Entropy in nearby galaxy clusters

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3/9

XMM-Newton observations of three poor clusters: Similarity in dark matter and entropy profiles down to low mass

*[*Pratt, G. and Arnaud, M. , 2005*]*

&

Structure and scaling of the entropy in nearby galaxy clusters

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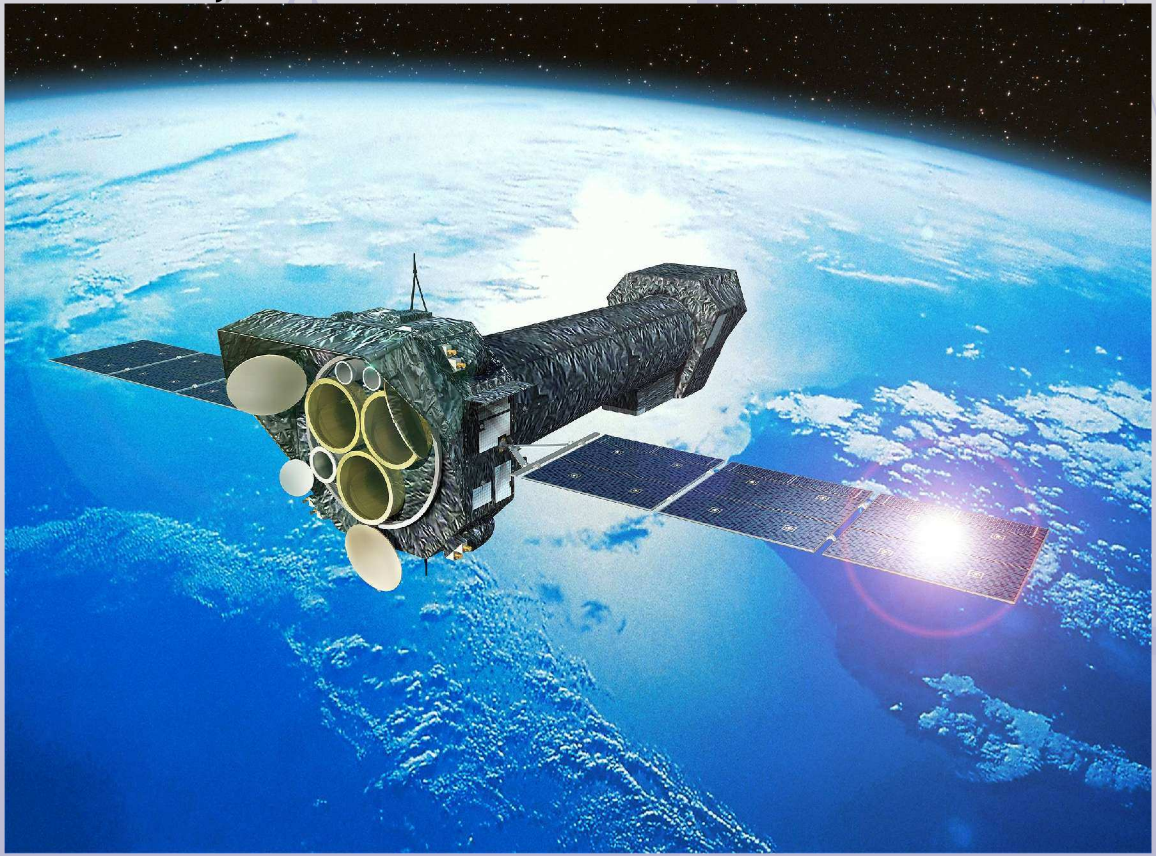
XMM-Newton

- NASA-ESA
- Launched 12 / 1999, still active
- Observes

  x-rays of

  0.2-12 keV

ESA



First paper:

XMM-Newton observations of three poor clusters: Similarity in dark matter and entropy profiles down to low mass

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Second paper:

Structure and scaling of the entropy in nearby galaxy clusters

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Motivation

- Better understanding of cluster formation / evolution
- See to what degree non-gravitational processes are significant
- Mass profile M(r)
  - Information about gravitational collapse
- Entropy is generated in shocks as gas is drawn into the potential well of the cluster
- Entropy profile S(r)
  - ICM accretion, thermodynamic history
  - Non-gravitational processes

These x-rays

- Intracluster medium (ICM) – hot gas
- Two quantities define x-ray properties
  - Entropy profile of the gas, S(r)
  - Shape of the gravitational potential well; M(r)

- Low-mass clusters
  - Non-gravitational, gravitational comparable

This paper

- Sample: A1991, A2717, MKW9
  - Three low-mass, cool clusters
  - $0.04 \le z \le 0.06$
  - kT = 2.65, 2.53, 2.58 keV
  - Combine with previous results for cool A1983 (kT = 2.2 keV) and hot A1413 (kT = 6.5 keV)
- Assumptions
  - ΛCDMH70: H_0=70 km s^{-1} Mpc^{-1}, Ω_m=0.3, Ω_Λ=0.7
  - Some SCDMH50: H_0=50 km s^{-1} Mpc^{-1}, Ω_m=1.0, Ω_Λ=0.0

Sample of clusters

- 10 systems
  - Temperatures:
    kT = 2 keV … 8.5 keV
  - Redshifts: $0.03 \leq z \leq 0.15$
- ΛCDMH70

Cluster	*z*	*T* (keV)
A1983	0.0442	2.18 ± 0.09
A2717	0.0498	2.56 ± 0.06
MKW9	0.0382	2.43 ± 0.24
A1991	0.0586	2.71 ± 0.07
A2597	0.0852	3.67 ± 0.09
A1068	0.1375	4.67 ± 0.11
A1413	0.1427	6.62 ± 0.14
A478	0.0881	7.05 ± 0.12
PKS0745	0.1028	7.97 ± 0.28
A2204	0.1523	8.26 ± 0.22

Overview

- Expectations from models of cluster formation, discrepancies *Mass and entropy
- Surface brightness profiles
  - Emission measure profiles
  - Gas density profiles
- Hardness ratio images
  - Temperature structure – dynamical state
- Annular spectral analysis & surface brightness profiles
  - Abundance profiles
  - Temperature profiles
    - Correct for projection, PSF effects (gas density profiles)
- Mass and entropy profiles
  - From gas density, temperature profiles
  - And scaled

Overview

- Larger sample size, - scaling parameters
- Entropy-temperature relation
  - At different fractions of virial radius
    - R_{200}: radius within which density is 200 times $\rho_c(z)$: $\rho_c(z) = 3h(z)^2 H_0 / 8\pi G$ $h^2(z) = \Omega_m(1+z)^3 + \Omega_\Lambda$
- Entropy-mass relation
- Entropy profiles, S(r)
  - Scaled with best-fitting S – T, S – M relations

Self-similar models

- Predict universal shape for dark matter distribution from ~$0.01r_{200}$ to ~$0.7r_{200}$, high and low mass clusters
- Predict central cusp
- X-ray observations can confirm

- Cluster formation governed solely by gravitational processes
- Imply that properties S, L_X would scale with powers of T, M
- Scaling is somewhat inconsistent with observations

Self-similar models

- Entropy (pseudoentropy) defined as $S = kT/n_e^{2/3}$ scales theoretically with temperature as $S \propto h(z)^{-4/3}T$
- But scales empirically closer to $S \propto T^{0.65}$
  - {second paper: 0.64±0.11}
- With radius, in model, scales as $S \propto r^{1.1}$
- But scales empirically like $S \propto r^{0.94\pm0.14}$ (with $T^{0.65}$ scaling)
  - {1.08±0.04}

Self-similar models

- Entropy scales with mass:

$$S \propto h(z)^{-2/3} M^{2/3}$$

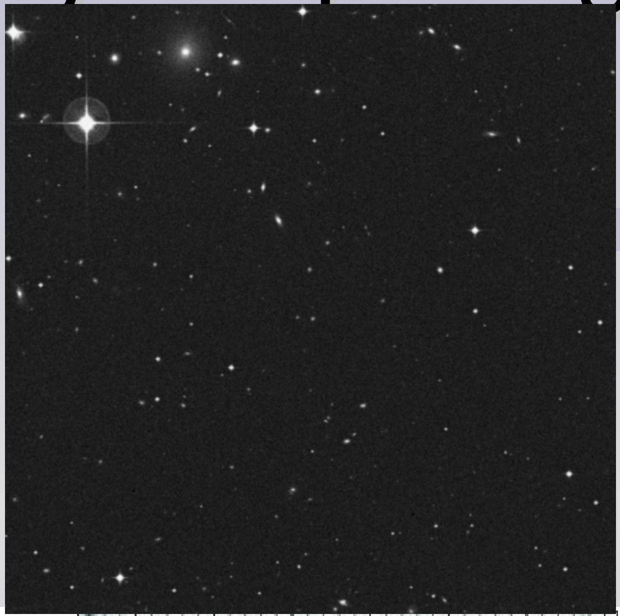
- Find:

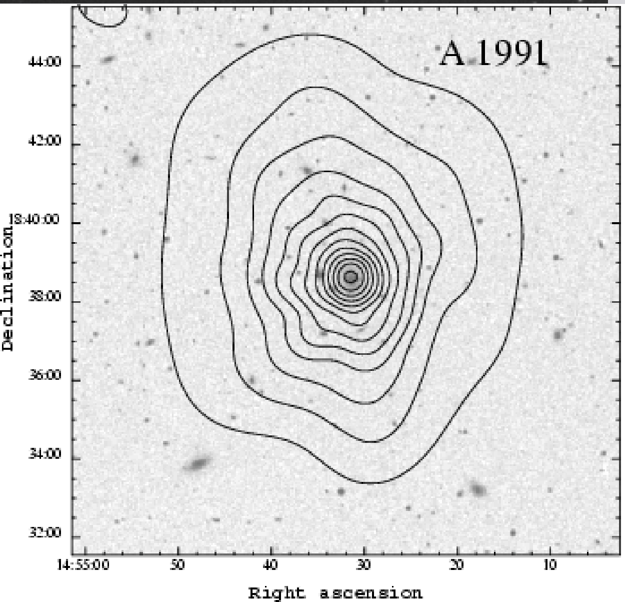
$$S_{2500} \propto h(z)^{-2/3} \, M_{15}^{0.44}$$

