Implementations of AGN feedback beyond the Illustris model: impact on the ICM

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(ITC/CfA Harvard => MPIA)

with
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Lars Hernquist (Harvard)
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Time since the Big Bang: 2.7 billion years

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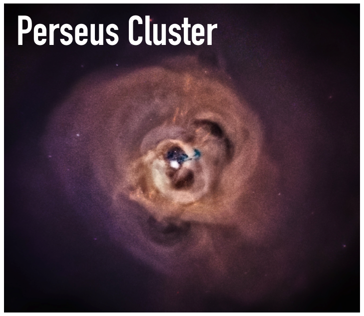
ILLUSTRIS

Scope of this Talk/Work

1. Propose an alternative approach to Simulate **Galaxy Clusters**

   With Arepo, calibrating the feedback/physics on large-scale cosmological volumes, prioritizing the outcome in terms of galaxy populations and stellar contents, across wide mass ranges, without retuning at different resolutions

2. Utilize **AGN feedback subgrid** models which have something to do with reality



3. Investigate effects of different AGN feedback on the **thermodynamical properties of the ICM**

   a. Gas density and temperature maps

   b. X-ray and SZ scaling relations

   c. Gas temperature, Entropy, SZ profiles

The iClusters Comparison Project

6 Zooms from Millennium XXL
in 5 different Implementations:

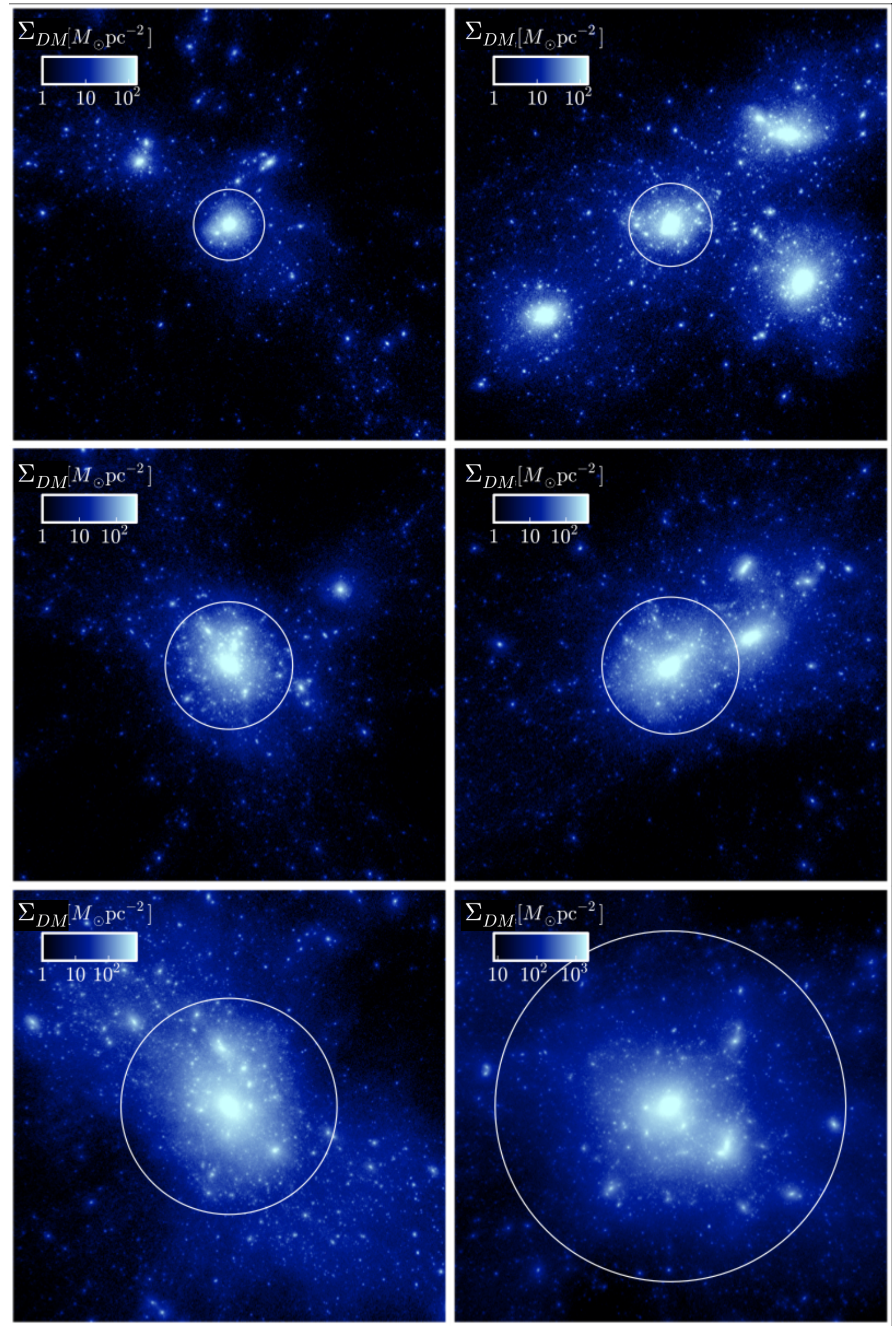
DARK MATTER ONLY
ADIABATIC/NON RADIATIVE

ILLUSTRIS
AURIGA
ILLUSTRIS-TNG

Mass range: 2×10^{13} - 3×10^{15} Msun (M_200c)

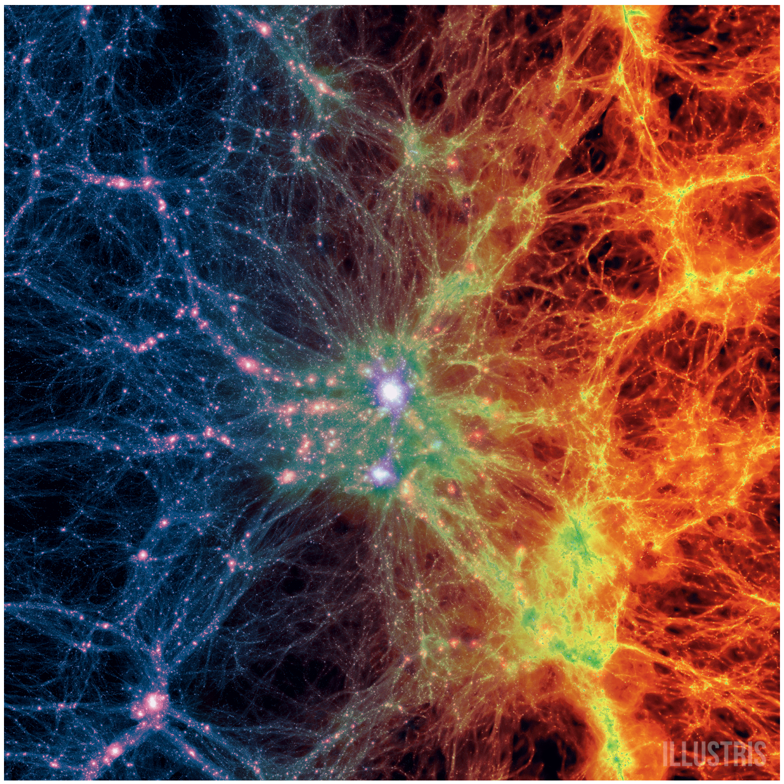
Res: 1.4/2.8 kpc softening, 1×10^{7}/ 6×10^{7} Msun

@ Odyssey (Harvard), @ Stampede (TACC), @ Hazelhen (Stuttgart)

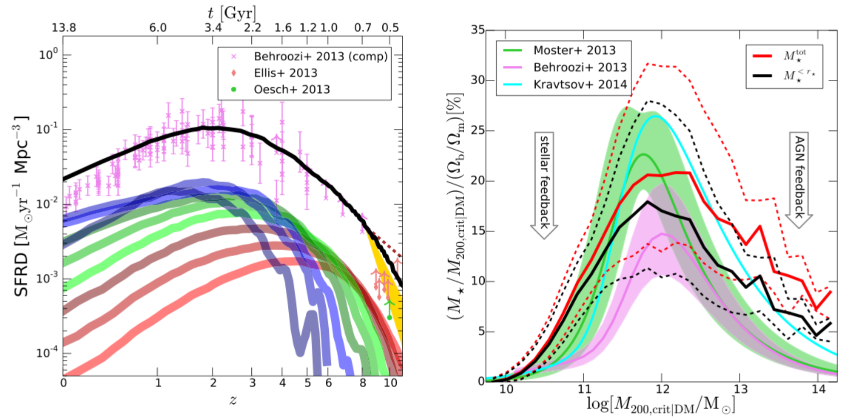


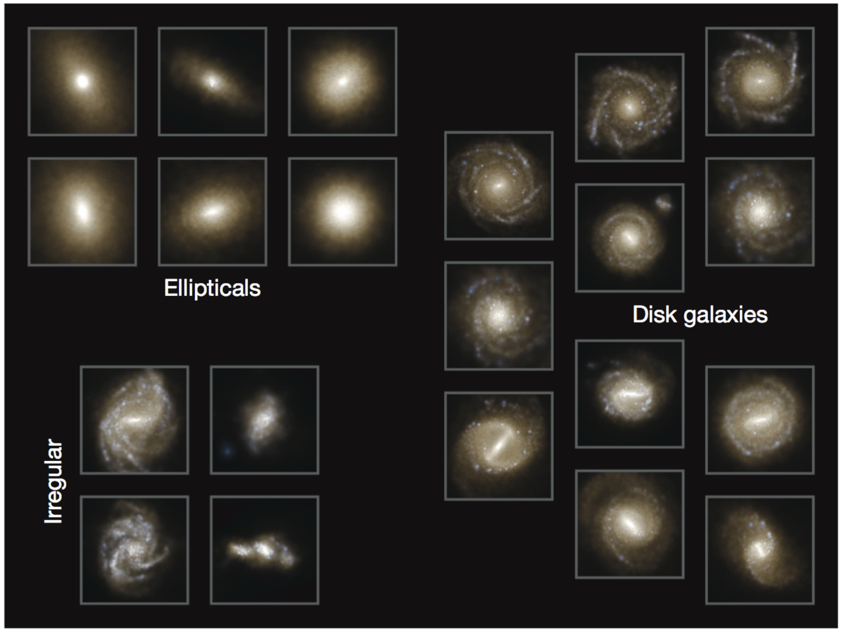
The subgrid models of reference (I): Illustris

106.5 Mpc Cosmological Box
(=> thousands of galaxies)
Mass Range: < 2×10^{14} Msun
Res: 0.7/1.4 kpc, 1.3×10^{6}/ 6.3×10^{6} Msun



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

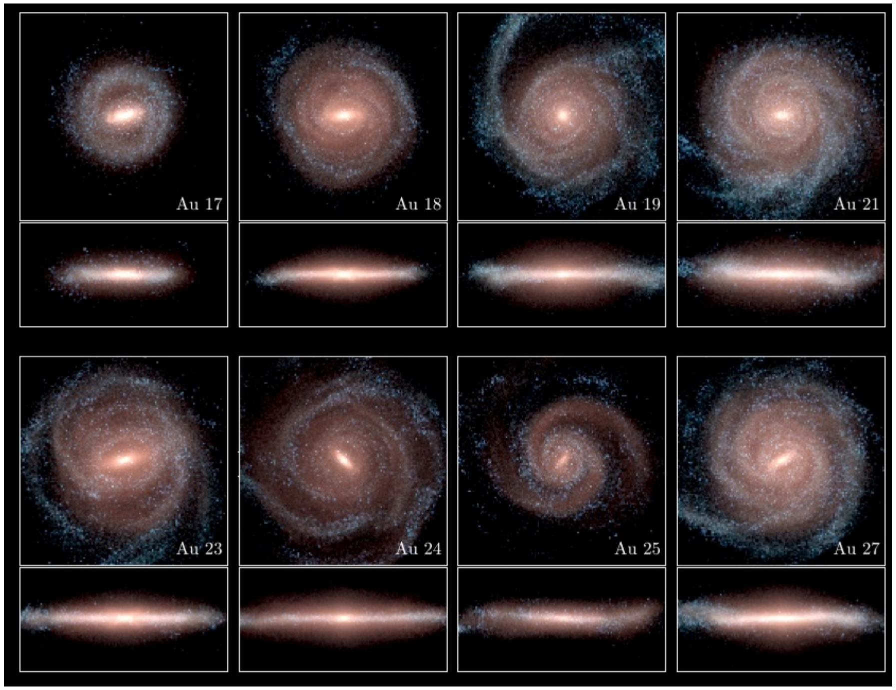


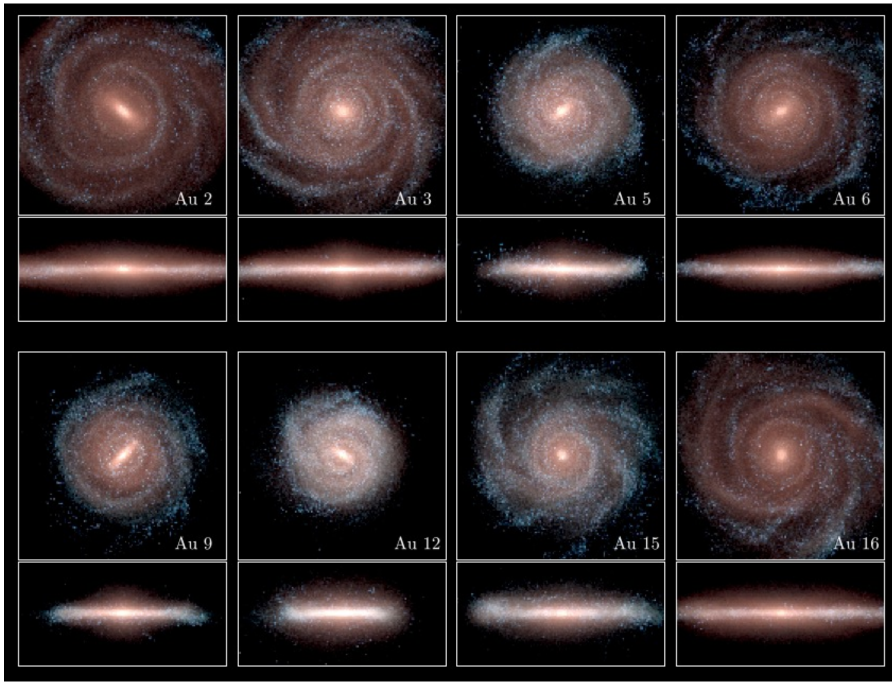


Vogelsberger et al. 2014a

The subgrid models of reference (II): The Auriga Galaxies

~30 Zoom-in Simulations
Mass Range: Milky-Way Galaxies
Res: << 0.7/1.4 kpc, 4x10^4/ 3x10^5 Msun





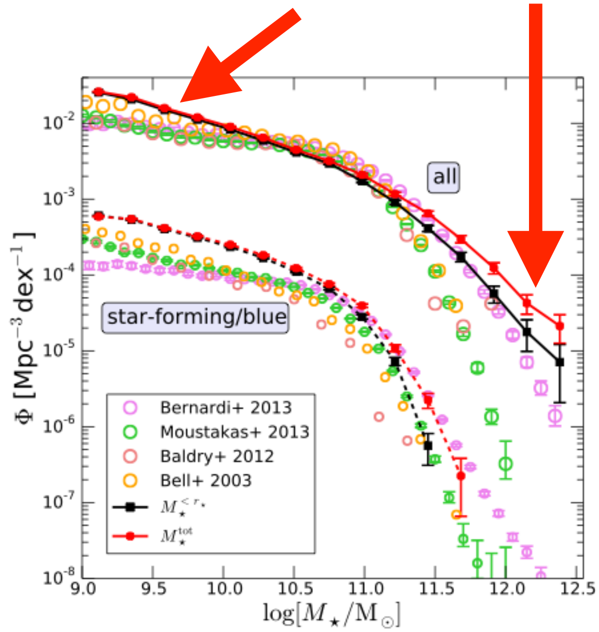
Credits: F. Marinacci

Grand et al. 2016, in prep
Grand et al. 2016ab, Monachesi et al. 2016, Gomez et al. 2016

