Structure, scaling and statistical properties of X-ray galaxy clusters

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Introduction and motivation

Cluster characteristics

5% stars in galaxies

80-85% dark matter*

10-15% gas in the intracluster medium (ICM)

$$M \sim 10^{13} - 10^{15}\, M_\odot$$

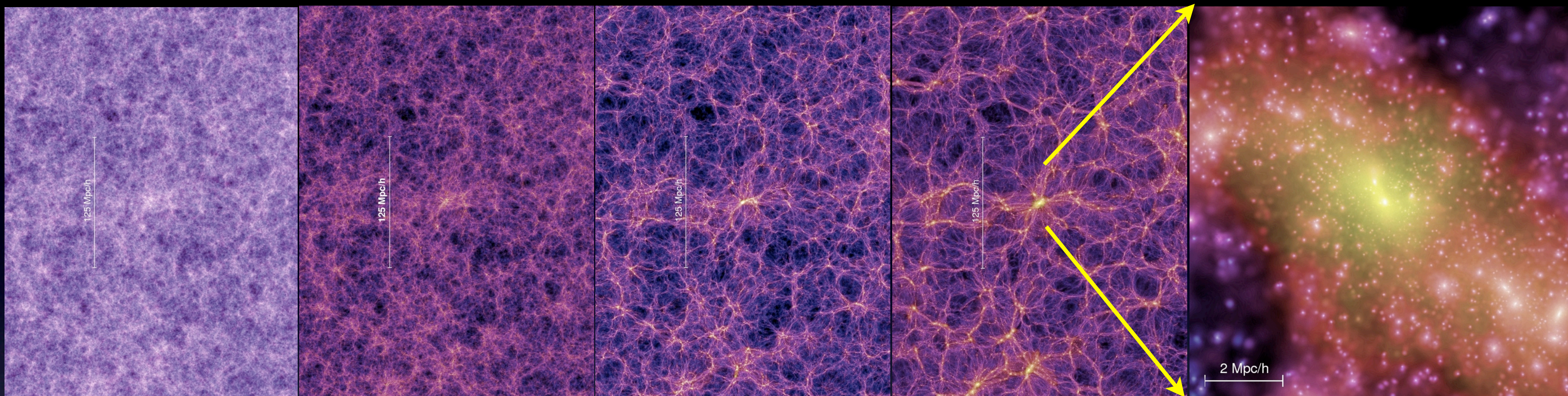
$$\begin{aligned} T &\sim 10^6 - 10^8 \mathrm{K}\ (1 - 15\ \mathrm{keV}) \\ n_e &\sim 10^{-4} - 10^{-2}\ \mathrm{cm}^{-3} \\ Z &\sim 0.3 Z_\odot \end{aligned}$$

*Zwicky (1933)

Coma superposition X-ray/optical

Formation

Springel et al, 2005



z=8.5 z=5.7 z=1.4 z=0.0 Cluster at z=0

Gravitational collapse of dark matter from primordial density fluctuations

Gas follows dark matter; shock heating ensues

Hierarchical growth - an evolving population

- Test of structure formation theory and ultimately, cosmology

Motivation

Gravitational physics

- Test predictions of dark matter collapse (structure, scaling)
- Effect of gravitational structure growth on ICM (compression and shock heating in dark matter potential)

Non-gravitational physics

- Radiative cooling of the gas
- Feedback from galaxies - supernovae, AGN
- (Enrichment)

Statistical properties

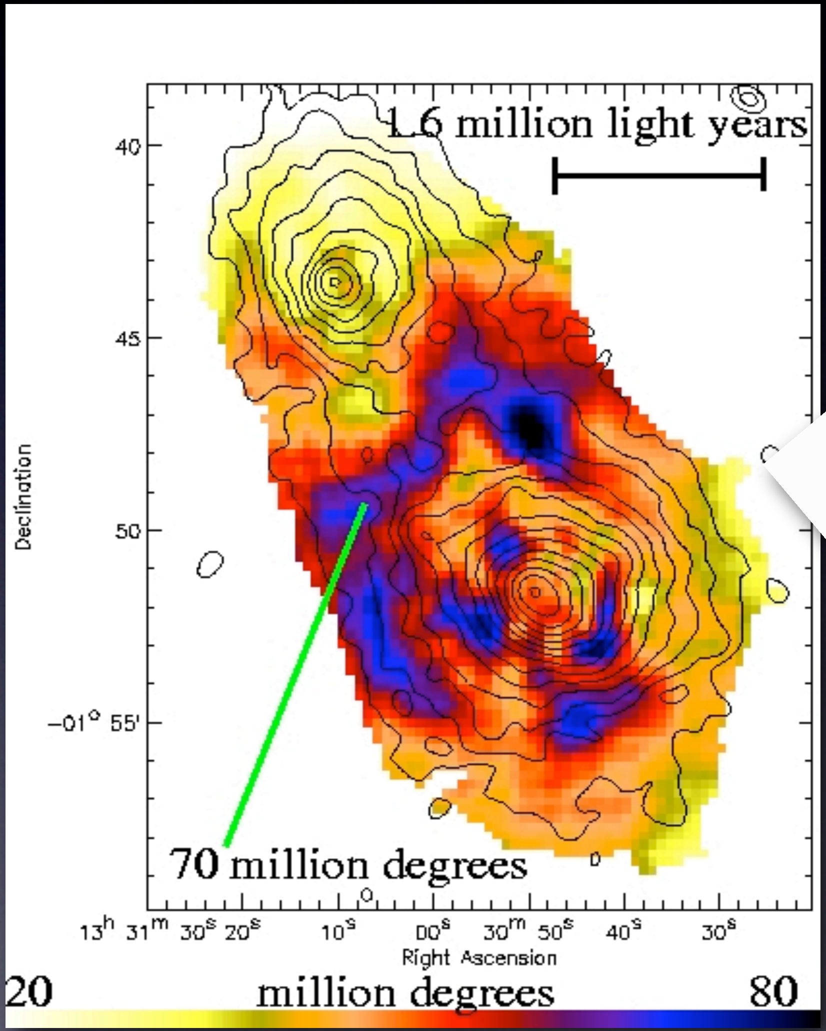
- Connection to growth of structure & cosmic web
- Cosmological applications

Formation, gravitational heating of ICM

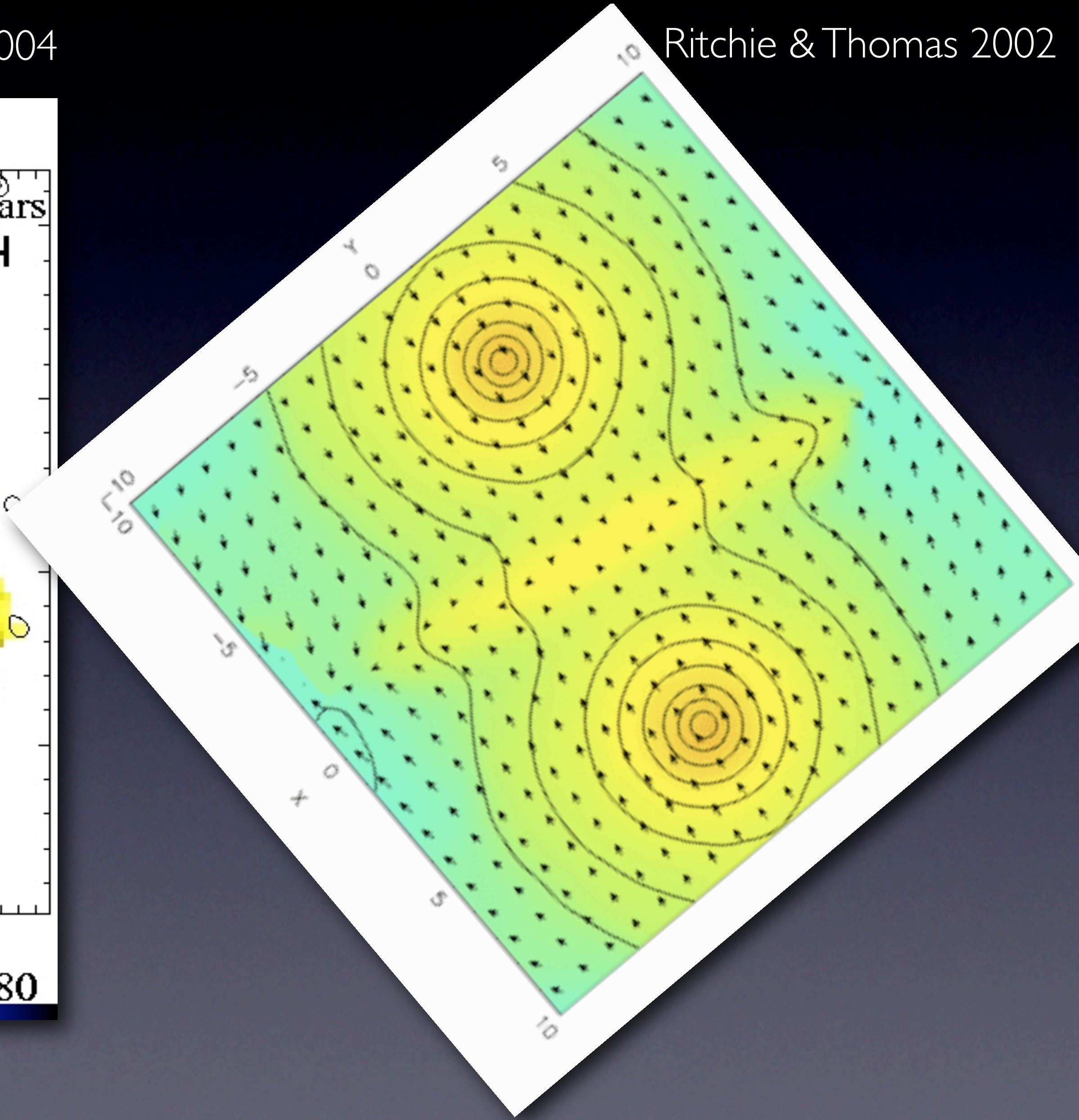
Formation

Hierarchical collapse

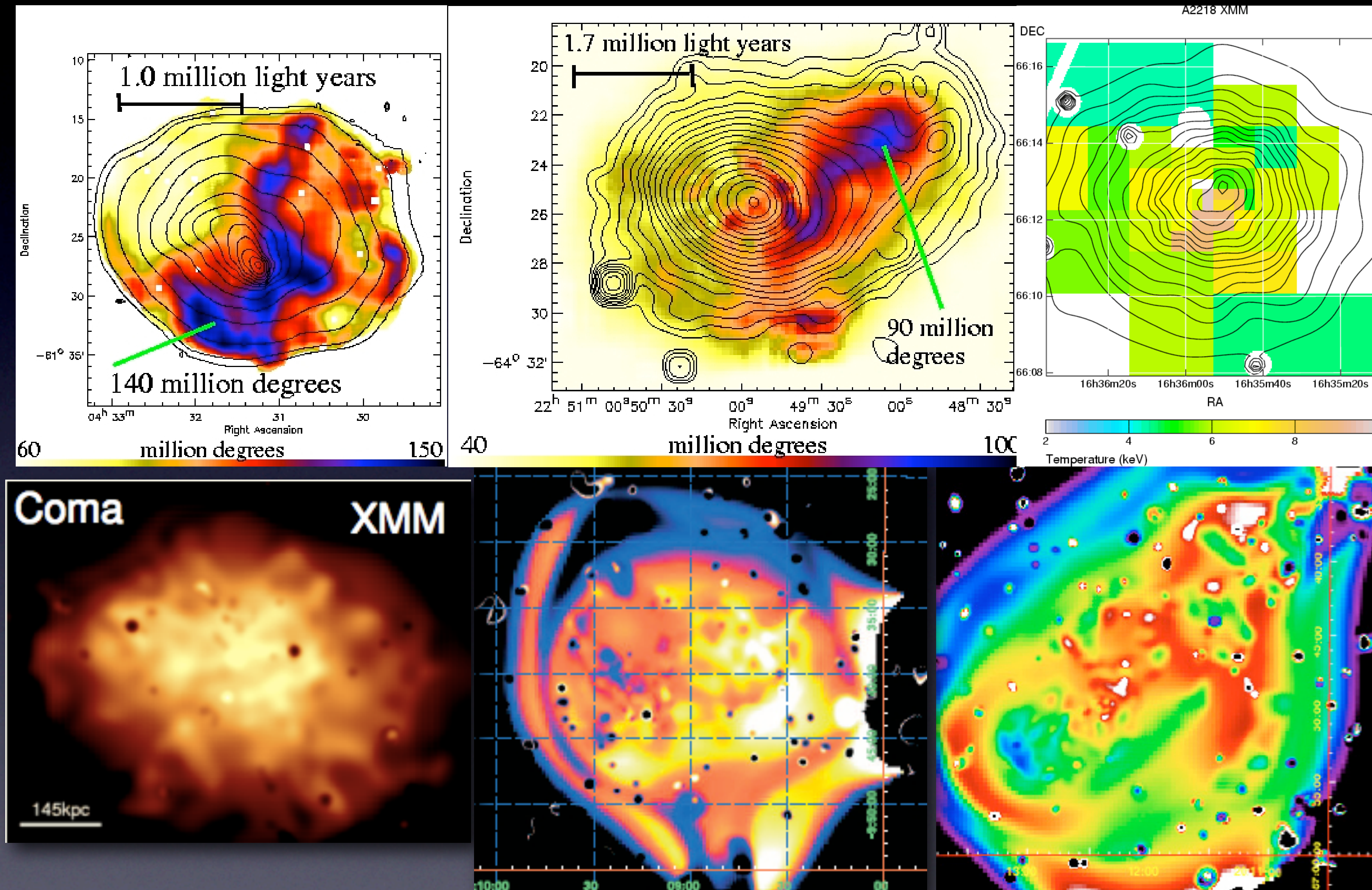
Belsole et al 2004



Ritchie & Thomas 2002

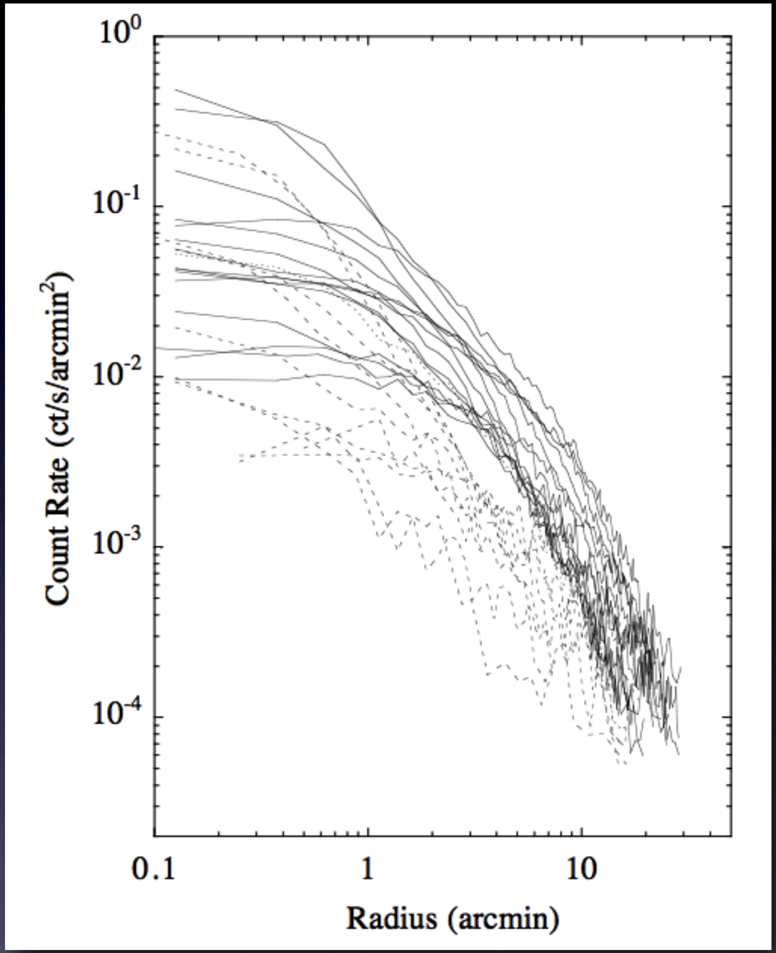


Merging cluster gallery

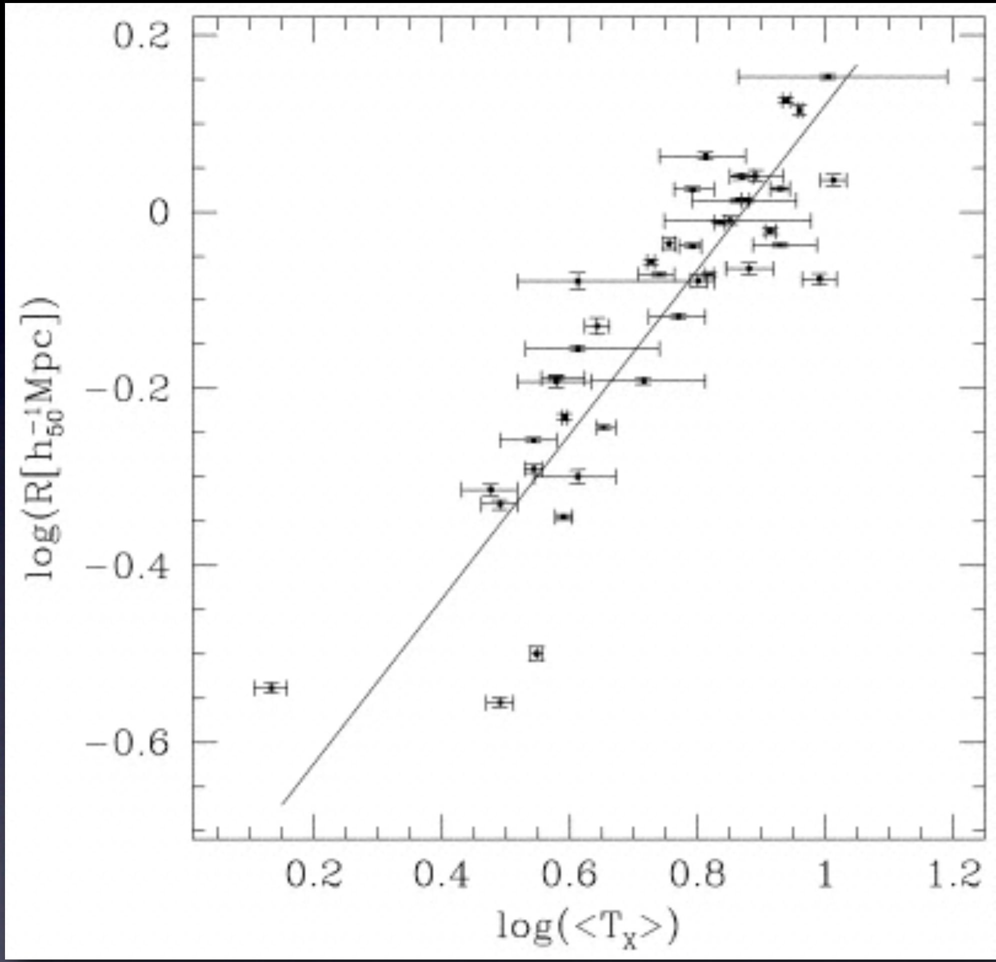


Sauvageot et al, 2005; Belsole et al, 2005; Pratt et al, 2005;
Schuecker et al. 2004; Briel et al, 2004; Henry et al, 2005

The ICM structure in general is quite regular



Surface brightness profiles;
Neumann & Arnaud 1999



Size-temperature relation;
Mohr & Evrard 1997

Regularity is expected

If

clusters form by gravitational collapse of dark matter

and

gas follows dark matter

then

clusters should be a self-similar and scale-free population

- scaling laws link global properties to mass (virial theorem)
- similarity in internal structure (universal DM density profile)

  $\Rightarrow$ small systems are scaled-down versions of larger systems

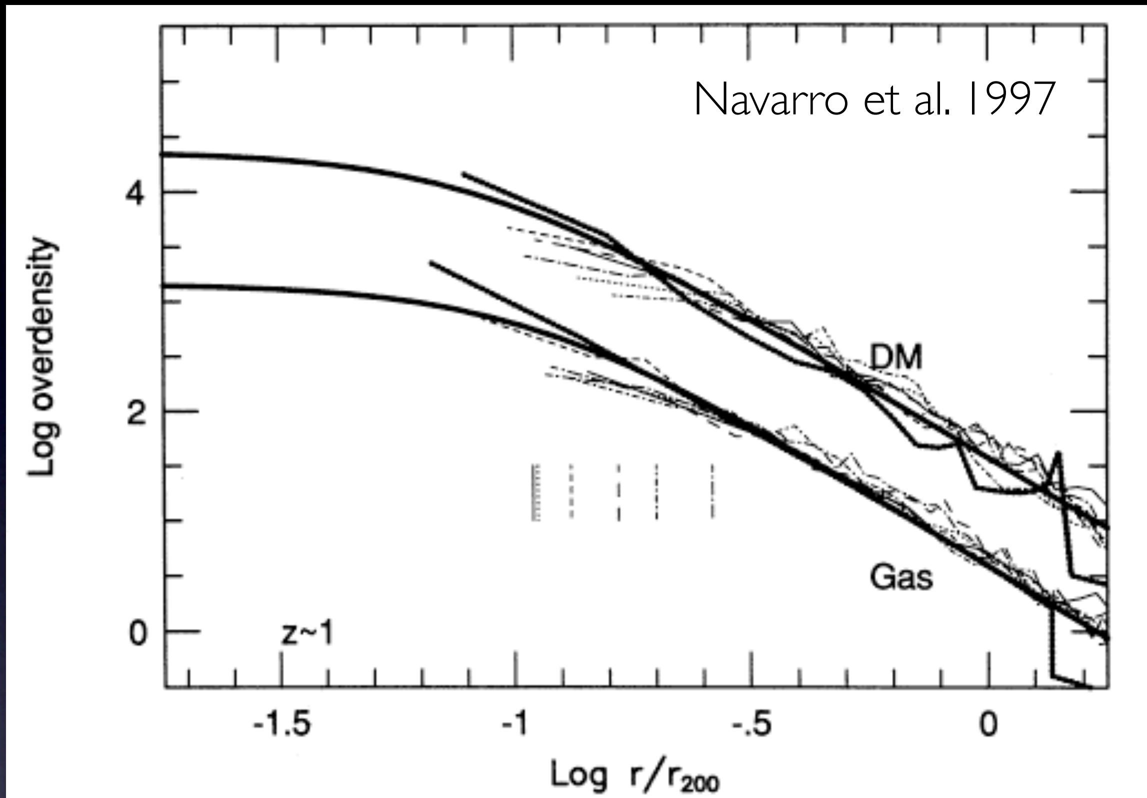
Scaling clusters

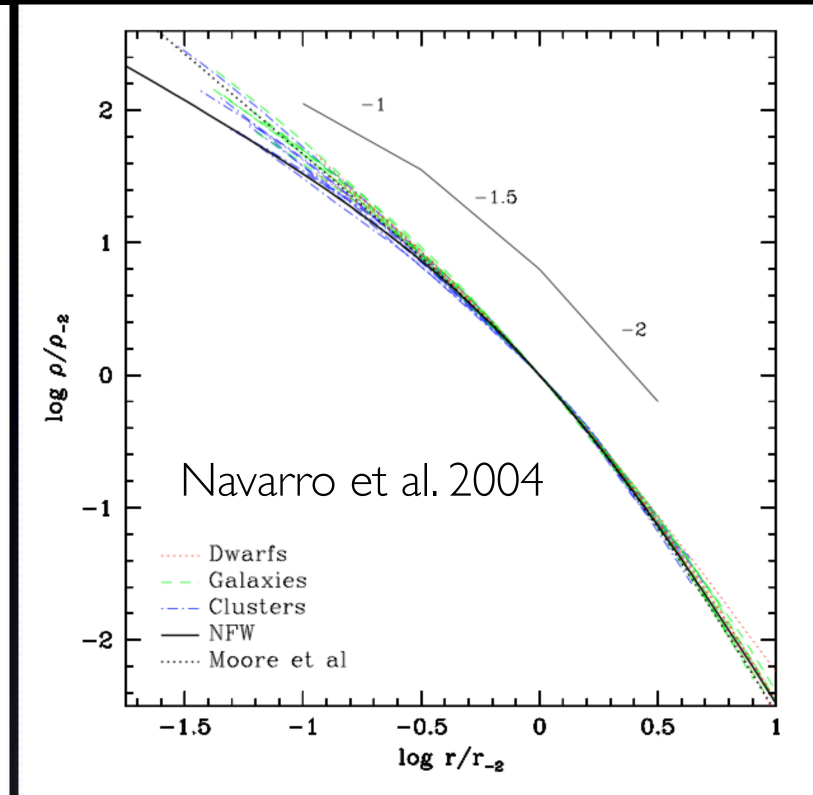
Assume a cluster represents a fixed density contrast wrt ρ_c

$$\frac{M_\delta}{R_\delta^3} = \frac{4\pi}{3}\delta\rho_c(z)$$

$$\delta = 2500,\ 500,\ 200\ldots$$

Structural similarity





Universal density profile of CDM haloes: $\rho_r = \dfrac{\rho_c(z)\delta_c}{(r/r_s)(1+r/r_s)^2}$

$$\left[\ \delta_c = \frac{200}{3}\frac{c^3}{[\ln(1+c) - c/(1+c)]} \quad ; \quad r_\delta = c_\delta r_s\ \right]$$

