# Simulations of Self-Interacting Dark Matter

## (a simulation perspective on SIDM)

Mark Vogelsberger

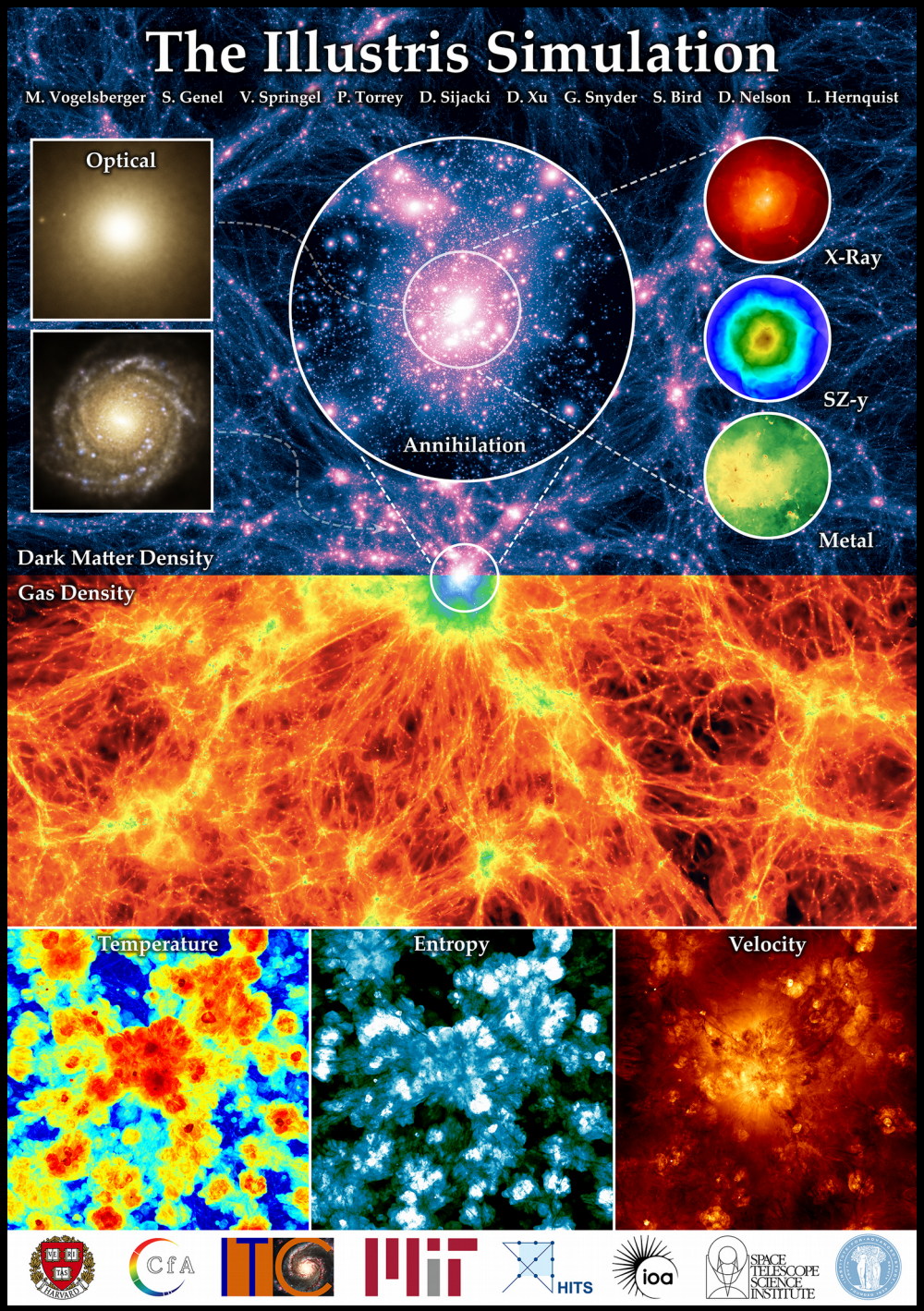
Tensions in the LCDM paradigm,

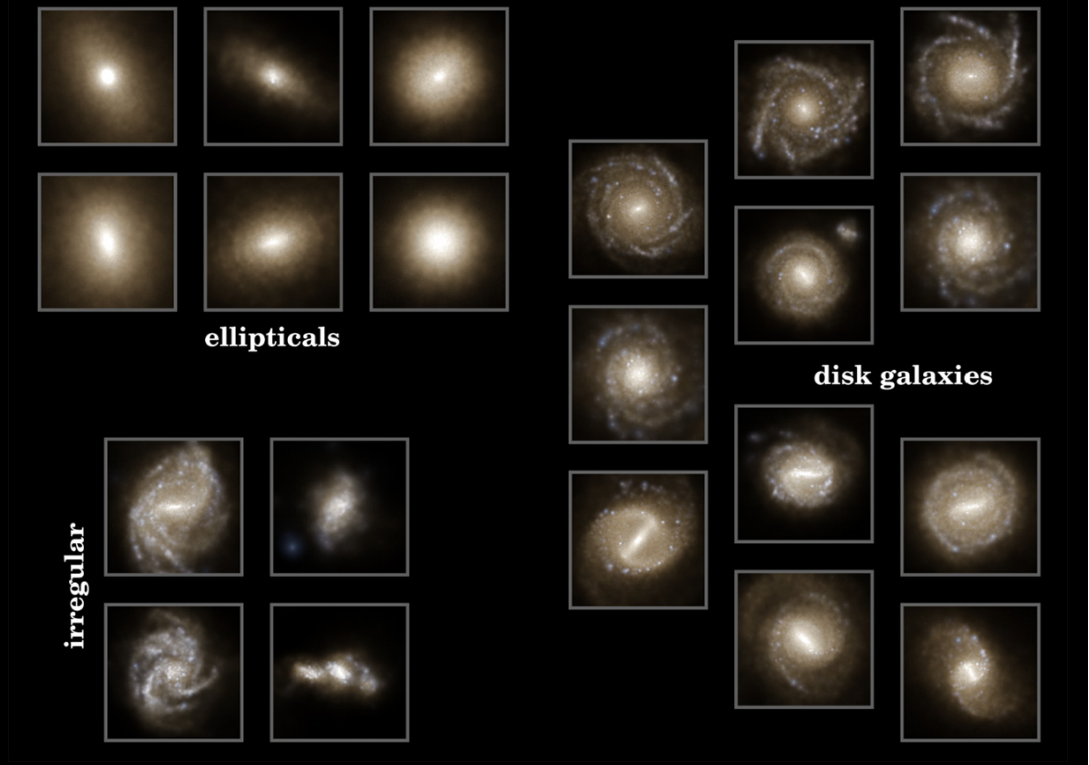
MITP, May 2018

Massachusetts Institute of Technology

# The Illustris Simulation

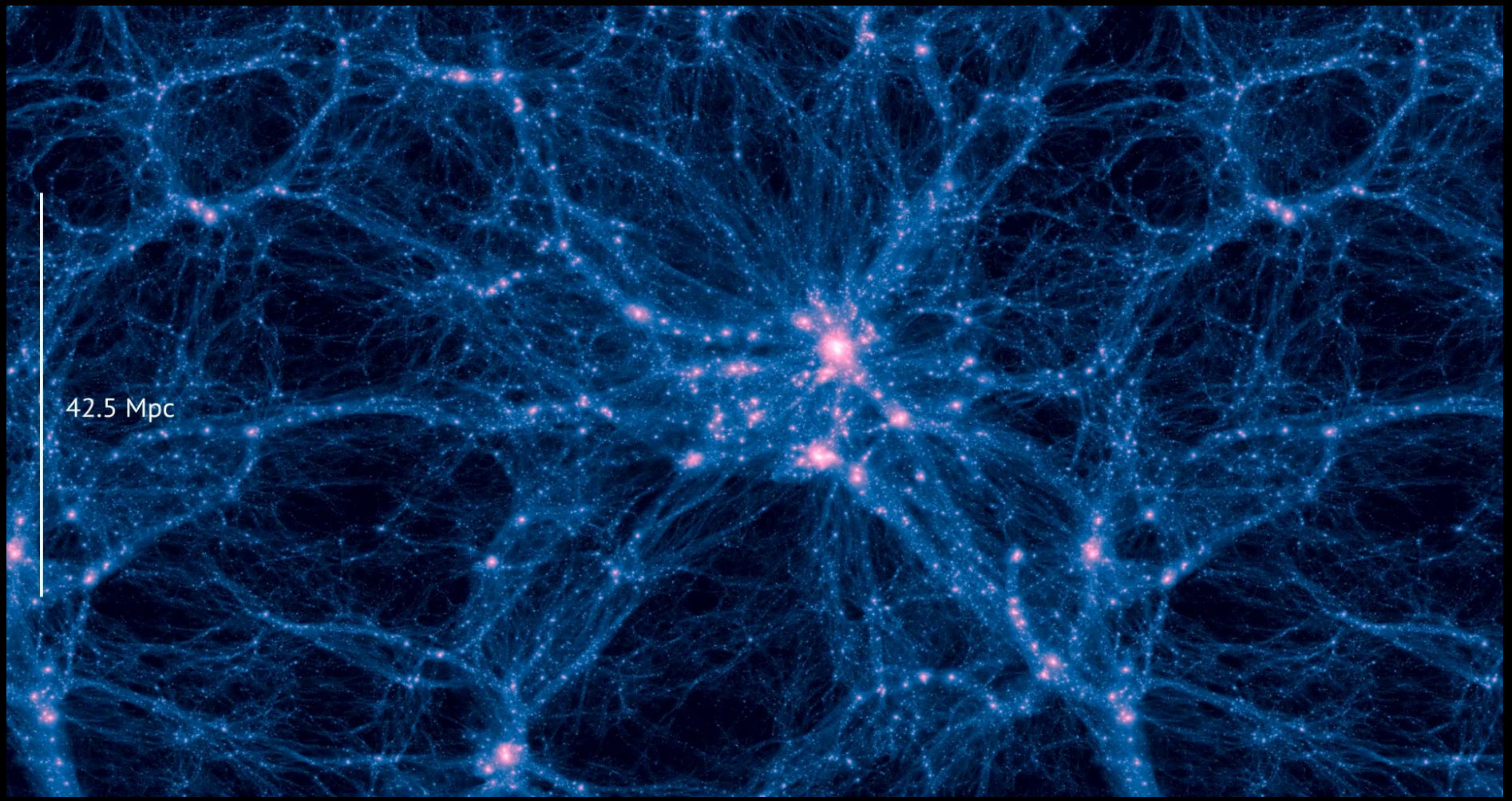
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist



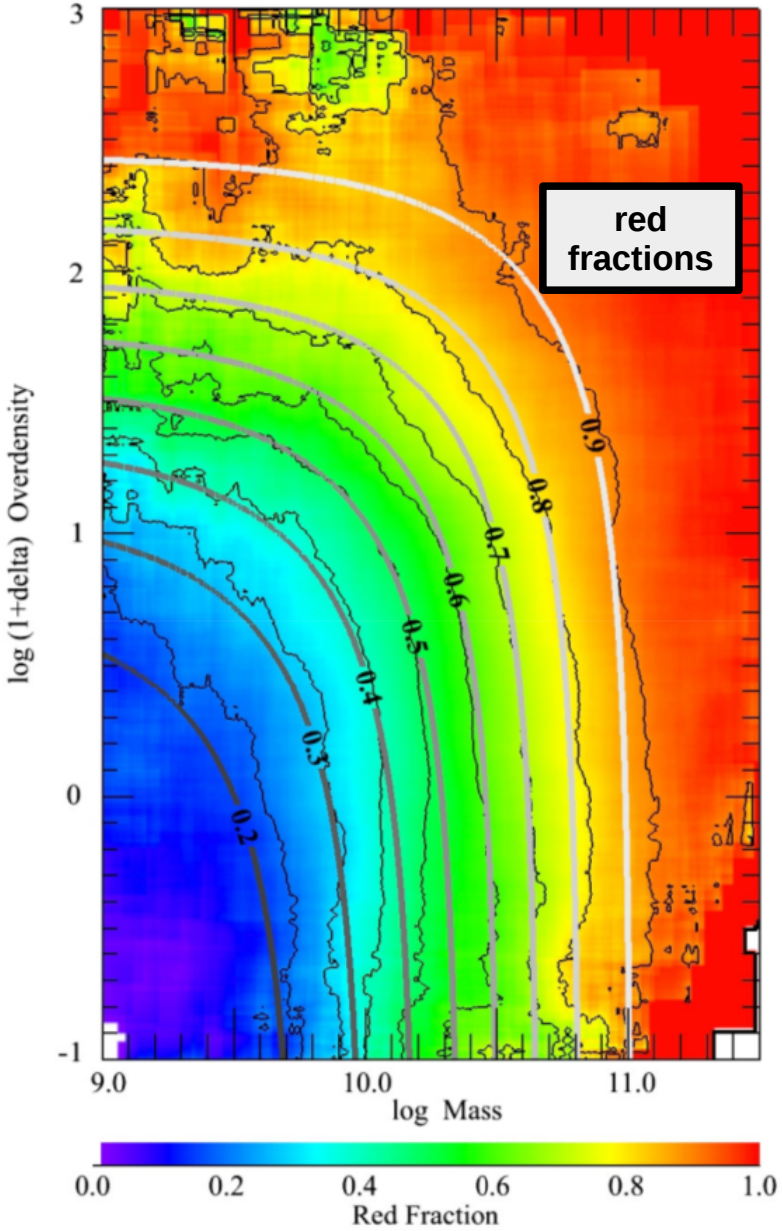

MV+ 2014 (Nature)

http://www.illustris-project.org


42.5 Mpc

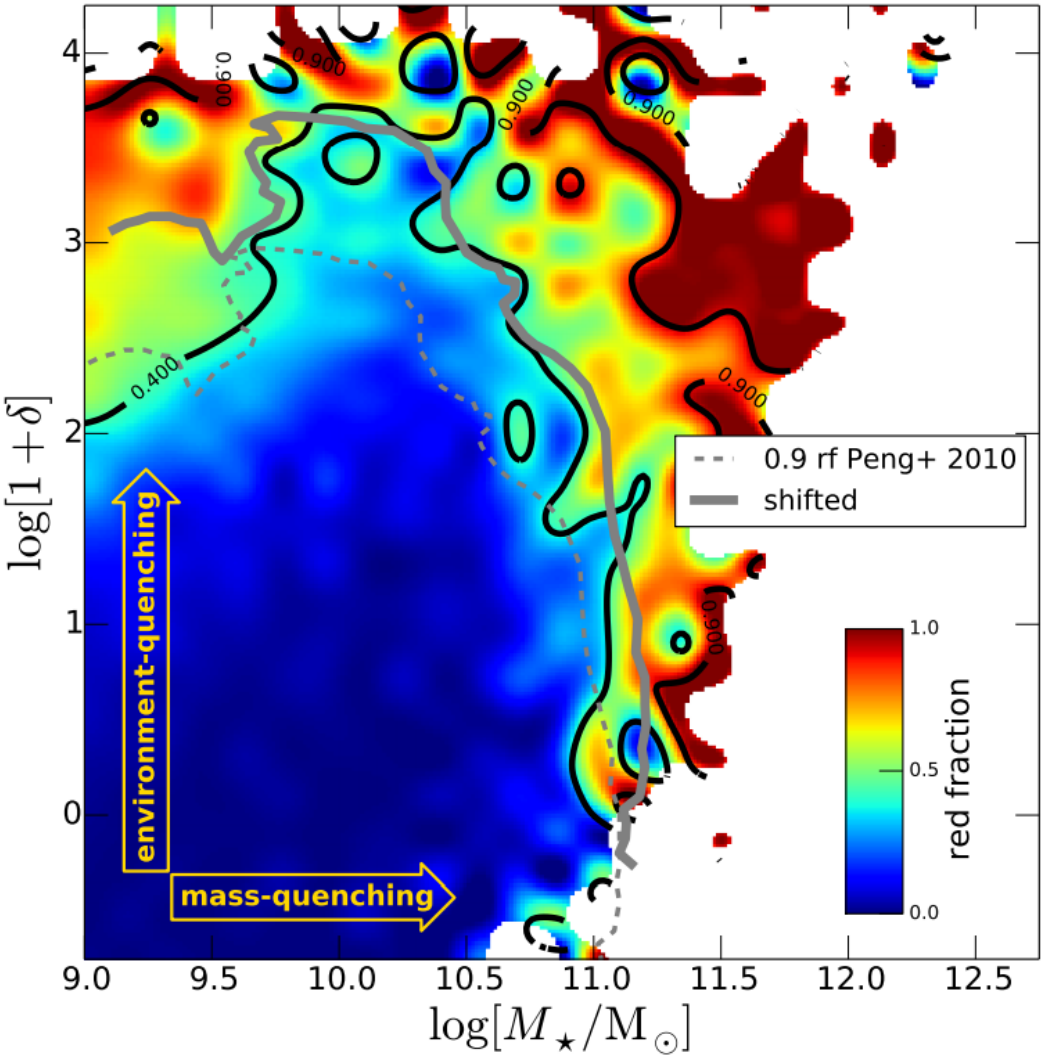
# Illustris: Results

Peng+ 2010




SDSS red fraction

MV+ 2014




Illustris red fraction

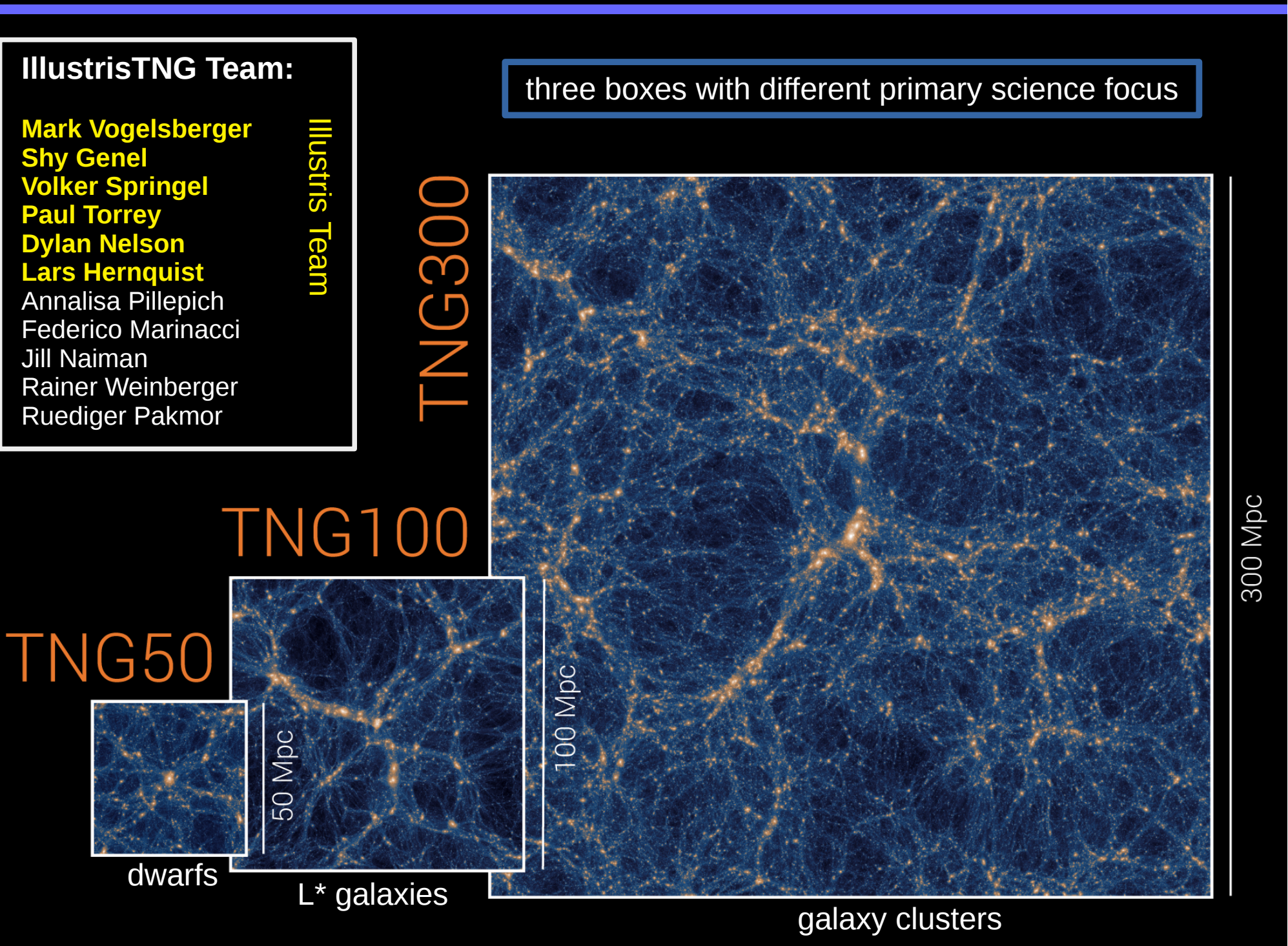
# The IllustrisTNG Simulations

**IllustrisTNG Team:**

**Mark Vogelsberger**
**Shy Genel**
**Volker Springel**
**Paul Torrey**
**Dylan Nelson**
**Lars Hernquist**
Annalisa Pillepich
Federico Marinacci
Jill Naiman
Rainer Weinberger
Ruediger Pakmor

