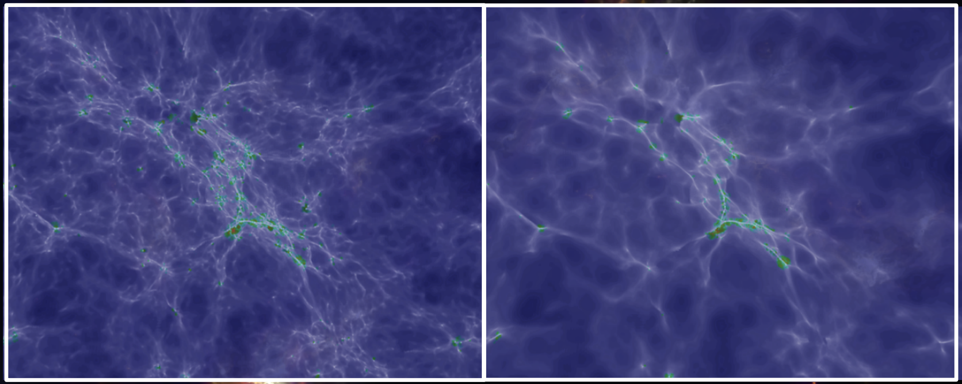
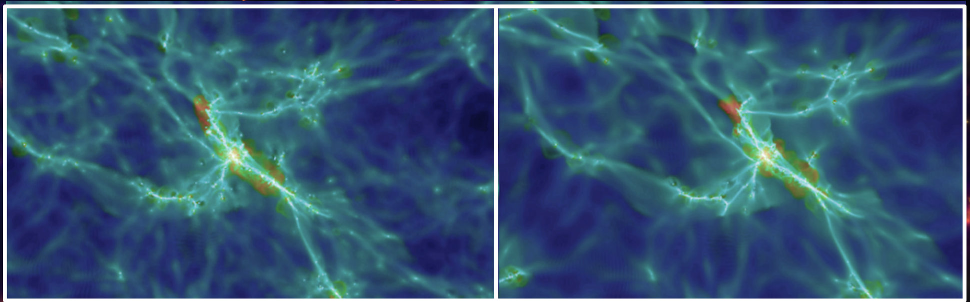
Simulating Structure Formation in SIDM

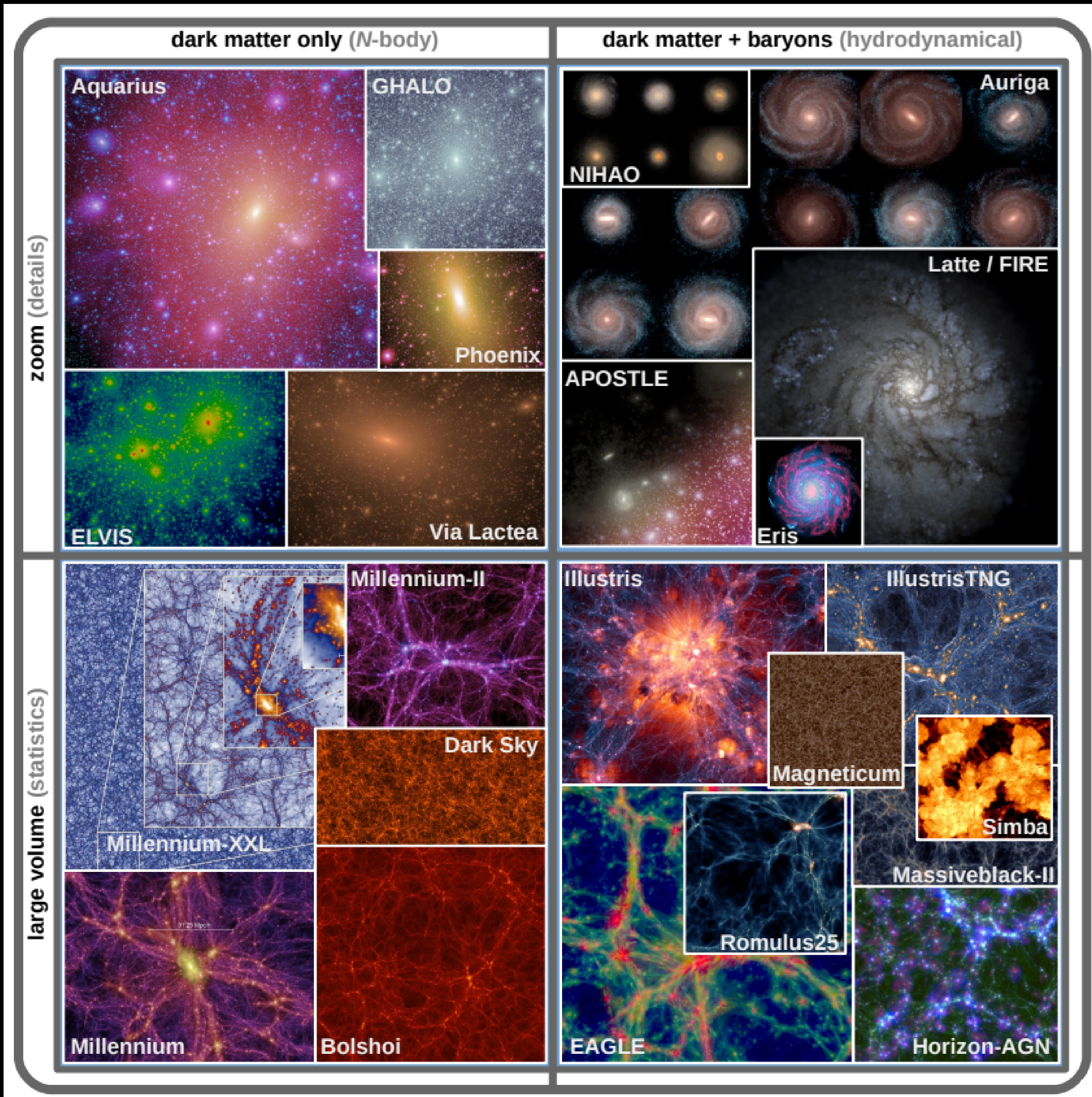
Mark Vogelsberger

Massachusetts Institute of Technology



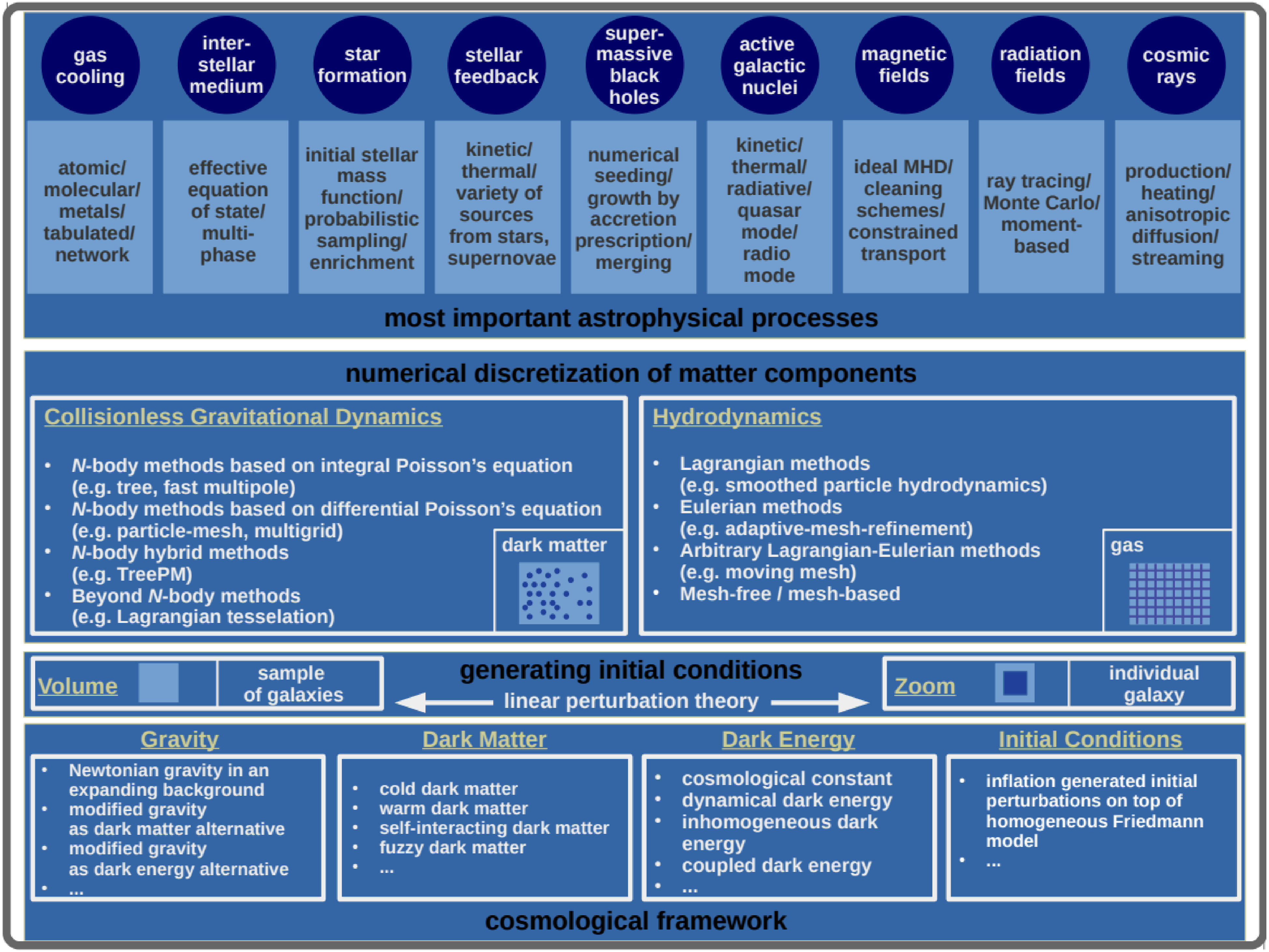


Cosmic Controversies Conference,
Chicago, October 2019



MV, Marinacci,
Torrey, Puchwein

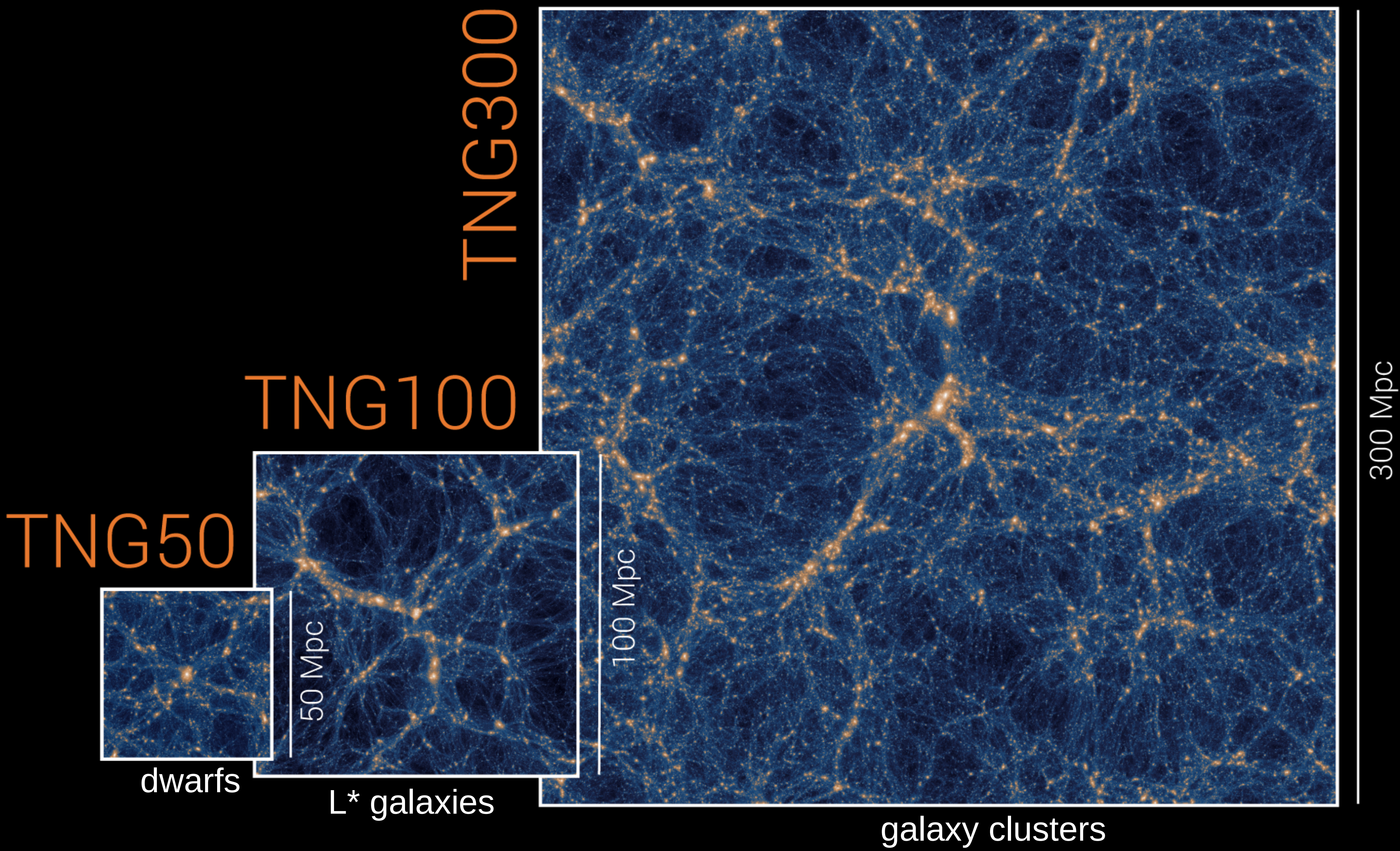
Nature Reviews Physics 2019



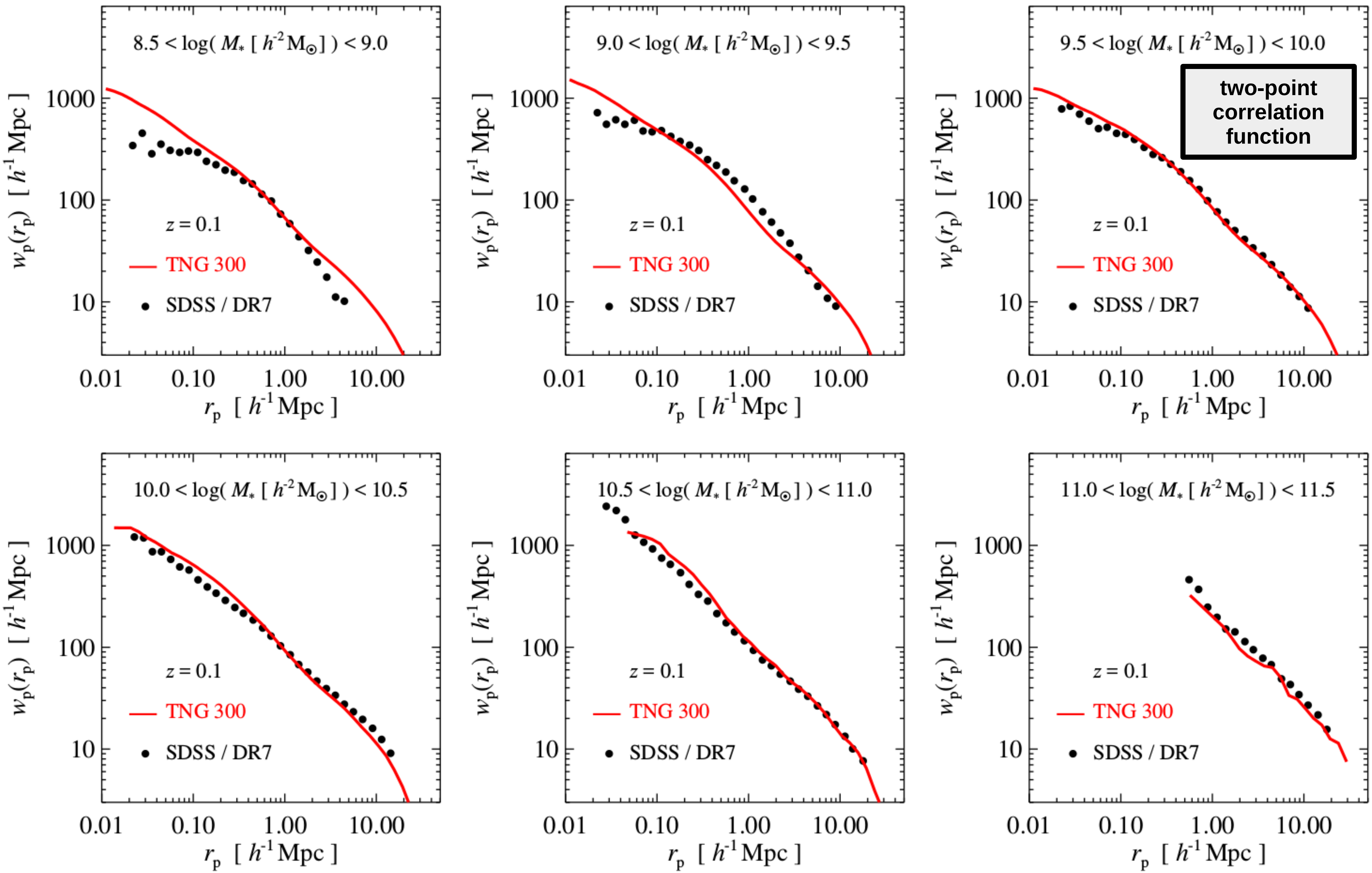
MV, Marinacci, Torrey, Puchwein
Nature Reviews Physics 2019

