Core Structure and Thermal Evolution of X-ray Clusters

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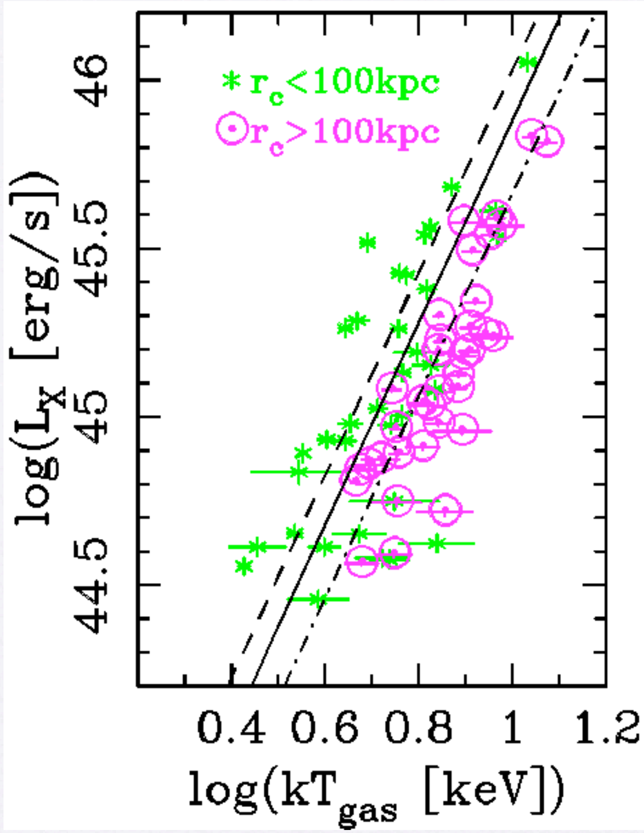
Motivation

☆ L_X–T relation of galaxy clusters

◆ L_X depends on both n_{gas} and T_{gas} ($L_X \propto n_{gas}^2\, T_{gas}^{1/2}$)

→ physical status and evolution of the ICM

◆ Inconsistency between the self-similar model (T^2) and the observations (T^3, significant scatter)



☆ Related observational results

◆ Connection between L_X–T and cluster core radius (Ota & Mitsuda 2002)

