Future prospects for galaxy formation simulations

Volker Springel

- **The past: The trouble with hydrodynamic simulations of galaxy formation**
- **The present:**
  Too good to be true?
- **The future: physical and numerical challenges**

Max-Planck-Institute
for Astrophysics

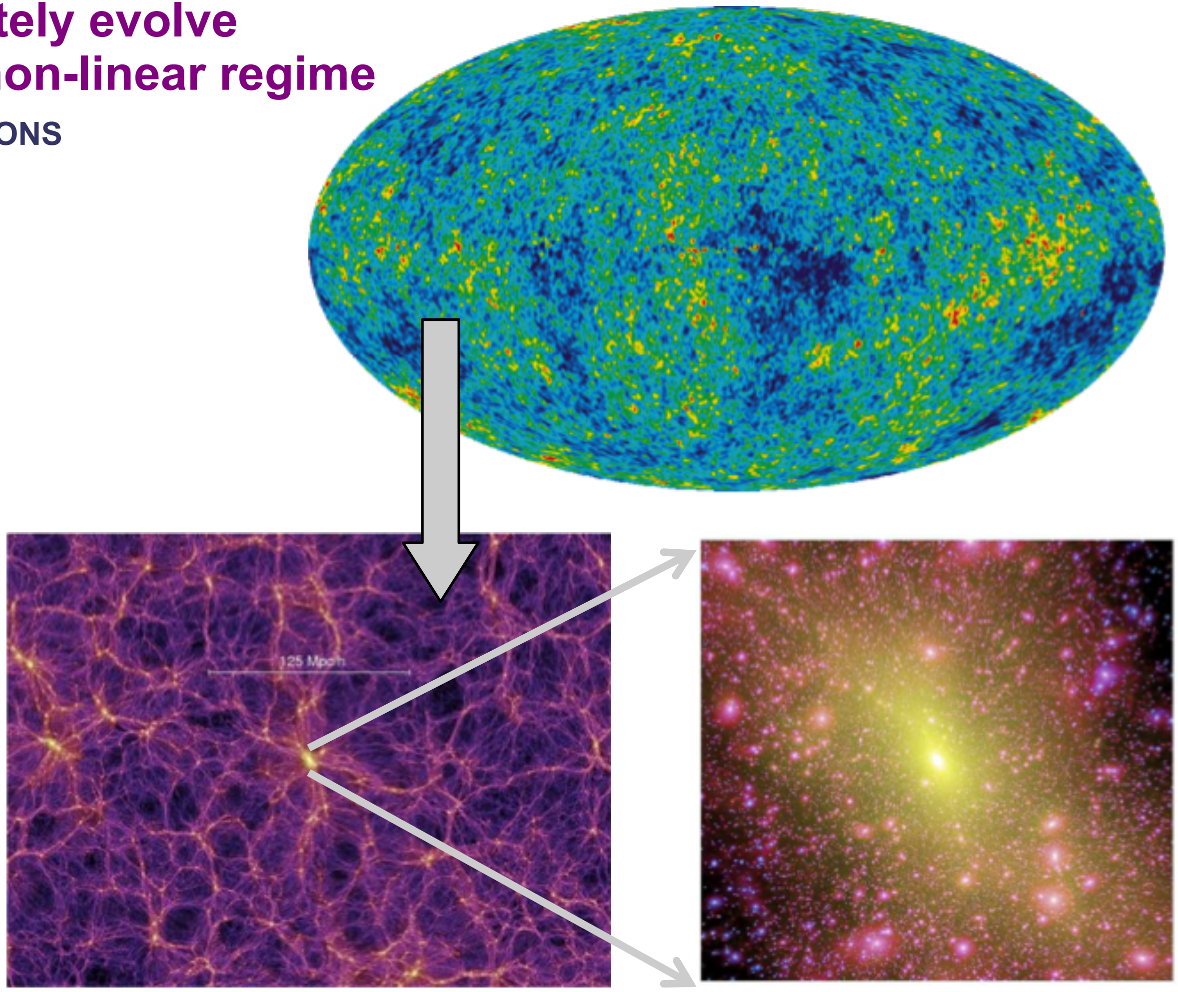
KICC 10th Anniversary Symposium
Cambridge, September 2019

N-body simulations accurately evolve cosmological ICs into the non-linear regime

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.

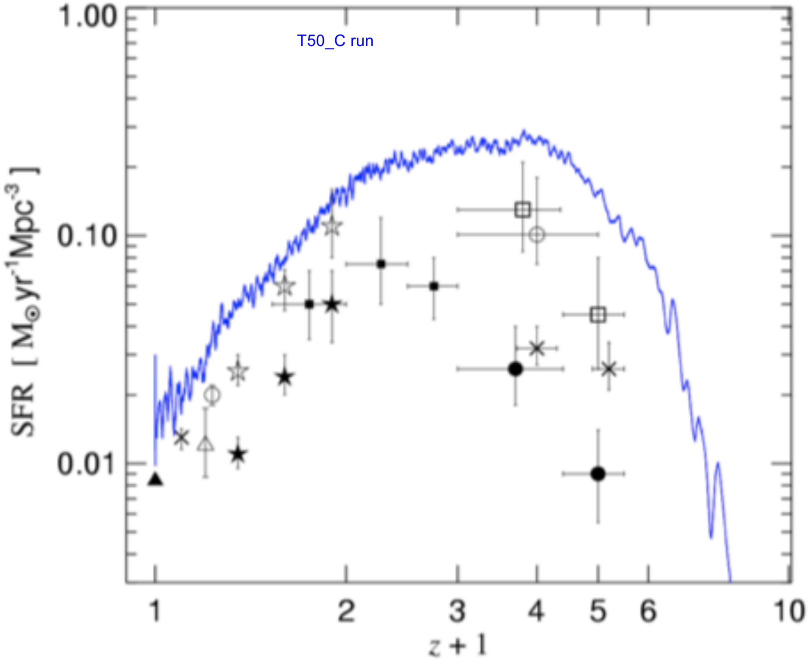


The overcooling problem refers to excess star formation produced by hydrodynamic simulations on essentially all halo mass scales

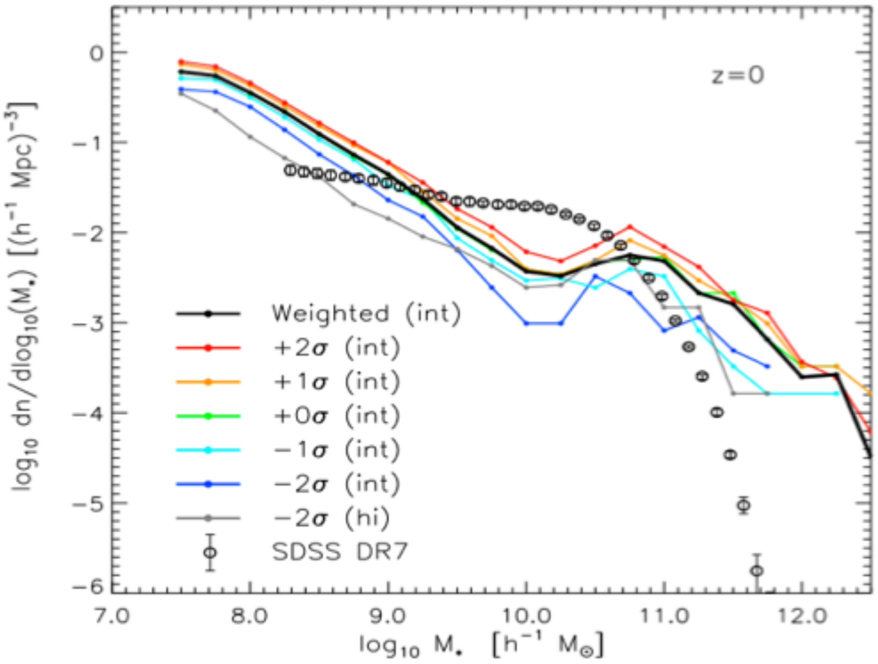
STAR FORMATION HISTORY AND LUMINOSITY FUNCTION FOR SIMULATIONS WITH WEAK / NO FEEDBACK

Baryon conversion efficiency without feedback excessively high (~ 30%-100%)

Springel & Hernquist (2003)



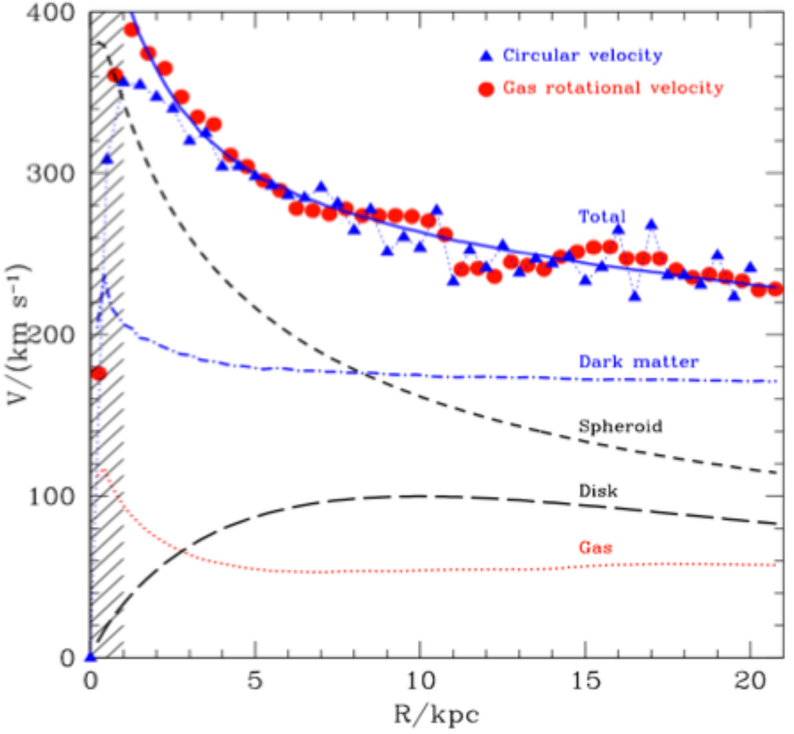
Crain et al. (2009)

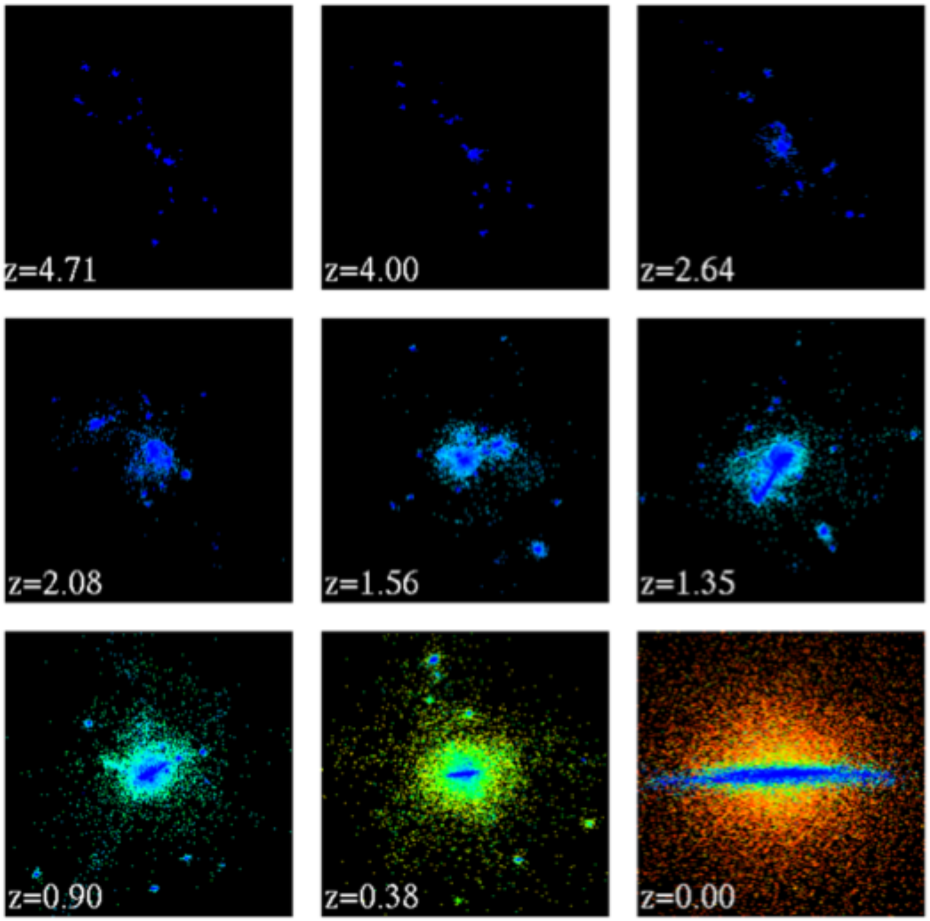


Massive bulges and peaked rotation curves in early simulations of disk galaxies

EXCESS BULGE FORMATION AND WEAK DISKS

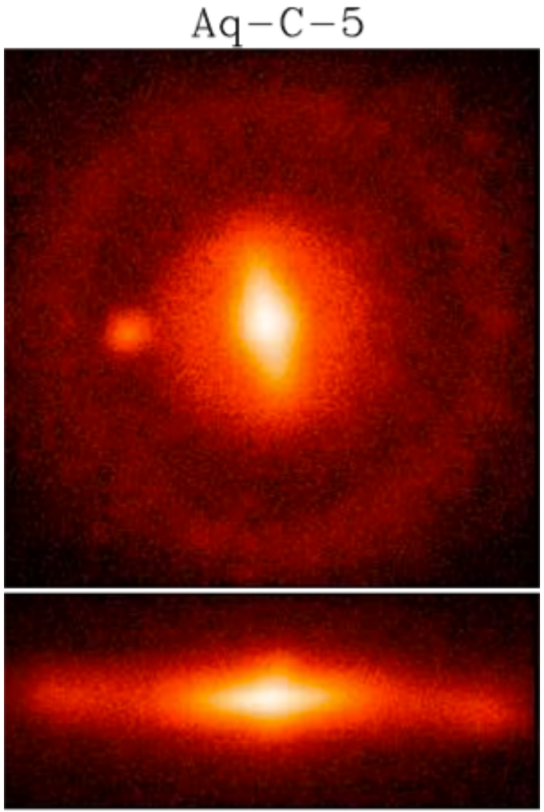
Abadi et al. (2003)



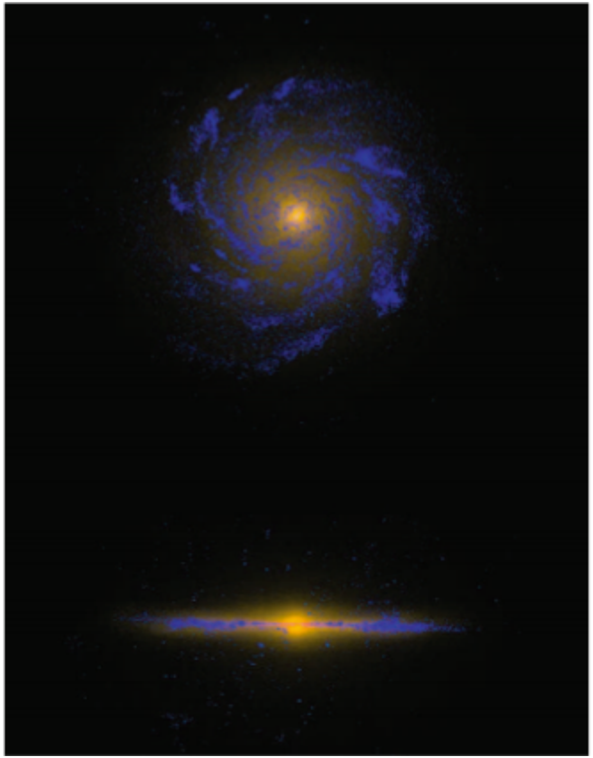


Gradual progress in forming realistic disk galaxis over the last decade

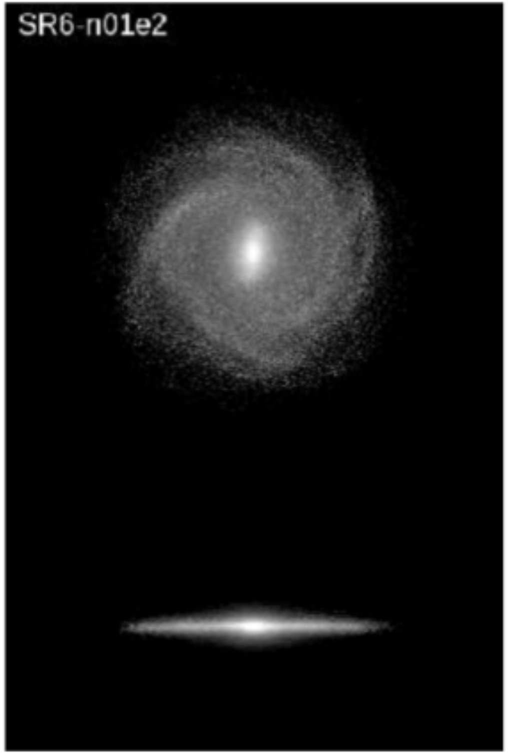
TOWARDS MILKY WAY GALAXIES OUT OF THE SUPERCOMPUTER



Scannapieco et al. (2011, 2012)



Guedes et al. (2011)

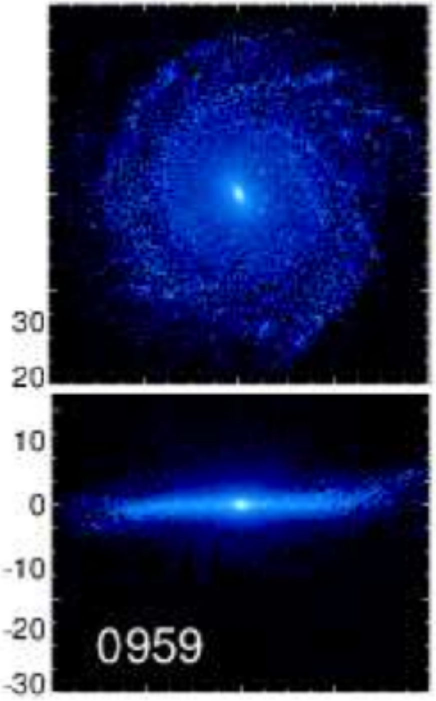


Agertz et al. (2011)

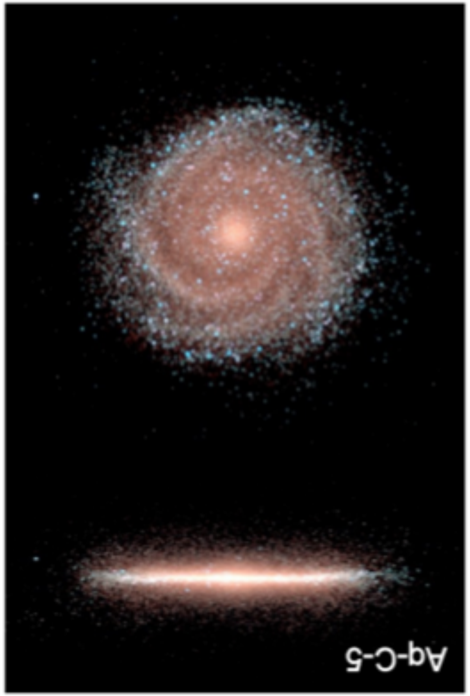
Increasingly realistic galaxies have been obtained in recent years

TOWARDS MILKY WAY GALAXIES OUT OF THE SUPERCOMPUTER

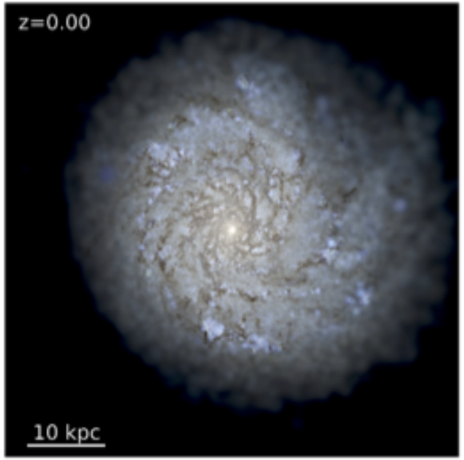
Stinson et al. (2013)



Aumer et al. (2013)



