Astrophysics & Cosmology with Galaxy Clusters: a Simulator's Perspective

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I. How much should we trust simulations?

II. What simulations are useful for?

II.a Calibration of mass proxies

II.b Universality of pressure profiles

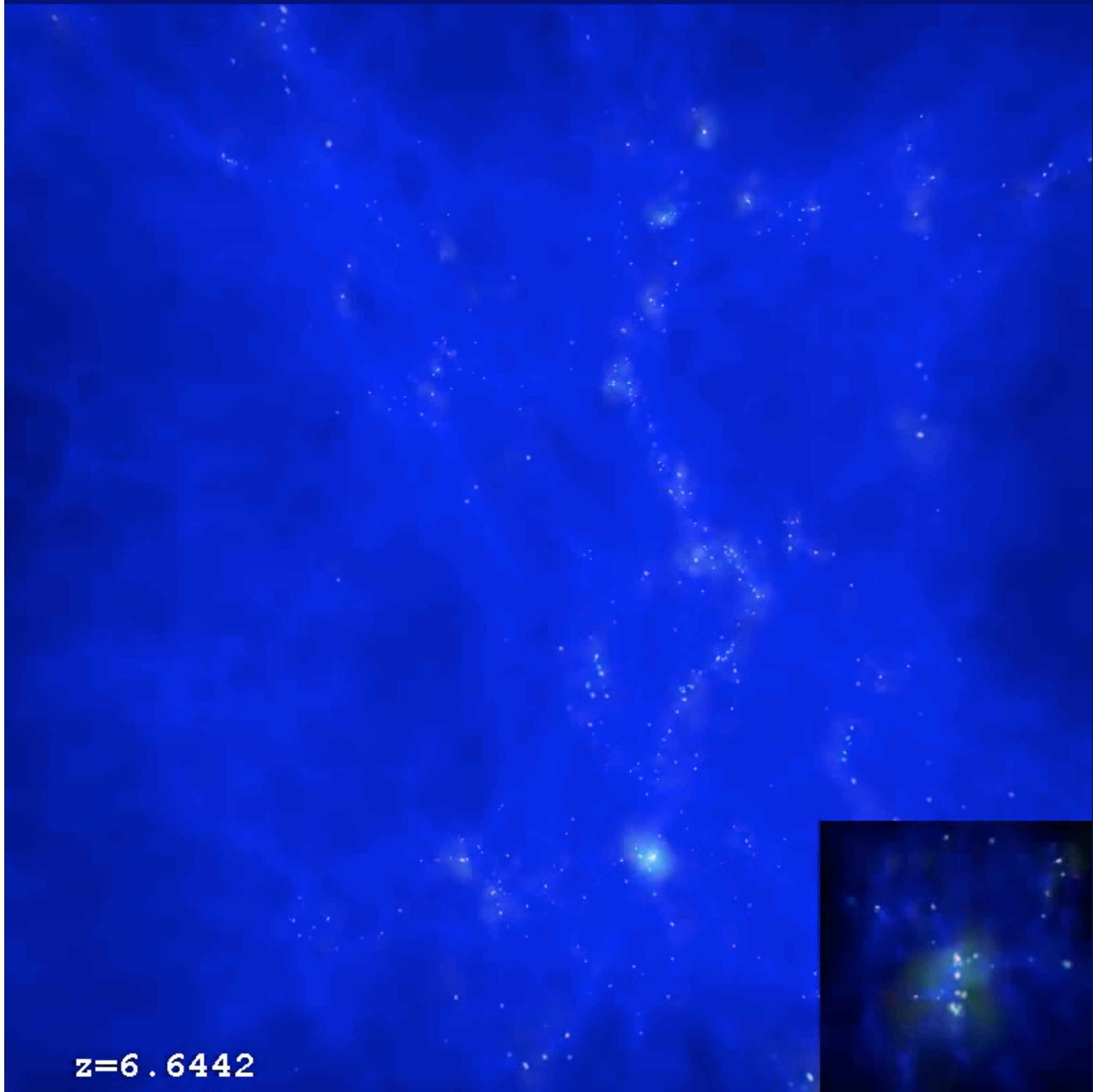
II.c Effect of gas-dynamics on the halo mass function

In collab. with: A. Bonafede, W. Cui, K. Dolag, D. Fabjan, M. Killedhar, M. Meneghetti, E. Rasia, G. Murante, B. Sartoris, L. Tornatore

Part 1:
Why should we trust simulations?

The role of hydrodynamic simulations

Movie by K. Dolag



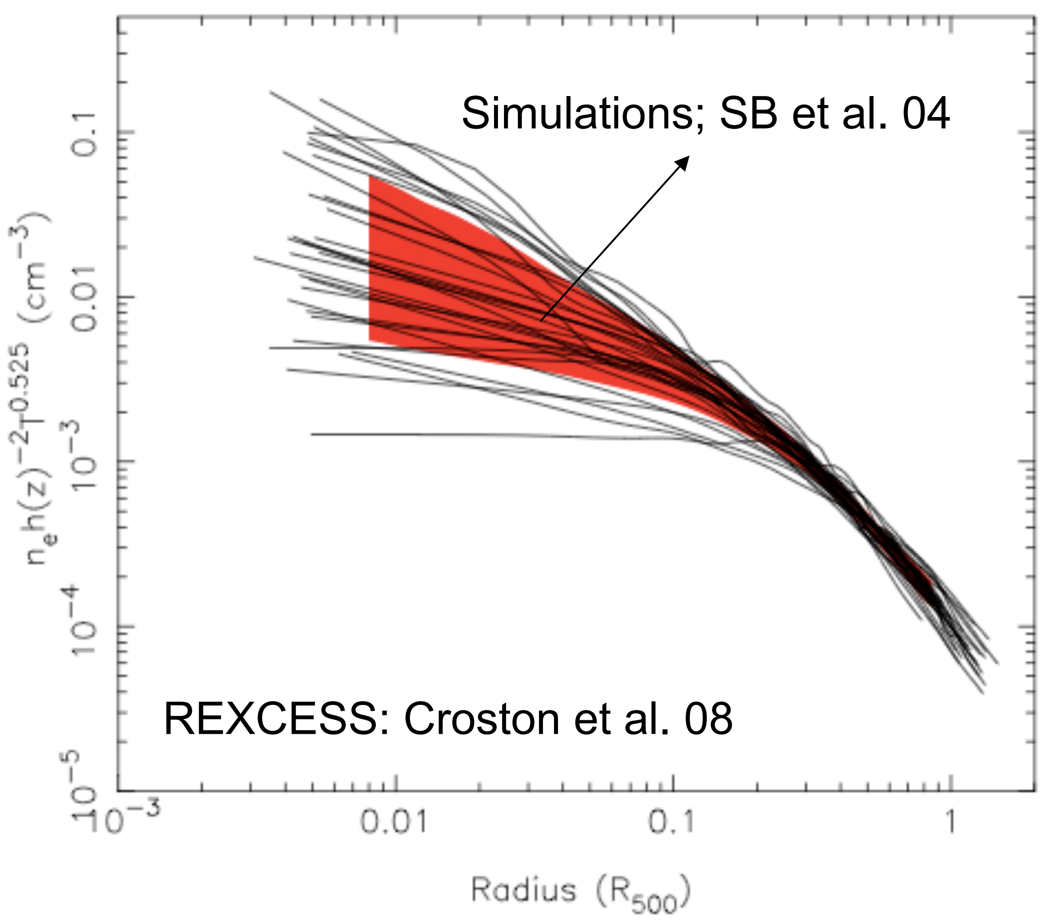
➔Define what's the regime where clusters are best modeled (and understood)

➔Understand and calibrate systematics and biases in mass measurements

➔Define and test "mass proxies": robustness and intrinsic scatter

(e.g. SB & Kravtsov '09)

