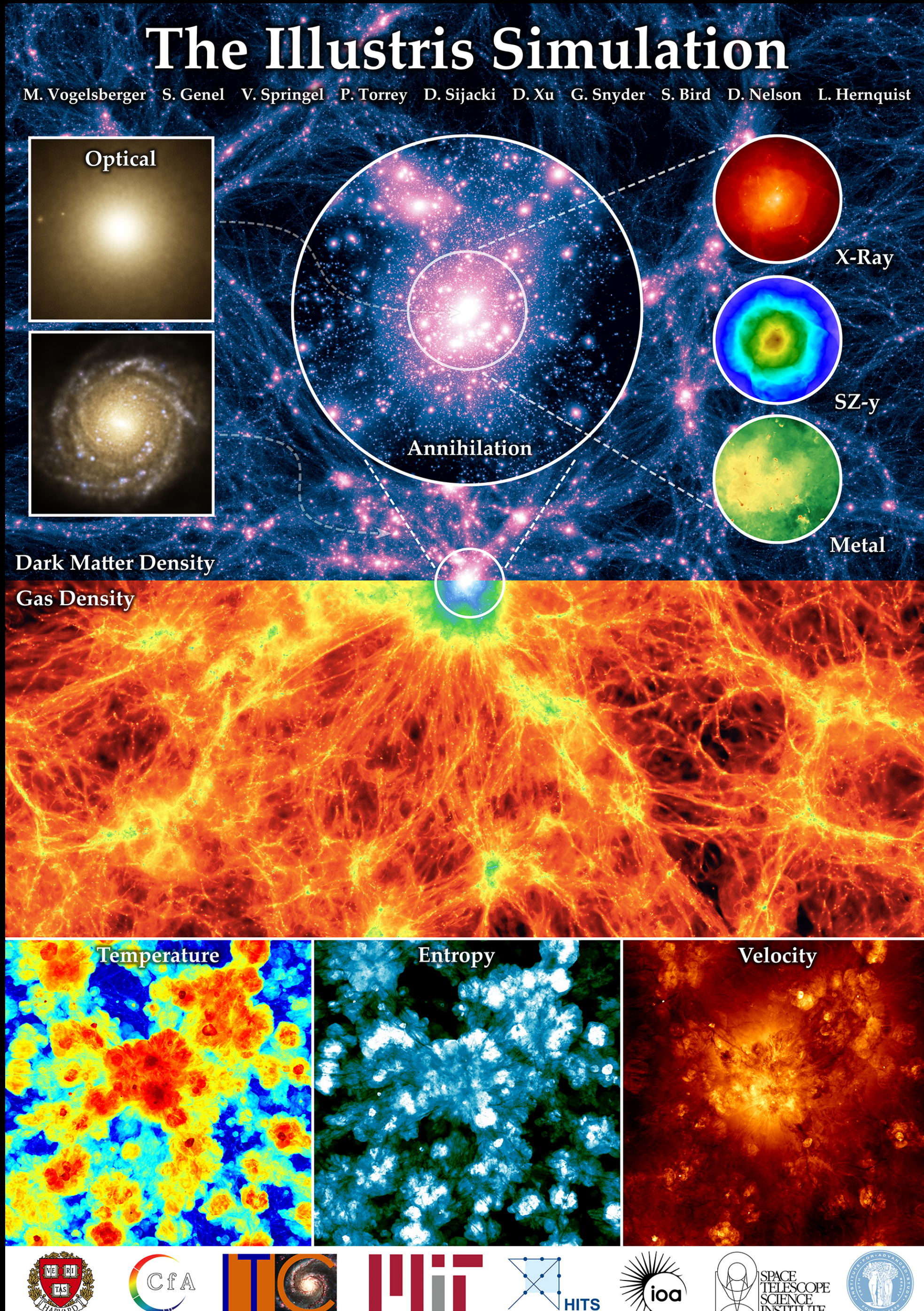
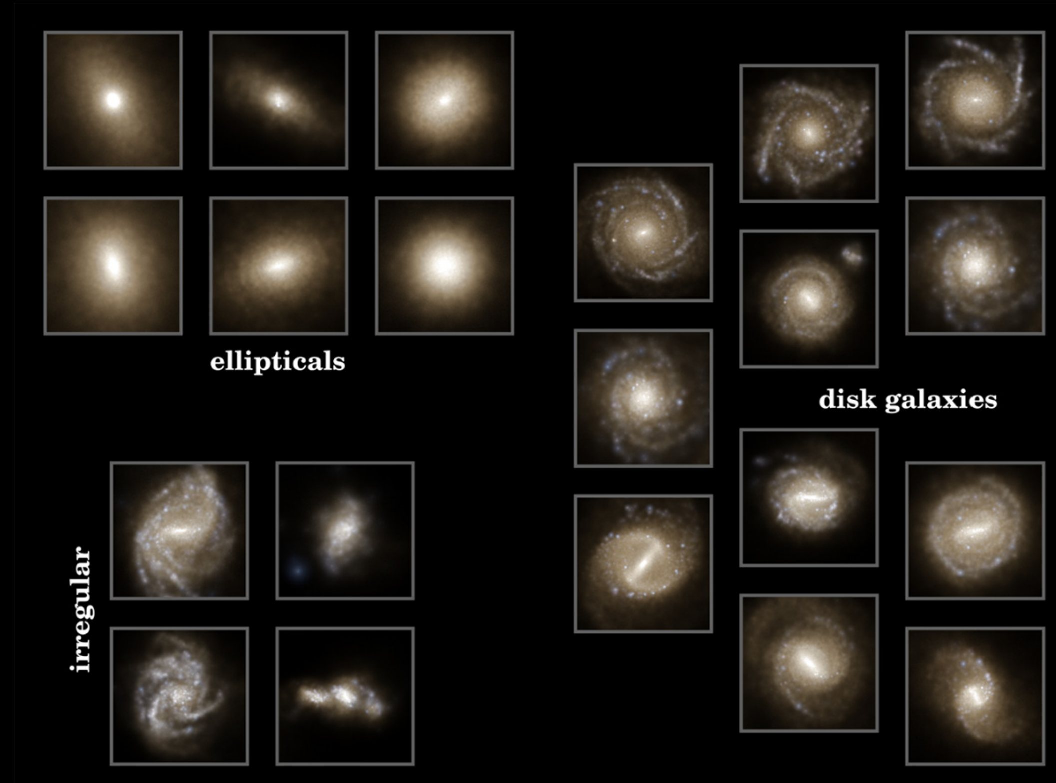
Simulations of Self-Interacting Dark Matter

Mark Vogelsberger

SIDM Workshop, Niels Bohr Institute
Copenhagen, August 2017

Massachusetts Institute of Technology





MV+ 2014

http://www.illustris-project.org

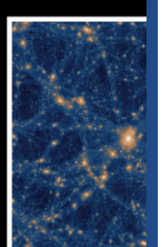
The IllustrisTNG Simulations

IllustrisTNG Team:

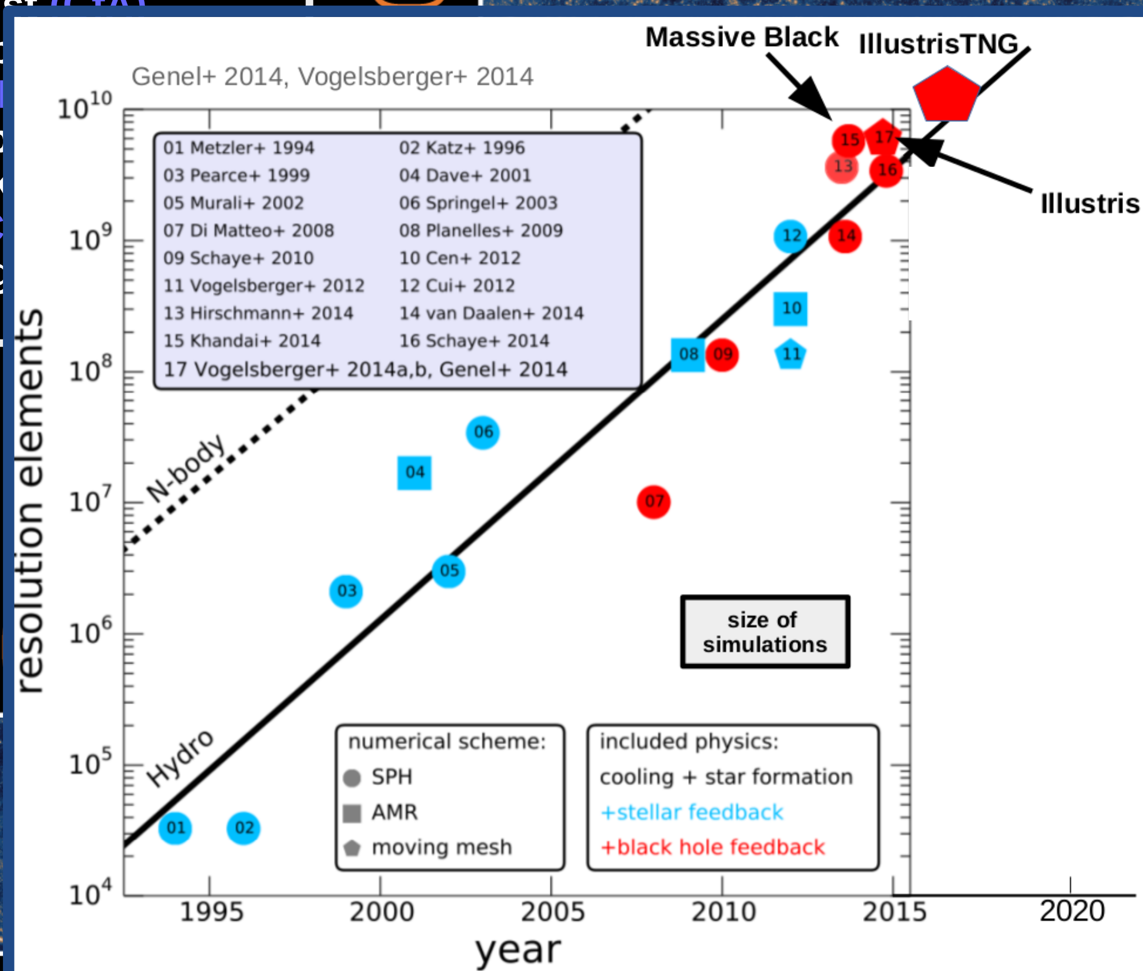
Annalisa Pillepich (MPIA)
Dylan Nelson (MPA)
Federico Marinacci (MIT)
Jill Naiman (CfA)
Lars Hernquist (CfA)
Mark Vogelsb
Paul Torrey (
Rainer Weinb
Ruediger Pak
Shy Genel (C
Volker Spring

- three boxes with different primary science focus
- in total ~200 million CPUh

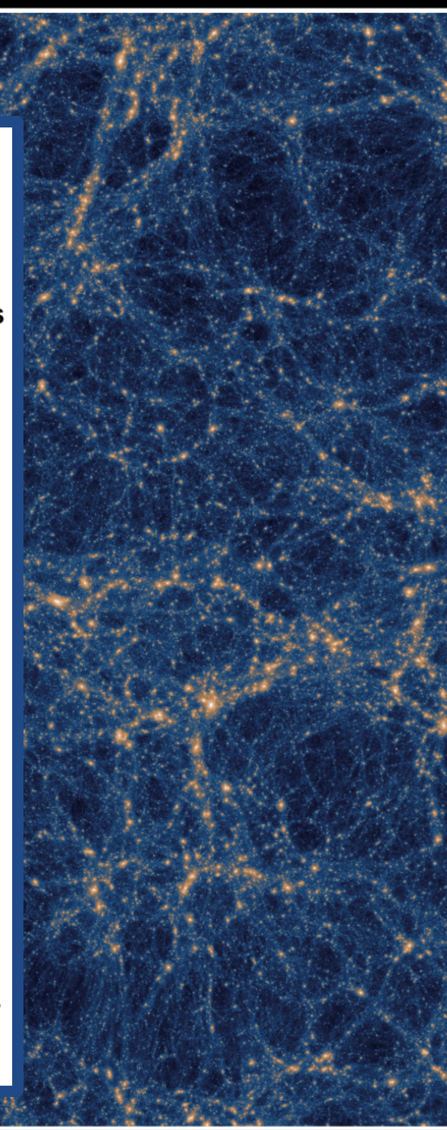
TNG5



dwarfs



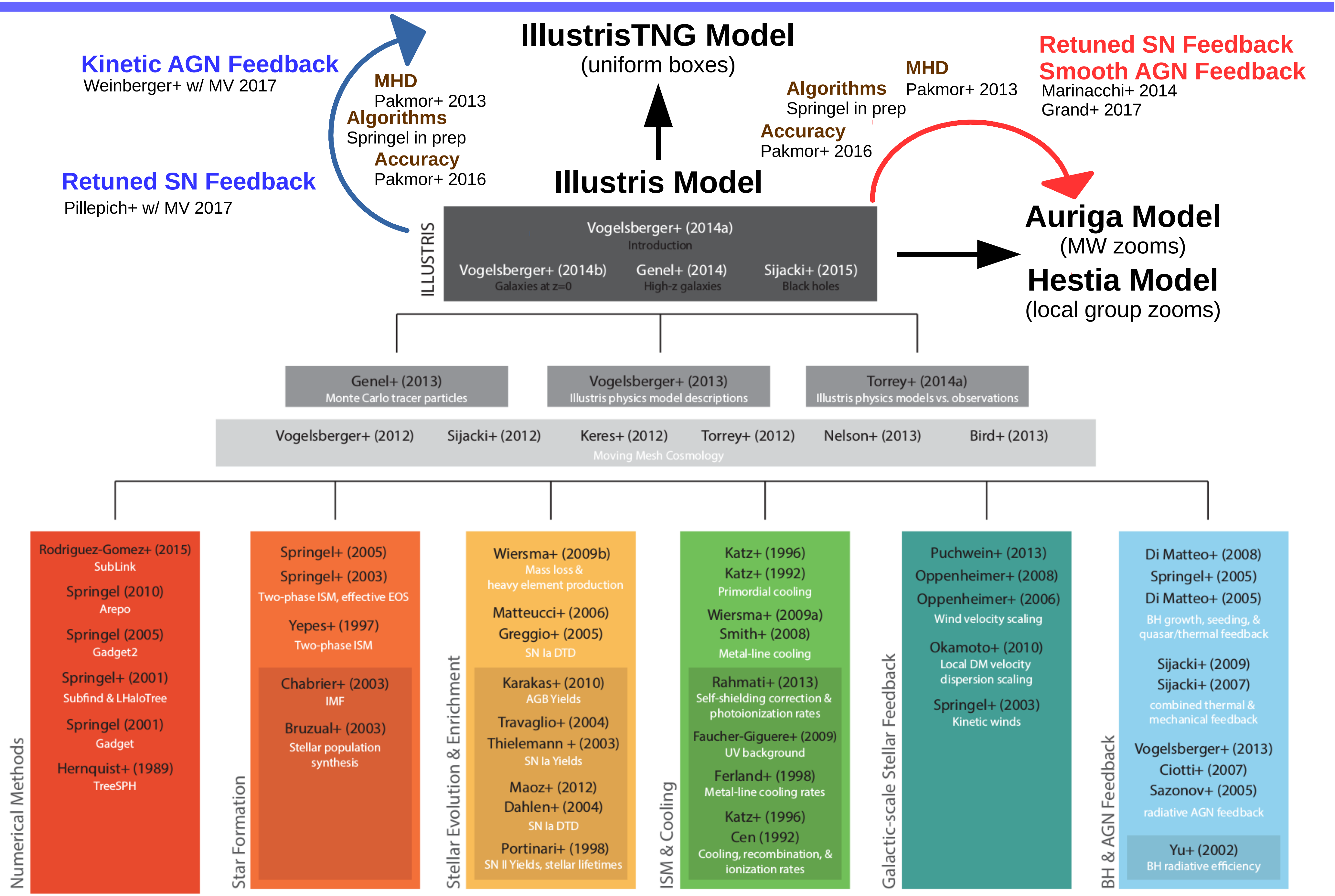
L* galaxies
(Illustris volume)



galaxy clusters

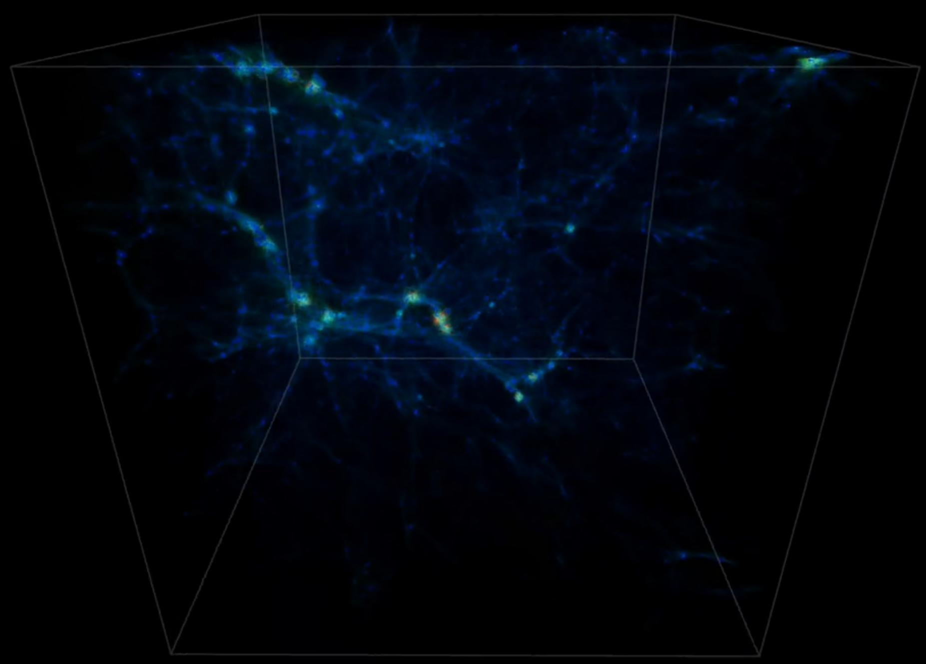
Credit: Dylan Nelson

Arepo Galaxy Formation Models: Illustris, IllustrisTNG, Auriga, Hestia

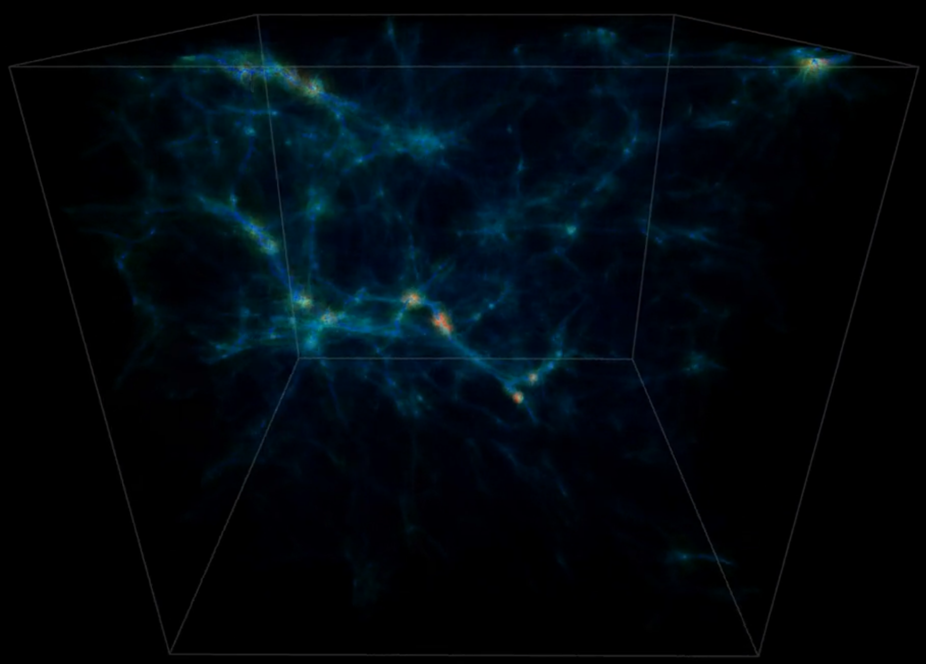


Nelson+ w/ MV 2015

Illustris (temperature)



