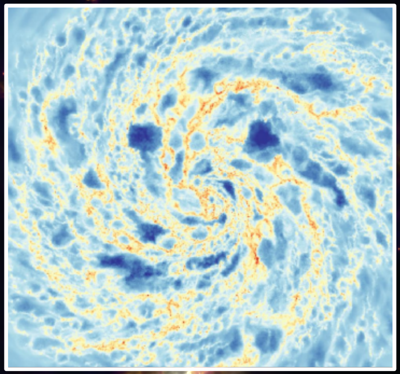
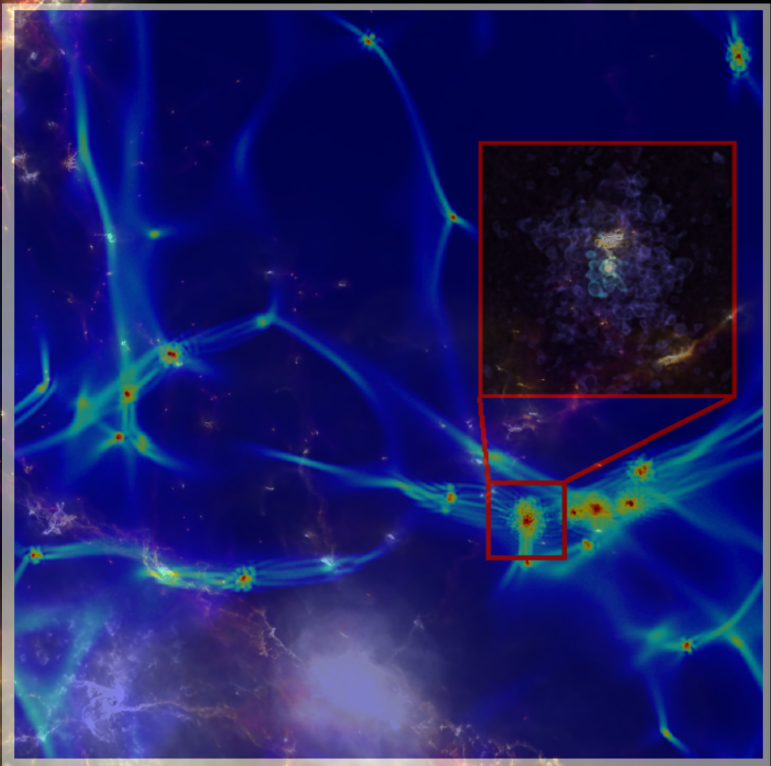
Galaxy Formation Simulations: Illustris, IllustrisTNG and Beyond

Mark Vogelsberger

Massachusetts Institute of Technology





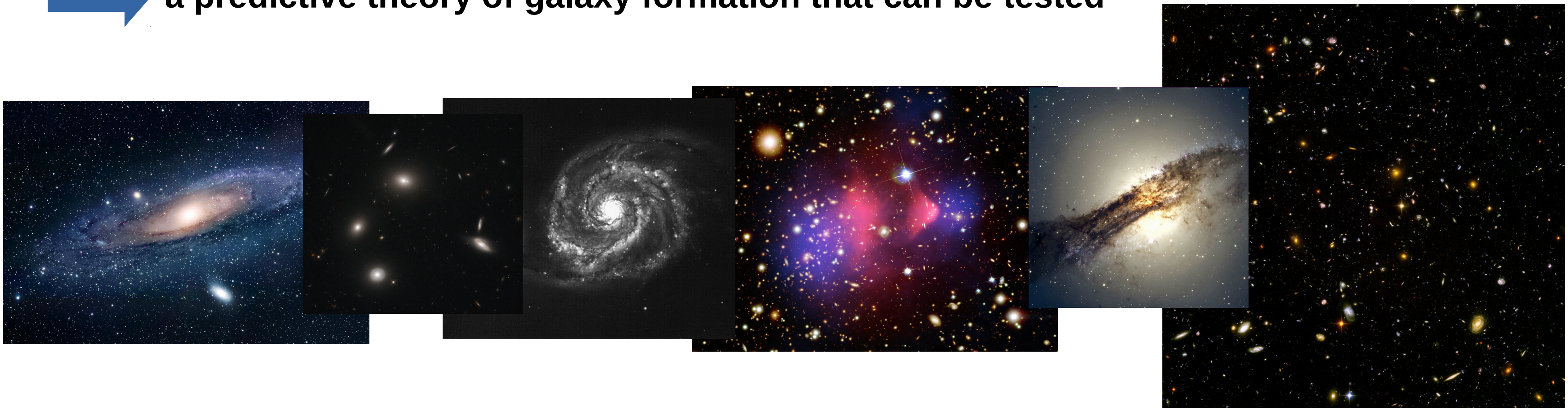
Cosmology 2018
October 2018, Dubrovnik

Introduction:

The Galaxy Formation Problem

Galaxy Formation Simulations: What is the goal?

➡ **a predictive theory of galaxy formation that can be tested**



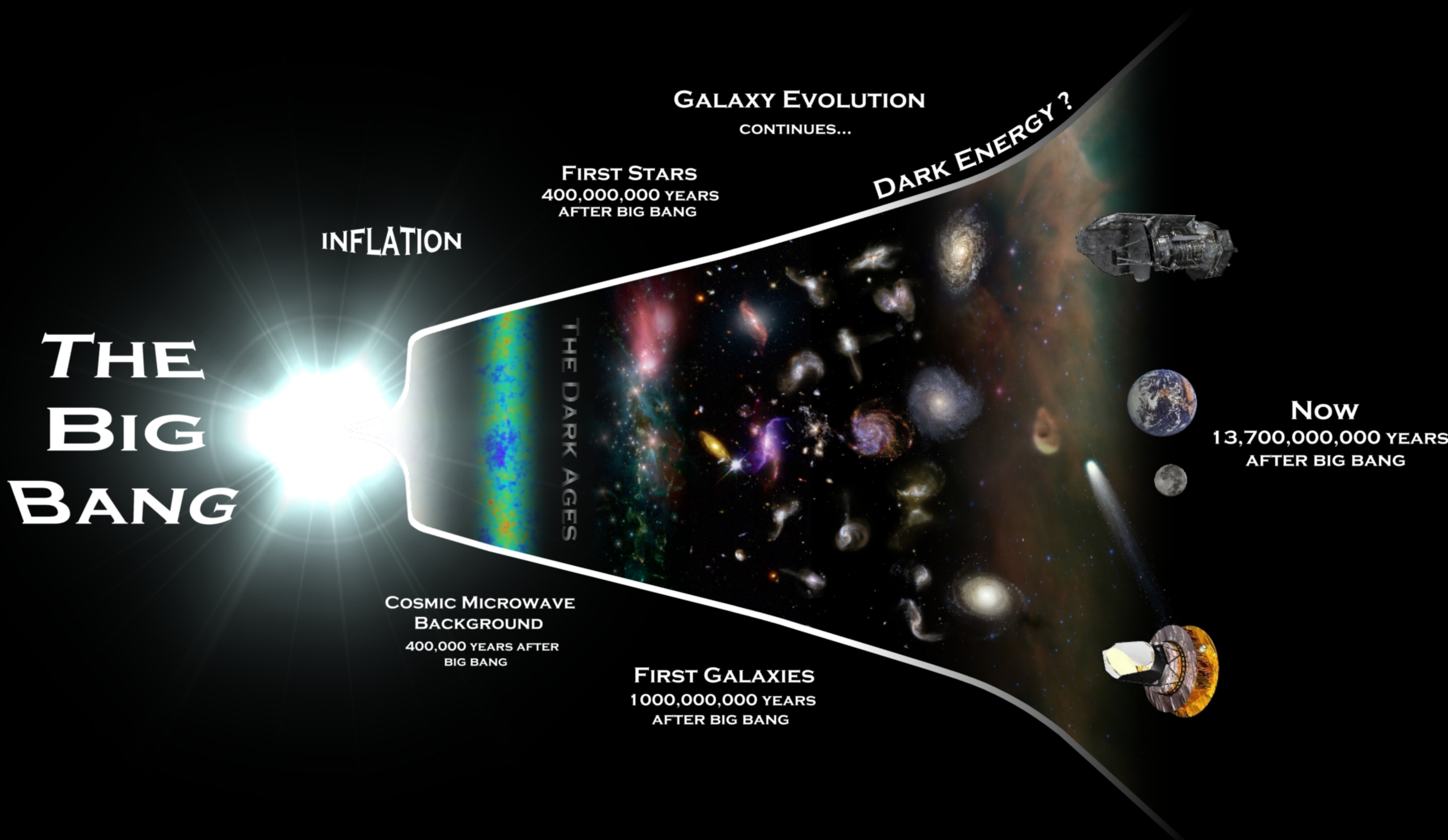
How?

complexity of the problem requires cosmological simulations:

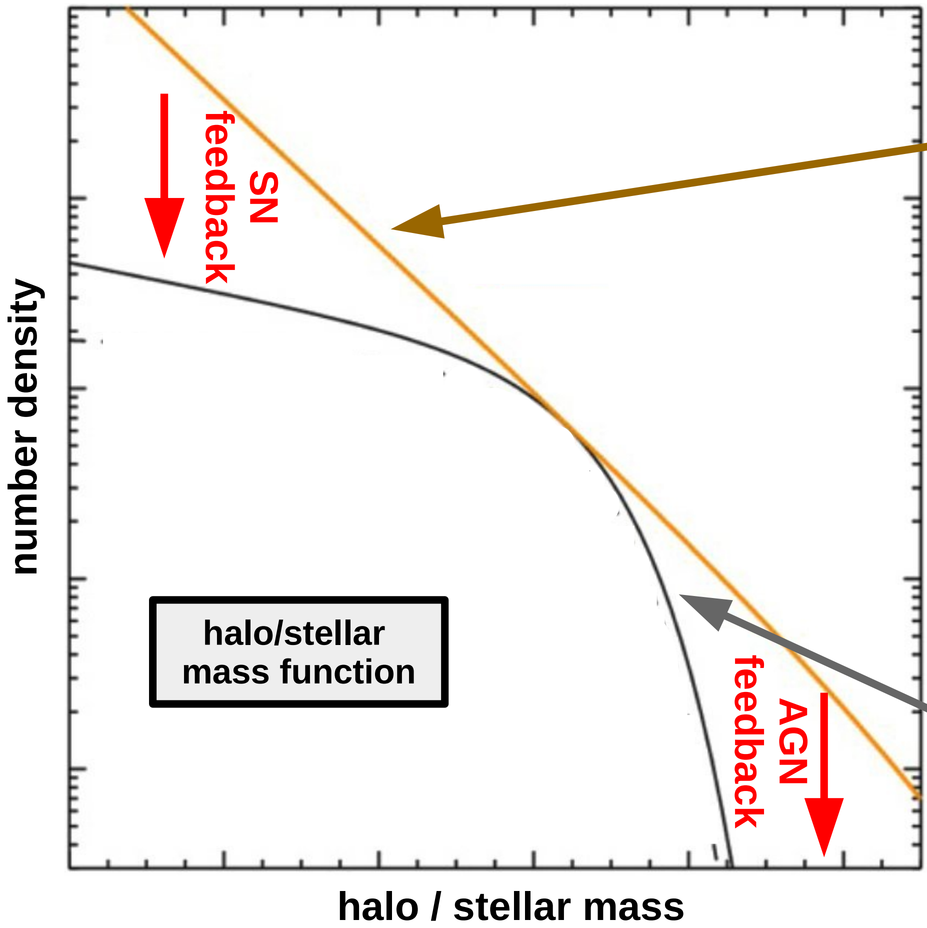
- **model dark matter, dark energy, and baryon physics**
- **include physical processes that impact galaxy formation**
- **use accurate and efficient numerical methods**
- **simulate statistically significant volume at high numerical resolution**
- **create mock observations to compare in detail with observational data**

The Framework

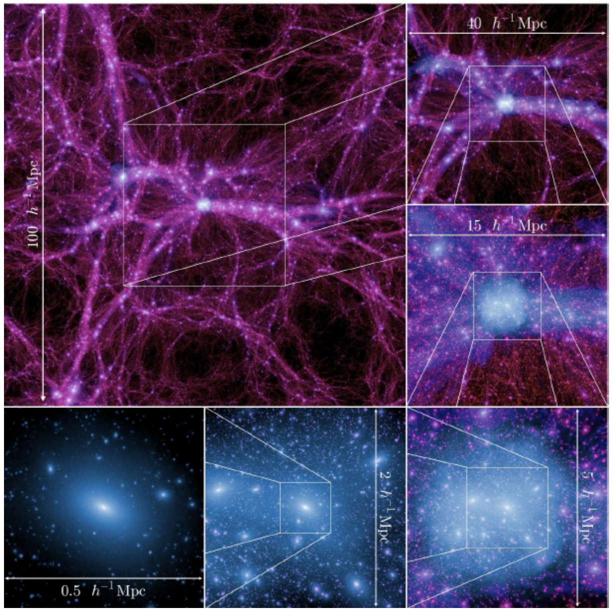
initial conditions → solve the equations of galaxy formation physics → **virtual universe**



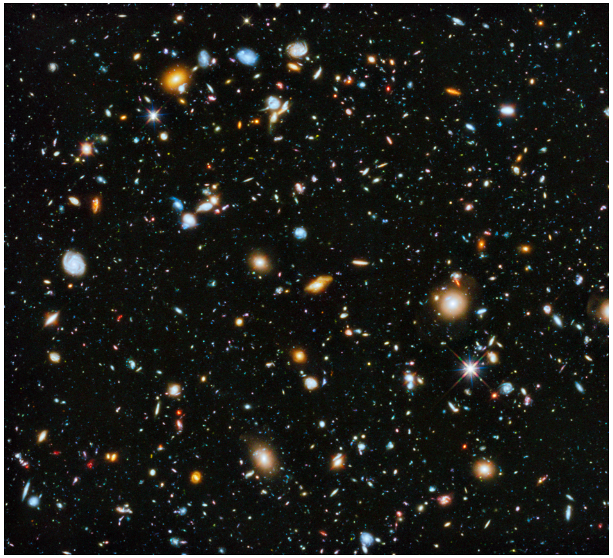
The Galaxy Formation Problem



Dark Matter: backbone of galaxy formation

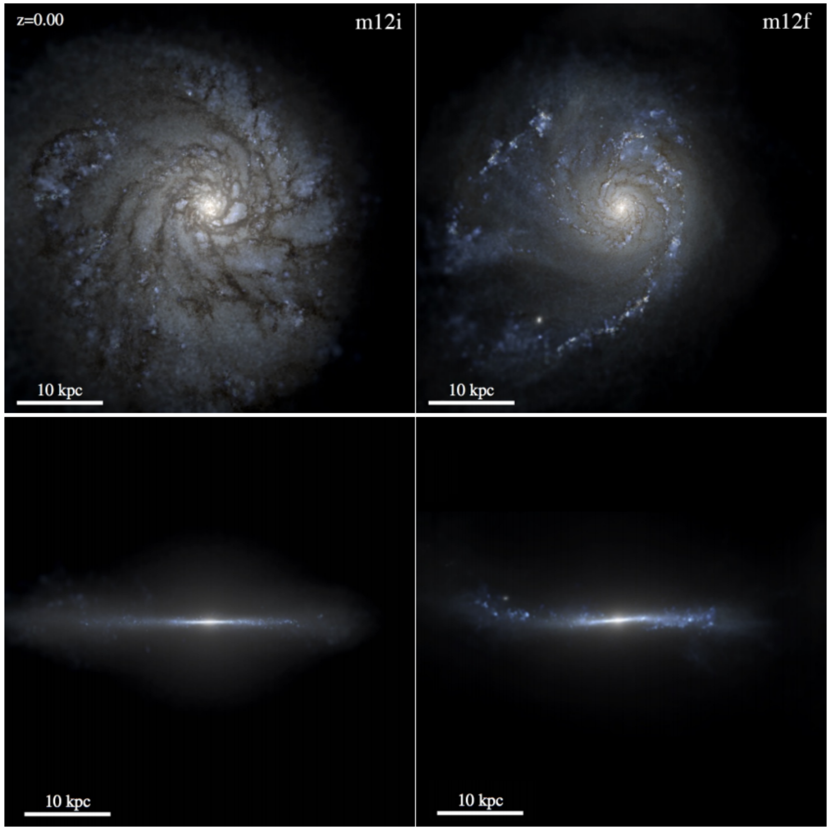


Galaxy Population



Two Approaches: Bottom-Up vs. Top-Down

Bottom-Up:



model *small* scales: approach *large* scales

+:

more detailed modeling of physical processes

--:

limited statistics to confront with observations

e.g., ERIS, FIRE, AURIGA, NIHAO, SILCC, APOSTLE, E-MOSAICS, FOGGIE, HESTIA

Top-Down:

model *large* scales: approach *small* scales

+:

lots of statistics to compare with data

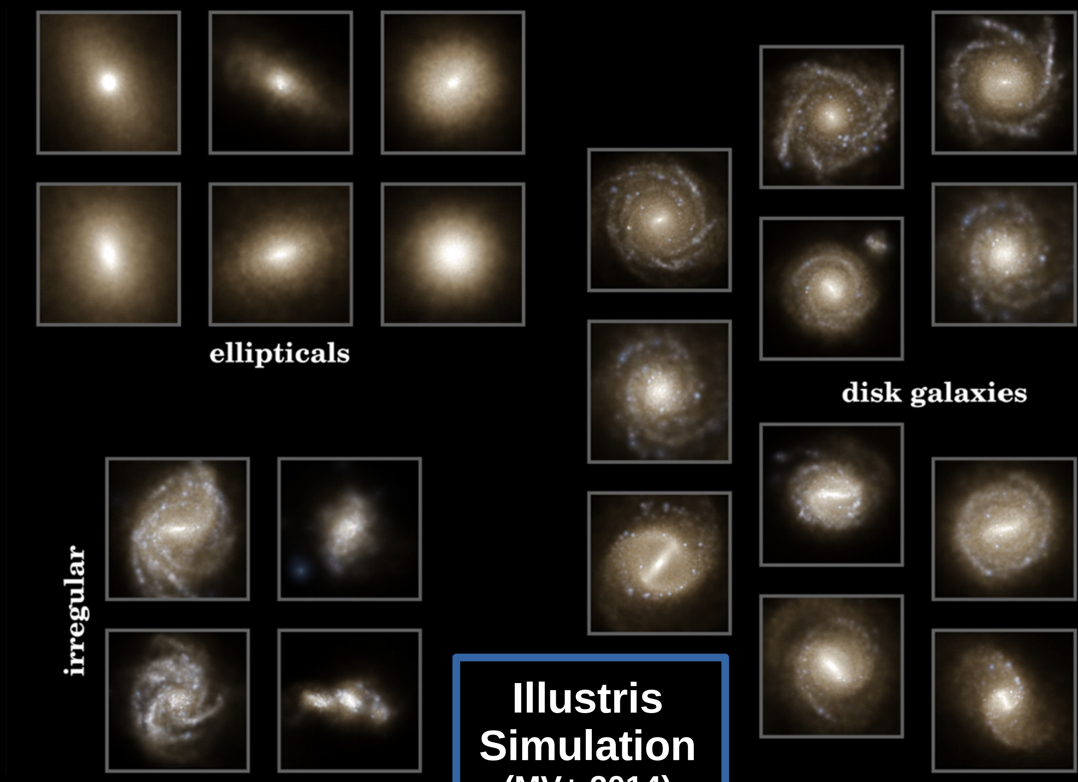
--:

rely on rather crude sub-resolution models

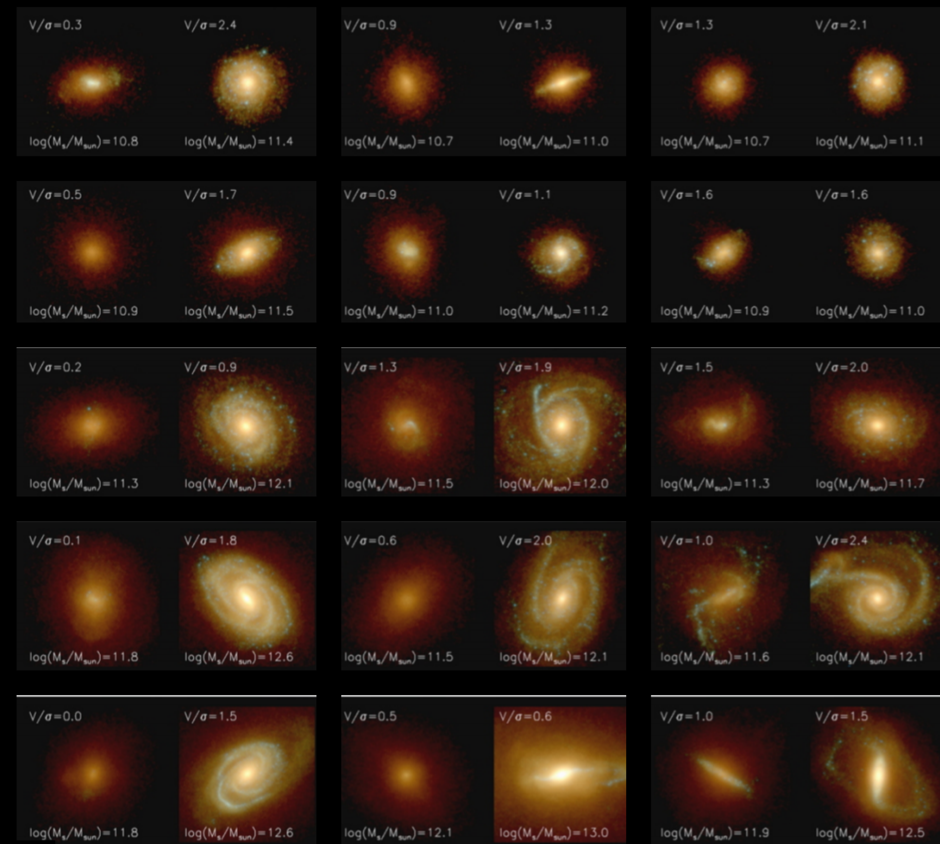
e.g., OWLS, ILLUSTRIS, EAGLE, HORIZON-AGN, MAGICC, MUFASA, MAGNETICUM, ILLUSTRIS-TNG, SIMBA

The Era Of Large-Scale Galaxy Formation Simulations:

