Core Collapse in Self-Interacting Dark Matter Halos

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Self Interactions in Milky Way Satellites

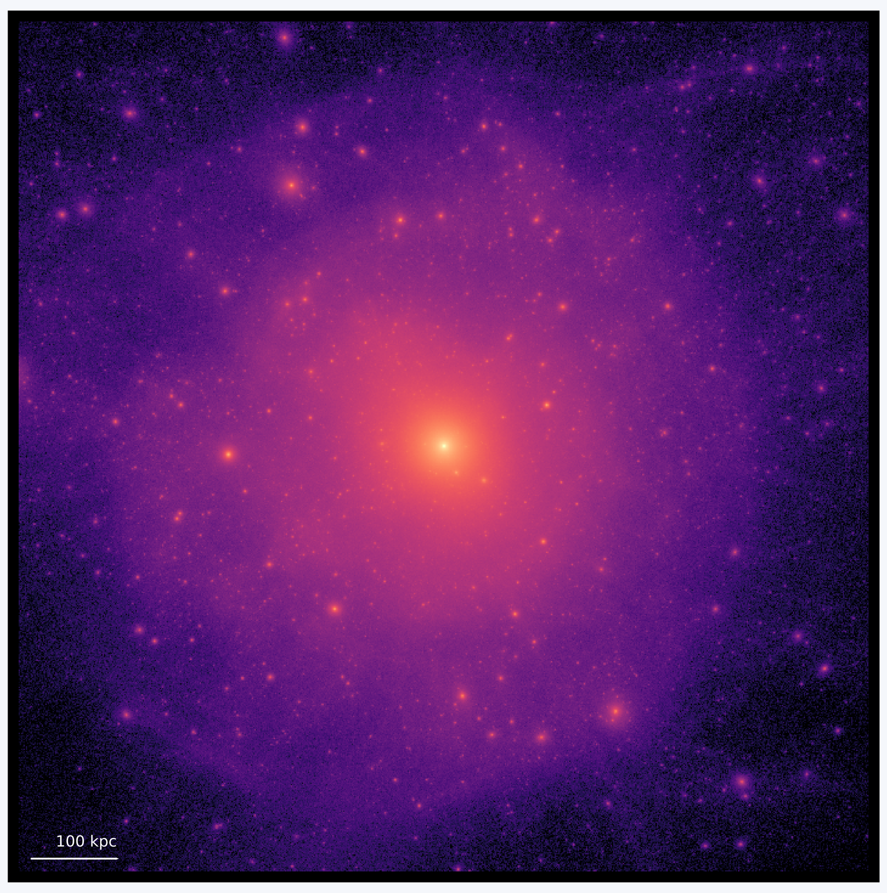

Fig. 1: Visualization of the Milky Way's SIDM halo with cross section of 5 cm^2/g.

Self-interacting dark matter (SIDM) is a compelling model because it could solve the small-scale structure formation problems and it arises generically in new physics models with dark sectors. Using simulations of the Milky Way with moderate cross sections (1-5 cm^2/g) , we motivate velocity-dependent cross sections with large values (>10 cm^2/g) at the velocities relevant for dwarf halos. Milky Way dwarf spheroidal galaxies play a critical role in testing the SIDM scenario because of their wide range of observed stellar and dark matter densities.

Large cross sections would allow core collapse to occur in some Milky Way subhalos such that they would be dense enough to match the densest ultra-faint and classical dwarf spheroidal galaxies in the Milky Way. Some of these halos may also be driven into the short-mean-free-path (SMFP) regime. We discuss the structure of the SMFP core, the relevant scaling relations, and how they depend on the particle physics model. We show a new approximate universality for the first time that improves predictions of the SMFP evolution and the mass of the black hole likely to be left behind.

