Scatter and evolution of the hot gas properties and of the dark matter profiles of massive galaxy clusters

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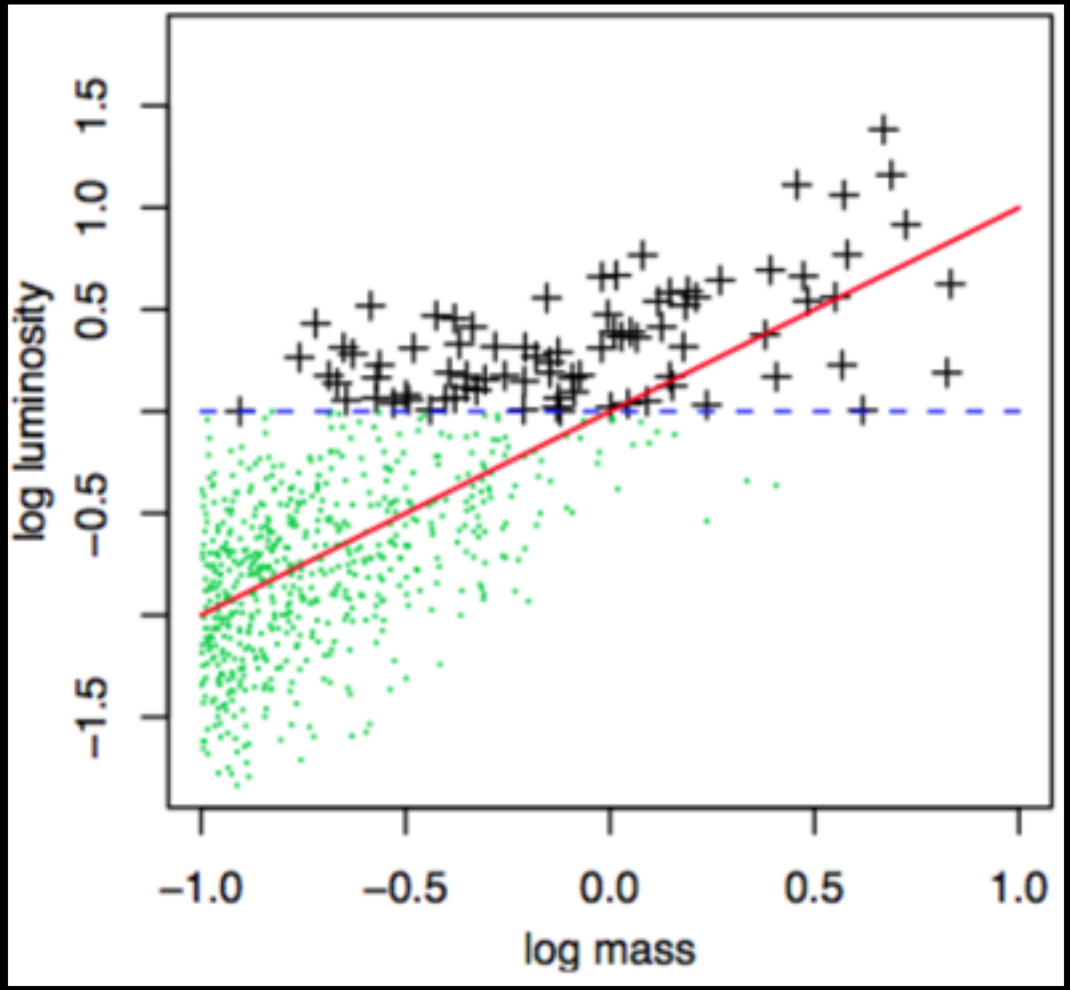
Scatter and evolution

- In order to do cosmology with galaxy clusters, one needs to rely heavily on cluster scaling relations. This is especially true **at high-redshift.**

➡ Guidance from cosmological hydrodynamical simulations is often required or desirable.

- The recent intracluster medium (ICM) 'sub-grid' physics models are faring relatively well at low-redshift compared to observation, but **what are they predicting for the scaling relations at higher-redshift?** Comparisons to the observed evolution of the scaling relations can help improve our understanding of the non-gravitational physics of the ICM.

- Scatter and covariance of the mass-observable relation must be well-constrained and properly included in the cosmological modelling.



