The Millennium Gas Simulations

Peter Thomas
and the Virgo Consortium

Conclusions

- We show that feedback from SNR and AGN in the L-Galaxies SA model are consistent with the observed properties of the ICM in clusters of galaxies

- We have re-run the Millennium simulation with the WMAP-7cosmology
- We have created merger trees and SA galaxy catalogues using the Guo 2011 version of L-Galaxies (contact me if you want to use them)
- We use the SA galaxies as input to a hydrodynamical simulation:
  - SNR contribute metals (but are inconsequential for entropy generation in massive halos)
  - AGN heat the gas (and can reproduce the entropy and metallicity profiles of clusters)

The **old** Millennium Gas Simulations

- Millennium Simulation:
  - Tracks CDM only (+SA galaxies)
  - N=2160^3 particles
  - L=500 h^{-1}Mpc (comoving)
  - WMAP1 cosmology (σ_8=0.9)

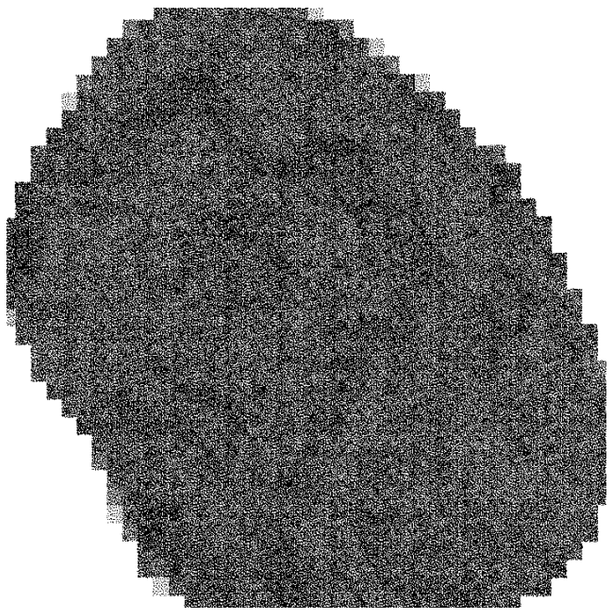
- Millennium Gas Simulation
  - Same large-scale structure as MS
  - Same volume as MS
  - Same cosmology as MS
  - Fewer (10^9) particles than MS
  - But also tracks gas (using SPH)

- Three models:
  - GO: gravity only
    entropy generation through shocks only
  - PC: preheating plus cooling
    gas is pre-heated to entropy floor of 200 keV cm^2 at z=4
  - FO: feedback only (no cooling)
    SN+AGN feedback using SA galaxies — for selected clusters only

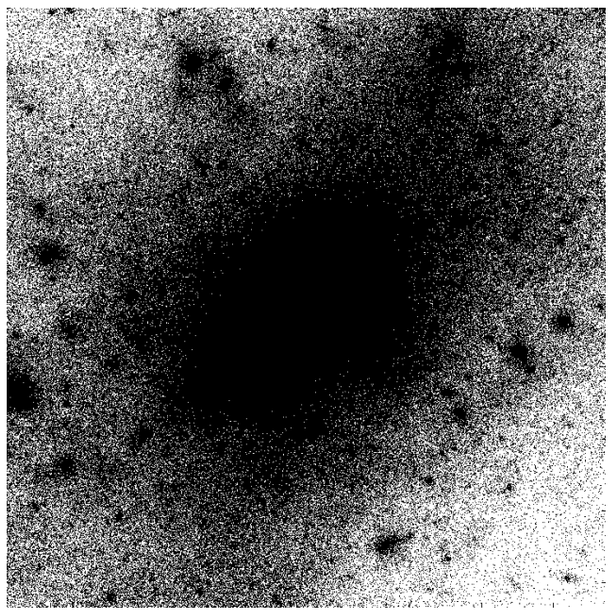
- See papers by:
  - Hartley et al. 2008 (X-ray L-T relation)
  - Stanek et al. 2010 (Scaling relations)
  - Short et al. 2011 (Evolution of scaling rel.)
  - Young et al. 2011 (Baryon fractions)
  - Kay et al. in prep (SZ scaling relations)

Combining semi-analytics with simulations

Chris Short, Peter Thomas, 2009, ApJ, 704, 915

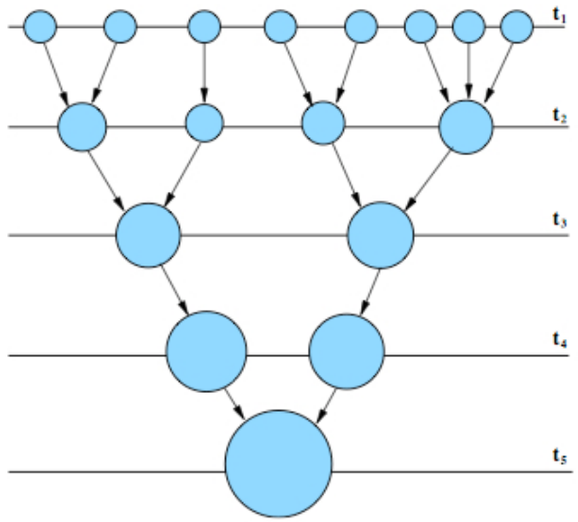


GADGET-2

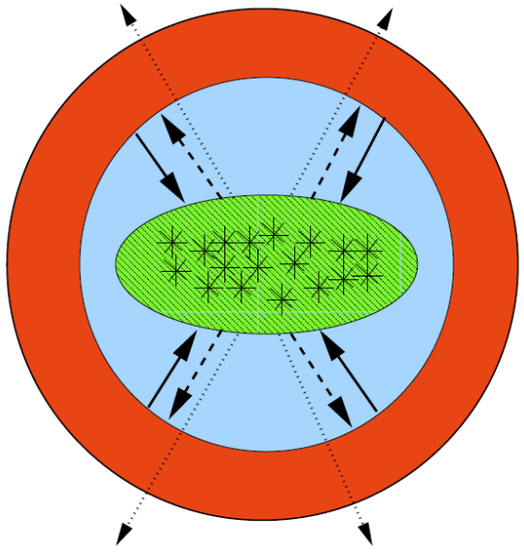


FoF

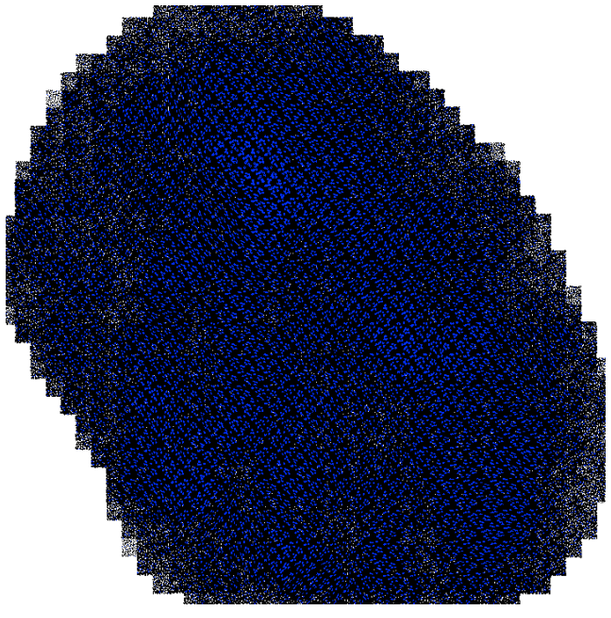
SUBFIND



SA model



Feedback



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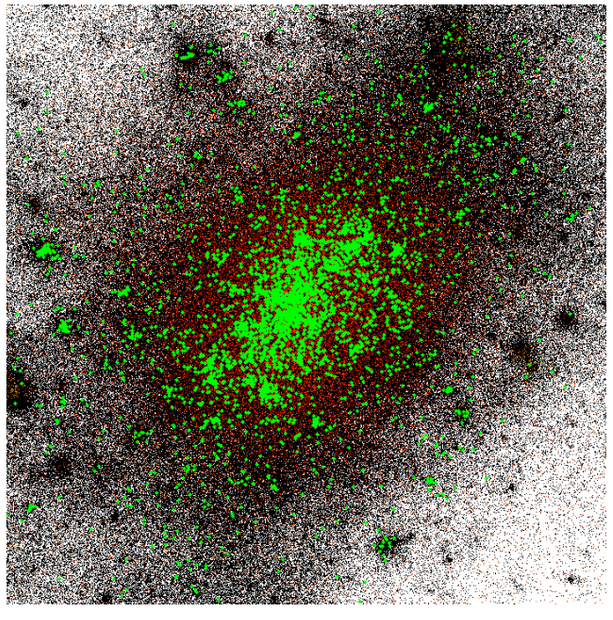


