Scatter and evolution of the hot gas properties of a realistic population of simulated groups and clusters

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Scatter and evolution

- Scatter is only mostly important for doing cosmology with galaxy clusters.

- 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.

  - **Galaxy groups are hugely important** in that respect as they are much sensitive than clusters.

cosmo-OverWhelmingly Large Simulations

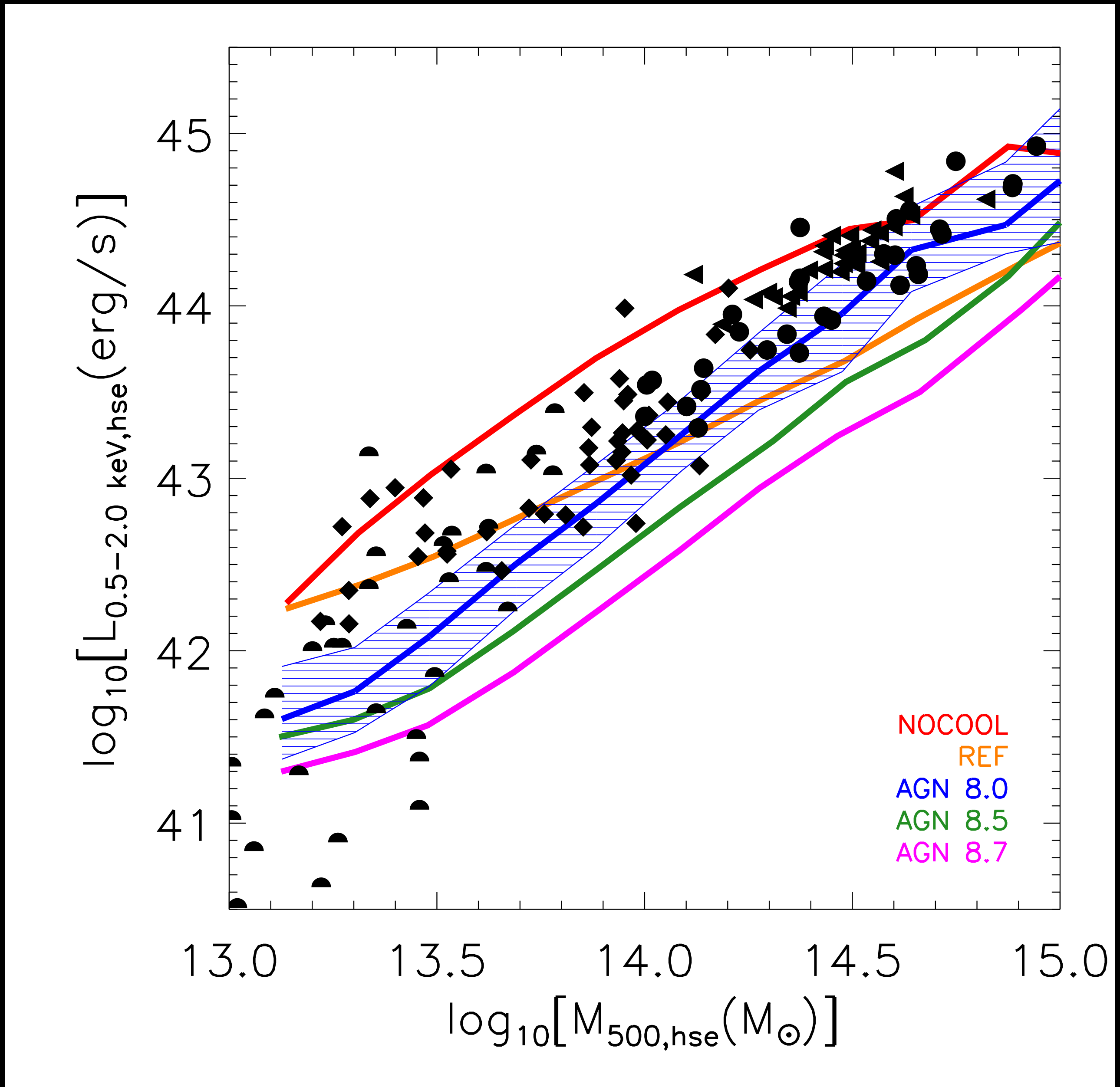
- 2.15 billion particles in 400 Mpc/h boxes with 4 kpc/h gravitational softening run using modified version of GADGET3 (Springel 2005) which resorts to **subgrid** modeling for **unresolved** small scale physics and **varying it. Especially the strength of the AGN feedback** (Booth & Schaye 2009).

- More than **25,000** groups and clusters with $M_{500}>10^{13}$ $M_{\odot}$ at z=0 in Planck cosmology.

Le Brun et al. 2014

X-ray observations

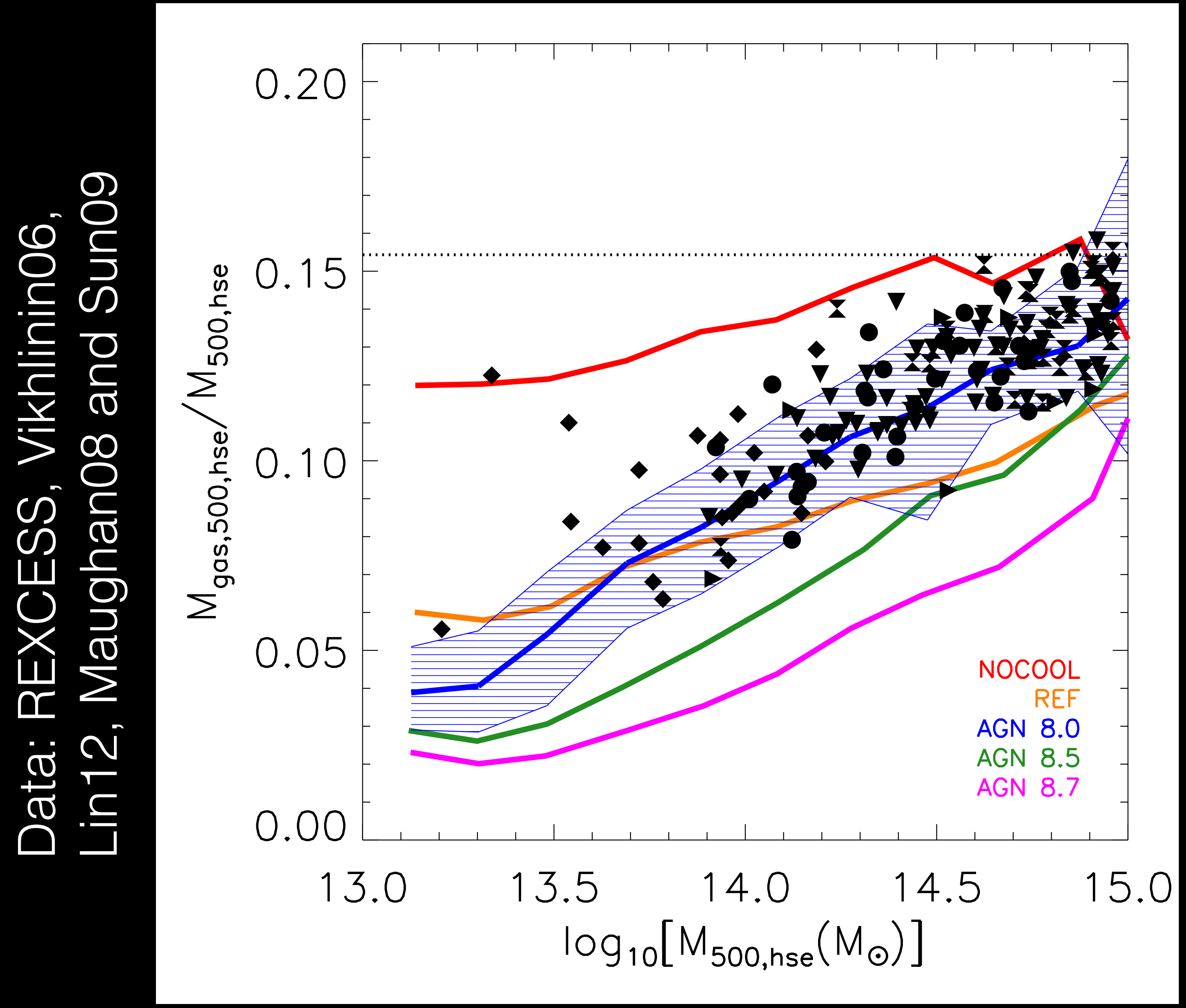
Data: Pratt09, Vikhlinin09, Sun09 and Osmond04



