Galaxy Clusters as Cosmological Probes and Astrophysical Laboratories

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About me

- 10/2011-08/2014: PhD at the University of Birmingham (until 12/2012) and Liverpool John Moores University (from 01/2013) on Galaxy Clusters as Cosmological Probes and Astrophysical Laboratories. I mainly collaborated with Ian McCarthy (LJMU), Joop Schaye (Leiden), Trevor Ponman (Birmingham), Jean-Baptiste Melin (SPP), Chris Collins (LJMU) and Gil Holder (McGill).

- Since 10/2014: post-doc at SAp, working on the evolution of the dark matter profiles of the most massive galaxy clusters since redshift 1 with Monique Arnaud, Gabriel Pratt, Romain Teyssier, Jean-Baptiste Melin, Hervé Aussel, Iacopo Bartalucci, Paula Tarrio-Alonso and Remco van der Burg.

Talk Outline

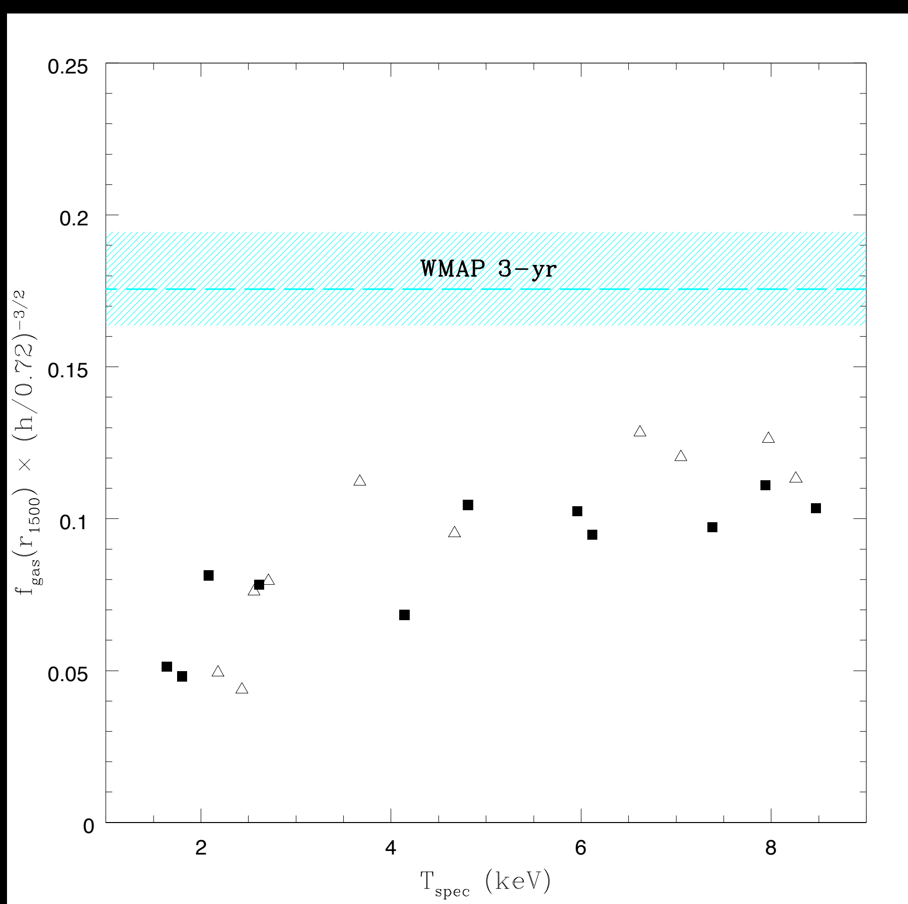
- Introduction
- Towards a realistic population of galaxy groups and clusters
- Scatter and evolution of hot gas properties
- Testing measurements of the hot gas content of dark matter haloes using synthetic skies
- Evolution of the dark matter profiles of the most massive galaxy clusters since redshift 1

A primer on galaxy clusters and hydrodynamical cosmological simulations

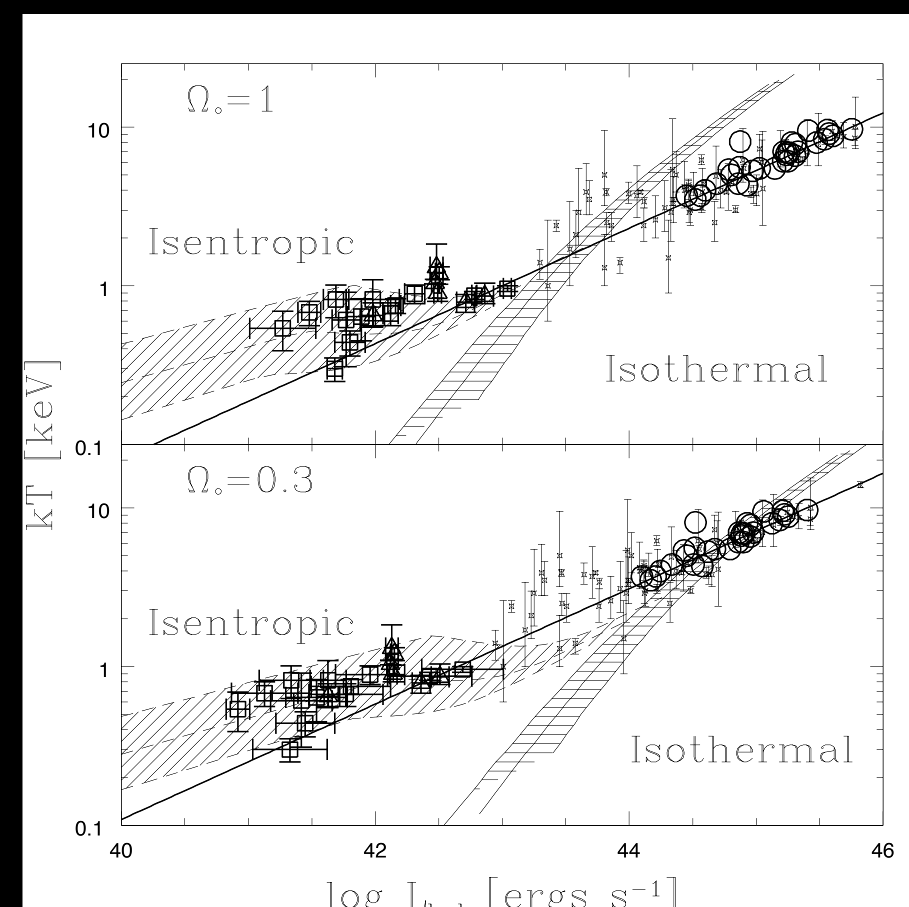
Groups and clusters

- Groups and clusters contain a **large fraction** of the **baryons** and **galaxies** at z=0
- They are the only systems where we can measure **all** the baryonic phases **directly**
- `Strange' things are happening:

1. Low baryon fractions
2. X-ray scaling relations



McCarthy et al. 2007

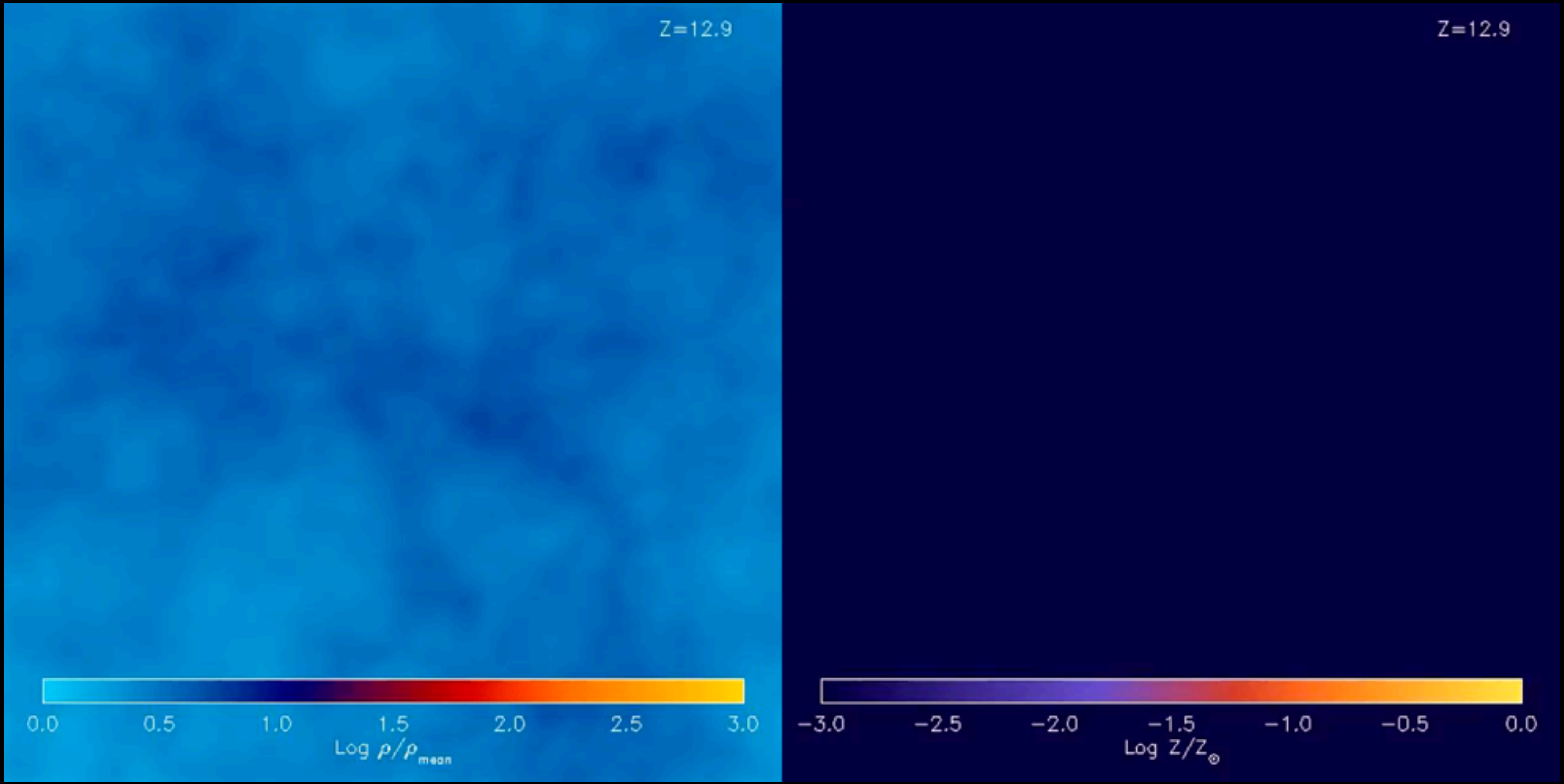


Balogh et al. 1999

Cosmological simulations

- Start from **initial conditions** (density perturbations) derived from observations of the Cosmic Microwave Background (CMB)
- Evolution using the laws of **gravity** of the **Dark Matter particles only**
- Dark Matter is **collisionless** i.e. does not feel the effects of pressure
- Hydrodynamical cosmological simulations also evolve **gas and star particles** with **all the relevant physics**
- In both cases, **highly non-linear** dynamics
- An example of this is the cosmo-OWLS suite of cosmological hydrodynamical simulations (e.g. Le Brun et al. 2014, McCarthy et al. 2014) which uses the Planck 2013 and WMAP7 cosmologies and resorts to **subgrid** modeling for **unresolved** small scale physics. It uses 2.15 billion particles in 400 Mpc/h boxes with 4 kpc/h gravitational softening run using modified version of GADGET3 (Springel 2005)

