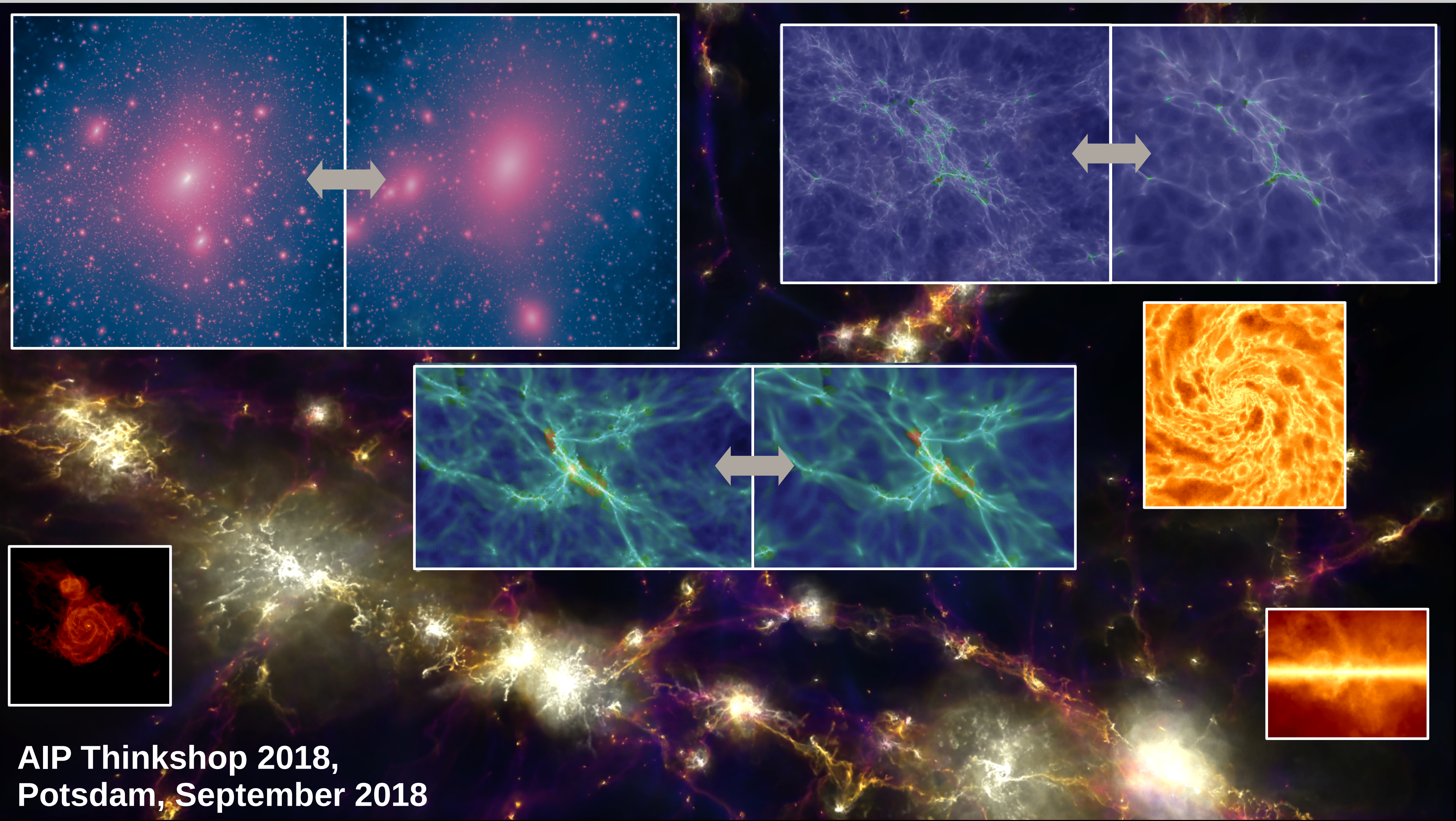
Simulating Galaxy Formation in CDM and SIDM

Mark Vogelsberger

Massachusetts Institute of Technology

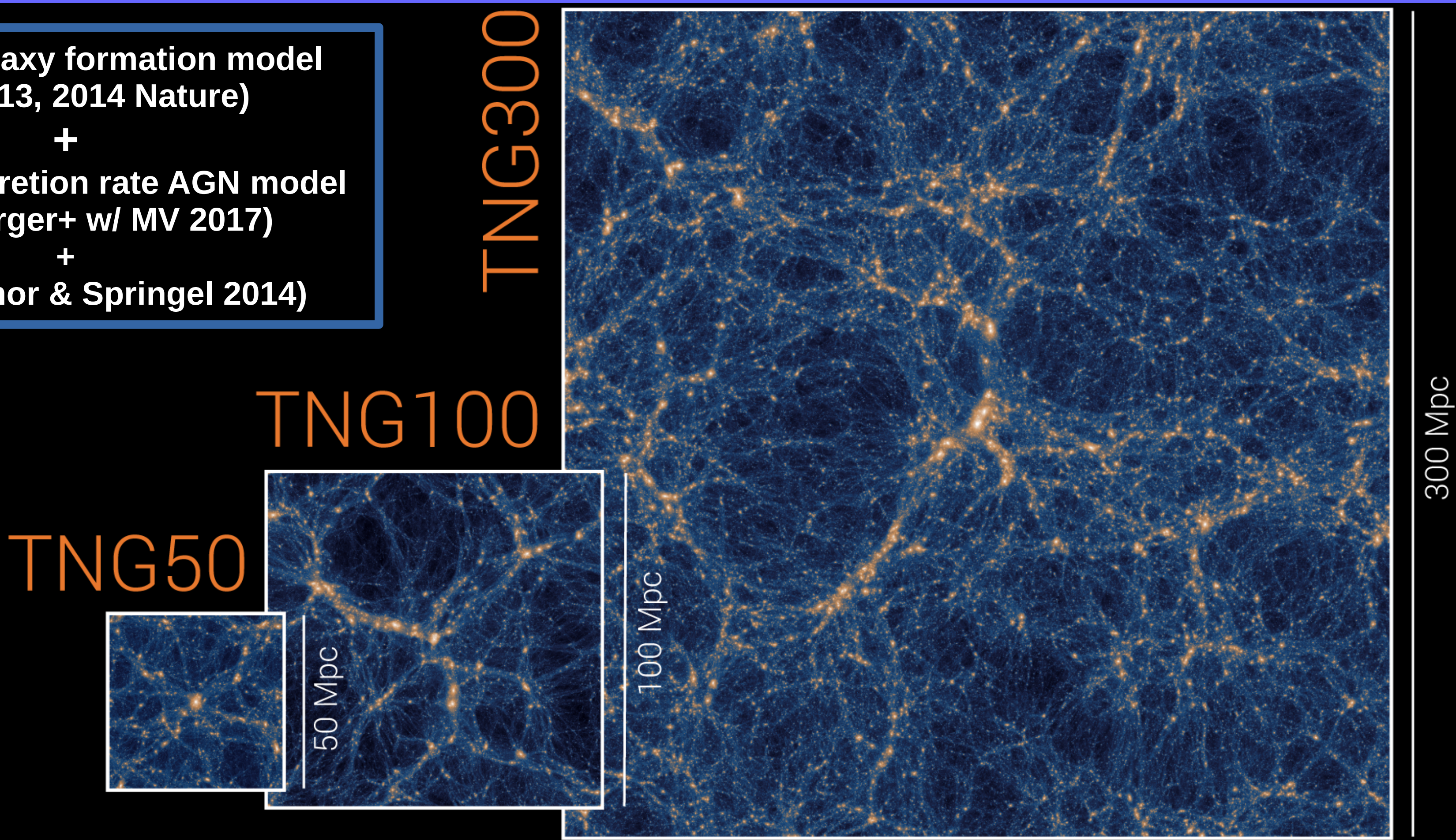


AIP Thinkshop 2018,
Potsdam, September 2018

The IllustrisTNG Simulations – Illustris Update

major updates

Illustris galaxy formation model
(MV+ 2013, 2014 Nature)
+
novel low accretion rate AGN model
(Weinberger+ w/ MV 2017)
+
MHD (Pakmor & Springel 2014)



	Illustris	TNG100	TNG50	TNG300
Overview:				
MHD	no	yes	yes	yes
Cosmology	WMAP7	Planck 2015	Planck 2015	Planck 2015
Box and Resolution:				
Lbox [Mpc]	106.5	110.7	51.7	302.6
# res elements	2 x 1820^3	2 x 1820^3	2 x 2160^3	2 x 2500^3
gas mass in the initial conditions [Msun]	1.26e6	1.39e6	8.47e4	1.1e7
DM mass [Msun]	6.26e6	7.46e6	4.54e5	5.88e7
~EpsilonBaryons [kpc]	0.7	0.7	0.3	1.5

IllustrisTNG Team

Springel, Nelson, Pakmor, Weinberger
(HITS/MPA)

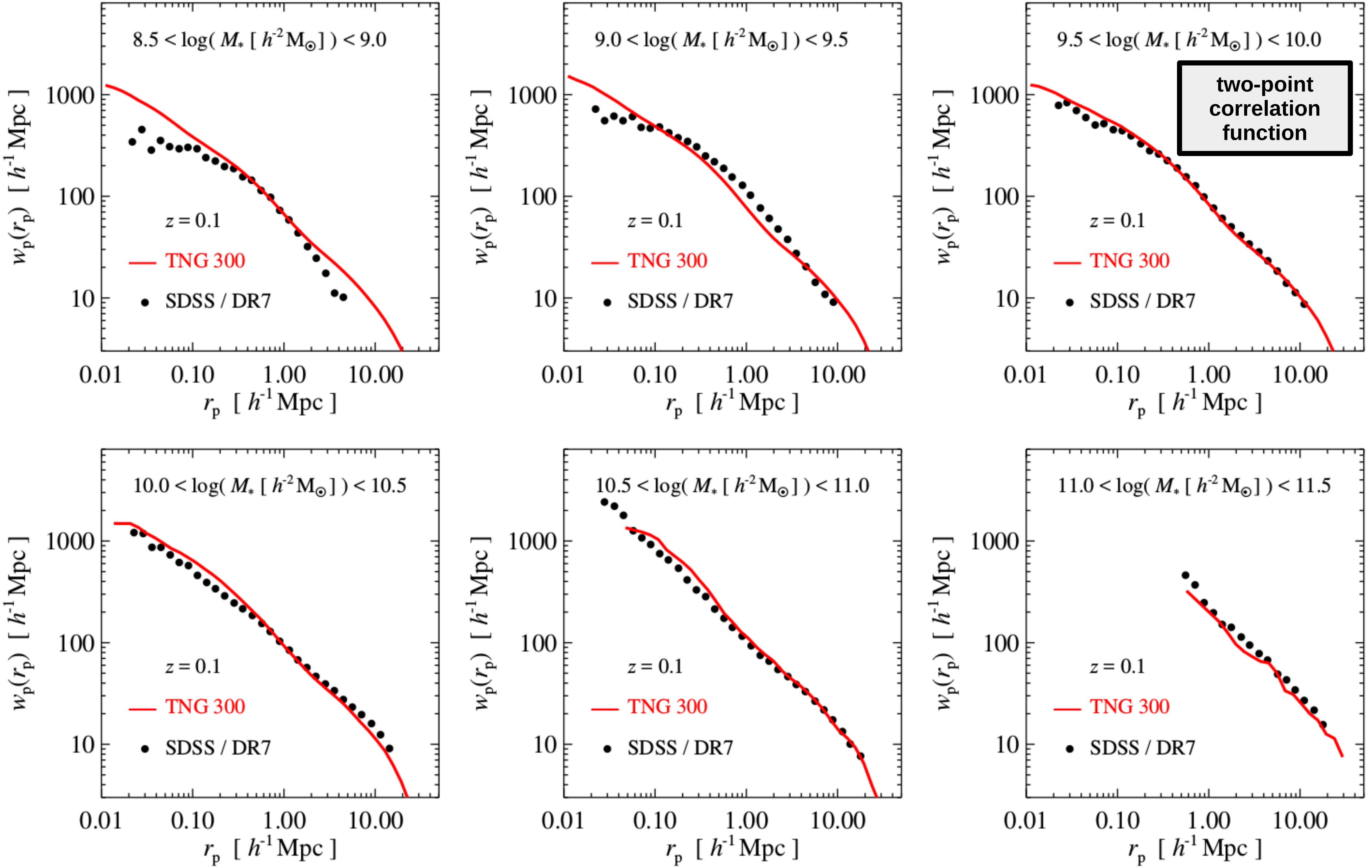
Genel
(CCA)

Vogelsberger, Marinacci, Torrey
(MIT)

Pillepich
(MPIA)

Hernquist, Naimann
(CfA)

