Simulating Galaxy Formation: Illustris, IllustrisTNG and Beyond

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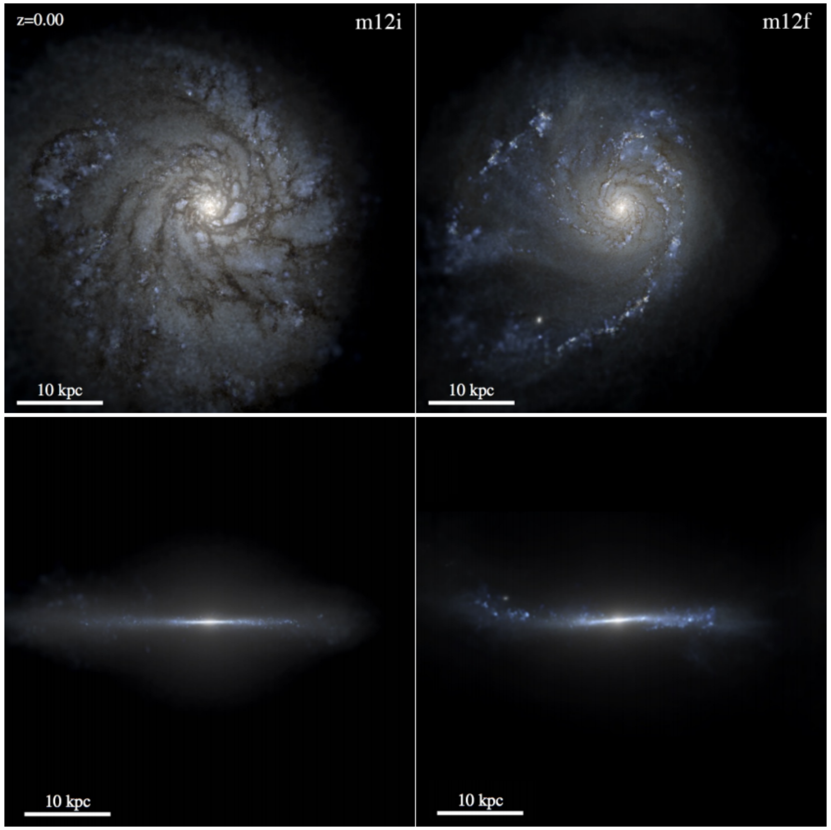
Massachusetts Institute of Technology

Conference on Shedding Light on the Dark Universe with Extremely Large Telescopes, July 2018

Simulation Approaches: Bottom-Up vs. Top-Down

Bottom-Up:



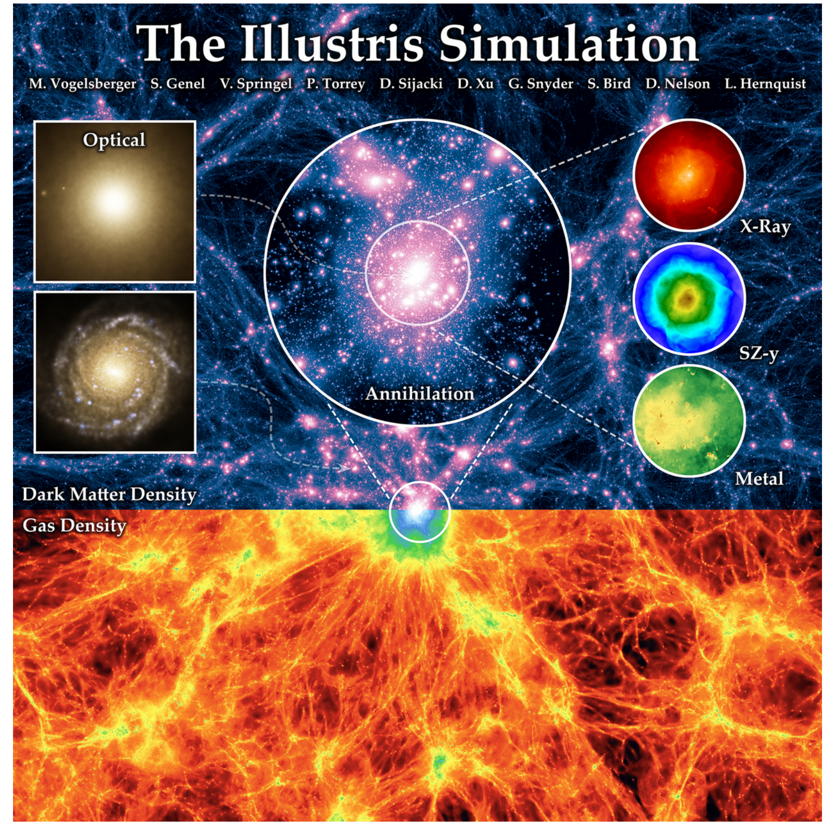
model *small* scales: approach *large* scales

<u>Pro:</u>
more detailed modeling of physical processes

<u>Con:</u>
little statistics to confront with observations

e.g., ERIS, FIRE, AURIGA, NIHAO

Top-Down:

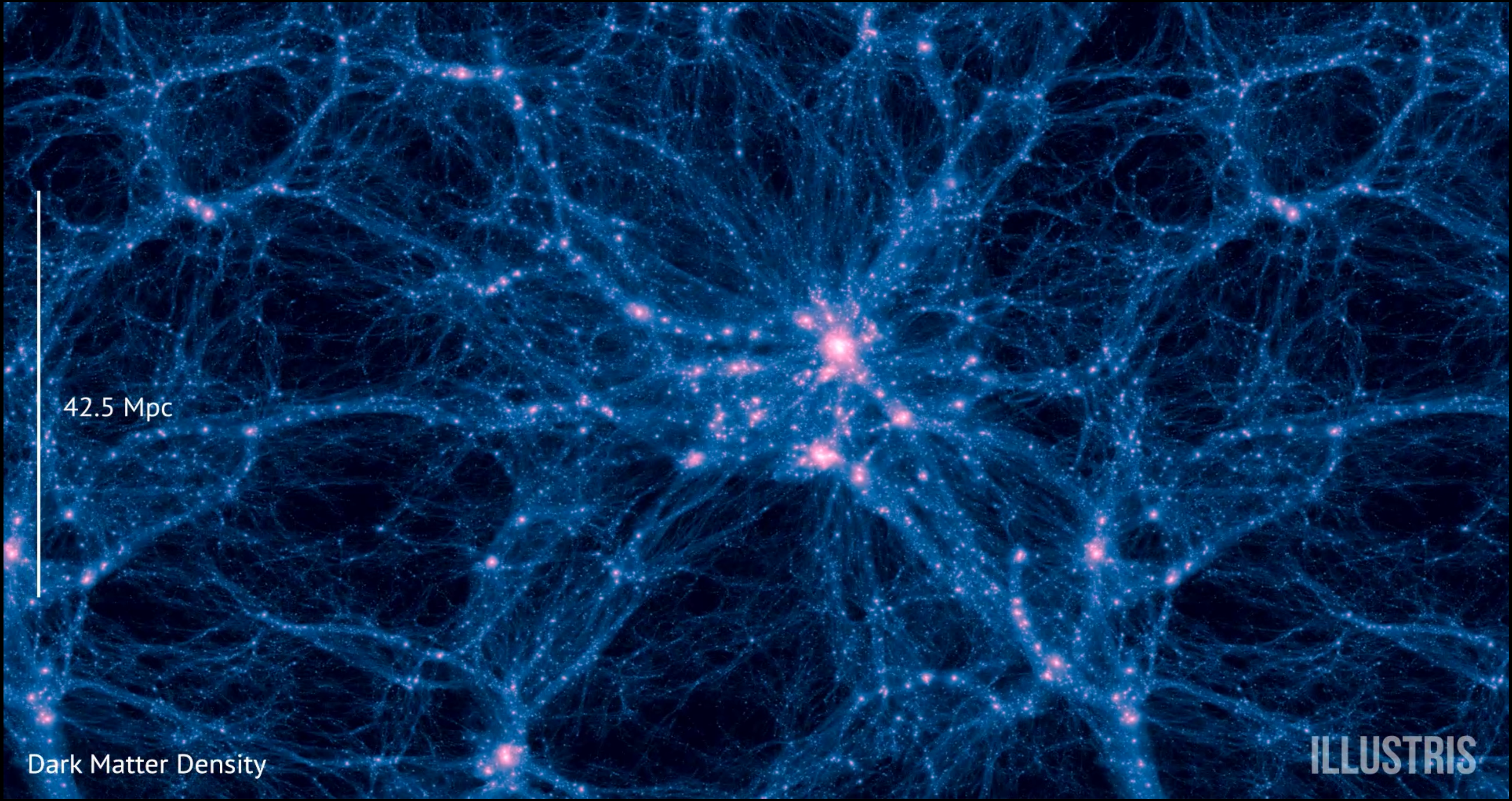


model *large* scales: approach *small* scales

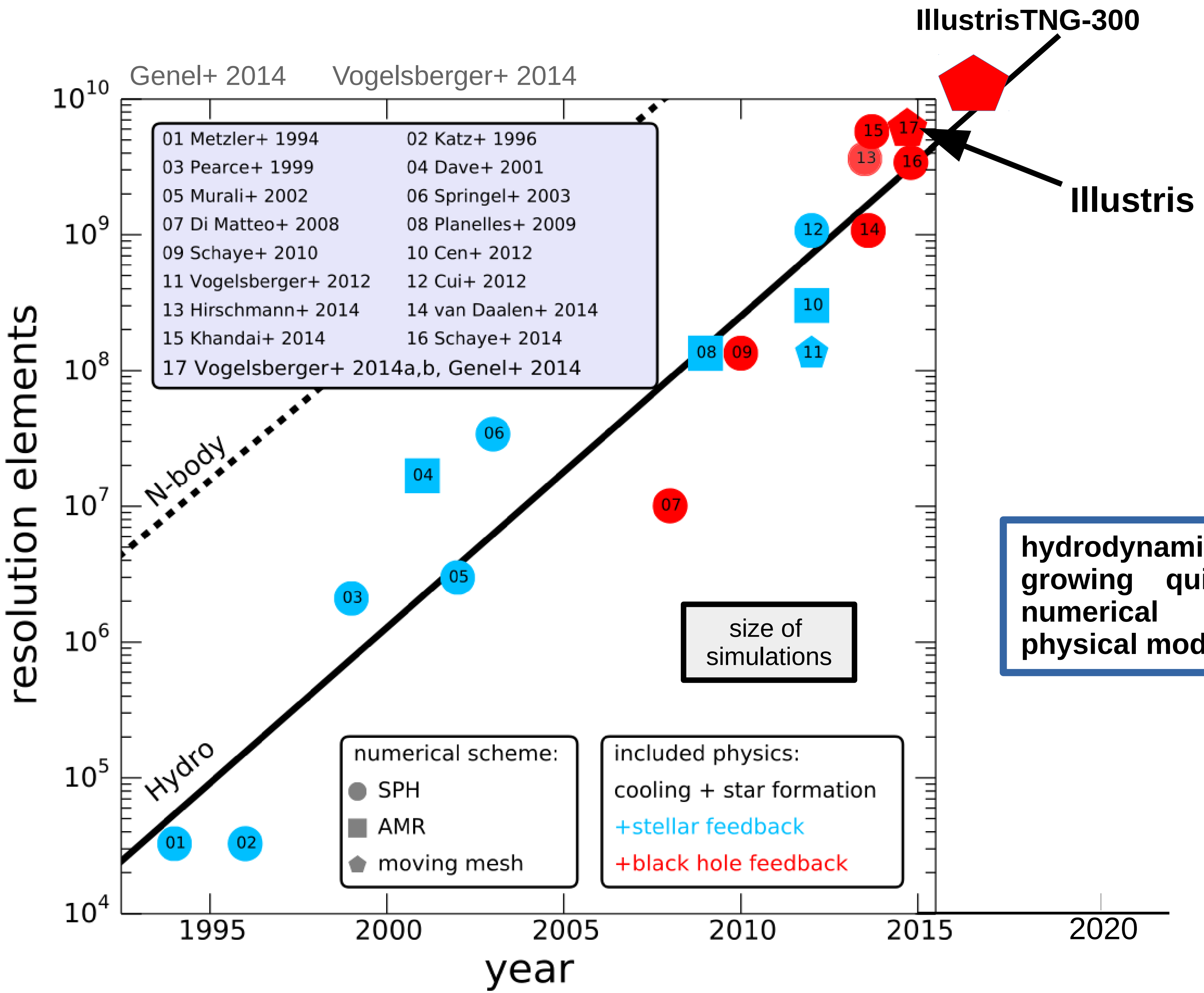
<u>Pro:</u>
lots of statistics to compare with data

<u>Con:</u>
rely on rather crude sub-resolution models

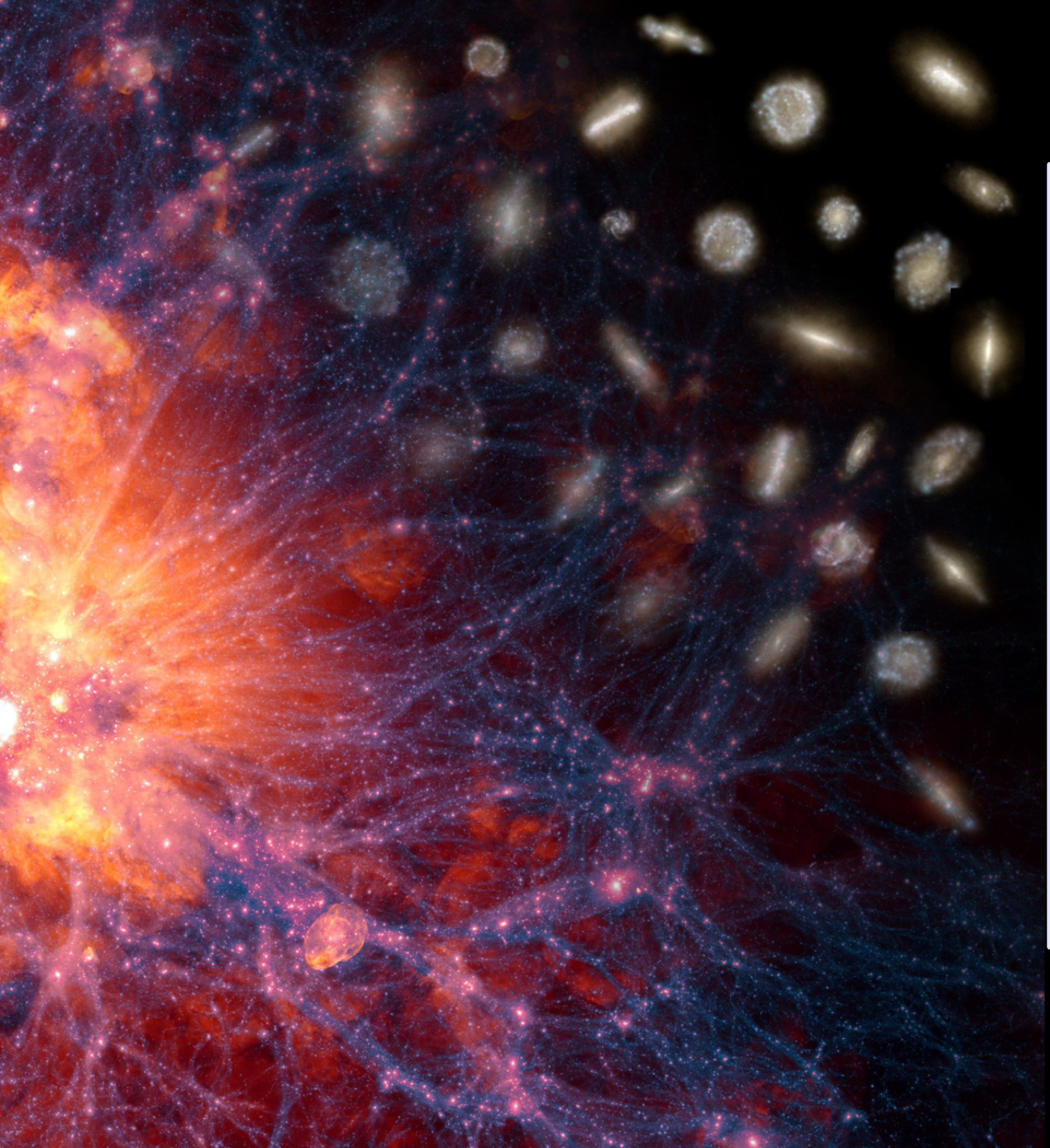
e.g., ILLUSTRIS, EAGLE, HORIZON-AGN, MUFASA, ILLUSTRIS-TNG