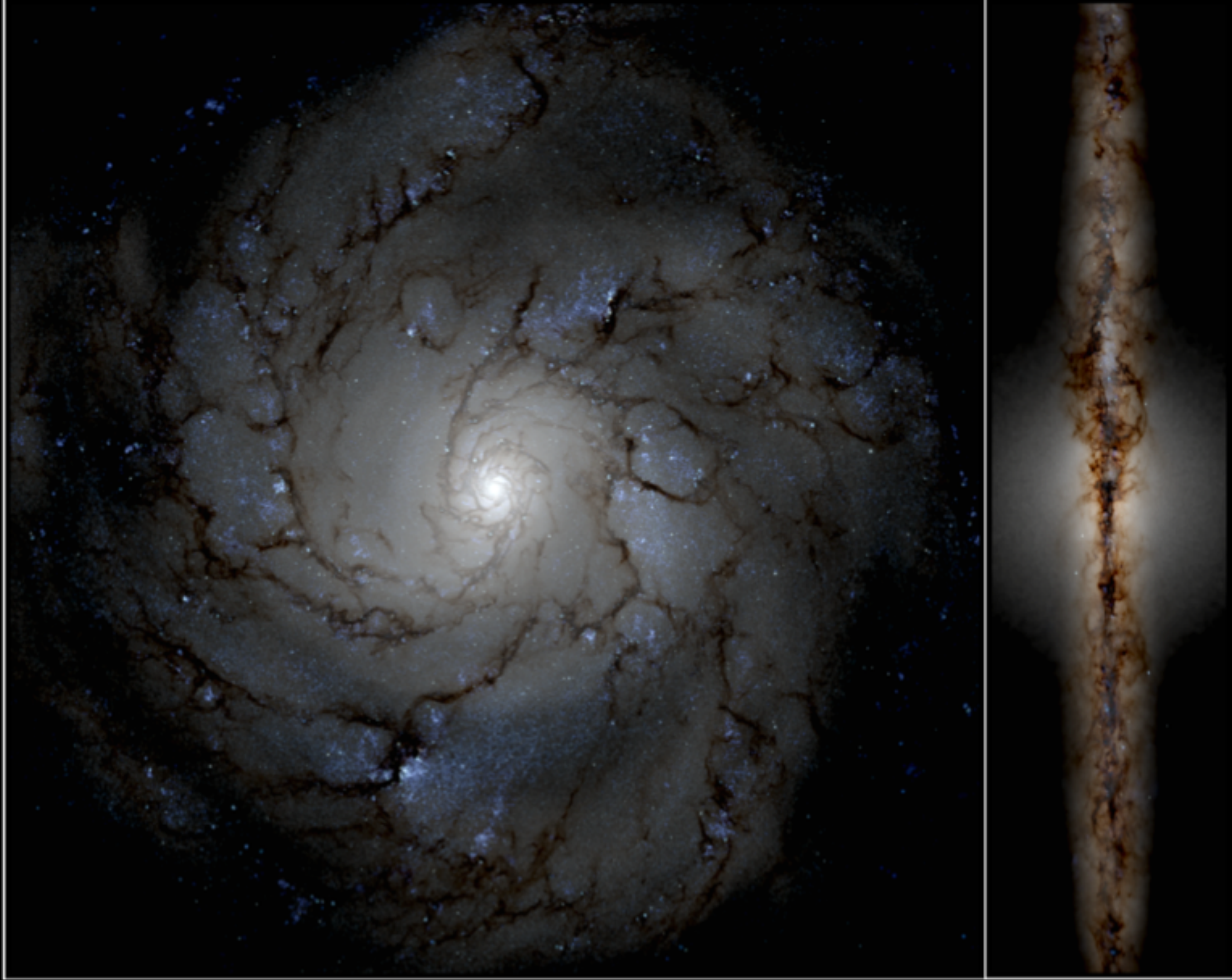
Marinacci et al. (2014)



Hopkins et al. (2014)

Including dust in mock stellar light images of simulated galaxies produces "pretty", visually realistic galaxies

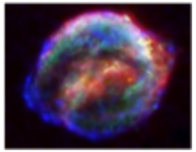
DUSTY IMAGE OF A SMUGGLE GALAXY, ASSUMING CONSTANT DUST-TO-METAL RATIO



Marinacci et al. (2019)

What physics is responsible for regulating star formation?

- Supernova explosions (energy & momentum input)



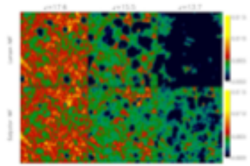
Kepler's Supernova

Bubble Nebula

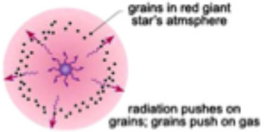
- Stellar winds

- AGN activity

Ciardi al. (2003)

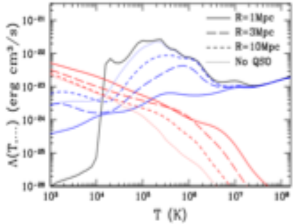


- Radiation pressure on dust

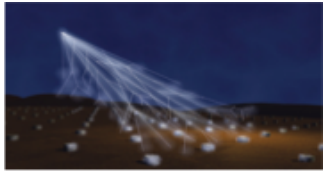


- Photoionizing UV background and Reionization

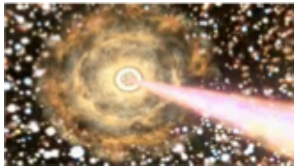
Gneding & Hollon (2012)

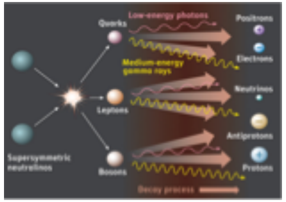


- Modification of cooling through local UV/X-ray flux
- Photoelectric heating



- Cosmic ray pressure
- Magnetic pressure and MHD turbulence





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

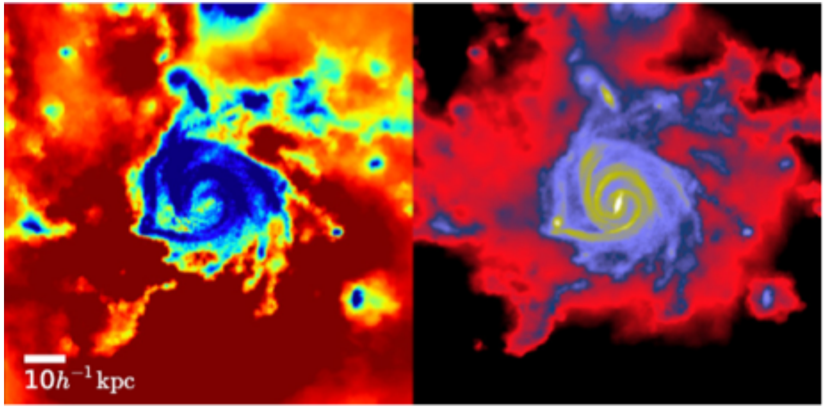
Code accuracy matters despite strong feedback processes

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

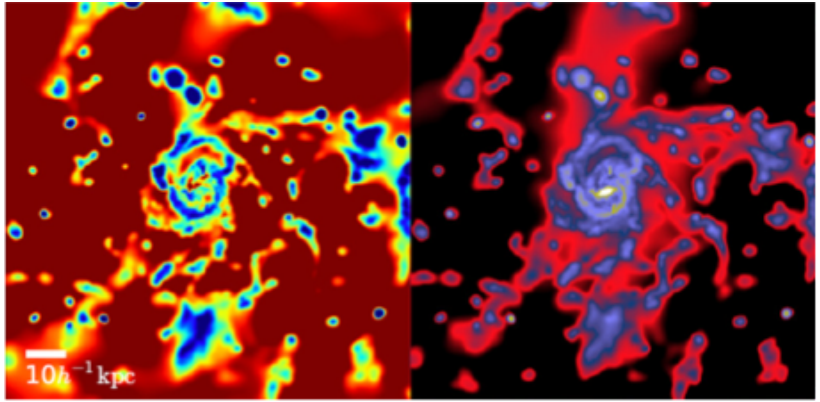
Effects due to feedback are typically stronger than code differences.

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

moving-mesh with AREPO



smoothed particle hydrodymamics with GADGET

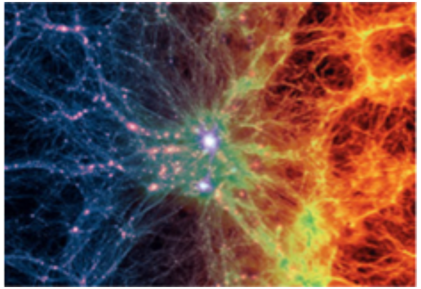


Vogelsberger et al. (2012)

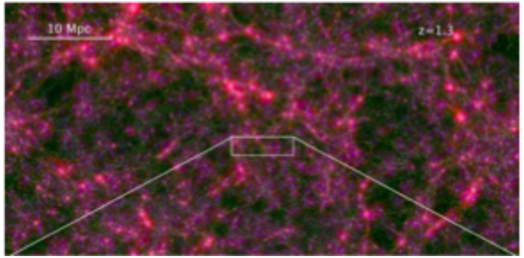
Hydrodynamical cosmological simulations of galaxy formation have made tremendous progress in recent years

AN INCOMPLETE OVERVIEW OF SOME OF THE LARGER PROJECTS

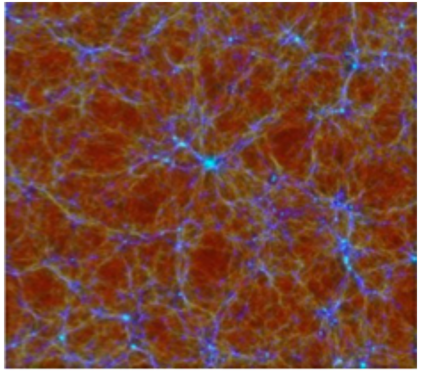
Illustris (Vogelsberger et al. 2014)



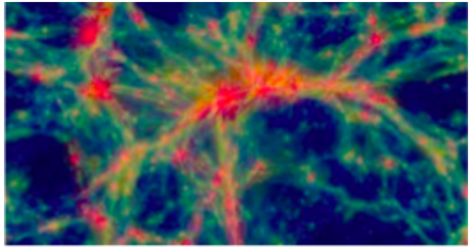
Horizon-AGN (Dubois et al. 2014)



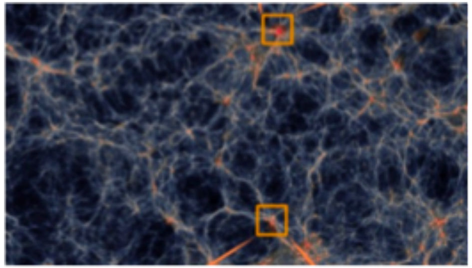
Magneticum (Dolag et al. 2014)



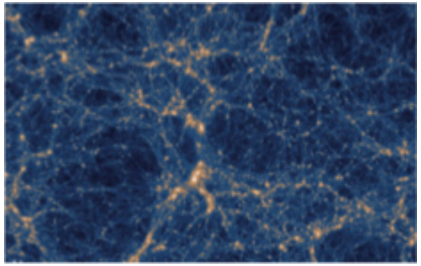
EAGLE (Schaye et al. 2015)



MassiveBlack II (Khandai et al. 2015)

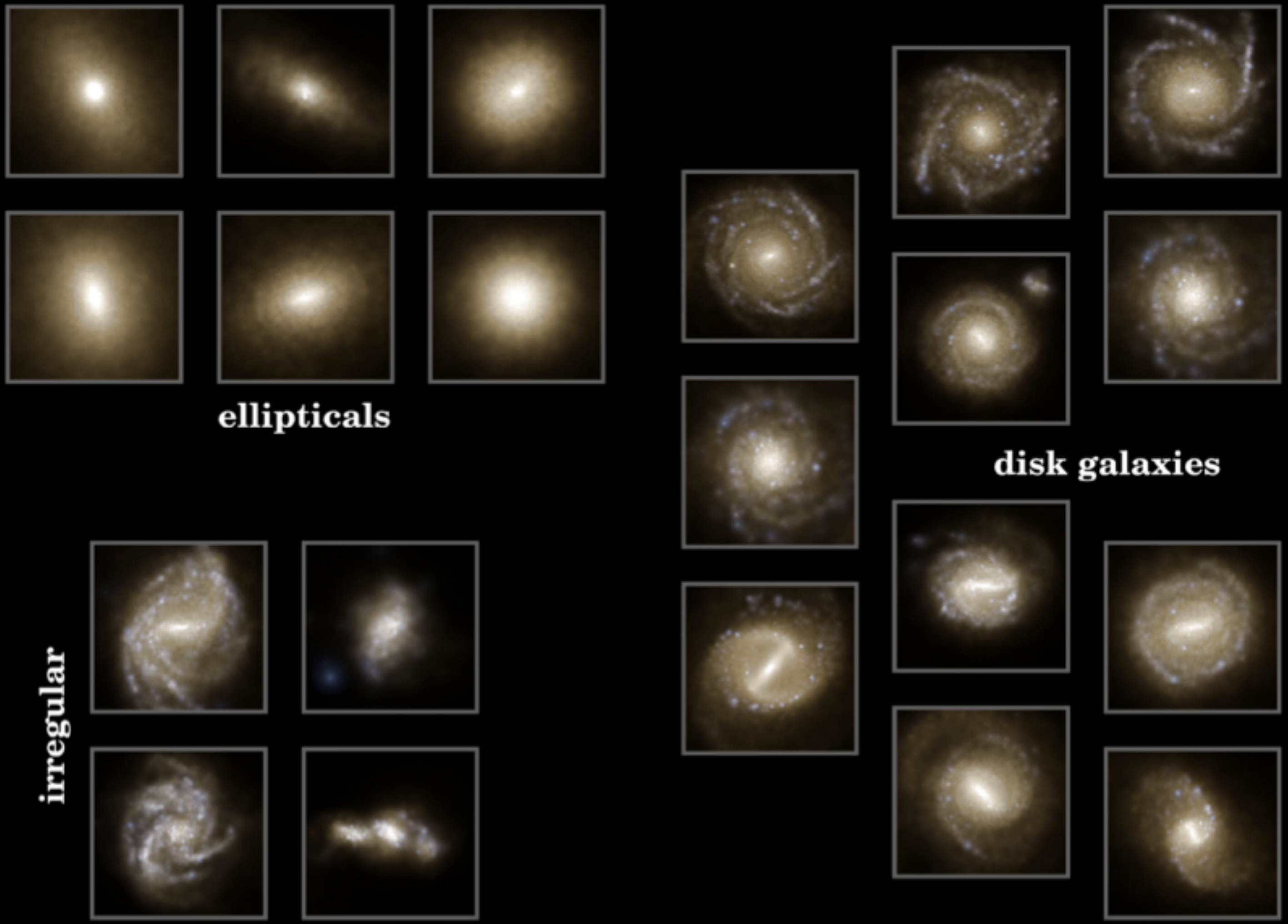


TNG (Illustris Collaboration 2017)



The Illustris simulation reproduces the morphological mix of galaxies

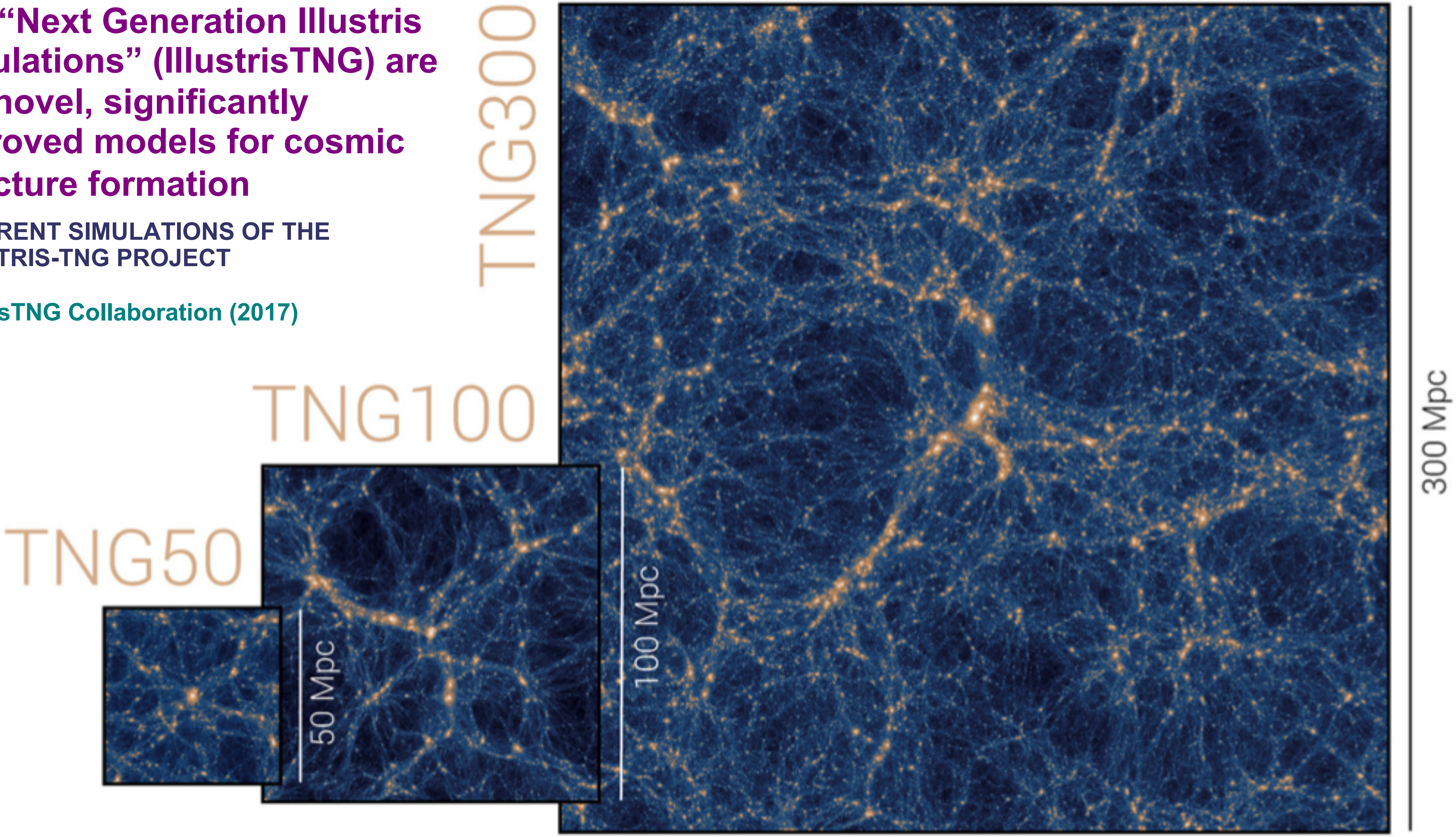
SIMULATED HUBBLE TUNING FORK DIAGRAM



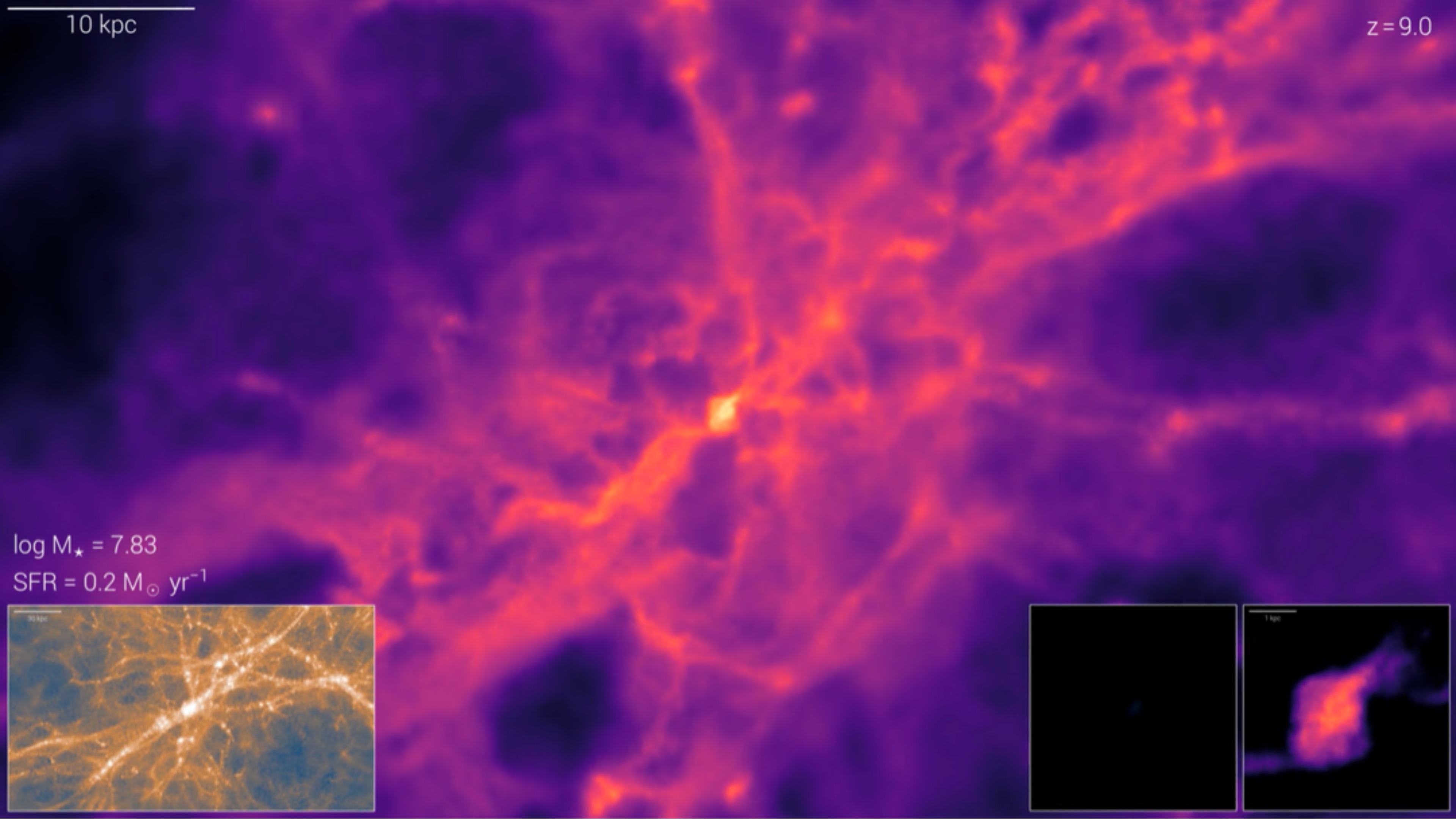
The "Next Generation Illustris Simulations" (IllustrisTNG) are our novel, significantly improved models for cosmic structure formation

