Cosmological Galaxy Formation Simulations after Illustris: **Introducing IllustrisTNG(*)**

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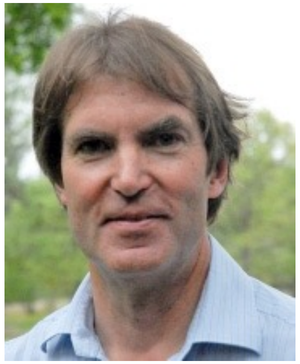
(*) TNG = The Next Generation

The TNG Team

Volker Springel



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Dylan Nelson

Rainer Weinberger

Federico Marinacci

Jill Naiman

Mark Vogelsberger

Shy Genel

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The TNG Goals

1. To address all the physical model issues identified in Illustris galaxies and haloes
2. To introduce new sub grid treatments, new physics, and numerical improvements
3. To significantly expand the scope and include new diagnostic tools

↓

A new effective galaxy-physics model with AREPO

A new set of large volume cosmological simulations

The TNG Model

AREPO + Illustris Framework +

- **Numerical improvements:**
  - Improved spatial gradients and time stepping
  - New gravity solver with recursive Hamiltonian splitting
  - Improved advection of the passive scalars (metal abundances)

Pakmor et al. 2016
Springel et al.

- **New physics and sub grid models:**
  - **MHD** (8-wave Powell divergence cleaning) *Pakmor et al. 2011, Pakmor & Springel 2013; see Volker's talk*
  - New low-accretion BH feedback: pulsed kinetic **BH-driven winds**
  - **Refined galactic wind feedback**
  - Revised some stellar evolution choices and new yield tables

Weinberger et al. 2017

this talk

- **Diagnostic tools:**
  - On the fly cosmological shock finder *Schaal & Springel 2015, Schaal et al. 2016*
  - Metal production tracking (all metals by SNIa, SNII, AGB + Fe by SNIa, SNII)
  - Subgrid model for neutron-star mergers, as r-process material sources (Europium)
  - (New Planck Cosmology)

The TNG Model

Simulating galaxy formation with black hole driven thermal and kinetic feedback

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Federico Marinacci,[5] Rüdiger Pakmor,[1] Dylan Nelson,[6] Shy Genel,[7†]
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Simulating Galaxy Formation with the IllustrisTNG Model

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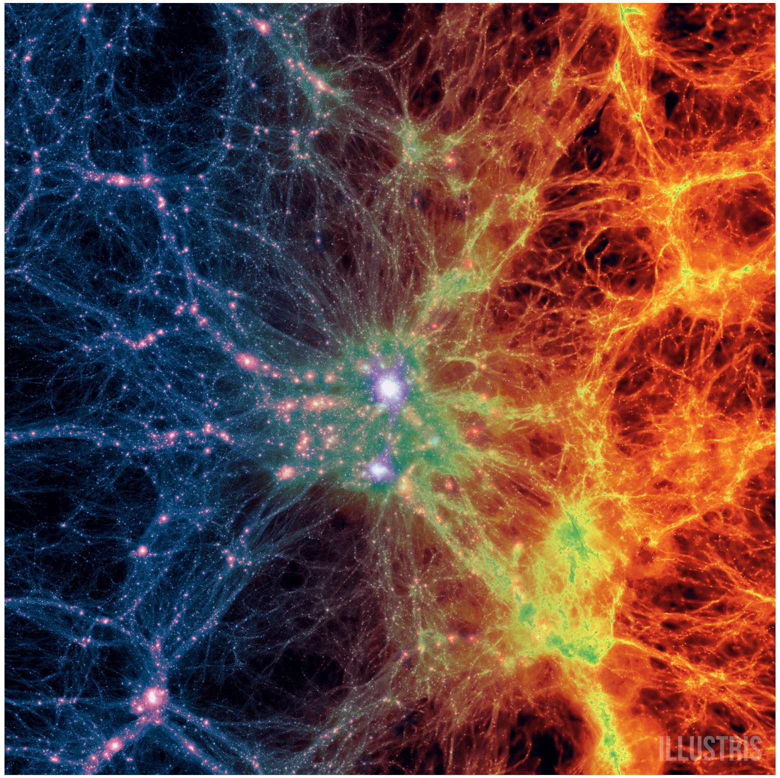
Jill Naiman[2], Rüdiger Pakmor[3], Lars Hernquist[2], Paul Torrey[7], Mark Vogelsberger[7],
Rainer Weinberger[3], and Federico Marinacci[7]

to be submitted

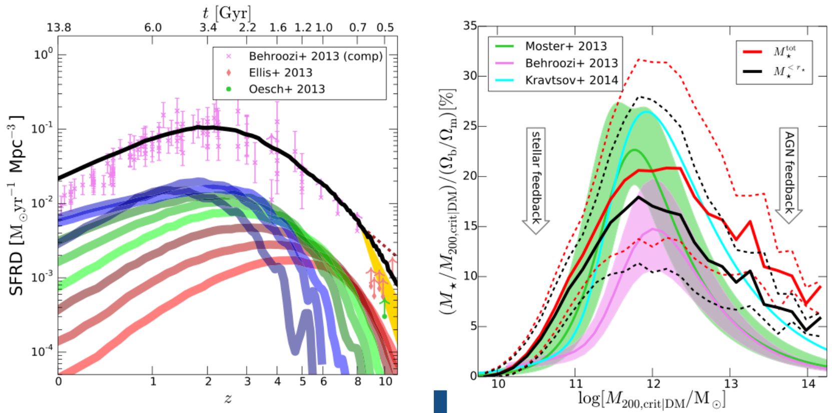
Illustris
and the overall approach

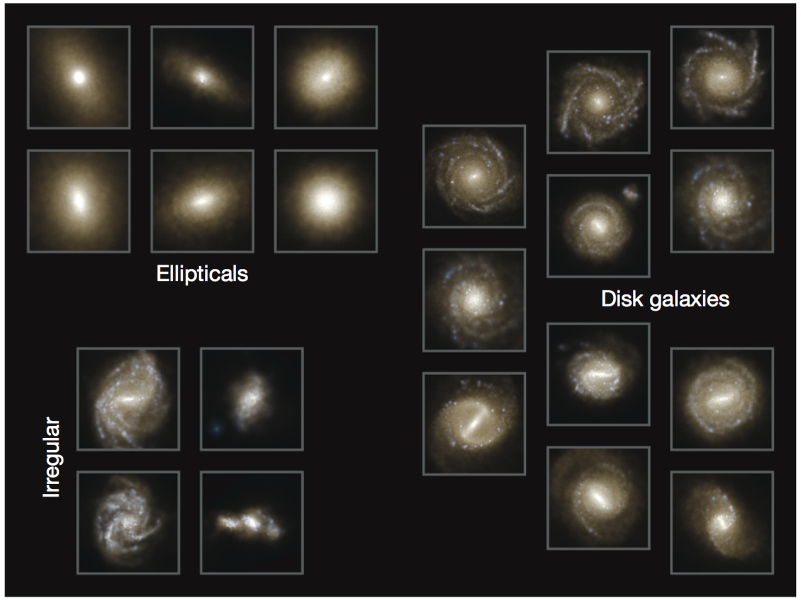
Illustris in one slide

AREPO Code
106.5 Mpc Cosmological Box
Halo Mass Range: < 2x10[14] Msun
Res: 0.7/1.4 kpc, 1.3x10[6]/ 6.3x10[6] Msun



Vogelsberger et al. 2014a,b, Genel et al. 2014, Sijiacki et al. 2015

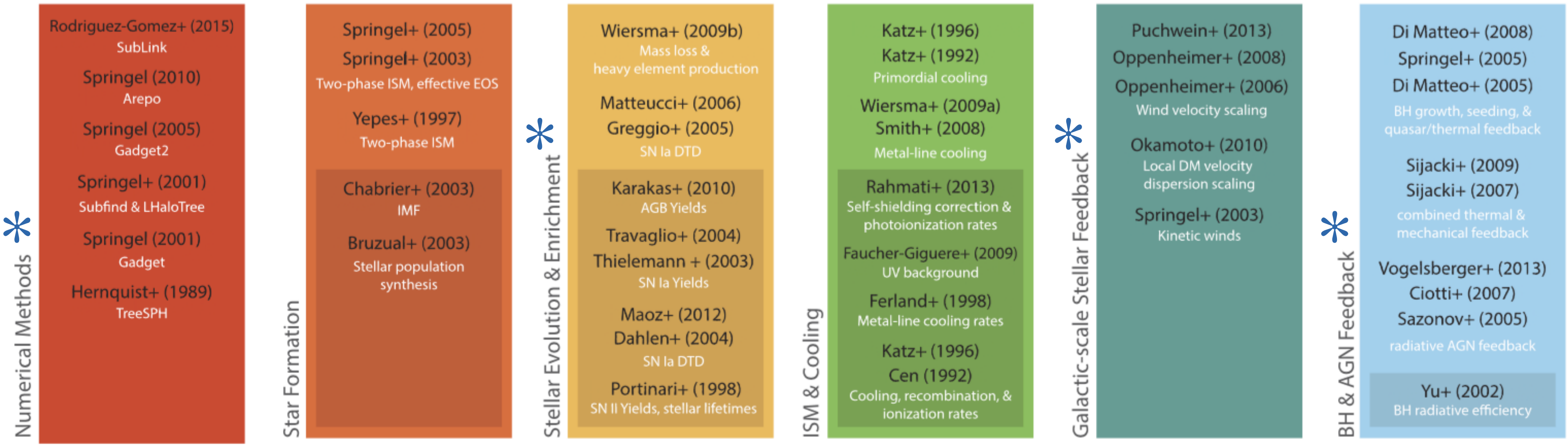




Vogelsberger et al. 2014a

The Illustris Galaxy Physics Model

Nelson, Pillepich et al. 2015



The overall model is based on choices *inspired* by observations and by other, more detailed, “ab initio" theoretical studies of individual processes

It necessarily entails a subgrid treatment of phenomena acting on scales smaller than 10-1000 parsec, and hence many choices in the numerical implementation and free parameters

* TNG modifications

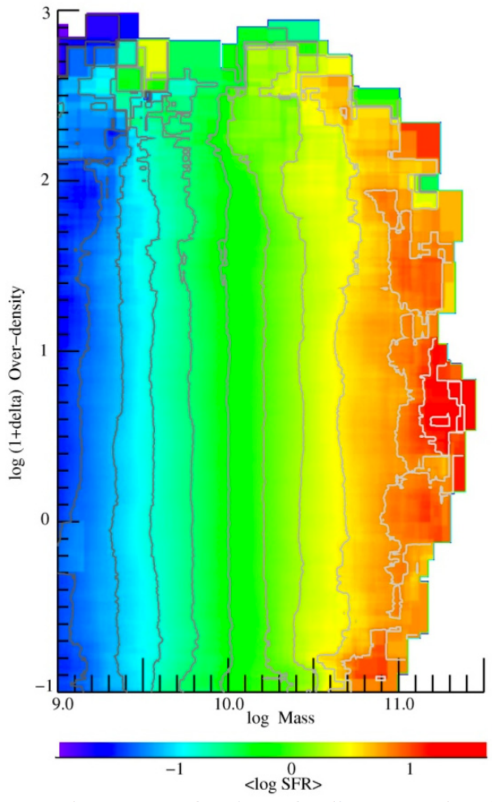
The overarching Idea

WORKING ASSUMPTION: LCDM as Cosmological framework => hierarchical growth of structure

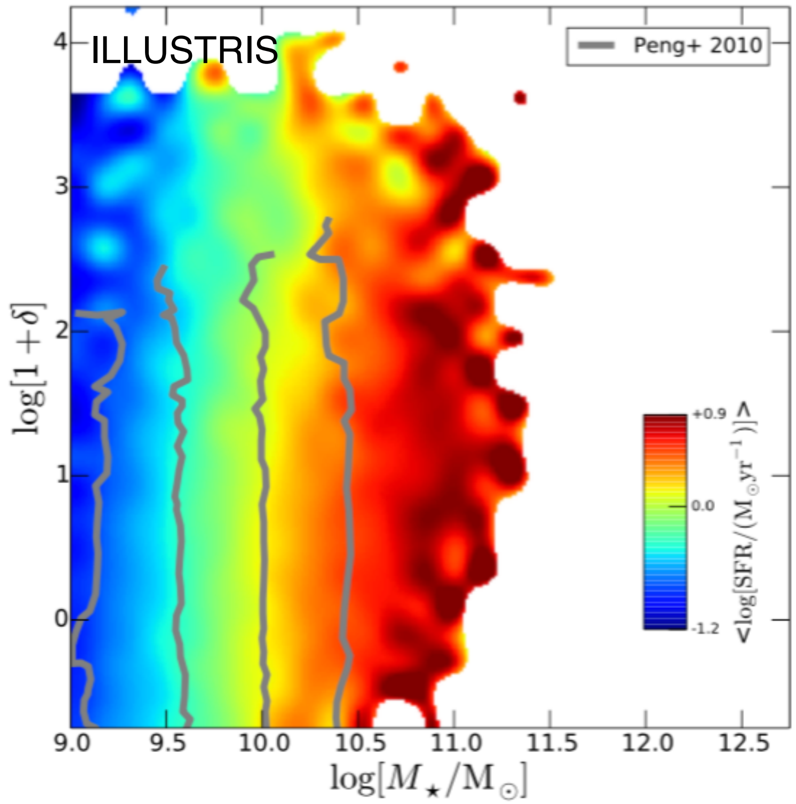
1. We are after an ***effective* theory** for galaxy formation that functions across the widest possible ranges of masses, redshifts, assembly histories, environments
2. We want not just to form galaxies, but also to take into account the effects of the **hierarchical growth of structure** (i.e. mergers, accretion, etc)
3. Once we get the **"average" galaxy population**, we want to use the simulation as exploration tool, e.g. to understand the physical origin of the galaxy-to-galaxy variations (the **scatter**) and the mechanisms behind the diverse galaxy pathways
4. A few observational constraints are used to *calibrate* the model, e.g. SFRD and/or the galaxy stellar mass function at z=0
5. To do so, we must simulate **thousands or tens of thousands of galaxies** => cosmological volumes with > tens Mpc side and sub grid prescriptions
6. Any *other* simulation outcome can be considered a **prediction, a gift** of the simulation: all of those, collectively, must be contrasted to observations to **validate** (or not) the model.

