

Title: Simulating Galaxy Formation: Illustris, IllustrisTNG and beyond

Speakers: Mark Vogelsberger

Series: Colloquium

Date: December 04, 2019 - 2:00 PM

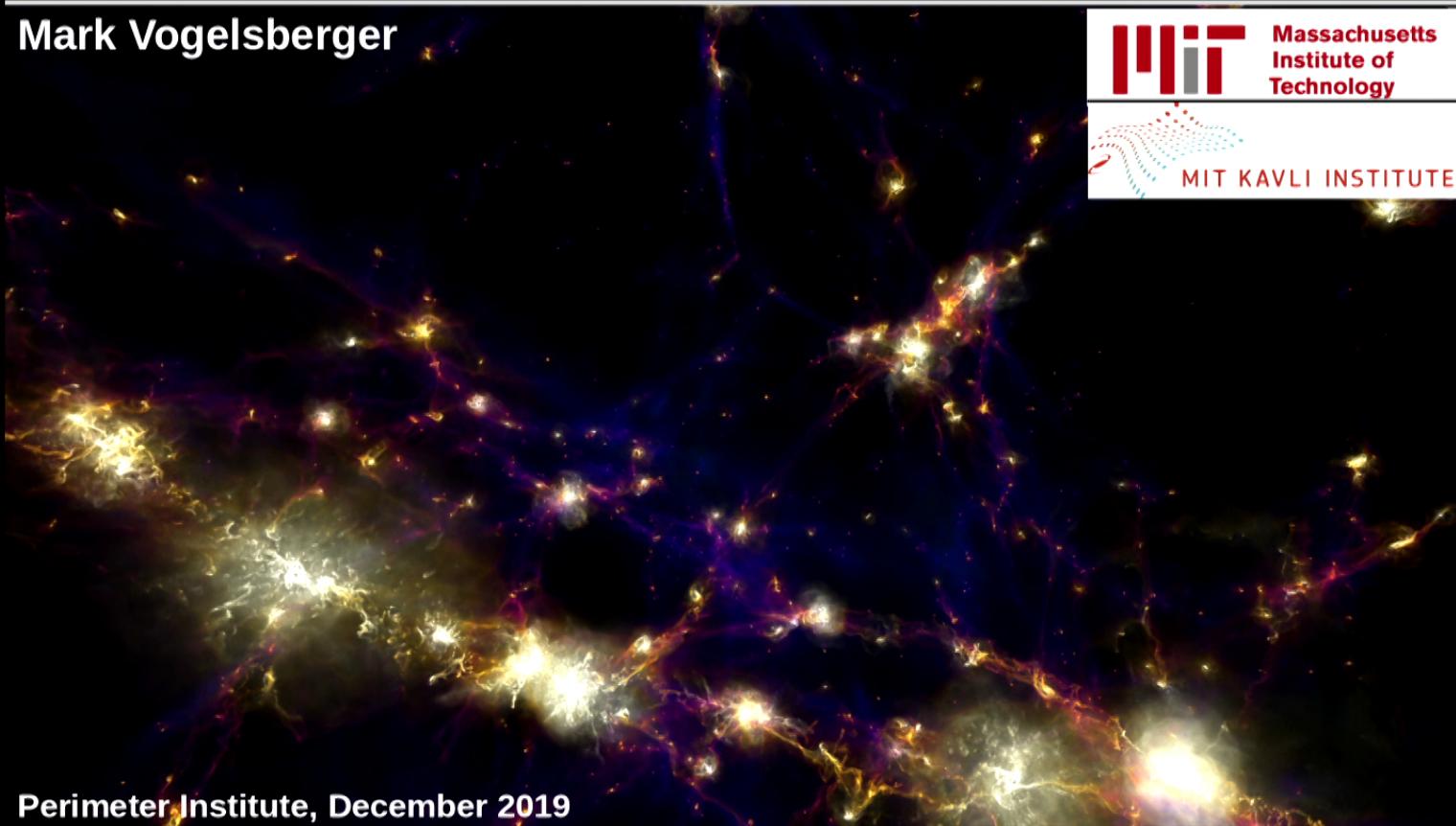
URL: <http://pirsa.org/19120025>

Abstract: Cosmological simulations of galaxy formation have evolved significantly over the last years.

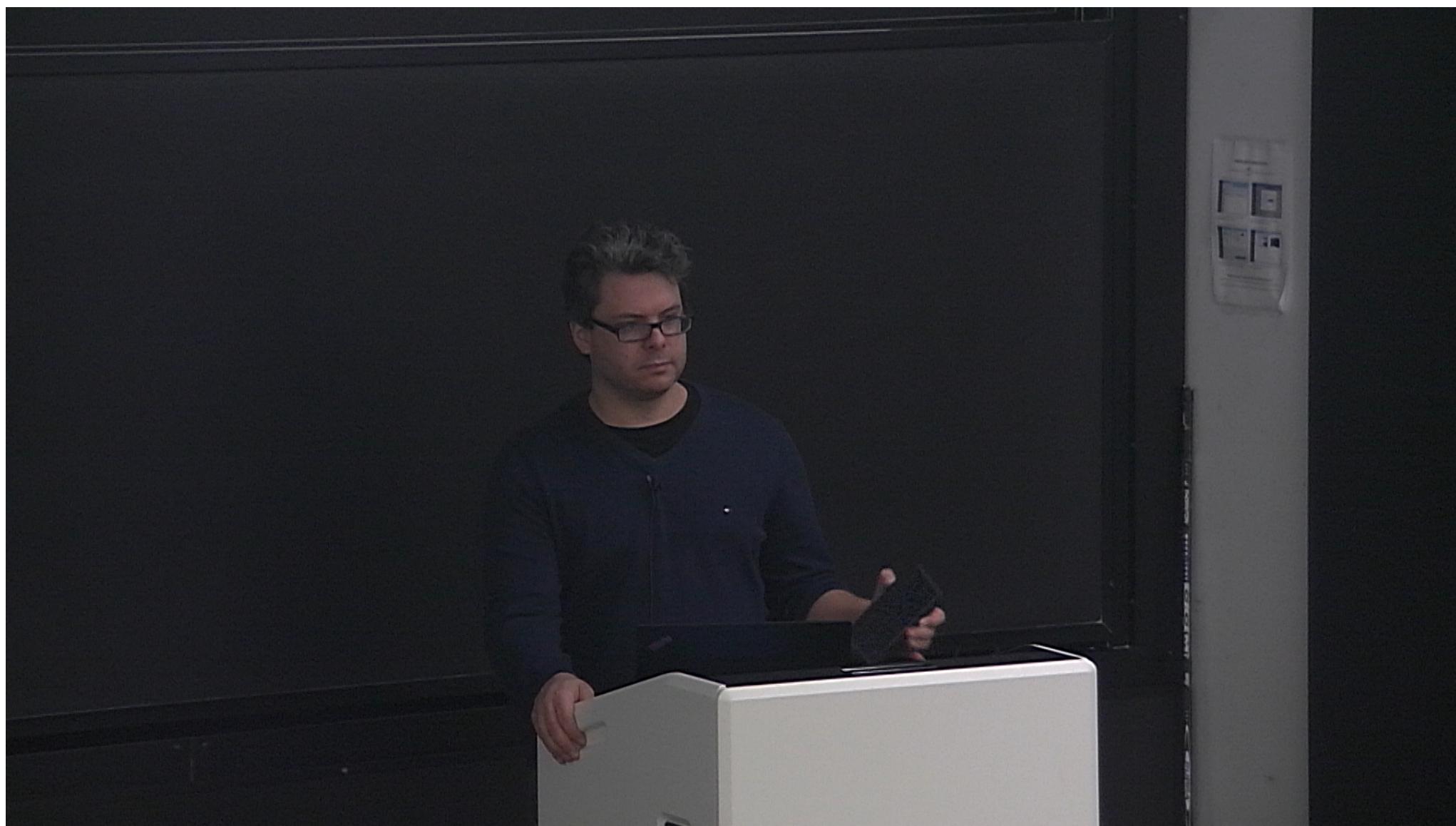
In my talk I will describe recent efforts to model the large-scale distribution of galaxies with cosmological hydrodynamics simulations. I will focus on the Illustris simulation, and our new simulation campaign, the IllustrisTNG project. After demonstrating the success of these simulations in terms of reproducing an enormous amount of observational data, I will also talk about their limitations and directions for further improvements over the next couple of years.

Simulating Galaxy Formation: Illustris, IllustrisTNG and beyond

Mark Vogelsberger



Perimeter Institute, December 2019

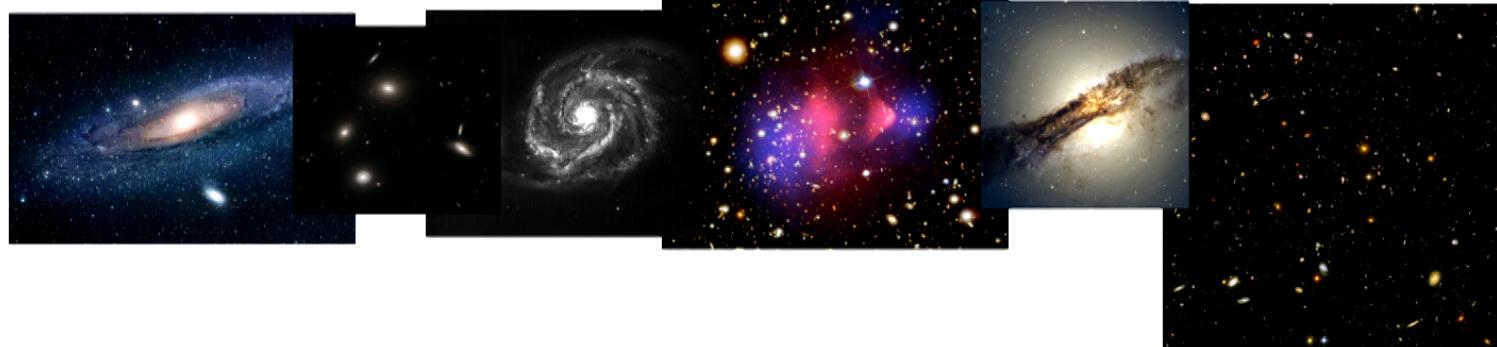


Introduction:

Cosmological Galaxy Formation Simulations

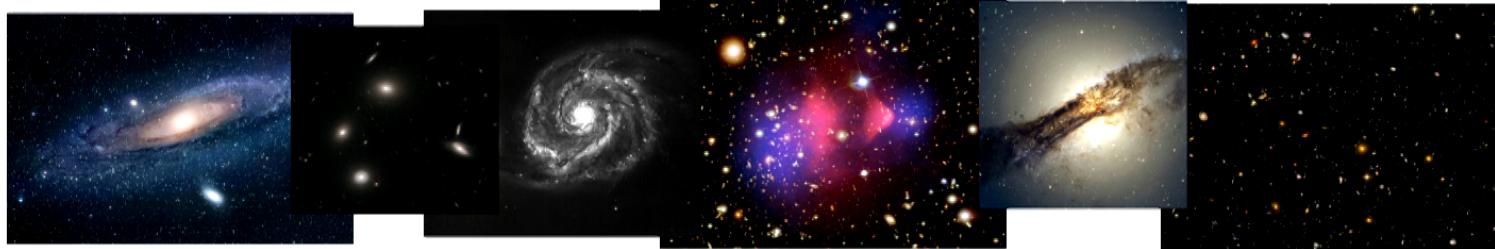
Cosmological Galaxy Formation Simulations

Goal: A theoretical and computational framework to understand how structures and galaxies in the Universe form and evolve starting from the smooth initial conditions of the early Universe.



Cosmological Galaxy Formation Simulations

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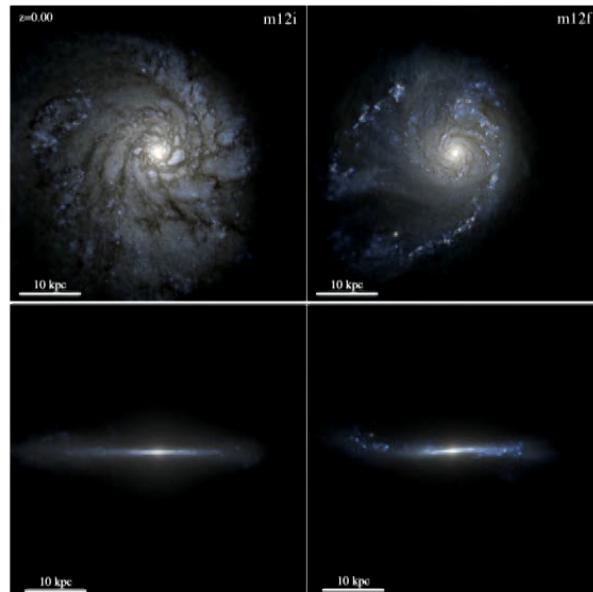


Complexity of the problem requires cosmological simulations:

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

Two Approaches: Bottom-Up vs. Top-Down

Bottom-Up / Small-scale Simulations:

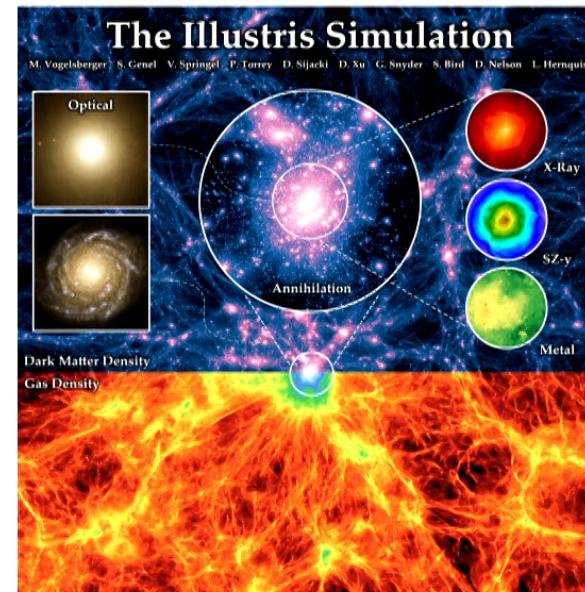


model small scales: approach large scales

pro:
detailed effective models for physical processes

con:
limited statistics to confront with observations

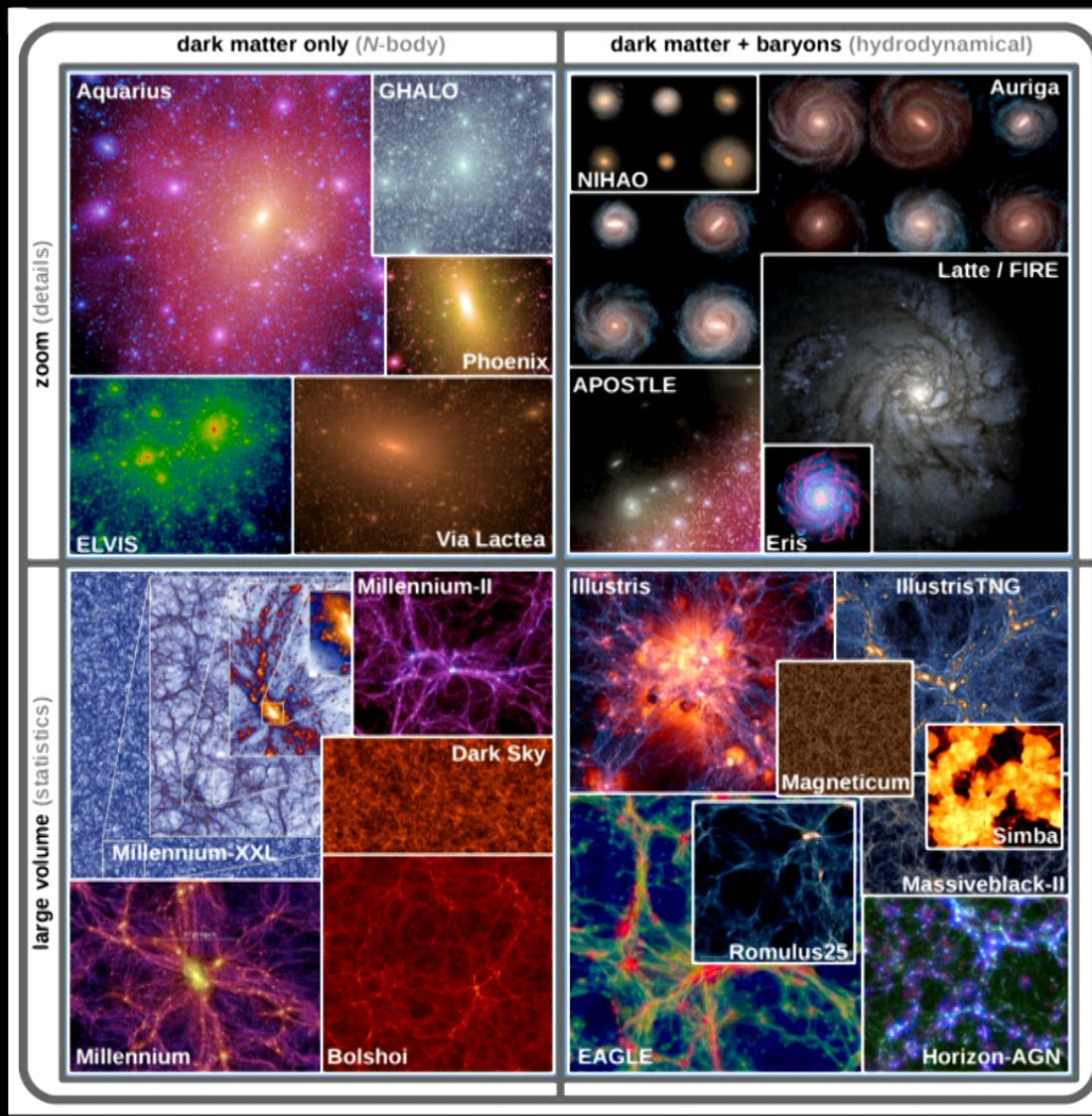
Top-Down / Large-scale Simulations:



model large scales: approach small scales

pro:
lots of statistics to compare with data

con:
rely on calibrated effective models

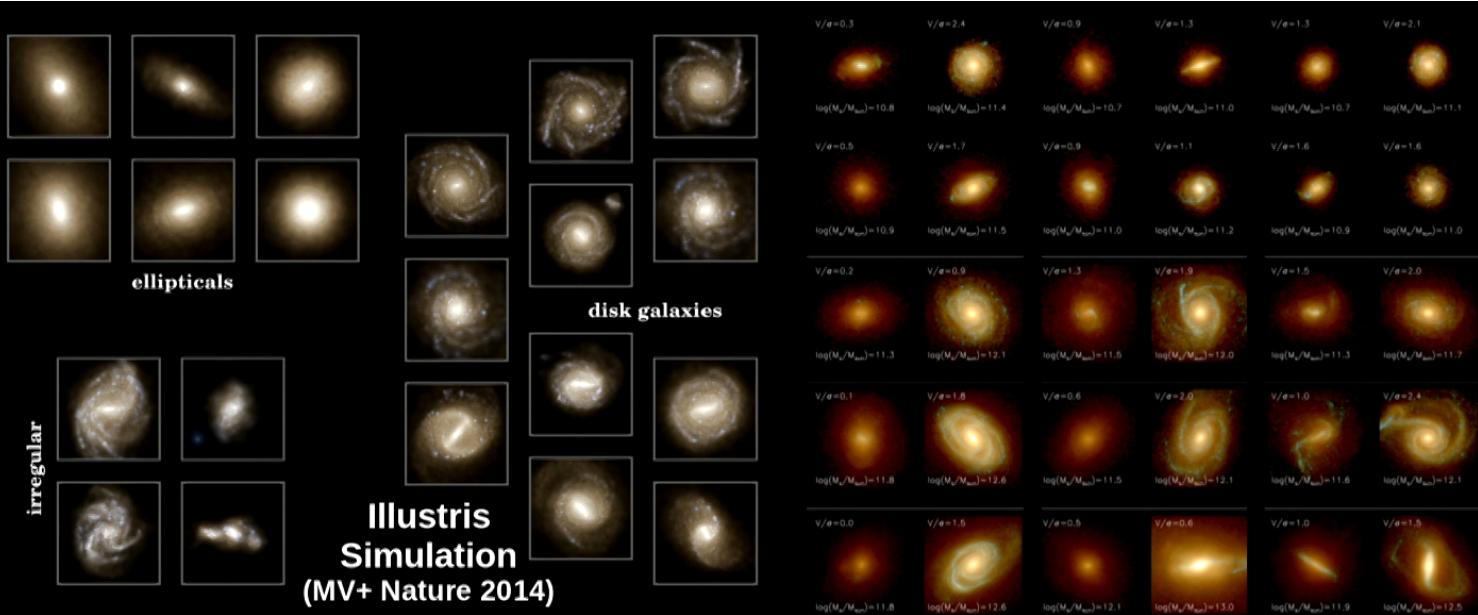


MV, Marinacci,
Torrey, Puchwein

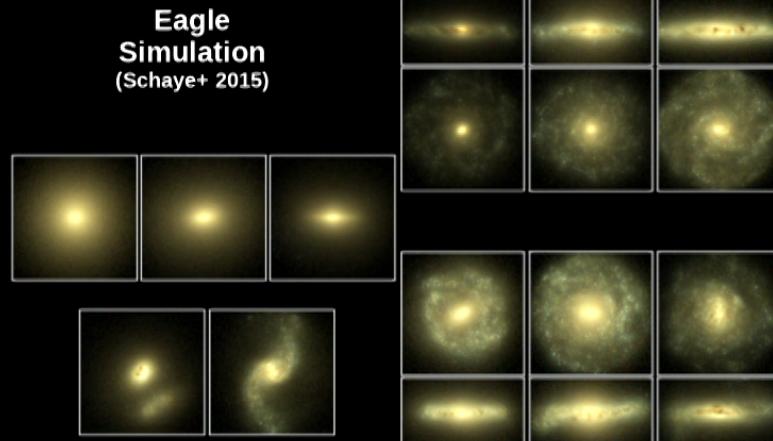
Nature Reviews Physics 2020

Large-Scale Cosmological Simulations

Mirrored Displays



Illustris
Simulation
(MV+ Nature 2014)

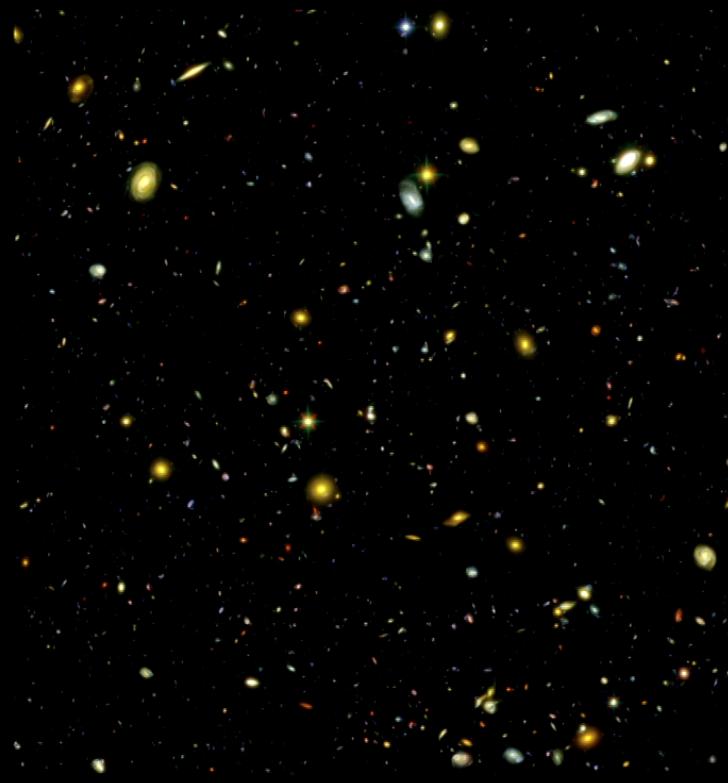


Eagle
Simulation
(Schaye+ 2015)

Horizon-AGN
Simulation
(Dubois+ 2016)

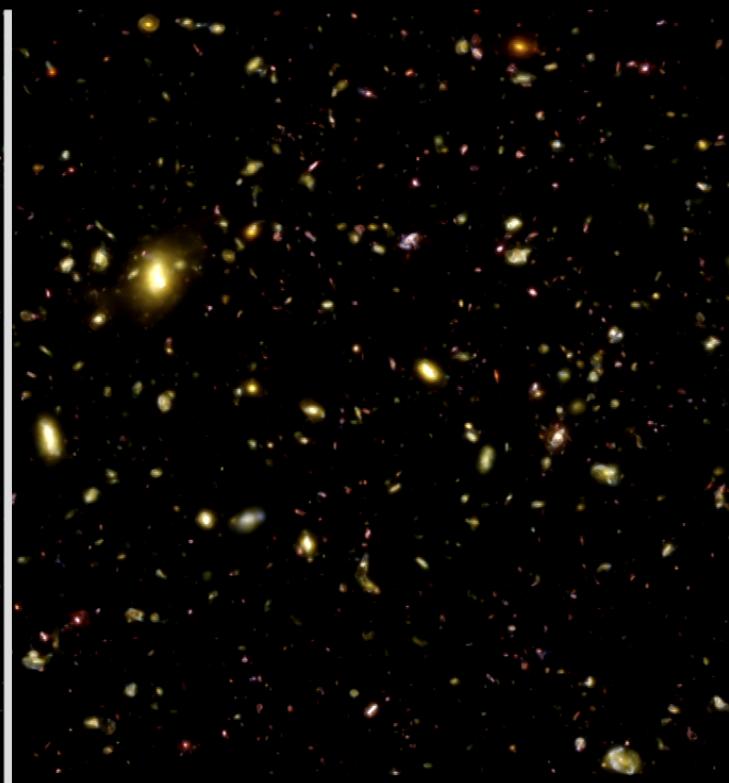
Illustris started
the era of large-scale
cosmological simulations