Scaling laws

If

Virial theorem holds $$\frac{GM_\delta}{R_\delta} \propto kT$$

and

Constant gas mass *fraction* $$f_{\rm gas} = M_{{\rm gas},\delta}/M_\delta = {\rm const.}$$

then

X-ray scaling laws for global properties:

$$T \propto M/R \propto R^2 \propto M^{2/3}$$

$$M \propto T^{3/2} \quad ; \quad R \propto T^{1/2}$$

$$L \propto T^2 \quad ; \quad L \propto M^{4/3}$$ (assuming Bremsstrahlung)

Matter distribution in regular clusters

X-ray cluster mass determination

Assuming hydrostatic equilibrium, spherical symmetry

$$M(r) = -\frac{kTr}{G\mu m_p}\left[\frac{d\ln n_e}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

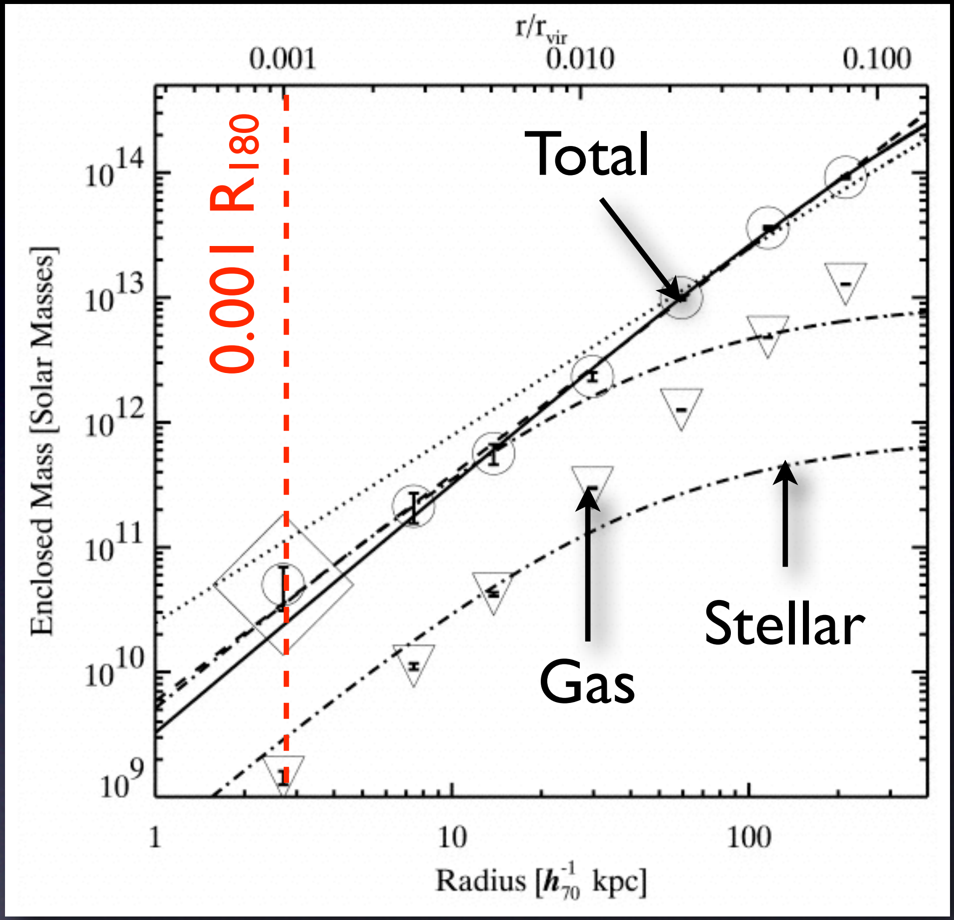
Fit with integrated NFW profile

$$M(r) = 4\pi\rho_c(z)\delta_c r_s^3 m(r/r_s)$$

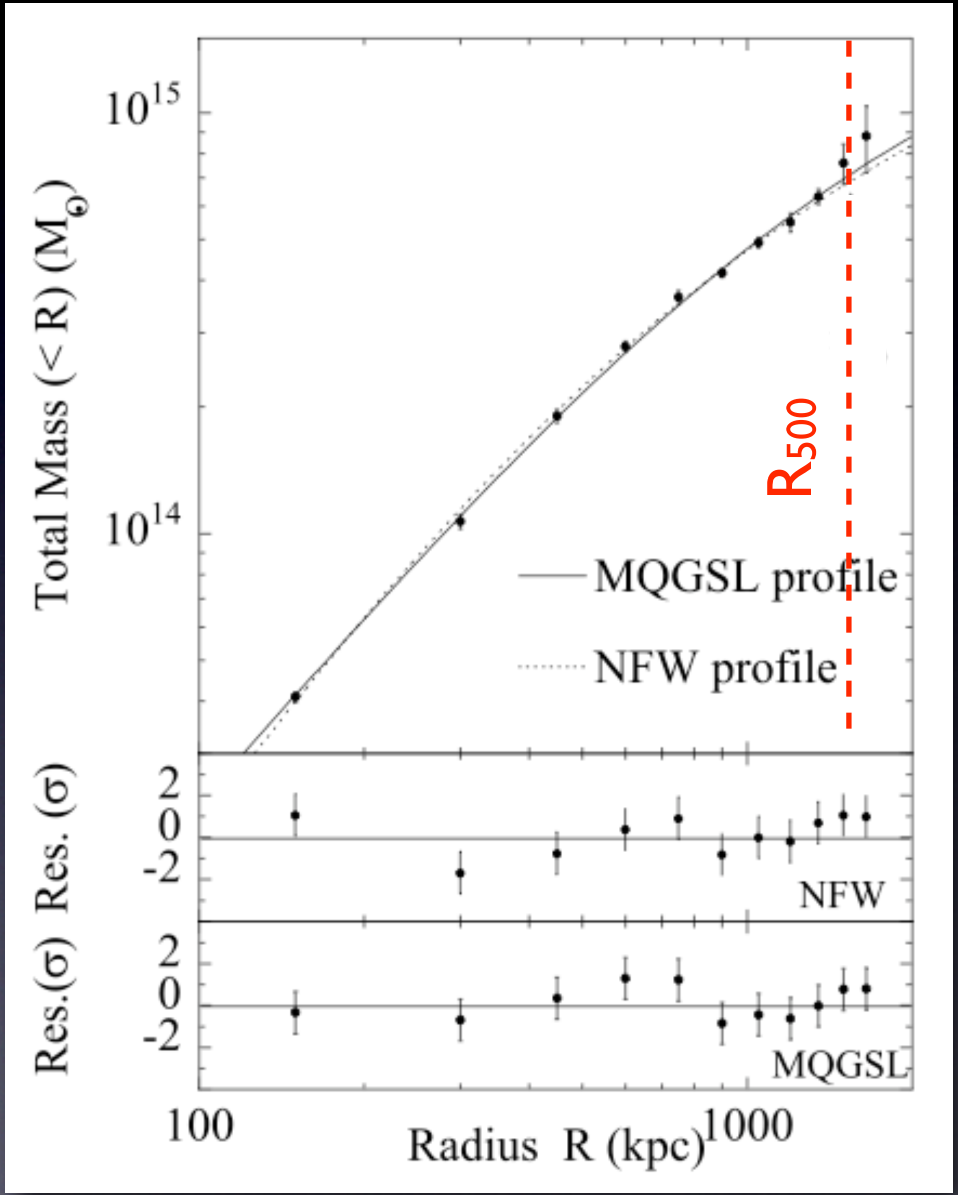
$$m(x) = \ln(1+x) - x/(1+x)$$

e.g., Suto et al. 1998

Mass profile modelling



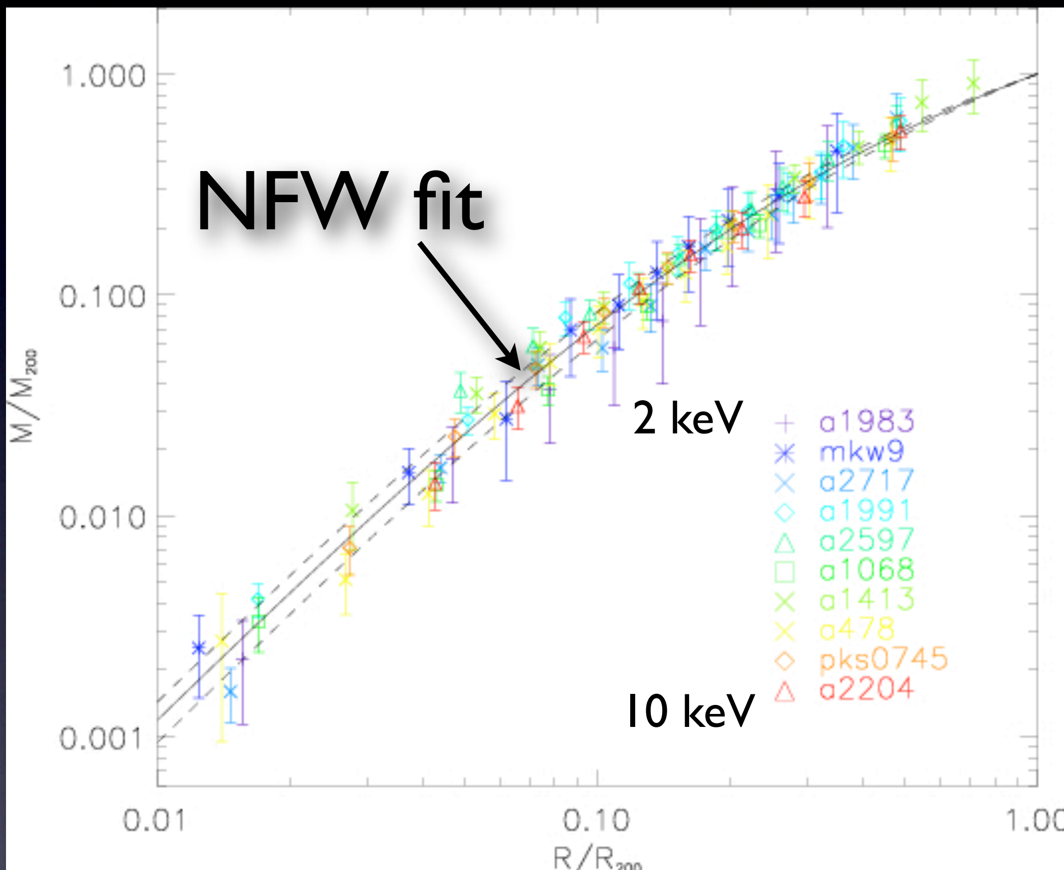
Lewis & Buote 2003 (Abell 2029)

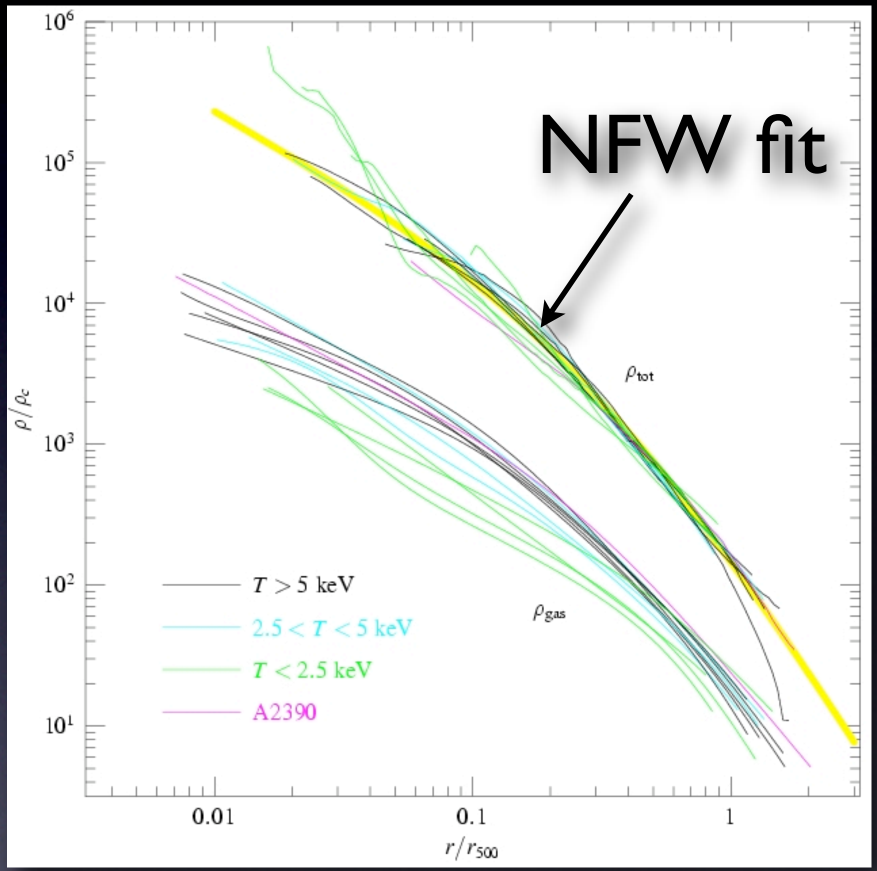


Pratt & Arnaud 2002 (Abell 1413)

Total mass/density profiles

Assume spherical symmetry, HE



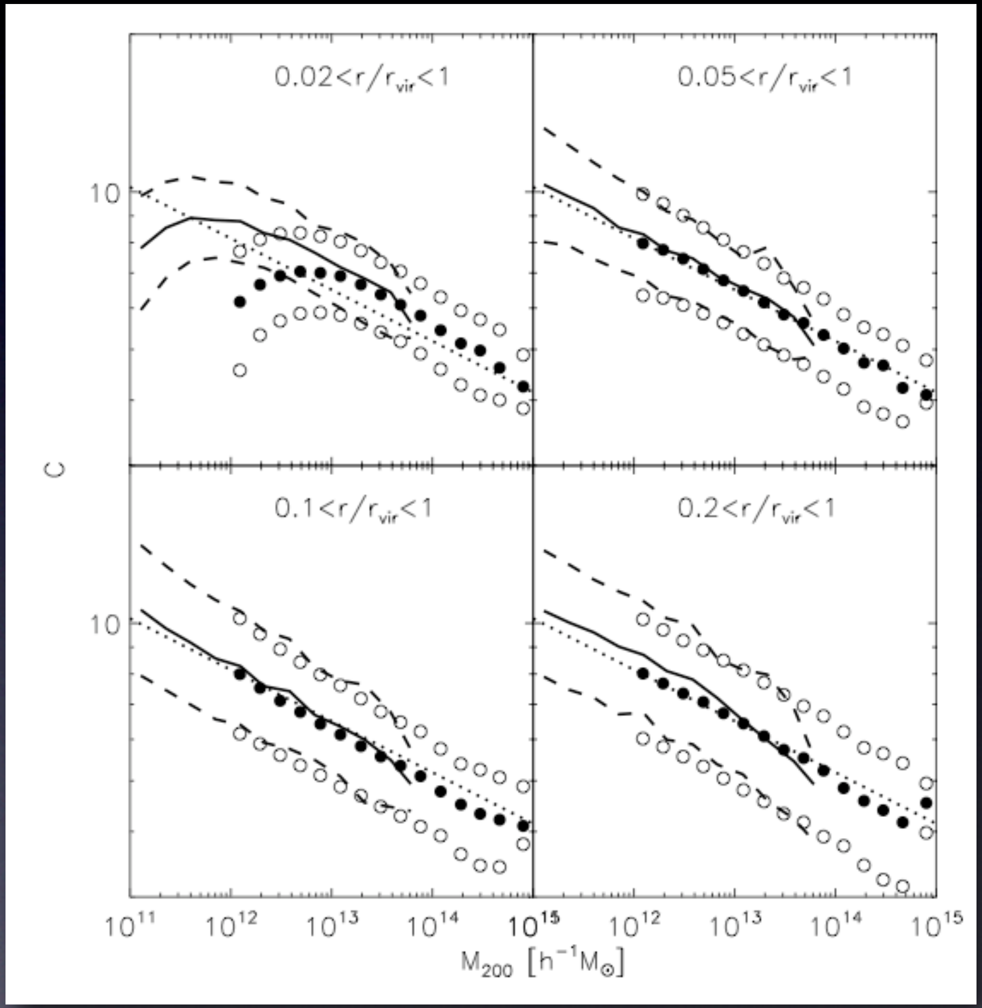


Pratt & Arnaud 2005;
Pointecouteau, Arnaud & Pratt 2005
(XMM, relaxed)

Vikhlinin et al 2006 (Chandra, relaxed)

Dark matter halo concentration

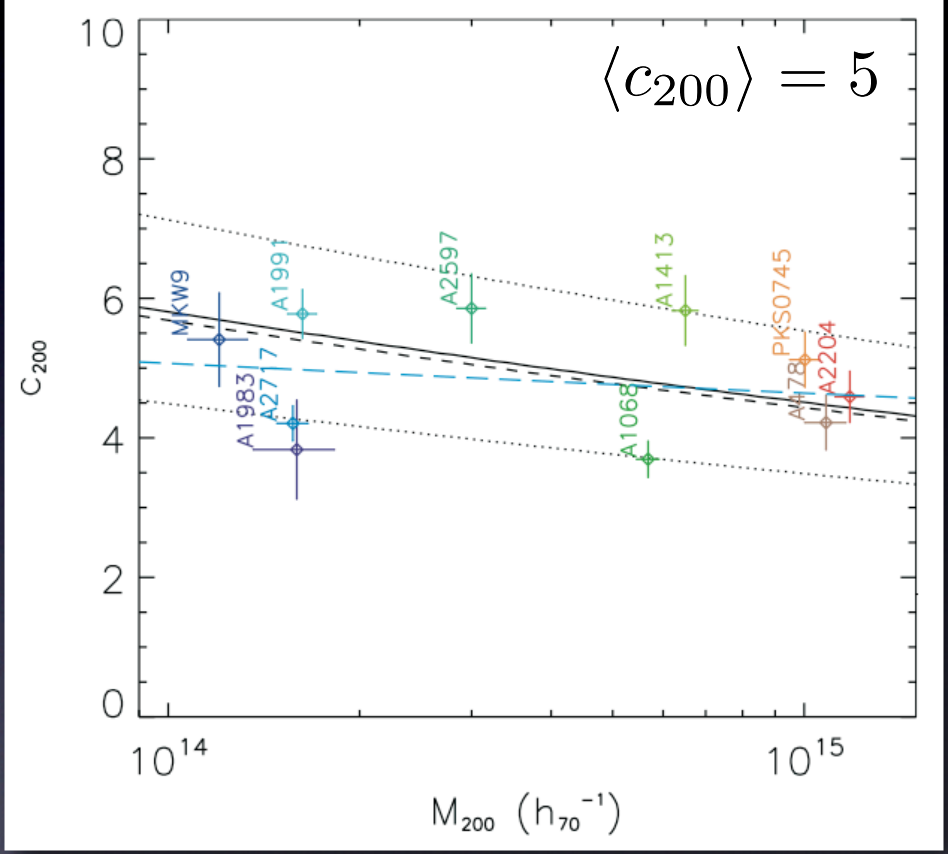
Mass-dependent, large scatter



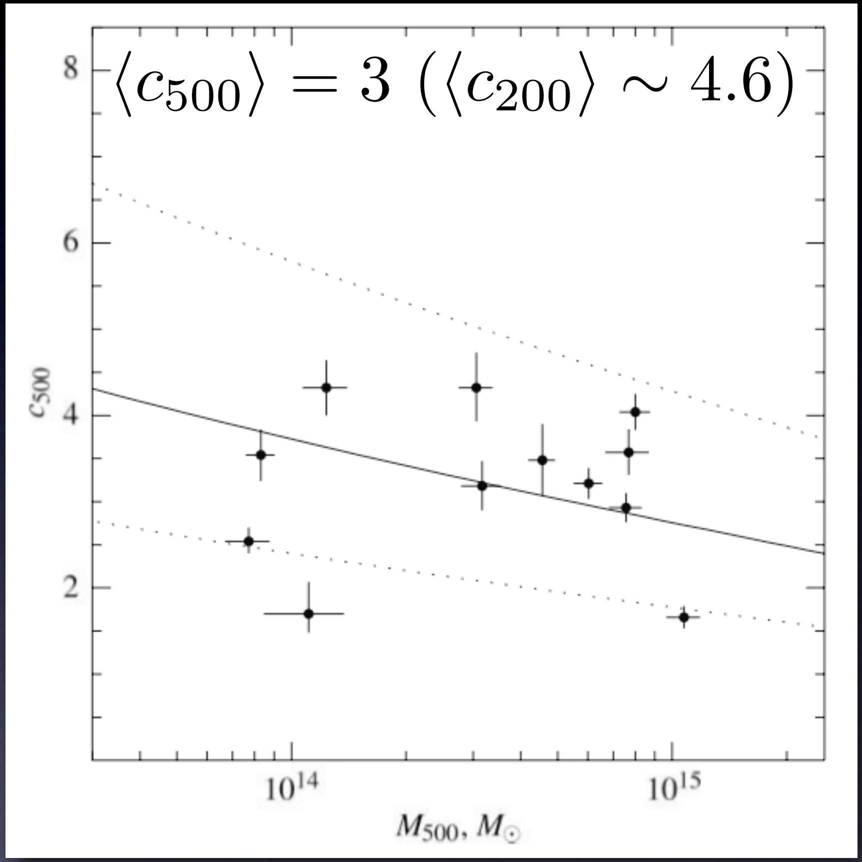
Neto et al. 2007

Dark matter constraints: *c* - *M* relation

Quantitative test of CDM scenario



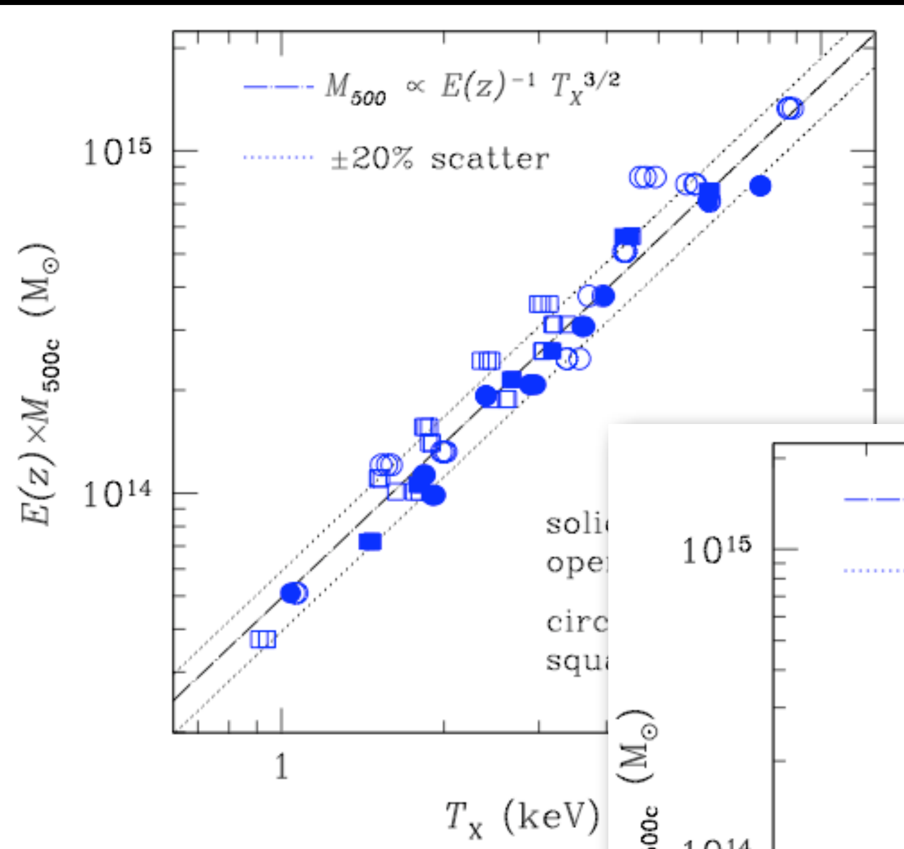
Pratt & Arnaud 2005;
Pointecouteau, Arnaud & Pratt 2005 (XMM, relaxed)
Simulations: Dolag et al. 2004