The IllustrisTNG Simulations

Illustris galaxy formation model (MV+ 2013, 2014 Nature)
+
novel low accretion rate SMBH model (Weinberger+ w/ MV 2017)

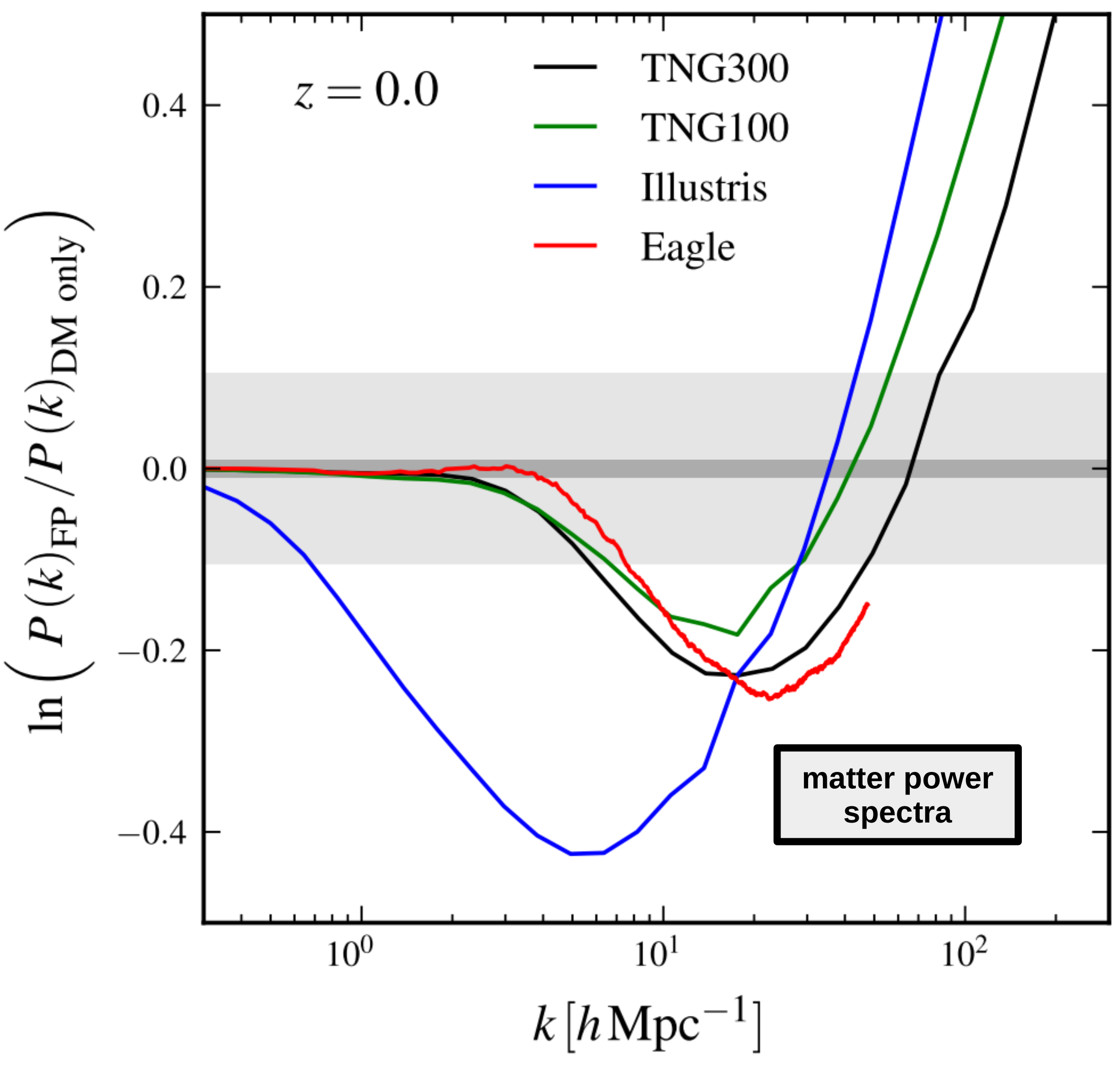


Galaxy Clustering: Simulation vs. Observations



Springel+ w/ MV 2018

Impact of Baryons on Matter Power Spectrum



baryon physics modifies matter power spectrum

inclusion of baryonic physics is crucial

Springel+ w/ MV 2018

Cold Dark Matter Alternatives

- missing satellites problem
- core/cusp problem
- too-big-to-fail problem
- diversity problem
- plane of satellites problem

small-scale
CDM problems

Cold Dark Matter Alternatives

Solutions:

- **baryonic physics (most small-scale problems have been identified in DM only simulations)?**
- **uncertainties in observations / measurements / modeling?**
- **DM is not exactly CDM?**

Cold Dark Matter Alternatives

- missing satellites problem
- core/cusp problem
- too-big-to-fail problem
- diversity problem
- plane of satellites problem

small-scale
CDM problems?

Cold Dark Matter Alternatives

- missing satellites problem
- core/cusp problem
- too-big-to-fail problem
- diversity problem
- plane of satellites problem
- generic WIMP not detected so far

small-scale
CDM problems?

'fundamental'
problem

Going beyond CDM: Some Candidates

Warm Dark Matter?

Self-Interacting Dark Matter?

BECDM?

...?

Going beyond CDM: Some Candidates

Warm Dark Matter?

Self-Interacting Dark Matter?

BECDM?

...?

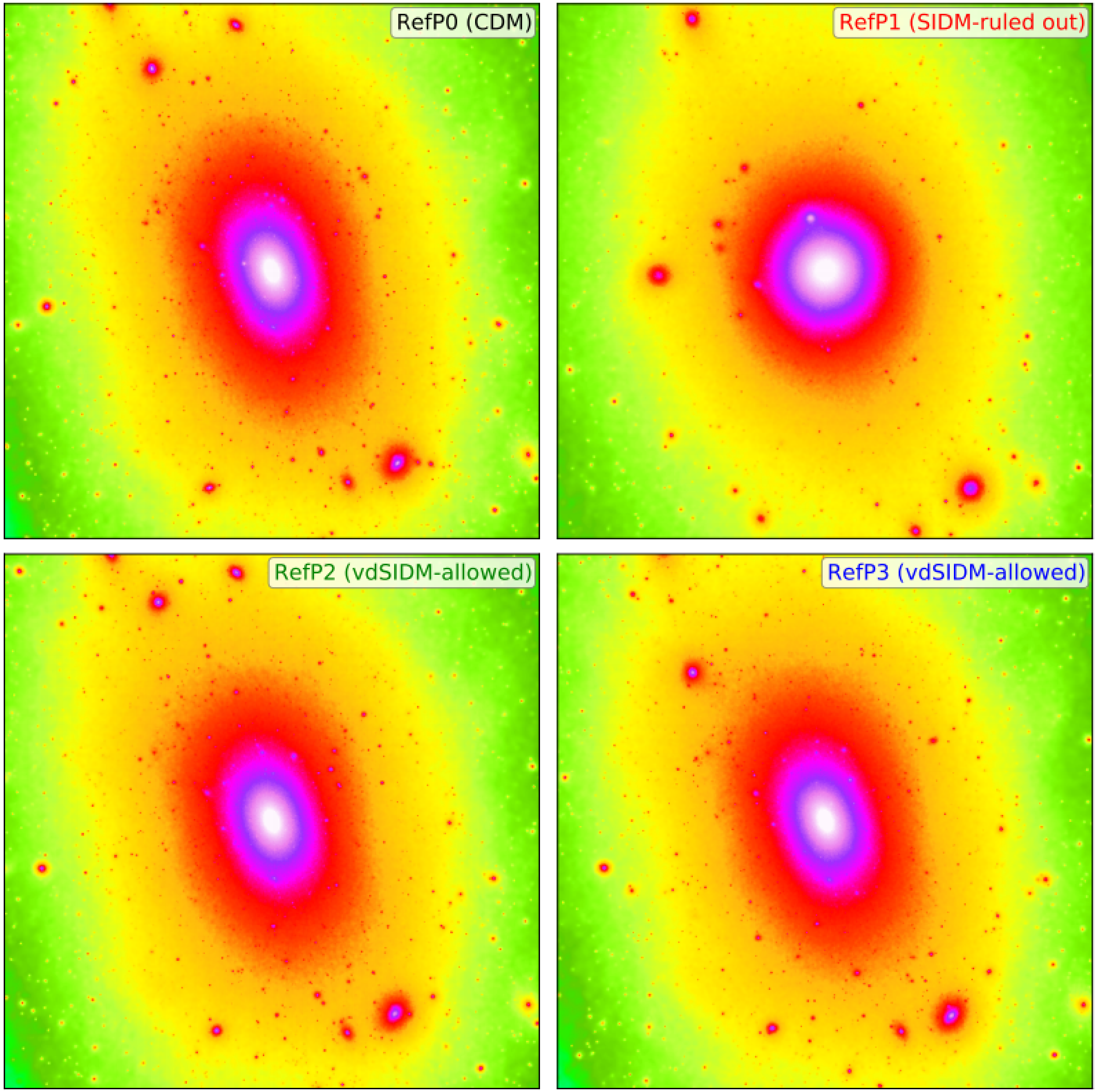
Observational Evidence for Self-Interacting Cold Dark Matter

David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton, New Jersey 08544
(Received 20 September 1999)

Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark matter particles are self-interacting with a large scattering cross section but negligible annihilation or dissipation. In this scenario, astronomical observations may enable us to study dark matter properties that are inaccessible in the laboratory.

To summarize, our estimated range of σ/m for the dark matter is between $0.45-450\ \mathrm{cm}^2/\mathrm{g}$ or, equivalently, $8 \times 10^{-(25-22)}\ \mathrm{cm}^2/\mathrm{GeV}$. Numerical calculations are essential for checking our approximations and refining our estimates. Even without numerical simulations, we can already make a number of predictions for the properties of galaxies in a self-interacting dark matter cosmology: (1) The centers of halos are spherical; (2) dark matter halos will have cores; (3) there are few dwarf galaxies in groups but dwarfs persist in lower density environments; and (4) the halos of dwarf galaxies and galaxy halos in clusters will have radii smaller than the gravitational tidal radius (due to collisional stripping). Intriguingly, current observations appear to be consistent with all of these predictions.