Mock Observations: Real vs. Virtual Universe

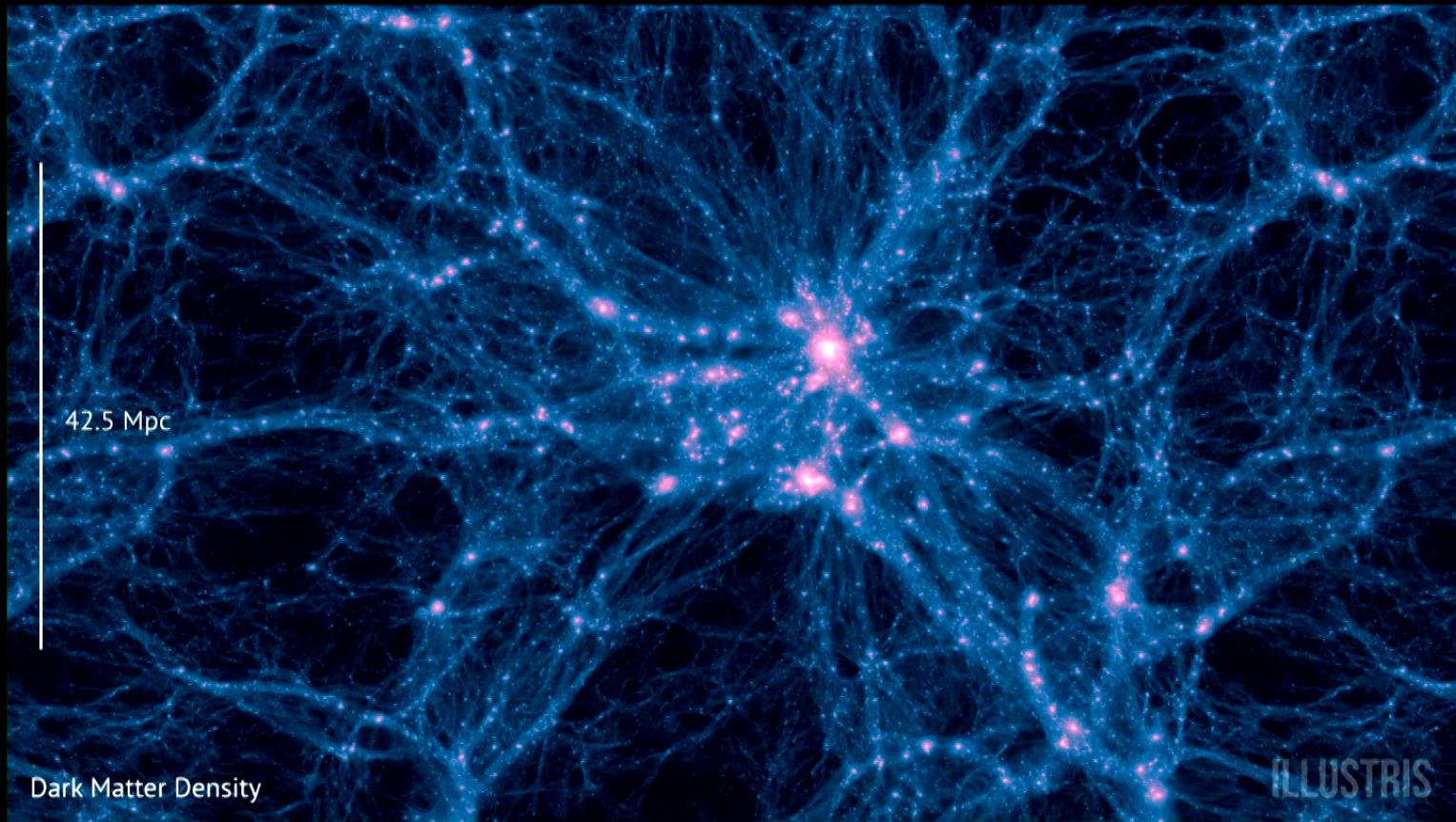


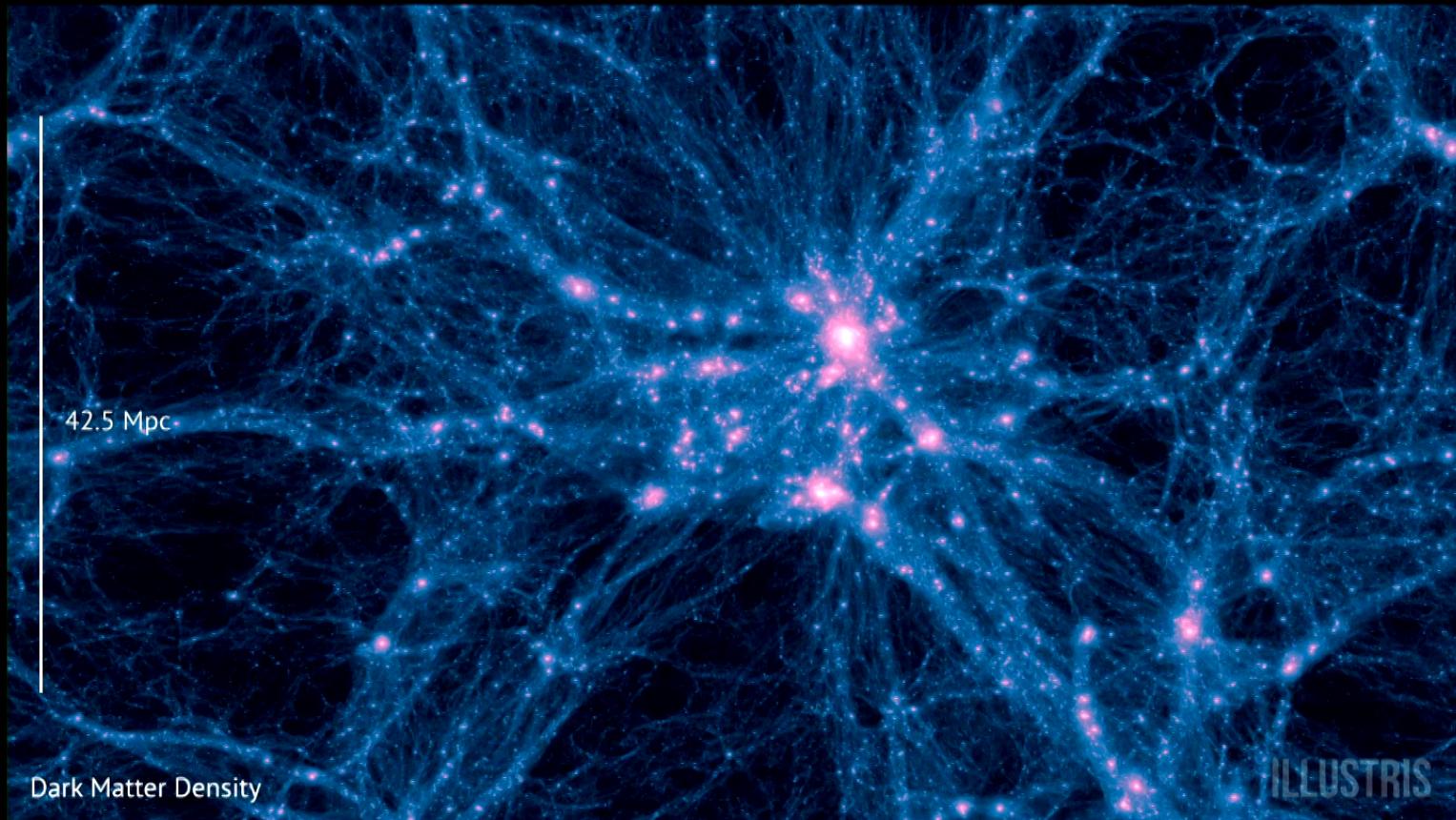
Hubble Space Telescope

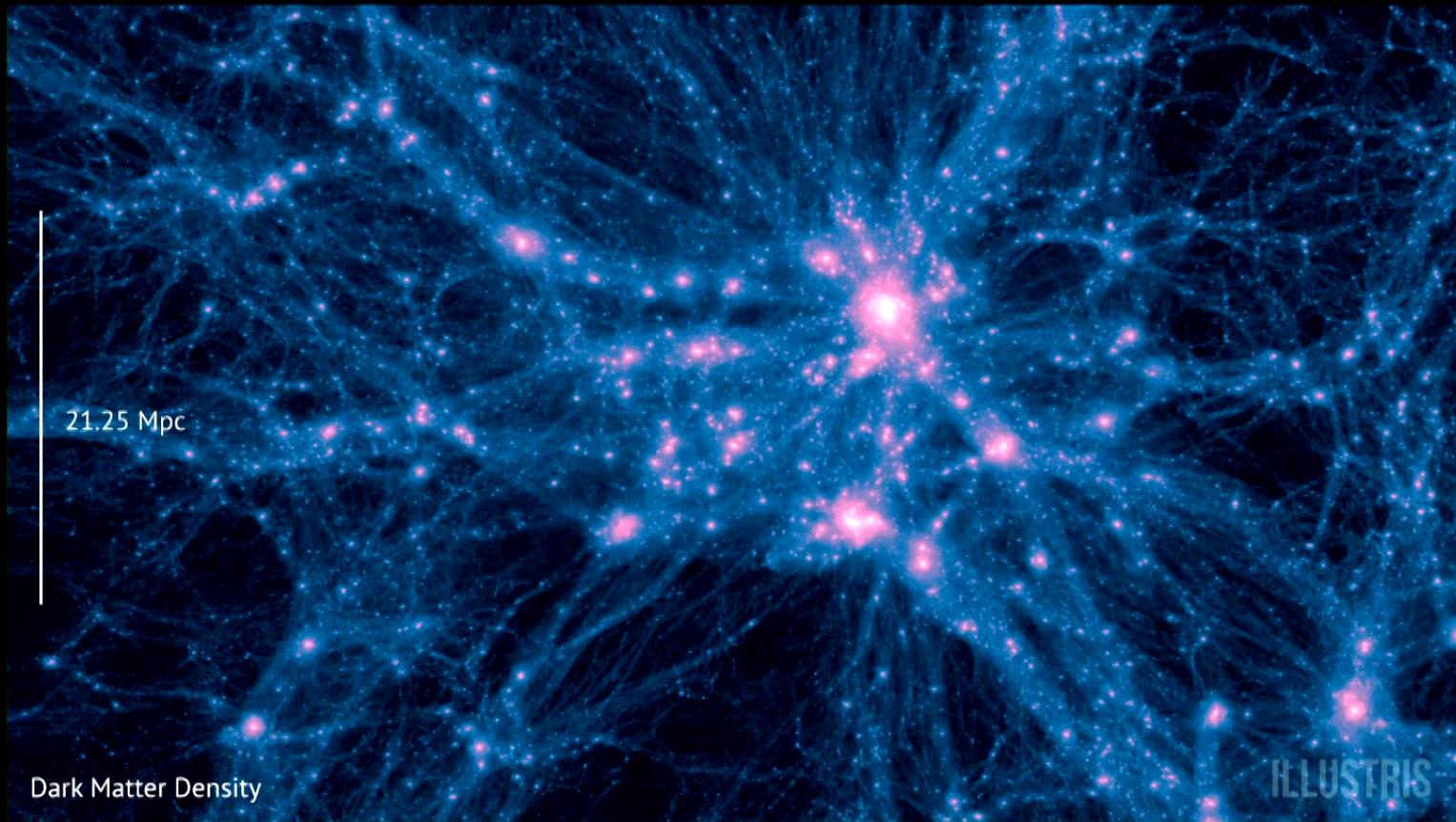
MV+ Nature 2014

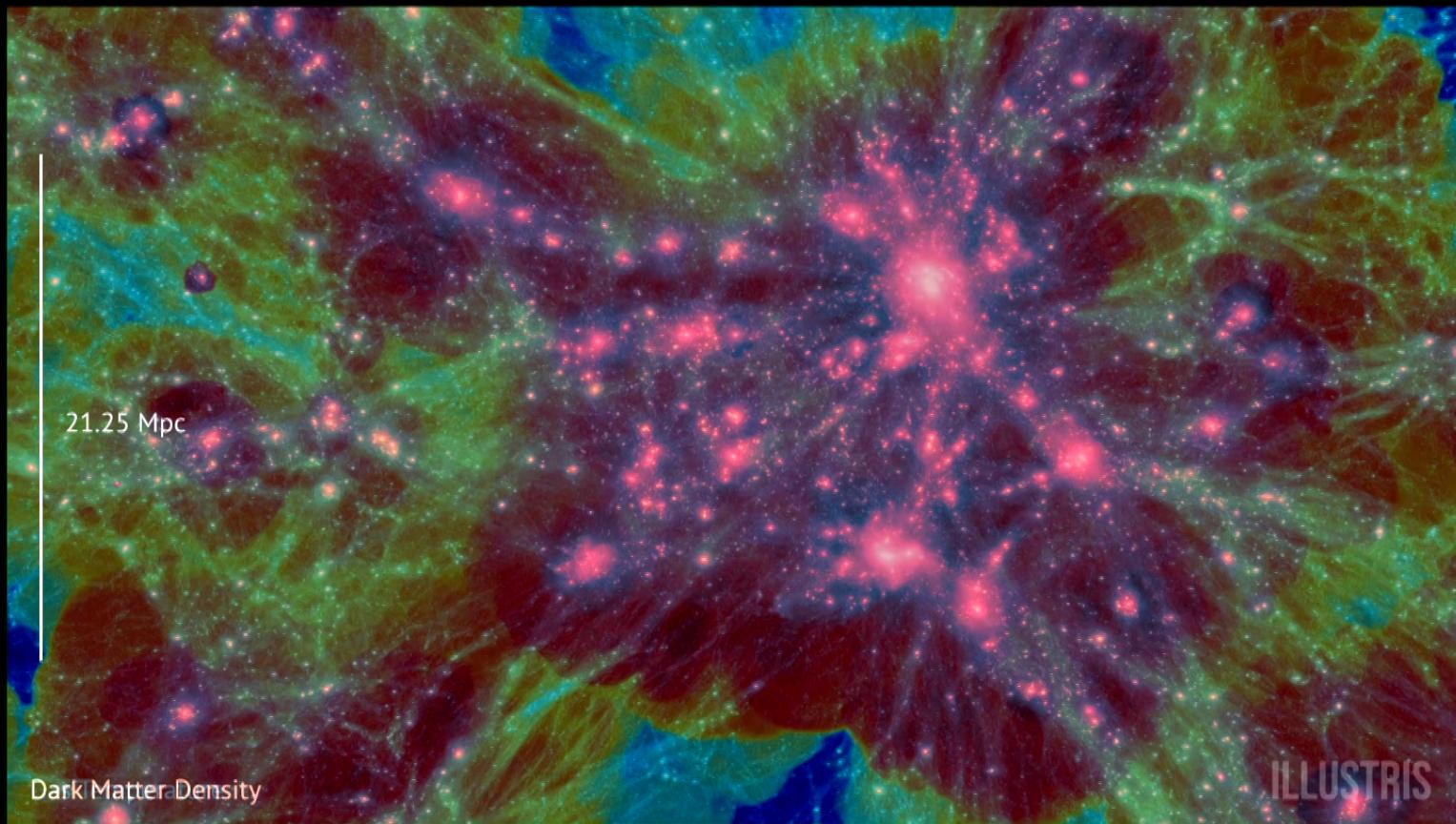


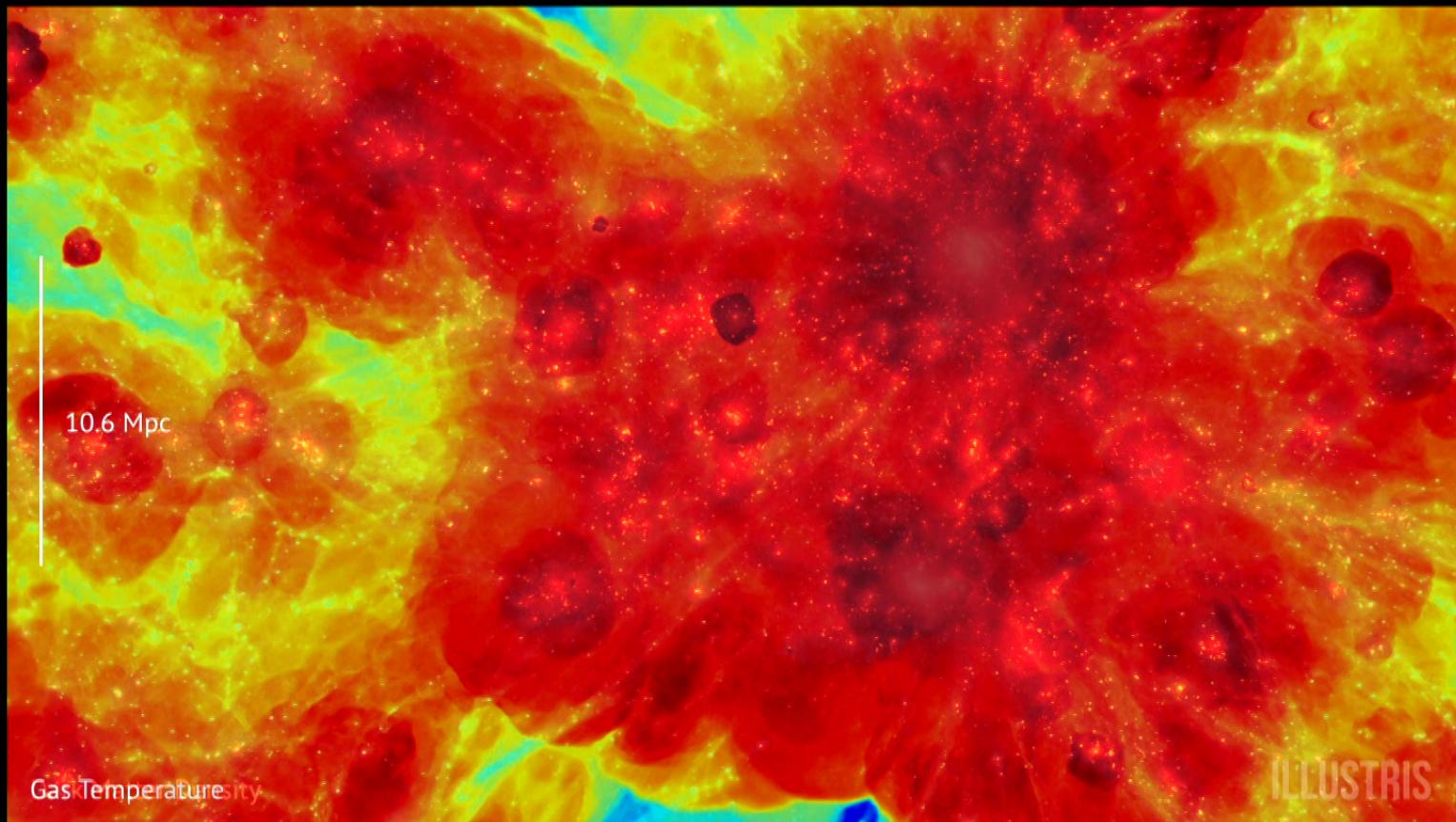
Illustris

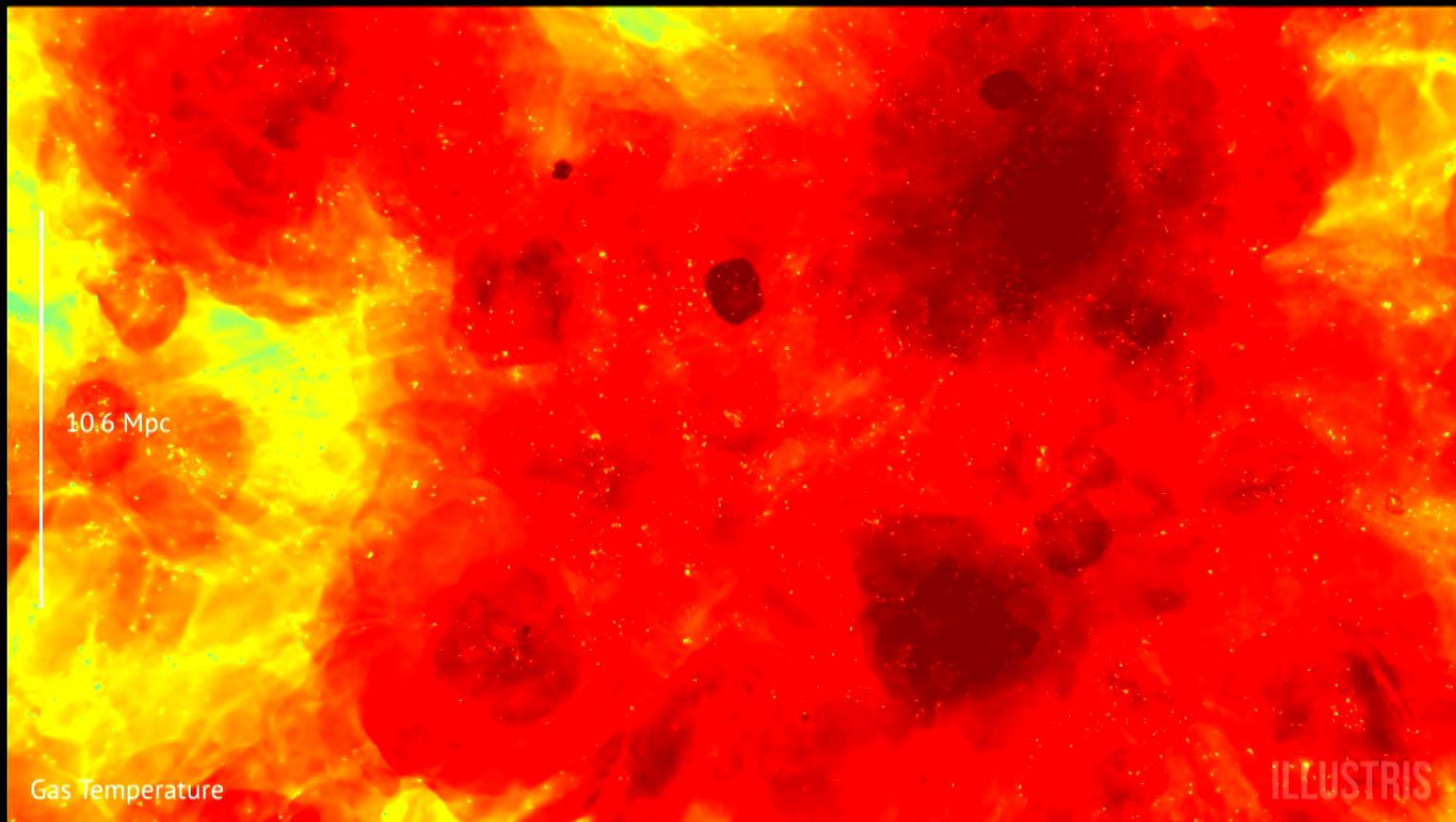


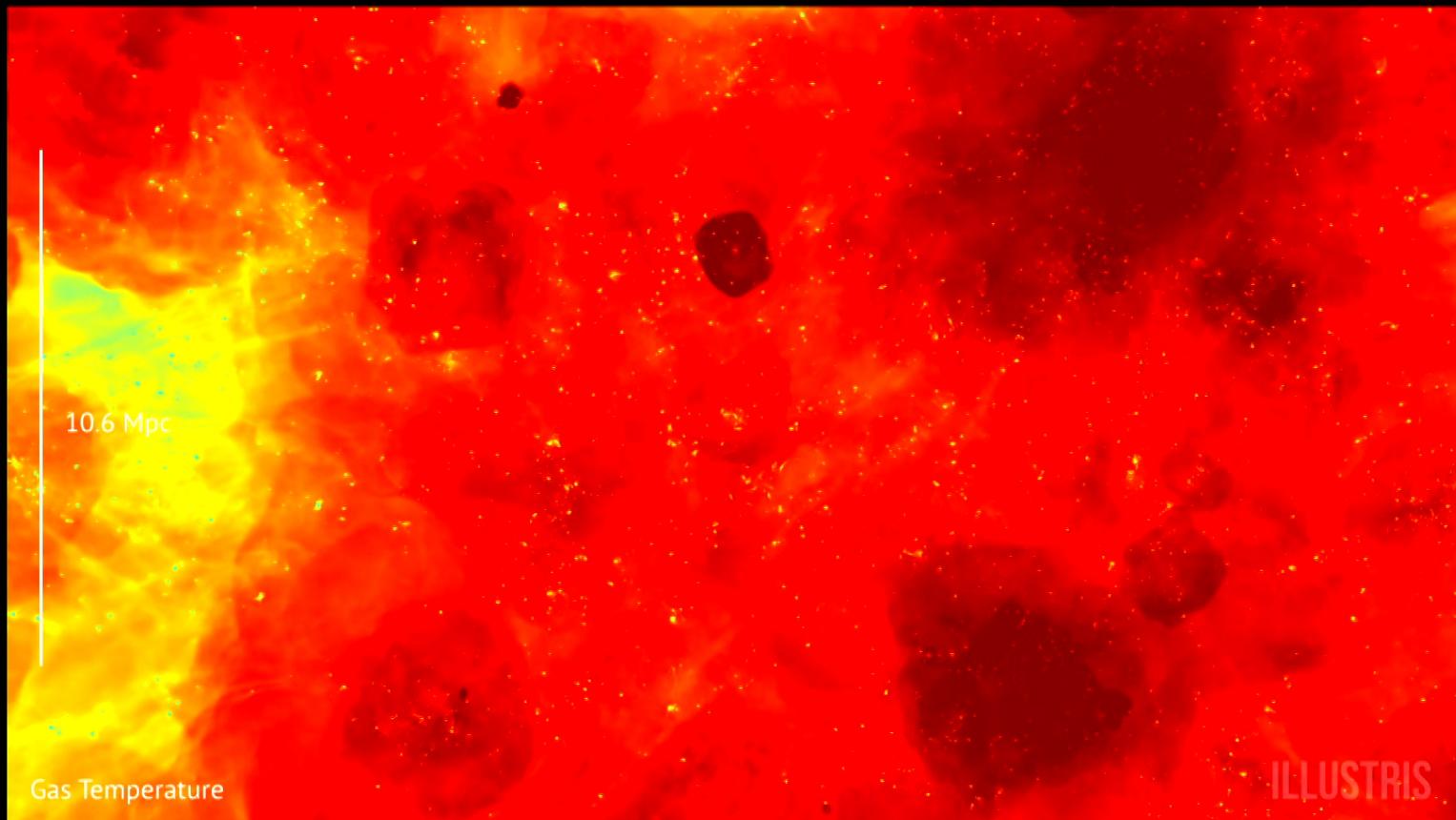


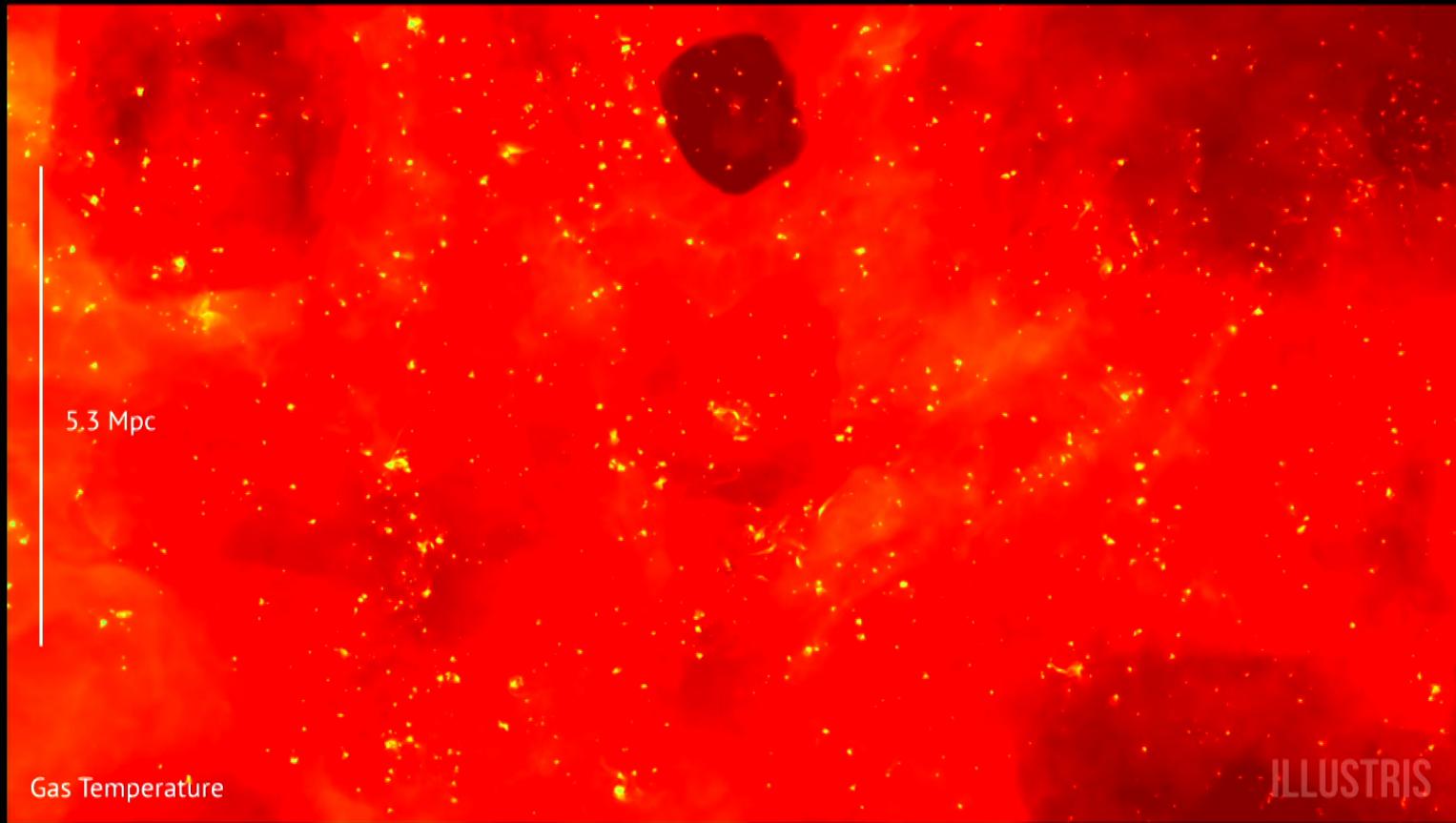


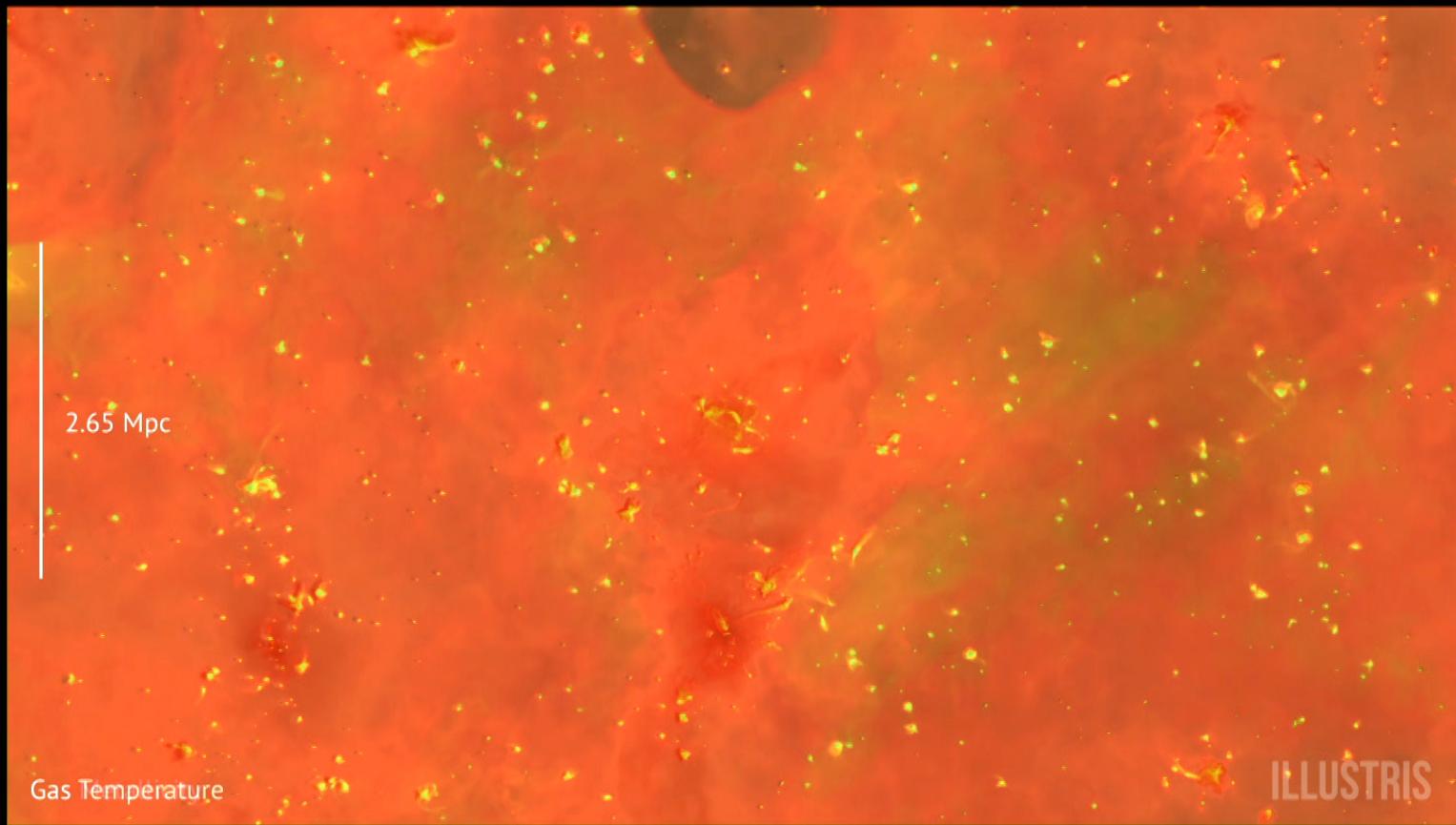


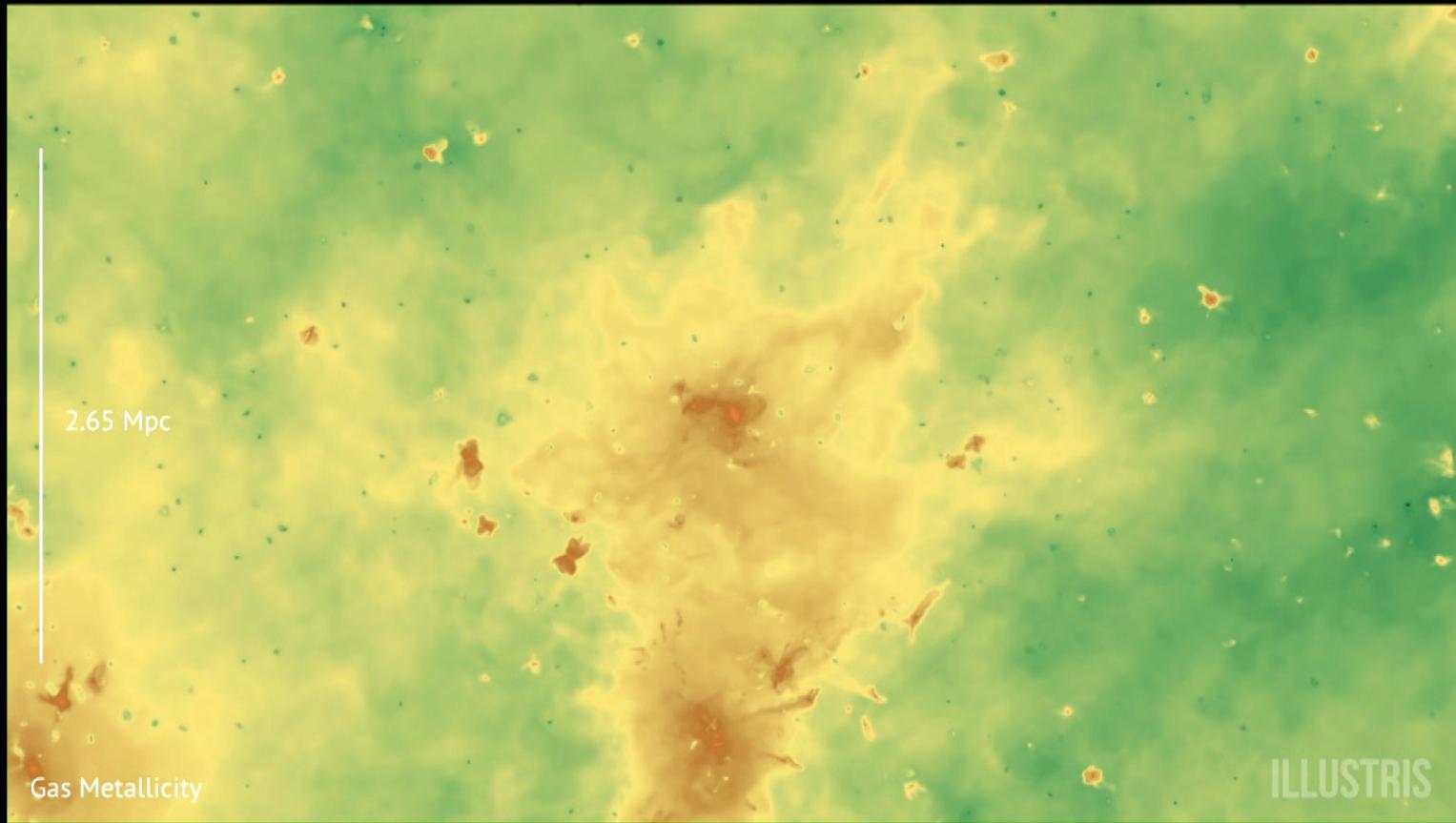


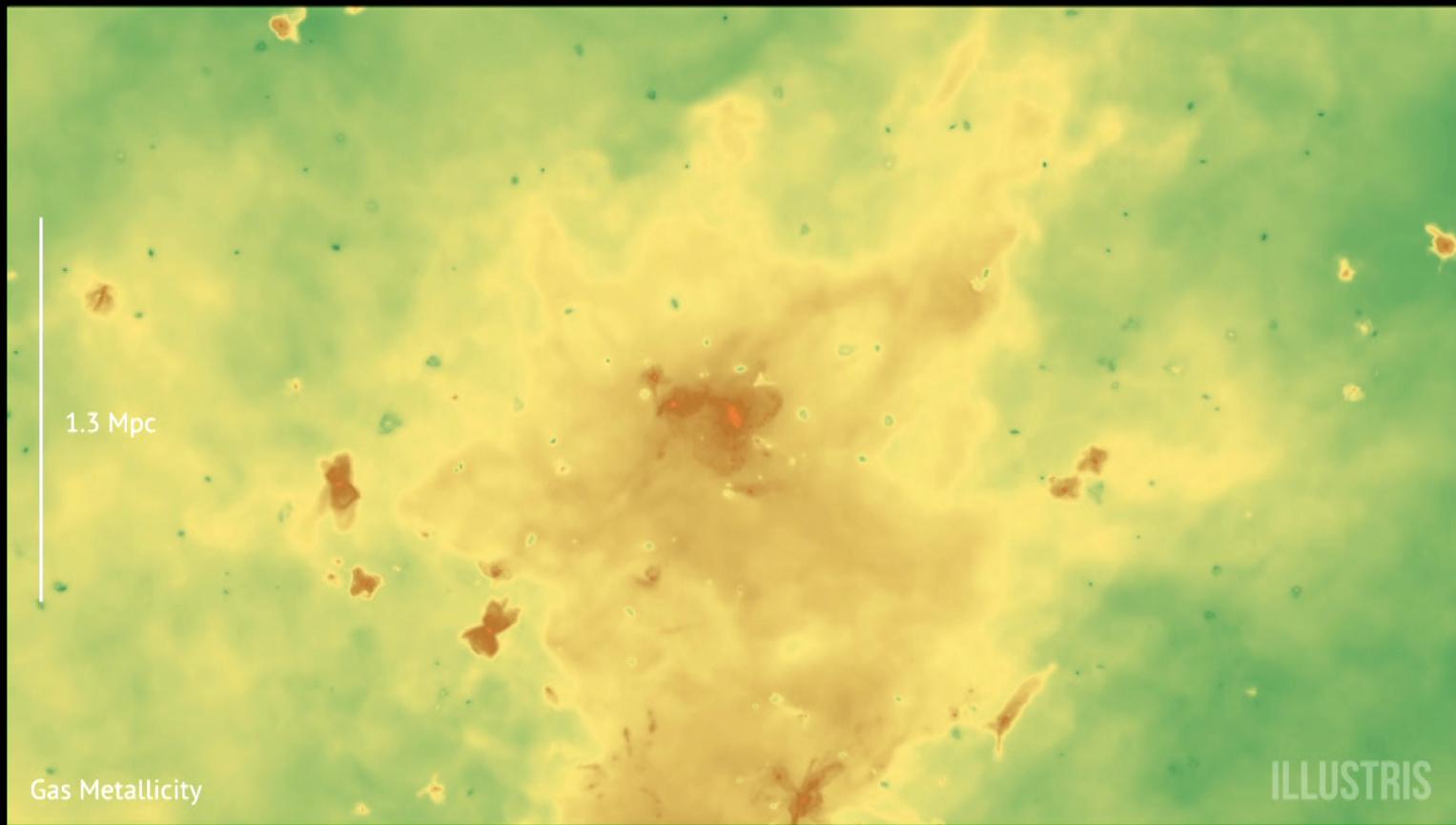


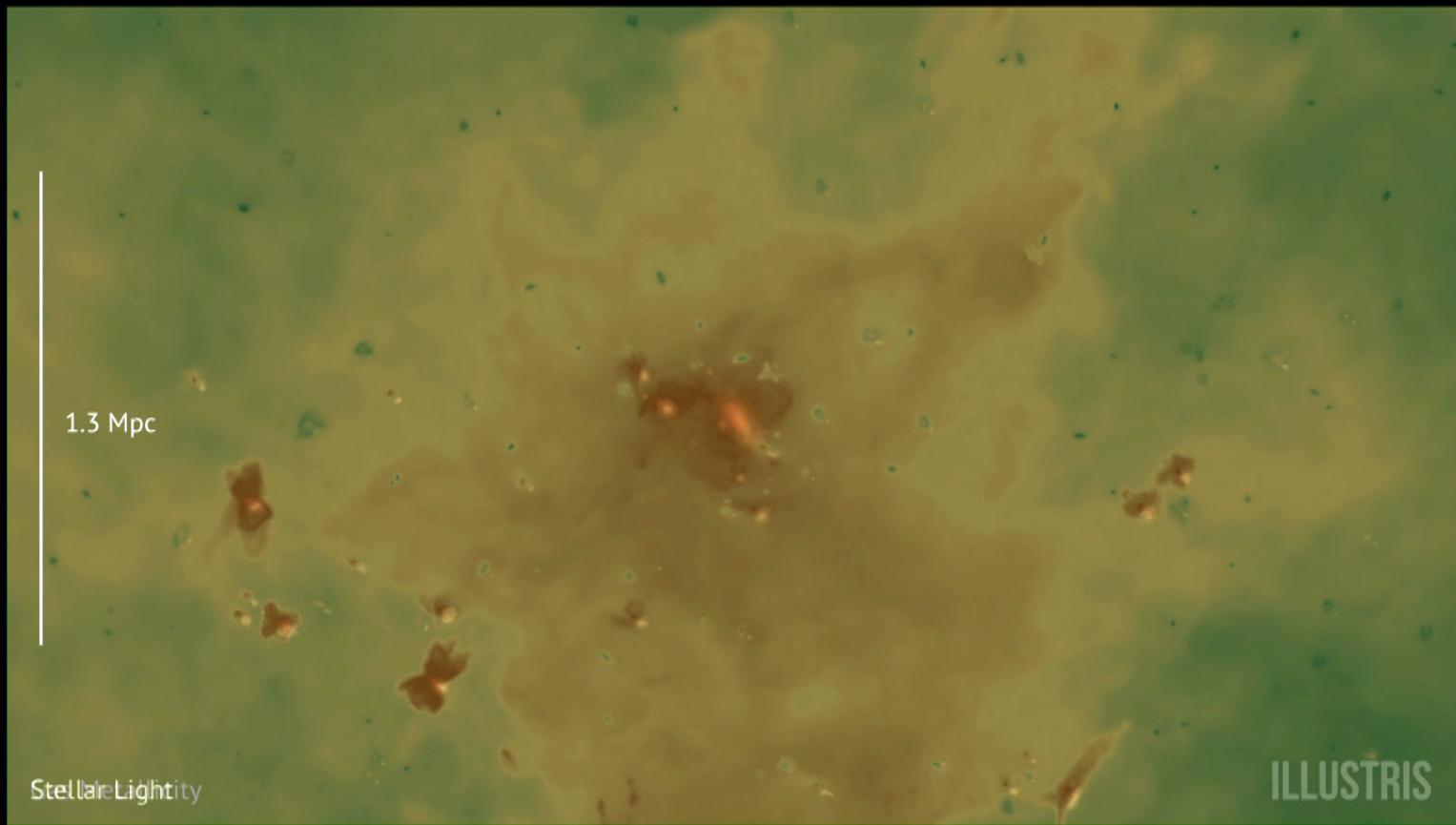






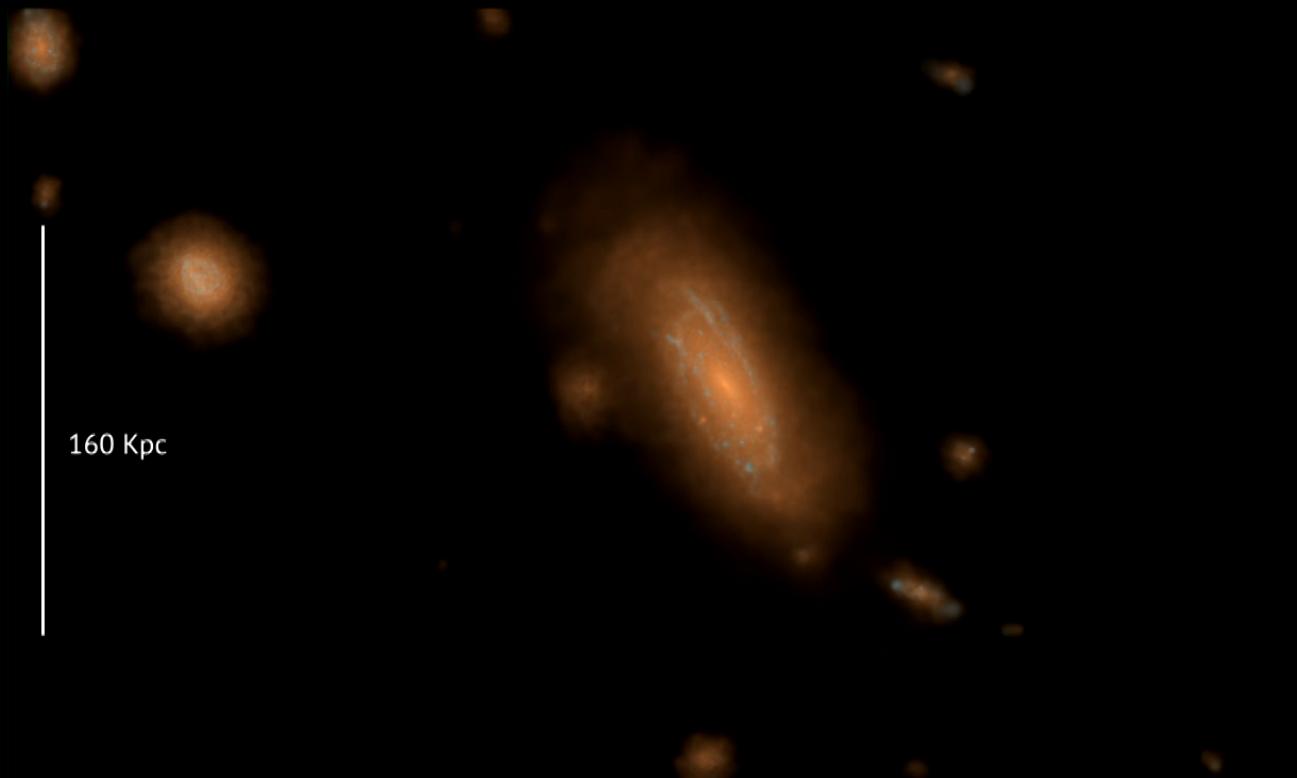










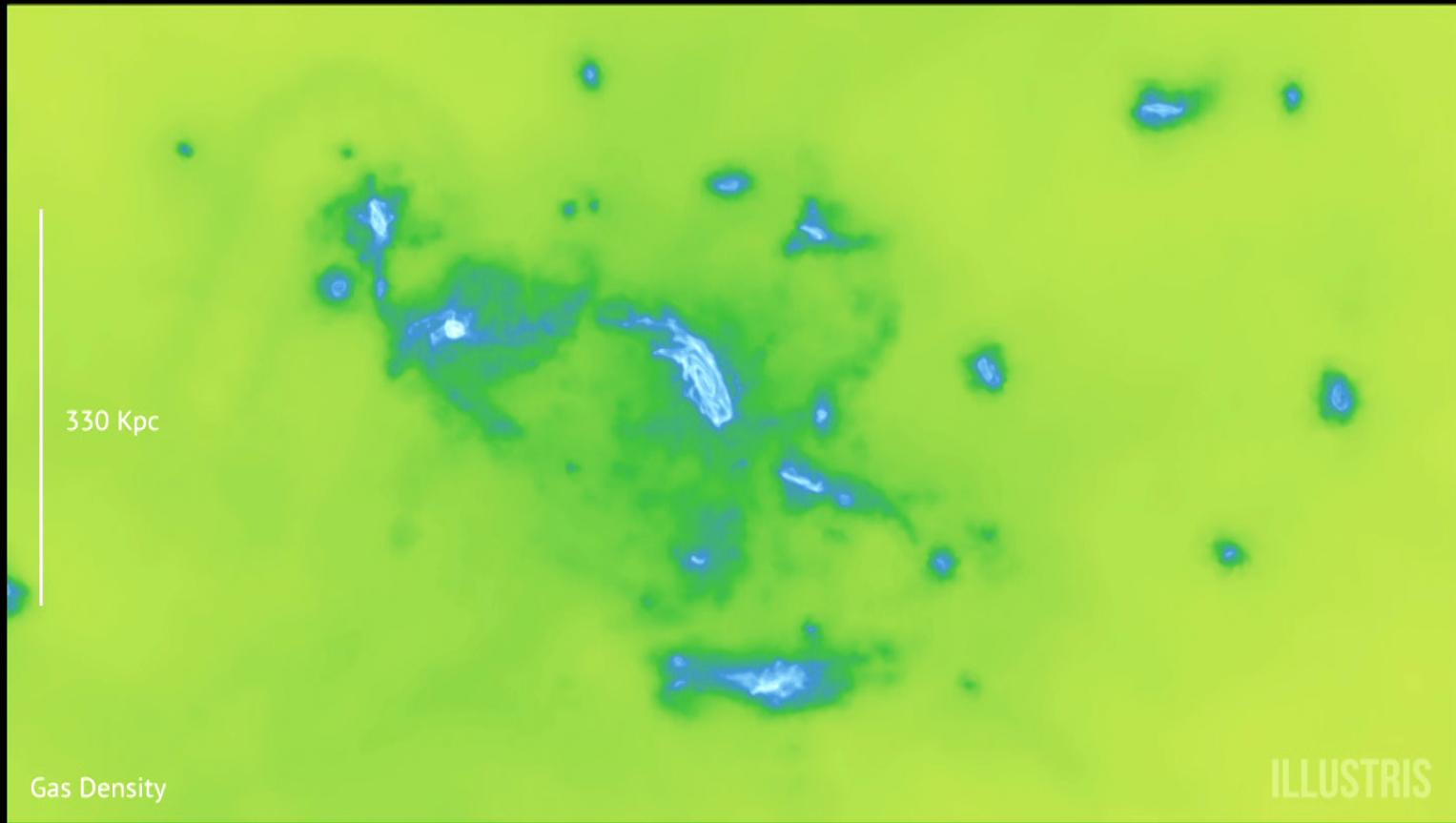


