Galaxy Formation, Jul. 18-22, 2011, Durham

The intracluster/intragroup medium

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Why groups/clusters are interesting and galformers should care about their hot gas

- **Contain a significant fraction of galaxies and the overall baryonic content of the universe** (both about 25-30% for $\log M_{vir} > 12.5$, ~2% for $\log M_{vir} > 14.5$).

- For the most massive of these systems (10^{15} solar masses), their bindings are huge – their contents should reflect that of the universe as a whole. Cosmology.

- The abundance of these objects (mass function) is a very sensitive probe of several important cosmological parameters, including the total matter density and normalization of the matter power spectrum. Cosmology.

- These are **the only systems in the universe for which it is presently possible to measure both the entire baryon content out to a large fraction of Rvir**. Possible because most baryons are in a hot, diffuse phase.

- **Galaxies likely regulate their SF by what they do to the hot gas component**.

Talk outline

- Thermodynamics of the ICM: implications for feedback

- Metallicity and abundance patterns

- Effects of ICM on orbiting galaxies

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Global X-ray properties of hot gas

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

self-similarity

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

thermal
bremsstrahlung

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

virial theorem

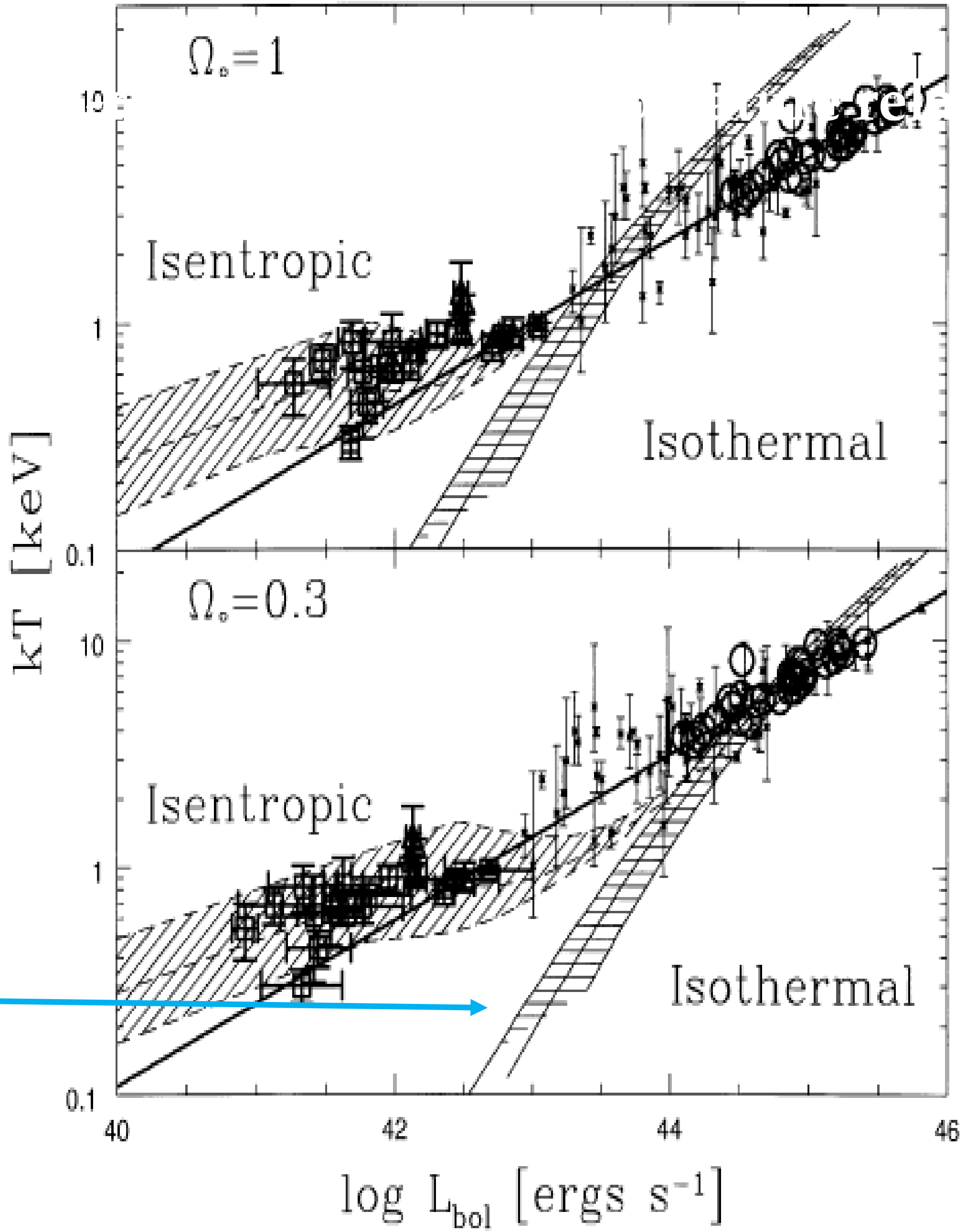
$$\longrightarrow dV \propto R^3 \propto T^{3/2}$$

Yields:

$$L_X \propto T^2$$

OBSERVED (e.g., Edge+ 90, Markevitch+ 96): $L_X \propto T^3$

Balogh et al. (1999)

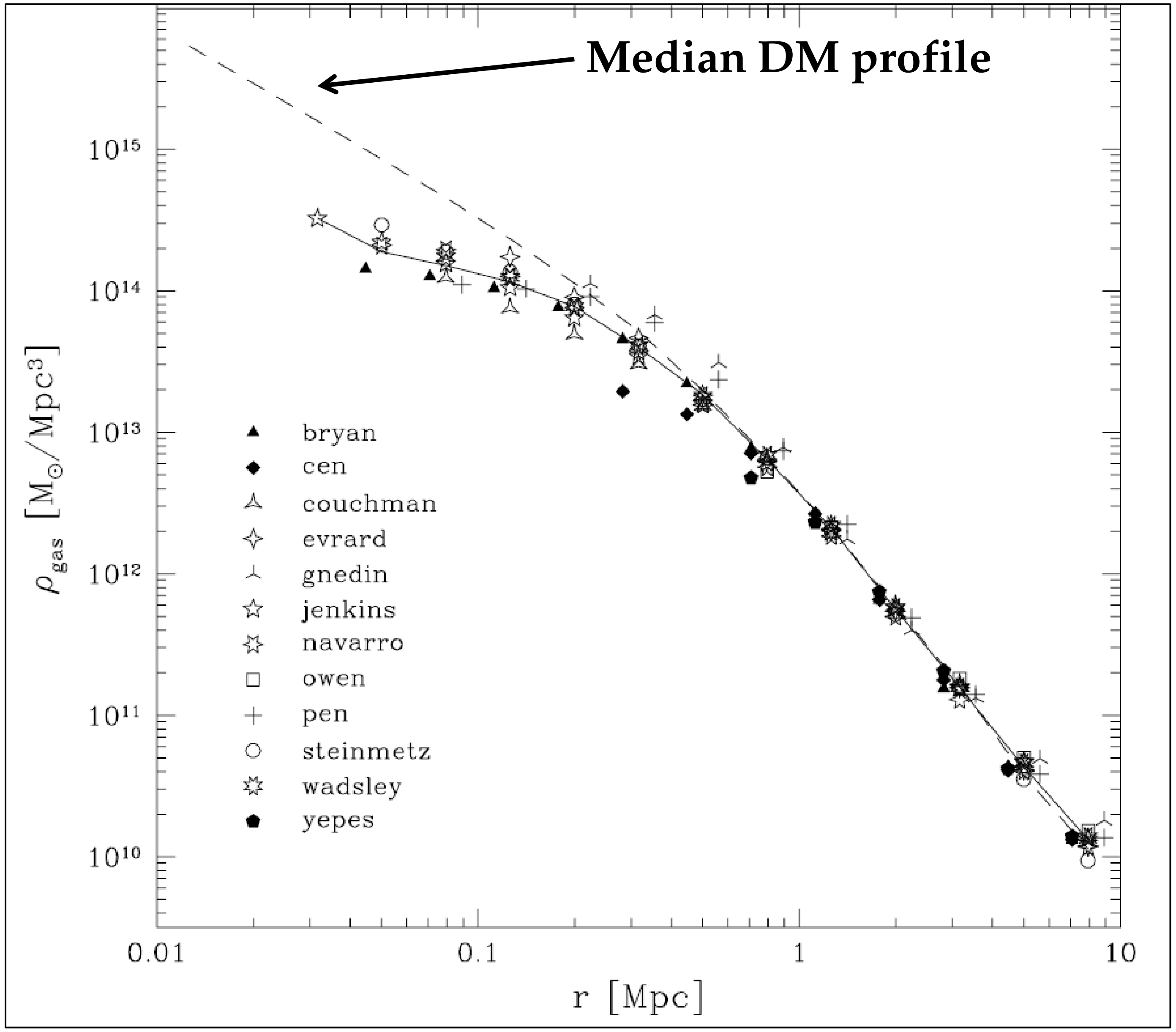


- **Self-similarity does not hold between groups and clusters. Groups have lower rho.**
- **No reason to expect it should for galaxies either (see Rob Crain's talk tomorrow)**

Distribution of the hot gas in non-radiative sims

- Distribution is essentially **gas tracing dark matter**, except in the very inner regions where the gas has a core (most likely due to energy exchange from DM to gas during mergers; McCarthy et al. 07). **Self-similar.**

- Most semi-analytic models for galaxy formation assume a hot gas distribution equivalent to (or similar to) that derived from non-radiative cosmological simulations. True for galaxies and groups/clusters – i.e., self-similarity is assumed.



Frenk et al. (1999)

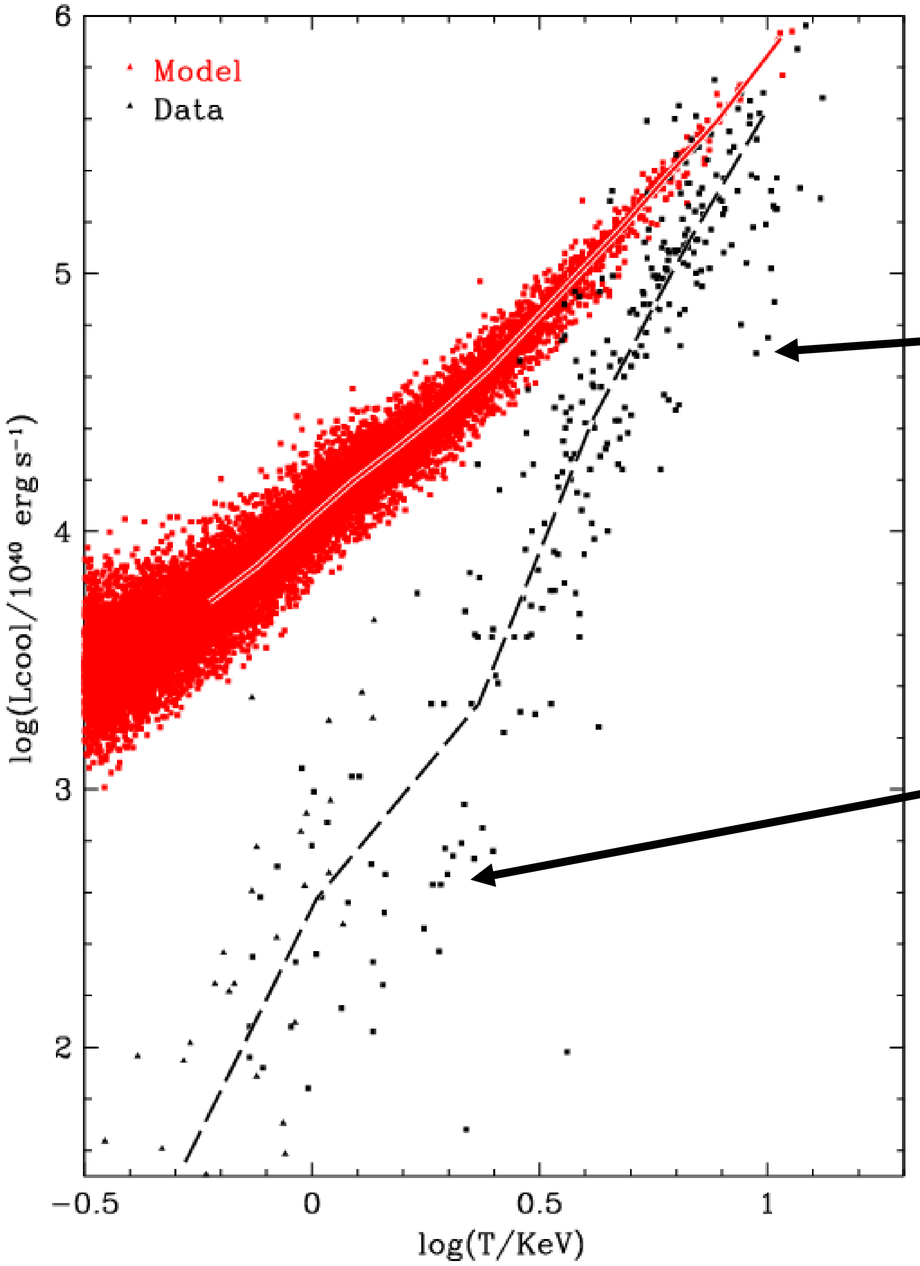
Evrard 90; Thomas & Couchman 92; NFW 95

SAMs and the X-ray universe

- Non-radiative models are obviously silly, as there is no star formation. Most SAMs account for SF by renormalizing the hot gas distribution while maintaining the same shape.

- B08 showed this cannot be an accurate treatment, as the models still greatly overpredict the X-ray luminosity, and the problem is much worse for X-ray observations of galaxies (see Rob Crain's talk).

- Cooling does not really operate this way, or feedback is important for the hot gas, or both.



Data from Horner et al.

Data from Osmond & Ponman

Bower et al. (2006) model
(from Bower, McCarthy, Benson 08)

Entropy as a diagnostic for heating/cooling

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

- 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.

