Self-similarity Breaking in Galaxy Clusters

The Birmingham-CfA Cluster Scaling Project

Alastair Sanderson

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

with
Trevor Ponman, Alexis Finoguenov, Ed Lloyd-Davies &
Maxim Markevitch

Outline

- Background & introduction to project
- Gas mass fraction
- ICM entropy
- Optical results
- Summary

Introduction

- Virialized systems comprise 3 distinct mass components. On average:
  - 2–5% Stars
  - 10–15% Hot gas
  - 80–85% Dark matter

($H_0 = 70$ km s^{-1} Mpc^{-1})

- Useful cosmological probes; yield important information on feedback & interaction processes

- Under simplest assumptions, expect such systems to be *self-similar* – i.e. optical light & gas trace mass, which simply scale with halo mass

- Observational evidence reveals simple scaling *not* obeyed for X-ray emitting IGM

- Extra physics needed e.g.
  - heating via energy injection
  - radiative cooling

The cluster scaling sample

- Detailed X-ray study, as majority of baryons reside in gaseous intergalactic medium ($\sim 10^{7-8}$ K, $\sim 10^{-3}$ cm^{-3})

- Main (X-ray) sample comprises 66 rich clusters, groups & individual galaxies (median $z =$ 0.035) with $kT \sim$ 0.4 – 17 keV
  $\rightarrow \quad \sim$ 200 kpc – 3 Mpc

- Have determined deprojected gas $T(r)$ & $\rho(r)$, corrected for effects of central cooling

- Optical sub-sample comprises 32 groups & clusters, with deprojected optical luminosity profiles

- Assume $H_0 = 70$ km s^{-1} Mpc^{-1}

(See Sanderson et al, 2003 for details)

Data Analysis

- *ASCA* & *ROSAT* data – combining Markevitch, Finoguenov & Lloyd-Davies samples + new analysis

- Use beta model for gas density and either linear or polytropic temperature profile:

$$\rho(r) = \rho(0)\left[1+\left(\frac{r}{r_c}\right)^2\right]^{-\frac{3}{2}\beta}$$

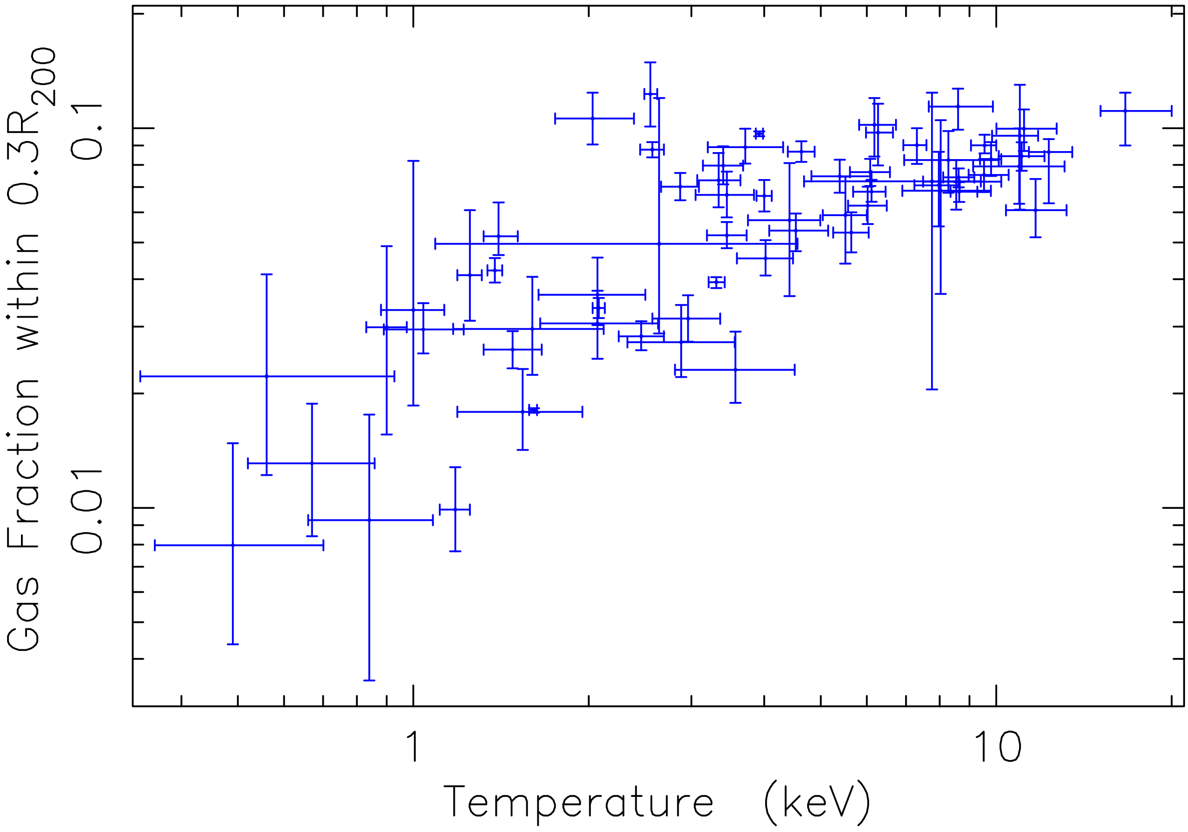
$$T(r) = T(0)\left[1+\left(\frac{r}{r_c}\right)^2\right]^{-\frac{3}{2}\beta(\gamma-1)}$$