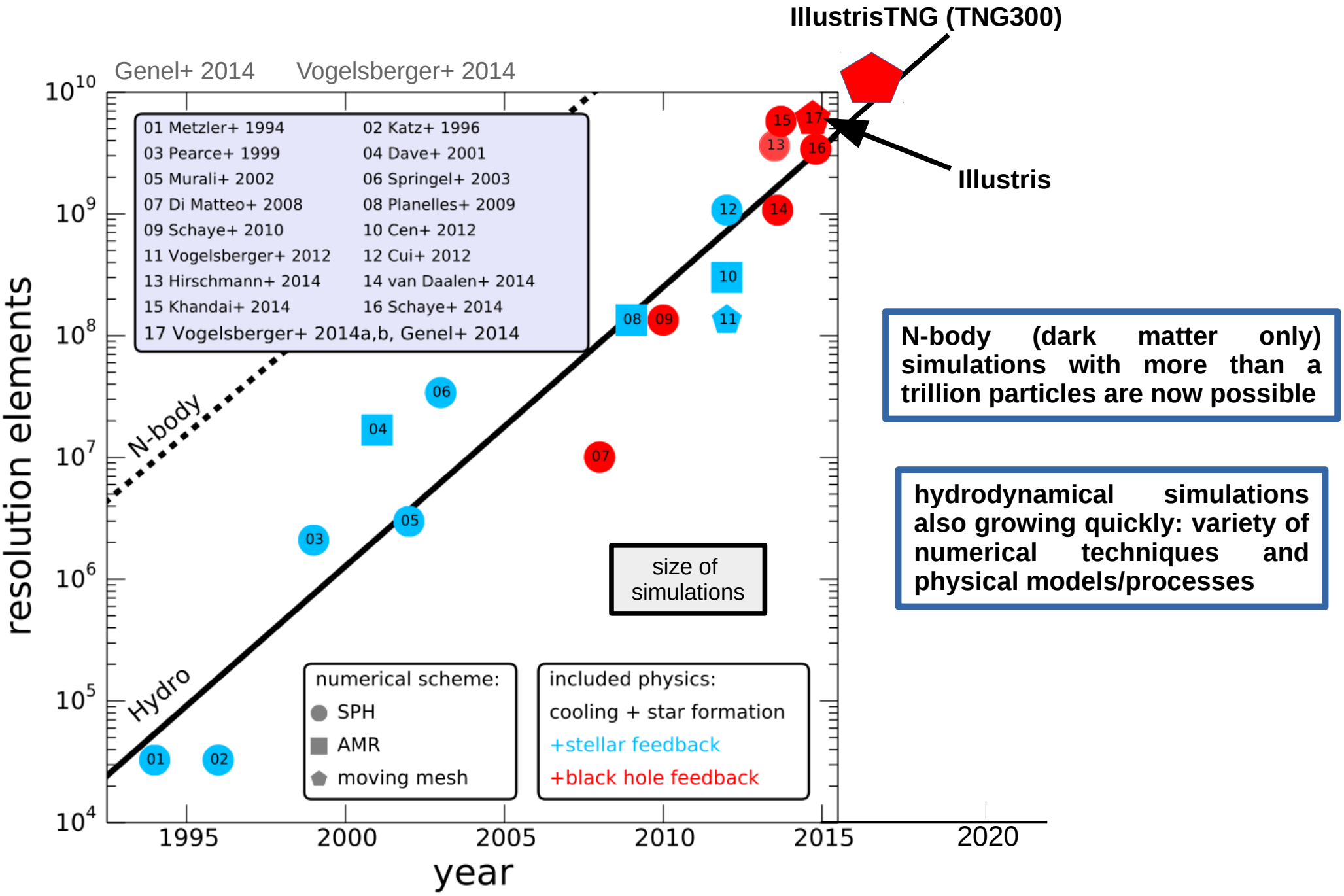
Illustris Team

three boxes with different primary science focus




redshift: 3.88
Mark Vogelsberger, Federico Marinacci (MIT)

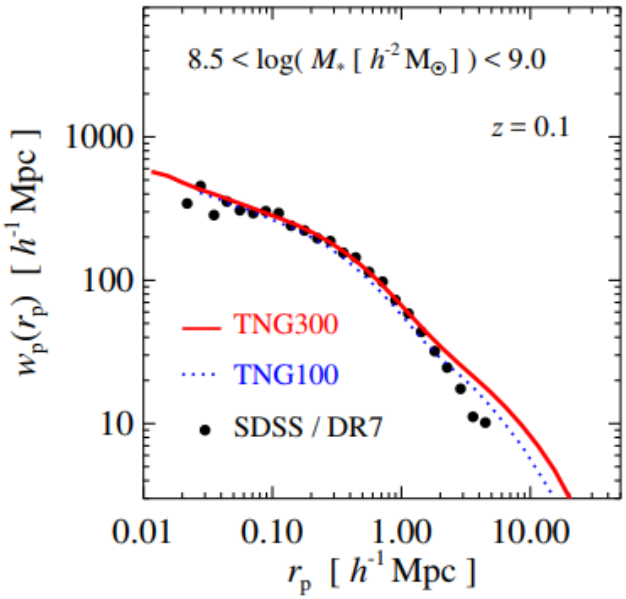
# The Evolution of Large-Scale Simulations

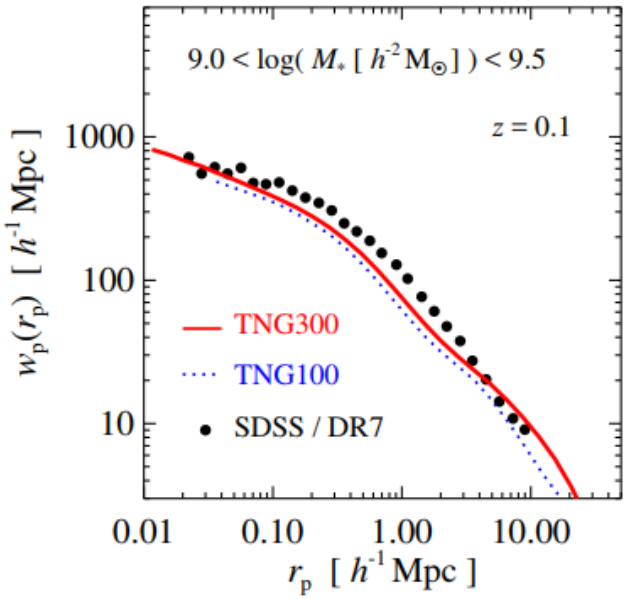


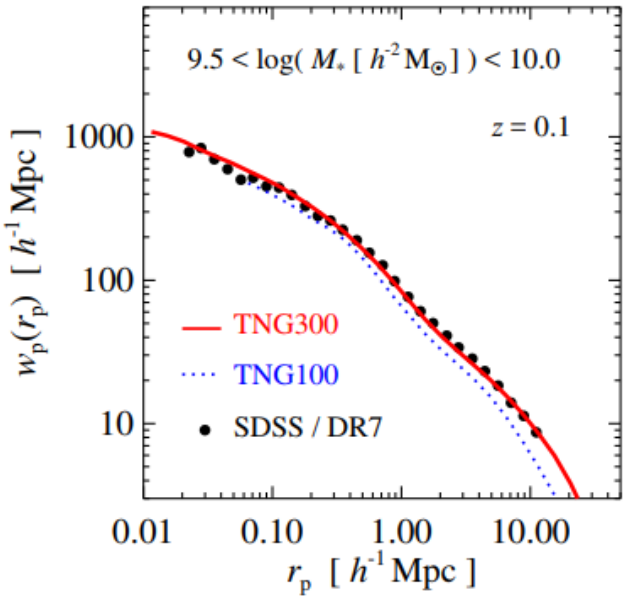

**N-body (dark matter only) simulations with more than a trillion particles are now possible**

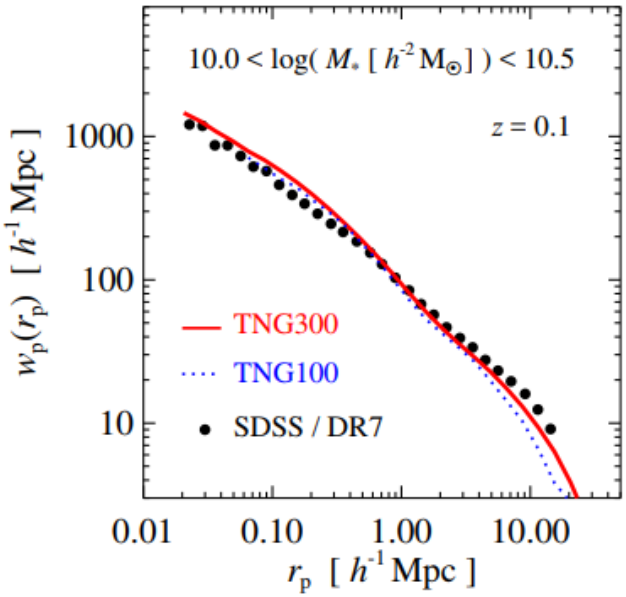
**hydrodynamical simulations also growing quickly: variety of numerical techniques and physical models/processes**

