# Calibrating the SIDM Gravothermal Catastrophe with N-body Simulations

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## Background

The nature of dark matter is one of the most persistent mysteries in our Universe. One dark matter candidate, self-interacting dark matter (SIDM), predicts that dark matter halos experience gravothermal catastrophe, a process where the halo's inner region rapidly increases in density and decreases in size. Models for the collapse process require calibration to N-body simulations, but the meaning of that calibration is unclear, and there are many differing values of the calibration parameter across the literature.

In this work we use the N-body code `Arepo` to study this calibration, and to extend the useful range of core-collapse models. **We show that the effective value of this calibration changes as a function of halo parameters and SIDM cross-section, but can be well described as a function of just one variable.** With this calibrated model, dark matter researchers can study the nature of SIDM without running costly numerical simulations.

## The Gravothermal Catastrophe

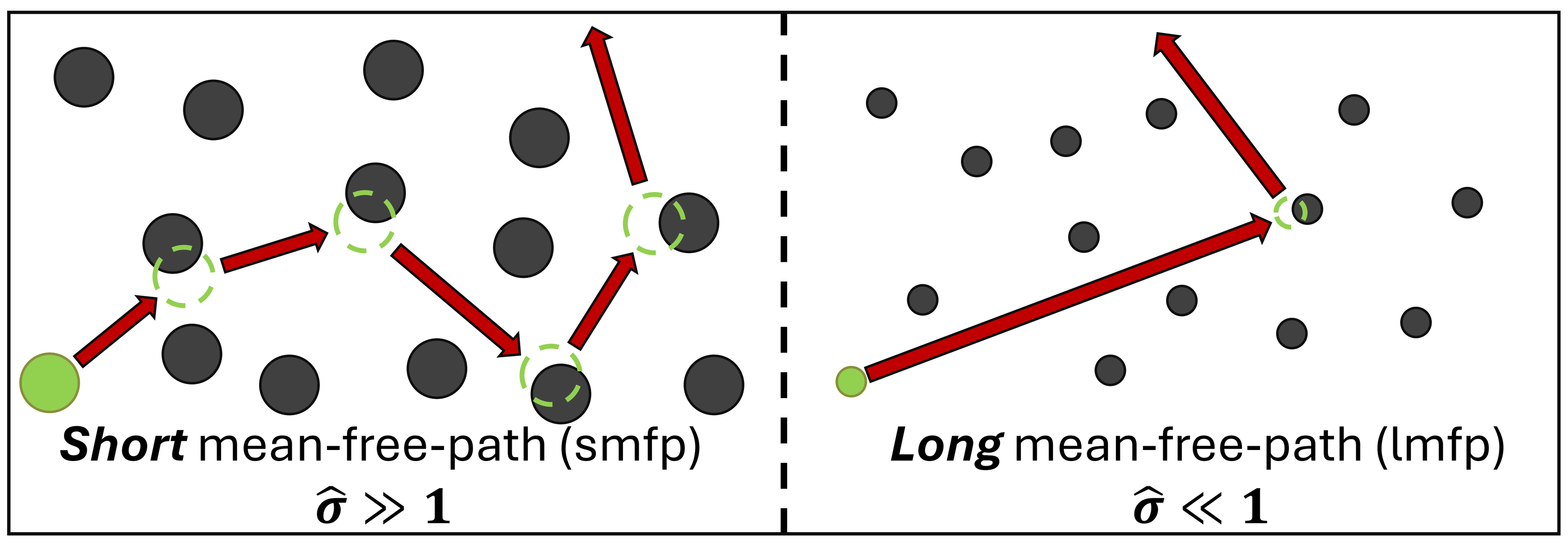


Figure 1. Two regimes for SIDM: smfp (dominated by self-scattering) and lmfp (dominated by gravitational interaction).

SIDM halos can be broadly categorized into the *long* mean-free-path and *short* mean-free-path regimes (Figure 1). The dimensionless cross-section $\hat{\sigma}$, a function of the initial halo parameters and SIDM cross-section, gives an approximation of which region best describes a halo.