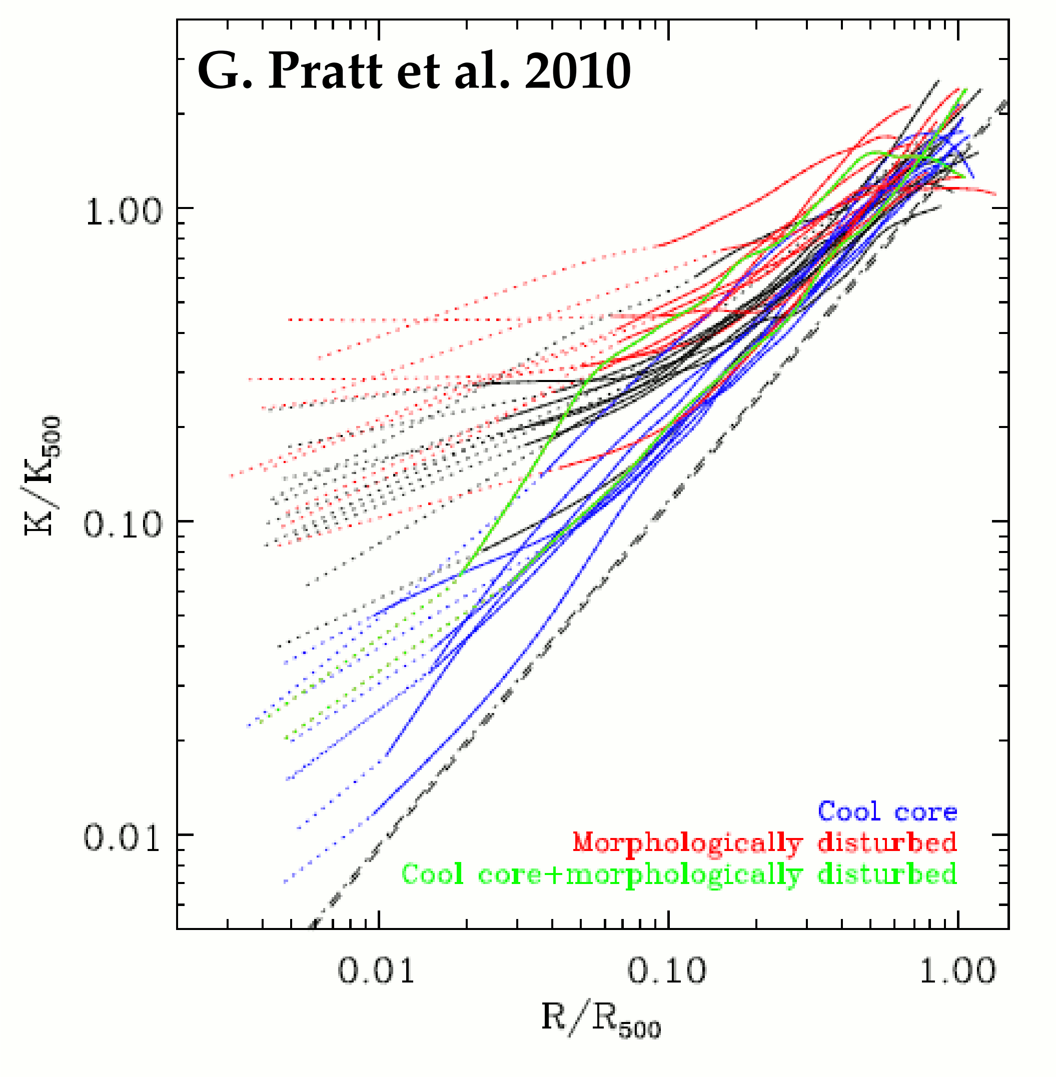
- Through hydrostatic equilibrium in the DM-dominated potential well, the entropy distribution fully determines the gas density and temperature distributions.

What sets the entropy of the hot gas?

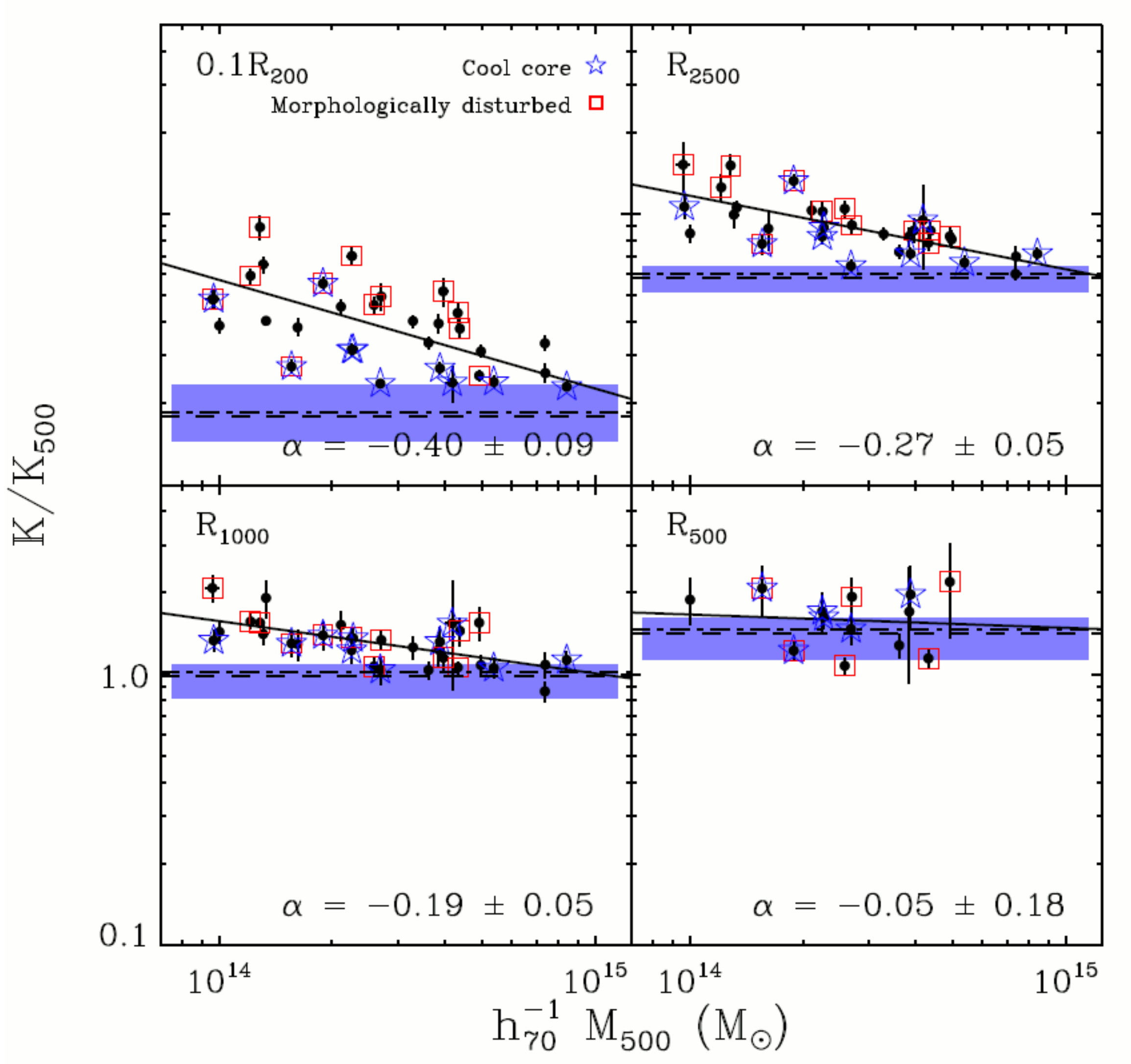
Groups and clusters have “excess” entropy

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

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 and at all radii for groups (Sun et al. 2009).

Ways to raise the entropy of the gas

Cooling

- Selectively removes the lowest entropy gas, increasing the volumetric entropy (e.g., Bryan 2000; Voit & Bryan 2001)

Direct Heating of the ICM (or proto-ICM)

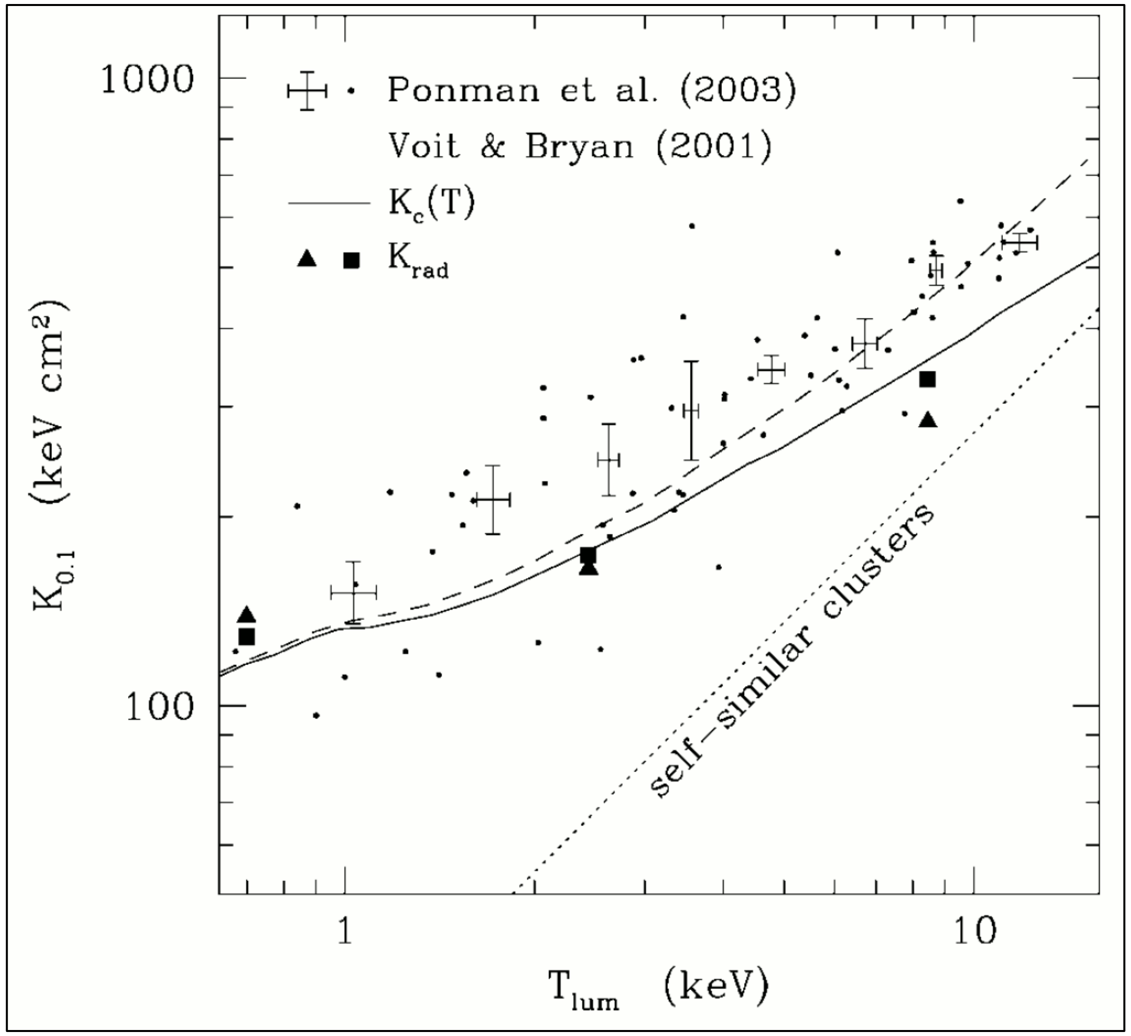
- Heat gas prior to collapse (preheating; e.g., Kaiser 1991; Evrard & Henry 1991)
- Heat gas after collapse (e.g., SNe or bubbles/jets) - **Brian McNamara's talk.** **AGN radio mode is sufficient to balance cooling but not to explain high entropy state of clusters.**

Gas expulsion

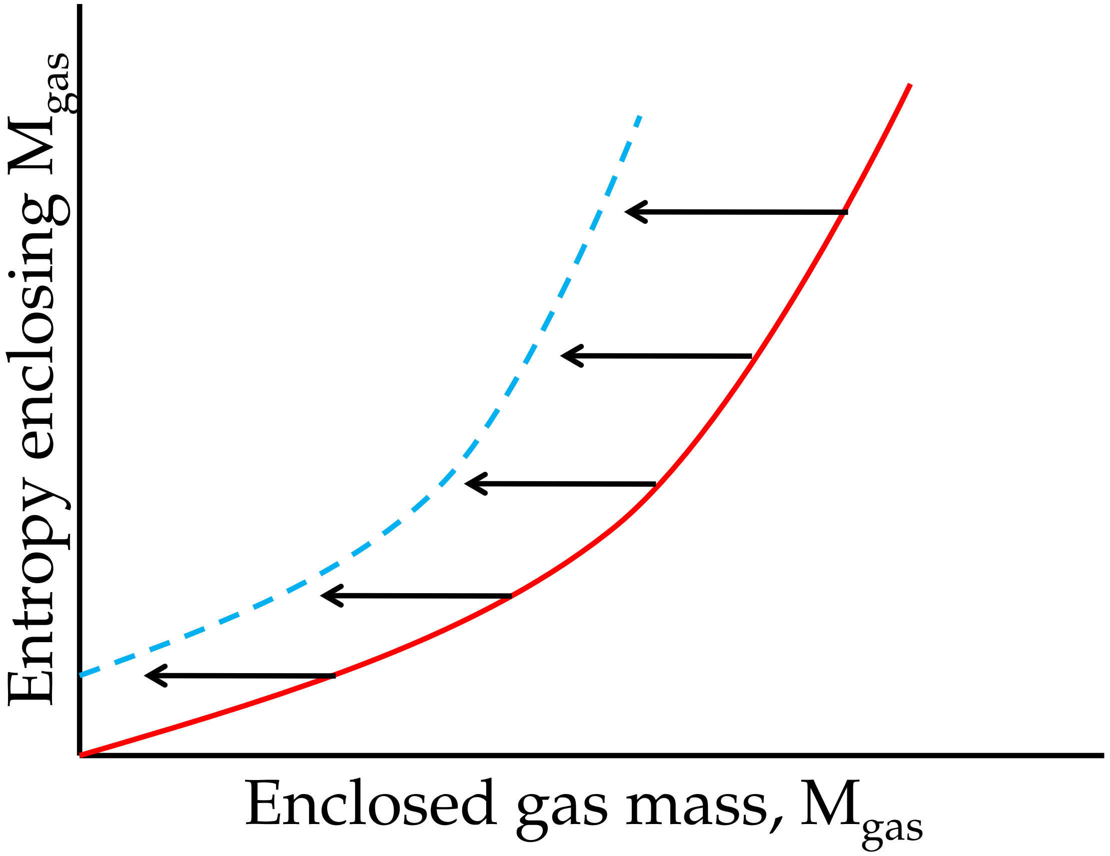
- Eject the lowest entropy gas from the system after collapse (again, expensive).
- Eject the lowest entropy gas from the high redshift progenitors (McCarthy et al. 2011)

