# Self-Interacting Dynamical Dark Matter and Its Observational Implications

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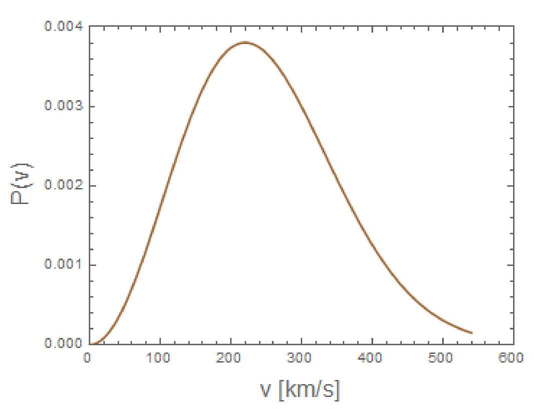
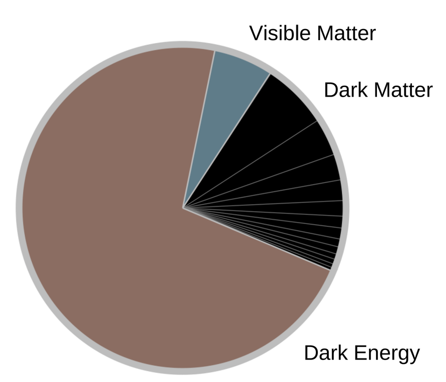
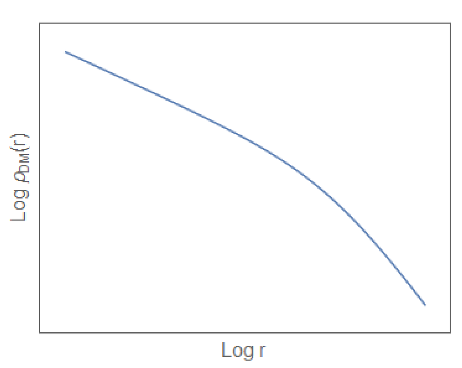
## Introduction

- Overwhelming evidence suggests that a mysterious form of matter makes up the vast majority of the matter in our universe. However, we have no idea what this "dark matter" is or what its properties are.
- The standard way of looking at dark matter (DM) is to say that it is made up of only one type of particle.
- Typically, the velocity distribution is taken to be a Maxwell-Boltzmann because that distribution provides a reasonable approximation to the distributions found in N-body simulation data [1,2].




- Simulations, along with rotation curve data, suggest that the density profile of the DM at large radii in the Milky Way has the following functional form.

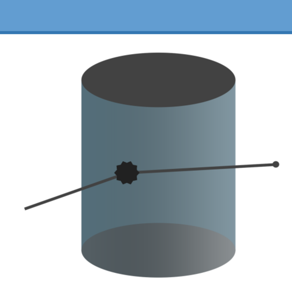



$$\rho_{NFW} = \frac{\rho_0}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2} \quad (1)$$

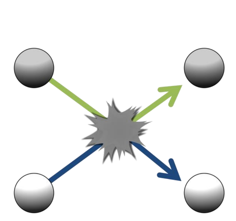
- In standard DM models, DM particles just pass through each other, but it's also possible that they scatter with each other. Self-interactions would allow energy exchange between DM particles [3].
- This would lead to a redistribution of DM density and a redistribution of velocities.
- We are interested in how density and velocity distributions would change if DM was self-interacting.
- Dynamical Dark Matter is the idea that dark matter can be made up of many different particles, giving us a multicomponent dark matter sector [4,5].
- In general, each component can have a unique velocity distribution and a unique density profile.

## Motivation and Objectives

- Our goal is to study the effects that self-interactions would have on Dynamical Dark Matter. We focus on the Milky Way, since we are also interested in direct detection.

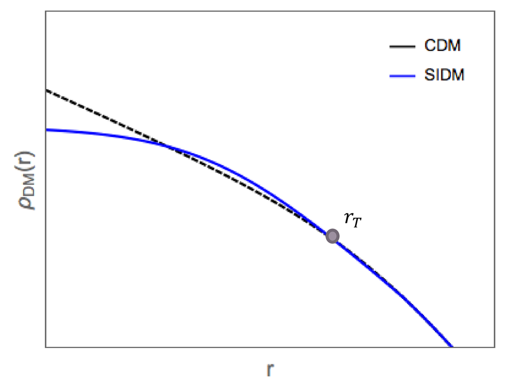


- In a direct detection experiment, physicists look for collisions between DM particles and visible matter.
- Information found here will help us know what to expect in these experiments.



## Method

- Understanding the effects of self-interactions on a single component DM case will eventually help us understand the Dynamical Dark Matter case.
- At smaller radii, where the DM density is higher, interactions become non-trivial.
- The transition point beyond which self-interactions start become unimportant is called the radius of thermalization ($r_T$).




$$\begin{cases} \rho(r) & r \le r_T \\ \rho_{NFW}(r) & r \ge r_T \end{cases} \quad (2)$$

- We use the Euler velocity equation and the Poisson equation to solve for the density profile at small radii.

