Galaxy groups and cosmic feedback

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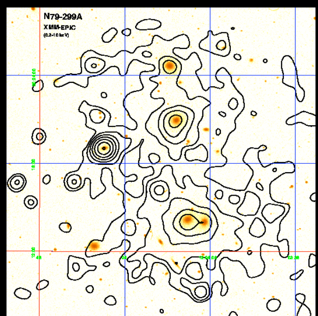
With thanks to: Alastair Sanderson, Ewan O'Sullivan, Jesper Rasmussen, Ian McCarthy, Abdul Alshino, Aurelia Pascut, Somak Raychaudhury

Preview

- Groups and feedback – introduction
- Evidence for feedback in groups
  - Scaling properties
  - Baryon fractions
  - Metals
  - AGN activity
  - Evolution
- Feedback simulations

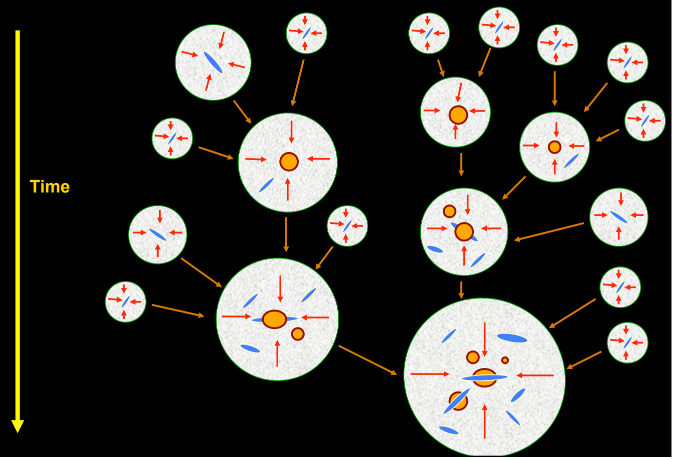
Galaxy groups - contents

- Galaxies
- Gas – mostly hot
- Dark matter - dominant

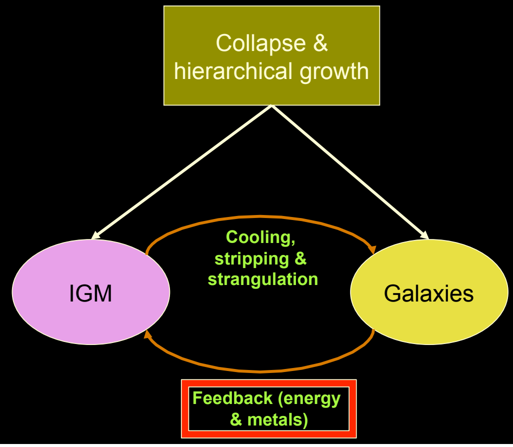


X-ray contours (XMM) on optical image

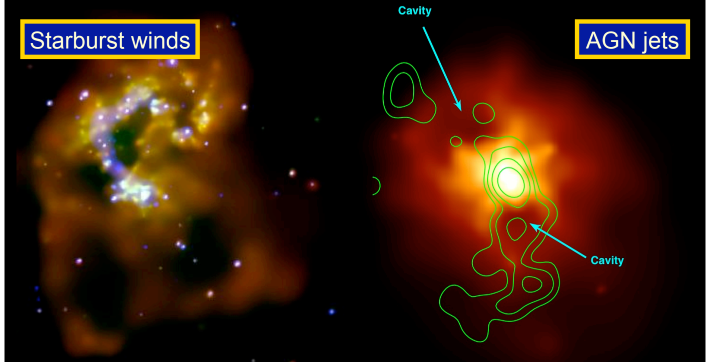
Hierarchical structure formation



Baryon physics



Cosmic feedback



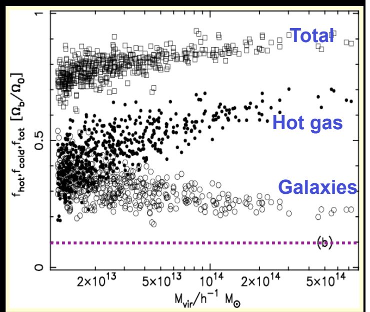
Deep Chandra observation of the Antennae - Fabbiano et al 2004

HCG62 group - Chandra image with 235 MHz GMRT contours - Raychaudhury et al 2009

The need for cosmic feedback

1. Overcooling

High resolution simulations with radiative cooling suffer from serious *overcooling*, resulting in galaxy mass fractions well above the ~10% observed, especially in groups.

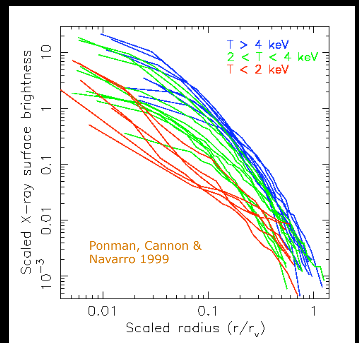


Muanwong et al 2002

The need for cosmic feedback

2. Similarity-breaking

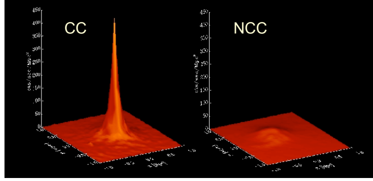
Overlay of scaled X-ray surface brightness profiles shows that emissivity (hence ρ_{gas}) is progressively suppressed and flattened in cool systems, relative to hot ones.