The subgrid models of reference (III): Illustris TNG

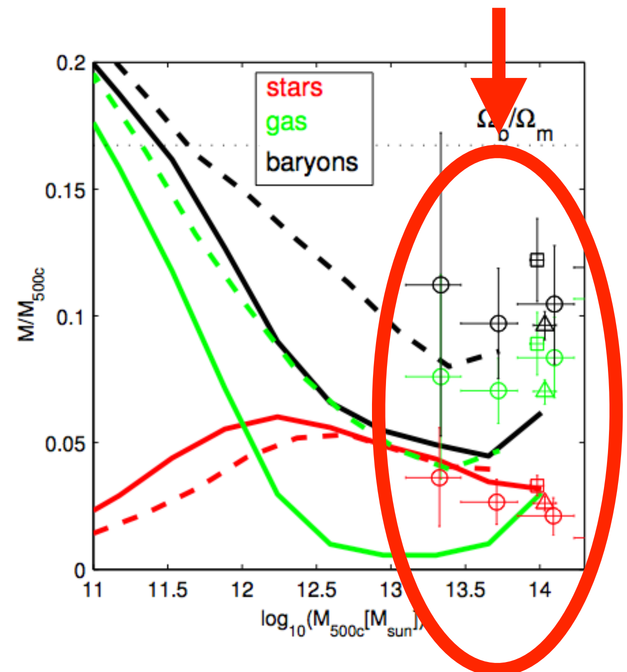
Replica of Illustris Box with updated physics models and Cosmology in order to improve upon some problems in the Illustris Simulation: *

Discrepancies in the Galaxy Stellar Mass Function



Vogelsberger et al. 2014a

Discrepancies in the Gas Content of massive Haloes

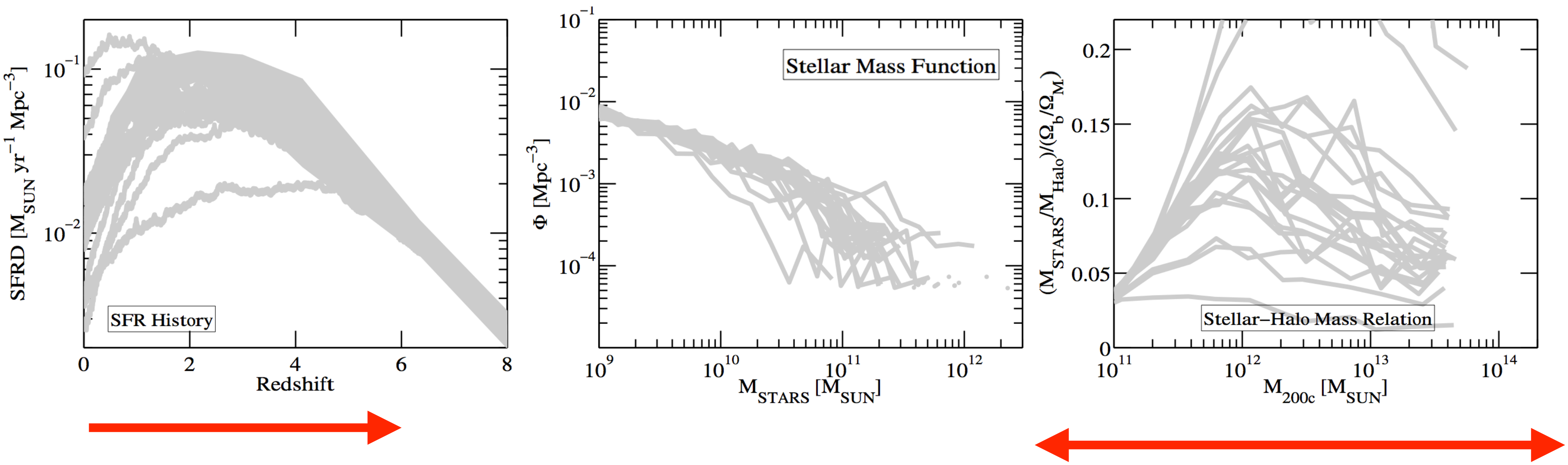


Genel et al. 2014

* … *expected to be finished by June 2016*

Digression Point #1

How easy is it, really, to get the right Mstars?



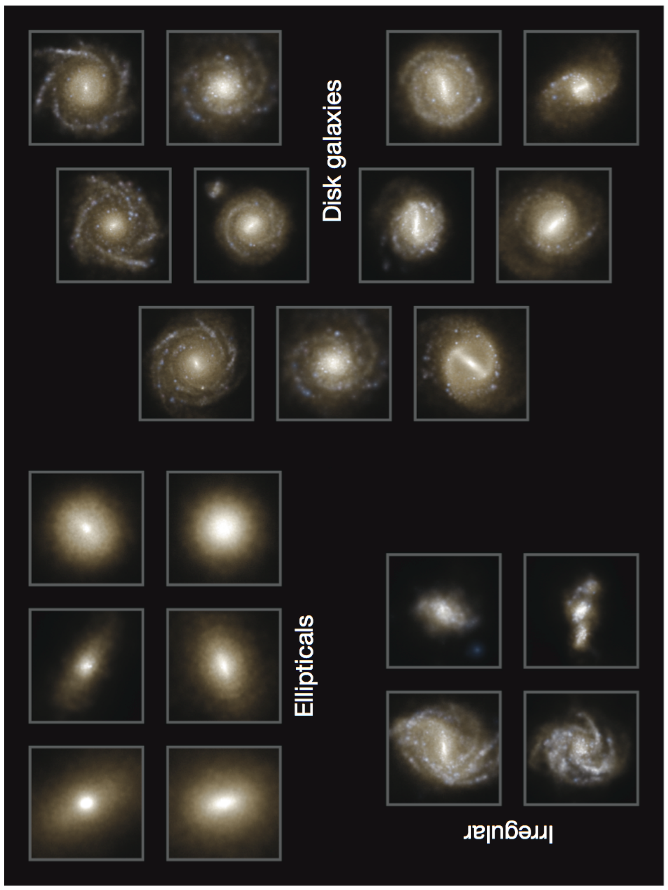
There has been enormous progress, but still now in the kpc-subgrid approach it is still quite hard
Overlooked challenges: the span of the desired mass range, or of redshift range…

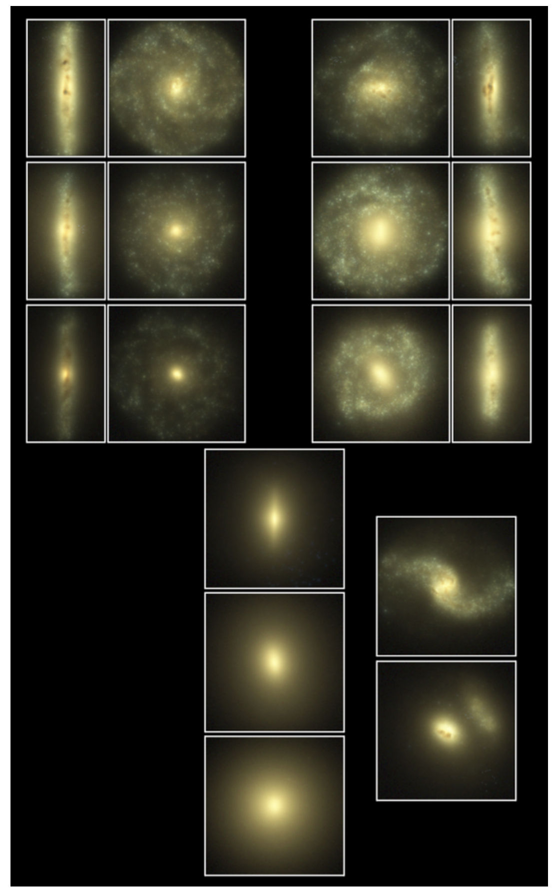
Digression Point #2

On the degeneracy among subgrid kpc-scale models

OK, similar success in getting realistic galaxies etc…

The Illustris Simulation



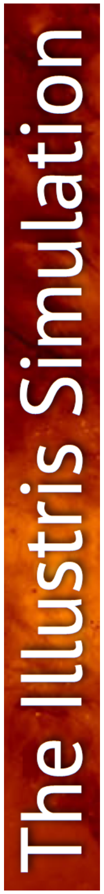


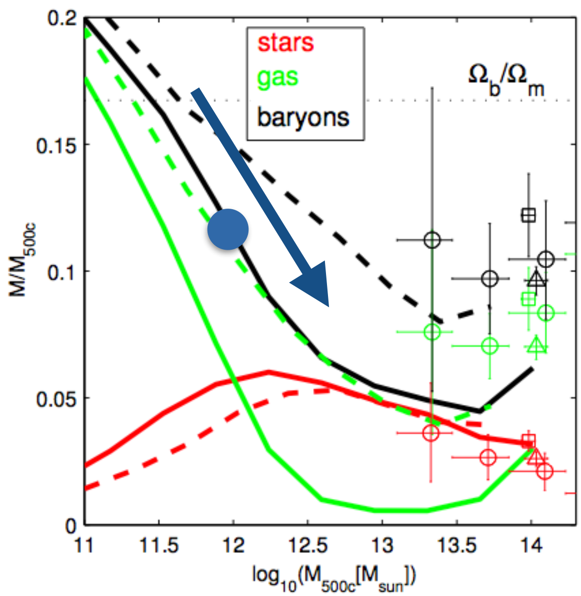
THE EAGLE PROJECT

Digression Point #2

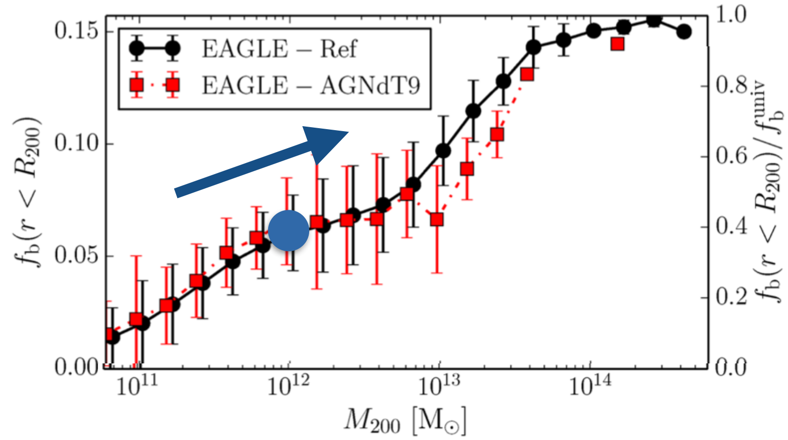
On the degeneracy among subgrid kpc-scale models

But the underlying mechanisms could be completely different.
In fact, look how different the baryonic fractions within haloes are:





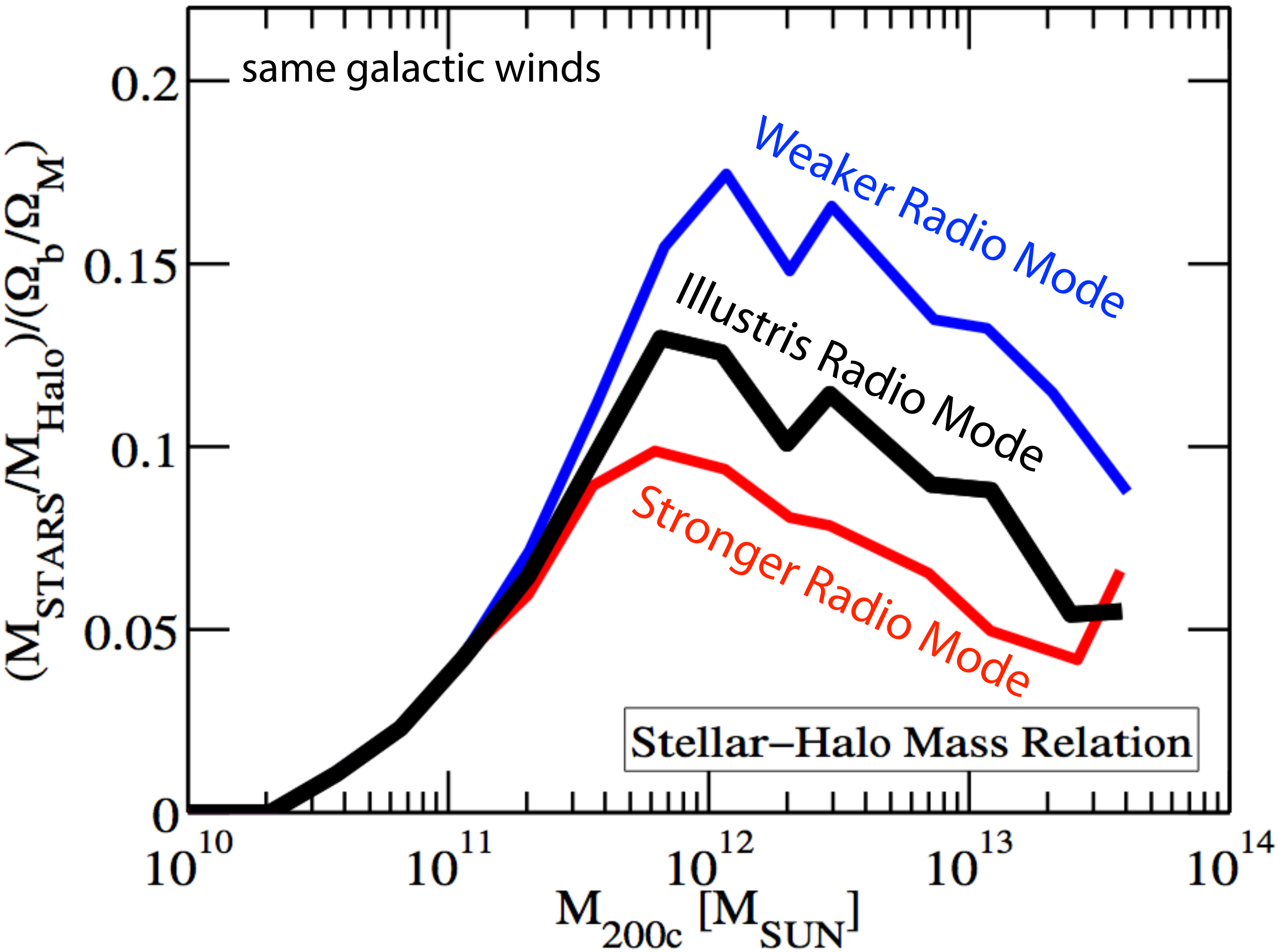
Genel et al. 2014



Schaller et al. 2015

Digression Point #3

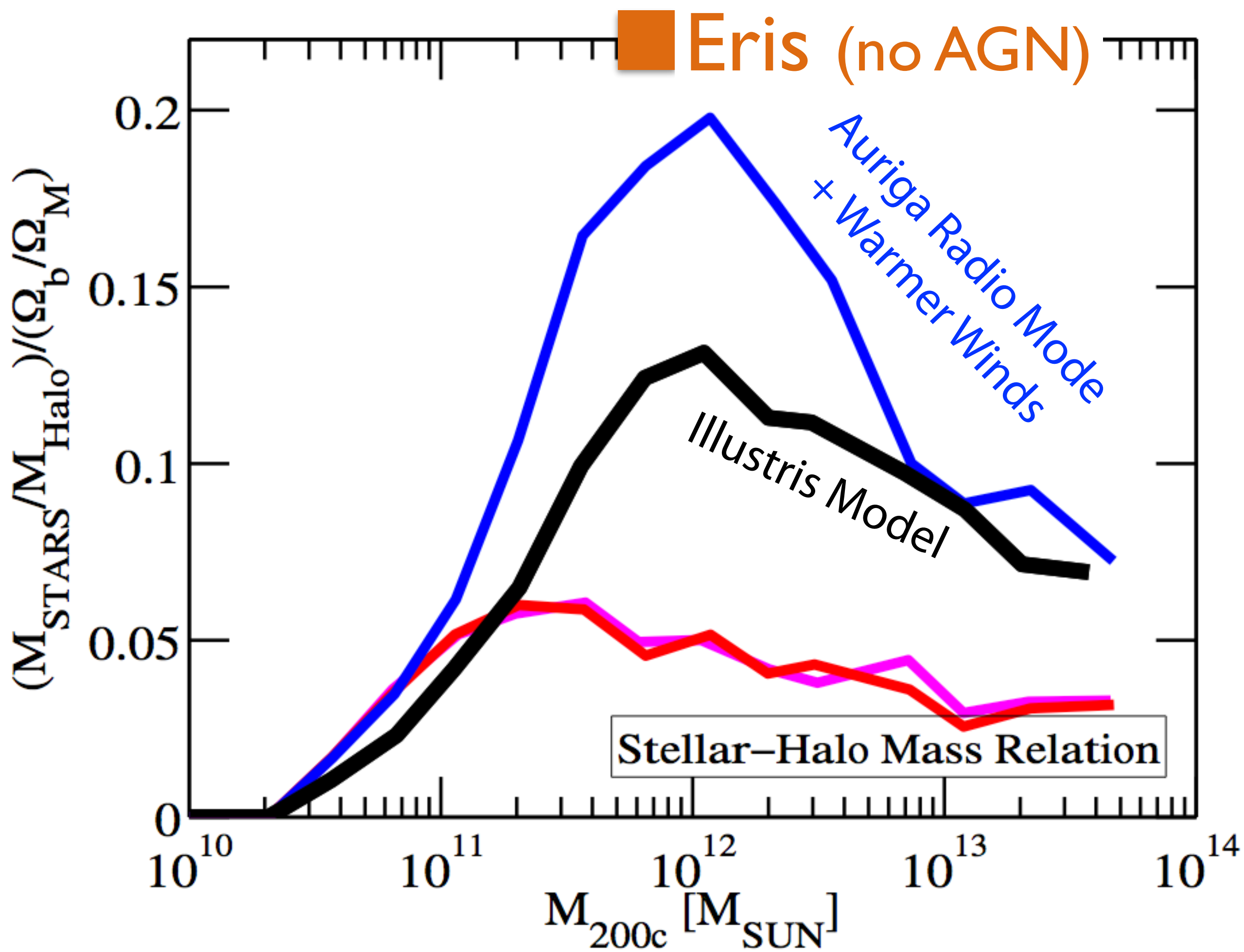
A cautionary note about e.g. galactic wind prescriptions