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\cdot\vec{v} + \frac{1}{\rho}\vec{\nabla}(\rho\sigma^2) = -\vec{\nabla}\phi \quad (3)$$

$$\nabla^2\phi = 4\pi G\rho_{tot} \quad (4)$$

- Using these, we are able to solve for the velocity dispersion, $\sigma$, a key point of information about the velocity distribution of the dark matter.
- We treat the SIDM as a fluid and we assume that the galaxy has achieved hydrostatic equilibrium. We also assume that the density profile is spherically symmetric.
- Self-interactions would allow DM particles to eventually thermalize, meaning they would have a constant temperature and therefore a constant velocity dispersion.

$$\sigma = \sqrt{\frac{k_B T}{m}} = [\text{const.}] \quad (5)$$

- In Eq. (5), $m$ is the DM particle's mass and $k_B$ is the Boltzmann constant.
- Given these assumptions we obtain a differential equation for the density profile of SIDM.

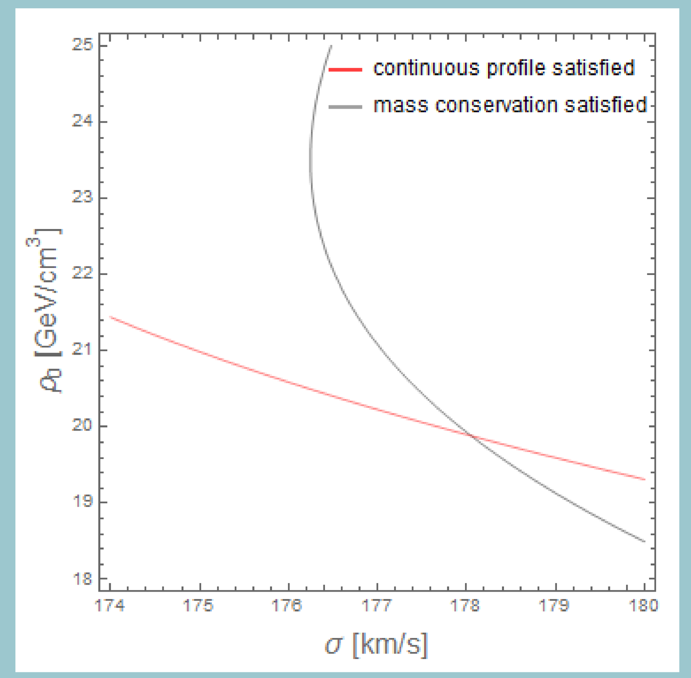
$$\frac{2}{r}\frac{\partial\rho}{\partial r} + \frac{1}{\rho}\left(\frac{\partial\rho}{\partial r}\right)^2 + \frac{\partial^2\rho}{\partial r^2} + \frac{4\pi G}{\sigma^2}\rho + \frac{4\pi G}{\sigma^2}\rho_{vis} = 0 \quad (6)$$

- Proper boundary conditions give us a viable density profile paired with its proper velocity dispersion [6,7,8].

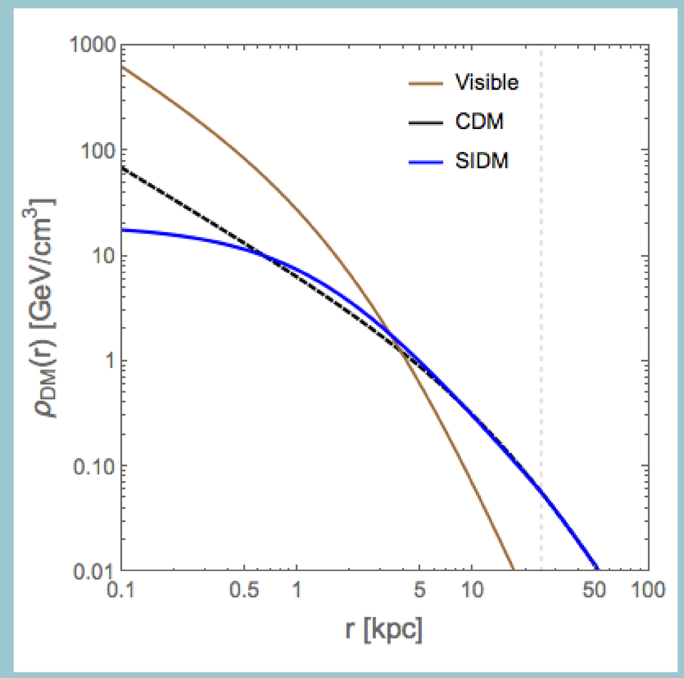
- Conditions:
  1. $M_{200} = \int_0^{r_{200}} 4\pi r^2\,\rho(r)\,dr$
  2. $\int_0^{r_T} 4\pi r^2\,\rho(r)\,dr = \int_0^{r_T} 4\pi r^2\,\rho_{NFW}(r)\,dr$
  3. $\rho(r_T) = \rho_{NFW}(r_T)$

- With these conditions, we have enough information to solve for the density profile and the velocity dispersion.
- To satisfy conditions 2 and 3, we plot ratios for different input parameters. When the ratio is equal to one, that particular condition is satisfied.