42.5 Mpc
Dark Matter Density
ILLUSTRIS

The Evolution of Large-Scale Simulations



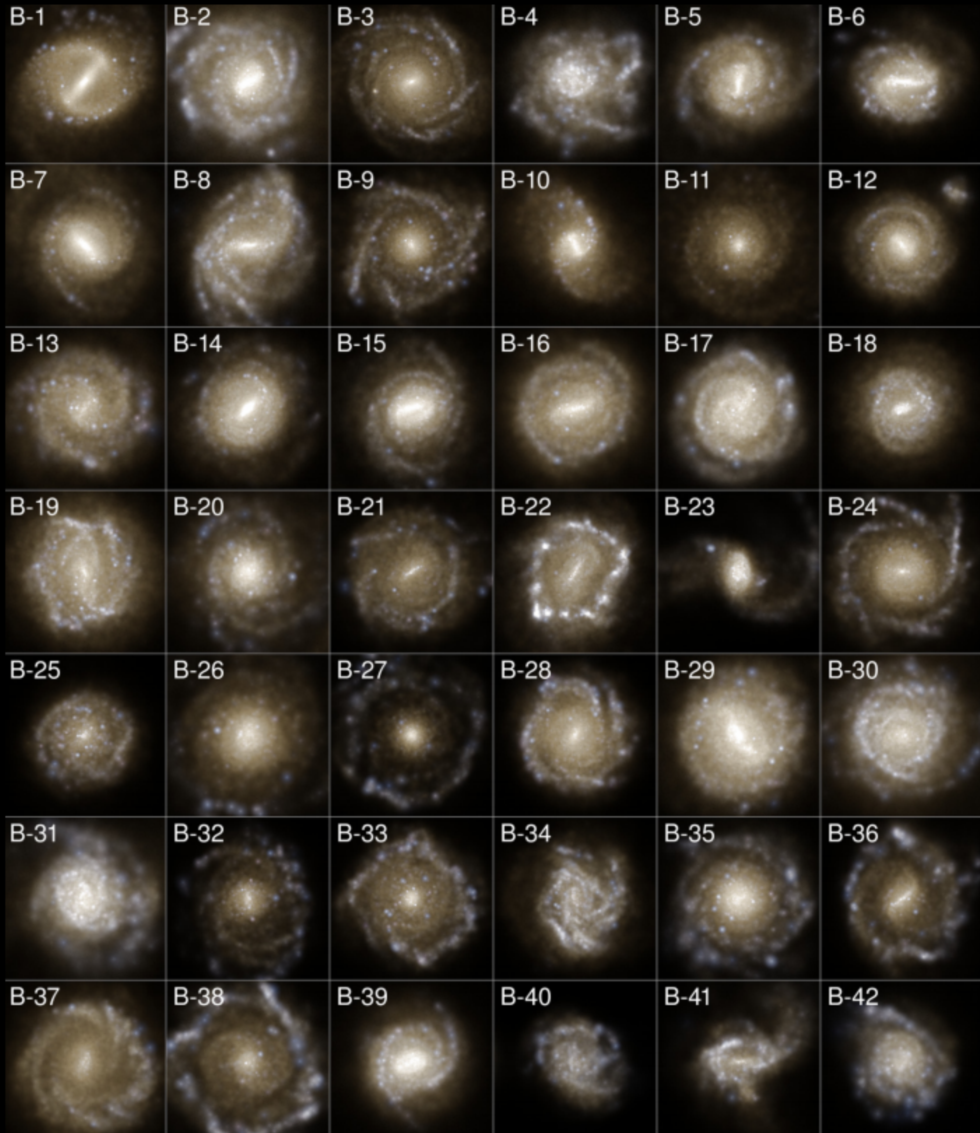
hydrodynamical simulations growing quickly: variety of numerical techniques and physical models/processes

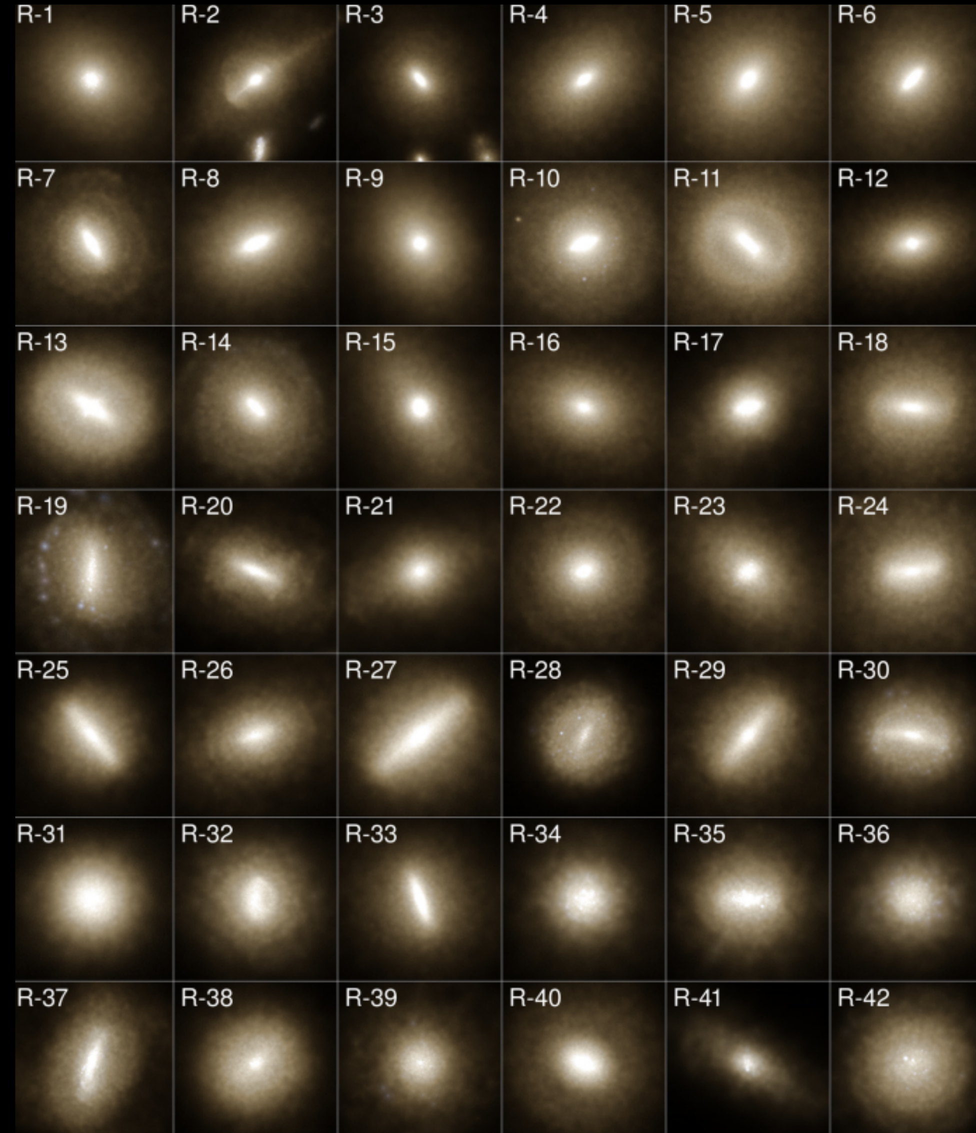


Illustris/IllustrisTNG Model:
- basic ingredients -

- <u>hydrodynamics:</u>
  quasi-Lagrangian moving mesh (Arepo, Springel 2010)
- <u>heating / cooling:</u>
  primordial, metal line
- <u>UV background:</u>
  with self-shielding correction
- <u>star formation / ISM:</u>
  effective EOS
- <u>chemical enrichment:</u>
  9 elements by SNIa, SNII, AGB
- <u>supernova feedback:</u>
  kinetic SNII feedback
- <u>supermassive black holes:</u>
  seeding, growth, merging
- <u>AGN feedback:</u>
  quasar, radio mode, radiative

MV+ 2013, 2014



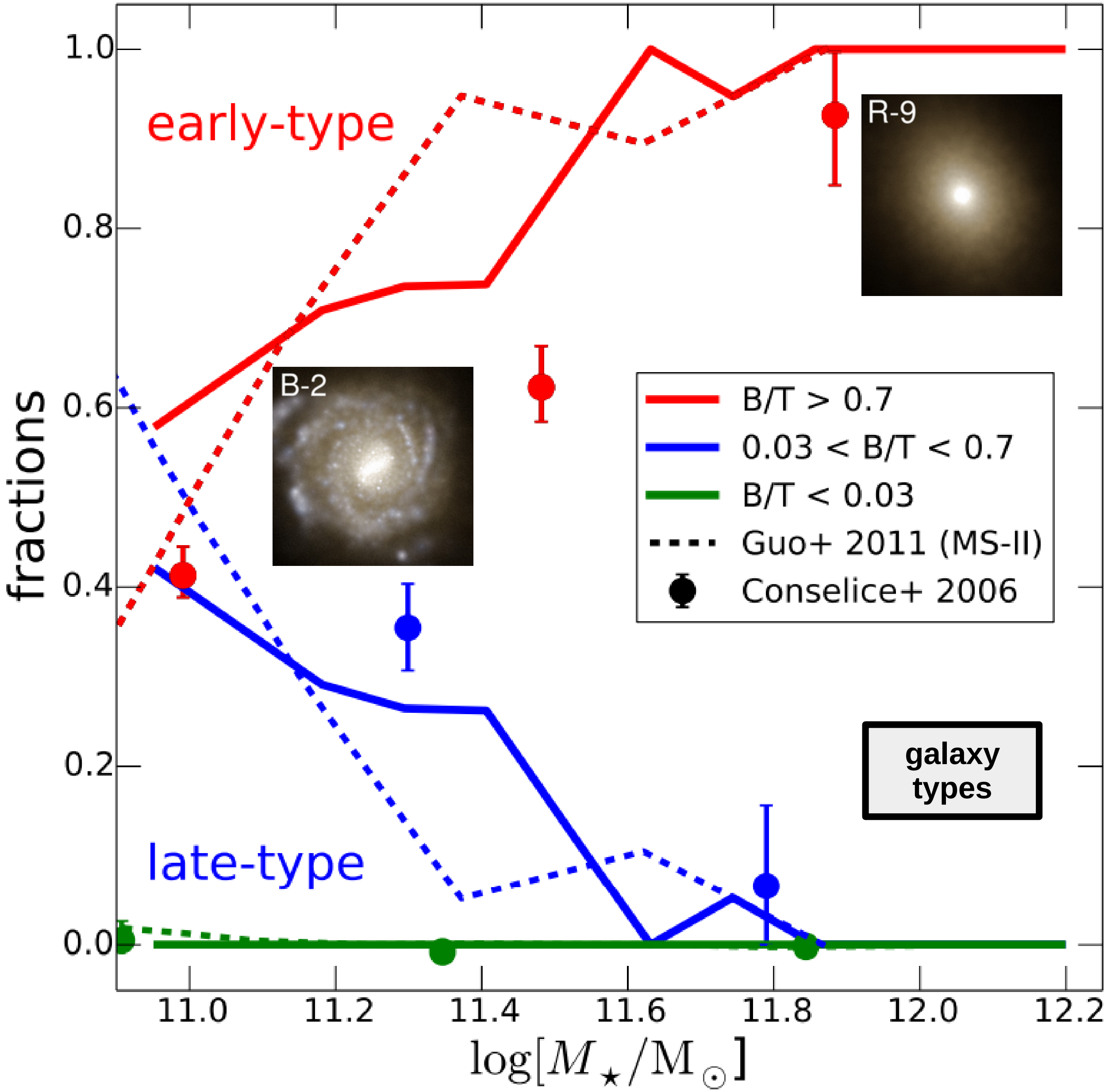


simulated disk galaxies: blue and star-forming

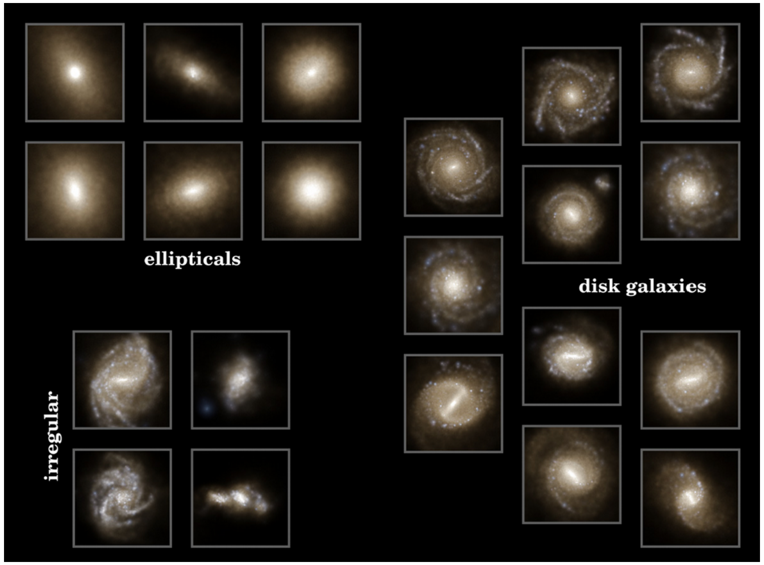
simulated elliptical galaxies: red and dead

MV+ 2014

Galaxy Diversity



simulations predict the observed fractions of different galaxy types



MV+ 2014 (Nature)

Mock HUDF

HST

simulation

MV+ 2014 (Nature)

