The Impact of Gas Expulsion by AGN-driven Winds on Galaxy Groups and Clusters

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Groups are not "scaled down" clusters

$$L_X = \int n_e \, n_H \, \Lambda(T, Z) \, dV$$

self-similarity

$$\rightarrow n_e \propto n_H \propto \rho \qquad \rho \neq \rho(M)$$

thermal bremsstrahlung

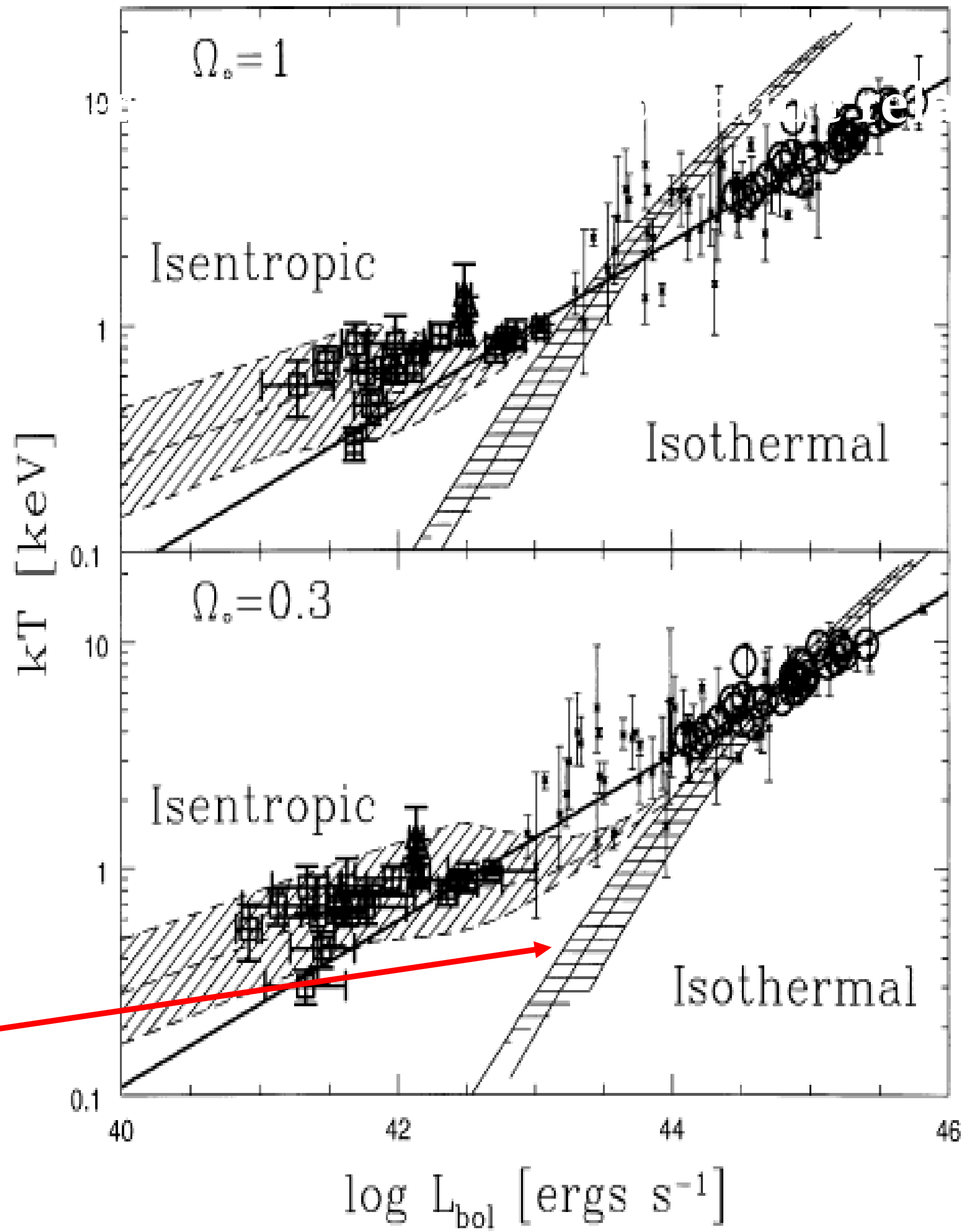
$$\rightarrow \Lambda(T) \propto T^{1/2}$$

virial theorem

$$\rightarrow dV \propto R^3 \propto T^{3/2}$$

$$L_X \propto T^2$$

Balogh et al. (1999)



Entropy of the hot gas

$$K \equiv \frac{P}{\rho^{5/3}} \propto \frac{T}{\rho^{2/3}} \qquad\qquad s \propto \ln K$$

• Conserved in any adiabatic process (e.g., expansion or compression).

• Heating always raises the entropy, while cooling always lowers it.

• Convection will sort the gas such that the lowest entropy material is at the bottom of the potential well.

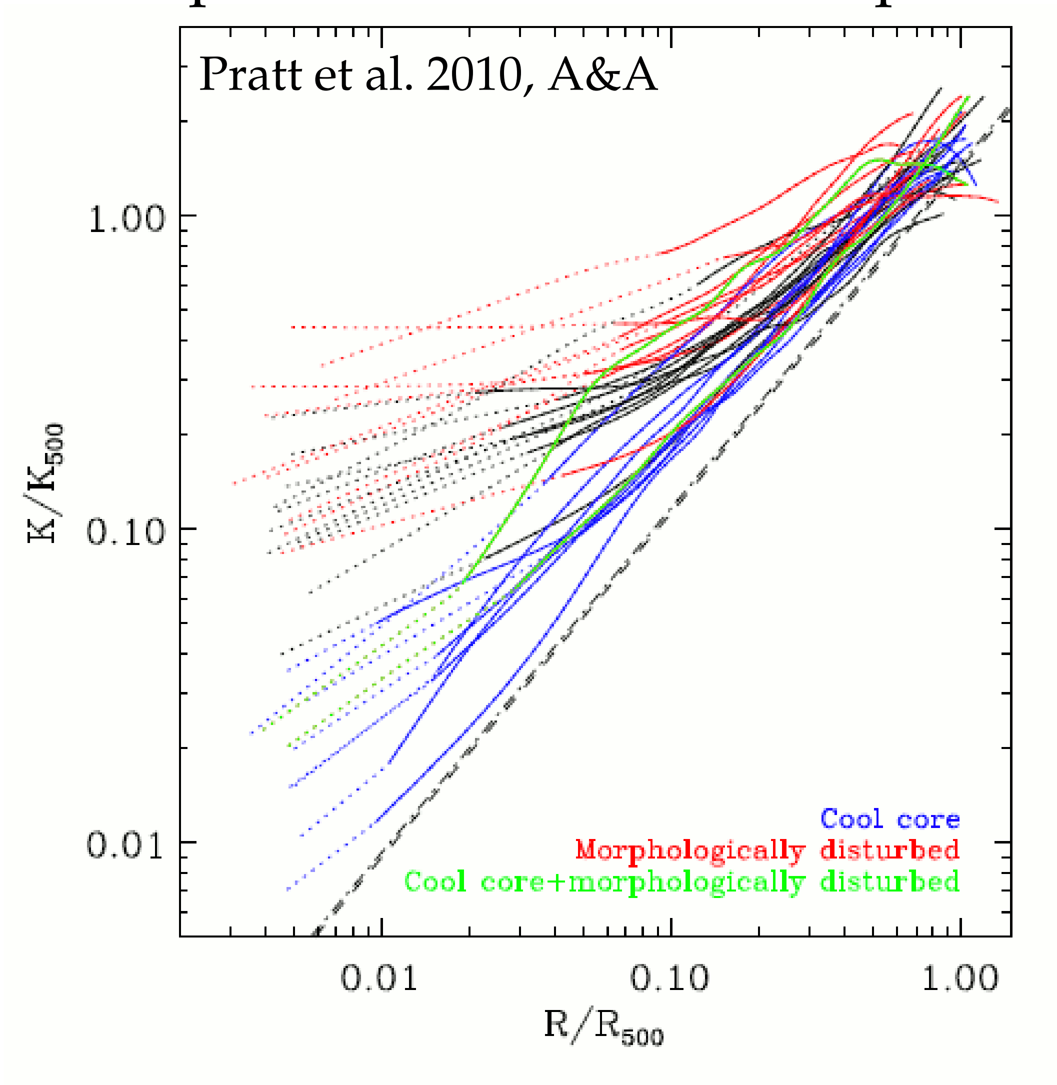
• Through hydrostatic equilibrium in the DM-dominated potential well, the entropy distribution fully determines the gas density and temperature distributions.

What sets the entropy of the hot gas?

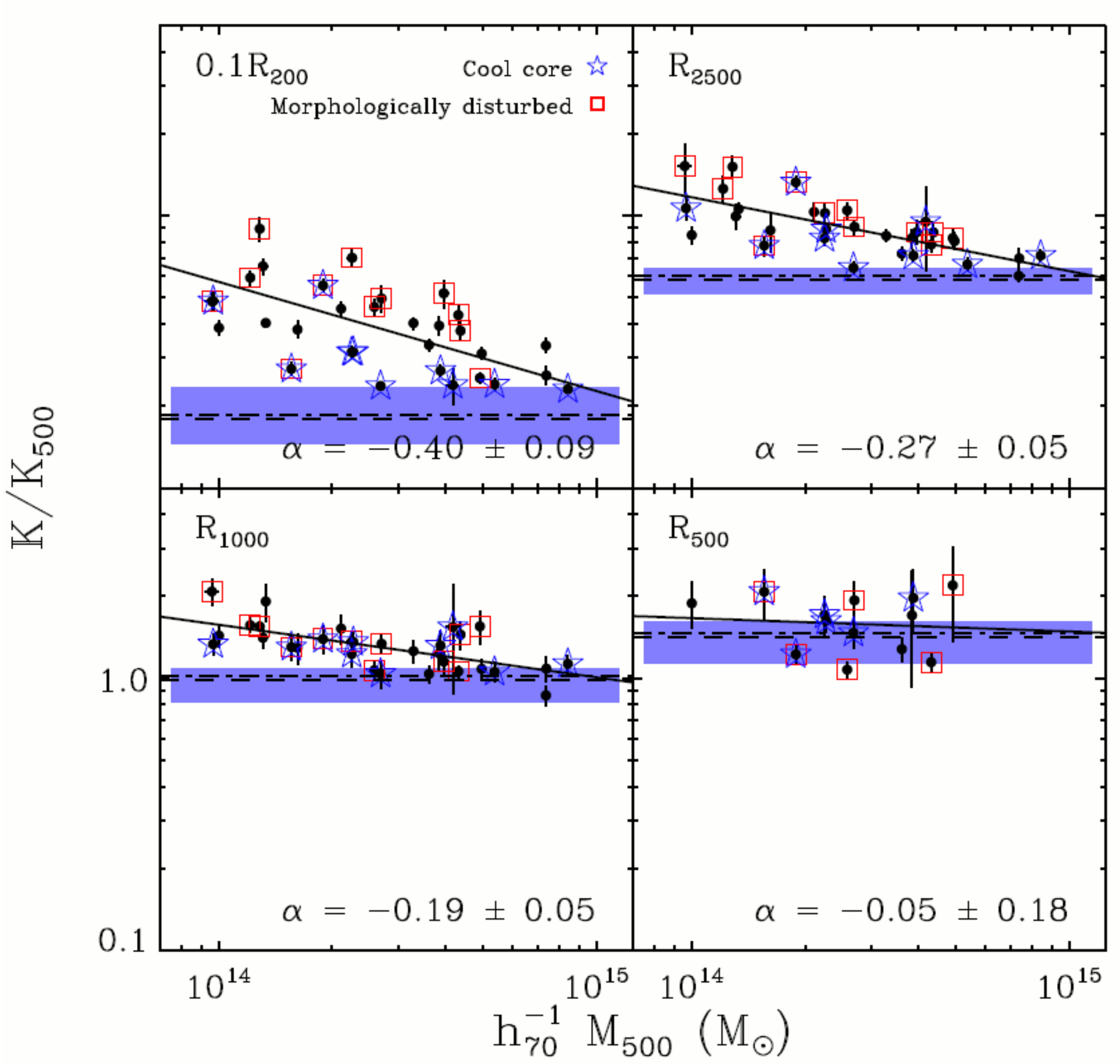
Groups and clusters have “excess” entropy

$$K \equiv \frac{P}{\rho^{5/3}} \propto \frac{T}{\rho^{2/3}} \qquad s \propto \ln K$$

XMM entropy profiles of a more representative cluster sample



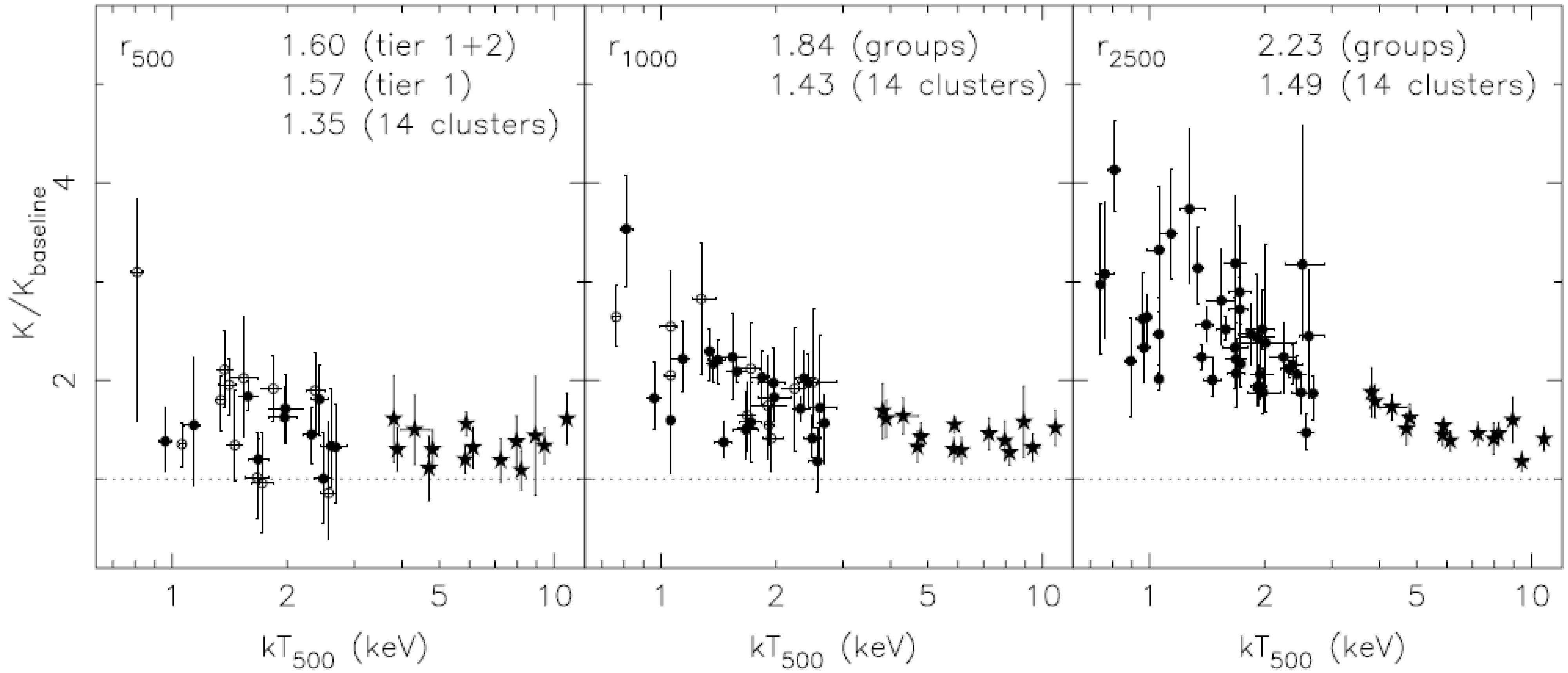
Entropy at a fixed characteristic radii vs. cluster mass, M500



• Self-similar model fails at small/intermediate radii for the most massive systems, but works pretty well at large radii for massive clusters.