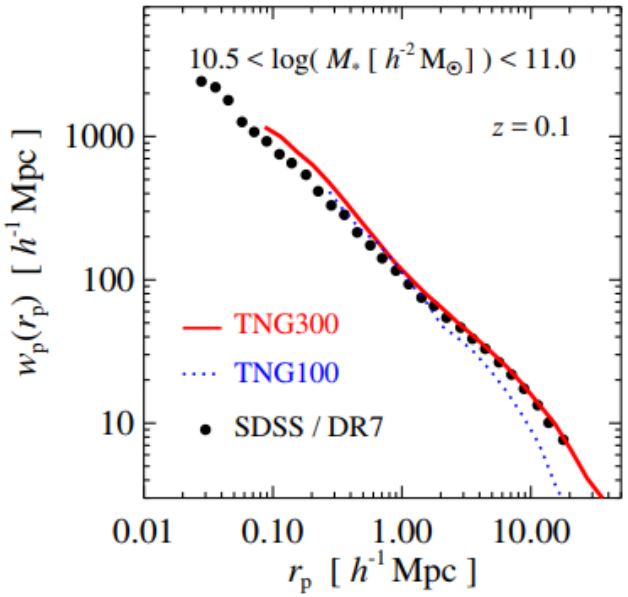
# IllustrisTNG: Results

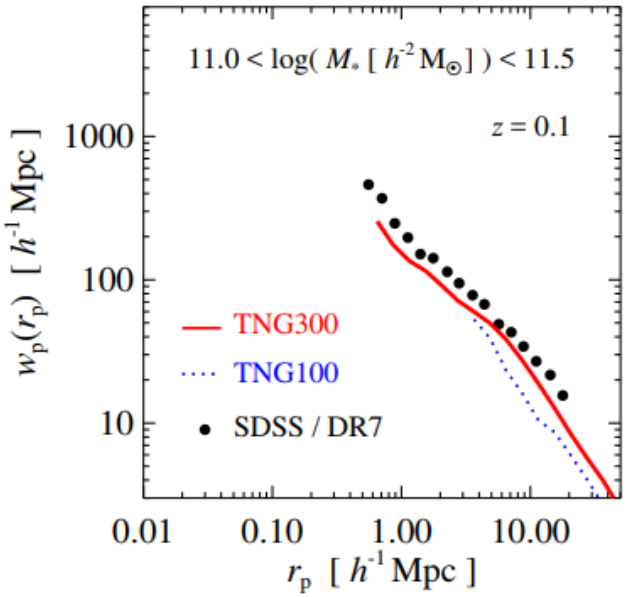


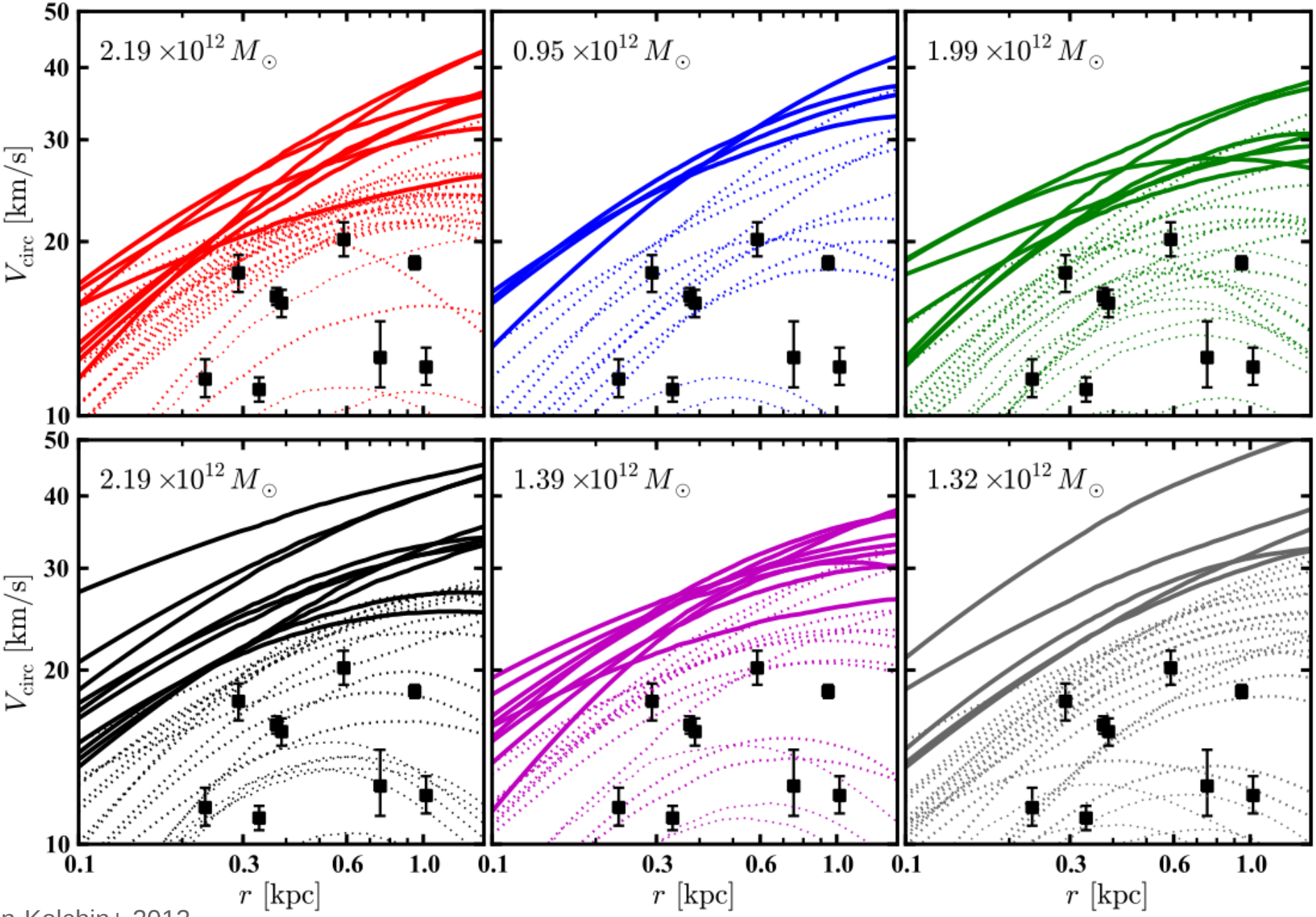




Springel+ w/ MV 2018

# CDM Issues, e.g. Too-Big-To-Fail Problem




Boylan-Kolchin+ 2012

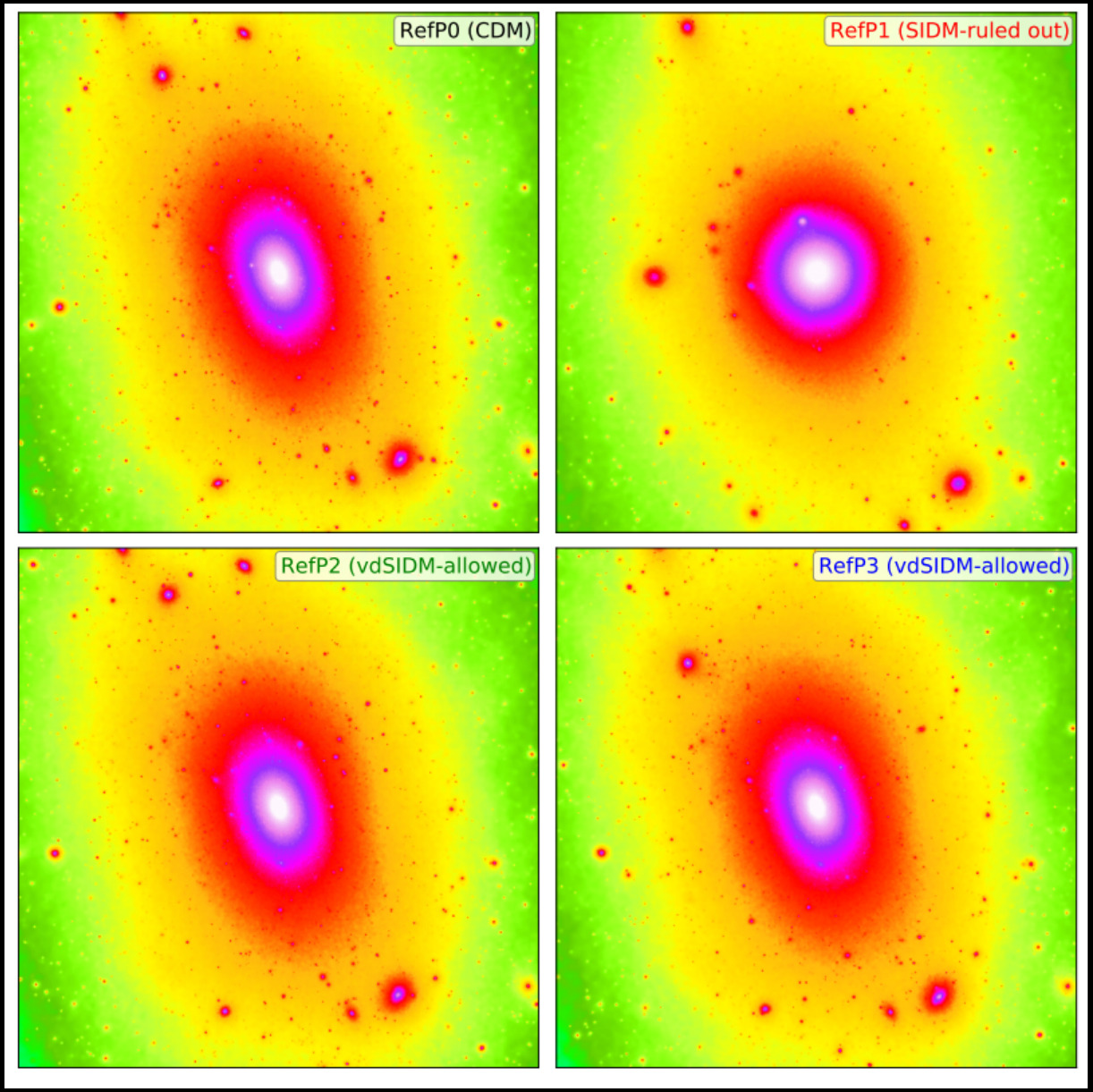
# Going beyond CDM: Many Possibilities

**Warm Dark Matter?**
**[CDM is cold]**

**Self-Interacting Dark Matter?**
**[CDM is collisionless]**

**Fuzzy Dark Matter?**

# The Outcome of SIDM Simulations




**motivation for SIDM comes from astrophysics and particle physics**

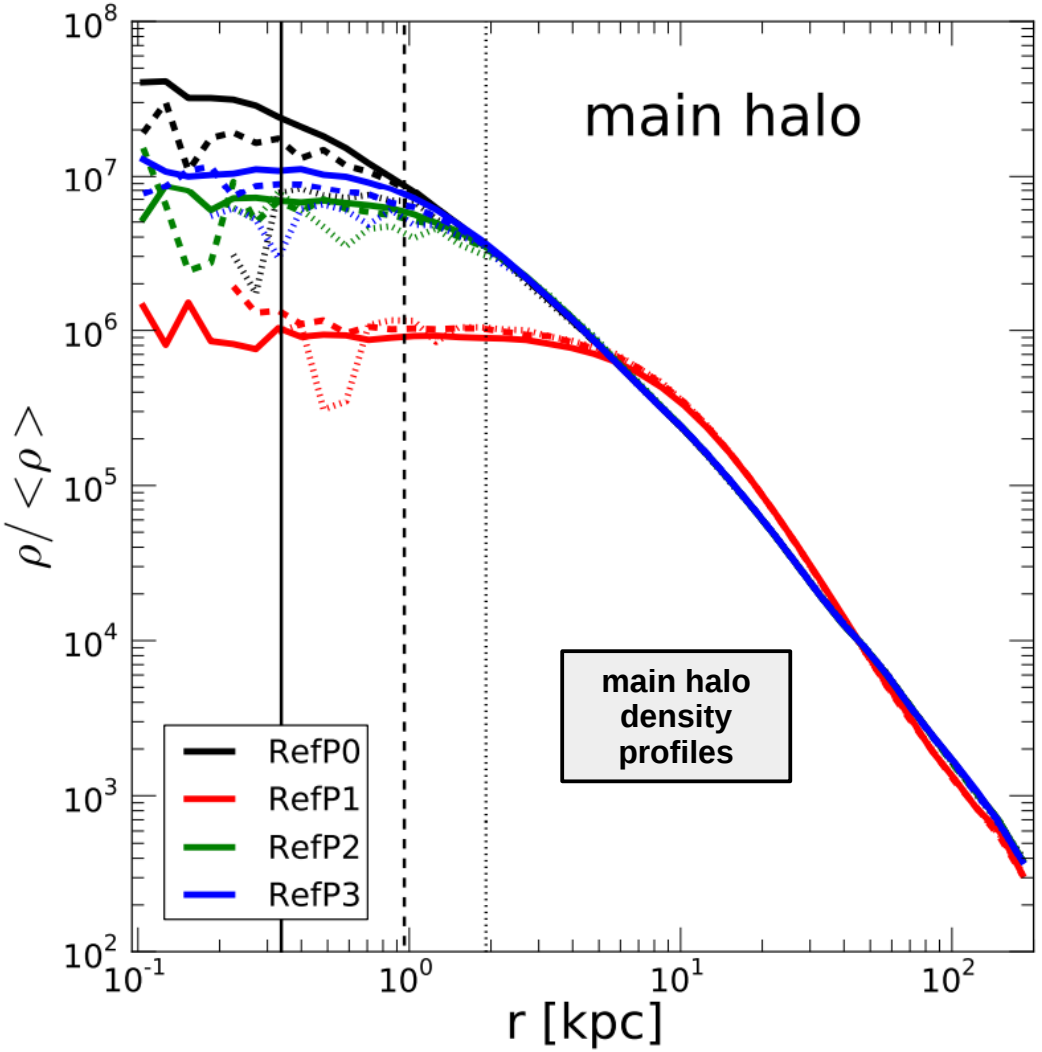
**impact of SIDM on dark matter density field of MW-like halos**

$$\Gamma_{\rm tot} = \int_V \frac{\rho(\vec{x})^2}{2m_\chi^2} \langle \sigma_T v \rangle (\vec{x})\, {\rm d}V,$$

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

MV+ 2012

# Impact on the Halo DM Density Profile



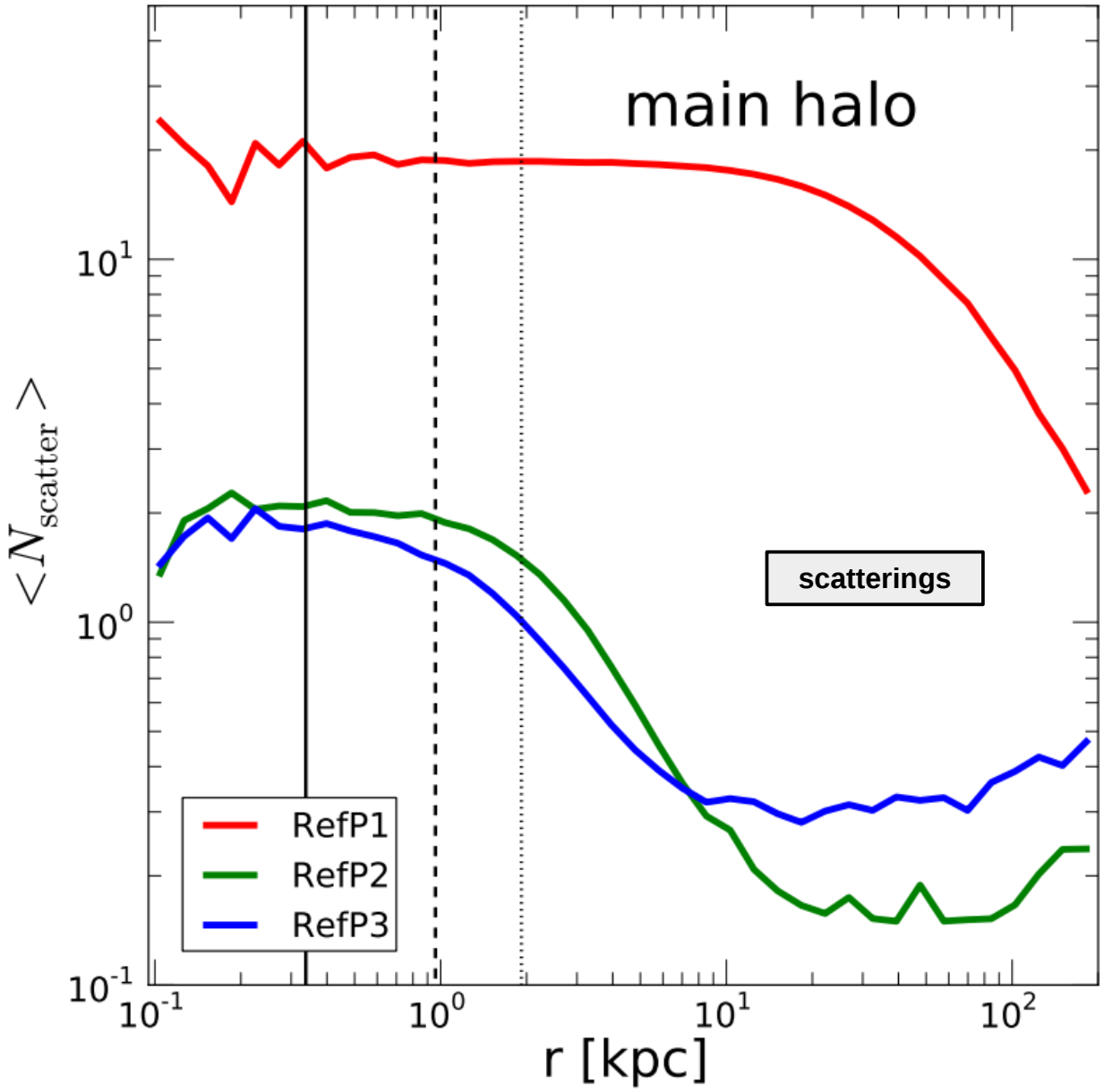

**impact of SIDM on main halo density profile → core formation**

**core formation: larger cores for larger cross sections**

**technical note: SIDM converges quicker than SIDM with resolution**

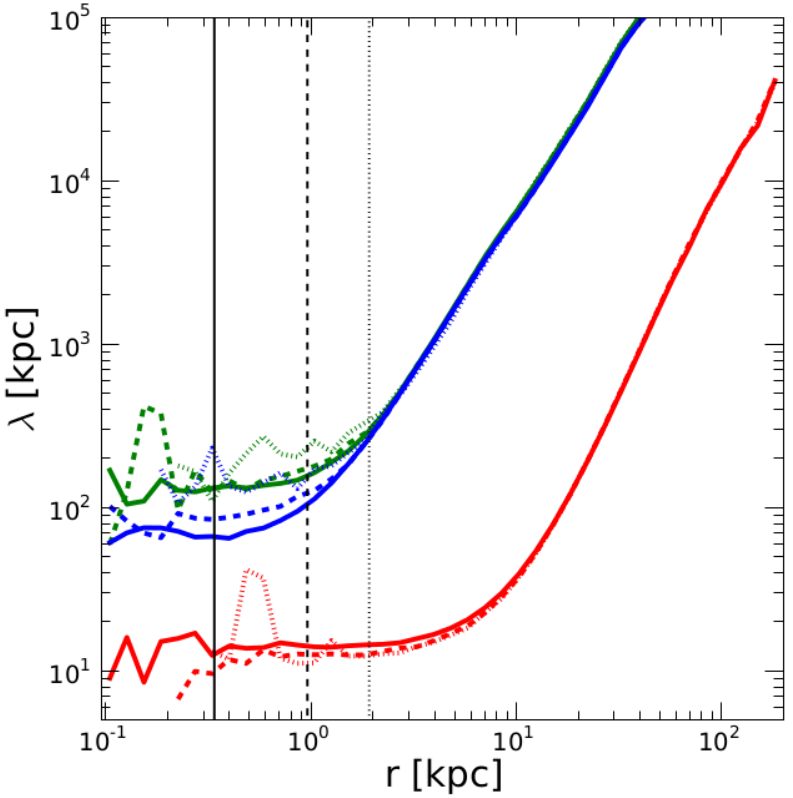
MV+ 2012

# Number of Scattering




**scatterings**

**typically only a few scattering per Hubble time are sufficient**

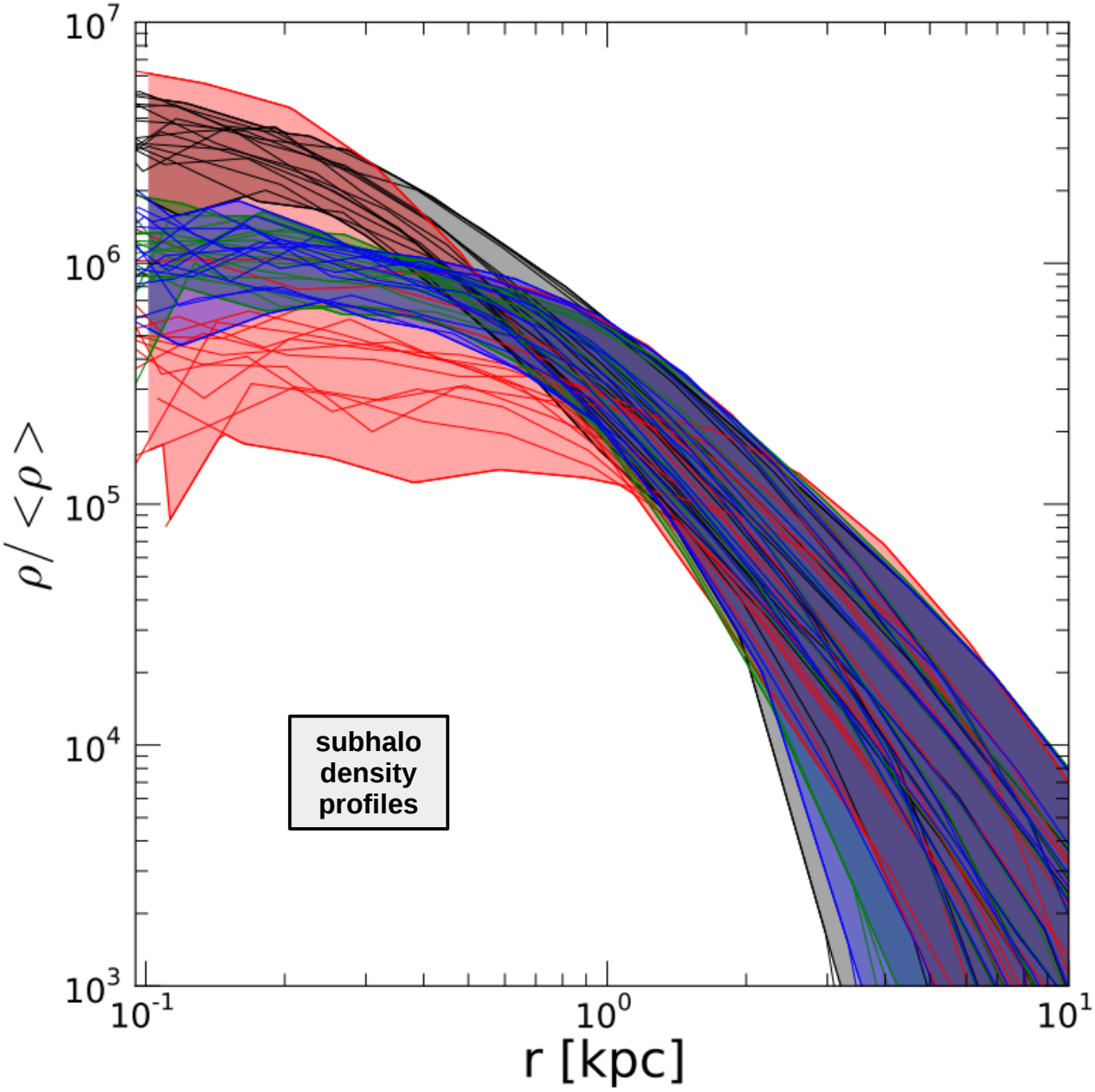



MV+ 2012

# Impact on Subhalo DM Density Profiles

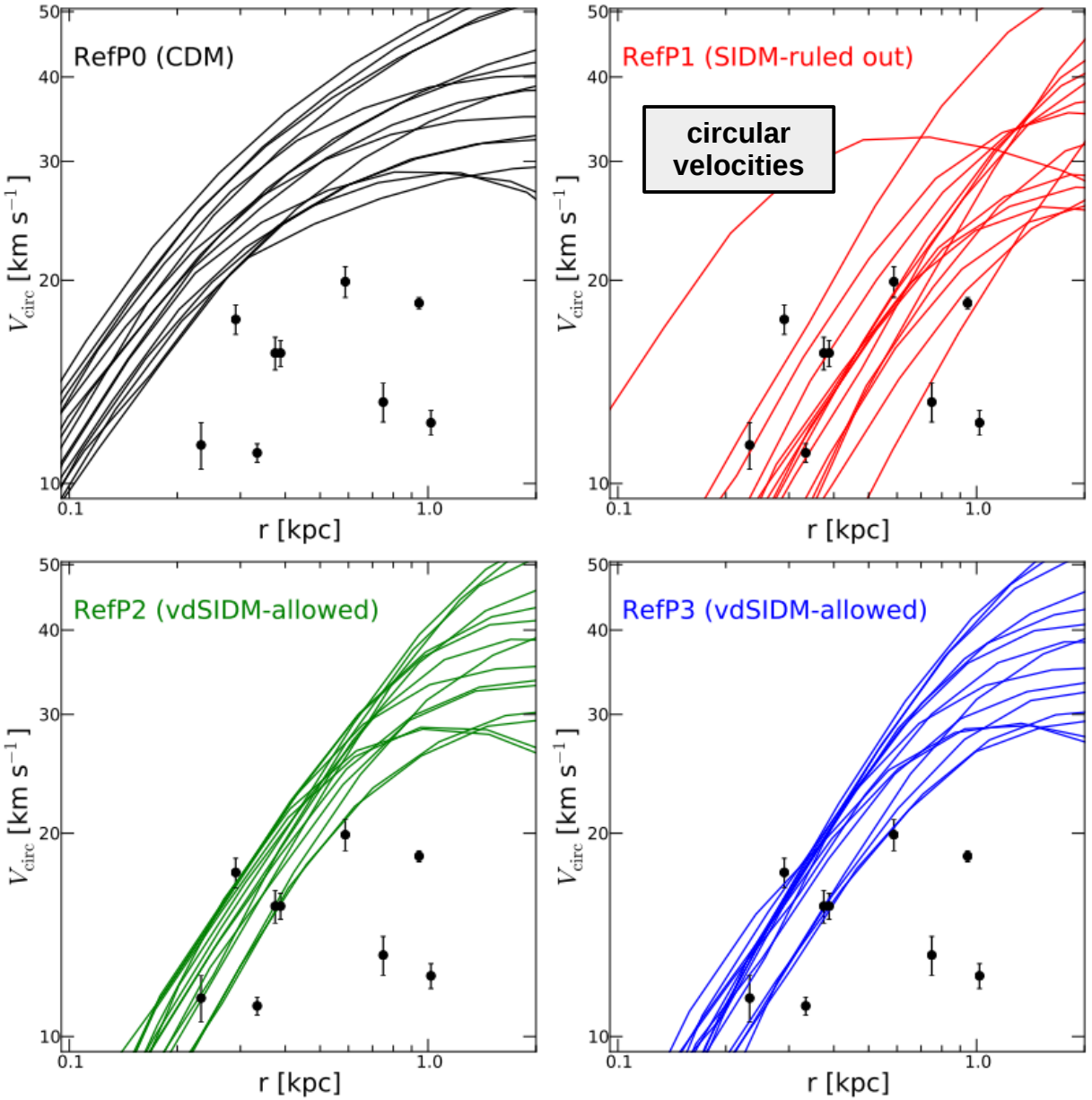
**core formation in subhalos: changes circular velocity profile**