The Illustris Simulation Project

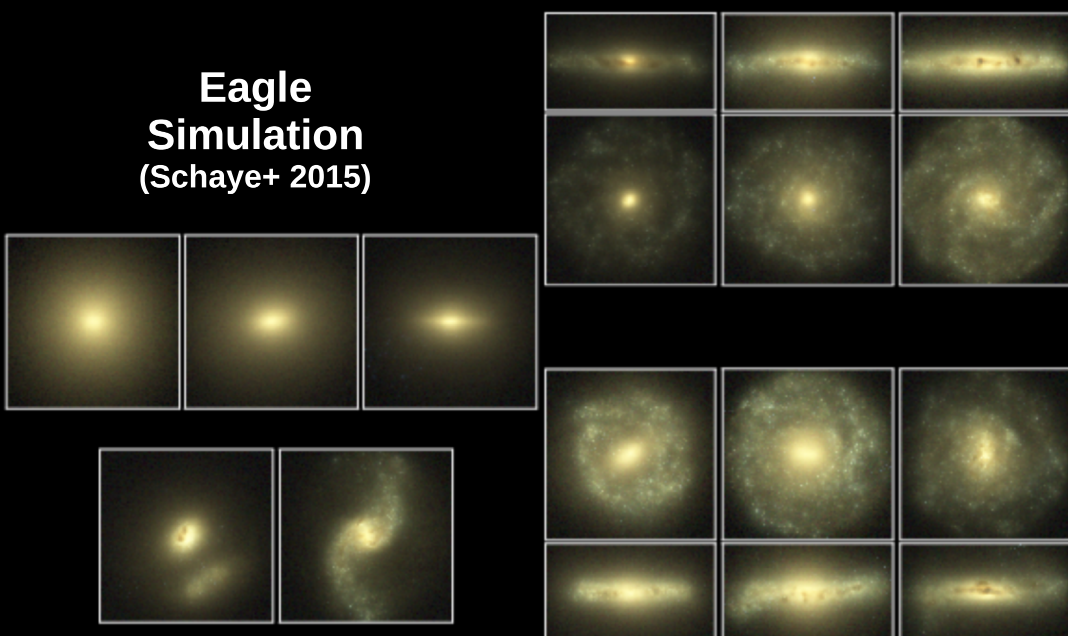


Illustris Simulation
(MV+ 2014)



Horizon-AGN Simulation
(Dubois+ 2016)

Eagle Simulation
(Schaye+ 2015)



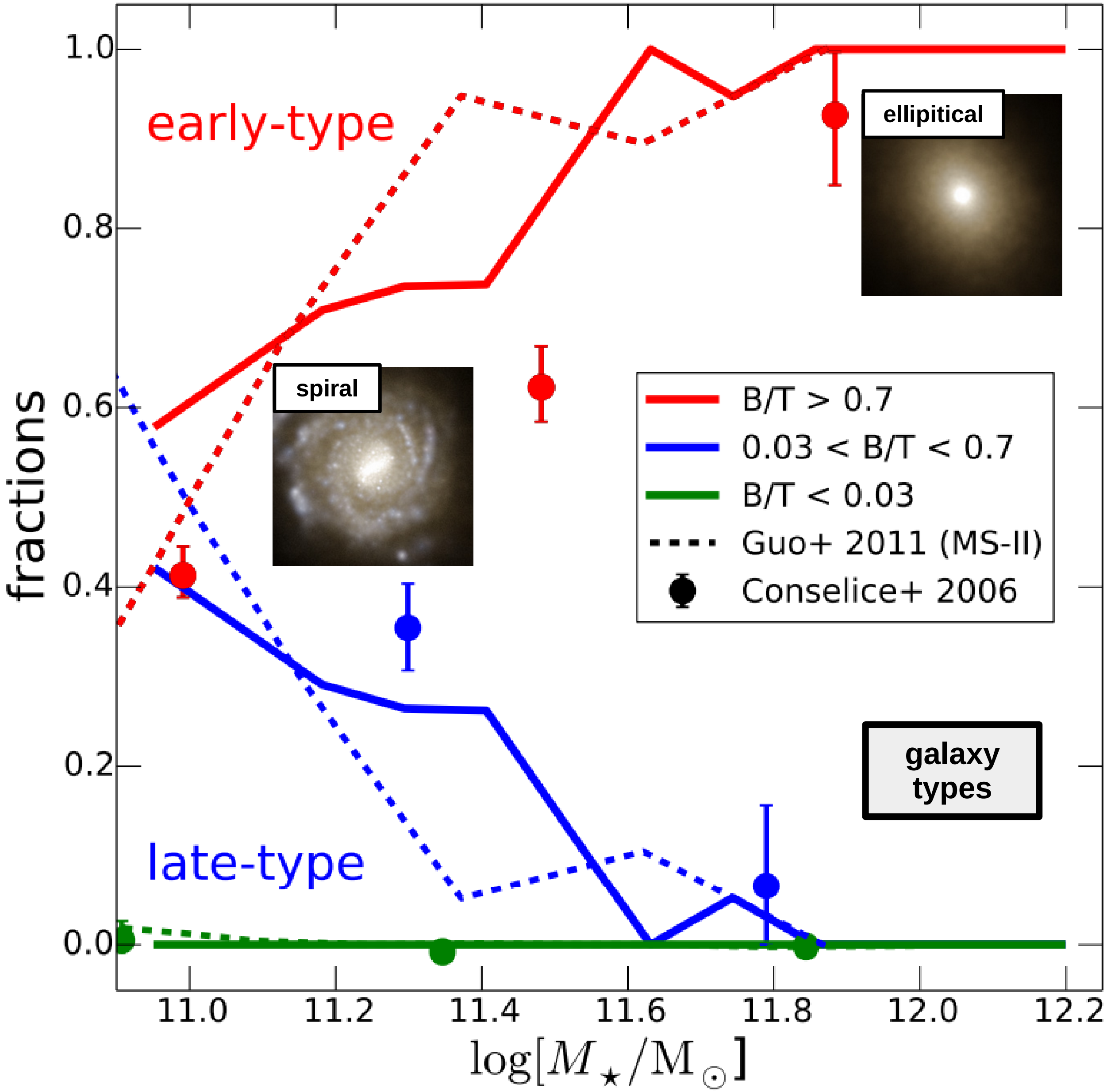
The Era of Large-Scale Full Volume Galaxy Formation Simulations

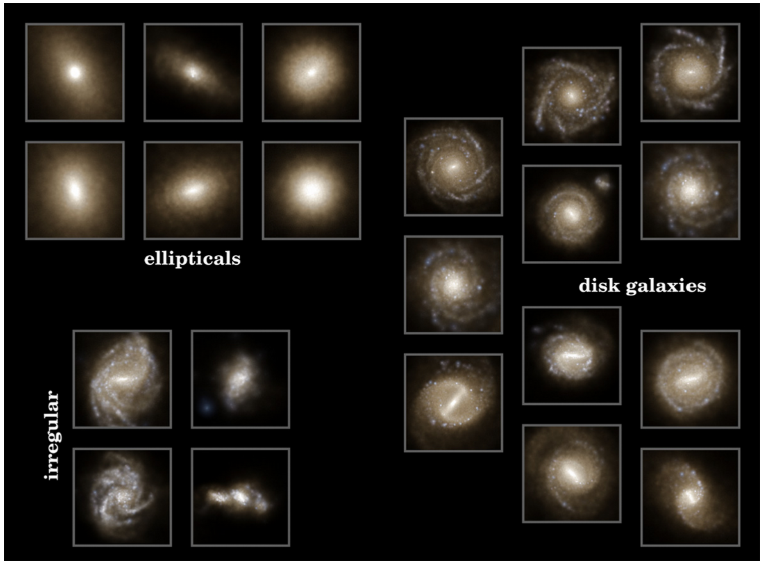
Mock Observations

HST | Illustris Simulation

MV+ 2014 (Nature)

Key Result: Galaxy Diversity





simulations predict the observed fractions of different galaxy types

MV+ 2014 (Nature)

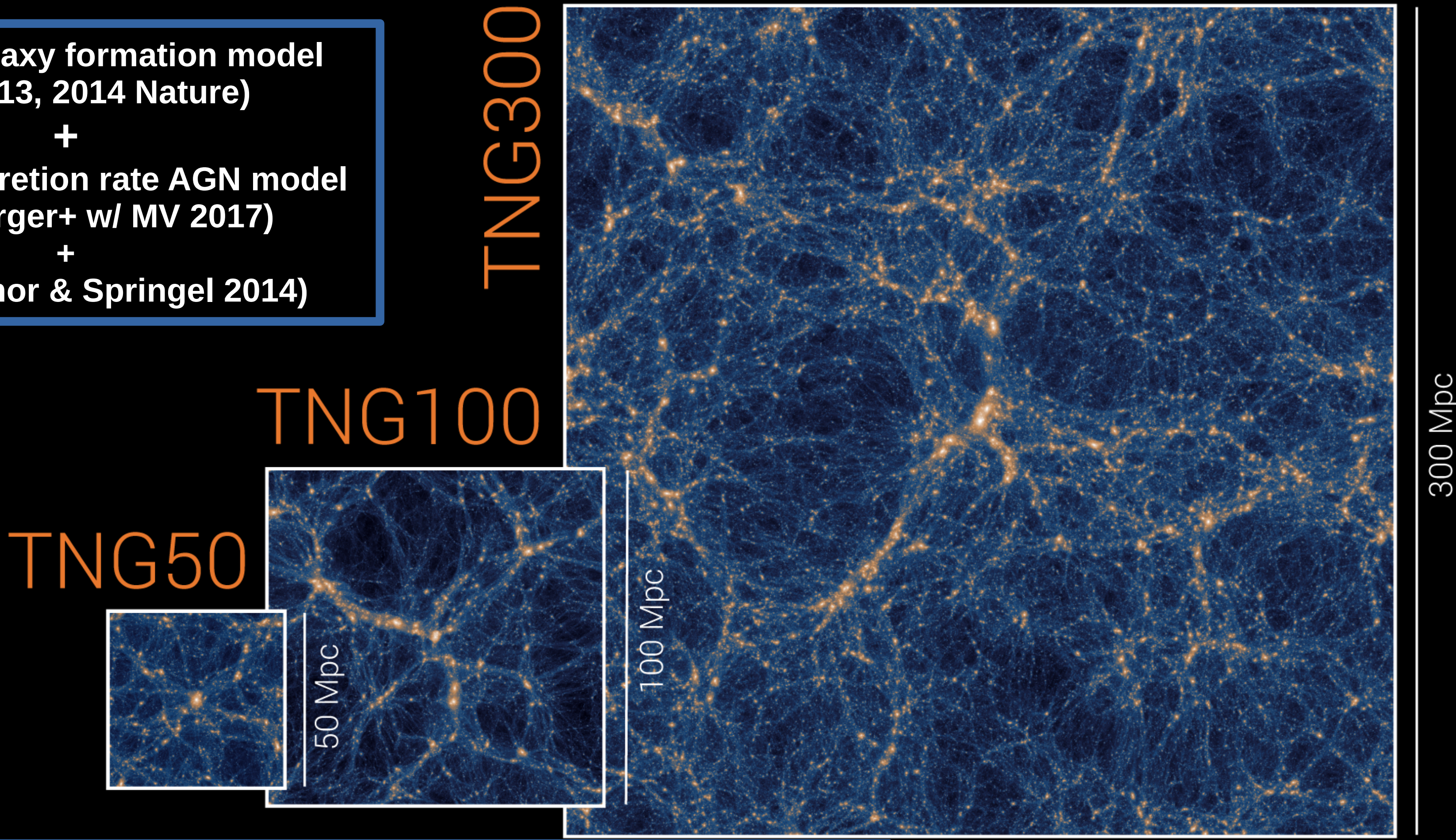
From Illustris To IllustrisTNG:

Refining The Galaxy Formation Model
+
Increasing The Dynamic Range

The IllustrisTNG Simulations

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

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

Vogelsberger, Marinacci, Torrey
(MIT)

Genel
(CCA)

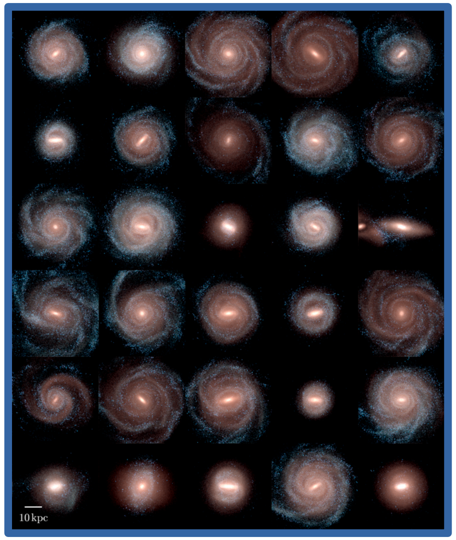
Pillepich
(MPIA)

Hernquist, Naimann
(CfA)

IllustrisTNG Team

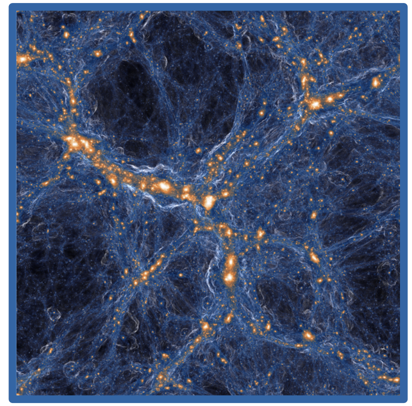
Illustris Project Galaxy Formation Model Family

Auriga



Grand+ 2017

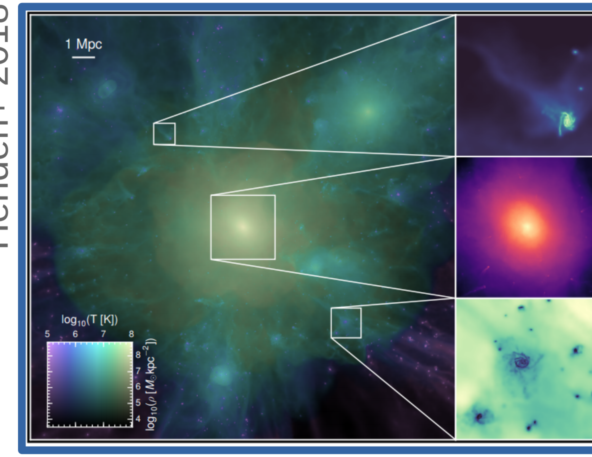
IllustrisTNG



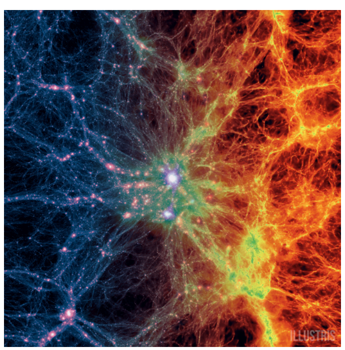
Nelson+ 2018

Fable

Henden+ 2018



Illustris Galaxy Formation Model



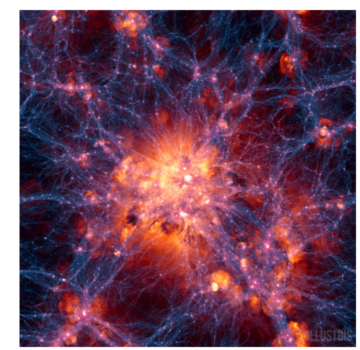
ILLUSTRIS

Vogelsberger+ (2014a)
Introduction

Vogelsberger+ (2014b)
Galaxies at z=0

Genel+ (2014)
High-z galaxies

Sijacki+ (2015)
Black holes



Genel+ (2013)
Monte Carlo tracer particles

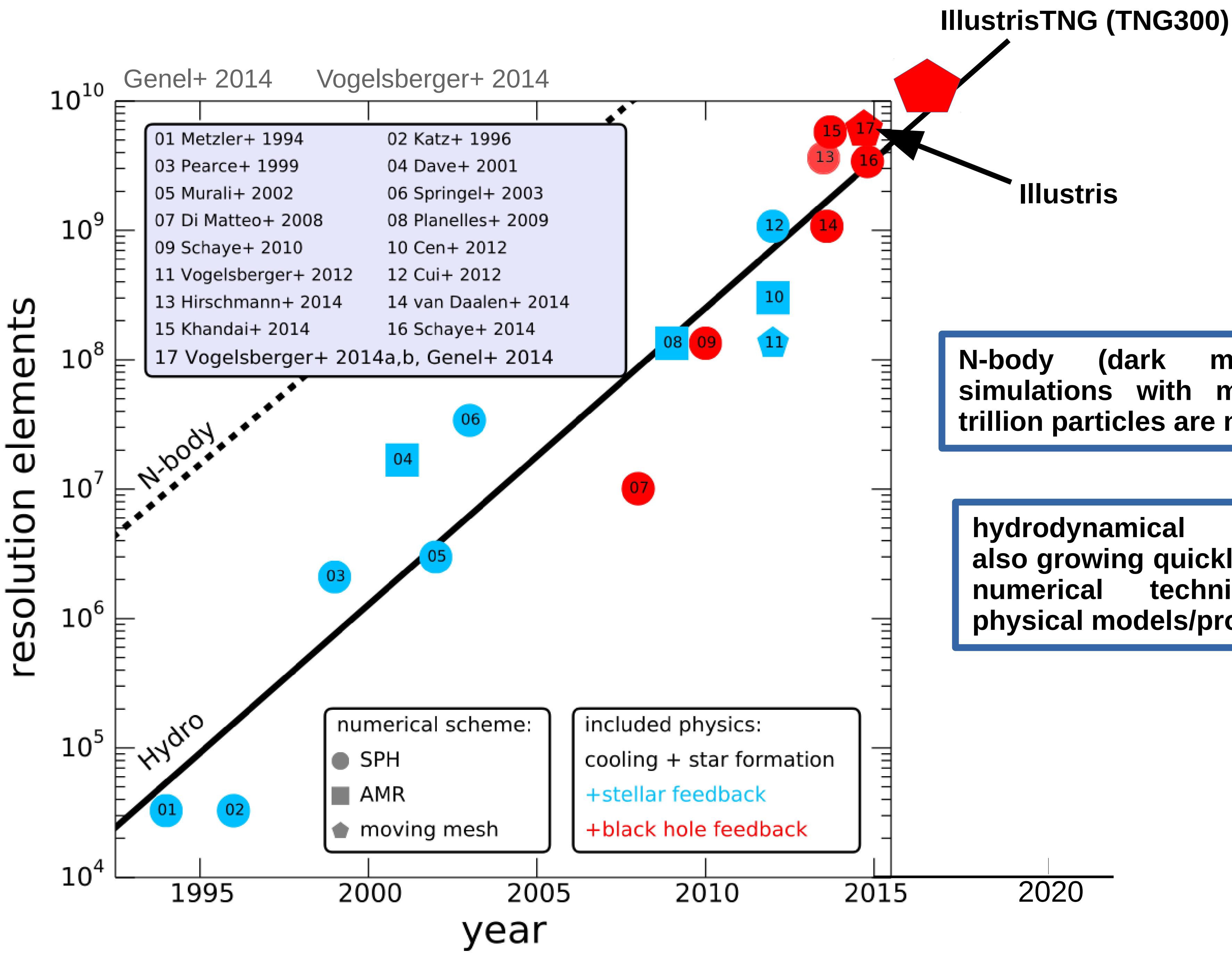
Vogelsberger+ (2013)
Illustris physics model descriptions

Torrey+ (2014a)
Illustris physics models vs. observations

Vogelsberger+ (2012) Sijacki+ (2012) Keres+ (2012) Torrey+ (2012) Nelson+ (2013) Bird+ (2013)

Moving Mesh Cosmology: the first galaxy formation simulations with the moving-mesh code Arepo

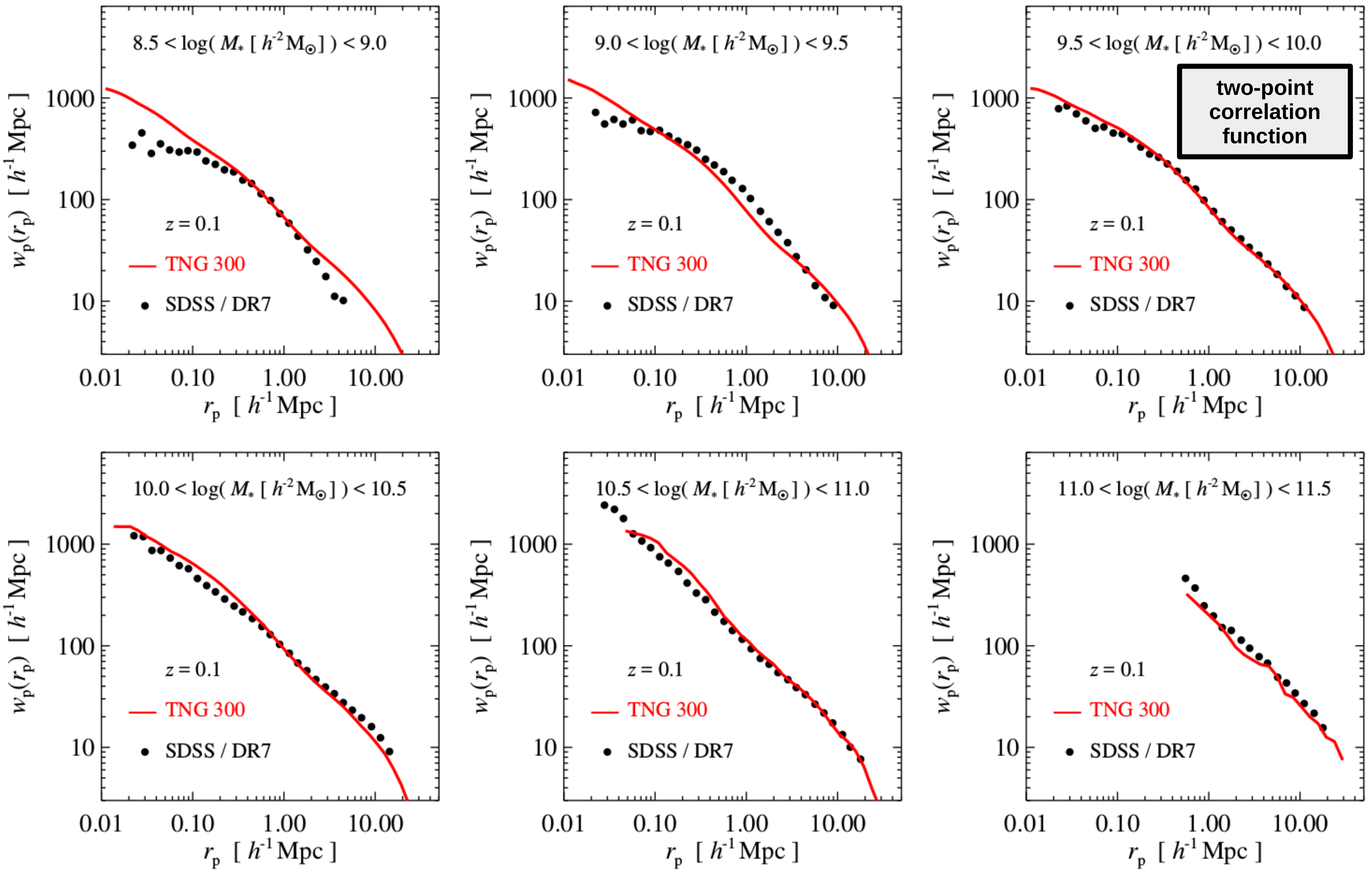
The Evolution of Large-Scale Simulations



