Galactic Probes of Dark-Sector Physics

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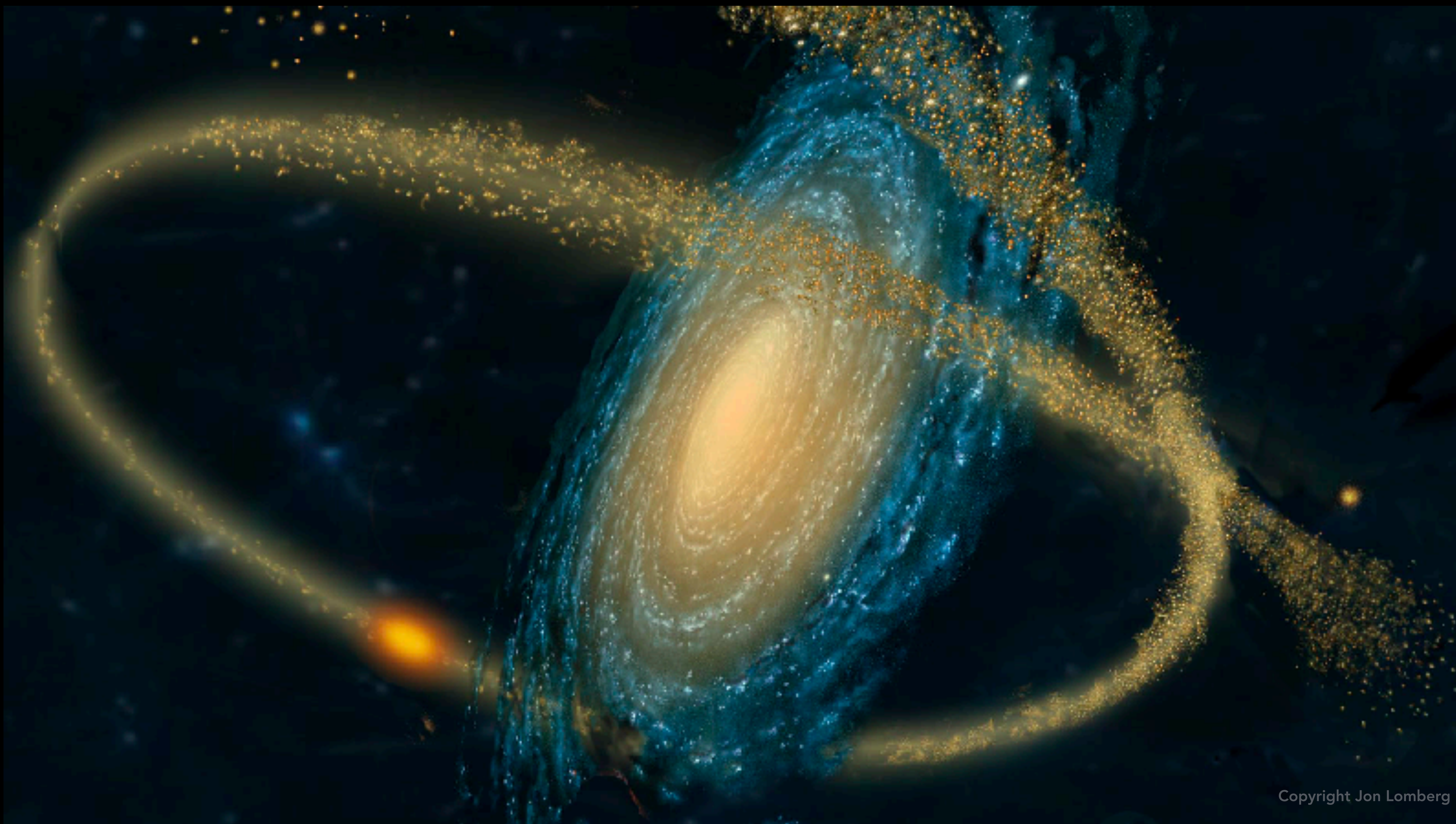
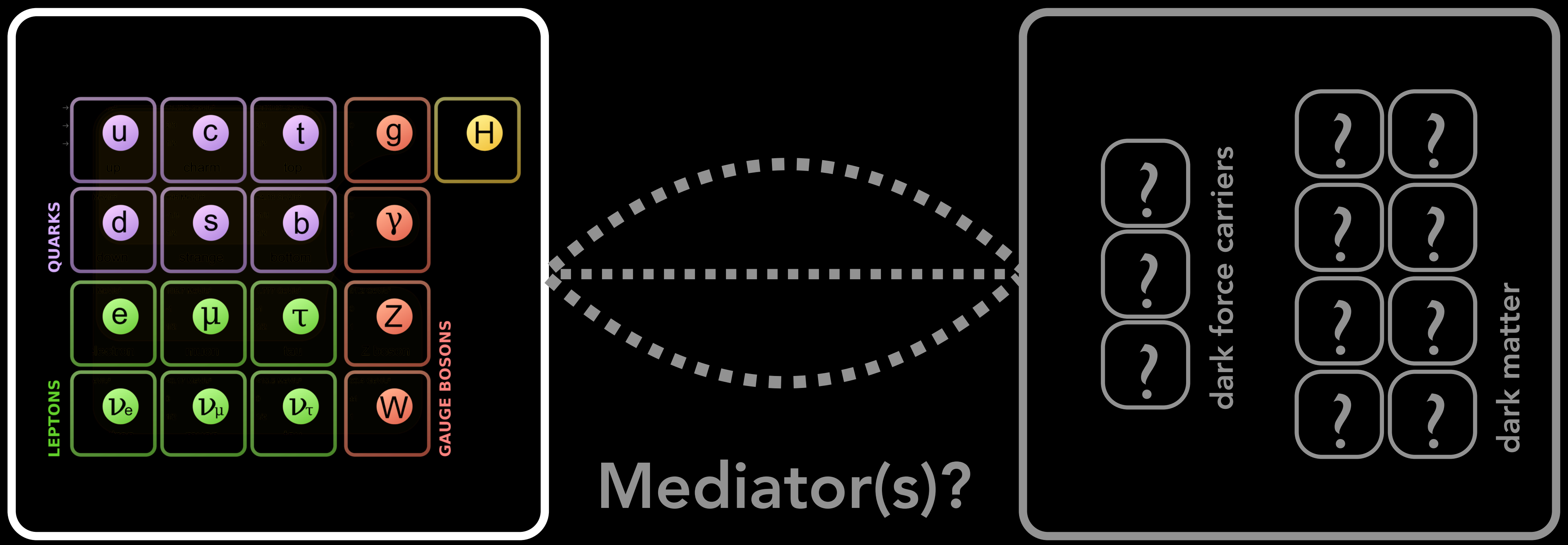
Princeton University



Theory of Dark Sectors



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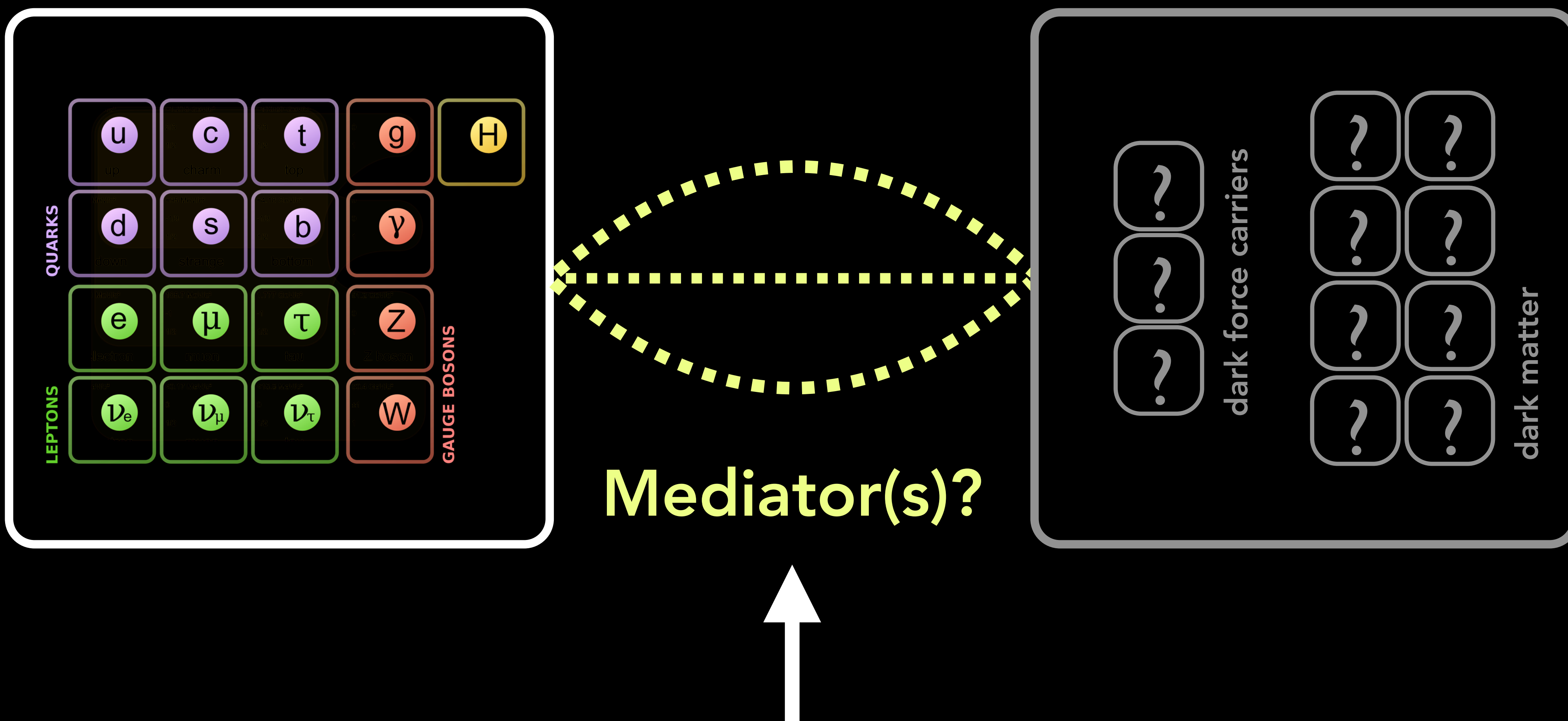


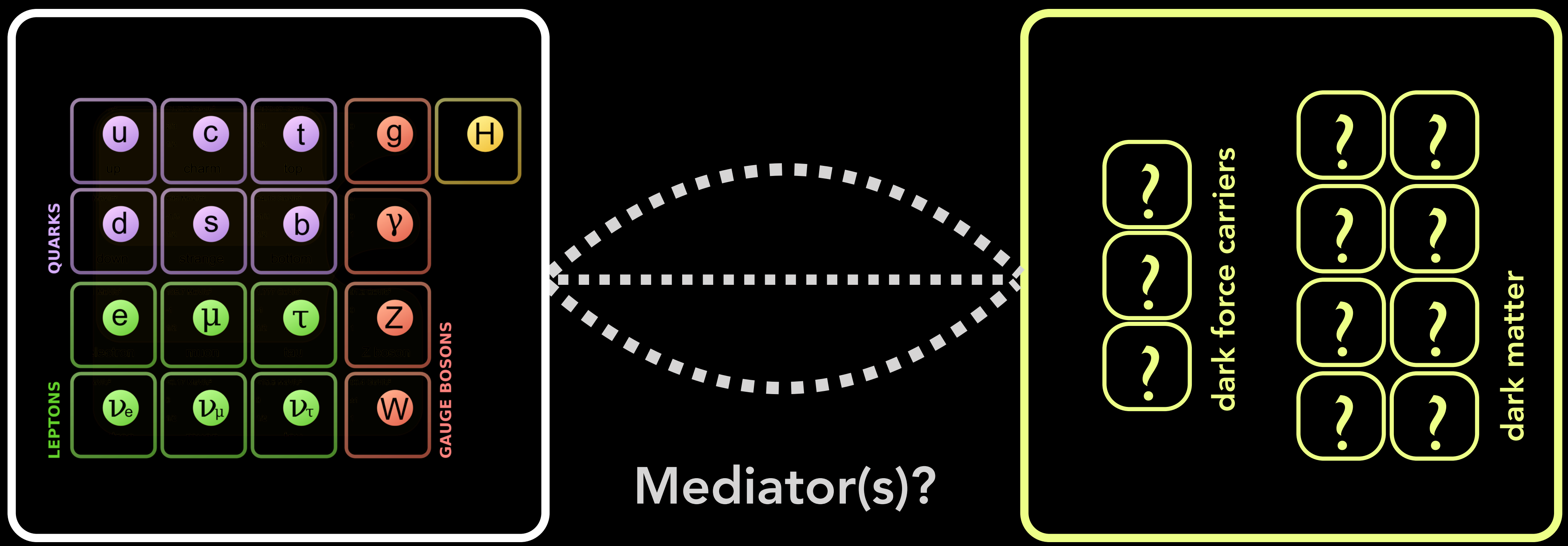
provide a ``portal"