DIFFERENT SIMULATIONS OF THE ILLUSTRIS-TNG PROJECT

IllustrisTNG Collaboration (2017)



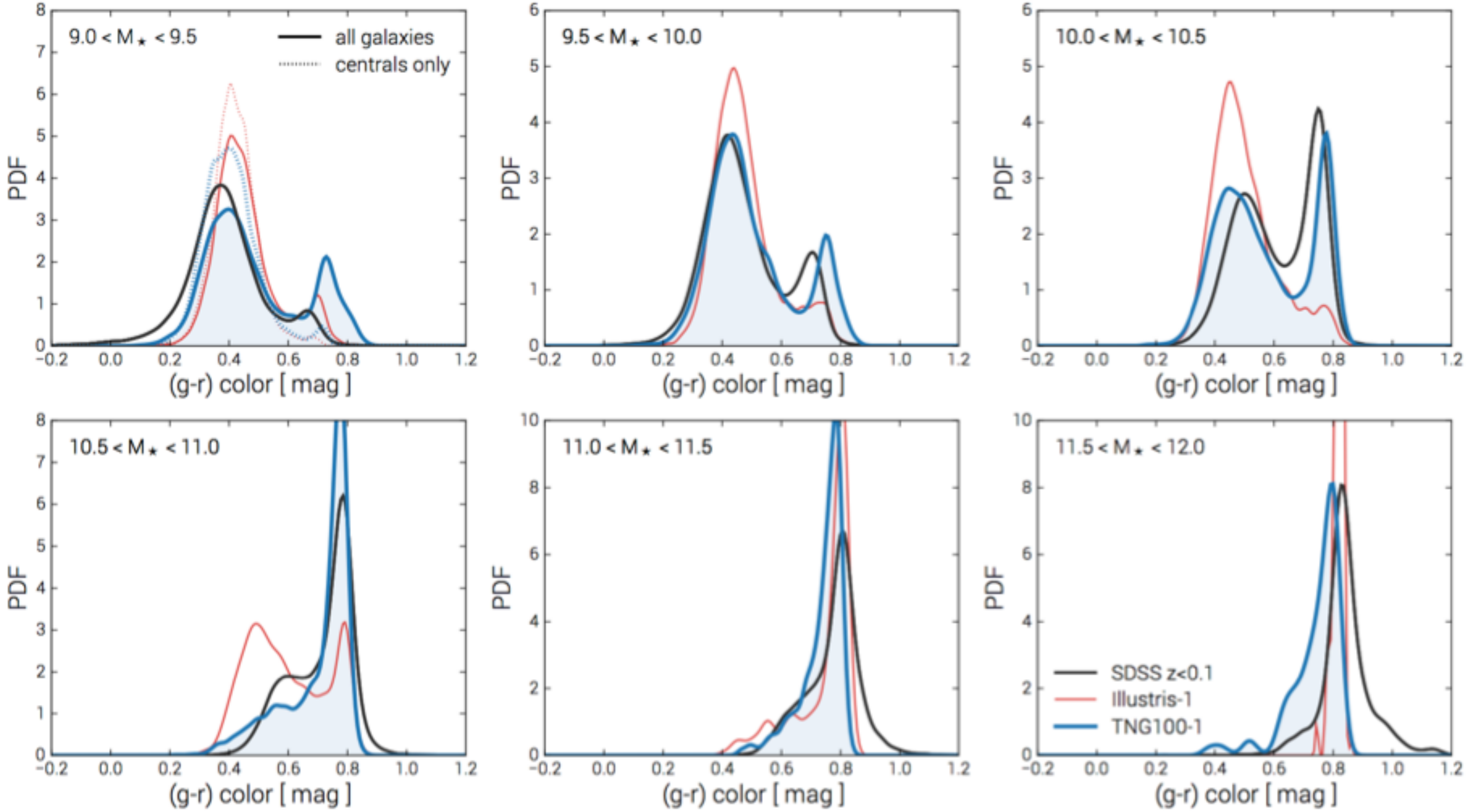
HazelHen, 7.4 Pflops
HLRS Stuttgart


10 kpc
z = 9.0
log $M_\star$ = 7.83
SFR = 0.2 $M_\odot$ yr^{-1}

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

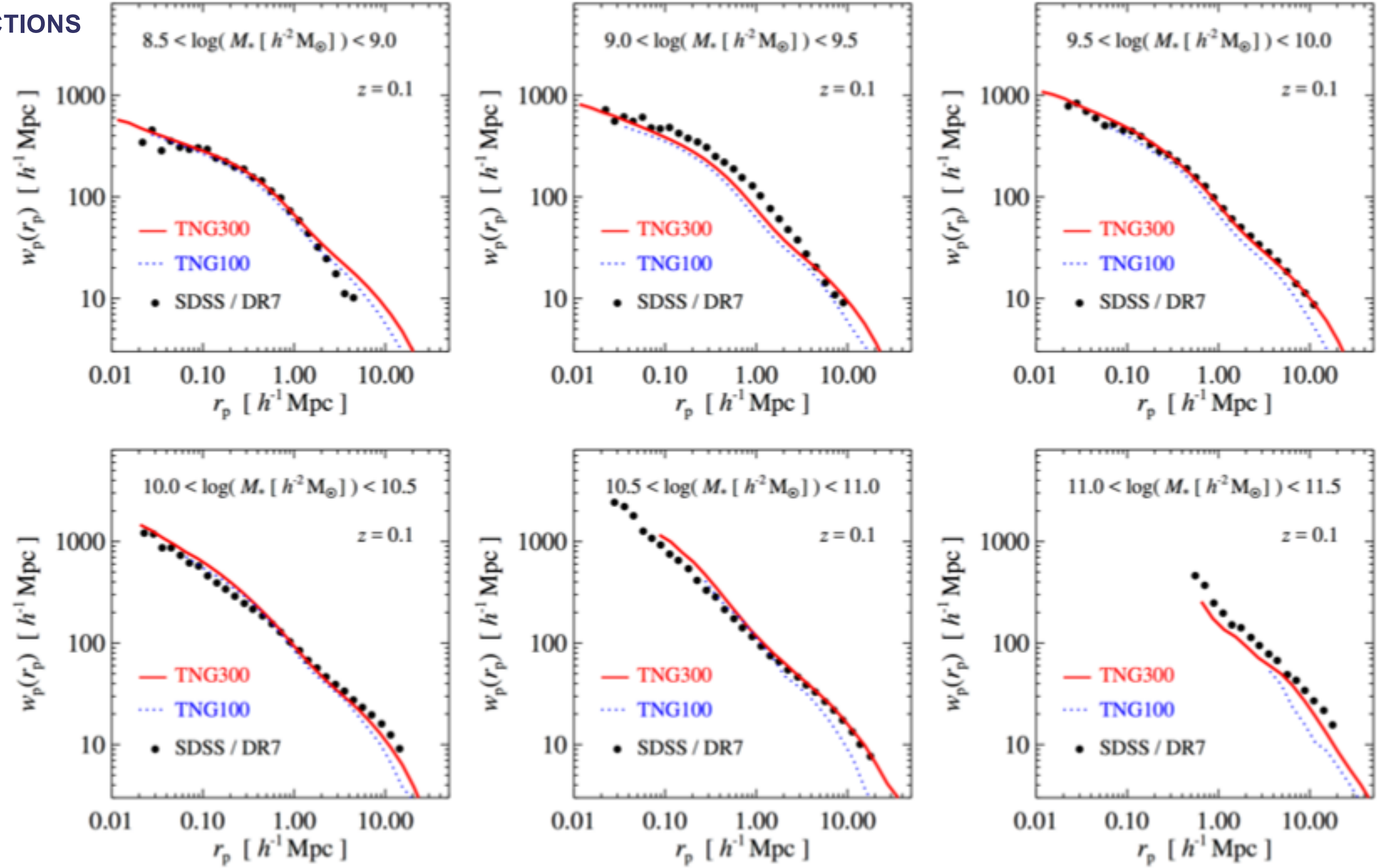
COLOR DISTRIBUTION OF GALAXIES OF DIFFERENT MASS COMPARED TO SDSS

Nelson et al. (2017)



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

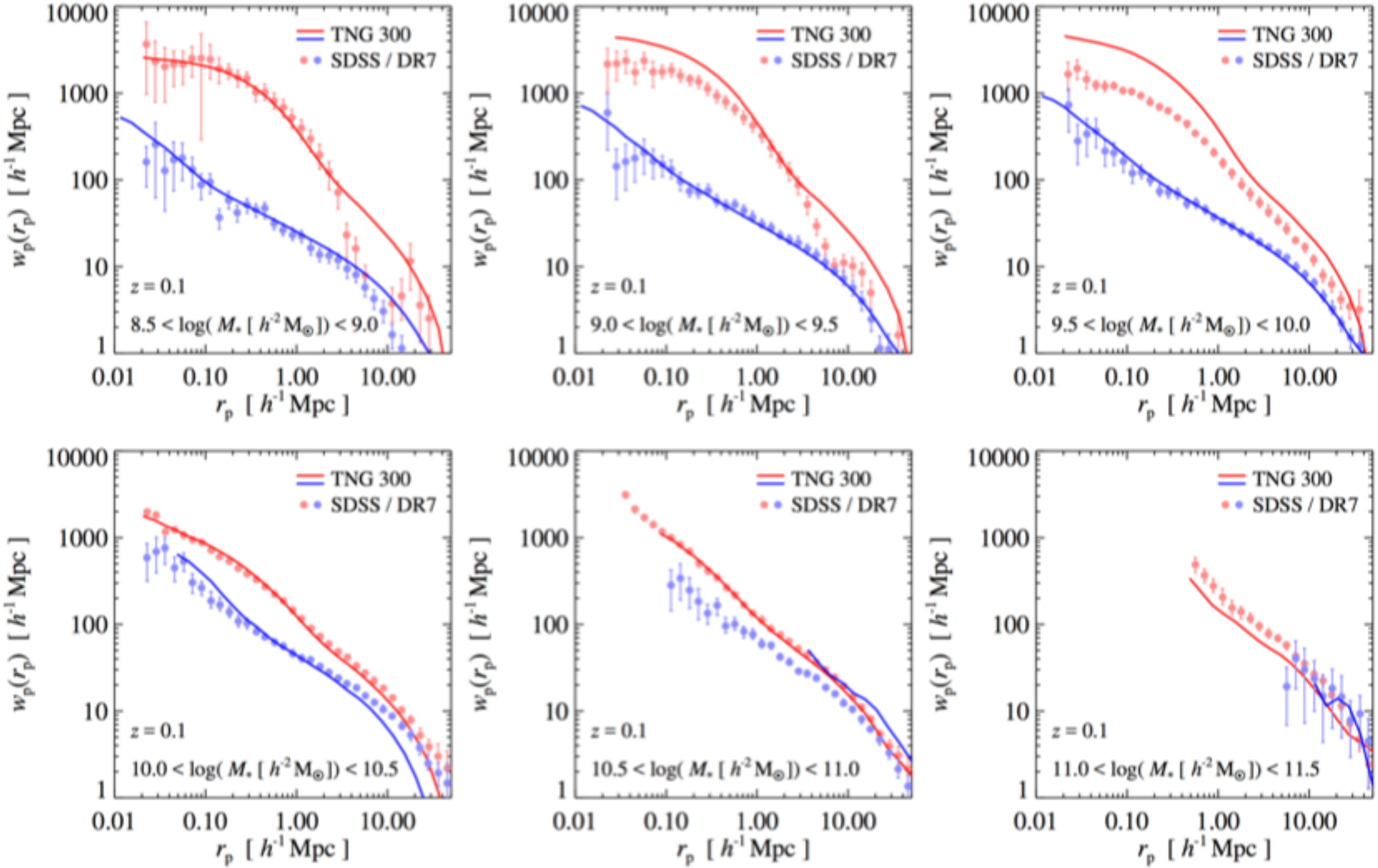
PROJECTED TWO-POINT FUNCTIONS IN DIFFERENT MASS BINS



Springel et al. (2018)

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

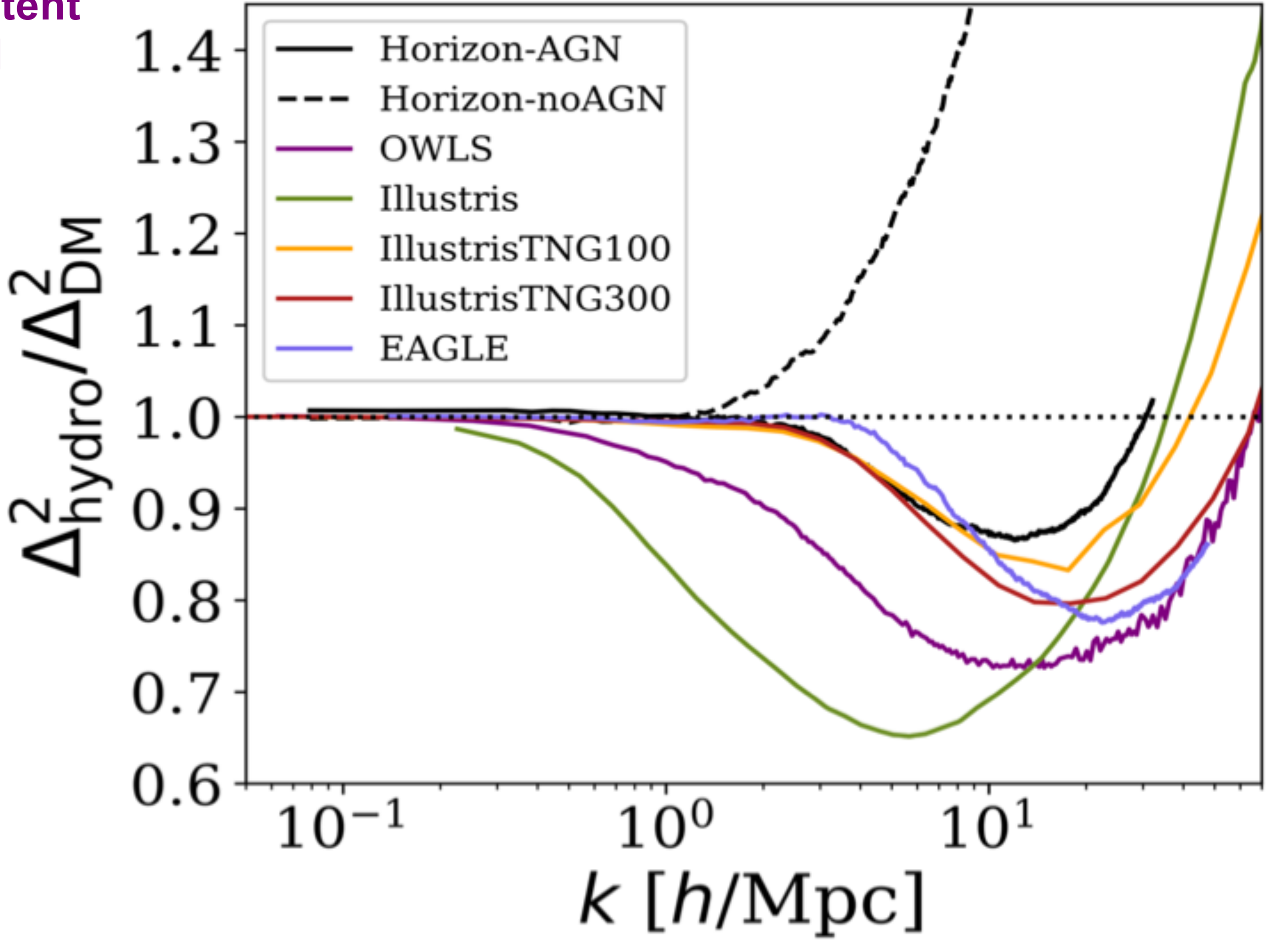
CLUSTERING IN DIFFERENT MASS AND COLOR BINS COMPARED TO SDSS



Springel et al. (2018)

Newer hydrodynamic models predict a reasonably consistent size of the influence of AGN feedback

COMPARISON OF BARYONIC IMPACT IN DIFFERENT HYDRO SIMULATIONS

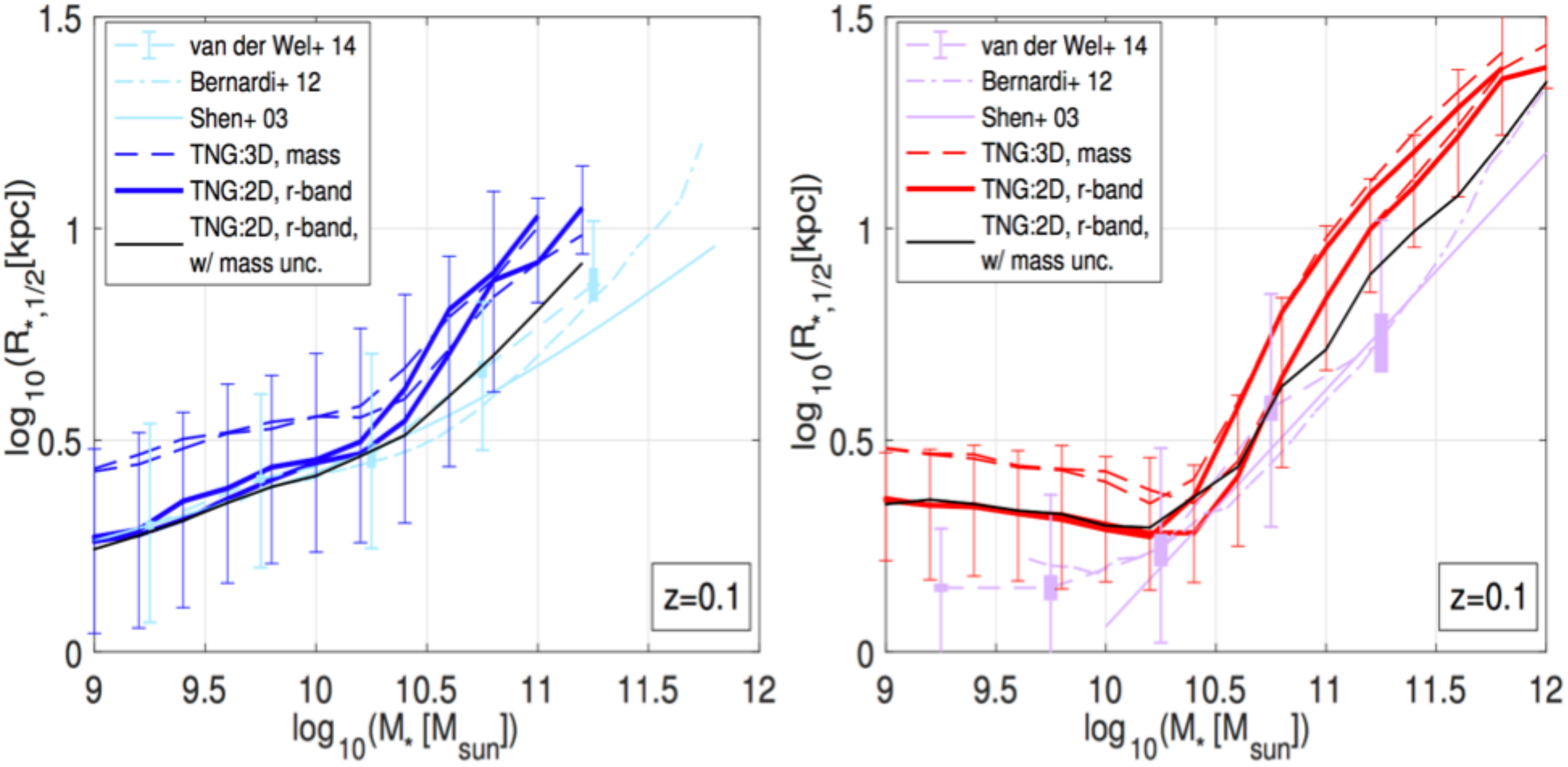


Chisari et al. (2018)