Gas Density Profiles

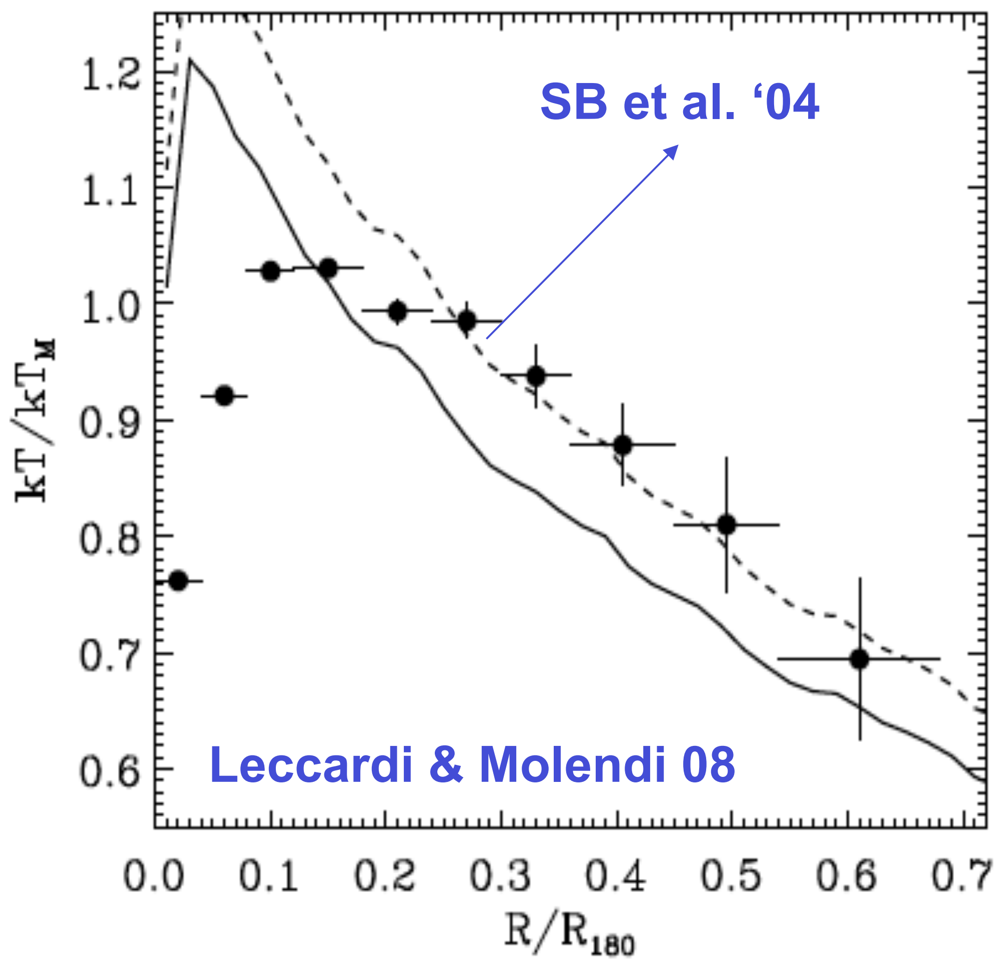


Croston et al. 08: comparison of XMM data with simulations.

See also Nagai et al. 07

➔ Excellent agreement, at least outside the cool core regions.

Temperature Profiles

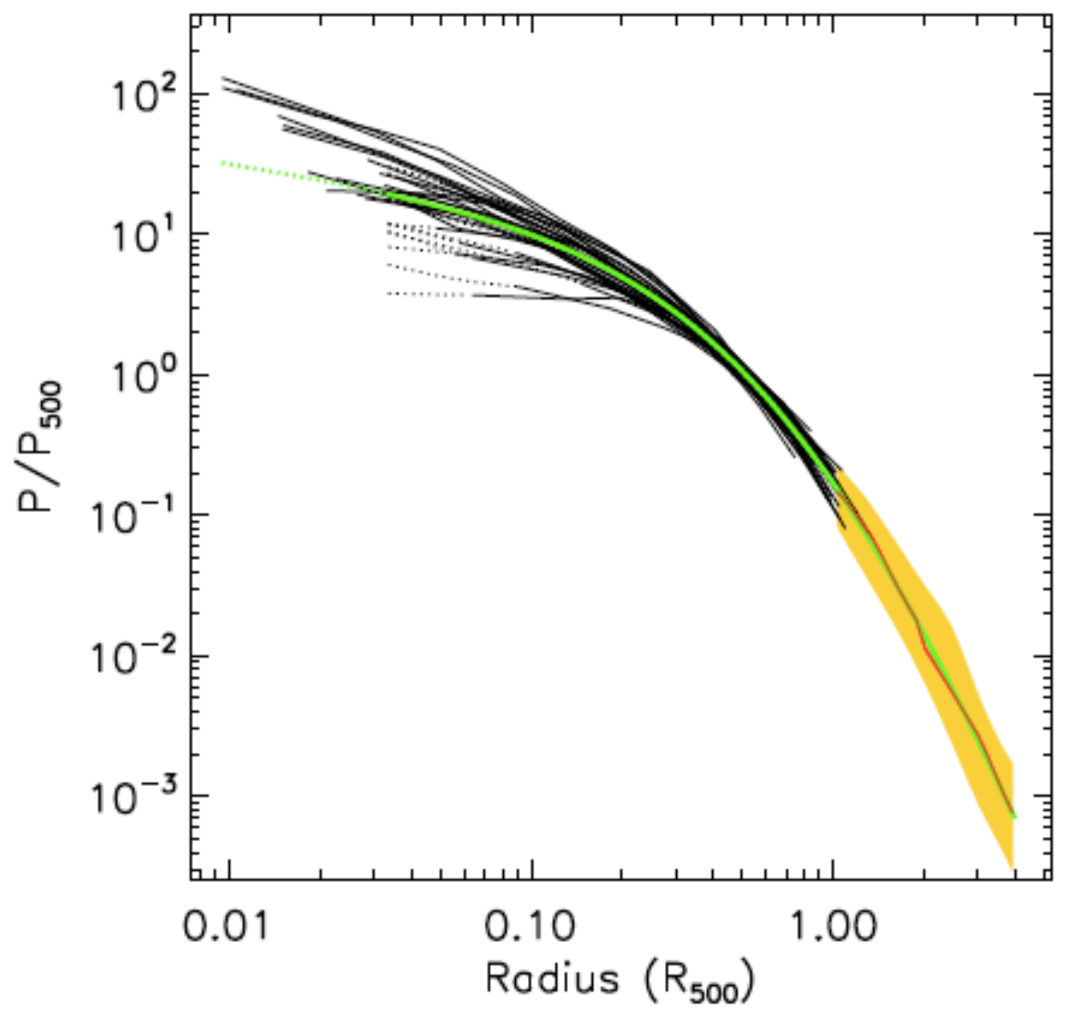


Loken et al. '02; SB et al. 04; Nagai et al. 07; Pratt et al. '07; Leccardi & Molendi '08:

1. Central profiles in simulations steep and negative
➔ Strong disagreement with data
➔ Requires introducing AGN feedback (e.g., Sijacki et al. 2007)

2. Excellent agreement outside the cool core regions!

Pressure Profiles



Arnaud et al. 2010:

- P-profiles from simulations: SB et al. '04 (SPH), Nagai et al. 07 (AMR), Piffaretti & Valdarnini 09 (SPH)
- Observed pressure profiles for REXCESS clusters (XMM)

➔ Excellent agreement out to R_{500}

➔ Simulations to extrapolate at larger radii

Part 2:
What simulations are useful for?

Does hydrostatic equilibrium hold?

- Hydrostatic equilibrium (HE):

$$M_{hyd}(<r) = -\frac{rkT}{G\mu m_p}\frac{d\ln(nkT)}{d\ln(r)}$$

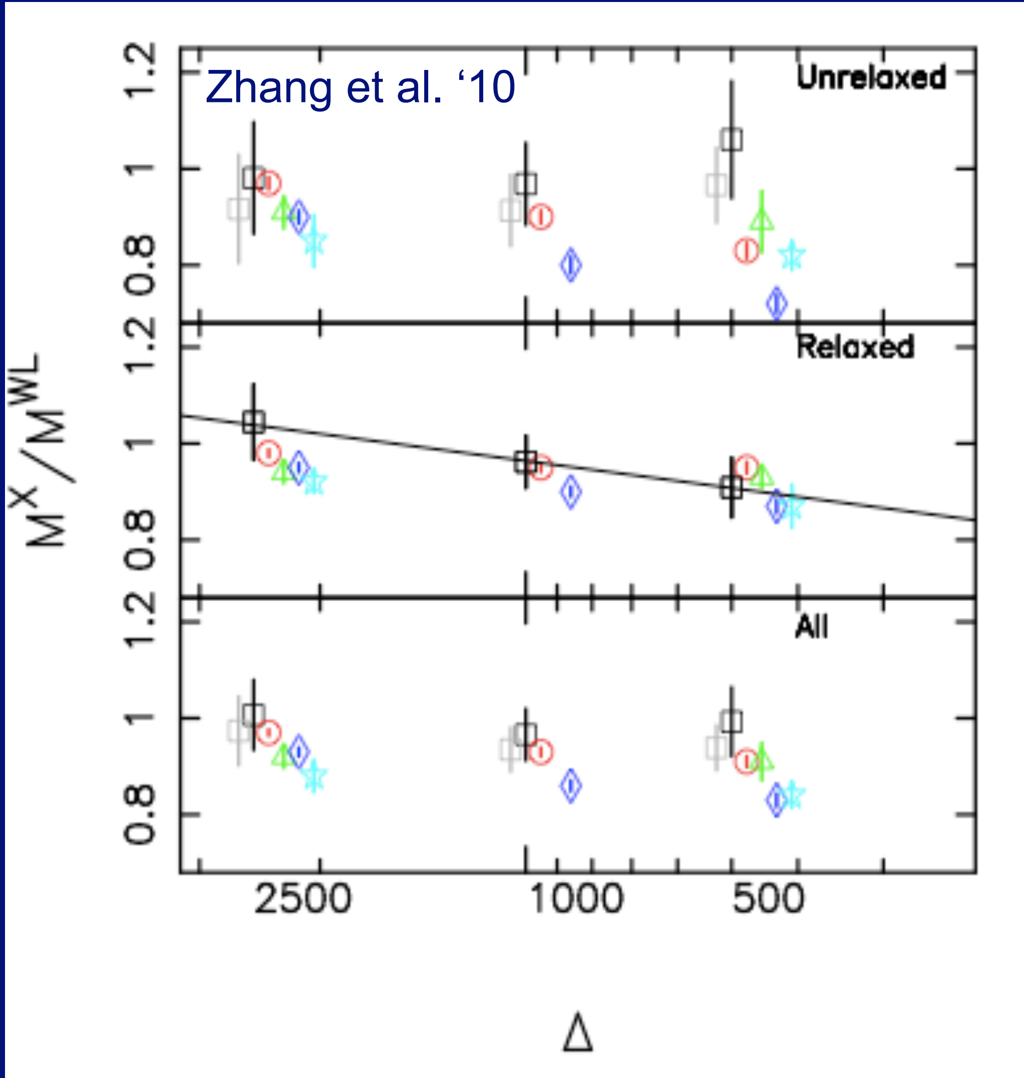
➔ HE violated at the ~10% level within r_{500}

