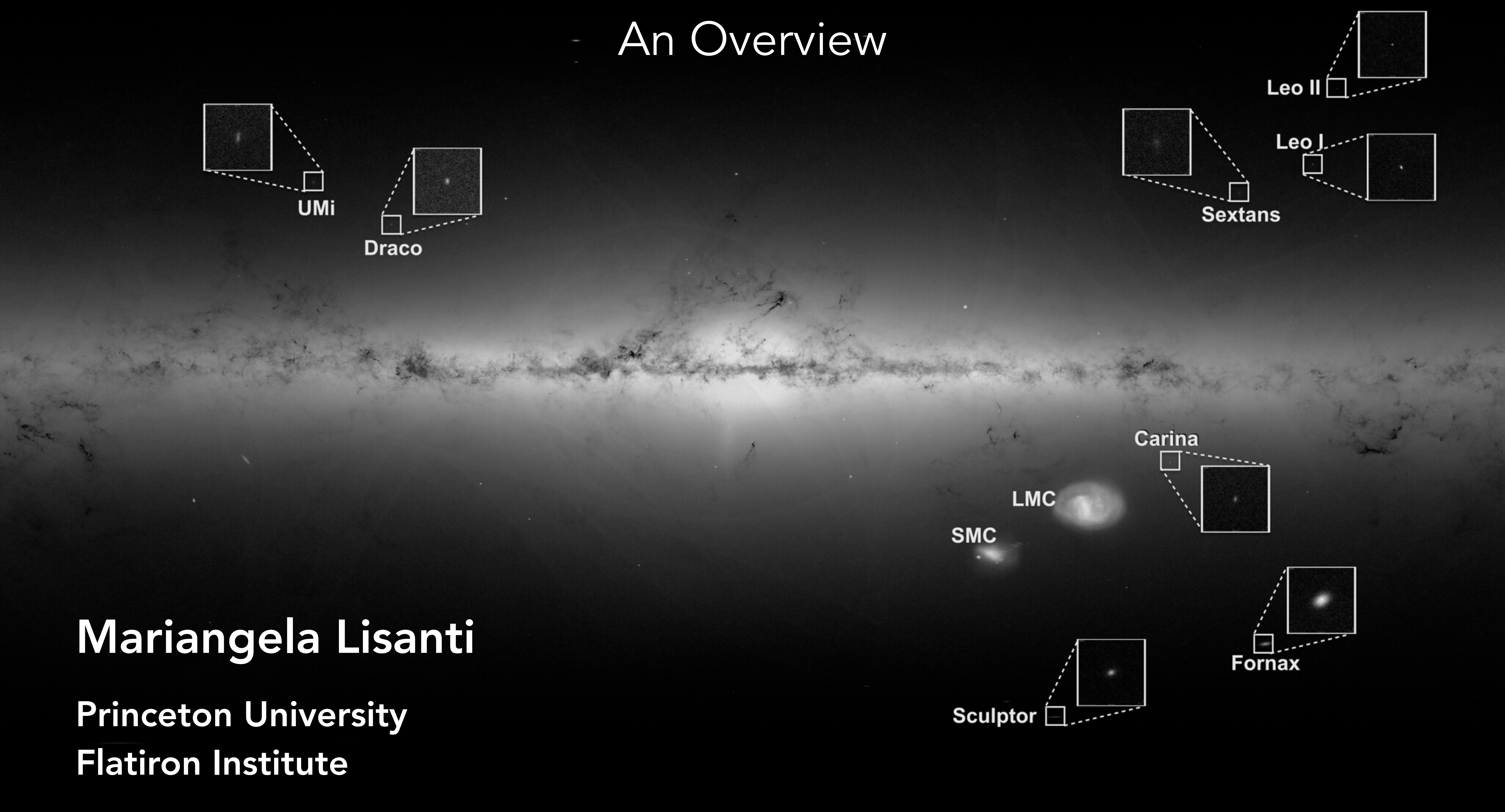
Astrophysical Probes of Particle Dark Matter

An Overview

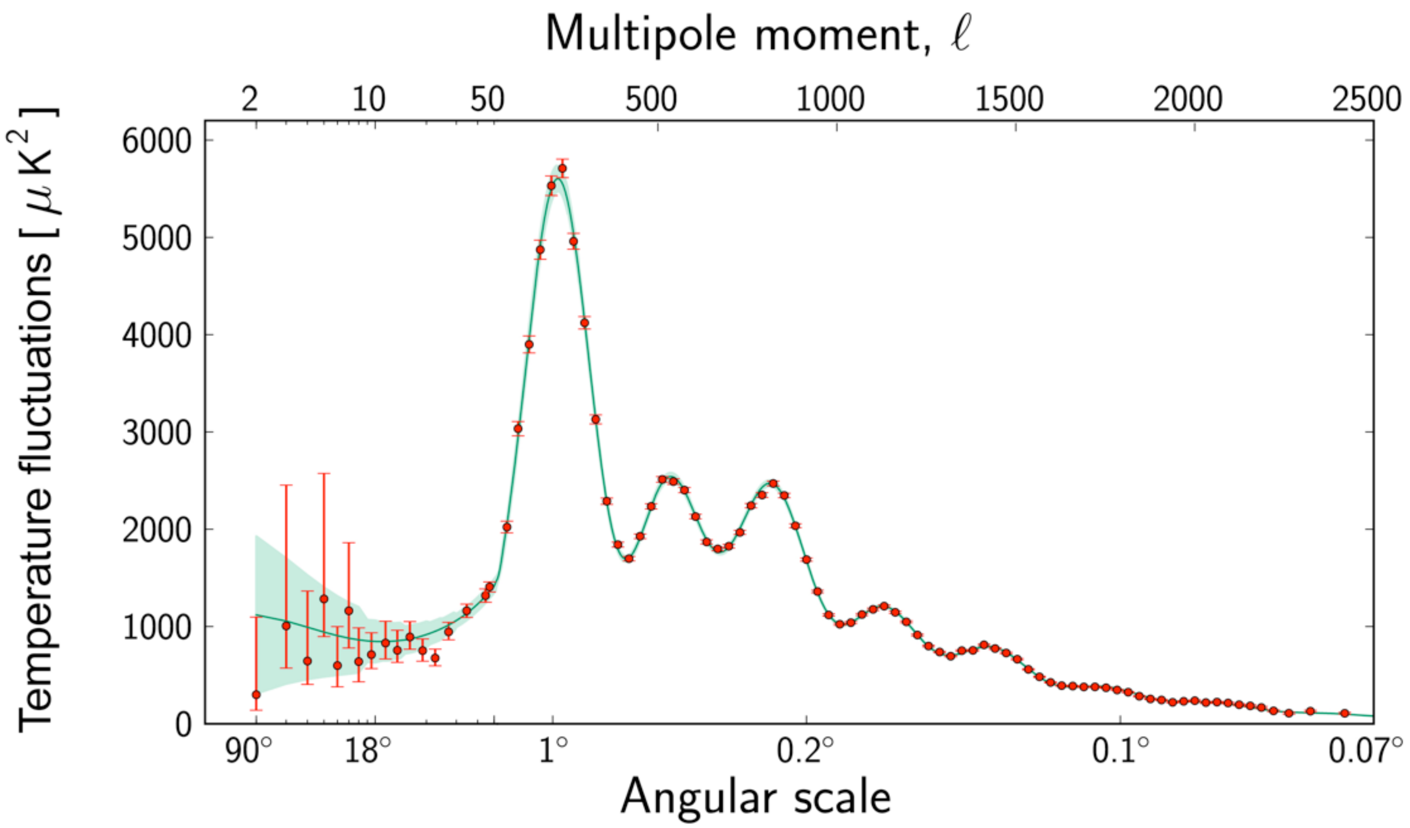


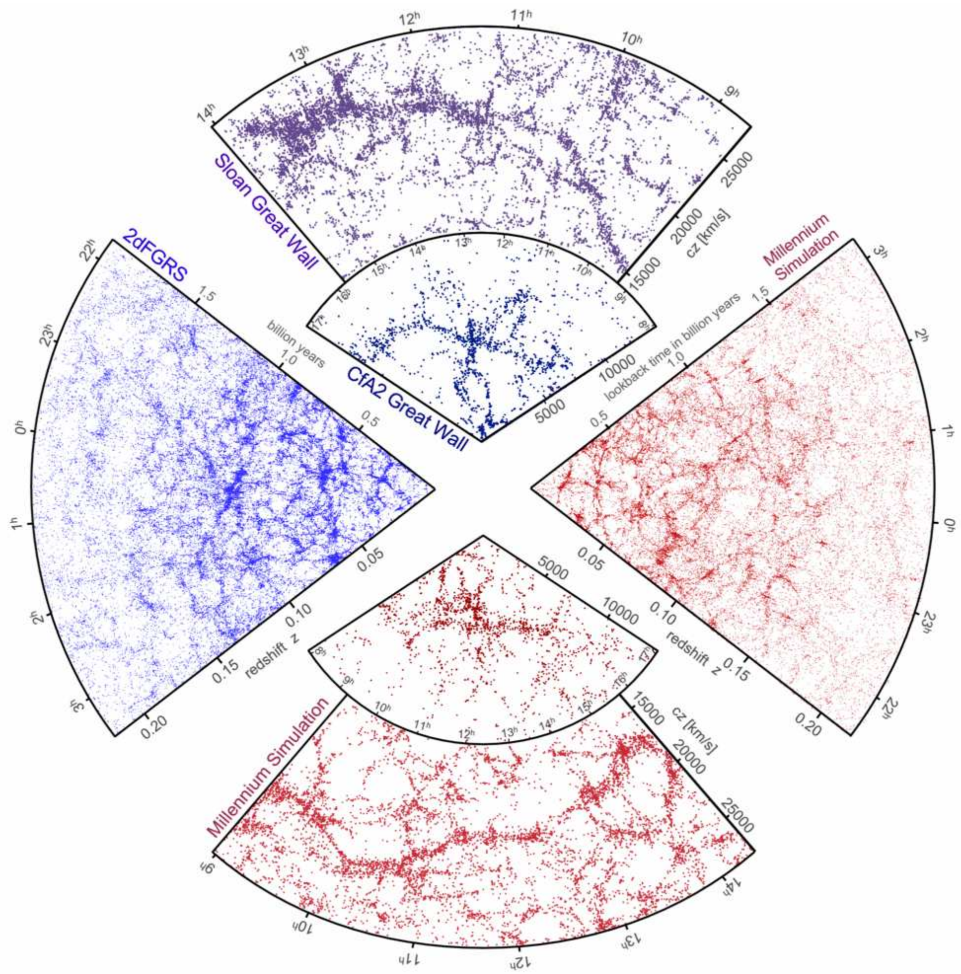
Mariangela Lisanti

Princeton University
Flatiron Institute

Cold Dark Matter

Spectacular confirmation of cold dark matter hypothesis
on the largest scales of the Universe





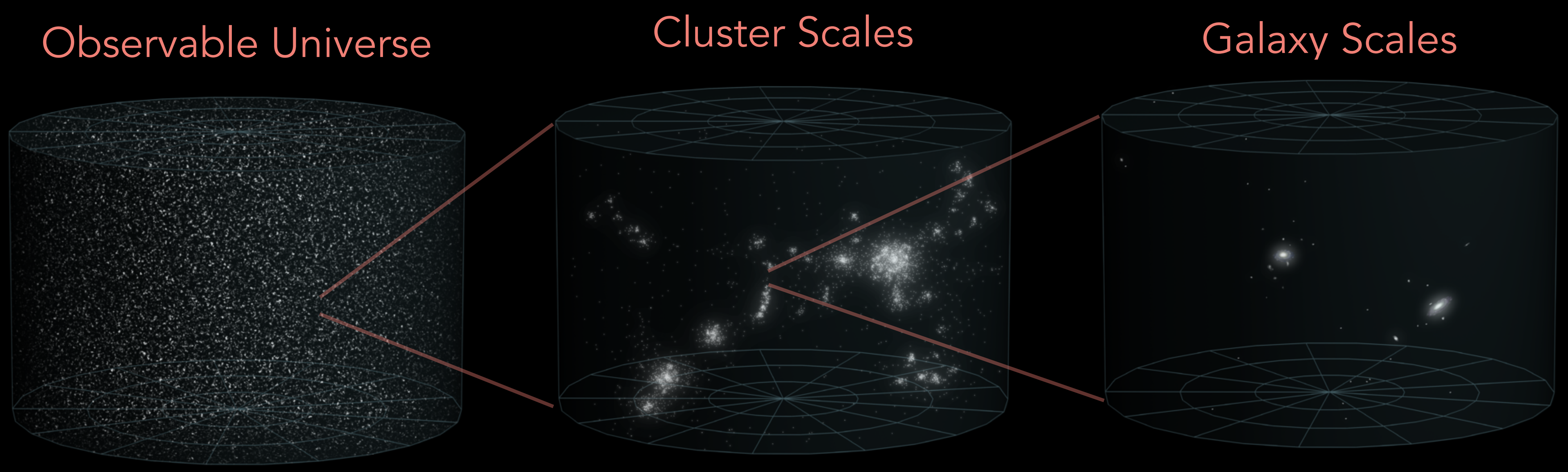
Planck Collaboration [1303.5076]

Springel, Frenk, and White [astro-ph/0604561]

Cold Dark Matter Paradigm

CDM must be stress-tested on all scales

Galactic and sub-galactic scales are the next frontier



Simulations: Andrew Z. Colvin

Outline

Galaxies in a CDM Framework

Self Interactions and Galaxy Formation

Current and Future Outlook of Observational Constraints

Galactic Evolution

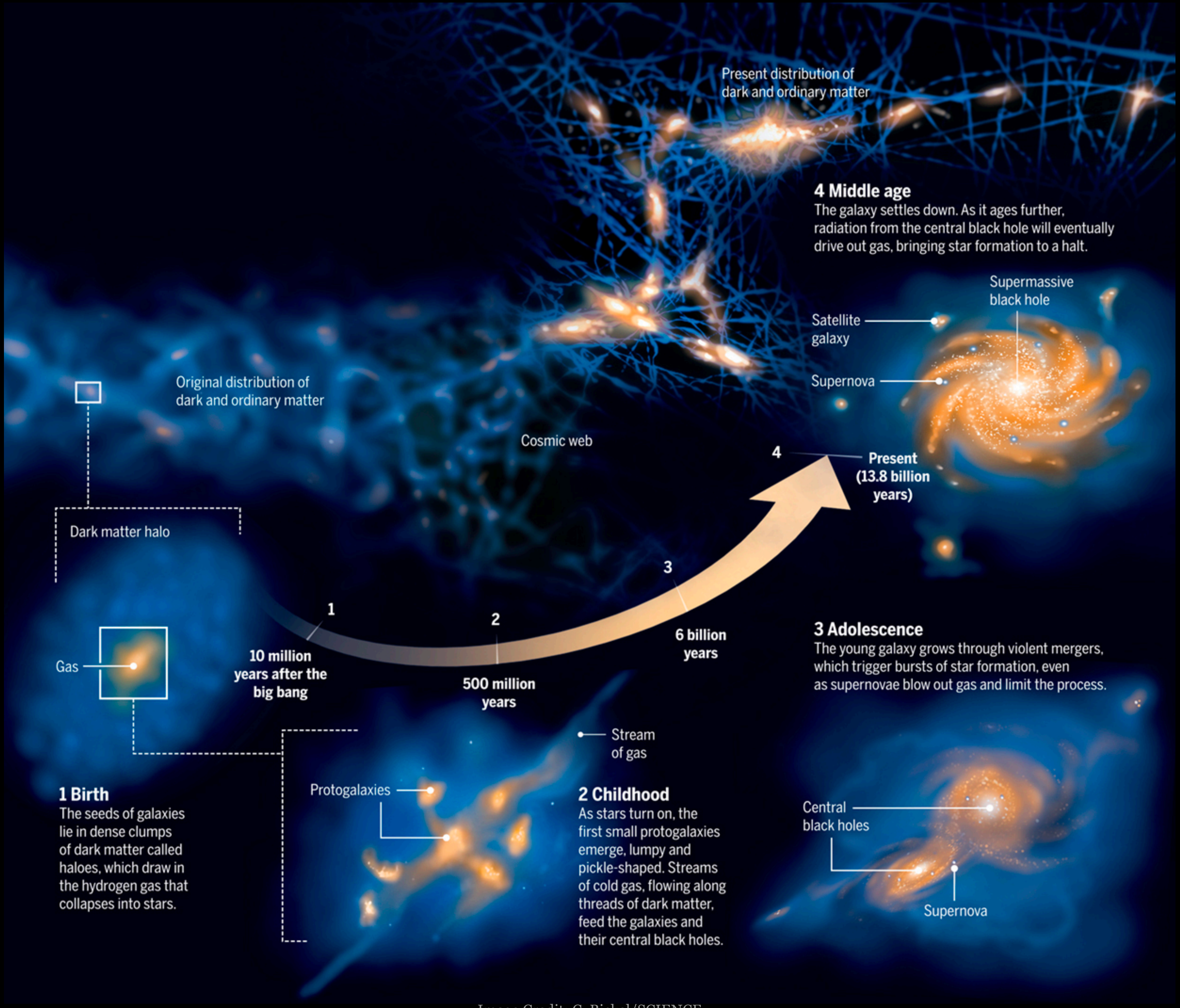
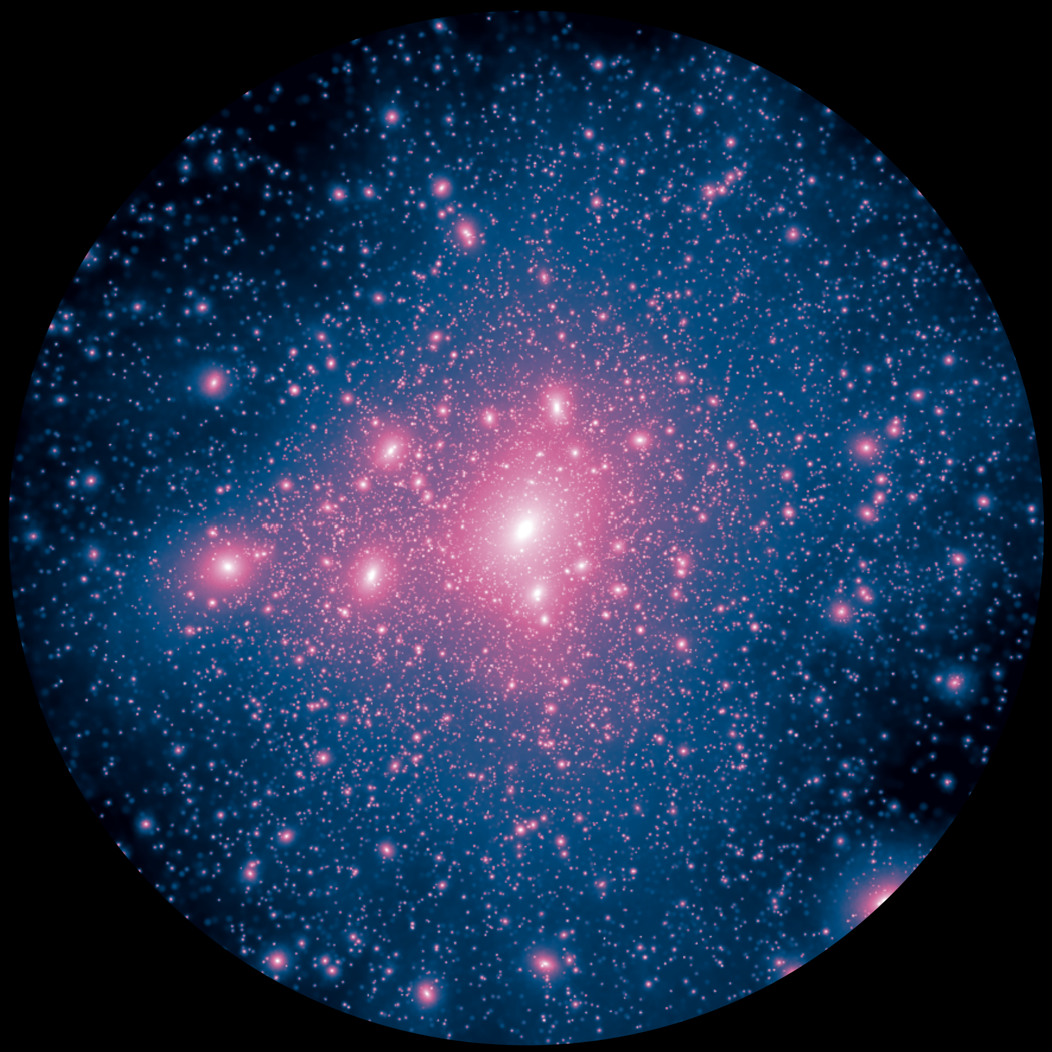