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

ILLUSTRIS-TNG GALAXY SIZES AS A FUNCTION OF STELLAR MASS

Genel et al. (2018)



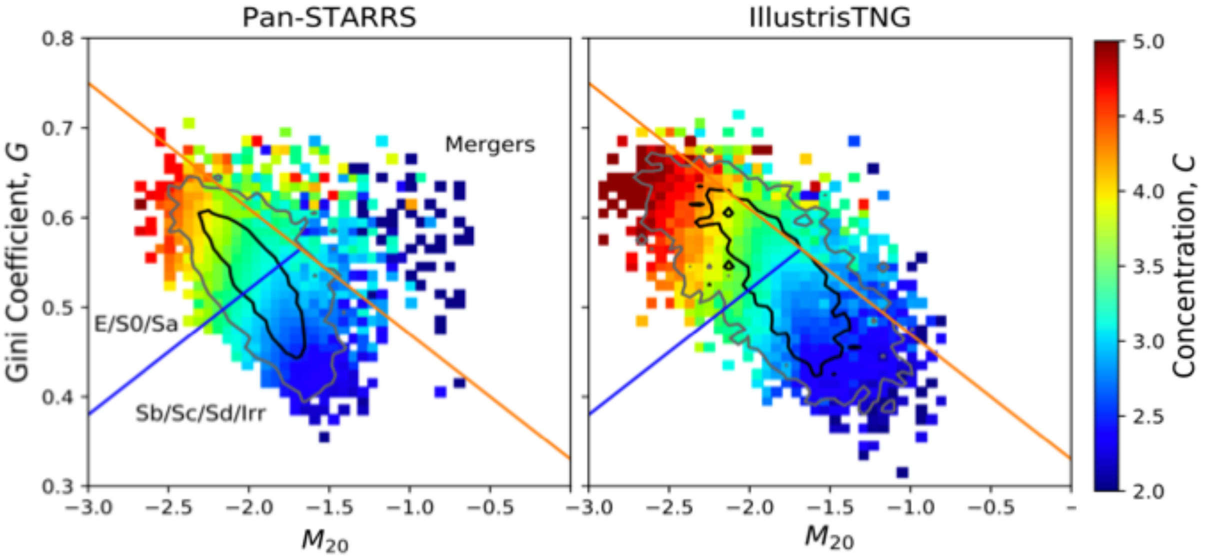
(a) Main-sequence / late-type galaxies

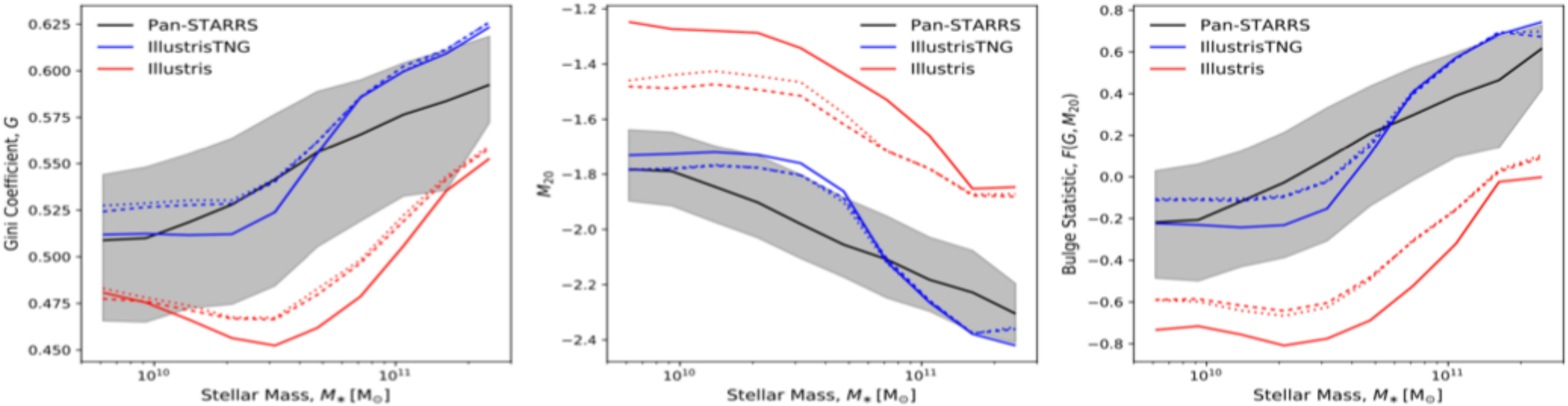
(b) Quenched / early-type galaxies

Various morphological indicators yield good agreement between TNG and Pan-STARRS

GINI, CONCENTRATION, BULGE-SIZE

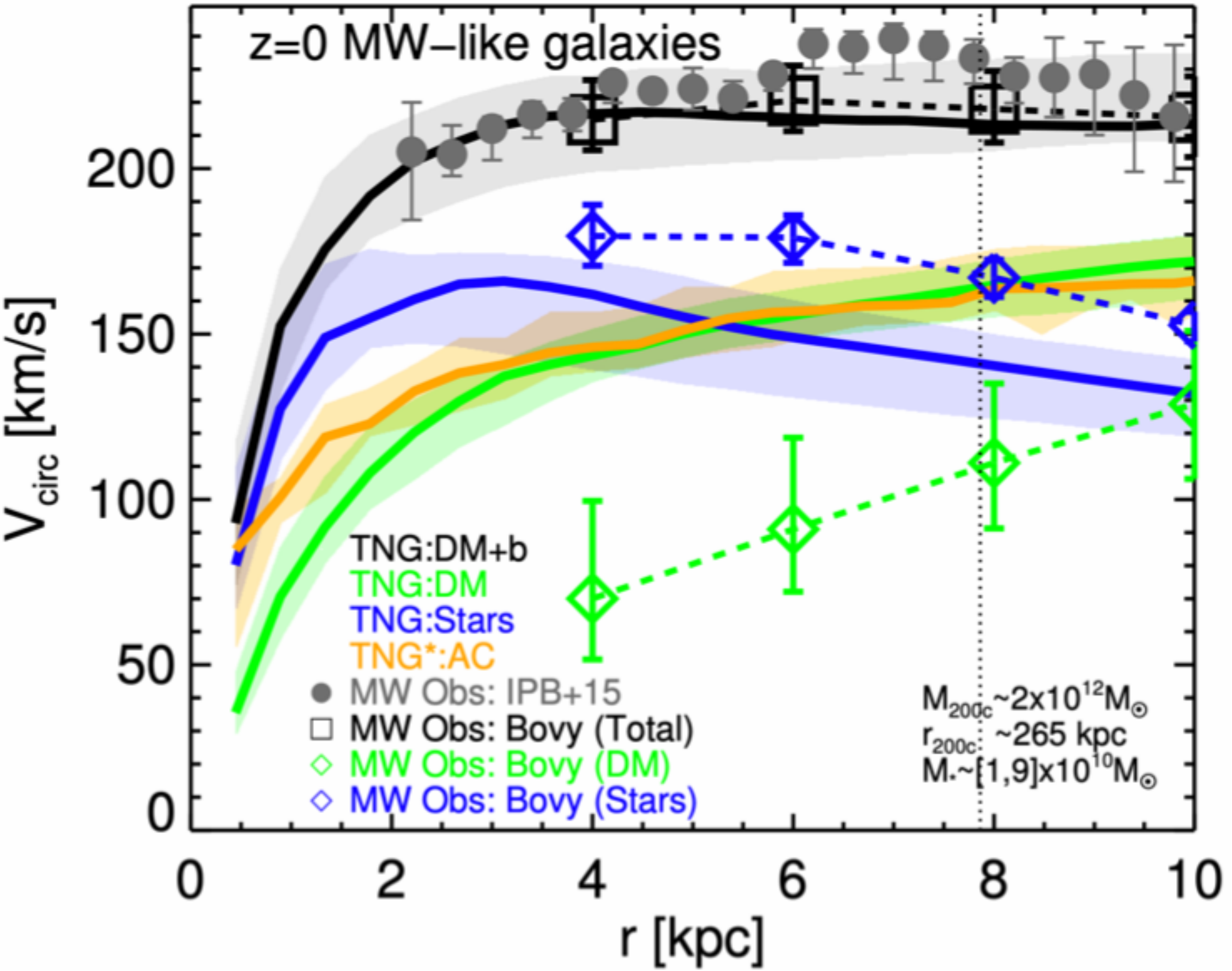
Rodriguez-Gomez et al. (2018)





Milky Way-like galaxies in LCDM reproduce observed rotation curves, but have high dark matter fractions

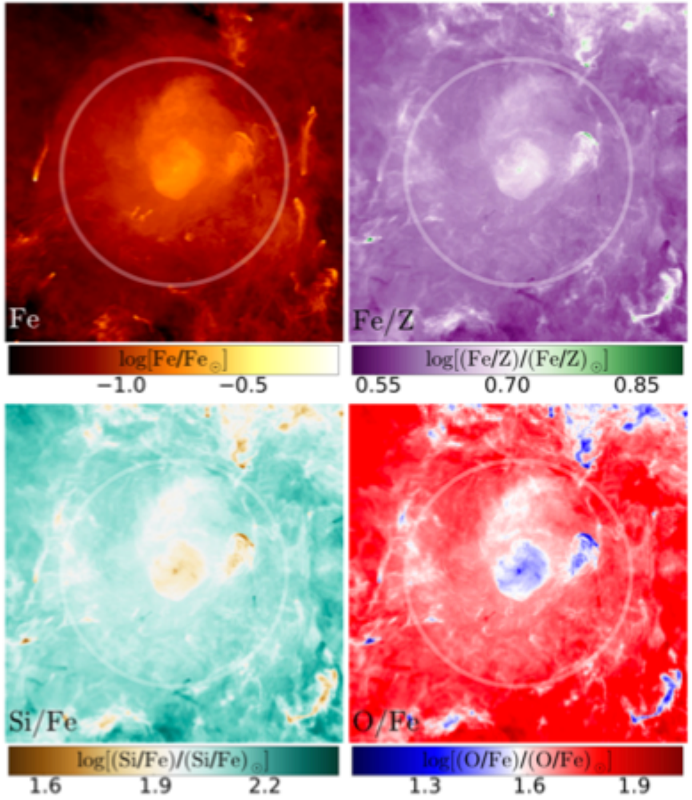
STACKED ROTATION CURVES IN ILLUSTRIS-TNG COMPARED TO DATA FOR MILKY-WAY(s)

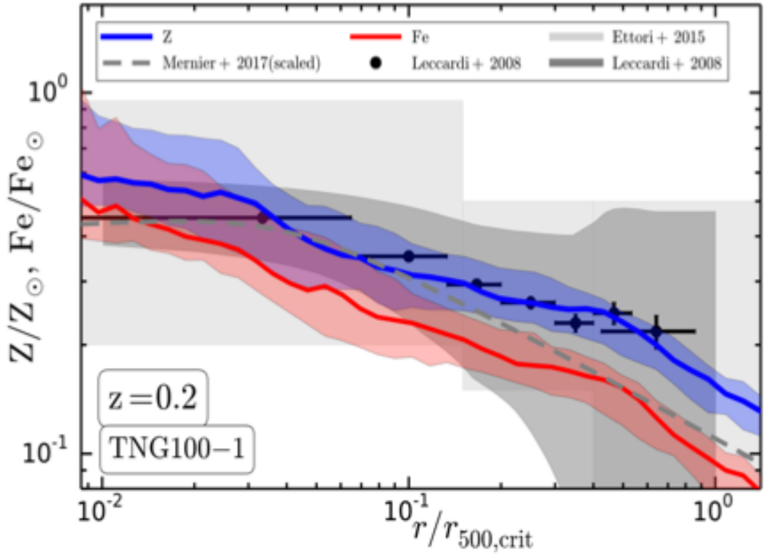


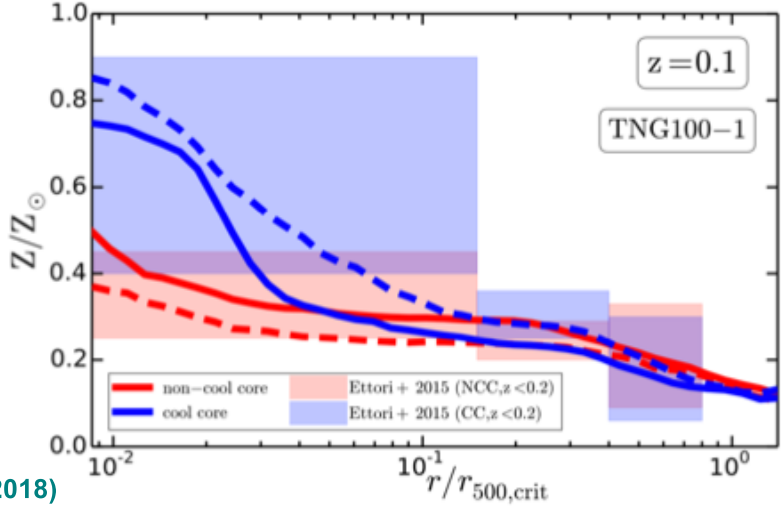
Lovell et al. (2018)

Observed metallicity profiles of galaxy clusters are reproduced by IllustrisTNG

METALLICITY MAPS AND PROFILES OF GALAXY CLUSTERS





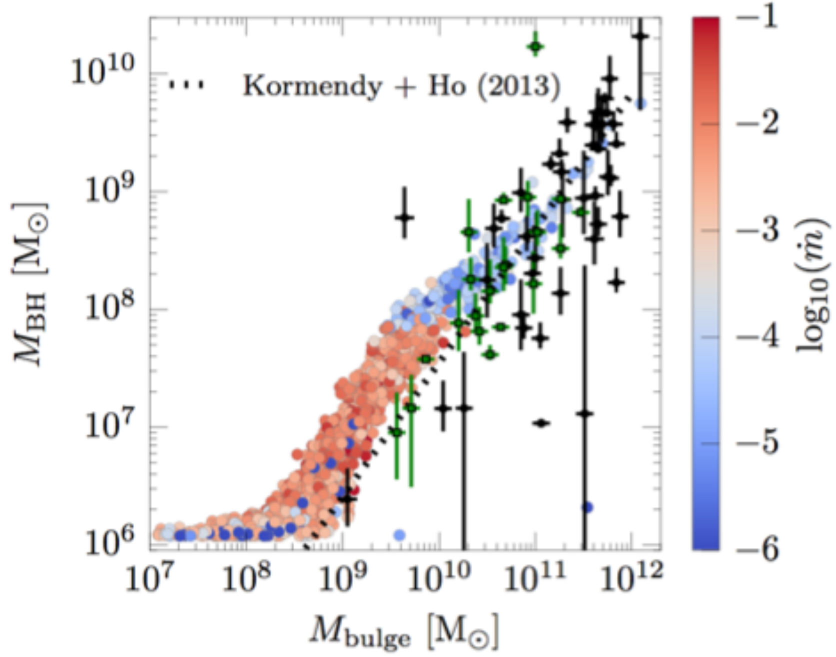


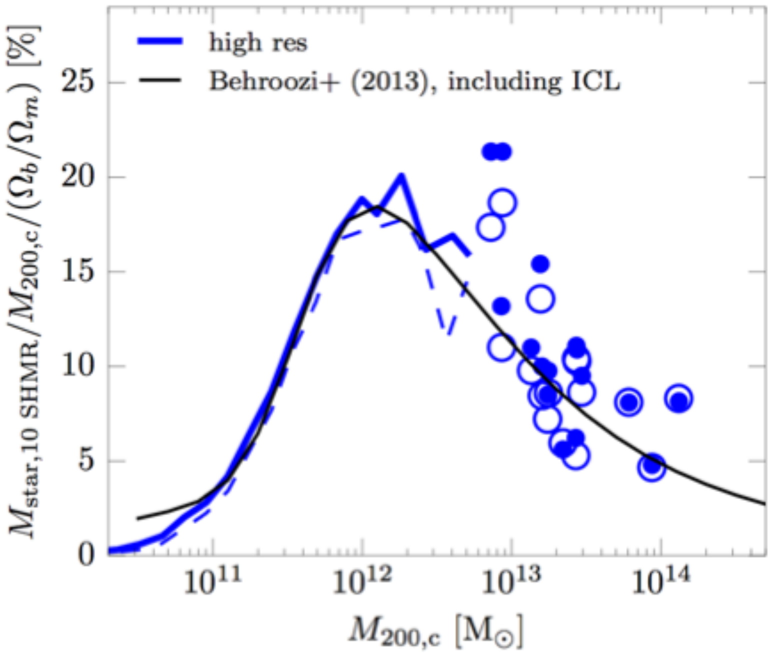
Vogelsberger et al. (2018)

What you put in is
what you get

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

IMPACT OF THE ILLUSTRIS-TNG AGN MODEL



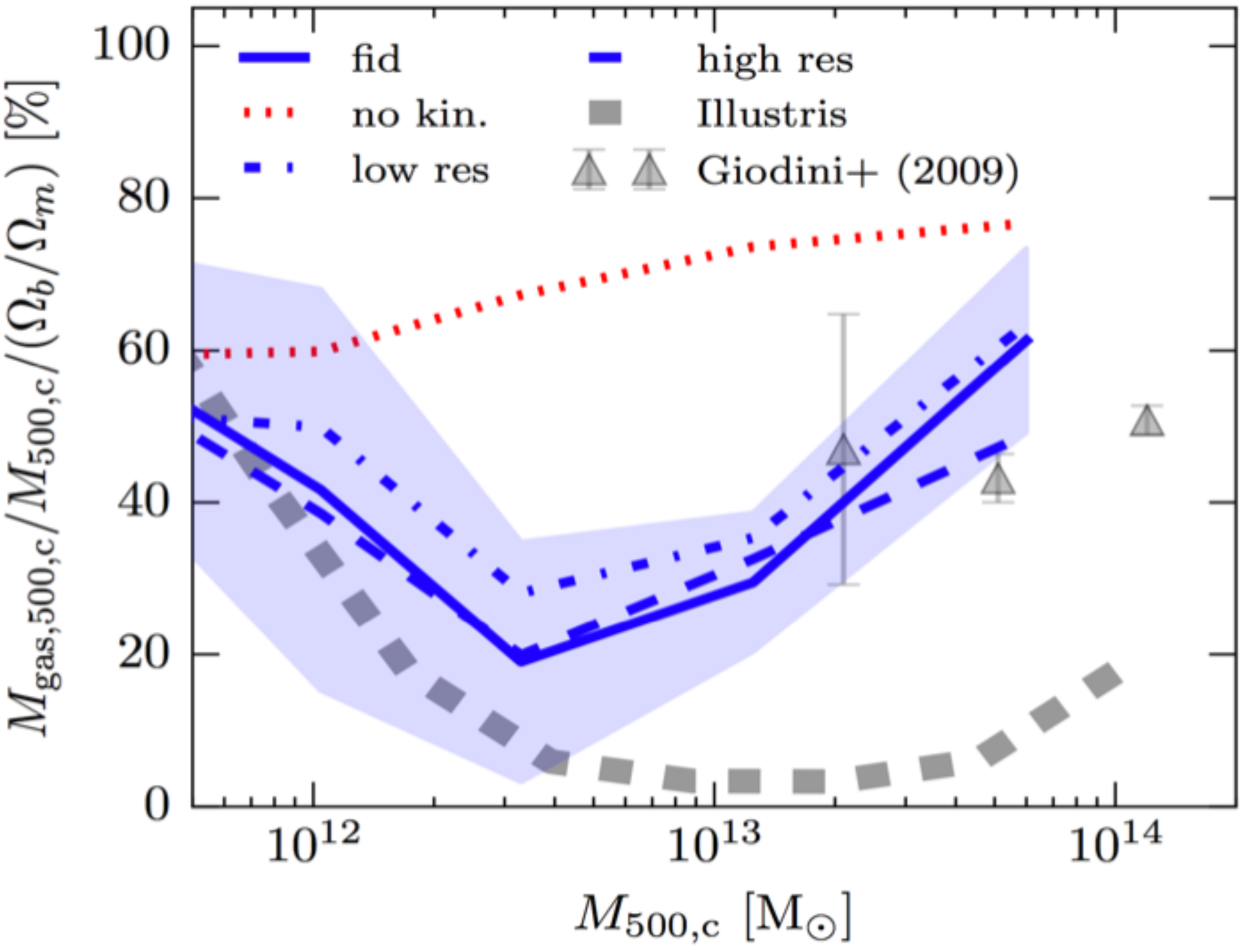


We obtain **sudden** quenching, setting in at around $M_* \sim 2 \times 10^{10}$ M_{sun}