Groups and clusters have “excess” entropy

Entropy at a fixed characteristic radii vs. system temperature for groups and clusters



Sun et al. 2009, ApJ, 693, 1142
(see also Ponman et al. 2003)

- Self-similar model fails **at all radii** for low mass groups. It systematically underpredicts the entropy (overpredicts the density).

Ways to raise the entropy of the gas

Cooling

• Selectively removes the lowest entropy gas, increasing the volumetric entropy (e.g., Bryan; Voit & Bryan 2001)

Direct Heating of the ICM (or proto-ICM)

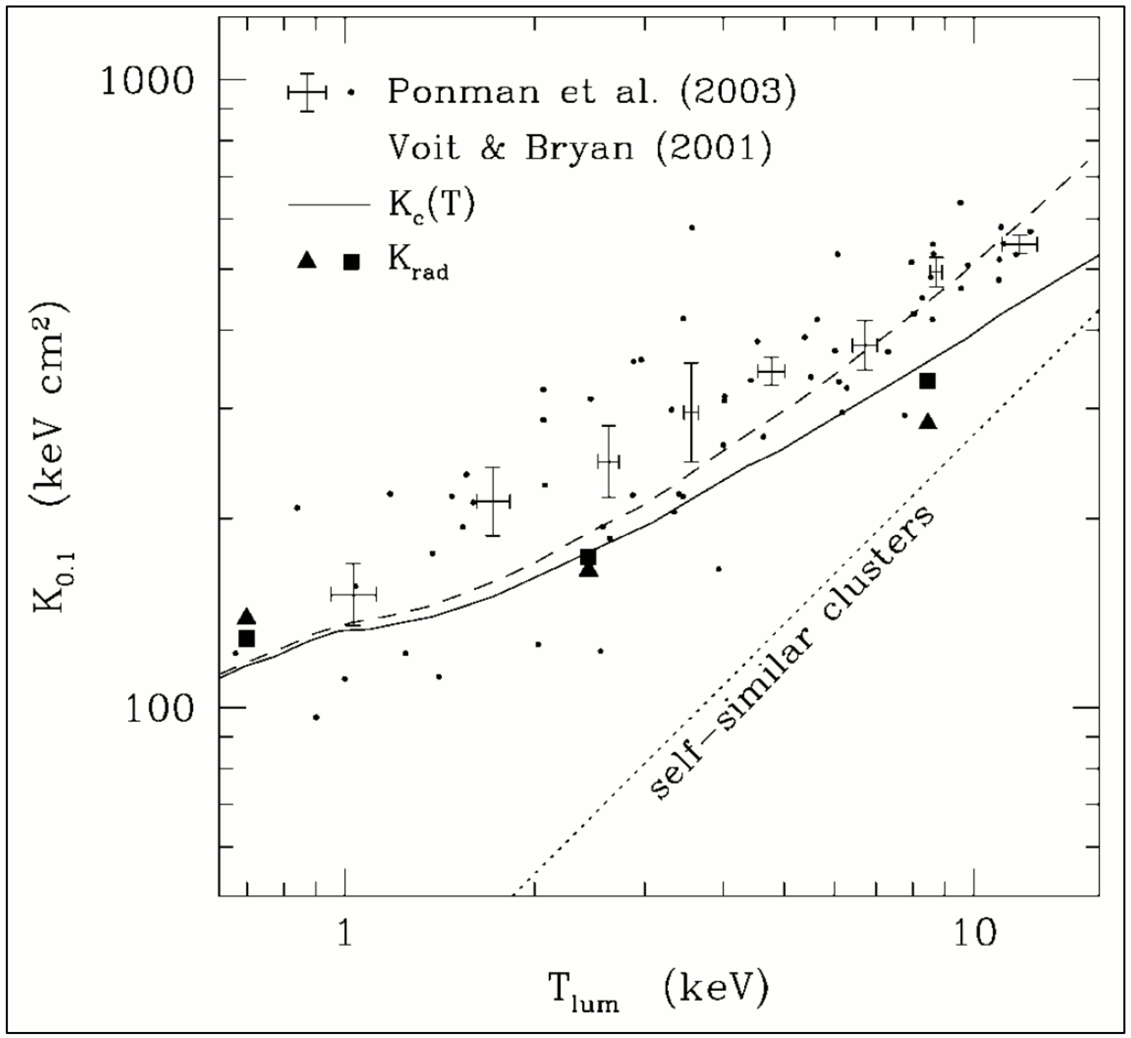
• Heat gas prior to collapse (preheating; e.g., Kaiser 1991; Evrard & Henry 1991)
• Heat gas after collapse (e.g., SNe or bubbles/jets)

Gas expulsion

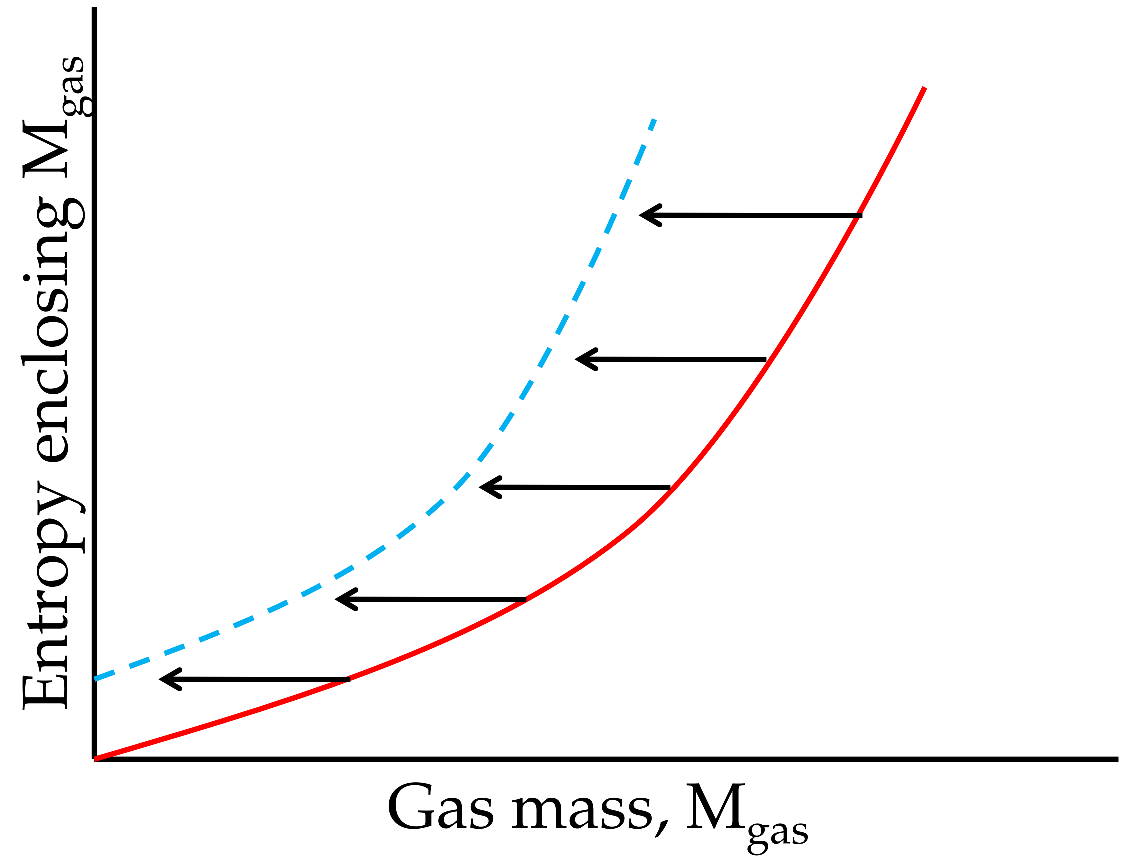
• Eject the lowest entropy gas from the system after collapse (e.g., Bower et al. 2008)
• Eject the lowest entropy gas from the high redshift progenitors (McCarthy et al. 2011)

Cooling and star formation

Radiative cooling raises the entropy of the gas by selectively removing the lowest entropy gas. "Truncates" the entropy distribution (Voit et al. 2002)



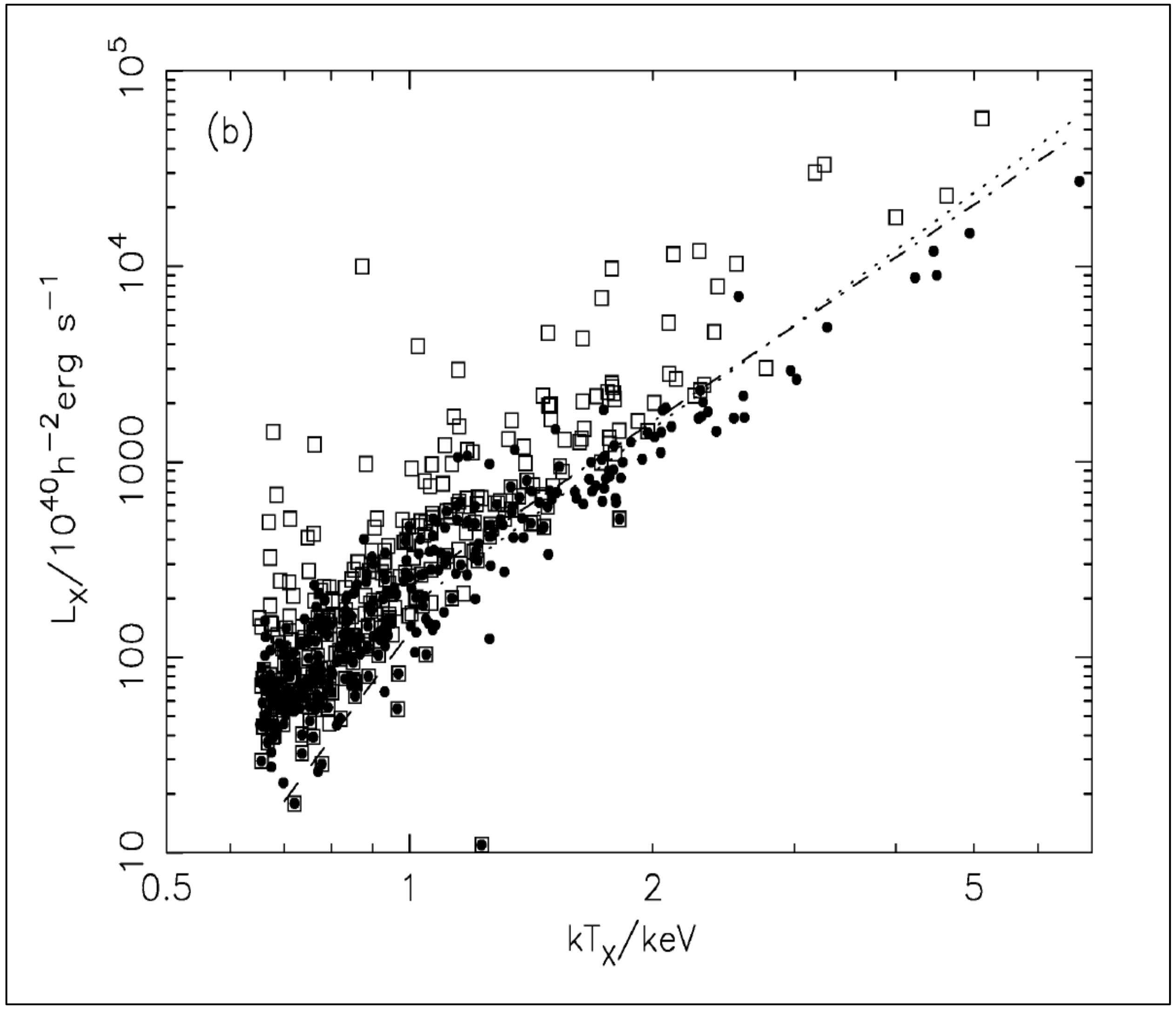
Voit & Ponman (2003)



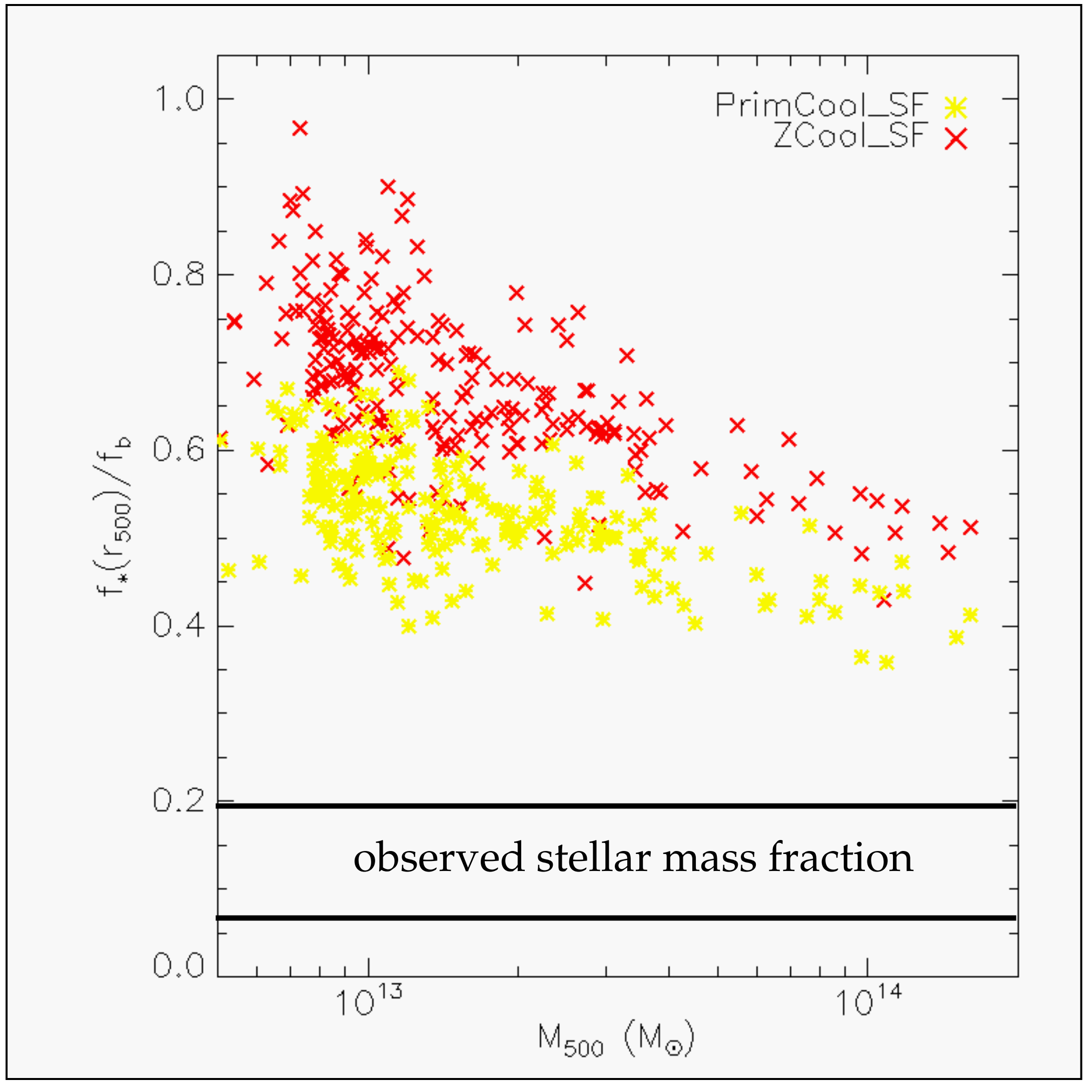
• Cooling only models do pretty well at getting the global entropy right.

