Convergence Tests of Self-Interacting Dark Matter Simulations

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Introduction

Self-interacting dark matter (SIDM) theory predicts that dark matter halos experience core-collapse, a process where the halo's inner region rapidly increases in density and decreases in size. The N-body simulations used to study this process can suffer from numerical errors when simulation parameters are selected incorrectly. Optimal choices for simulation parameters are well studied for cold dark matter (CDM), but are not deeply understood when self-interactions are included. In order to perform reliable N-body simulations and model core-collapse accurately we must understand the potential numerical errors, how to diagnose them, and what parameter selections must be made to reduce them. We use the `Arepo` N-body code to perform convergence tests of core-collapsing SIDM halos across a range of halo concentrations and SIDM cross-sections, and quantify potential numerical issues related to mass resolution, timestep size, and gravitational softening length. **Our tests discover that halos with fewer than 10^5 simulation particles, a resolution typically not met by subhalos in N-body simulations, suffer from significant discreteness noise that leads to variation and extreme outliers in the collapse rate.** This work shows that simulation parameters which that yield converged results for some halos and SIDM models do not necessarily yield convergence for others.

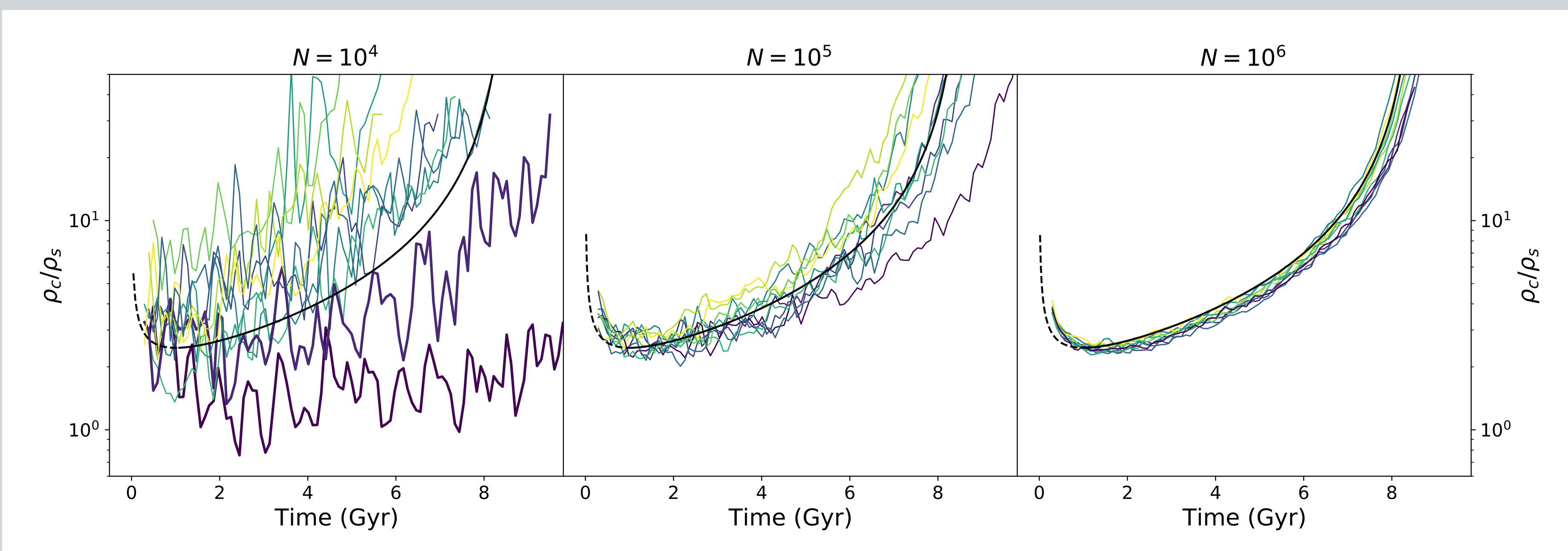

Figure 1. Realization noise tests for simulation C50T9. Each panel shows the halo central density as a function of time for a particular number of particles N. Each line corresponds to a different initial condition realization of the halo. The thin black line in each panel is the gravothermal model[1] fit to the highest resolution data.

Methods

We simulate isolated dark matter only halos with a constant scattering cross-section, represented here as a cross-section per unit mass σ/m. To make sure our results are robust for a diverse halo population, we test extreme values of the initial halo concentration c_{200m} and collapse timescale t_c. The table below shows the four physical halos we simulate, all of which have an initial mass of $M_{200m} = 10^{10.5}$.

Simulation	c_{200m}	t_c (Gyr)	σ/m (cm^2/g)	$\hat{\sigma}$
C10T9	10	9	1892	7.03
C10T225	10	225	17.65	0.0656
C50T9	50	9	5.688	0.267
C50T225	50	225	0.1764	0.00827

The dimensionless parameter $\hat{\sigma}$ is defined as $(\sigma/m)\rho_s r_s$, and $\hat{\sigma} \ll 1$ corresponds to a very weak scattering regime where the mean free path is much larger than a typical particle orbit. For each of these halos, we run simulations spanning a grid in particle number, softening length, and timestep size. This poster is focused on the particle number results, but detailed results for all three parameters can be found in our paper[2].

To measure the collapse time variance caused by initial condition noise, we run 10 realizations for each particle number choice, varying only the random seed used when sampling particles from the initial mass distribution. For these tests we fix the timestep size and softening length, based on our other convergence testing results[2]. We calculate the halo central density for each halo as a function of time, and determine the collapse time to be the time at which the central density passes an arbitrary threshold.