Weinberger et al. (2017)

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

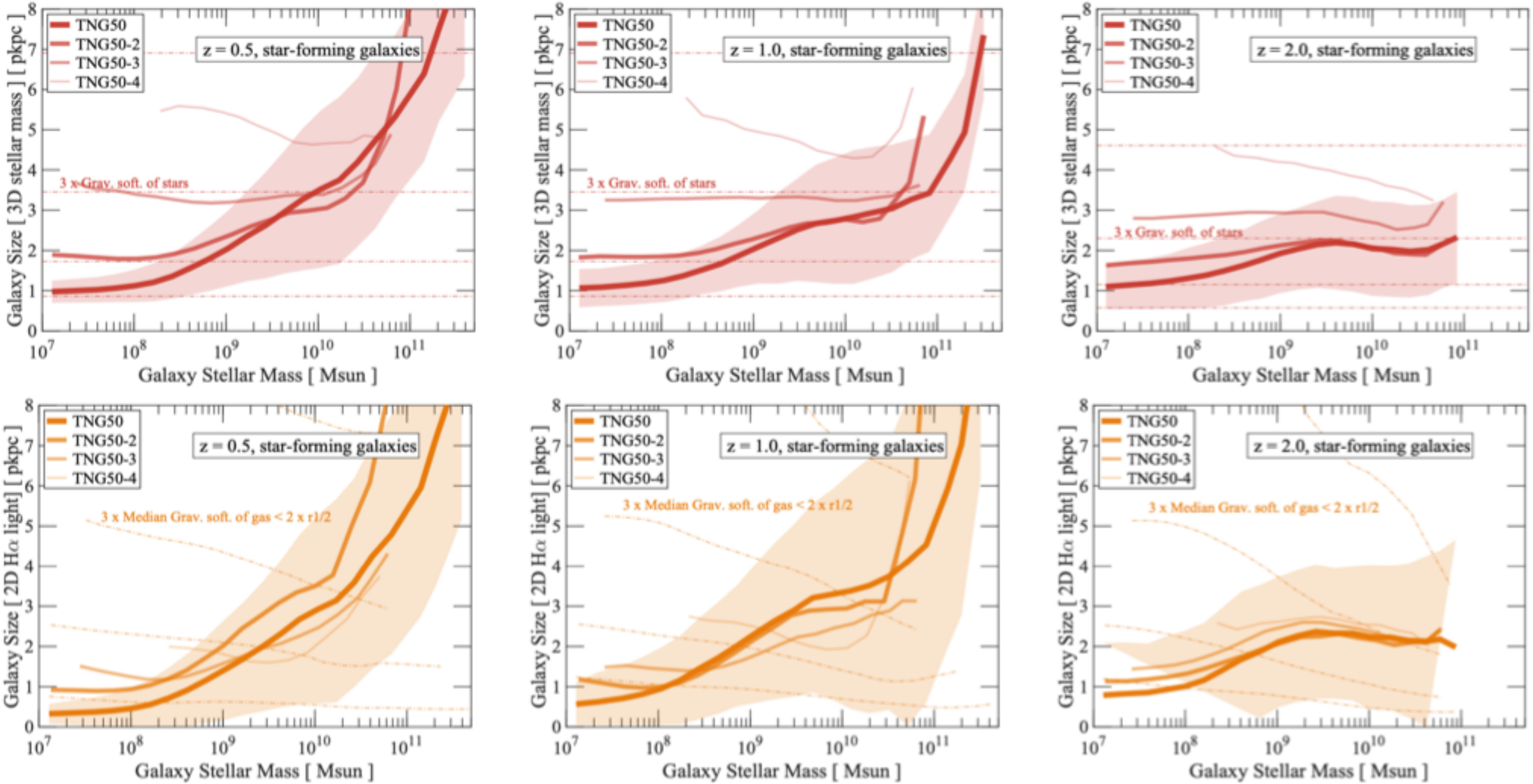


Weinberger et al. (2017)

Systematic resolution studies can establish fiducial converged results

GALAXY SIZES IN TNG AS A FUNCTION OF NUMERICAL RESOLUTION AND STELLAR MASS

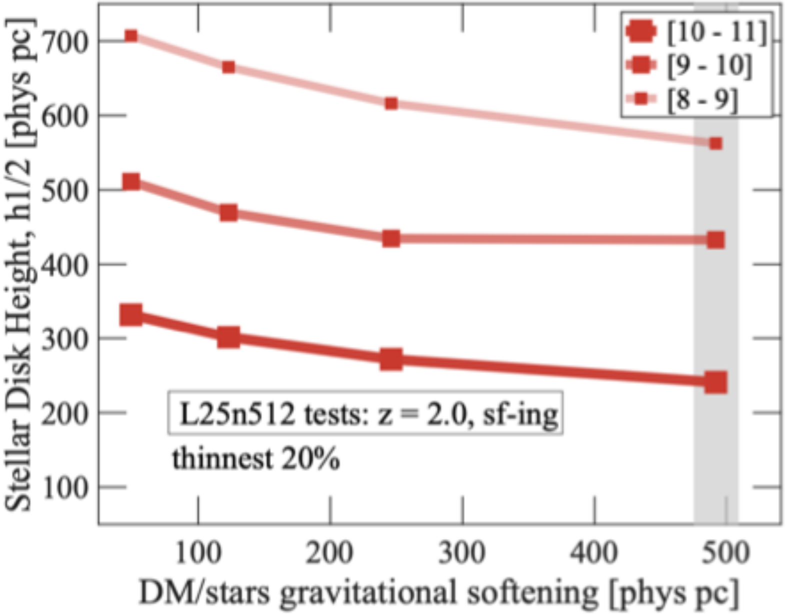
Pillepich et al. (2018)

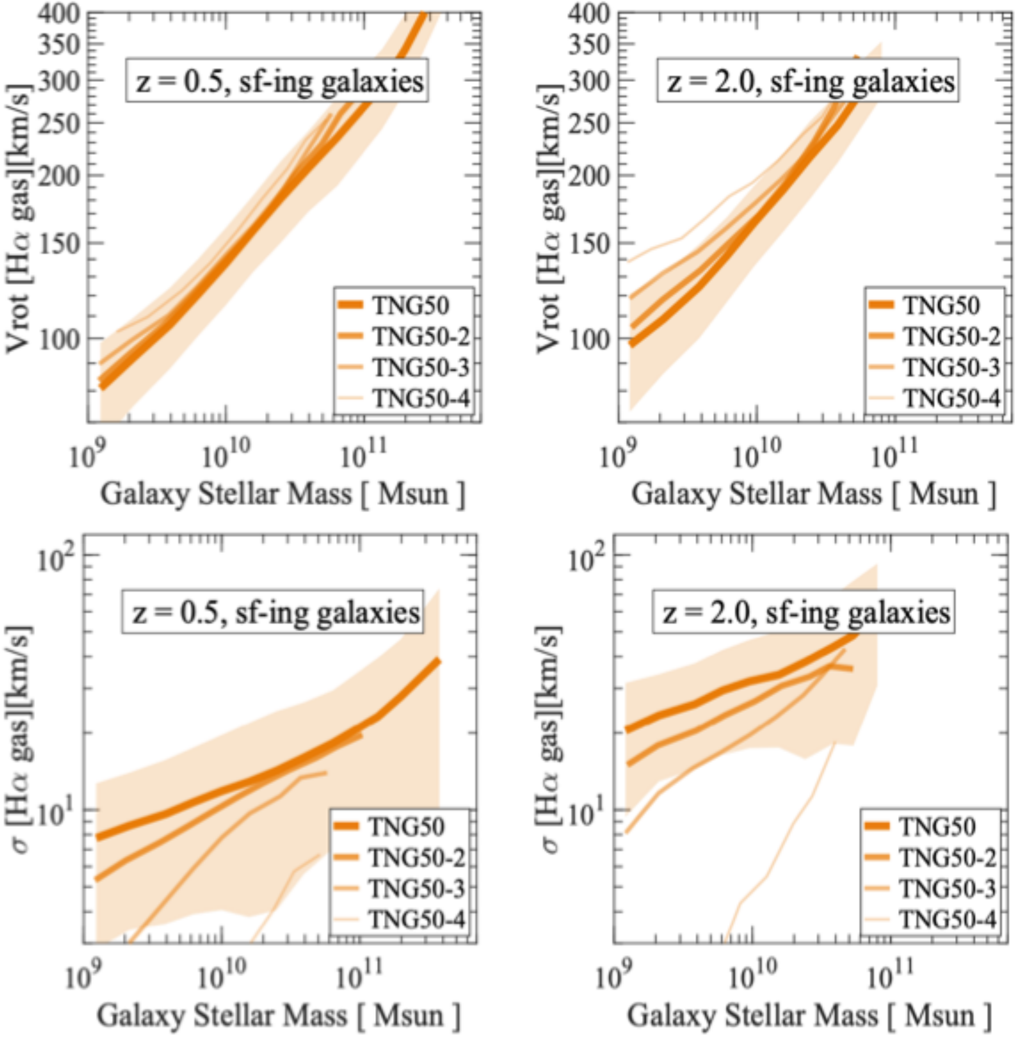


Galaxy kinematics converges reasonably well, but disk heights are hard

RESOLUTION TESTS WITHIN TNG

Pillepich et al. (2018)

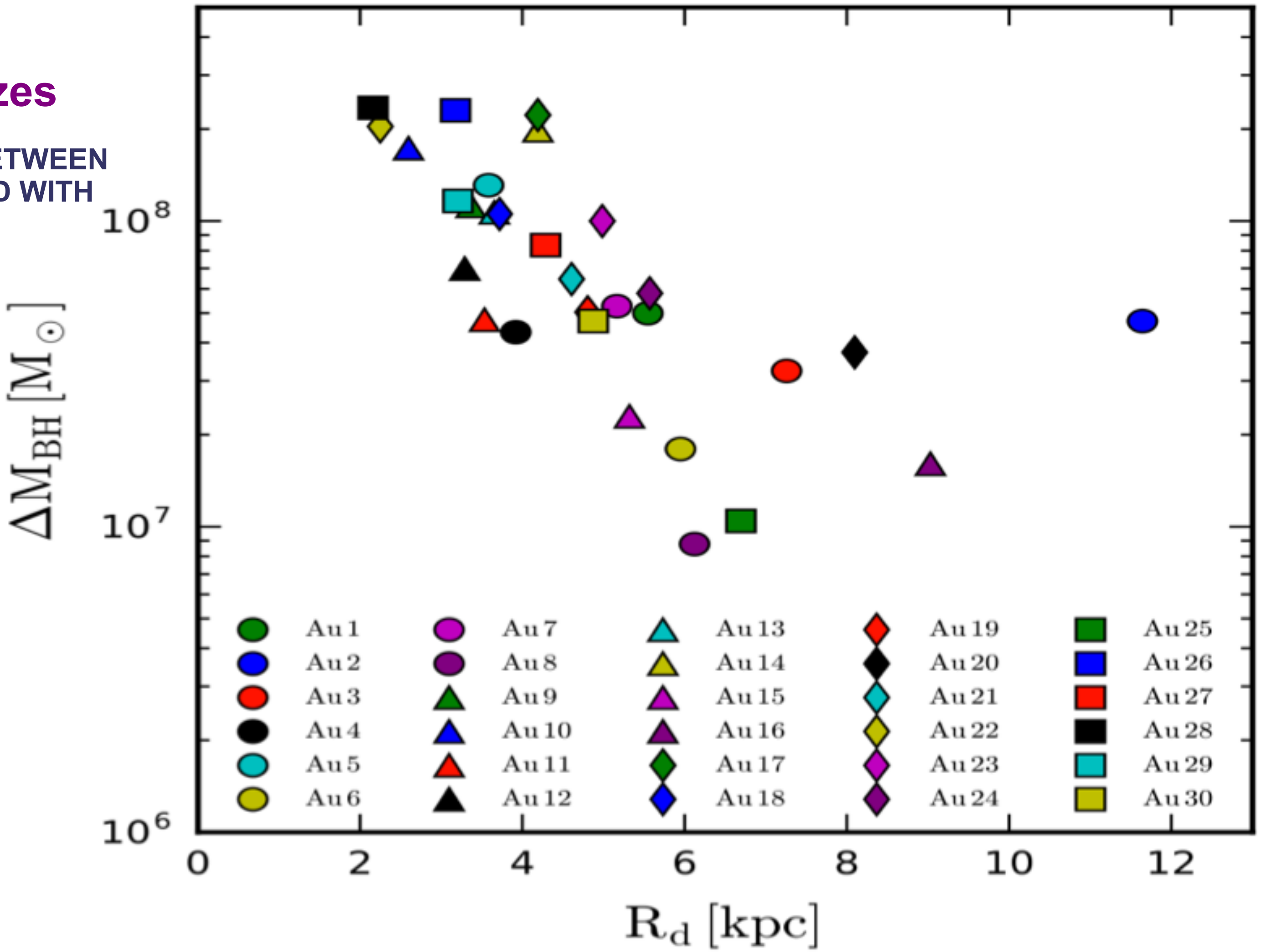




The best: testable new predictions from simulations

Black hole growth influences disk sizes

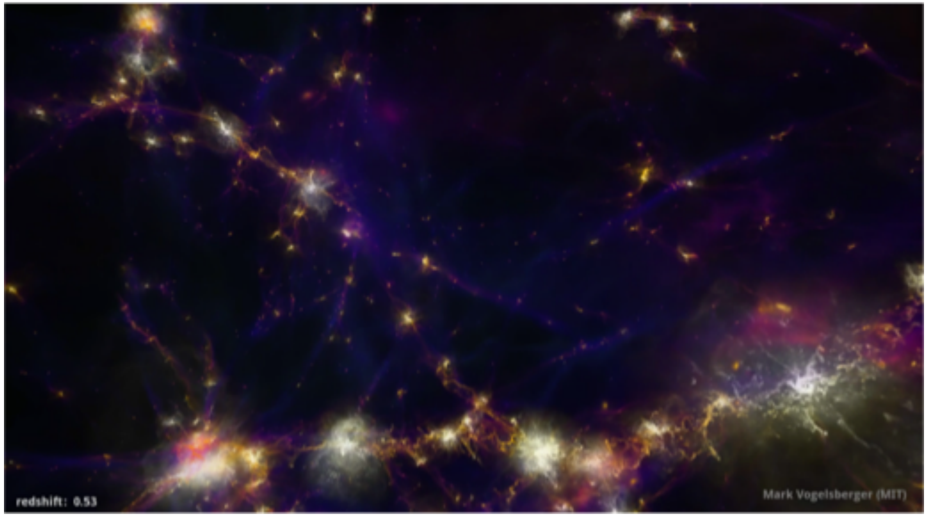
BLACK HOLE GROWTH BETWEEN Z=1 AND Z=0 CORRELATED WITH DISK SCALE LENGTHS

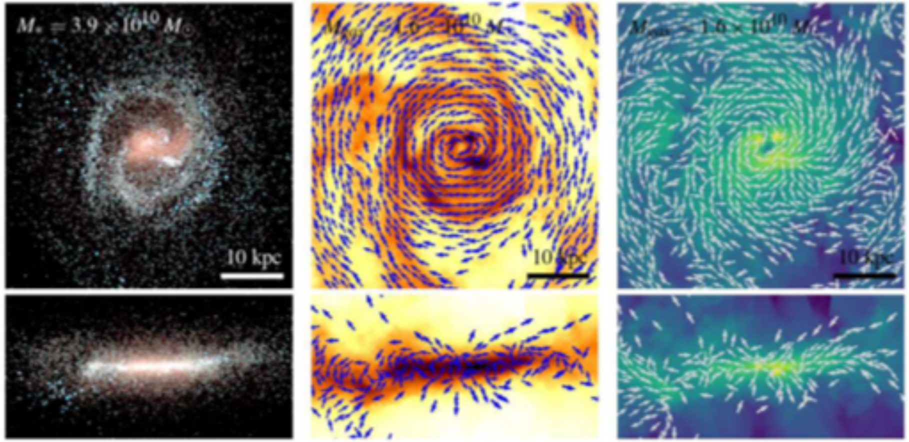


Grand et al. (2016)

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

MAGNETIC FIELD STRENGTH IN ILLUSTRIS-TNG

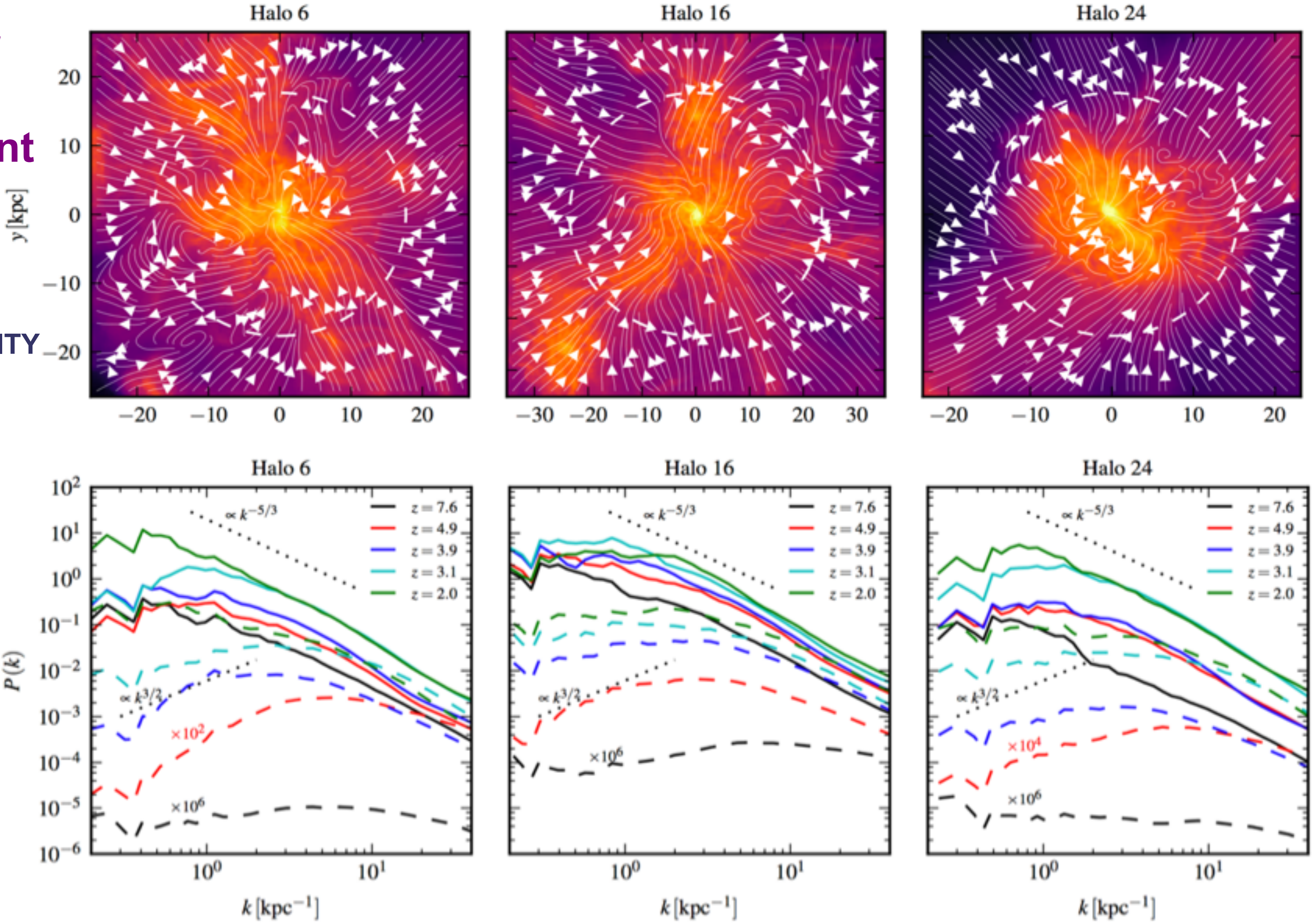




Marinacci et al. (2018)