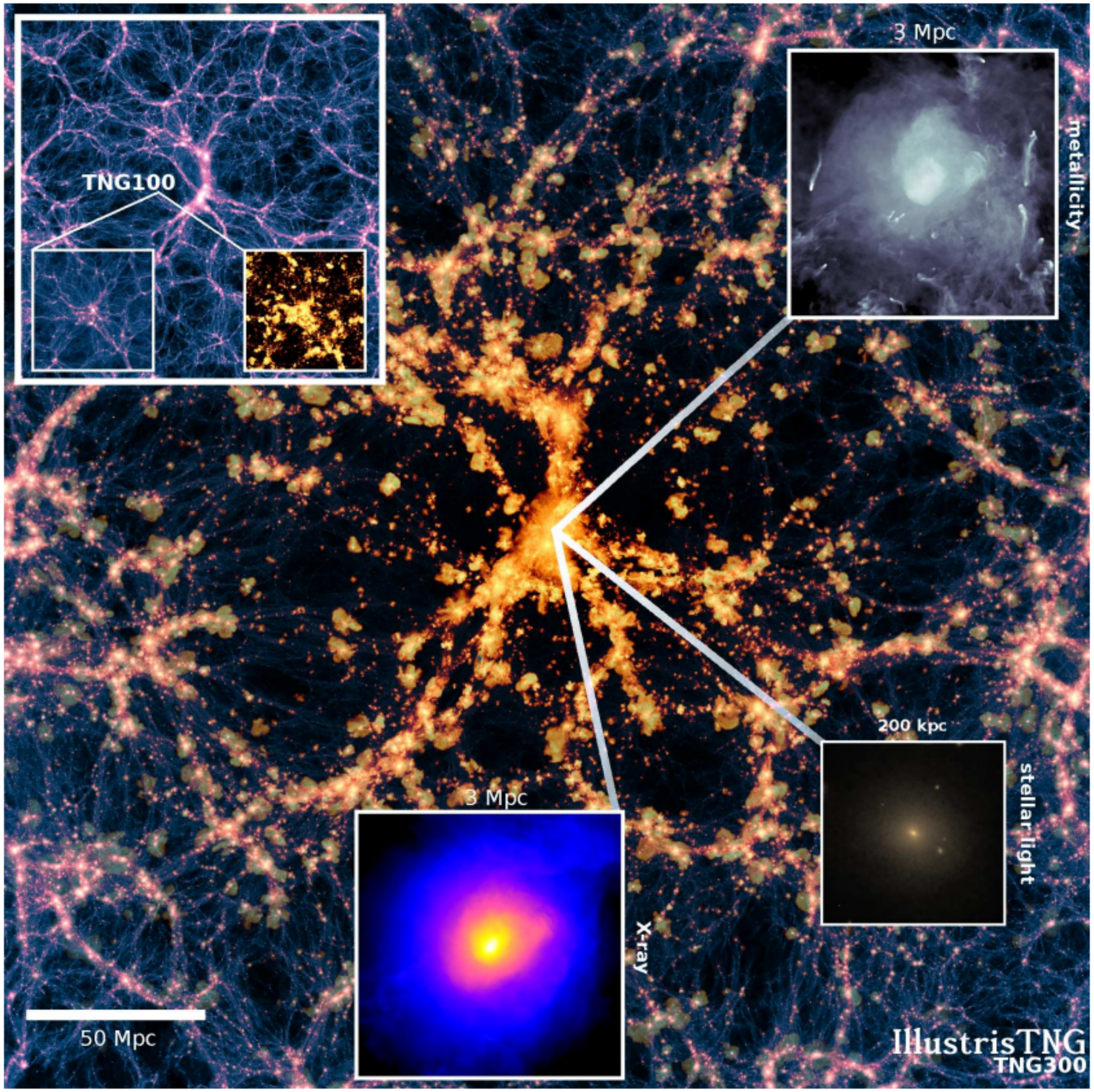
IllustrisTNG: Galaxy Clustering

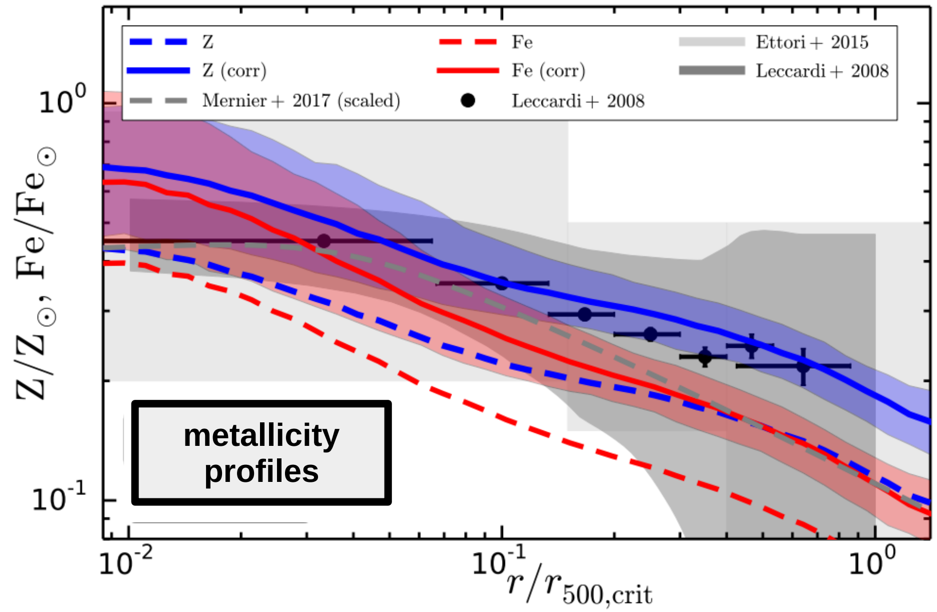


Springel+ w/ MV 2018

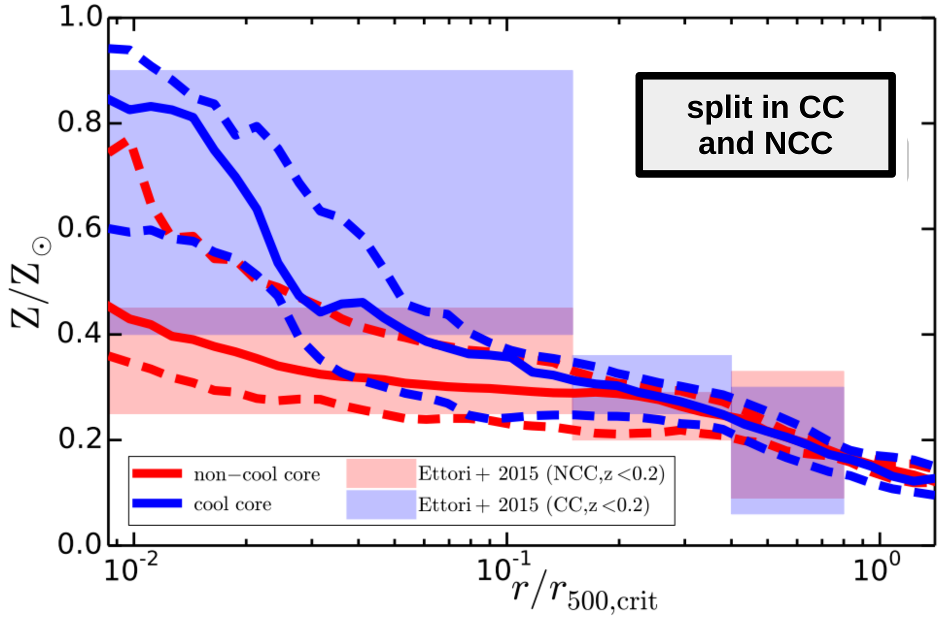
good agreement with observational data

IllustrisTNG: Galaxy Clusters



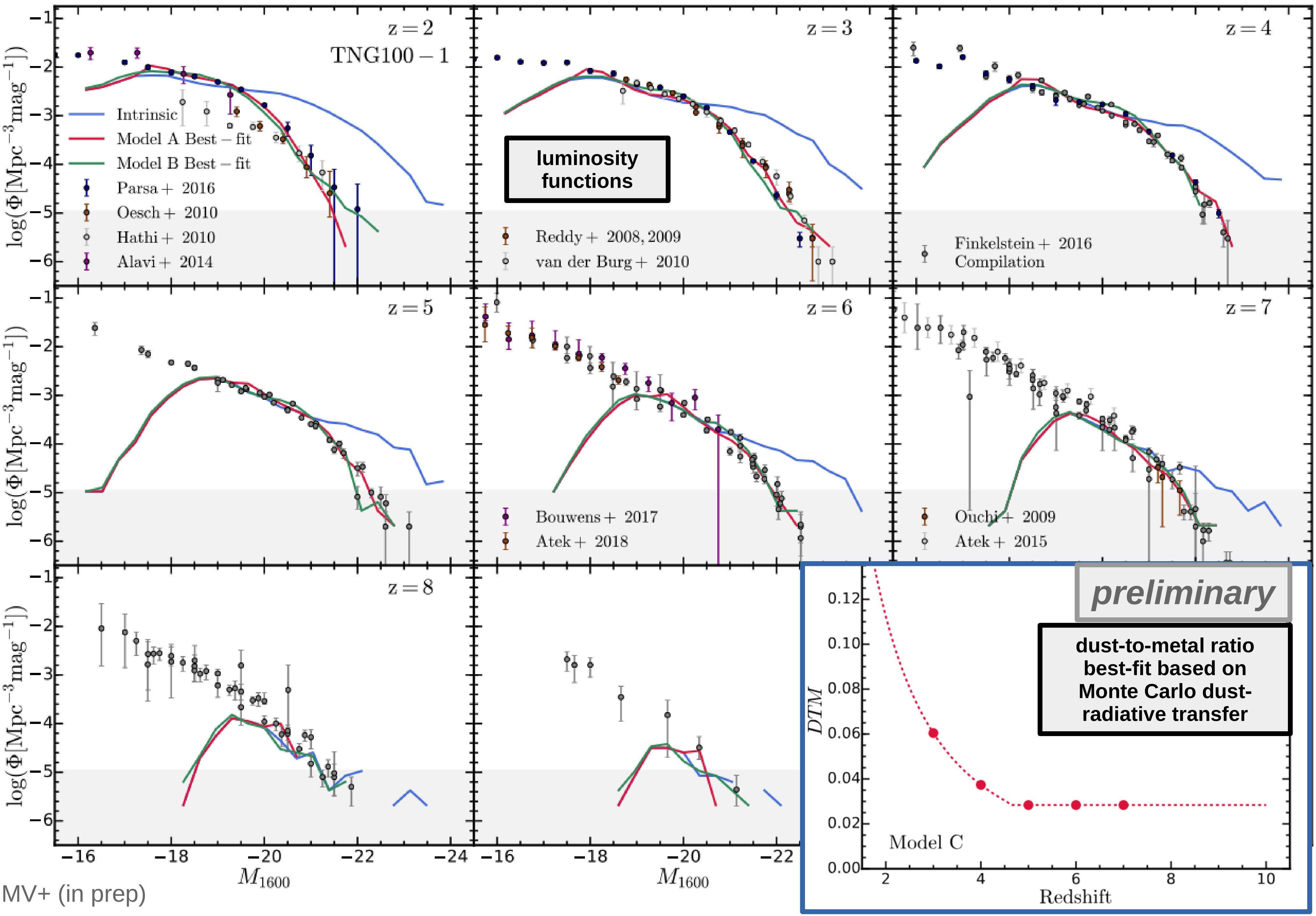


iron abundance CC/NCC dichotamy



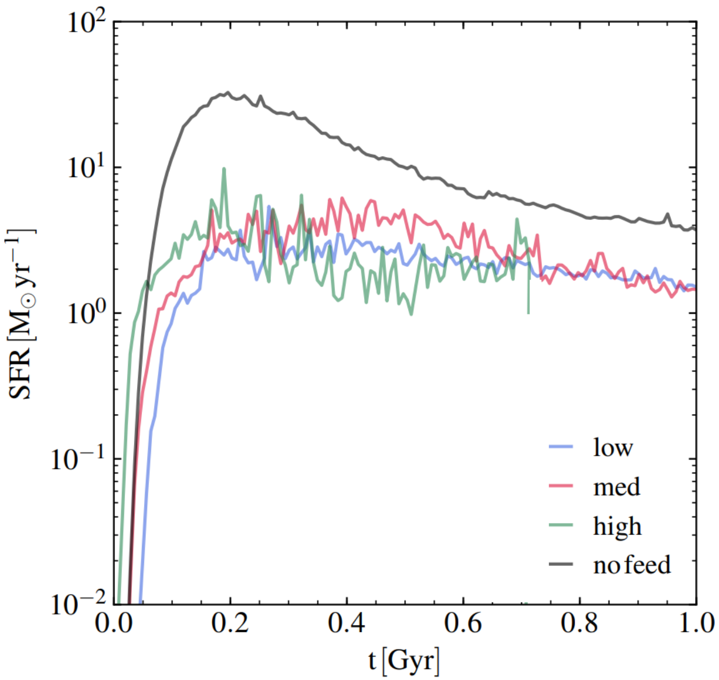
MV+ 2018

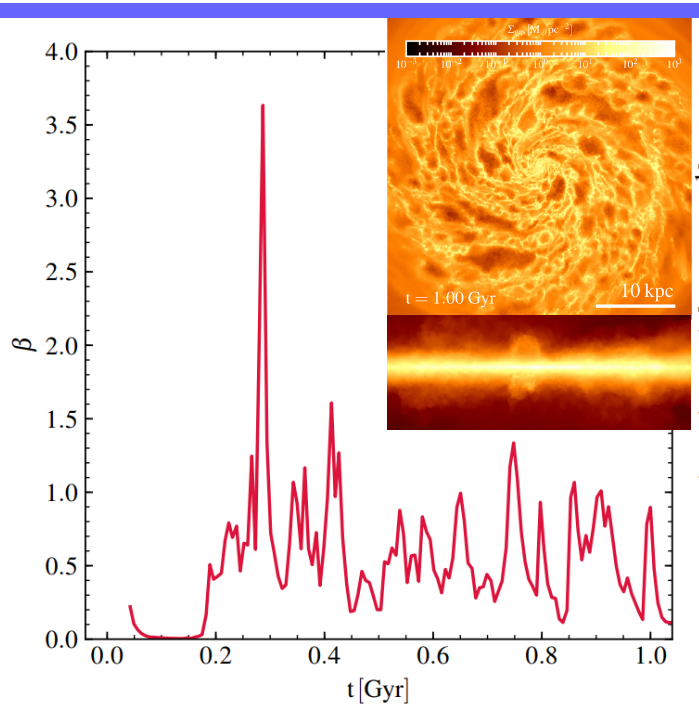
TNG50 + TNG100 + TNG300: Predictions for the *JWST* Era

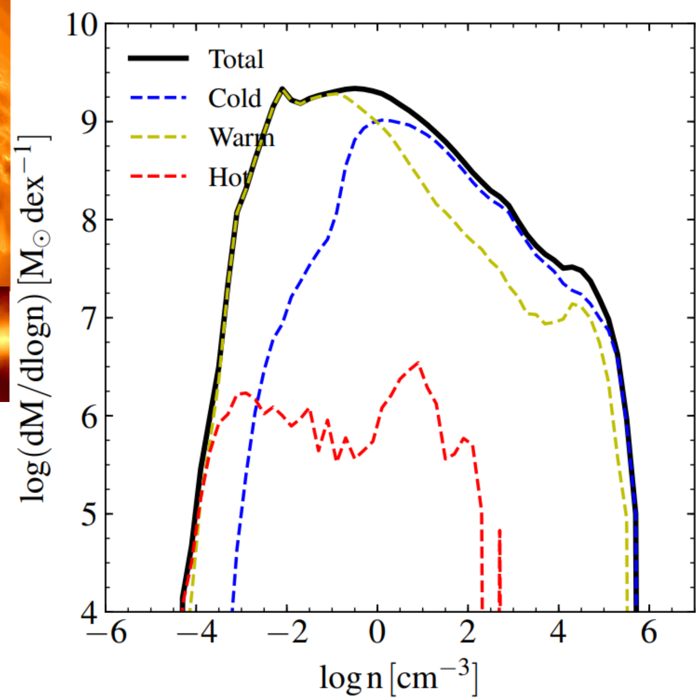


MV+ (in prep)

Beyond IllustrisTNG: Explicit Stellar Feedback / Multiphase ISM in Arepo





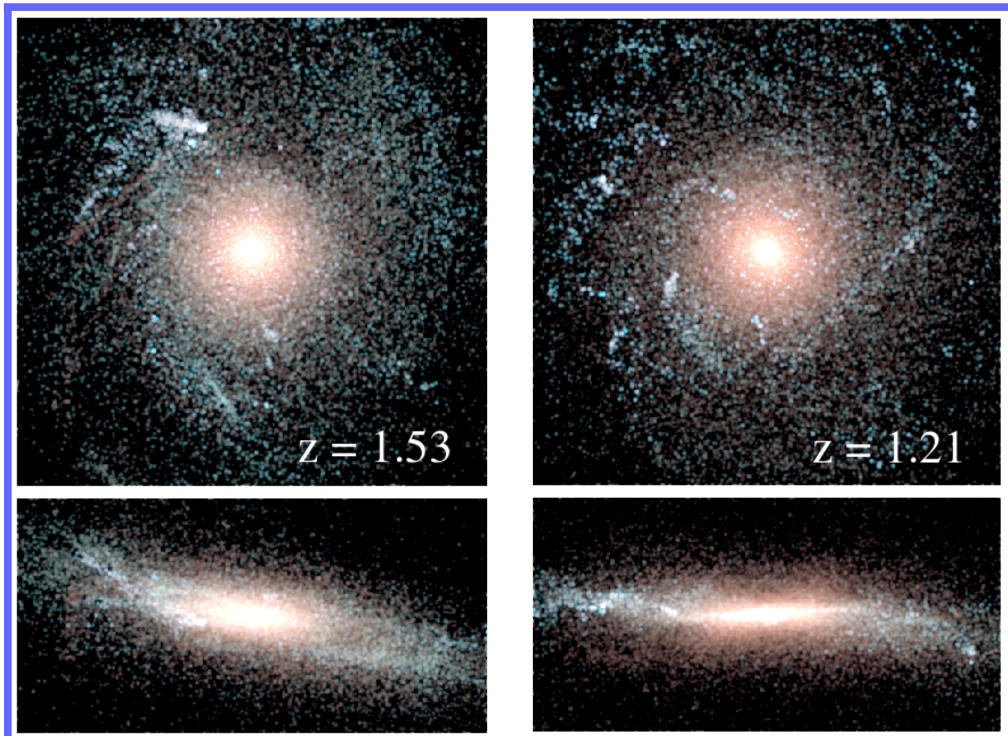


Marinacci, Sales, MV, Torrey (in prep)
[see also Laura's talk]