The feedback model

- Type II supernova feedback:

$$\Delta E_{\rm ejected} = \frac{1}{2}\epsilon_{\rm halo} v_{\rm SN}^2 \Delta M_* - \frac{1}{2}\epsilon_{\rm disk} v_{\rm vir}^2 \Delta M_*$$

Total energy available

Energy used to reheat cold disk gas

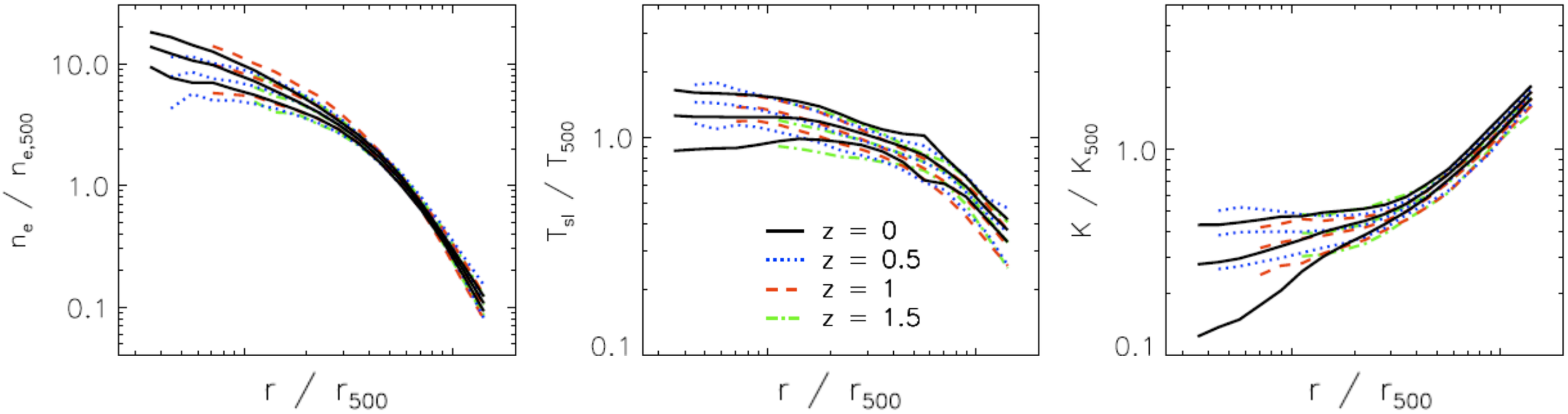
- AGN feedback:
  - Adopt the Bower et al. (2008) AGN feedback prescription used in GALFORM
  - Available heating energy is given by:

$$\Delta E_{\rm BH} = \min \begin{cases} 0.1 \Delta M_{\rm BH} c^2 & \text{Radio mode} \\ \epsilon \Delta E_{\rm Edd} & \text{Quasar mode} \end{cases}$$

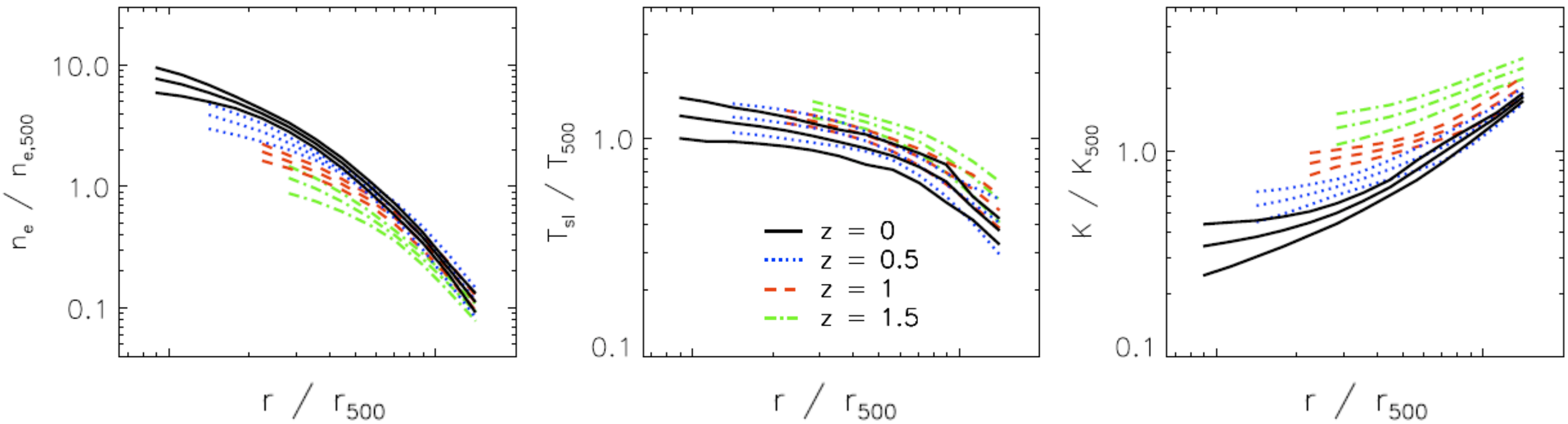
where $\epsilon = 0.02$ is the disk structure parameter

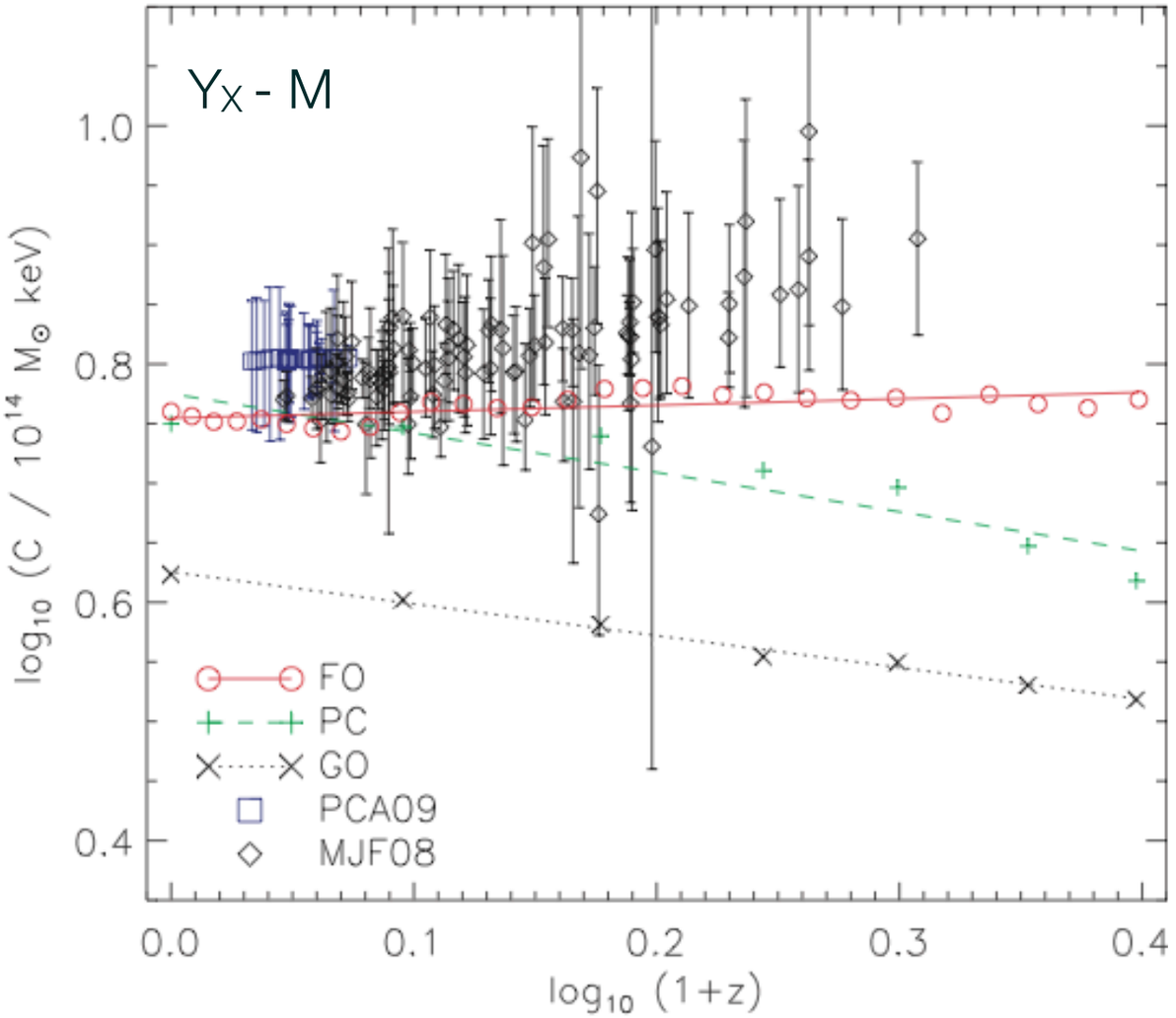
Evolution of profiles, Short et al 2010, MNRAS, 408, 2213