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)



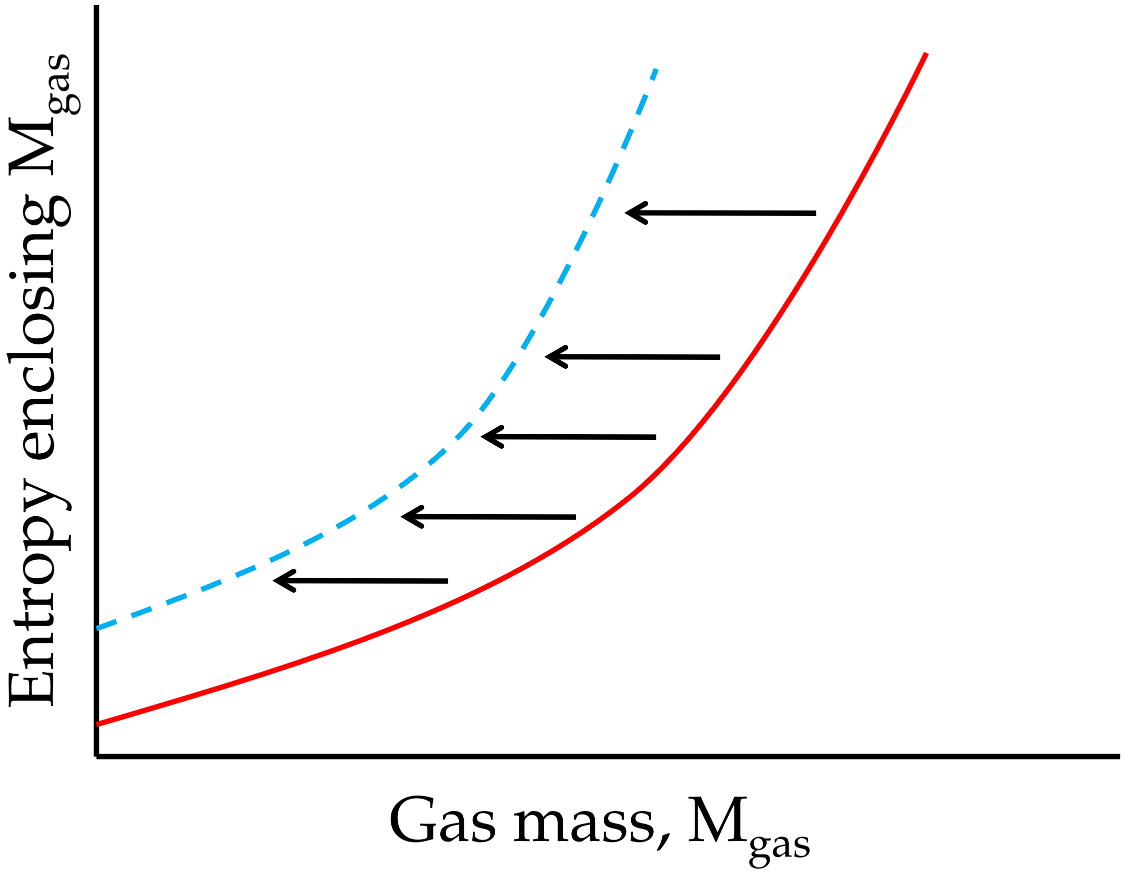
Voit & Ponman (2003)



- A cooling only model does pretty well at getting the global entropy right, but fail horribly in the optical world (severe overcooling). Coincidence that it gets the right global properties? Probably not...

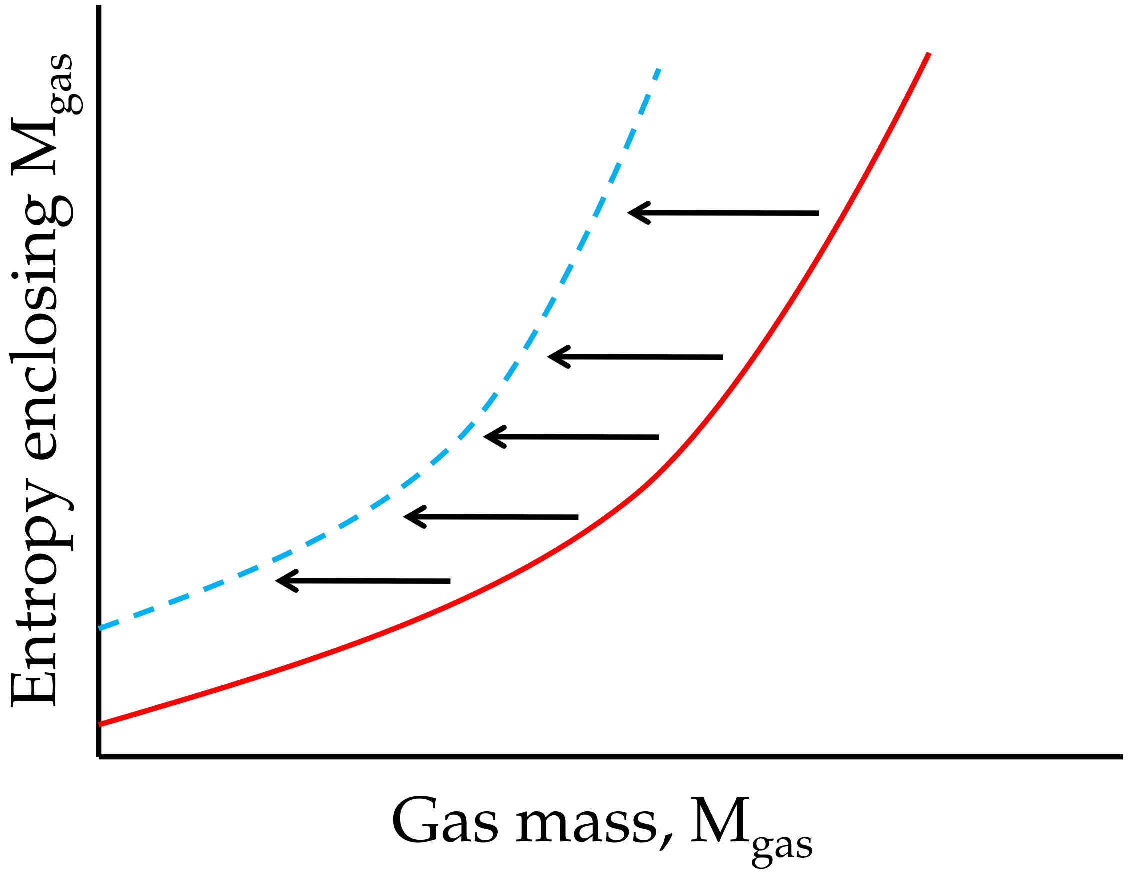
Can heating act like cooling?

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.

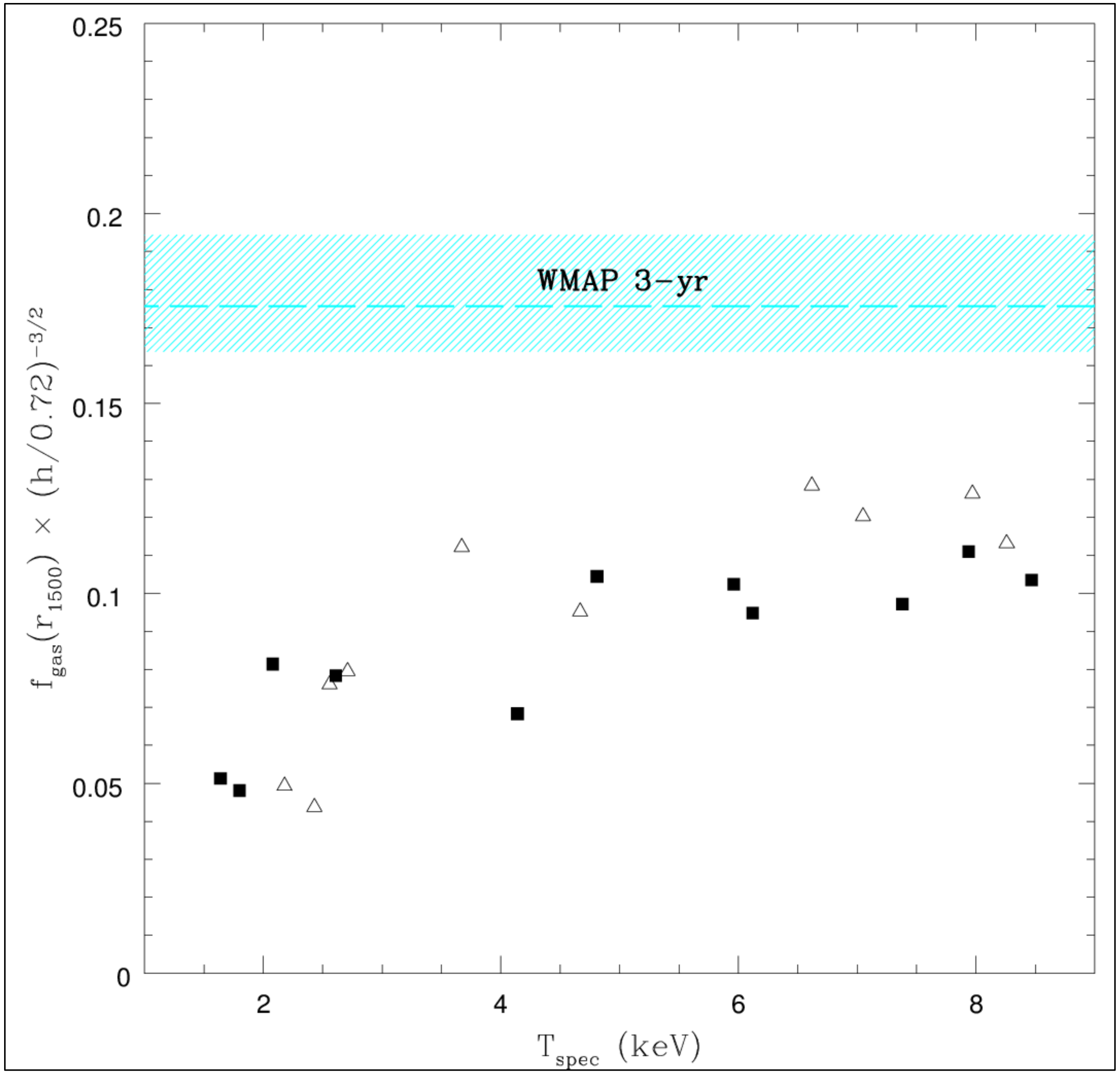
Evidence for expulsion: missing baryons

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?

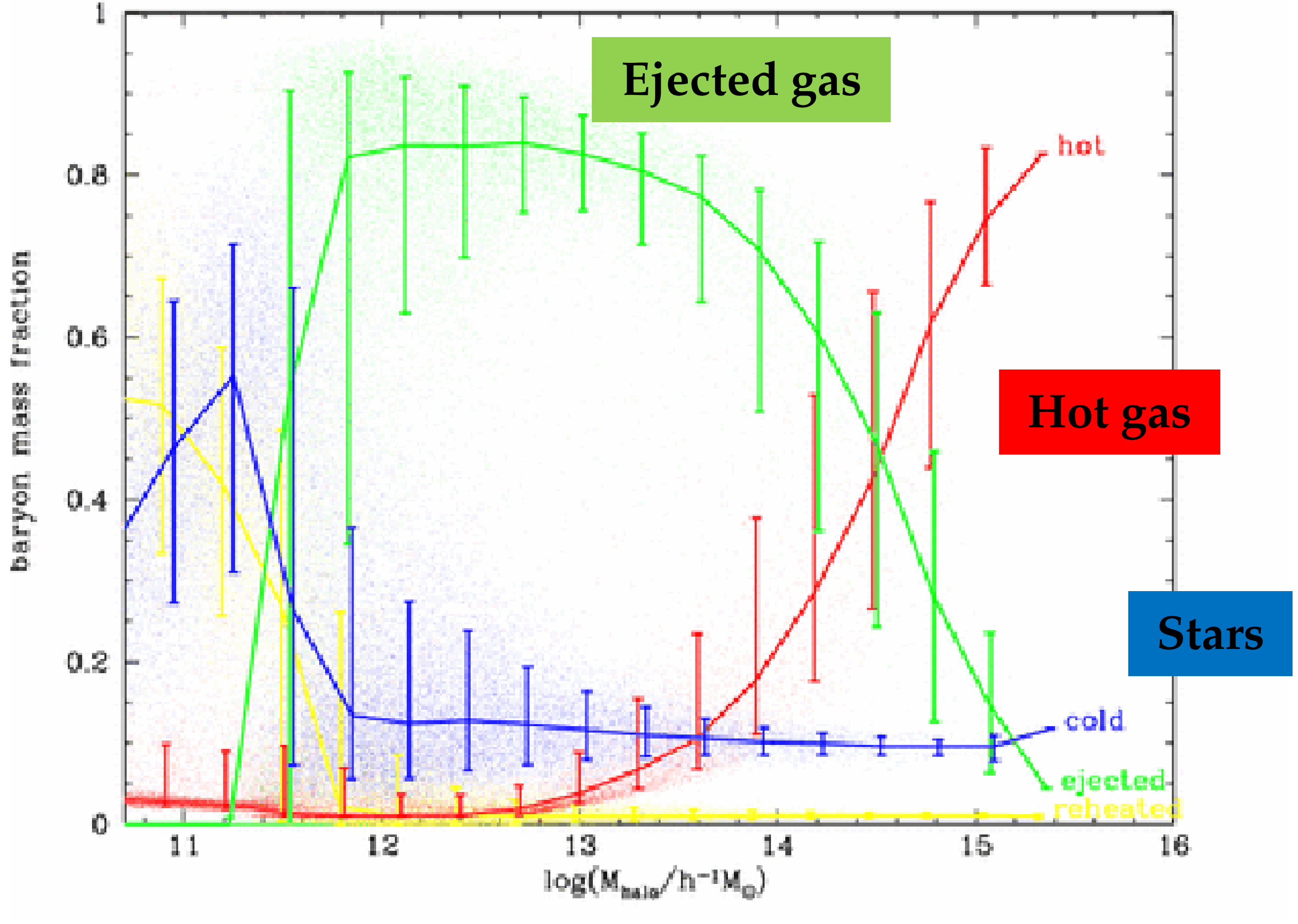


McCarthy et al. (2007)

Allowing for gas ejection in SAMS

Bower, McCarthy, Benson (2008)