➔ Larger deviations at larger radii ($>R_{500}$)

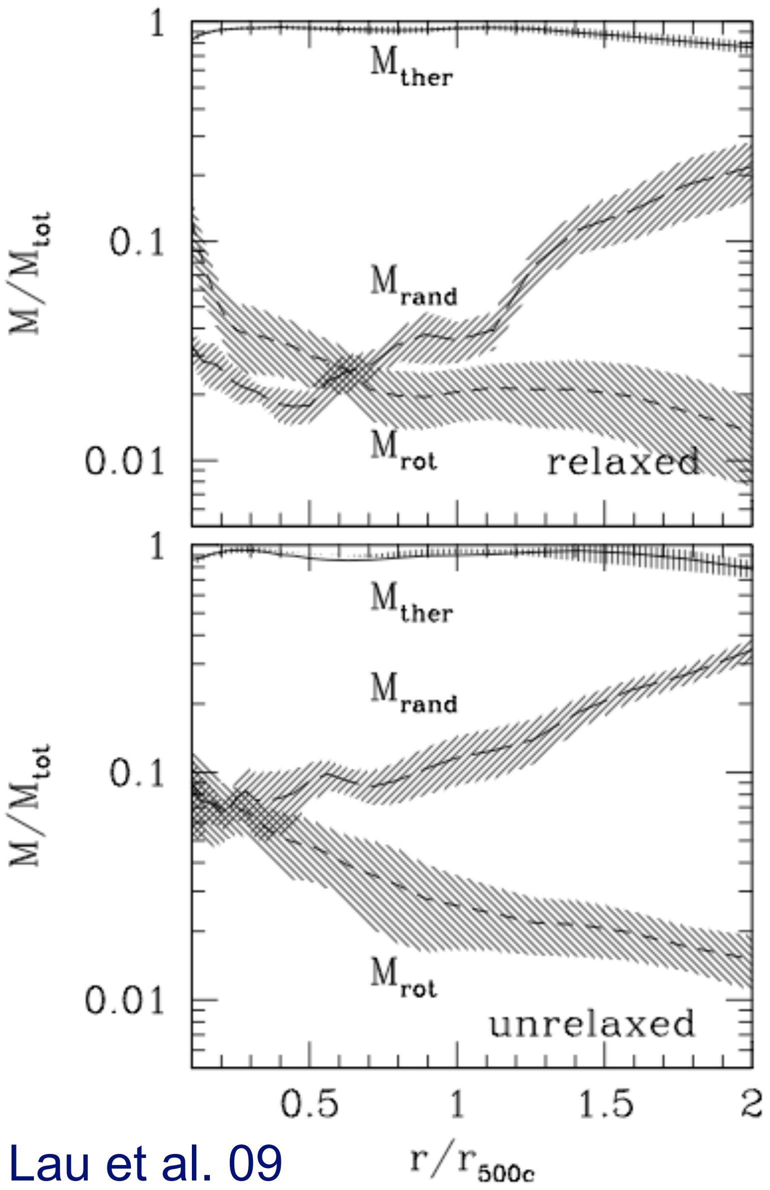
➔ Larger scatter in the core regions ($<0.15R_{500}$)

See also Rasia et al. 2006, Nagai et al. 2007, Morandi et al. 2007, Piffaretti & Valdarnini 2008

- Level of HE violation in simulations comparable to the X-ray/lensing mass ratio (e.g. Zhang et al. '10; talk by A. Mahdavi)



Tracing the origin of HE violation



Lau et al. 09

➔ Non-thermal pressure support from subsonic turbulent motions e.g. Rasia et al. 04, 06, Faltenbacher et al. 05, Lau et al. 09

Lau et al. 09:

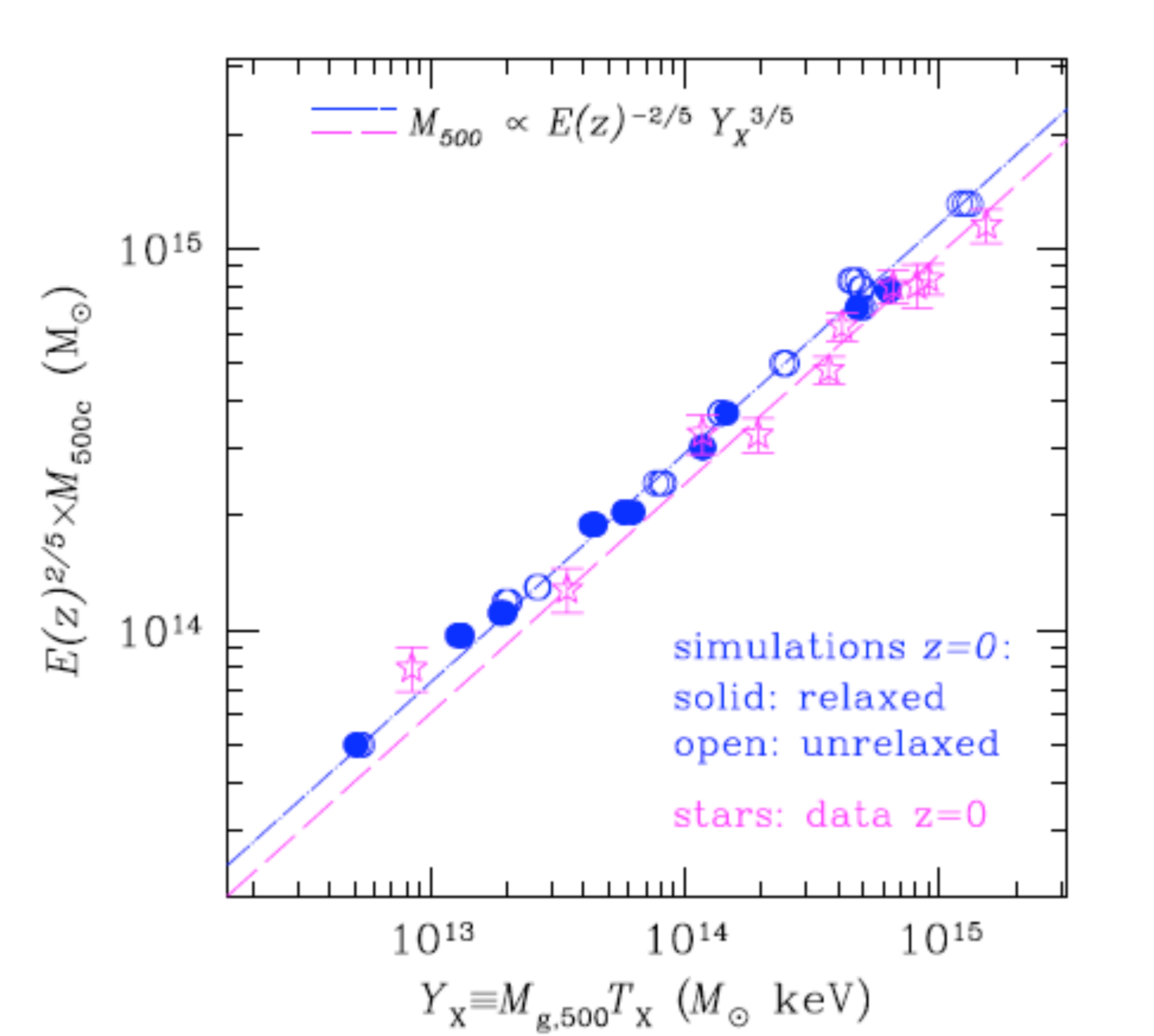
Different contribution to total mass estimate from HE equation

➔ Non-thermal contributions increasing at larger radii

➔ At R_{500} : <10% for relaxed clusters and ~15% for unrelaxed clusters

Mass proxies: X-ray "pressure"

Kravtsov et al. '06



X-ray "pressure":

