Examining numerical convergence of self-interacting dark matter core collapse in a cosmological context

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Abstract

Dark matter self-interactions can give rise to a variety of dark matter profile slopes in their inner regions. In particular, gravo-thermal collapse, the end-state of a self-interacting dark matter halo, produces density slopes higher than in the cold dark matter (CDM) only paradigm. Modeling these systems in a cosmological context is the ultimate goal to compare predictions in the self-interaction dark matter (SIDM) cosmology to CDM. However, recent work [1, 2, 3] has shown that simulating these systems is incredibly challenging. The goal of this visit was to compare different numerical codes and methods being used to simulate core-collapse in SIDM halos.

1 Summary

Self-interacting dark matter (SIDM) was initially proposed to solve the “small-scale” problems of ΛCDM [6]. Recently core-collapse, the ultimate fate of an SIDM halo, has become of great interest to the dark matter and astrophysical communities. In particular, it has been proposed that this general feature of the SIDM model can give rise to diversity of rotation curves [5], as well as over-dense substructure in clusters [7]. However, in order to derive accurate predictions for the number of collapsed structures, and their $z = 0$ densities, we must ensure that we trust our numerical results and do proper convergence

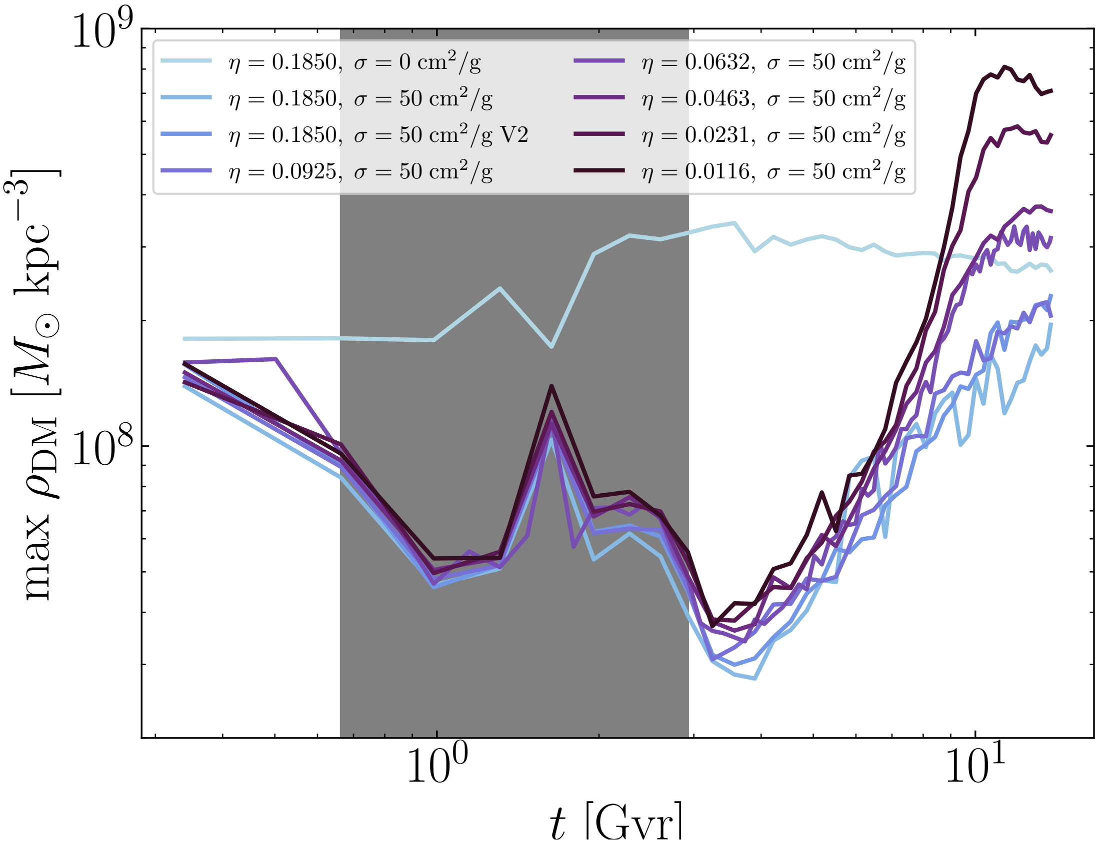

Figure 1: Average dark matter density within 1 kpc of SIDM halo vs comsic time colored by η. Smaller η corresponds to smaller acceleration timestep. As this timestep is decreased, the end-state density increases in ChaNGa simulations.

testing. In this vein, numerical challenges have been pointed out by a number of studies [1, 2, 3]. The purpose of this visit was to further examine the numerical issues associated with time-stepping, and densities of these core-collapsed halos.

In most SIDM simulations, there are two relevant time-scales associated with numerical time-stepping. The first limits the number of interactions per time-step. This time-step for the ith particle is give as:

$$dt_{\mathrm{SIDM,i}} = \frac{\kappa}{\sigma_T/m_\chi\ \rho_{DM,i}\ v_{\mathrm{rel,i}}} \tag{1}$$

where κ is the limiting self-interaction probability, $\rho_{DM,i}$ is the local DM density, and $v_{\mathrm{rel,i}}$ is the relative velocity between interacting particles.

The second time-step is the acceleration time-step given as:

$$dt_a = \eta\sqrt{\frac{\epsilon}{|a|}} \tag{2}$$

where ϵ is the gravitational softening and $|a|$ is the local acceleration. Then η is a calibrated quantity that sets the size of the overall timestep. This value has been determined via convergences testing for CDM [4], but not in SIDM.

During this visit we discussed how altering κ and η change the density evolution of an SIDM halo in a cosmological setting, compared to previous work. We compared results from [1, 2, 3] and unpublished results from cosmological collapse simulations in ChaNGa. We find in cosmological simulations that decreasing η alters the end state density, and that this value is significantly smaller in SIDM compared to CDM, even outside of the regime of convergence. We additionally determined that values of $\kappa < 0.1$ are likely very important and motivated us to perform additional simulations, lowering this value by an order-of-magnitude. Continued collaborations and testings are on-going since the end of the visit.

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