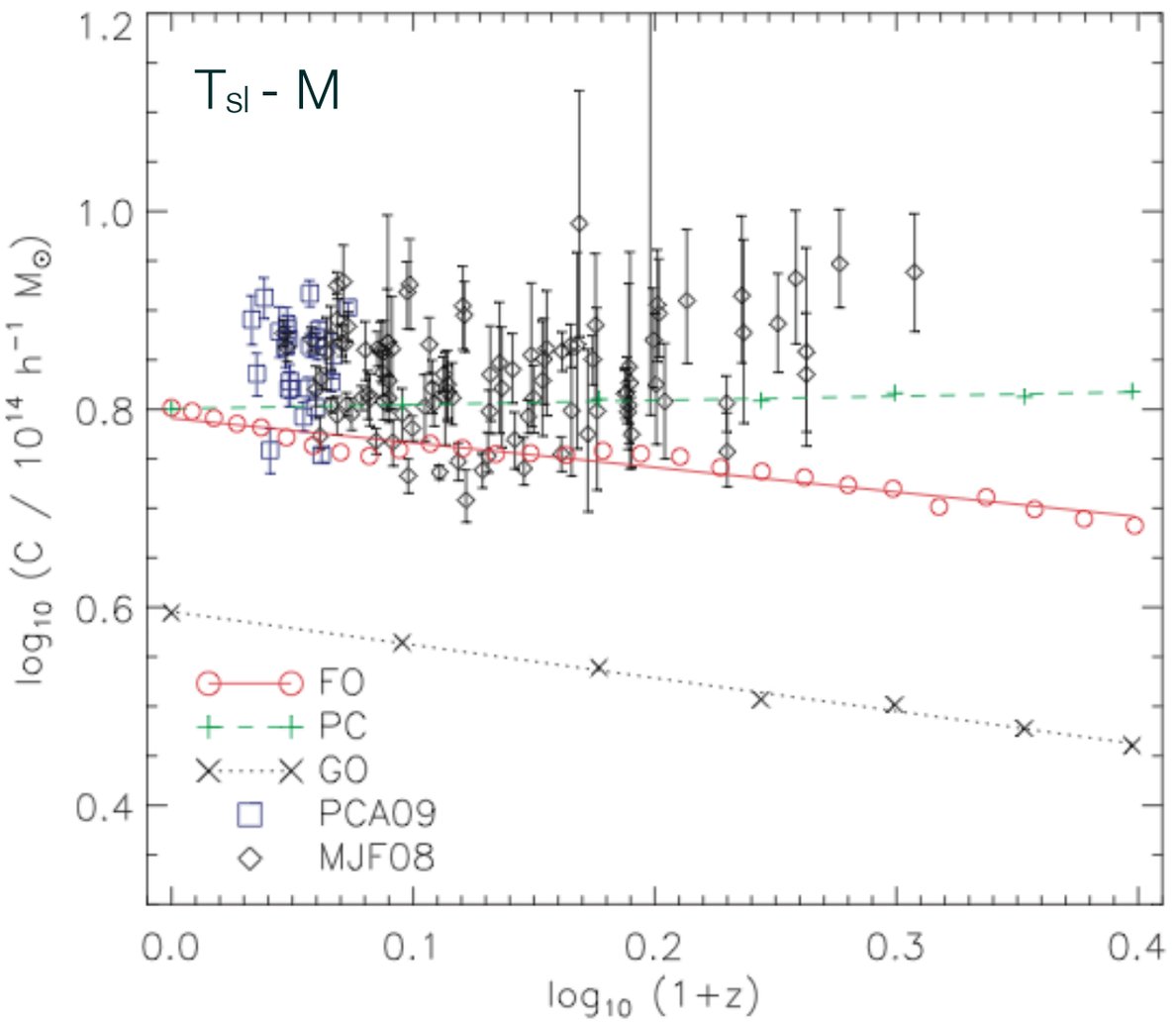
Feedback

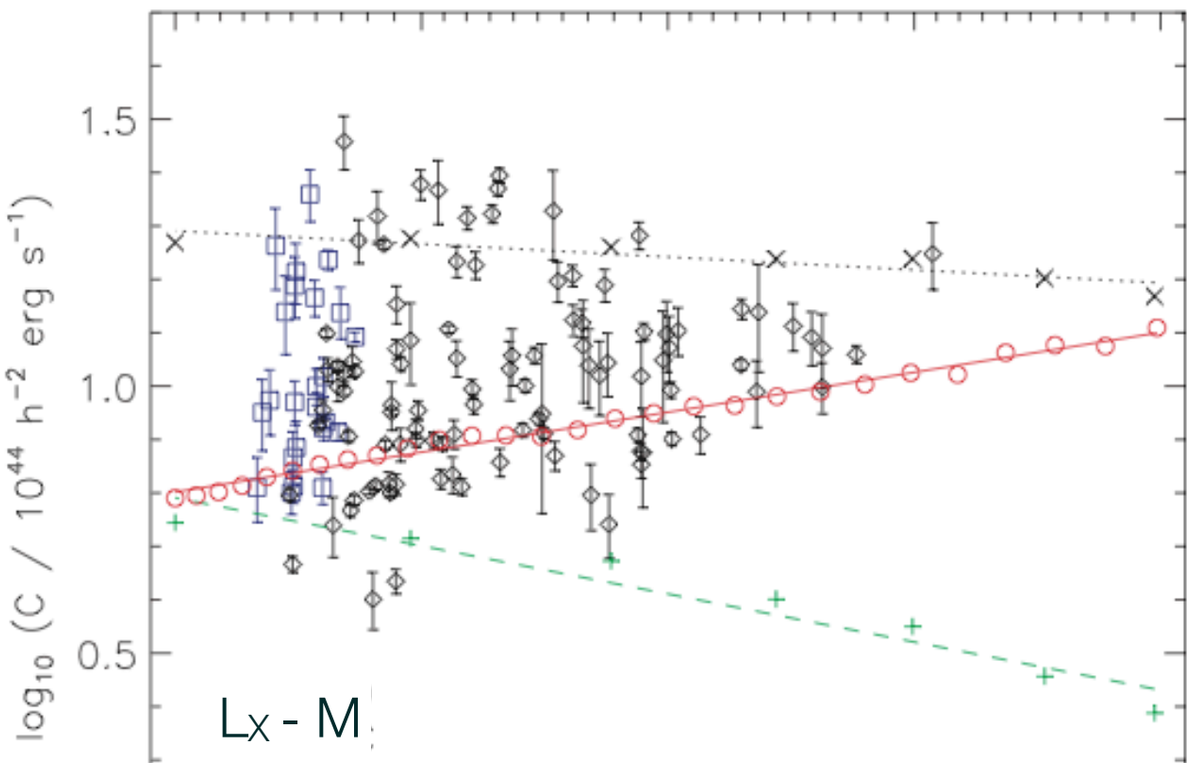


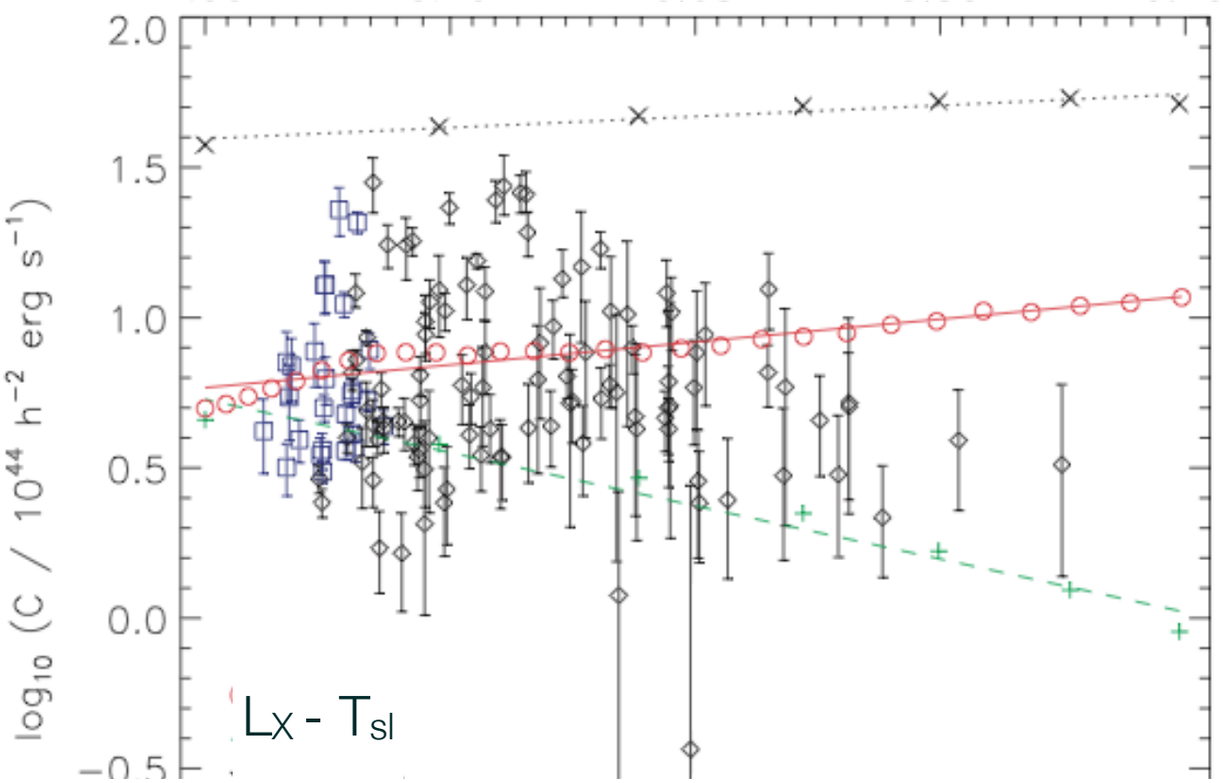
Preheating




Y_X - M
1.0
0.8
0.6
0.4
$\log_{10}$ (C / 10^{14} $M_\odot$ keV)
FO
PC
GO
PCA09
MJF08
0.0
0.1
0.2
0.3
0.4
$\log_{10}$ (1+z)


T_{sl} - M
1.2
1.0
0.8
0.6
0.4
$\log_{10}$ (C / 10^{14} h^{-1} $M_\odot$)
FO
PC
GO
PCA09
MJF08
0.0
0.1
0.2
0.3
0.4
$\log_{10}$ (1+z)


1.5
1.0
0.5