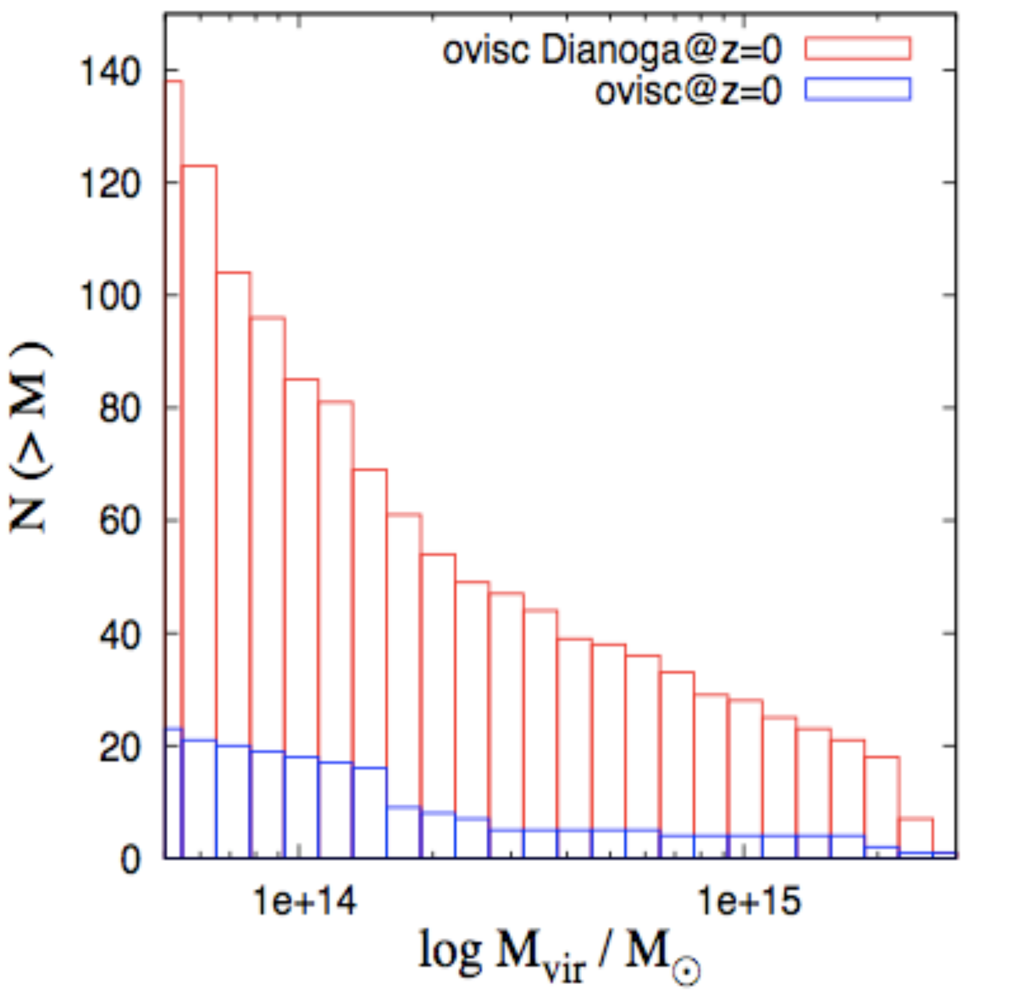
$$Y_X = M_{gas} T_X$$

➔ T_X computed by excising $r < 0.15\, r_{500}$

1. Similar to Compton-y from SZ observations.
2. Very small intrinsic scatter: ~ 5-7 % !
3. About 15 % offset wrt Chandra results.

Testing the robustness of mass proxies

Fabjan et al. '11; Bonafede et al. in prep



<u>Increase the statistics of simulated clusters:</u>

- Use a 1 h^{-1} Gpc box simulated at low res. with 1024^3 DM parts
- 29 Lagrangian regions around as many massive clusters

➔ 25 clusters with $M_{200}>10^{15}\ h^{-1}\ M_{\odot}$

➔ Non-radiative and radiative runs

<u>Increase the variety of ICM physical processes:</u>

- 18 clusters/groups with 7 different physics:

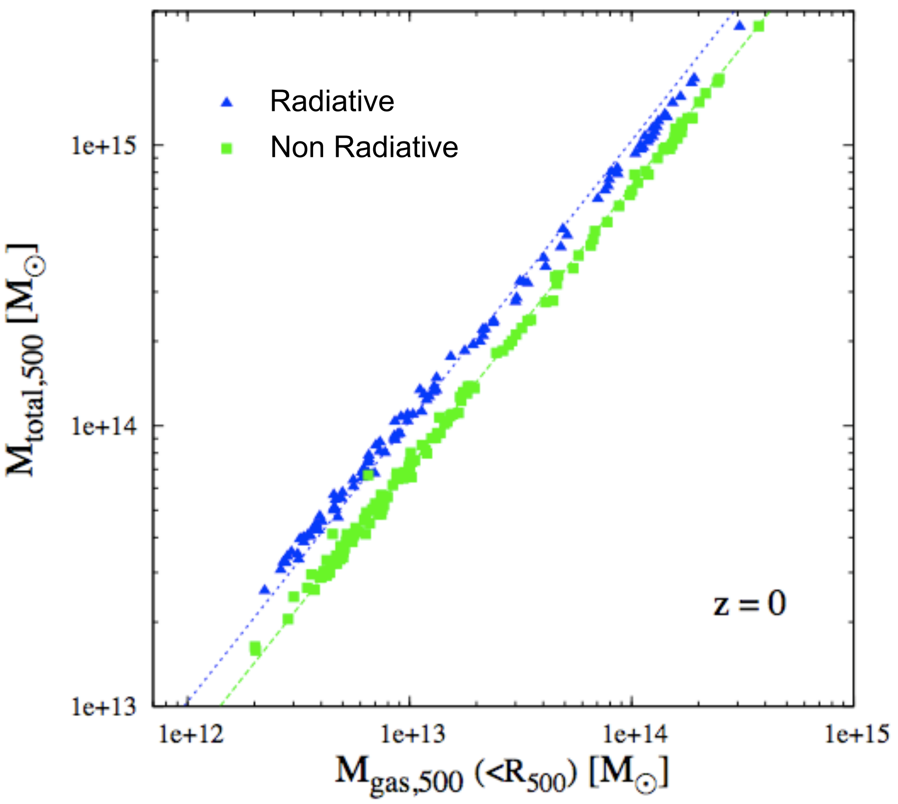
➔ Changing artificial viscosity

➔ Including thermal conduction

➔ Changing feedback strength and source (SN and AGN)

See talk by S. Gottloeber

Scaling relations @ z=0



(see also Stanek et al. 09)