- Need feedback of some sort to solve overcooling problem
- AGN 8.0 model broadly reproduces relation over two orders of magnitude in mass
- Increased heating temperatures result in under-luminous systems at all masses

Le Brun et al. 2014

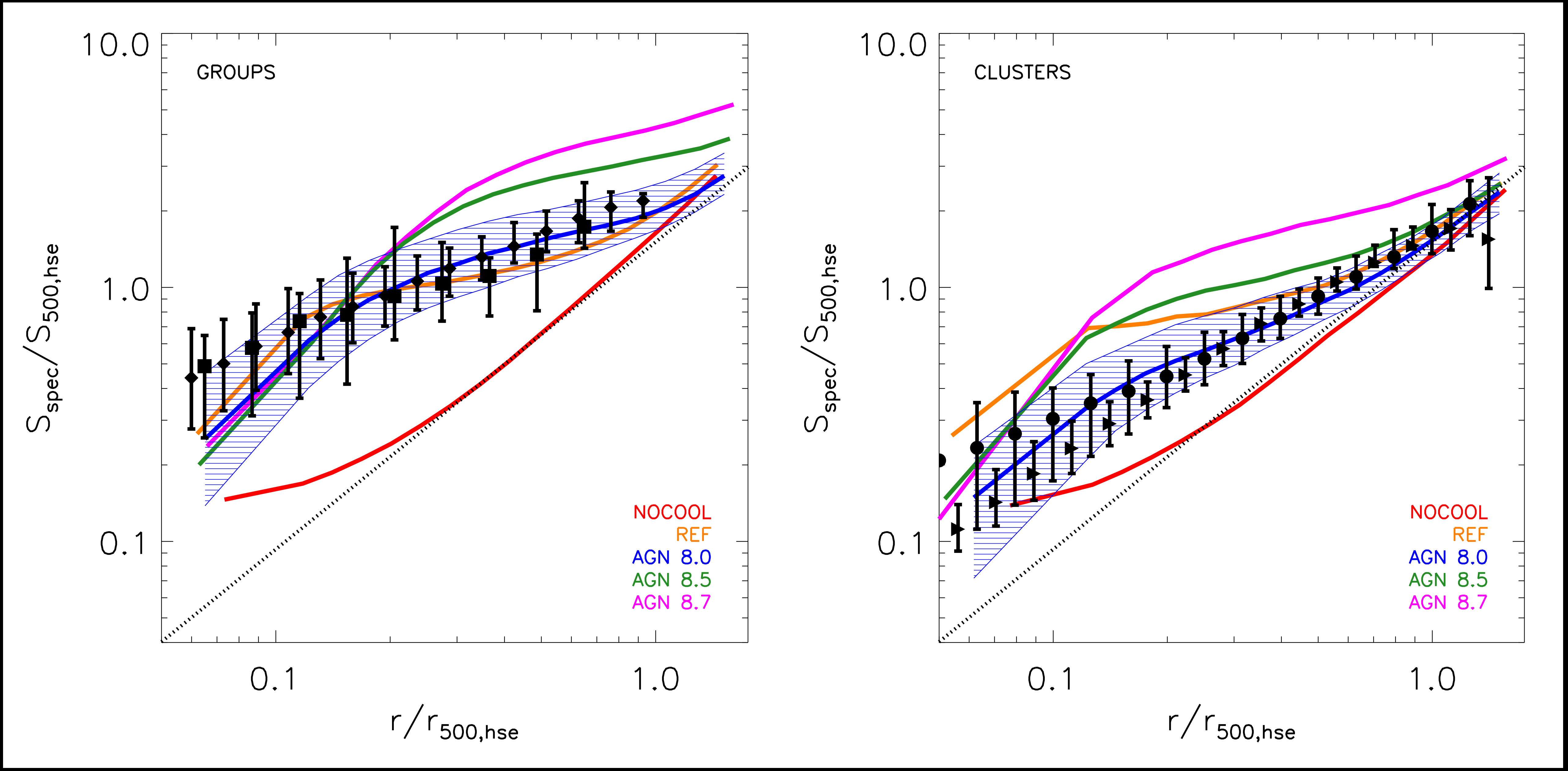
X-ray observations



- Observed trend and scatter reproduced extremely well by AGN 8.0
- Achieved primarily by ejection of gas from high-redshift progenitors
- Increased heating temperatures result in too much gas being ejected
- REF also yields reasonable f_{gas} but relation is flatter than observed. Here, low f_{gas} are achieved by overly efficient SF.