Portals are restricted by Standard Model symmetries

Some Important Portals

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

Theory of Dark Sectors

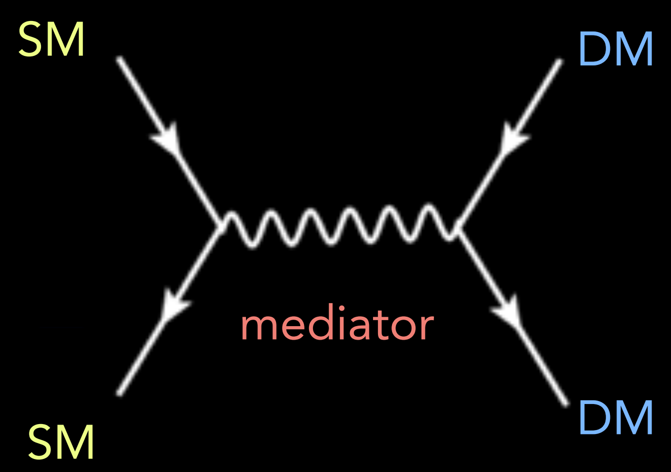


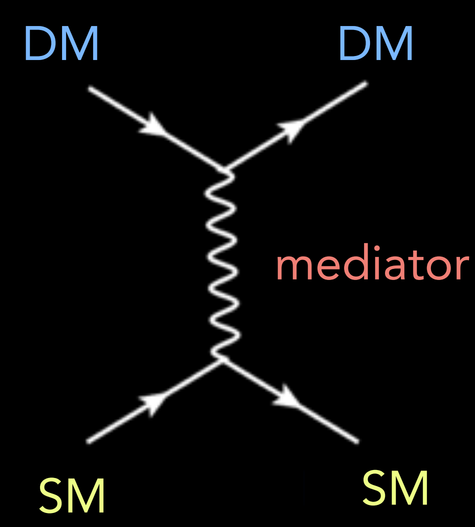
New dark forces? Multiple dark matter states?

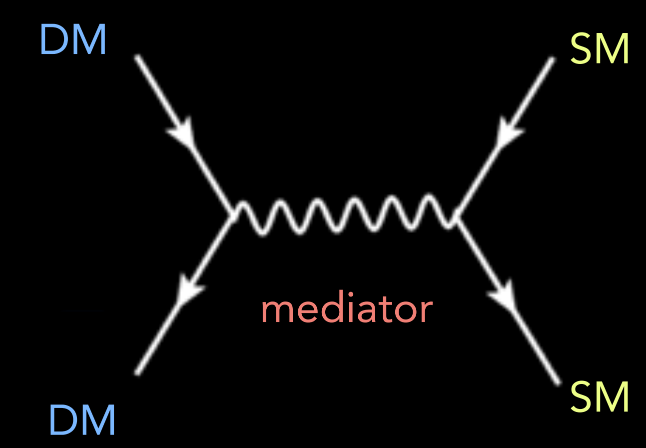
- affects dark matter production in early Universe
- leads to self interactions and/or dissipative interactions
- affects possible discovery channels

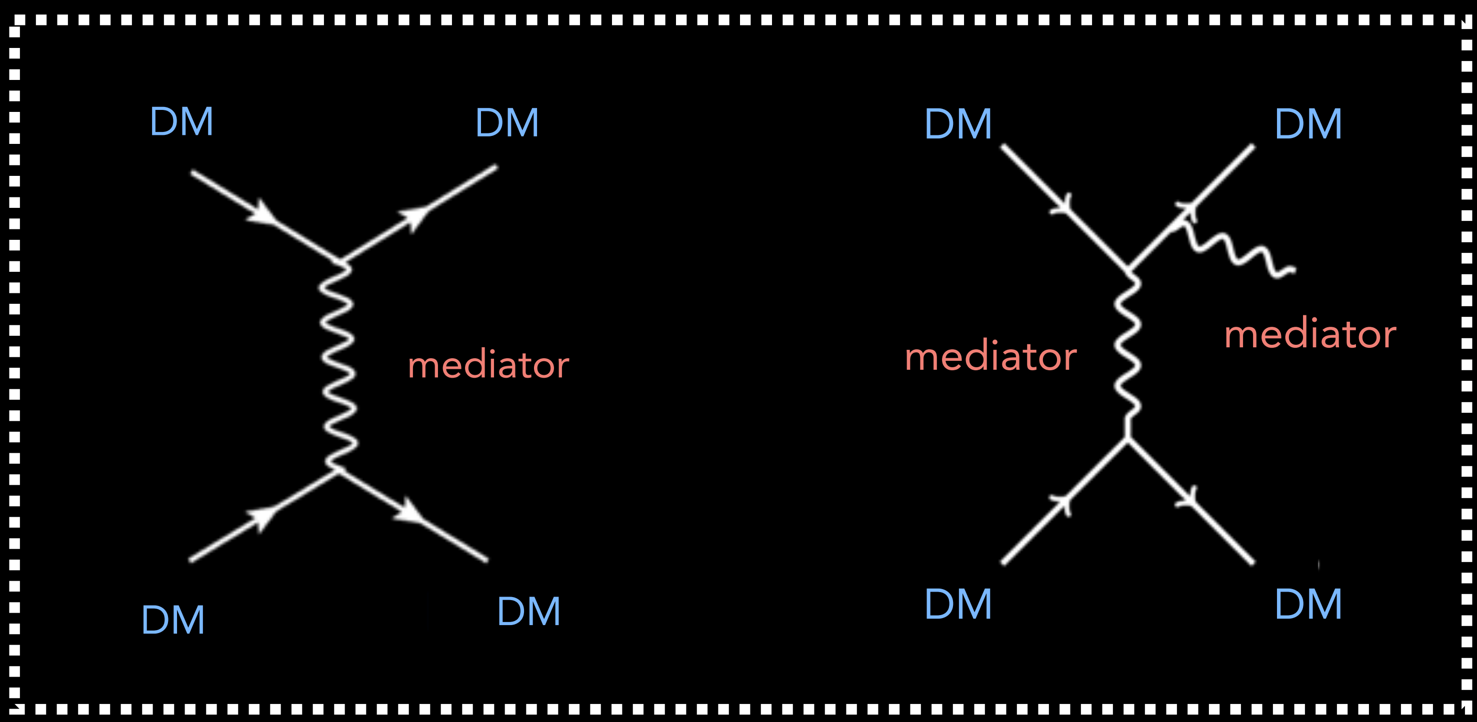
A Toy Model

Dark sectors can lead to a spectacular range of signals

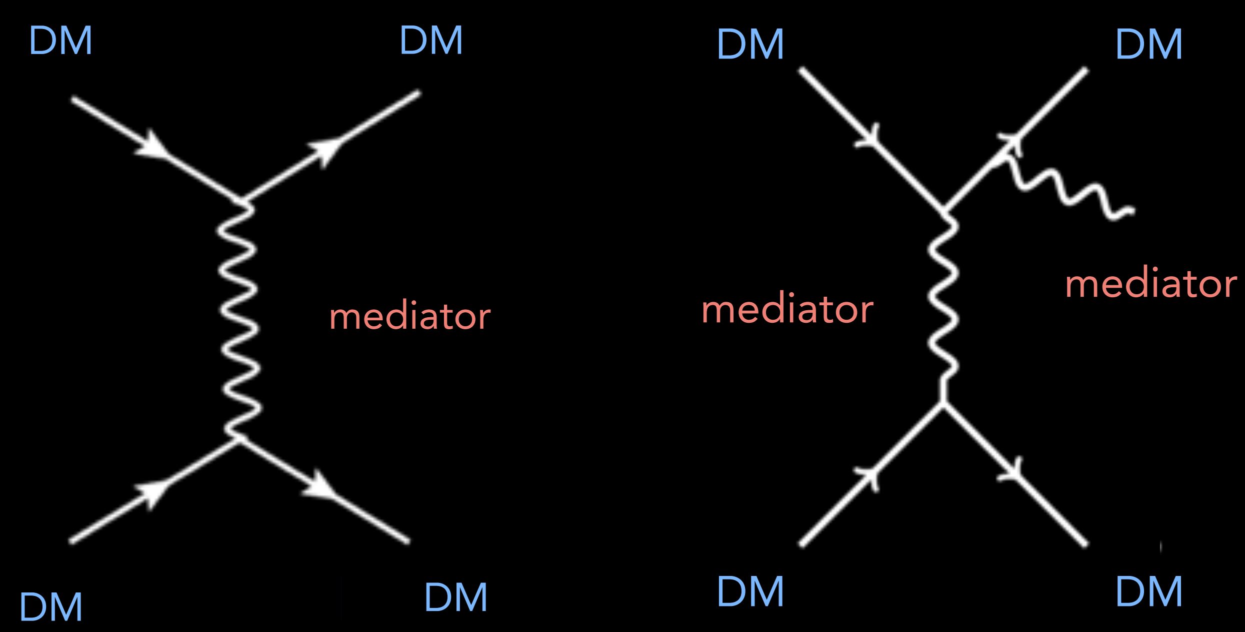








How do dark matter particles interact with each other?



Are self interactions allowed?

If so, are they elastic?

Do they dissipate energy?

Galactic observables play an integral role in answering this fundamental question about dark sectors

Self Interactions in a Galaxy

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

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

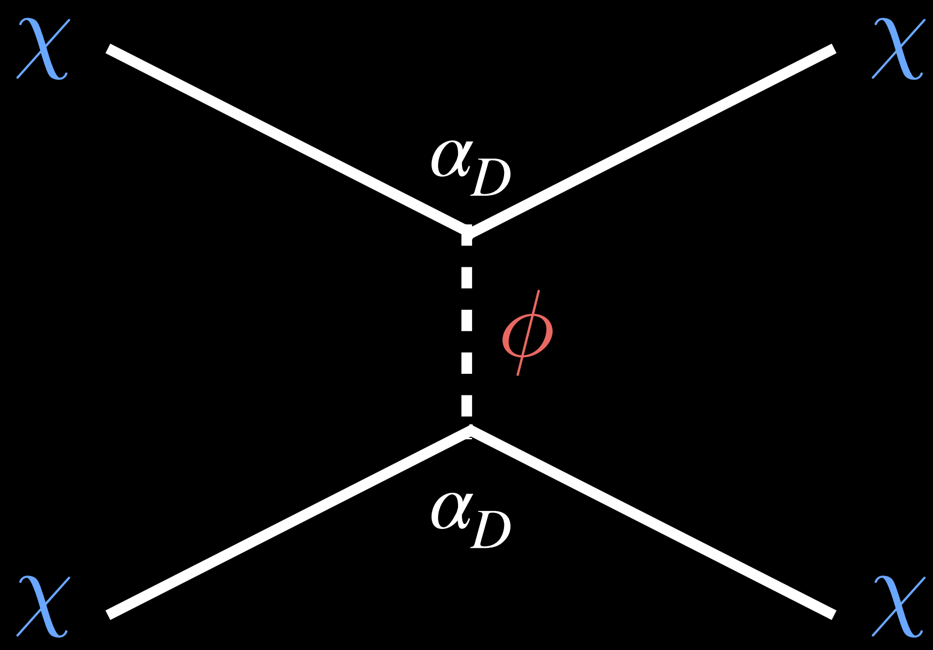
Spergel and Steinhardt [astro-ph/9909386]

