Investigating Dark Matter through Cosmological Simulations and Comparisons with Observations

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Motivation: Dark Matter on Galaxy Scales

The standard paradigm of the cosmological model is ΛCDM with CDM being cold dark matter. It successfully explains the large scales, but it faces problems at small scales such as the core-cusp problem. Observations indicate cored density profiles while simulations predict a more cusp-looking density profile. A solution to this is the alternative dark matter model, self-interacting dark matter (SIDM), which introduces interactions between the dark matter particles.

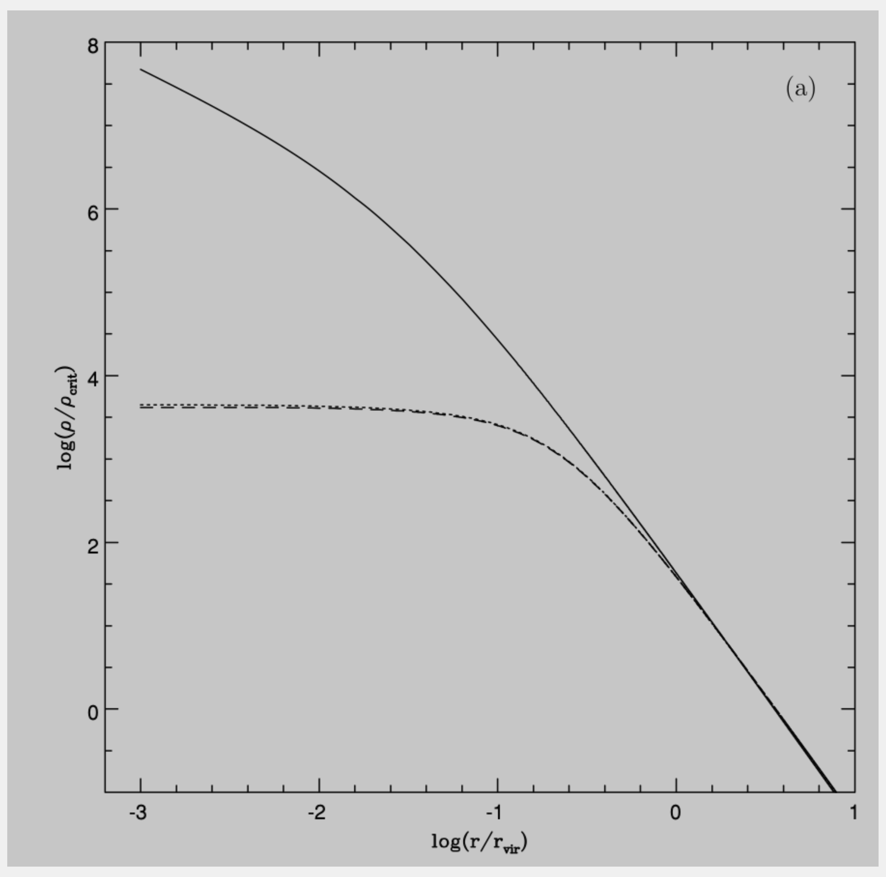
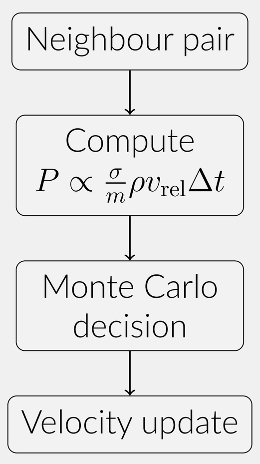


Figure 1. A visual representation of the core-cusp problem, a small-scale problem of the CDM model. The solid line represents the cuspy density model while the dashed line represents the more cored observed density profile [Popolo, 2008].

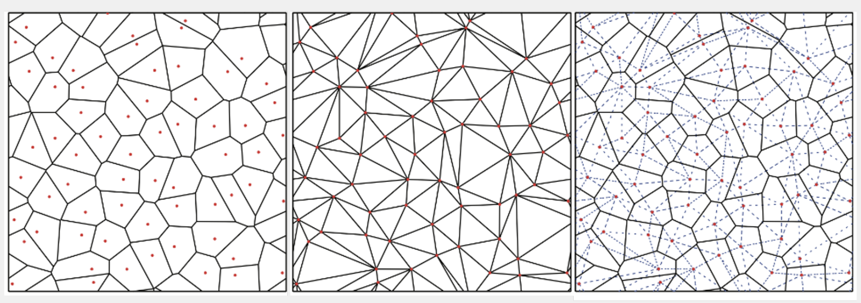
In CDM, dark matter is treated as effectively collisionless meaning that the dark matter particles only interact through gravity. Consequently, dark matter haloes develop steep central density profiles and hierarchical structures through gravitational evolution. In SIDM, an additional non-gravitational self-interaction is introduced between dark matter particles. These interactions allow particles to exchange energy and momentum through scattering, which can modify the internal structure of dark matter haloes while leaving the baryonic matter unaffected directly.