Le Brun et al. 2014

Entropy profiles



Data: Sun09, Johnson09

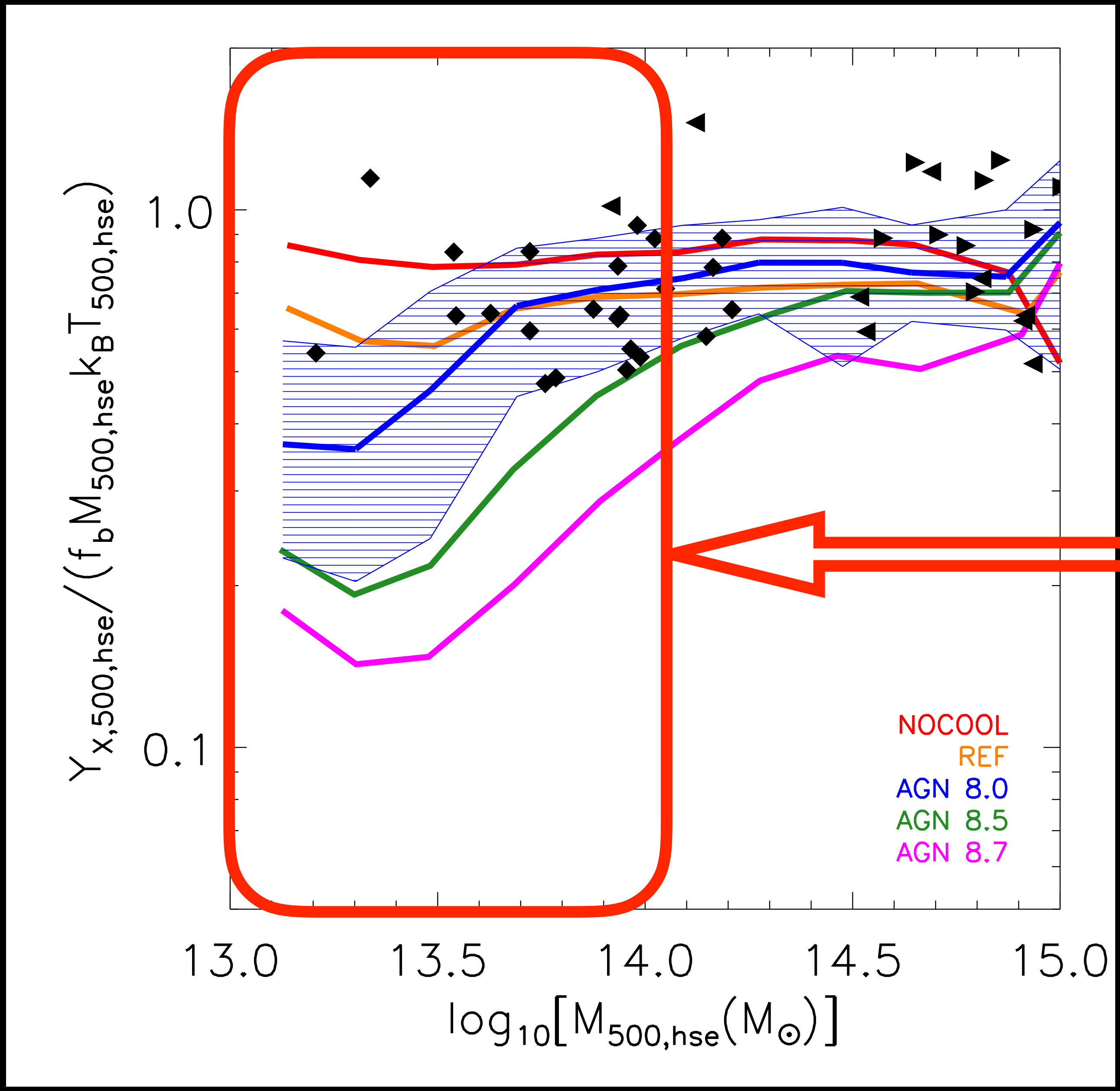
Data: Pratt10, Vikhlinin06

- All radiative models yield profiles that are similar to the observed ones in the central regions of groups but in clusters only AGN 8.0 provides an adequate match.
- At larger radii, the AGN models with increased heating temperatures have too large entropies due to ejection of too much gas from progenitors.

Le Brun et al. 2014

Sunyaev-Zel'dovich properties

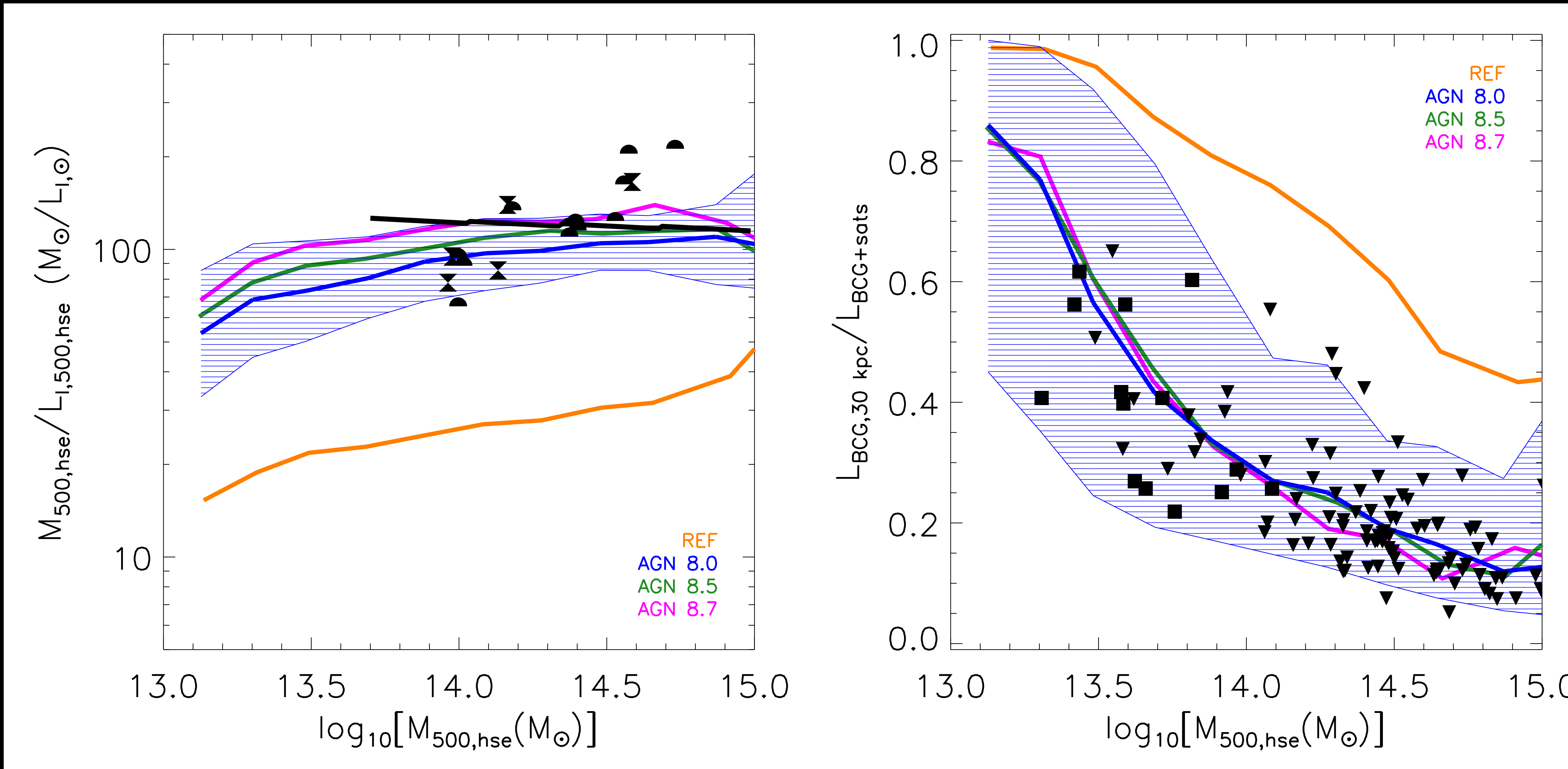
Data: Vikhlinin06, Planck Intermediate Results IV, Sun09