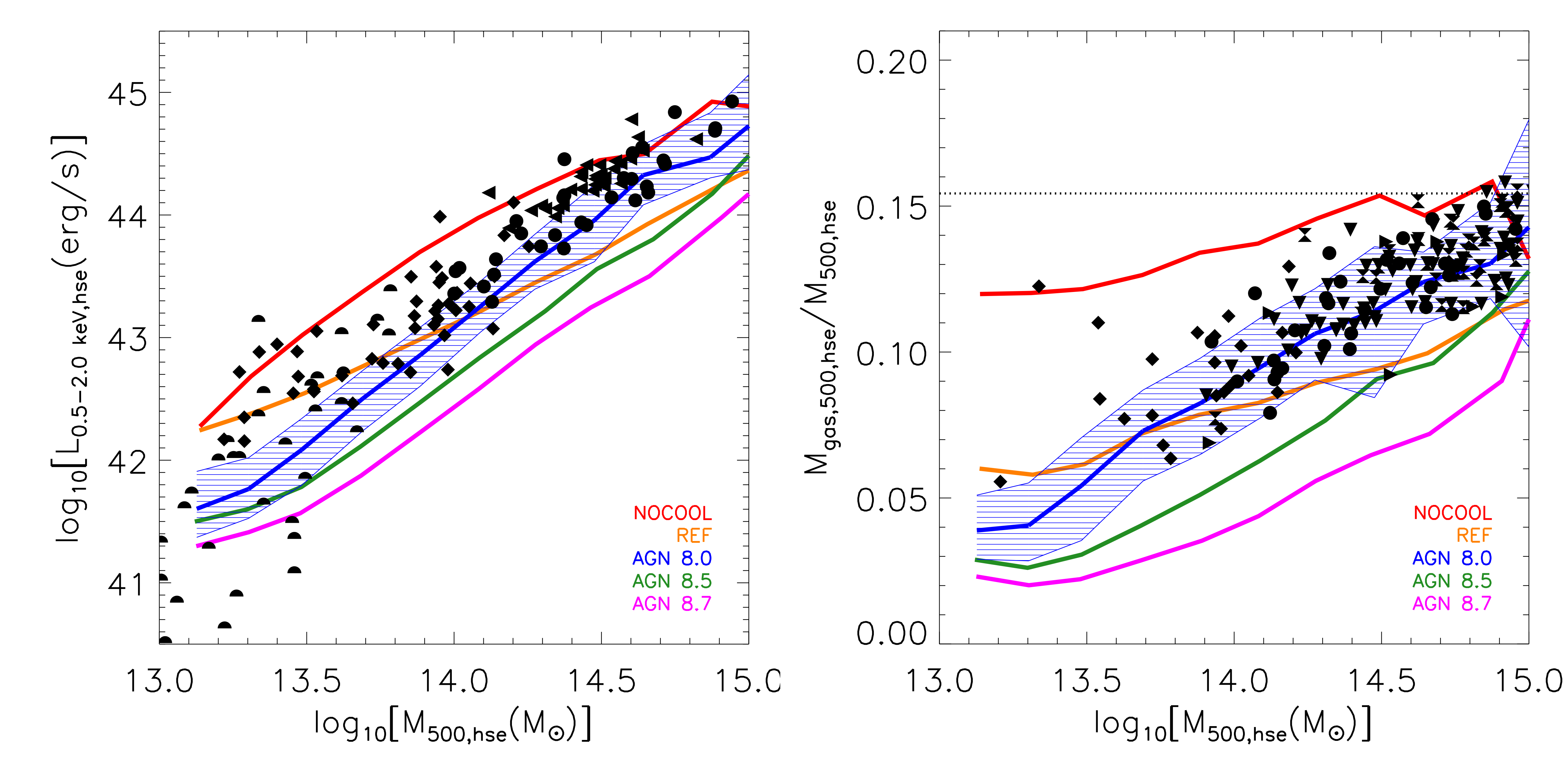
Cosmological simulations



Towards a realistic population of galaxy groups and clusters

Le Brun et al. 2014

X-ray observations



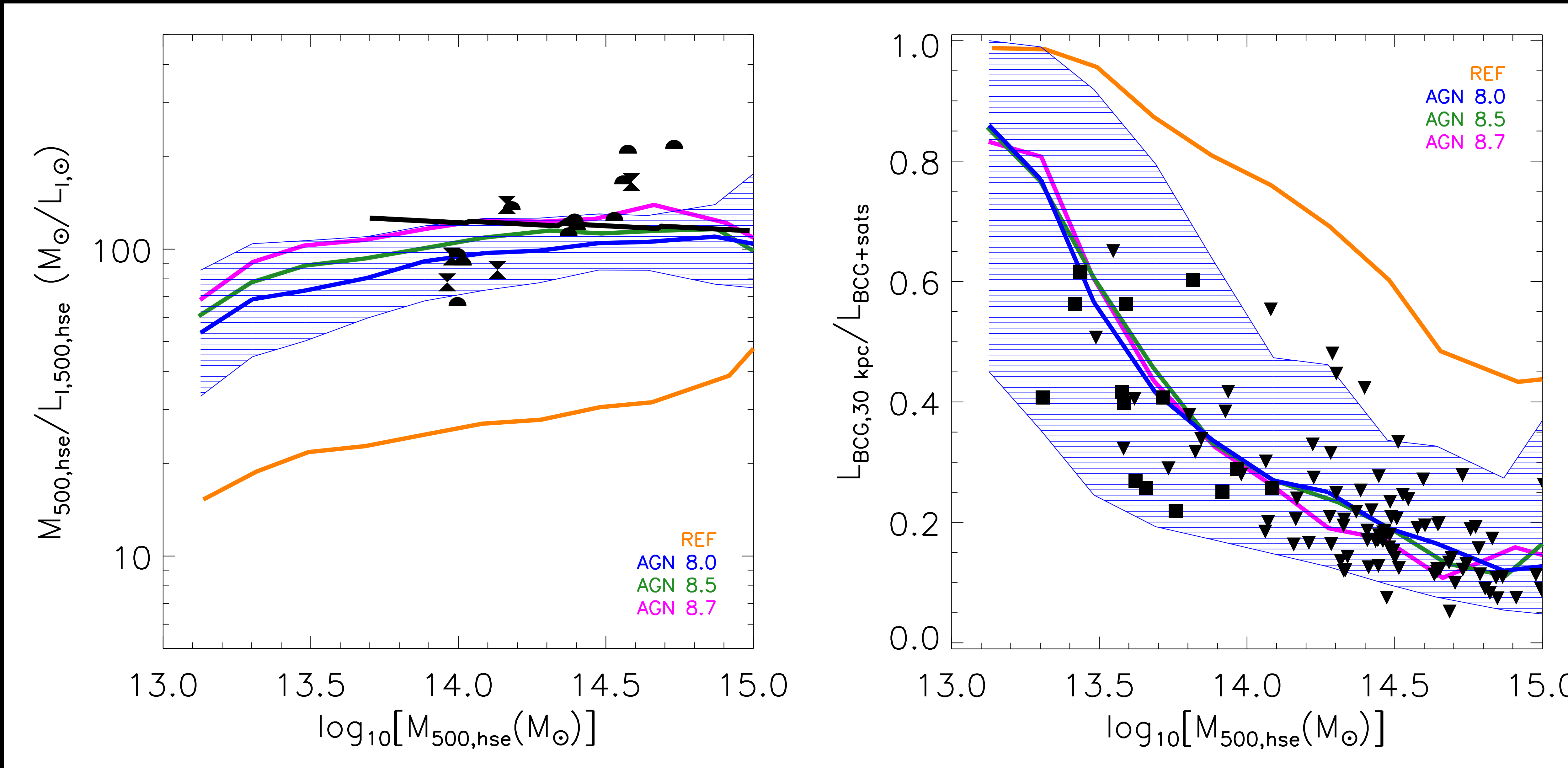
Data: Pratt09, Vikhlinin09, Sun09 and Osmond04

Data: REXCESS, Vikhlinin06, Lin12, Maughan08 and Sun09

- Need feedback of some sort to solve overcooling problem
- AGN 8.0 model broadly reproduces relations over two orders of magnitude in mass

Optical properties

Le Brun et al. 2014



Data: Sanderson13, Gonzalez13 and Budzynski14

Data: Rasmussen09 and Lin04

- Only AGN feedback can yield the high observed total mass-to-light ratios
- REF is a factor of three to five too low and yields BCGs which are too dominant
- All the AGN models yield similar stellar fractions in the BCG

Scatter and evolution of the hot gas properties

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.

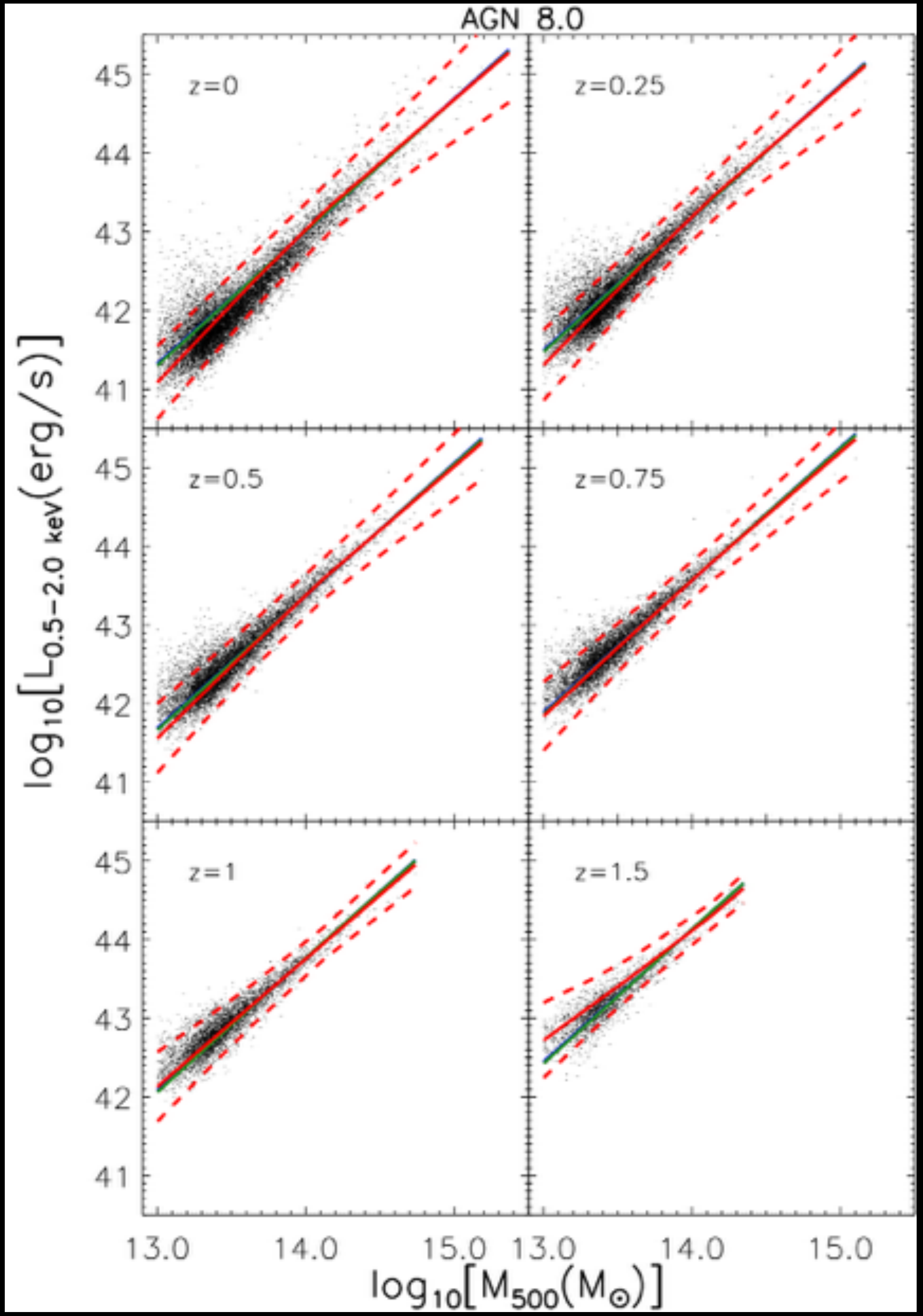
- The recent intracluster medium (ICM) ‘sub-grid’ physics models are faring relatively well at low-redshift compared to observation, but **what are they predicting for the scaling relations at higher-redshift?** Comparisons to the observed evolution of the scaling relations can help improve our understanding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

