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Simulating Self-Interacting Dark Matter in Galaxy Formation on Frontera

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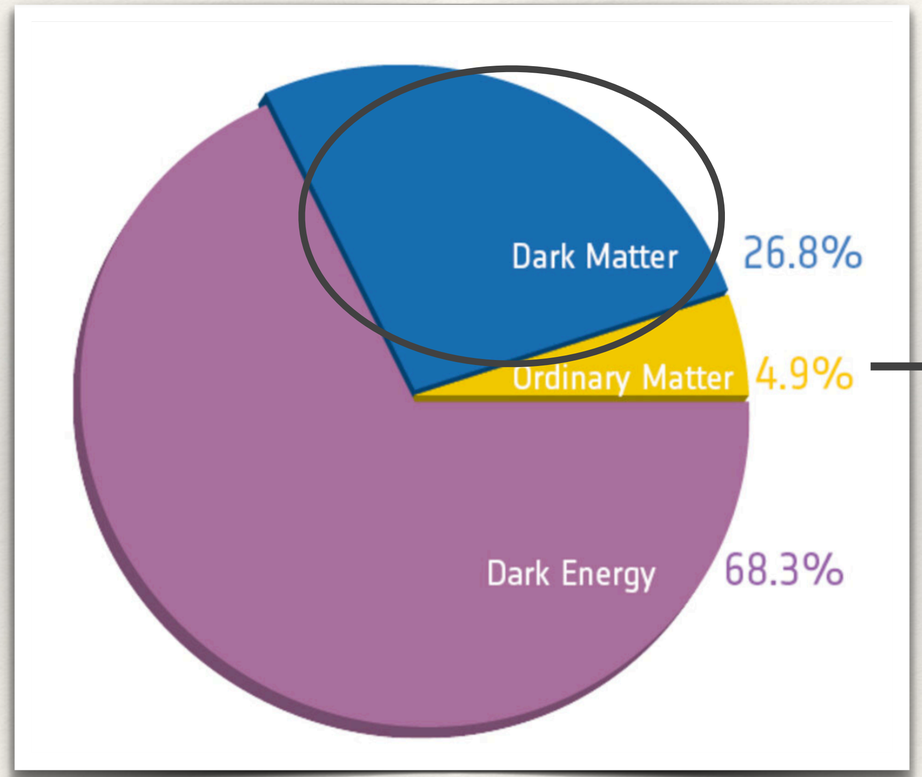
What makes up the Universe?