Quite different Wind Mass Loadings "prescriptions" according to the **ensemble** of the choices

Digression Point #3

A cautionary note about e.g. galactic wind prescriptions



Quite different Wind Mass Loadings "prescriptions" according to the **ensemble** of the choices

Black Hole Formation and Feedback (I)

Courtesy of C. Popa

	Illustris	Illustris – TNG ★	Auriga
Black Hole Formation	$M_{BH} = 10^5 M_\odot$ seeded inside all haloes with $M > 5 \times 10^{10} M_\odot$		
Black Hole Growth $\dot{M}_{BH}$	All accretion rates Eddington limited: $\dot{M}_{eff} = \min\left(\dot{M}_{BH}, \dot{M}_{Edd}\right)$		
	$100\, \dot{M}_{Bondi}$	$\dot{M}_{Bondi} \max\left(1, \frac{M_{BH}}{M_{pivot}}\right)$	$\dot{M}_{Bondi} + \frac{R(T,z) L_{Xray}}{\epsilon_f \epsilon_r c^2}$
Quasar Feedback (rapid growth)	$\dot{M}_{eff} > 0.01 \dot{M}_{Edd}$	$\dot{M}_{eff} > 0.05 \dot{M}_{Edd}$	always
	$\dot{E} = \epsilon_f \epsilon_r \dot{M}_{eff} c^2$ distributed isotropically to neighboring gas cells		
Radio Feedback (slow growth)			

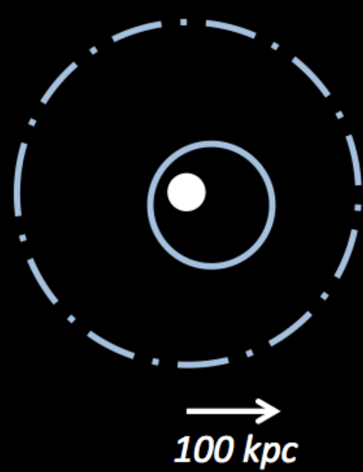
ILLUSTRIS: "A Unified Model for AGN…", Sijacki et al. 2007
AURIGA: Grand et al., in prep, Popa et al. in prep
ILLUSTRIS-TNG: "A new AGN feedback model: BH-driven wind", Weinberger, Springel et al. in prep

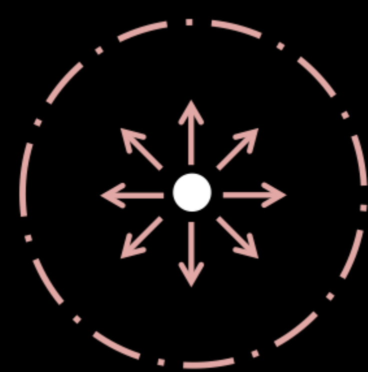
★ Here, not exactly the final implementation we have converged on, for Illustris++ and in Weinberger et al.

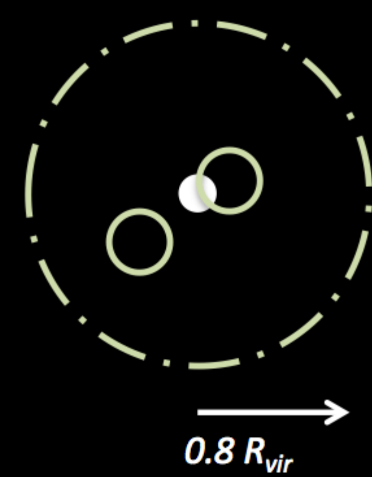
Black Hole Formation and Feedback (II)

Courtesy of C. Popa

	Illustris	Illustris – TNG	Auriga
Radio Feedback (slow growth)	$\dot{M}_{eff} < 0.01\dot{M}_{Edd}$	$\dot{M}_{eff} < 0.05\dot{M}_{Edd}$	always
$\dot{E} = \epsilon_f \epsilon_r \dot{M}_{eff} c^2$	Thermal feedback inflates 1 hot bubble	Kinetic feedback momentum distributed isotropically to neighboring gas cells	Thermal feedback inflates a few small hot bubbles
$\epsilon_f = 0.35$ $\epsilon_f = 0.07$ $\epsilon_f = 0.1$	$R = R_0 \left(\frac{E/E_0}{\rho_{gas}/\rho_0} \right)^{1/5}$ $E = \epsilon_f \epsilon_r c^2 \delta M_{BH}$		$R = 0.1\,R_{vir}$ $E = \sum_i 0.05 m_i \bar{u}_{gas}$

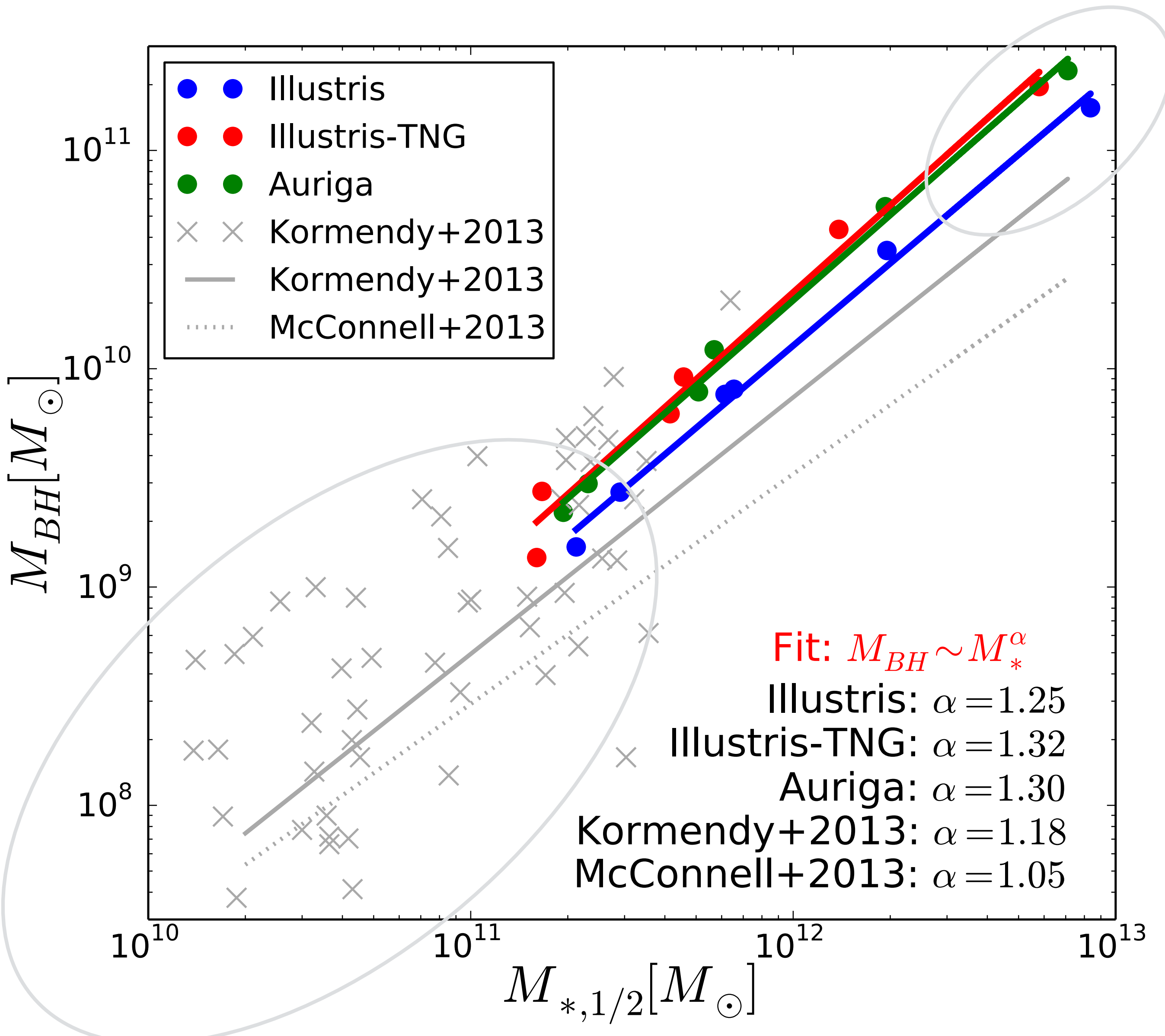






Consistent BH Mass - Stellar Mass Relations

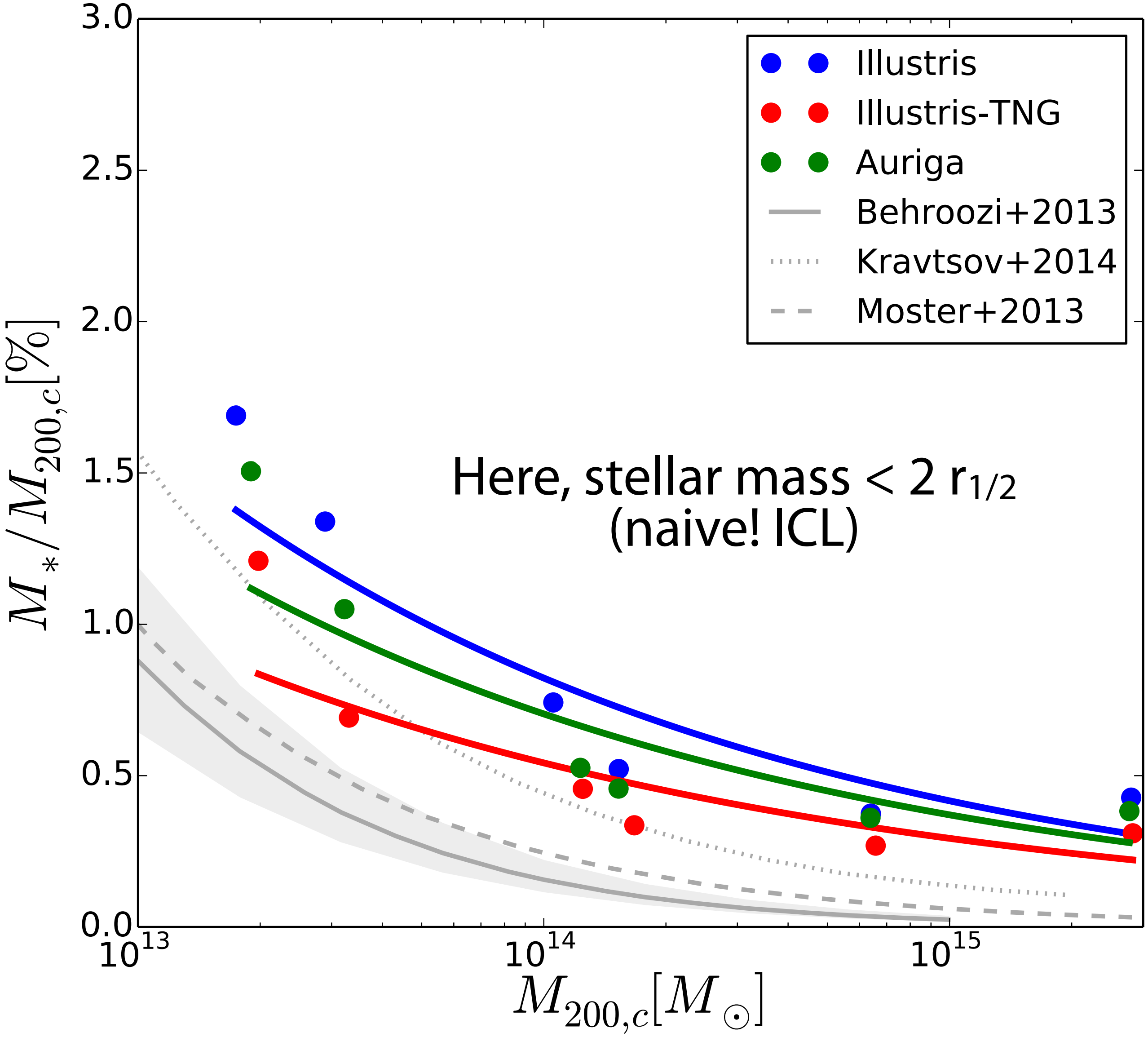
? too massive ?



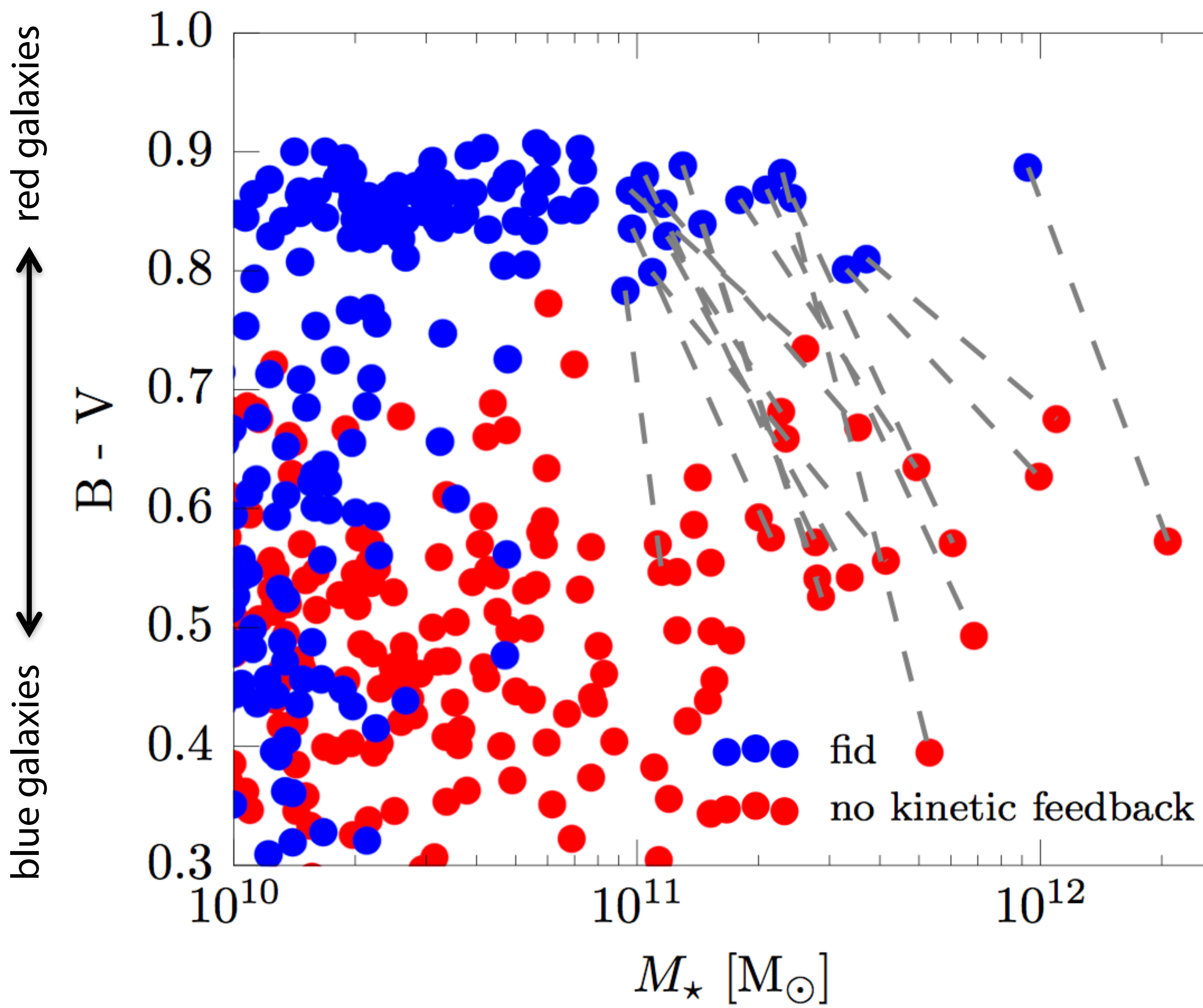
Illustris Box regime

(we are good also there!)