Y_X

Self-similar: $$M_{tot,500} = C_Y E(z)^{-2/3} Y_X^{3/5}$$

➔Weak (but sizeable) sensitivity to ICM physics

➔Always close to self-similar prediction

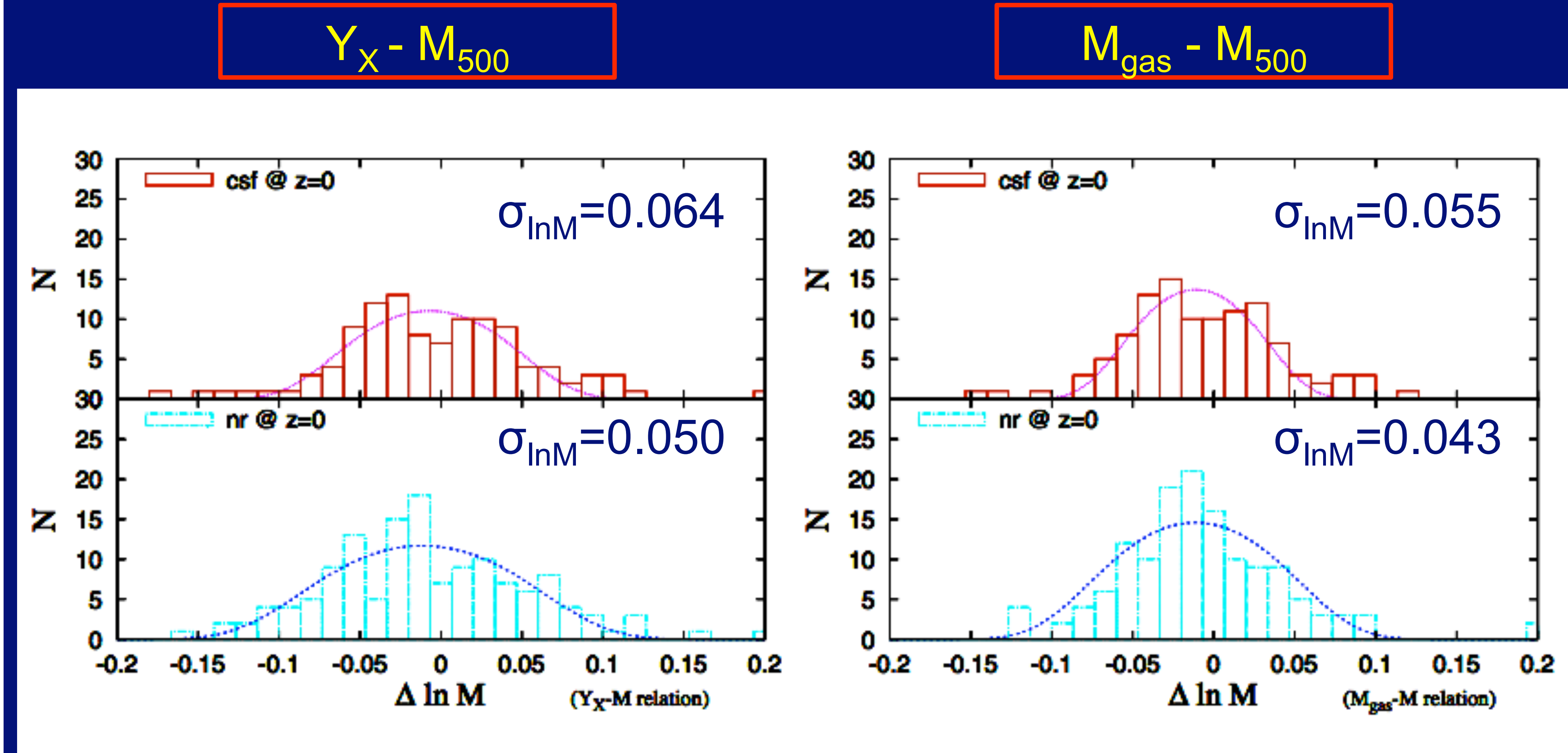
M_{gas}

Self-similar: $$M_{tot,500} = C_{Mg} M_{gas,500}$$

➔More sensitive to ICM physics

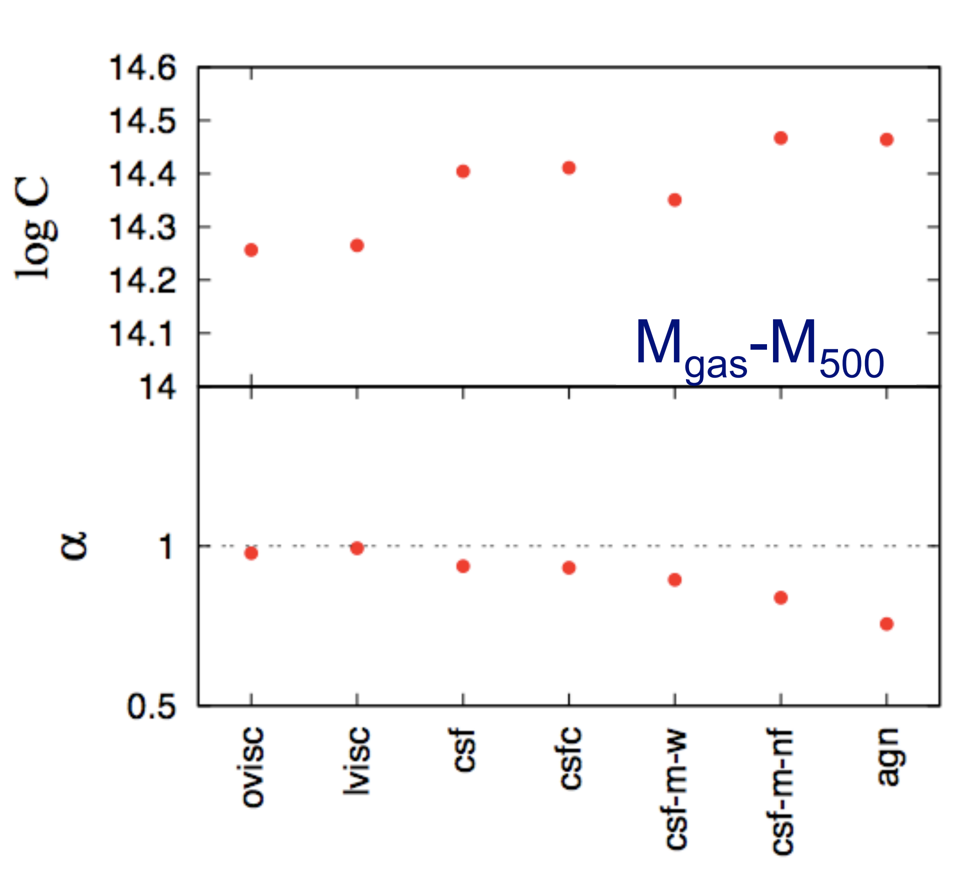
➔Larger deviations from self-similar slope for the radiative runs

Distribution of the intrinsic scatter



- ➔ Scatter always very small and almost Gaussian-distributed
- ➔ Sligltly smaller scatter for M_{gas} - M_{500}
- ➔ Slightly large scatter in non-raditive runs

Stability against changing the ICM physics



ovisc: nr-standard viscosity
lvisc: nr-reduced viscosity
csf: cooling+SF
csfc: cooling+SF+conduction
csf-m-nf: chemical enrichment
csf-m-w: chemical enrichment+winds
csf-m-agn: chemical enrichment+AGN

Y_X

$$M_{tot,500} = C_Y E(z)^{-2/3} Y_X^{\alpha}$$

➔Weak dependence of normalization on ICM physics

➔Slope always very close to self-similar

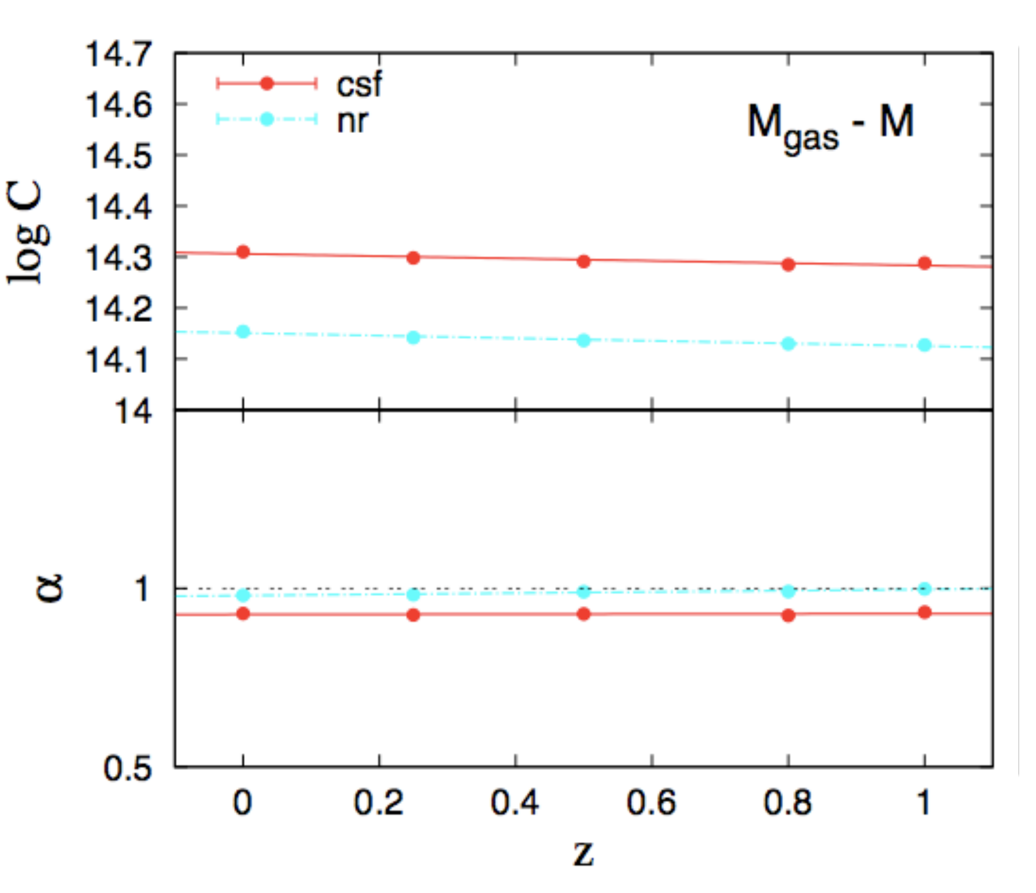
M_{gas}

$$M_{tot,500} = C_{Mg} M_{gas,500}^{\alpha}$$

➔More sensitive dependence of amplitude on ICM physics

➔Larger deviations from self-similar slope in radiative runs

Evolution of scaling relations…



Y_X

$$M_{tot,500} = C_Y E(z)^{-2/3} Y_X^{\alpha}$$

➔ Normalization and slope in agreement with self-similar predictions!