Examples of predictions/gifts/applications: on galaxy quenching

Thousands of galaxies are needed to validate quenching theories



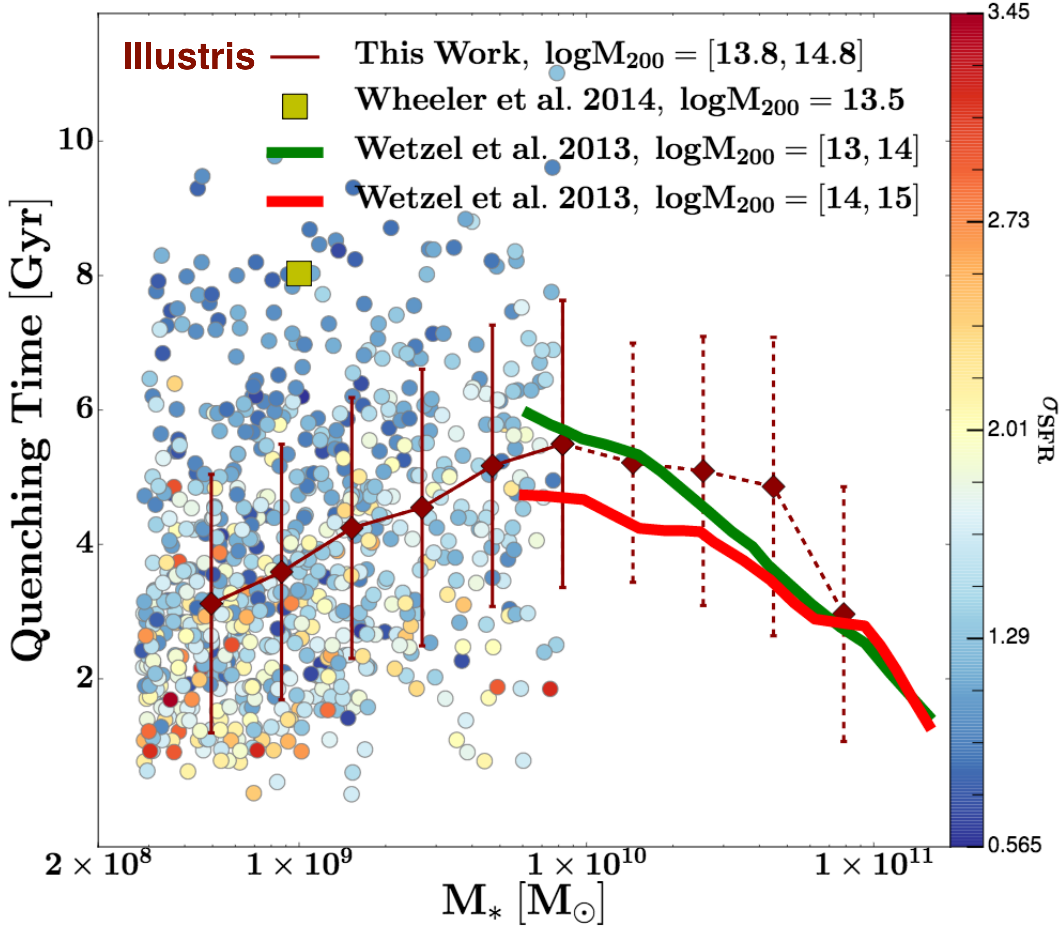
Peng et al. 2010



Vogelsberger et al. 2014

Examples of predictions/gifts/applications: on quenching in clusters

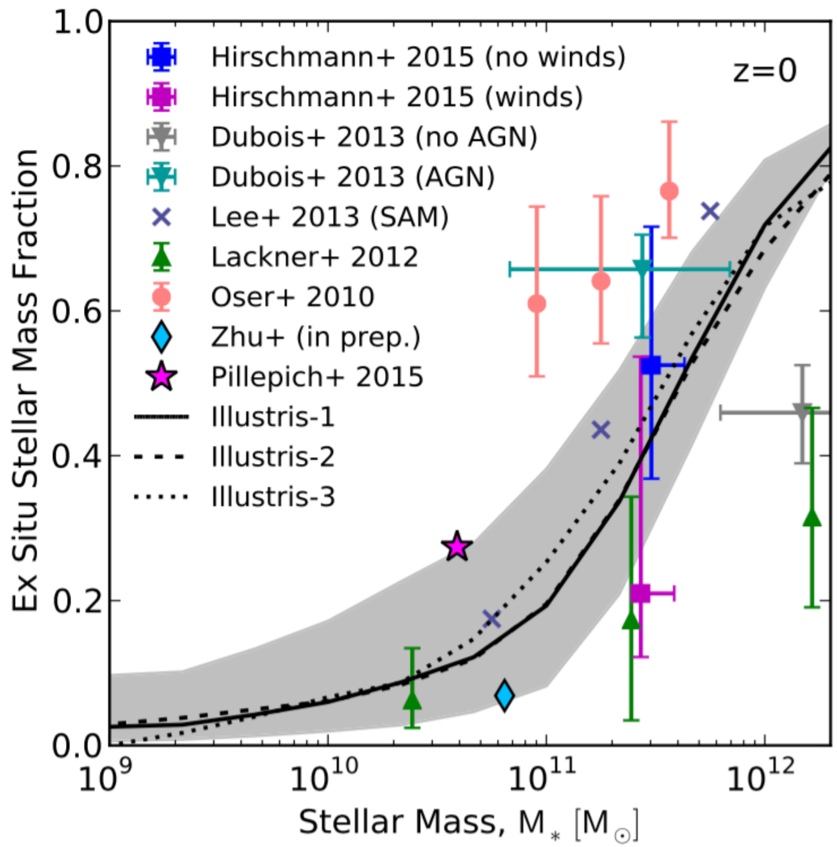
Hundreds of satellite galaxies are needed to understand quenching mechanisms in massive haloes, and those massive haloes need to exhibit sensible properties



Mistani, Sales, Pillepich et al. 2016

Examples of predictions/gifts/applications: on stellar growth by mergers

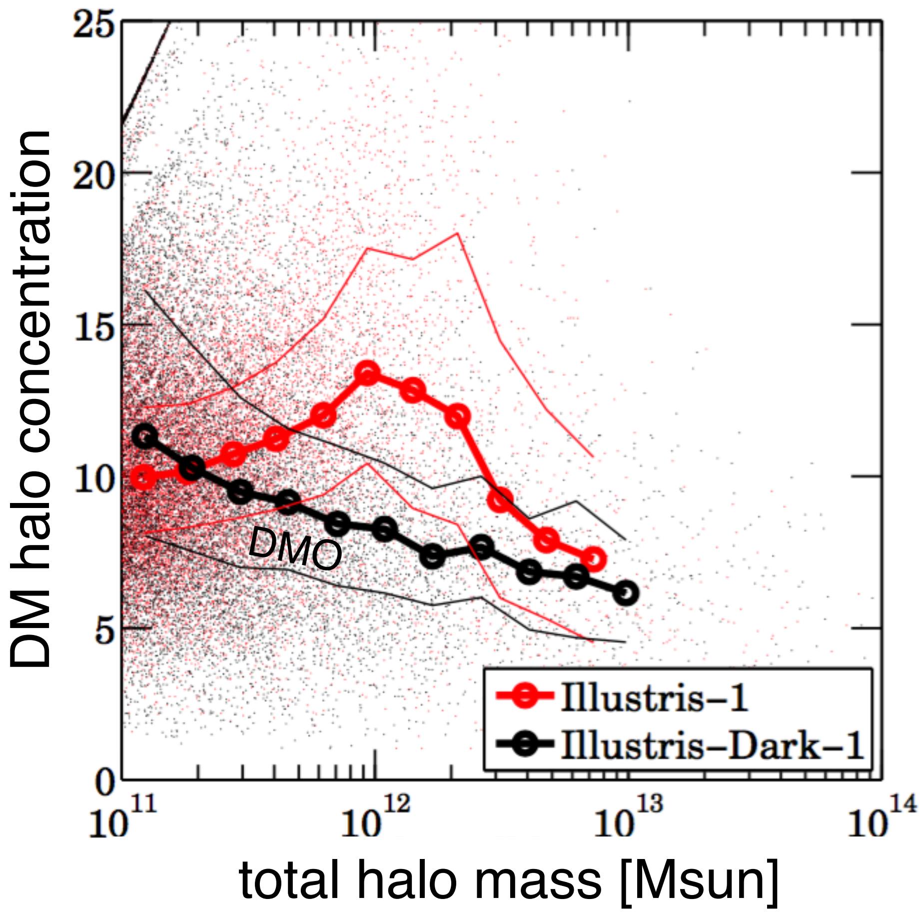
Thousands of galaxies are needed to predict the average fraction of stars accreted via hierarchical growth or the impact of mergers on morphologies



Pillepich et al. 2014
Rodriguez-Gomez, Pillepich, et al. 2016
Rodriguez-Gomez, Sales, et al. 2016

Examples of predictions/gifts/applications: effects of baryons on DM?

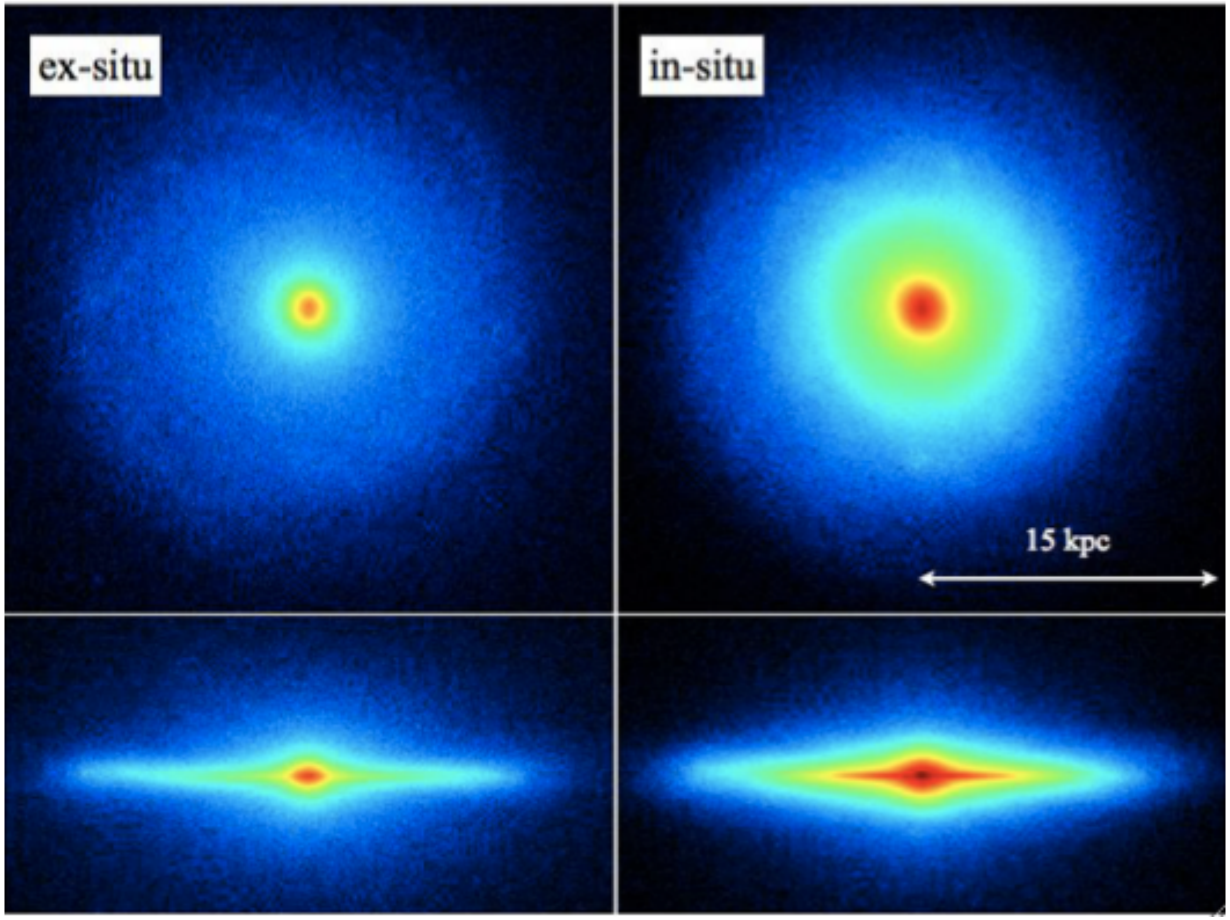
How robust are gravity-only predictions in the presence of galaxies and gas accretion and outflows?



Chua, Pillepich, et al. 2017

Examples of predictions/gifts/applications: DM disks? Ex-situ disks!

How often do we get DM co rotating on the stellar disk plane? And what about accreted stars?



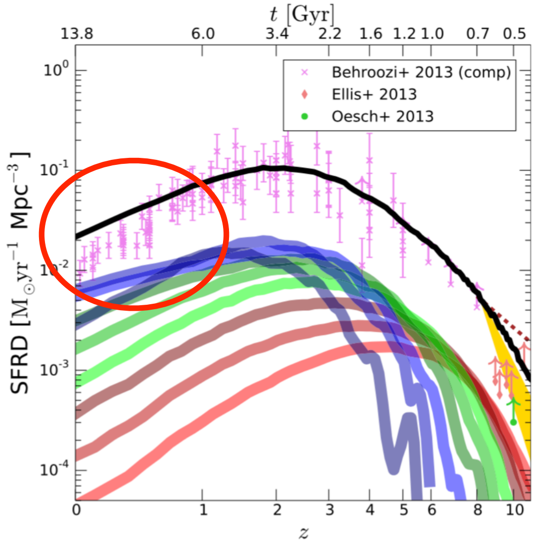
Eris Disk

Pillepich et al. 2014, 2015

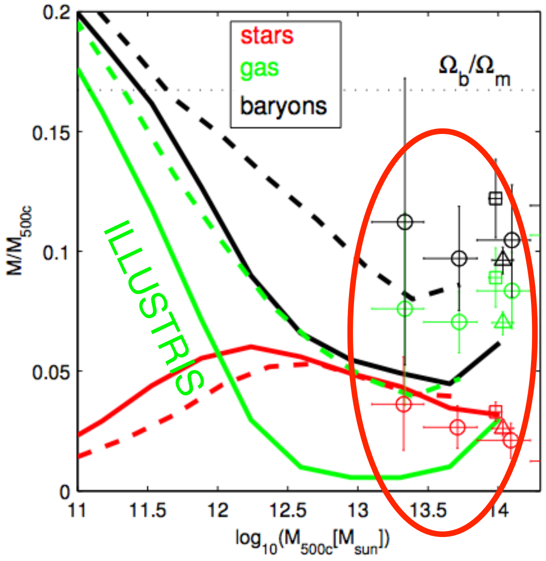
Towards IllustrisTNG

Illustris Limitations, i.e. issues identified in the Illustris galaxies

1. Too high Cosmic SFRD at z<1
2. Too high galaxy stellar mass function at z=0 at the low & high mass ends
3. Too extended stellar sizes for galaxies < 10^10 Msun
4. Spurious ring-like features at z=0
5. Too low halo gas fractions with R500 in haloes > 10^13.5 Msun
6. Not well enhanced galaxy color bimodality