Progressively better Stellar Content in the BCGs



Progressively better Stellar Content in the BCGs



Weinberger, Springel in prep

The quenching is all done by the "radio" mode

e.g. galaxies would be very blue without the Illustris-TNG kinetic feedback

as in Horizon-AGN.
…In the EAGLE model?

The functioning of the three feedback models

Halo 5: 7x10^{14} Msun

Illustris

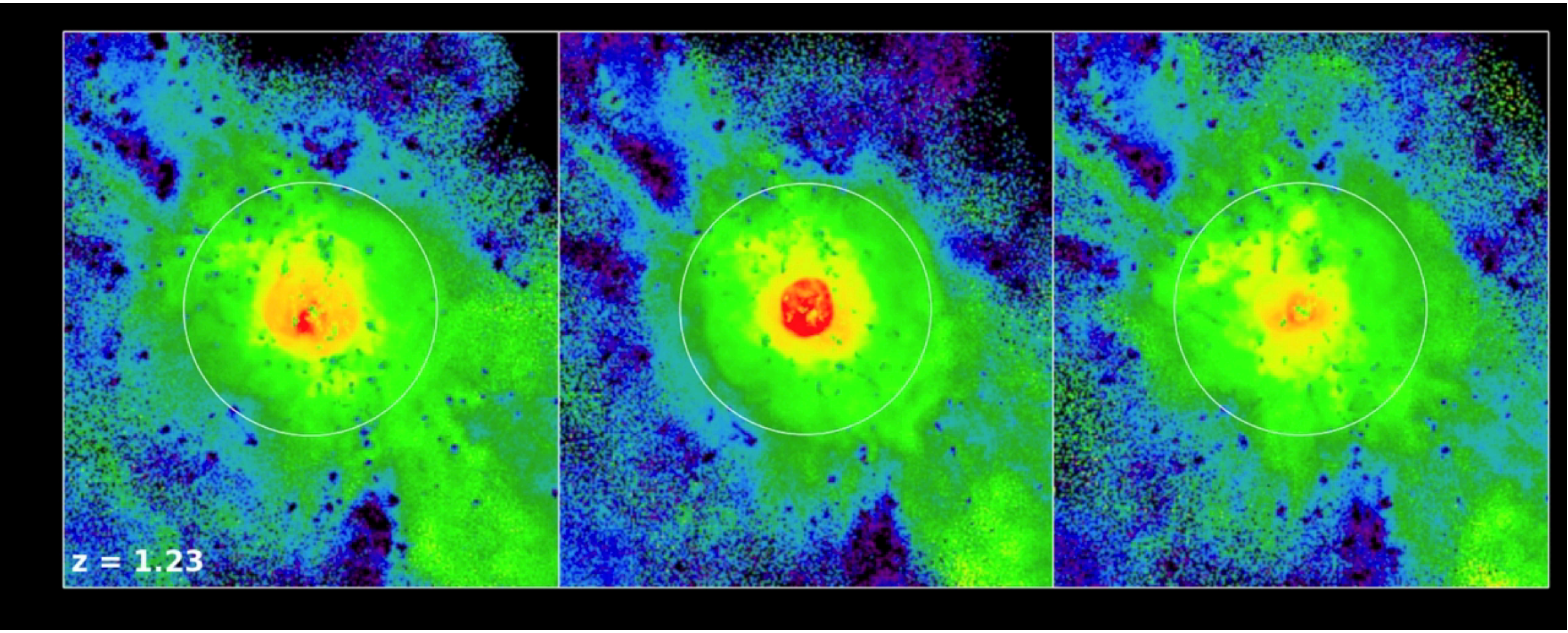
Thermal feedback
inflates one large, hot bubbles every time δM_{BH} is above a threshold

Illustris – TNG

Kinetic feedback
momentum distributed isotropically to neighboring gas cells

Auriga

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



The functioning of the three feedback models

Halo 2: 4×10^{13} Msun

Illustris

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

Illustris – TNG

Kinetic feedback
momentum distributed isotropically to neighboring gas cells

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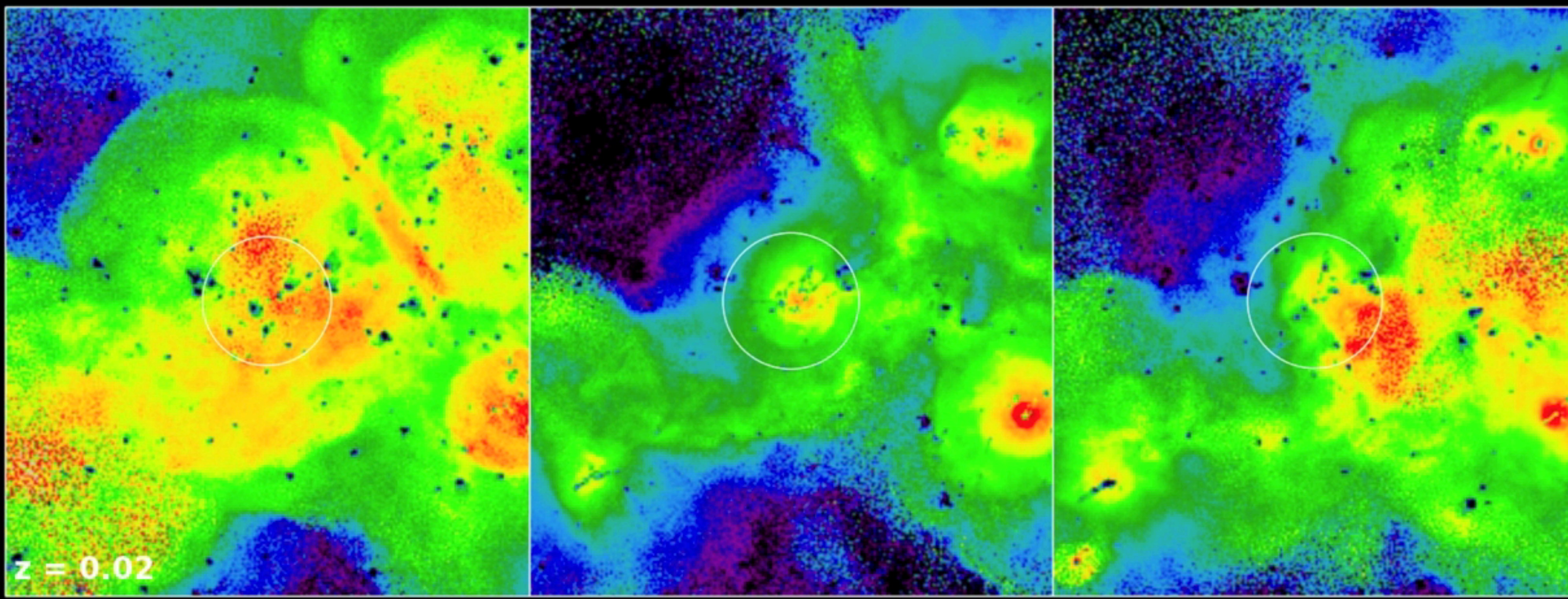
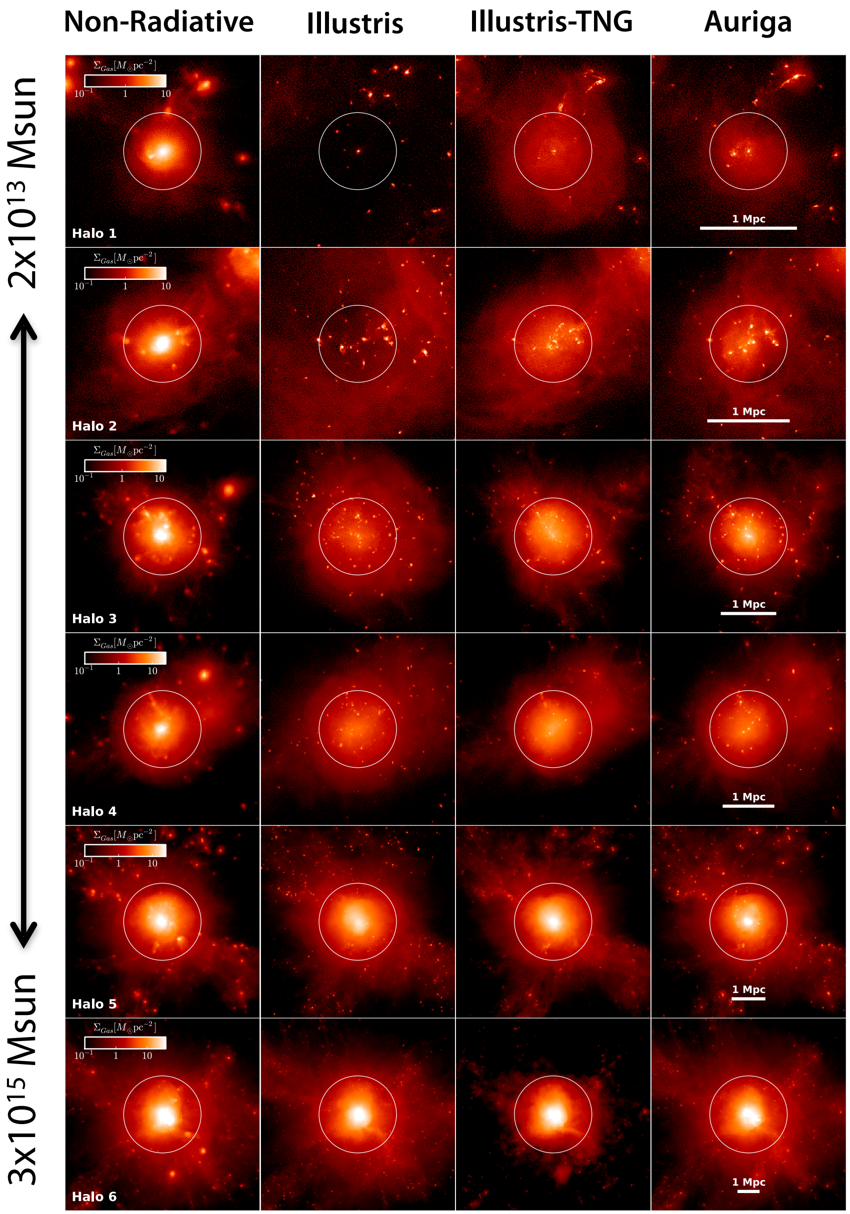


Results (to be demonstrated in the following slides)



1. Different AGN feedback numerical implementations produce quite different gaseous haloes in clusters

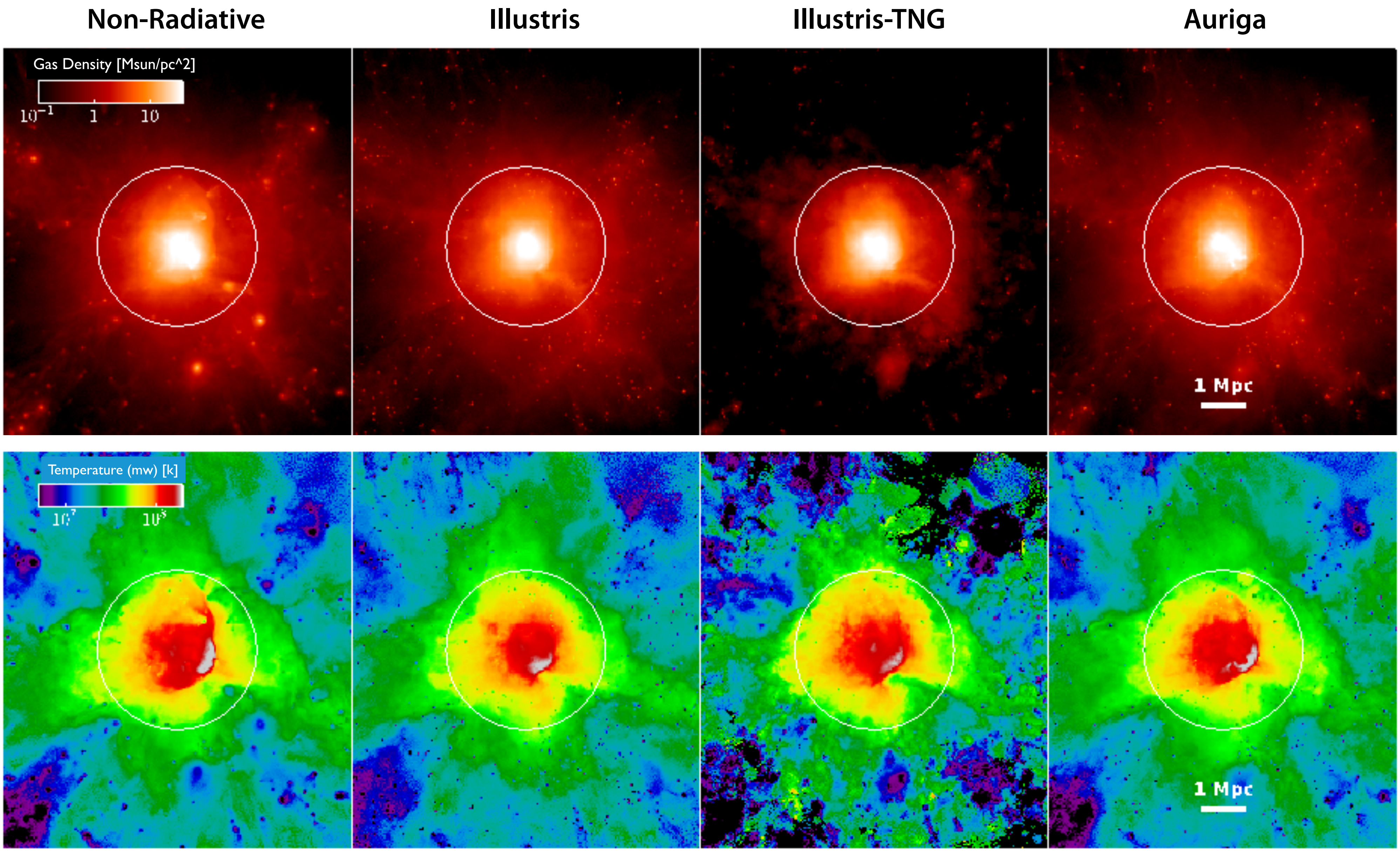
2. However, this is true mostly towards the group-scale haloes

3. For haloes > 6x10^{14} Msun, the three models are essentially indistinguishable (and very close to the predictions of the self-similar model)