The Outcome of SIDM Simulations

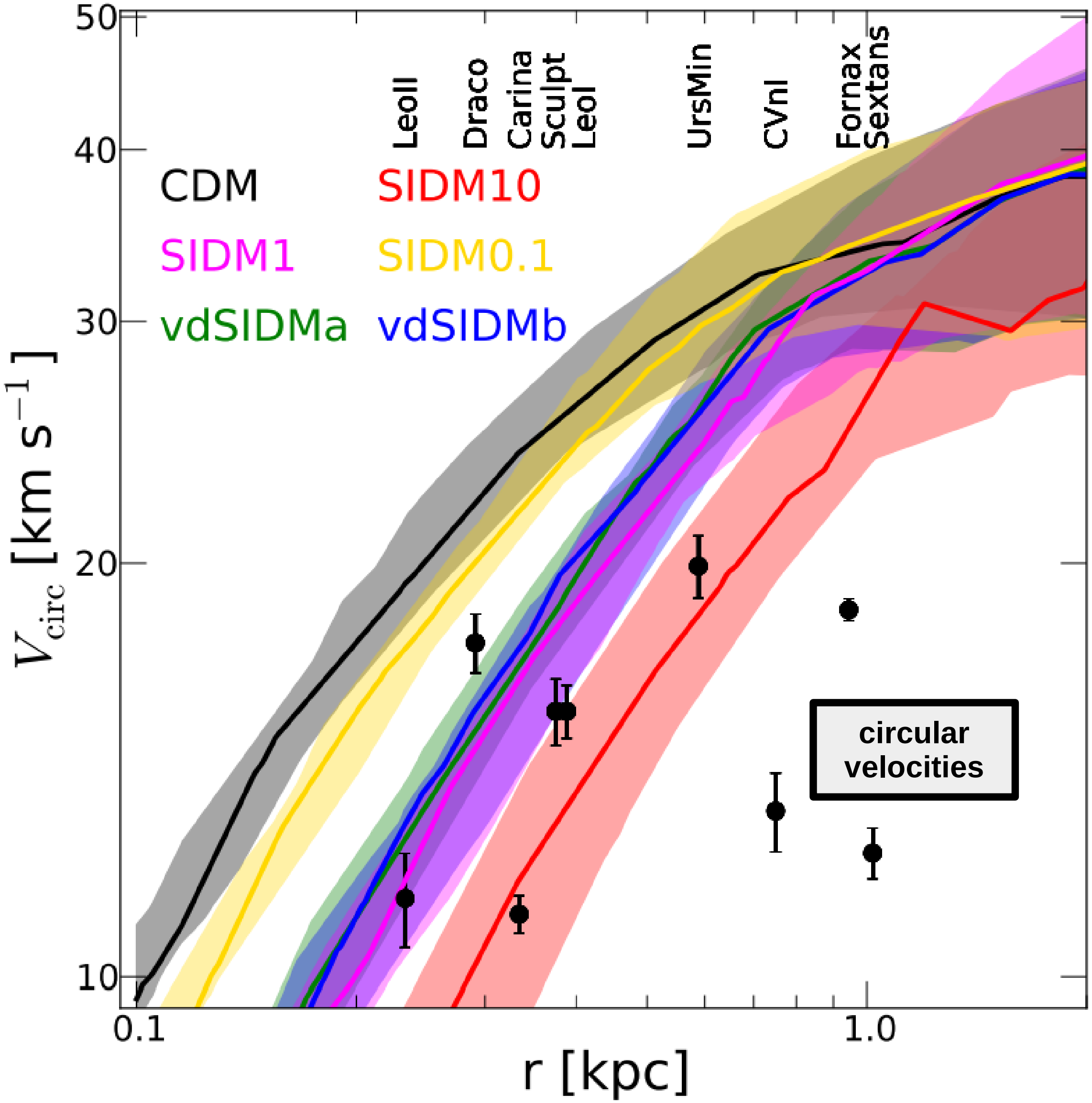


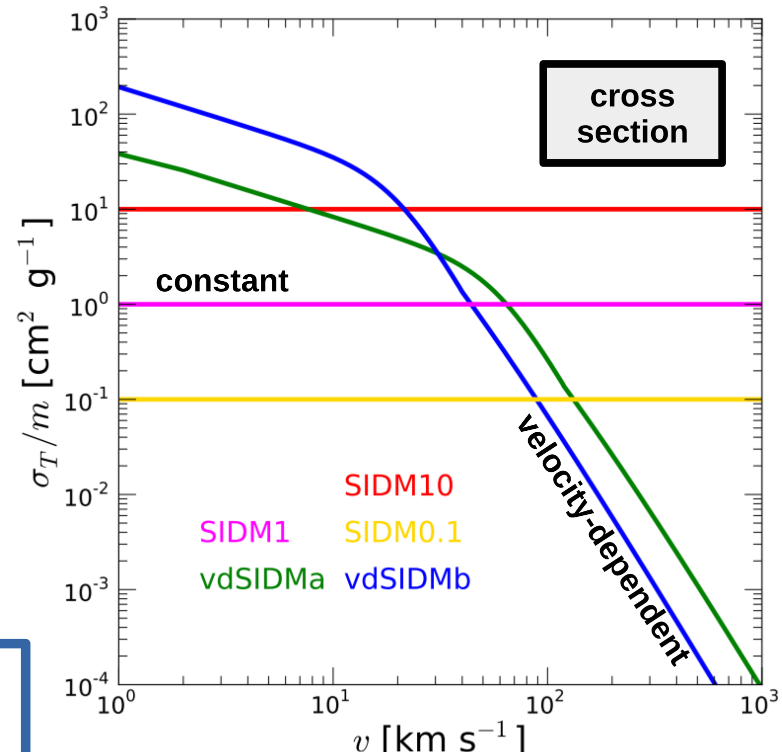
Name	Type	$\sigma_T^{\max}/m_\chi$ [cm^2 g^{-1}]	$v_{\max}$ [km s^{-1}]
RefP0	CDM	/	/
RefP1	SIDM (ruled out)	10	/
RefP2	vdSIDM (allowed)	3.5	30
RefP3	vdSIDM (allowed)	35	10

impact of SIDM on dark matter density field of MW-like halos

MV+ 2012

Self-Interacting Dark Matter: Implications for Subhalos





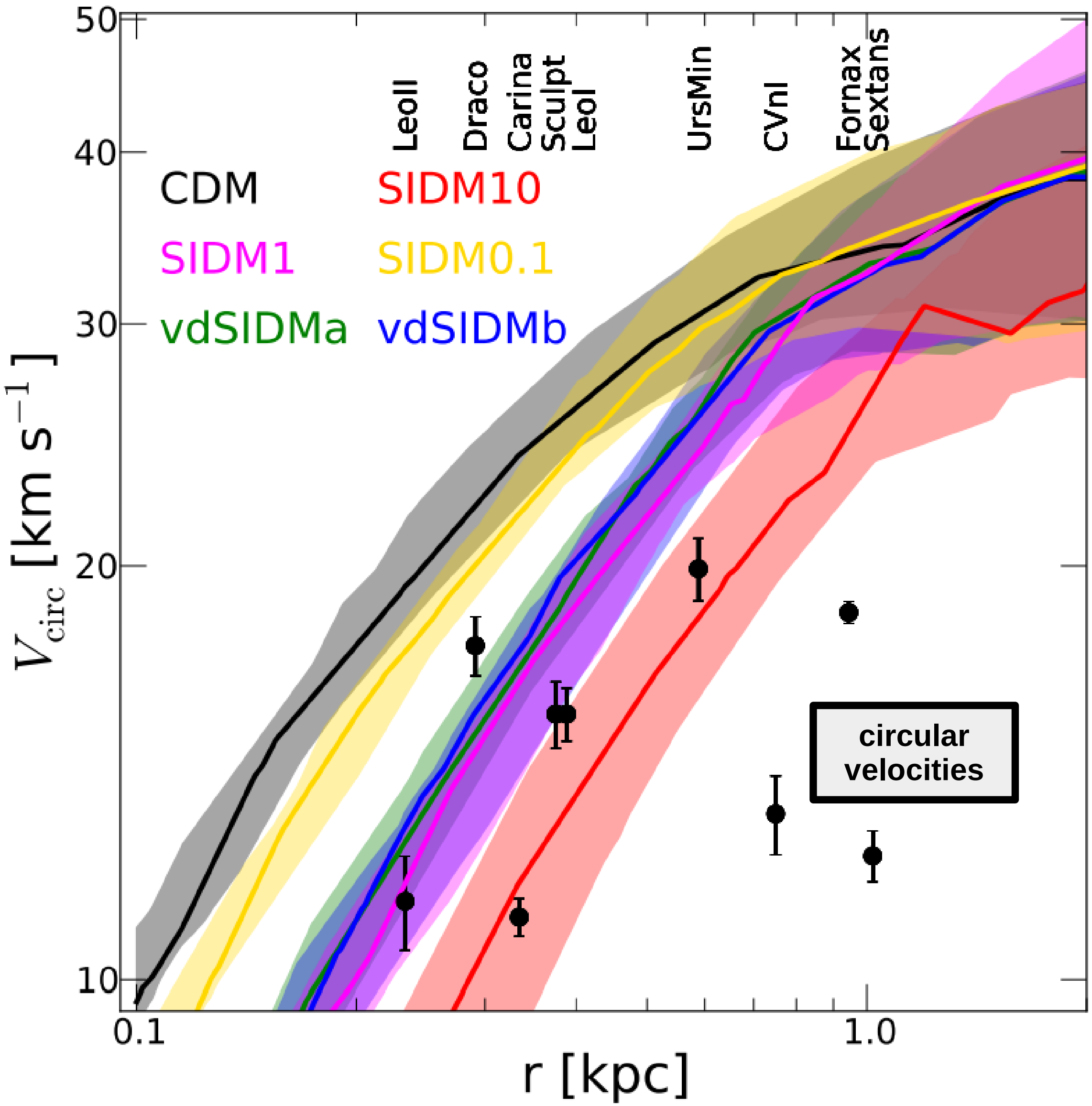
MV, Zavala, Loeb 2012

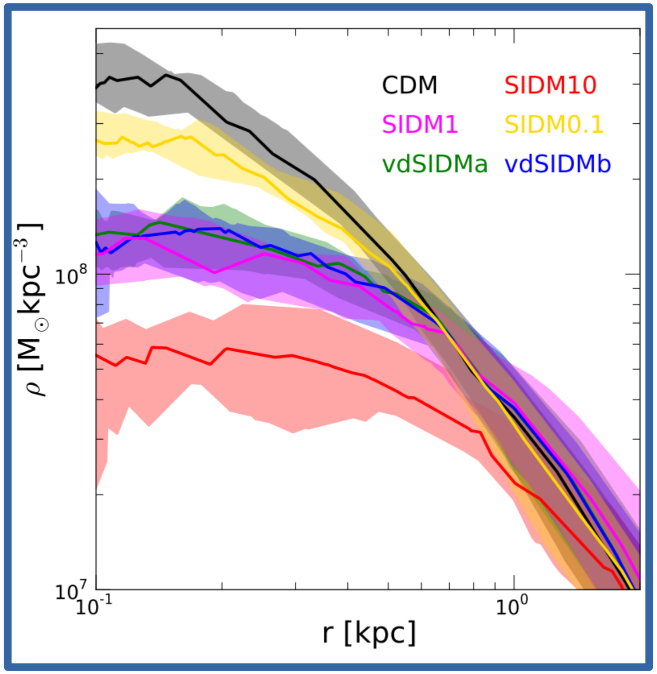
Zavala, MV, Walker 2013

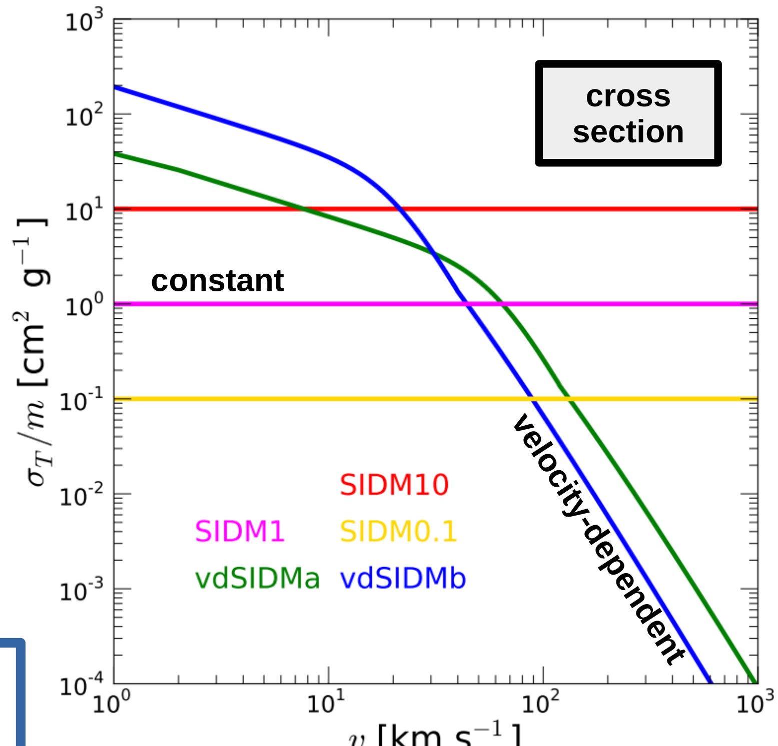
SIDM simulations alleviate the tension with TBTF problem

can be achieved with constant and velocity-dependent cross sections

Self-Interacting Dark Matter: Implications for Subhalos







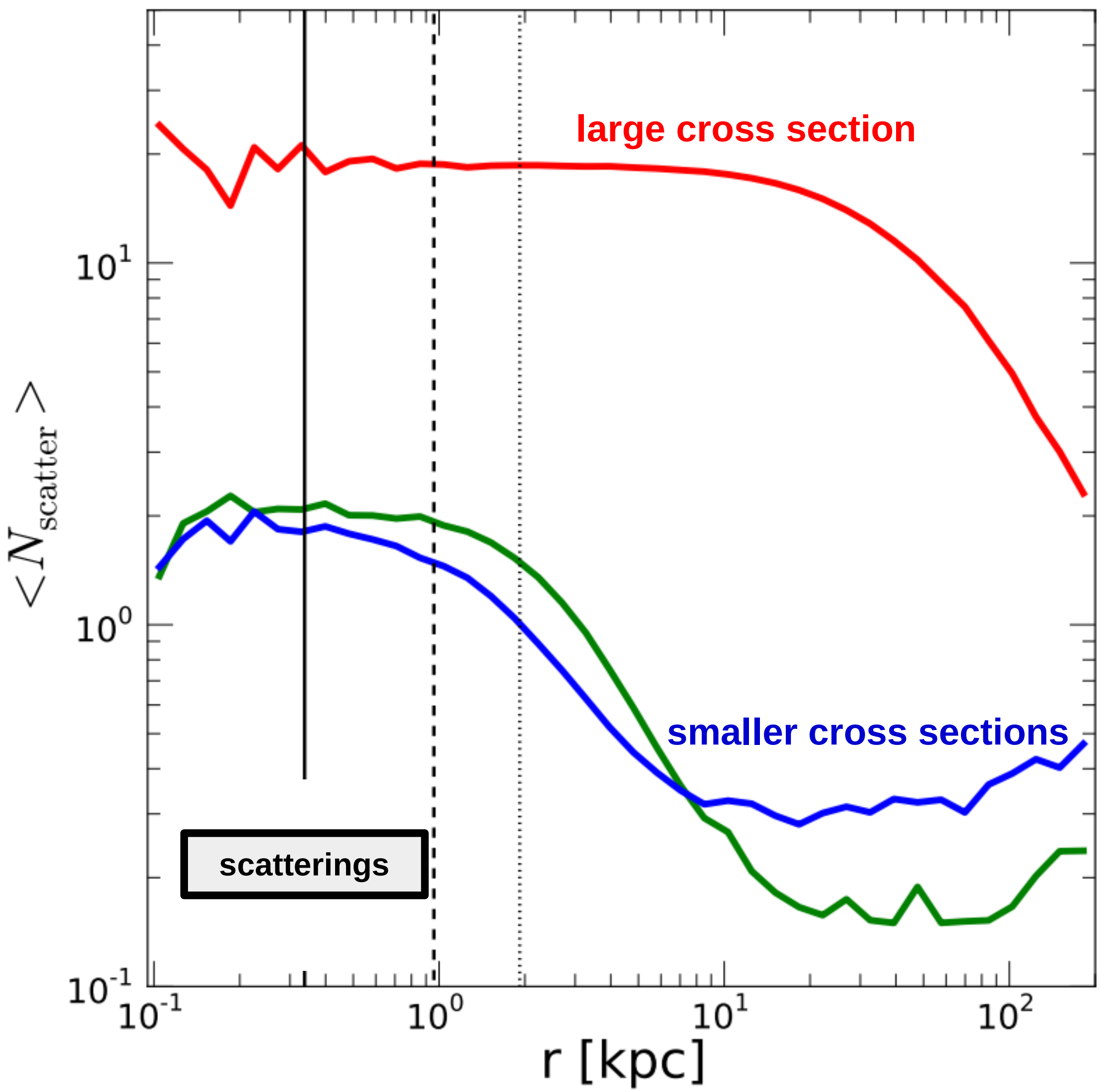
MV, Zavala, Loeb 2012

Zavala, MV, Walker 2013

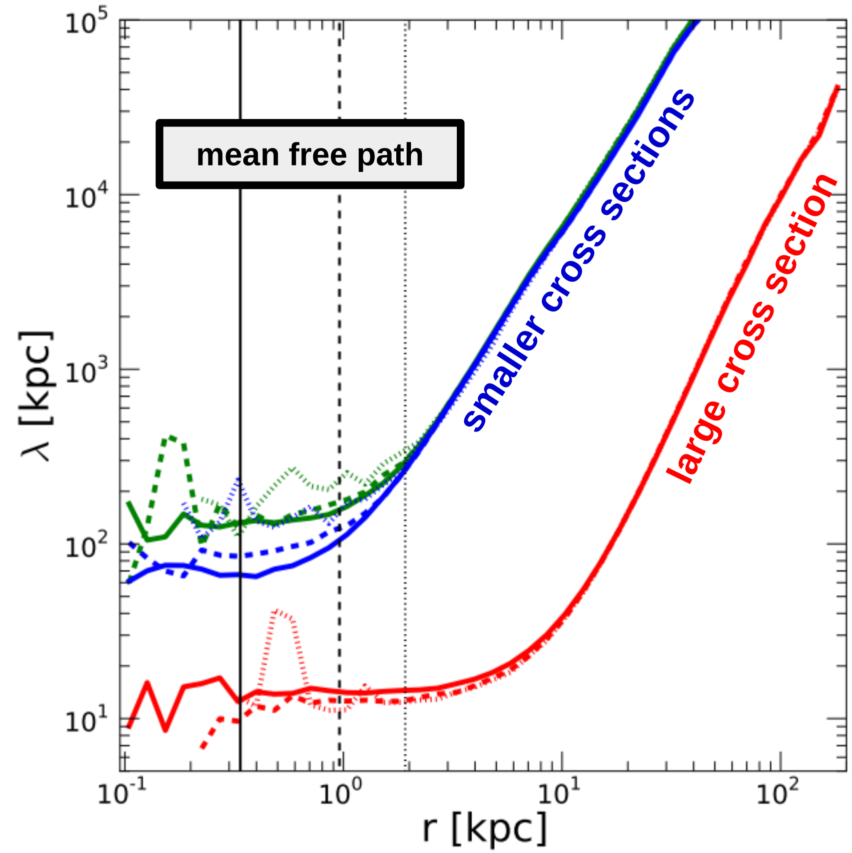
SIDM simulations alleviate the tension with TBTF problem

can be achieved with constant and velocity-dependent cross sections

How often do SIDM particles scatter on average?