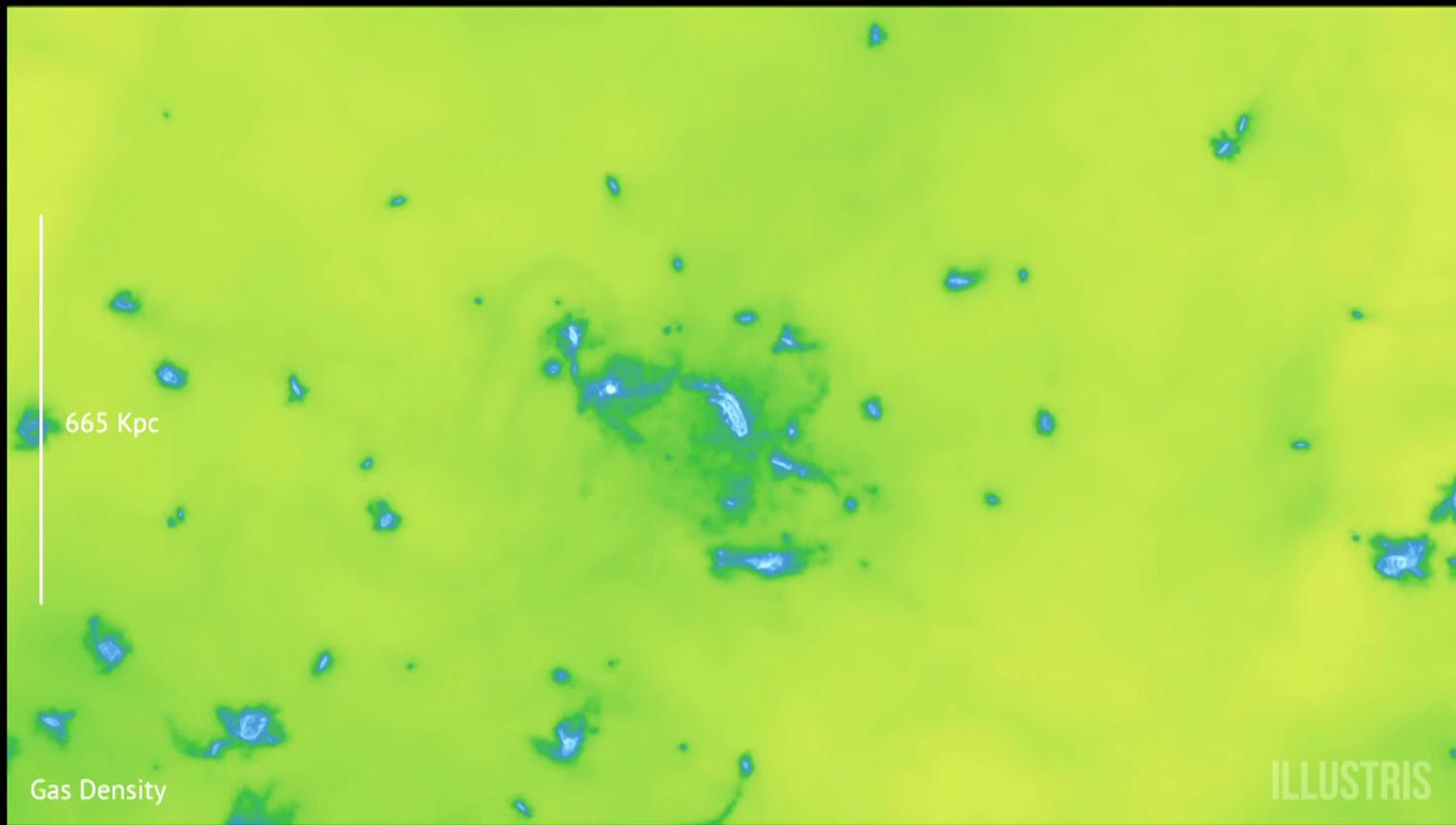
80 Kpc

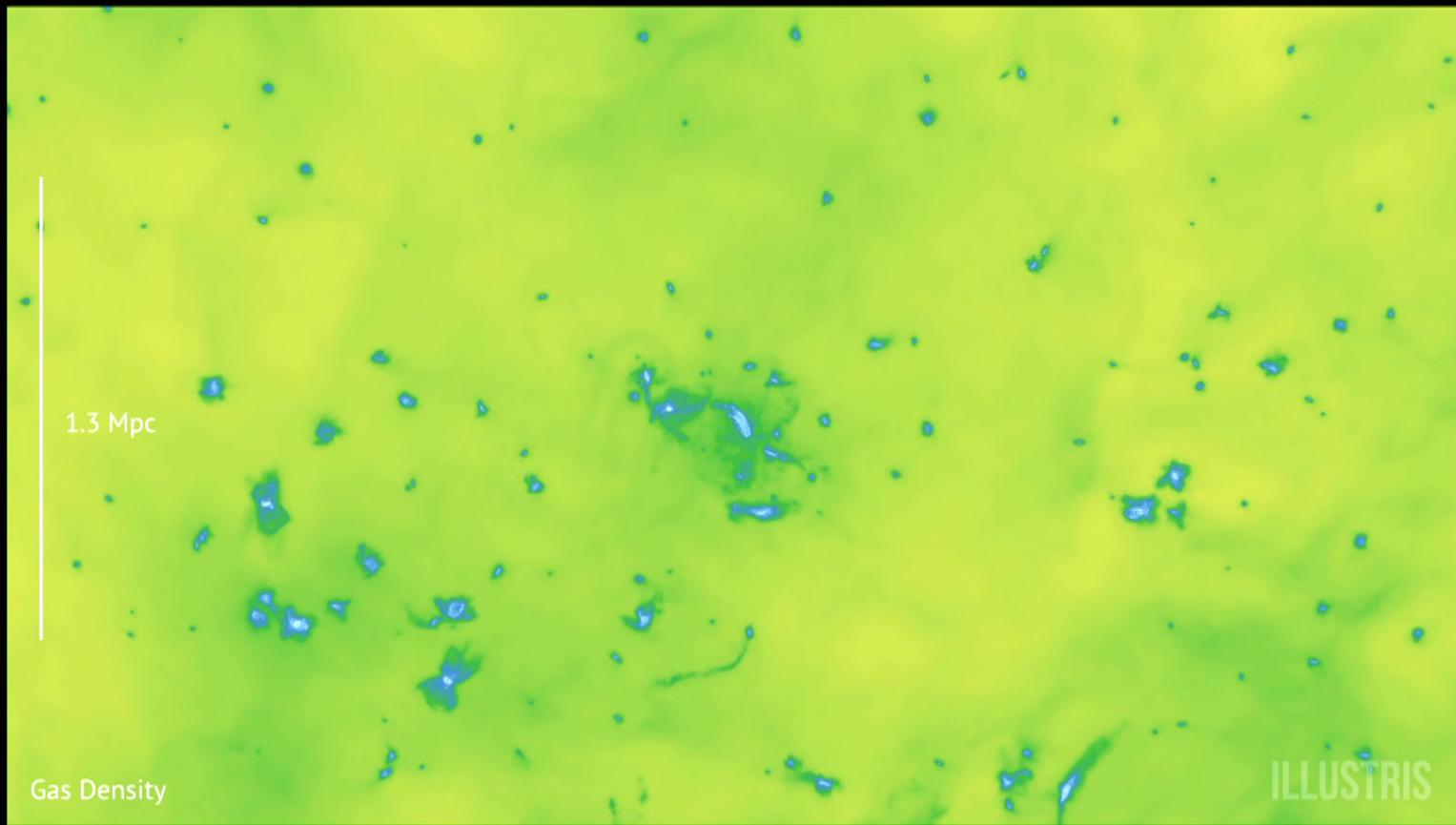
Stellar Light

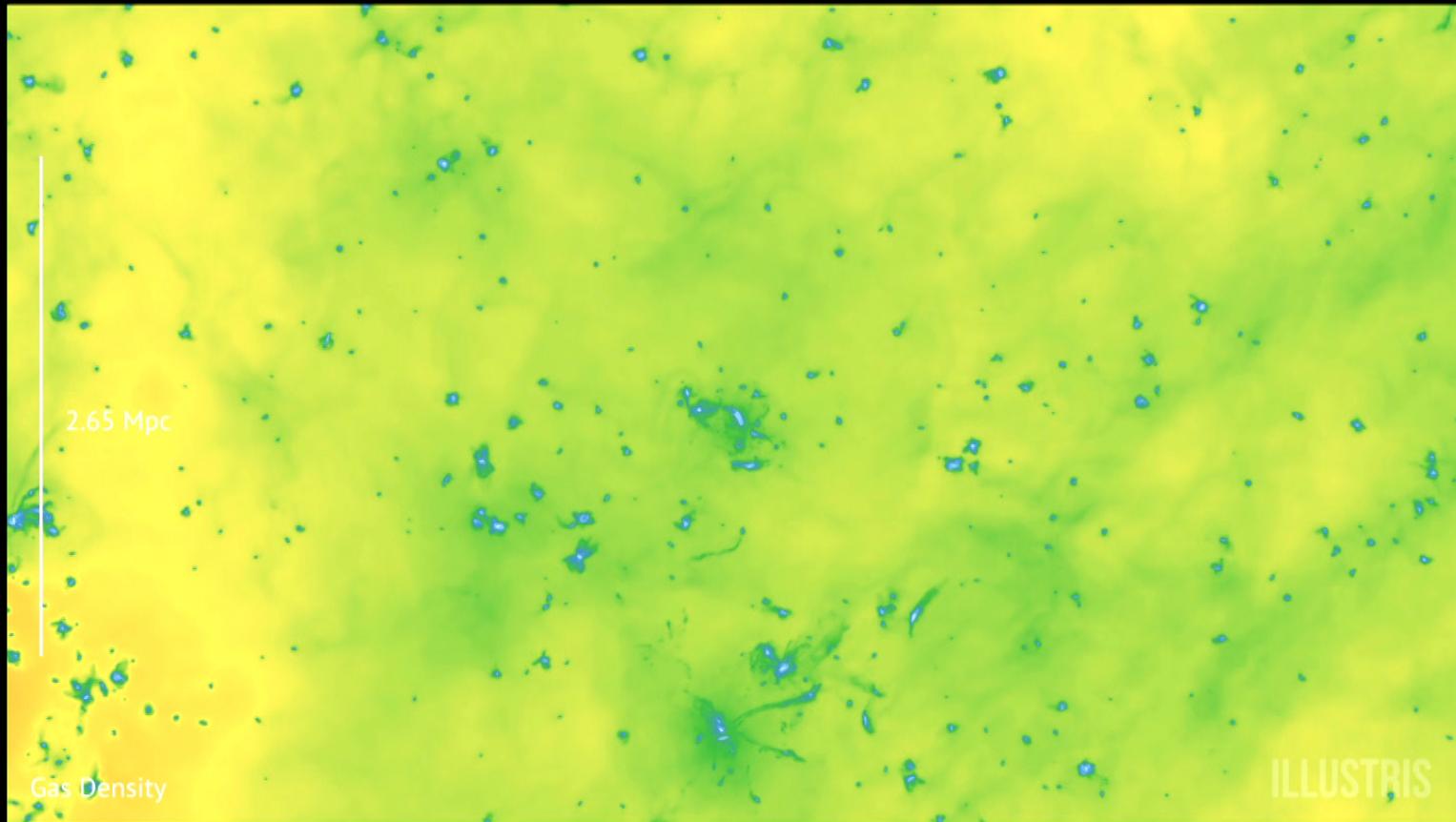
ILLUSTRIS

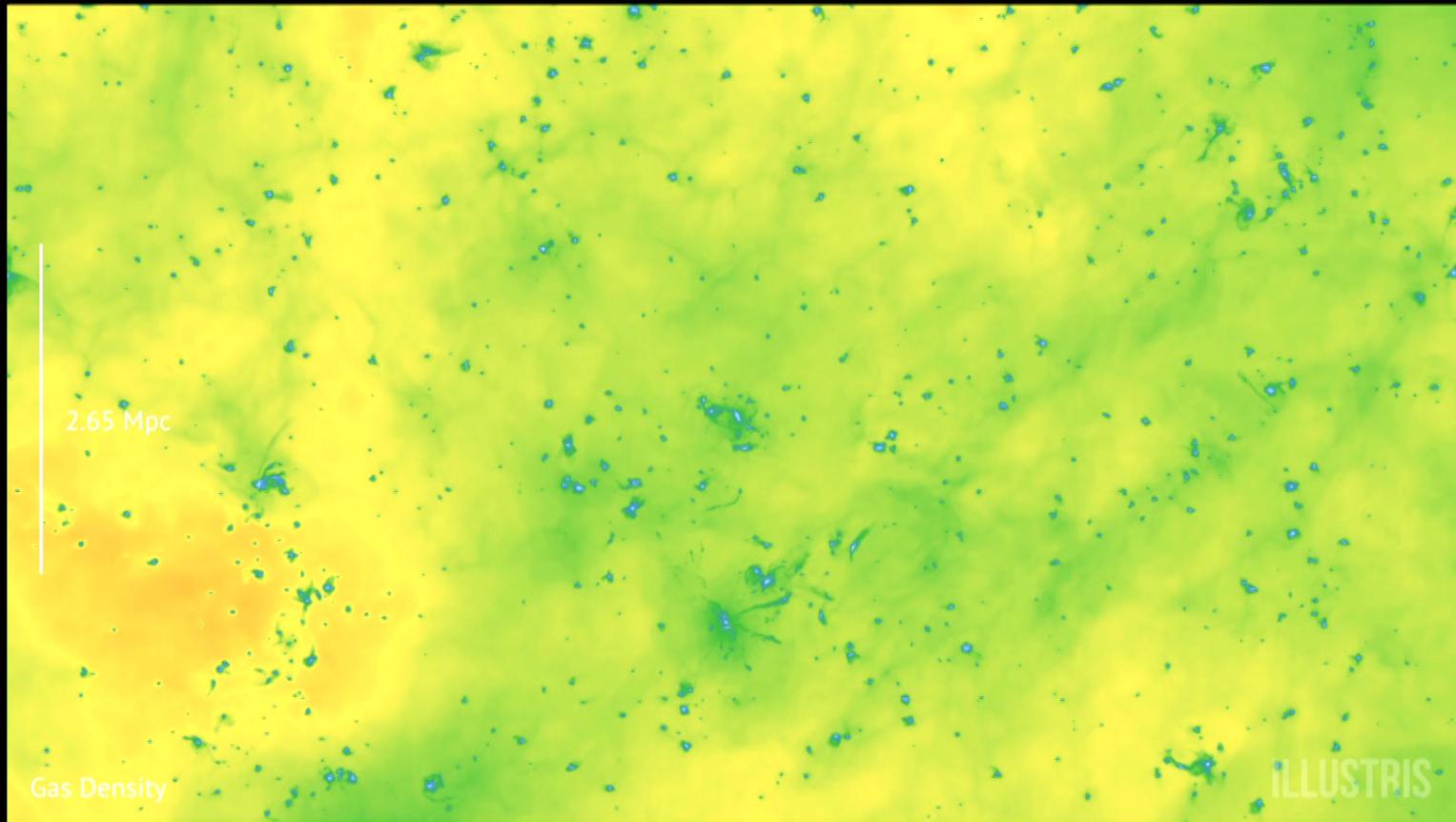








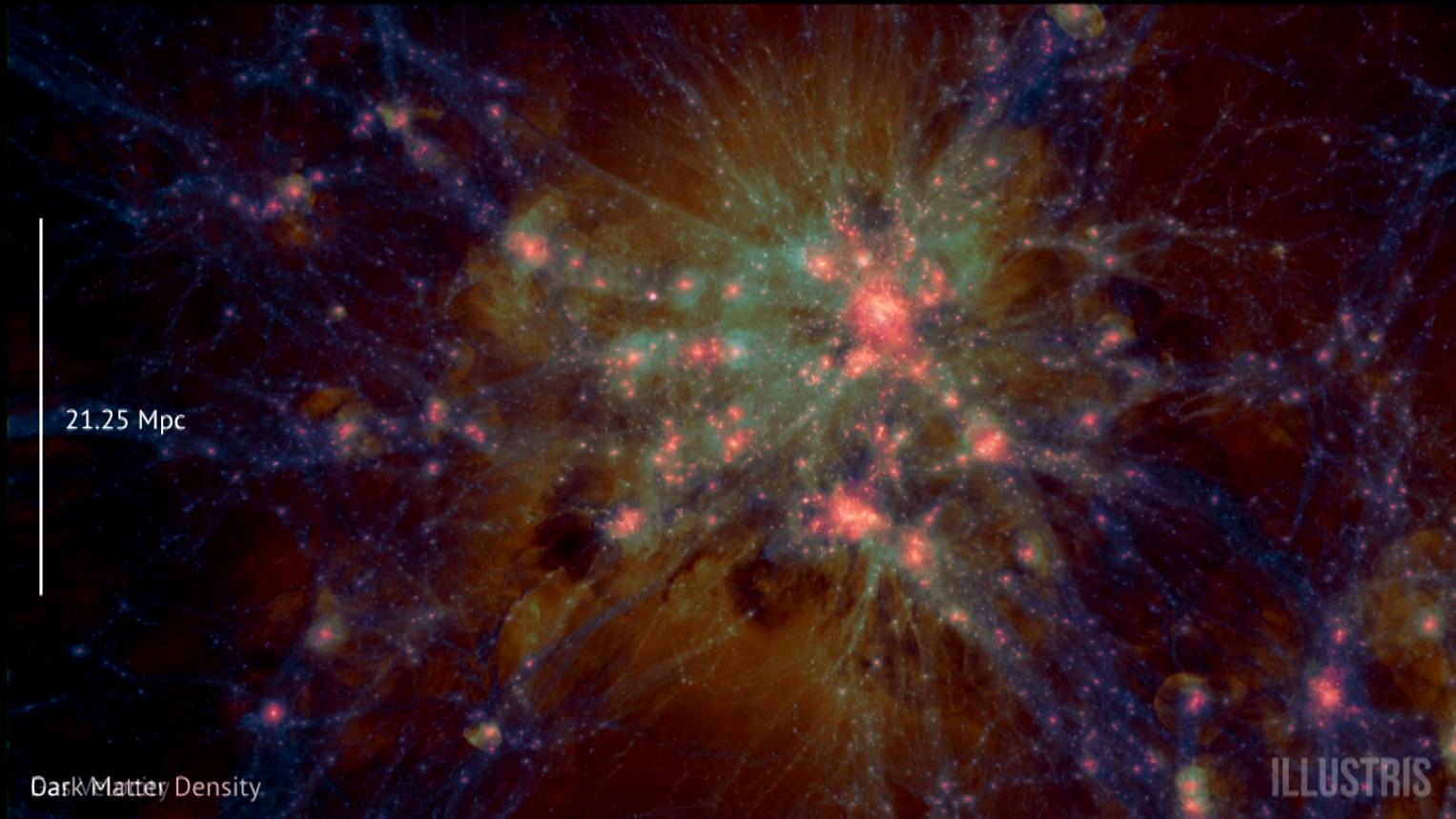


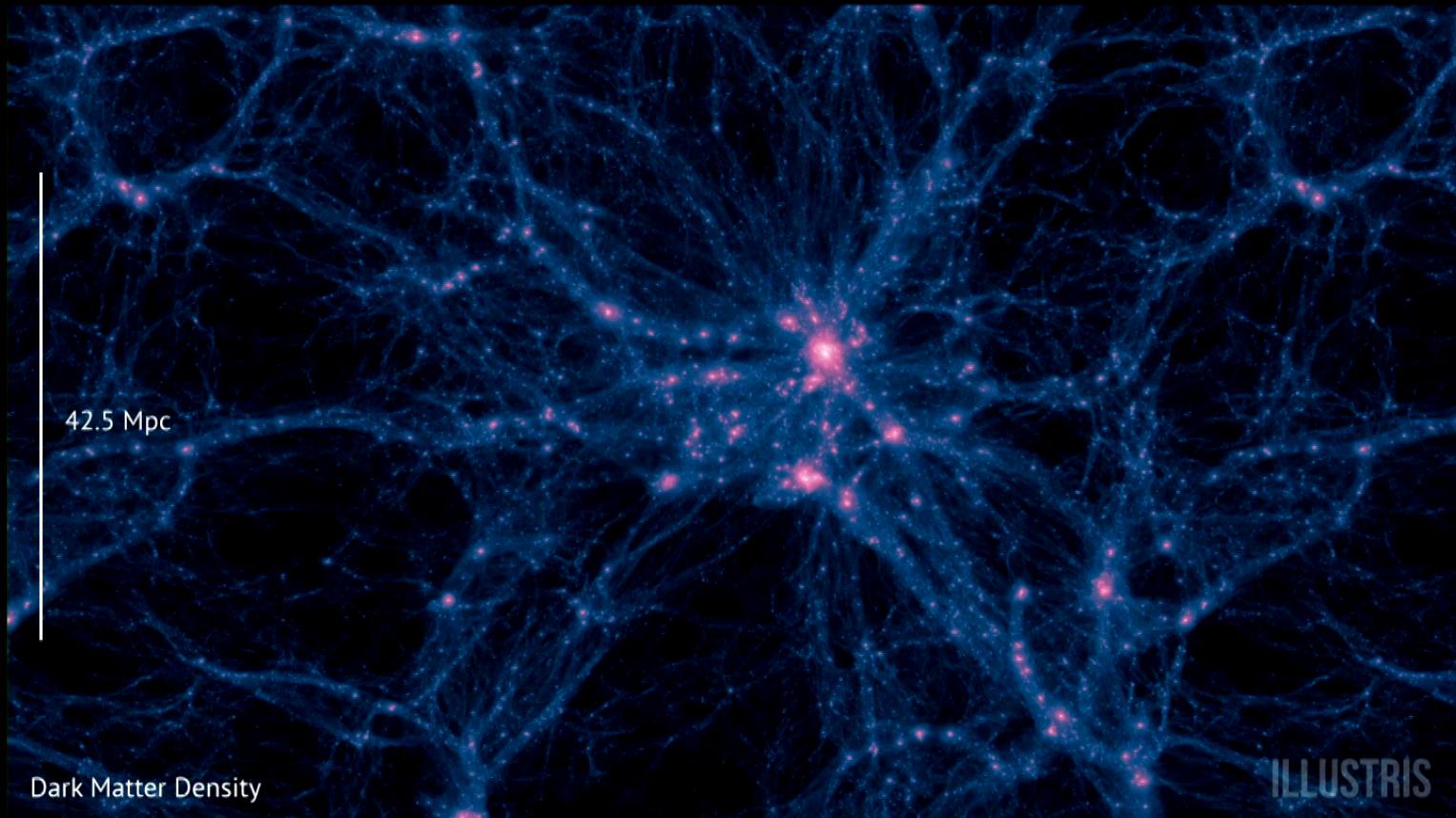


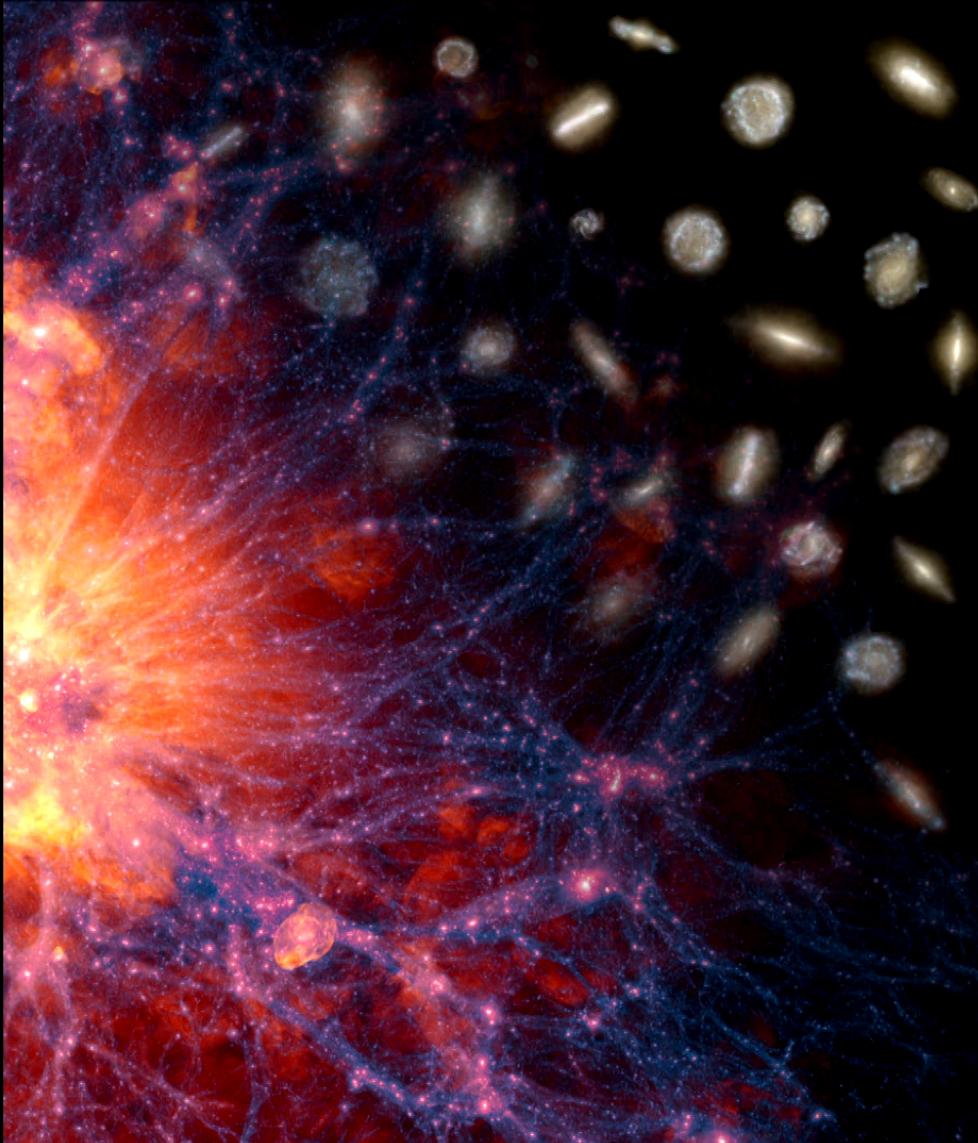








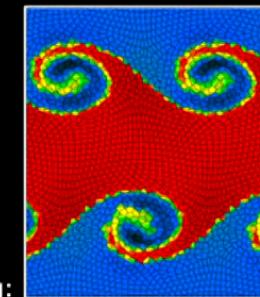




Illustris Model: - basic ingredients -

- hydrodynamics:
quasi-Lagrangian finite volume moving mesh scheme
(Arepo, Springel 2010)
- heating / cooling:
primordial, metal
- UV background:
with self-shielding correction
- star formation / ISM:
effective EOS / probabilistic
- chemical enrichment:
SNIa, SNII, AGB
- supernova feedback:
SNIa, SNII feedback