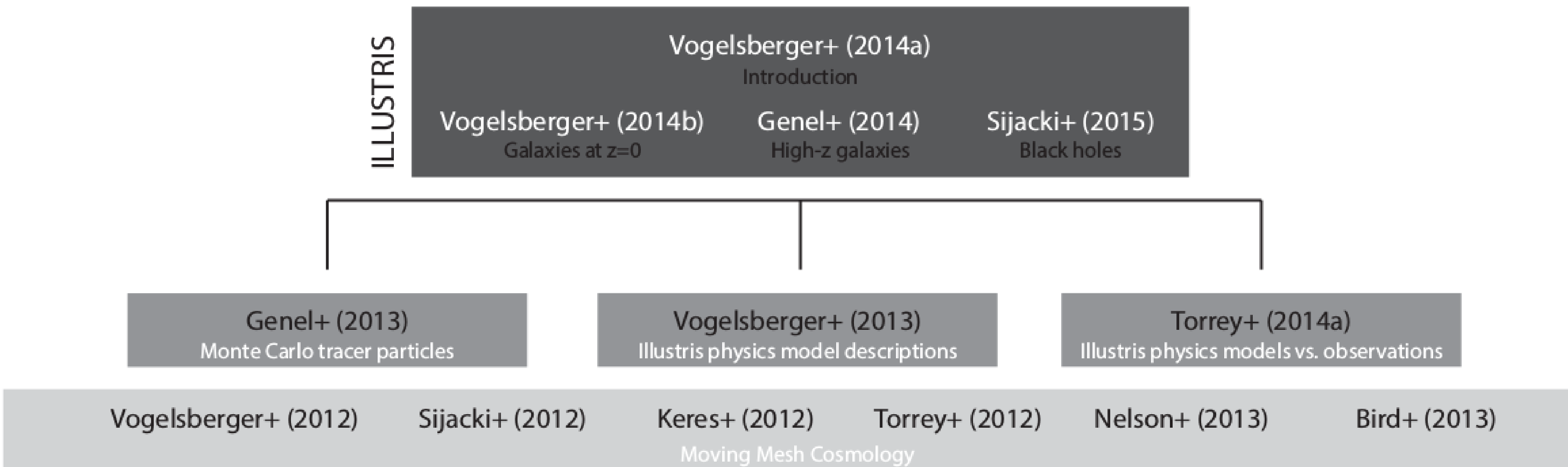
Illustris → **IllustrisTNG**

Galaxy Formation Model

IllustrisTNG Model

↑

Illustris Model



IllustrisTNG model is an update of the **Illustris model**

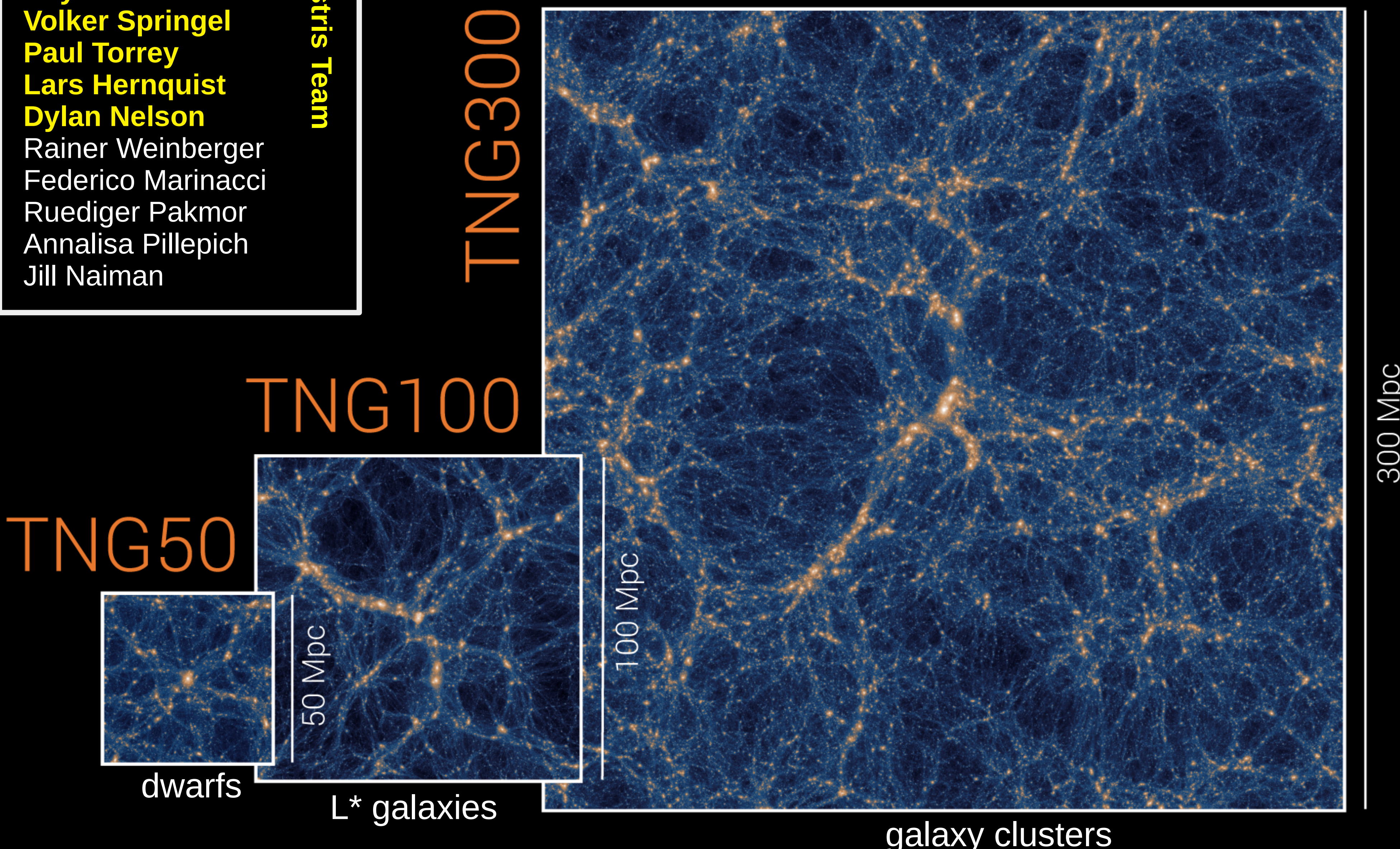
The IllustrisTNG Simulations

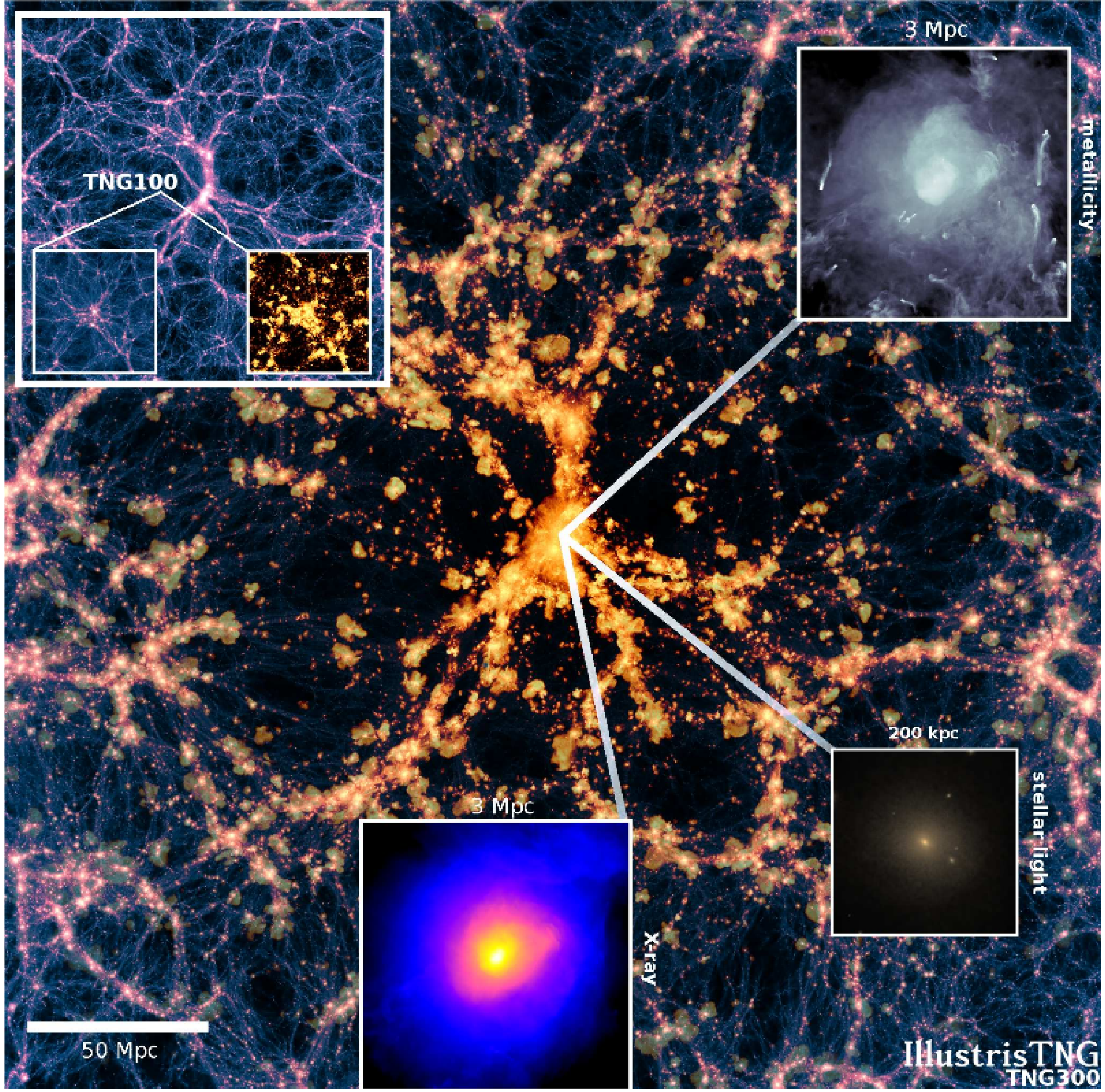
IllustrisTNG Team:

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

Illustris Team

three boxes with different primary science focus
(~250 million CPUh)





Number of Resolution Elements:

TNG300:
2 x 2500^3 ~ 31 billion

TNG100:
2 x 1820^3 ~ 12 billion

TNG50:
2 x 2160^3 ~ 20 billion

MV+ 2018

IllustrisTNG Simulation	Run	box side length $[h^{-1}\mathrm{Mpc}]$	[Mpc]	N_{gas}	N_{dm}	N_{tracer}	m_{b} $[h^{-1}\mathrm{M}_\odot]$	m_{dm} $[h^{-1}\mathrm{M}_\odot]$	ϵ $[h^{-1}\mathrm{kpc}]$
TNG300	TNG300-1	205	302.6	2500^3	2500^3	2×2500^3	7.44×10^6	3.98×10^7	1.0
	TNG300-2	205	302.6	1250^3	1250^3	2×1250^3	5.95×10^7	3.19×10^8	2.0
	TNG300-3	205	302.6	625^3	625^3	2×625^3	4.76×10^8	2.55×10^9	4.0
TNG100	TNG100-1	75	110.7	1820^3	1820^3	2×1820^3	9.44×10^5	5.06×10^6	0.5
	TNG100-2	75	110.7	910^3	910^3	2×910^3	7.55×10^6	4.04×10^7	1.0
	TNG100-3	75	110.7	455^3	455^3	2×455^3	6.04×10^7	3.24×10^8	2.0

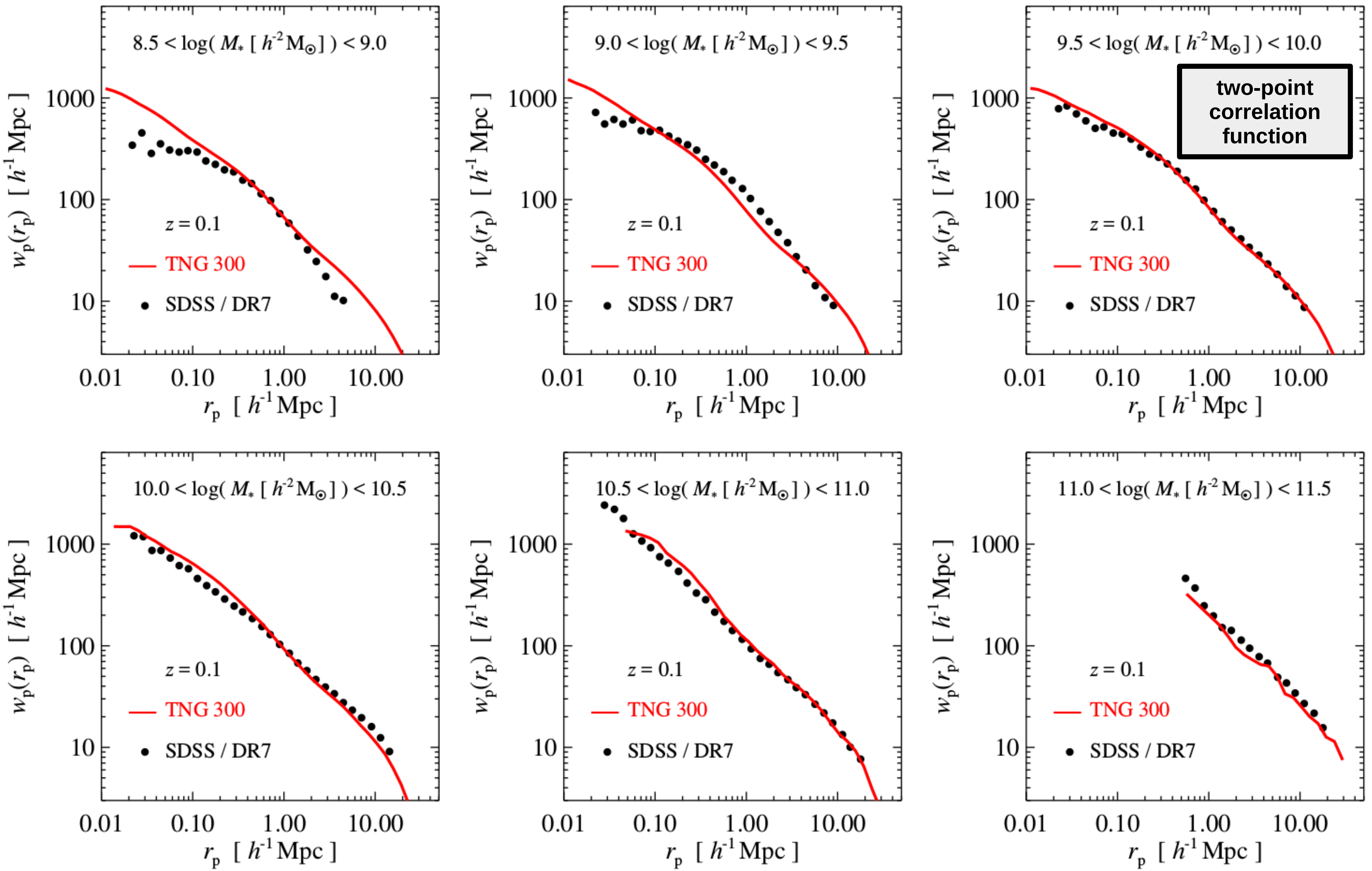

redshift: 3.88
Mark Vogelsberger, Federico Marinacci (MIT)

IllustrisTNG: Some First Results

First Papers

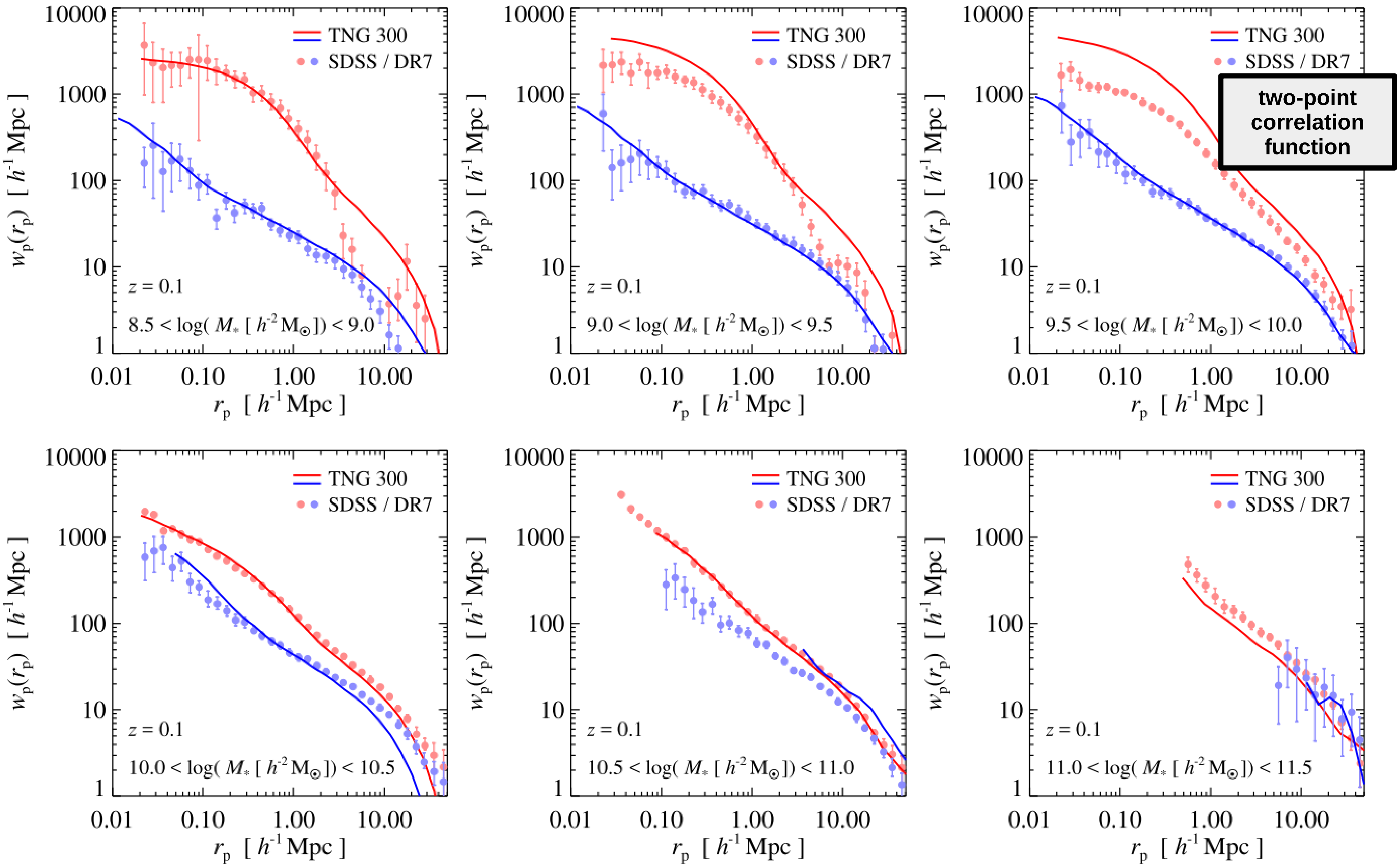
- **Matter Clustering** (Springel+ 2018)
- **Metals in Clusters** (Vogelsberger+ 2018)
- **Magnetic Fields and Radio Halos** (Marinacci+ 2018)
- **R-Process Enrichment** (Naiman+ 2018)
- **Stellar Content of Halos** (Pillepich+ 2018)
- **Galaxy Colors** (Nelson+ 2018)
- **Galaxy Sizes** (Genel+ 2018)