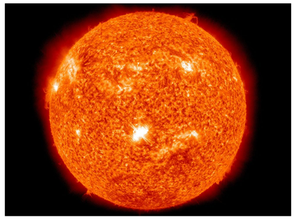


ESA/Planck Collaboration

Galaxies

NASA

Stars



NASA/SDO/AIA

Planets

NASA

*not to scale

laptops

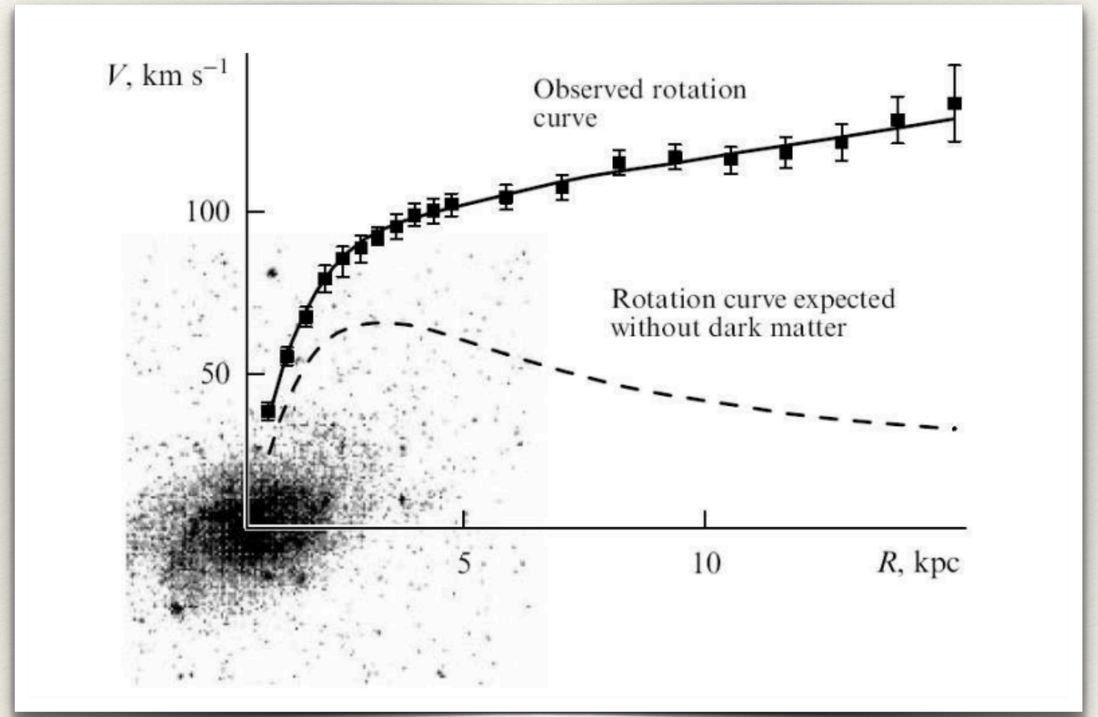
Humans

Frontera super computer

TACC

How do we know dark matter exists?

1. **Galaxy rotation curves**
2. Gravitational lensing



Zasov et al

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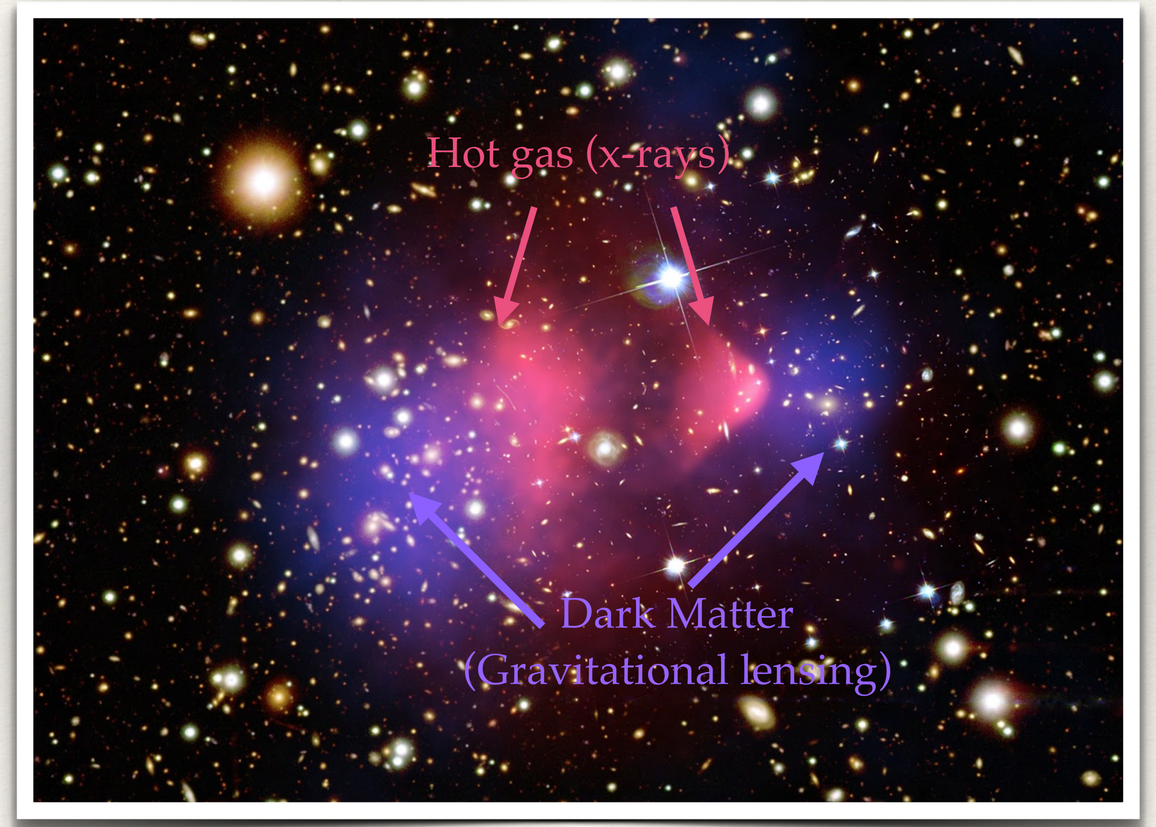
The Bullet Cluster

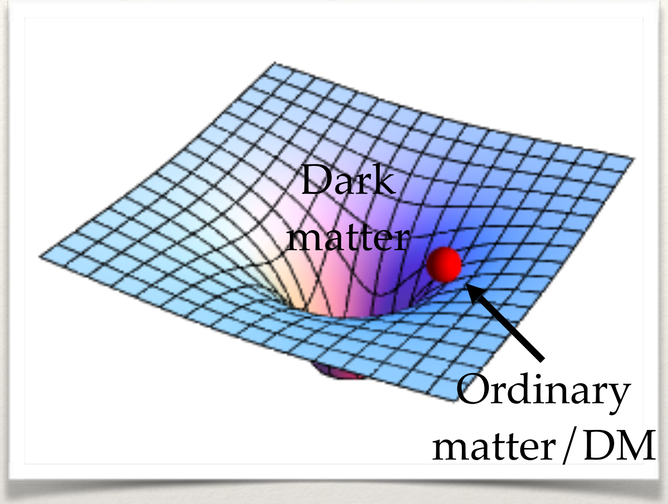


NASA/CXC

What is the “flavor” of dark matter?