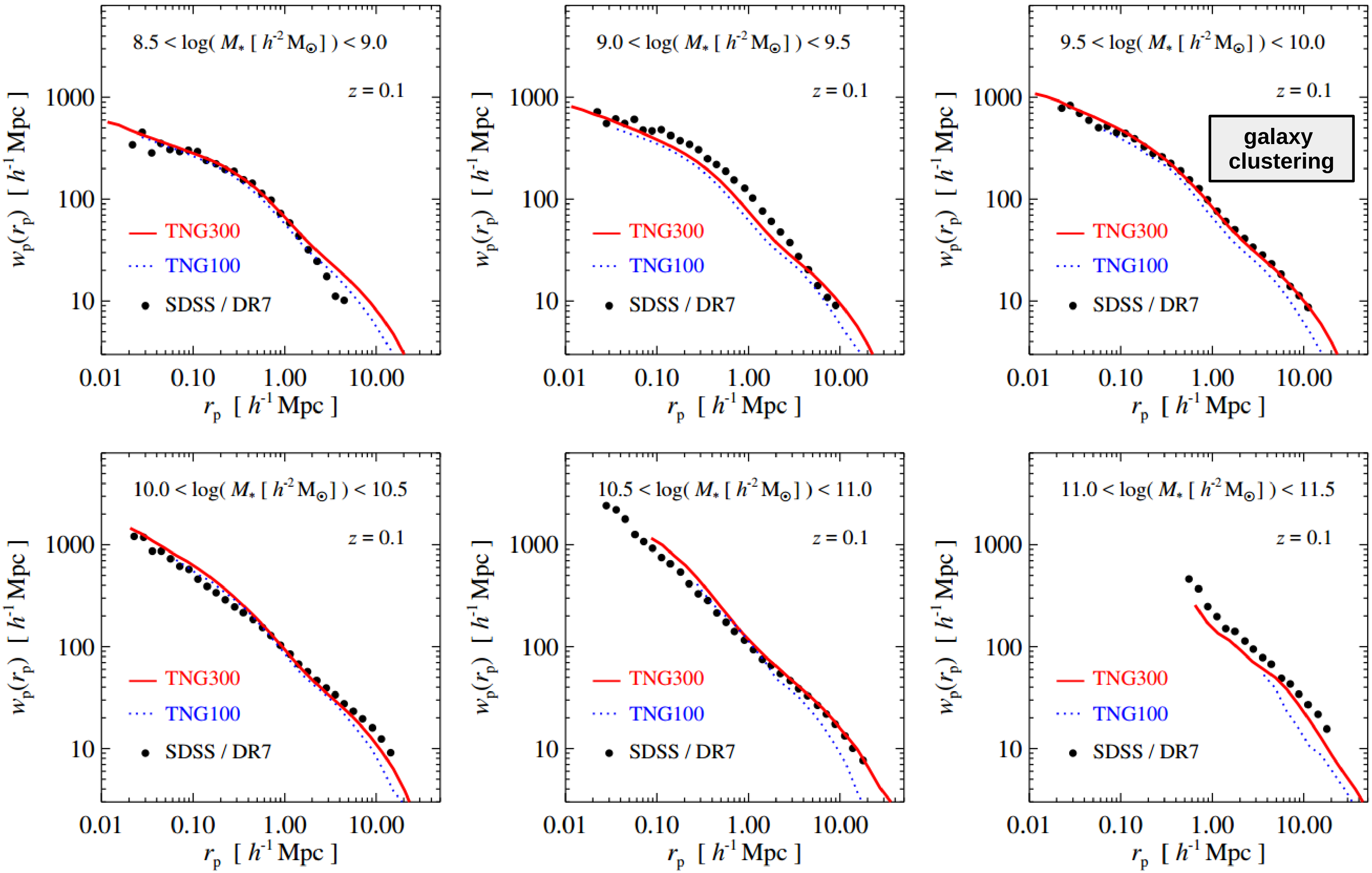
IllustrisTNG (temperature)



redshift : 3.94
Time since the Big Bang : 1.6 billion years

Mark Vogelsberger (MIT)

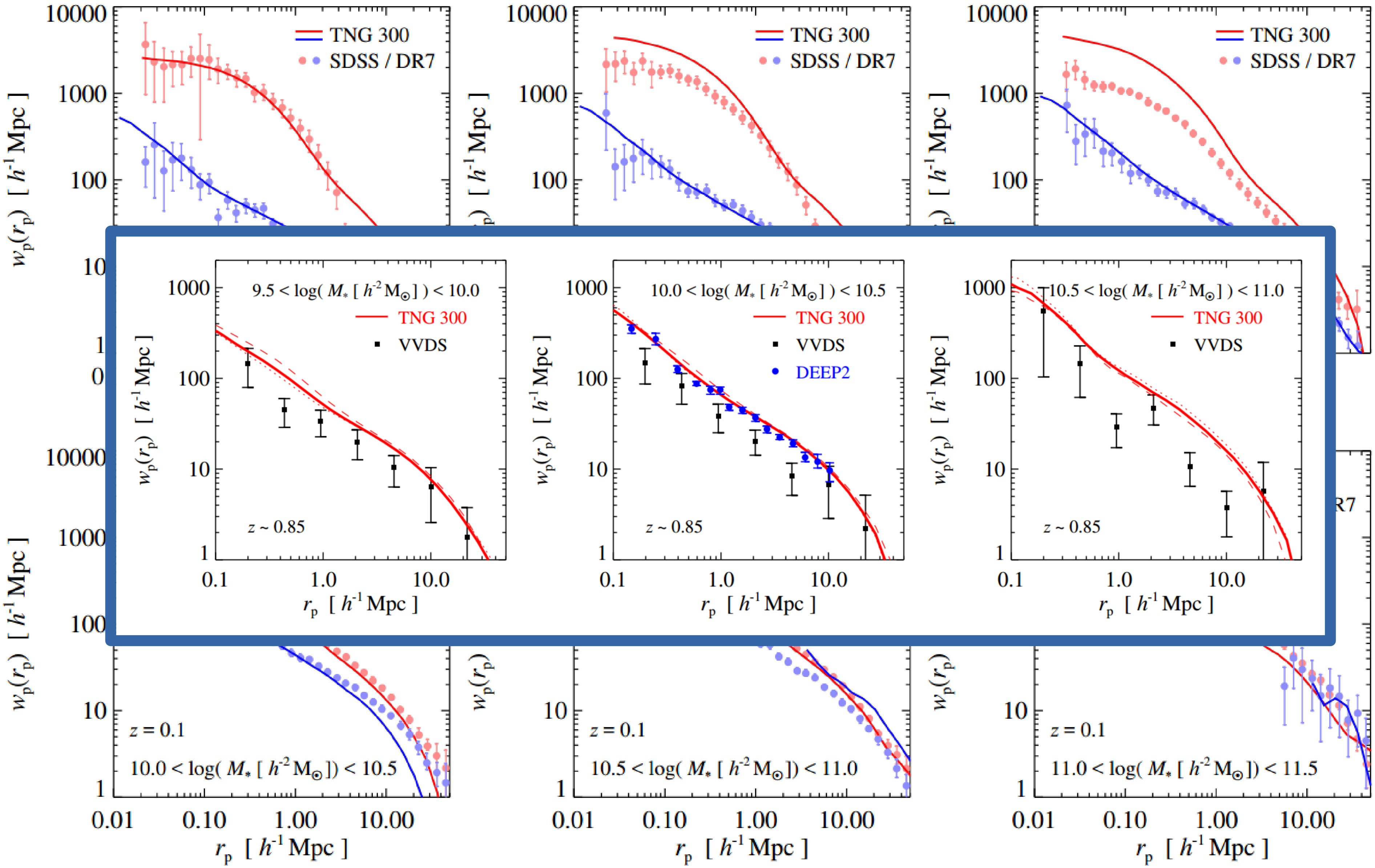
Large Scales: CDM works



Springel+ w/ MV 2017

LCDM clustering

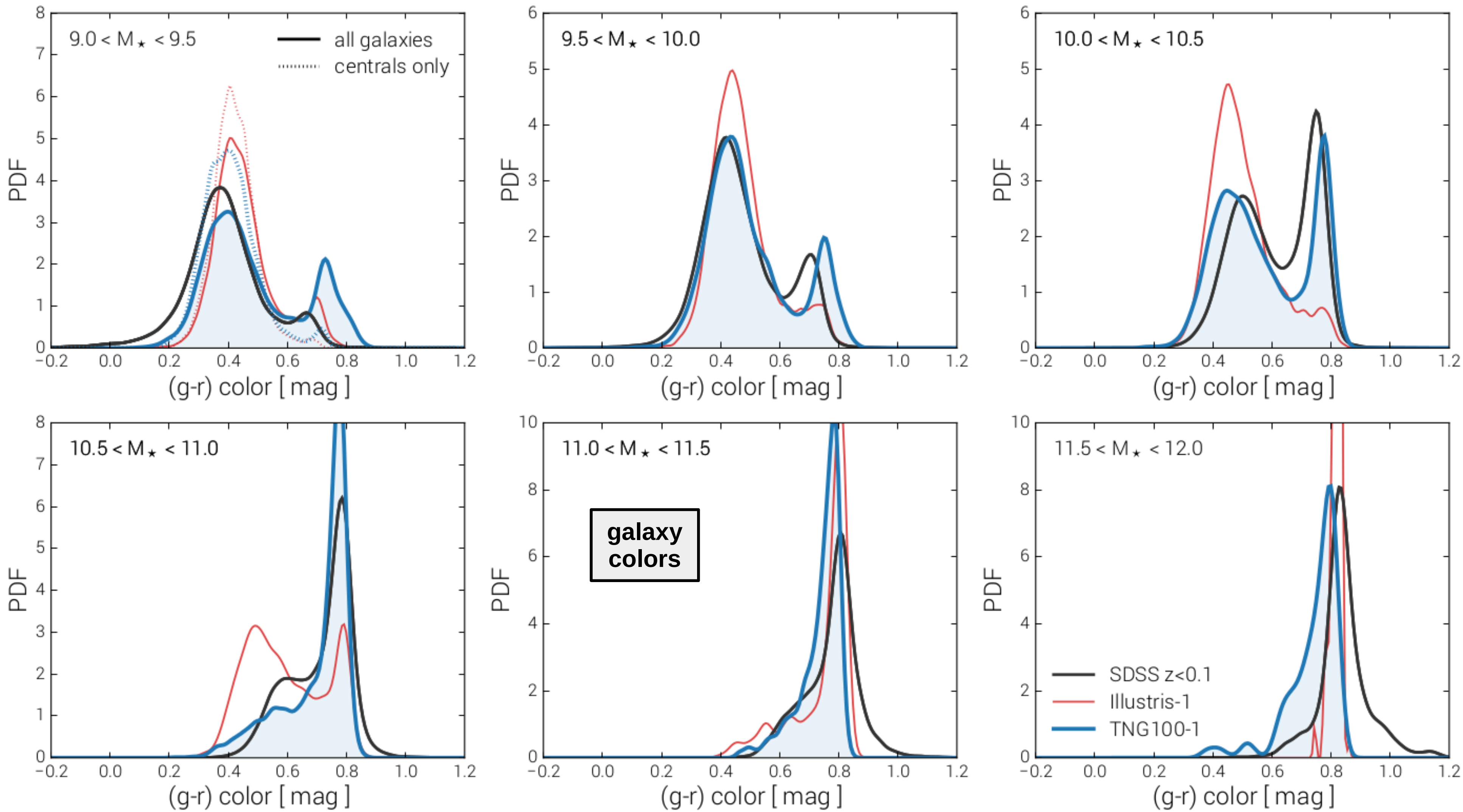
Large Scales: CDM works



Springel+ w/ MV 2017

LCDM clustering

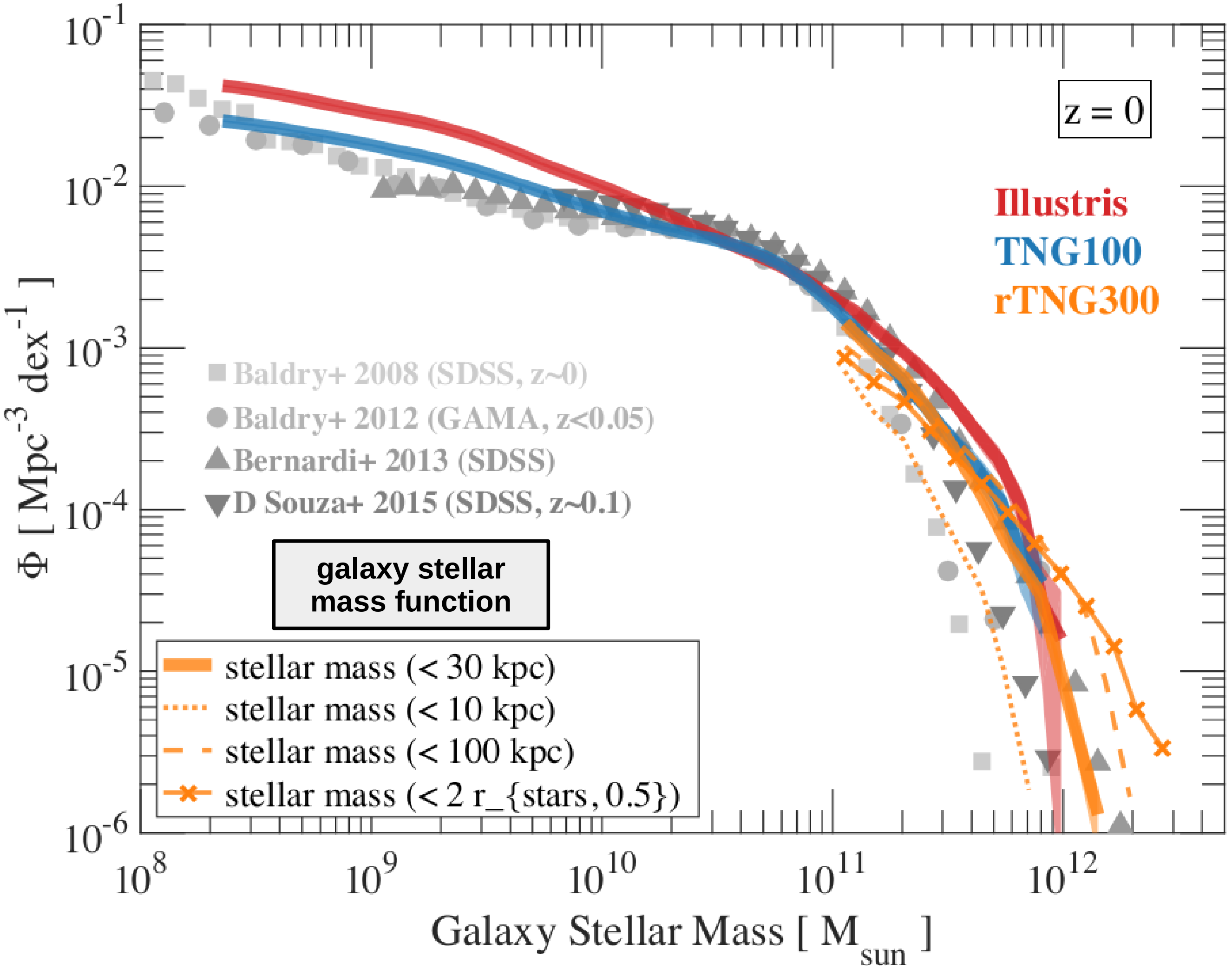
Large Scales: CDM works



Nelson+ w/ MV 2017

LCDM colors

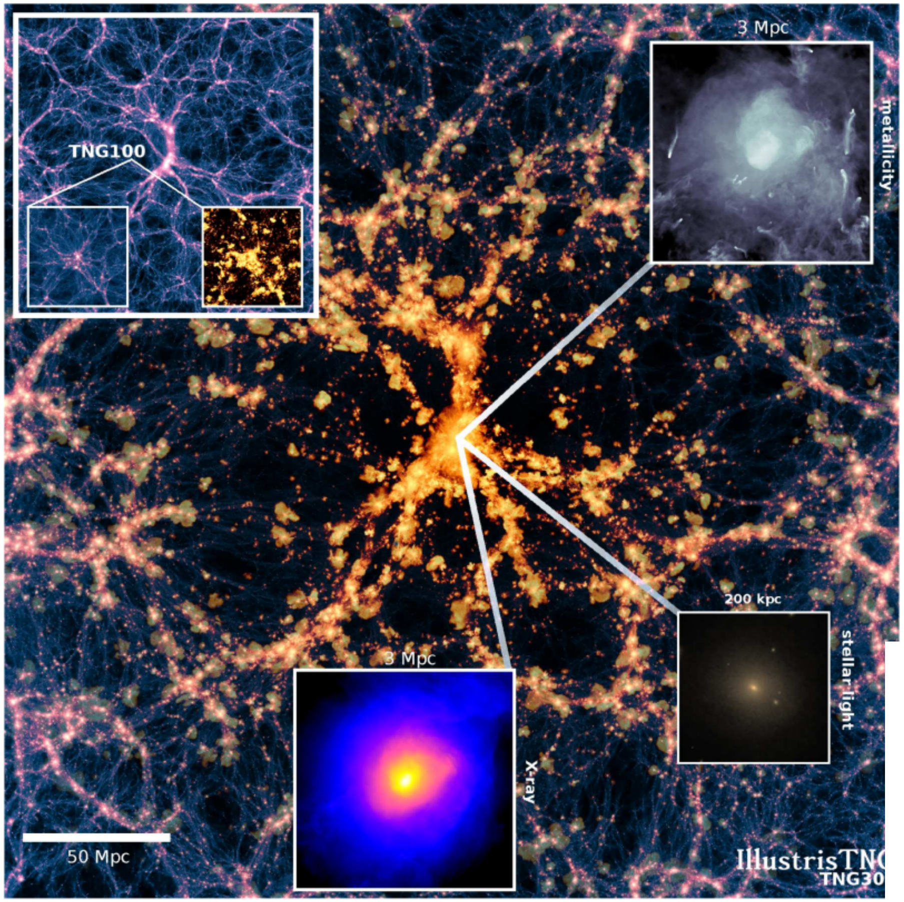
Large Scales: CDM works



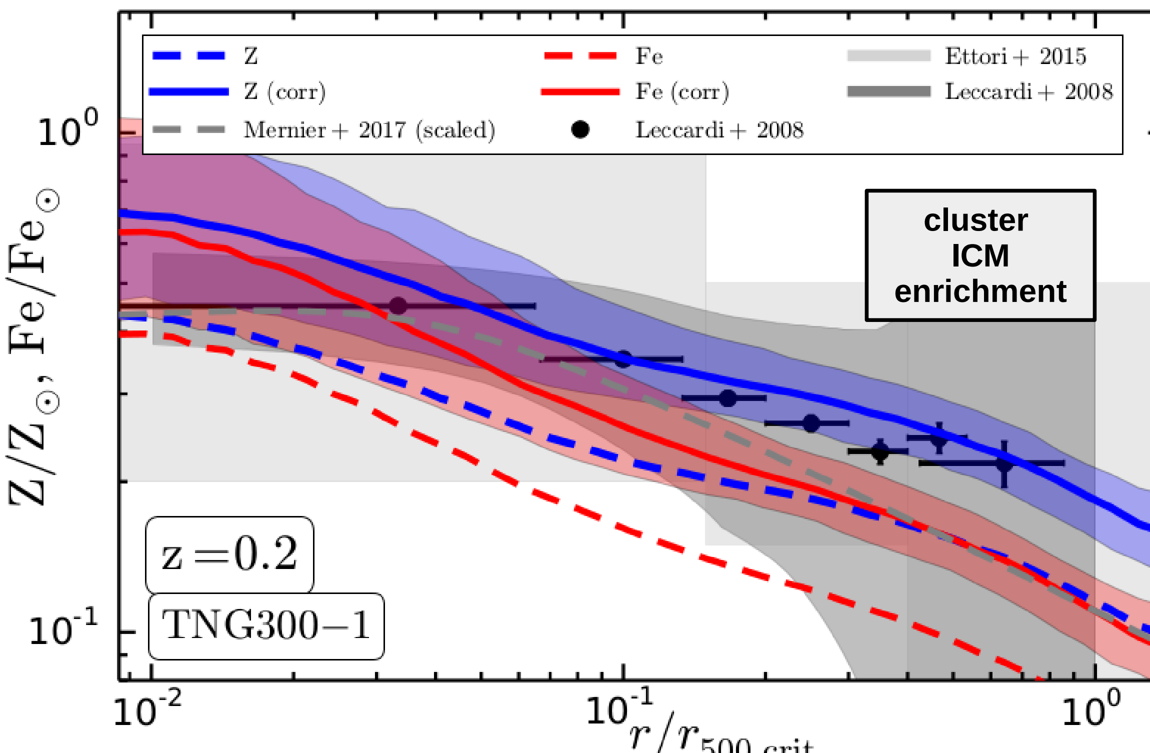
Pillepich+ w/ MV 2017

LCDM tuned stellar masses

Large Scales: CDM works



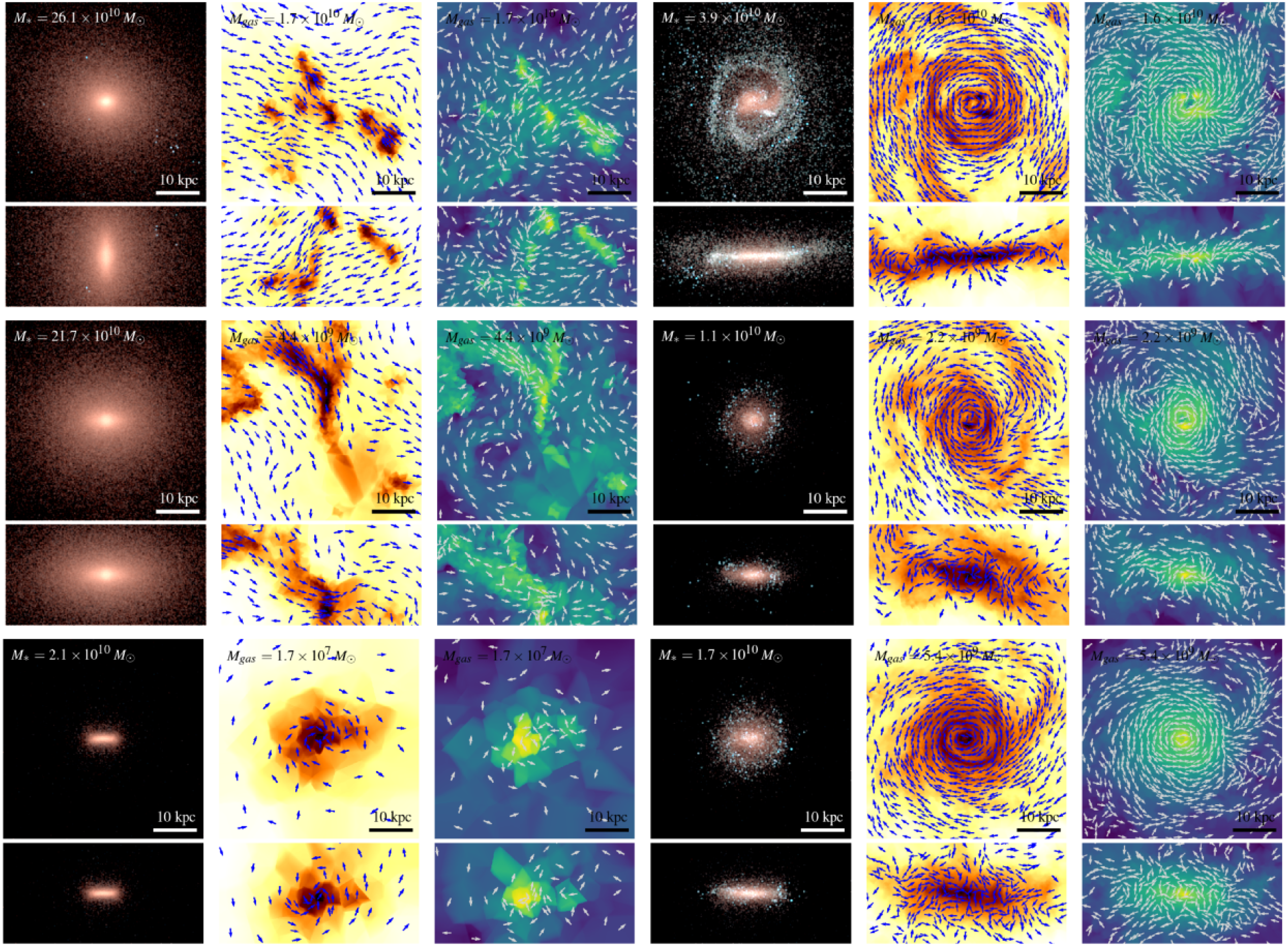
LCDM metals in clusters



MV+ 2017


redshift: 3.88
Mark Vogelsberger, Federico Marinacci (MIT)