Image Credit: C. Bickel/SCIENCE

Small-Scale Structure

Dark Matter Halo & Subhalos



Vogelsberger et al. (2016)

Milky Way Dwarf Galaxies

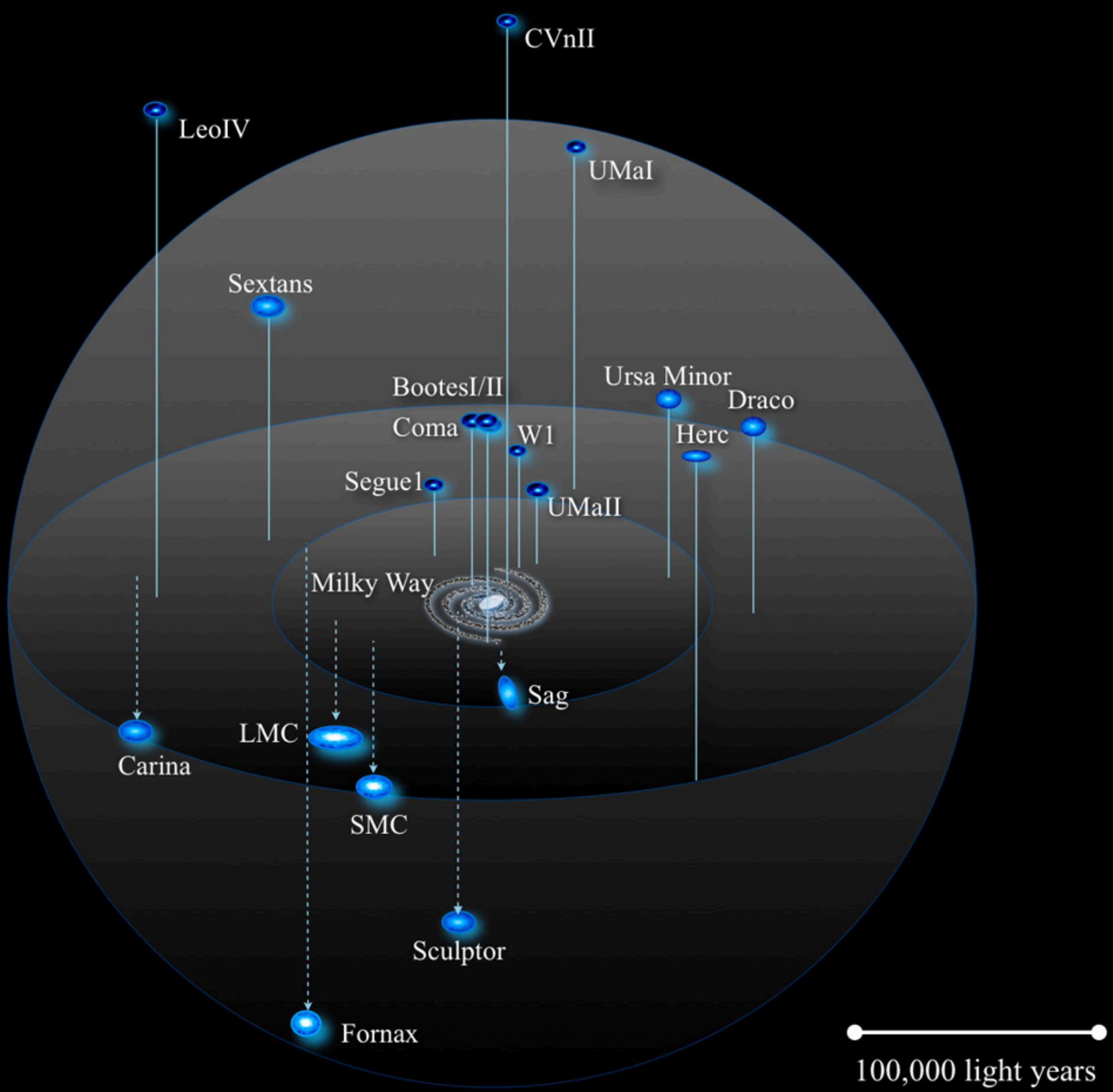


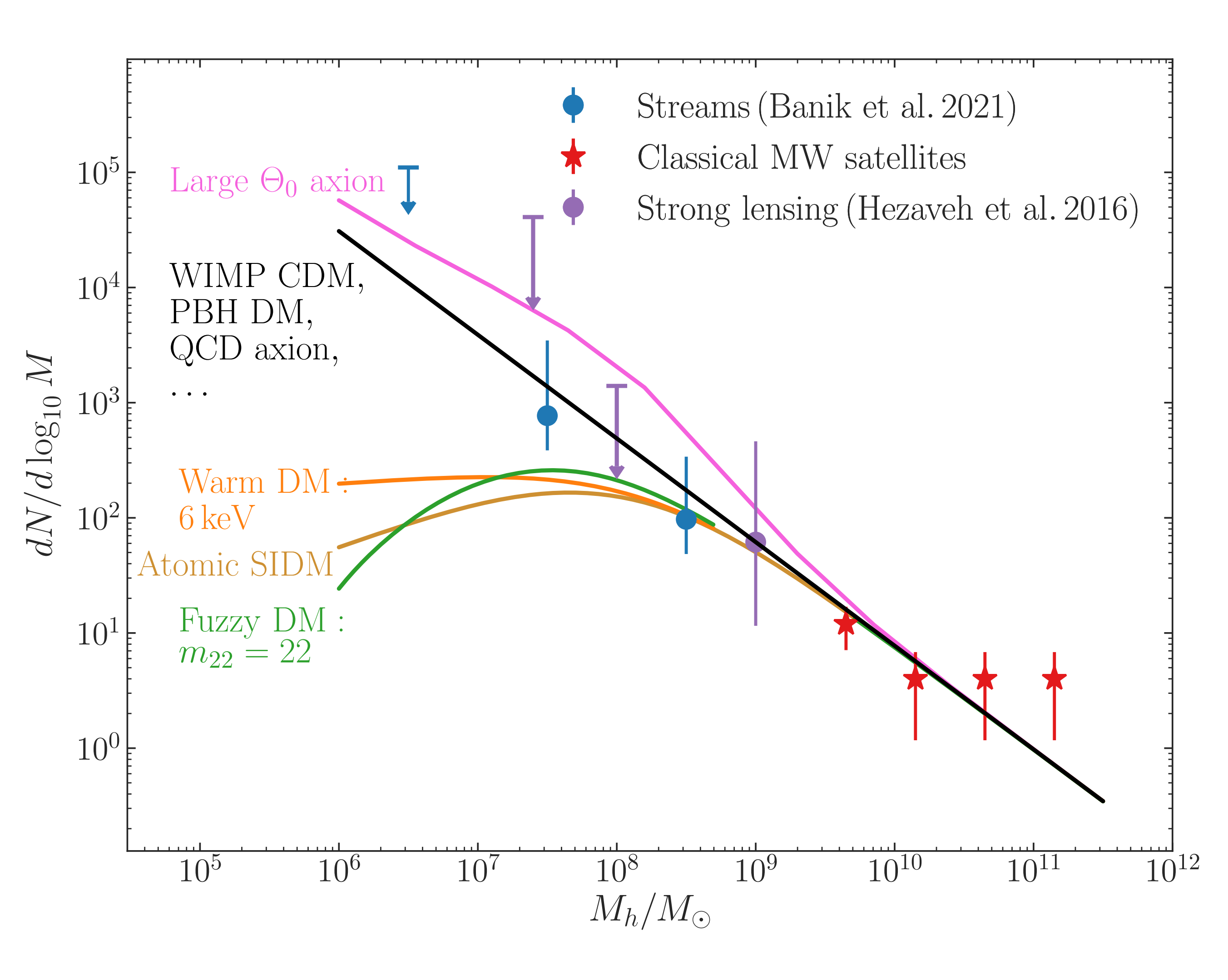
Image Credit: J. Bullock, M. Geha, R. Powell

Minimum Halo Mass

CDM predicts many halos down to Earth-scale masses

Green et al. [astro-ph/0309621]; Diamond et al. [astro-ph/0501589]

Sharp prediction of the theory

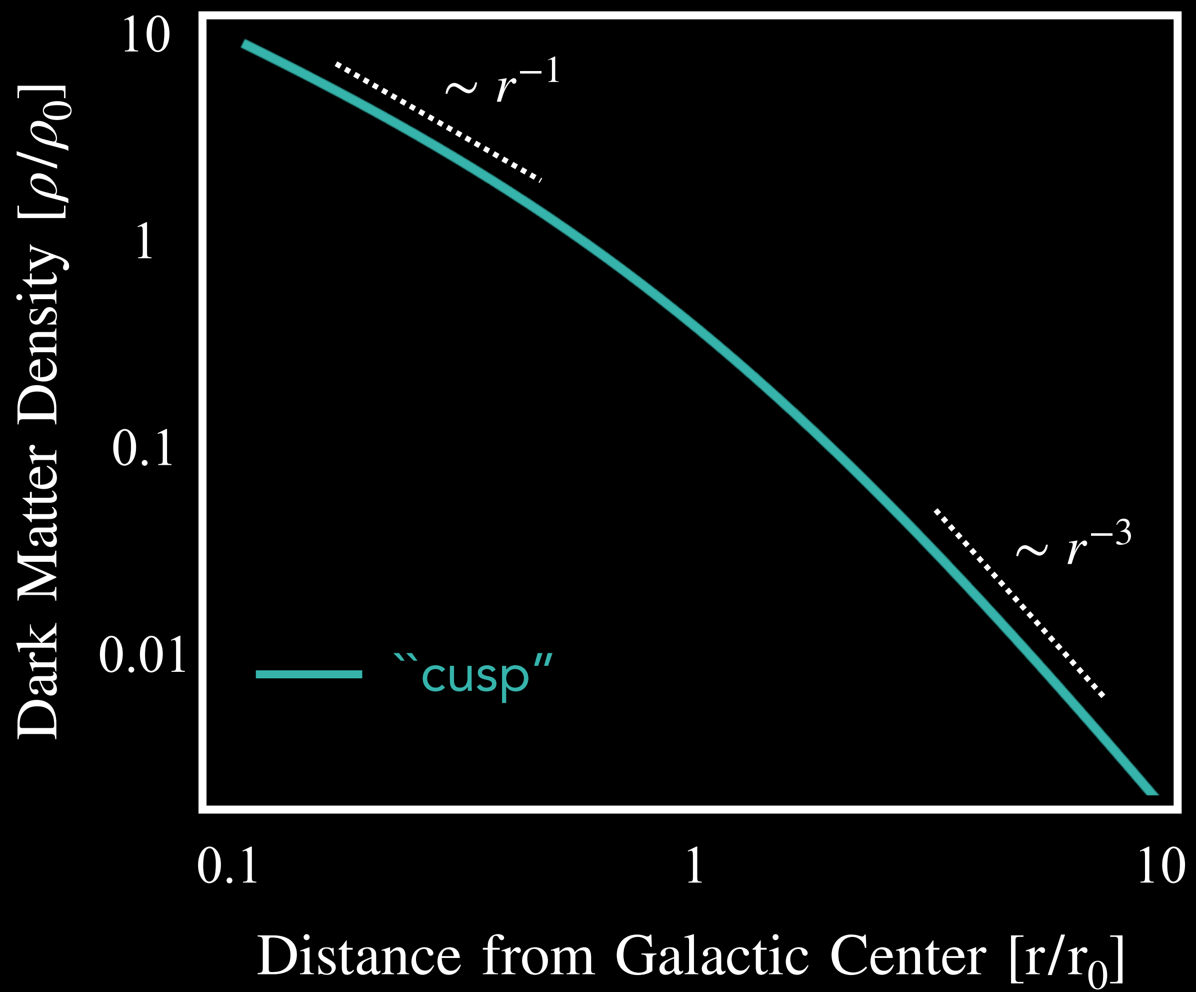


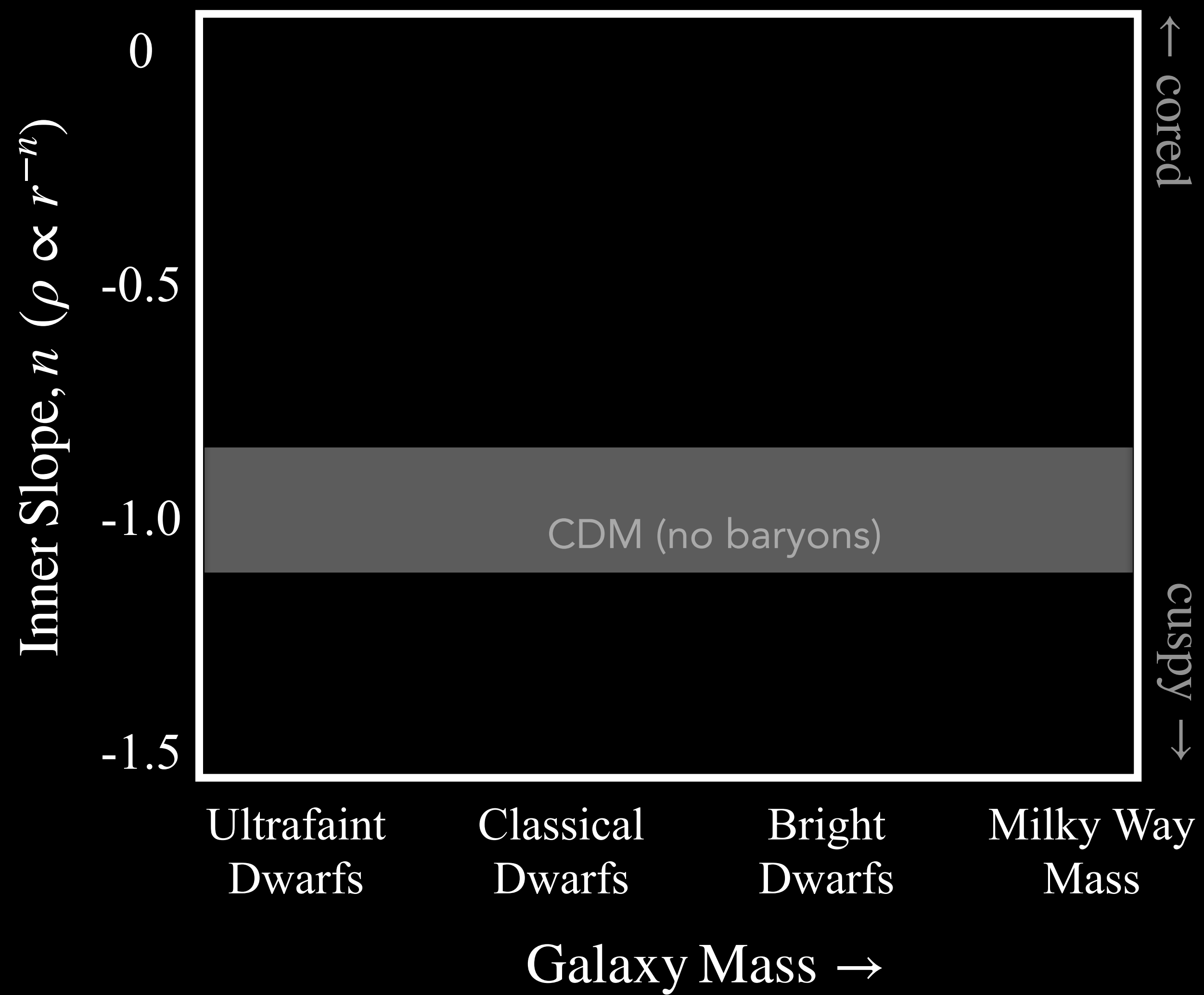
Banik et al. [1911.02663]

Universal Profile in CDM

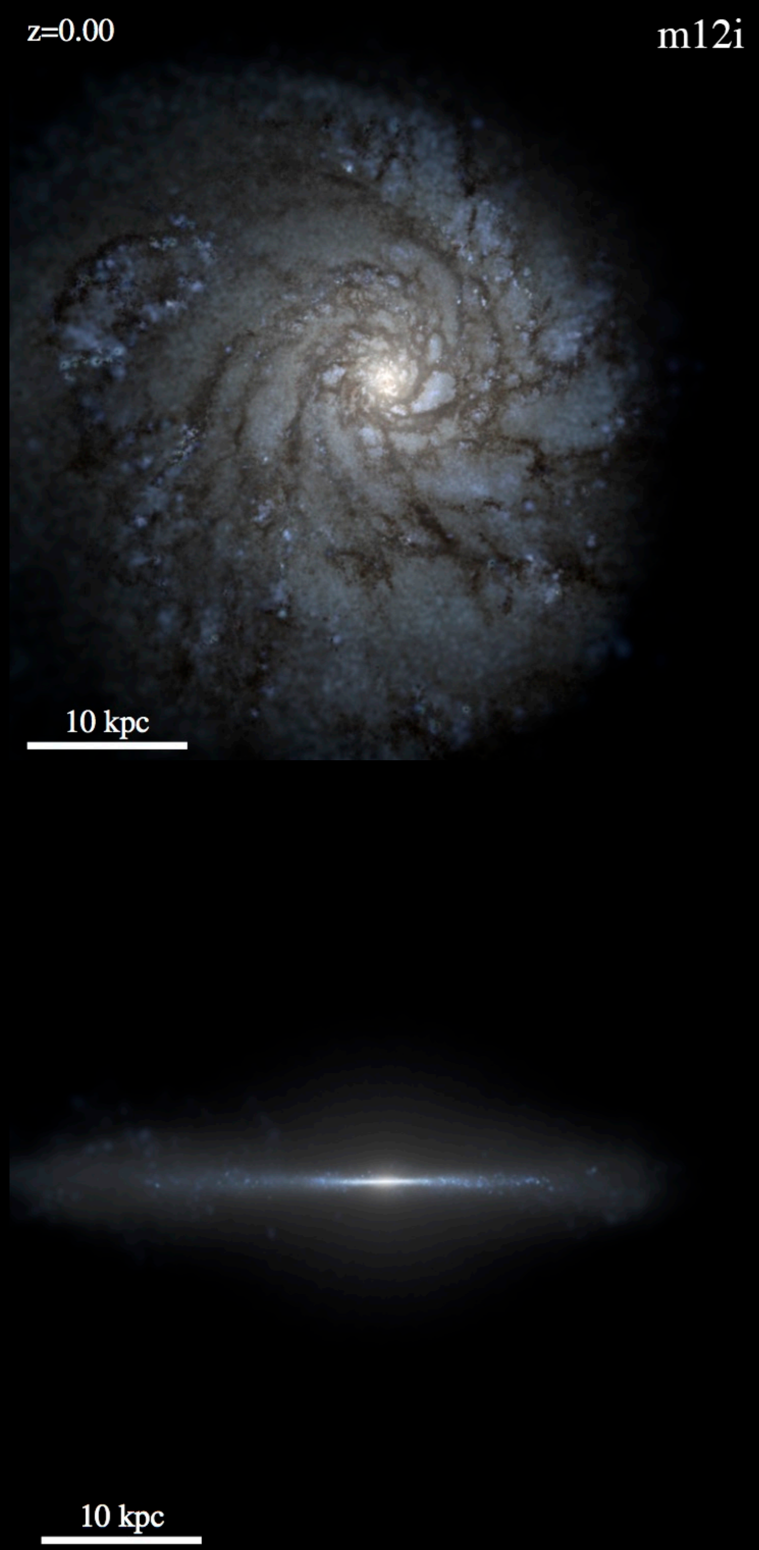
Universal density profile for halos observed in dark-matter only simulations