NASA 2017

Two simple types of dark matter

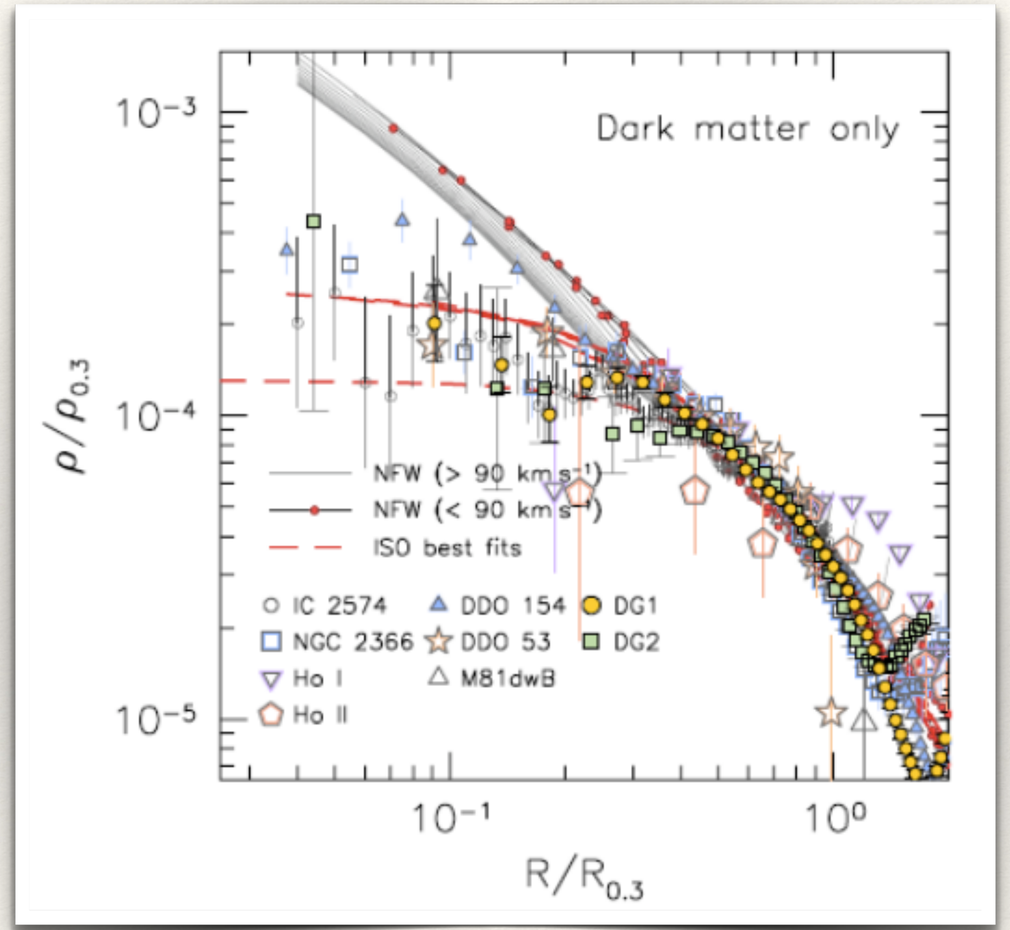


Cold Dark Matter = CDM
DM that **just** attracts ordinary and other dark matter gravitationally