N-Body Simulation with AREPO

AREPO is a moving-mesh hydrodynamics code used for gravitational N-body simulations. The initial cosmological density and velocity fields are generated using MUSIC.



(a) Schematic SIDM scattering module.



(b) Voronoi and Delaunay tessellations used in AREPO. Gas is represented by Voronoi cells whose mesh-generating points move with the flow, while the Delaunay tessellation defines neighbouring cells across which hydrodynamic fluxes are computed [Springel, 2010].

Large Scale Structure

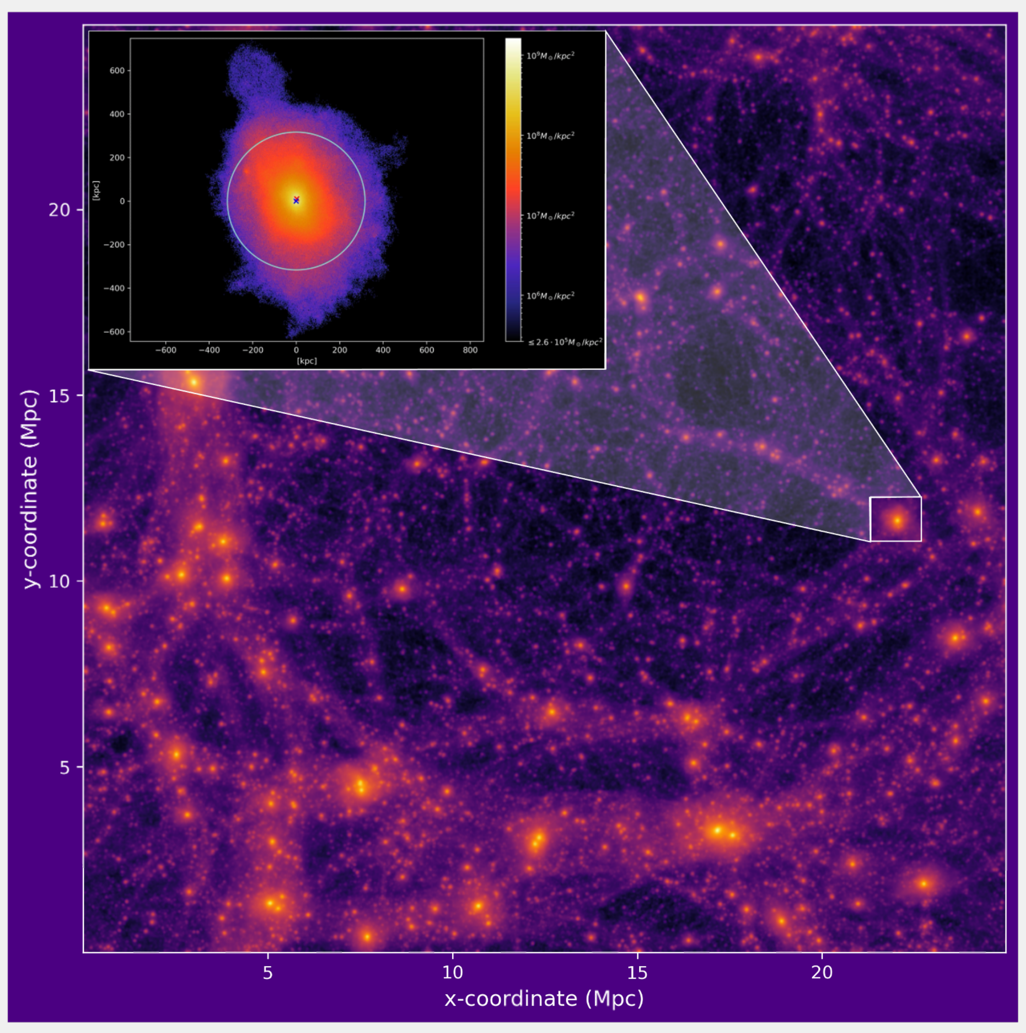


Figure 3. Large scale structure of SIDM simulation with a zoom-in on a halo structure

The SIDM simulation exhibits the characteristic cosmic web with filaments and clusters. At large scales SIDM reproduces the same structure as CDM, indicating the self-interactions primarily affects the internal structure of halos. The zoom-in highlights an individual halo illustrating how halo structure is ingrained into the large structure.