Profile is `cuspy' in central region





Baryonic Physics



Hopkins et al. [1702.06148]

Astrophysical processes that play a key role in simulating realistic galaxies:

gas cooling	interstellar medium	magnetic fields
star formation	radiation fields	cosmic rays
stellar feedback	active galactic nuclei	black holes

Prescriptions are needed to model physics below the resolution limit of a simulation

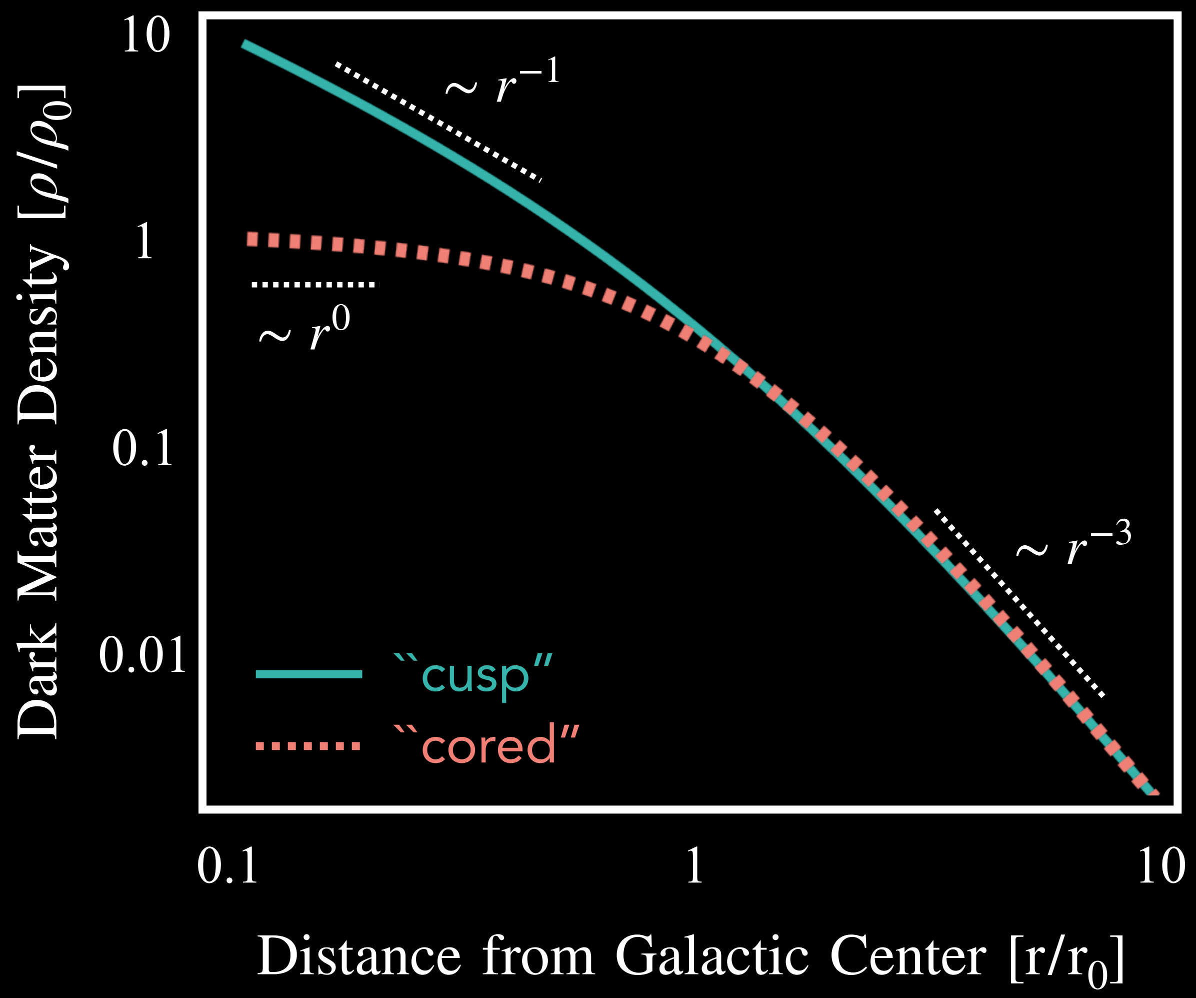
Sub-resolution modeling introduces an inherent systematic uncertainty into the simulation

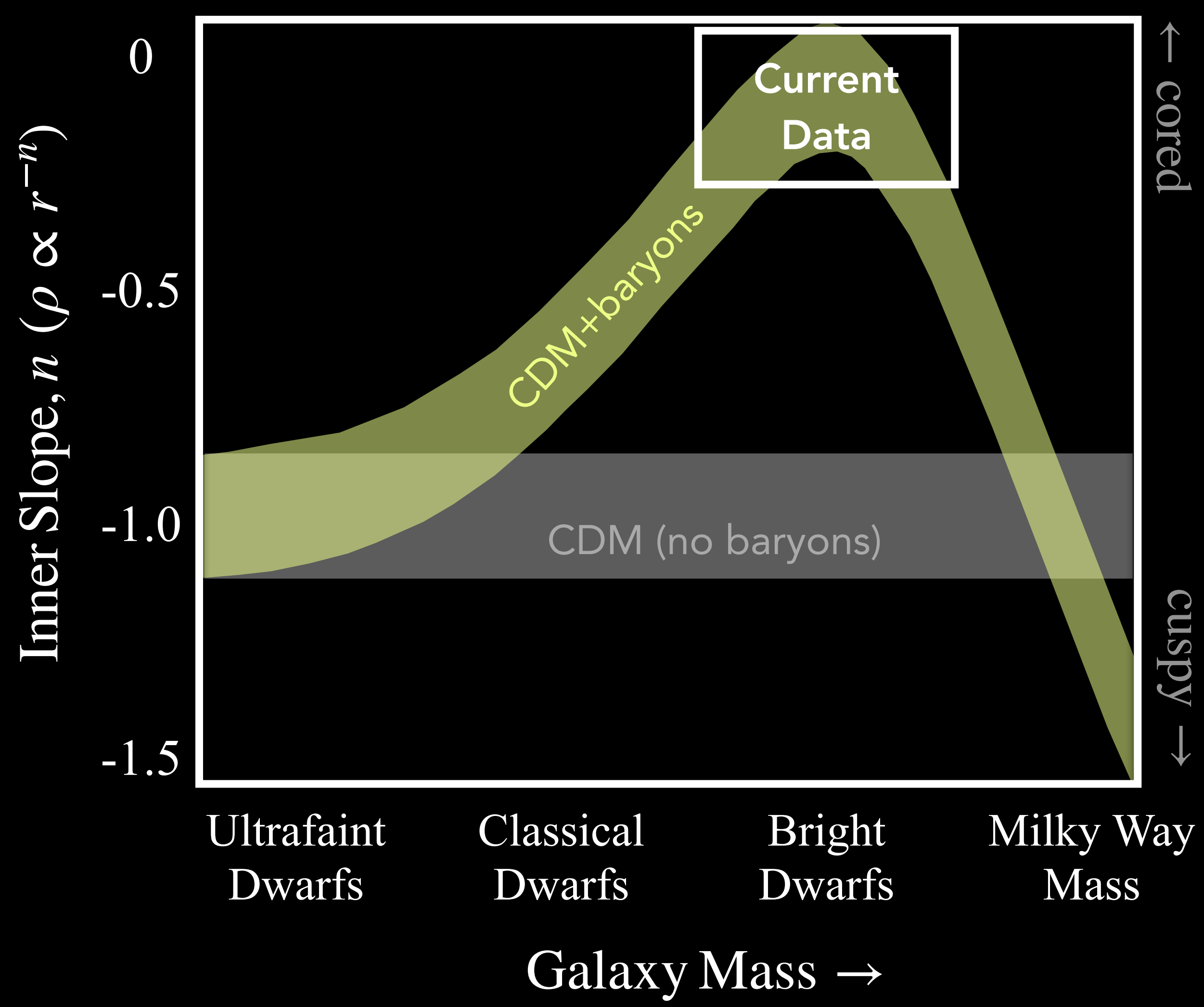
see Vogelsberger et al. [1909.07976] for a review

Internal Halo Properties

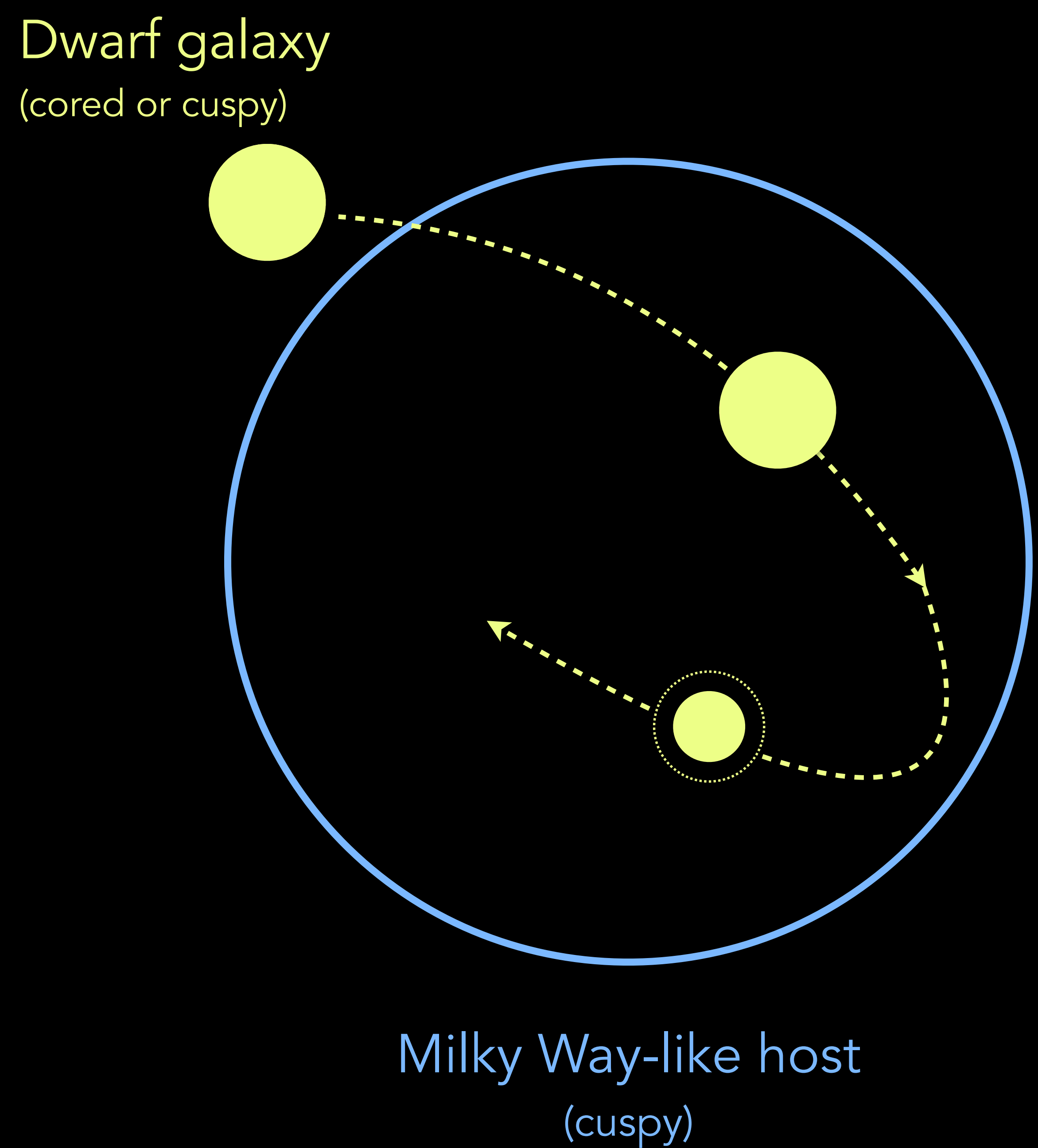
Energy injection from baryonic feedback processes can `core' the inner-most regions of CDM halos

Coring efficiency depends on subhalo mass





Dwarf Galaxy Orbital Evolution



Equation of motion for dwarf galaxy

$$\mathbf{a}_{\rm tot} = -\nabla\Phi + \mathbf{a}_{\rm DF}$$

host potential — dynamical friction

Tidal forces strip mass from outskirts of dwarf at a rate of

$$\frac{dM_{\rm dwarf}}{dt} \propto -\frac{M_{\rm dwarf}(>\text{tidal radius})}{\text{dynamical time}}$$

Where does dark matter physics play a key role in galactic evolution?

- Minimum halo mass
- Internal density distribution of host and satellite
- Satellite mass loss during orbit
    - Tidal disruption
- Drag forces felt by satellite during orbit
    - Dynamical friction

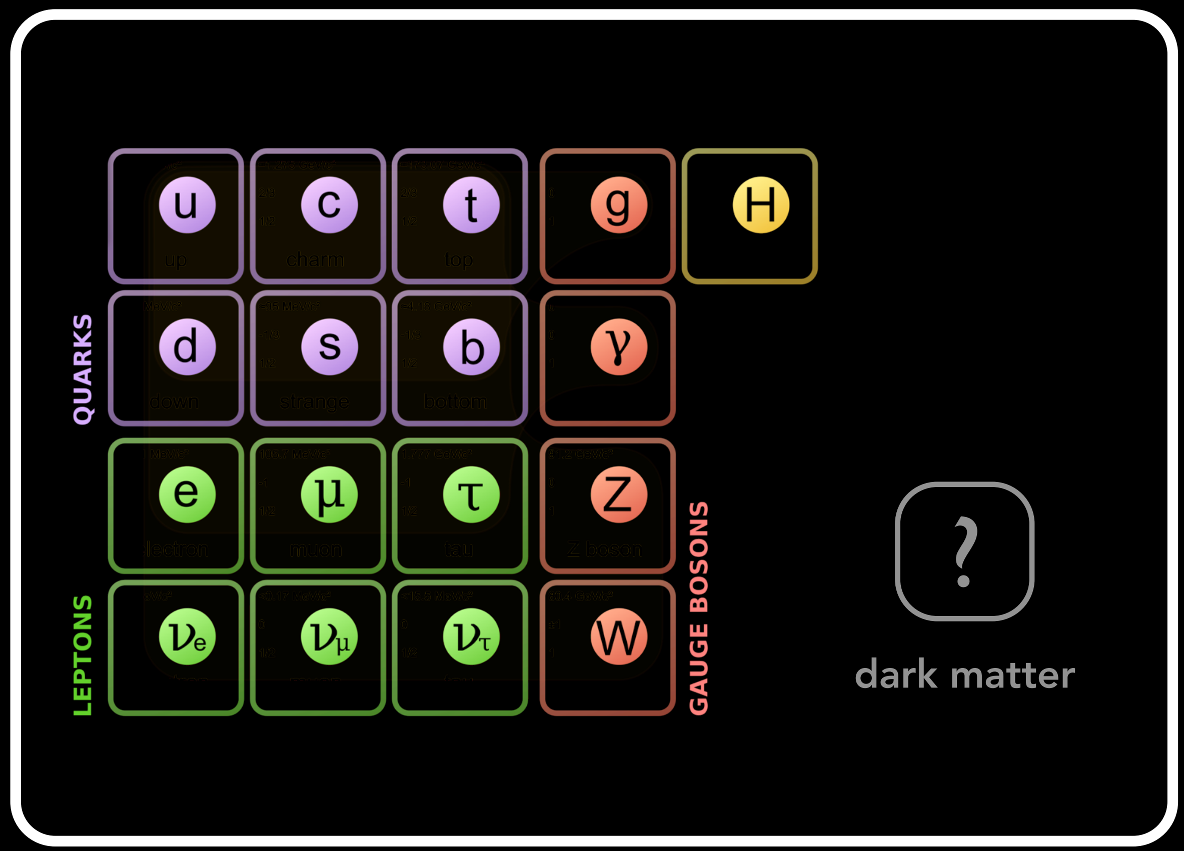
Outline

Galaxies in a CDM Framework

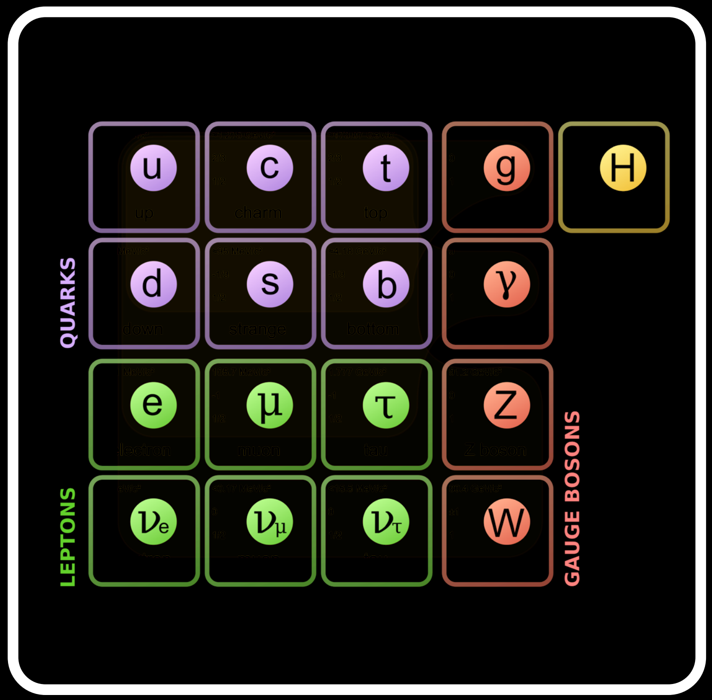
Self Interactions and Galaxy Formation

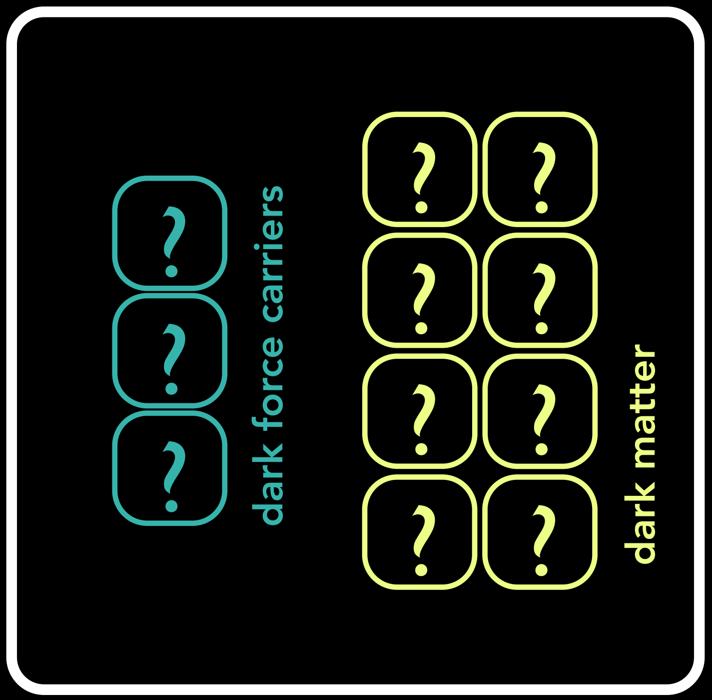
Current and Future Outlook of Observational Constraints