Cooling and star formation

Cosmological sims with cooling but no feedback



Muanwong et al. (2002)

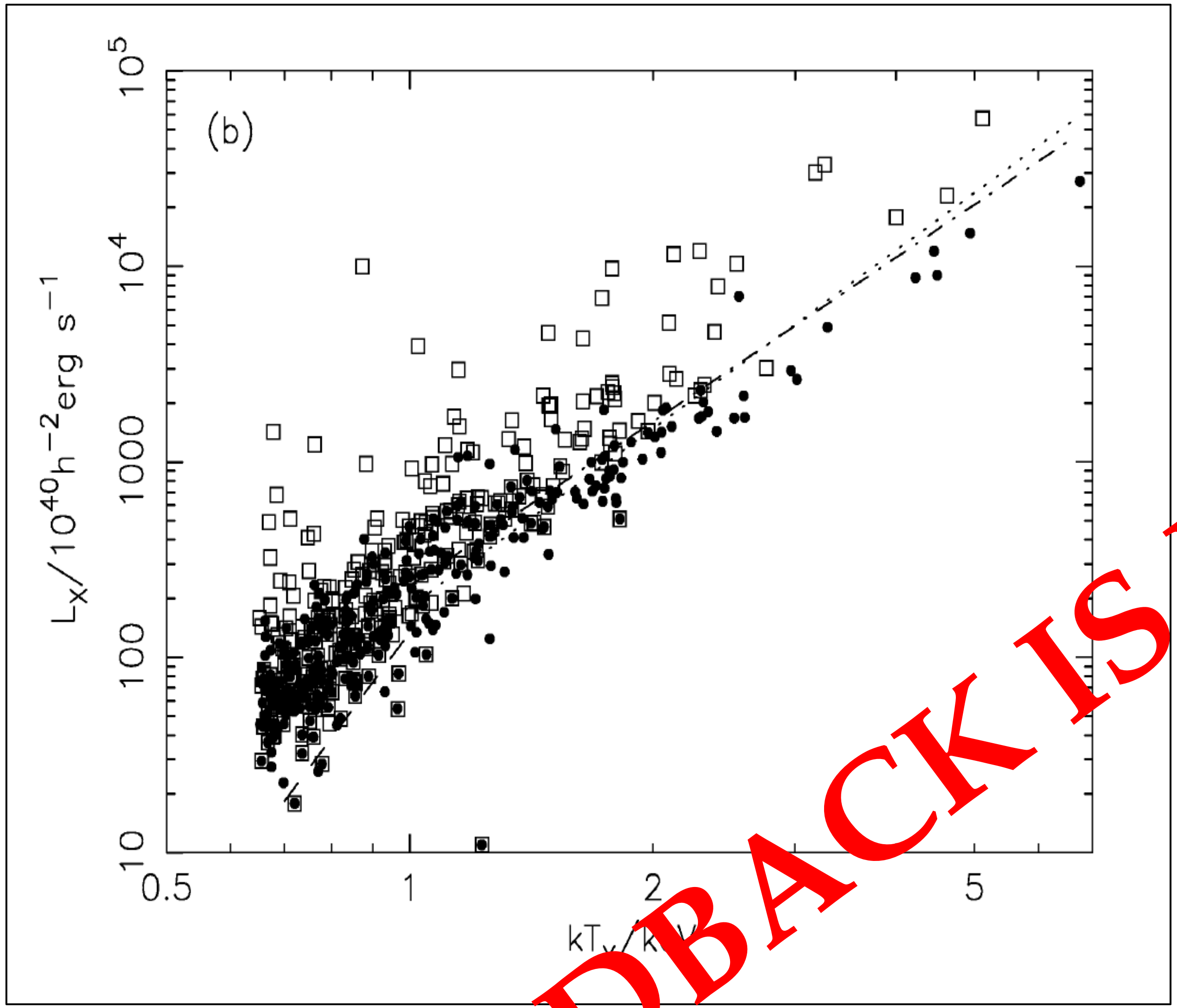


McCarthy et al. (2011)

- Looks ~OK in X-ray (global props, don't forget). Fails horribly in the "optical" regime.
- Cooling must be reduced at high redshift.

Cooling and star formation

Cosmological sims with cooling but no feedback



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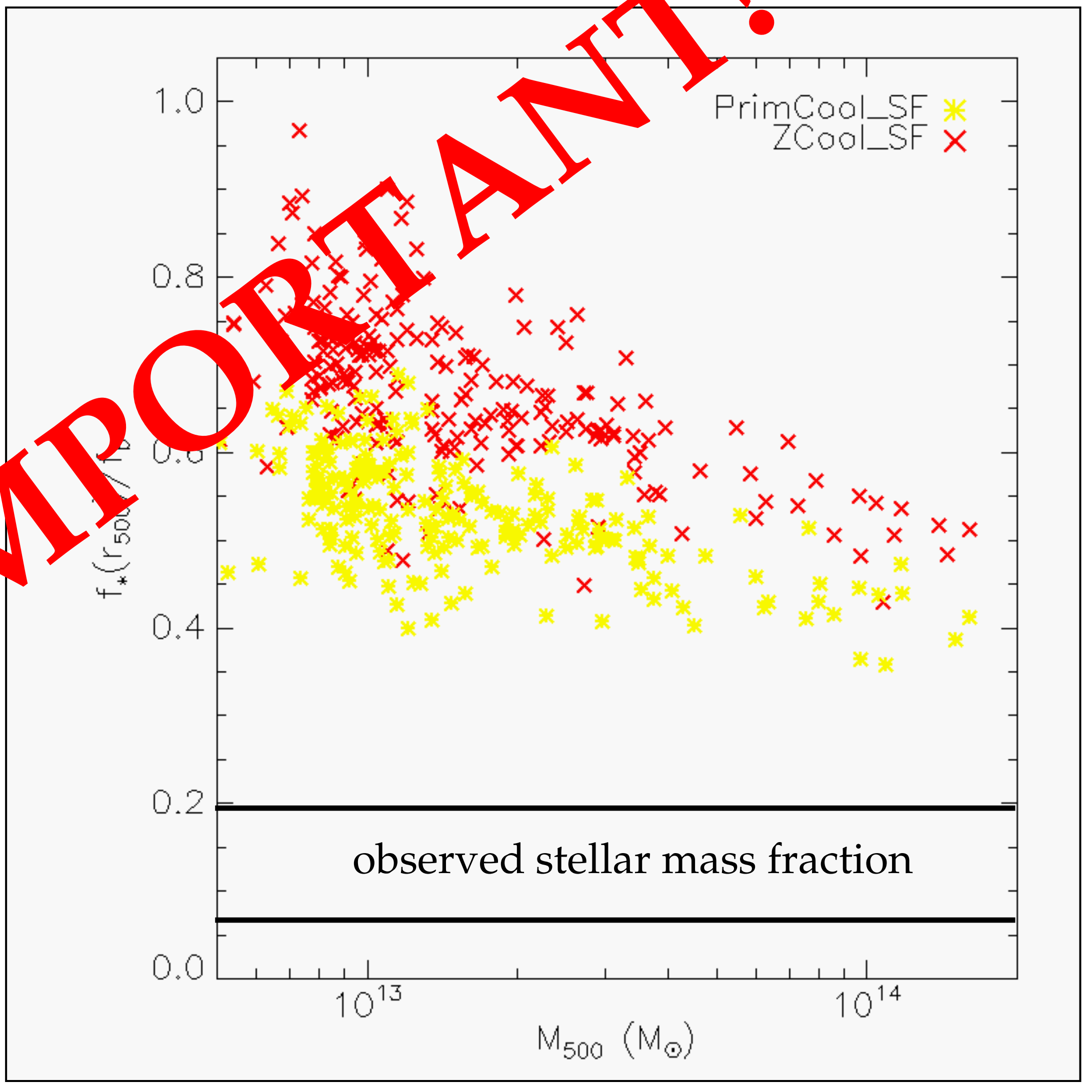

McCarthy et al. (2011)

FEEDBACK IS IMPORTANT!

• Looks ~OK in X-ray (global props, don't forget). Fails horribly in the "optical" regime.

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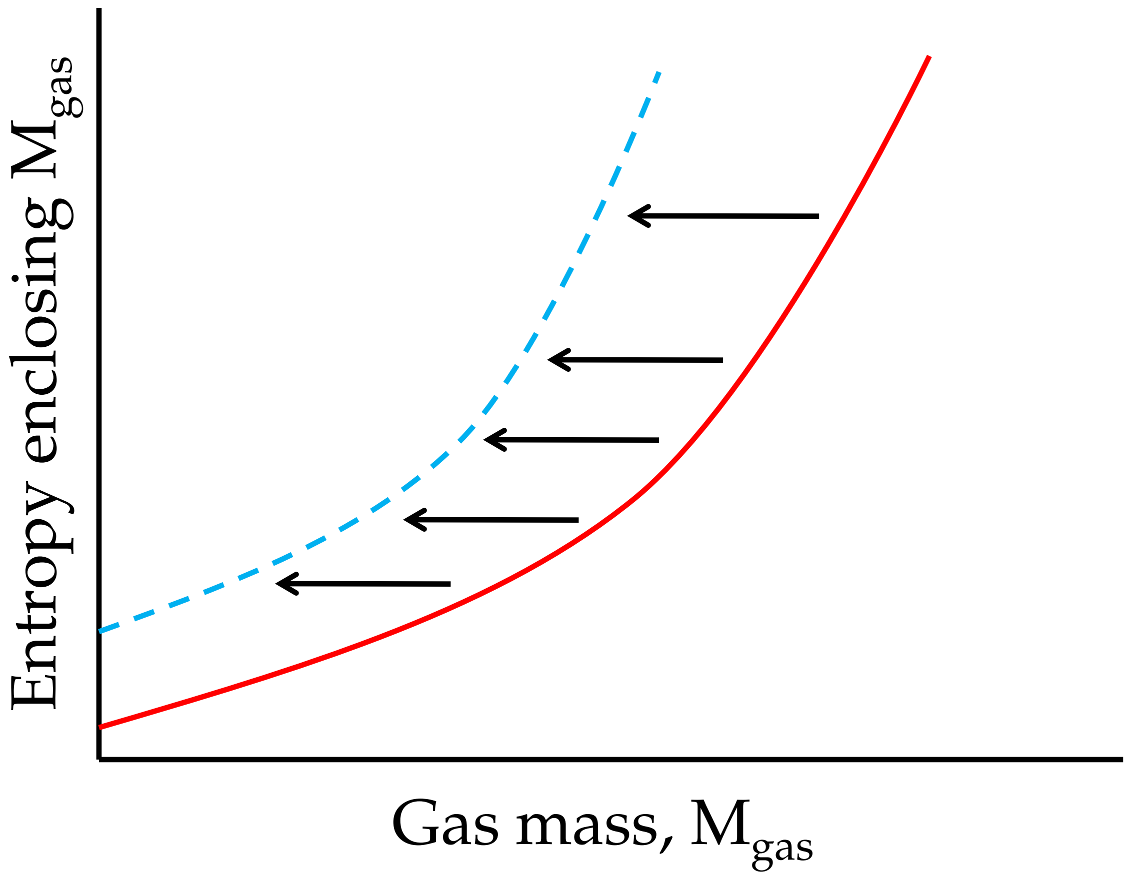
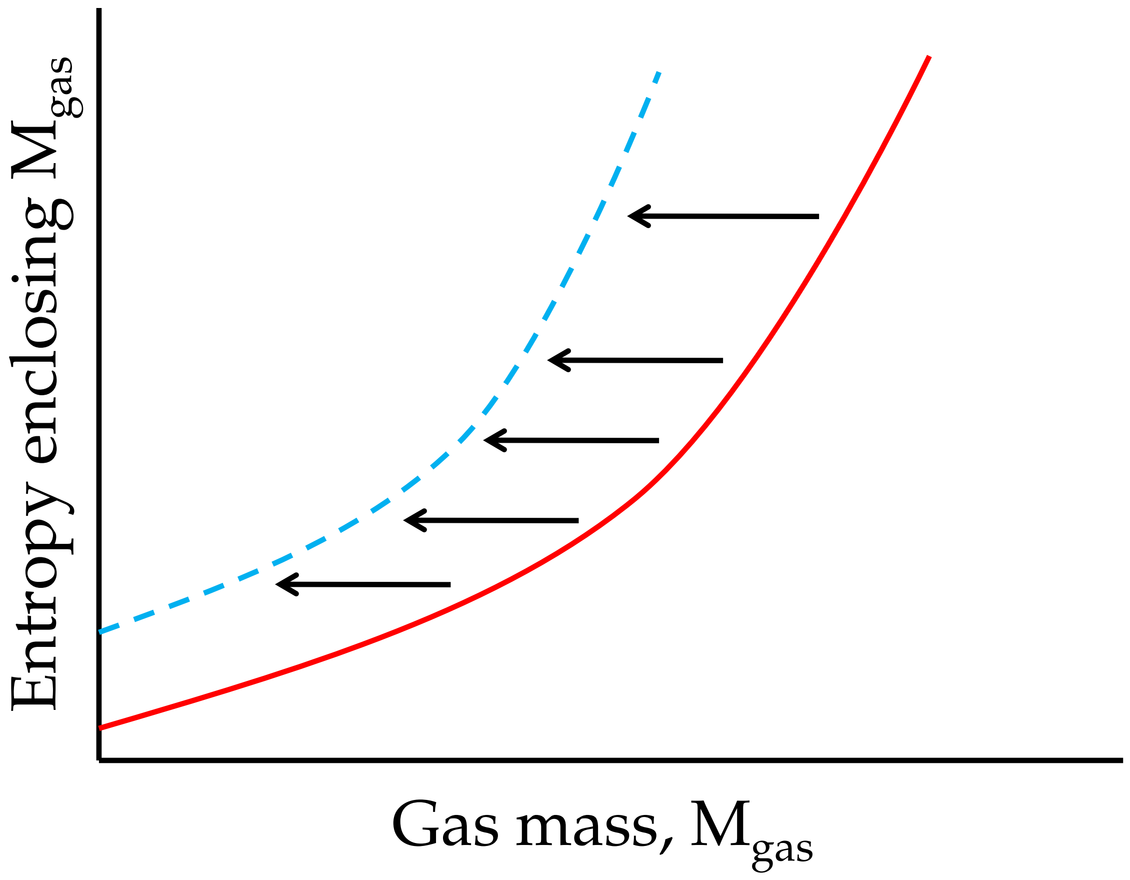
Can heating act like cooling?

THE EFFECTS OF RADIATIVE COOLING



Can heating act like cooling? Yes

THE EFFECTS OF GAS EXPULSION



Voit et al. (2002) – truncation could also result from an “extreme form of heating”.
Heating must target lowest-entropy gas.