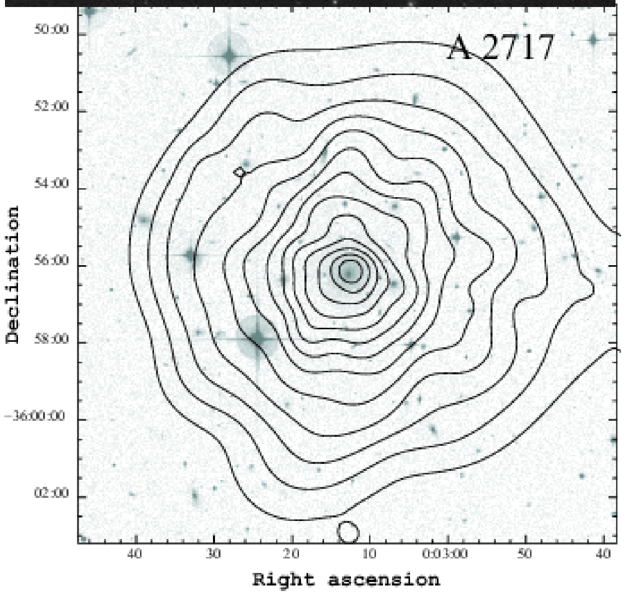
Possible non-gravitational processes

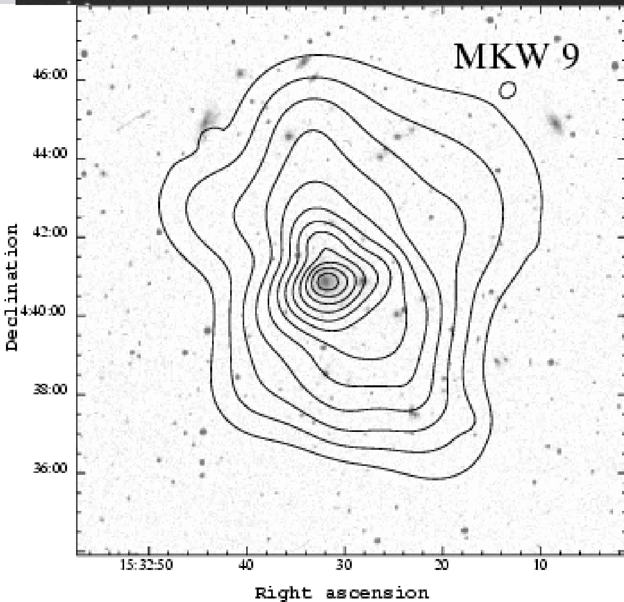
- Preheating of gas before accretion
  - Early supernovae
    - ‘seems too localized to have a significant effect in smoothing the accreting gas’
  - Early AGN activity
  - Only is unlikely for lack of observed isentropic cores
- Internal heating after accretion
- Cooling
  - Predicts higher stellar mass fraction than observed
- Likely
  - Interplay between cooling and feedback, combined with some preheating

X-ray morphologies



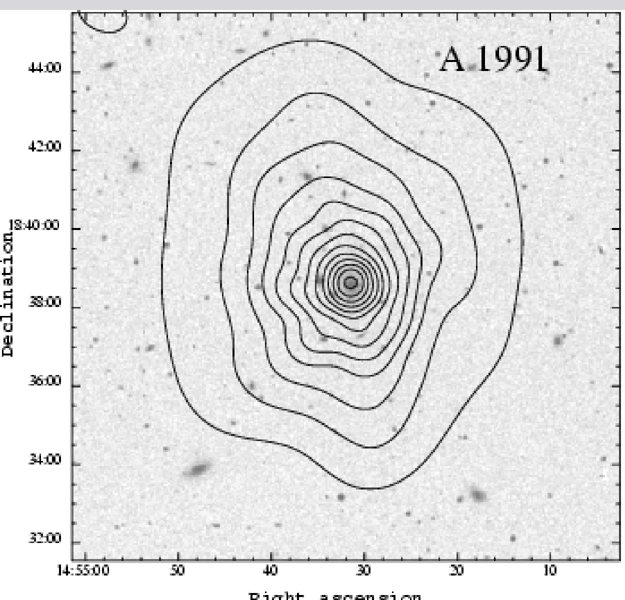


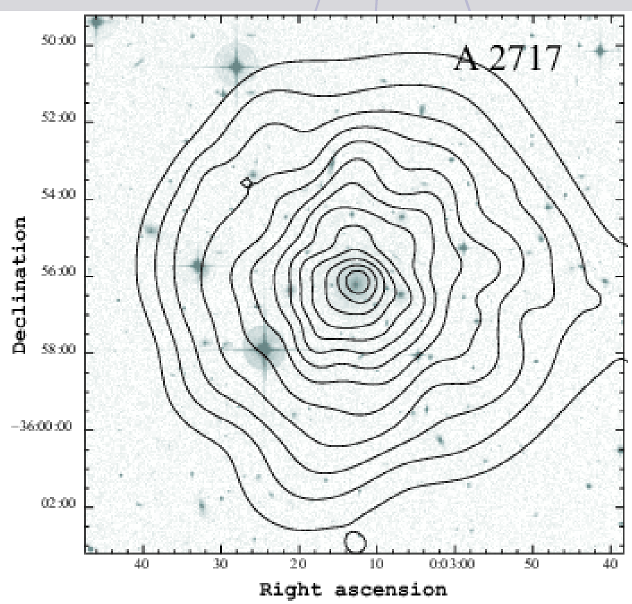


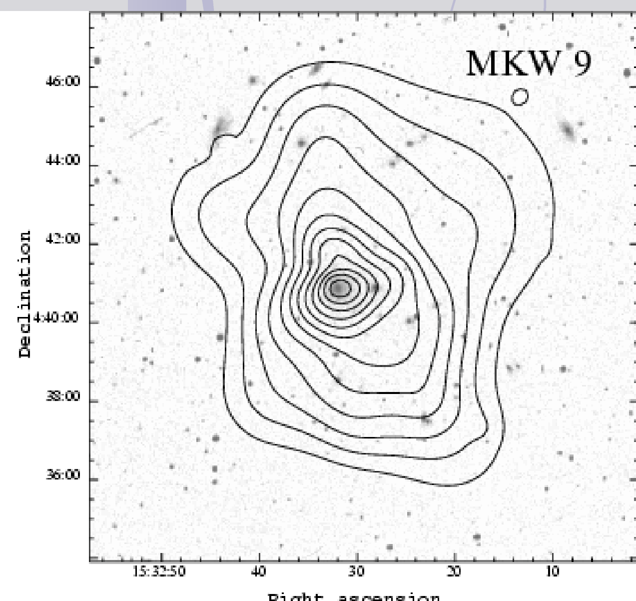


X-ray morphologies

- A1991 and A2717: symmetric x-ray isophotes → relatively relaxed
- MKW9 asymmetrical
  - A2717 centered on central galaxy ACO 2717 BCG
  - A1991 somewhat off-center from central galaxy ACO 1991A
  - MKW9 centered on central galaxy UGC 9886







Surface brightness profiles

- Λ – emissivity of the hot gas – depends sensitively on gas abundance / temperature
- Data reduction
  - Masking of point sources
  - Looking at 0.3 – 3.0 keV bands
  - Corrected for emissivity variations - temperature / abundance profiles fitted to functional forms
  - Λ(radius) estimated with a MEKAL model (a thermal equilibrium plasma emission model), normalized to its value at large radius

Surface brightness profiles

- Directly proportional to emission measure profile, EM(r)
- Can be fitted from parametric model for the gas density profile, $n_e(r)$ (incorporating XMM-Newton PSF)
- Double isothermal β model (BB)
  - Pratt & Arnaud, 2002
  - Assumes that both the inner and outer gas density profiles can be described by β models, but with different parameters

Gas density profile - double isothermal β model

- $n_H(r)$ = the gas density radial profile
- R_{cut} = free parameter

$$r < R_{cut} \quad n_H(r) = n_{H,0} \left[1 + \left(\frac{r}{r_{c,in}}\right)^2\right]^{-\frac{3\beta_{in}}{2}}$$

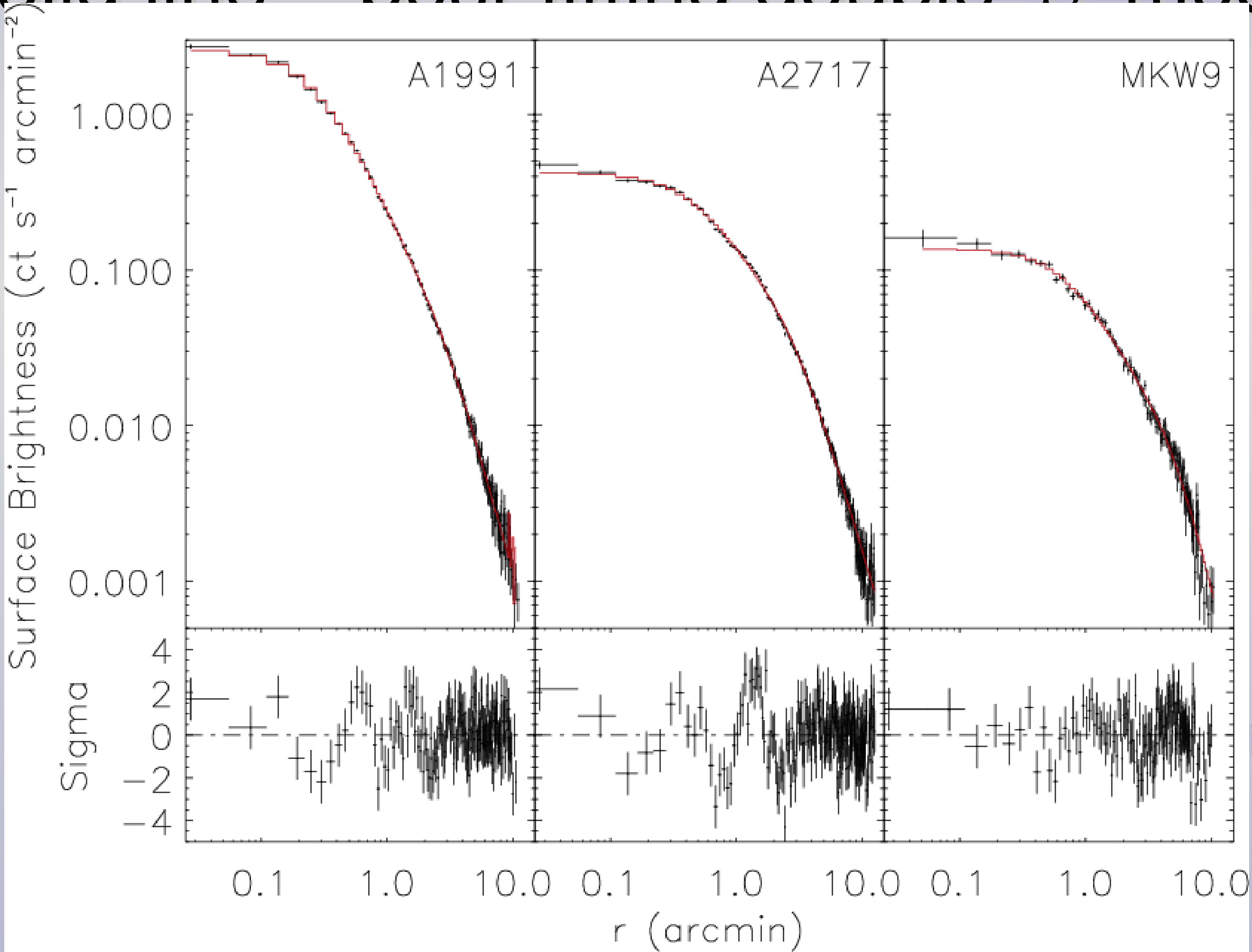
$$r > R_{cut} \quad n_H(r) = N \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-\frac{3\beta}{2}}.$$

$$\beta_{in} = \beta \frac{1 + \left(\frac{r_{c,in}}{R_{cut}}\right)^2}{1 + \left(\frac{r_c}{R_{cut}}\right)^2},$$

$$N = n_{H,0} \frac{\left[1 + \left(\frac{R_{cut}}{r_{c,in}}\right)^2\right]^{\frac{-3\beta_{in}}{2}}}{\left[1 + \left(\frac{R_{cut}}{r_c}\right)^2\right]^{-\frac{3\beta}{2}}}$$

