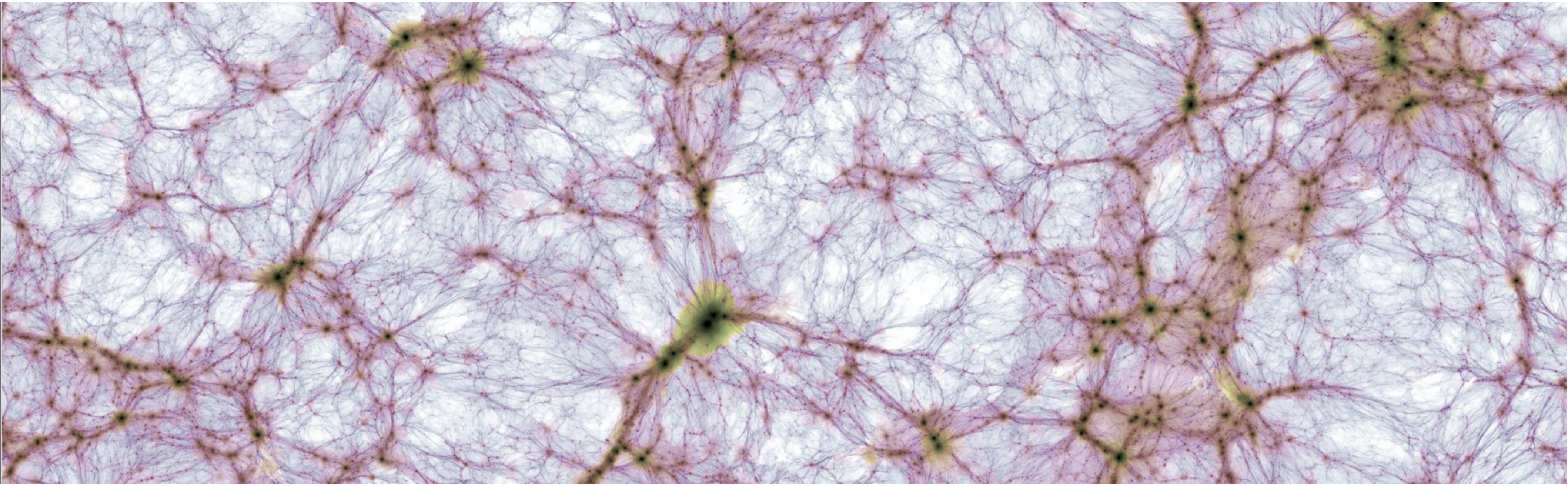
Cosmological insights into feedback

Volker Springel



- **Why we need feedback in the first place**
- **Types of simulations and their modelling limitations**
- **The Next Generation Illustris Simulations (IllustrisTNG)**

Max-Planck-Institute
for Astrophysics

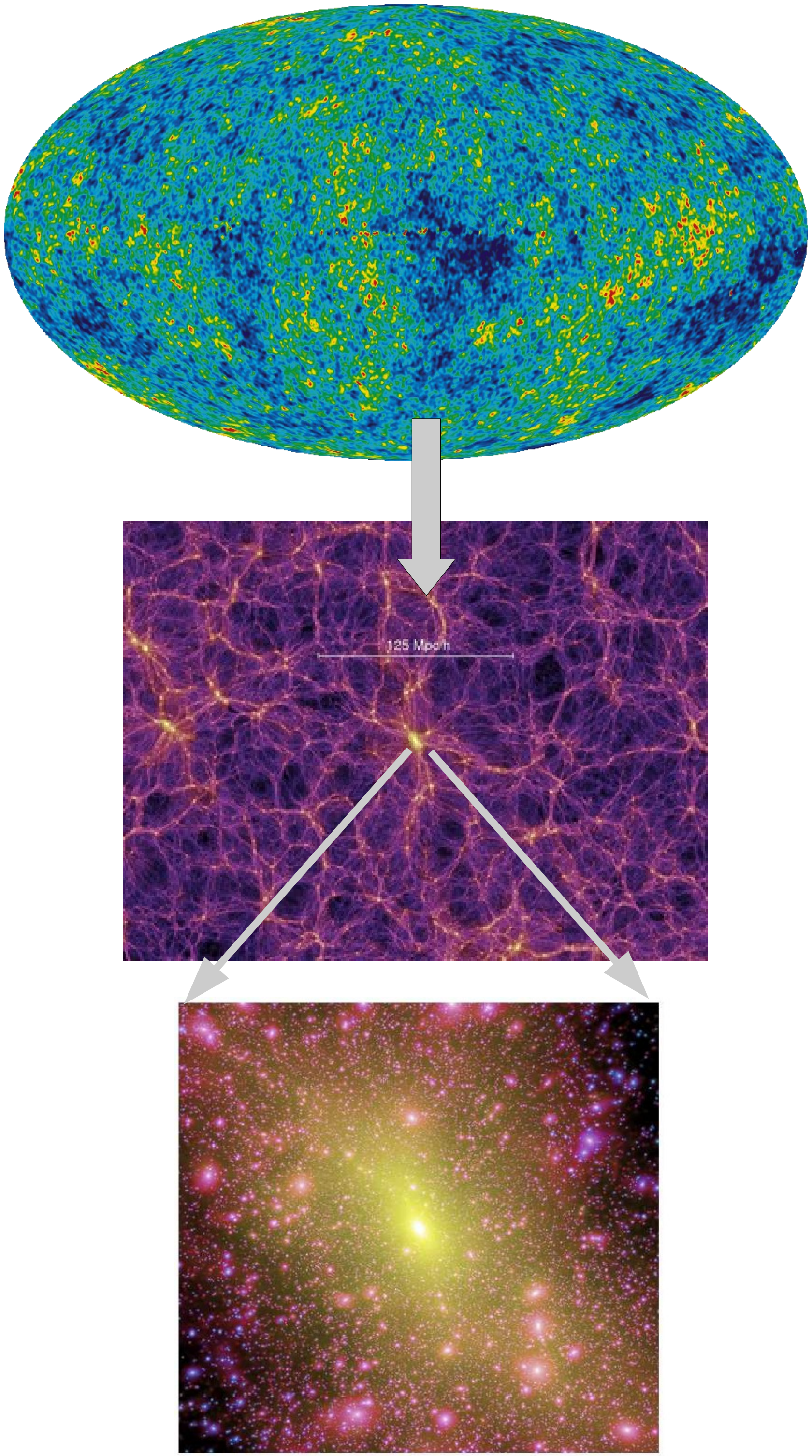
15th Potsdam Thinkshop
"The role of feedback in galaxy formation"
Potsdam, September 2018

N-body simulations accurately follow the growth of dark matter halos

PREDICTIONS FROM N-BODY SIMULATIONS

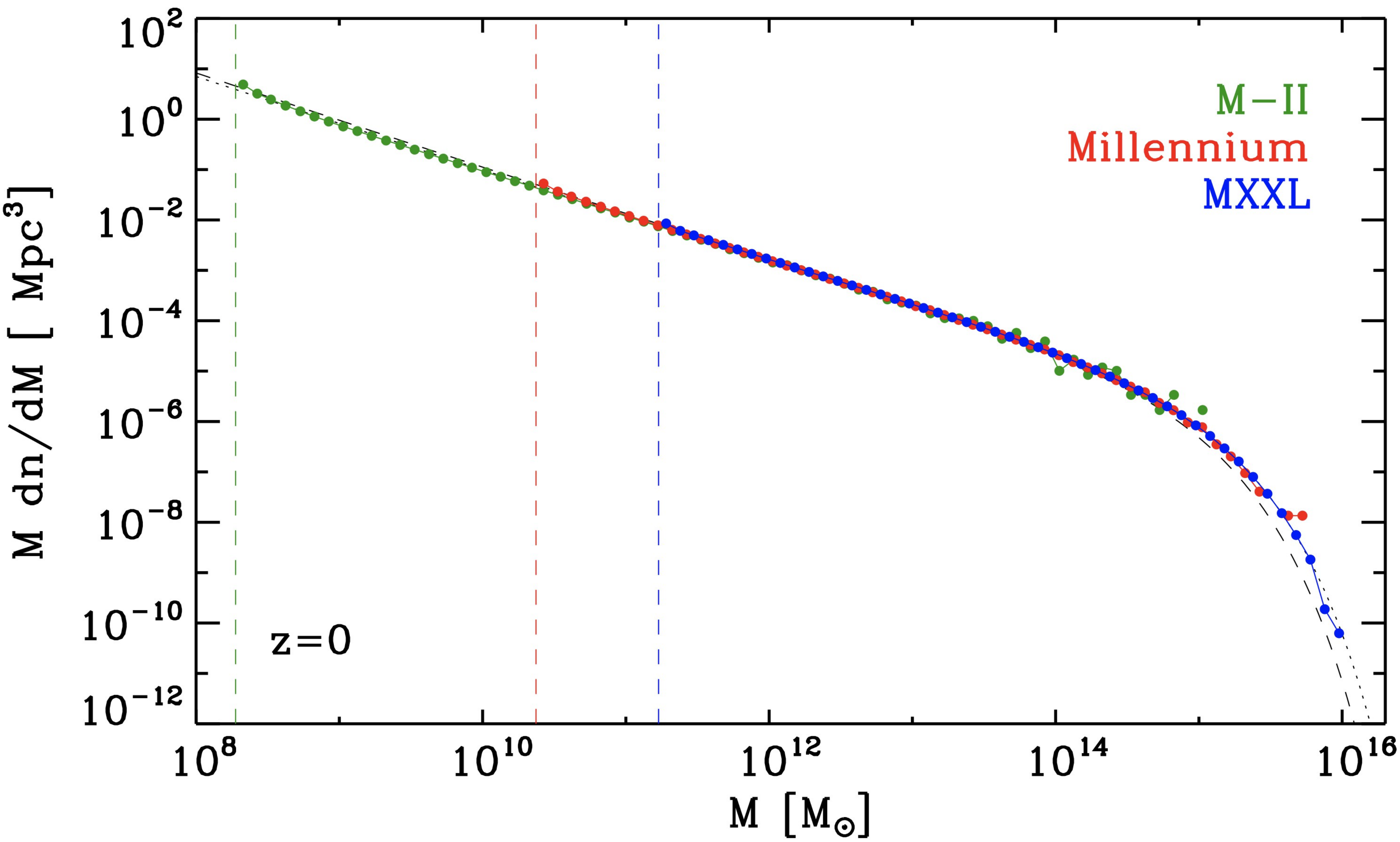
- Abundance of halos as a function of mass and time
- Their spatial distribution
- Internal structure of halo (e.g. density profiles, spin)
- Mean halo formation epochs
- Merger rates
- Gravitational lensing statistics
- ....

Dark matter structure growth is well understood.



The expected halo abundance in ΛCDM is well understood

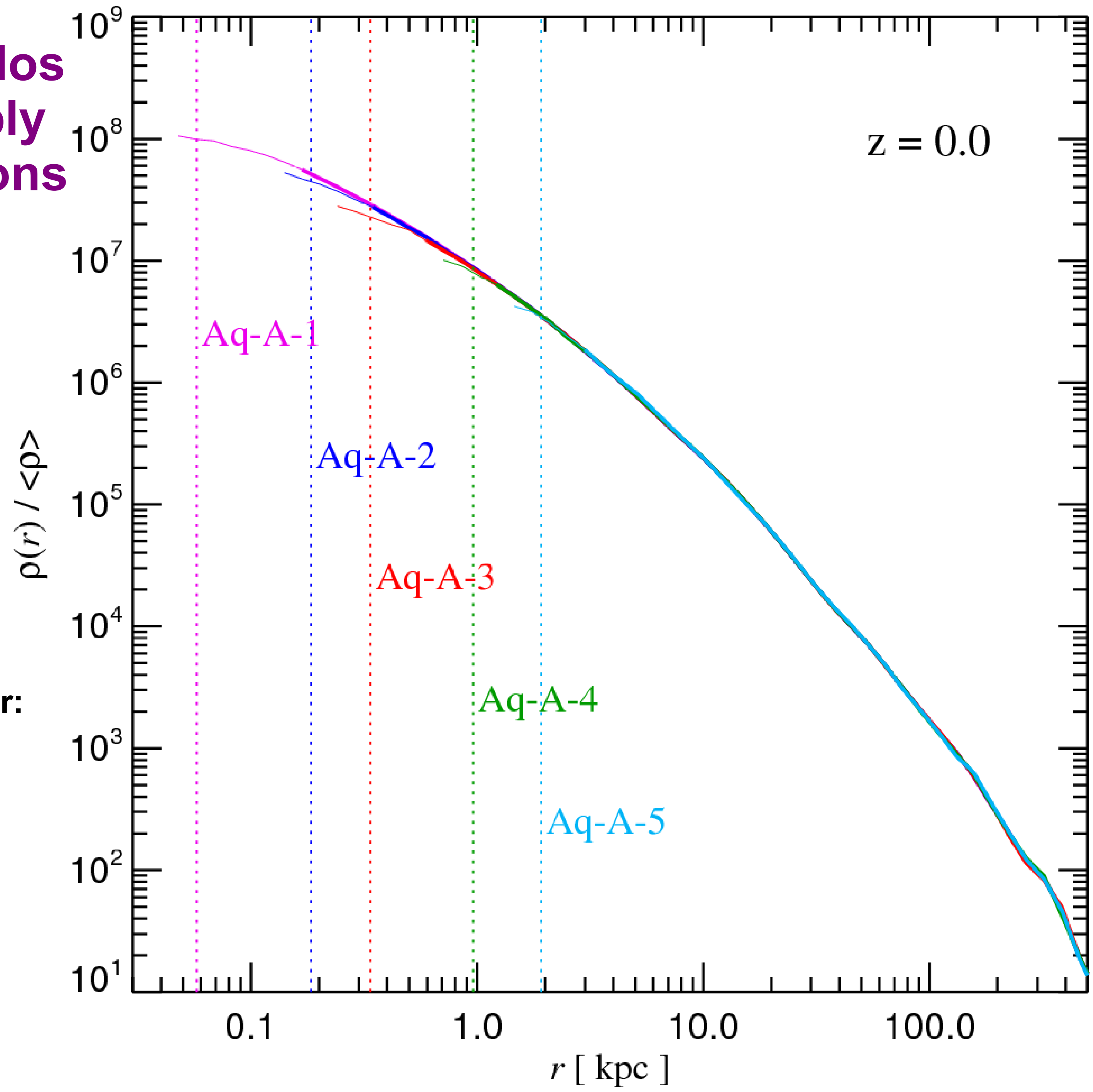
THE DARK MATTER HALO MASS FUNCTION OVER EIGHT ORDERS OF MAGNITUDE IN MASS



Angulo et al. (2012)

The structure of cold dark matter halos is determined reliably by N-body simulations

DENSITY PROFILE AS A FUNCTION OF RADIUS



Fundamental importance for:

Rotation curve of galaxies

Internal structure of galaxy clusters

Gravitational lensing

DM annihilation

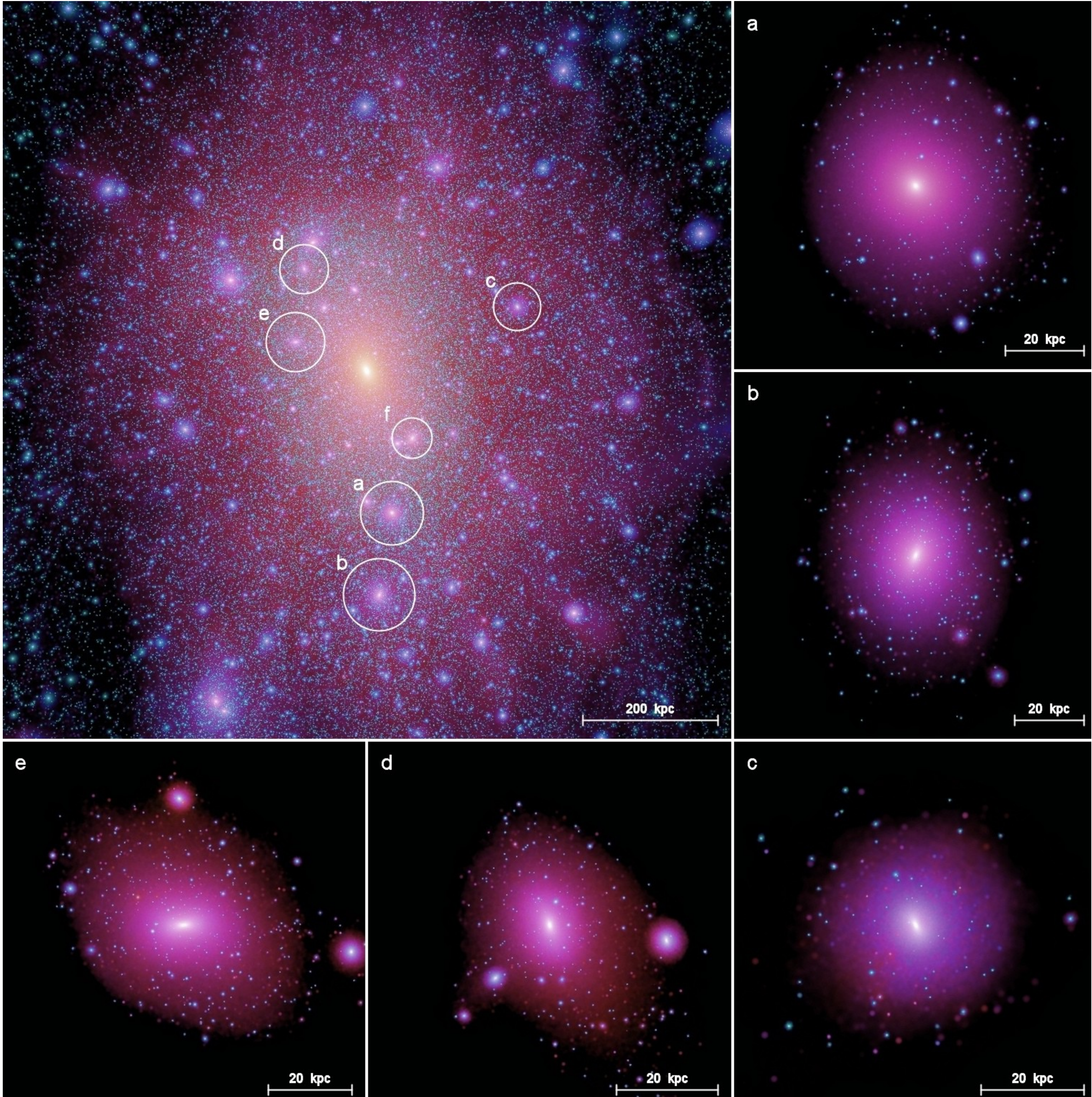
Galaxy mergers

The phase-space structure of galactic halos is very rich and filled with substructures