Y_X is in fact sensitive to ICM physics as arbitrarily large amounts of gas ejection cannot be compensated by T increase as T forced to be always close to T_{vir} by HSE

Le Brun et al. 2014

Optical properties



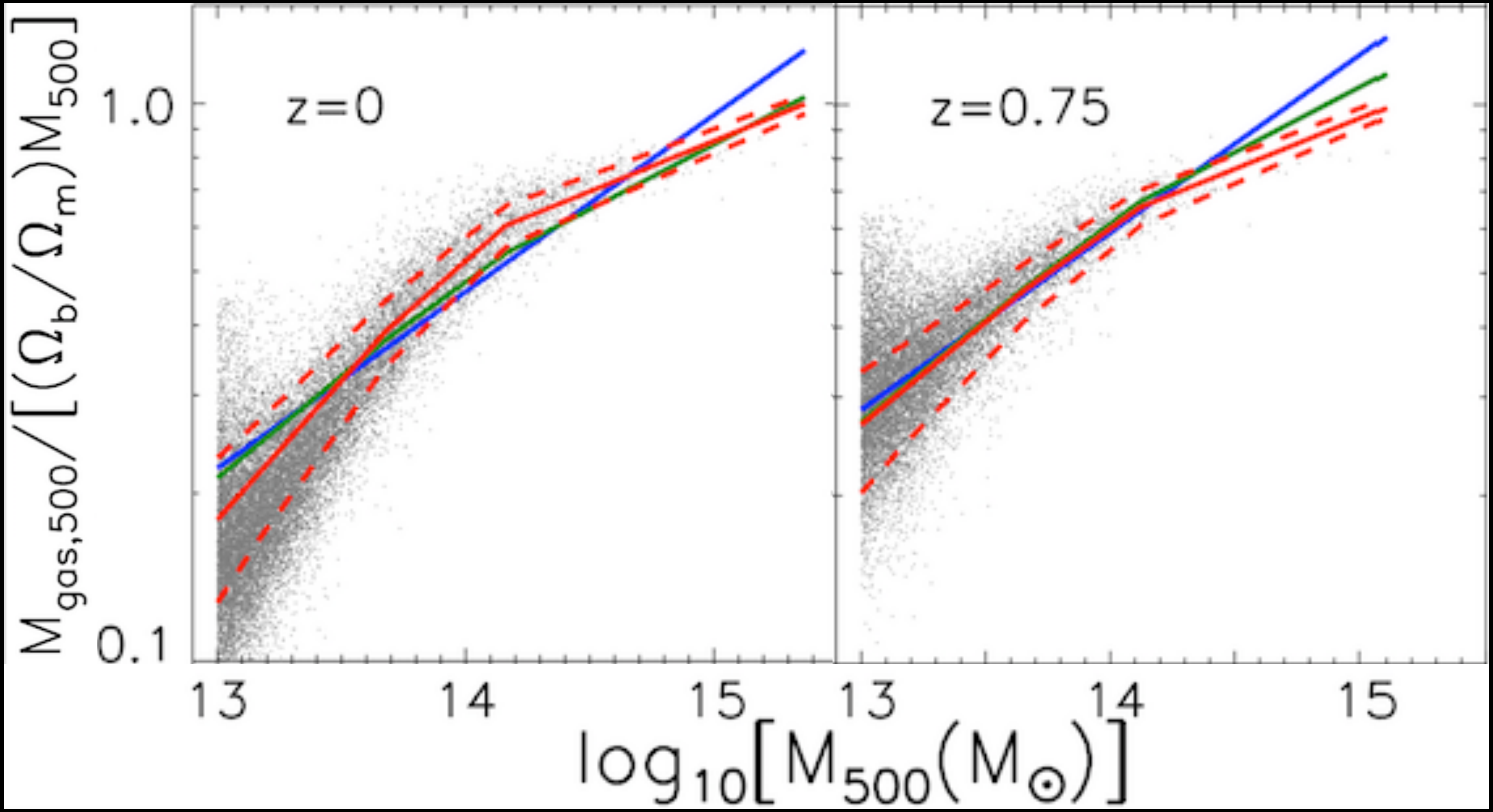
Data: Sanderson13, Gonzalez13 and Budzynski14

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

Fitting of relations

Le Brun et al. 2016a submitted (arXiv: 1606.04545)