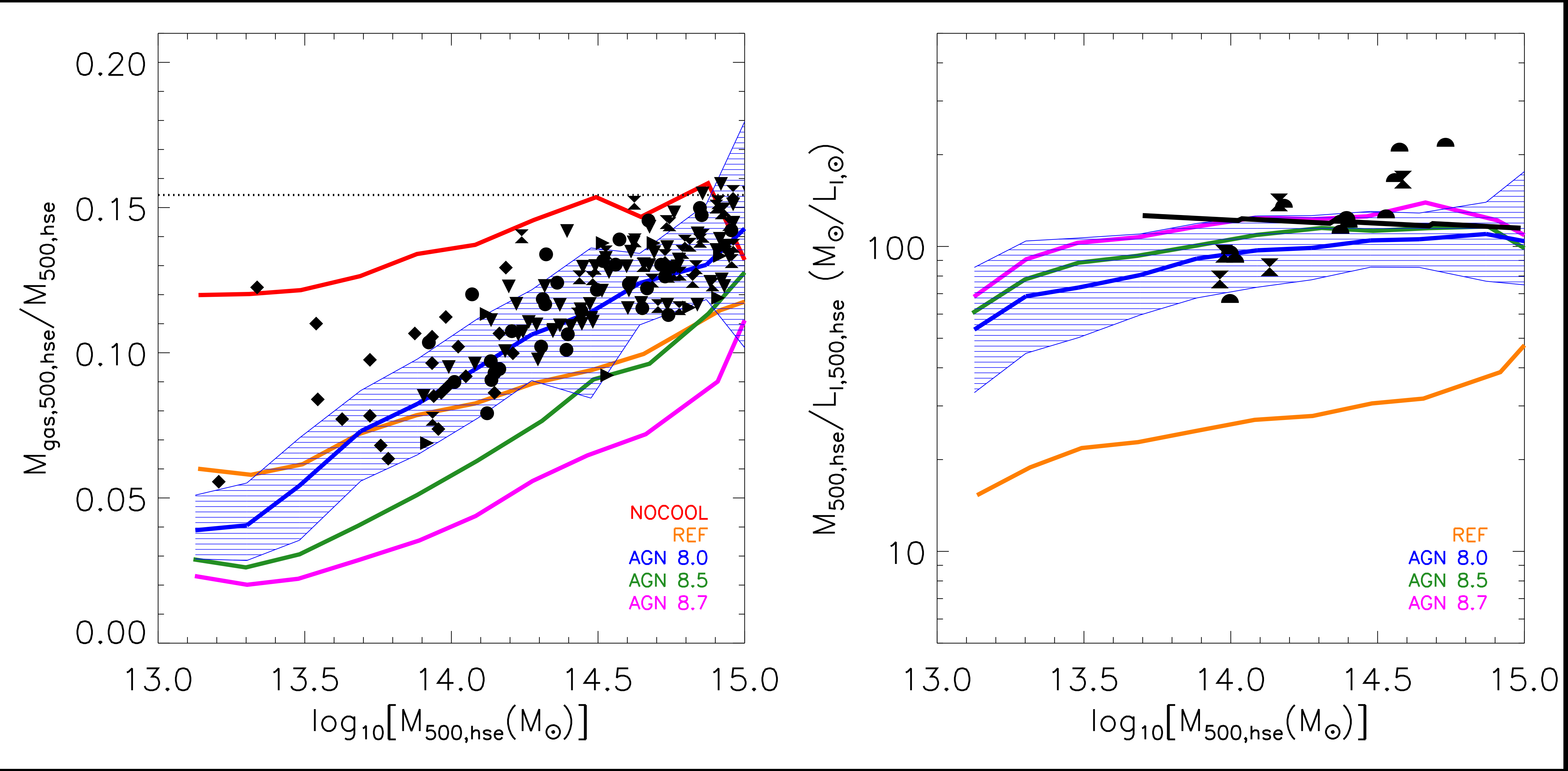
Allen, Evrard & Mantz 2011

cosmo-OverWhelmingly Large Simulations

- 2.15 billion particles in 400 Mpc/h boxes with 4 kpc/h gravitational softening run using modified version of GADGET3 (Springel 2005)
- Resorts to **subgrid** modeling for **unresolved** small scale physics and **varying** it: **metal-dependent** radiative cooling (Wiersma et al. 2009a), chemodynamics and stellar evolution (Wiersma et al. 2009b), star formation (Schaye & Dalla Vecchia 2008), **kinetic** supernova feedback (Dalla Vecchia & Schaye 2008) and **AGN feedback** (Booth & Schaye 2009).
- AGN feedback is ensured to be efficient.
- More than **14,000** groups and clusters with $M_{500}>10^{13}\ M_{\odot}$ at z=0 in Planck cosmology.
- Produce synthetic X-ray data and **mimic observational analysis techniques (including HSE analysis).**

Le Brun et al. 2014

Benchmarking using local observations



Data: Pratt09, Vikhlinin06, Lin12, Maughan08 and Sun09

Data: Sanderson13, Gonzalez13 and Budzynski14

- Need feedback of some sort to solve overcooling problem
- Only AGN feedback can yield the high observed total mass-to-light ratios

Fitting of relations

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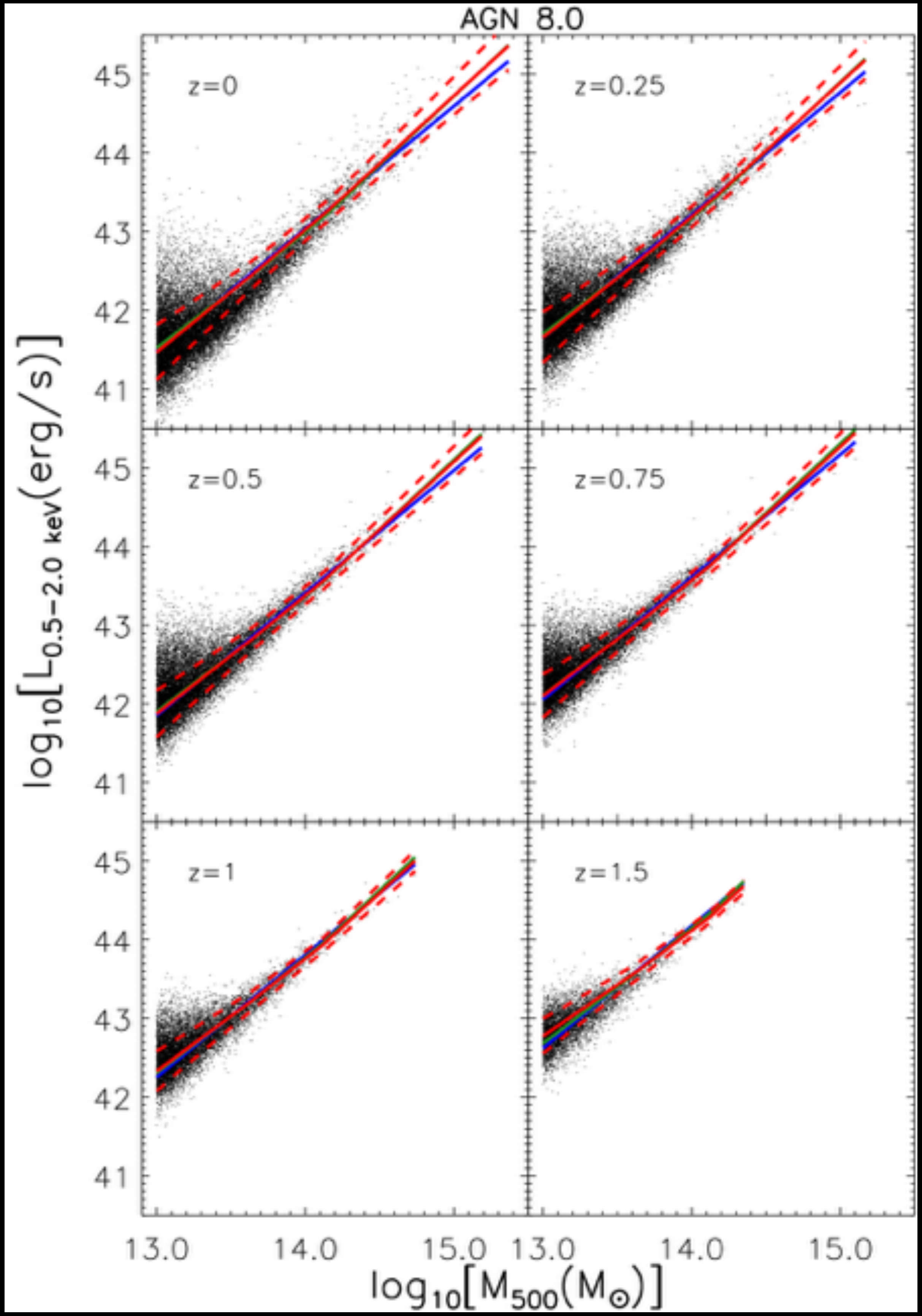
Fit evolving (broken) power-laws to the **median scaling relation** and **log-normal scatter**

Blue: evolving power-law
Green: evolving broken power-law
Red: **evolving broken** power-law with **redshift-dependent low-mass mass slope**



Necessary to **break** the power-law and to make the **low-mass mass slope redshift-dependent** as leads to a decrease in χ^2 (e.g. for L-M, it decreases from 0.767 to 0.399 in the case of the AGN 8.0 simulation)