References

[1] Yang, Shengqi et al. (2023). *Gravothermal Solutions of SIDM Halos: Mapping from Constant to Velocity-dependent Cross Section.*

[2] Mace, Charlie et al. (2024). *Convergence tests of self-interacting dark matter simulations*

Results

Figure 1 shows the central density evolution for the C509T9 halo for 10^4, 10^5, and 10^6 particles. We see that 10^4 particle halos have wide variation in collapse time, including one outlier that has a much longer collapse time than the rest of the sample. Even the 10^5 particle halo has collapse times spanning roughly 2 Gyr, a substantial variation for the 9 Gyr collapse timescale. At 10^6 particles the collapse time is more tightly clustered.

Figure 2 shows how the collapse time scatter varies with particle number for each of the four halos. We find that all four cases behave similarly, and present a prediction for scatter in halo collapse time. **These results show that halos require particle counts well above 10^4 particles to resolve the core-collapse process. Subhalos in N-body simulations often do not meet this resolution requirement, and may experience artificial variance in central density as a result.** Inaccuracies in subhalo density profiles could affect SIDM's success in solving current issues with CDM predictions, such as the halo diversity problem.

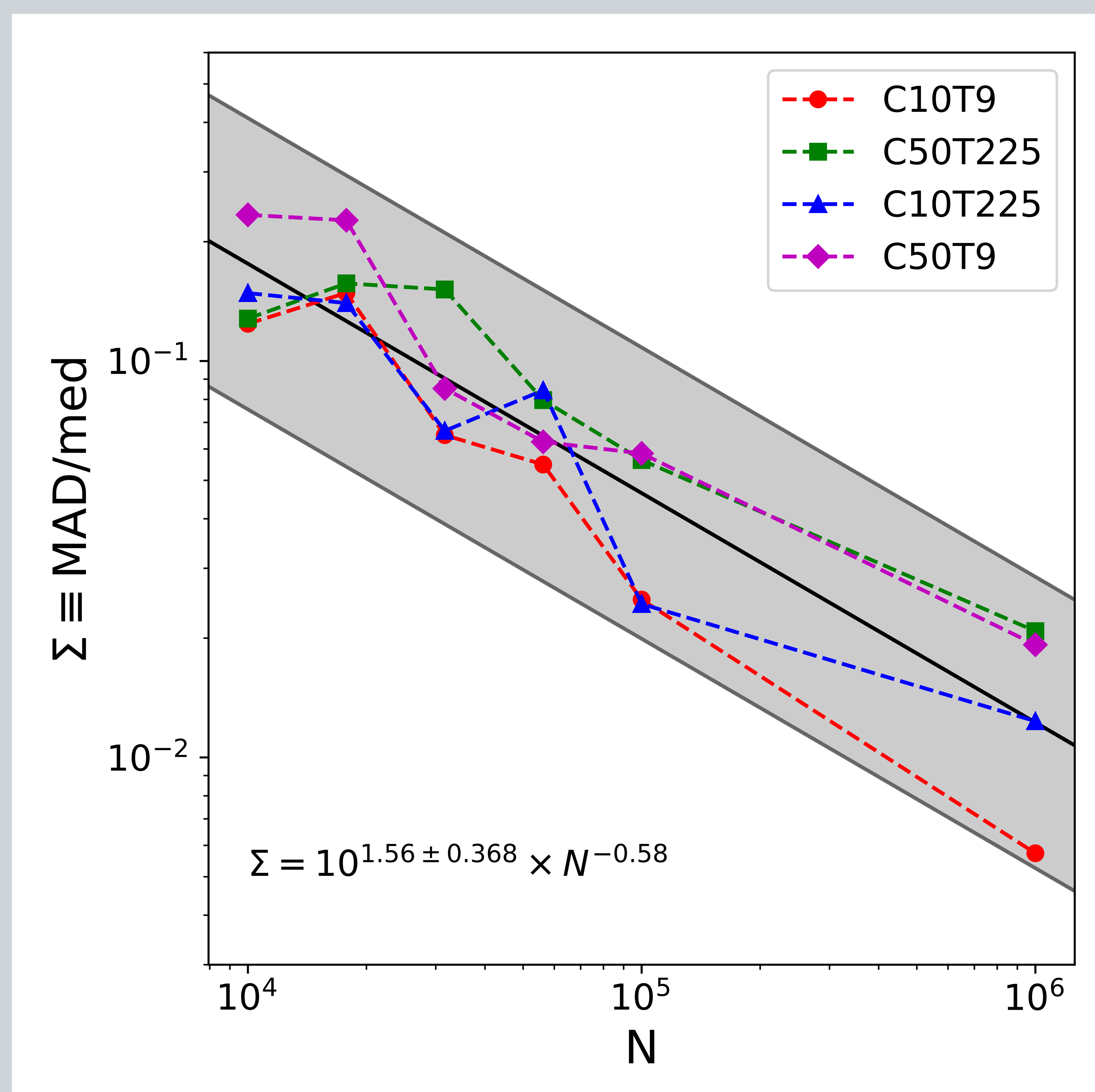

Figure 2. Halo collapse time variation as a function of particle number N. Variation in collapse time is quantified as the median absolute deviation divided by the median. Each line corresponds to a physical halo from the table, and our fit is shown in the bottom left corner.