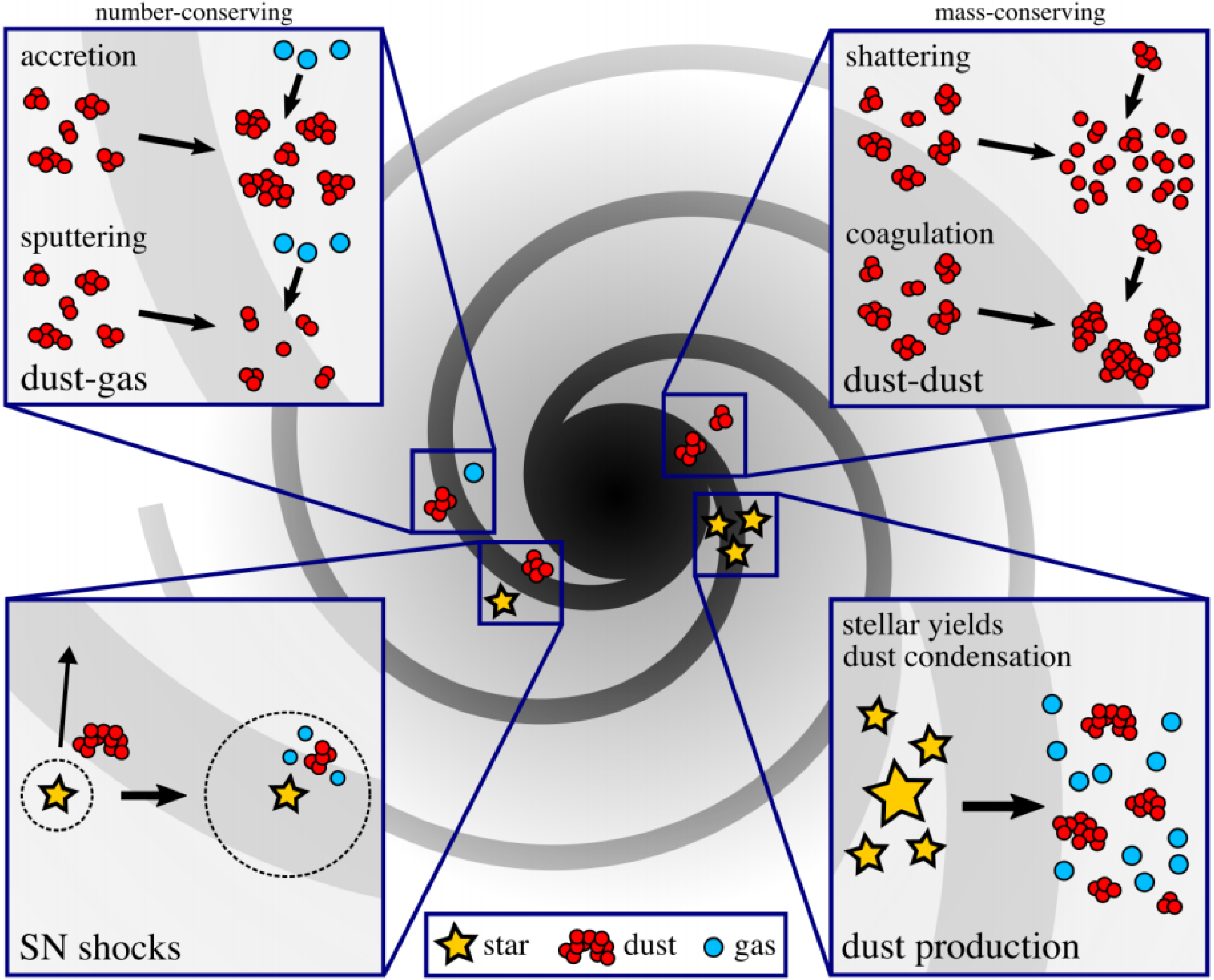
Resolution level	$\epsilon_\star$ (pc)	ϵ_g (pc)	m_g ($M_\odot$)
low	35	15	9.0×10^4
intermediate	15	7	1.1×10^4
high	5	2.5	1.4×10^3

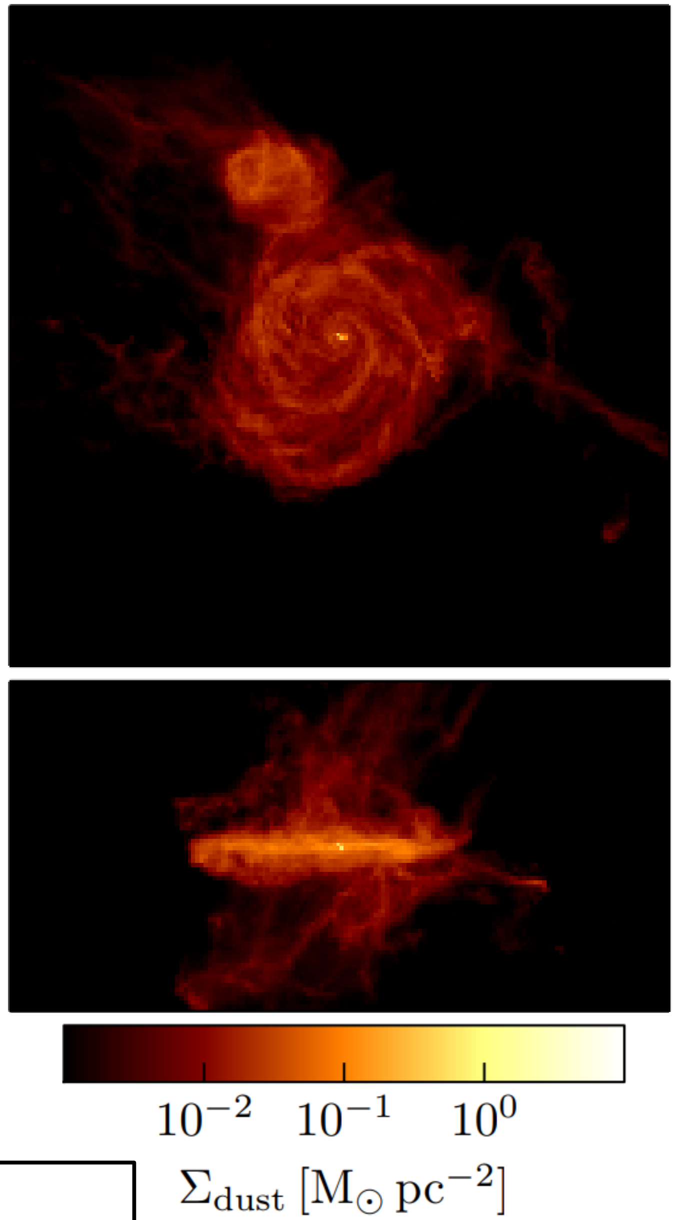
- cooling down to 10K
- SN feedback (energy and momentum)
- radiative feedback from massive stars (photoionization and radiation pressure)
- feedback from OB stars and stellar winds

preliminary



Beyond IllustrisTNG: Galactic Dust in Arepo



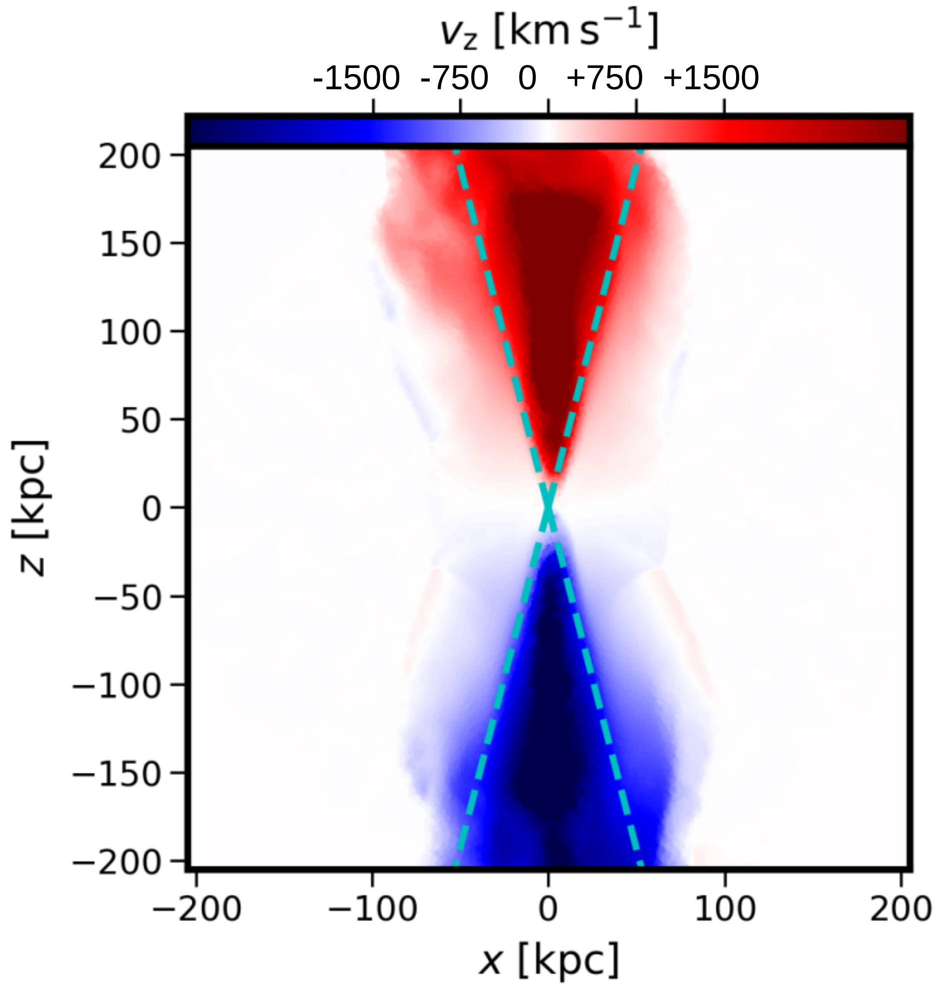


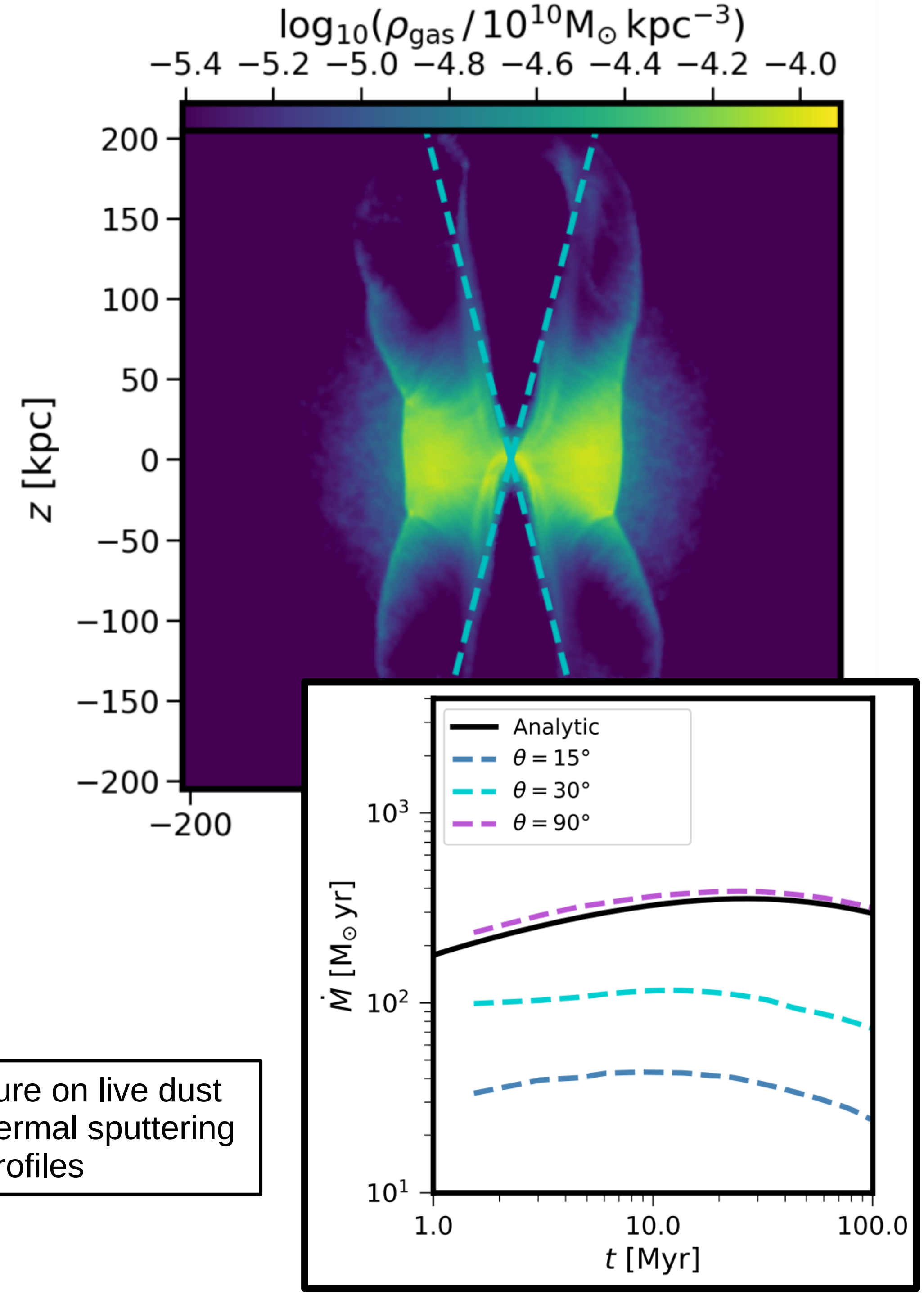
McKinnon, Torrey MV+ 2016, 2017

McKinnon, MV+ 2018

- tracks grain size distribution
- models dust-gas and dust-dust interactions
- coupled to stellar evolution model
- coupled to radiation-hydrodynamics (Arepo-RT)

Beyond IllustrisTNG: Radiative AGN Feedback in Arepo





Barnes, Kannan, MV, Marinacci (in prep)

Kannan, MV+ 2018 (Arepo-RT)

[see also Rahul's talk]

- radiation pressure on live dust
- accounts for thermal sputtering
- different dust profiles

preliminary

CDM Problems?

Problems:

- **core/cusp problem**
- **missing satellites problem**
- **diversity problem**
- **plane of satellites problem**
- **(generic WIMP has not been detected so far)**

Solutions:

- **baryonic feedback (many problems have been identified in DM only simulations)**
- **systematic uncertainties in observations**
- **DM is not exactly CDM**

CDM Problems?