4. Although extremely different in nature, the new IllustrisTNG model and the Auriga return very similar clusters

Effects of different Feedback: gas maps

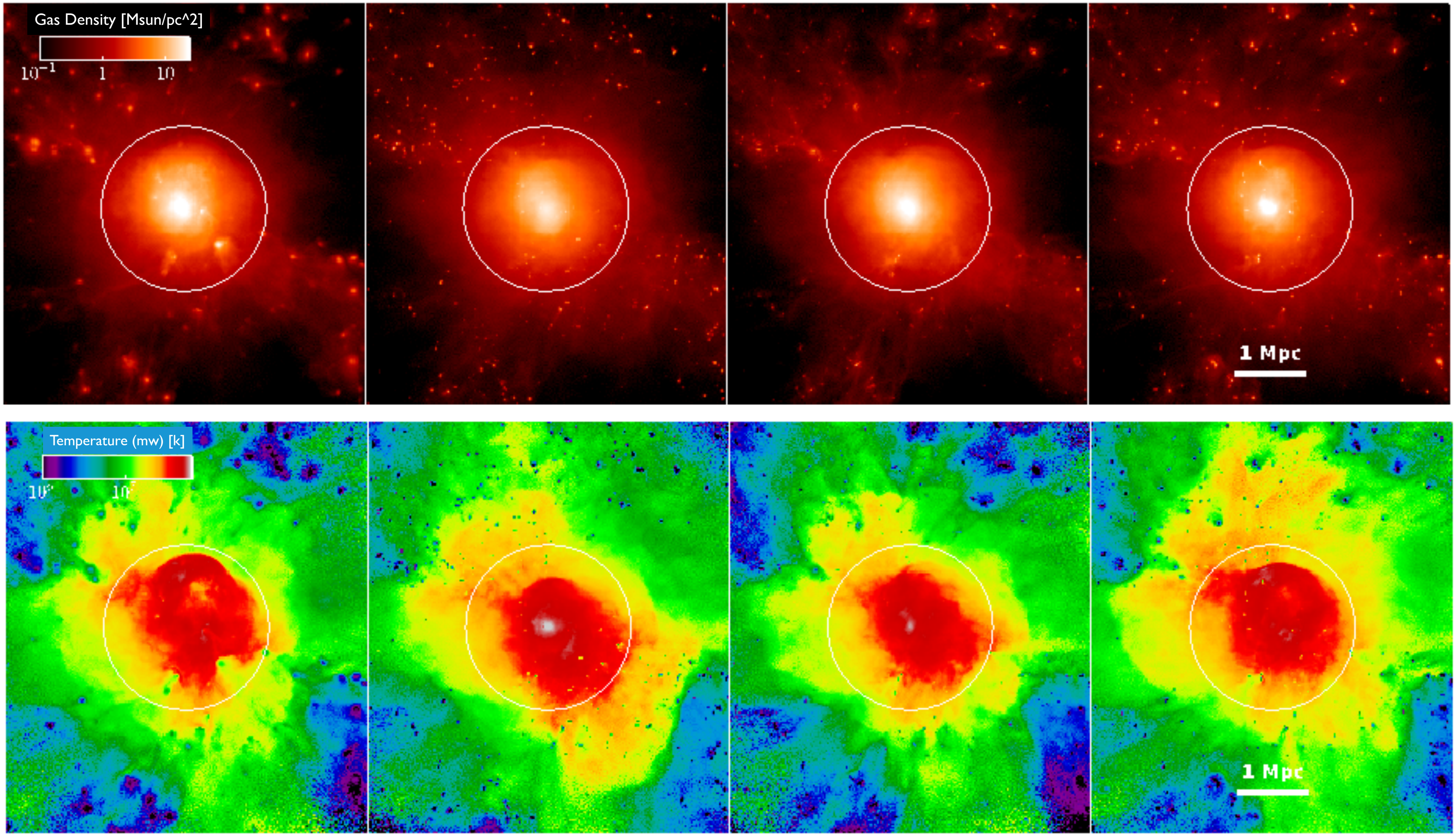
Halo 6: 3×10^{15} Msun



Effects of different Feedback: gas maps

Halo 5: 7×10^{14} Msun

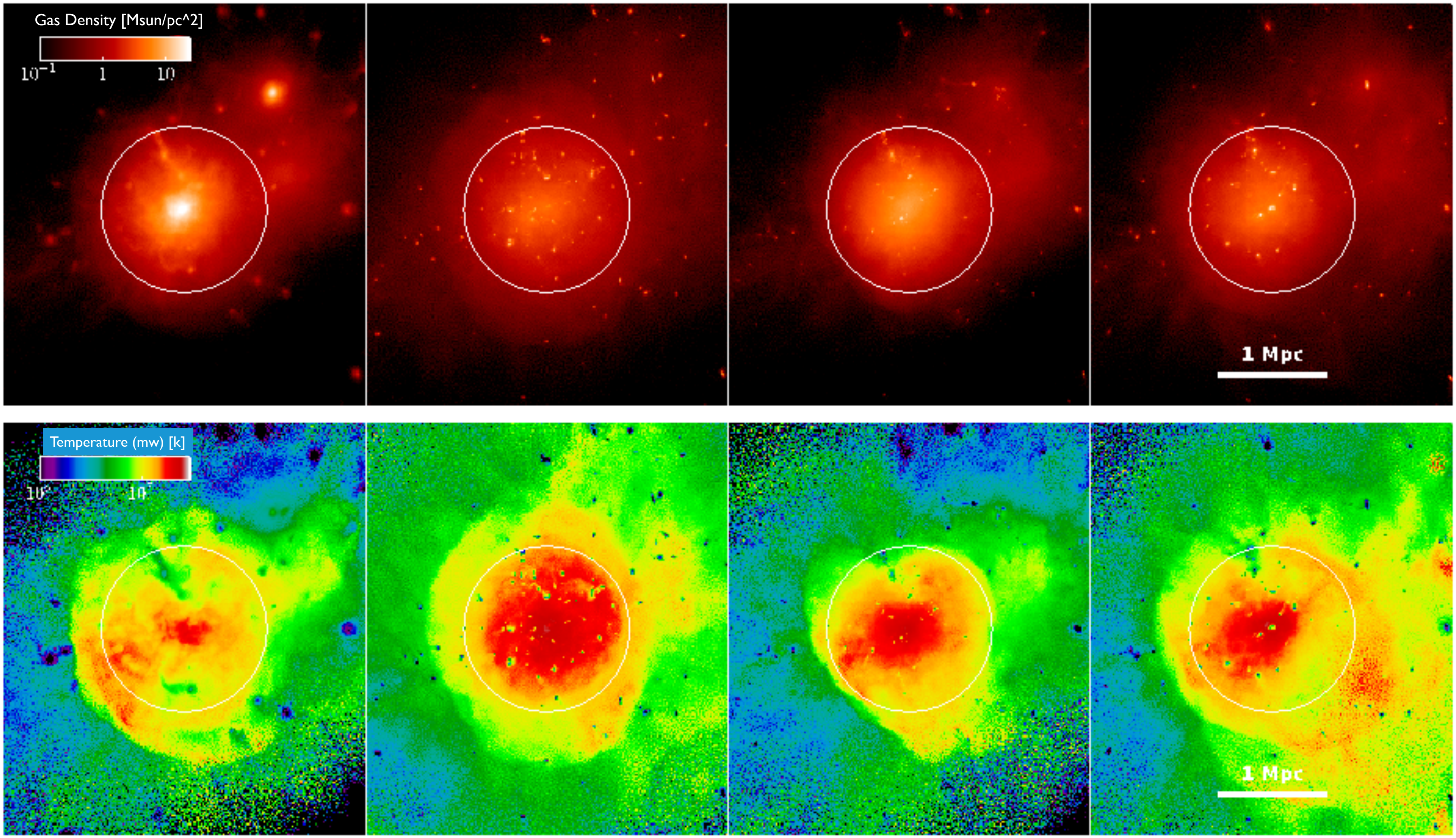
Non-Radiative	Illustris	Illustris-TNG	Auriga



Effects of different Feedback: gas maps

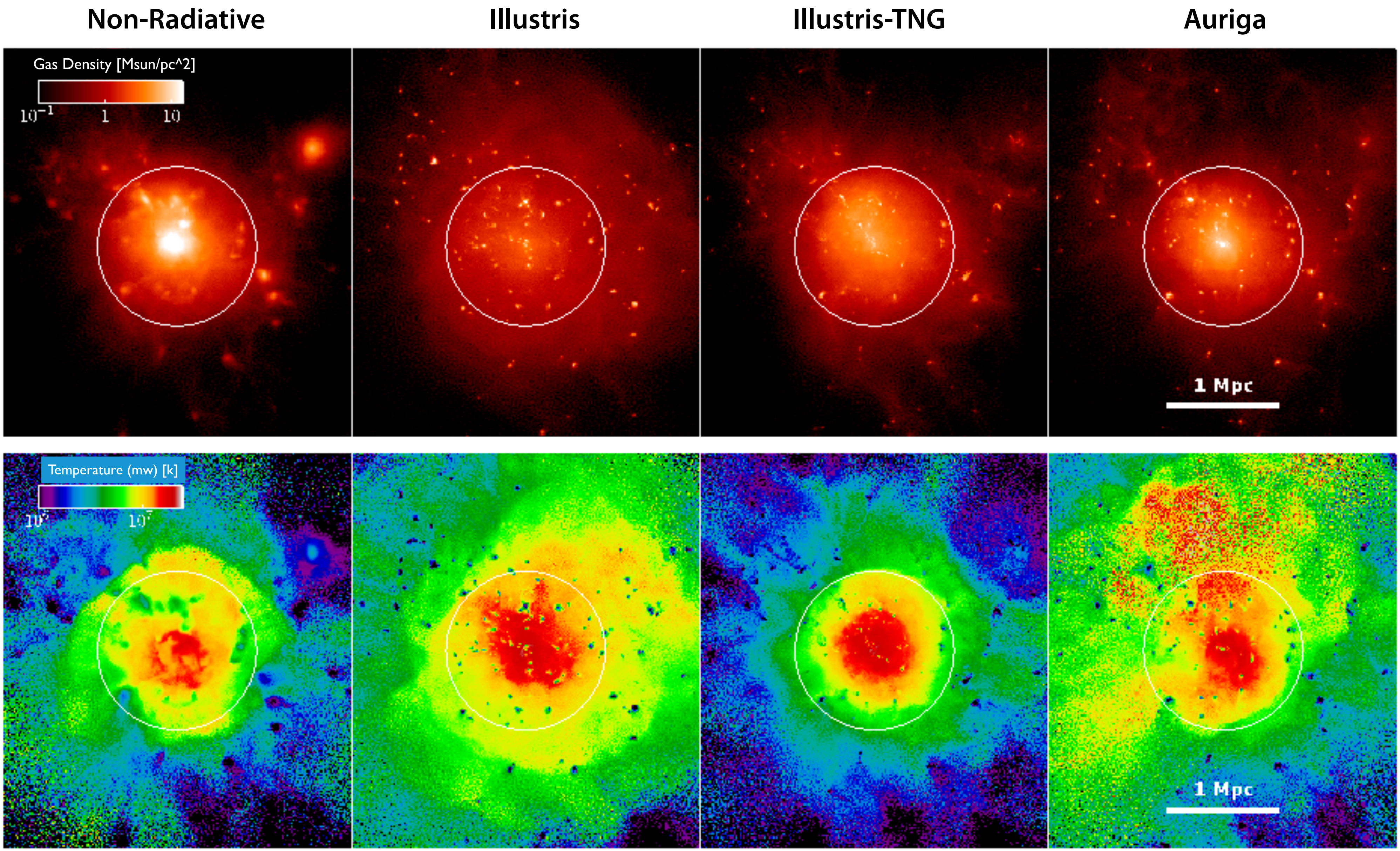
Halo 4: $2x10^{14}$ Msun

Non-Radiative | Illustris | Illustris-TNG | Auriga



Effects of different Feedback: gas maps

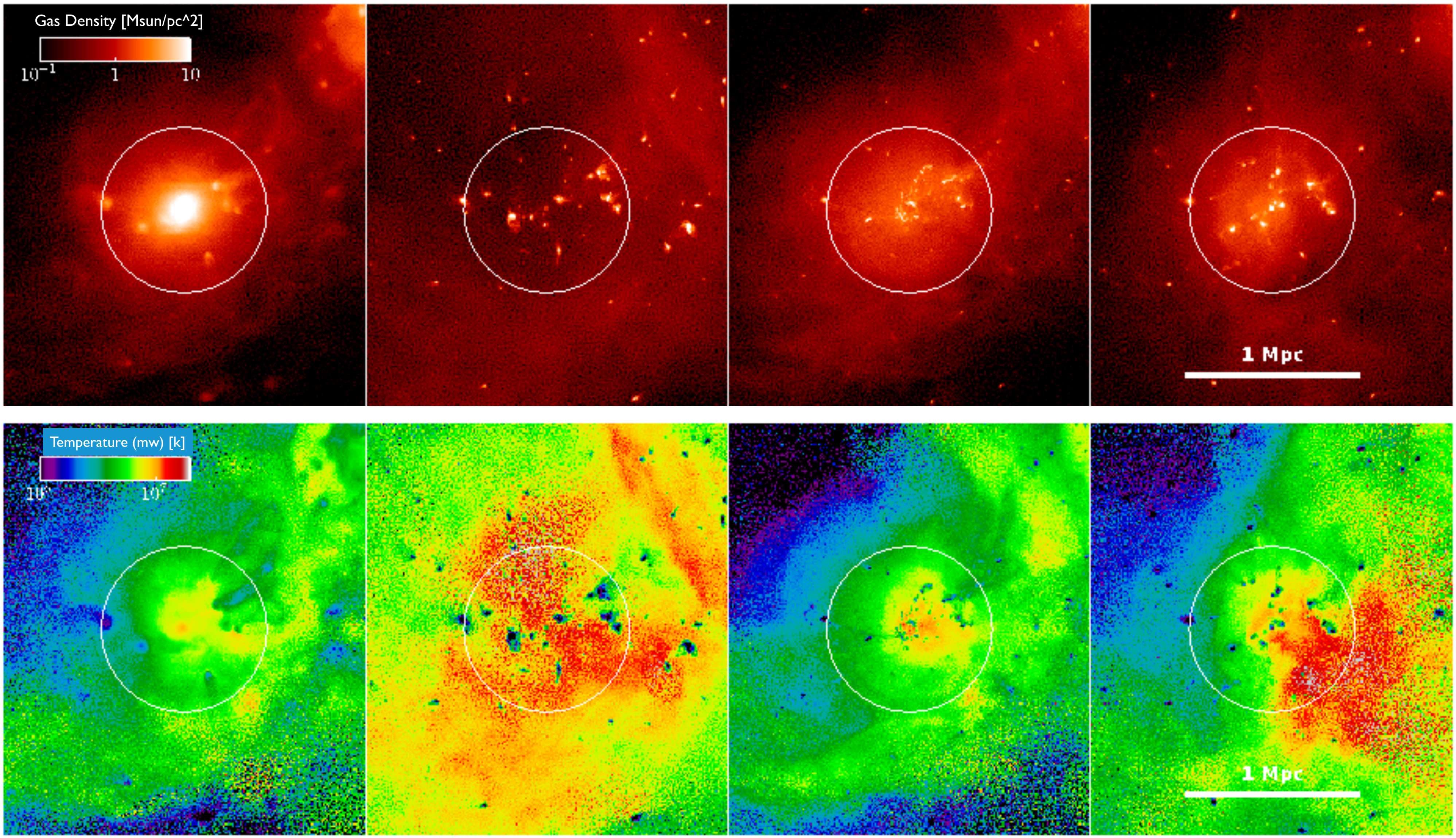
Halo 3: 1x10^{14} Msun



Effects of different Feedback: gas maps

Halo 2: $4x10^{13}$ Msun

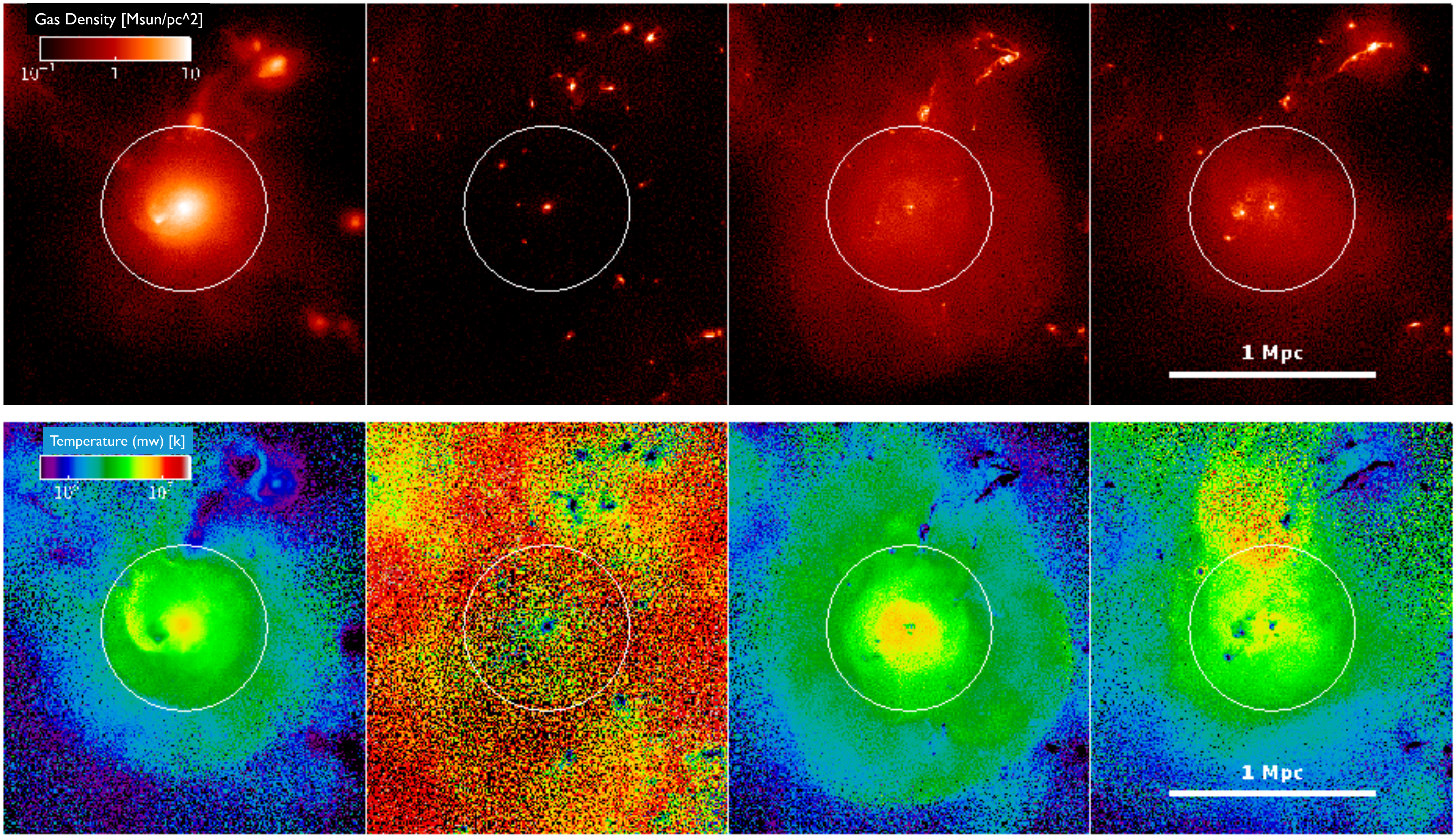
Non-Radiative | Illustris | Illustris-TNG | Auriga



