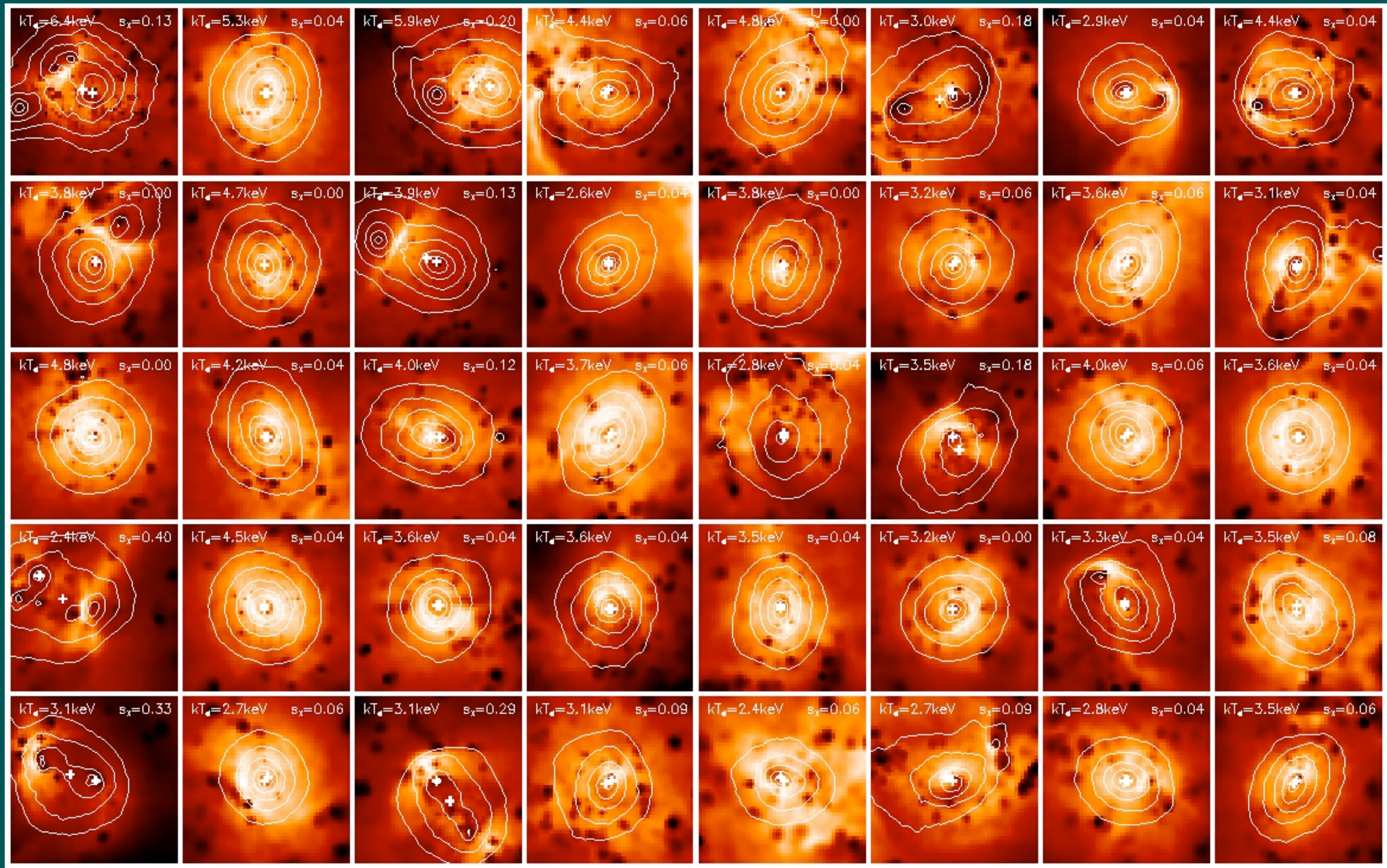
The formation and evolution of clusters

University of Sussex

Peter Thomas
University of Sussex

Part 1: Simulated cluster catalogues



Evolution of cluster scaling relations

University of Sussex

with

Scott Kay

Joy Muanwong

David Rowley

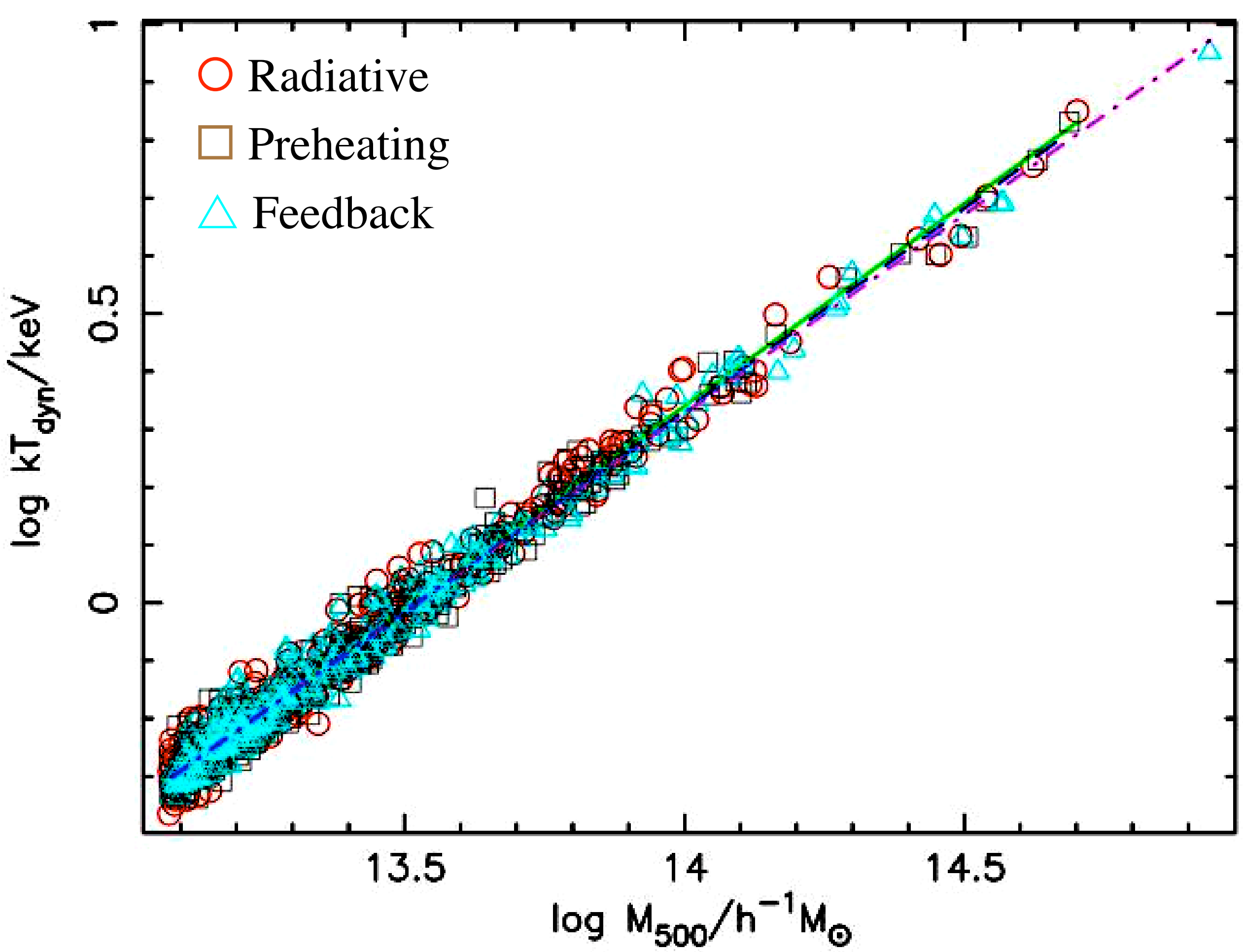
Evolution of cluster scaling relations

University of Sussex

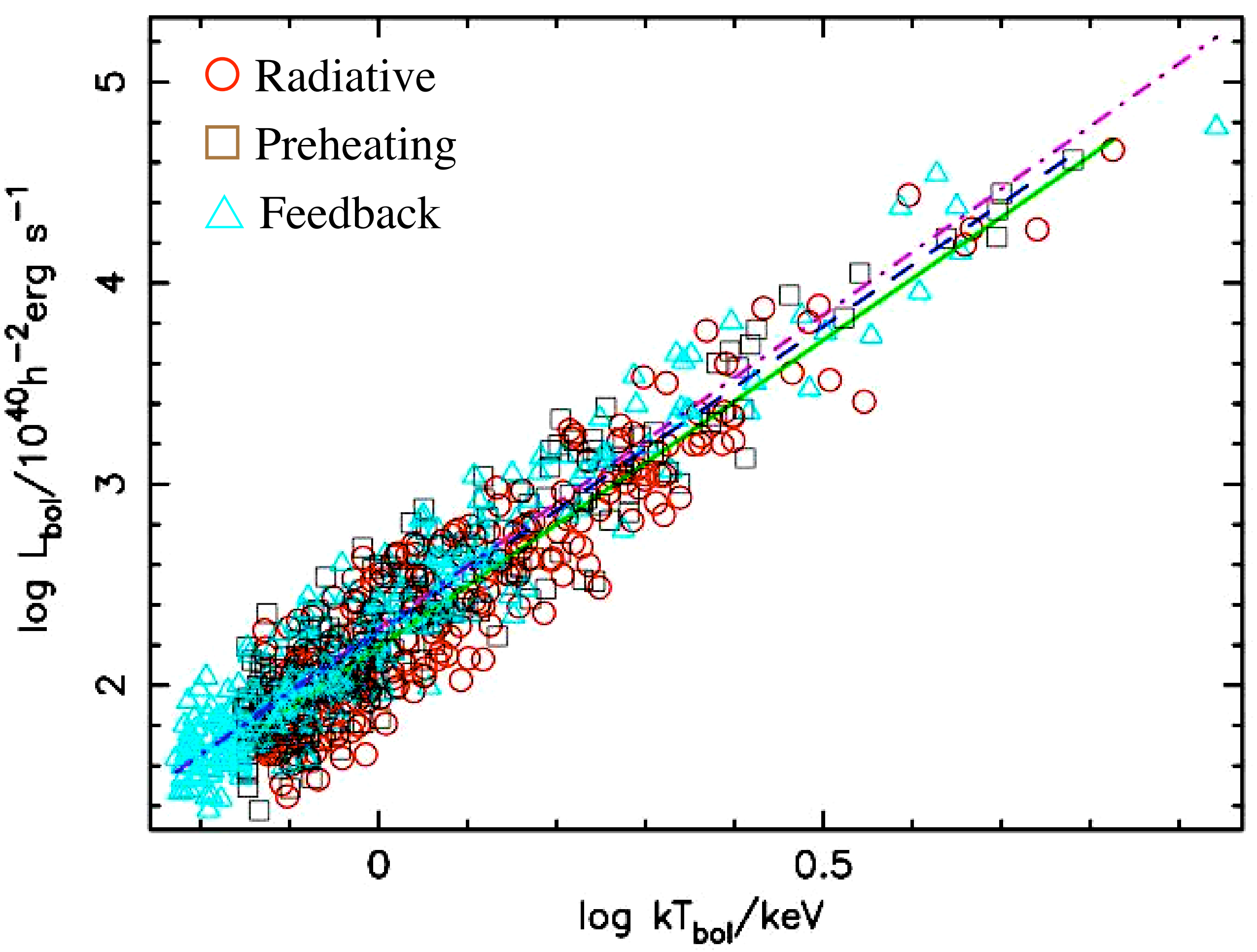
- Three different physical models:
  - Radiative (no additional physics)
  - Preheating (1.5 keV/particle at z=4)
  - Feedback (10% probability of raising entropy of cooled gas by 1000 keV cm^{2})

- $N_{DM} = N_{gas} = 160^3$–256^3
- L = 100–120 h^{-1}Mpc
- ΛCDM, σ_8=0.9
- $M_{DM} = 0.7$–$2.1 \times 10^{10} h^{-1} M_{\odot}$, $M_{gas} = 1.3$–$2.6 \times 10^{9}\, h^{-1} M_{\odot}$

Temperature - mass, z=0



Luminosity - temperature, z=0



Scaling relations

University of Sussex

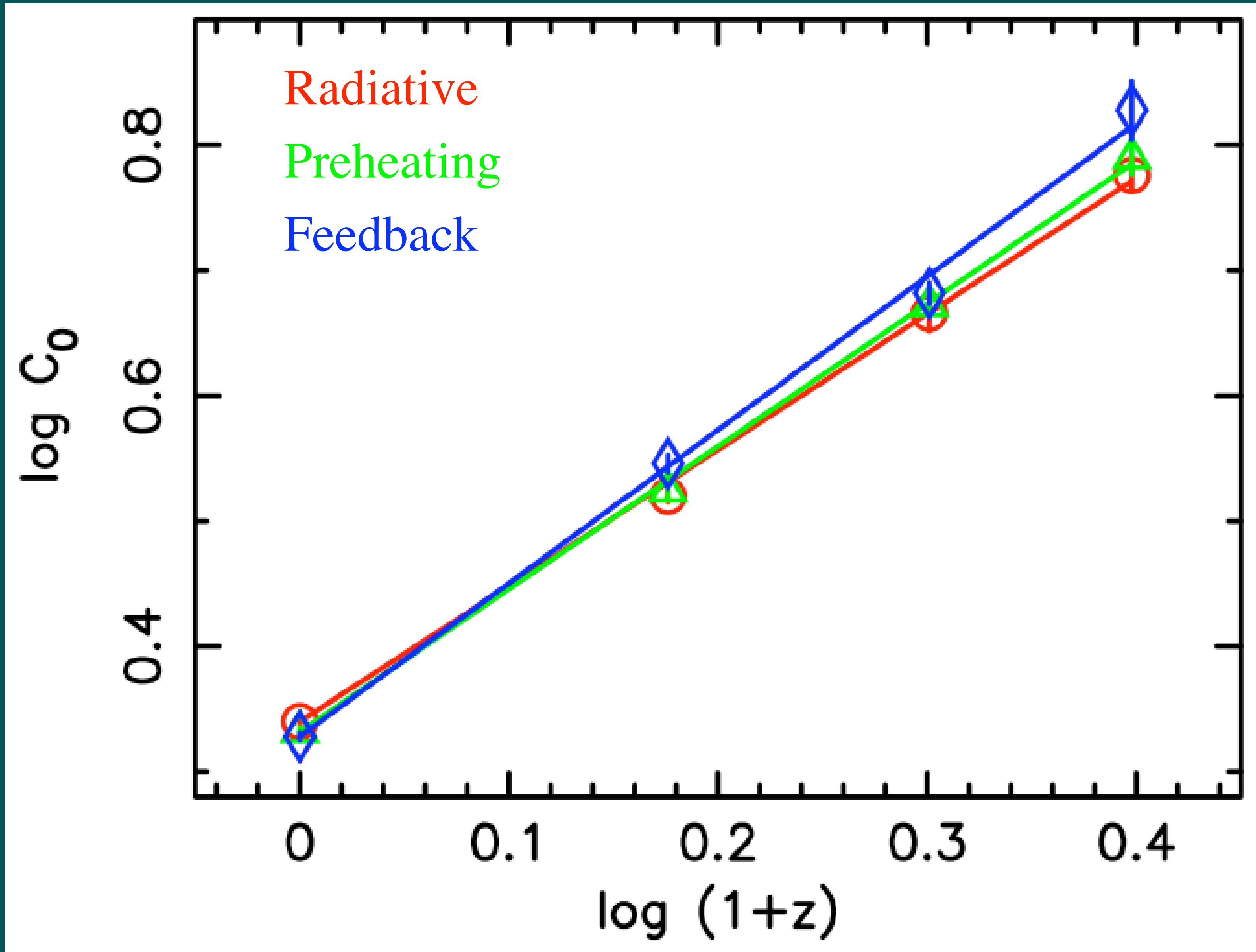
$$\log T = \log(1+z) + \frac{2}{3}\log M$$

$$\log L = \frac{7}{2}\log(1+z) + \frac{4}{3}\log M$$

$$\log L = \frac{3}{2}\log(1+z) + 2\log T$$

$$\log L_{\mathrm{bol}} = A\log(1+z) + \alpha\log T_{\mathrm{bol}}$$

T_{dyn}-M_{500} evolution



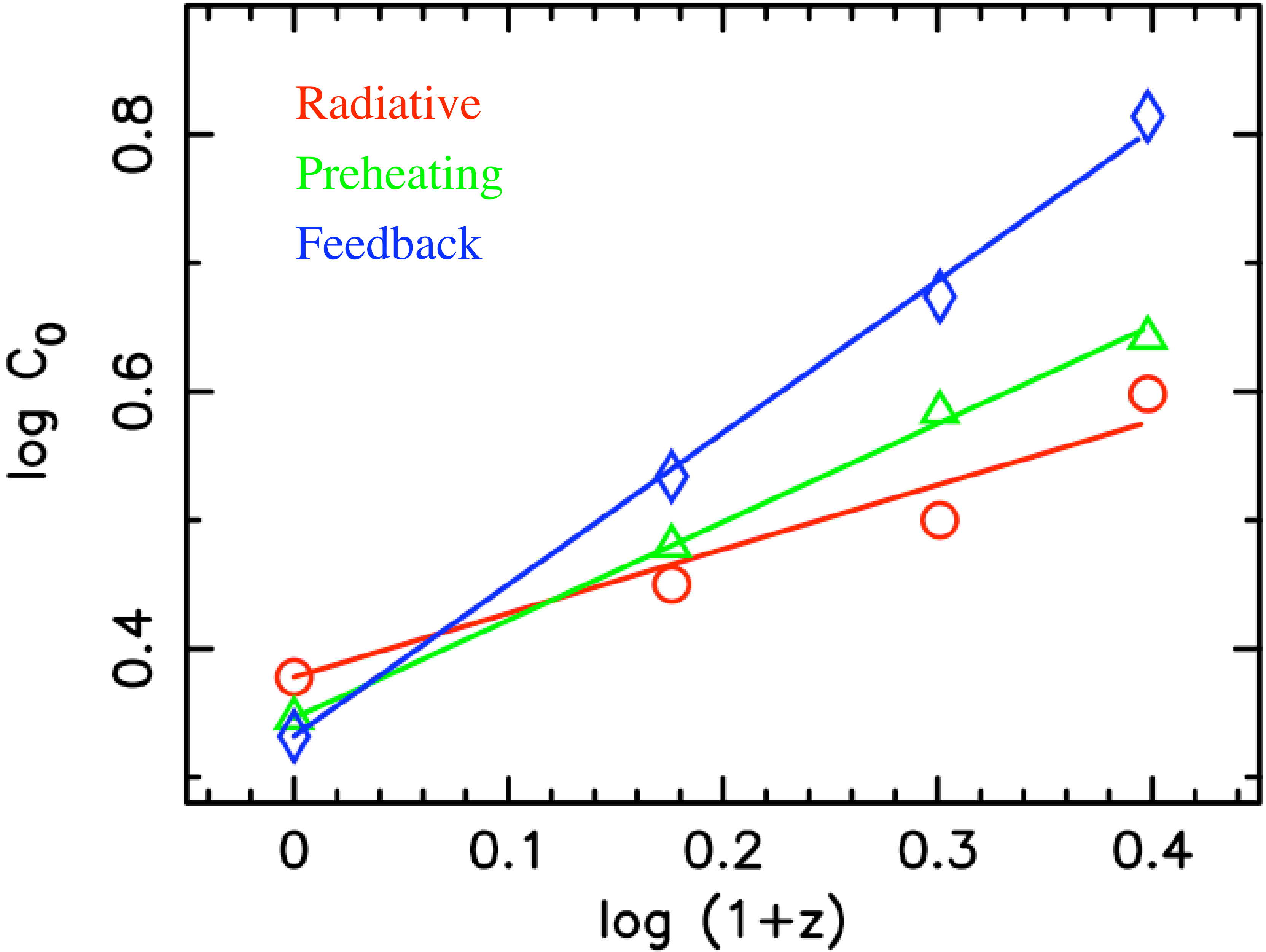
Evolution parameters
T_{dyn}-M_{500}

University of Sussex

$$\log T_{\mathrm{dyn}} = A \log(1+z) + \alpha \log M_{500}$$

Model	A	α
Radiative	1.1	0.70
Preheating	1.1	0.70
Feedback	1.2	0.69

T_X-M_{500} evolution

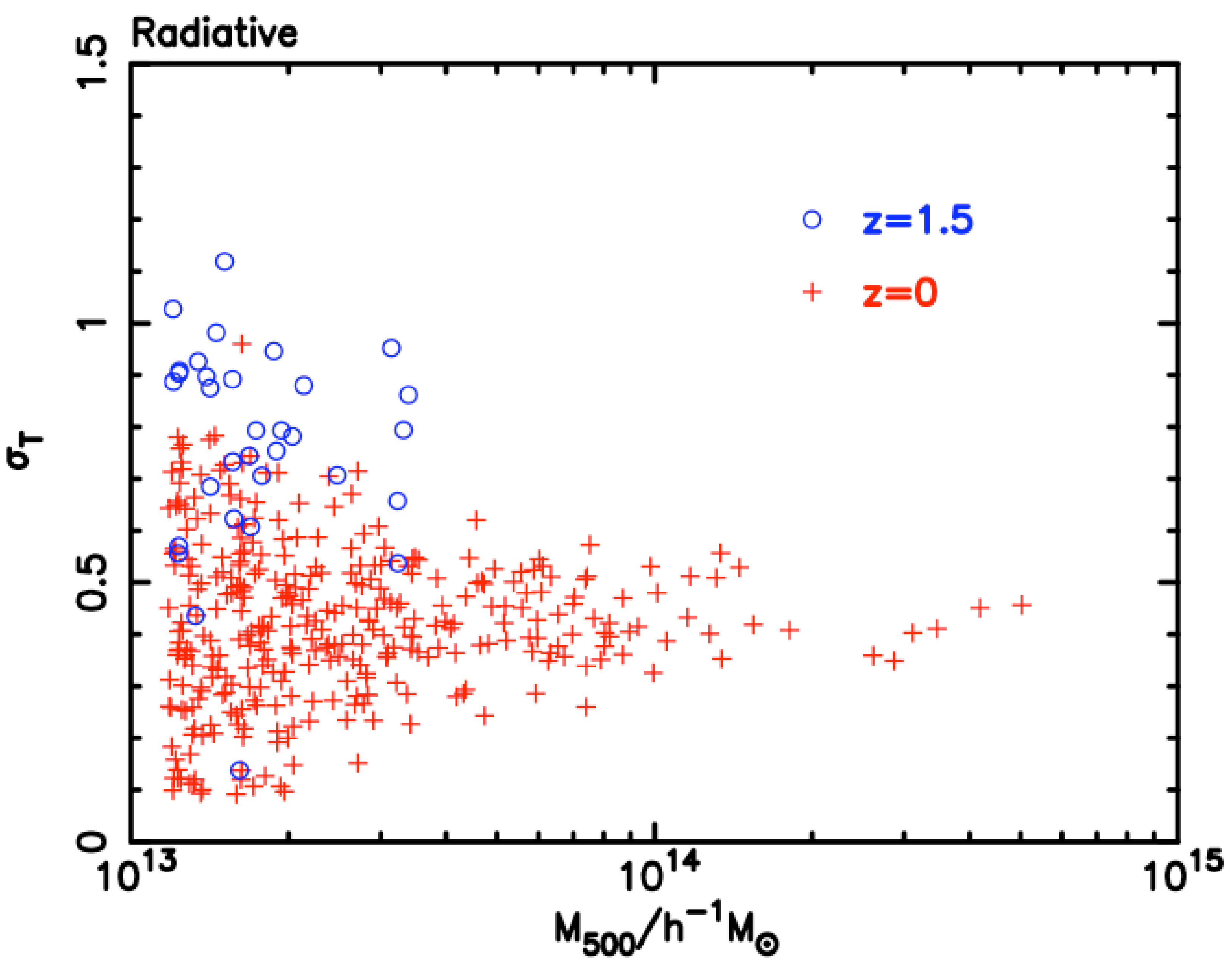


Evolution parameters
T_X-M_{500}

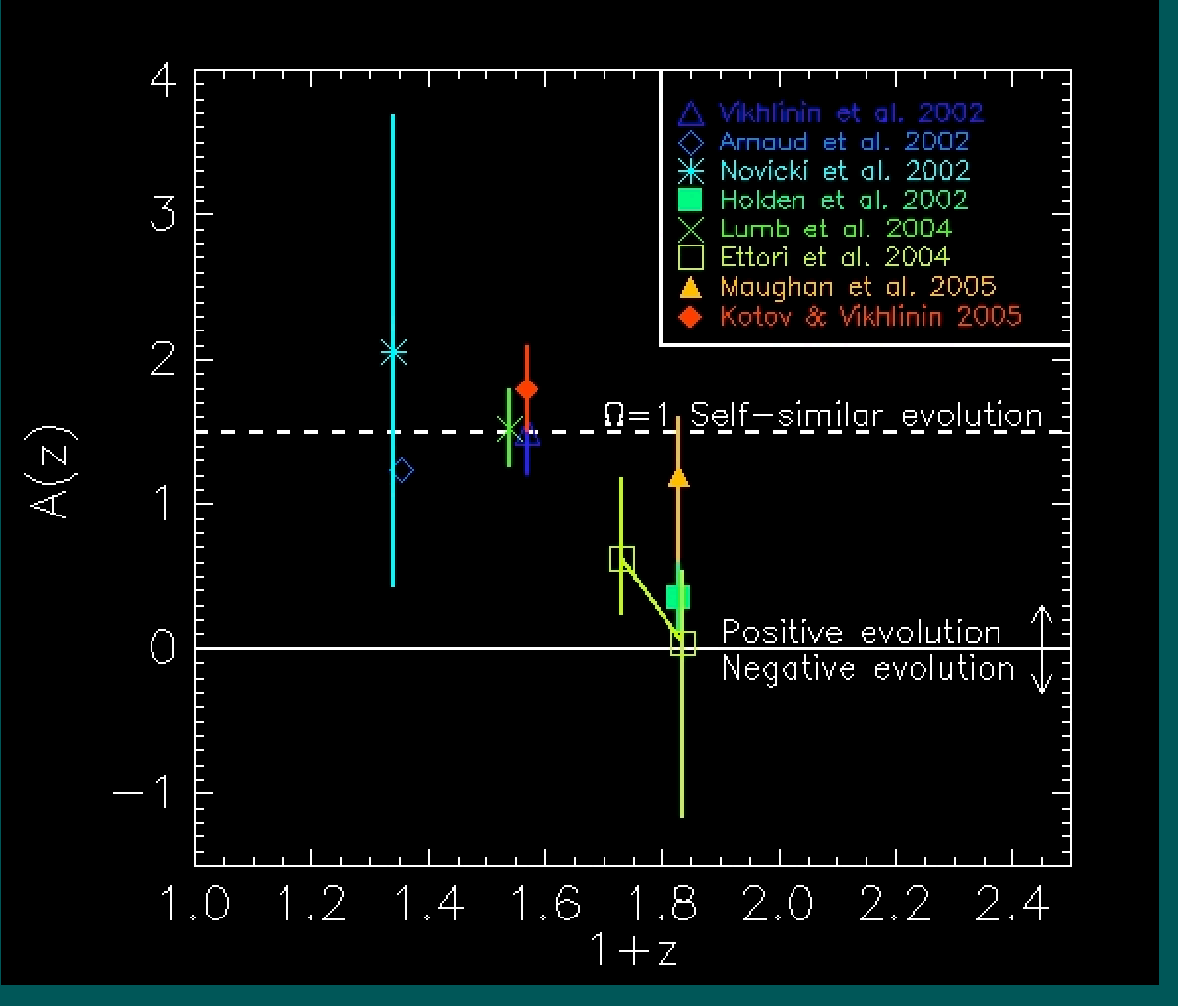
$$\log T_X = A \log(1+z) + \alpha \log M_{500}$$