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

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

Benchmark SIDM Model

Dark matter particles interact via a light mediator

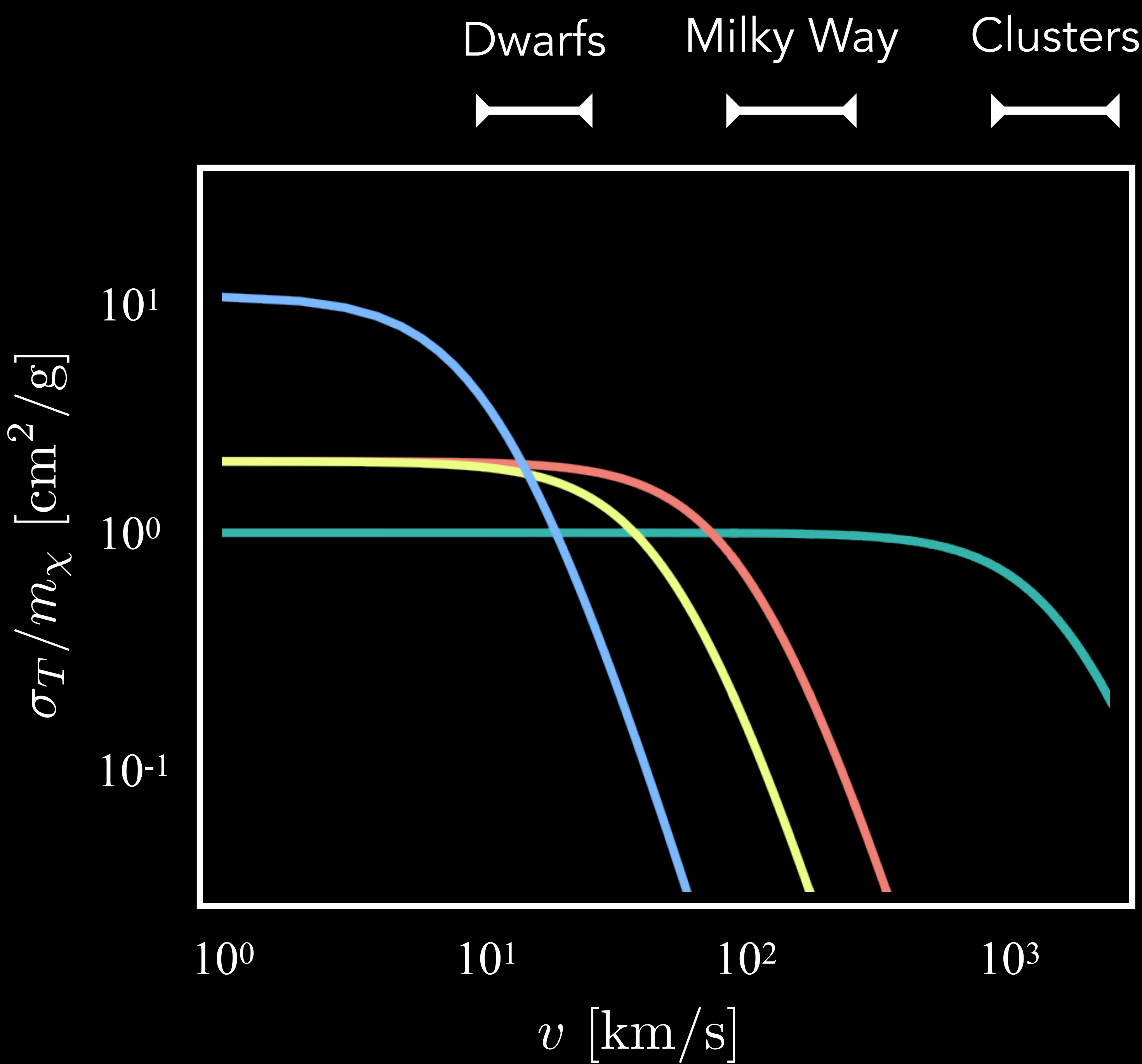


$$L_{\text{int}} = \begin{cases} g_D \, \bar{\chi} \gamma^\mu \chi \phi_\mu \\ g_D \, \bar{\chi} \chi \phi \end{cases}$$

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]

Benchmark SIDM Model



Anisotropic, velocity-dependent self scattering

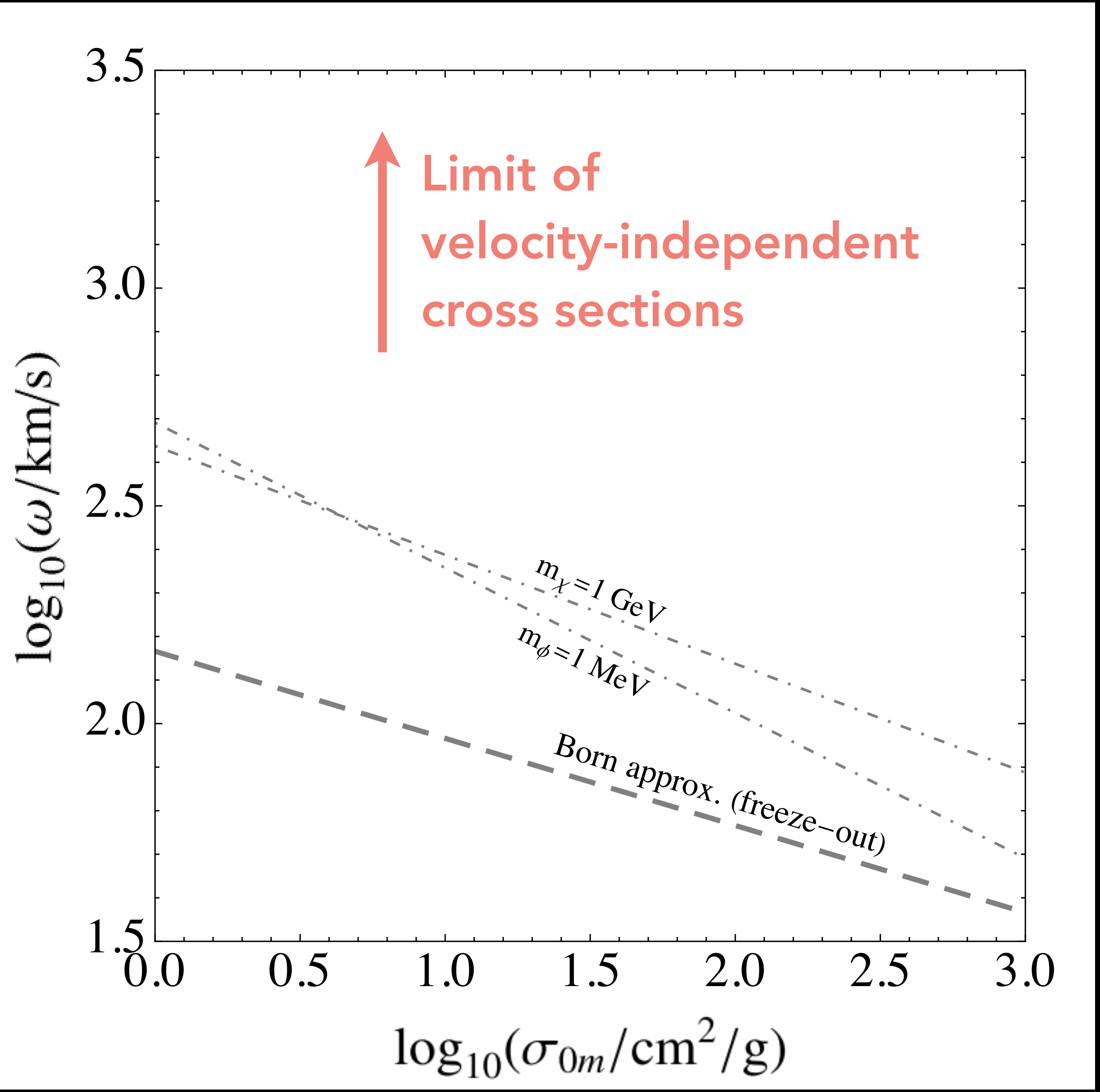
$$\frac{d\sigma}{d\theta} = \frac{\sigma_0 \sin\theta}{2\left[1 + \frac{v^2}{\omega^2}\sin^2\frac{\theta}{2}\right]^2}$$

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

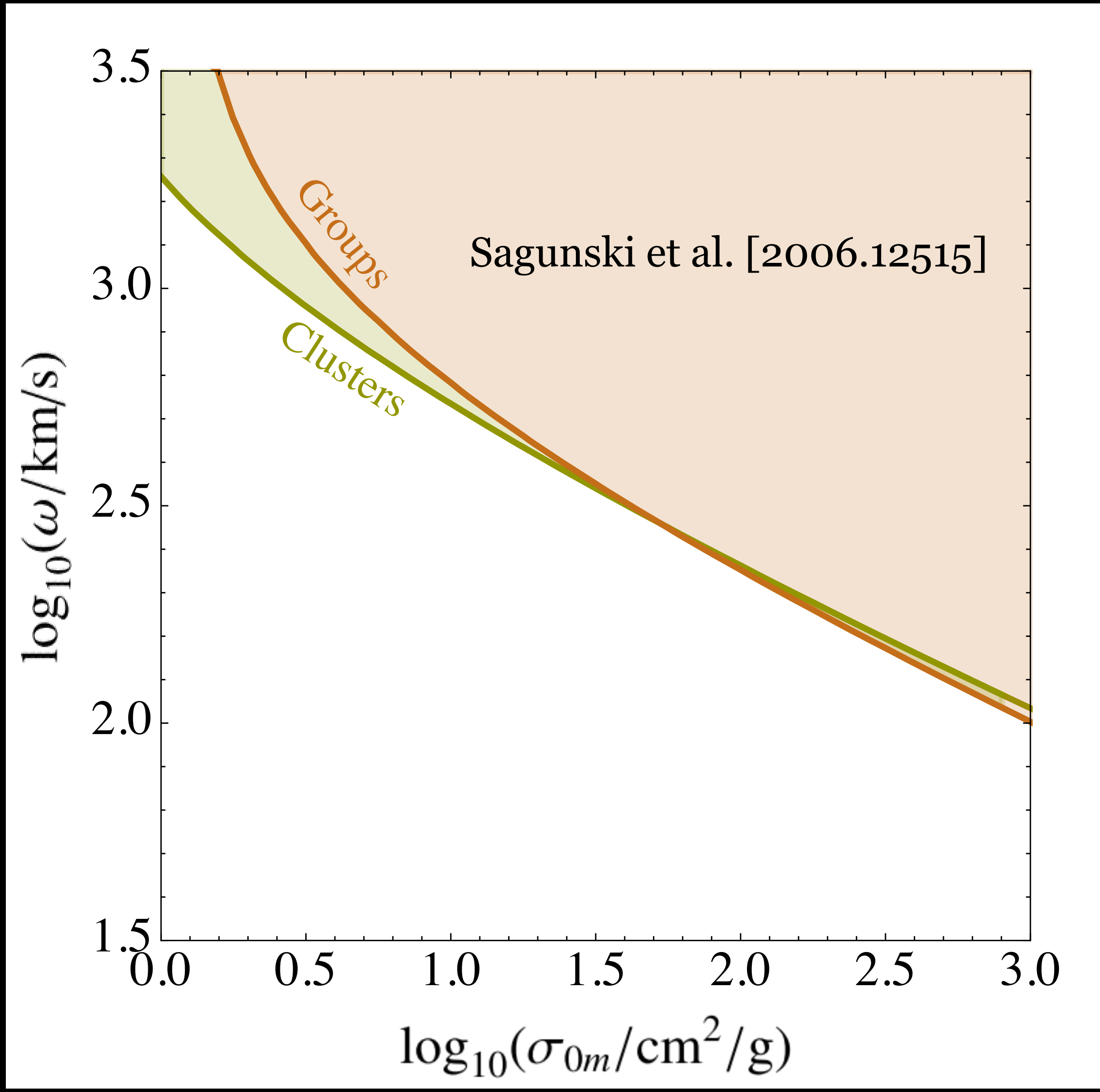
Parameter Space



$\sigma_{0m} = \sigma_0/m_\chi$

Constraints from Clusters & Groups

Groups and clusters place strong constraints for velocities ~1000-2000 km/s



$\sigma_{0m} = \sigma_0/m_\chi$

Relaxed groups: $\sigma/m_\chi \lesssim 0.5$ cm²/g

Relaxed clusters: $\sigma/m_\chi \lesssim 0.19$ cm²/g

Sagunski et al. [2006.12515]