The Need for Core Collapse

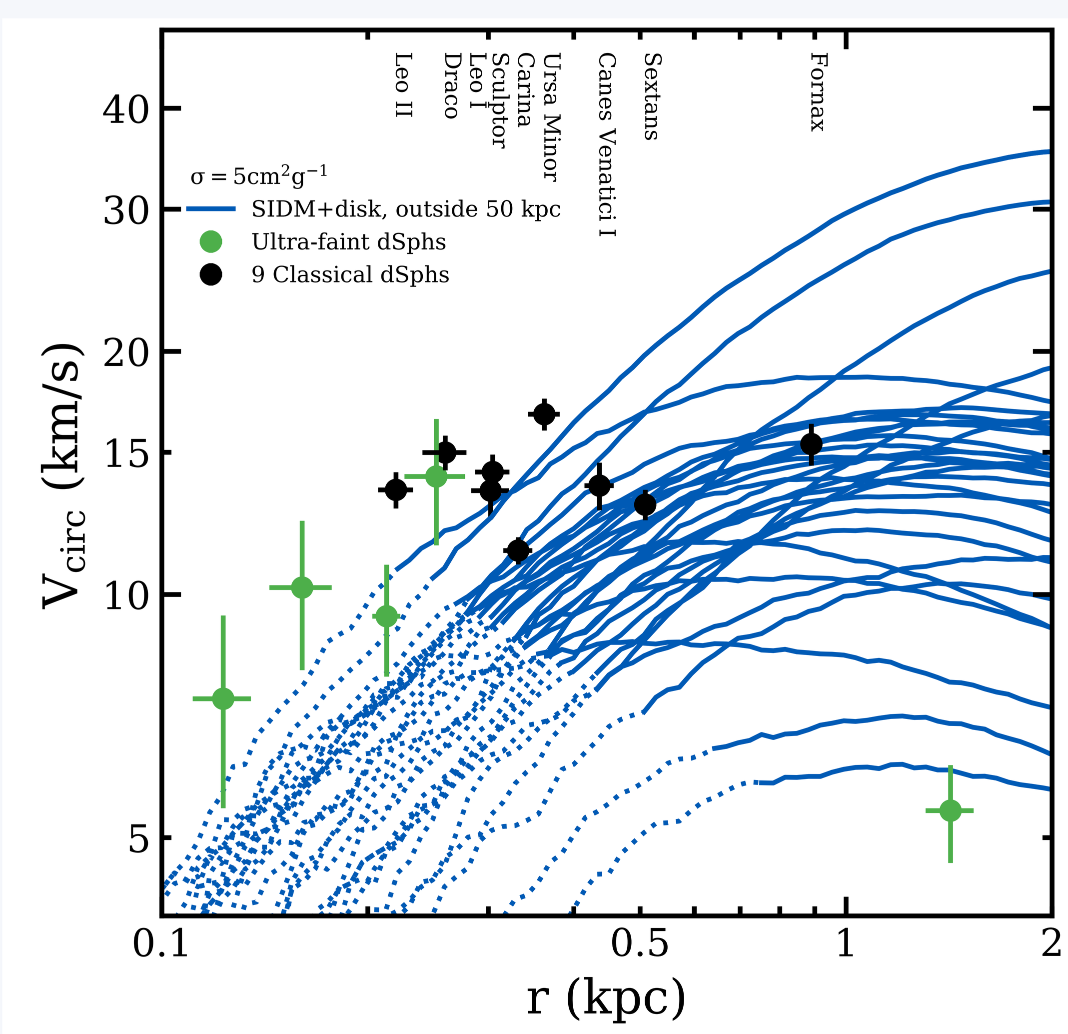

Figure 2 shows that the low-density classical dwarfs can be hosted by the simulated subhalos. However, the high density of the densest dwarfs cannot be explained. This shows that a cross section of 5 cm^2/g is insufficient to induce core collapse in MW subhalos. Thus, we arrive at the conclusion that SIDM cross sections must be larger than 5 cm^2/g at the velocities relevant for the Milky Way dwarfs. In the context of velocity-dependent models, there is a large parameter space where this can happen.

