The intragroup medium

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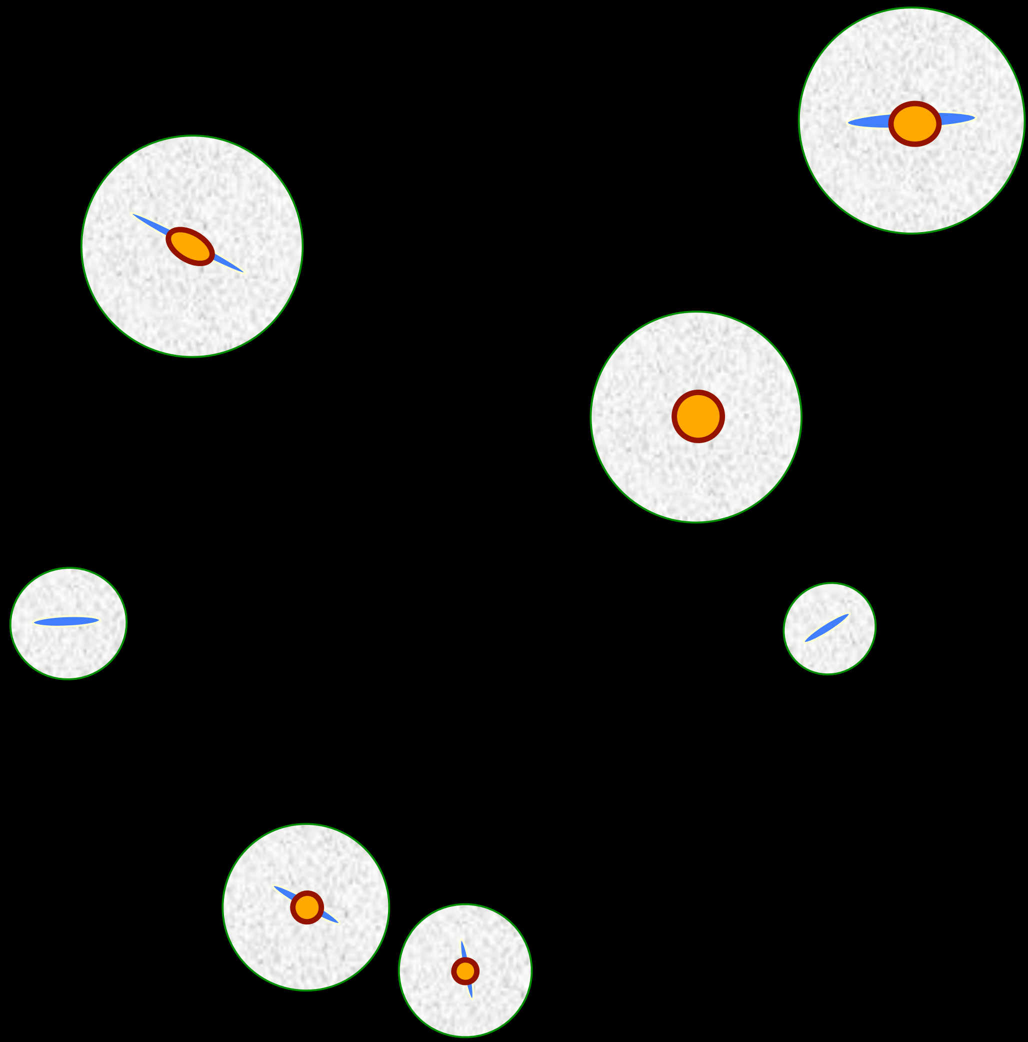
Preview

- A zeroth-order model for group formation
- Complications, complications…
- The intergalactic medium at large
- Intergalactic gas in groups
- Some observed properties & their implications
- Conclusions

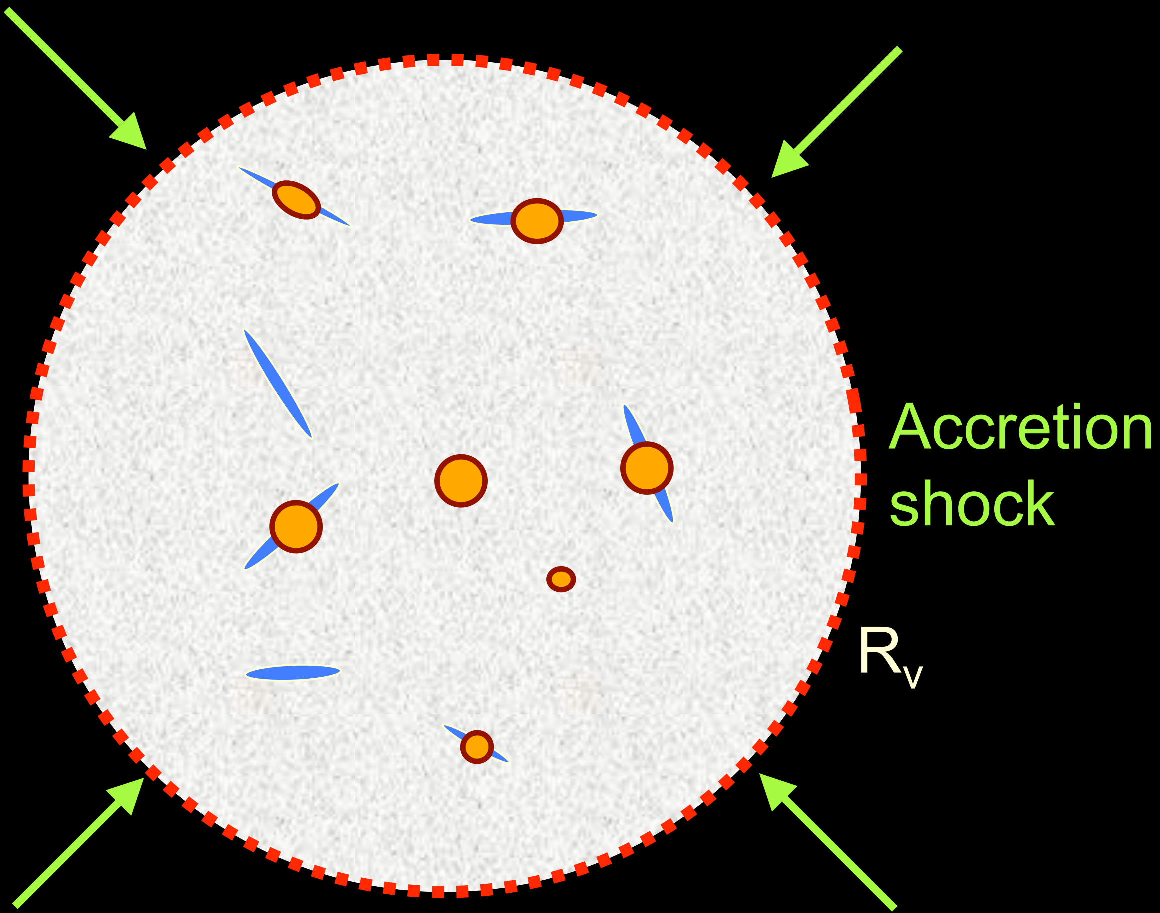
Zeroth order model

- Galaxies form by baryon cooling within dark halos.
- These then cluster into groups.

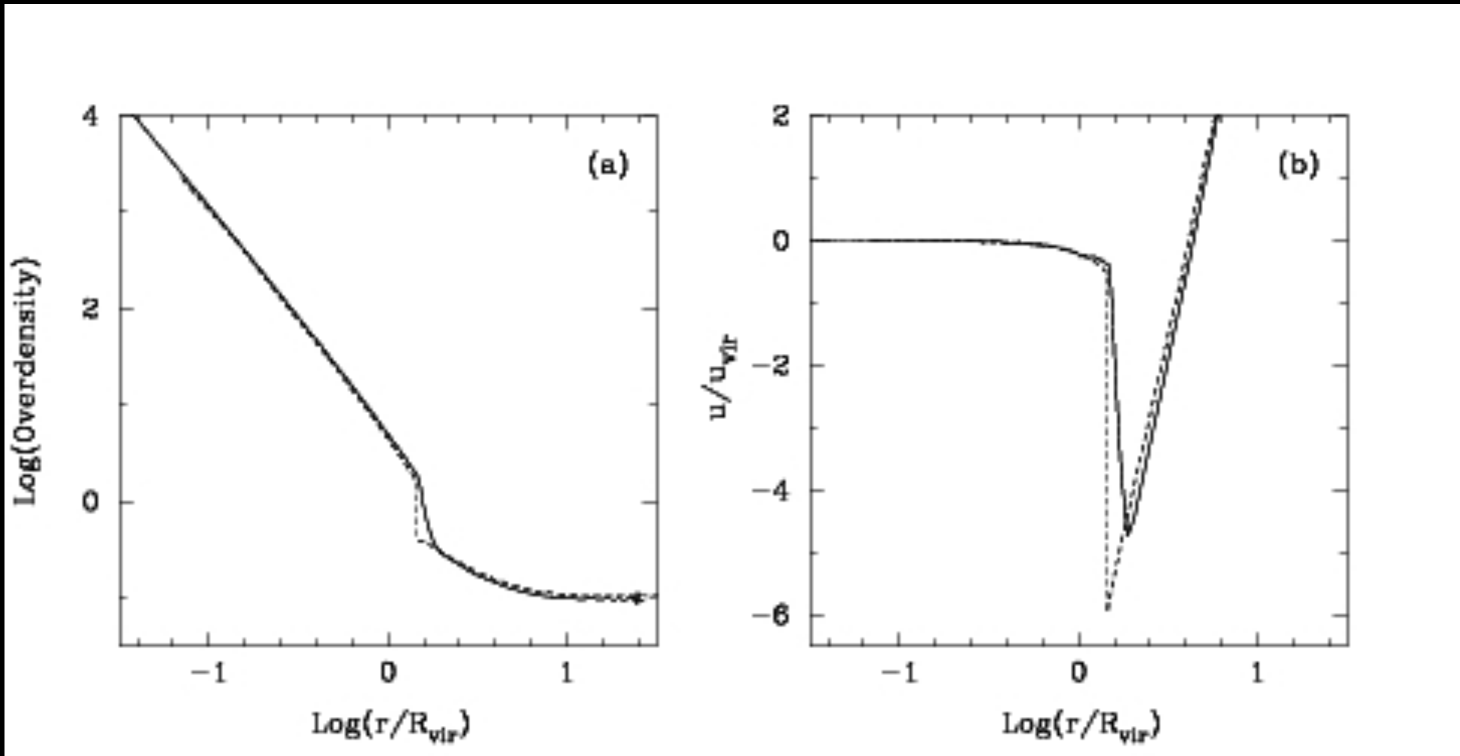


Zeroth order model

- Galaxies form by baryon cooling within dark halos.
- These then cluster into groups.
- Galaxy dark halos merge.
- Infalling gas is compressed and shocked at R_v.



Zeroth order model

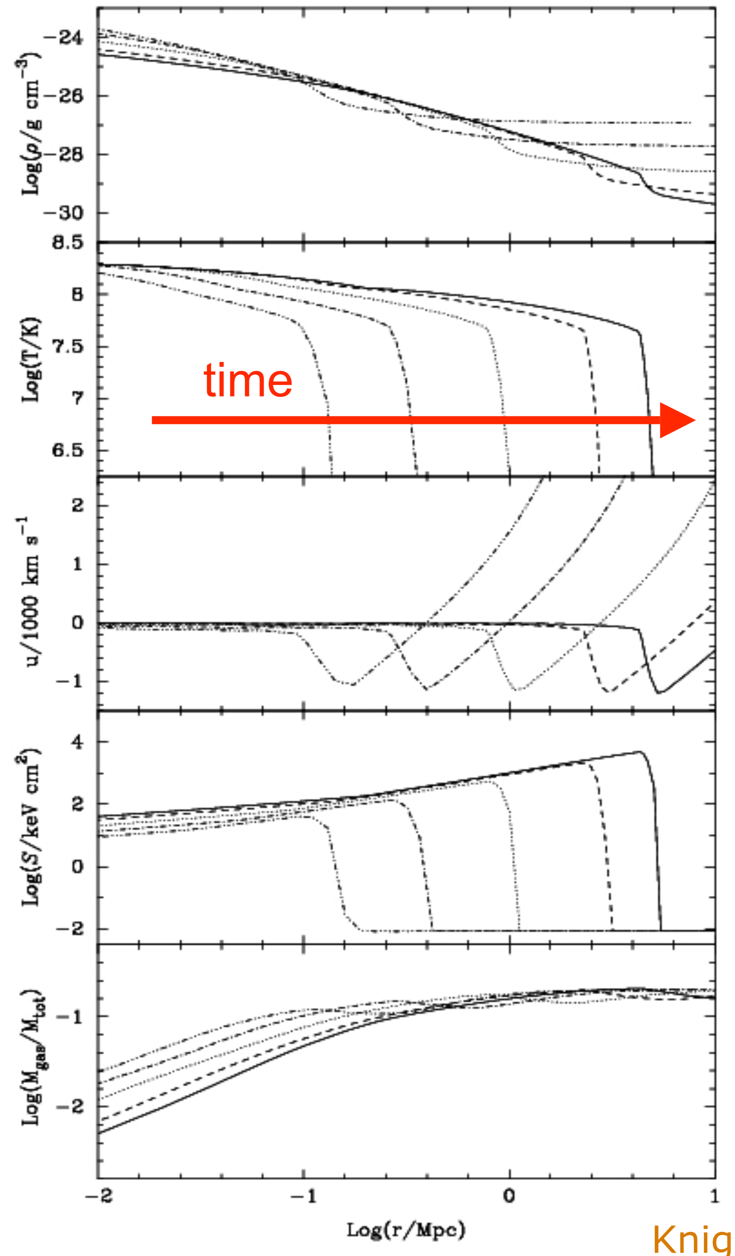


Knight & Ponman 1997

- Gas is stopped and shock heated to ~T_{vir} at radius R_v.
- HI outside galaxies destroyed.

Zeroth order model

Shock then expands with R_v as the group grows self-similarly.

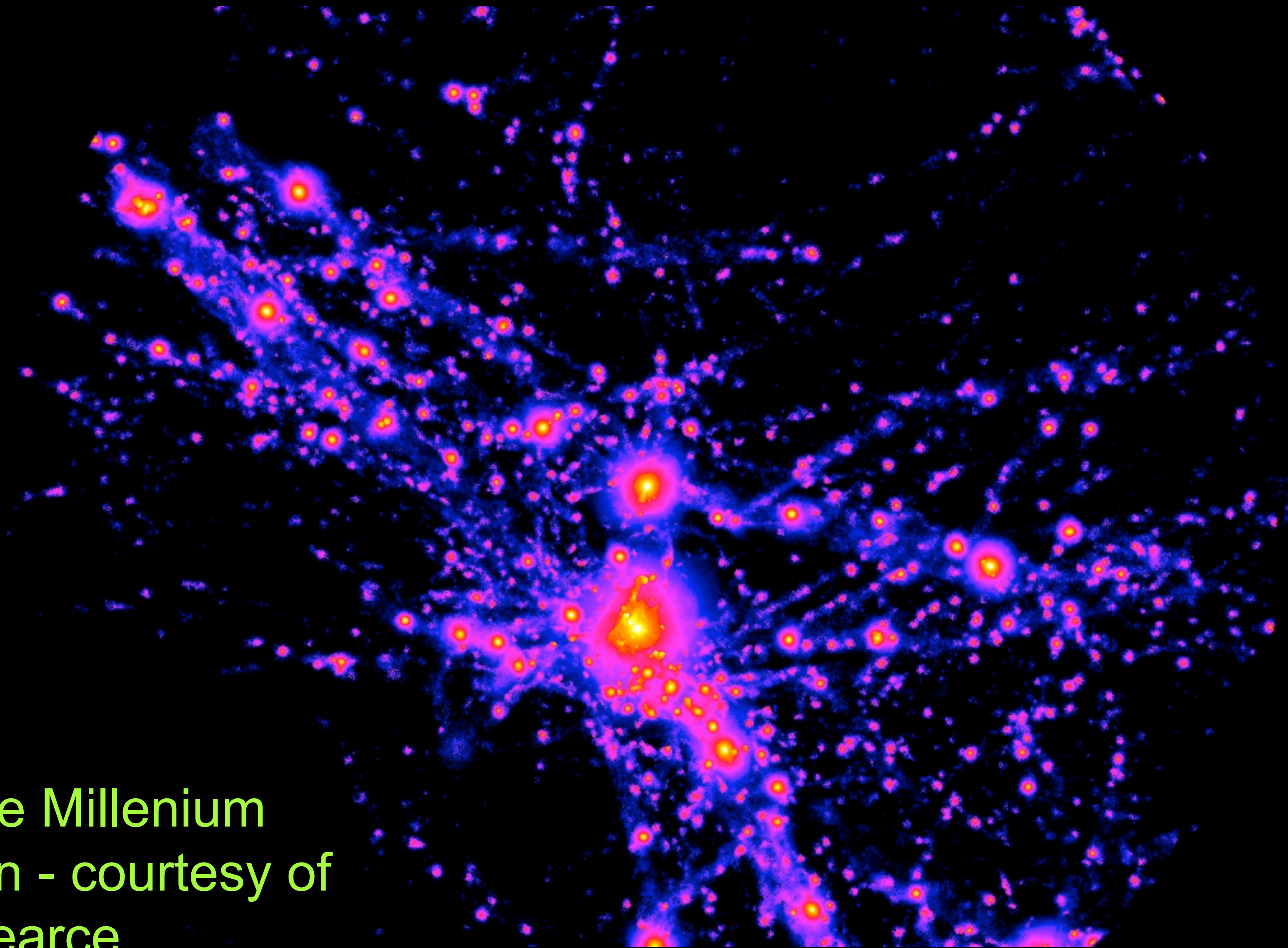


Knight & Ponman 1997

Complications

- Geometry - non-spherical
- Hierarchical growth
- Galaxy interactions
- Cooling
- Feedback - SNe and AGN