- Derive gravitating mass, assuming hydrostatic equilibrium:

$$M_{grav}(r) = -\frac{kT(r)\,r}{G\mu m_{\mathrm{p}}}\left[\frac{\mathrm{d}\ln\rho}{\mathrm{d}\ln r}+\frac{\mathrm{d}\ln T}{\mathrm{d}\ln r}\right]$$

- Virial radius, mean temperature etc., all derived *self-consistently*

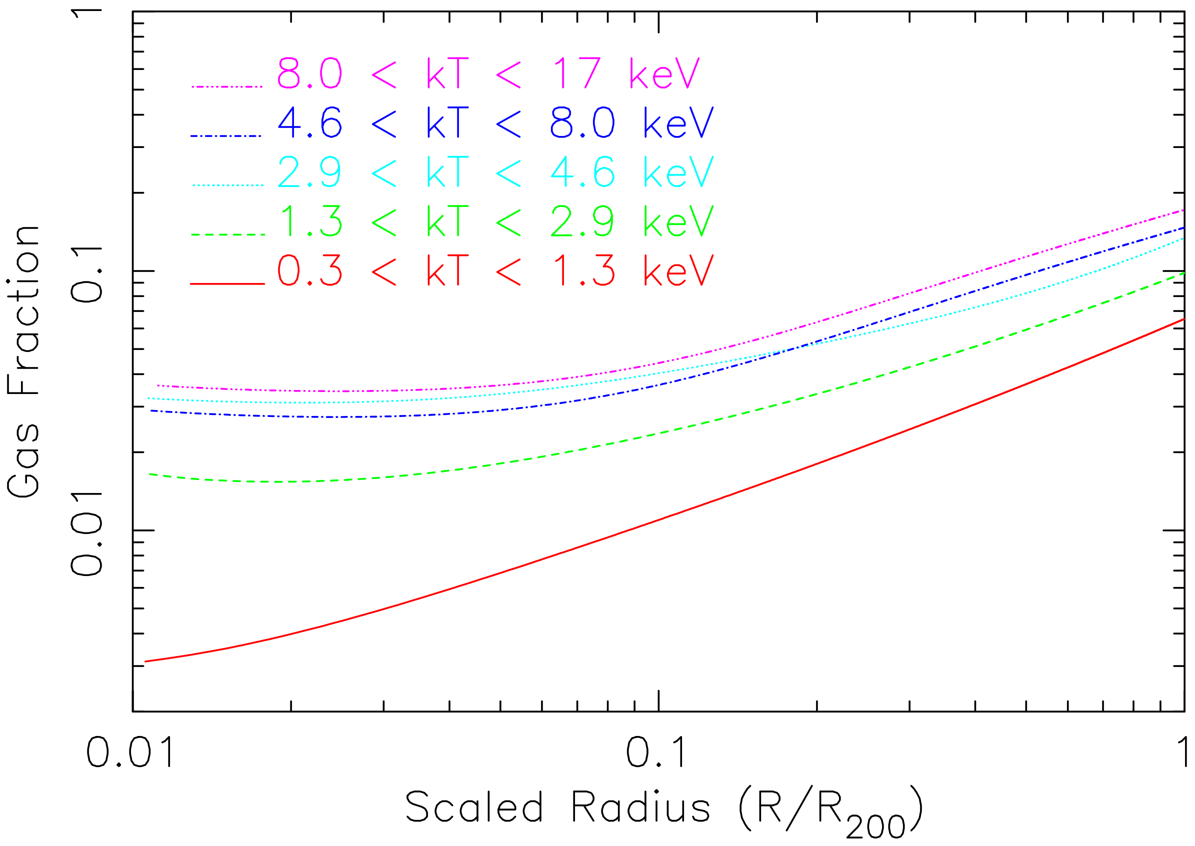
Gas fraction vs temperature



Gas fraction at $0.3R_{200}$ as a function of emission-weighted temperature

- 6σ trend: groups have significantly less gas at $0.3R_{200}$ than clusters—reflects their flatter gas density profiles
- Where is missing gas in cooler systems?

Gas fraction profiles