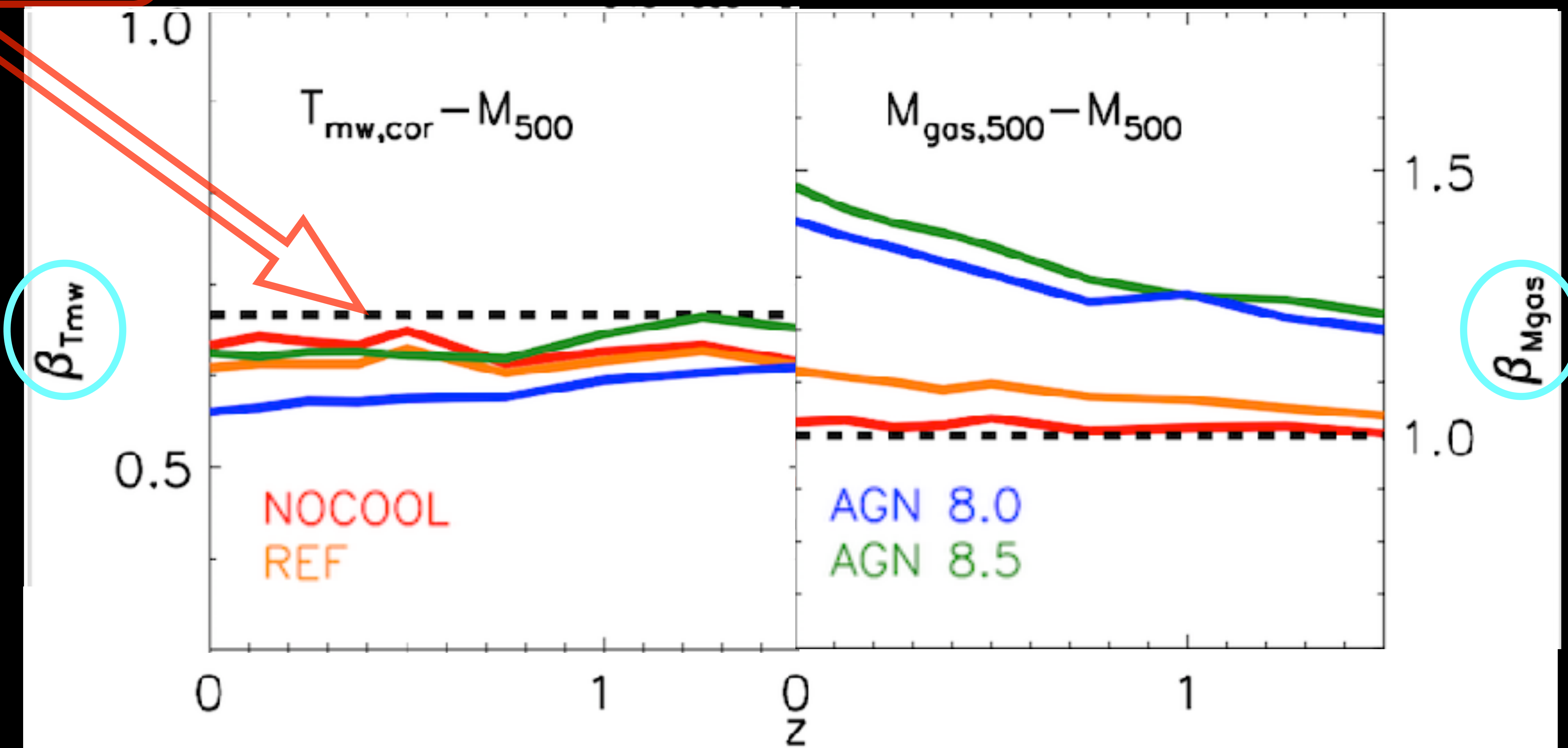


- In order to fit the median and scatter over t**wo orders of magnitude in mass**, one needs to **break** the power-law and to make the **low-mass mass slope redshift-dependent.**
- **Scatter slightly higher for groups**

Self-similar expectation for the slope

Evolution of mass slope

Le Brun et al. 2016a submitted (arXiv: 1606.04545)

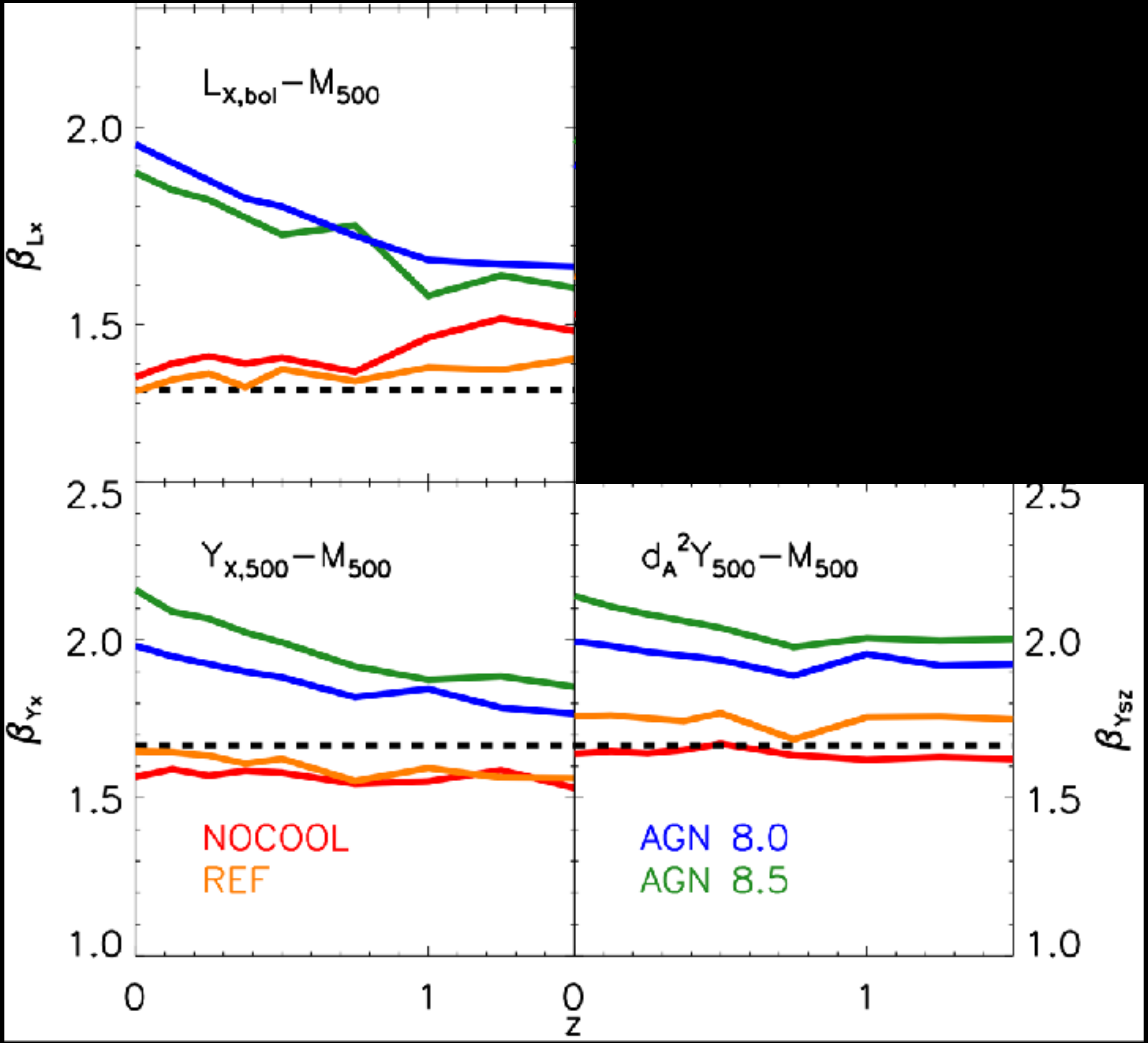


- **Deviations** from SS **increase** with **increasing feedback intensity**.
- M_{gas}-M_{500} **steeper** than SS for **all** the **radiative models due to ejection from progenitors**.