Self-similar expectation for the slope

Evolution of mass slope

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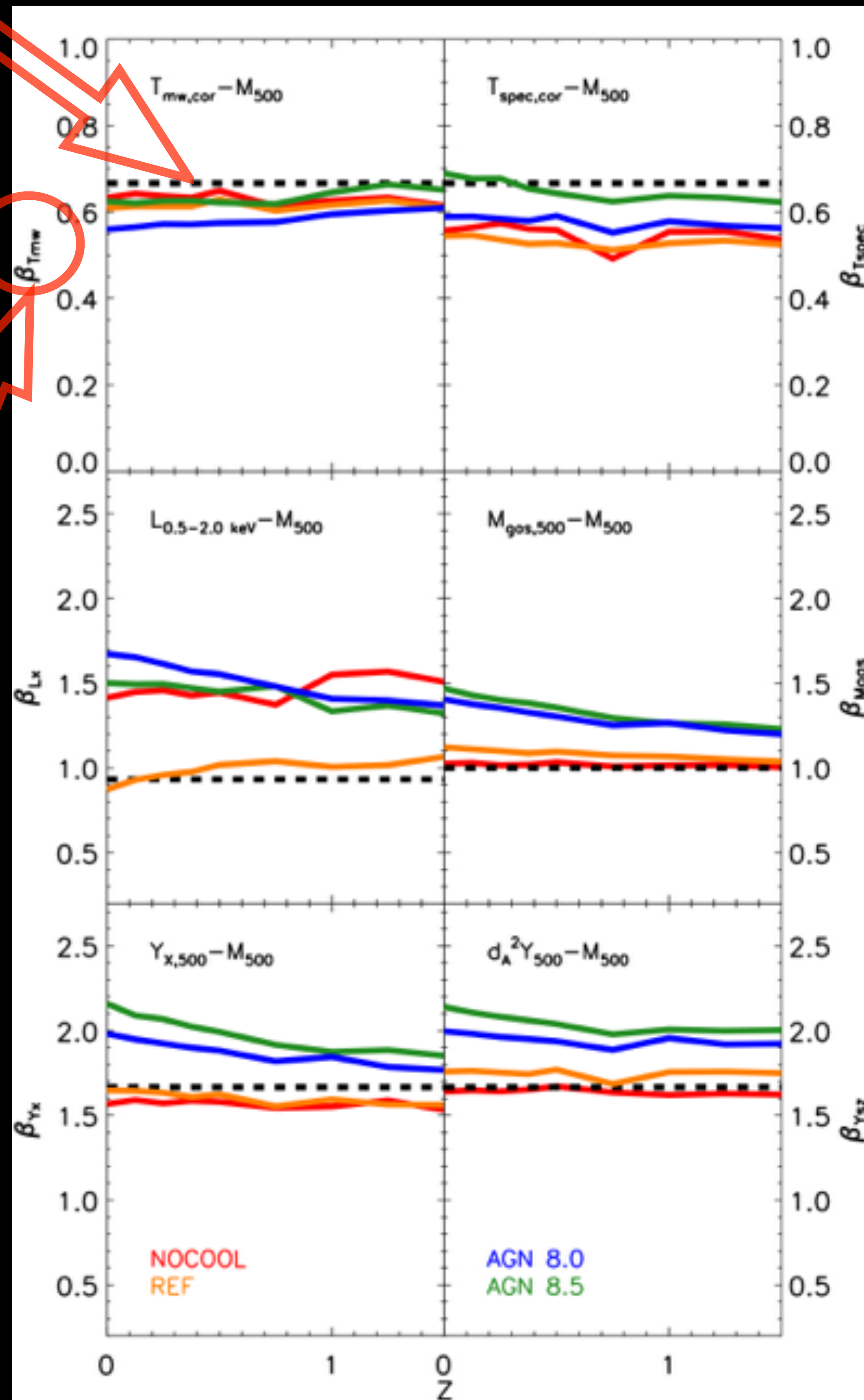
$$Y = 10^A E(z)^\alpha \left(\frac{M_{500}}{10^{14}\ \mathrm{M}_\odot} \right)^\beta$$



- Mass-temperature **slightly shallower** than self-similar (SS) for all models.
- M_{gas}-M_{500} **steeper** than SS for **all** the **radiative models**. **Deviations** from SS **increase** with **increasing feedback intensity**.

Evolution of normalisation

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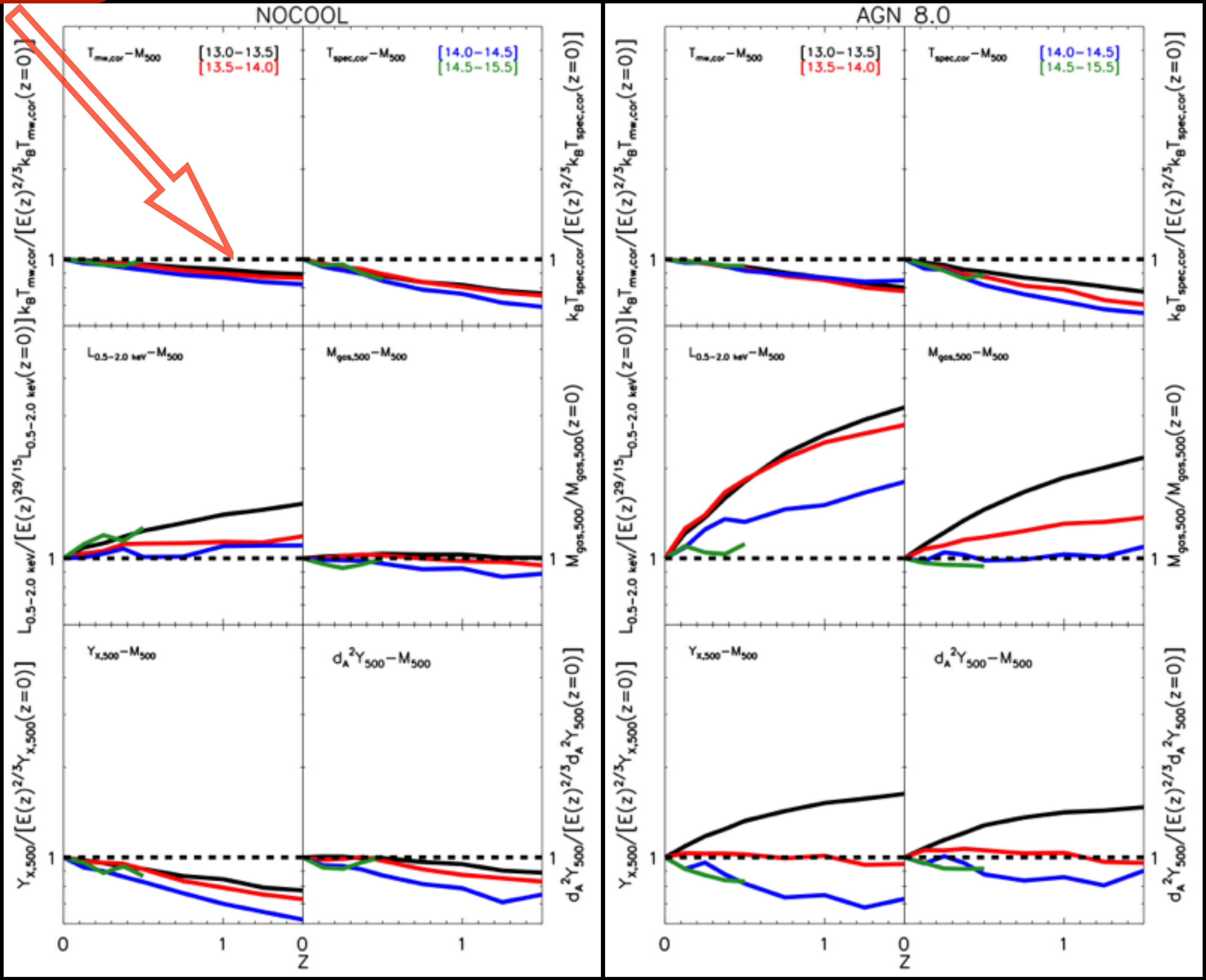
Self-similar expectation for the evolution