$\log_{10}$ (C / 10^{44} h^{-2} erg s^{-1})
L_X - M

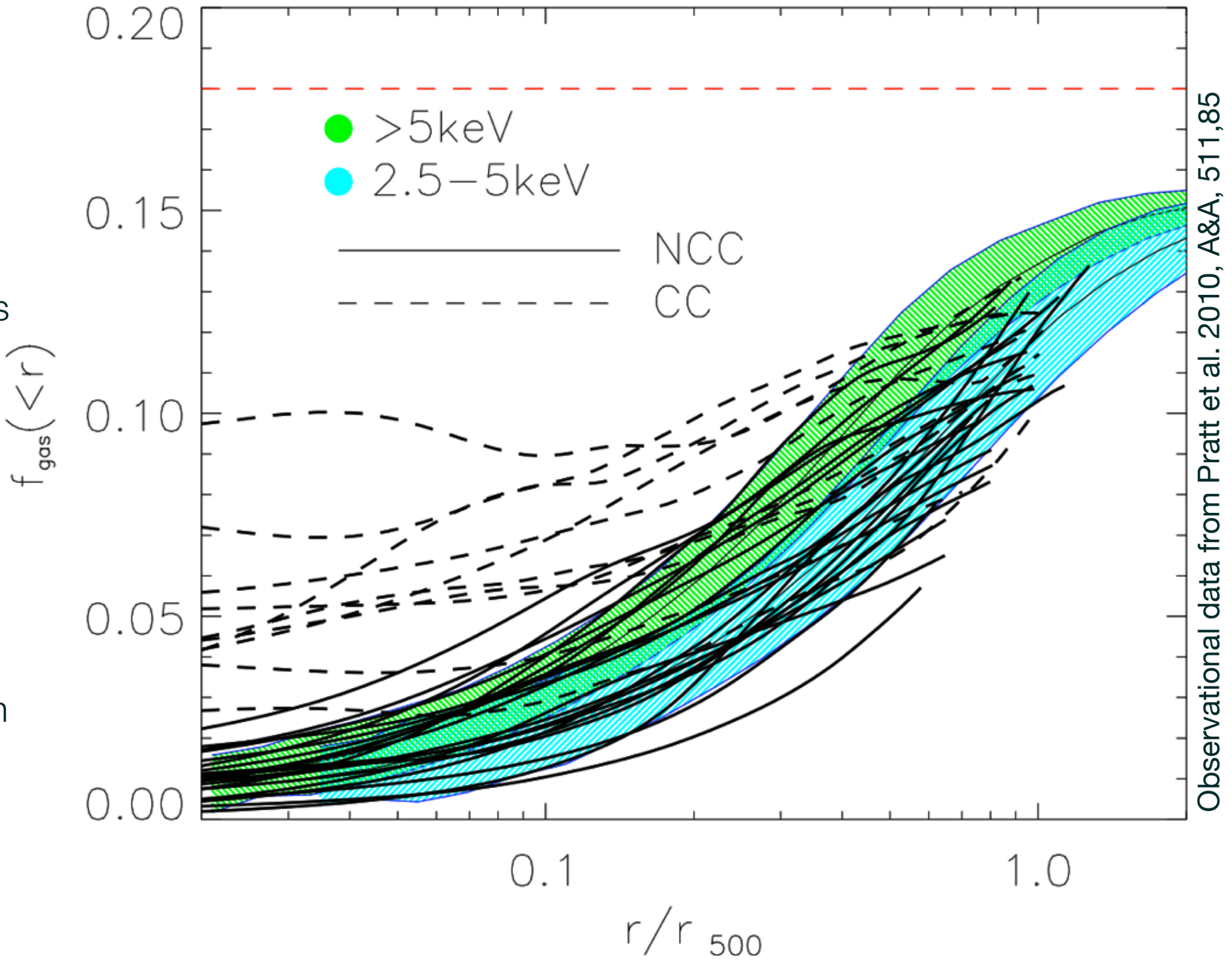

2.0
1.5
1.0
0.5
0.0
$\log_{10}$ (C / 10^{44} h^{-2} erg s^{-1})
L_X - T_{sl}

Evolution of the baryon fraction - ruling out preheating

Owain Young, Peter Thomas, Chris Short, Frazer Pearce, 2011, MNRAS, 413, 691

We resimulate clusters from the Millennium simulation using a variety of physical models for entropy generation.