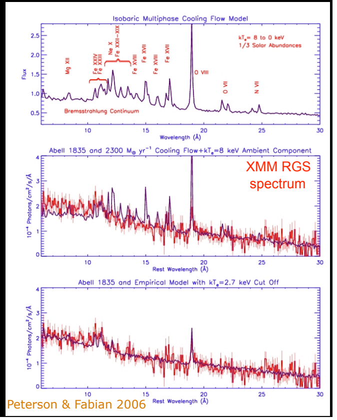


The need for cosmic feedback

3. Cooling in cluster cores

High resolution X-ray spectroscopy shows that gas in cluster cores does not appear to cool in quantity by more than a factor ~3, despite often having cooling time $<<t_H$



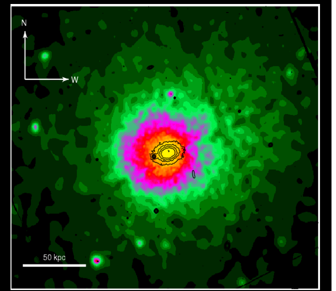


Peterson & Fabian 2006

Intergalactic gas in groups

Virialised systems have overdensities $\delta\rho/\rho>100$, allowing emission from the hot ($>10^6$ K) intergalactic medium (IGM) to be detected. This gas will bear the marks of cosmic feedback.

This is especially true in galaxy groups, which have shallower potential wells than richer clusters, and also give stronger X-ray emission lines from metals.



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

Preview

- Groups and feedback – introduction
- Evidence for feedback in groups
  - Scaling properties
  - Baryon fractions
  - Metals
  - AGN activity
  - Evolution
- Feedback simulations

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

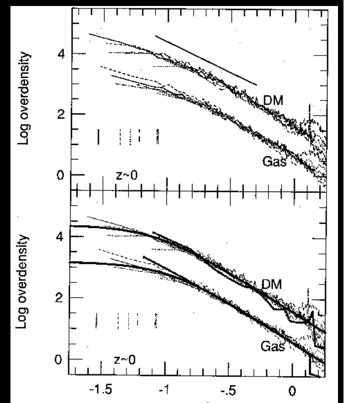
$T\sim M/R \sim R^2 \sim M^{2/3}$ from V.T.

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

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

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

$\rightarrow L_X\sim T^2$

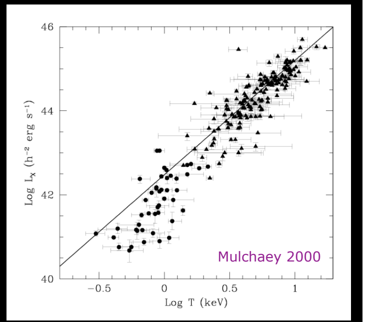


(Navarro et al 1995)

Scaling: 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, $L \propto T^{\sim 3}$ for clusters, with possible further steepening to $L \propto T^4$ in the group regime.



Further insight into this steeper trend in L_X can be obtained by looking at the gas entropy.

Scaling: IGM entropy

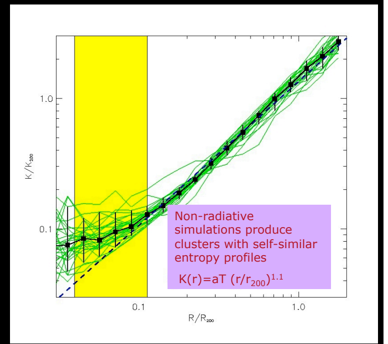
The *entropy* of the IGM is an especially useful property for two reasons:

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

Define "entropy" as

$K = T/n^{2/3}$

(so true thermodynamic entropy is $s = k \ln K + s_0$.)

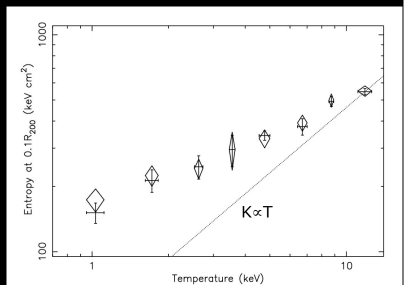


Voit, Kay & Bryan 2004

Scaling: IGM entropy

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 $K \propto T$.

→ Excess entropy in groups relative to clusters.