Scatter

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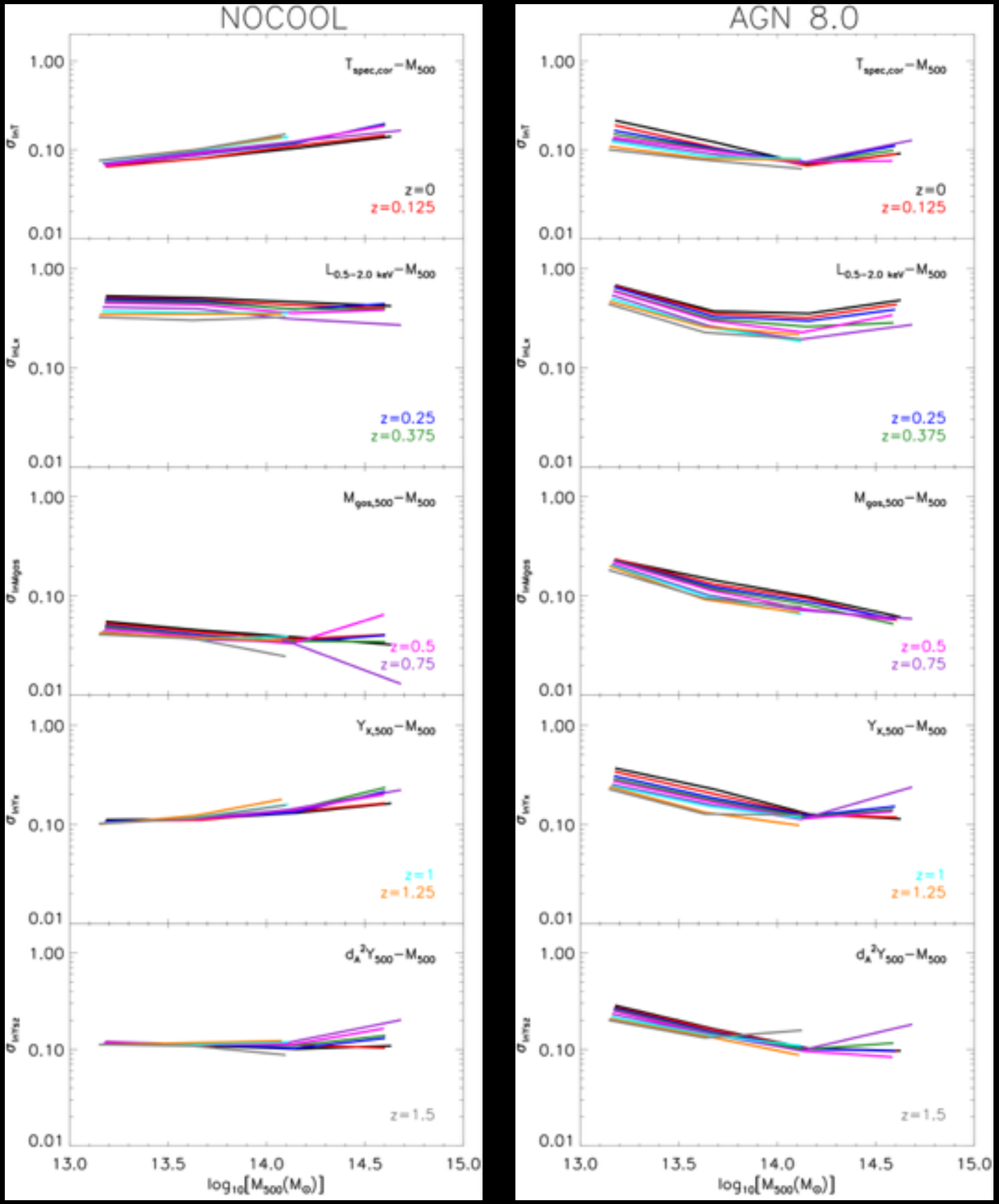
All but one of the hot gas proxies examined here have a **similar scatter** at **fixed total mass** of **about 10 per cent**.



The **X-ray luminosity** has a **significantly larger scatter** at fixed total mass (about **three times higher**).

Scatter

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Due to the uncertain non-gravitational physics of galaxy formation. The unphysical non-radiative model (NOCOOL) was excluded from its computation.

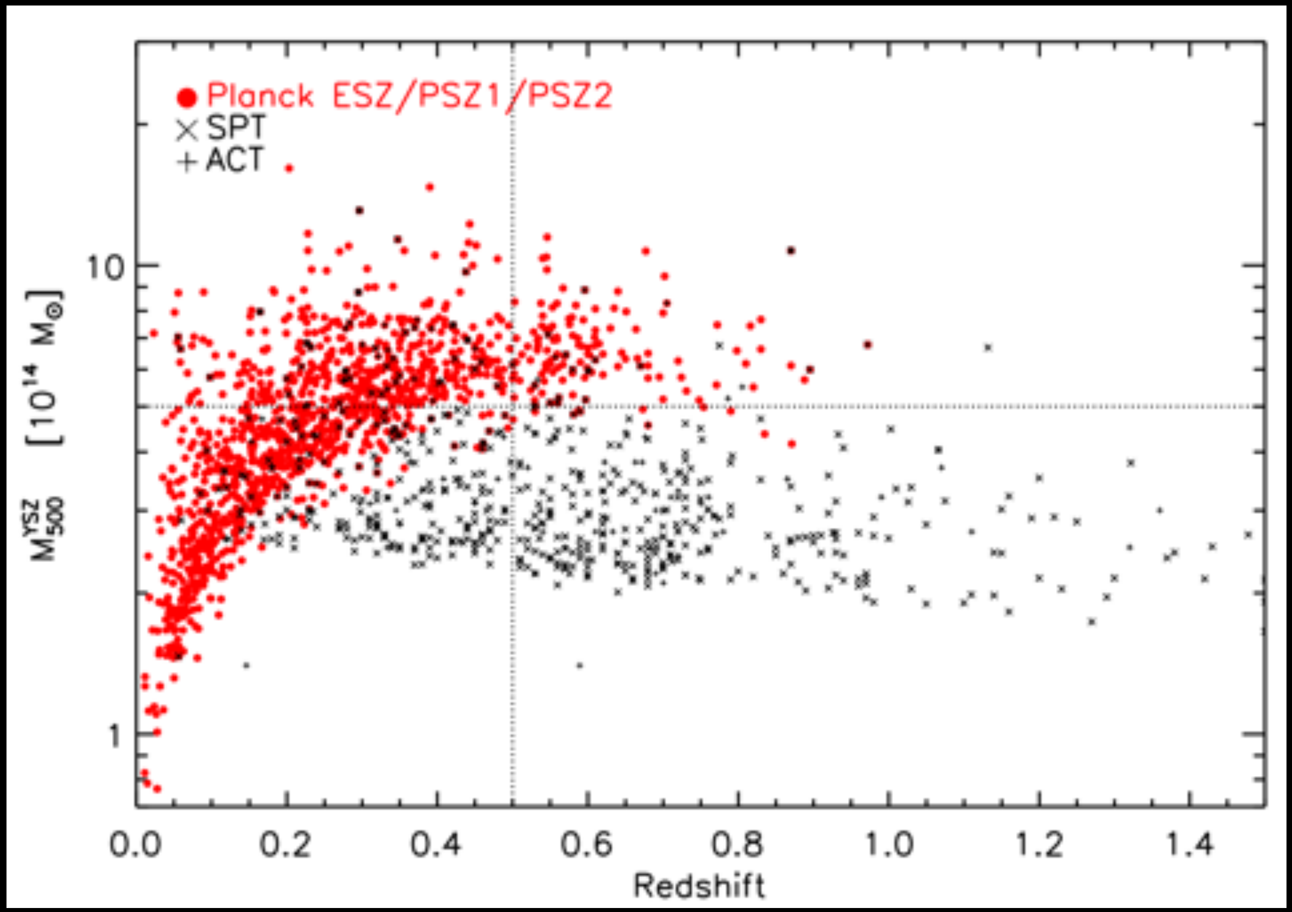
Scaling relation	$\sigma_{\ln Y\,|\,M}$	$\sigma_{\ln M\,|\,Y}$	Zero-point uncertainty in Y
$T_{spec,cor} - M_{500}$	~ 5 %	~ 10 %	~ 5 %
$L_{0.5-2.0keV} - M_{500}$	~ 25 %	~ 20 %	~ 45 %
$M_{gas,500} - M_{500}$	~ 10 %	~ 5 %	~ 25 %
$Y_{X,500} - M_{500}$	~ 10 %	~ 5 %	~ 25 %
$d_A^2 Y_{500} - M_{500}$	~ 10 %	~ 5 %	~ 20 %
$M_{500,hse,spec} - M_{500}$	~ 15 %	~ 20 %	~ 5 %