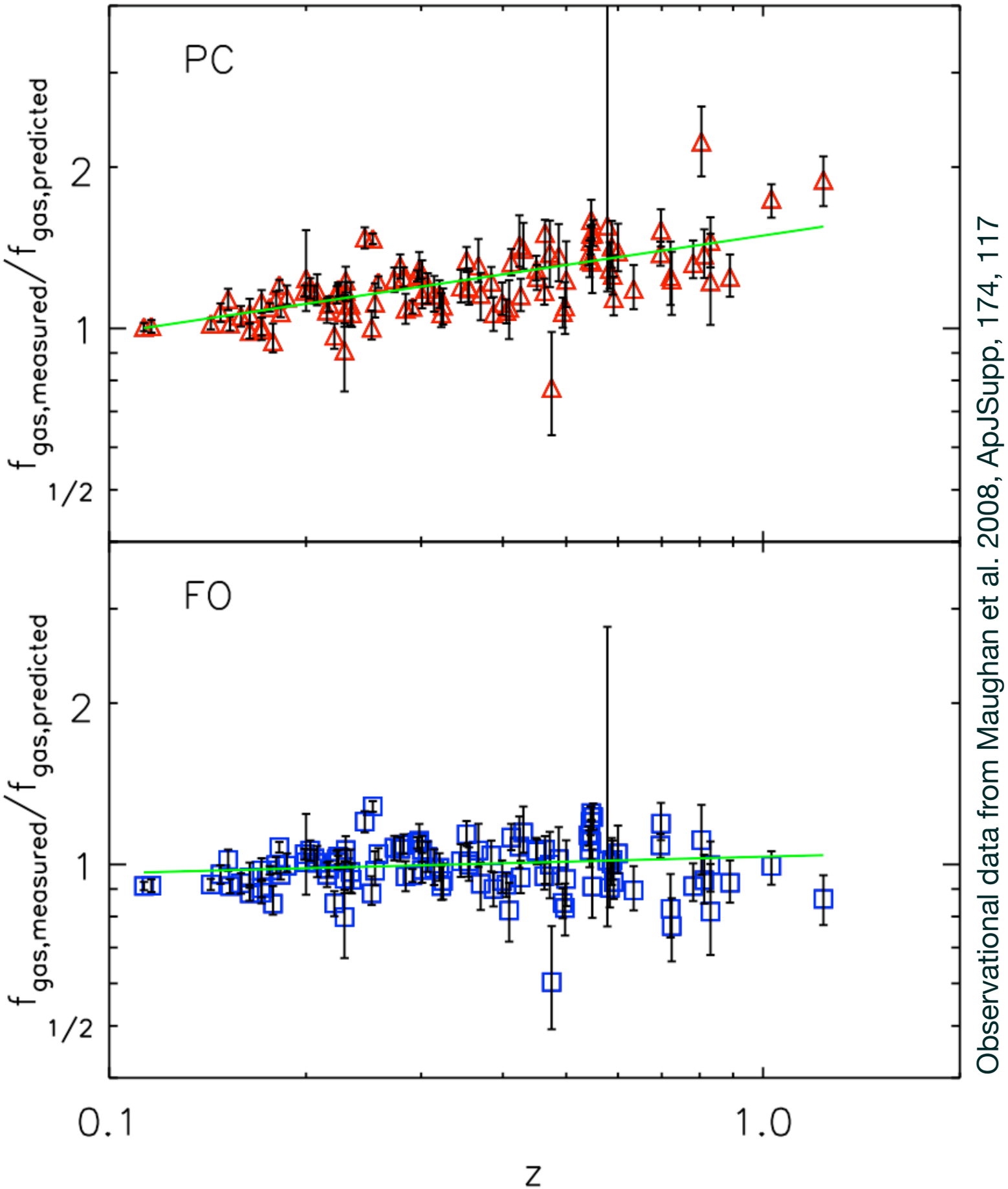
Both preheating and feedback models match the gas fraction profiles of non-cool-core (NCC) clusters.



This figure shows the ratio of the observed to predicted gas fractions within r_{500}.

The feedback (FO) model is consistent with a constant value of unity. However, this is ruled out for the preheating (PC) model with high significance.

This argues strongly against a preheating model for entropy generation in the intracluster medium.



Entropy

K [keV cm^2]

Observed — CC

Observed — NCC

Old feedback scheme

New feedback scheme

Density

n_e [cm^{-3}]

Temperature

T_{sl} [keV]

r / r_{500}

Metallicity

$Z_{emw,sm}$ [Z_{sun}]