Mean gas fraction profiles, grouped by X-ray temperature.

- $f_{\rm gas}$ rises monotonically with radius ($> 0.03R_{200}$), normalization increases with temperature
- Hot gas is most extended mass component
  ⇒ Most influenced by heating/cooling mechanisms
- Rising $f_{\rm gas}$ profile predicted by simulations, *even without heating/cooling* (e.g. Santa Barbara comparison project – Frenk et al. , 1999)
- Does group $f_{\rm gas}$ “catch up” with clusters within $R_{\rm v}$?

Gas entropy: an overview

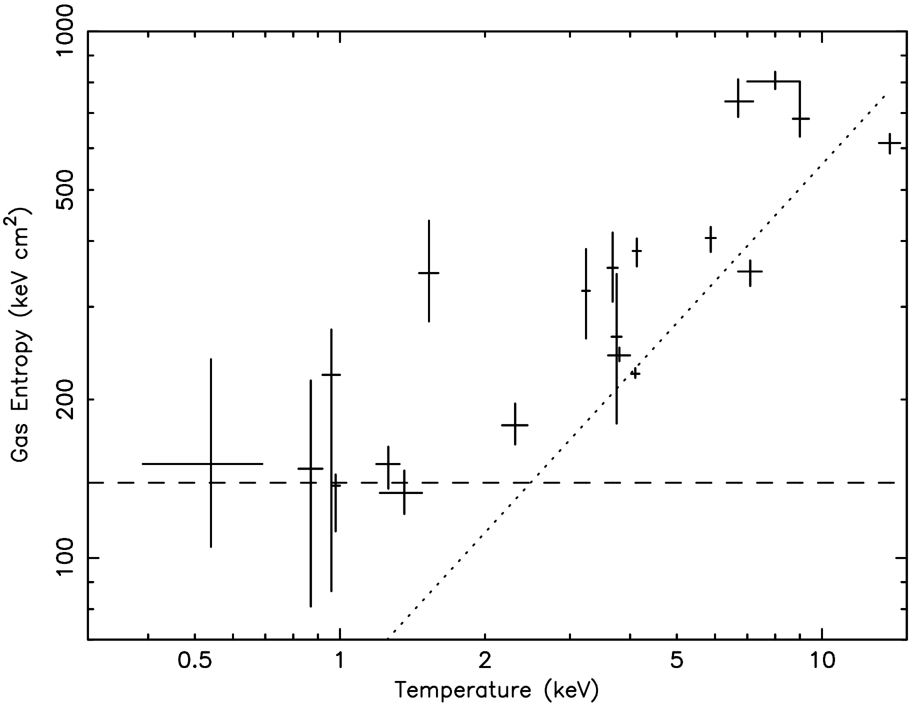
- For an ideal gas, ignoring constants & logs, defined as