Model	A	α
Radiative	0.5	0.59
Preheating	0.8	0.61
Feedback	1.2	0.64

Evolution of temperature substructure

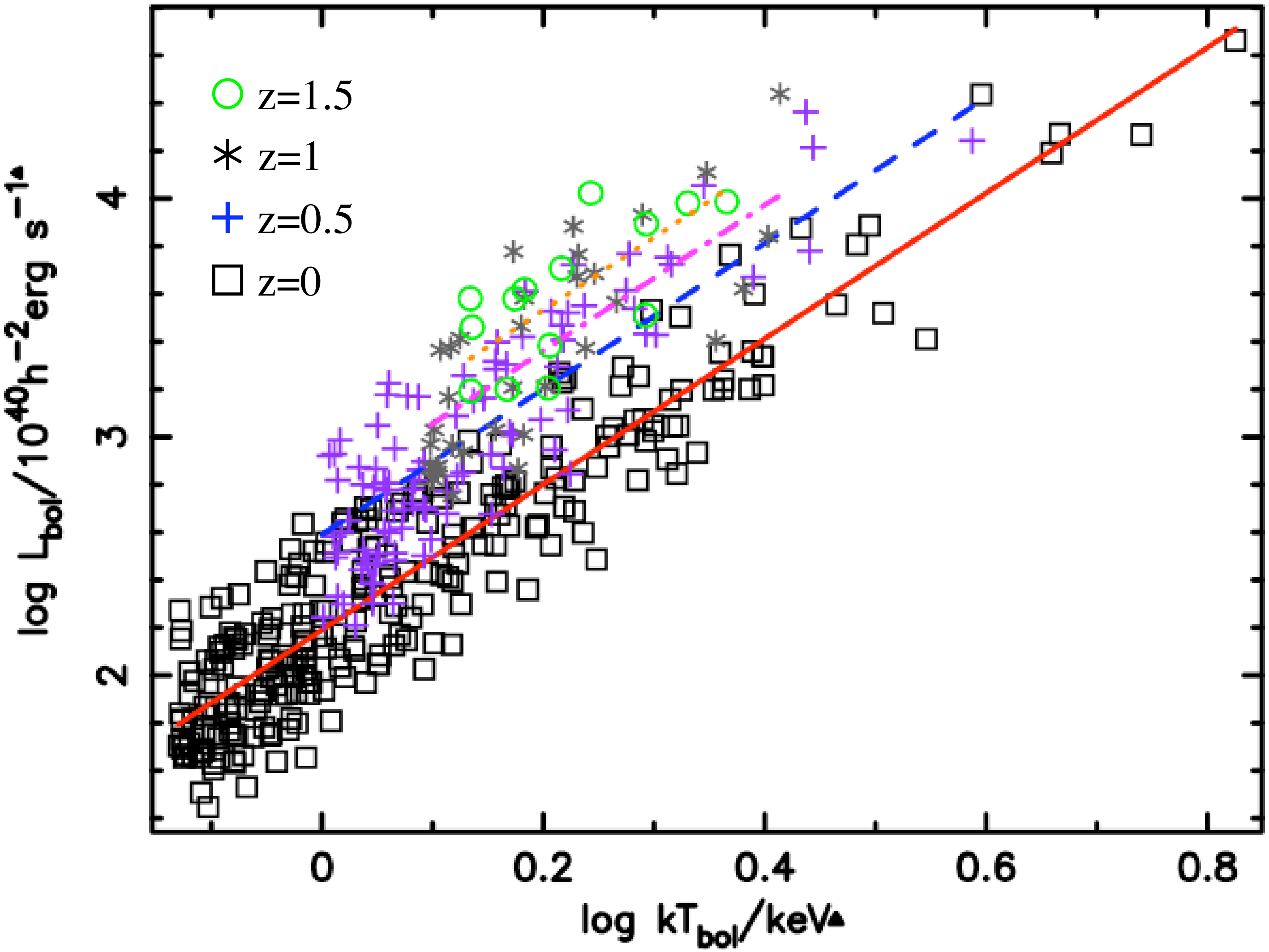


Observed L-T evolution



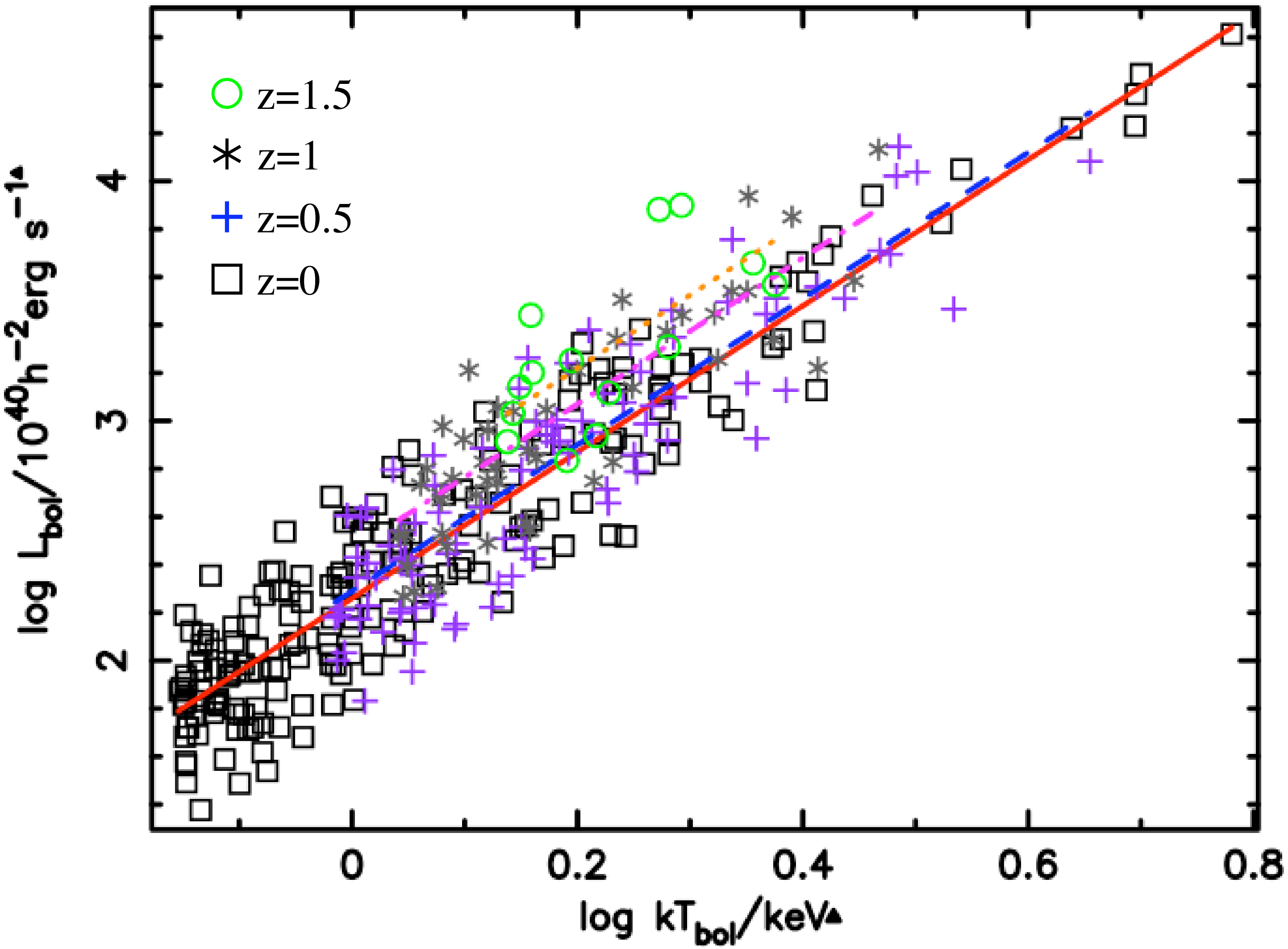
Luminosity - temperature evolution

Radiative



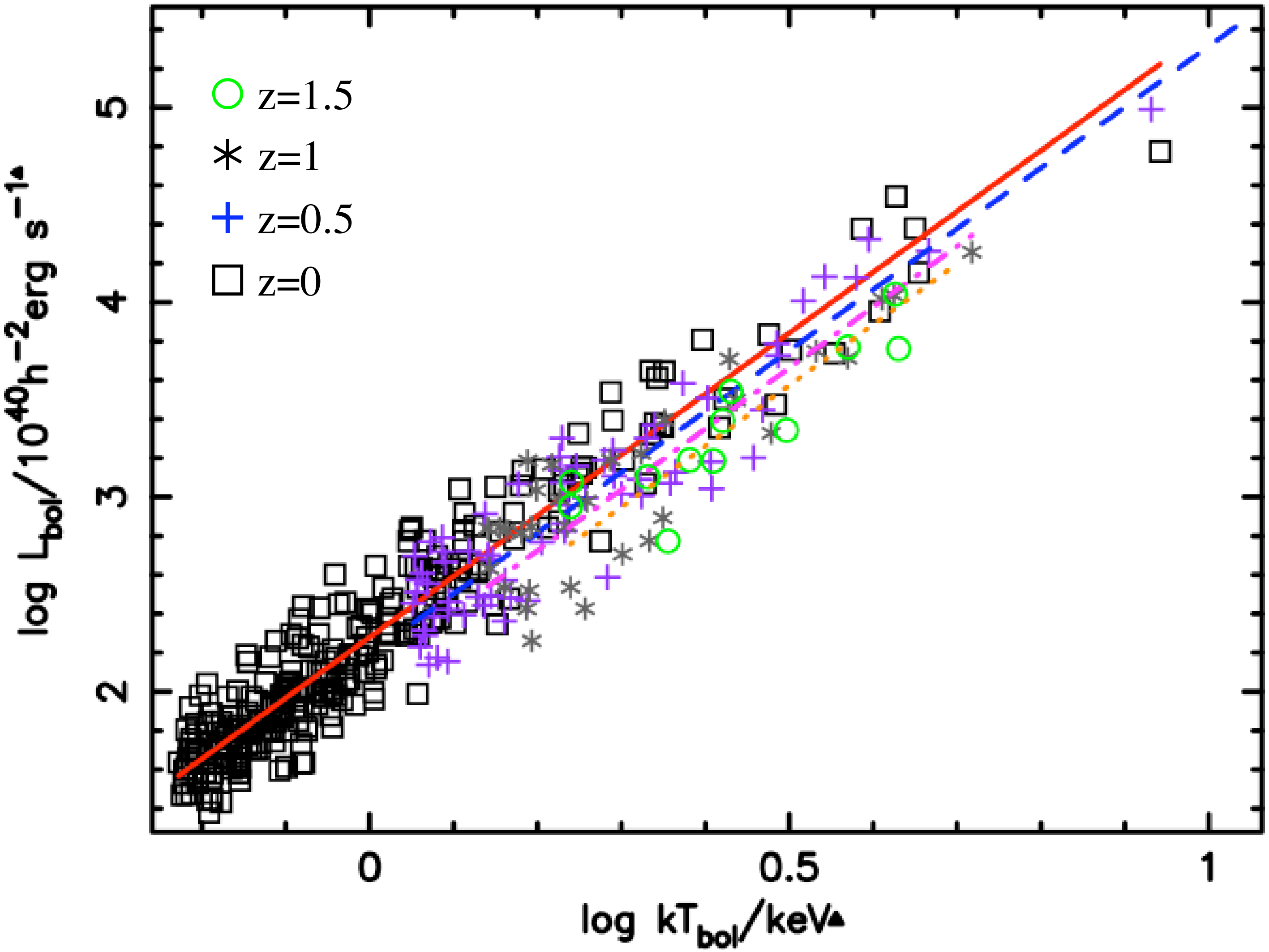
Luminosity - temperature evolution

Preheating

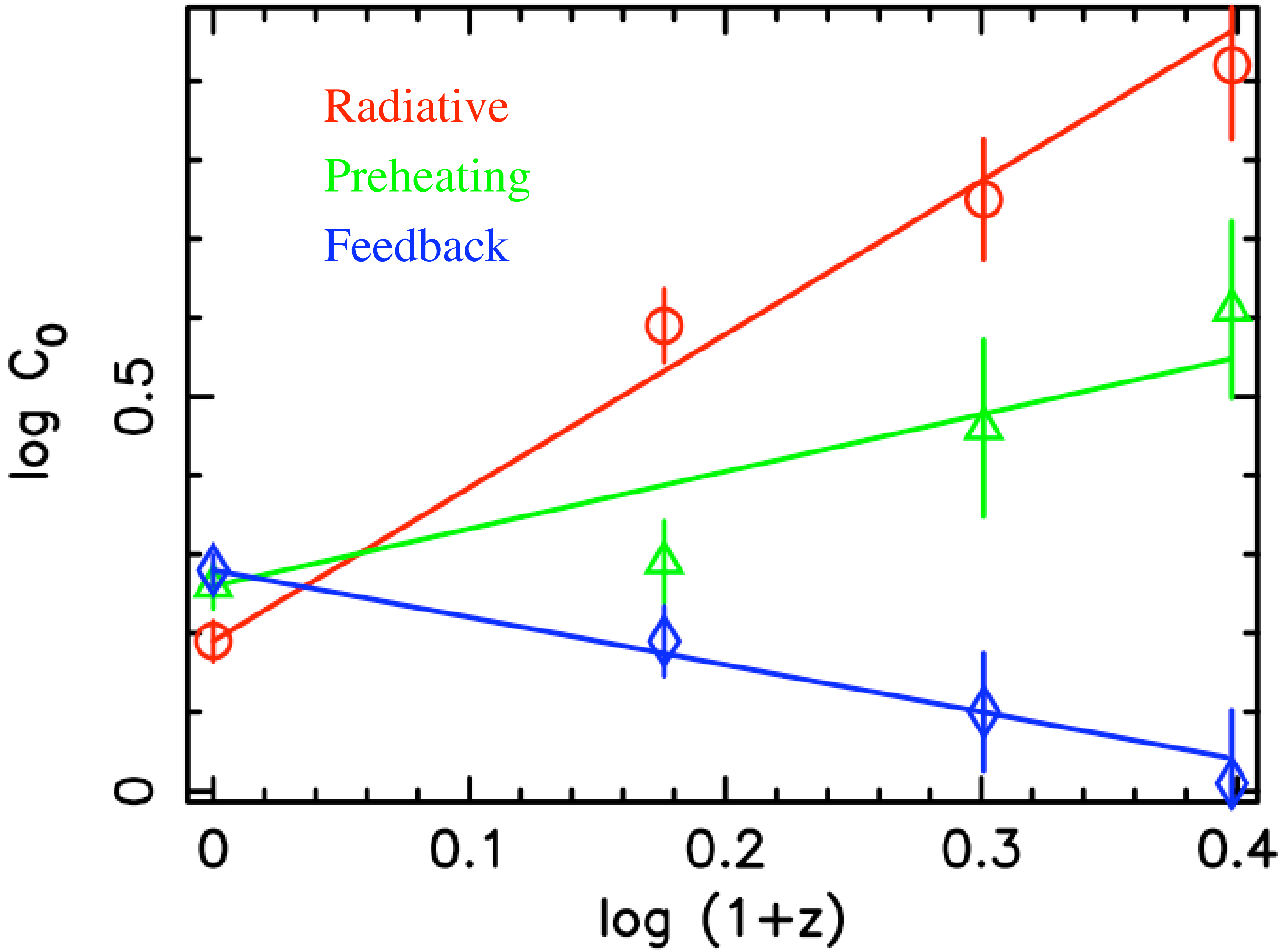


Luminosity - temperature evolution

Feedback



L_X-T_X evolution



Evolution parameters

University of Sussex

$$\log L_{\rm bol} = A \log(1+z) + \alpha \log T_{\rm bol}$$

Model	**A**	**α**
Radiative	1.9	3.06
Preheating	0.7	3.05
Feedback	-0.6	3.13

Conclusions 1

University of Sussex

Different physical models can have very different evolution properties for cluster scaling relations.

Feedback models (targeted entropy injection) show less evolution than preheating models (distributed entropy injection).

The observational picture is still uncertain but seems to favour preheating models.
Caveat: we have to measure temperatures properly.

SZ scaling relations

University of Sussex

with

Scott Kay

Andrew Liddle

Antonio da Silva

SZ Scaling relations

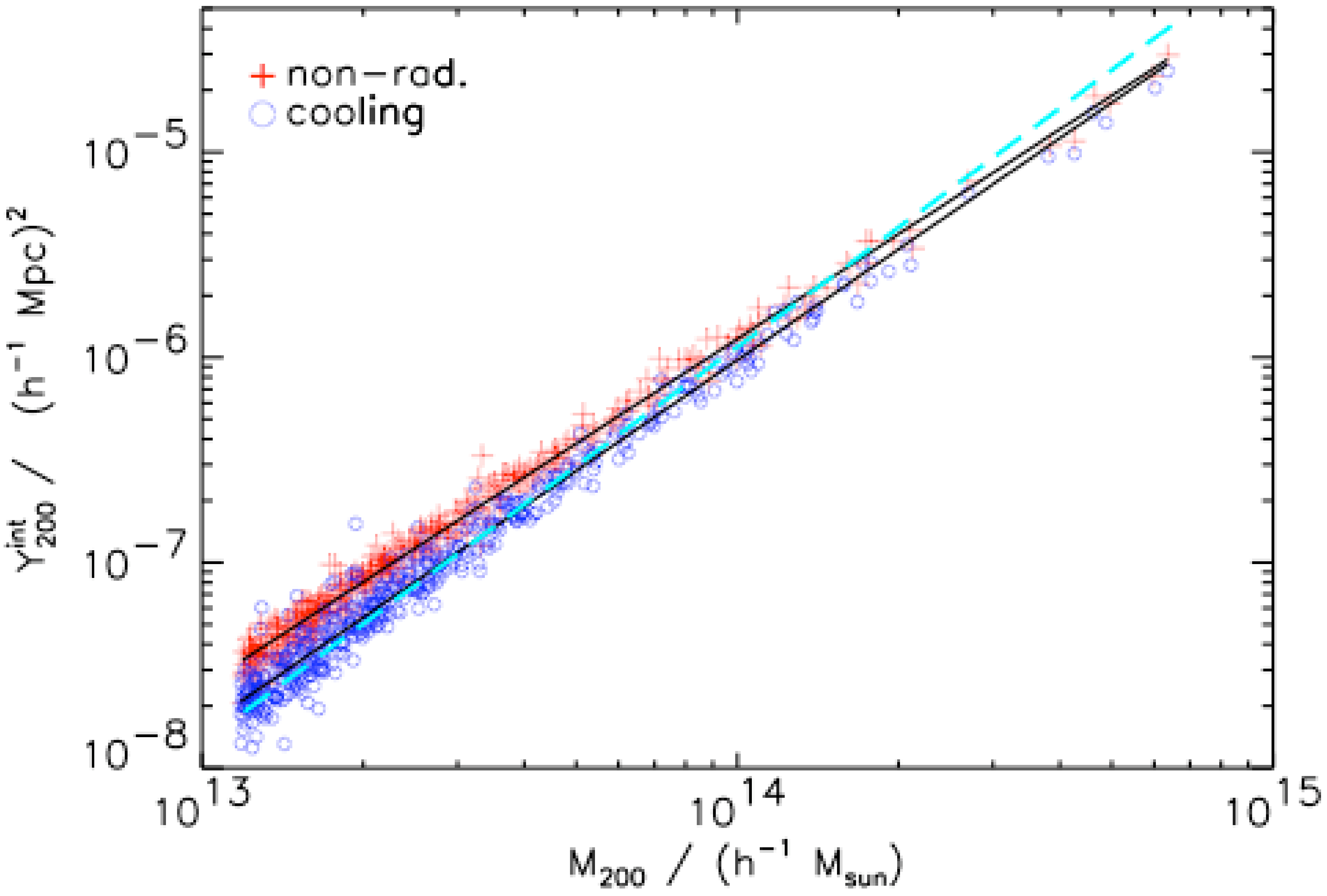
$$Y_{\text{int}} = Y d_A^2 = \frac{k_B \sigma_T}{m_e c^2} \int n_e T_e \, \mathrm{d}V$$

$$\log Y_{\text{int}} = \log(1+z) + \frac{5}{3} \log M$$

$$\log Y_{\text{int}} = -\frac{3}{2} \log(1+z) + \frac{5}{2} \log T$$

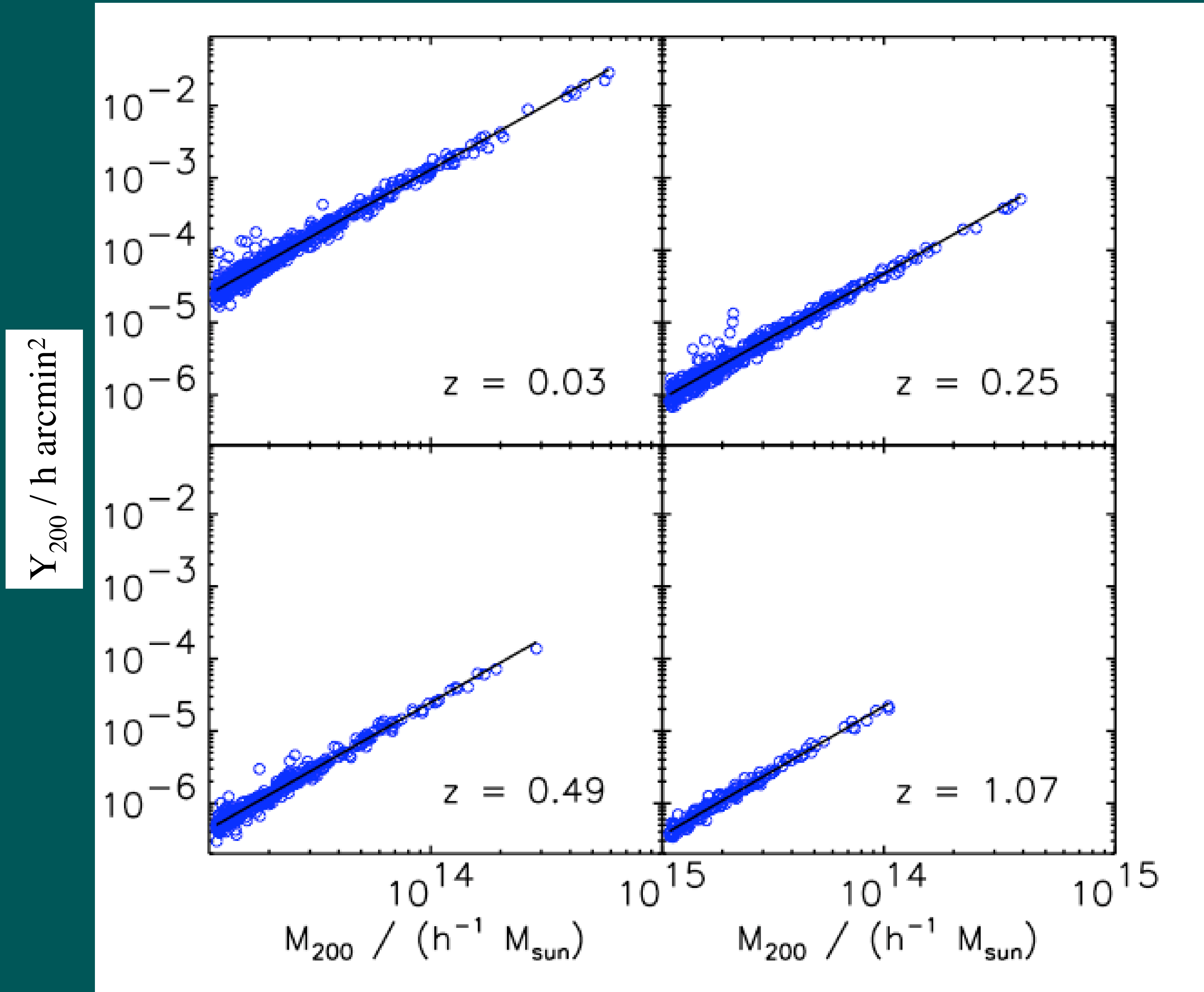
$$\log Y_{\text{int}} = -\frac{27}{8} \log(1+z) + \frac{5}{4} \log L_X$$