Density profiles

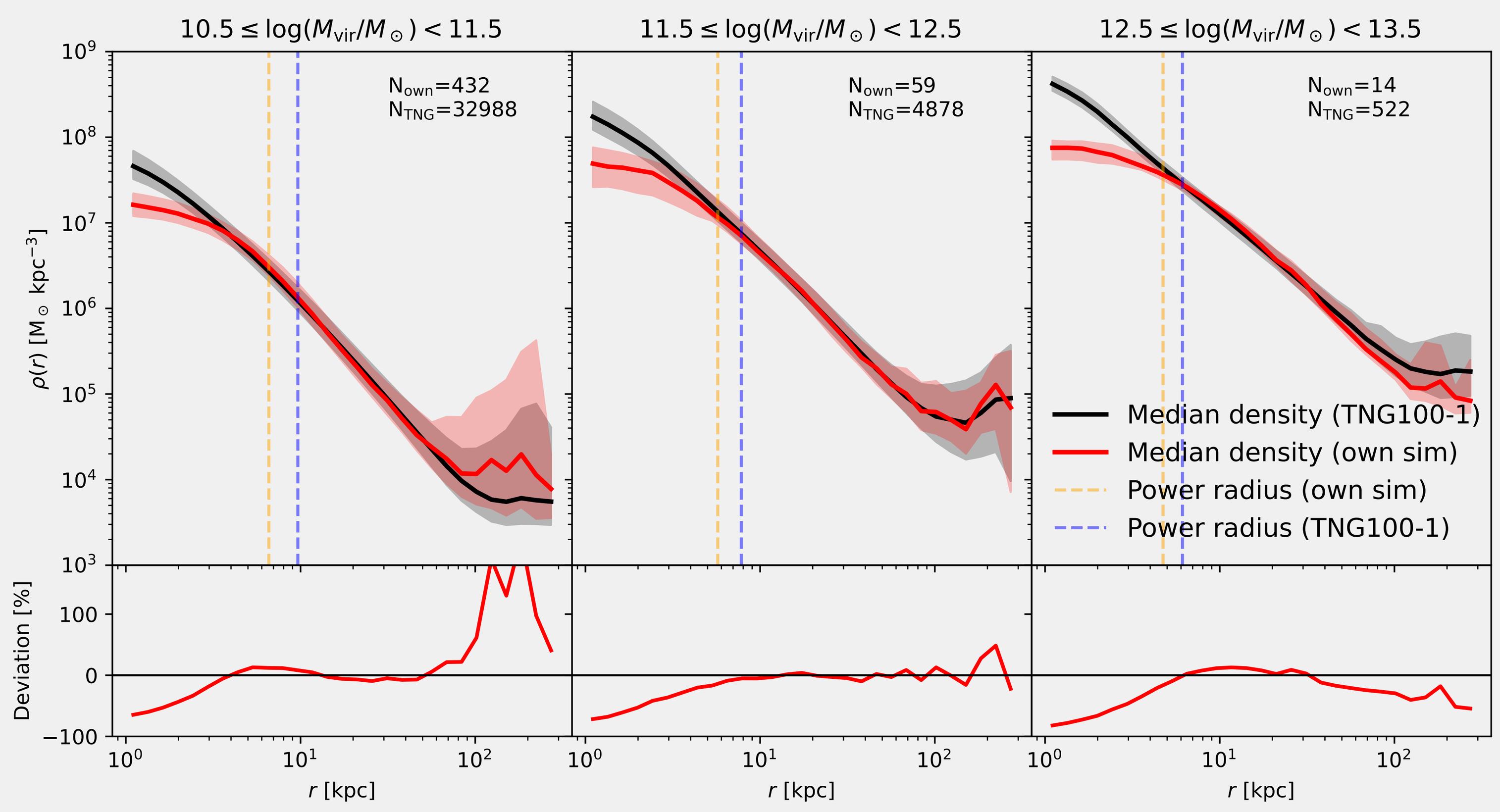


Figure 4. Dark matter density profiles as a function of radius for different halo mass bins. Median profiles from the SIDM simulation (red) are compared to TNG100-1 (black), with shaded regions indicating the interquartile range. Vertical dashed lines mark the Power radius for each simulation. The lower panels show the relative deviation between SIDM and TNG100-1, highlighting differences in the inner halo structure.

The density plot show that both simulations follow a similar large-scale structure, while the SIDM halos systematically develop lower central densities than TNG100-1. This reflects the impact of self-interactions, which redistributes the dark matter in the inner halo producing a core-like density profile.