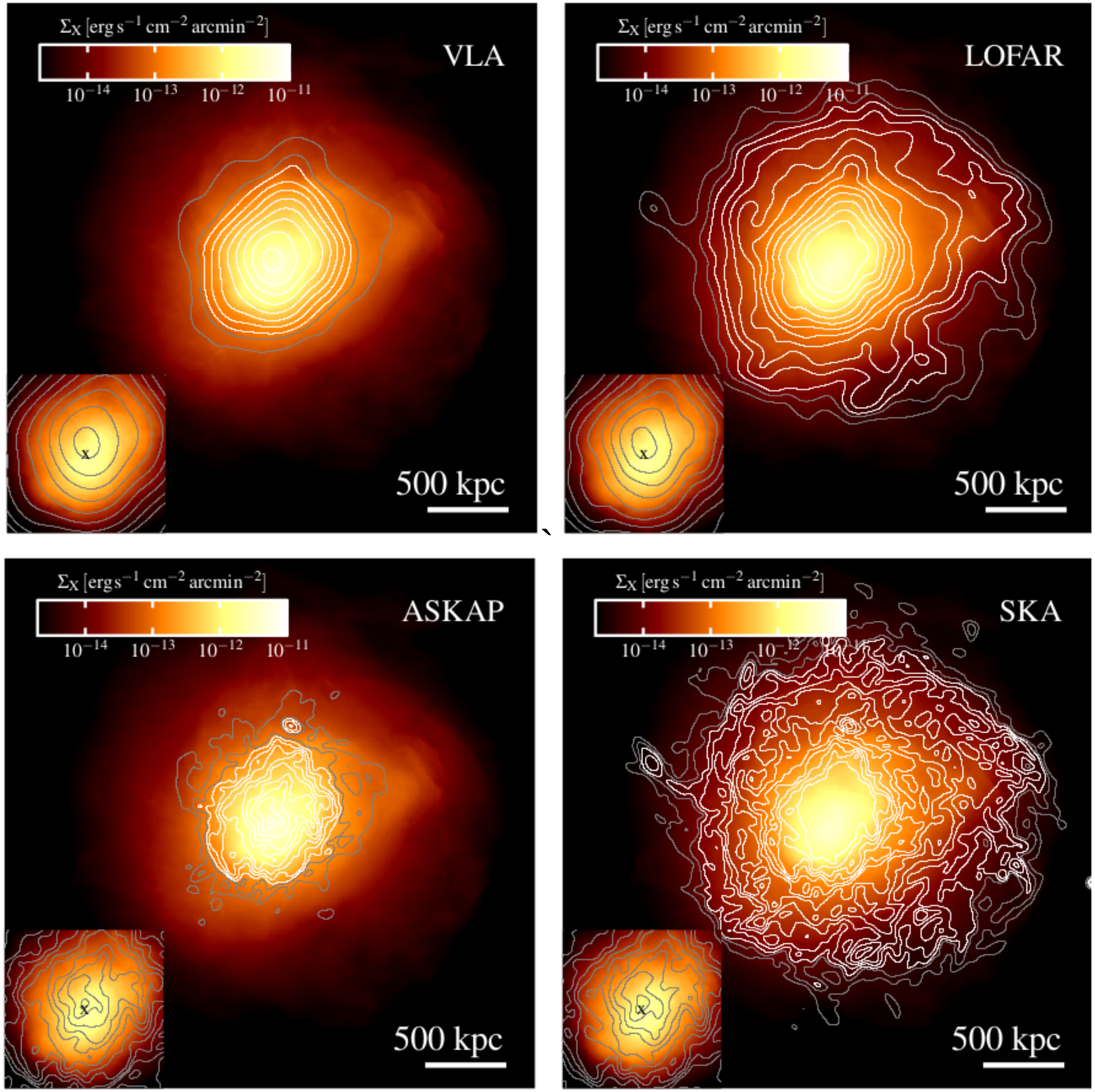
Large Scales: CDM works

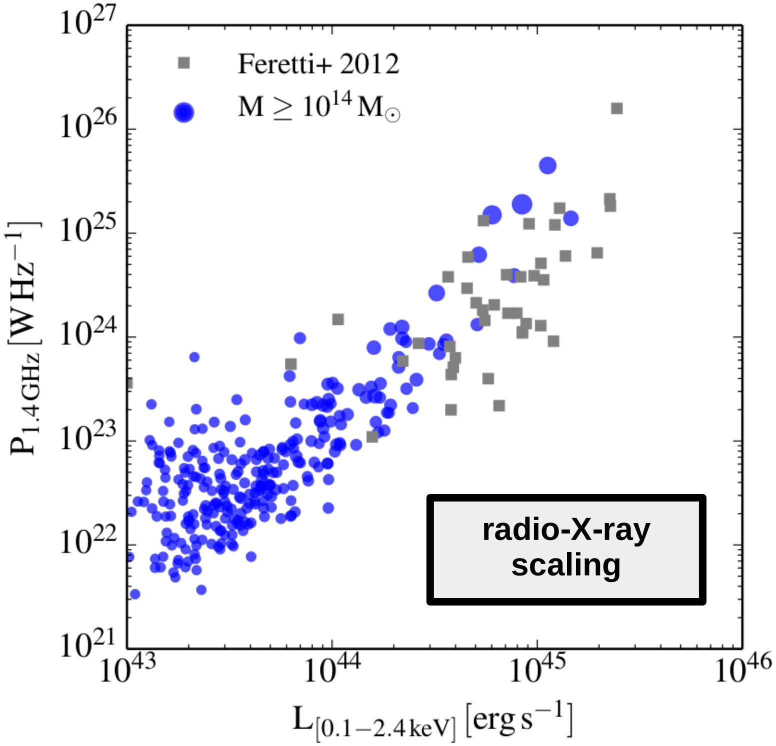


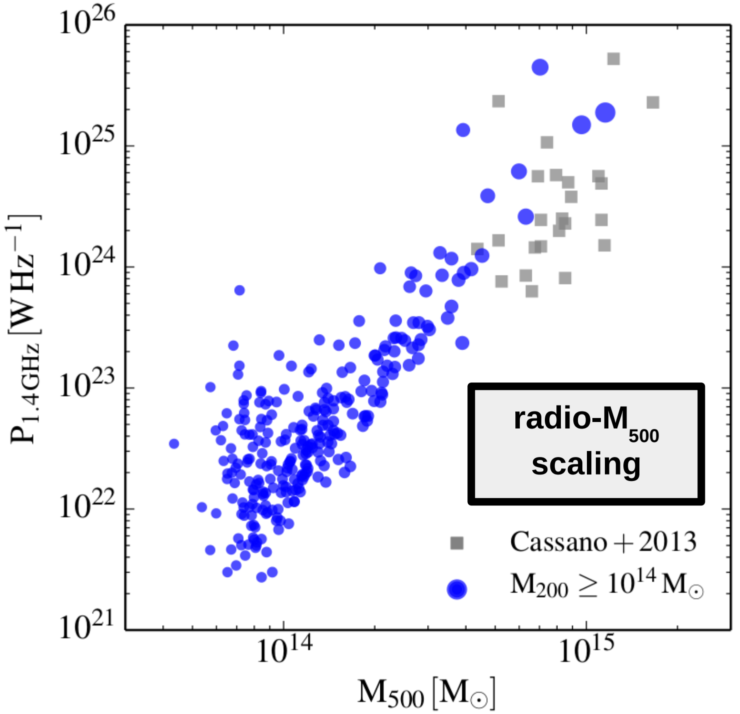
Marinacci, MV+ 2017

elliptical galaxies **LCDM magnetic fields** **disk galaxies**

Large Scales: CDM works



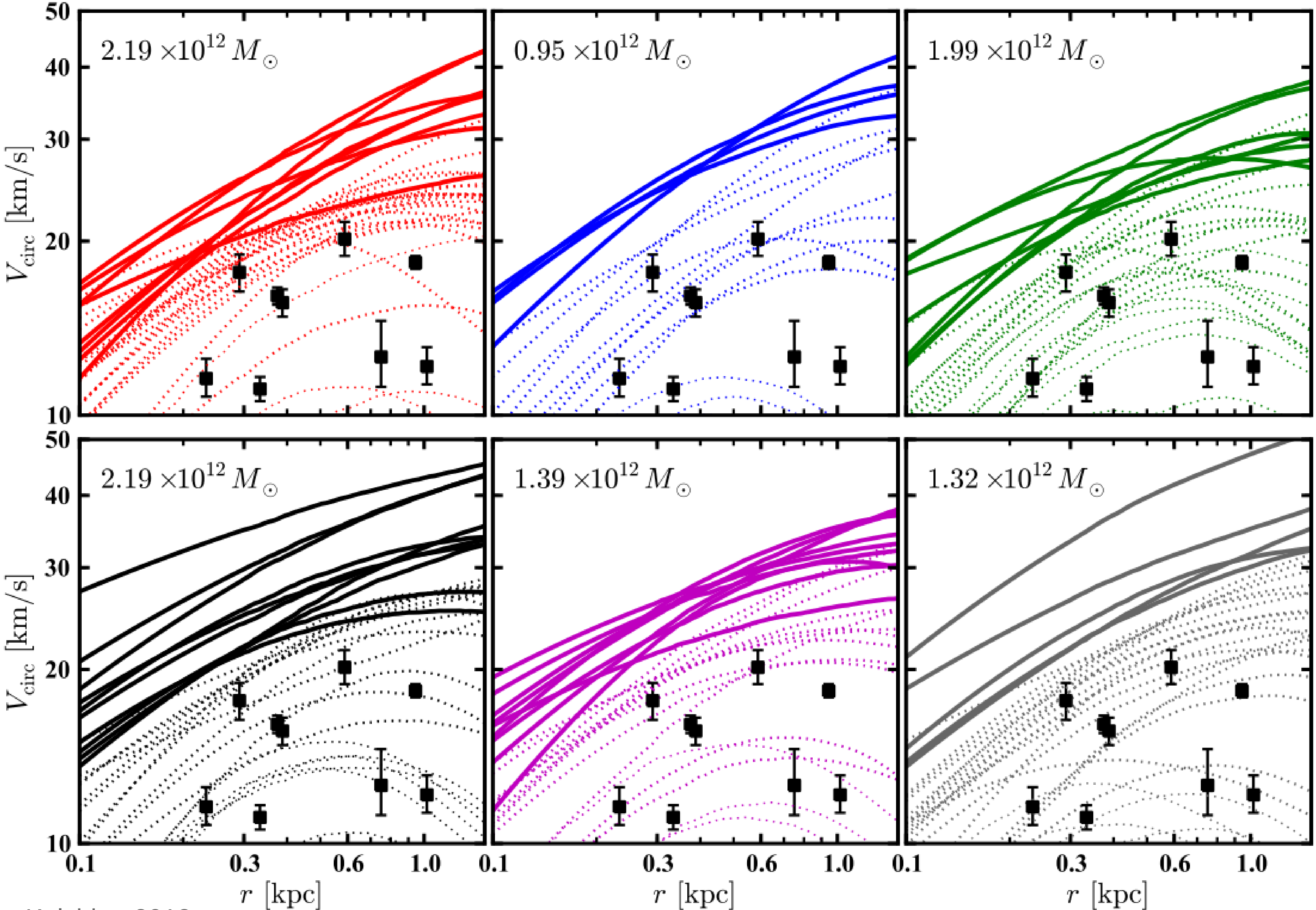




LCDM radio halos

Marinacci, MV+ 2017

CDM Issues: Too-Big-To-Fail Problem



Boylan-Kolchin+ 2012

Going beyond CDM: Many Possibilities

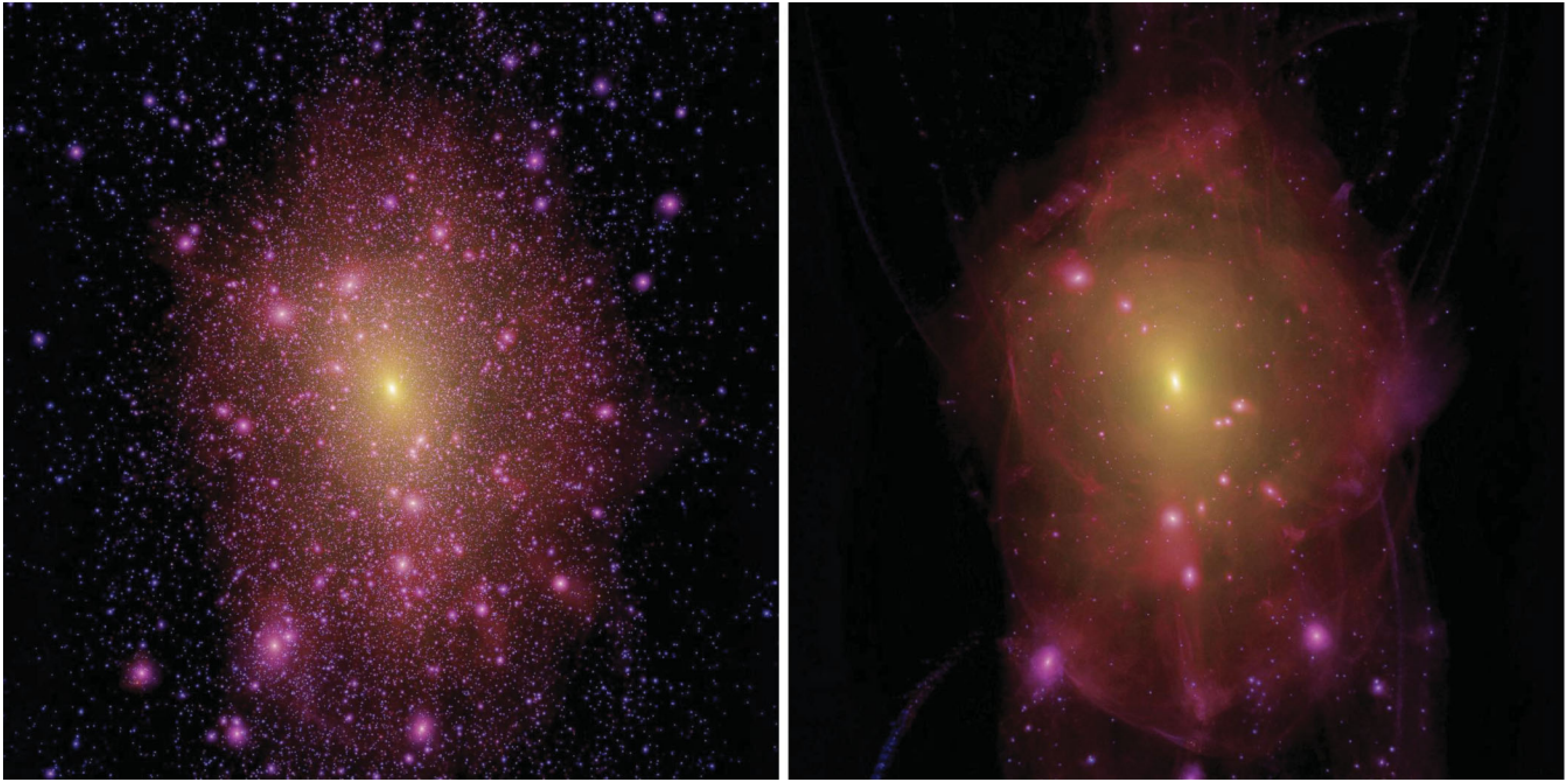
Warm Dark Matter?

Self-Interacting Dark Matter?

Fuzzy Dark Matter?

...?