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

Evolution of mass slope

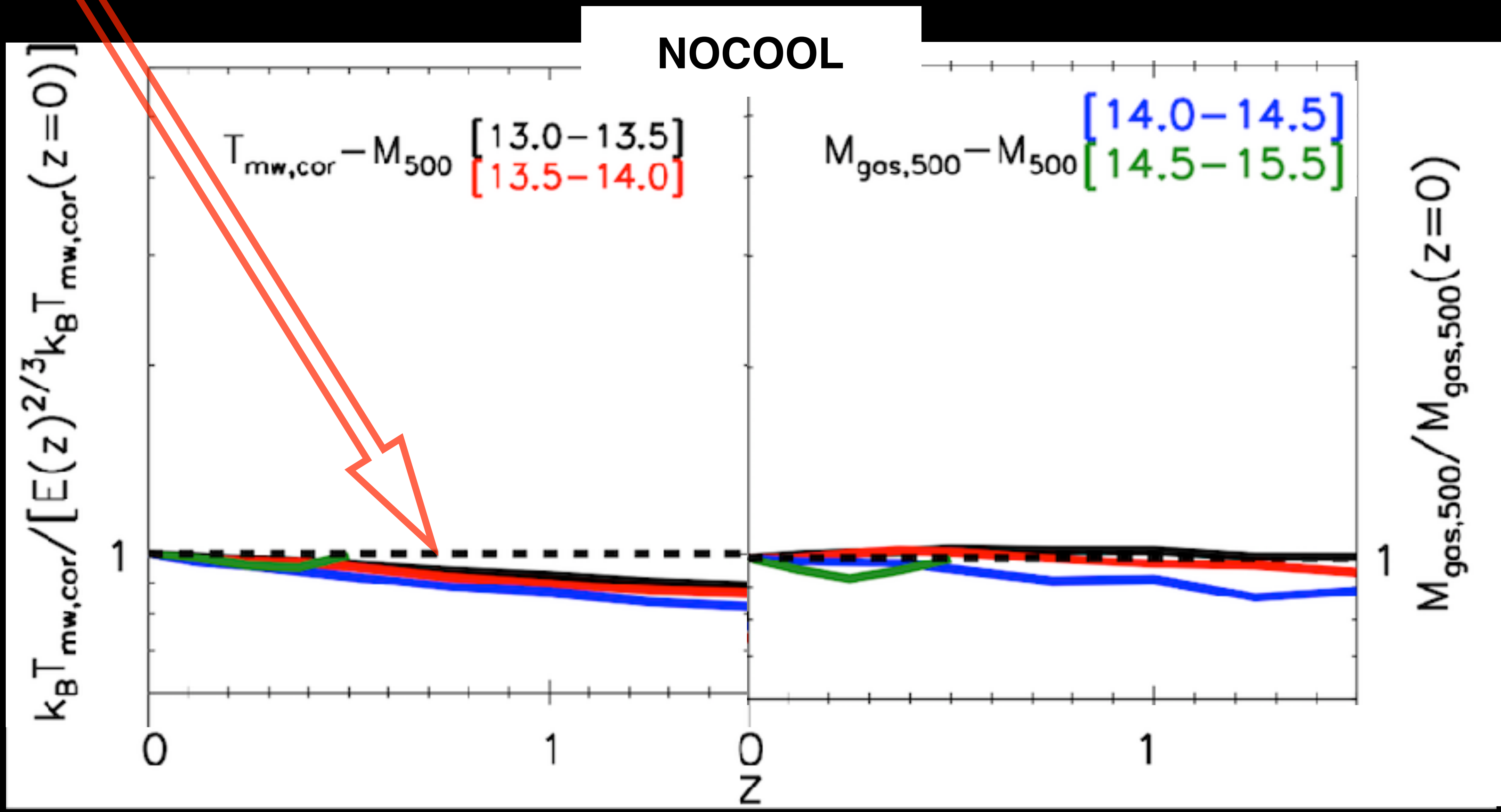
Le Brun et al. 2016a submitted (arXiv: 1606.04545)



Evolution of normalisation

Le Brun et al. 2016a submitted (arXiv: 1606.04545)