Y_{int}-M_{200}

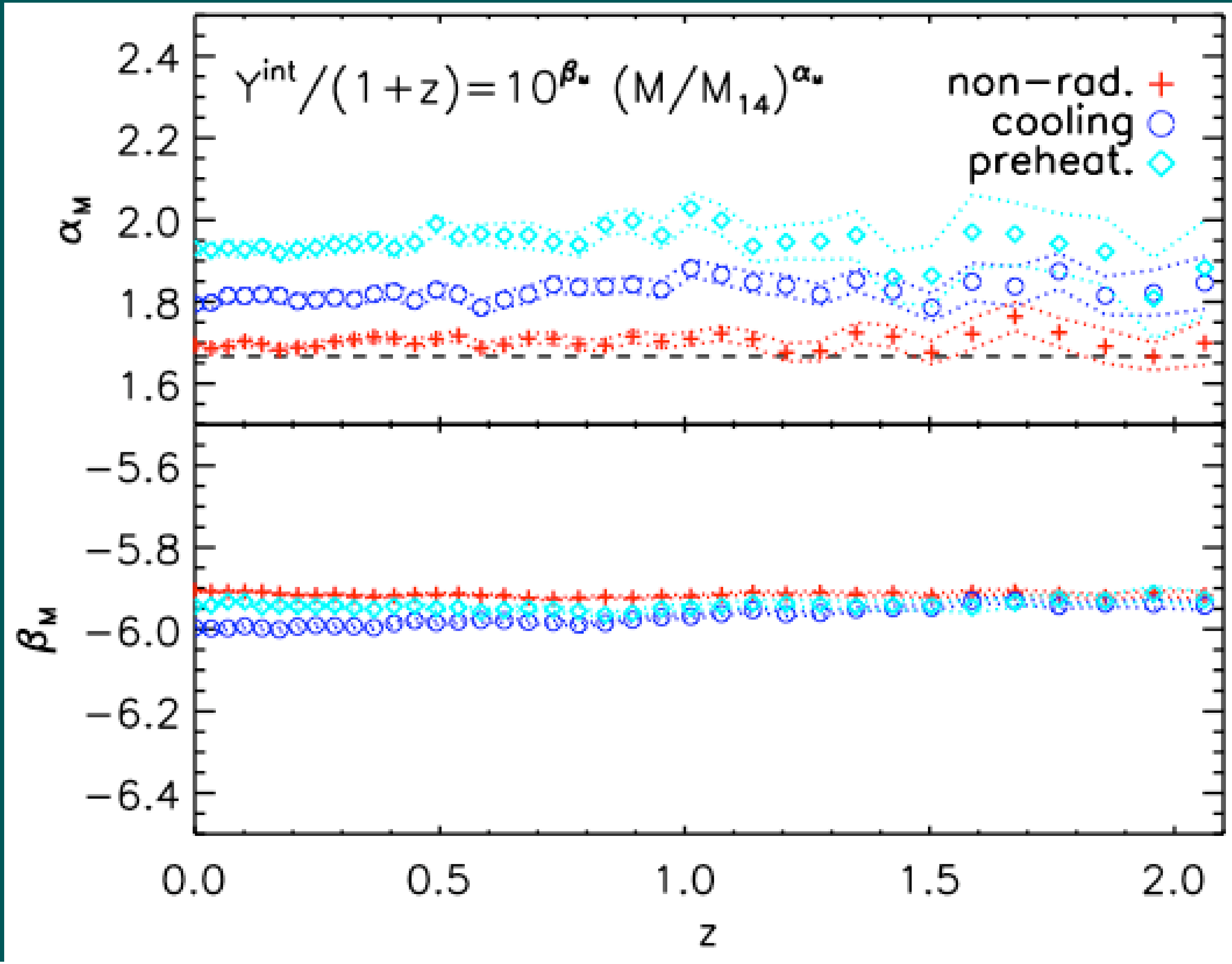


non-rad.
cooling
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Y_{200}^{int} / $(h^{-1}$ Mpc$)^2$
10^{13}
10^{14}
10^{15}
M_{200} / $(h^{-1}$ $M_{sun})$

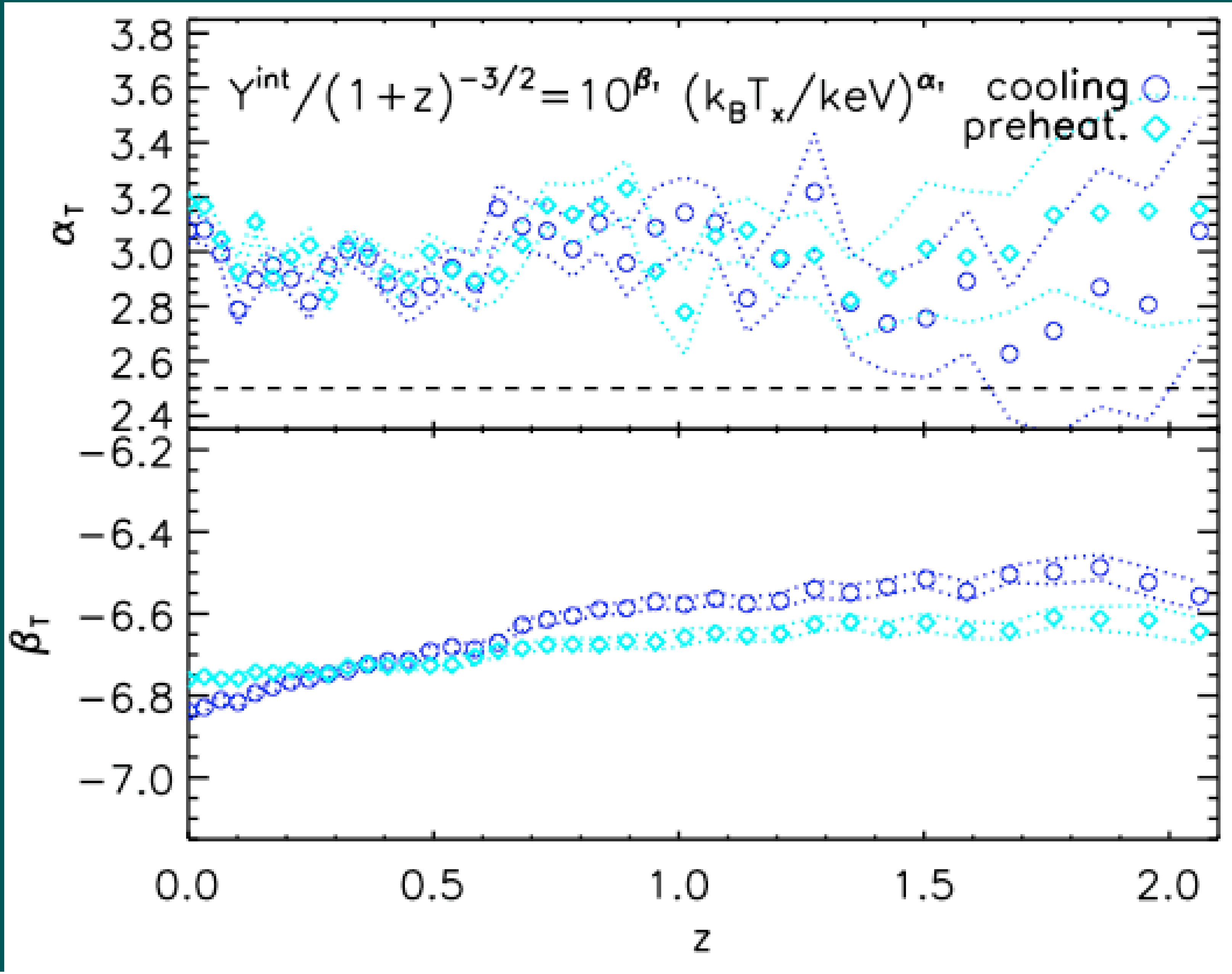
Y-M_{200} evolution



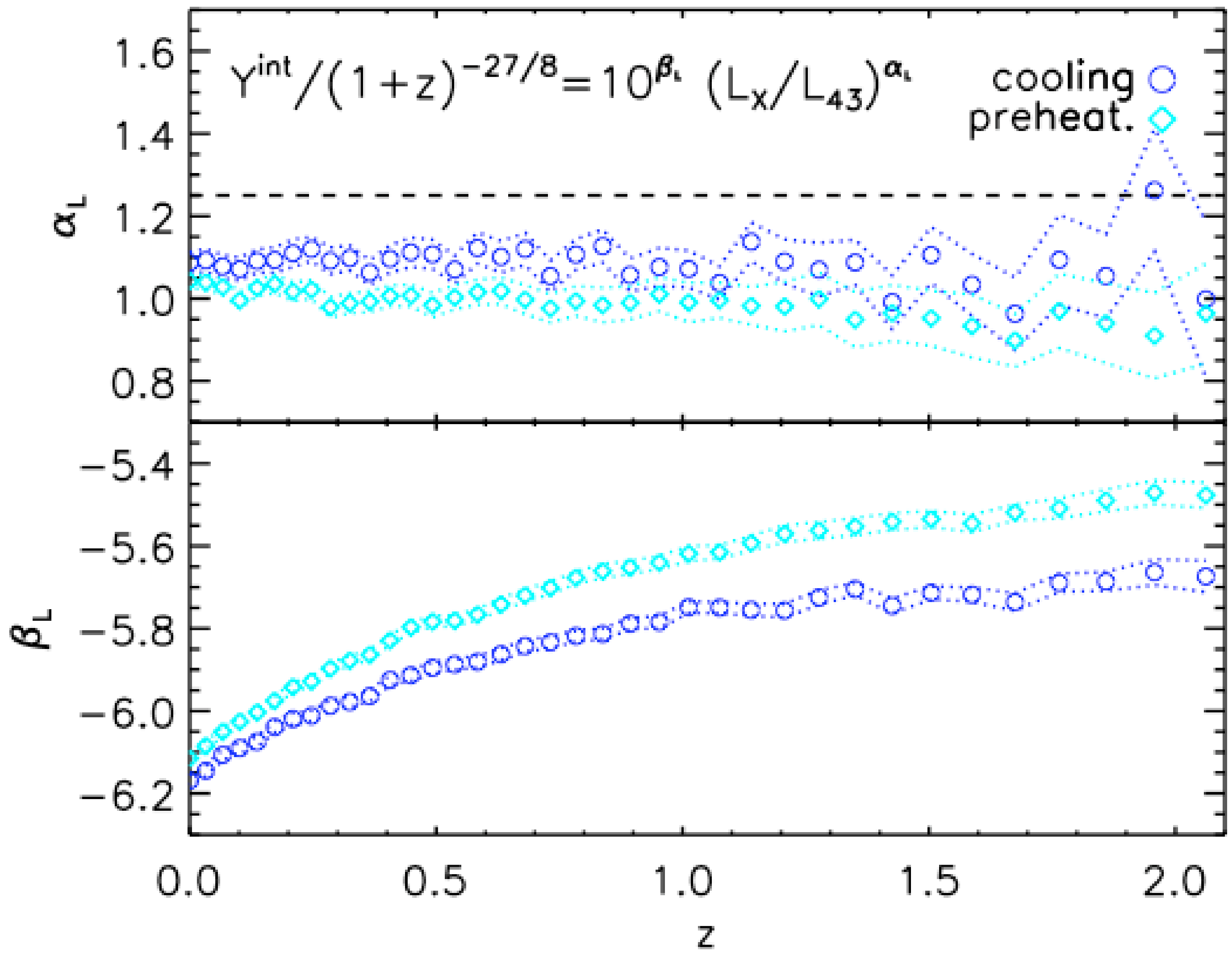
Y_{int}-M_{200} evolution



Y_{int}-T_X evolution



Y_{int}-L_X evolution



Conclusions 2

University of Sussex

The SZ integrated Y parameter is largely unaffected by cluster physics.

Evolution in Y-T_X and Y-L_X is largely driven by evolution in the X-ray properties.

CLEF
CLuster Evolution & Formation

University of Sussex

Astronomy Centre, Sussex

IAS, Orsay

LATT, Toulouse

with

Antonio da Silva

Scott Kay

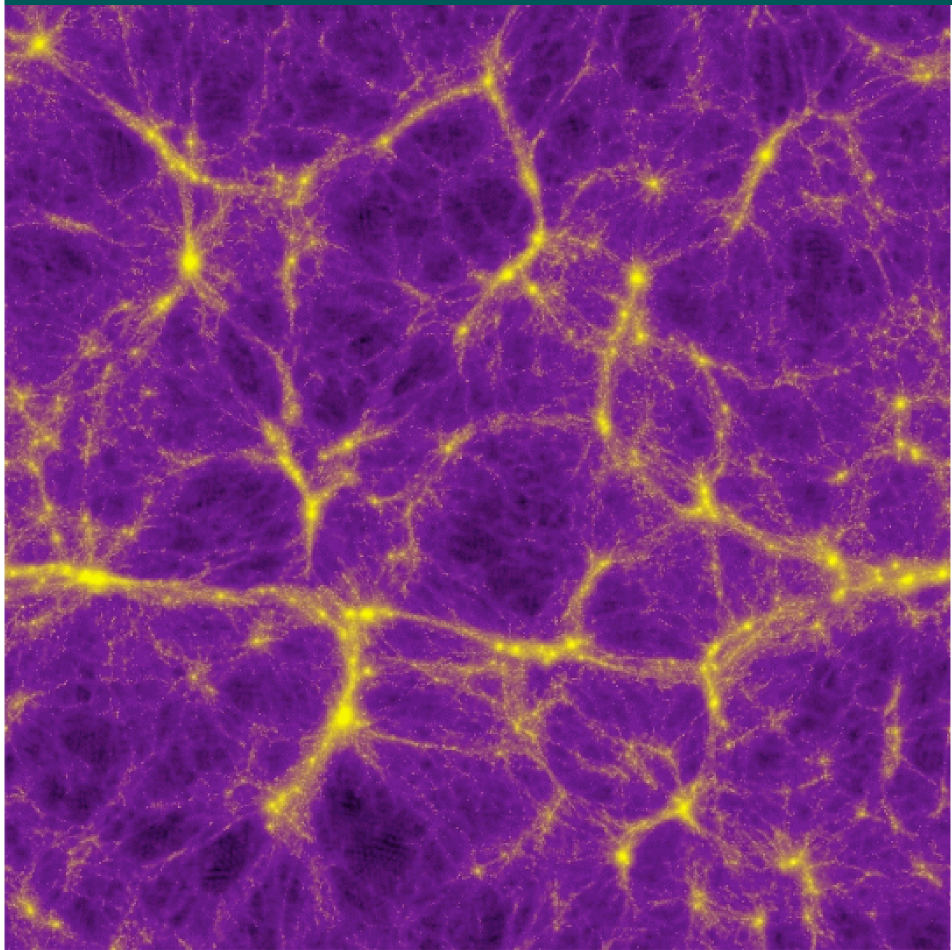
CLEF
CLuster Evolution & Formation

University of Sussex

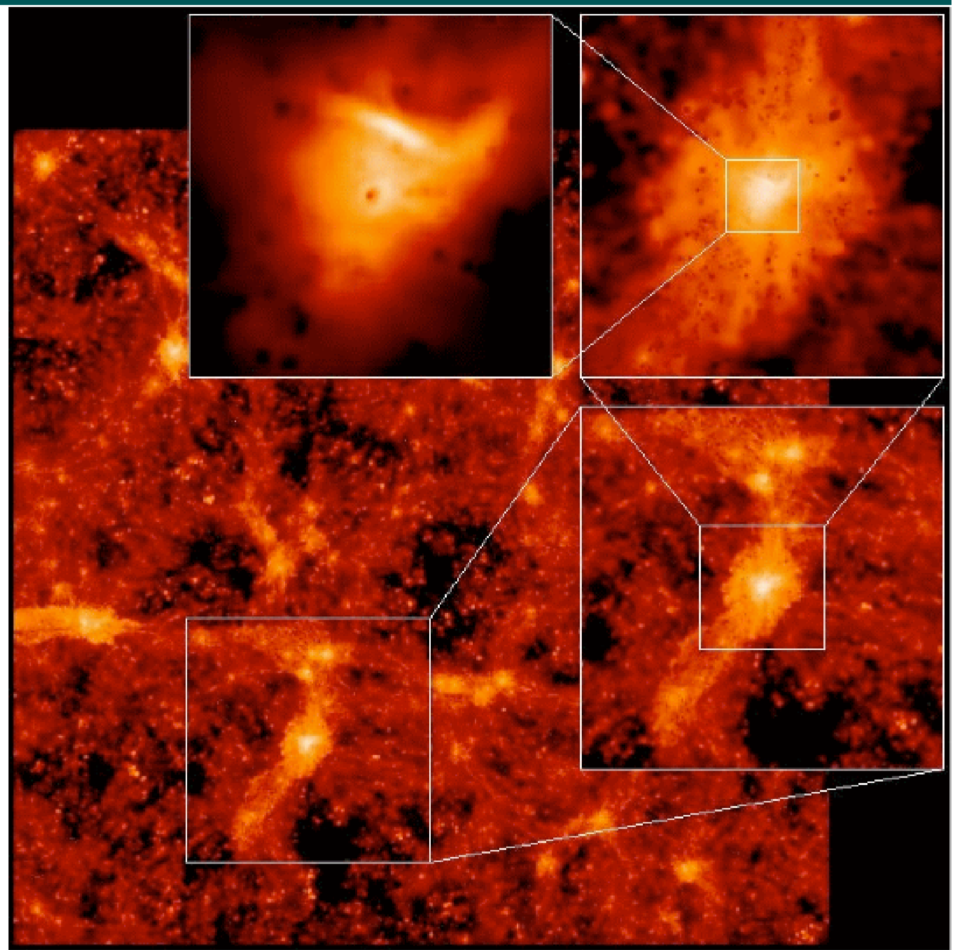
- Medium-resolution cluster catalogues
- >400 (60) clusters with kT_{vir}> 1 (3) kev
- 60,000 hours at CINES, Montpelier

- N_{DM} = N_{gas} = 428^3
- L = 200 h^{-1}Mpc
- h=0.7, _=0.7, _=0.2, _b=0.0486, σ_8=0.9
- M_{DM} = 7.1x$10^9 h^{-1} M_\odot$, M_{gas} = 1.4x10^9 $h^{-1} M_\odot$
- Feedback, Z=0.3$Z_\odot$, 10% of cooled particles given an entropy excess of 1000 keV cm^2

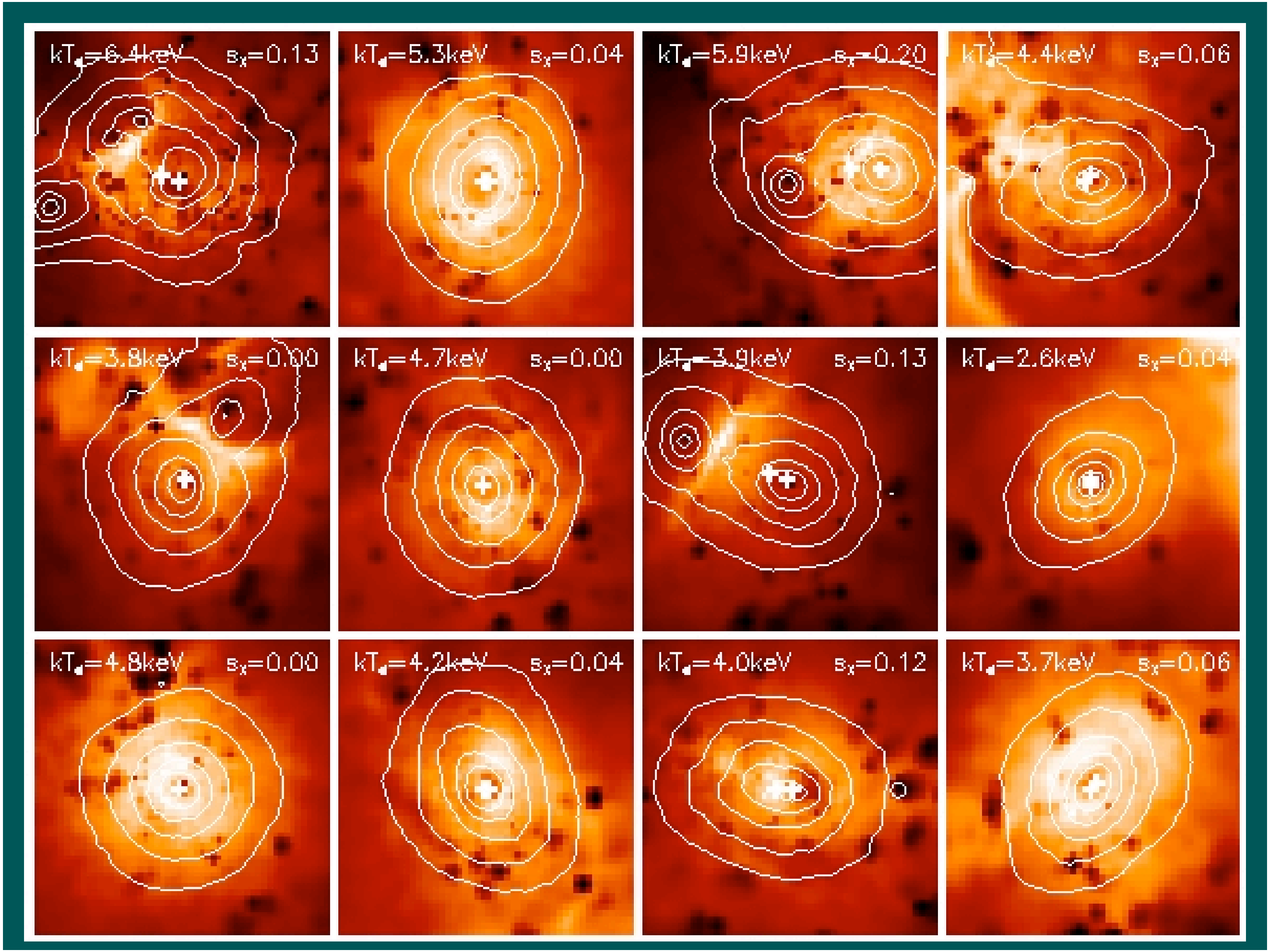
Gas distribution



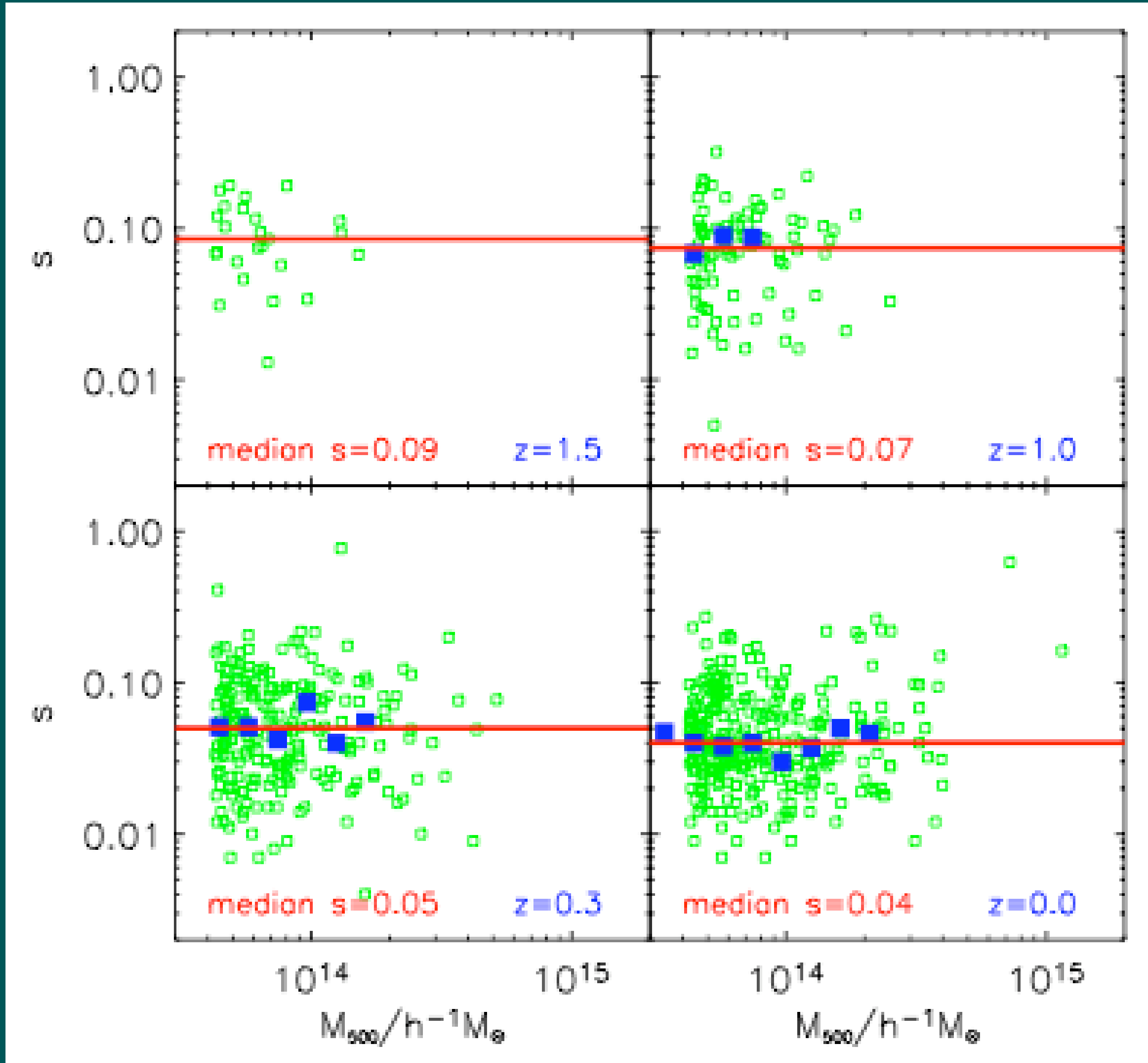
Surface brightness



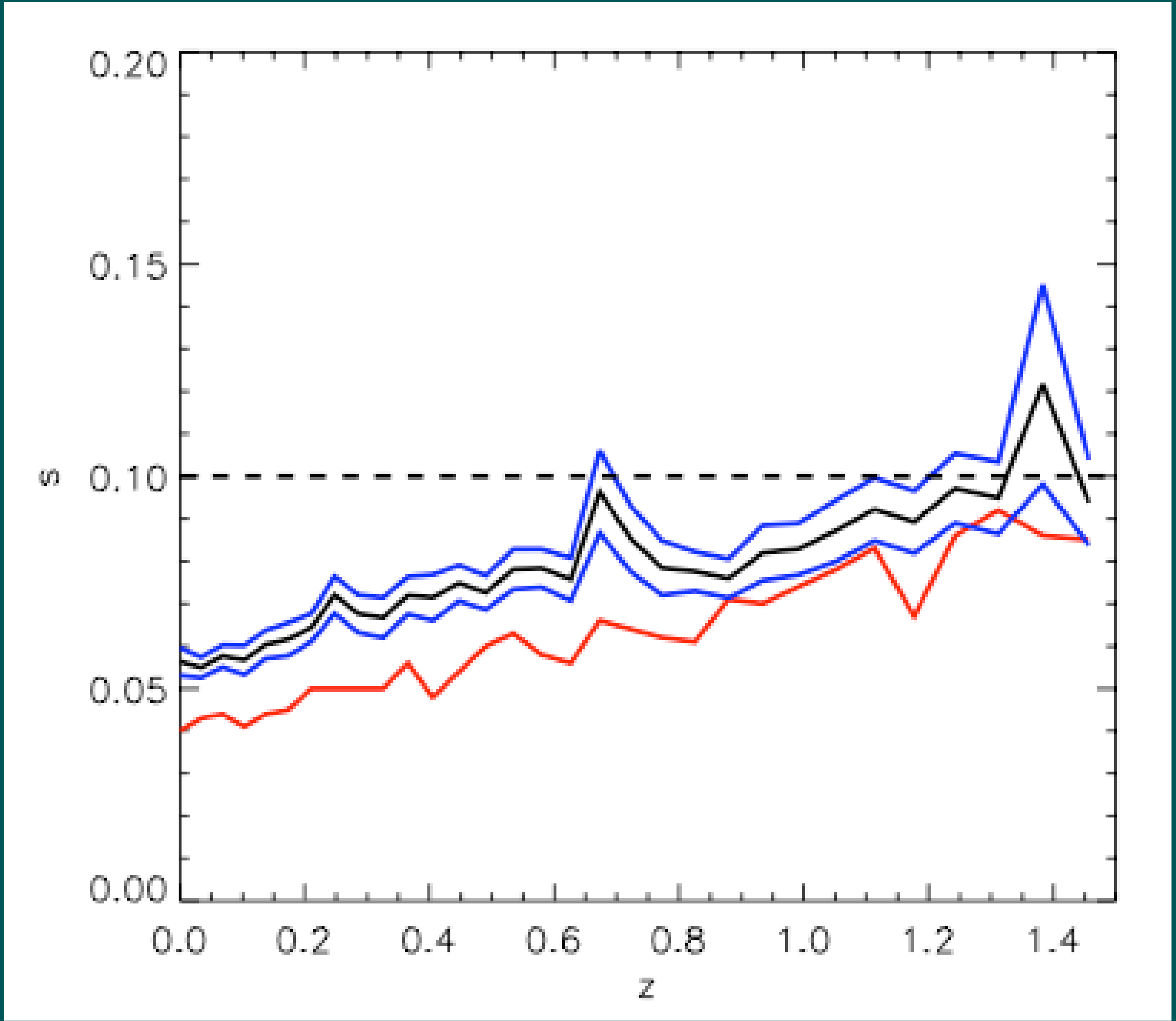
Mass-weighted temperature


kT$_{ew}$=6.4keV s$_x$=0.13
kT$_{ew}$=5.3keV s$_x$=0.04
kT$_{ew}$=5.9keV s$_x$=0.20
kT$_{ew}$=4.4keV s$_x$=0.06
kT$_{ew}$=3.8keV s$_x$=0.00
kT$_{ew}$=4.7keV s$_x$=0.00
kT$_{ew}$=3.9keV s$_x$=0.13
kT$_{ew}$=2.6keV s$_x$=0.04
kT$_{ew}$=4.8keV s$_x$=0.00
kT$_{ew}$=4.2keV s$_x$=0.04
kT$_{ew}$=4.0keV s$_x$=0.12
kT$_{ew}$=3.7keV s$_x$=0.06