$$S = \frac{kT}{n_{\mathrm{e}}^{2/3}}$$

- Entropy conserved in any adiabatic process

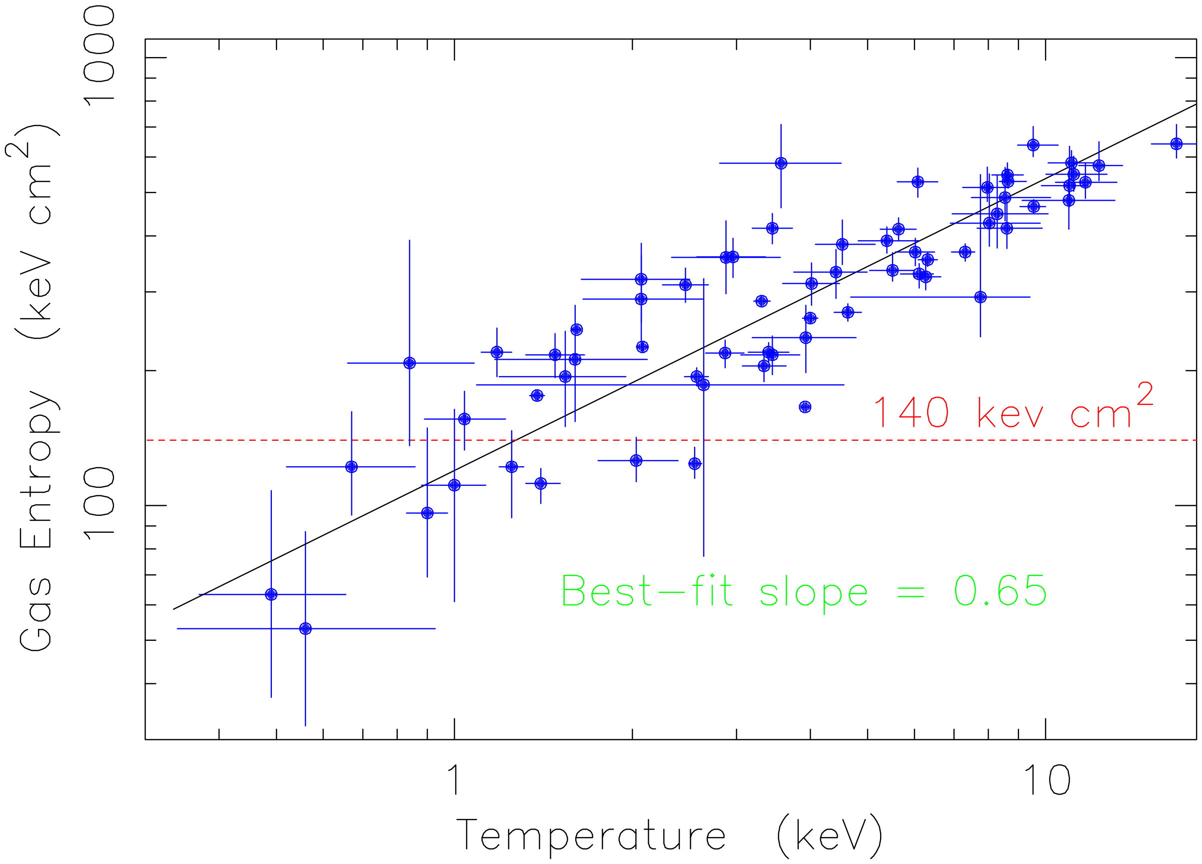
  $\Rightarrow$ Powerful probe of non-gravitational physics