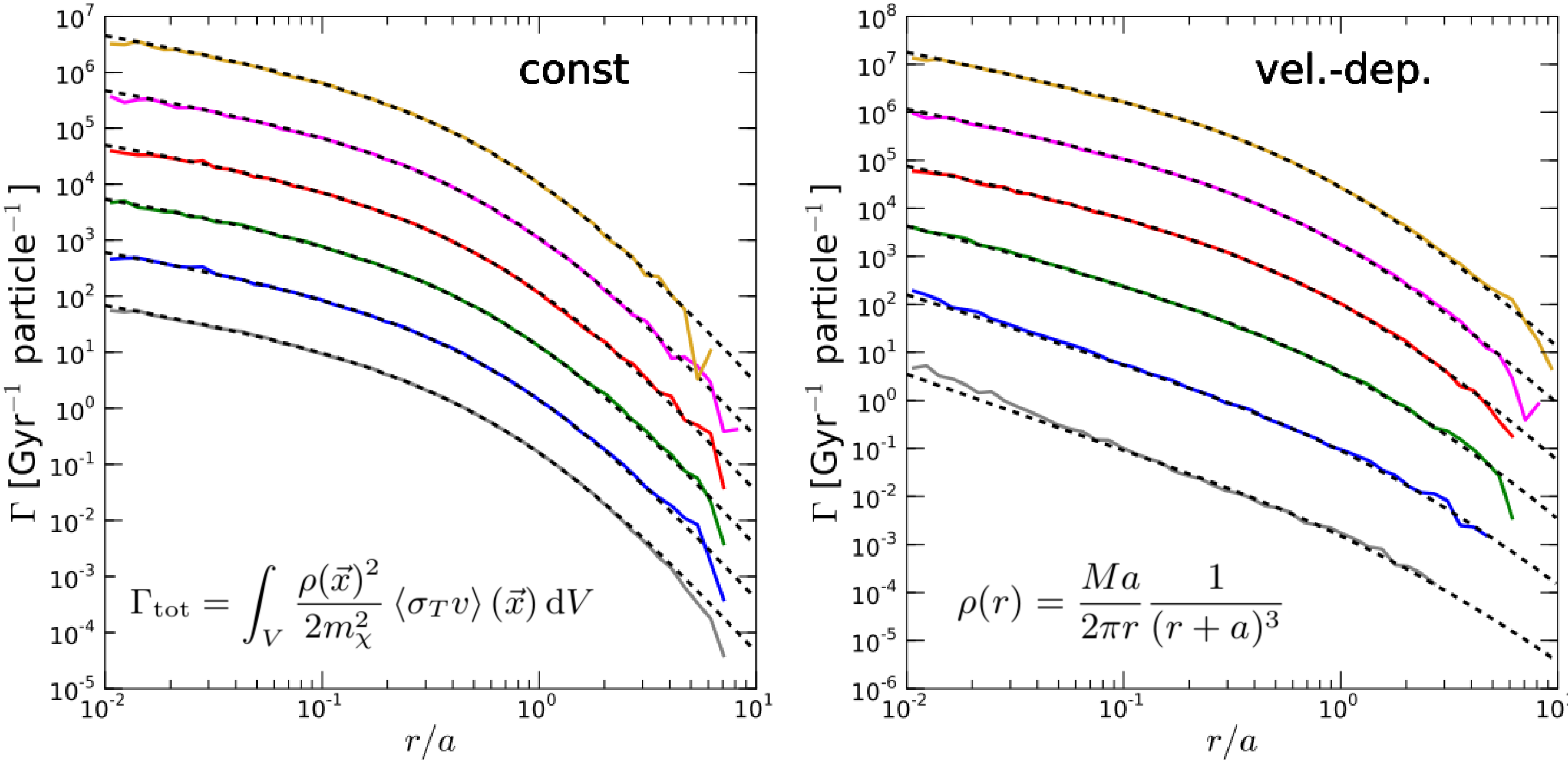
WDM Simulations



a warm dark matter halo:
suppression of substructure

Lovell+ 2012

Simulating SIDM



$$\frac{\sigma_T}{\sigma_T^{\rm max}} \approx \begin{cases} \frac{4\pi}{22.7}\, \beta^2 \ln\left(1+\beta^{-1}\right), & \beta < 0.1 \\ \frac{8\pi}{22.7}\, \beta^2 \left(1+1.5\beta^{1.65}\right)^{-1}, & 0.1 < \beta < 10^3 \\ \frac{\pi}{22.7} \left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2, & \beta > 10^3, \end{cases}$$

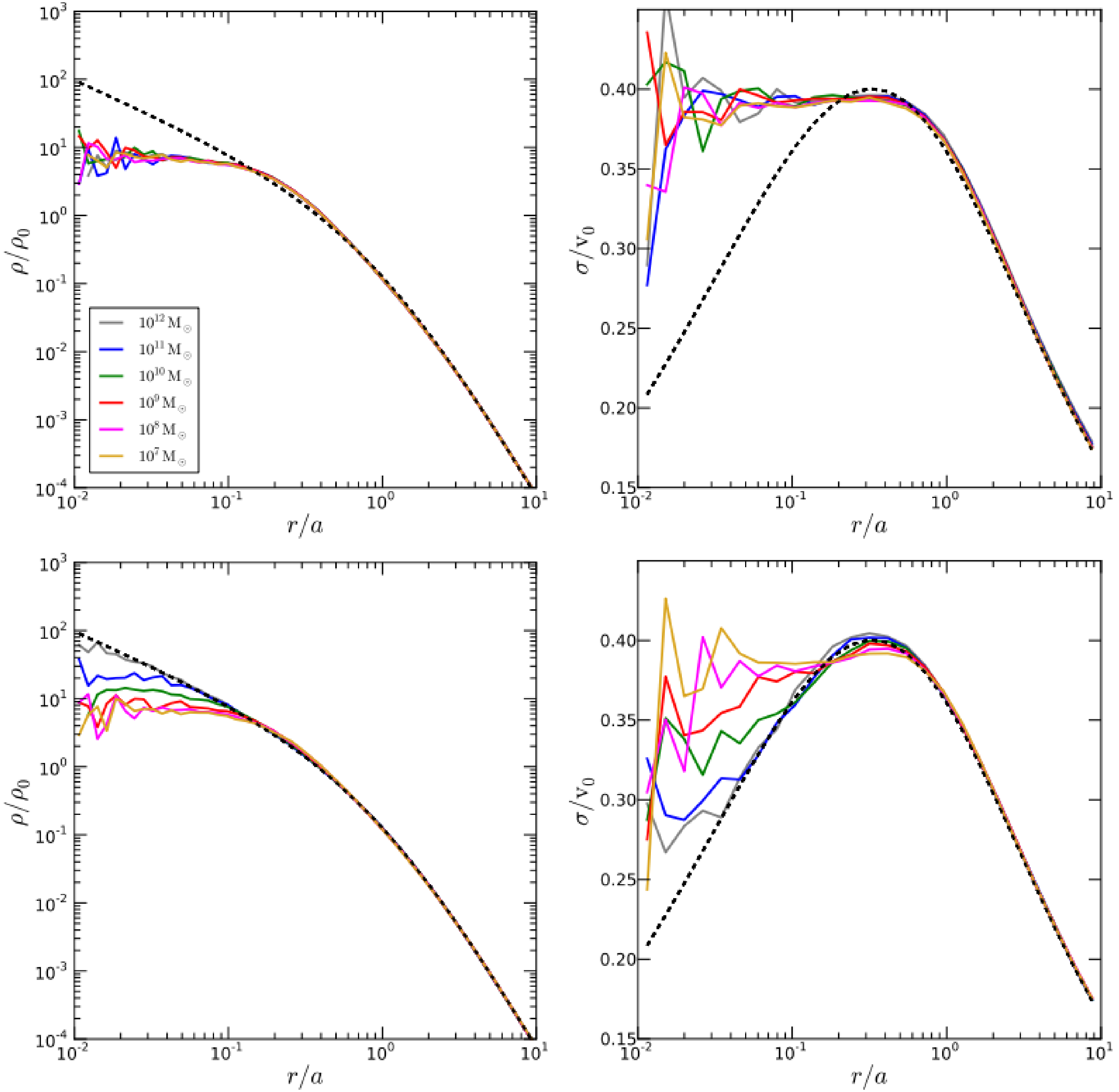
$$\beta = \pi v_{\rm max}^2 / v^2$$

N = 10^6
epsilon = 0.006 x a

$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij}, h_i)\, \sigma_T(v_{ij}) v_{ij}\, \Delta t_i$$

MV, Zavala & Loeb 2012

Simulating SIDM

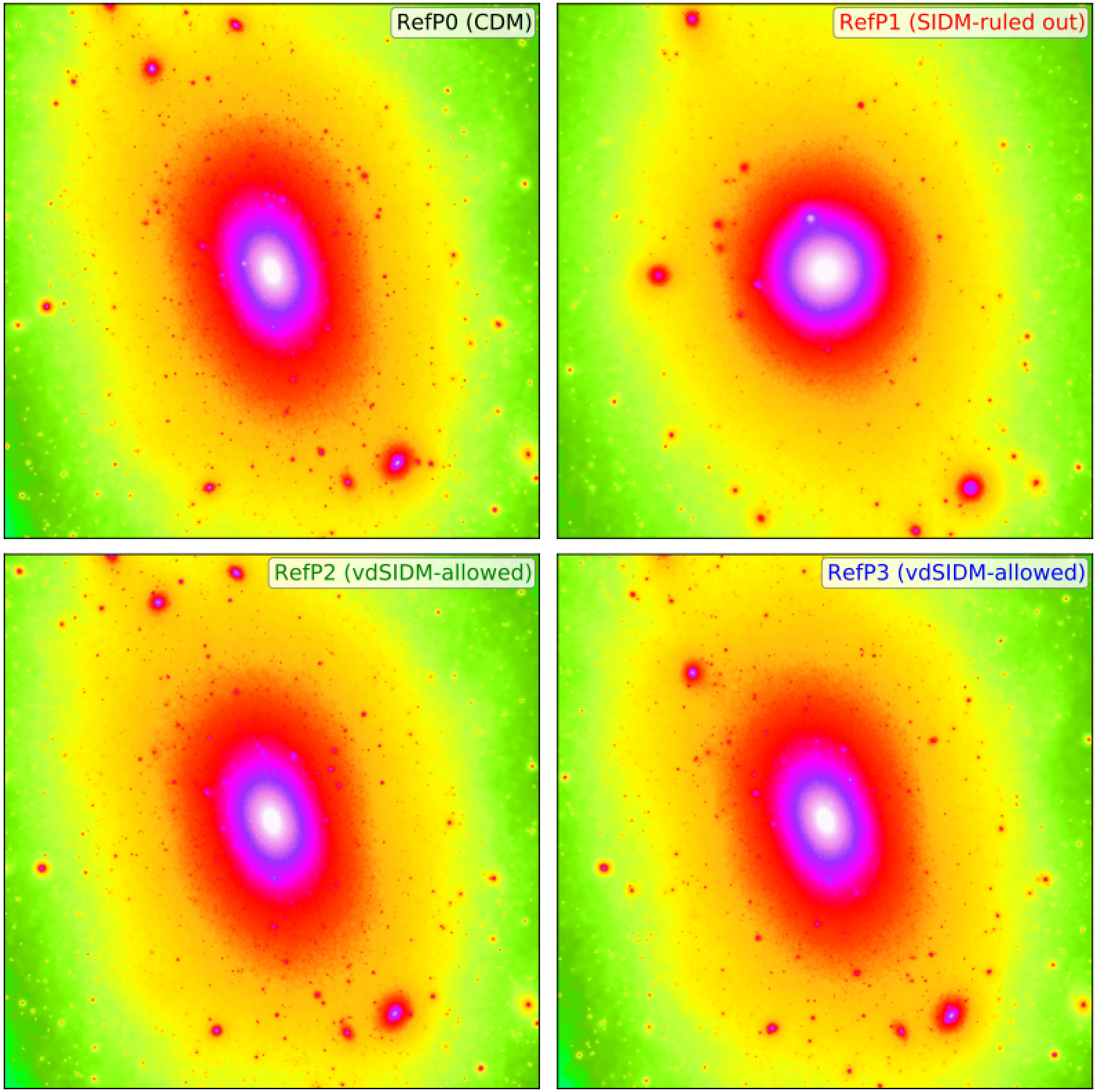


constant cross section

vel-dep cross section

MV, Zavala & Loeb 2012

The Outcome of Cosmological SIDM Simulations



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

$$\frac{\sigma_T}{\sigma_T^{max}} \approx \begin{cases} \frac{4\pi}{22.7}\,\beta^2 \ln\left(1+\beta^{-1}\right), & \beta < 0.1 \\ \frac{8\pi}{22.7}\,\beta^2 \left(1+1.5\beta^{1.65}\right)^{-1}, & 0.1 < \beta < 10^3 \\ \frac{\pi}{22.7}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2, & \beta > 10^3 \end{cases}$$

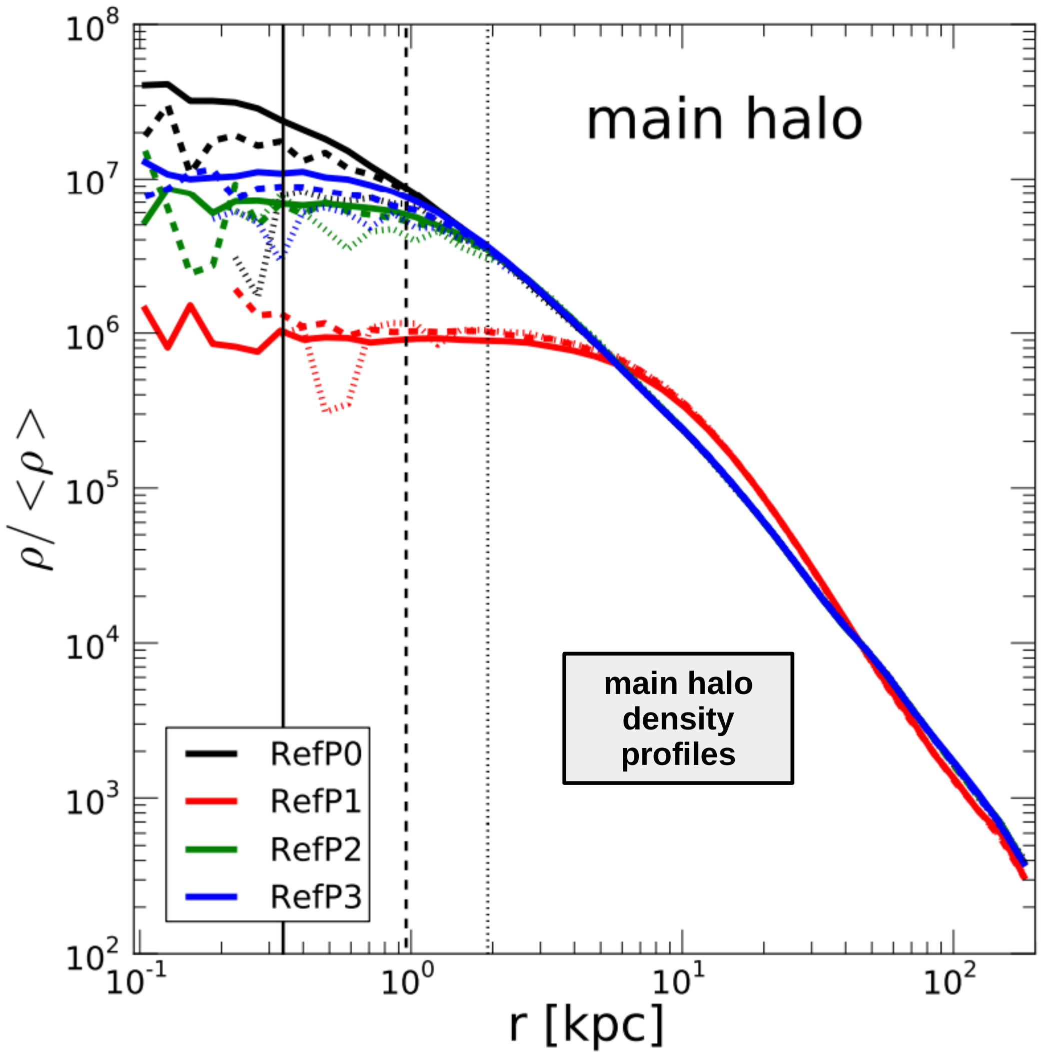
impact of SIDM on dark matter density field of MW-like halos

M = 4.9 x 10^4 M_{sun}
epsilon = 120pc

based on Aquarius ICs

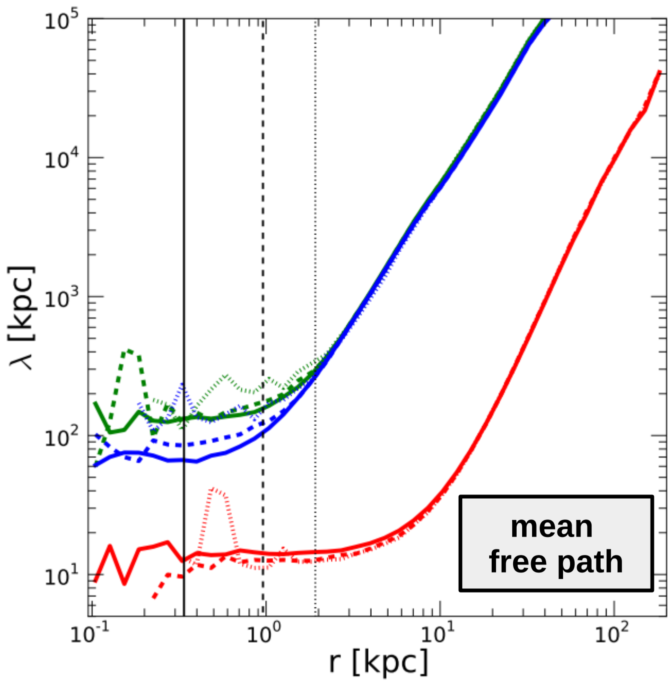
MV, Zavala & Loeb 2012

Impact on the Main Halo DM Density Profile



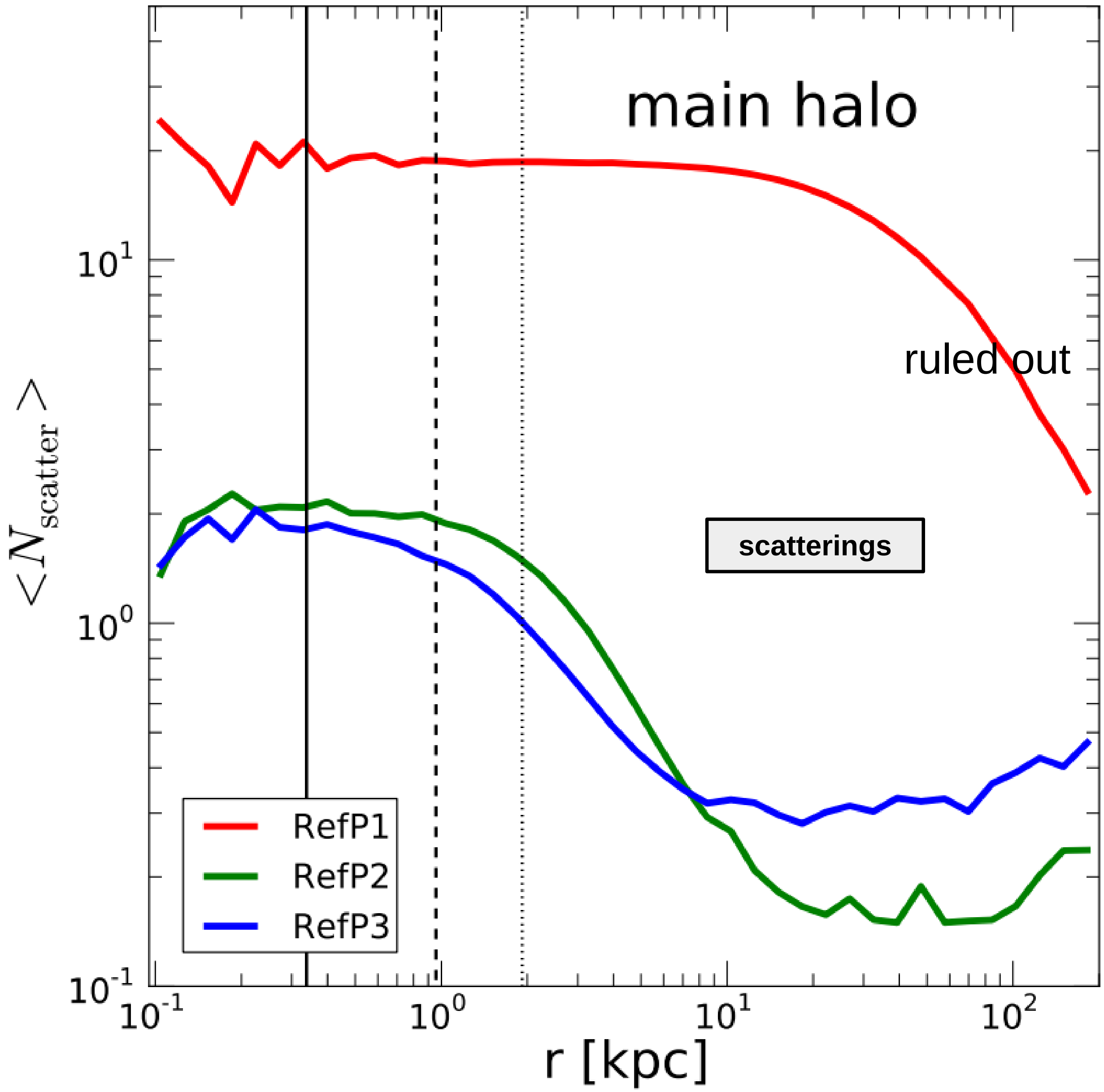
impact of SIDM on main halo density profile → core formation