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

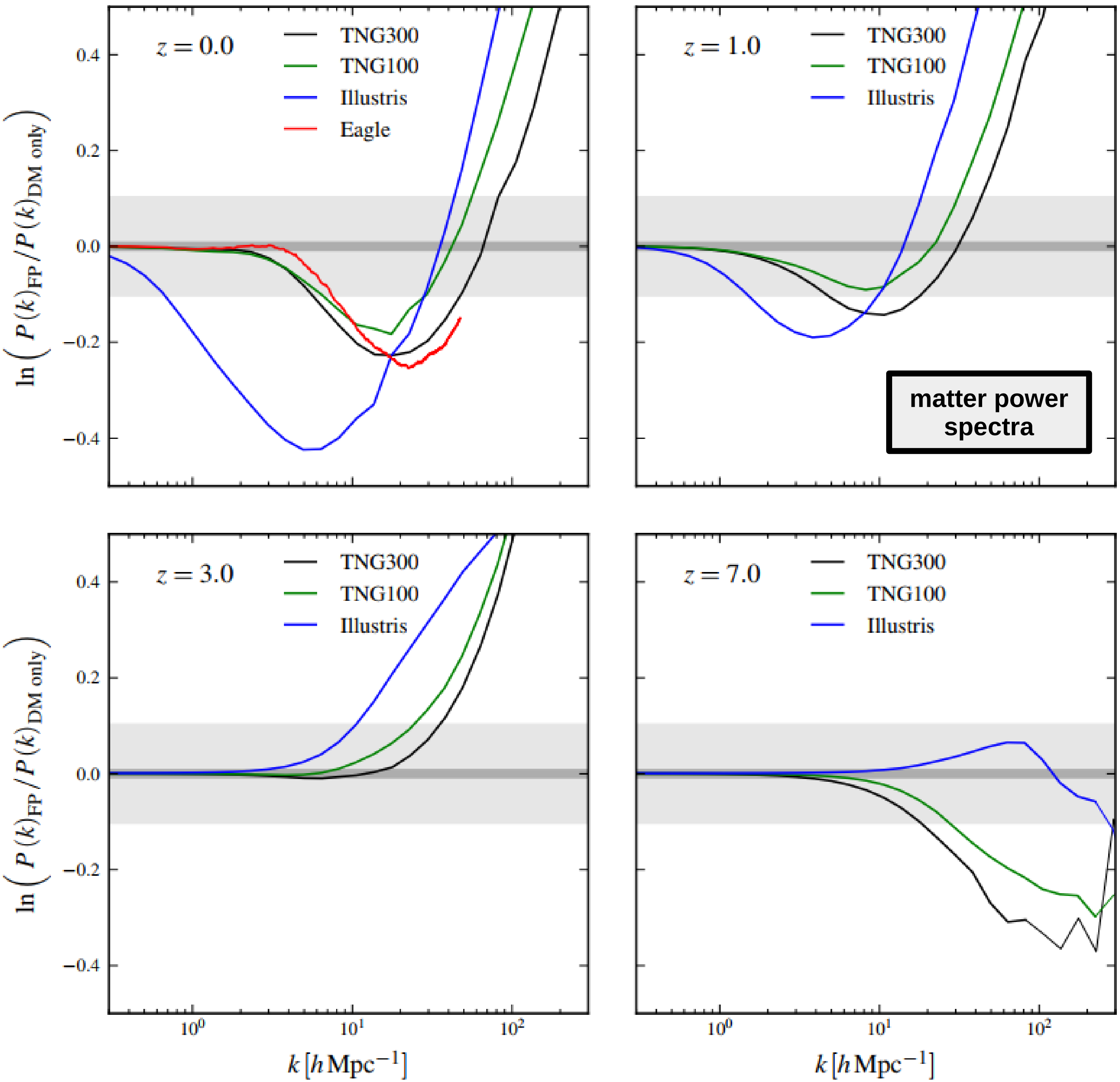
hydrodynamical simulations also growing quickly: variety of numerical techniques and physical models/processes

IllustrisTNG: Galaxy Clustering



Springel+ w/ MV 2018

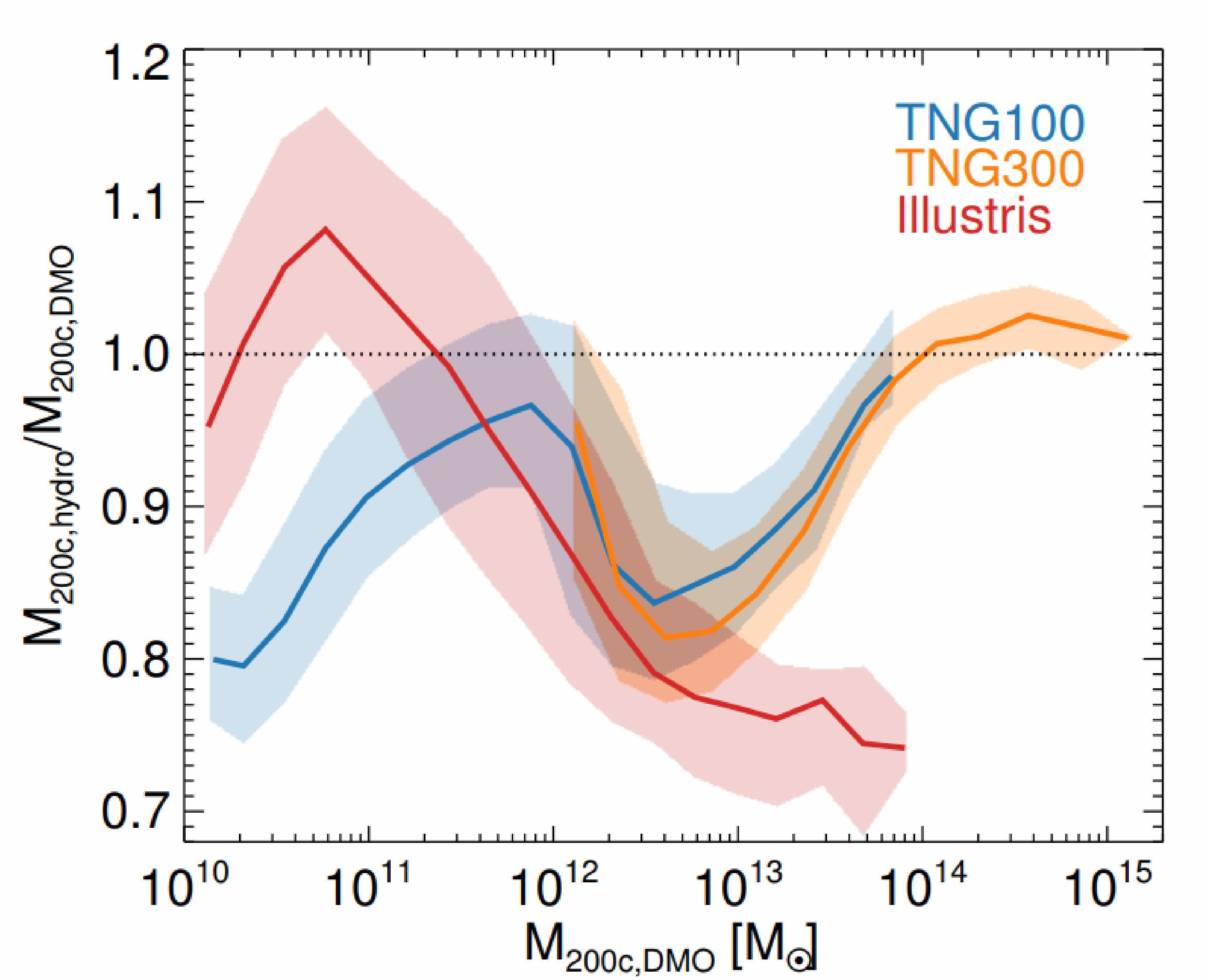
Impact of Baryons



baryon physics modifies matter power spectra

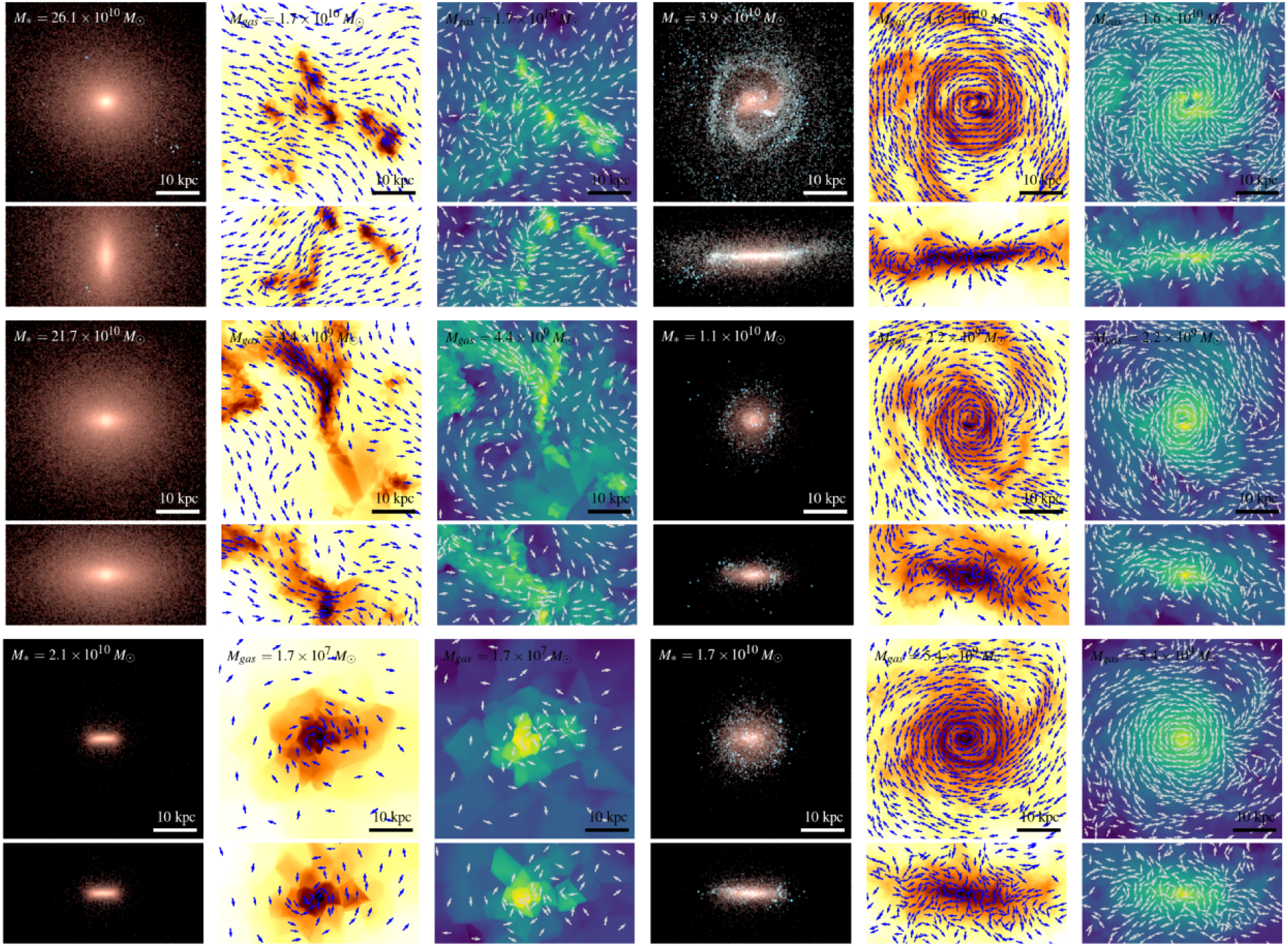
Springel+ w/ MV 2018

Impact of Baryons



Lovell+ w/ MV 2018

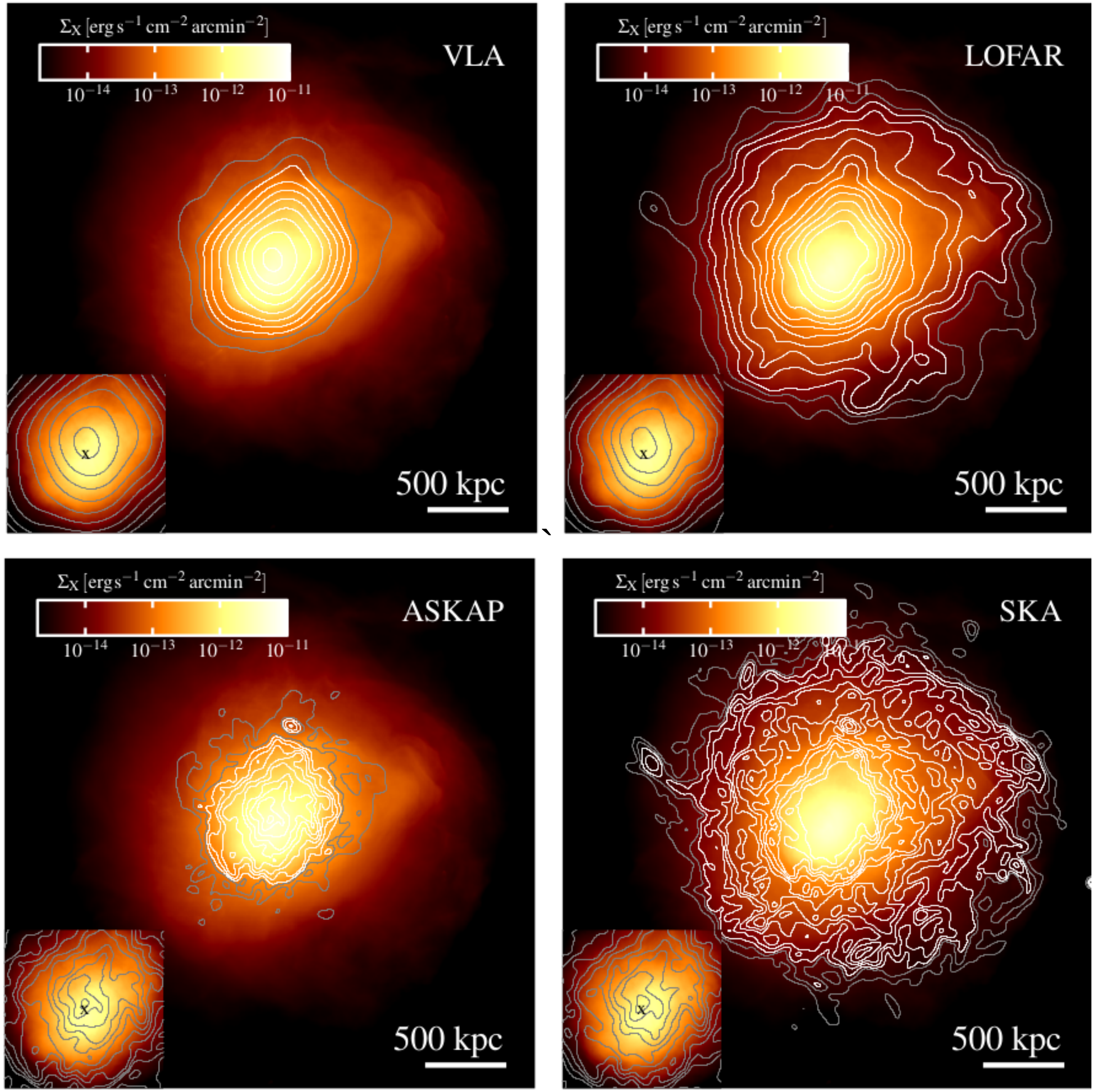
Topology of Magnetic Fields



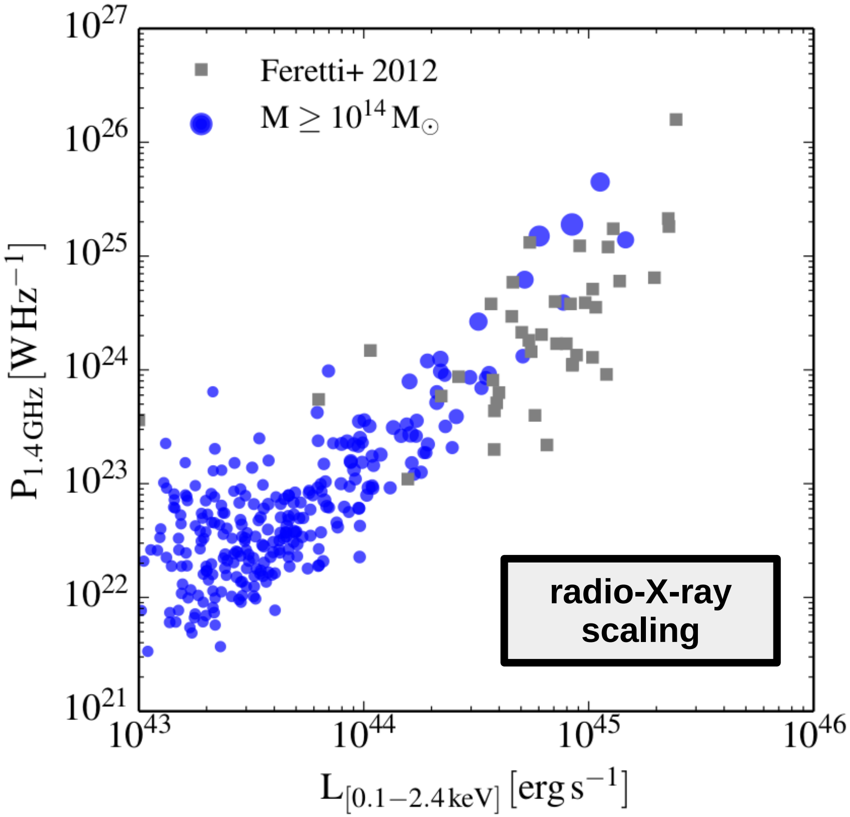
Marinacci, MV+ 2018

elliptical galaxies **disk galaxies**

Modeling Radio Halos



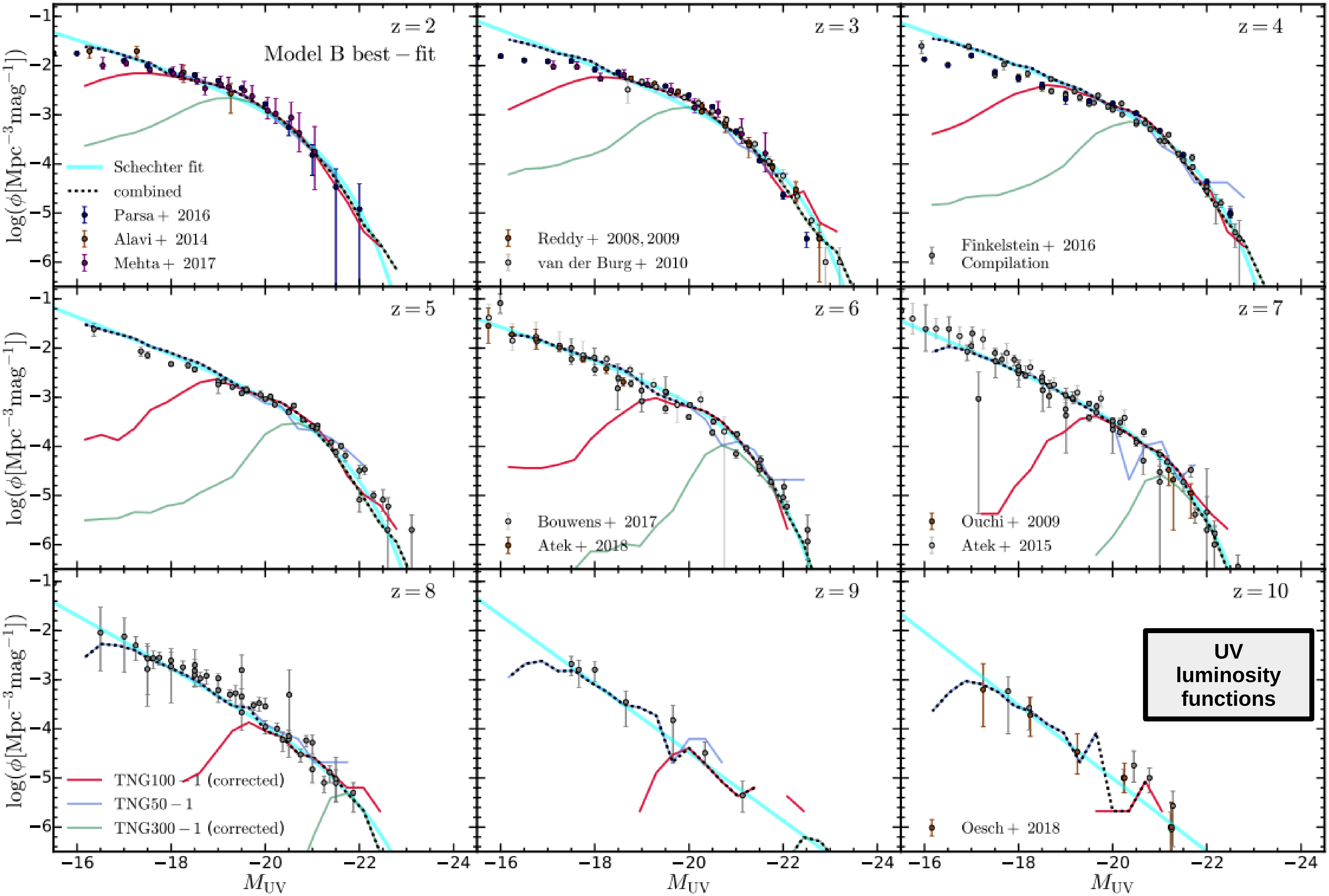
radio emission provides a probe of magnetic field strength