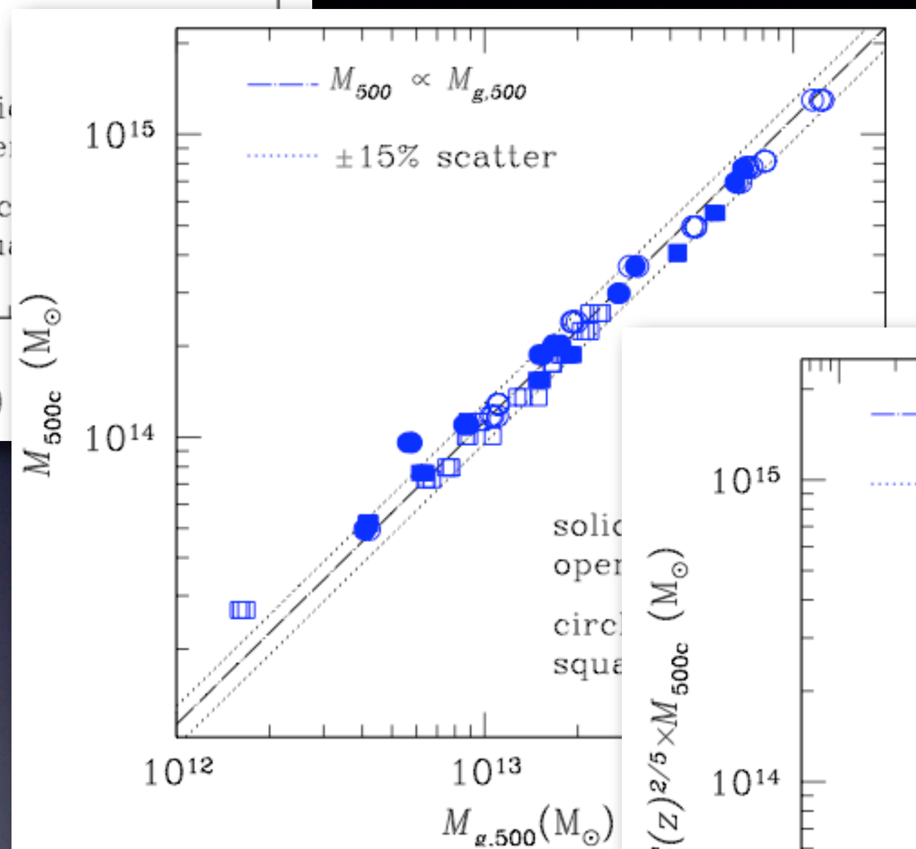


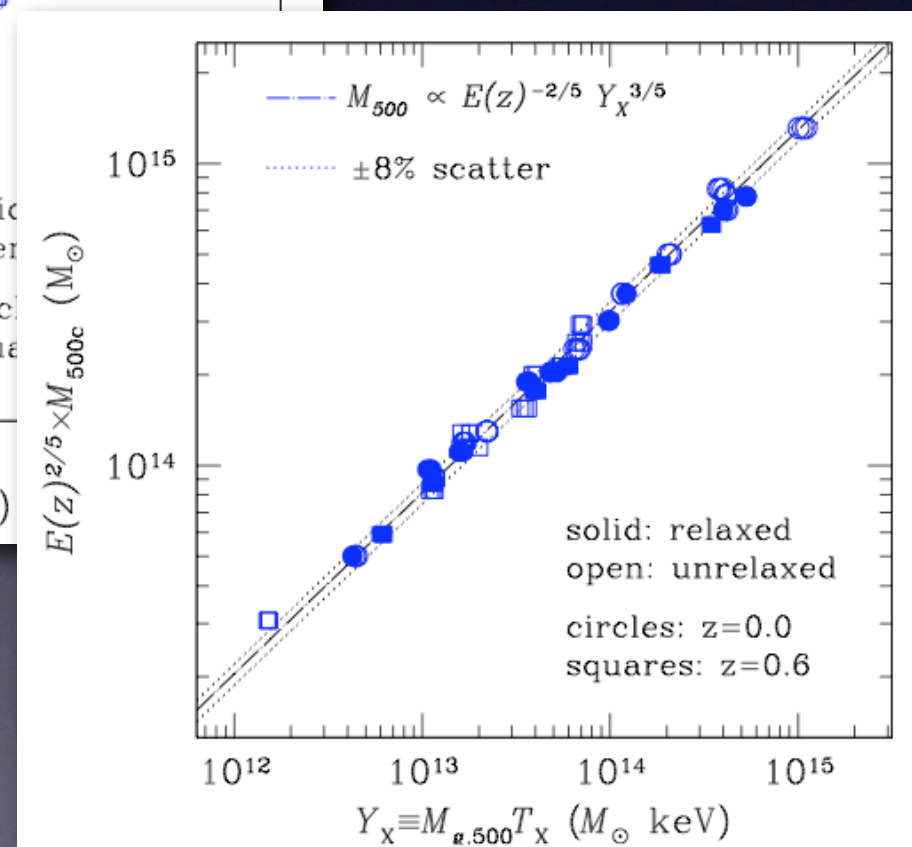
Vikhlinin et al 2006 (Chandra, relaxed)
see also: Sato et al 2000, Gastaldello et al. 2007, Buote et al. 2007, Humphrey et al. 2006, Schmidt & Allen 2007

Mass proxy relations

The dark matter-ICM connection



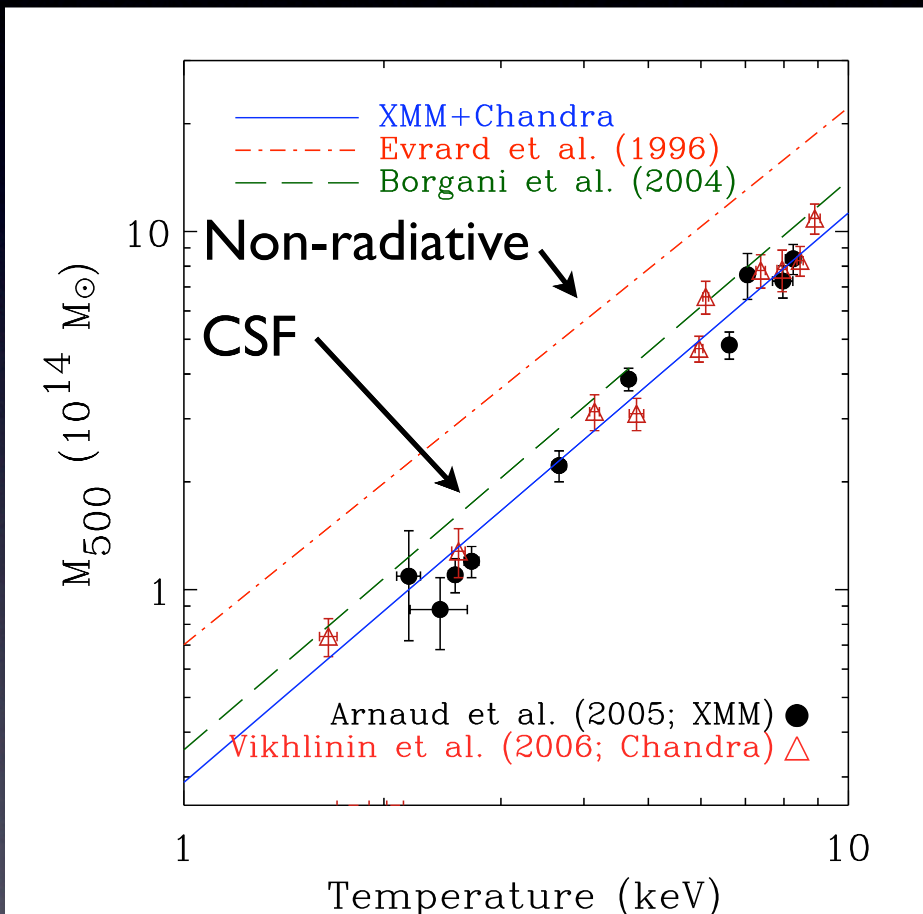




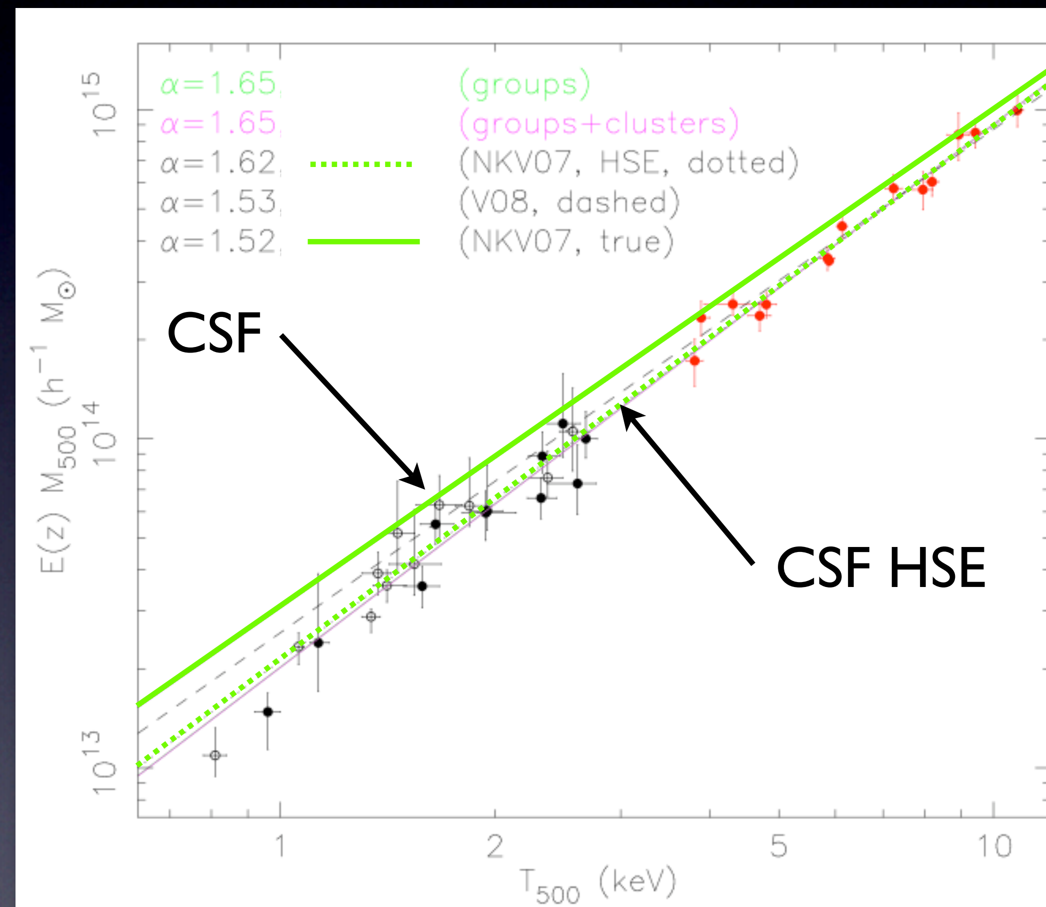
Kravtsov et al. 2006
(cosmological numerical simulations)

$M - T$ relation

Assume spherical symmetry, HE, regular systems



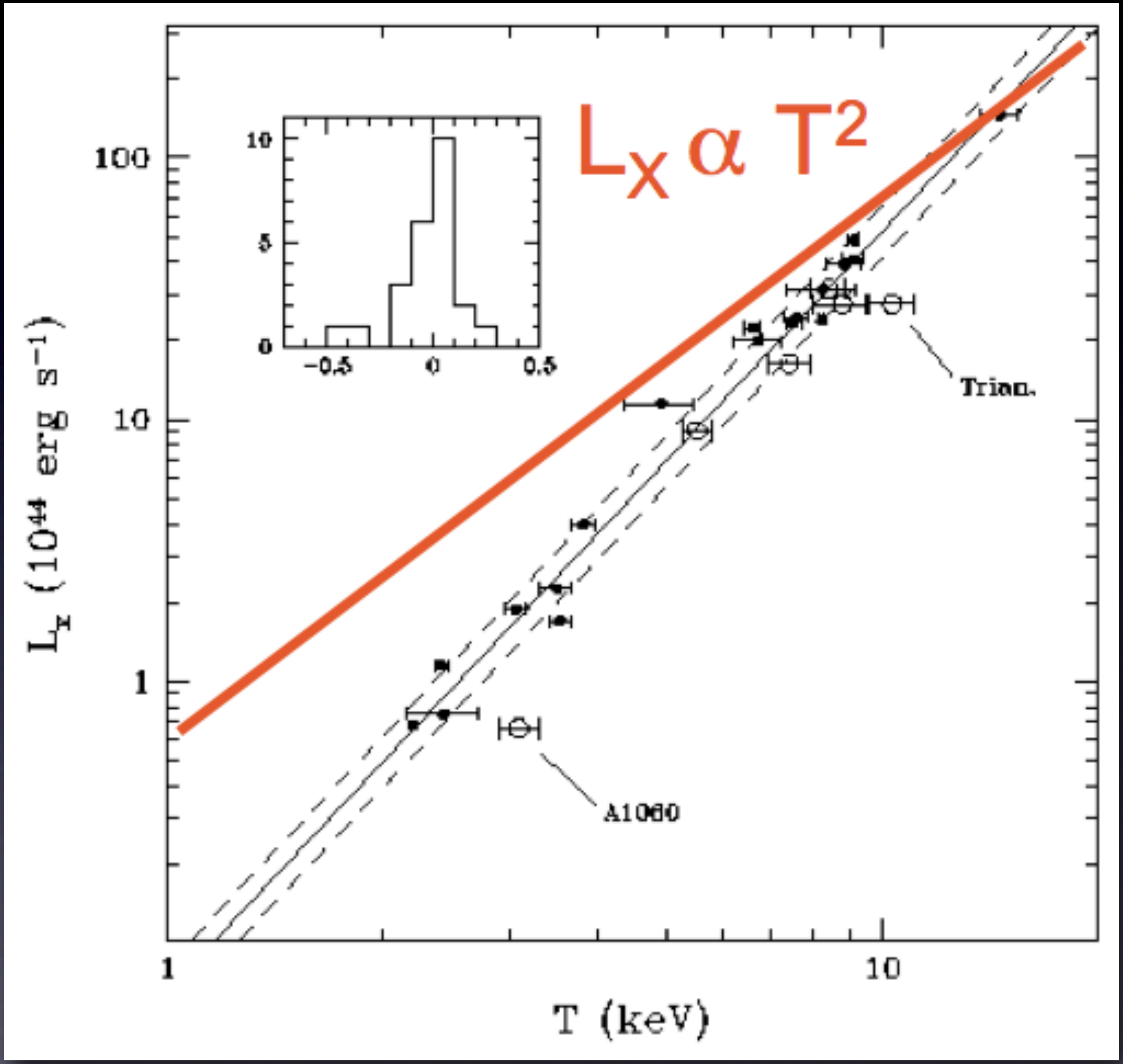
Pratt 2006



Sun et al. 2009

Effects of non-gravitational processes on ICM in regular clusters

$L_X - T$ relation

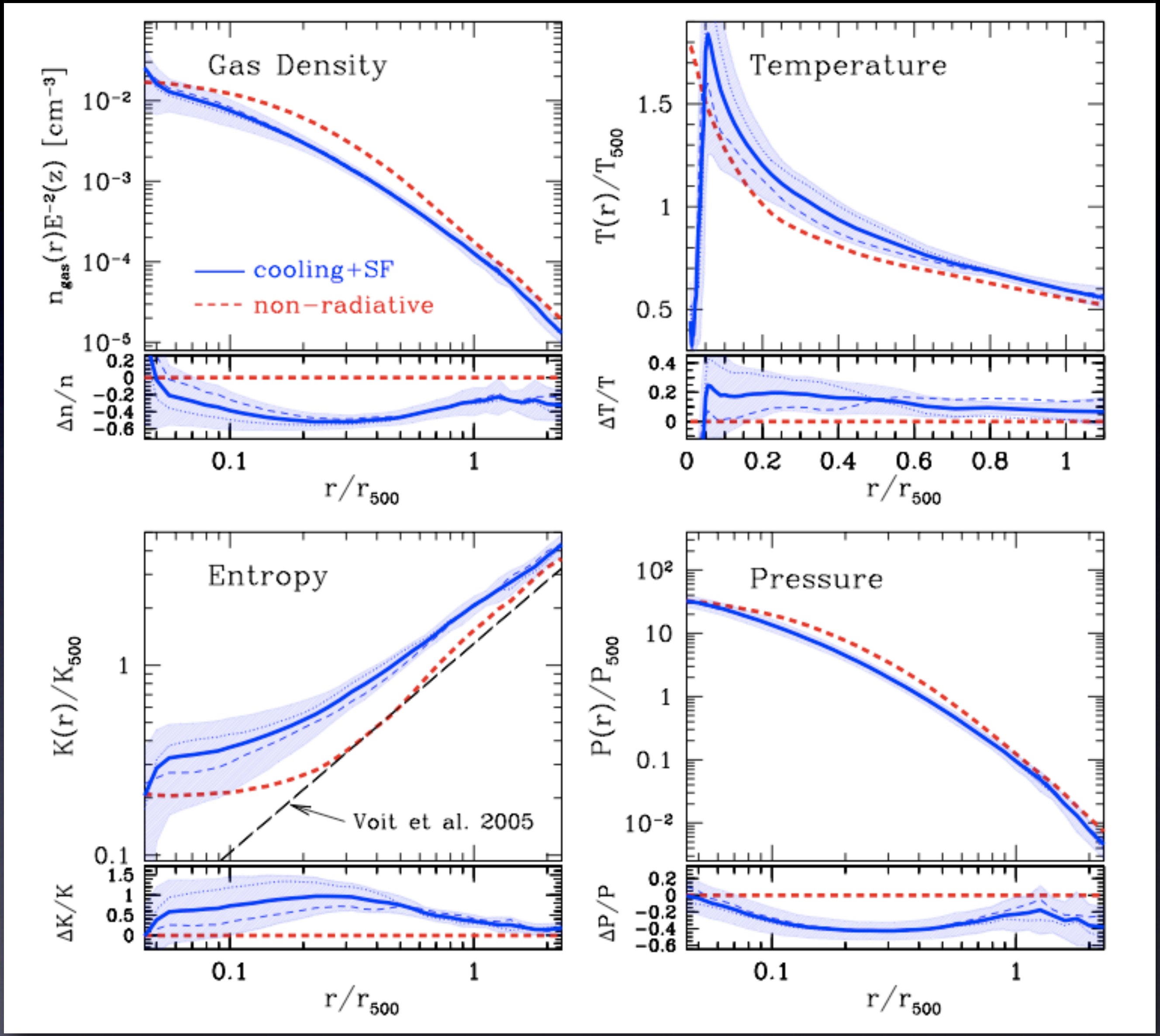


Arnaud & Evrard 1999

Entropy

- X-ray astronomer's entropy: $K = kT/n_e^{2/3}$
- Records the thermodynamic history of ICM
- X-ray properties determined by entropy and shape of gravitational potential
- Spatial resolution $\Rightarrow$ radial constraints

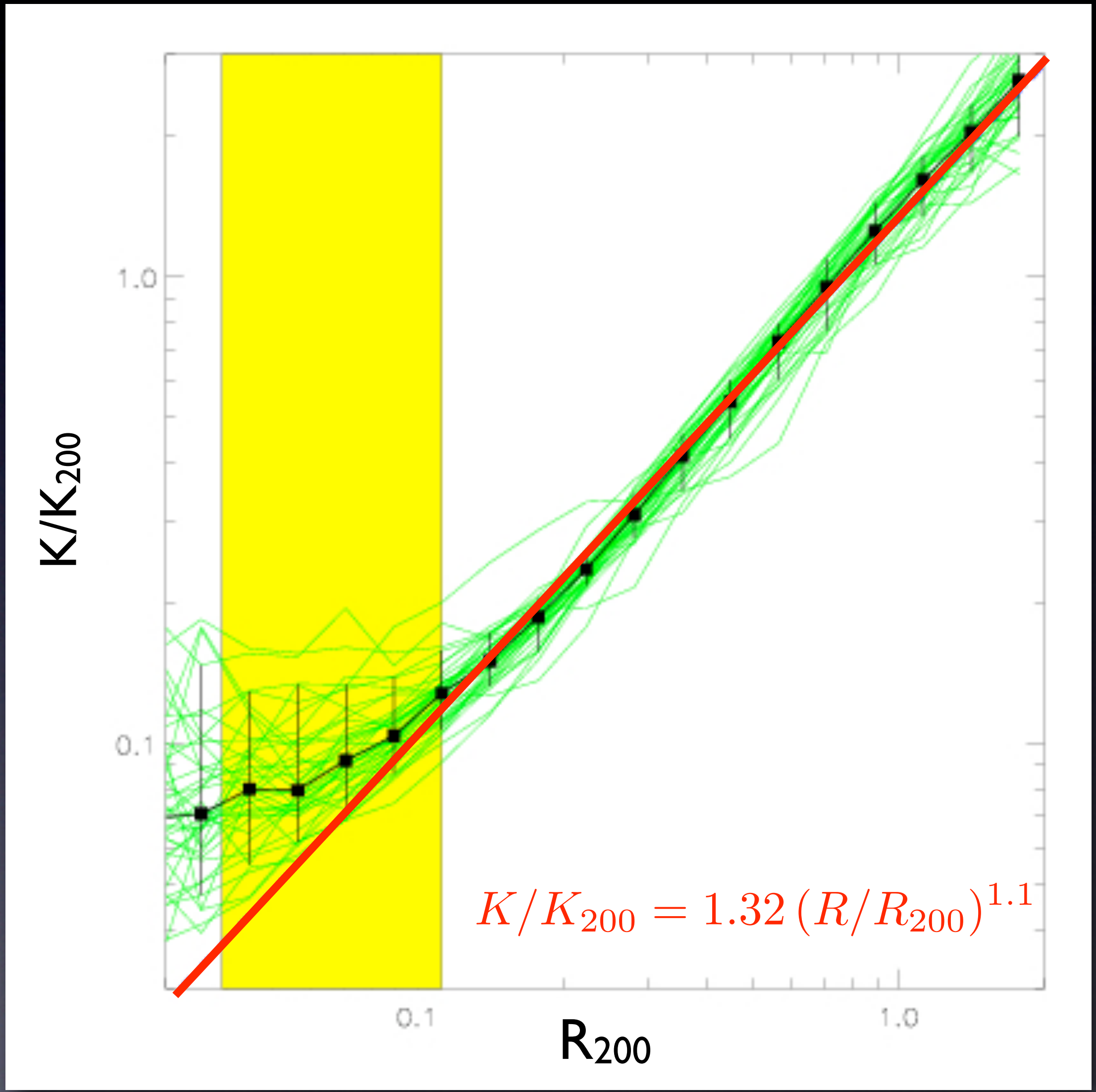
Why entropy?



Nagai et al, 2007

Baseline entropy expectations

40 clusters from 'non-radiative' cosmological simulations



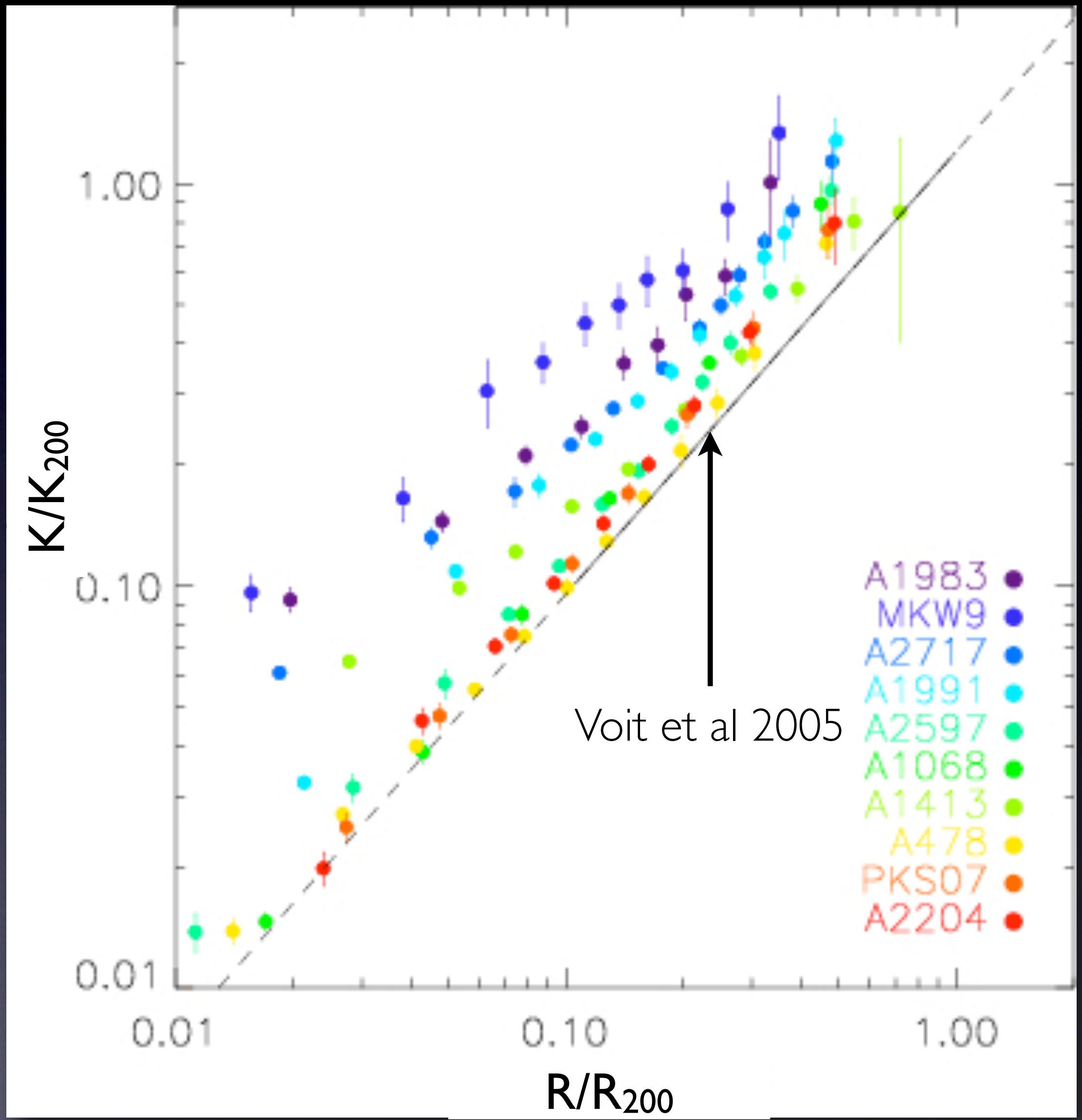
$$K_{200} = \frac{1}{2}\left[\frac{2\pi}{15}\frac{G^2 M_{200}}{f_b H(z)}\right]^{2/3}$$

$$K/K_{200} = 1.32(R/R_{200})^{1.1}$$

Voit, Kay & Bryan 2005

Scaled entropy profiles

10 regular local systems

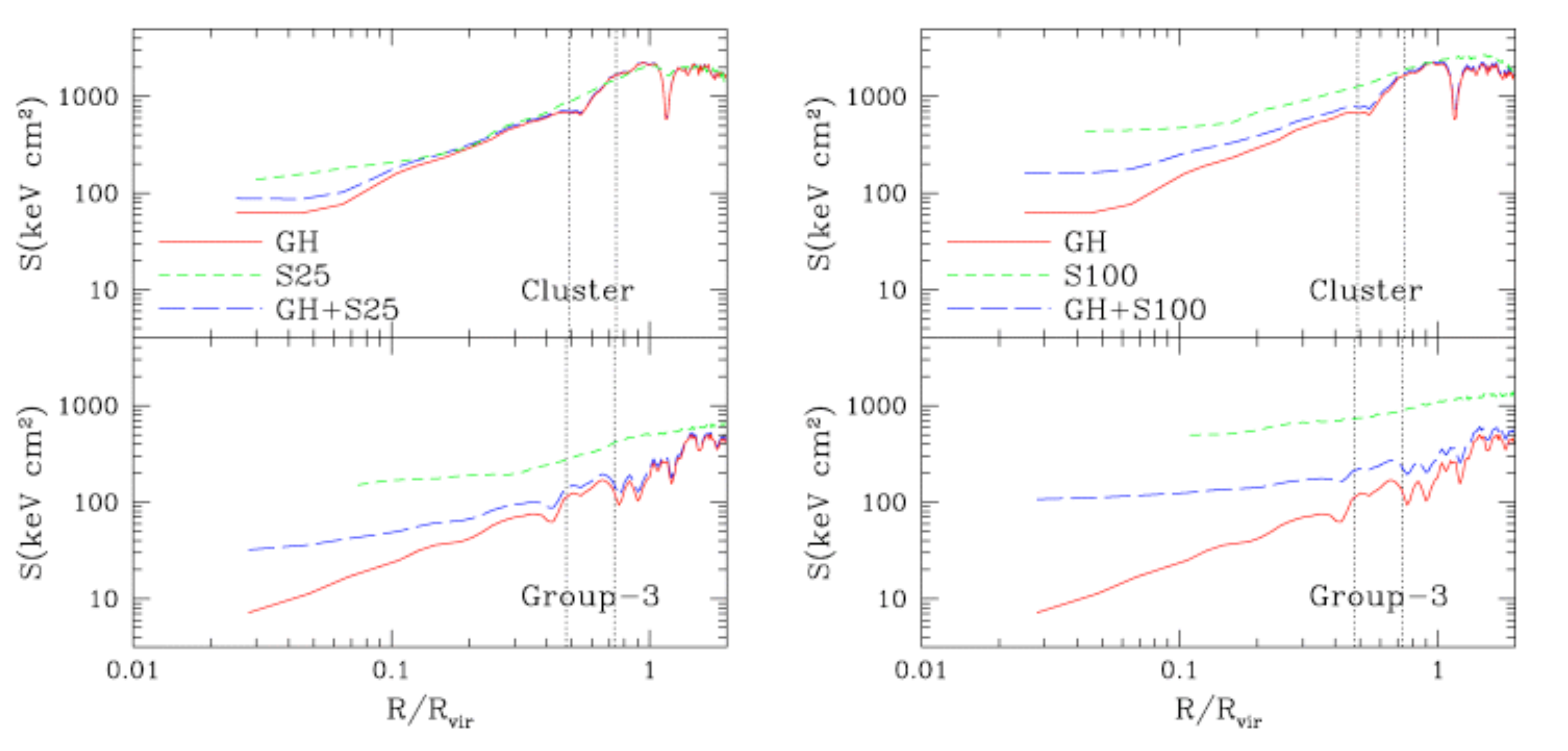


2 keV

10 keV

Pratt et al 2006

Entropy profiles - 'CSF' simulations



Borgani et al. 2005

Generalising to the cluster population

Representative sample of local X-ray clusters

REXCESS
PI: H. Böhringer

Argument

Cannot observe all clusters in the Universe

- Use scaling laws to link observables to mass

Need smaller samples *representative* of entire population

- Good coverage of mass range (estimated via proxy)
- Unbiased wrt physical characteristics (morphology, cool core...)