HALO IN HALOS IN HALOS IN THE AQUARIUS SIMULATIONS

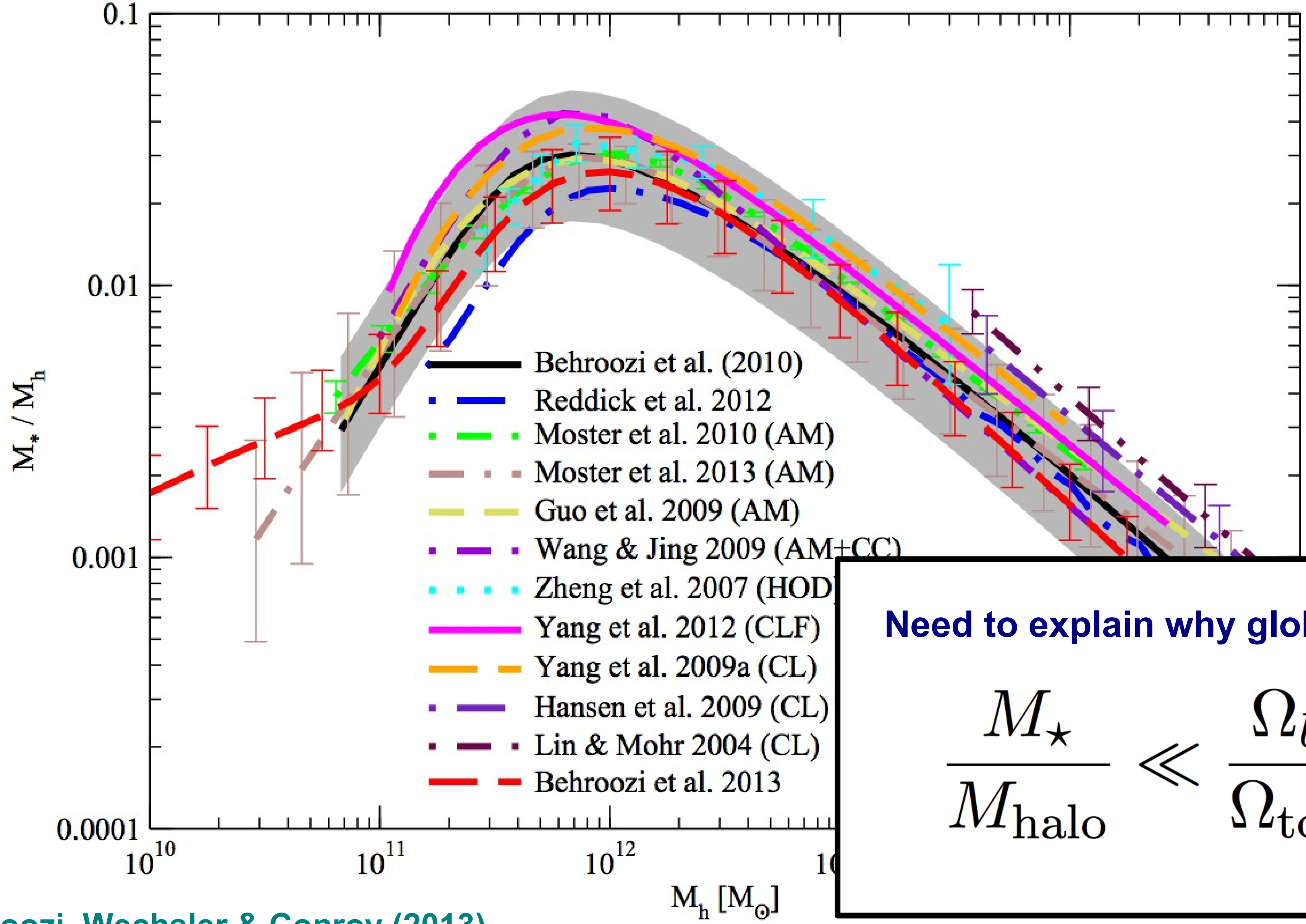
Note that the hierarchy is not strictly self-similar – there are somewhat fewer substructures in subhalos than in field halos within the same overdensity

Springel et al. (2008)



Abundance matching gives the expected halo mass – stellar mass relation in ΛCDM

VERY STRONG MODULATION OF STAR FORMATION EFFICIENCY WITH HALO MASS



Need to explain why globally:

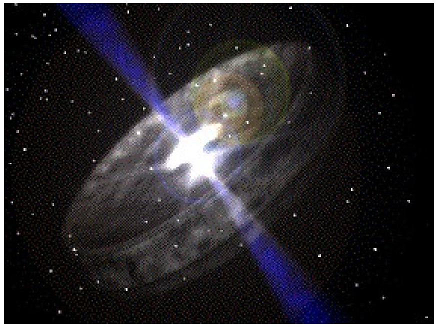
$$\frac{M_\star}{M_{\rm halo}} \ll \frac{\Omega_b}{\Omega_{\rm tot}}$$

Behroozi, Wechsler & Conroy (2013)

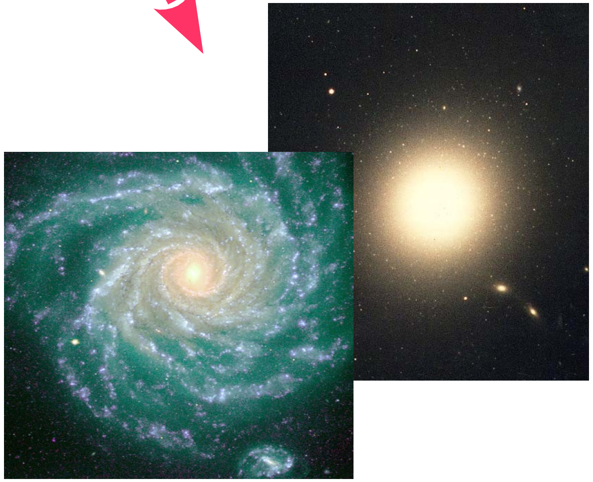
Black hole energetics suggests that they could influence the evolution of galaxies

COMPARING SUPERNOVA AND BLACK HOLE ENERGIES

quasars / AGN



What's the connection?



galaxies

Quasars release plenty of energy

$$L_Q \sim 10^{12}\, L_\odot \qquad t_Q \sim 10^7 - 10^8\,\mathrm{yr}$$

$$E_Q \sim 10^{60} - 10^{61}\,\mathrm{erg}$$

a billion supernovae !

But how does AGN energy couple to halo gas?

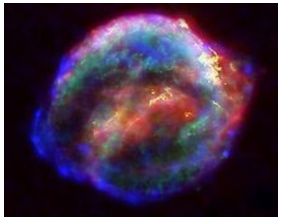
Total available feedback energy from BHs is comparable to that of supernovae

$$\rho_{\rm BH} \simeq 0.001\,\rho_\star \qquad E_{\rm BH}/V \simeq 0.1\,\rho_{\rm BH}\,c^2$$

$$E_{\rm SN}/V \simeq \frac{10^{51}\,\mathrm{erg}}{100\,\mathrm{M}_\odot}\,\rho_\star$$

$$\frac{E_{\rm BH}}{E_{\rm SN}} \simeq 1.8$$

What physics is responsible for feedback in the first place?

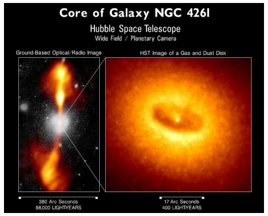


Kepler's Supernova

- **Supernova explosions (energy & momentum input)**

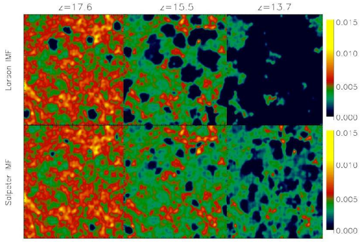
Bubble Nebula

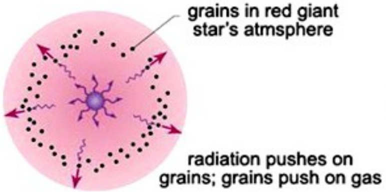
- **Stellar winds**



- **AGN activity**

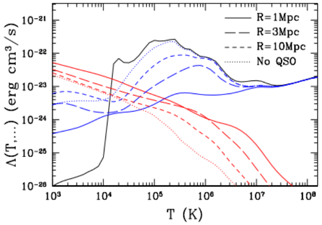
Ciardi al. (2003)



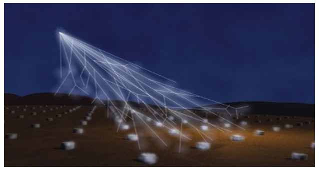


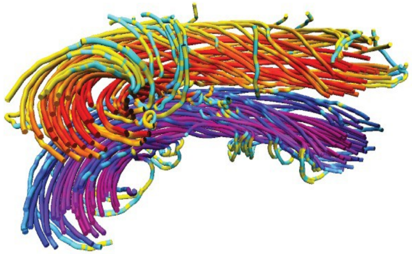
- **Radiation pressure on dust**
- **Photoionizing UV background and Reionization**

Gneding & Hollon (2012)

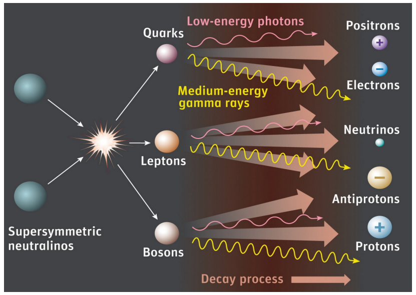


- **Modification of cooling through local UV/X-ray flux**
- **Photoelectric heating**



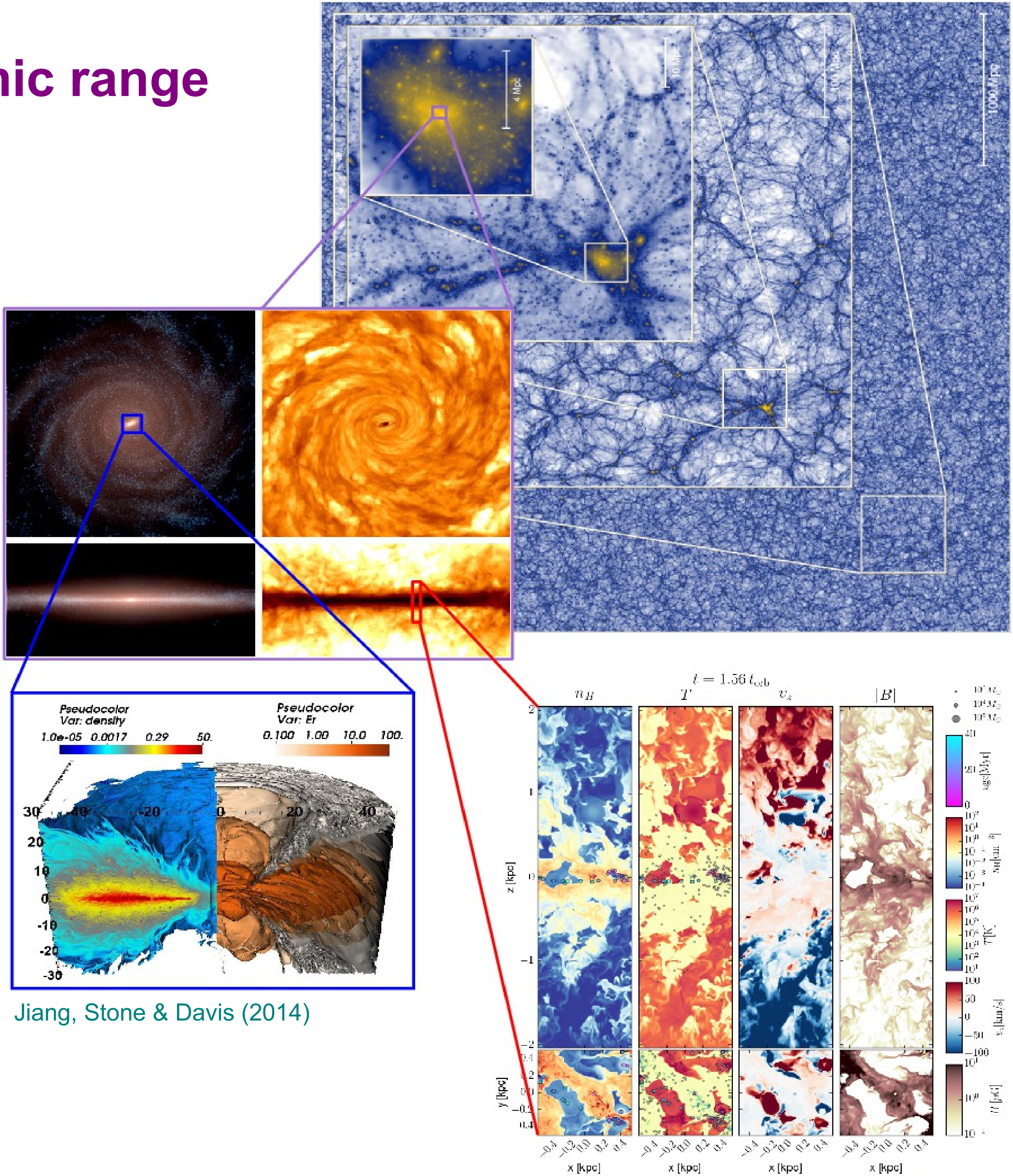


- **Cosmic ray pressure**
- **Magnetic pressure and MHD turbulence**



- **TeV-blazar heating of low density gas**
- **Exotic physics (decaying dark matter particles, etc.)**

The dynamic range challenge



Angulo et al. (2012)

Grand et al. (2016)

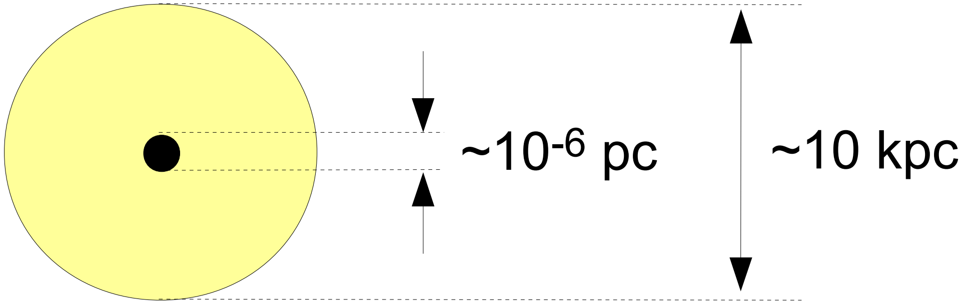
Jiang, Stone & Davis (2014)

Kim & Ostriker (2016)

The multi-scale nature of many astrophysical problems makes subgrid models inevitable

THE DYNAMIC RANGE PROBLEM IN GALAXY FORMATION

A supermassive BH in a galaxy

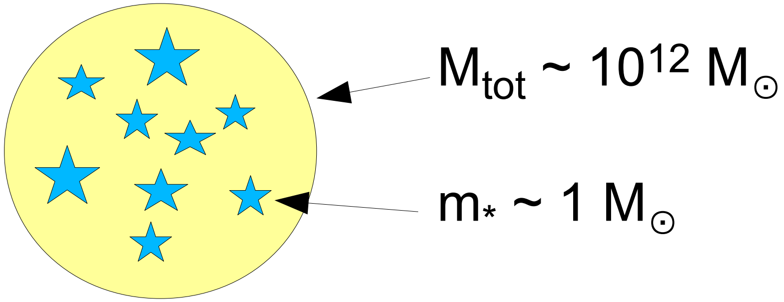


$\sim 10^{-6}$ pc

~ 10 kpc

dynamic range of 10^{10}

Star formation in a normal galaxy



$M_{tot} \sim 10^{12}\ M_\odot$

$m_* \sim 1\ M_\odot$

mass dynamic range of 10^{12}

Ab initio treatment infeasible, need sub-grid treatment:
Get macro-world right without knowing about quarks.

The subgrid problem is here to stay

HOW DO WE ARRIVE AT PREDICTIVE AND RELIABLE SIMULATION MODELS ?

- **DNS** in galaxy formation **is impossible**.
- There will always be **unresolved scales with physics that affects the resolved scales** – how should they be treated?
- Obvious answer: **Through approximations** (aka subgrid models)
- Best to have **subgrid scale come in at natural divides**, which minimizes the number of tunable parameters

  (e.g., use the results of the stellar community as subgrid input, not simulate stars themselves!).
- Second best: Use **filtered equations** derived from coarse graining (“LES”)
- In practice, **ad-hoc heuristic approaches** based on physical intuition are often used to implement feedback processes.

In the numerical models, need to distinguish between:

physical fidelity

(which physics is included/neglected, which approximations are made, etc.)

numerical accuracy

(what errors are made due to discretization noise, limited resolution, gravitational softening, etc.)

They are mixed in some simulation models in a non-separable way.

Code accuracy matters despite strong feedback processes

COMPARISON OF GAS AND TEMPERATURE FIELDS IN AREPO VS EQUIVALENT SPH SIMULATIONS

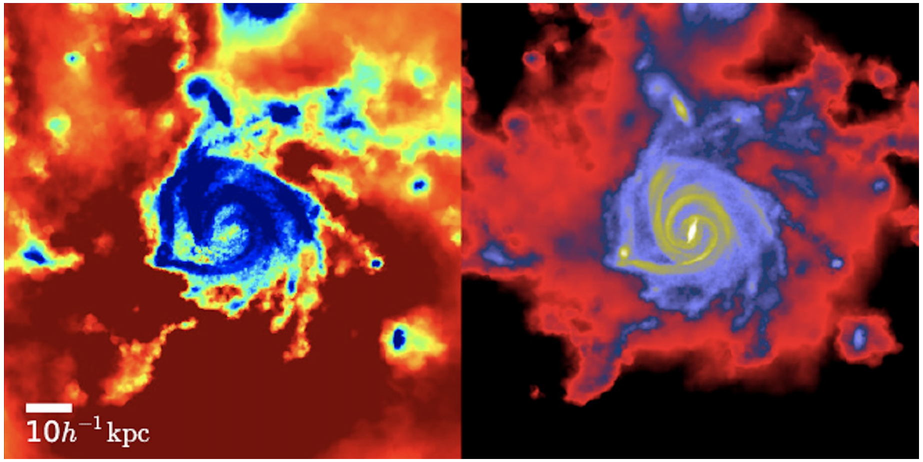
Effects due to feedback are typically stronger than code differences.