radio-X-ray scaling

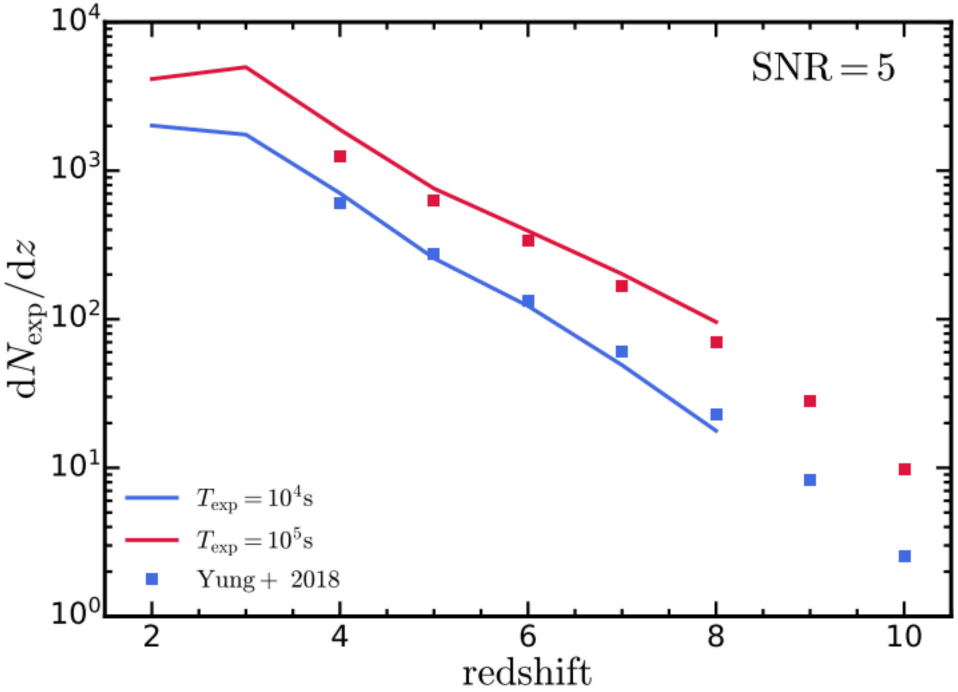
Marinacci, MV+ 2018

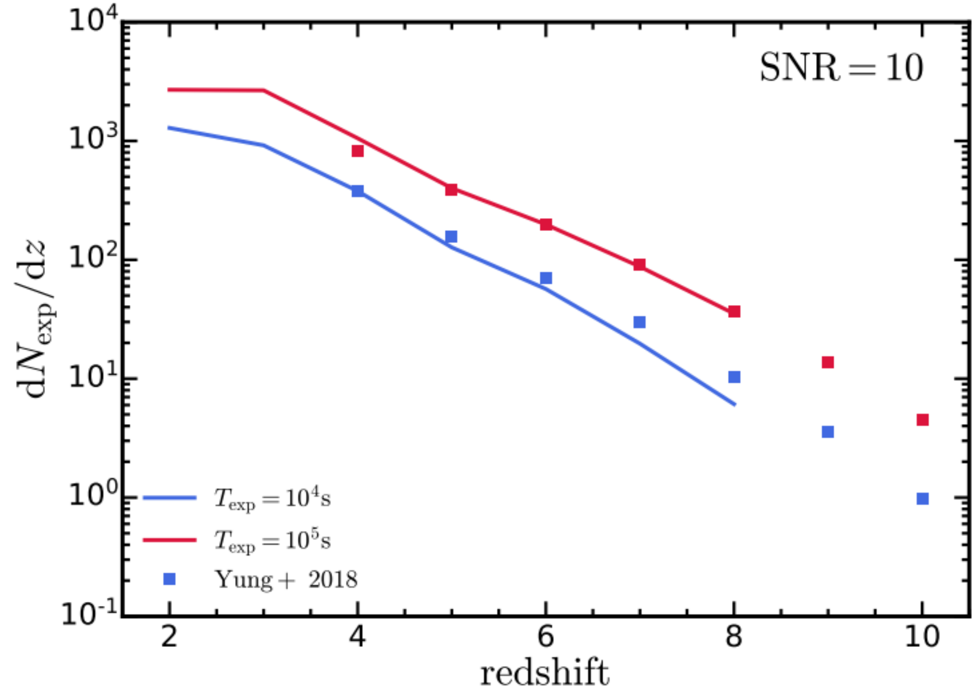
TNG50 + TNG100 + TNG300: Predictions for the *JWST* Era



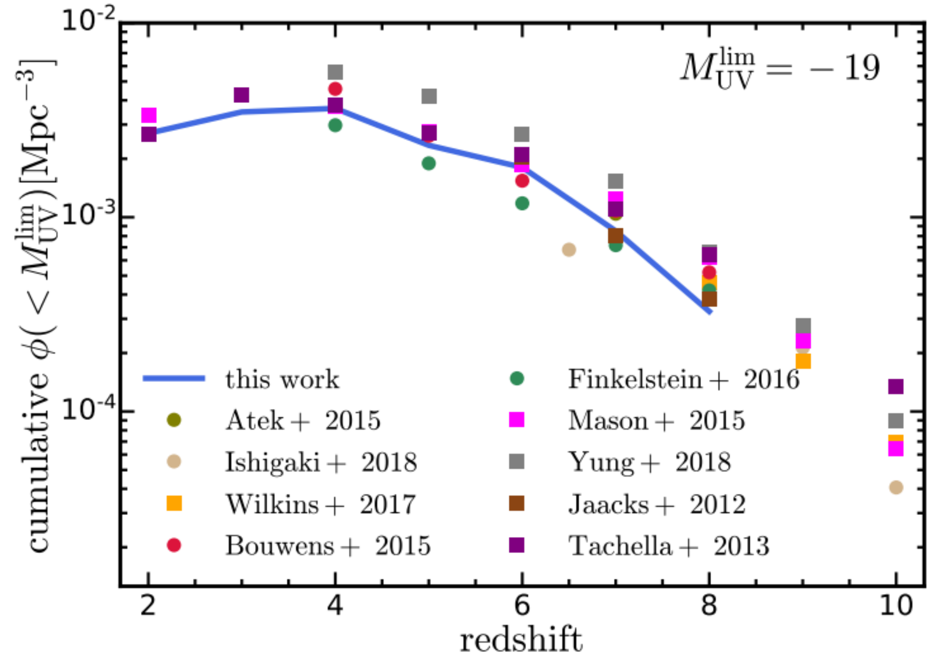
MV+ (in prep) - *preliminary*

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





expected number of galaxies in F200W band in *JWST* NIRCam field of view for different exposure times and signal-to-noise ratios



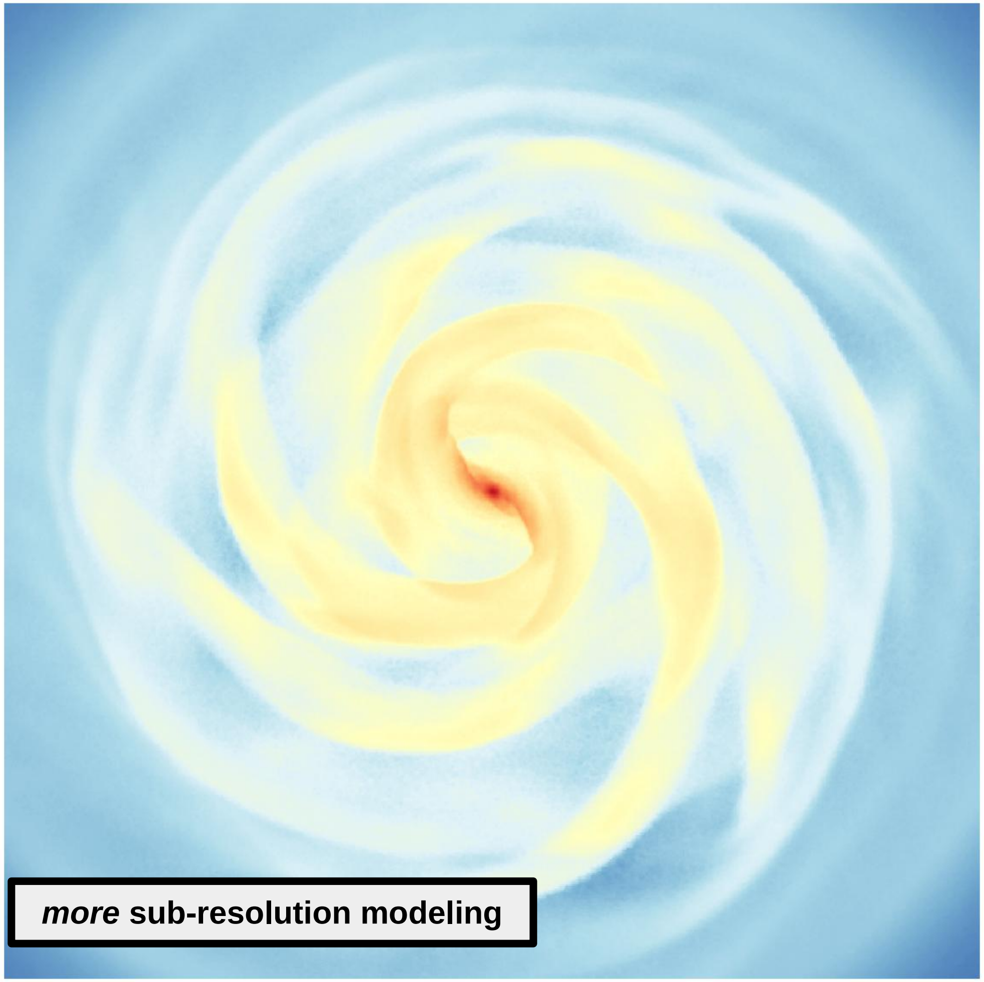
MV+ (in prep) - *preliminary*

Beyond IllustrisTNG:

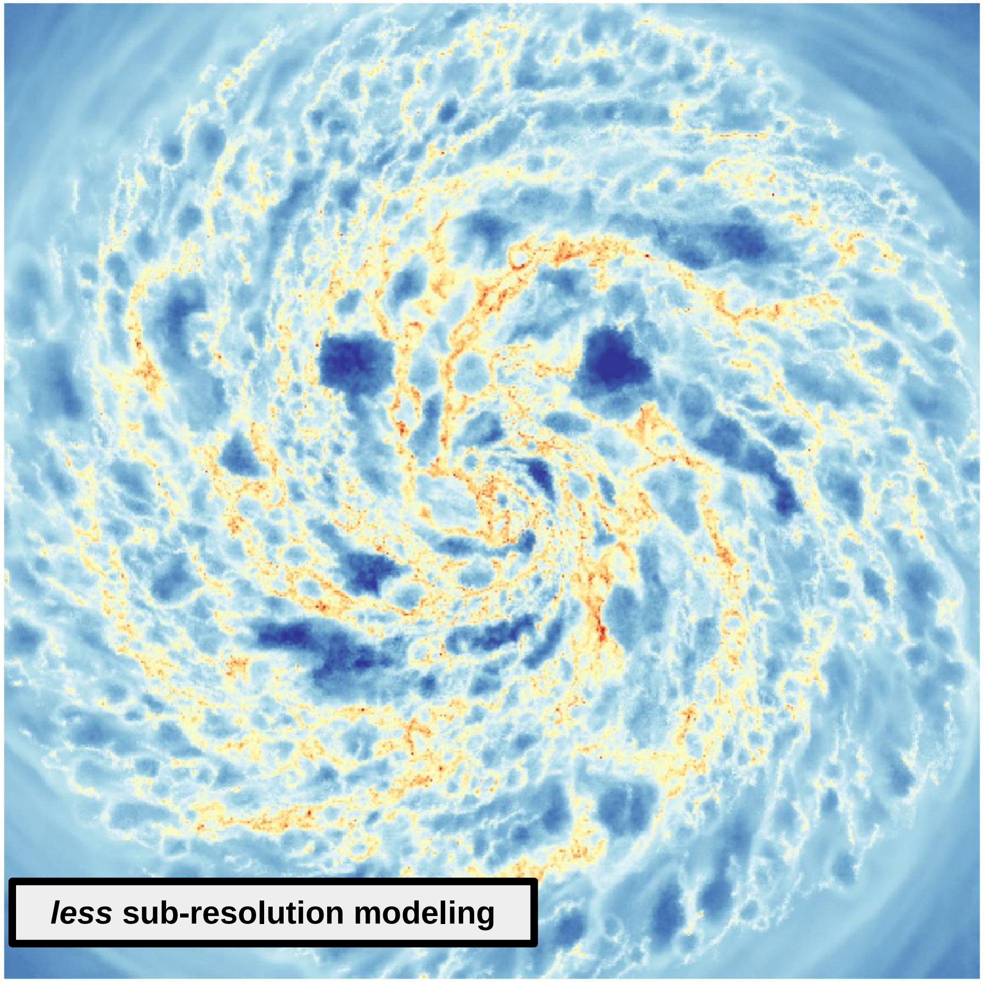
The Frontiers of Galaxy Formation Models

Improve Galaxy Formation Model

IllustrisTNG model



novel model



Why is a more explicit feedback model important?

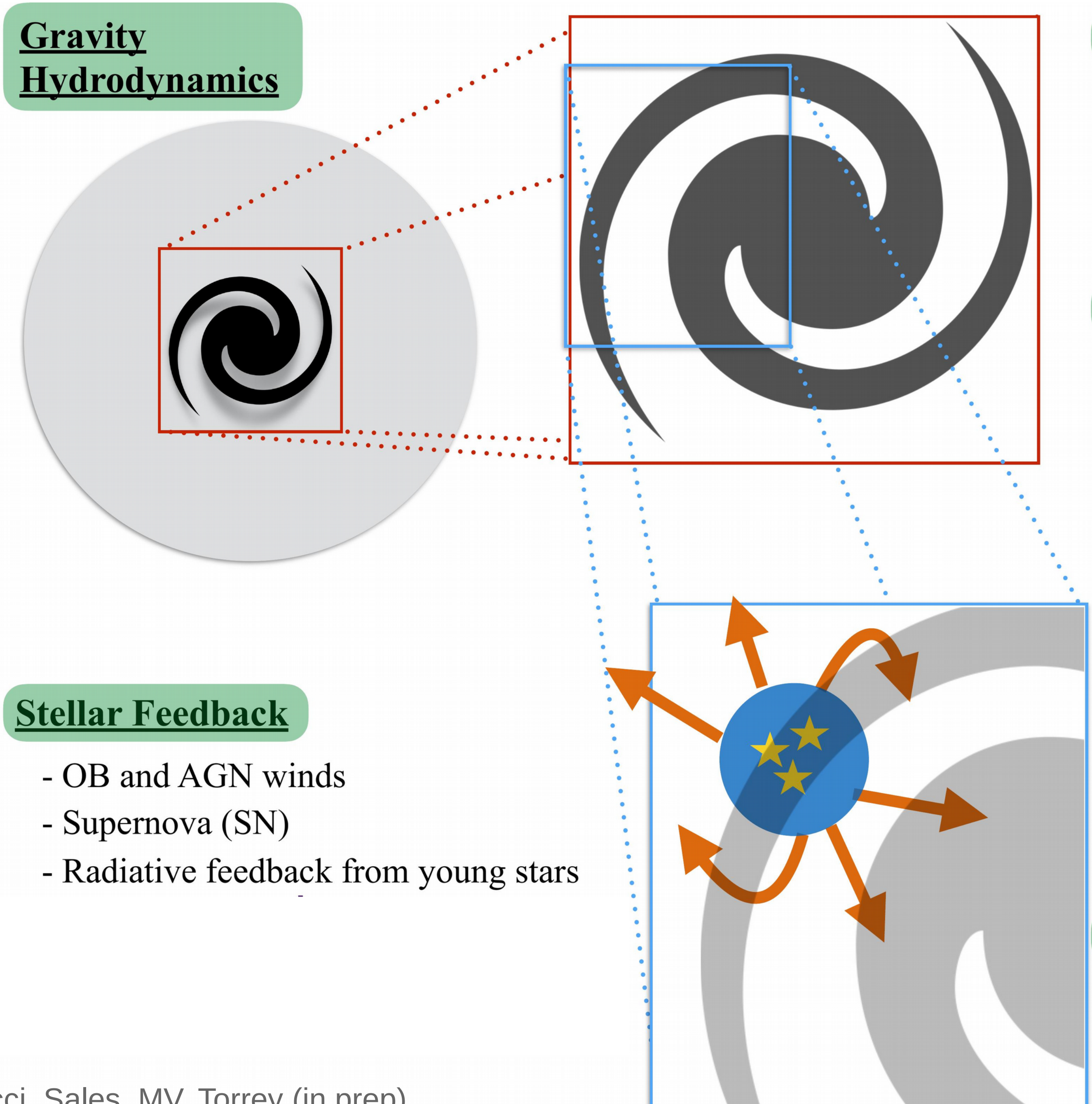
- requires less prescribed ad-hoc calibrations → more predictive
- match the numerical resolution of the simulation → more details

Consequences of more explicit models?

- more self-consistent descriptions of baryon processes and their interplay
- implications for baryon-dark matter interactions

Novel Explicit Galaxy Formation Model

Gravity
Hydrodynamics



Gas Cooling

- Equilibrium H + He
- Metals
- Low temperature
- Self-shielding

Gas Heating

- Cosmic rays
- Photoelectric heating

Stellar Feedback

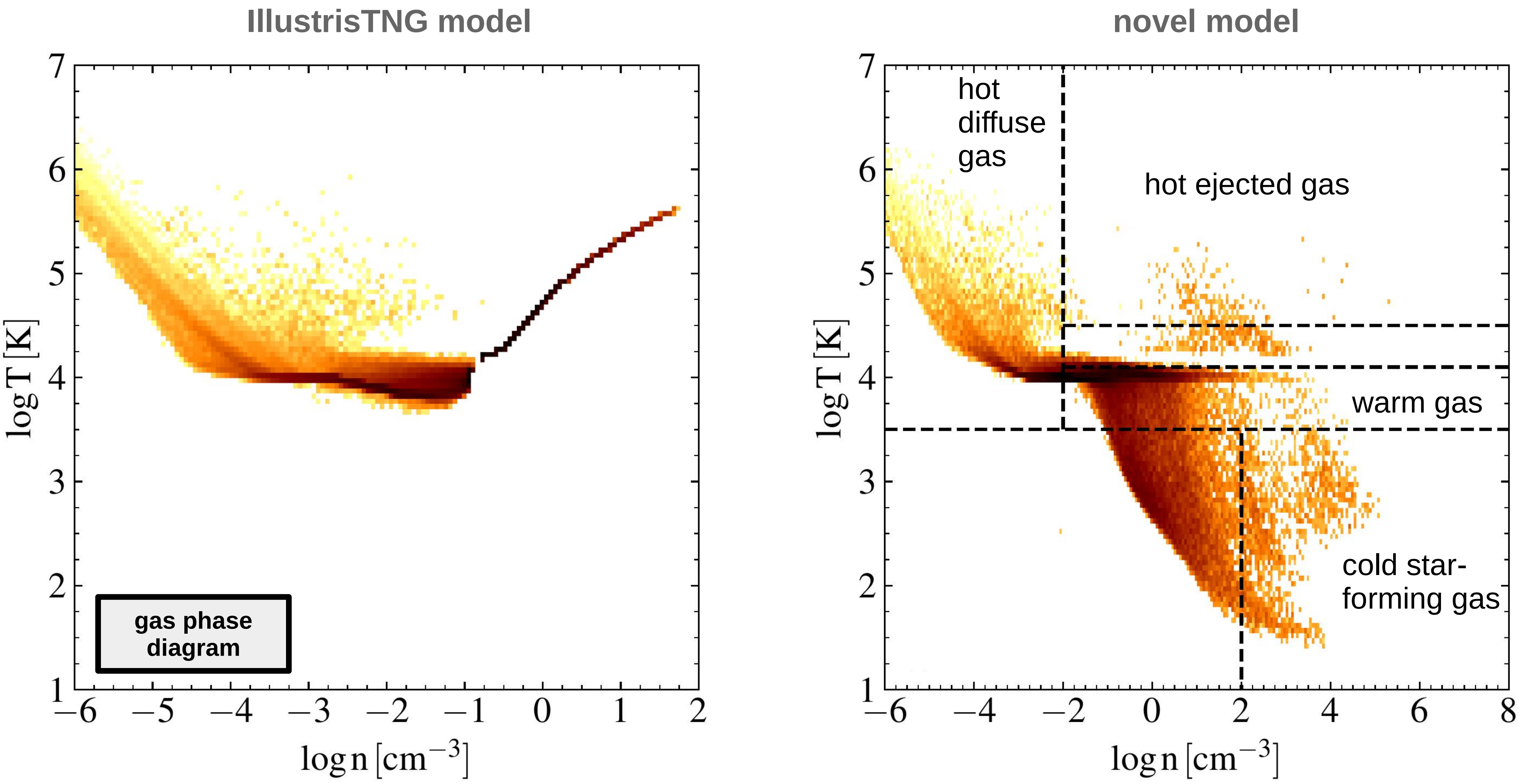
- OB and AGN winds
- Supernova (SN)
- Radiative feedback from young stars

Star Formation

- Stellar Evolution
- Metallicity
- H2-based

Marinacci, Sales, MV, Torrey (in prep)