Problems:

- core/cusp problem
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- (generic WIMP has not been detected so far)

Solutions:

- baryonic feedback (many problems have been identified in DM only simulations)
- systematic uncertainties in observations
- DM is not exactly CDM

for the rest of the talk: assume that DM is *not* CDM

Going beyond CDM: Candidates

Warm Dark Matter?

Self-Interacting Dark Matter?

BECDM?

...?

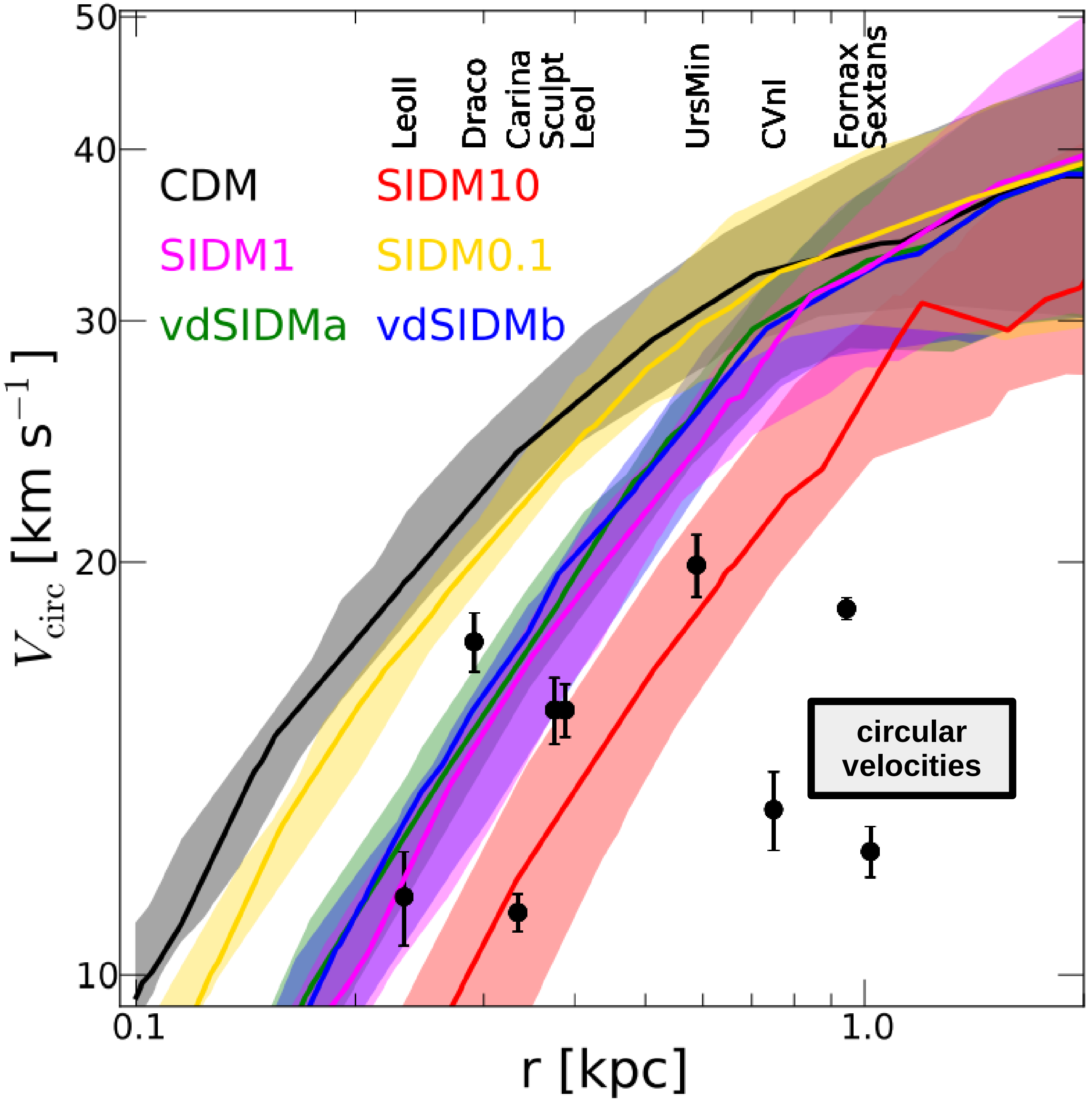
Observational Evidence for Self-Interacting Cold Dark Matter

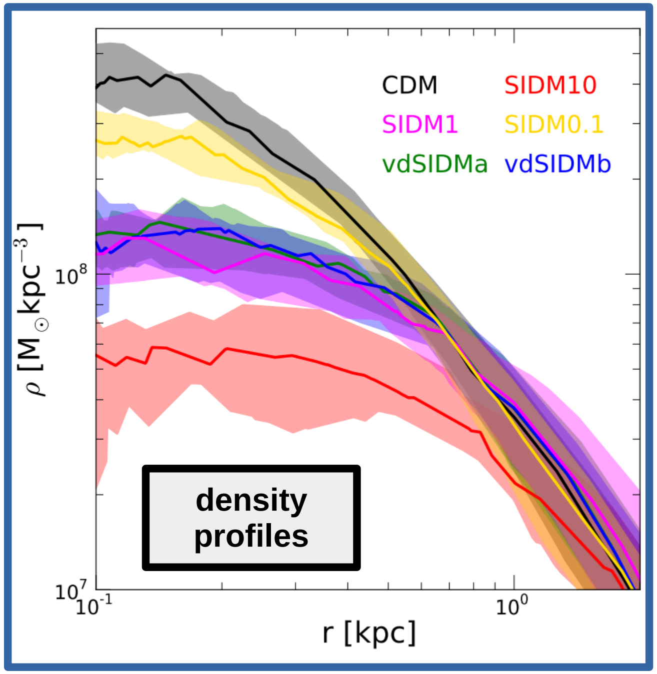
David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton, New Jersey 08544
(Received 20 September 1999)

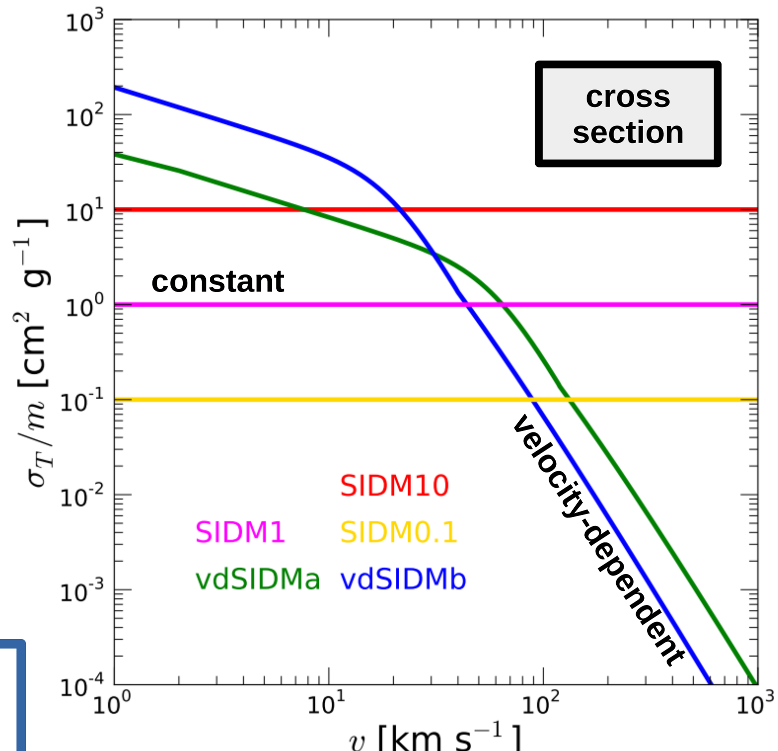
Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark 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.

Self-Interacting Dark Matter: Implications for Subhalos







MV, Zavala, Loeb 2012

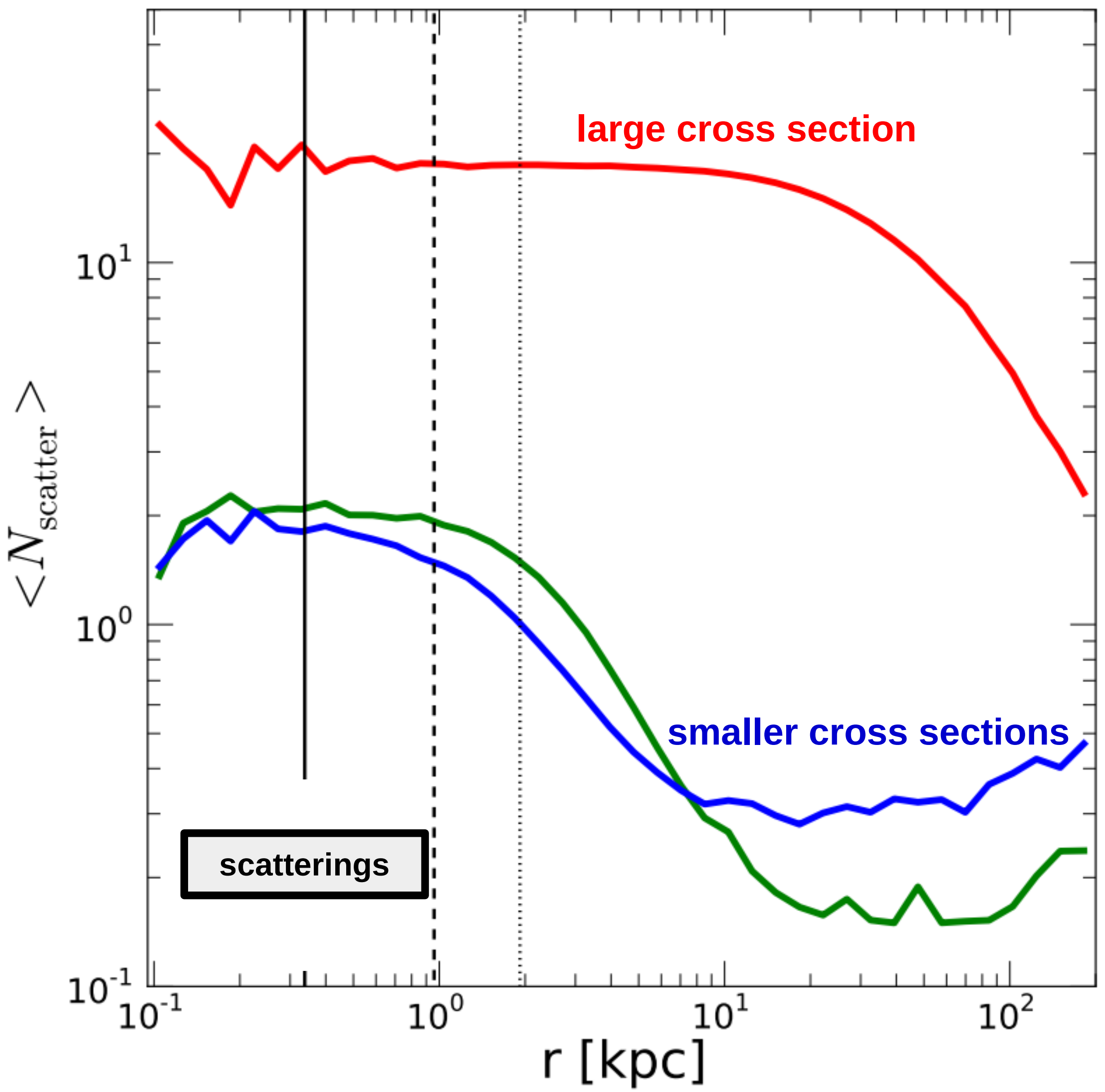
Zavala, MV, Walker 2013

[see also Rocha+ 2013]

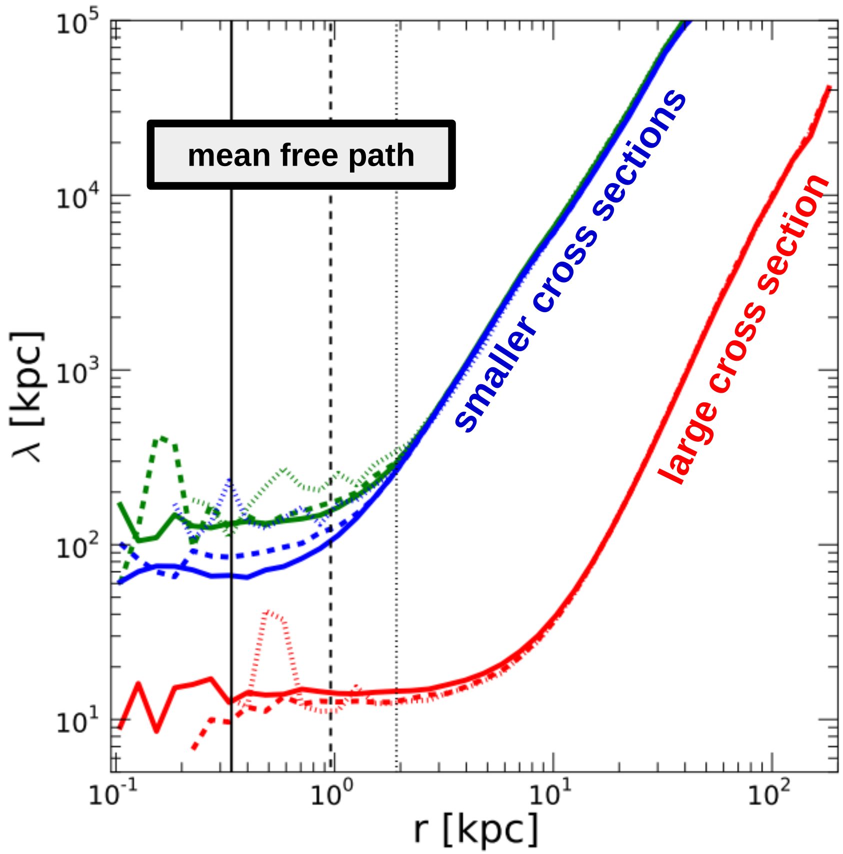
SIDM simulations alleviate the tension with TBTF problem

can be achieved with constant and velocity-dependent cross sections

How often do SIDM particles scatter on average?