Non-spherical geometry



Gas in the Millenium
simulation - courtesy of
Frazer Pearce

Complications

- Geometry - non-spherical
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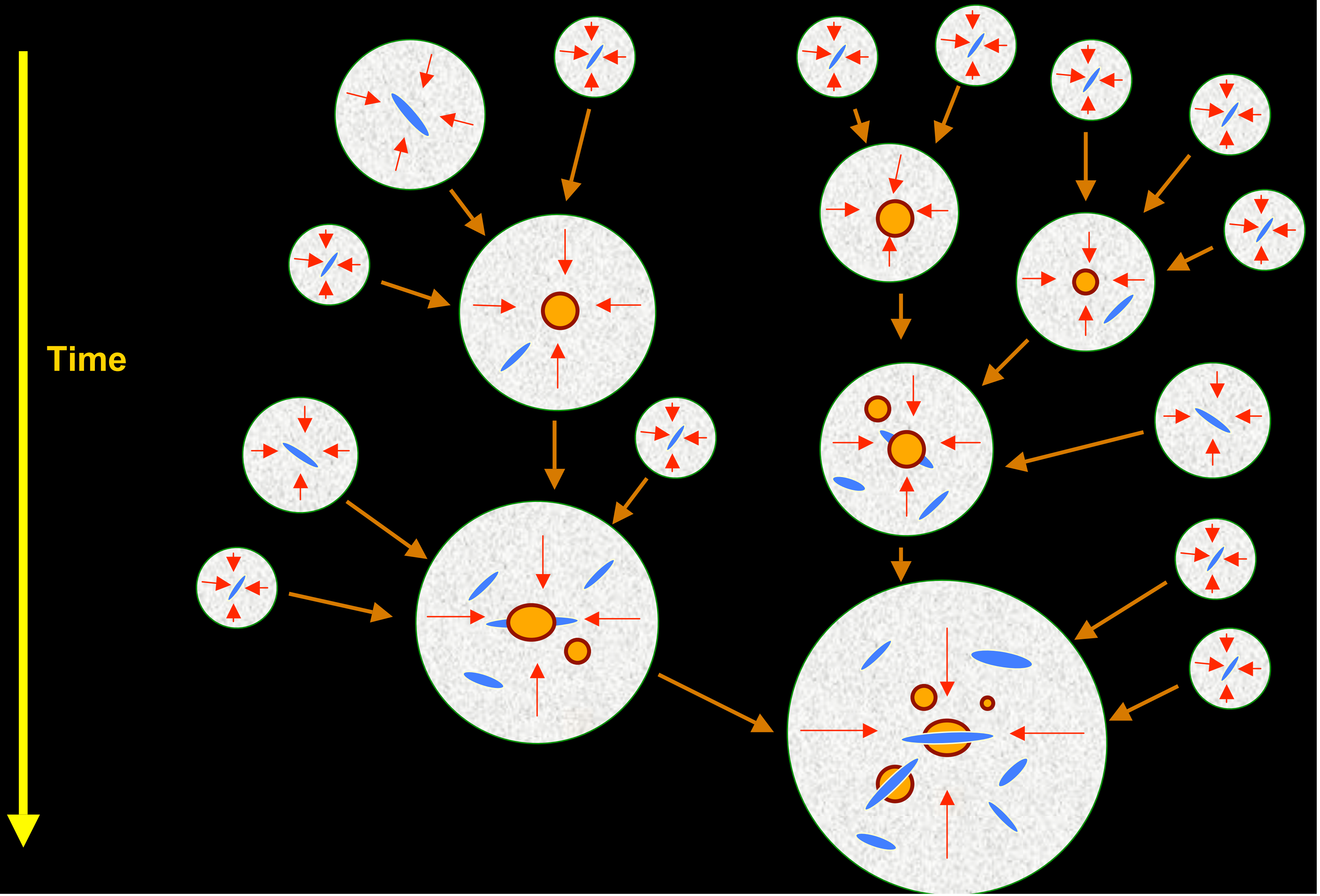
Hierarchical structure formation



Complications

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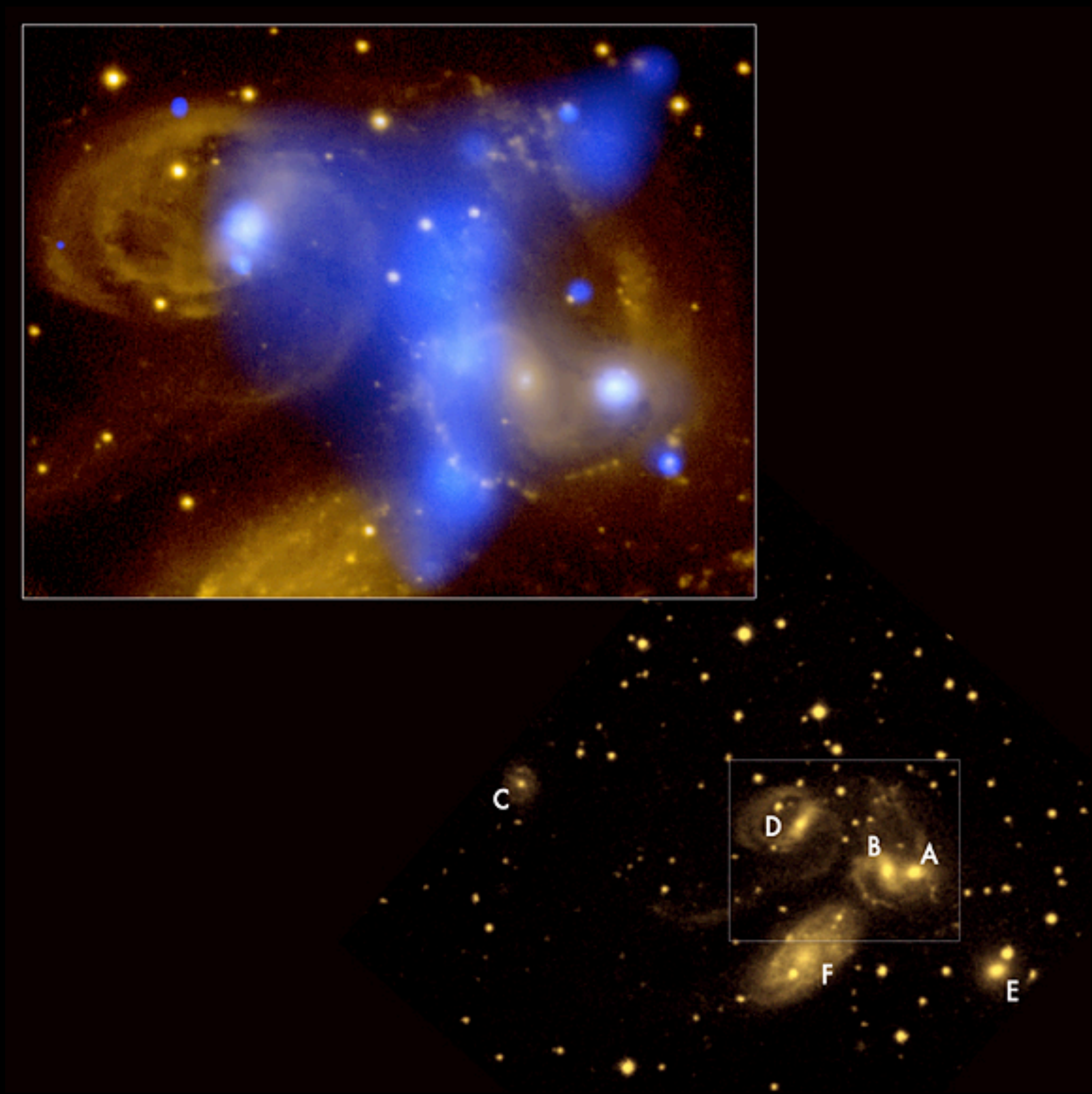
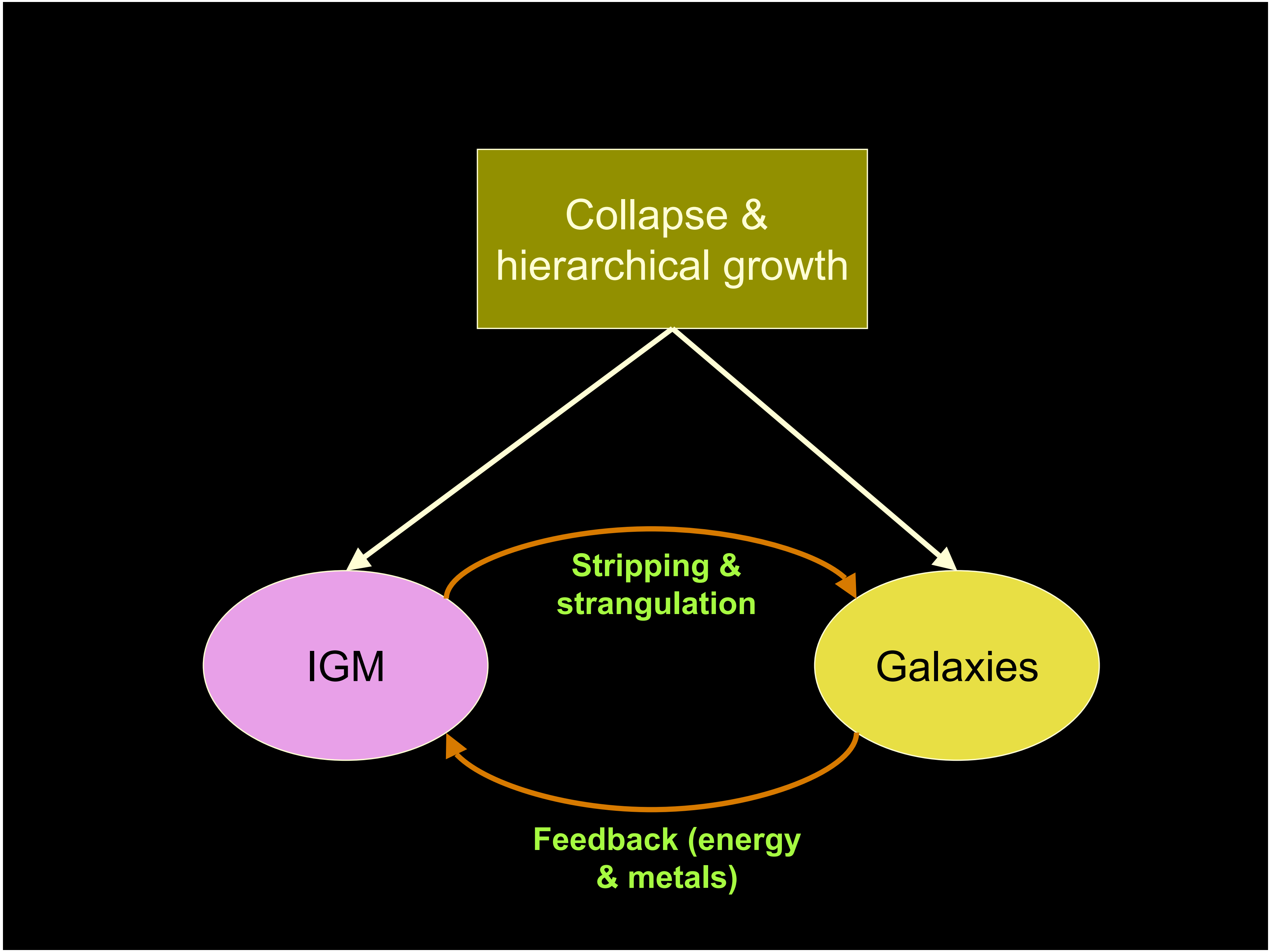
Galaxy interactions



Interacting galaxies in Stephan's Quintet (Chandra+optical)

- Trinchieri, Sulentic et al


Collapse & hierarchical growth
IGM
Galaxies
Stripping & strangulation
Feedback (energy & metals)

Complications

- Geometry - non-spherical
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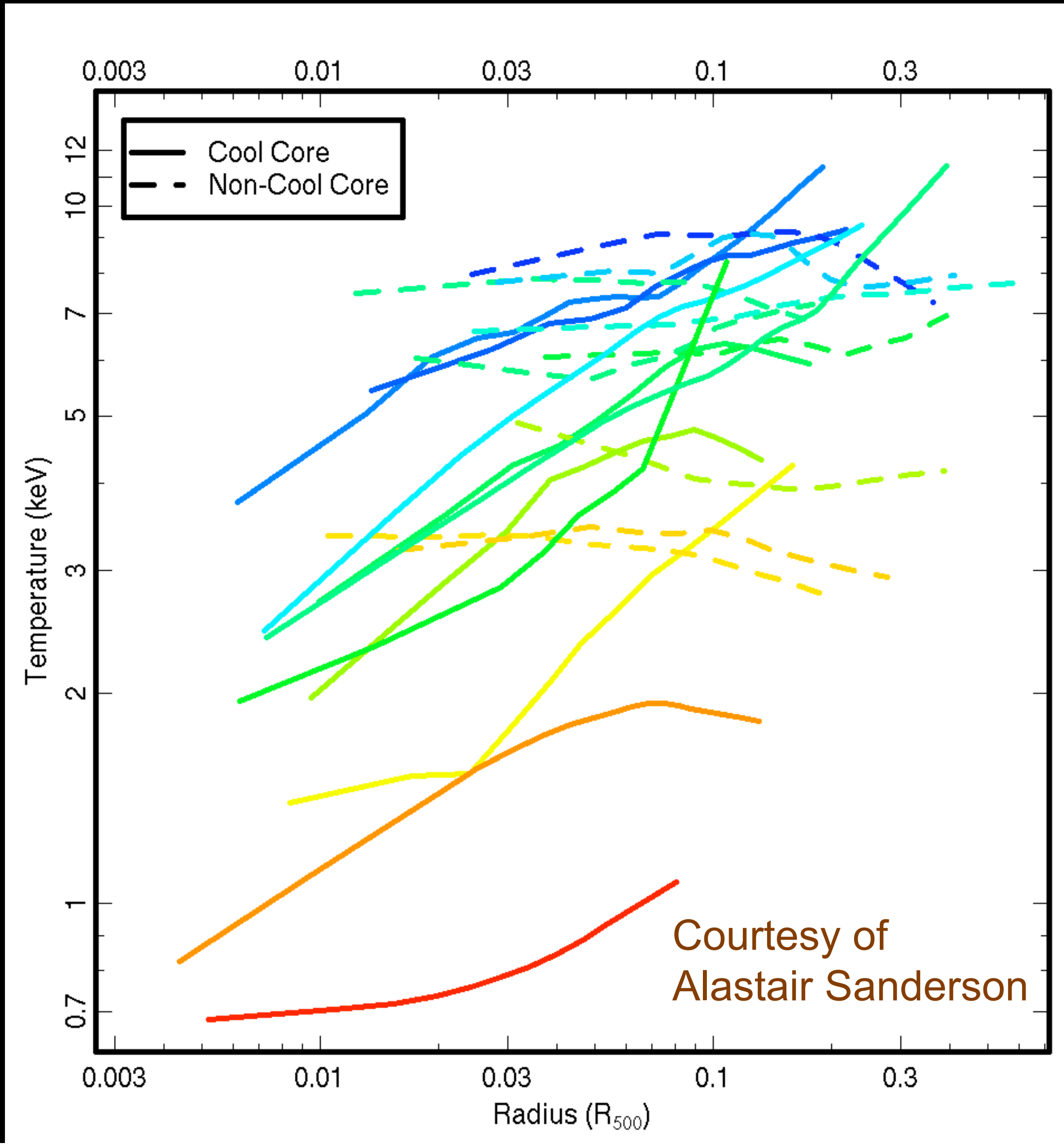
- Galaxy interactions
- Cooling
- Feedback - SNe and AGN

Cooling

Clusters

Groups



Complications

- Geometry - non-spherical
- Hierarchical growth
- Galaxy interactions
- Cooling
- Feedback - SNe and AGN

Feedback - energy injection

Deep Chandra observation of the Antennae - Fabbiano et al 2004

The intergalactic medium at large

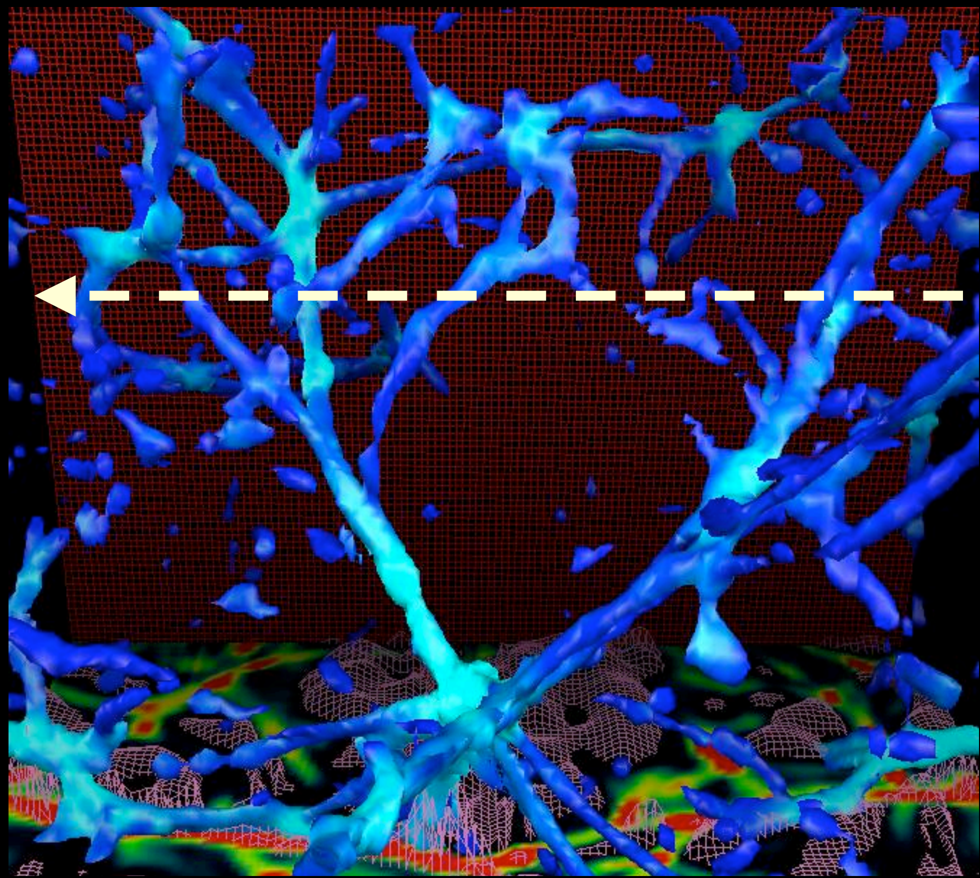
- The baryon contribution to Ω is constrained (e.g. by WMAP and Big Bang nucleosynthesis studies) to be $\Omega_b \approx 0.045\ h_{70}^{-2}$.
- This corresponds to mean density $\rho_b \approx 2.5 \times 10^{-7}$ amu cm^{-3}.
- Gas with density $<10^{-5}$ cm^{-3} can currently only be studied in absorption.

The intergalactic medium at large

At z~2-4 most of the baryons appear to reside in the Lyman-α absorption systems, with T~30000 K.

These also contain metals, with abundances up to ~0.1 solar.

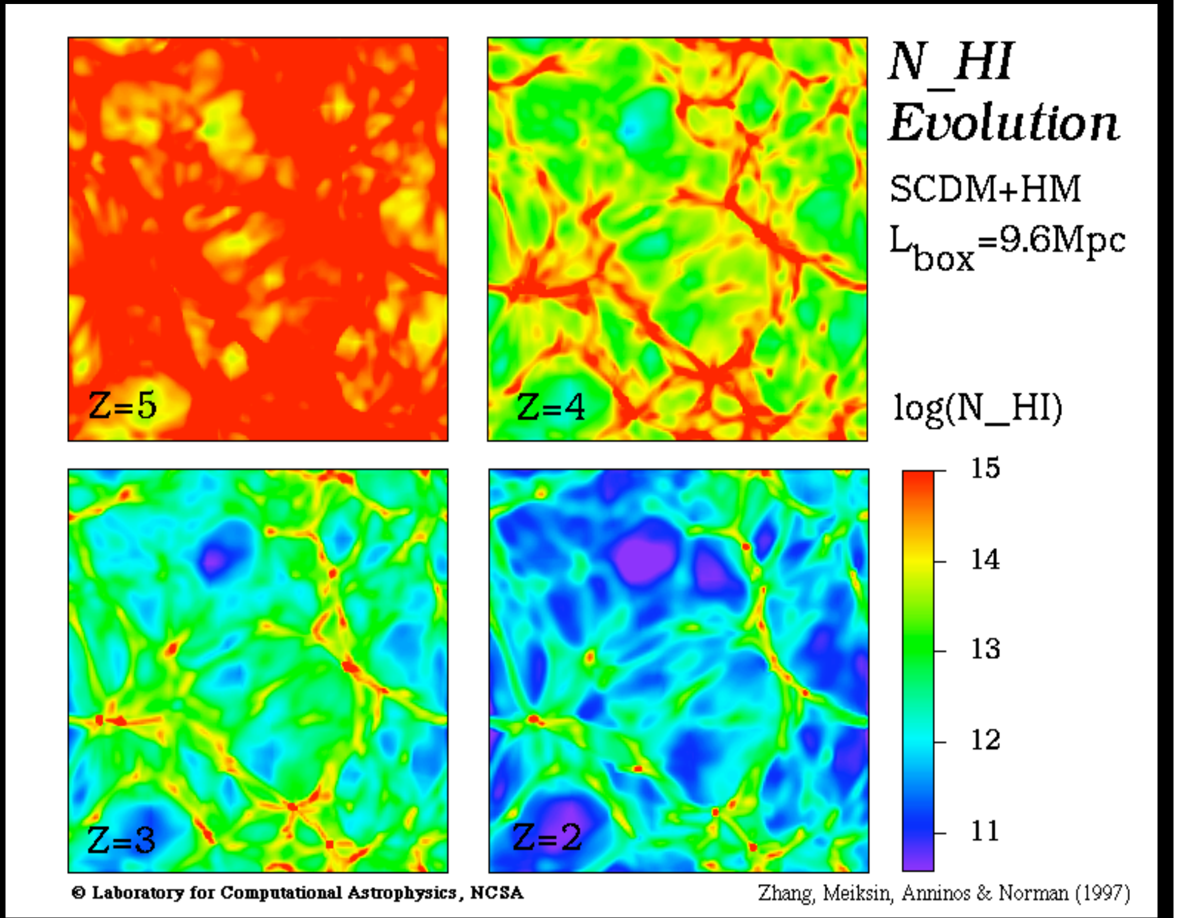
Simulations suggest that the Lyman forest "clouds" are filamentary structures, photoionized by UV flux from stars and AGN. Colder gas is concentrated into galaxies.