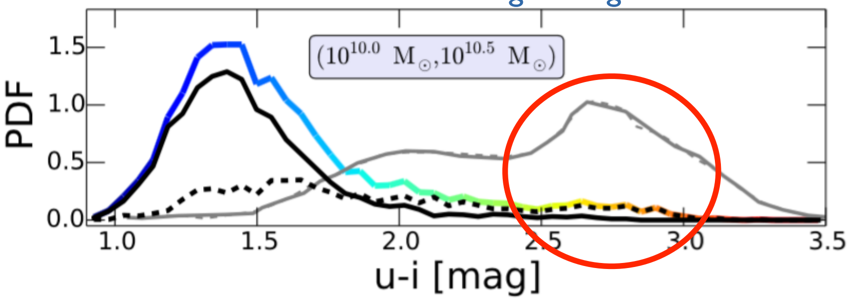


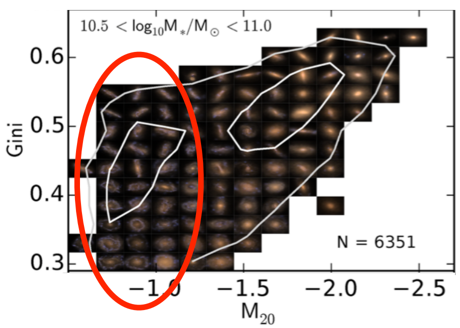
Vogelsberger et al. 2014b

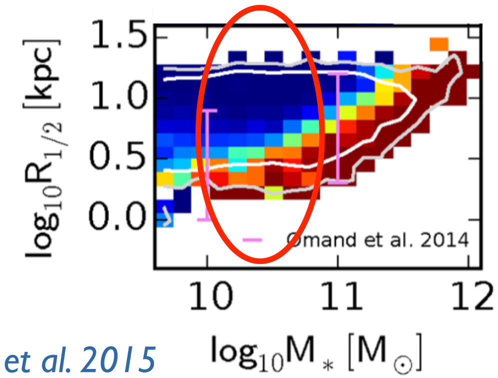


Genel et al. 2014

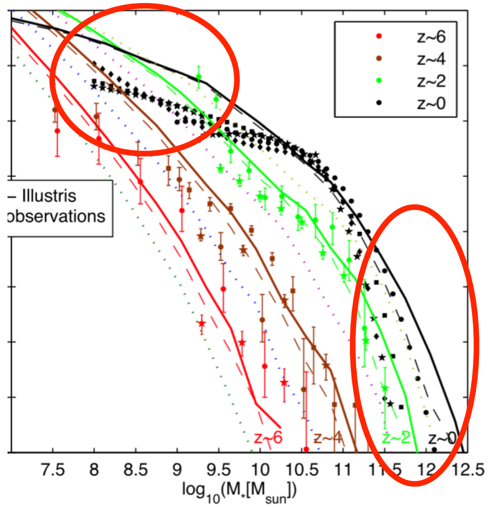
Vogelsberger et al. 2014







Snyder et al. 2015



Genel et al. 2014

The TNG strategy

Phenomenology: All issues identified above are related to inefficient SF suppression and inadequate feedback mechanisms

Direction: Modification or complete revisions of the feedback prescriptions, both at the low and high mass end

Procedure:

- We have identified the Illustris issues to solve
- We have made educated guesses as to how to modify the feedback prescriptions in order to solve such issues
- We have simulated the Illustris model and TNG variations on the same cosmological volumes and zooms
- We have retained the implementation that -in comparison to Illustris- exhibits better promises to solve the identified problems

Focus/*Calibration* Observables:

stellar content of galaxy population

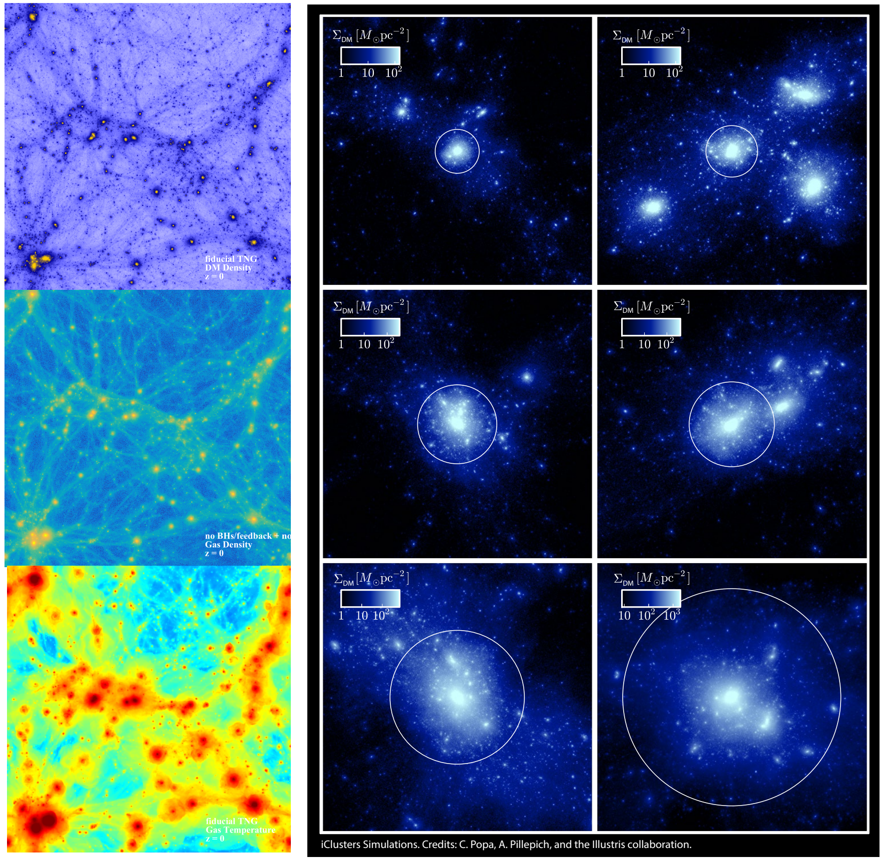
halo gas fraction

BH mass relation

Note: not an actual chi^2-based calibration against observational constraints, but relative comparison to Illustris outcome.
Complications: resolution, sample variance, need for careful mocks of the sims

Study Simulations at fiducial resolution

cosmological volumes 37 Mpc or 45 Mpc side



zooms of MW and galaxy clusters up to 3x10^15 Msun

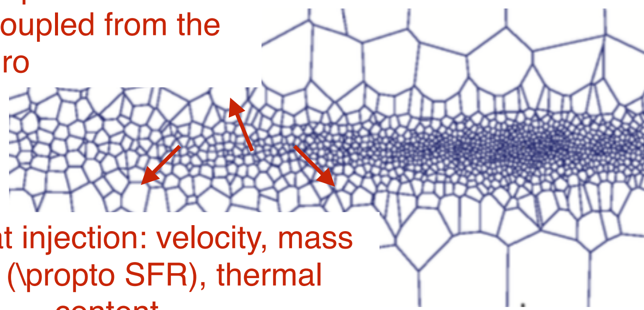
On the Galactic Winds

Galactic Winds Implementation

Phenomenology of the issue: Illustris galactic winds are not effective enough at high redshifts and in small galaxies (haloes < 10^12 Msun)

wind particles are spawned from sf-ing gas cells, decoupled from the hydro

Mesh in a disk (V. Springel)



Choices at injection: velocity, mass loading (\propto SFR), thermal content

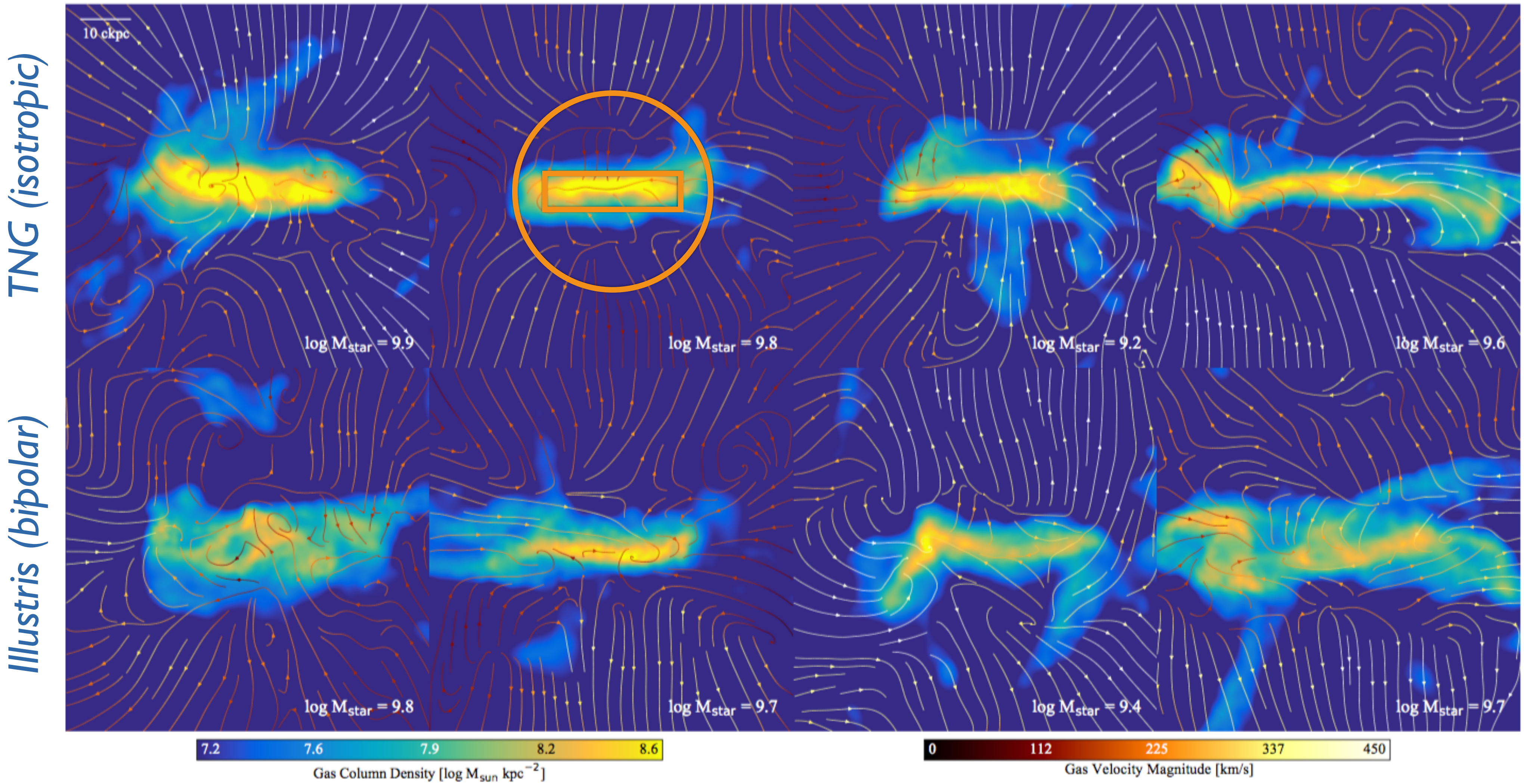
Galactic Winds

ILLUSTRIS		TNG
non local, from sf-ing gas	General Approach	non local, from sf-ing gas
bipolar	Directionality	isotropic
cold	Thermal Content	warm
$\propto$ local σ_{DM}	Injection Velocity	$\propto$ local σ_{DM} with H(z) scaling
-	Injection Mass Loading	gas-metallicity (Z) dependent
no	Injection Velocity Floor	yes: 350 km/s

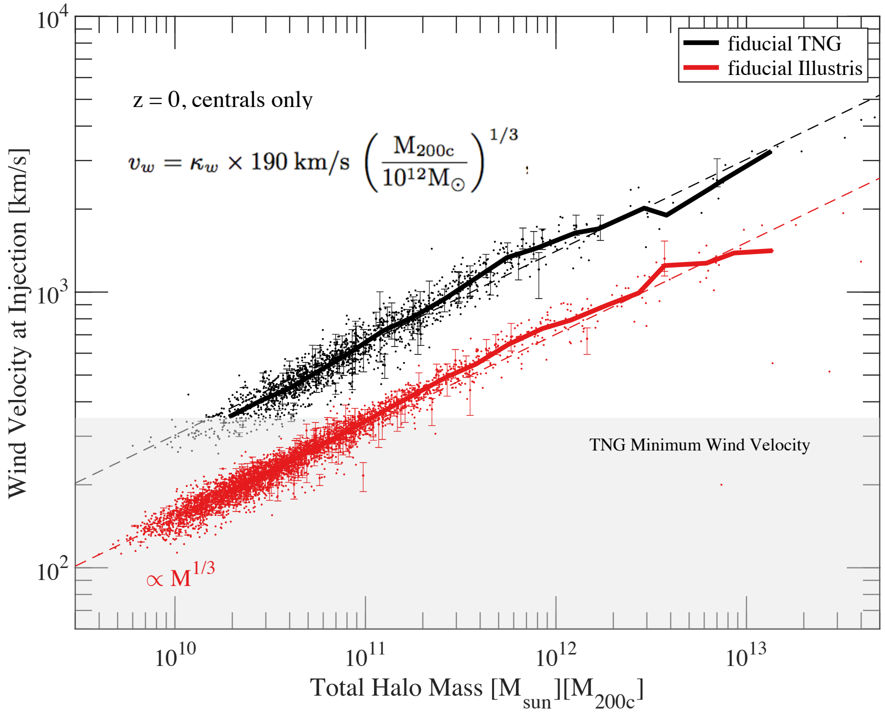
TNG Solution: Overall faster winds at all masses and redshifts, energy of the winds relatively larger in low mass systems in comparison to MW-like haloes

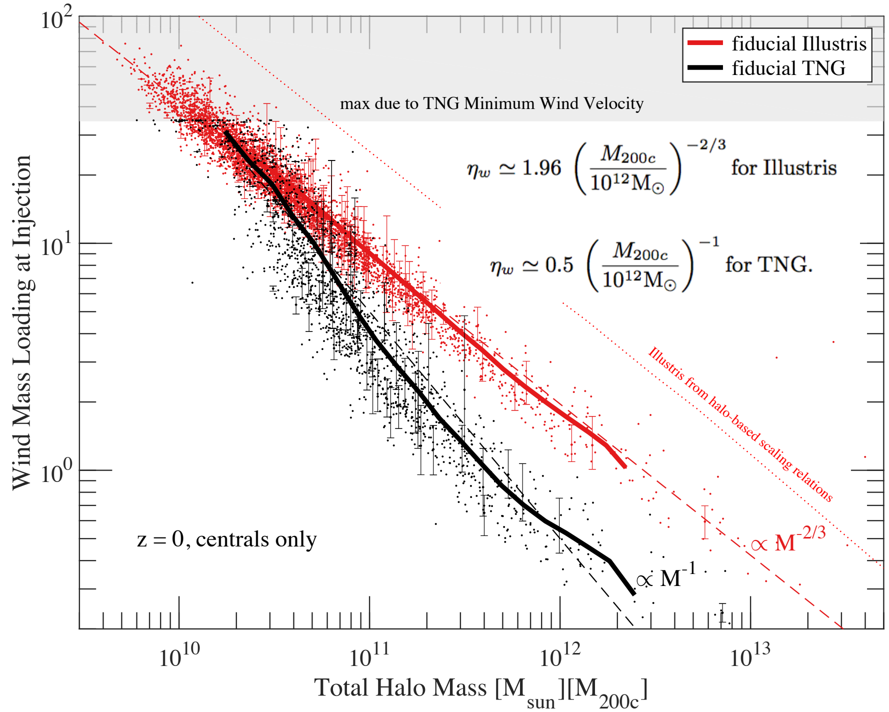
See also Schaye et al. 2015, Henriques et al. 2012, ….