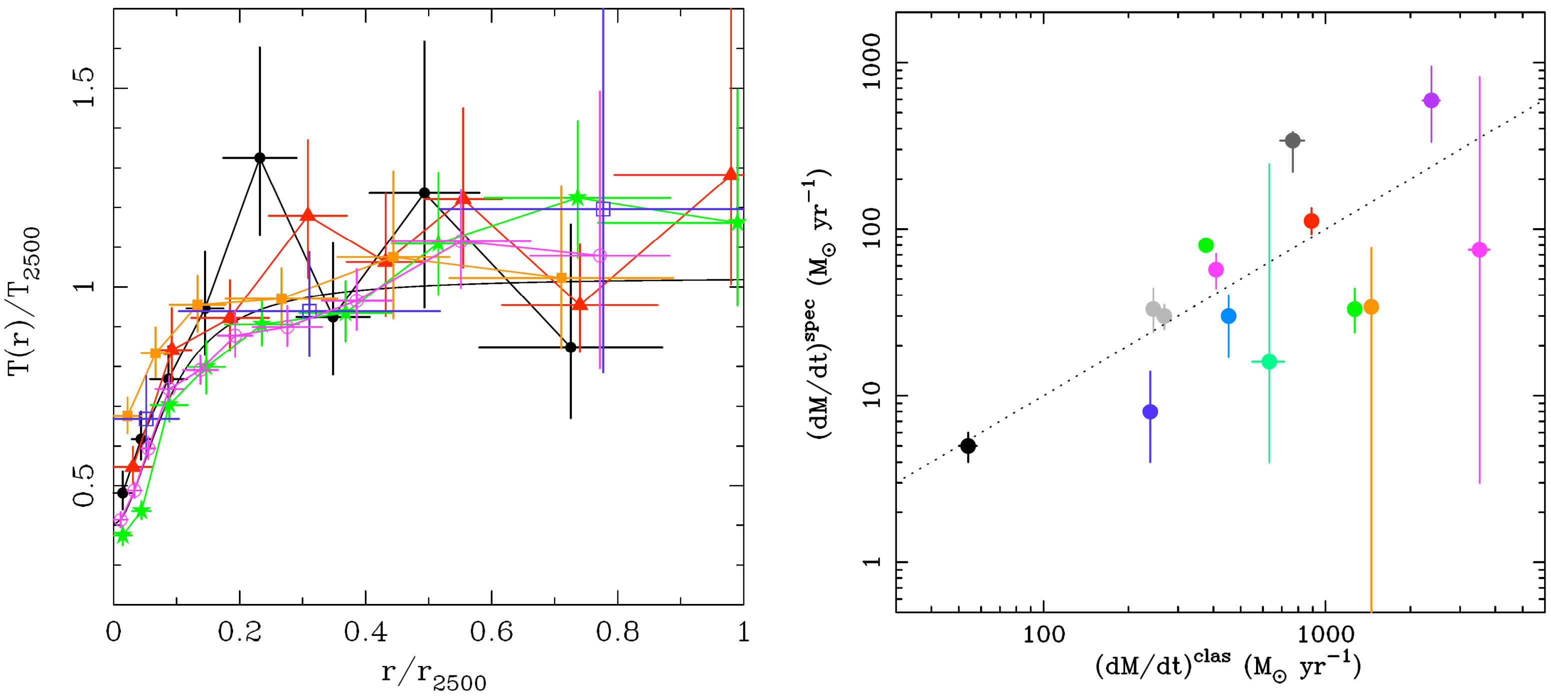
◆ 'Universal temperature profile' in cooling-flow clusters (e.g. Kaastra et al.)

→ *Cooling in the core may have much impact on Lx-T*

Observational approach to core structure and thermal evolution of the ICM

Temperature profiles of CF clusters

$T_{min} \sim (0.3\text{–}0.4)T_0$ $\qquad$ $\dot{M}_{spec} \sim \dot{M}_{prof}/10$



Fabian
astro-ph/0210150

Agenda

1. Review on a uniform X-ray analysis of a large number of ROSAT & ASCA distant clusters (Ota 2001; Ota & Mitsuda 2002, 2004)
2. L_X–T relation and thermal evolution of ICM
   - L_X–T and its connection to fundamental X-ray parameters in the light of radiative cooling
   - L_x–$T\beta$ and X-ray morphology
   - Discussion on the thermal evolution
     - Possibility of "quasi-hydrostatic state" of gas in regular clusters

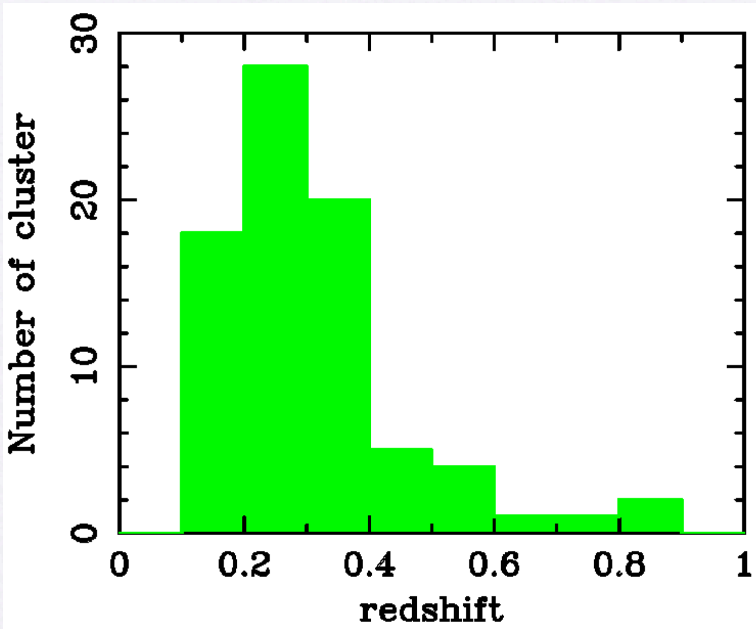
$\Omega_{\rm M} = 0.3, \Omega_\Lambda = 0.7, H_0 = 70$ km/s/Mpc