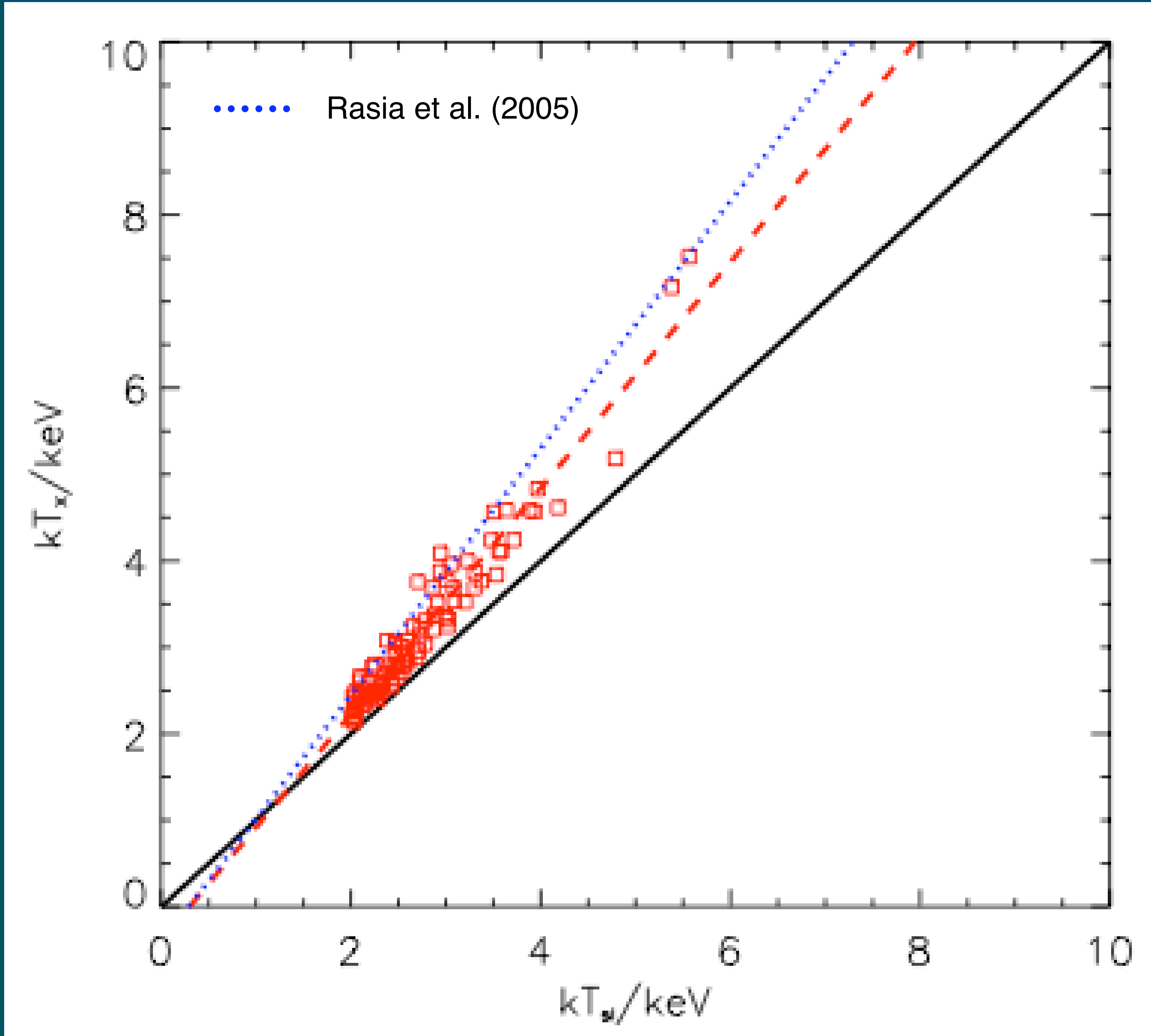
Substructure evolution



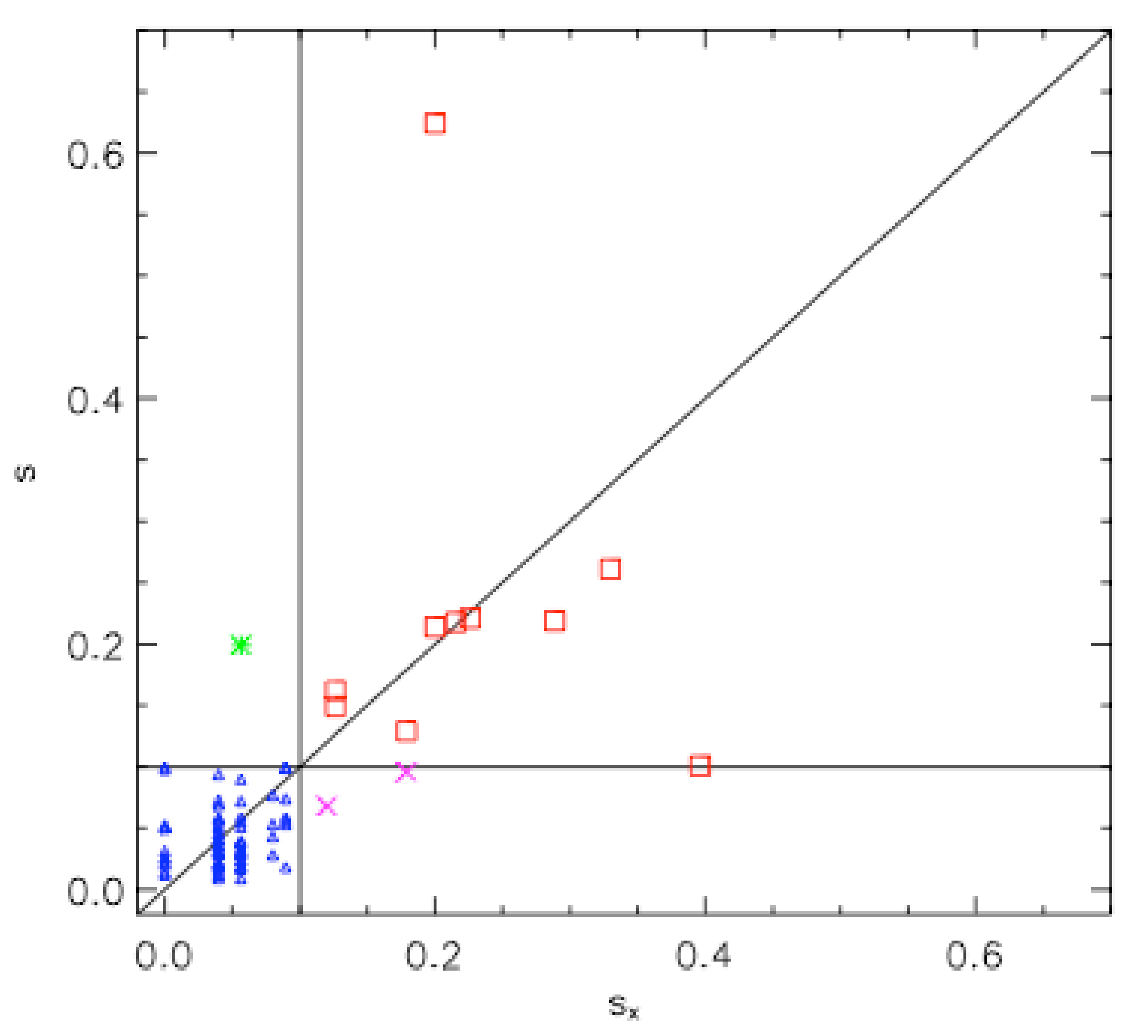
Substructure evolution



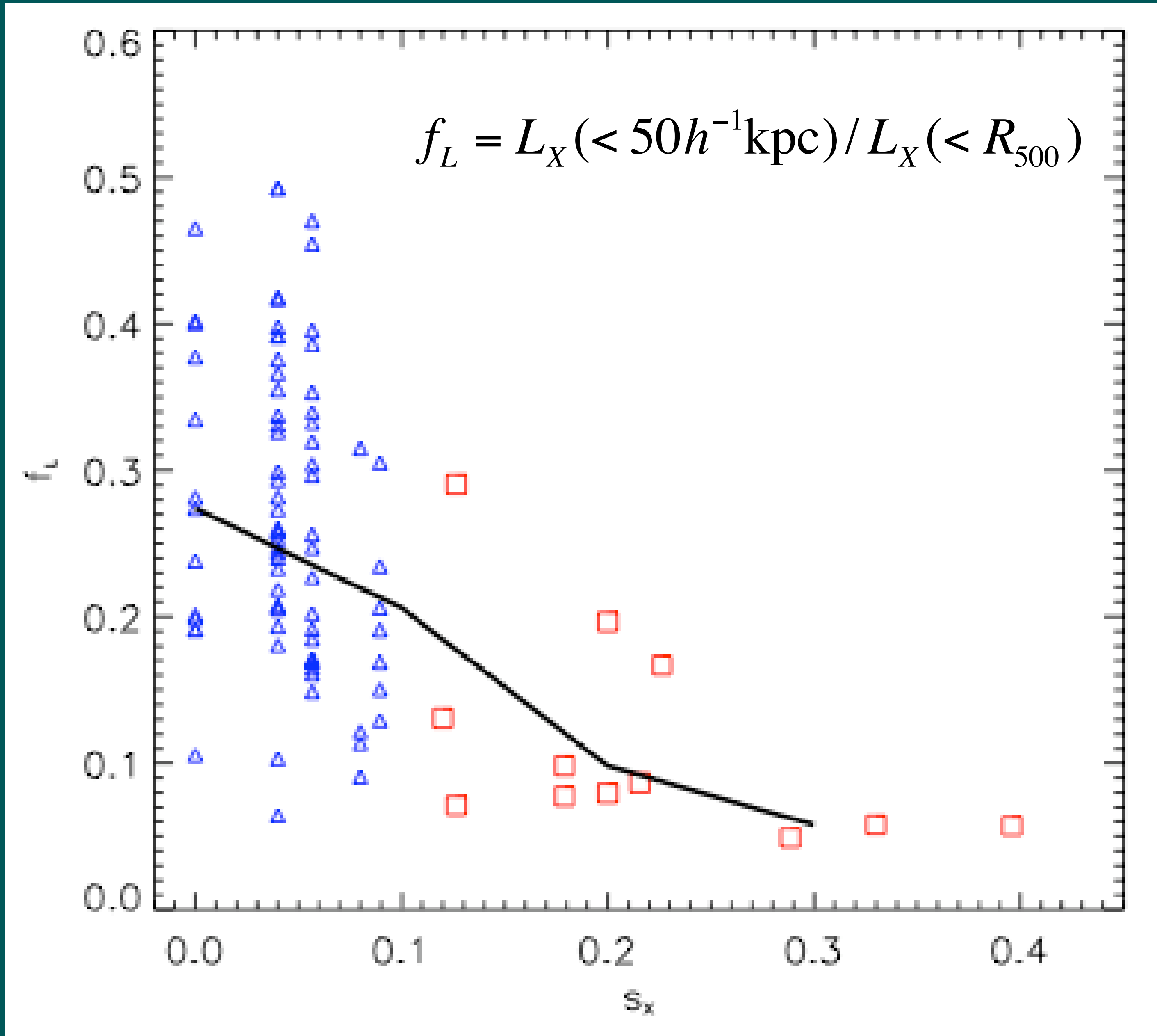
Emission-weighted versus spectroscopic temperature



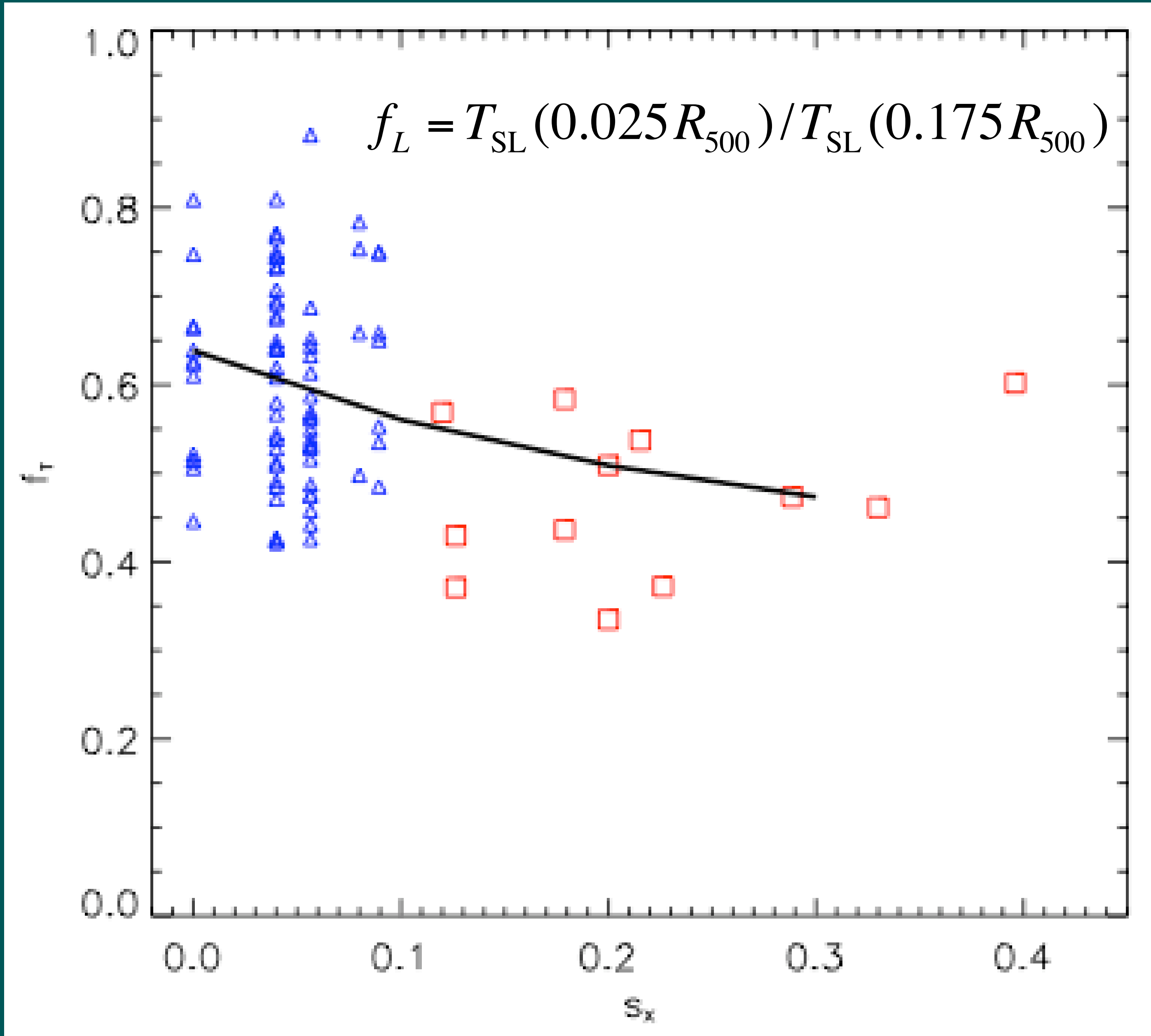
3-d versus 2-d substructure



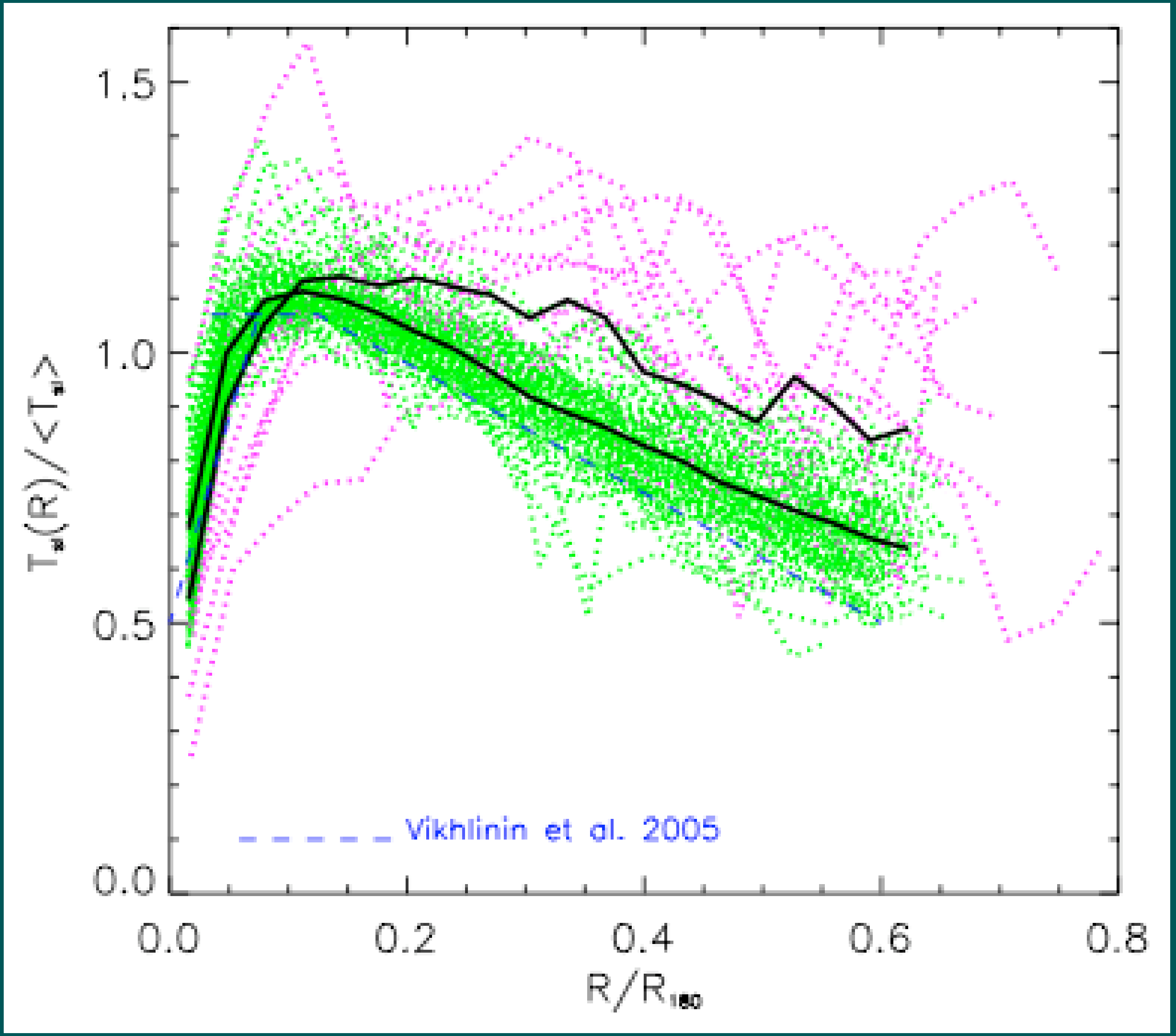
Luminosity concentration versus substructure



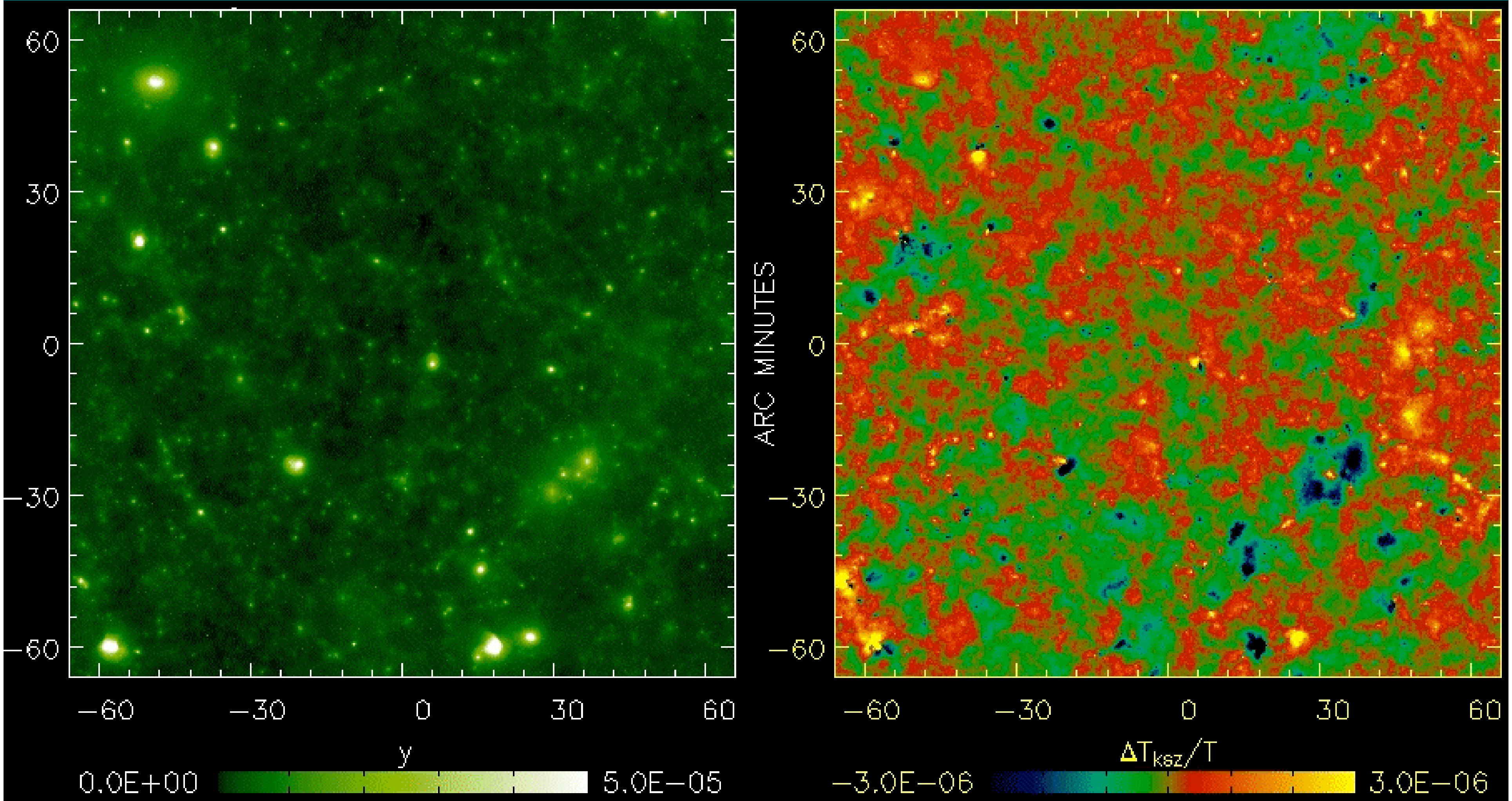
Temperature concentration versus substructure



Projected temperature profiles



SZ maps



60
30
0
-30
-60
-60
-30
0
30
60
y
0.0E+00
5.0E-05
ARC MINUTES
$\Delta T_{ksz}/T$
-3.0E-06
3.0E-06

with

Frazer Pearce

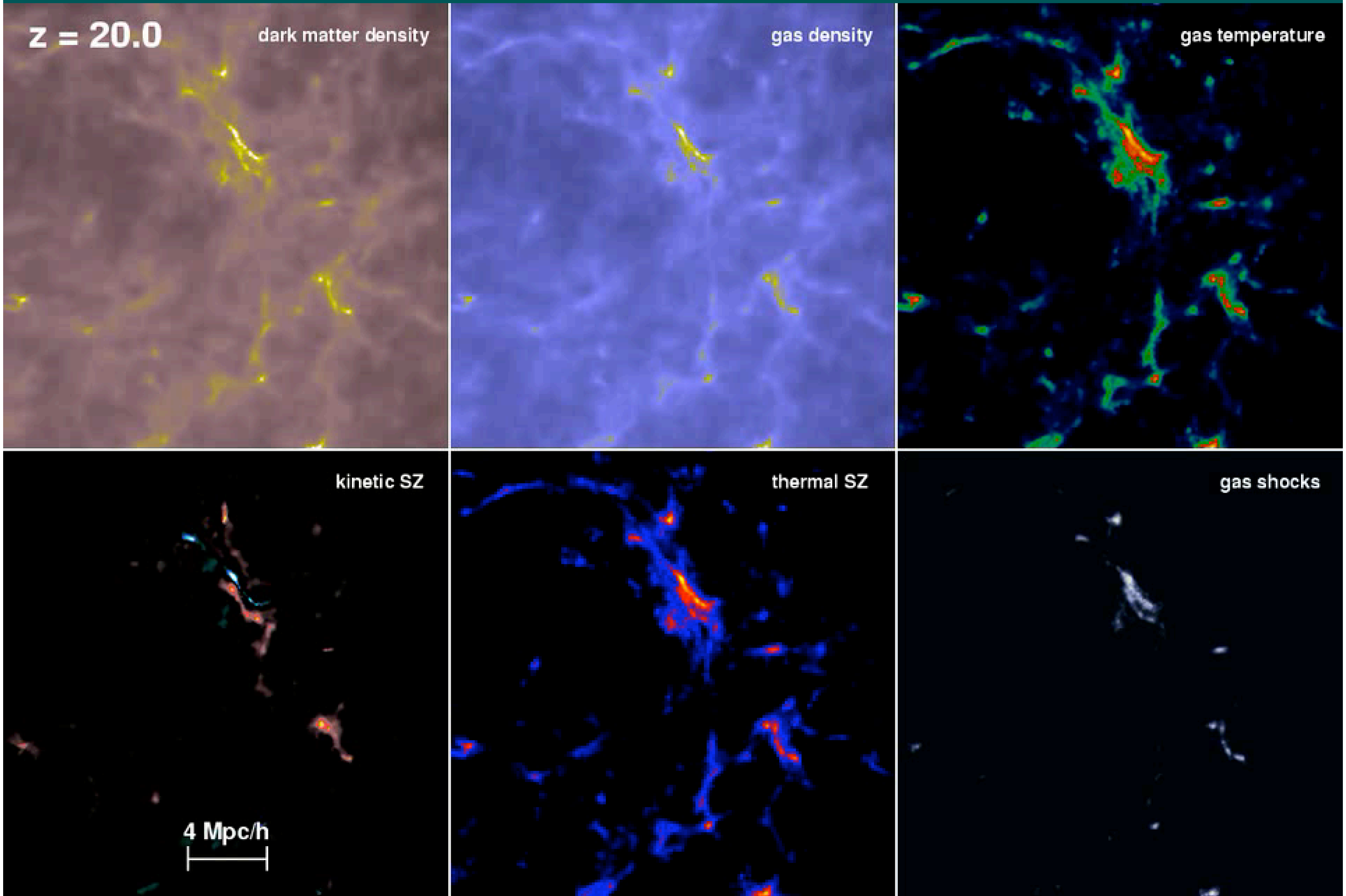
et al.