Amplification of B-field occurs through turbulent small-scale dynamo

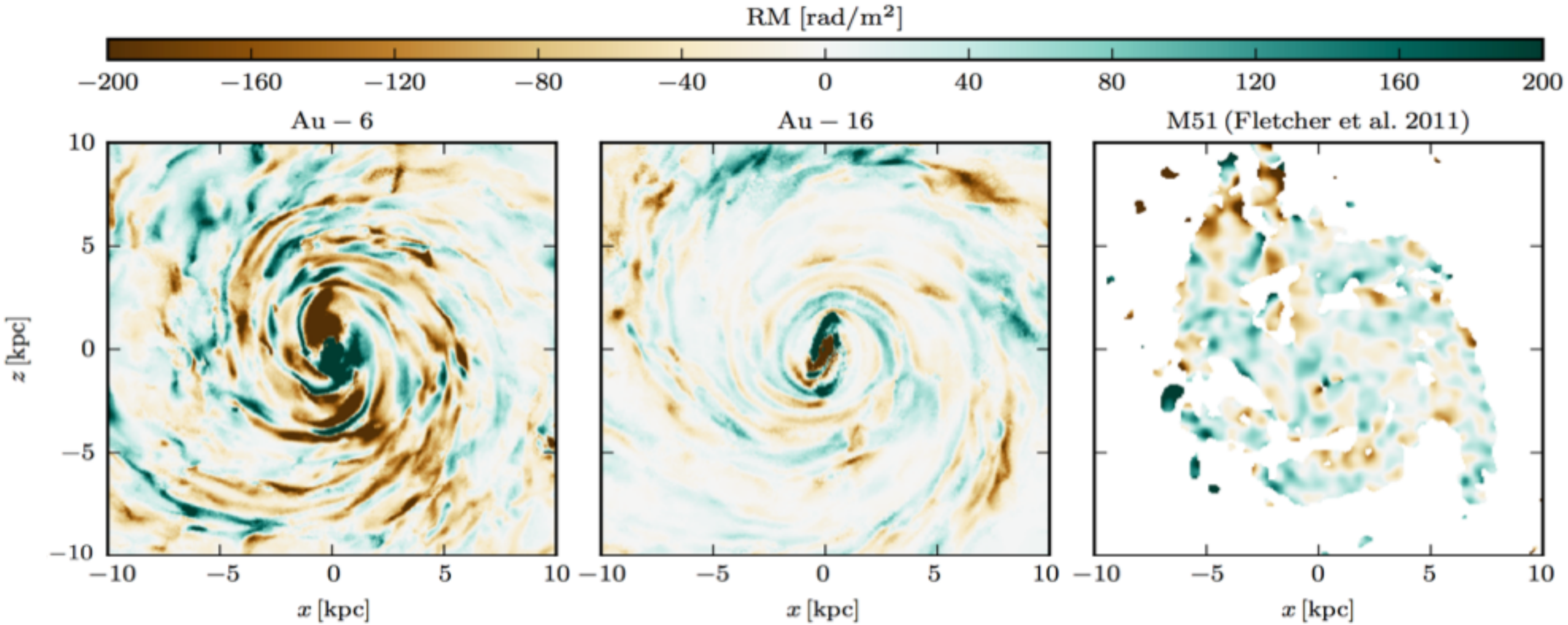
VELOCITY FIELD AND EVOLUTION OF VELOCITY AND B-FIELD POWER SPECTRA



Pakmor et al. (2017)

Faraday rotation maps provide one of the best ways to observationally probe the magnetic field in galaxies

COSMOLOGICAL PREDICTIONS FROM AURIGA COMPARED TO OBSERVATIONS OF M51

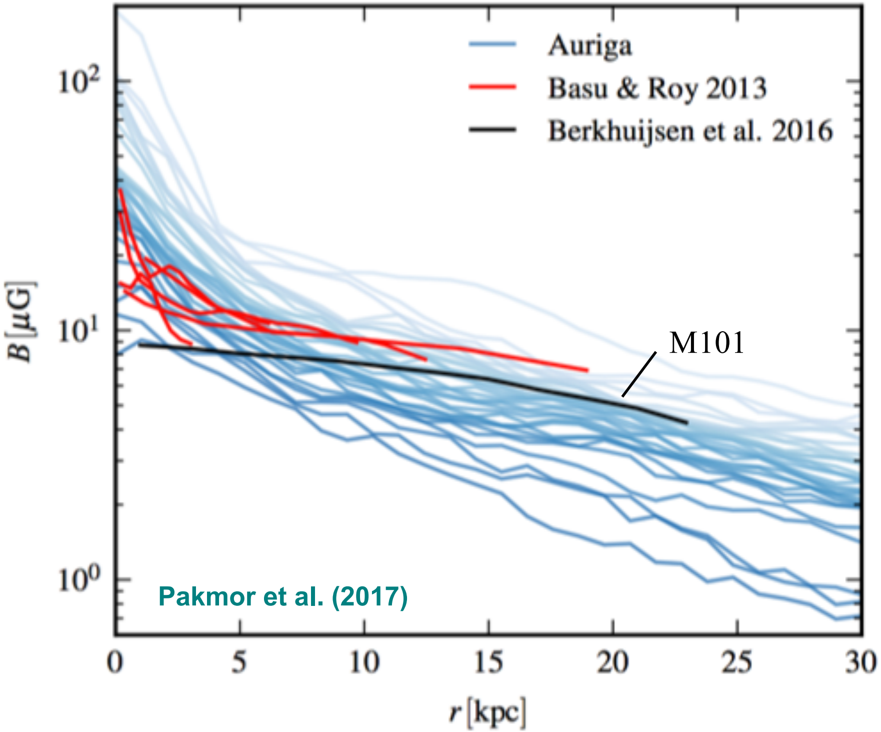


$$RM = \frac{e^3}{2\pi m_e^2 c^3} \int n_e(l) \vec{B}(l) \cdot d\vec{l},$$

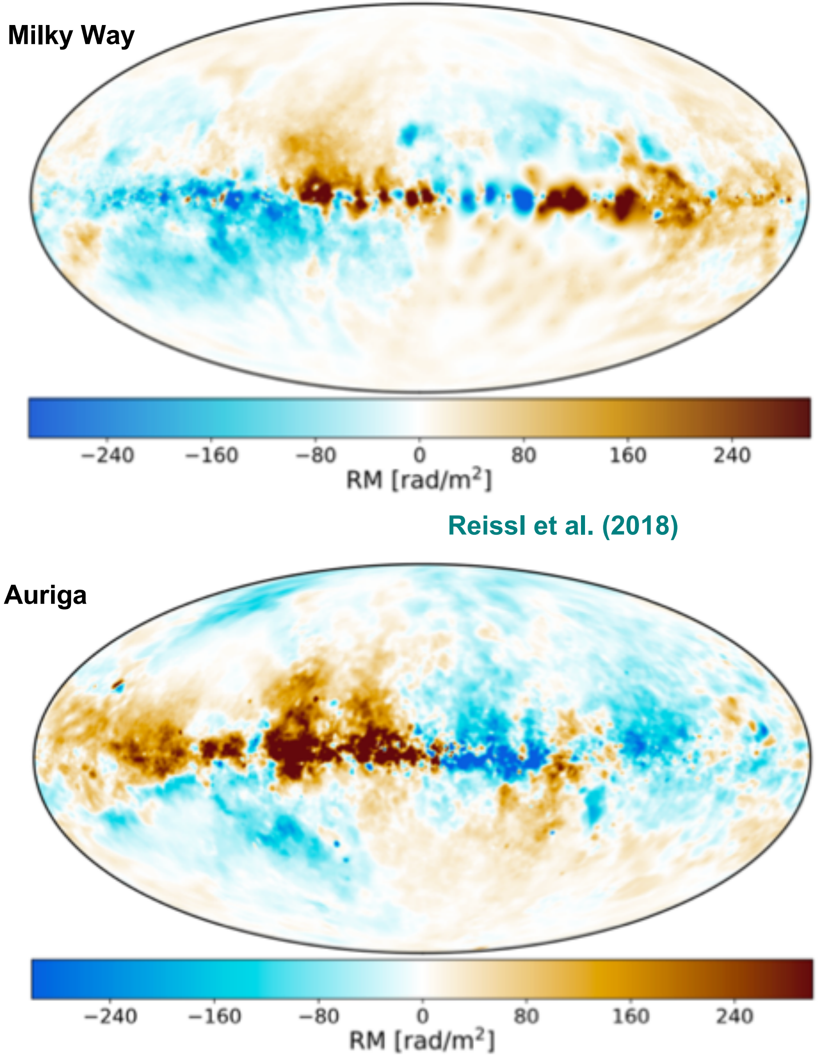
Pakmor et al. (2018)

The predicted radial magnetic field strength and Faraday rotation signal matches the Galaxy very well

B-FIELD STRENGTH AND FARADAY ROTATION MAPS



Pakmor et al. (2017)

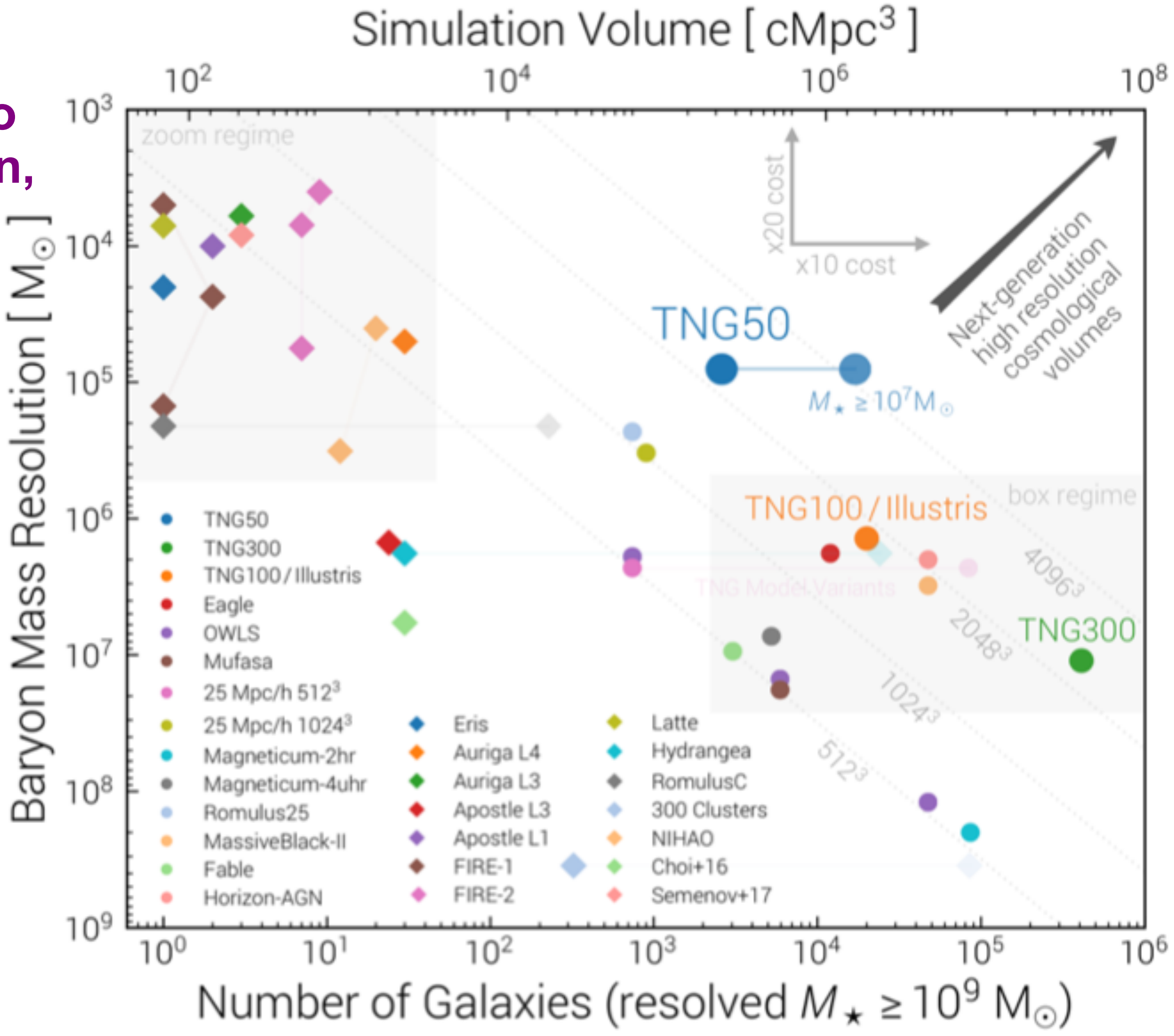


Reissl et al. (2018)

Some trends for the future

The next simulation generations will continue to push volume and resolution, in part at the same time

THE UNIQUE SPOT OF TNG50 IN SIMULATION PARAMETER SPACE

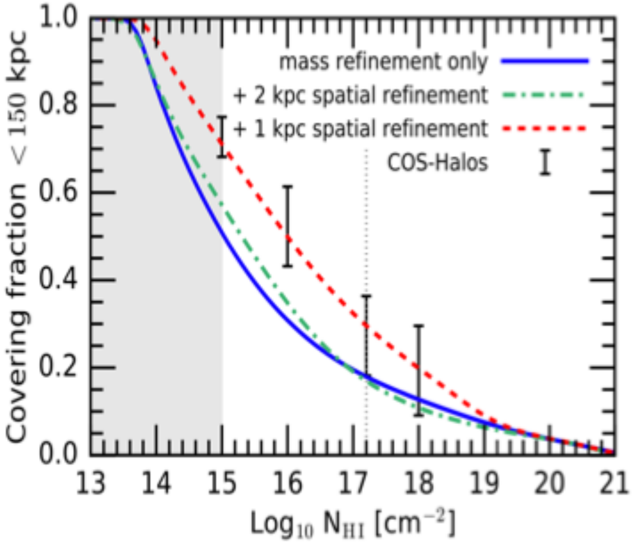


Nelson et al. (2019)

Refining the CGM resolves more cooler HI clumps

SUPER-LANGRANGIAN ZOOM SIMULATIONS OF THE CIRCUM-GALACTIC MEDIUM

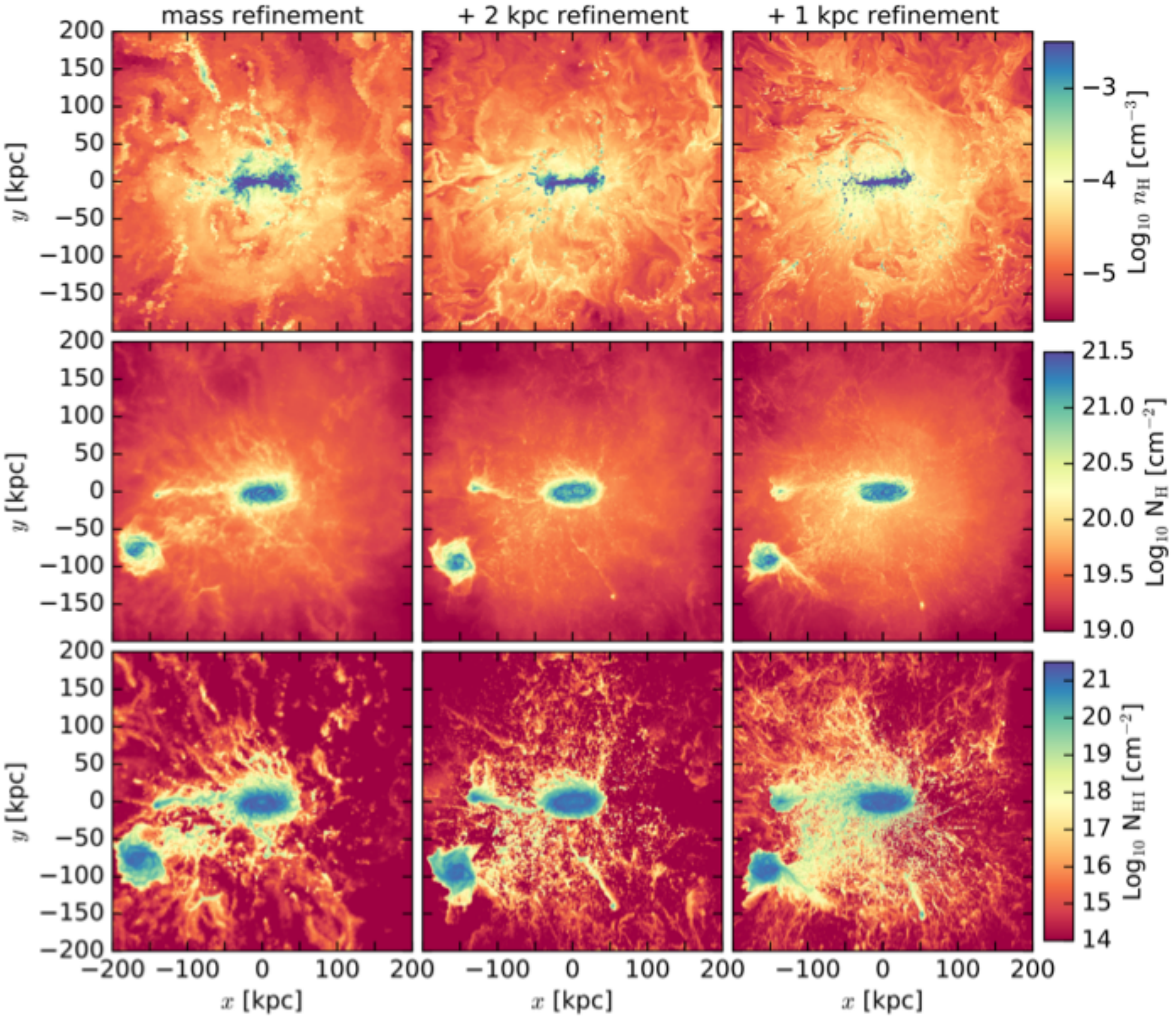
van de Voort et al. (2018)



see also:

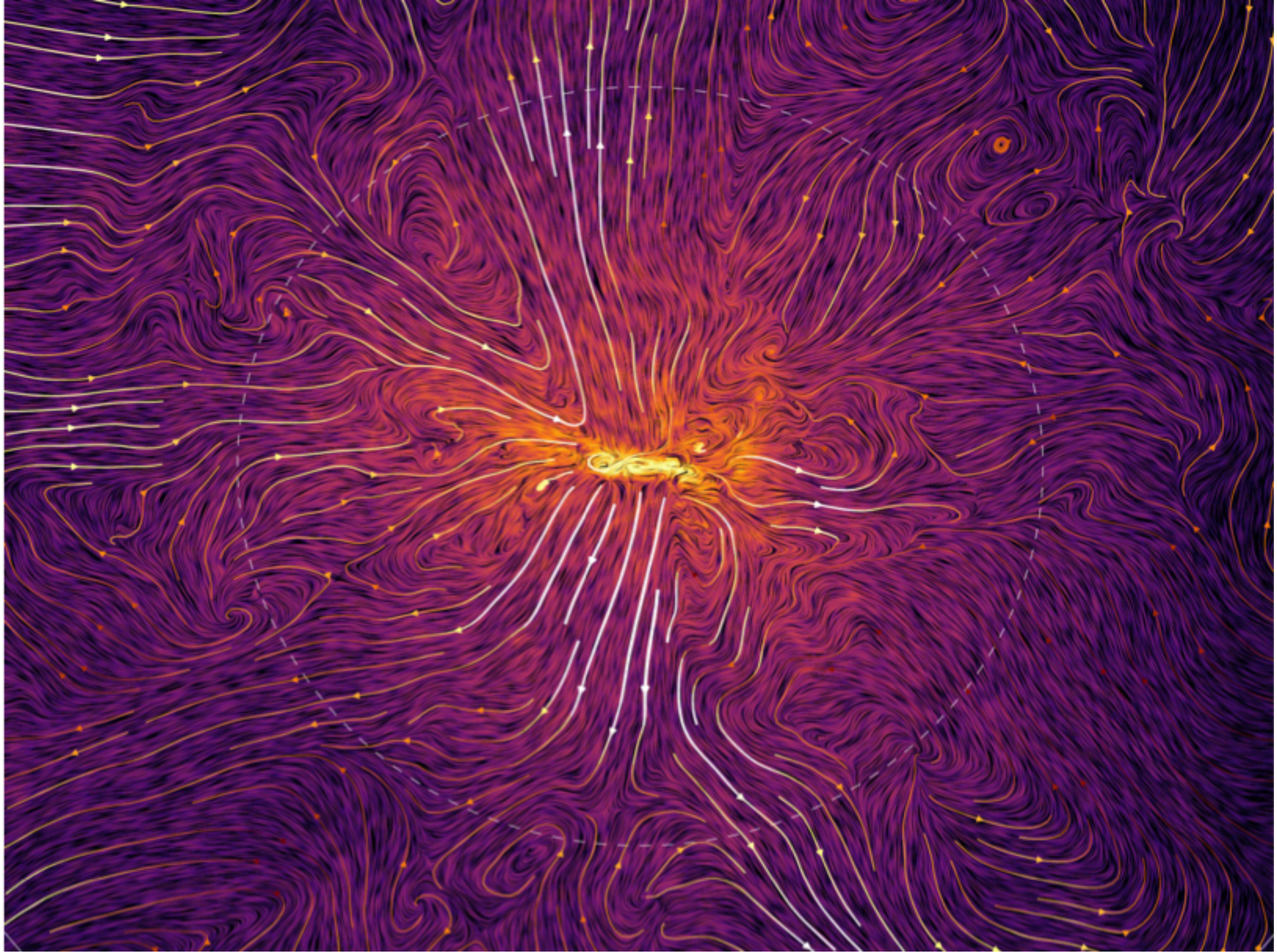
Hummels et al. (2018)

Suresh et al. (2019)



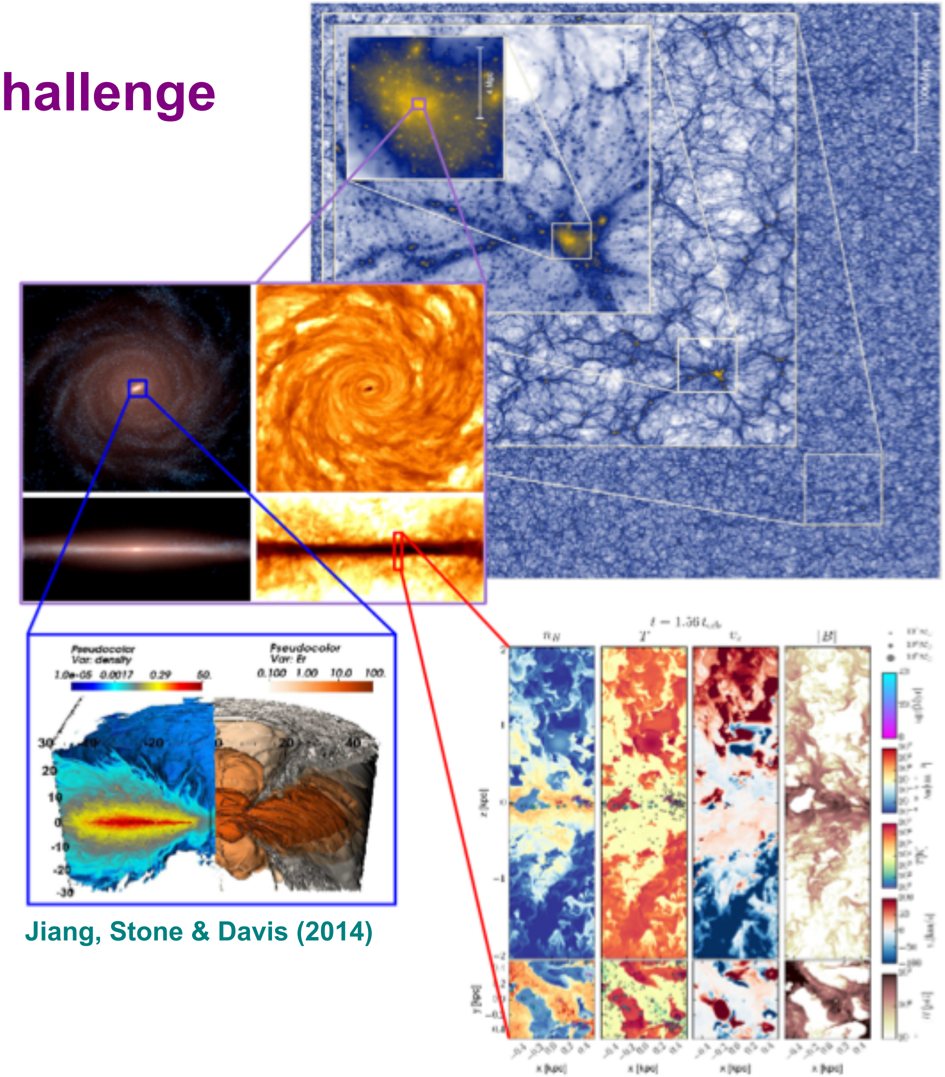
How can galaxies shed a substantial fraction of their baryonic content?

FLOWS IN THE CIRCUM-GALACTIC MEDIUM IN A GALAXY FROM THE TNG-50 SIMULATION



Nelson et al. (2019)

The dynamic range challenge



Angulo et al. (2012)

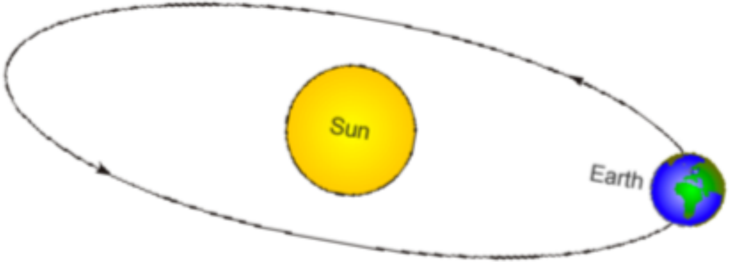
Grand et al. (2016)

Jiang, Stone & Davis (2014)

Kim & Ostriker (2016)

Adding cosmic rays to galaxy formation simulations makes the dynamic range problem much harder

GYRO-RADIUS COMPARED TO THE SIZE OF A GALAXY



Milky Way-like galaxy:

$$r_{\text{gal}} \sim 10^4\ \text{pc}$$

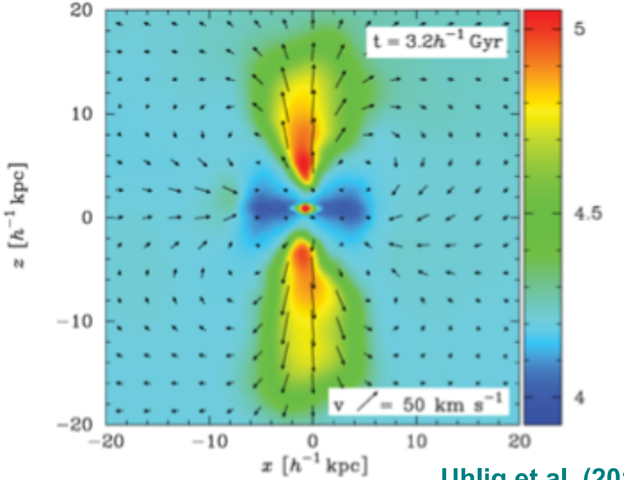
gyro-orbit of GeV cosmic ray:

$$r_{\text{cr}} = \frac{p_\perp}{e\,B_{\mu\text{G}}} \sim 10^{-6}\ \text{pc} \sim \frac{1}{4}\ \text{AU}$$

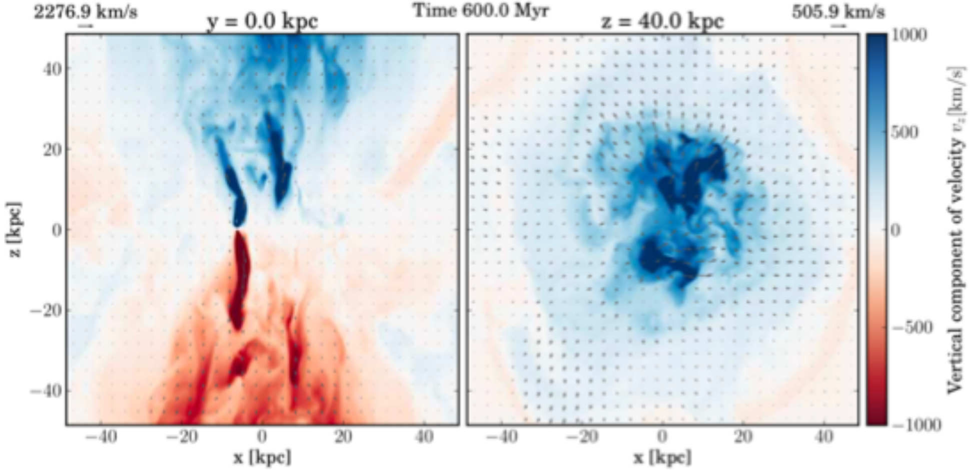
→ **Need to develop an effective two-fluid theory that can be treated with hydrodynamical methods**

Cosmic rays can drive galactic winds when coupled with transport processes

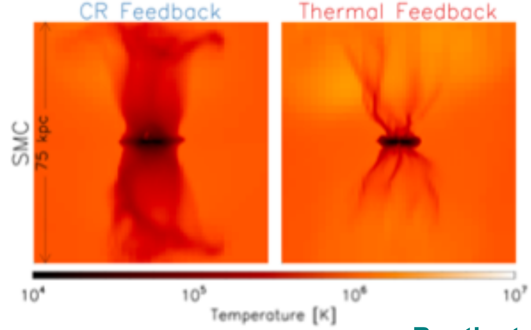
DISK SIMULATIONS BY DIFFERENT GROUPS



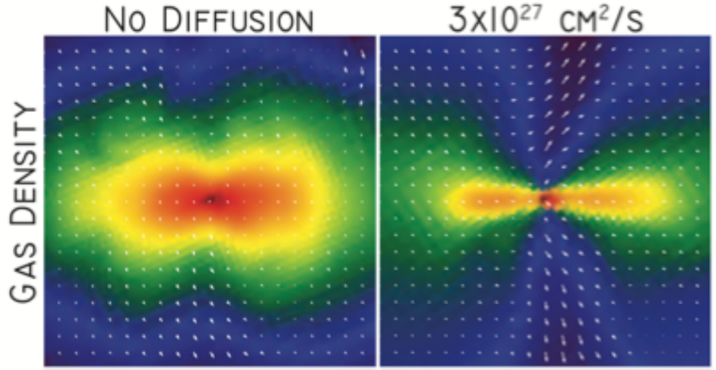
Uhlig et al. (2012)



Hanasz et al. (2013)



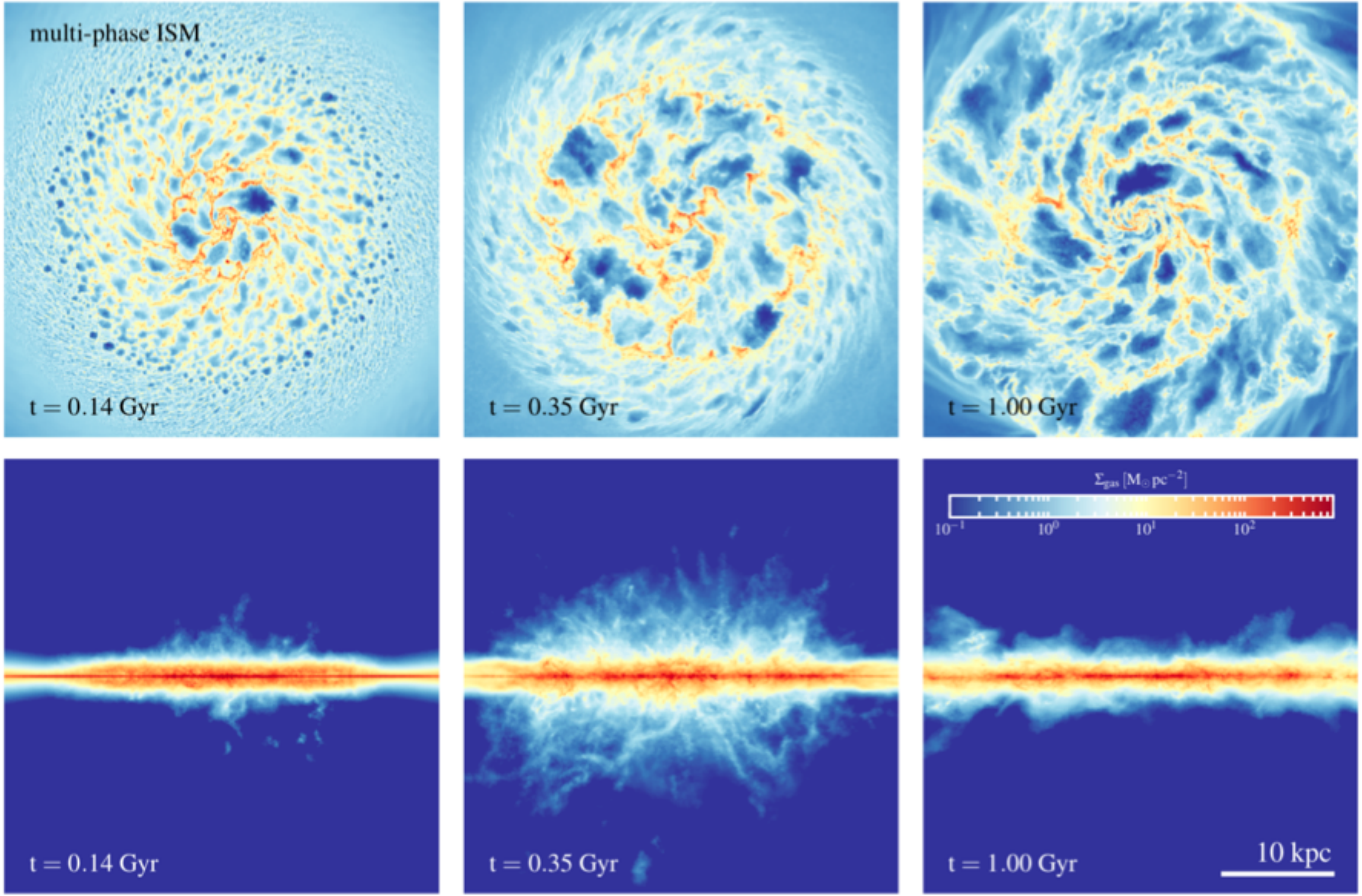
Booth et al. (2013)



Salem et al. (2014)

Resolved multi-phase ISM disk simulations

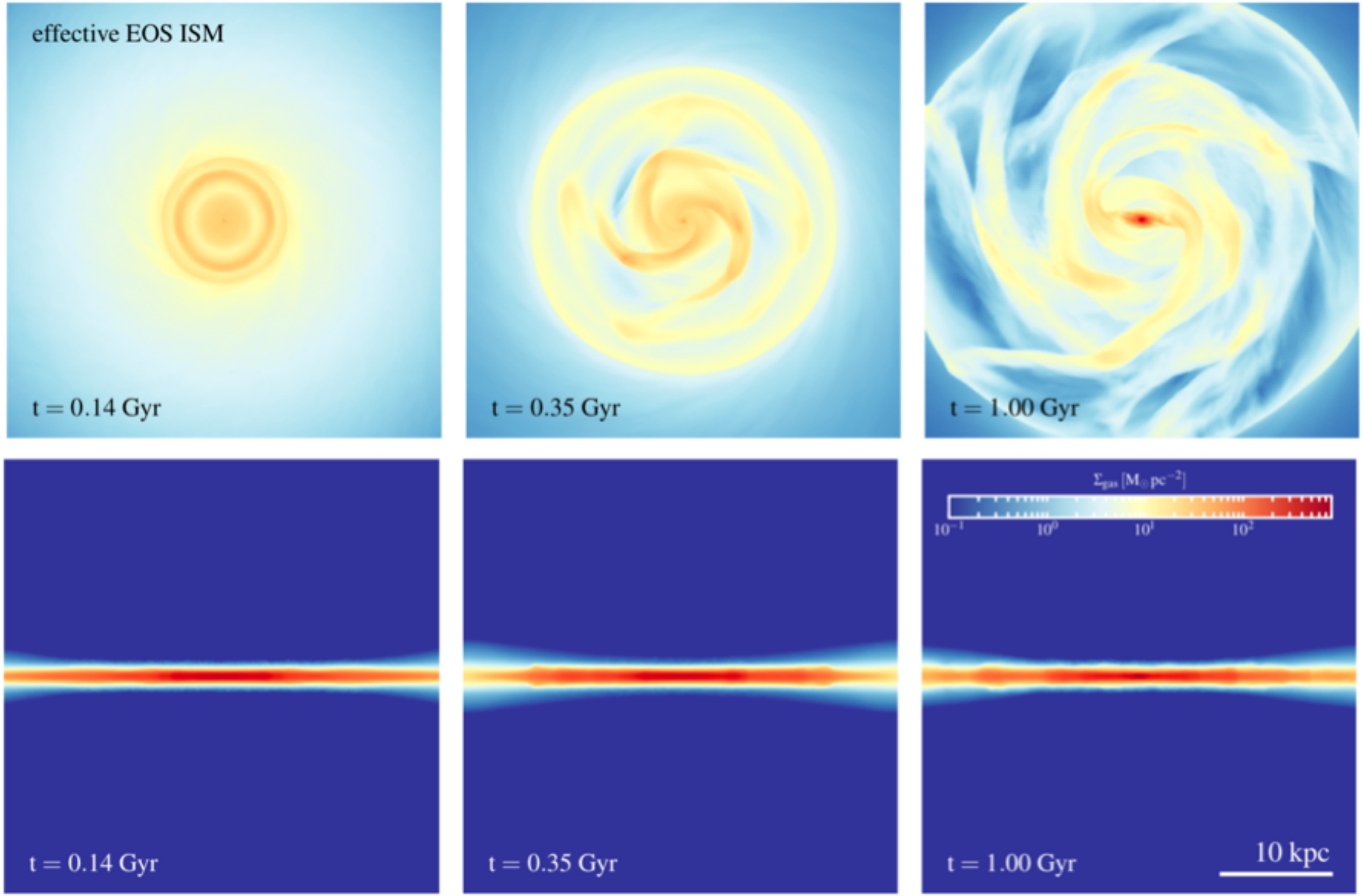
AN ISOLATED DISK GALAXY WITH THE NEW SMUGGLE MODEL IN AREPO



Marinacci et al. (2019)

Old ISM sub-grid models need to be overcome

GAS DENSITY IN AN ISOLATED DISK GALAXY WITH THE SPRINGEL & HERNQUIST MODEL (2003)