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




MV+ 2012

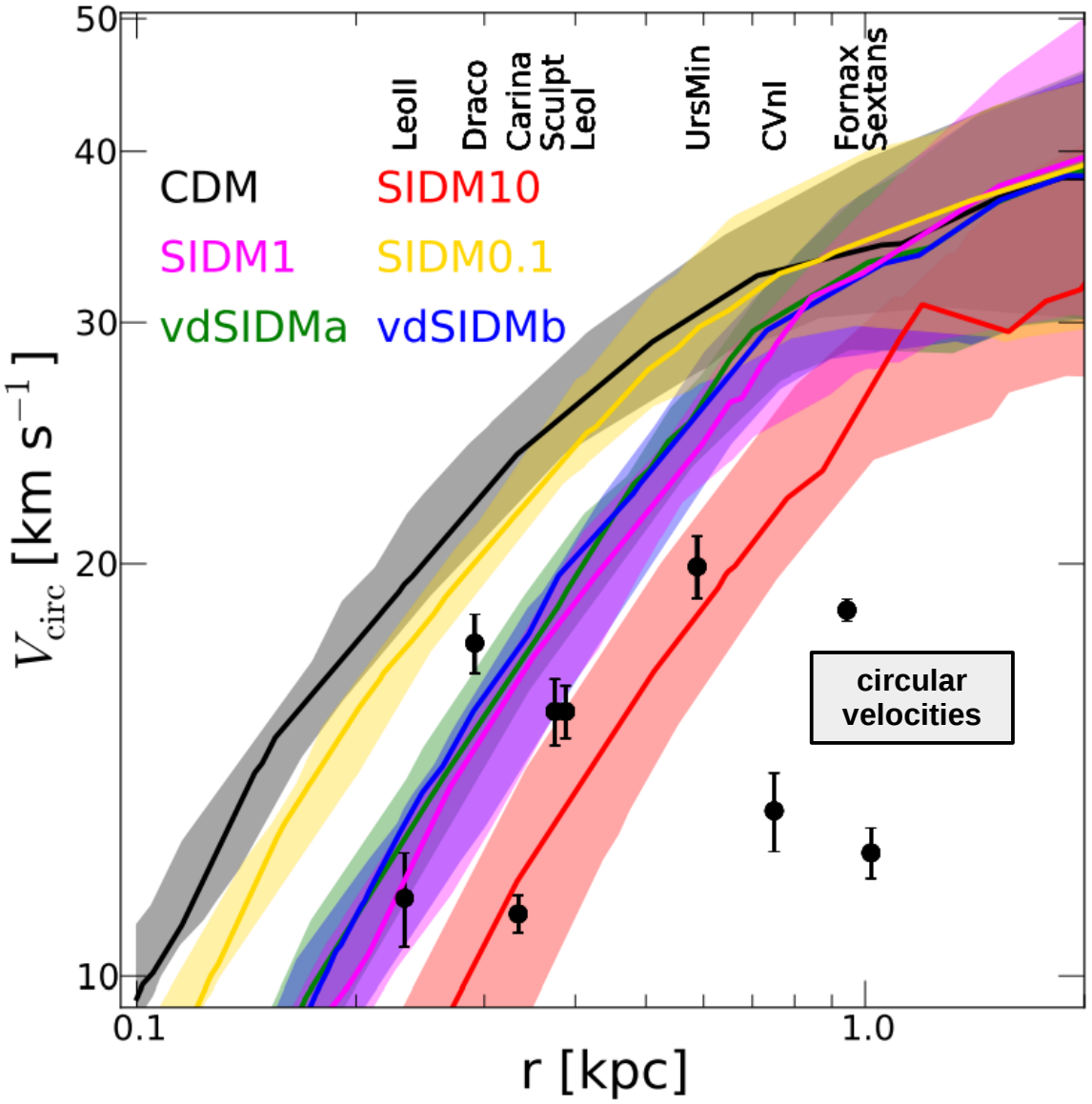
# Circular Velocity Curves



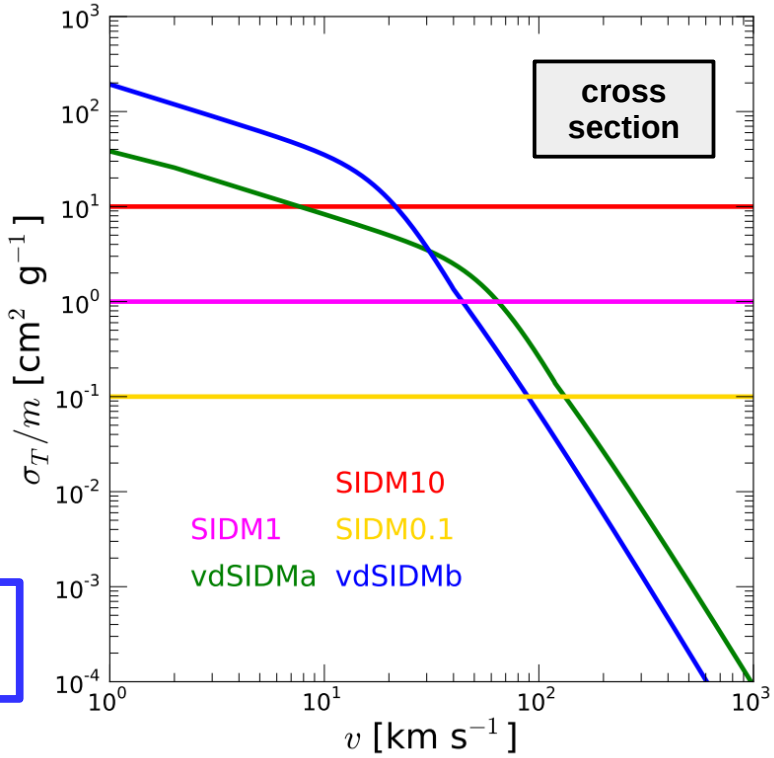

**'solving' the TBTF problem with SIDM**

MV+ 2012

# Self-Interacting Dark Matter




**SIDM simulations with velocity-dependent cross sections: alleviating the tension with the TBTF problem**

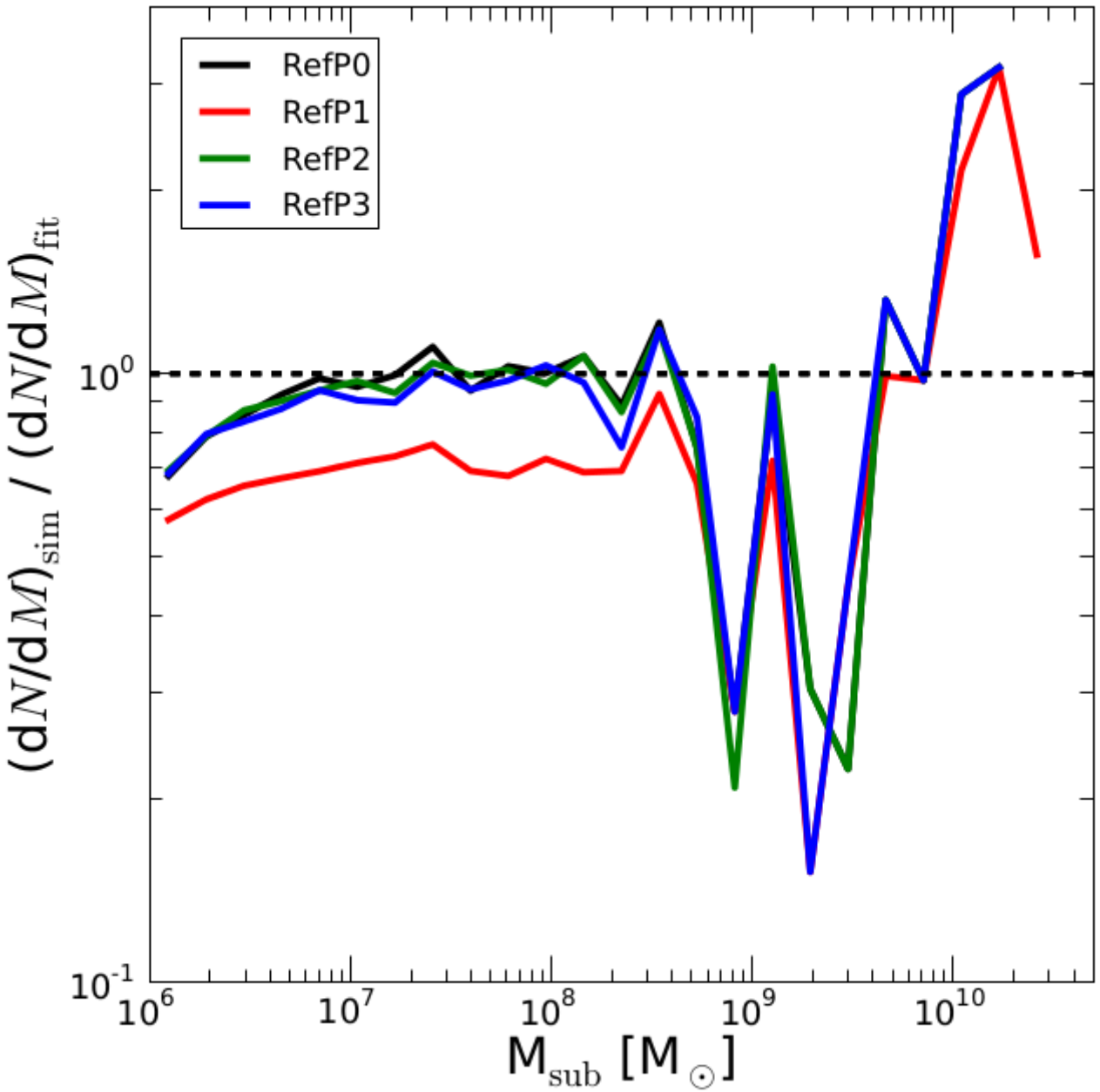



**velocity-dependent cross sections avoid cluster constraints**

Zavala, MV, Walker 2013

see also Rocha+ 2013

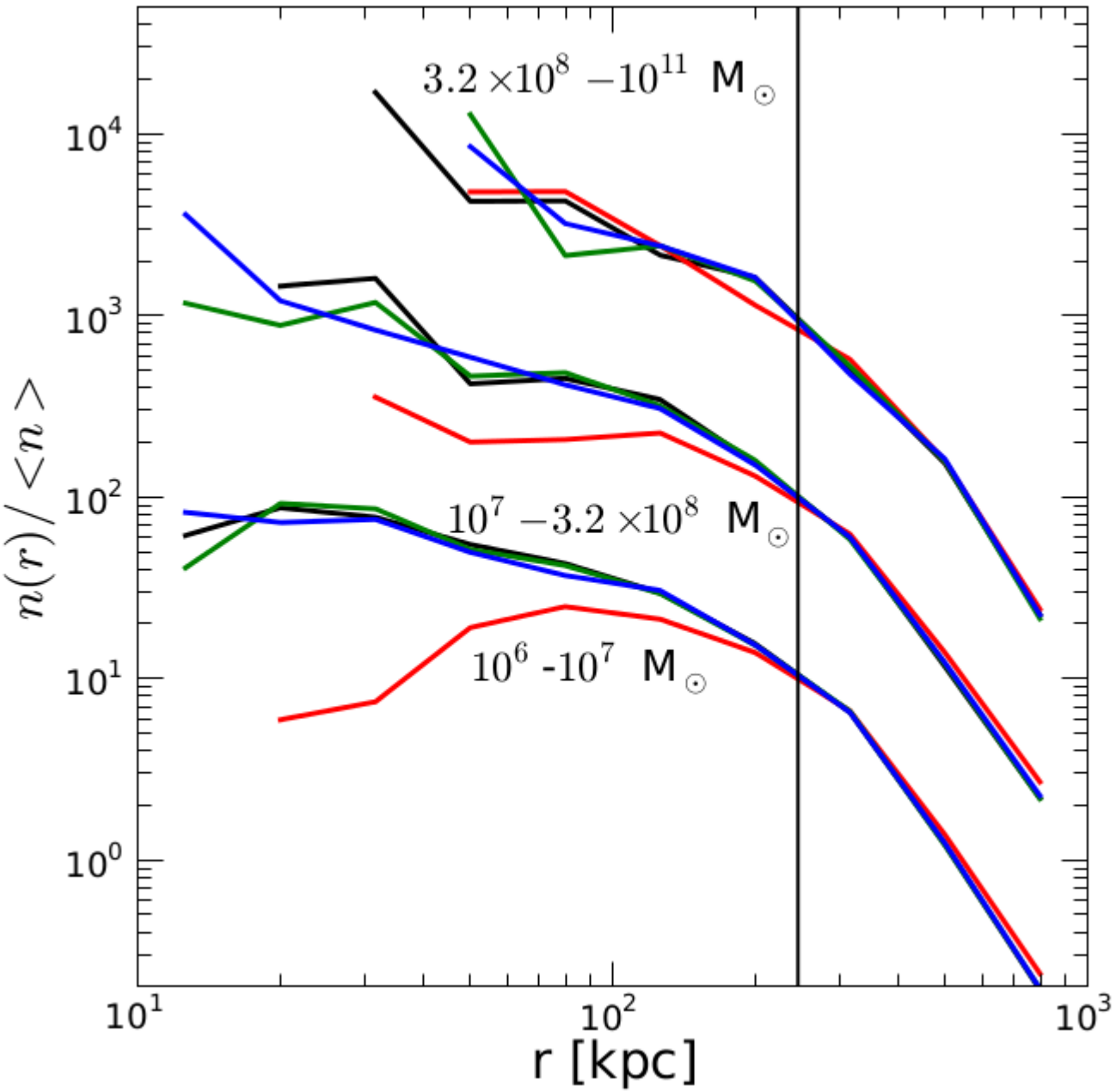
# Impact on Subhalo Abundance




**only large cross section can alter the abundance. Typically SIDM does not 'remove' subhalos**

MV+ 2012

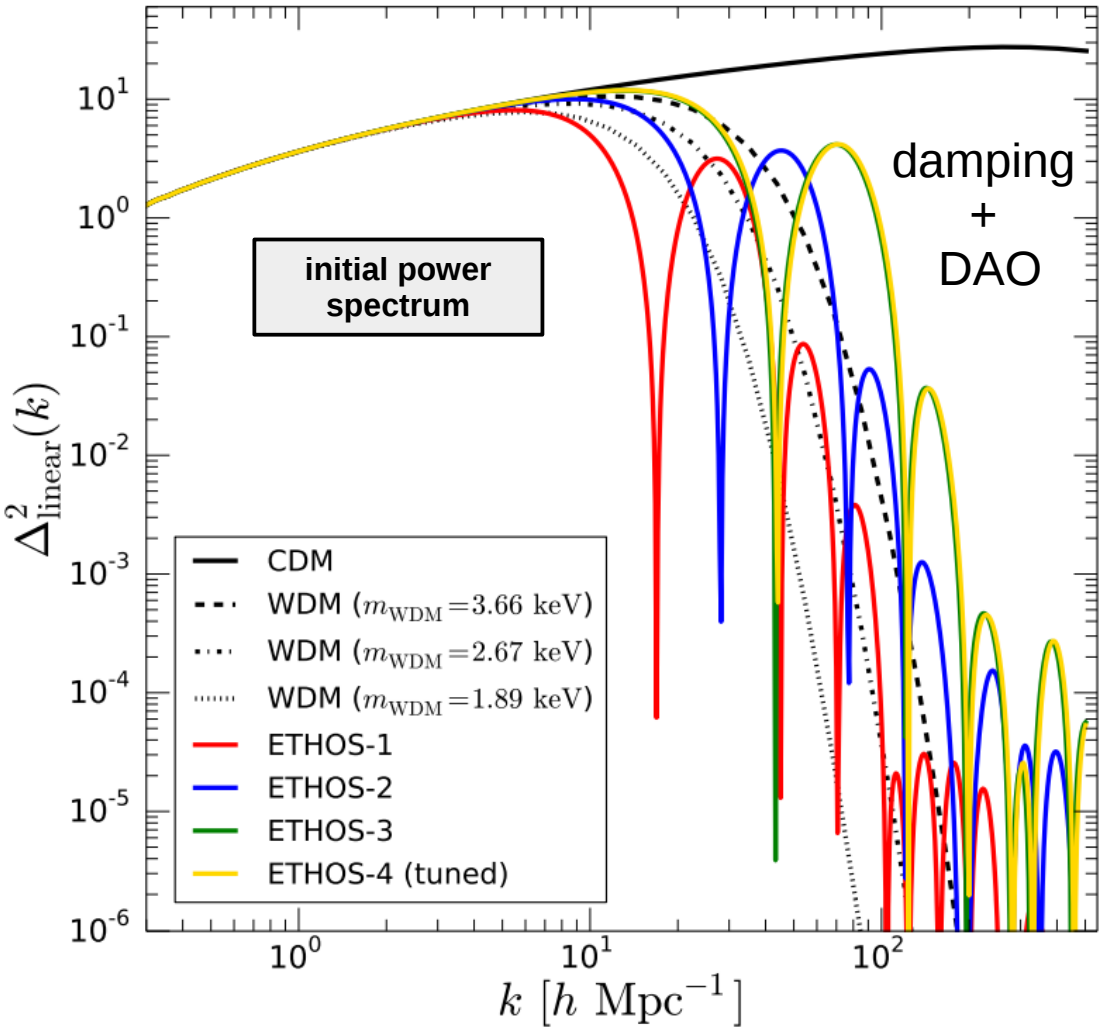
# Impact on Subhalo Abundance

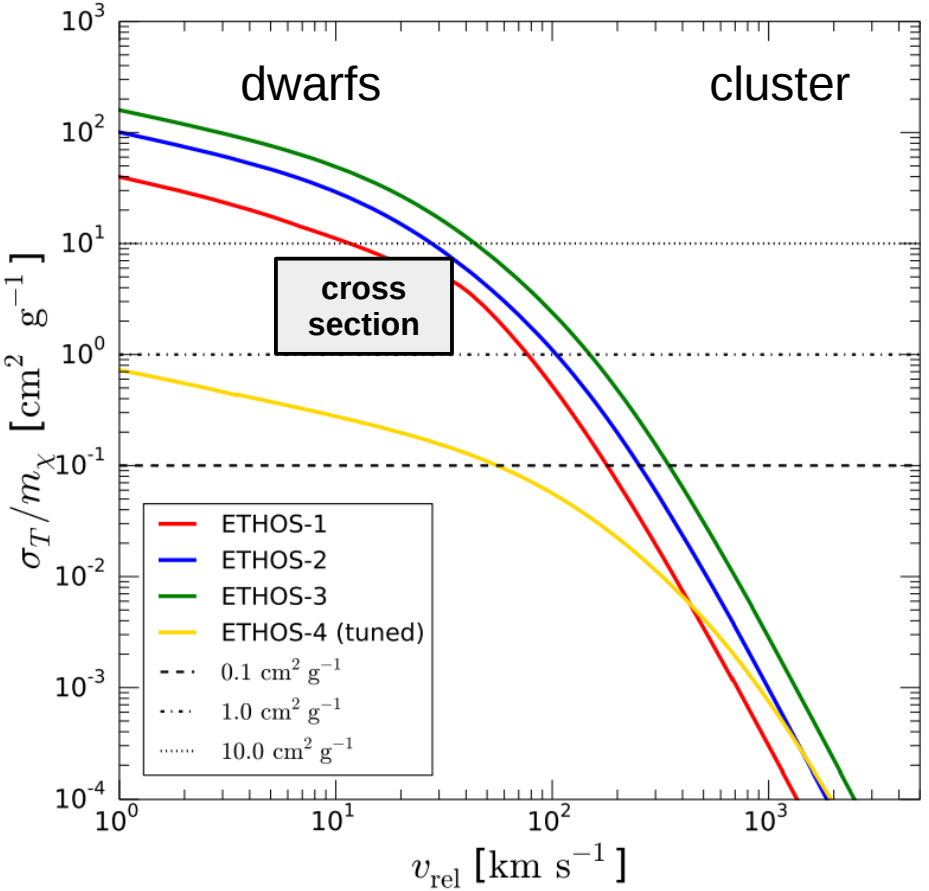