core formation: larger cores for larger cross sections



MV, Zavala & Loeb 2012

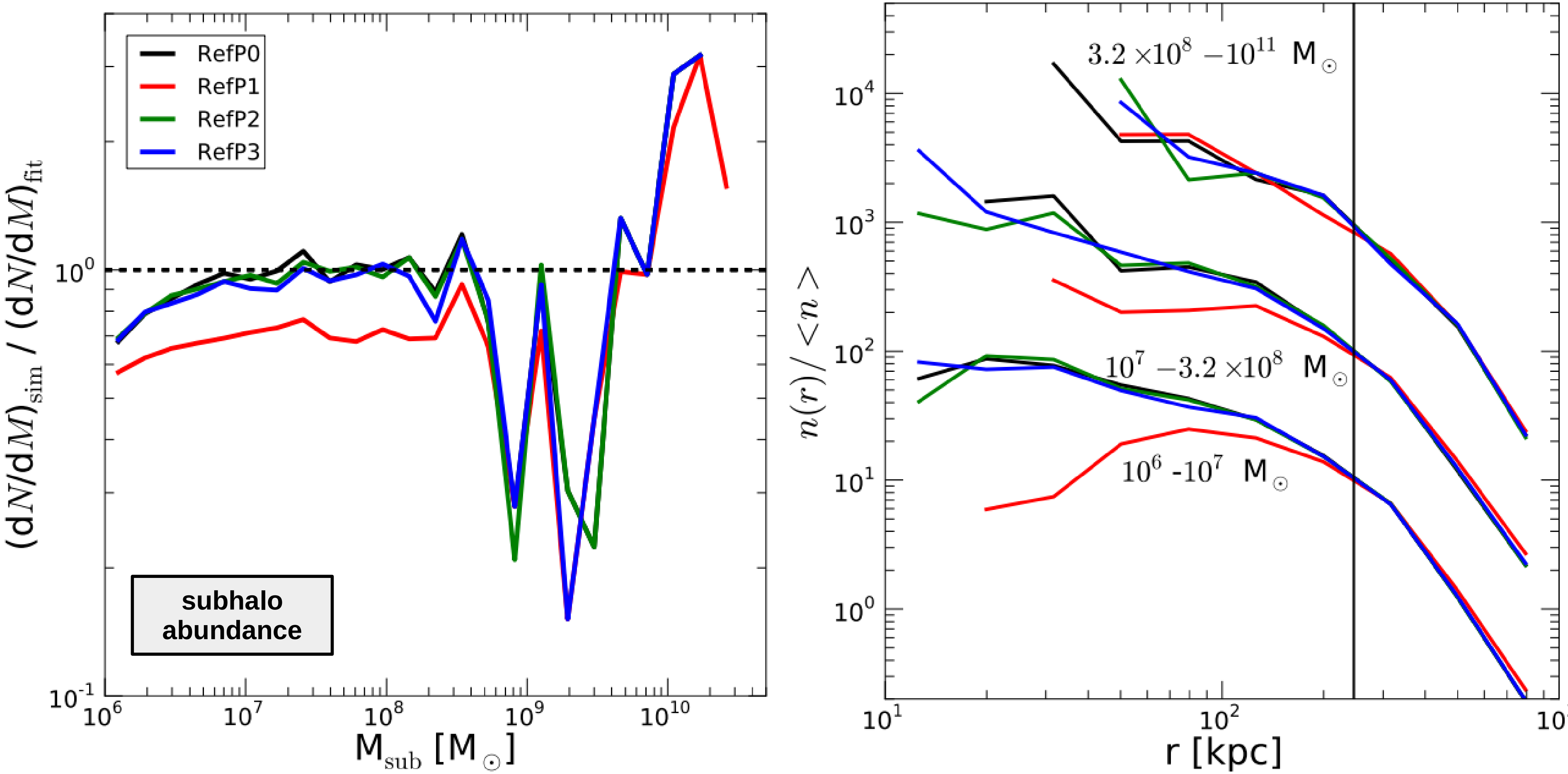
Number of Scattering



typically only a few scattering events per Hubble time are sufficient

MV, Zavala & Loeb 2012

Impact on Subhalo Abundance



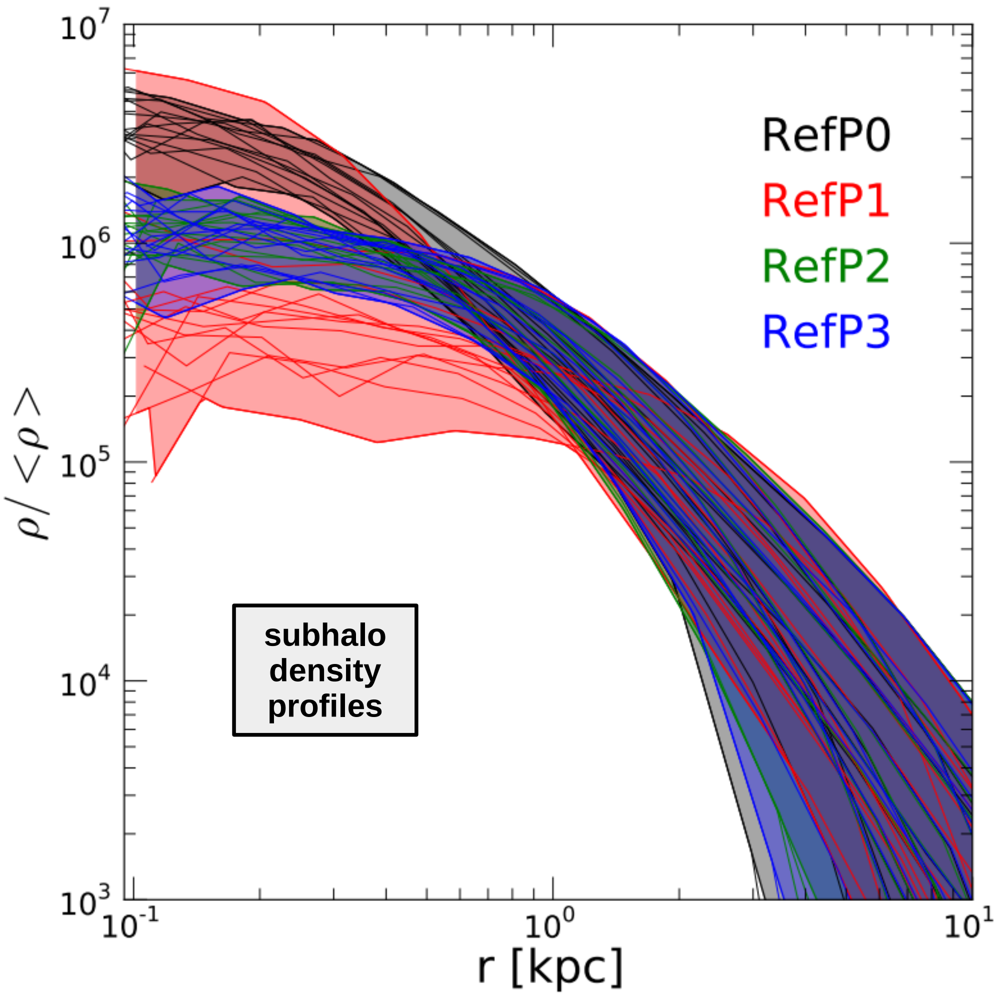
viable models have no significant impact on subhalo abundance

MV, Zavala & Loeb 2012

Impact on Subhalo Density Profiles

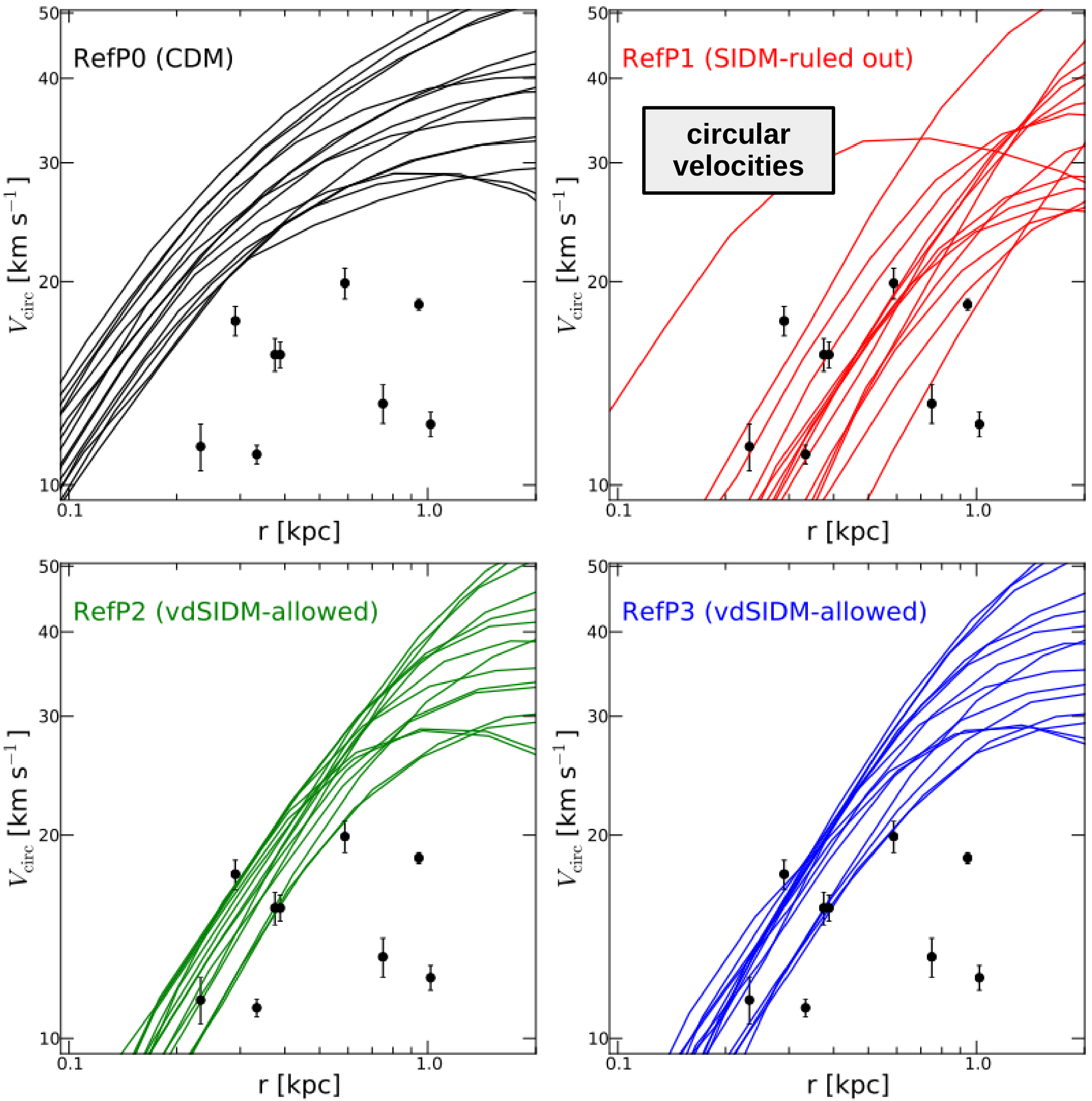
core formation in subhalos: changes circular velocity profile

this addresses the TBTF problem since it also changes the circular velocity profiles



MV, Zavala & Loeb 2012

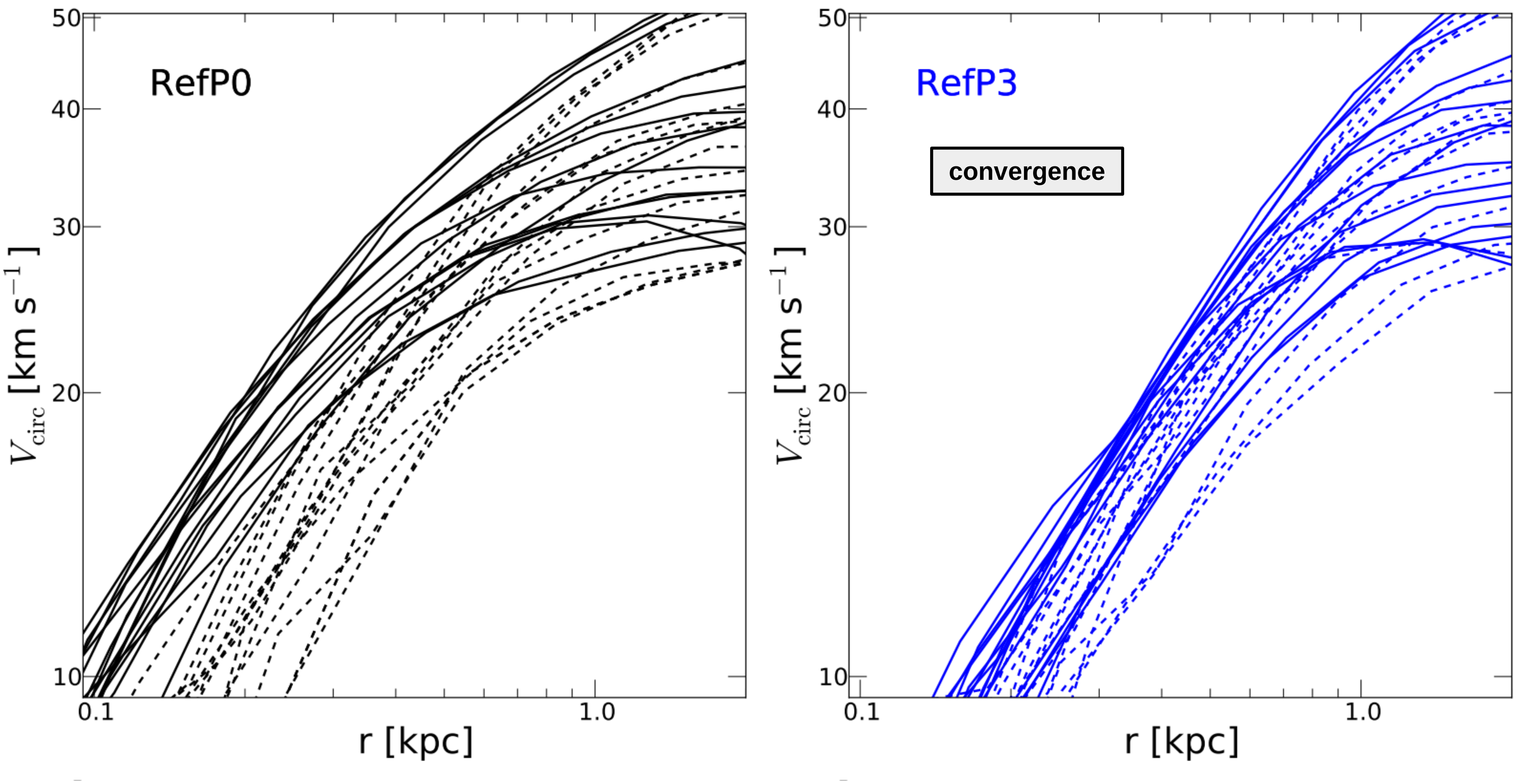
Circular Velocity Curves



'solving' the TBTF problem with SIDM

MV, Zavala & Loeb 2012

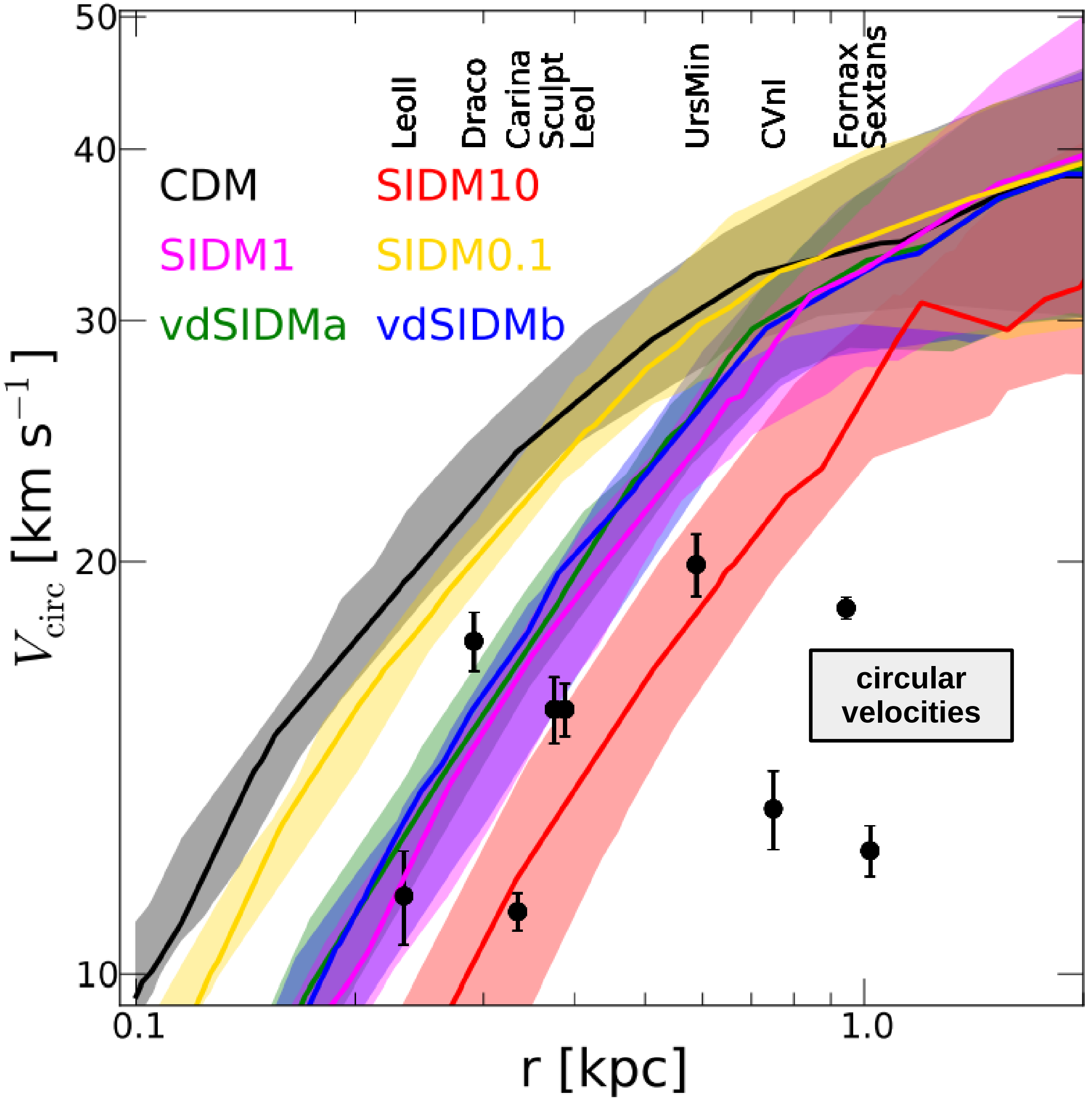
Circular Velocity Curves – Numerical Convergence

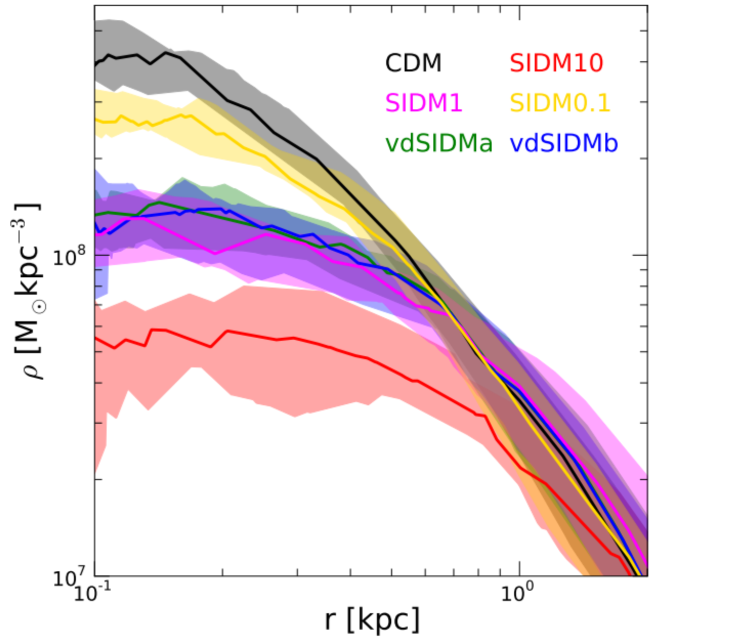


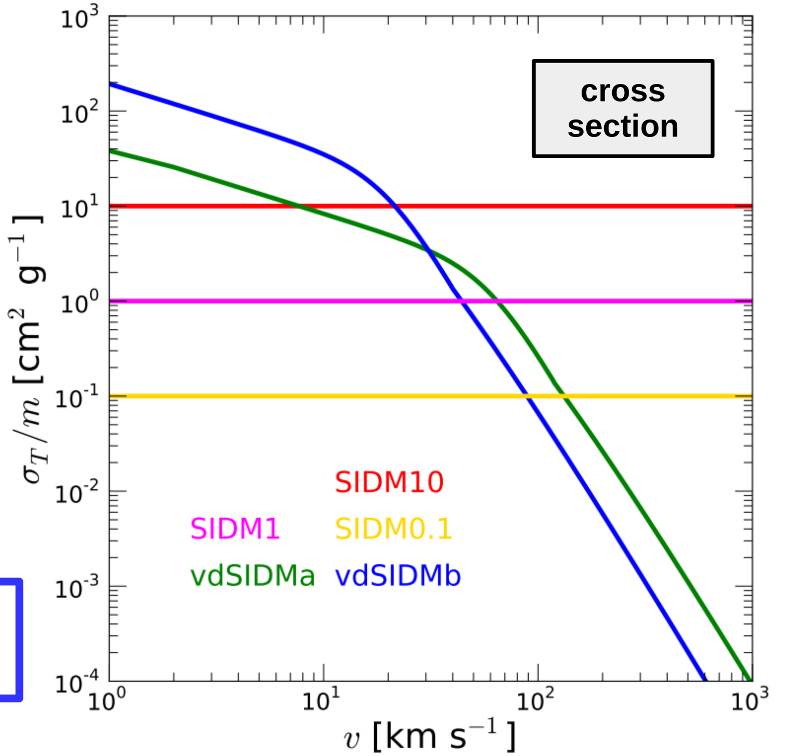
easier to achieve convergence for SIDM models