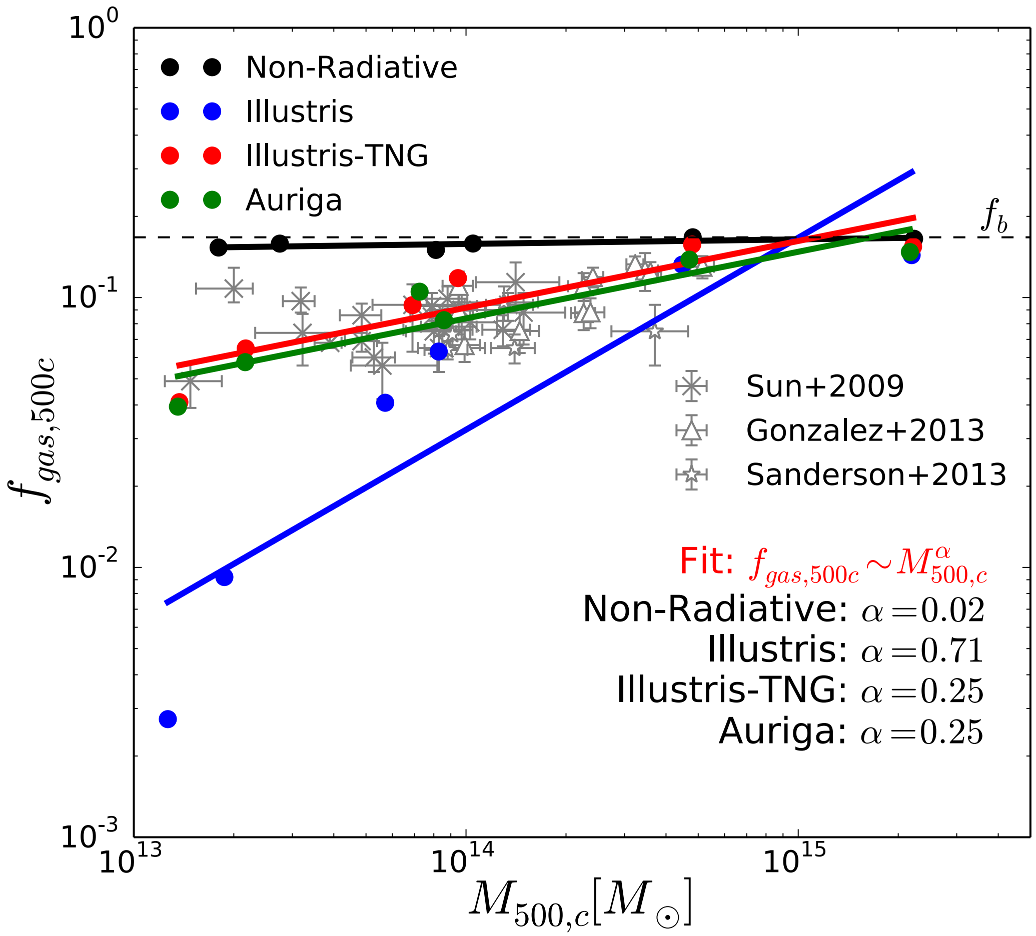
Effects of different Feedback: gas maps

Halo 1: $2x10^{13}$ Msun

Non-Radiative | Illustris | Illustris-TNG | Auriga



Gas Fractions (hot and cold halo)



In the Illustris model, clusters are devoided of gas (< 10^{14} Msun)

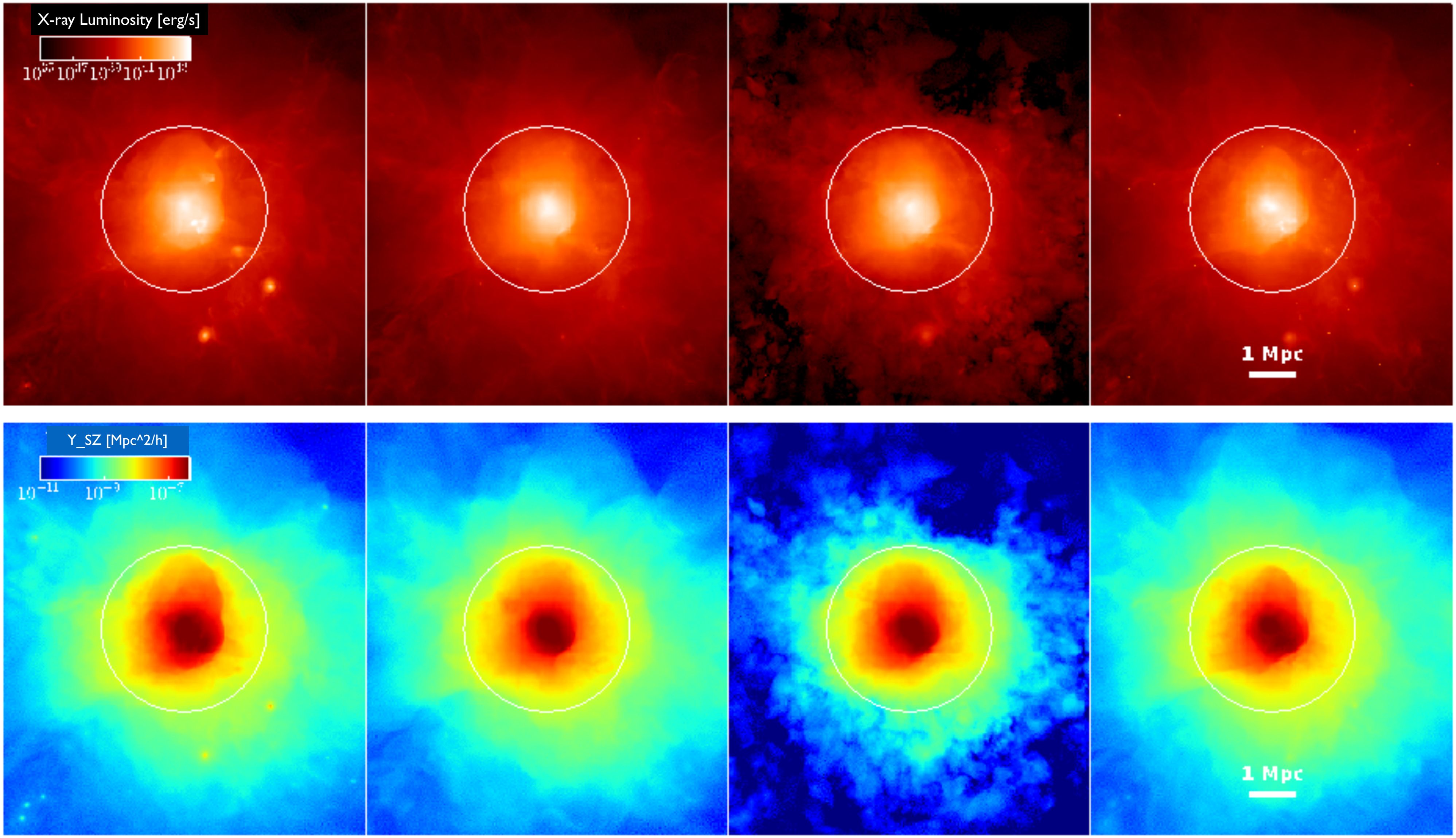
The Auriga and IllustrisTNG models are in good agreement with each other and observations

In fact, gas fractions across *all* models would be consistent when measured within a larger radius

Effects of different Feedback: observable signals

Halo 6: $3x10^{15}$ Msun

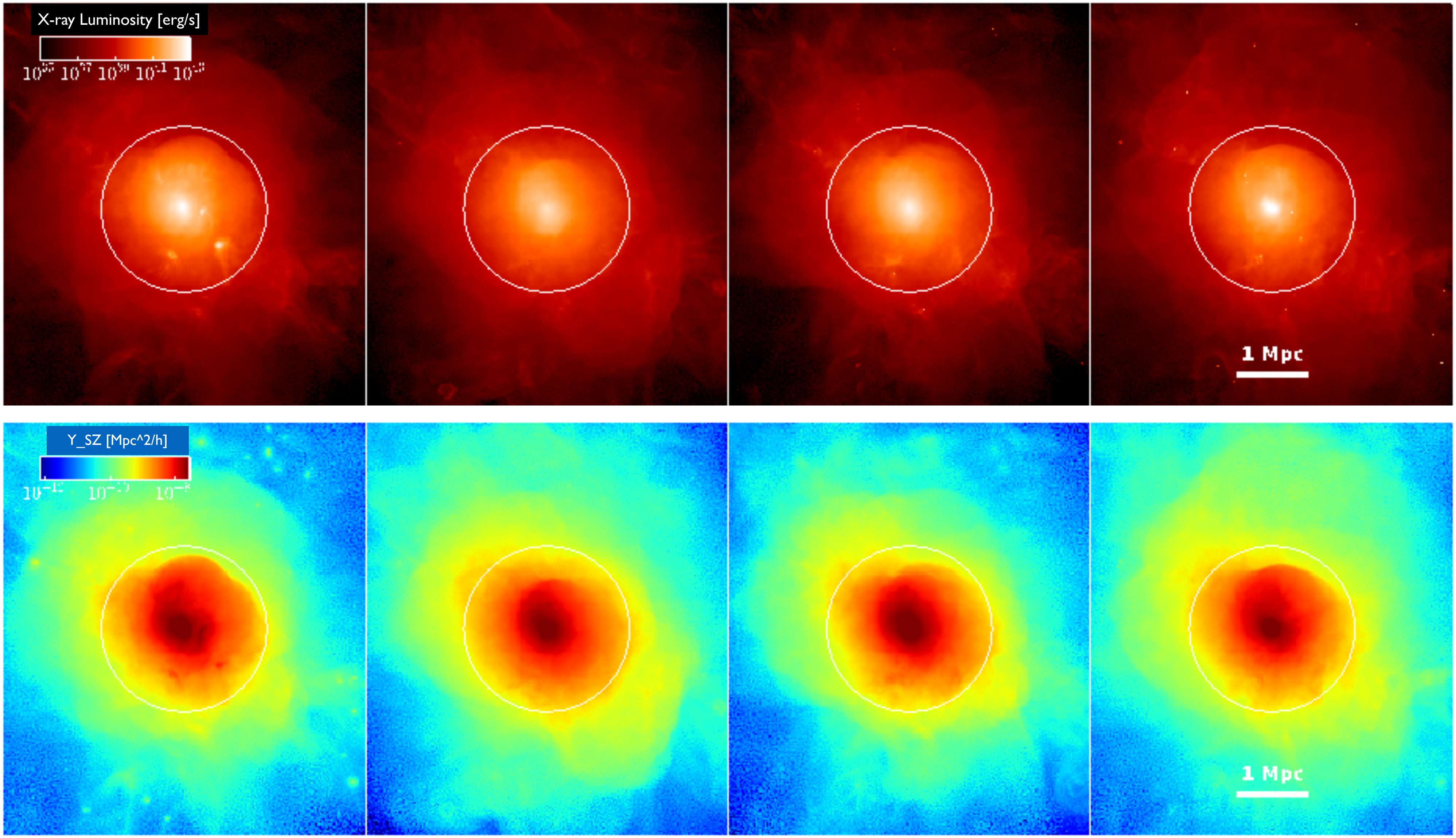
Non-Radiative | Illustris | Illustris-TNG | Auriga