Fitting of relations

Le Brun et al.
in preparation

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**

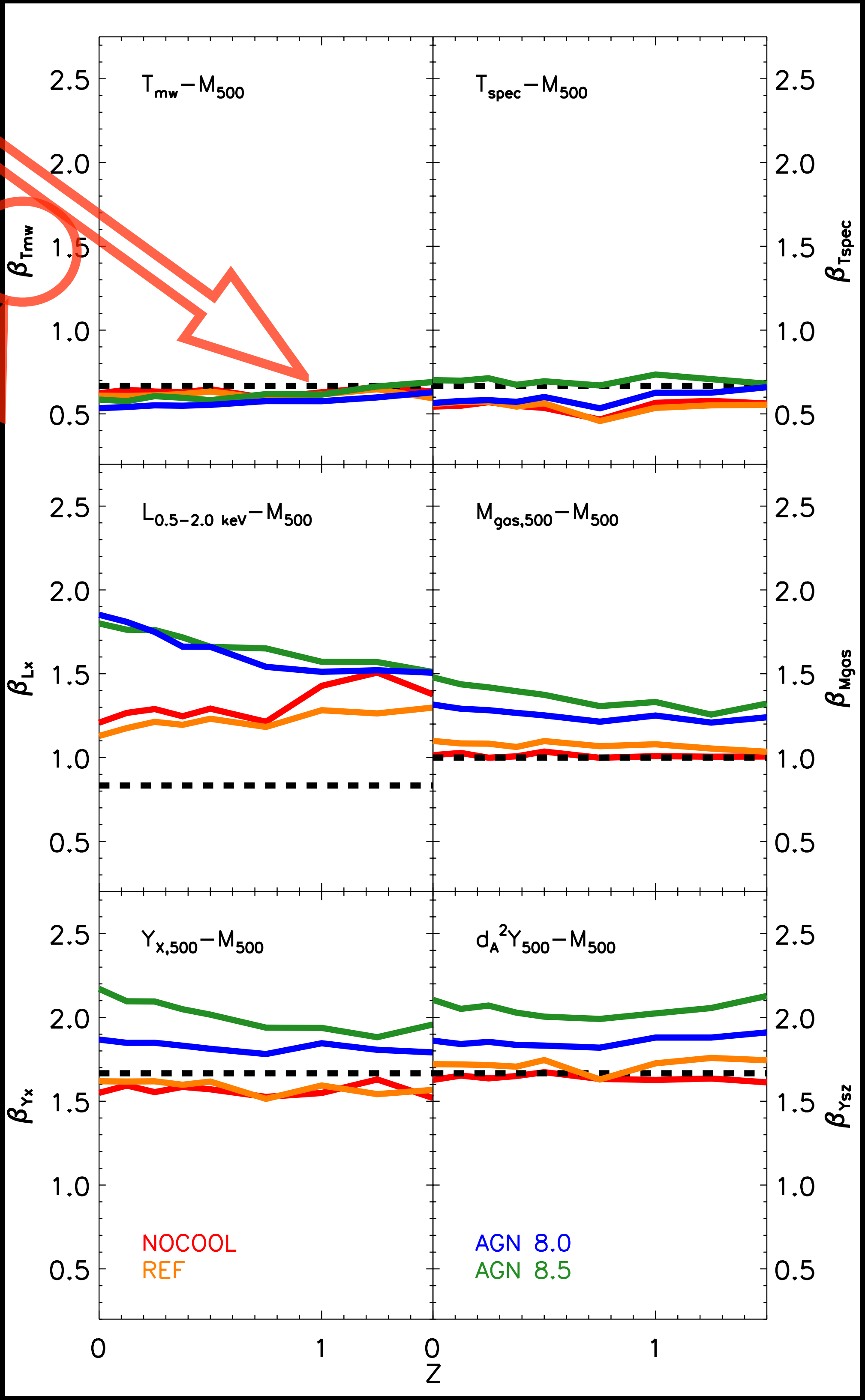
Necessary to **break** the power-law and to make the **low-mass mass slope redshift-dependent** as leads to a decrease in χ^2 (e.g. for L-T, it decreases from 0.345 to 0.216 in the case of the AGN 8.0 simulation)

Self-similar expectation for the slope

Evolution of mass slope

Le Brun et al. in preparation

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



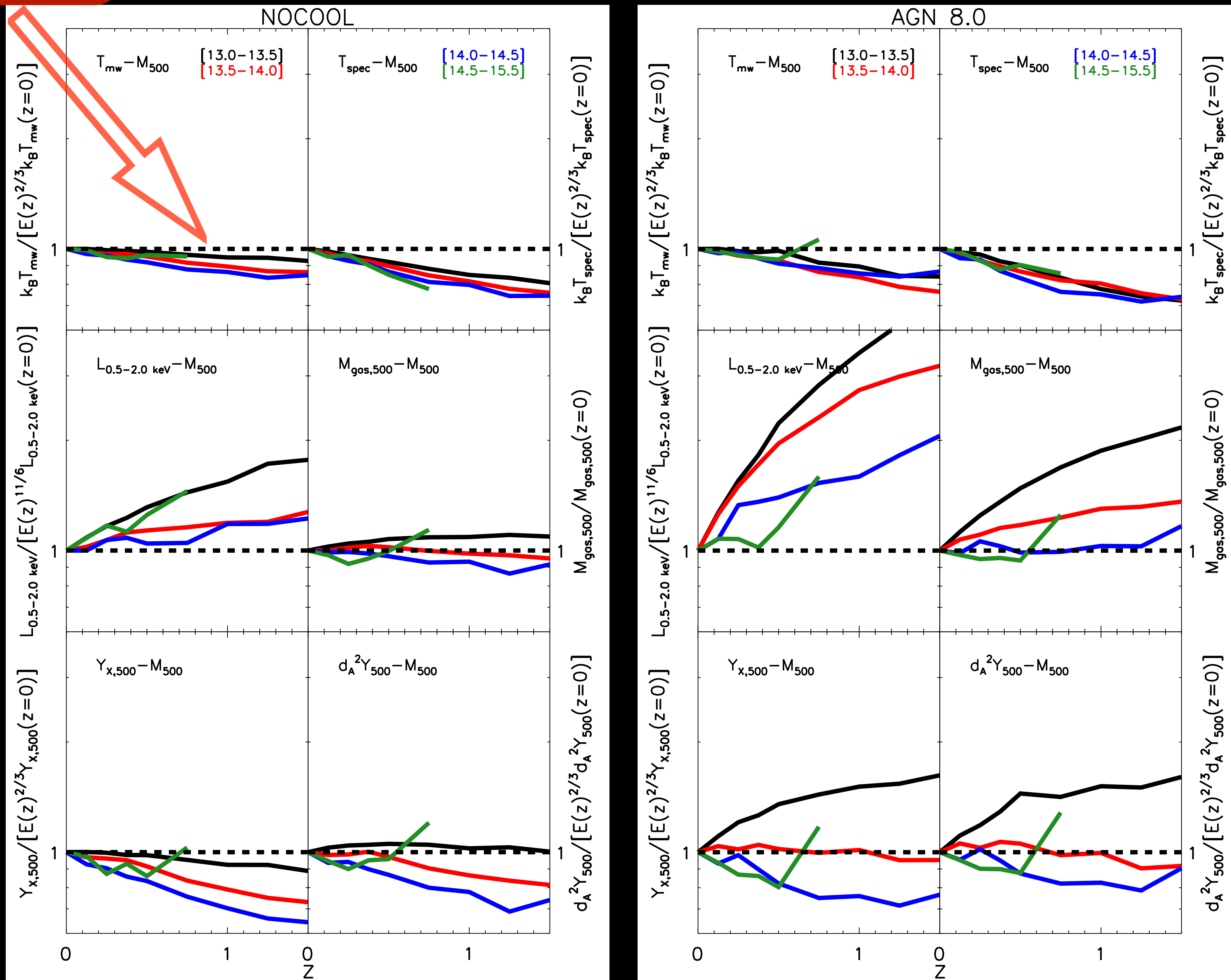
- Mass-temperature **slightly shallower** than self-similar (SS) for all models.
- M_{gas}-M_{500} **steeper** than SS for **all** the **non-radiative models**. **Deviations** from SS **increase** with **increasing feedback intensity**.

N.B. All the quantities have been computed within r_{500} **without core-excision.**