The intergalactic medium at large

The density of forest clouds drops sharply over the range z=3 to 1.5

Simulations predict that at low z, most of the IGM has been driven to higher temperatures, by shock heating in collapsing filaments.



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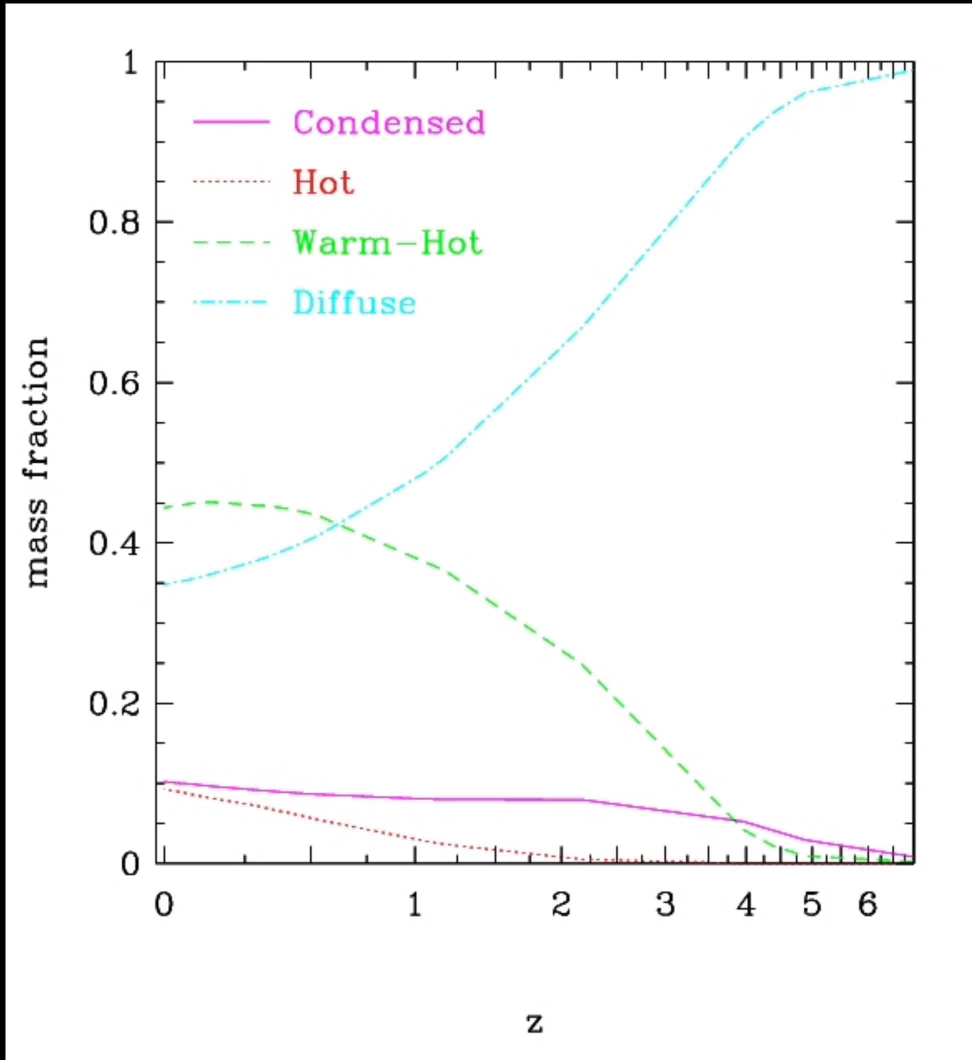
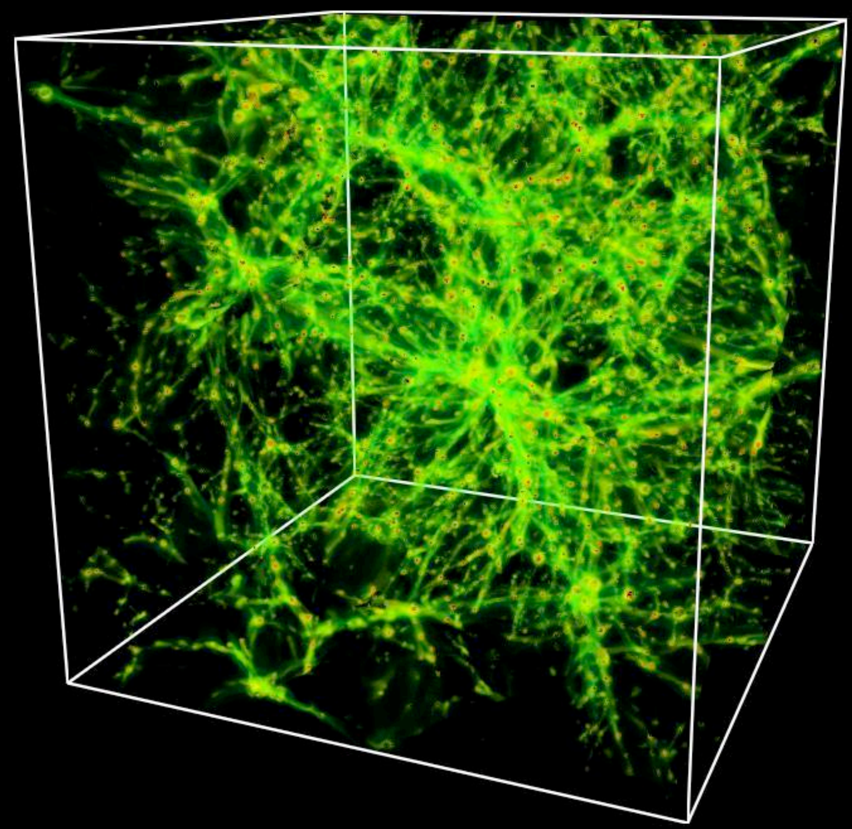


The intergalactic medium at large

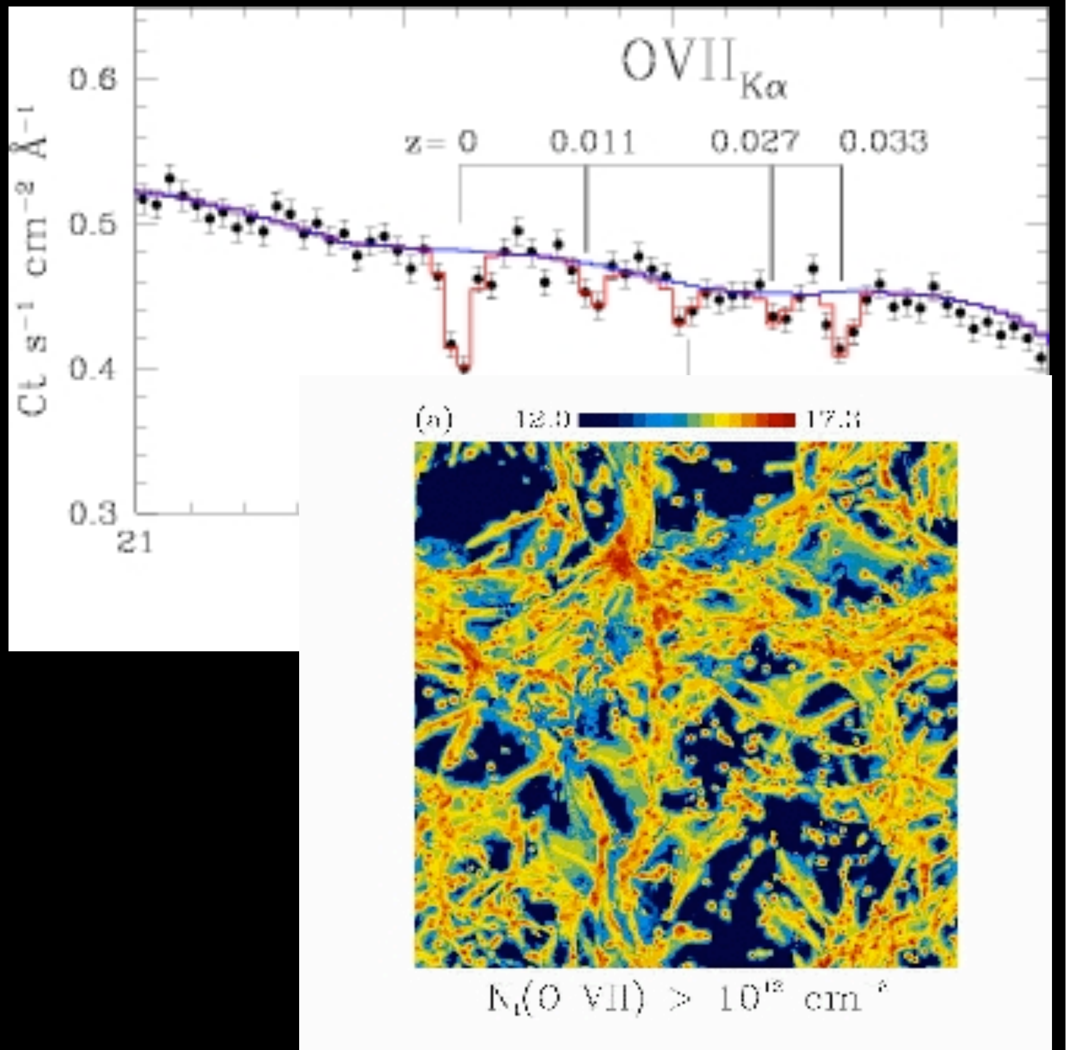
Most of the IGM is left in the "Warm-Hot Intergalactic Medium", with $T \sim 10^5$-10^6 K.



Dave et al 2001

The intergalactic medium at large

- This “warm” gas has been detected in absorption against background AGN in the far UV and X-ray.
- Observed incidence seems to agree with simulations.
- WHIM features at z=0 may be associated with the Local Group, or may be Galactic.



Fang et al 2002

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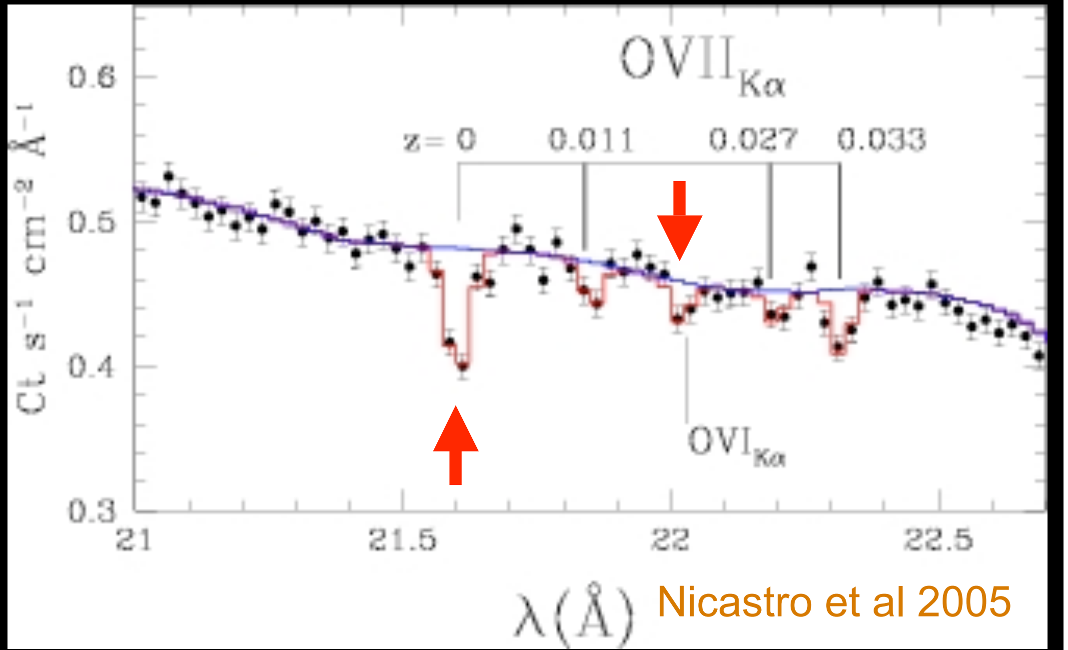


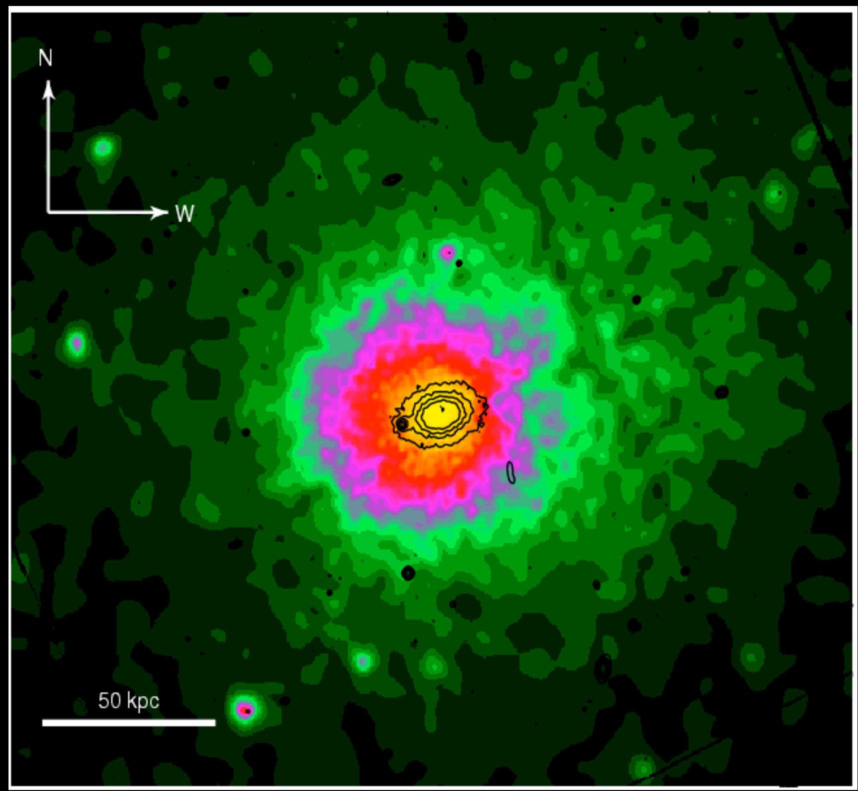
Chandra LETG spectrum

Intergalactic gas in groups

Virialised systems have overdensities $\delta\rho/\rho > 100$, allowing *emission* from hot baryons to be detected.

Compression & shocks during collapse and virialisation should heat most baryons in groups and clusters of galaxies to $T > 10^6$ K.

→ X-ray emission

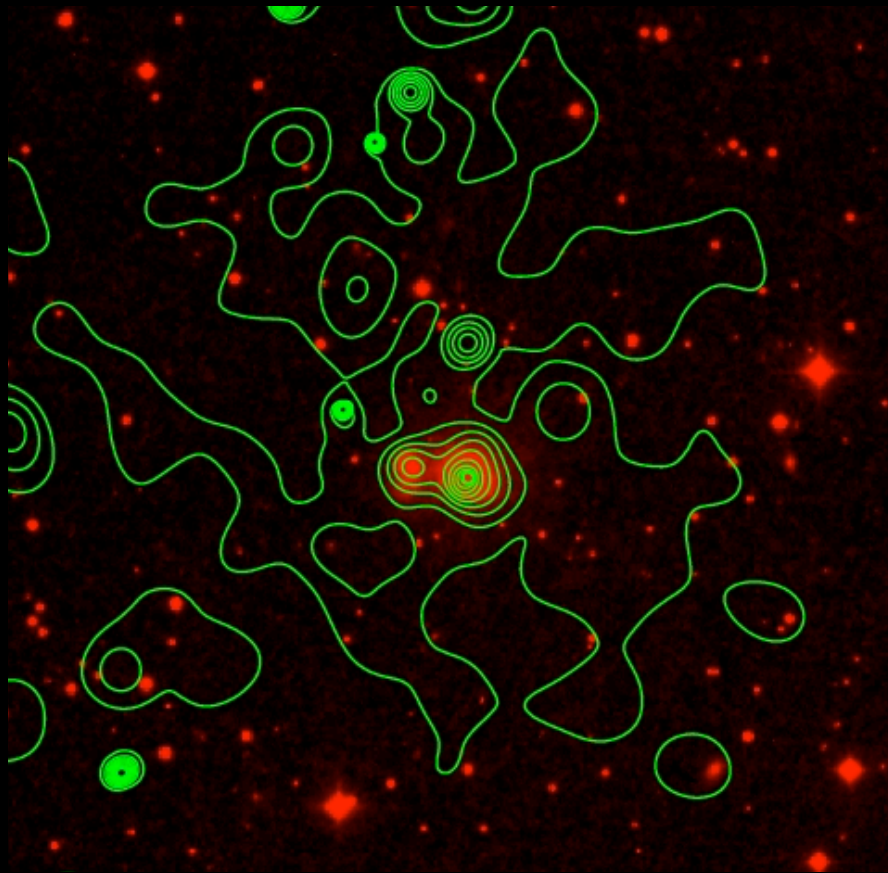


XMM mosaic of MKW4, with optical contours - O'Sullivan et al 2003

Intergalactic gas in groups

Even some very poor groups, with low velocity dispersions, have detectable intergalactic X-ray emission, though this may be very irregular.

E.g. Chandra study of the NGC 1587 group, which has only $\sigma \approx 100$ km s^{-1}.