1. A uniform X-ray analysis of distant clusters with ROSAT & ASCA

Ota (2001)
Ota & Mitsuda (2002,2004)

The sample

- Ota (2001); Ota & Mitsuda (2004)
  - analyzed ROSAT & ASCA data on 79 distant clusters with $0.1<z<0.82$ under β-model
  - Note: In L_X-T analysis, we use 69 clusters ($0.1<z<0.56$) excluding high-z clusters with large uncertainties and 3CR clusters.



cf.
45 nearby, $z<\sim0.1$
(Mohr et al. 1999)
28 highz, $0.4<z<1.3$
(Ettori et al. 2004)

Spatial analysis and spectral analysis

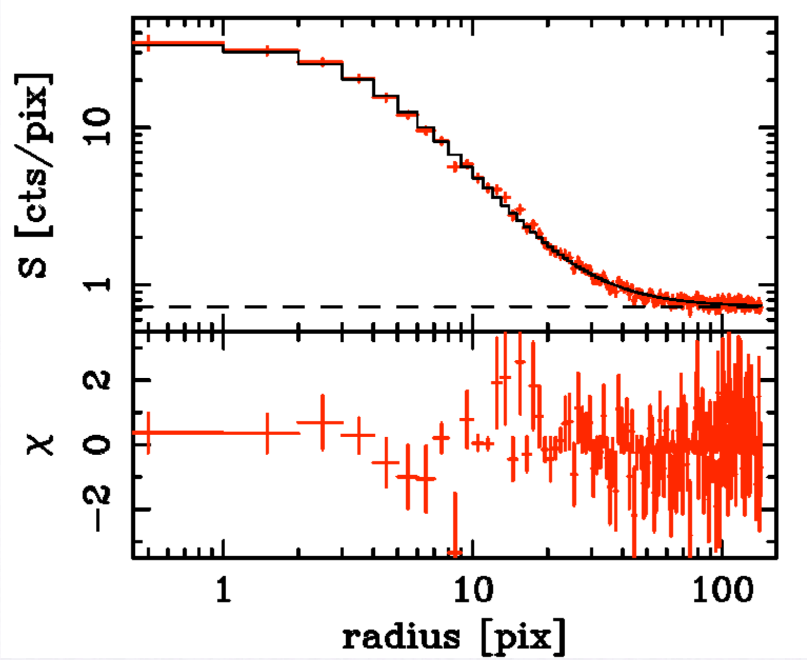
- Spatial analysis with ROSAT HRI
  - Isothermal β-model fitting → β, r_c, S_0 (n_{e0})
  - Double-β gives significantly (marginally) better fit to 9 (7) regular clusters
  - X-ray morphology. 69→41 Regular + 28 Irregular

- Spectral analysis with ASCA GIS($r<6'$) & SIS($r<3'$)
  - Raymond-Smith model → T; emission-weighted temperature, L_X; bolometric luminosity within r_{500}