It is often argued that one can hence ignore hydrodynamical code inaccuracies in galaxy formation...

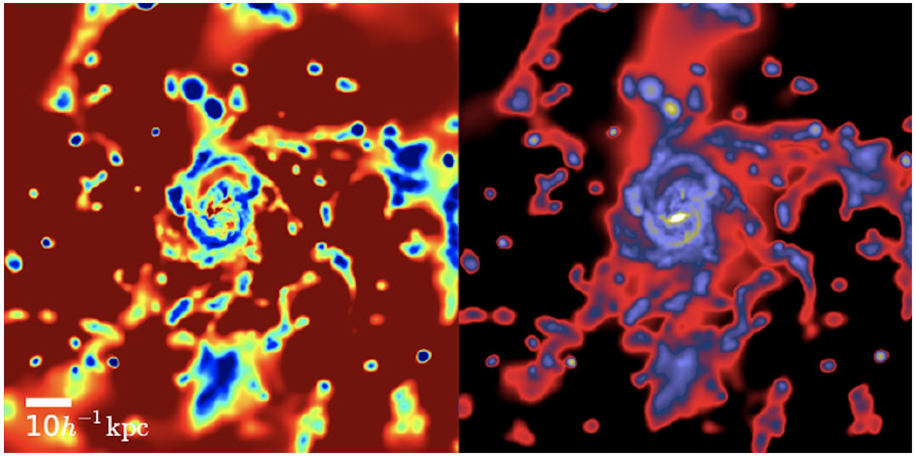
“There is no excuse to use inaccurate methods” (J. Stone).

He said this with respect to studies of isolated processes amenable to ab-initio treatment, because here one solves the fundamental equations directly.

moving-mesh with AREPO



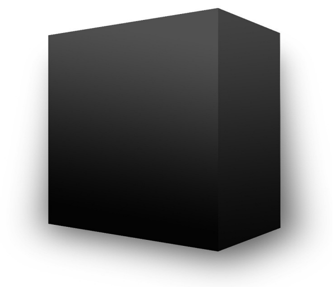
SPH with GADGET



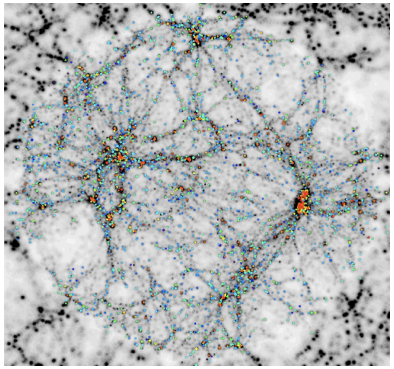
Vogelsberger et al. (2012)

The various types of galaxy formation simulations each have different strengths and weaknesses

THE MOST COMMON SIMULATION SETUPS

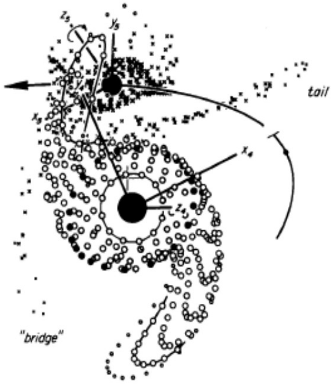


Periodic cosmological boxes:
- known initial conditions
- unbiased, representative mix of objects and histories
- most abundant objects poorly resolved
- difficult to get good resolution and good statistics
- inconveniently big data, very expensive



Zoom simulations:
- correct cosmological context
- high resolution in individual objects
- selection of target objects subjective
- statistical inferences for whole galaxy population problematic

Constrained realizations:
- simplified comparison to local universe
- unique possibilities for near-field cosmology
- quality of ICs new uncertainty
- results may not be representative for universe as a whole



Isolated toy simulations:
- initial conditions fairly arbitrary
- allows experimentation and tests of physical ideas
- generalization to cosmological case may be misleading
- relatively cheap, short turn-around times
- many simulations are possible

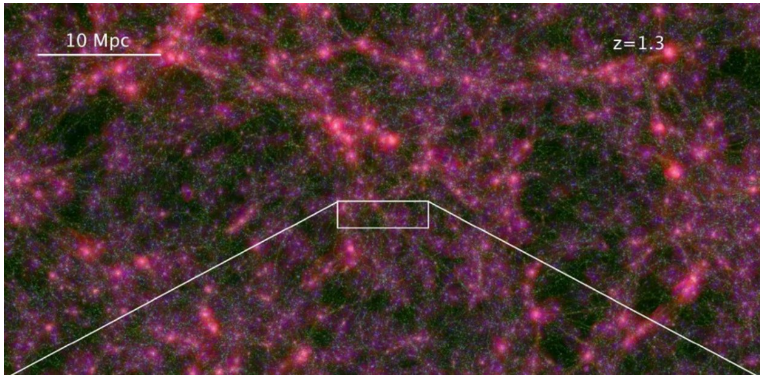
Important: Running to z=0 is required for every convincing model of galaxy formation

Hydrodynamical cosmological simulations of galaxy formation have made tremendous progress in recent years

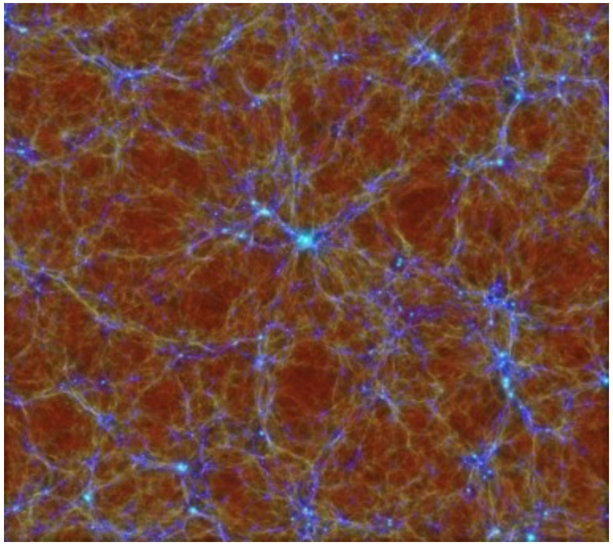
AN INCOMPLETE OVERVIEW OF SOME OF THE LARGER PROJECTS

Illustris (Vogelsberger et al. 2014)

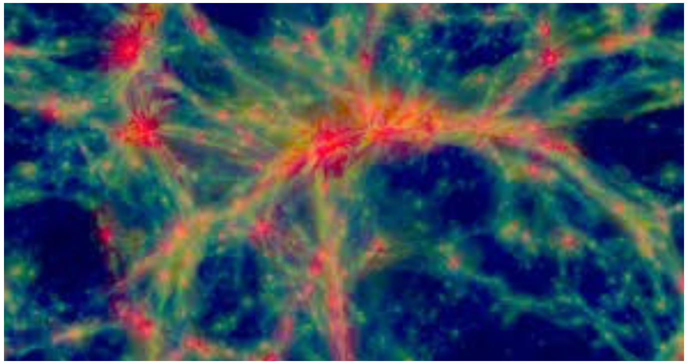
Horizon-AGN (Dubois et al. 2014)



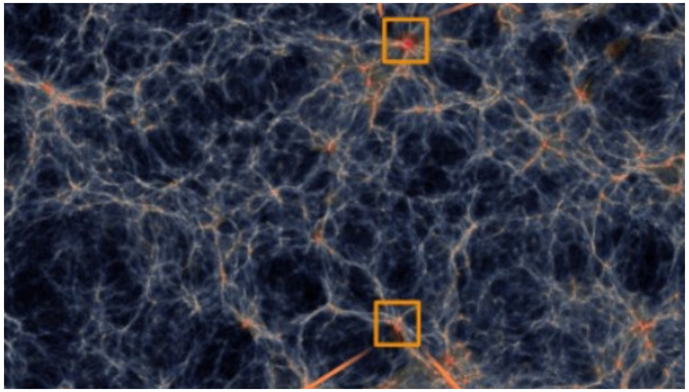
Magneticum (Dolag et al. 2014)



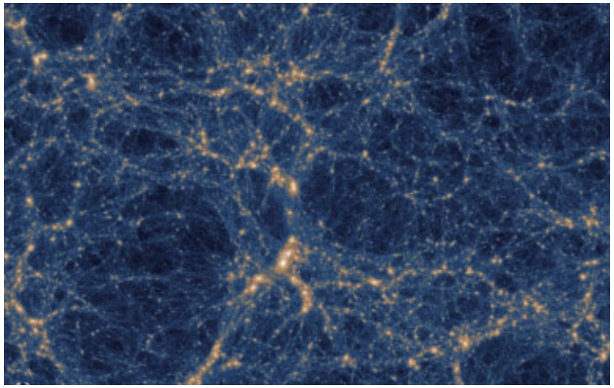
EAGLE (Schaye et al. 2015)



MassiveBlack II (Khandai et al. 2015)



TNG (Illustris Collaboration 2017)



The Illustris and IllustrisTNG cosmological simulations

Galaxy formation physics in the Illustris simulations

Cooling and metal enrichment

- Nine elements followed independently
- Mass and metal loss of stars treated continuously over time based on stellar population synthesis models (similar to Wirsma et al. 2009)
- Ionization balance and cooling from H and He followed with direct chemical network (Katz et al. 1996)
- Metal line cooling added through CLOUDY lookup tables in density, temperature and redshift
- Simple self-shielding correction (Rahmati et al. 2013)

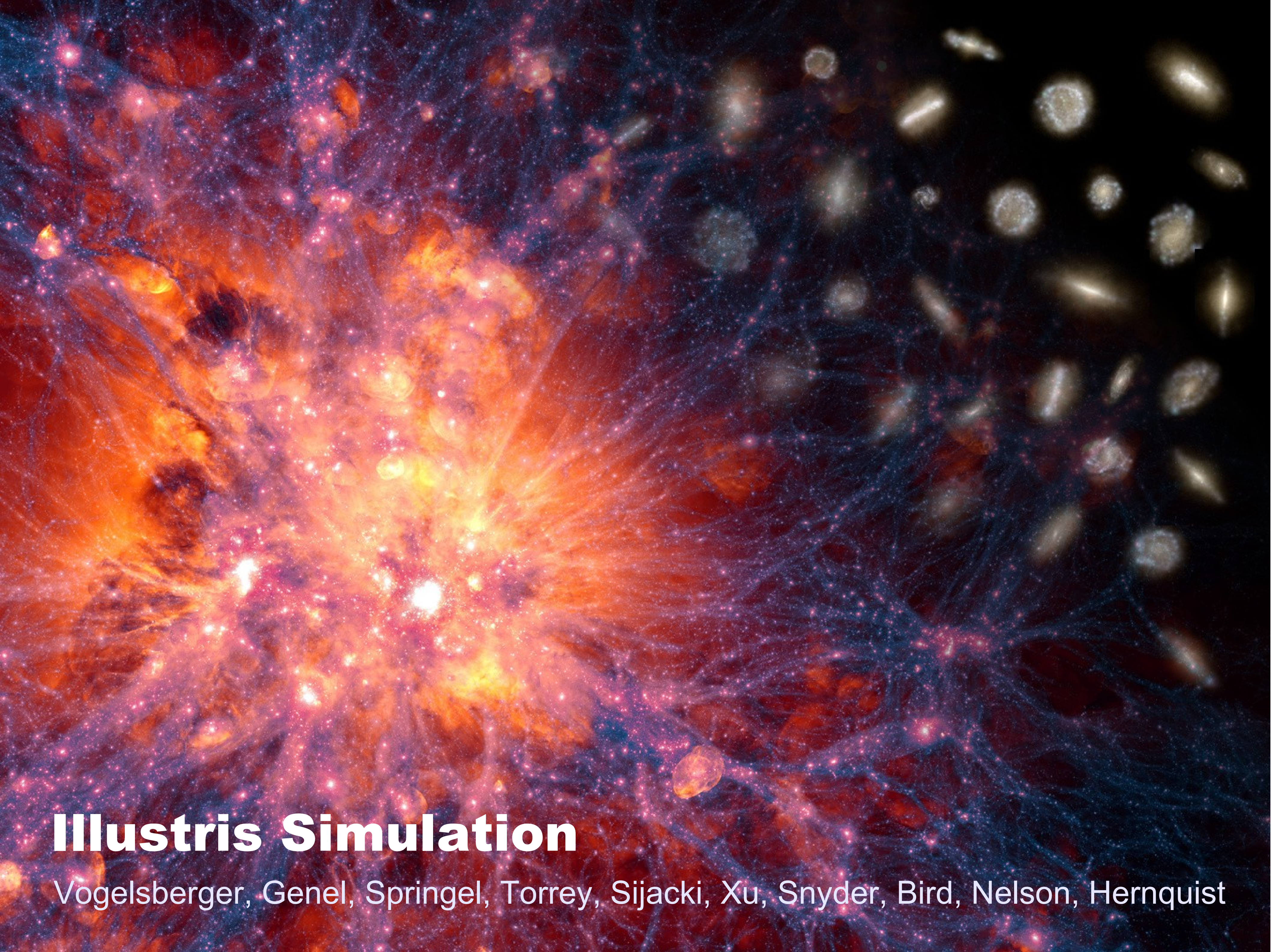
Star formation and winds

- Variant of Springel & Hernquist (2003)
- Cold dense gas stabilized by an ISM equation of state
- Winds are phenomenologically introduced, with an energy given as a fixed fraction of the supernova energy
- The wind velocity is variable, the mass flux follows for energy-driven winds
- Fiducial model scales wind with local dark matter velocity dispersion
- Winds are launched outside of star-forming gas, and metal-loading can be reduced if desired

Black hole accretion and feedback

- Black hole seeding and accretion model (Springel et al. 2005)
- Quasar-mode feedback for high accretion rates
- Radio-mode feedback for low accretion rates based on bubble-heating model (Sijacki et al. 2006)
- Radiative AGN feedback (change in heating/cooling due to variation of UVB) in proximity to an active black hole
- Reduction of accretion rate in low-pressure/low-density regimes to avoid large hot bubbles around black holes in quiescent state
- Black holes tied to potential minimum of halos

Vogelsberger et al. (2013)

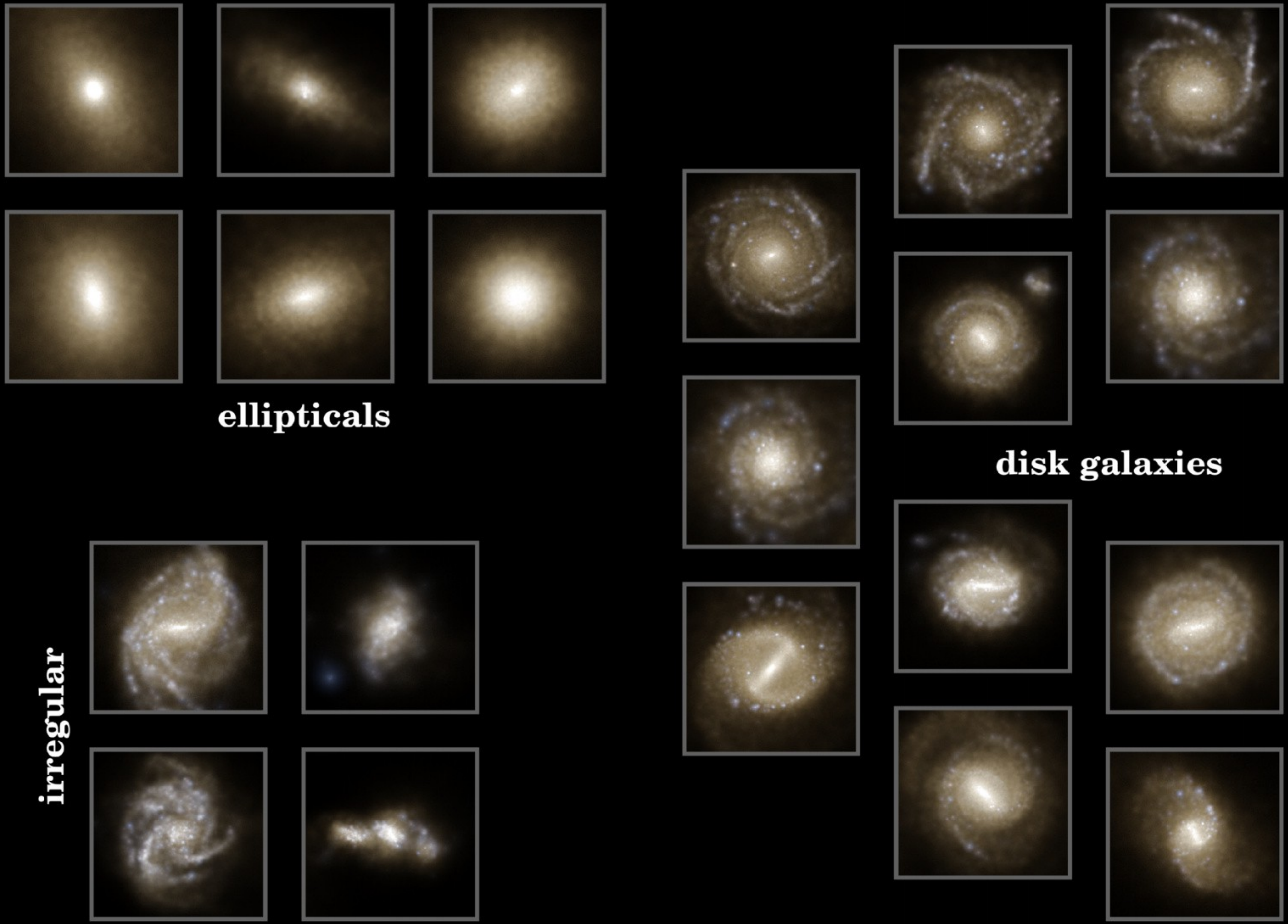


Illustris Simulation

Vogelsberger, Genel, Springel, Torrey, Sijacki, Xu, Snyder, Bird, Nelson, Hernquist