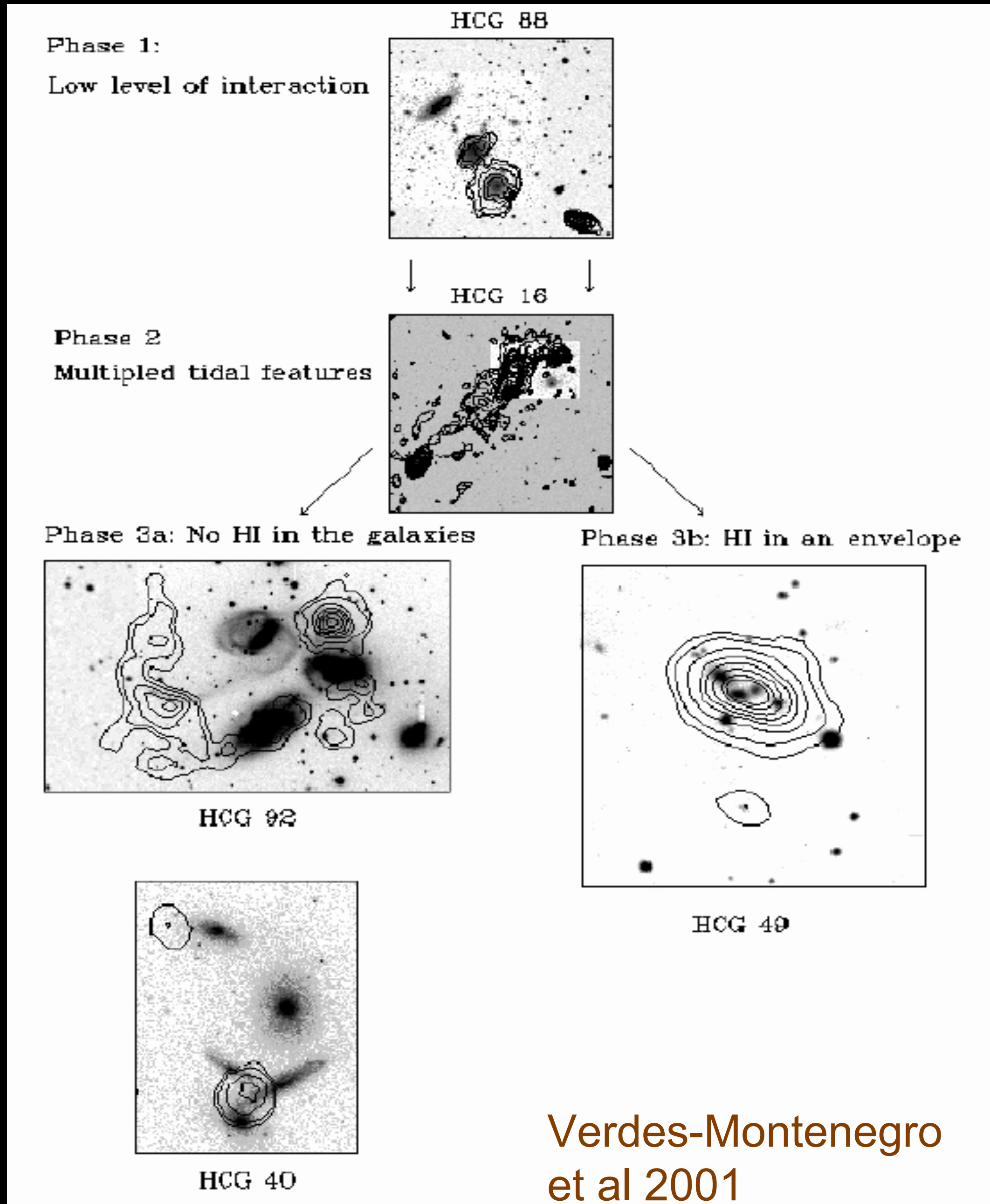


Helsdon et al 2004

Intergalactic gas in groups

Cold gas (HI) is also found outside galaxies in some groups.

However, aggregate HI mass is typically $\sim 10^9$-10^{11} $M_\odot$, whereas *total* gas content of a 10^{13} $M_\odot$ group should be $\sim 10^{12}$ $M_\odot$.



Verdes-Montenegro et al 2001

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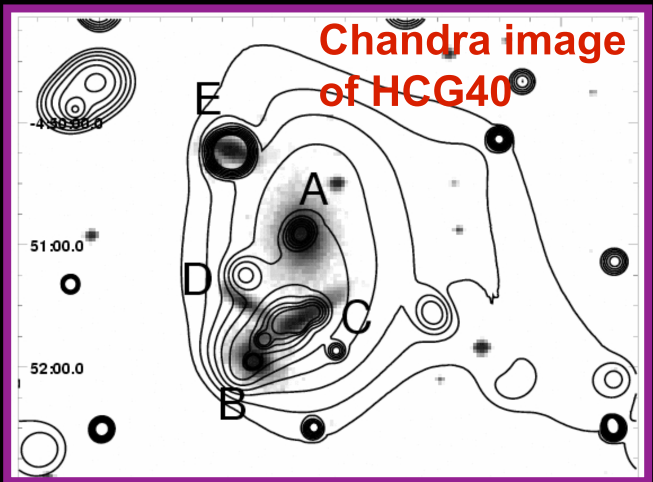
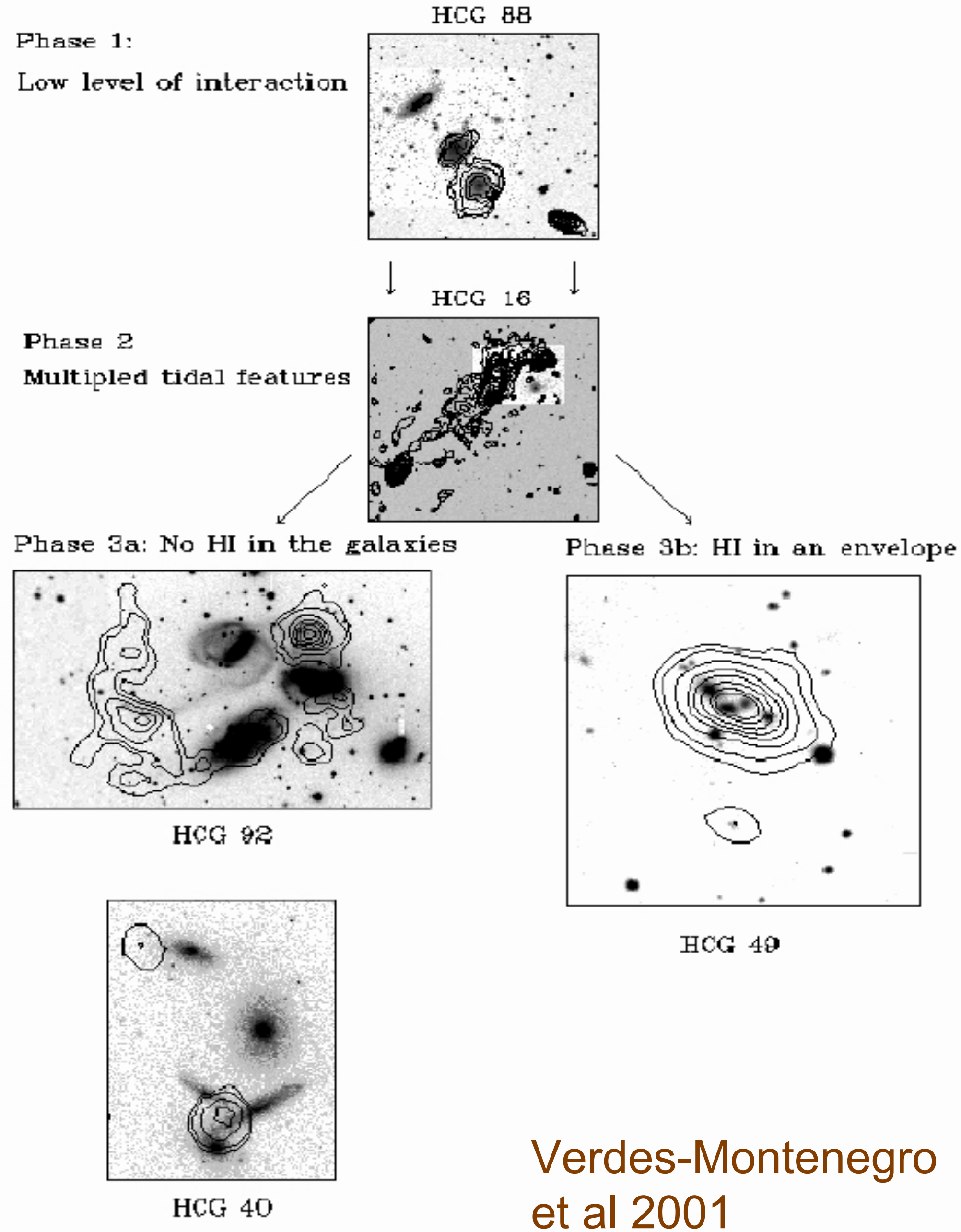




Verdes-Montenegro et al 2001

Some interesting gas properties

- Scaling properties of hot gas - entropy
  - AGN heating and entropy
  - Shock amplification
- Metals in the group gas
- Gas stripping in groups
- The evolutionary status of optically selected groups
- Fossil groups

Scaling properties

Cosmological simulations including gravity and simple gas physics produce dark halos which are almost self-similar, when scaled to a radius enclosing fixed overdensity (e.g. r_{200}).

Also, gas tracks dark matter within these halos. This behaviour would generate clusters with well-defined X-ray scaling relations.
For fixed z:

$\langle\rho\rangle \sim M/R^3$ is same for all systems

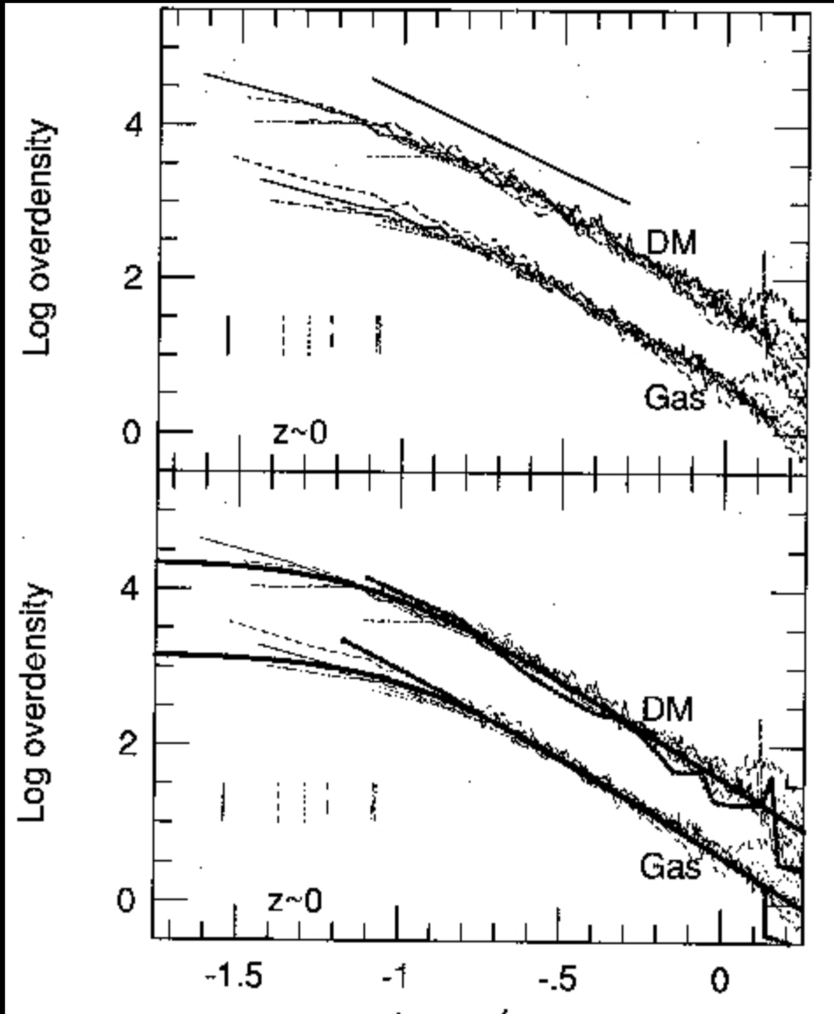
$T \sim M/R \sim R^2 \sim M^{2/3}$ from V.T.

$\therefore\ r_{200} \sim T^{1/2}$

$L_X \sim \rho^2 \cdot V \cdot \Lambda(T) \sim \rho^2 \cdot T^{3/2} \cdot \Lambda(T)$

where $\Lambda(T) \sim T^{1/2}$ for bremss,

$\rightarrow L_X \sim T^2$

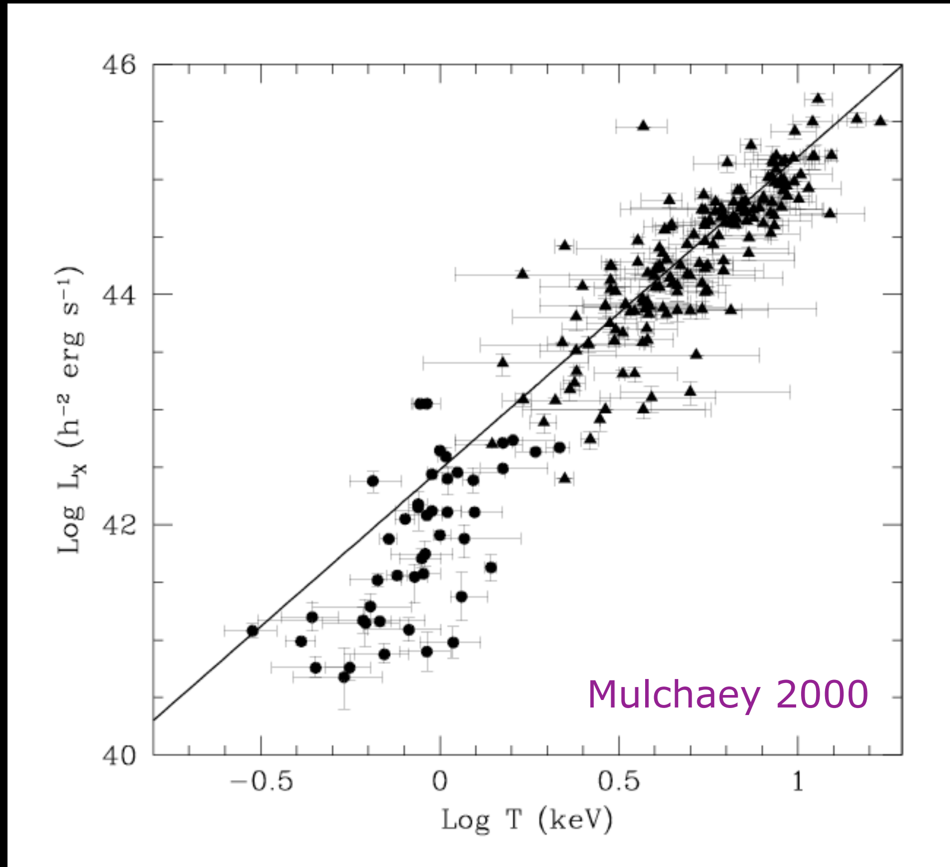


(Navarro et al 1995)

The L:T relation

It has been clear for many years that the cluster L:T relation does not follow the $L \propto T^2$ slope expected for self-similar systems.

In practice, $L \propto T^3$ for clusters, with possible further steepening to $L \propto T^4$ in group regime (notwithstanding slope of 2.5 in GEMS group sample derived by Osmond & Ponman 2004!).



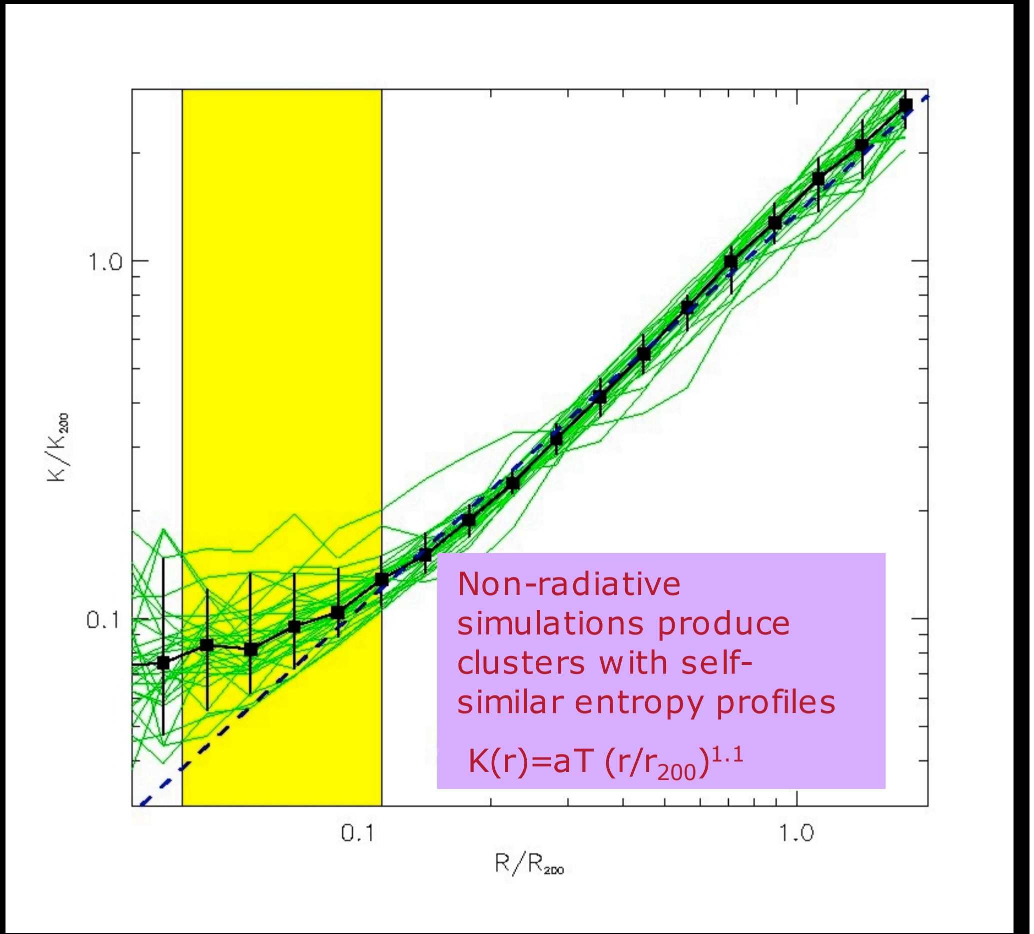
What is causing this effect?

Entropy in the intragroup medium

It is helpful to consider the *entropy* of the IGM:

- Gas will always rearrange itself such that entropy increases outward
- Entropy is conserved in any adiabatic rearrangement of gas

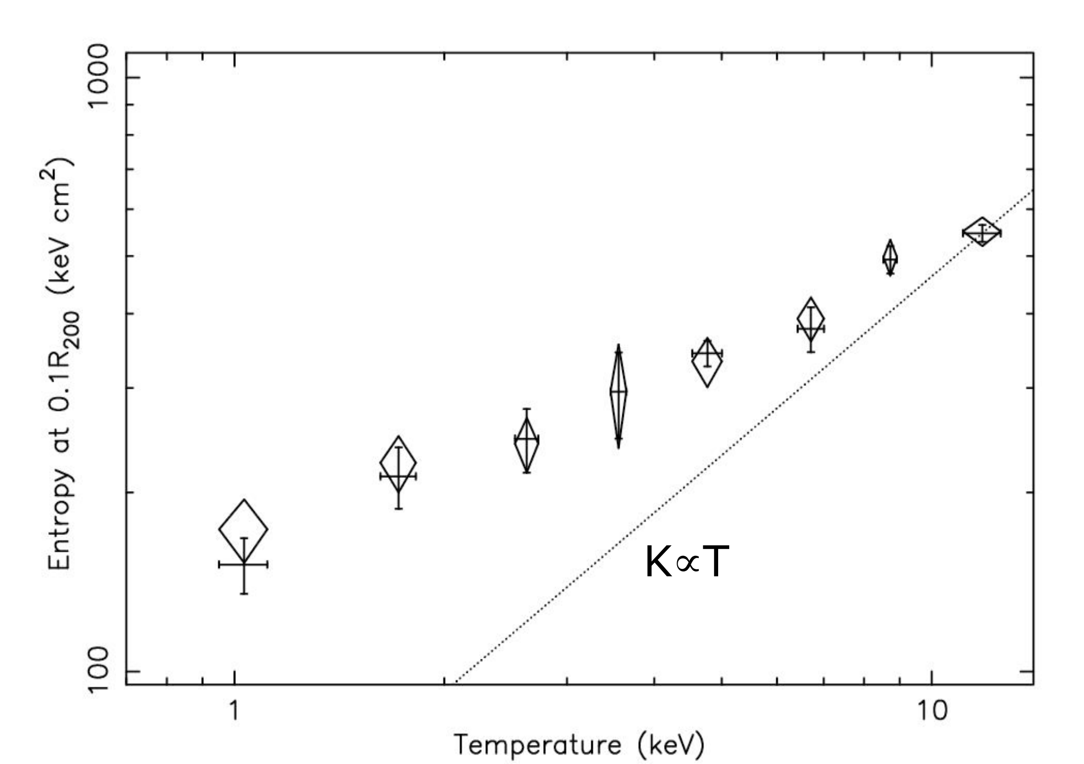
Define “entropy” as $K=T/n^{2/3}$ (so true thermodynamic entropy is $s=k \ln K + s_0$.)