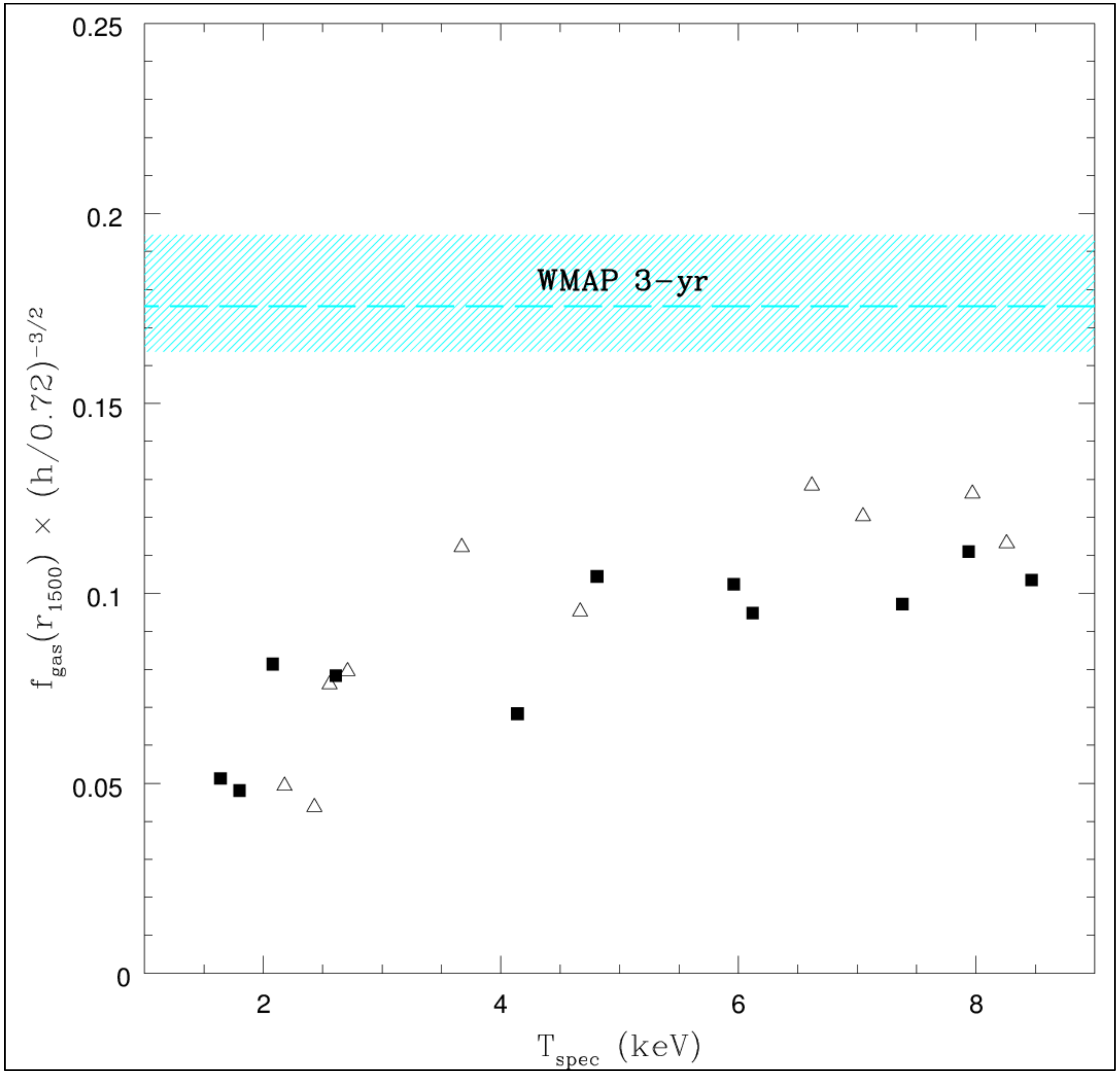
Evidence for expulsion: missing baryons?

Groups have lower gas mass fractions than clusters (Vikhlinin et al. 2006; Croston et al. 2008; Sun et al. 2009). All systems have lower than universal.

Are the missing baryons in stars? (e.g., Gonzalez et al. 2007)

Different cosmology?

Eject gas preferentially from groups?



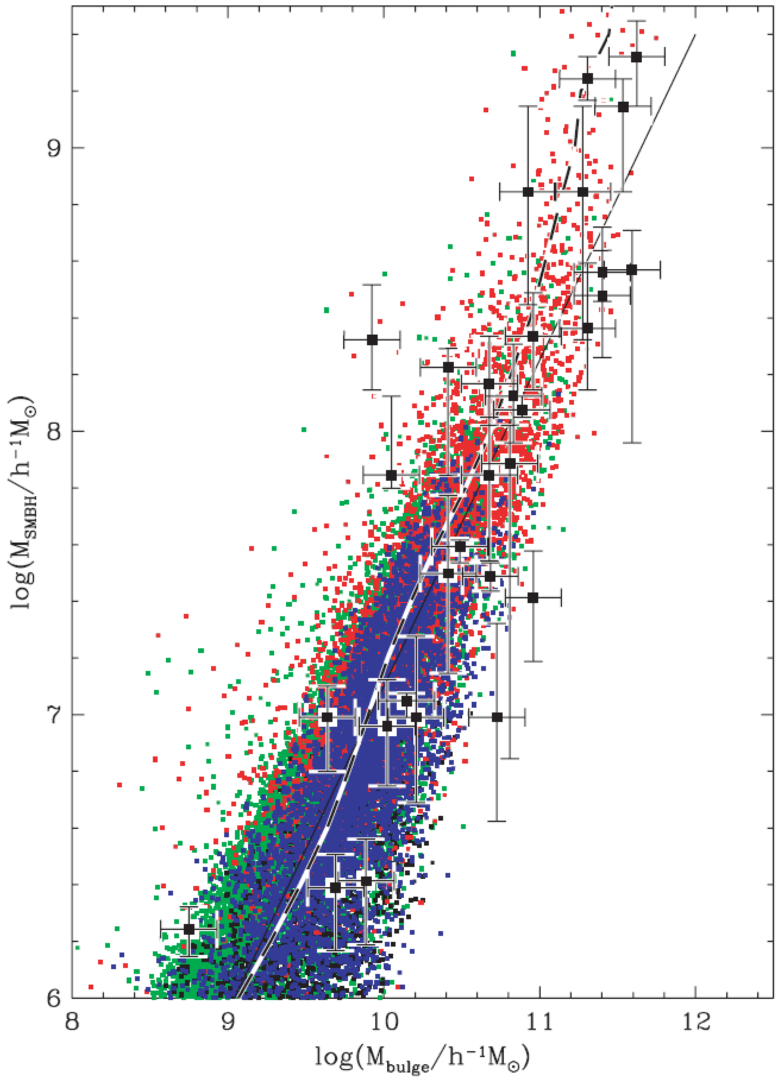
McCarthy et al. (2007)

Gas expulsion in a semi-analytic model of galaxy formation, GALFORM

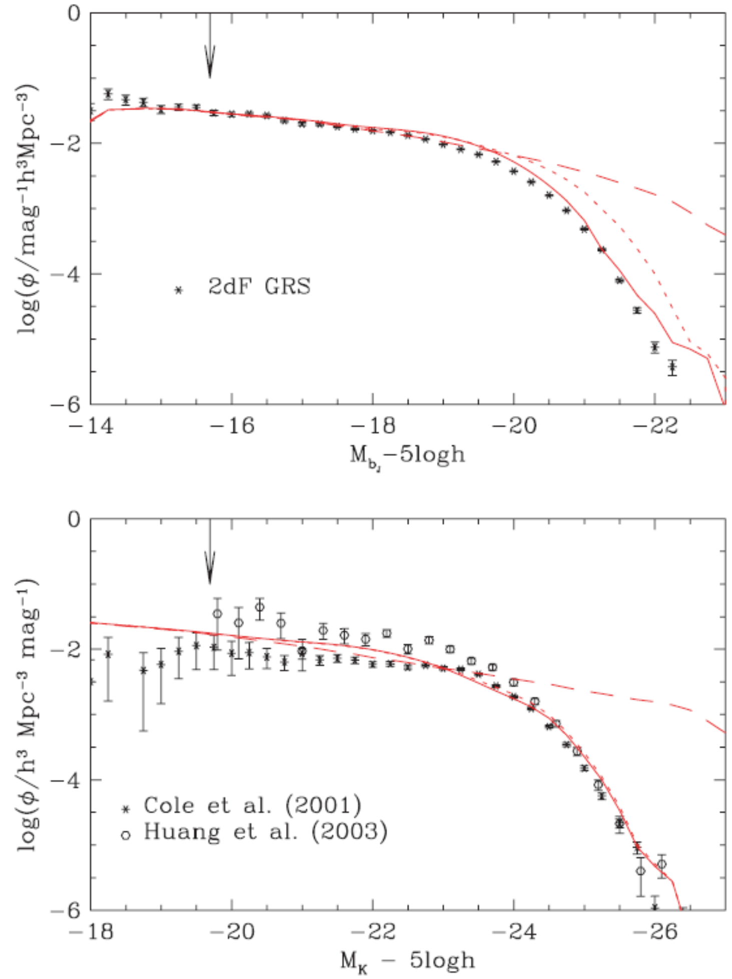
Bower, McCarthy, Benson (2008), MNRAS

SAMs and the optical universe

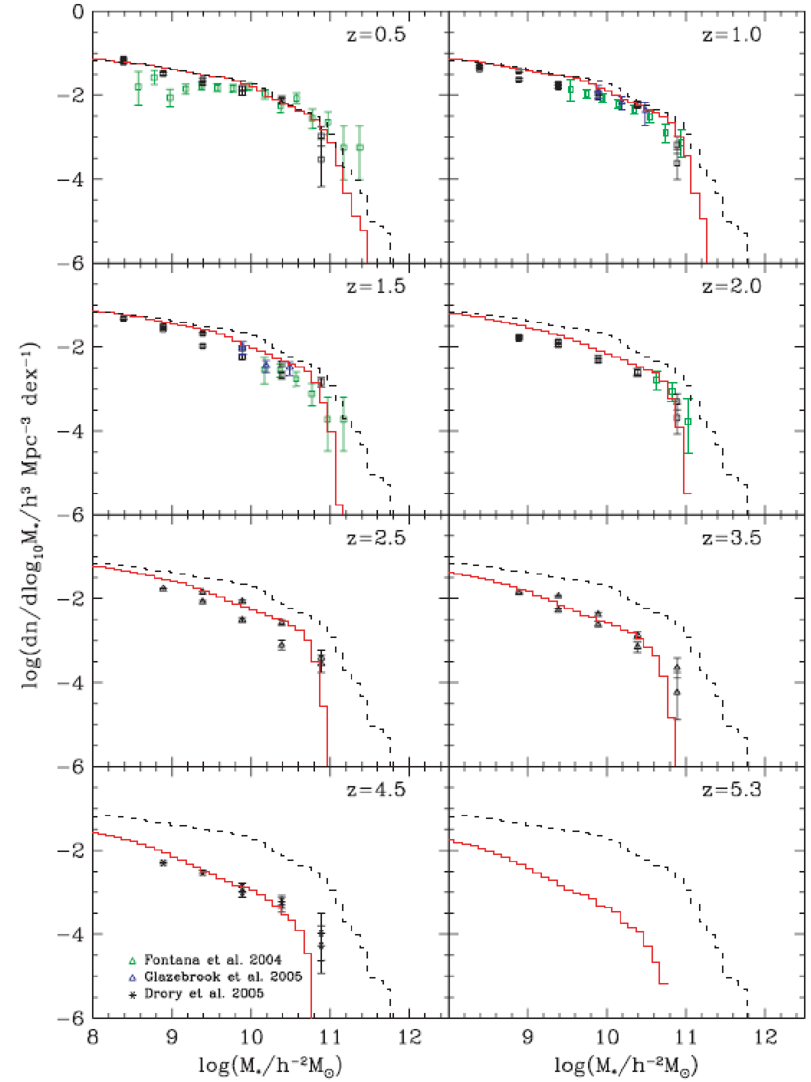
BH scaling relations



Galaxy LFs



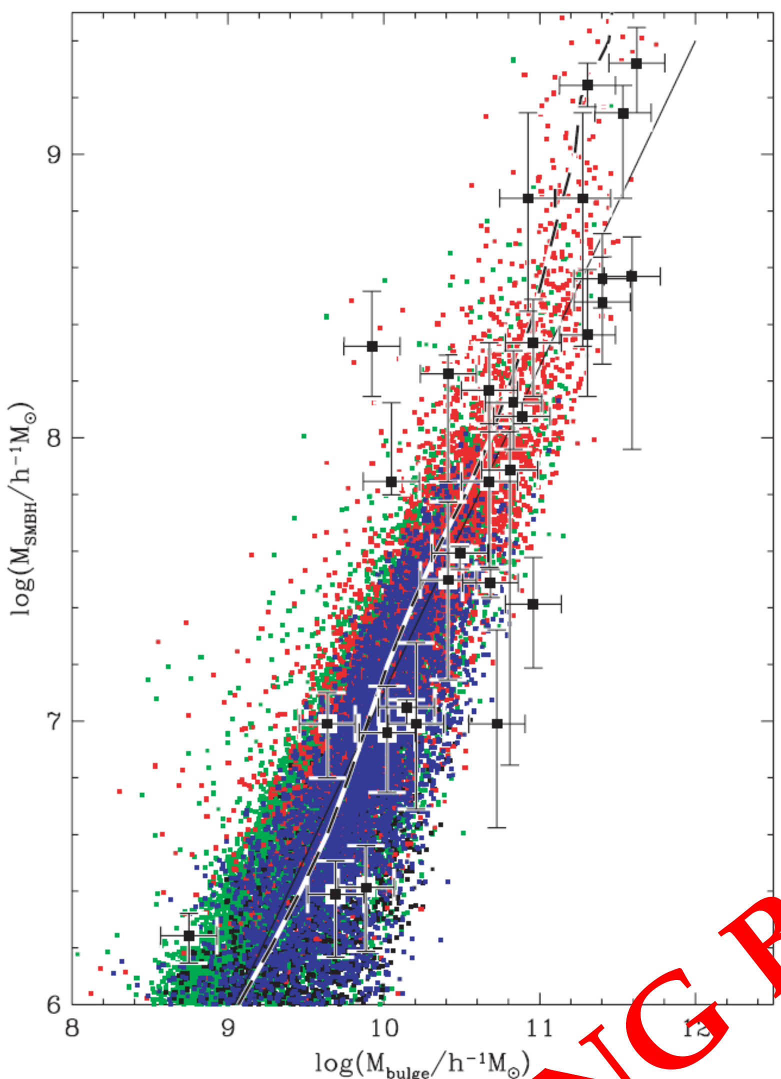
Evolution of LFs

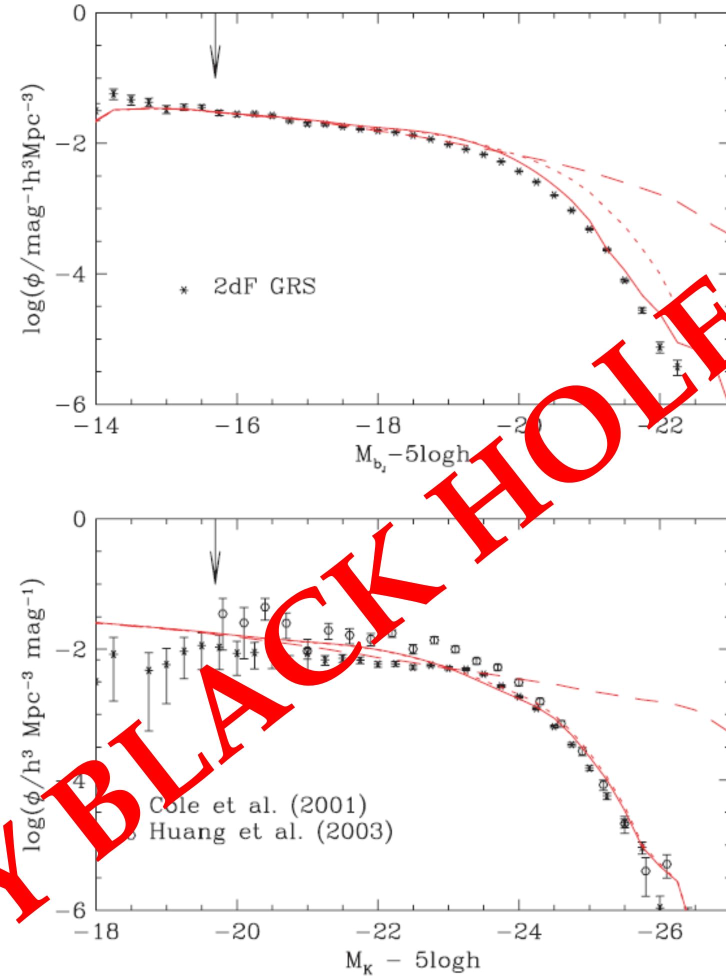


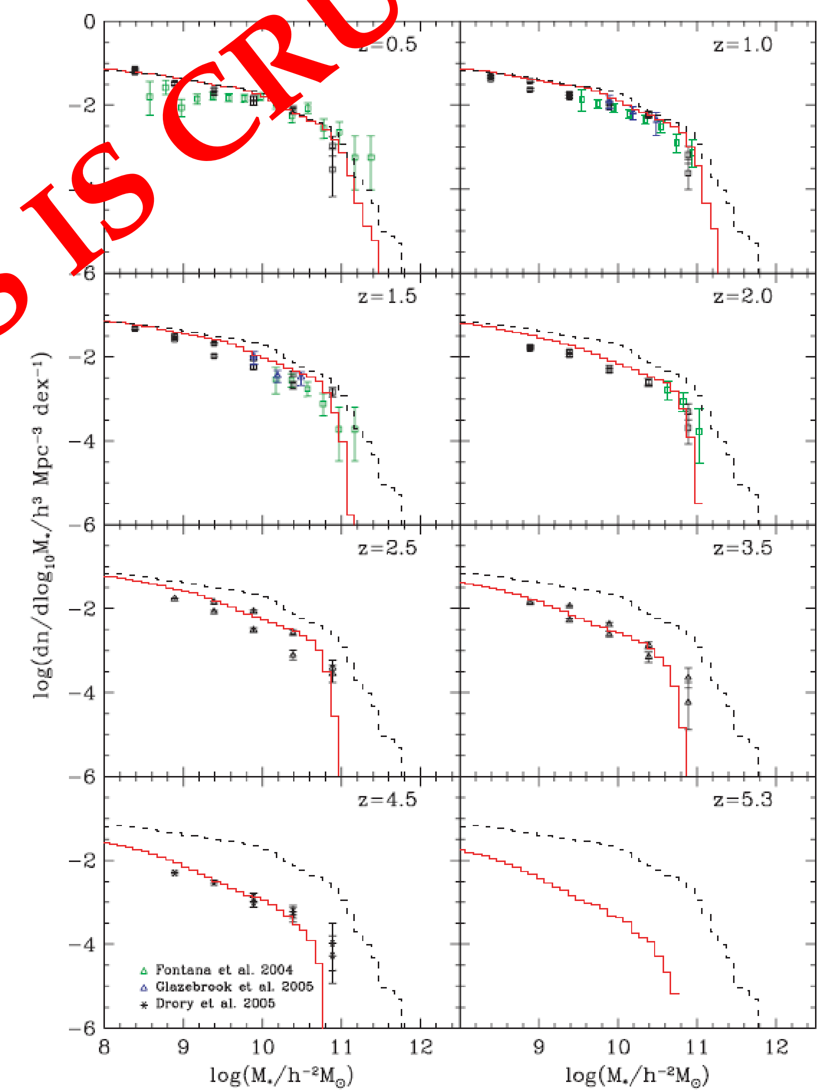
Bower et al. (2006) (see also Croton et al. 2006; De Lucia & Blaizot 2007; Somerville et al. 09)

- Tuned to match (e.g.) LF, make predictions for other observables. Great success in matching many key global/statistical properties of the galaxy population.