Surface brightness profiles

Solid line – best-fitting double β model

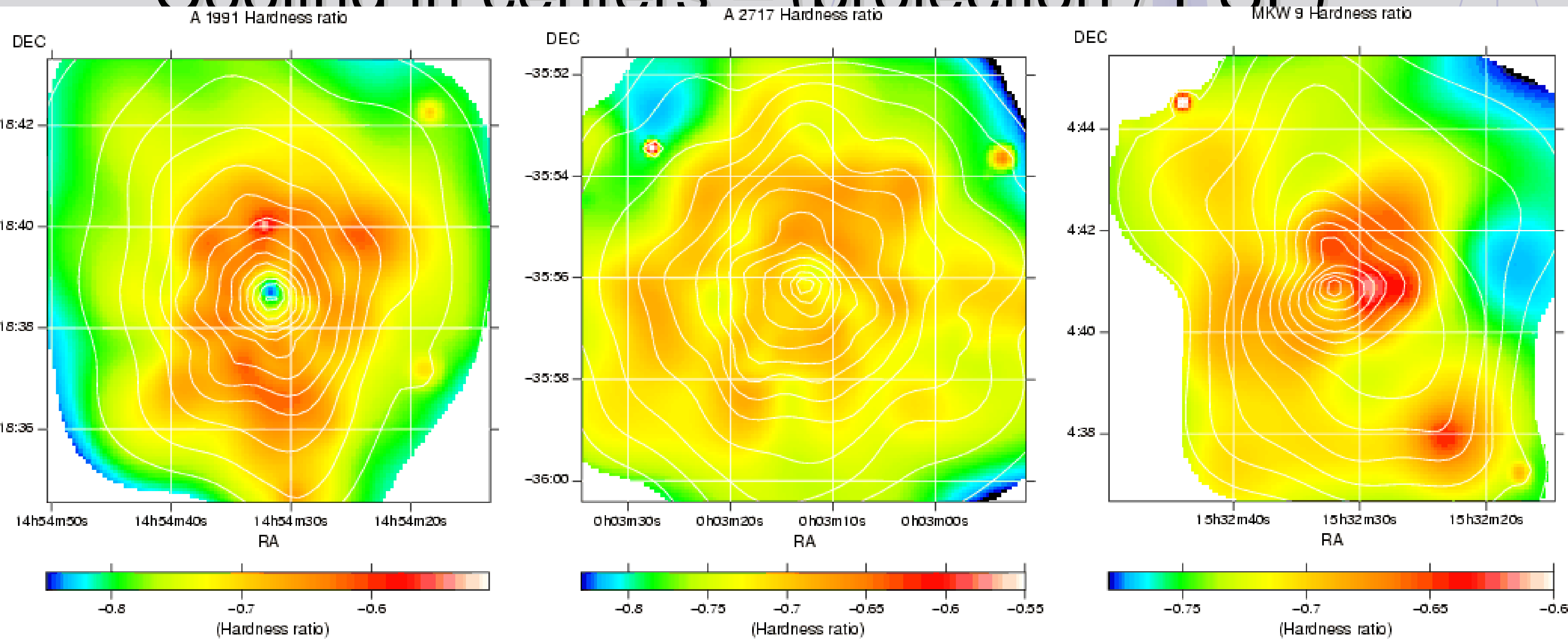


Temperature distributions – hardness ratio images

- Hardness ratio: ratio of counts in different wave bands – a measure of the spectral slope of a source – an indirect measure of temperature
- Source / background images subtracted, smoothed images with smoothing scale of 2.5 σ - 4 σ
- *Not* corrected for difference between local cluster backgrounds and blank-sky backgrounds at low energies
  - HR values cannot be converted directly, reliably into temperatures
  - HR decline toward outer regions an artifact
- Valuable for understanding the temperature structure

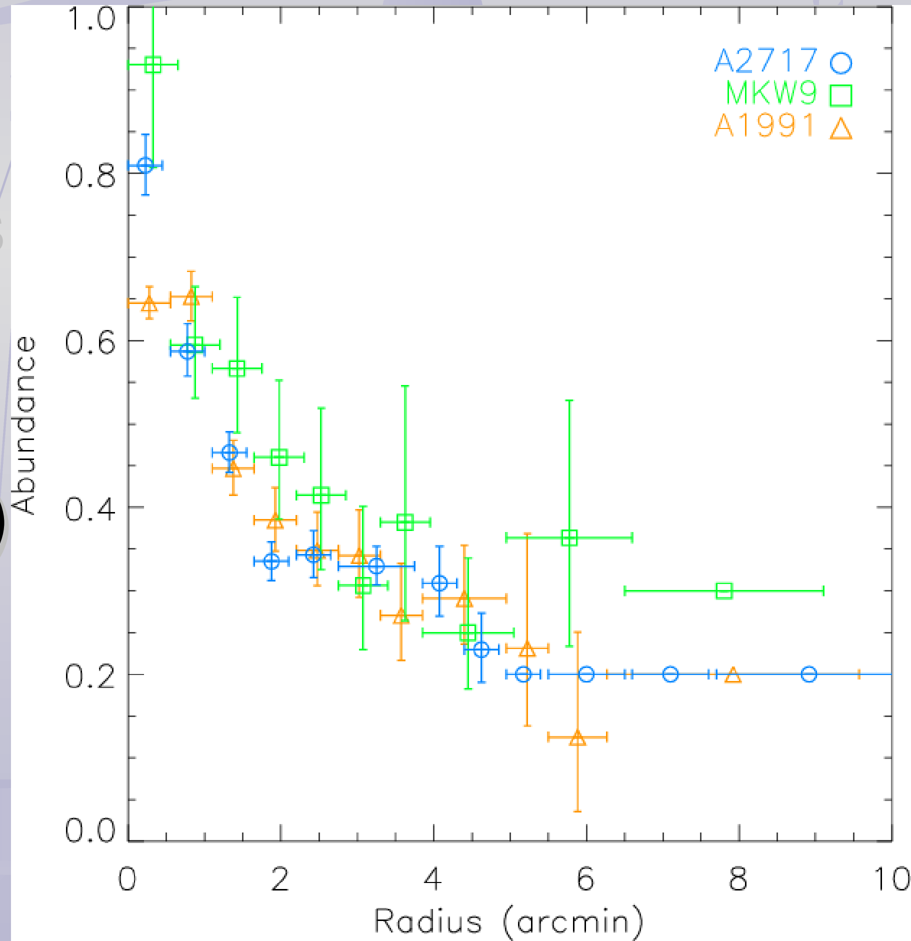
Temperature distributions – hardness ratio images

- Again, A1991 and A2717 symmetrical
- MKW9 asymmetrical – not entirely relaxed
- Cooling in centers – (projection / PSF)



Projected abundance / radial temperature profiles

- Annular spectral analysis
  - Spectra of circular annuli
  - Fitted with parameters of temperature (→), abundance (rel to '89 Anders and Grevesse)
- Projected abundance profiles →



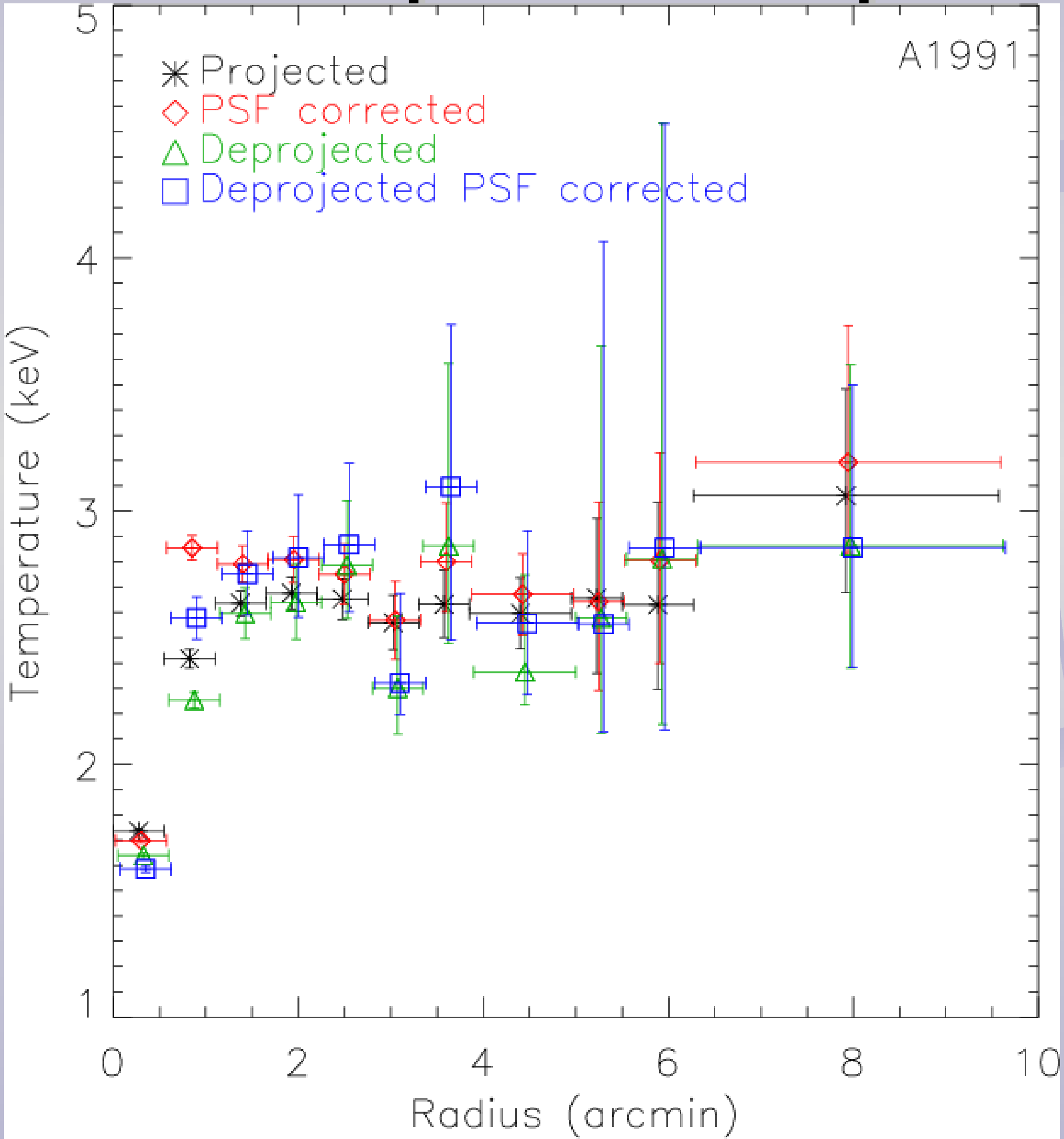
Radial temperature profiles

- Correction for projection, PSF effects
- Unreal cooling in center of clusters
- Use modeling method, annular spectra modeled with a linear combination of absorbed isothermal MEKAL models –

$$S_i^{\bigcirc}(E) = \mathrm{WABS}(N_{\mathrm{H}}^i) \sum_{j=1}^{n} a_{i,j} \mathrm{MEKAL}(T_j, Z_j).$$

- (PSF) / projection correcting – the $a_{i,j}$ redistribution coefficients are the EM contributions of (ring j to ring i) / shell j to ring i.