Galactic Winds Implementation: e.g. on Directionality



Galactic Winds Implementation: velocity and energy at injection



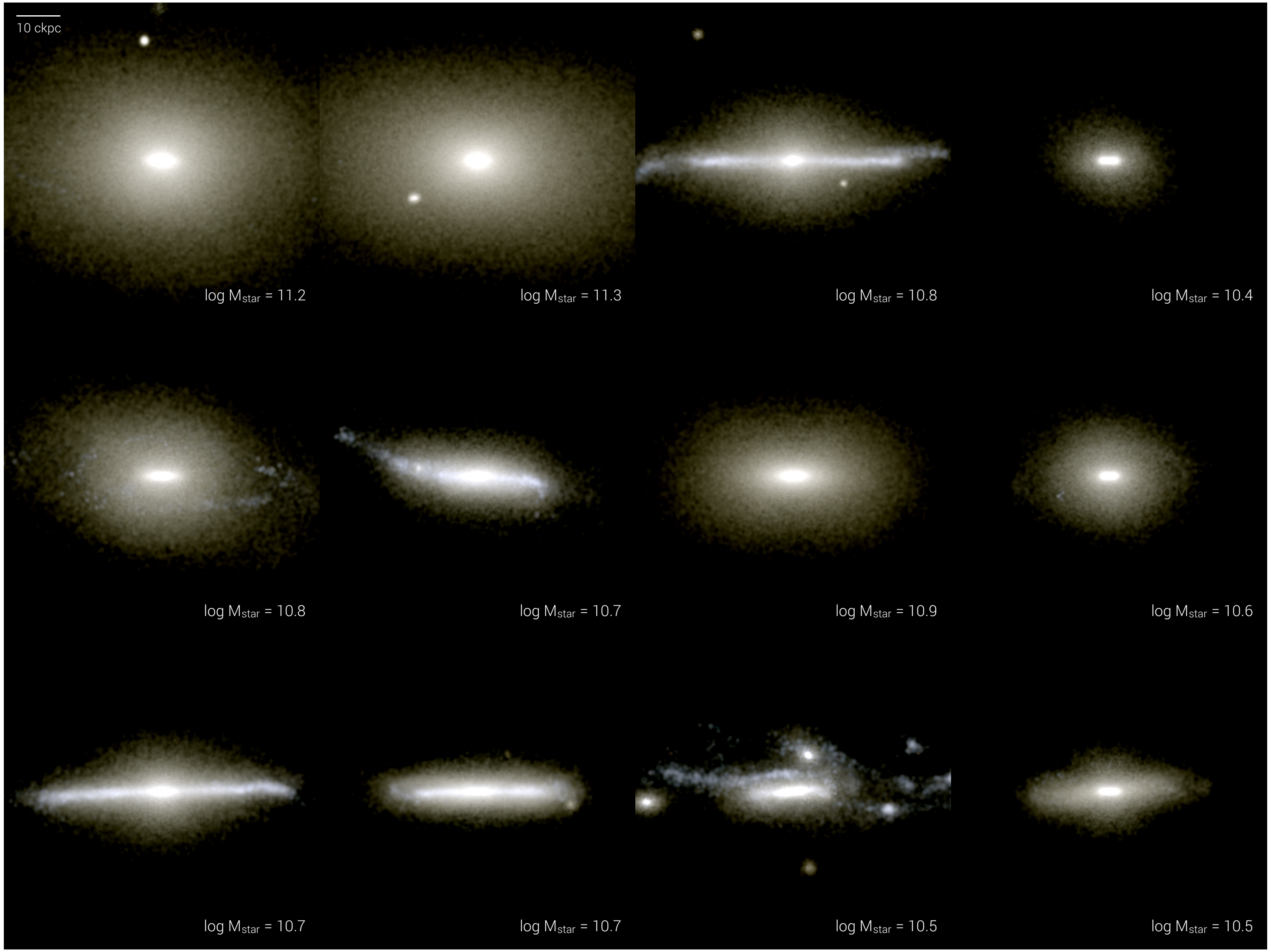


At injection: faster winds with a minimum at 350 km/s;
lower wind energy for winds spawning from high metallicity gas

=> more energetic and faster gas outflows in the CGM
i.e. more effective galactic winds at preventing SF at high redshifts and in small galaxies
(relatively to MW-like galaxies)

The desired outcome of TNG galactic winds

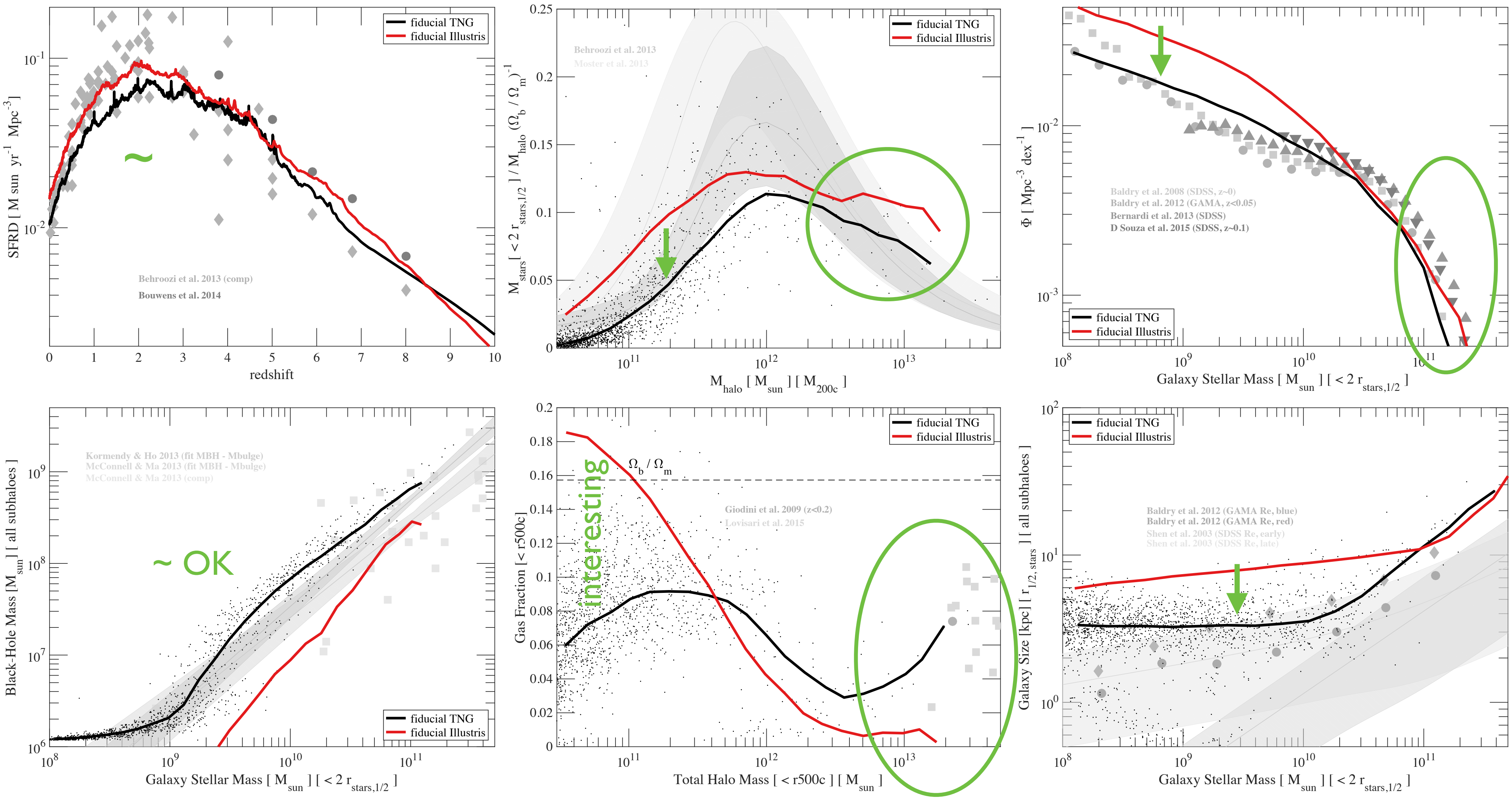
[L12.5n512 box]



Credits D. Nelson

The desired outcome of TNG galactic winds

[L25n512 box]



On the AGN feedback

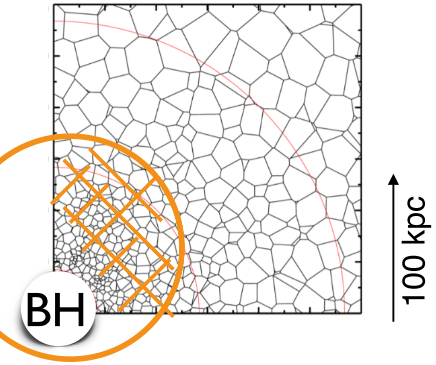
See also Choi et al. 2012, 2014, 2015; Dubois et al. 2010, 2012

BH Feedback Implementation

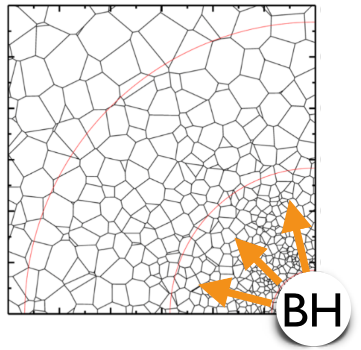
Phenomenology of the issue: Illustris BH feedback is too violent, removes all the gas from the halo and yet does not quench the central galaxies

BHs and BH Feedback

ILLUSTRIS		TNG
$1 \times 10^5 \mathrm{M}_\odot \mathrm{h}^{-1}$	BH Seed Mass	$8 \times 10^5 \mathrm{M}_\odot \mathrm{h}^{-1}$
$5 \times 10^{10} \mathrm{M}_\odot \mathrm{h}^{-1}$	FoF Halo Mass for BH seeding	$5 \times 10^{10} \mathrm{M}_\odot \mathrm{h}^{-1}$
$\alpha = 100$ Boosted Bondi-Hoyle	BH Accretion	Un-boosted Bondi-Hoyle (w/ v_A)
parent gas cell, Eddington limited	BH Accretion	nearby cells, Eddington limited
fixed to halo potential minimum	BH Positioning	fixed to halo potential minimum
Two: "Quasar/Radio"	BH Feedback Modes	Two: "High/Low Accretion State"
Thermal Injection around BHs	High-Accr-Rate Feedback	Thermal Injection around BHs
Thermal 'Bubbles' in the ICM	Low-Accr-Rate Feedback	BH-driven kinetic wind
constant: 0.2	Low/High Accretion Transition: χ	BH-mass dependent, $\leqslant 0.1$



TNG Solution: New low-accretion feedback mode, implemented as a **BH-driven wind** that impacts the gas surrounding the BH



BH Feedback on Halo Scales

Zoom Cluster 5: 7×10^{14} Msun

Illustris

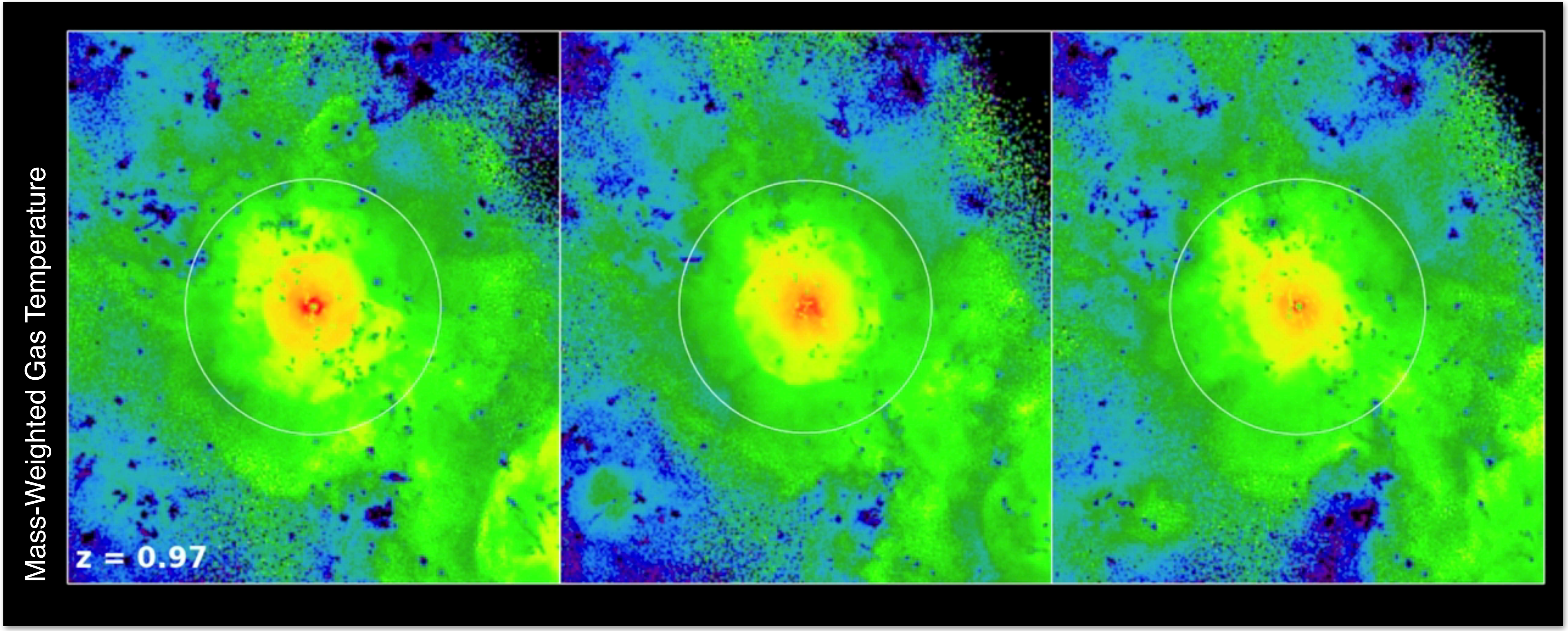
Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

TNG

Kinetic feedback
kicks in random directions to neighboring gas cells

Auriga

Thermal feedback
Inflates as many small, hot bubbles as needed, when δM_{BH} is above a threshold