OR

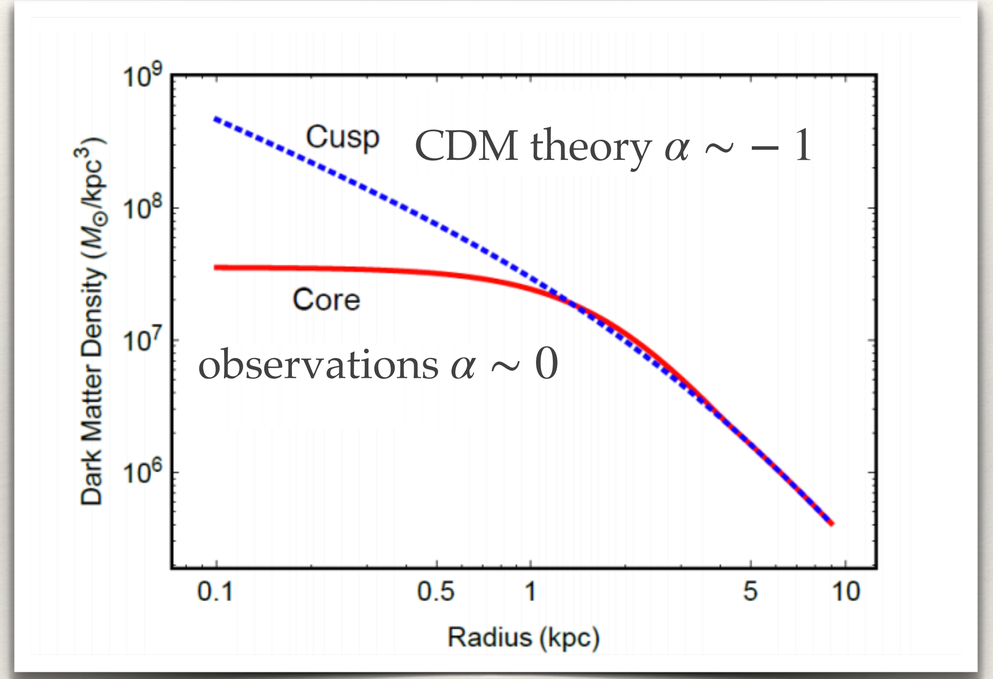
Self-interacting Dark Matter = SIDM
DM that does more and also 'interacts' with itself like **invisible** billiard balls

Small Scale Problems: Core-Cusp



Oh et al., 2011

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



Tulin & Yu 2018

- 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.)

A possible solutions to the core-cusp problem

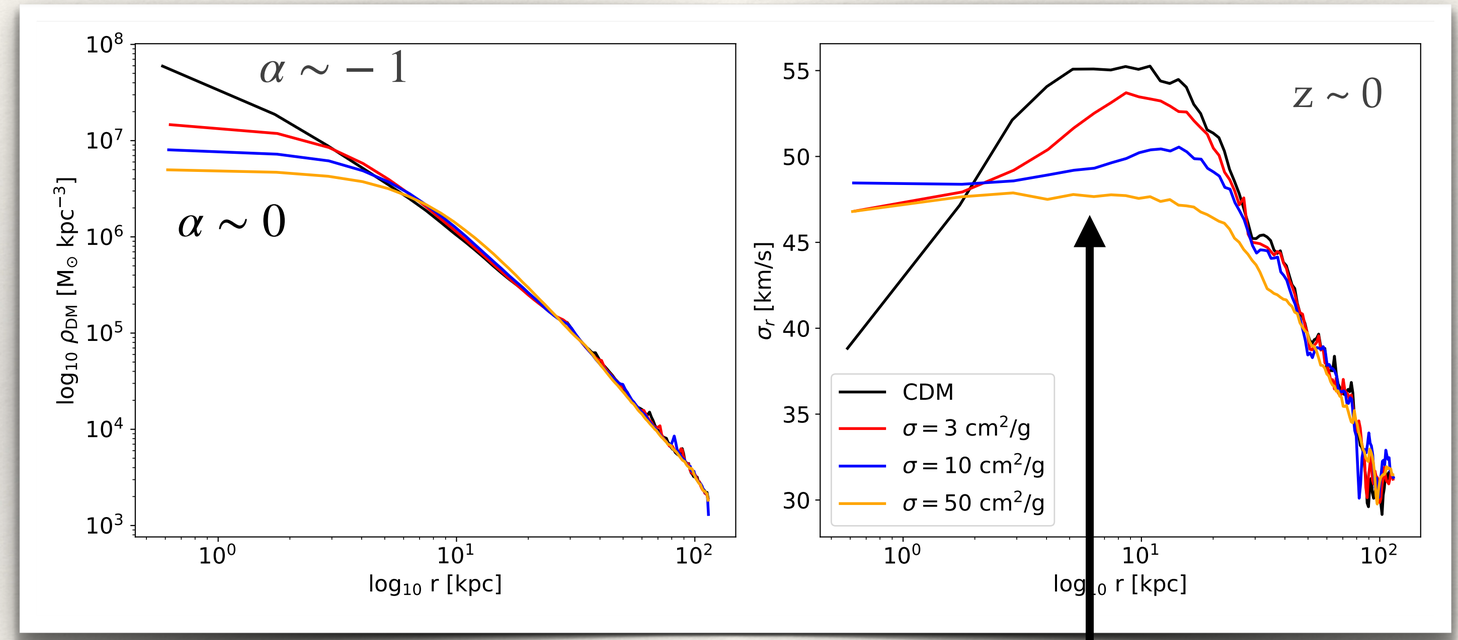
Self-interacting dark matter?