➔ Same evolution of radiative and non-radiative physics

M_{gas}

$$M_{tot,500} = C_{Mg} M_{gas,500}^{\alpha}$$

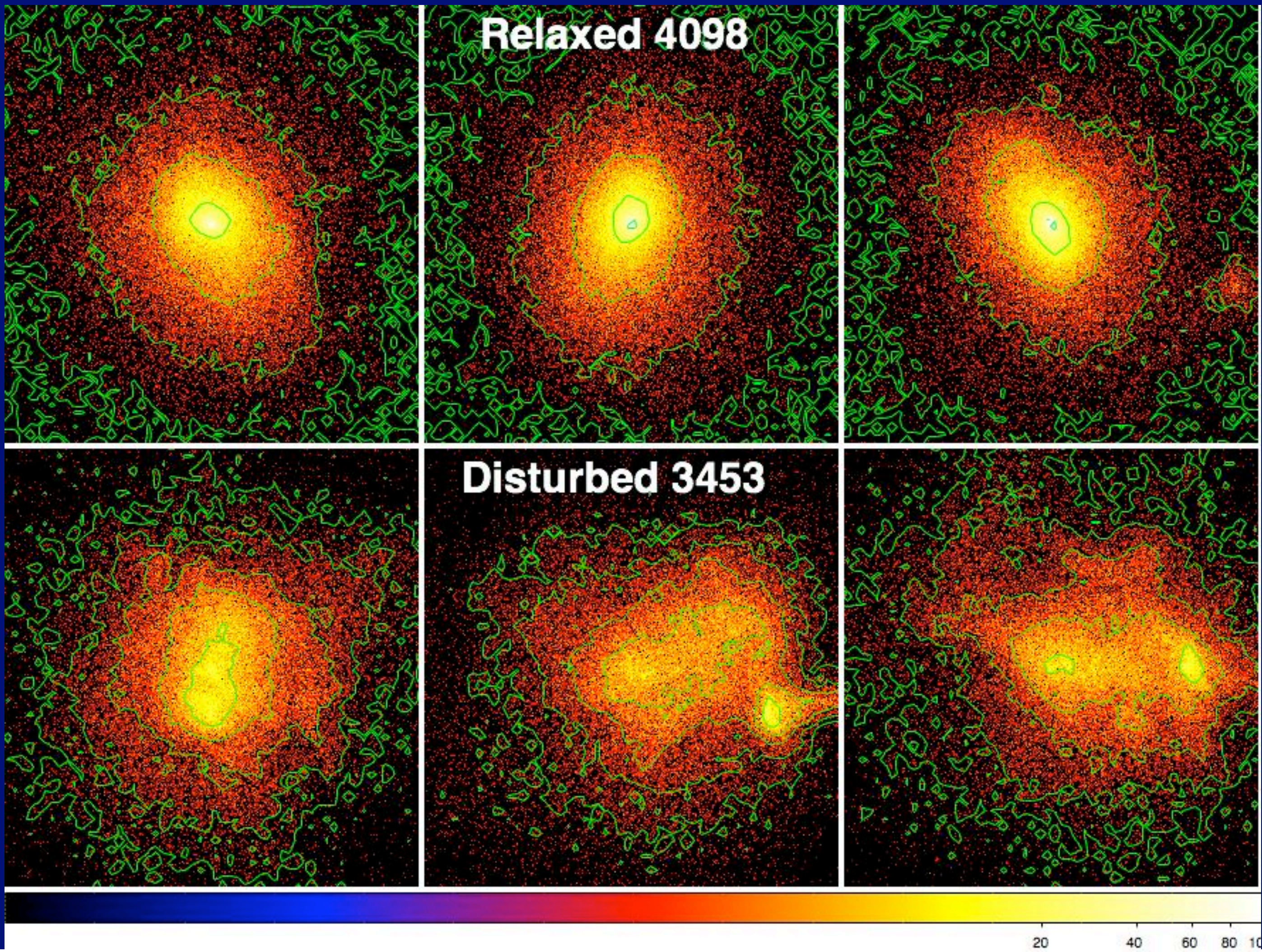
➔ Self-similarity only for non-radiative physics

➔ No significant evolution of slope and normalization

Next: mimicking X-ray observations

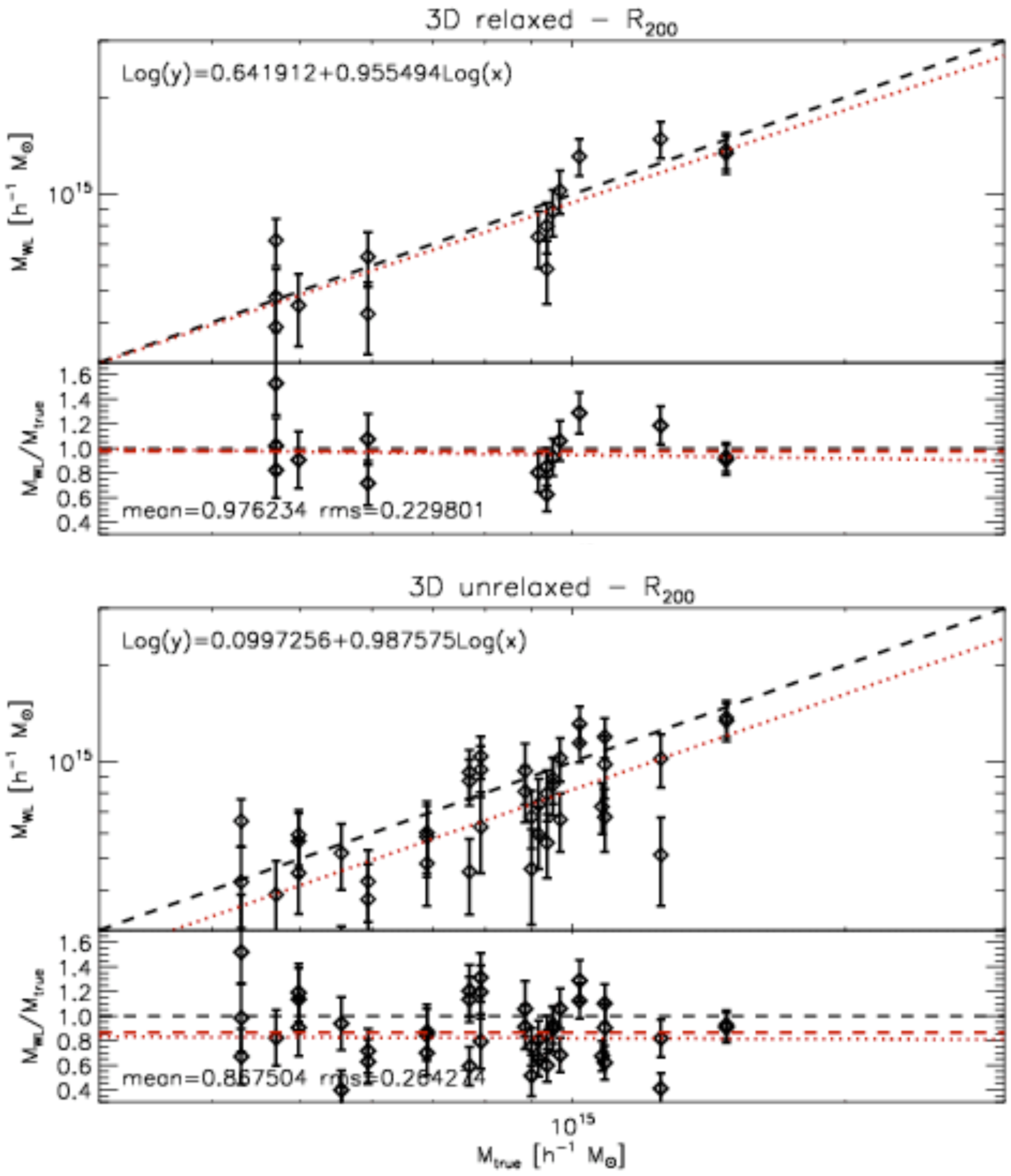
Rasia et al. in prep

- ➔ Event files from X-MAS Chandra simulator (Rasia et al. 08) with 100 ks exp. time
- ➔ [0.7-2] keV X-ray image (16 x 16 arcmin^2)



… and X-ray/lensing mass comparison

Meneghetti et al. in prep



HST-ACS lensing of a massive simulated cluster at z=0.25

Based on the SkyLens tool (Meneghetti et al. 2008)

At R_{200}:

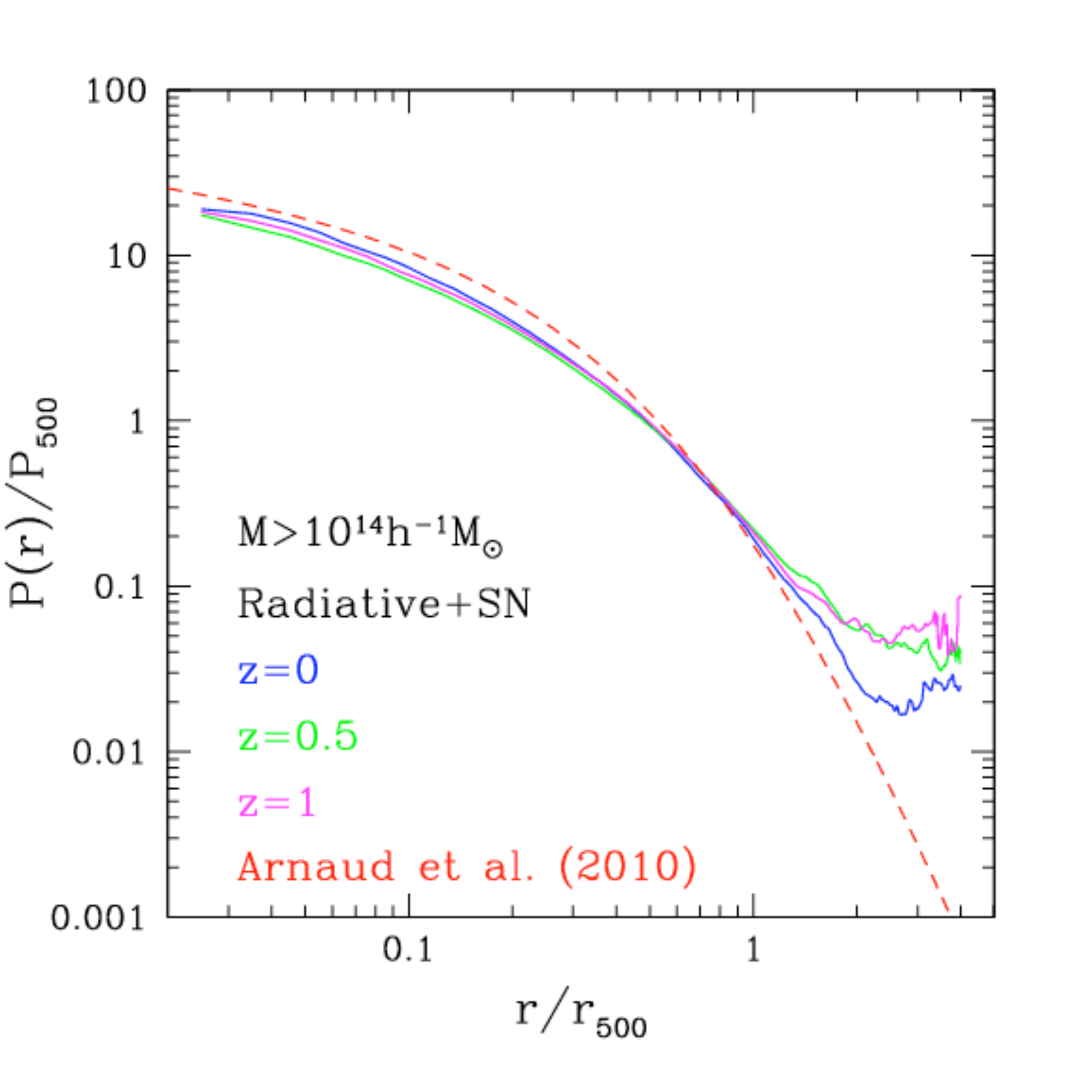
Relaxed clusters:

- ➔ Negligible bias: < 3%
- ➔ Intrinsic scatter: ~ 20%

Unrelaxed clusters:

- ➔ Non-negligible bias: ~15%
- ➔ Intrinsic scatter: ~ 25%

How universal is the Universal Pressure Profile?



Relevant for:

1. Deprojection of Y_{SZ} in observations of galaxy clusters
2. Templates for SZ power spectrum (see D.Nagai's and N.Battaglia's talk)

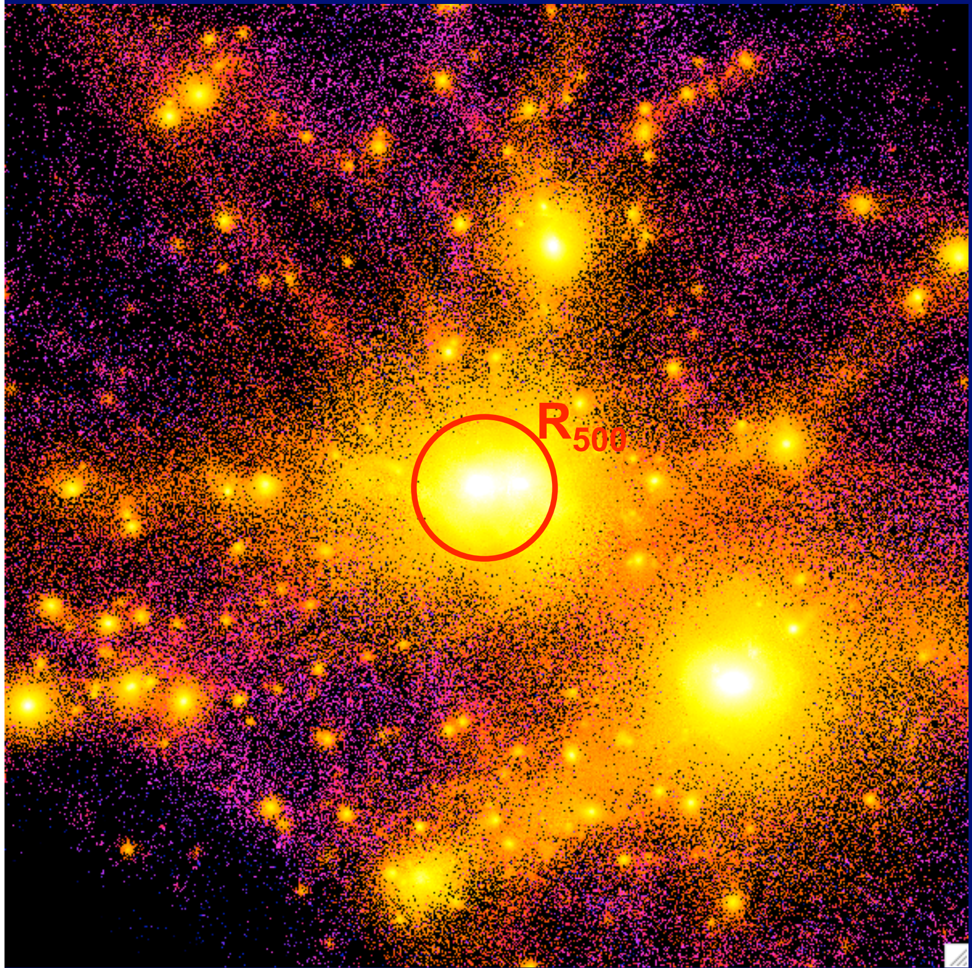
➔ Massive clusters: Quite close to UPP at $r < r_{500}$

➔ Redshift evolution: ~ self similar at $r < r_{500}$

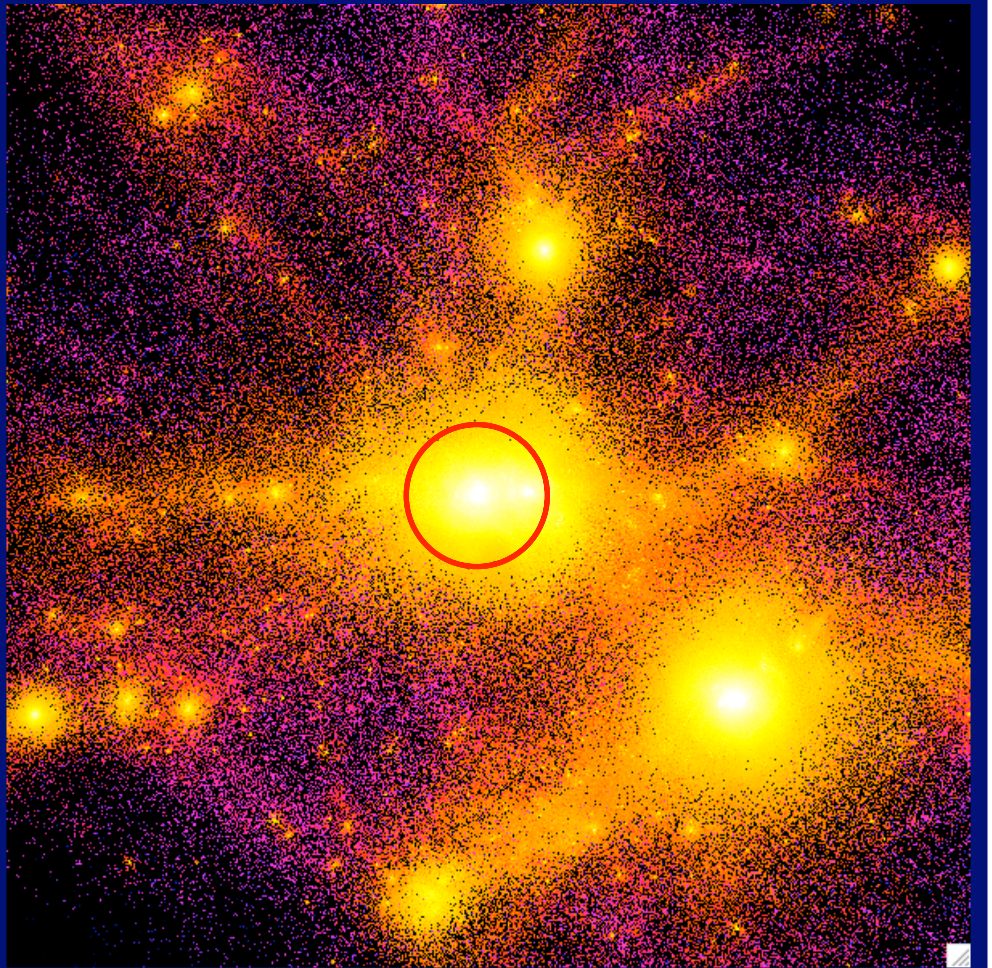
➔ Significant effect of clumping for $r > r_{500}$