SAMs and the optical universe







HEATING BY BLACK HOLES IS CRUCIAL

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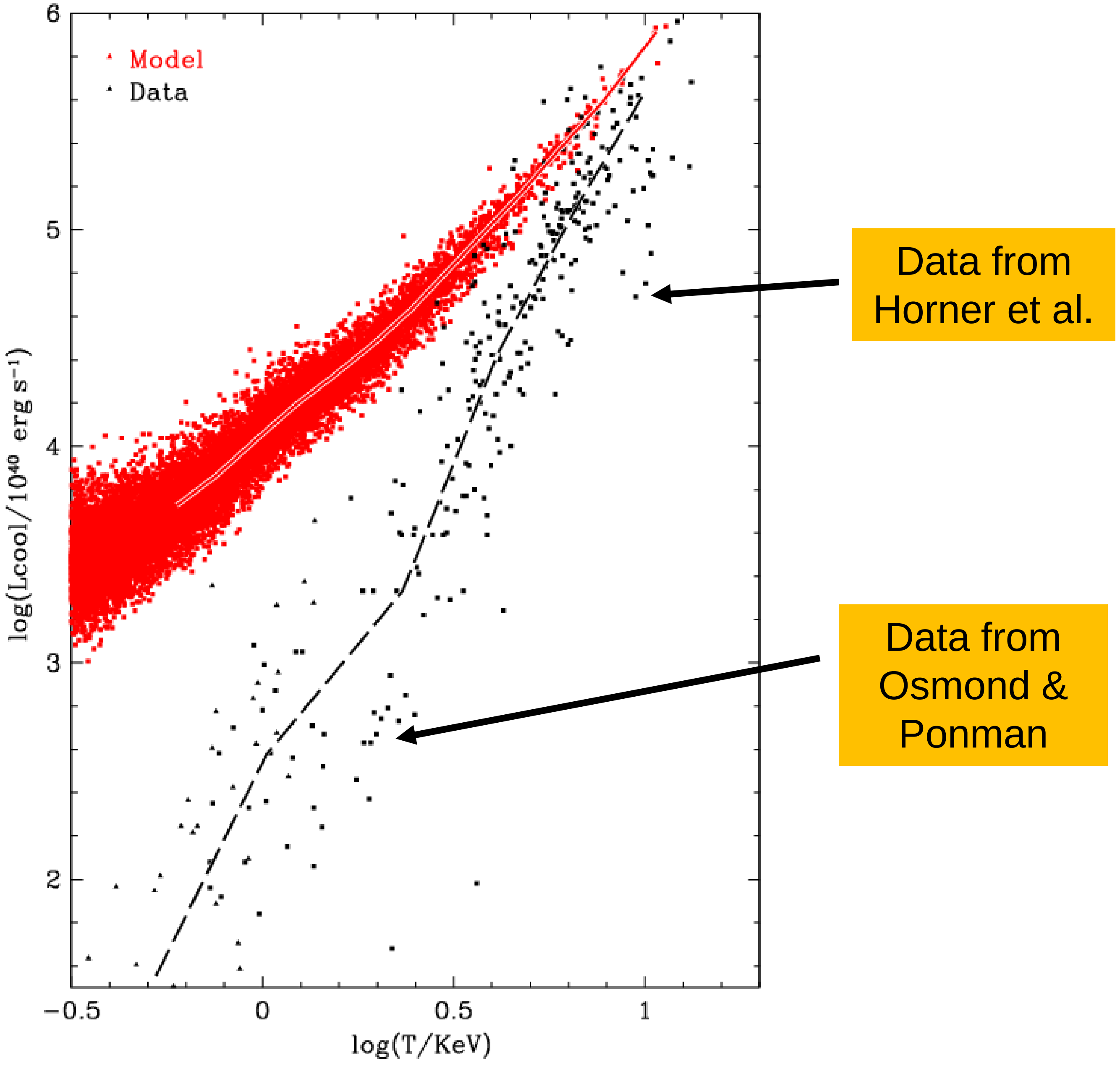
SAMs and the X-ray universe (ssshhh!)

Model in which baryon fraction is fixed fraction

- Typically, in SAMS heating of hot gas does not occur. “Heating” merely stops cooling. (Can heat cold gas to T_{vir}, but that’s it.)
- What happens when excess energy is allowed to heat/eject gas?

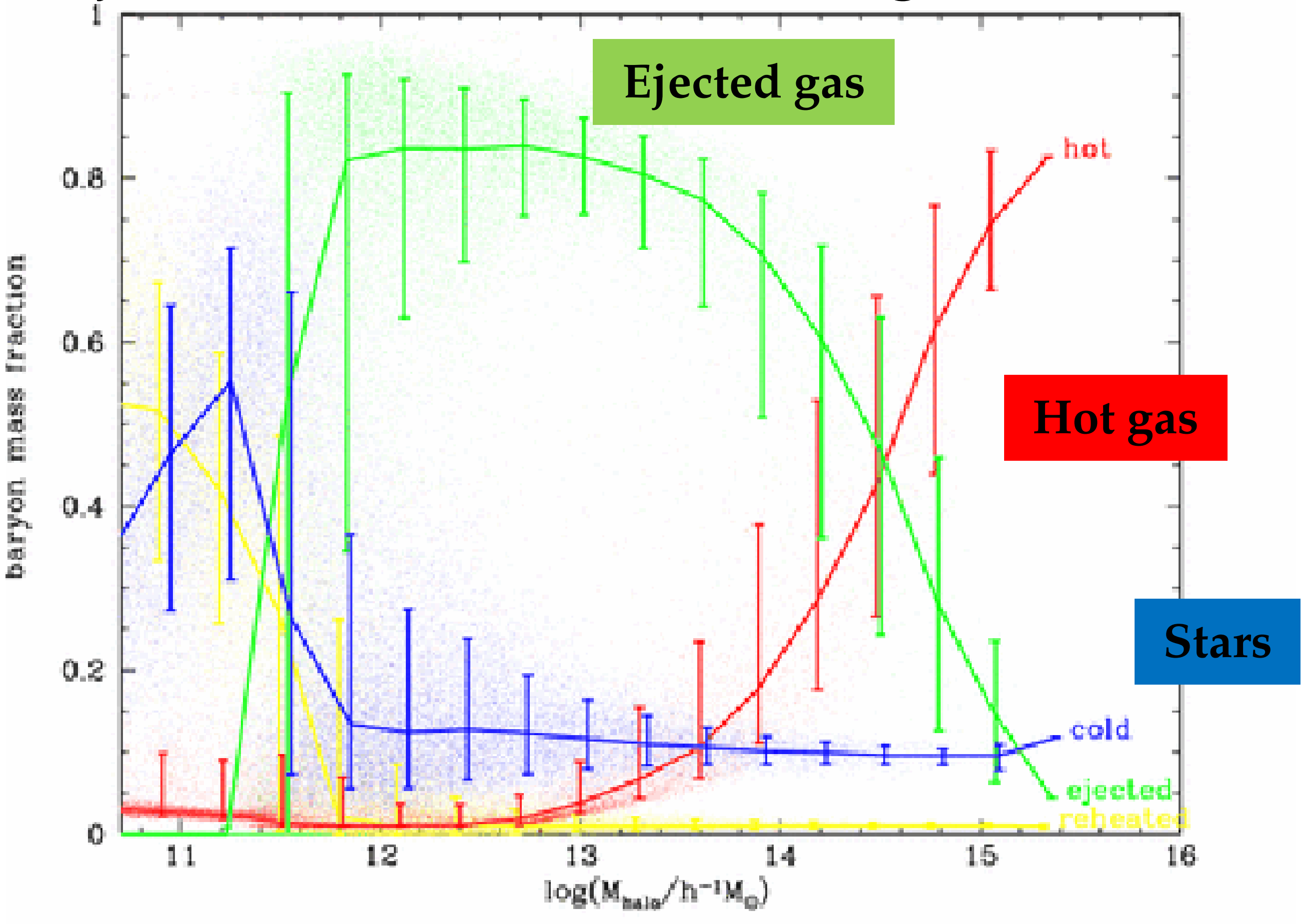


Bower et al. (2008)

Allowing for gas ejection

Bower et al. (2008)

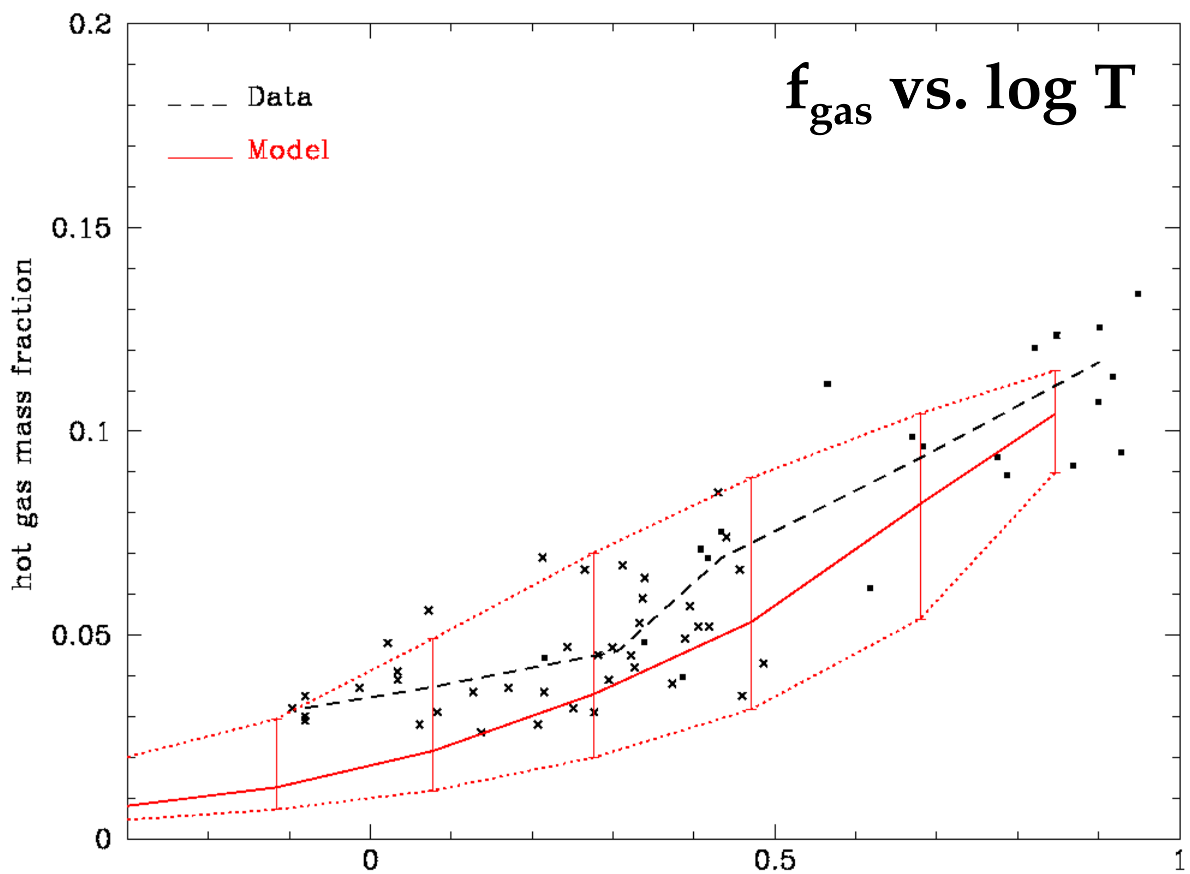
Ejection dominates below log M < 14.5



L_{heat} is the smaller of:

$$\varepsilon_{SMBH} L_{Eddington}$$

$$\eta_{SMBH} \, 0.1 \dot{M}_{cool} c^2$$

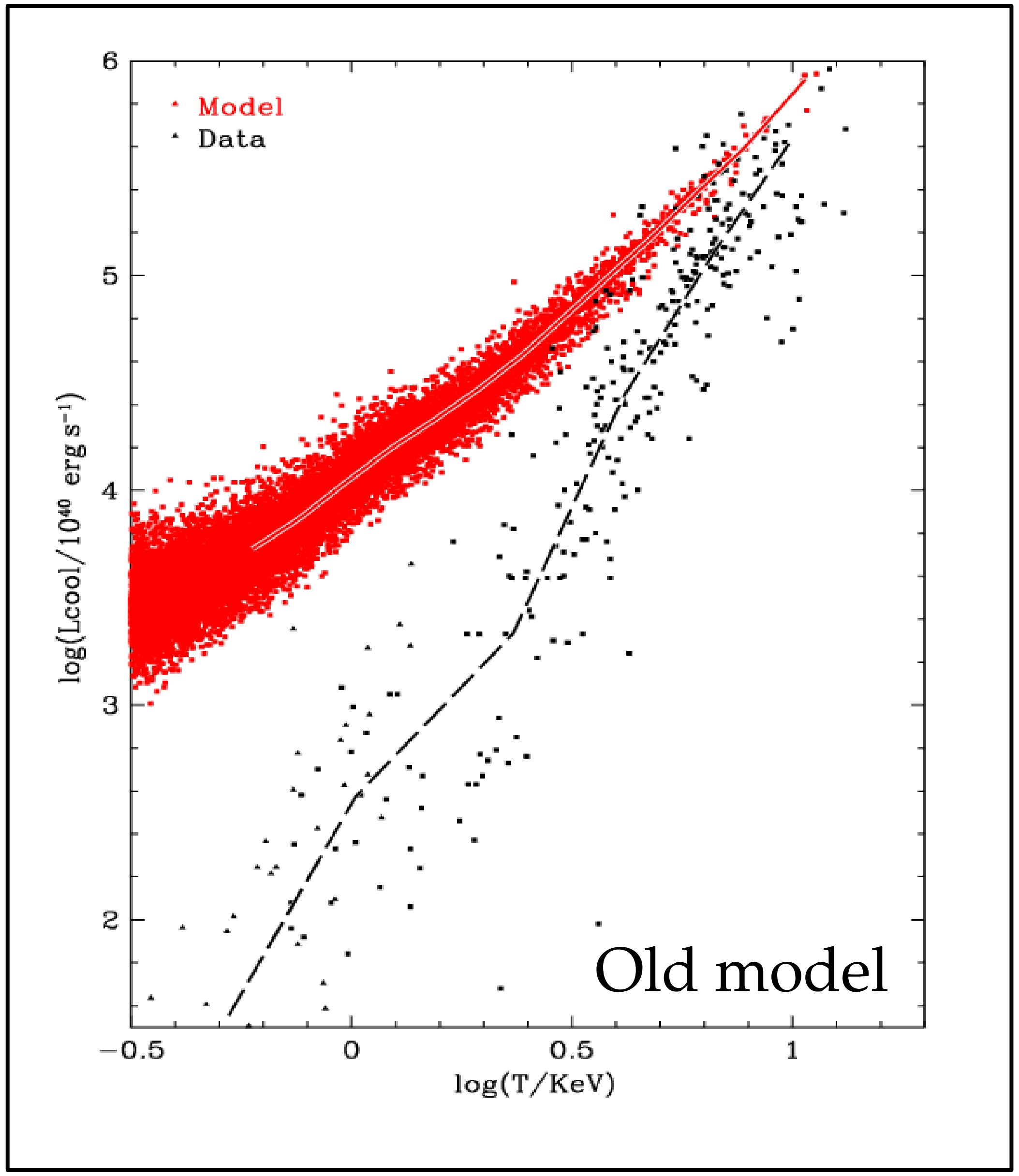


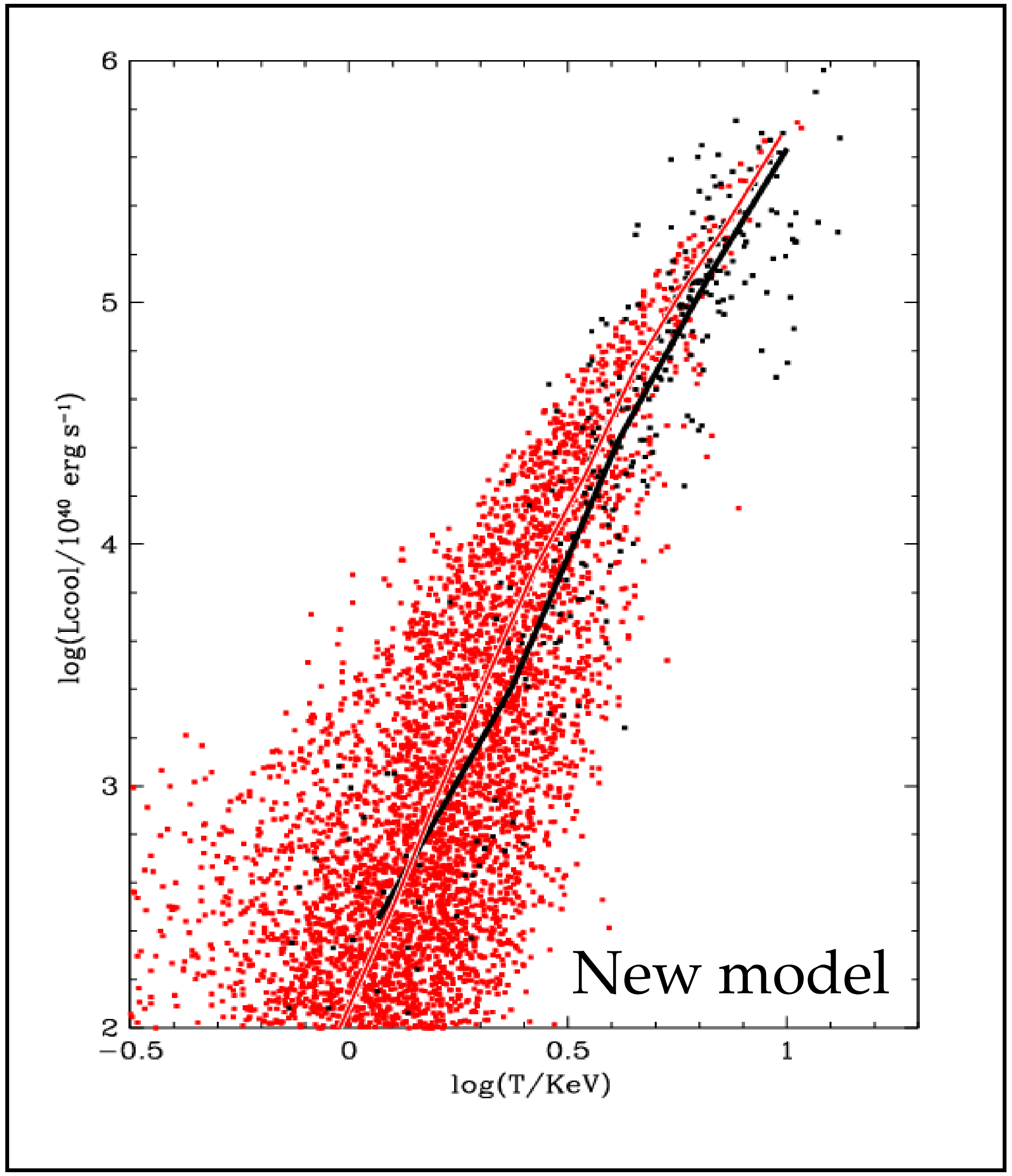
If $L_{heat} > L_{cool}$, gas is "ejected" from the system at a rate:

$$\frac{dM_{gas}}{dt} = \frac{L_{heat} - L_{cool}}{v_{halo}^2 / 2}$$

Gas can return later, if the halo grows significantly.

SAMs and the X-ray universe, revisited





• Other parameters of the model (e.g., merger timescale, yields, SN efficiency) need to be modified to maintain match to galaxy LF.
• BH scalings differ between B06 and B08 (linearity breaks down at high halo mass) in new model, a consequence of requiring more energy to eject gas.

Gas expulsion in the OverWhelmingly Large Simulations (OWLS)

McCarthy, Schaye, Bower et al. (2011), MNRAS
McCarthy, Schaye, Ponman et al. (2010), MNRAS

BH growth and AGN feedback

Booth & Schaye (2009)

Variant on Springel et al. 2005, Di Matteo et al. 2008

• Black hole (BH) seeds placed at the centre of haloes that exceed some threshold mass. Given some seed mass.

• BHs grow by mergers with other BHs and by accretion of neighbouring gas.

• Gas accretion rate is the *smaller* of Bondi and Eddington rates:

$$\dot{m}_{\rm accr} = \alpha \frac{4\pi G^2 m_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}} \qquad \dot{m}_{\rm Edd} = \frac{4\pi G m_{\rm BH} m_{\rm p}}{\epsilon_{\rm r} \sigma_{\rm T} c}$$

• Typically, α = 100-300 in the literature (to account for inability to resolve density near BH). But this overestimates accretion rate for cases where Bondi radius is resolvable.

• A certain fraction of rest mass energy of accreted gas is used to heat local gas *thermally*

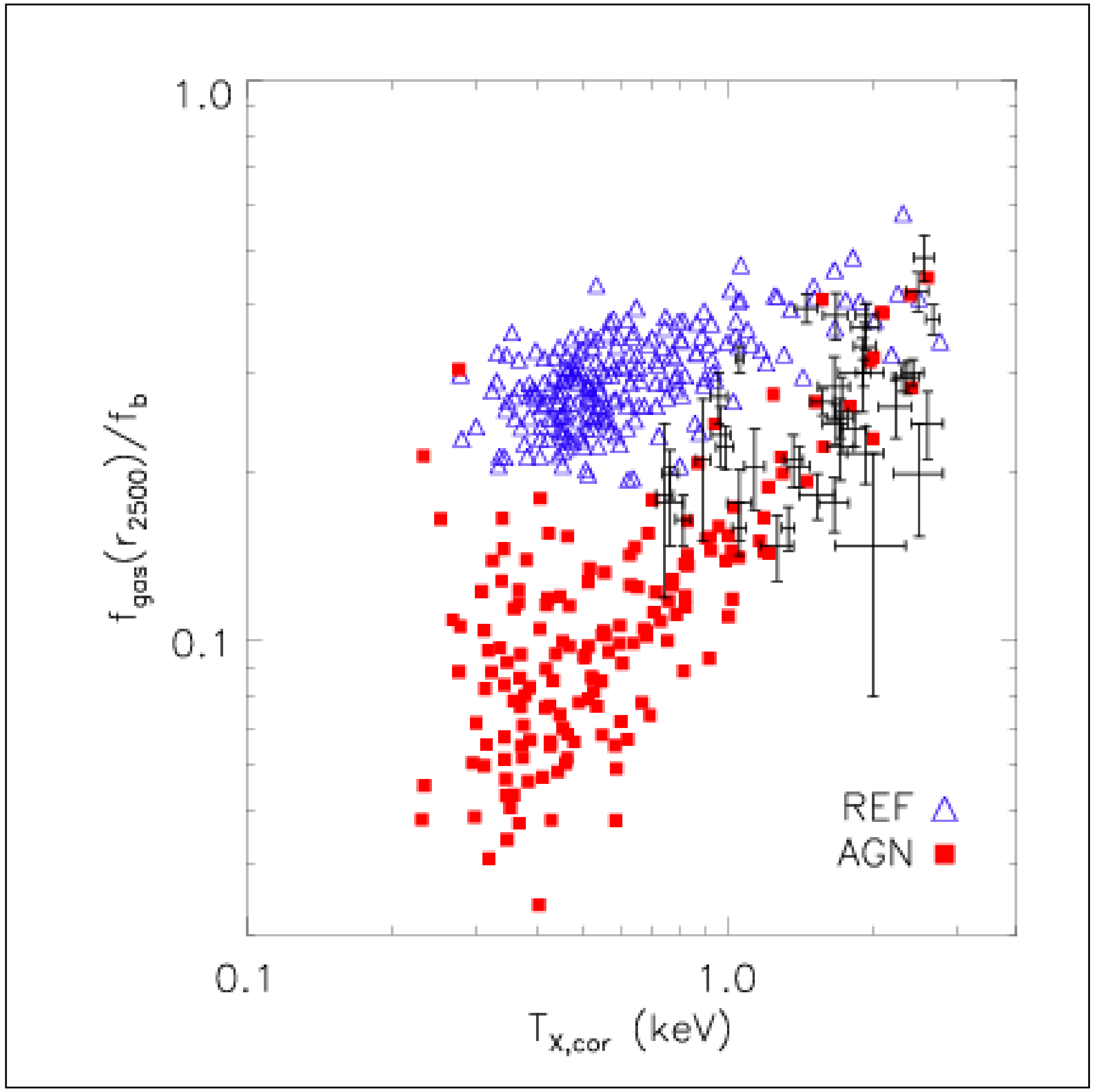
$$E_{feed} = \varepsilon_f \varepsilon_r \dot{m}_{BH} c^2 \Delta t$$

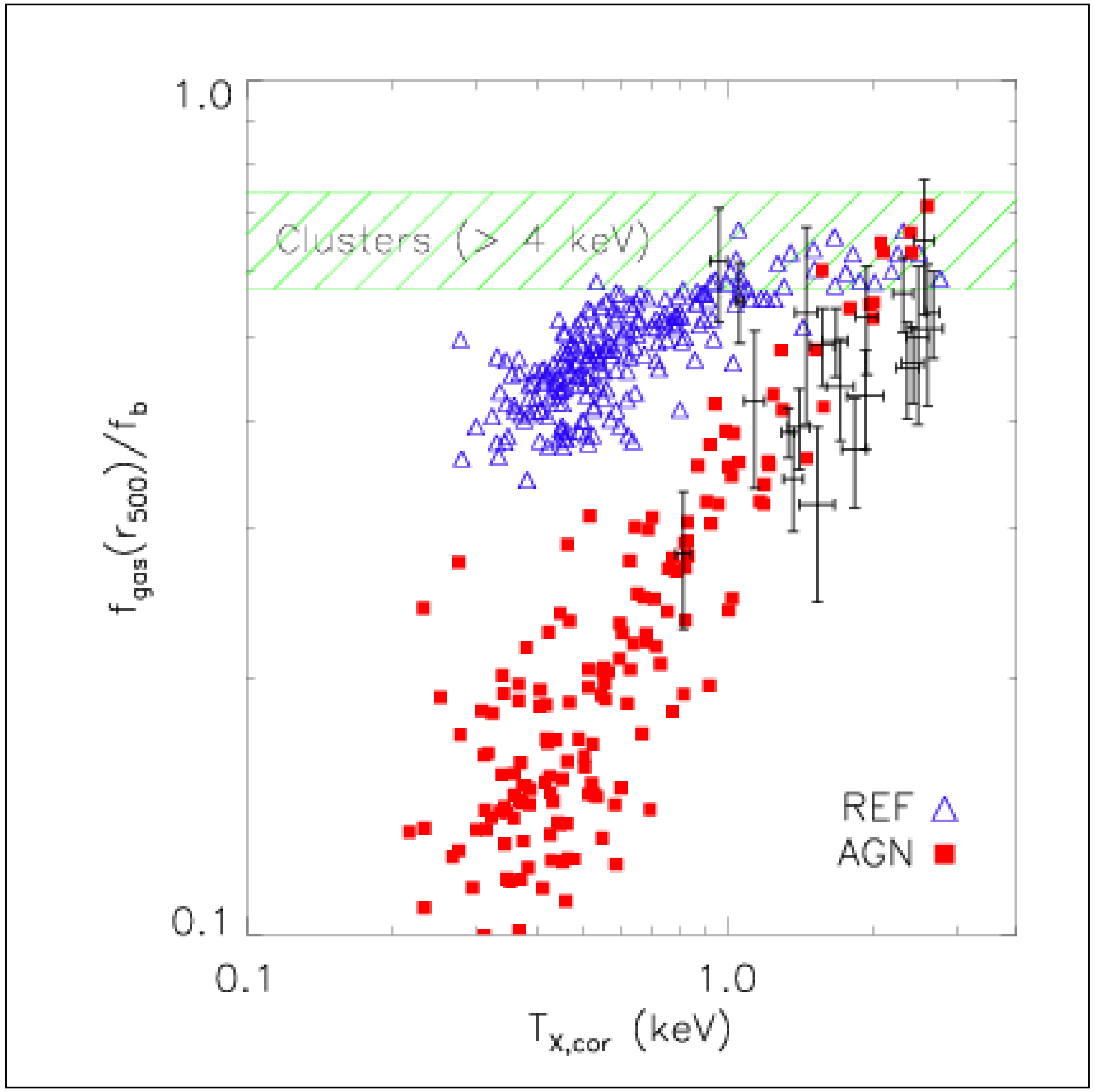
See also Sijacki et al. (2007); Fabjan et al. (2010)

McCarthy et al. (2010), MNRAS, 406, 822

Gas mass fractions within r_{2500} and r_{500}

Data from M. Sun et al. (2009)