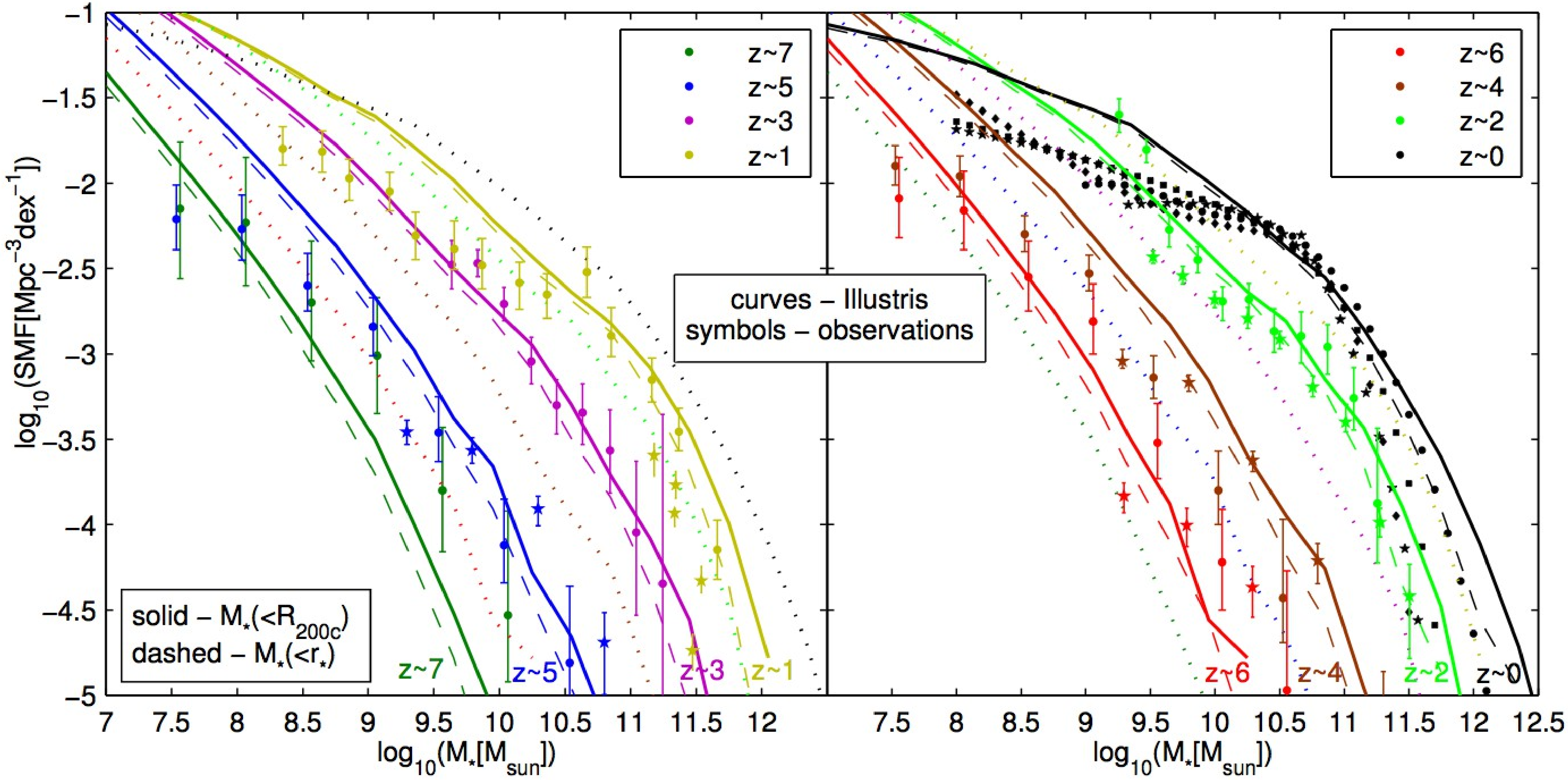
The Illustris simulation reproduces the morphological mix of galaxies

SIMULATED HUBBLE TUNING FORK DIAGRAM



The stellar mass functions match observations at high redshift well

STELLAR MASS FUNCTIONS OF ILLUSTRIS COMPARED TO OBSERVATIONS AT DIFFERENT EPOCHS



Genel et al. (2014)

People in the “Next Generation Illustris Simulations” team

A COLLABORATION BETWEEN HEIDELBERG, HARVARD, AND THE MIT

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Massachusetts Institute of Technology

Jill Naiman

Harvard University

Mark Vogelsberger

Massachusetts Institute of Technology

Shy Genel

Center for Computational Astrophysics, Flatiron Institute

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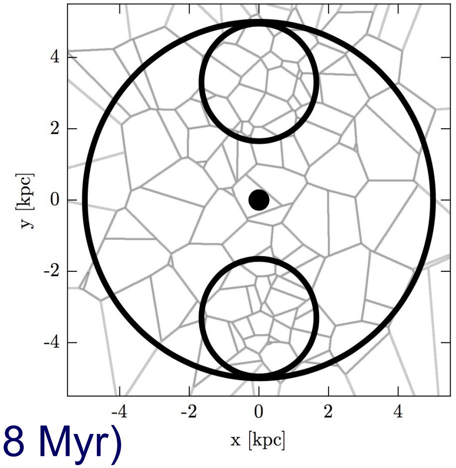
Massachusetts Institute of Technology

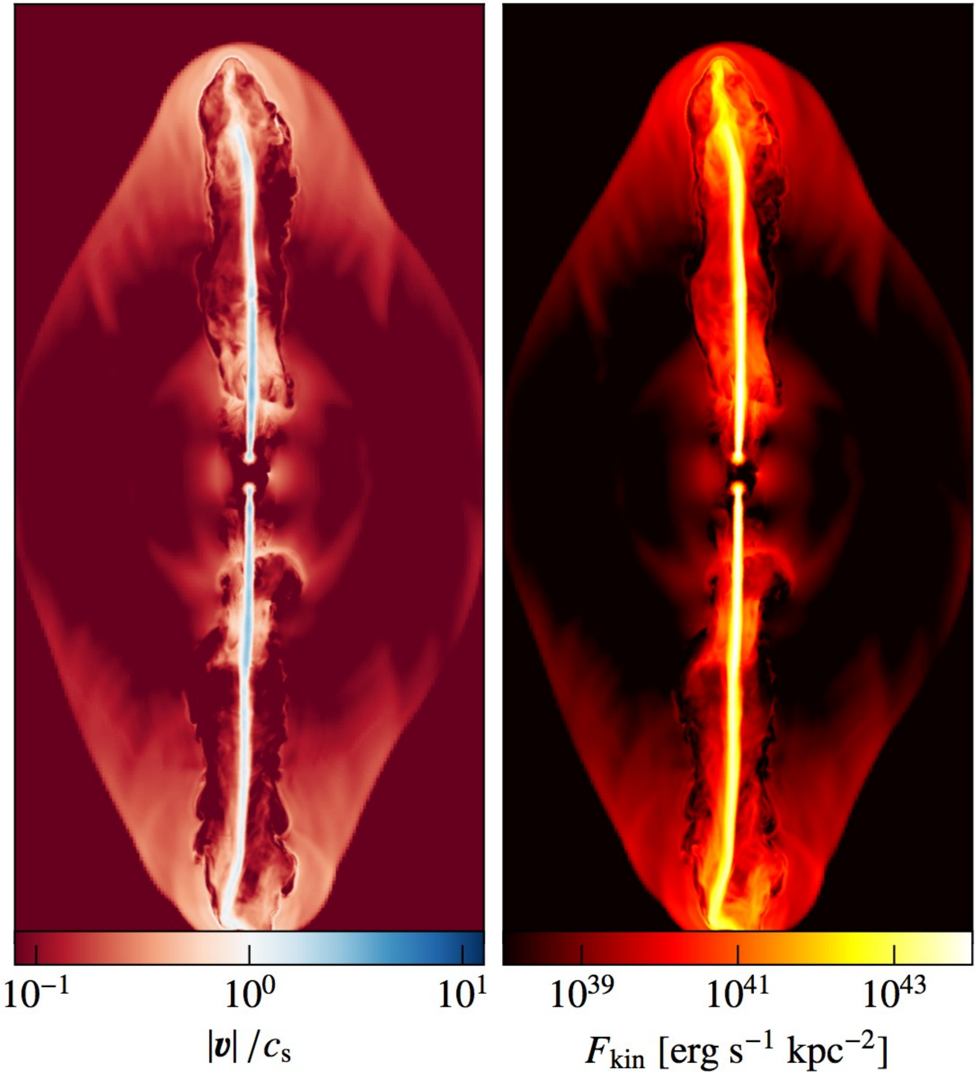
Jet injection by BHs can be modelled at high-resolution in individual "zoom" galaxy cluster simulations

HEATING CLUSTERS THROUGH JET-ICM INTERACTIONS

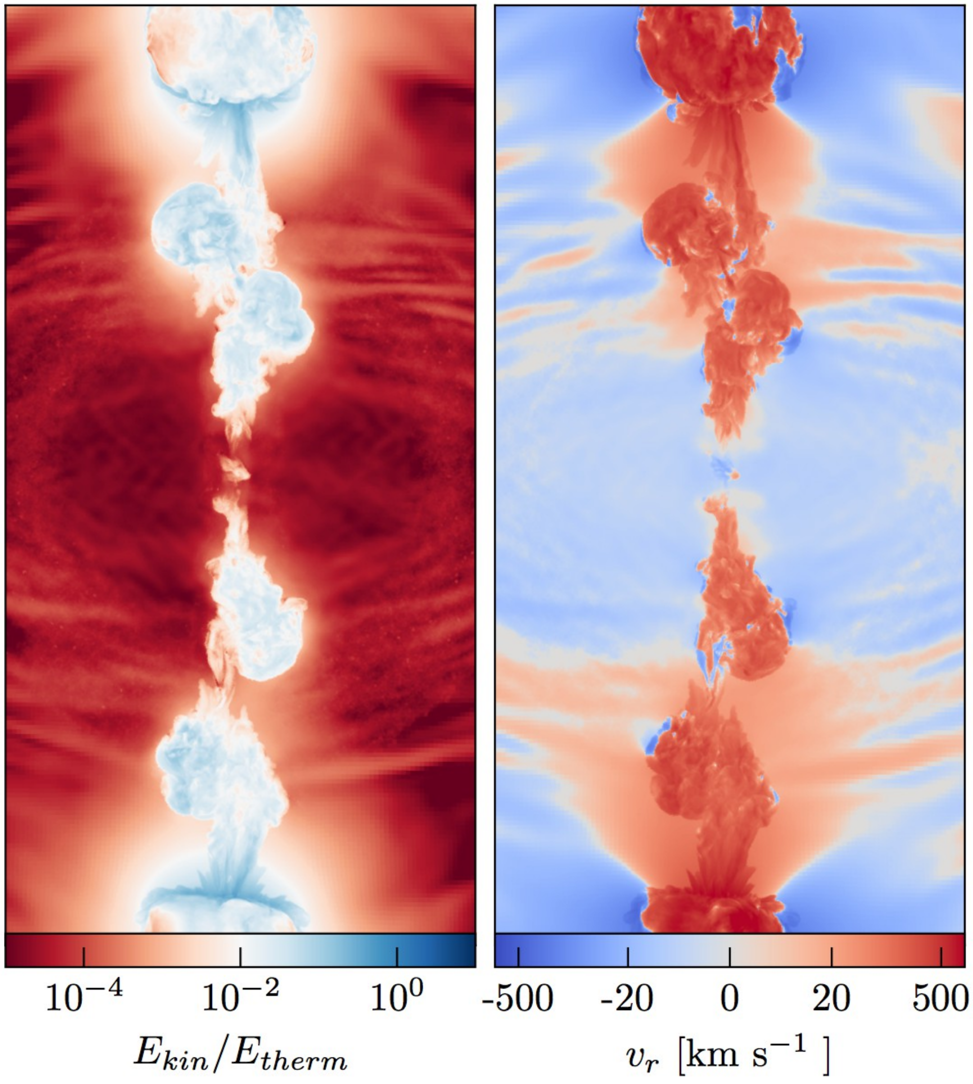
Weinberger et al. (2017)



Jet after 42 Myr

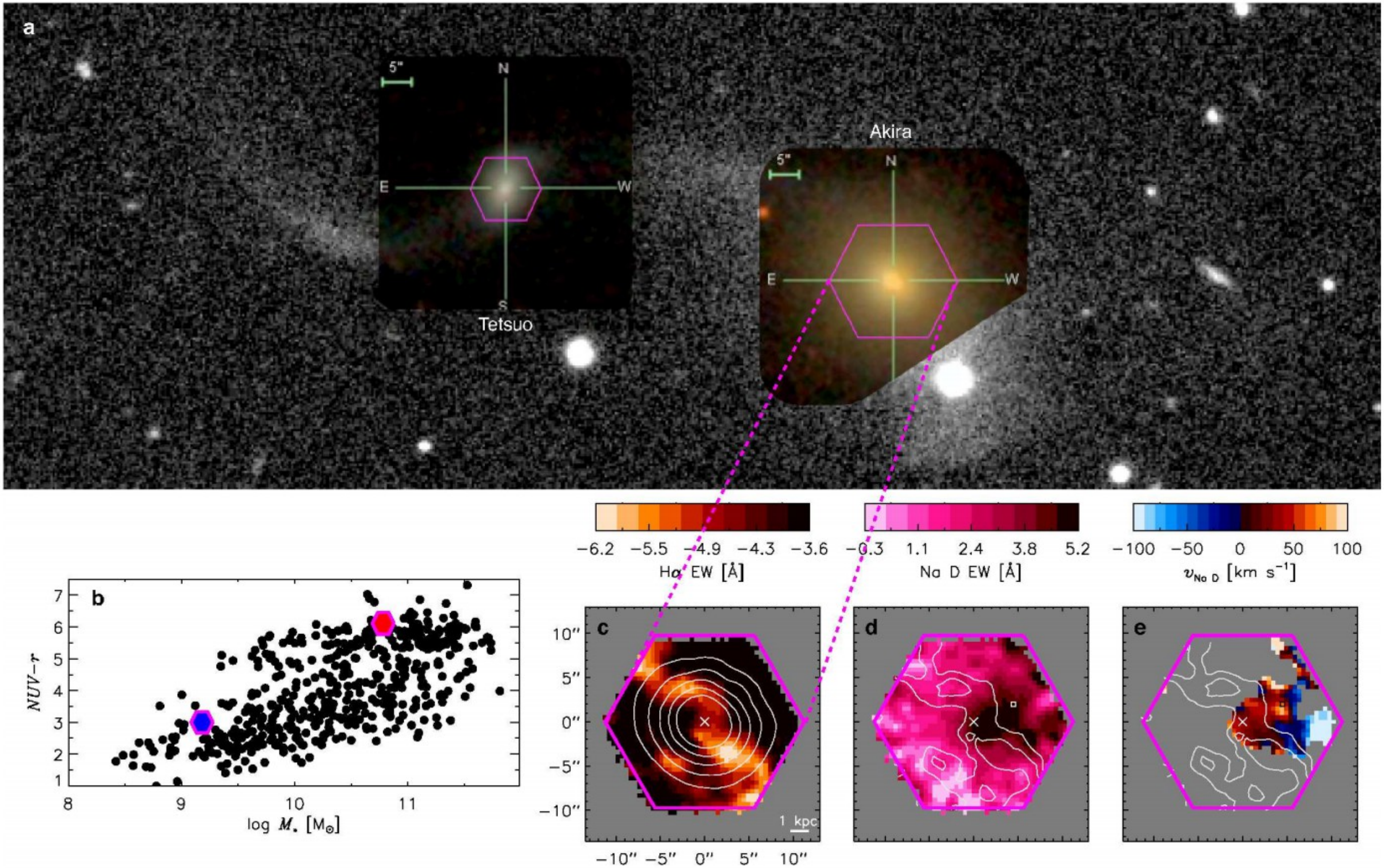


ICM after lobe passage (168 Myr)



Intense winds from supermassive black holes may keep ‘red geyser’ galaxies turned off

EXAMPLE OF OBSERVATIONAL EVIDENCE FOR BLACK HOLE WINDS



Cheung et al. (2016, Nature, 533, 504)

(Genzel et al. 2014, Förster Schreiber et al. 2014)

We have adopted a simple model for kinetic AGN winds in cosmological simulations of galaxy formation

ILLUSTRIS-TNG AGN MODEL AND ITS IMPACT

$$\dot{M}_{\rm Bondi} = \frac{4\pi G^2 M_{\rm BH}^2 \rho}{c_s^3}$$

$$\dot{M}_{\rm Edd} = \frac{4\pi G M_{\rm BH} m_p}{\epsilon_r \sigma_{\rm T} c}$$

We distinguish a “high” and a “low” accretion flow state:

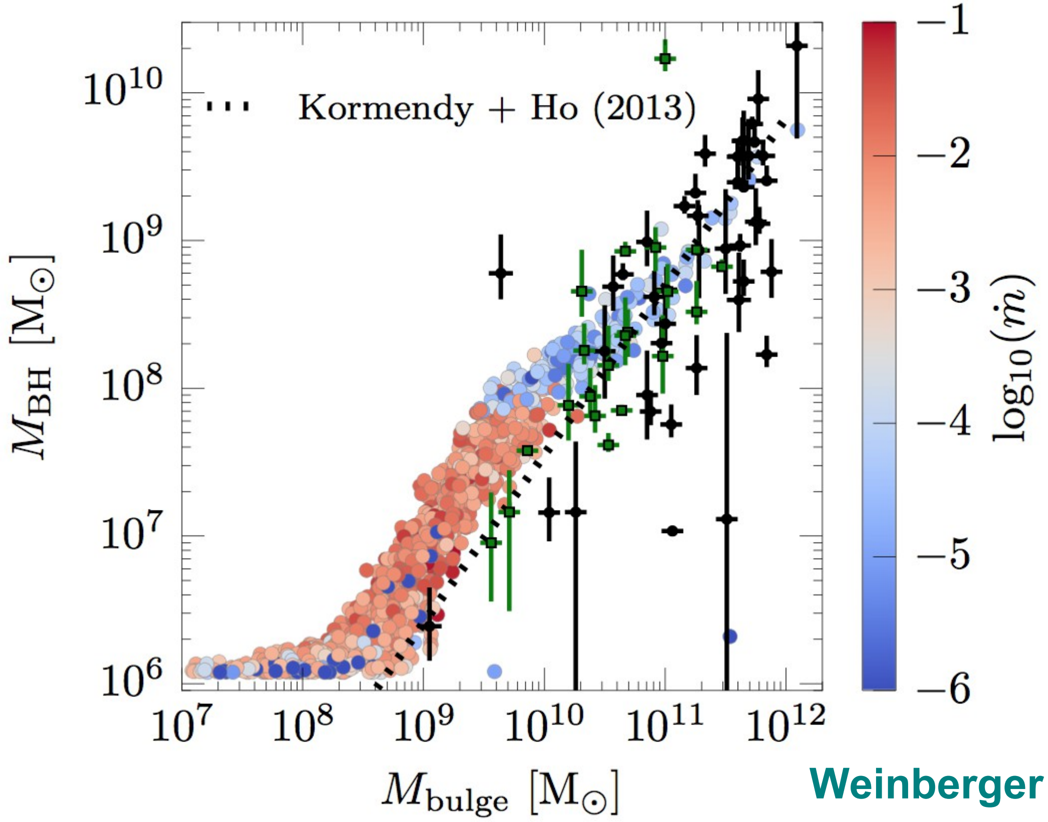
$$\frac{\dot{M}_{\rm Bondi}}{\dot{M}_{\rm Edd}} \geq \chi = \min\left[\chi_0 \left(\frac{M_{\rm BH}}{10^8\,{\rm M}_\odot}\right)^\beta, 0.1\right]$$