- Entropy must rise monotonically with radius for convective stability



Entropy at $0.1R_{\mathrm{v}}$ vs emission-weighted temperature (Lloyd-Davies et al., 2001)

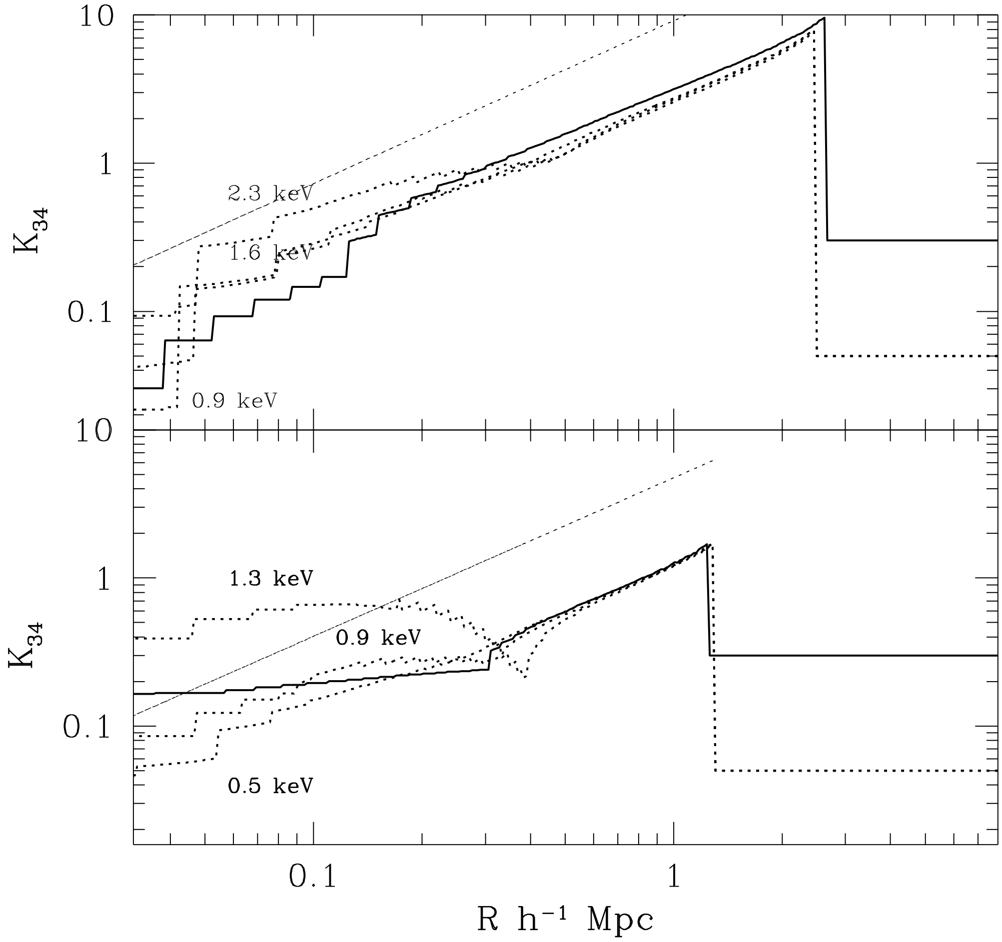
Entropy vs temperature



Entropy at $0.1R_{200}$ vs emission-weighted temperature

- Slope (0.65 ± 0.05, excluding the 2 galaxies) flatter than self-similar prediction of $S(r) \propto kT$
- Good agreement with simple cooling model of Voit & Bryan, 2001
- Excess entropy – more apparent in cooler systems, but no evidence of entropy “floor”