Ejection really kicks in below log M < 14.5

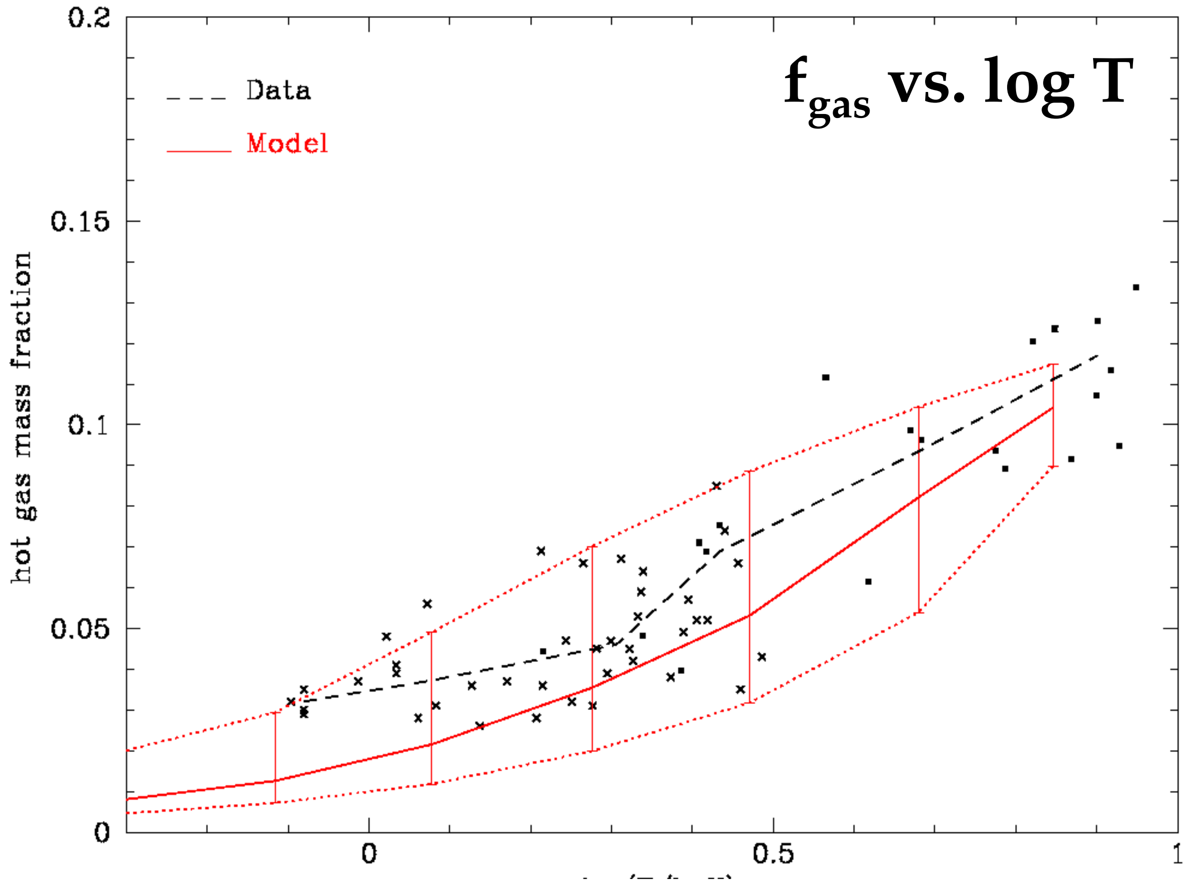


L_{heat} is the smaller of:

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

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

f_{gas} vs. log T

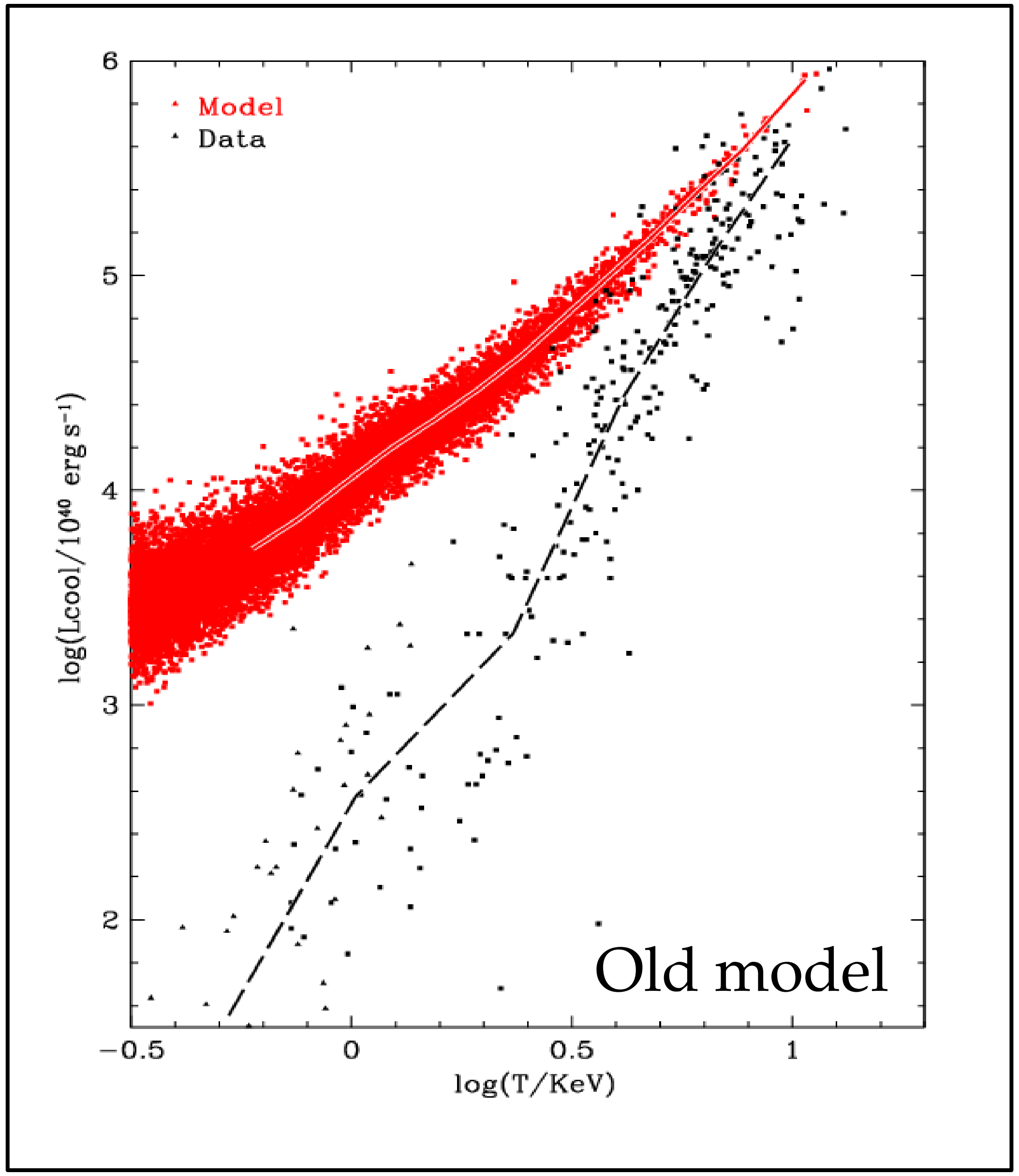


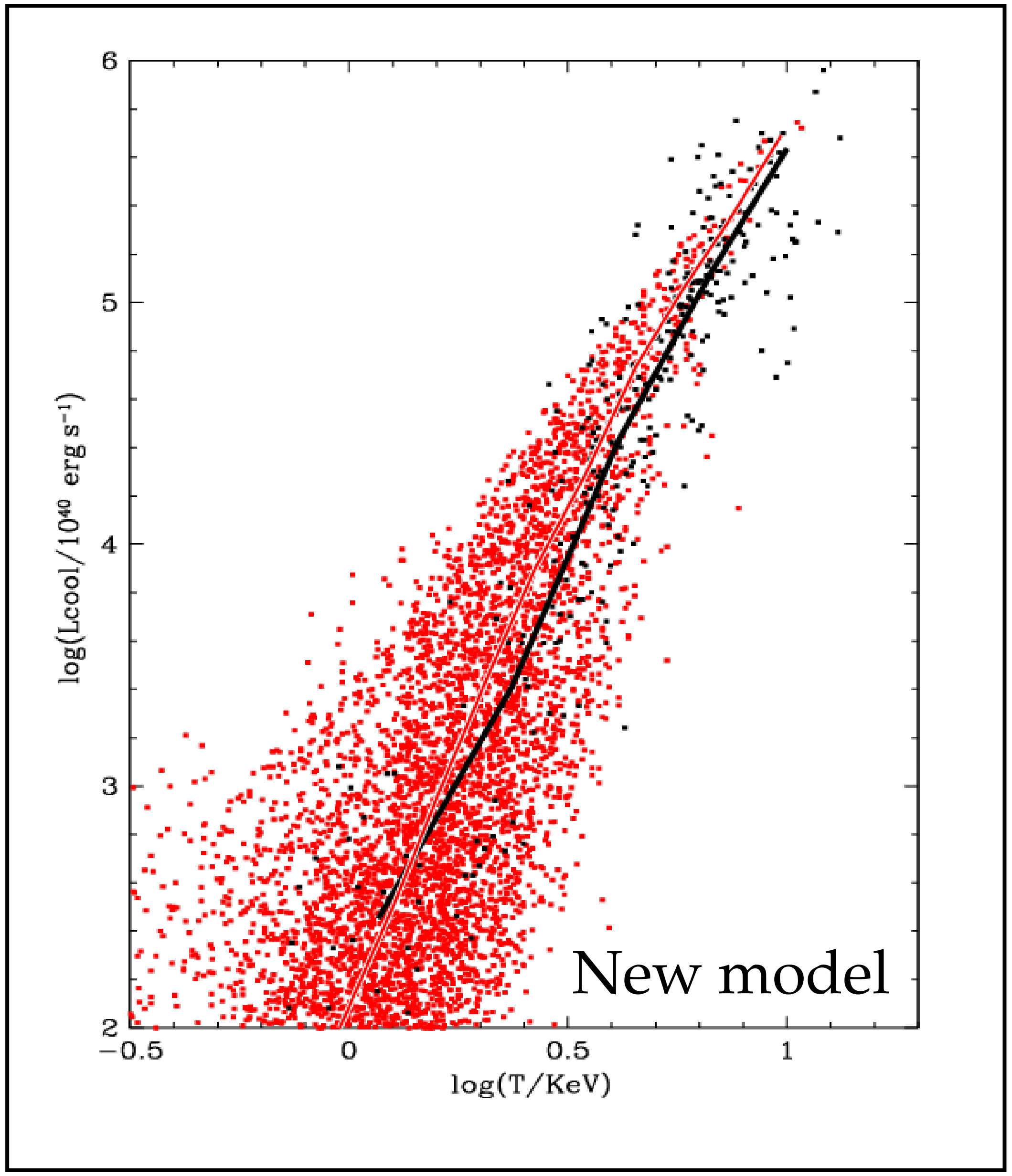
If $L_{heat} > L_{cool}$, gas is "ejected" from the system at a rate:

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

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.

Schaye

Gas expulsion via AGN 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:

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

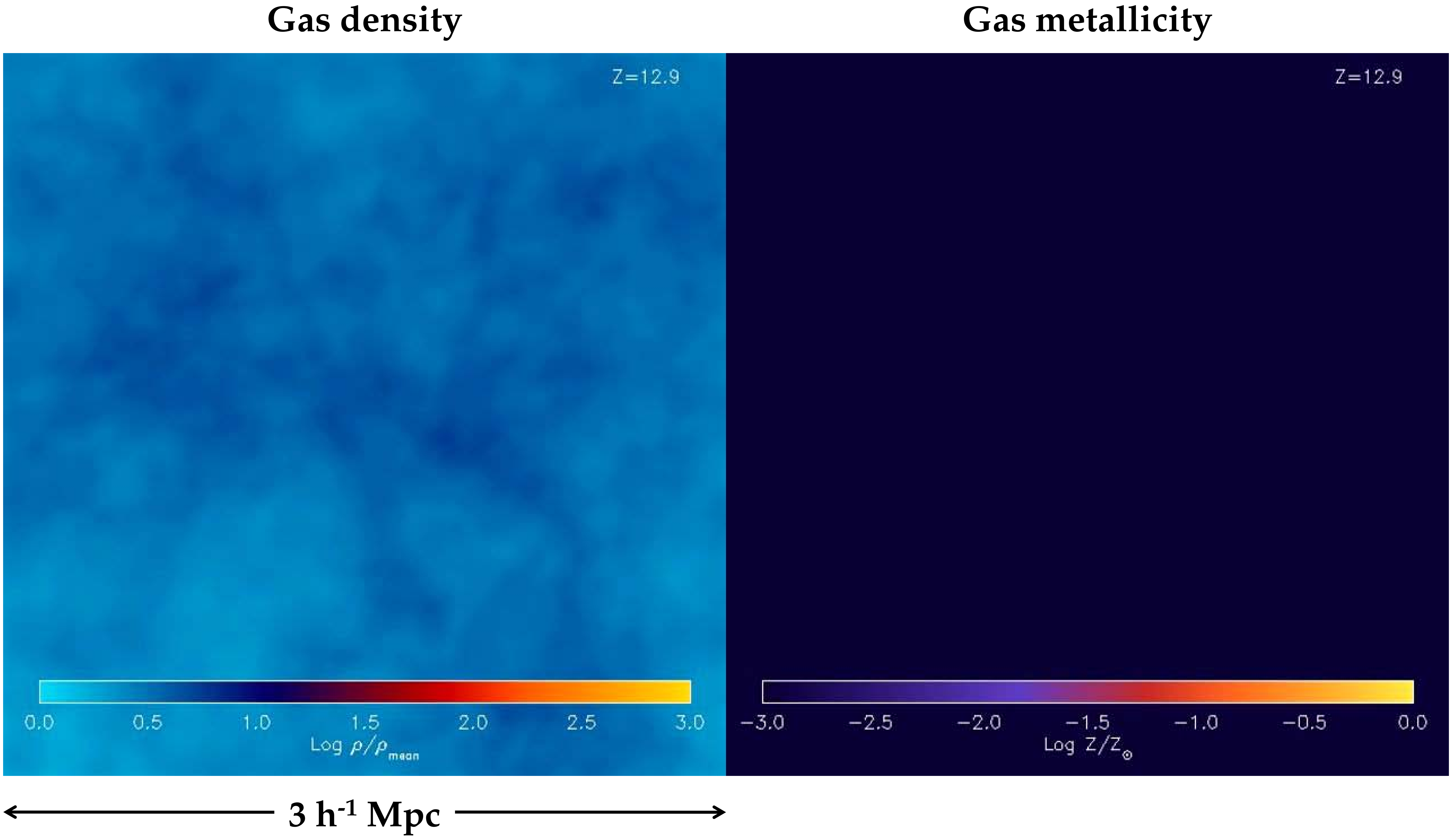
- Typically, α = 100-300 in the literature (to account for inability to resolve density near BH). But this overestimates accretion rate for cases where Bondi radius is resolvable.