Pure thermal feedback in “high” quasar mode:

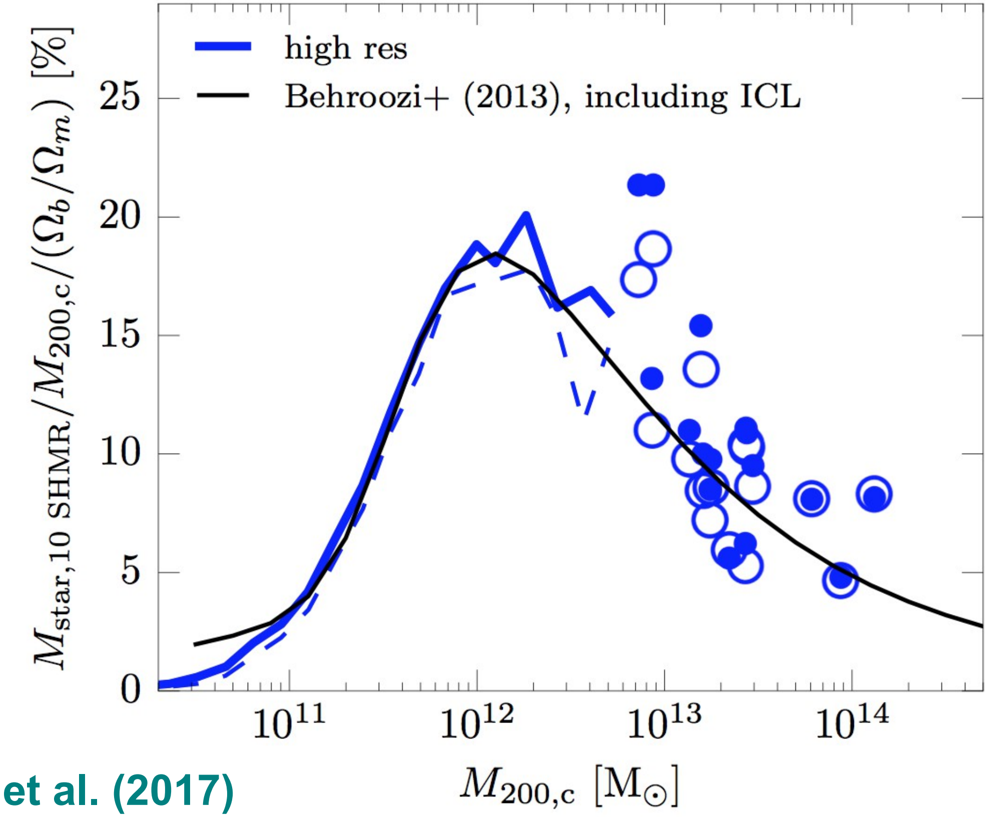
$$\Delta\dot{E}_{\rm high} = \epsilon_{\rm f,high}\epsilon_{\rm r}\dot{M}_{\rm BH}\,c^2$$

Pure kinetic feedback in “low” radio mode:

$$\Delta\dot{E}_{\rm low} = \epsilon_{\rm f,kin}\dot{M}_{\rm BH}c^2.$$



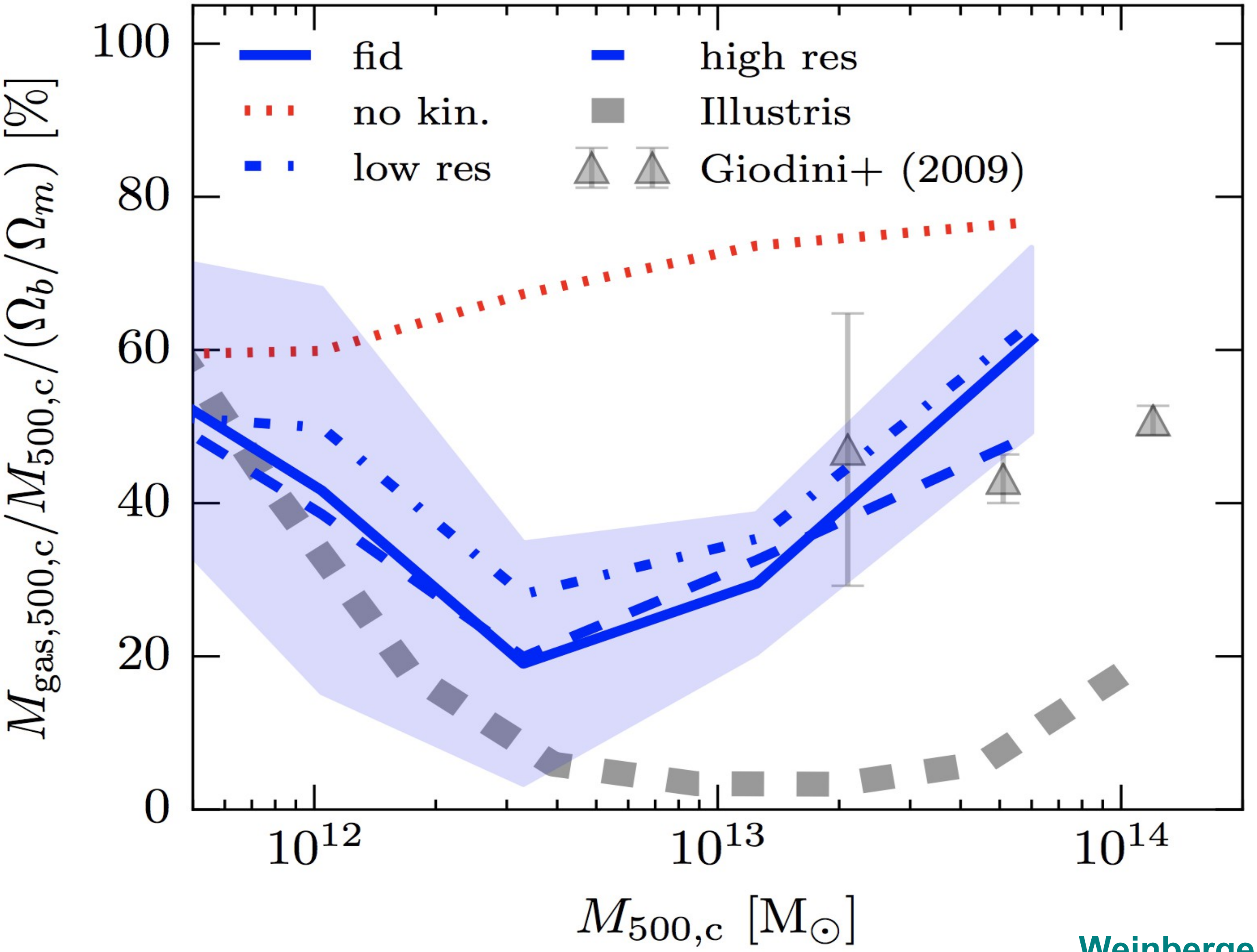
Weinberger et al. (2017)



We obtain **sudden** quenching, setting in at around $M_* \sim 2\times10^{10}\,M_{\rm sun}$

The gas fractions in galaxy groups and poor clusters provide a sensitive constraint on viable AGN feedback models

GAS FRACTIONS WITH THE NEW ILLUSTRIS-TNG AGN MODEL

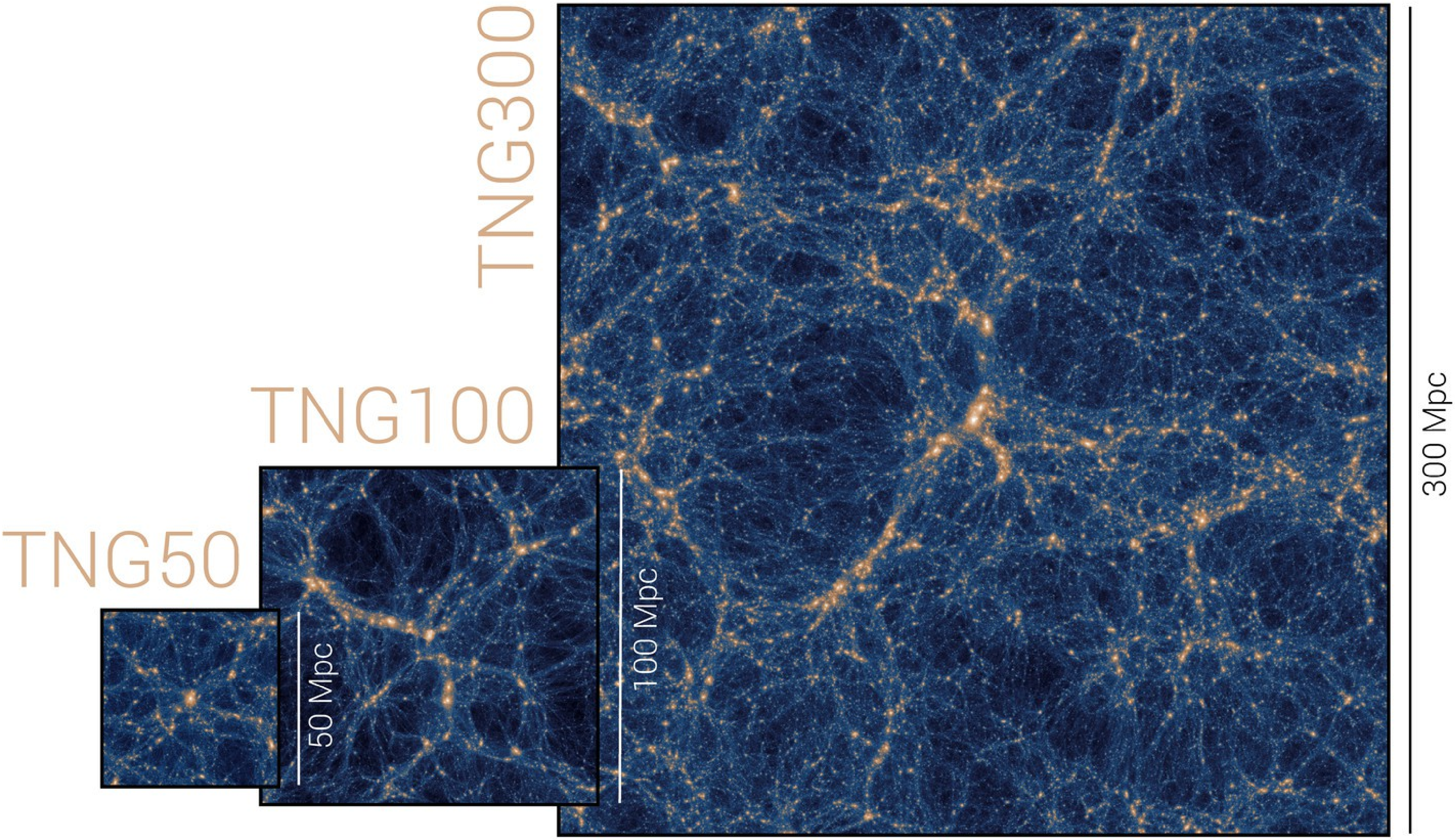


Weinberger et al. (2017)

The “Next Generation Illustris Simulations” (IllustrisTNG) are our novel, significantly improved models for cosmic structure formation

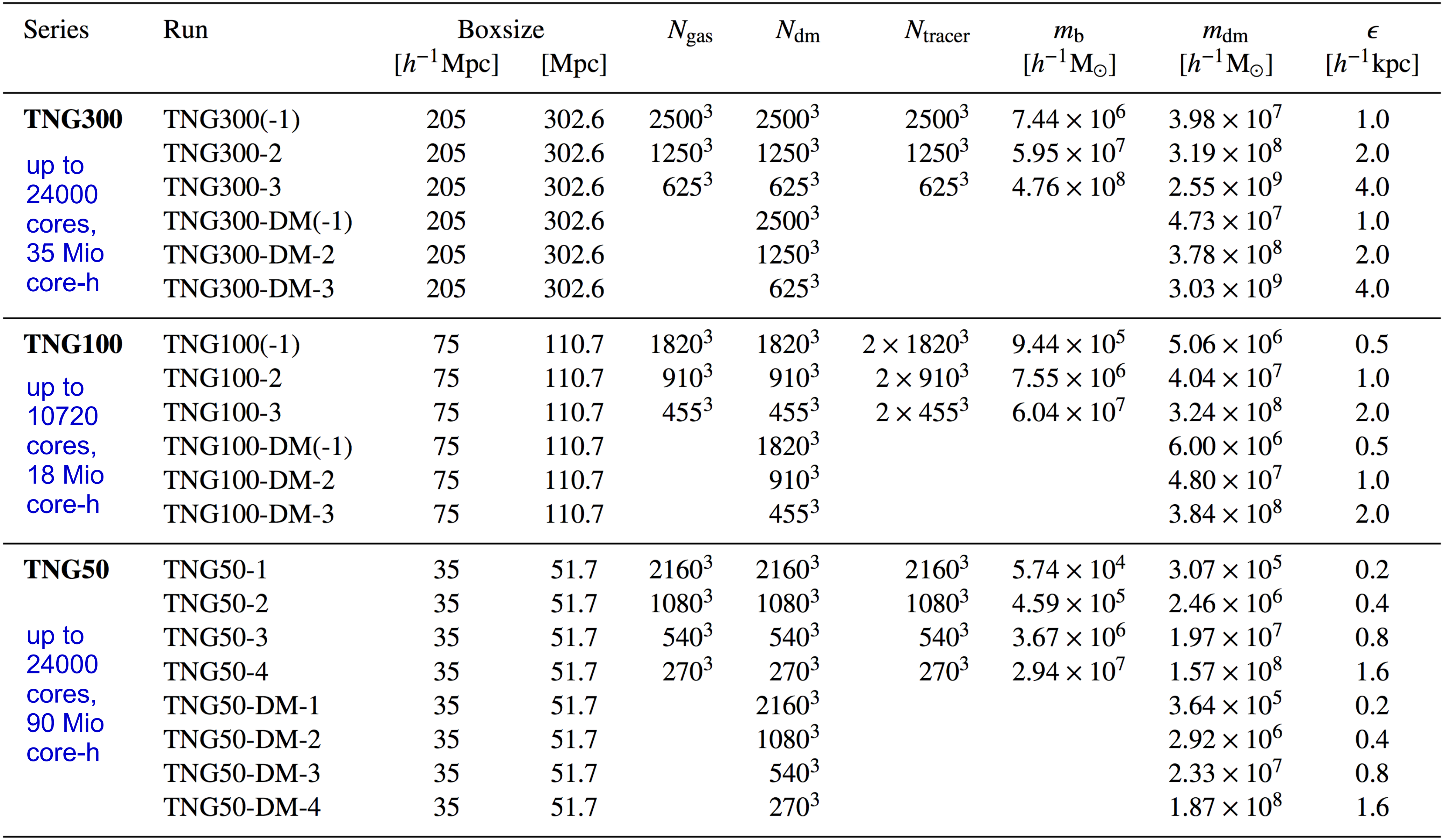
DIFFERENT SIMULATIONS OF THE ILLUSTRIS-TNG PROJECT

IllustrisTNG Collaboration (2017)



Overview over the simulation set of IllustrisTNG

RUNS WERE DONE ON HAZEL-HEN AT HLRS WITH CPU-TIME GRANTED BY GCS



Series	Run	Boxsize		$N_{\rm gas}$	$N_{\rm dm}$	$N_{\rm tracer}$	$m_{\rm b}$	$m_{\rm dm}$	ϵ
		$[h^{-1}{\rm Mpc}]$	[Mpc]				$[h^{-1}{\rm M}_\odot]$	$[h^{-1}{\rm M}_\odot]$	$[h^{-1}{\rm kpc}]$
TNG300 up to 24000 cores, 35 Mio core-h	TNG300(-1)	205	302.6	2500^3	2500^3	2500^3	7.44×10^6	3.98×10^7	1.0
	TNG300-2	205	302.6	1250^3	1250^3	1250^3	5.95×10^7	3.19×10^8	2.0
	TNG300-3	205	302.6	625^3	625^3	625^3	4.76×10^8	2.55×10^9	4.0
	TNG300-DM(-1)	205	302.6		2500^3			4.73×10^7	1.0
	TNG300-DM-2	205	302.6		1250^3			3.78×10^8	2.0
	TNG300-DM-3	205	302.6		625^3			3.03×10^9	4.0
TNG100 up to 10720 cores, 18 Mio core-h	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
	TNG100-DM(-1)	75	110.7		1820^3			6.00×10^6	0.5
	TNG100-DM-2	75	110.7		910^3			4.80×10^7	1.0
	TNG100-DM-3	75	110.7		455^3			3.84×10^8	2.0
TNG50 up to 24000 cores, 90 Mio core-h	TNG50-1	35	51.7	2160^3	2160^3	2160^3	5.74×10^4	3.07×10^5	0.2
	TNG50-2	35	51.7	1080^3	1080^3	1080^3	4.59×10^5	2.46×10^6	0.4
	TNG50-3	35	51.7	540^3	540^3	540^3	3.67×10^6	1.97×10^7	0.8
	TNG50-4	35	51.7	270^3	270^3	270^3	2.94×10^7	1.57×10^8	1.6
	TNG50-DM-1	35	51.7		2160^3			3.64×10^5	0.2
	TNG50-DM-2	35	51.7		1080^3			2.92×10^6	0.4
	TNG50-DM-3	35	51.7		540^3			2.33×10^7	0.8
	TNG50-DM-4	35	51.7		270^3			1.87×10^8	1.6