- supermassive black holes:
seeding, growth, merging
- AGN feedback:
quasar, radio mode, radiative
- novel Monte Carlo tracer particles:
to follow gas mass flows

MV+ 2013, 2014
Torrey, MV+ 2014



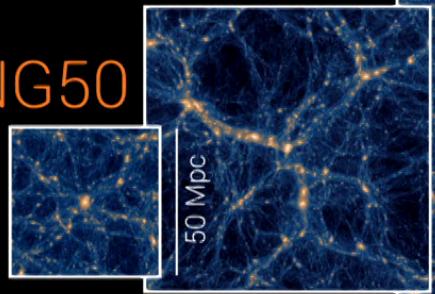
The IllustrisTNG Simulations

Illustris galaxy formation model
+
numerical and model improvements
+
additional simulation volumes

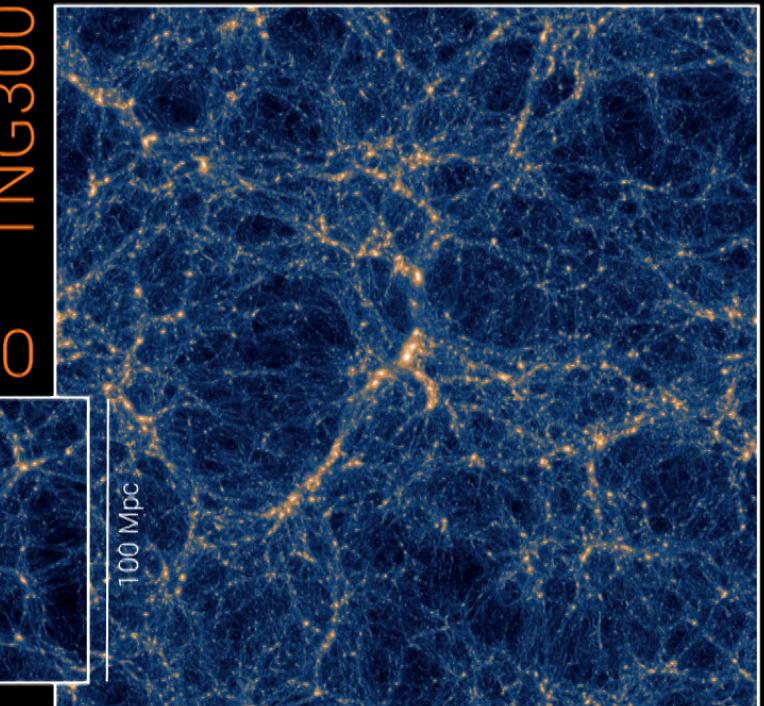
(~200 million CPU hours)

TNG100

TNG50



TNG300



300 Mpc

IllustrisTNG Team

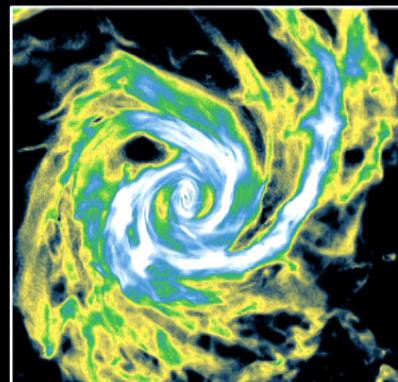
Vogelsberger, Marinacci, Torrey (MIT)

Springel, Nelson, Pakmor (MPA)

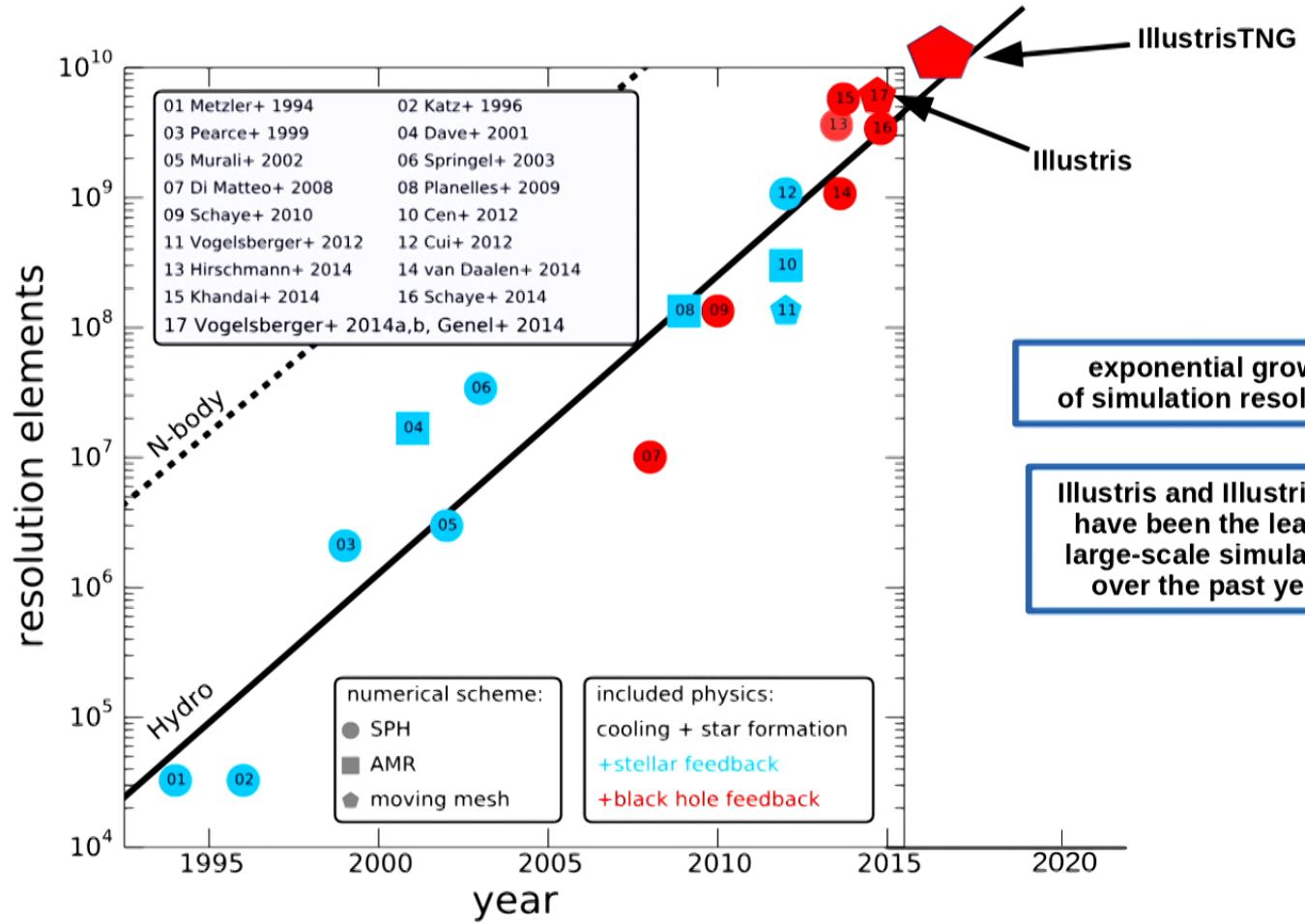
Genel (CCA)

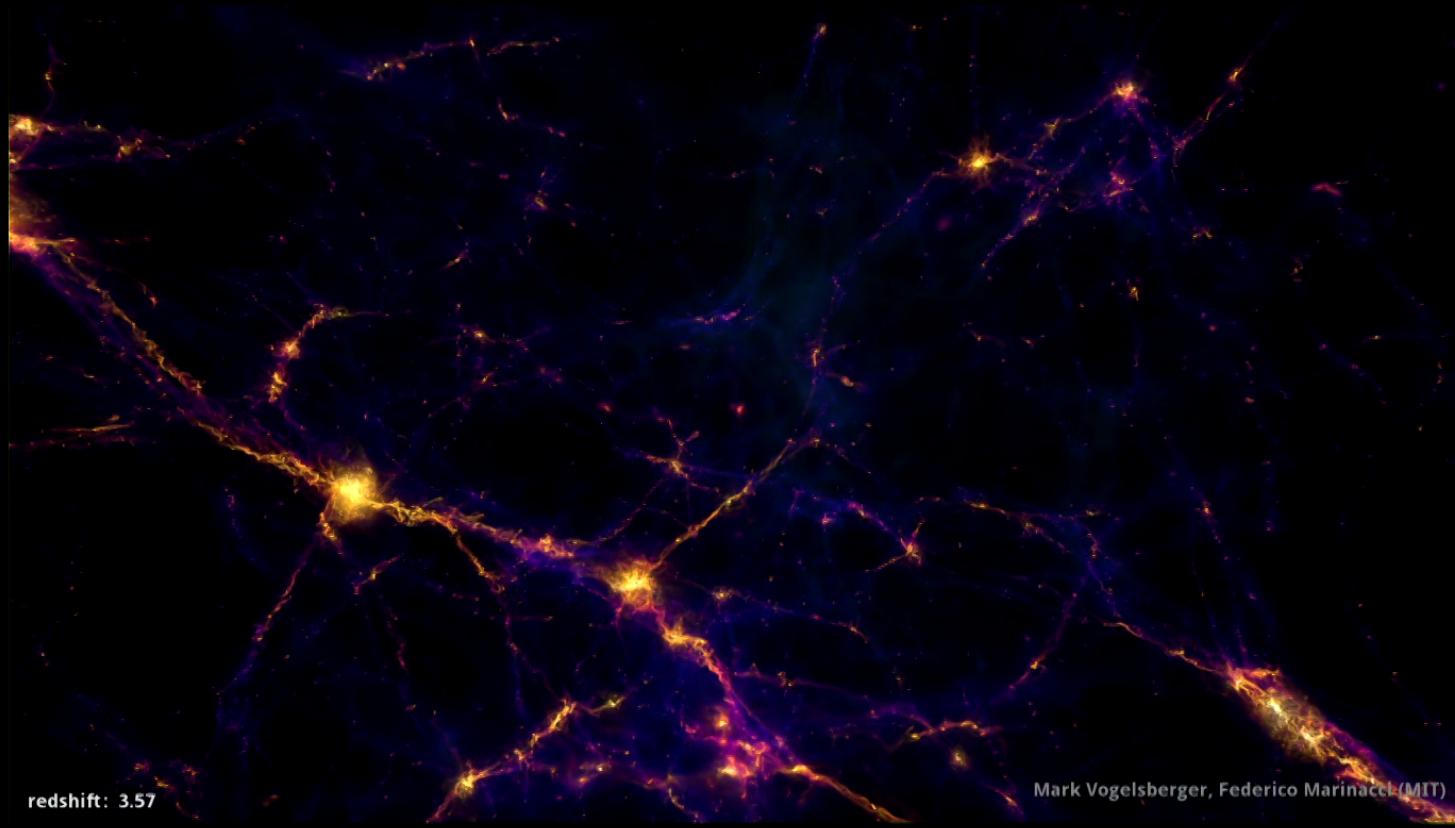
Pillepich (MPIA)