Self-similar expectation for the evolution

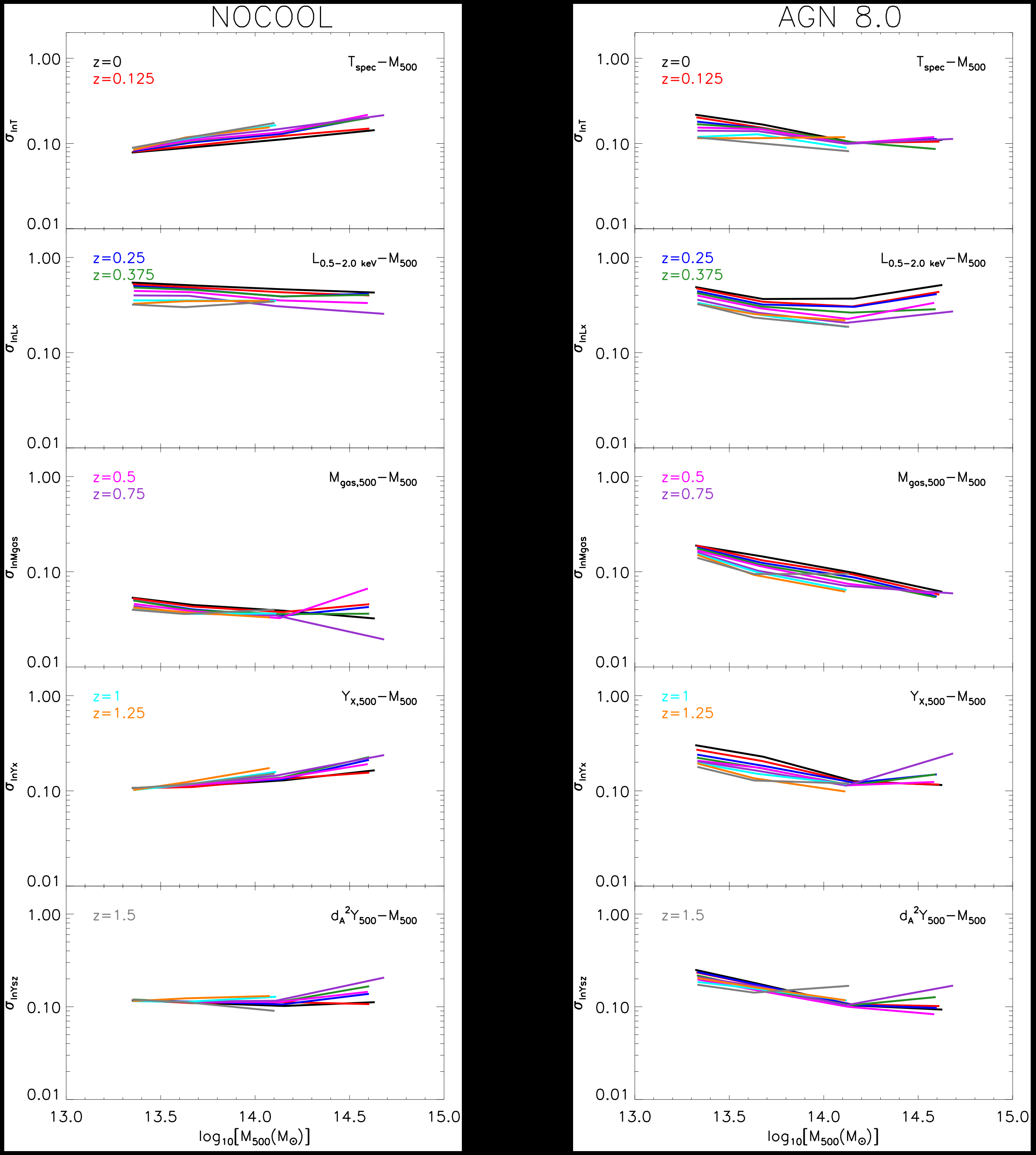
Evolution of normalisation

Le Brun et al. in preparation



Scatter

Le Brun et al. in preparation



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

Le Brun et al.
in preparation

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
$T_{spec} - M_{500}$	~ 10 %	~ 20 %	~ 10 %
$L_{0.5-2.0keV} - M_{500}$	~ 30 %	~ 20 %	~ 45 %
$M_{gas,500} - M_{500}$	~ 10 %	~ 10 %	~ 20 %
$Y_{X,500} - M_{500}$	~ 10 %	~ 5 %	~ 30 %
$d_A^2 Y_{500} - M_{500}$	~ 10 %	~ 5 %	~ 20 %

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

Conclusions

- Some AGN feedback models can produce a **realistic population** of galaxy groups and clusters, broadly reproducing **both** the **median** trend and, for the first time, the **scatter** in physical properties over approximately **two decades in mass** (10^{13} $M_{\odot} \leq M_{500} \leq 10^{15}$ $M_{\odot}$) and **1.5 decades in radius** ($0.05 \leq r/r_{500} \leq 1.5$).

- 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.

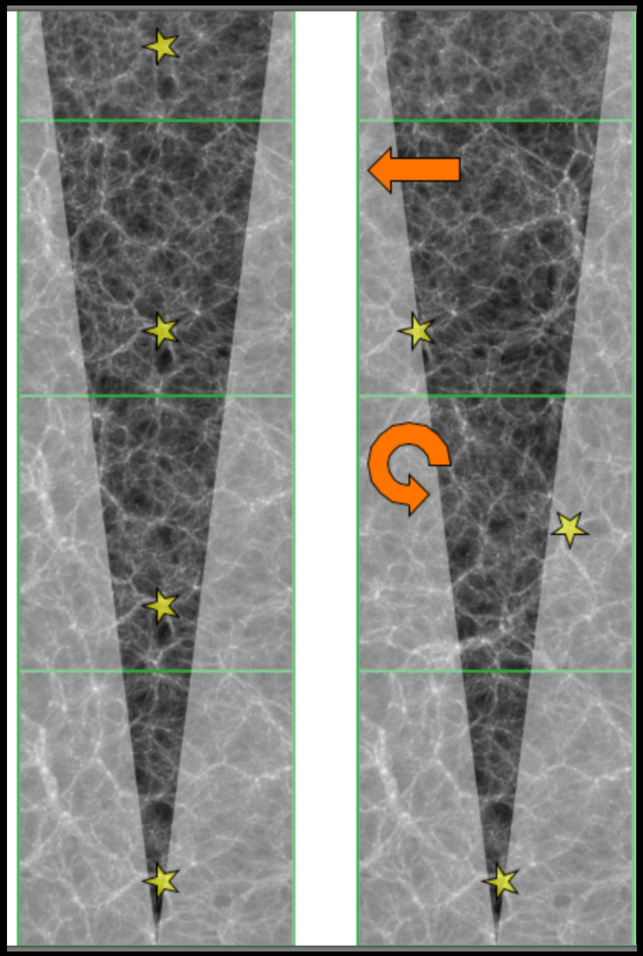
- The log-normal scatter **varies** only **mildly** with **mass and non-gravitational physics** but displays a **relatively strong redshift dependency** (decreasing with increasing redshift).

- **X-ray temperature** is the **'best'** overall mass proxy **while X-ray luminosity** is the **poorest**.

Testing Sunyaev-Zel'dovich measurements of the hot gas content of dark matter haloes using synthetic skies