Observational data from Pratt et al. 2010, A&A, 511,85

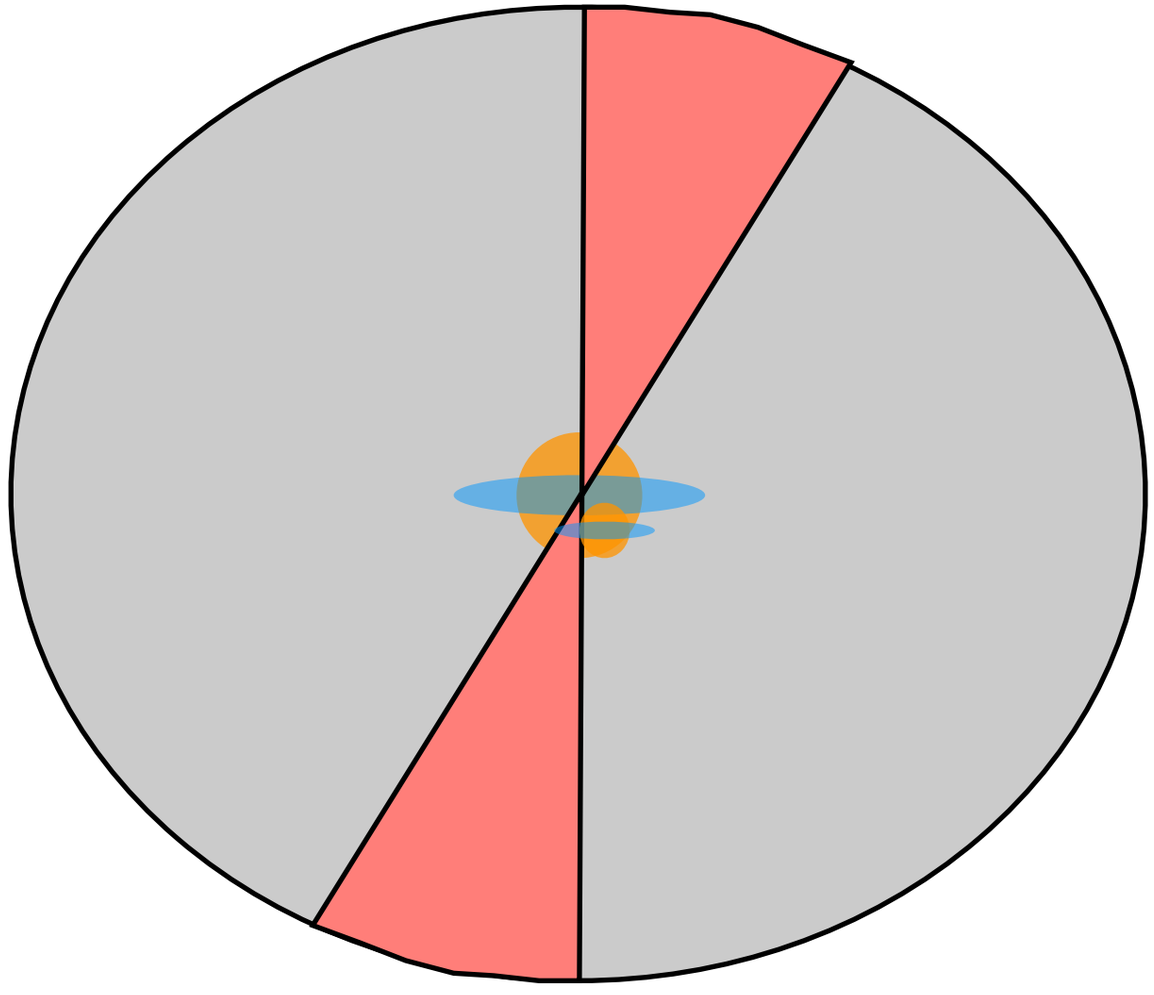
An improved feedback mechanism

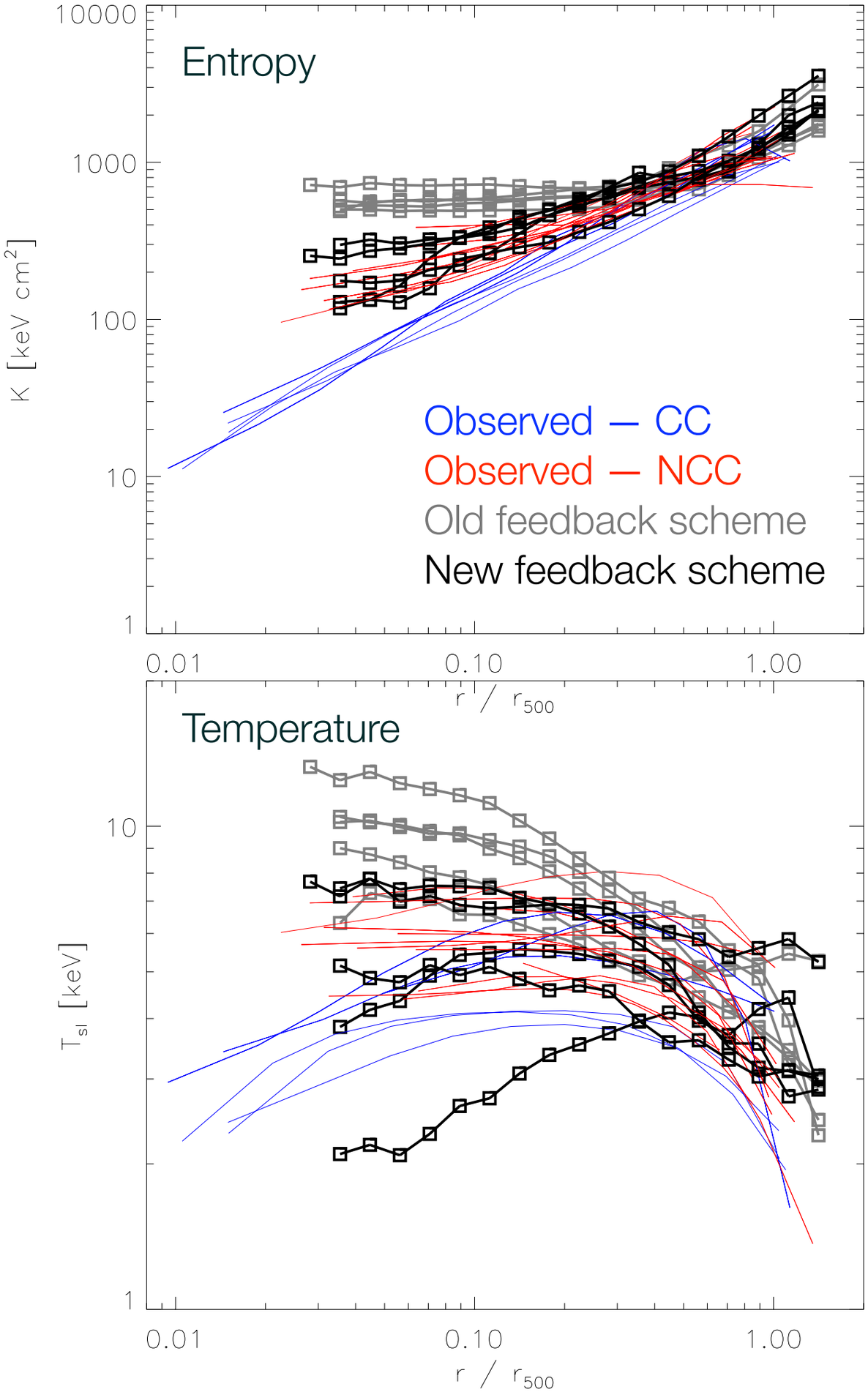
Chris Short, Peter Thomas

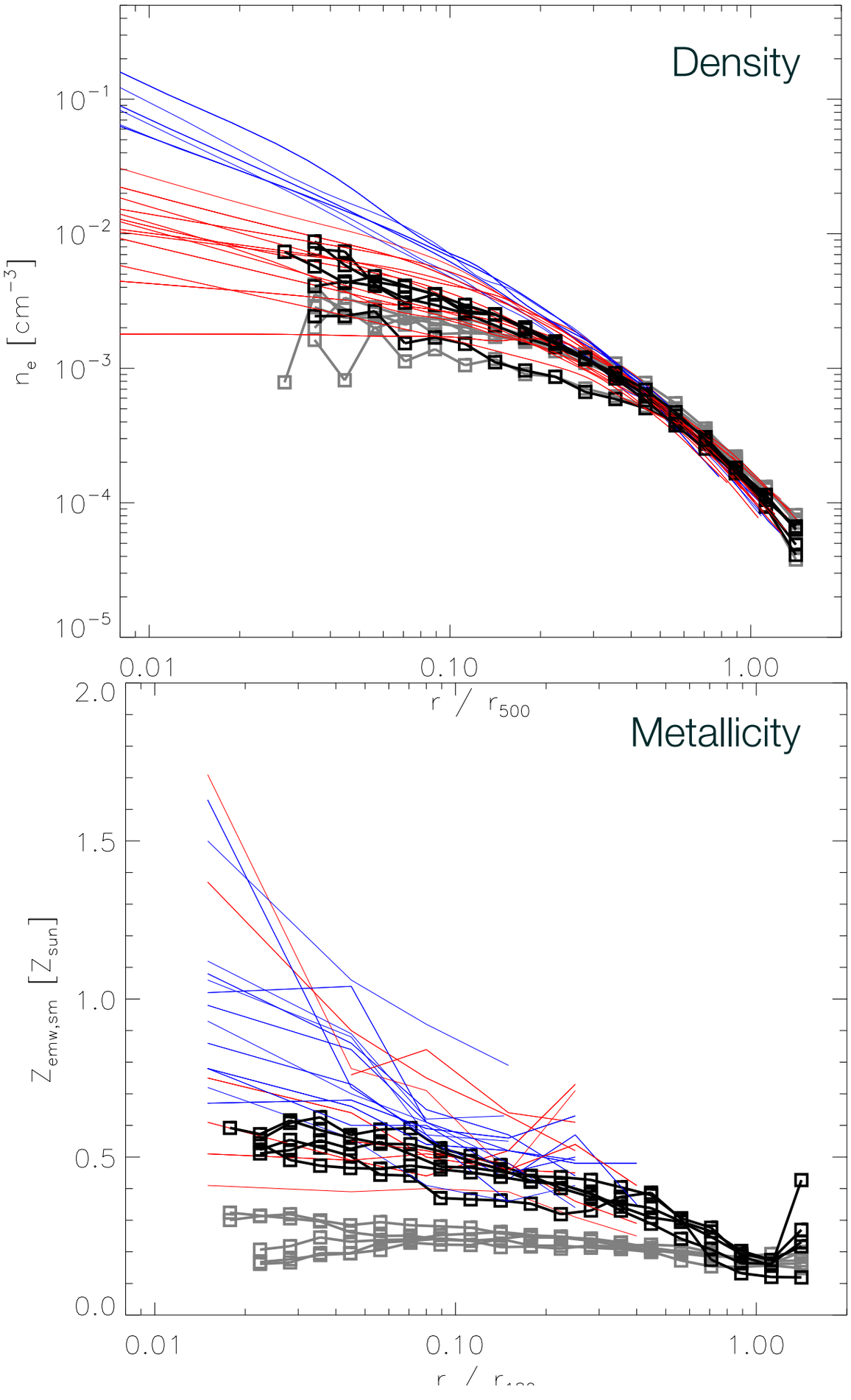
- Heating dominated by AGN.
- Radio jet/bubble affects only a fraction of particles
- Heating occurs with a duty cycle of 10^8 yr