Radial temperature profiles



Radial temperature profiles

- Outer regions of deprojected, PSF-corrected profiles
  - Subject to unphysical jumps which would lead to mass discontinuities
- Now use a temperature profile composed of the inner three annuli, + projected temp profiles thereafter

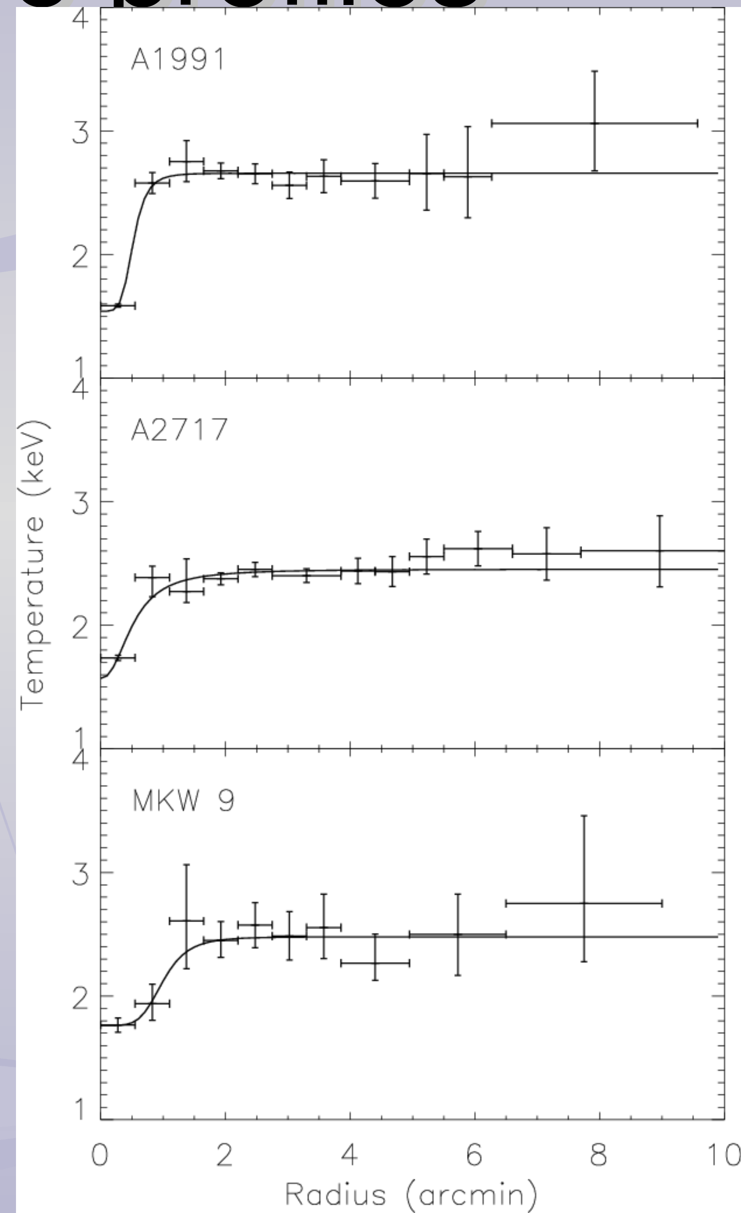
Radial temperature profiles

- Solid lines are best fit to:

$$T = T_0 + T_1[(r/r_c)^n/(1 + (r/r_c)^n)].$$

- With parameters:

Cluster	T0	T1	rc	*n*
	(keV)	(keV)		
A1991	1.54	1.12	0 : 52	5.
A2717	1.57	0.88	0 : 52	2.28
MKW9	1.76	0.72	1 : 00	5.



Global temperature

- Spectra of events in 0.1 $r_{200} \leq r \leq 0.3\ r_{200}$
  - Higher than 0.4 r_{200}, very little emission
  - Lower than 0.1 r_{200}, cooler gas
- r_{200} from best-fit NFW mass model – later
- Temperature and abundance values:
  - A1991, MKW 9 in agreement
  - A2717 higher than previous, probably better

Cluster	***kT***	***Z***
	(keV)	**($Z_{\odot}$)**
A1991	$2.65^{+0.05}_{-0.05}$	$0.33^{+0.03}_{-0.02}$
A2717	$2.53^{+0.05}_{-0.05}$	$0.34^{+0.02}_{-0.02}$
MKW9	$2.58^{+0.15}_{-0.15}$	$0.37^{+0.07}_{-0.06}$

Calculating mass profiles

- Combine gas density and temperature profiles
- → total gravitational mass profile
- Mass calculated at each radius of temp profile using an adapted Monte Carlo method
  - Assumptions – hydrostatic equilibrium, spherical symmetry

Mass profile modeling

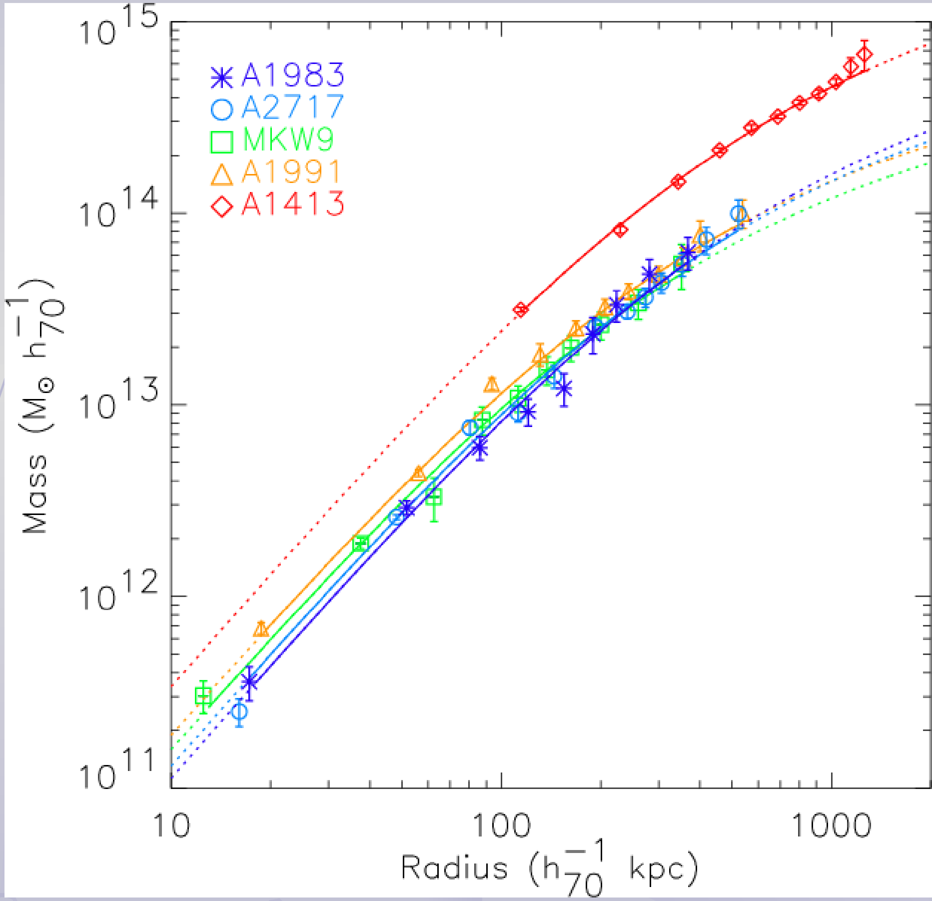
- Fitted to density distribution by Navarro et al. (**NFW**) $\rho(r) \propto [(r/r_s)(1 + r/r_s)]^{-1}$
  - Parameters: normalization factor, scaling radius r_s;

    Or, mass M_{200} and concentration parameter $c_{200} = r_{200}/r_s$
    - M_{200}: mass contained within virial radius

Mass profile modeling.. fits

Parameter	A1991	A2717	MKW9
ΛCDMH70			
c_{200}	$5.7^{+0.4}_{-0.3}$	$4.2^{+0.3}_{-0.3}$	$5.4^{+0.7}_{-0.7}$
r_s (kpc)	191^{+19}_{-17}	261^{+27}_{-24}	186^{+45}_{-34}
r_{200} (kpc)	1105	1096	1006
M_{200} ($10^{14}\ M_{\odot}$	1.63	1.57	1.20
χ^2/ν	9.98/9	15.8/10	4.0/8
SCDMH50			
c	$5.6^{+0.4}_{-0.3}$	$4.1^{+0.3}_{-0.2}$	$5.3^{+0.7}_{-0.7}$
r_s (kpc)	260^{+26}_{-23}	358^{+37}_{-33}	255^{+61}_{-46}
r_{200} (kpc)	1466	1466	1358
M_{200} ($10^{14}\ M_{\odot}$	2.17	2.12	1.63
χ^2/ν	9.98/9	15.8/10	4.0/8

Results from the NFW fits to the mass profiles



Integrated total gravitating mass profiles, 1 σ errors

NFW mass profiles & cluster dynamical states

- A2717 not a great NFW fit
  - Maybe halo unrelaxed
- MKW9
  - Unrelaxed.
- Also: use relation between M_{200} and dark matter velocity dispersion

$$\sigma_{\rm DM} = 1075[h(z)\, M_{200}/(10^{15}\, h_{100}^{-1}\, M_{\odot})]^{1/3}\ \mathrm{km\ s^{-1}},$$

and compare with optically-derived velocity dispersions

NFW mass profiles & cluster dynamical states

- Agreement good
- Esp. for A2717
- So total mass estimates from NFW fits are trustworthy.
- And no cluster is very far from equilibrium.