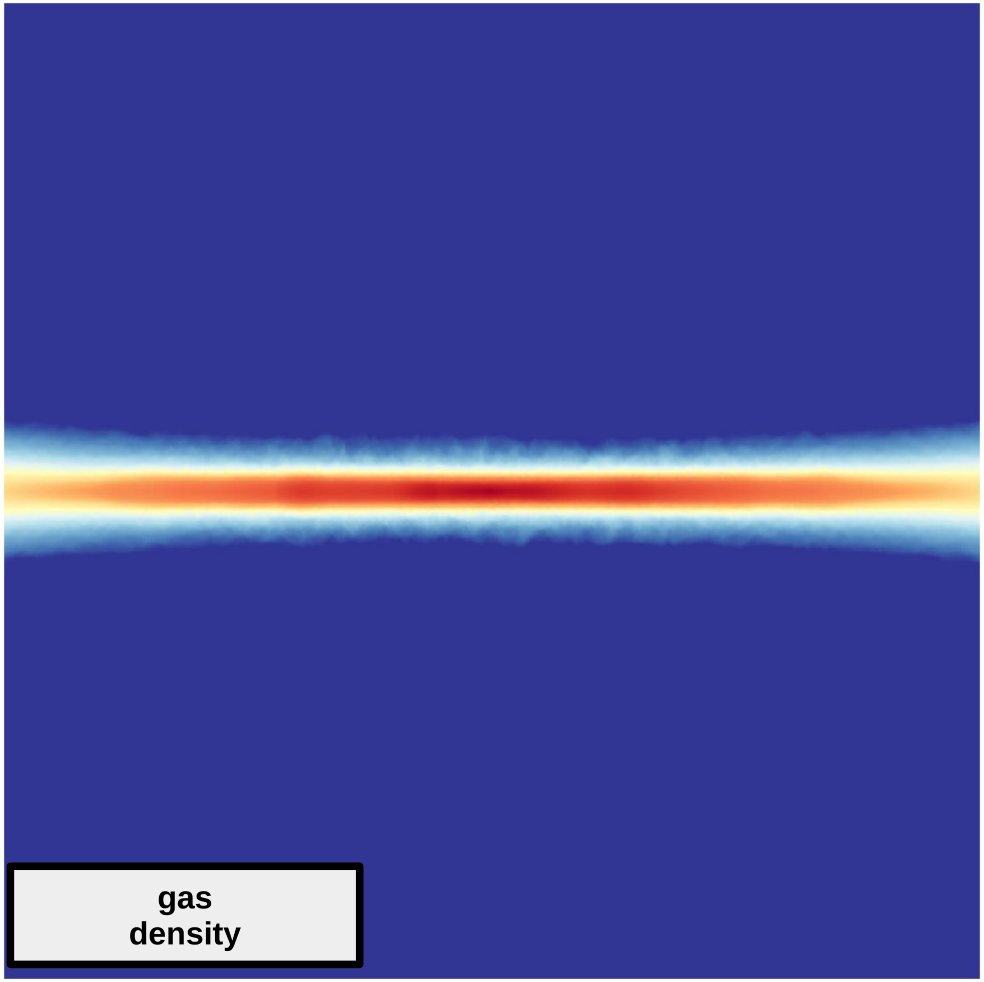
Novel Explicit Galaxy Formation Model



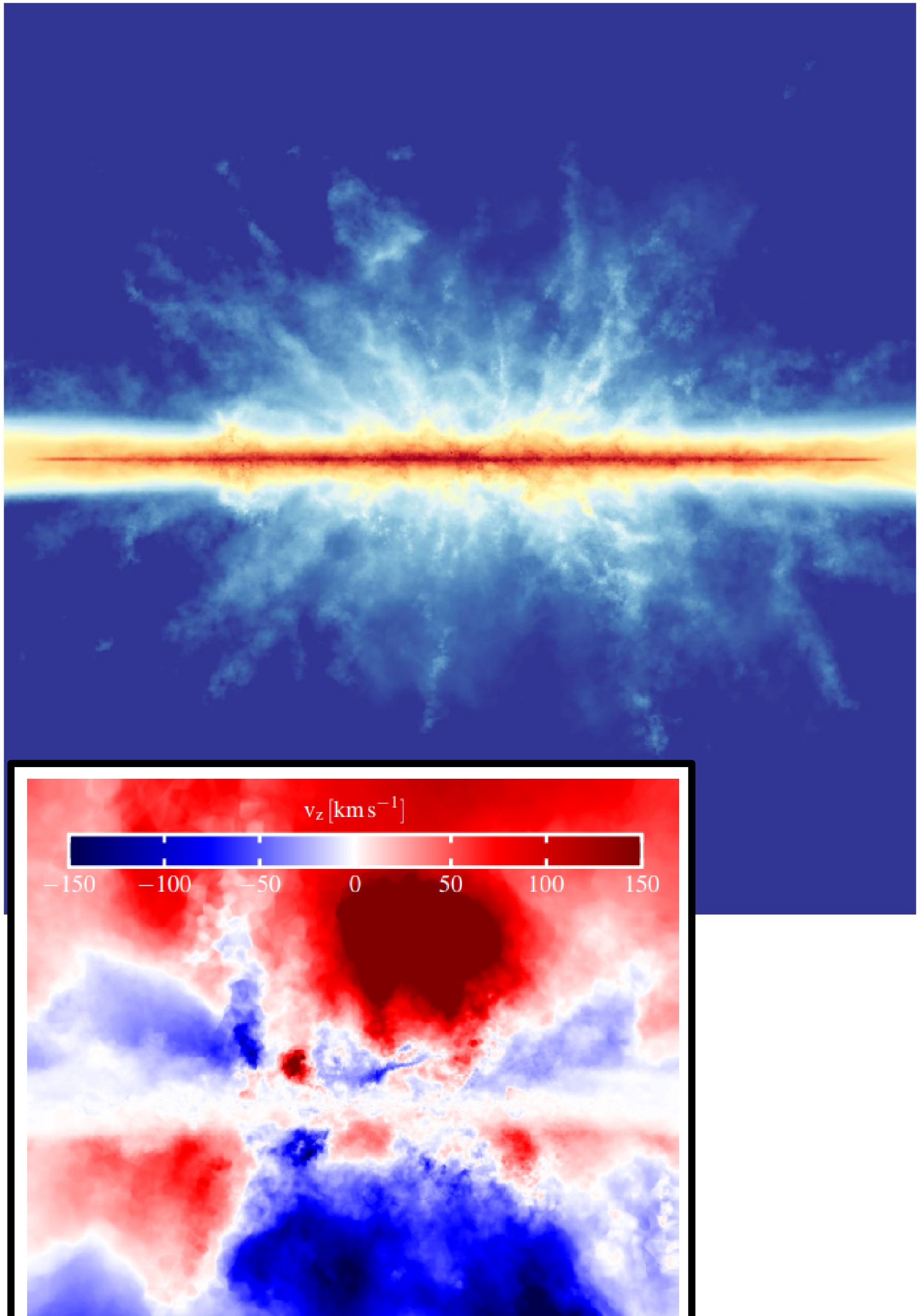
Marinacci, Sales, MV, Torrey (in prep)

Novel Explicit Galaxy Formation Model

IllustrisTNG model



novel model

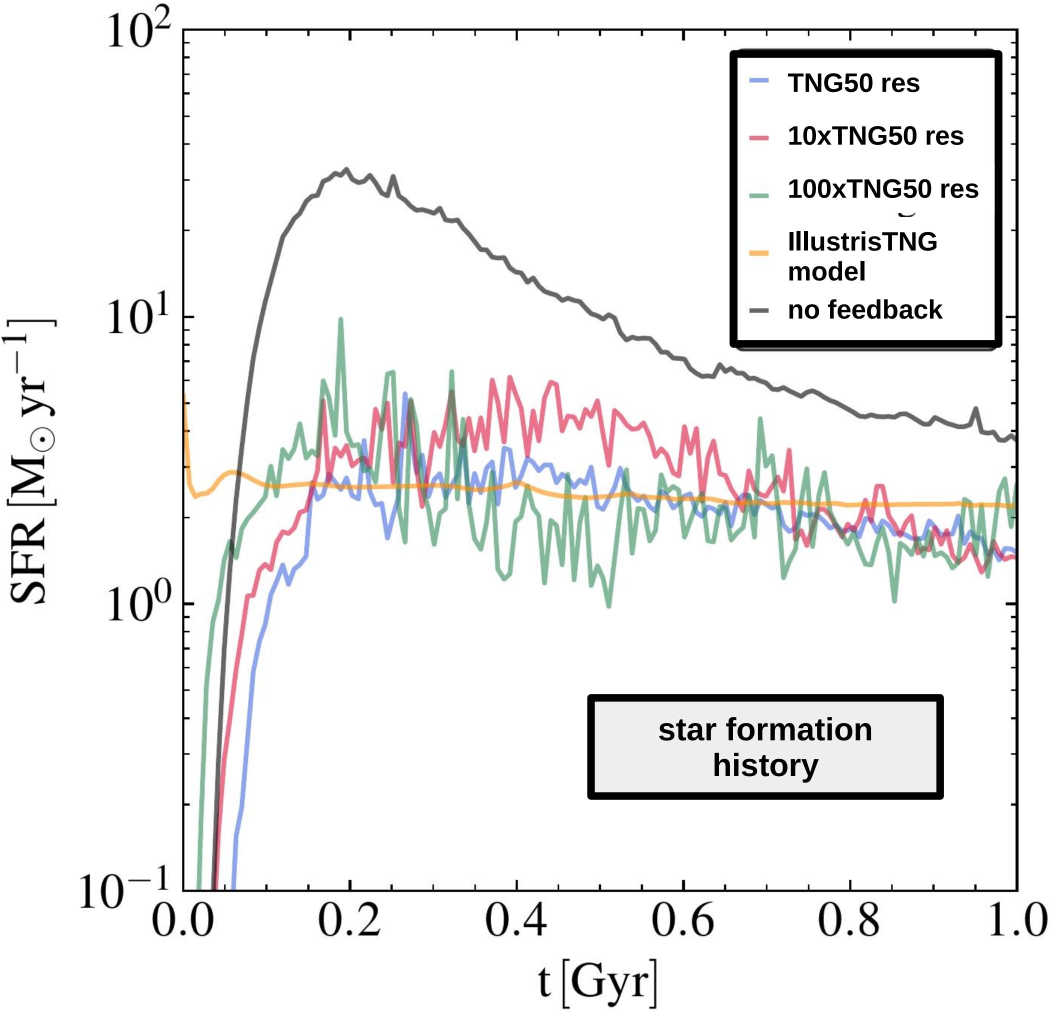


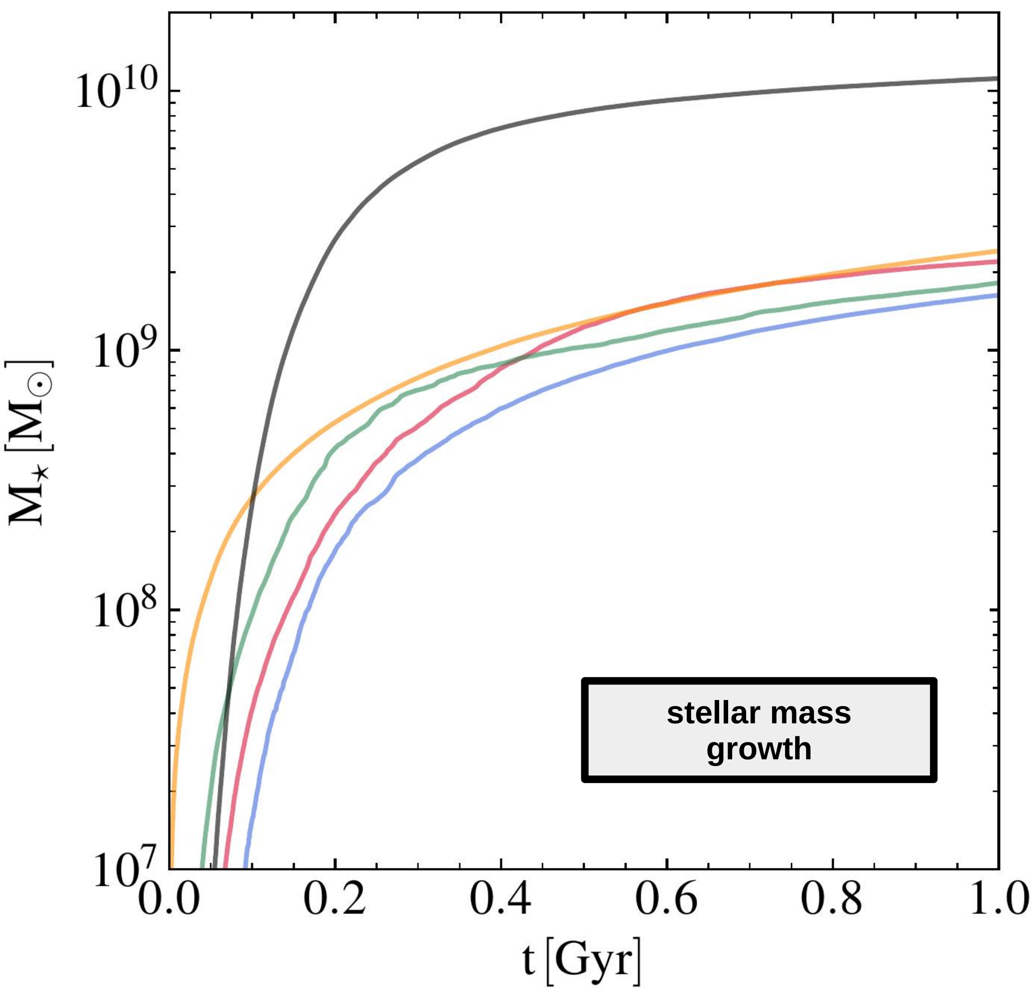
self-consistent generation of galactic outflows

Marinacci, Sales, MV, Torrey (in prep)

Novel Explicit Galaxy Formation Model

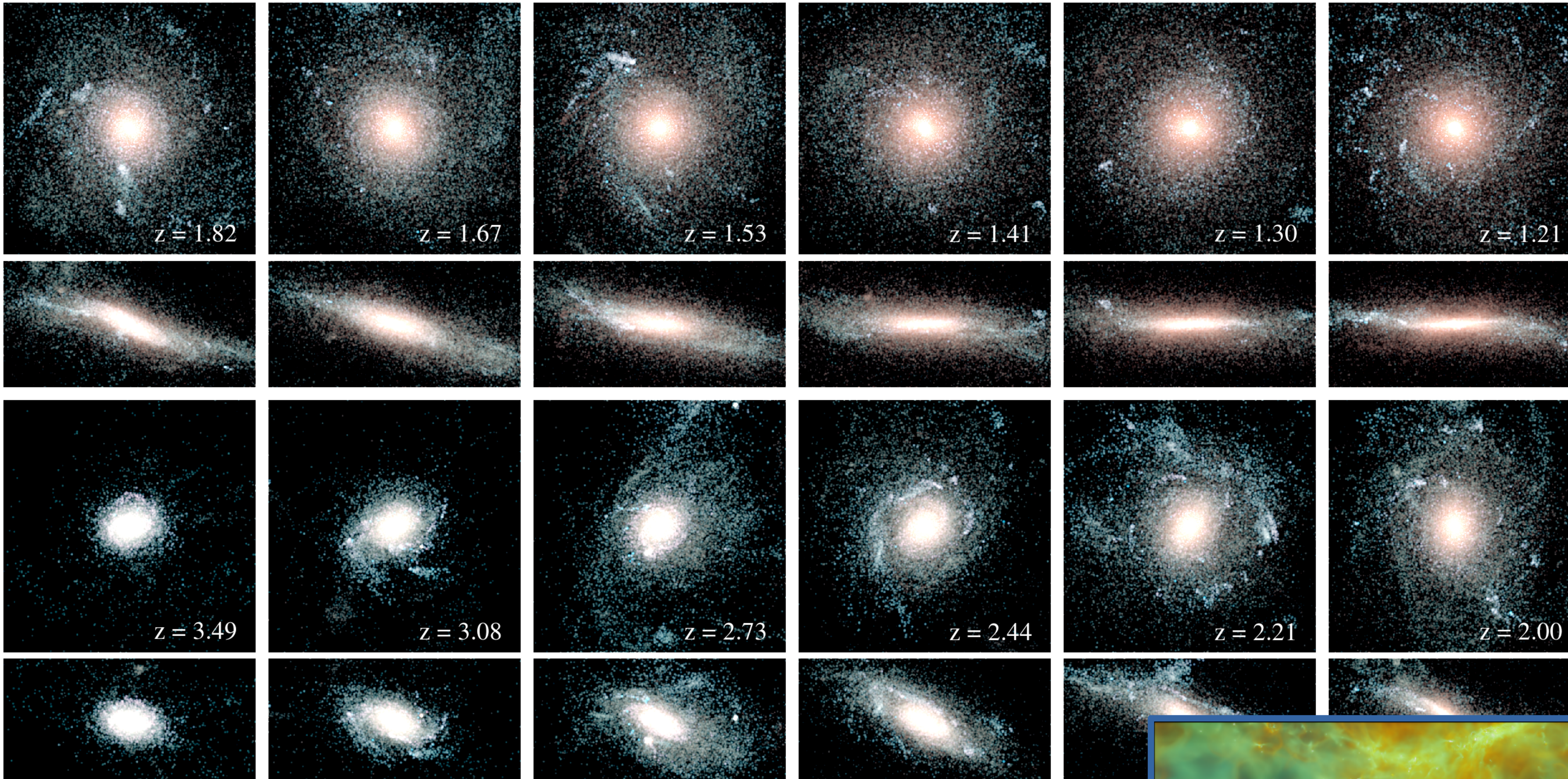
novel model convergences at resolution of currently feasible large-scale full volume simulations

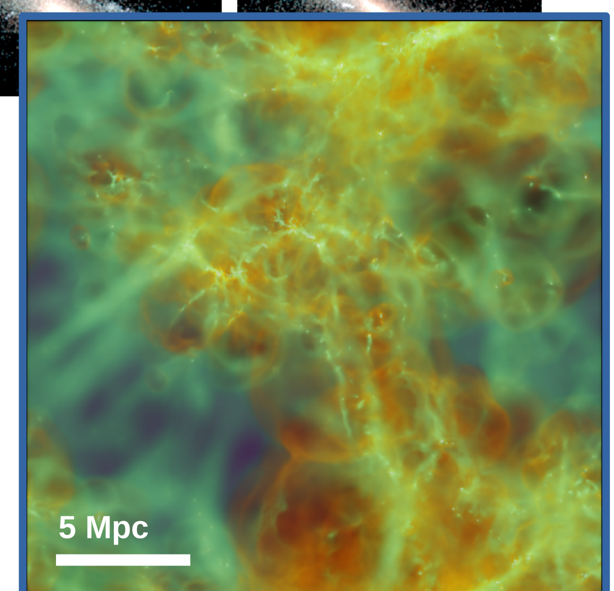




Marinacci, Sales, MV, Torrey (in prep)

Novel Explicit Galaxy Formation Model



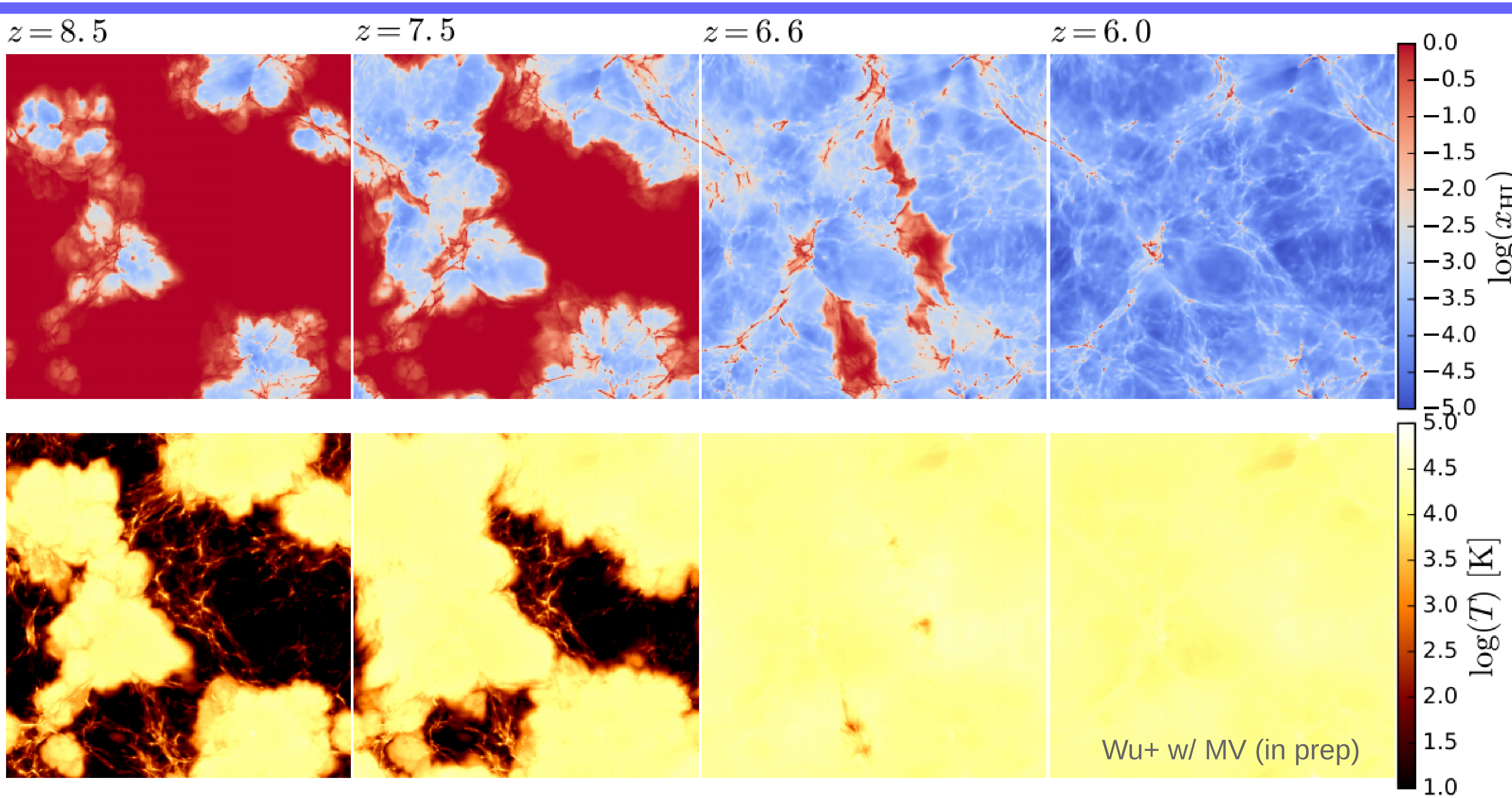


first cosmological simulations using the novel explicit model

Marinacci, Sales, MV, Torrey (in prep) - *preliminary*

Torrey, Marinacci, Sales, MV (in prep) - *preliminary*

Missing Physics



Many physical processes often not included in volume simulations:

- **radiation-hydrodynamics (e.g., for re-ionization studies, 21cm, feedback)**
- **cosmic rays (e.g., import feedback channel)**
- **plasma physics (e.g., thermal conduction, viscosity)**
- **dust physics (e.g., coupling to radiation and chemistry)**
- **...**

Beyond CDM:

The Frontiers of Dark Matter Physics

Beyond CDM: CDM Problems?

Problems:

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

small-scale CDM problems

- generic WIMP / axions not detected so far

'fundamental' problem

Solutions:

- baryon physics (most small-scale problems have been identified in DM only simulations)
- systematic uncertainties in observations / measurements
- DM is not exactly CDM

Beyond CDM: Dark Matter Alternatives

Warm Dark Matter?