Systems grouped into 8 temperature bins

Scaling: IGM entropy

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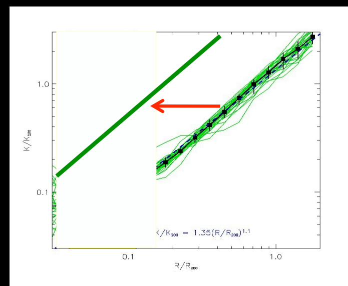
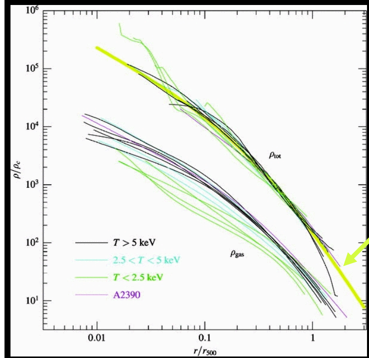


Rise in entropy can result from cooling!

But a lot of cooling (~50% of mass) is needed to give enough excess entropy in groups.

Baryon fractions - gas

Scaling properties
Baryon fractions
Metals
AGN activity
Evolution

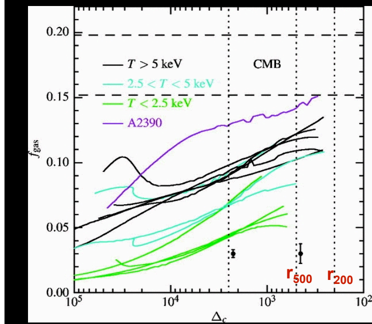


One of the most careful X-ray analyses of clusters is the Chandra study of 13 relaxed clusters by Vikhlinin et al (2006).

When scaled to r_{500}, the total mass profiles are roughly self-similar, and are reasonably represented by an NFW profile with c=3.

Gas profiles are flatter than total mass, and flatten further in cool clusters (green).

Baryon fractions - gas



Vikhlinin et al 2006

Hence gas fraction rises with radius, and starts to approach cosmic values ($f_b = \Omega_b / \Omega_m = 0.17 \pm 0.01$) as $r \rightarrow r_{200}$ in the richest clusters.

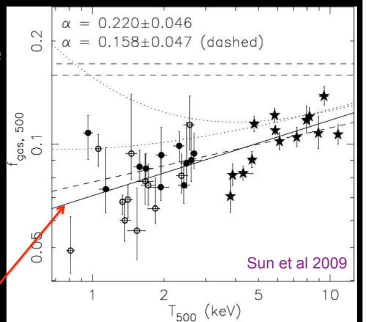
Baryon fractions - gas

The most substantial survey of the hot gas content of X-ray bright groups conducted to date is that of Sun et al (2009). Based on Chandra observations of a total of 43 nearby groups – 23 of which have useful data extending to r_{500}.

Combining these with 14 clusters from Vikhlinin, Sun derives scaling relations between f_{gas} and T & M_{500}, via BCES orthogonal regression, giving:

$$f_{gas} = 0.0708\ T^{0.22}$$

$$f_{gas} = 0.0616\ (M_{500}/10^{13}M_{\odot})^{0.135}$$

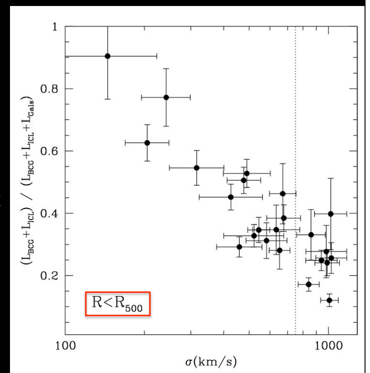


Sun et al 2009

Baryon fractions - stars

In contrast to the gas fraction, the stellar mass fraction is found to be higher in groups than in clusters. This is especially true when one allows for intracluster light – e.g. Krick & Bernstein (2007), Gonzalez et al (2005,2007).

Separation of ICL from the BCG light is somewhat arbitrary, but the BCG +ICL contribution is much more well-defined. Gonzalez et al (working in I band) found a strong trend for this to dominate the total system light in group-mass systems.



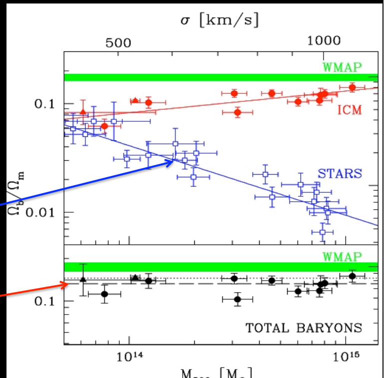
Gonzalez et al 2007

Baryon fractions

Including this significant ICL component, Gonzalez et al derive very high stellar mass fractions in poor groups,

$f_* = 0.041\,(M_{500}/10^{14}M_\odot)^{-0.64}$

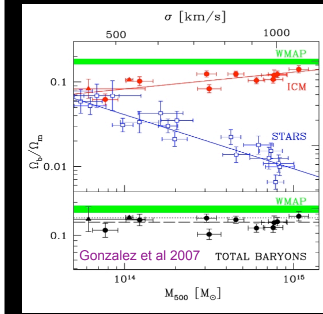
This strong trend is sufficient to counteract the drop in gas fraction in groups, giving constant baryon fraction down to halo mass ~$5\times10^{13}M_\odot$.