Galaxy Clustering



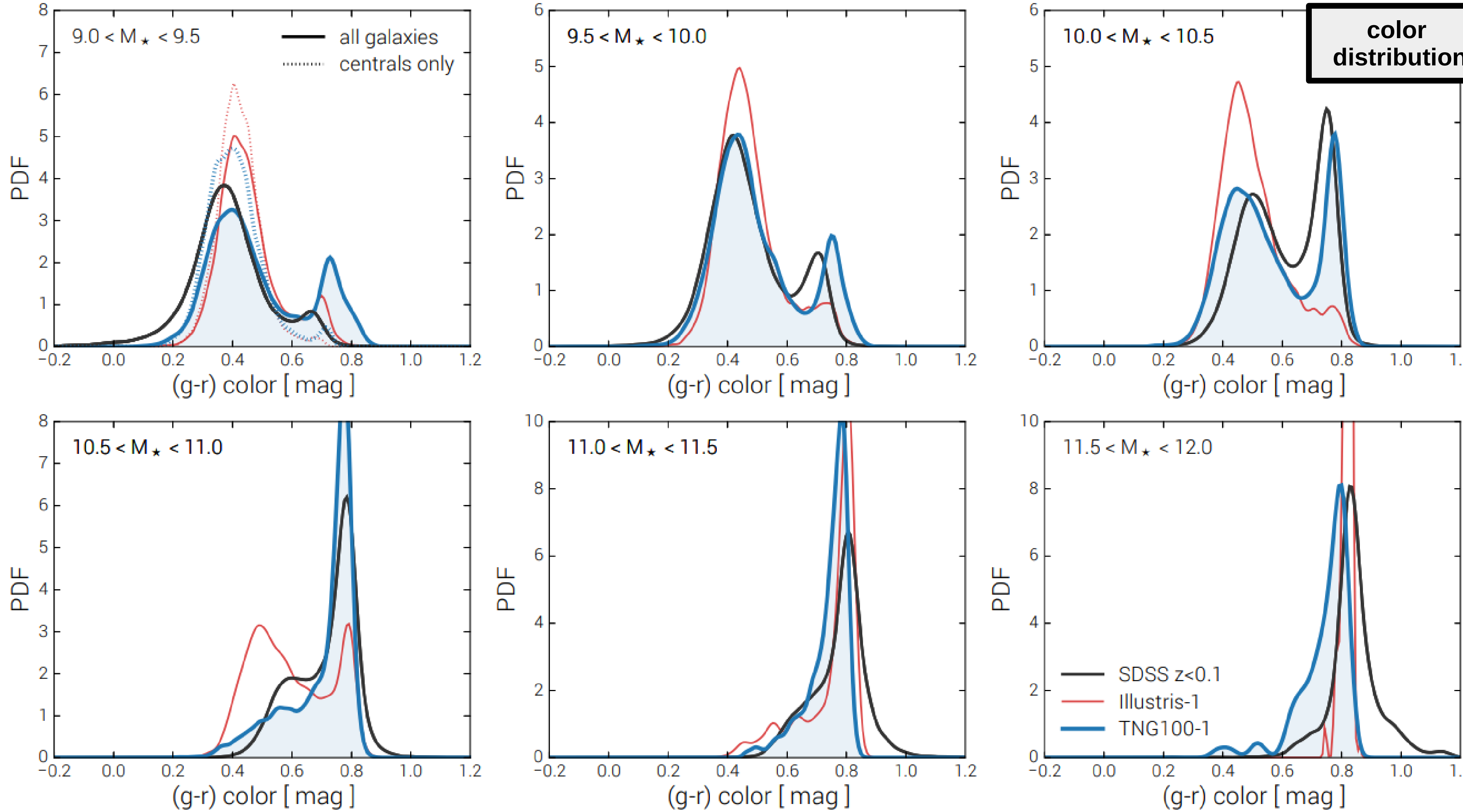
Springel+ w/ MV 2018

Galaxy Clustering

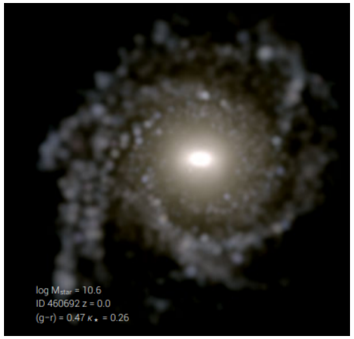
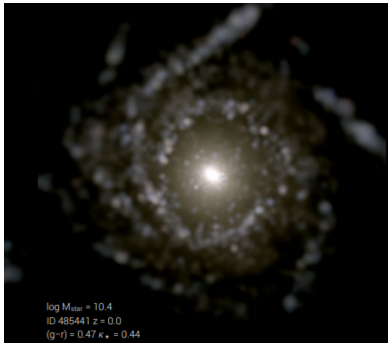
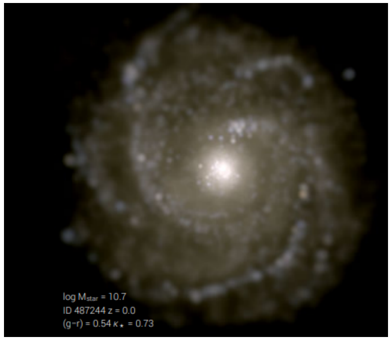