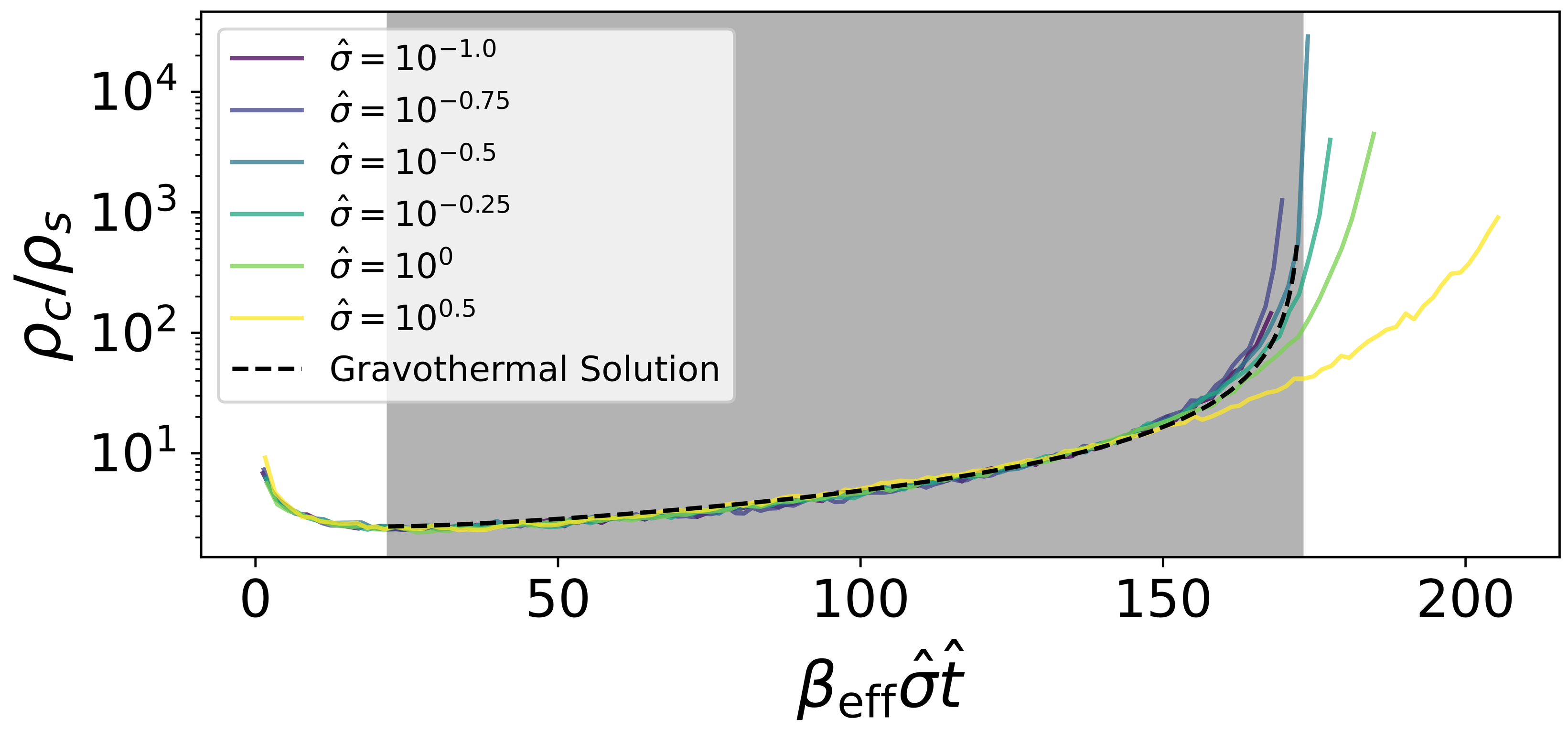


Figure 2. The halo central density evolution for several different $\hat{\sigma}$ values. The dashed line is the expected evolution in the lmfp regime, with $\beta_{\rm eff}$ as a fit parameter.

Figure 2 shows an example of gravothermal core-collapse for halos with various $\hat{\sigma}$ values. Numerical gravothermal fluid models have been successful in predicting the evolution of halos in the lmfp regime [1], but those models face two major challenges:

1. These models **require calibration** to N-body simulations to get an accurate heat transfer rate.
2. These models **break down** as $\hat{\sigma}$ approaches 1, limiting their application.

To resolve these issues, we derive a model for an effective calibration parameter $\beta_{\rm eff}$, based on the expected variation in heat transfer between the smfp and lmfp regimes:

$$\beta_{\rm eff}(\hat{\sigma}) = \frac{1}{0.20\hat{\sigma}}\left((0.20\beta\hat{\sigma})^{-\alpha} + \left(\frac{0.63}{\hat{\sigma}}\right)^{-\alpha}\right)^{-1/\alpha}.$$

This model is a function of $\hat{\sigma}$, with two fit parameters $\beta$ and $\alpha$.