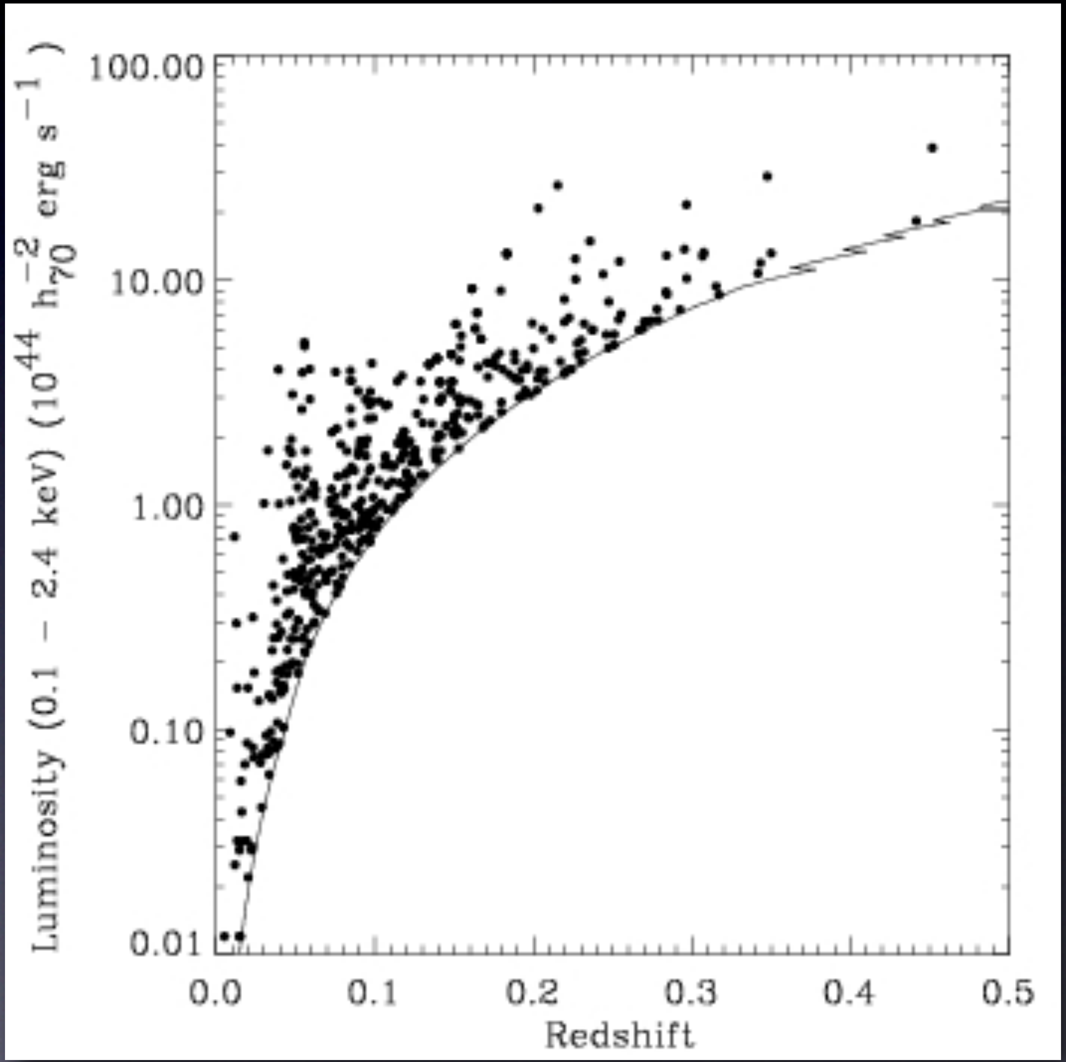
X-ray observations currently the most efficient and well-tested way to find clusters

- Signature of well-developed potential wells
- n_e^2 dependence ⇒ projection effects not a problem

⇒ signal is significant from 10s to 1000s of sigma

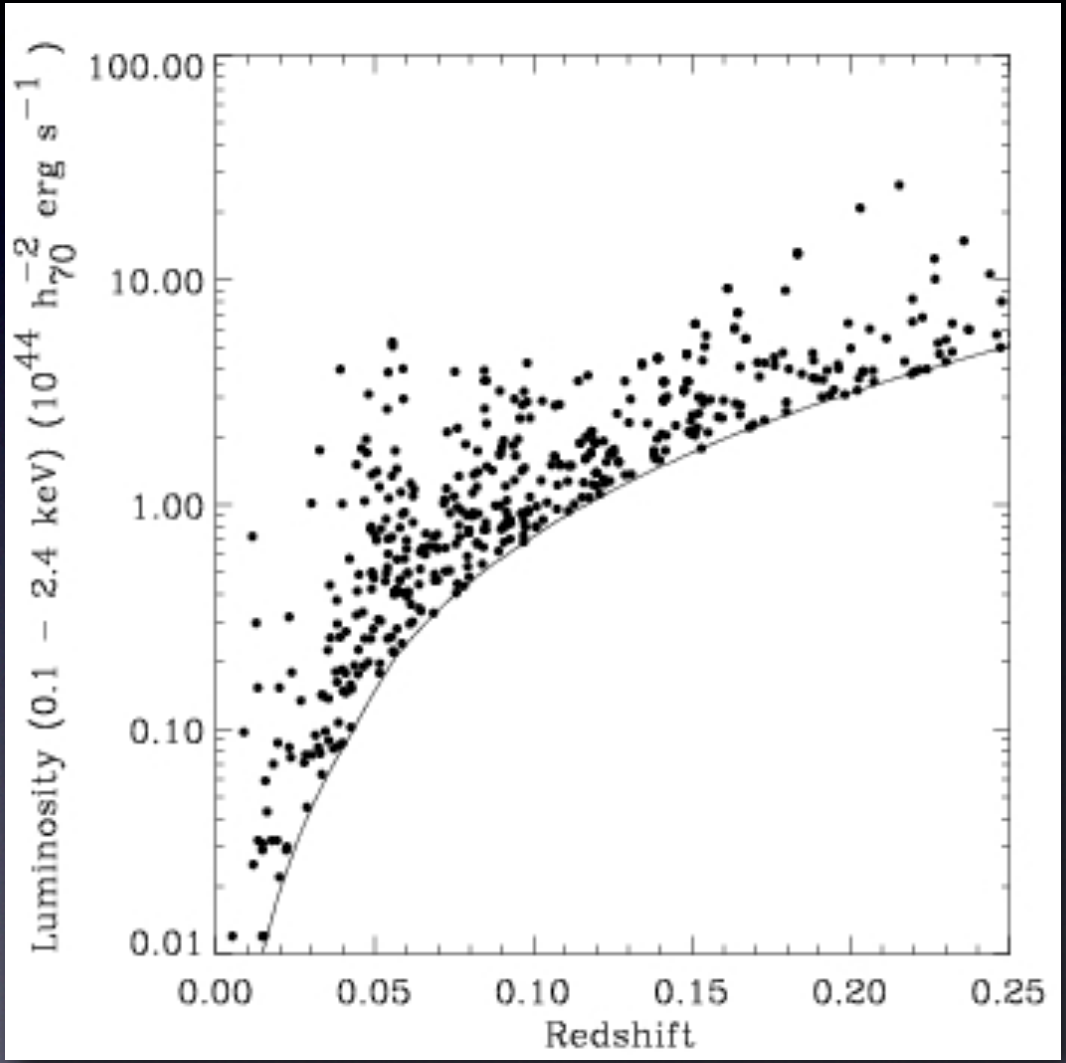
Defining a representative X-ray cluster sample

REFLEX cluster catalogue (Bohringer et al 2004; ex-ROSAT)



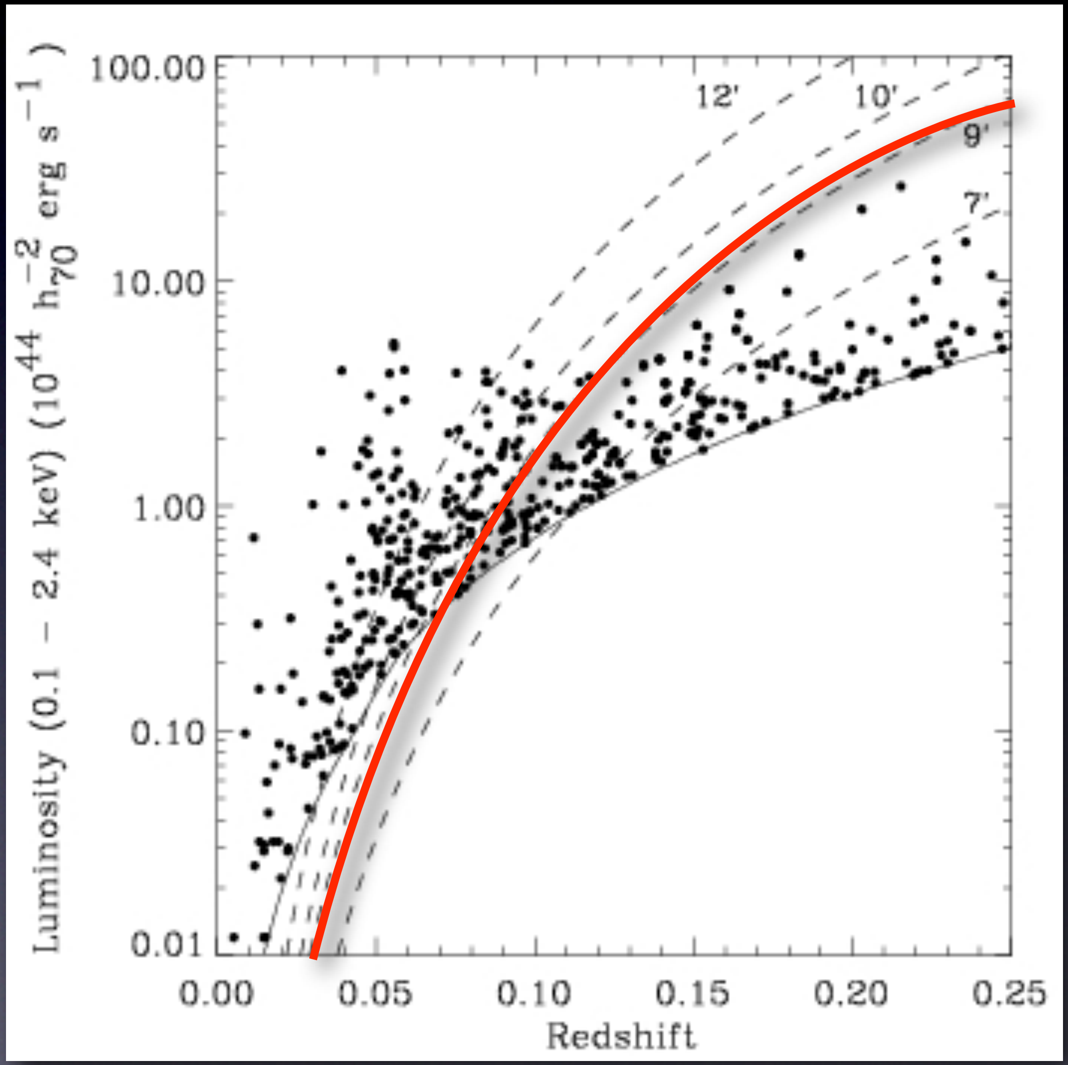
Nearby clusters

(z < 0.25)



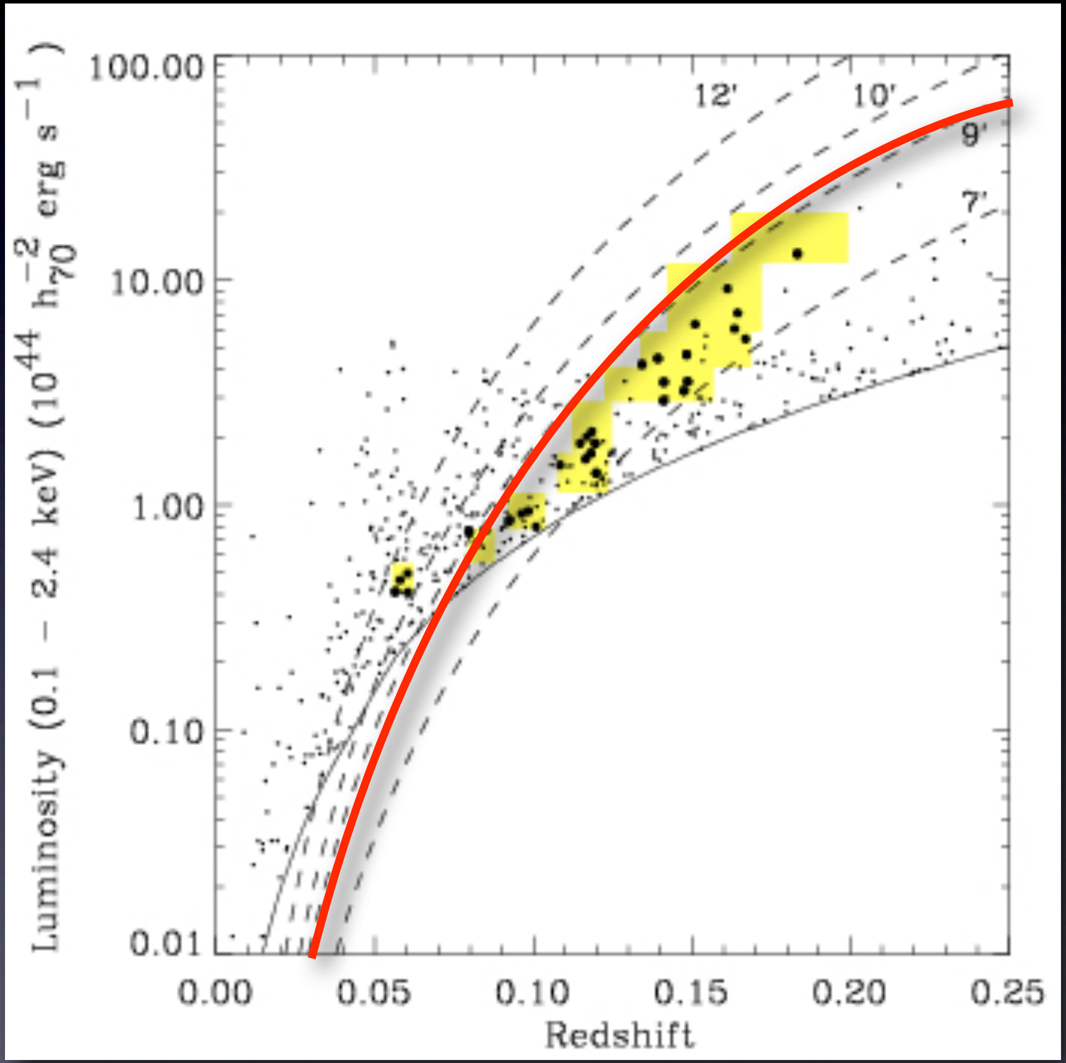
XMM field of view constraints

$R_{500} < 9'$ (except lowest and highest L_X bins)

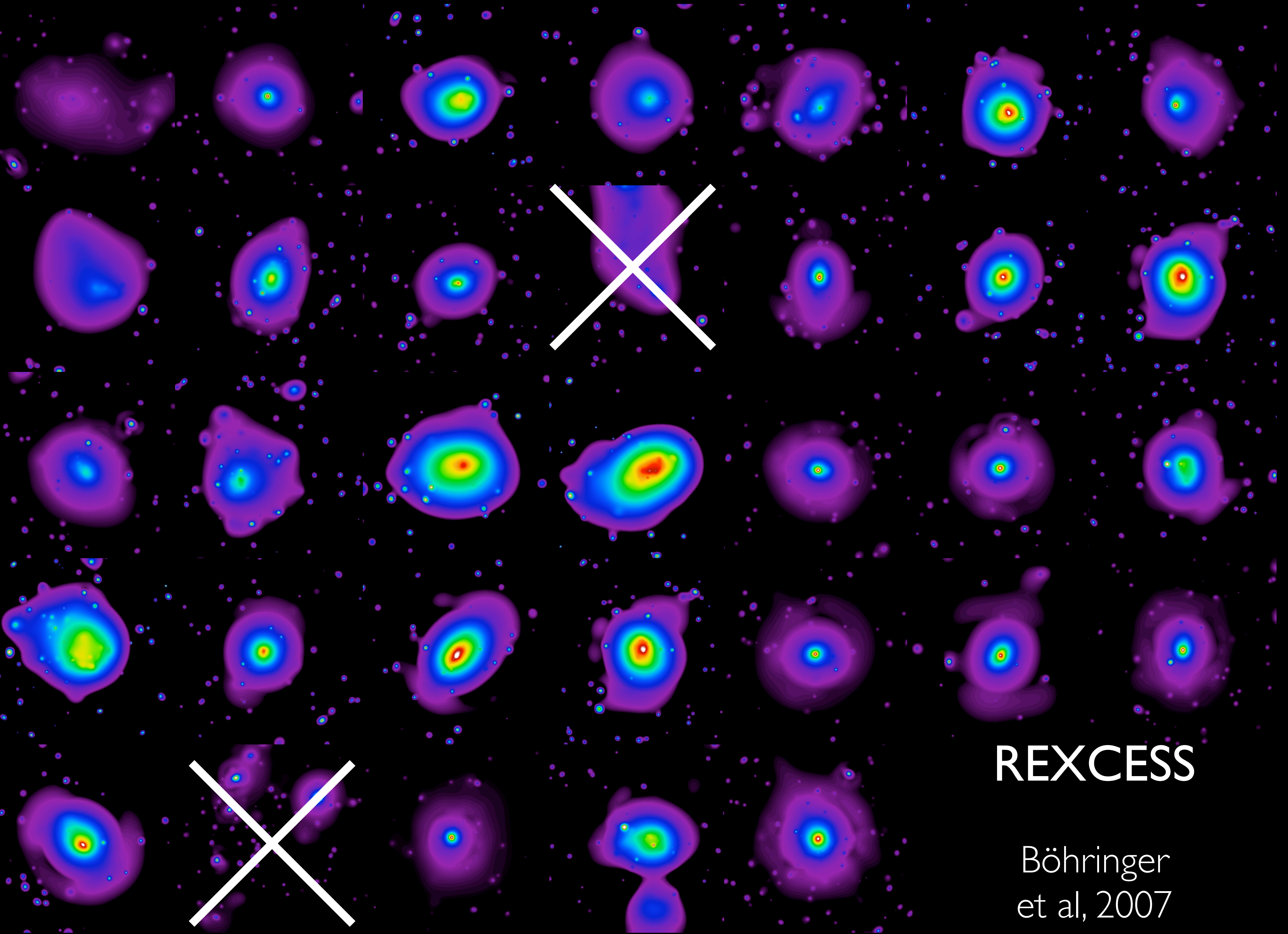


Sample luminosity function in logarithmic L_X bins (8)