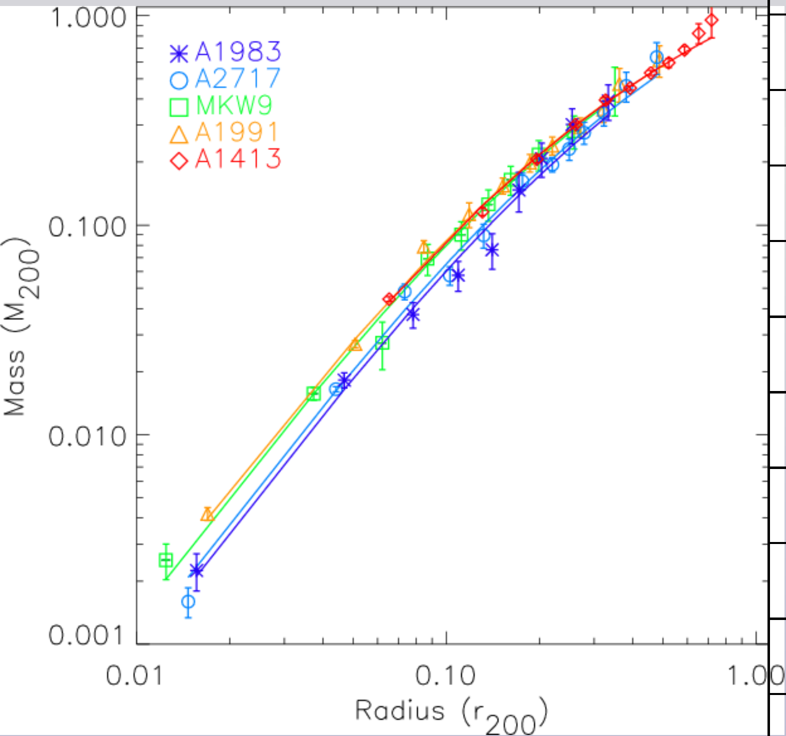
Cluster	σ_{DM} km/s	σ_{opt} km/s	Reference
A1991	**526**	631^{+147}_{-137}	Girardi et al. (1997)
A2717	**520**	541^{+65}_{-41}	Girardi et al. (1997)
MKW9	**474**	579^{+331}_{-337}	Beers et al. (1995)

Dark matter velocity dispersions calculated from the $\sigma_{DM} - M_{200}$ relation vs. the optically-derived galaxy velocity dispersions

- Differences in dynamical states don't seem to affect the NFW fit values

Scaled mass profiles

Mass profiles



Relative dispersion

Radius	ΛCDMH70		SCDMH50	
	σ/m	S_{B1}/C_{B1}	σ/m	S_{B1}/C_{B1}
Scaled mass: NFW best fit model				
0.05 r_{200}	0.18	0.19	0.18	0.19
0.1 r_{200}	0.15	0.16	0.15	0.16
0.3 r_{200}	0.08	0.09	0.08	0.08
0.5 r_{200}	0.04	0.05	0.04	0.04
Scaled mass: interpolated data				
0.05 r_{200}	0.18	0.20	0.17	0.18
0.1 r_{200}	0.25	0.25	0.24	0.24
0.3 r_{200}	0.06	0.02	0.06	0.04
0.5 r_{200}	0.13	0.13	0.13	0.12

Entropy profiles

S vs. T

S vs. M

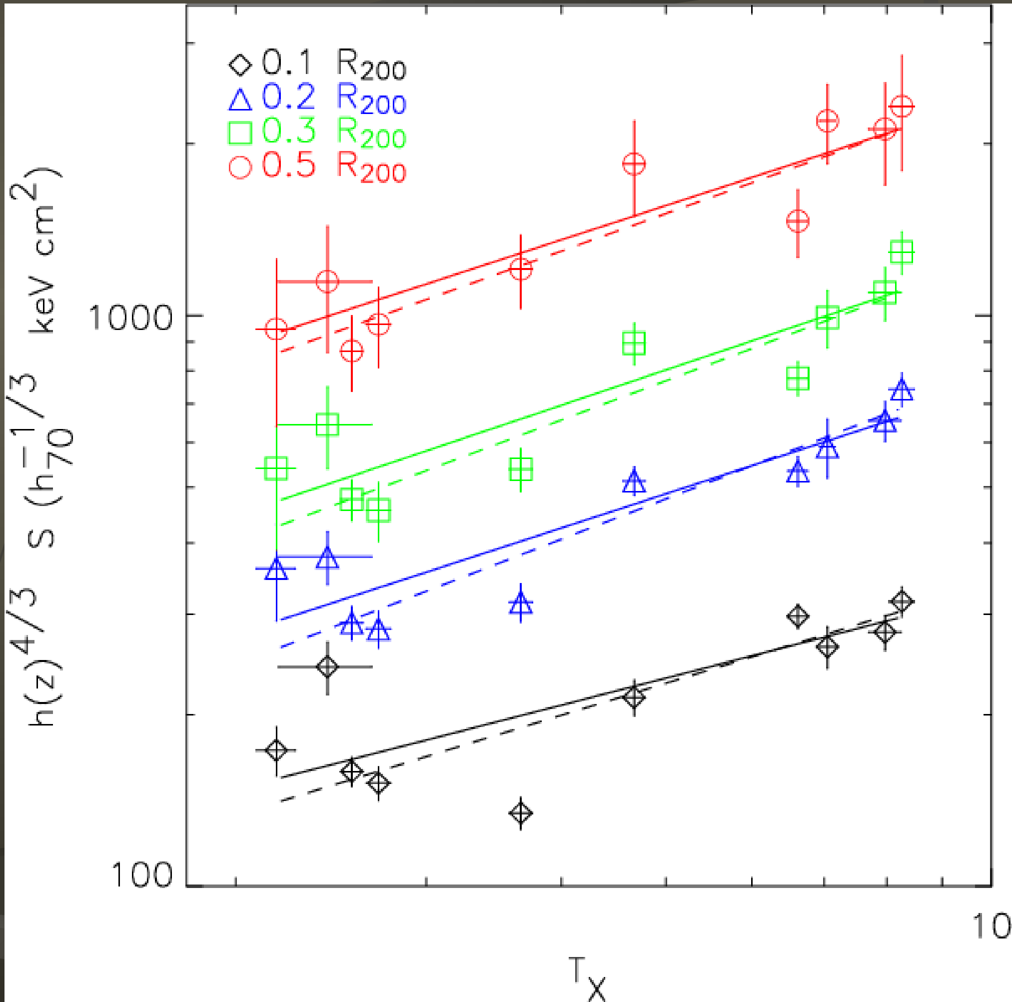
S vs. r, scaled with S-T, S-M

Entropy – temperature relation

- Self-similar expectation: $S \propto h(z)^{-4/3} T$
- Data fitted with power law

$$h(z)^{4/3} S_x = A[T_{spec}/5 \text{ keV}]^{\alpha}$$

  using three regression methods



S vs. T

- At 0.3 R_{200}:
  - Gas density / T measurements well constrained – least affected by PSF, projection effect correction problems
  - Outside cooling cores
  - Known from *Chandra* no significant T gradients

$$S_{0.3} \propto T^{0.64\pm0.11}$$

- Slope stable after 0.2 R_{200}
- Intrinsic scatter largest at 0.1 R_{200}

Radius		$\sigma_{\log}$		
R_{200}	α	raw	stat	int
WLS				
0.1	0.58 ± 0.05	0.079	0.030	0.073
0.2	0.73 ± 0.06	0.058	0.035	0.047
0.3	0.71 ± 0.07	0.074	0.043	0.060
0.5	0.68 ± 0.12	0.070	0.078	-
BCES				
0.1	0.49 ± 0.15	0.082	0.030	0.076
0.2	0.62 ± 0.11	0.063	0.034	0.052
0.3	0.64 ± 0.11	0.078	0.043	0.065
0.5	0.62 ± 0.08	0.074	0.078	-
WLSS				
0.1	0.47 ± 0.14	0.083	0.030	0.077
0.2	0.67 ± 0.10	0.059	0.035	0.048
0.3	0.69 ± 0.12	0.075	0.043	0.061
0.5	0.68 ± 0.12	0.070	0.078	-

S – M relation

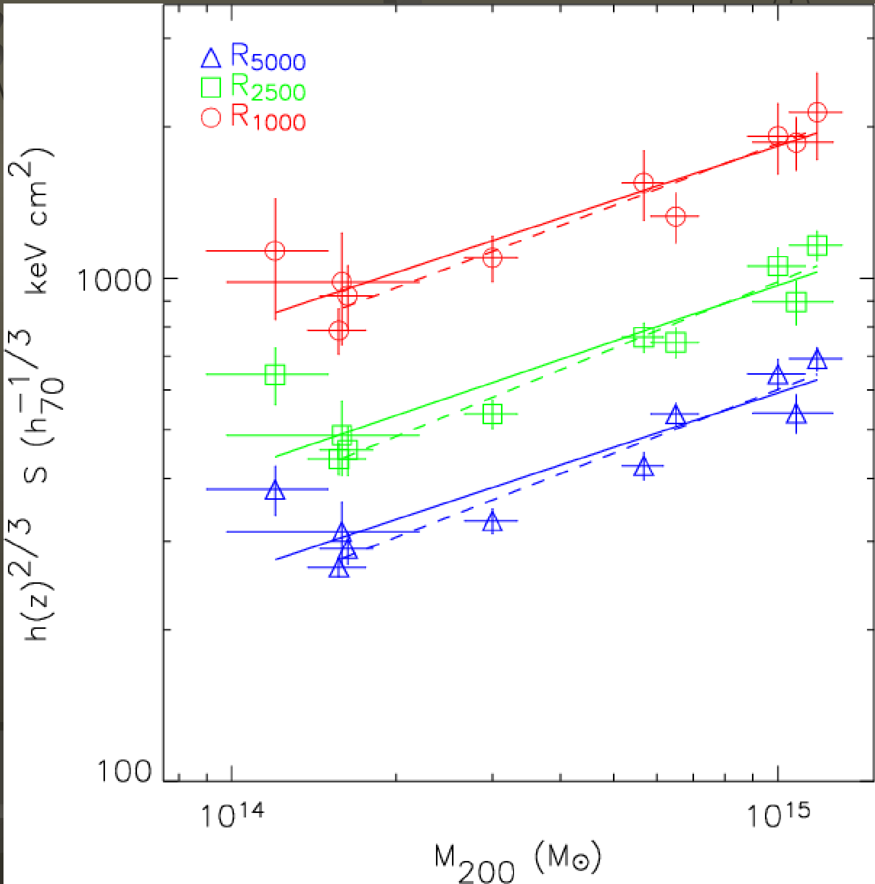
- Self-similar prediction:

$$S \propto h(z)^{-2/3} M^{2/3}$$

- Best fit is shallower
- Consistent with S – T, M – T relations

$$h(z)^{2/3}\, S_\delta = B_\delta \times (M_{200}/5.3 \times 10^{14}\ M_\odot)^\beta$$