BH Feedback on Halo Scales

Zoom Cluster 2: 4×10^{13} Msun

Illustris

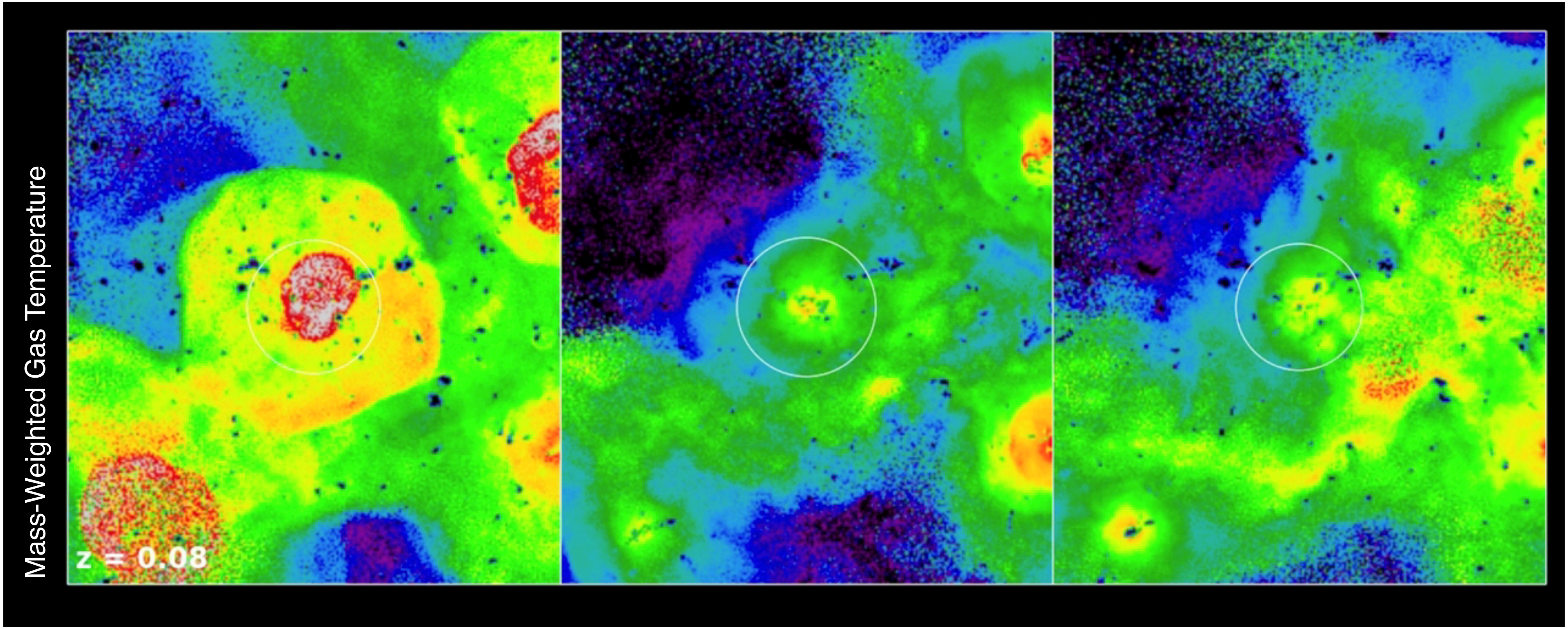
Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

TNG

Kinetic feedback
kicks in random directions to neighboring gas cells

Auriga

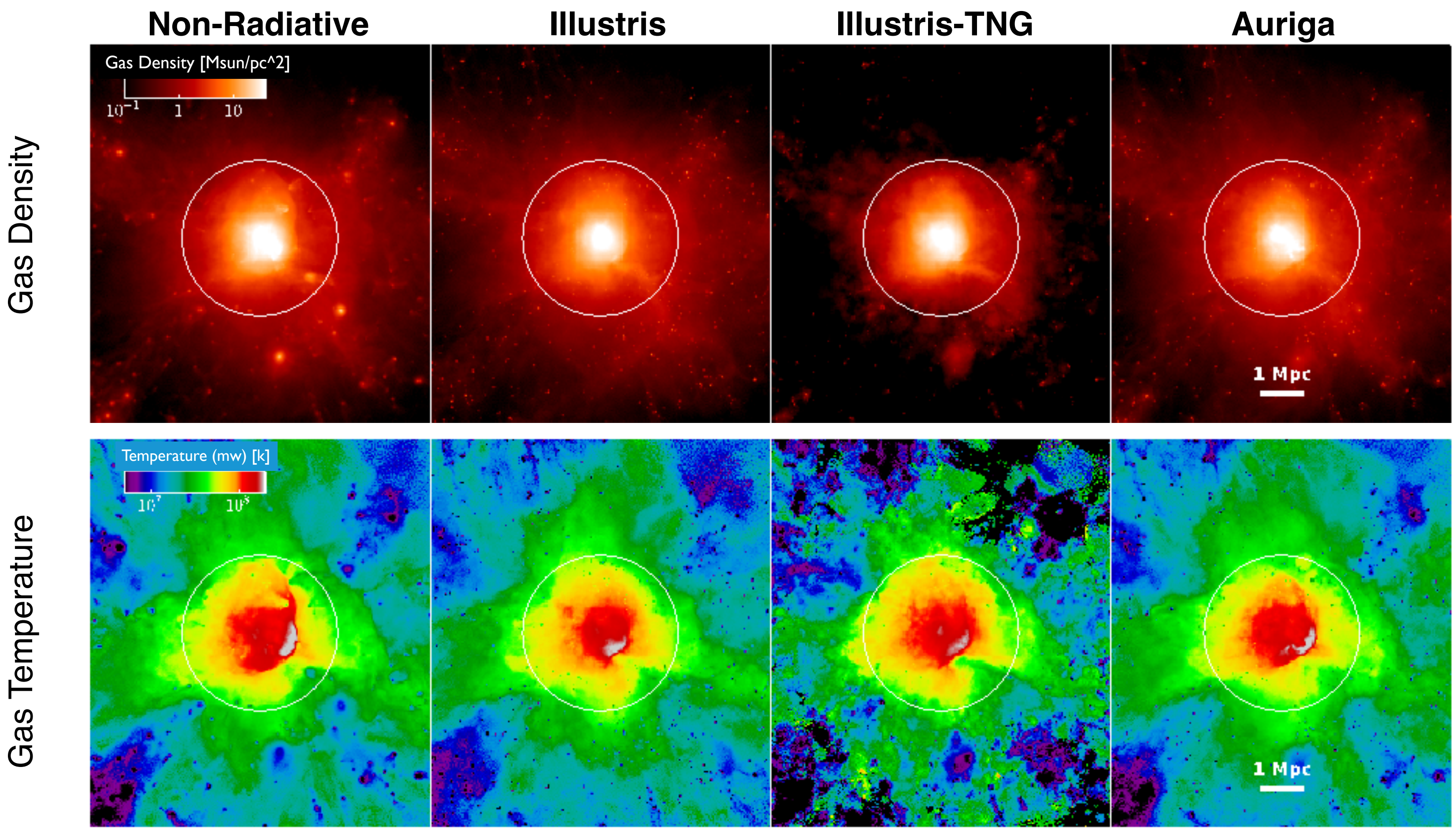
Thermal feedback
Inflates as many small, hot bubbles as needed, when δM_{BH} is above a threshold



BH Feedback on Halo Scales

Zoom Cluster 6: 3x10^{15} Msun

The differences in the AGN feedback mechanisms appear more and more manifest towards low masses

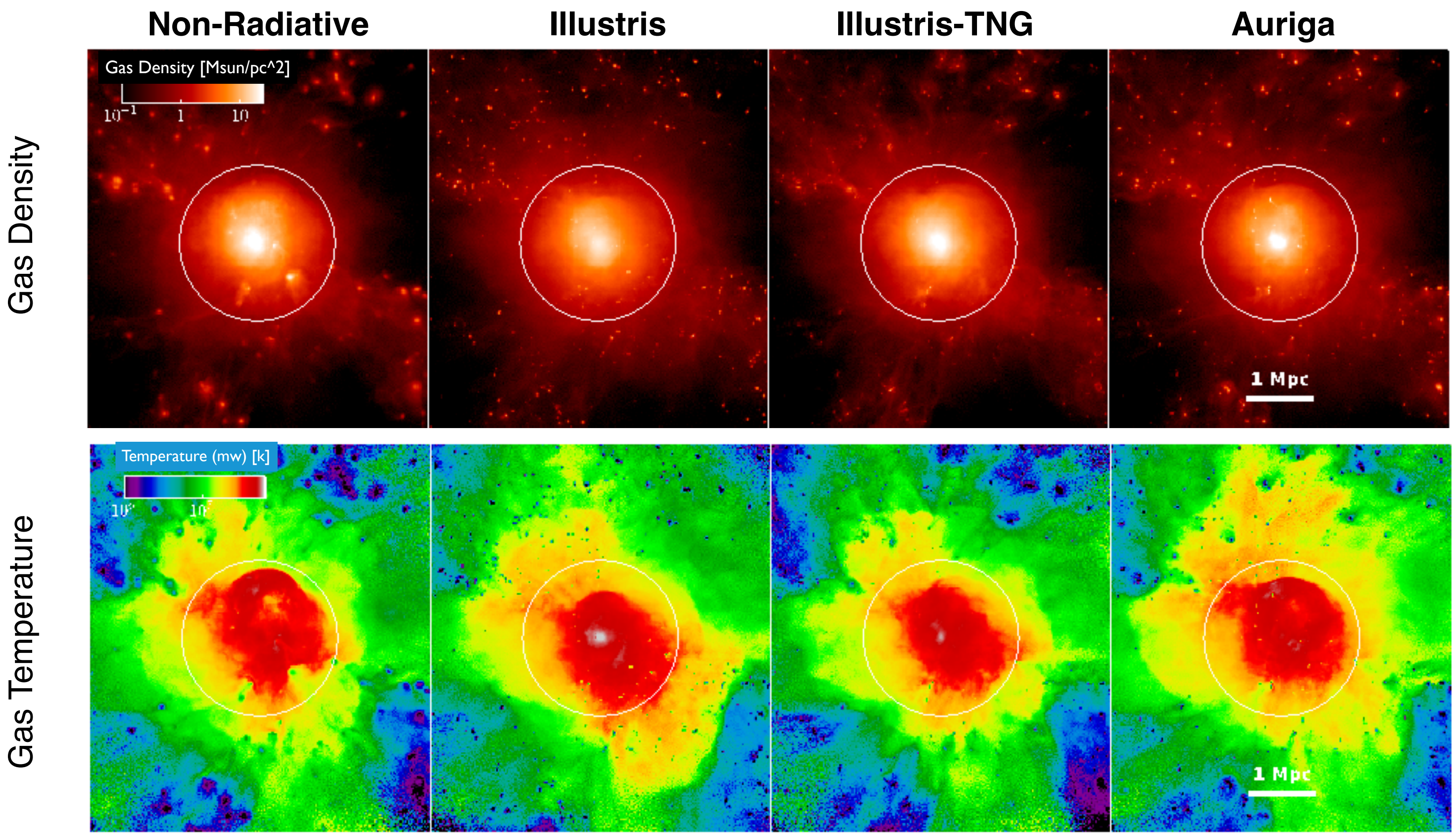


Credits: C. Popa

BH Feedback on Halo Scales

Zoom Cluster 5: 7×10^{14} Msun

The differences in the AGN feedback mechanisms become more and more manifest towards low masses

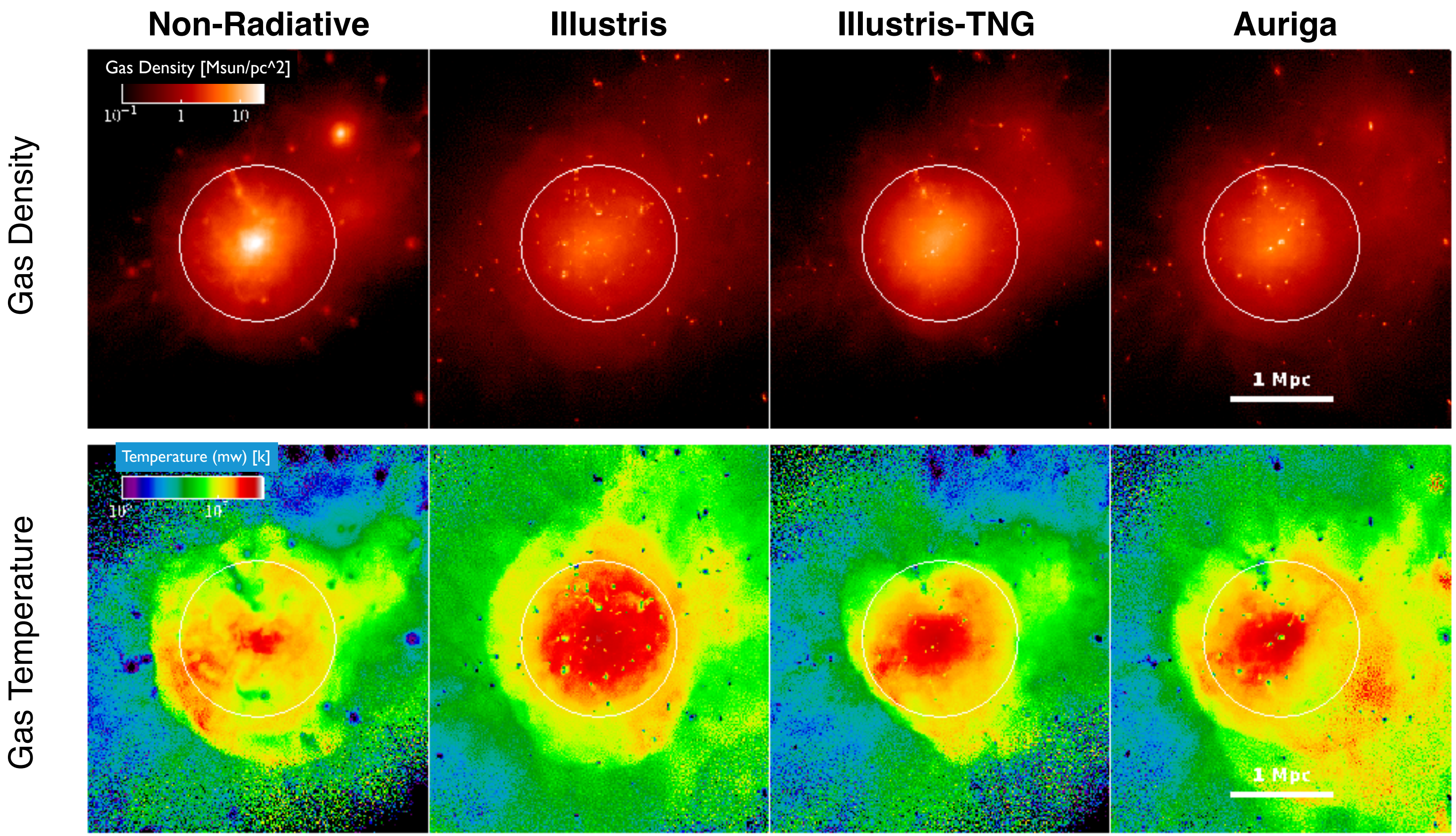


Credits: C. Popa

BH Feedback on Halo Scales

Zoom Cluster 4: 2x10^{14} Msun

The differences in the AGN feedback mechanisms become more and more manifest towards low masses