Voit, Kay & Bryan 2004

Entropy in the intragroup medium

Study, of 66 systems by Ponman, Sanderson & Finoguenov (2003), showed that $K(0.1r_{200})$ scales as $K \propto T^{2/3}$, rather than the self-similar scaling of $K \propto T$.



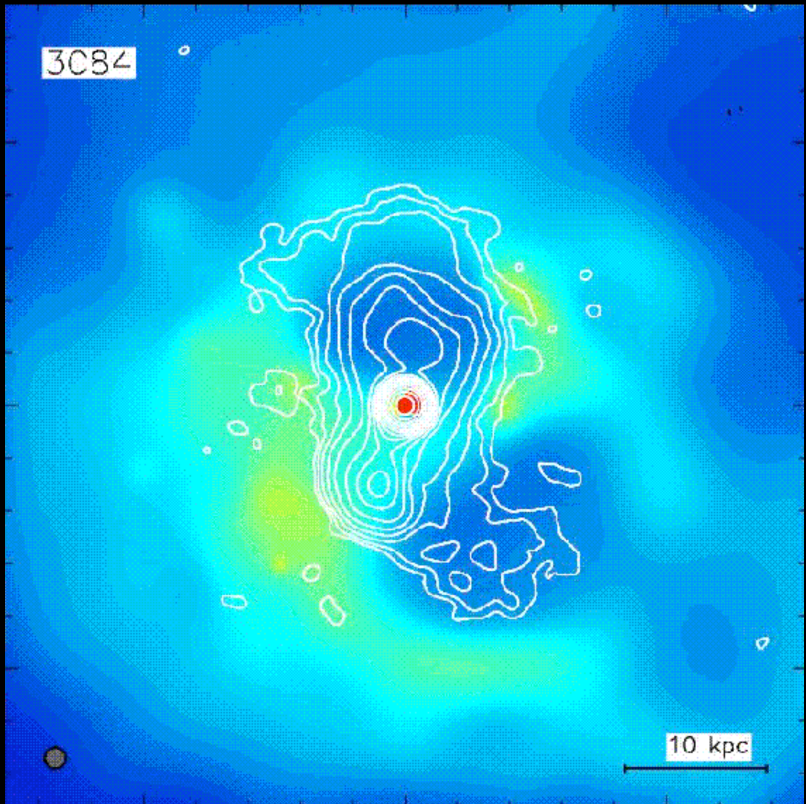
Systems grouped into 8 temperature bins

Entropy in the intragroup medium

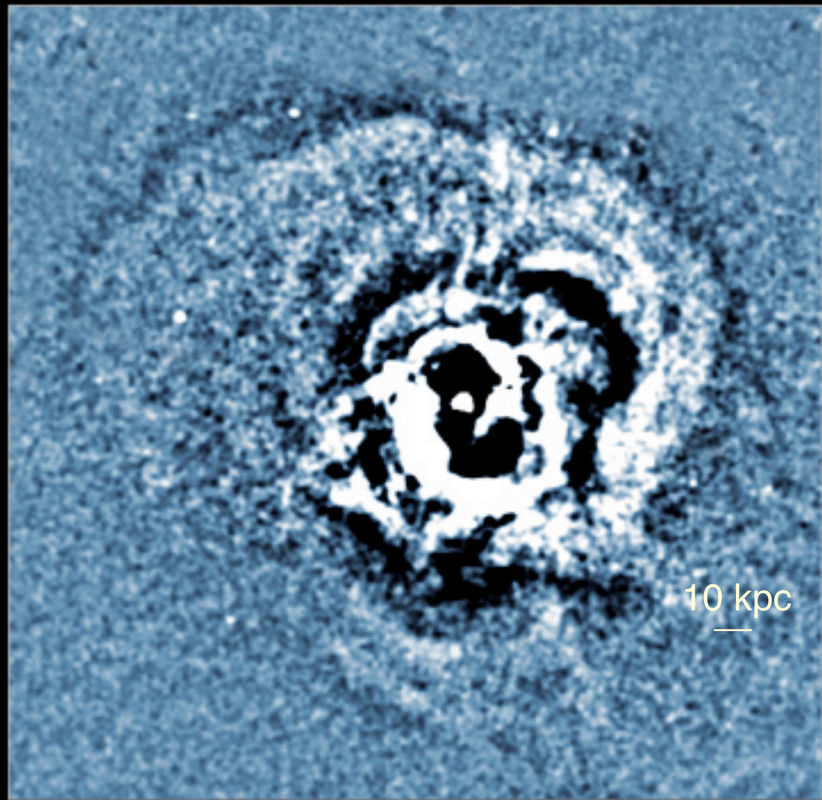
- Extra baryon physics is required to account for observed entropy behaviour in groups/clusters
- Cooling can raise the entropy, but to match observed properties requires ~50% of the baryons to cool in group-sized halos
- Hence we are seeing evidence for extra energy injection - i.e. feedback
- Two potential sources: nuclear energy (SNe), and gravitational energy (AGN)
- Can observations give clues as to when and how the feedback is provided?

AGN heating?

The most promising solution to the cooling flow problem in clusters seems to be feedback from a central AGN.



Perseus Cluster & 3C 84

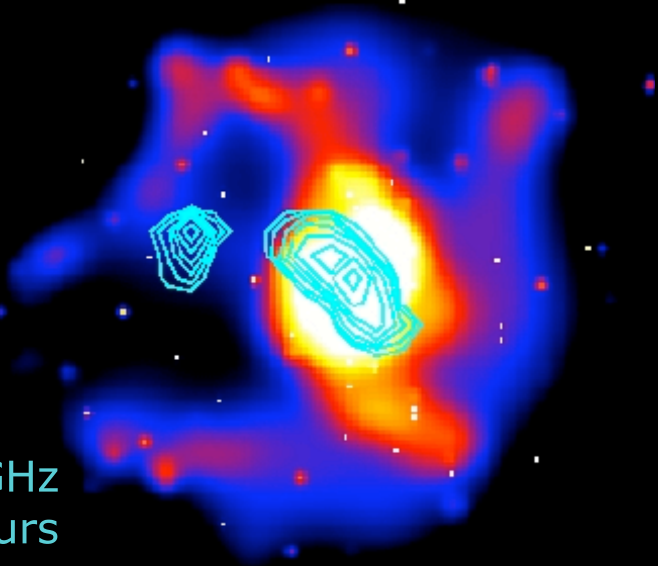


Sound Waves in Perseus

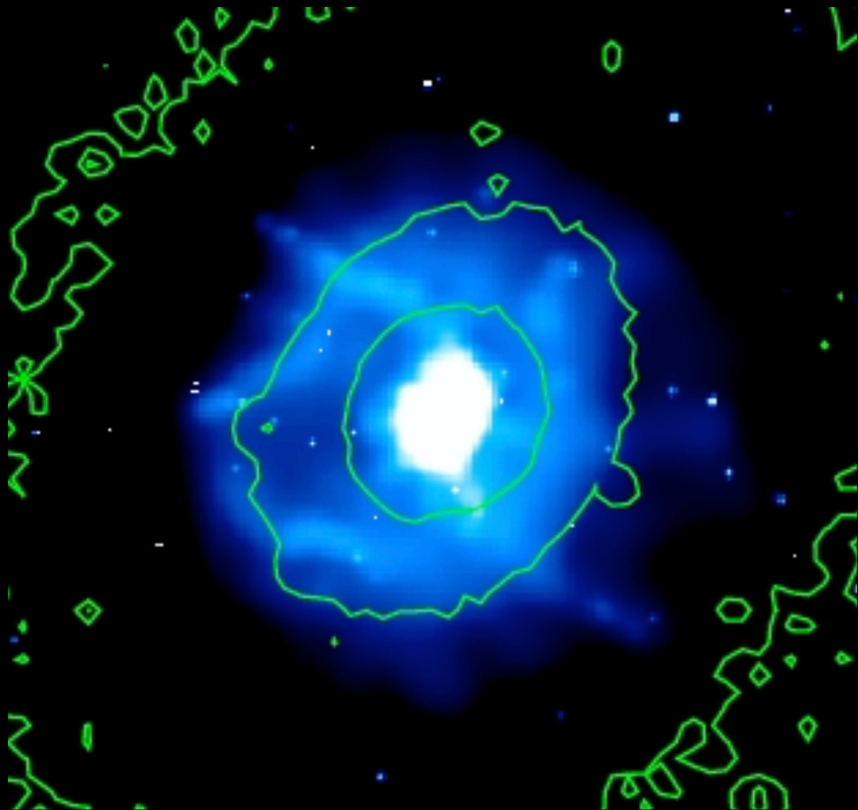
AGN heating?

Chandra has uncovered complex structures within the cores of many groups & clusters

In many cases this seems to be associated with activity in a central active galaxy.



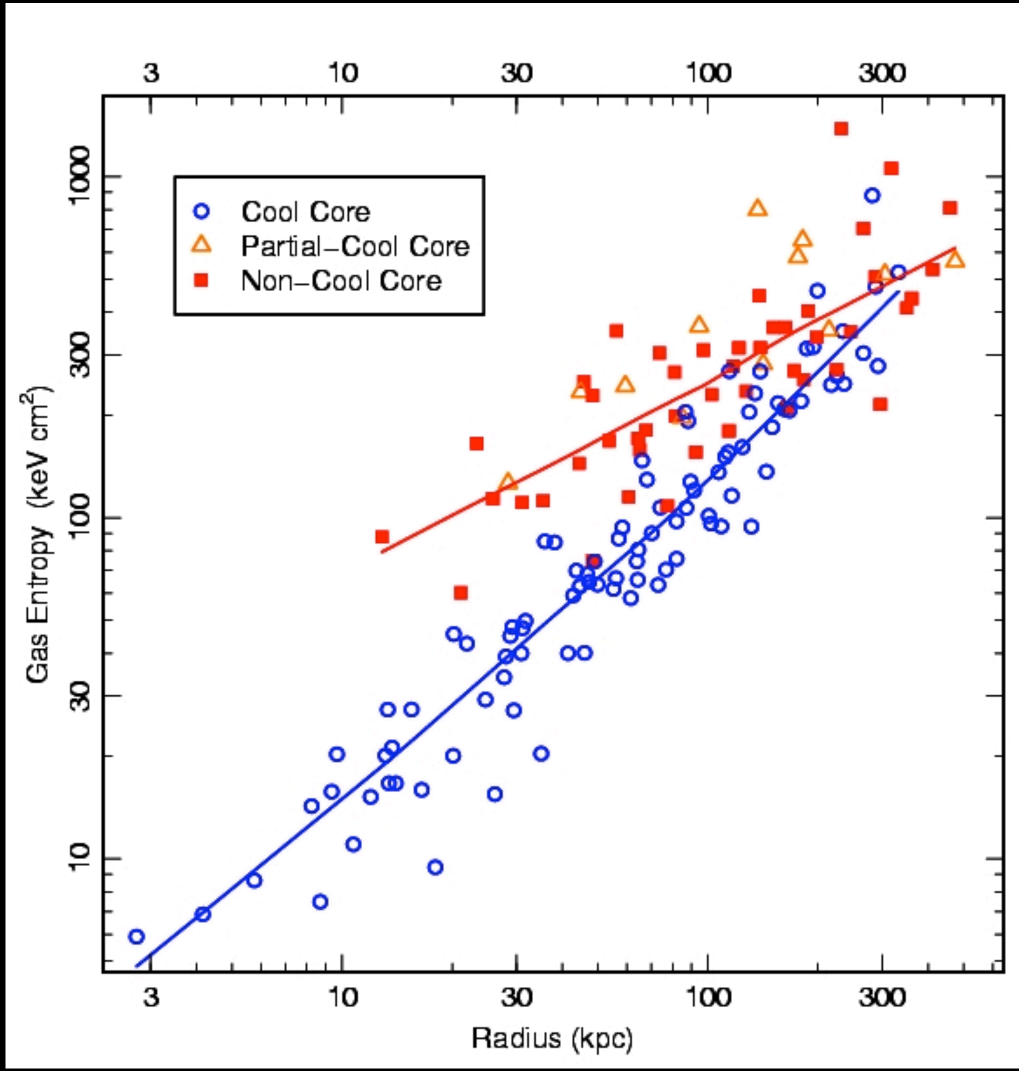
VLA 1.4 GHz contours



Chandra observation of the NGC 4636 group

AGN heating?

However, observed entropy profiles do not show isentropic cores.

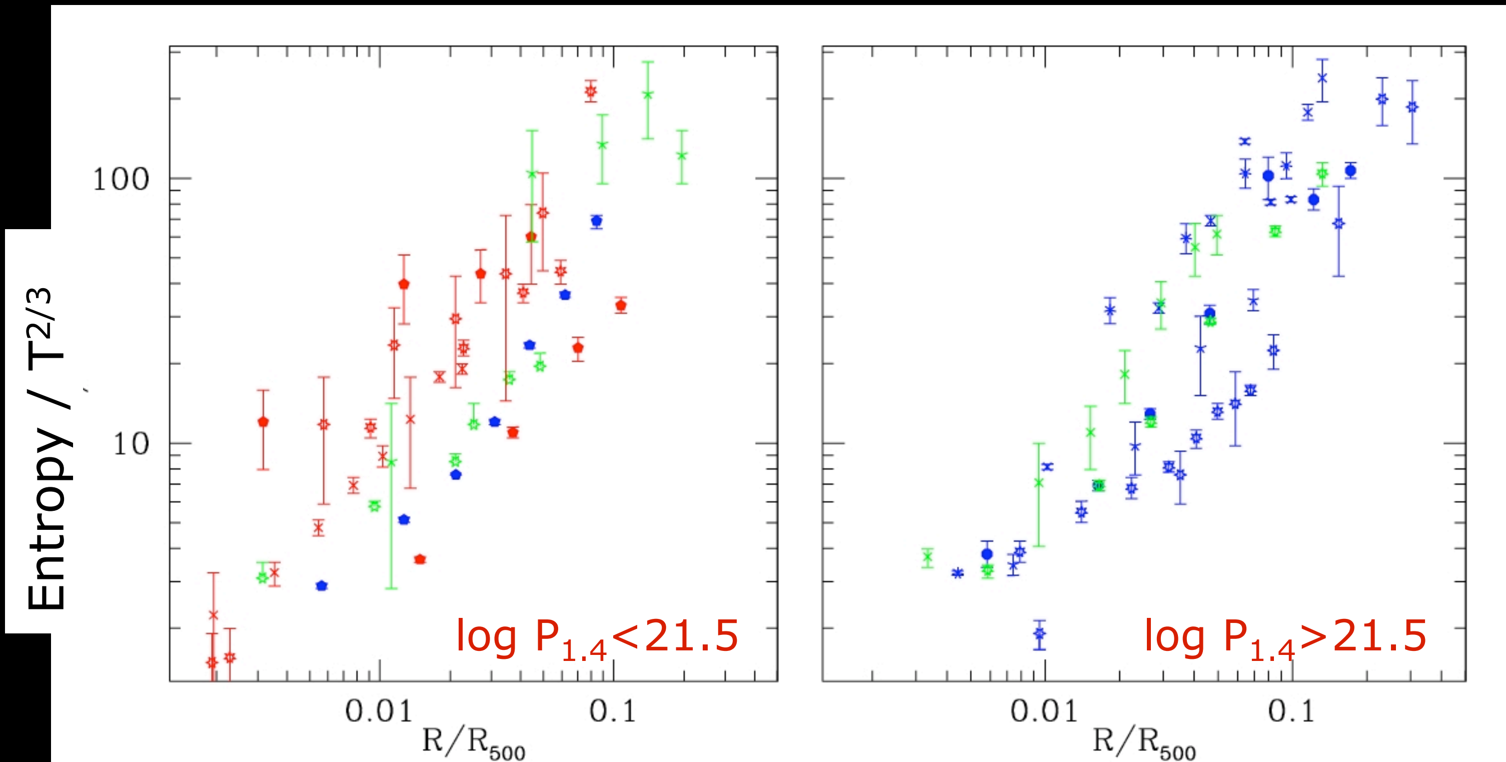


Alastair Sanderson - 20 clusters with T>2 keV

AGN heating?

Try cutting profiles on radio properties:

Jetha, Ponman & Sakelliou

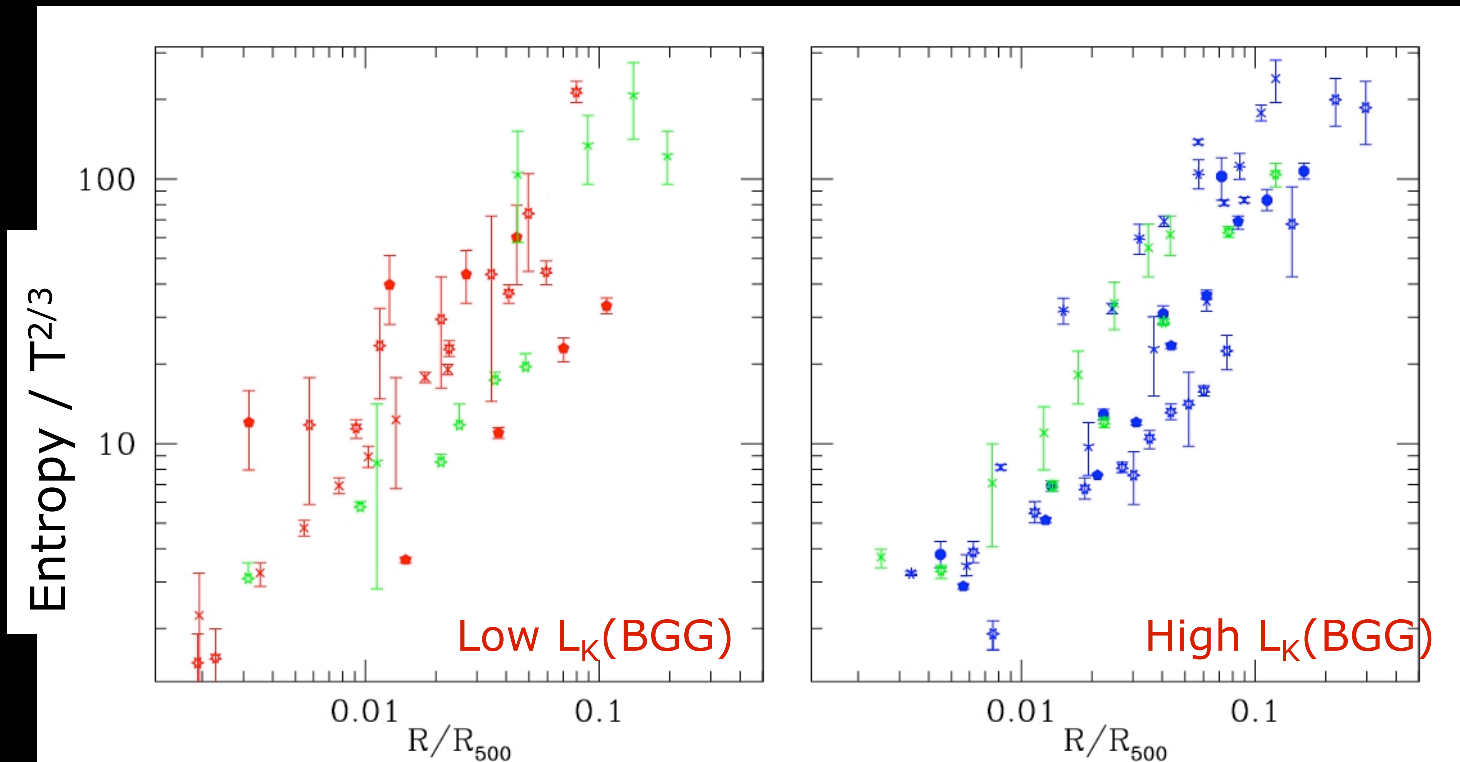


No apparent difference in entropy profiles

AGN heating?