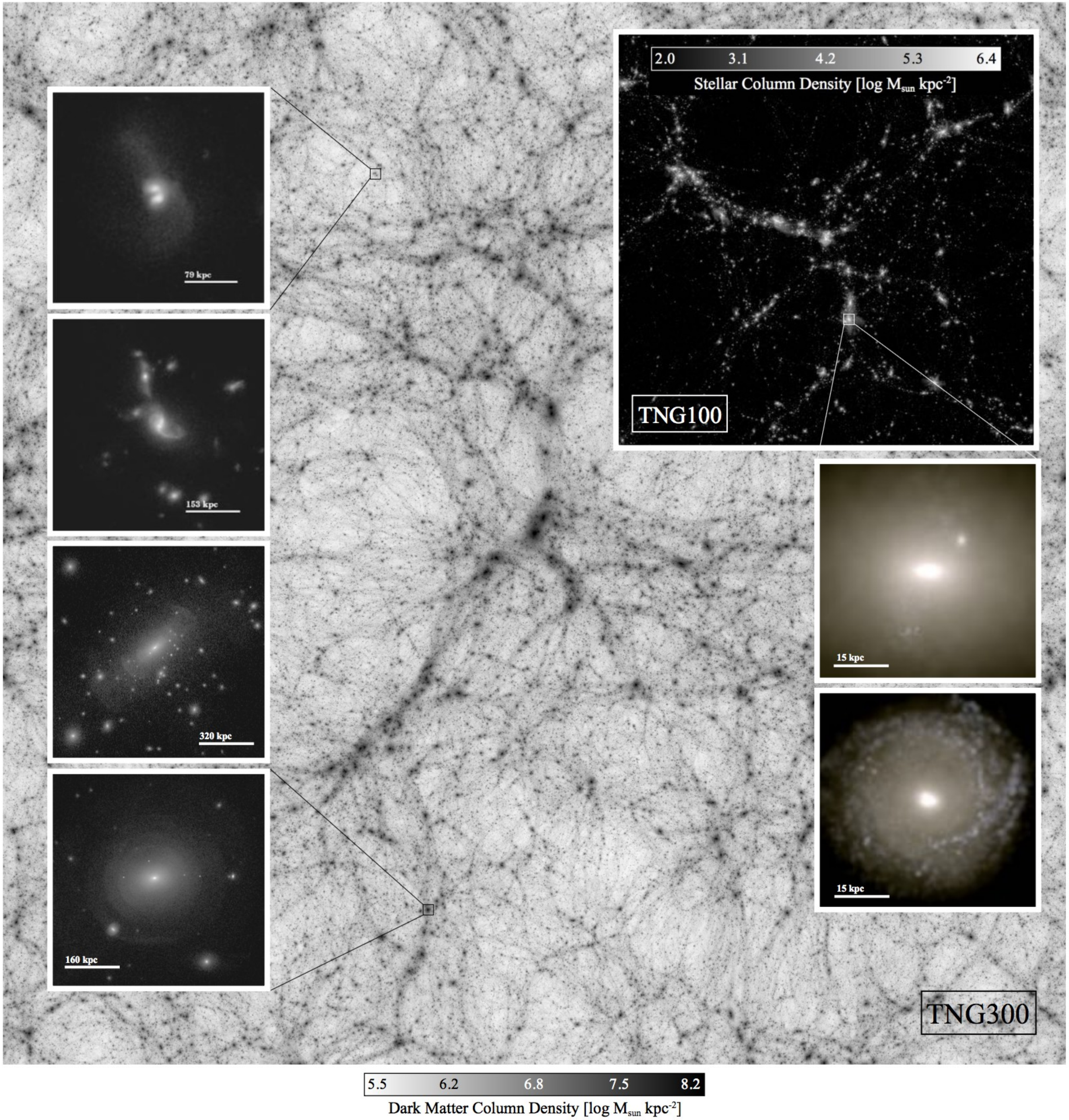
IllustrisTNG was executed on **Hazel Hen** in Stuttgart, Germany

GCS
Gauss Centre for Supercomputing

7.4 PFlops

IllustrisTNG gives detailed predictions for the spatial distribution of stars, and its relation to the underlying dark matter backbone

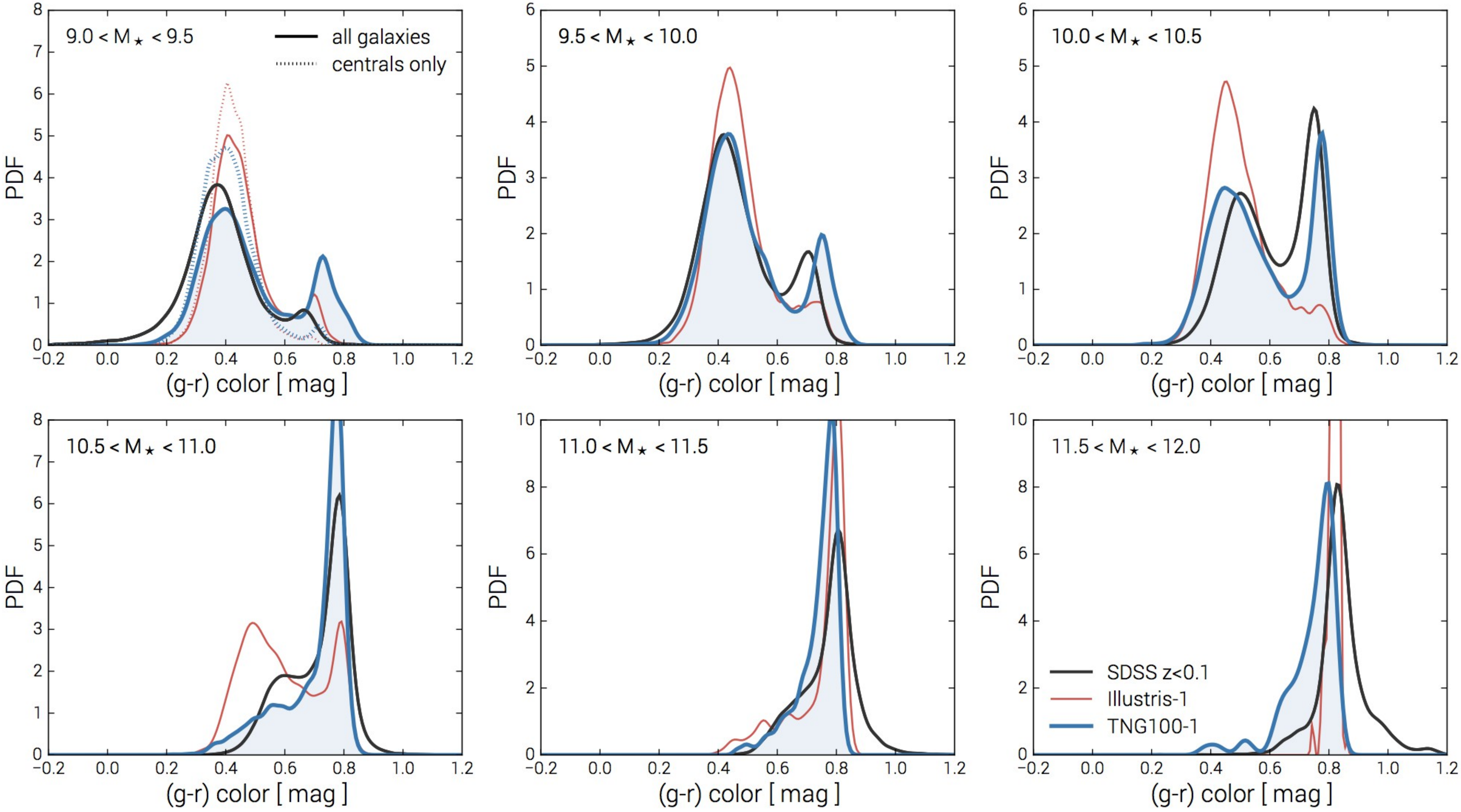
DARK MATTER AND STELLAR DENSITY IN ILLUSTRIS-TNG



Pillepich et al. (2018)

IllustrisTNG reproduces the observed color-bimodality of galaxies thanks to AGN feedback

COLOR DISTRIBUTION OF GALAXIES OF DIFFERENT MASS COMPARED TO SDSS

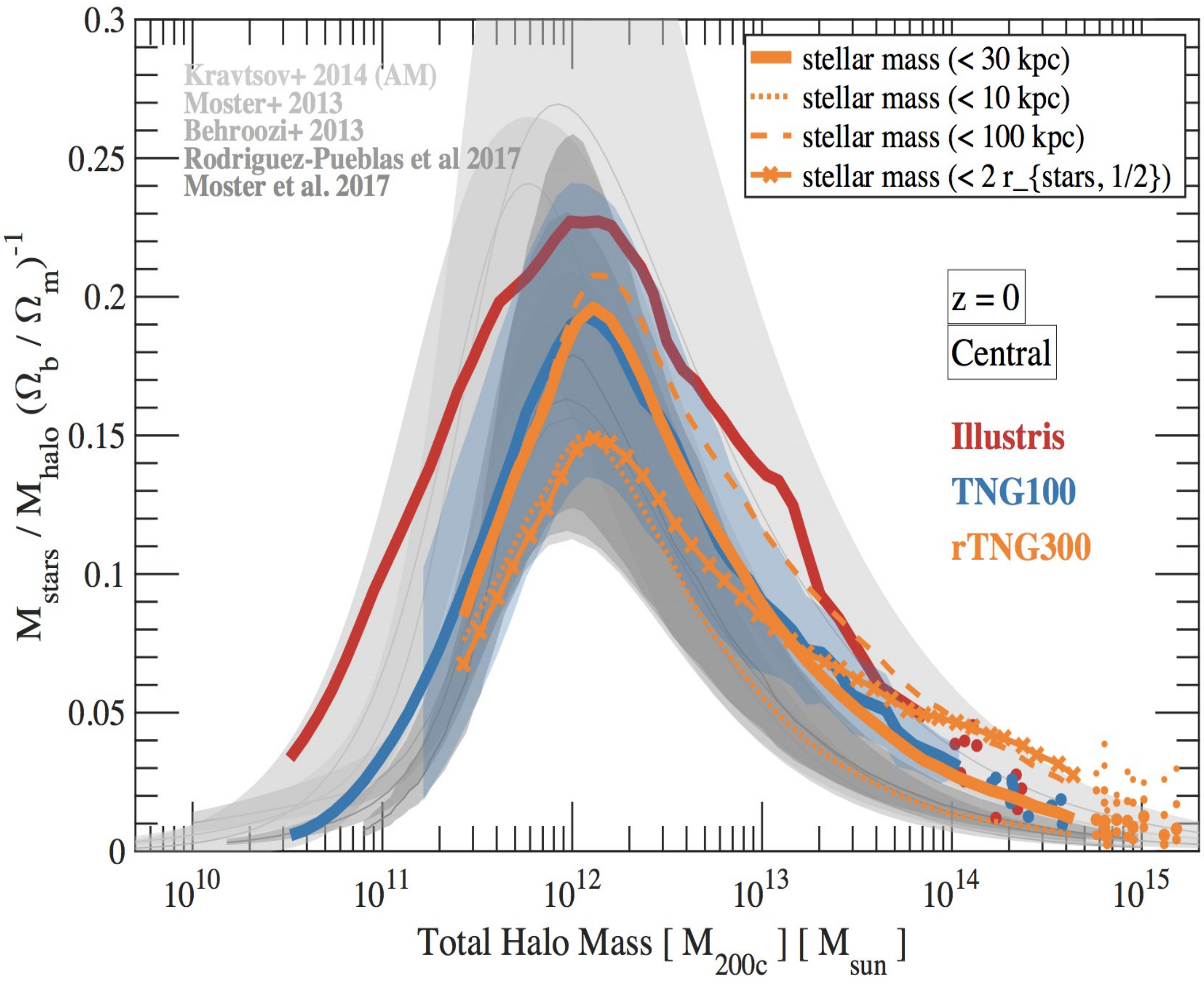


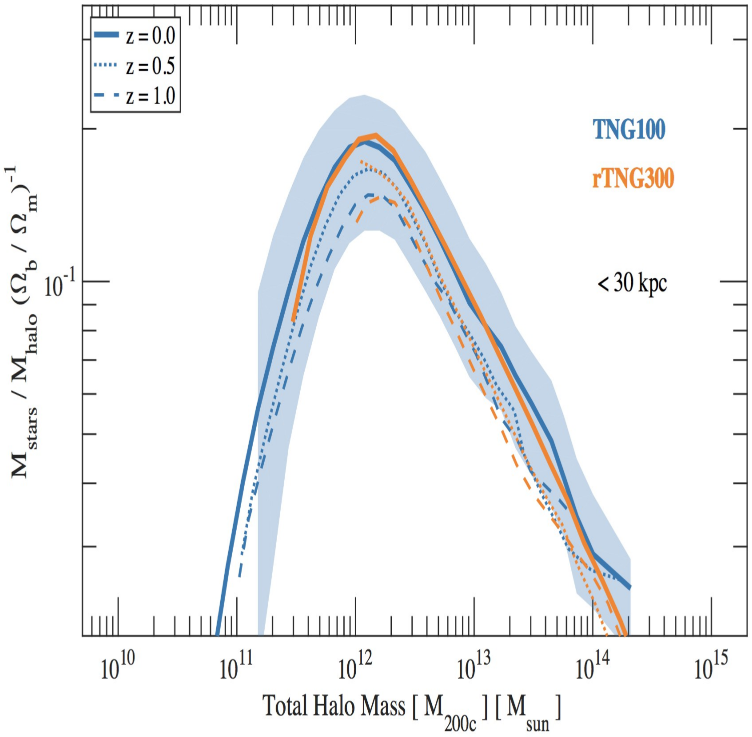
Nelson et al. (2017)

The new feedback model in TNG produces a sharp characteristic scale in the halo – stellar mass relationship

ILLUSTRIS COMPARED TO ABUNDANCE MATCHING MODELS FOR THE SMHM RELATION

Pillepich et al. (2018)