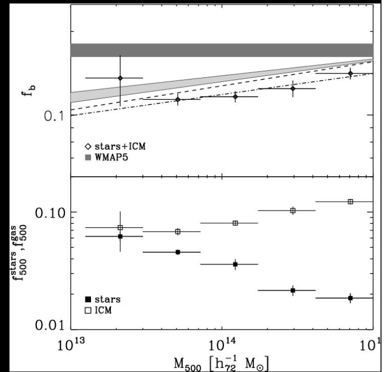


Gonzalez et al 2007

Baryon fractions

The steep trend, $f_* \sim M^{-0.64}$, found by Gonzalez et al is controversial.





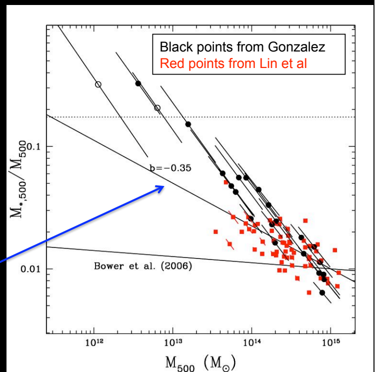
Giodini et al 2009

Baryon fractions

Balogh et al (2008) argue that this steep trend in f_* is incompatible with CDM hierarchical structure formation, since large systems form largely from the merger of small ones, and so cannot have much lower unless there has been a lot of additional recent star formation within groups, which is ruled out by galaxy colours.

They find that the steepest allowed relation is $f_* \sim M^{-0.35}$.

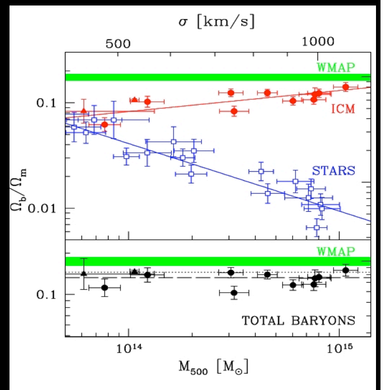
They also note the substantial mass errors (black bars) arising from the use of velocity dispersion to derive M_{500}.



Balogh et al 2008

Baryon fractions

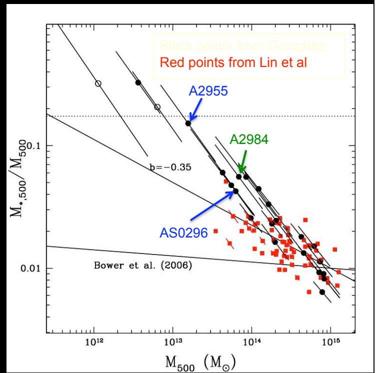
Both the Gonzalez and the Giodini studies assembled optical and X-ray data for <u>different</u> systems.



Baryon fractions

Both the Gonzalez and the Giodini studies assembled optical and X-ray data for different systems.

Study is currently underway (Sanderson, Sivanandam) to obtain good X-ray data for some of the low mass systems in the Gonzalez sample, to derive gas masses and X-ray estimates of M_{500}.

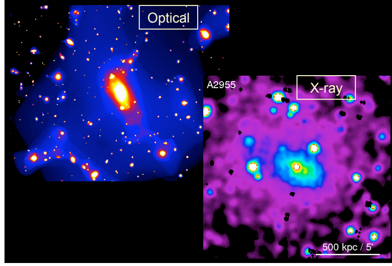


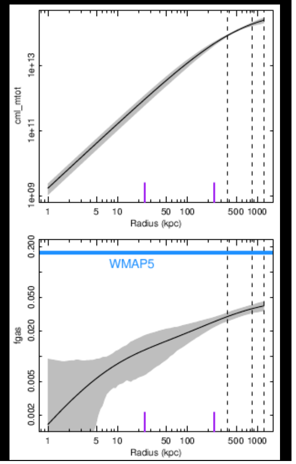
Balogh et al 2008

Baryon fractions

Example - Abell 2955

- Optical image showing ICL
- XMM X-ray image
- X-ray gas T,ρ analysis
- Inferred total mass and gas fraction





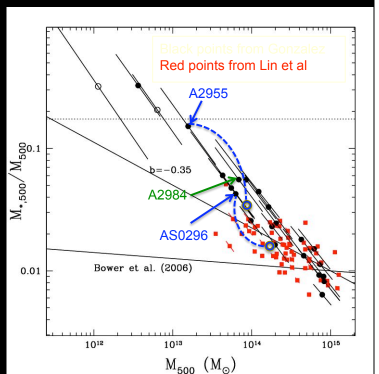
Baryon fractions

The results for both A2955 and AS0296, are that the X-ray inferred masses are substantially (3-6x) larger than those inferred from the system velocity dispersion.

This moves them to new positions as shown here (Sanderson et al, in prep.) – beyond their statistical errors.

