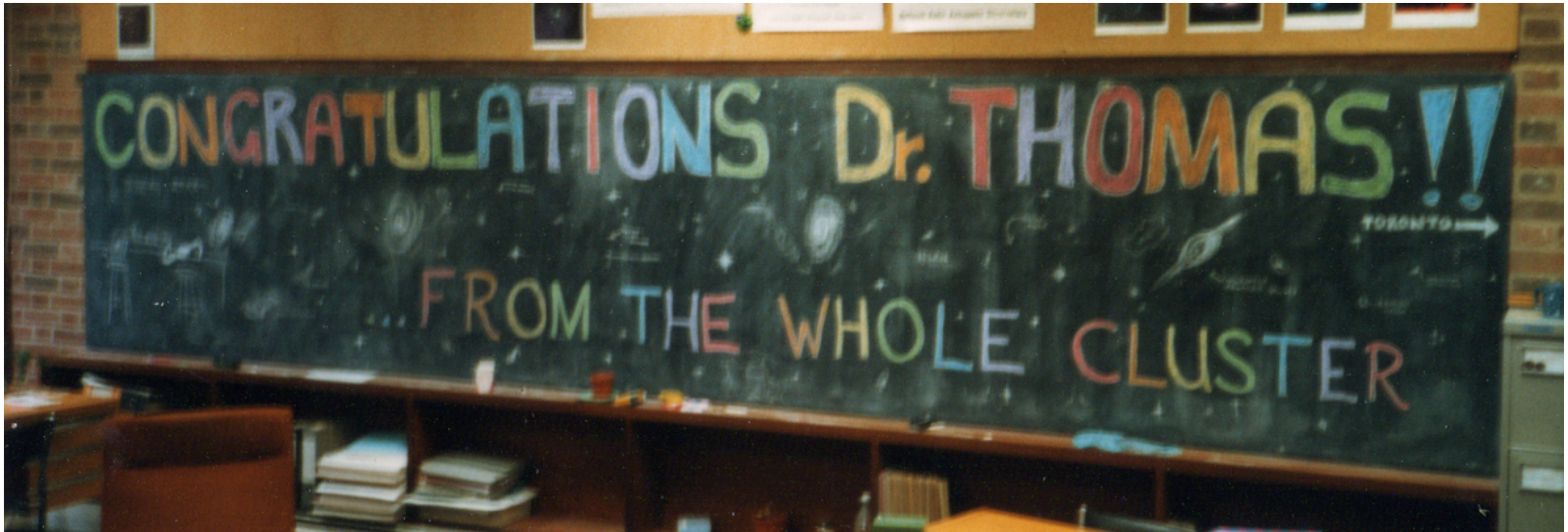
Simulations of galaxy clusters

Peter Thomas - Astronomy Centre, University of Sussex


CONGRATULATIONS Dr. THOMAS!!
TORONTO
...FROM THE WHOLE CLUSTER

Mon. Not. R. astr. Soc. (1986) **220,** 949–969

A cooling flow in the giant, elliptical galaxy NGC 4472

Peter A. Thomas *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

Mon. Not. R. astr. Soc. (1986) **221,** 1049–1056

A lower limit to the binding mass of early-type galaxies

A. C. Fabian,[1] P. A. Thomas,[1] S. M. Fall[2,3] and R. E. White III[1]

Cool core

Mon. Not. R. astr. Soc. (1986) **222,** 655–672

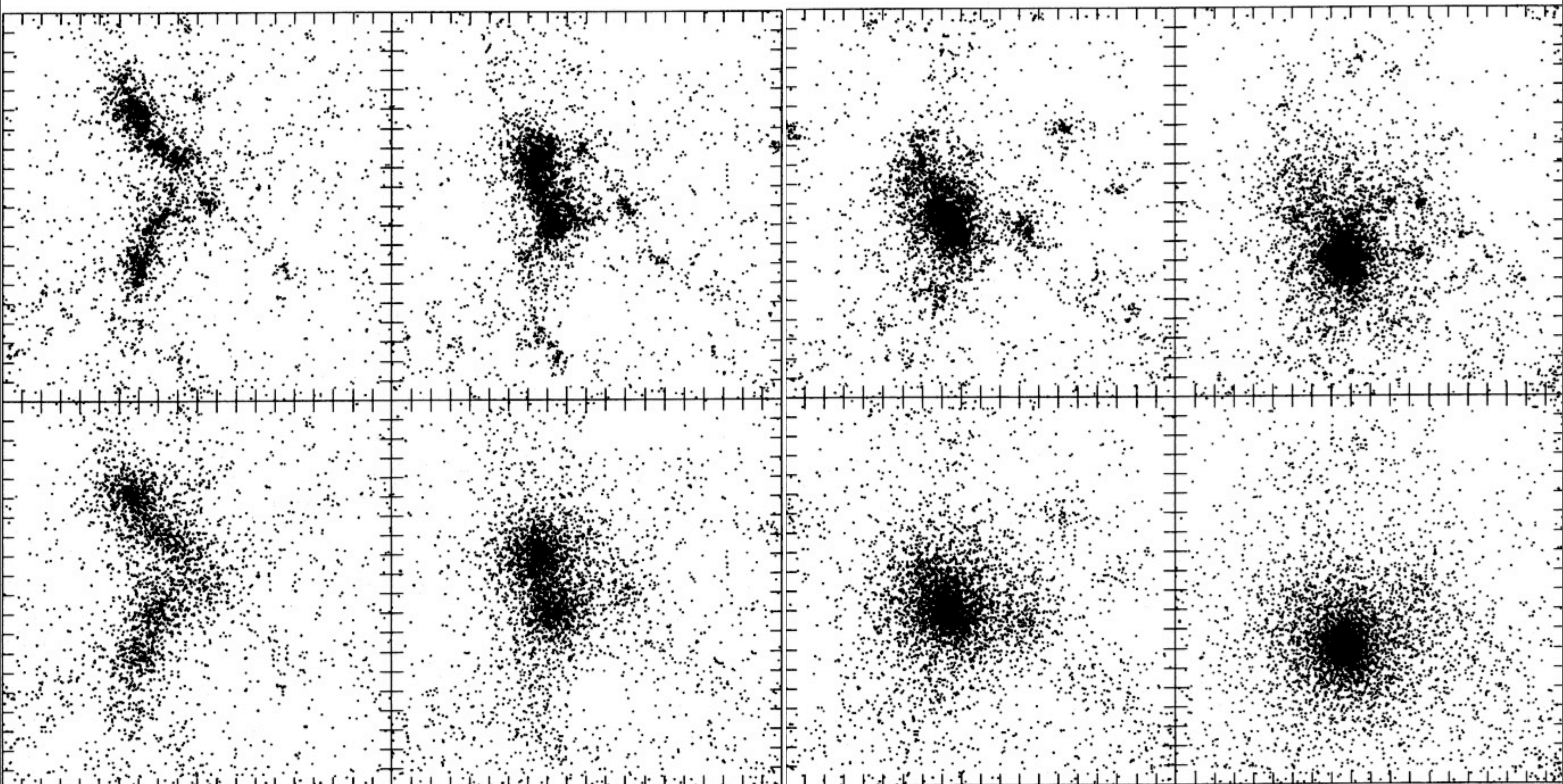
The prevalence of cooling flows in early-type galaxies

P. A. Thomas and A. C. Fabian *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

K. A. Arnaud, W. Forman and C. Jones *Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*

First cluster simulations with gas

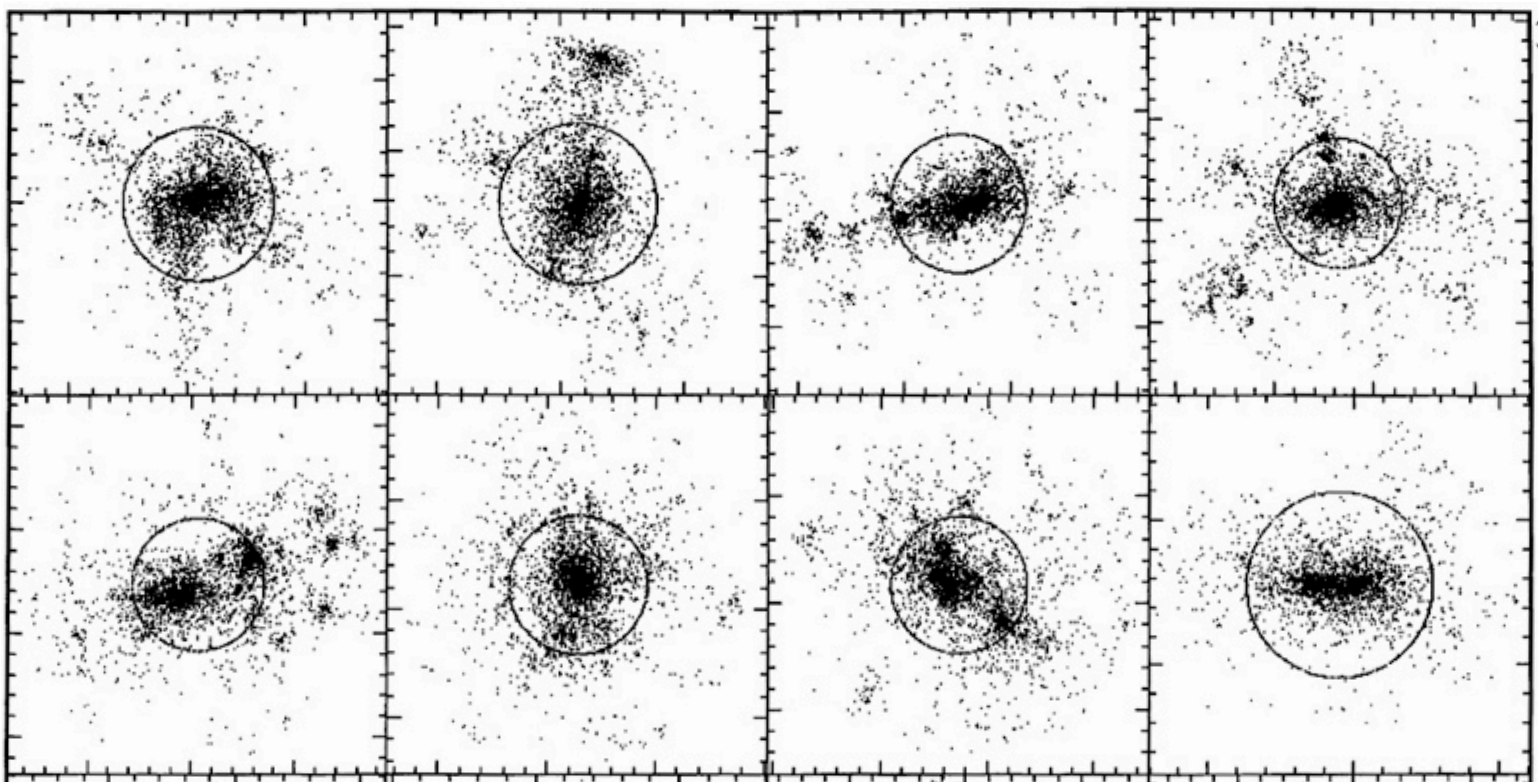
$N = 2 \times 32^3$; box = 25 h^{-1} Mpc; $M_{dark}=1.2 \times 10^{11}\ h^{-1}\ M_o$



Thomas & Couchman (1992)

Cluster catalogues: dark matter only

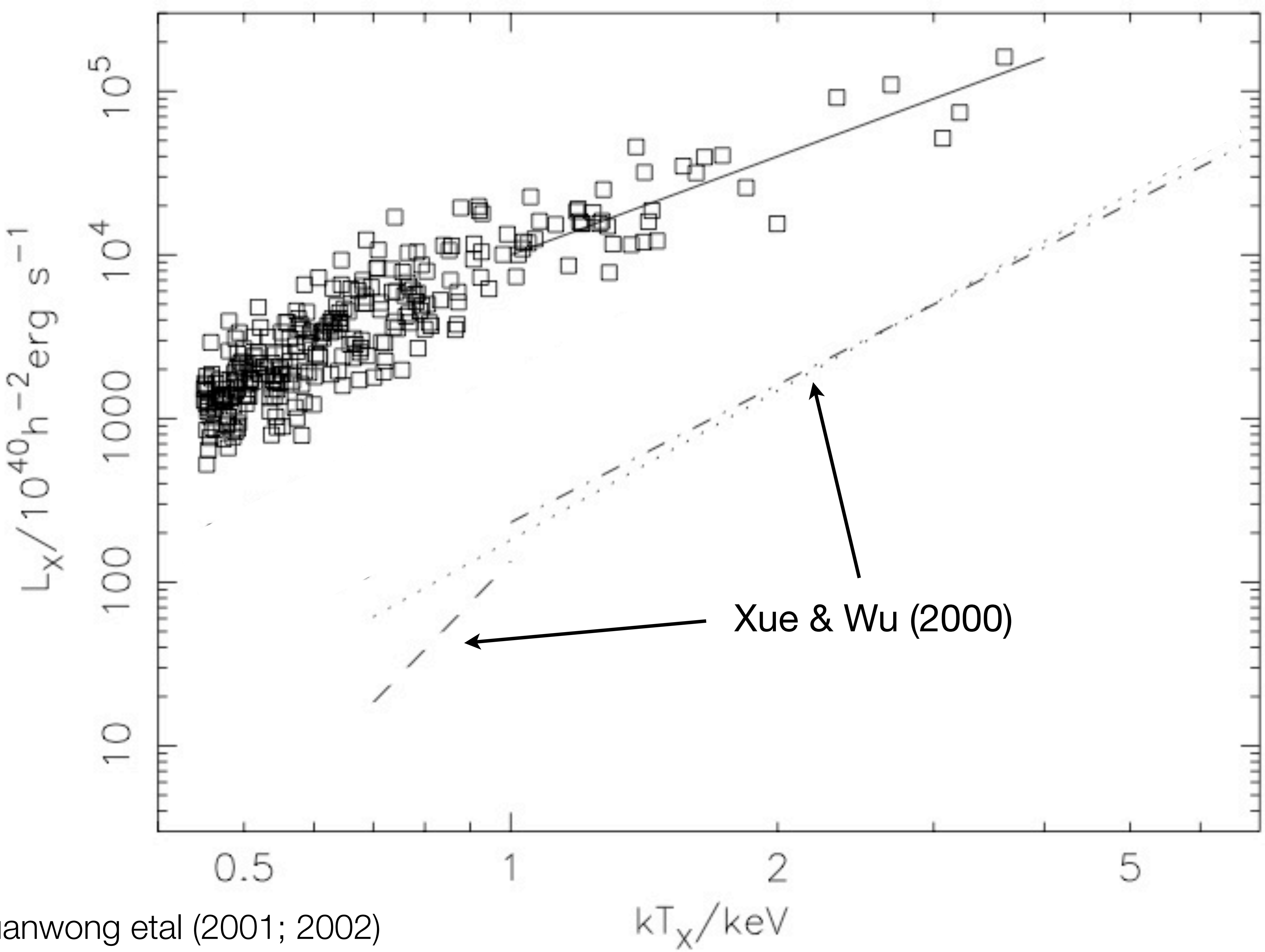
N = 256^3; box = 239.5 h^{-1} Mpc; M_{dark}=1-2 x 10^{11} h^{-1} M_o