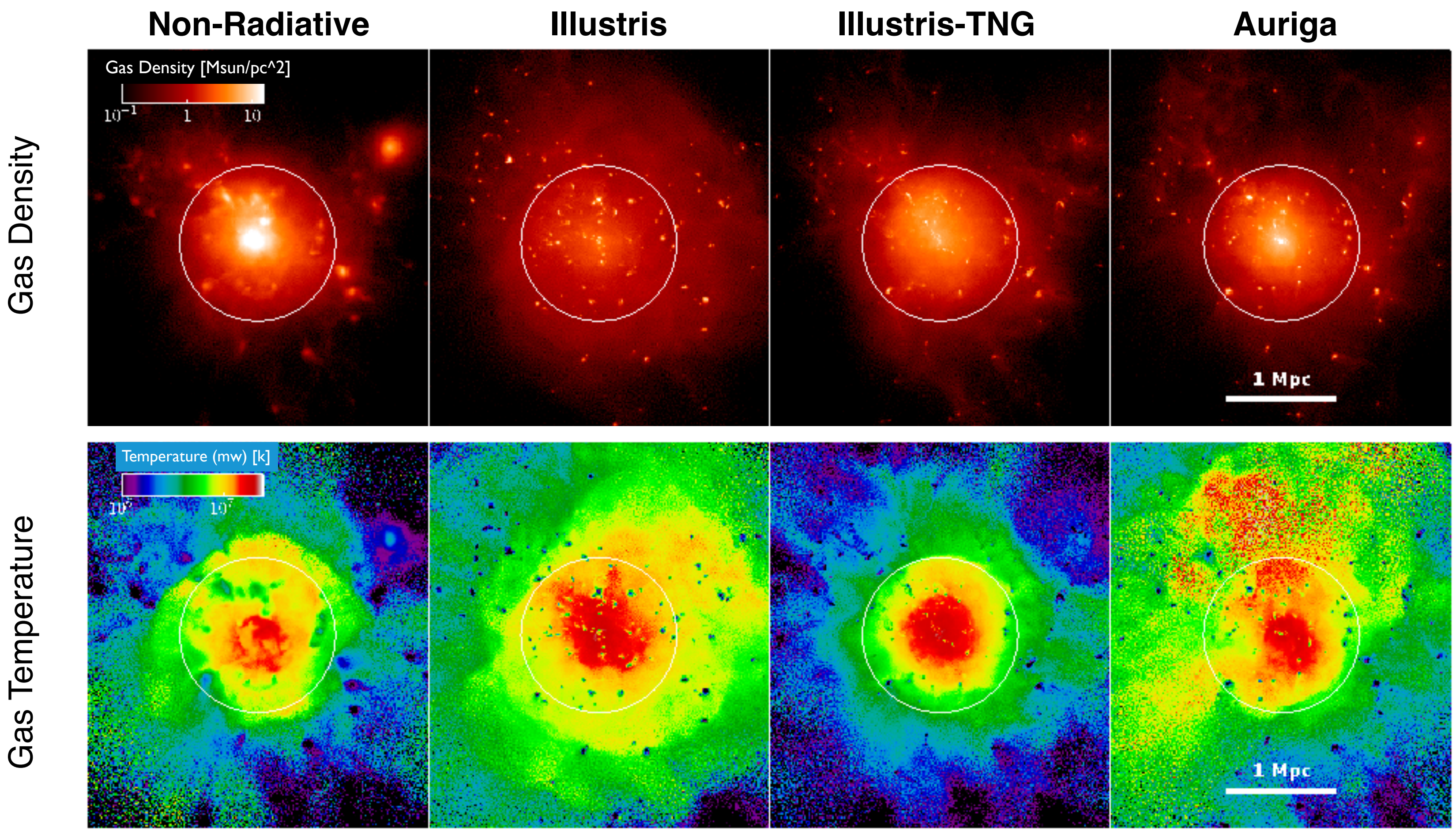


Credits: C. Popa

BH Feedback on Halo Scales

Zoom Cluster 3: 1x10^{14} Msun

The differences in the AGN feedback mechanisms become more and more manifest towards low masses

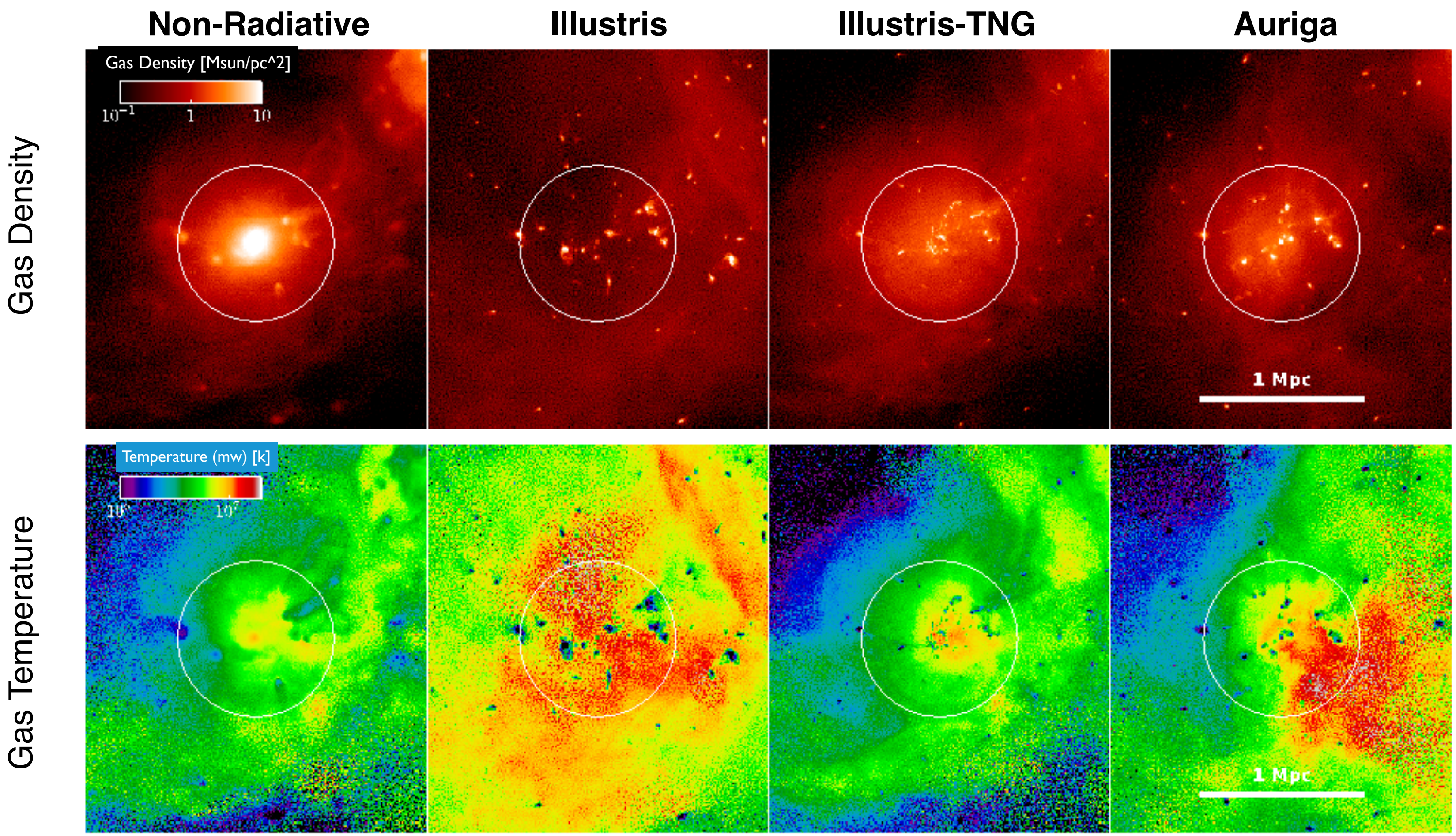


Credits: C. Popa

BH Feedback on Halo Scales

Zoom Cluster 2: 4x10^{13} Msun

The differences in the AGN feedback mechanisms become more and more manifest towards low masses

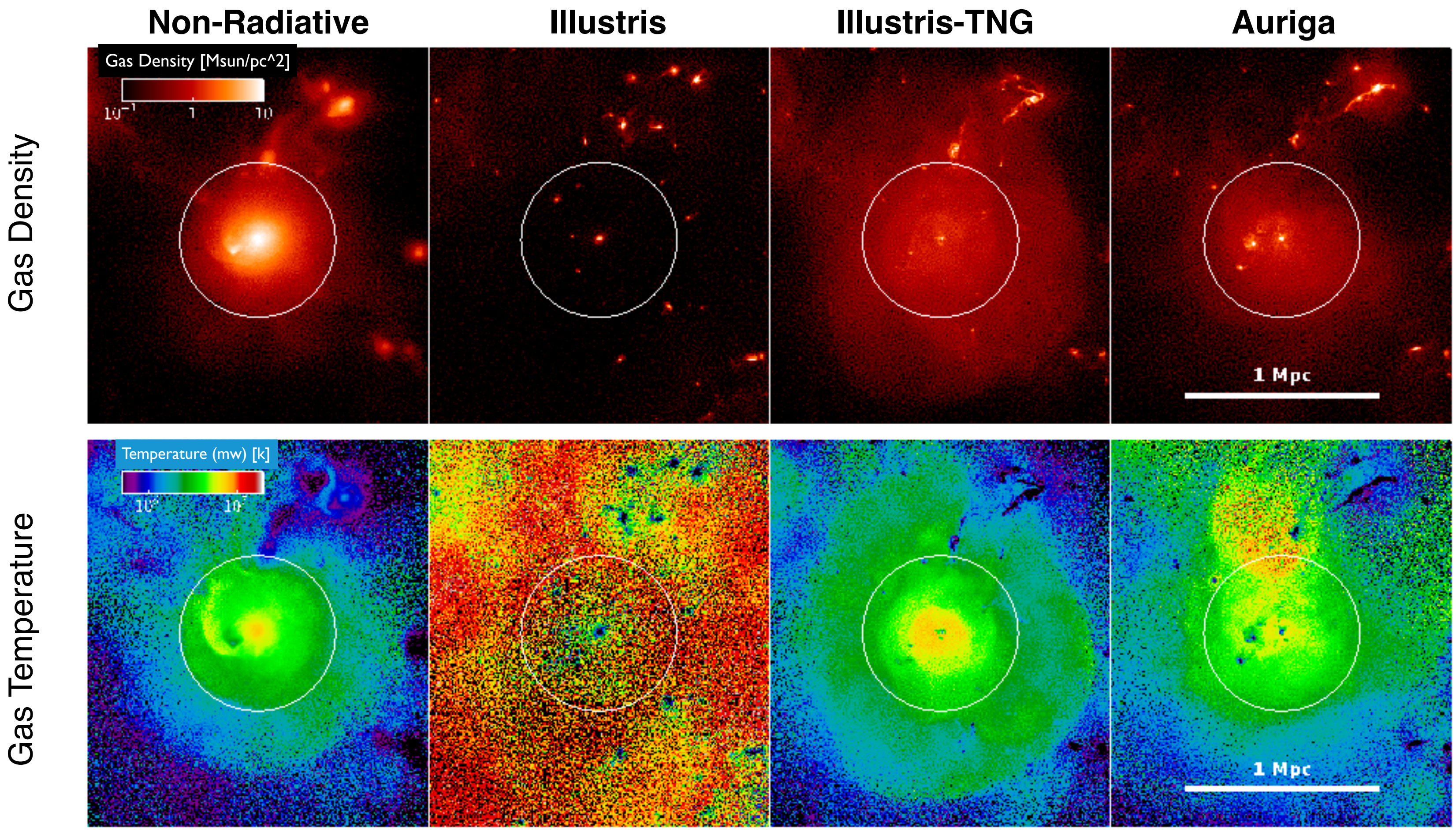


Credits: C. Popa

BH Feedback on Halo Scales

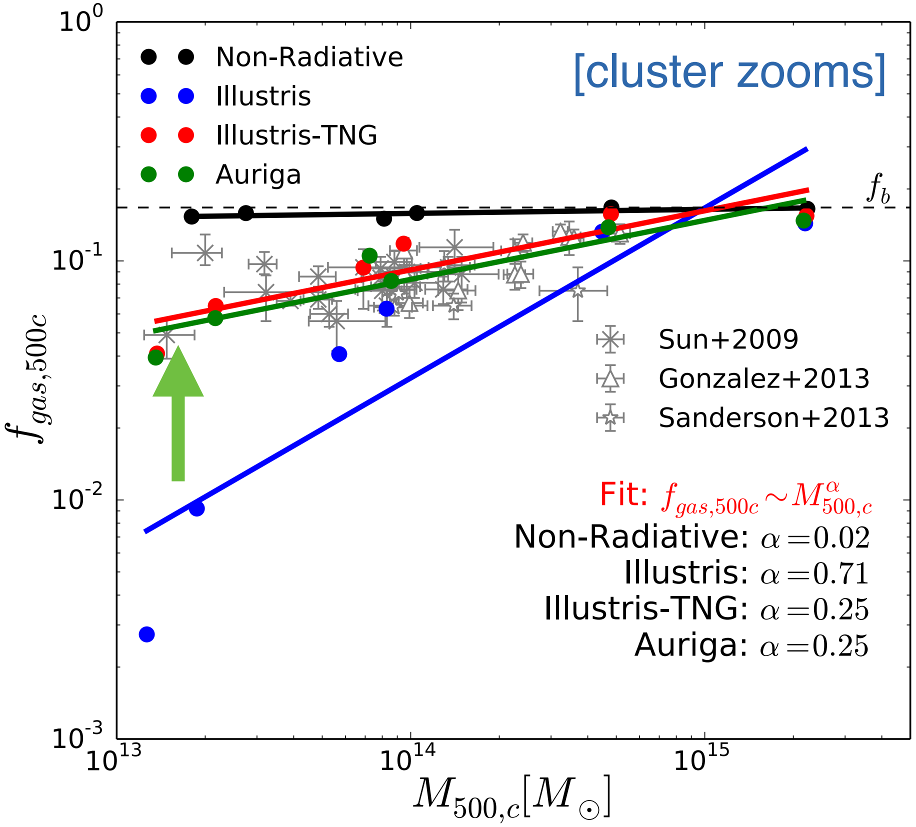
Zoom Cluster 1: $2x10^{13}$ Msun

The differences in the AGN feedback mechanisms become more and more manifest towards low masses