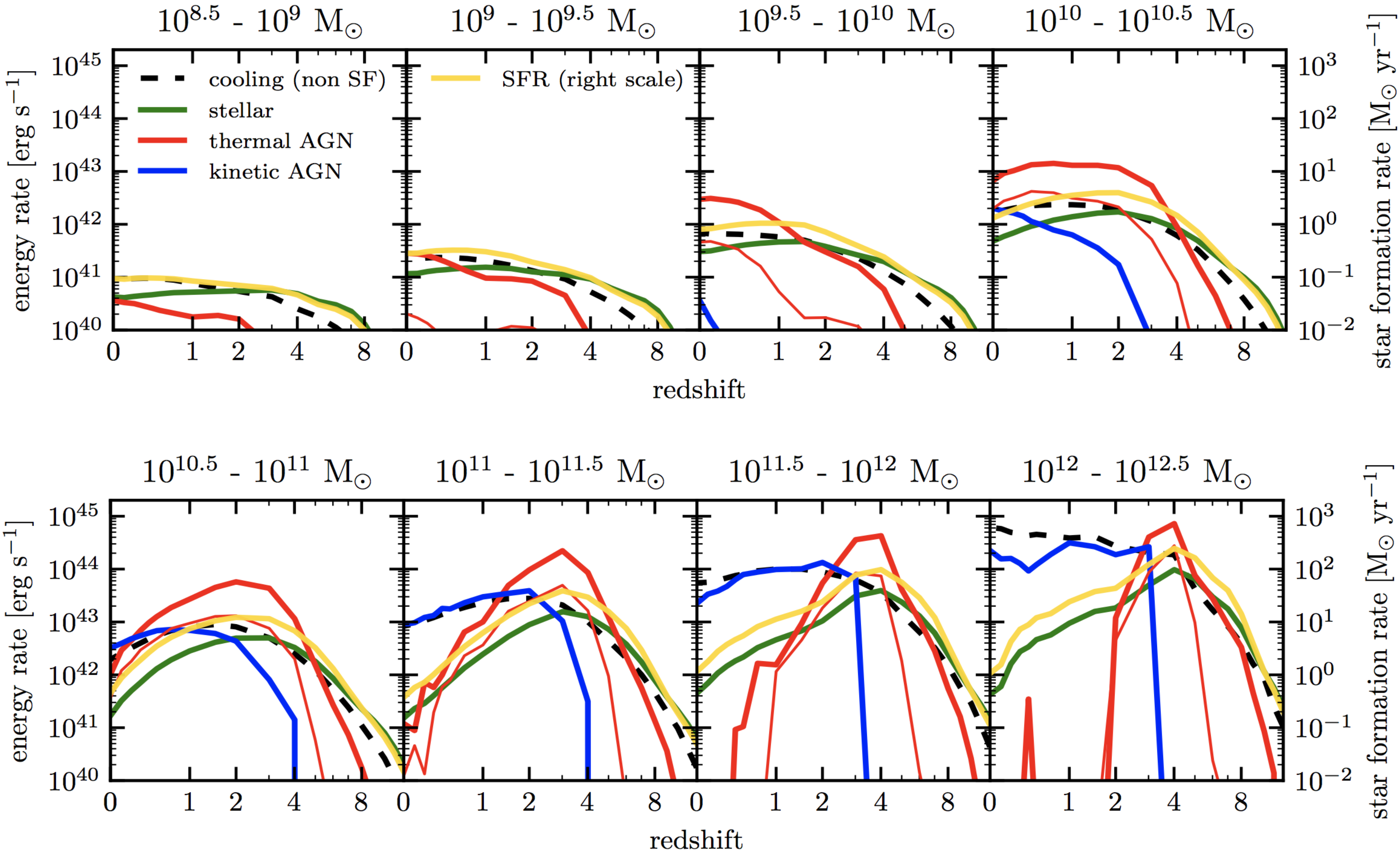




Kinetic AGN feedback takes over at late times in large galaxies

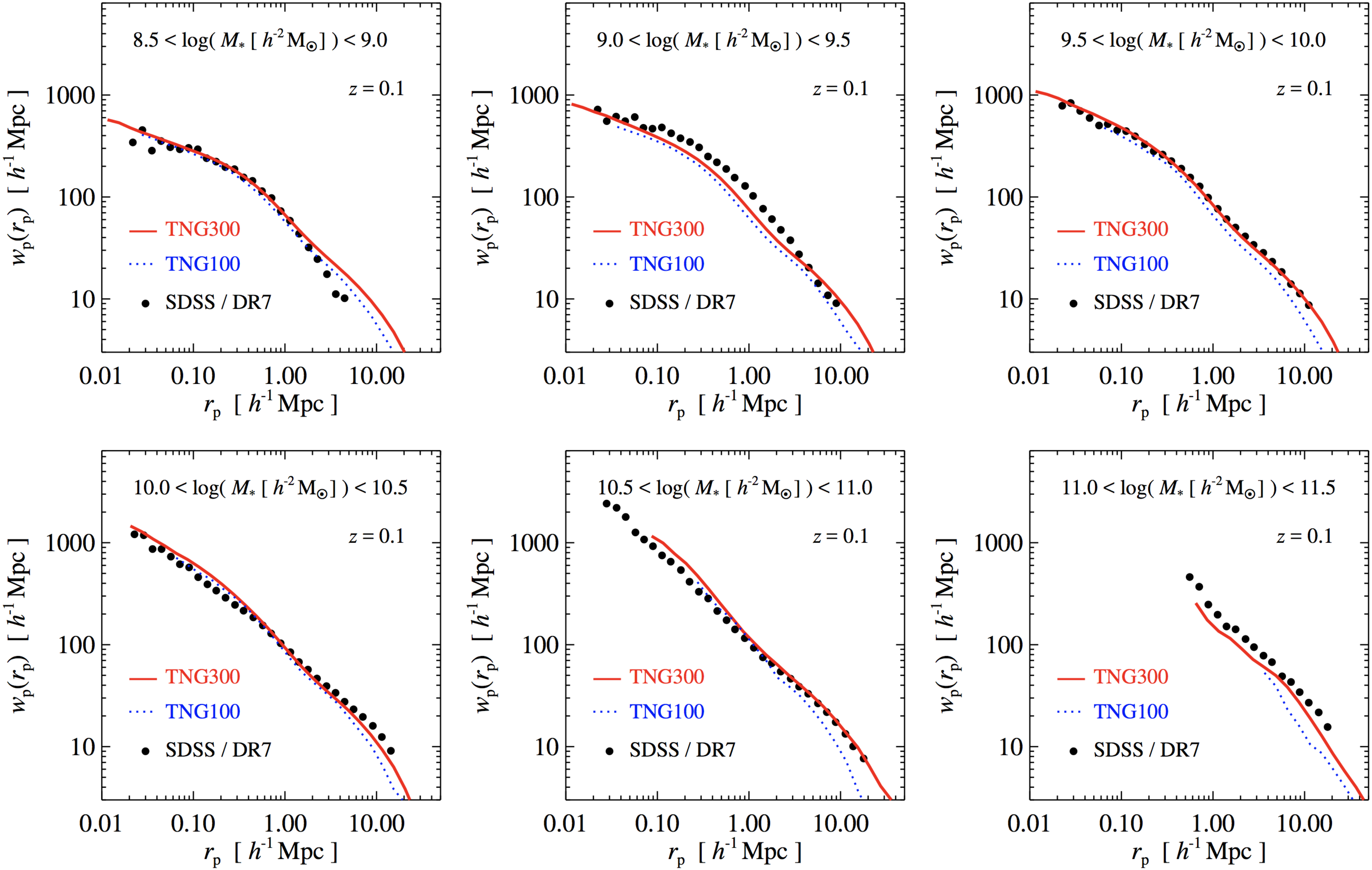
FEEDBACK ENERGY AS A FUNCTION OF TIME AND FINAL STELLAR MASS

Weinberger et al. (2018)



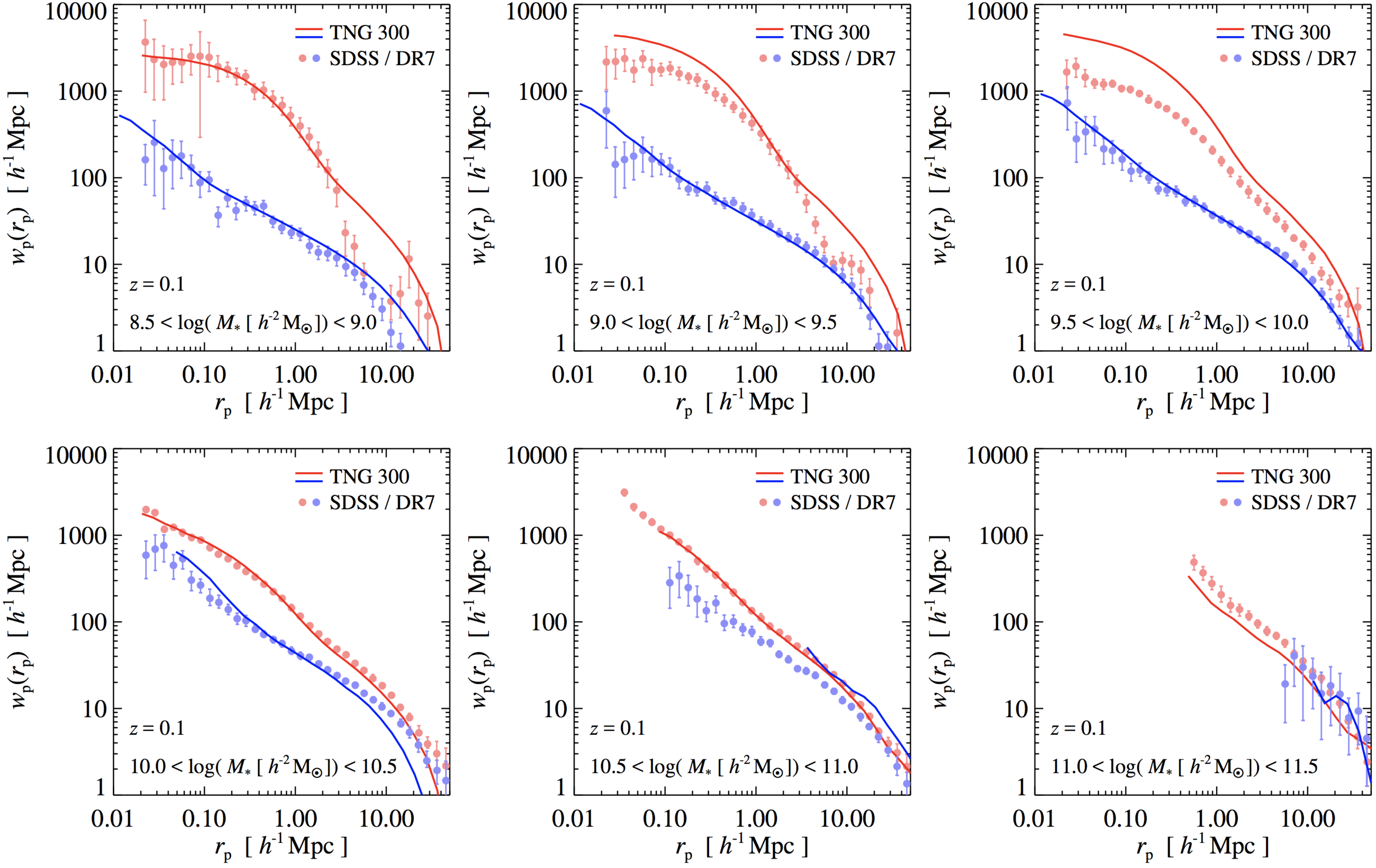
IllustrisTNG predicts galaxy correlation functions in good agreement with the most accurate galaxy surveys

PROJECTED TWO-POINT FUNCTIONS IN DIFFERENT MASS BINS



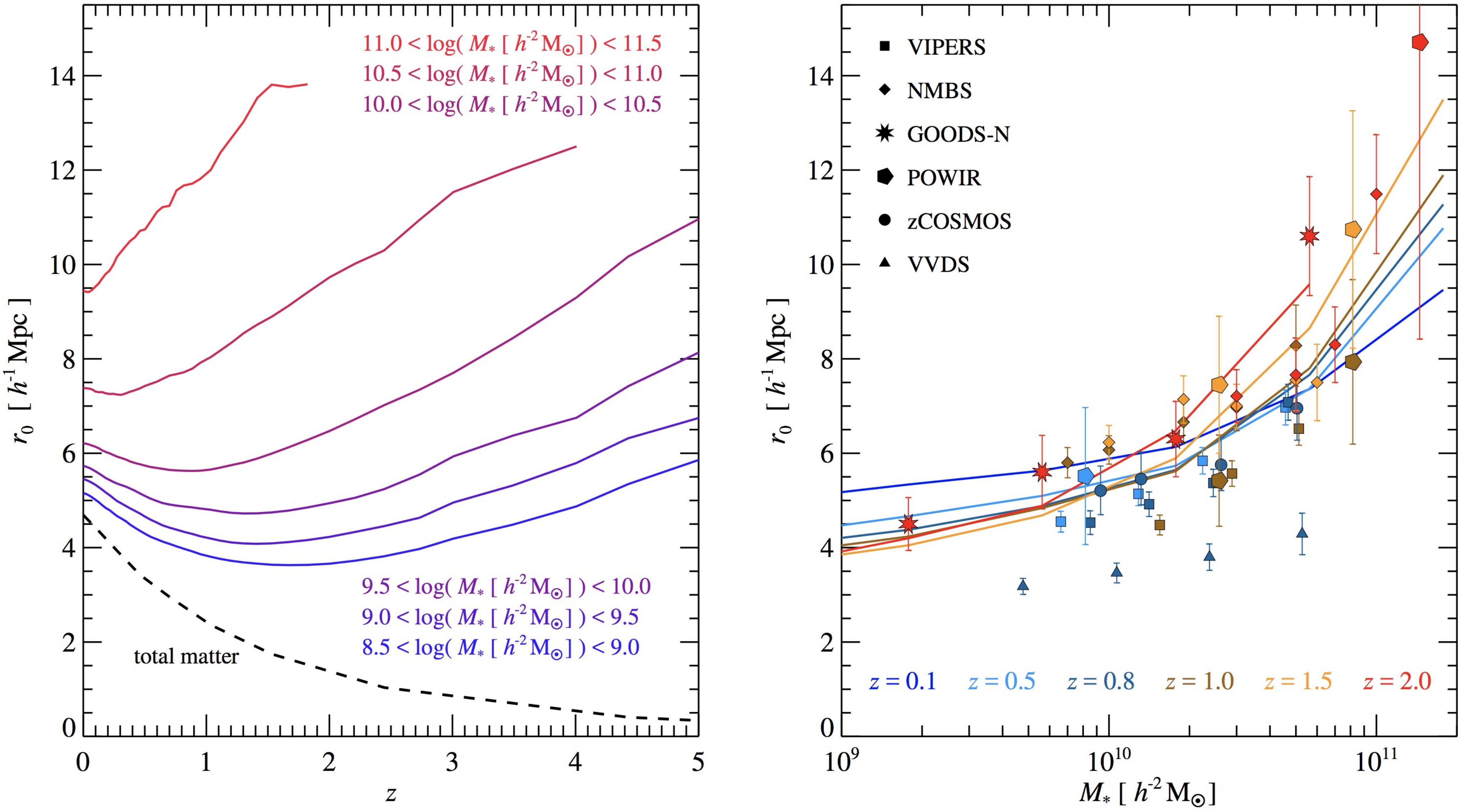
IllustrisTNG predicts pronounced differences in the clustering of red and blue galaxies in good agreement with data

CLUSTERING IN DIFFERENT MASS AND COLOR BINS COMPARED TO SDSS



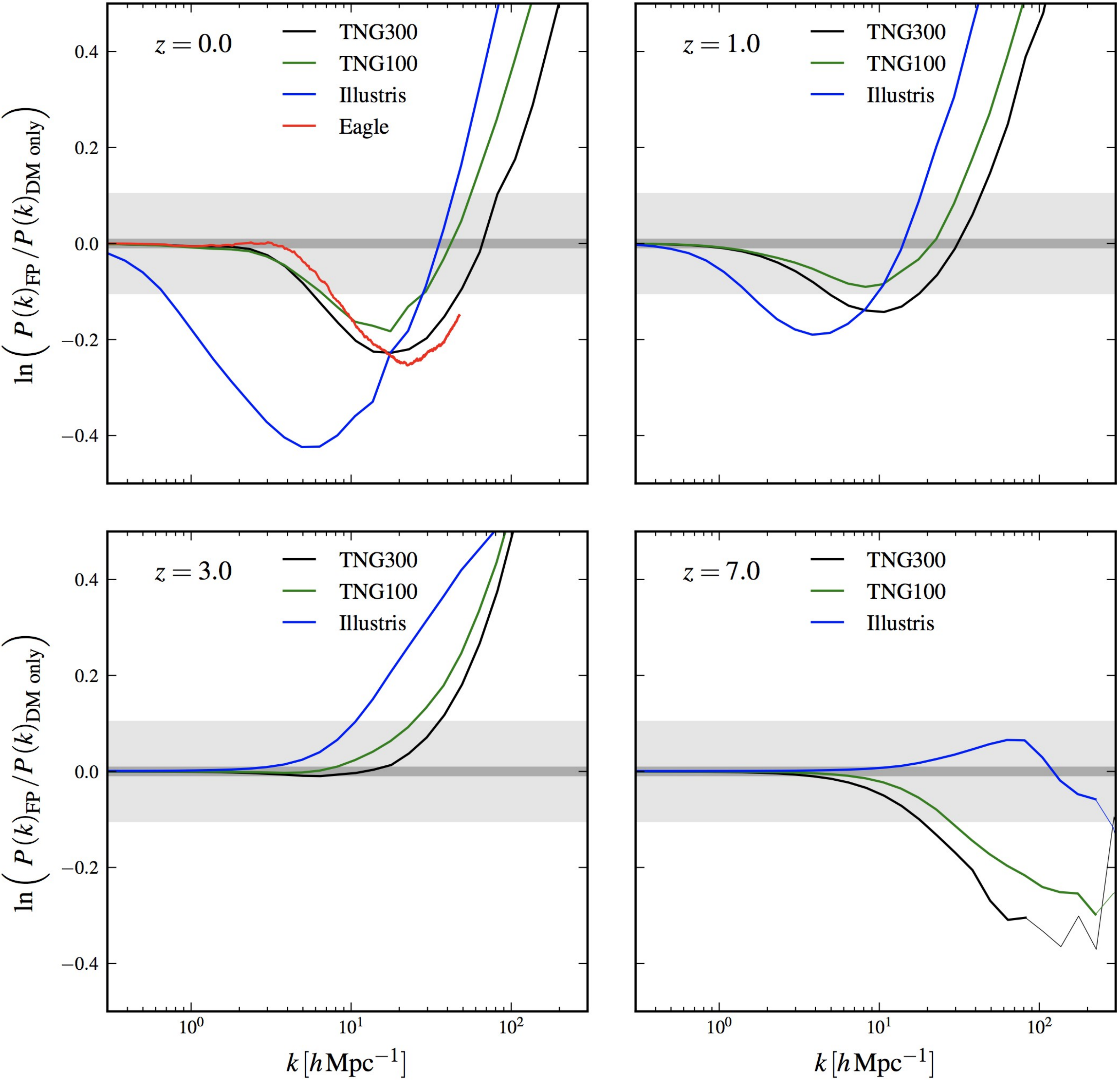
IllustrisTNG predicts that the correlation length of galaxy clustering depends both on stellar mass and redshift

CORRELATION LENGTH AS A FUNCTION OF REDSHIFT AND STELLAR MASS



Baryonic affects on the matter power spectrum are at the 20% level on scales of k~10 h/Mpc

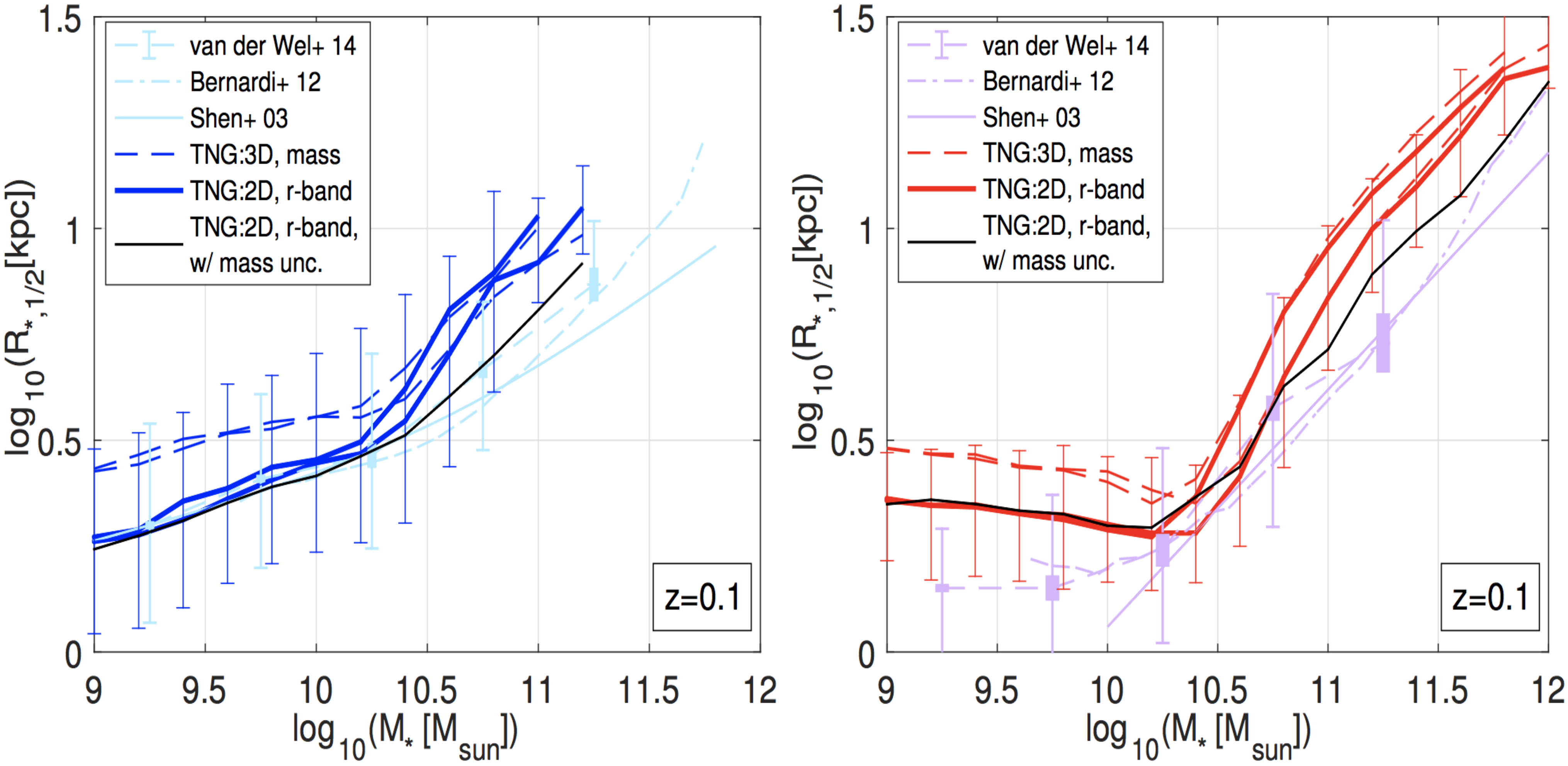
RELATIVE IMPACT ON POWER SPECTRUM AT DIFFERENT EPOCH AND IN DIFFERENT SIMULATIONS