Theory of Dark Sectors



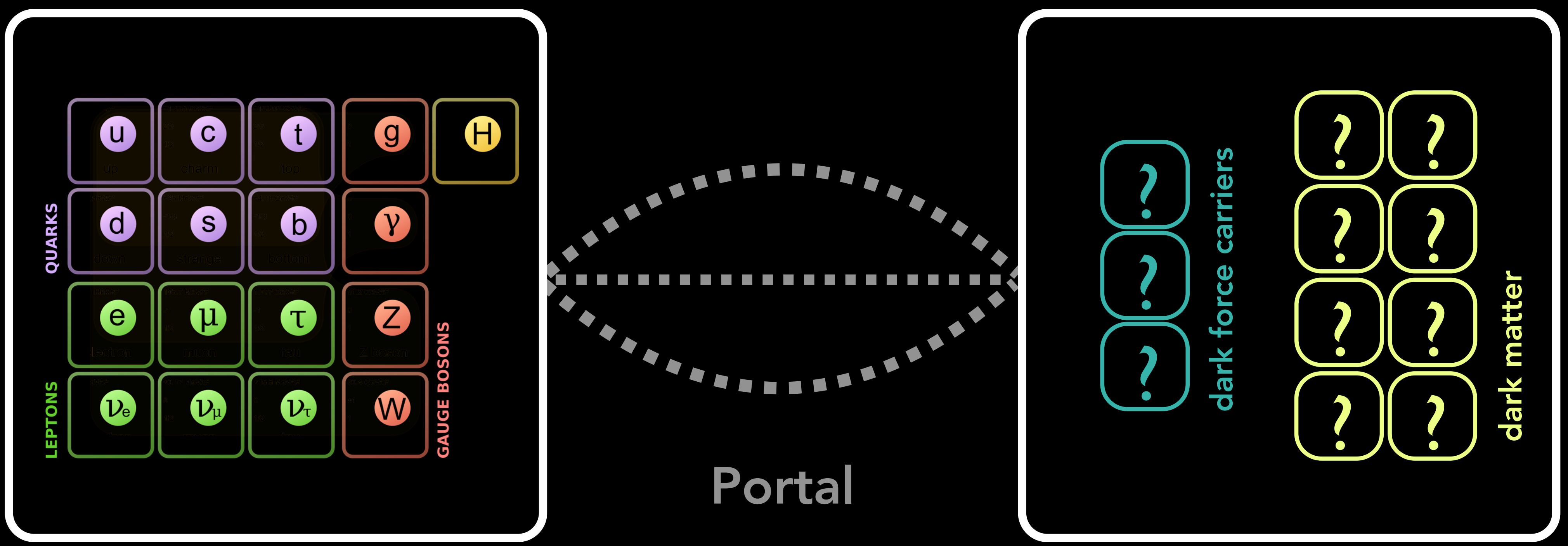
Theory of Dark Sectors





New dark forces? Multiple dark matter states?

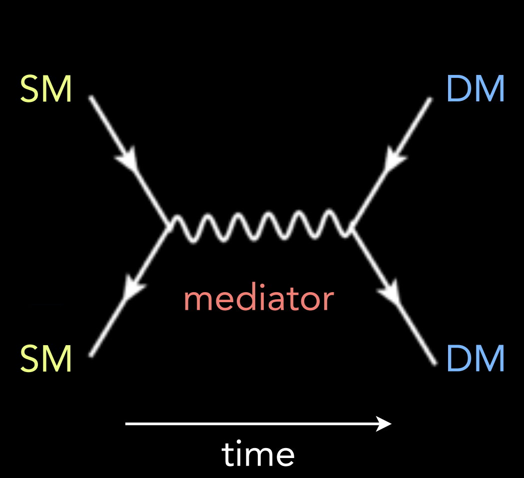
Theory of Dark Sectors



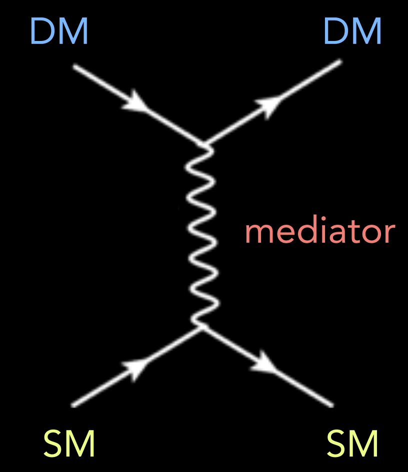
Some important portals being actively studied:

$\epsilon F_Y^{\mu\nu} F'_{\mu\nu}$	dark photon	$\kappa (HL) N$	sterile neutrinos
$\lambda H^2 S^2 + \mu H^2 S$	dark Higgs	$\frac{1}{f_a} \epsilon F^{\mu\nu} \tilde{F}_{\mu\nu} a$	axions & axionlike particles (ALPs)

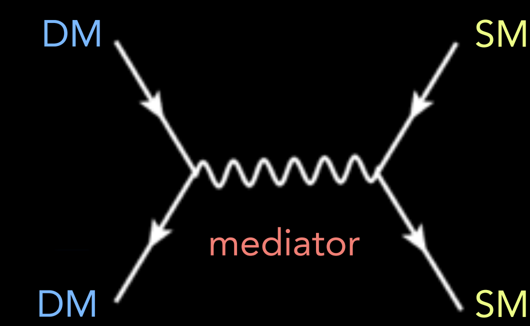
Broad Program of Study Needed



DM Production in Colliders

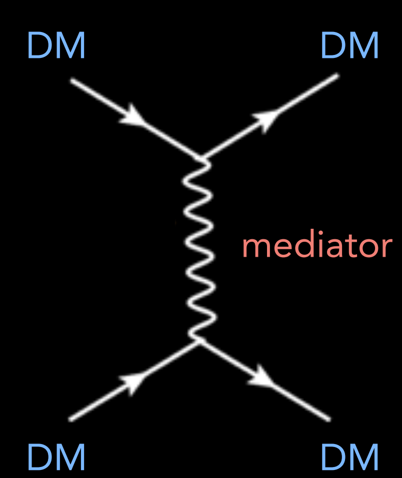


DM Scattering in Laboratory

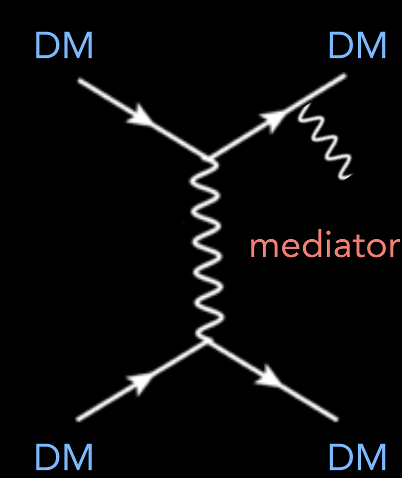


DM Annihilation

Interplay between different phenomena is highly non-trivial



Self-Interacting DM



Dissipative DM

Self-Interacting Dark Matter (SIDM)

Over the age of the Universe,
~one self-interaction near galactic center if

$$\frac{\sigma}{m_\chi} \sim 1 \ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

Spergel and Steinhardt [astro-ph/9909386]

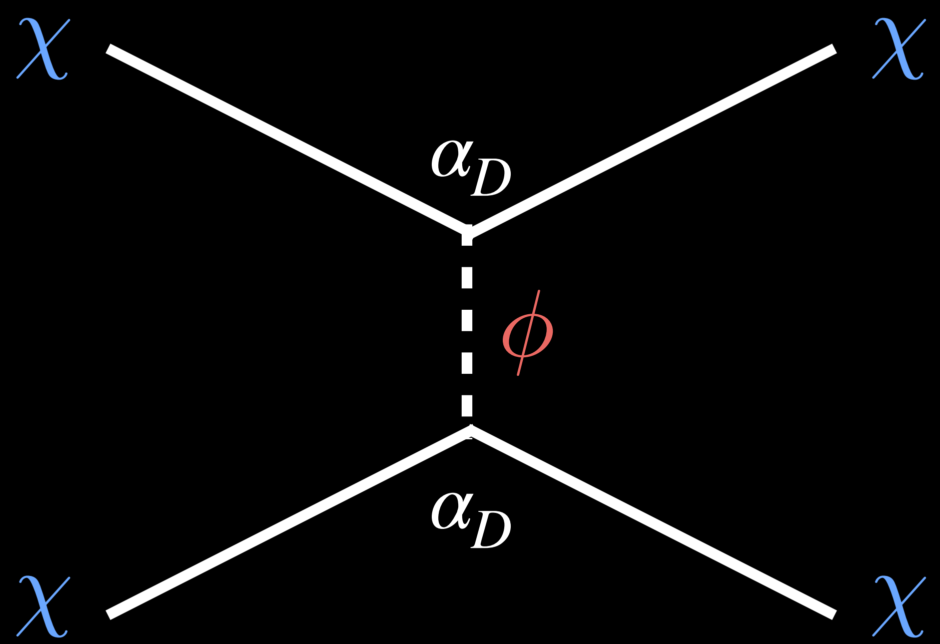
This is a typical cross section for dark sectors with light mediators

e.g., ~10 GeV dark matter with ~10 MeV mediator ($\alpha_D \sim 0.01$)

Kaplinghat et al. [1508.03339]

SIDM Model

Dark matter particles interact via a light mediator

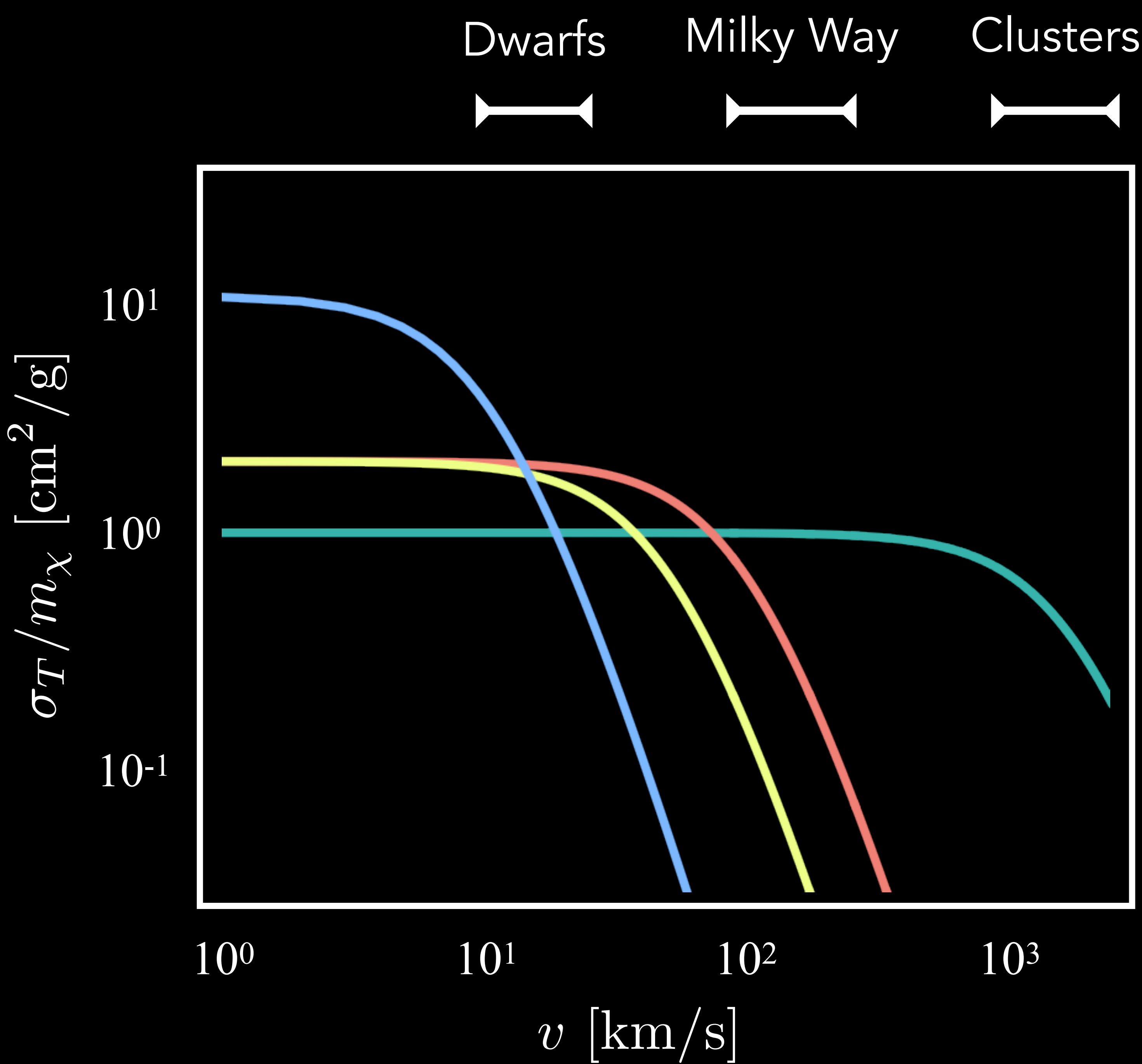


$$L_{\text{int}} = \begin{cases} g_D\,\bar{\chi}\,\gamma^\mu\,\chi\,\phi_\mu \\ g_D\,\bar{\chi}\,\chi\,\phi \end{cases}$$

Self scattering described by Yukawa potential
in non-relativistic limit

Feng et al. [0905.3039]; Loeb and Weiner [1011.6374]; Kaplinghat, Tulin and Yu [1508.03339]

SIDM Model



Anisotropic, velocity-dependent self scattering

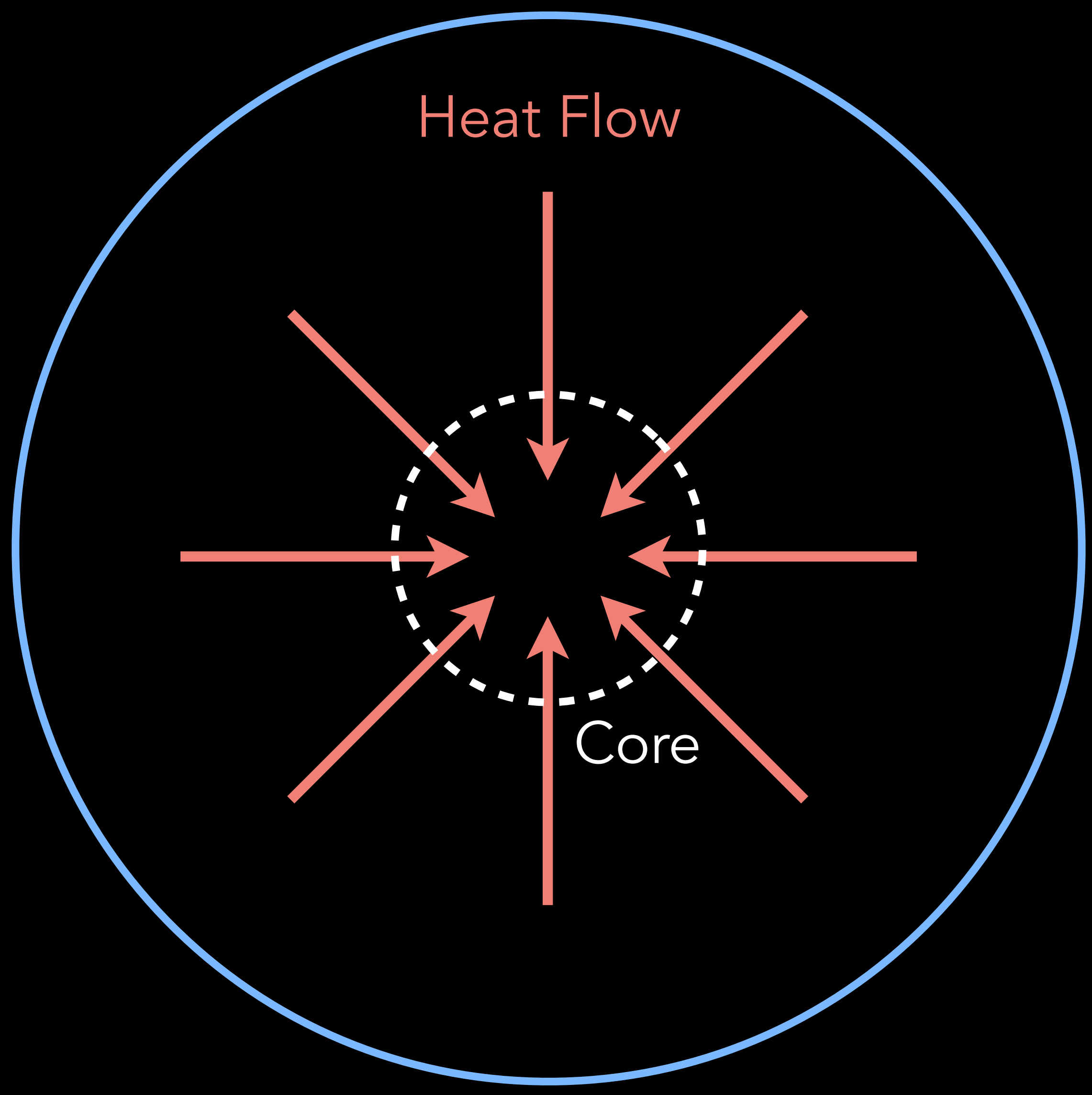
$$\frac{d\sigma}{d\theta} = \frac{\sigma_0 \sin\theta}{2\left[1 + \frac{v^2}{\omega^2}\sin^2\frac{\theta}{2}\right]^2}$$