MV, Zavala & Loeb 2012

Self-Interacting Dark Matter



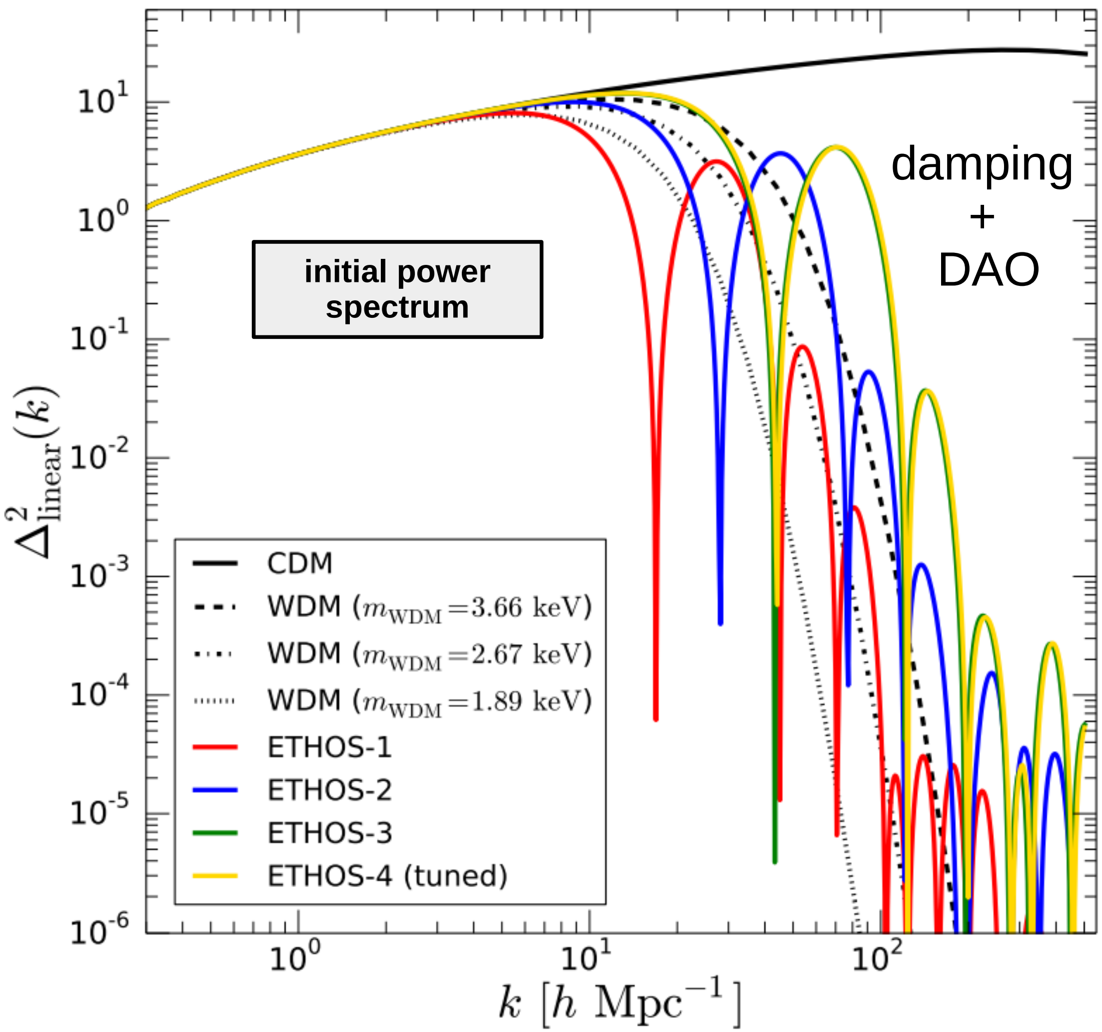




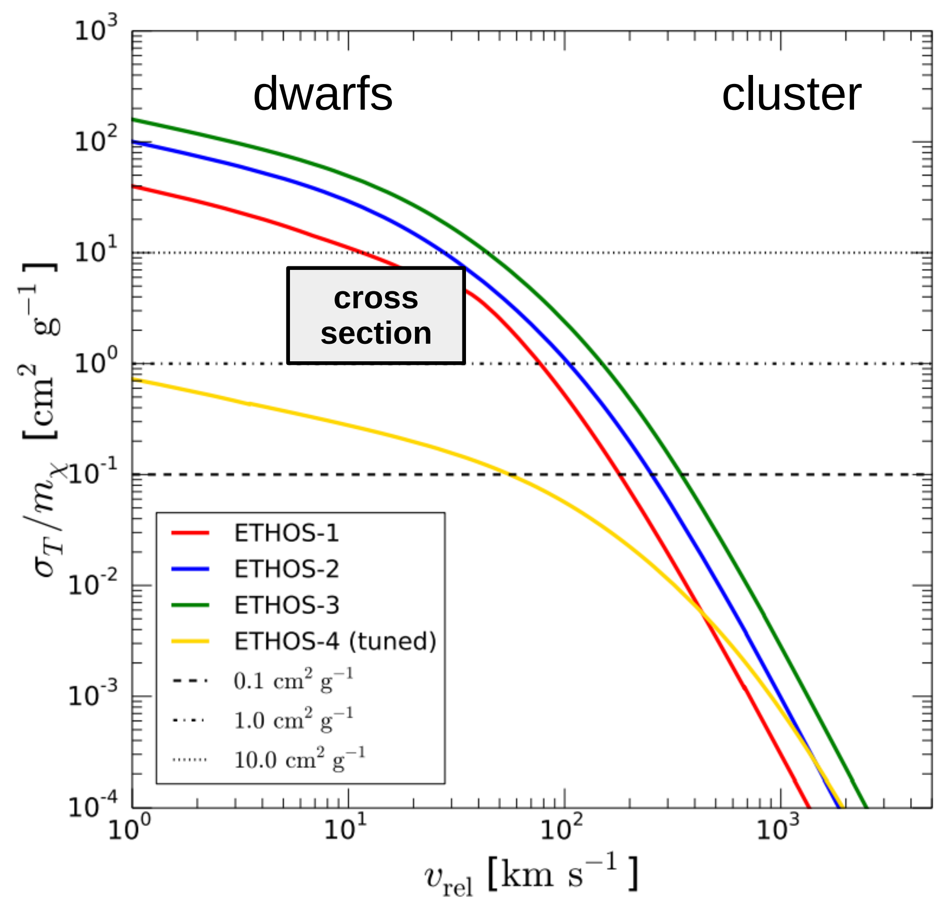
Zavala, MV & Walker 2013

velocity-dependent cross sections avoid cluster constraints

ETHOS – Effective Theory of Structure Formation: Ingredients



initial power spectra: dark acoustic oscillations due to DM interactions with relativistic particles in early Universe

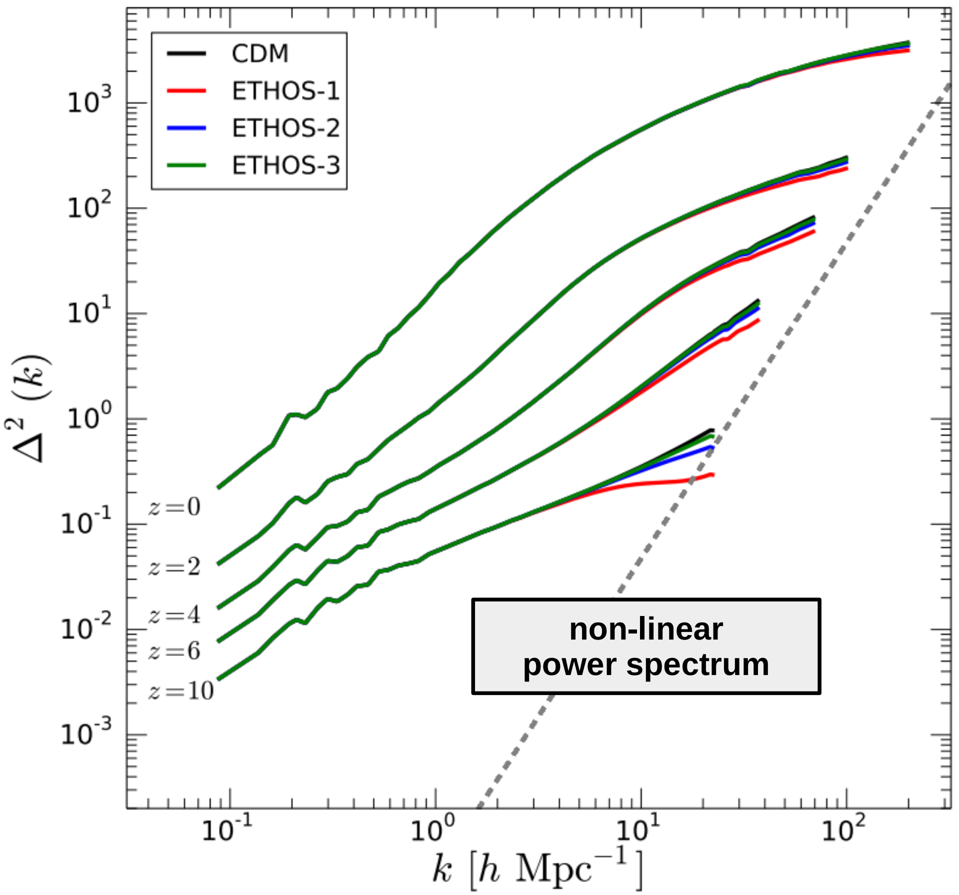


self-interaction cross sections: DM interactions with itself in late Universe

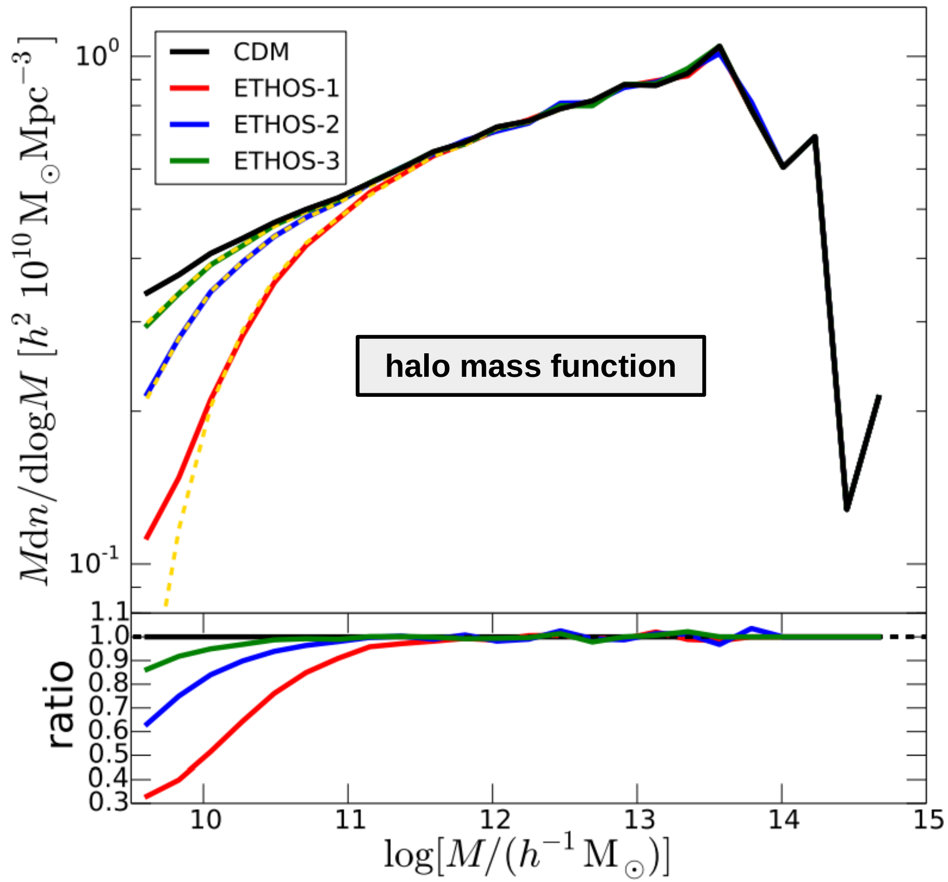
MV+ 2016 (first ETHOS simulations)

Cyr-Racine+ w/ MV 2016 (ETHOS theory foundations)