Thomas & the Virgo Consortium (1998)

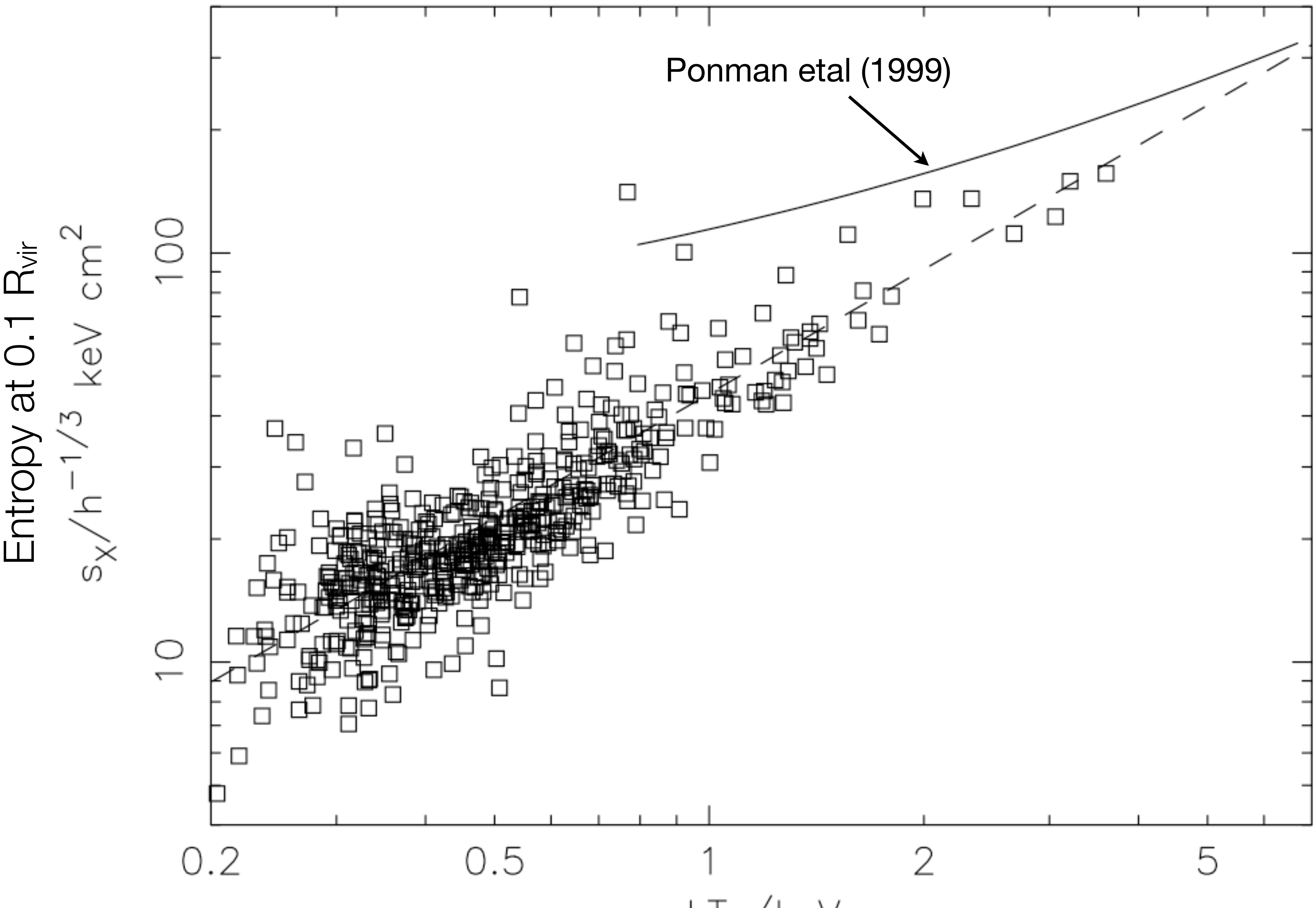
Cluster catalogues: gas plus dark matter

N = 160^3; box = 100 h^{-1} Mpc; M_{dark}=2 x 10^{11} h^{-1} M_o



Muanwong etal (2001; 2002)

Solution as an entropy excess



Muanwong etal (2001; 2002)

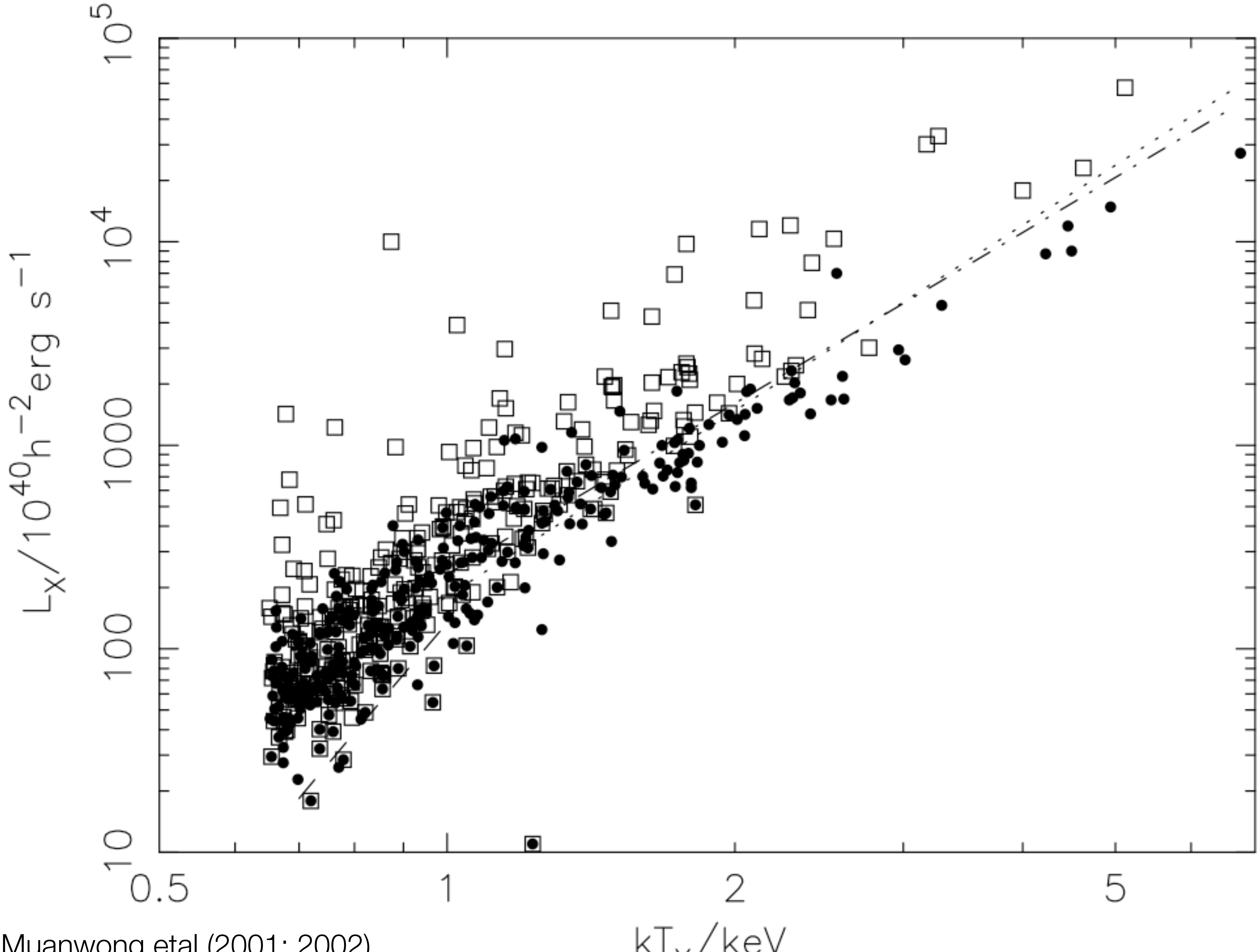
Ways to increase entropy

- Cooling: removes low-entropy gas from the core of the cluster.

- Preheating: widespread heating of gas prior to cluster formation.

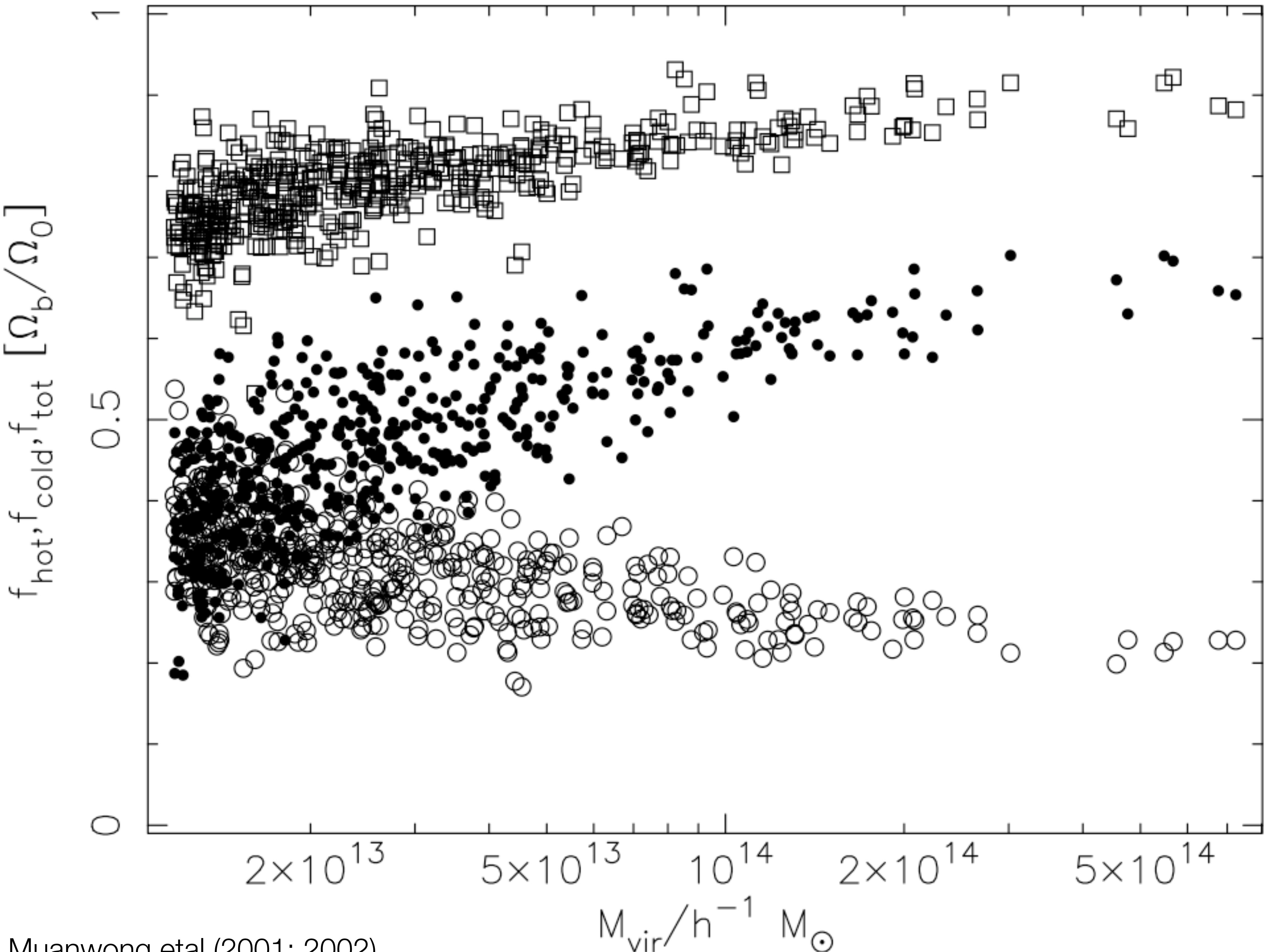
- Feedback: targeted heating in response to cooling of gas (via snr and agn).

Radiative cooling



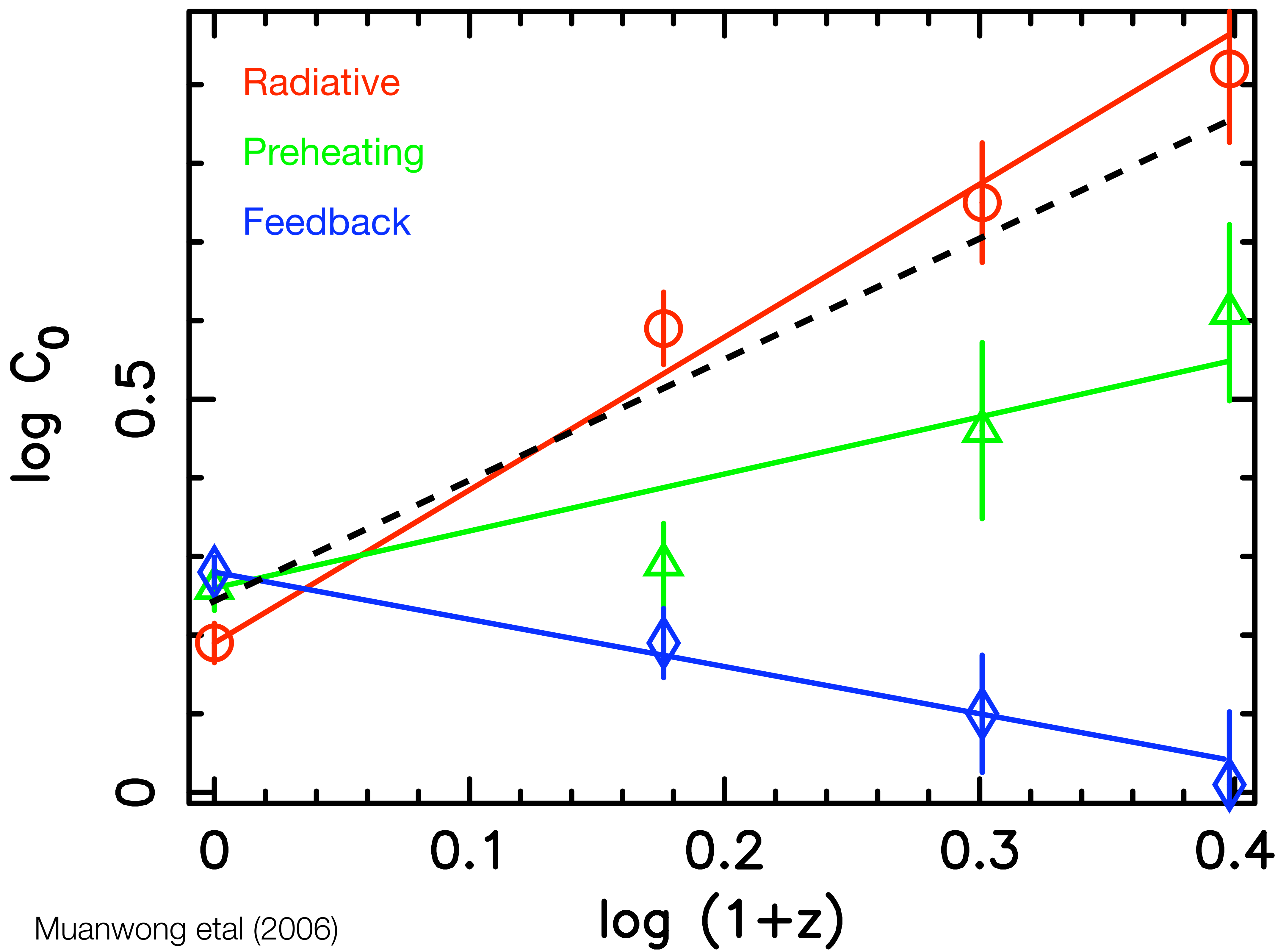
Muanwong etal (2001; 2002)