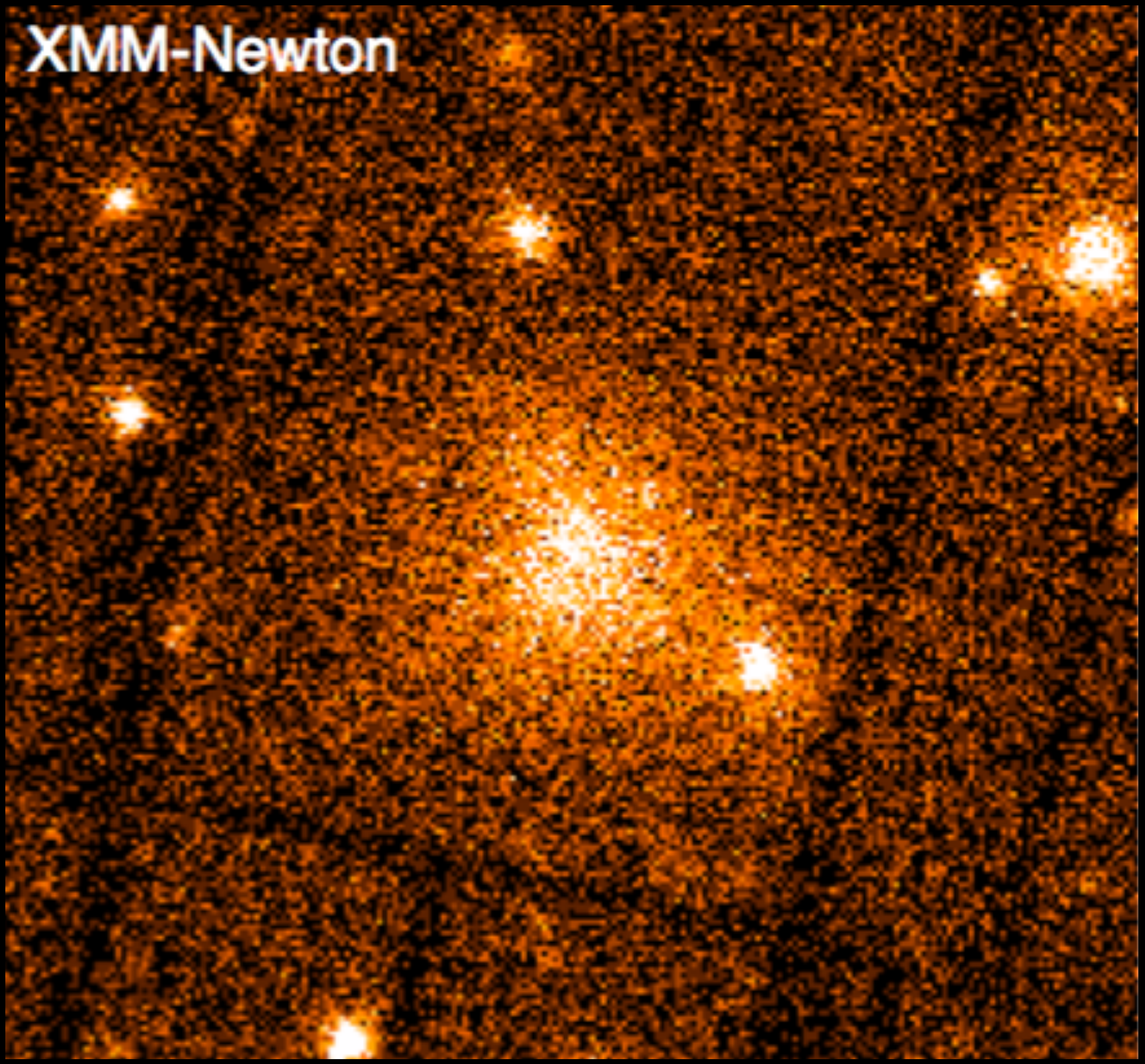
- **X-ray temperature** is the **'best' mass proxy** among considered hot gas properties
- **X-ray luminosity** is the **poorest** one.

Evolution of dark matter profiles

- A powerful test of the standard cosmological model (ΛCDM) uses the evolution of the dark matter density profiles of the most massive galaxy clusters of the Universe up to high redshift (z~1).
- The standard cosmological model has so far mainly been tested in the local Universe and this was done using mostly samples that were not selected for being representative of the population.
- The detection of large and representative samples of the most massive galaxy clusters of the Universe up to redshift z~1 has been recently enabled large surveys using the Sunyaev-Zel'dovich effect.
- It requires a systematic comparison between observations of a galaxy clusters in several redshift slices and cosmological simulations of clusters with characteristics as similar as possible to that of the observations.