Fig. 2: Circular velocity of the 30 subhalos that reside between 50 kpc and the host halo virial radius at z=0 that are resolved at r_{max}. We compare to the nine classical dwarf spheroidal MW satellite galaxies (black), which all reside outside 50 kpc from the MW center. We also compare to ultra-faint dwarfs (green). For all dwarfs, we plot the sphericallized half-light radius, $r_{1/2}$ and velocity at half-light radius, $V_{1/2}$. The dotted lines correspond to regions where the subhalos are not resolved, containing less than 200 particles.

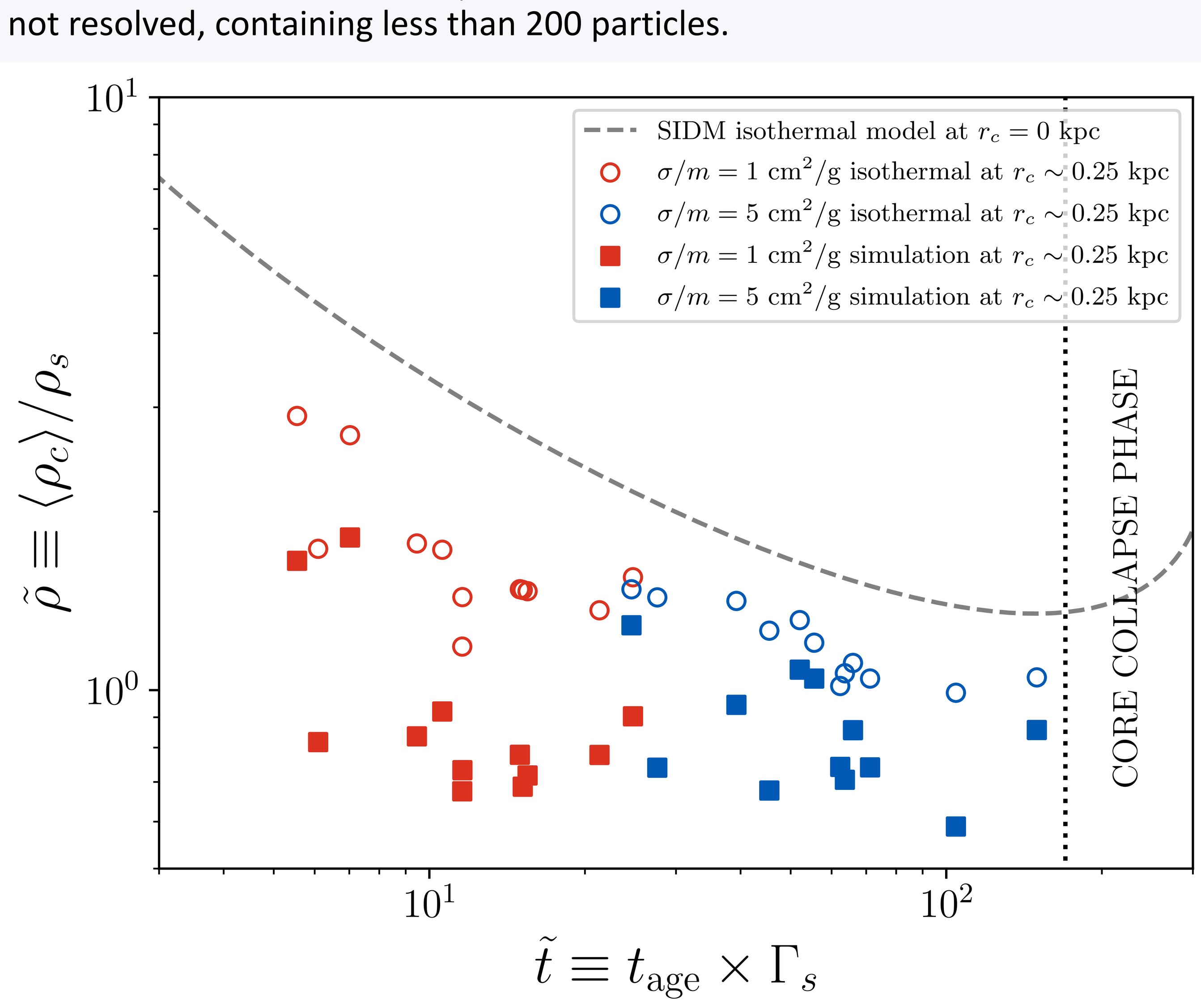

Figure 3 shows that no subhalos in our simulations with moderate cross sections have entered the core collapse phase. We expect to see core collapsed subhalos in cosmological simulations with cross sections greater than 10 cm^2/g .

Fig. 3: Average core density as a function of time. The squares show the densities and timescales of the subhalo pairs in the S1 (red) and S5 (blue) simulations. The circles show the predicted densities and timescales of the subhalo pairs, calculated from their V_{max} and r_{max} values. For both the squares and circles, we define the core radius, r_{max} , as the innermost resolved radius, which is about 0.25 kpc. The dashed grey line shows the density at the center (r=0) of a subhalo predicted by the isothermal model.

Core Collapse in Isolated Halos

We explore the gravothermal evolution of isolated spherical initially NFW halos with various cross-sections and velocity dependences. We find a new universal solution that characterizes the evolution of all halos, regardless of the initial profile or particle physics.

Gravothermal evolution occurs in self-gravitating systems that transfer heat from their hot and dense inner regions to their cooler dilute outer regions. This causes the core of the halo to heat up in a runaway process that drives the core of the halo to collapse.

The stages of gravothermal evolution can be described as follows:

- Stage 0: Core expansion
- Stage 1: Core contraction, Long-Mean-Free-Path (LMFP) evolution, LMFP self-similar solution and universal solution exists
- Stage 2: No universal solution
- Stage 3: New SMFP universality found, black hole formation and mass predictions occur in this regime

Our newfound SMFP universal solution allows us to predict the evolution of halos in the SMFP regime where changes occur rapidly. The universal solution offers a more accurate prediction of the resulting mass of the black hole formed after the core of the halo collapses.