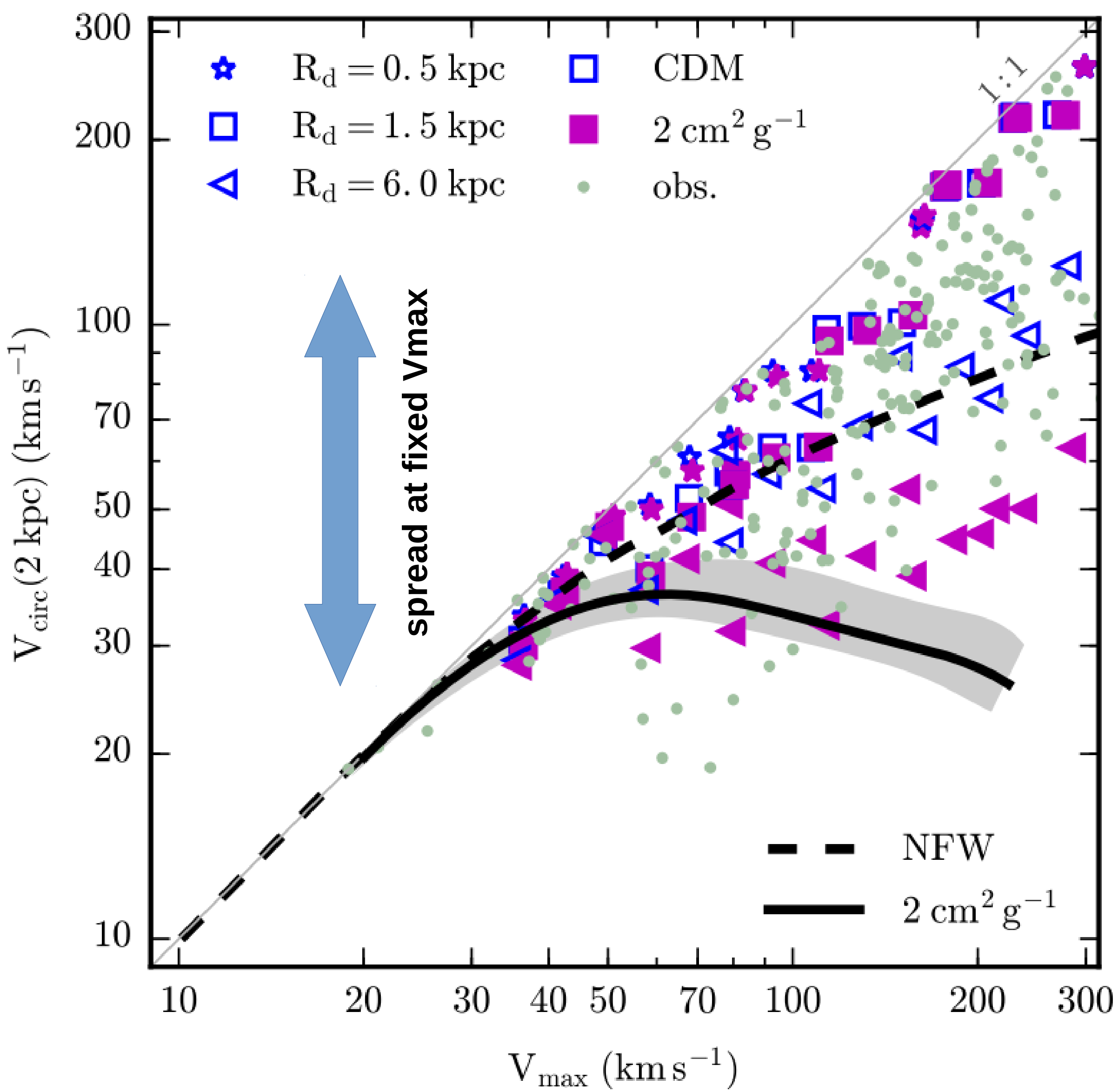
typically only a few scattering events per Hubble time are sufficient to create cores



~100 kpc mean free path in inner halo

MV, Zavala, Loeb 2012

Diversity in SIDM?



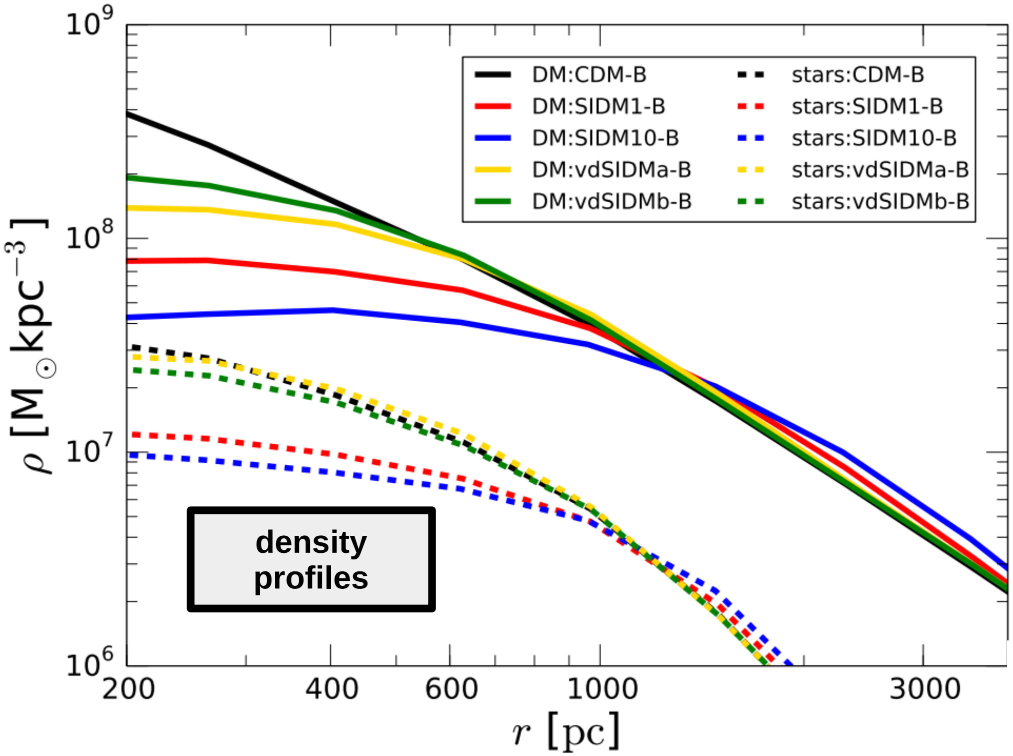
increased diversity in SIDM simulations

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, Sales+ w/ MV 2017

[see also Ren+ 2018]

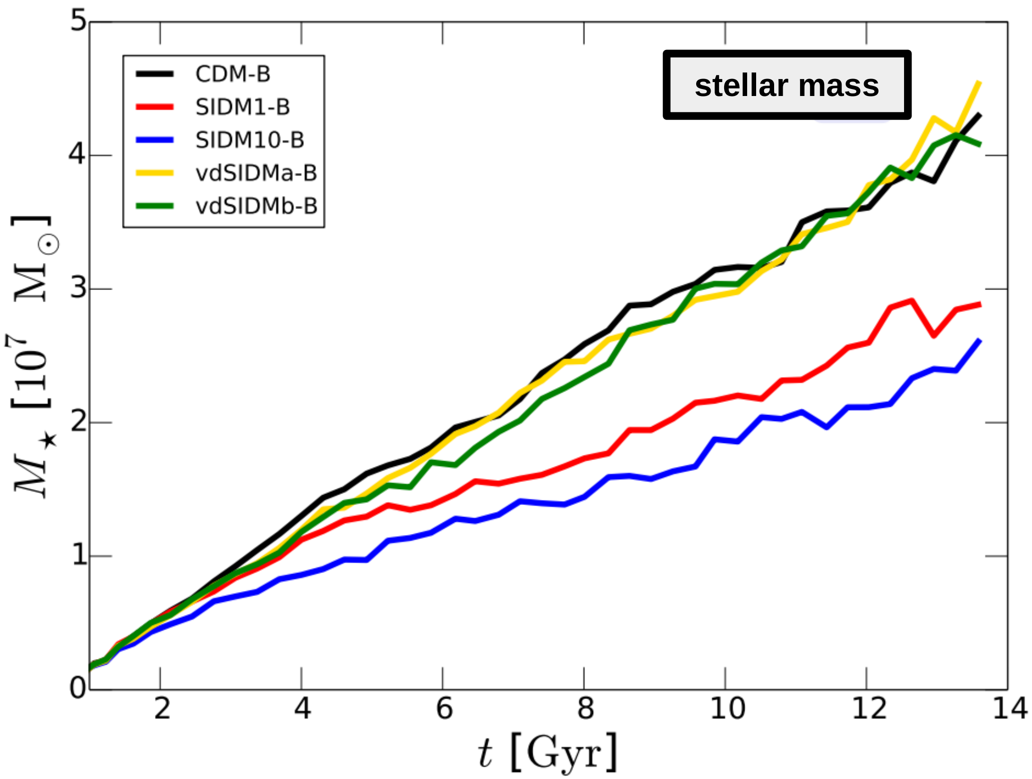
SIDM: DM + Baryons



MV+ 2014

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

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



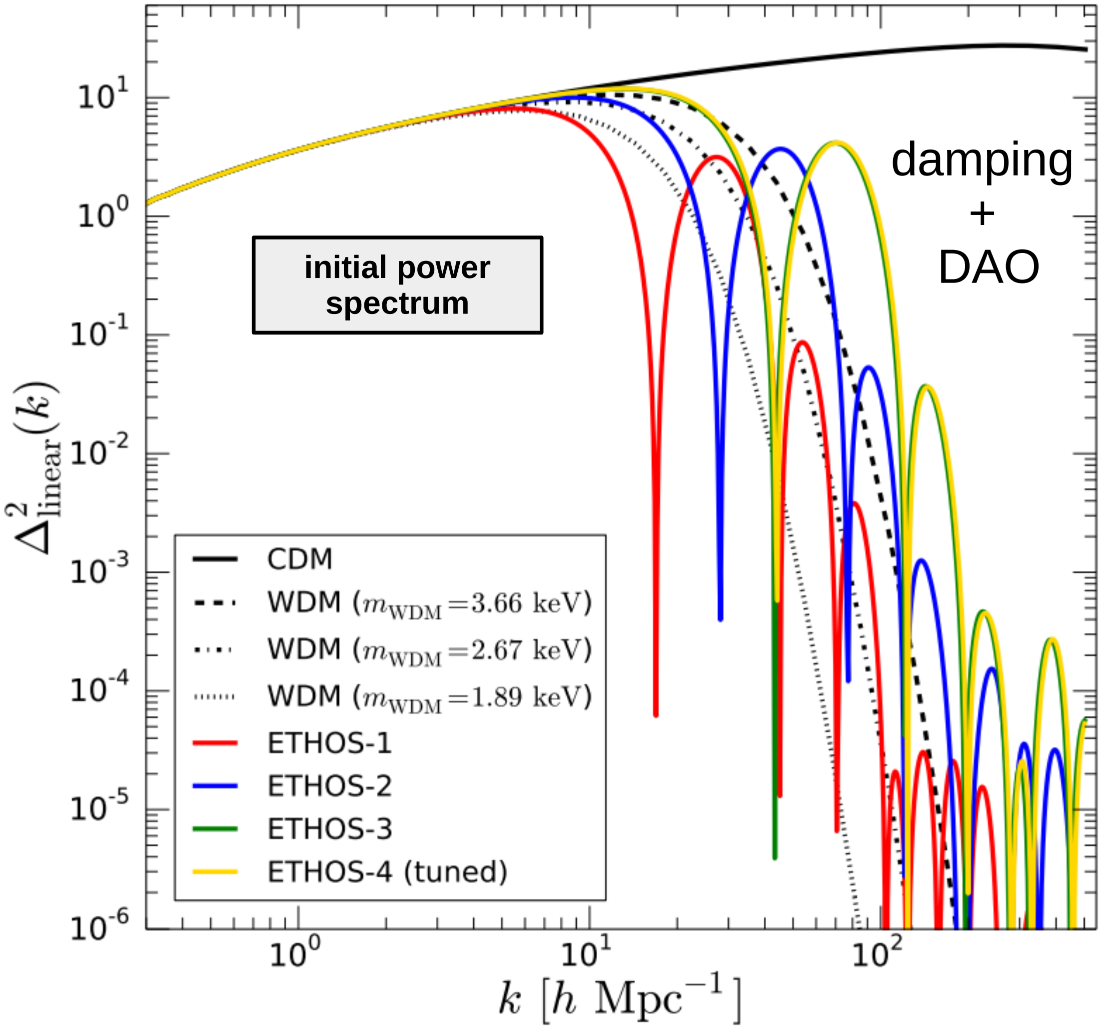
Based on our results, the discovery of dark matter cores on the scale of $r_{1/2}$ in field dwarf galaxies with $M_\star \lesssim 3 \times 10^6\ M_\odot$ would imply one of the following: (1) dark matter is cold but the implementation of astrophysical processes in current codes is incomplete; (2) there is a large scatter in the halo masses of dwarf galaxies with $M_\star \lesssim 3 \times 10^6\ M_\odot$; 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]

[see also Harvey+ 2018]

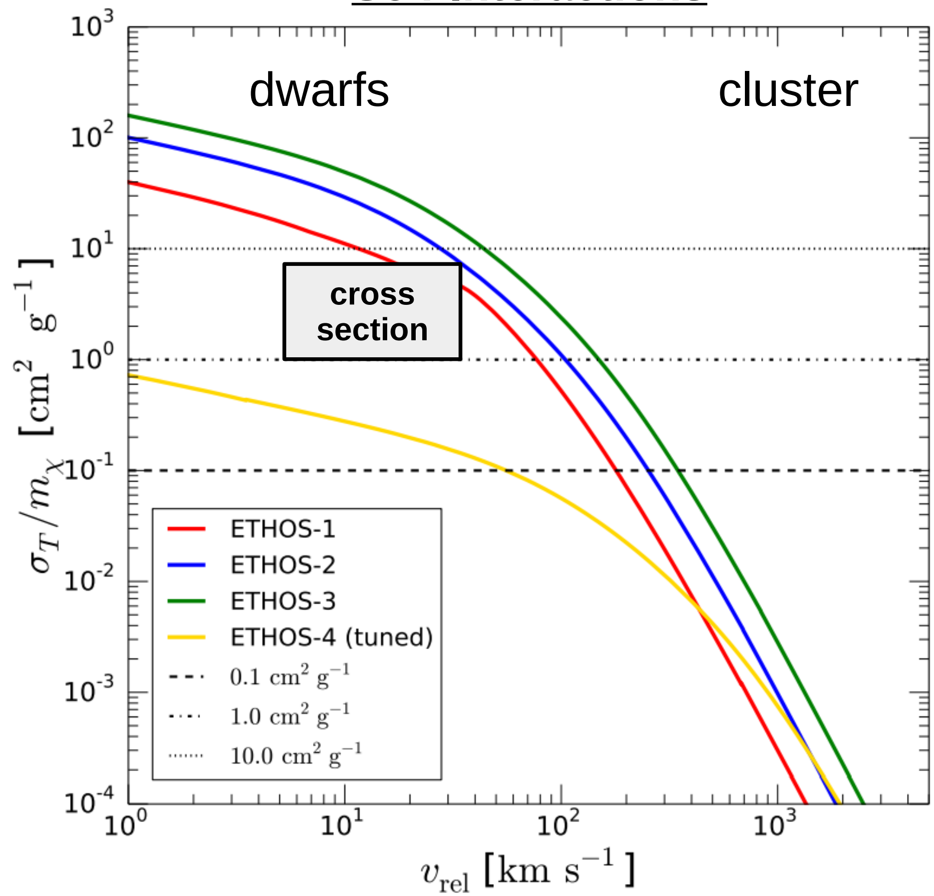
ETHOS – Effective Theory of Structure Formation: Ingredients

Initial Conditions



Effective theory of Structure formation (ETHOS) enables simulations in almost any microphysical dark matter model. Maps microphysics into physical linear matter power spectrum and self-interaction transfer cross section.