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)

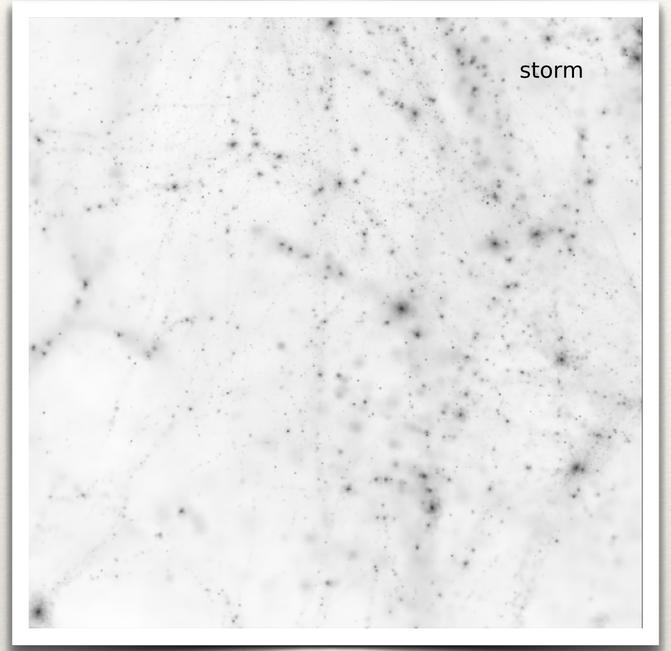
storm dwarf volume simulations run using Frontera

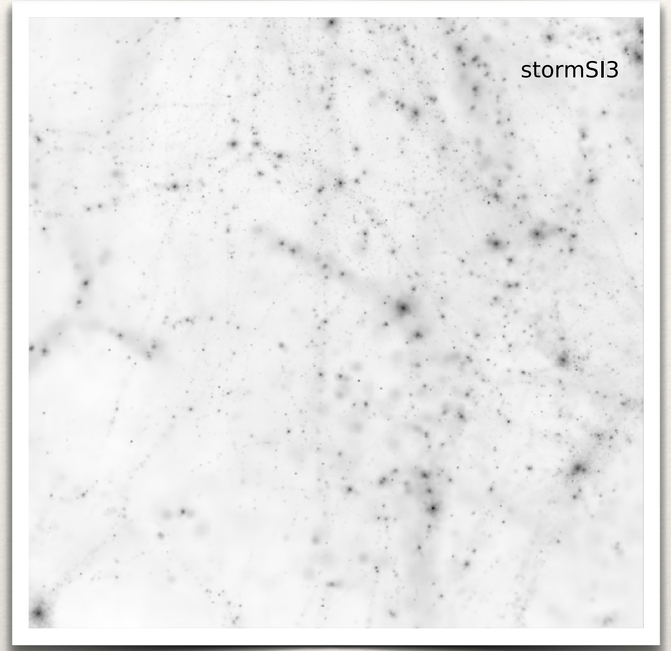


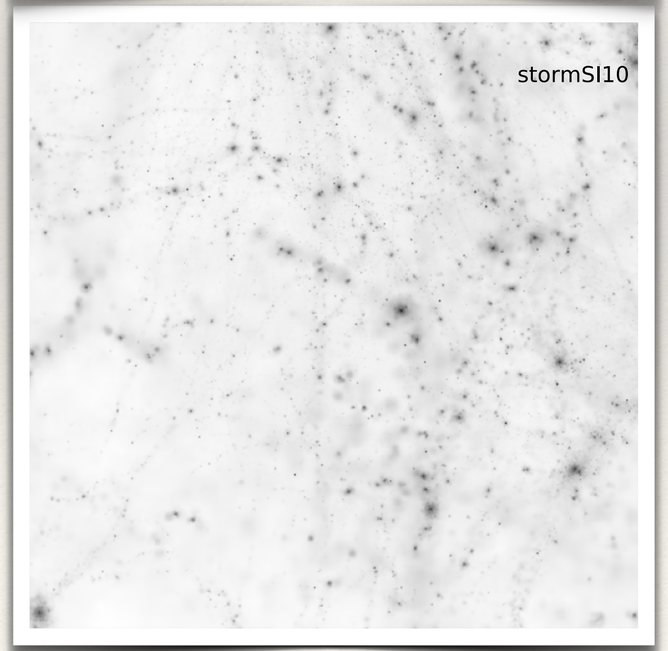
Inner halo thermalized by the outer halo when particles are self-interacting