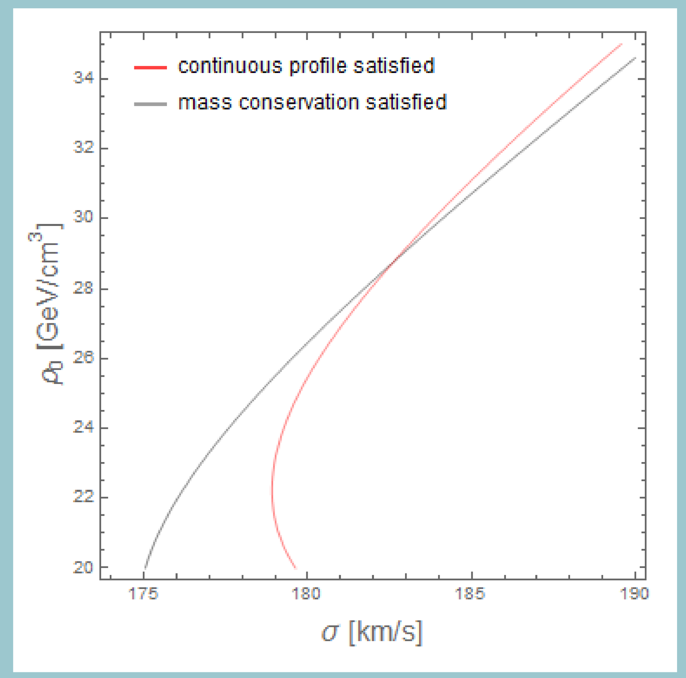
## Figures and Findings



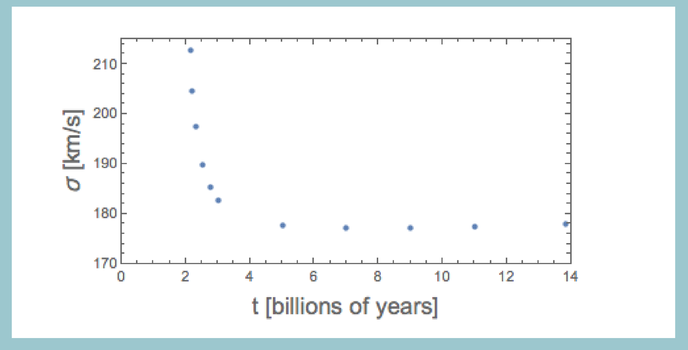

A contour plot shows combinations of our input parameters that solve our boundary conditions. An intersection marks where both conditions are satisfied.




By using the pair of input parameters that satisfy both conditions, we obtain the SIDM density profile for small radii in the Milky Way.



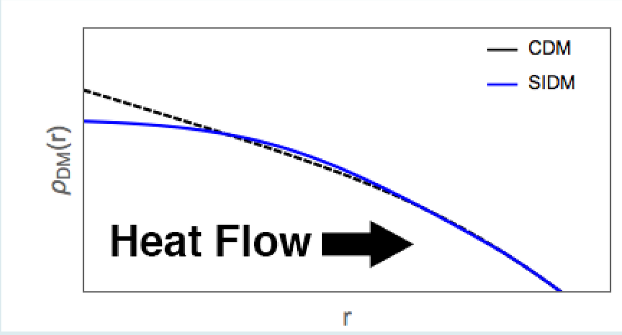

To study the evolution of the SIDM profile, we alter the input for time. This input comes from our definition of $r_T$. Here we set the time to 3 billion years rather than 13.82, the current age of the universe.




This plot shows how the velocity dispersion is changing over time. The variable $t$ represents the time in billions of years. The values for the velocity dispersion asymptote around t= 2.1 billion years. This is nonphysical and indicates that our analysis isn't valid for such early times (while still being appropriate for t= now).

## Interpretation of Results

- Our analysis provides us with a valid density profile for SIDM at the current age of the universe.
- We expect the SIDM profile to converge to our CDM profile as time goes to zero. However, because heat flow in the system becomes important at very early times, the approximations typically used to treat systems like this at present time are no longer reliable.
- To address this issue we need to modify our calculations to include information about heat flow across the SIDM halo. In this regime, Eq. (5) no longer holds and the velocity dispersion can vary as a function of radius. Likewise, our second boundary condition can no longer be assumed.
- A suitable formalism for incorporating these effects has been developed in the context of analyzing other astrophysical systems [9].




## Future Work

- From here we want to build in assumptions about heat flow that will allow us to look at the dark matter halo profile at very early times.
- We then want to extend our findings to a multicomponent dark matter case. In general, each component of Dynamical Dark Matter can have a unique density profile along with a unique velocity dispersion.
- This uniqueness will change what we expect for the total collision rate between dark matter particles and visible particles in direct detection experiments.

### References

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