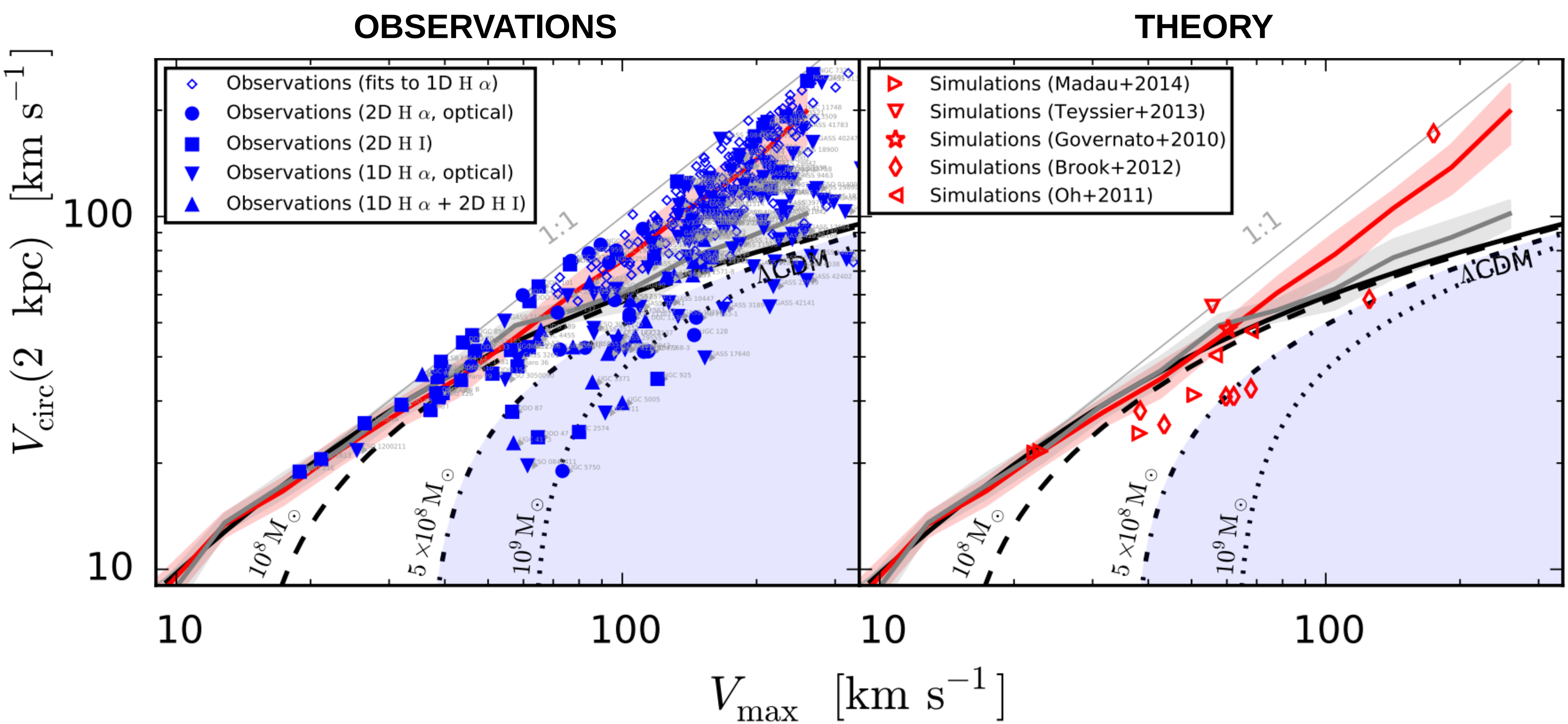
typically only a few scattering events per Hubble time are sufficient to create cores



~100 kpc mean free path in inner halo

MV, Zavala, Loeb 2012

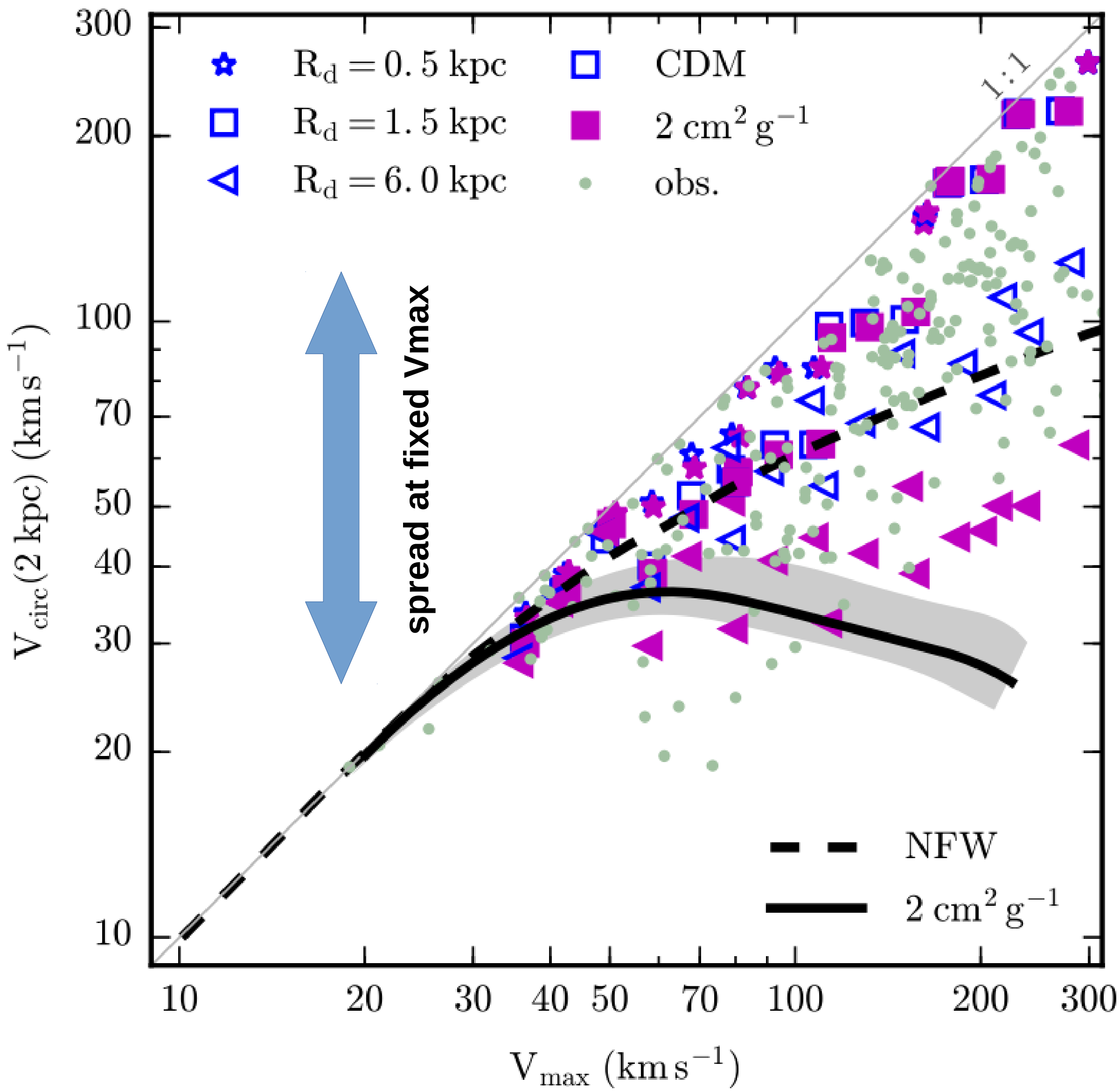
CDM: The Diversity Problem



"The **severity of the problem** … with the **apparent failure of 'baryon physics' to solve it** begs for the consideration of various alternatives [like] **'self-interacting' dark matter**,..."

Oman+ 2015

Diversity in SIDM?



increased diversity in SIDM simulations

self-interactions allow lower V_{circ}(2kpc) [low central densities in both baryons and dark matter]; high values of V_{circ}(2kpc) still achieved with compact baryonic disks

Creasey+ w/ MV 2017

[see also Ren+ 2018]

ETHOS – Effective Theory of Structure Formation: Ingredients

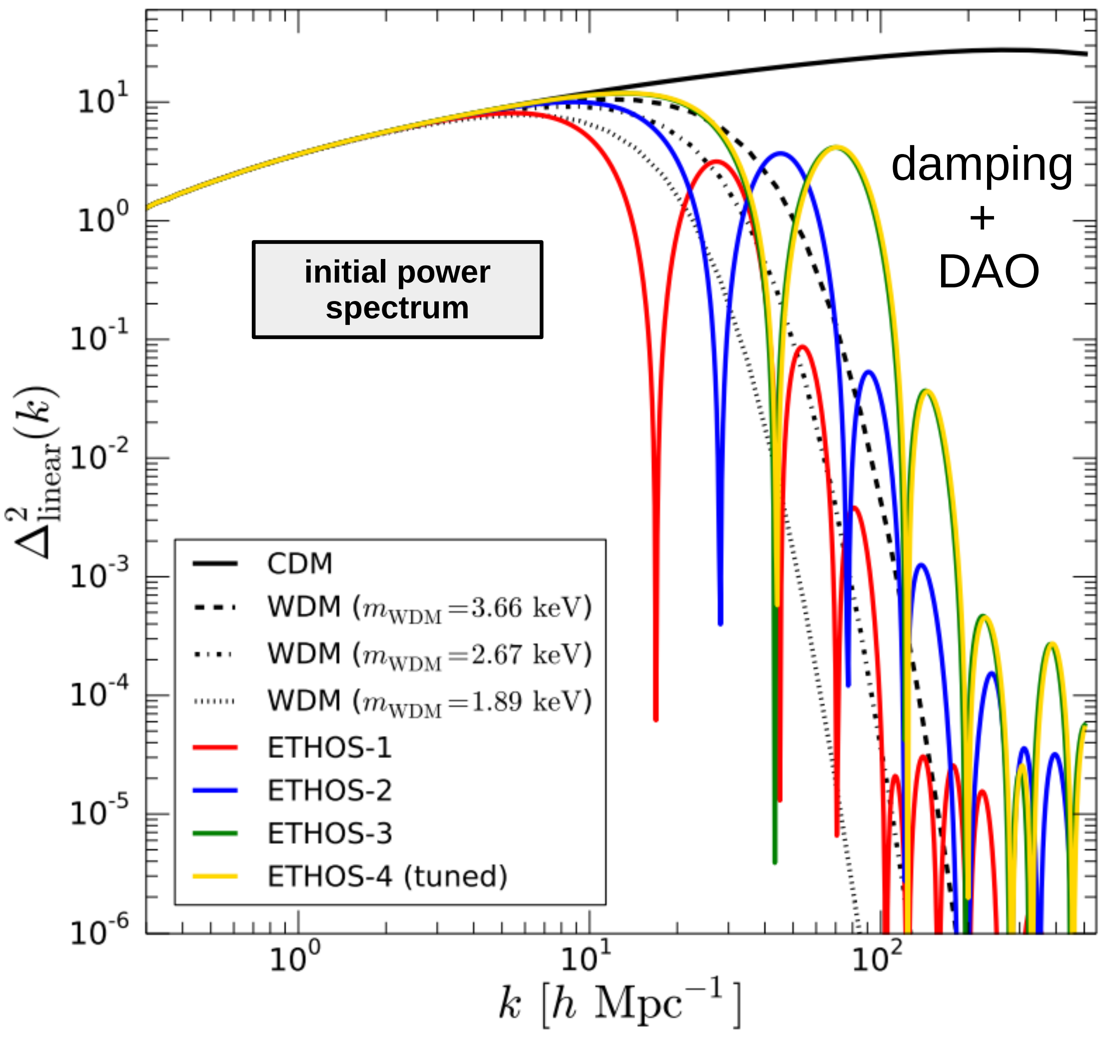
Basic Idea:

I) Effective theory of structure formation (ETHOS) enables cosmological structure formation to be computed in almost any microphysical model of dark matter physics.

II) Framework maps detailed microphysical theories of particle dark matter interactions into physical effective parameters that shape linear matter power spectrum and self-interaction transfer cross section of nonrelativistic dark matter.

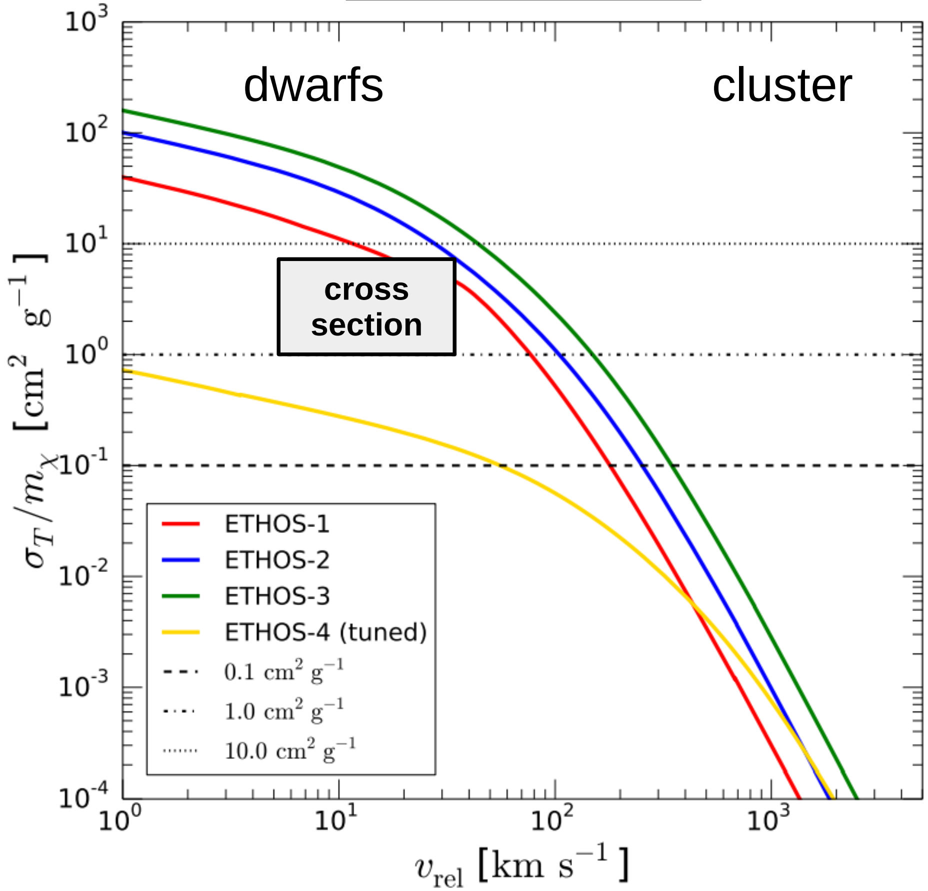
ETHOS – Effective Theory of Structure Formation: Ingredients

Initial Conditions



self-interactions affect evolution of early and late universe
=
self-consistent SIDM model