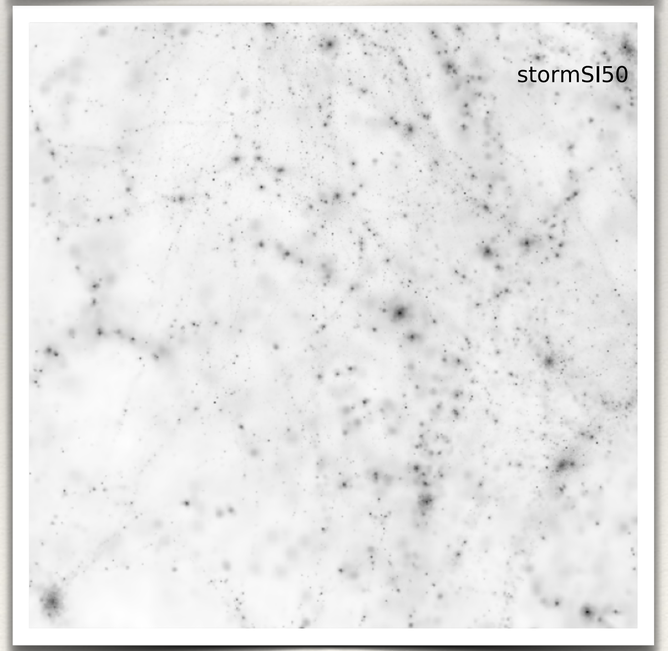
ΛSIDM Inherits all of the Success of ΛCDM at Large Scales