Radiative cooling: star fractions

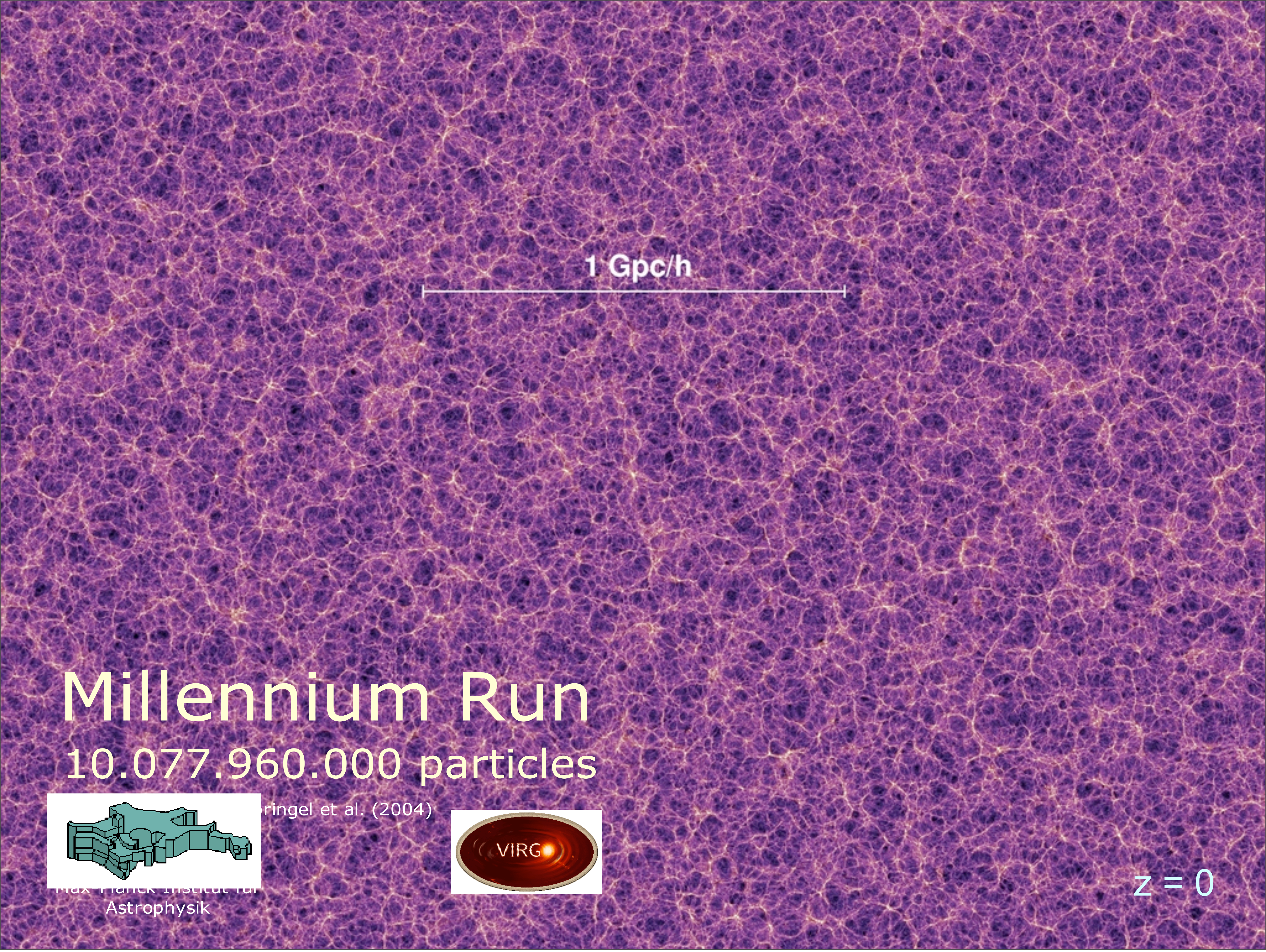


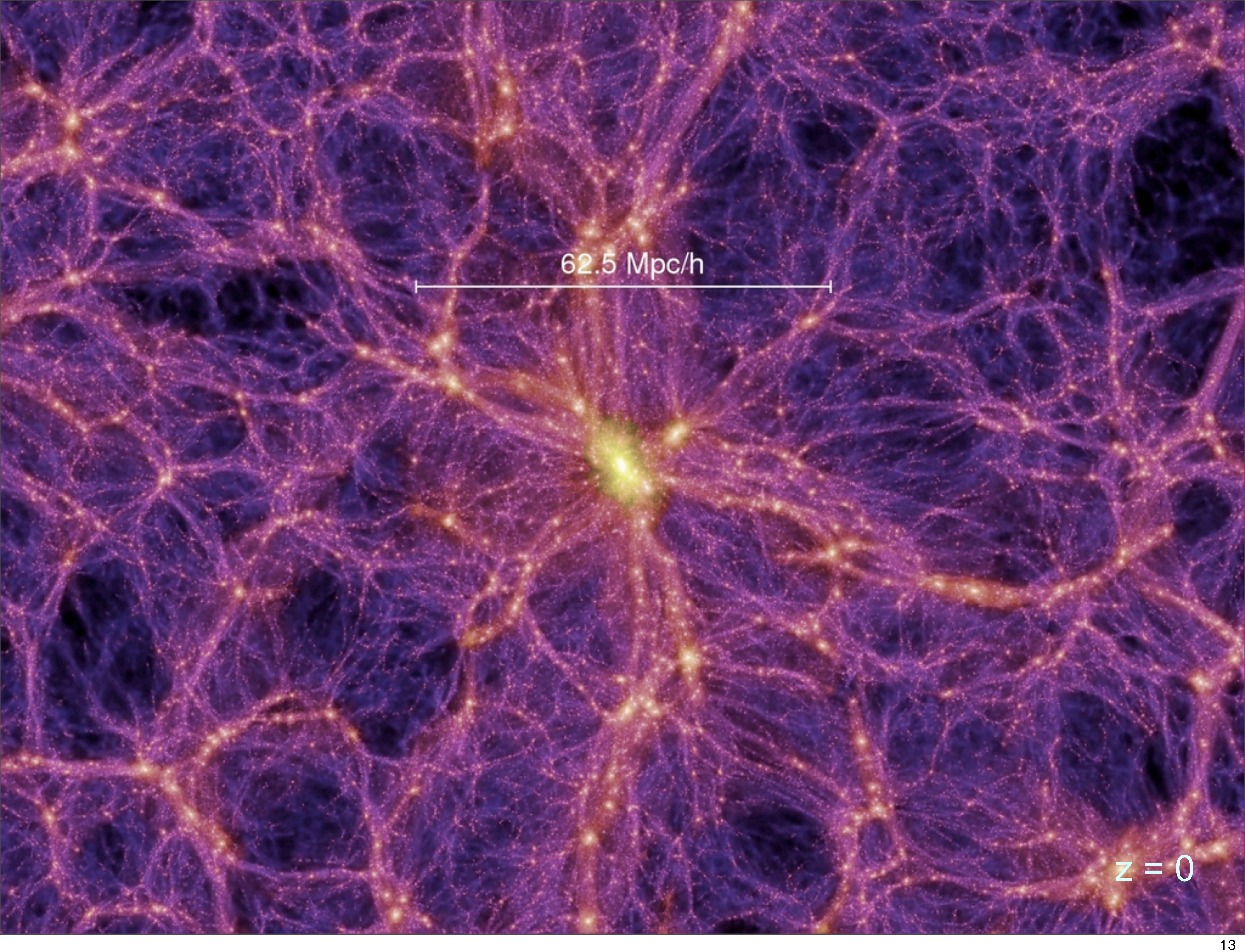
Muanwong etal (2001; 2002)

Evolution of the L-T relation



Muanwong etal (2006)

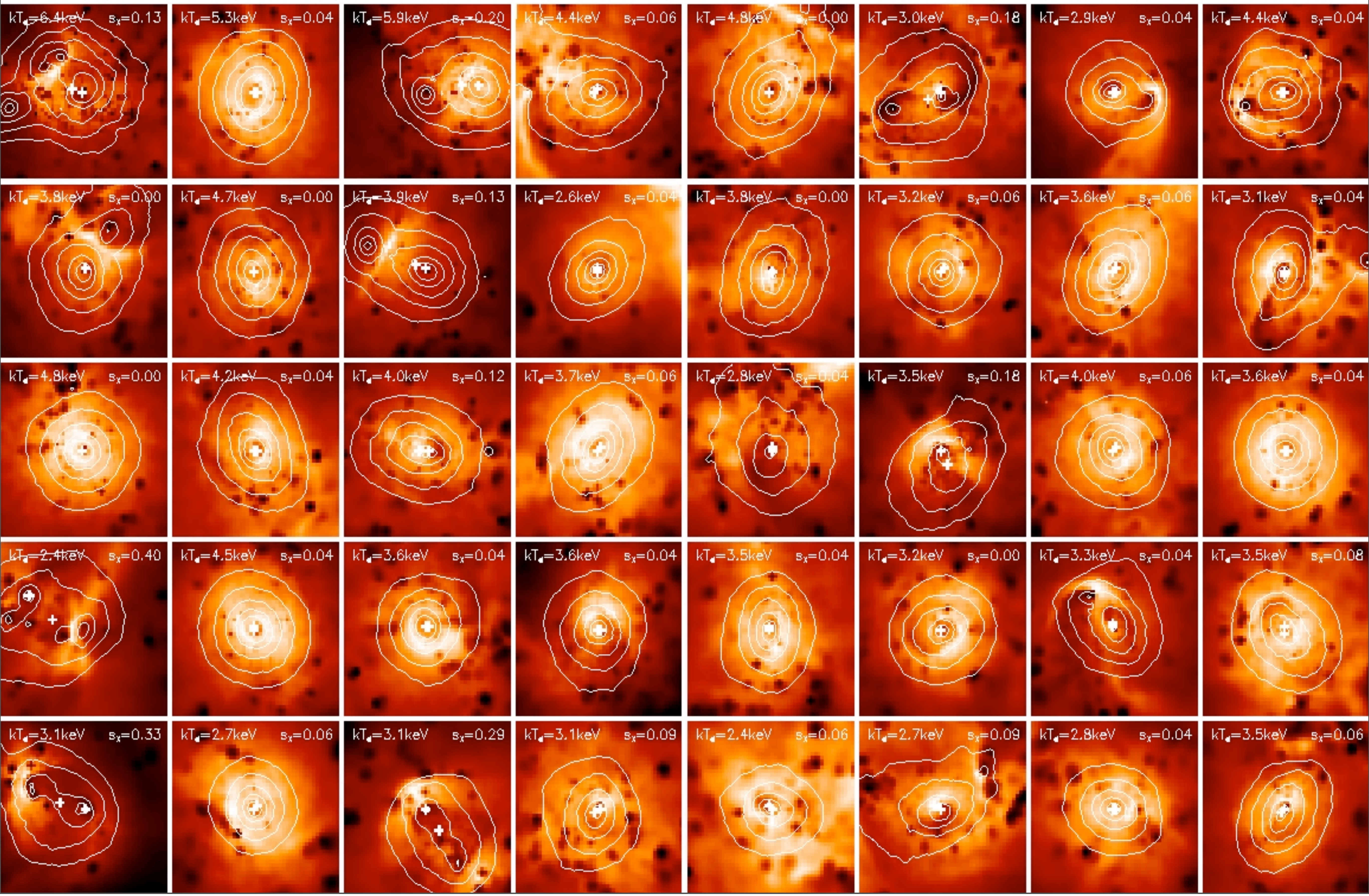

1 Gpc/h
Millennium Run
10.077.960.000 particles
pringel et al. (2004)
Astrophysik
z = 0


62.5 Mpc/h
z = 0

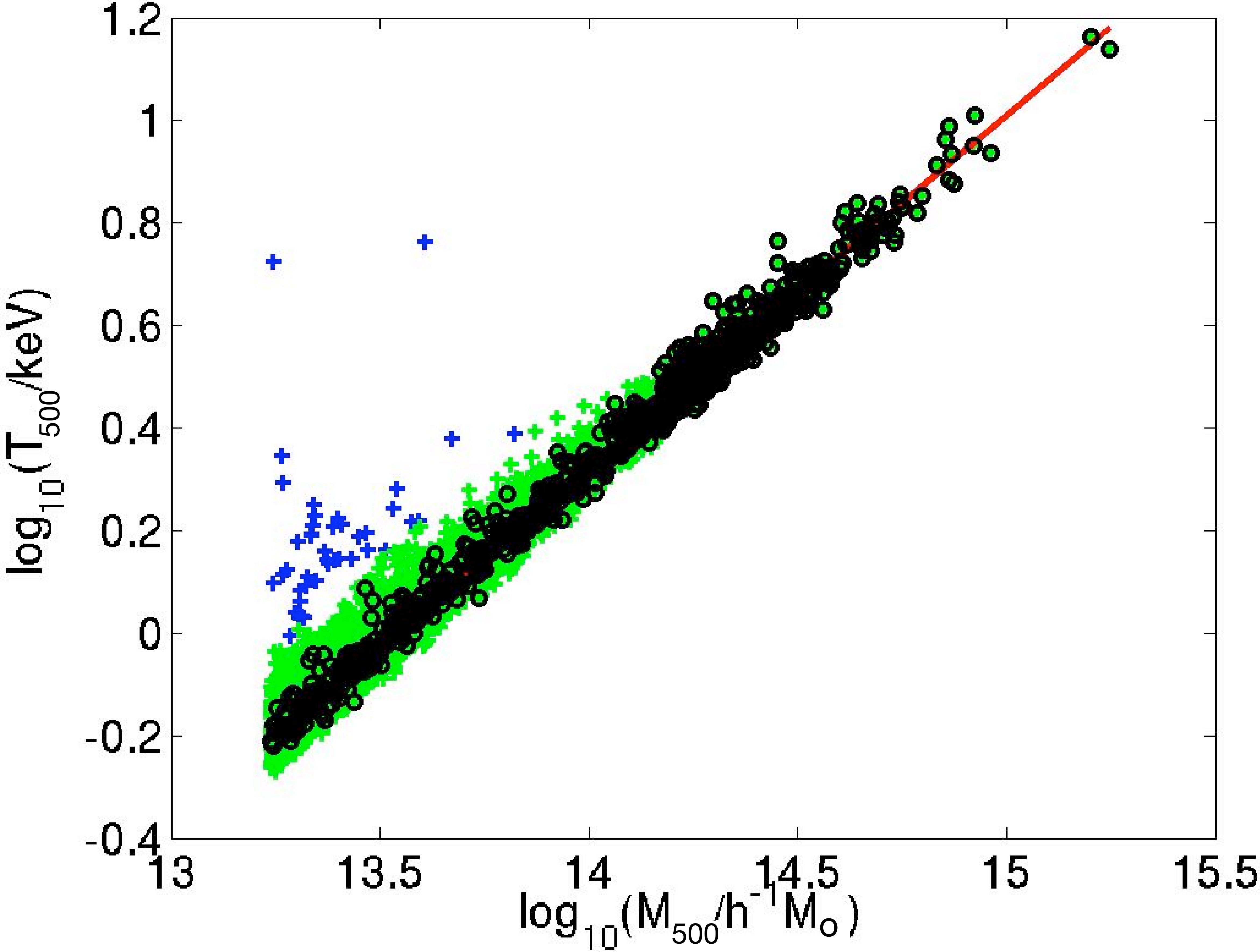
Millennium Gas project

- Same initial conditions as Millennium Simulation
- Ω_m=0.25, Ω_Λ=0.75, σ_8=0.9
- 500 h^{-1}Mpc box
- 500,000,000 each of dm + gas particles
- dm + gas mass 1.73x10^{10} $h^{-1}M_o$
- ~80 clusters with T_{vir}>5 keV
- Variety of runs with different physics: adiabatic; preheating; feedback