Millennium Gas Project

University of Sussex

- Series of 1 billion particle SPH simulations
- Same volume and phases as Millennium DM run
- Build up physics gradually
- 160 outputs equally spaced in time

- N_{DM} = N_{gas} = 500,000,000
- L = 500h^{-1}Mpc
- h=0.73, _=0.75, _=0.25, _$_b$=0.045
- M_{DM} = 1.01x$10^{10}h^{-1}M_{\odot}$, M_{gas} = 2.4x10^{9} $h^{-1}M_{\odot}$


z = 20.0
dark matter density
gas density
gas temperature
kinetic SZ
thermal SZ
gas shocks
4 Mpc/h

The growth of individual clusters

University of Sussex

with

Scott Kay

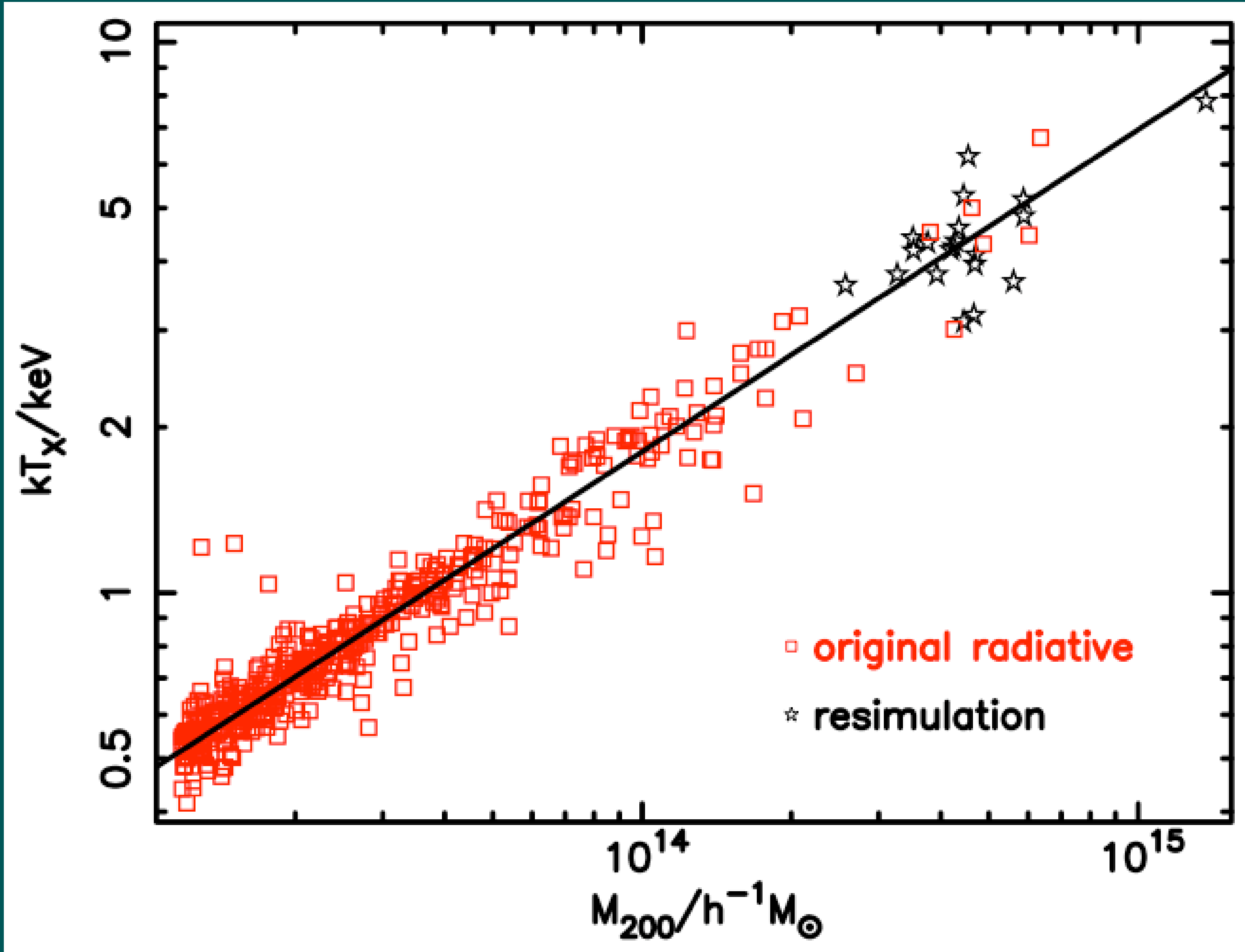
David Rowley

The growth of individual clusters

University of Sussex

- Resimulations
- $L=200h^{-1}$Mpc box
- $N=160^3$_2.320^3
- h=0.71, _=0.65, _=0.35, $\_{b}$=0.038
- $M_{DM} = 2.1x10^{10}h^{-1}M_{\odot}$, $M_{gas} = 2.5x10^{9}\ h^{-1}M_{\odot}$
- Radiative, $Z=0.3(t/t_0)Z_{\odot}$

Resimulated clusters



Growth of mass

— M_{vir}

— M_{500}

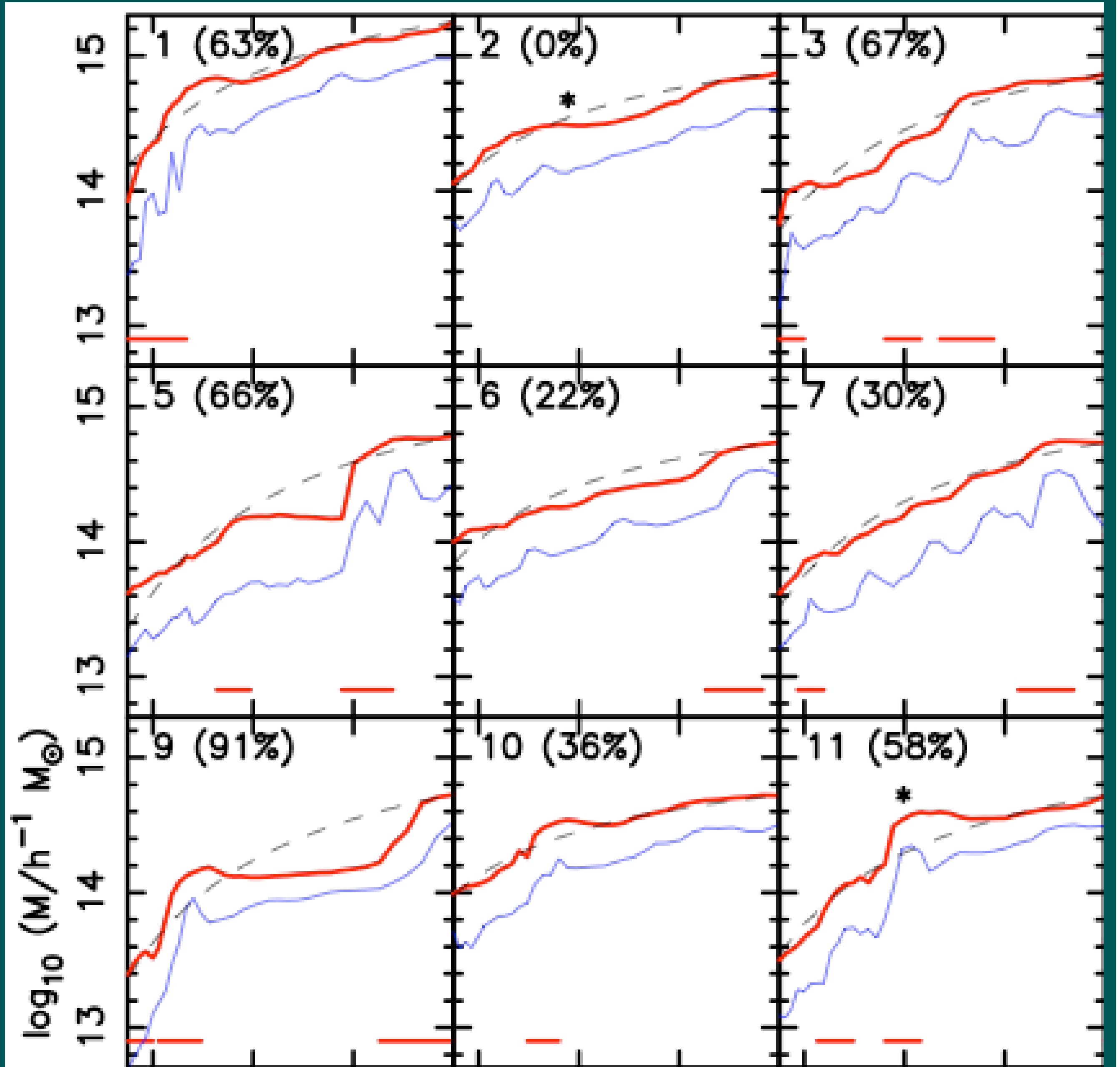
Formation time

(Wechsler etal 2002)