33 clusters; $L_X > 4 \times 10^{43}$ erg s^{-1}



Pratt et al 2007, Böhringer et al 2007



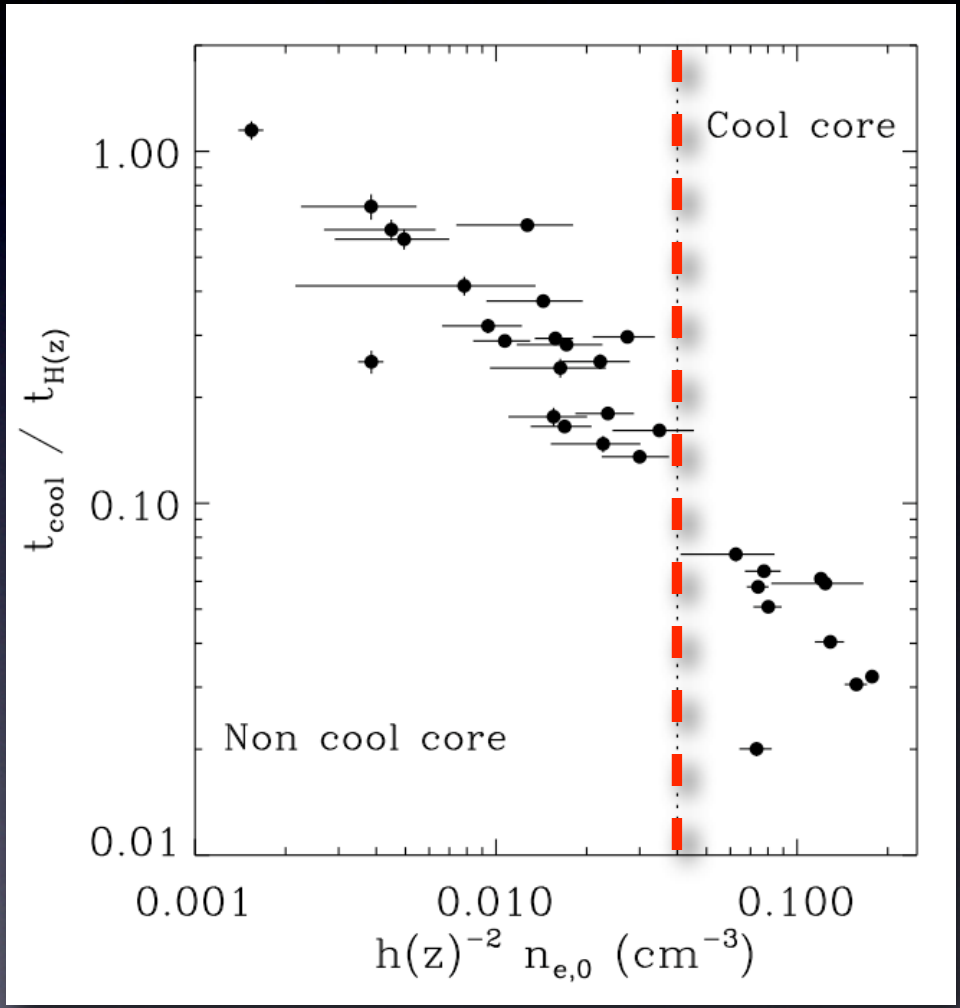
REXCESS

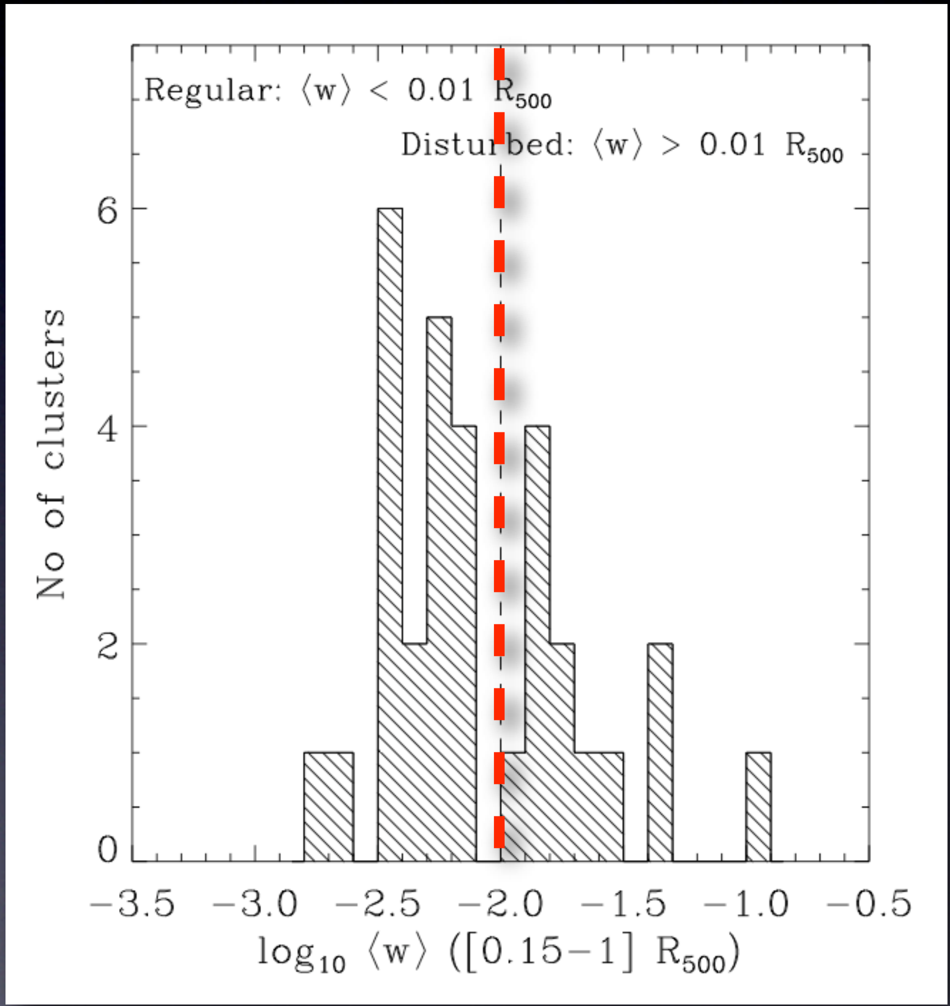
Böhringer
et al, 2007

Subsample definition

30% most extreme by two measures

non cool core cool core relaxed unrelaxed

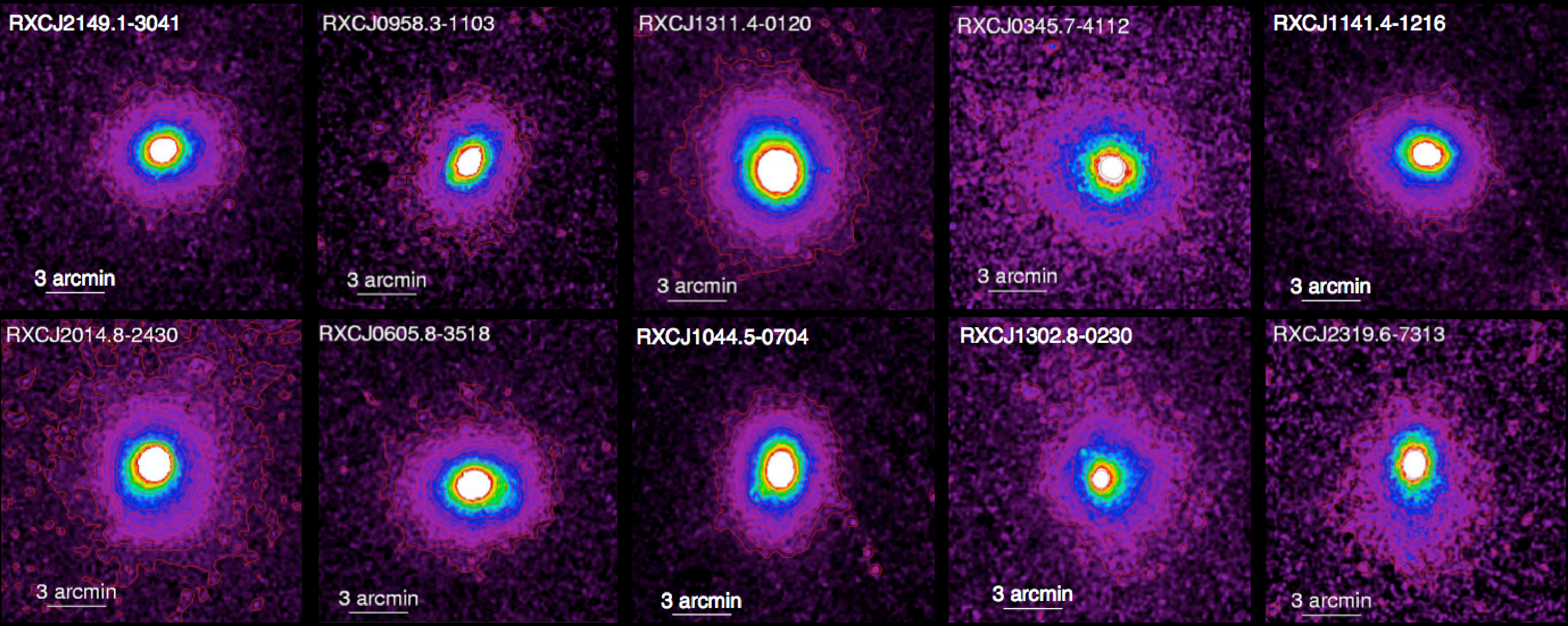




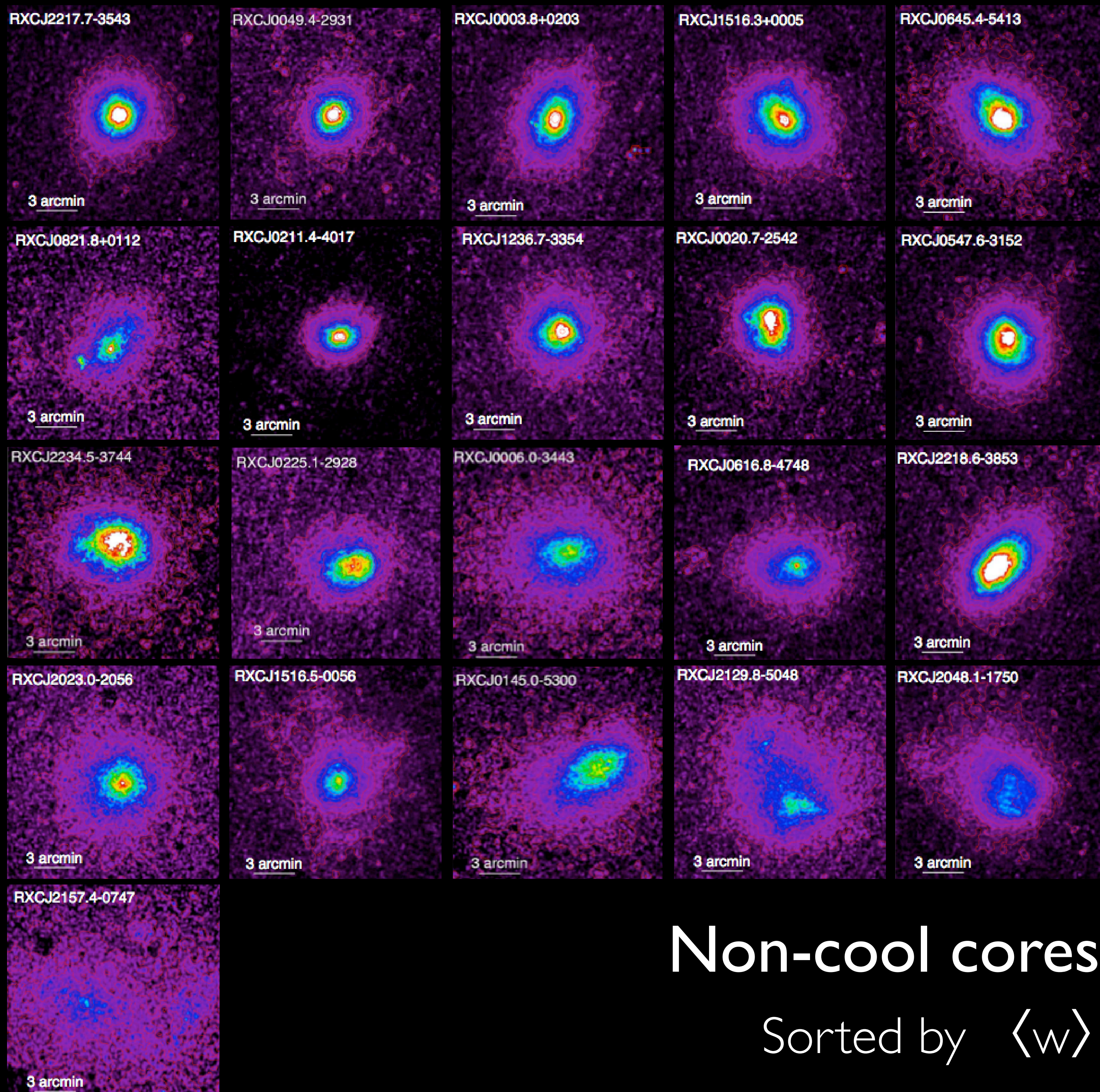
Pratt et al 2009

Cool cores

Sorted by ⟨w⟩



Cool core and unrelaxed



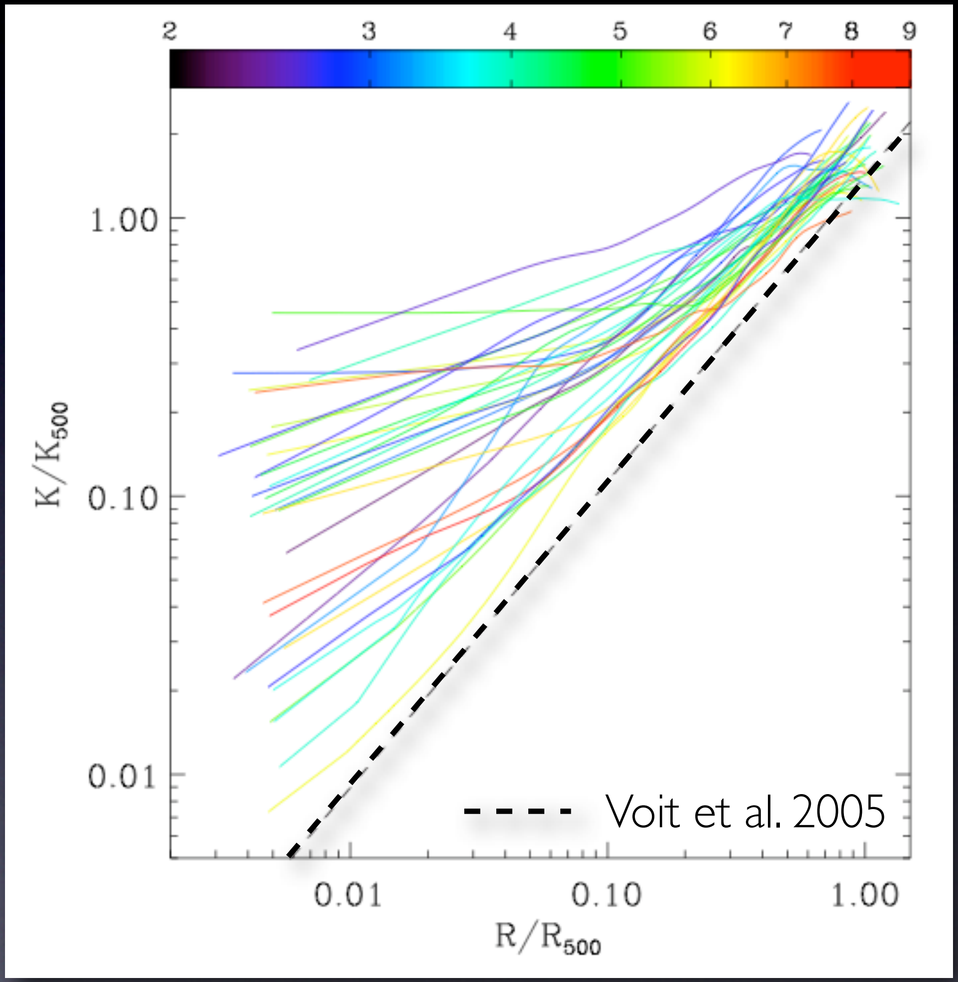
Non-cool cores

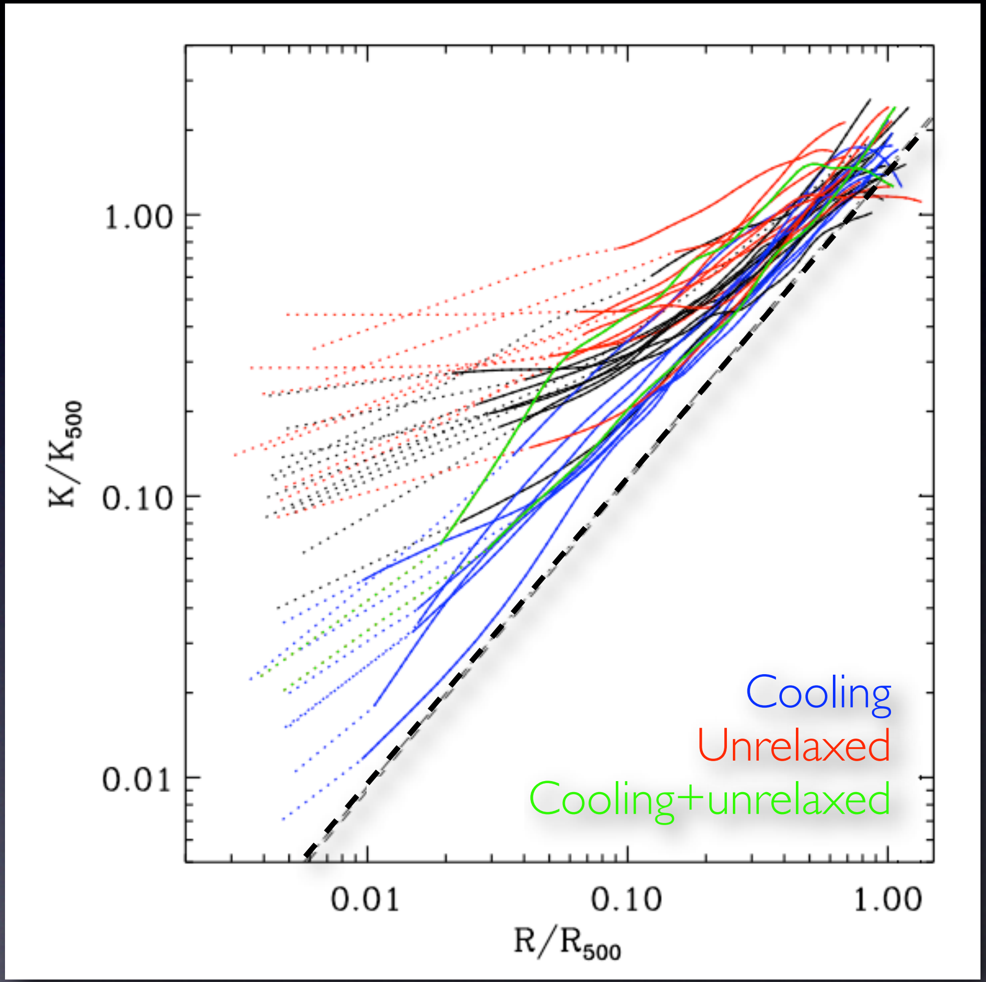
Sorted by $\langle w \rangle$

Entropy profiles

Entropy

Same tendency with T/M, but distinct subsample segregation

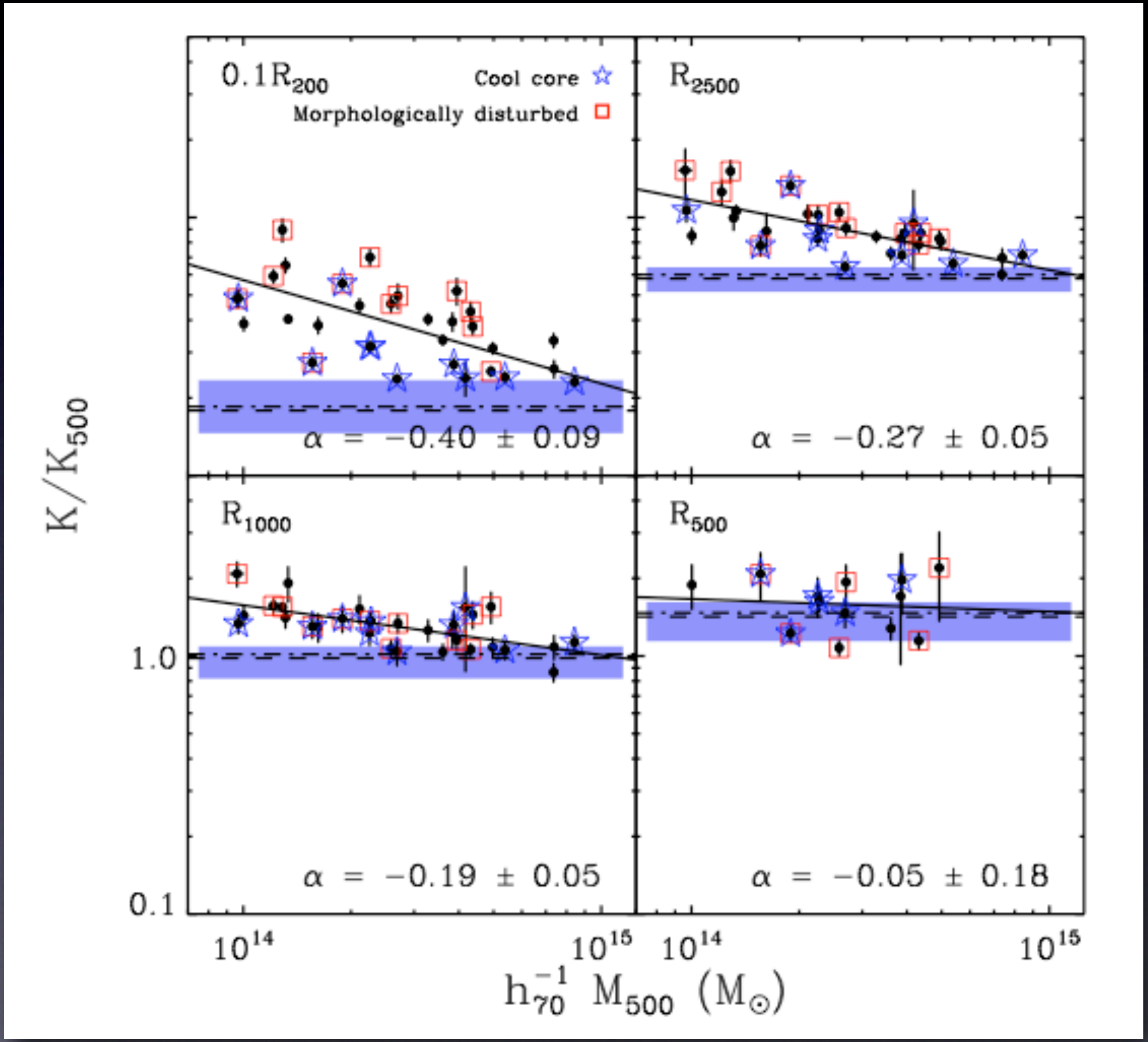




Pratt et al. arXiv:0909.3776

Entropy scaling vs 'non-radiative' expectations

Progressively more self-similar with increasing radius



Pratt et al. arXiv:0909.3776

Why this distribution of *central* entropies?

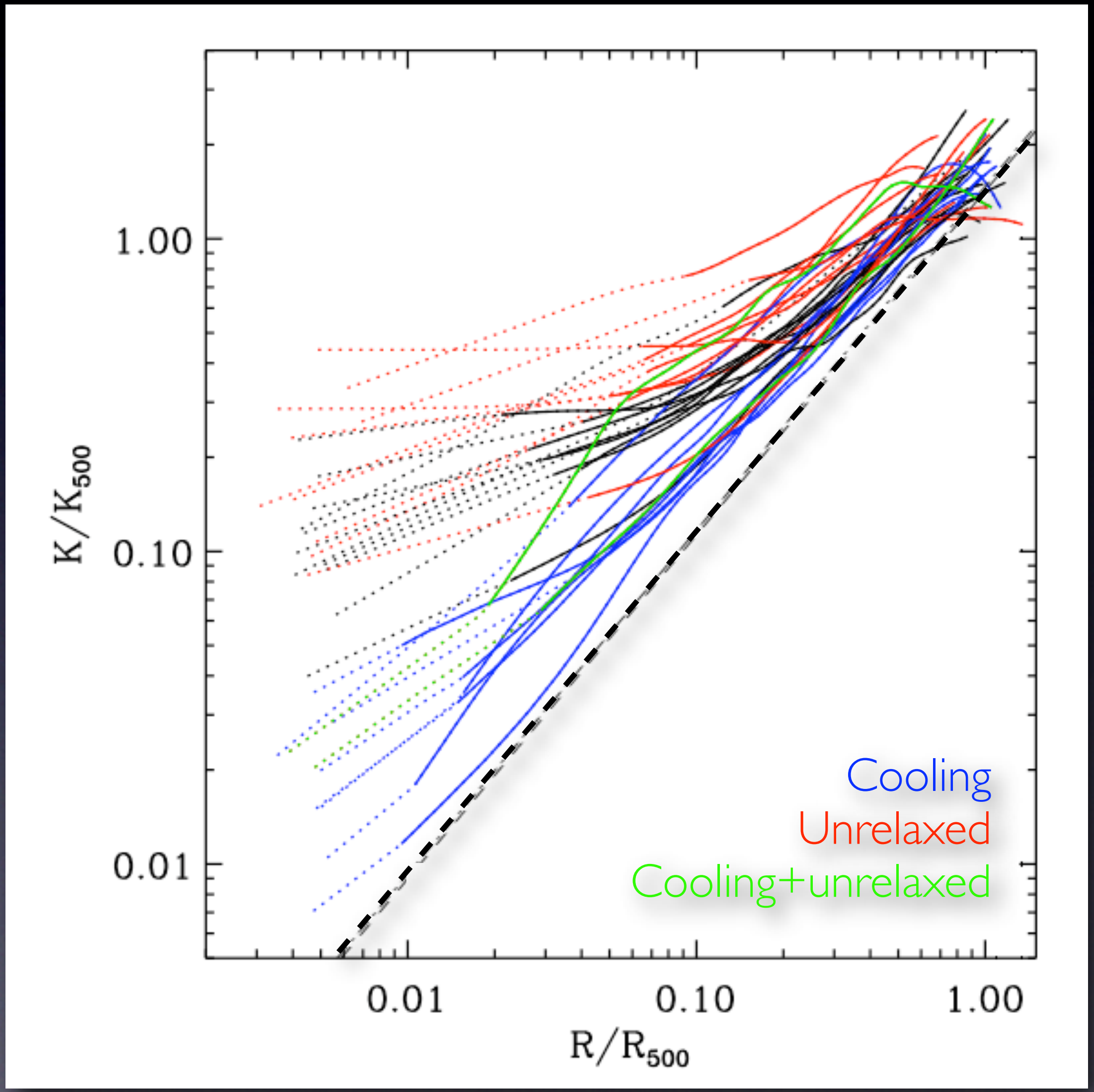
aka: cool-core / non-cool-core connection

Non-cool cores

- early merging activity
- higher (relative) level of early extra heating
- cool core never developed
- lower (relative) f_{gas}