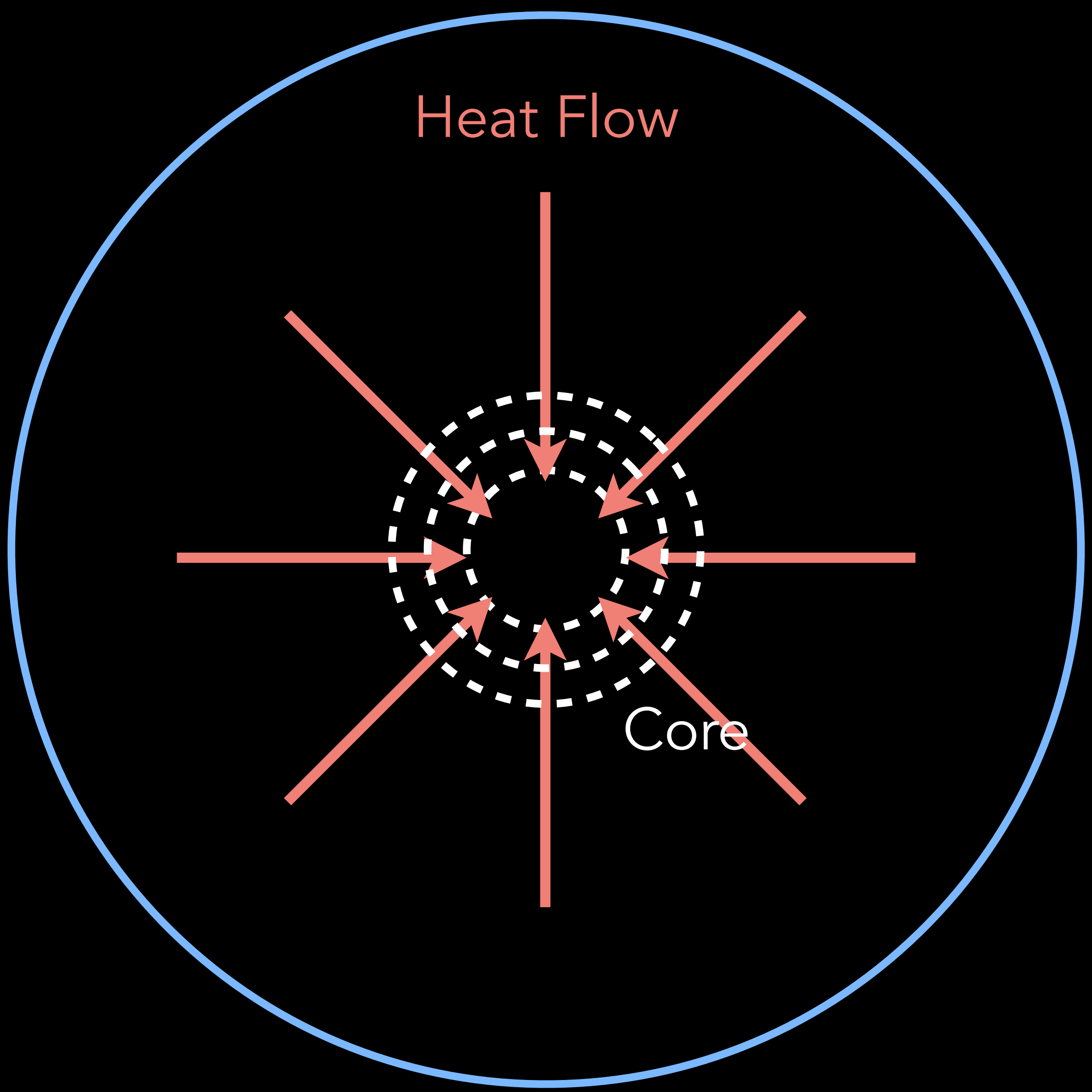
BCG oscillations: $\sigma/m_\chi \lesssim 0.39$ cm²/g

Harvey et al. [1812.06981]

Merging clusters: $\sigma/m_\chi \lesssim 2$ cm²/g

Wittman et al. [1701.05877]

Heat Transfer in an SIDM Galaxy



Stage 1: Core Formation

Self interactions transfer heat *inwards*

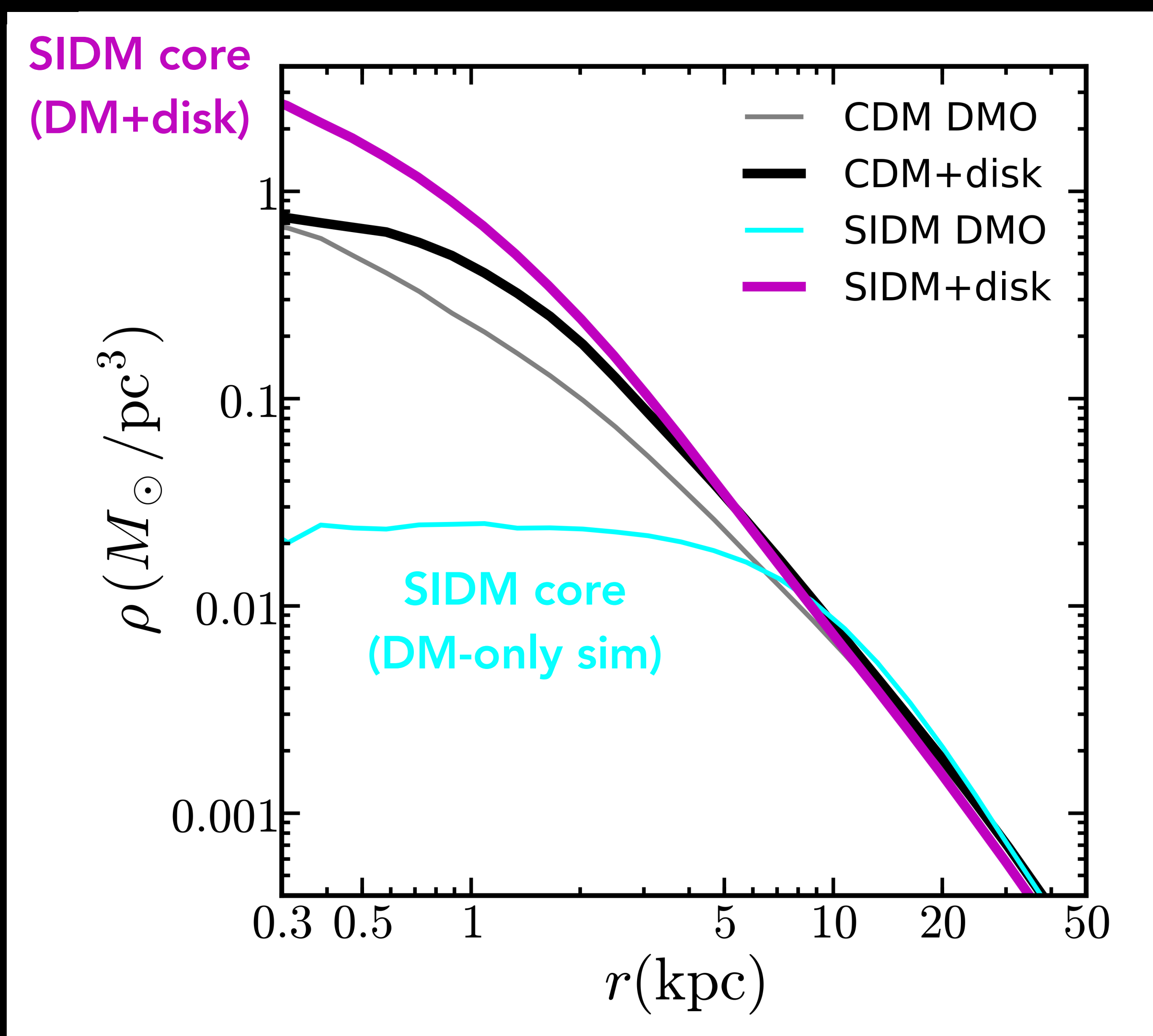
→ Formation of isothermal core

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

Core Formation

SIDM responds to gravitational potential of baryons in galaxy

Kaplinghat et al. [1311.6524]; Sameie et al. [1801.09682]



Robles et al. [1903.01469]

Dark-matter dominated systems:
cored profile

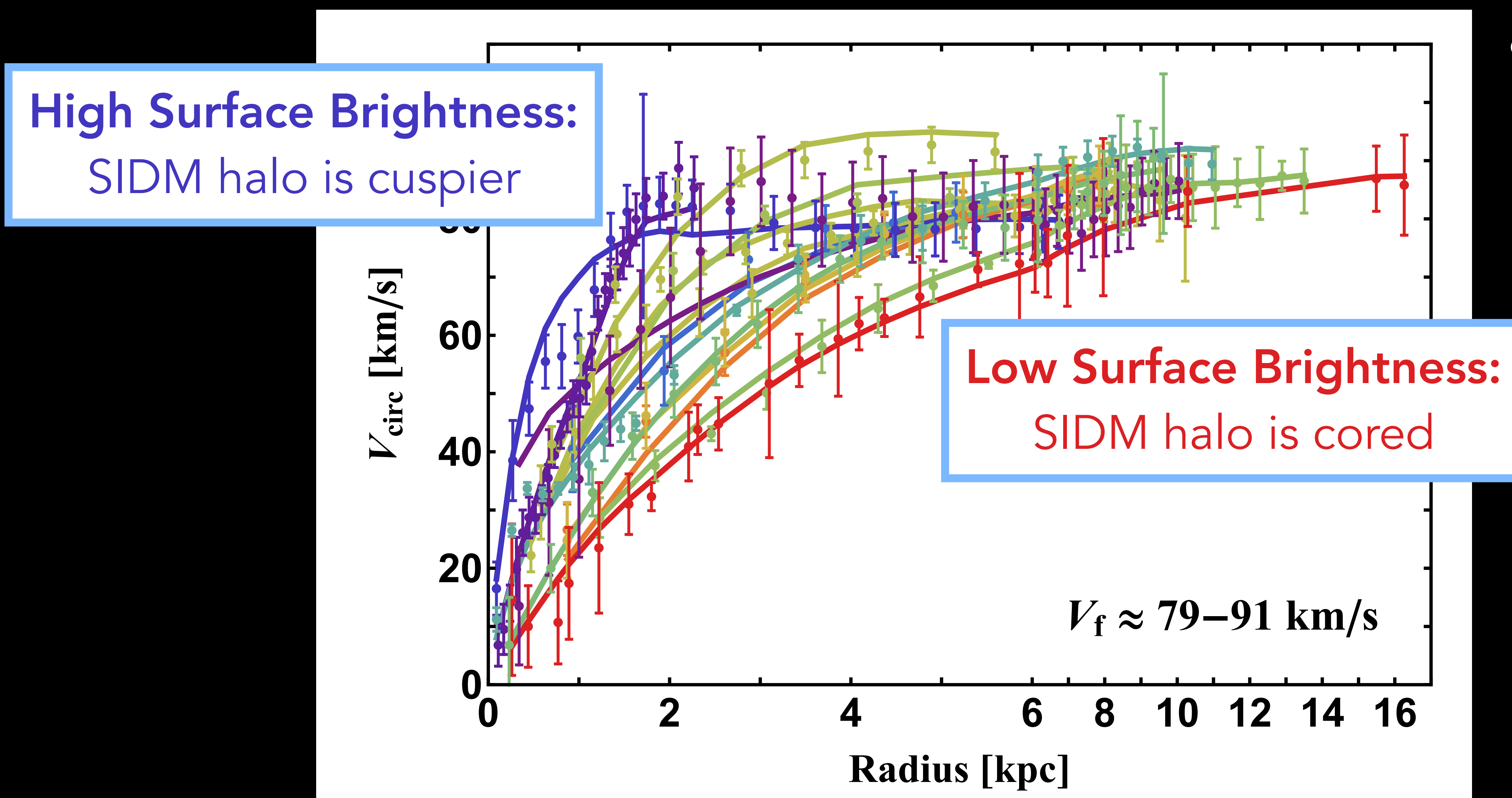
Baryon-dominated systems:
approx. cuspy profile

Galaxy Diversity Problem

SIDM yields wide variation of halo distributions (depending on galaxy properties)

May explain observed diversity of rotation curves

Ren et al. [1808.05695]



data: SPARC galaxies
lines: SIDM theory

Kamada et al. [1611.02716]; Creasey et al. [1612.03903]; Kaplinghat et al. [1911.00544]; Santos-Santos et al. [1911.09116]