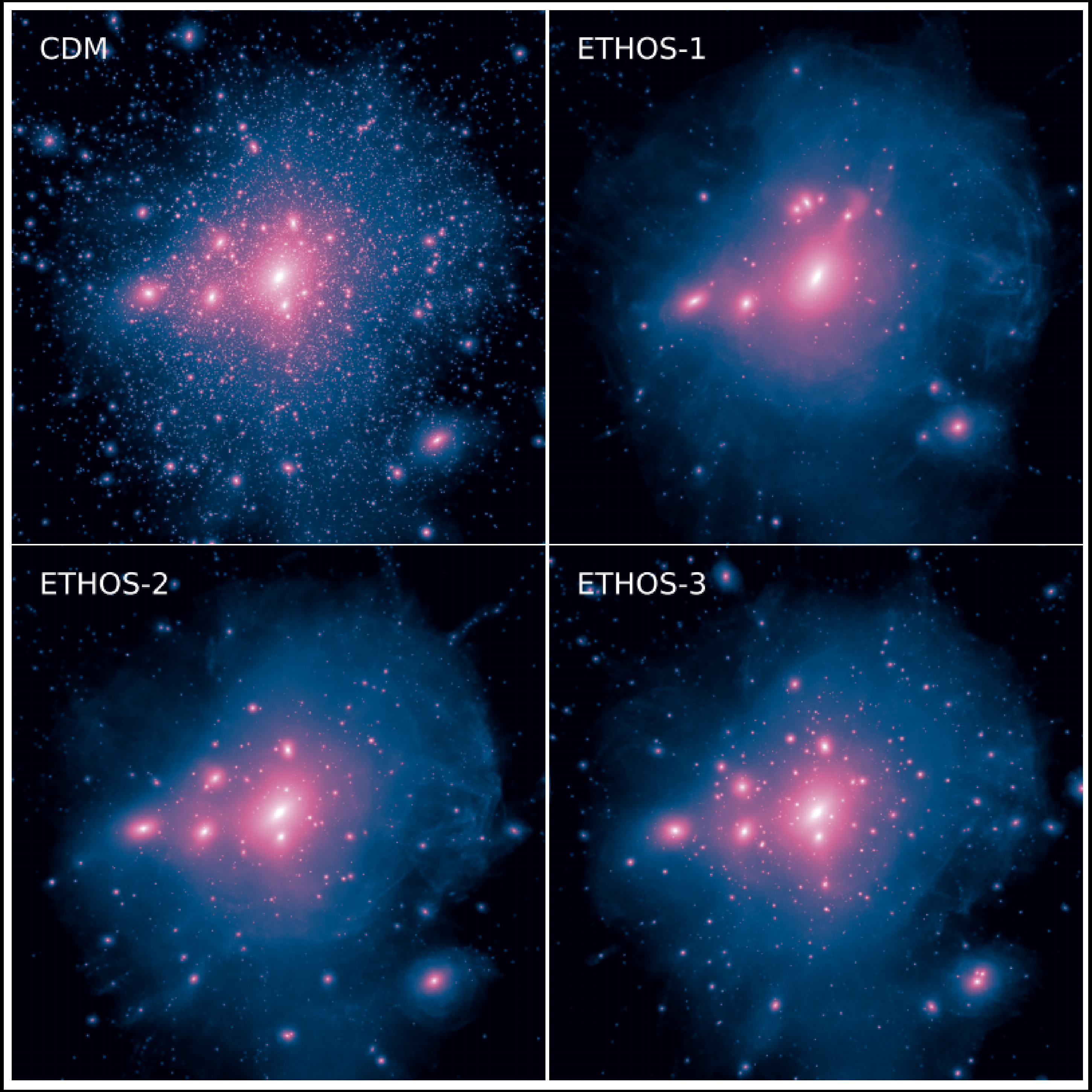
Self-Interactions



Cyr-Racine+ w/ MV2016

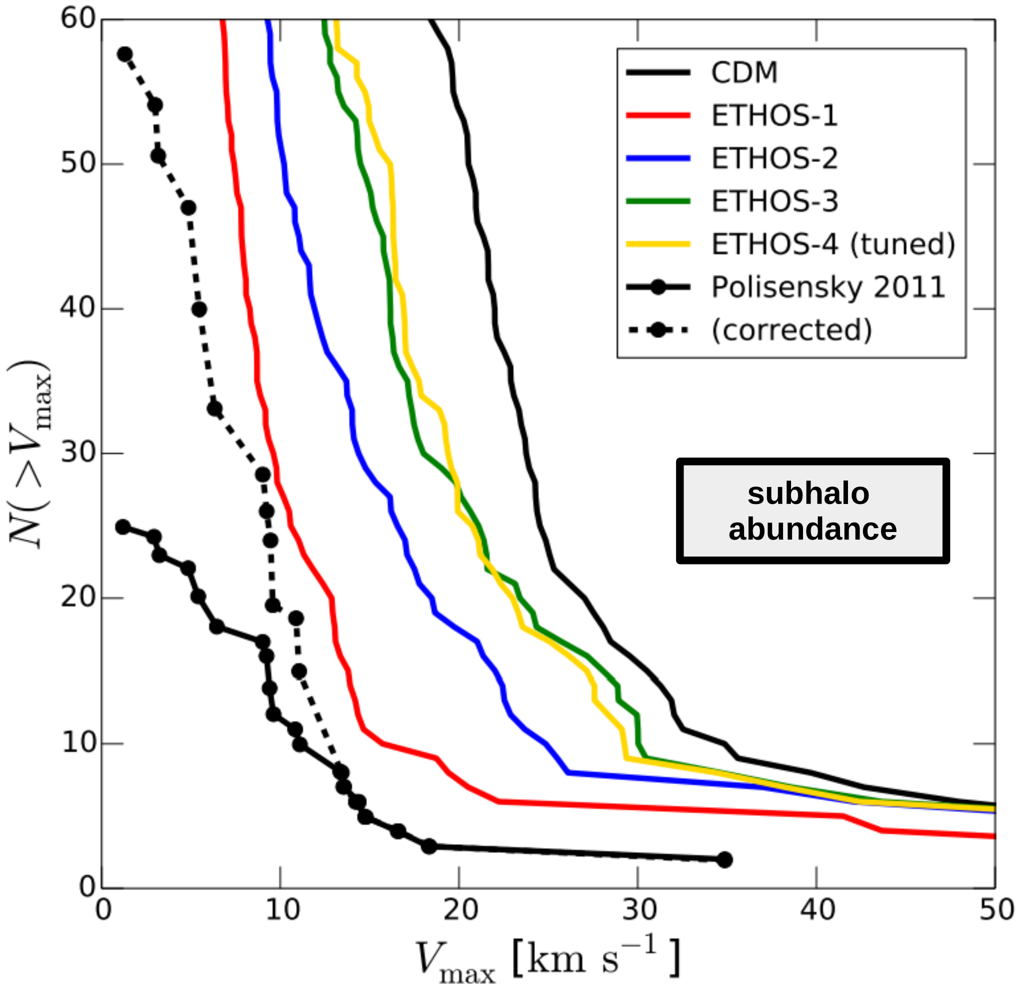
MV+ 2016

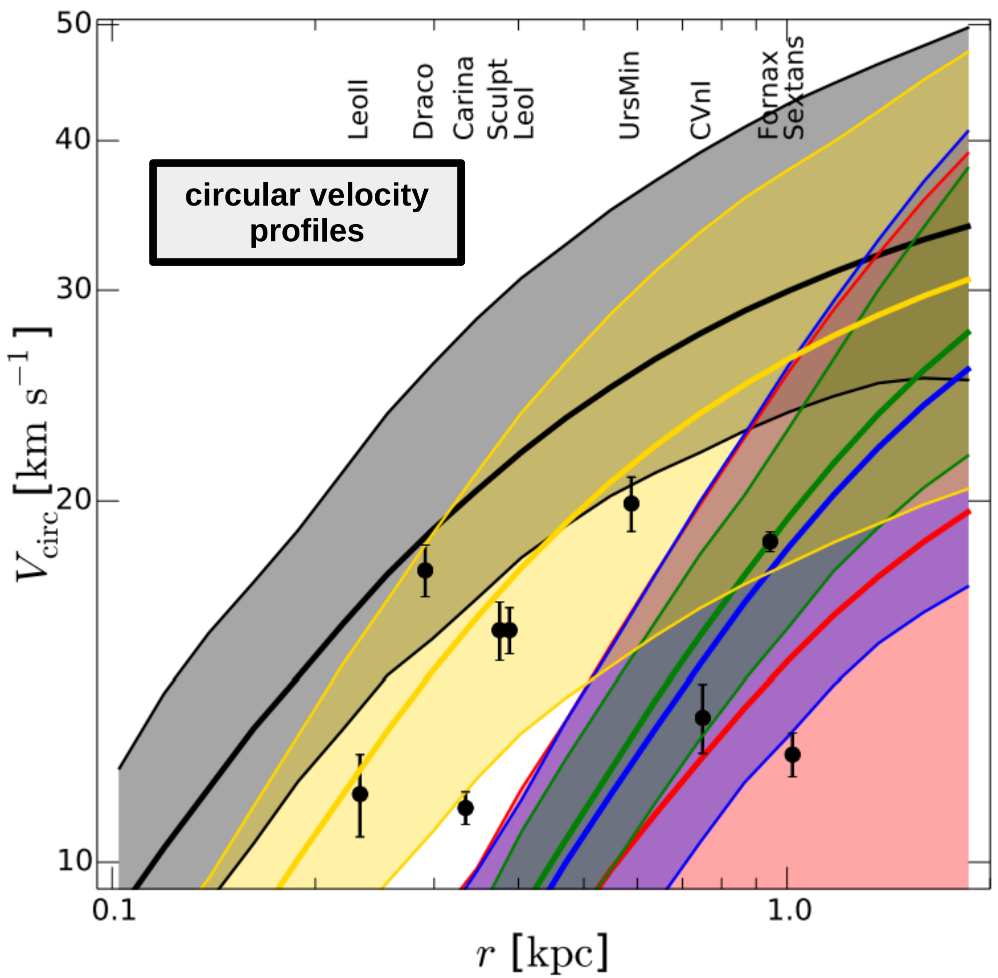
ETHOS: A Milky Way-like Halo Simulation



MV+ 2016

ETHOS: Impact on Milky Way Subhalos

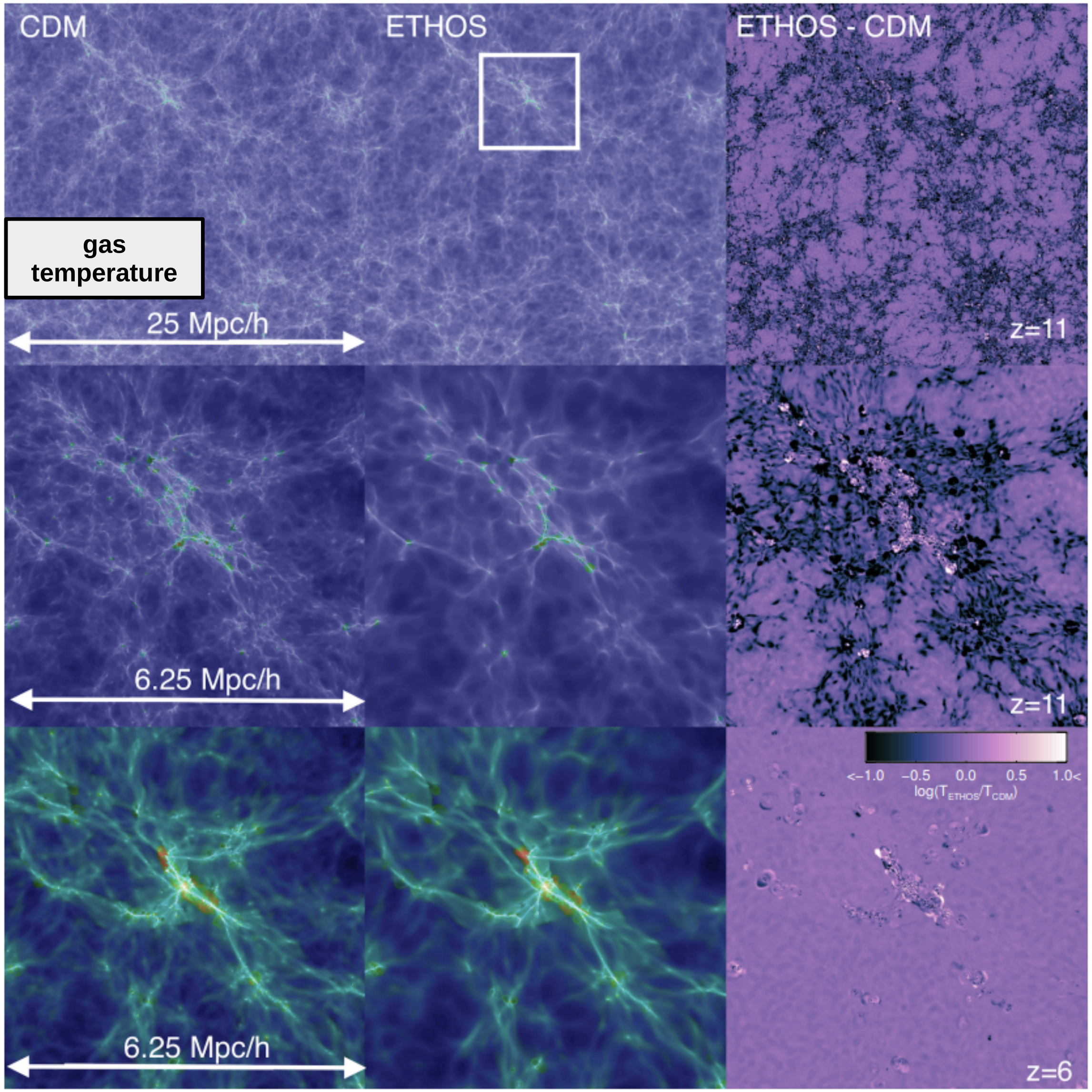




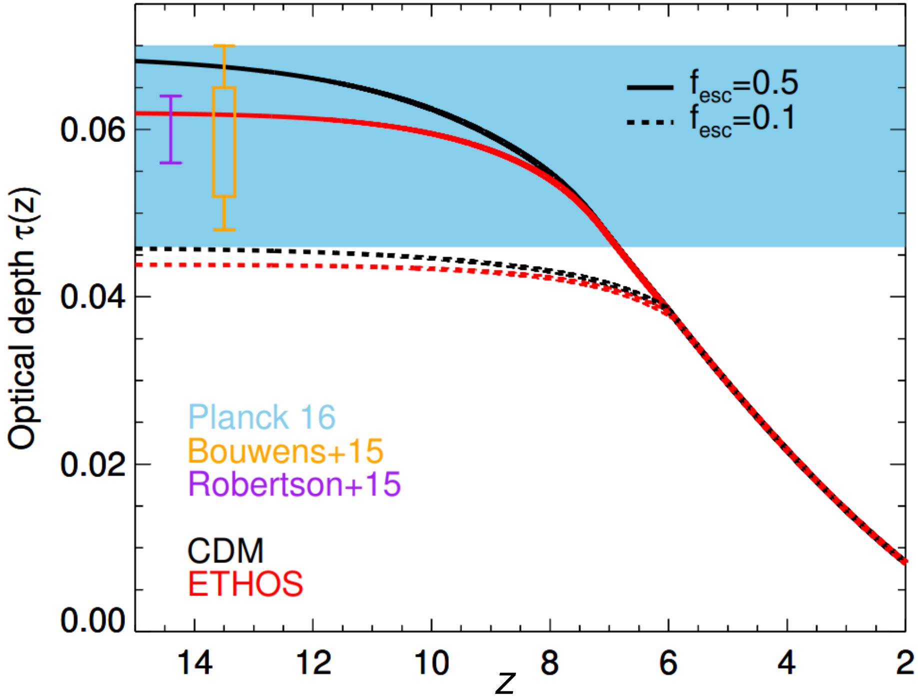
both CDM abundance and structural problems can be alleviated simultaneously → **addresses missing satellites and TBTF problems**

