Simulating Self-Interacting Dark Matter in Galaxy Formation on Frontera

Akaxia Cruz
NSF Graduate Research Fellow, University of Washington Physics
in collaboration with
Tom R. Quinn, Alyson Brooks, Ferah Munshi, Jordan Van Nest, Sean Tulin, Annika Peter, Marta Volonteri, Andrew Pontzen, Michael Tremmel, Nicole Sanchez, and Arianna Di Cintio

: akaxiacruz.com  : admcruz@uw.edu
How do we know dark matter exists?

1. Galaxy rotation curves
2. Gravitational lensing
How do we know dark matter exists?

1. Galaxy rotation curves
2. Gravitational lensing

The Bullet Cluster

- Hot gas (x-rays)
- Dark Matter (Gravitational lensing)
What is the “flavor” of dark matter?
Two simple types of dark matter

Self-interacting Dark Matter = SIDM
DM that does more and also ‘interacts’ with itself like invisible billiard balls

Cold Dark Matter = CDM
DM that just attracts ordinary and other dark matter gravitationally

OR
Small Scale Problems: Core-Cusp

- Cusped profiles are predicted by standard CDM-only simulations (NFW 1997).
- Cored DM profiles are observed in nature (Moore et al. 1994, Flores & Primack 1994, Oh et al., 2011, etc.)

Inner halo: $\rho(r) \sim r^{\alpha}$

Oh et al., 2011

Tulin & Yu 2018
A possible solutions to the core-cusp problem

Self-interacting dark matter?

1. To help alleviate issues on small scales, a non-standard dark matter model needs to be able to relax dark matter densities galactic scales

2. CDM does a great job on large scales (above ~ Mpc) — any non-CDM model needs to preserve this success
Self-Interacting Dark Matter

- Spergel & Steinhardt, 2000 proposed DM with a mean free path ranging from 1 kpc to 1 Mpc would naturally impact galaxies and clusters while preserving the success of CDM.
- Large scattering cross-sections may be due to:
  - hard, short-range interactions like neutron-neutron scattering at low energies
  - or soft long-range interactions mediated by the exchange of a light (or massless) particle. See for example (Cruz & McQuinn 2022; arXiv 2202.12464)
SIDM Inherits all of the Success of ΛCDM at Large Scales

• “Storm” dwarf volume simulations run on Frontera using Charm N-Body GrAvity solver (ChaNGa) a N-Body, Barnes-Hut tree and smooth particle hydrodynamics code

• These dwarf volume were run in CDM and with various constant SIDM cross-section (a measure of how much dark matter interacts with itself) between $\sigma_T = 3\text{cm}^2/\text{g} - 50\text{cm}^2/\text{g}$

• The simulations include just dark matter physics and were run using ~15000 normal Frontera node hours
A possible solutions to the core-cusp problem

Ordinary matter physics such as supernova feedback?

Fry et al. 2015

baryons = ordinary matter = gas + stars
Small scale problems: diversity of rotation curves

- Spitzer Photometry and Accurate Rotation Curves data
- CDM predicts nearly identical rotation curves for systems with similar maximum circular velocities
- Observations show diversity in dwarf galaxy rotation curves for fixed $V_{\text{max}} \sim 80$ km/s

For fixed $V_{\text{max}} \sim 80$ km/s, observations show diversity in dwarf galaxy rotation curves. CDM theory predicts nearly identical rotation curves for systems with similar maximum circular velocities. However, observations show diversity in dwarf galaxy rotation curves for fixed $V_{\text{max}} \sim 80$ km/s. Santos-Santos et al. 2020
Simulating core collapse on Frontera

- Working on simulating very small ultra-faint dwarf galaxies in the velocity range where diversity of rotation curves is maximized
- We are preforming ‘zoom-in’ simulations which focus computing resources in the galaxy of interest (a Draco-like galaxy)
- One challenge with these simulations is that gravothermal collapse is a run away process so the dark matter density keeps increasing
- \( \Gamma_{SI} \sim \rho_{dm} \rightarrow dt \) becomes smaller and smaller, which can case simulation run times to increase dramatically
Thank you!
Questions?
Method: Smooth Particle Hydrodynamic Simulations

General Overview

- Smoothed particle hydrodynamic simulations make use of millions-billions of individuals particles
- Particles are smoothed over to generate smooth, differentiable qualities
- Which are then used to solve hydrodynamic equations for gas and stars
- Smoothing is also used to find local DM densities and velocities

- **Additional physics:**
  - Star formation occurs if the local density of gas in a region surpasses some threshold
  - Supernova occur based on the mass and age of star particles and energy is ejected into the surrounding 64 particles
  - Local densities and velocities are used to locally determine dark matter interaction rates, which are then used in a collisional Boltzmann equation which is solved using a monte carlo method. Single simulation particles are thus treated as a phase space patch. SIDM is dissipation less!