Simulated entropy profiles

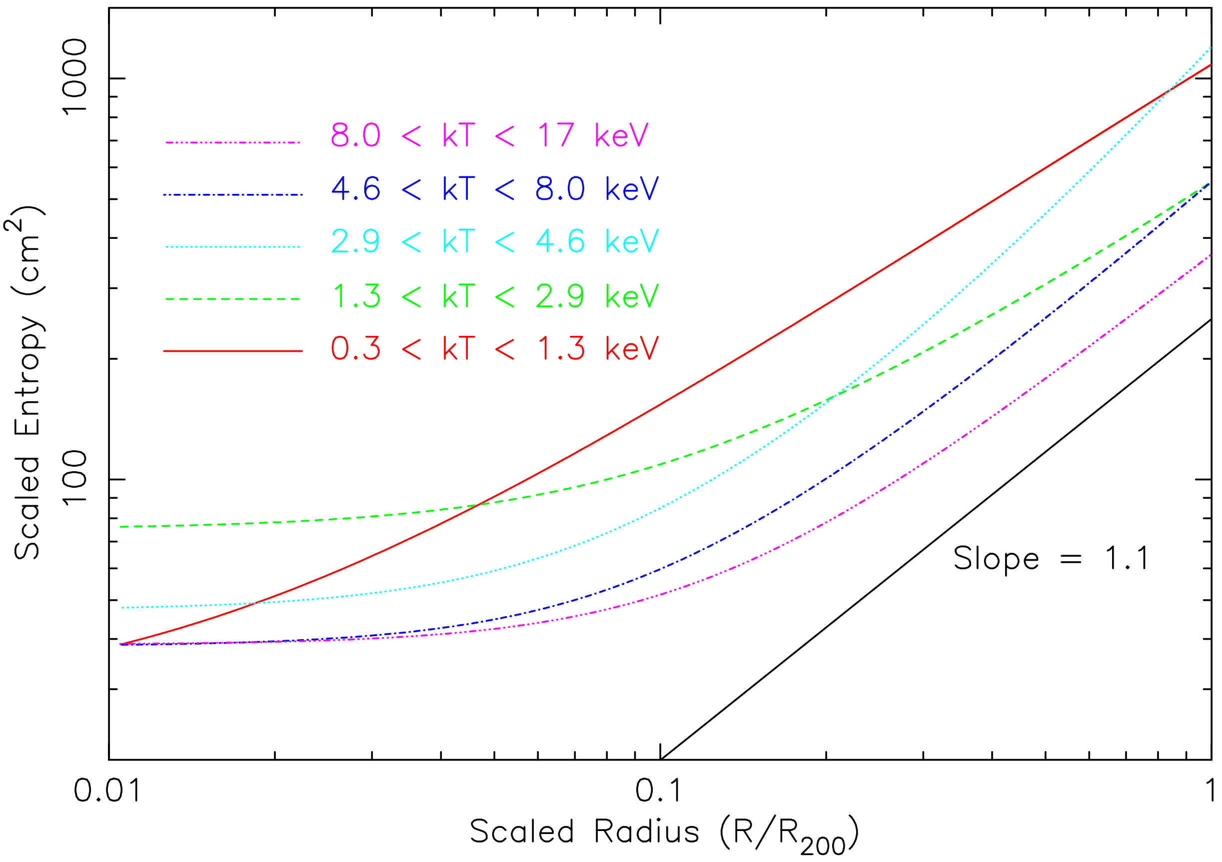


Entropy profiles for a rich cluster ($M = 10^{15} h^{-1} M_{\odot}$, upper panel) and a small cluster ($M = 10^{14} h^{-1} M_{\odot}$, lower panel).