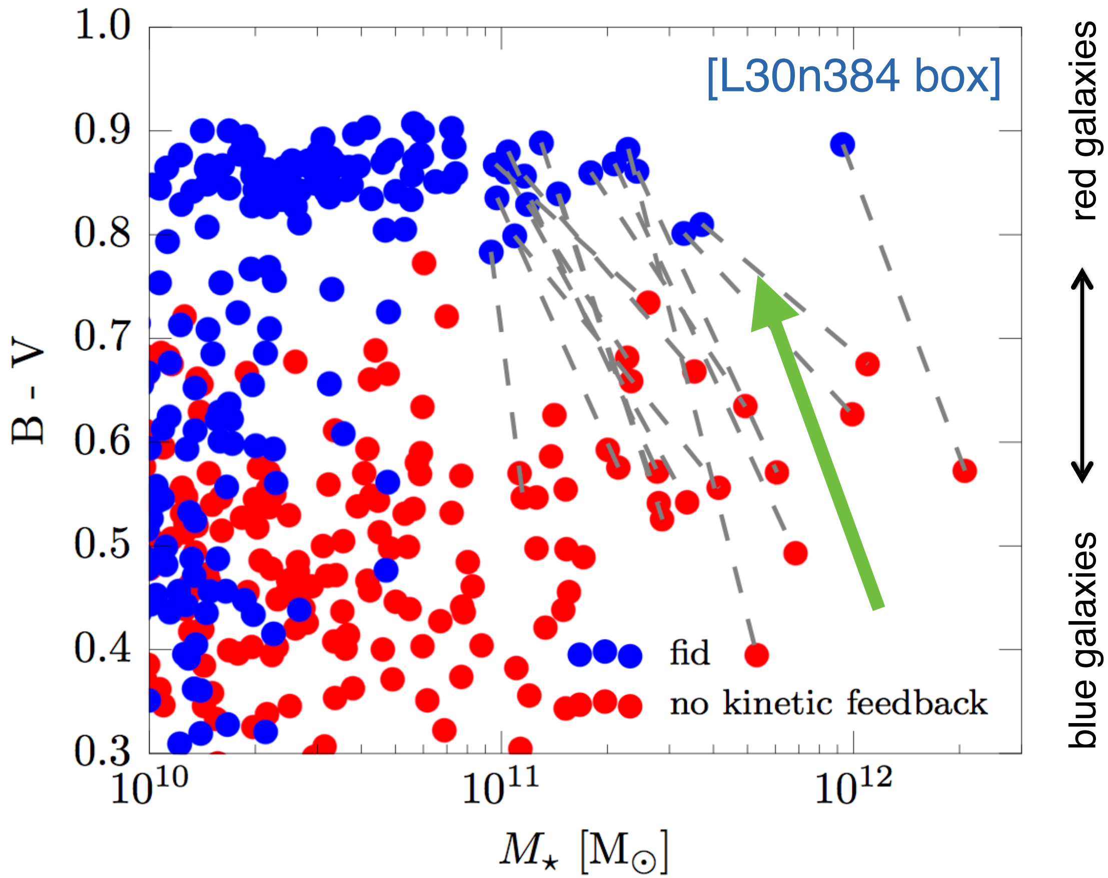


Credits: C. Popa

The desired outcome of TNG BH kinetic feedback



In the Illustris model,
clusters are devoid of gas (< 10^{14} Msun)
Not anymore in TNG



In the Illustris model, massive galaxies were too
blue compared to SDSS.
The BH kinetic feedback makes them red

Credits: C. Popa, A. Pillepich et al.

Weinberger, Springel, et al. 2017

Conclusions and
Looking ahead

The TNG Goals

improved by the BH-driven winds

1. To address all the physical model issues identified in Illustris galaxies and haloes

   1. Too high Cosmic SFRD at z<1
   2. Too high galaxy stellar mass function at z=0 at the low & high mass ends
   3. Too extended stellar sizes for galaxies < 10^10 Msun
   4. (Spurious ring-like features at z=0)
   5. Too low halo gas fractions with R500 in haloes > 10^13.5 Msun
   6. Not well enhanced galaxy color bimodality

improved by minimum wind velocity and Z-dependence

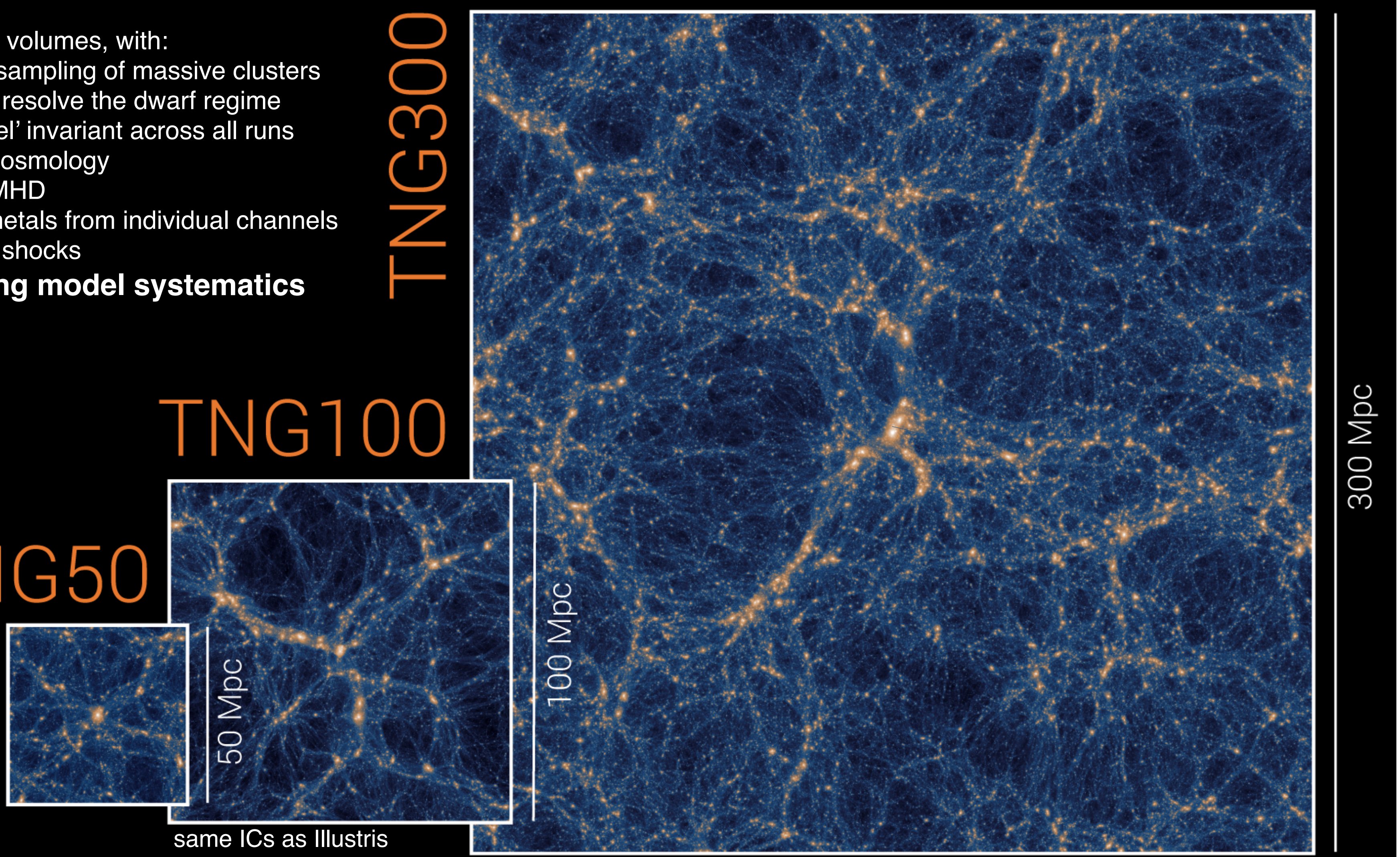
2. To introduce new sub grid treatments, new physics, and numerical improvements

3. To significantly expand the scope and include new diagnostic tools

The TNG Simulations

Three flagship volumes, with:

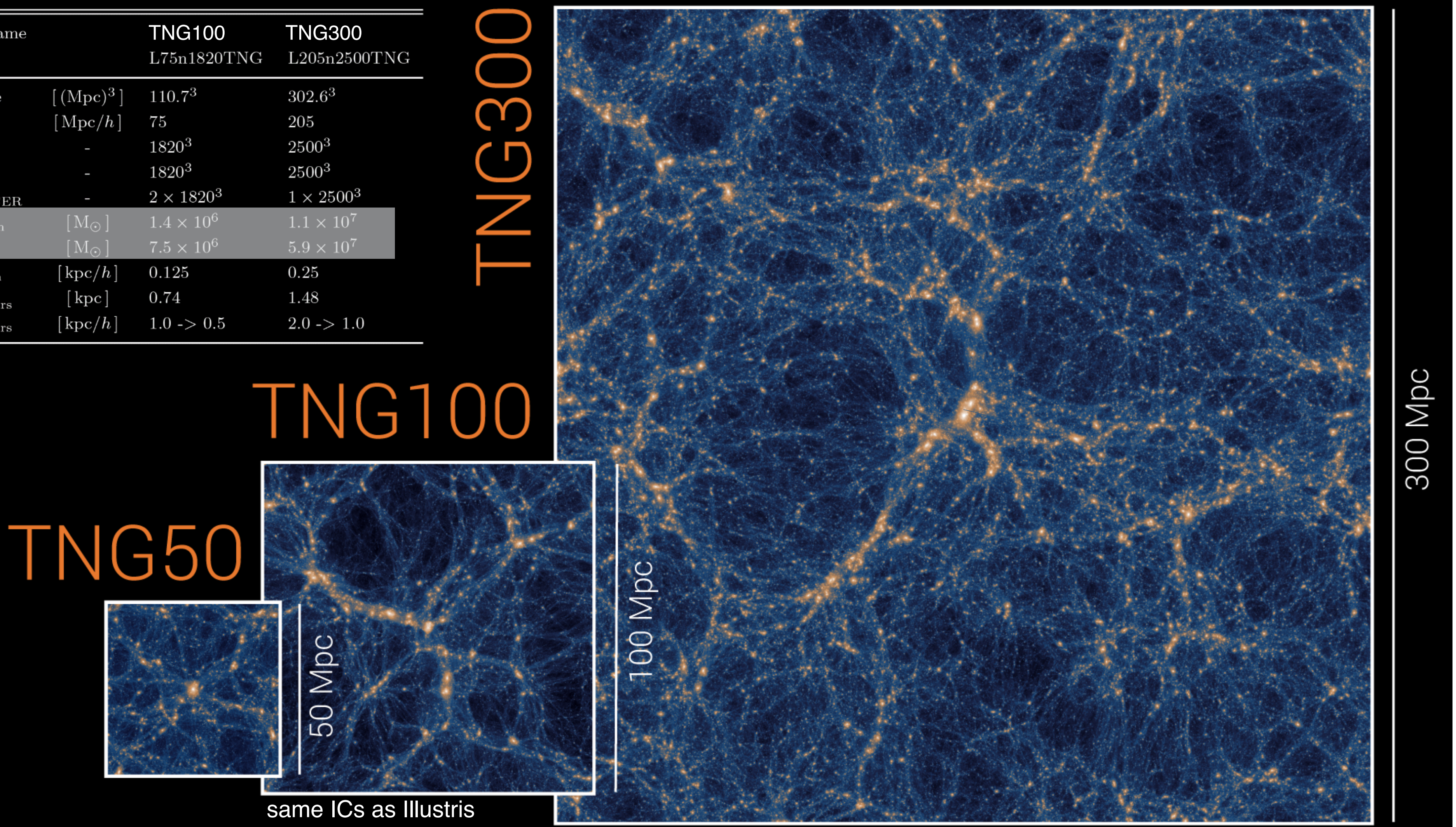
- Statistical sampling of massive clusters
- Starting to resolve the dwarf regime
- 'TNG model' invariant across all runs
- Updated Cosmology
- Including MHD
- Tracking metals from individual channels
- Identifying shocks
- **Assessing model systematics**