- M_{200} the total mass obtained from NFW fits to the mass profiles



S vs. M

- $S_{2500} \propto h(z)^{-2/3} \; M_{15}^{0.44}$

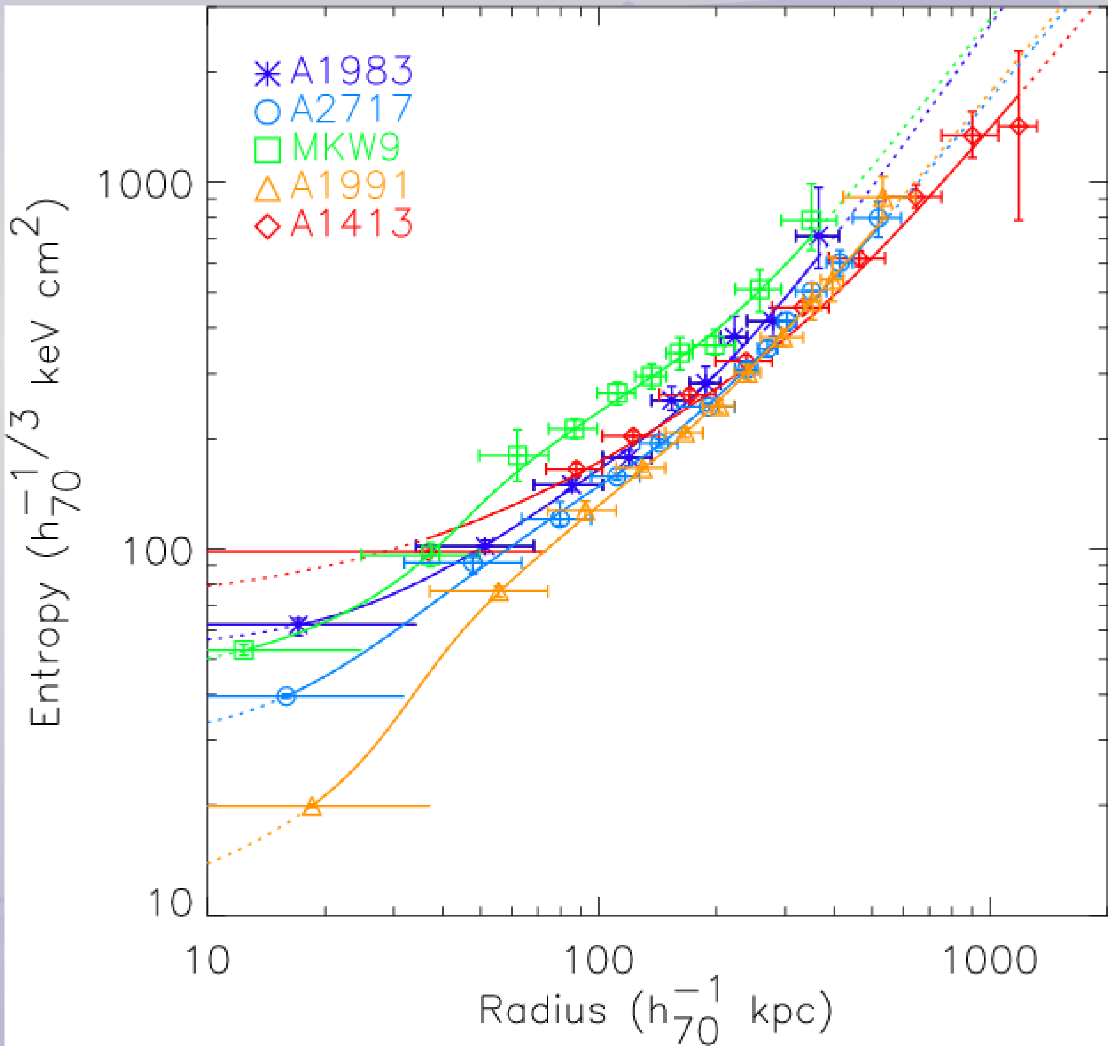
- Consistent with

S – T, S – M relations

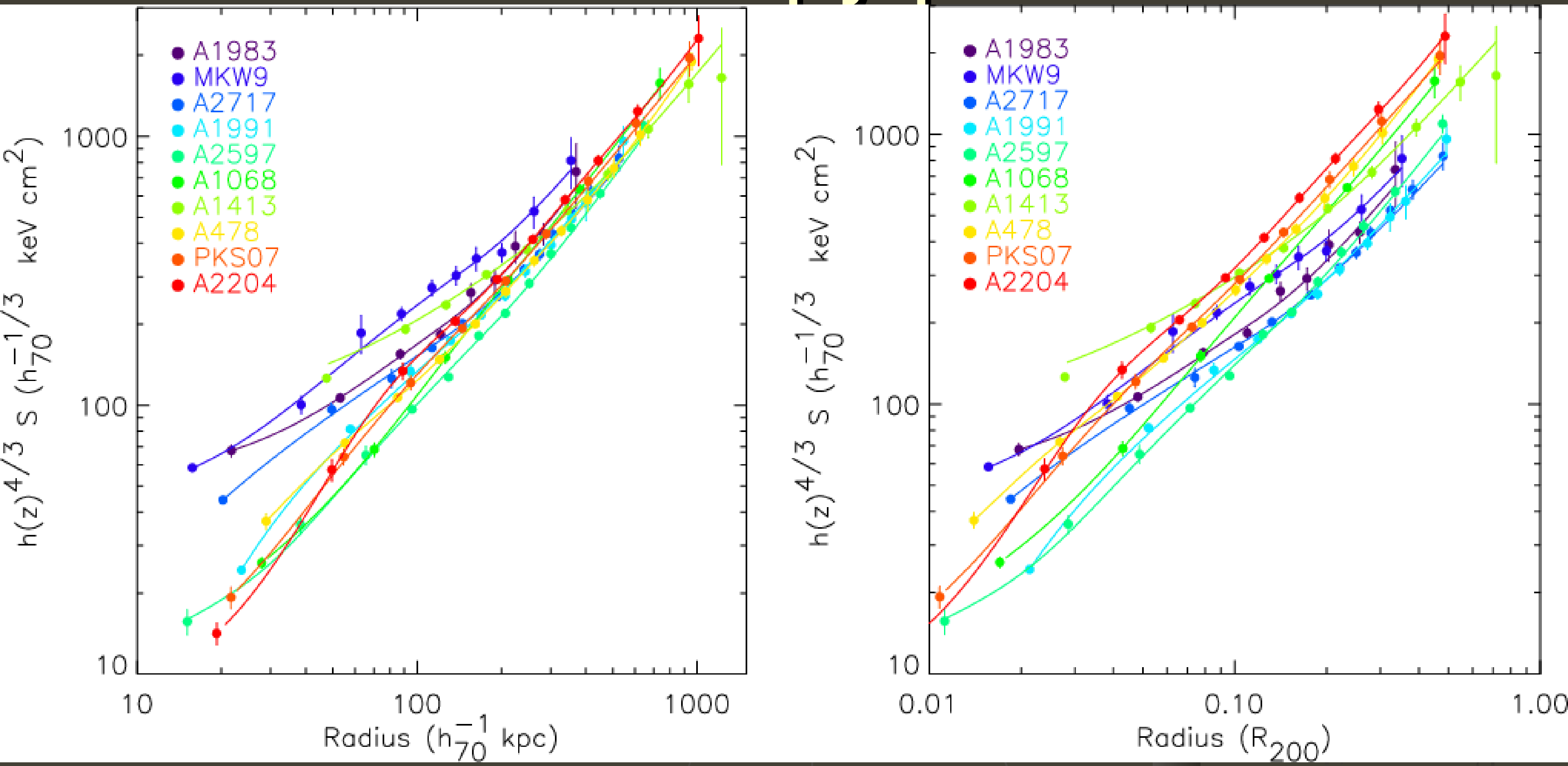
δ	B	β	$\sigma_{\log}$		
	keV cm^{-2}		raw	stat	int
Full	sample				
5000	471 ± 18	0.36 ± 0.10	0.058	0.034	0.046
2500	765 ± 30	0.37 ± 0.10	0.059	0.041	0.043
1000	1460 ± 47	0.36 ± 0.06	0.059	0.065	-
Excl.	MKW9				
5000	459 ± 37	0.43 ± 0.10	0.039	0.035	0.017
2500	741 ± 43	0.44 ± 0.08	0.035	0.041	-
1000	1430 ± 46	0.41 ± 0.04	0.042	0.063	-

Raw entropy profiles

- $S = kTn_e^{-2/3}$
- Analytic model gas density profile
- Solid – analytic temp distribution model
- Dotted – observed temp profile



Raw entropy profiles



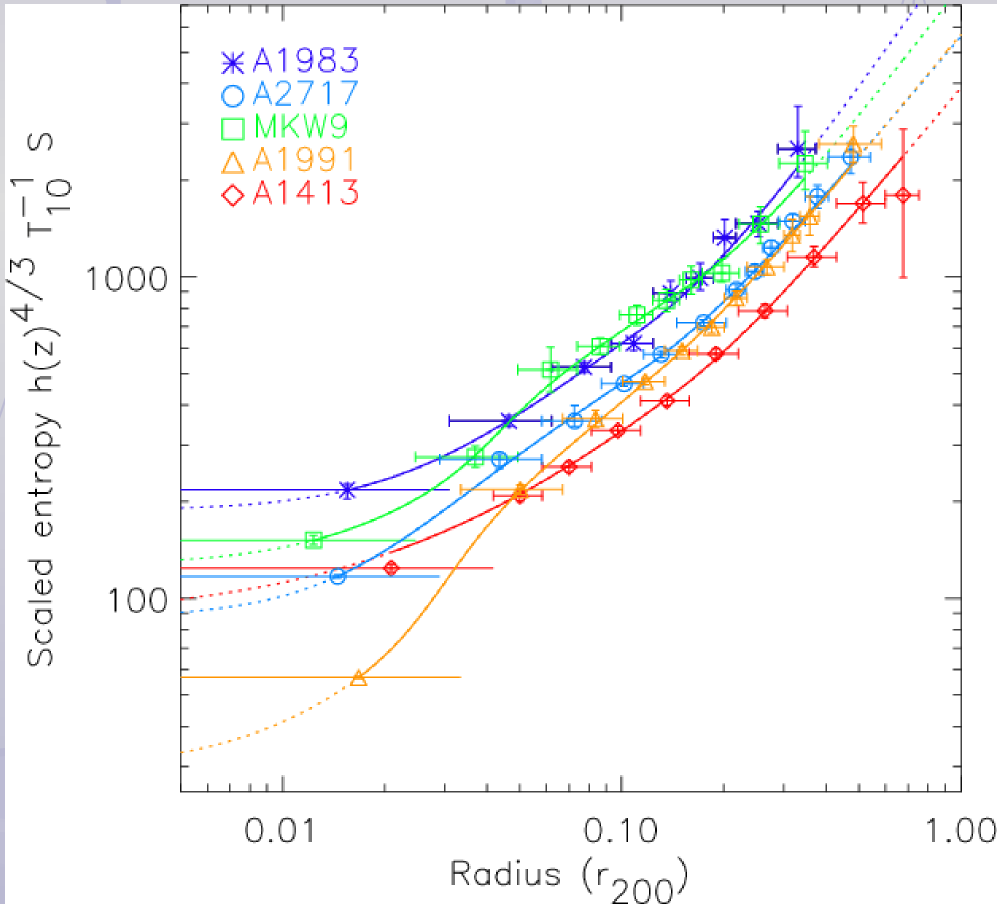
- All profiles increase monotonically with radius
- None have isentropic core

Scaled entropy profiles

- T_{10} = global temperature in units of 10 keV
- Self-similar scenario: clusters form at constant density contrast, gas follows dark matter

$$\overline{n_e} \propto \overline{\rho_{DM}} \propto \rho_c(z) \propto h^2(z)$$

- Then $S \propto h(z)^{-4/3} T$ and the scaled entropy profiles of all clusters should coincide