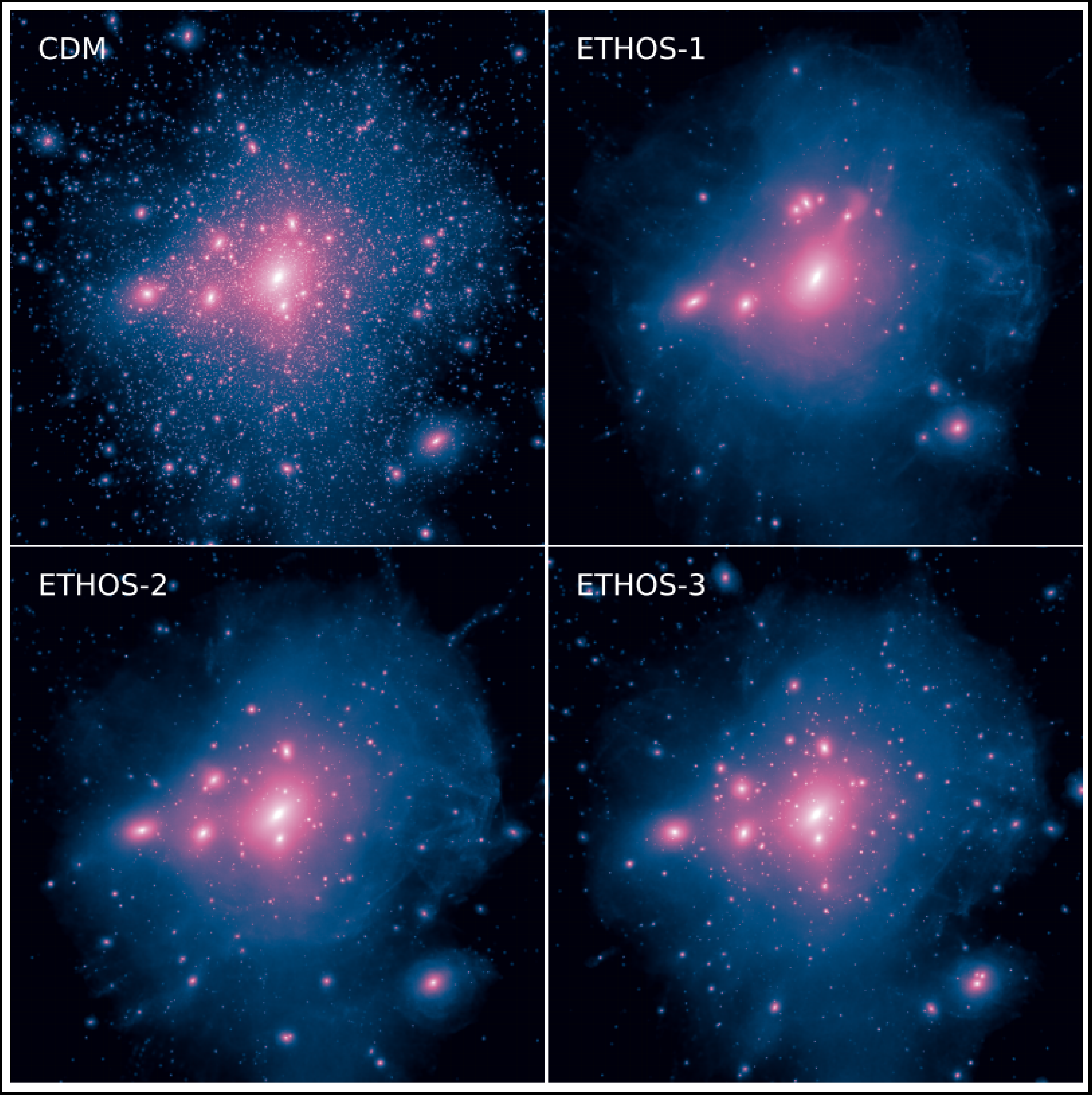
Self-Interactions



MV+ 2016

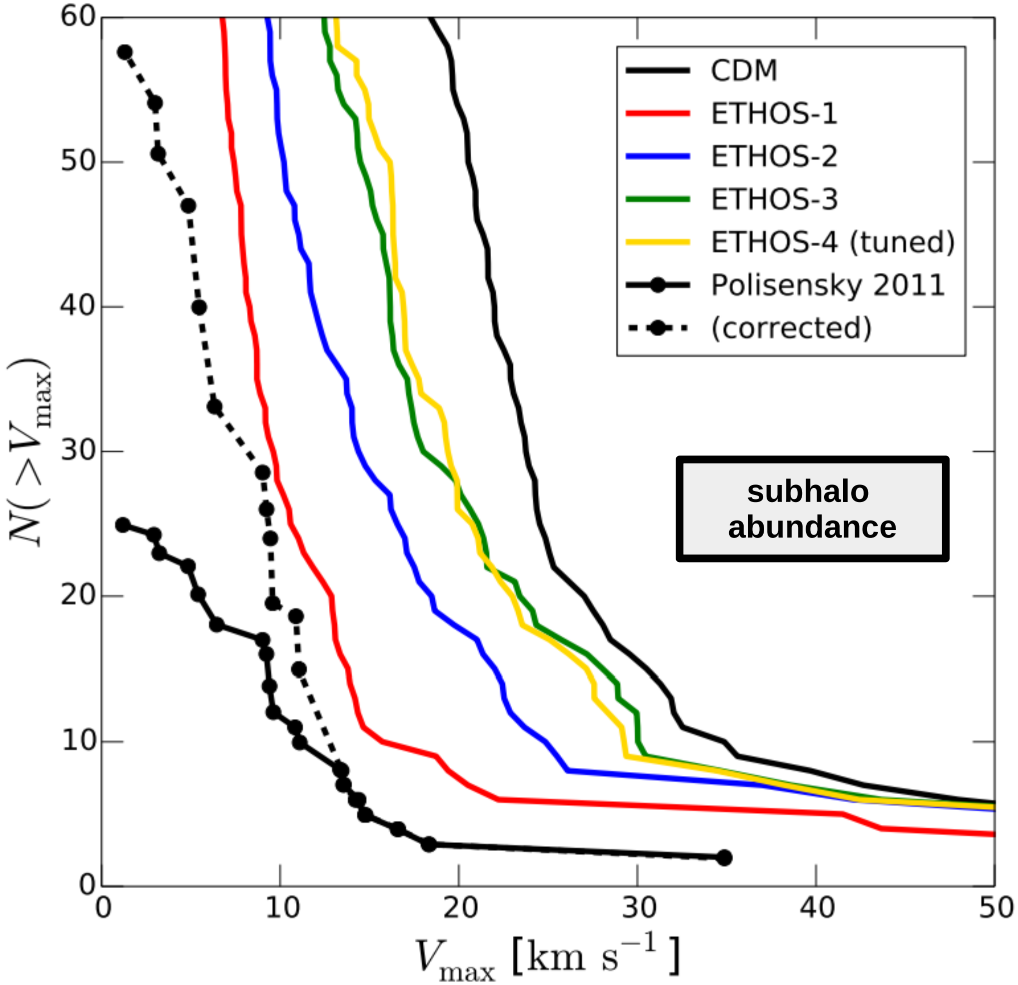
Cyr-Racine+ 2016

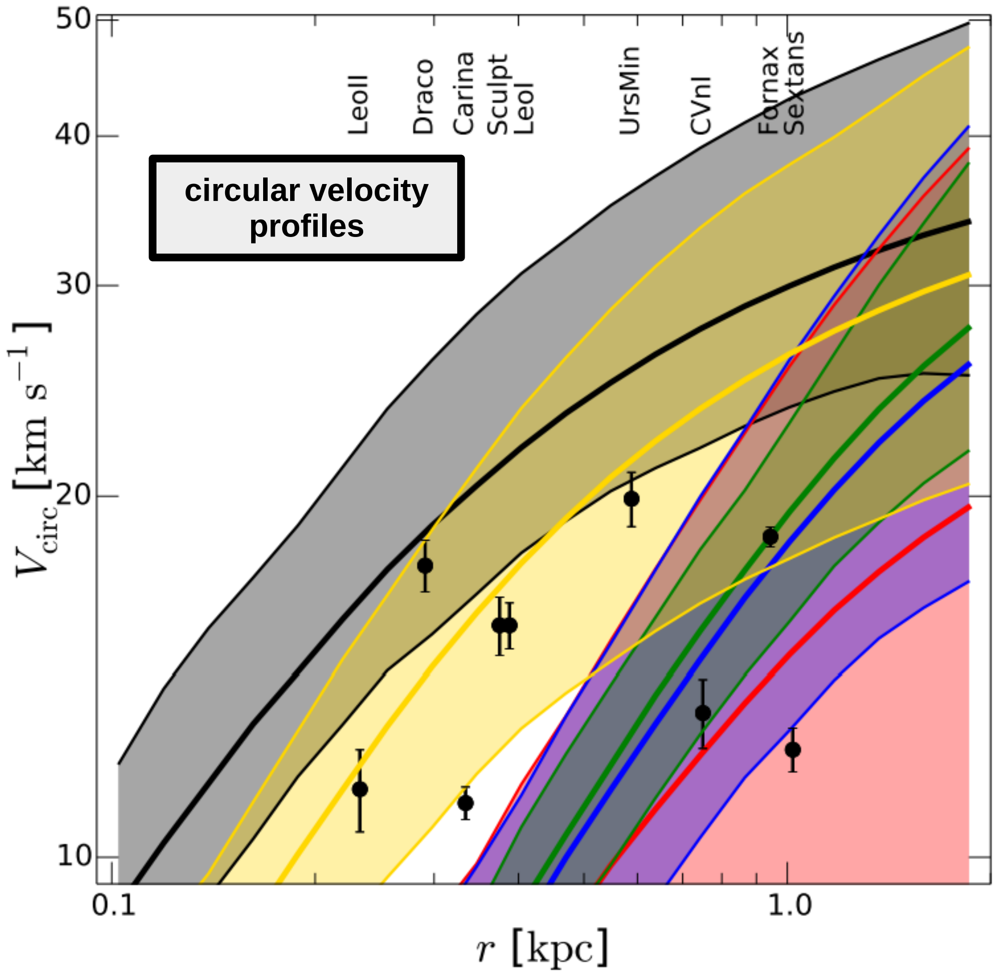
ETHOS: A Milky Way-like Halo Simulation



MV+ 2016

ETHOS: Impact on Milky Way Subhalos





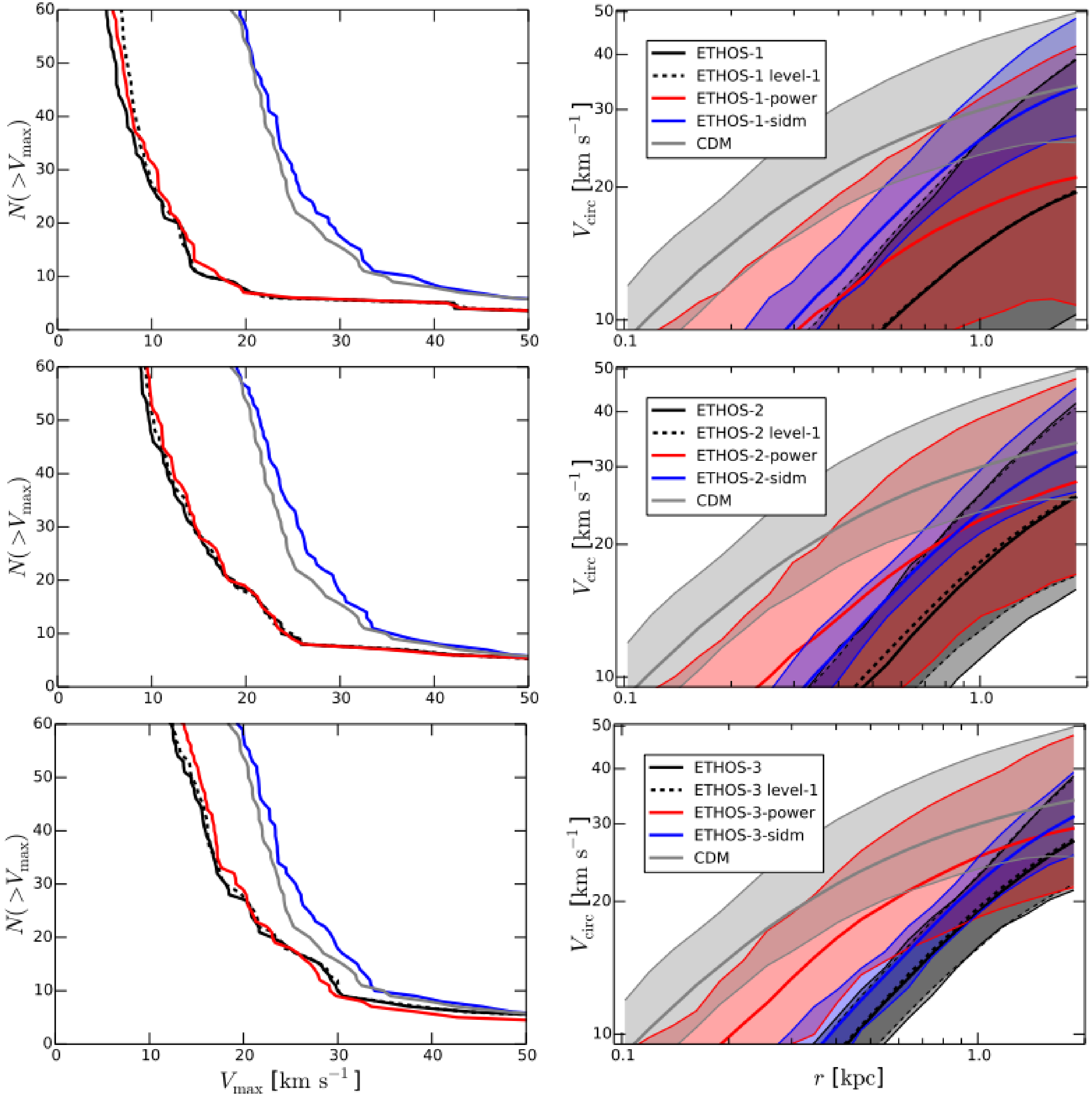
both CDM abundance and structural properties altered simultaneously