Credits: D. Nelson+A.Pillepich

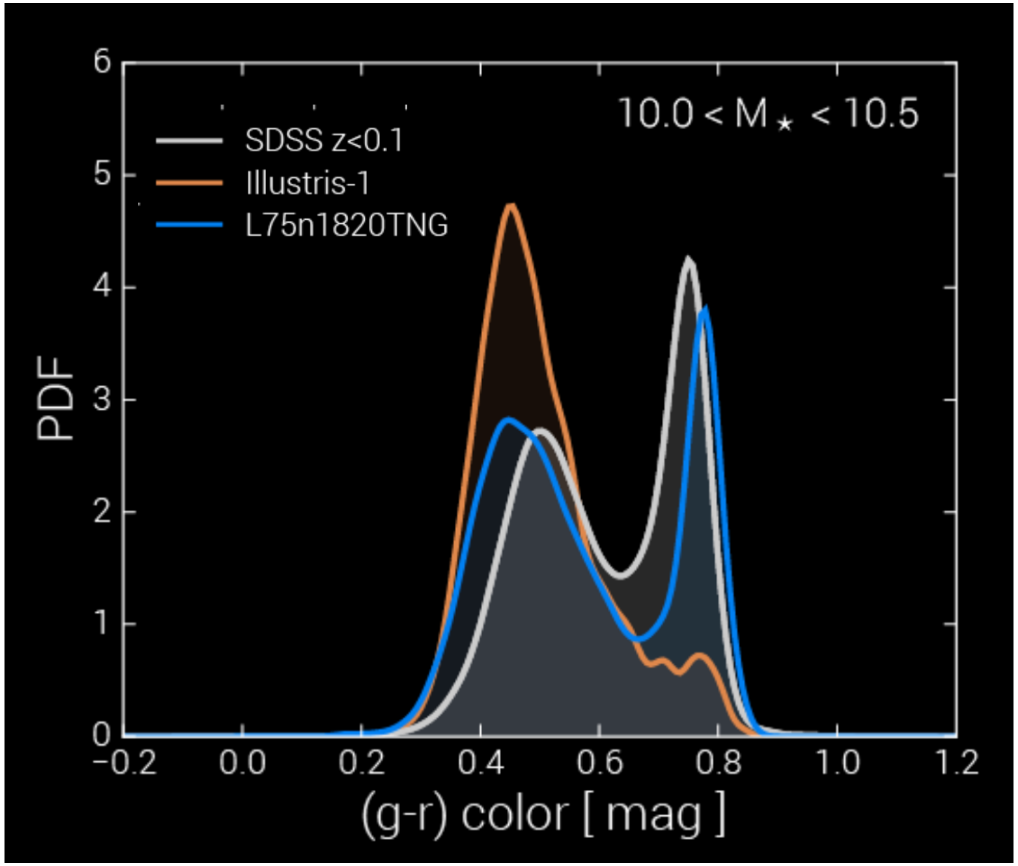
The TNG Simulations

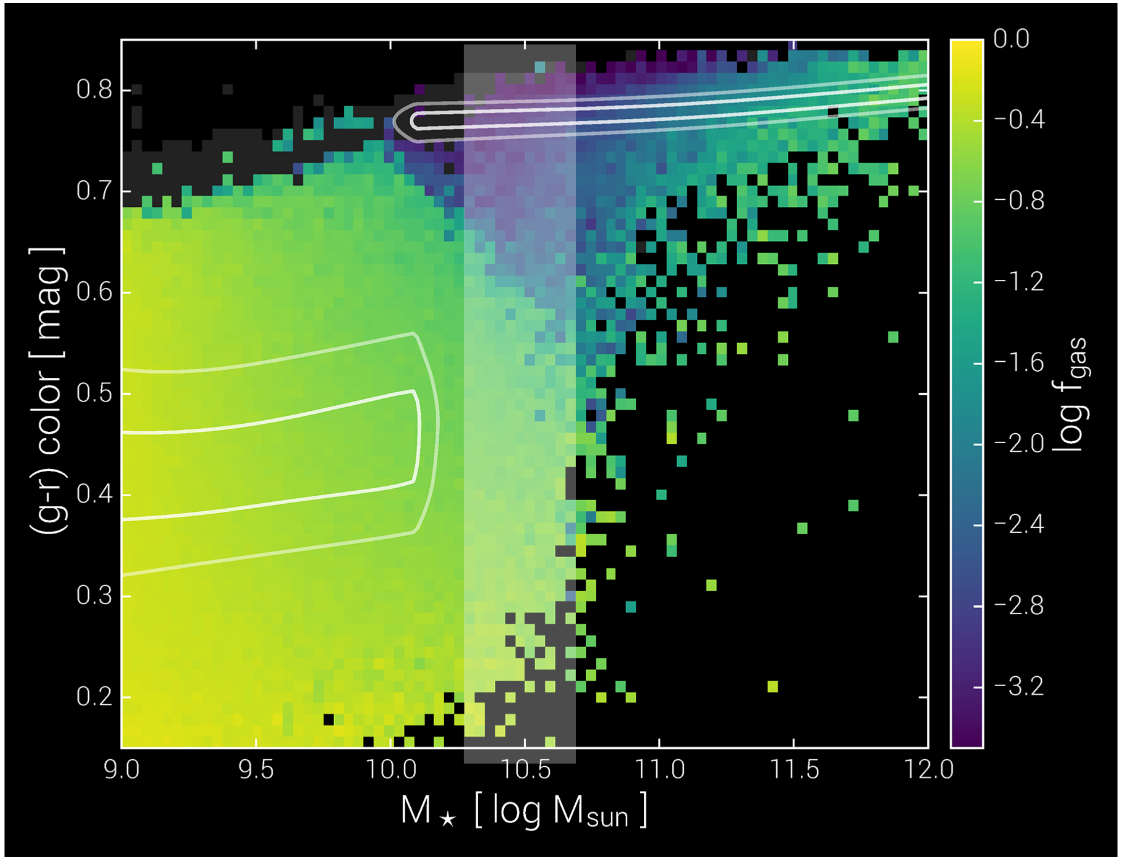
Run Name		TNG100 L75n1820TNG	TNG300 L205n2500TNG
Volume	$[(\mathrm{Mpc})^3]$	110.7^3	302.6^3
$L_{\rm box}$	$[\mathrm{Mpc}/h]$	75	205
$N_{\rm GAS}$	-	1820^3	2500^3
$N_{\rm DM}$	-	1820^3	2500^3
$N_{\rm TRACER}$	-	2×1820^3	1×2500^3
$m_{\rm baryon}$	$[\mathrm{M}_\odot]$	1.4×10^6	1.1×10^7
$m_{\rm DM}$	$[\mathrm{M}_\odot]$	7.5×10^6	5.9×10^7
$\epsilon_{\rm gas,min}$	$[\mathrm{kpc}/h]$	0.125	0.25
$\epsilon_{\rm DM,stars}^{z=0}$	$[\mathrm{kpc}]$	0.74	1.48
$\epsilon_{\rm DM,stars}$	$[\mathrm{kpc}/h]$	1.0 -> 0.5	2.0 -> 1.0



Credits: D. Nelson+A.Pillepich

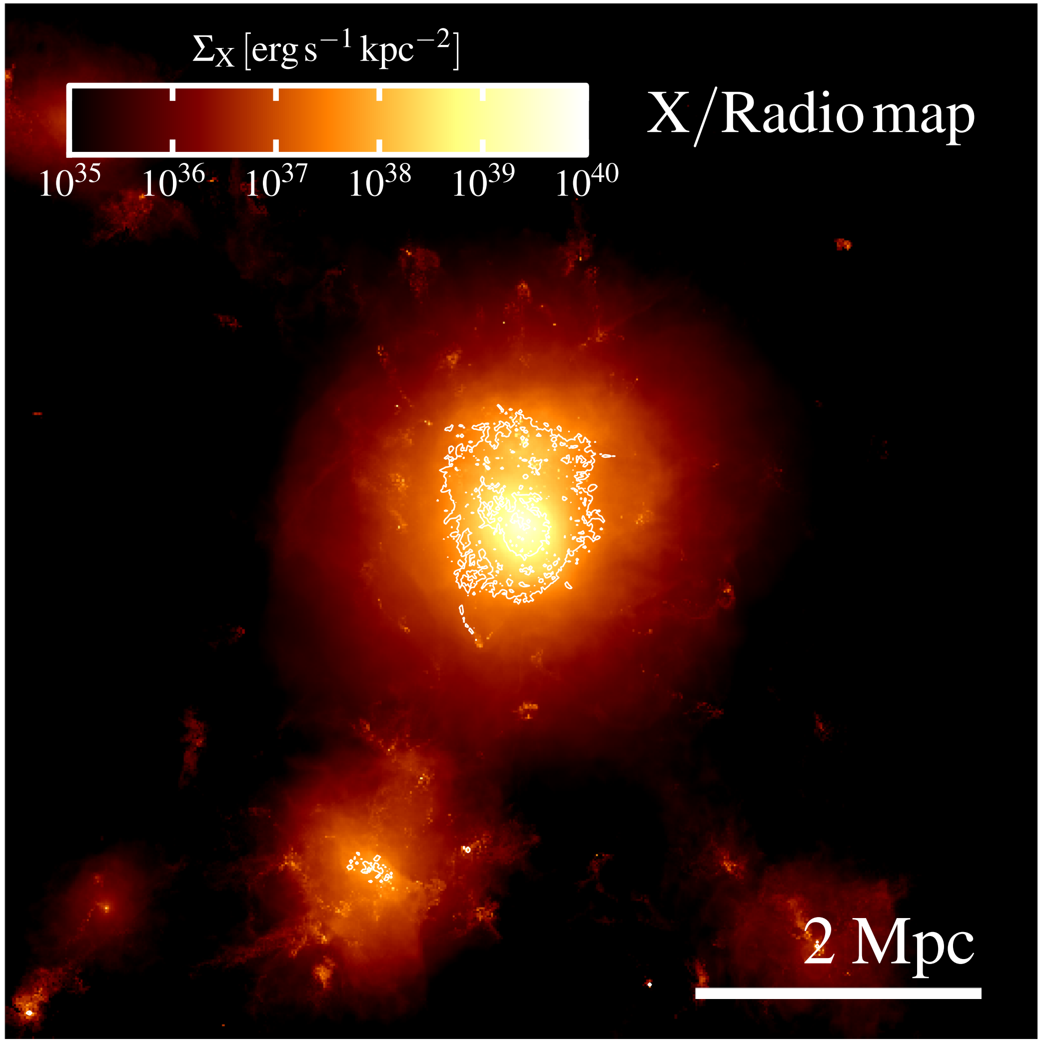
The TNG Simulations: on galaxy colours and the green valley





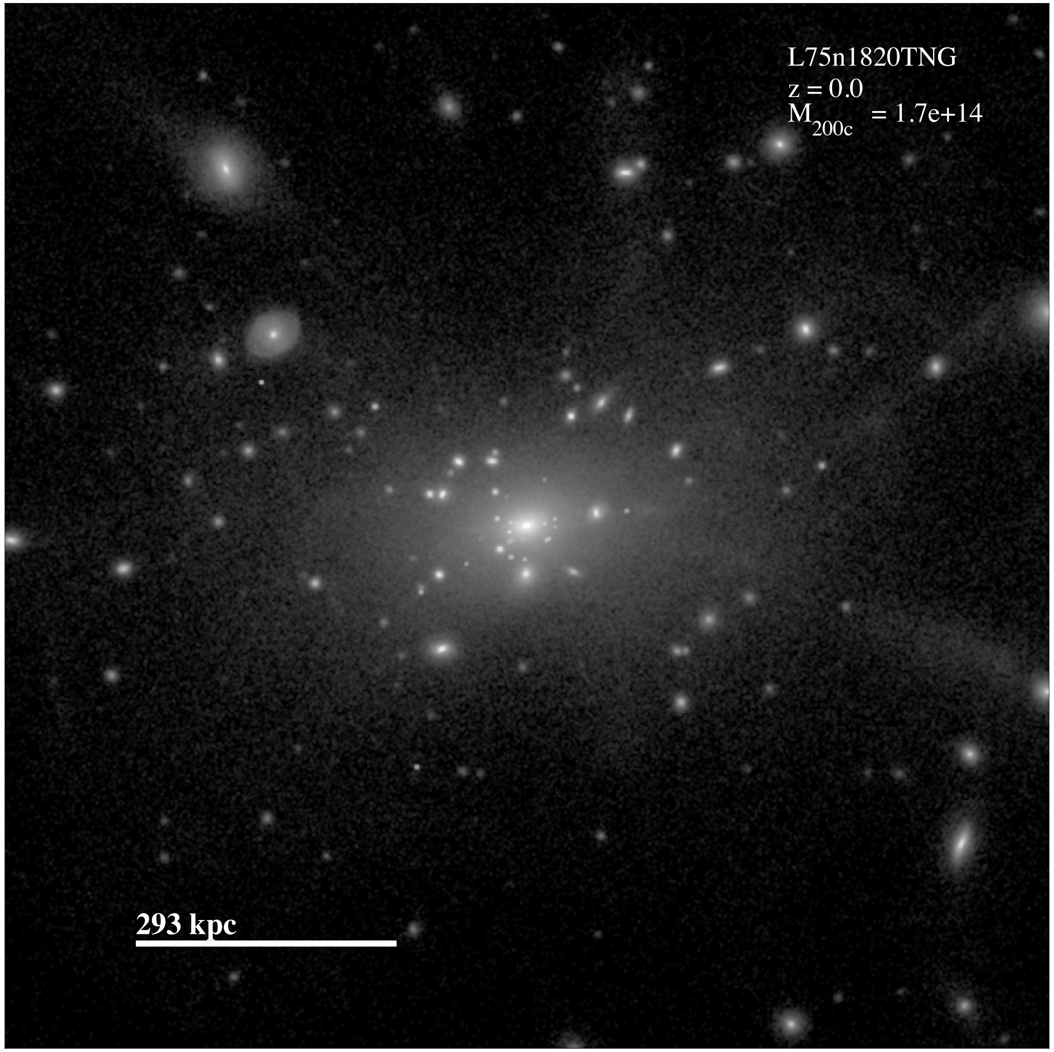
Nelson et al. in prep

The TNG Simulations: on B fields and radio haloes



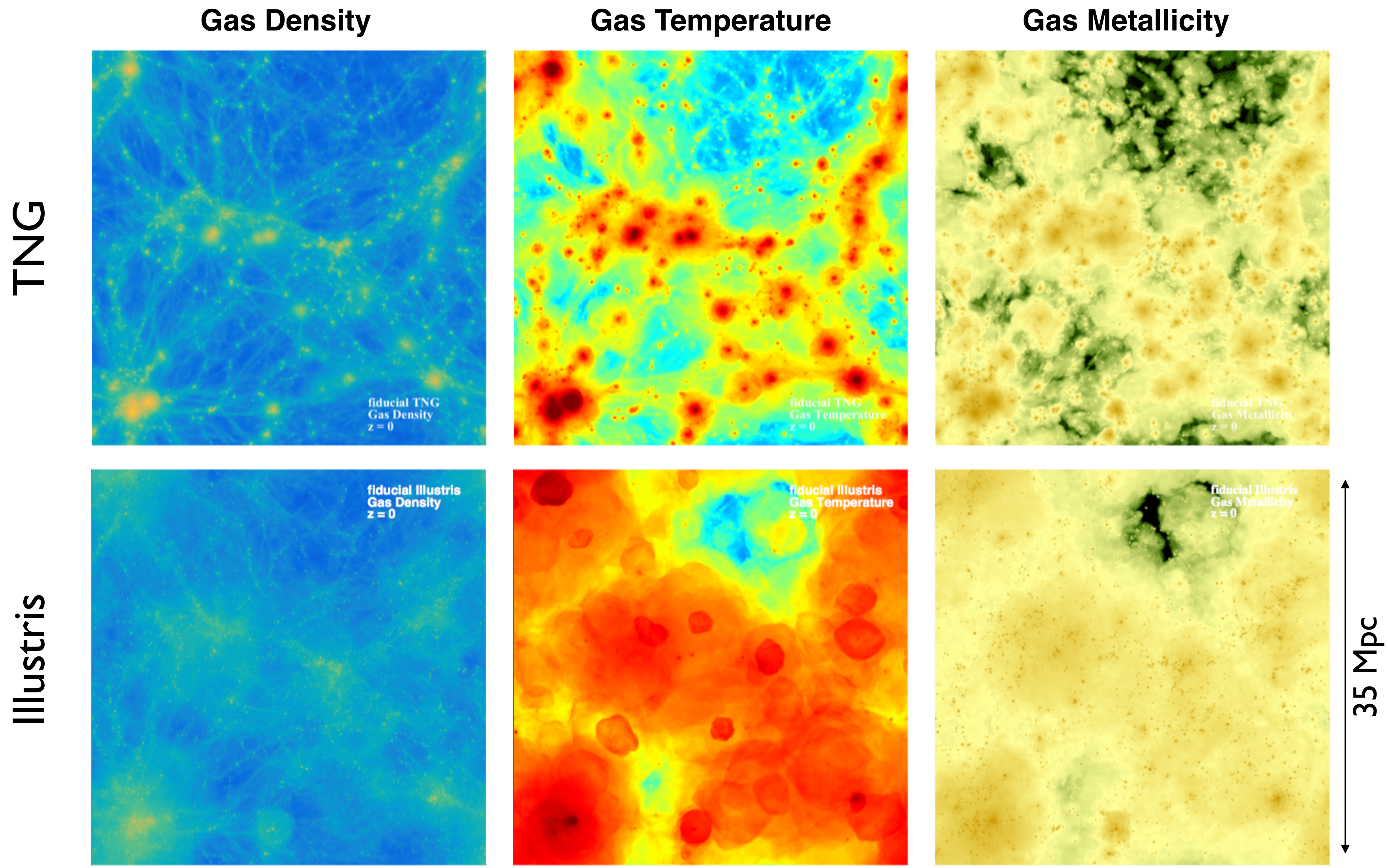
Marinacci et al. in prep

The TNG Simulations: on the assembly and properties of the ICL



Pillepich et al. in prep

The TNG Simulations: on the enrichment of the IGM



~11 Mpc

Credits: Dylan Nelson (MPA)