Rotation curves

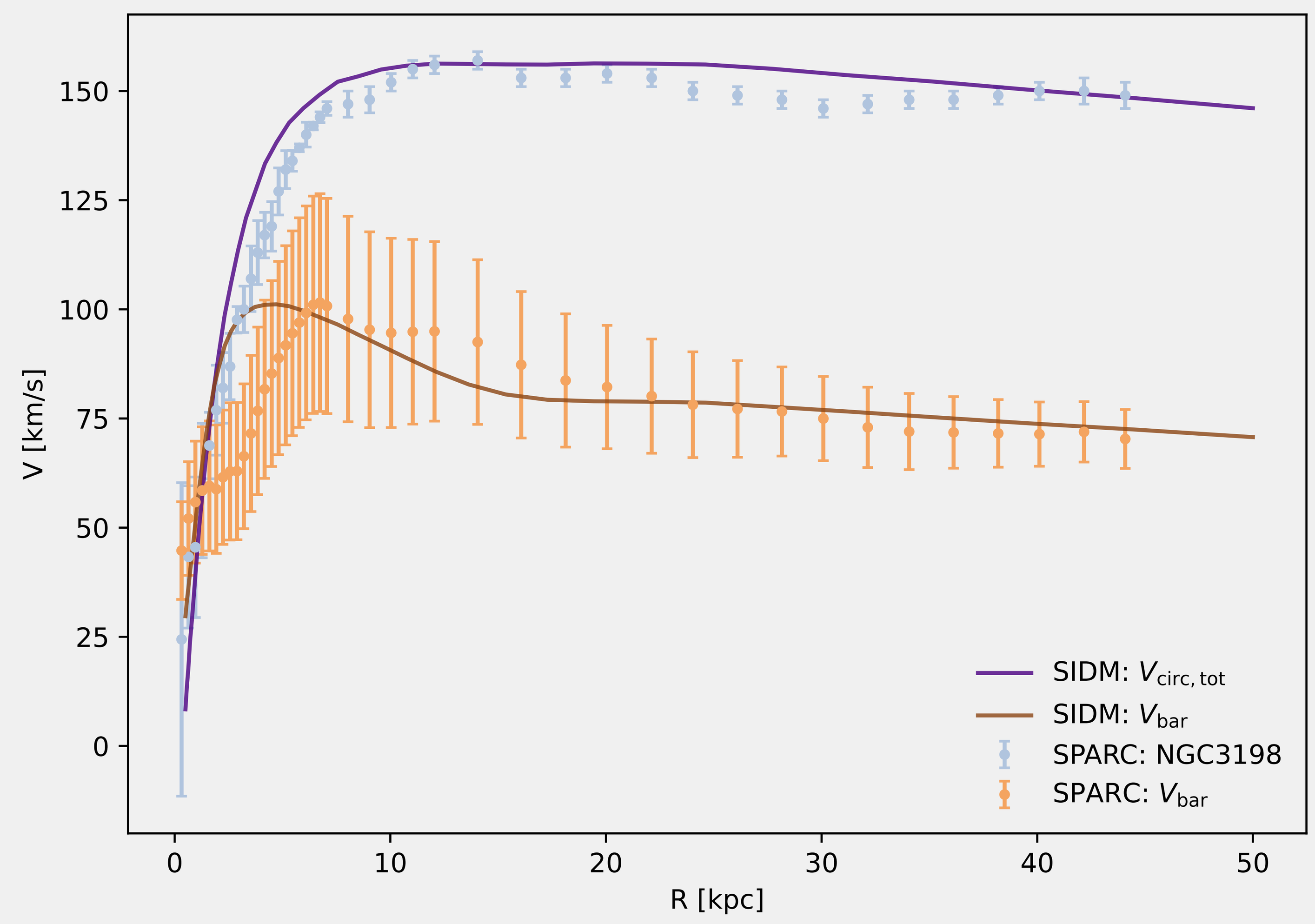


Figure 5. Observed rotation curve of NGC3198 from SPARC (light purple points), alongside the contribution from baryonic matter (orange) and the total rotation curve (solid purple line) and baryonic contribution (solid brown line) predicted by the SIDM simulation.

The simulated SIDM galaxy reproduces the overall shape and flat outer behaviour of the observed SPARC rotation curve. The baryonic contribution alone cannot explain the observed velocities, highlighting the dominant role of dark matter in the outer regions of the galaxy.

Conclusion

- SIDM preserves the large-scale halo structure predicted by collisionless CDM.
- Self-interactions mainly affect the dense inner halo, where they reduce central densities and can form cores.
- This provides a possible explanation for small-scale tensions such as the core-cusp problem and the diversity of rotation curves.
- The simulated total circular velocity curve is consistent with the observed rotation curve of NGC 3198.
- Overall, SIDM remains consistent with large-scale structure while offering a physically motivated modification on galactic scales.

References and Data Sources

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