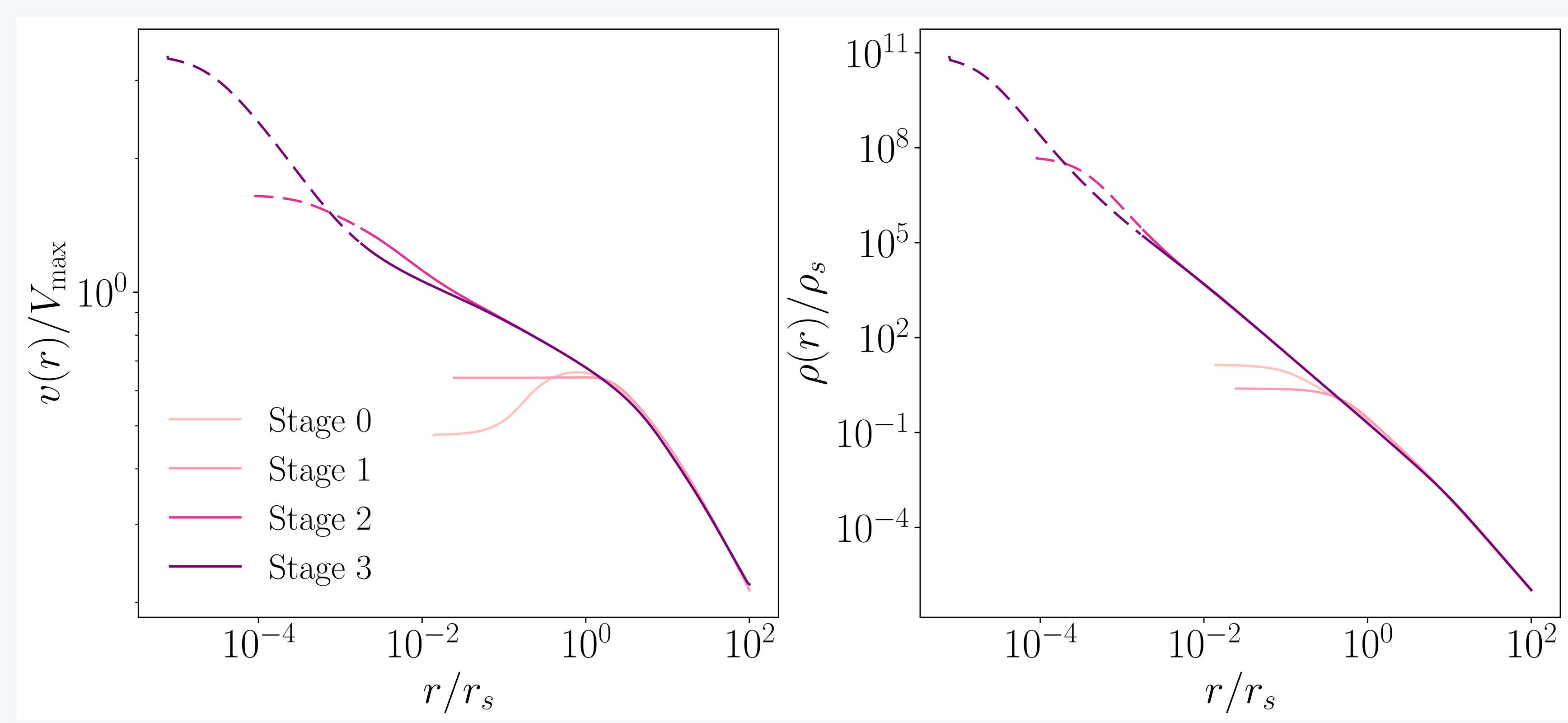

Fig. 4: Velocity (left) and density (right) profiles with respect to radius of an isolated SIDM halo. Each curve represents a different stage of the gravothermal evolution of the halo, showing how its central velocity and density begins to rapidly increase in late stages.