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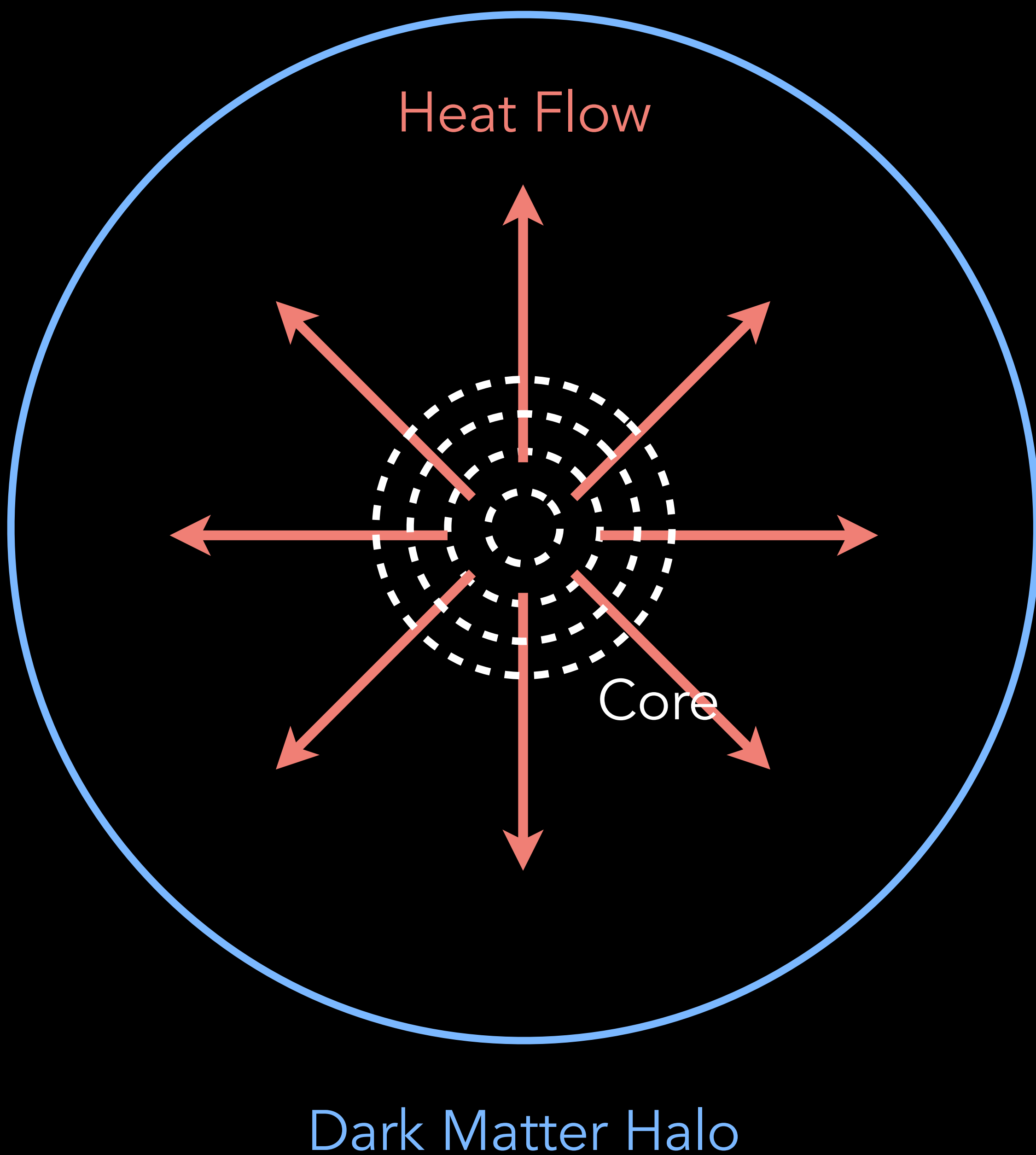


Stage 1: Core Formation

Self interactions transfer heat *inwards*

→ Formation of isothermal core

Stage 2: Core Collapse

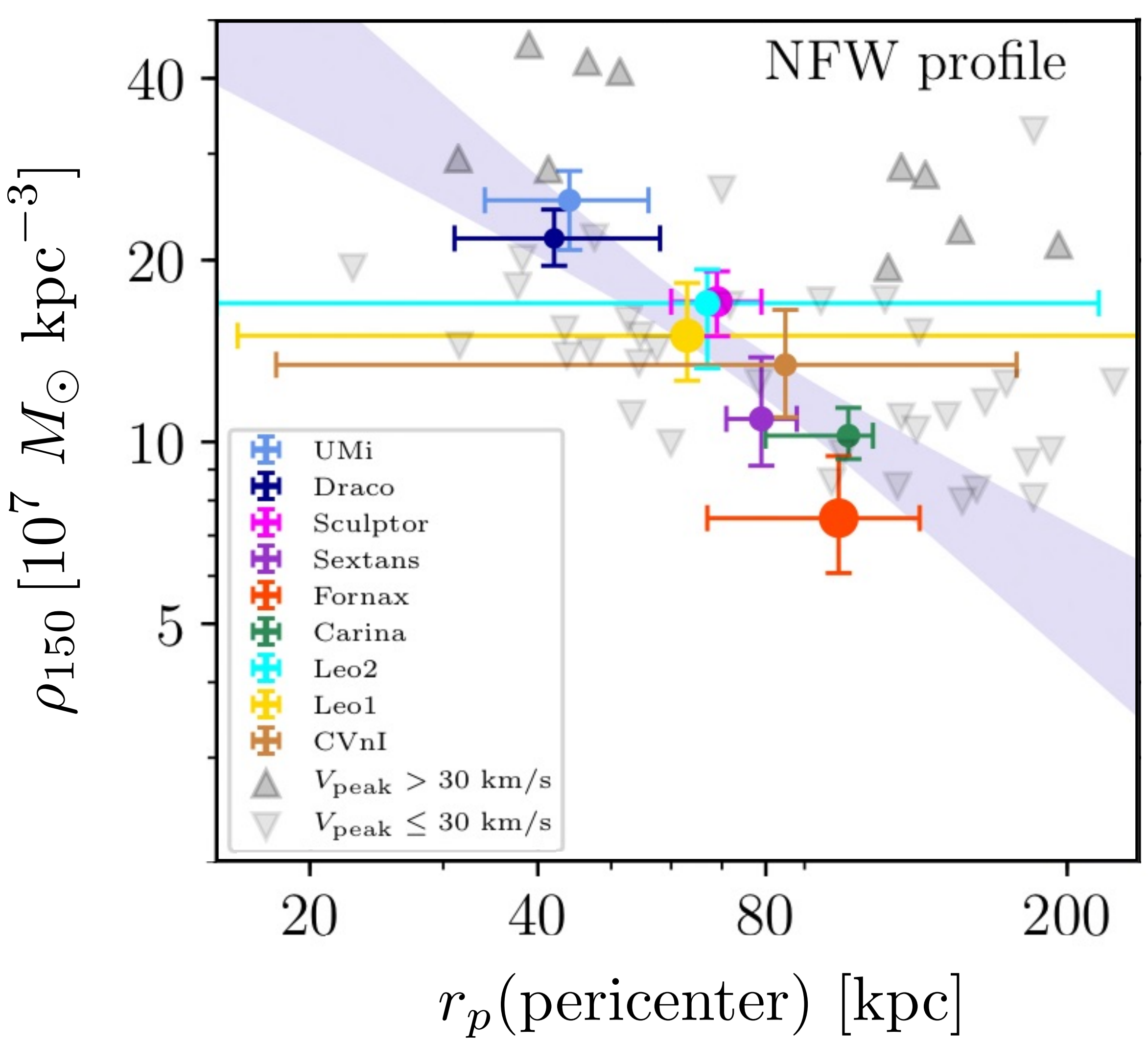
Self interactions transfer heat *outwards*

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

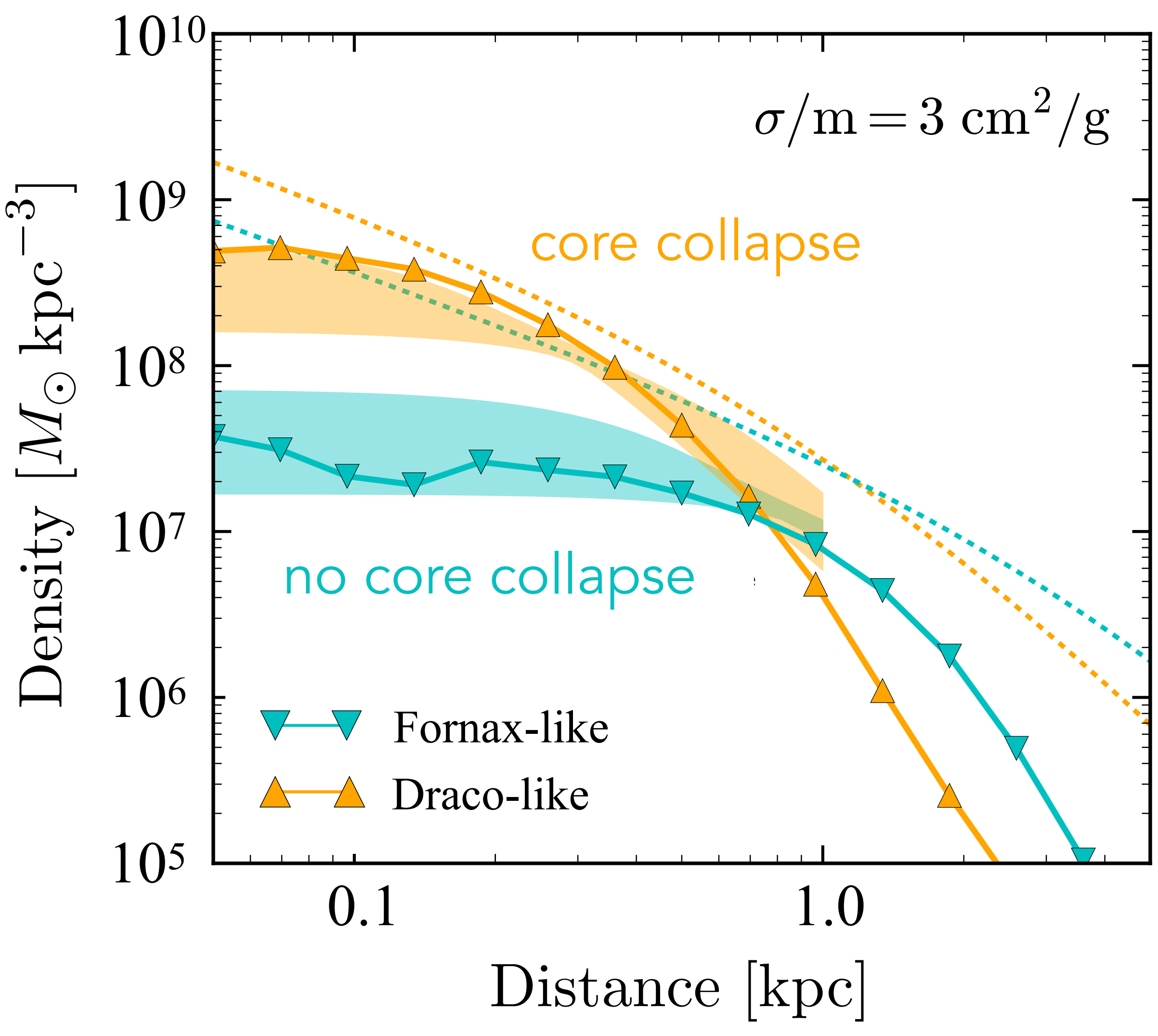
Balberg et al. [astro-ph/0110561]; Koda and Shapiro [1101.3097]; Elbert et al. [1412.1477]; Essig et al. [1809.01144]; Nishikawa et al. [1901.0049]; Kahlhoefer et al. [1904.10539]; Turner et al. [2010.02924]

Gravothermal Core Collapse

Gravothermal collapse can potentially explain the range of observed central densities for Milky Way dwarf galaxies



Kaplinghat et al. [1904.04939]