Springel+ w/ MV 2018

Galaxy Colors

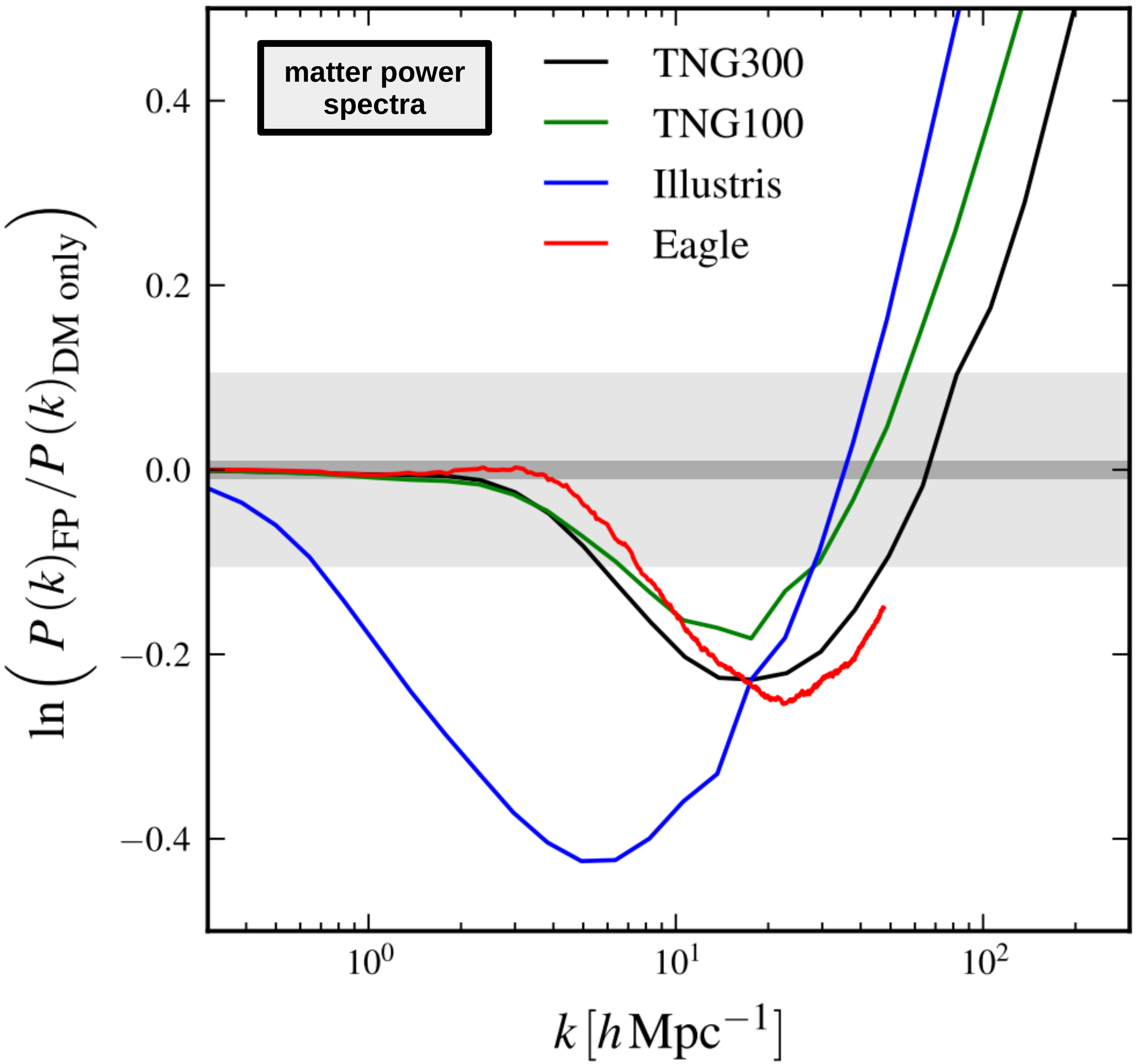


color distribution

Nelson+ w/ MV 2018

Impact of Baryons on Matter Power Spectrum

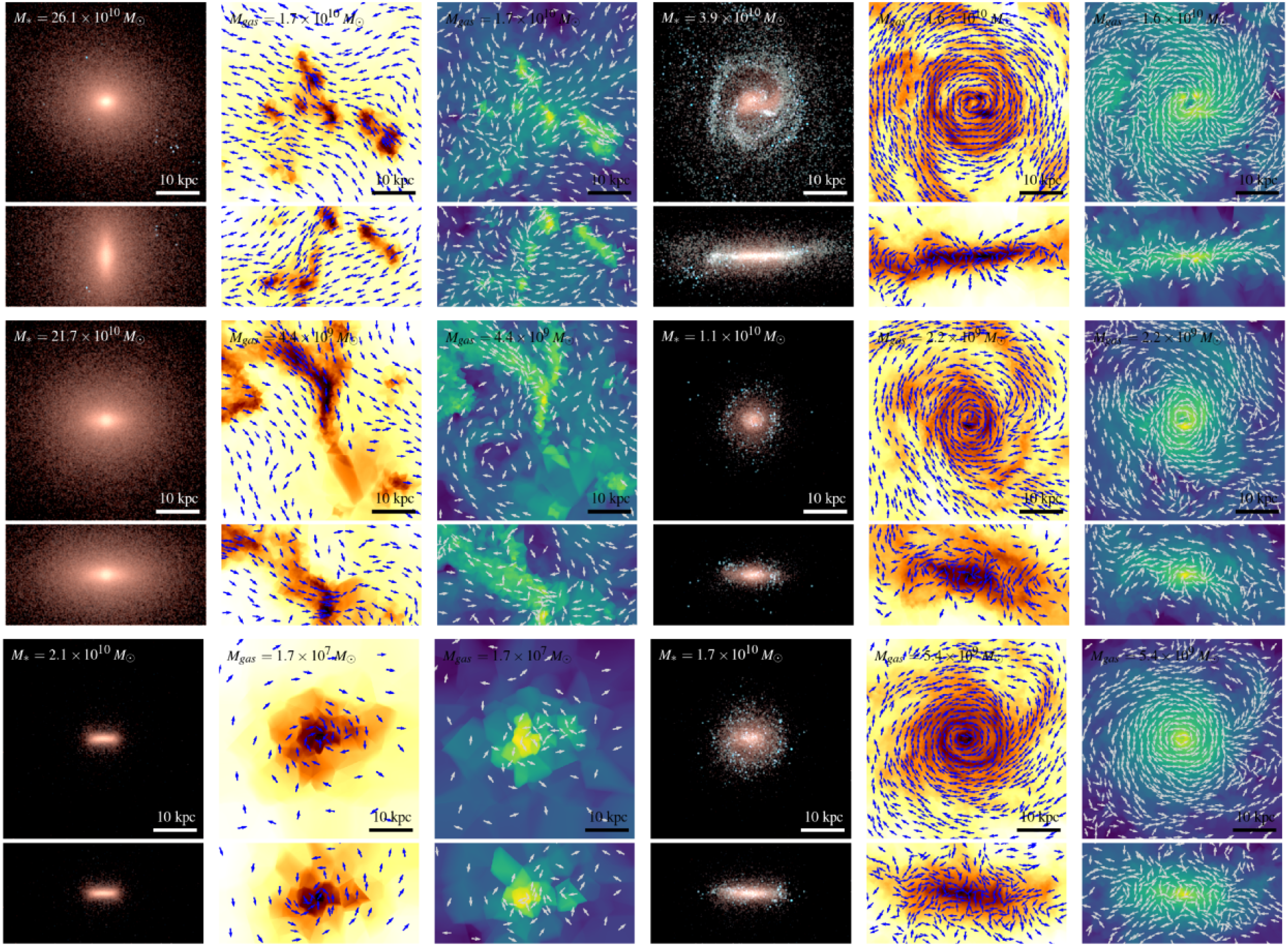


baryon physics modifies matter power spectra

EAGLE and IllustrisTNG produce similar effect

Springel+ w/ MV 2018

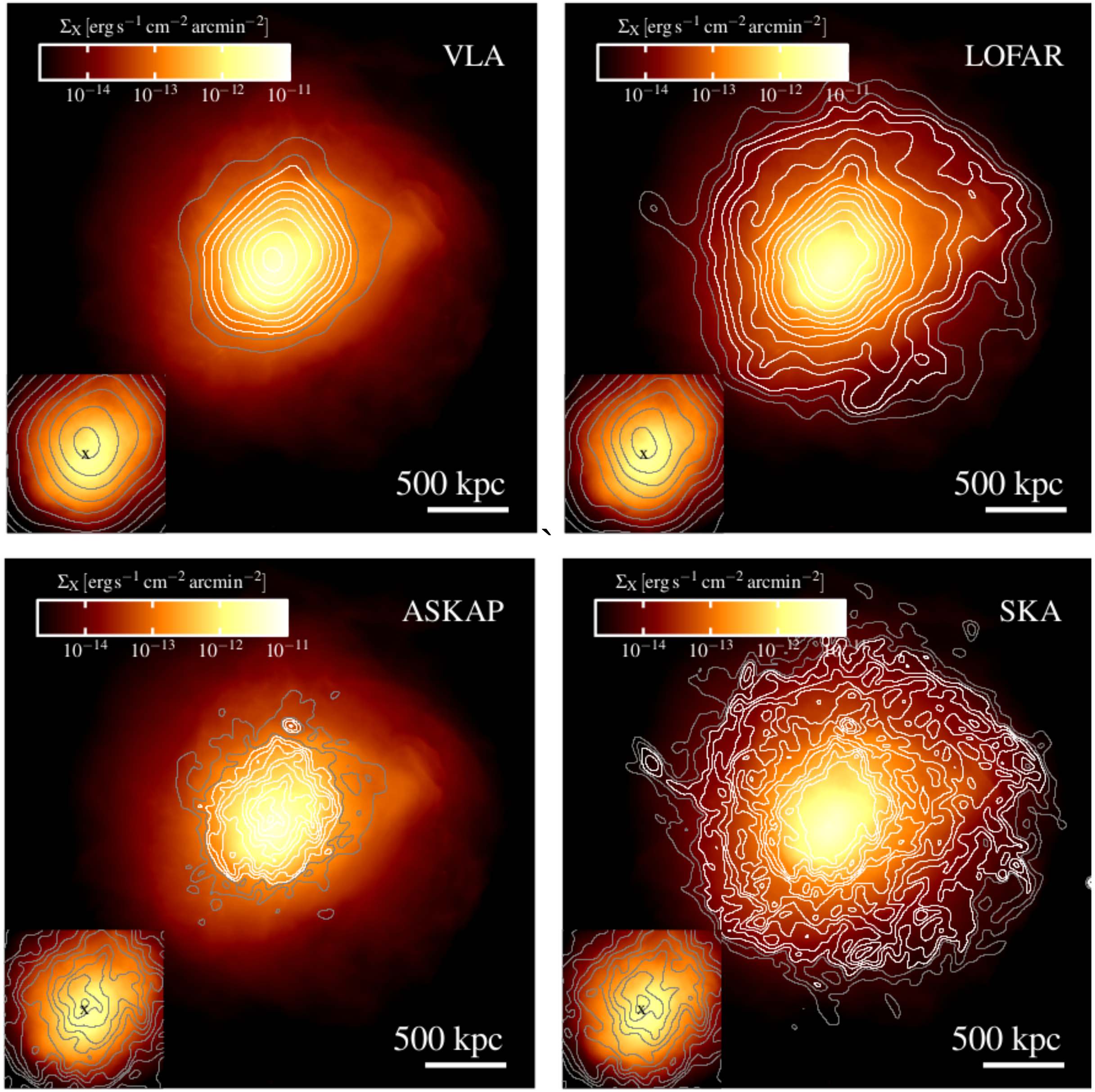
Topology of Magnetic Fields



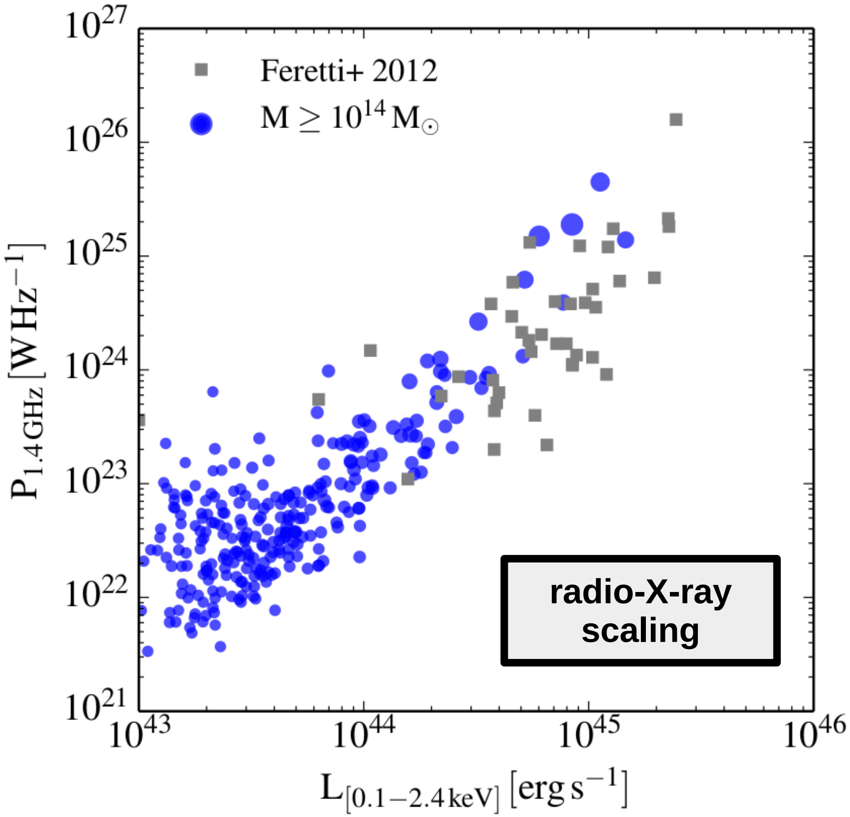
elliptical galaxies **disk galaxies**

Marinacci, MV+ 2018

Modeling Radio Halos

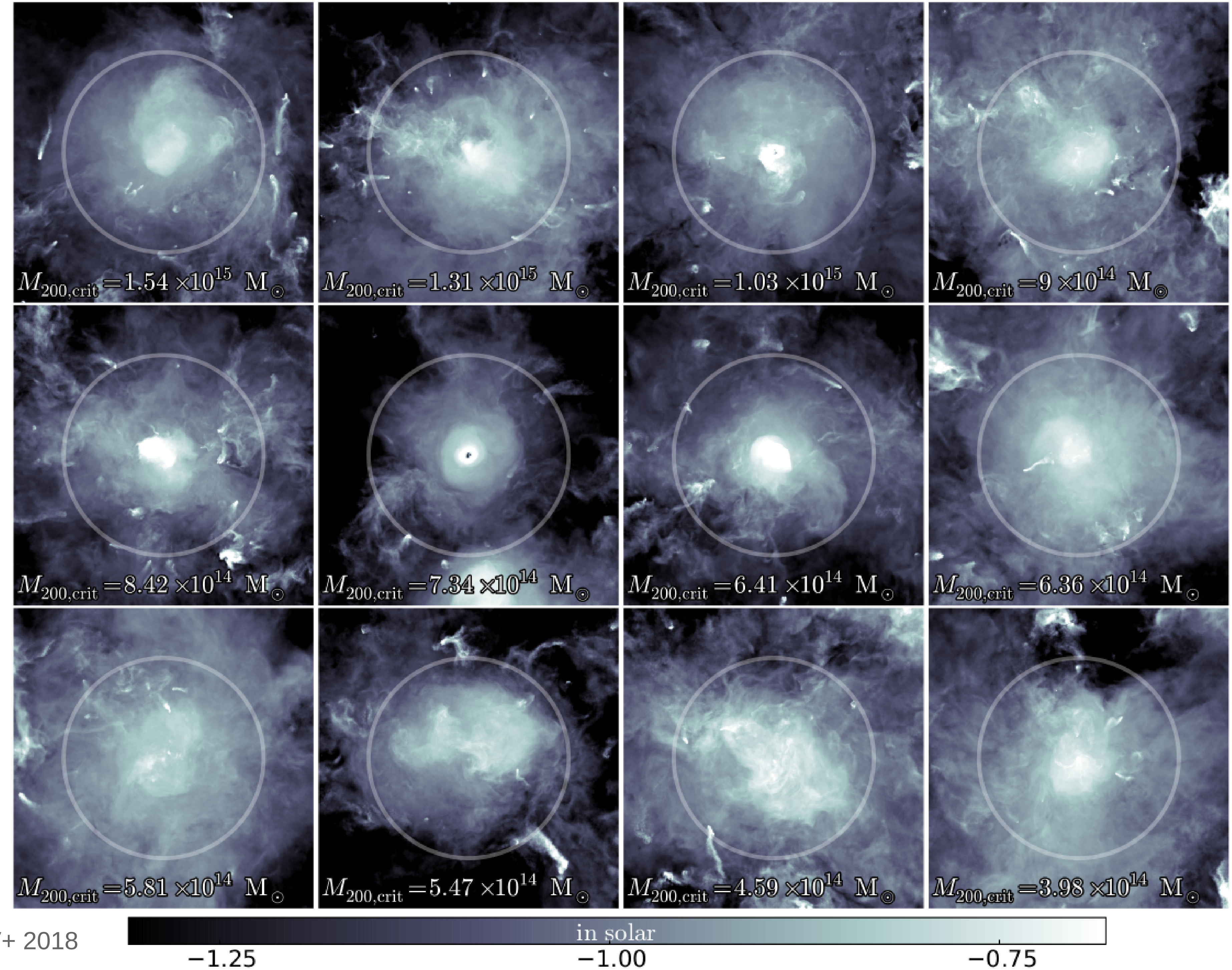


radio emission provides another probe of magnetic field strength



Marinacci, MV+ 2018

Metals in the ICM

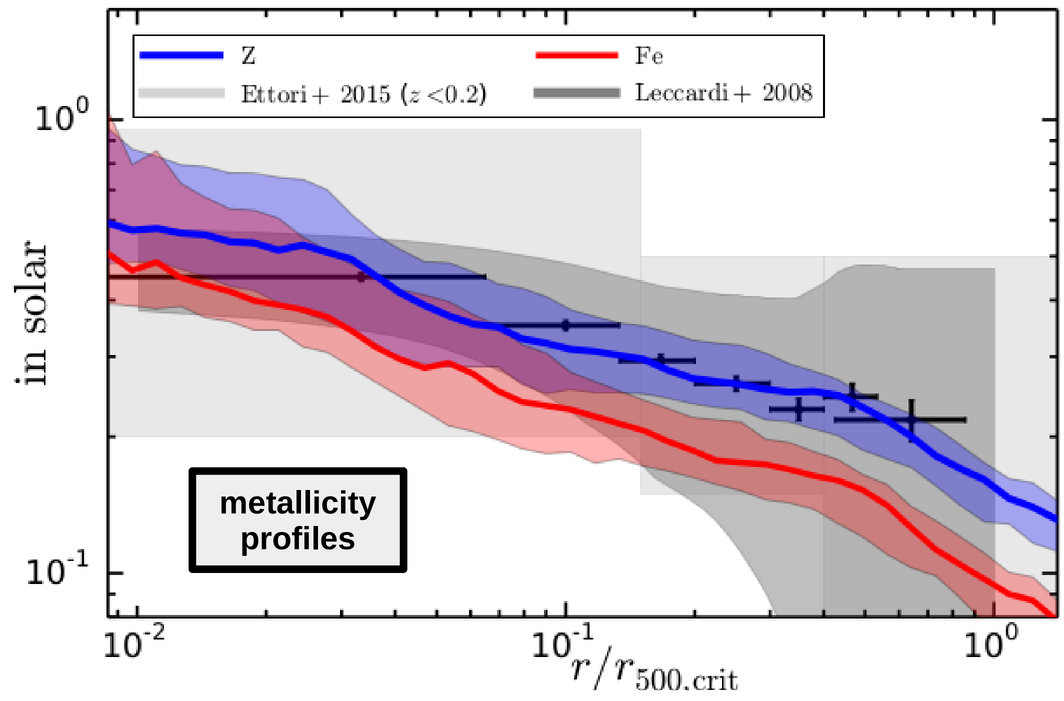


MV+ 2018

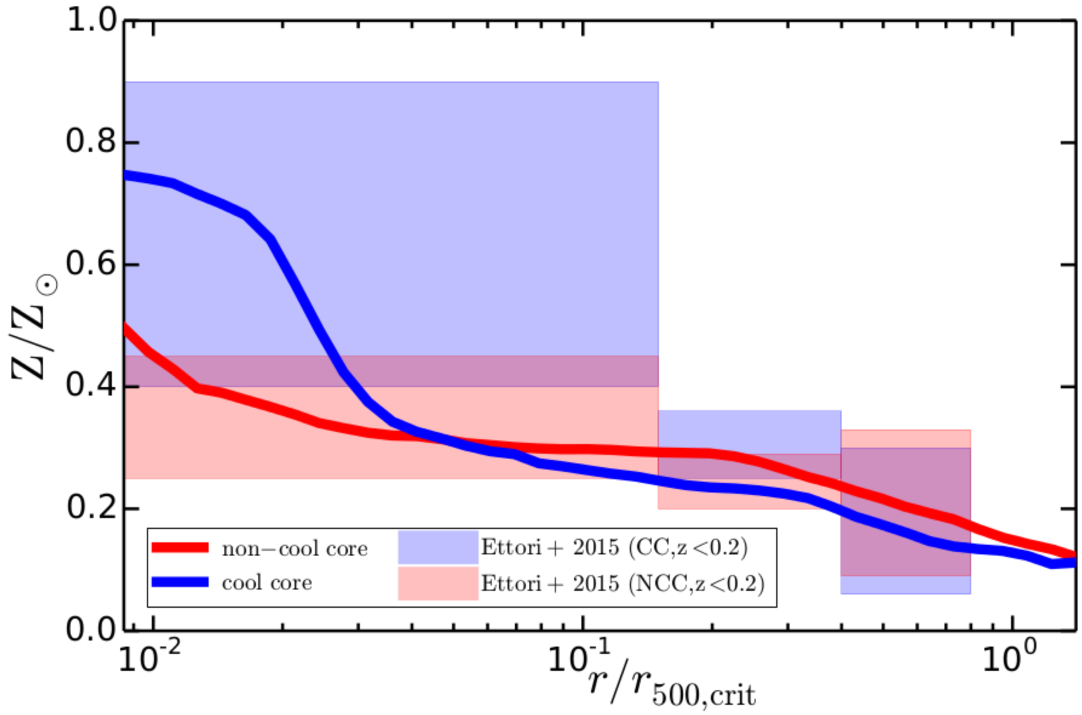
ICM Metallicity Profiles

two cluster samples:

- **TNG300 contains ~300 clusters with mass resolution ~10^7 M_{sun}**
- **TNG100 contains ~20 clusters with mass resolution ~10^6 M_{sun}**
- **(TNG50 contains 1 cluster with mass resolution ~10^5 M_{sun})**