Self-similar expectation for the evolution



Evolution of normalisation

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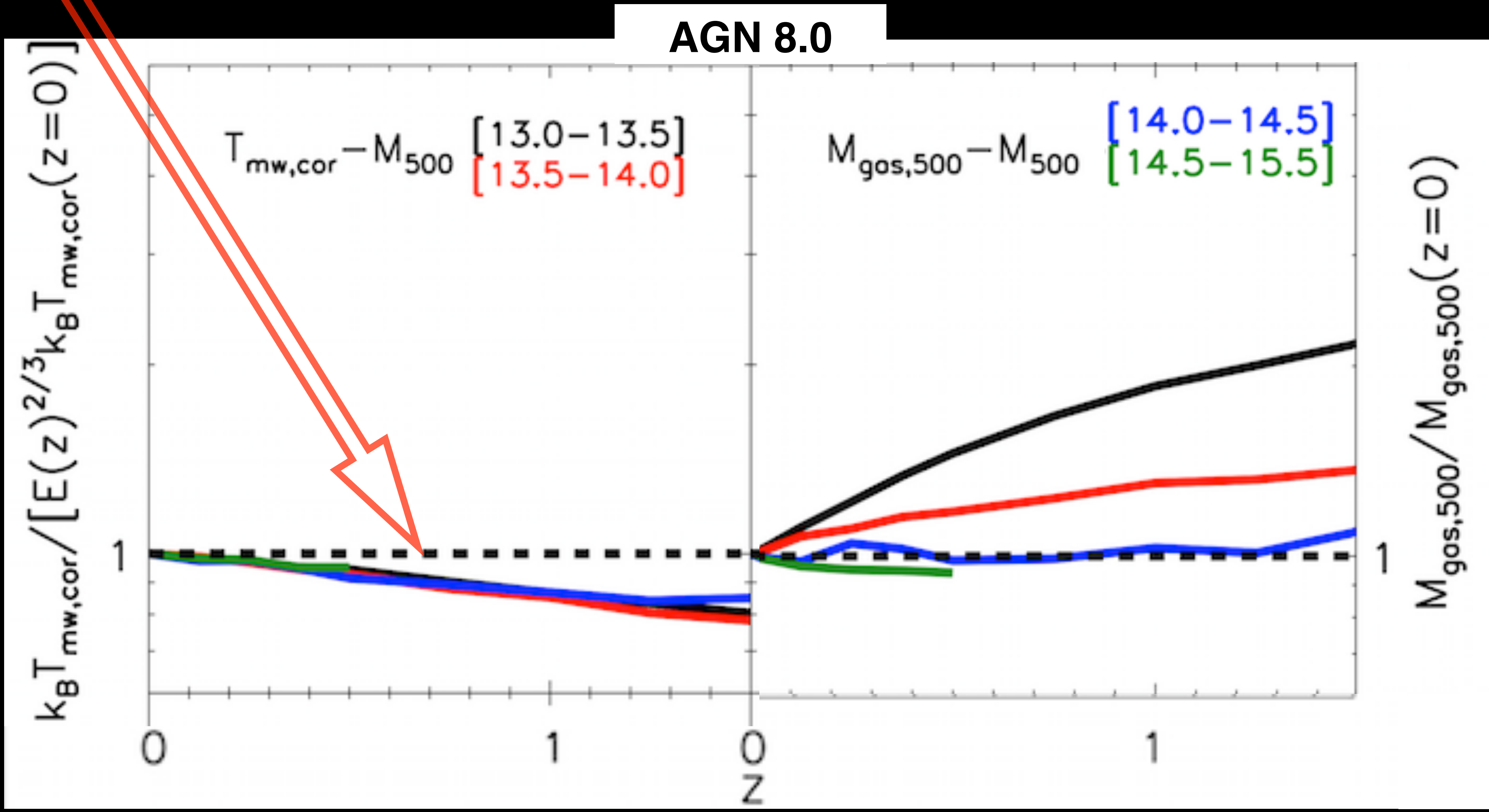
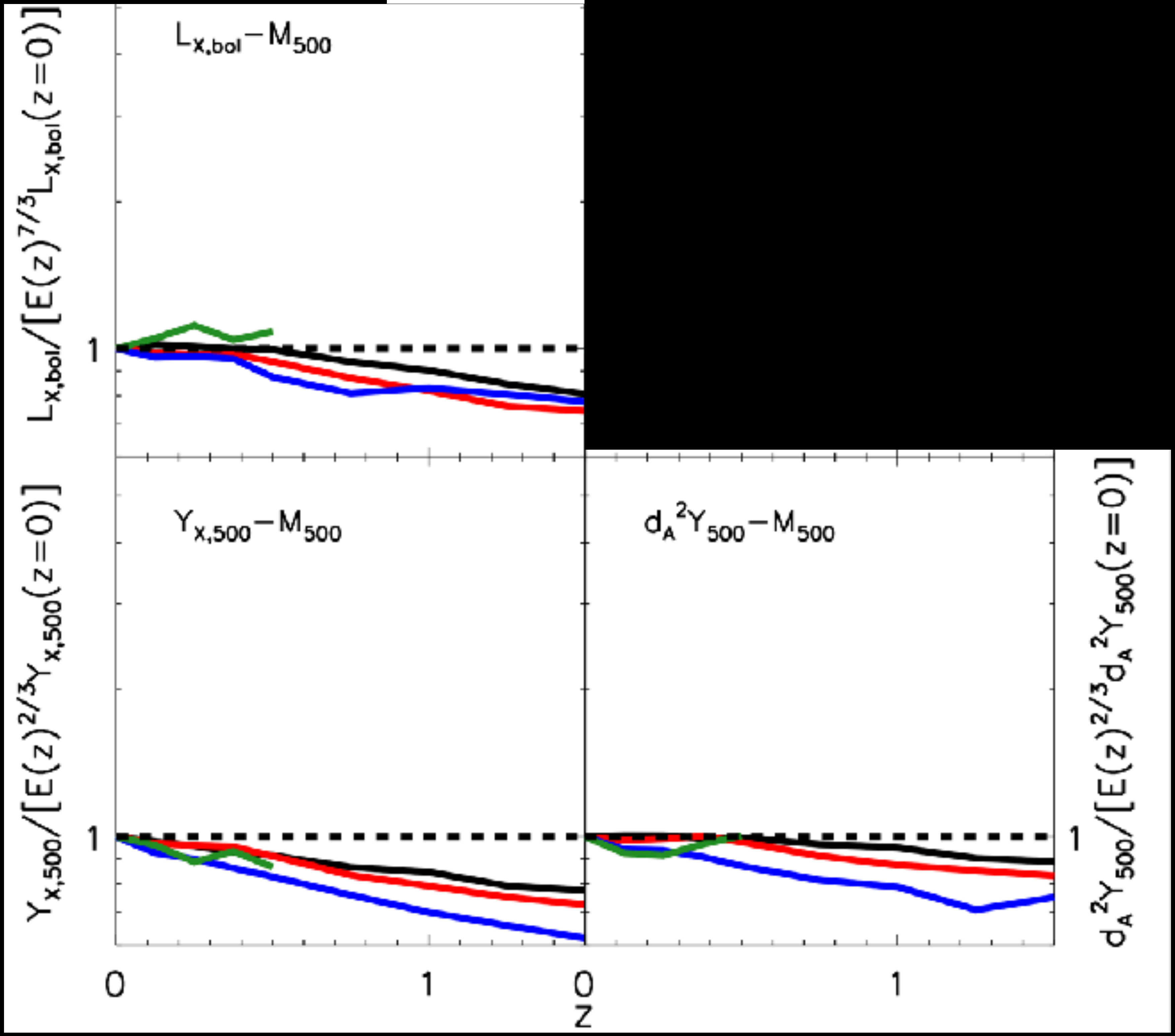
Self-similar expectation for the evolution



Evolution of normalisation

Le Brun et al. 2016a submitted (arXiv: 1606.04545)