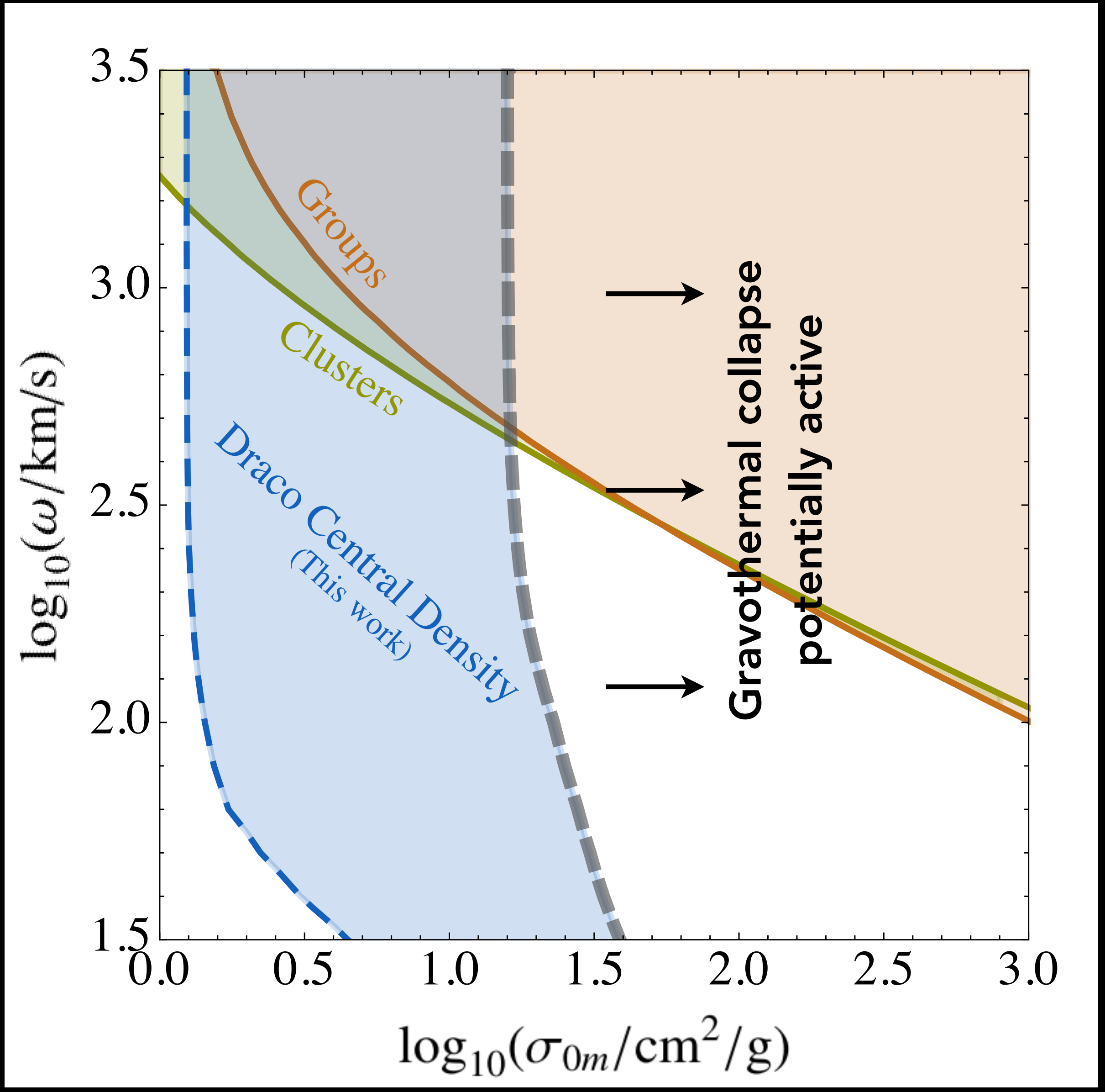


Sameie et al. [1904.07872]

Draco Isothermal Constraint

Heating of isothermal core should not reduce Draco's present-day central density more than 2σ below measured value

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



see also:
Read et al. [1805.06934]

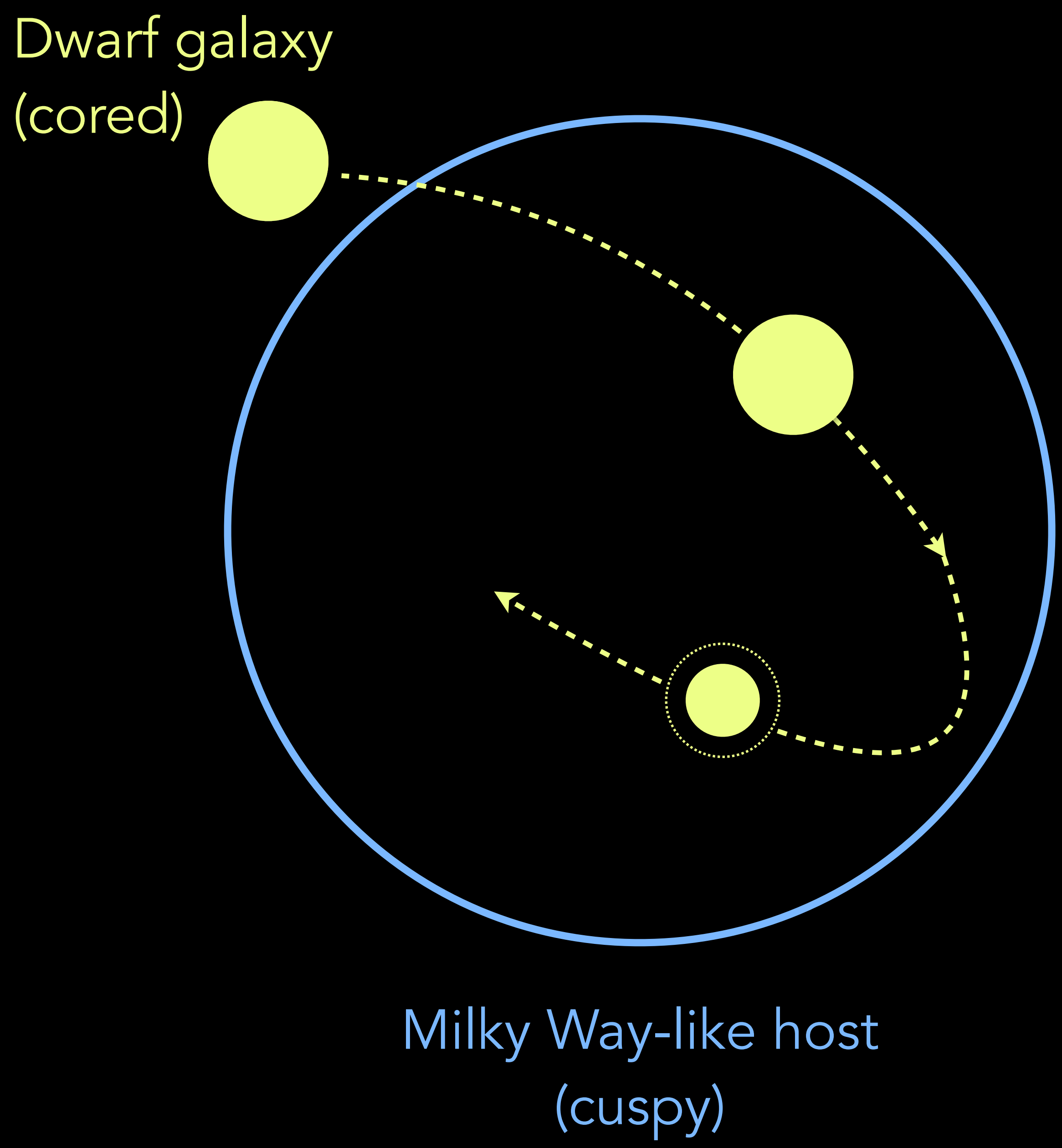
$\sigma_{0m} = \sigma_0/m_\chi$

Orbital Evolution

SIDM can significantly affect the orbits of dwarf galaxies

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

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



Tidal Stripping

- Tidal forces remove dark matter from dwarf galaxy
- Mass loss more pronounced for cored density profile

Orbital Evolution

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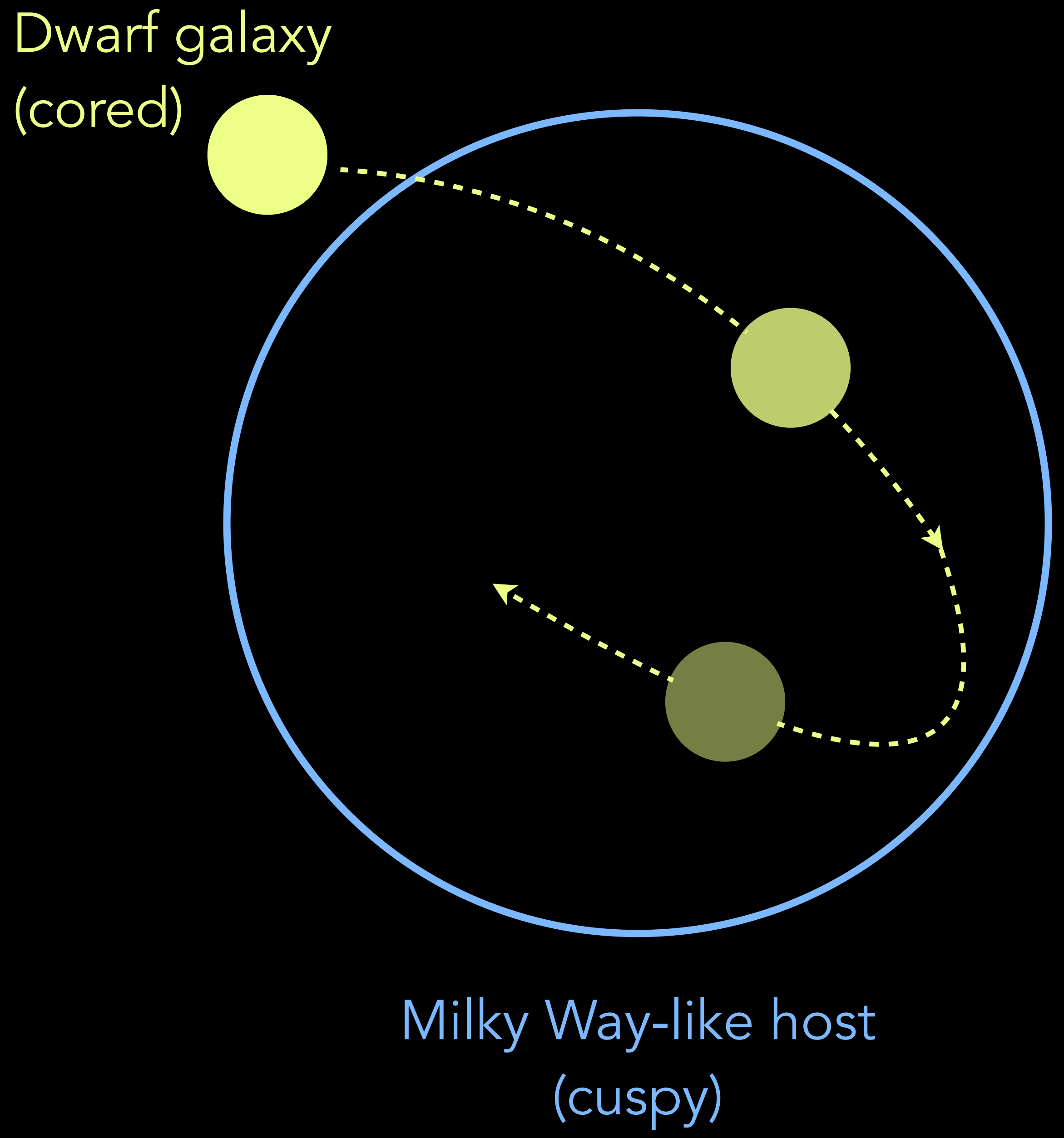
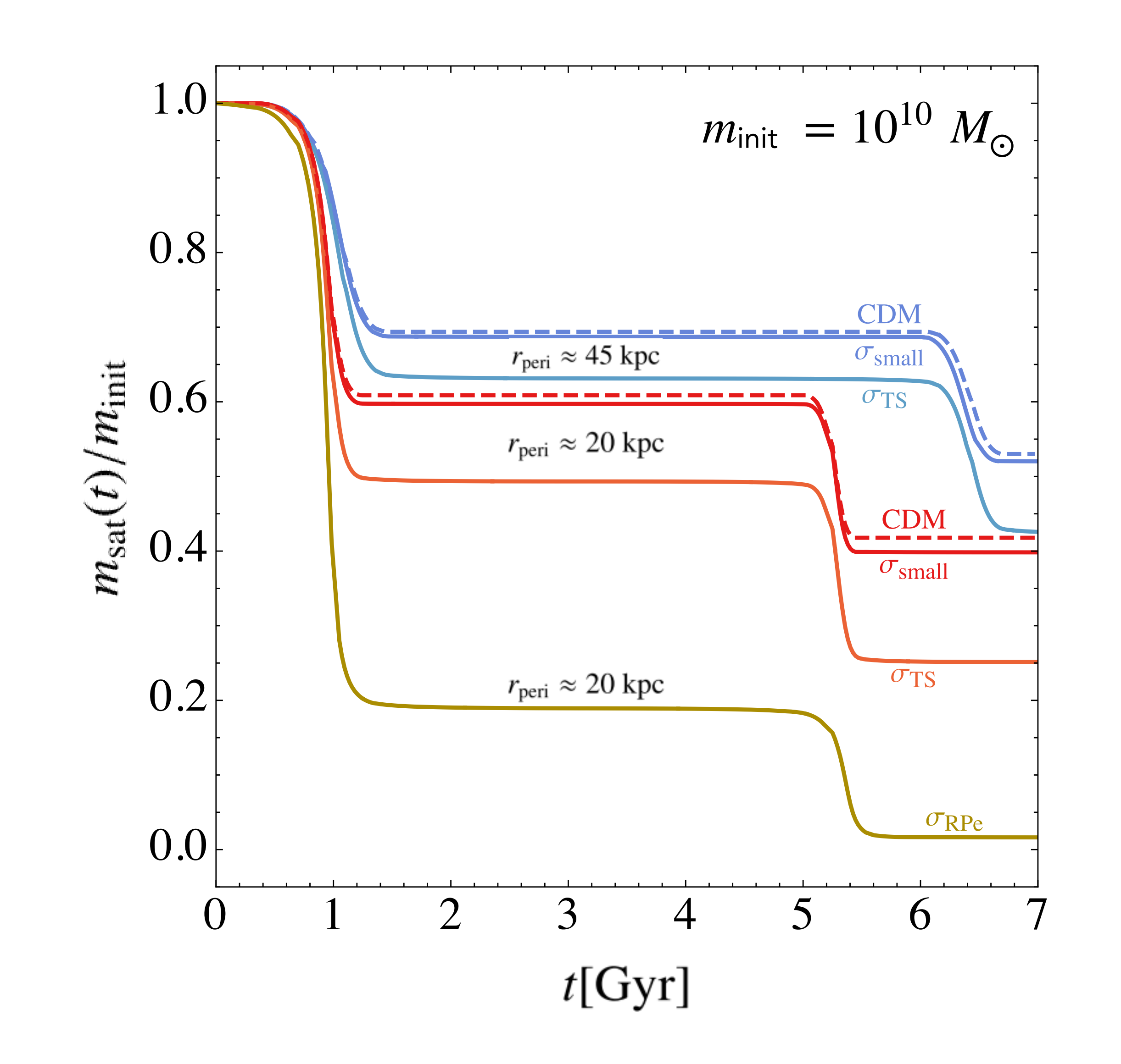