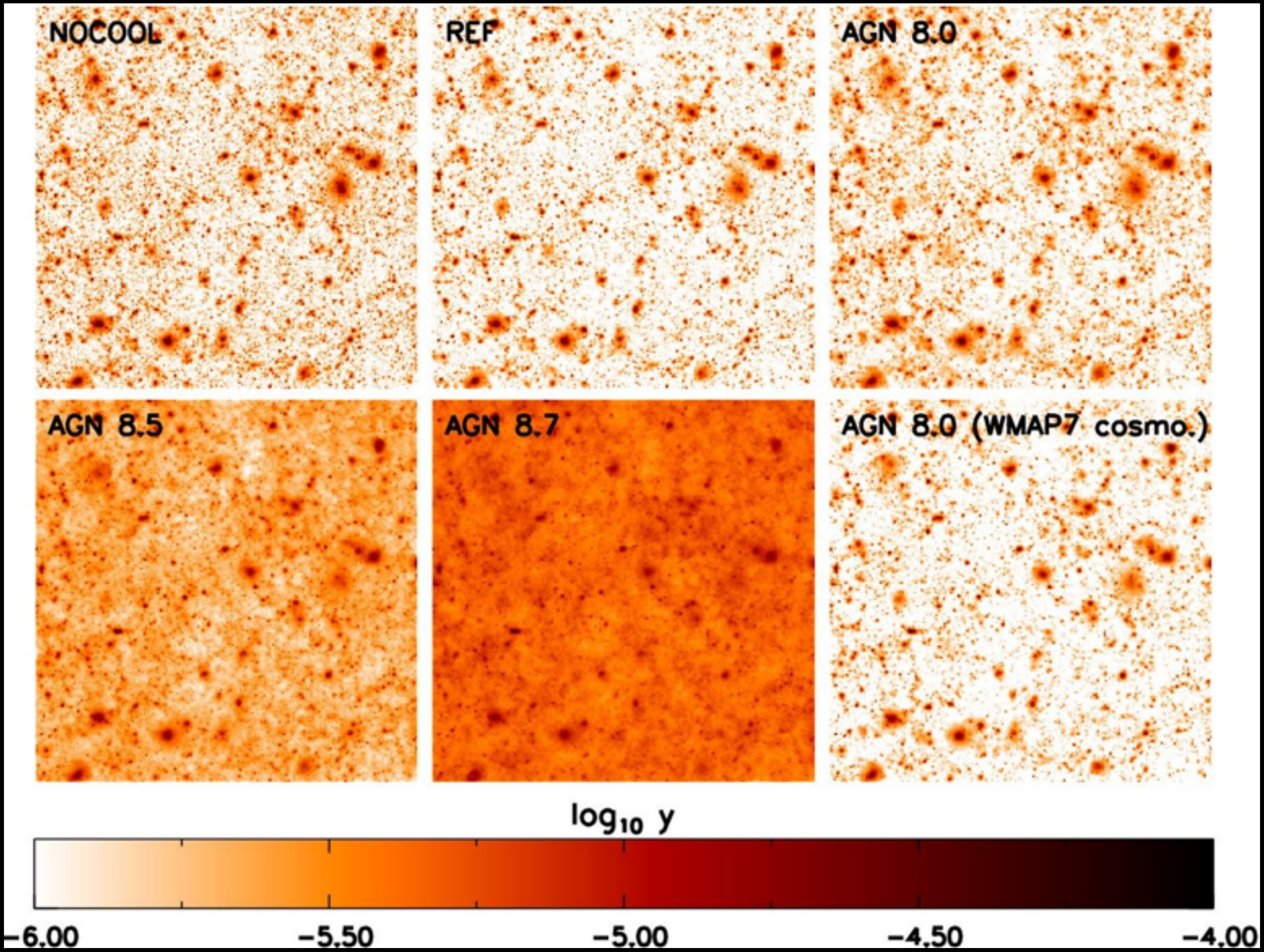
Synthetic surveys from cosmo-OWLS

- Developed light cone software using a method derived from the ones used by Blaizot et al. 2005 and Kitzbichler & White 2007. Except that it is applied to gas, star, BH and DM particles as well as groups and galaxies.
- 10 (quasi-)independent 5 degrees by 5 degrees surveys up to z=3 for each physical model
- X-ray maps and spectra can be generated using APEC and the density, temperature and chemical composition: we are following the abundances of the 11 elements which contribute the most to the radiative cooling (H, He, C, N, O, Ne, Mg, Si, S, Ca and Fe))
- SZ maps
- Optical/IR maps using e.g. the Bruzual & Charlot stellar population synthesis code
- Galaxy and cluster catalogues
- AGN catalogues
- Shear maps



Blaizot et al. 2005

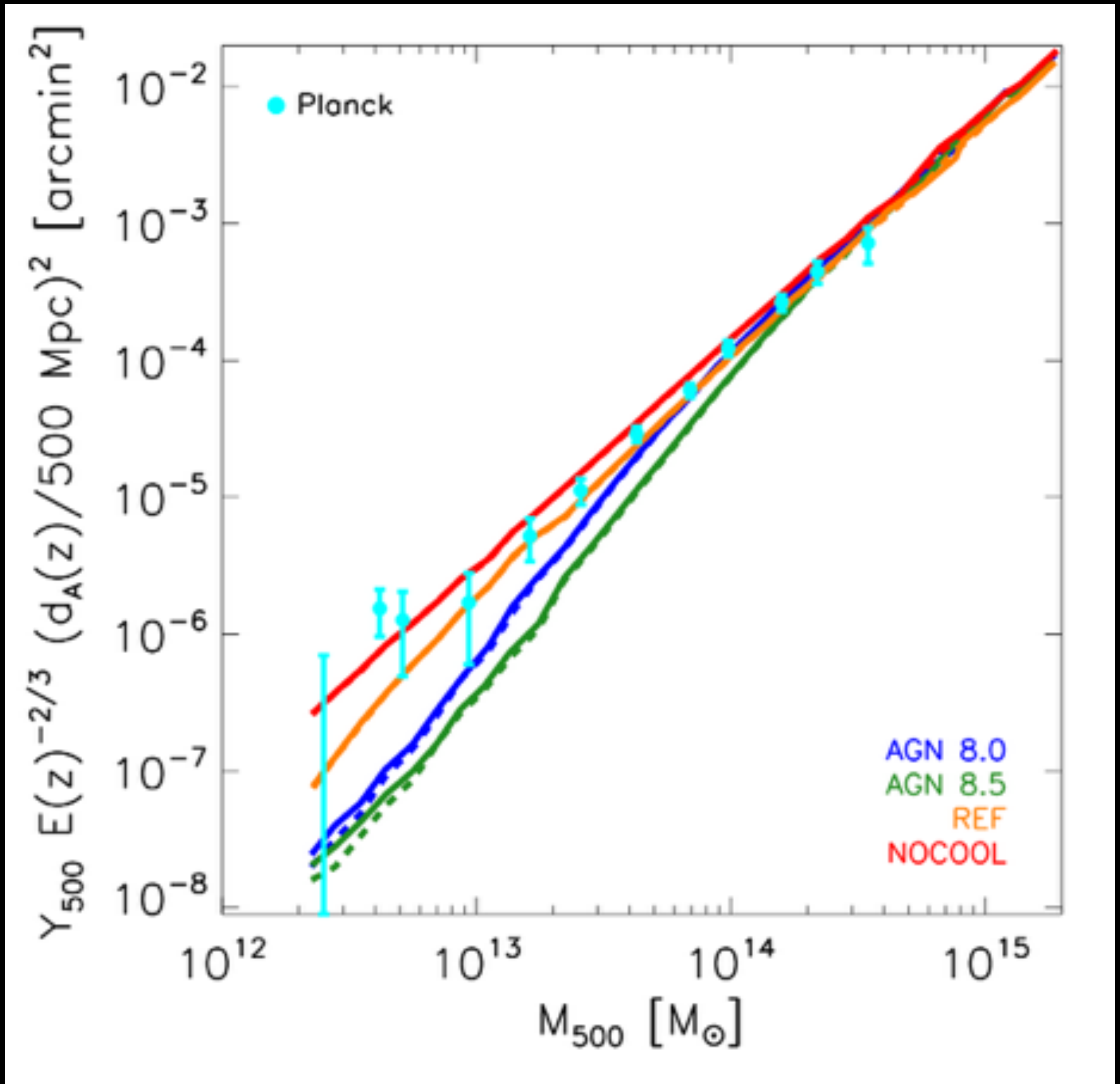
Synthetic surveys from cosmo-OWLS



McCarthy et al. 2014

Le Brun et al. 2015

The need for synthetic tSZ observations



- Visible steepening in the galaxy and group regimes when AGN feedback is included.
- Taken at face value, the Planck results favour an approximately self-similar Y_{500}-M_{500} as obtained in non-radiative simulations such as NOCOOL

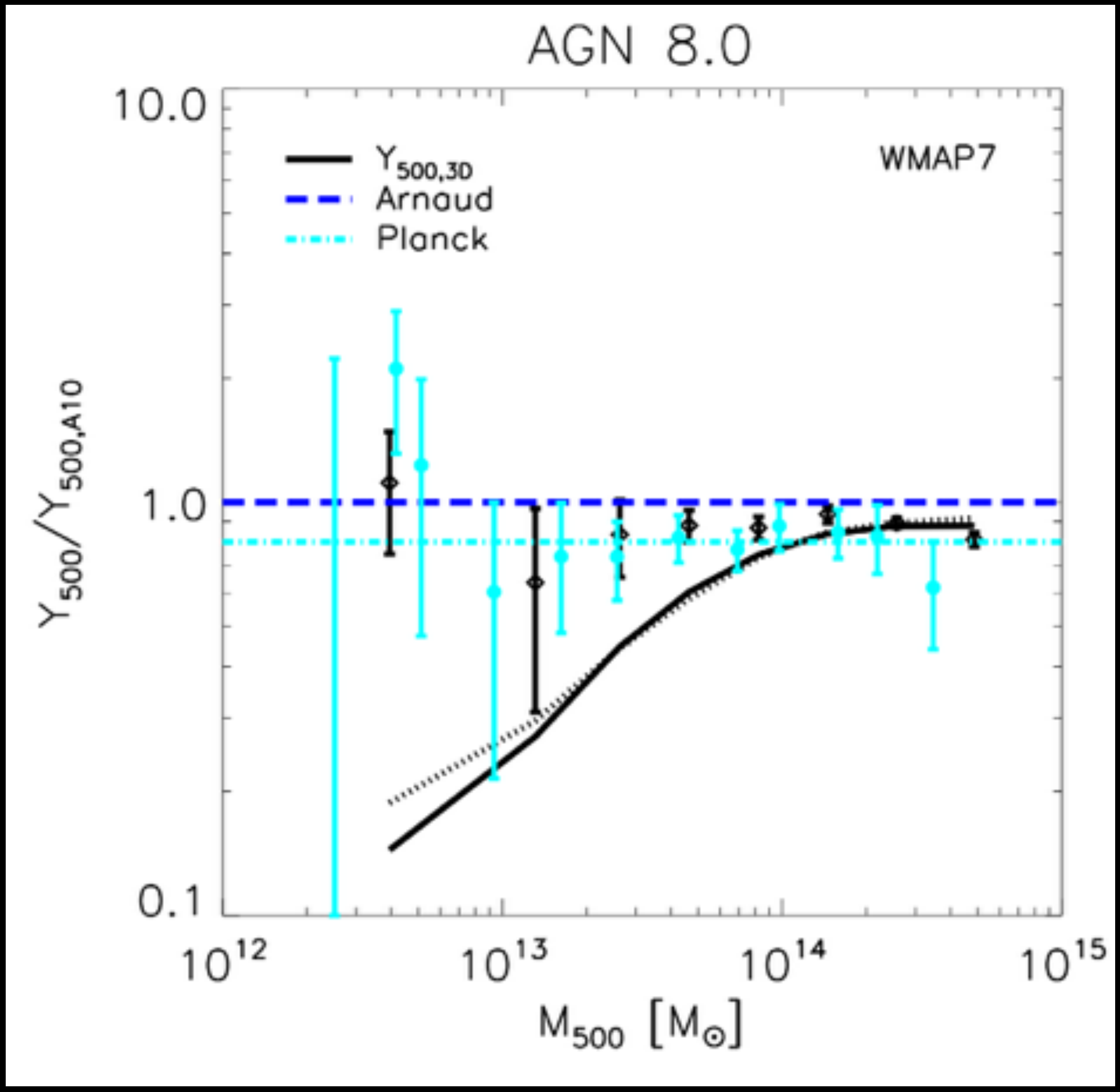
➡ **surprising as ruled out by X-ray observations**

