Snowmass2021 - Letter of Interest

Novel Properties of Self-Interacting Dark Matter Halos

Thematic Areas:
(CF1) Dark Matter: Particle Like
(CF3) Dark Matter: Cosmic Probes
(TF08) Theory frontier/Models
(TF09) Theory frontier/Astro-particle physics and Cosmology
(CompF2) Theoretical Calculations and Simulation

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Abstract:
In many newly proposed models, dark matter belongs to a dark sector that has its own interactions. If the interactions within the dark sectors are significant, these models predict novel properties in halo dynamics, which could be tested with astrophysical observations. We discuss theoretical challenges and opportunities for modelling dark-sector interactions in halo formation and evolution.

The existence of dark matter (DM) in the Universe is inferred from its gravitational influence on normal matter. Over the past decades, terrestrial dark matter searches have put strong constraints on its interactions with the standard model particles. This leads to speculation that dark matter may reside in a dark sector that contains its own interactions, but couples to the visible sector very weakly if there is any [1, 2]. The dark sector models permits a vast varieties of self-interactions among DM particles. Such interaction may provide solutions to some small-scale problems of the cold dark matter model (see [3] for a review). Astrophysical observations of DM self-interactions can also provide an important way to explore the nature of DM and dark sectors.

The structure and evolution of DM halos play a crucial role in galaxy formation and evolution. Self-interactions between DM particles can transport heat within a halo and permit "gravothermal" evolution [4]. A DM halo generically evolves through two stages: (1) core expansion (formation). The self-interactions thermalize the central region of the halo with its hotter outer region. This results in a large density core, in contrast to a density cusp predicted in the CDM model. (2) Core collapse. After the core maximally expanded, the self-interactions continuous to transport heat out of the center while the central temperate keeps increasing, resulting in a steep density profile, see Fig. 1 (left). The core collapse is a runaway process as shown in Fig. 1 (right).

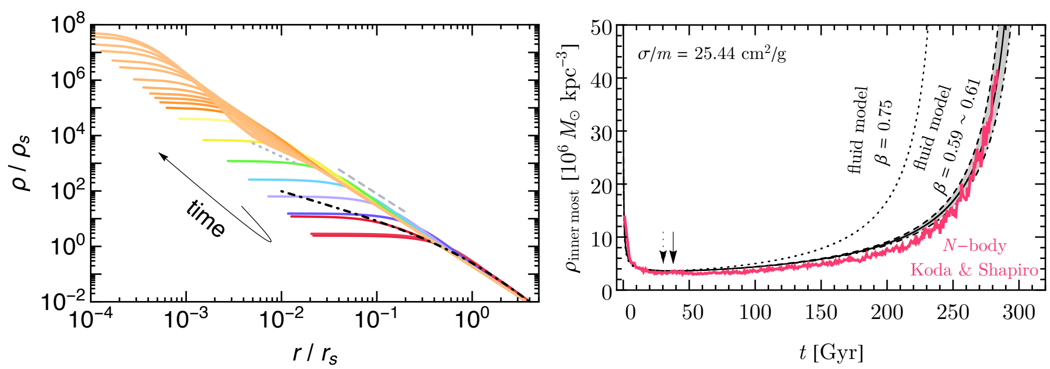

Figure 1: Left: the evolution of the density profile during the gravothermal evolution. The cuspy initial profile (black dot-dashed line) first expands to a core profile (red lines), then collapses into a higher core density and steep density profile (from red to green to orange lines). Right: the evolution of central density with respect to the time. The initial core expansion is followed by a long core collapse period that exhibits runaway manner. The red (black) lines are results from N-body (semi-analytical) simulations.

DM halos with a wide range of mass scales have been observed and their DM distributions will be explored through both lensing and substructure distribution. Based on those observations, the rich structure of the DM halo during different stages of gravothermal evolution can be used to test DM and dark sector models. If the self-interactions are purely elastic with the cross section strength $\sigma/m \sim 1\,\mathrm{cm}^2/\mathrm{g}$, favored to explain galactic observations [3], it takes ~ 10 Gyr to form a core with size comparable to the scale radius of the halo and takes more than 100 Gyr for it to deeply enter the collapse phase. Refs. [5, 6, 7, 8] show that a larger core with lower central density could form if the DM particles are heated from energy release due to dark-sector interactions. Refs. [9, 10, 11] show that the core collapse could be significantly accelerated if DM self-interactions are dissipative. By the end of the core-collapse, a massive black hole could form at the halo center [12, 13], which may provide an explanation for the observed high red-shift quasars (e.g. [14]).

In addition, cosmological environments could affect evolution history of a DM halo with dark matter self-interactions. For example, the core collapse can be accelerated with significant tidal stripping [15, 16, 17], central baryonic component [18, 19, 20]. It can be also significantly slowed by large mass accretion [21] or reset by major mergers. For subhalos residing inside a relative hotter host halo, the self-interaction tends to disrupt them through evaporation [22] and ram pressure [23], which can help distinguish the velocity dependence of the self-interaction cross section.

We propose to further study novel properties of SIDM halos in the following aspects.

- Phenomenological models. It is important to develop "simplified" models that capture essential features of dark-sector interactions. Existing examples include the Yukawa interaction model that describes the velocity-dependent self-interactions, and the inelastic SIDM model that describes the dissipative self-interactions. More work is needed along the lines.

- Halo dynamics. There are two popular methods used to study halo dynamics of SIDM: semi-analytical fluid simulations and N-body simulations.

  - Semi-analytical methods. They are built on simplified assumptions such as the DM halo is in a quasi-hydrostatic equilibrium and the halo evolution is spherical symmetric. It will be interesting and important to explore semi-analytical methods beyond those assumptions to deal with, e.g., halos with significant angular momentum.
  - N-body simulations. They are built on the first principle and provides a more realistic picture of the halo evolution. Due to the limit on computational resource, current Monte-Carlo-based N-body simulations cannot resolve the halo profile as deep as the semi-analytical method. They are also inefficient to simulate halos in the collapse phase, where the central dark matter density is extremely high. Therefore, it is important to explore new N-body algorithms (e.g. [11]) to address those problems. Another challenge in N-body simulations is to differentiate physical SIDM effects from numerical and algorithmic uncertainties, including artificial disruption [24, 25] and halo finding [23]. It is also important for N-body simulations to explore an extensive set of SIDM models.
  - Cross validations between N-body simulations and semi-analytical methods. The N-body simulations provide an important avenue to validate assumptions of the semi-analytical method and calibrate parameters that cannot be calculated from the first principle [9, 17, 26]. On the other hand, the semi-analytical method provide physical intuitions to understand the N-body simulations as well as an independent check for numerical artifacts and the validity of different algorithms.

- Cosmological history. To compare with the observations and interpret the results, a systematic way to address the cosmological initial conditions and environment effects on the SIDM halo evolution is needed.

- Degeneracies. The core formation is degenerate with baryonic effects such as outflow. Subhalo evaporation and ram-pressure disruption are potentially degenerate with baryonic disruption mechanisms including tidal heating and stripping by central galaxies. The fastening of the core collapse is degenerate with a high halo concentration. A comprehensive study of cosmological evolution of SIDM halos could help us better understand those degeneracies.

Many dark-sector models predict that DM has strong self-interactions, leading to novel properties in halo dynamics. To test those models with astrophysical observations, we need to better understand halo formation and evolution in the presence of the interactions. We plan to provide a detailed report on this topic for the Snowmass 2021 study.

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