Large Scale Statistics

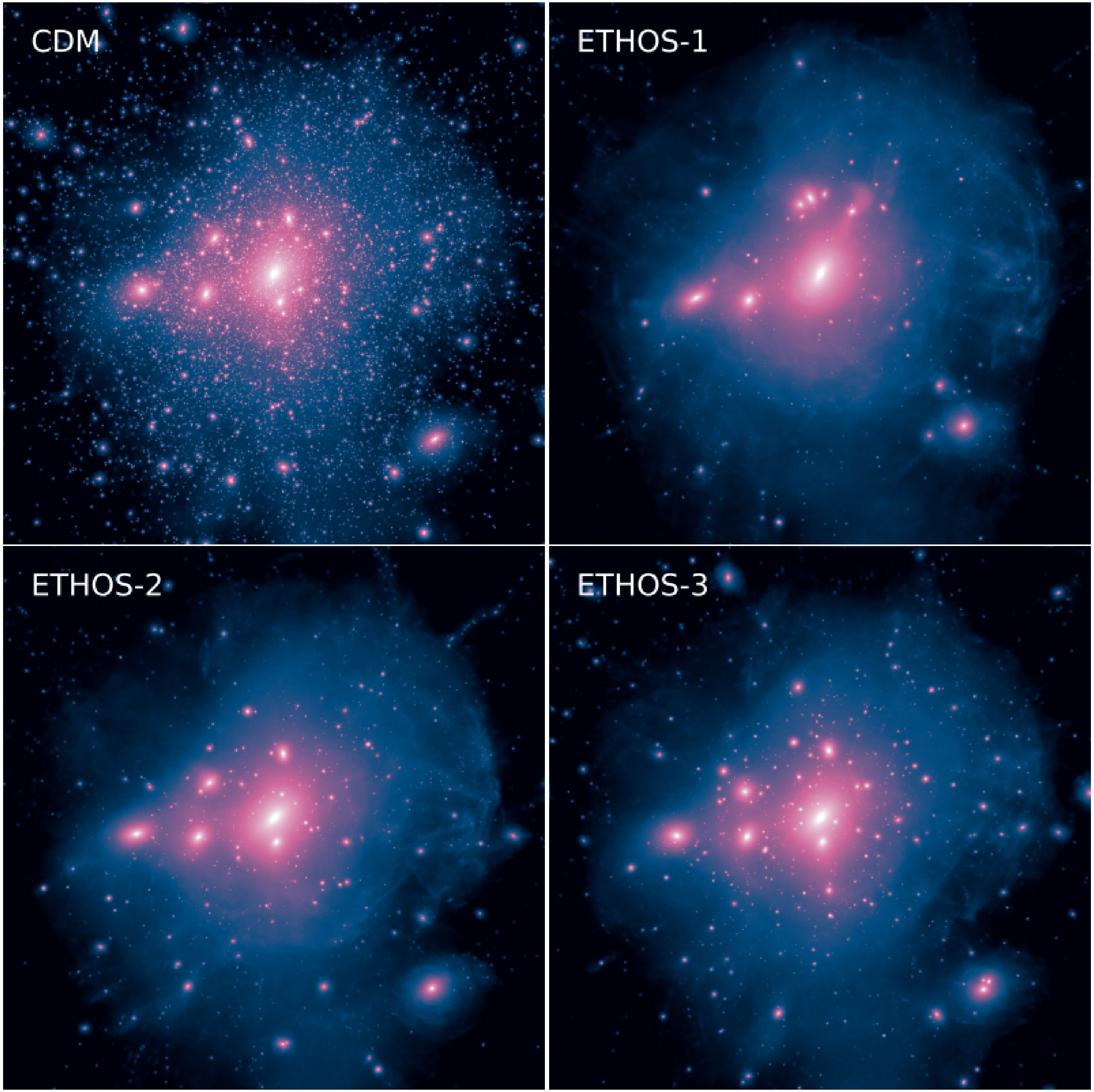


impact on halo mass function due to transfer function cutoff



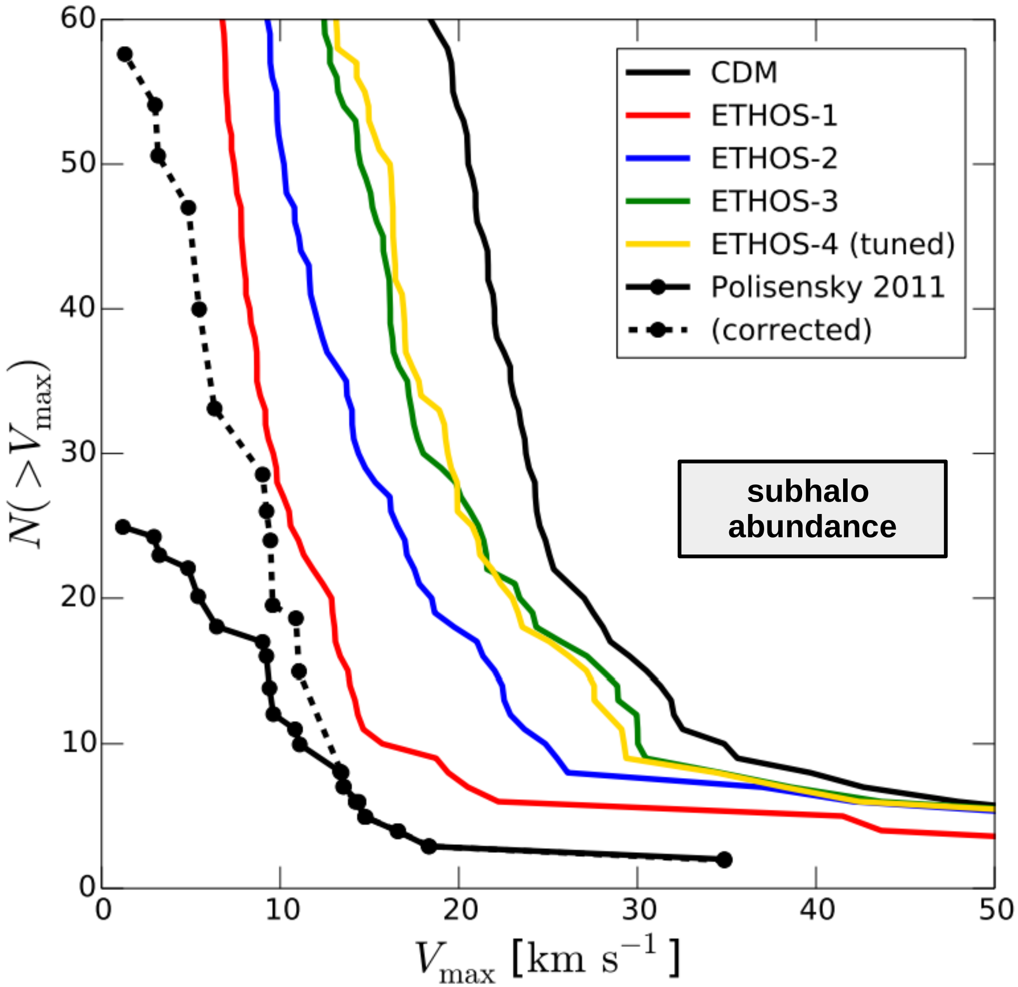
MV+ 2016

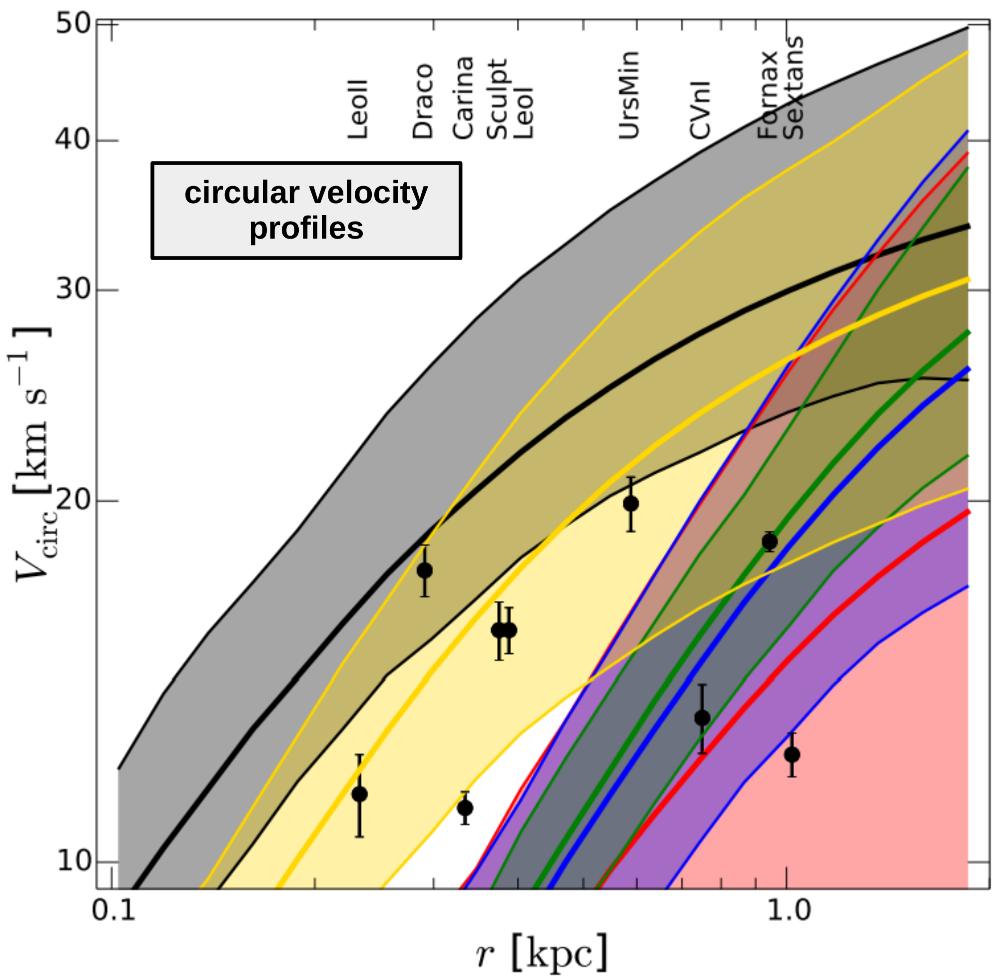
Milky Way-like DM Halo



MV+ 2016

ETHOS: A tuned Model





both CDM abundance and structural problems can be alleviated simultaneously

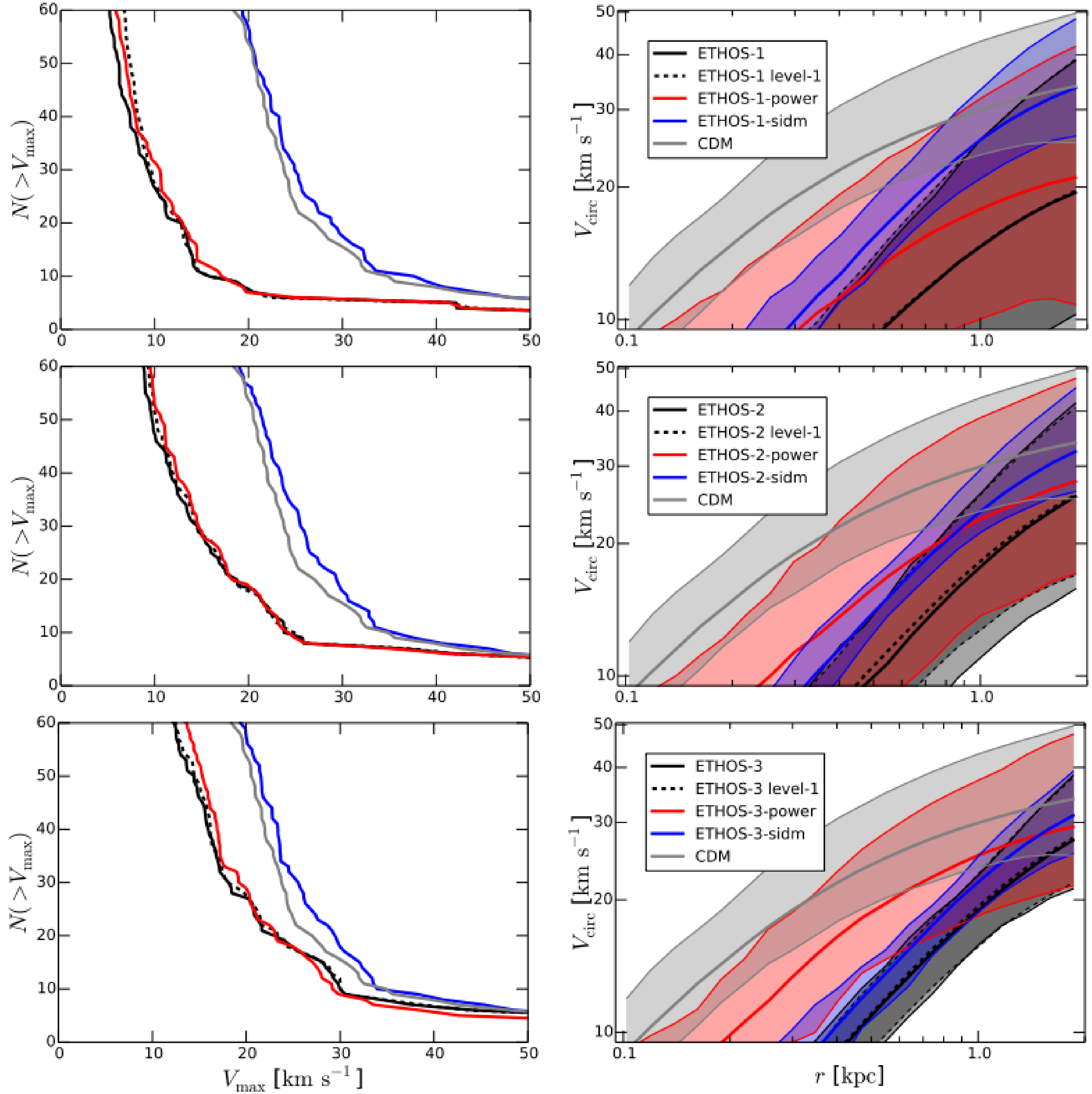
→ **addresses missing satellite and TBTF problem**

MV+ 2016

ETHOS: Damping vs. SIDM

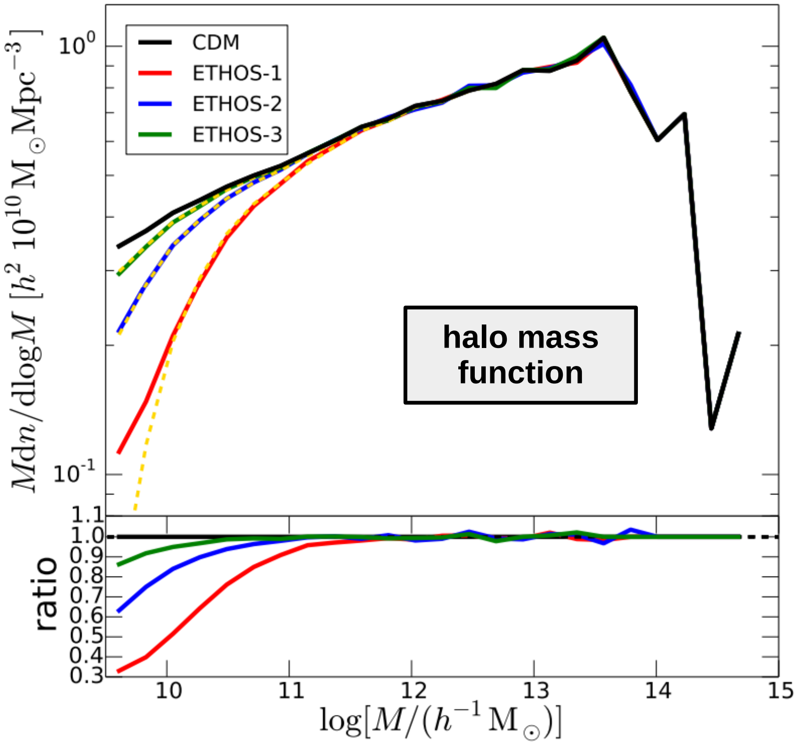
disentangling the impact of SIDM and power spectrum modifications

self-interactions do not change the subhalo abundance



MV+ 2016

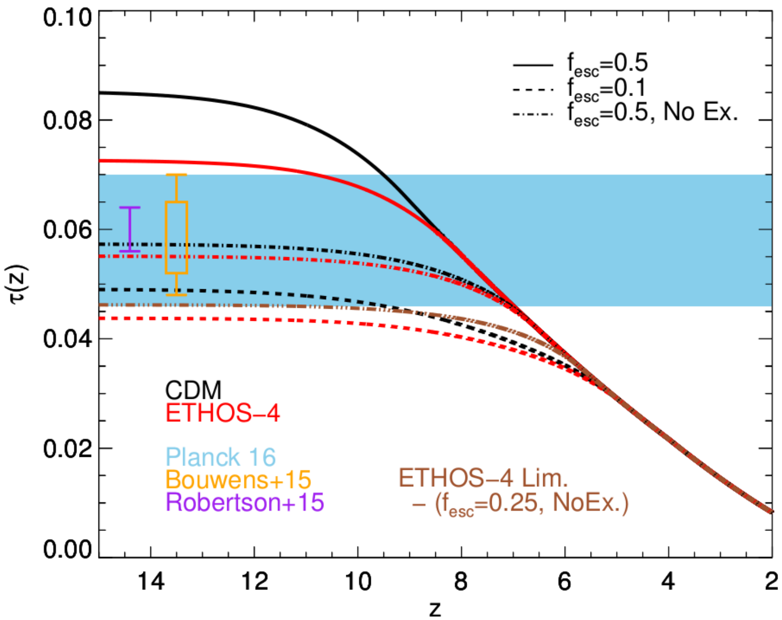
Halo Mass Function and High Redshift Universe