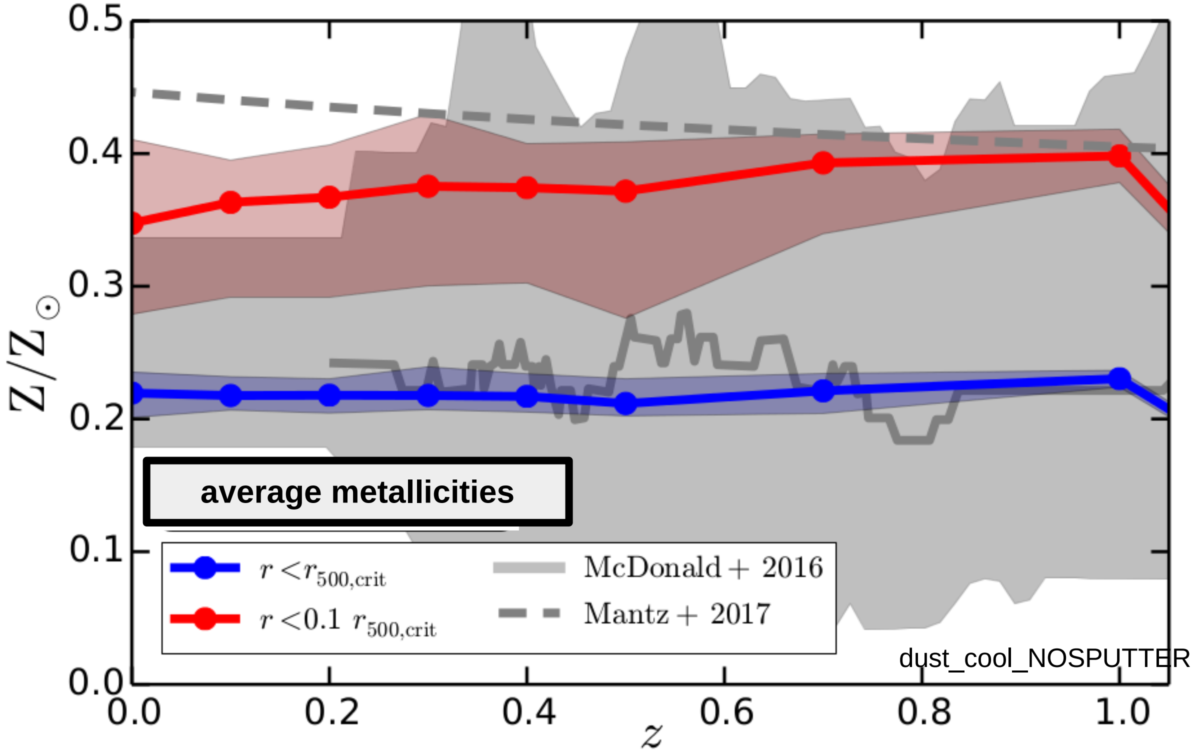


CC/NCC Dichotomy of metallicity profiles



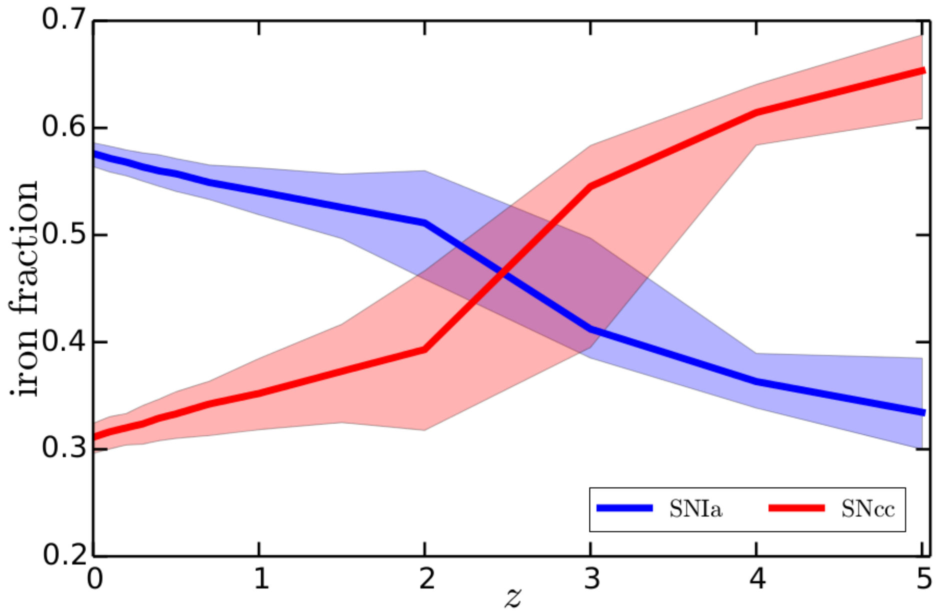
MV+ 2018

Metallicity Redshift Evolution



constant average metallicity out to z~1 in agreement with recent observational data

enrichment at early times due to SNcc, at late times due to SNIa; crossing at around z~2.5



MV+ 2018

Beyond Illustris and IllustrisTNG?

Dust Content of Galaxies

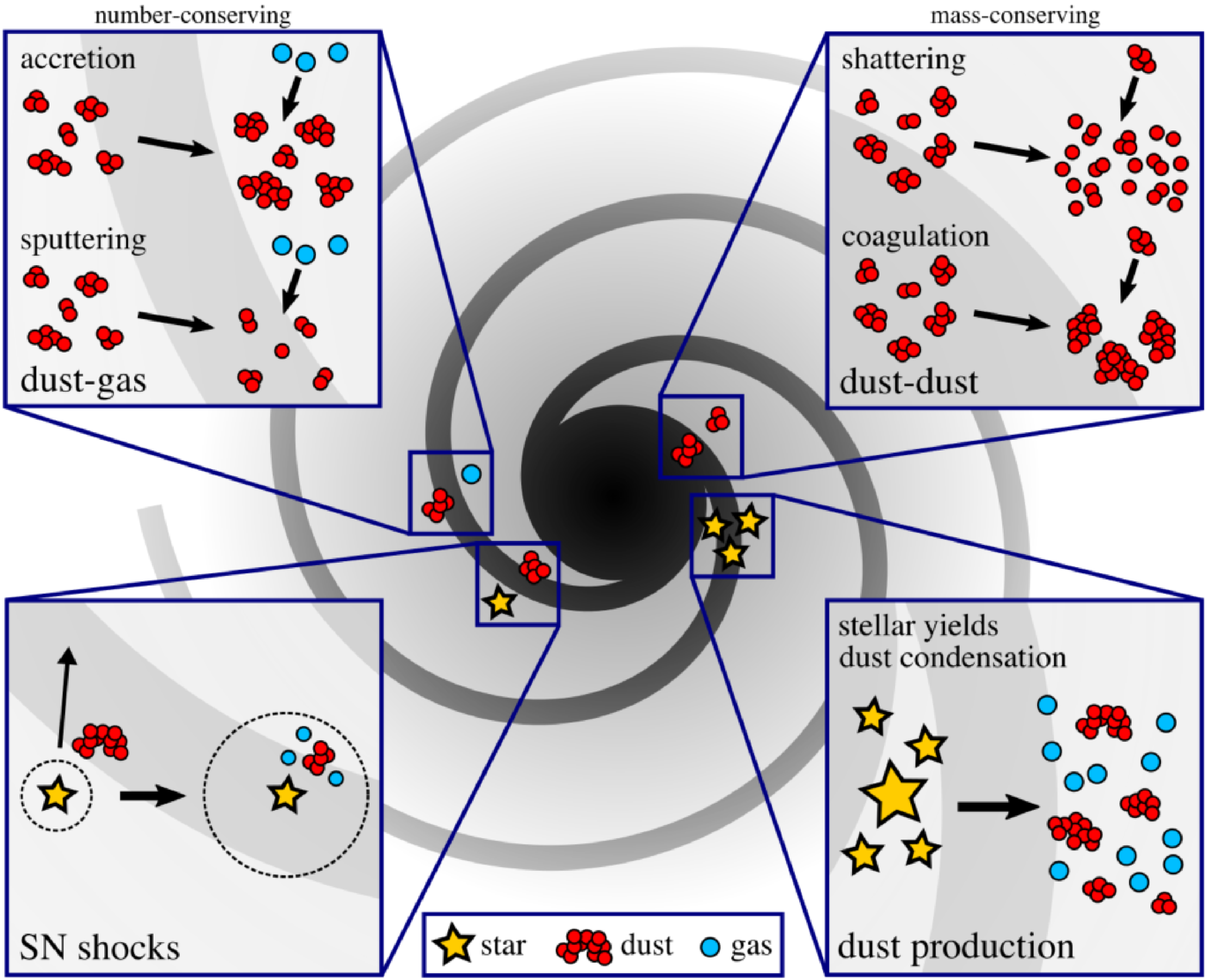
- dust mass function
- cosmic dust density
- dust rich high redshift galaxies
- dust-to-gas ratios
- dust-to-stellar-mass ratios

Impact of Dust on Physics of Galaxies

- chemistry
- heating / cooling
- star formation
- radiation-dust interaction
- stellar spectra

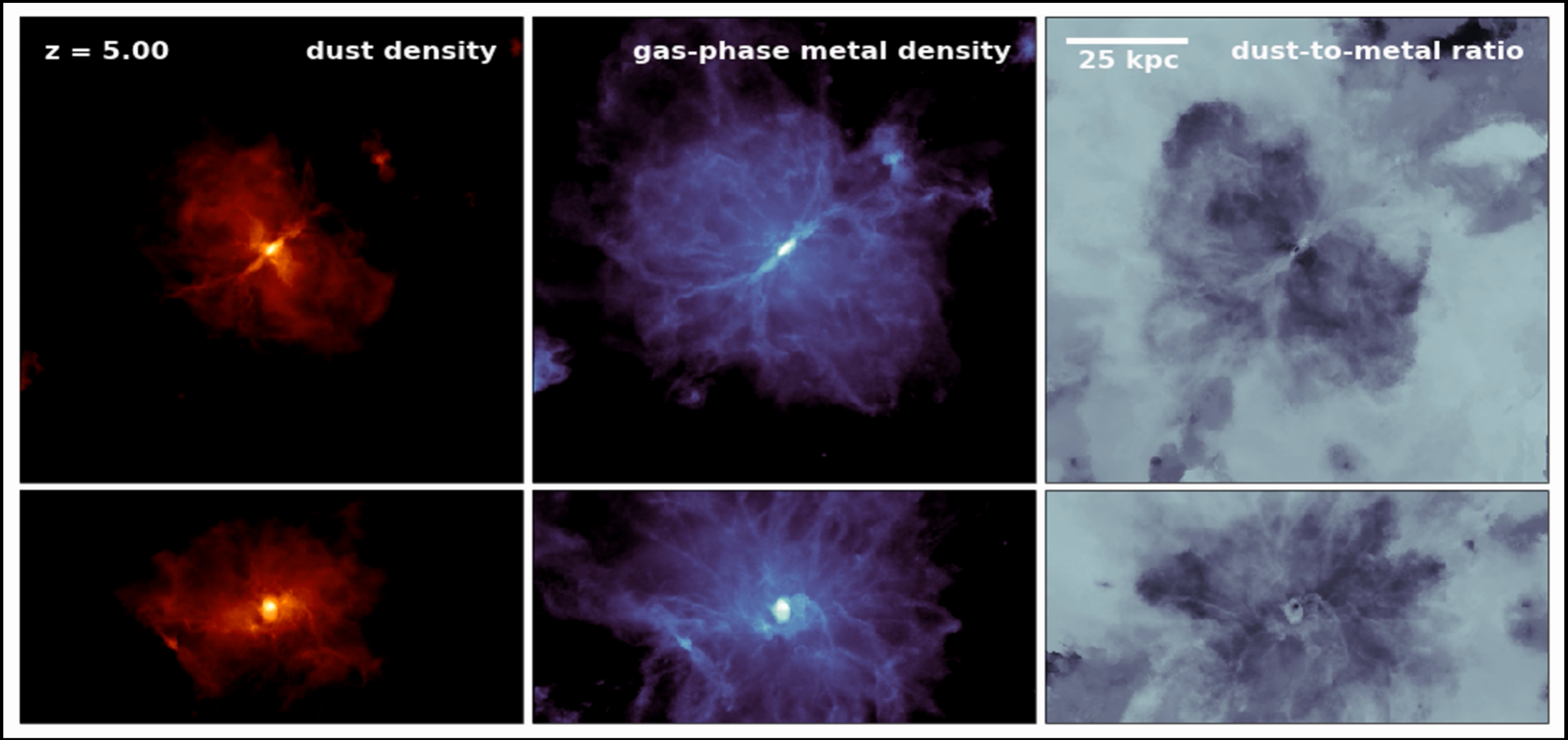
currently mostly simplified models:
→ no detailed spatial resolution
→ no cosmological context
→ no detailed galaxy formation physics
→ no large scale statistics
→ no detailed coupling to other physics