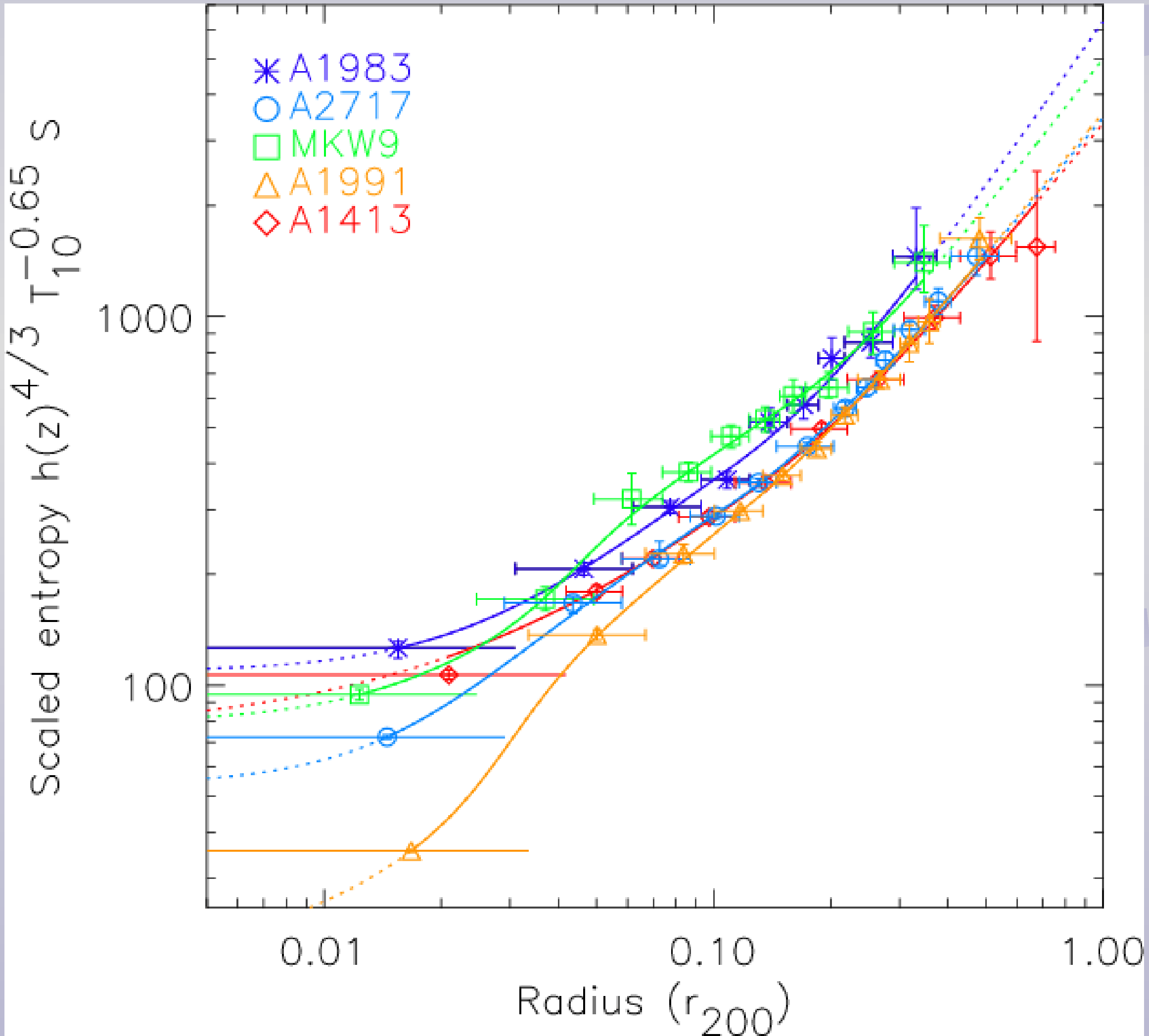


Scaled entropy profiles

Radius	ΛCDMH70		SCDMH50	
	σ /m	S_{B1}/C_{B1}	σ /m	S_{B1}/C_{B1}
Scaled Entropy: T^{-1} scaling				
0.05 r_{200}	0.30	0.28	0.28	0.26
0.1 r_{200}	0.30	0.29	0.29	0.28
0.3 r_{200}	0.30	0.29	0.28	0.26
0.5 r_{200}	0.34	0.33	0.31	0.31
Scaled Entropy: $T^{-0.65}$ scaling				
0.05 r_{200}	0.22	0.22	0.21	0.20
0.1 r_{200}	0.22	0.24	0.21	0.21
0.3 r_{200}	0.20	0.26	0.18	0.20
0.5 r_{200}	0.24	0.29	0.21	0.19

Scaled entropy profiles

Better as $S \propto T^{0.65}$



Scaled entropy profiles

- Region 0.05 – 0.1 r_{200} well approximated by power law

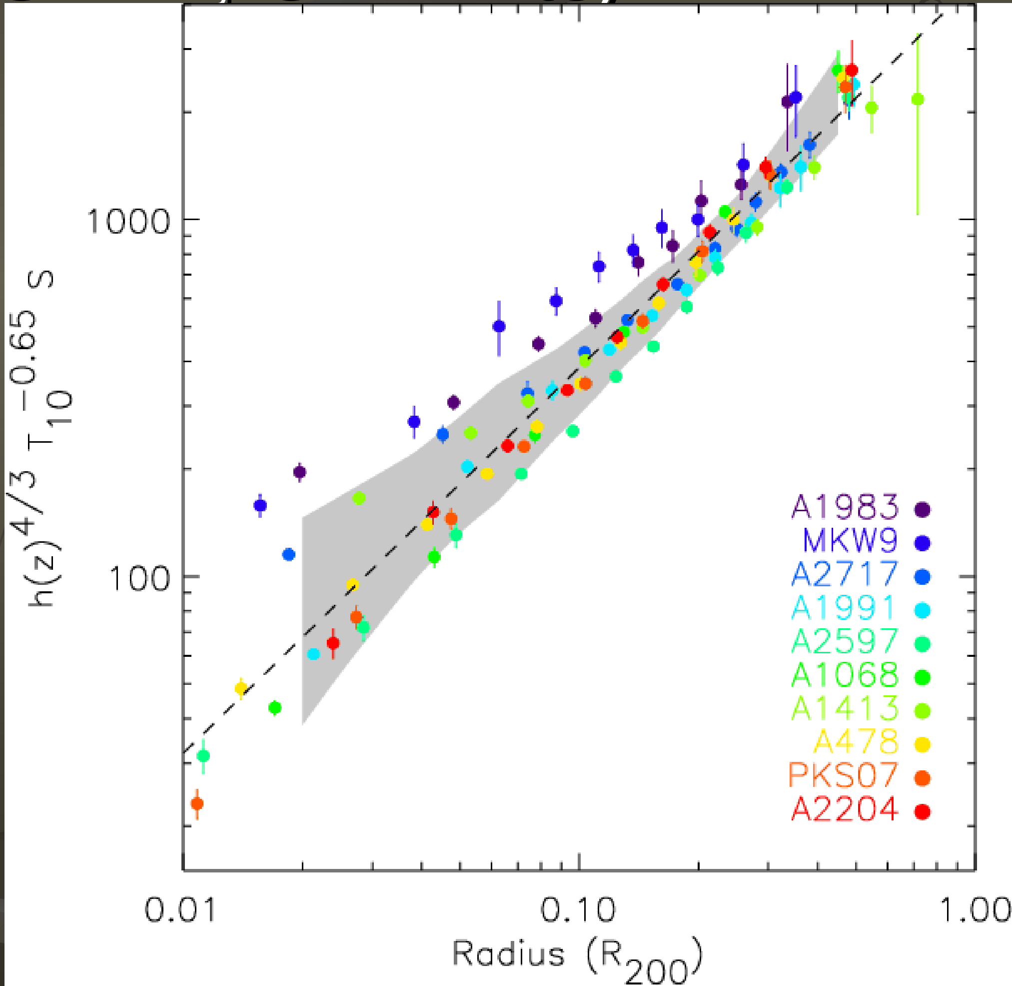
$$h(z)^{4/3}T_{10}^{-0.65}S(r) = 470\left(\frac{r}{0.1\,r_{200}}\right)^{0.94\pm0.14} h_{70}^{-1/3}\ \mathrm{keV\,cm^2},$$

- Slope close to but shallower than the $S \propto r^{1.1}$

  expected from analytical models of shock heating in spherical collapse

Scaled entropy profiles

- (scaled by the best S – M, S – T fits)
- $S \propto r$.08±0.04
  - $S \underset{\sim}{\propto} r^{1.1}$ expected for shock heating in spherical collapse
- Consistent



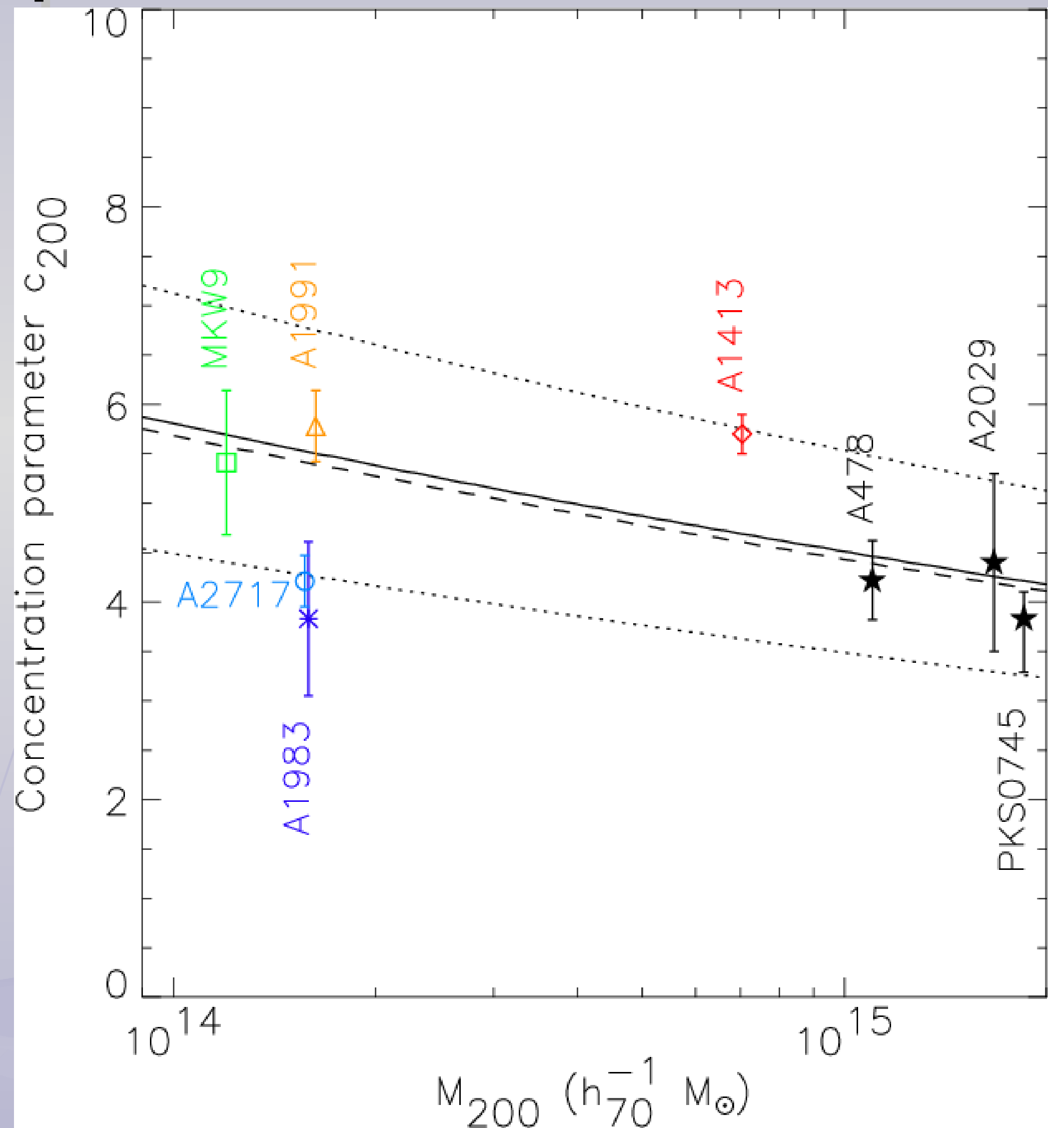
Discussion

The gravitational collapse of the dark matter – qualitative check

- Simulations predict a universal form with a central cusp - seen
- NFW – best fit; King model –rejected
- Mass profiles similar for cool clusters and the hot cluster A1413 – shape near universal