Tozzi, P. & Norman, C., 2000, ApJ, 542, 106

- Solid curves show external heating case (pre-heating)
- Predict $S(r) \propto r^{1.1}$ within shock region
- Predict flat entropy core from pre-heated IGM

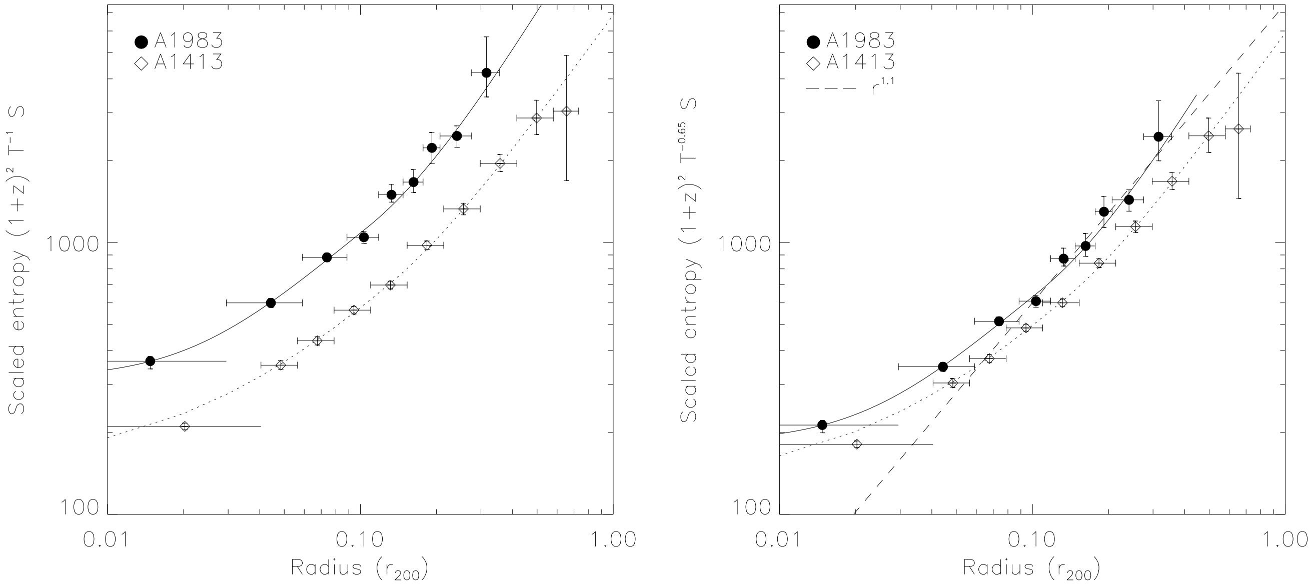
Scaled entropy profiles



Mean entropy profiles (scaled by kT), grouped by temperature (from Ponman, Sanderson & Finoguenov, 2003: PSF03).

- Entropy rises monotonically with radius
- Cooler systems have a greater entropy excess
- Asymptotic logarithmic slope consistent with accretion shock entropy
  – e.g. Tozzi & Norman, 2000 model predicts $S(r) \propto r^{1.1}$
- **No evidence of large isentropic core**
  ⇒ Incompatible with standard preheating