Two free parameters

$$\sigma_0 \equiv 4\pi\alpha_D^2 m_\chi^2/m_\phi^4$$
$$\omega \equiv m_\phi/m_\chi$$

see Tulin and Yu [1705.02358] for review

Heat Transfer in an SIDM Galaxy



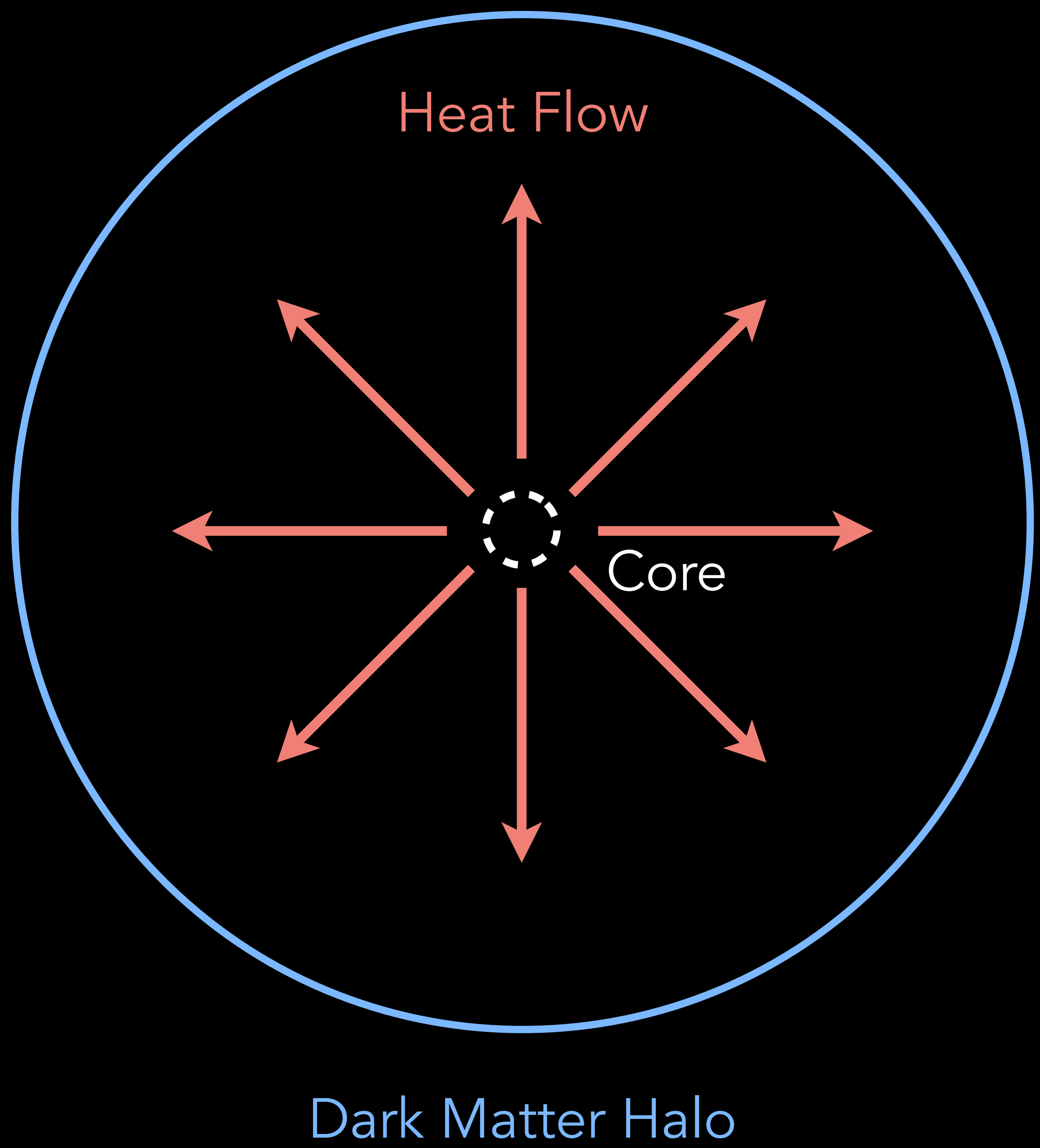
Stage 1: Core Formation

Self interactions transfer heat *inwards*

→ Formation of isothermal core

Vogelsberger et al. [1201.5892]; Zavala et al. [1211.6426]; Robles et al. [1903.01469]; Zavala et al. [1904.09998]

Heat Transfer in an SIDM Galaxy



Stage 1: Core Formation

Self interactions transfer heat *inwards*

→ Formation of isothermal core

Stage 2: Core Collapse

Self interactions transfer heat *outwards*

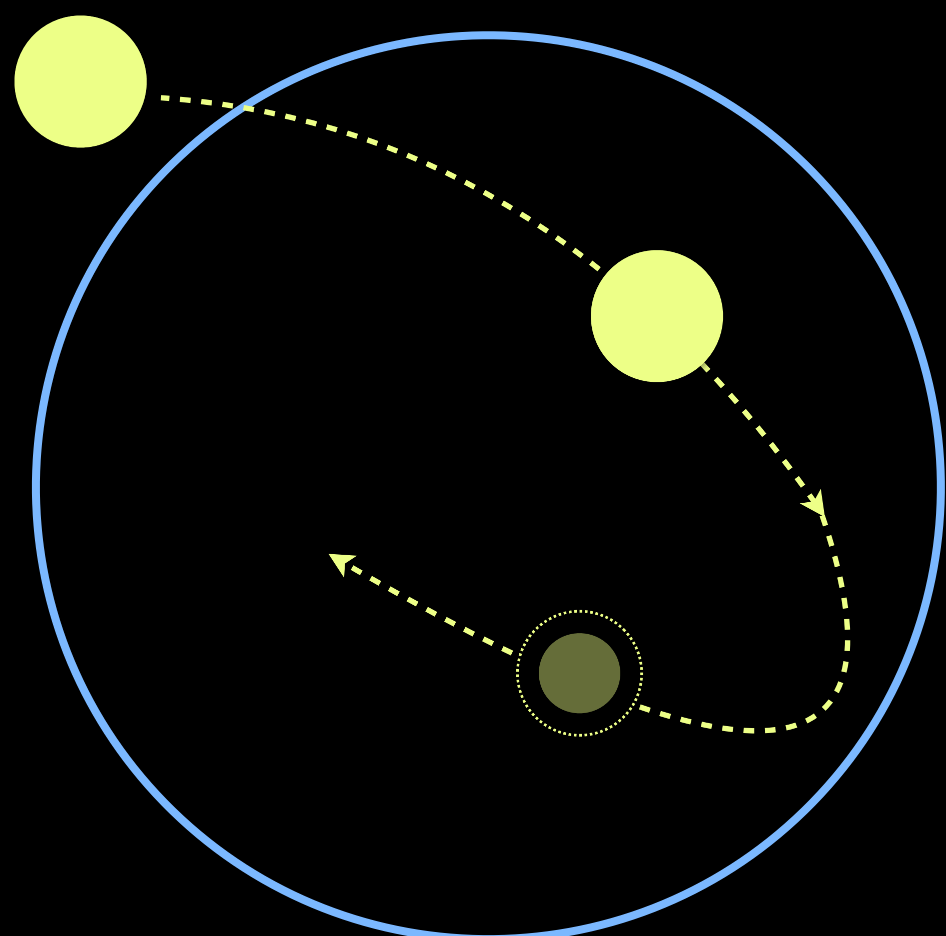
→ Core heats up and shrinks
→ Tidal stripping reduces collapse time

Balberg et al. [astro-ph/0110561]; Koda and Shapiro [1101.3097]; Elbert et al. [1412.1477];
Essig et al. [1809.01144]; Nishikawa et al. [1901.0049]; Kahlhoefer et al. [1904.10539]; Turner et al. [2010.02924]

Orbital Evolution

SIDM can affect orbital evolution of dwarf galaxies

O. Slone, F. Jiang, **ML**, M. Kaplinghat [2108.03243]



Tidal Stripping

Mass-loss more pronounced for cored dwarf galaxies

Ram-Pressure Evaporation

Additional mass loss from scattering between dark matter in dwarf and host

Dooley et al. [1603.08919]; Kummer et al. [1706.04794]; Nadler et al. [2001.08754]; Correa [2007.02958]

Where does dark matter physics play a key role in galactic evolution?

- Minimum halo mass
- Internal density distribution of host and satellite
- Satellite mass loss during orbit
  - Tidal disruption
  - Ram-pressure evaporation
- Drag forces felt by satellite during orbit
  - Dynamical friction
  - Ram-pressure deceleration

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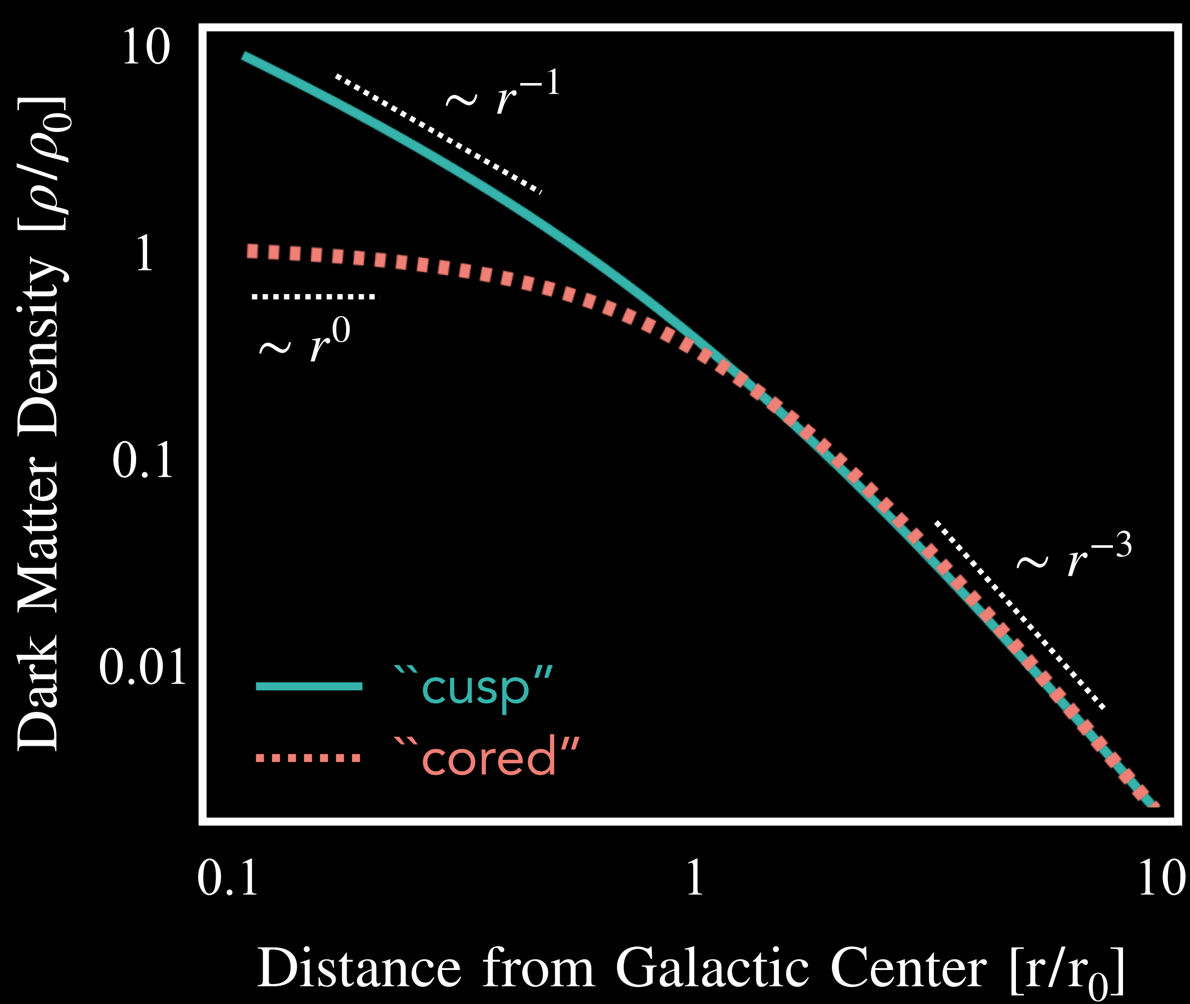
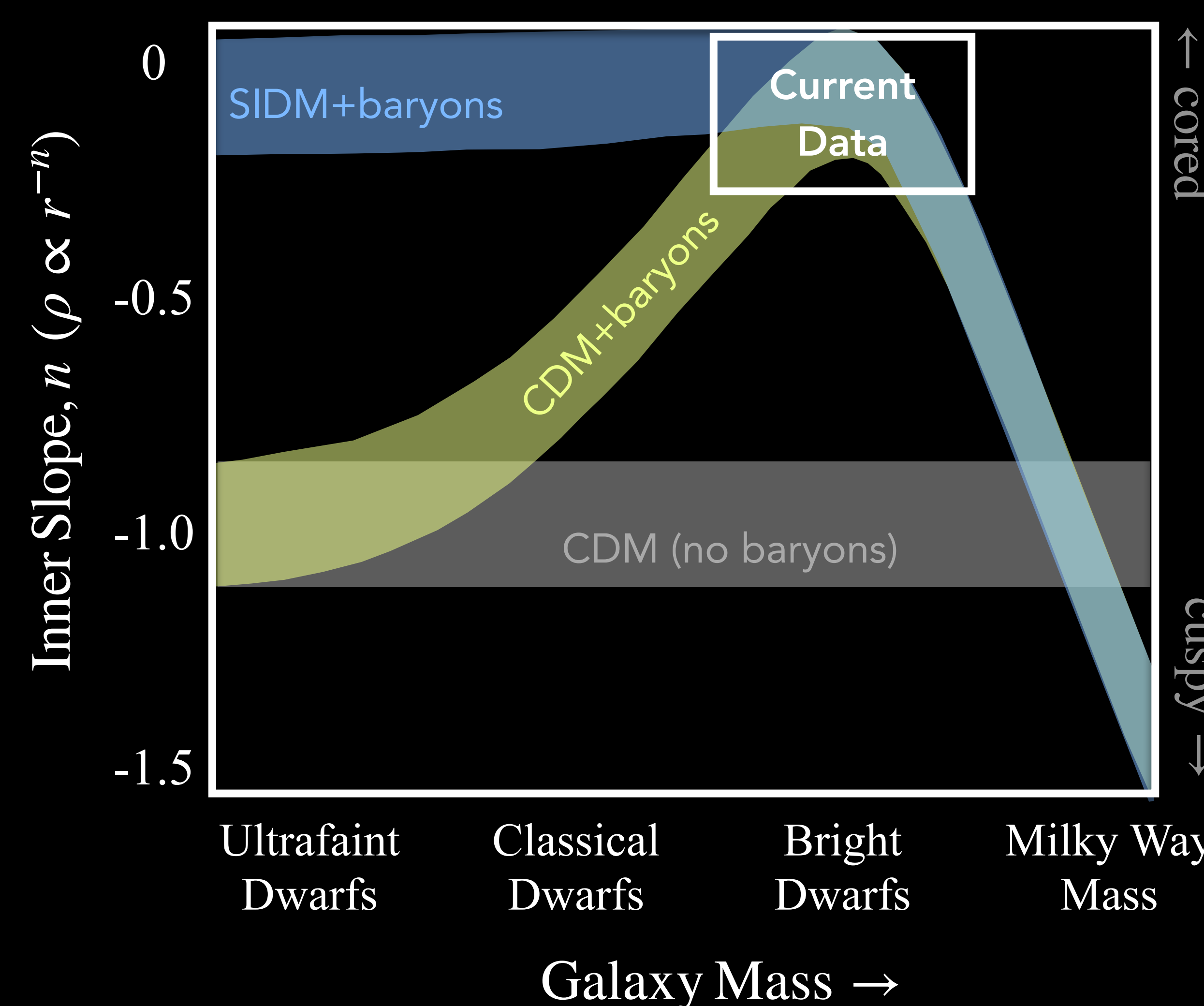
Internal Halo Properties

Dark matter self interactions can transfer heat throughout halo, redistributing the matter distribution





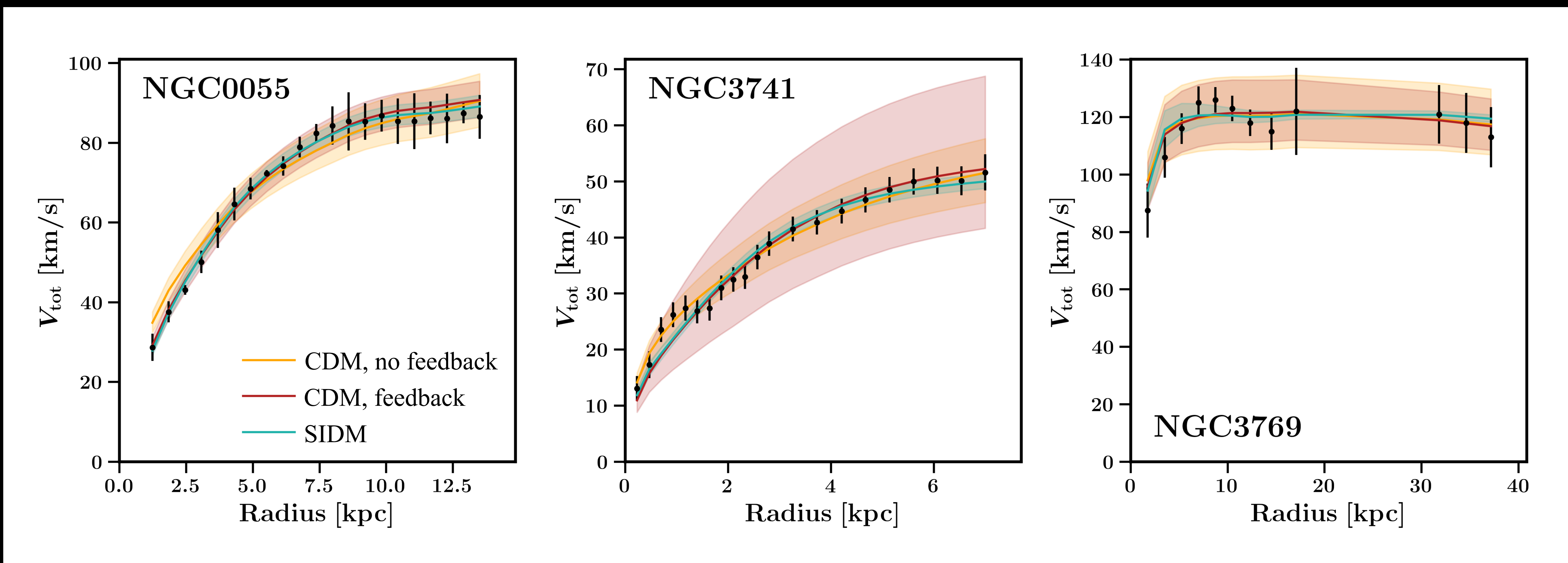
Aidan Zentner

Siddharth Dandavate

Oren Slone

SIDM and Field Galaxies

Rotation curves of 90 SPARC galaxies show no strong statistical preference for SIDM vs. feedback-affected CDM models