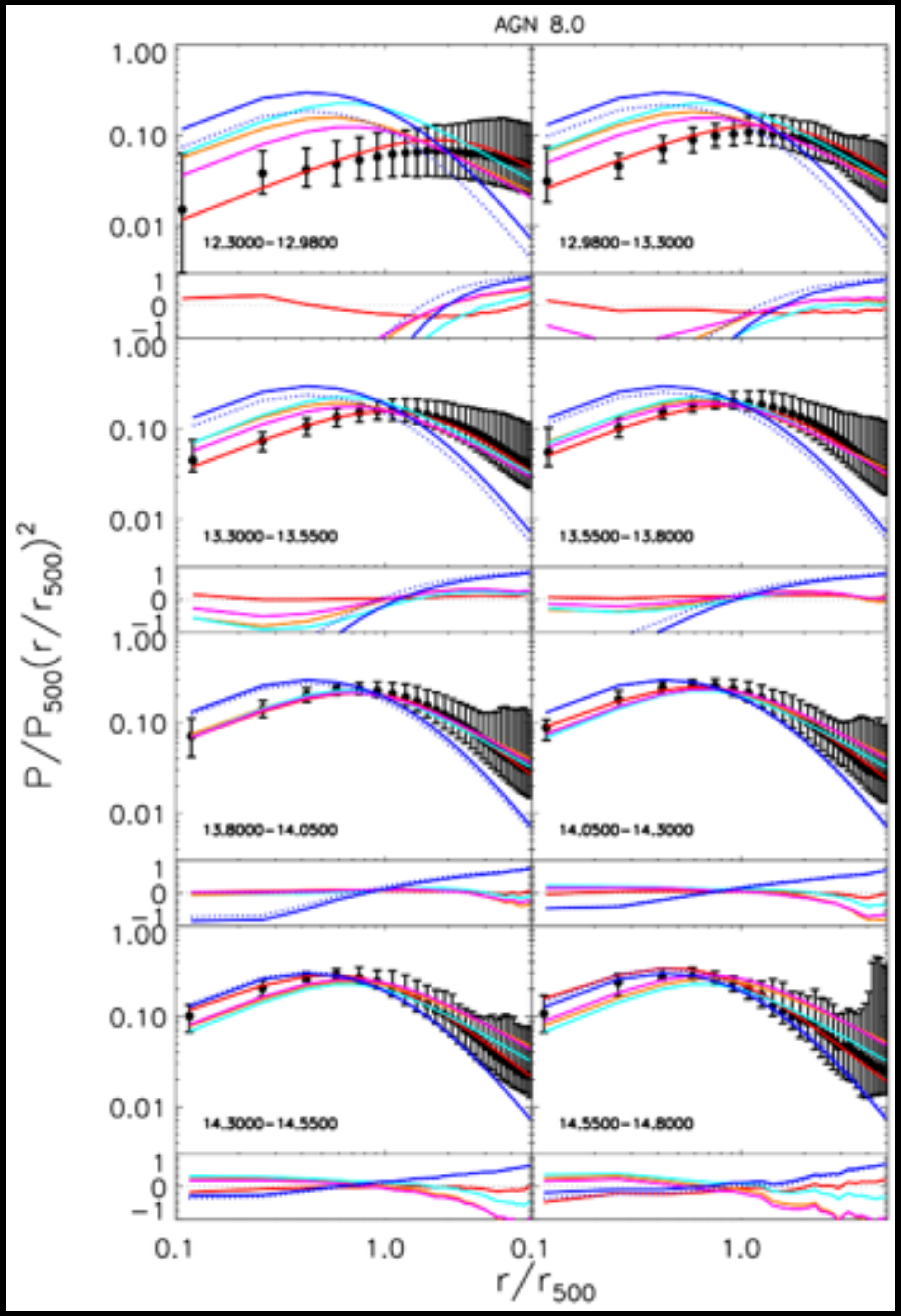
- However, Y_{500} not directly measured by Planck