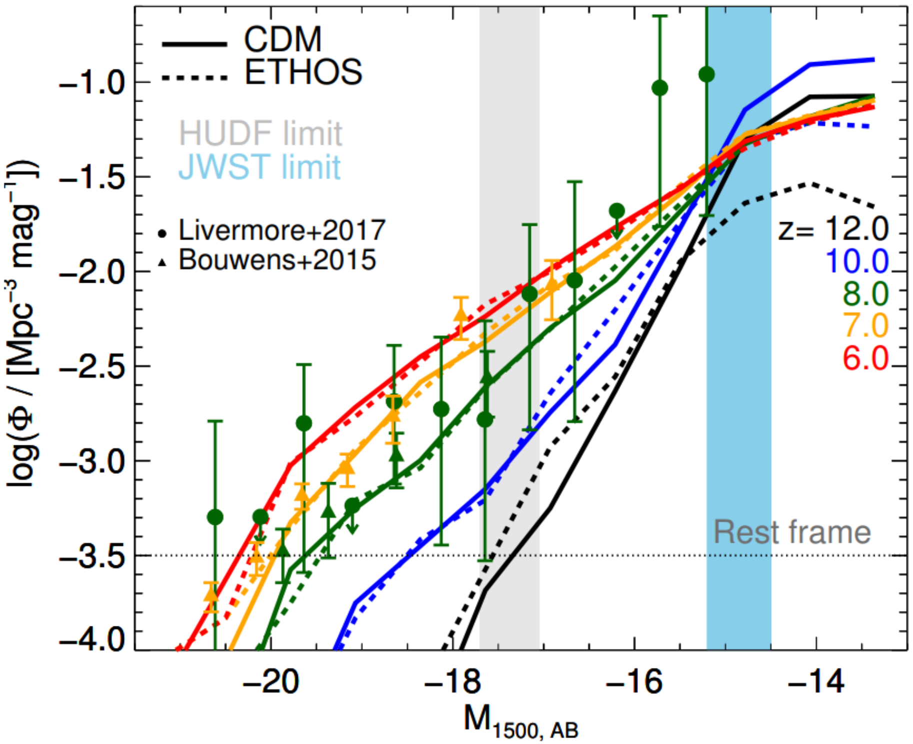
MV+ 2016

ETHOS: The High-Redshift Universe



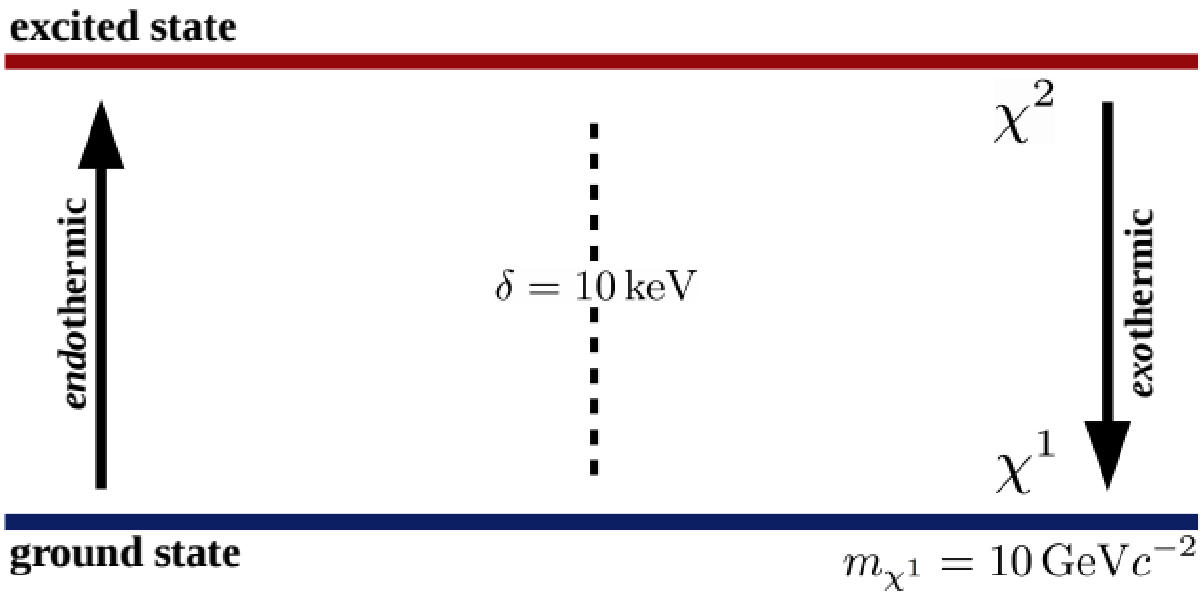
Lovell, Zavala, MV+ 2018

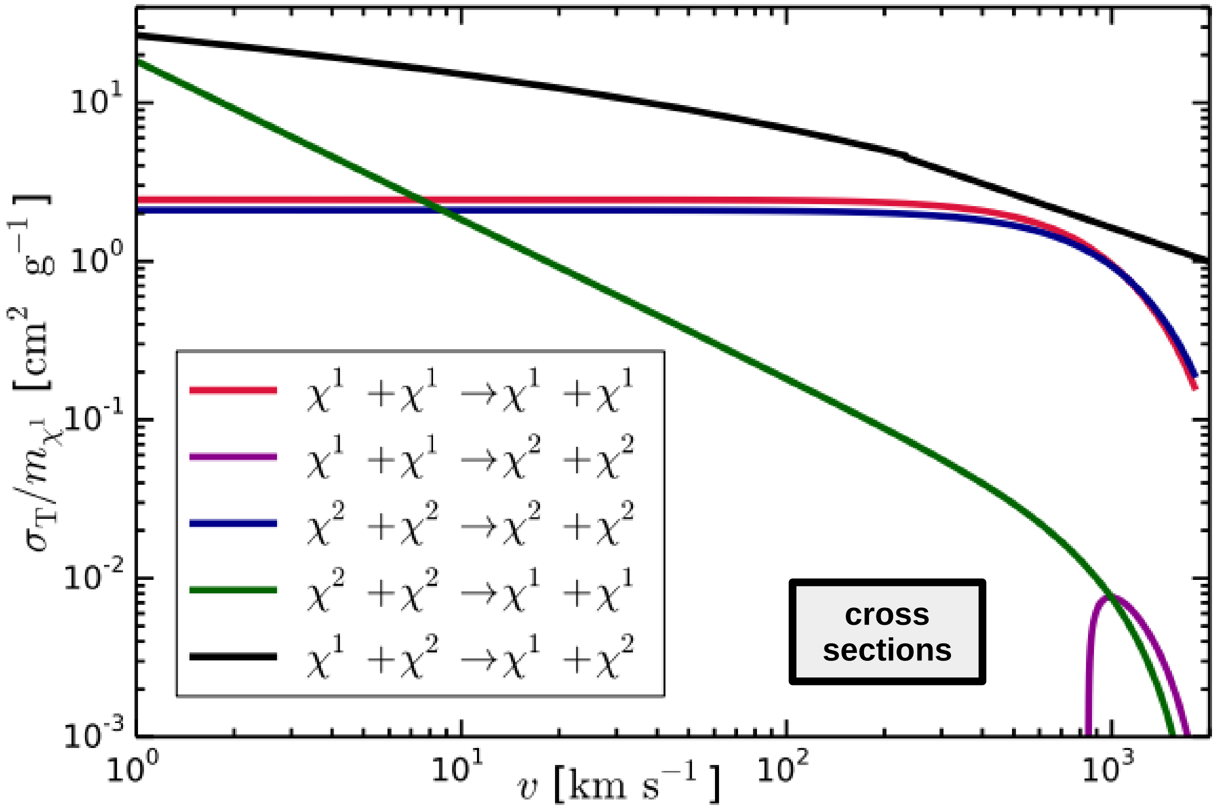




ETHOS models consistent with optical depth and high redshift luminosity function measurements

Inelastic SIDM: Two-State SIDM Model





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

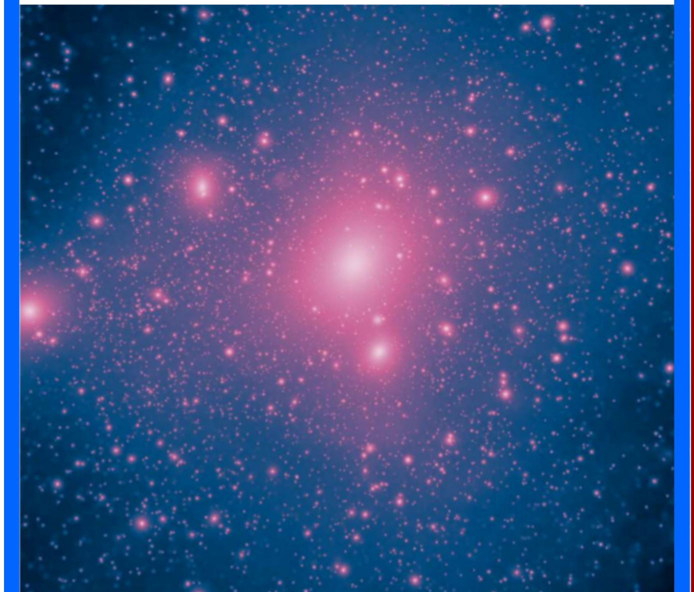
specific model allows exothermic, but no endothermic reactions

MV, Zavala, Schutz, Slatyer 2018

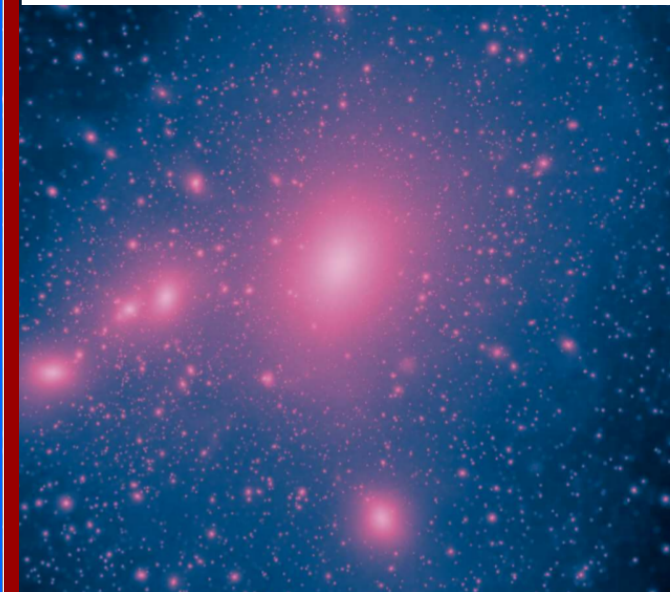
[see also Todoroki & Medvedev 2018]