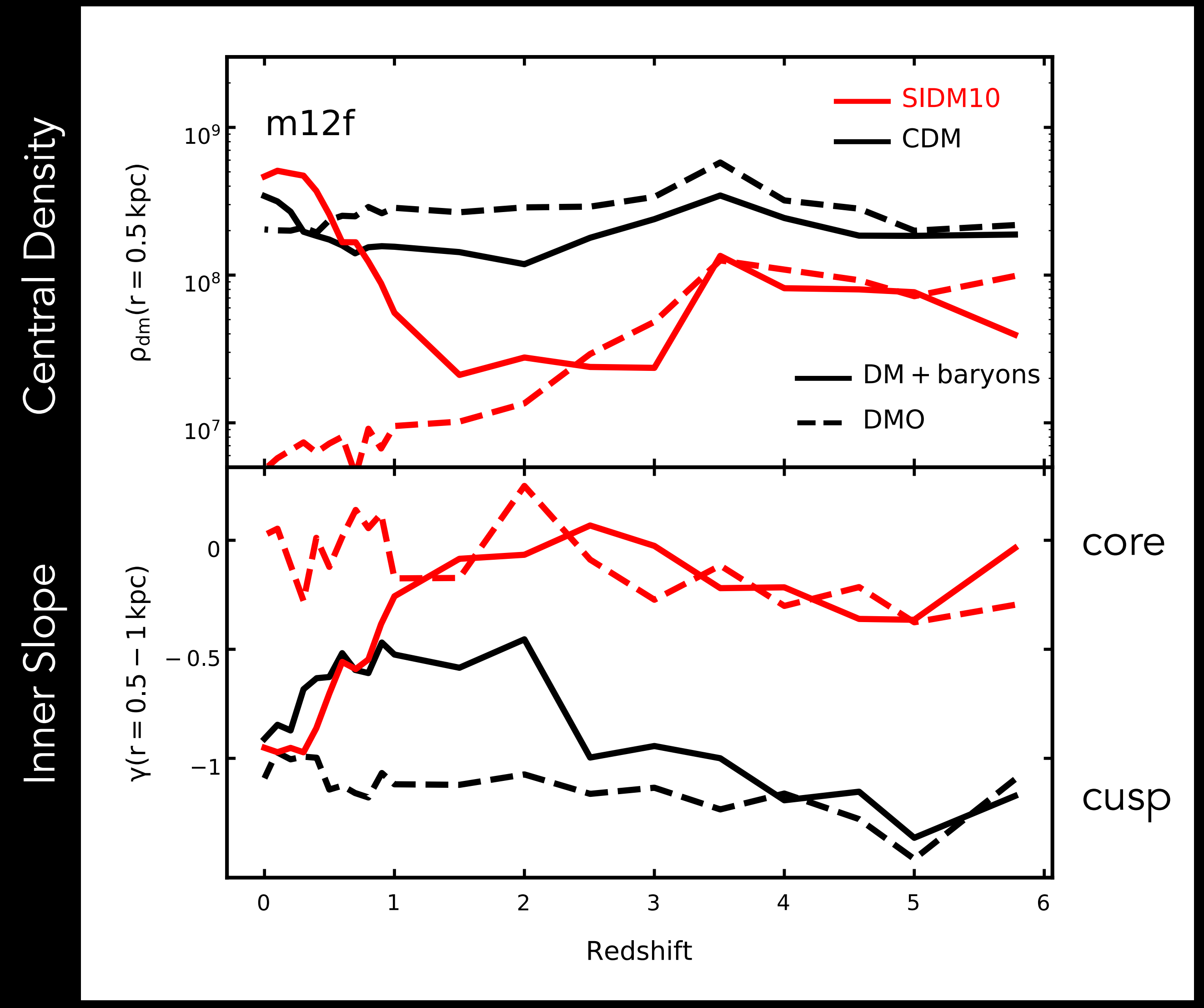


Zentner, Dandavate, Slone, and **ML** [2202.00012]

See also: Katz et al. (2016), Li et al. (2019), Ren et al. (2019), Kaplinghat et al. (2020), Li et al. (2020)

SIDM + Baryonic Feedback

Baryonic feedback effects are not as important in SIDM halos

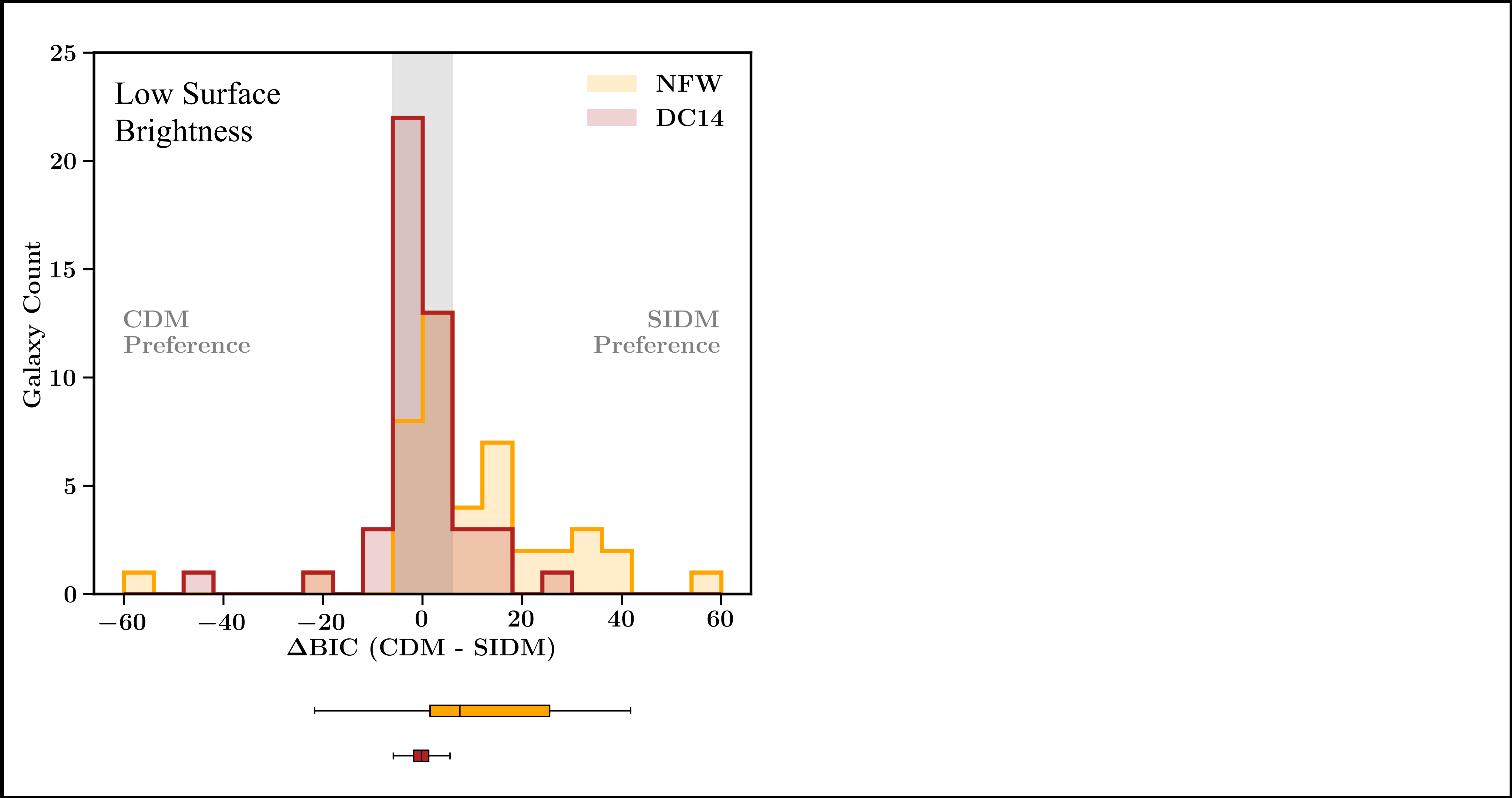


Sameie et al. [2102.12480]

SIDM and Field Galaxies

NFW model disfavored for low surface brightness galaxies

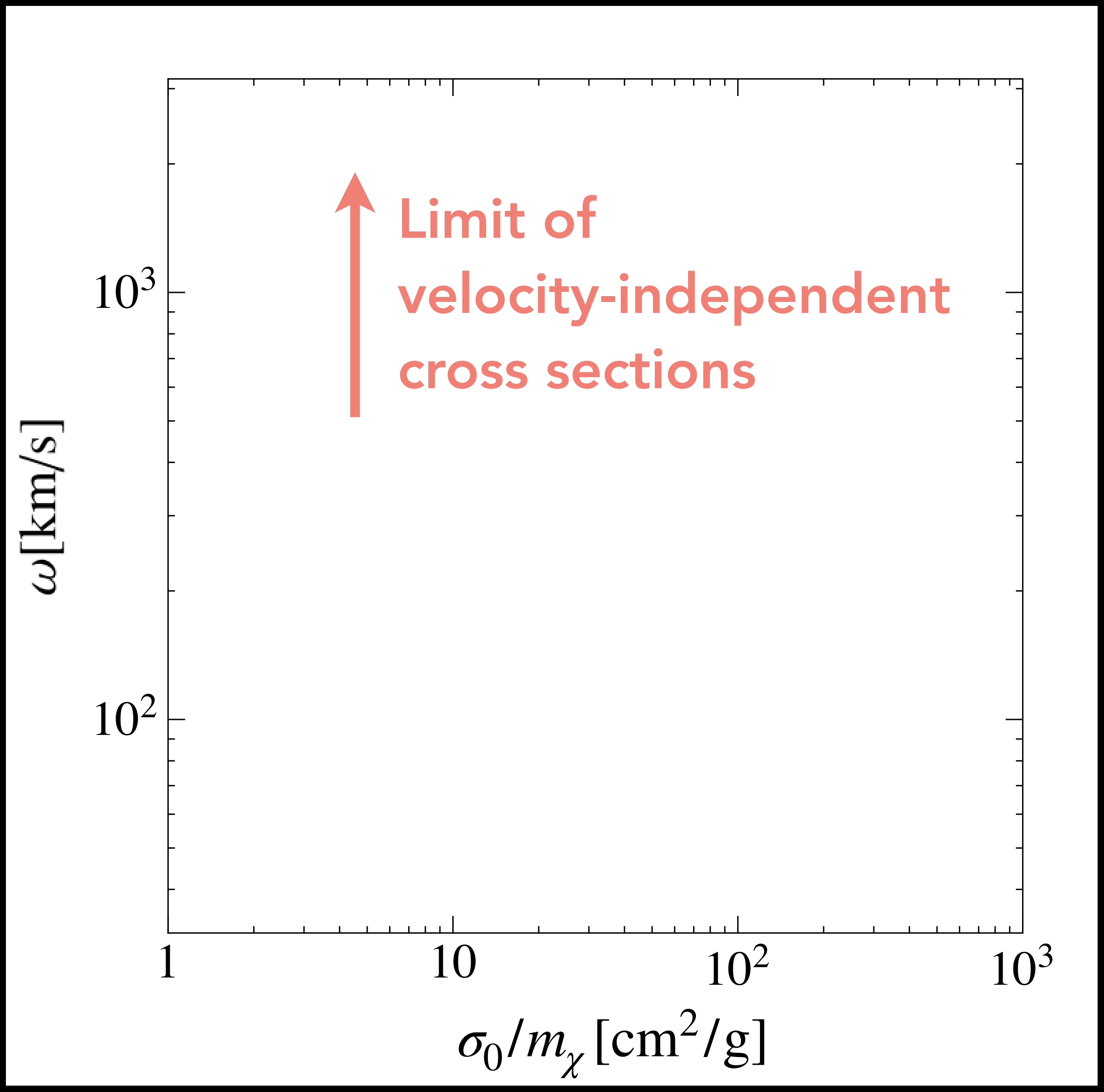
No strong preference for SIDM or feedback-affected CDM models



Zentner, Dandavate, Slone, and **ML** [2202.00012]

Summary of Current Constraints

Velocity Scale

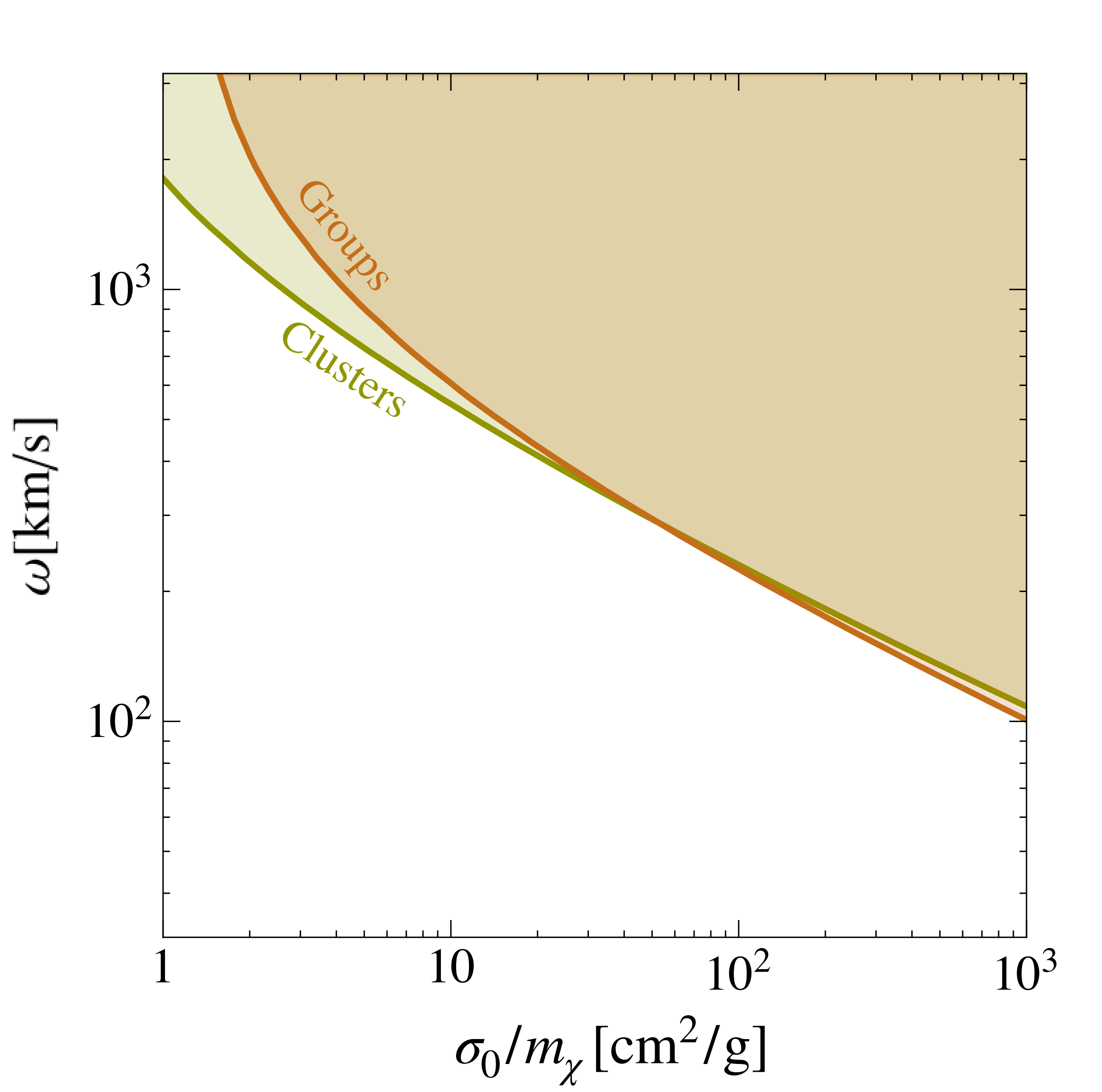


SIDM cross section

Self-scattering Cross Section

$$\frac{d\sigma}{d\theta} = \frac{\sigma_0 \sin\theta}{2\left[1 + \frac{v^2}{\omega^2}\sin^2\frac{\theta}{2}\right]^2}$$

Summary of Current Constraints



Velocity Scale

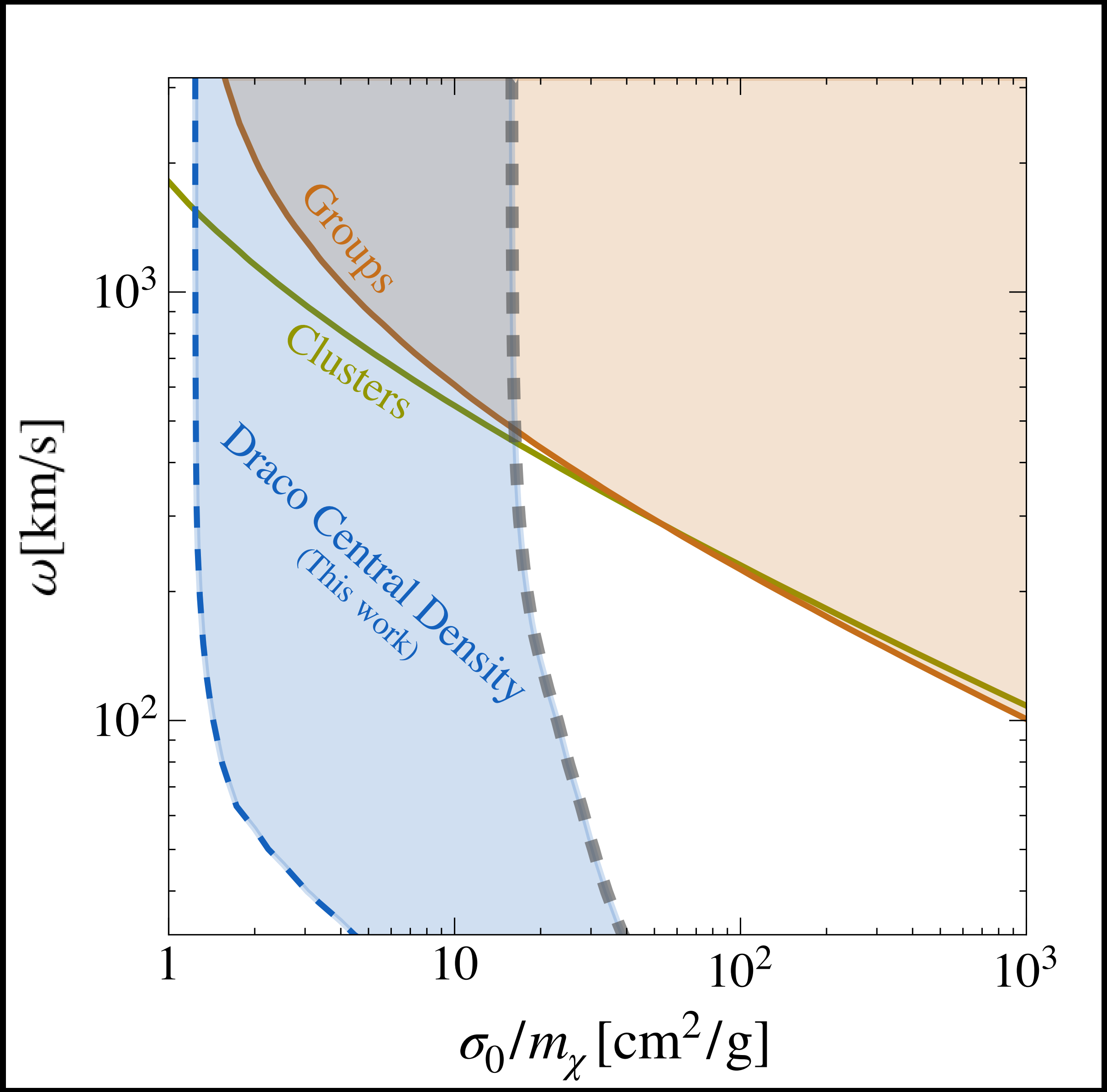
SIDM cross section

Non-observation of large cores in relaxed groups/clusters constrain self interactions at velocities ~ 10^3 km/s