Pressure maps

Non radiative

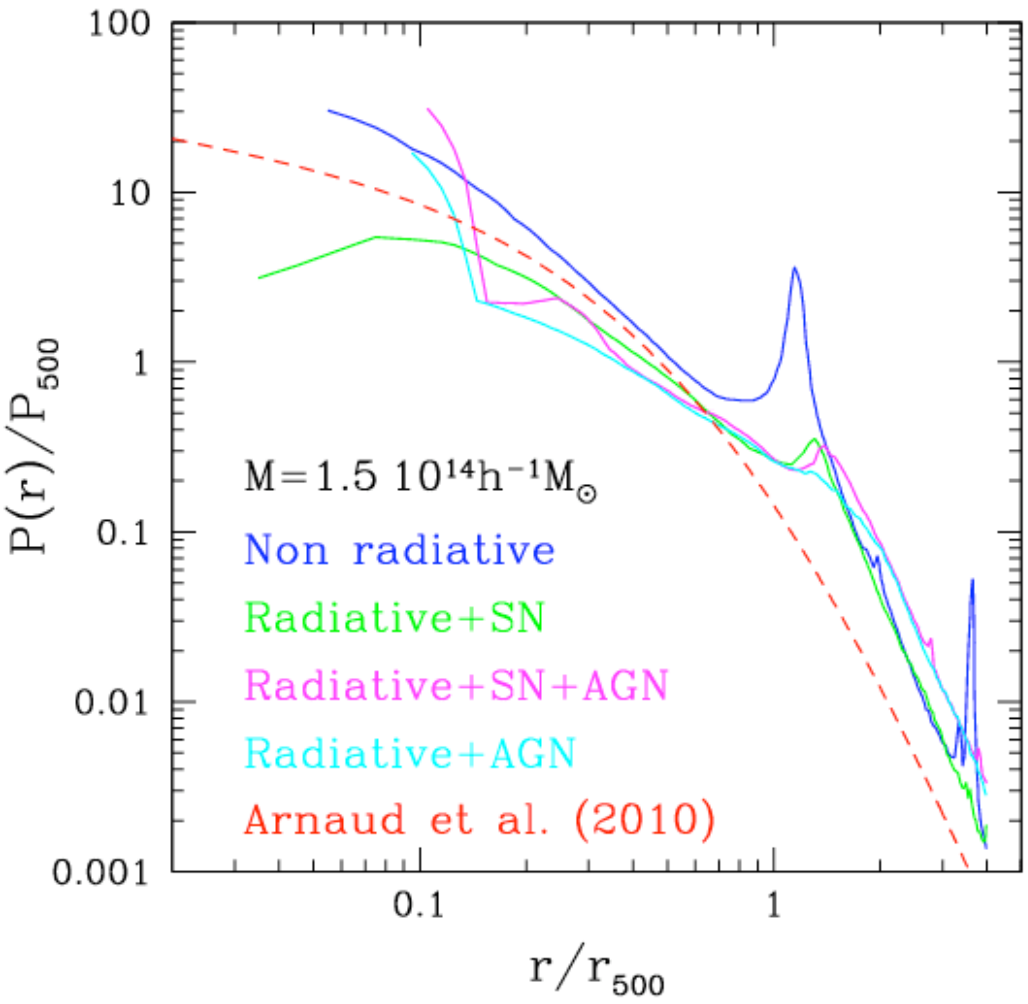


Radiative



➔ Pressure clumping decreased by (over)cooling in small halos: removal of gas with short cooling time.

Effect of changing the physics



Cooling + SF: reduce the effect of gas clumping

→ Gas converted into stars

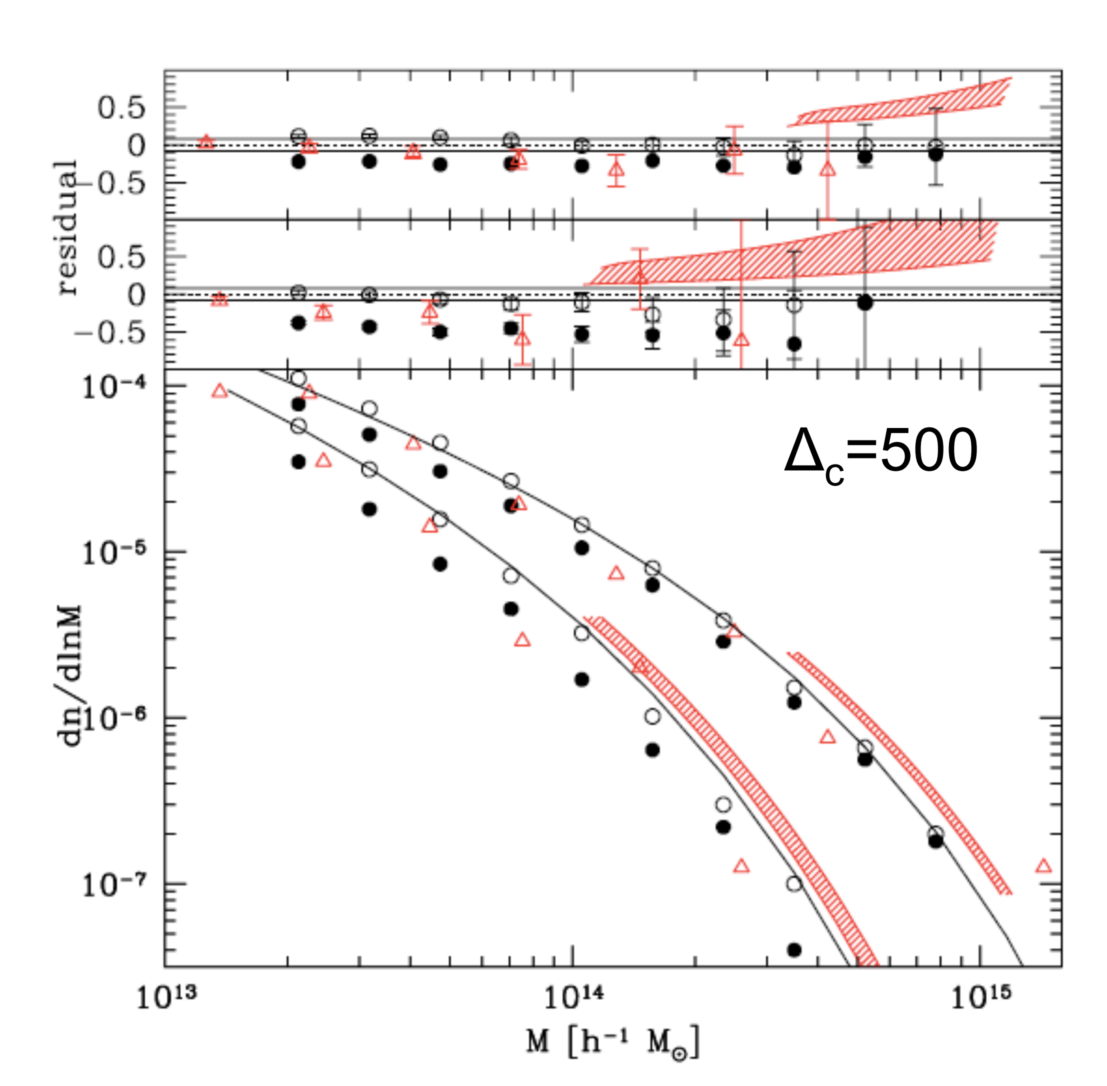
AGN feedback: increase pressure at $r > r_{500}$

→ IGM pressurized at the peak of BH accretion before cluster assembly

(see also Battaglia et al. ‘10)

→Stronger clumping in NR runs

Effect of gas-dynamics on the MF



Stanek et al. '09:

- GADGET Millennium gas simulations (non-radiative and radiative/pre-heated)
- Comparison with DM results using the Tinker et al. fitting function
- Comparison with ART simulations by rescaling to account for different cosmological parameters

➔ MF variations of 10% (and more)

Summary

$0.1 < R/R_{500} < 1$: Gas dynamics relatively simple and well described by cosmological hydro simulations

➔ Simulations useful to calibrate them as cosmological tools:

1. Level of violation of hydrostatic equilibrium

2. Definition and calibration of robust and stable mass proxies

3. Accurate calibration of the halo MF including effect of baryons required

A lesson for future (beyond eROSITA) X-ray cluster surveys:

- Detect $\sim 10^3$ photons for $\sim 10^4$ clusters to measure mass proxies
- Resolve cluster cores at high redshift to reduce scatter in the M-X calibration:

10 arcsec @ z=1 ➔ 110 h^{-1} kpc comoving