Effects of different Feedback: observable signals

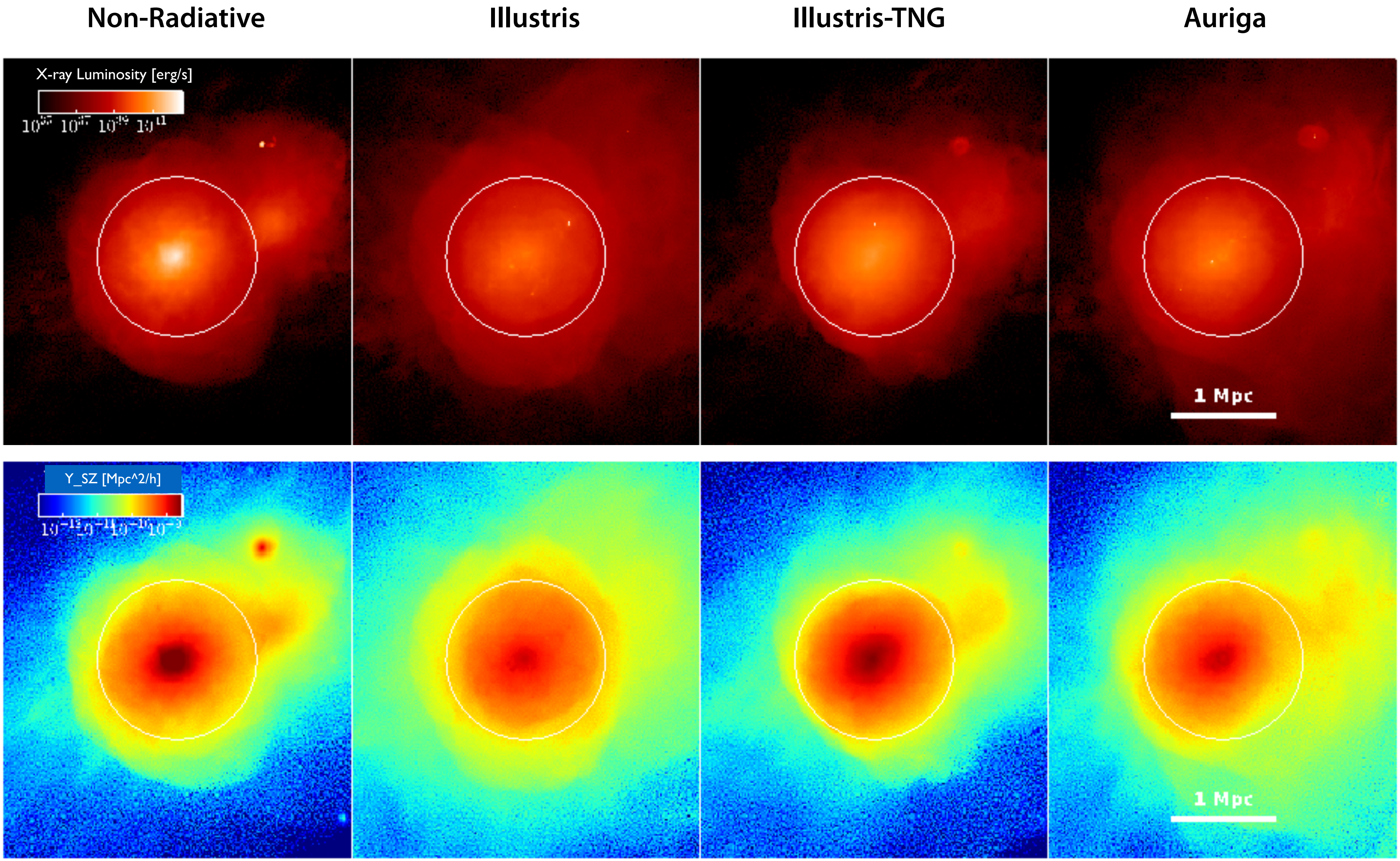
Halo 5: $7x10^{14}$ Msun

Non-Radiative	Illustris	Illustris-TNG	Auriga



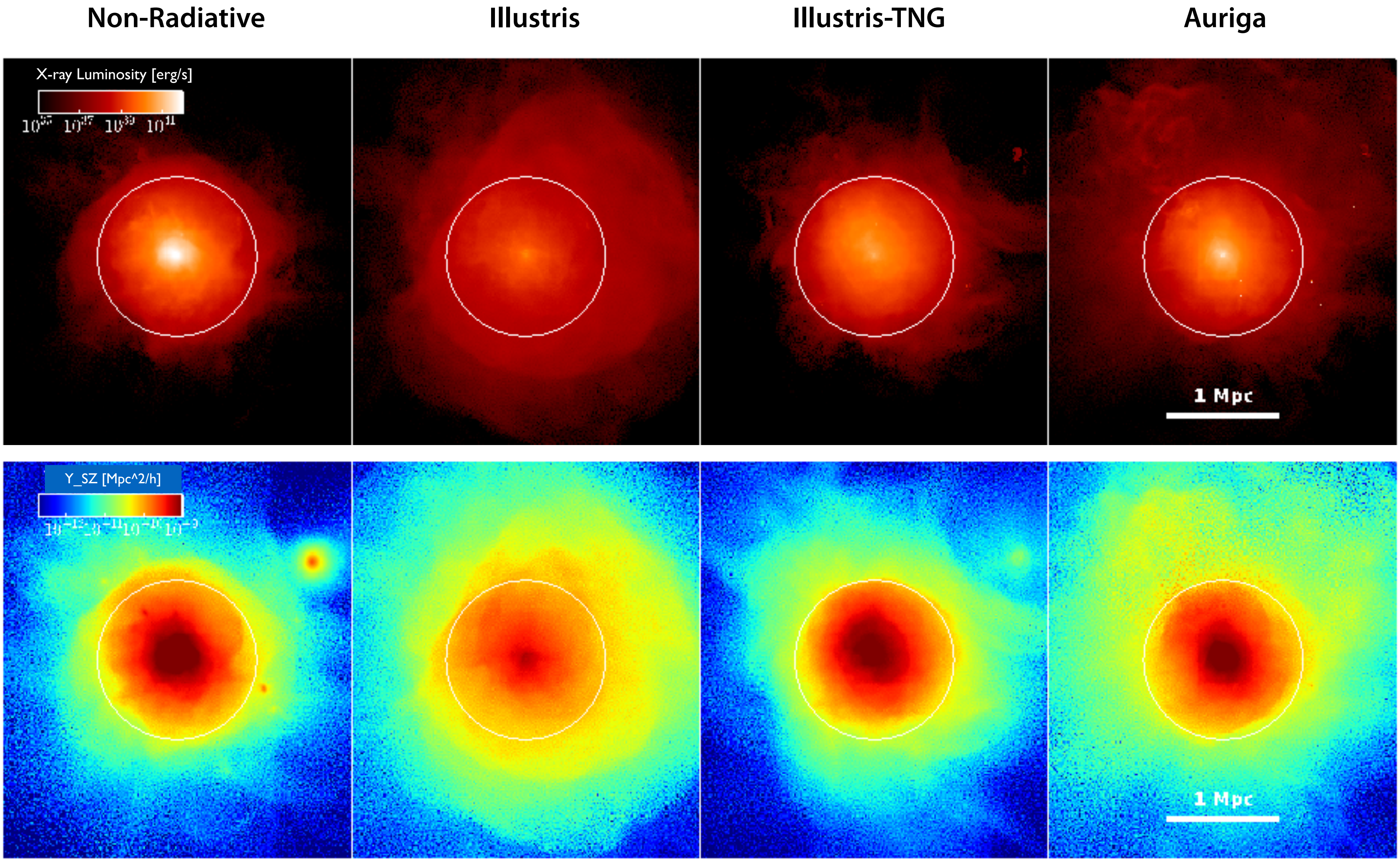
Effects of different Feedback: observable signals

Halo 4: 2×10^{14} Msun



Effects of different Feedback: observable signals

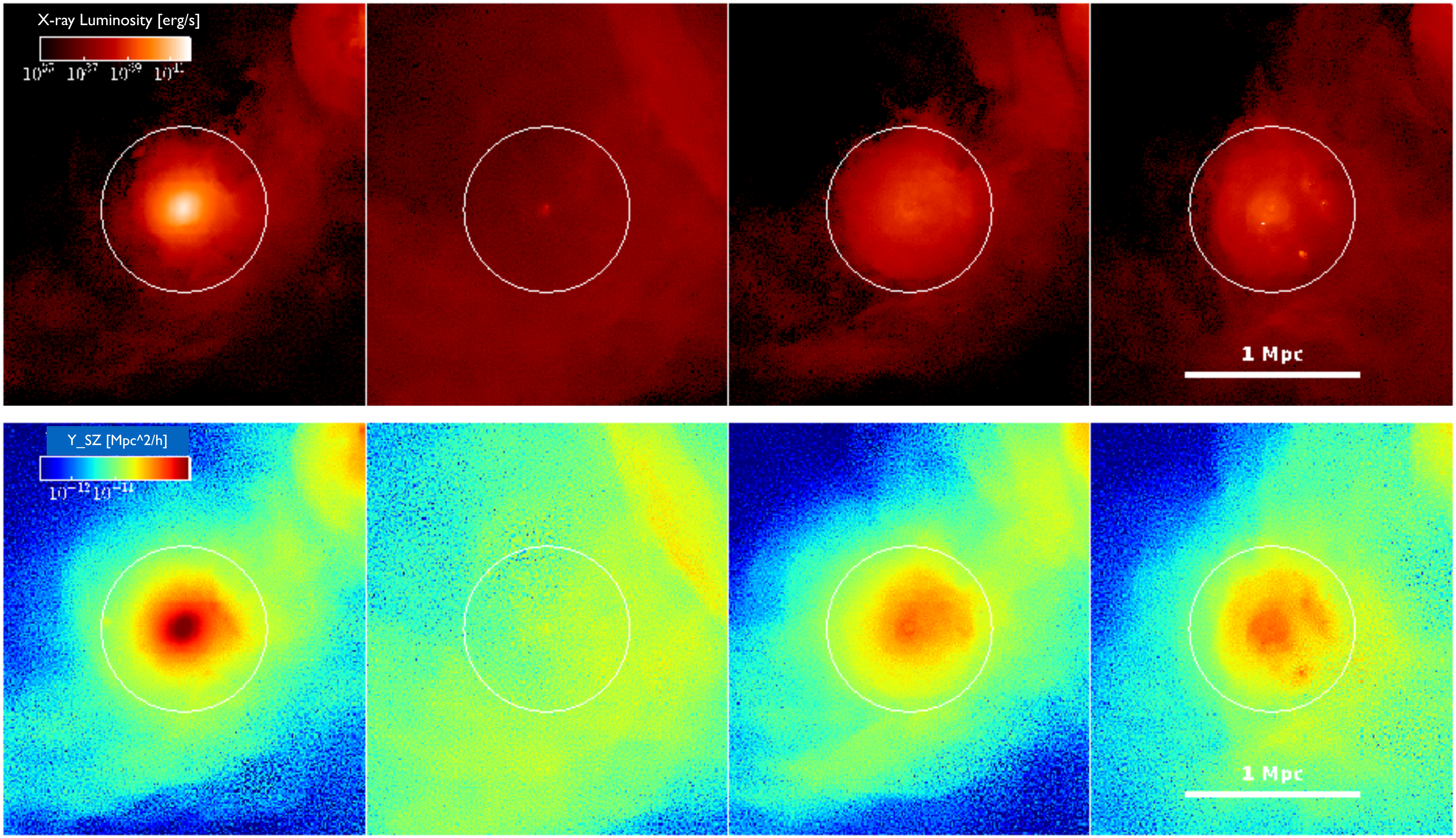
Halo 3: $1x10^{14}$ Msun



Effects of different Feedback: observable signals

Halo 2: 4×10^{13} Msun

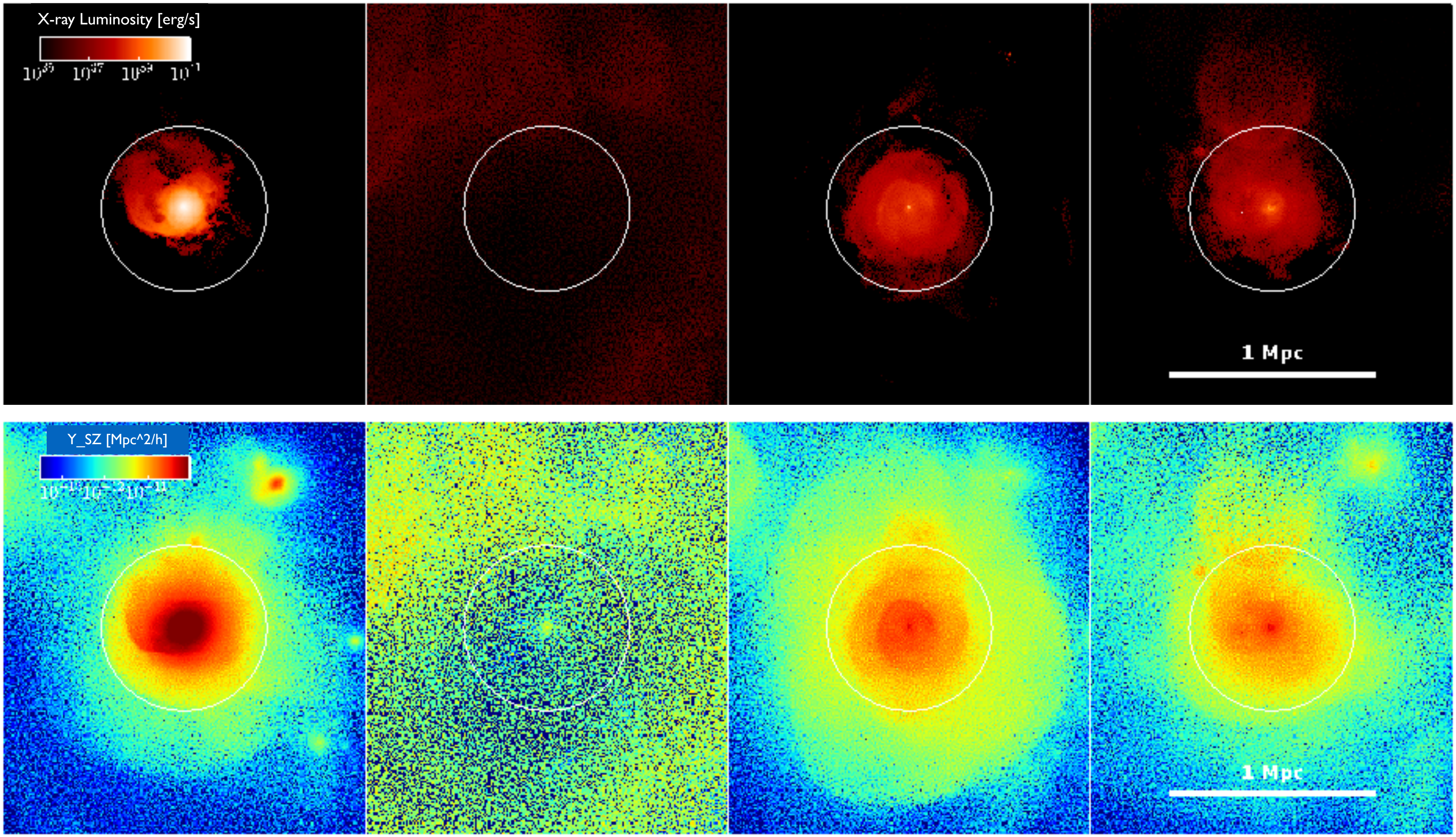
Non-Radiative | **Illustris** | **Illustris-TNG** | **Auriga**



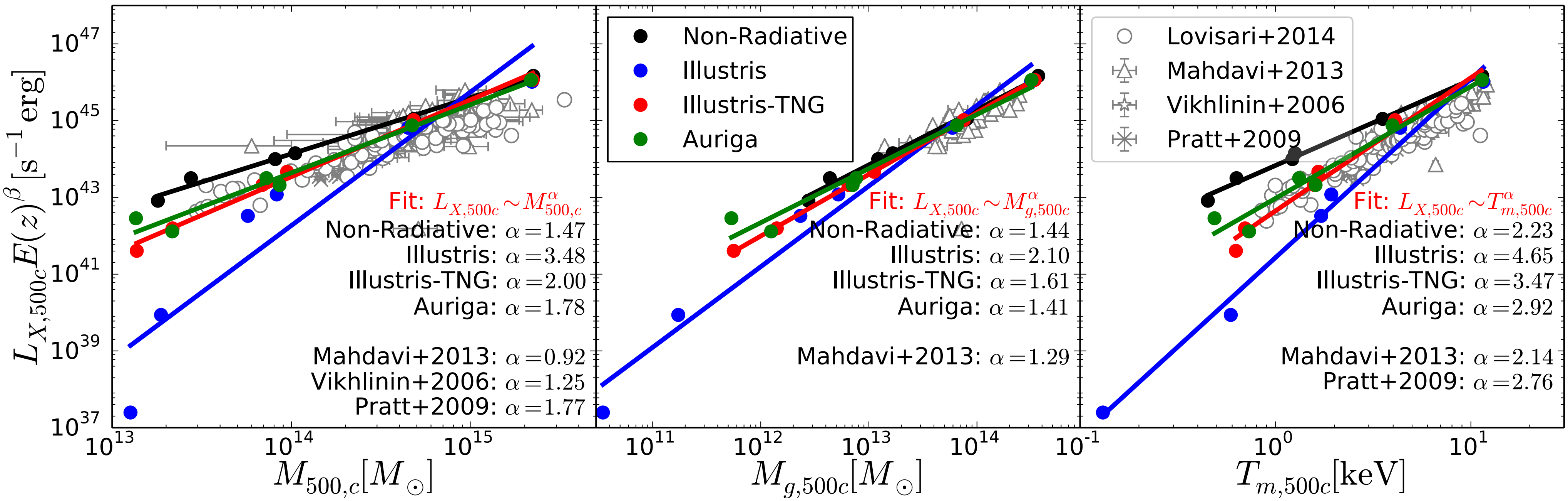
Effects of different Feedback: observable signals

Halo 1: $2x10^{13}$ Msun

Non-Radiative | Illustris | Illustris-TNG | Auriga



X-ray Scaling Relations



Self Similar X-ray Luminosity

$L_X \sim M^{4/3} E(z)^{7/3}$

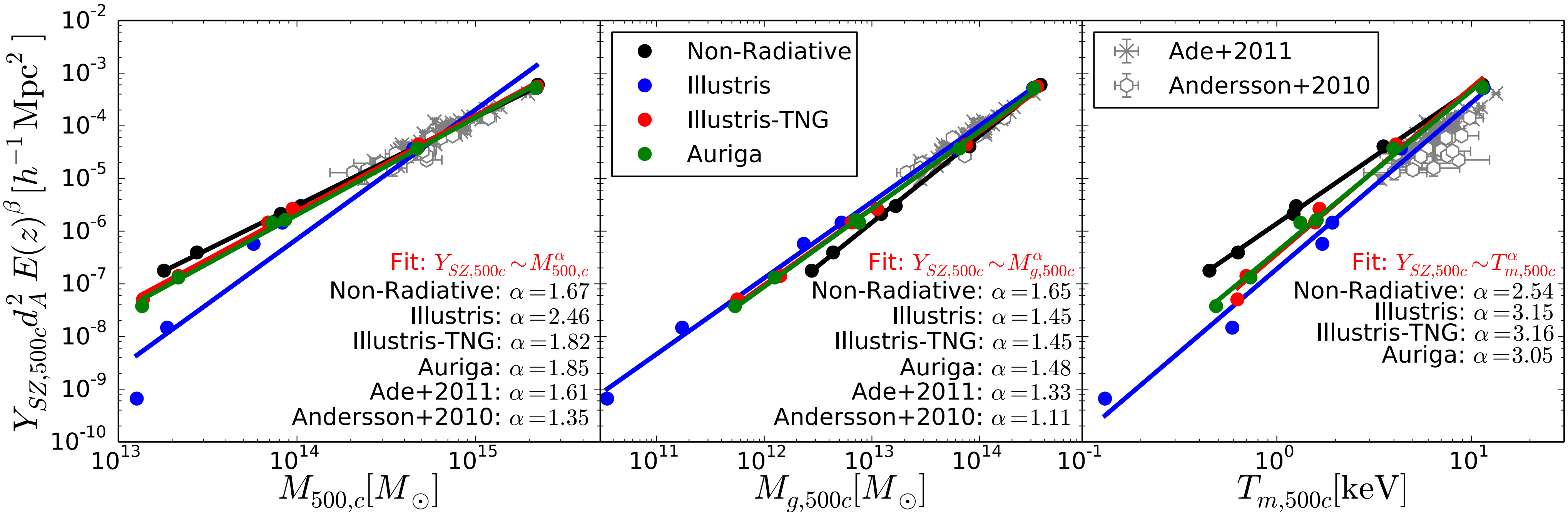
$L_X \sim M_{gas}^{4/3} E(z)^{7/3}$

$L_X \sim T^2 E(z)$

In the Illustris model, the luminosity-mass relation is much steeper than expected