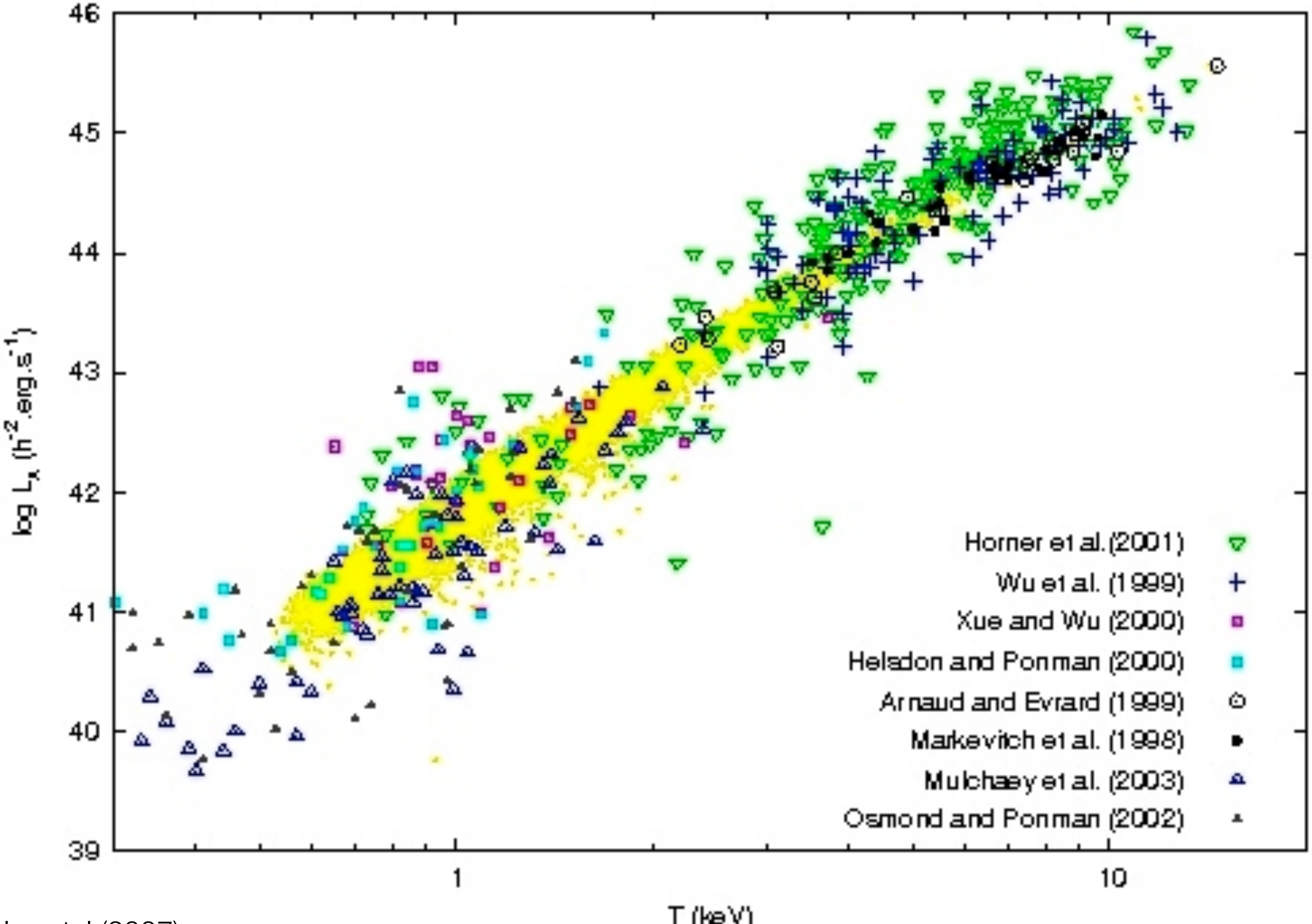
CLEF cluster catalogues



Millennium Gas clusters



L_X-T_X, preheating run

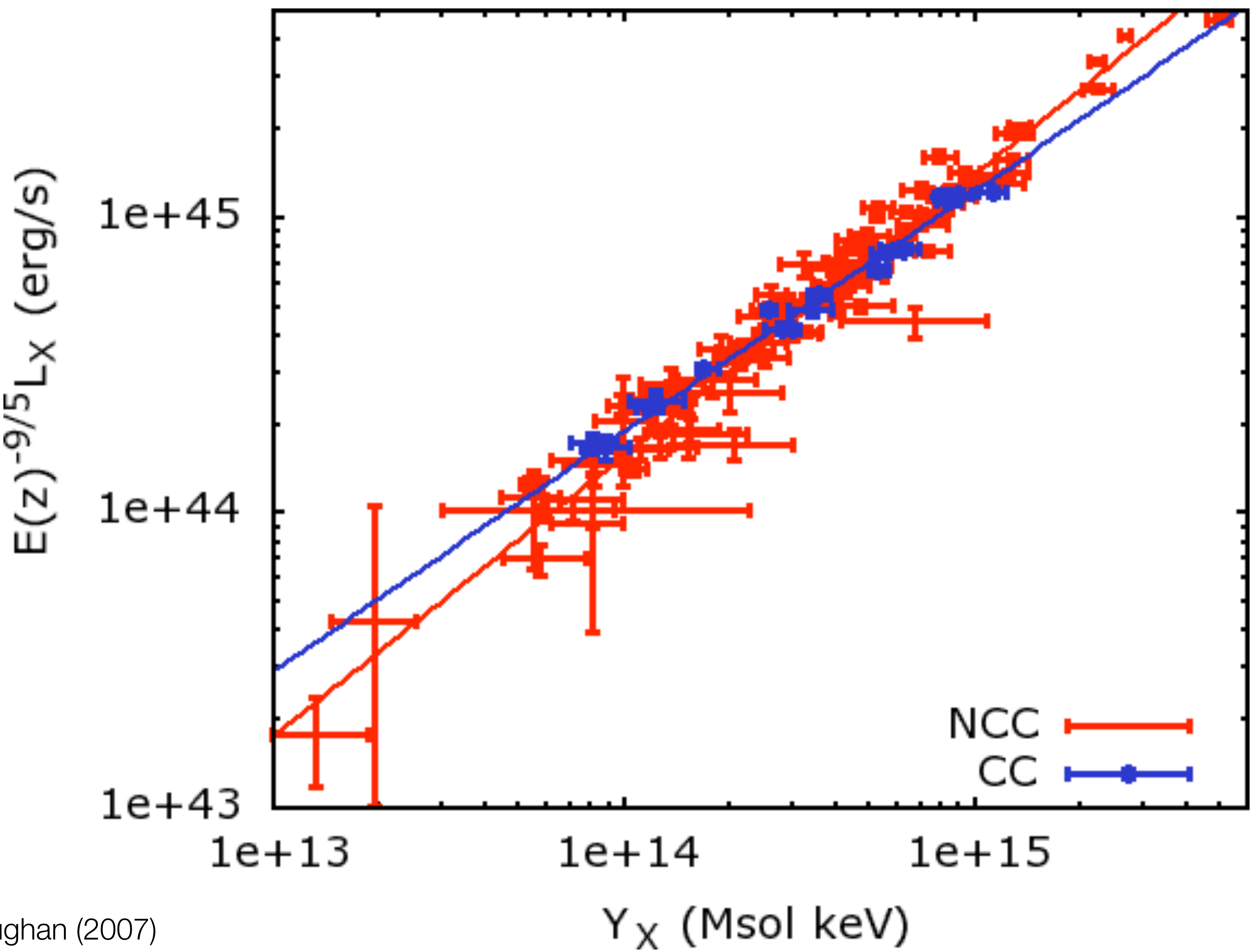


Hartley etal (2007)

Hartley etal (2007)

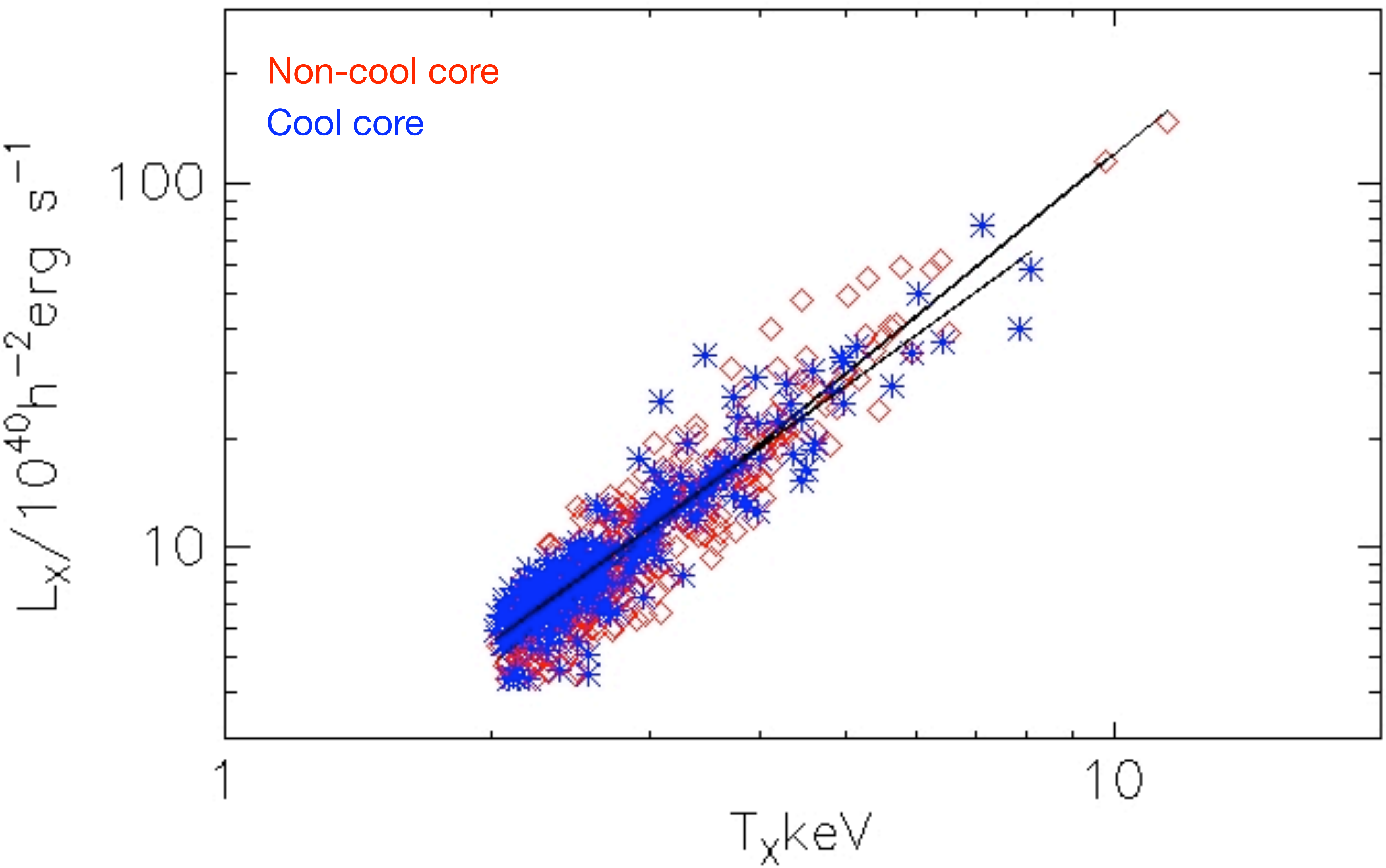
Cool cores

T(R/R_{500} < 0.15) < T(0.15 < R/R_{500} < 0.3)

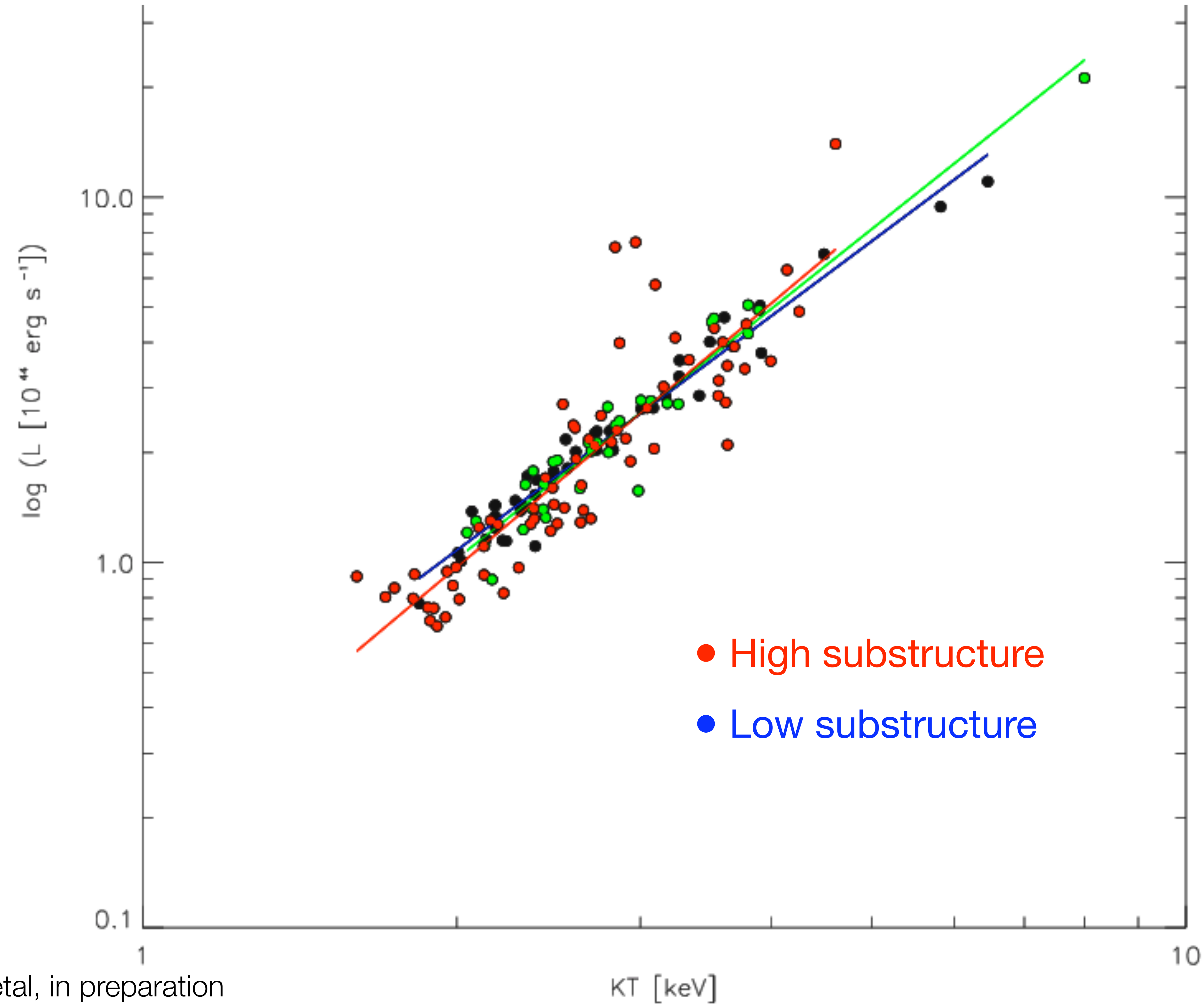


Maughan (2007)