Elastic vs. Inelastic SIDM

Elastic SIDM

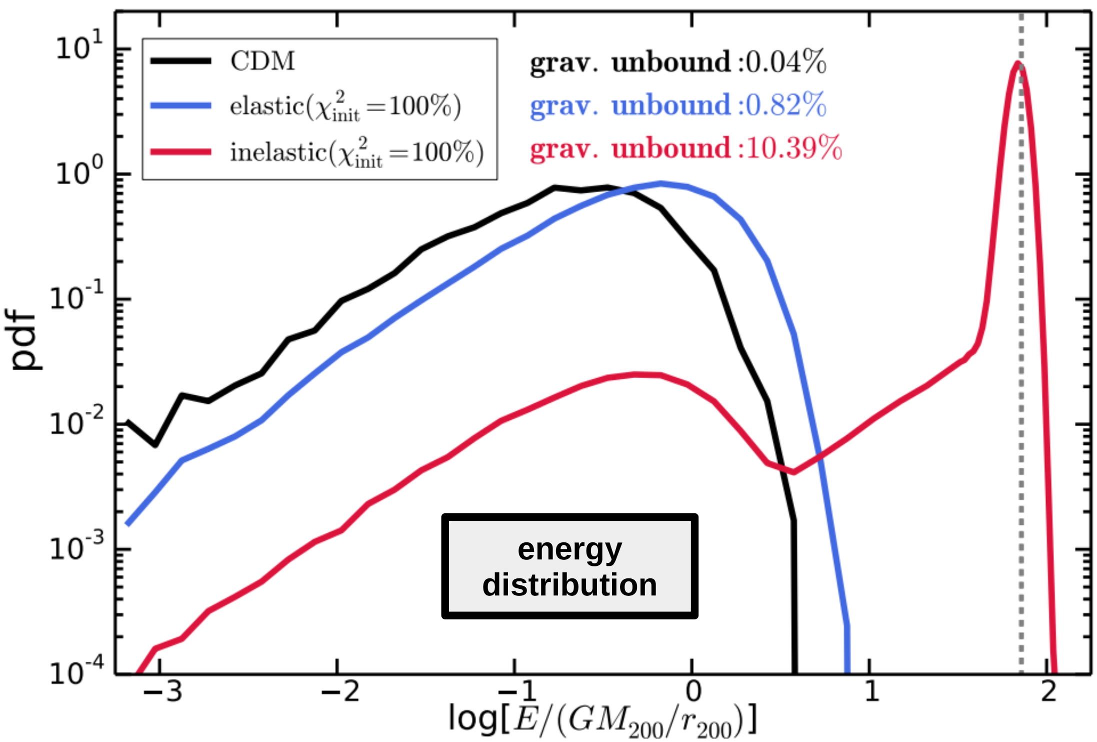


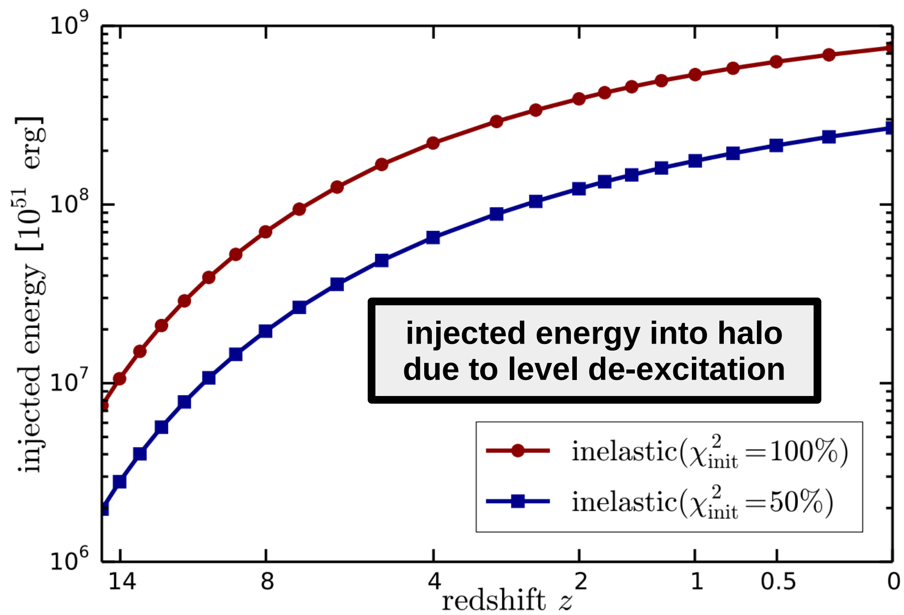
Inelastic SIDM



exothermic reactions ‘evaporate’ halo cores

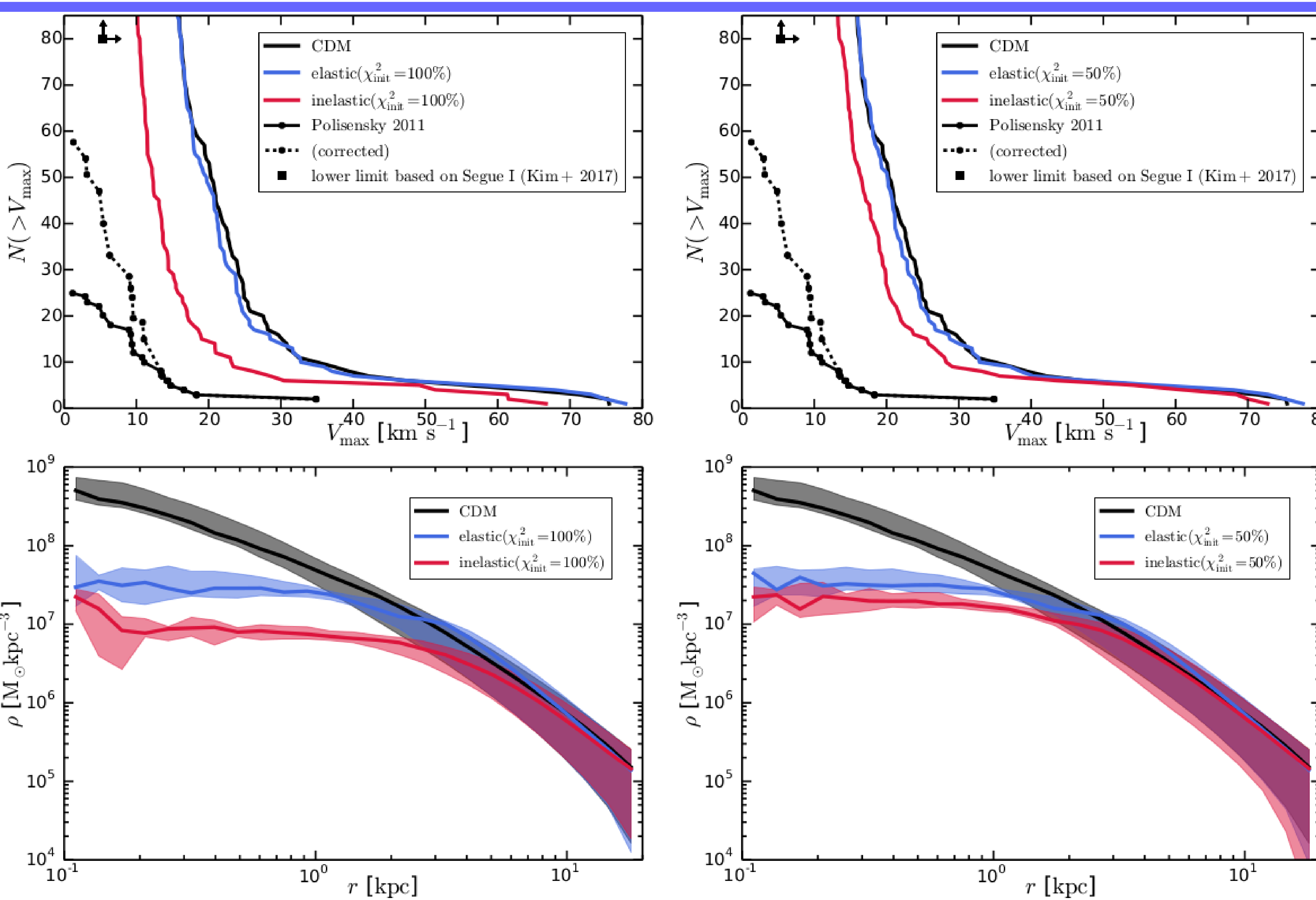
energy injection is equivalent to a few 100 million supernovae type II





MV, Zavala, Schutz, Slatyer 2018

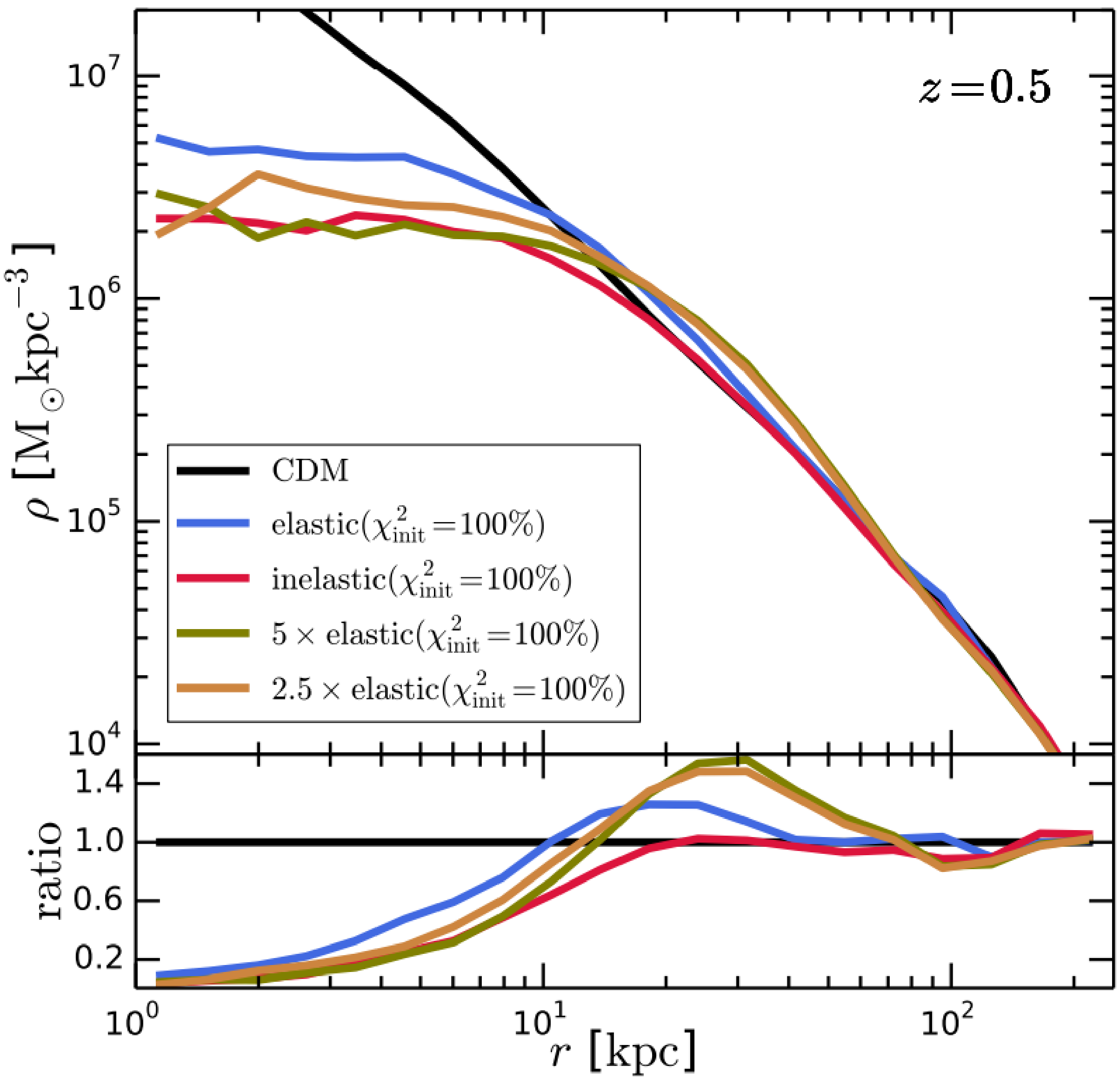
Subhalo Properties



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

MV, Zavala, Schutz, Slatyer 2018

Implications for Cross Section Constraints

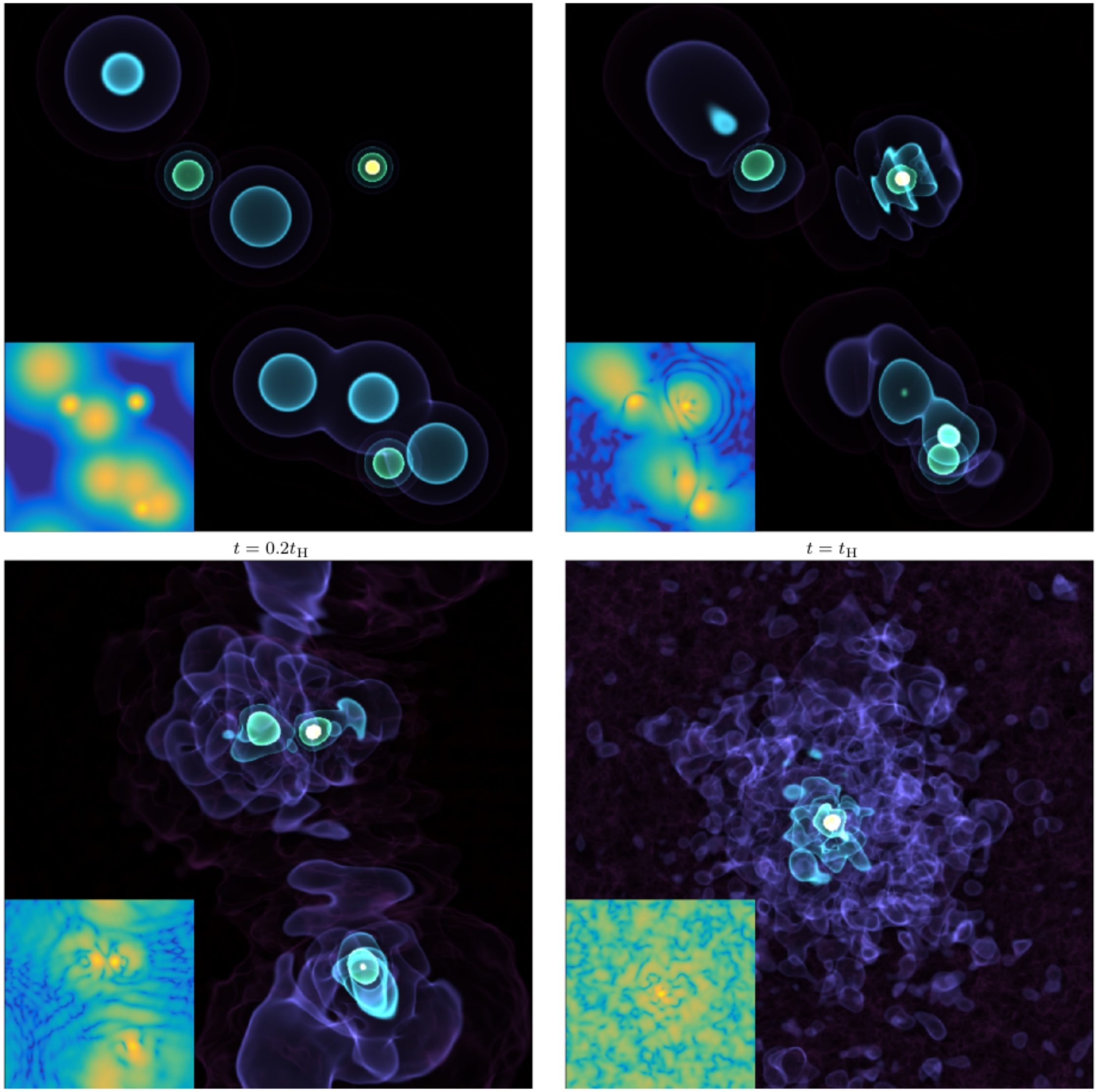


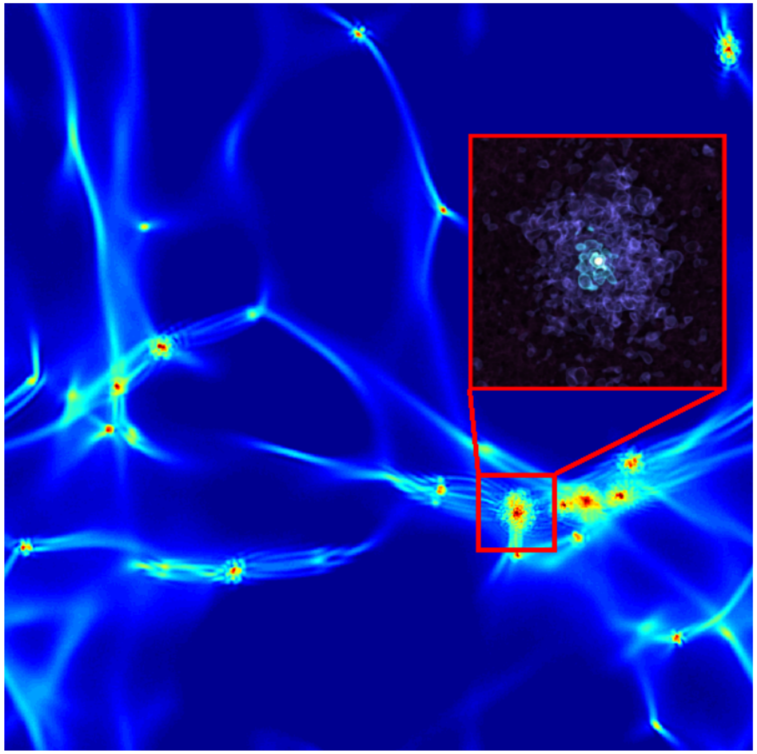
an elastic model with a ~5 times larger cross section leads to a central density reduction similar to the inelastic model

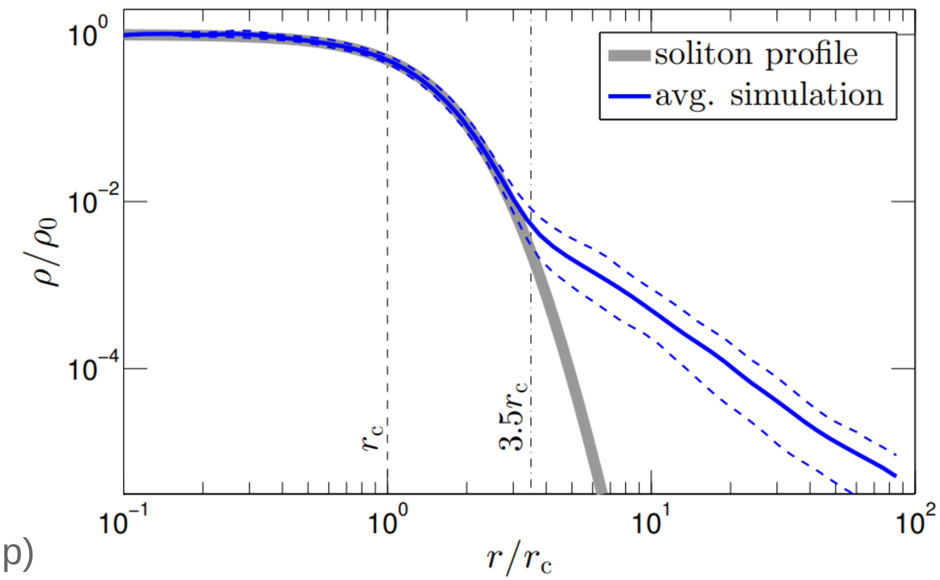
implications for cross section constraints?

MV, Zavala, Schutz, Slatyer 2018

Addendum: Ultralight Axions – BECDM – Fuzzy DM







$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi$$

$$\nabla^2 V = 4\pi G(\rho - \overline{\rho})$$

Mocz, MV+ 2017

Mocz+ w/ MV (in prep)

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**
- **Retuning of feedback physics?**
- **How to distinguish baryonic feedback effects from alternative DM?**