At the highest mass end, the various AGN models return very similar results

SZ Scaling Relations



Self-similar SZ Parameter

$Y_{SZ} \sim M^{5/3} E(z)^{2/3}$

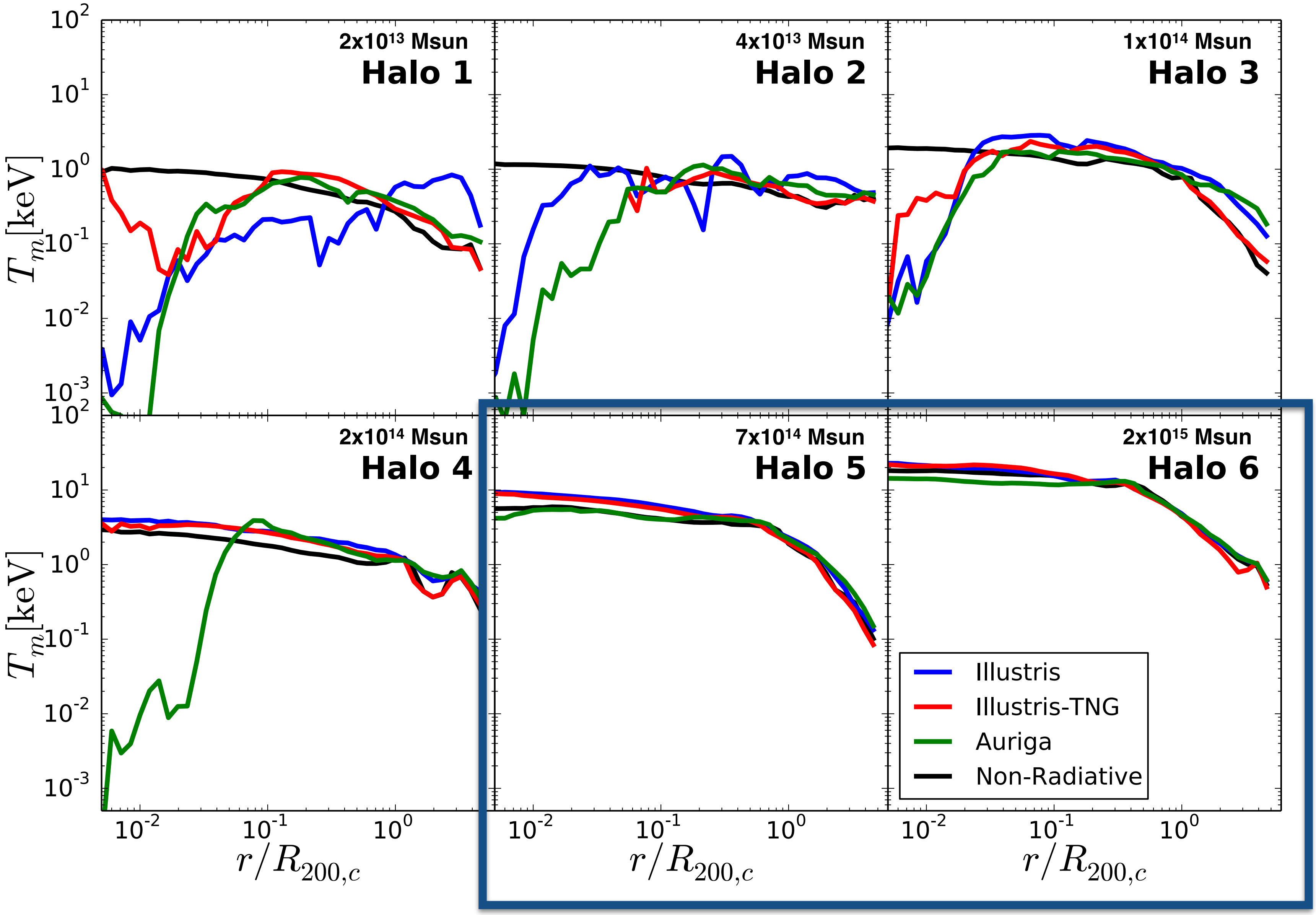
$Y_{SZ} \sim M_{gas}^{5/3} E(z)^{2/3}$

$Y_{SZ} \sim T^{5/2} E(z)^{-3/2}$

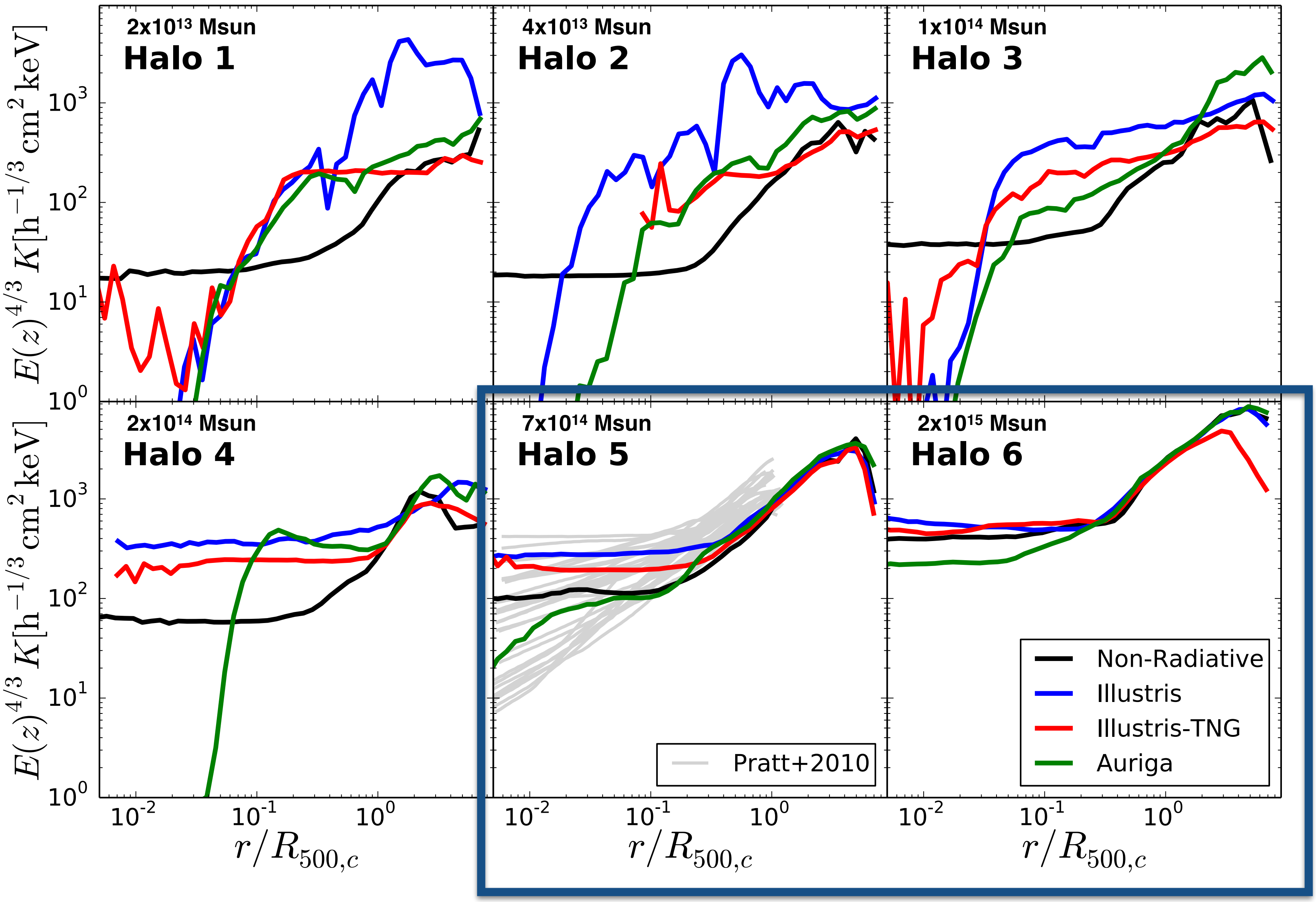
The same conclusions as for the X-ray scaling relations hold here

The SZ effect is less sensitive to the actual physics implementation of the feedback

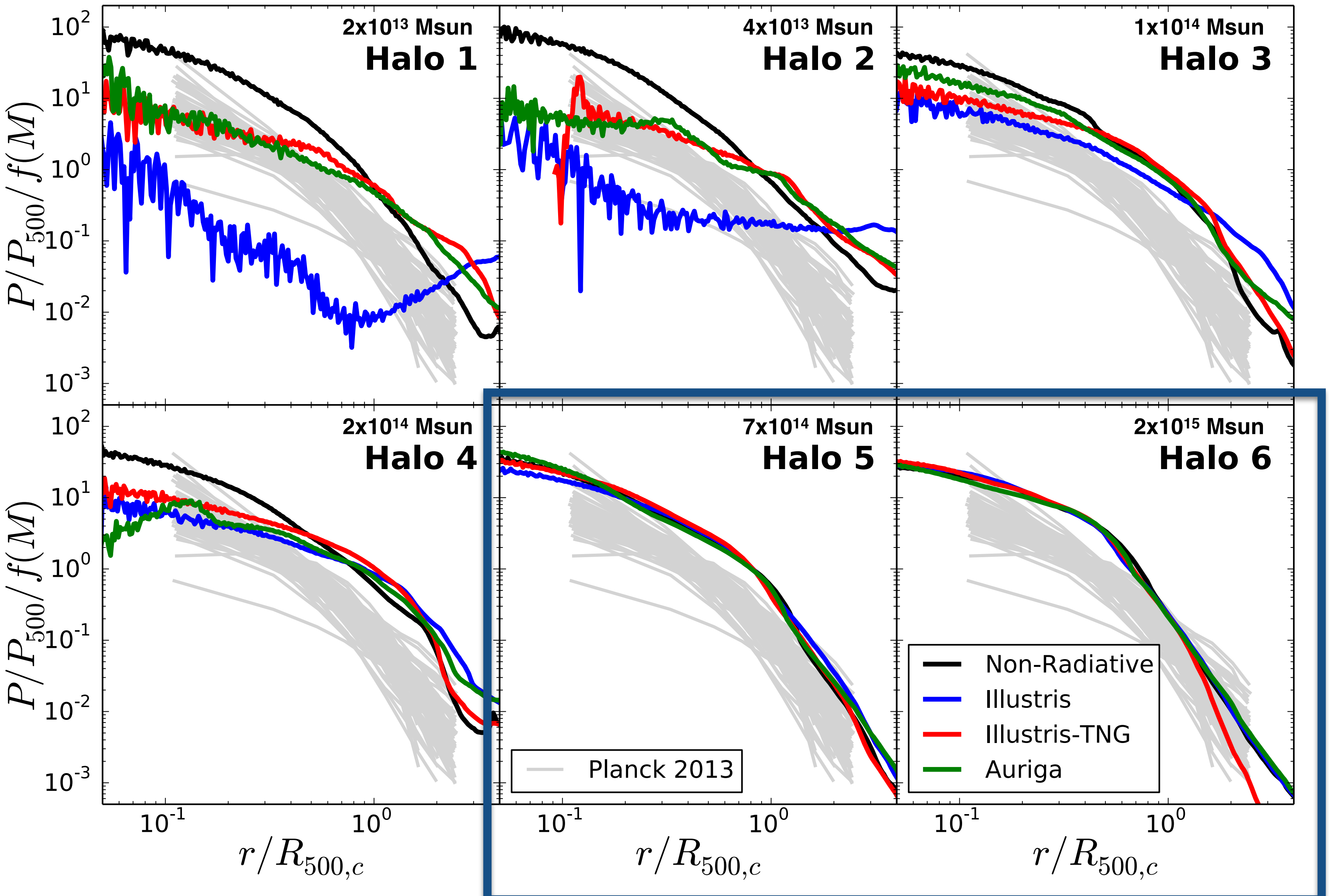
Profiles: Temperature



Profiles: Entropy



Profiles: SZ Pressure



Conclusions (I)

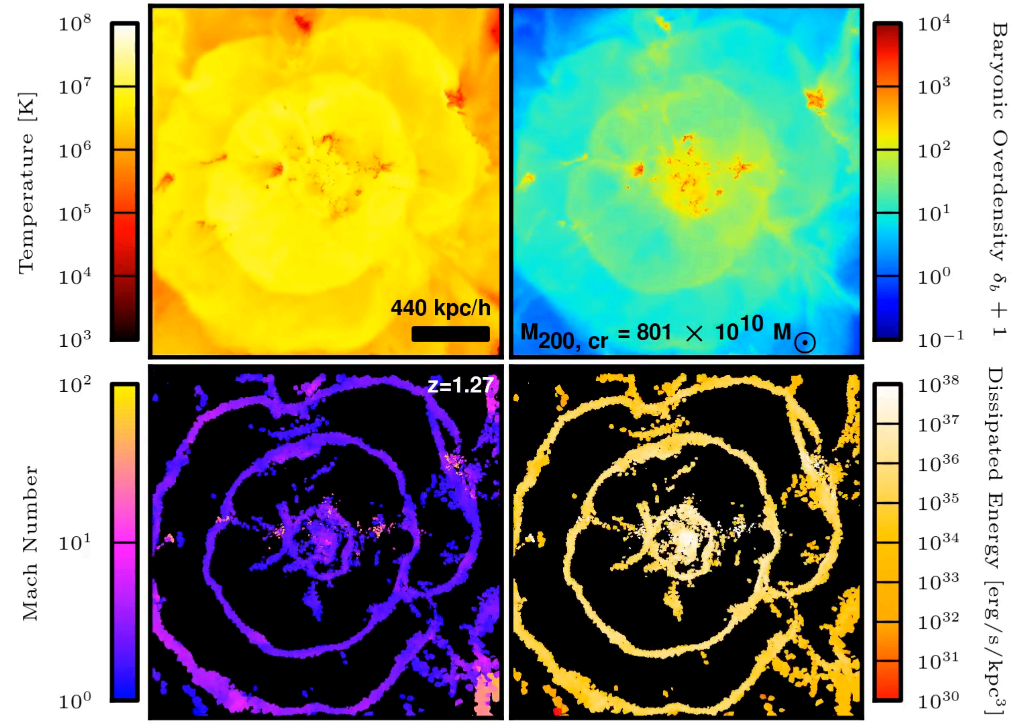
The radio feedback in Illustris is too violent at group-scale masses
(see movie to the right)

and yet:

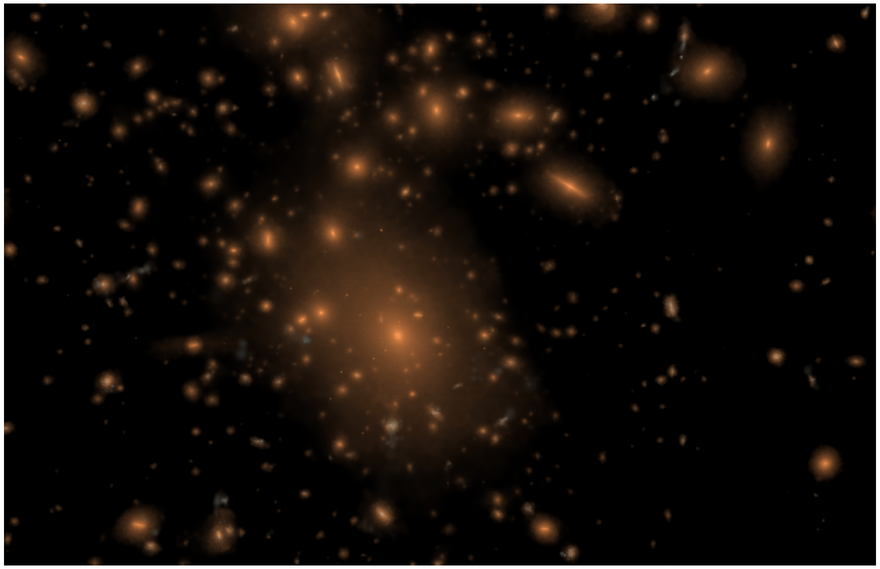
a. the BHs at fixed Mstars are smaller

b. the central galaxies in those high-mass haloes are not quenched enough and are too massive

c. still, the overall galaxy population at lower masses (e.g. L* galaxies) reproduce many observations and look like real galaxies



Illustris, Schaal et al. 2016, submitted



Illustris, www.illustris-project.org

Conclusions (II)

For haloes > a few 10^{14} Msun, somewhat different feedback models return very similar thermodynamical properties of the ICM

Such properties are in turn in the ball park of the self-similar predictions

This is the case not only for the integral ICM properties, but also for the inner profiles!

Therefore:

- Numerically, it is fundamental to explore AGN feedback across an extended halo mass range (only because we are doing subgrid?)
- The groups-scale gaseous haloes emerge as a quite awesome regime to study!
- The properties of the galaxies (stars) ultimately determines which feedback implementation is to be chosen (+ additional diagnostics of the ICM plasma)