- 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)

Gas expulsion by AGN



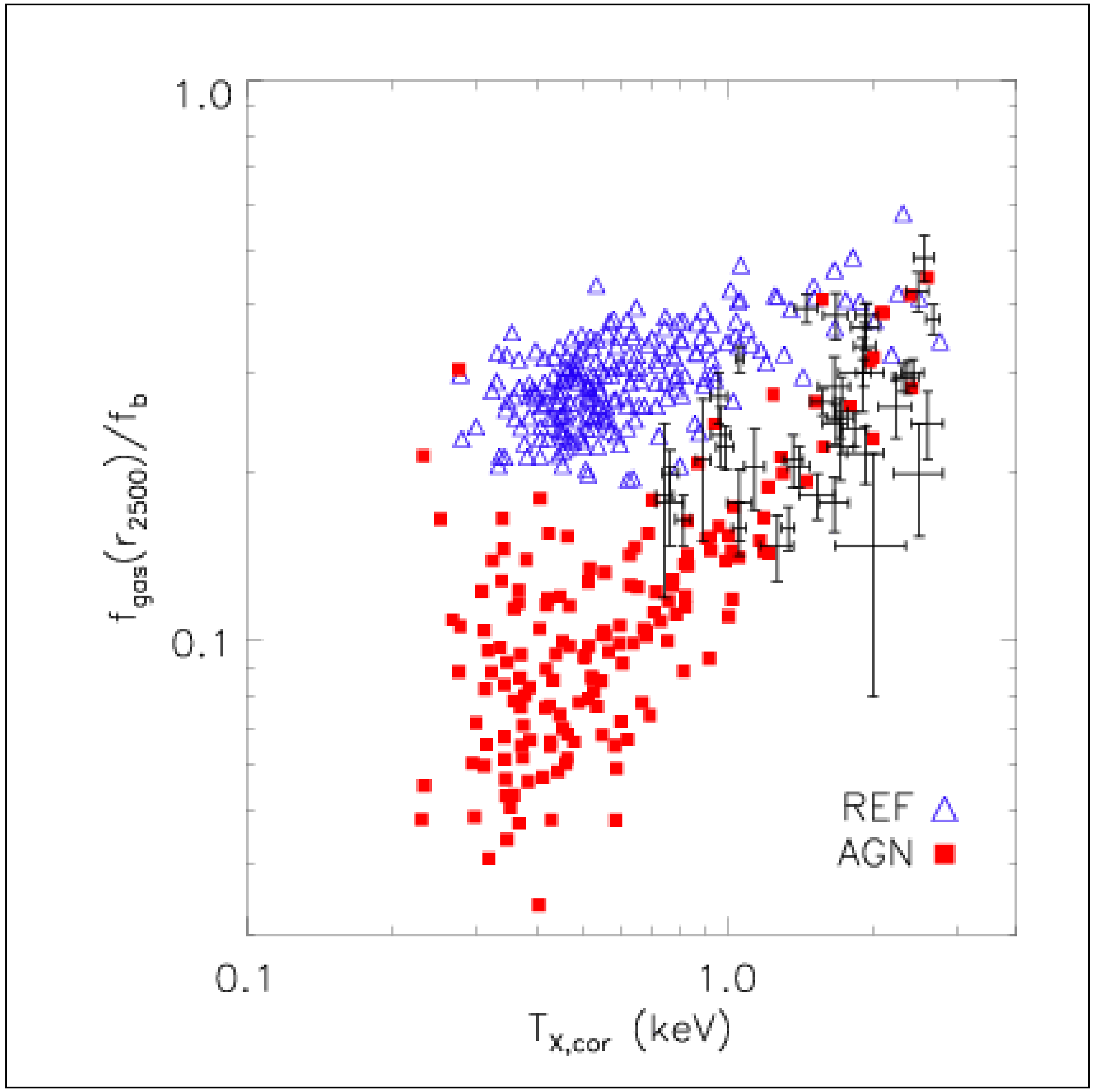
M_{200} (z=0) ~ 10^{14} Msun

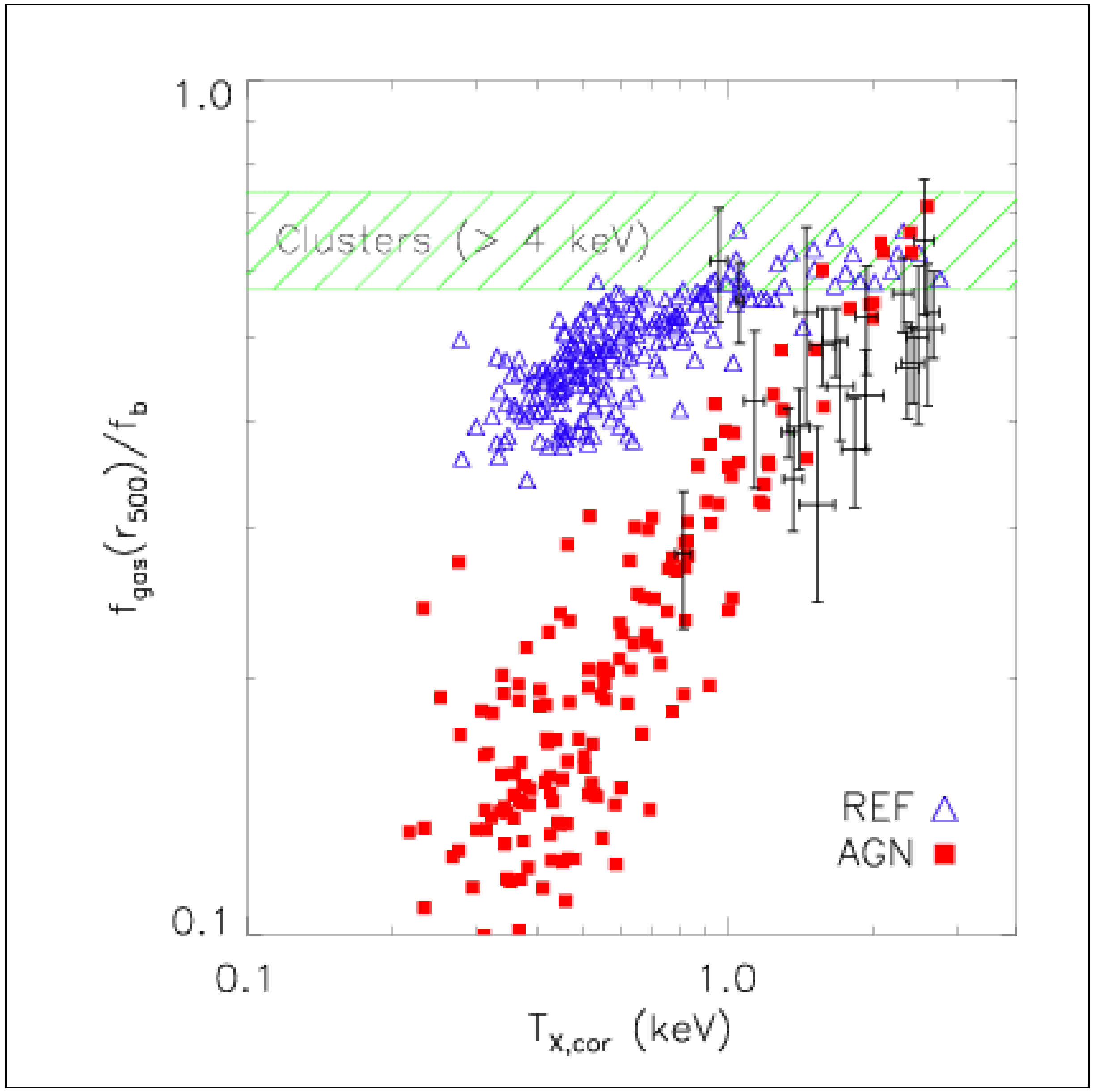
From OWLS (credit: Craig Booth)

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

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

Data from M. Sun et al. (2009)

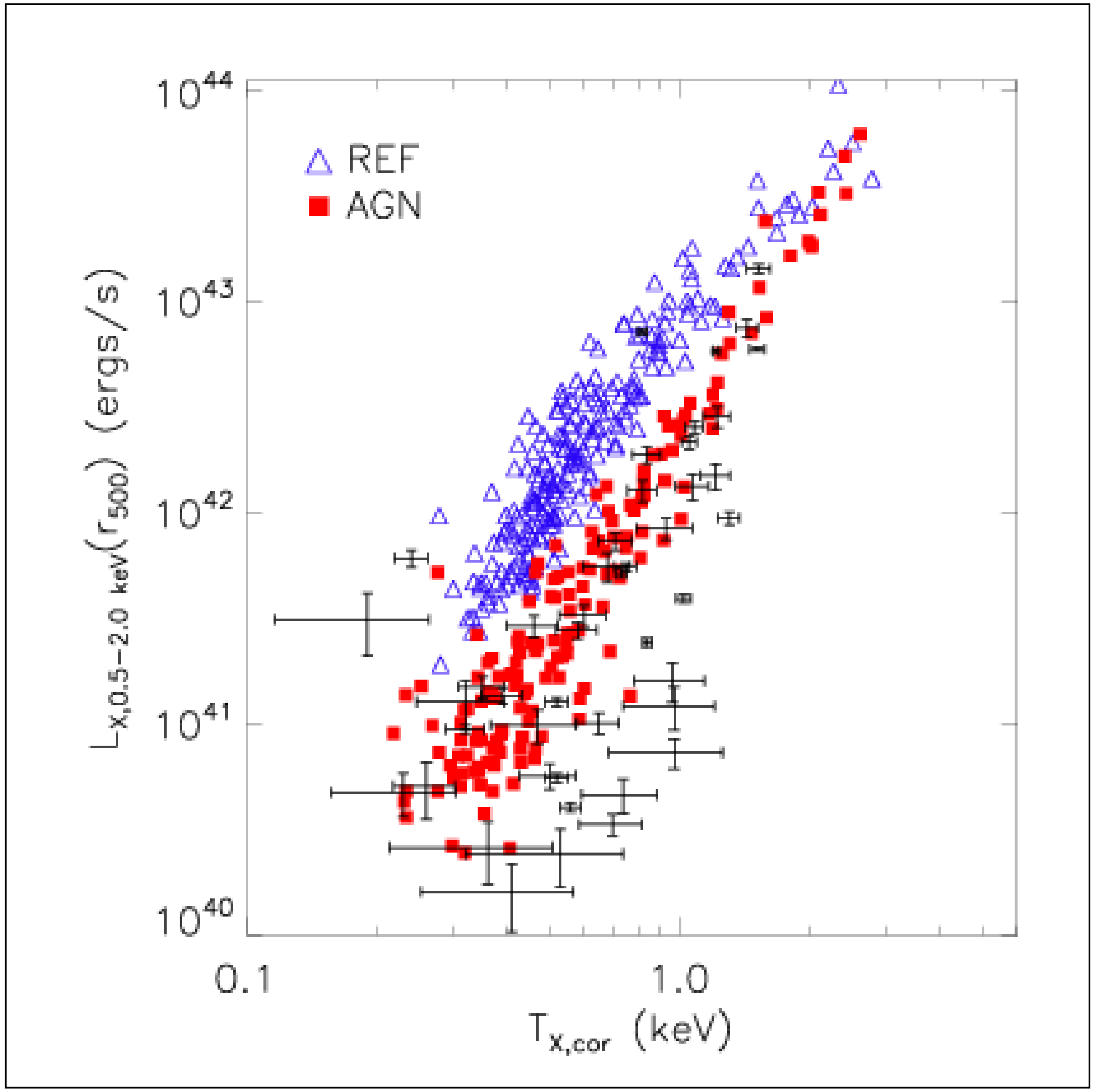


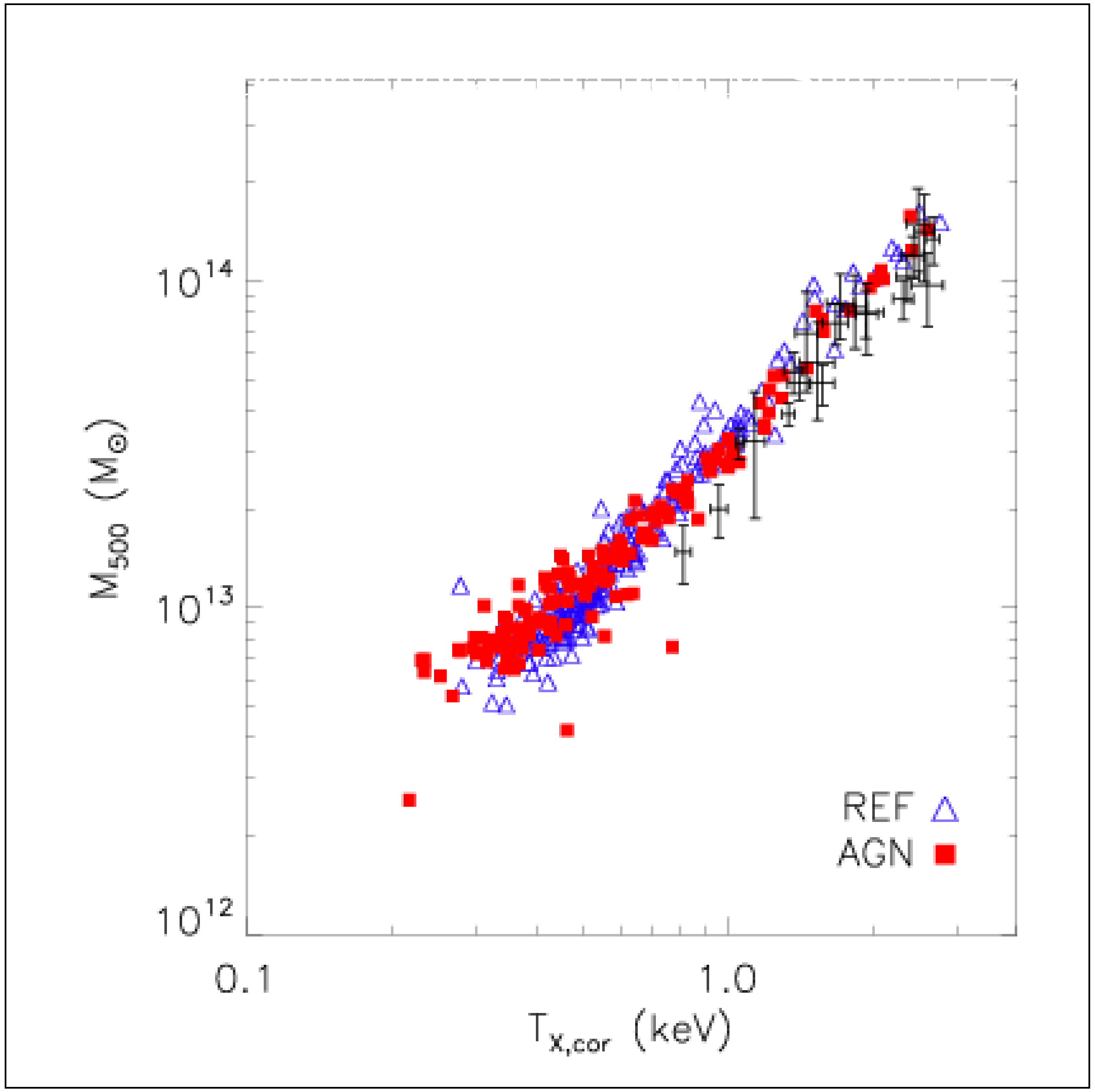


- Energy input from supermassive black holes blows gas out of haloes at z~2. Yields gas mass fractions in good agreement with observations (see also Bower et al. 2008; Puchwein et al. 2008; Short & Thomas 2009). Runs converge for $M > \sim 10^{14}$ M_{sun}.