Cool cores in the preheating simulation

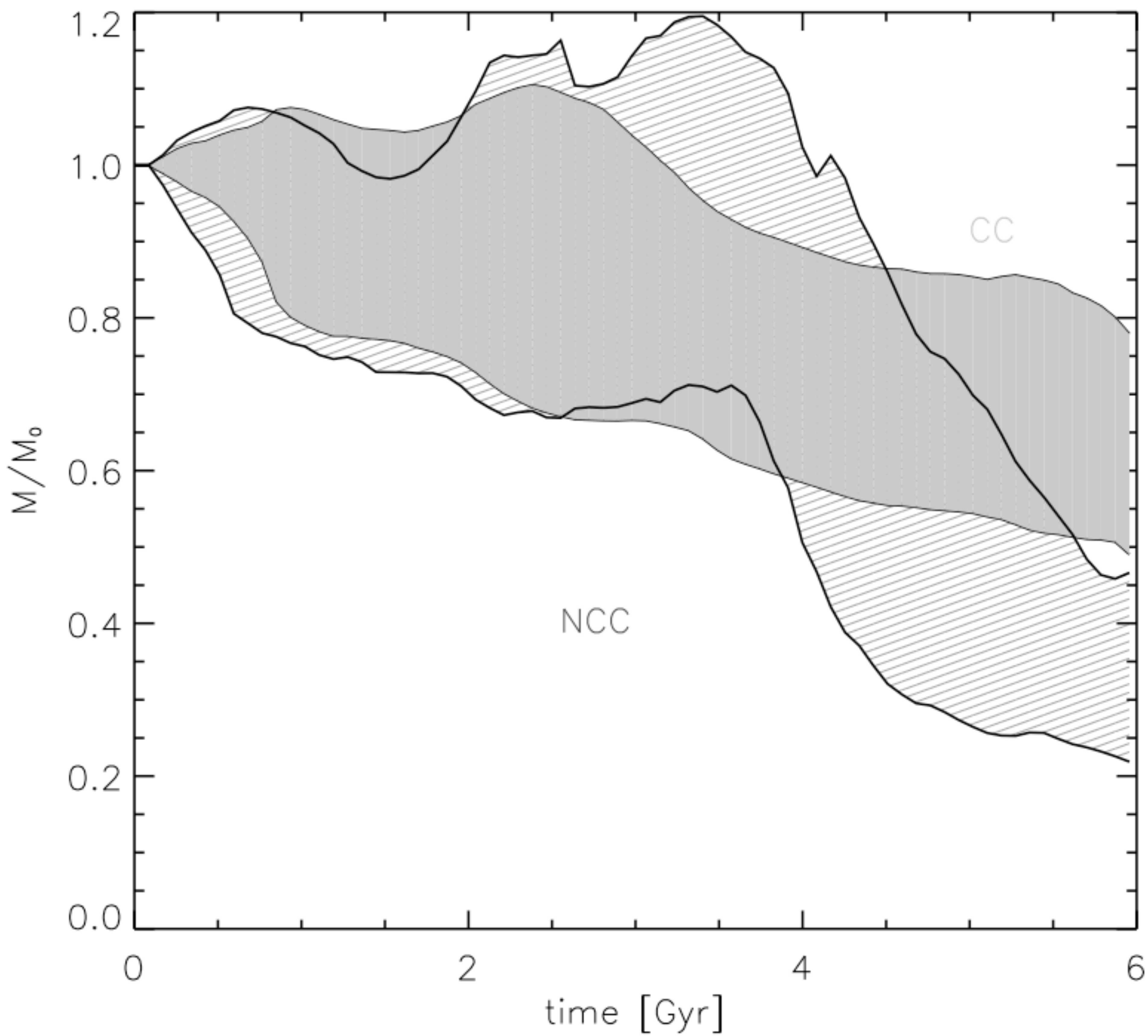


Relationship between substructure and L-T

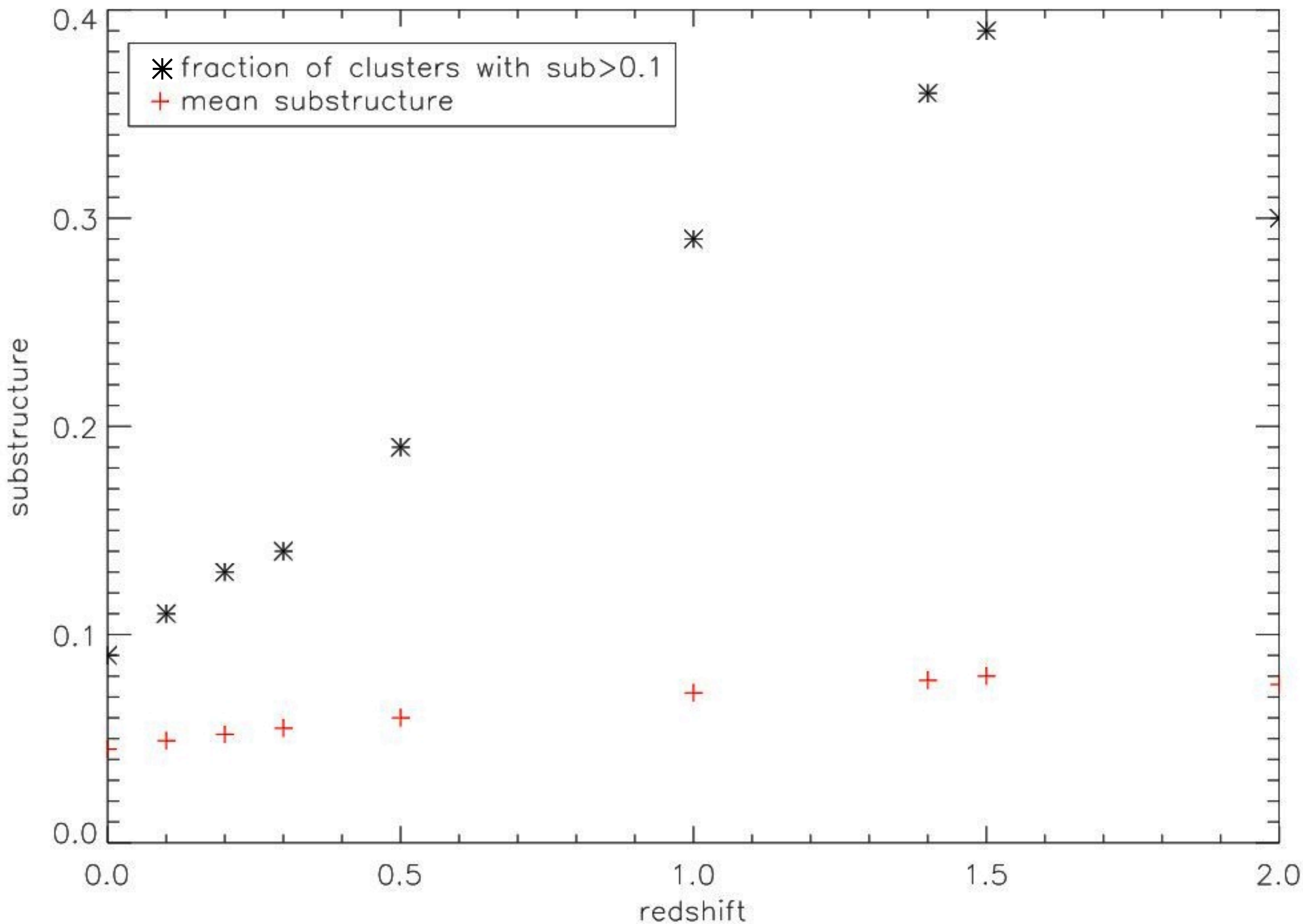


Gazzola etal, in preparation

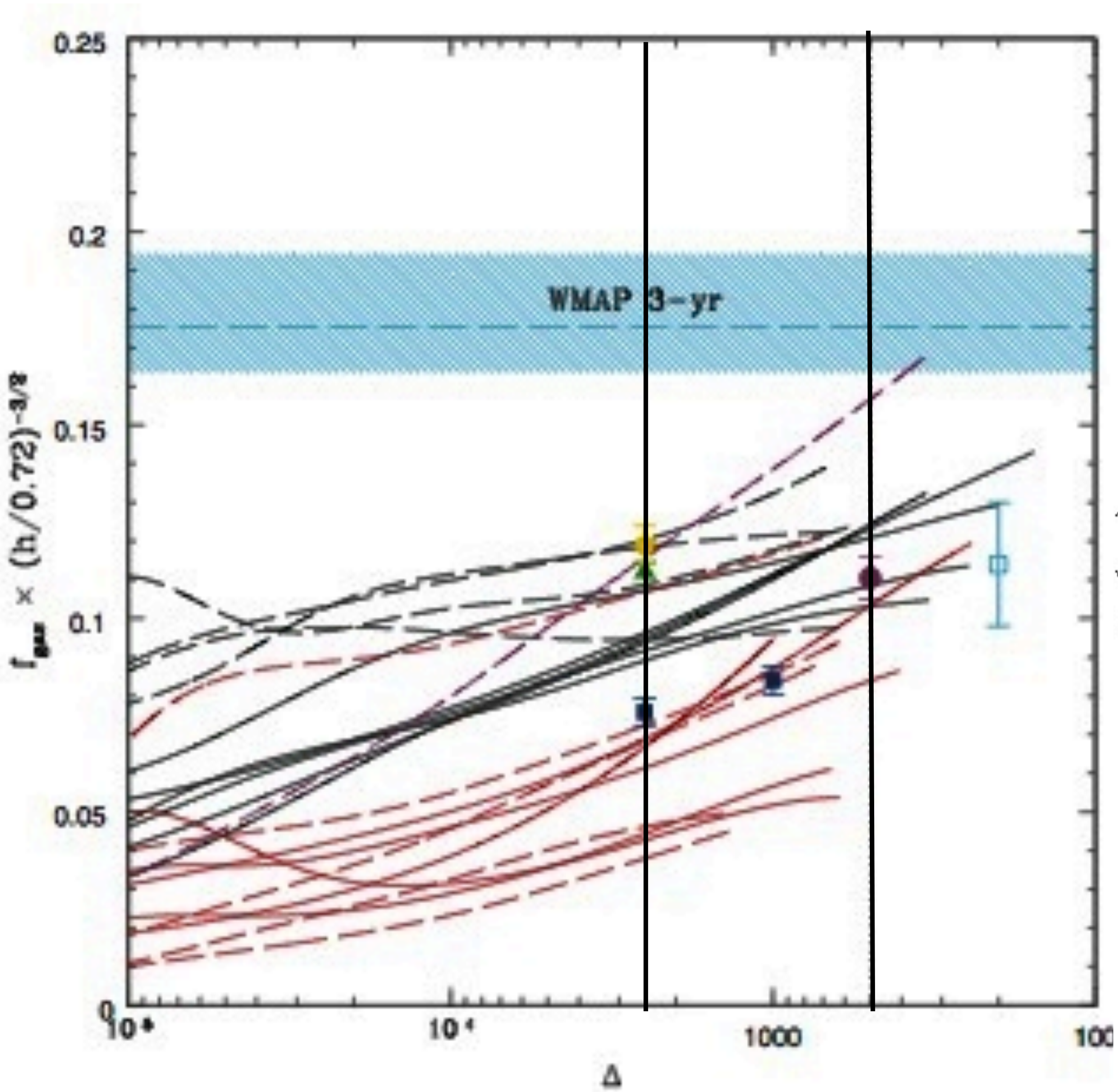
Relation between cool cores and formation time



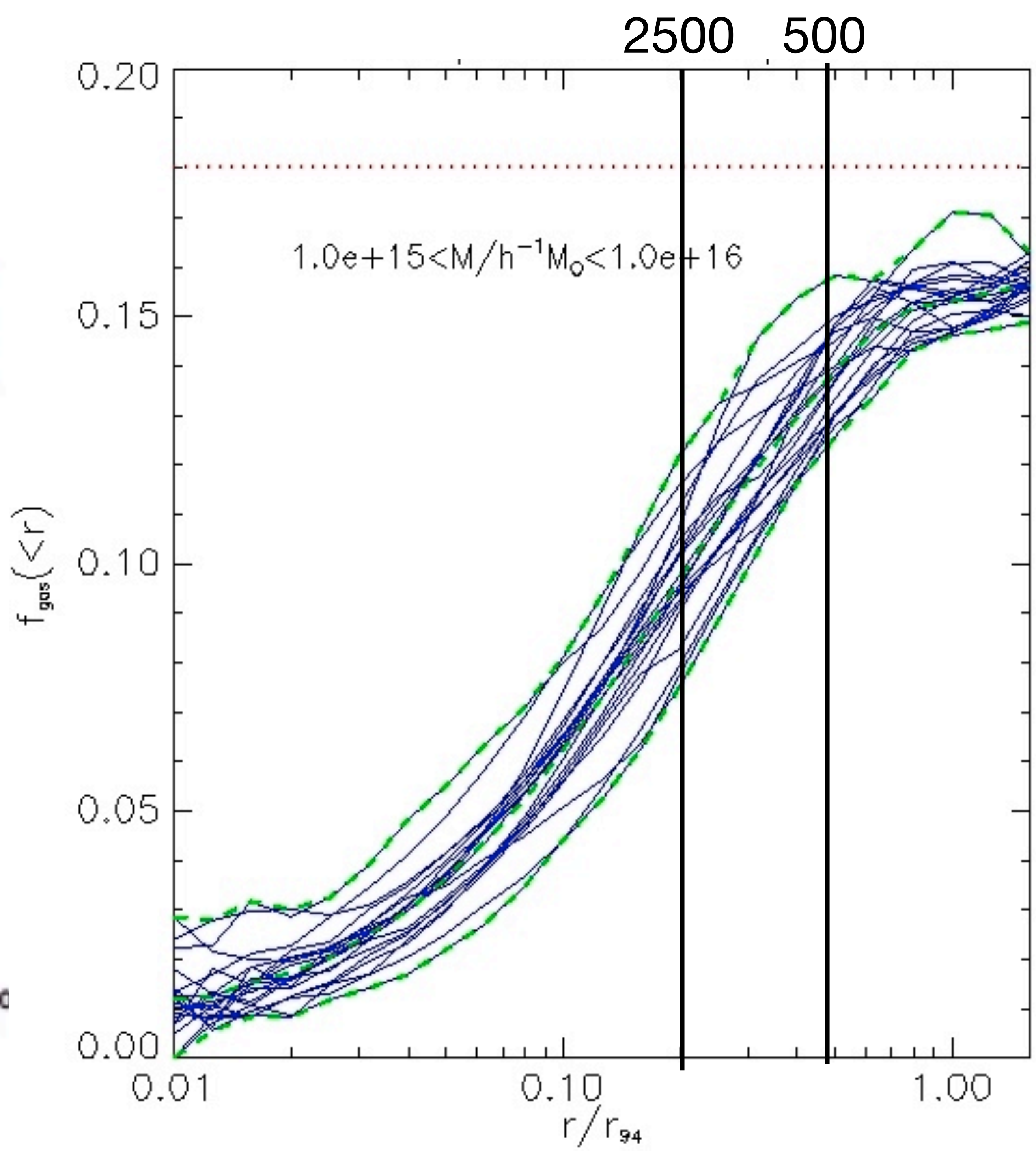
Evolution of substructure



Gas fraction profiles



McCarthy, Bower & Balogh (2007)