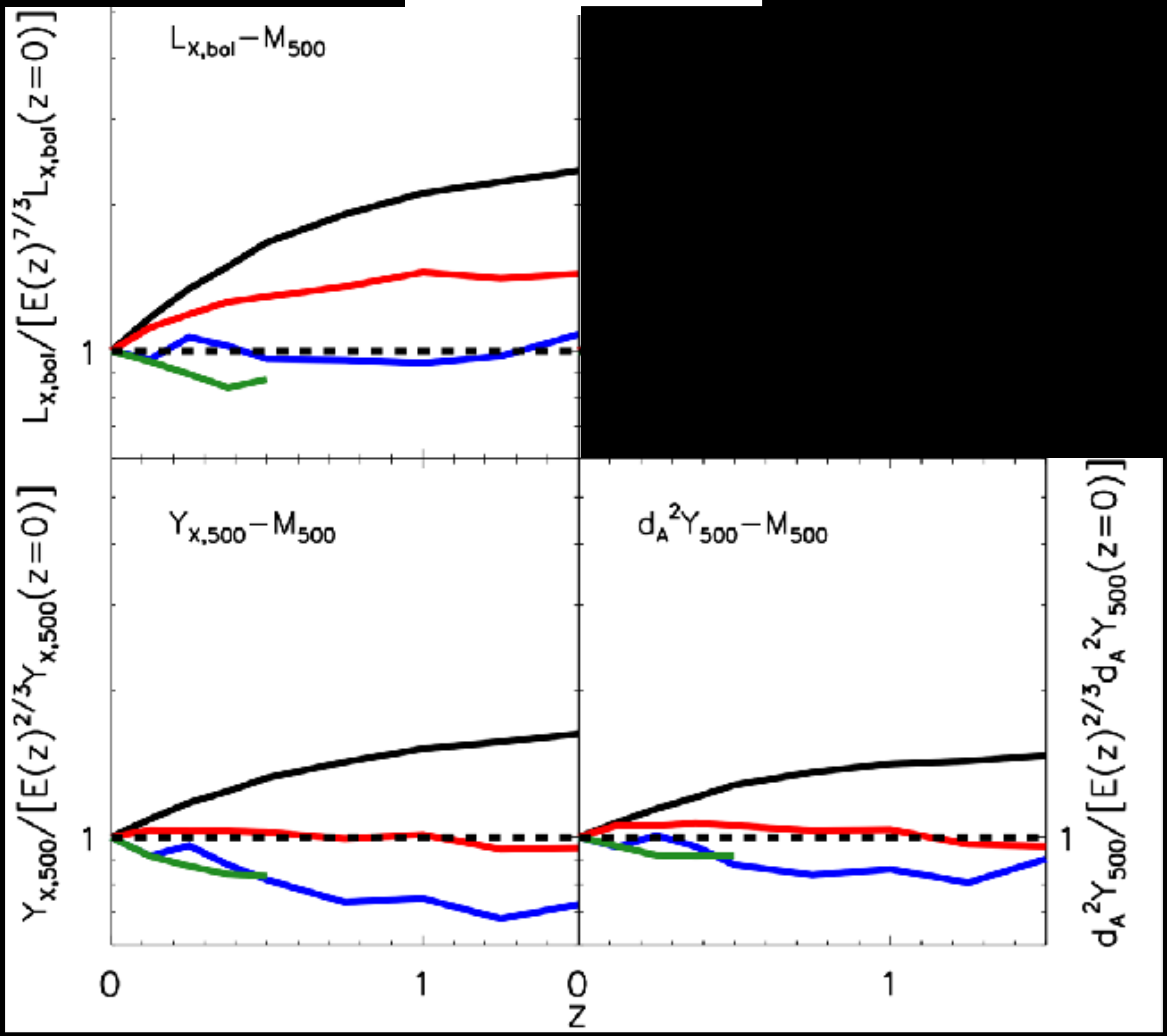
NOCOOL



Evolution of normalisation

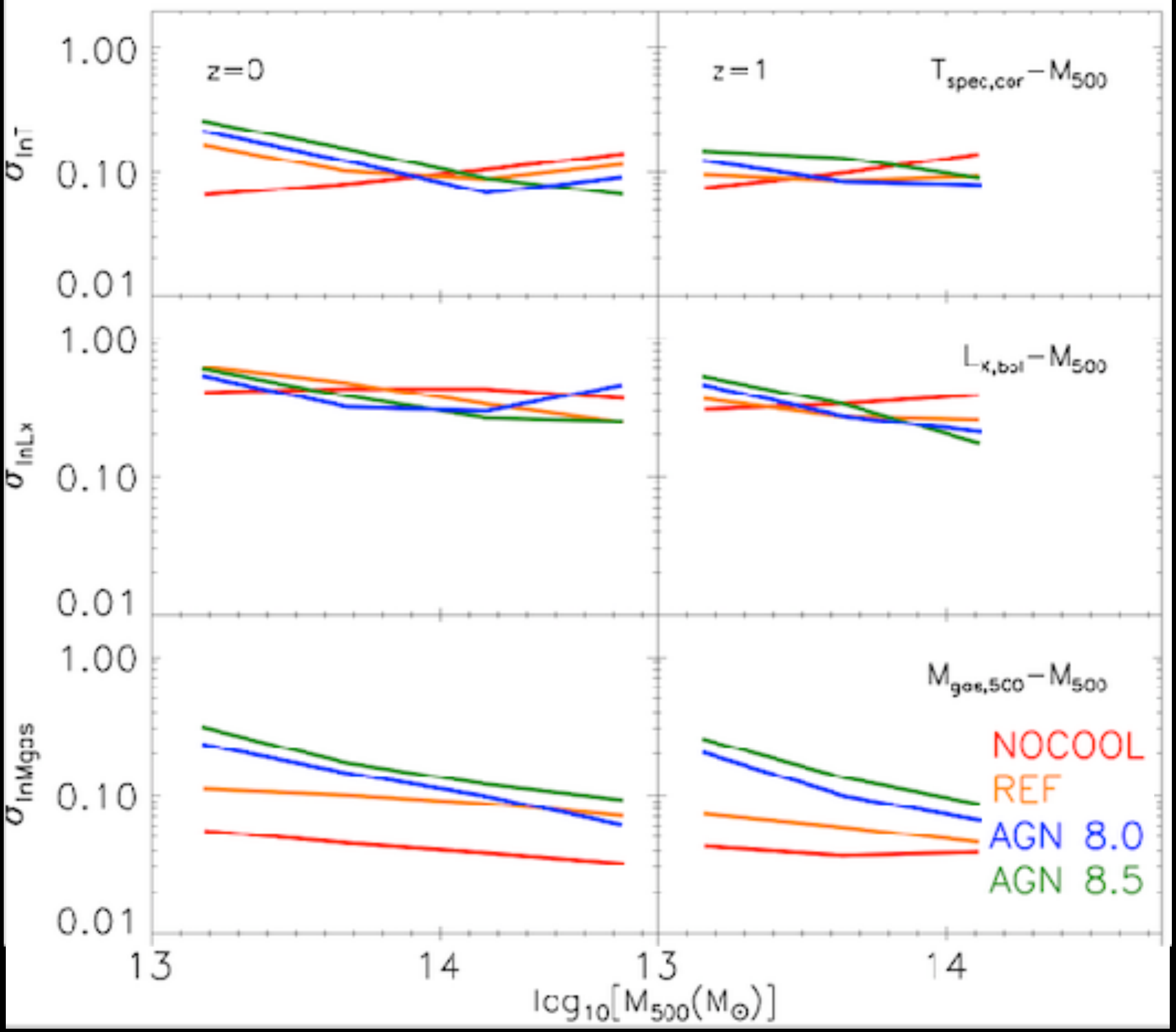
Le Brun et al. 2016a submitted (arXiv: 1606.04545)

AGN 8.0



Scatter

Le Brun et al. 2016a submitted (arXiv: 1606.04545)



- **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. 2016a submitted (arXiv: 1606.04545)

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 %	≈ 20 %	≈ 5 %
$L_{bol} - M_{500}$	≈ 25 %	≈ 25 %	≈ 40 %
$M_{gas,500} - M_{500}$	≈ 10 %	≈ 10 %	≈ 25 %
$Y_{X,500} - M_{500}$	≈ 10 %	≈ 15 %	≈ 25 %
$d_A^2 Y_{500} - M_{500}$	≈ 10 %	≈ 10 %	≈ 20 %
$M_{500,hse,spec} - M_{500}$	≈ 15 %	≈ 25 %	≈ 5 %

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

Conclusions

- In order to fit the median and scatter over two decades in mass, one needs **evolving broken power-laws with redshift dependent indices at group-scale**.

- The predictions of the self-similar model **break down when efficient feedback is included**.

  - Particularly true at **late-times** and **for groups and low-mass clusters**.

  - But deviations from self-similarity do **not** necessarily mean **effects of non-gravitational physics**.

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

  - **Groups** tend to have **slightly (a factor of 2 to 3) higher scatter** and this **only at low-redshift**.