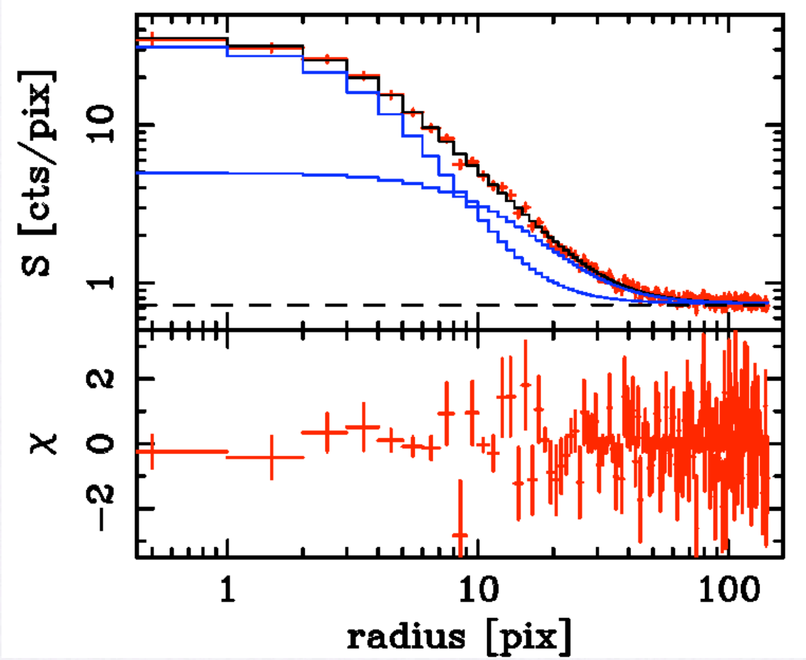
- See OM04 for the complete catalogue and scaling relations (M_{gas}, M_{500}, f_{gas}, r_{500}, T, L_X, r_c, β, Z, ...)