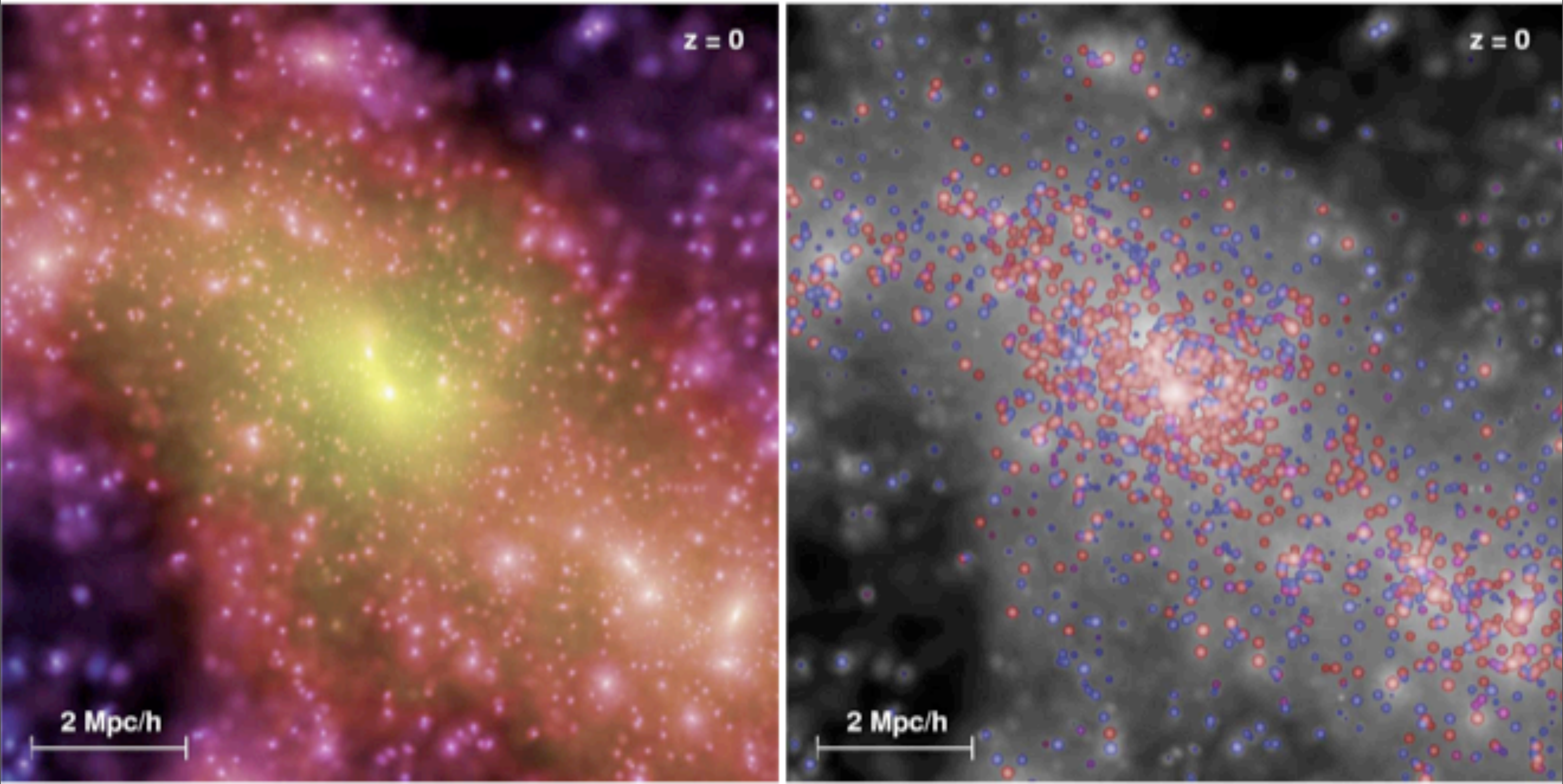
Young etal, in preparation

Semi-analytic models

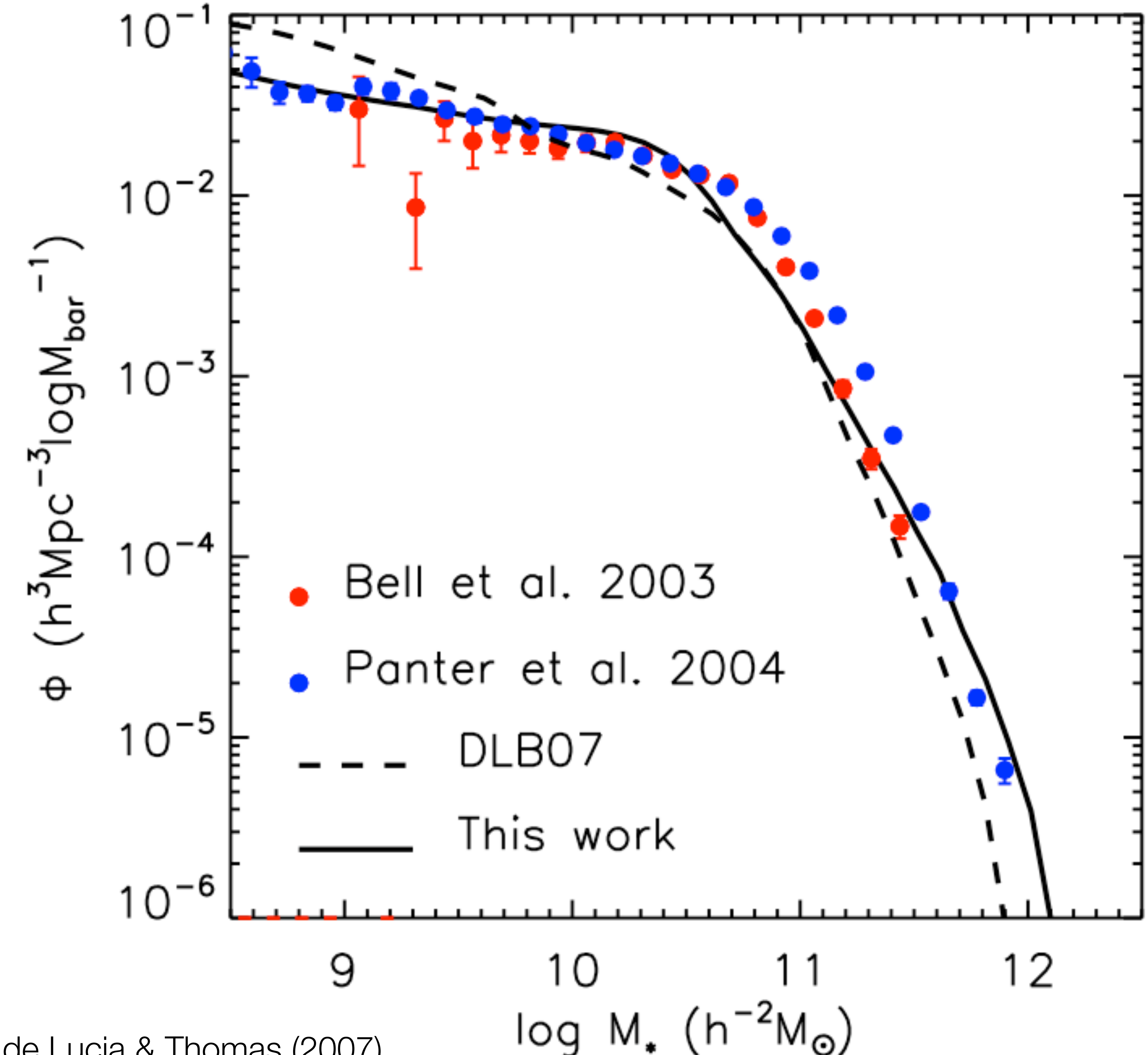
Semi-analytic models

- Simple model for gas in dark-matter halos
- Radiative cooling of gas in halos
- Conversion of cold gas into stars
- Feedback from snr
- Black hole formation via accretion of gas in mergers
- Feedback from quasars
- Suppression of star formation in massive galaxies via radio-mode agn

Galaxies in the Millennium Simulation

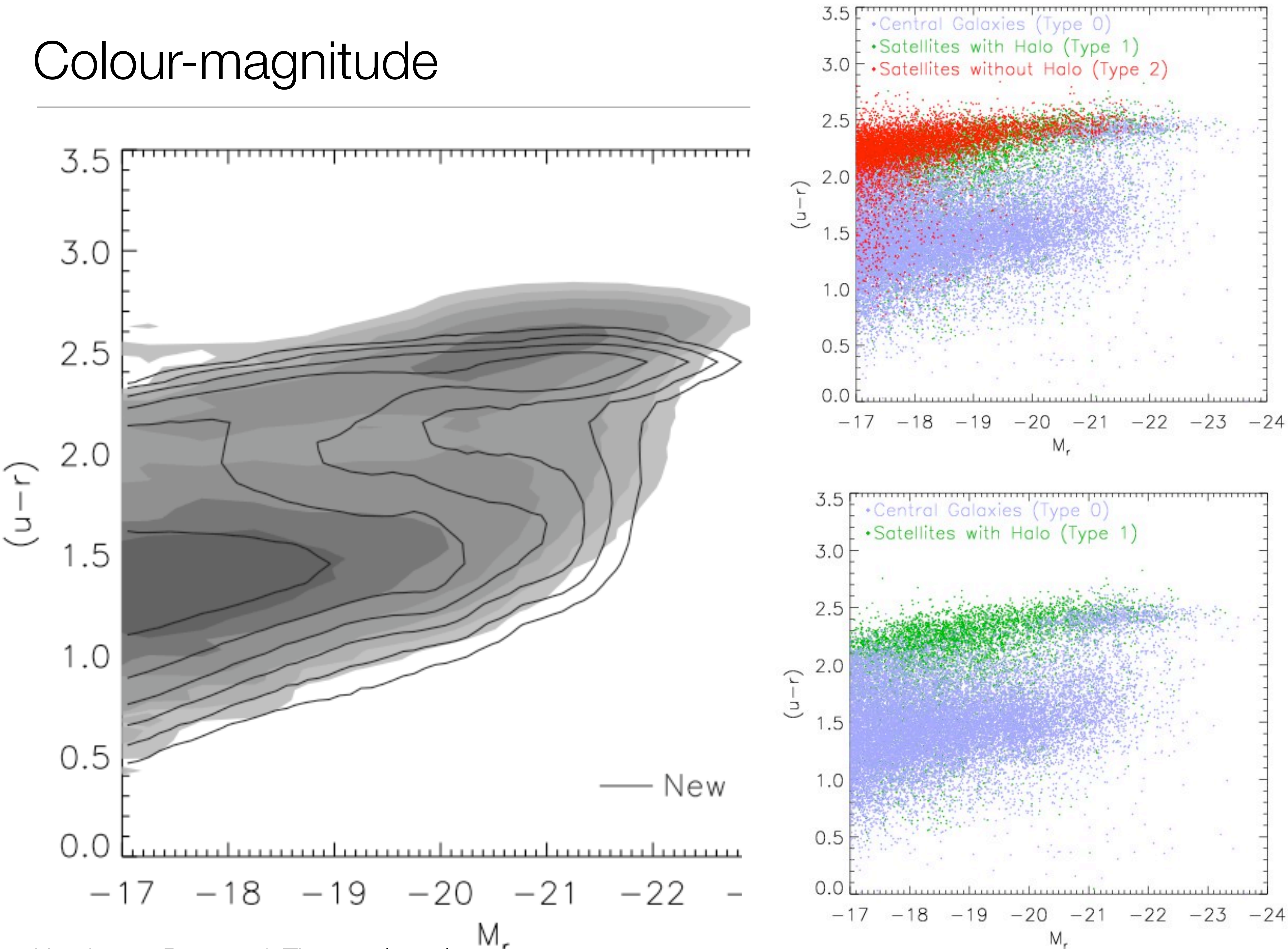


Mass function



Bertone, de Lucia & Thomas (2007)