Sagunski et al. [2006.12515]

Oren Slone

Summary of Current Constraints



Velocity Scale

SIDM cross section

Non-observation of large cores in relaxed groups/clusters constrain self interactions at velocities ~ 10^3 km/s

Sagunski et al. [2006.12515]

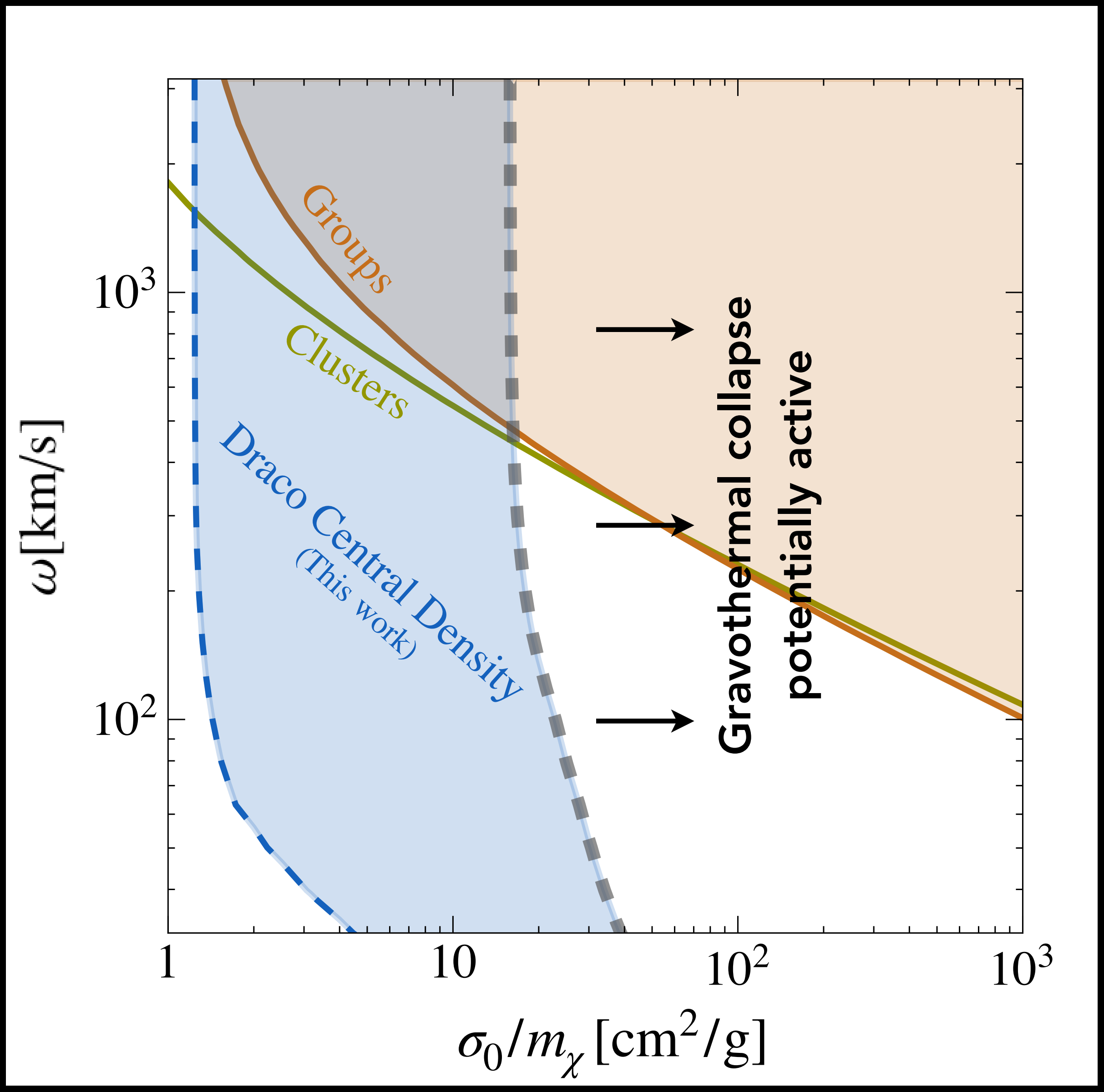
Concentrated central density in Draco dwarf inconsistent with a core

O. Slone, F. Jiang, **ML,** M. Kaplinghat [2108.03243]
Read et al. [1805.06934]

Oren
Slone

Summary of Current Constraints

Velocity Scale



SIDM cross section

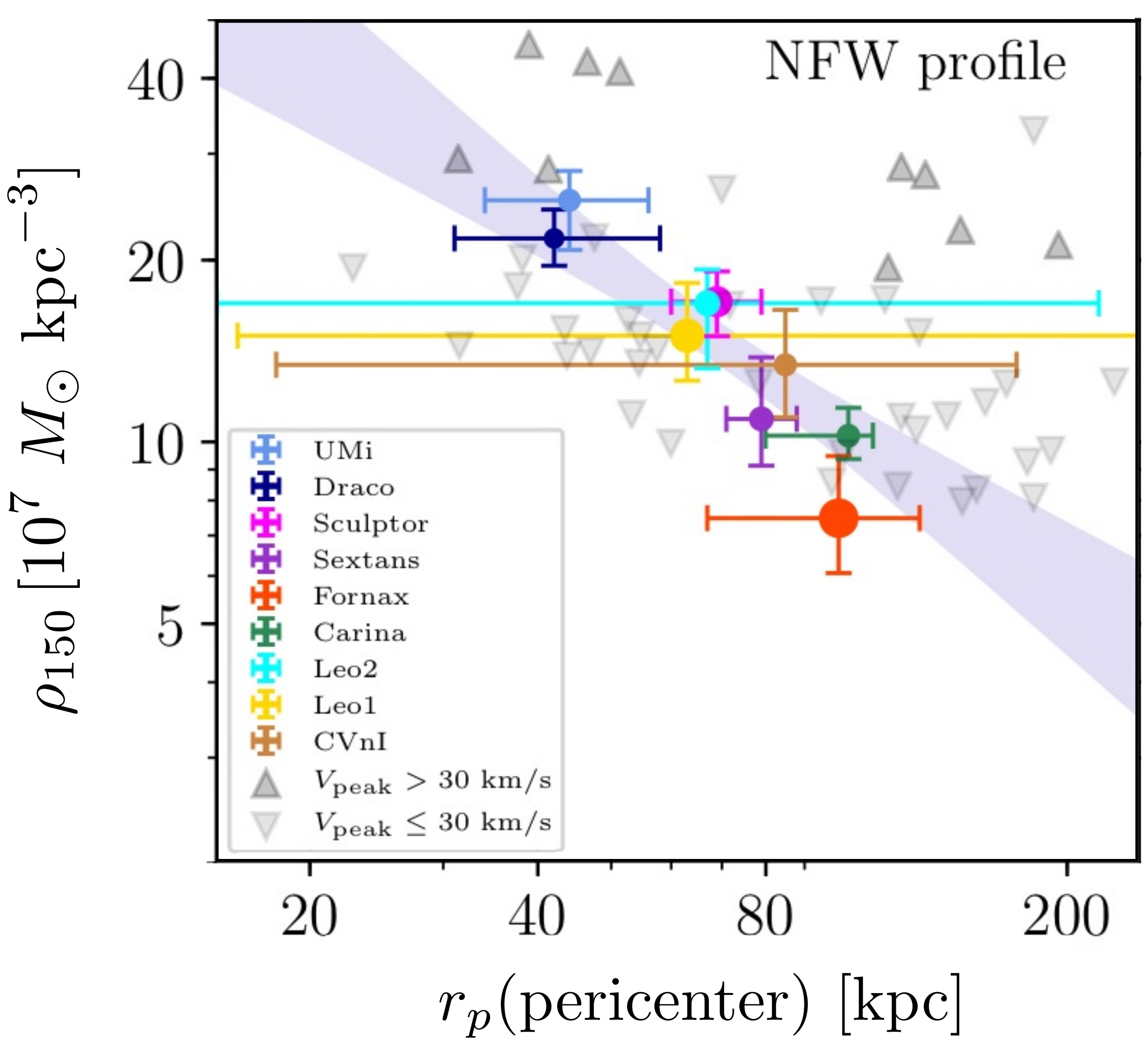
Observational Consequences:

SIDM models favor velocity-dependent interactions

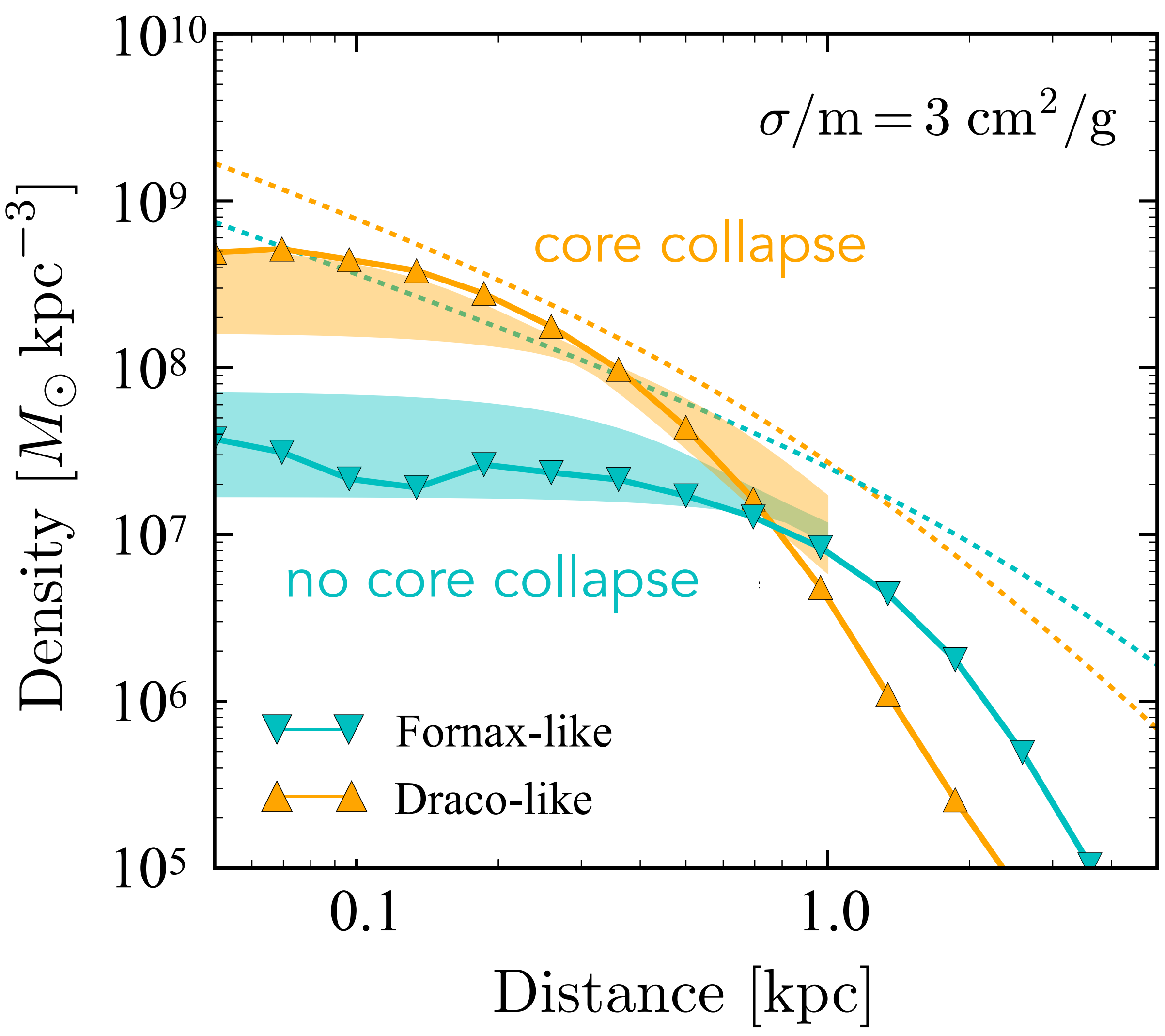
Gravothermal collapse must occur for densest dwarf galaxies

Gravothermal Core Collapse

Gravothermal collapse can lead to distinctive correlations between a dwarf's central density and its orbit

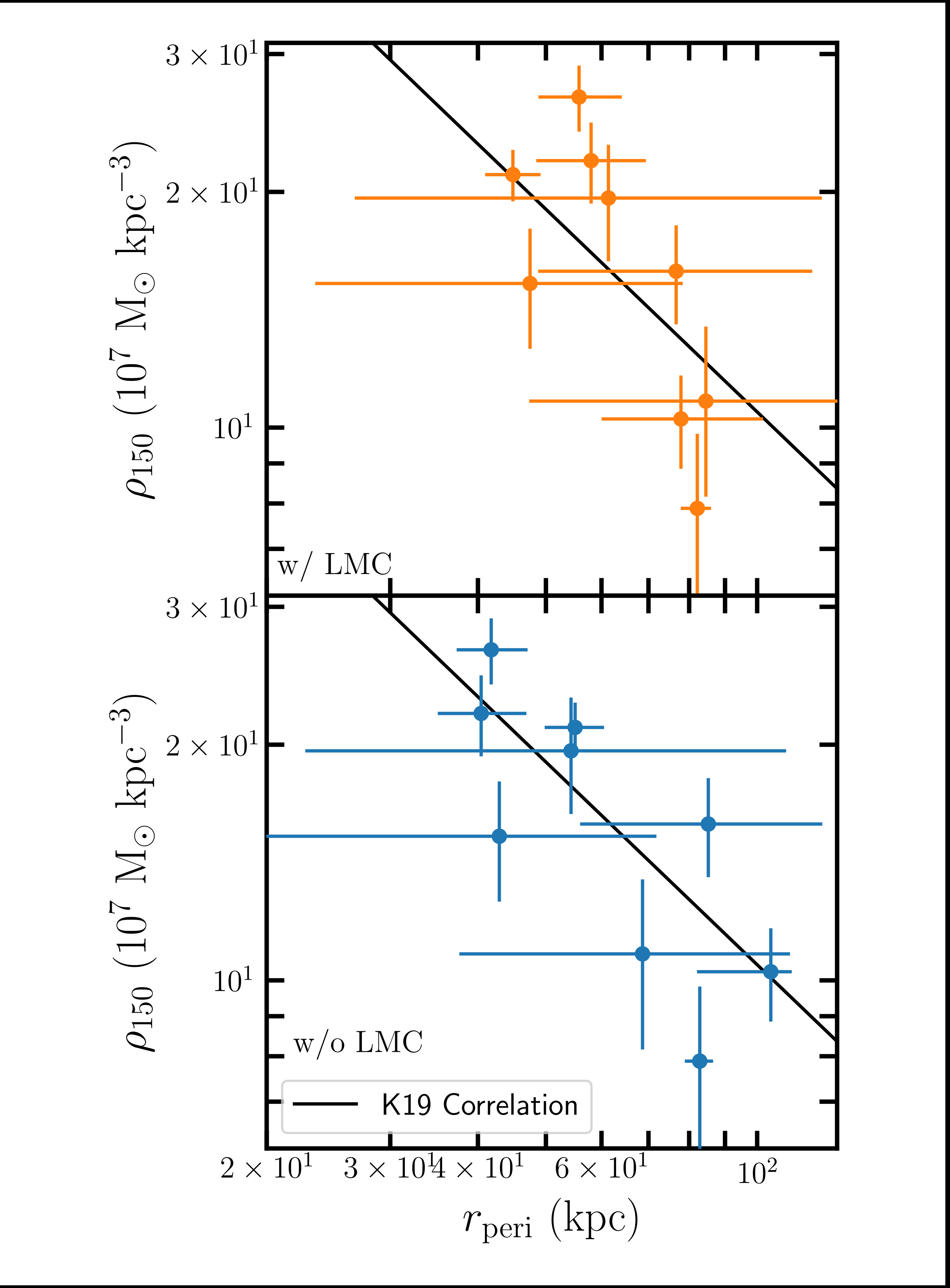


Kaplinghat et al. [1904.04939]



Sameie et al. [1904.07872]

Gravothermal Core Collapse



Pace et al. [2205.05699]

Future outlook…

Dwarf Galaxies and Streams

Astrometric, photometric, & spectroscopic surveys integral in mapping the Milky Way's dwarf galaxies and the stellar streams they leave behind

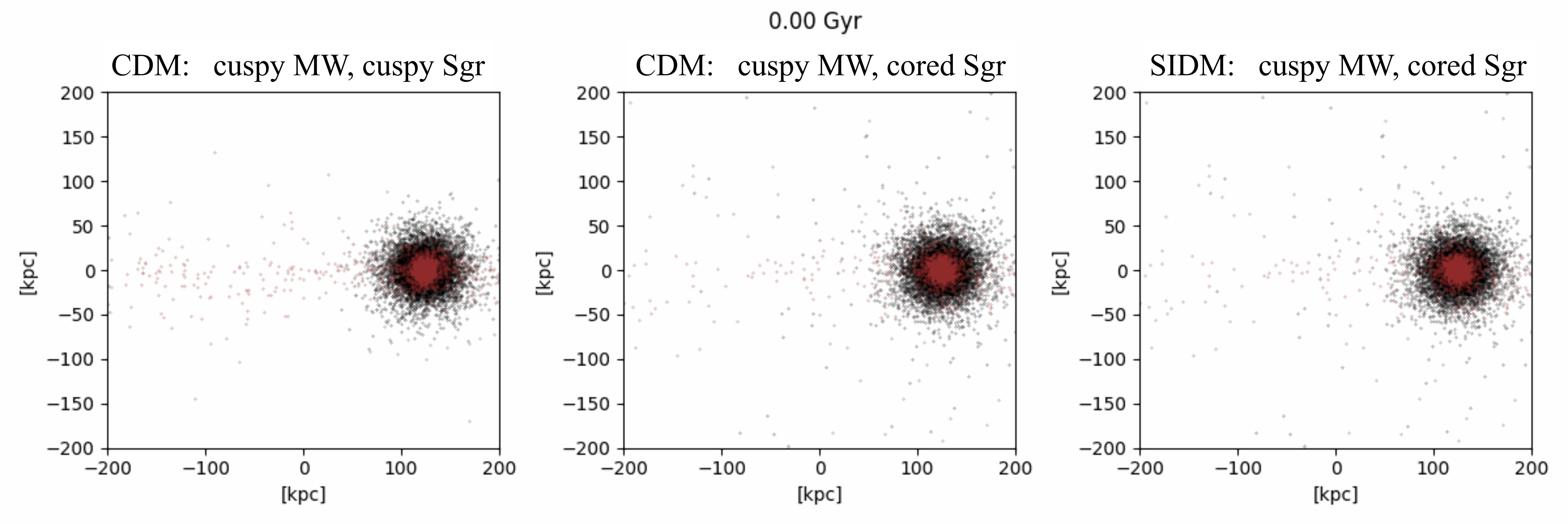
Credit: S. Payne-Wardenaar/K. Malhan, MPIA