Surface brightness fitting

Single β-model



Double β-model



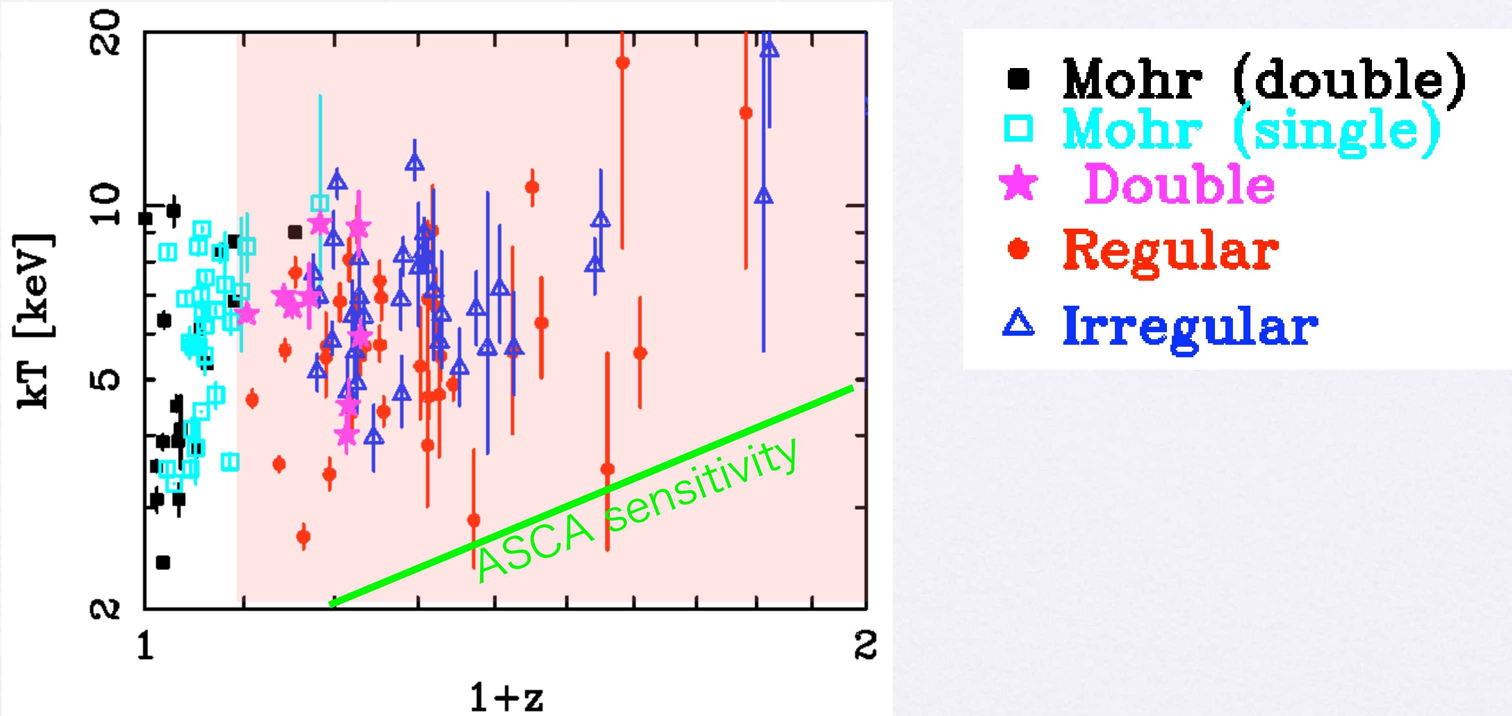
X-ray properties of the sample

- Redshift dependence
  - No clear z evolution in T, β-model parameters at $z<0.5$
  - L_X–T is steeper at $z>0.3$? but not statistically significant →

    we perform the analysis regardless of z
- Density structure
  - Two distinct peaks at 50 and 200 kpc in r_c histogram
  - Coincidence with two r_c values of double-β clusters
  - r_c is correlated with X-ray morphology, n_{e0}, presence of cD galaxy, L_X–T etc.
    - Significant difference between $r_c < 100$ and $r_c > 100$ kpc.

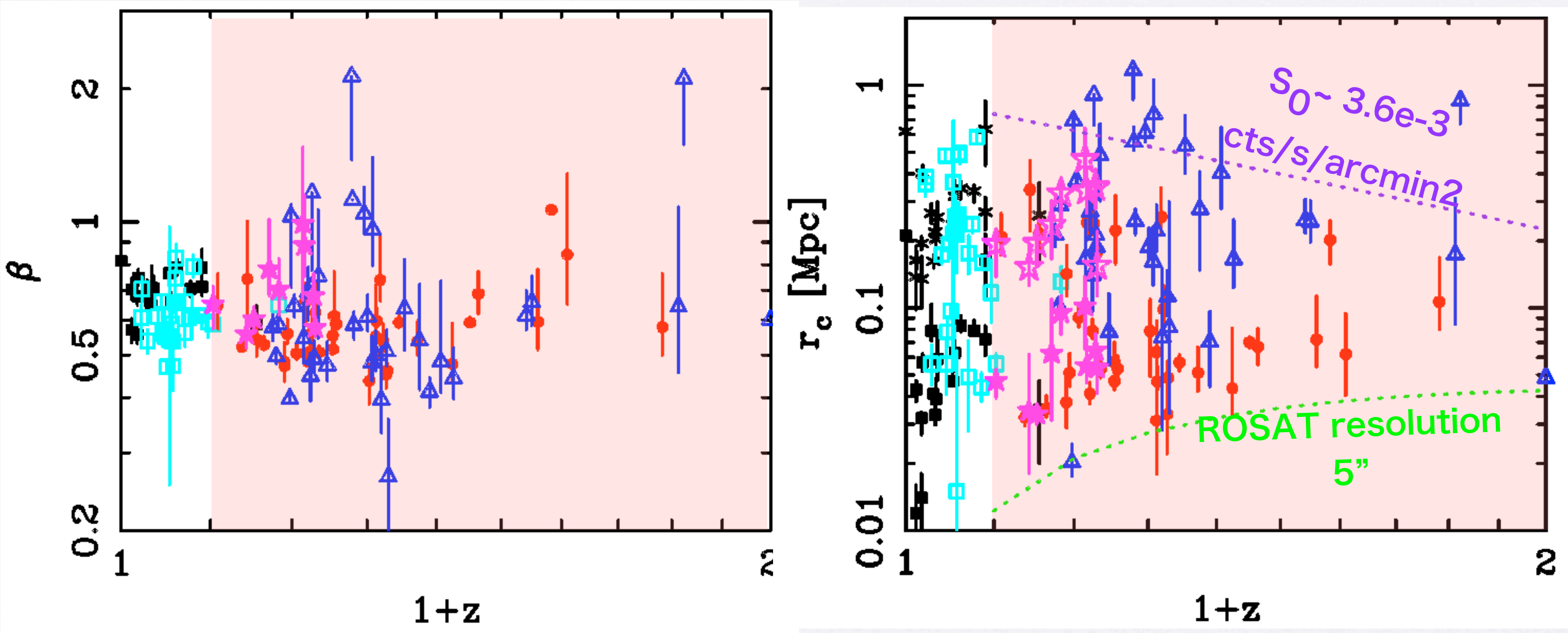
      → *Two classes of cluster type? Different stages of evolution?*