Colour-magnitude

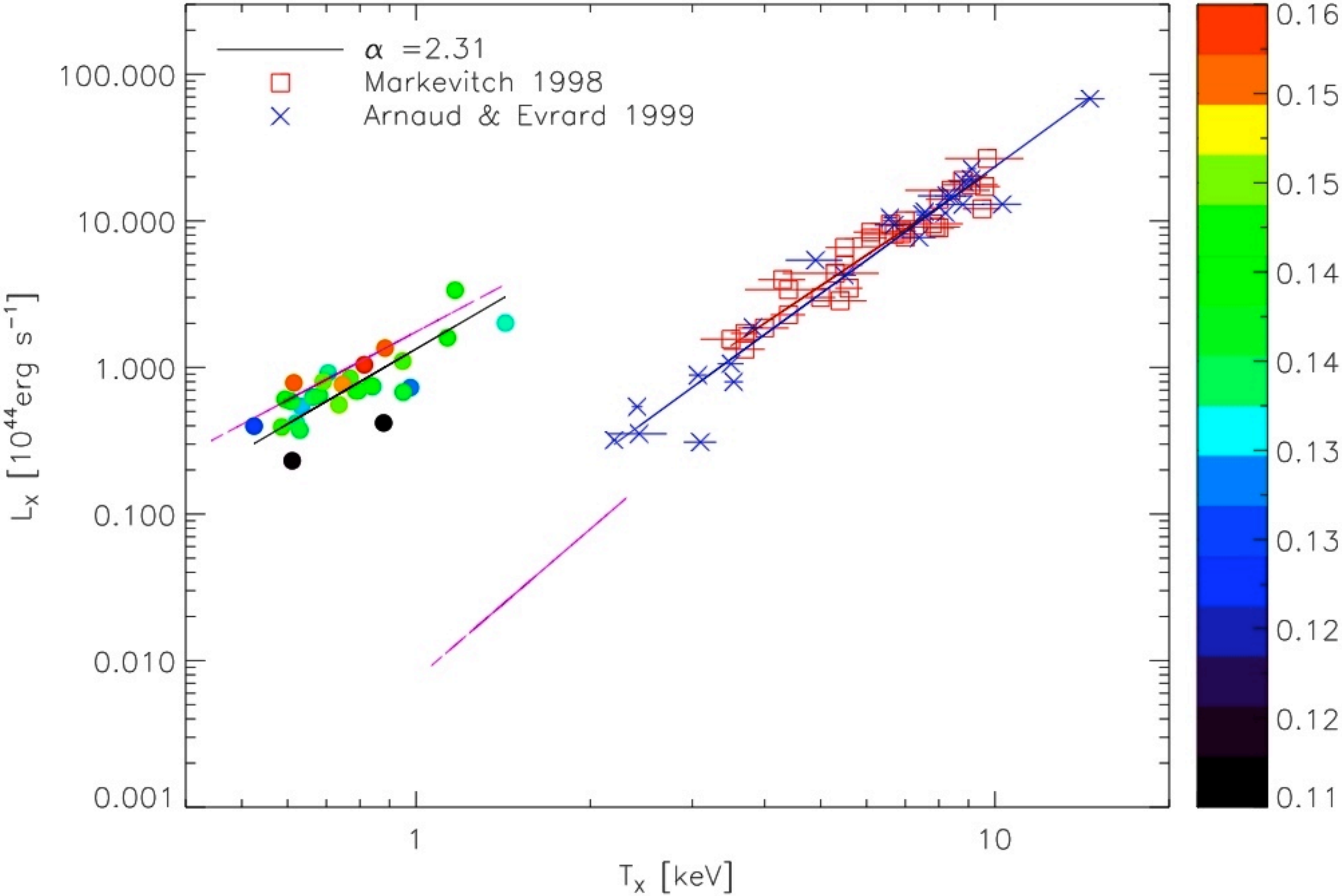


Henriques, Bertone & Thomas (2008)

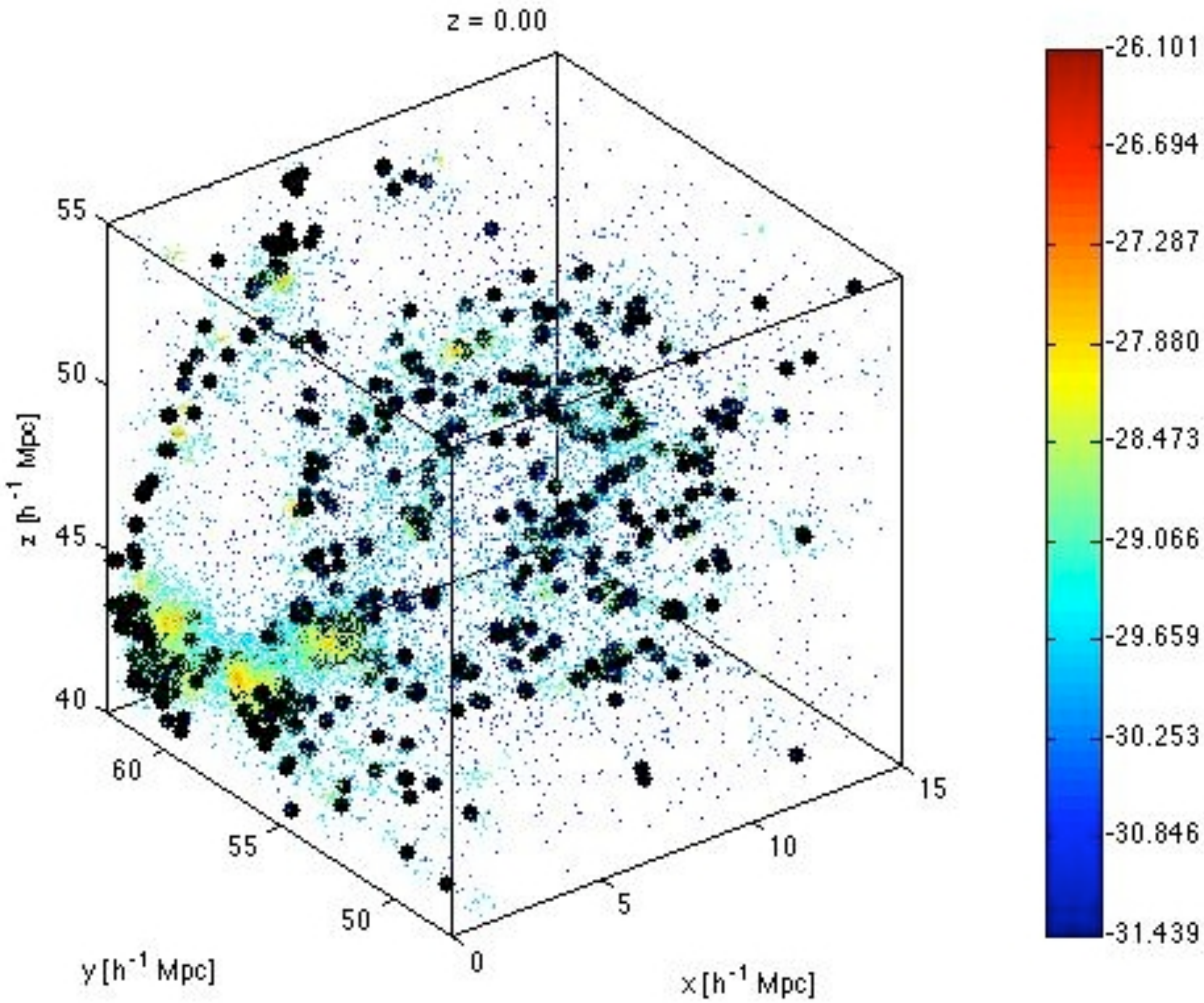
Combining simulations with semi-analytic models

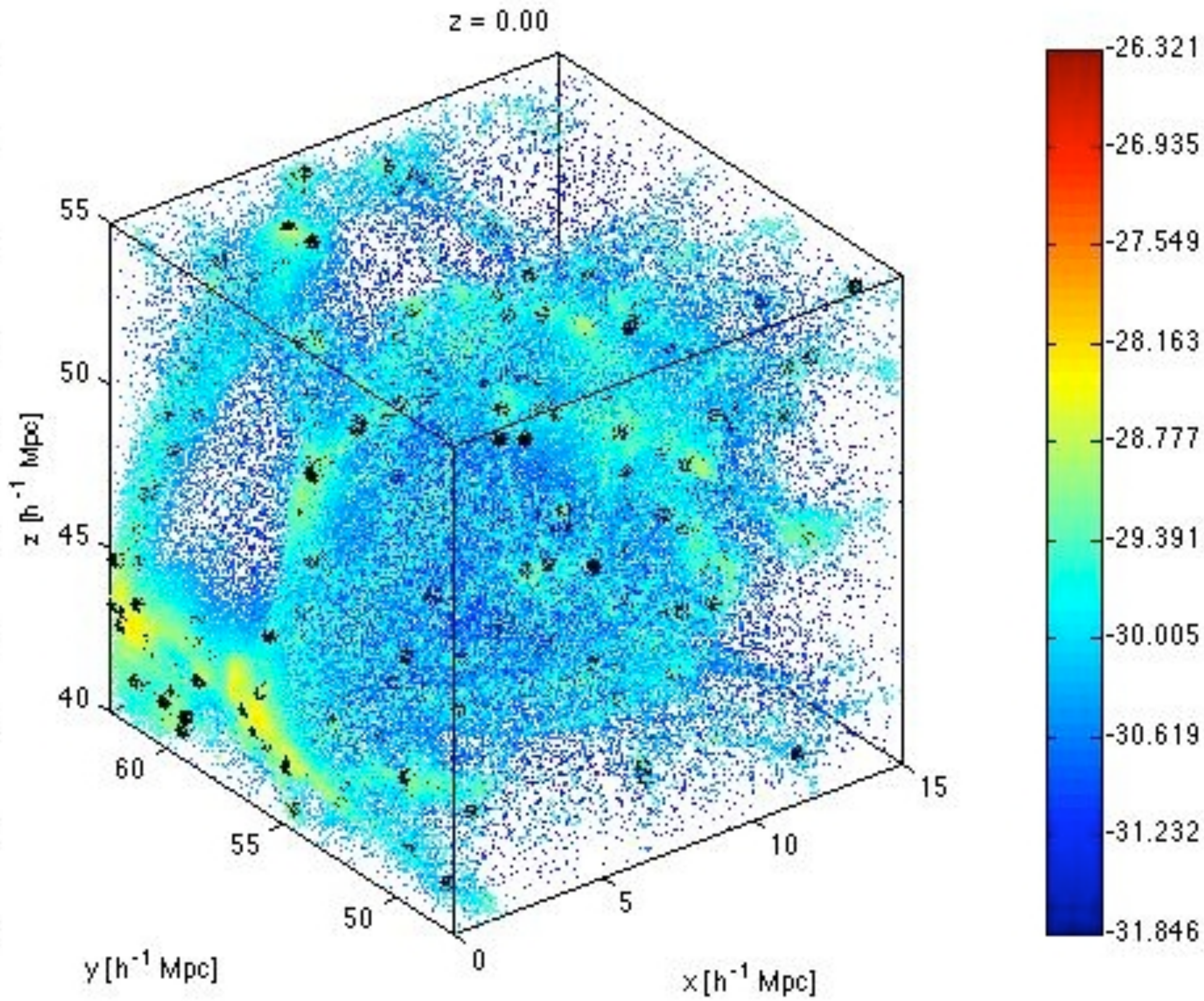
- Construct initial conditions identical to the Millennium simulation, but with the lower mass resolution of the Millennium gas run
- SAMs built on dark matter merger trees constructed from the Millennium simulation
- Assume the gas particles have zero gravitational mass
- Evolve the initial conditions with Gadget 2, assigning the correct mass to gas particles for SPH calculations
- Neglect radiative cooling since the bulk of the gas in clusters has a long cooling time
- At each Millennium output, use data from the SAMs to calculate feedback from SNR, AGN, etc, and inject this energy into the gas
- Examine resulting properties of galaxy clusters and the ICM