- SNR important for injection of metals
- In clusters most metals are accreted
  — so inject within R_{vir}

- Optimal parameters:
  - Heating efficiency = Bower model
  - Radial extent affected = R_{vir}
  - Heating fraction per duty cycle = 0.01







Observational data from Pratt et al. 2010, A&A, 511,85

Entropy slope

$K(r_{1000}) / K(0.1 r_{200})$

10

1

Observations

New feedback scheme

Entropy normalisation

$K(r_{1000})$ [keV cm^2]

1000

L_X - T_{sl}

$L_{x,bol}$ [10^{44} h^{-2} erg s^{-1}]

10.0

1.0

0.1

10

T_{sl} [keV]

Metallicity slope

$Z(0.25r_{180}) / Z(0.045r_{180})$

1

10

T_{sl} [keV]

Observational data from Pratt et al. 2010, A&A, 511,85

The **new** Millennium Gas Simulation

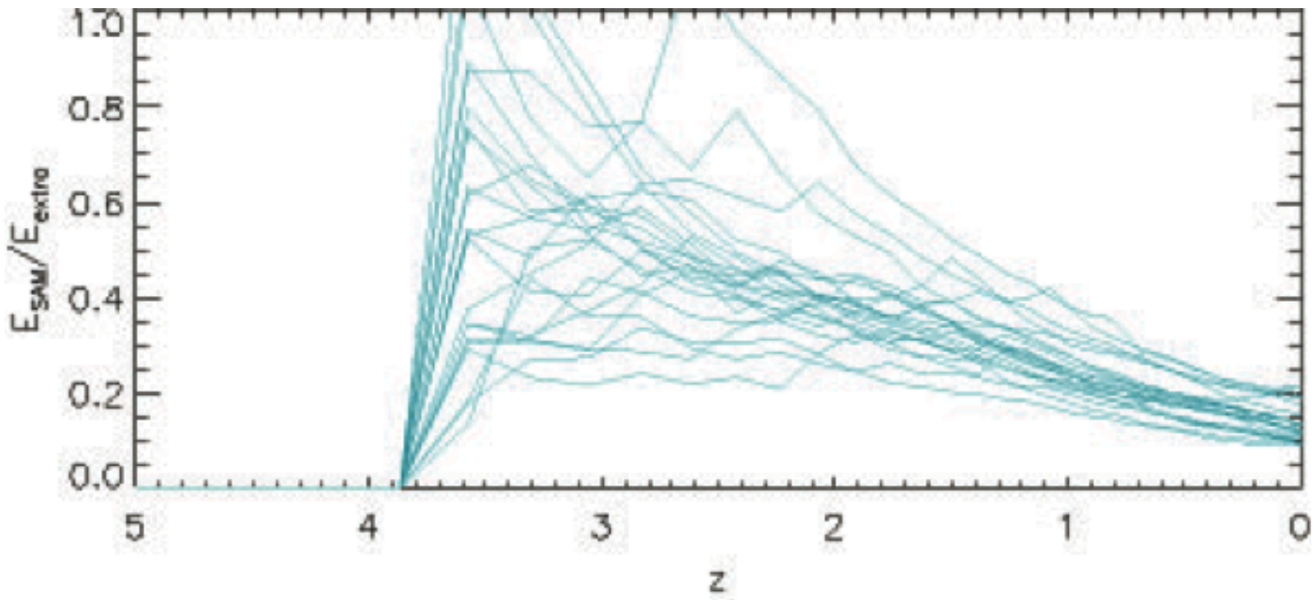
- Simulation details:
  - WMAP-7 cosmology
  - Full Millennium Simulation resolution
  - Guo et al 2011 semi-analytics
  - Improved AGN feedback scheme
  - Metal enrichment from Type II, Type 1a & AGB
  - Without and with radiative cooling

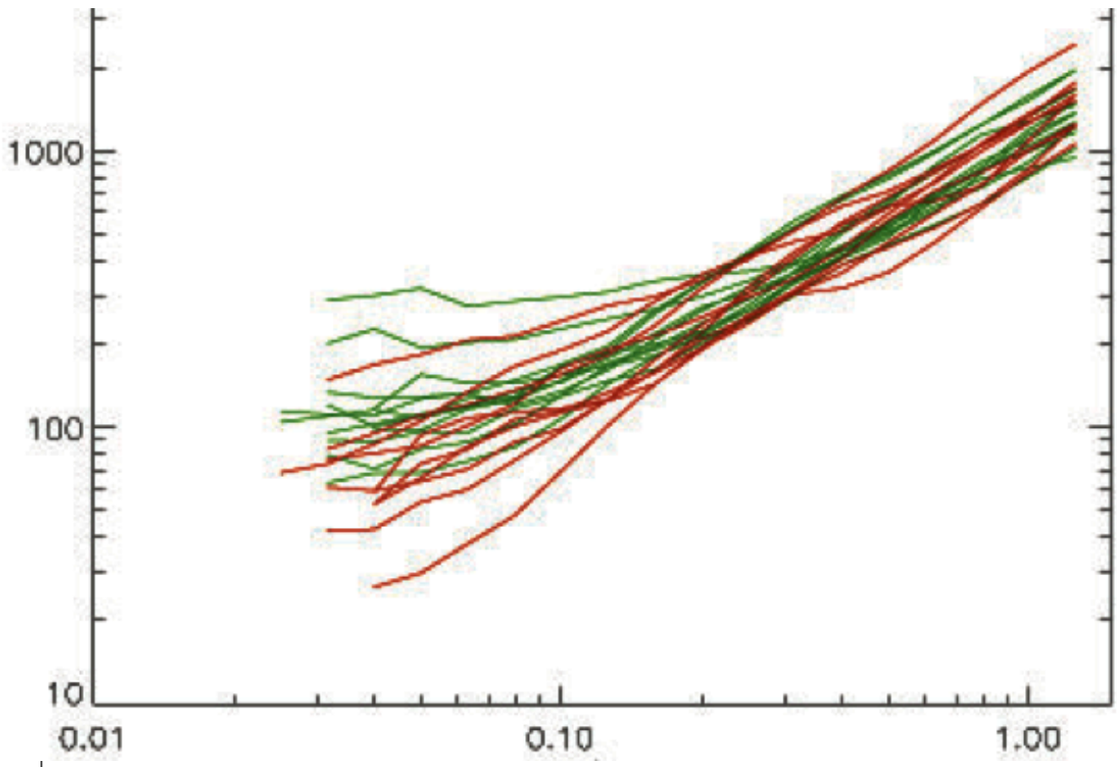
- Status:
  - Testing complete in smaller boxes
  - DM-only simulation complete
  - SA model catalogue constructed
  - Gas simulation started