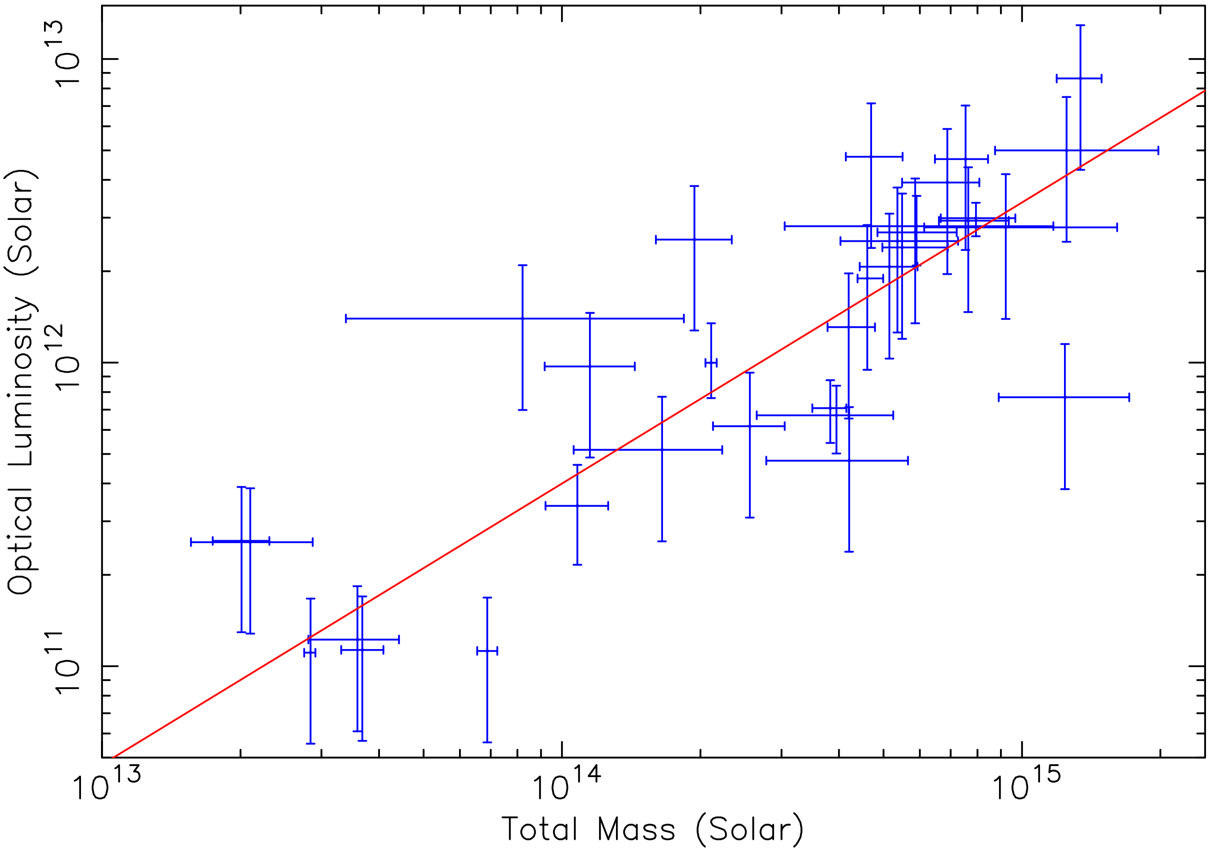
XMM-Newton observation of the poor cluster A1983



From Pratt & Arnaud, 2003

- A1983 $kT \sim 2$ keV ; A1414 $kT \sim 7$ keV
- No isentropic core present in A1983
- Right: Scaled with $S \propto (1+z)^{-2} {T_X}^{0.65}$ from PSF03
- Right: Dashed line is $S \propto r^{1.1}$ (shock heating) normalized to scaled entropy of a 10 keV cluster from PSF03

Optical Luminosity vs Halo Mass



Optical luminosity within R_{200} (B_j band) as a function of Total mass within R_{200} **for the optical sample**.

- Surface density fits to APM data
- Derive normalization from aperture luminosities in literature (Mainly Girardi et al. , 2002)
- Red line is best fitting power-law: $L_\mathrm{B,j} \propto M^\alpha$, where $\alpha = 0.93 \pm 0.10$
- Logarithmic slope consistent with self-similar prediction of 1

Summary

- The intergalactic medium is less dense & more extended in smaller halos
  - ⇒ heating and/or cooling

- No evidence of isentropic cores or entropy floor

- Stellar properties broadly self-similar
  - ⇒ Star formation only slightly enhanced in groups

- Need both heating **and** cooling

- Preheating may act mainly to reduce gas density along accreting filaments