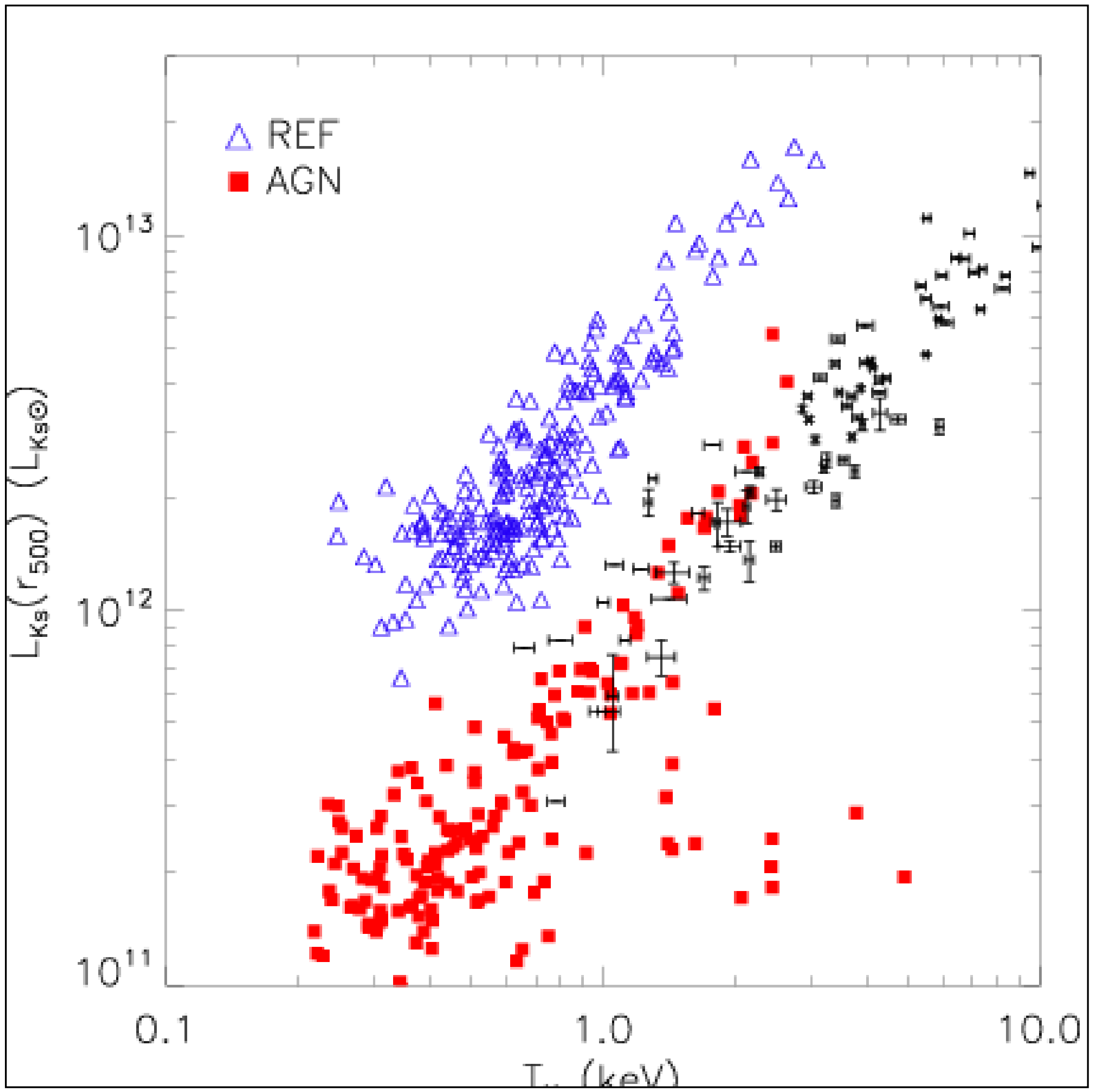




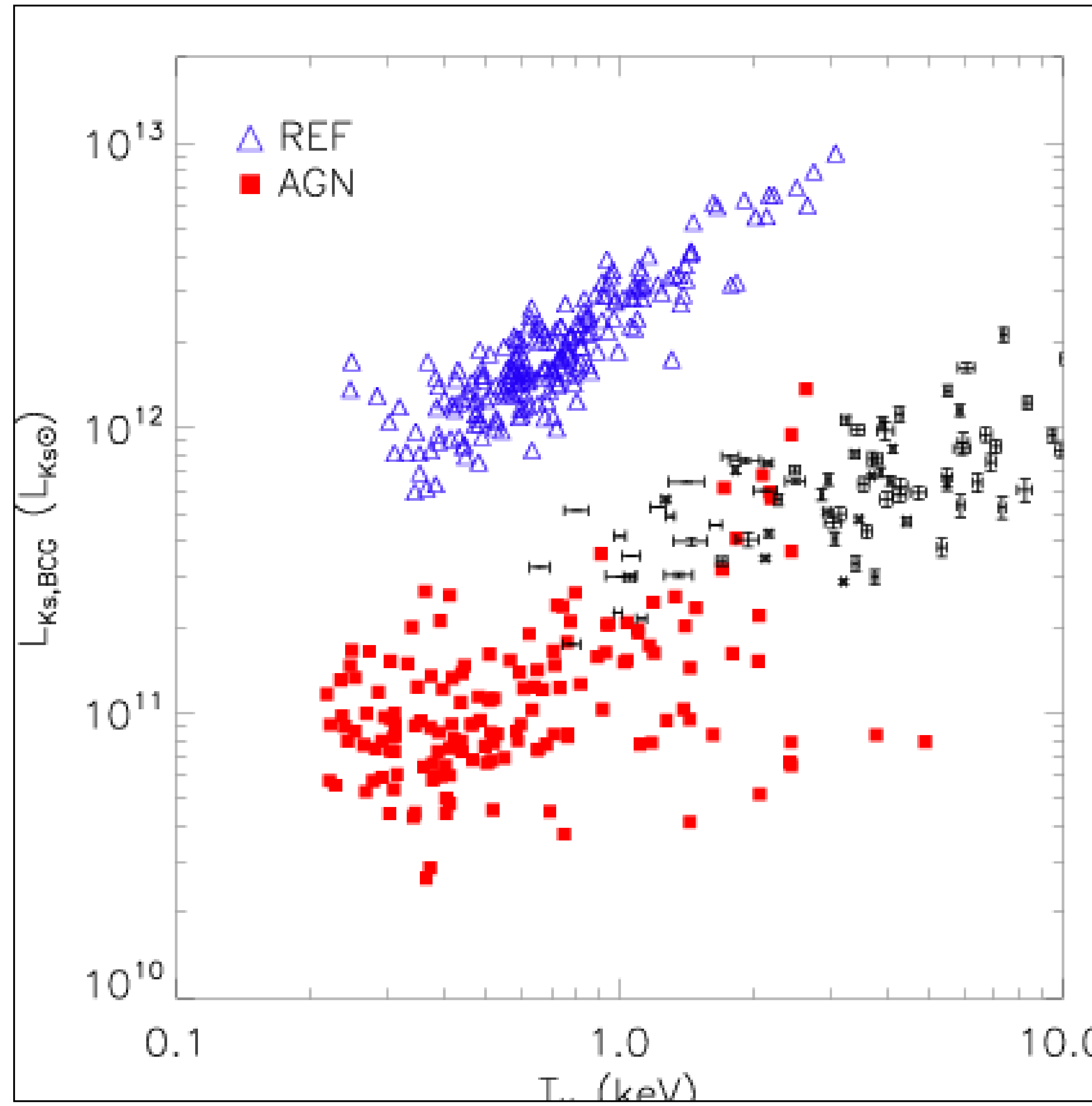
- Energy input from supermassive black holes blows gas out of haloes at z~2. Yields gas mass fractions in good agreement with observations (see also Bower et al. 2008; Puchwein et al. 2008; Short & Thomas 2009). Runs converge for M > ~10^{14} M_{sun}.

Star formation efficiency: K-band luminosities

Data from Lin & Mohr (2004); Rasmussen & Ponman (2009); Horner (2001)



$L_K(r_{500})$ vs. T_x



$L_{K,BCG}$ vs. T_x

'Cooling crisis' of cosmological simulations is resolved on the scale of groups

How exactly do AGN do this in OWLS?

McCarthy et al. (2011), MNRAS

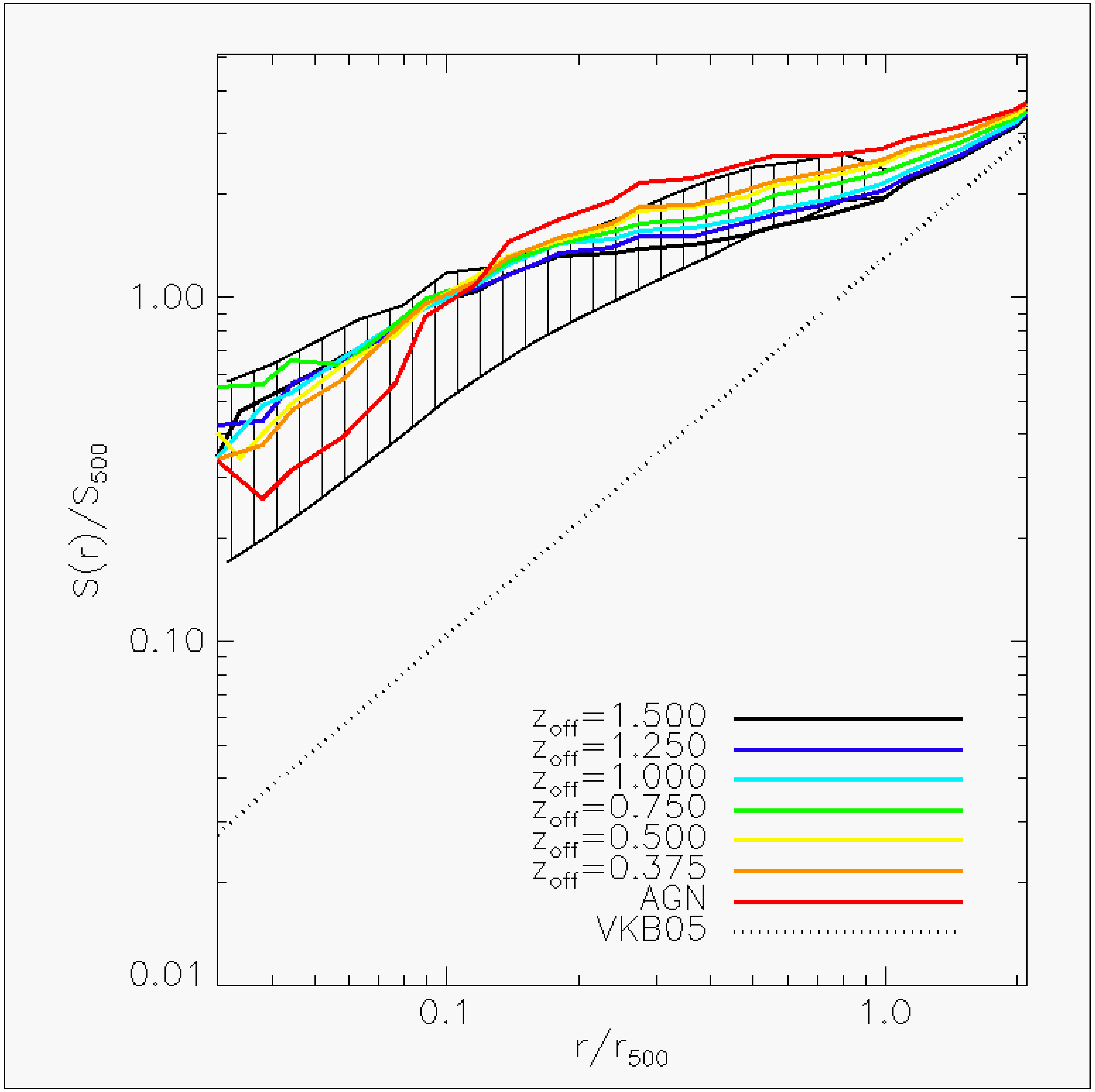
They heat the gas, duh! But what does this mean? They raise its entropy. But how and when and what gas?

1. Raise the entropy of the proto-IGrM; i.e., “preheating” (Kaiser 1991; Evrard & Henry 1991).
2. Raise the entropy of the IGrM after group collapse (energetically expensive; see McCarthy et al. 2008).
3. Eject gas from collapsed group (e.g., Voit et al. 2002; Bower et al. 2008). Also energetically expensive.
4. Eject gas from high-z progenitors of groups…

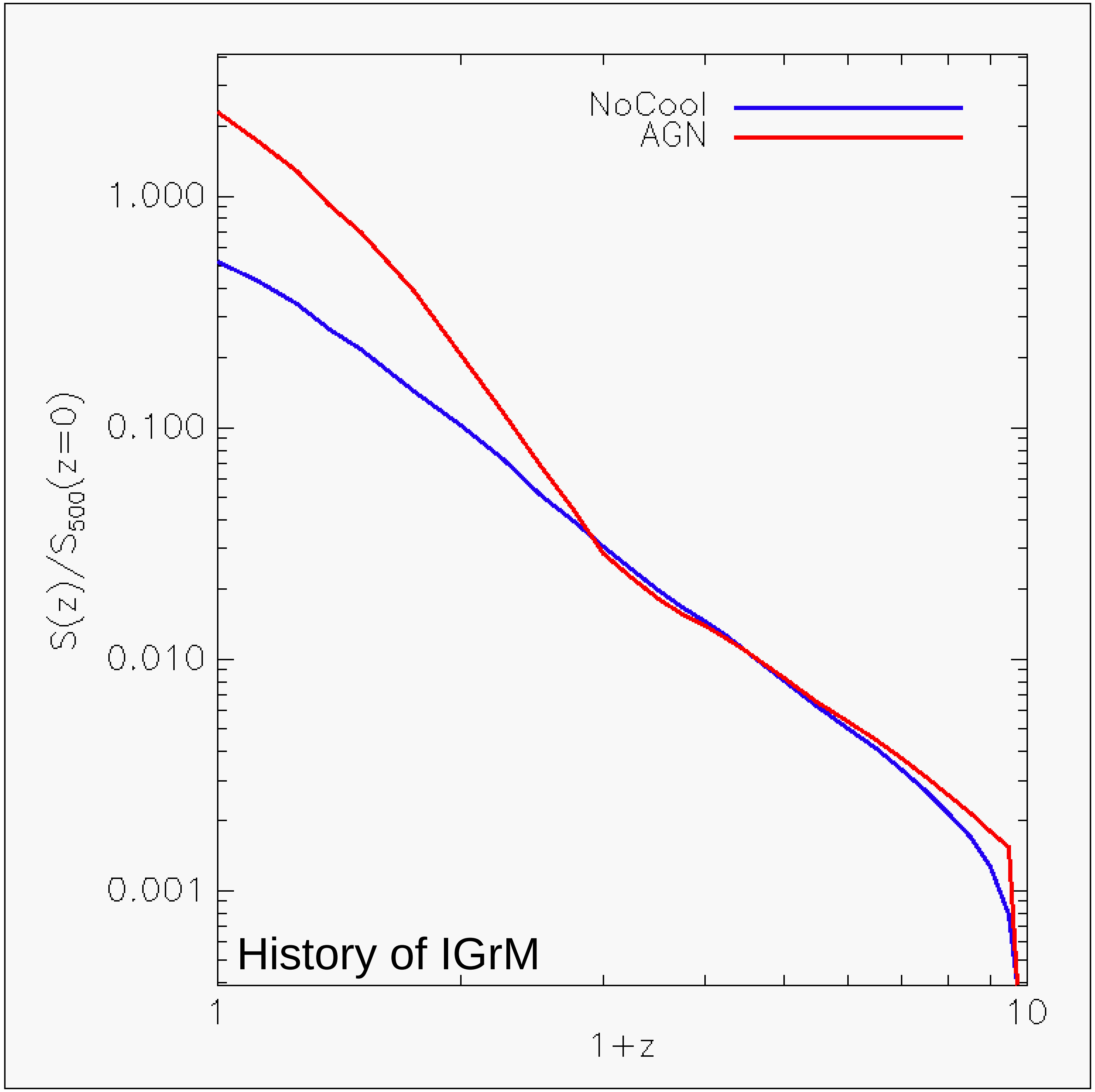
First two scenarios you actually heat the IGrM. Last two are different.

Explicitly turning off late-time AGN feedback

- No big difference, implying excess entropy at z=0 was a result of high-z feedback.