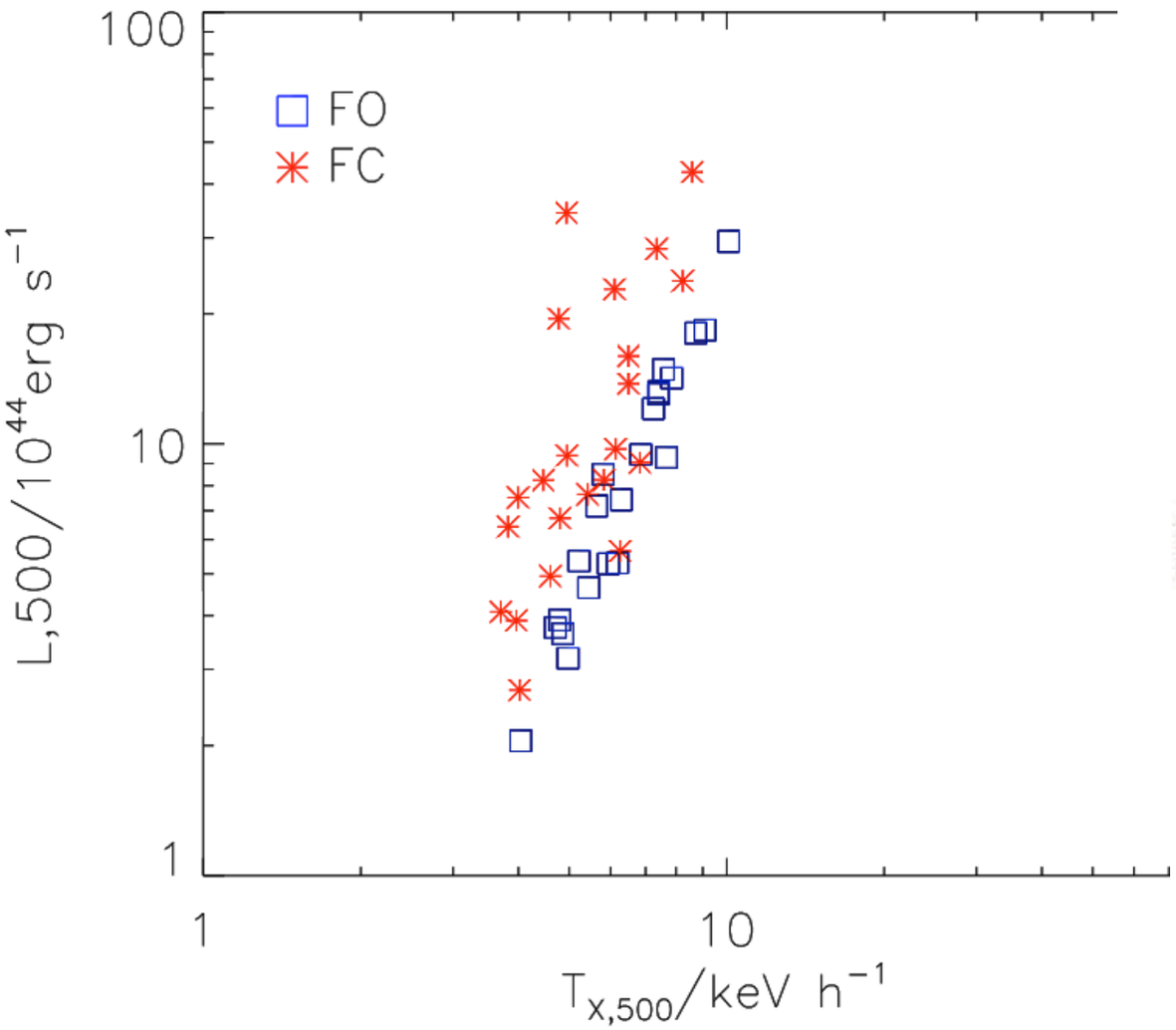
- Data products:
  - SA galaxy catalogue
  - X-ray/SZ cluster catalogues
  - Maps and full datacubes for each cluster

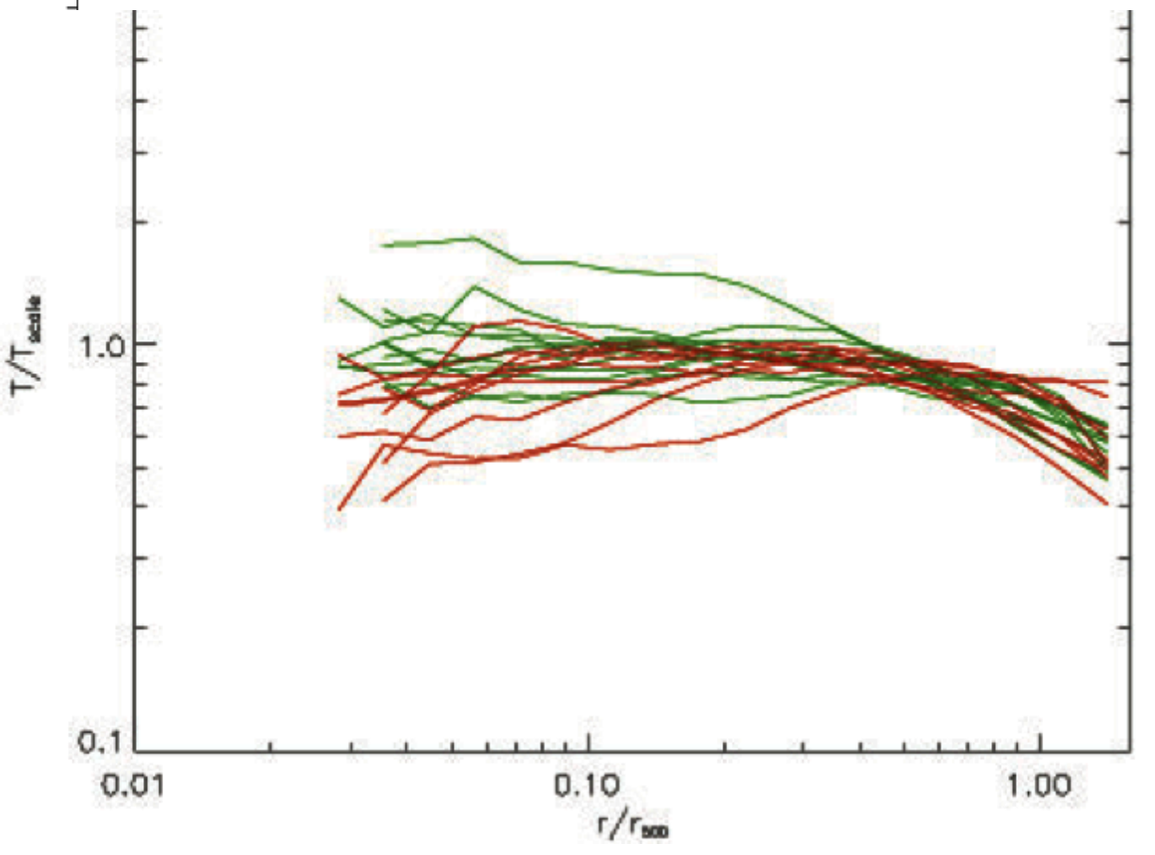
- Science:
  - SZ scaling relations and power spectra
    - ★relative contribution of core/halo/ filaments
    - ★evolution
    - ★radio source contamination
  - X-ray properties of galaxy clusters and groups
    - ★in the WMAP-7 cosmology
    - ★self-consistent stellar population
    - ★entropy profiles that resemble those of NCC clusters
    - ★realistic population of both NCC and CC clusters
  - Metal enrichment of ICM/IGM/WHIM from a self-consistent stellar population and feedback model
  - Holistic models for clusters extending to high redshift: X-ray, optical, SZ, radio

Simulating cool-core systems Owain Young









Conclusions

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- We have created merger trees and SA galaxy catalogues using the Guo 2011 version of L-Galaxies (contact me if you want to use them)
- We use the SA galaxies as input to a hydrodynamical simulation:
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