Or cut on L_K(BGG) as proxy for black hole mass:

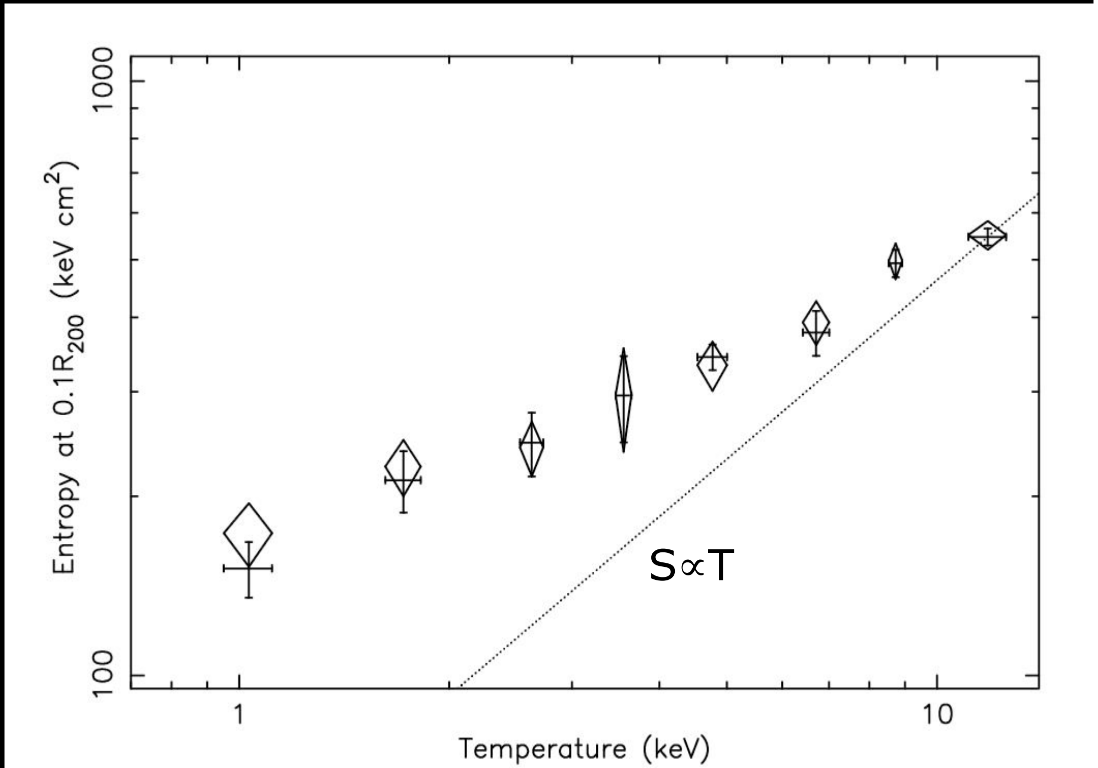
Jetha, Ponman & Sakelliou



Still no difference…

Entropy at large radii

PSF03 also found that the $S \propto T^{2/3}$ scaling seen at $0.1r_{200}$ applied at larger radii (e.g. r_{500}).



Ponman, Sanderson & Finoguenov 2003

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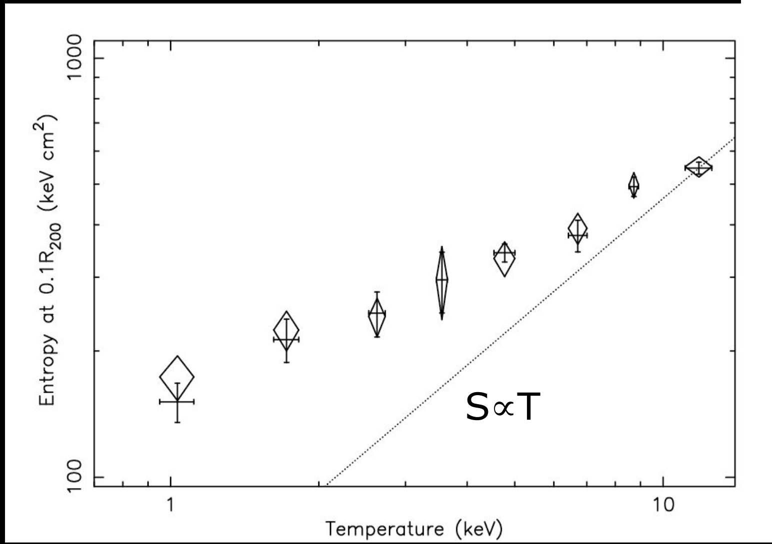
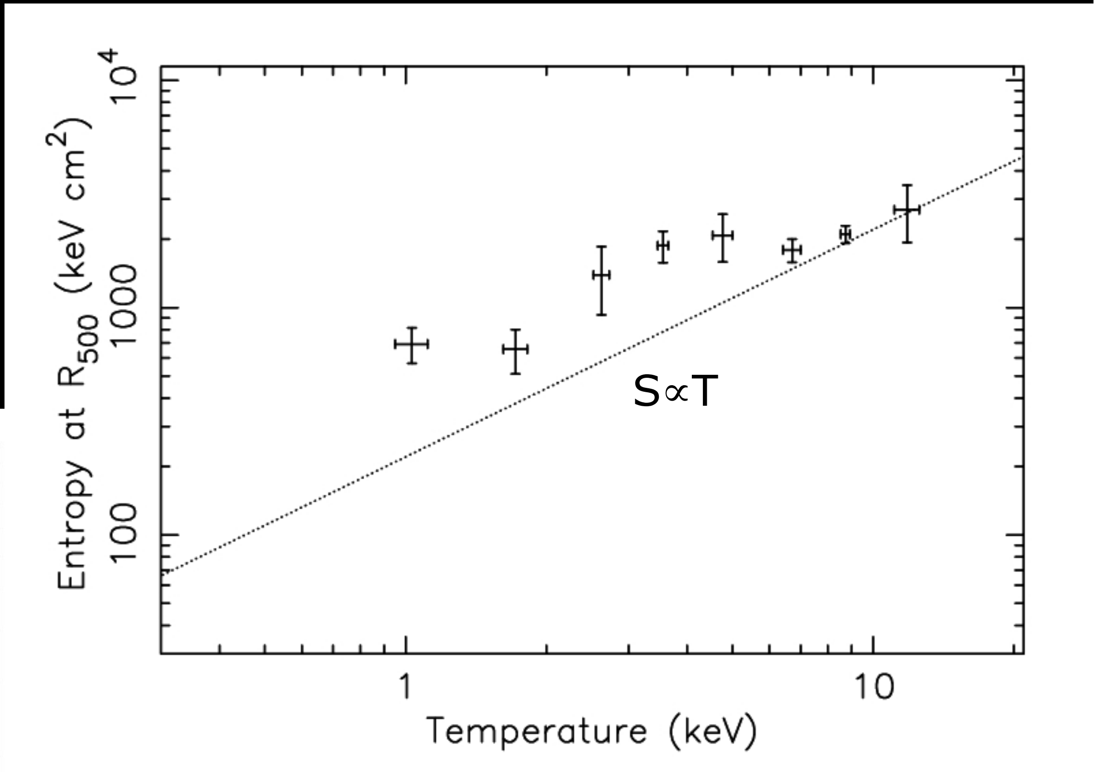


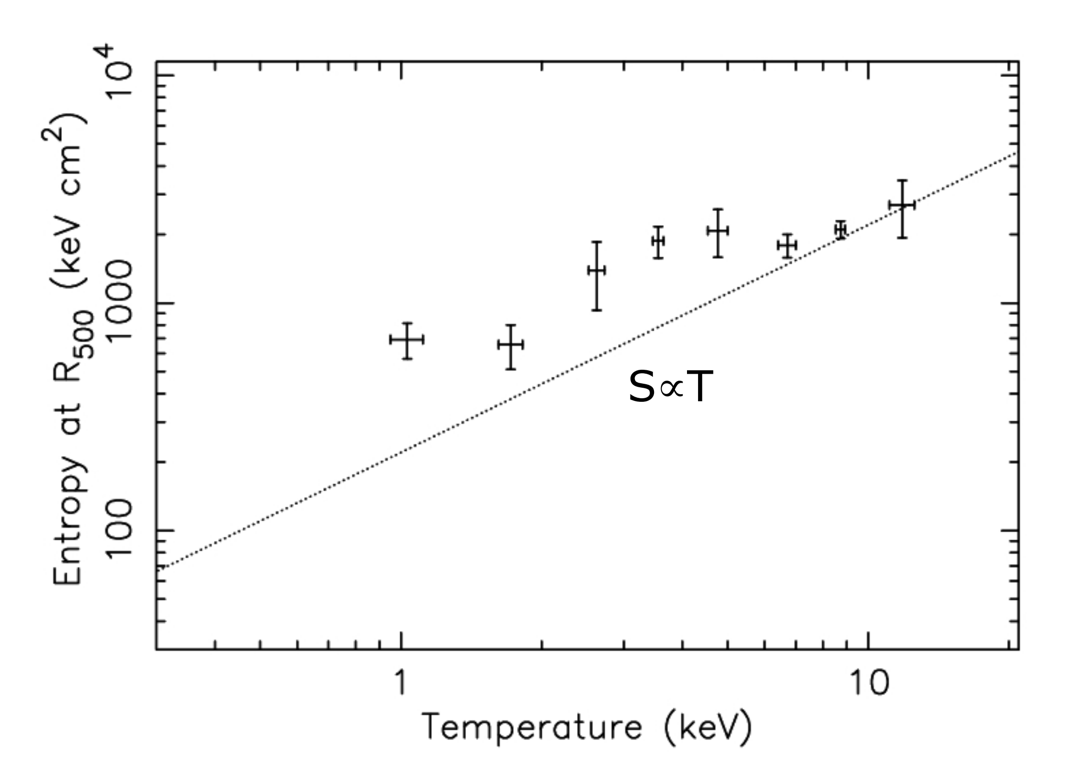


Ponman, Sanderson & Finoguenov 2003

Entropy at large radii

PSF03 also found that the $S \propto T^{2/3}$ scaling seen at $0.1r_{200}$ applied at larger radii (e.g. r_{500}).

This involves excess entropies of several hundred keV cm^2, which sounds energetically very challenging.

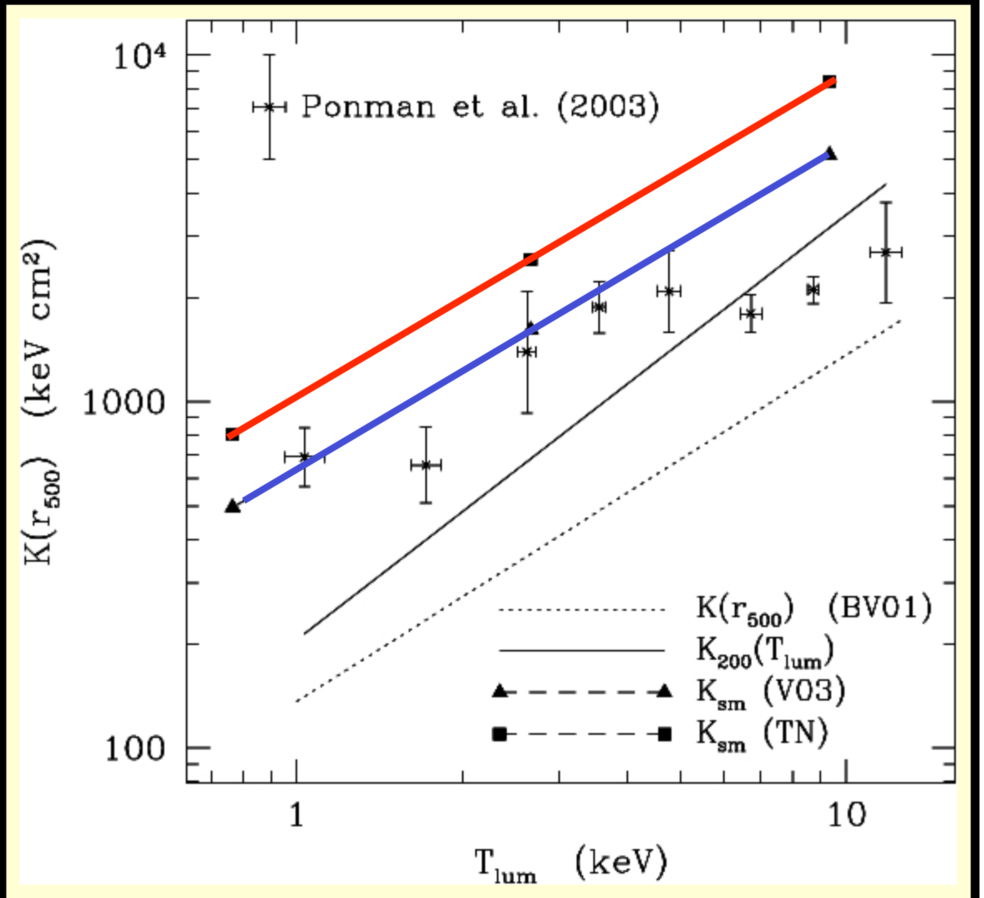


Ponman, Sanderson & Finoguenov 2003

Entropy amplification

How to generate such large amounts of extra entropy in these outer regions?

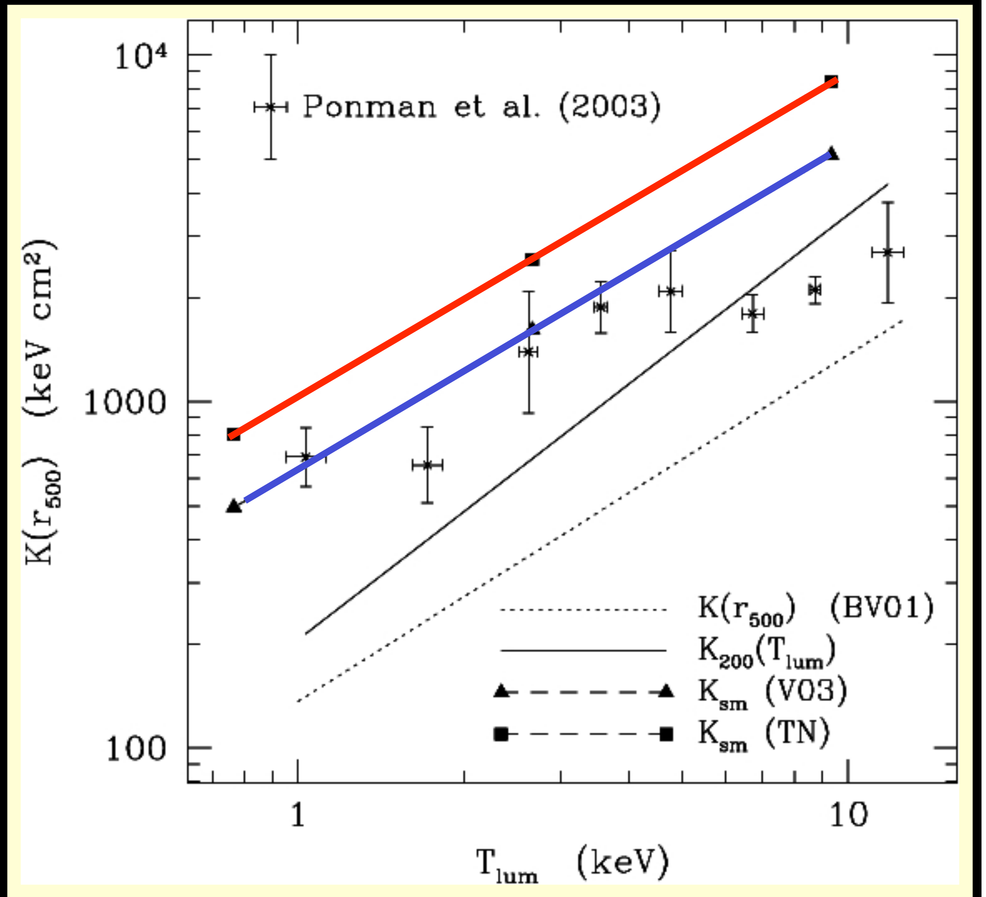
A clue is available from the fact that *smooth* accretion can generate entropies as high as those observed, whilst accretion in unheated cosmological simulations does not.



Voit & Ponman 2004

Entropy amplification

If feedback within filaments feeding clusters leads to smoother accretion, then the pre-shock entropy of accreting gas will be raised. The accretion shock then raises this value by a *factor* – shock multiplier effect.



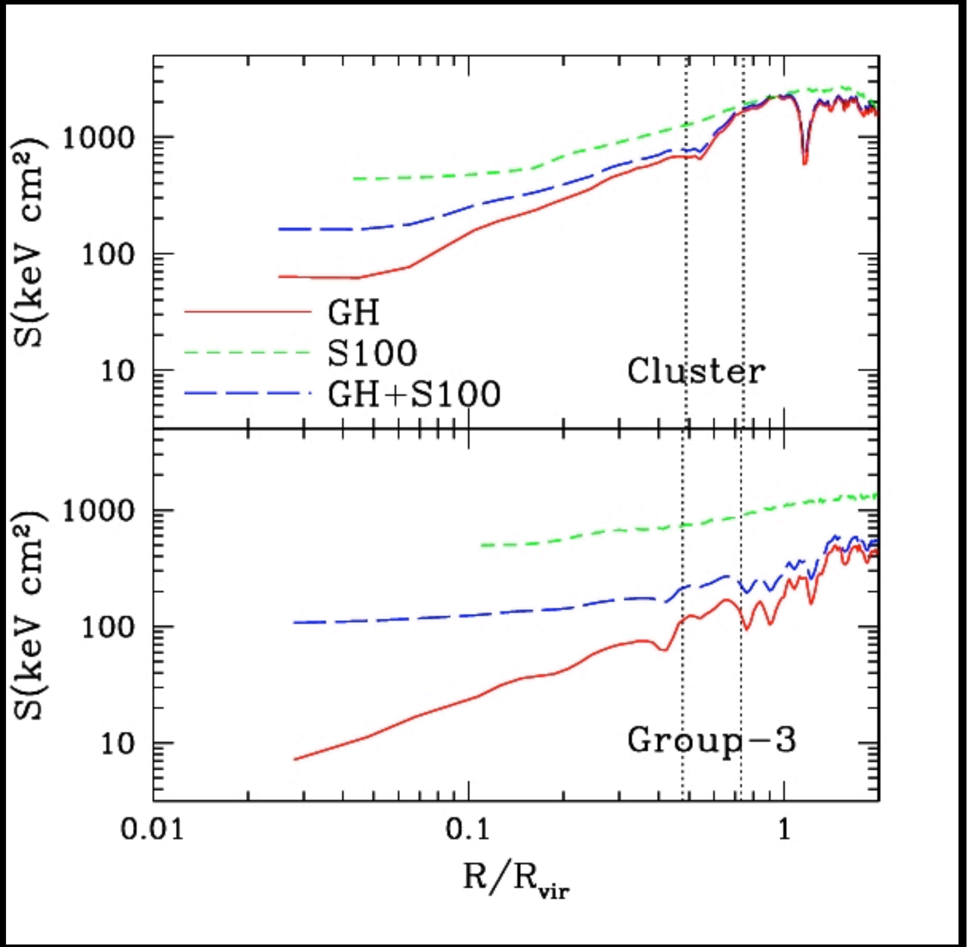
Voit & Ponman 2004

Entropy amplification

Borgani et al tested this idea by comparing entropy profiles in clusters derived from the same cosmological simulations with and without preheating and feedback.