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

L_X-T and M_{500}-T relations



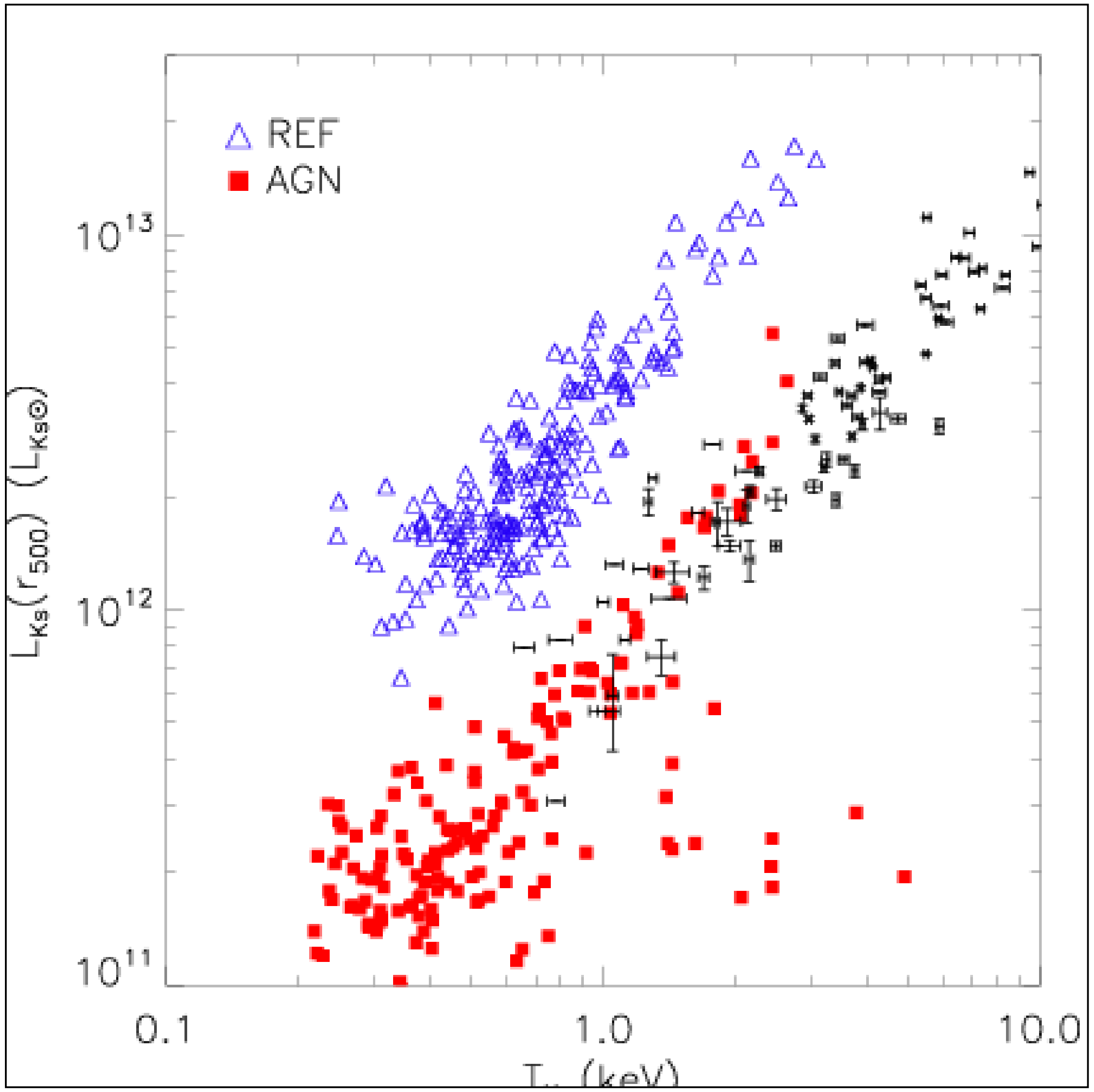


Data from Osmond & Ponman (2004) and M. Sun et al. (2009)

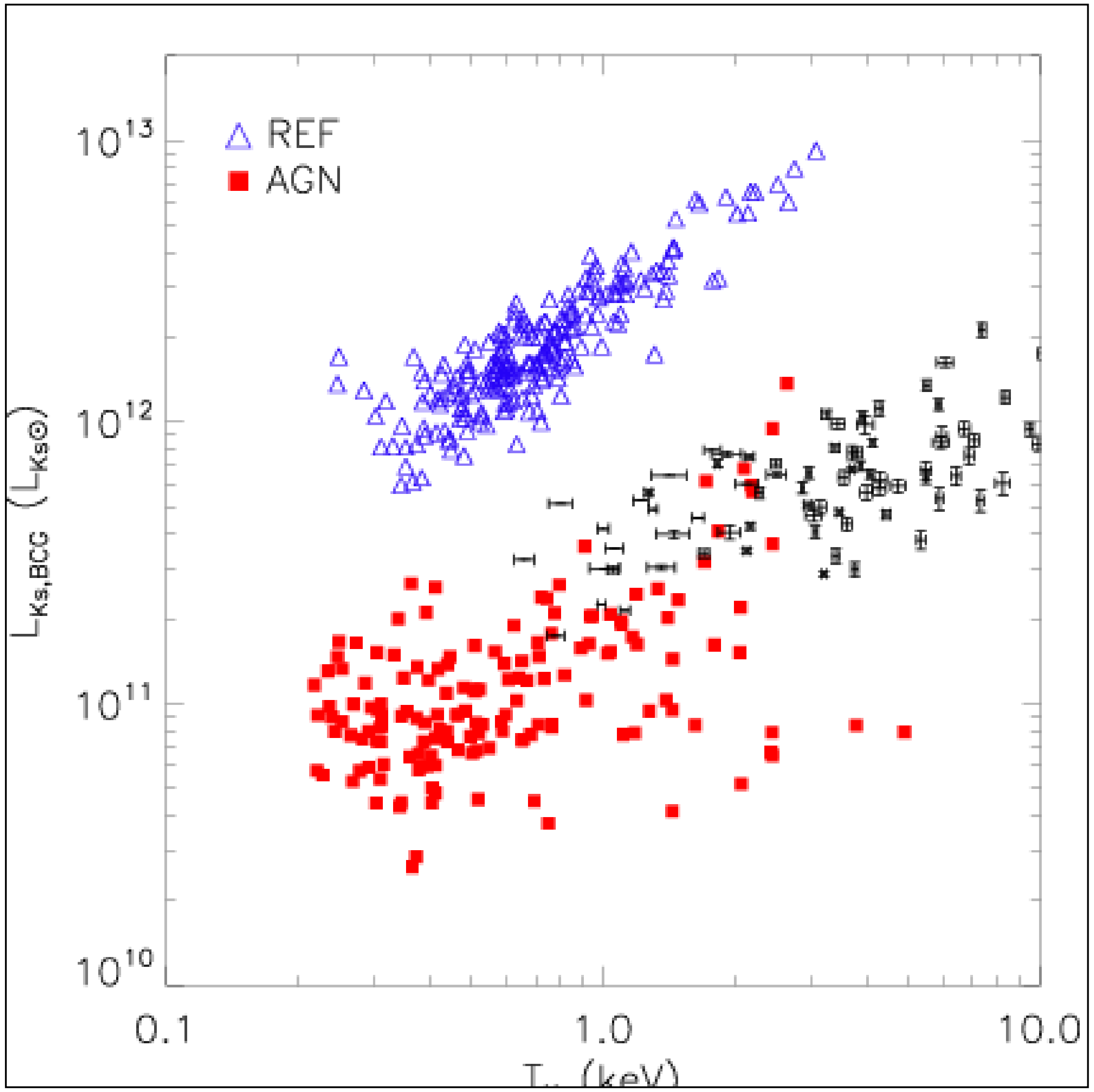
McCarthy et al. (2010), MNRAS, 406, 822

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

Other things the OWLS AGN simulation gets right:

- Entropy and temperature profiles.

- BCG stellar age (+scatter)

- Fraction of BCGs presently forming stars (~15%) at a detectable rate (> a few solar masses per year).

- Total iron mass and iron radial profile of the ICM. Shape of silicon profile and abundance is correct to factor of ~2 level (best you could expect).

- Entropy vs. temperature relation.

Does all of this simultaneously and with **no explicit tuning** to get any group properties right.

How? Gas expulsion from ~L* progenitors at z ~ 1.5. See also Davé et al. (2008).

Talk outline

- Thermodynamics of the ICM: implications for feedback

- Metallicity and abundance patterns

- Effects of ICM on orbiting galaxies

Why metallicity?

- Cooling rate of the hot gas in galaxies and groups is dominated by metal-line cooling!

- Tells you something about progenitors of the metals (constrains SF history as well as SN models).

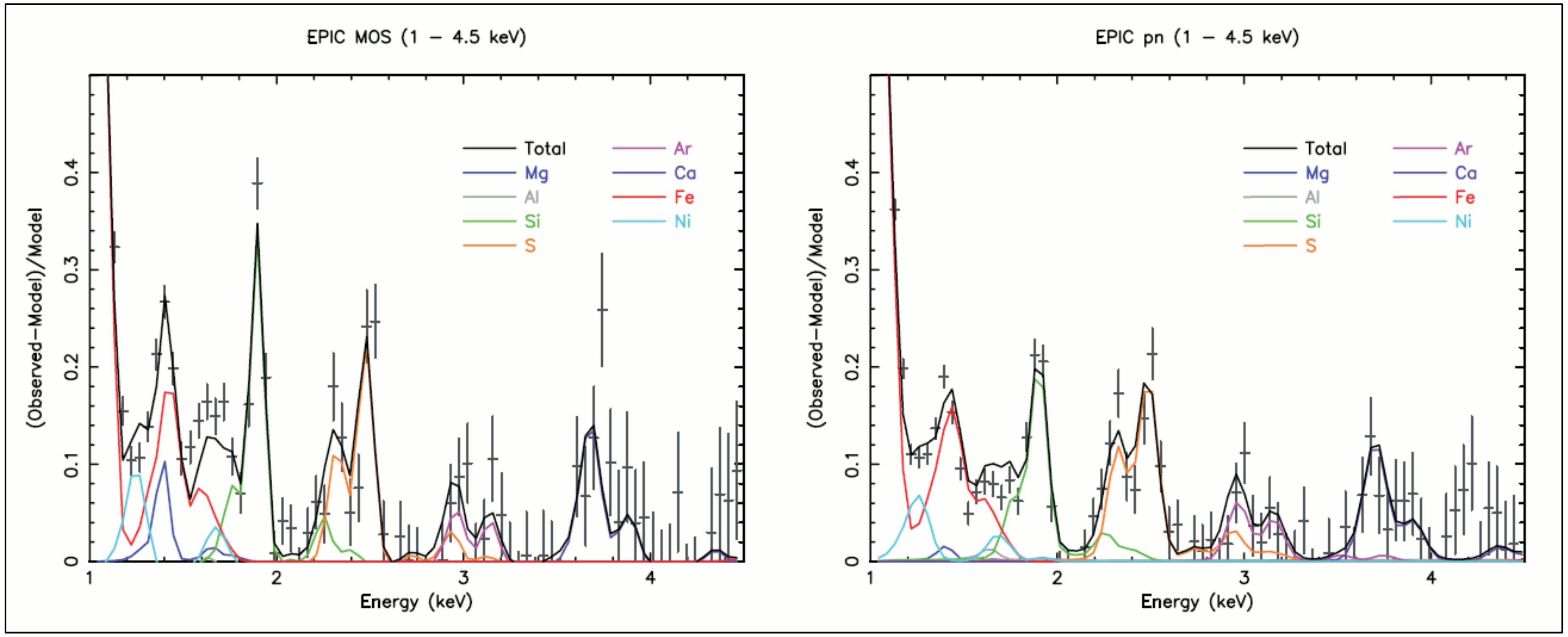
- Tells you something about how efficiency of mechanisms for getting gas out of galaxies (e.g., winds, bubbles, strangulation) and into the ICM.

Abundances from X-ray spectroscopy

Precision abundances from XMM for up to 9 elements

Uncertainties in theoretical yields prevent from absolute determination of SNIa fraction. Both contribute.