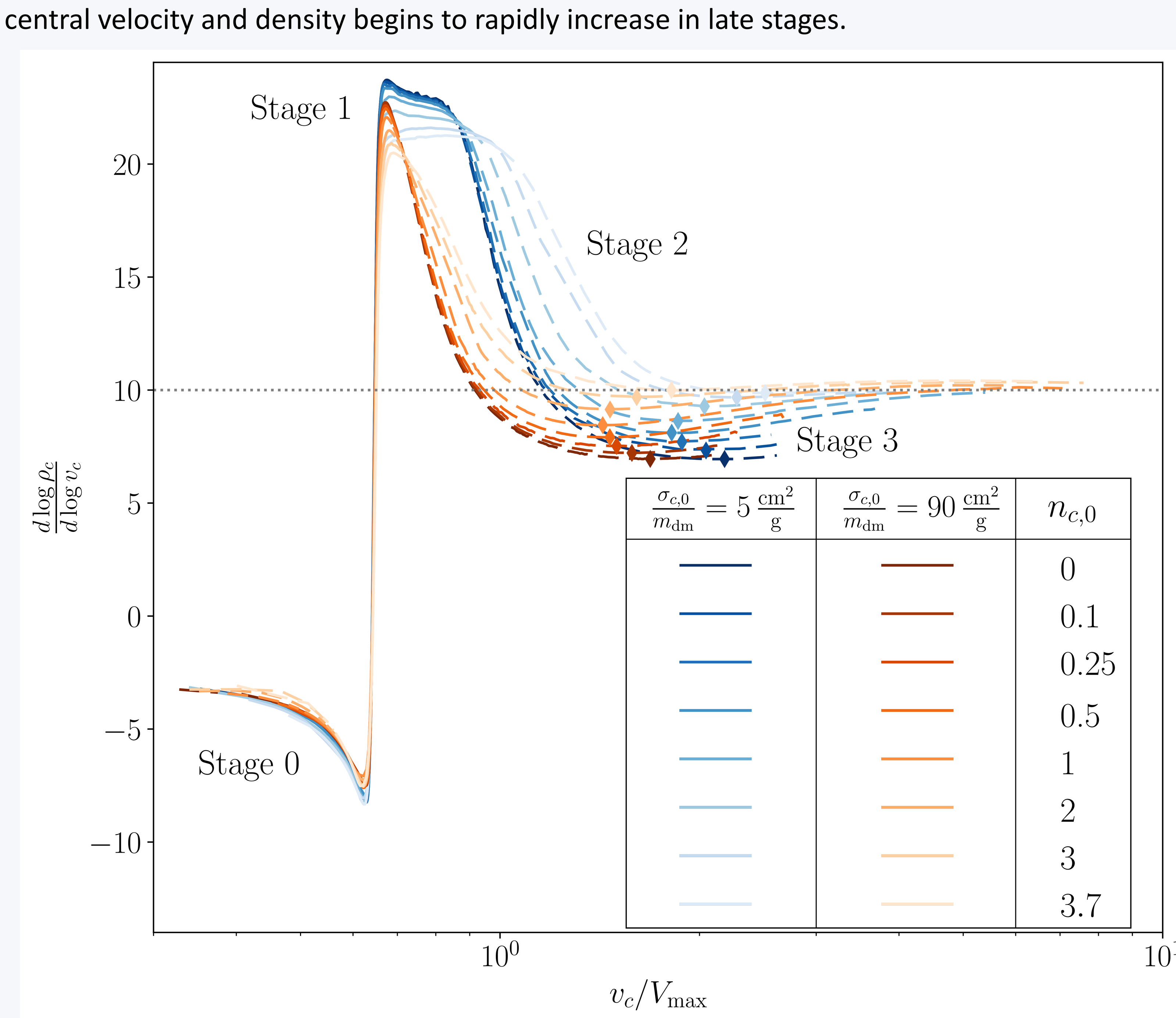

Fig. 5: Slope of the central density with respect to the central velocity of an isolated SIDM halo. Stages are labeled as shown in text.

Summary and Discussion

Using high-resolution N-body simulations and comparing to the Milky Way satellites, we find that the inner density profiles of SIDM subhalos with a moderate cross section of 1-5 cm^2/g are not dense enough to host the densest observed dwarfs. An SIDM model with a cross section larger than 10 cm^2/g at the subhalo circular velocity scale will cause core collapse to occur faster and would lead to some subhalos having high enough central densities to be consistent with the inferred densities in ultra-faint dwarf spheroidal galaxies.

Using isolated NFW halos, we find that all halos undergoing gravothermal evolution are inevitably driven into core-collapse, which is expected to leave behind black holes. We find a new universality deep in the core-collapse regime that universally characterizes the evolution of all halos. We find in this regime a new relation with which to estimate the mass of the resulting black hole that may be left behind. This newfound universality offers a tool through which to explain the diversity of Milky Way satellites that seem to require large cross-sections to explain.

References and collaborators

1. Maya Silverman, James S Bullock, Manoj Kaplinghat, Victor H Robles, Mauro Valli. Motivations for a large self-interacting dark matter cross-section from Milky Way satellites. *Monthly Notices of the Royal Astronomical Society*, Volume 518, Issue 2, January 2023, Pages 2418–2435, https://doi.org/10.1093/mnras/stac3232
2. Sophia Gad-Nasr, Kimberly K. Boddy, Manoj Kaplinghat, Nadav Joseph Outmezguine, and Laura Sagunski. On the Late-Time Evolution of Velocity-Dependent Self-Interacting Dark Matter Halos. (In preparation, 2023)