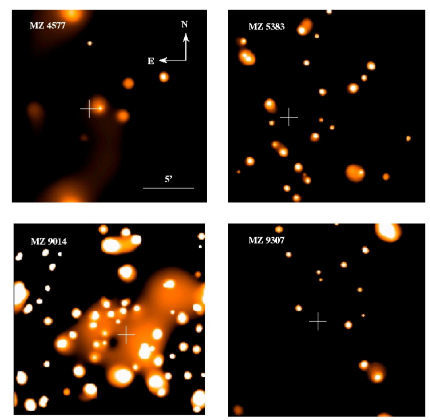
However, the XMM analysis of Sivanandram for A2984 essentially confirms its mass, and hence its position on the plot.

Nonetheless, the very high stellar fractions for poor groups now look less secure.



Baryon fractions - groups without hot gas?

- 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 9 of these systems show weak/irregular or no hot IGM in 8 of them - very different from X-ray selected groups.

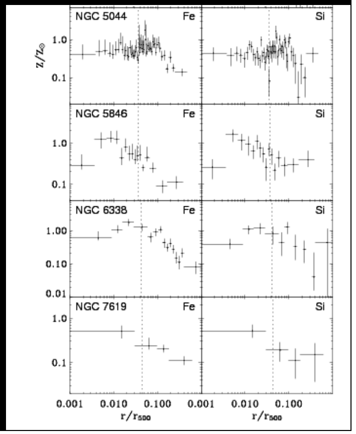


Rasmussen et al 2006

Scaling properties AGN activity
Baryon fractions Evolution
Metals

Metals in groups

Analysis of Chandra data for 15 galaxy groups – all but one with cool cores. APEC hot plasma model fits with Fe and Si abundances free, and 2T model when statistically preferred.

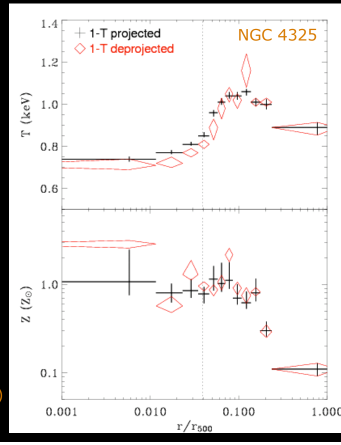


Rasmussen & Ponman (2007)

Metals in groups

Analysis of Chandra data for 15 galaxy groups – all but one with cool cores. APEC hot plasma model fits with Fe and Si abundances free, and 2T model when statistically preferred.

No deprojection. Tests indicate this is a small effect



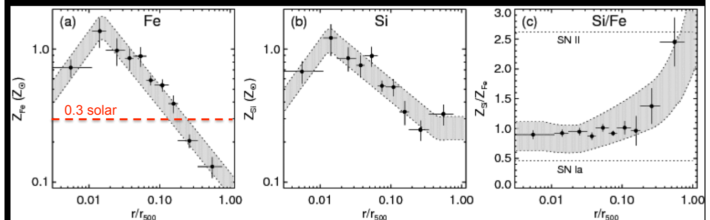
Rasmussen & Ponman (2007)

Metals in groups

Stacking the profiles for all 15 groups gives rather well-defined abundance profiles for Fe and Si (Grevesse & Sauval system).

The Fe abundance drops well below the typical minimum value of 0.3 solar typically seen in clusters.

Si/Fe rises steeply outside $0.2r_{500}$, and adopting WDD2 model from Iwamoto et al (1999) for SNIa, and Nomoto et al (2006) yields for core collapse SNe, we can decompose the metals into SNIa and SNII contributions.



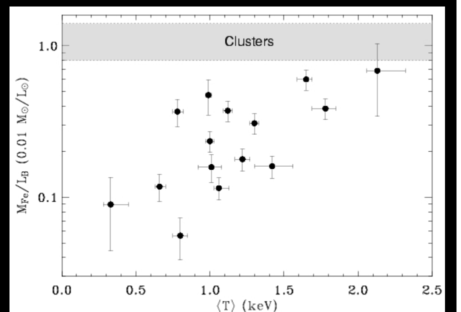
Rasmussen & Ponman (2009)

Metals in groups

Integrating the iron mass within r_{500}, we find the iron mass in groups, scaled to the total optical luminosity, is much lower than in clusters.

Metals have evidently been lost in groups.

This loss appears to apply to both SNII and SNIa products.



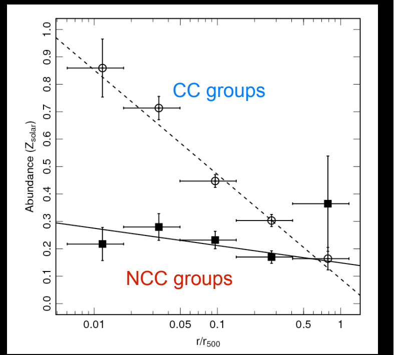
Rasmussen & Ponman (2009)

Metals in groups

The Rasmussen et al Chandra study contained almost entirely cool core (CC) groups.

From an XMM study of 28 nearby groups (2dXGS), we also have information on the properties of NCC groups, which turn out to have essentially flat abundance profiles.

This suggests that whatever eliminated the cool cores also caused substantial mixing of the IGM, eliminating the central abundance peak.