Self-Interacting Dark Matter?

BECDM?

...?

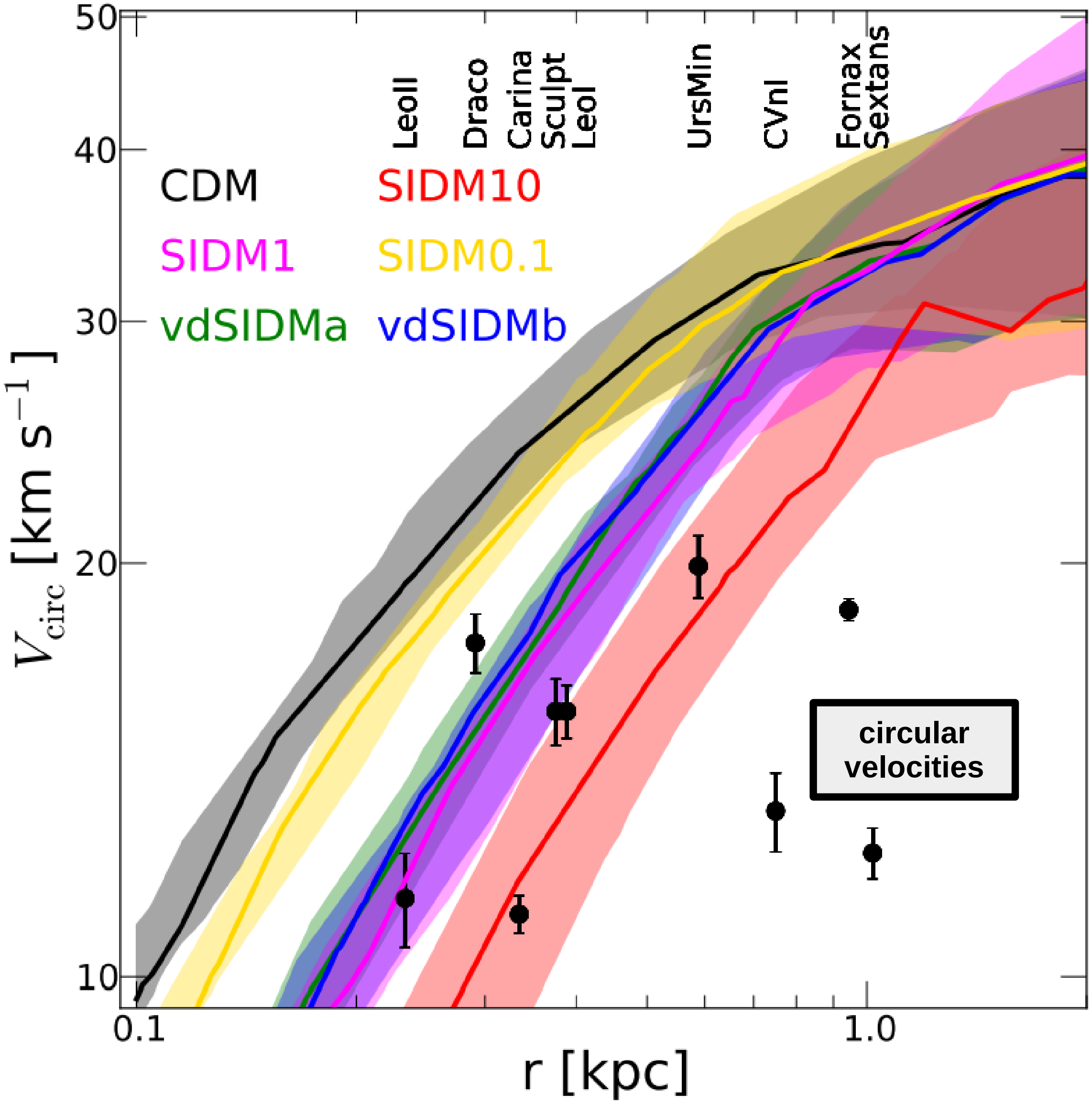
Observational Evidence for Self-Interacting Cold Dark Matter

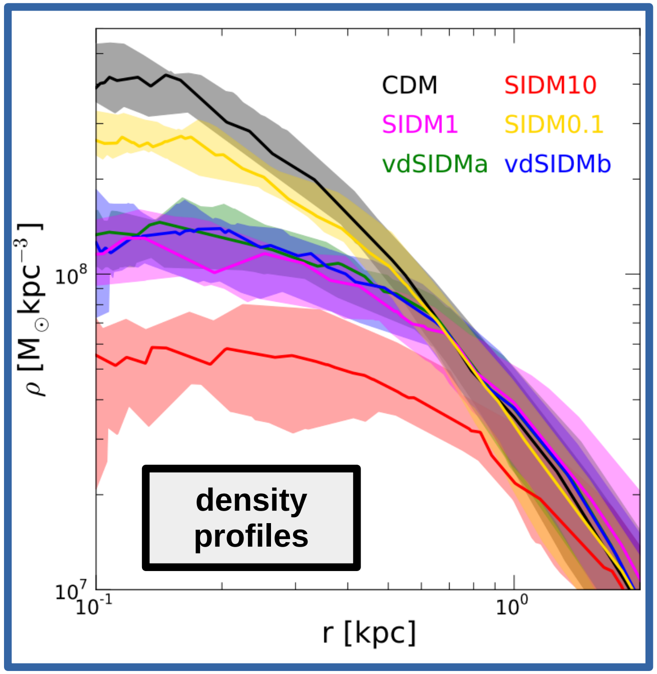
David N. Spergel and Paul J. Steinhardt
Princeton University, Princeton, New Jersey 08544
(Received 20 September 1999)

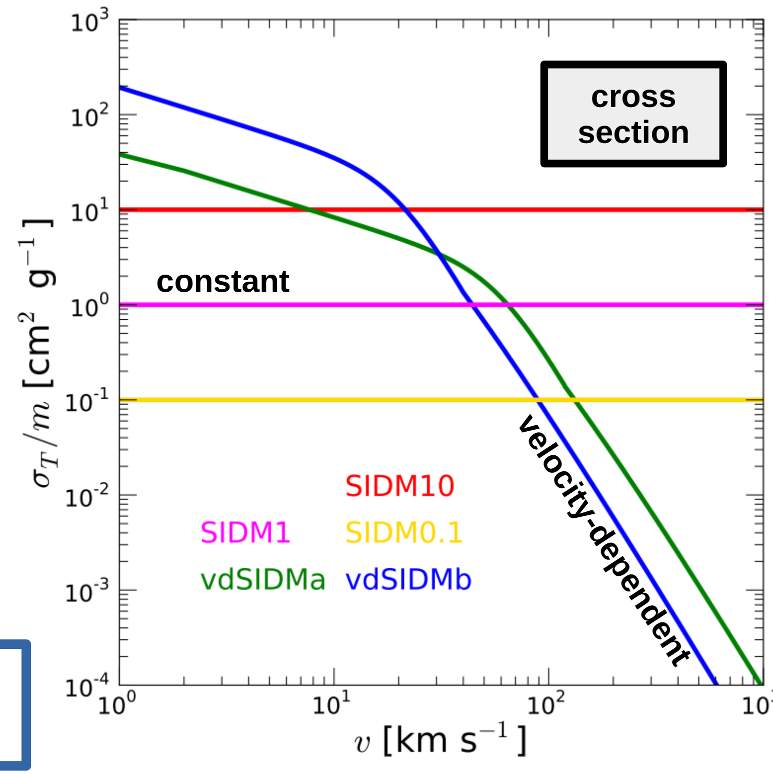
Cosmological models with cold dark matter composed of weakly interacting particles predict overly dense cores in the centers of galaxies and clusters and an overly large number of halos within the Local Group compared to actual observations. We propose that the conflict can be resolved if the cold dark 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 cm^2/g or, equivalently, $8 \times 10^{-(25-22)}$ cm^2/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 DM Subhalos







MV, Zavala, Loeb 2012

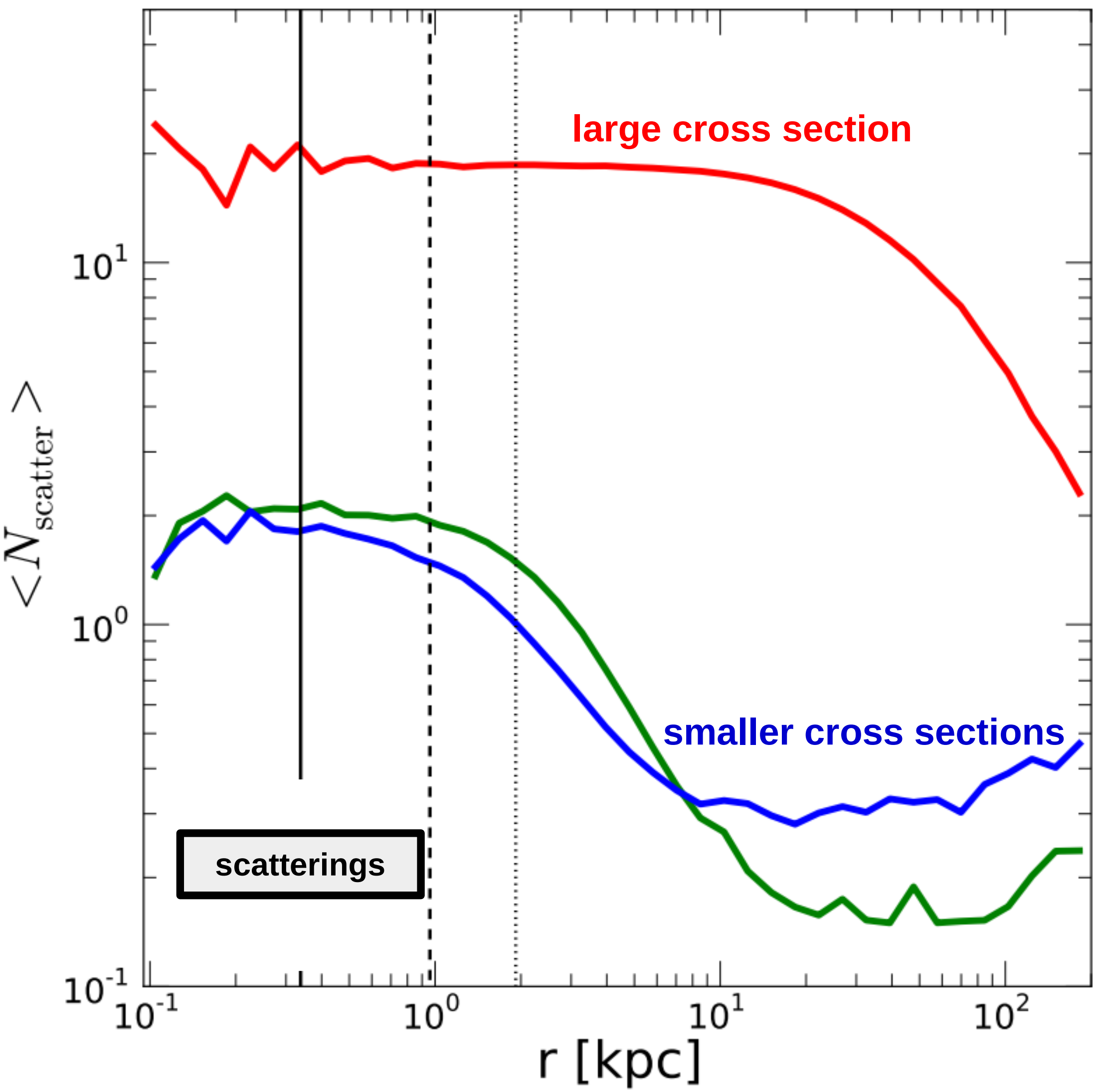
Zavala, MV, Walker 2013

[see also Rocha+ 2013]

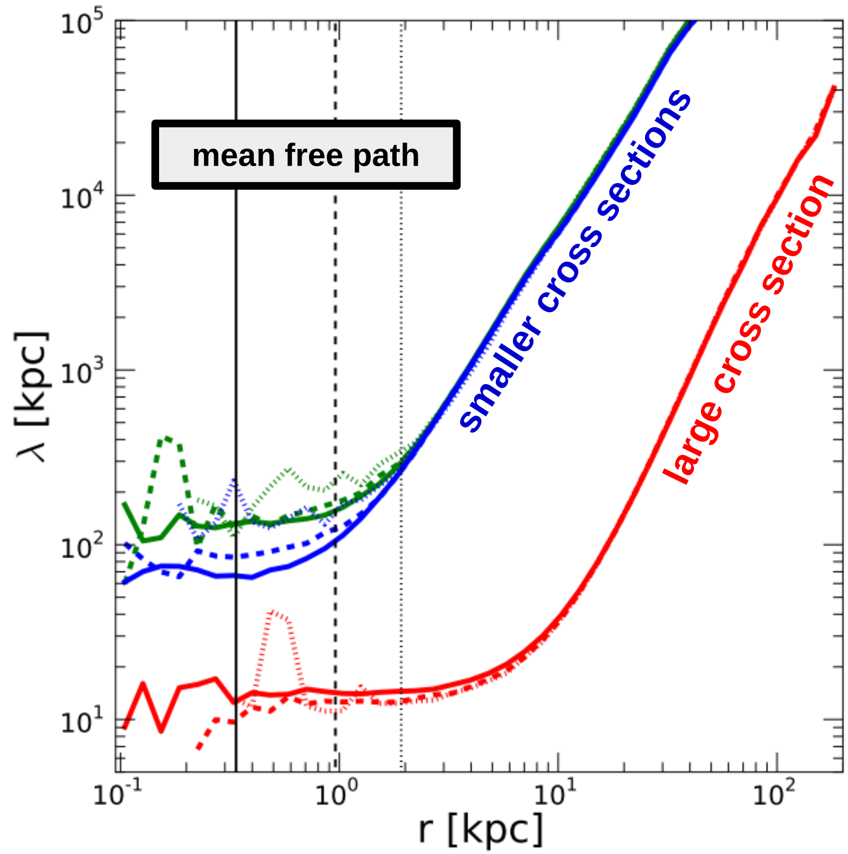
SIDM simulations alleviate the tension with TBTF problem

can be achieved with constant and velocity-dependent cross sections

How often do SIDM particles scatter on average?



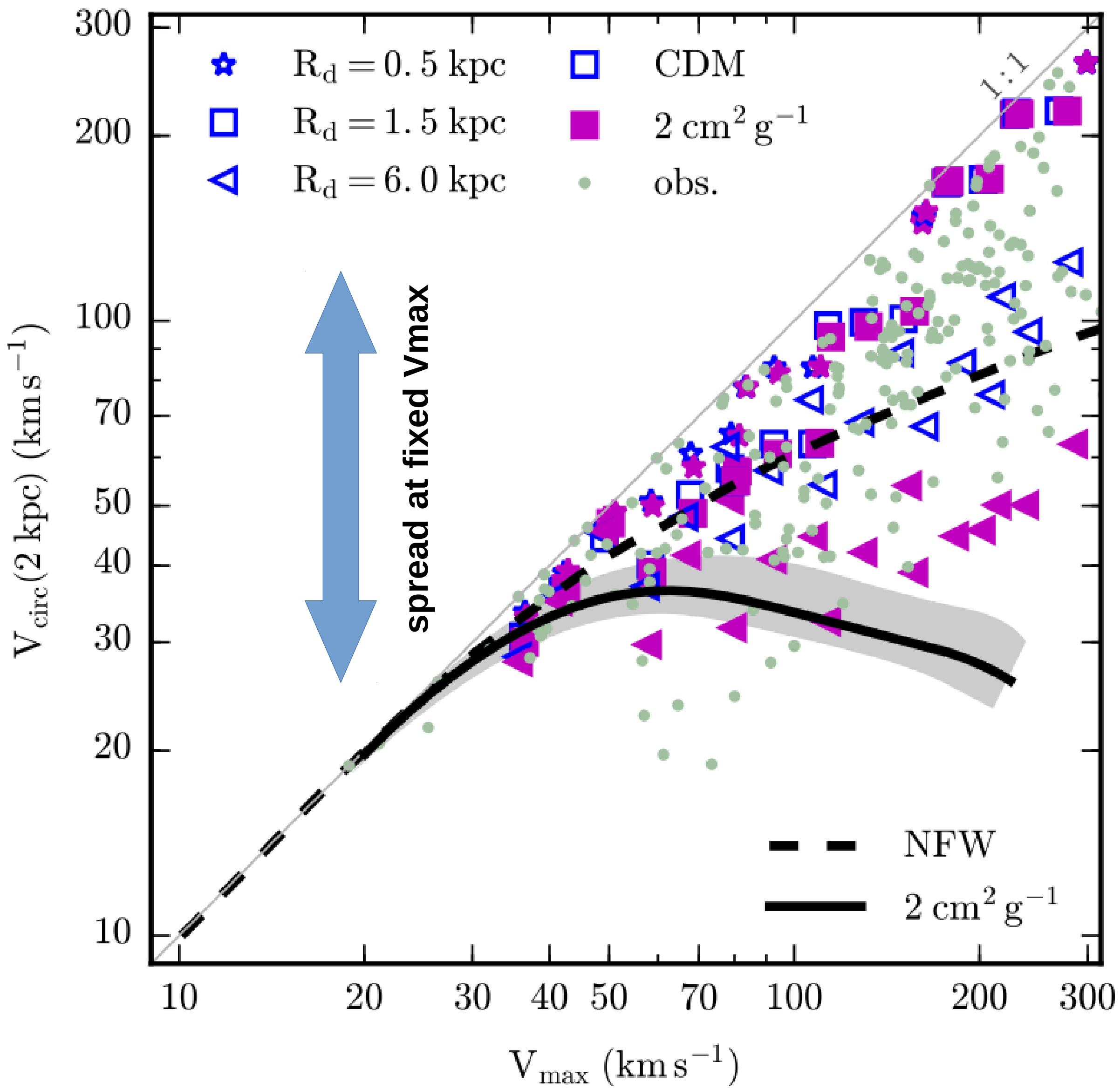
typically only a few scattering events per Hubble time are sufficient to create cores



~100 kpc mean free path in inner halo

MV, Zavala, Loeb 2012

Diversity in SIDM?



increased diversity in SIDM simulations

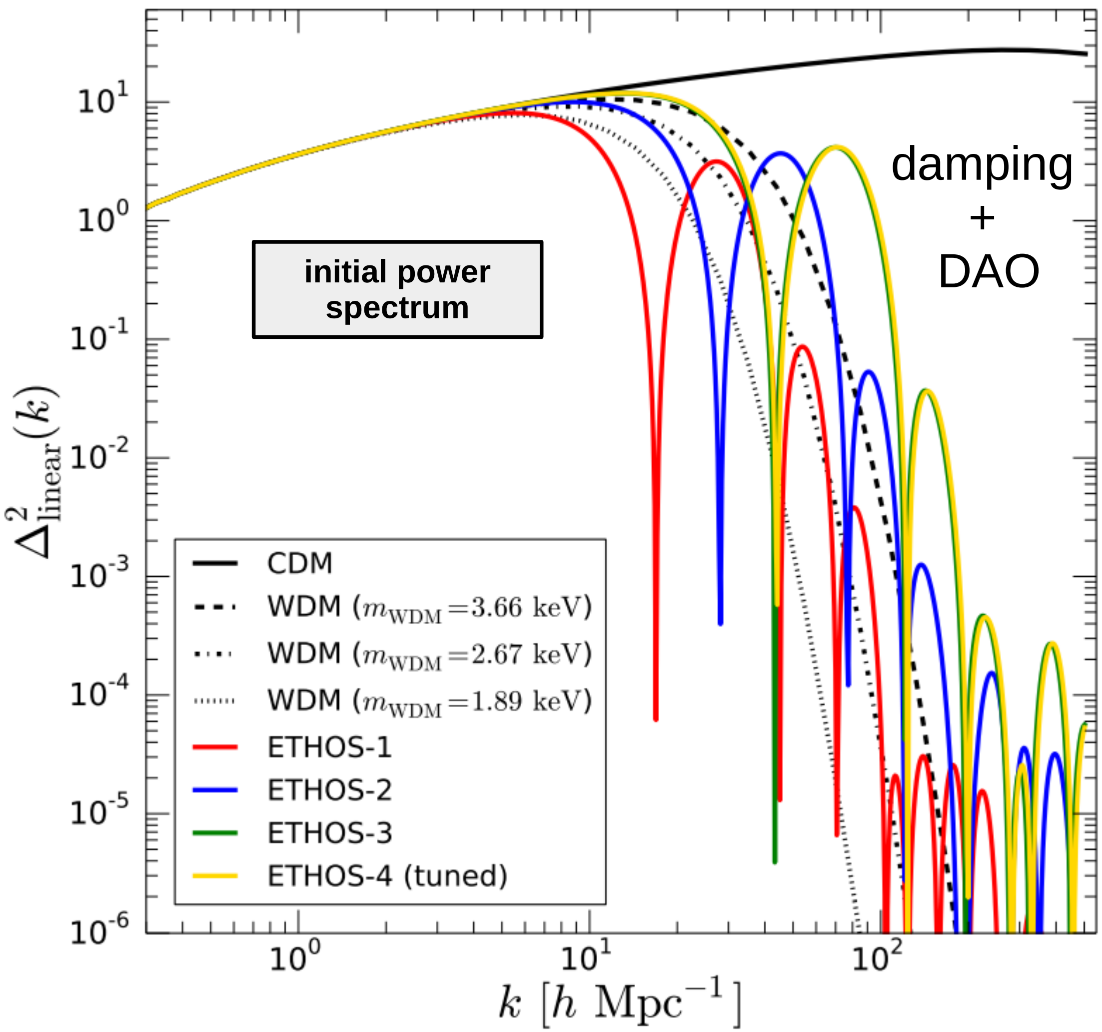
self-interactions allow lower V_{circ}(2kpc) [low central densities in both baryons and dark matter]; high values of V_{circ}(2kpc) still achieved with compact disks

Creasey, Sales+ w/ MV 2017

[see also Ren+ 2018]