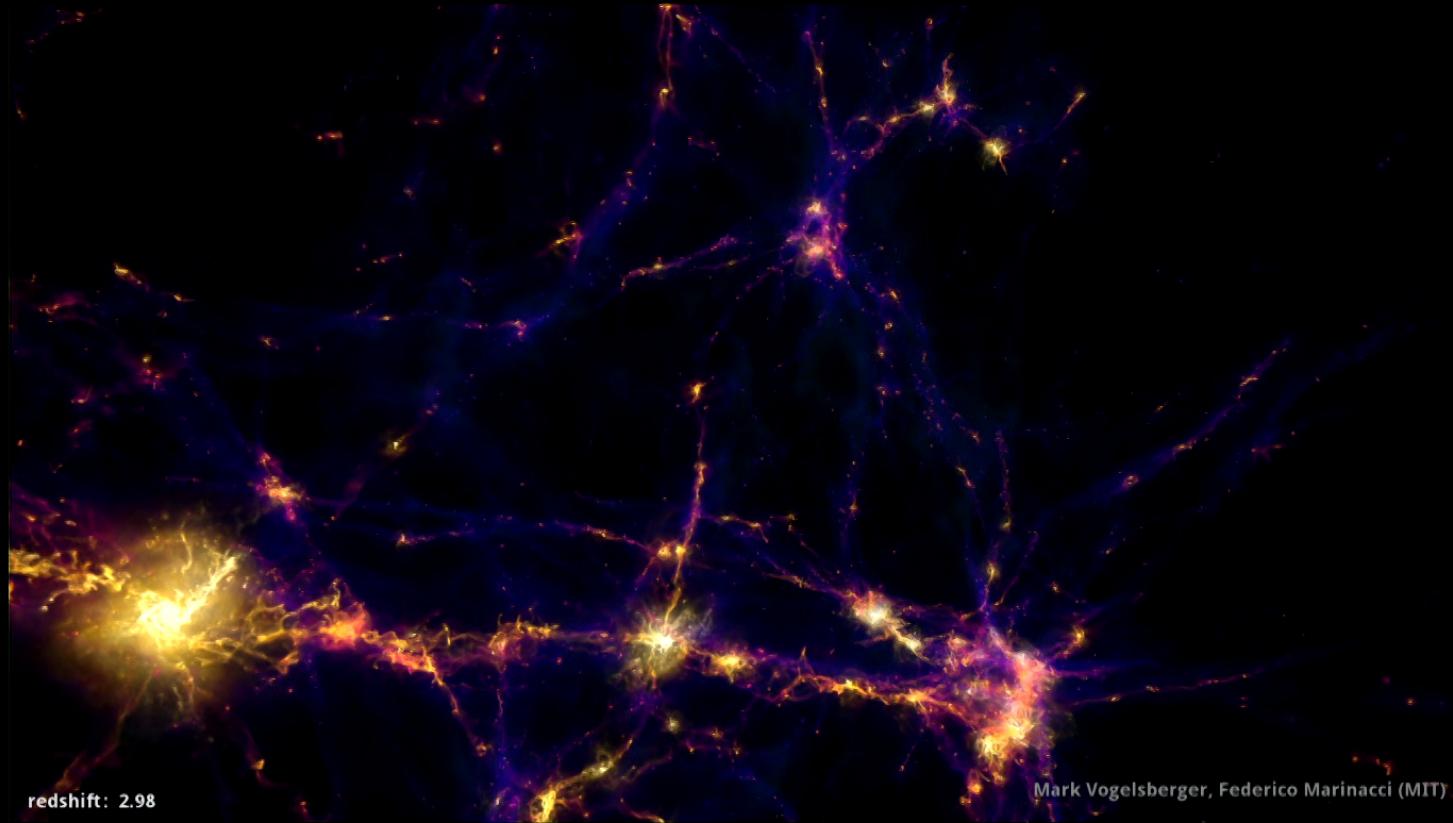
Hernquist, Weinberger, Naiman (CfA)



The Evolution of Cosmological Simulations

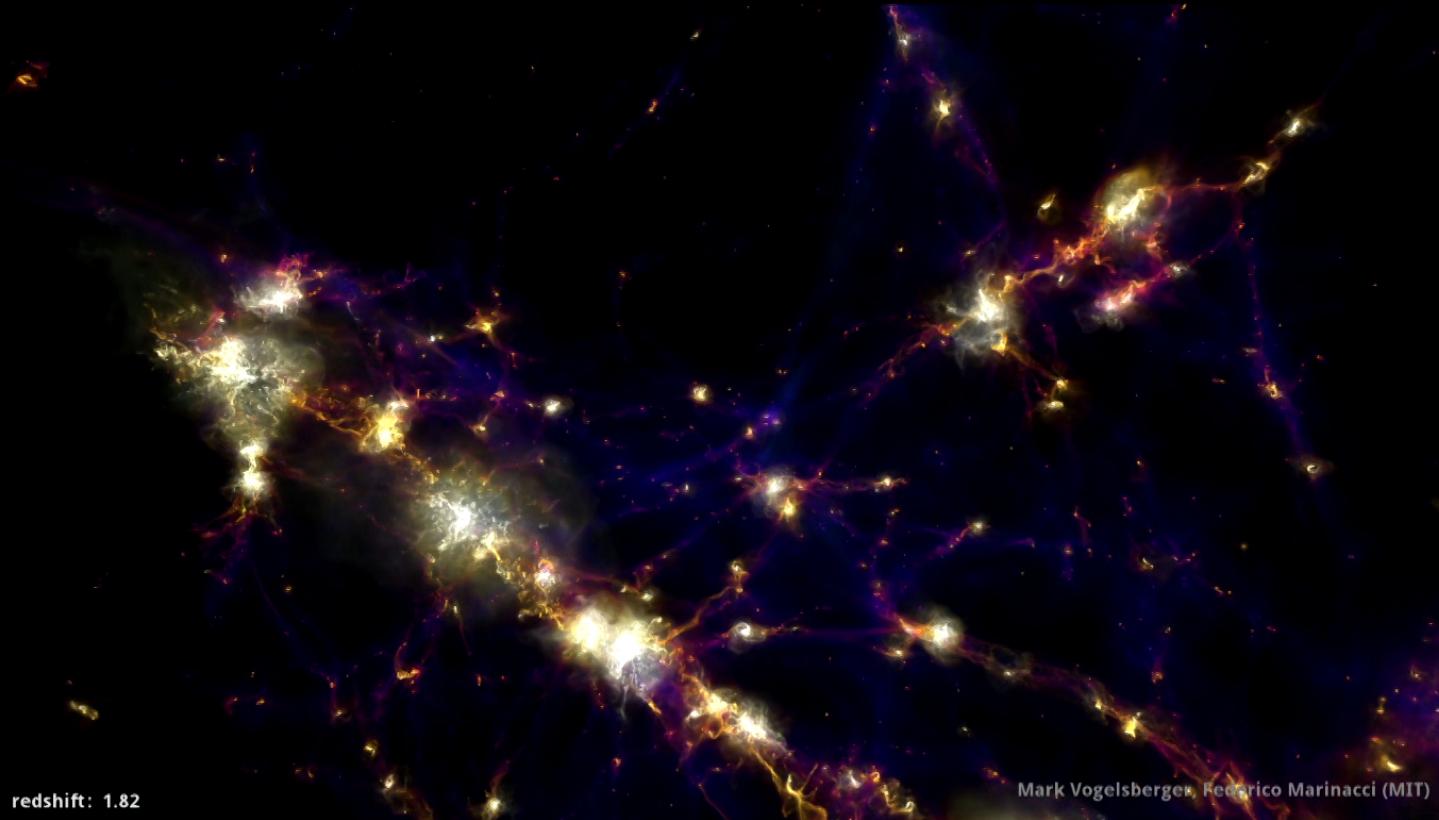


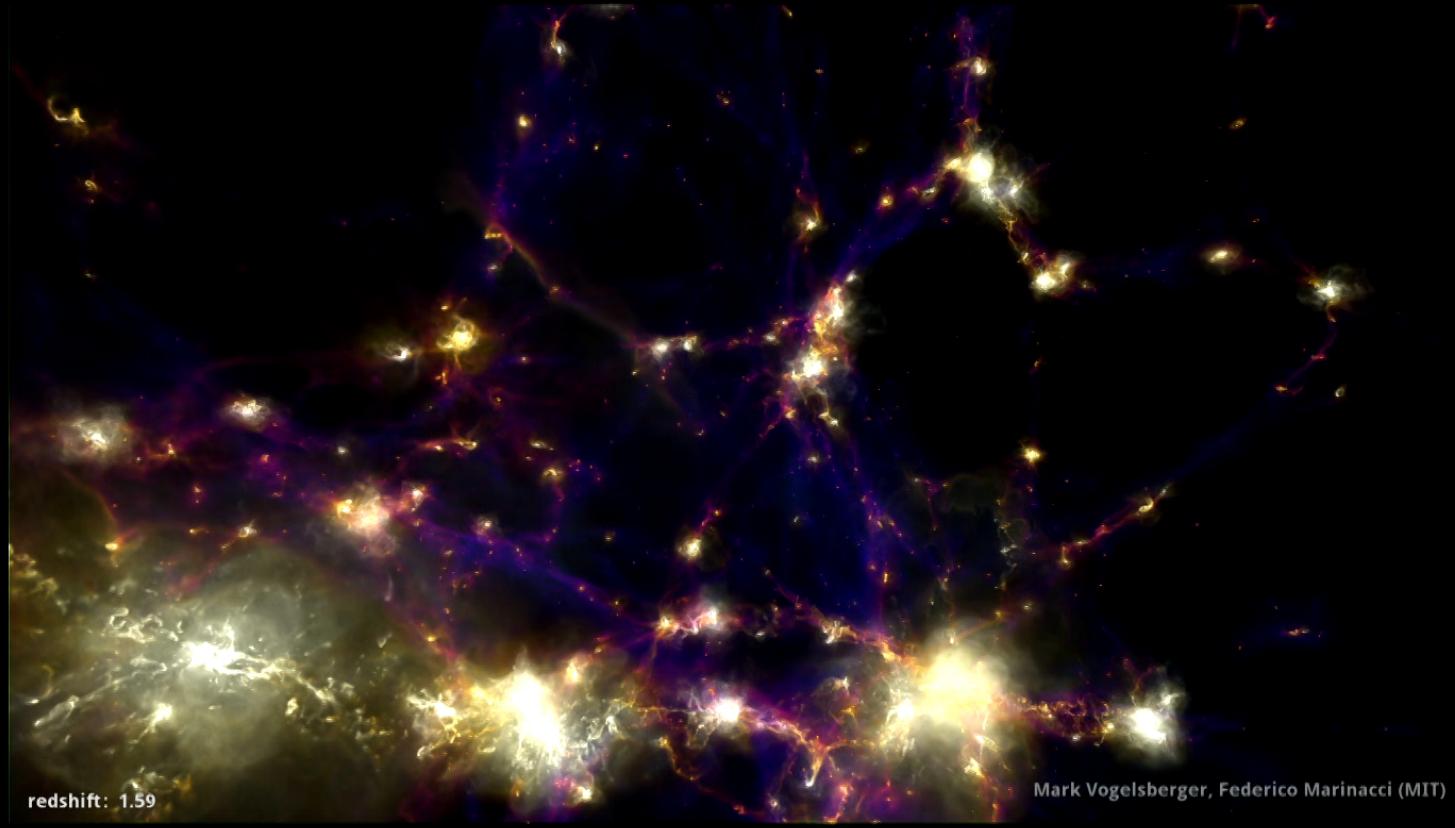


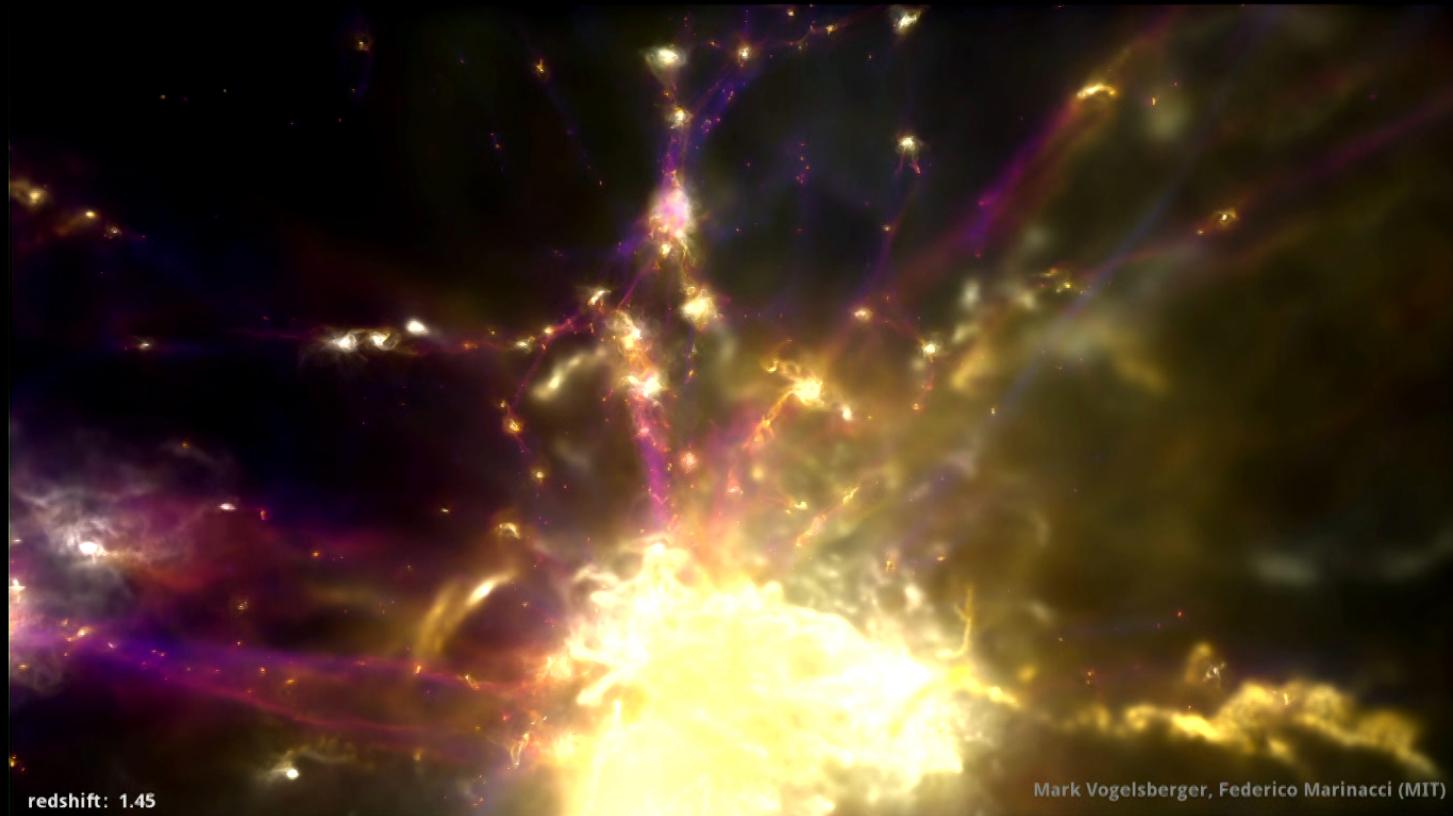


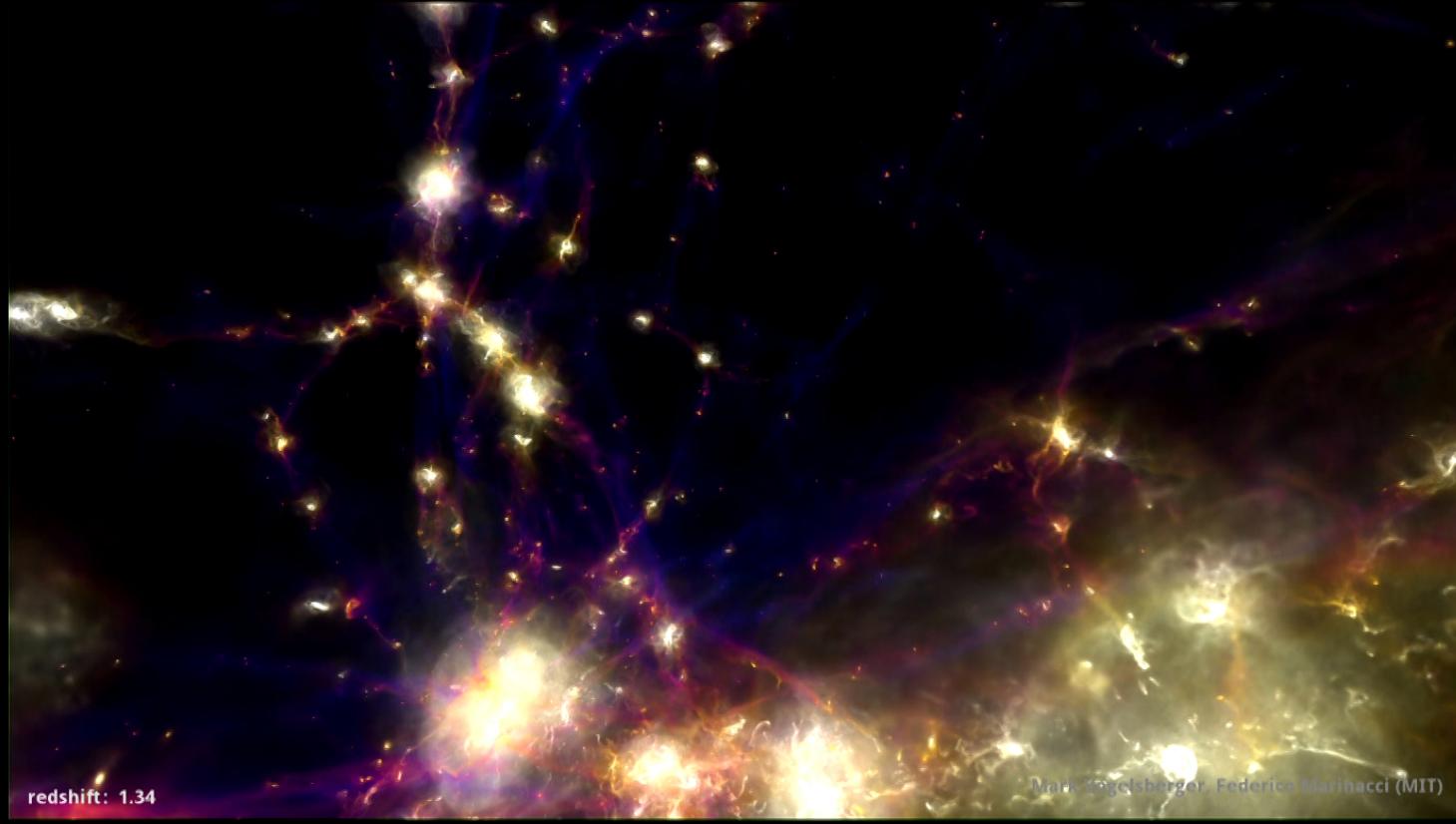






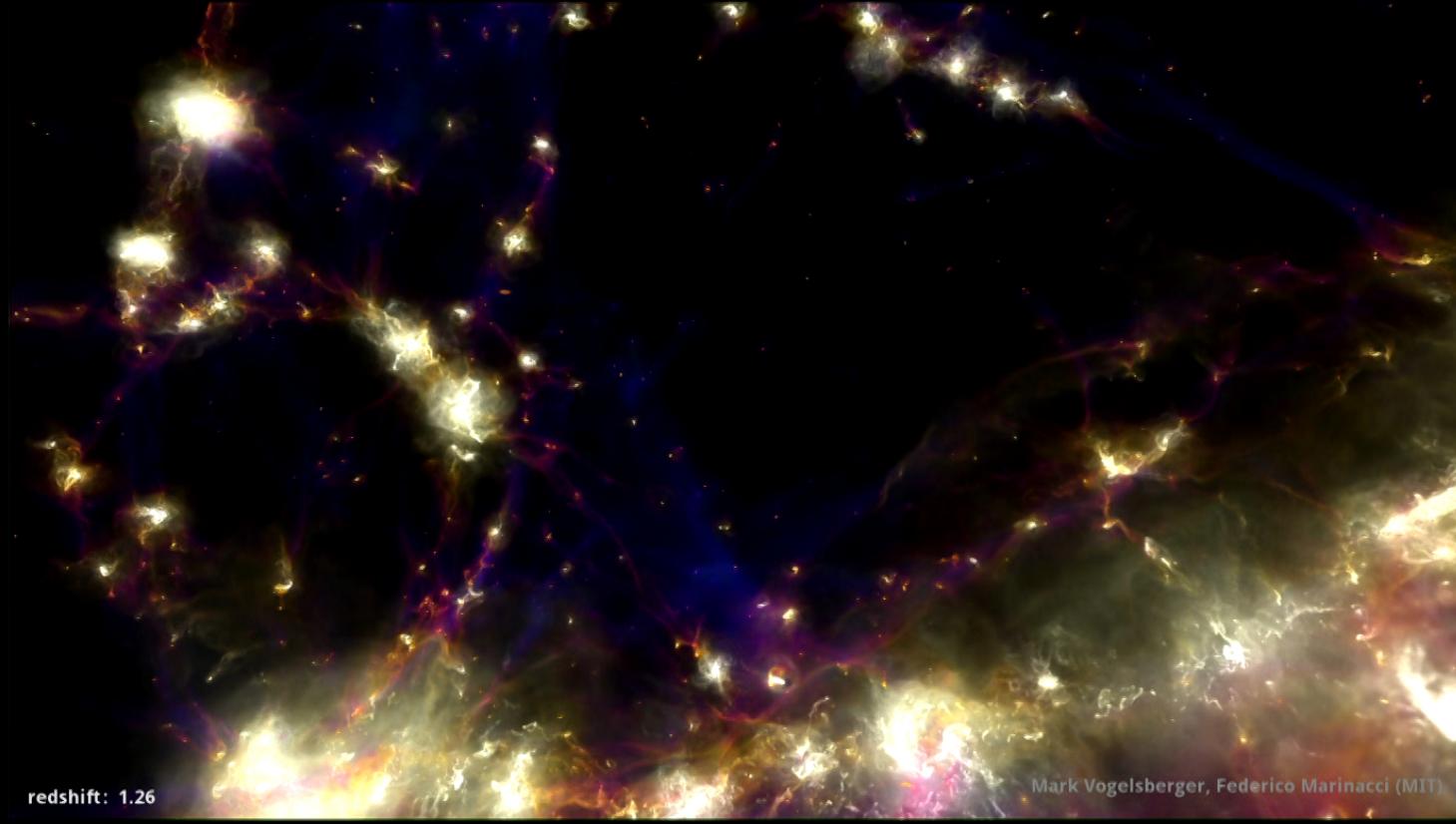






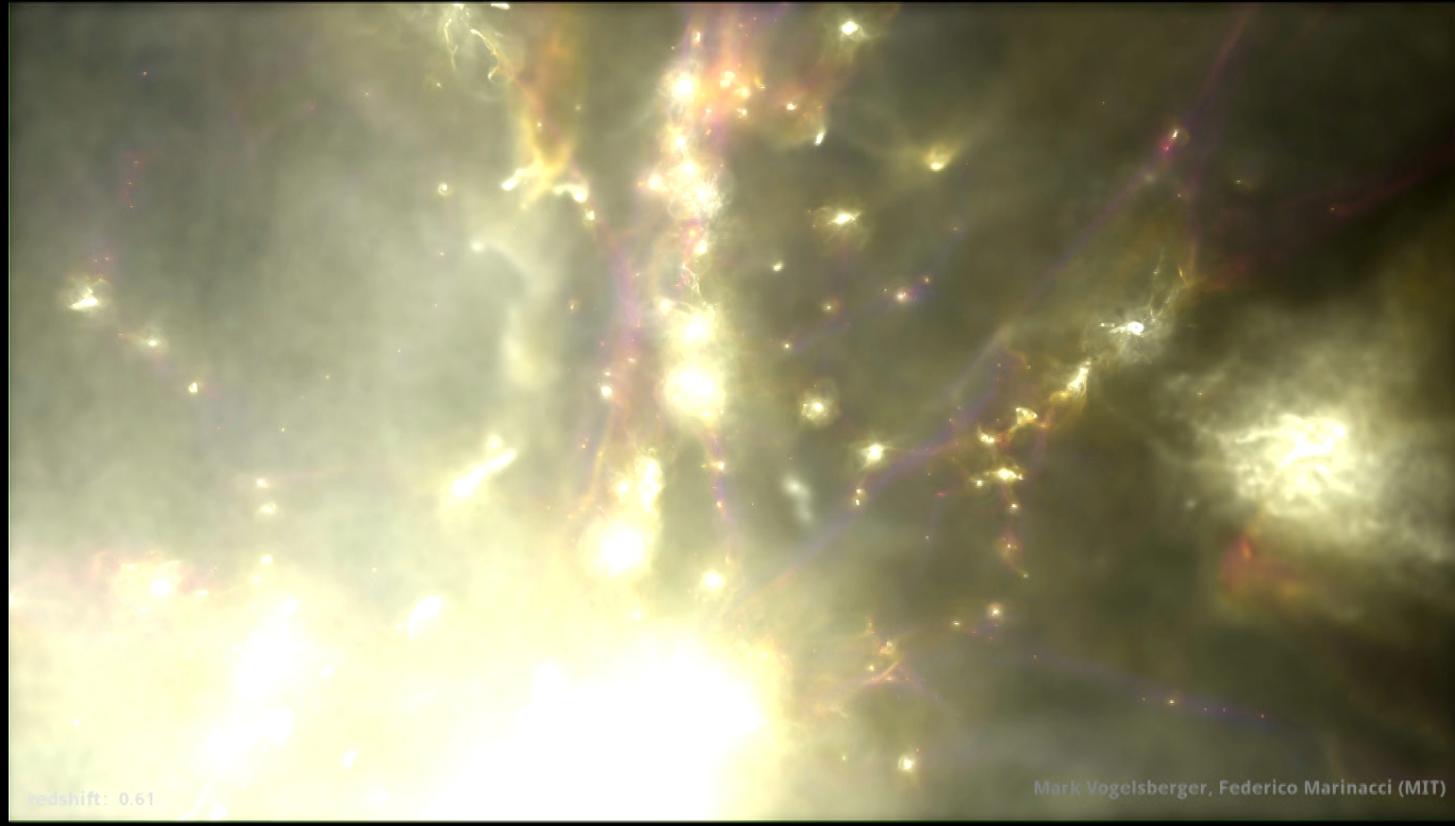
redshift: 1.34

Mark Vogelsberger, Federico Marinacci (MIT)