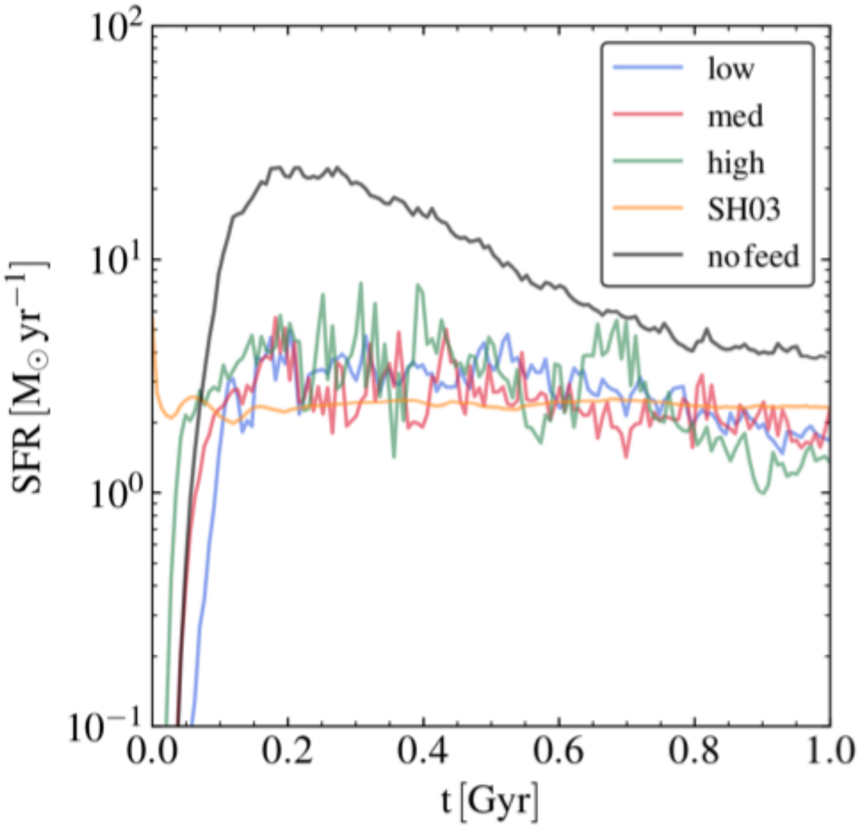


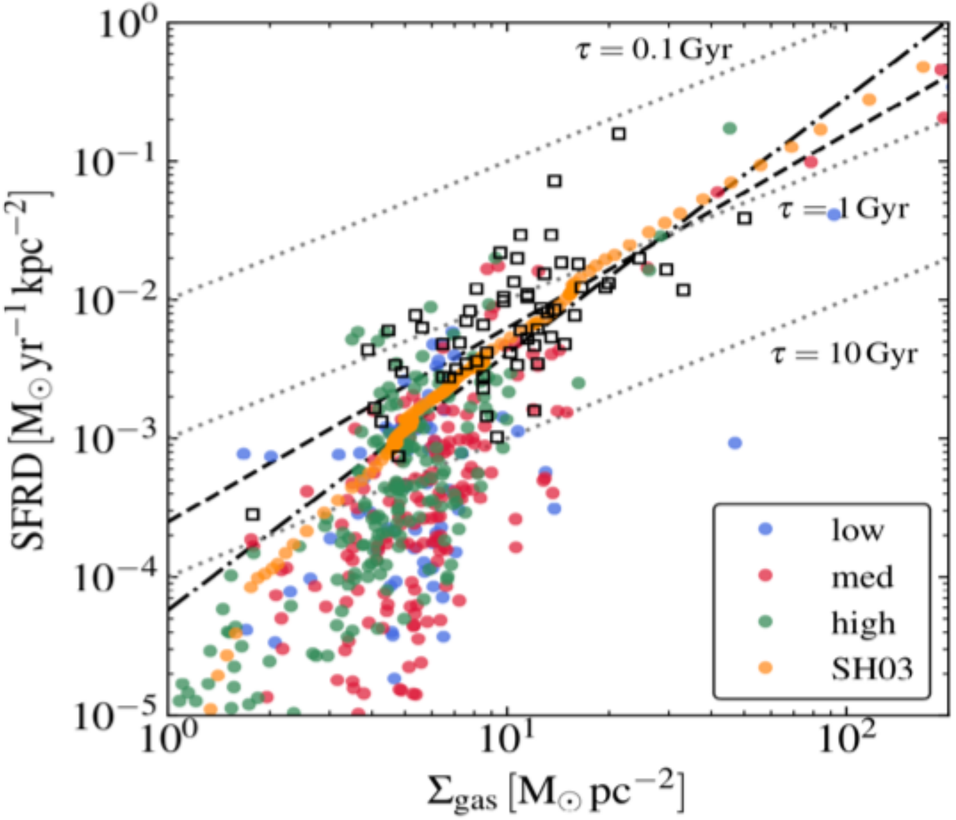
Marinacci et al. (2019)

Global star-formation properties not necessarily very different

STAR FORMATION IN ISOLATED DISK GALAXIES RUN WITH SMUGGLE AND SH2003

Marinacci et al. (2019)

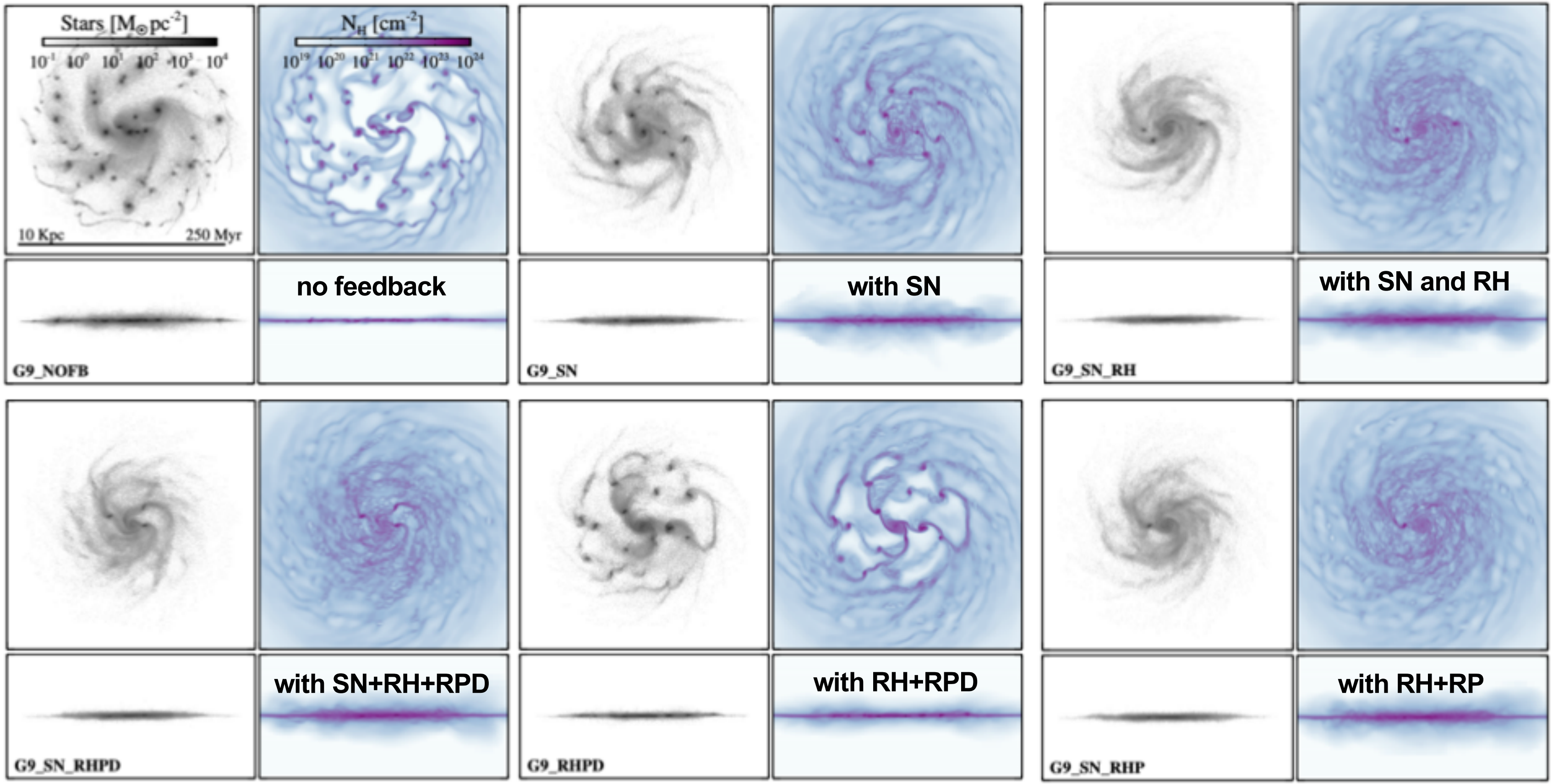




Radiation pressure provides at most weak feedback on galaxy scales

THE FRONTIER OF SELF-CONSISTENT RADIATION-HYDRODYNAMIC SIMULATIONS

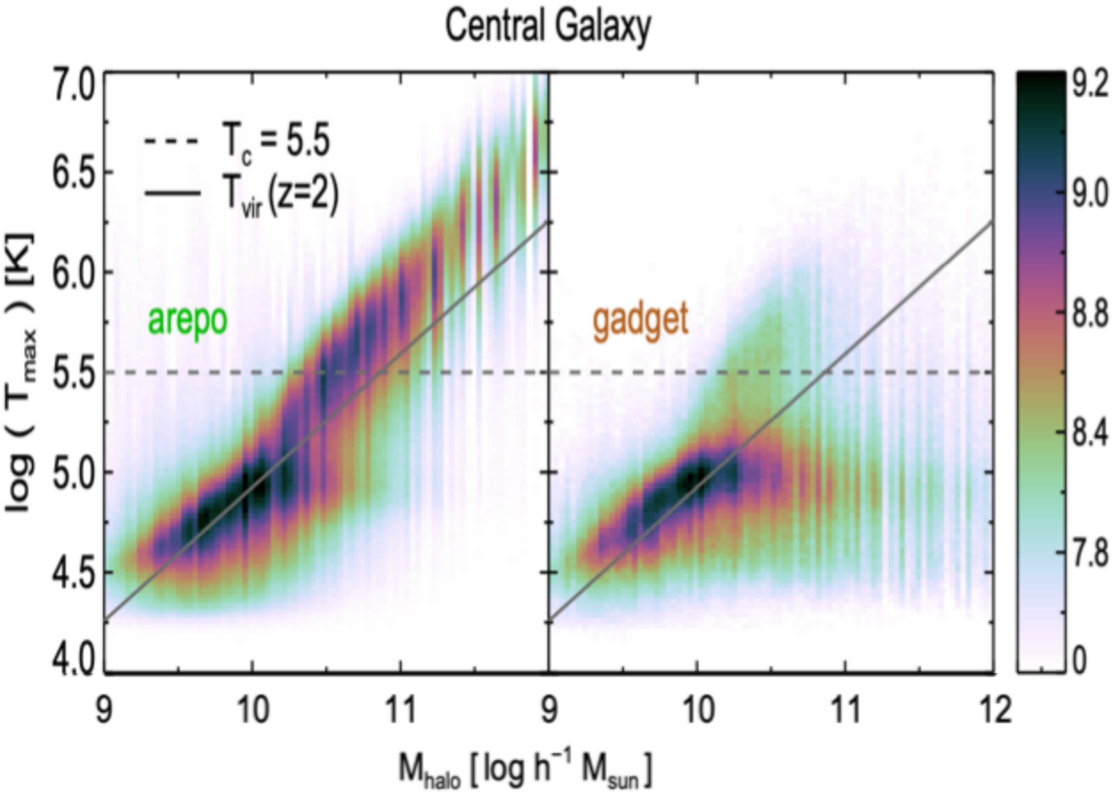
Rosdahl et al. (2015)

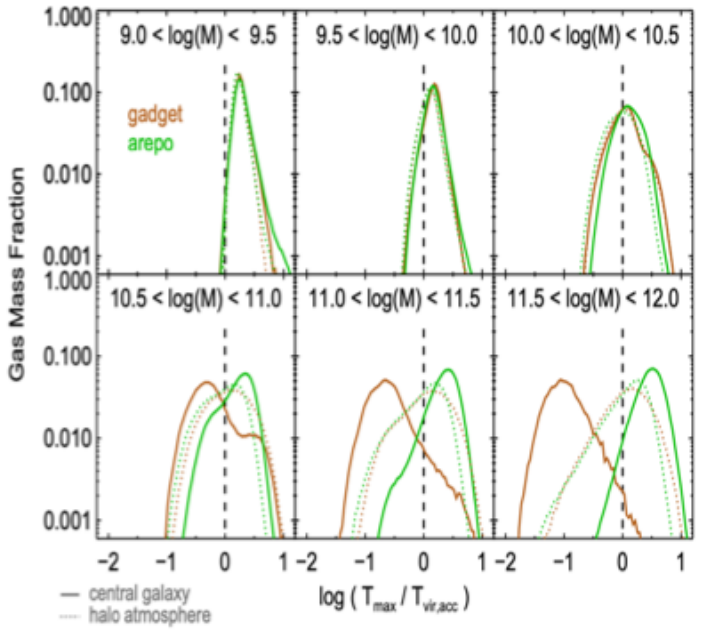


Cold, stream-fed accretion has been overstated for numerical reasons

PAST MAXIMUM TEMPERATURE OF GAS ACCRETED ON GALAXIES IN DIFFERENT METHODS

Nelson et al. (2013)





More accurate and scalable simulation codes

Discontinuous Galerkin (DG) approaches offer higher accuracy at given computational cost and retain data locality at high order

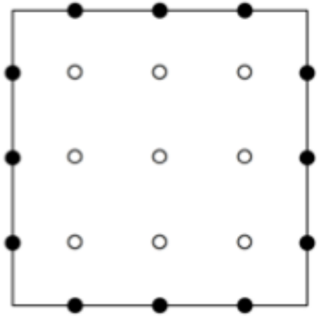
BASIC DISCONTINUOUS GALERKIN EQUATIONS

$$\frac{\partial}{\partial t}u + \vec{\nabla}\vec{F}(u) = 0$$

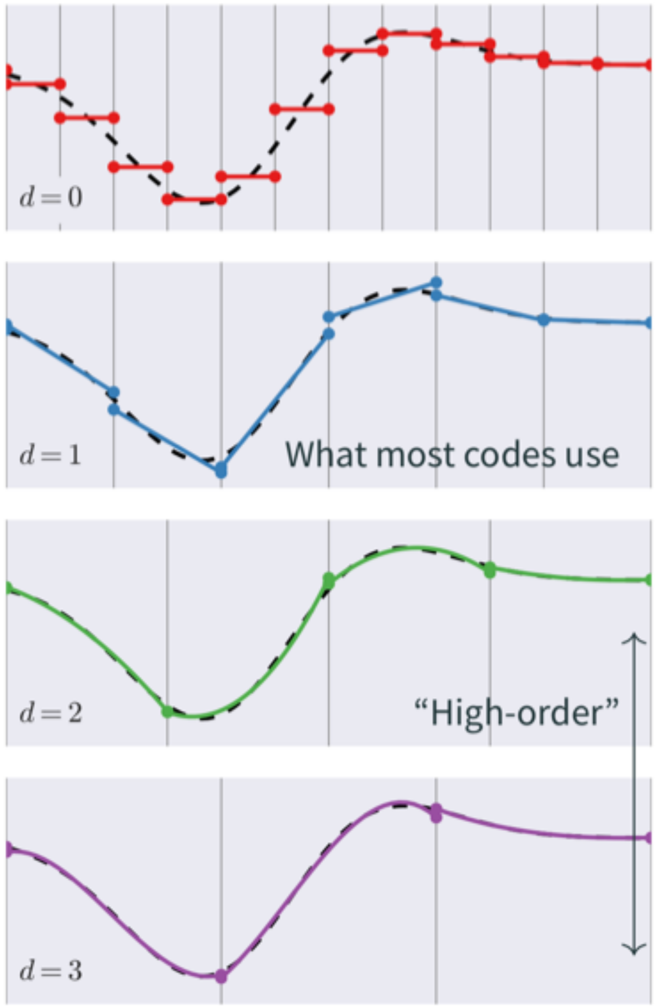
$$\frac{\partial}{\partial t}\underbrace{\int_K u\,\phi_j\,\mathrm{d}V}_{|K|w_j} + \oint_{\partial K}\phi_j\vec{F}(u)\vec{n}\,\mathrm{d}S - \int_K \vec{F}(u)\vec{\nabla}\phi_j\,\mathrm{d}V = 0$$

Schaal et al. (2015)
Guillet et al. (2019)

Riemann solvers plus Gaussian quadrature

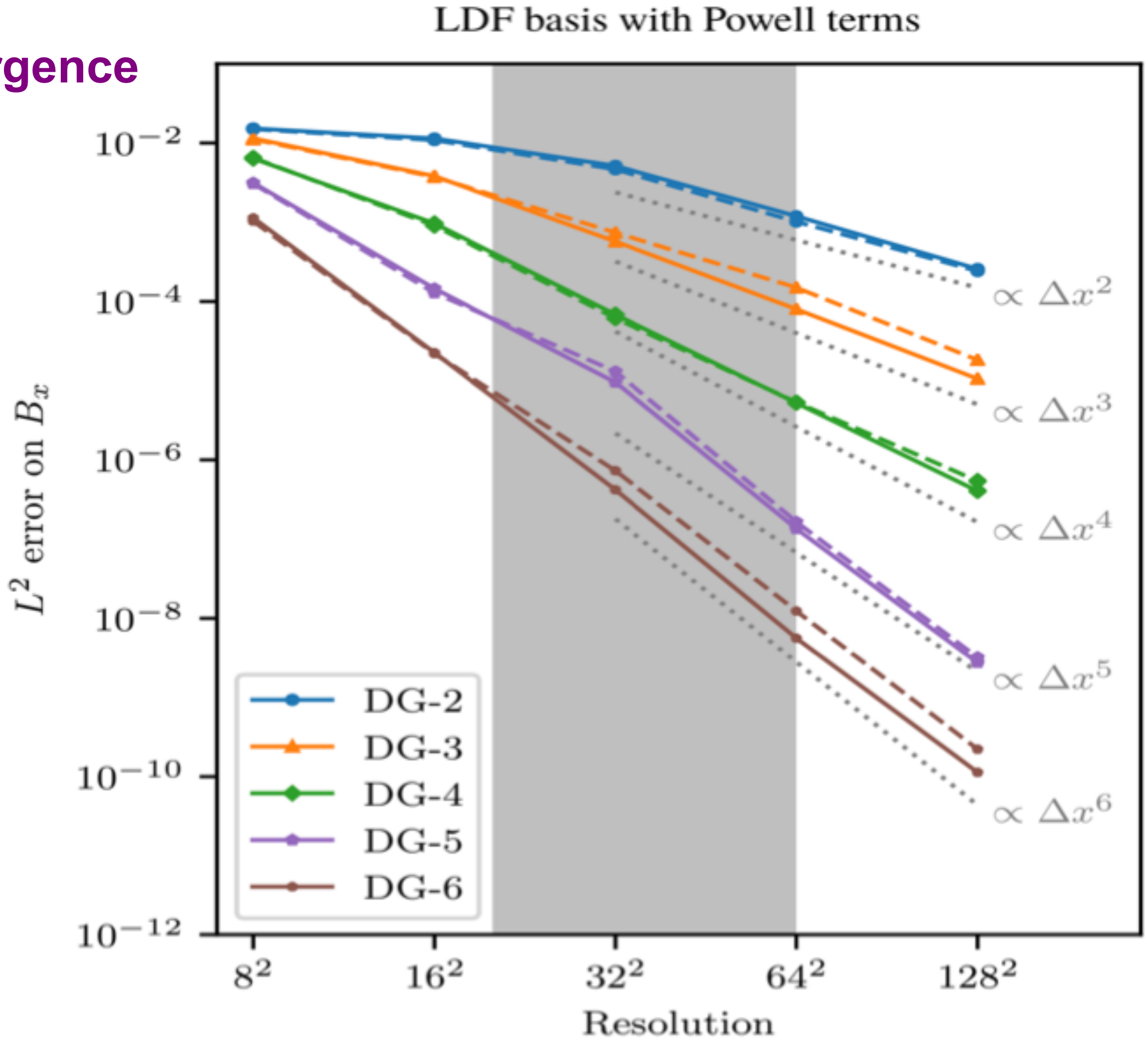


approximation uses 12 reals in each panel



We achieve 6-th order convergence in smooth MHD problems

SMOOTH MHD VORTEX ADVECTION TEST



Guillet et al. (2019)

It still has to be seen whether DG methods can survive in harsh astrophysical environments…

THE REALITY TEST WE ARE FACING

High-order DG methods

Astro / cosmo codes

Guillet et al. (2019)

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

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.

Take home points

- Recent hydrodynamical cosmological simulations have made substantial **progress towards successfully forming galaxies within ΛCDM**.

- Much of the **small-scale physics of feedback** remains however poorly understood.

- **Multi-scale, multi-physics** simulations will be **necessary** to understand the associated fundamental astrophysical questions.

- There are **numerous discrepant claims** about the **relative importance of different physics –** it is clear that some data is matched for the wrong reason.

- As a guide to the **most robust results,** look for those that are **found independently by different groups and different codes.**