Pilot study of mass profiles at z~1

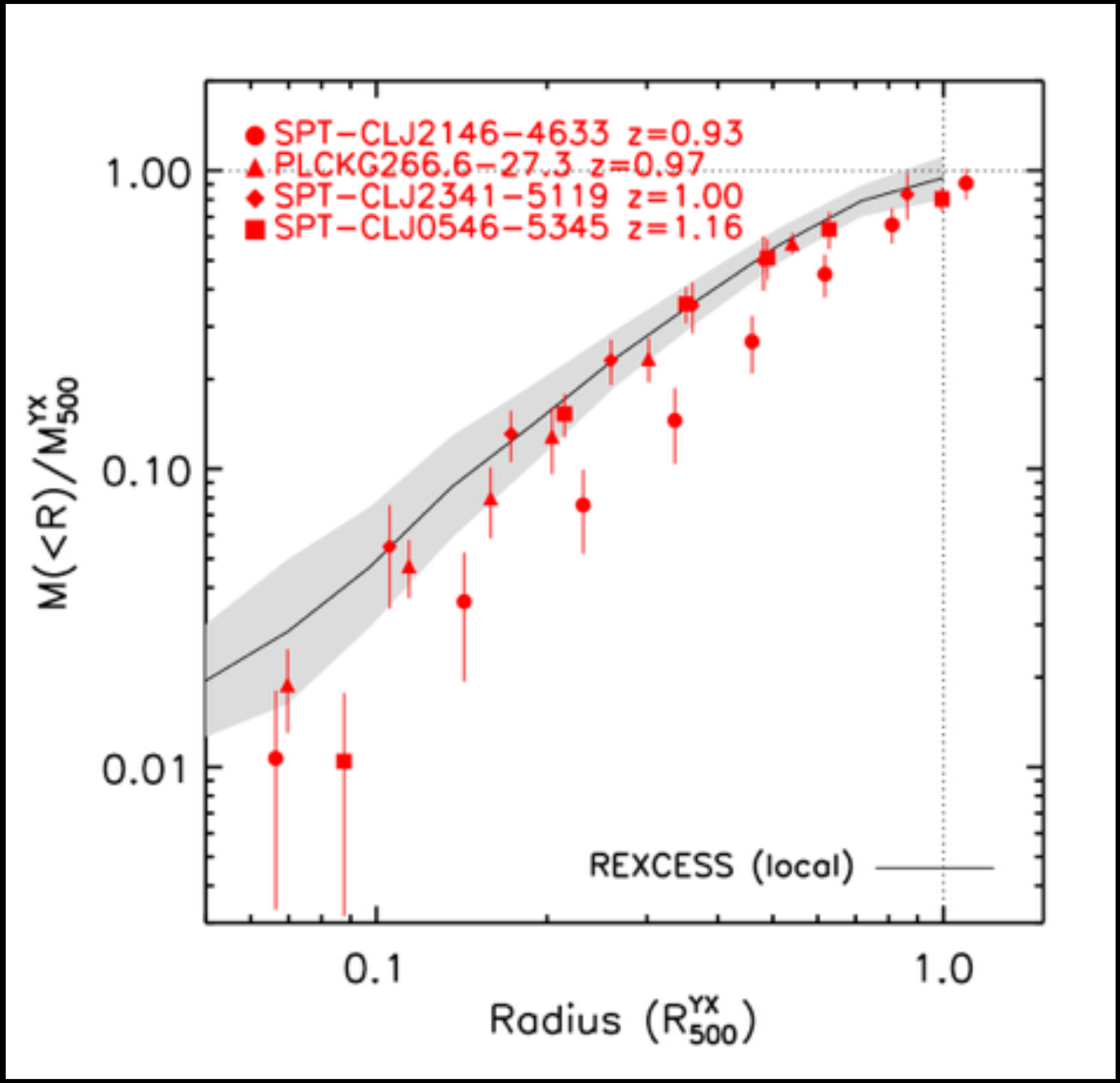




Data: Bleem15 (SPT), Hasselfield13 (ACT), PC VII 2011 (ESZ), PC XXIX 2013 (PSZ1), PC XXVIII 2015 (PSZ2)

Figures courtesy of Monique Arnaud

Pilot study of mass profiles at z~1



Arnaud, Bartalucci et al. in prep.

- Suggest less concentrated than average local cluster
- Higher dispersion? consistent with theory?
- Need larger sample and new numerical simulations

Simulations

Le Brun et al. in preparation

- No existing hydrodynamical cosmological simulations combines a large enough volume and a high enough resolution to simulate the most massive galaxy clusters as:

  - they are rare and appear in large volumes (need to simulate volumes of Gpc3)

  - high resolution (of the order of the kpc) is required to resolve their internal structure.

- Our new approach : generate a set of several large dark-matter only cosmological simulations of intermediate resolution (1 Gpc/h on a side with 2048^3 particles) and subsequently perform “zoom” hydrodynamical simulations at kpc-resolution in the regions containing a high-mass cluster. All the simulations are done with the AMR code RAMSES (Teyssier 2002) on the brand-new OCCIGEN supercomputer at CINES in Montpellier using a GENCI computing time-allocation.