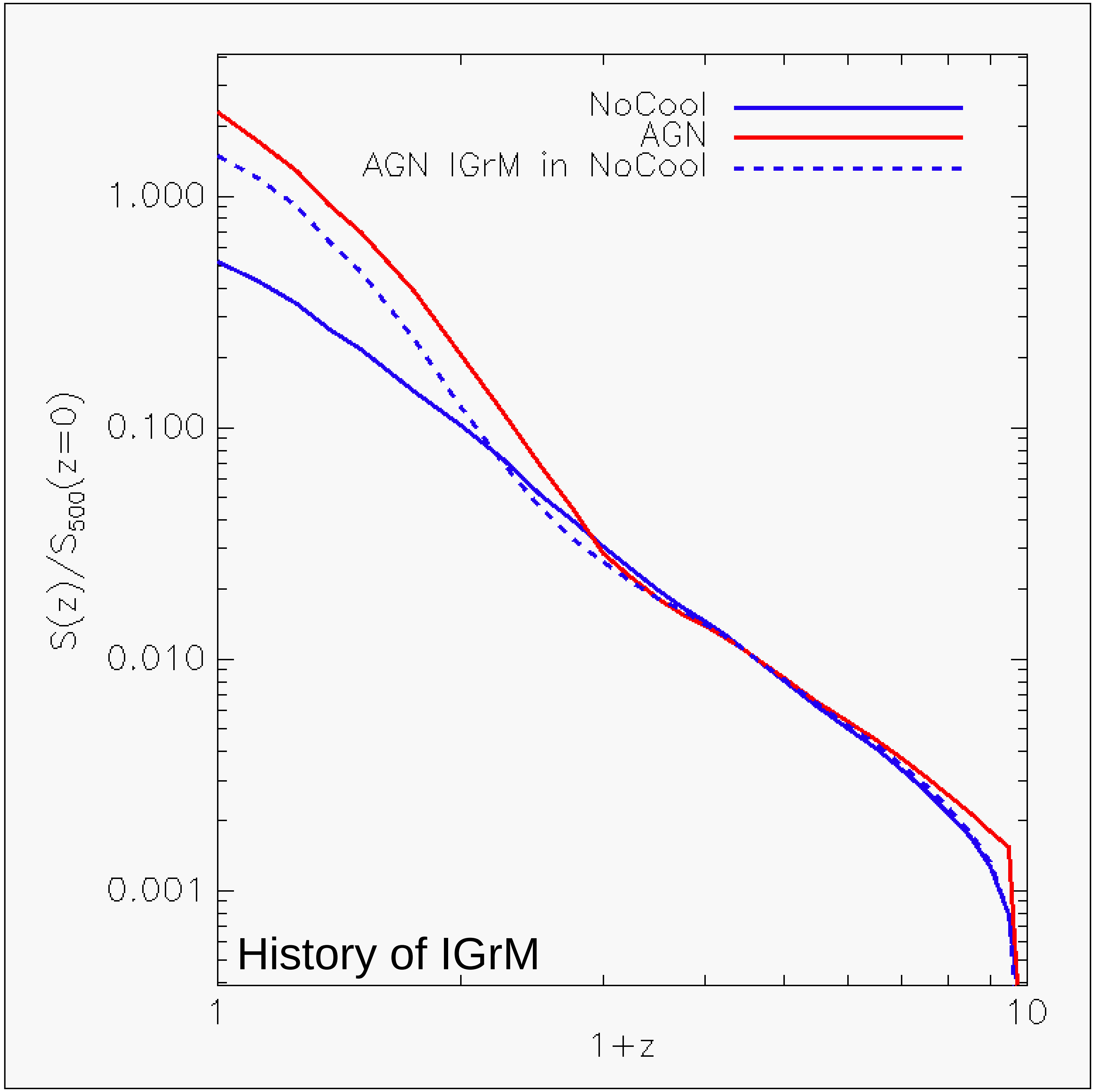


Lagrangian entropy histories



Simulations have identical ICs. Follow a gas parcel over cosmic time in different sims to isolate effects of feedback, cooling, etc.

Lagrangian entropy histories



Simulations have identical ICs. Follow a gas parcel over cosmic time in different sims to isolate effects of feedback, cooling, etc.

Summary and conclusions

• The global thermodynamic properties of groups and clusters suggest that gas expulsion is an important process. The baryon deficit provides further evidence of this.

• SMBHs are the only source we know of that has sufficient energy to eject gas from such massive haloes.

• Implementing gas ejection in GALFORM results in a simultaneous match to the galaxy population and the global properties of the ICM (with some tuning).

• BH growth and accretion in cosmological hydrodynamic simulations (OWLS) *naturally* leads to gas ejection and results in both global and radial profiles in good agreement with X-ray data and global optical data.

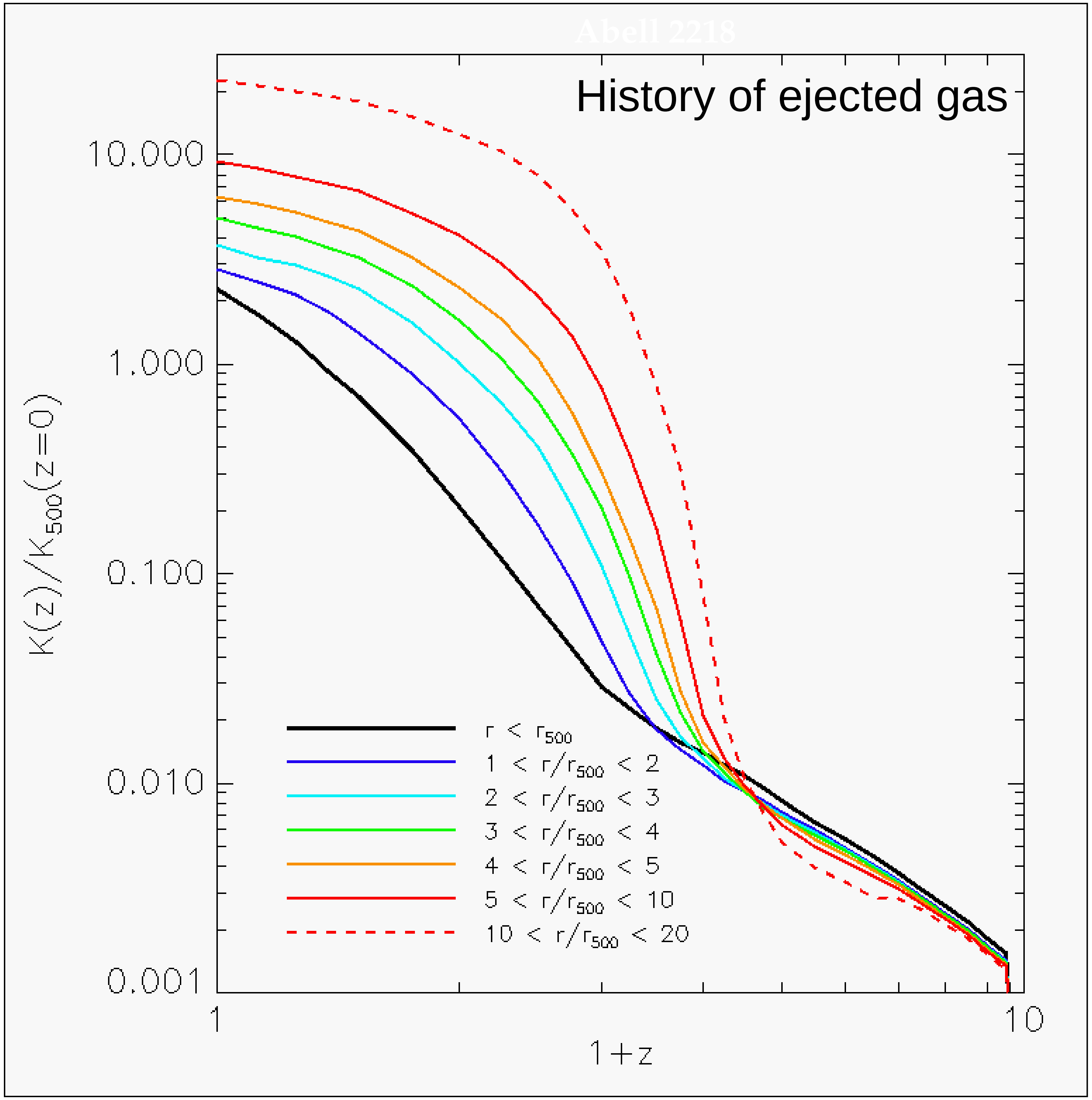
• Whether it is quasar mode (as in OWLS) or radio mode (as in GALFORM) that dominates remains an open question. In both cases, however, most of the ejection happens at high redshift (especially in OWLS).

• Implications for galaxy population at high-z, SZ effect, BH scalings at high masses and evolution.

The End.

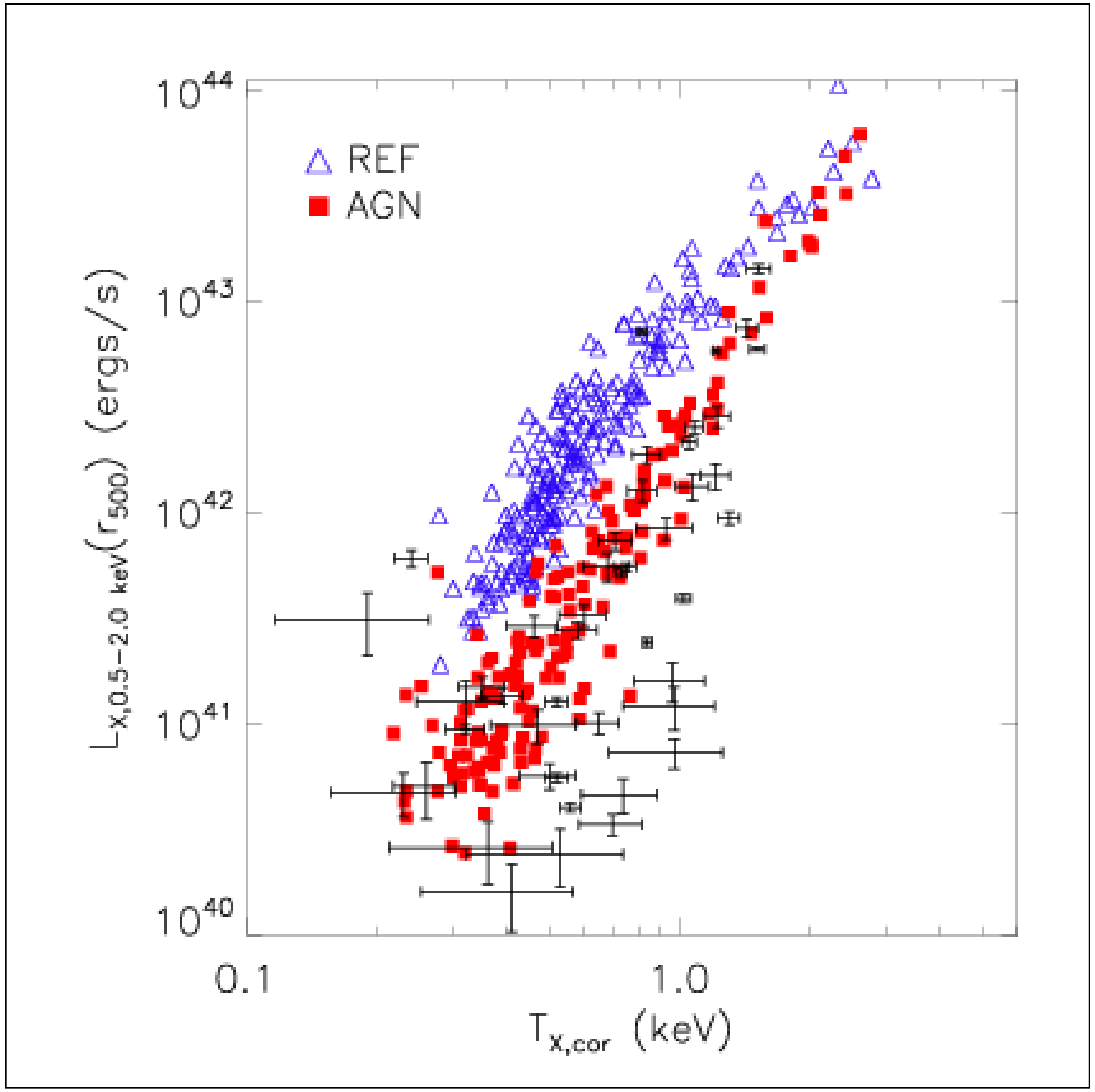
Lagrangian entropy histories

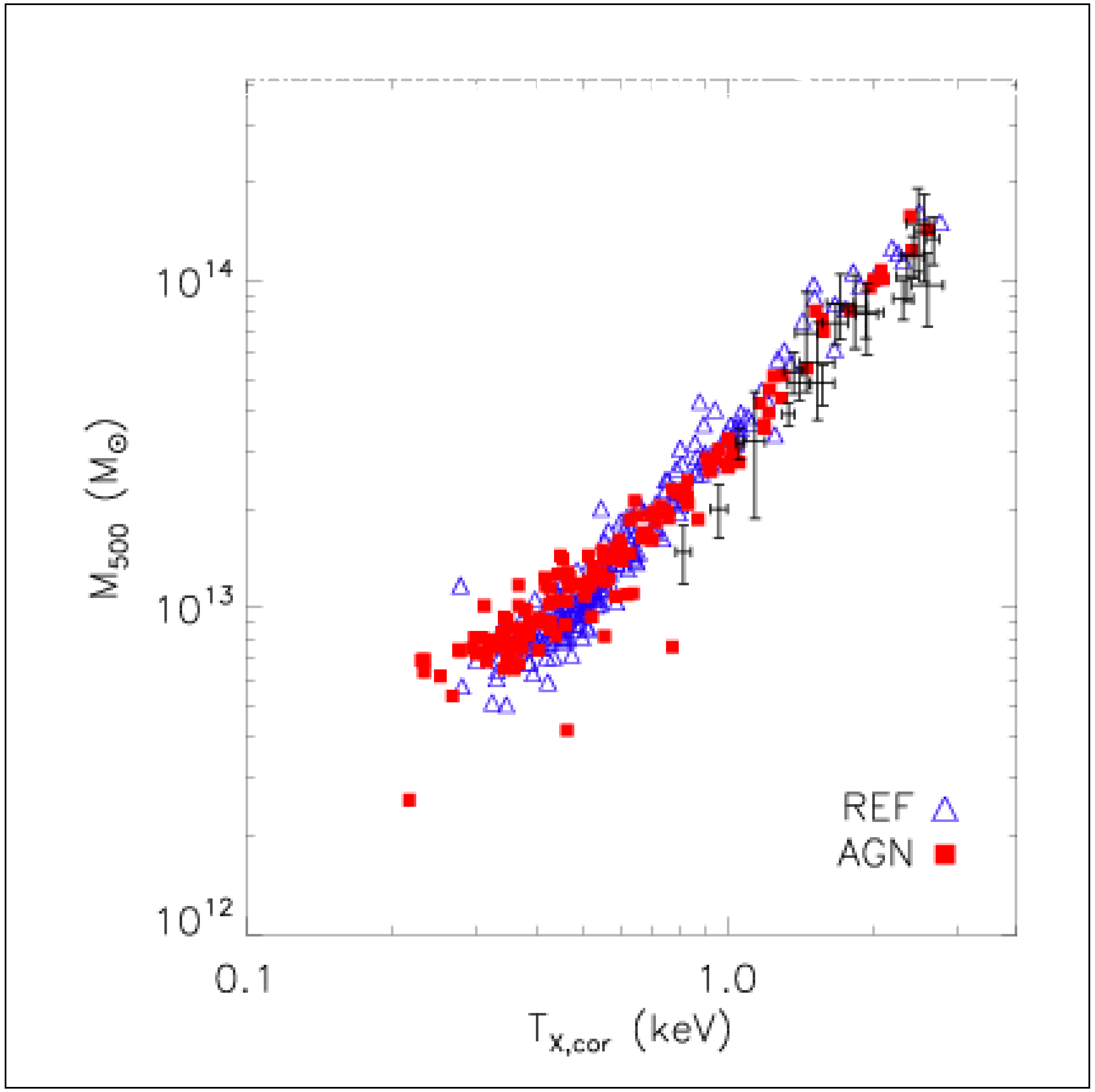
- Gas ejected at 2 < z < 4 (roughly).
- During phase when BH accretion is mainly Eddington-limited.



McCarthy et al. (2010), MNRAS, 406, 822

L_X-T and M_{500}-T relations





Data from Osmond & Ponman (2004) and M. Sun et al. (2009)