored and cuspy dark matter density profiles, depending stellar distributions of galaxies, in good agreement with the data. On the other hand, CDM simulations with strong baryonic feedback[11] could produce galaxy analogs with large density cores (UGC 05750, IC 2574), but not those with high baryon concentrations (UGC05721, UGC 08490, NGC 1705). We have tested SIDM with a large sample containing more than 130 spiral galaxies over a wide mass range[4] and shown it provides the best global fit to the data, compared to other fits using different CDM halo models in the literature[12].

Fig. 1 (right) shows mass profiles profiles for an SIDM halo model, compared to the upper limits on the dynamical mass of NGC 1052-DF2. The self-interactions push dark matter particles from inner to outer halos and speed up tidal mass of the inner halo, leading to better agreement with the observations than its CDM counterpart. SIDM is more favorable for the formation of dark-matter-deficient galaxies like NGC

1052-DF2 and -DF4 [10].

The economical explanation for diverse dark matter distributions across the entire range of observed galactic systems, argues in favor of the idea that dark matter particles have large self-interactions. With upcoming observational facilities in the next decade, we propose to further explore the self-interacting nature of dark matter in the following directions.

- **Galaxies in the field**. Since environmental effects are absent for galaxies in the field, they provide relatively clean tests of SIDM and CDM. The existing studies mainly focus on fitting to kinematics of spiral galaxies. As the next step, it is crucial to understand dynamical processes that lead to diverse dark matter distributions in the spirals, together with their stellar surface brightness. We also propose to extend analyses to newly discovered galaxies with novel properties. For example, recent observations of ultra-diffuse galaxies in the field show that they are baryon dominated in the inner regions [15–17], challenging CDM predictions.
- **Galactic systems in the environment**. Properties of satellite galaxies are related to their evolution history in the tidal field of their host. Recent Gaia [18] measurements of orbits of the Milky Way satellites [19] shed new light on their dynamics. For the bright satellites of the Milky Way, there exhibits an anti-correlation between their central dark matter density and pericenter [7], implying the importance of tidal interactions in shaping properties of the satellites. Overall, SIDM predicts more diverse dark matter distributions in subhalos, as its subhalo could be in core-expansion (low density) or core-collapse (high density) phases [20,21], depending on halo concentration and orbit. Such effects could also be tested with ultra-diffuse galaxies discovered in the Coma Cluster [22,23].
- **Cosmological hydrodynamical Simulations.** SIDM has profound implications for galactic dynamics. For example, SIDM predicts that the final dark matter density profile follows an isothermal distribution in the presence of baryon potential, robust to formation history of individual galaxies. This unique feature makes possible for analyzing kinematics data of a large sample without relying on N-body simulations. However, SIDM simulations are necessary to fully explore assembly history of galaxies and study their statistical properties in the cosmological context. In addition, to reproduce observables, SIDM may require a treatment of baryonic feedback processes different from those developed for CDM. As of today, none of CDM simulations with baryonic feedback could reproduce the full range of diverse stellar and dark matter distributions [12]. We propose to reassess feedback models within the SIDM framework.
- **Particle physics modeling and complementary searches.** SIDM is a framework that connects microscopic particle physics of dark matter (10^{-12} cm) to astrophysical observables (10^{21} cm). It also has rich implications for cosmological observations and particle physics phenomenology [1]. For example, it generically predicts massless degrees of freedom in the dark sector, which could be detected at future CMB experiments. If SIDM couples to the standard model particles, it could be produced at particle colliders, resulting in signals of displaced vertices. Terrestrial dark matter experiments in the coming decade will provide complementary searches for the self-interacting nature of dark matter.

We hope to address a pressing question facing the dark matter physics community, i.e., how can we learn the nature of dark matter if it does not interact with ordinary mater aside from gravity? This so-called "nightmare" scenario is plausible, given theoretical motivations for hidden-sector dark matter models and the fact that we have not observed positive signals in conventional dark matter searches. In this scenario, astrophysical probes become the only way to uncover the nature of dark matter. We take well-motived SIDM theory and explore its novel predictions by leveraging astronomical observations, hydrodynamical simulations of galaxy formation and particle physics modeling.

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