Simulations

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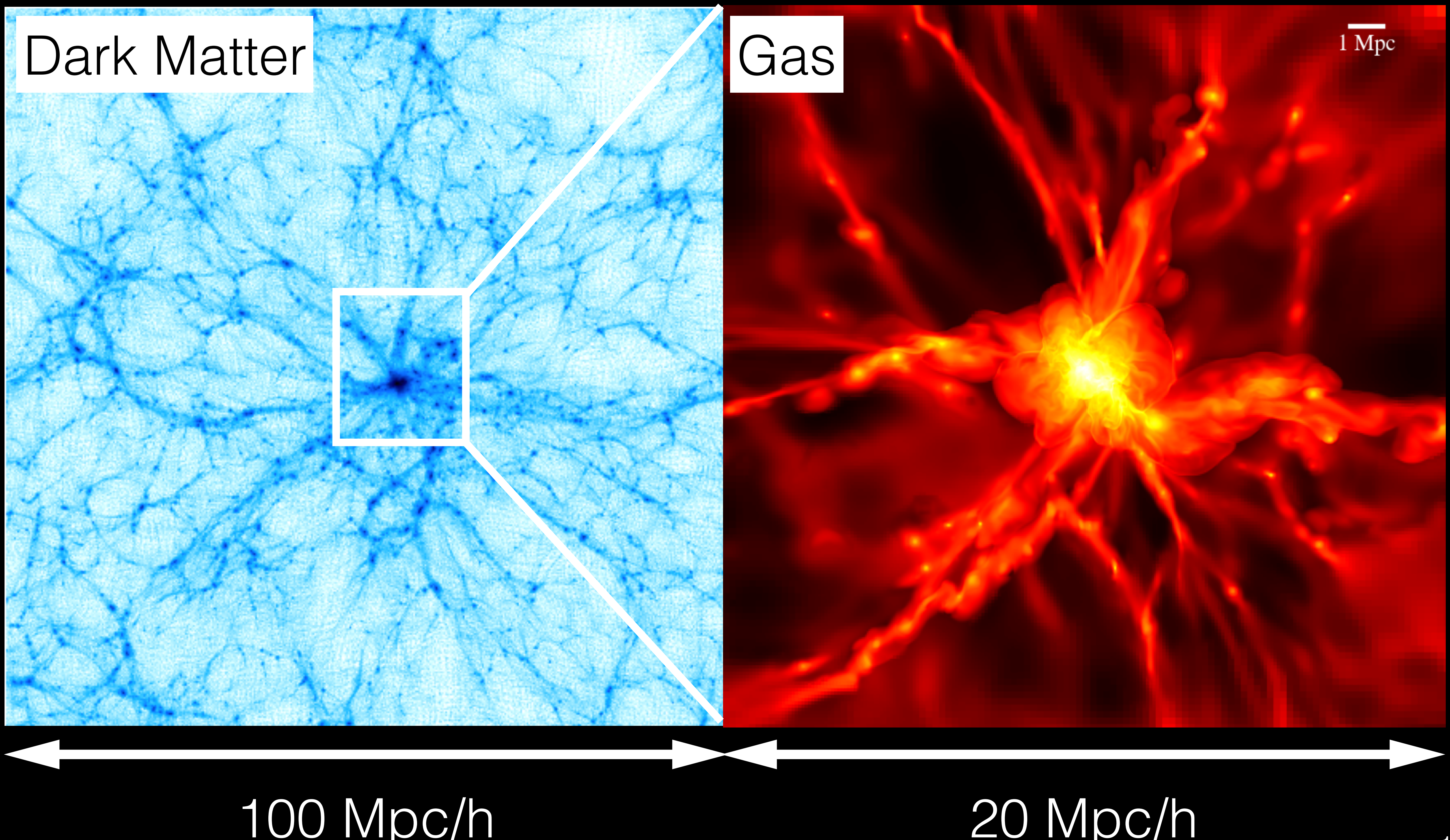
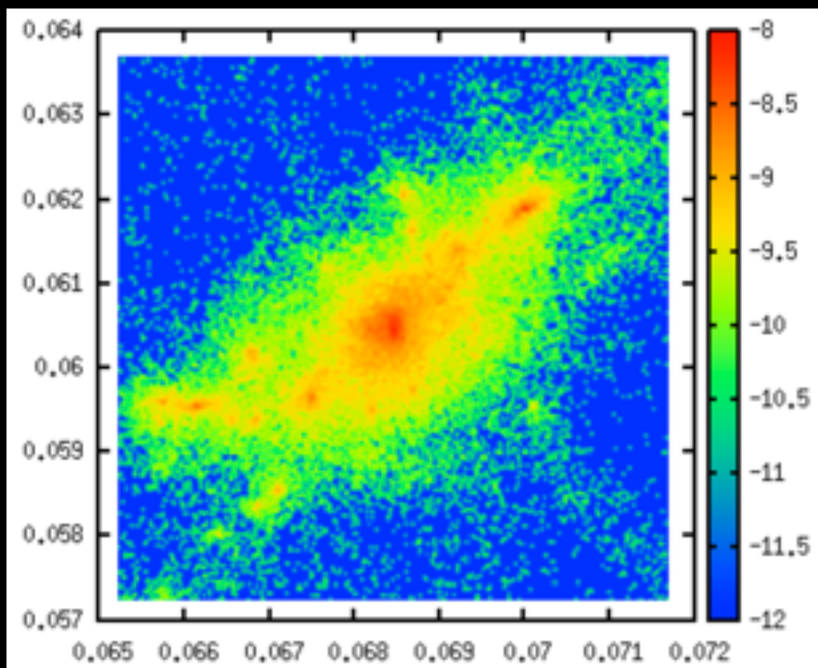
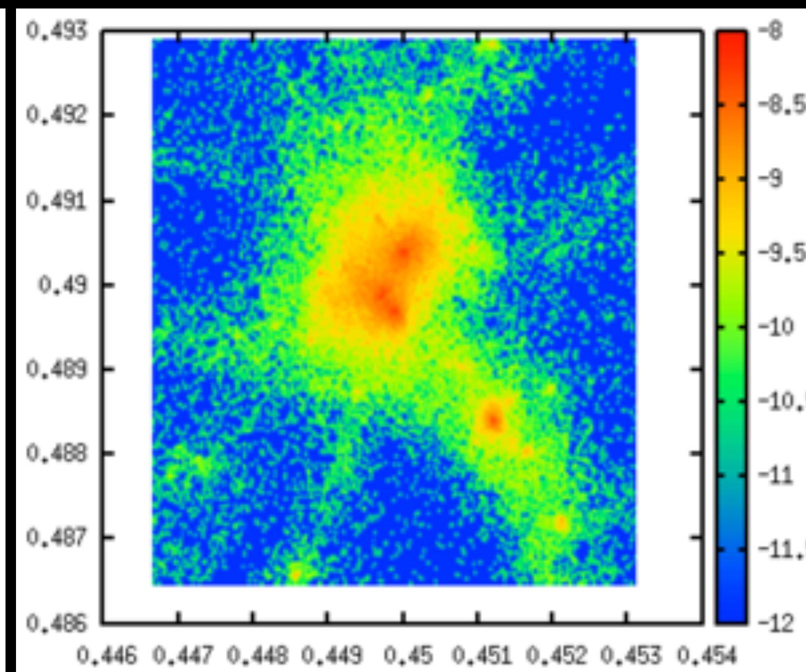
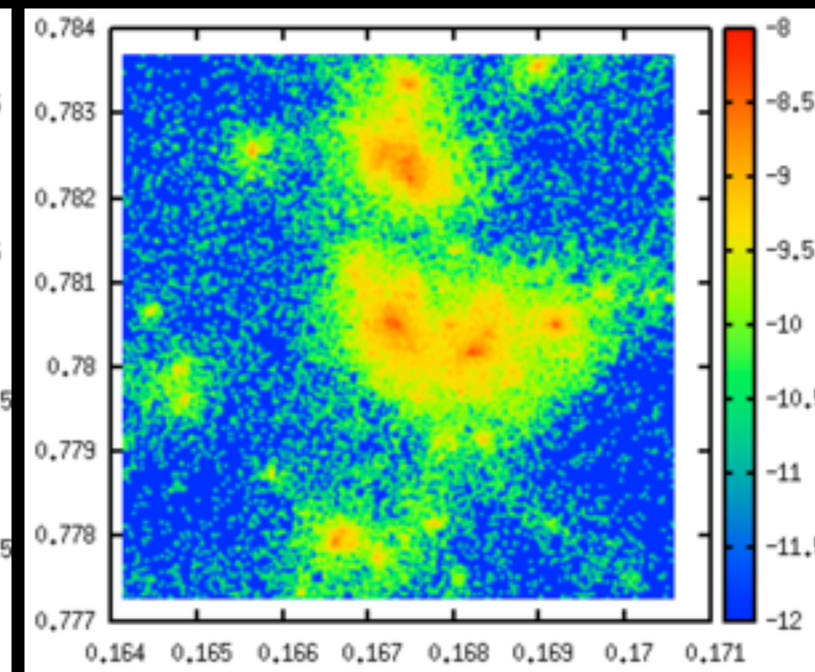


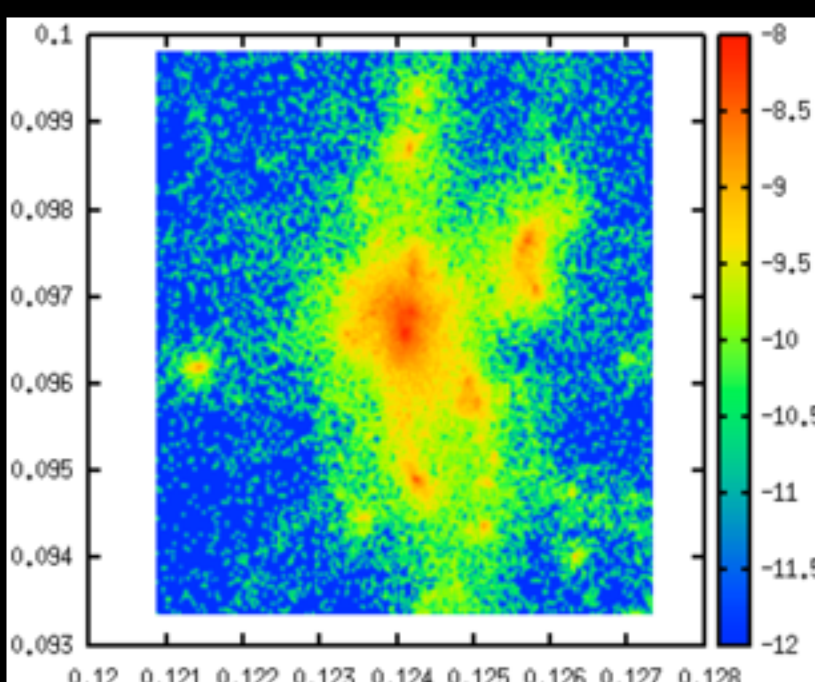
Most galaxy clusters at z=1 are disturbed