In the absence of radiative cooling, preheating to an entropy floor of 100 keV cm^2 (at z=3) results in strong entropy amplification.

However the entropy profiles for groups are much too flat.

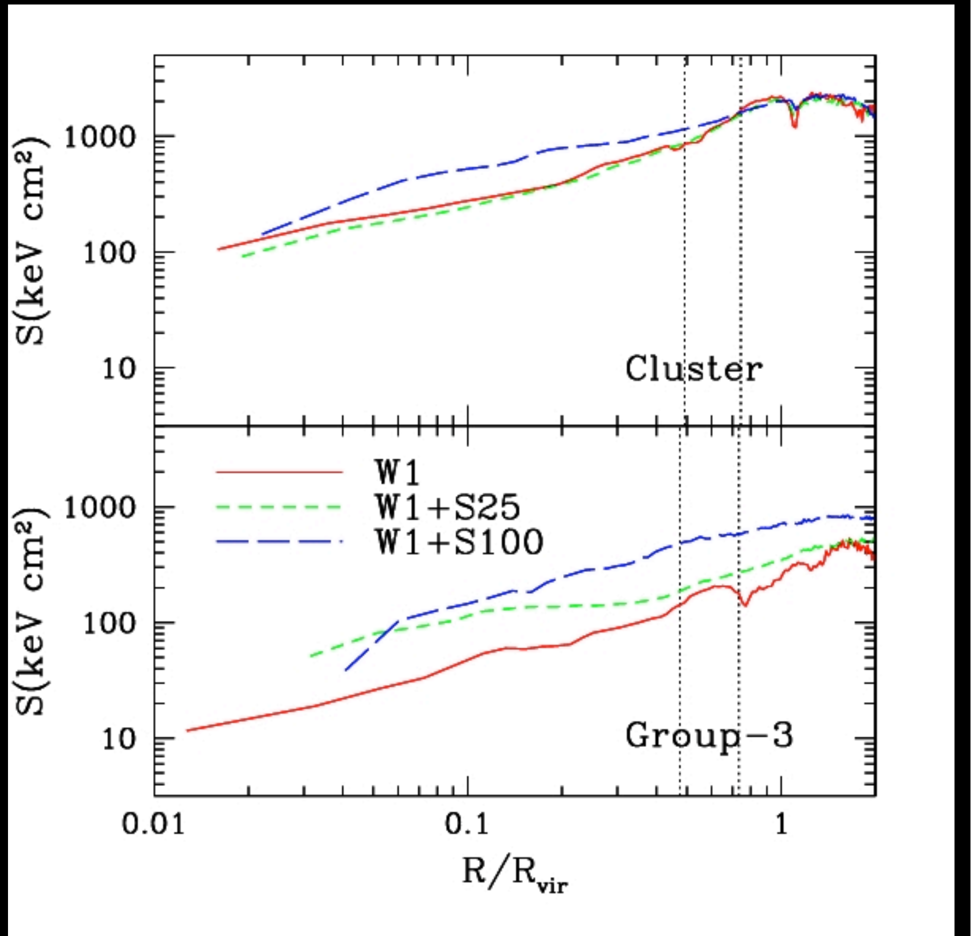


Borgani et al 2005

Entropy amplification

When radiative cooling and feedback from galaxies were included, the amplification achieved was minimal, unless preheating was included in addition to the winds.

A combined wind+preheating model was moderately successful, but produced entropy profiles in clusters flatter than those observed.



Borgani et al 2005

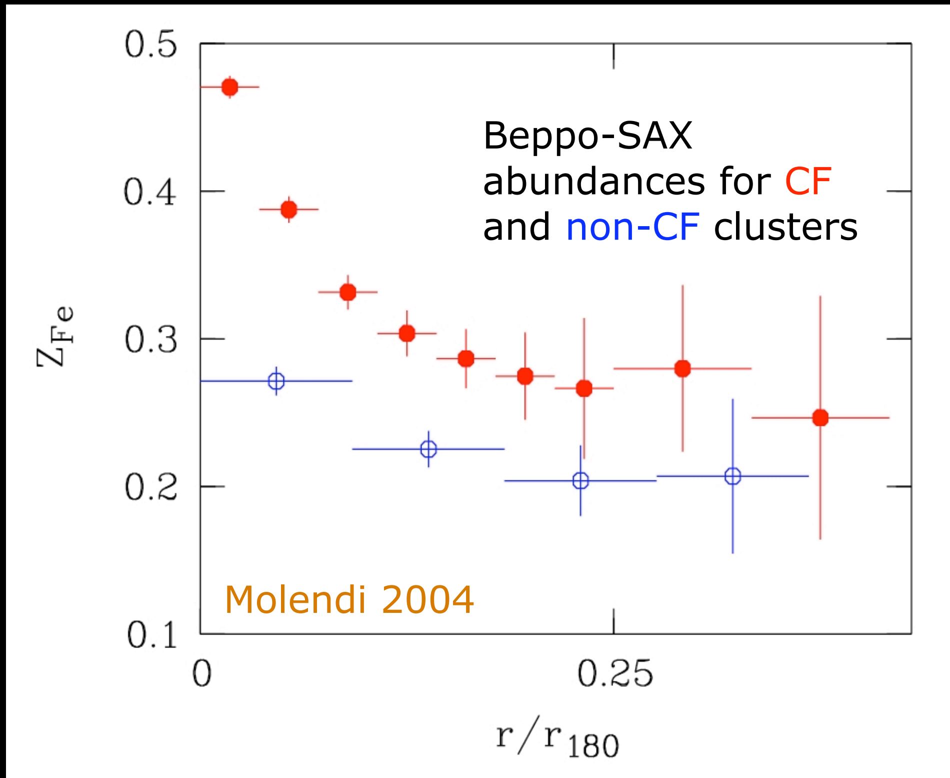
Entropy in the intragroup medium

Speculation:

- AGN heating within groups & clusters may counteract cooling, and hence prevent large amounts of mass deposition and central galaxy growth
- However, it does not have a major effect on the surrounding IGM
- The similarity breaking is largely the product of activity (AGN and/or SNe) within precursor filaments

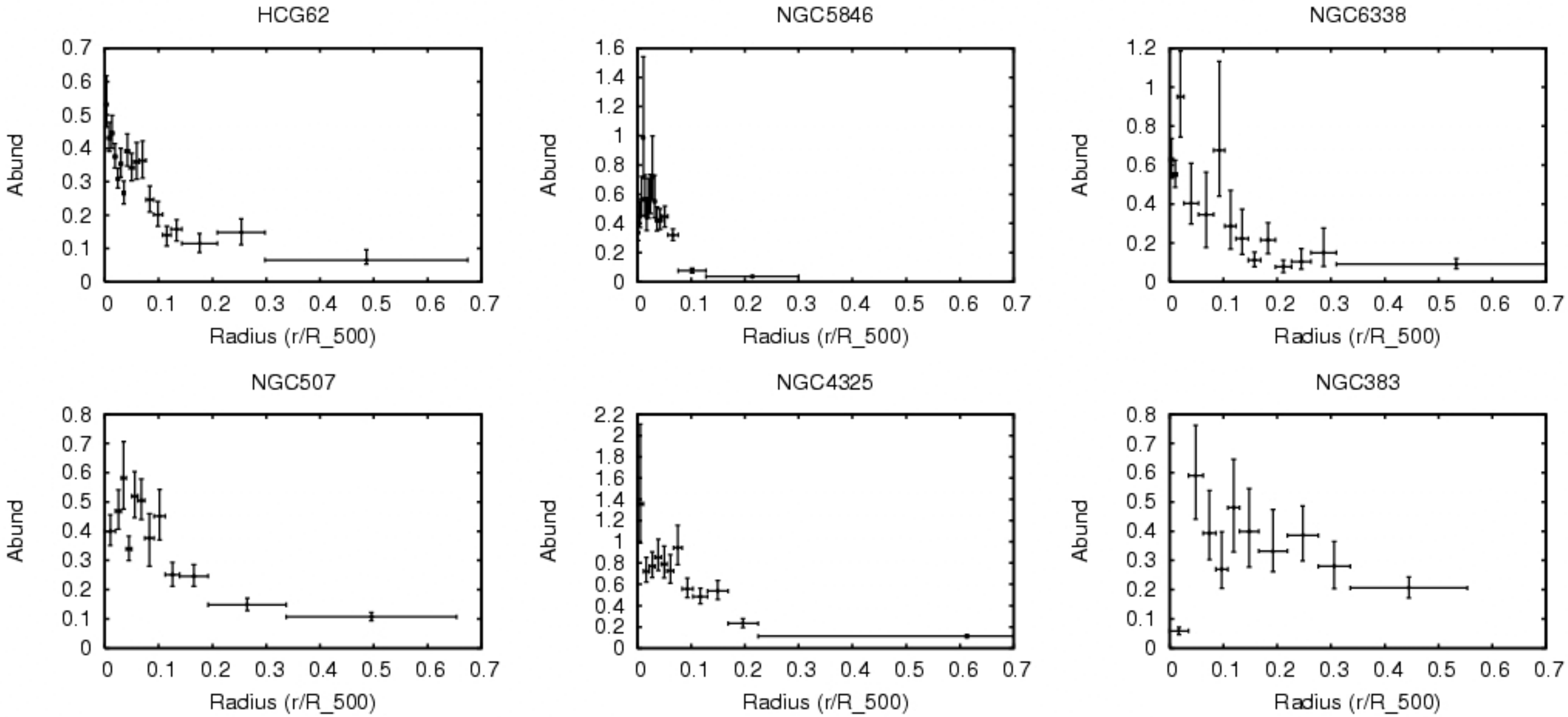
Metal abundances in the ICM

- Metallicity in clusters often shows a central enhancement, outside which it drops to 0.2-0.3 solar.
- XMM results (e.g. Pratt & Arnaud) confirm these features.
- The central peak may be plausibly explained by ejecta from the central galaxy - with predominantly SNIa origin (lower O/Fe).



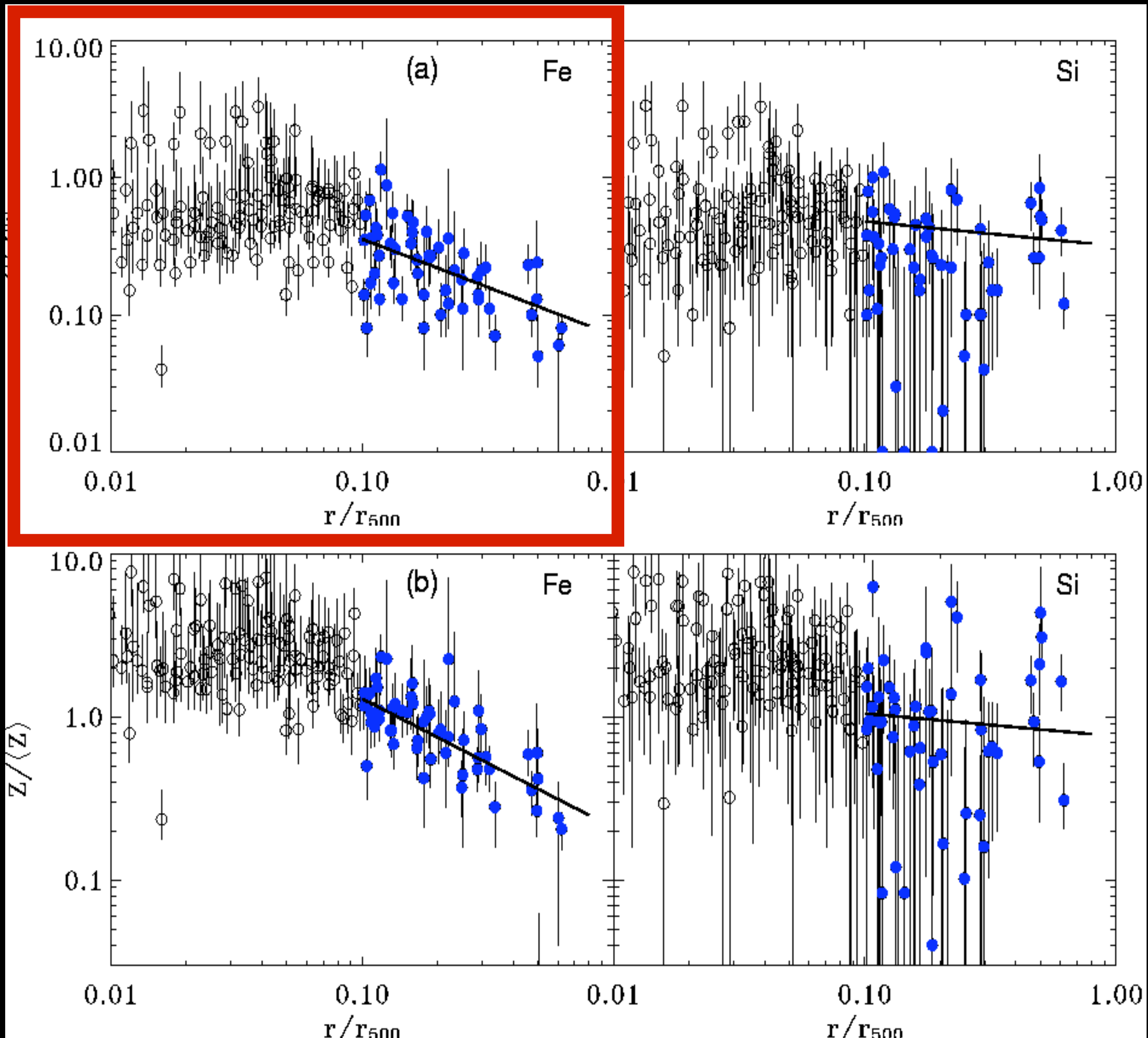
Are abundances in groups lower?

A montage of group abundance profiles from Chandra (Helsdon) suggests that they drop to ~0.1 solar outside the core region (cf Buote et al 2004 study of NGC5044).



Are abundances in groups lower?

Analysis by Jesper Rasmussen (more later) of Chandra data for 15 groups, confirms that iron abundance does drop rapidly to ~0.1 solar, by r~0.2r_{200}.



Metal abundances in the ICM

Where did the metals go?

Metal abundances in the ICM

Where did the metals go?

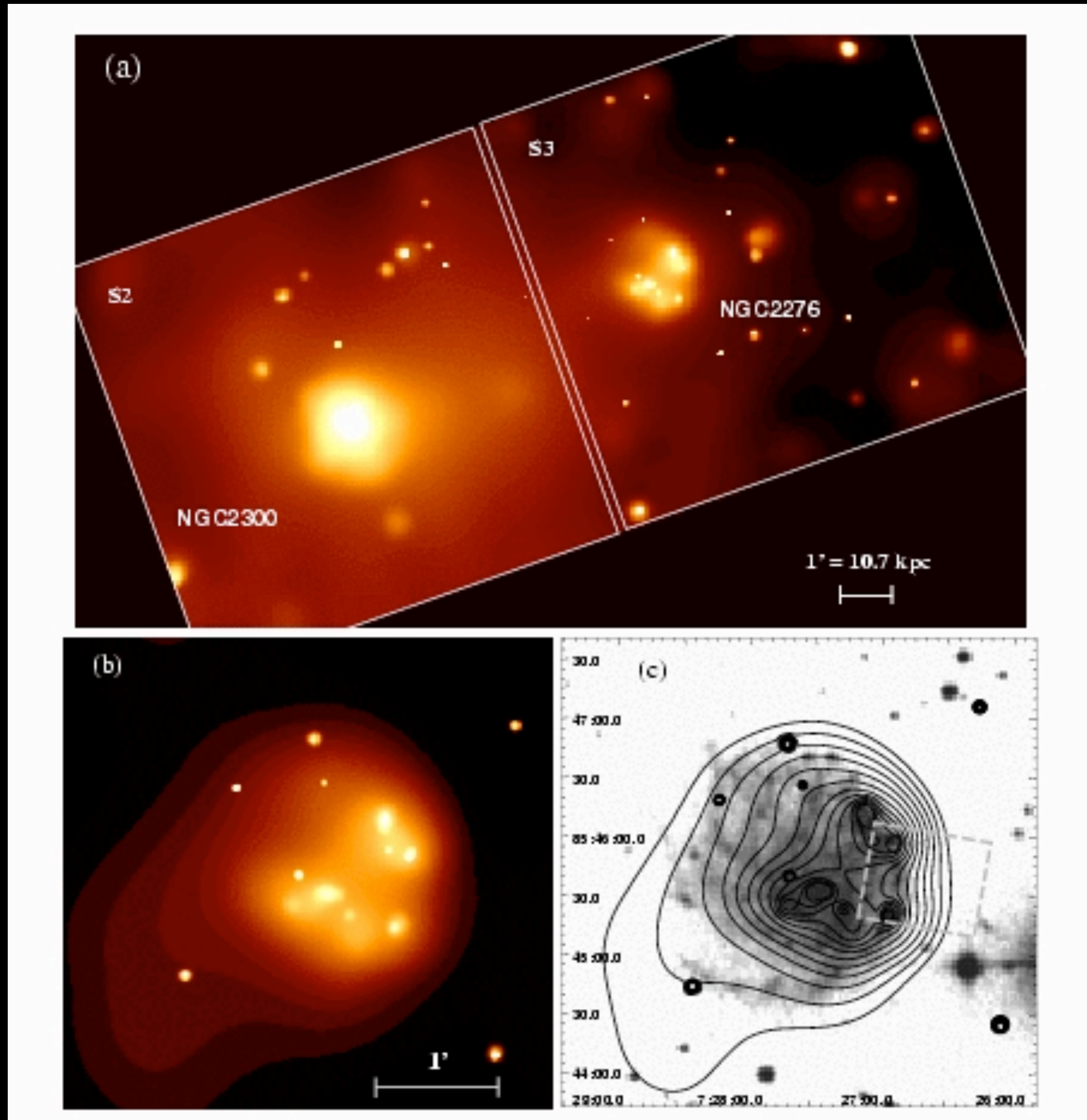
Another speculation:

- If entropy is raised in precursor filaments via injection of SNII-enriched galactic winds, then this higher entropy gas could expand out of filaments and be hard for a modest group to capture.