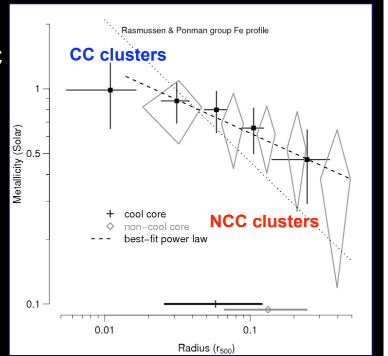


Johnson et al, in prep

Metals in groups

However, in galaxy clusters, the abundance profiles in CC and NCC systems are similar.

Does this mean that NCC groups and NCC clusters have different origins?
Or that mixing is less thorough, or less recent in clusters?

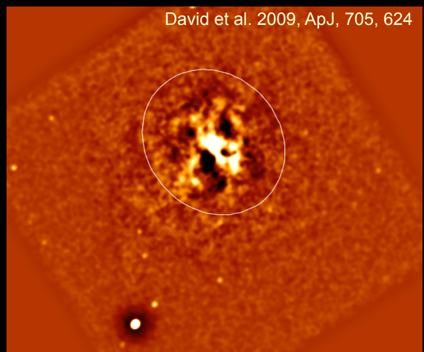


Sanderson et al 2008

Observed AGN activity: NGC5044

Scaling properties
Baryon fractions
Metals
AGN activity
Evolution

- One of the brightest nearby galaxy groups (L_X~10^{43} erg/s)
- Prior observations reveal some structure in X-ray + a radio point source
- X-ray image shows numerous cavities, filaments, fronts.
- Cavities are small but spread throughout the core, not just along main axis.
- At 1.4 GHz, only a central point source is detected.



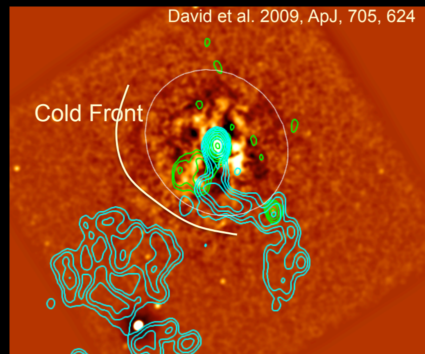
80ks 0.3-2 keV Chandra unsharp masked image, D_{25} ellipse overlaid

Observed AGN activity: NGC 5044

At 235 MHz:

1. Detached radio lobe to the SE.
2. Filament following X-ray channel
3. Correlation between X-ray surface brightness front, filament and detached lobe.

We are seeing structures formed in two separate outbursts, and their interaction with the environment.



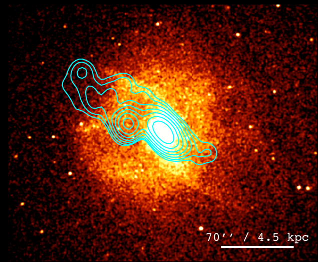
0.3-2 keV Chandra unsharp image, D_{25} ellipse overlaid
GMRT: 610 MHz contours 235 MHz contours

Observed AGN activity: other examples

- Dong et al. (2010) study: 26 of 51 nearby groups have definite or probable cavities.
- All 26 are CC systems.
- Only 4 NCC groups in sample, but none have cavities.

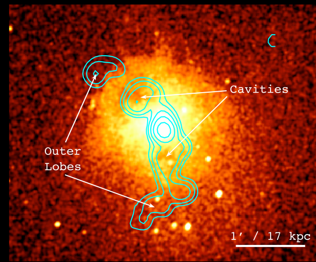
Observed AGN activity: other examples

NGC 4636 (Baldi et al. 2009)



235 MHz contours on 150 ks ACIS-I
Multiple cavities at similar radii on both sides of core?

HCG 62 (Gitti et al. 2010)

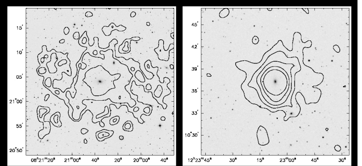


235 MHz contours on 165 ks ACIS-S
Clear inner cavity pair, but more complex at radius of outer lobes?

Scaling properties | AGN activity | Baryon fractions | Evolution | Metals

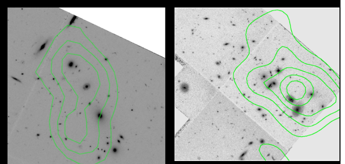
Evolution of group properties

Low redshift groups almost always show X-ray emission centred on an early-type brightest group galaxy (BGG).



Mulchaey et al 2003

However, the situation is different for some intermediate redshift groups.



No dominant BCG | Spiral BGG

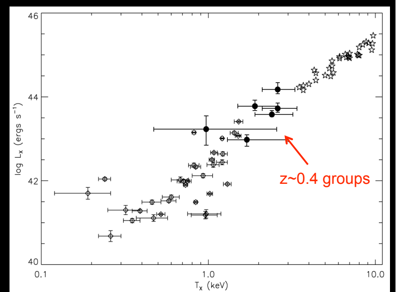
Jeltema et al 2006

Evolution of group properties

Also, optical studies show a significant increase with redshift in the fraction of group galaxies with active star formation

But......