– – $M=M_0e^{2af(1-1/a)}$

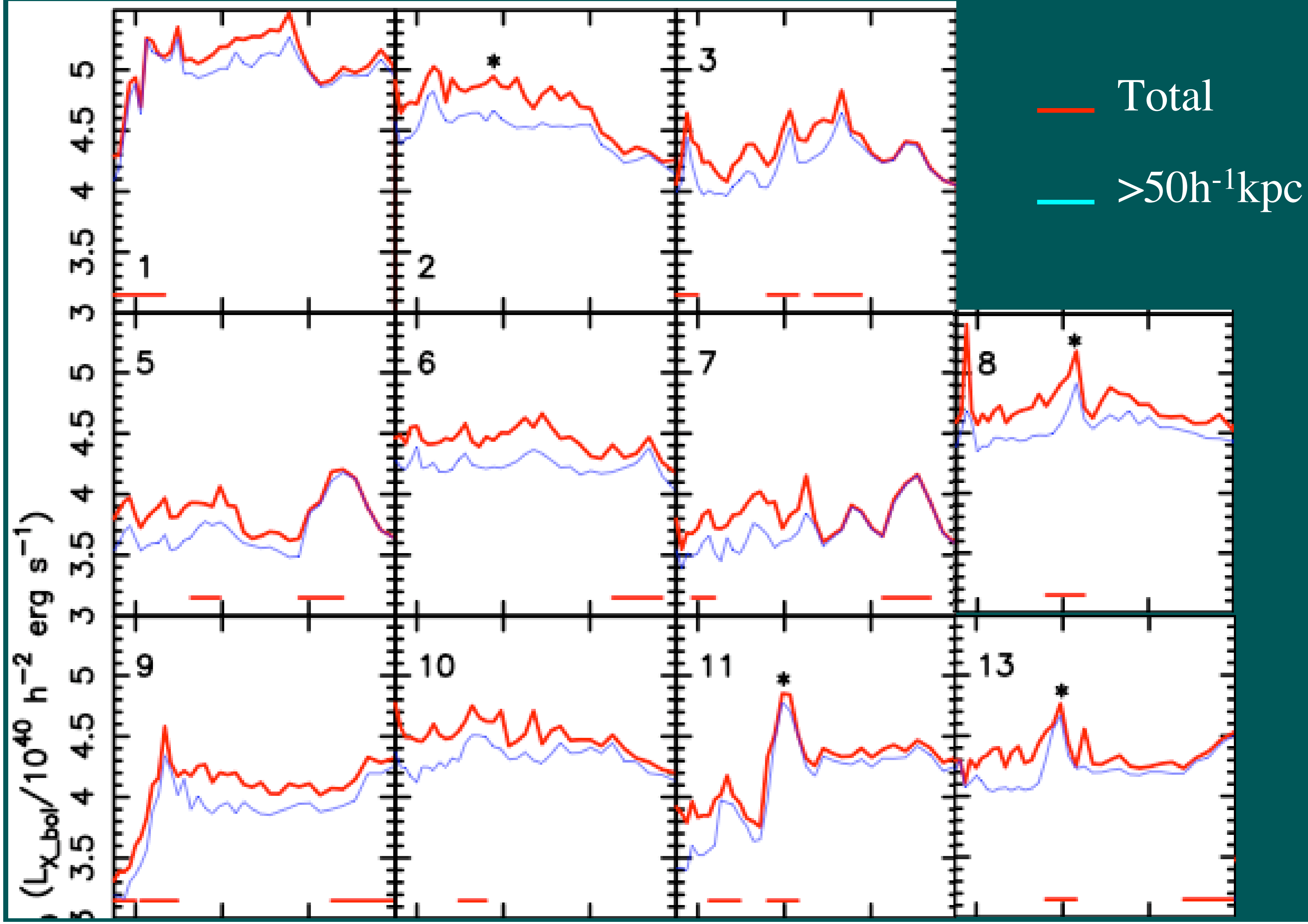
Major mergers

- ~_ the mass
- ~_ of the time

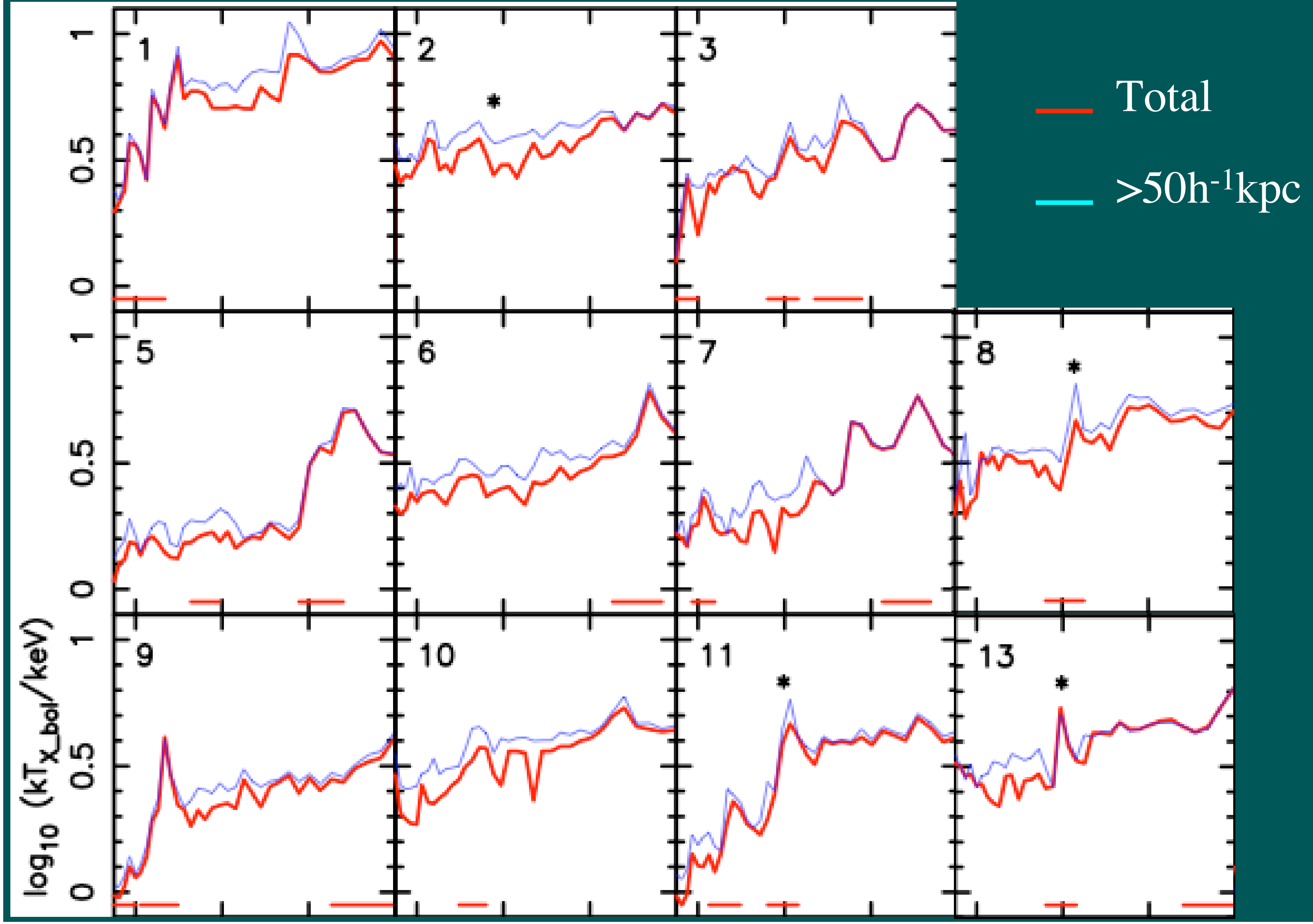


a= 0.4 0.6 0.8 1.0

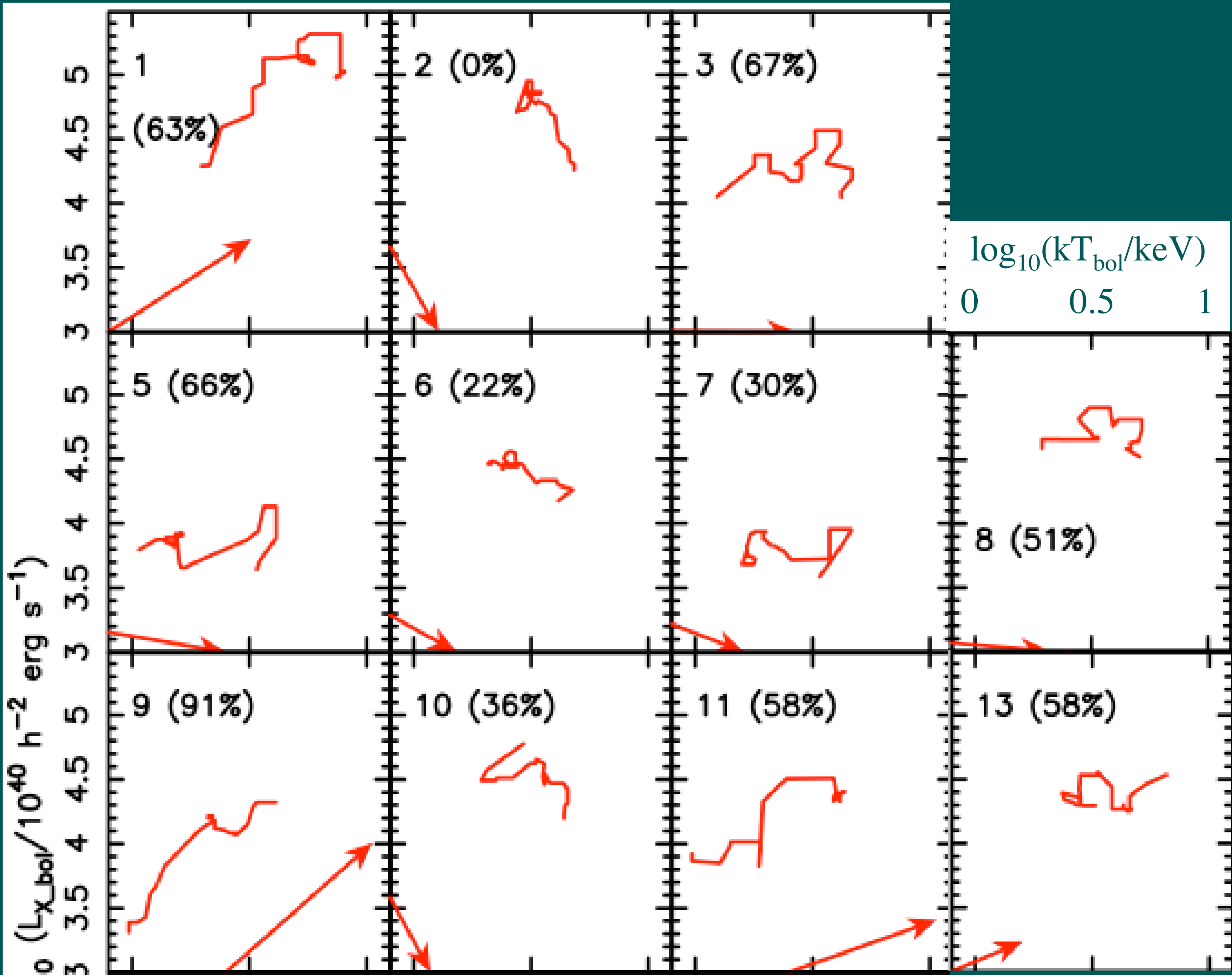
Bolometric luminosity



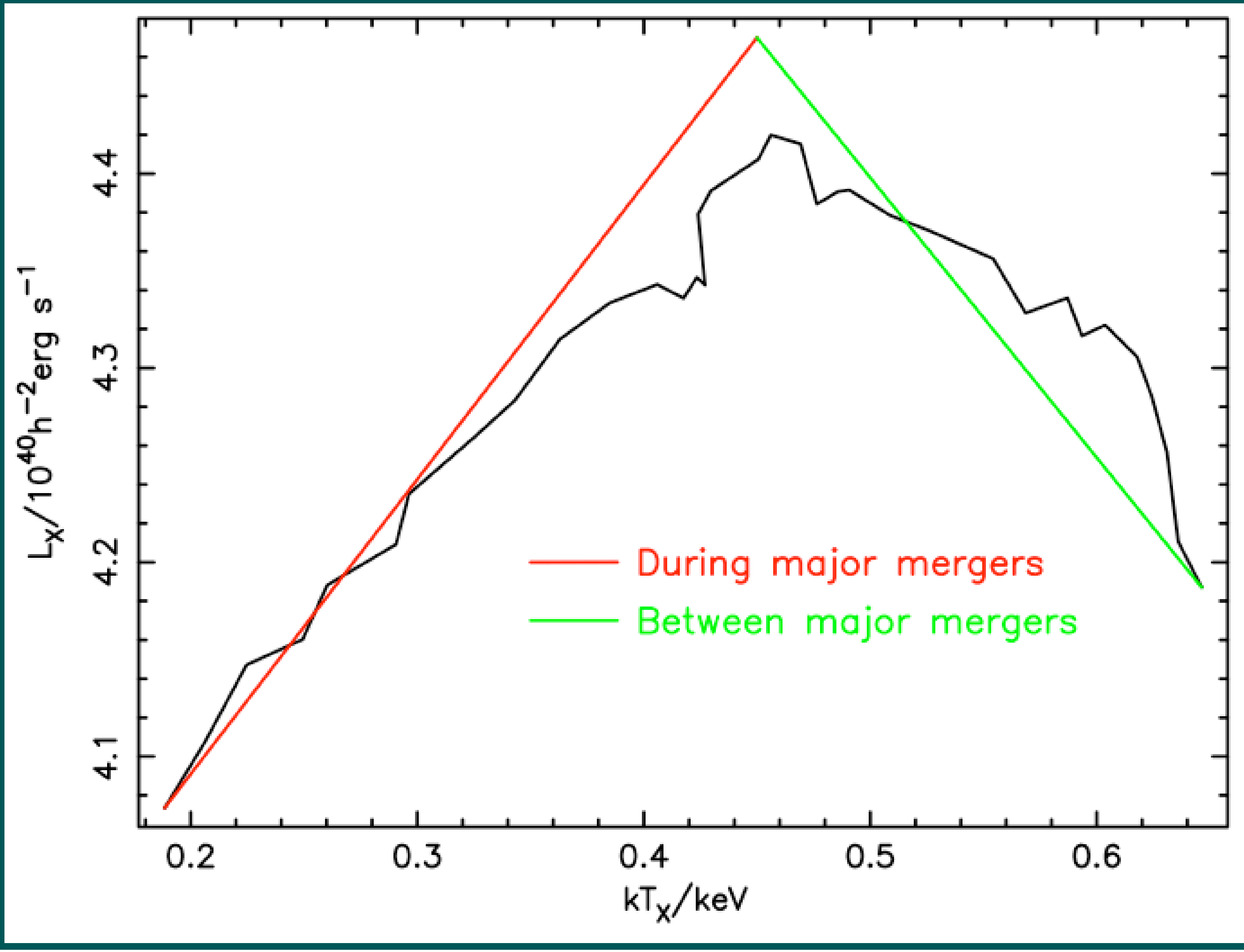
Bolometric temperature



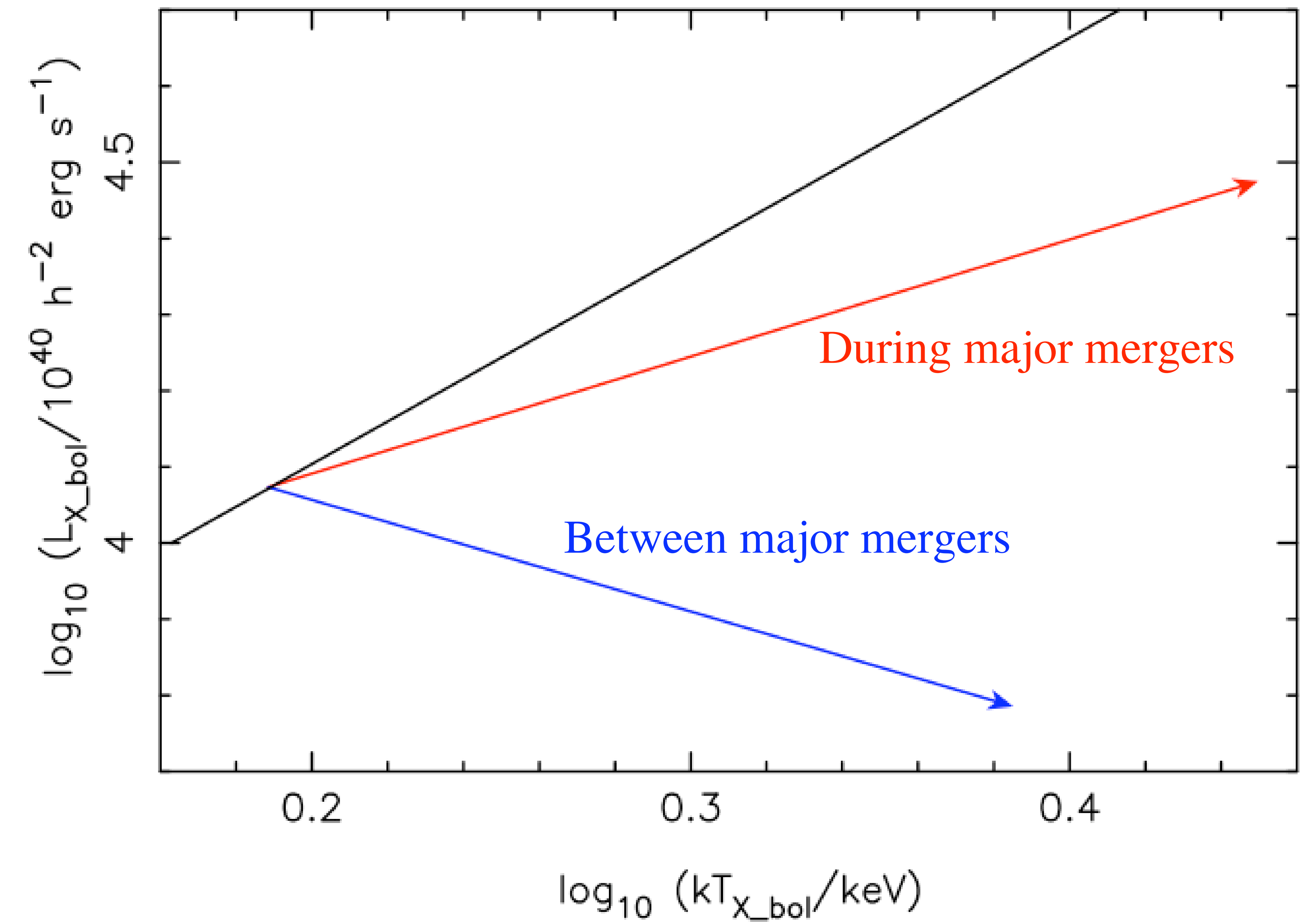
Luminosity-temperature evolution



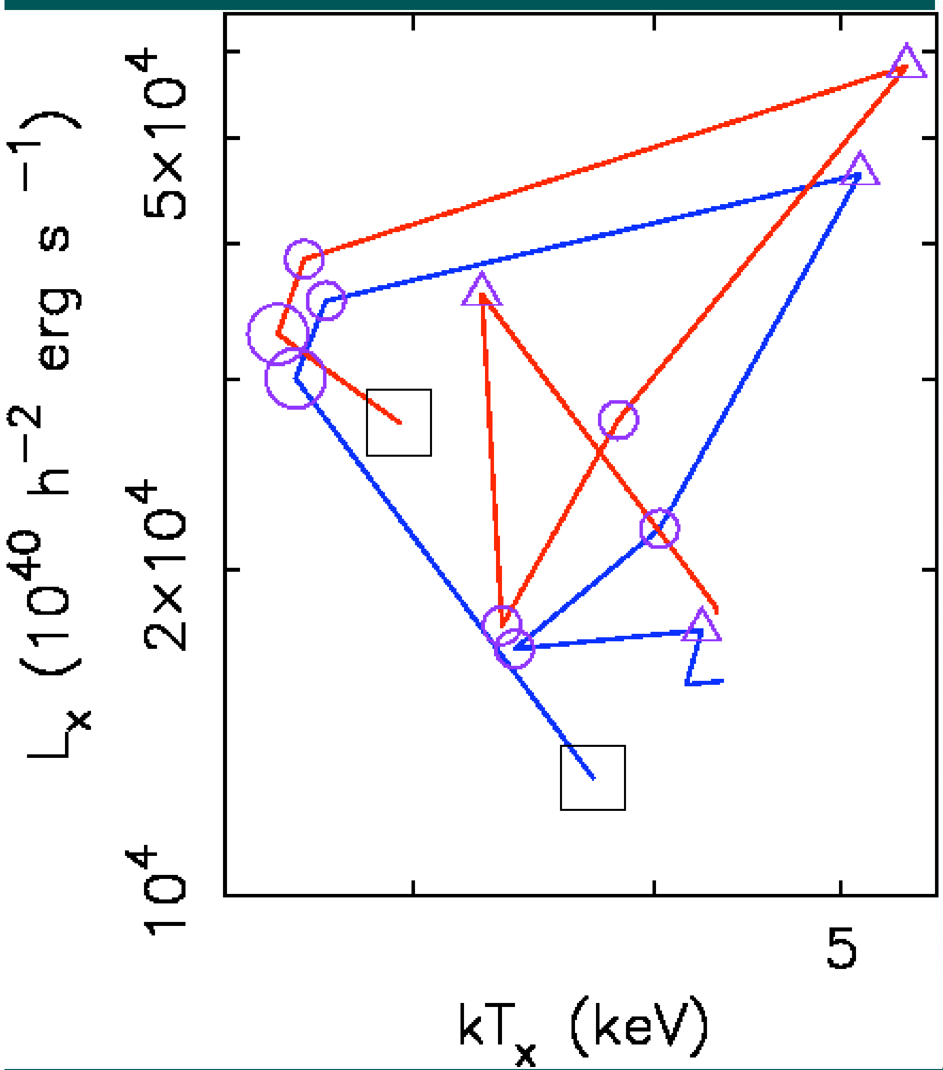
Drift over time of L_X-T_X

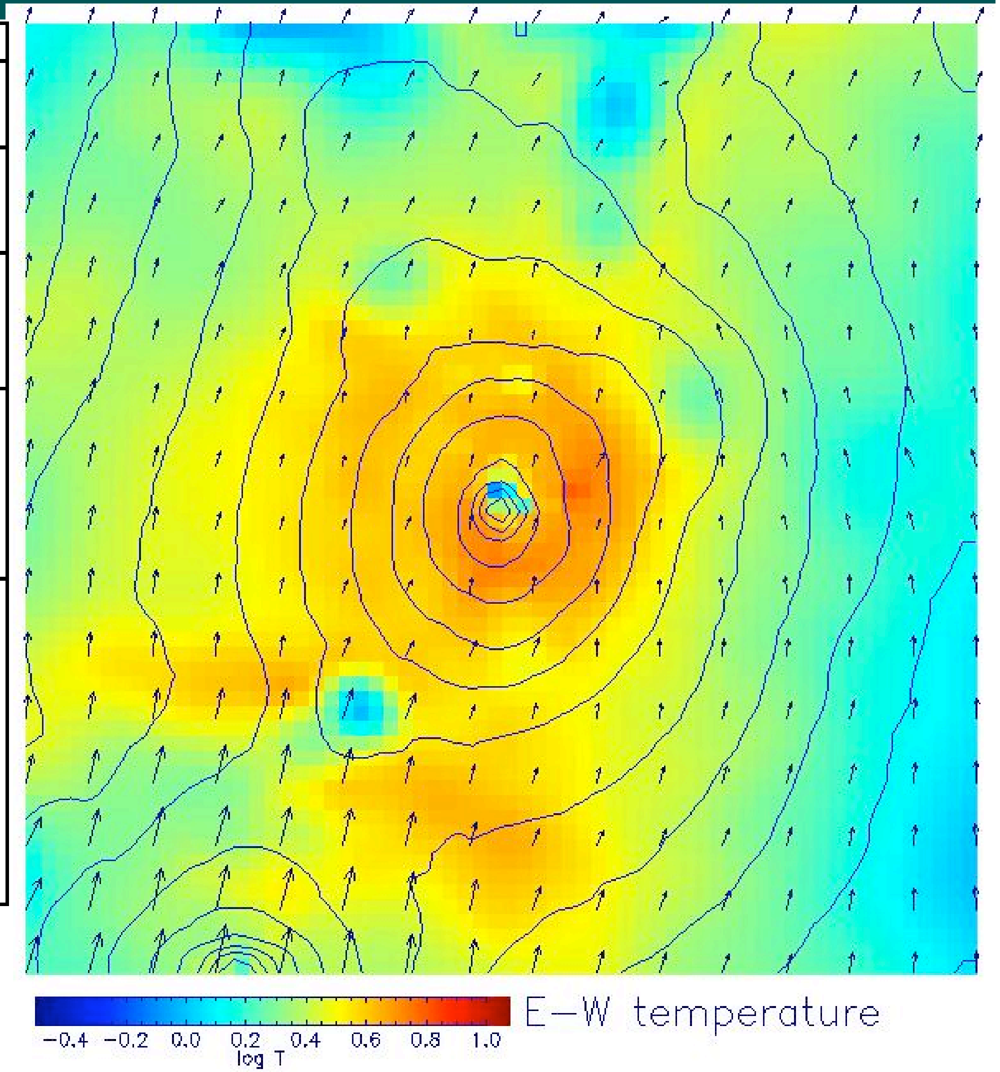


Drift of L_X-T_X relative to mean relation

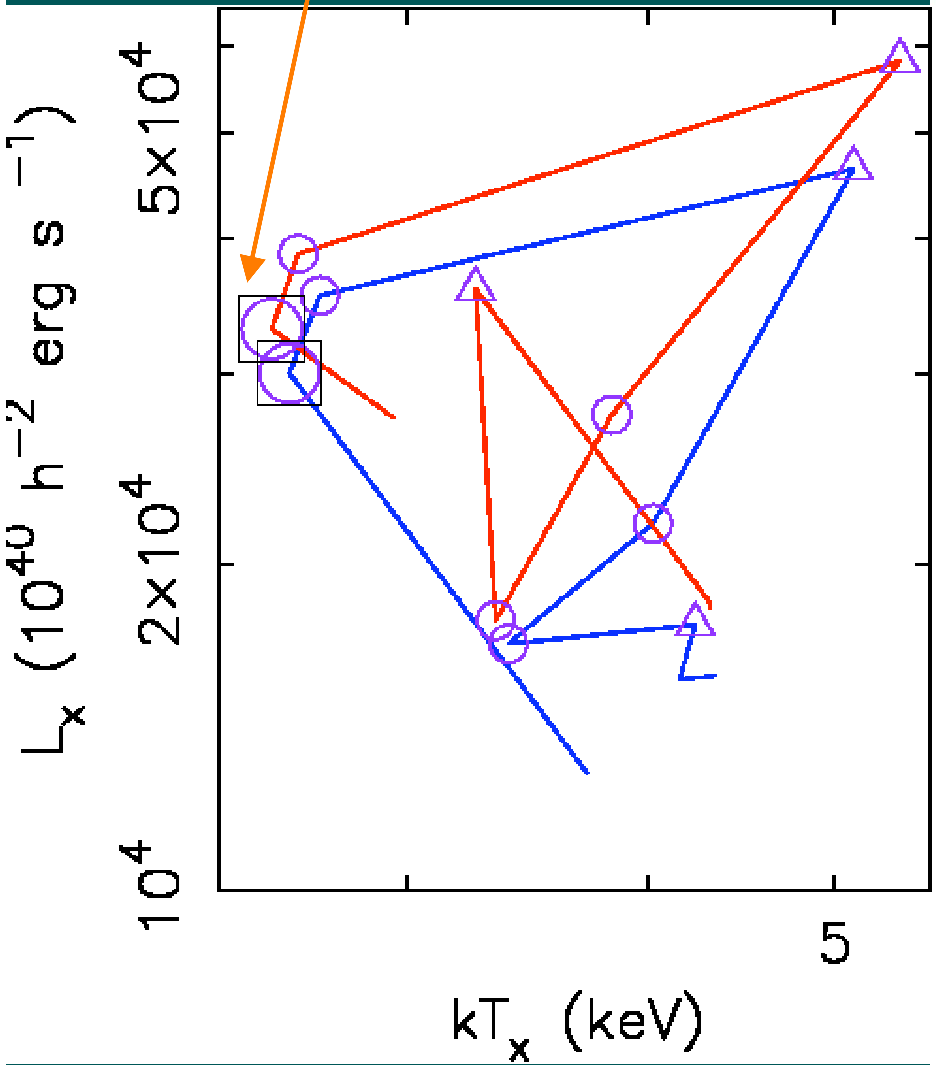


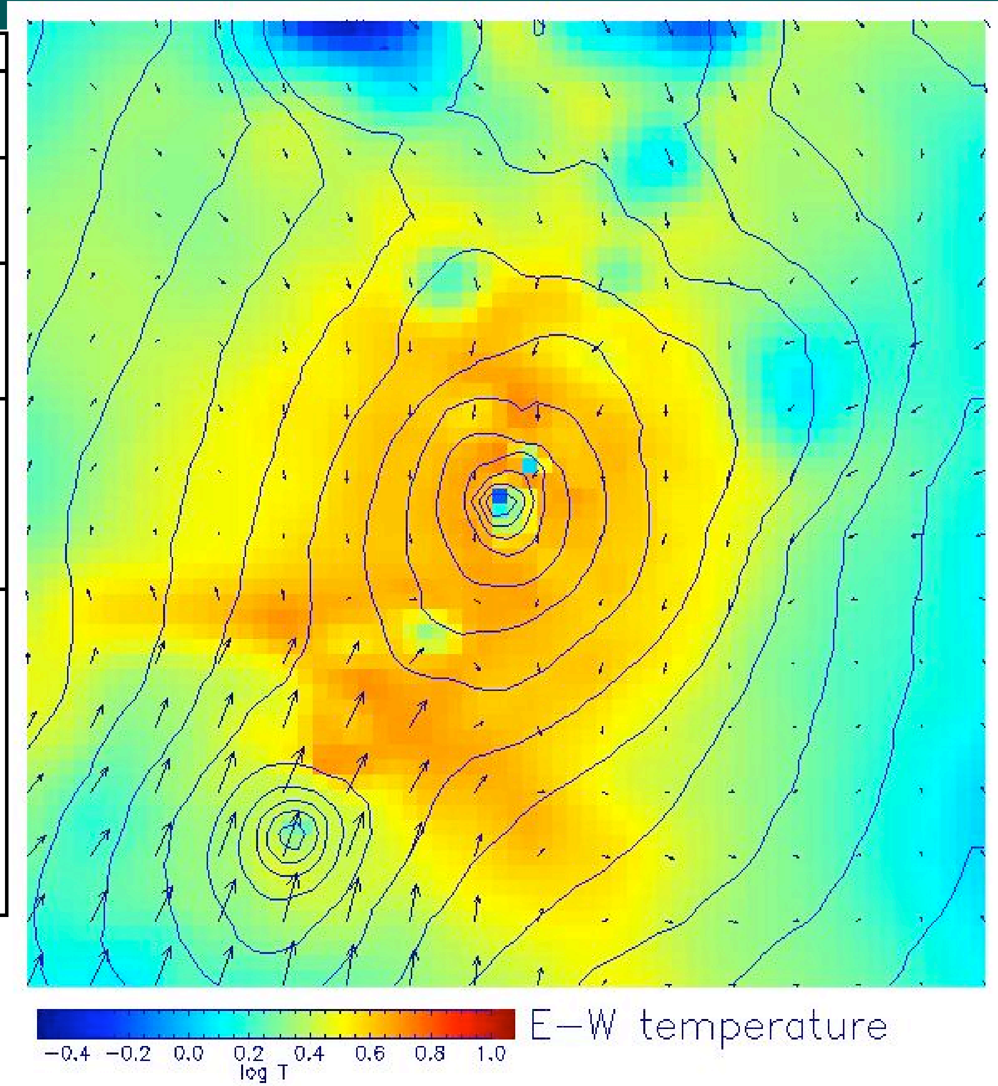
Example: double-peaked merger



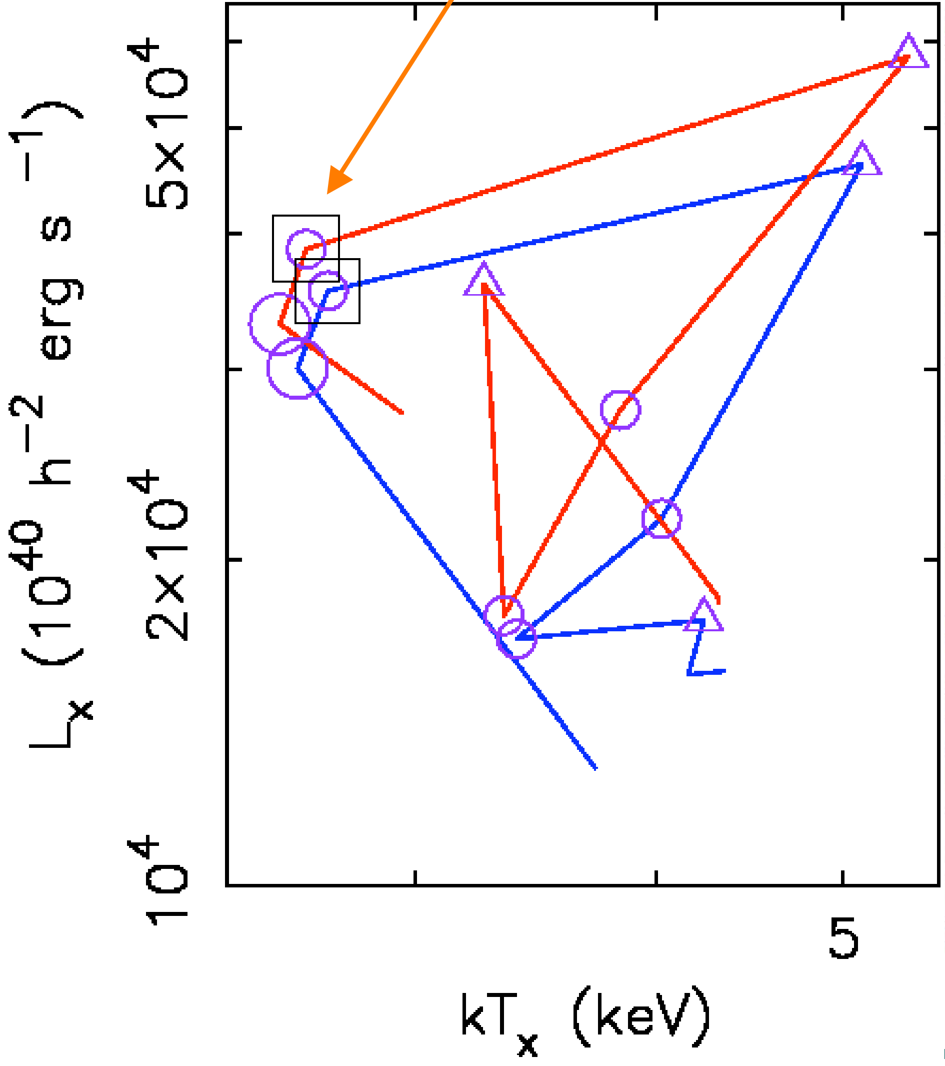


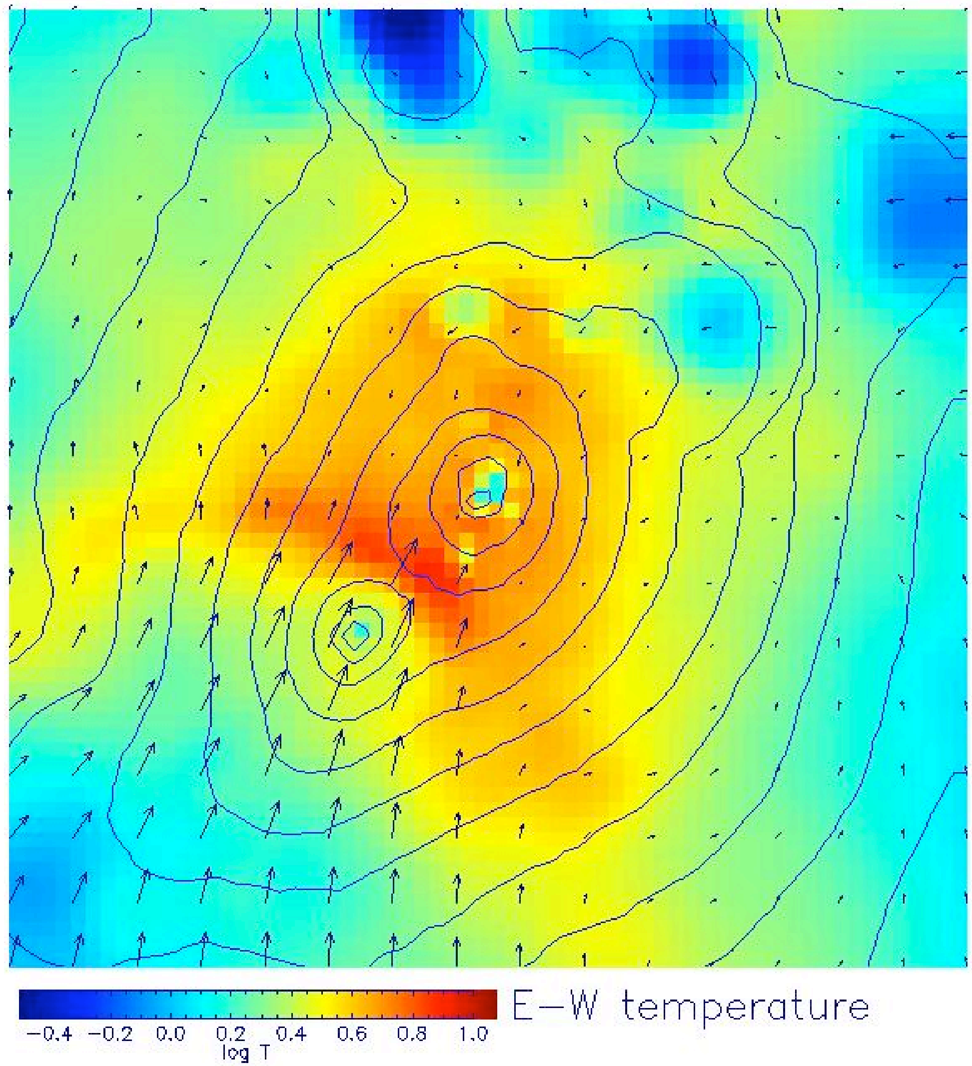
Here the cluster is an obvious binary



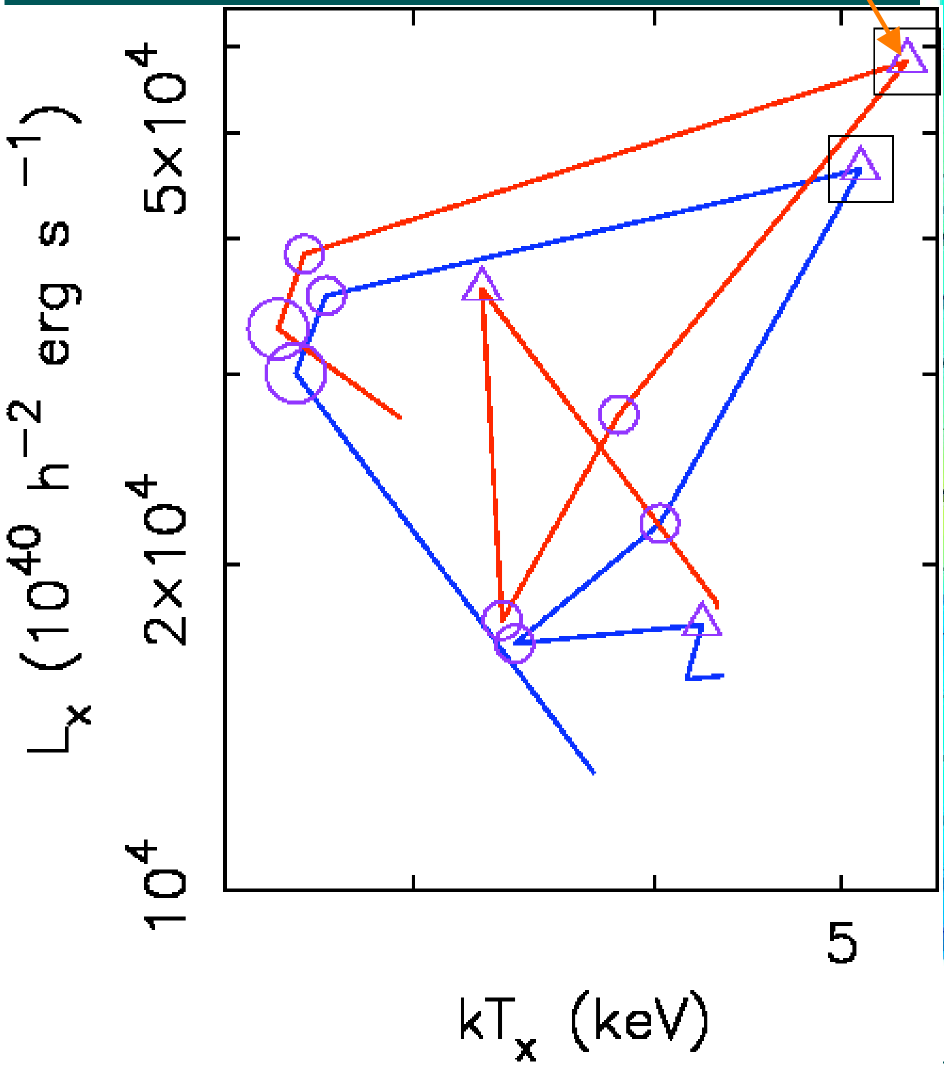


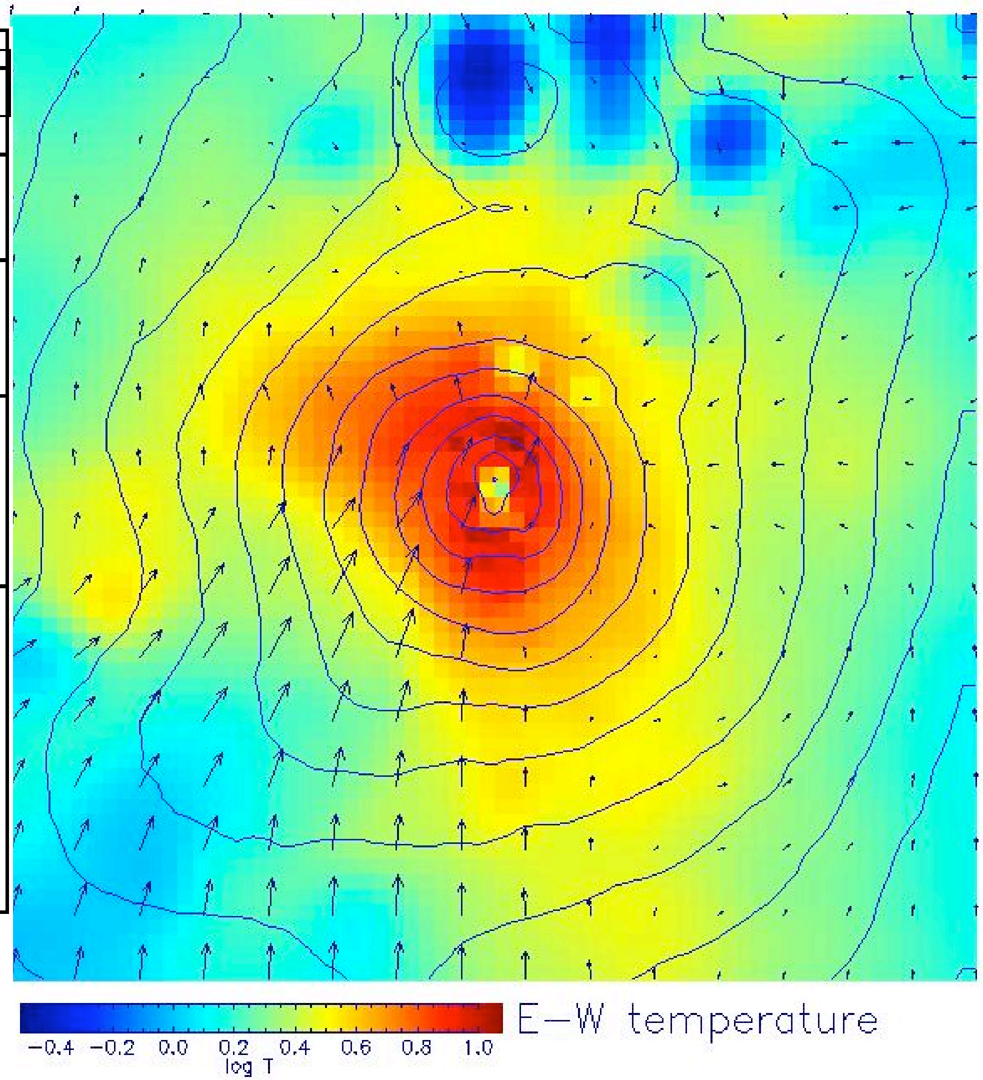