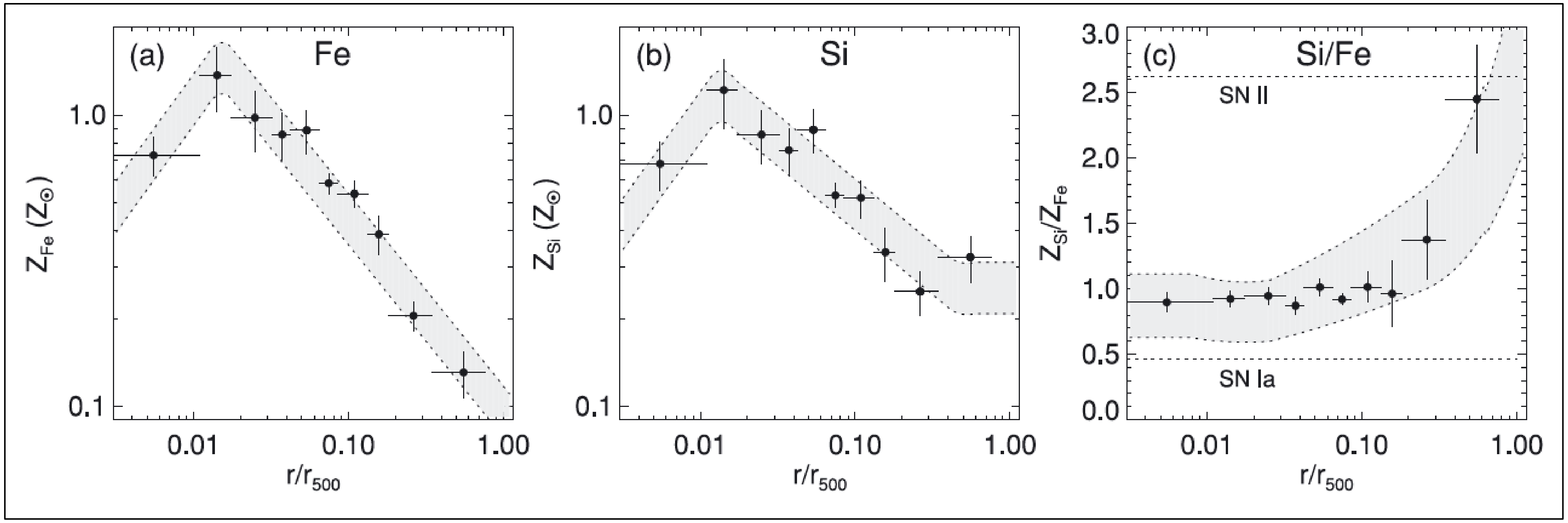
de Plaa et al. 2007



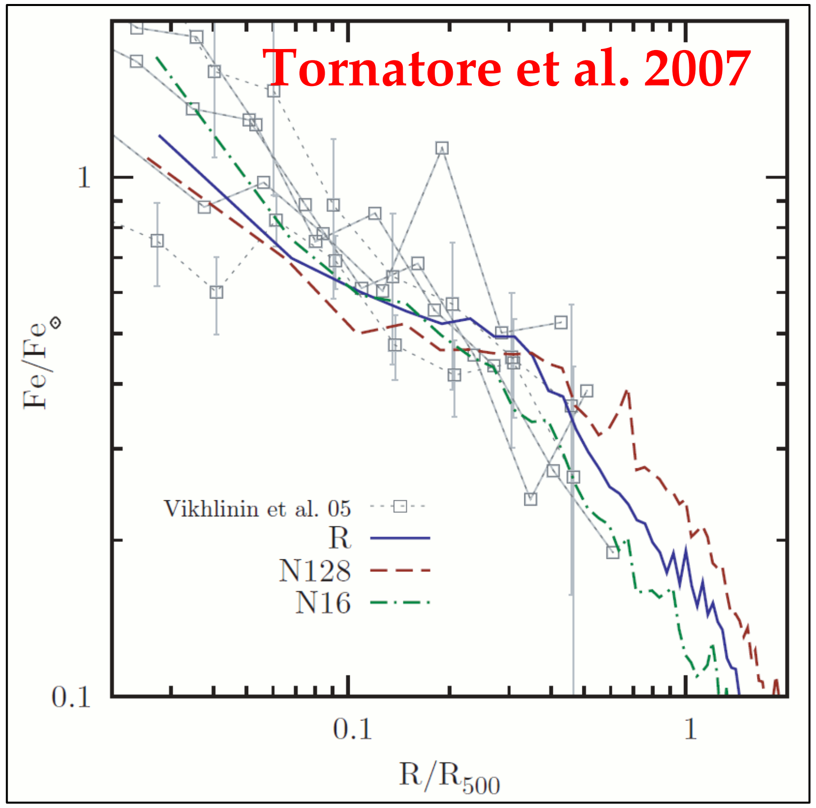
Radial variation of Fe and Si from Chandra and Suzaku.

Si/Fe rise suggests SNII more important at large radii.

Rasmussen & Ponman 2009

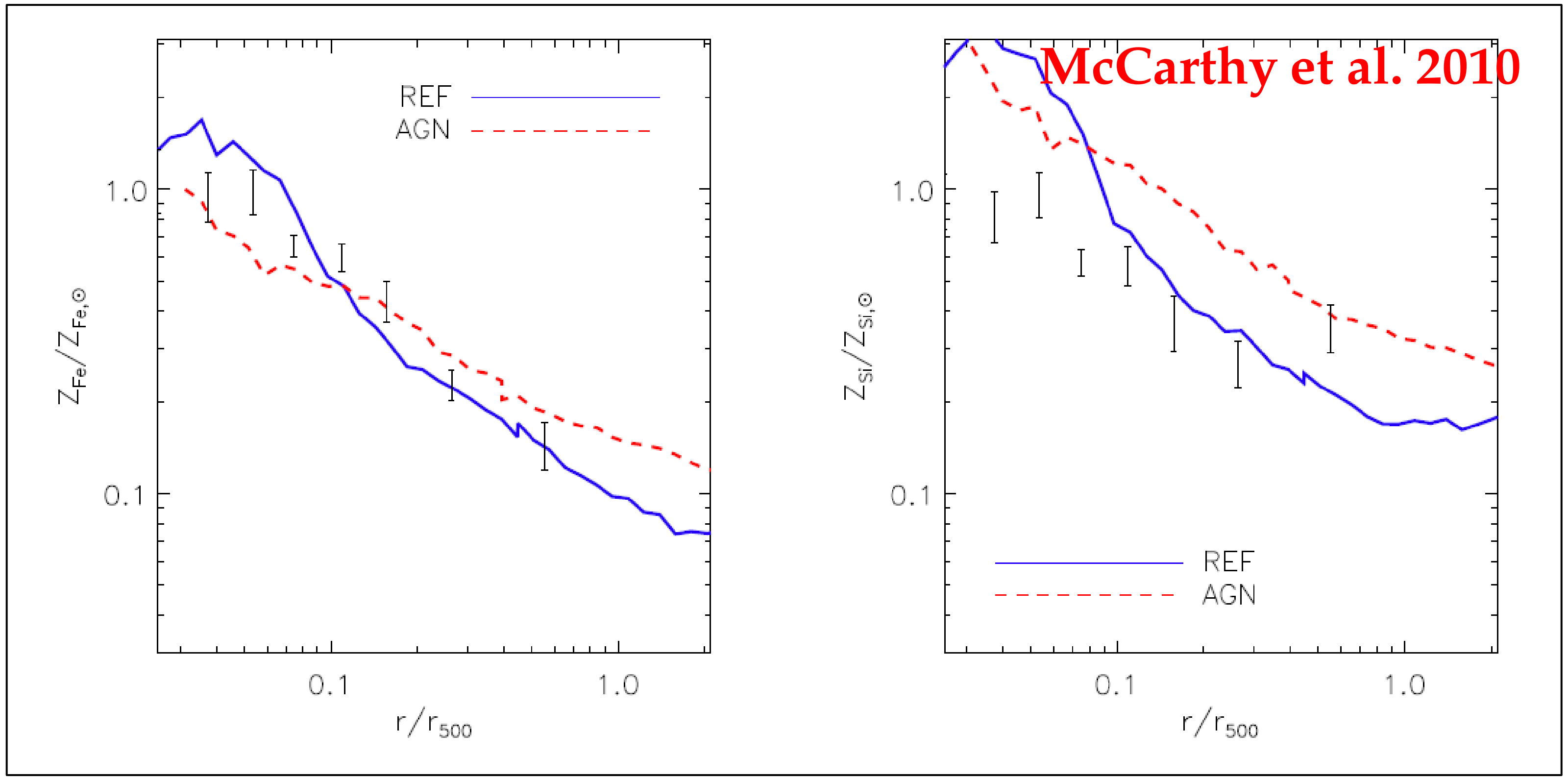


How cosmological sims fair


Tornatore et al. 2007

- Simulations adopt empirical yields and SNIa rates (both uncertain at factor of 2 level). Include metal production from SNII, SNIa, and stellar evolution (AGB).

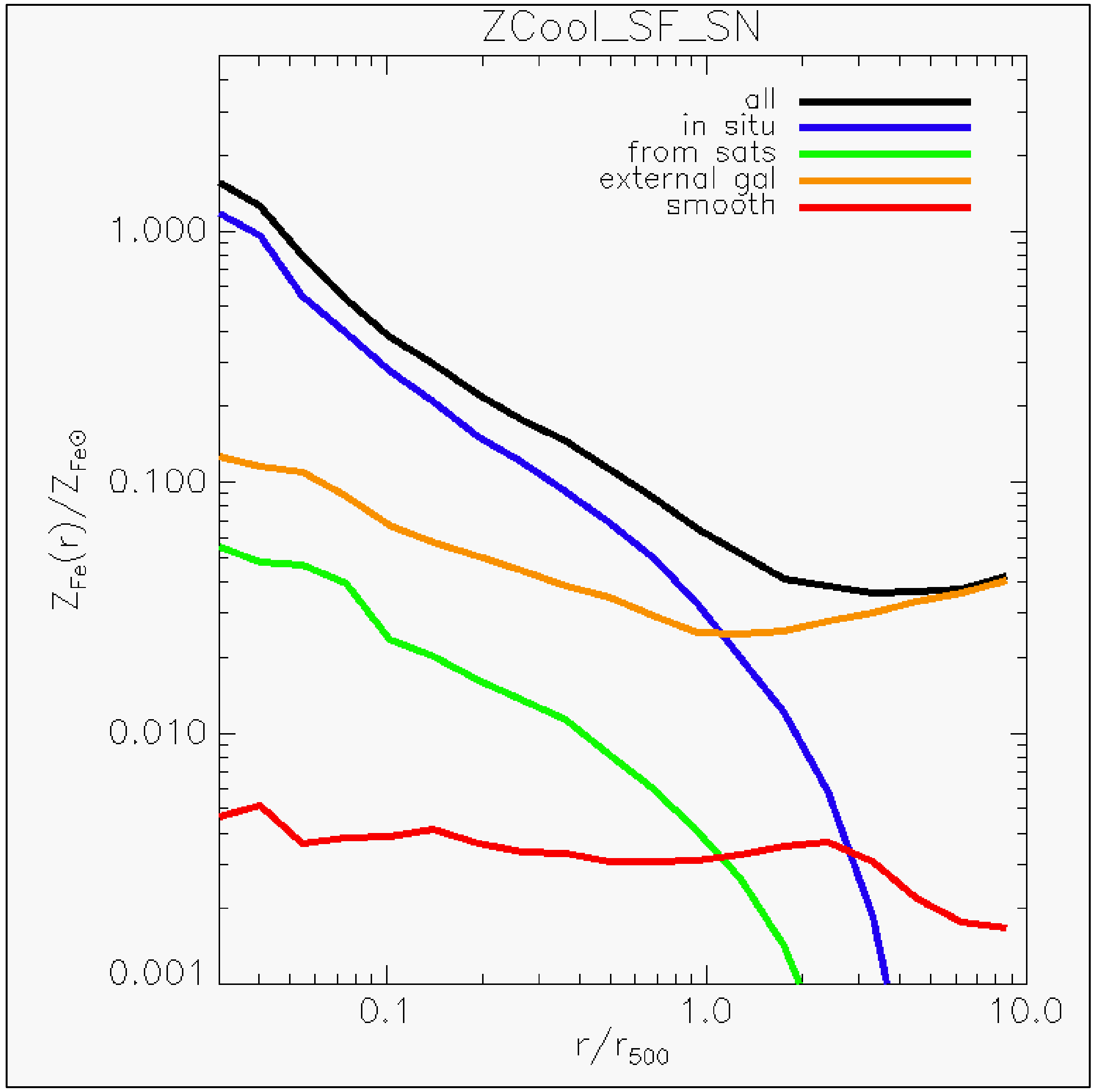
- Can reproduce absolute abundances of Fe and Si and radial variation with standard universal IMF (e.g., Chabrier). No need for varying IMFs or Pop III (doesn't rule them out though).

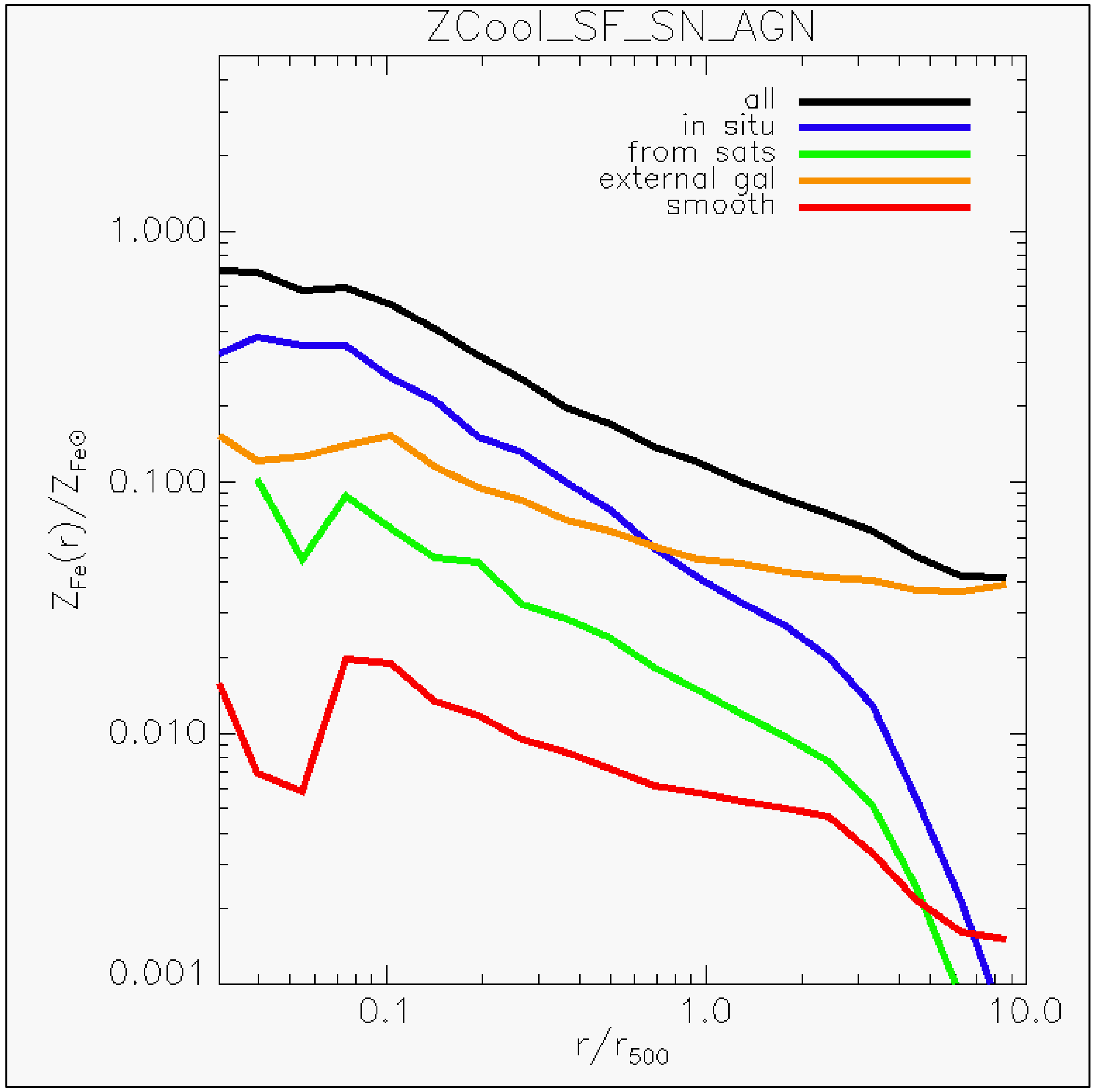

McCarthy et al. 2010

(SAMs cannot easily be modified to make predictions for radial variation in metallicity)

Metallicity of the hot gas: how and where

McCarthy et al., in prep





- Track metals in a Lagrangian way in OWLS. Within ~r_{500} the bulk of the metals were produced not orbiting galaxies but by the BCG+ICL (injection, rather than ejection).