**only large cross section can alter the abundance. Typically SIDM does not 'remove' subhalos**

MV+ 2012

# ETHOS – Effective Theory of Structure Formation: Ingredients

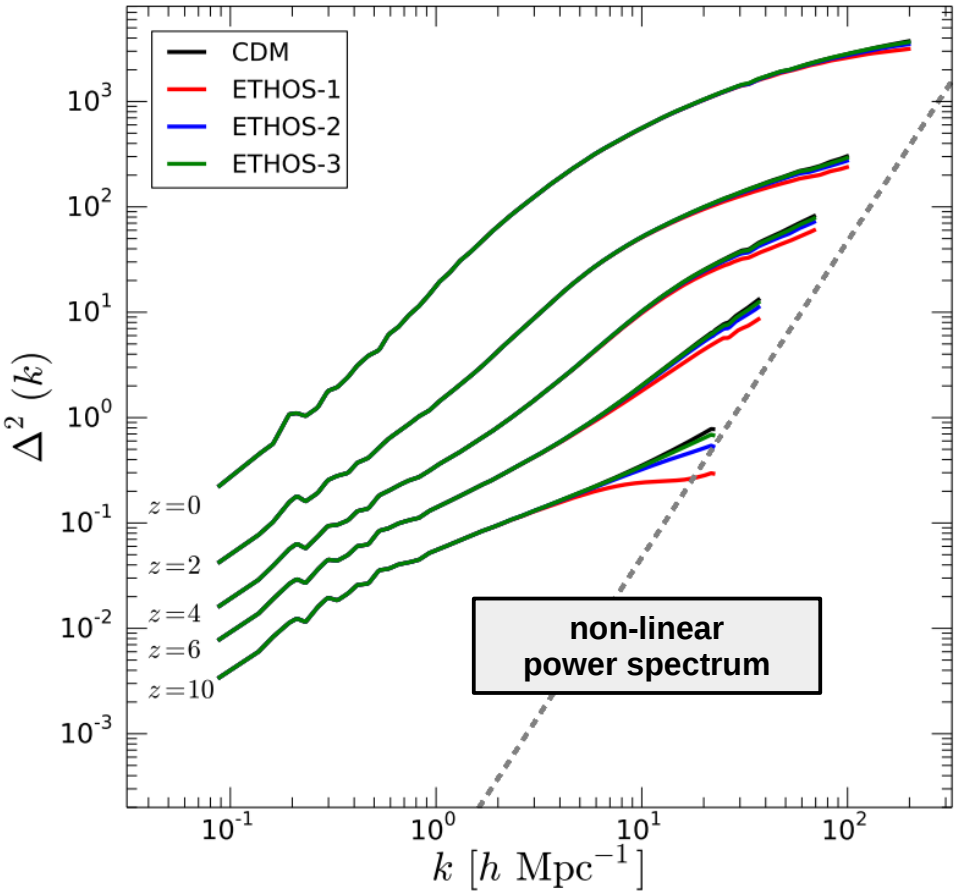


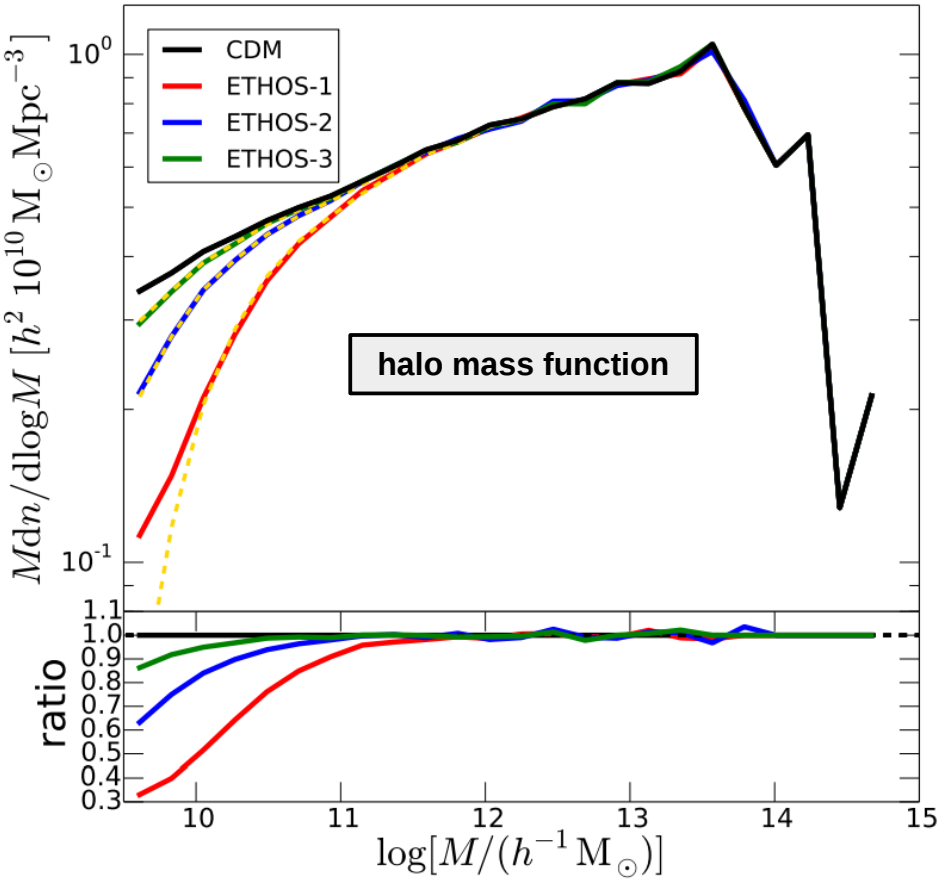

MV+ 2016

Cyr-Racine+ w/ MV 2016

# Large Scale Statistics

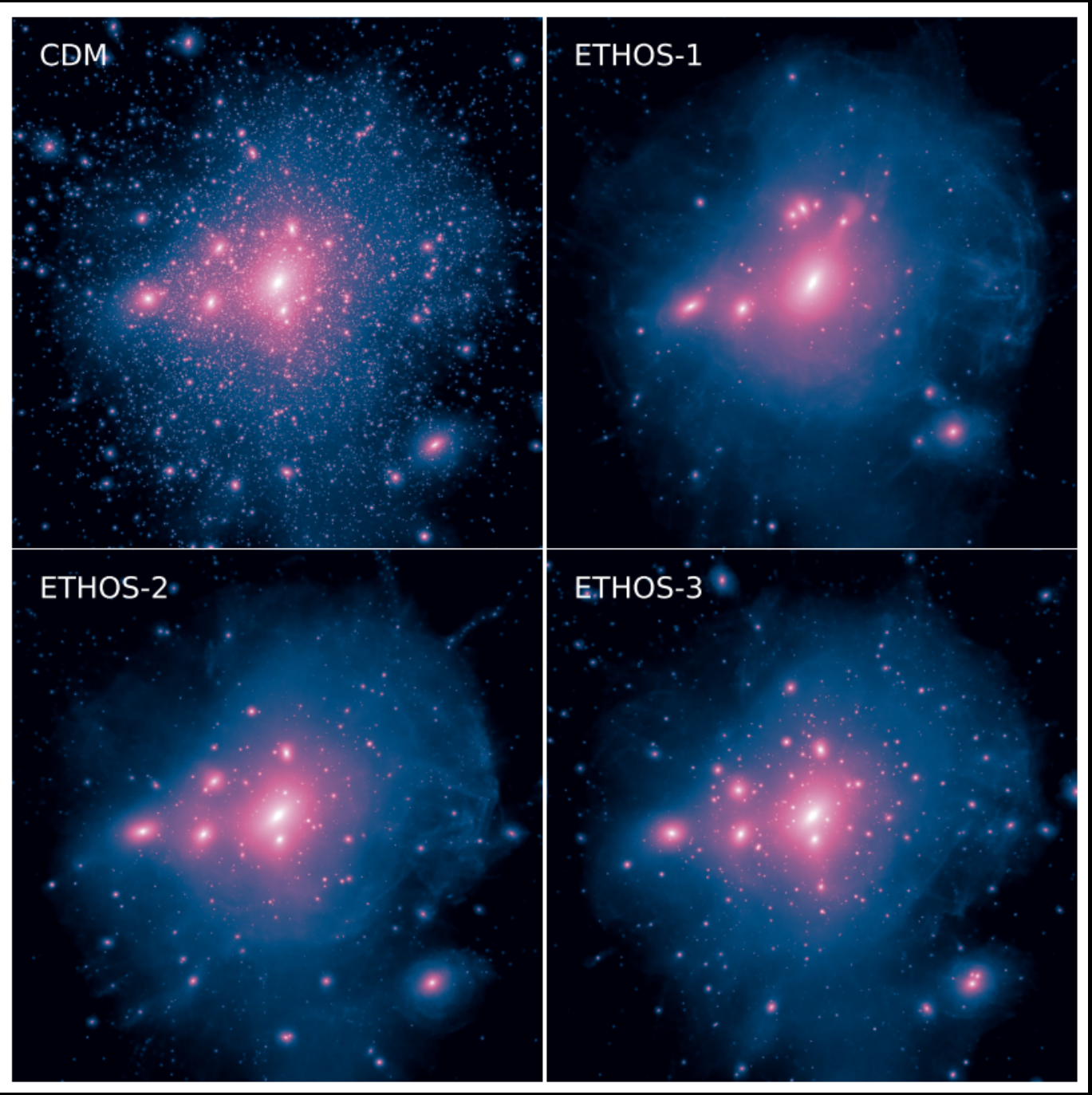



**impact on halo mass function due to transfer function cutoff**

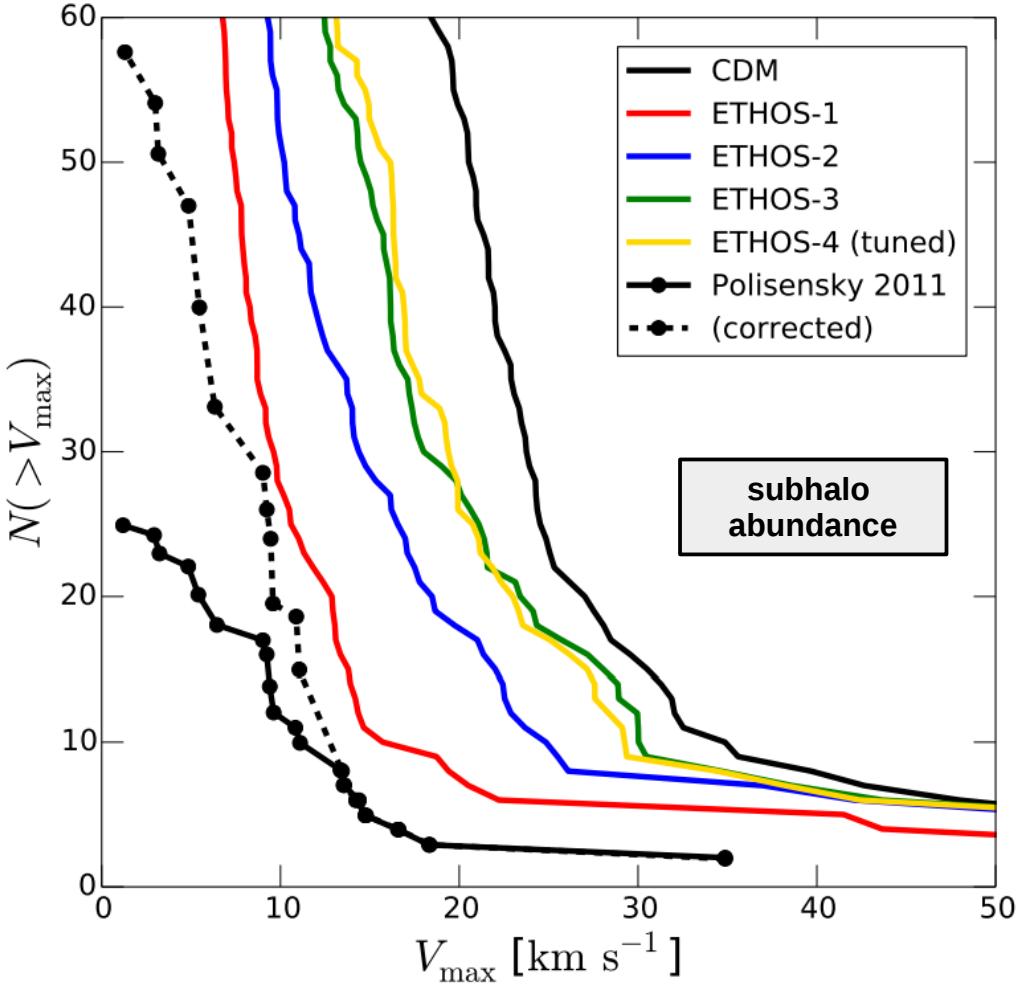


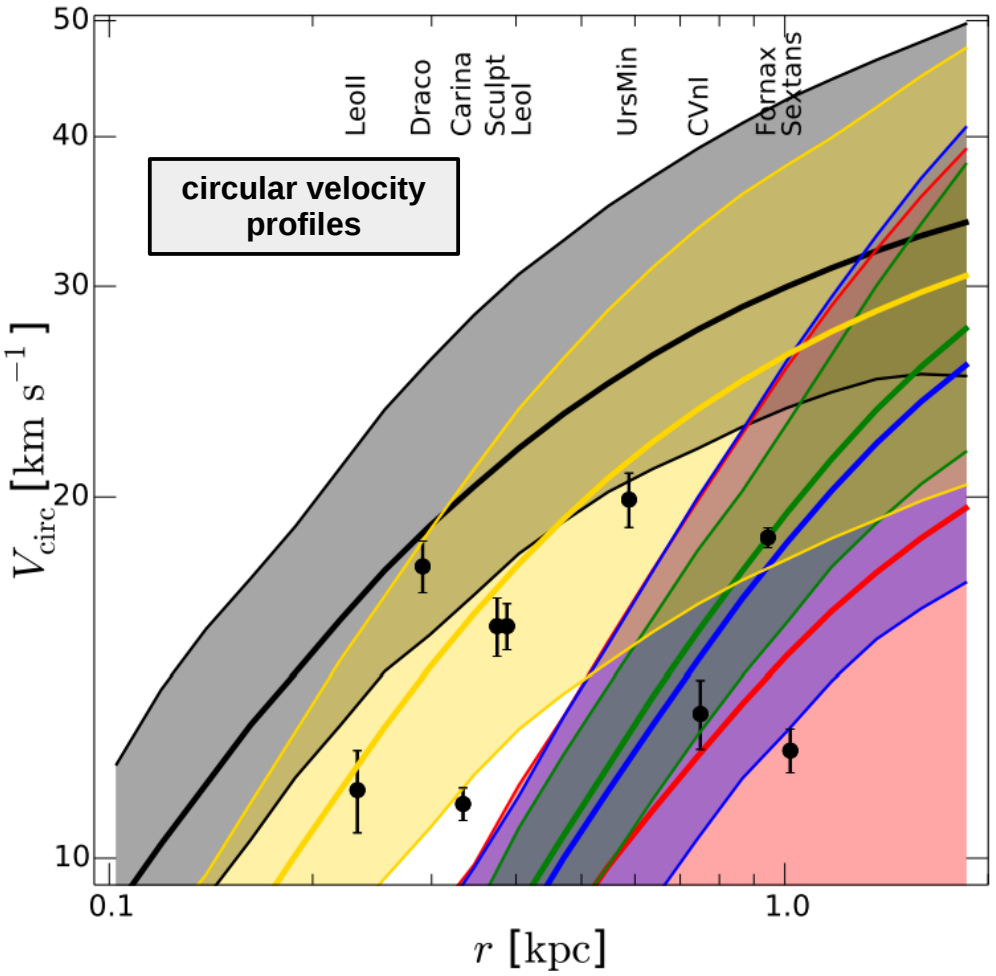

MV+ 2016

# ETHOS: An Effective Theory For Structure Formation



# ETHOS: A tuned Model




**both CDM abundance and structural problems can be alleviated simultaneously**

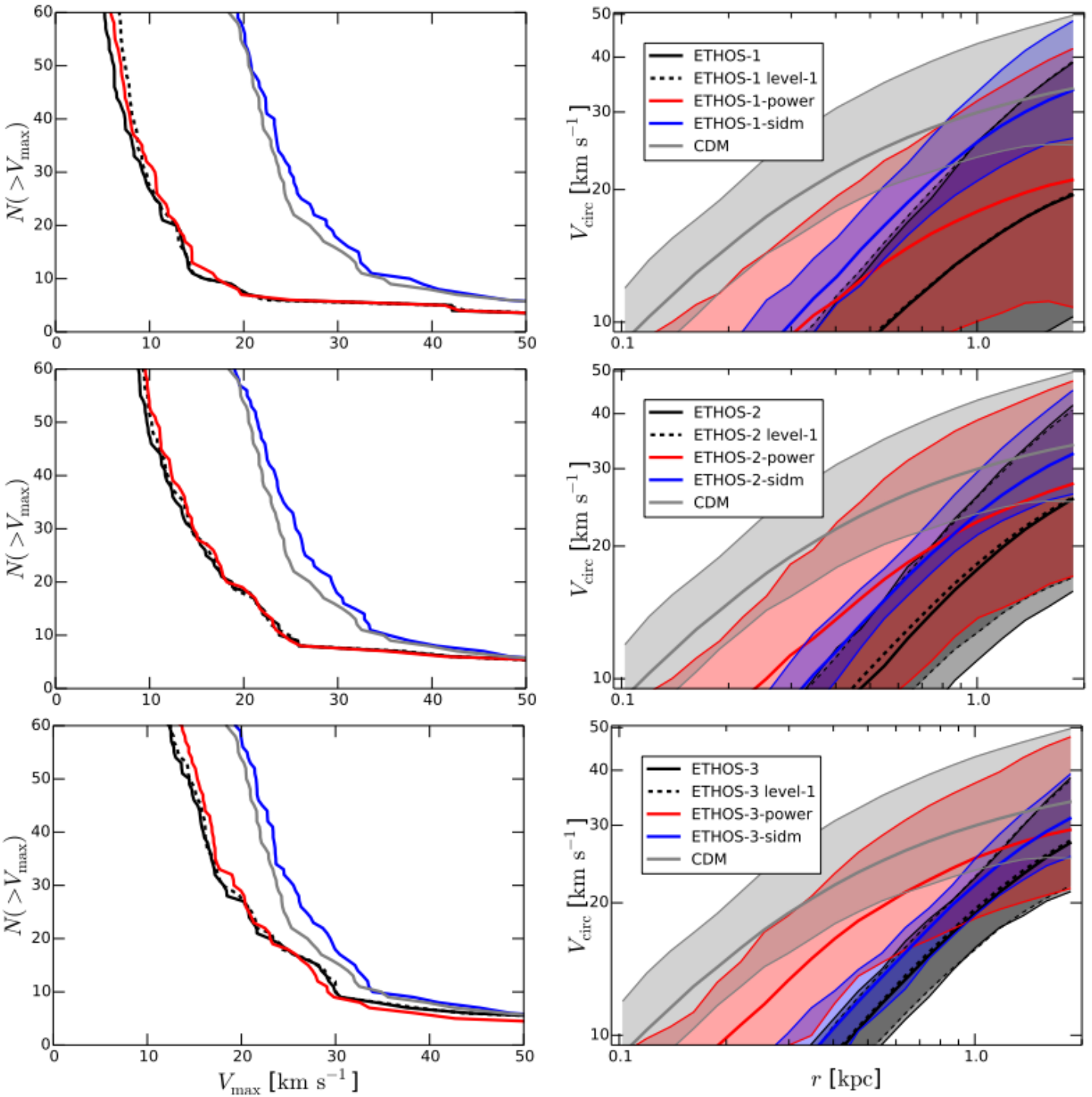
**addresses missing satellite and TBTF problem**

MV+ 2016

# ETHOS: Damping vs. SIDM

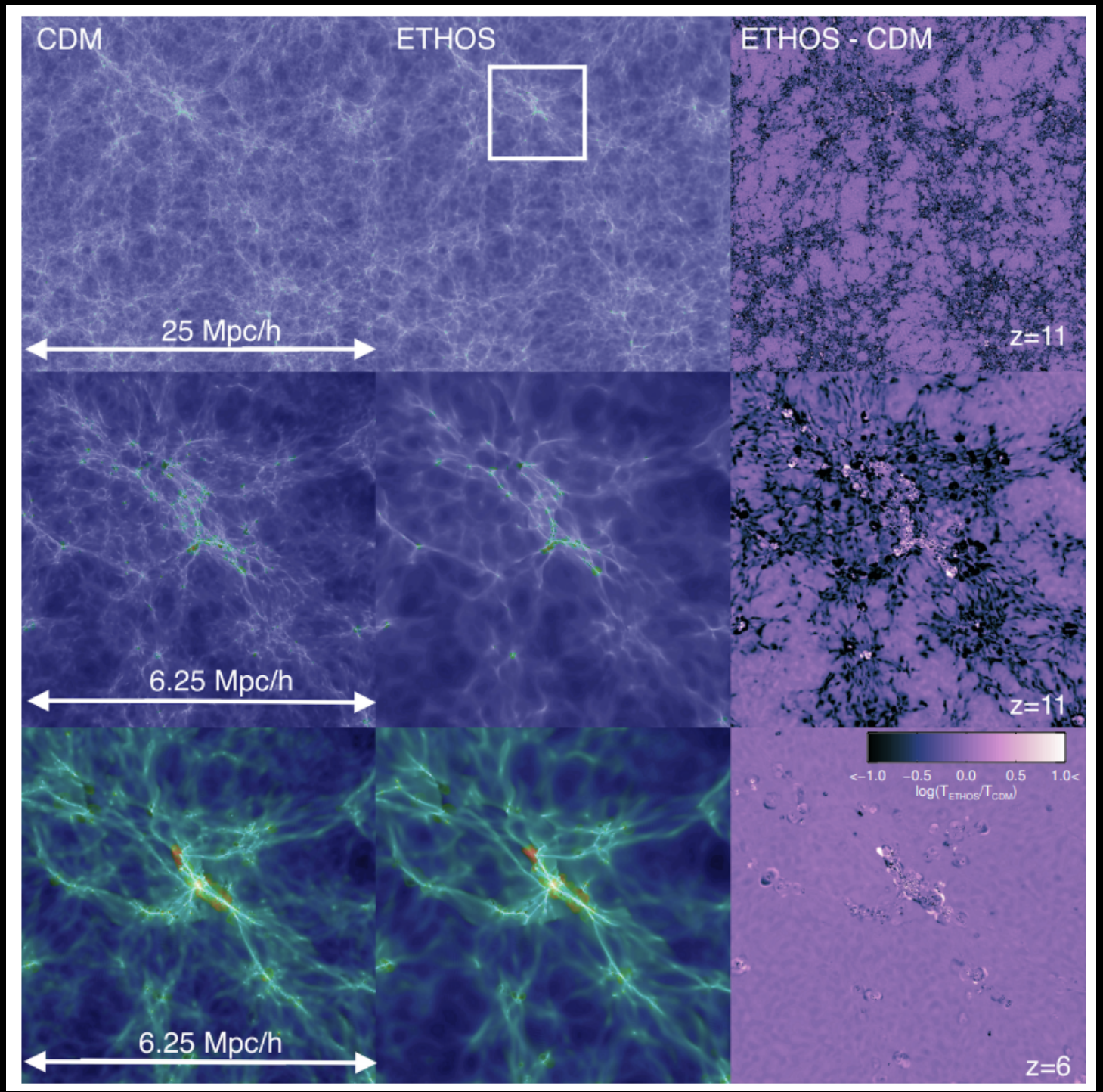
**disentangling the impact of SIDM and power spectrum modifications**