Cool cores

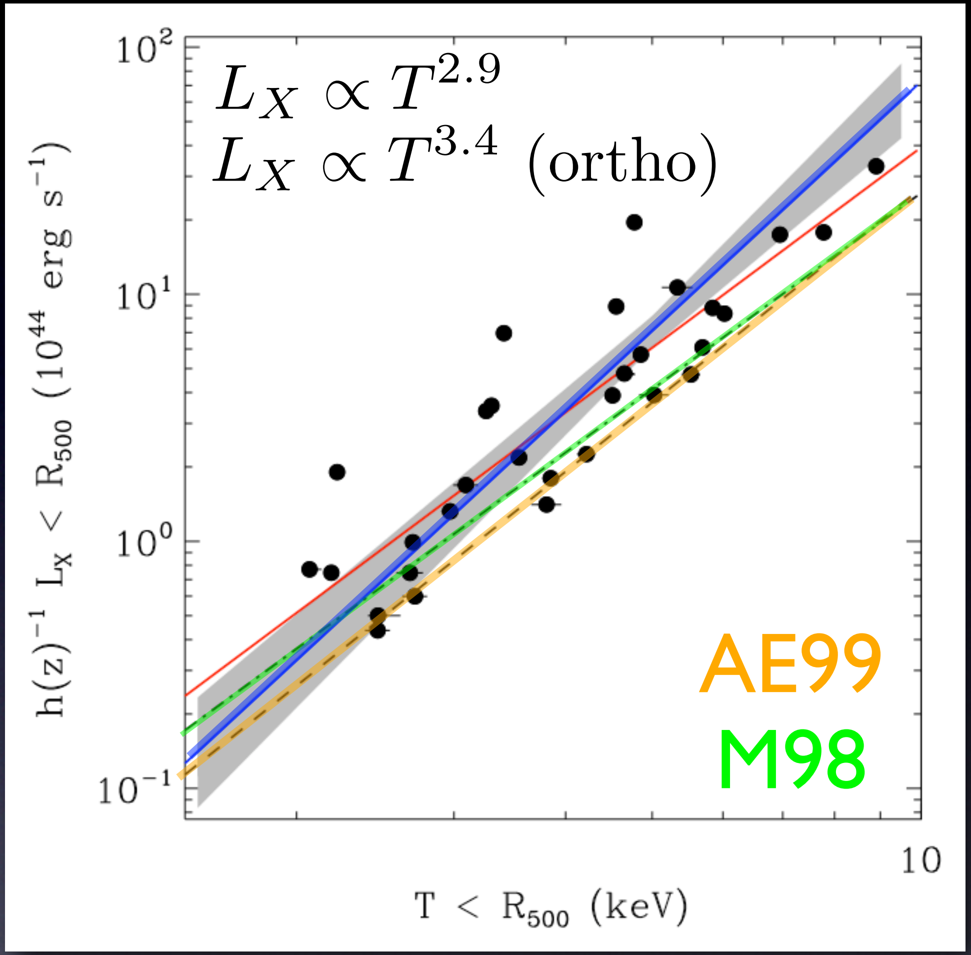
- less early merging activity
- lower (relative) level of early extra heating
- cool core developed, maintained by non-catastrophic cooling/feedback loop
- higher (relative) f_{gas}

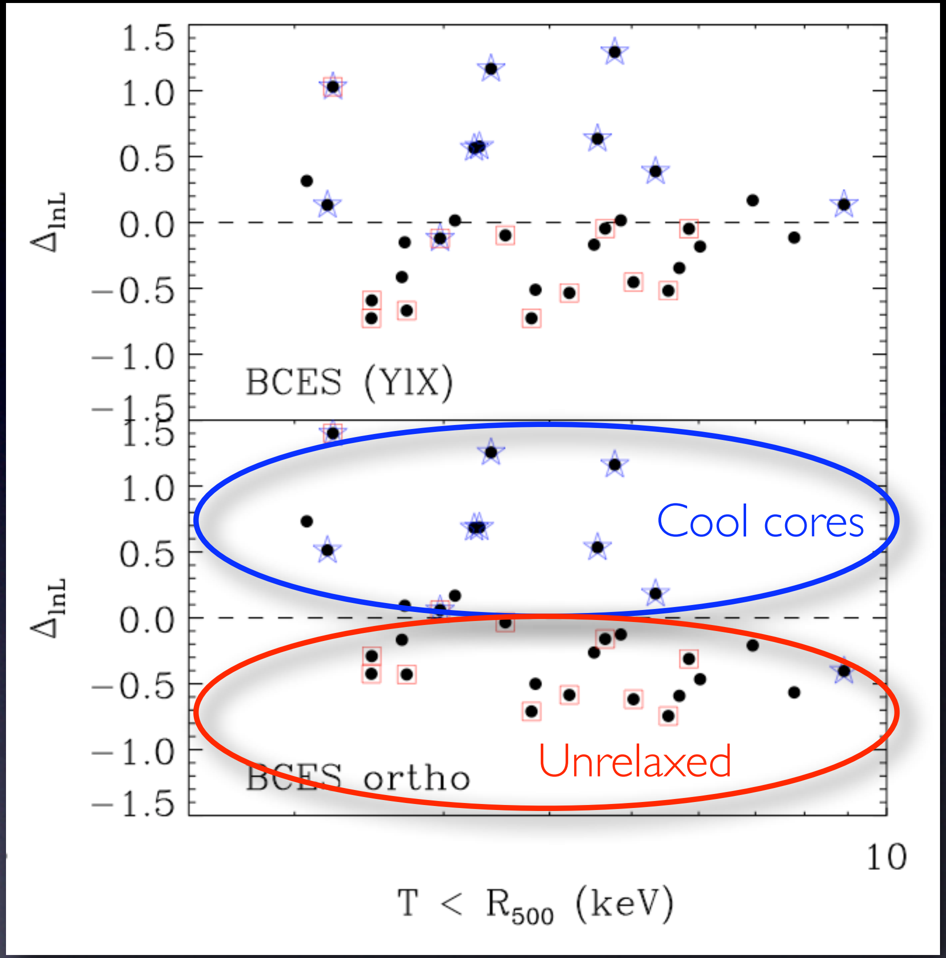


Pratt et al. arXiv:0909.3776

Effect on global properties

$L - T$

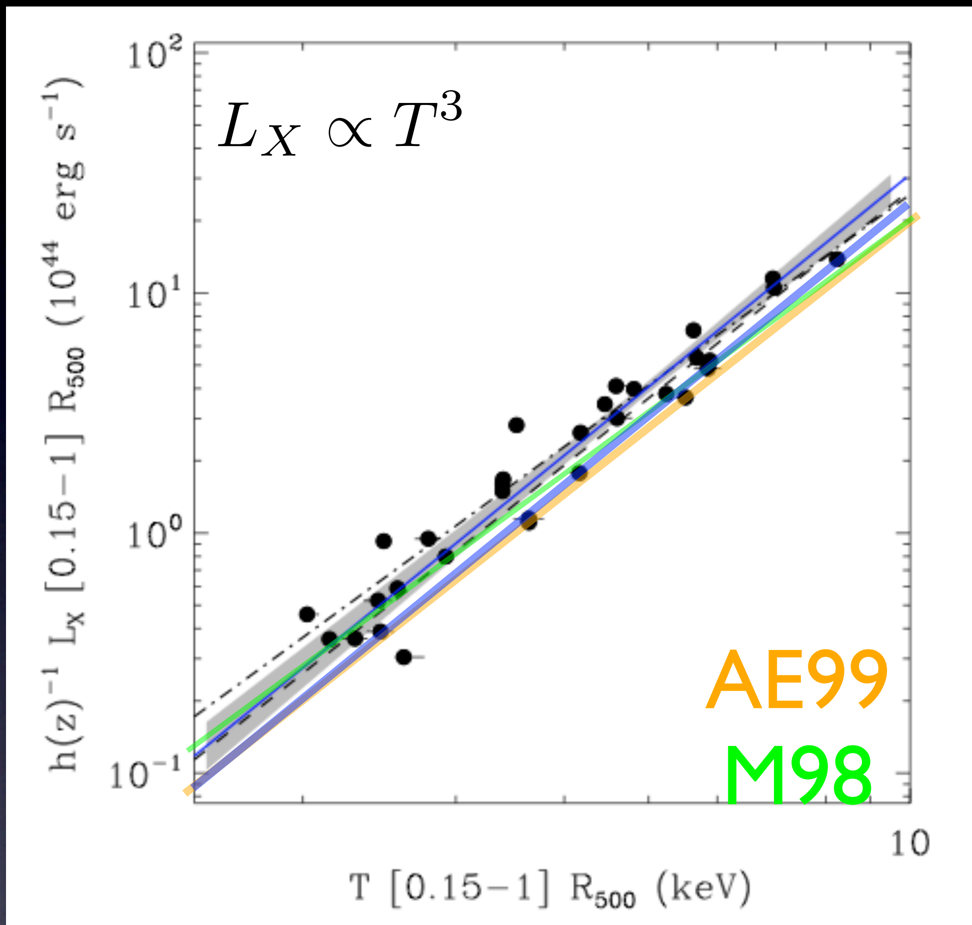


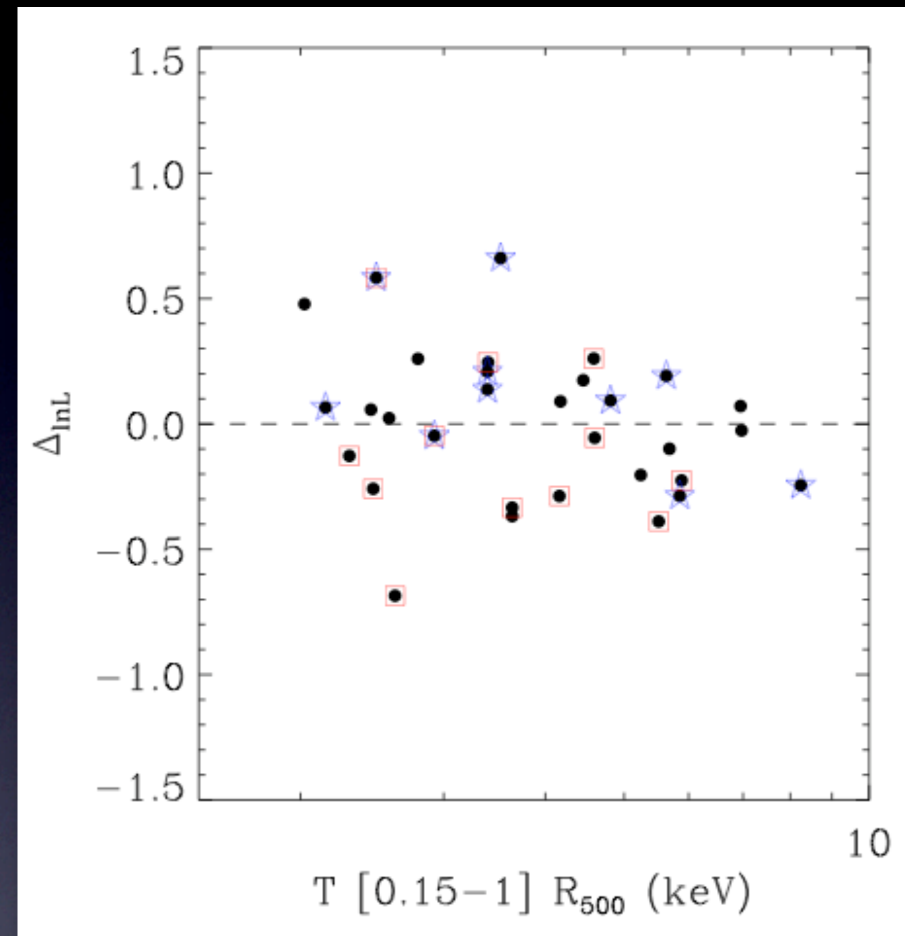


Pratt et al 2009

- 70 per cent scatter in $\ln(L_X)$
- Slope dependent on fitting method
- Cool cores high, unrelaxed low, wrt mean relation

$L - T$ (R < 0.15 R_{500} excluded)

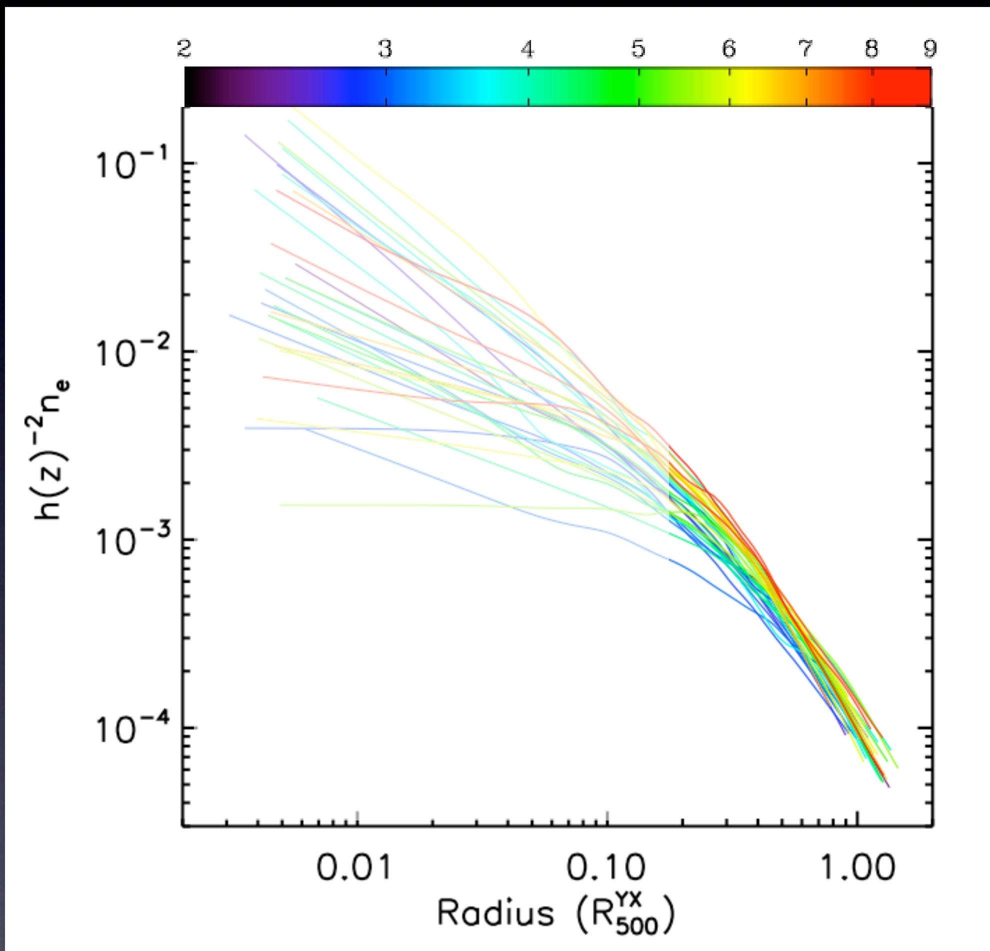


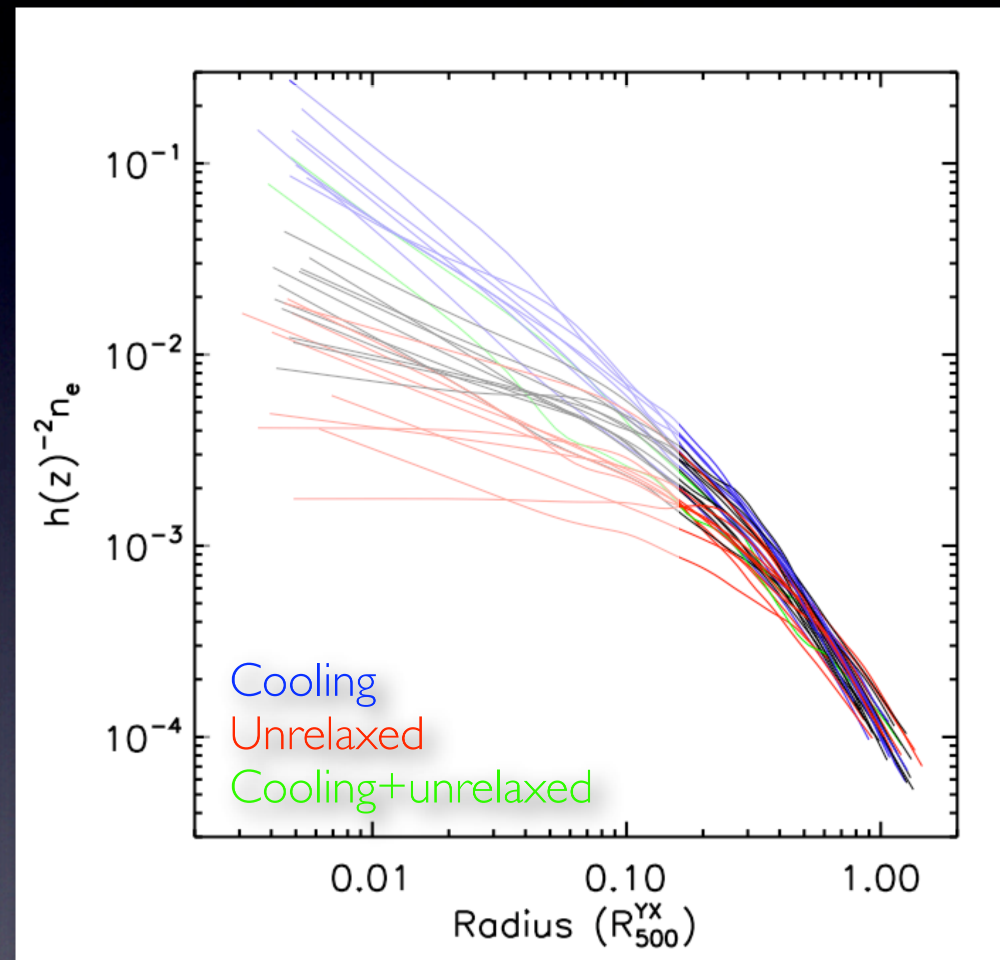


Pratt et al 2009

- 40 per cent scatter in ln(L_X)
- Slope ~independent of fitting method
- Same normalisation and slope as other relations but slope still steeper than 2
- Segregation much less evident

Density





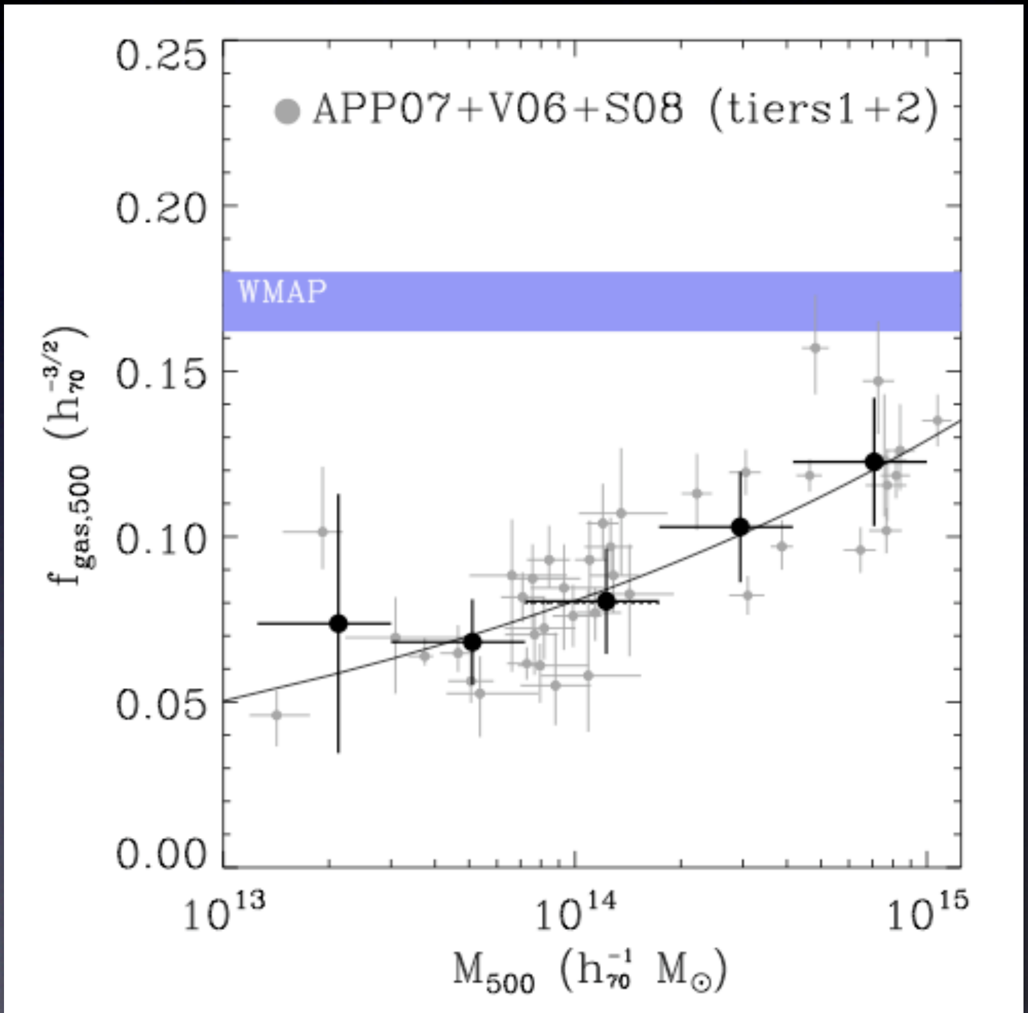
Croston et al 2008;
Croston et al 2006 for non-parametric deconvolution method