- ● stellar stream
- ☆ globular cluster
- ❐ dwarf galaxy

SIDM and the Sgr Stream

PRELIMINARY

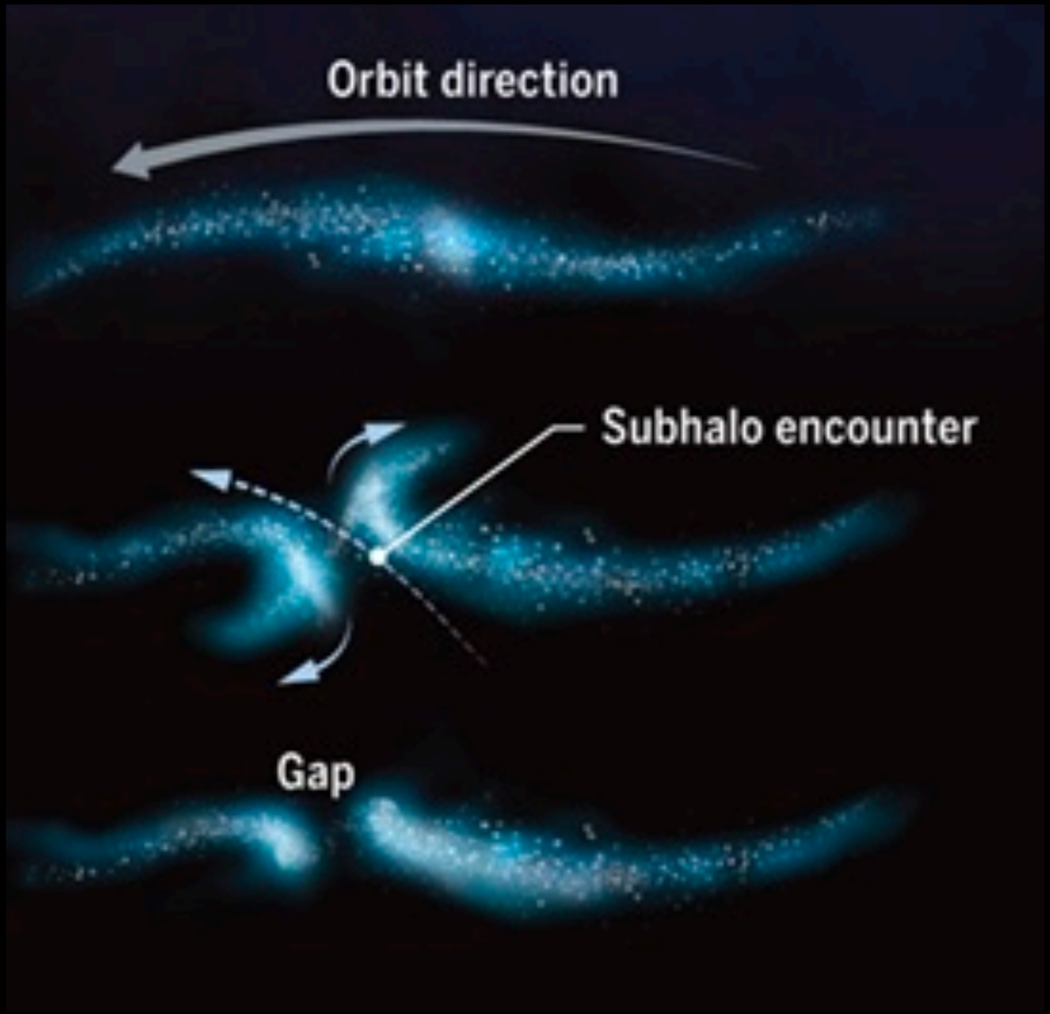
Hainje, Slone, Lisanti, and Erkal (in progress)



Black: dark matter
Red: stars

Tests of Small-Scale Structure

Dark matter subhalos in the Milky Way halo can perturb stellar streams



Credit: C. Bickel/SCIENCE

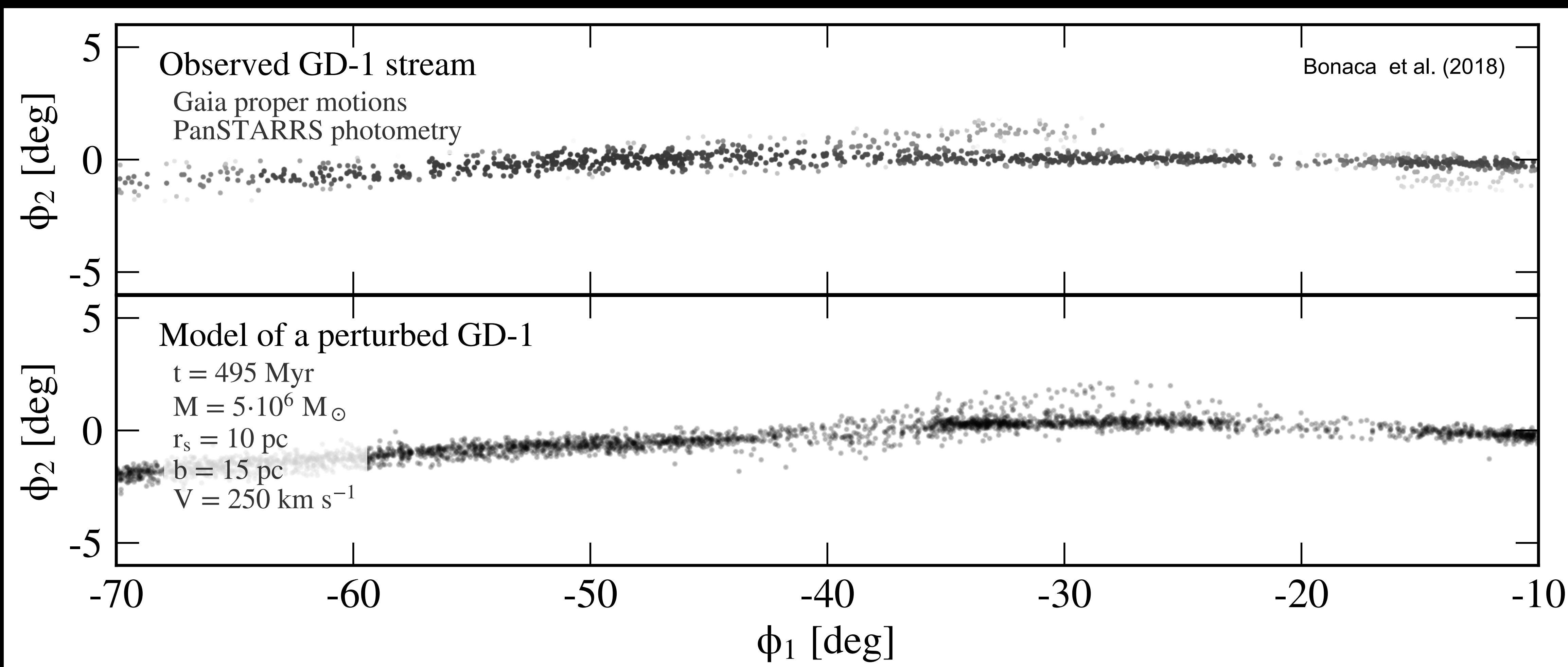
In some cases a subhalo can actually break the stream by flying through it

e.g., Ngan and Carlberg [1311.1710]; Erkal et al. [1606.04946]

The GD-1 Stream

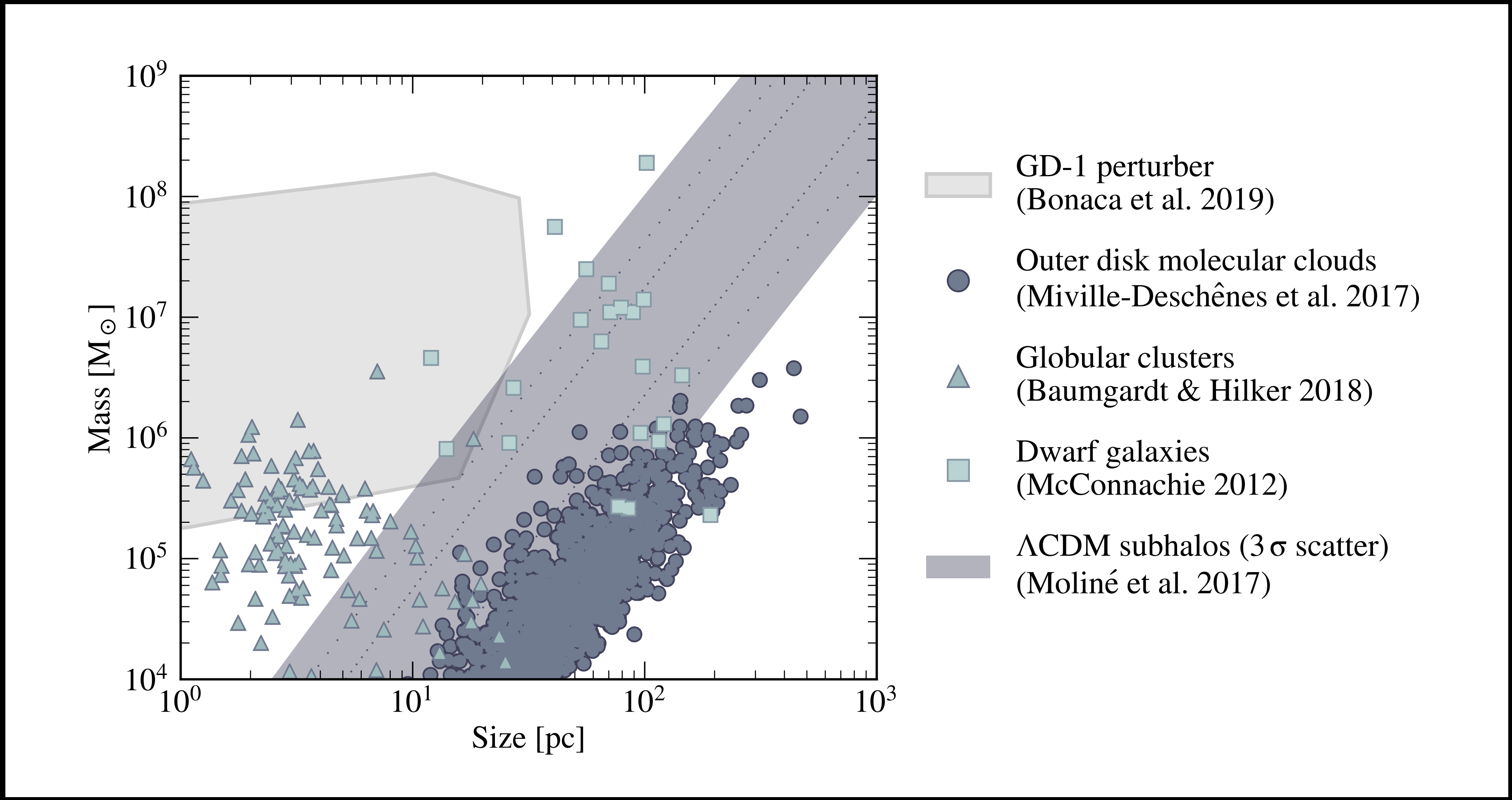
Do perturbations in GD-1 provide first evidence of a dark matter subhalo in Milky Way?

Price-Whelan & Bonaca [1805.00425]; Bonaca et al. [1811.03631]



The GD-1 Stream

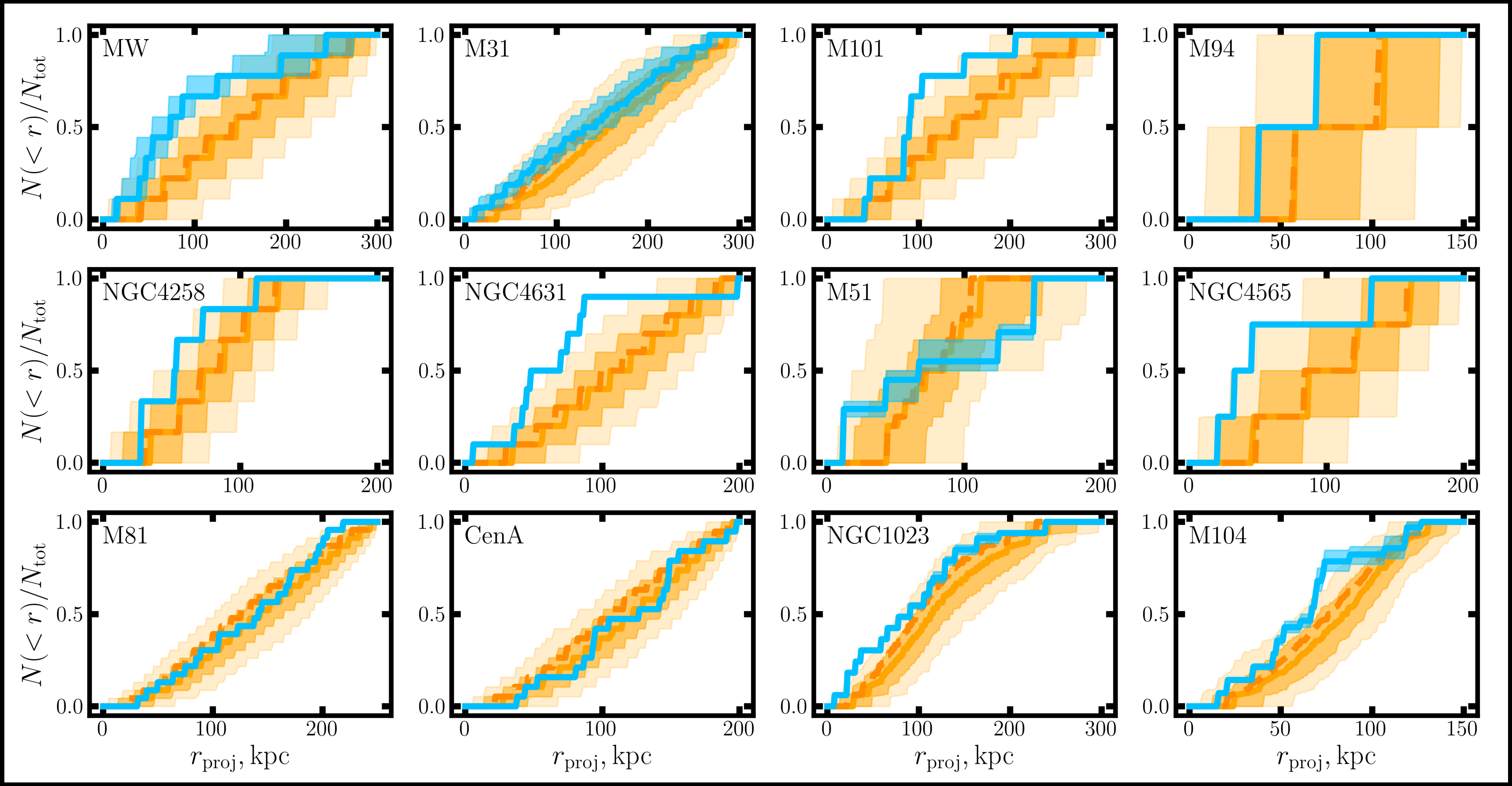
If a dark subhalo, the GD-1 perturber may be more concentrated than expected of CDM halos of similar mass



Bonaca et al. [1811.03631]

Dwarf Galaxies about MW-like Systems

Current and future observations are opening the possibility of studying the population statistics of dwarf galaxies around MW-like hosts

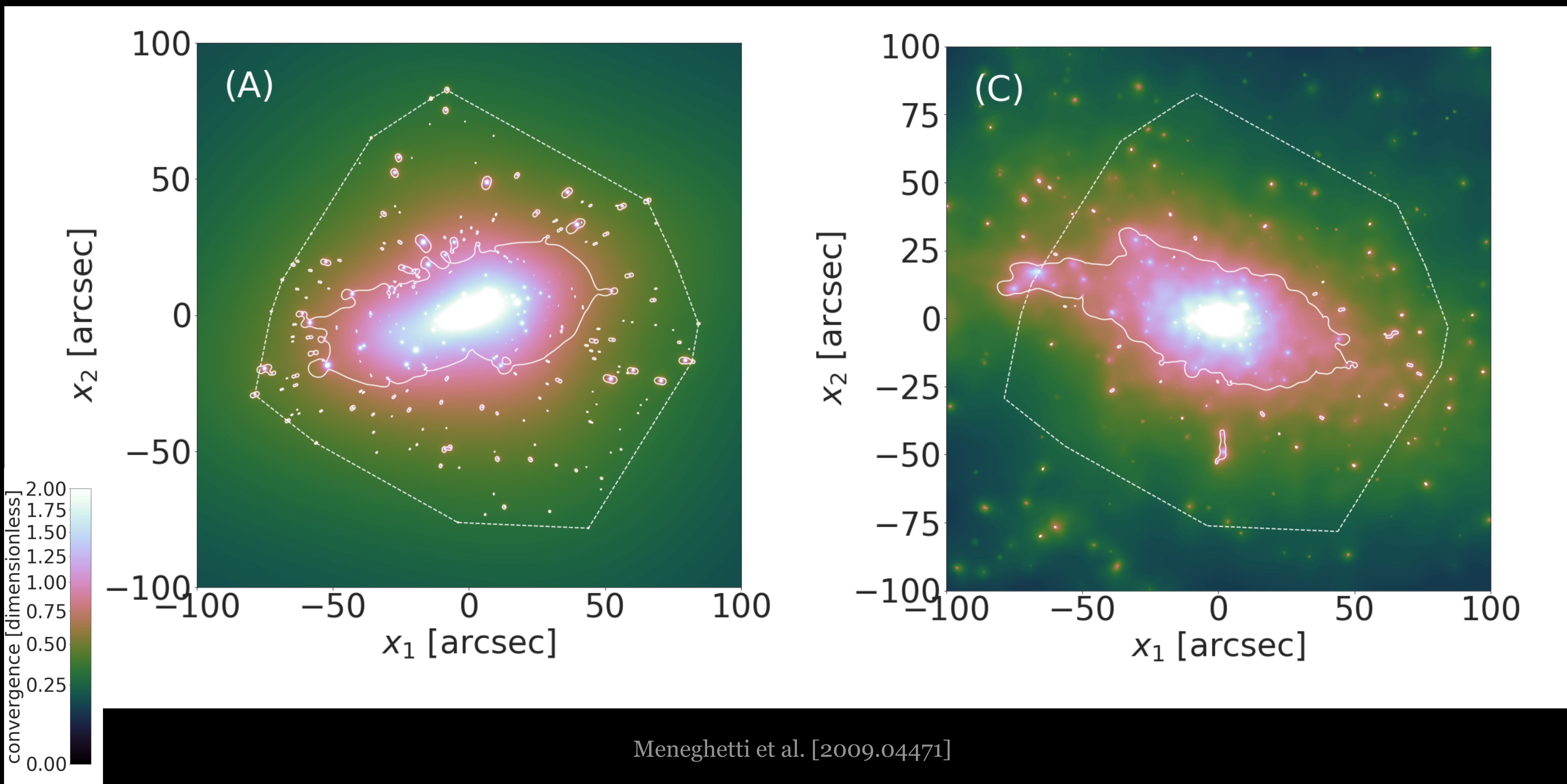


Carlsten et al. [2006.02444]

Gravitational Lenses in Clusters

Cluster substructures lens more efficiently than expected for CDM

Observed | **CDM Simulation**



Meneghetti et al. [2009.04471]

see Yang and Yu [2102.02375] for possible SIDM interpretation

Conclusions

Dark sector physics leads to rich phenomenology on galactic and sub-galactic scales

Self-interactions in dark sector directly impact galactic evolution in a variety of ways

Current and future astrophysical observations providing important tests of self-interacting dark matter