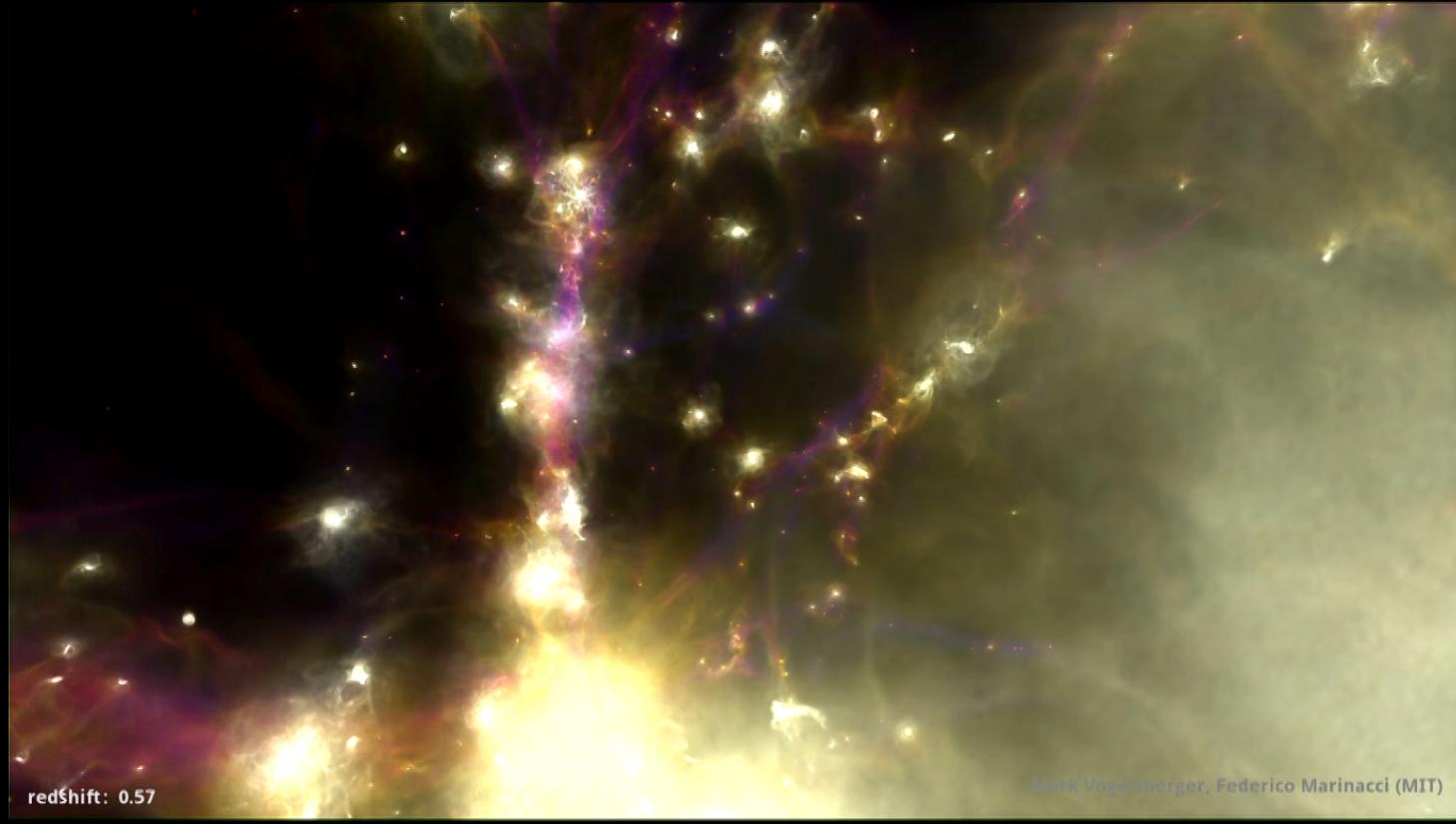
redshift: 1.26

Mark Vogelsberger, Federico Marinacci (MIT)

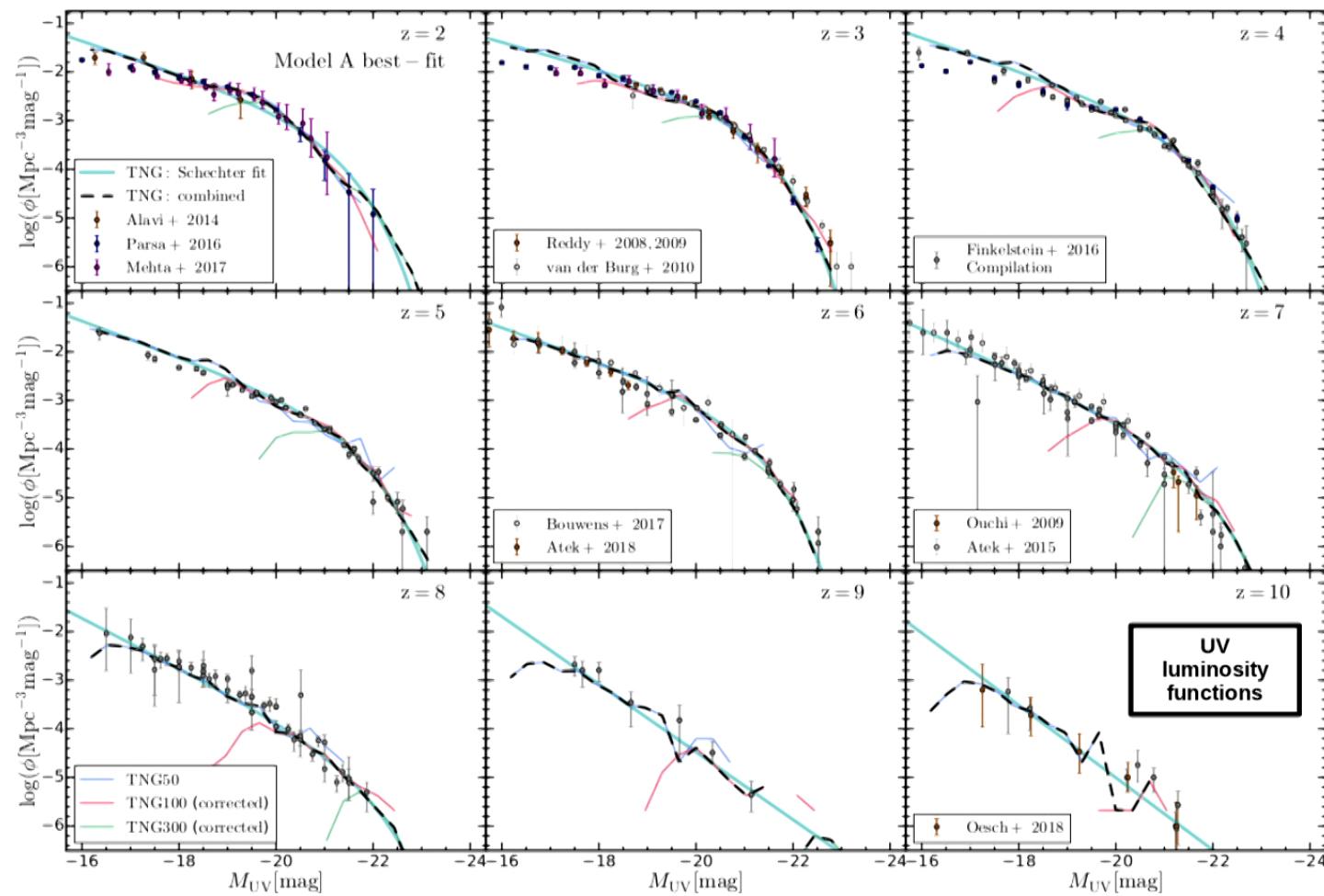


redshift: 0.61

Mark Vogelsberger, Federico Marinacci (MIT)



Predictions for the Upcoming James Webb Space Telescope



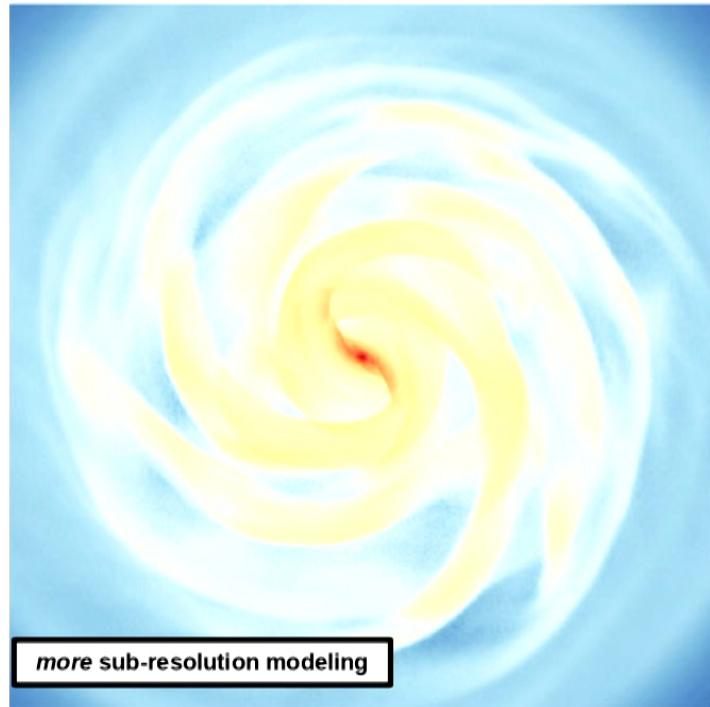
MV+ 2020

excellent agreement with existing Hubble Space Telescope data

Novel Galaxy Formation Models

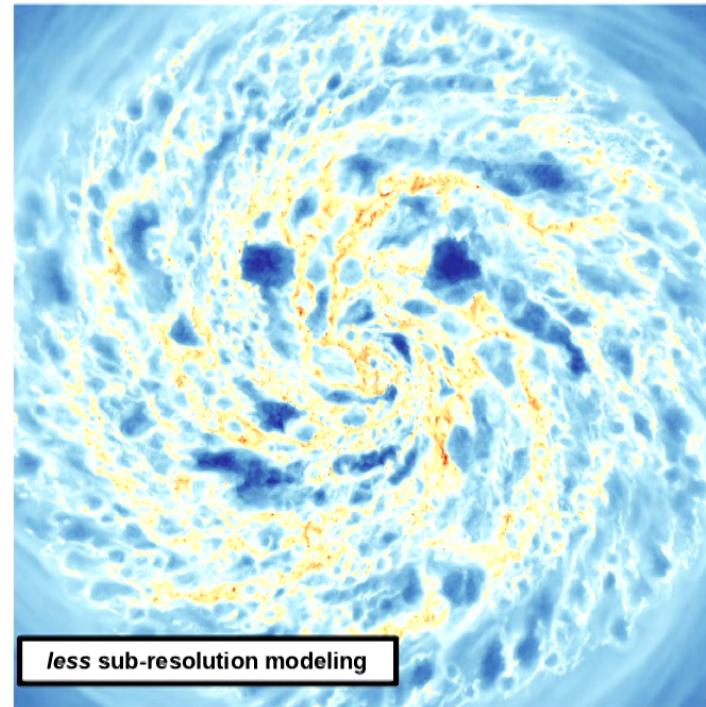
Stars and Multiphase Gas in Galaxies – SMUGGLE Model

typical effective ISM model



more sub-resolution modeling

SMUGGLE model



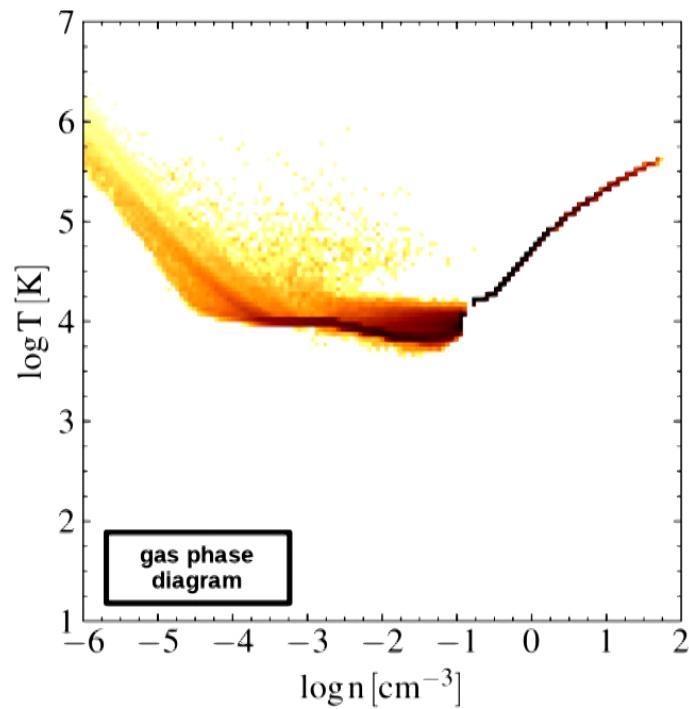
less sub-resolution modeling

Marinacci, Sales, MV, Torrey, Springel 2019

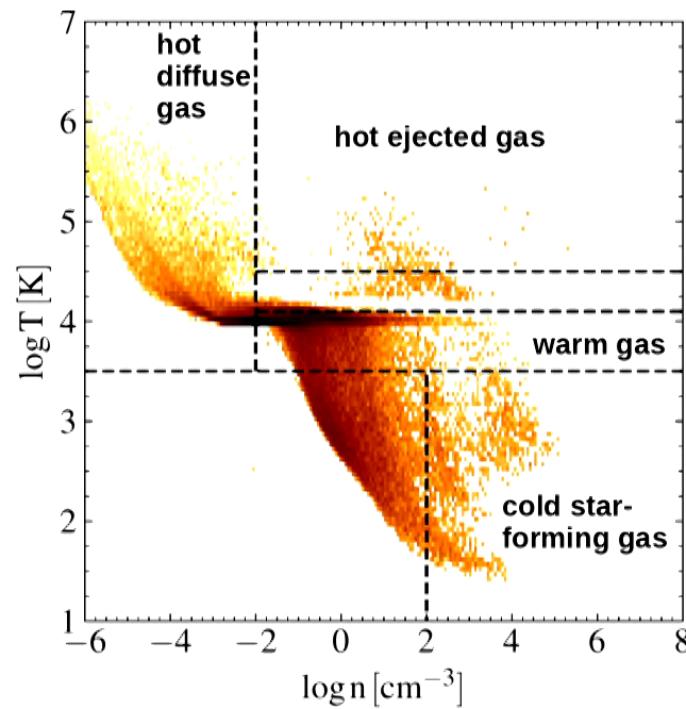
interstellar medium gas of a Milky Way-like galaxy
for a typically employed effective ISM model and the novel SMUGGLE model

Novel Explicit Galaxy Formation Model

typical effective ISM model

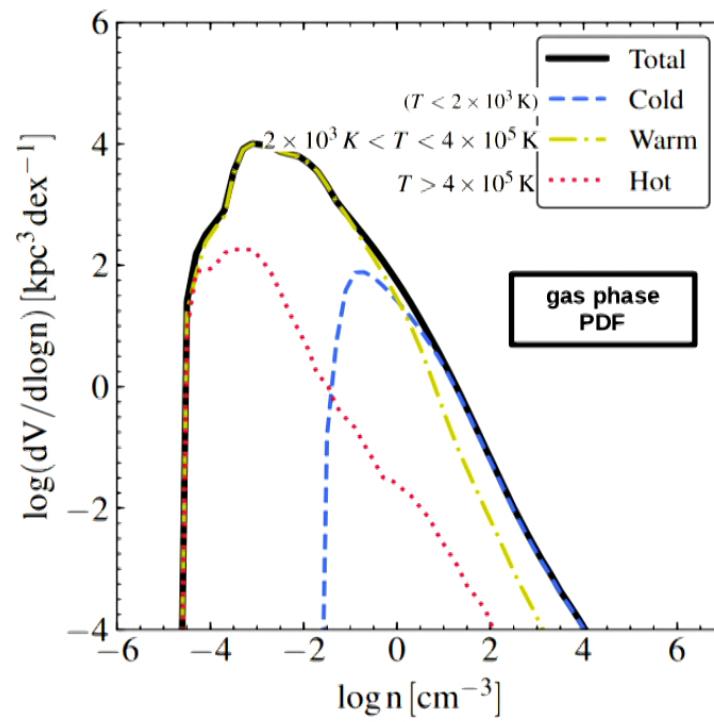
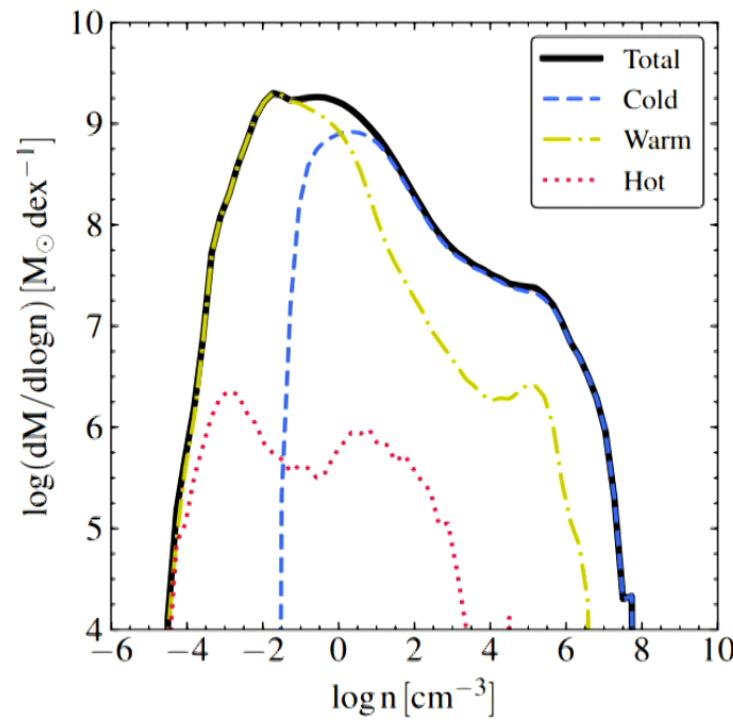


SMUGGLE model

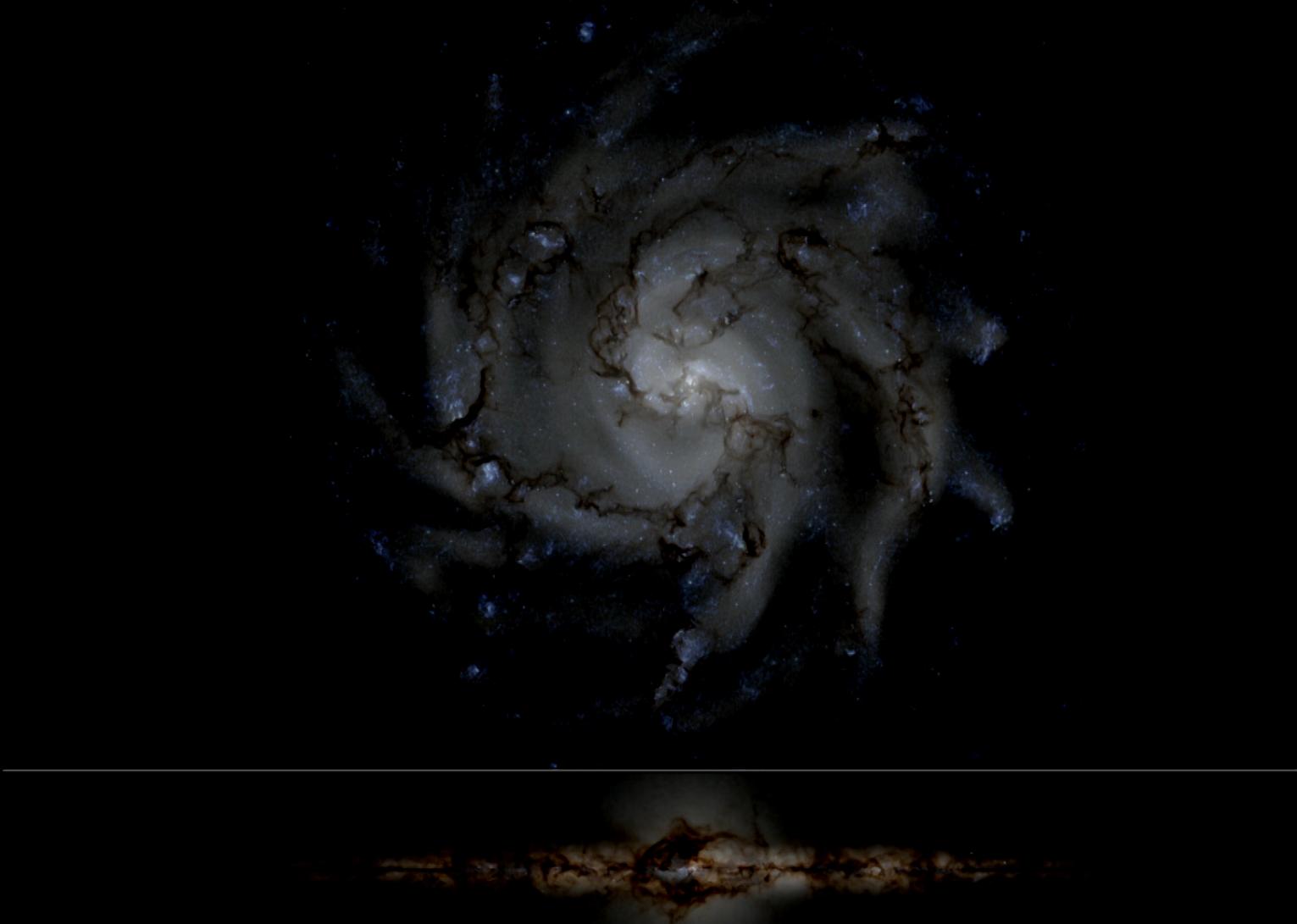


Marinacci, Sales, MV, Torrey, Springel 2019

Different Gas Phases



Marinacci, Sales, MV, Torrey, Springel 2019



Marinacci, Sales, MV, Torrey, Springel 2019

A mirrored display showing a portrait of a man and a horizontal strip. The portrait is a classical-style painting of a man with curly hair, wearing a dark robe. The image is displayed on a screen that appears to be a mirror, as the left side of the image is a normal view and the right side is a reversed, mirrored view. Below the portrait is a horizontal strip of the same image, also split into a normal and a mirrored portion.

Alternative Dark Matter Models

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?

Going beyond CDM: Some Candidates

Warm Dark Matter?

Self-Interacting Dark Matter?

BECDM?

...?

Self-Interacting Dark Matter

Observational Evidence for Self-Interacting Cold Dark Matter

David N. Spergel and Paul J. Steinhardt

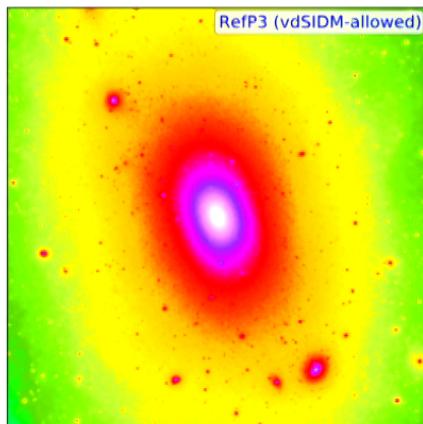
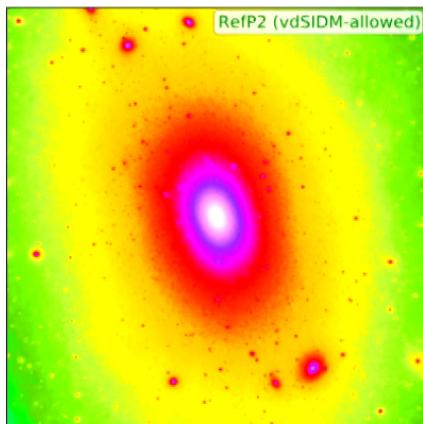
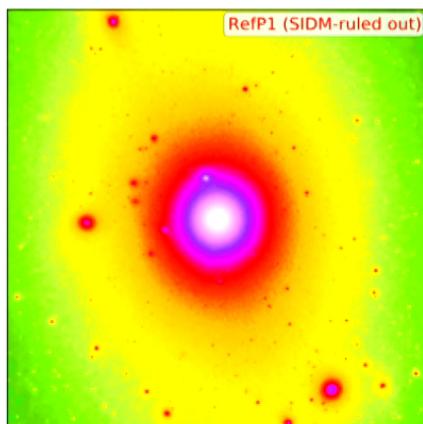
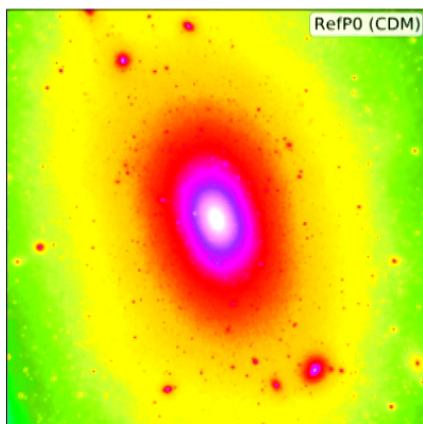
Princeton University, Princeton, New Jersey 08544

(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 $0.45\text{--}450 \text{ cm}^2/\text{g}$ or, equivalently, $8 \times 10^{-(25\text{--}22)} \text{ cm}^2/\text{GeV}$. 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

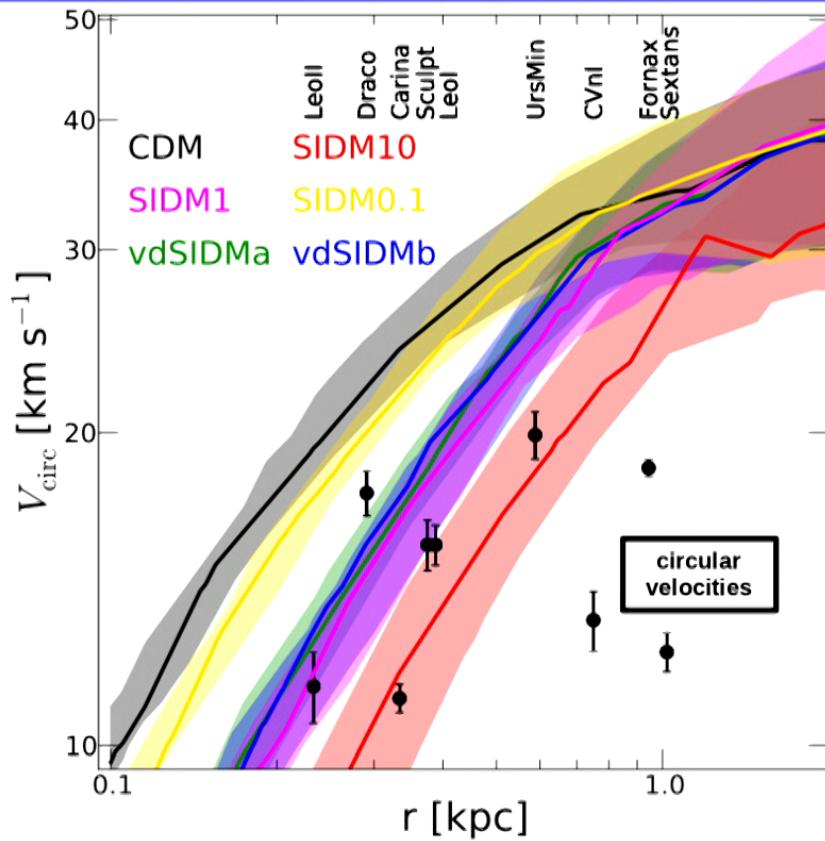


Name	Type	$\sigma_T^{\max} / m_X [\text{cm}^2 \text{g}^{-1}]$	$v_{\max} [\text{km s}^{-1}]$
RefP0	CDM	/	/
RefP1	SIDM (ruled out)	10	/
RefP2	vdSIDM (allowed)	3.5	30
RefP3	vdSIDM (allowed)	35	10