Origin of scaling relation slopes

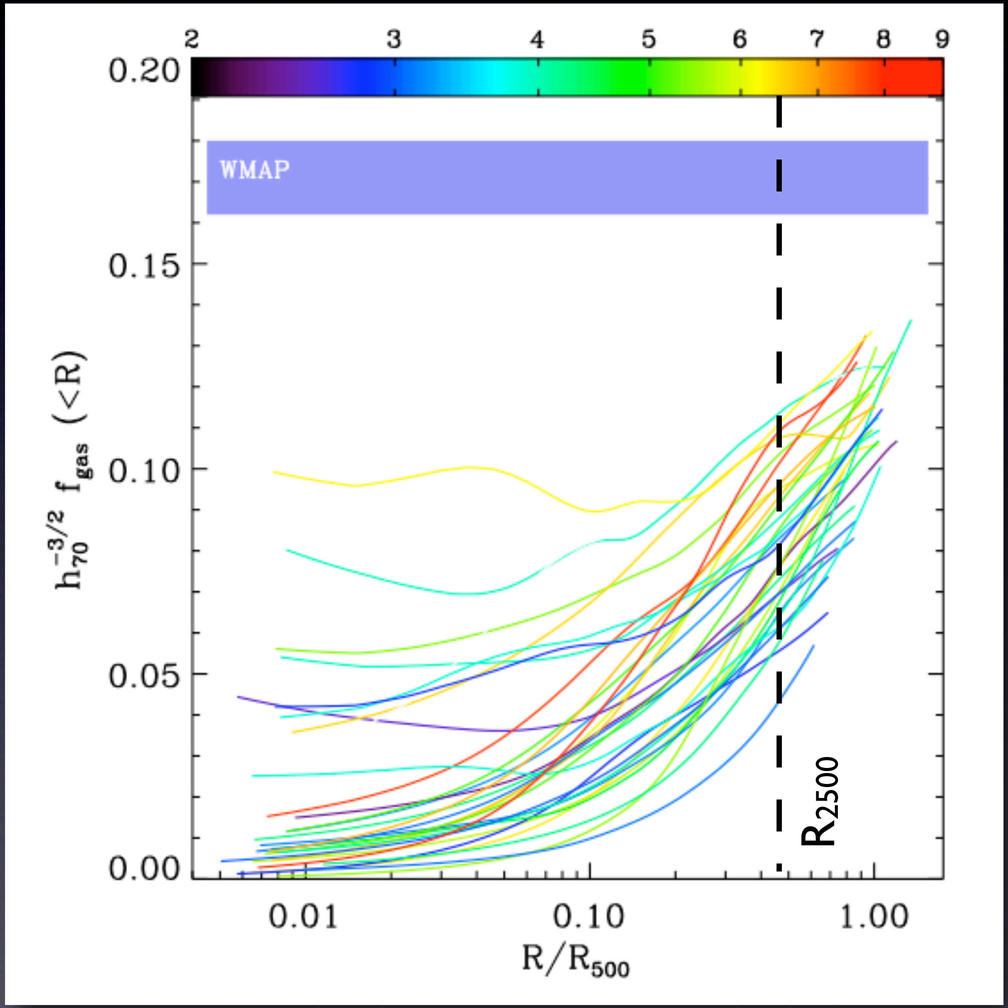
f_{gas}

Mass & radial dependence

total

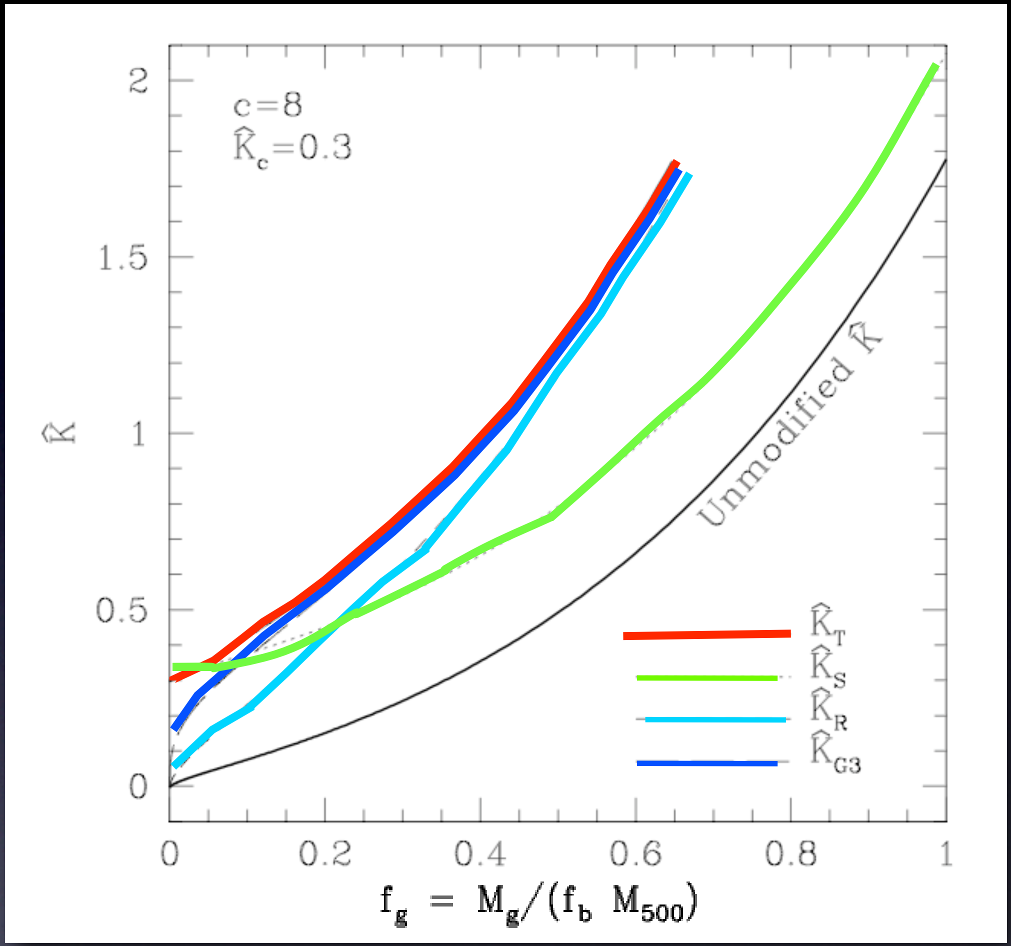


profile

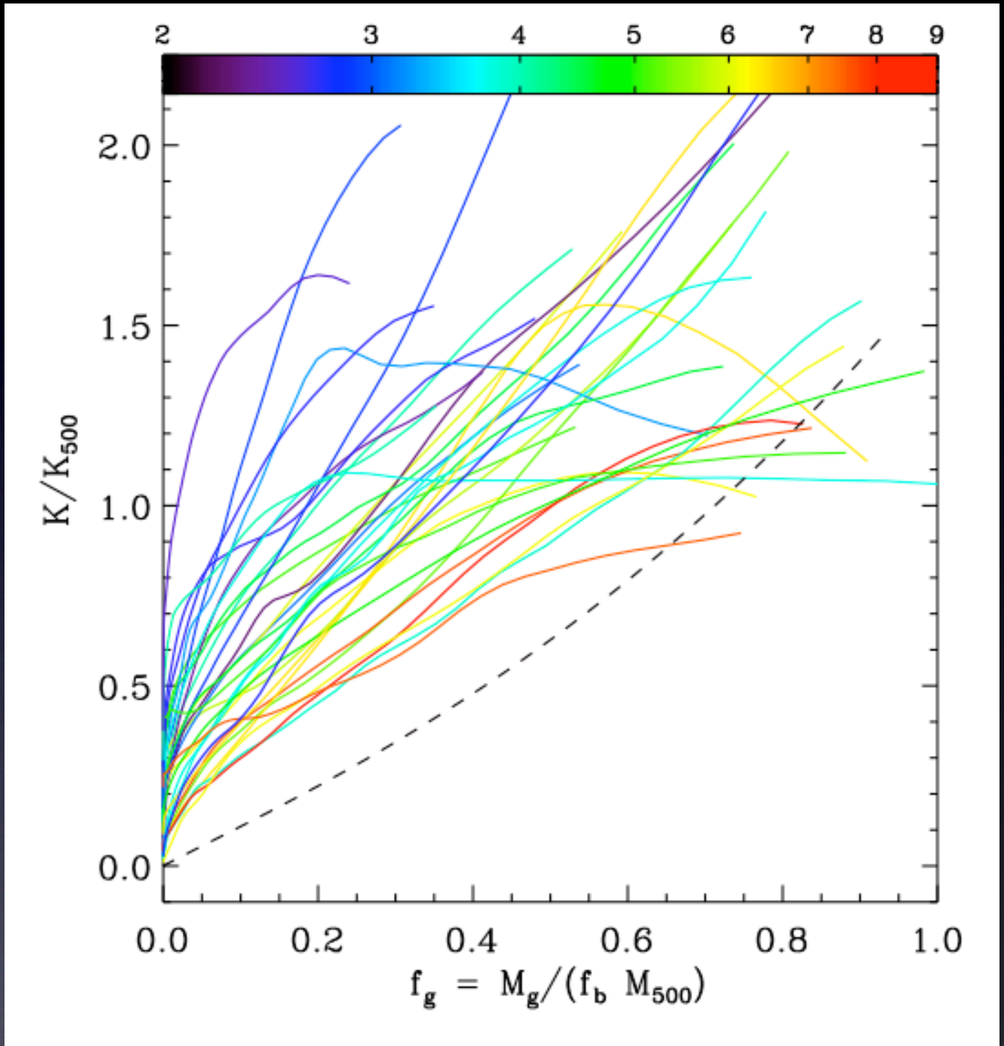


Pratt et al. 2009 & arXiv:0909.3776

Entropy modification



Voit et al 2002

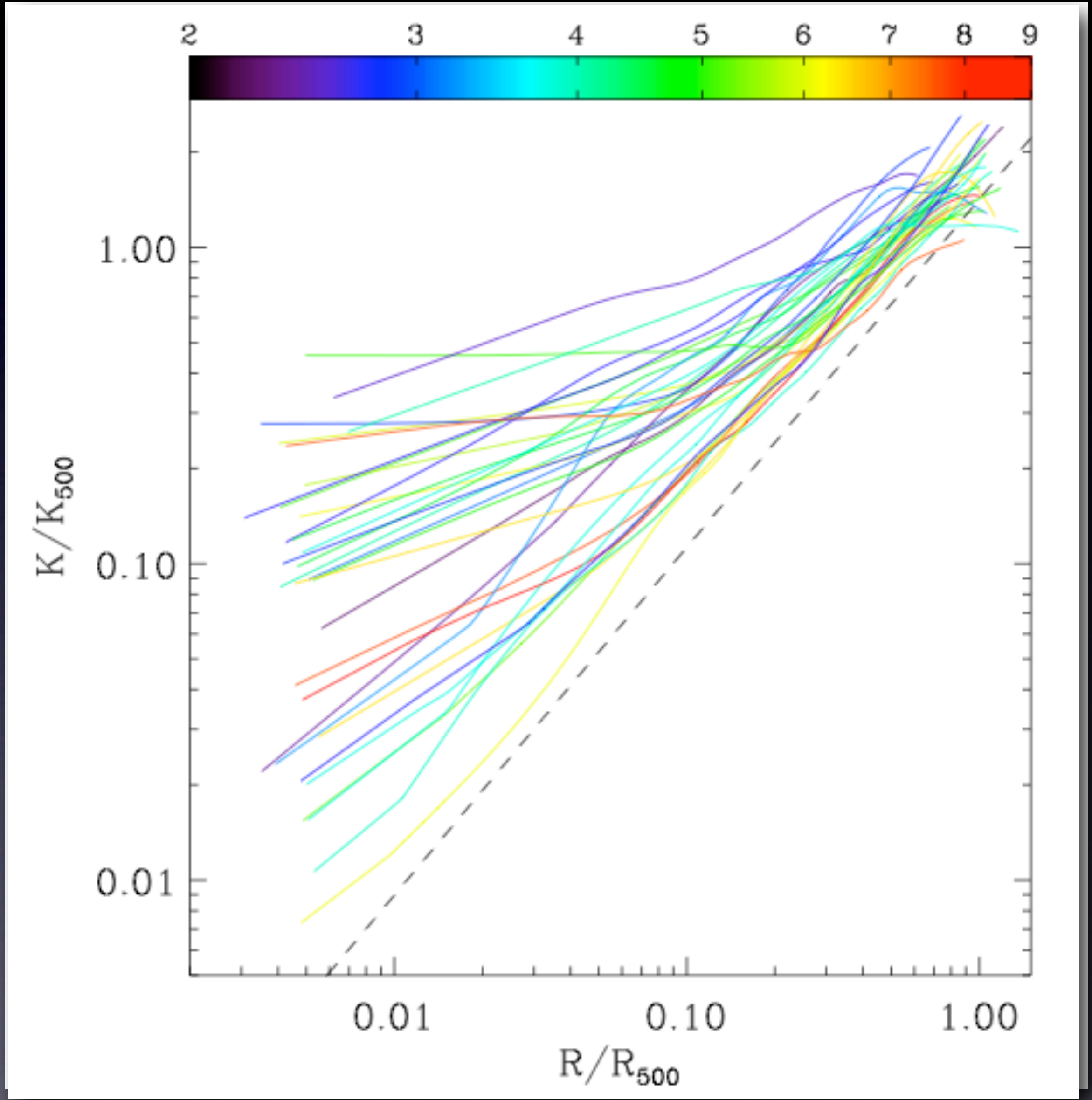


Pratt et al. arXiv:0909.3776

T ~ removal of gas
S ~ preheating
R ~ cooling

$K*f_{gas}$

Simultaneous radial and normalisation correction



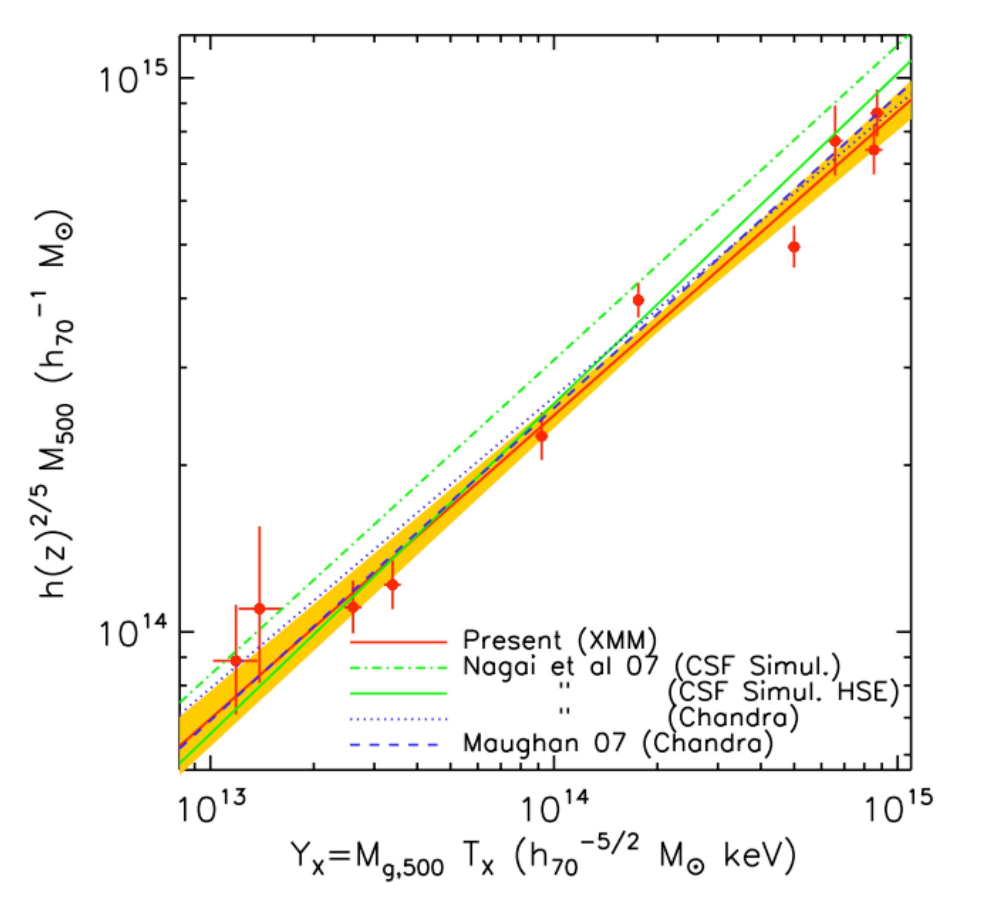
Pressure

$$P = n_e\, kT$$

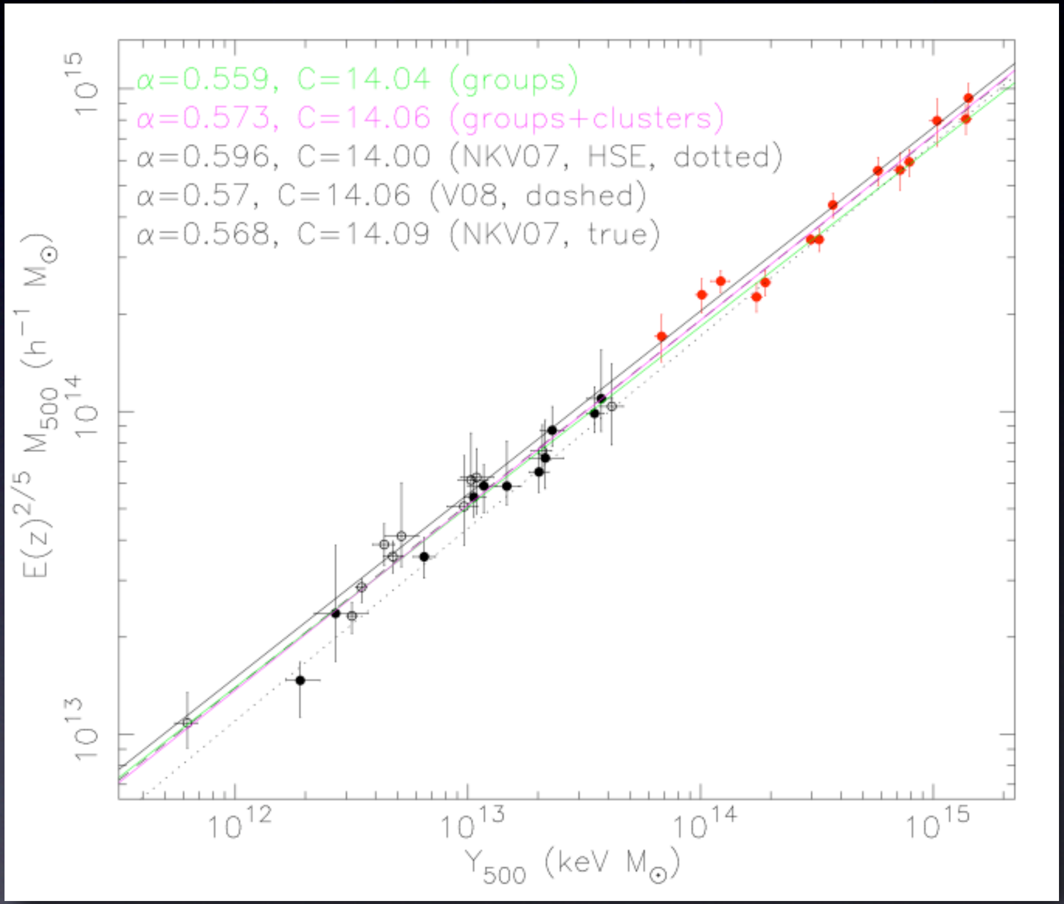
$M - Y_X$ relation

$$Y_X = M_{g,500}\, T$$

Slope close to self-similar, very low scatter



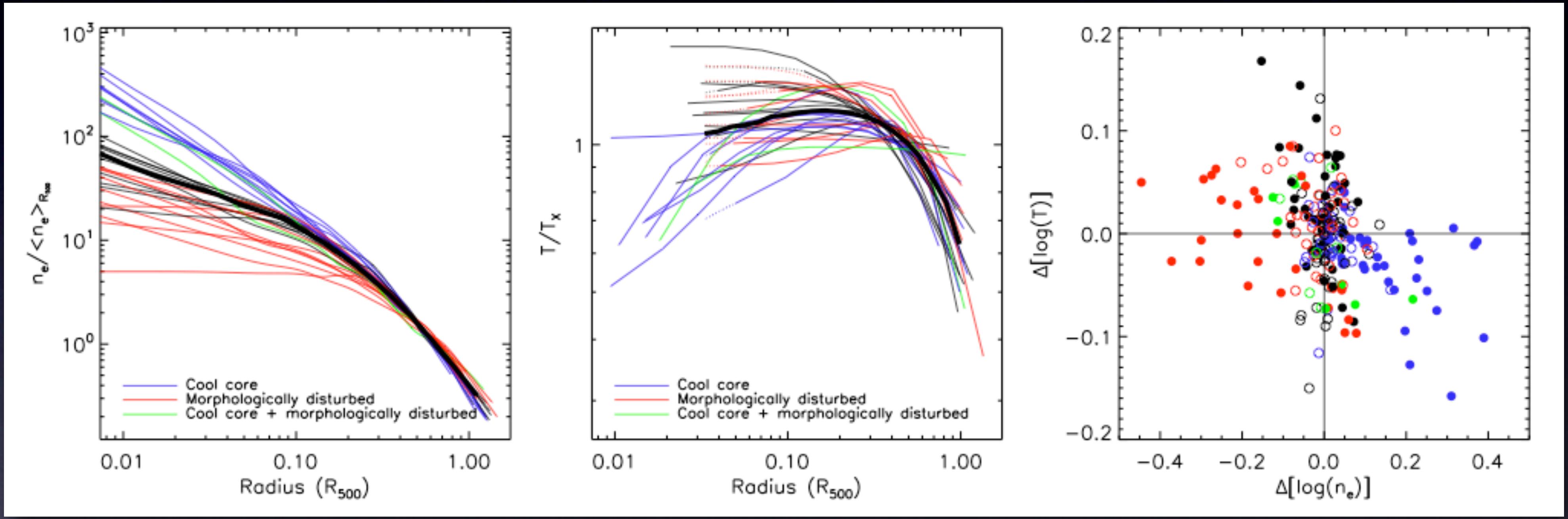
Arnaud et al. 2007



Sun et al. 2009

Anticorrelation of temperature and density in core

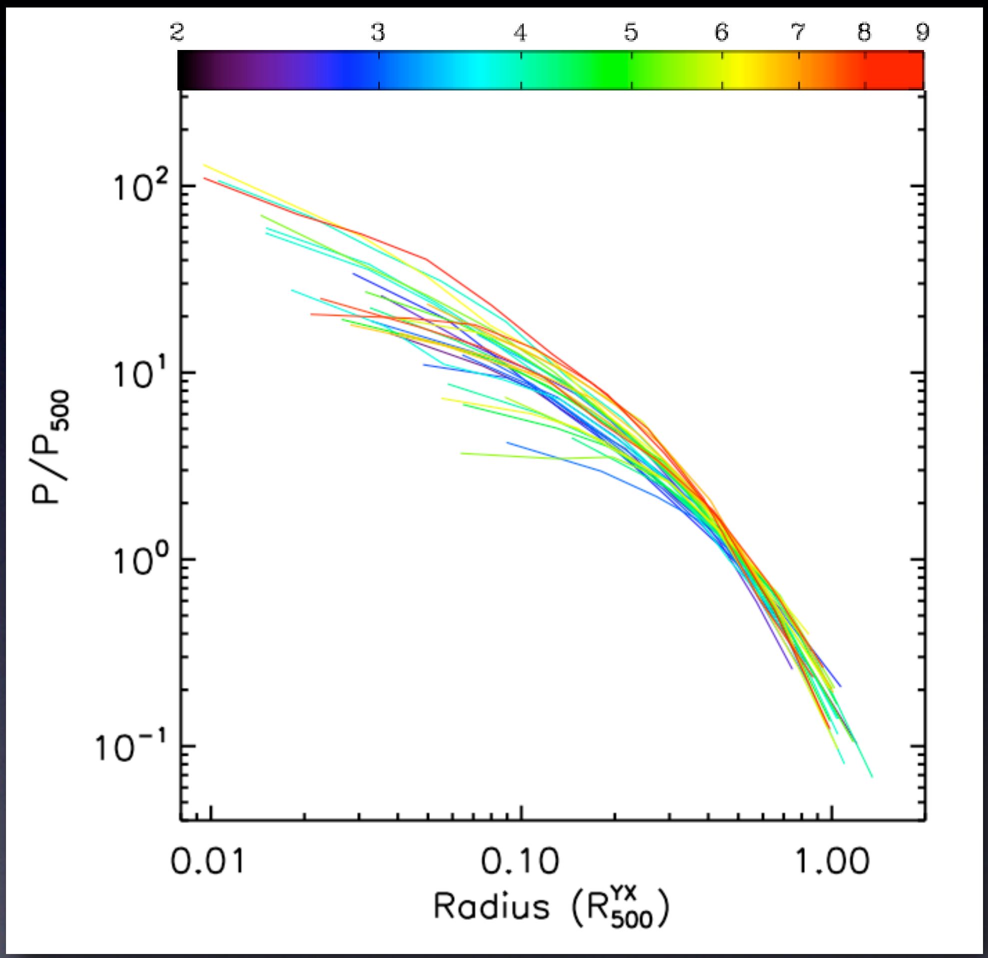
Same segregation

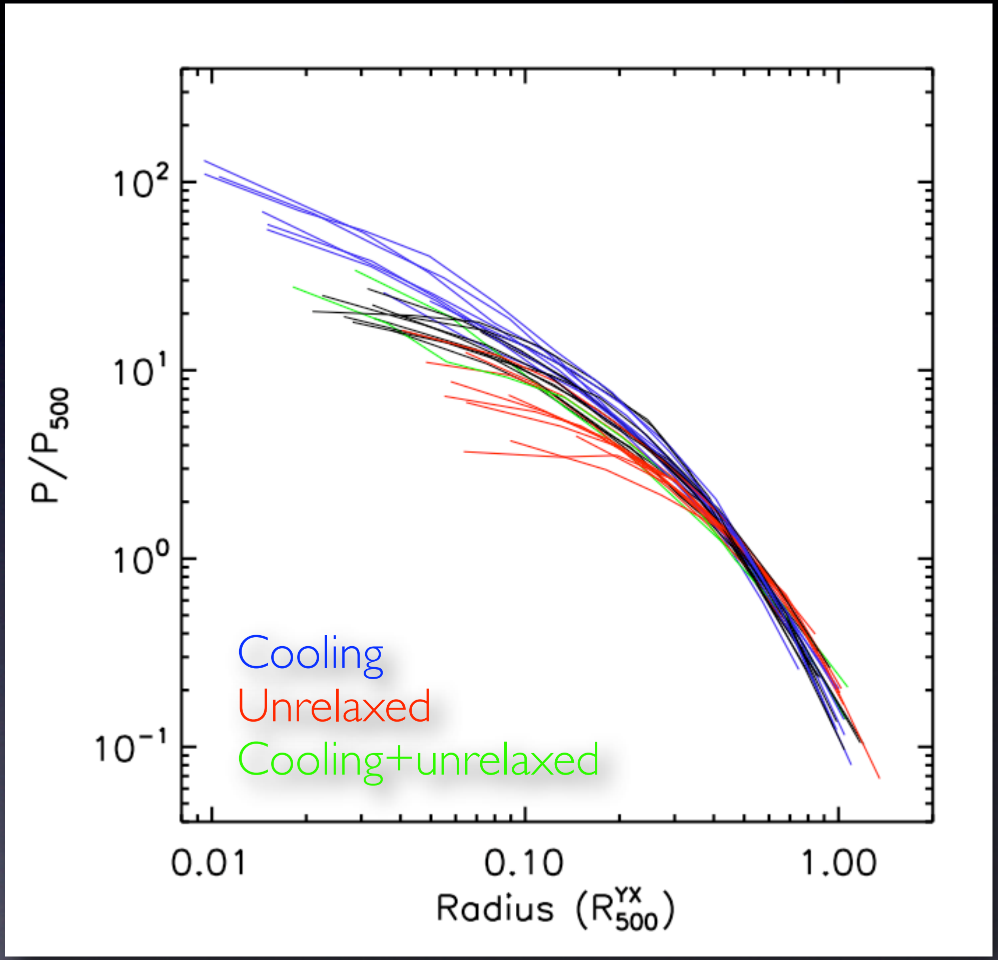


Arnaud et al. arXiv:0910.1234

Pressure

Anticorrelation minimises effects of non-gravitational processes

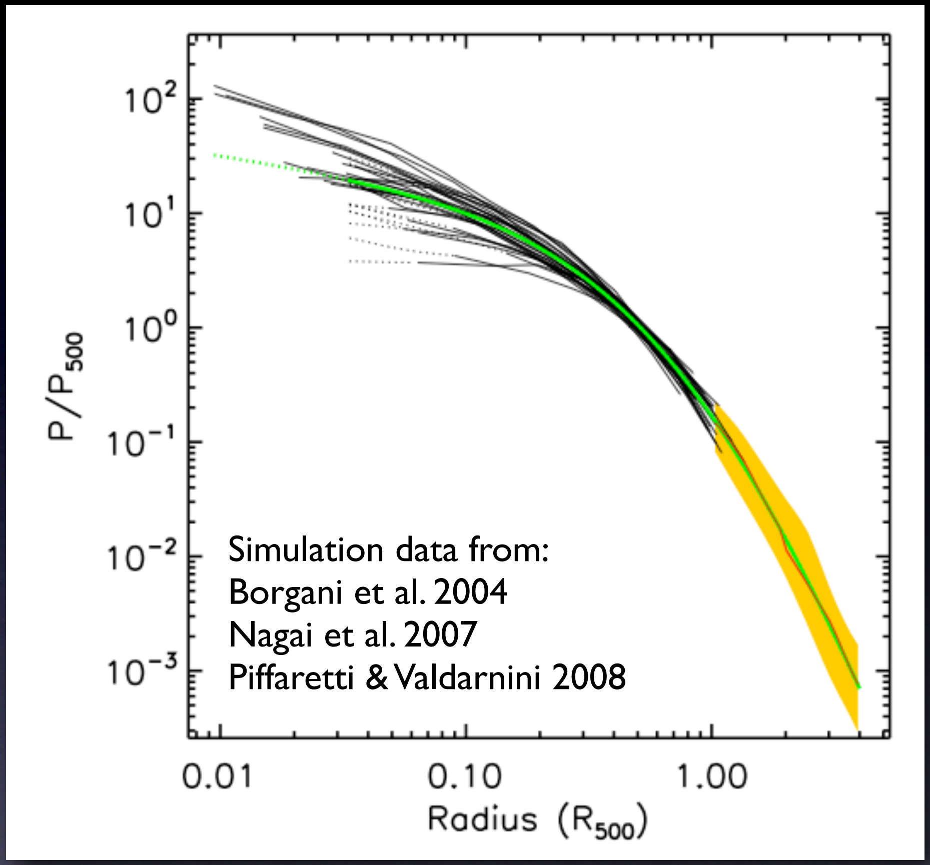


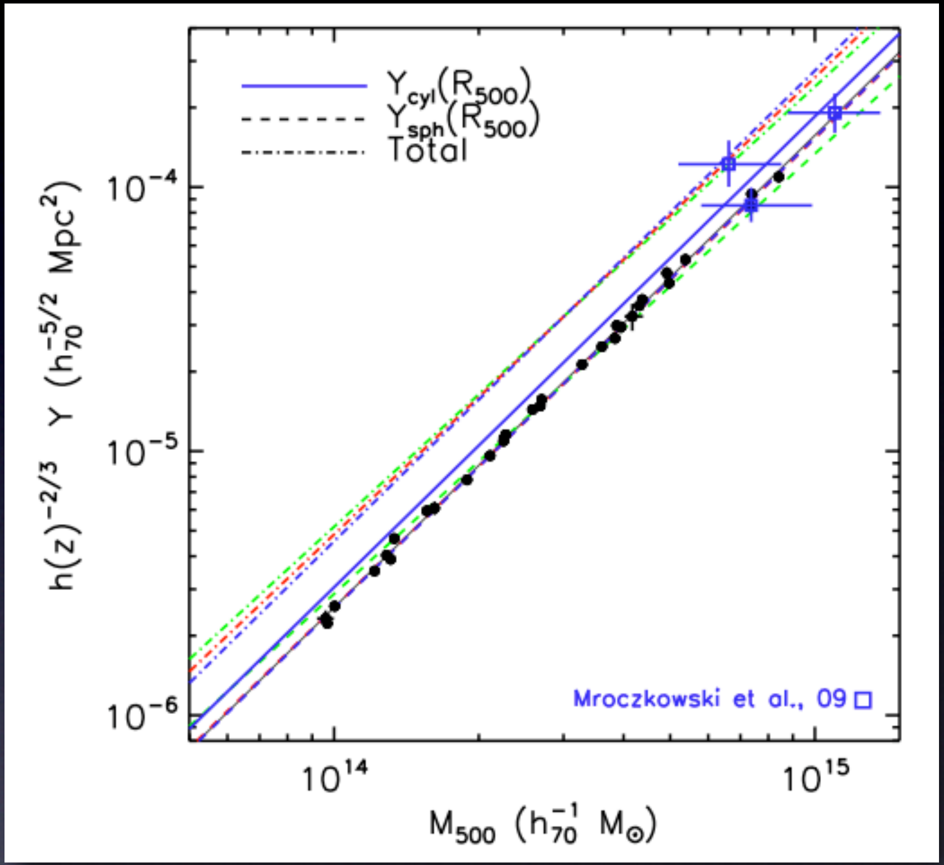


Arnaud et al. arXiv:0910.1234

Predicted SZ relations from X-ray profile+simulations

Small scatter, close to self-similar





Arnaud et al. arXiv:0910.1234

- SZ effect: scattering of Compton scattering of CMB photons by ICM

$$Y_{\rm SZ} D_A^2 = (\sigma_{\rm T}/m_{\rm e}c^2) \int P_{\rm e} dV$$

- Combine observations [0.03-1] R_{500} and simulations [1-5] R_{500}

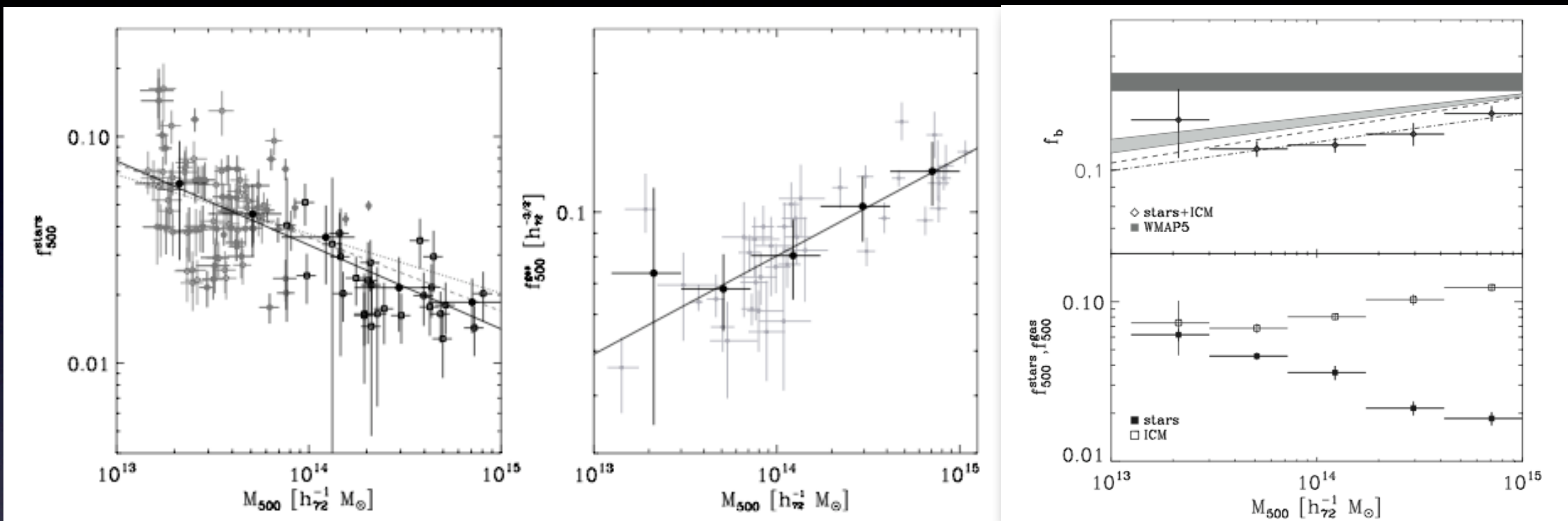
Conclusions

- X-ray clusters are very regular objects outside the core
  - Need to detect $R > R_{2500}$ to fully see this, though
- X-ray clusters become more self-similar with increasing radius
  - Non-gravitational processes preferentially affect core regions
- Scatter in L_X relations caused primarily by cool core effects
  - Exclude or correct for this, and relations tighten dramatically
- Deviation from standard self-similarity due to variation of f_{gas} with mass, radius
- Representative samples key to unlocking potential of larger cluster population for precision cosmology