10 Mpc

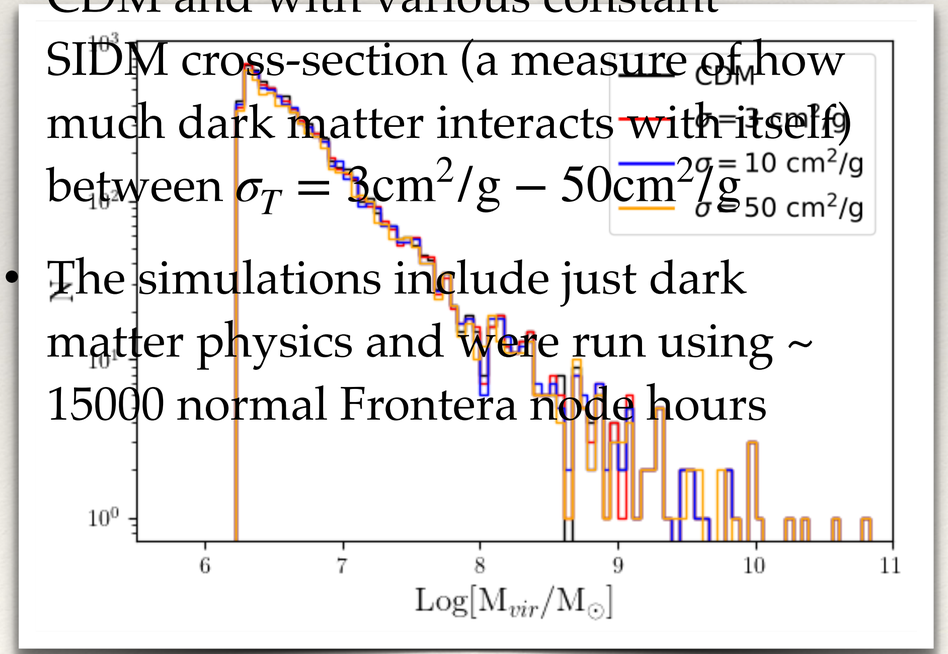






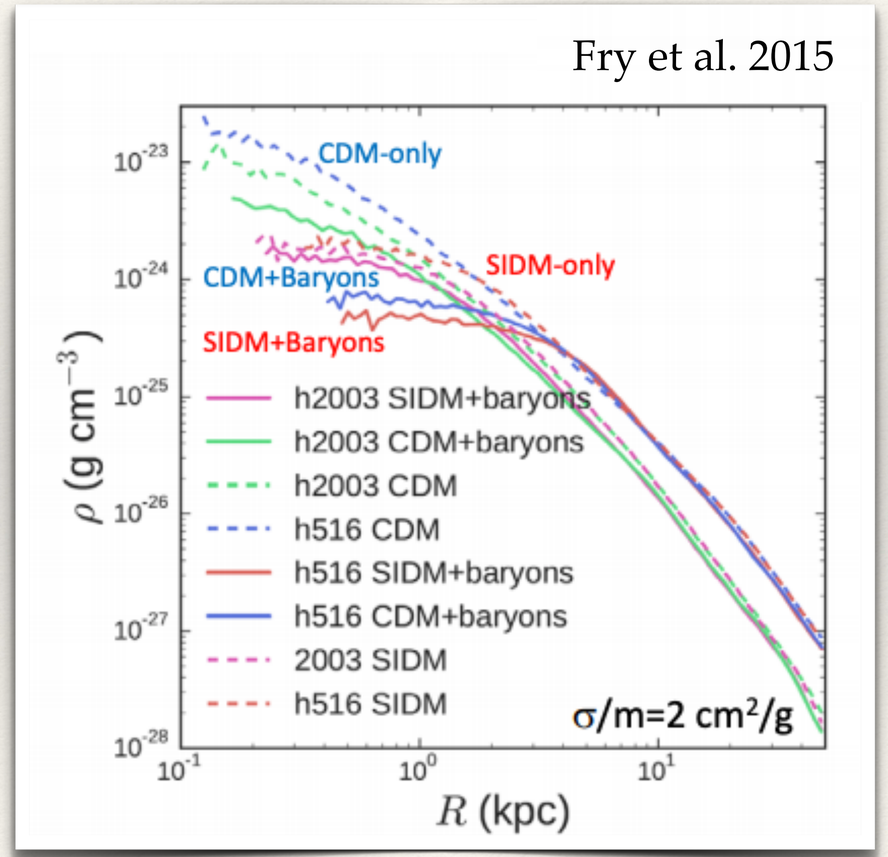


- "Storm" dwarf volume simulations run on Frontera using Charm N-Body GrAvity solver (ChaNGa) a N-Body, Barnes-Hut tree and smooth particle hydrodynamics code
- These dwarf volume were run in CDM and with various constant SIDM cross-section (a measure of how much dark matter interacts with itself) between $\sigma_T = 3\text{cm}^2/\text{g} - 50\text{cm}^2/\text{g}$
- The simulations include just dark matter physics and were run using ~ 15000 normal Frontera node hours



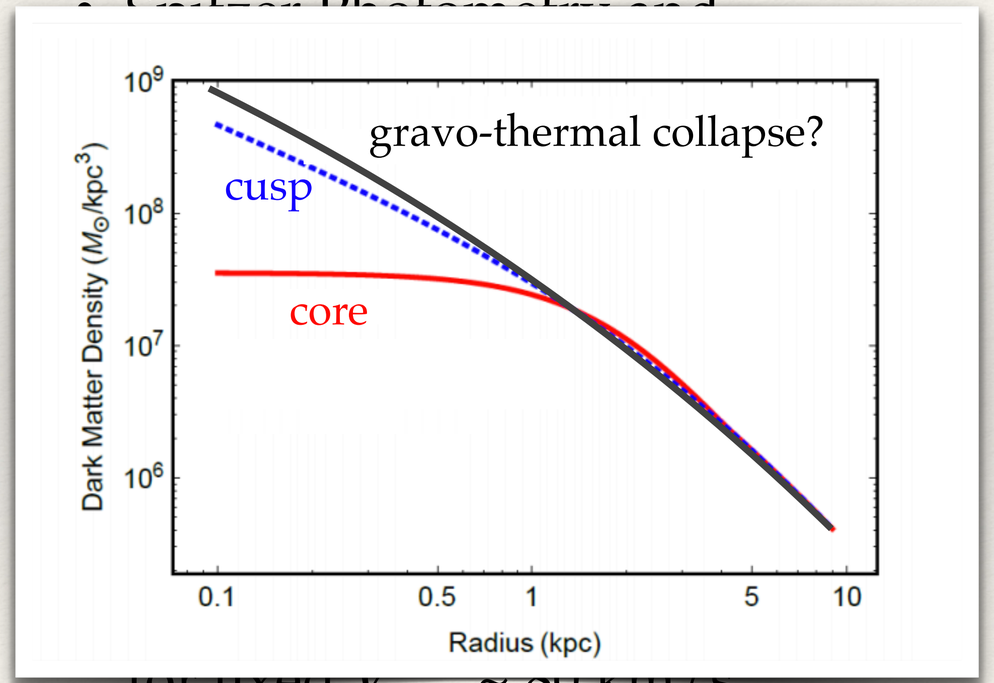
A possible solutions to the core-cusp problem

Ordinary matter physics such as supernova feedback?