MV+ 2016

ETHOS: Damping vs. SIDM

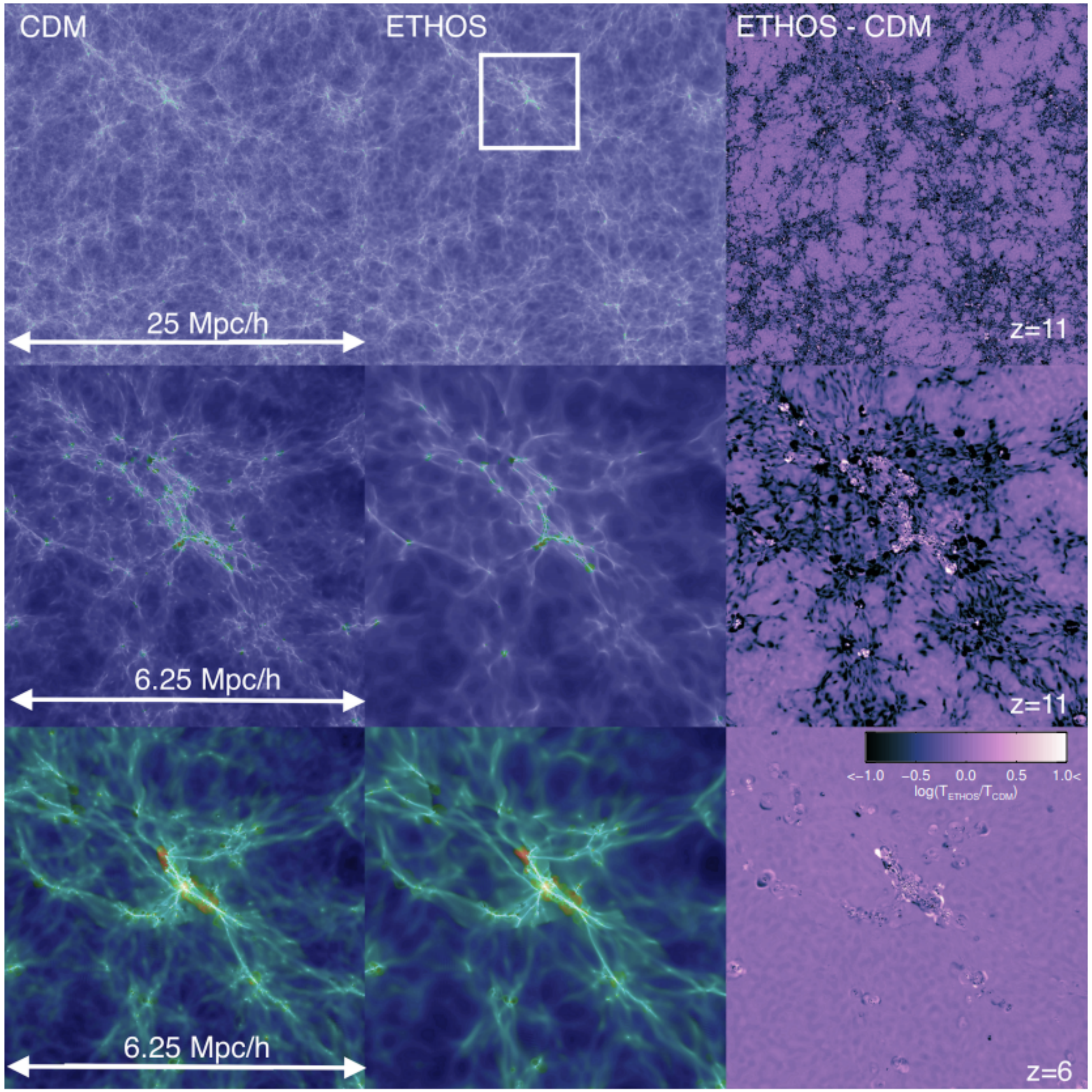
disentangling the impact of SIDM and power spectrum modifications

self-interactions do not change the subhalo abundance

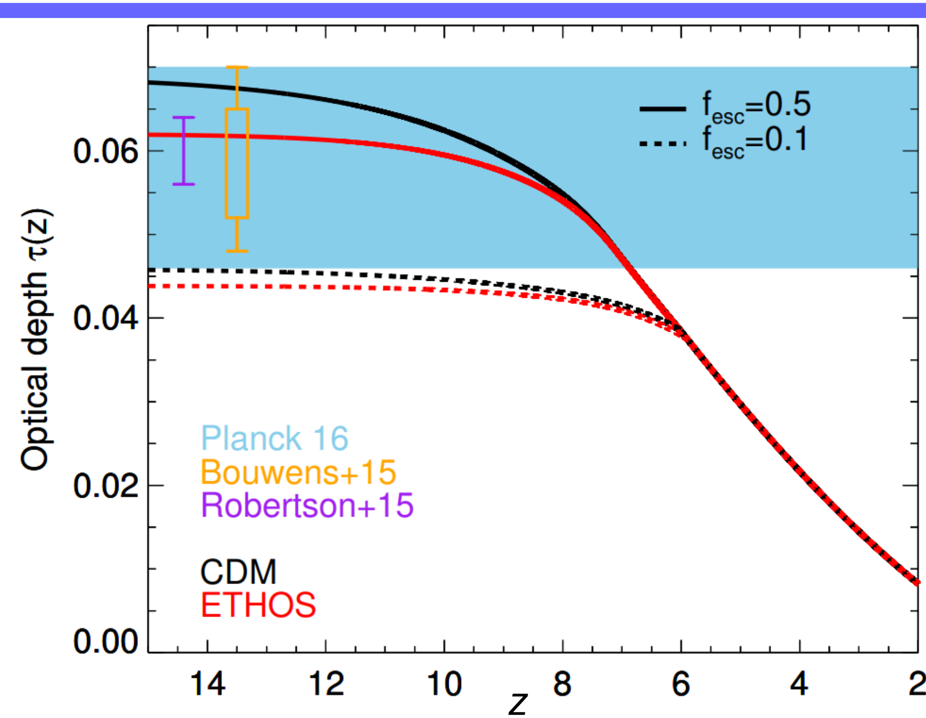


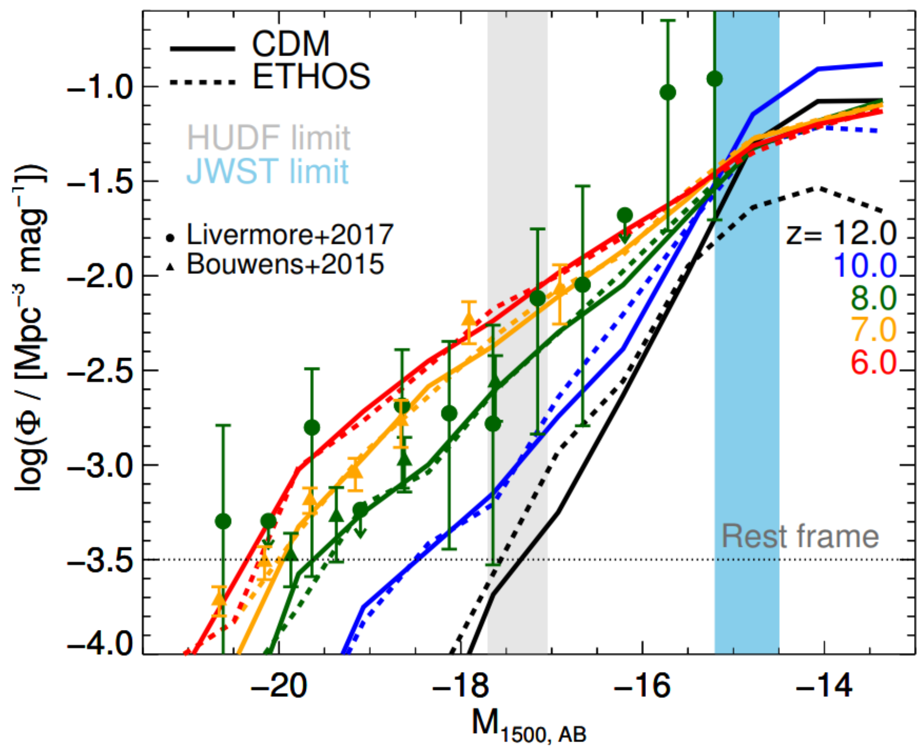
MV+ 2016

ETHOS: The High-Redshift Universe

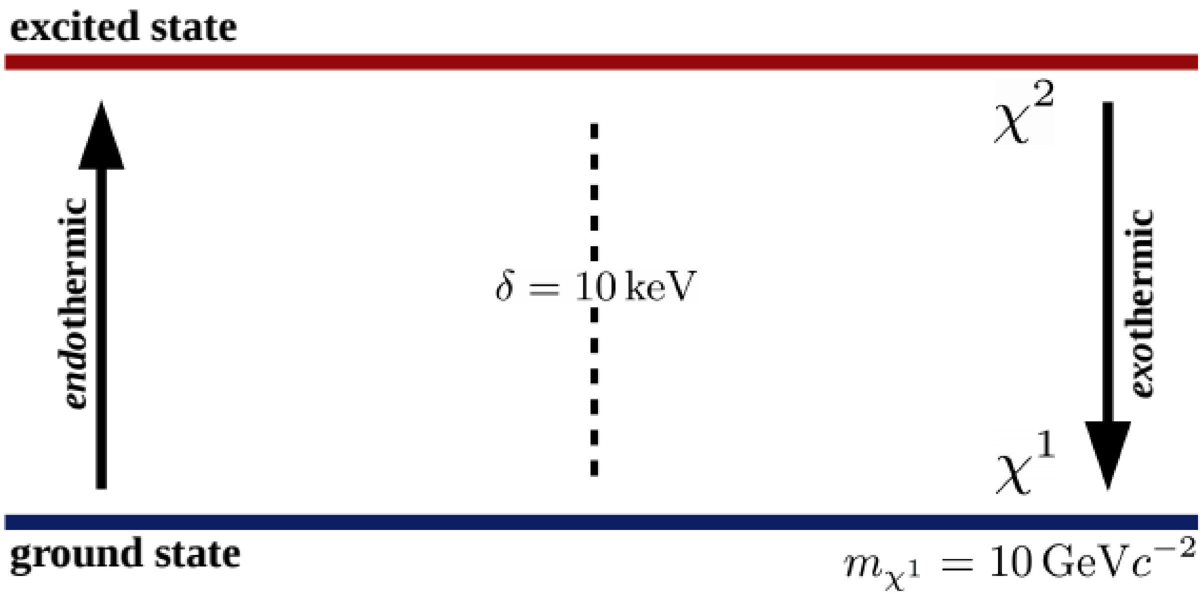


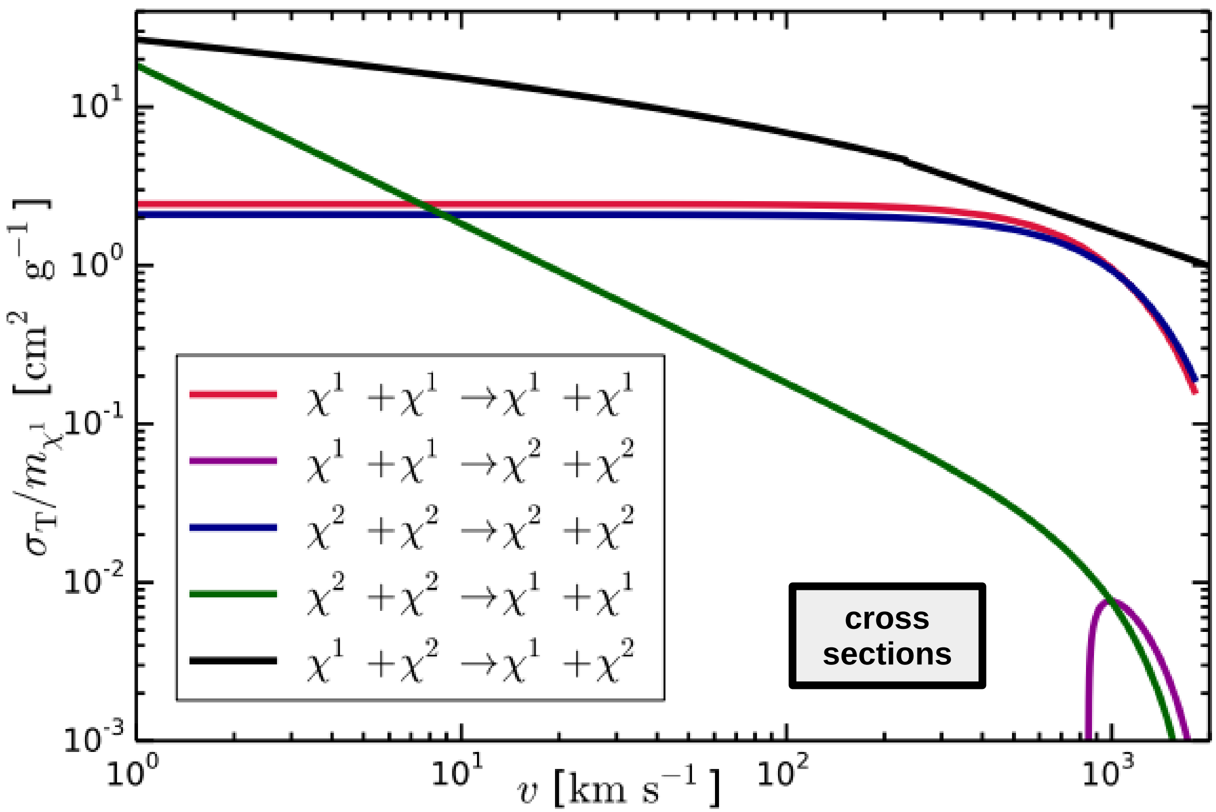
Lovell, Zavala, MV+ 2018





Inelastic SIDM: Two-State SIDM Model





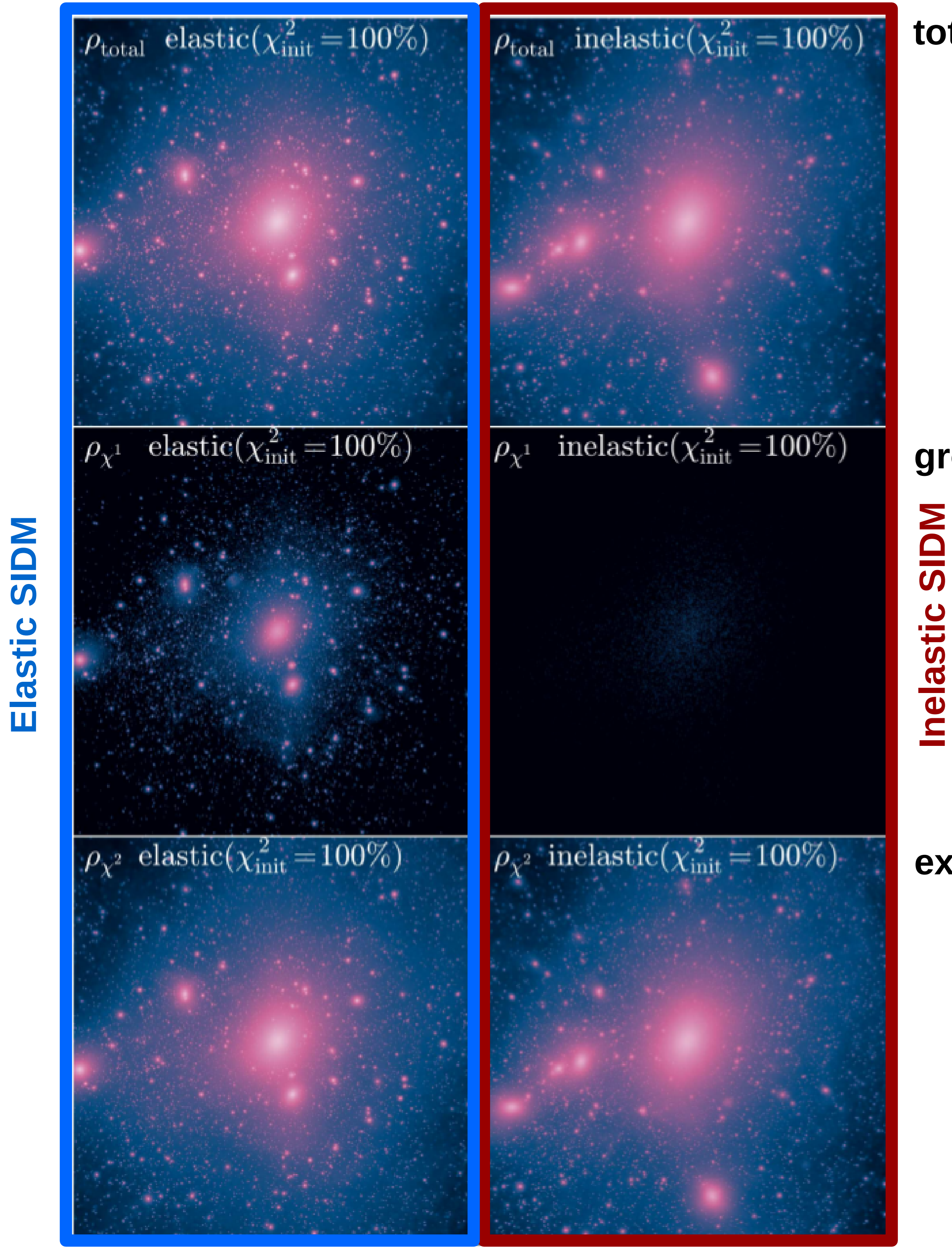
How does structure formation change if we allow for inelastic collisions?