Ram-Pressure Evaporation

- Mass loss from scattering between dark matter in dwarf and host
- Efficient mass removal over entire extent of dwarf

Orbital Evolution

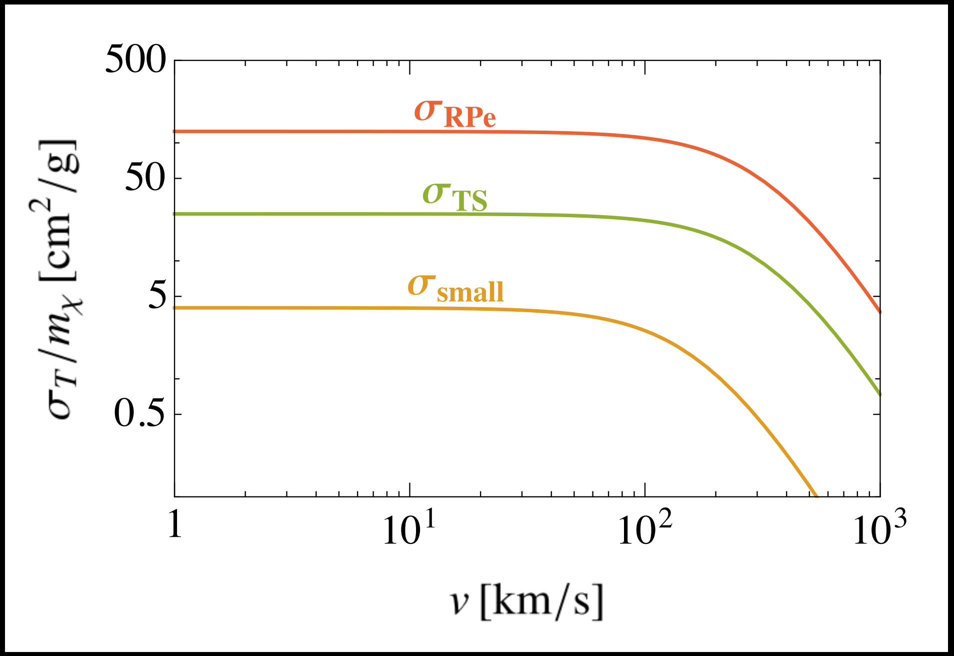
Evolution about Milky-Way like Host



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

The mass-loss mechanism that dominates depends on SIDM parameters

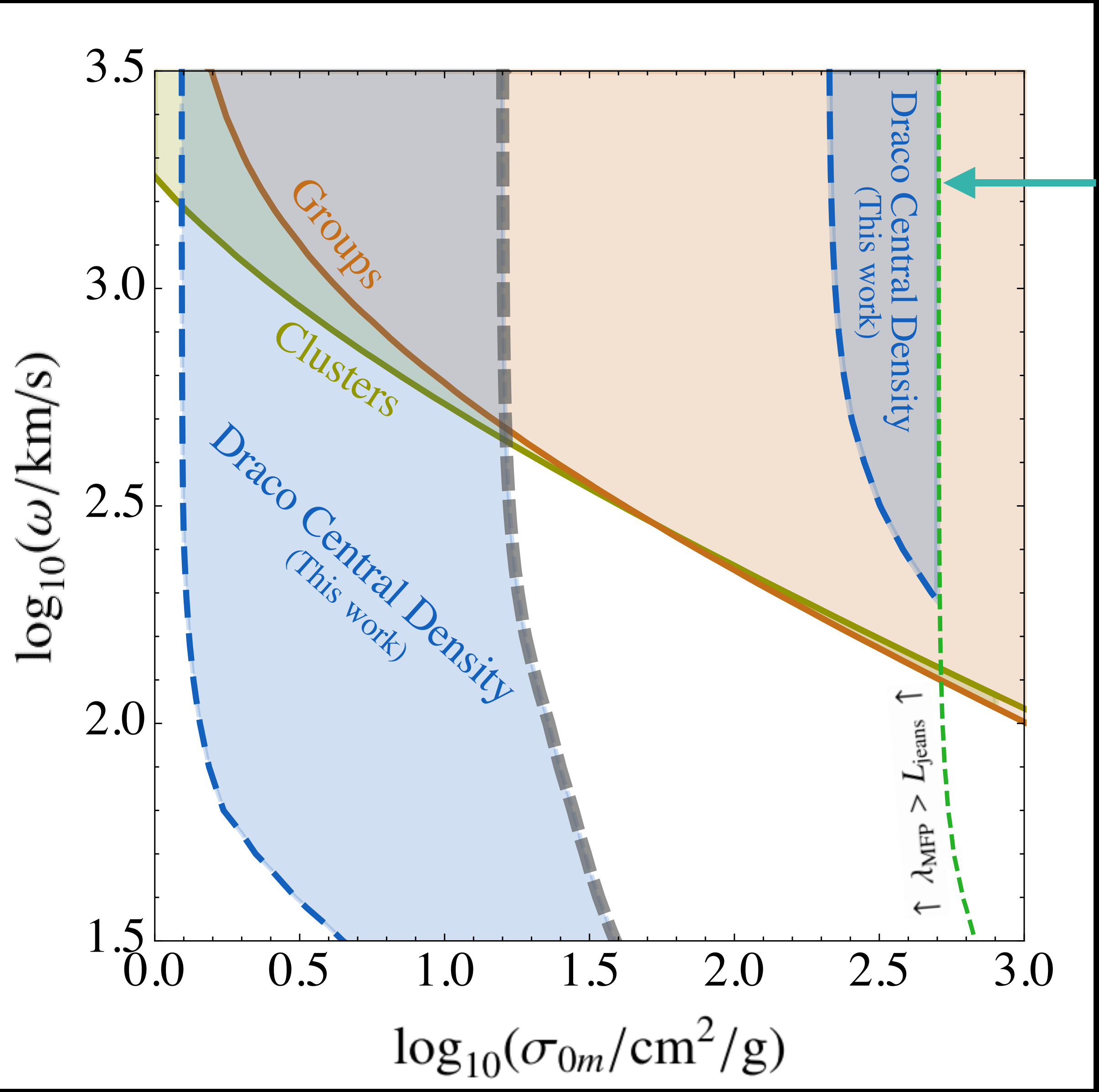
σ_{TS} , σ_{small} , σ_{RPe} are three SIDM examples



Draco Ram-Pressure Constraint

Ram-pressure evaporation should not remove so much mass from the central regions of Draco to be inconsistent with observations

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



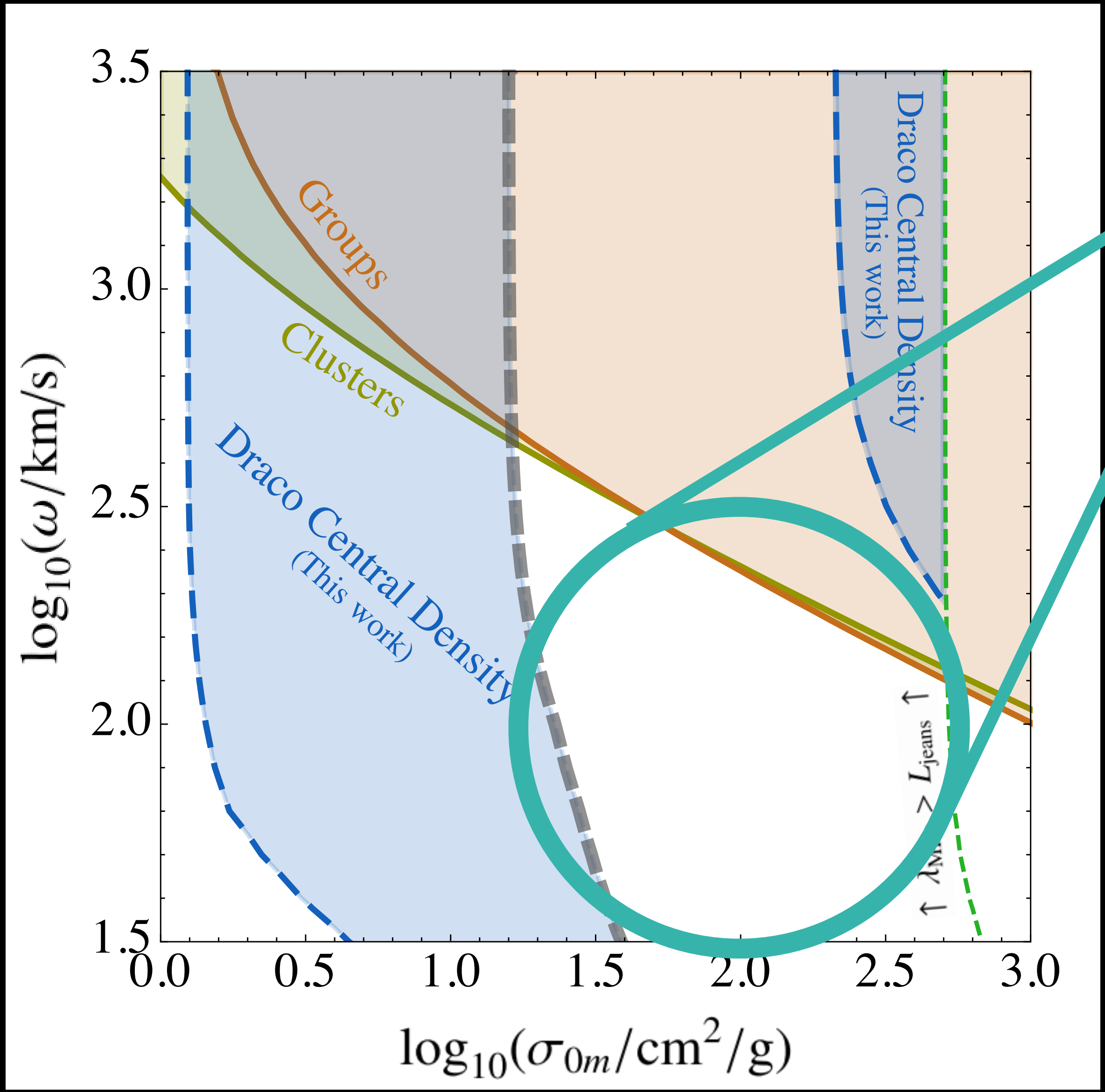
conservatively assumes initially fully gravothermally collapsed halo