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

MV+ 2012

Self-Interacting Dark Matter: Implications for Subhalos

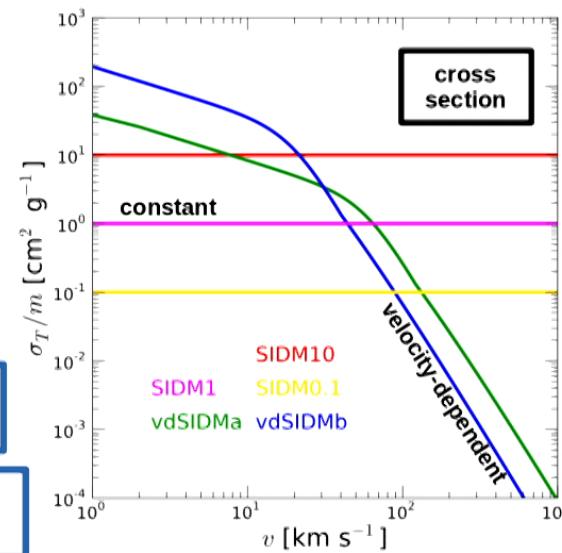


MV, Zavala, Loeb 2012

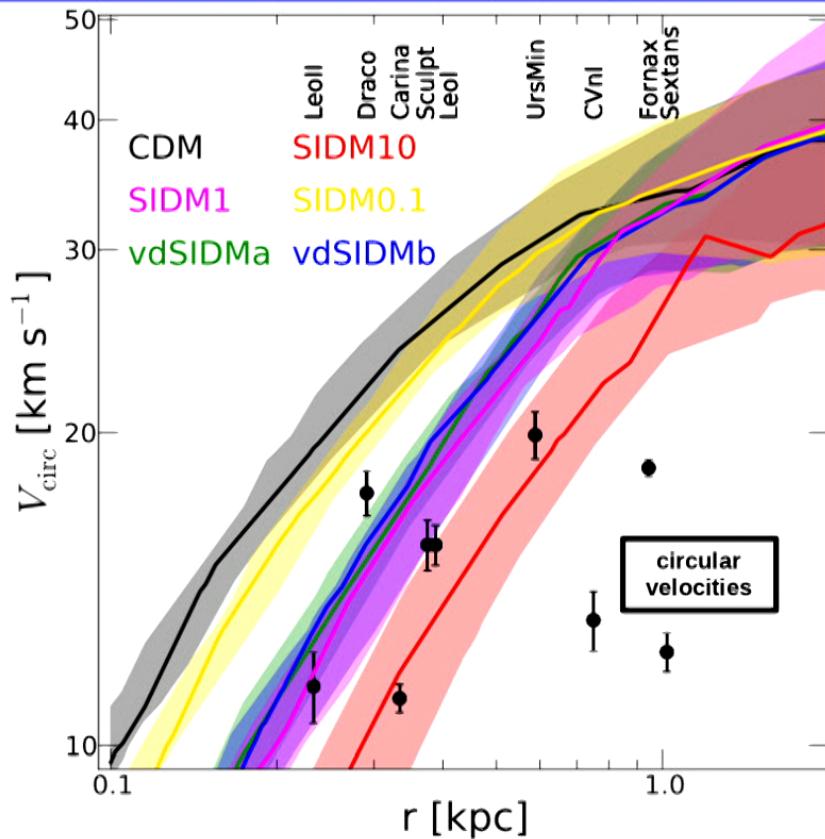
Zavala, MV, Walker 2013

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

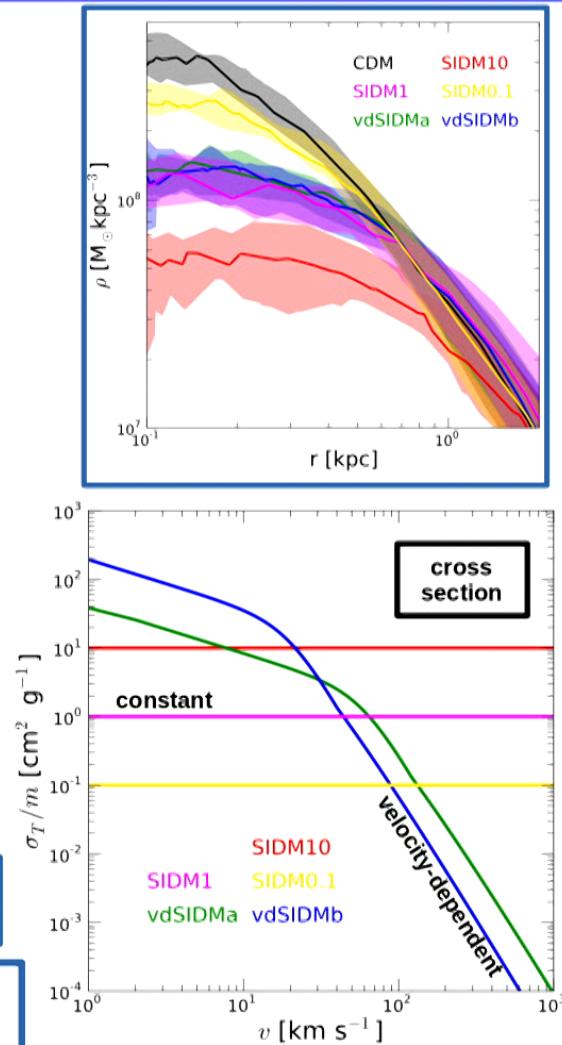


MV, Zavala, Loeb 2012

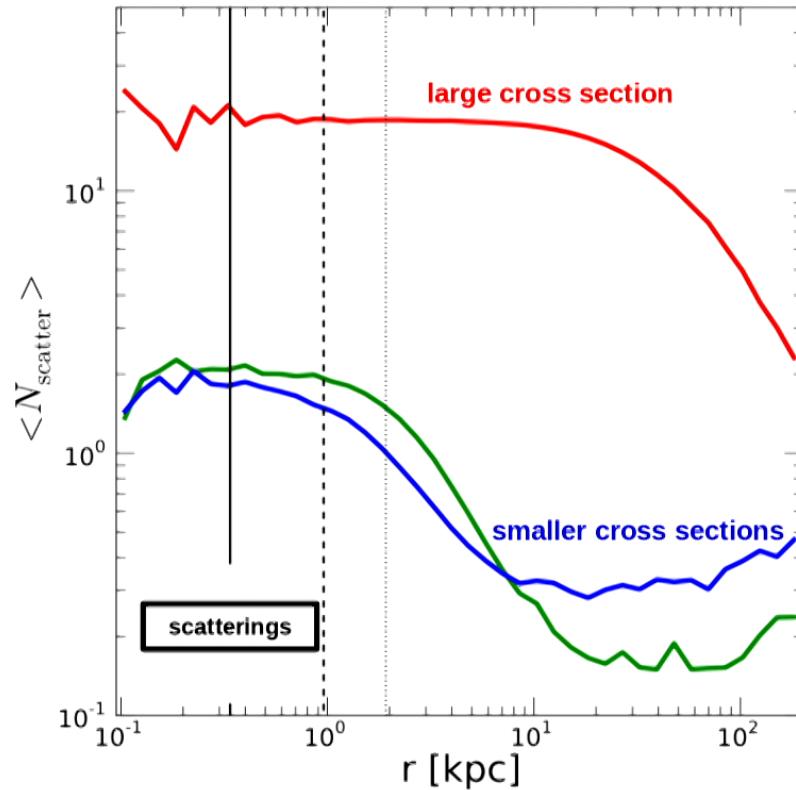
Zavala, MV, Walker 2013

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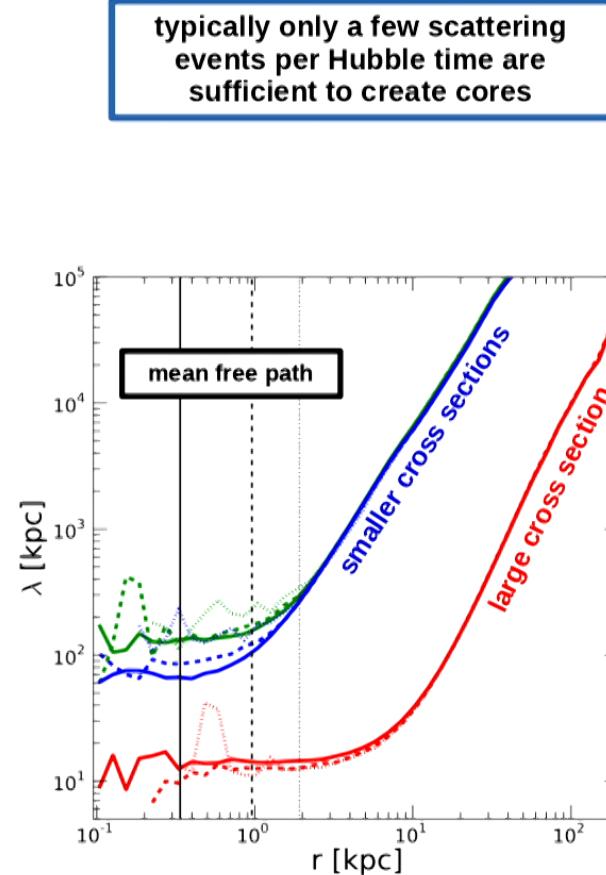


How often do SIDM particles scatter on average?



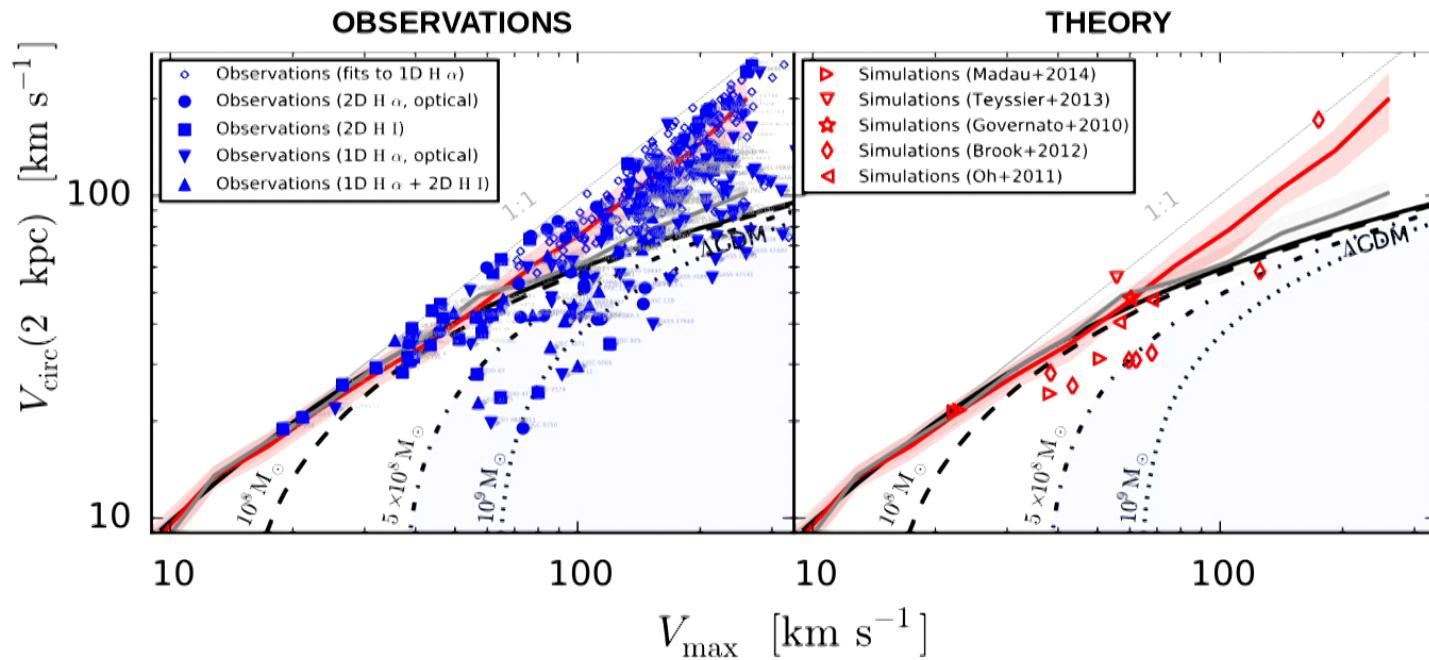
-100 kpc mean free path in inner halo

MV, Zavala, Loeb 2012



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

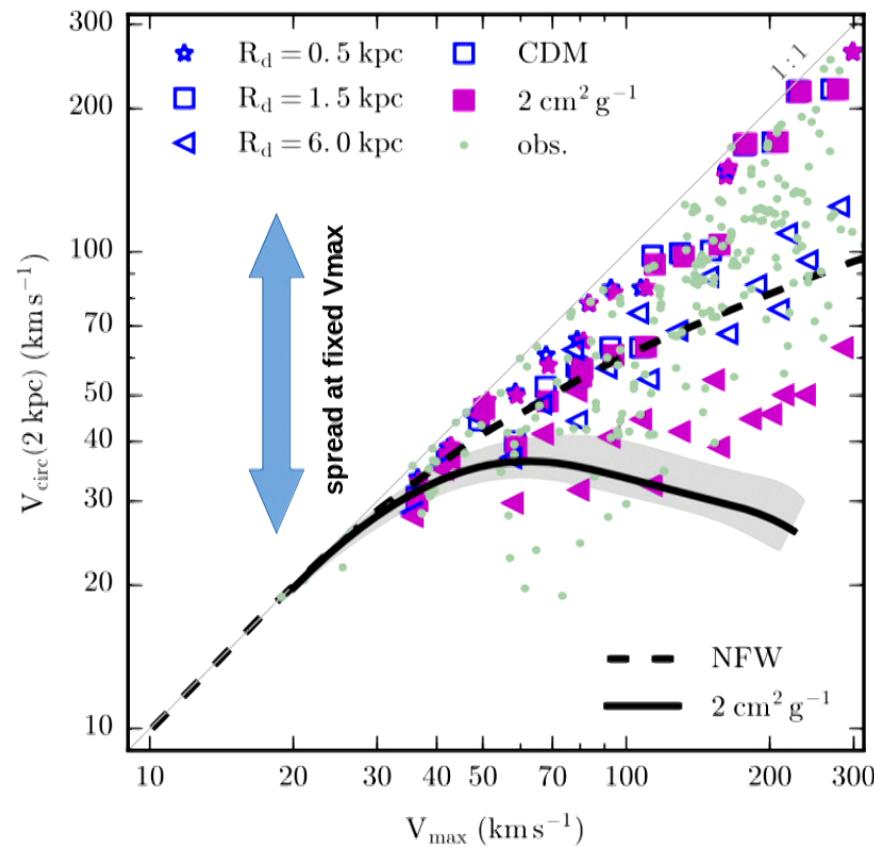
CDM: The Diversity Problem



"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 $V_{\text{circ}}(2 \text{kpc})$ [low central densities in both baryons and dark matter]; high values of $V_{\text{circ}}(2 \text{kpc})$ still achieved with compact baryonic disks

Creasey+ w/ MV 2017

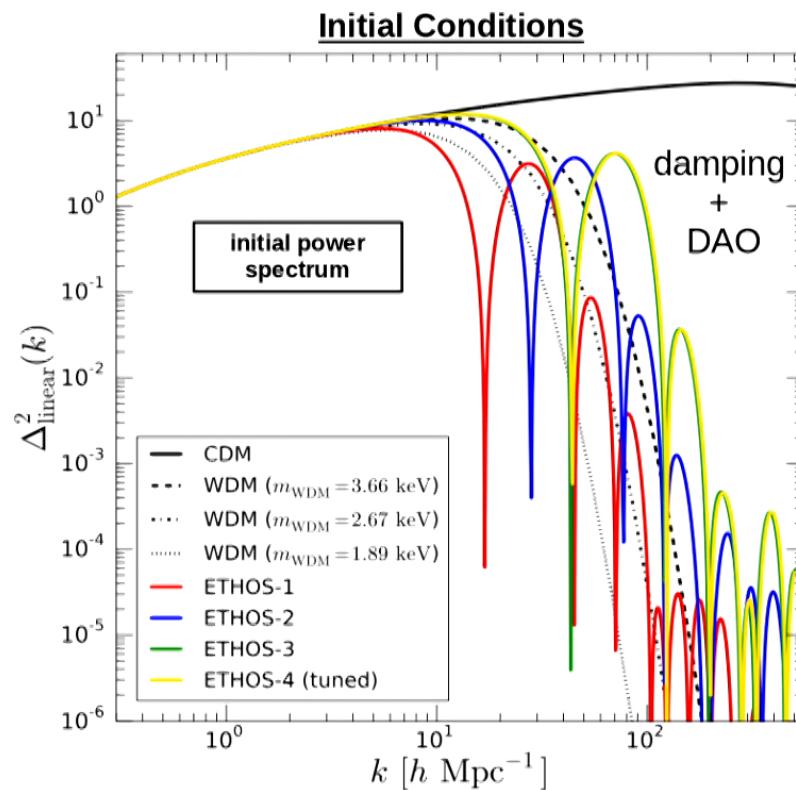
[see also Ren+ 2018]

ETHOS – Effective Theory of Structure Formation: Ingredients

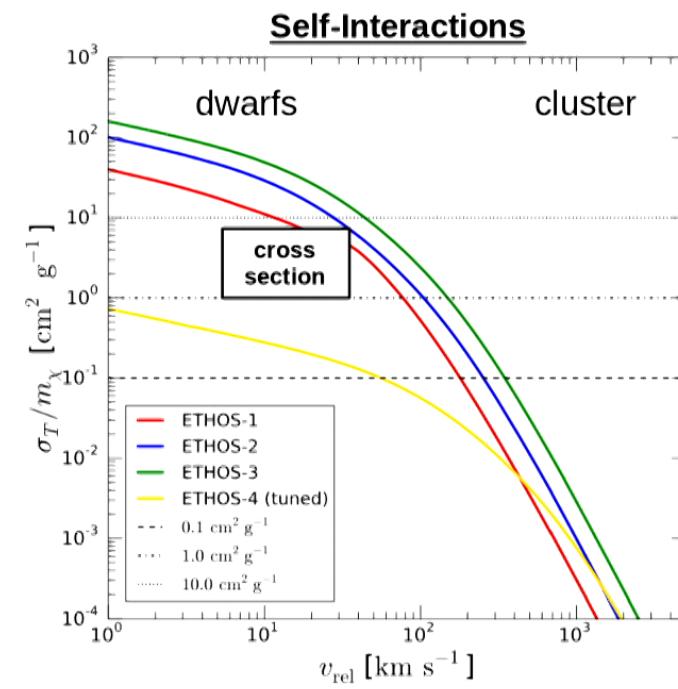
Basic Idea:

- 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



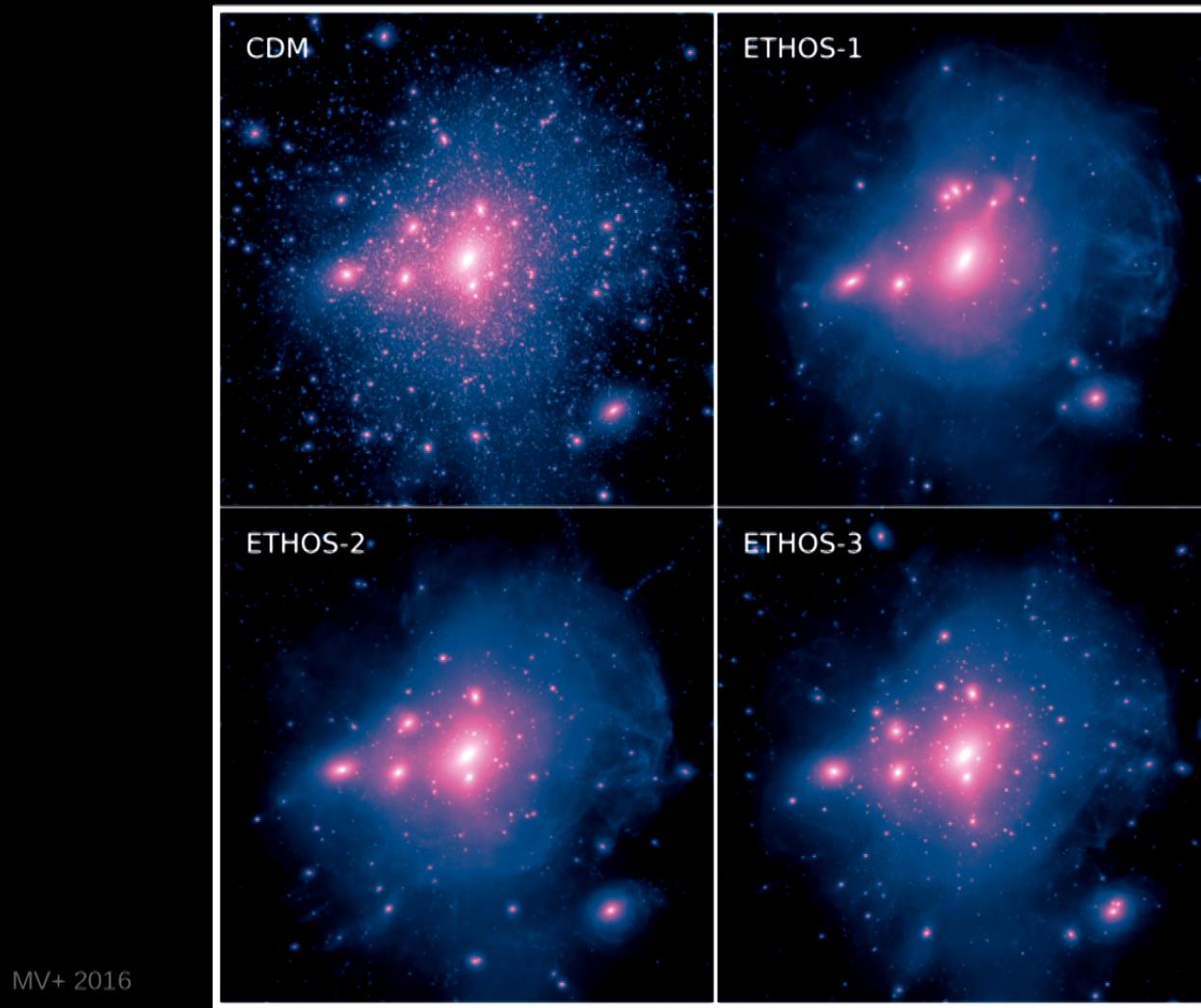
self-interactions affect evolution
of early and late universe
= self-consistent SIDM model



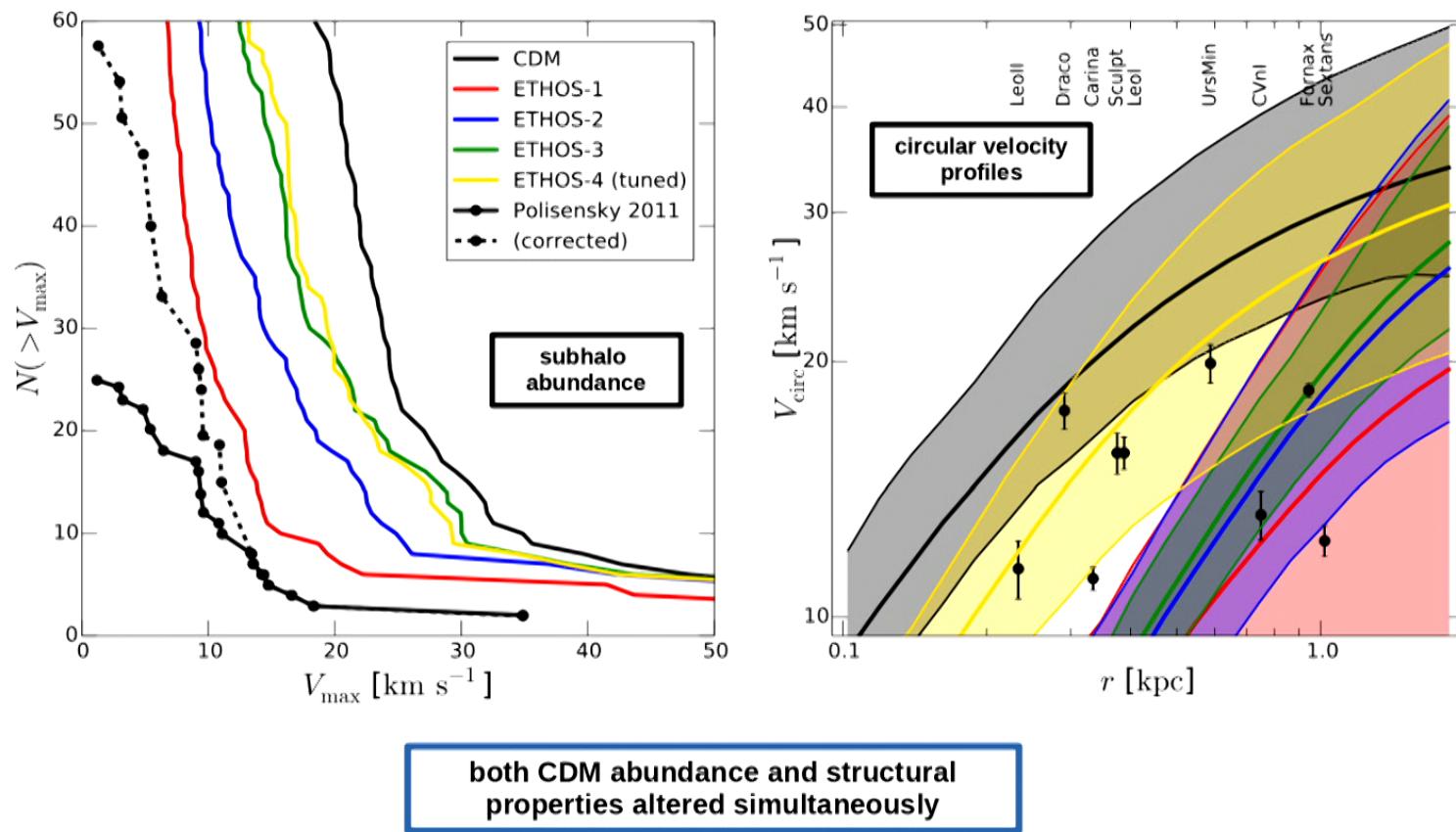
MV+ 2016

Cyr-Racine+ 2016

ETHOS: A Milky Way-like Halo Simulation



ETHOS: Impact on Milky Way Subhalos

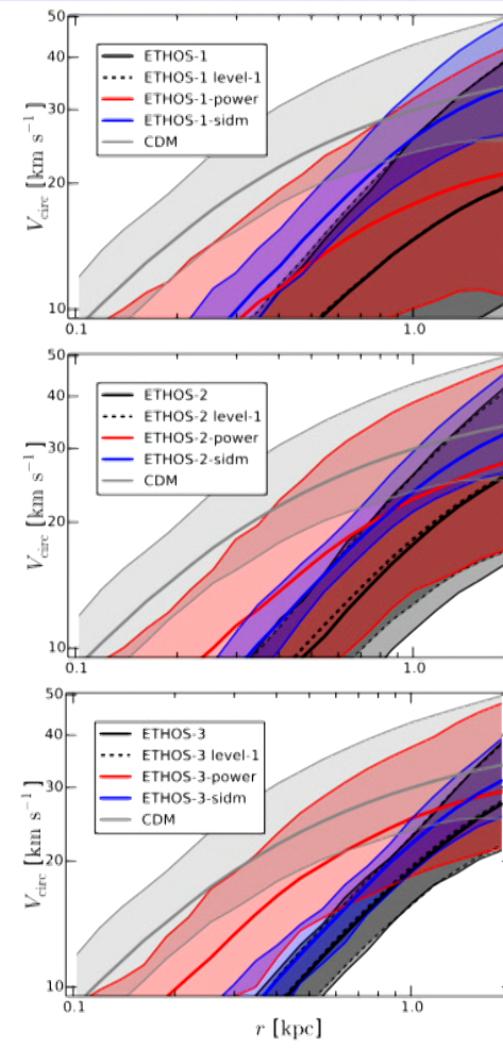
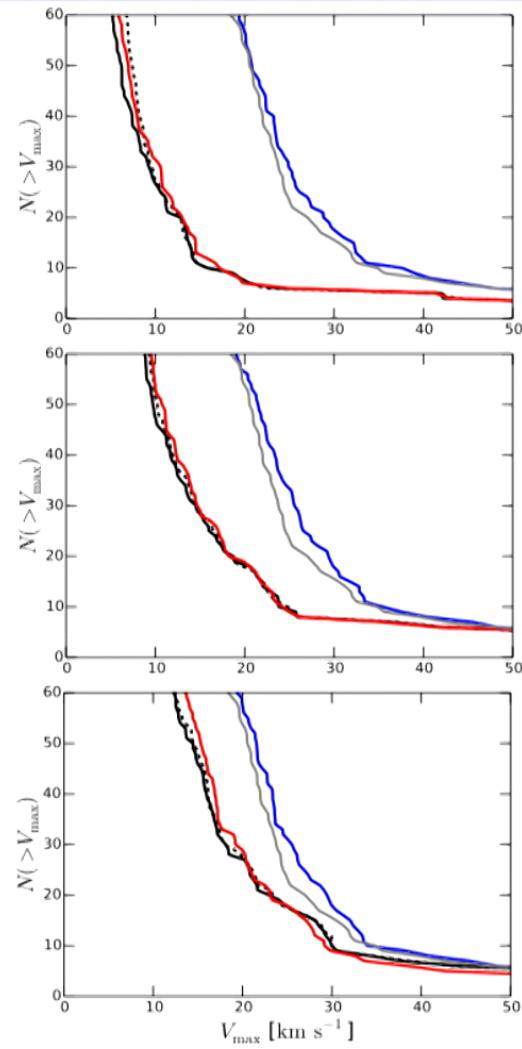