The limited data available shows no evolution in the L_X-T relation of groups.

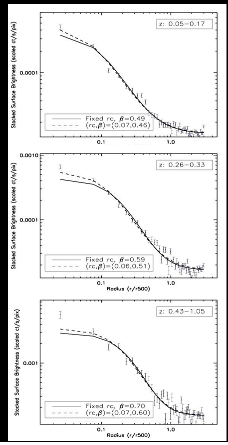


Jeltema et al 2006

Evolution of group properties

However, a study of 27 X-ray selected groups and poor clusters from the XMM-LSS survey, shows evidence for an increase in the strength of cool cores with redshift.

This contrasts with the opposite behaviour reported in richer clusters (e.g. Santos et al 2008).

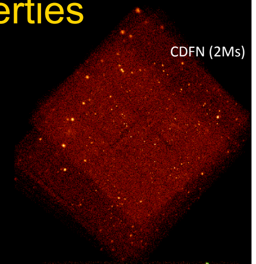


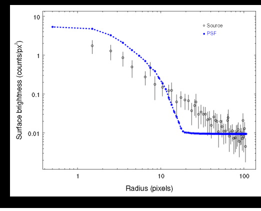
Alshino et al 2006

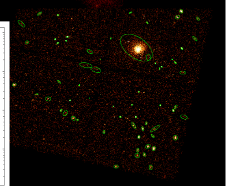
Evolution of group properties

Chandra is really better suited to detailed study of the structure of high z groups, so we have started the Chandra Deep Group Survey (CDGS).

We aim to find and study 50-100 groups at z~0.3-0.6 in the deepest Chandra fields.







Some conclusions

Evidence for the action of extra "baryon physics" in groups:

- Steepened L_X-T relation
- Large excess entropy in the IGM
- Higher stellar fraction than clusters
- Possibly lower overall baryon fraction
- Relative lack of metals (SNIa and SNII)
- Different abundance profiles in CC and NCC groups
- Common activity from a central AGN in CC groups
- Evolution in CC properties different from clusters?

How to interpret these results?

→ Simulations can help

Preview

- Groups and feedback – introduction
- Evidence for feedback in groups
  - Scaling properties
  - Baryon fractions
  - Metals
  - AGN activity
  - Evolution
- Feedback simulations

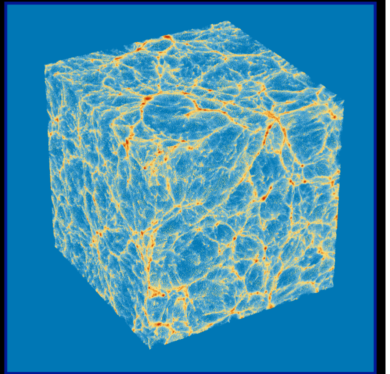
Group simulations - OWLS

Schaye et al. (2010)

OWLS is a suite of >40 cosmological (100 h^{-1} Mpc) simulations specially designed to explore different feedback models.

Many runs with same initial conditions but different baryon physics – cooling, SF, chemistry, SNe, AGN.

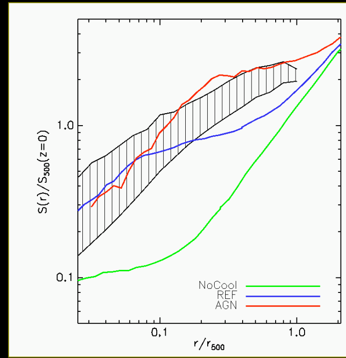
Compare results with group properties (McCarthy et al 2010a, 2010b) .



Group simulations - OWLS

• REF model includes cooling and SN-powered winds. AGN model also has AGN feedback (Booth & Schaye 2009).

• Both models show excess entropy with respect to the purely gravitational self-similar model (green).



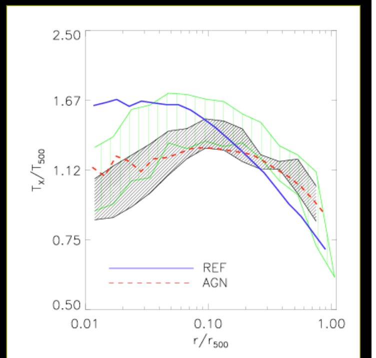
Data (hatched) from M. Sun et al. (2009)

Group simulations - OWLS

• REF model includes cooling and SN-powered winds. AGN model also has AGN feedback (Booth & Schaye 2009).

• Both models show excess entropy with respect to the purely gravitational self-similar model (green).

• The REF model gives too high a gas temperature in the core. This is due to the central potential being too deep, as a result of too much central baryon deposition.