specific model allows exothermic, but no endothermic reactions

MV, Zavala, Schutz, Slatyer 2019

[see also Todoroki & Medvedev 2018]

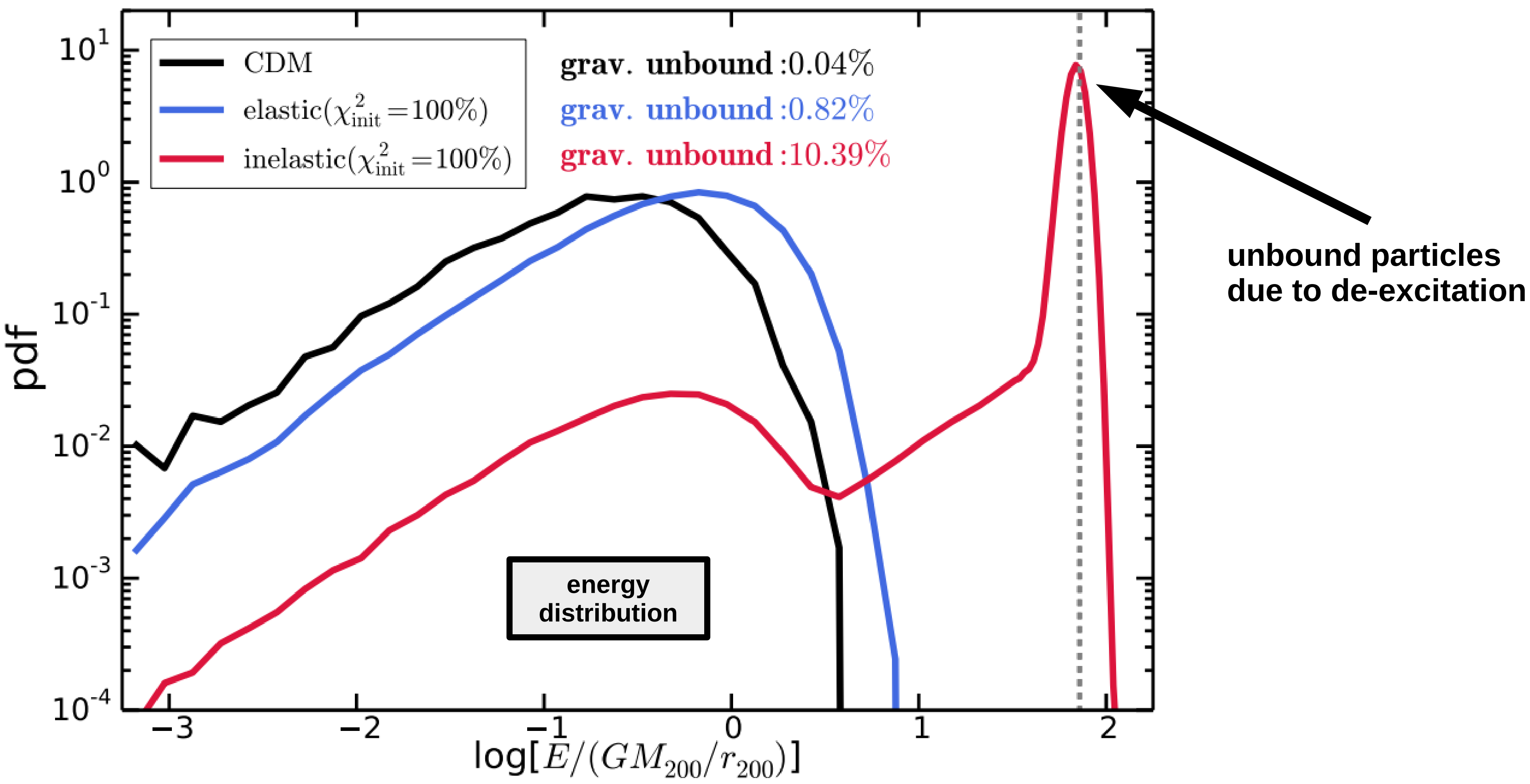
Elastic SIDM vs. Inelastic SIDM



exothermic reactions
'evaporate' halo cores

MV, Zavala, Schutz, Slatyer 2019

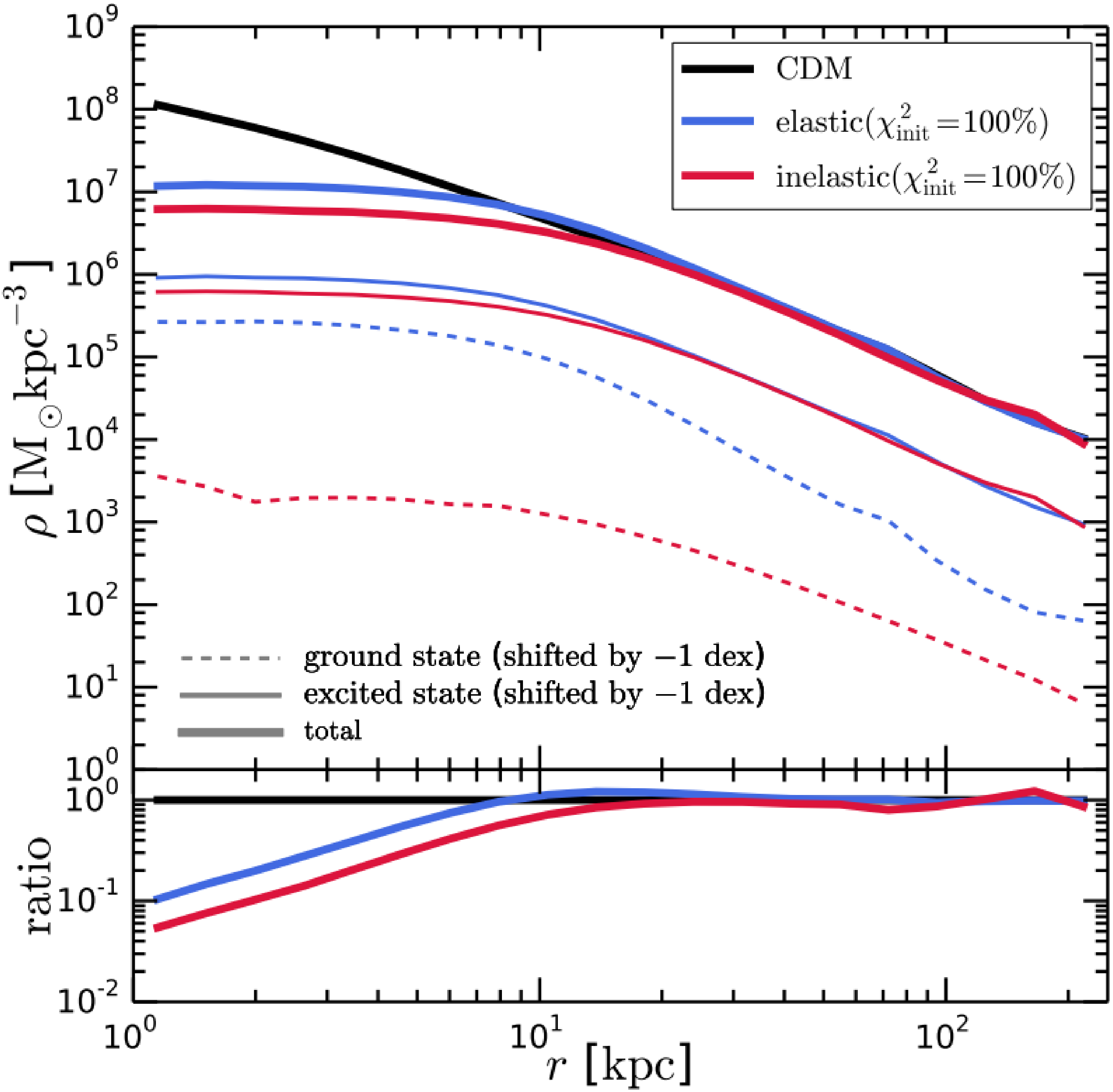
Evaporation: Unbinding Dark Matter Particles From Halo



dimensionless energy distribution of gravitationally unbound particles

MV, Zavala, Schutz, Slatyer 2019

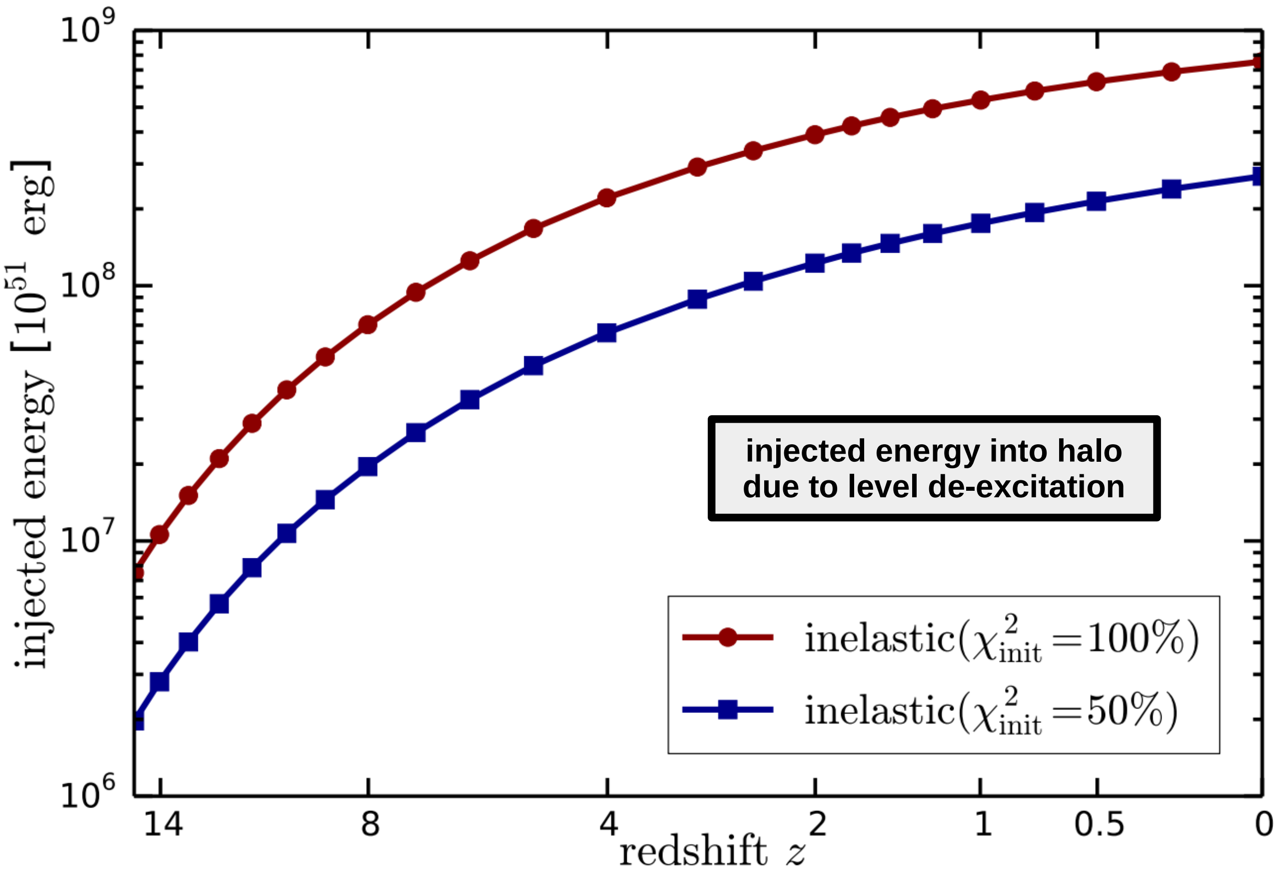
Inelastic SIDM: Halo Dark Matter Density Profiles



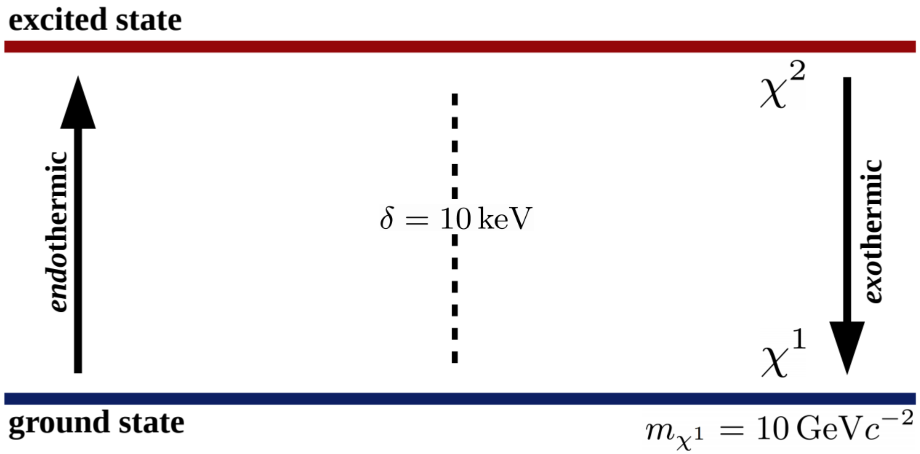
more efficient core formation within inelastic SIDM