MV+ 2016

ETHOS: Damping vs. SIDM

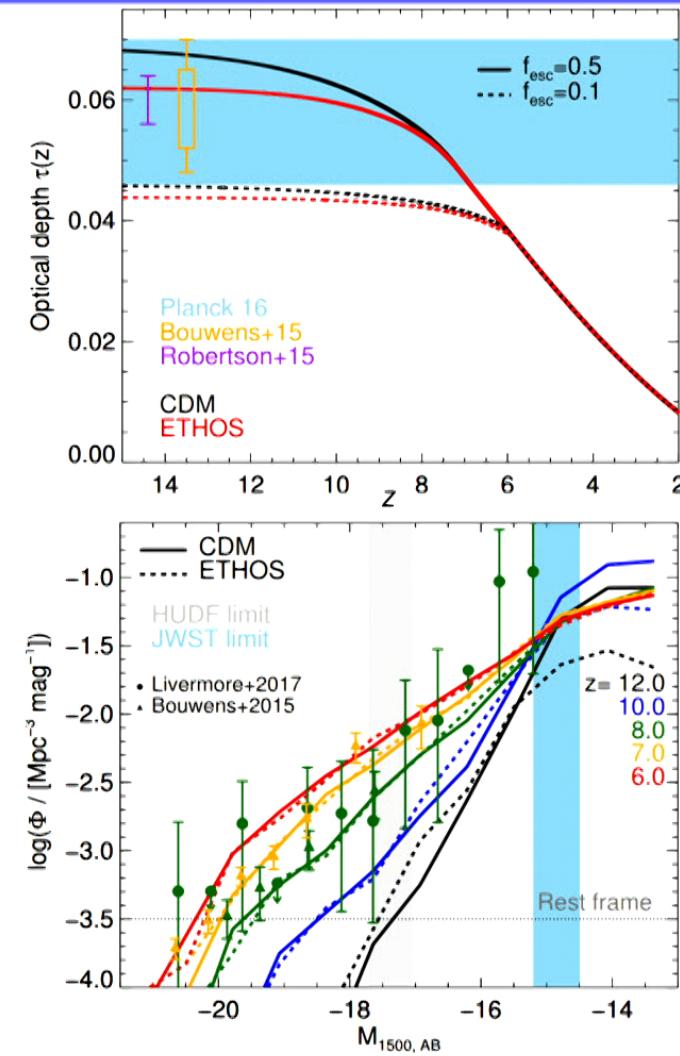
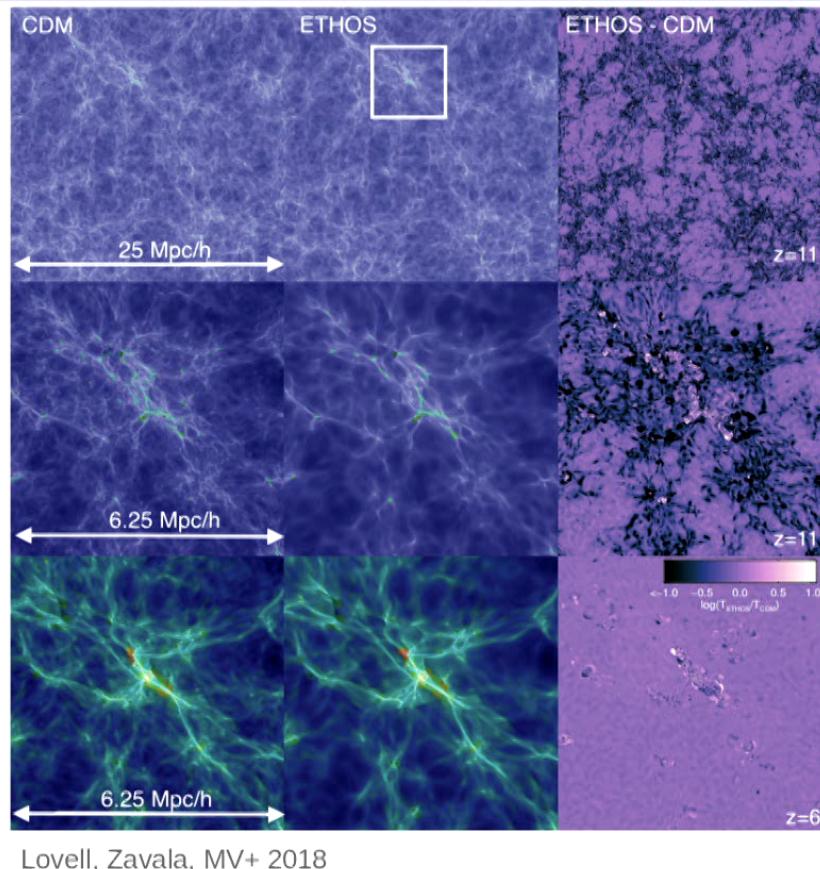
disentangling the impact of SIDM and power spectrum modifications

self-interactions do not change the subhalo abundance

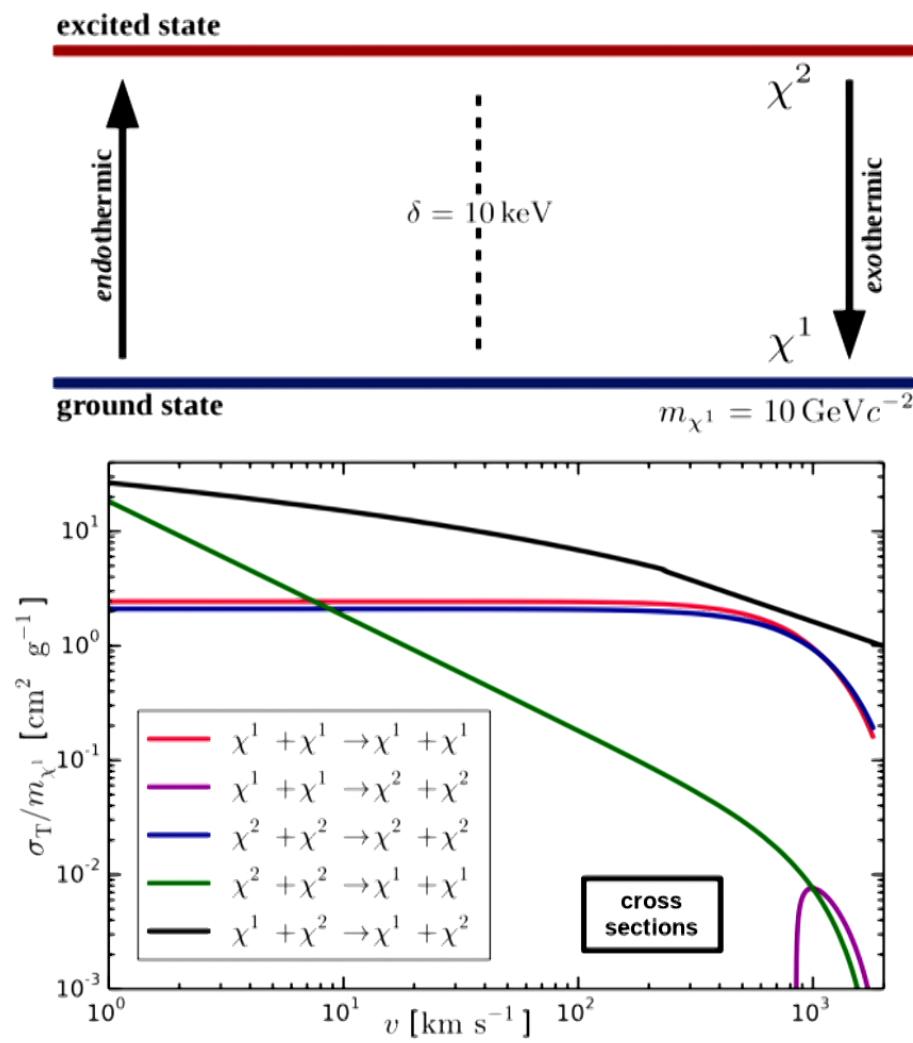


MV+ 2016

ETHOS: The High-Redshift Universe



Inelastic SIDM: Two-State SIDM Model

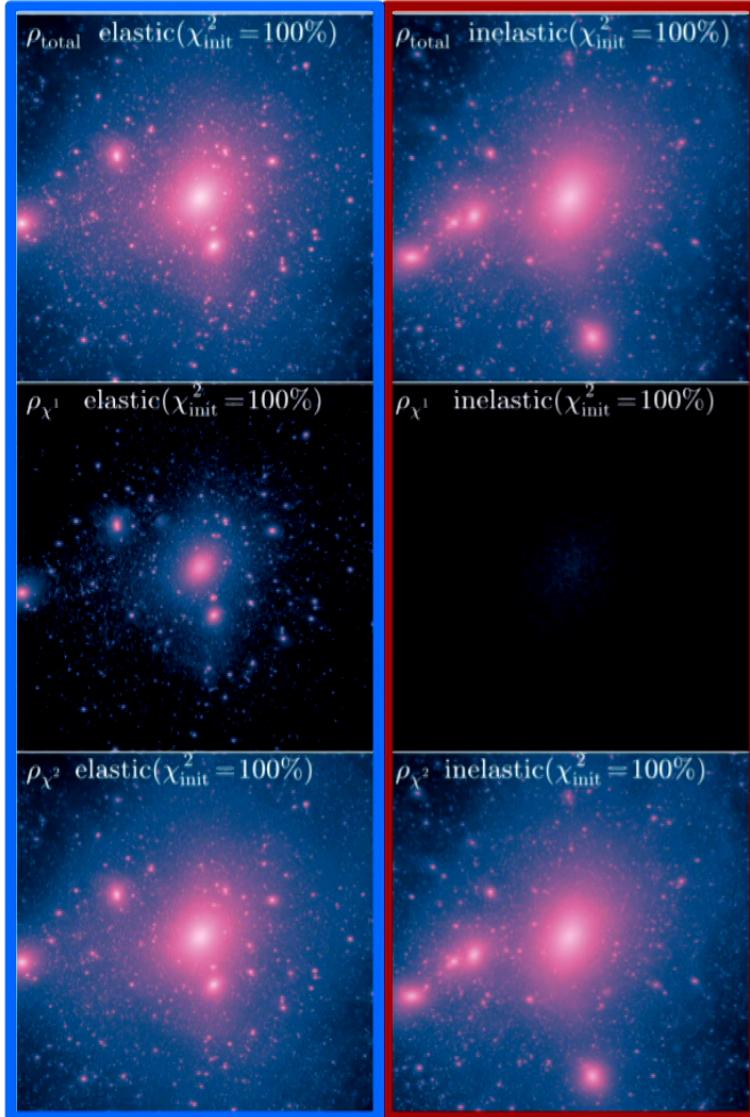


How does structure formation change if we allow for inelastic collisions?

specific model allows exothermic, but no endothermic reactions

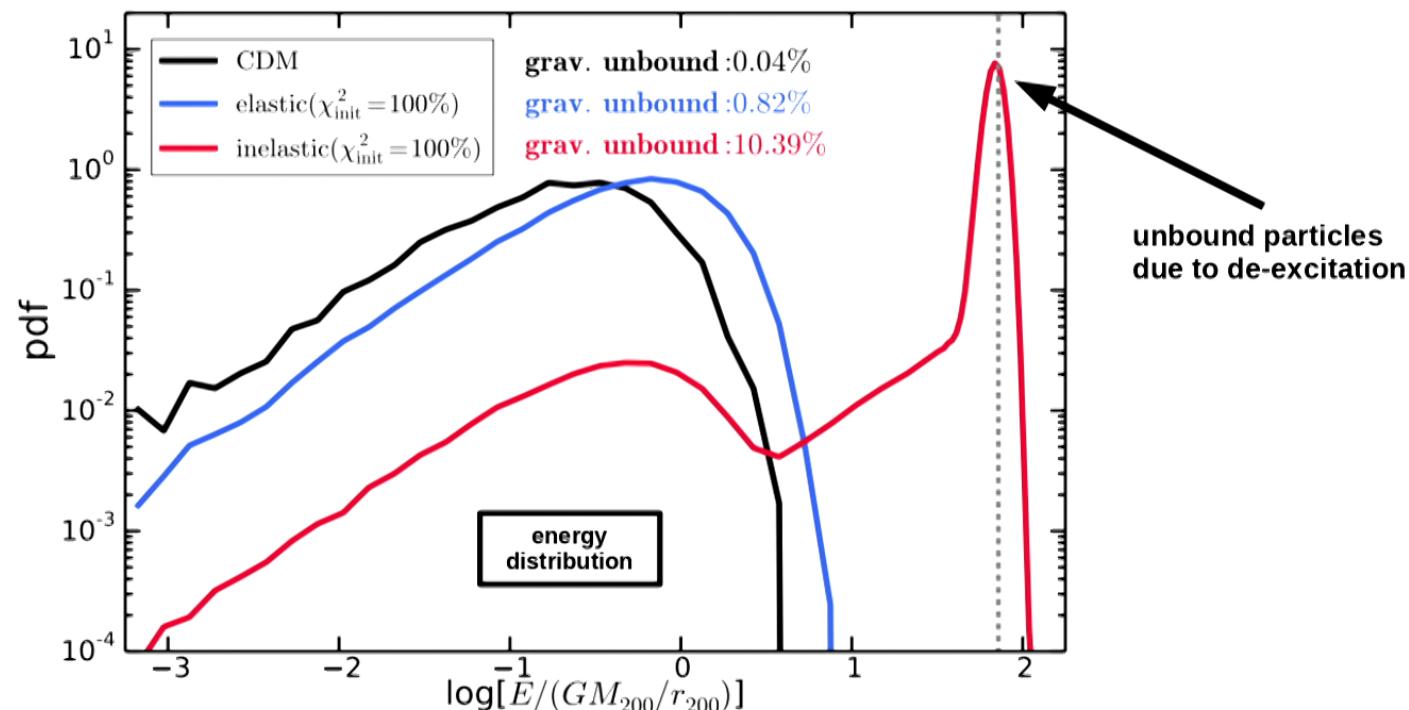
MV, Zavala, Schutz, Slatyer 2019

[see also Todoroki & Medvedev 2018]

Elastic SIDM**total DM density****ground state DM density****Inelastic SIDM****excited state DM density****Elastic SIDM**
vs.
Inelastic SIDM**exothermic reactions**
'evaporate' halo cores

MV, Zavala, Schutz, Slatyer 2019

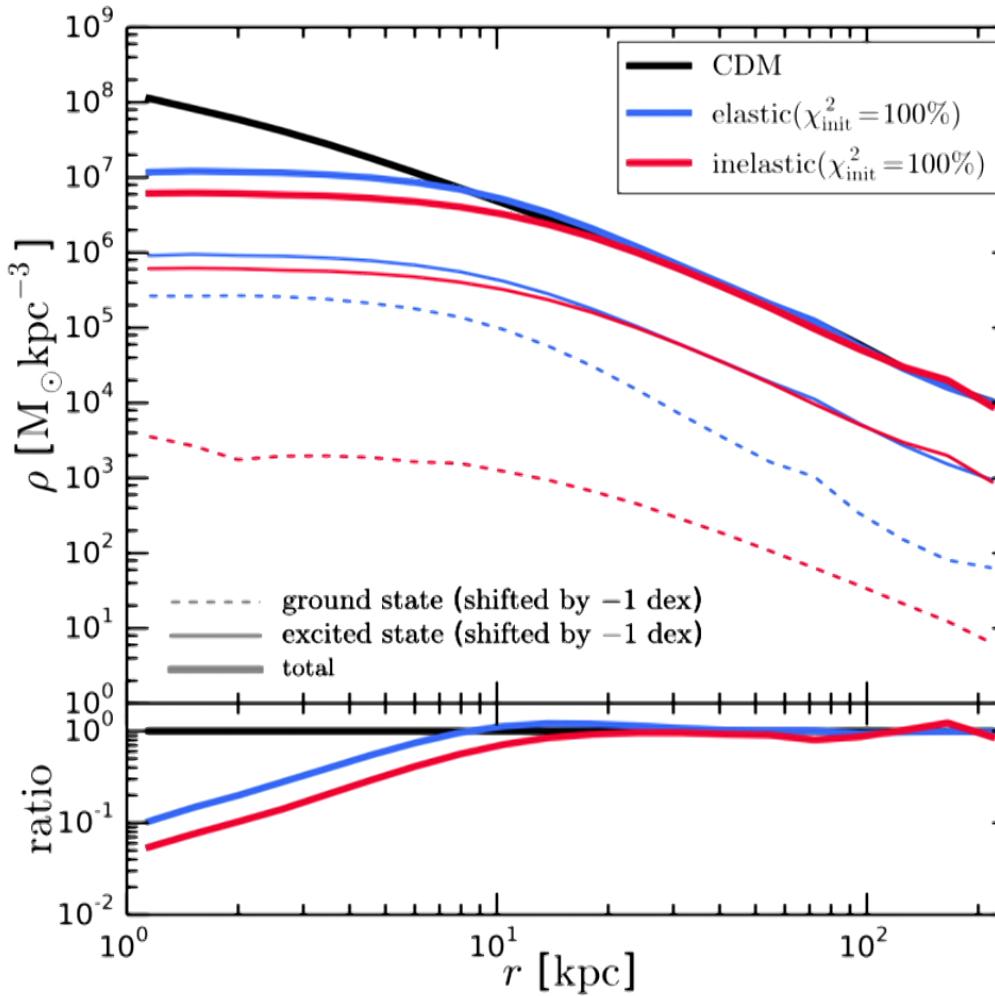
Evaporation: Unbinding Dark Matter Particles From Halo



dimensionless energy distribution of
gravitationally unbound particles

MV, Zavala, Schutz, Slatyer 2019

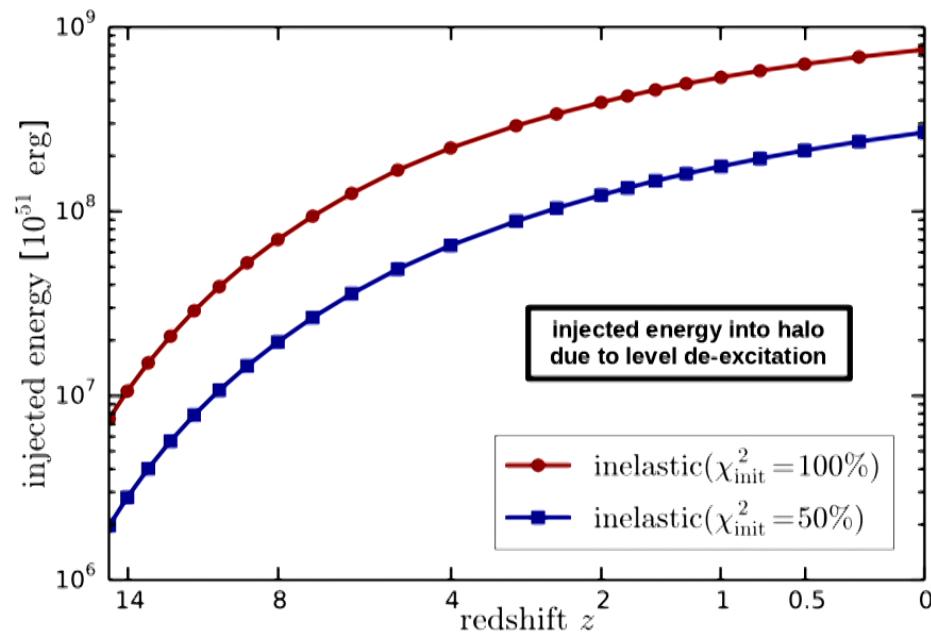
Inelastic SIDM: Halo Dark Matter Density Profiles



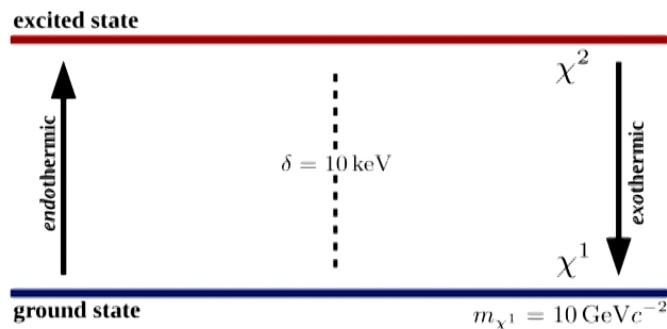
more efficient core formation within inelastic SIDM

MV, Zavala, Schutz, Slatyer 2019

Inelastic SIDM: Injected Energy

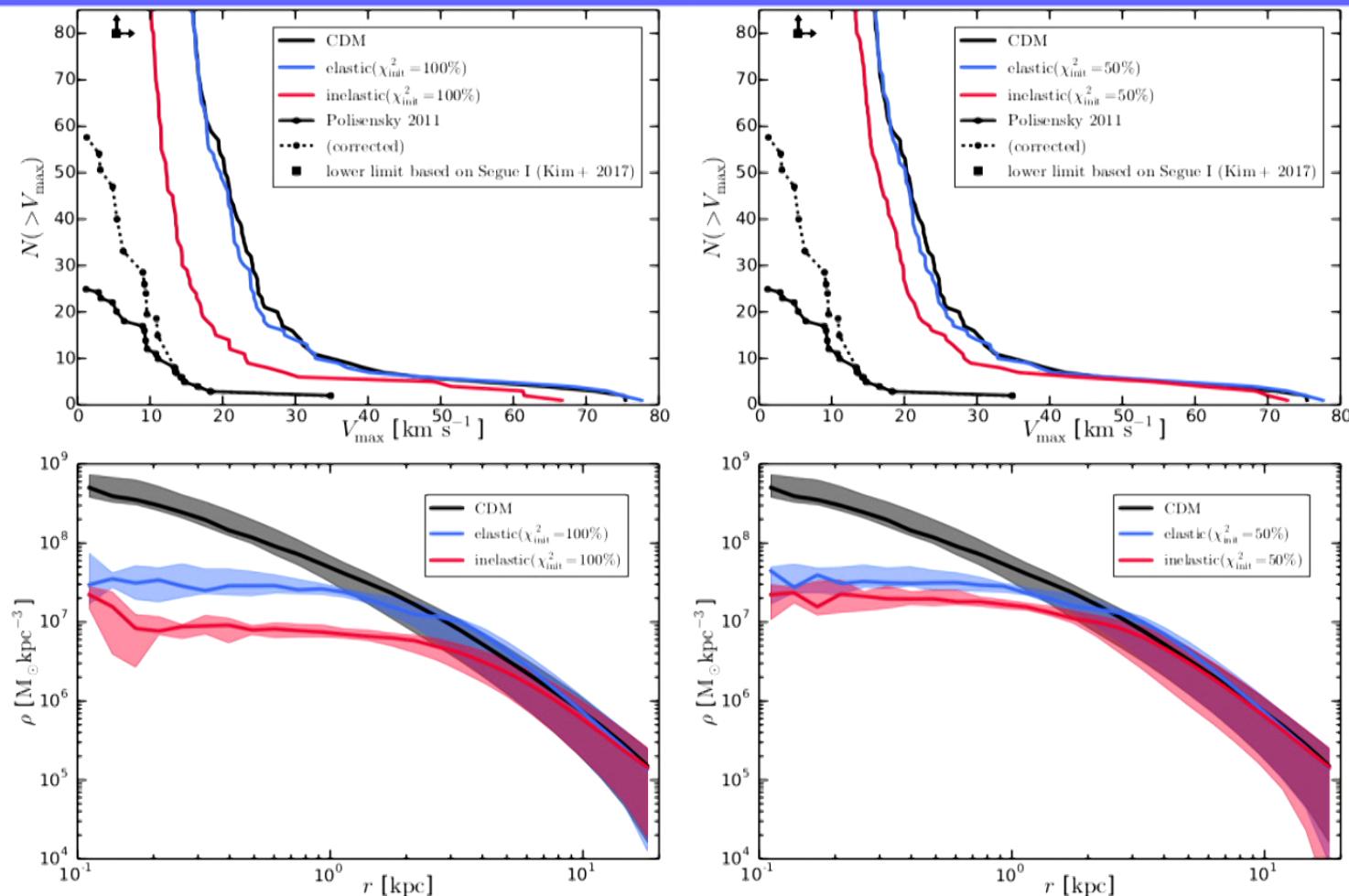


energy injection is equivalent to a few 100 million supernovae type II



MV, Zavala, Schutz, Slatyer 2019

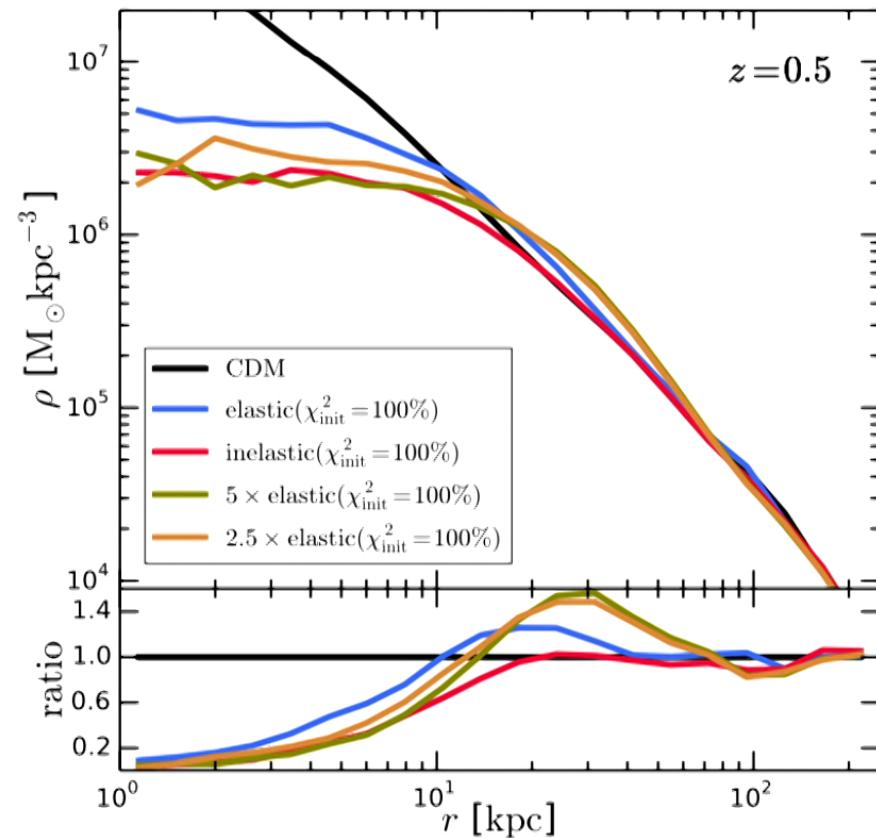
Subhalo Properties



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

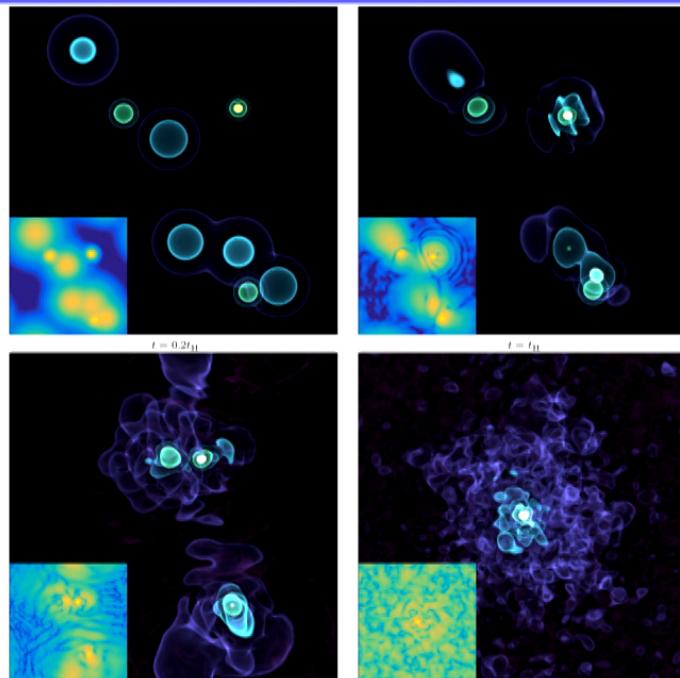


an elastic model with a ~ 5 times larger cross section leads to a central density reduction similar to the inelastic model

implications for cross section constraints?

MV, Zavala, Schutz, Slatyer 2019

Ultra-light Axions

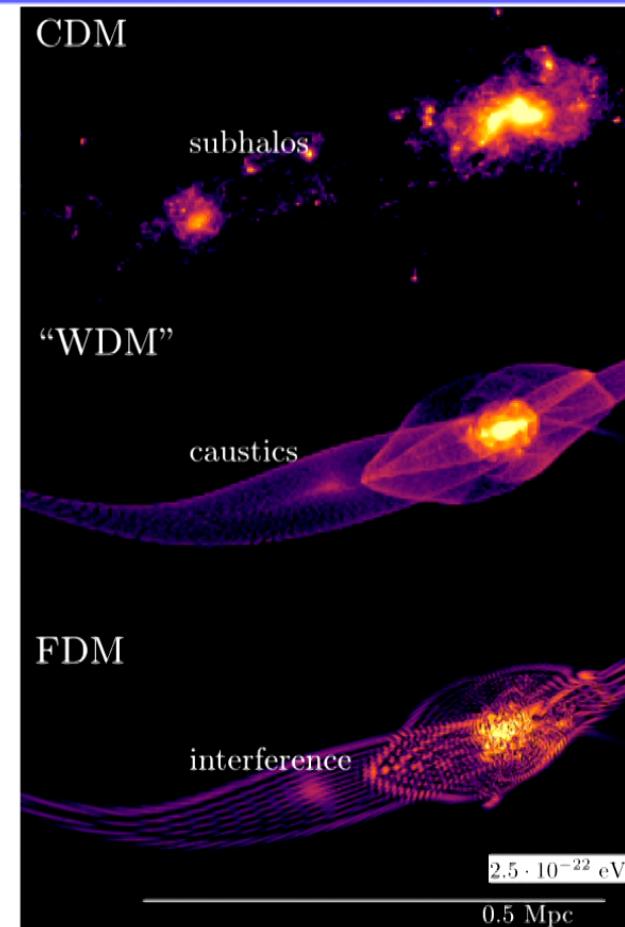


requires novel simulation
techniques beyond N-body

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

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

Mocz, MV+ 2017



first hydrodynamical simulations
of an ultra-light axion universe

Mocz, Fialkov, MV+ PRL 2019

Conclusion

cosmological simulations like Illustris and IllustrisTNG provide now a wide range of theoretical predictions that agree remarkably well with observational data on a wide range of scales

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Two Main Frontiers

Astrophysical Frontier

novel numerical models to overcome scale gap and to address missing astrophysical processes to approach the regime of **approximate ab initio** simulations

Cosmological Frontier

exploration of **alternatives for dark matter, dark energy, gravity** to constrain cosmological framework and to overcome potential discrepancies between theory and observations

ETHOS: The High-Redshift Universe