Test results in milli-Millennium box

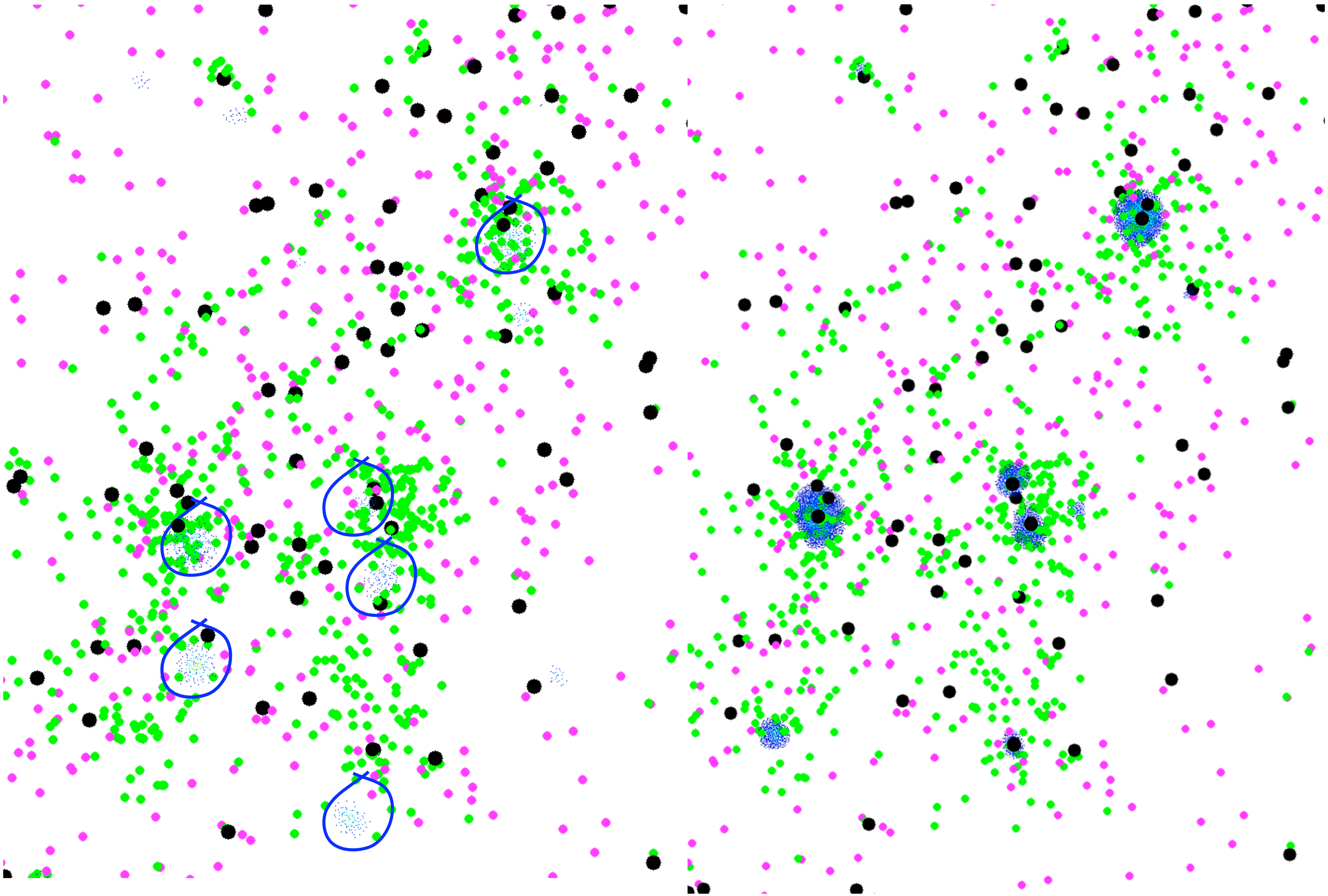


Resolution Issues

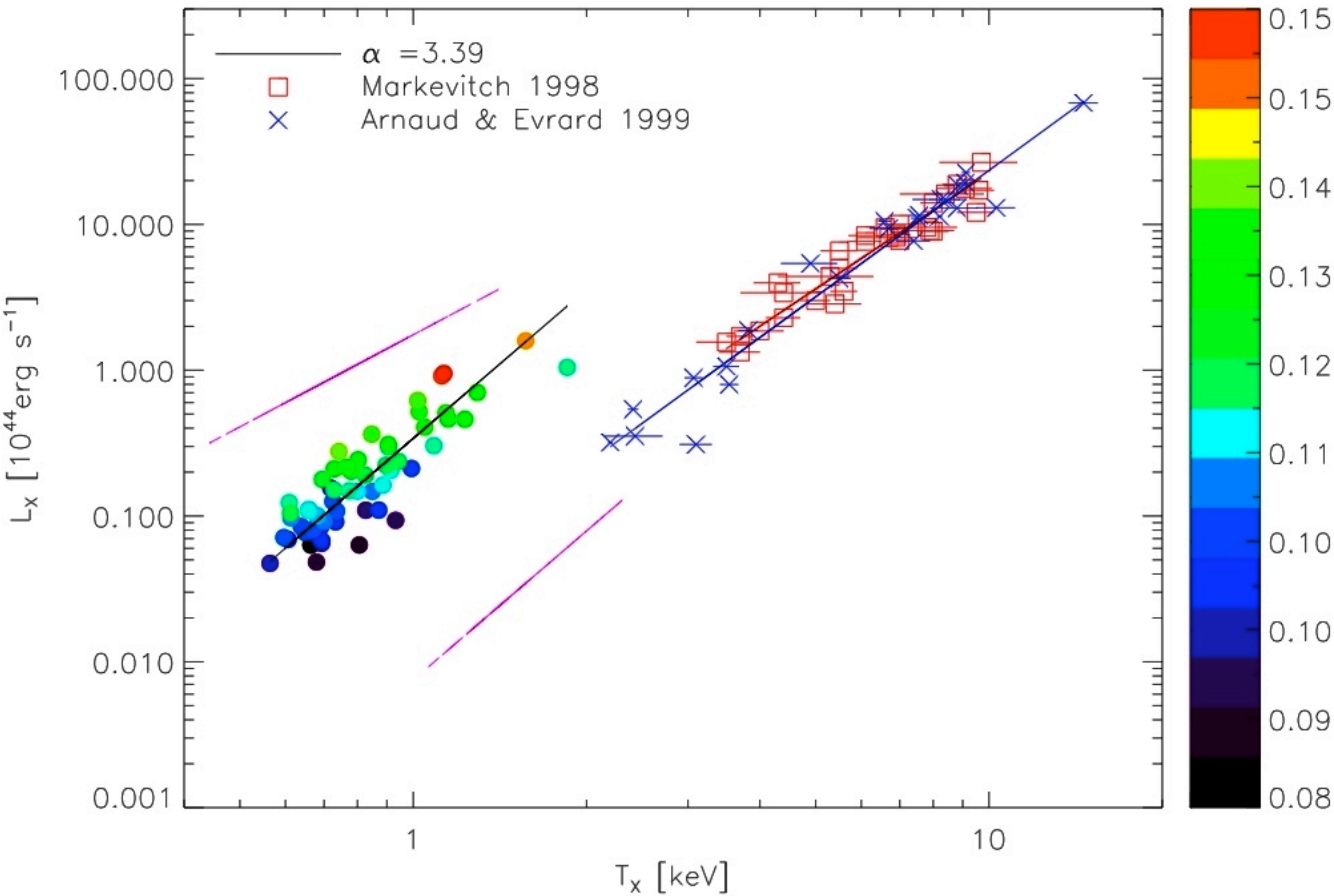




Resolution effects



Star-formation, stellar feedback + quasars



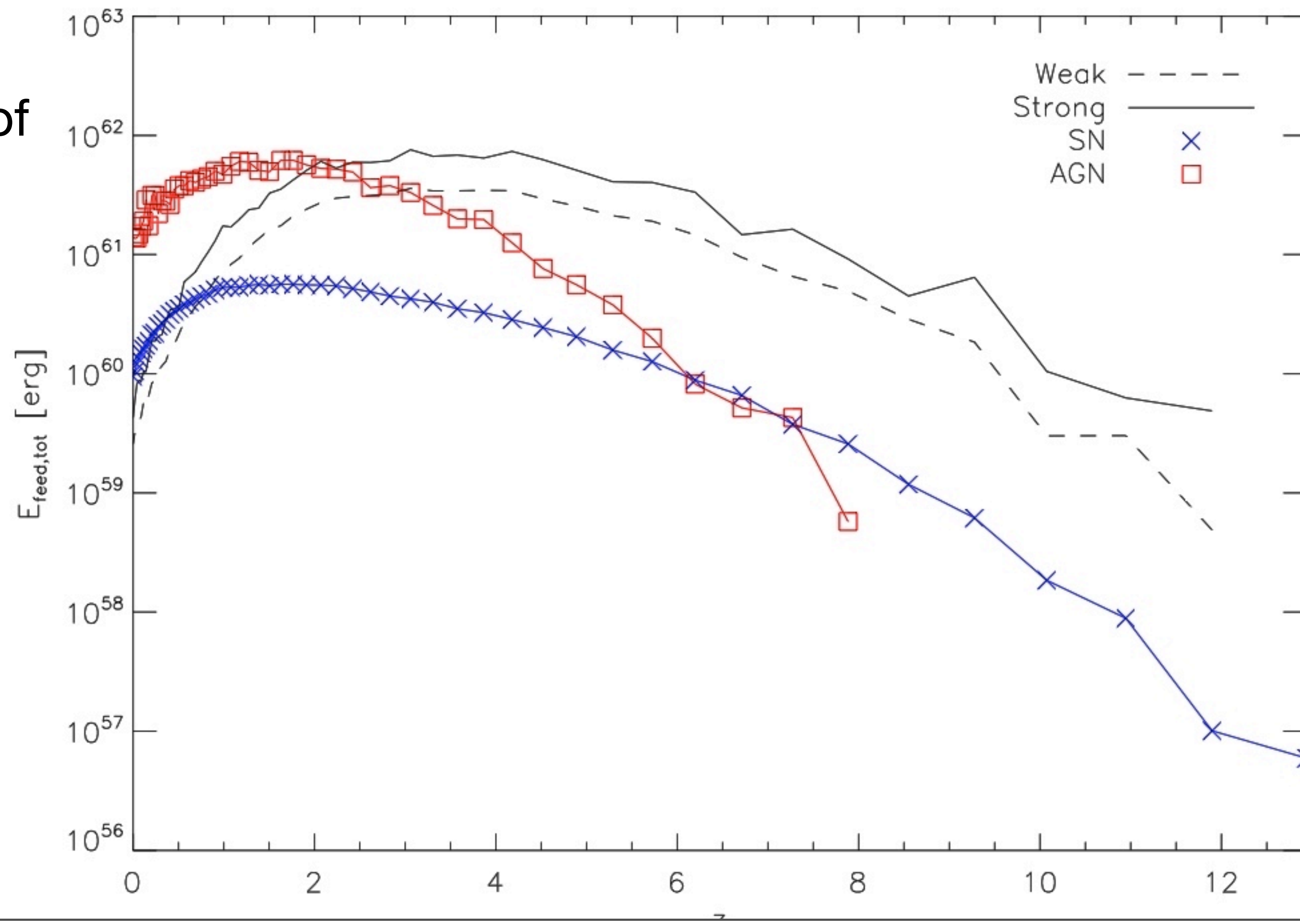
Feedback energy

- In L-Galaxies, the energy of ejecta per solar mass of stars formed is

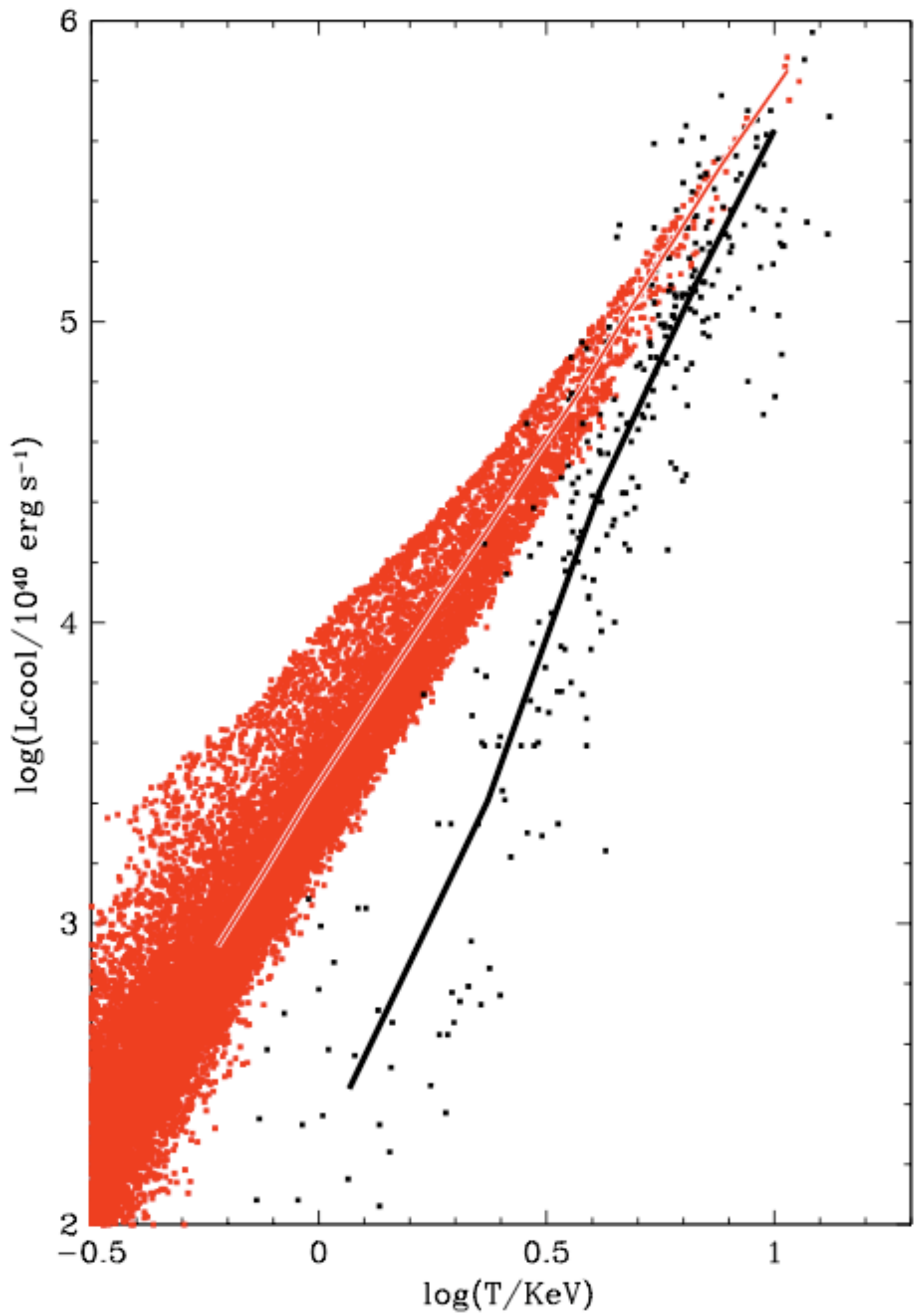
$$\Delta E_{ejected} \approx 10^{43} \left[\varepsilon_{halo} \left(\frac{v_{SN}}{\mathrm{km\ s^{-1}}} \right)^2 - \varepsilon_{disc} \left(\frac{v_{vir}}{\mathrm{km\ s^{-1}}} \right)^2 \right] \left(\frac{\Delta m_*}{M_\odot} \right) \mathrm{erg}$$

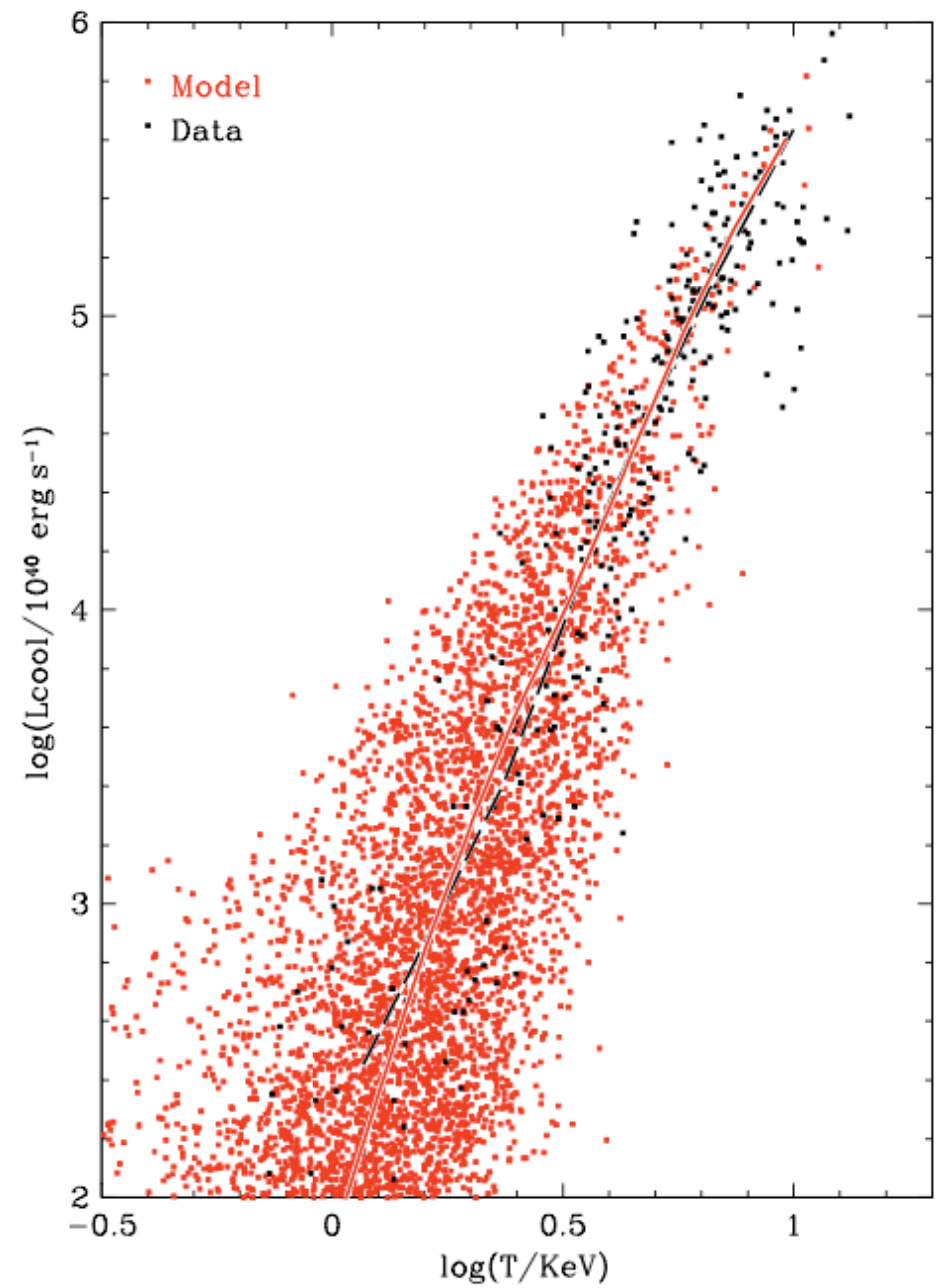
- In the strong feedback model of Kay et al 2004, the amount of energy released by type 2 supernovae per solar mass of stars formed is between 4 and 740 times greater:

$$\Delta E_{SN} \approx 5 \times 10^{48} \left(\frac{\Delta m_*}{M_\odot} \right) \mathrm{erg}$$



The need for extra feedback





Bower (Birmingham 2008)

Conclusions

- Cluster simulations have gradually increased in size over the last 20 years. We now have the ability to generate catalogues with a decent sample of massive clusters.

- Phenomenological models of entropy generation can give clusters whose global properties match those of observed clusters. We still cannot resolve/match the properties of cluster cores.

- Self-consistent feedback simulations are not possible as we cannot resolve galaxy and AGN formation. We have started a programme to combine semi-analytic models with simulations. Initial results show that it is hard to generate enough entropy to match the observations.