**self-interactions do not change the subhalo abundance**



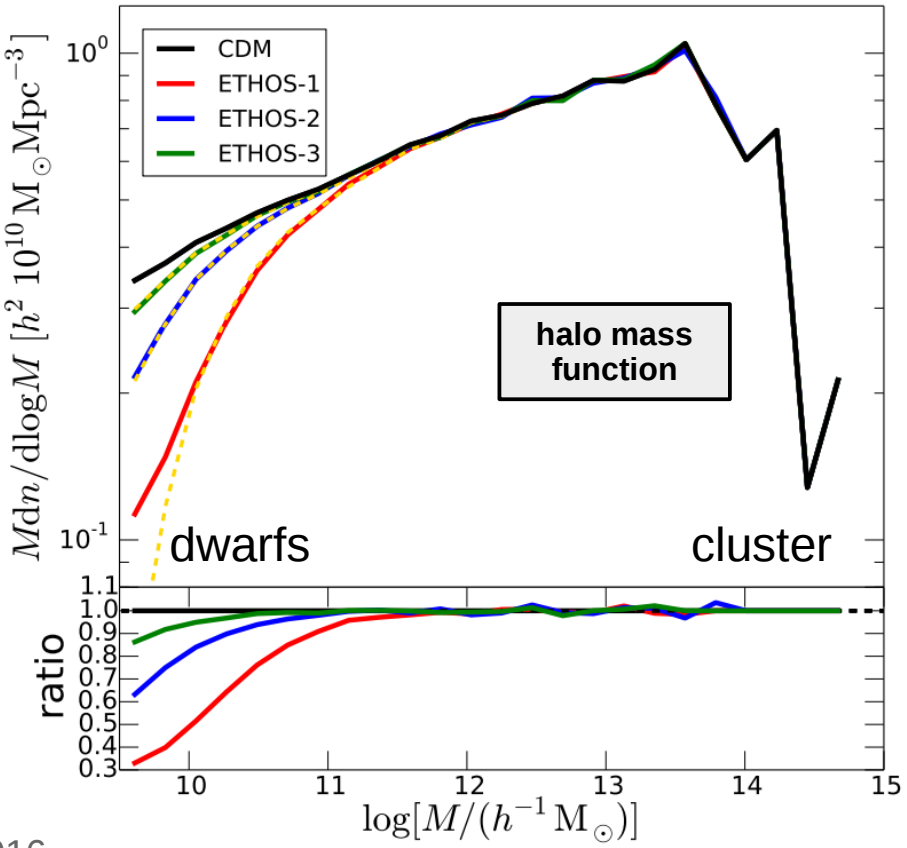

MV+ 2016

# High Redshift Universe




Lovell, Zavala, MV+ 2018

# High Redshift Universe




MV+ 2016

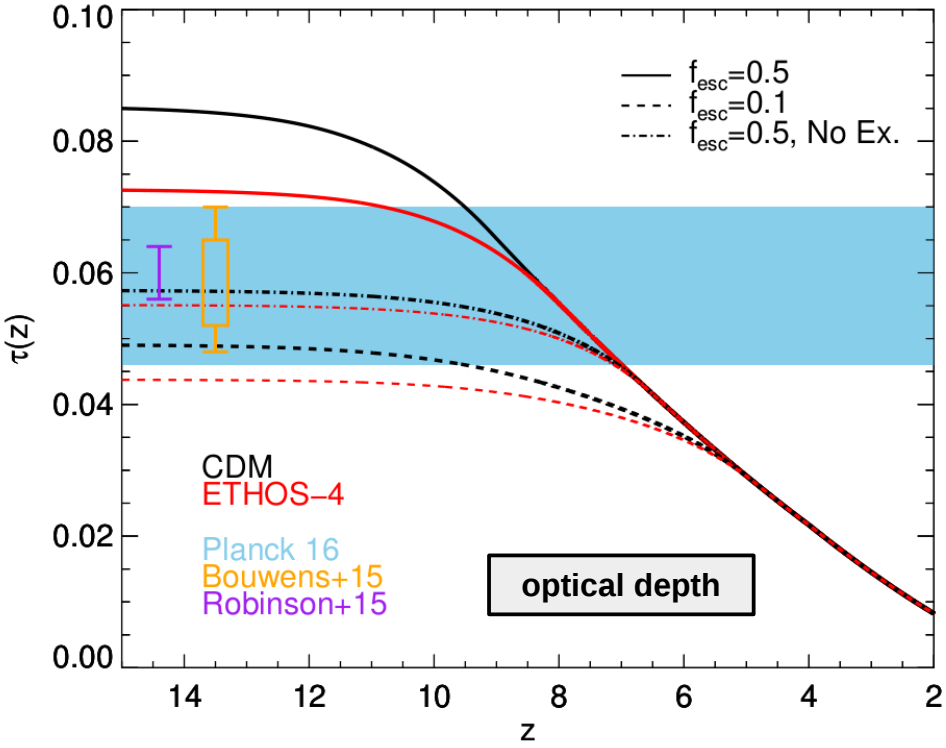
optical depth of one specific ETHOS model explore with full hydro simulations using IllustrisTNG model

**ETHOS model constructed based on local group passes observational tests at high z**

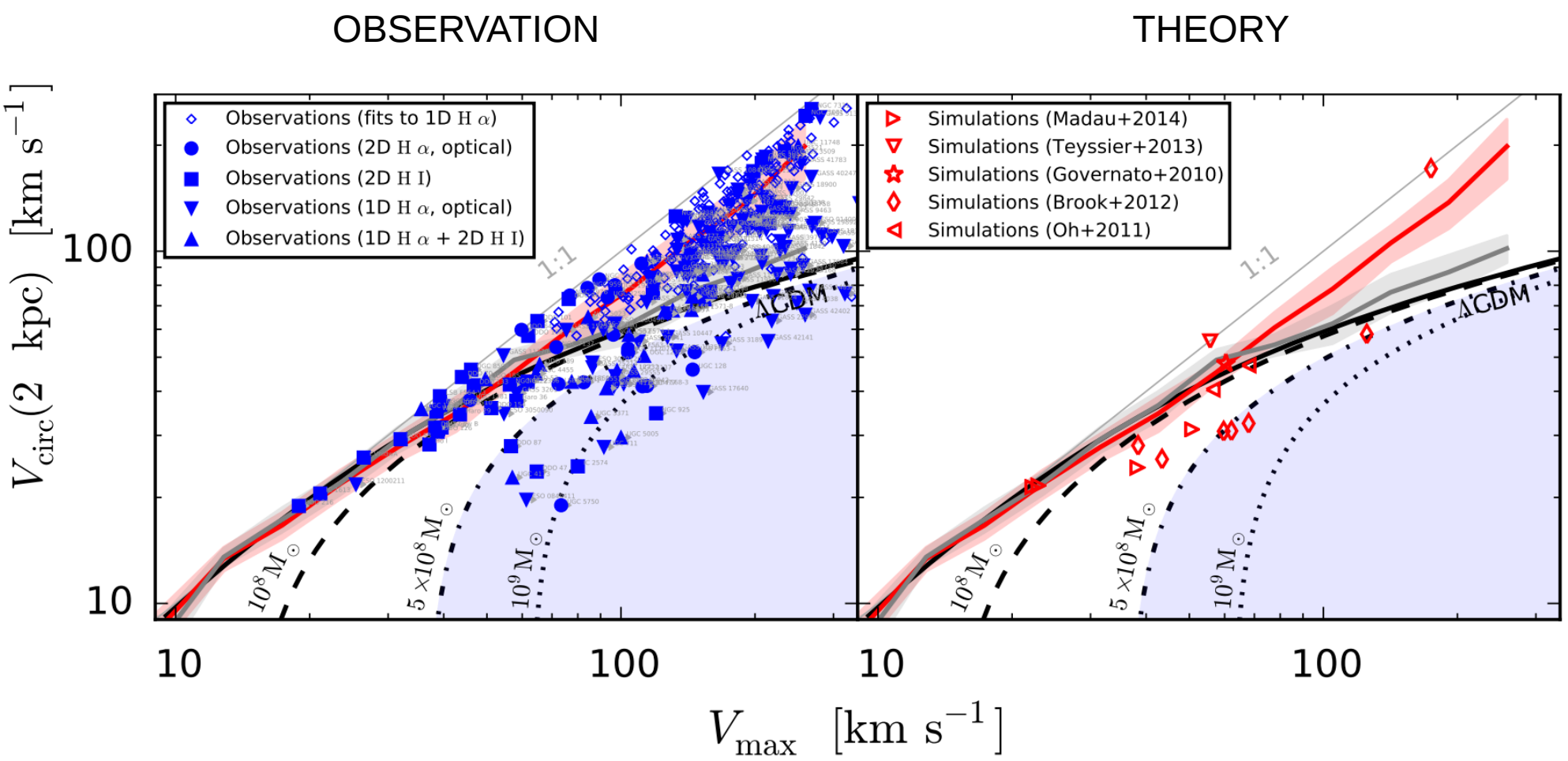
**impact on halo mass function due to reduction in power at small scales**

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

Lovell, Zavala, MV+ 2018



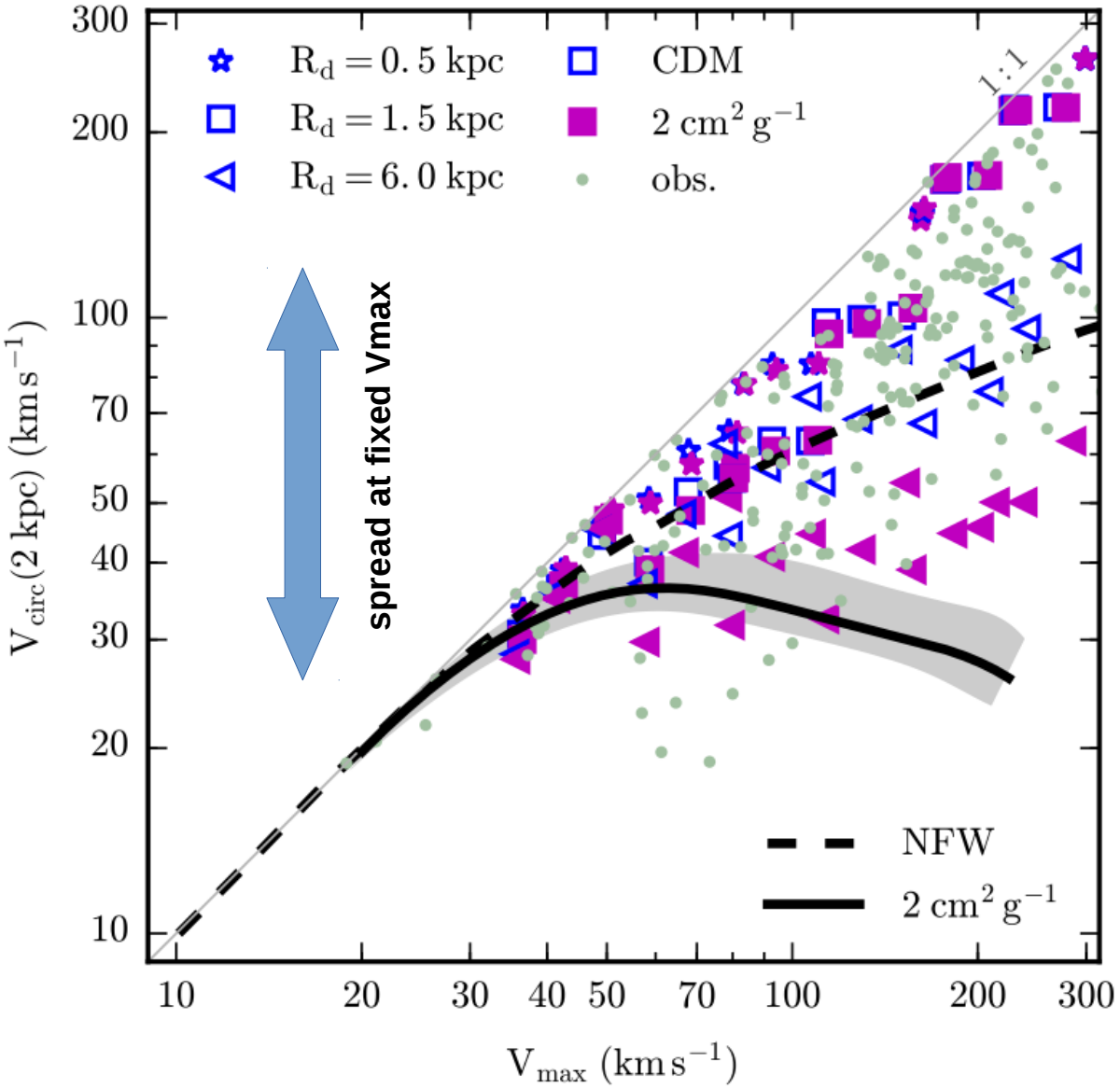
# CDM: Diversity?




"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

# SIDM: Diversity?




**add baryonic potential of a disk to mimic baryonic effects**

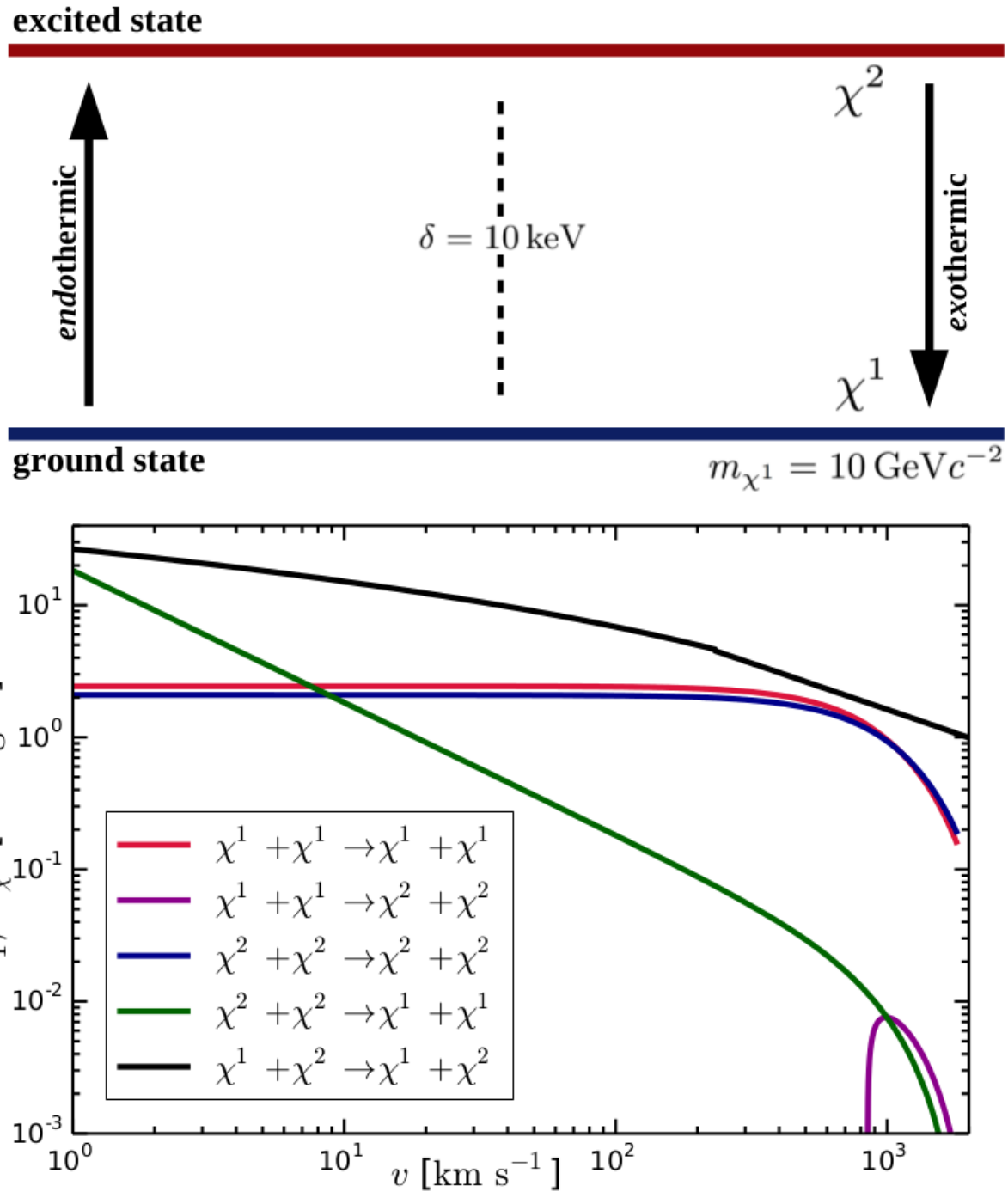
**SIDM leads to 50% increase in spread: self-interactions allow lower $V_{circ}$(2kpc); high values still possible for compact disks**

Creasey+ w/ MV 2017

# Inelastic SIDM:exo- and endothermic reaction

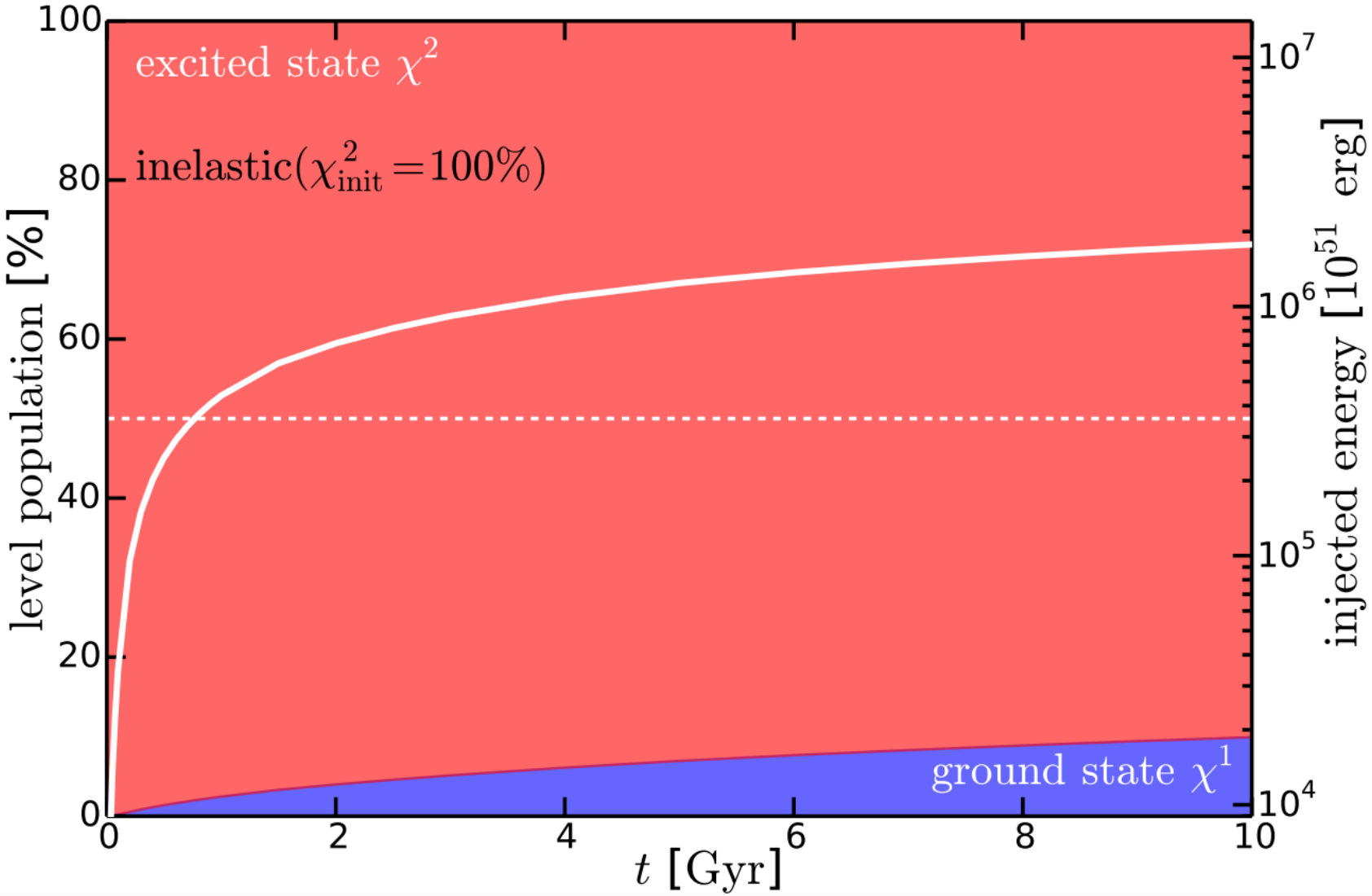
**nearly all SIDM simulations so far considered only elastic collisions**