Springel et al. (2017)

The sizes of different galaxies types reproduce observed trends with stellar mass well

ILLUSTRIS-TNG GALAXY SIZES AS A FUNCTION OF STELLAR MASS



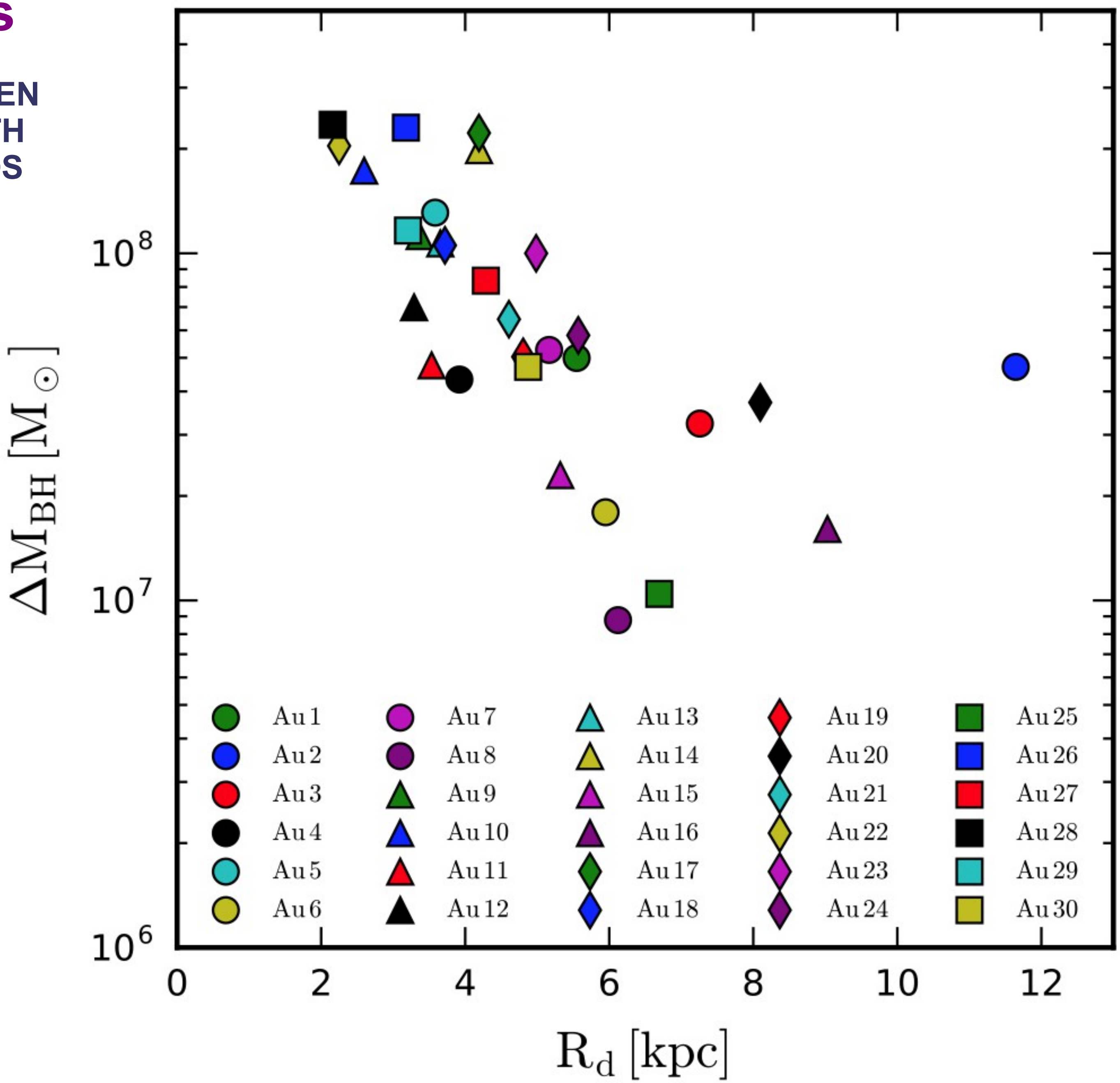
(a) Main-sequence / late-type galaxies

(b) Quenched / early-type galaxies

Genel et al. (2018)

Black hole growth influences disk sizes

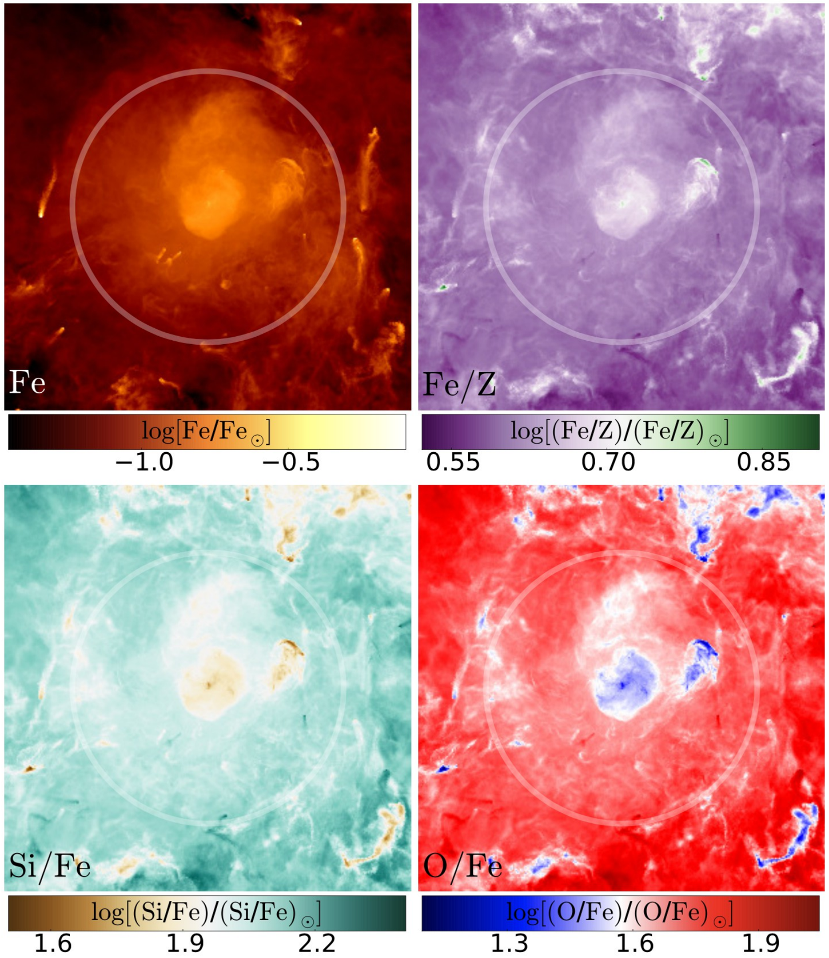
BLACK HOLE GROWTH BETWEEN Z=1 AND Z=0 CORRELATES WITH DISK SCALE LENGTHS IN HALOS OF MILKY WAY MASS

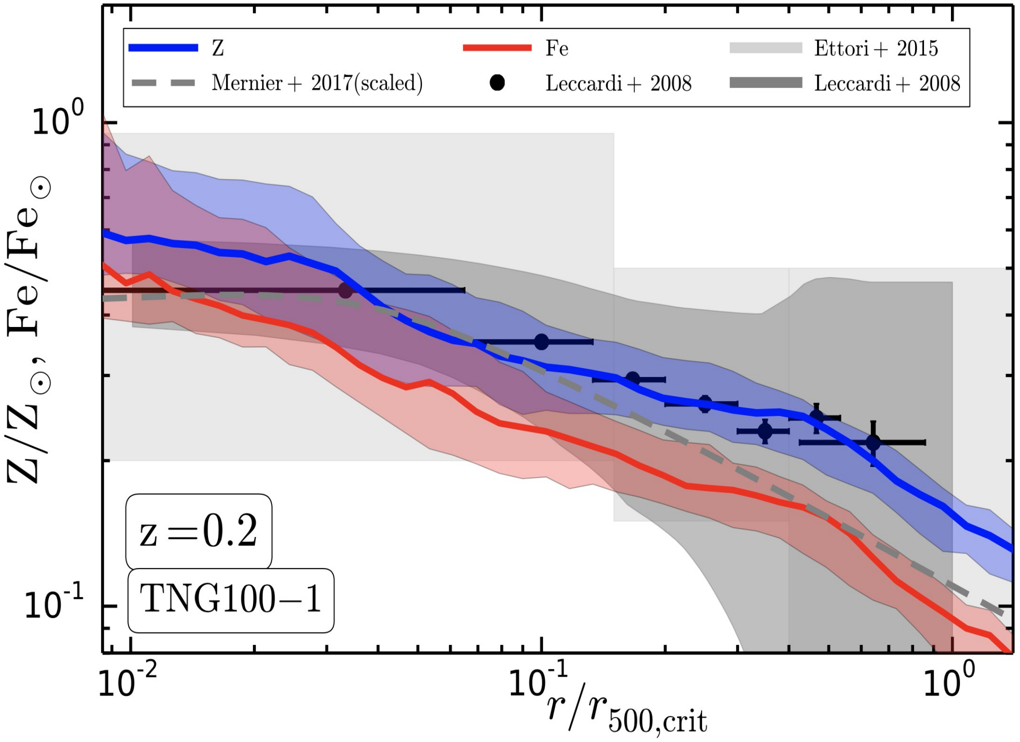


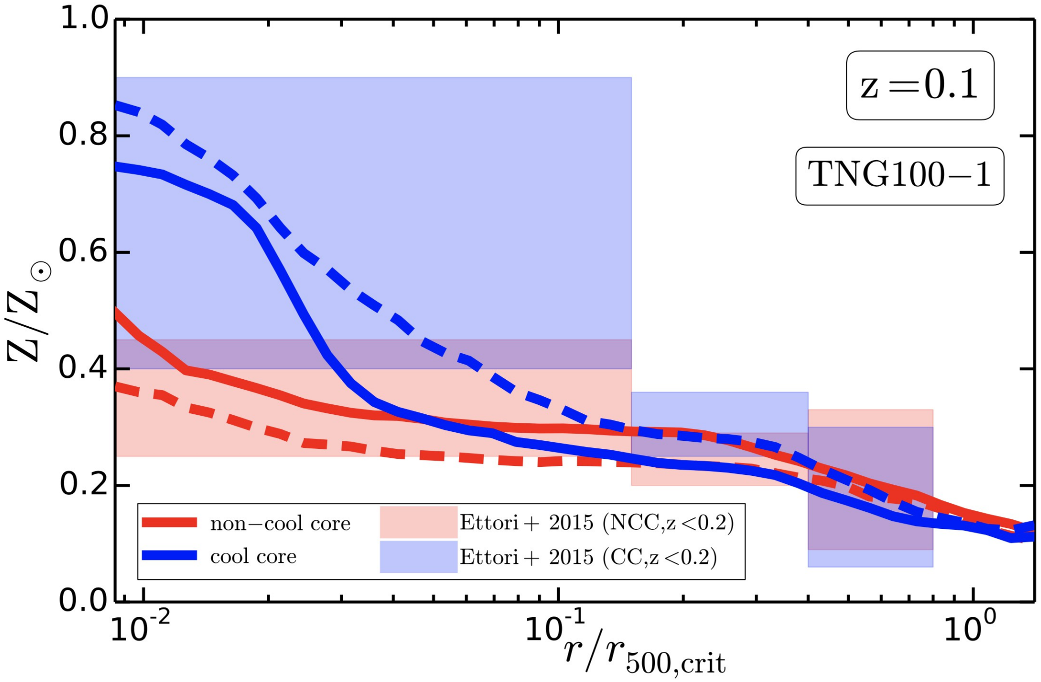
Grand et al. (2016)

Observed metallicity profiles of galaxy clusters are reproduced by IllustrisTNG

METALLICITY MAPS AND PROFILES FOR RICH GALAXY CLUSTERS







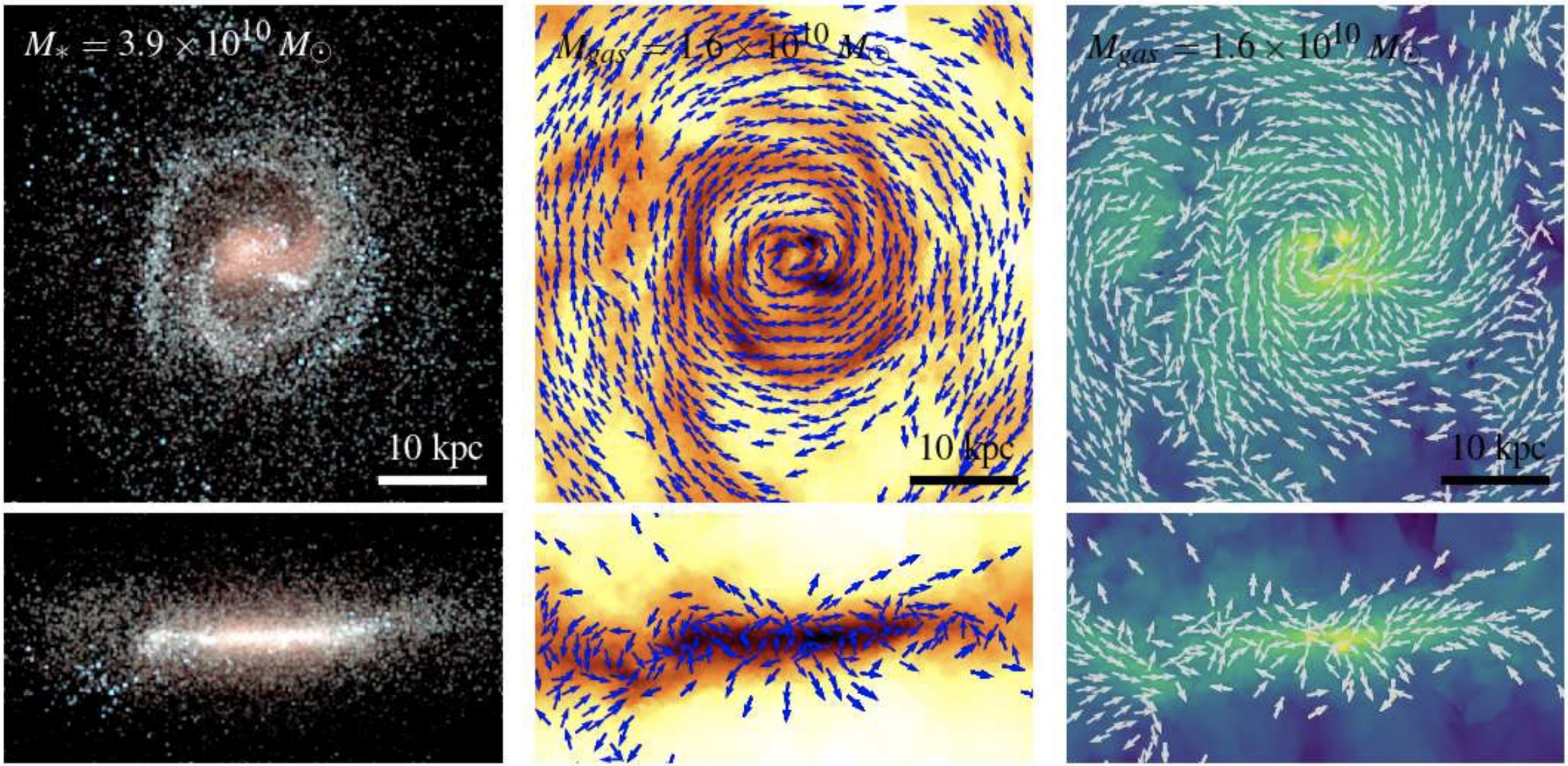
Vogelsberger et al. (2017)

Our MHD simulations of galaxy formation predict the amplification of primordial fields in halos and galaxies

MAGNETIC FIELD STRENGTH IN A SMALL REGION OF ILLUSTRIS-TNG

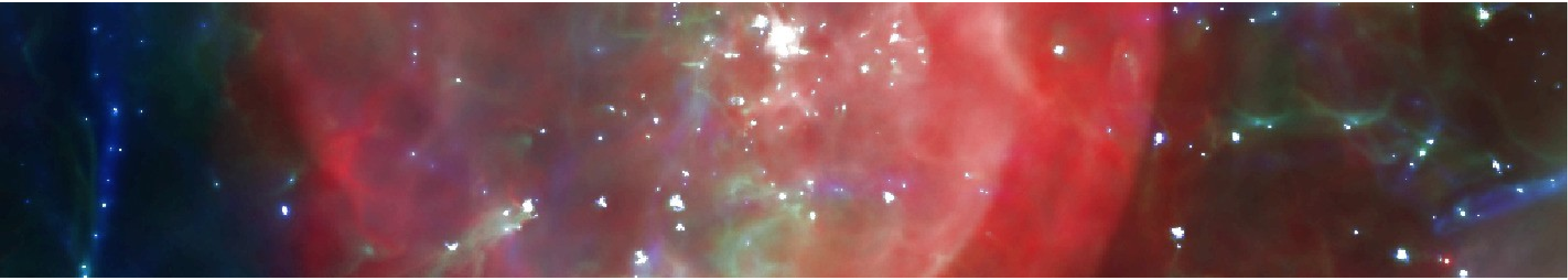
The IllustrisTNG simulations predict the magnetic field strength and field topology in galaxies

STELLAR MASS, GAS DENSITY AND MAGNETIC FIELD STRENGTH IN A TYPICAL SPIRAL



Marinacci et al. (2018)

Take home points



- Strong, scale-dependent feedback is needed to reconcile ΛCDM with galaxy observations
- (Analytic) sub-grid models with clean interface to resolved scales can decouple numerical nuisance parameters from physical models
- Precise feedback physics still unclear, understanding dwarf galaxy suppression and baryon loss from galaxies is probably key for further progress
- Black hole feedback critical for quenching of massive galaxies
- Magneto-hydrodynamic cosmological simulations of ΛCDM such as IllustrisTNG can now quite successfully predict galaxy morphologies, clustering, and quenching, as well as diffuse gas properties in the CGM, IGM, and ICM, from high-z to the present
- A small-scale dynamo driven by feedback generated turbulence can efficiently amplify tiny seed fields already at high redshift to the observed strength in galaxies