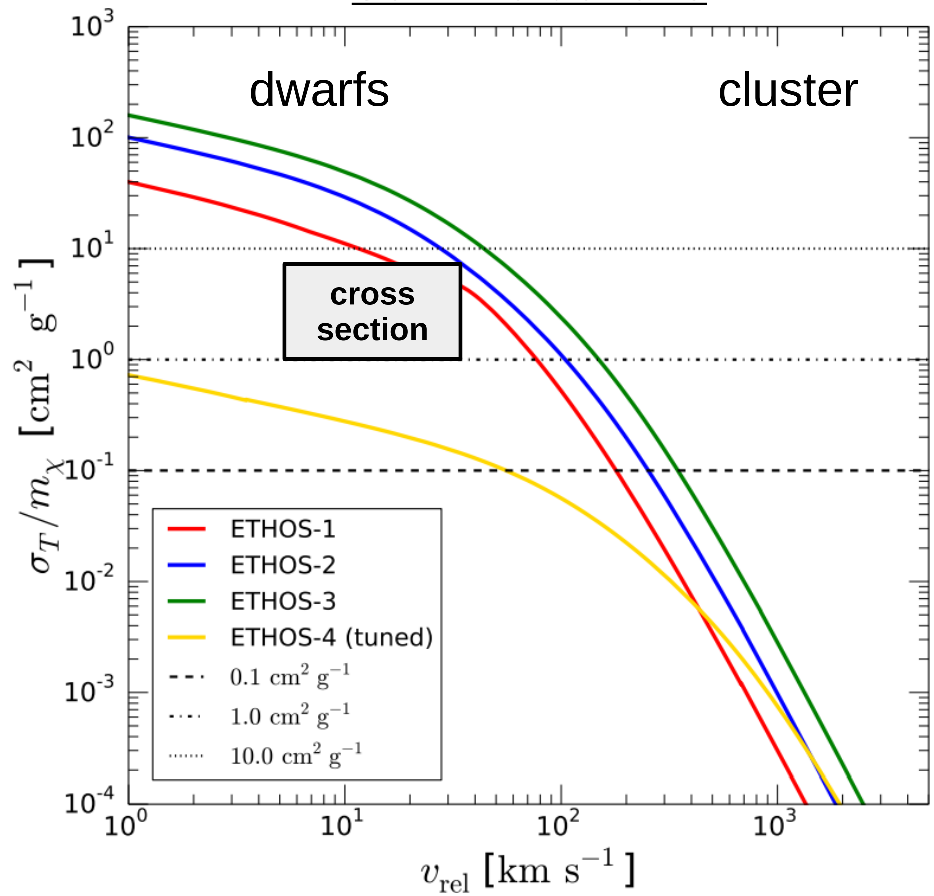
ETHOS – Effective Theory of Structure Formation: Ingredients

Initial Conditions



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

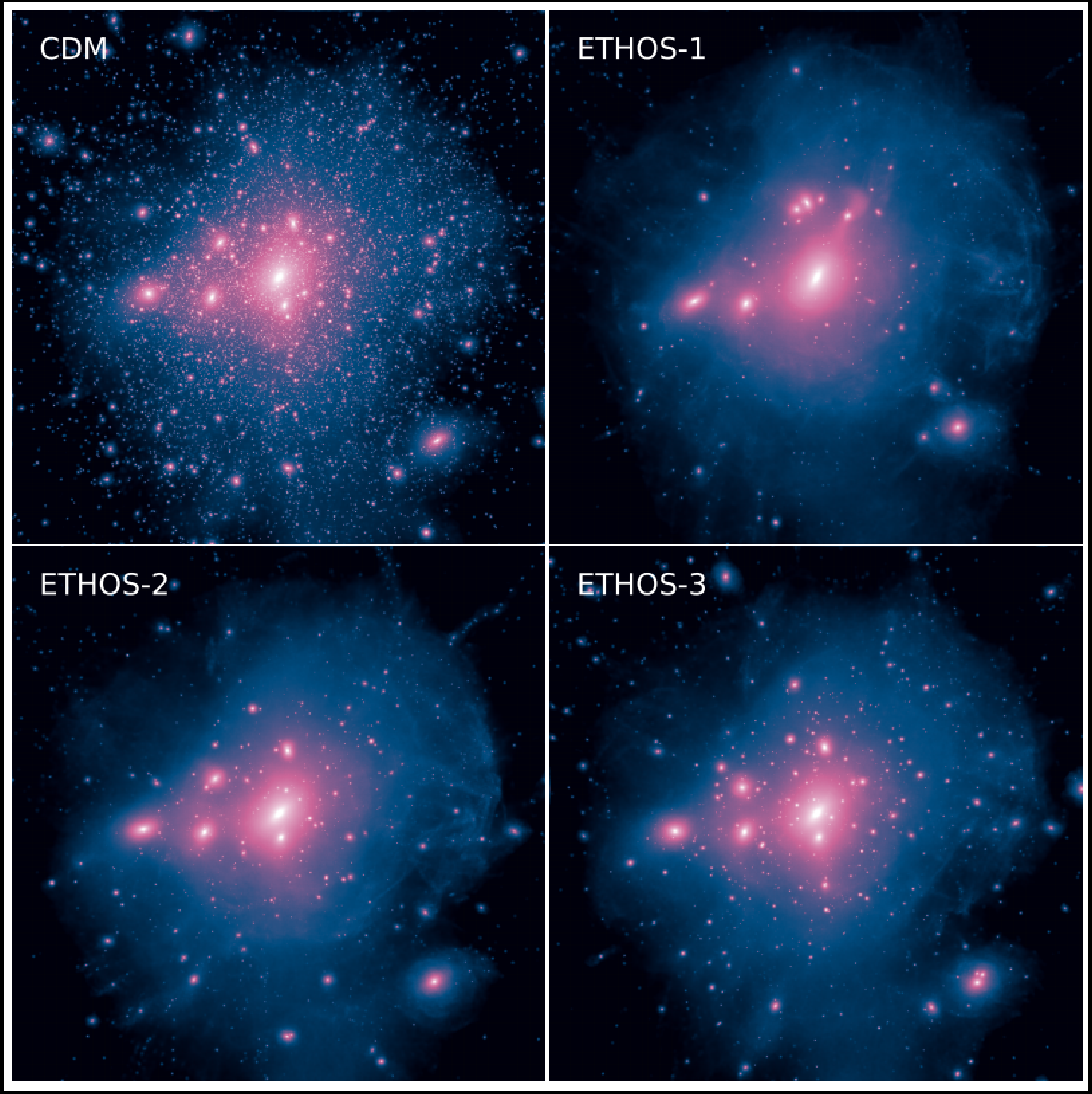
Self-Interactions



Cyr-Racine+ w/ MV2016

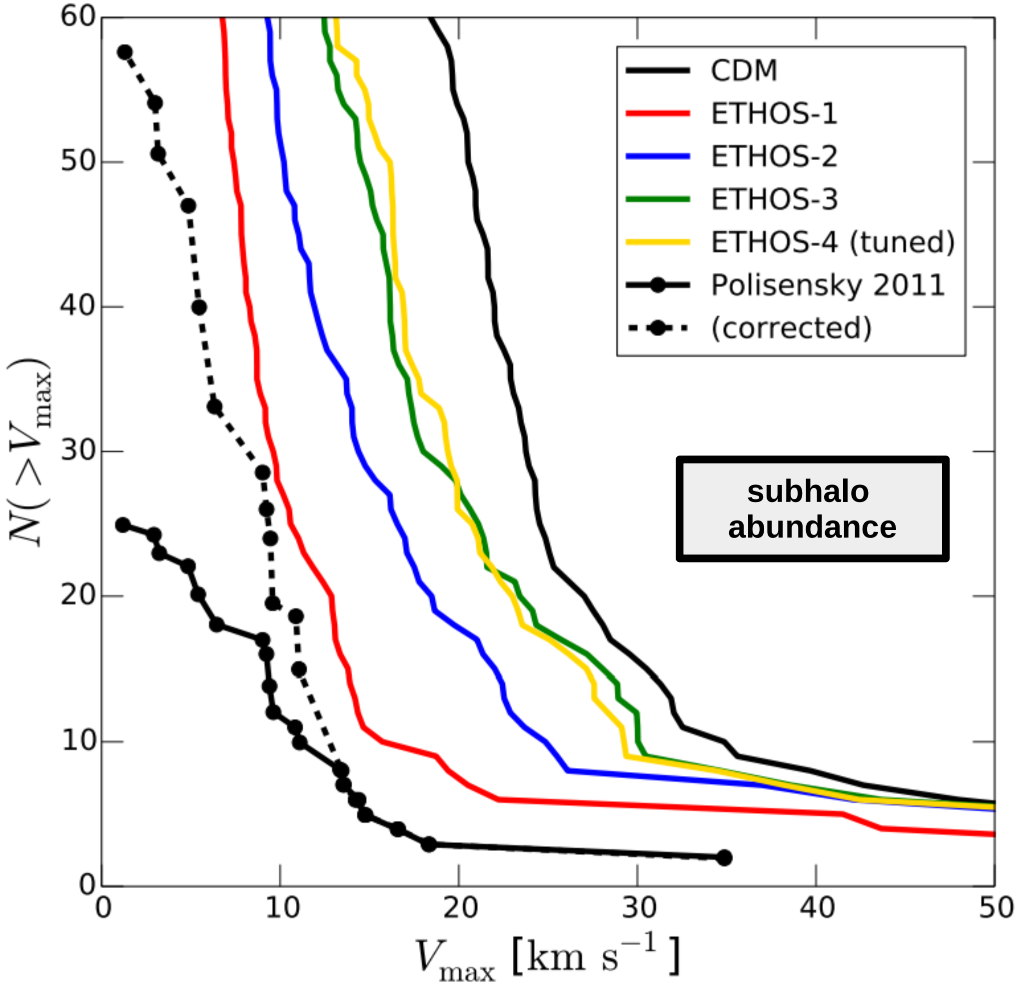
MV+ 2016

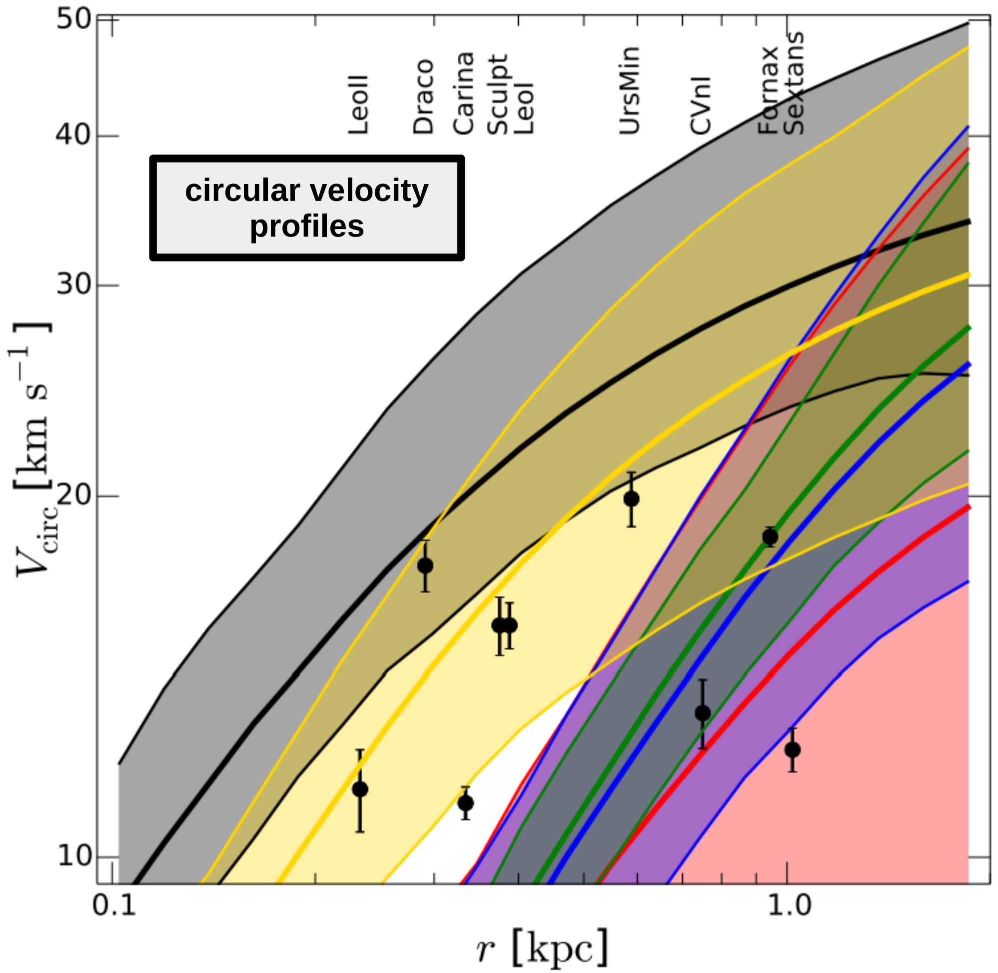
ETHOS: A Milky Way-like Halo Simulation



MV+ 2016

ETHOS: Impact on Milky Way DM Subhalos

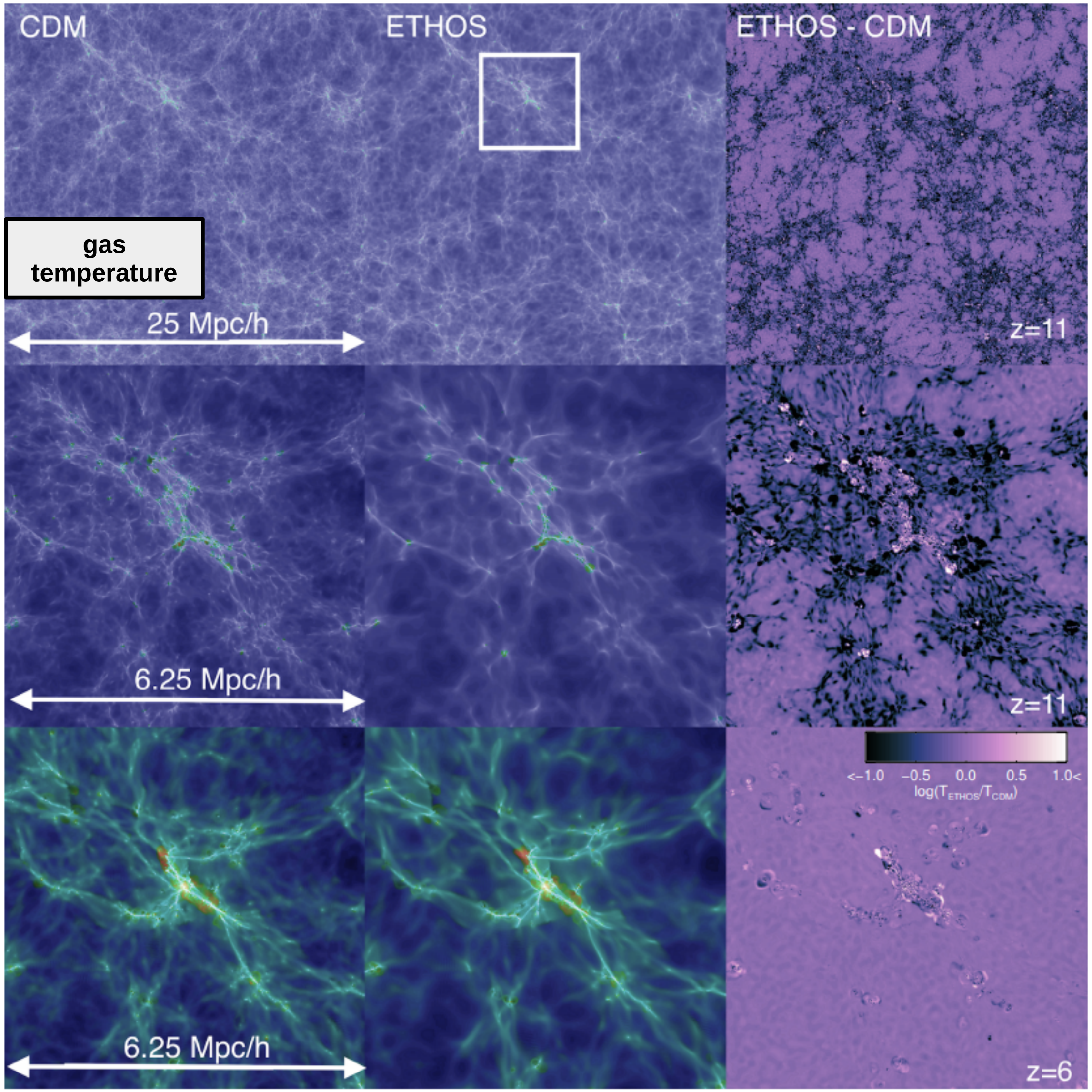


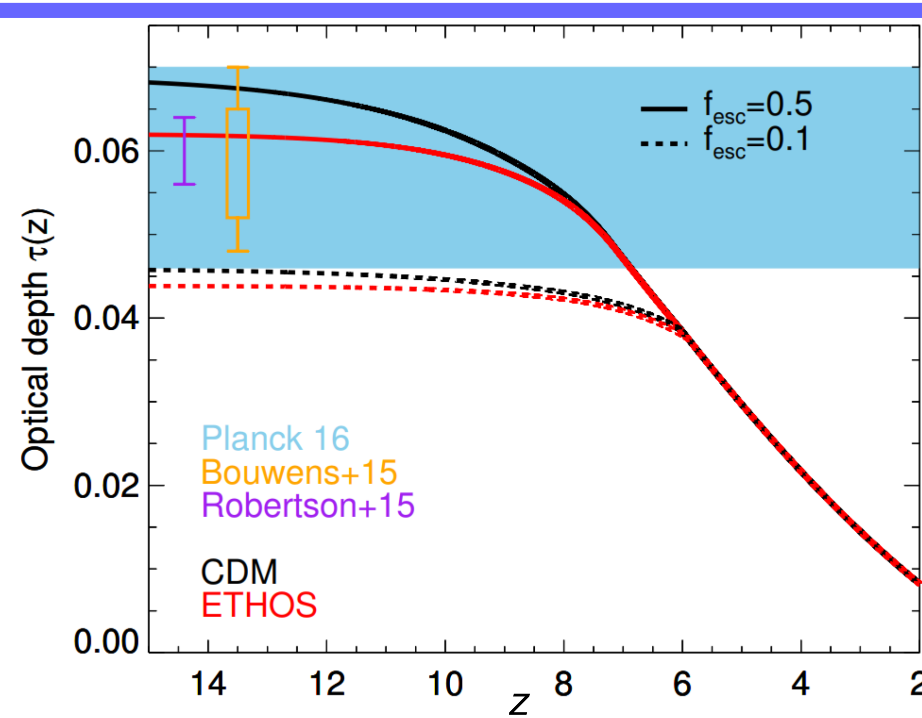


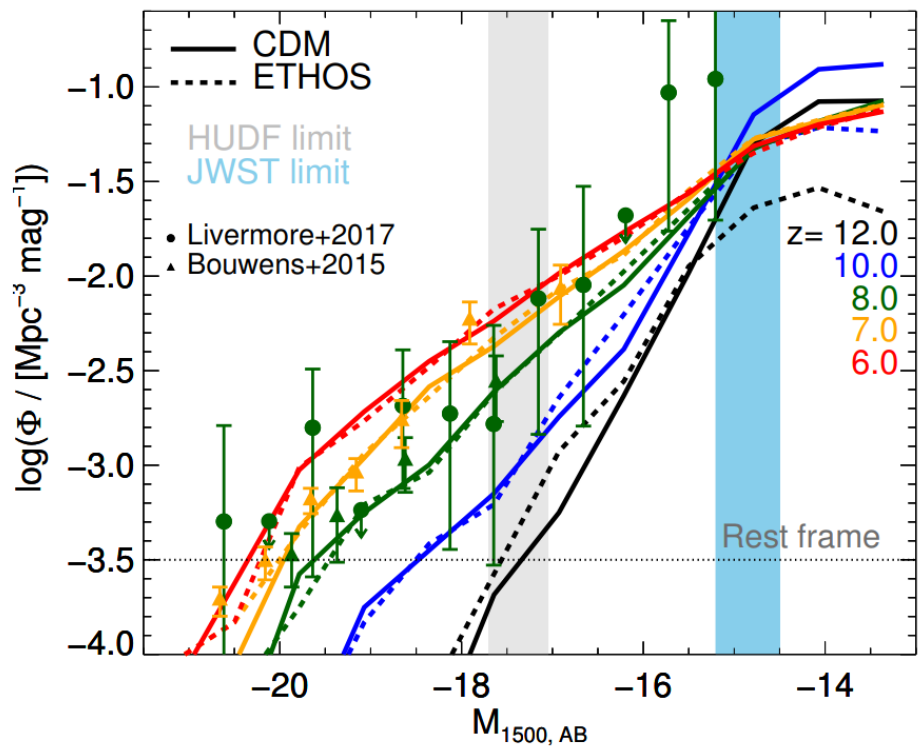
both CDM abundance and structural problems can be alleviated simultaneously