**how does structure formation change with exothermic collisions?**




MV+ 2018

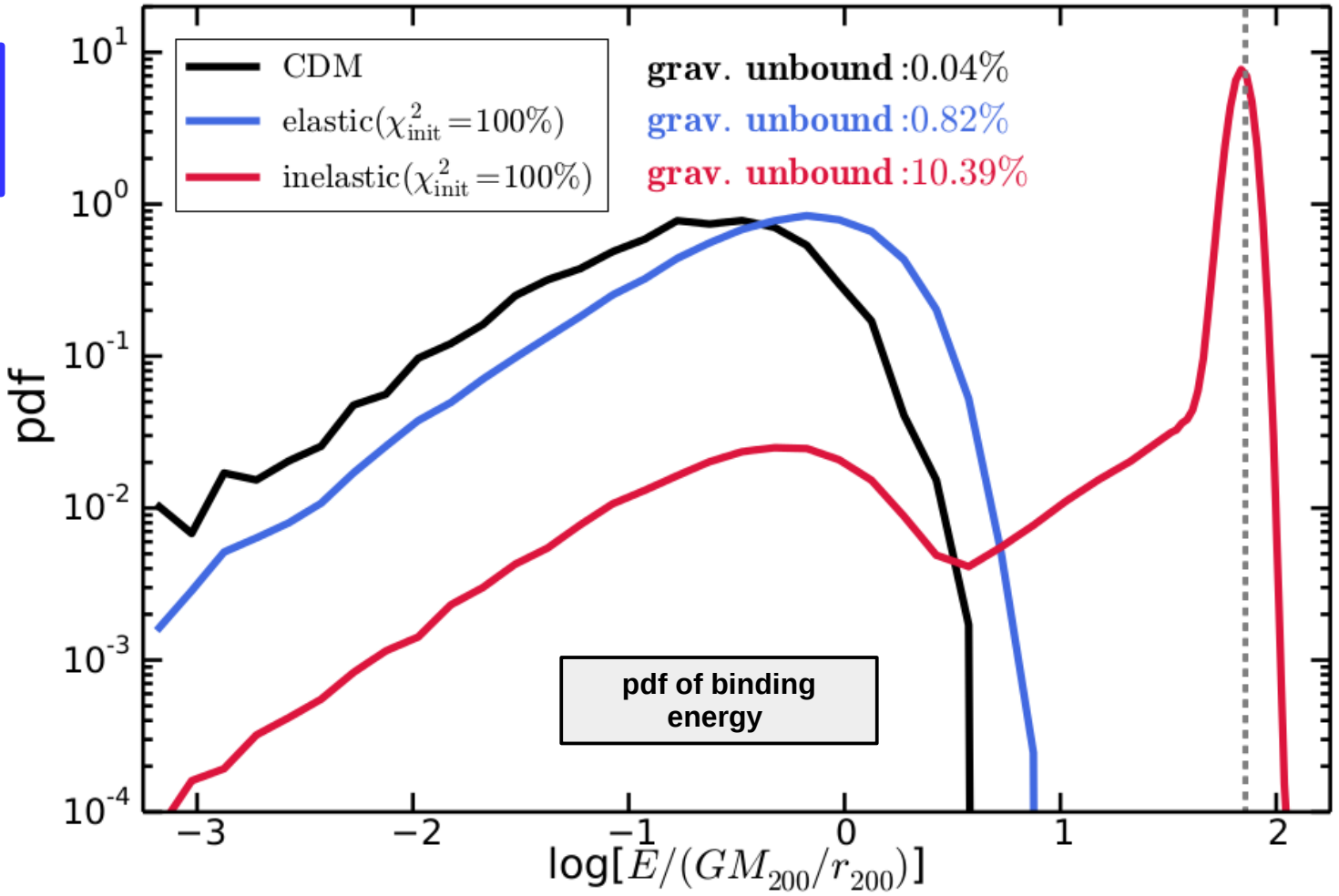
# Inelastic SIDM:exo- and endothermic reaction