➡ **need synthetic SZ observations**

Le Brun et al. 2015

The need for synthetic tSZ observations



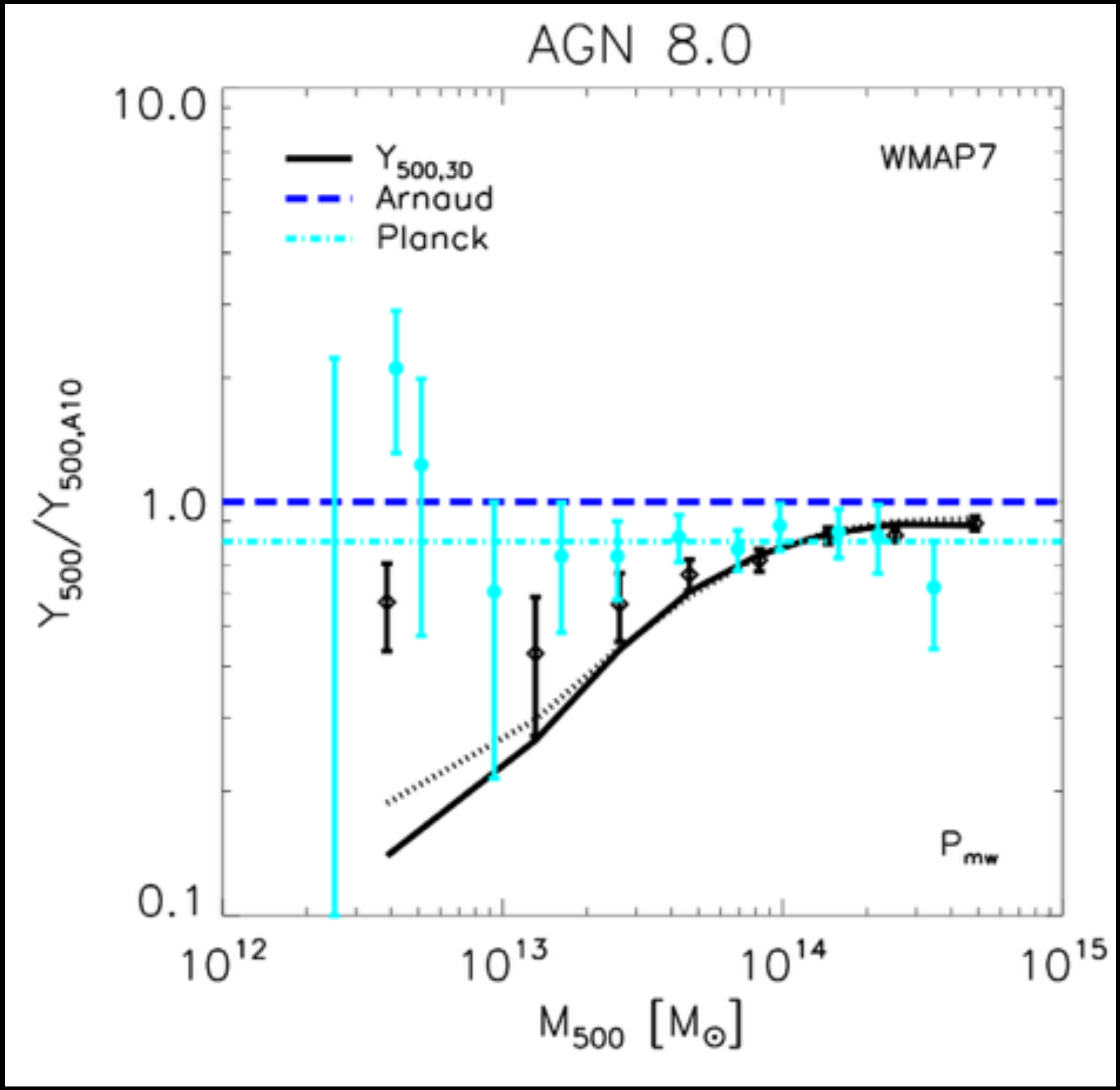


- The amplitude of the bias increases with decreasing halo mass and increasing AGN feedback intensity, reaching **nearly an order of magnitude at the lowest halo masses**.
- Shape of pressure profile is quite strongly **mass-dependent**

➡ **need to make two of the GNFW coefficients (normalisation and concentration) mass-dependent**

Le Brun et al. 2015

Non-universal pressure profile



- Adopt the altered pressure profile template derived for the AGN 8.0 model for the MMF

➡ **the bias is largely removed**

➡ **majority of the bias due to the use of an inappropriate spatial filter in the matched filter**

Conclusions

- Taken at face value, the Planck results favour a close to self-similar Y_{500}-M_{500}

➡ galaxies, groups and clusters all have a gas fraction which is close to the universal baryon fraction and independent of mass

- MMF recovers a nearly unbiased Y_{500}-M_{500} for models which neglect efficient feedback but there is a **significant bias for models which invoke the AGN feedback required for reproducing X-ray and optical observations of groups and clusters**

- The amplitude of the bias increases with decreasing halo mass, reaching **nearly an order of magnitude overestimate in Y_{500} at $M_{500} \sim 10^{13}\ M_{\odot}$**

- The **vast majority of the bias comes from the assumption of a fixed spatial template** (the universal pressure profile) which becomes a **poor description of the hot gas distribution at low-masses in models which include AGN feedback**

Evolution of the dark matter profiles of the most massive galaxy clusters since redshift 1

Evolution of dark matter profiles

- Cosmological simulations all predict that in CDM cosmologies:

1. Dark matter profiles are self-similar

2. They follow a universal functional form which is peaked in the centre (e.g. a Navarro, Frenk & White (NFW) profile)

- 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

➡ numerous unanswered questions remain: e.g. Do the structure of the dark matter profiles of the **global** population, and especially its **dispersion and evolution**, obey the predictions from the standard model?

➡ testing the standard model using the evolution of dark matter profiles for an **unbiased** sample, coming from the most massive galaxy clusters detected by Planck and SPT up to a redshift of 1 and confronting the results with a tailor-made simulated sample whose characteristics have to be as similar as possible to the ones of the observed sample

Evolution of dark matter profiles

- Need:

1. 30 clusters with $M_{500} \geq 5 \times 10^{14}$ $M_\odot$ in each of the redshift bins up to redshift 1

2. a high-spatial resolution of a few kpc in order to math the resolution of the observations and more importantly to enable the characterisation of their inner structure

- Unfortunately, these two characteristics are incompatible

➡ doing three large (1 Gpc/h on a side with 2048^3 DM particles) intermediate spatial (~30 kpc) and mass (~10^{10} $M_\odot$) resolutions DM only simulations using the latest Planck2 cosmology

➡ zooming at high resolution (a few kpc) on 30 galaxy clusters in each of the 4-5 redshift bins (z=1.1-0.9, 0.9-0.7, 0.7-0.5 and local z<0.5) first with only DM, then with adiabatic gas and finally the non-gravitational physics of galaxy formation will be progressively added for a subsample of the zooms

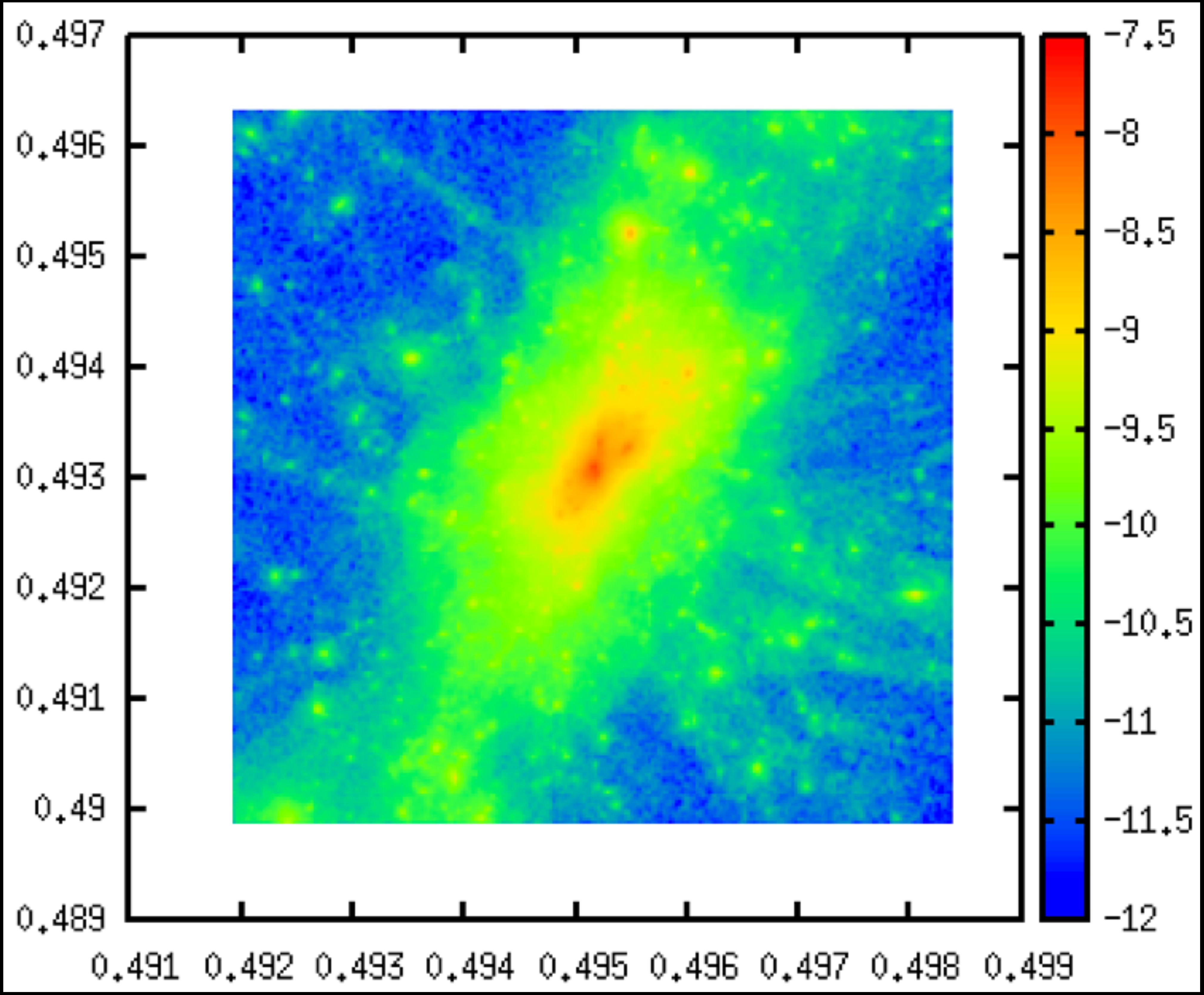
Evolution of dark matter profiles

- 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

- OCCIGEN has 50 544 cores (peak speed of 2.1 PFlops (top 26 in the last top 500)) and 202 TB of distributed memory

- The large runs are done on 4096 cores and the DM-only zooms on a few 100s

Evolution of dark matter profiles



Evolution of dark matter profiles