Perspectives

Perspectives (1)

Groups - where the action is

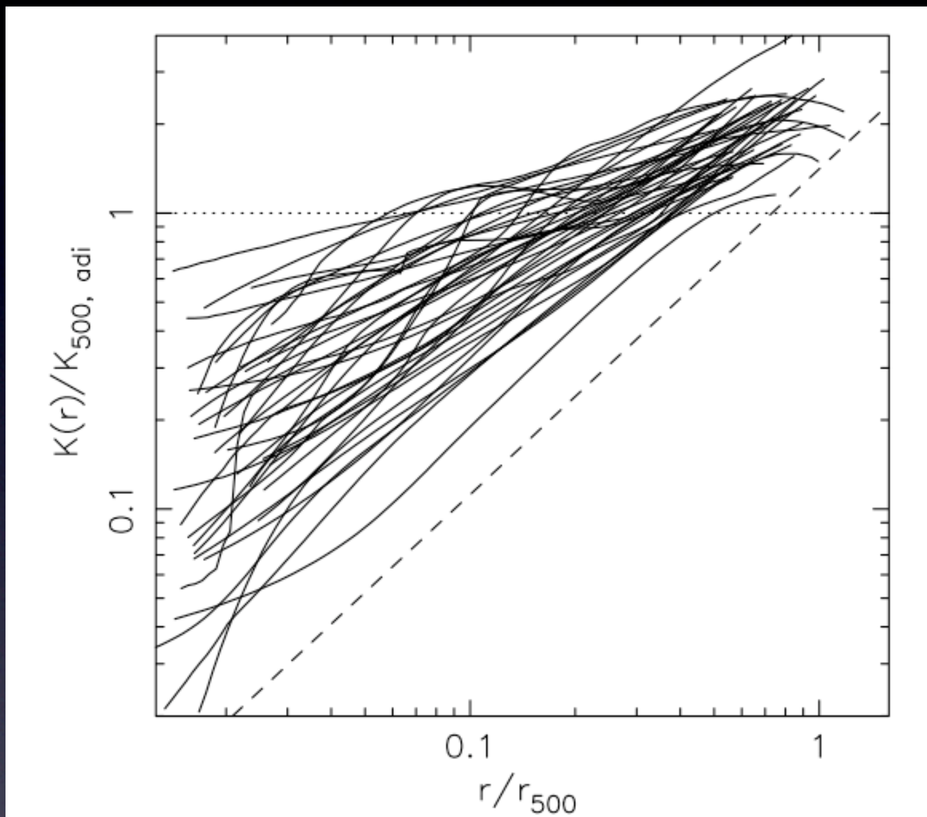


Giodini et al.2009

- Groups ($\lesssim 2\mathrm{keV}$ or $10^{14}\,M_\odot$) key to understanding non-gravitational processes
- Anti-correlation of f_{gas} and f_{star} insufficient to reconcile total baryon fraction with WMAP ⇒ clear baryon loss at group scale
- Better observations (X-ray AND optical) needed

Perspectives (1)

Groups - where the action is

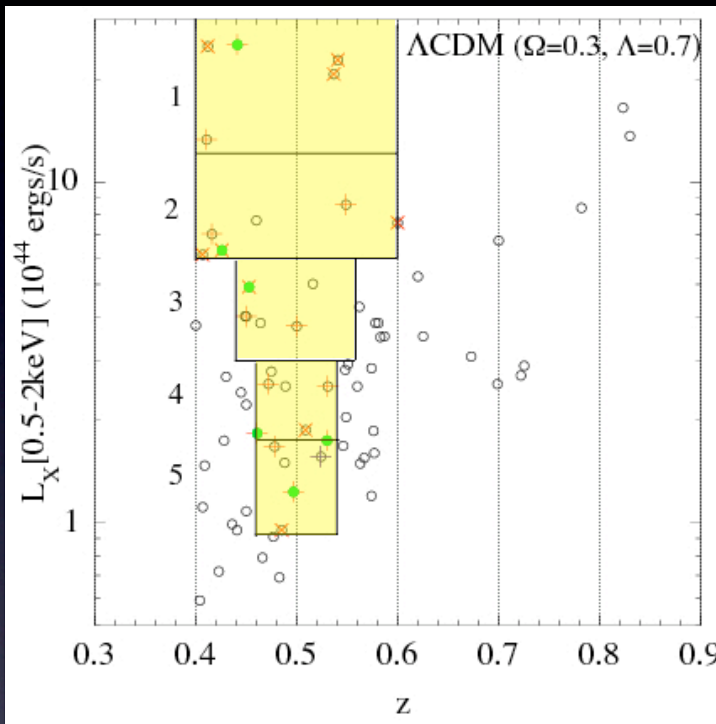


Sun et al. 2009;
morphologically relaxed systems only

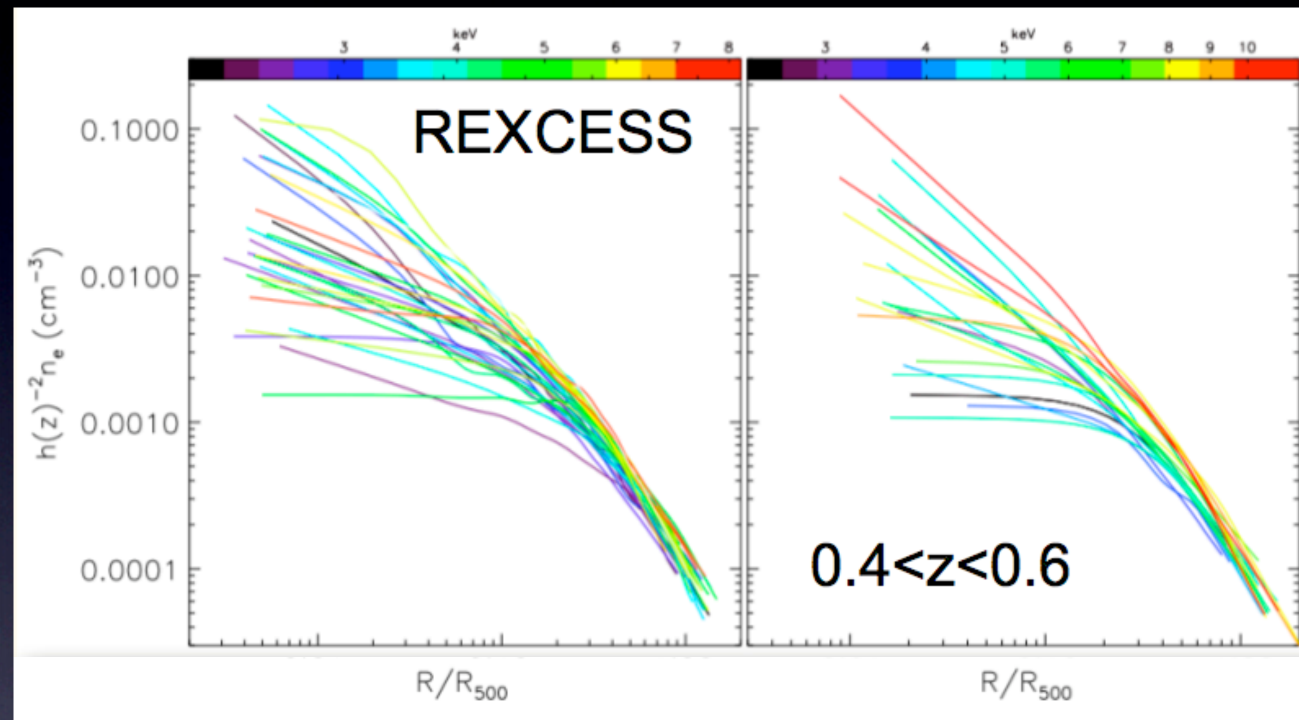
- Only relaxed systems so far have high-quality observations; several proposals to observe representative samples

Perspectives (2)

Evolution



Arnaud et al. in prep.



Pointecouteau et al. in prep.

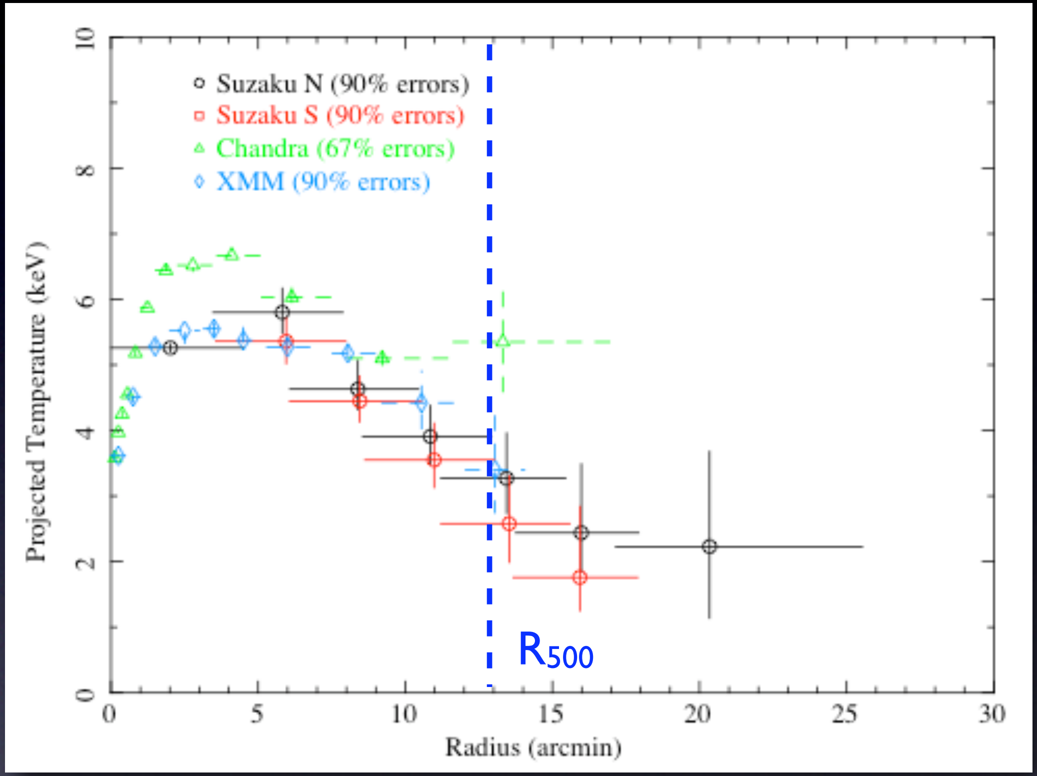
- Representative sample of 20 system at 0.4 < z < 0.6 observed in XMM LP (PI: M Arnaud)
- Multiwavelength follow-up, including lensing, radio
- Work ongoing...

Perspectives (3)

Line broadening - application to turbulence, AGN heating

Perspectives (4)

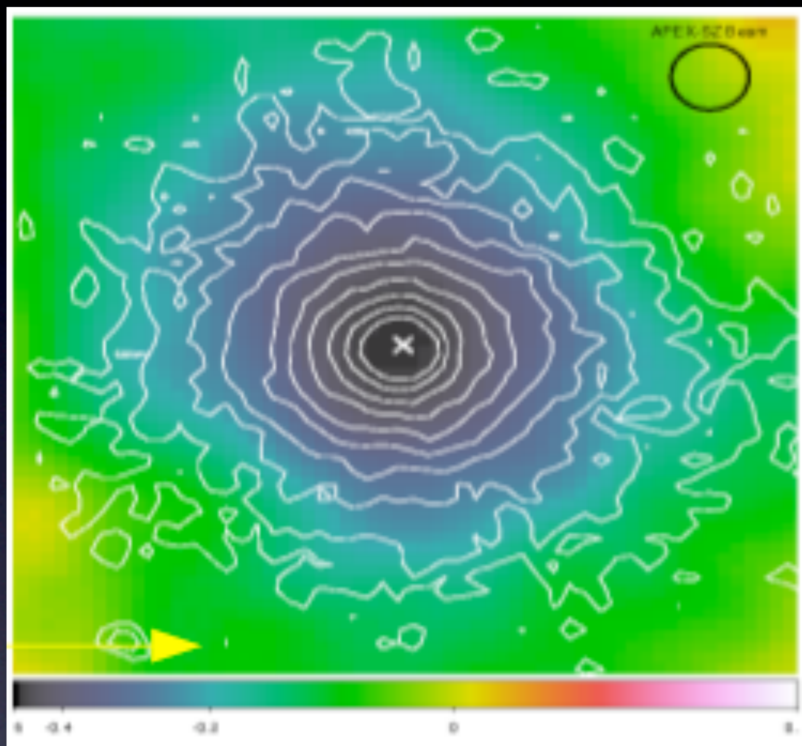
Exterior regions



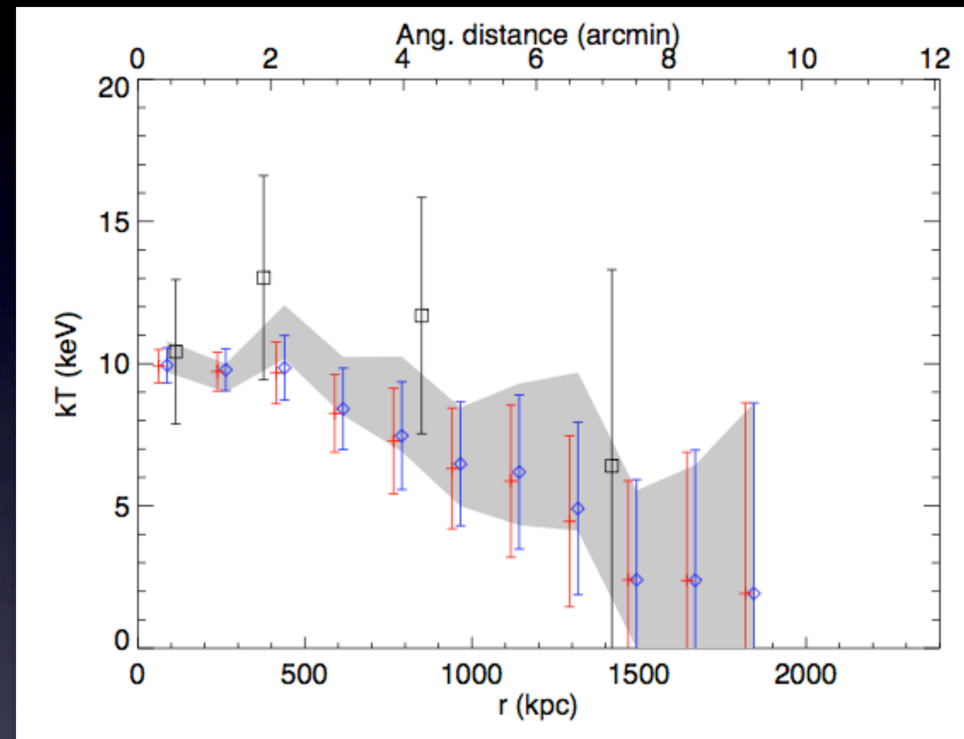
Bautz et al. 2009 (A1795)

- Region beyond R_{500} largely unexplored, but interesting
- Suzaku spatial resolution not optimal

Perspectives (5)
SZ



Basu et al. in prep. (A2204)

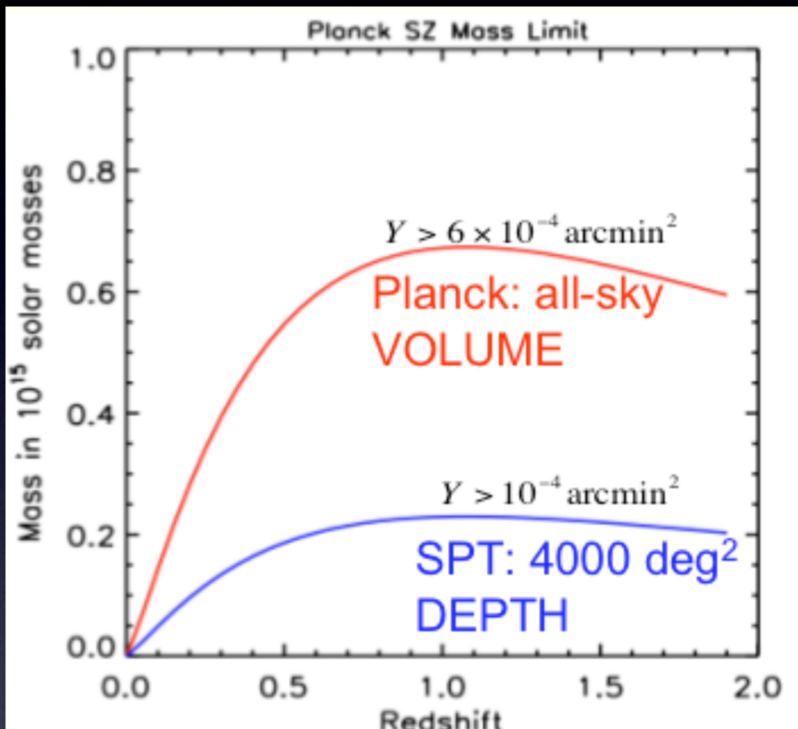


Nord et al. 2009 (A2163)

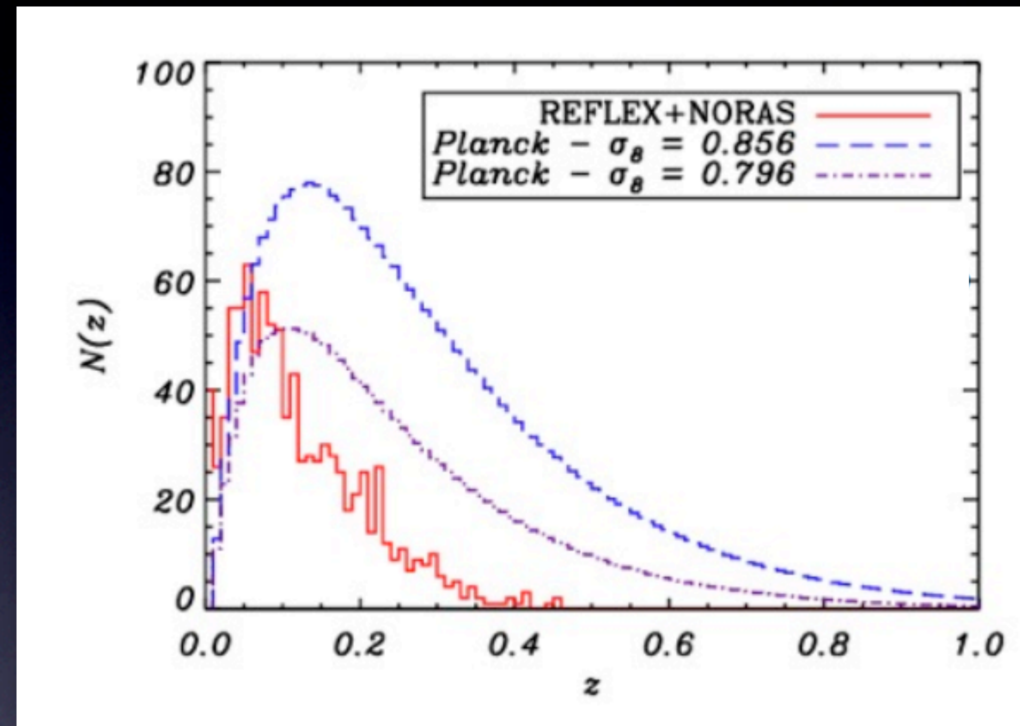
- SZ observations are an alternative probe of the ICM
- n_e dependence; should be more sensitive at larger R
- Now able to directly derive physical parameters without X-rays (APEX)

Perspectives (6)

Surveys & cosmology



Bartlett et al. 2008



Chamballu et al. 2009

- Tradeoff volume vs depth
- Planck ALL-SKY survey to detect > 2000 massive clusters, many at high z
- SPT SZ survey covering 4000 deg2
- eROSITA, WFXT ALL-SKY X-ray surveys
- PanSTARRS, DES, etc in optical

Thanks

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