MV+ 2018

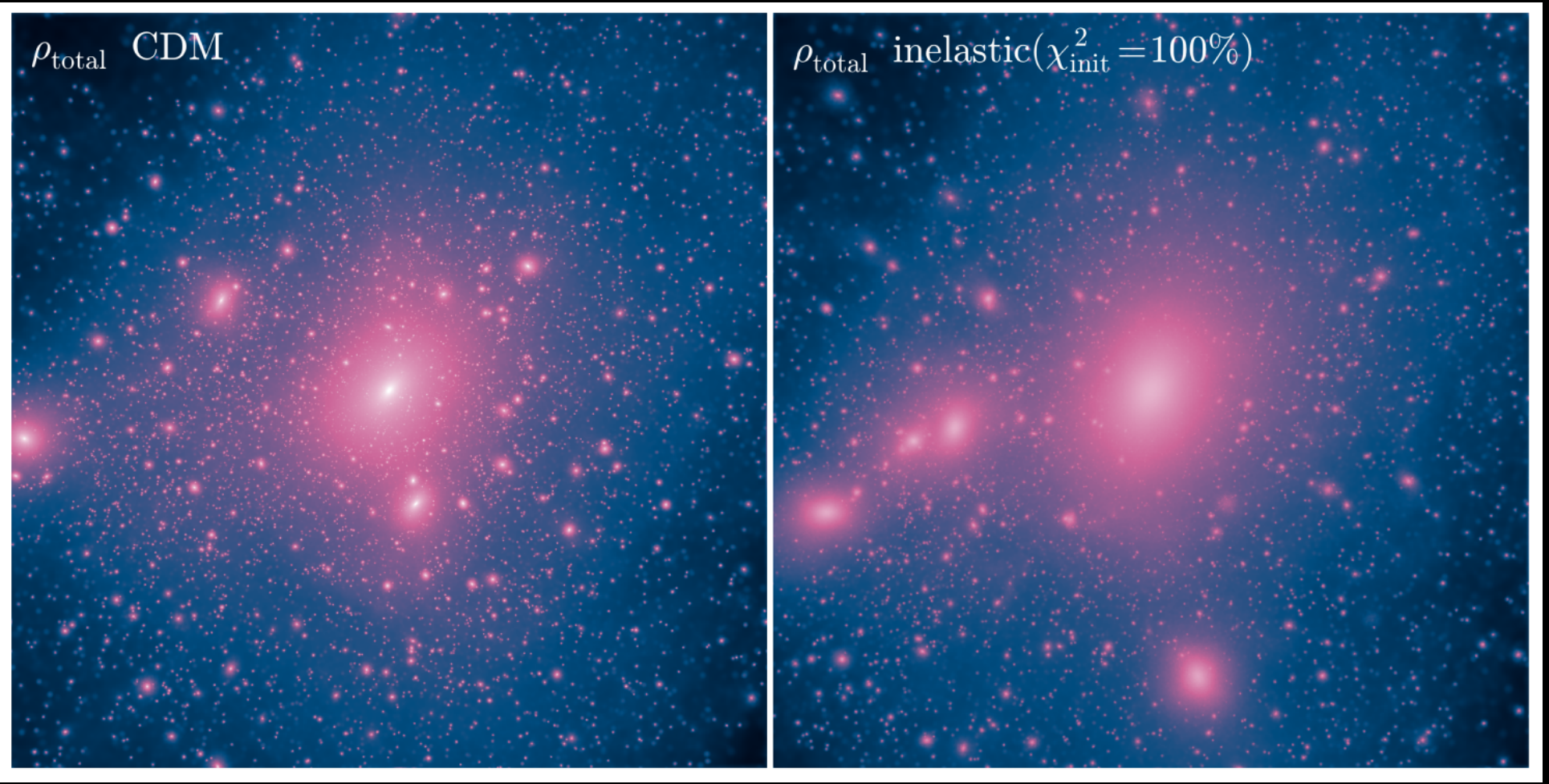
# Inelastic SIDM: Isolated Halo

**‘evaporating’ halos: gravitationally unbind scatter particles**



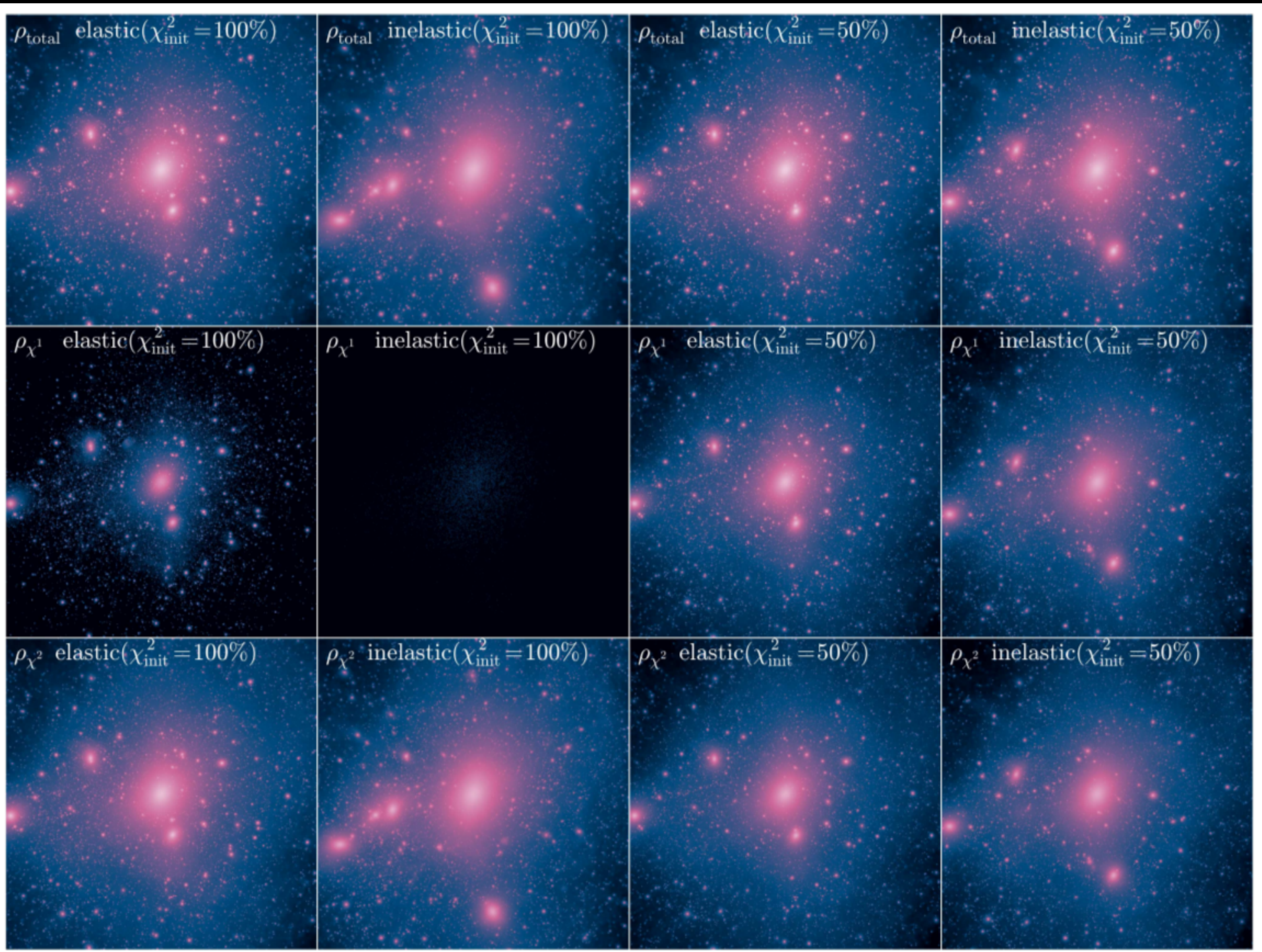

MV+ 2018

# Inelastic SIDM: Milky Way-like Halo



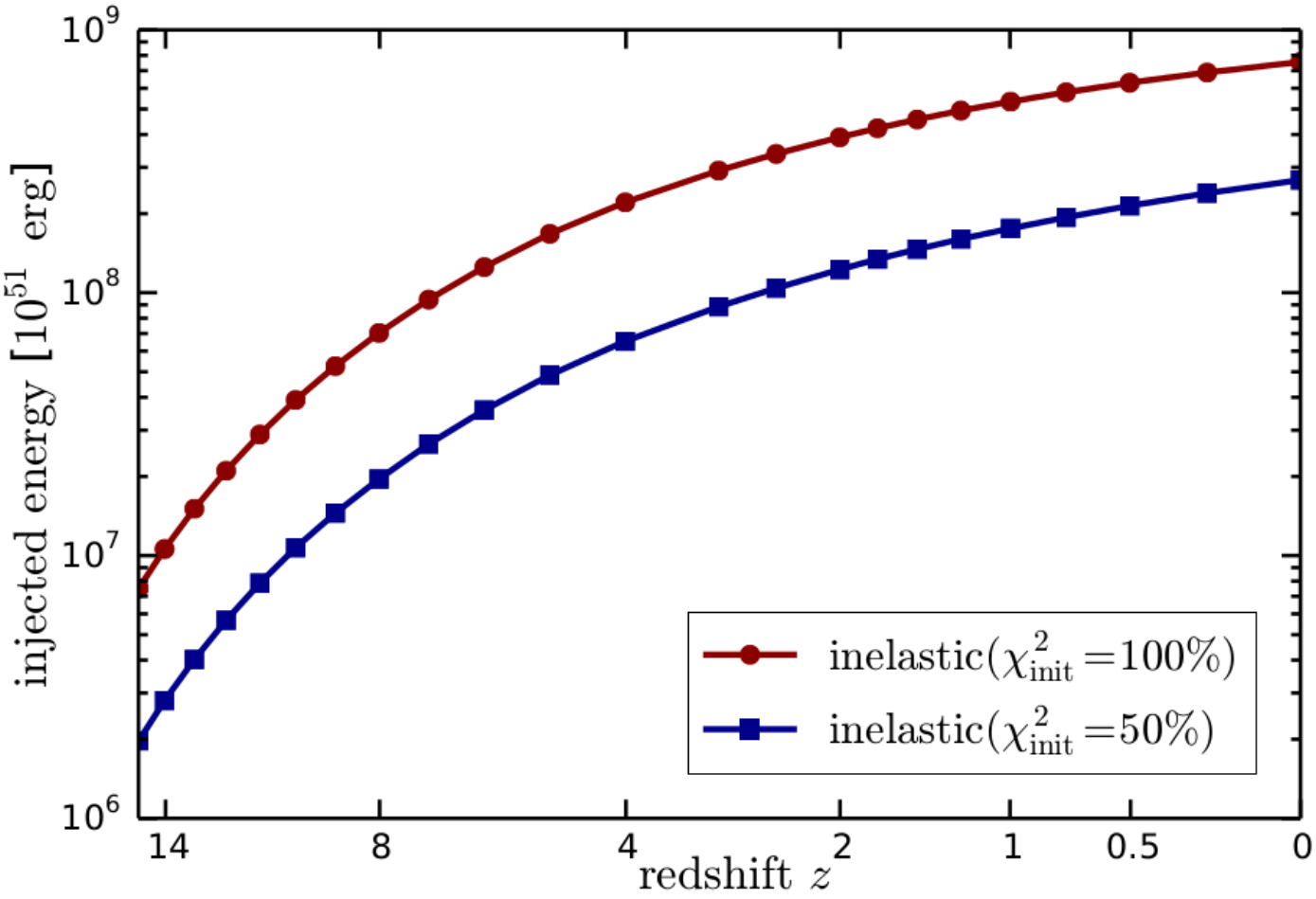

MV+ 2018

# Inelastic SIDM: Milky Way-like Halo



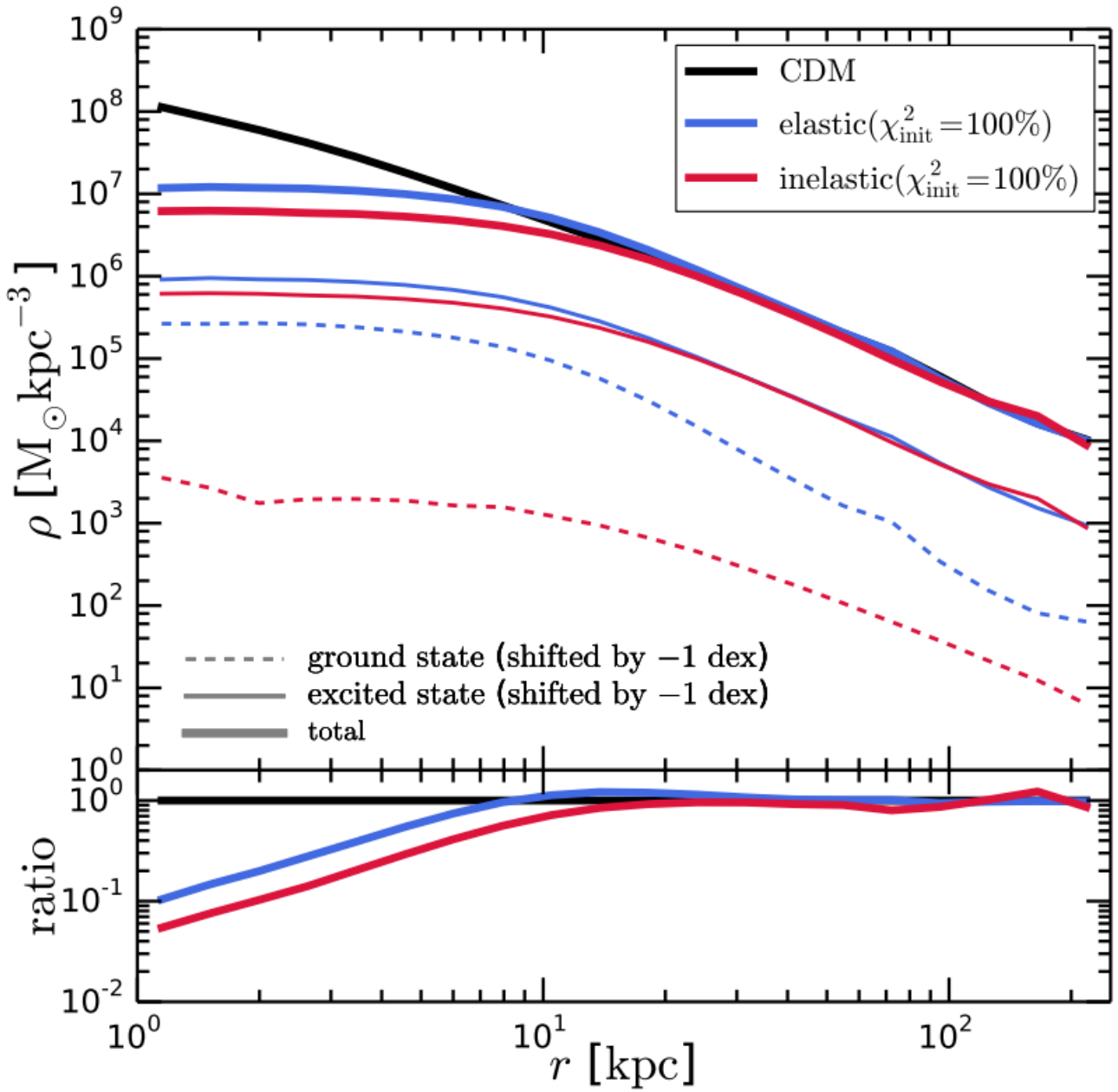
# Inelastic SIDM: Milky Way-like Halo

**injected energy due to level decay**



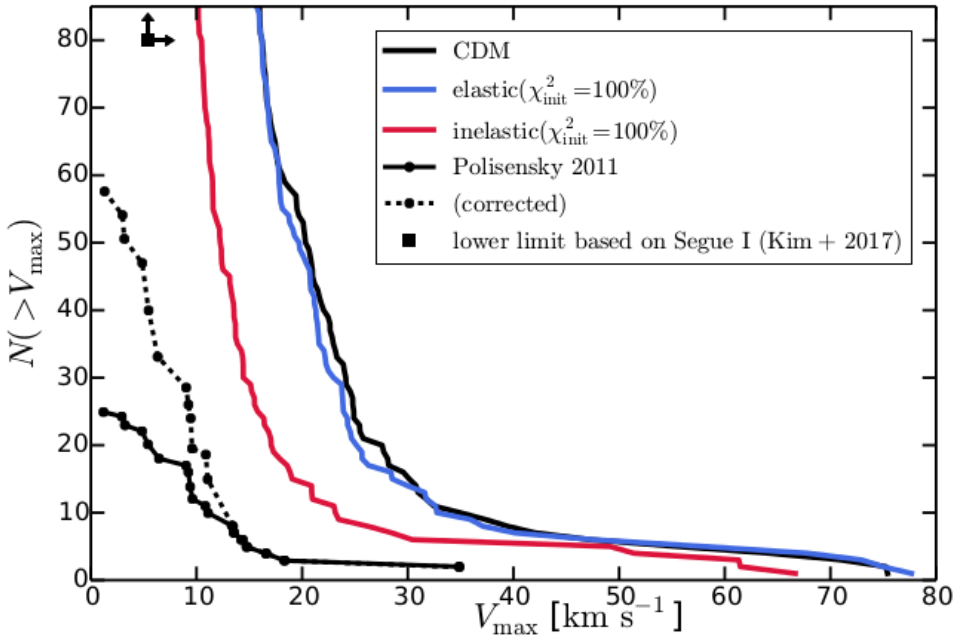

MV+ 2018

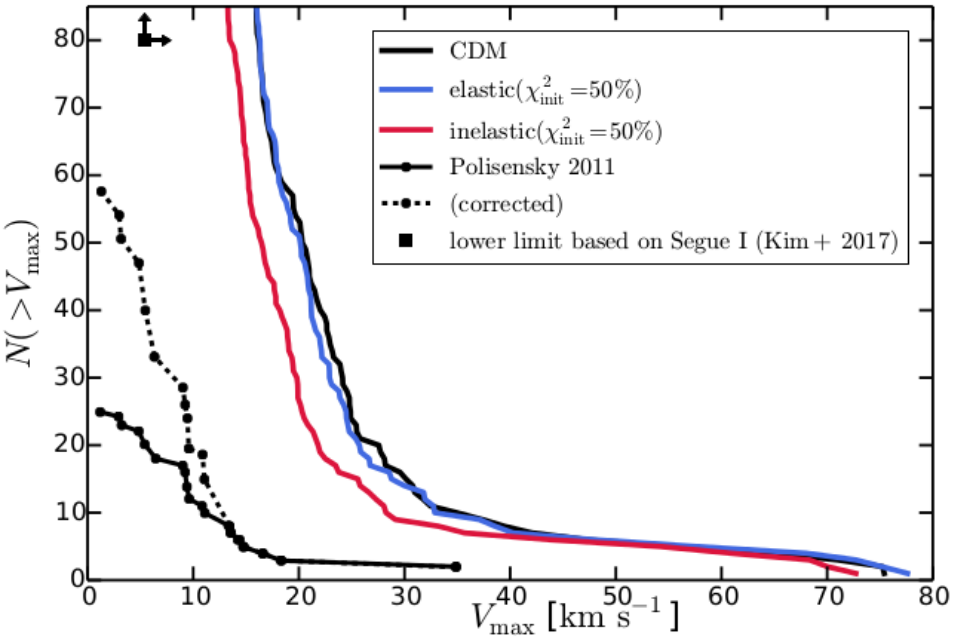
# Inelastic SIDM: Milky Way-like Halo

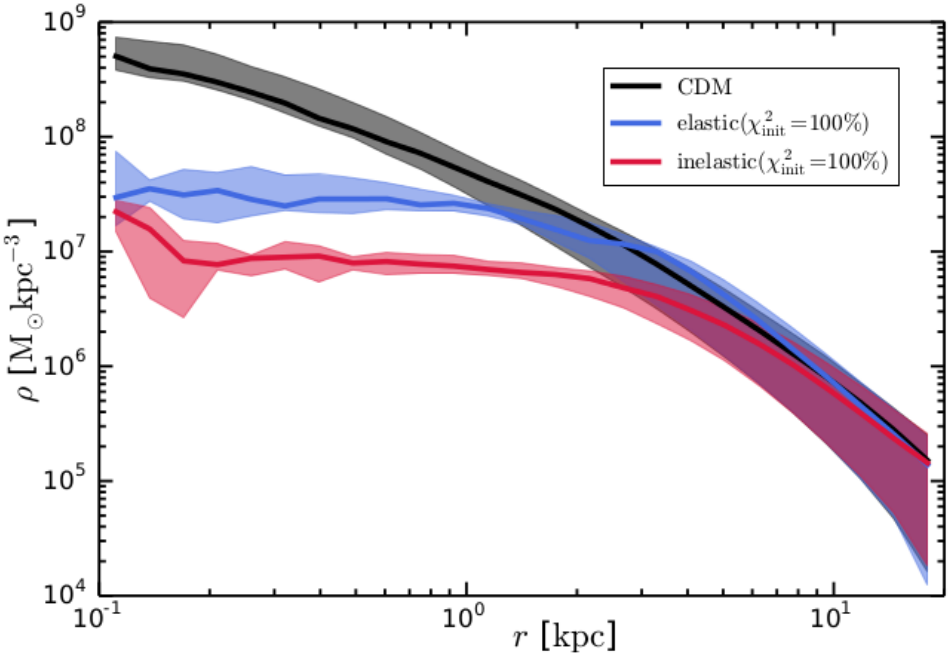


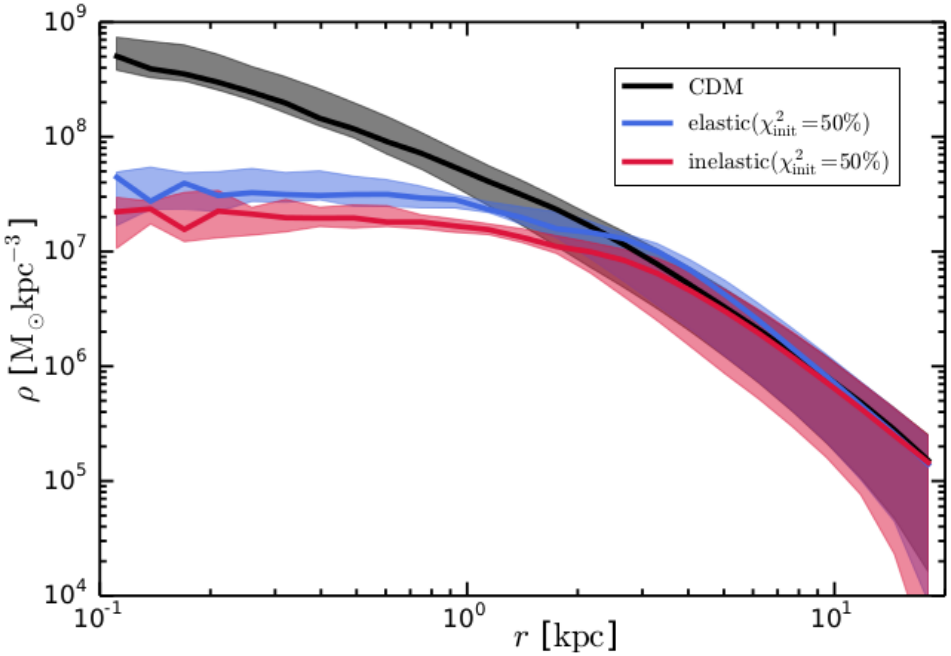

**main halo density profile**

# Inelastic SIDM: Milky Way-like Halo



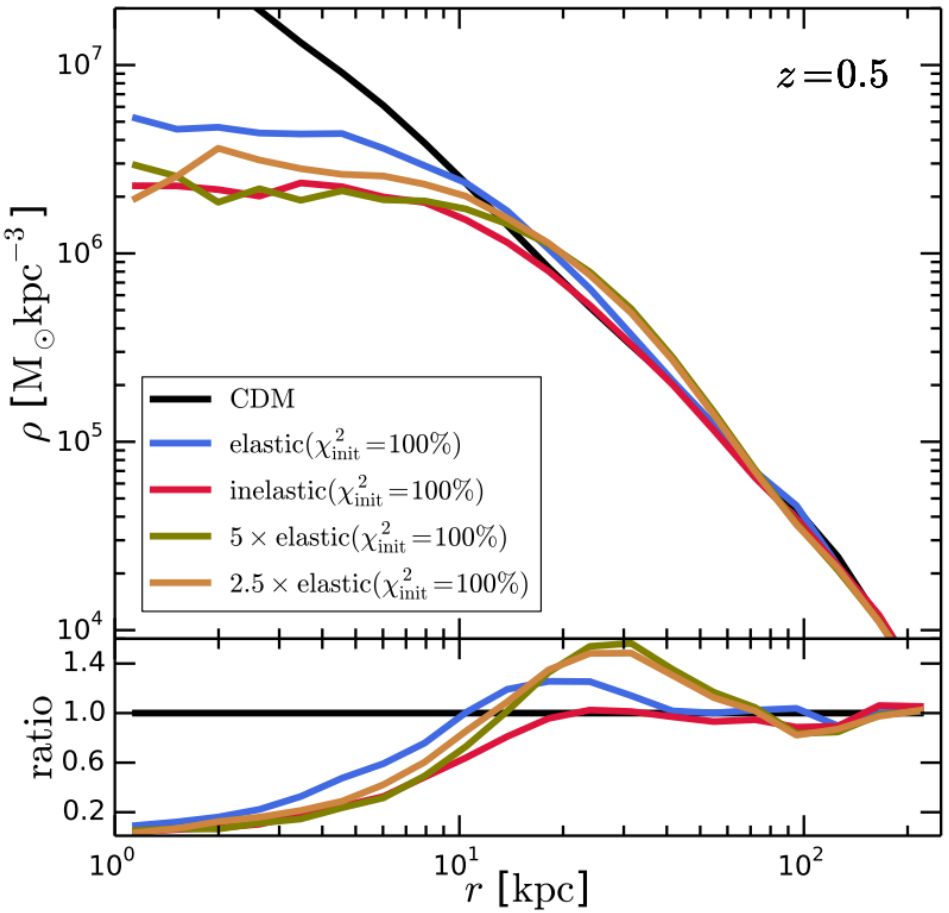



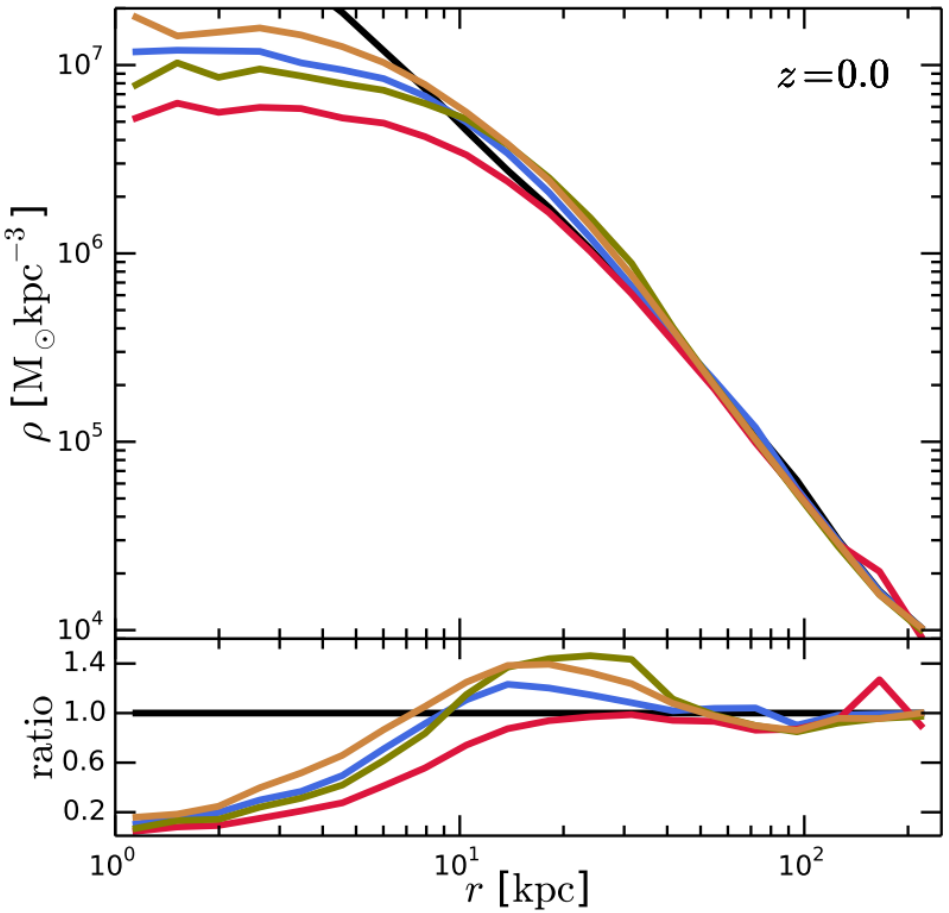




MV+ 2018

# Inelastic SIDM: Milky Way-like Halo



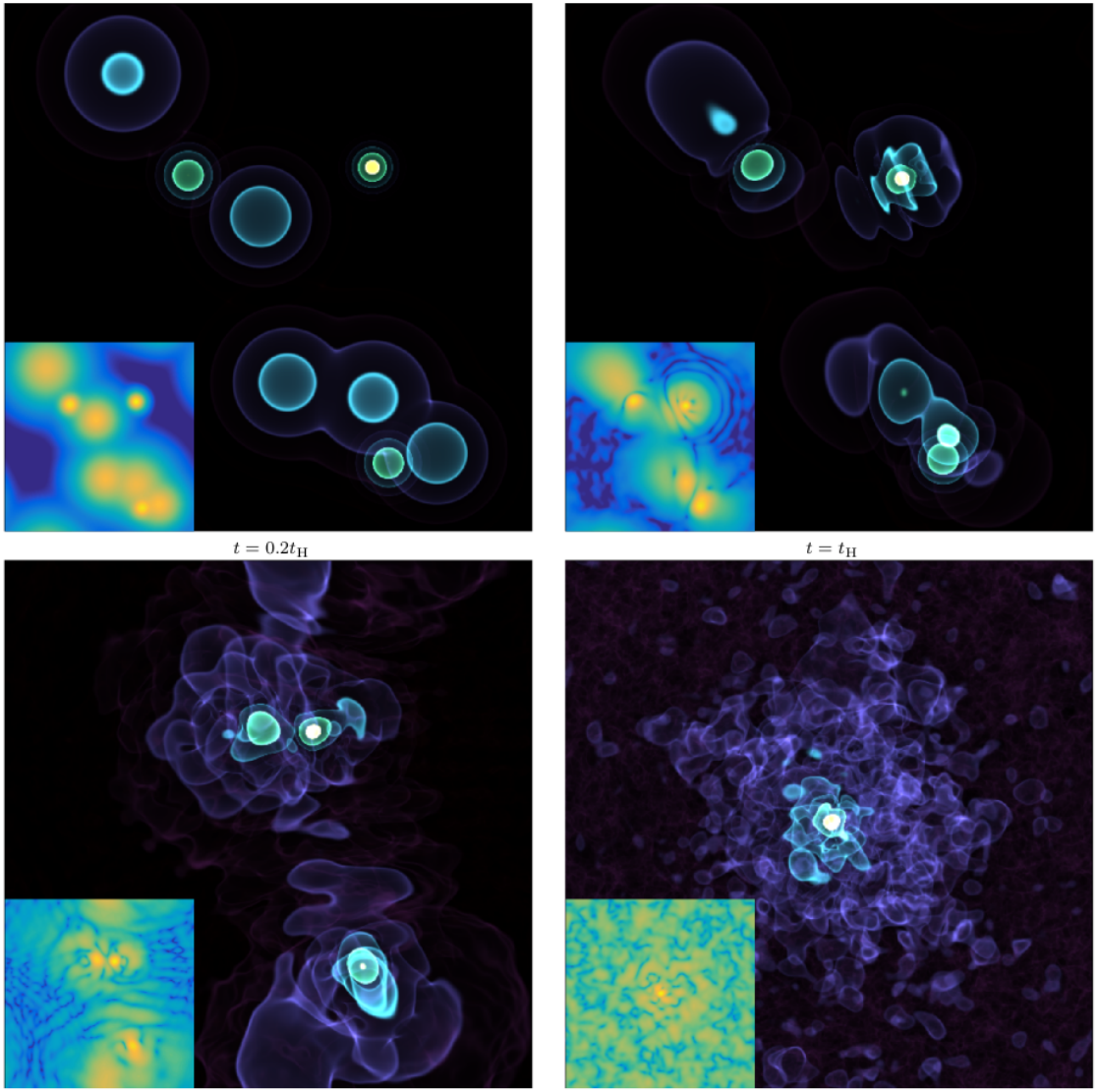



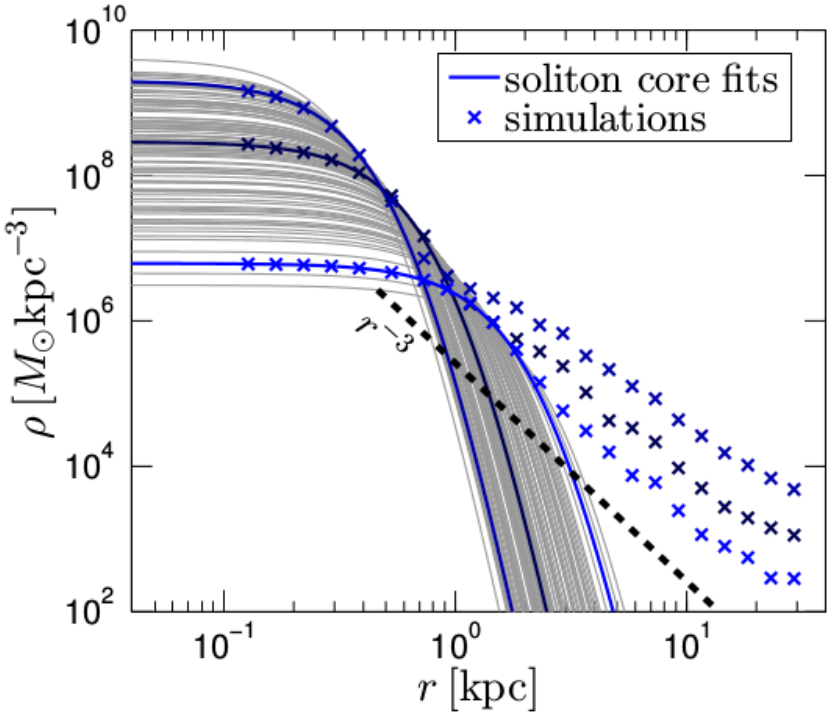

**inelastic SIDM does not increase DM density at intermediate radii**

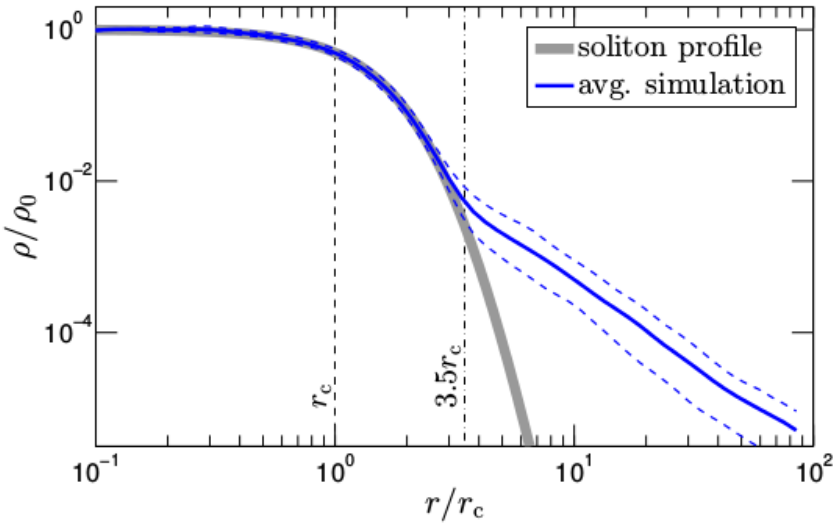
**inelastic SIDM creates larger cores/lower densities for same cross section normalization**

**inelastic SIDM avoids core collapse**

# Other Alternatives? Ultralight Axions - BECDM




Mocz, MV+ 2017

**cores through quantum pressure**

# Summary

- SIDM provides a promising alternative to CDM to alleviate small-scale CDM problems
- velocity-dependent cross sections avoid cluster-scale constraints and are natural
- more general models also consider modifications of initial power spectra leading to other interesting effects
- inelastic models create larger cores for the same cross section normalization