## Results

We run 96 simulations across a variety of halo and SIDM parameters to test our $\beta_{\rm eff}$ model and to fit the $\beta$ and $\alpha$ parameters. We select numerical parameters based on our previous SIDM convergence study [2].

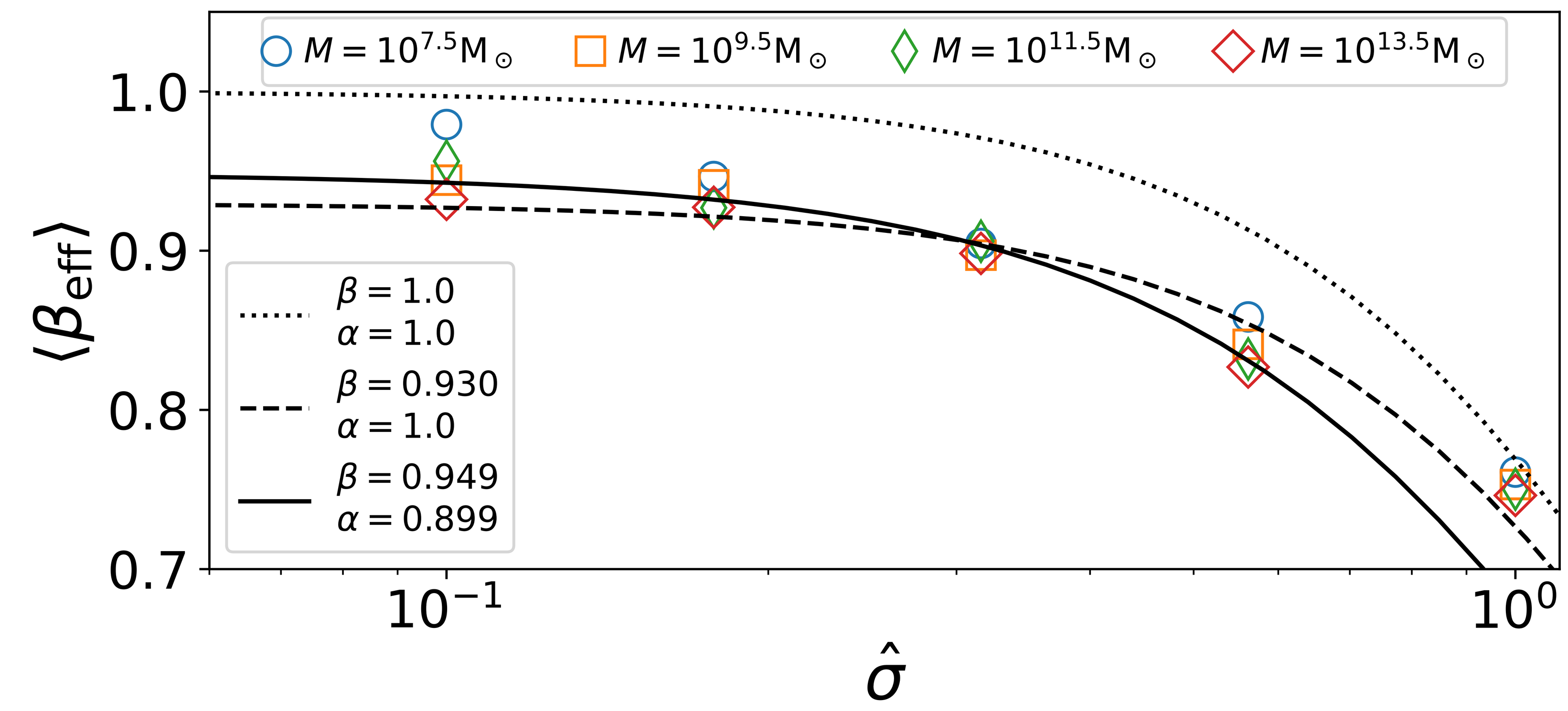


Figure 3. The effective calibration parameter $\beta_{\rm eff}$ as a function of $\hat{\sigma}$. Different halo masses are shown by marker, and each $\beta_{\rm eff}$ value is averaged over halo concentrations. Each line is a fit to Equation 1, with 0, 1, or 2 free parameters.