Here the cluster is an obvious binary

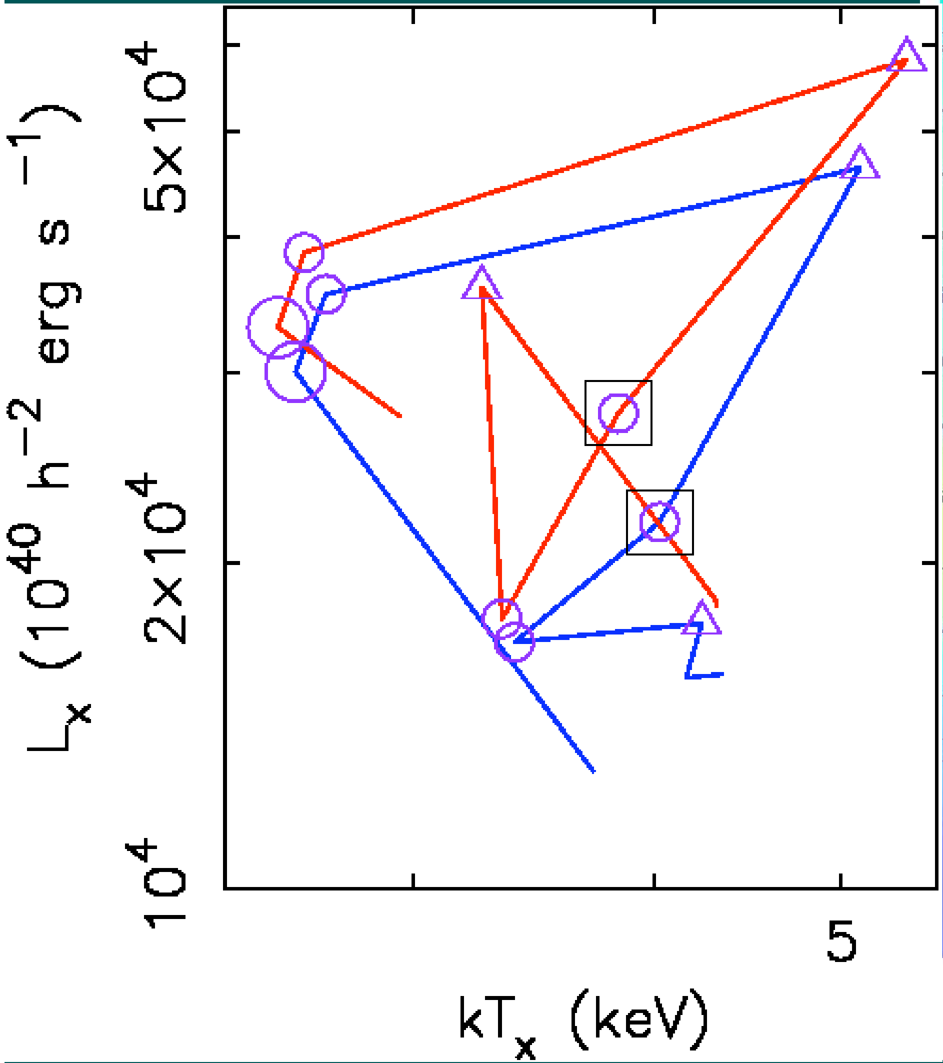




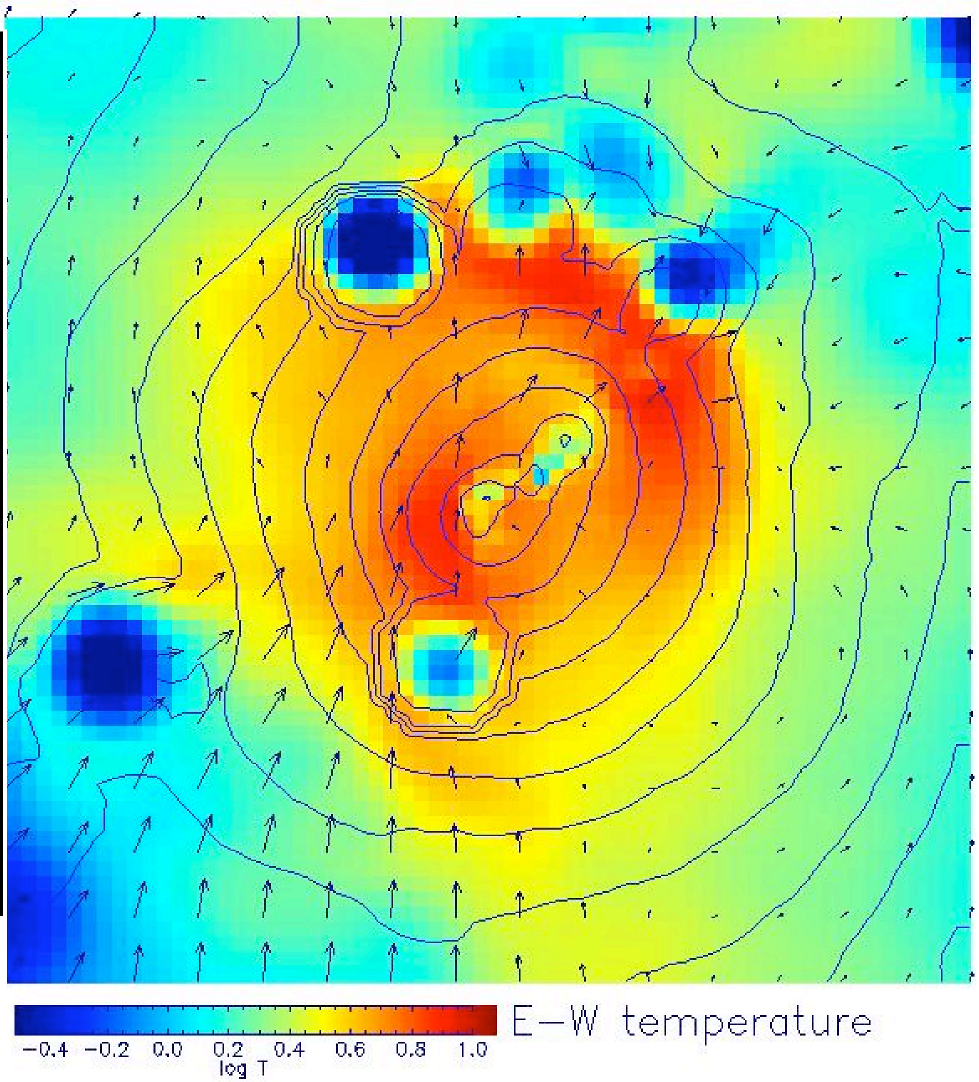
At its brightest the cluster is regular in appearance and displaced parallel to the L-T relation



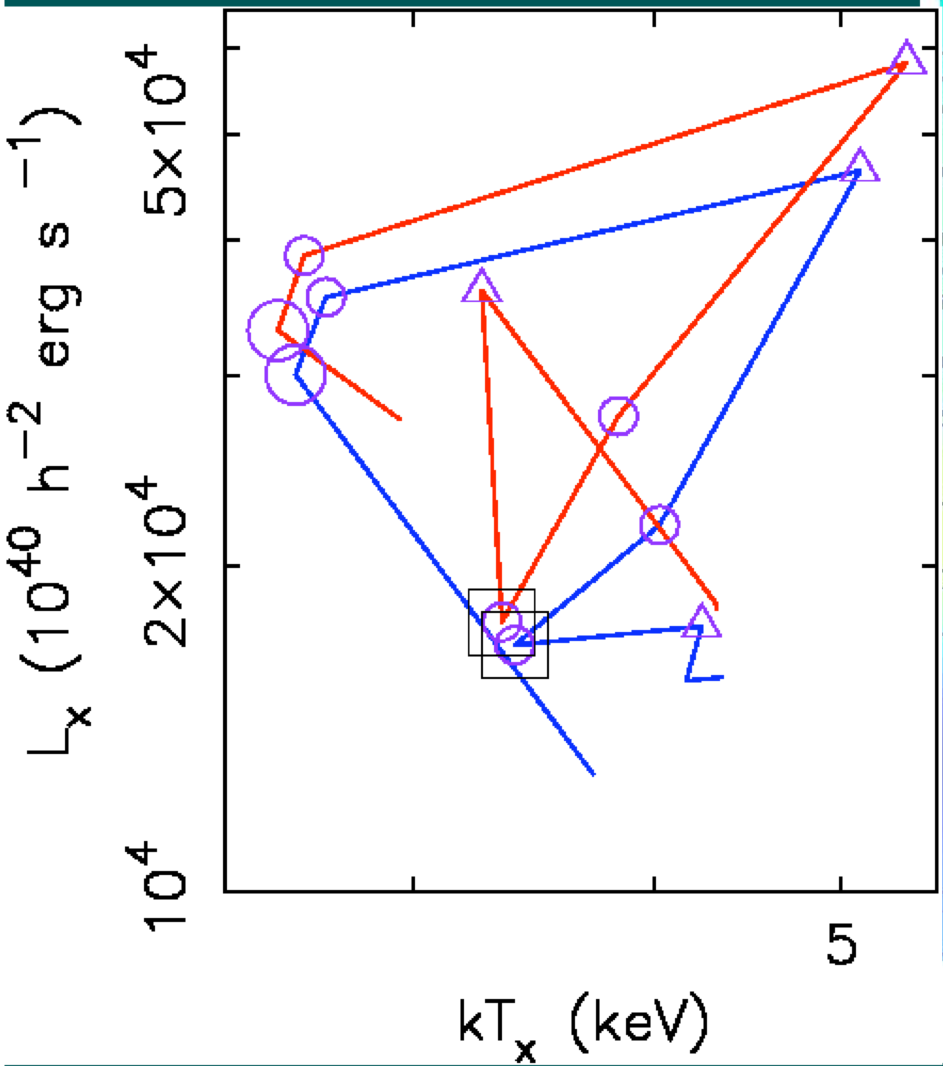


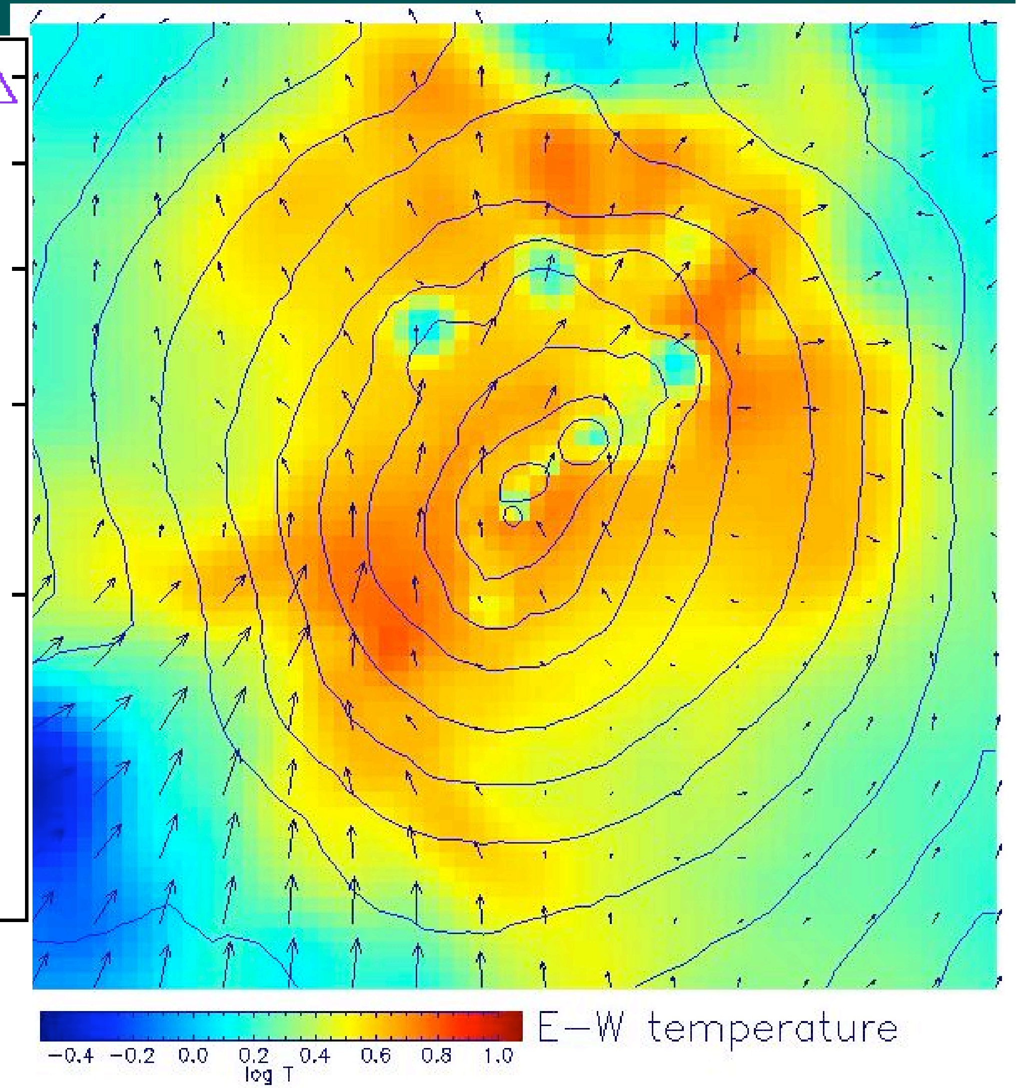


L_x (10^{40} h^{-2} erg s^{-1})
10^4
2×10^4
5×10^4
5
kT_x (keV)

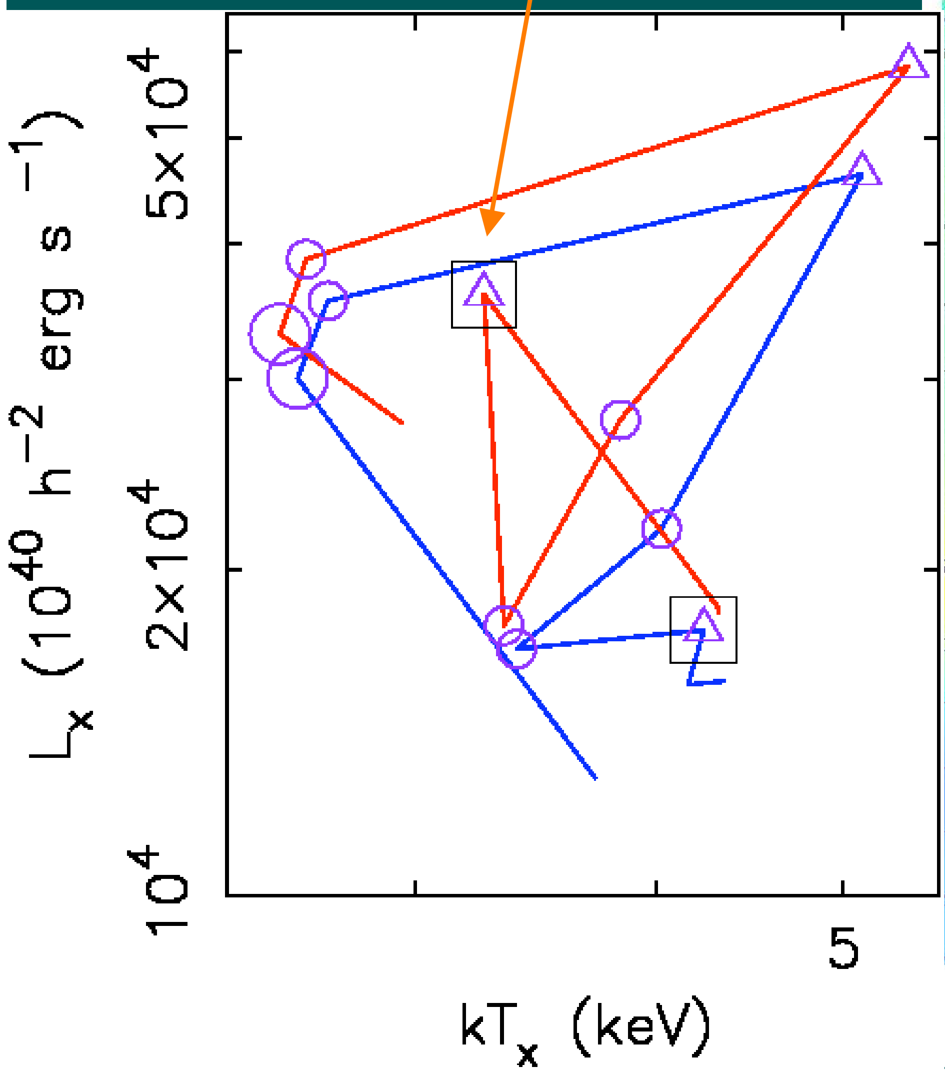


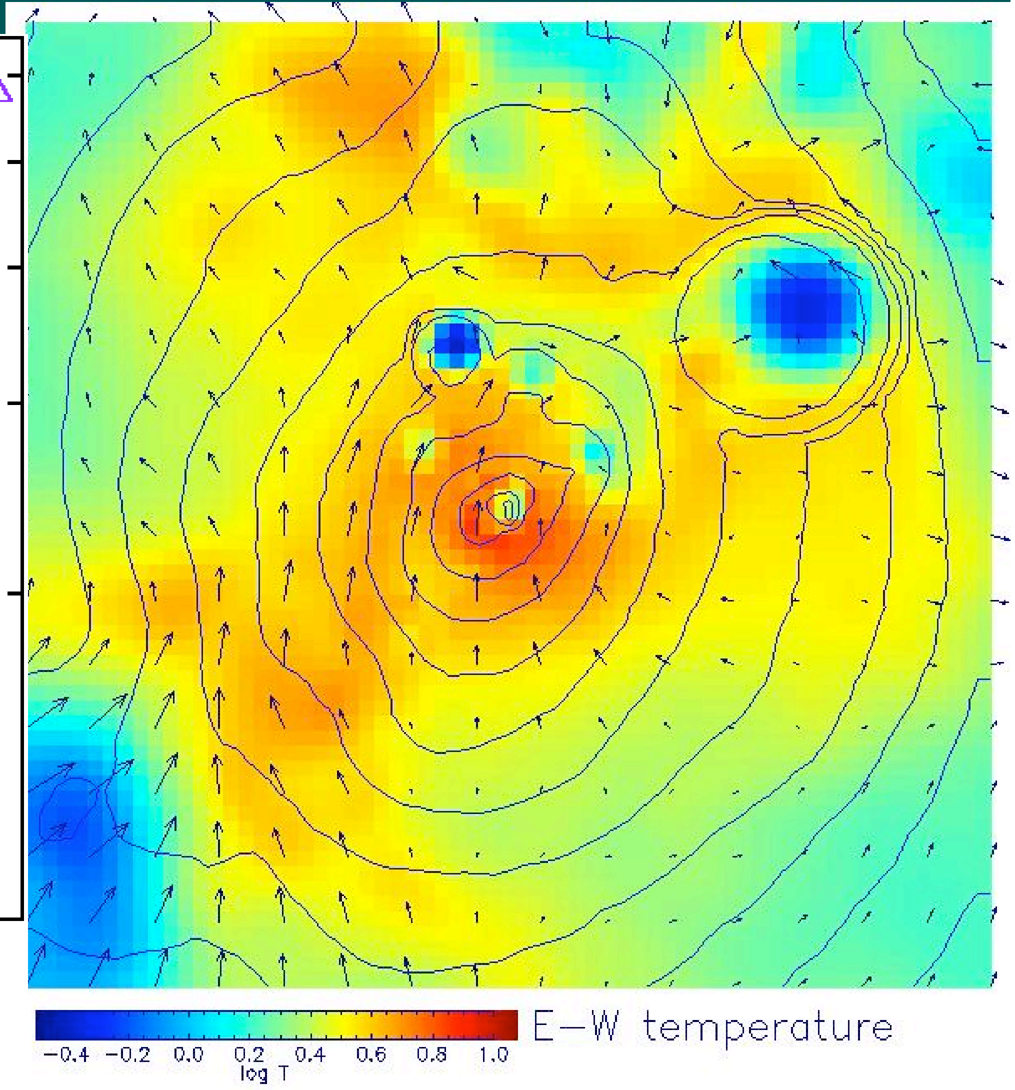
E−W temperature
−0.4 −0.2 0.0 0.2 0.4 0.6 0.8 1.0
log T

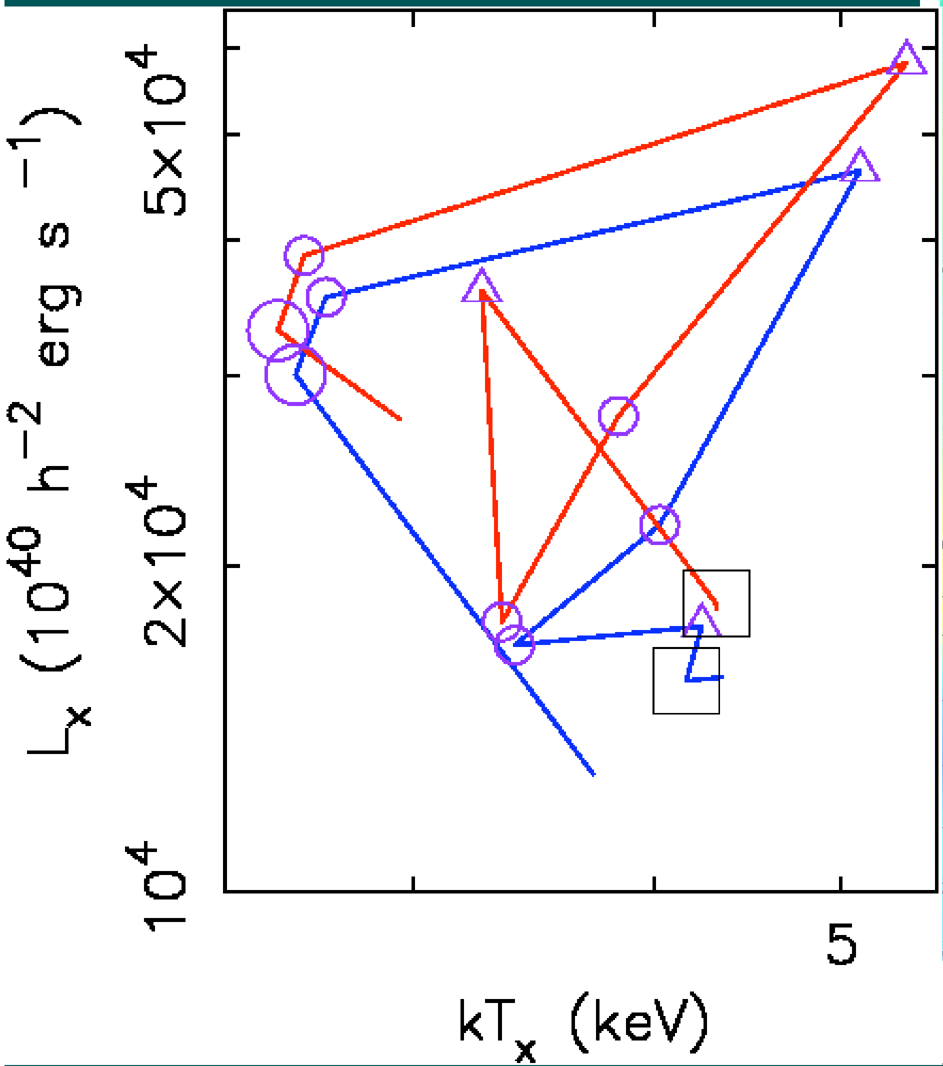

L_x (10^40 h^−2 erg s^−1)
5×10^4
2×10^4
10^4
5
kT_x (keV)


E−W temperature
−0.4 −0.2 0.0 0.2 0.4 0.6 0.8 1.0
log T

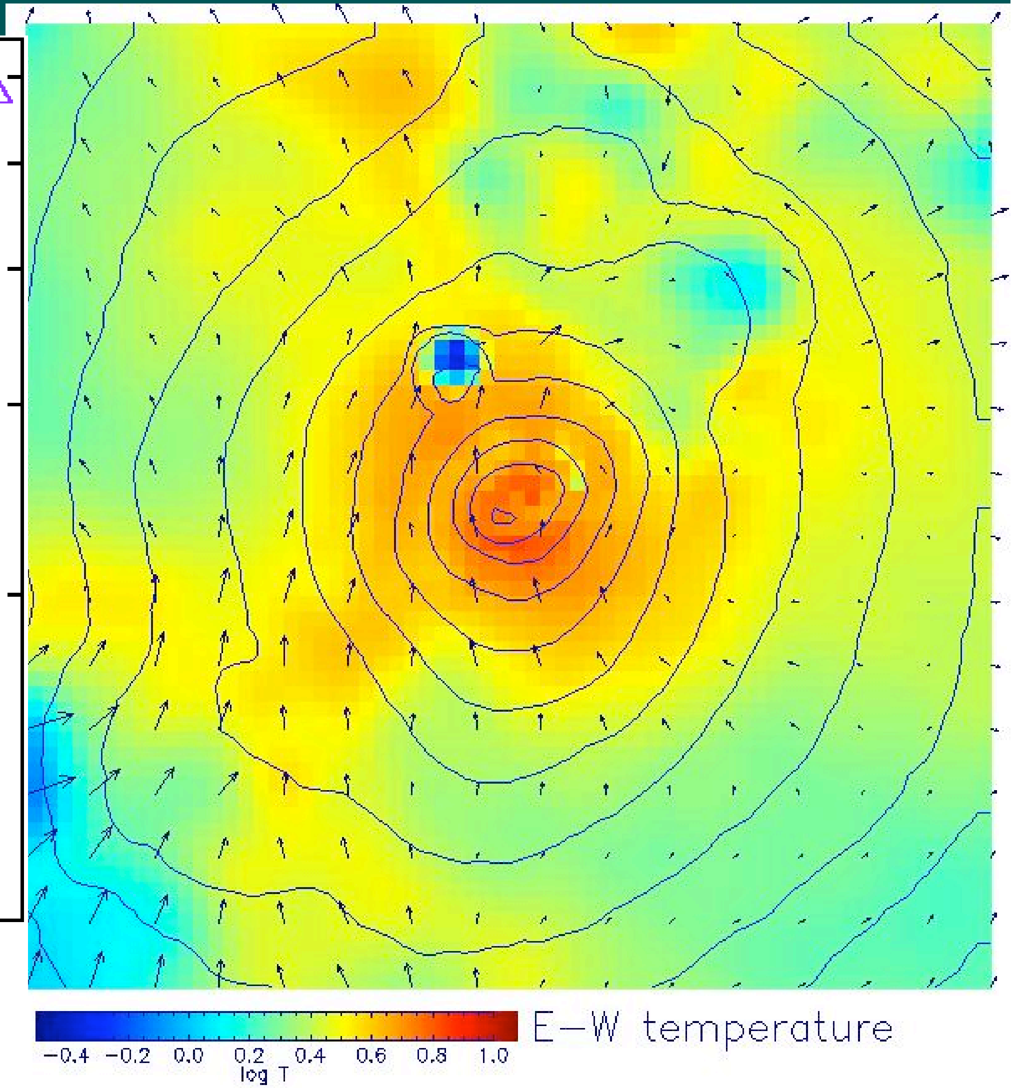
The cluster here is again bright and regular in appearance,
This time with a cool core—a cooling flow cluster.