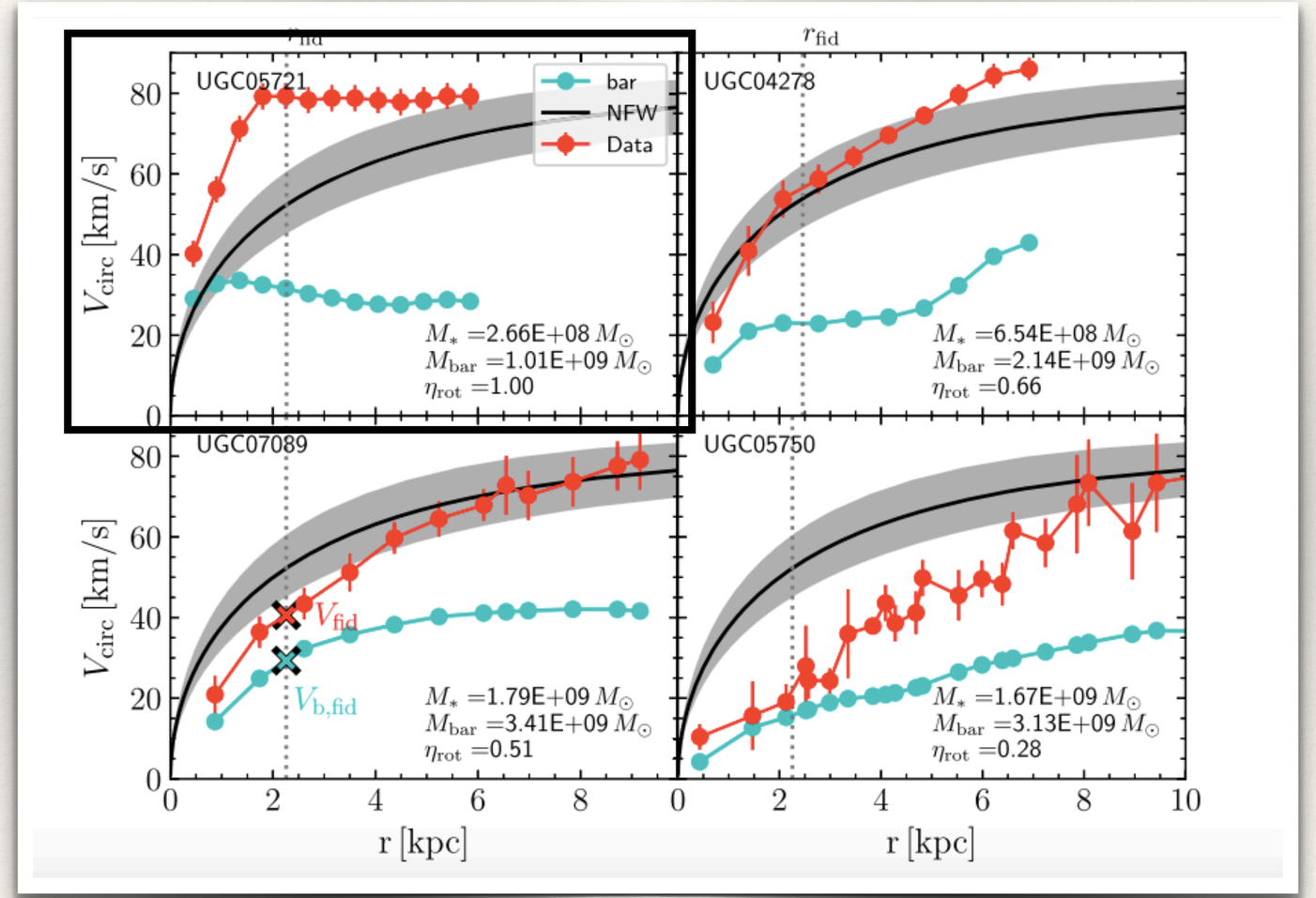


baryons = ordinary matter = gas + stars

Small scale problems: diversity of rotation curves



for fixed $V_{max} \sim 80$ 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
- $\Gamma_{\mathrm{SI}} \sim \rho_{dm} \rightarrow dt$ becomes smaller and smaller, which can case simulation run times to increase dramatically

Draco dwarf spheroidal

Thank you!
Questions?

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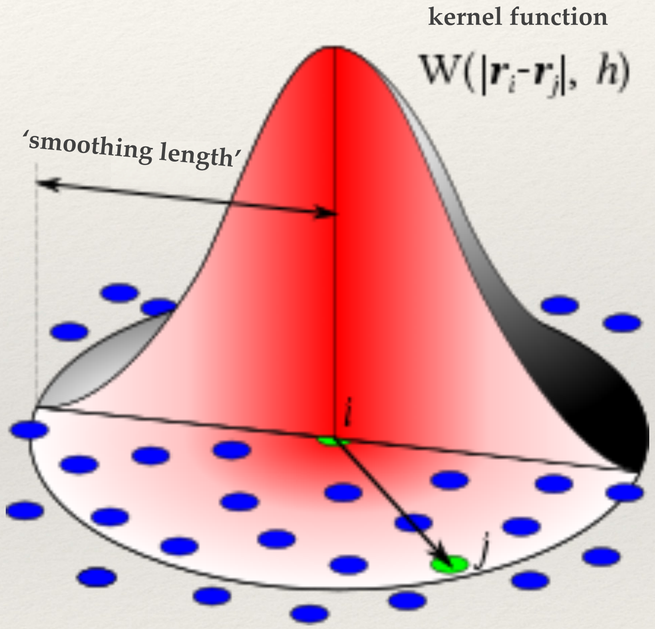
Method: Smooth Particle Hydrodynamic Simulations

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!



32 or 64 particles