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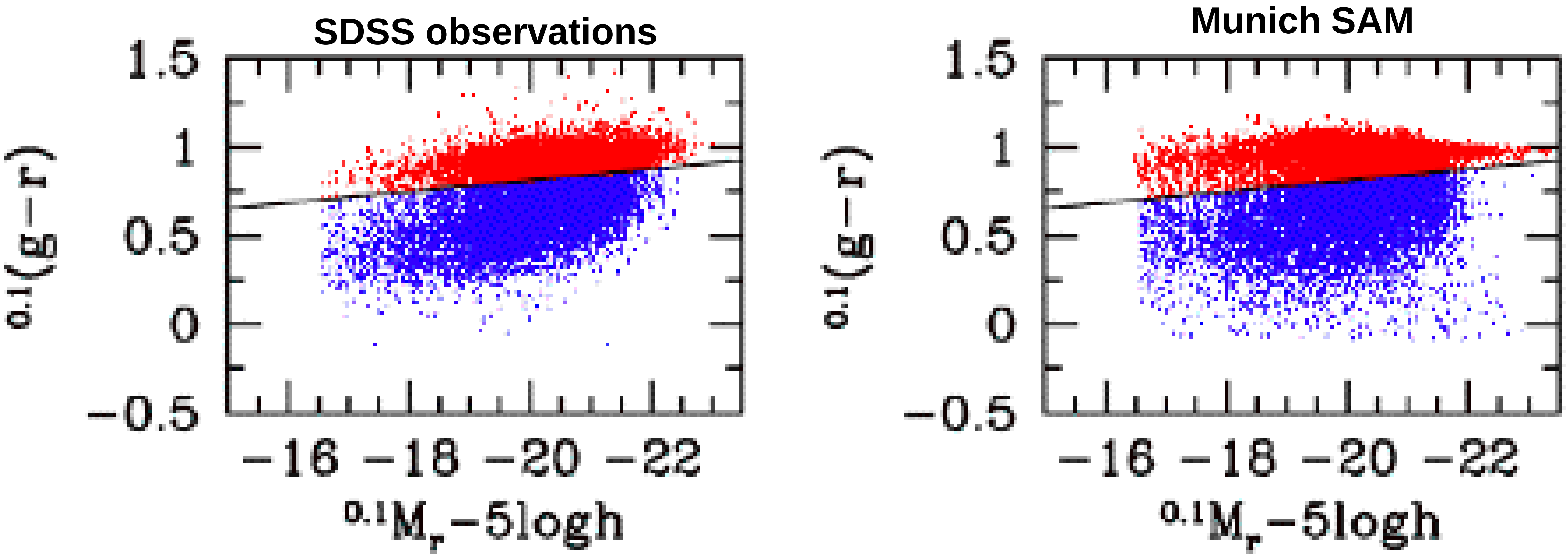
How red and dead?


SDSS observations

Munich SAM

Weinmann et al. (2006)

- SAMs with complete/instantaneous removal of satelite's hot gas halo predict a satellite population that is too red.

- A likely solution is that strangulation is not as efficient as this.

Efficiency of strangulation - models

The condition for strangulation (removal of hot gas halo) is:

$$P_{ram} \equiv \rho_{\rm gas,p} v_{\rm sat}^2 > P_{\rm grav} \equiv \alpha \frac{G M_{\rm tot,sat}(r) \rho_{\rm gas,sat}(r)}{r} ,$$

with $\alpha \approx 2$

Calibrated off of hydrodynamic simulations in McCarthy, Frenk et al. (2008)

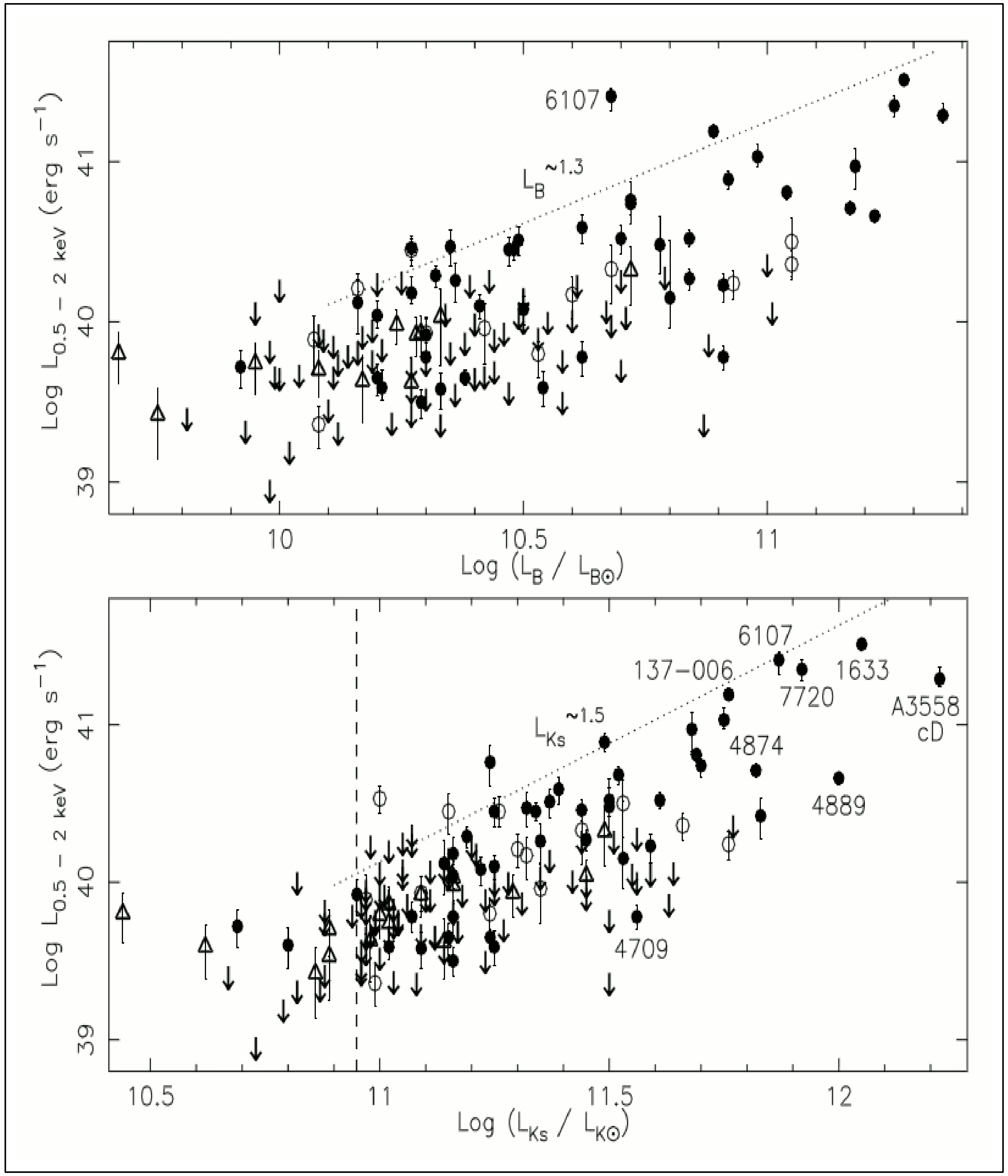
- Depends on orbital distribution, which can be got from cosmological simulations
- Depends on total mass distribution of satellite (at large radii NFW should be fine)
- Depends on gas mass distribution in ICM and satellite.

Typical parameters suggest that many massive galaxies may be able to hang onto to a fair chunk of their initial hot gas mass.

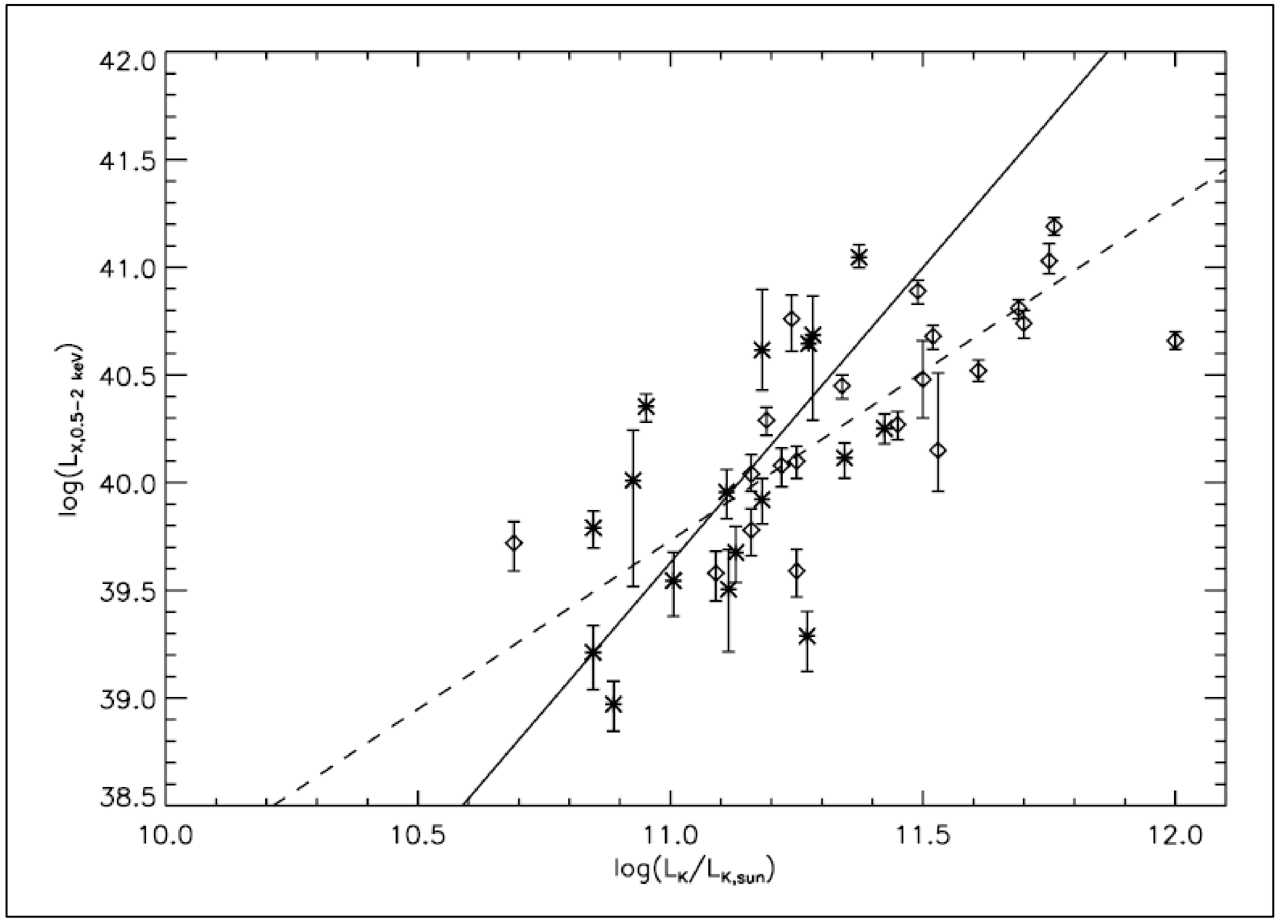
Font et al. (2008) found when you incorporate this condition into GALFORM you find an improved agreement with SDSS red fractions (see also Weinmann et al. 2010).

Efficiency of strangulation: direct observations

Sun et al. 2007



Jeltema et al. 2008



- For $\log L_K > 10.8$ or so, 60-70% of galaxies in groups and clusters have their own detectable hot gas haloes.

- GIMIC simulations (Crain et al.) reproduce this result.

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.

- AGN at high redshift (z ~ 1-2) from group progenitors naturally accomplish this. Not energetically feasible to do so at low redshift even with AGN.

- Current SAMs do not treat the ejection process in a realistic way and therefore the cooling rates that are inferred are likely to be incorrect (overestimated). Efficiency of feedback required is therefore likely overestimated.

- **Metal-line cooling dominates the radiative cooling rates of the hot gas in galaxies and groups of galaxies. Strong gradients are observed in Fe and Si.** Si/Fe profile suggests SNII become increasingly important at large radii. Uncertainties on theoretical yields prevent a quantitative statement of absolute contribution of SNIa and SNII.

- OWLS AGN reproduces the metallicity and Si/Fe radial trend with standard (Chabrier) IMF. Tracking in simulation suggests most metals from BCG+ICL.

- Strangulation, while important for low-mass galaxies, is not very efficient for most massive galaxies, according to simulations and X-ray observations.

The End.