We find that **our model accurately describes the evolution of halos** with $\hat{\sigma} < 1$, and fit parameters $\beta = 0.949$ and $\alpha = 0.899$ (Figure 3). The success of this model shows that regardless of the specific concentration, mass, and cross-section of a halo, its evolution can be predicted with just $\hat{\sigma}$.

## Applications

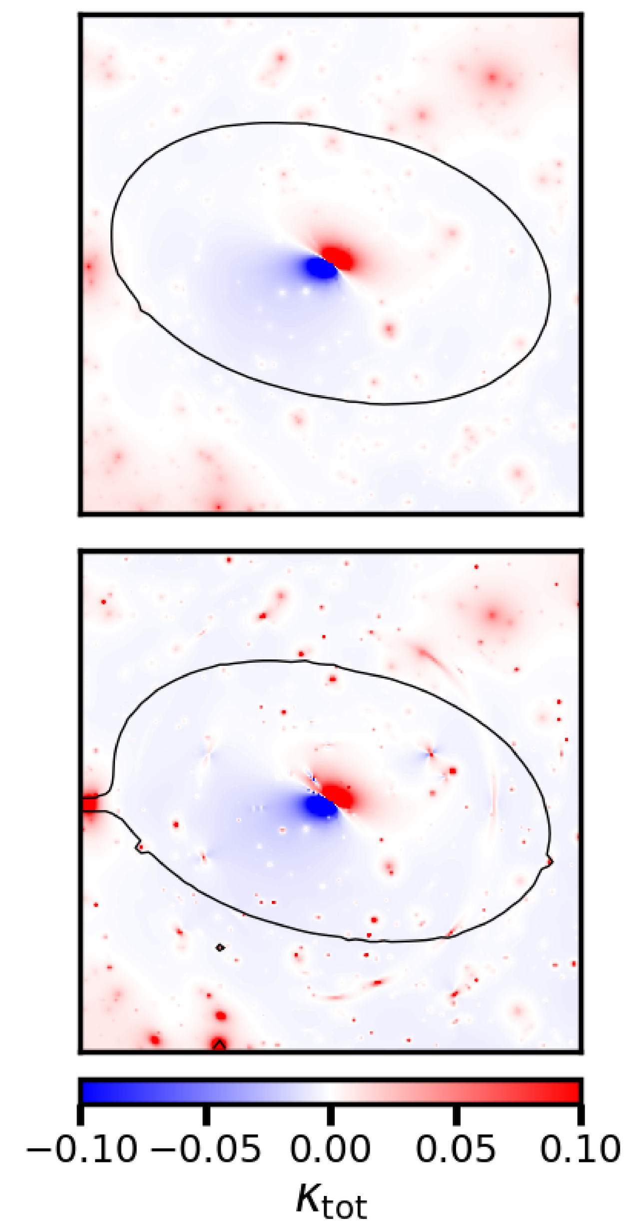


Figure 4. Substructure lensing convergence maps for CDM halos (top) and SIDM halos (bottom).

Our $\beta_{\rm eff}$ model allows dark matter researchers to:

- Model core-collapsing halos without expensive N-body simulations
- Apply lmfp core-collapse models for halos with $\hat{\sigma}$ close to 1

While the predicted variation in $\beta_{\rm eff}$ is small, there are applications that call for this level of precision.

One such application for precise collapse timescales is substructure lensing, where the gravitational lensing caused by dark subhalos within a galaxy can be used to infer the properties of dark matter. If subhalos of the lensing galaxy undergo gravothermal core-collapse, the properties of the lensed image can change drastically (Figure 4). Since the end of the core-collapse evolution is extremely quick, small changes in collapse time could lead to large changes in observable quantities.

## Future Work

During the final year of my PhD I am working on several projects, some of which may continue into post-doctoral work:

1. **Applying this core-collapse model** to substructure lensing predictions, to make testable predictions for SIDM.
2. **Running hydrodynamical simulations** of merging clusters to study observable signatures of SIDM.
3. **Further study of N-body simulations** with SIDM, and an investigation of where unexplained numerical errors originate.
4. **Studying how tidal effects alter core-collapse** with OSU graduate students Angelica Whisnant and Chloe Zheng.

## References

[1] Shengqi Yang *et al.* Gravothermal solutions of sidm halos: Mapping from constant to velocity-dependent cross section. *The Astrophysical Journal*, 946(1):47, Mar. 2023.

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