MV, Zavala, Schutz, Slatyer 2019

Inelastic SIDM: Injected Energy

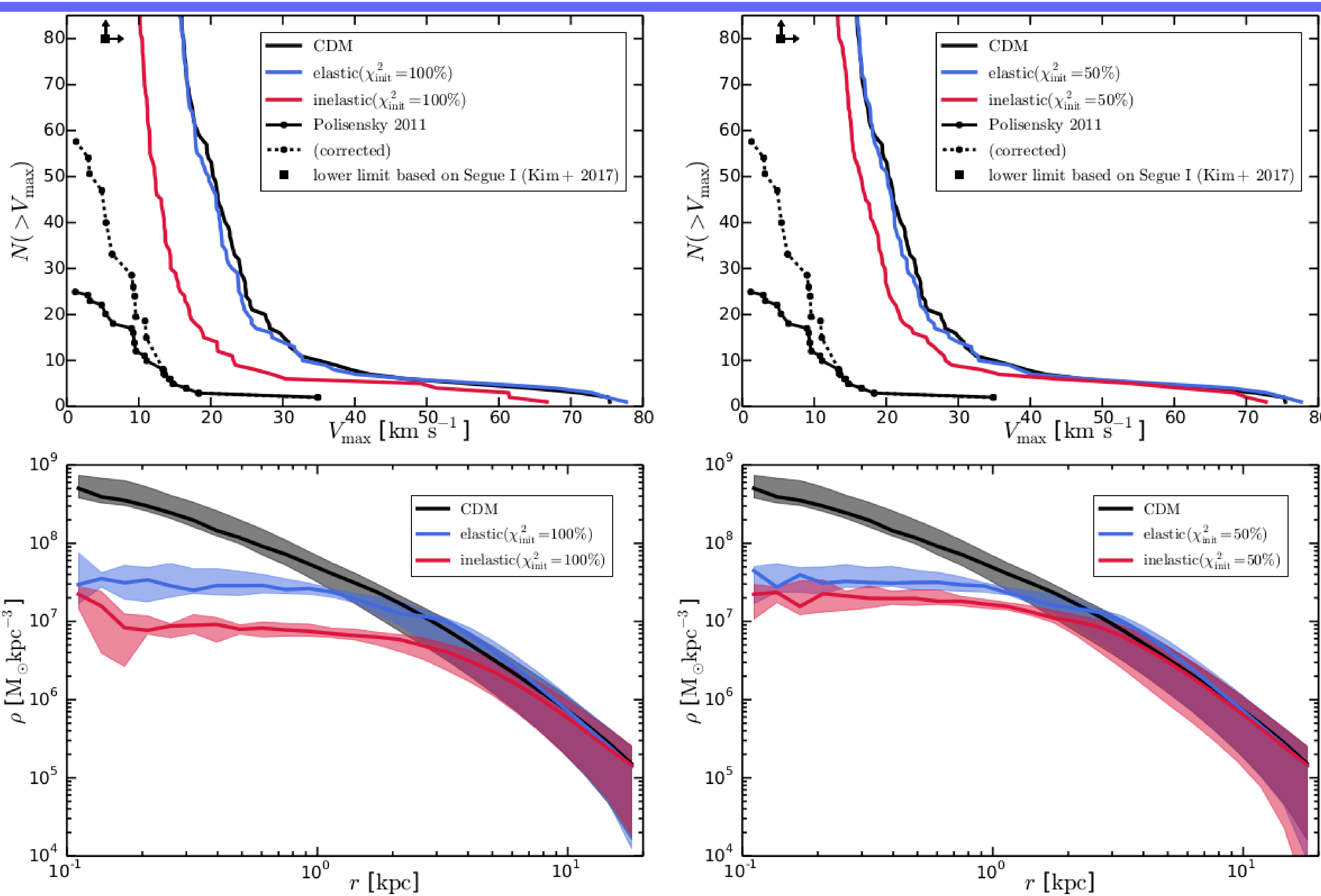


energy injection is equivalent to a few 100 million supernovae type II



MV, Zavala, Schutz, Slatyer 2019

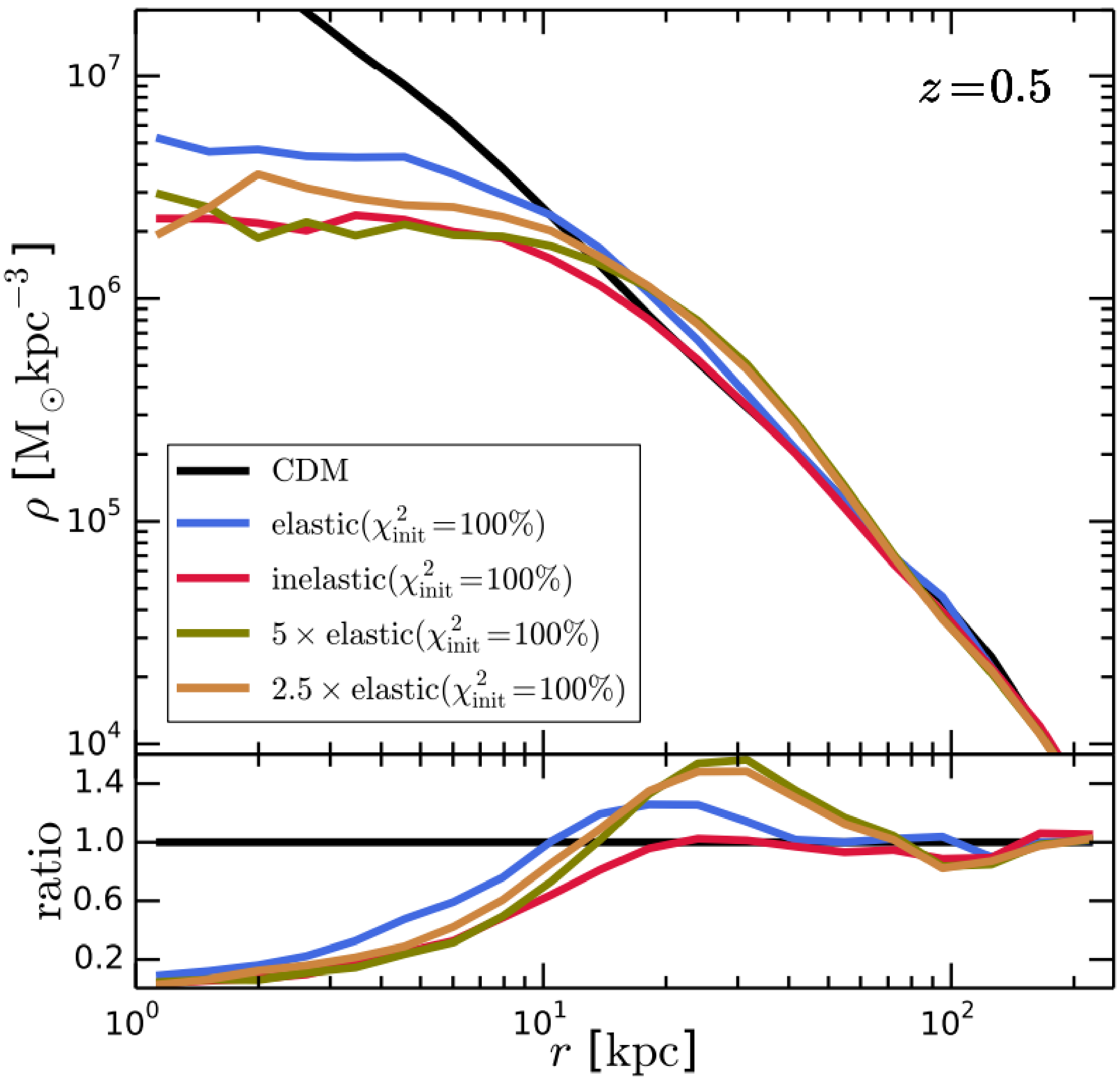
Subhalo Properties



inelastic SIDM creates larger subhalo cores than elastic SIDM for the same cross section normalization

MV, Zavala, Schutz, Slatyer 2019

Comparison to Elastic Models: Implications for Cross Section Constraints



an elastic model with a ~5 times larger cross section leads to a central density reduction similar to the inelastic model

implications for cross section constraints?

MV, Zavala, Schutz, Slatyer 2019

Summary

- **CDM galaxy formation simulations reproduce observed galaxy population on large scales (e.g., clustering, luminosity functions, etc.)**

- **SIDM can alleviate outstanding small-scale CDM problems (e.g., too-big-to-fail problem, diversity problem, etc.)**

- **ETHOS: self-consistent SIDM models with modified initial conditions (i.e. early and late self interactions)**

- **inelastic SIDM creates larger density cores for the same cross section normalization (i.e. can create same core sizes as elastic models with smaller cross section normalization)**

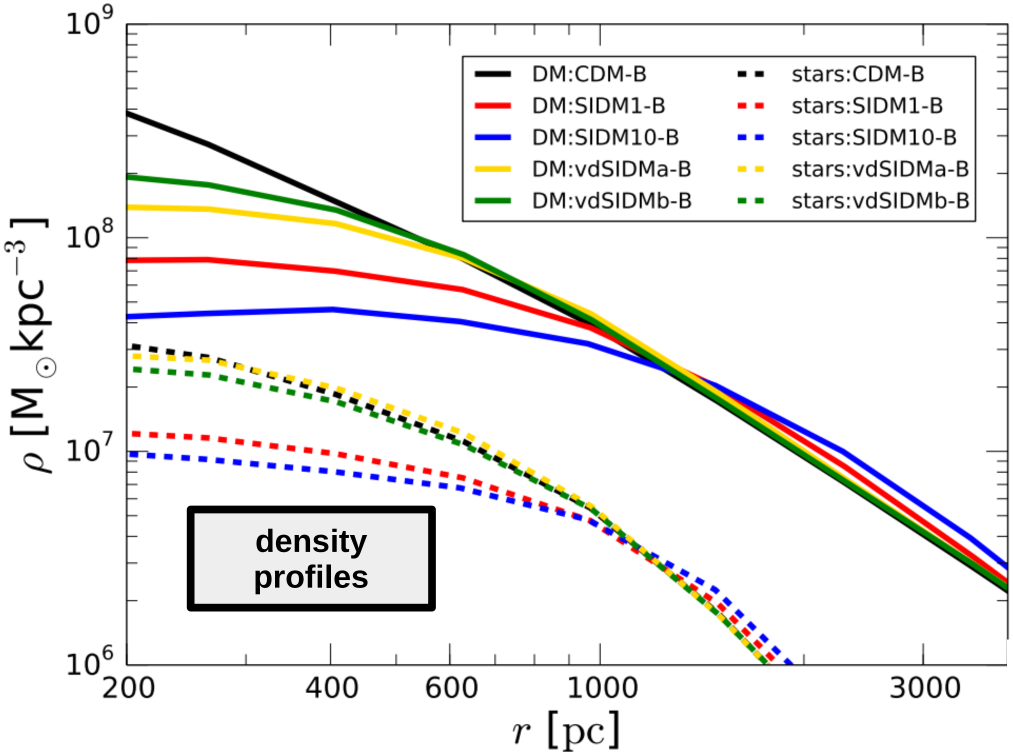
Summary

- CDM galaxy formation simulations reproduce observed galaxy population on large scales (e.g., clustering, luminosity functions, etc.)
- SIDM can alleviate outstanding small-scale CDM problems (e.g., too-big-to-fail problem, diversity problem, etc.)
- ETHOS: self-consistent SIDM models with modified initial conditions (i.e. early and late self interactions)
- inelastic SIDM creates larger density cores for the same cross section normalization (i.e. can create same core sizes as elastic models with smaller cross section normalization)

Future?

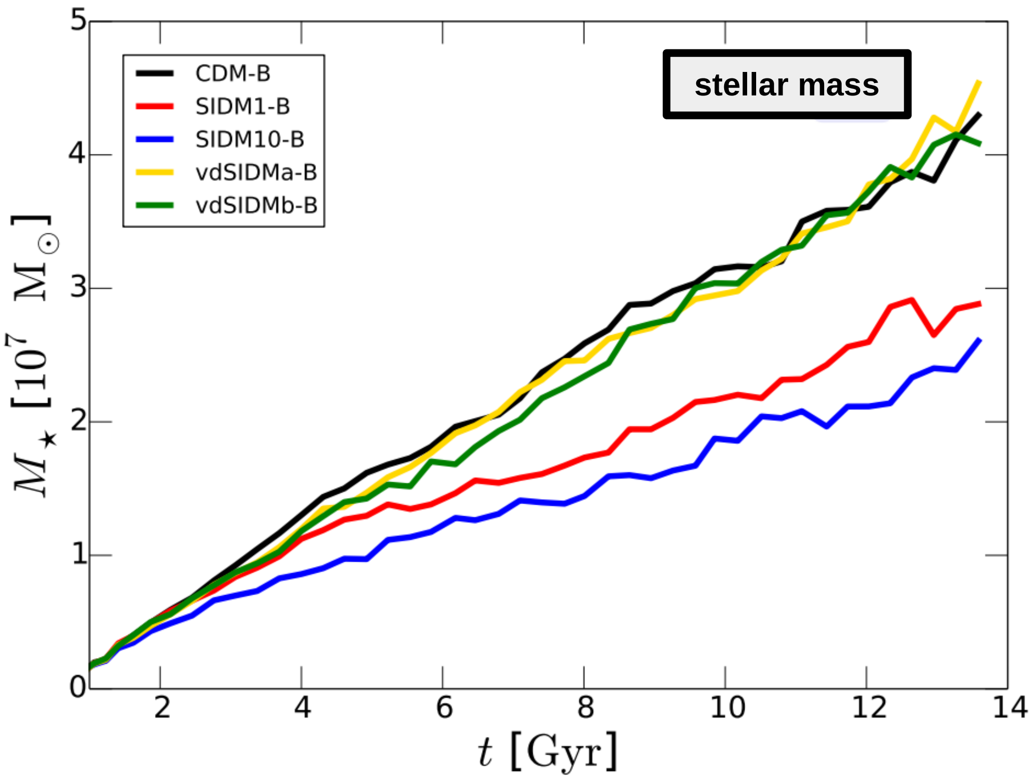
- More SIDM simulations with baryonic physics and better understanding of their interplay.
- Retuning of feedback physics?
- How to distinguish baryonic feedback effects from alternative DM?

SIDM: DM + Baryons



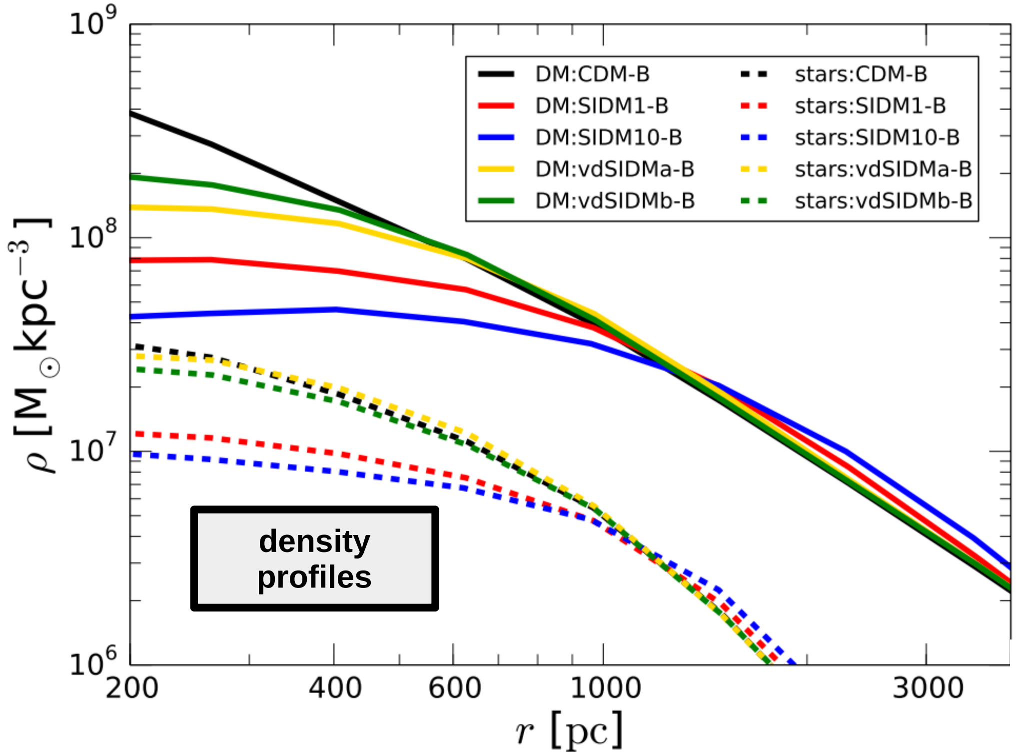
dwarf galaxy within CDM and different SIDM models with baryons using Illustris (~IllustrisTNG) galaxy formation model

MV+ 2014



stellar density profile correlates with central cross section leading to lower central densities for models with larger central cross sections

SIDM: DM + Baryons



dwarf galaxy within CDM and different SIDM models with baryons using Illustris (~IllustrisTNG) galaxy formation model

MV+ 2014

Based on our results, the discovery of dark matter cores on the scale of $r_{1/2}$ in field dwarf galaxies with $M_\star \lesssim 3 \times 10^6\ \mathrm{M_\odot}$ would imply one of the following: (1) dark matter is cold but the implementation of astrophysical processes in current codes is incomplete; (2) there is a large scatter in the halo masses of dwarf galaxies with $M_\star \lesssim 3 \times 10^6\ \mathrm{M_\odot}$; or (3) dark matter has physics beyond that of a cold and collisionless thermal relic – perhaps self-interactions of the kind explored here.

Robles+ 2017 [SIDM + FIRE]