$\sigma_{0m} = \sigma_0 / m_\chi$

Next Steps

Velocity-dependent cross sections that lead to gravothermal collapse are favored within SIDM framework

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



$\sigma_{0m} = \sigma_0/m_\chi$

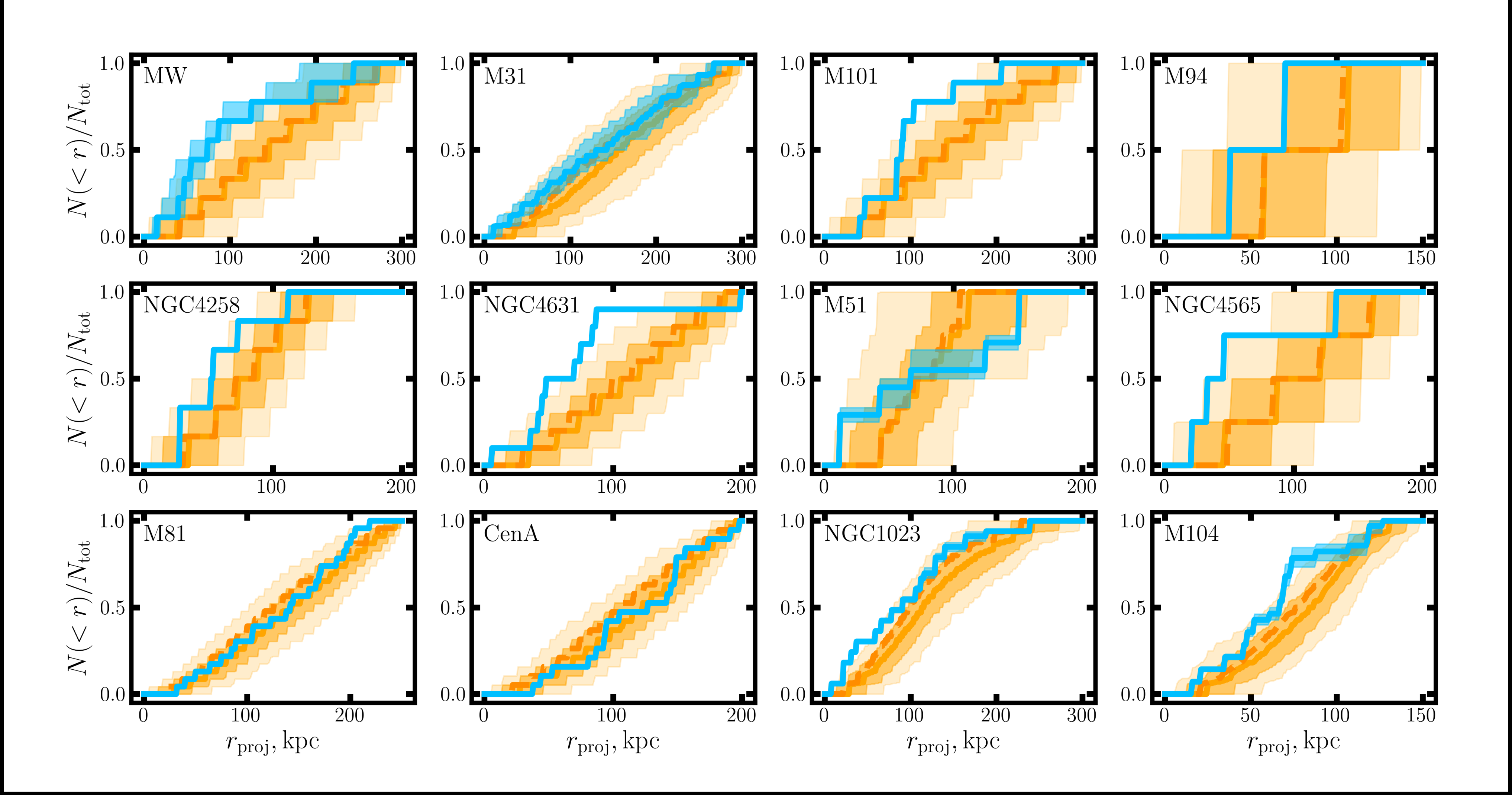
To Target Remaining Parameter Space:

- Carefully analyze properties of individual Milky Way dwarf galaxies
- Study population statistics of satellites around Milky-Way like hosts
- Understand implications for lenses in galaxy clusters

works in progress with D. Folsom, F. Jiang, M. Kaplinghat, C. Leinz, O. Slone, …

The Local Group

Observational data rapidly becoming available on abundance of dwarf galaxies around Milky Way-like galaxies



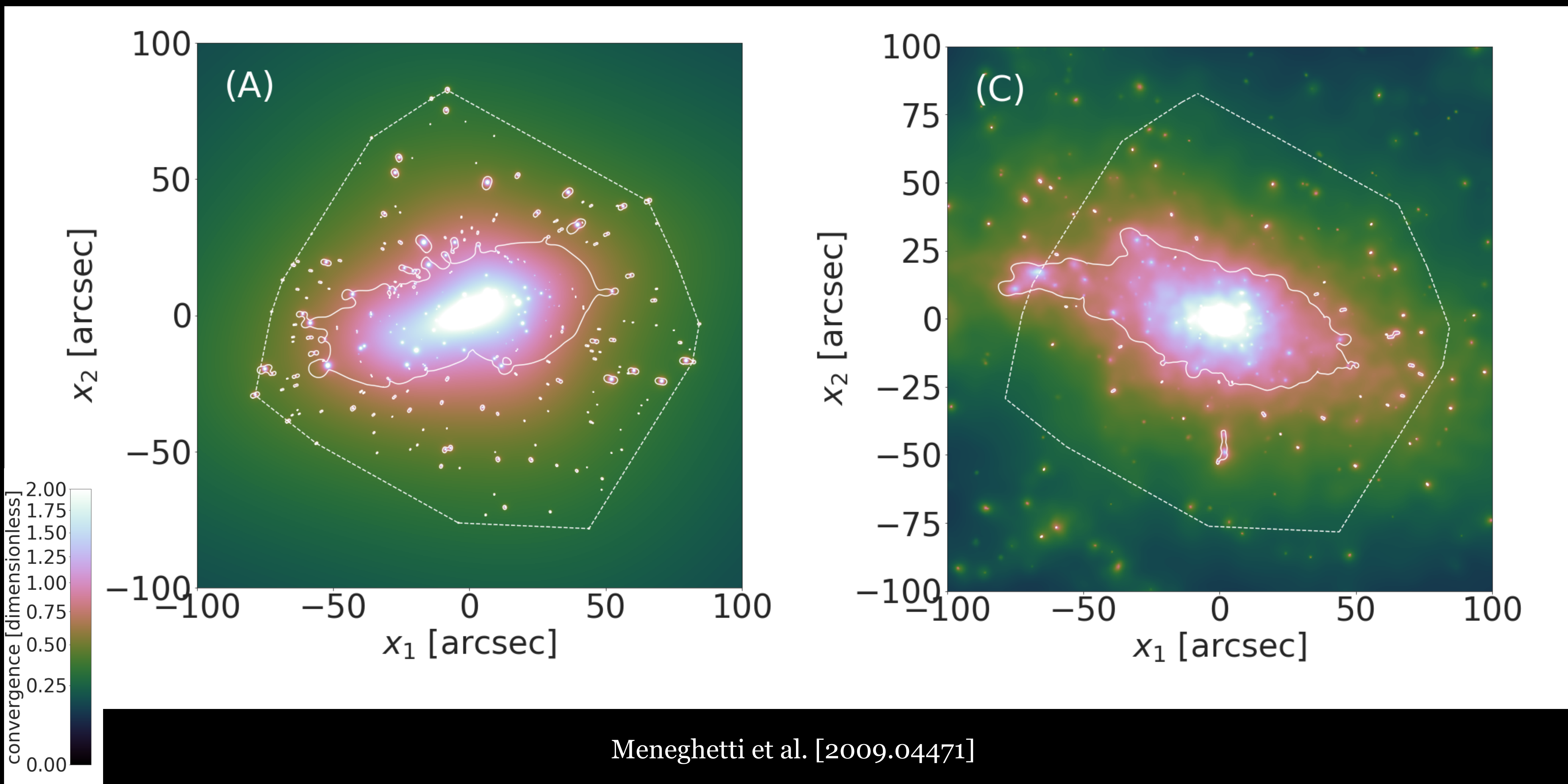
Carlsten et al. [2006.02444]

see also SAGA survey, Mao et al. [2008.12783]

Gravitational Lenses about 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 theory interpretation

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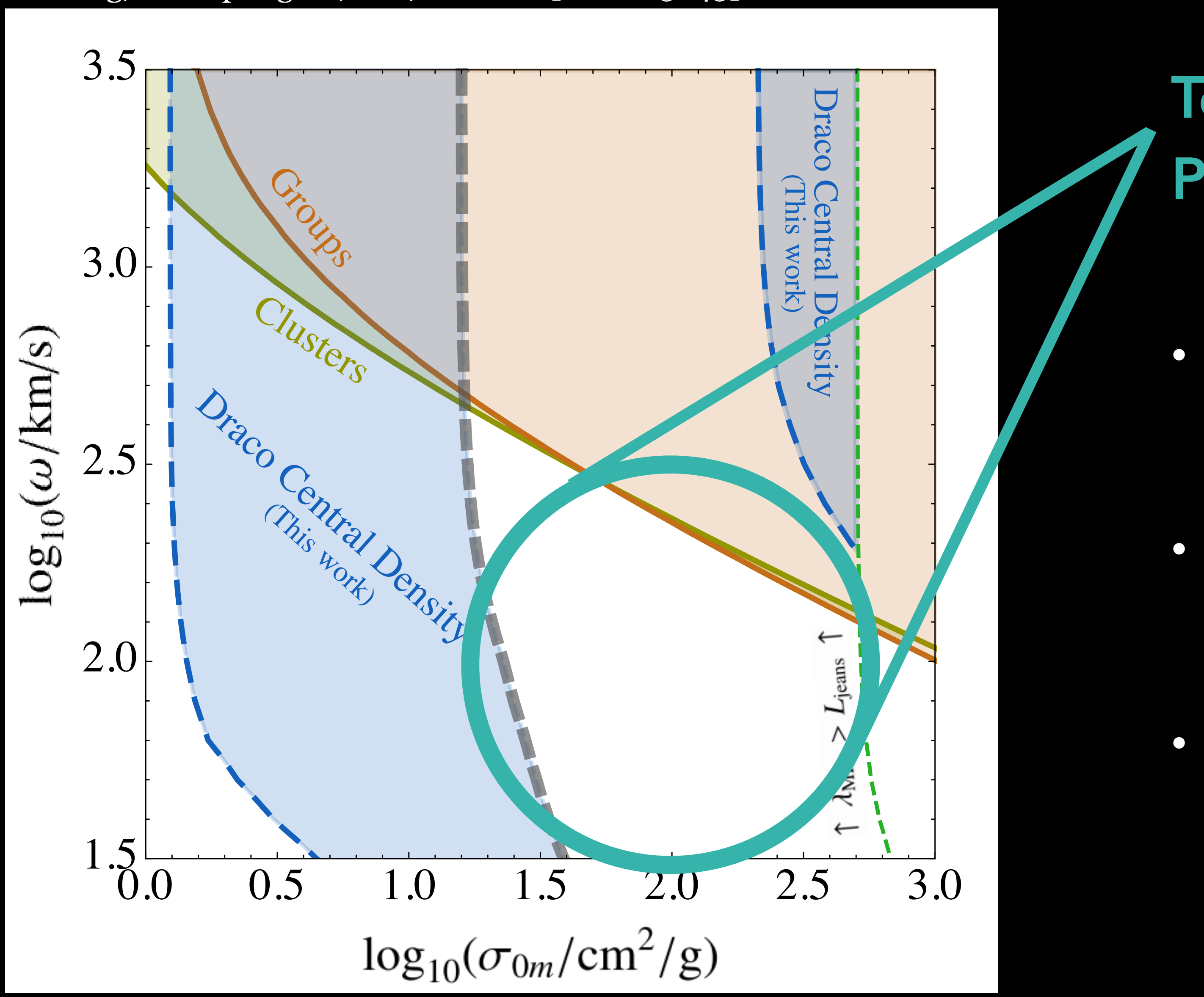

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