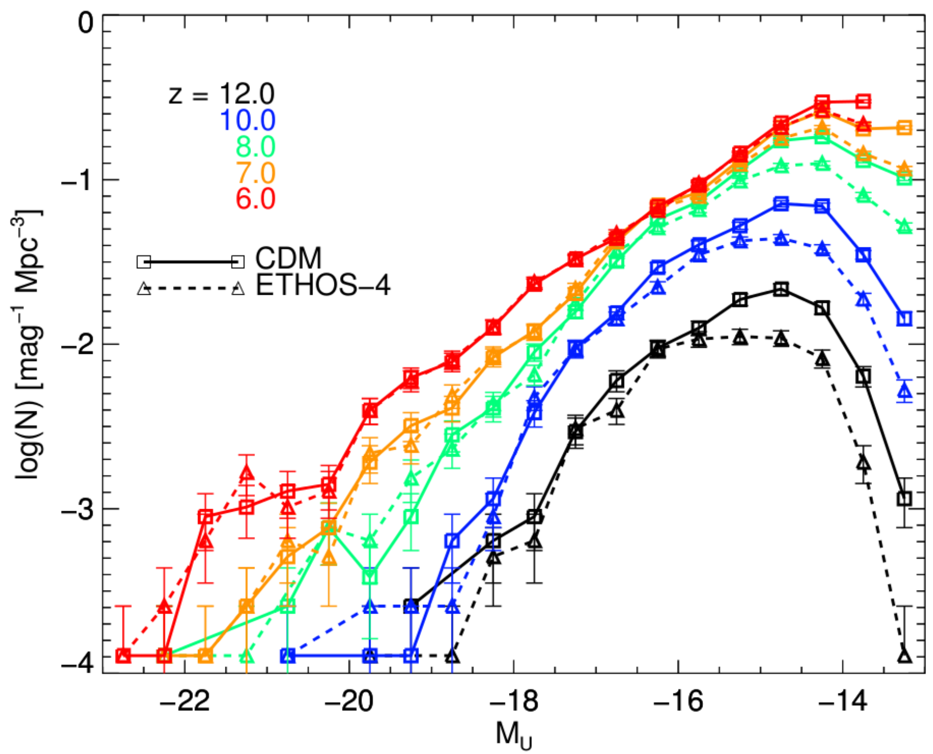


impact on halo mass function due to reduction of power at small scales

late time self-interactions typically do not affect the halo abundance

Lovell, Zavala, MV+ in prep

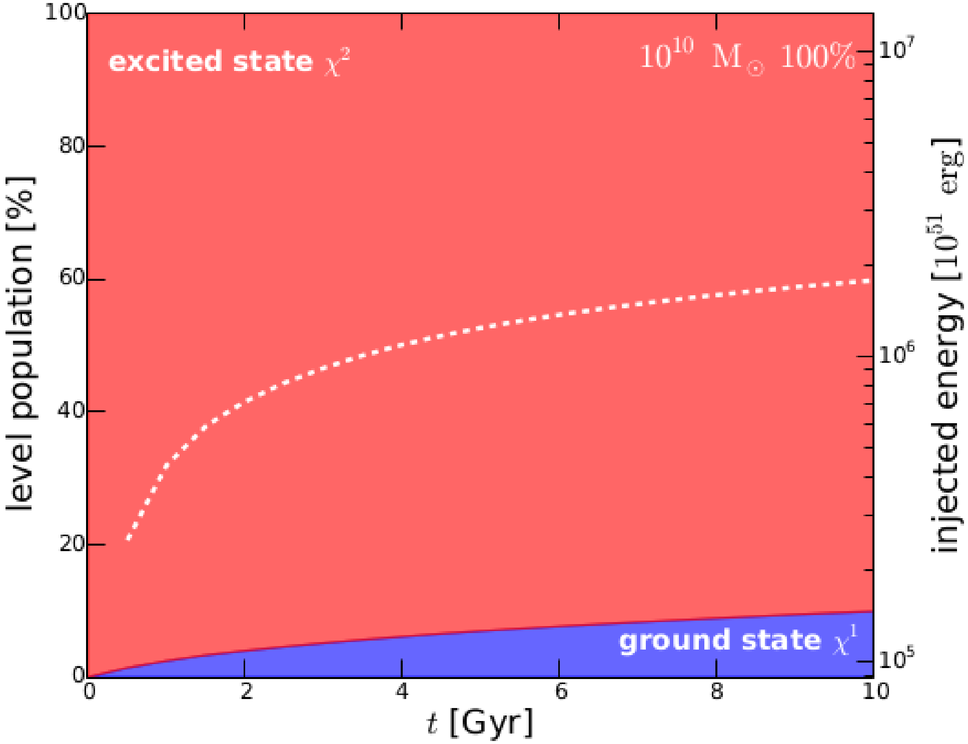


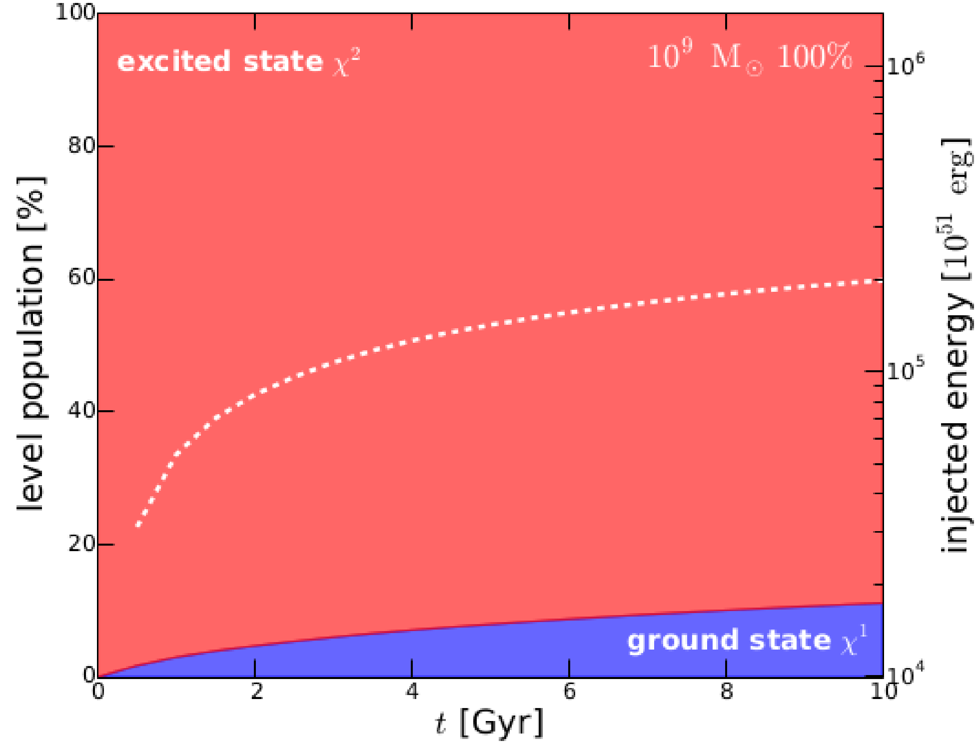


Inelastic SIDM

Inelastic SIDM *(preliminary)*

Inelastic SIDM

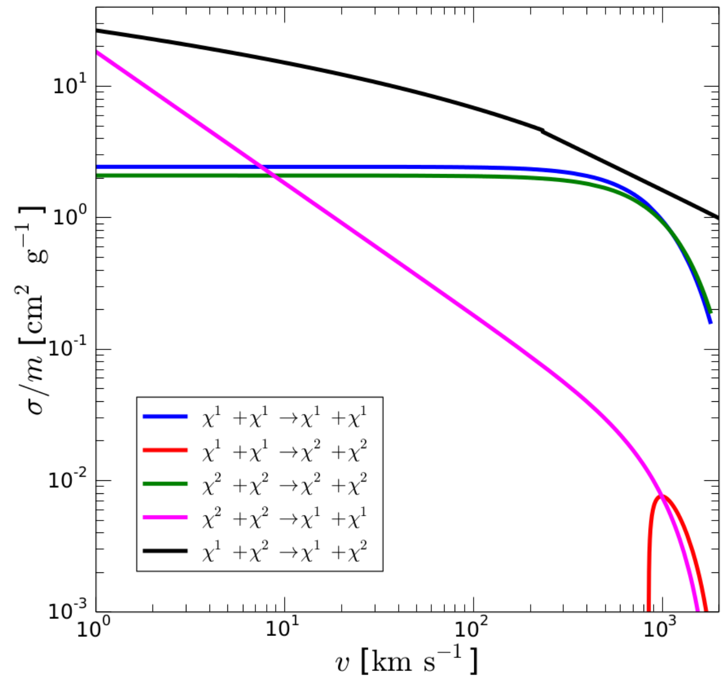




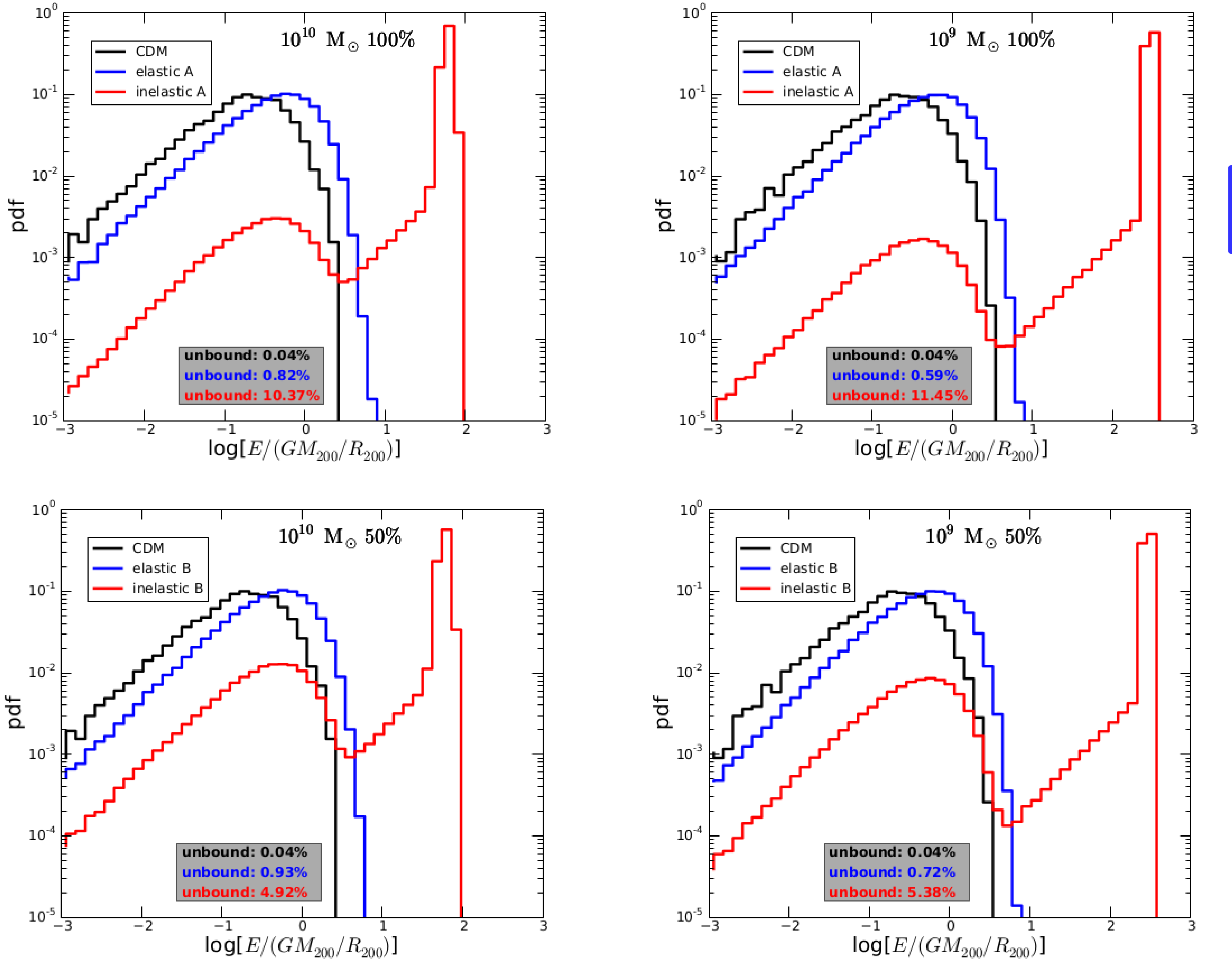
MV, Zavala+ in prep

Schutz, Slatyer 2014

$$\delta = 10\,\mathrm{keV},\ m_\chi = 10\,\mathrm{GeV}$$



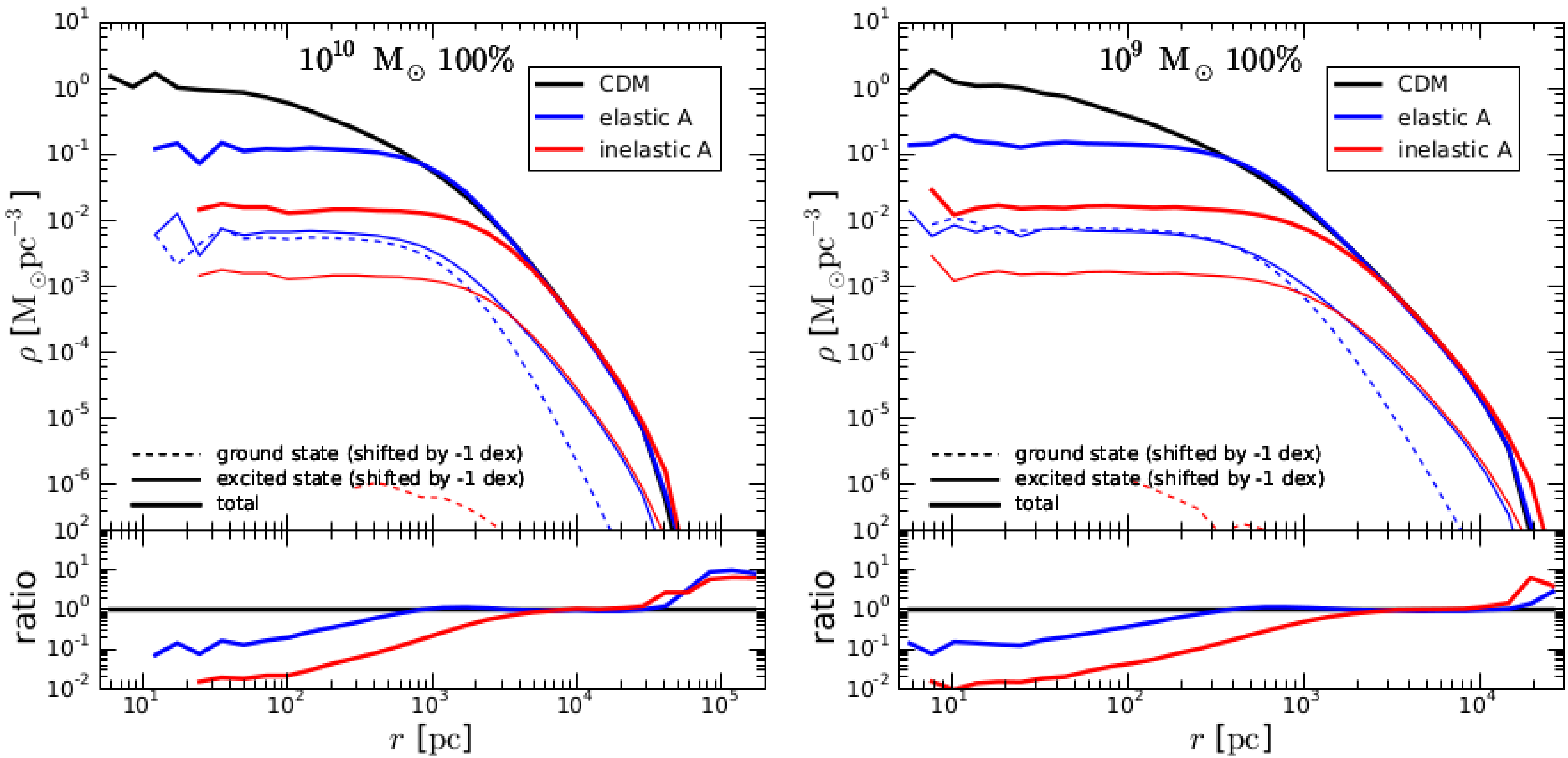
Inelastic SIDM



unbinding DM particles

MV, Zavala+ in prep

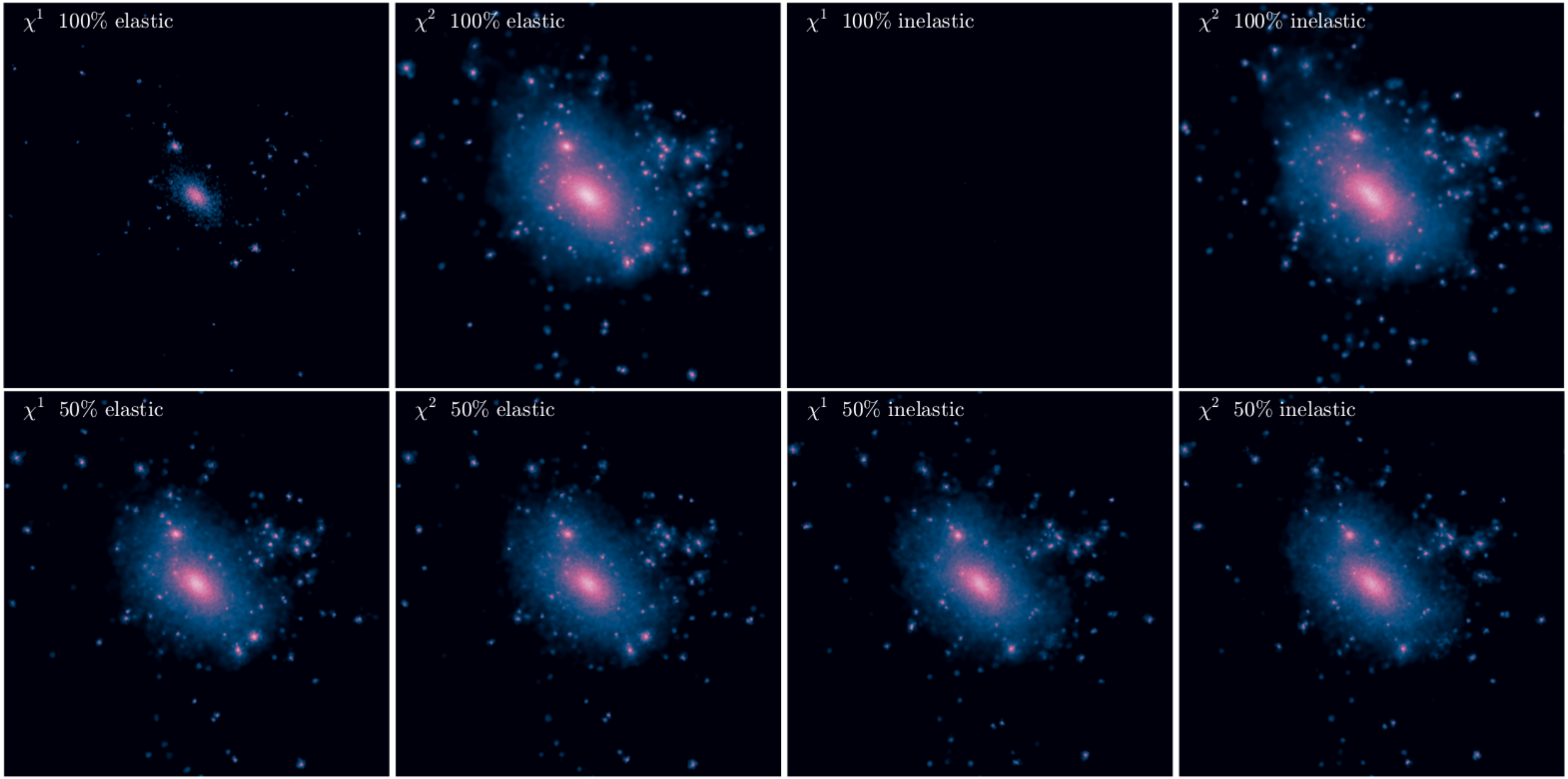
Inelastic SIDM



larger cores for inelastic models

MV, Zavala+ in prep

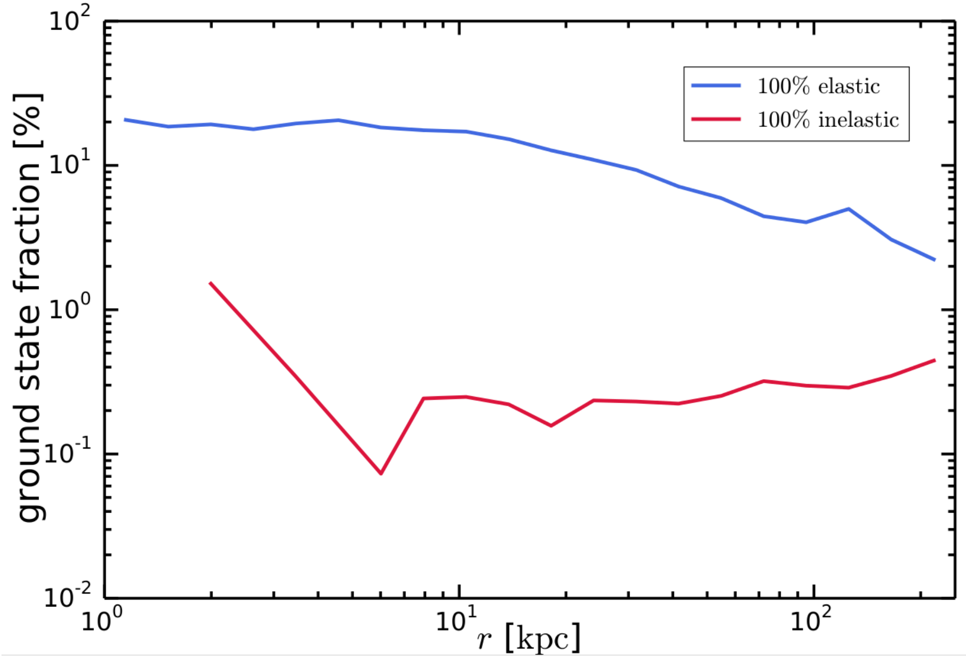
Inelastic SIDM



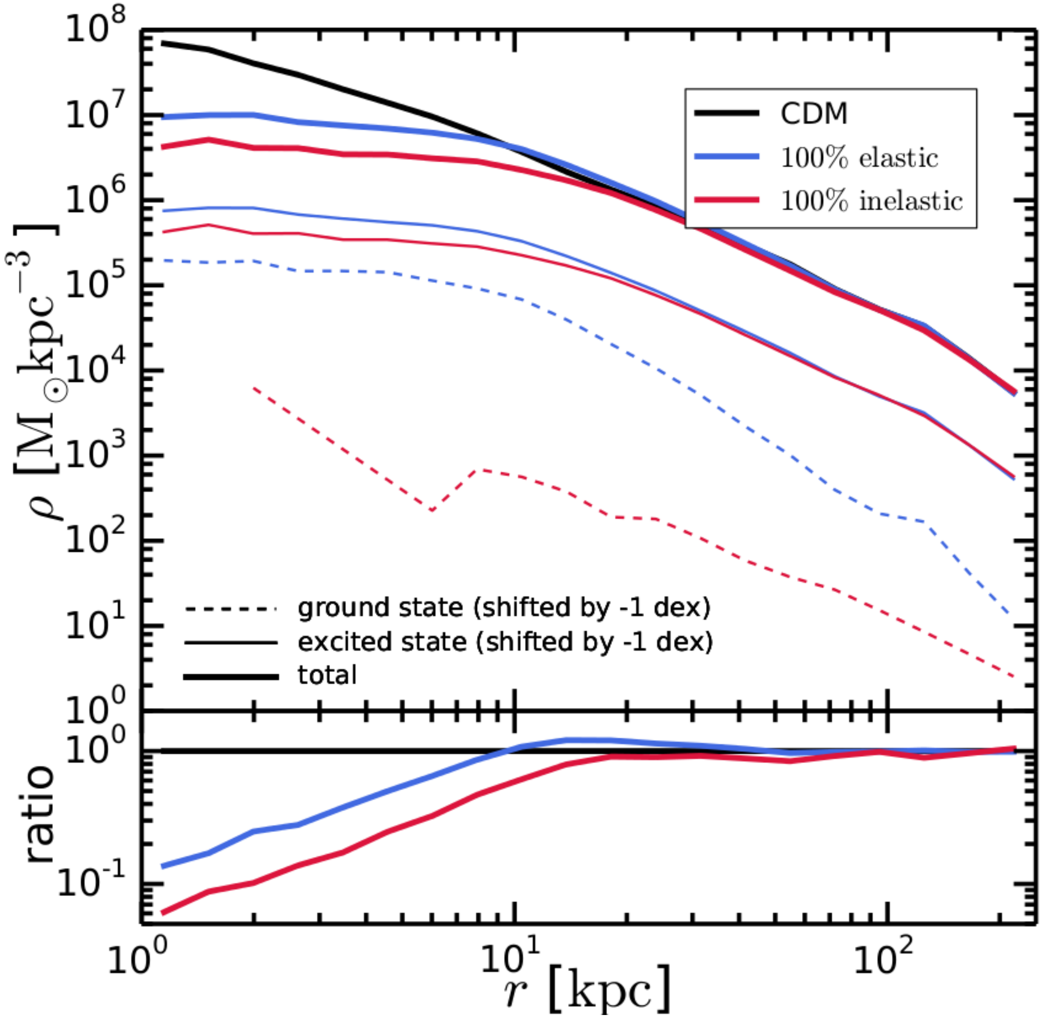
MV, Zavala+ in prep

Milky Way-like halo

Inelastic SIDM

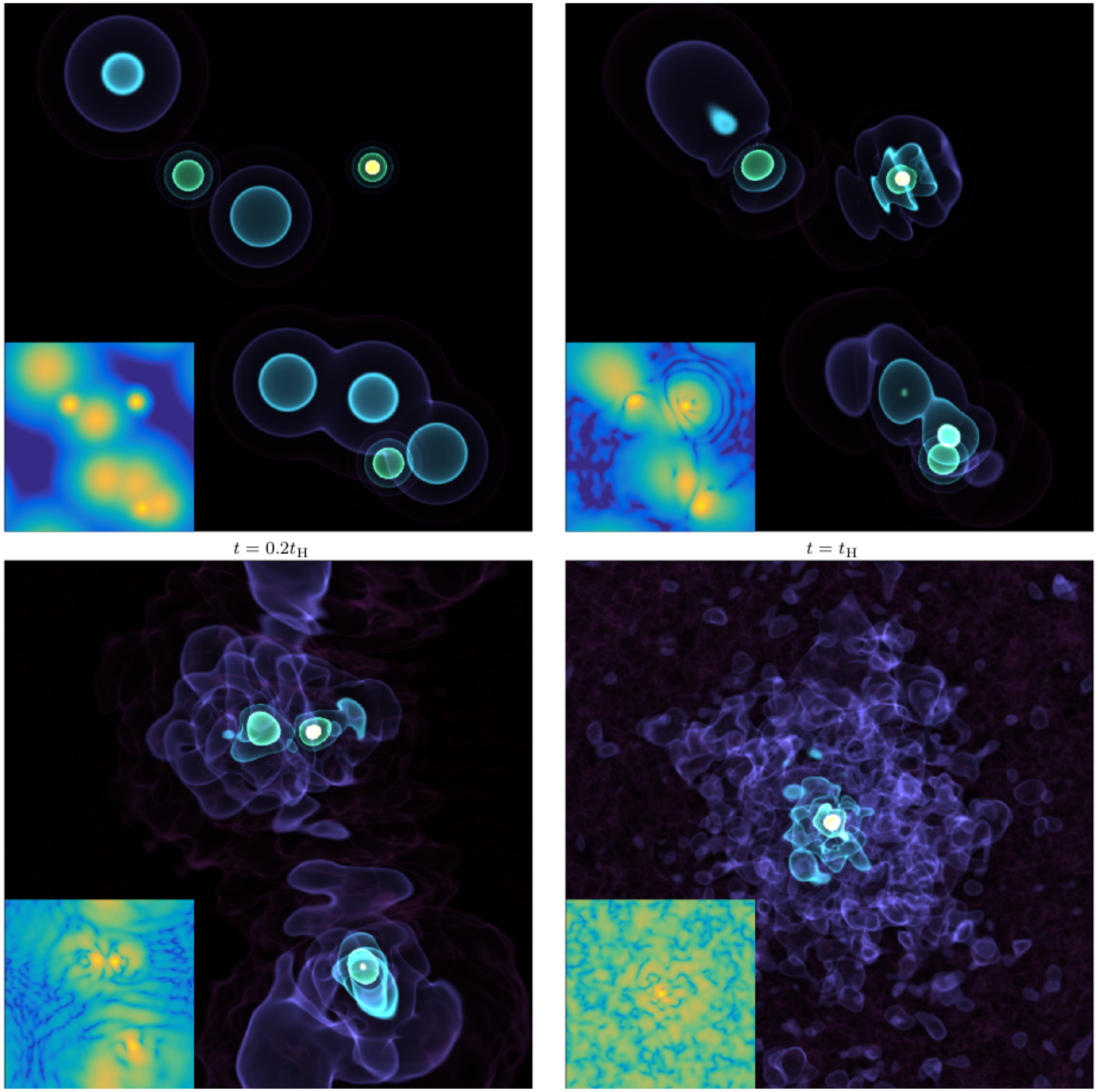


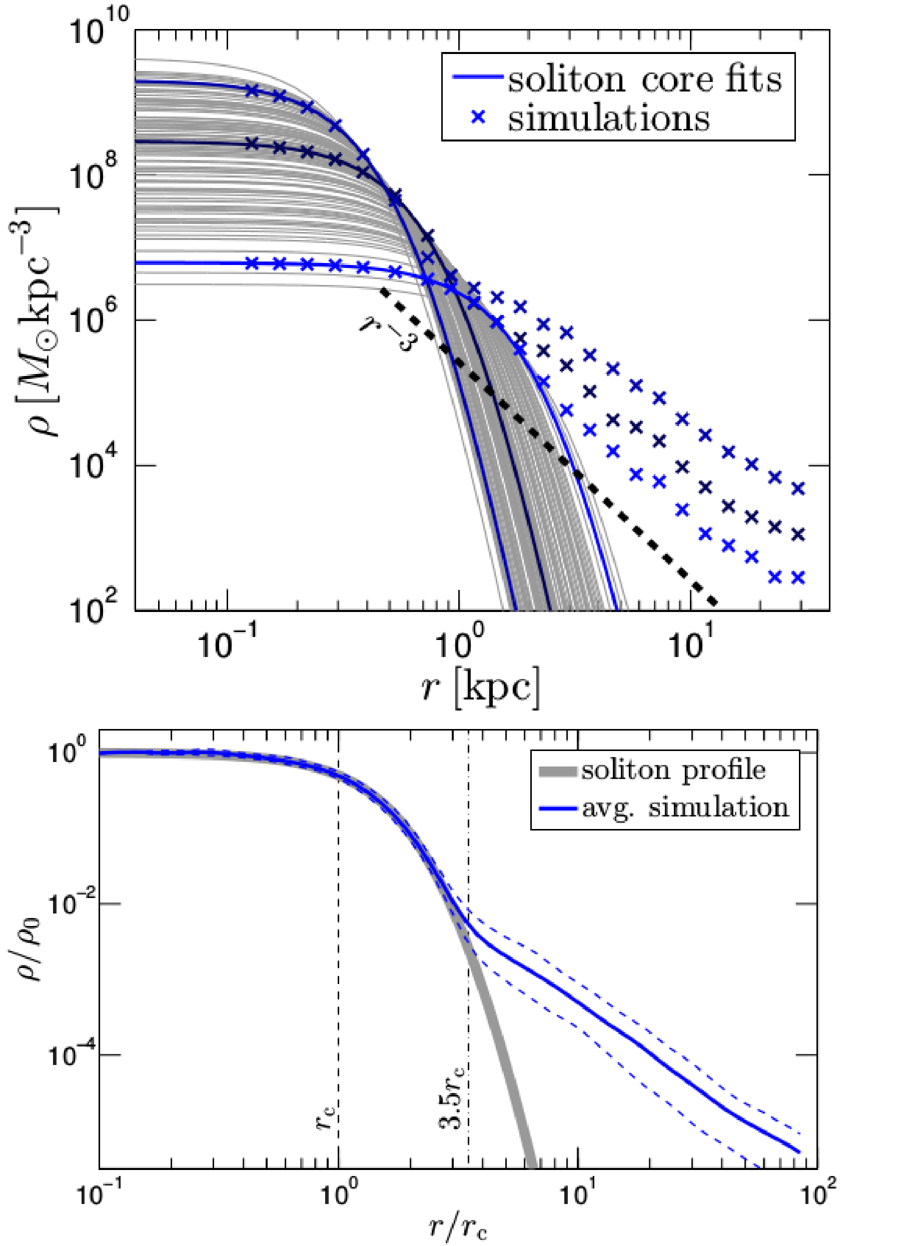
Milky Way-like halo



MV, Zavala+ in prep

Ultralight Axions - BECDM





Mocz, MV+ 2017

core formation through quantum pressure

Summary

CDM cosmological hydro simulations:

- reproduce many observed properties of the galaxy population
- reached a dynamic range to simultaneously simulate the dwarf and the cluster scale
- still depend on rather crude models for various physical processes (e.g., AGN feedback)

Self-Interacting Dark Matter:

- provides a promising alternative to CDM to alleviate small-scale CDM problems
- velocity-dependent cross sections avoid cluster-scale constraints
- more general models also consider modifications of initial power spectra leading to other interesting effects
- inelastic SIDM models