Gas stripping from group galaxies

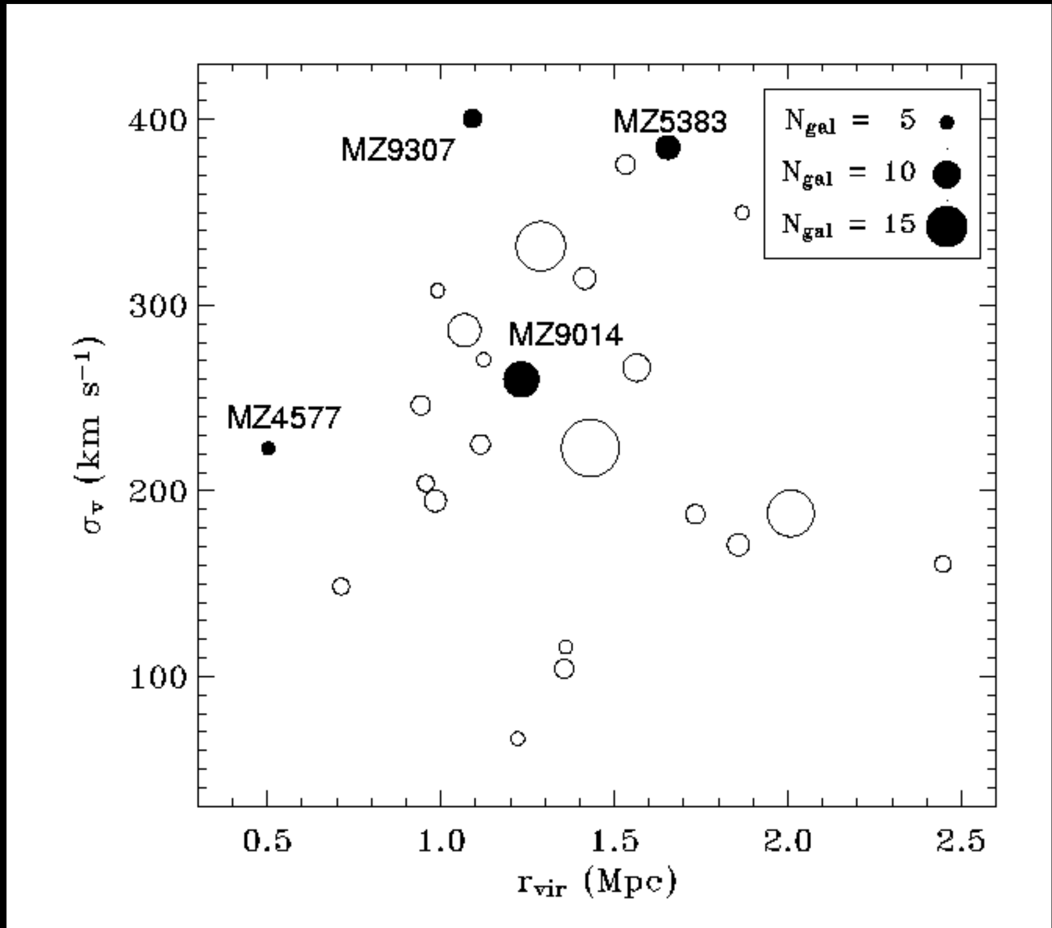
- NGC2276 is a starforming spiral with peculiar HI morphology located in the X-ray bright NGC2300 group.
- New Chandra data show a head-tail morphology, with a probable bow shock.
- It appears that gas is pumped up by star formation, and then removed by stripping, at a rate of ~5 $M_\odot$ /yr
- I.e. stripping <u>can</u> occur in groups after all.

Rasmussen et al 2006



Properties of FoF-selected groups - the *XI* project

- Birmingham-Carnegie project using XMM and IMACS to study optically-selected groups.
- Sample of 25 groups at z~0.06 extracted by Merchan & Zandivarez (2002) from a FoF analysis of the 2dFGRS.



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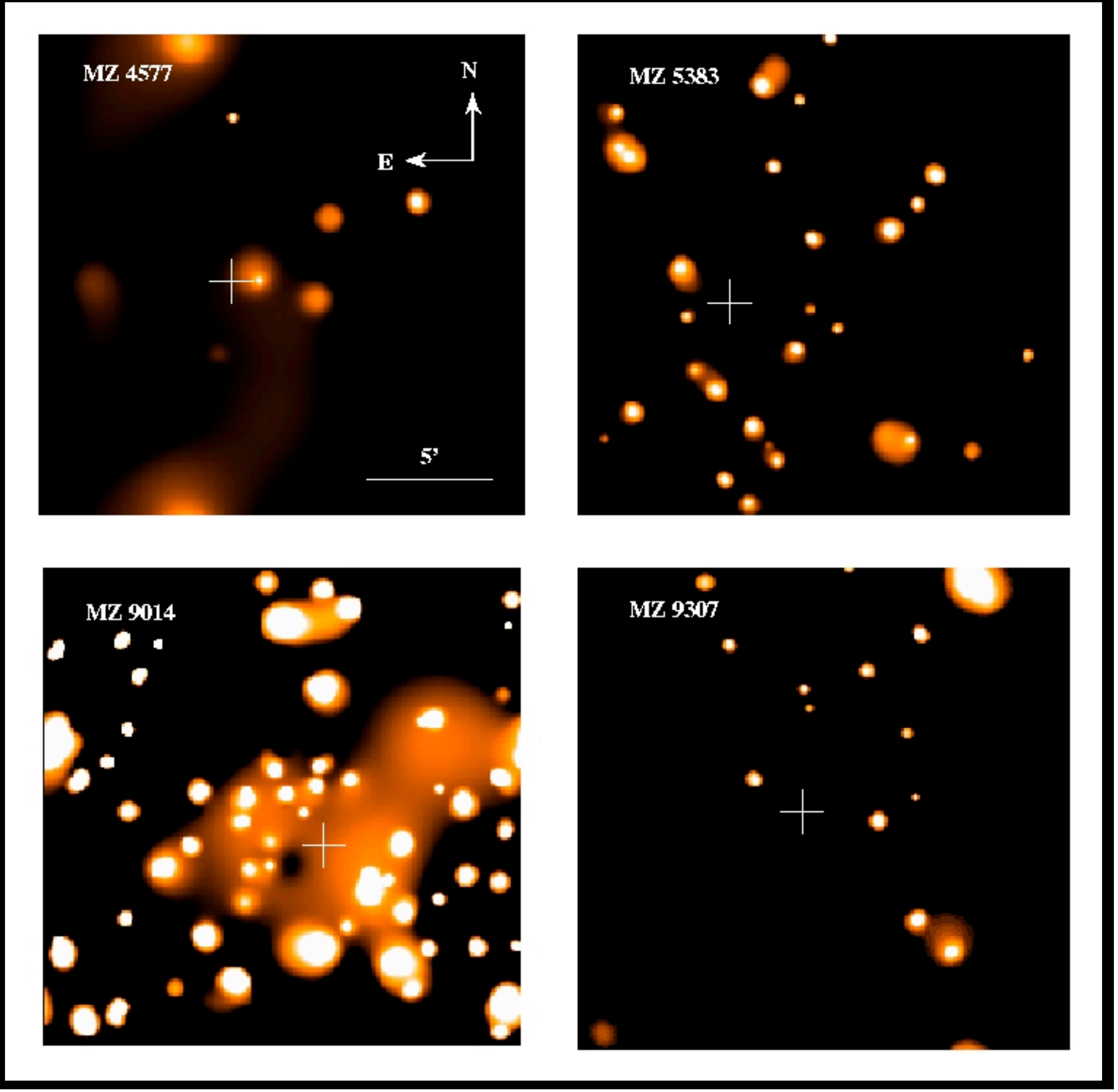
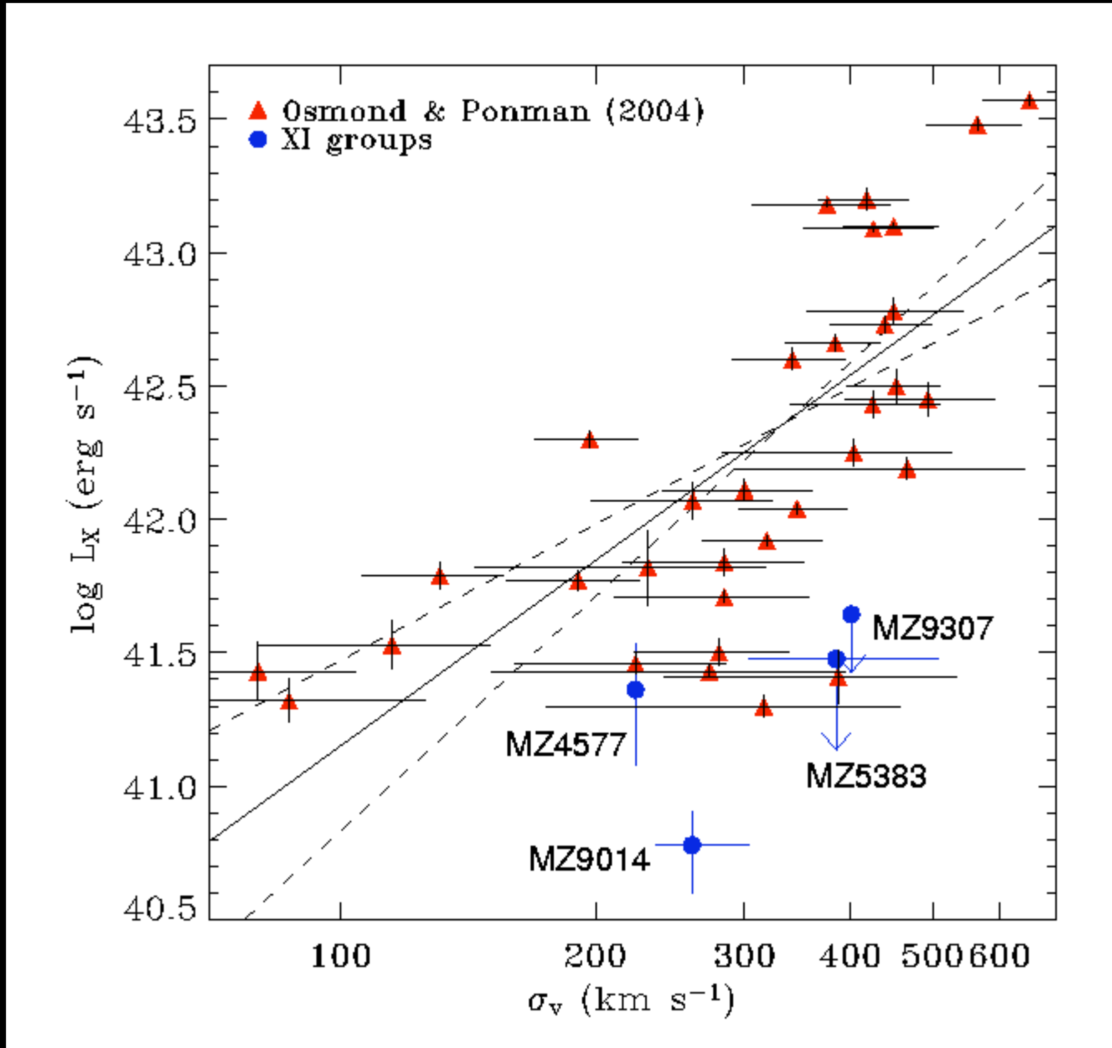
- Birmingham-Carnegie project using XMM and IMACS to study optically-selected groups.
- Sample of 25 groups at z~0.06 extracted by Merchan & Zandivarez (2002) from a FoF analysis of the 2dFGRS.
- XMM observations of the first 4 systems show weak/irregular or no hot IGM - very different from X-ray selected groups



Rasmussen et al 2006

Properties of FoF-selected groups - the *XI* project

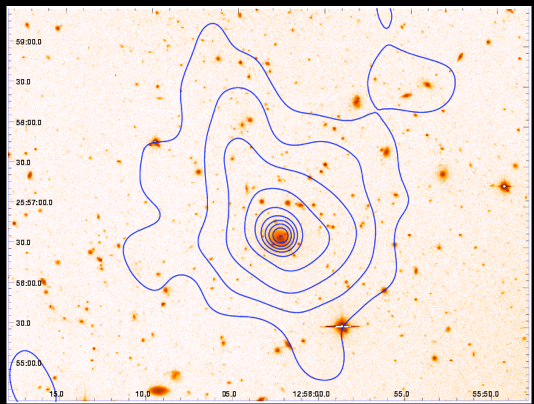
- Birmingham-Carnegie project using XMM and IMACS to study optically-selected groups.
- Sample of 25 groups at z~0.06 extracted by Merchan & Zandivarez (2002) from a FoF analysis of the 2dFGRS.
- XMM observations of the first 4 systems show weak/irregular or no hot IGM - very different from X-ray selected groups
- These groups all fall at the bottom of the L-sigma relation.



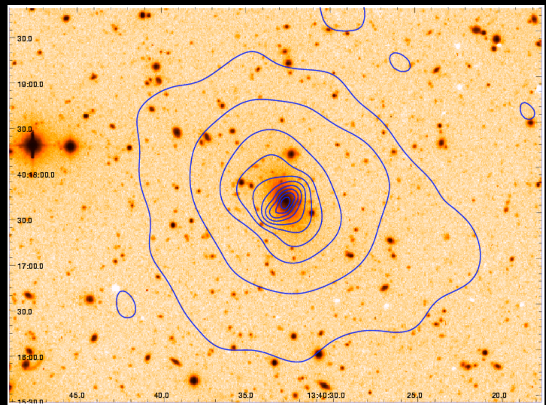
Rasmussen et al 2006

Fossil groups

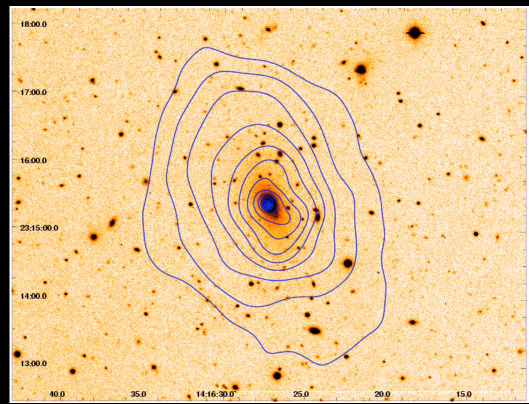
Chandra observations of the volume limited sample of Jones et al (2003)



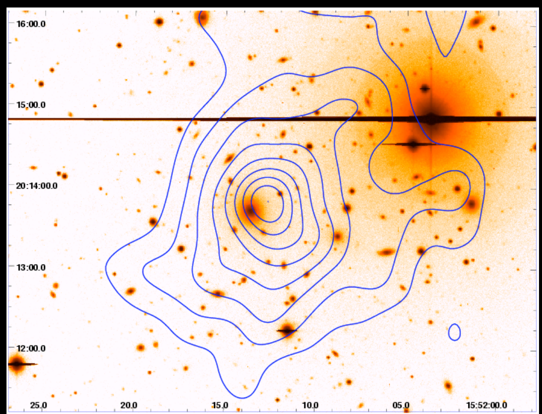
J1256.0+2556   z=0.232



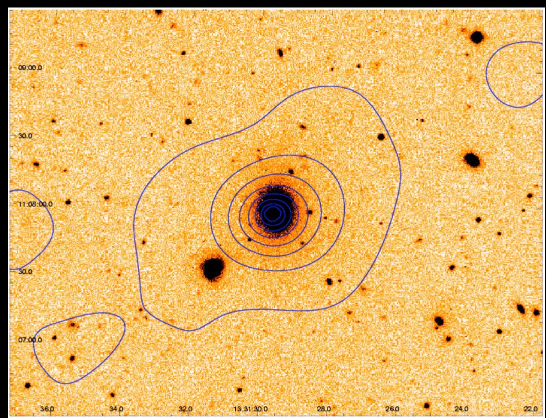
J1340.0+4023   z=0.171



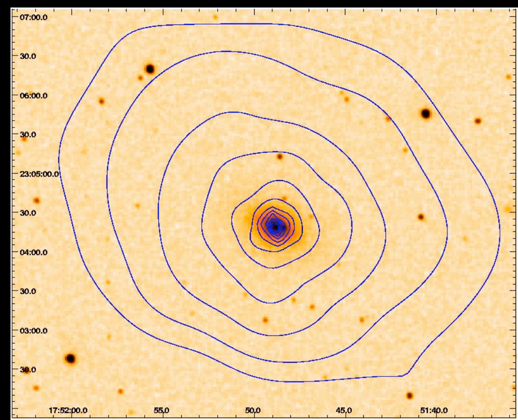
J1416.4+2315   z=0.137



J1552.2+2013 z=0.135



J1331.5+1108   z=0.081

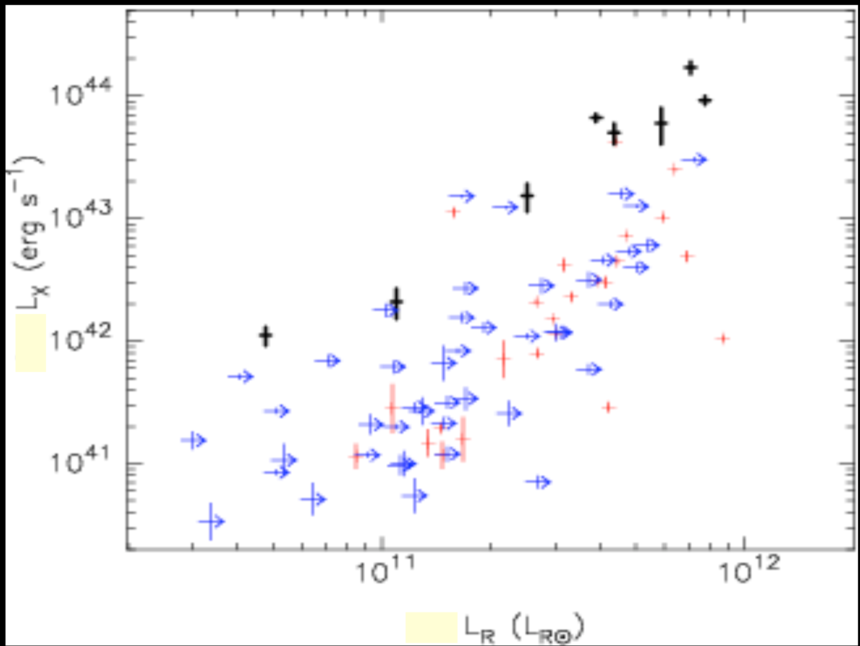


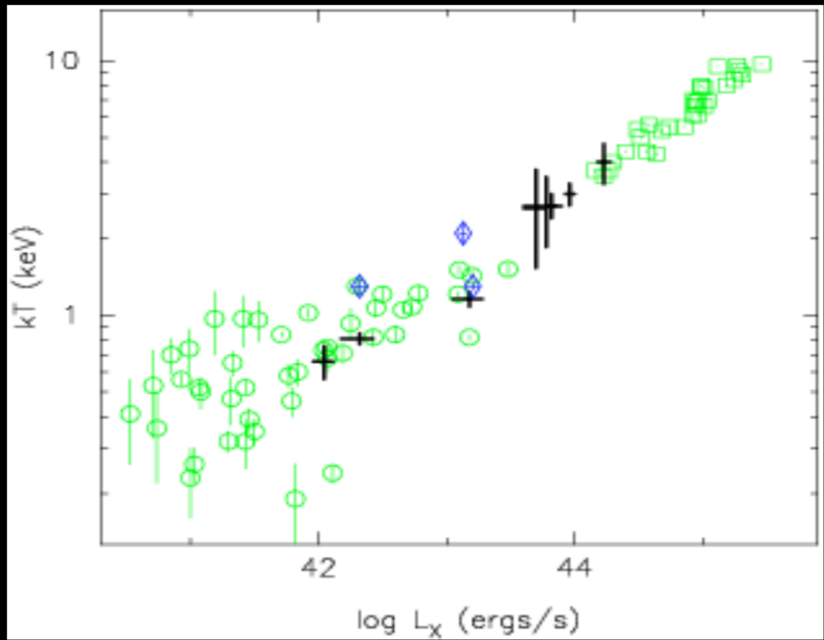
NGC 6482   z=0.0131

Fossil groups

Chandra observations of the volume limited sample of Jones et al (2003)

- Confirms the high L_X/L_R of fossils
- However, L-T relation is normal
- Conspiracy? T raised as well as L_X, due to high concentration?





Khosroshahi et al 2006

Conclusions

- Similarity breaking in the hot IGM in groups might be due largely to energy injection in precursor structures. Both entropy and metallicity behaviour may be telling us this.
- Gas can apparently be stripped from group galaxies, if it is roughed up first. Analagous to Chris Mihos' IC light generation.
- Optically-selected groups appear to have very different X-ray properties to most of the systems which X-ray astronomers have been studying. Could much of their gas be in the warm (WHIM) phase?
- Fossil groups are emerging as the best candidates for old undisturbed supergalactic structures, and warrant a lot more study.