MV+ 2016

ETHOS: The High-Redshift Universe



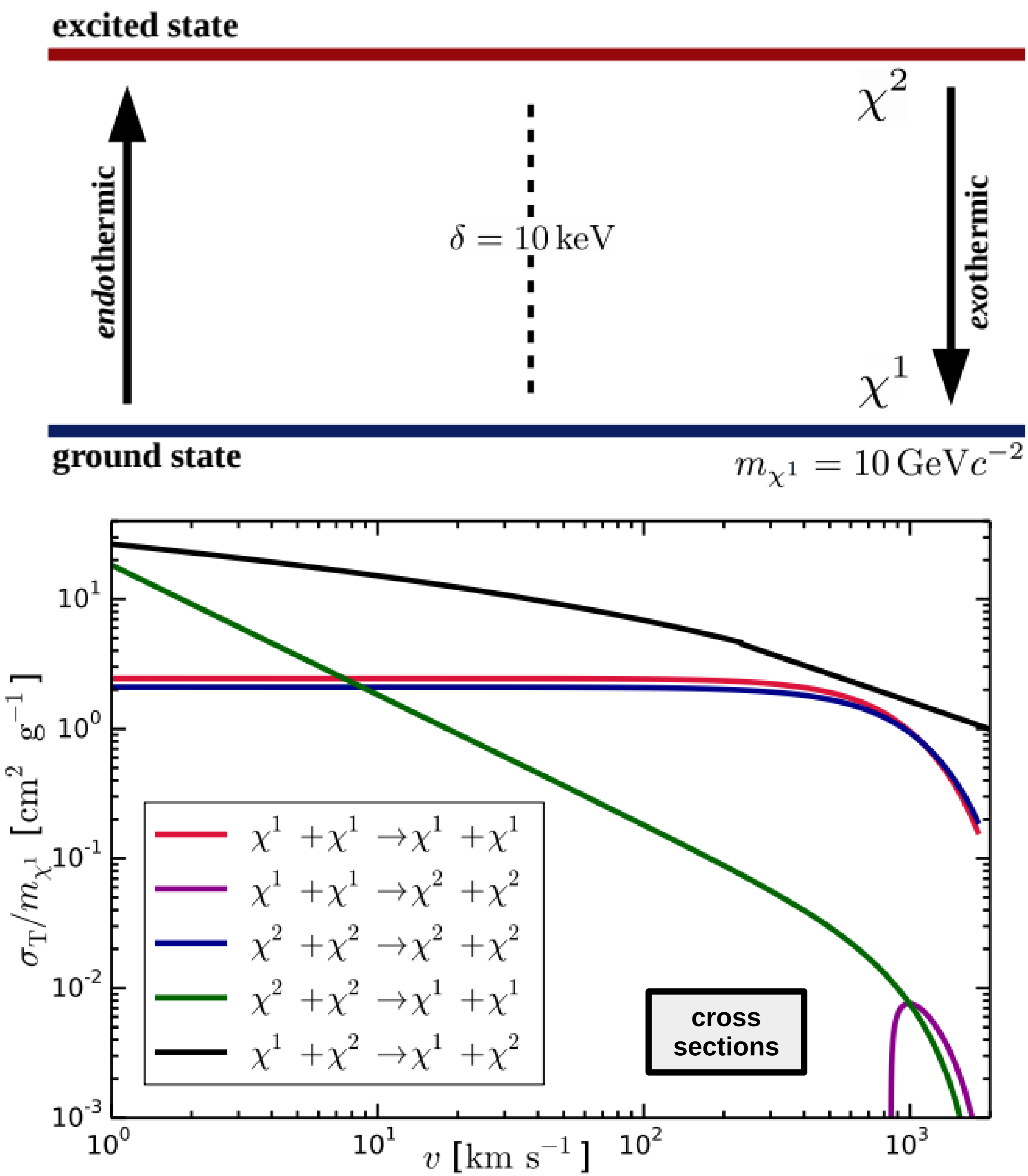




Lovell, Zavala, MV+ 2018

ETHOS models consistent with high redshift data

Inelastic SIDM: Two-State SIDM Model



specific model allows exothermic, but no endothermic reactions

MV, Zavala, Schutz, Slatyer 2018

[see also Todoroki & Medvedev 2018]

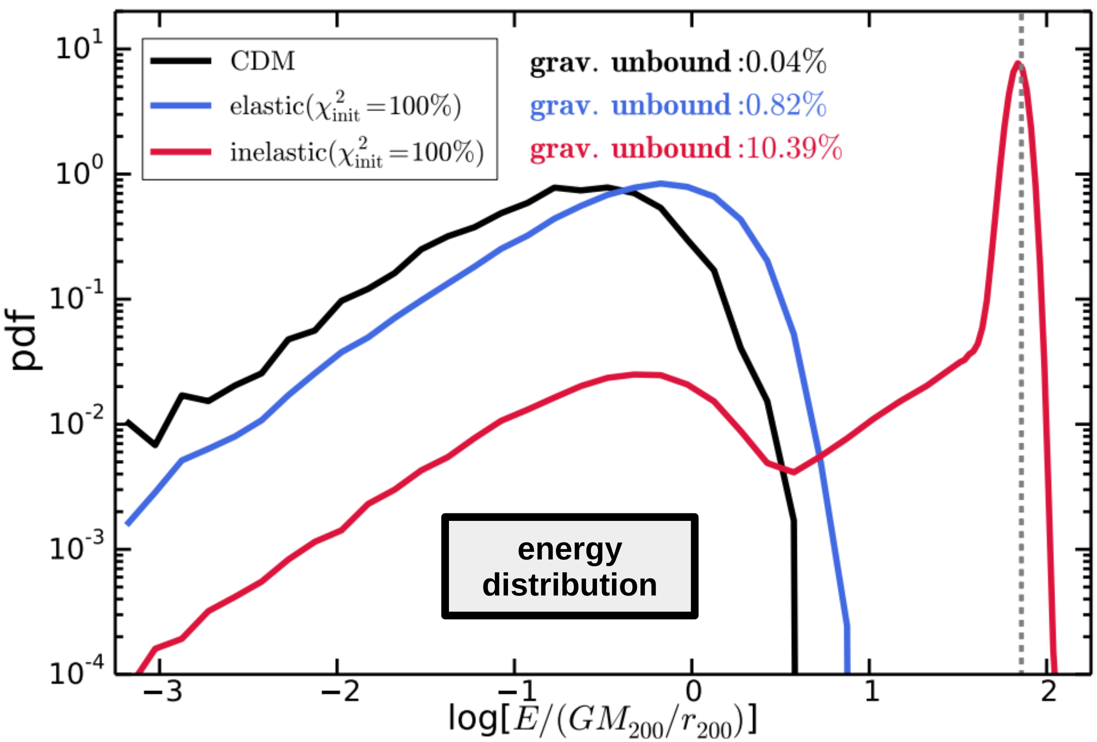
Elastic vs. Inelastic SIDM

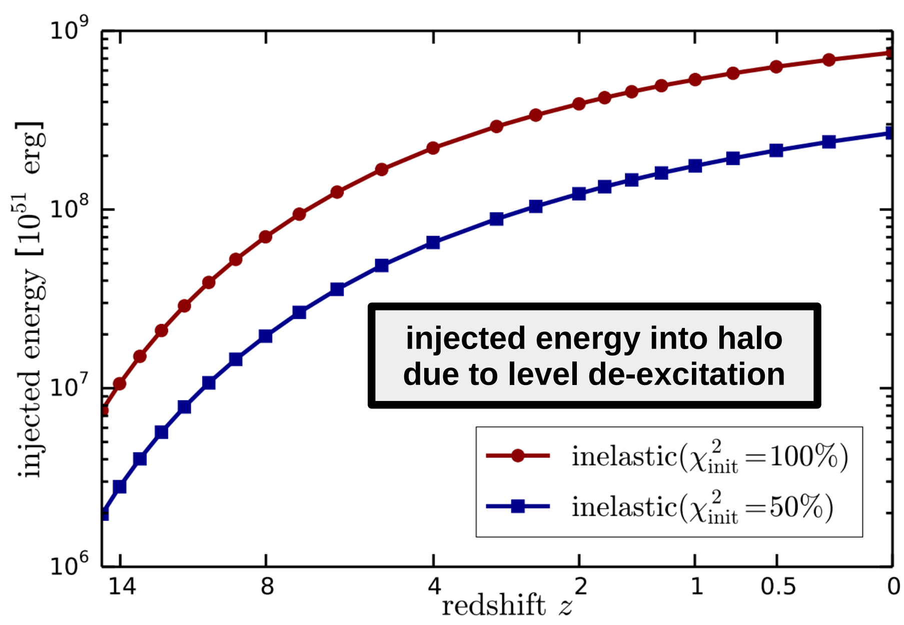
Elastic SIDM

Inelastic SIDM

exothermic reactions ‘evaporate’ halo cores

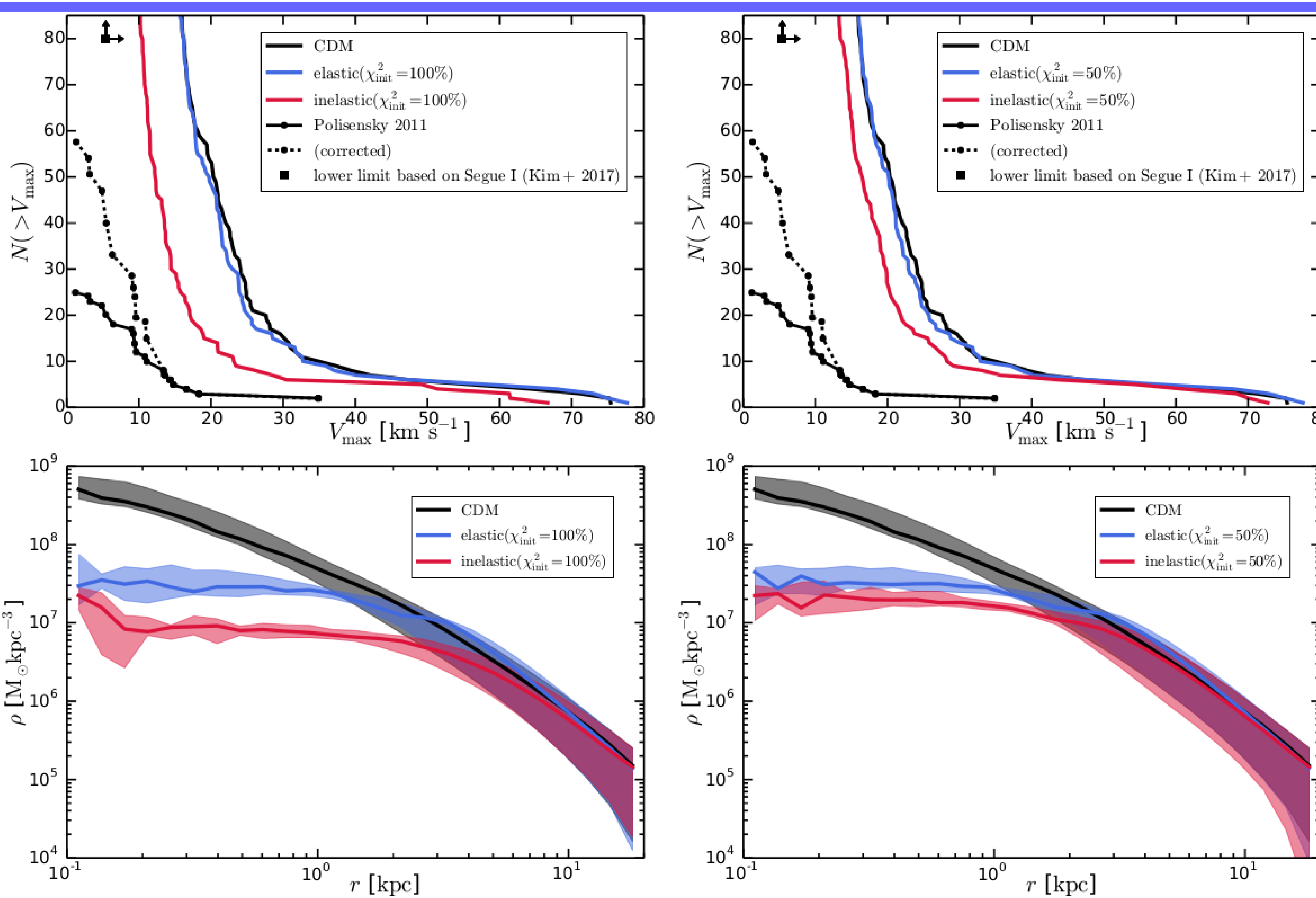
energy injection is equivalent to a few 100 million supernovae type II





MV, Zavala, Schutz, Slatyer 2018

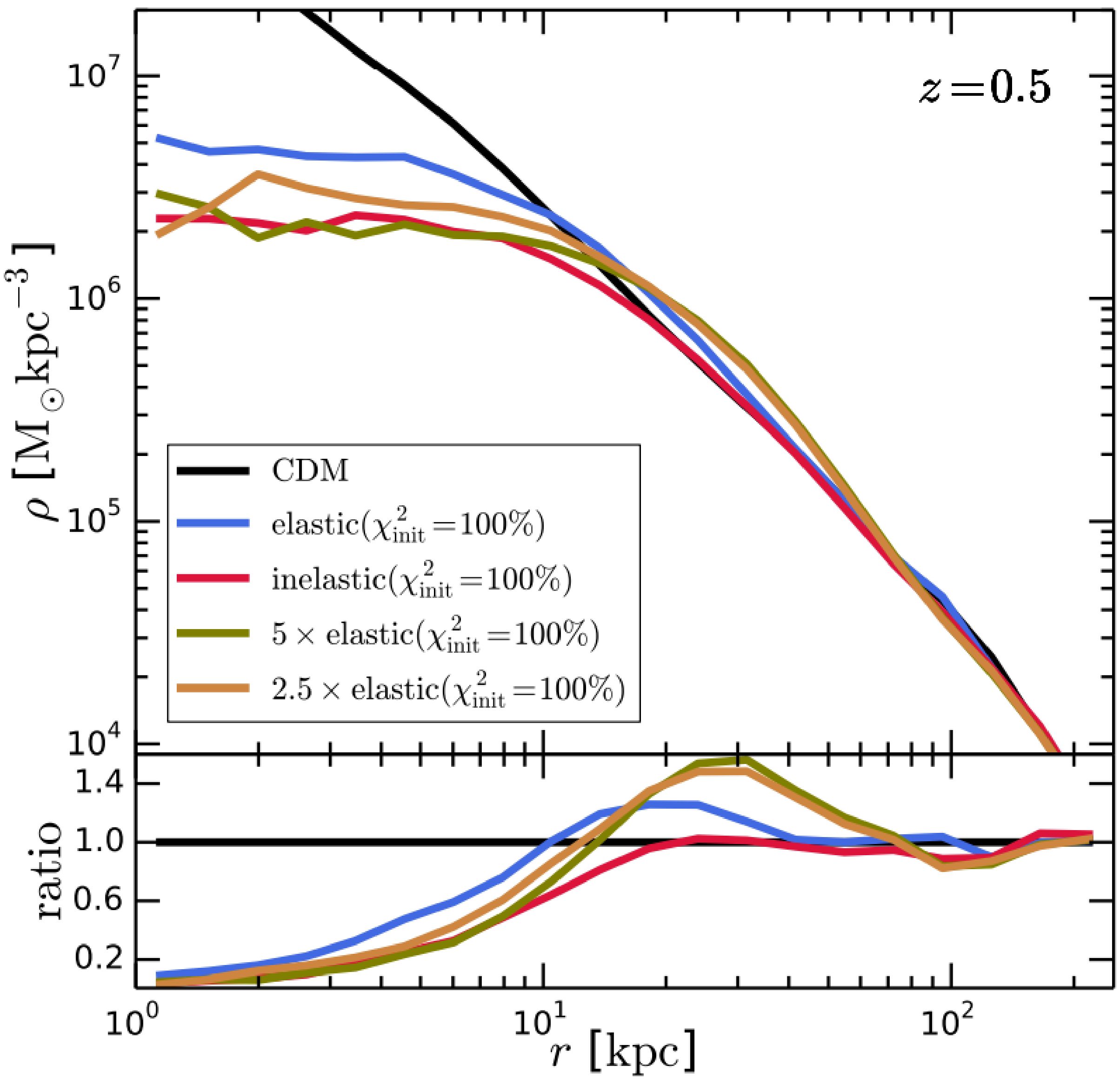
DM Subhalo Properties



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

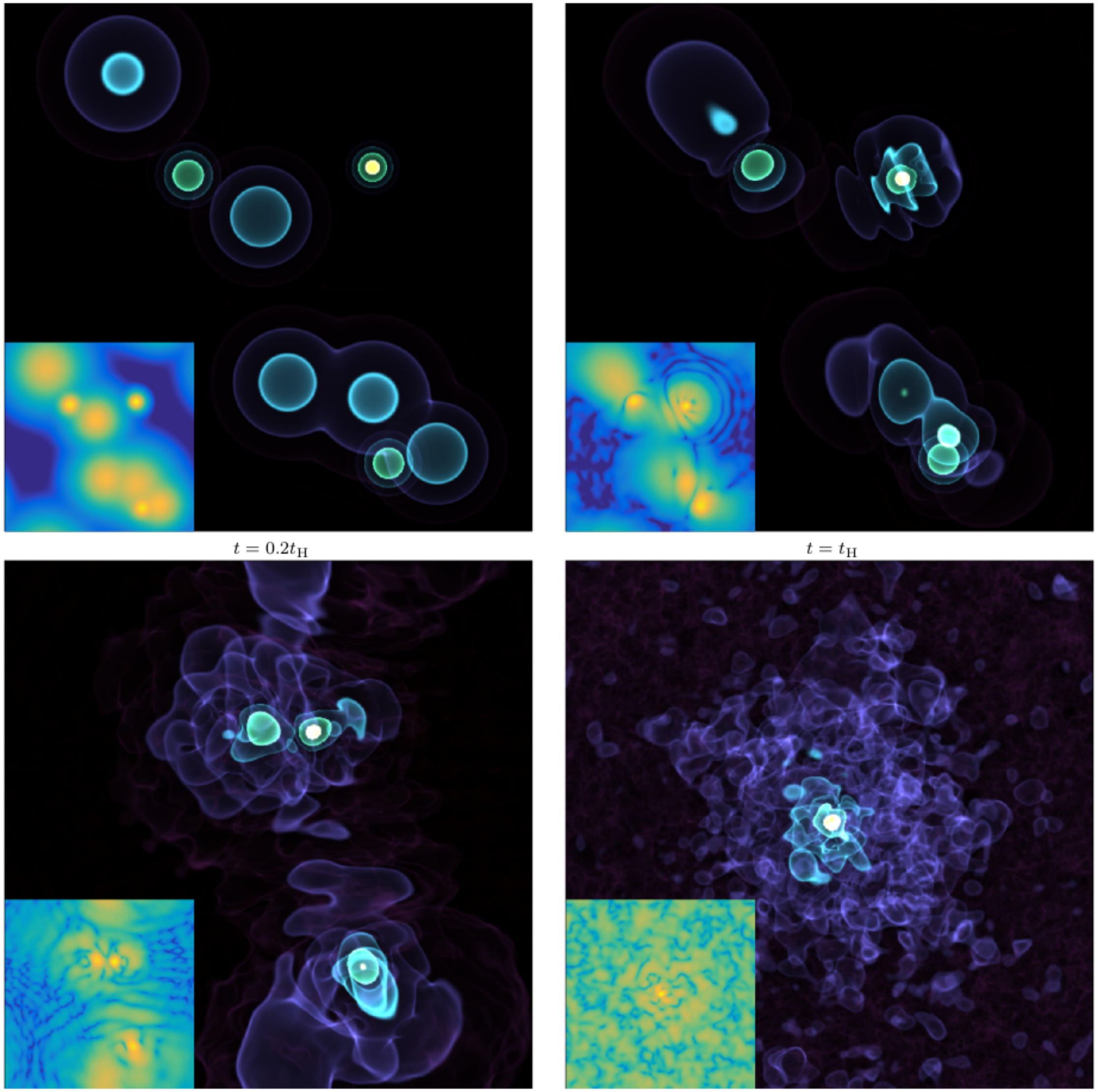


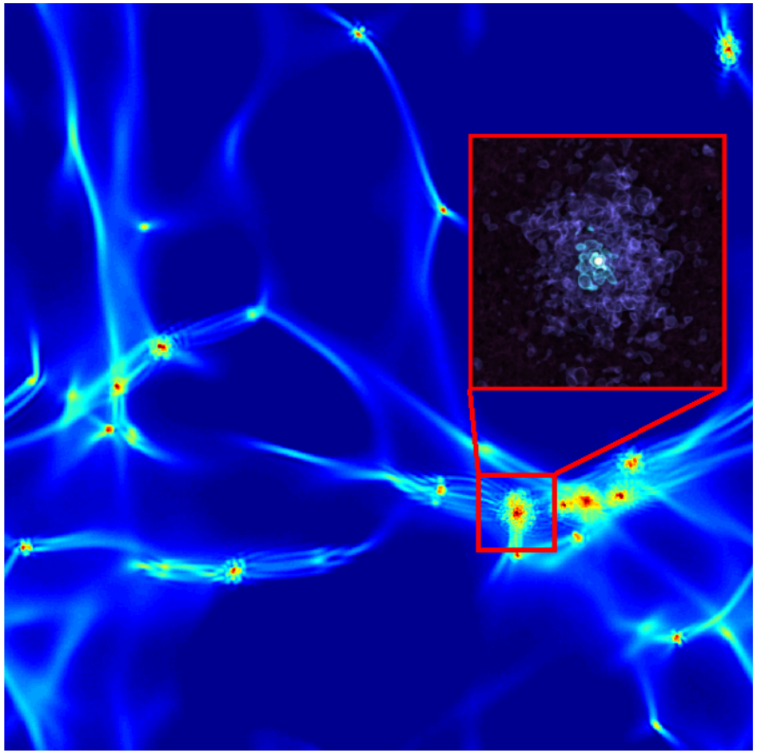
an elastic model with a ~5 times larger cross section leads to a central density reduction similar to the inelastic model

implications for cross section constraints?

MV, Zavala, Schutz, Slatyer 2018

Ultralight Axions – BECDM – Fuzzy DM – Scalafield DM





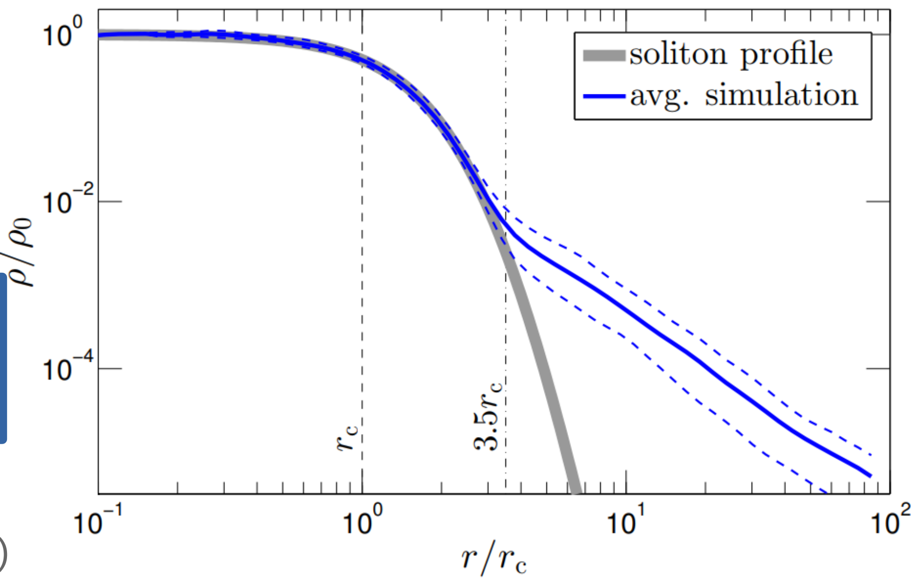
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi$$

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

requires novel simulation techniques

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

- **large-scale galaxy formation simulations with more explicit baryon physics (e.g., feedback)**
- **hydrodynamical simulations of alternative DM models (e.g., SIDM, WDM, BECDM)**
- **key question: How to distinguish baryon effects from alternative DM?**