Temperature vs redshift



No clear redshift evolution.

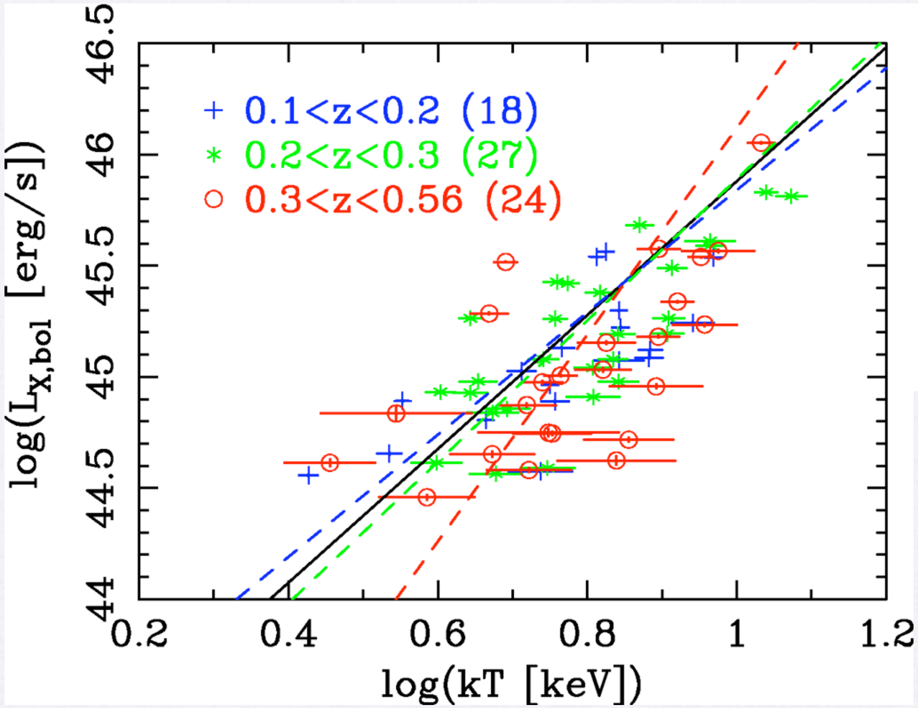
β-model parameters vs redshift



* Very large dispersion

* Systematic difference between Regular/Irregular clusters
* Less clusters with rc~100kpc

Redshift dependence of L_X–T



$L_X \propto T^{2.75^{+0.85}_{-0.71}}$ for 0.1<z<0.2

$L_X \propto T^{3.18^{+0.92}_{-0.84}}$ for 0.2<z<0.3

$L_X \propto T^{4.65^{+2.33}_{-1.86}}$ for 0.3<z<0.56

steepening at z>~0.3 ?