Simulating Cosmic Dust on a Moving Mesh

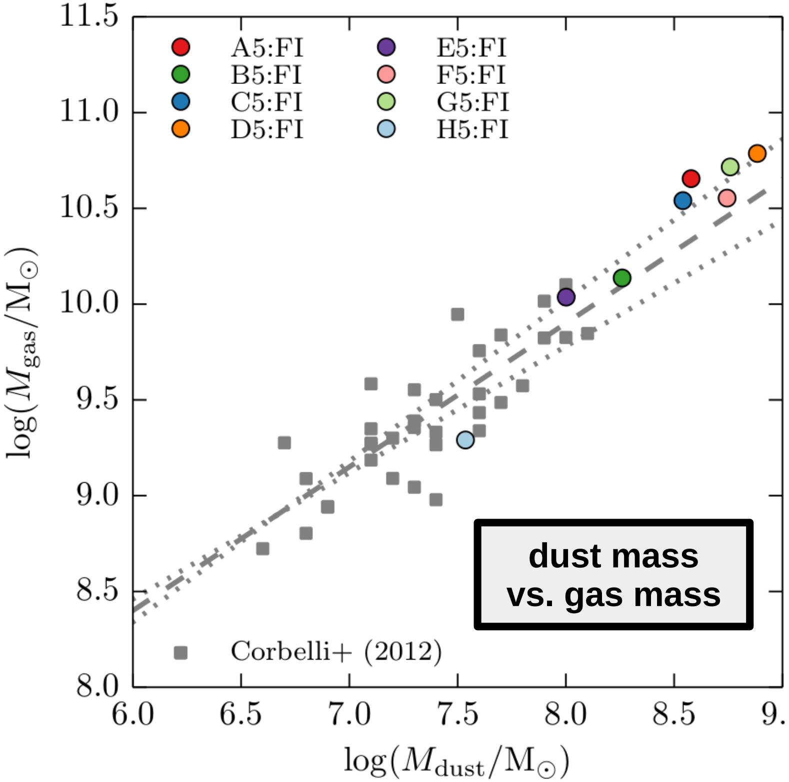


McKinnon, MV, Torrey, Marinacci, Kannan 2018

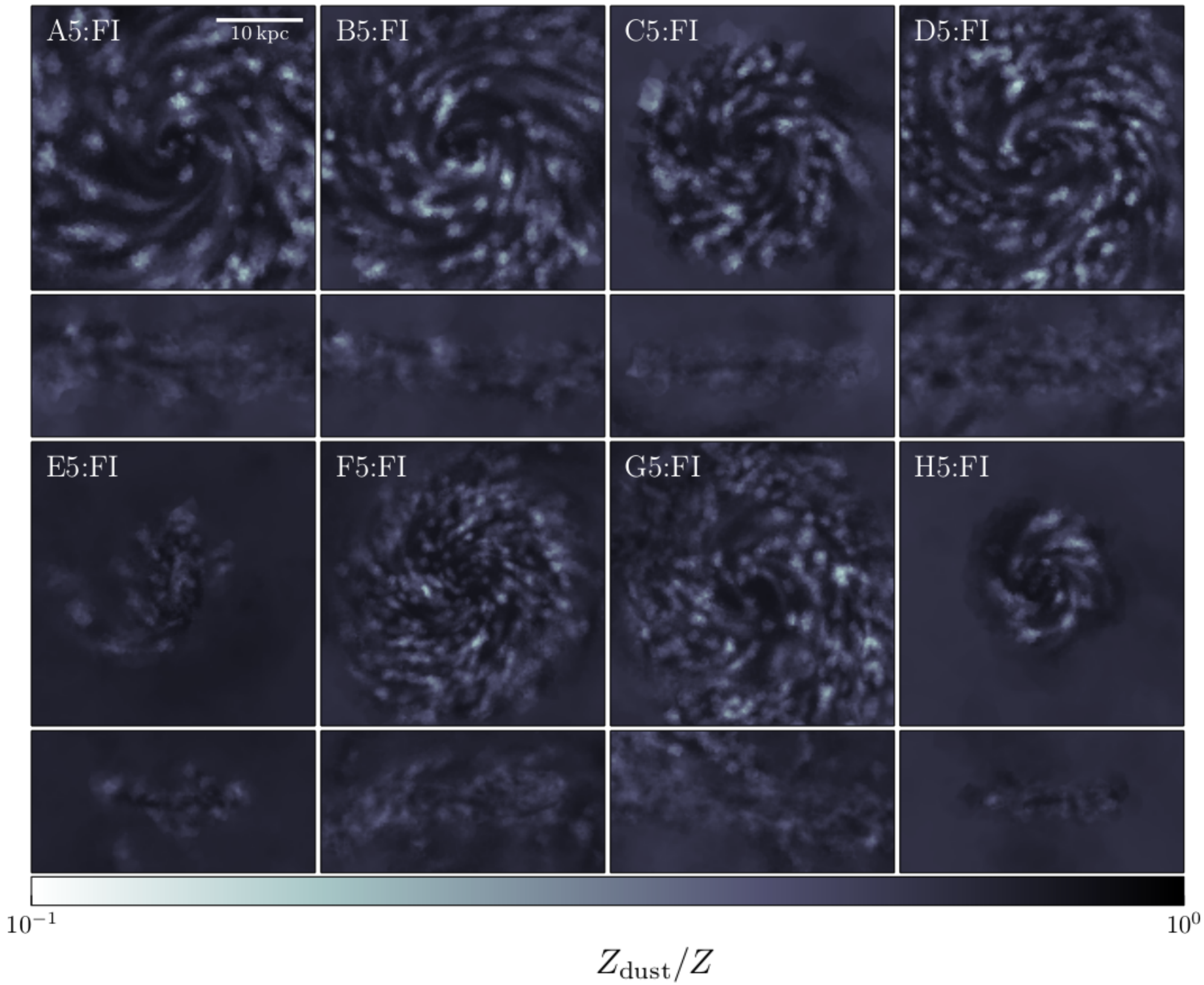
Dust Evolution



Dust Scaling Relations

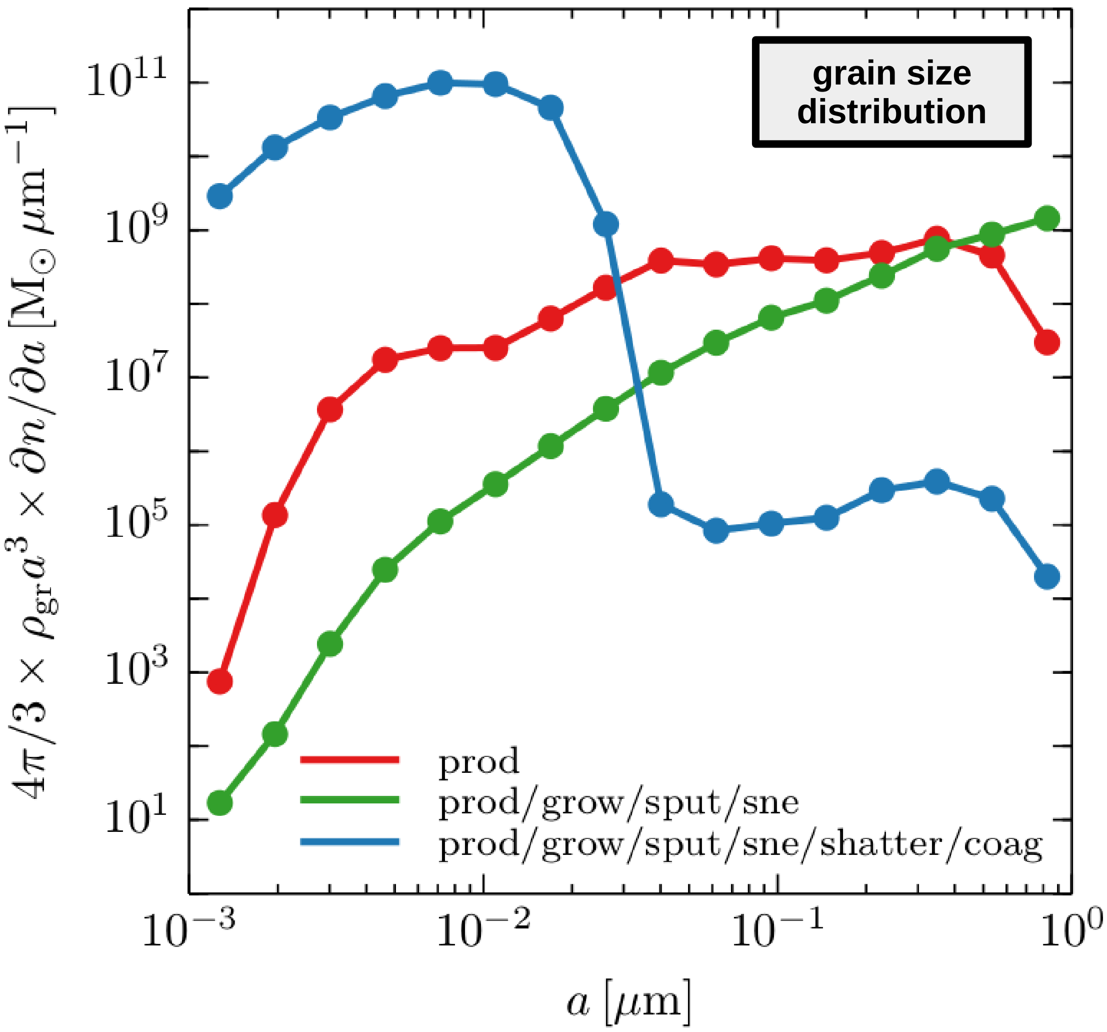


dust model reproduces key scaling relations



McKinnon, Torrey, MV 2016

Impact of Dust Physics



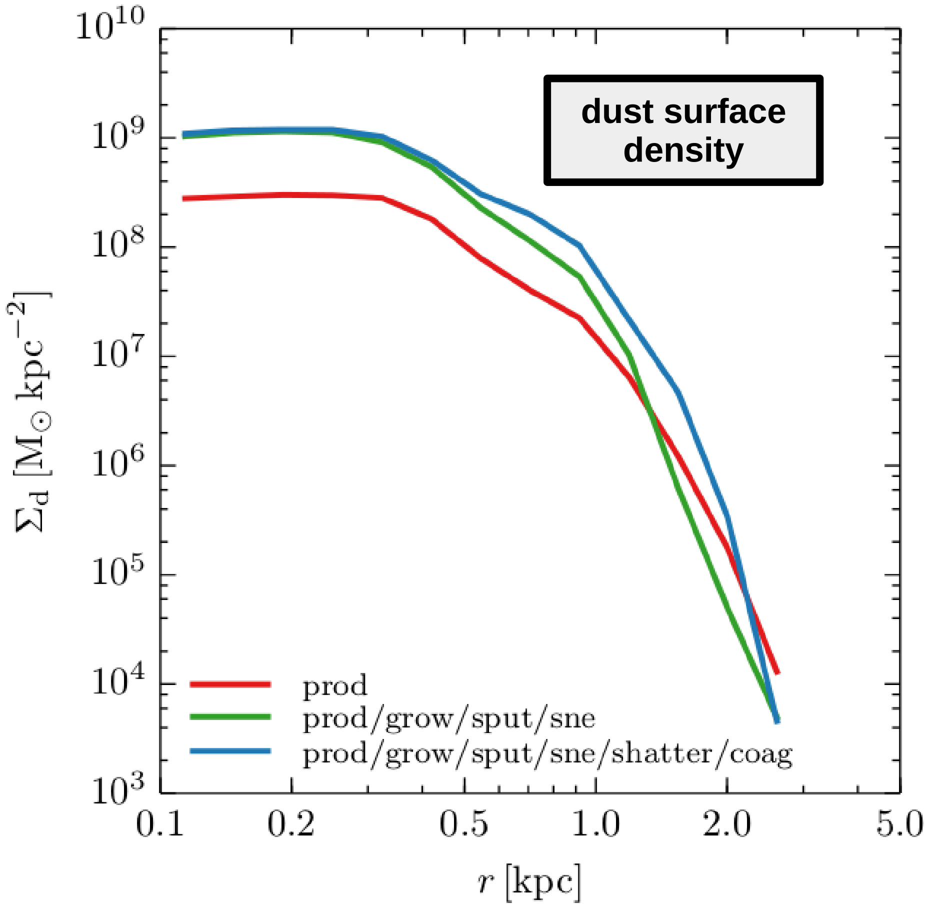
prod:
production only

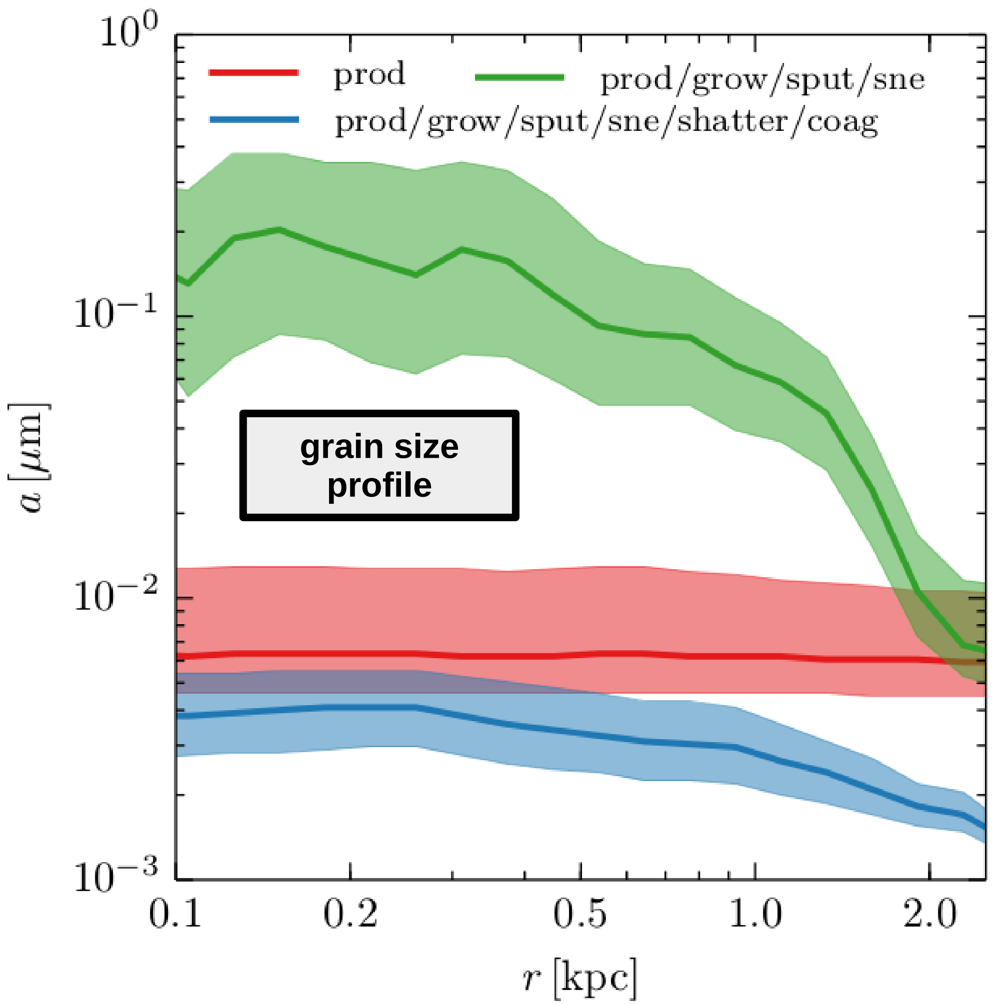
prod/grow/sput/sne:
+ growth + sputtering + SN