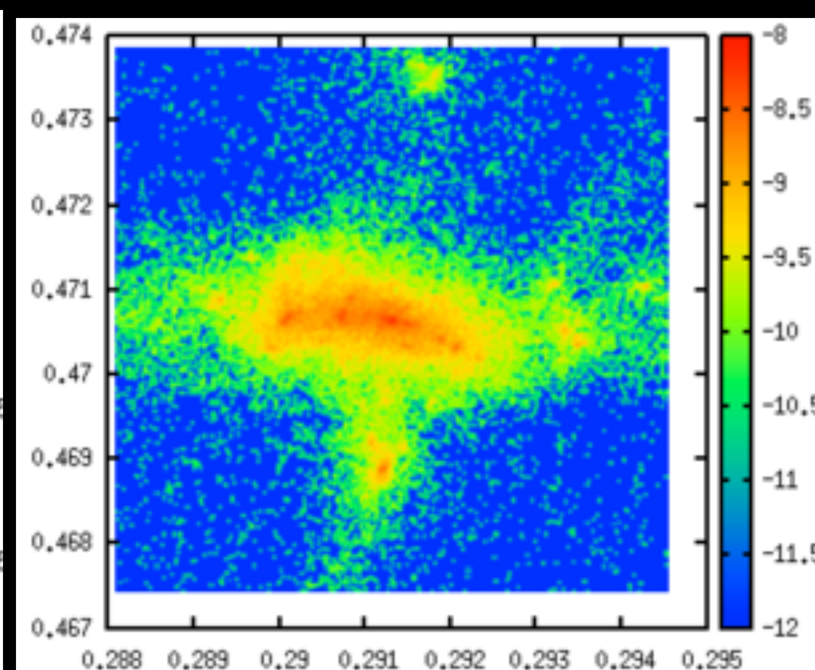


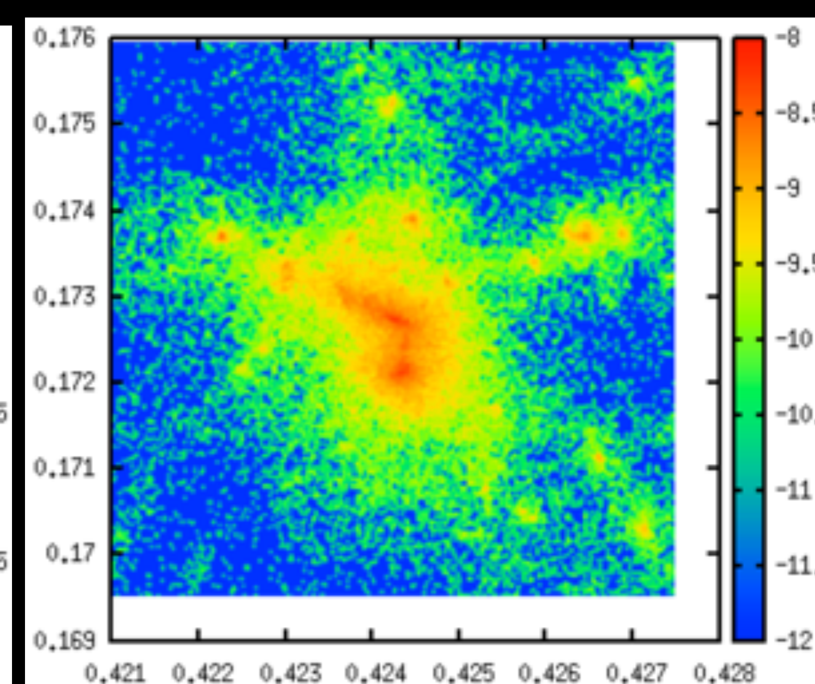




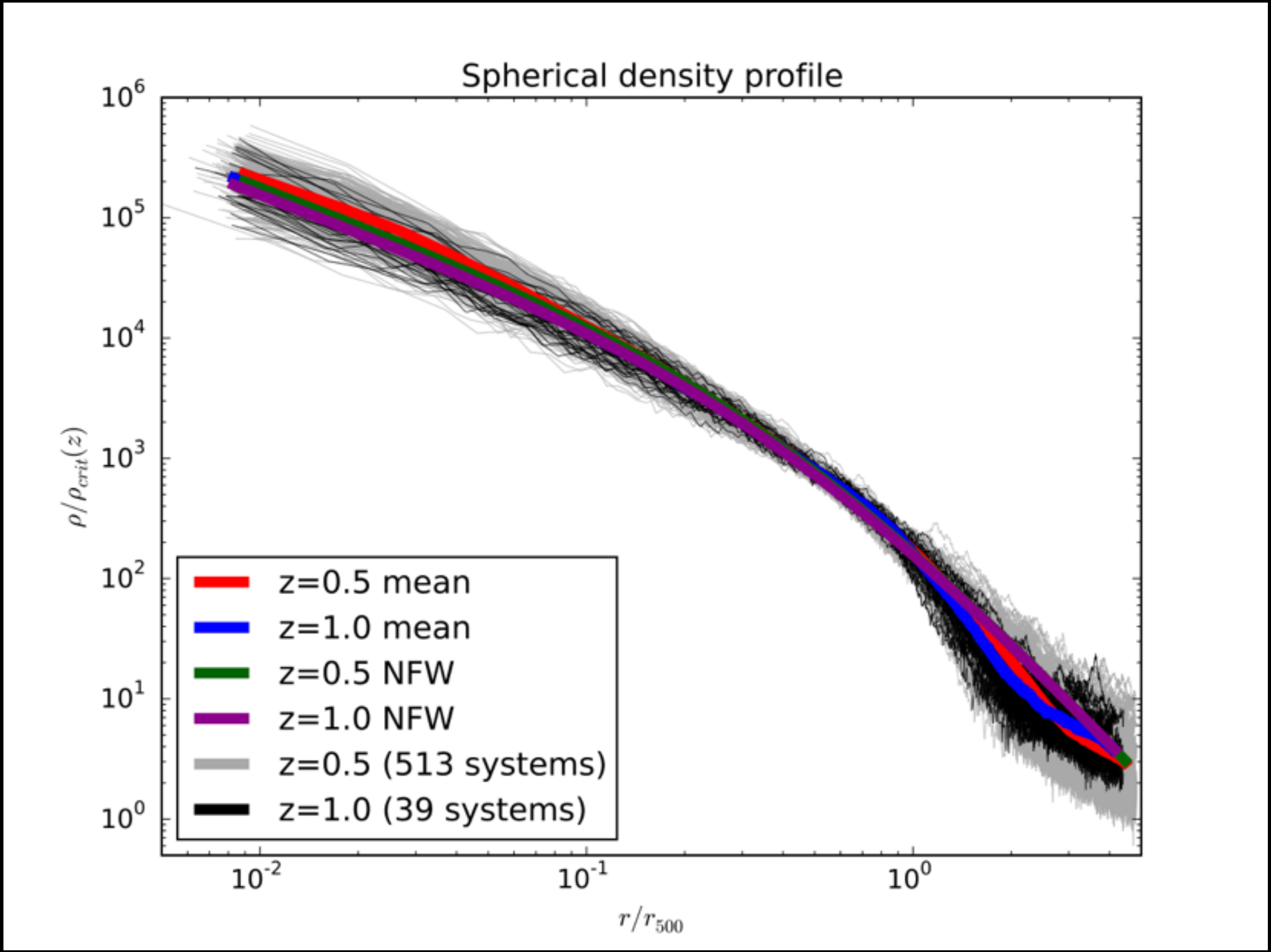
The Turtle cluster The Horse cluster The Rubber Duck cluster







Evolution of DM profiles between z=0.5 and 1



Conclusions

- The median relations and the scatter about them are reasonably well modelled by **evolving broken power-laws with redshift dependent low-mass power-law indices**.
- The predictions of the self-similar model **break down when efficient feedback is included**, for both mass slope and evolution.
- The log-normal scatter **varies** only **mildly** with **mass and non-gravitational physics** but displays a **relatively strong redshift dependency** (decreasing with increasing redshift).
- **X-ray temperature** is the **'best'** overall mass proxy **while X-ray luminosity** is the **poorest**.
- Most massive galaxy clusters at z=1 are disturbed.