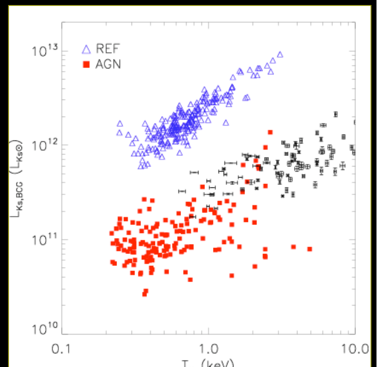


Data (hatched) from M. Sun et al. (2009) and Rasmussen & Ponman (2009)

Group simulations - OWLS

• This excessive buildup of cool baryons in the centre of the halo for the REF model can be clearly seen by looking at the K band luminosity of the BGG.

• The AGN feedback model avoids this, and matches the observed luminosities quite well.



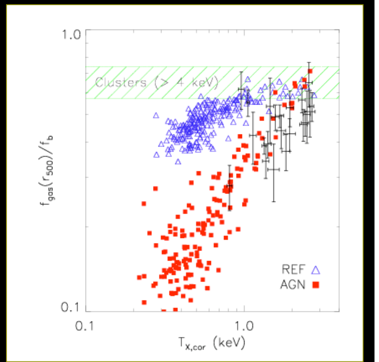
Data from Rasmussen & Ponman (2009) and Horner (2001)

Group simulations - OWLS

In the AGN model, energy input from supermassive black holes blows gas out of haloes at z~2.

This yields gas mass fractions in good agreement with observations.

The REF model gives gas fractions higher than observed at T<2 keV.



Data (black) from Sun et al (2009)

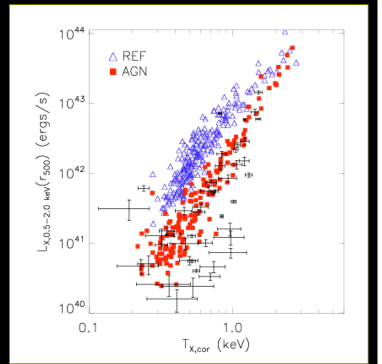
Group simulations - OWLS

In the AGN model, energy input from supermassive black holes blows gas out of haloes at z~2.

This yields gas mass fractions in good agreement with observations.

The REF model gives gas fractions higher than observed at T<2 keV.

As a result, the AGN model provides a better match to the observed L_X-T relation.

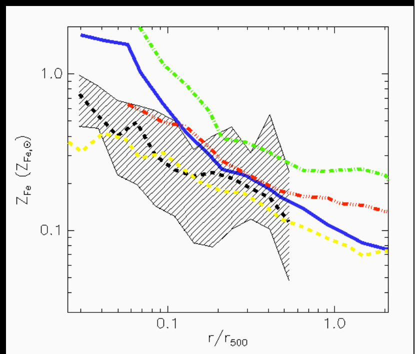


Data (black) from Psnond & Ponman (2004) and Sun et al (2009)

Galaxy groups in OWLS

Comparison between some model Fe profiles and those from the Rasmussen & Ponman (2009) study.

The AGN feedback model (red) does not do badly.

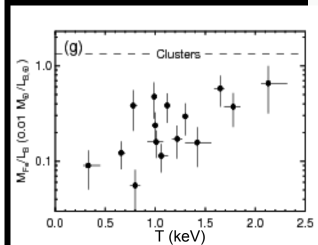


Data (hatched) from Rasmussen & Ponman (2009)

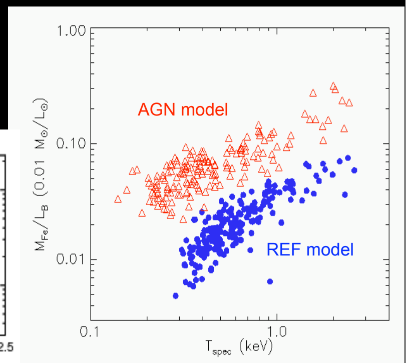
Galaxy groups in OWLS

IMLR is far too low for the default wind model (due to the its excessive star formation).

It is also low for the AGN feedback model, but this may be within yield uncertainties.

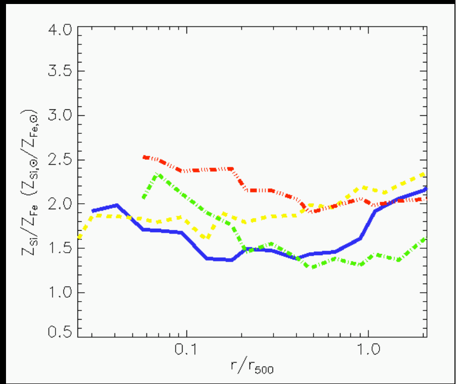


Rasmussen & Ponman (2009)



Galaxy groups in OWLS

However, at present none of the models produces solar abundance ratios in group cores, nor the rise in Si/Fe seen in the RP study at $r>0.2r_{500}$.



Conclusions from simulations

- Cooling plus supernova feedback can generate the excess entropy seen in groups
- However, AGN feedback appears to be required to match observed gas and stellar? fractions
- AGN also match the observed L_X-T relation and prevent excessive growth in the BGG

Still to be investigated:

- Adundance ratios (SNIa and SNII input)
- Properties of CC and NCC groups
- Evolution in group properties