prod/grow/sput/sne/shatter/coag:
+ shattering + coagulation

McKinnon, MV, Torrey, Marinacci, Kannan 2018

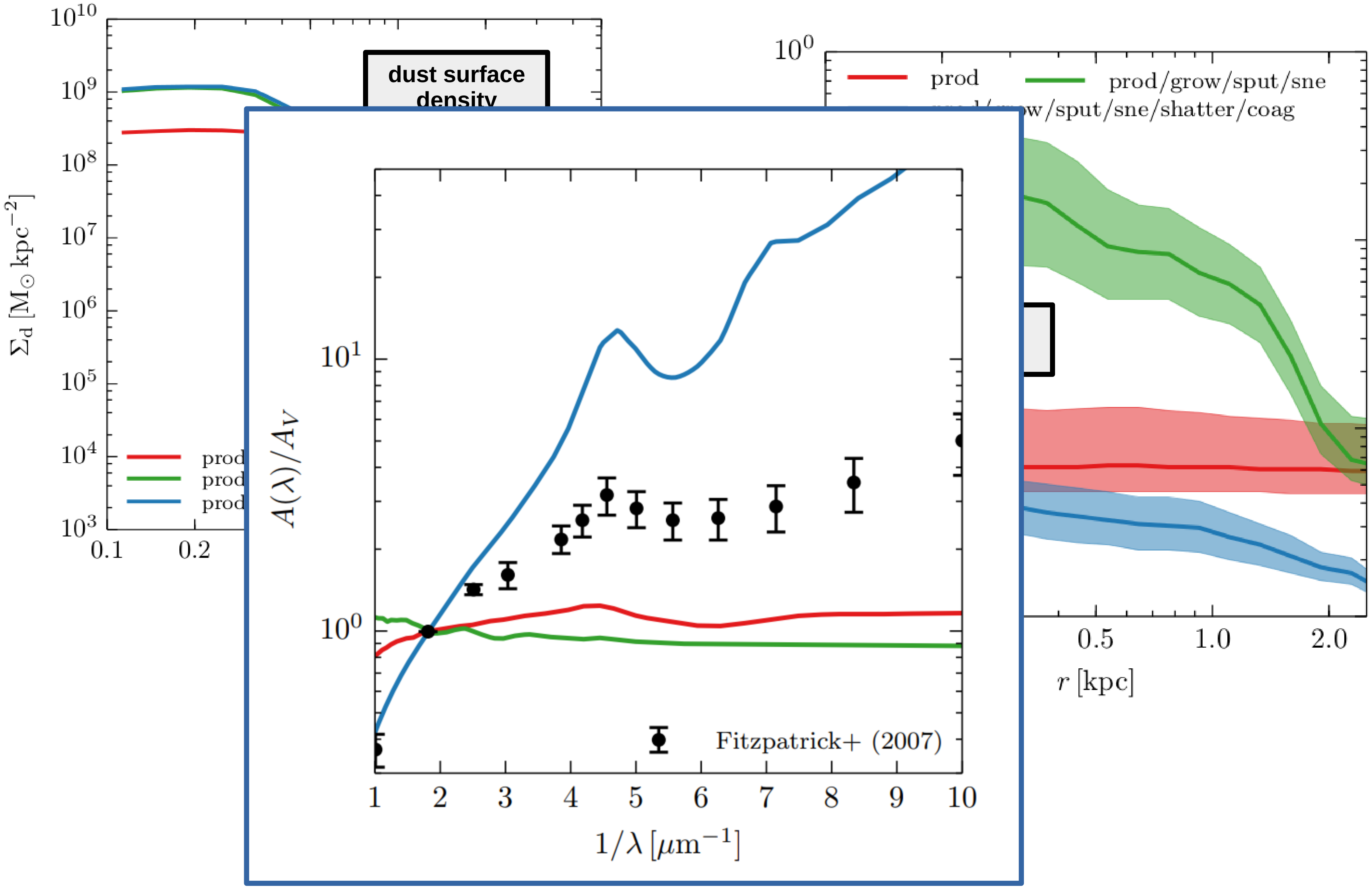
Impact of Dust Physics





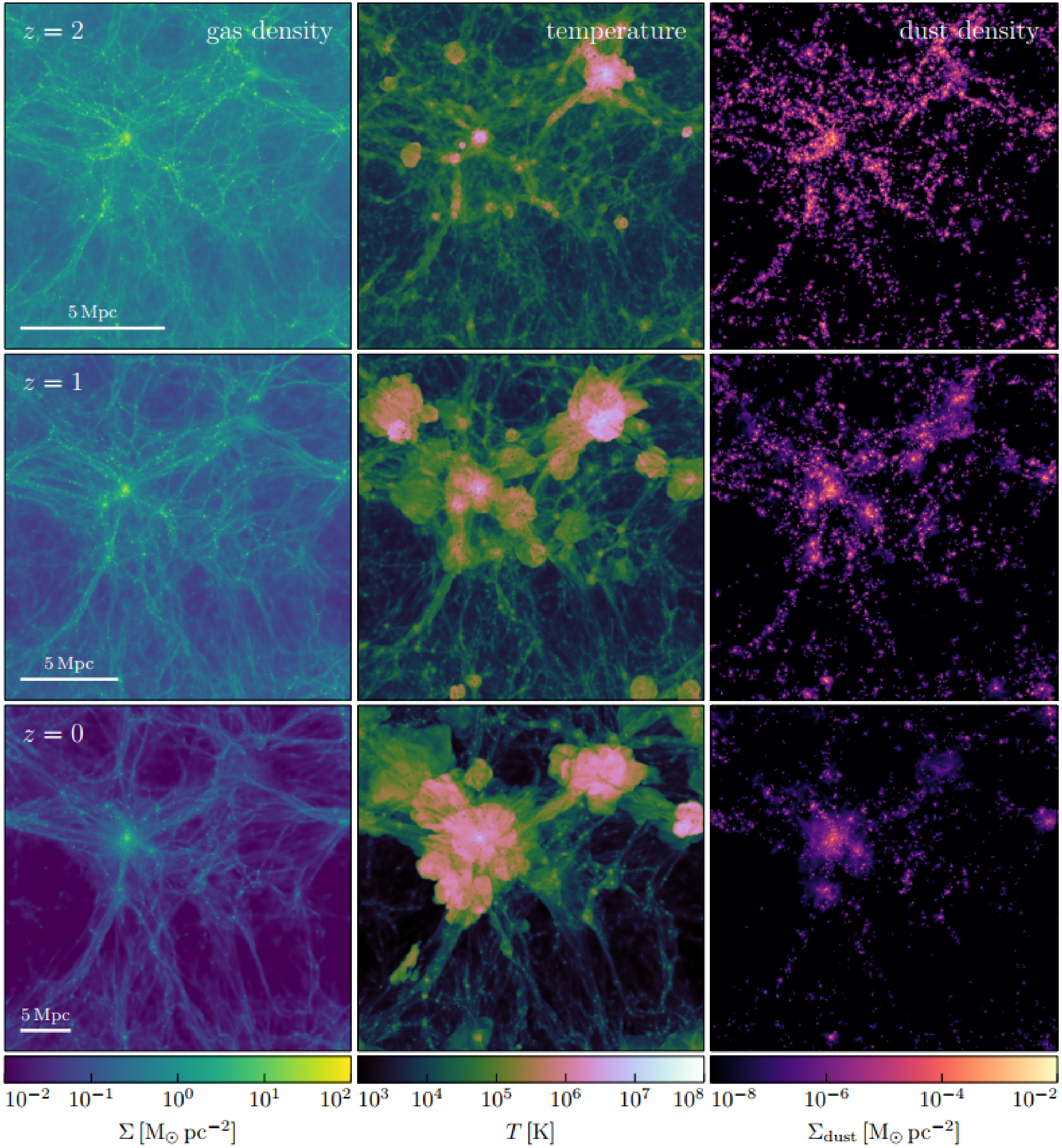
McKinnon, MV, Torrey, Marinacci, Kannan 2018

Impact of Dust Physics



McKinnon, MV, Torrey, Marinacci, Kannan 2018

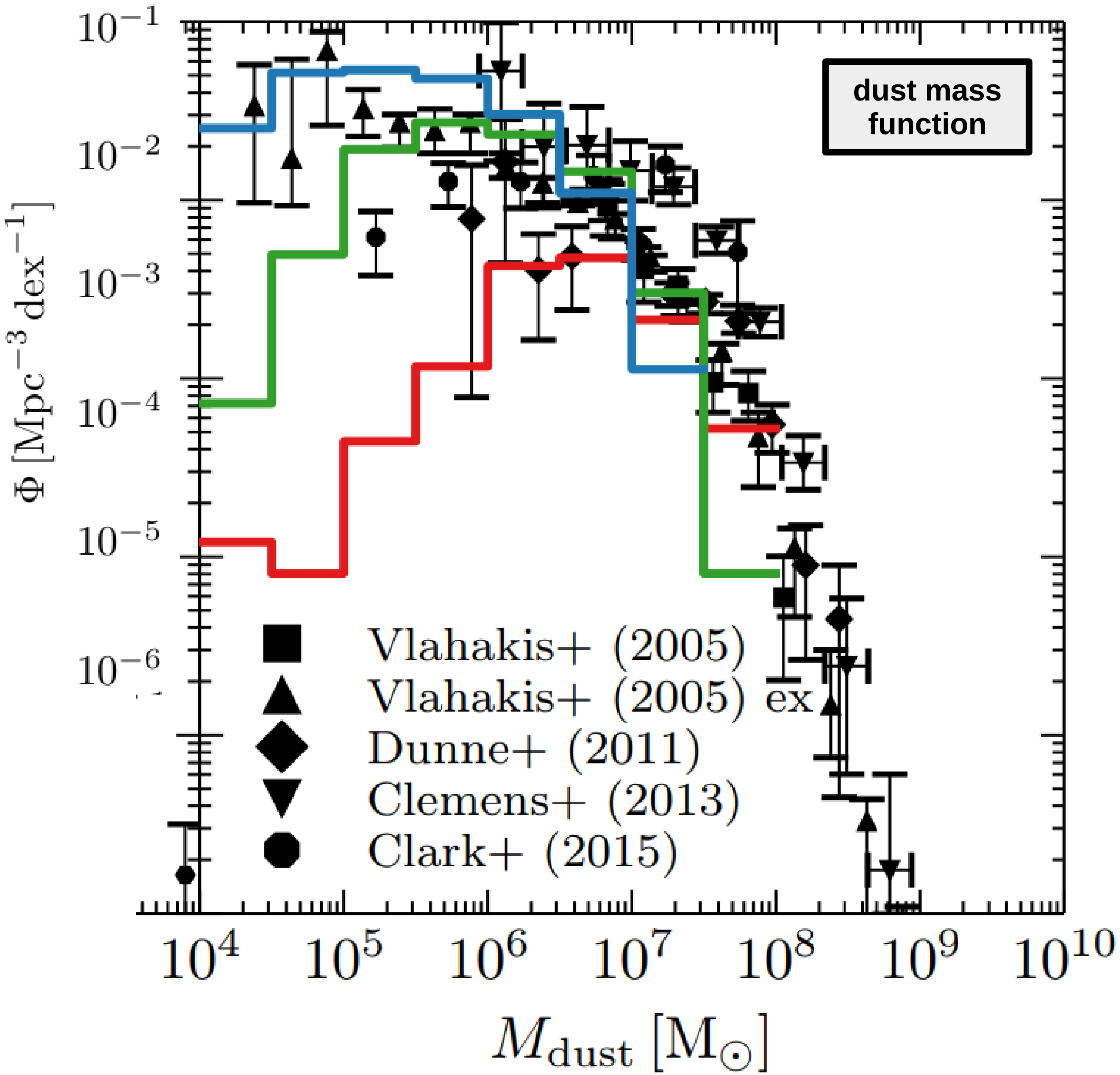
Large-scale Dust Distribution



probing large-scale dust statistics

McKinnon, Torrey, MV, Hayward, Marinacci 2017

Large-scale Dust Distribution



probing large-scale dust statistics

McKinnon, Torrey, MV, Hayward, Marinacci 2017

AREPO-RT: Radiation hydrodynamics on a moving mesh

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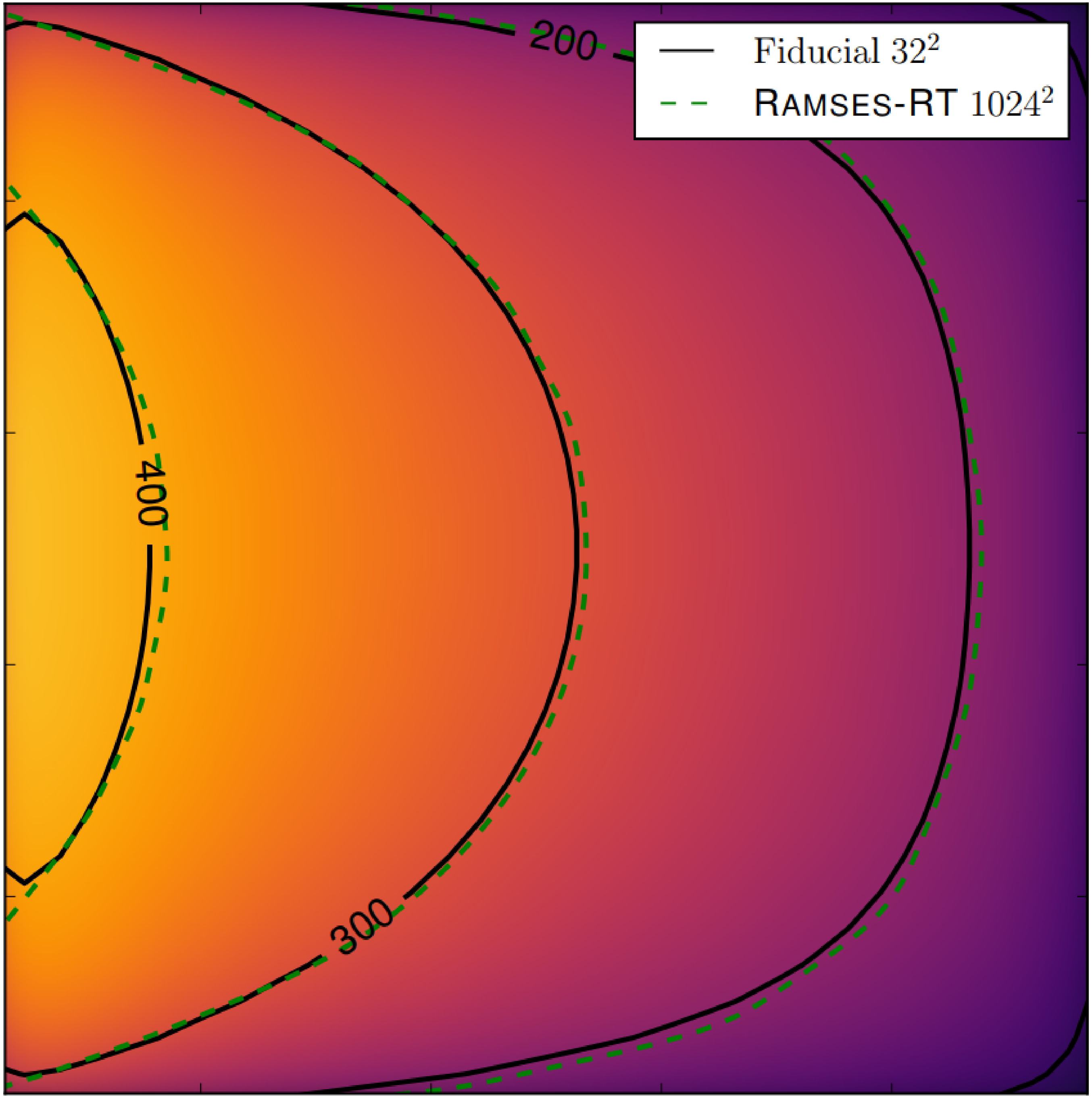
Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We introduce AREPO-RT, a novel radiation hydrodynamic (RHD) solver for the unstructured moving-mesh code AREPO. Our method solves the moment-based radiative transfer equations using the M1 closure relation. We achieve high-order accuracy by using a slope limited linear spatial extrapolation and a first order time prediction step to obtain the values of the primitive variables on both sides of the cell interface. A Harten-Lax-Van Leer flux function, suitably modified for moving meshes, is then used to solve the Riemann problem at the interface. The implementation is fully conservative and compatible with the individual timestepping scheme of sc Arepo. It incorporates atomic Hydrogen (H) and Helium (He) thermochemistry, which is used to couple the ultra-violet (UV) radiation field to the gas. Additionally, the infrared radiation is coupled to the gas under the assumption of local thermodynamic equilibrium between the gas and the dust. We successfully apply our code to a large number of test problems, including applications such as the expansion of H II regions, radiation pressure driven outflows and the levitation of optically thick layers of gas by trapped IR radiation. The new implementation is suitable for studying various important astrophysical phenomena, such as the effect of radiative feedback in driving galactic scale outflows, radiation driven dusty winds in high redshift quasars, or simulating the reionisation history of the Universe in a self consistent manner.

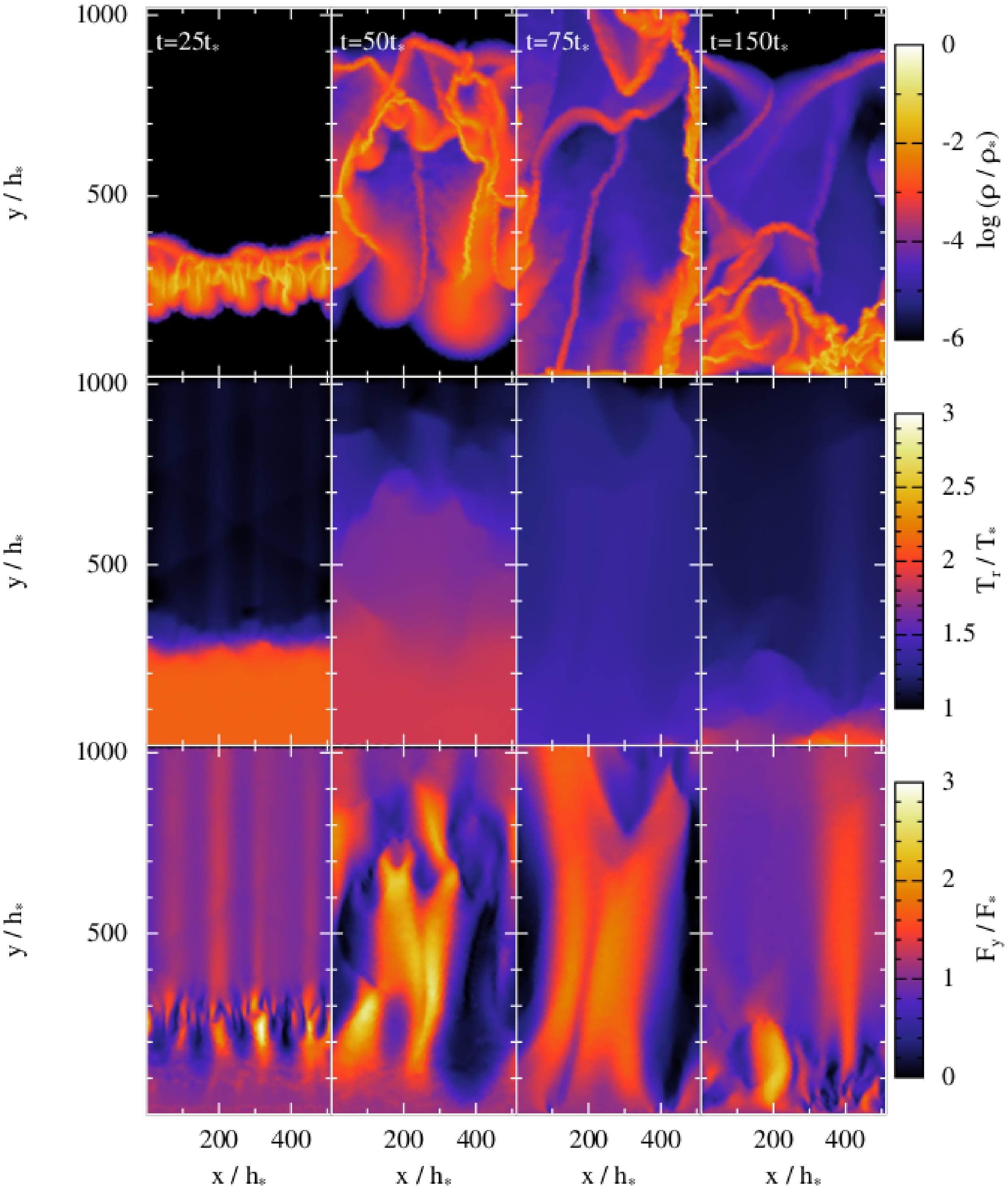
Radiation Hydrodynamics on a Moving Mesh



better convergence properties than Ramses-RT

Kannan, MV+ 2018

Coupling Dust to Radiation



radiation pressure on dust

Kannan, MV+ 2018

Conclusions

large scale galaxy formation simulations (Illustris, IllustrisTNG, …) can now reproduce the galaxy population very well

IllustrisTNG model is a recalibrated / updated version of the Illustris model

New developments:
additional physical processes (dust, radiation, ...)