The gravitational collapse of the dark matter – quantitative check

- Concentration parameters c_{200} ($= r_{200}/r_s$) should increase for lower mass systems
- Clusters + literature
- Solid line: $z = 0.0$
- Dashed: $z = 0.15$



Dark matter collapse

- Dark matter profiles of local clusters nearly universal, w/ central cusp as expected from NFW model
- Concentration parameters in very good agreement with theory → physics of collapse is understood

Entropy profiles v. theory

- Departures from self-similar picture – non-gravitational processes
  - Or, due to a flaw in the gravitational collapse model?
  - This study says no.
- Pure cooling / simple preheating models insufficient
  - Spherical preheating – predict a break in S – T relation and large isentropic cores – rule out
  - Pure cooling models – predict overcooling at odds with observed mass fraction of the stellar component – rule out

Entropy profiles v. theory

- Beyond core region ($r > 0.1\ R_{200}$):

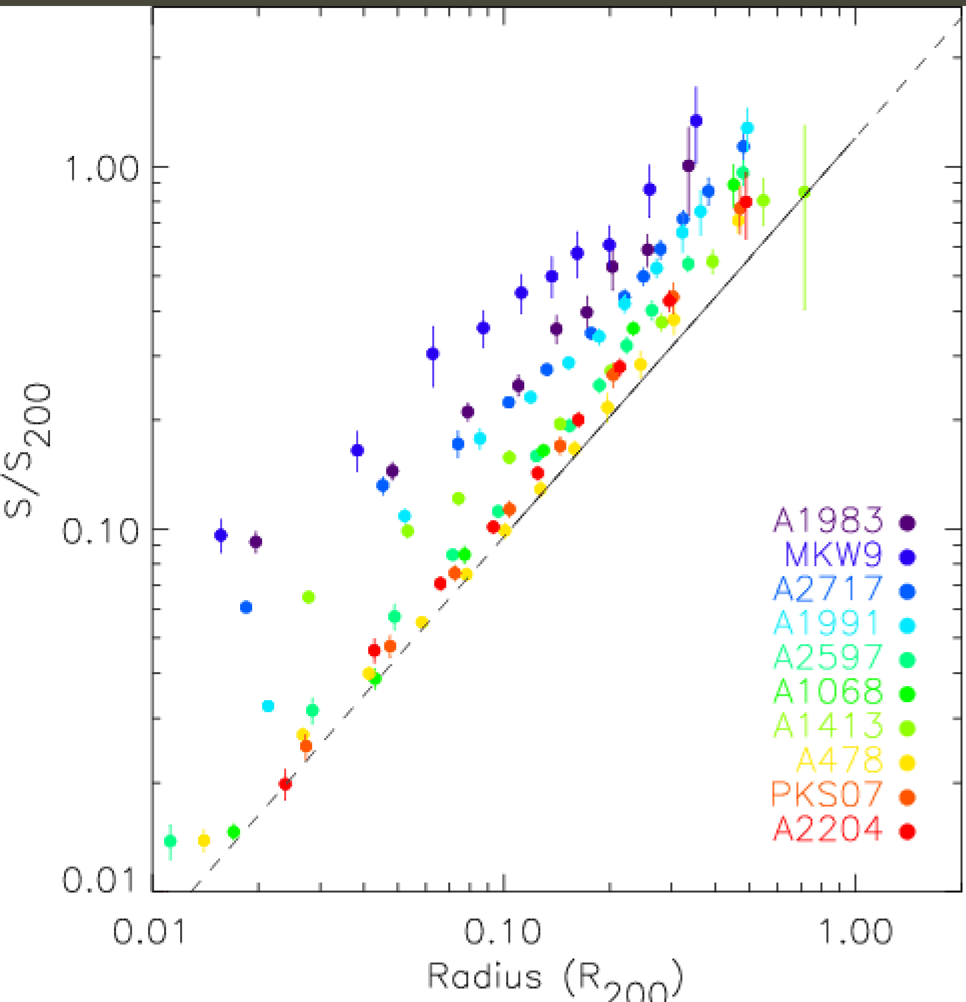
  profiles self-similar; shape consistent with model but with shallower temperature / mass scaling than expected
- In core region:

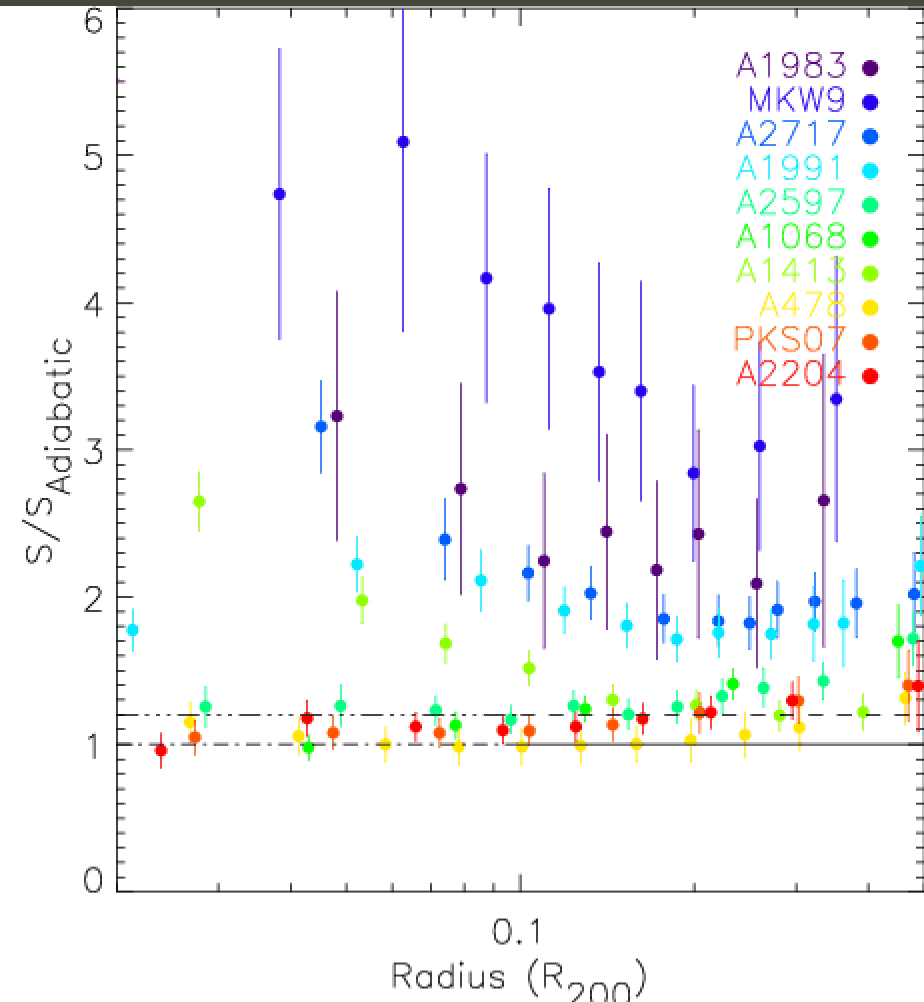
  Break of similarity – dispersion increases with decreasing radius

Modified scaling

- Modified scaling: excess of entropy in low mass objects relative to more massive systems, as compared to the expectation from pure shock heating
- Quantify absolute value of excess, see if an excess is also present for more massive systems
- Adiabatic numerical simulations – Voit, '05

Modified scaling





Modified scaling

- Richer systems:
  - Entropy in good agreement with pure gravitational collapse prediction
  - Only ~20% higher
  - Can be accounted for by the difference in observed M – T relation and modeled
- Poorer systems:
  - S ~2.5 times higher at 0.2 R_{200} for A1983 than gravitational heating prediction
  - Excess – density of ICM is affected at lower mass
- Entropy boosted at accretion shock

Modified scaling

- ICM entropy highly sensitive to the density of the incoming gas
- A smoothing of the gas density by preheating in filaments and/or infalling groups would boost entropy production at the accretion shock
- Affects low-mass systems more – accrete smaller halos more affected by smoothing due to preheating
- No isentropic core because the amount of initial preheating is substantially less than the characteristic entropy of the final halo

- Result in self-similarity down to low mass, with modified scaling

Similarity break in core

- Entropy dispersion ~60% at 0.02 R_{200}
- Six clusters – strong radiative cooling
  - Very self-similar power law profiles, dispersion ~13% between 0.01 and 0.1 R_{200}
  - Consistent with quasi-steady-state models that include radiative cooling
- Four clusters – shallower entropy profiles
  - AGN energy input
  - Strong bursts / *weak shocks*
  - Old merging events – mixing high / low S gas

Conclusion

- Confirmed physics of dark matter collapse is understood
- Entropy profiles – in $0.05\ r_{200} \leq r \leq 0.5\ r_{200}$, self-similar but scale with T, r shallower than gravity-only, pure shock heating model

$$S(r) \propto T^{0.65\pm0.05}(r/r_{200})^{0.94\pm0.14}$$

- Large dispersion in $r \leq 0.05\ r_{200}$ – variety of cooling core histories

Conclusion

- Entropy scales with temperature:

  $$S_{0.3} \propto T^{0.64\pm0.11}$$

- With radius:

  $$S \propto r^{1.08\pm0.04}$$

- Modified scaling thought due to smoothing of accreted gas density by preheating
  - Would affect low-mass systems more, as seen
- Large dispersion in core thought due to
  - Some clusters are cooling flow clusters
  - Some – energy coming from weak shocks from AGN activity, effects of old mergers

- The end