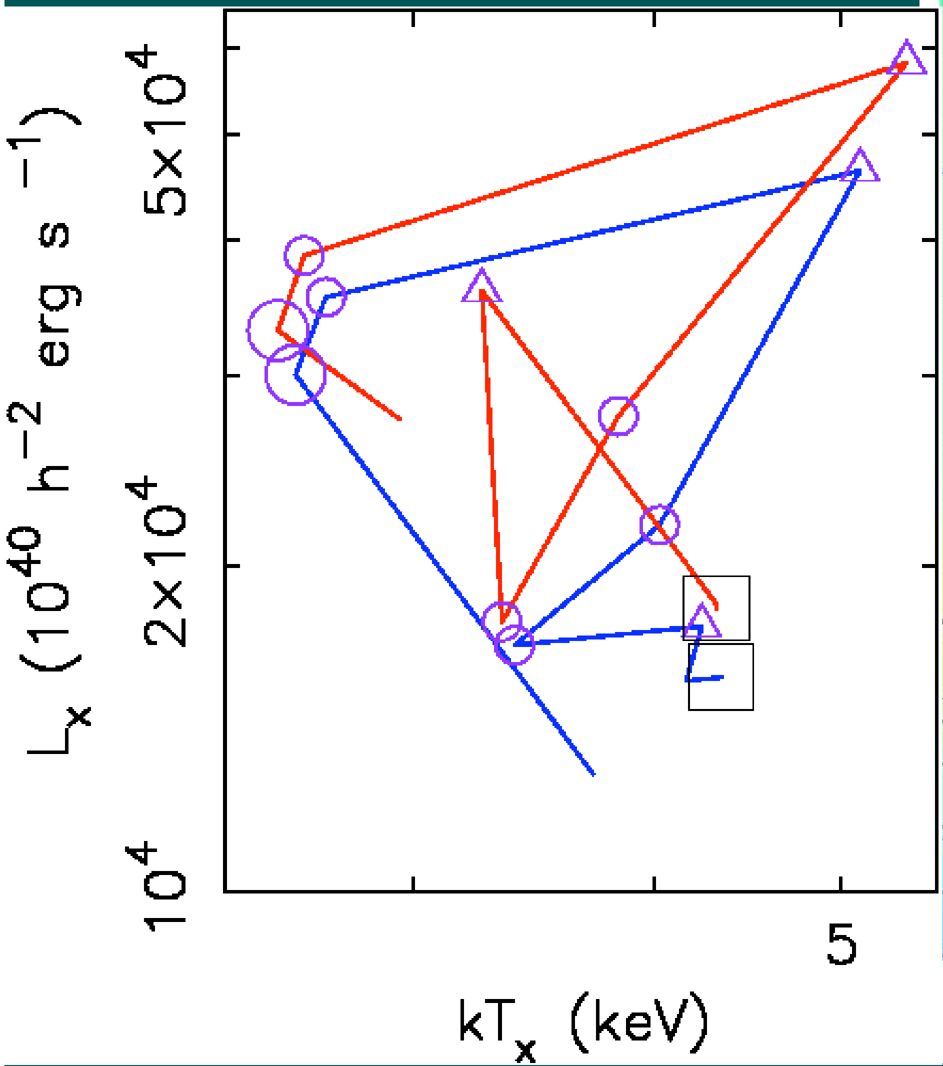




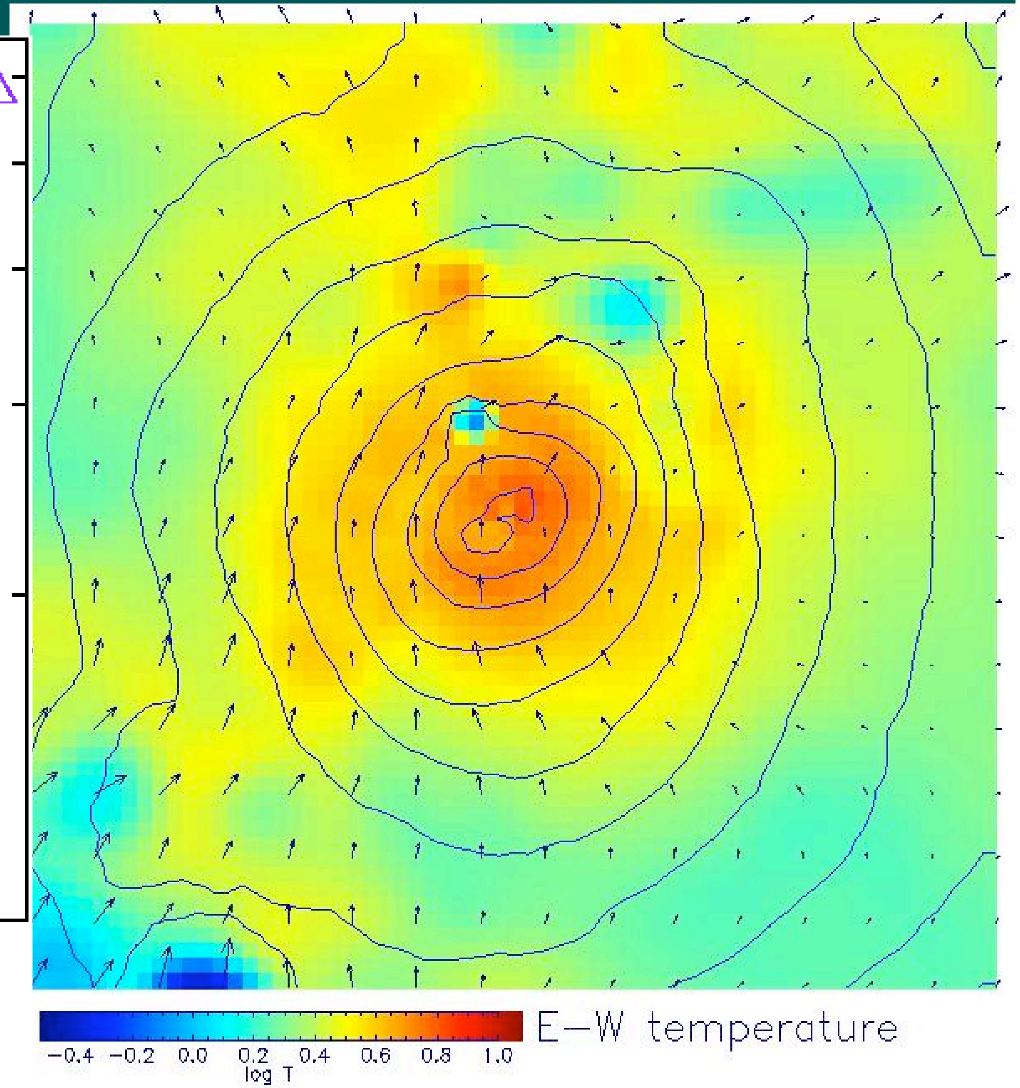
L_x (10^{40} h^{-2} erg s^{-1})
10^4
2×10^4
5×10^4
5
kT_x (keV)



E−W temperature
−0.4 −0.2 0.0 0.2 0.4 0.6 0.8 1.0
log T

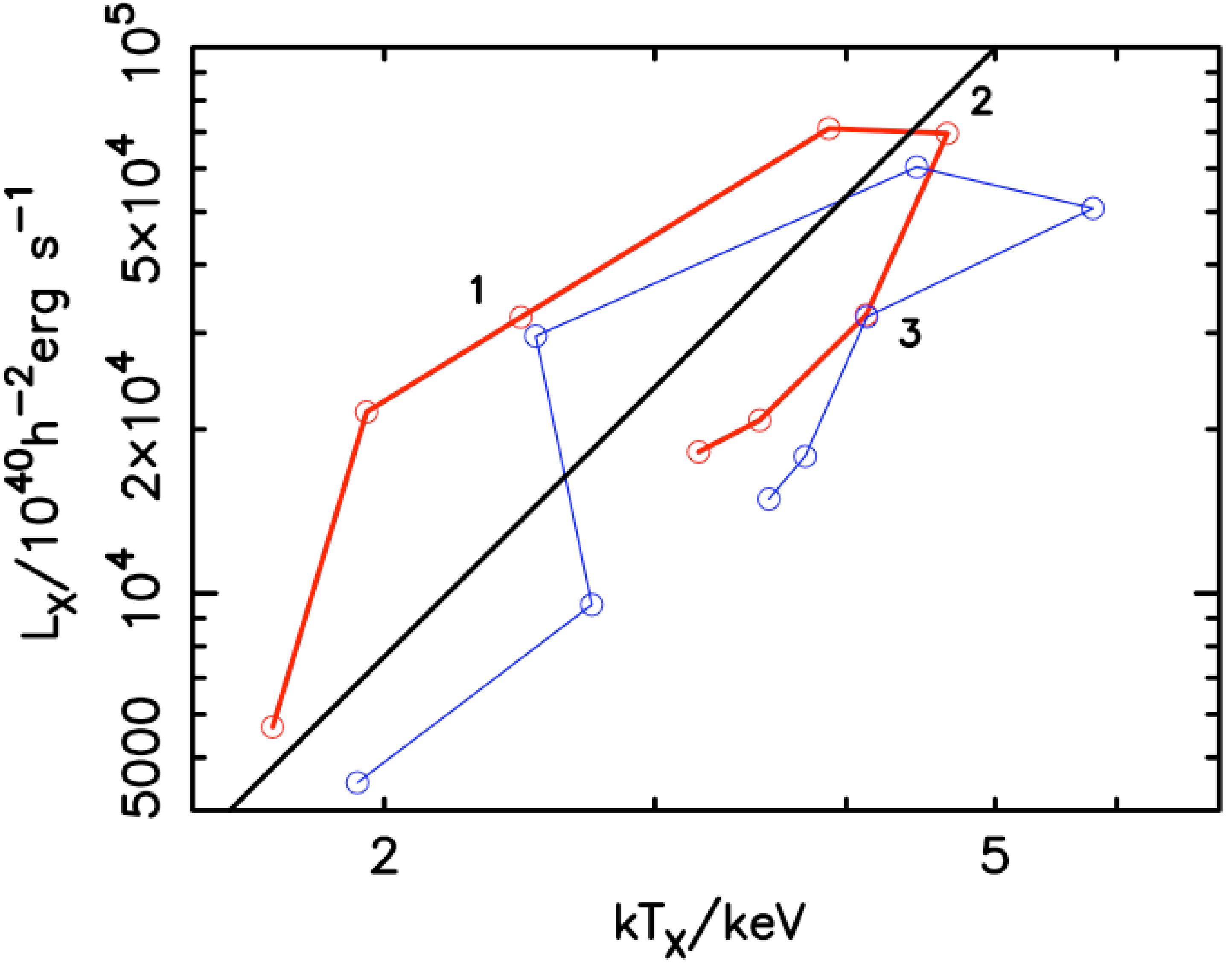


L_x (10^{40} h^{-2} erg s^{-1})
5×10^4
2×10^4
10^4
5
kT_x (keV)



E–W temperature
−0.4 −0.2 0.0 0.2 0.4 0.6 0.8 1.0
log T

Example: permanent jump in luminosity



Conclusions 3

University of Sussex

Clusters grow both by smooth accretion and via major mergers.

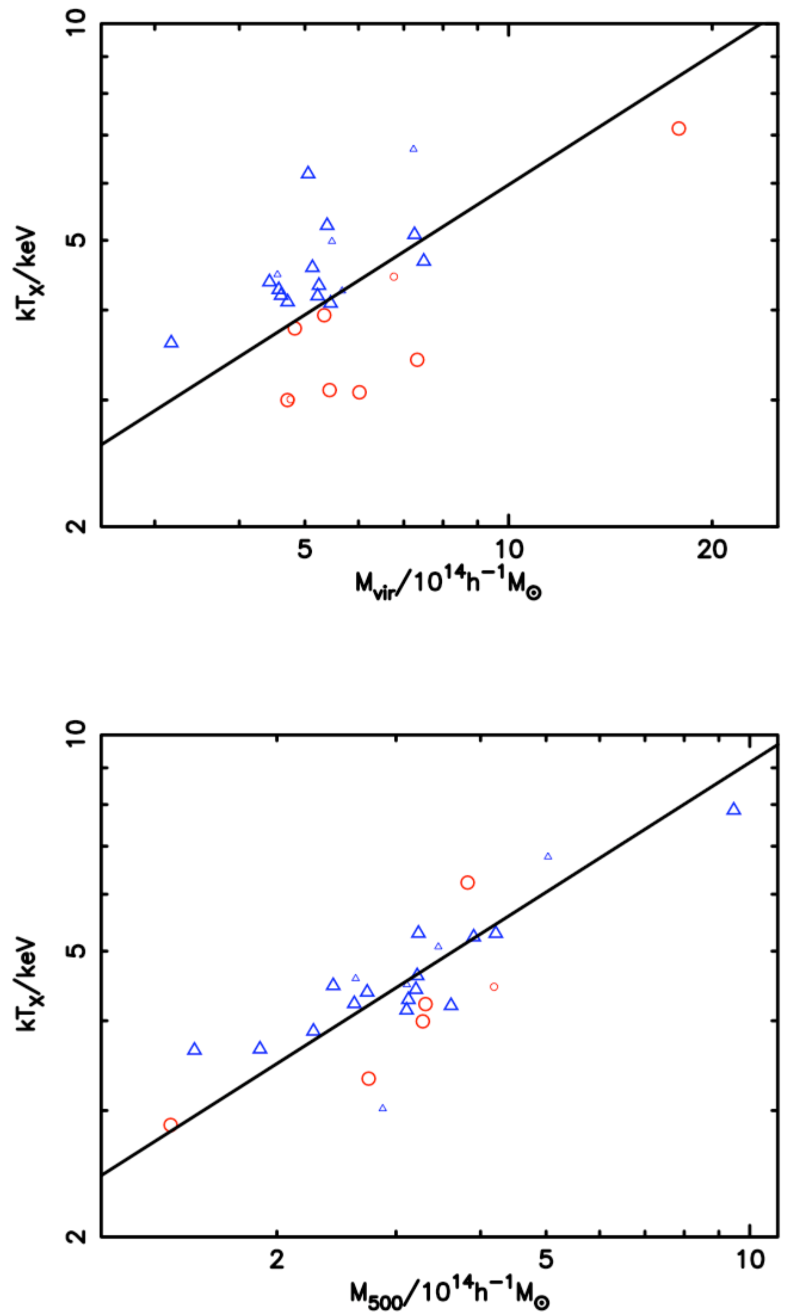
Major mergers tend to push the luminosity up the L_X-T_X relation. Between times the luminosity decreases, drifting with the mean L_X-T_X relation.

At the peak of the merger, the cluster often looks relaxed. Occasionally there is a second peak with a cool core making the cluster look instantaneously like a large cooling flow.

T_X-M relation

— is much tighter and less affected by substructure if properties are measured within R_{500} rather than R_{vir}.

Similarly for L_X-M and, to a lesser extent, L_X-T_X.



High-resolution resimulations of individual clusters

University of Sussex

with

Adrian Jenkins

Scott Kay

High-resolution resimulations of individual clusters

University of Sussex

•High-resolution resimulations

•L=479h^{-1}Mpc box

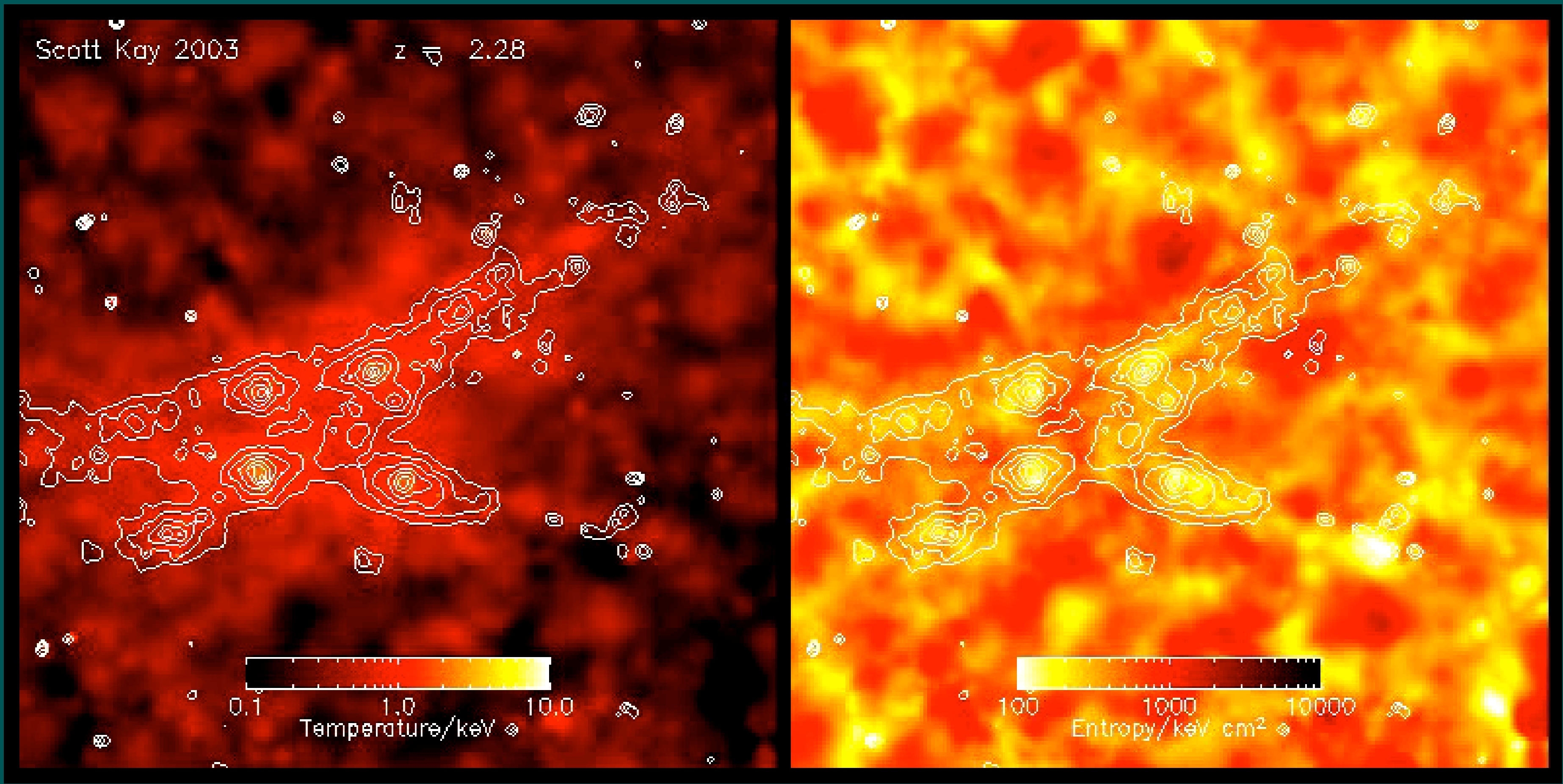
•N=variable

•h=0.7, _=0.7, _=0.3, $\_{b}$=0.045, σ_8=0.9, soft=3h^{-1}kpc

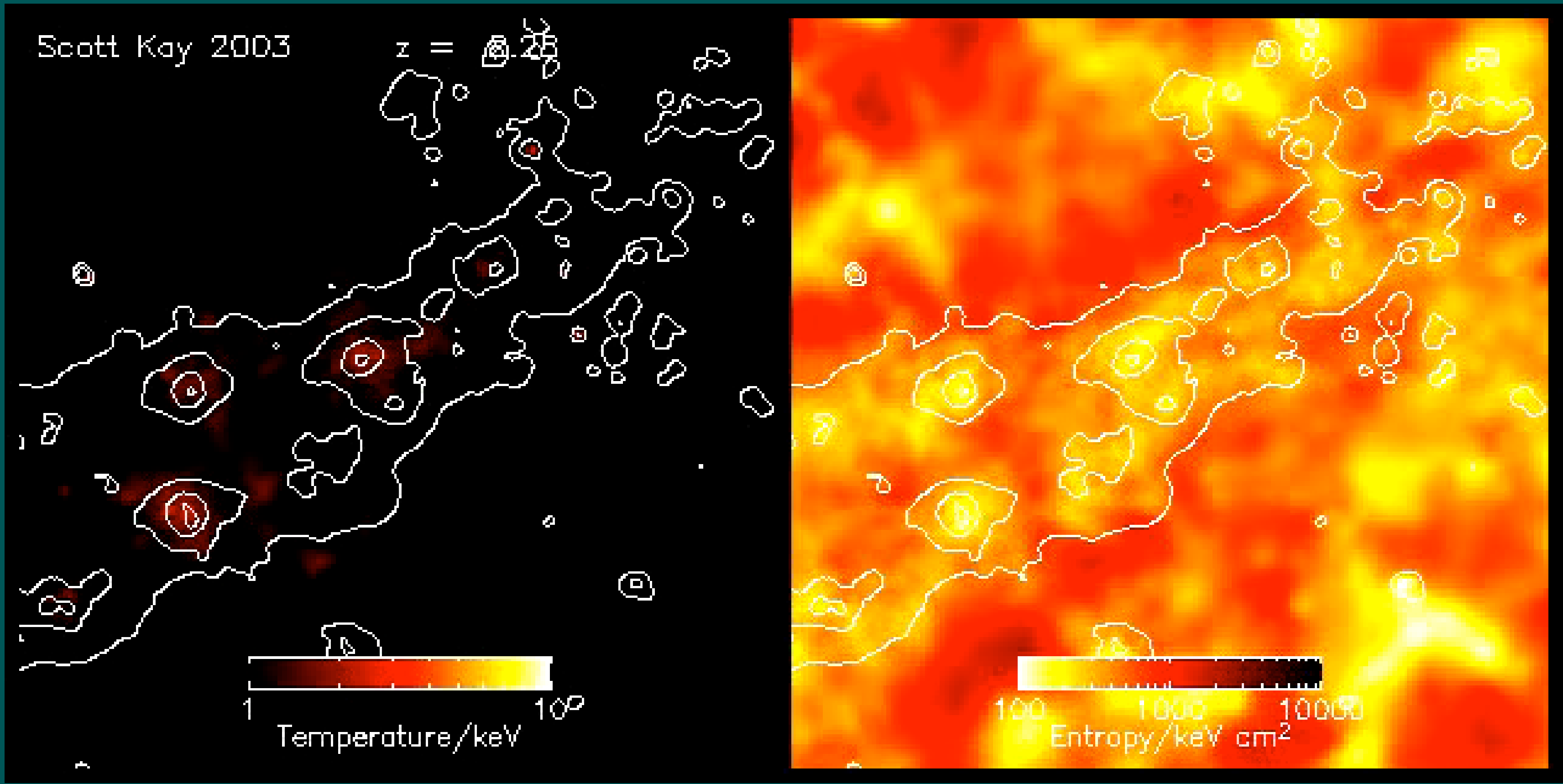
•M_{DM} = 8.4x$10^8 h^{-1} M_\odot$, M_{gas} = 1.5x10^8 $h^{-1} M_\odot$

•Feedback, Z=0.3$Z_\odot$, 10% of cooled particles given an entropy excess of 1000 keV cm^2

Temperature and entropy evolution



Temperature and entropy evolution



Conclusions

University of Sussex

Clusters show a wide range of formation histories.

The evolution of the intracluster medium provides a strong probe of cluster physics.