cf. Ettori et al. 2004 reported a steep slope of 3.72±0.47 for high-z clusters (0.4<z<1.3)

Lx-T for higher-z

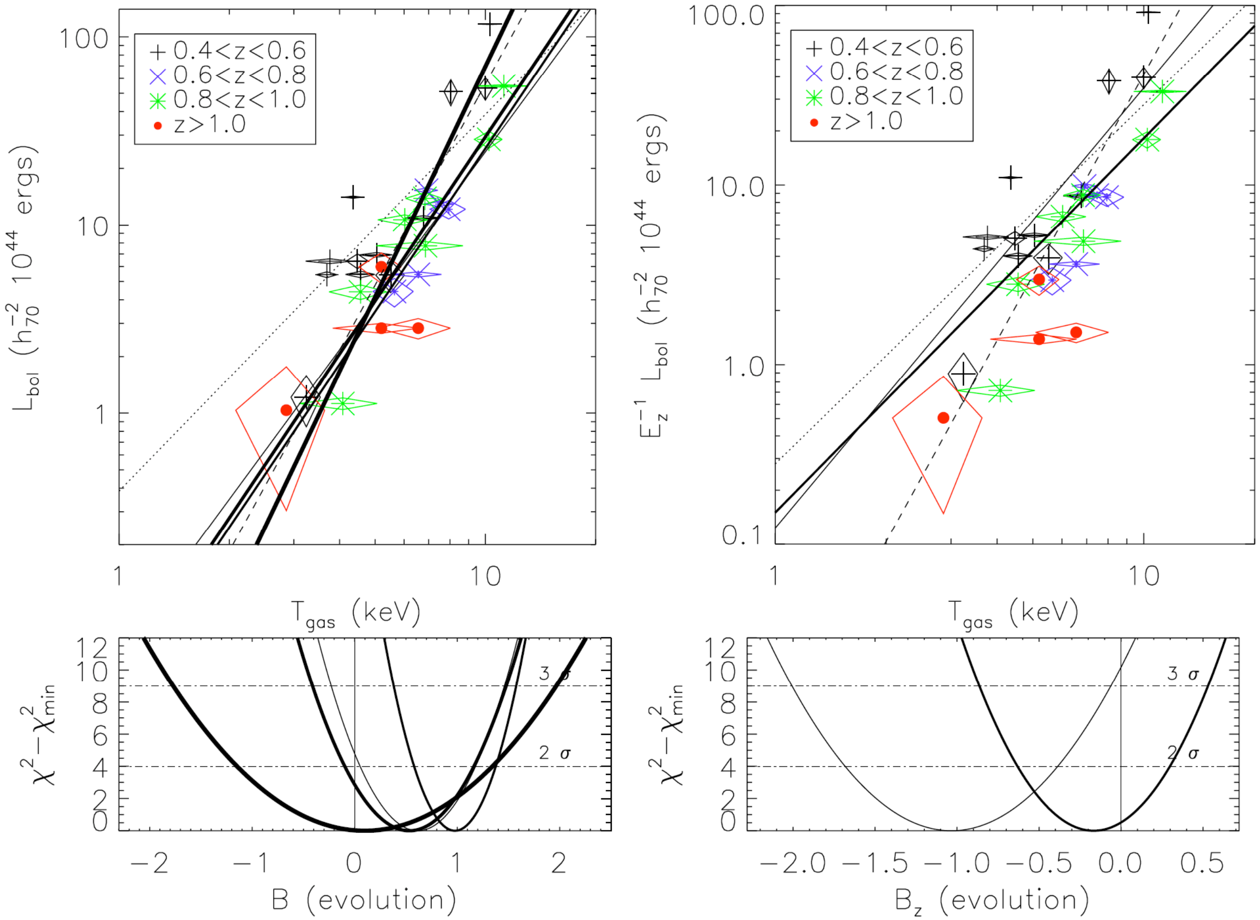
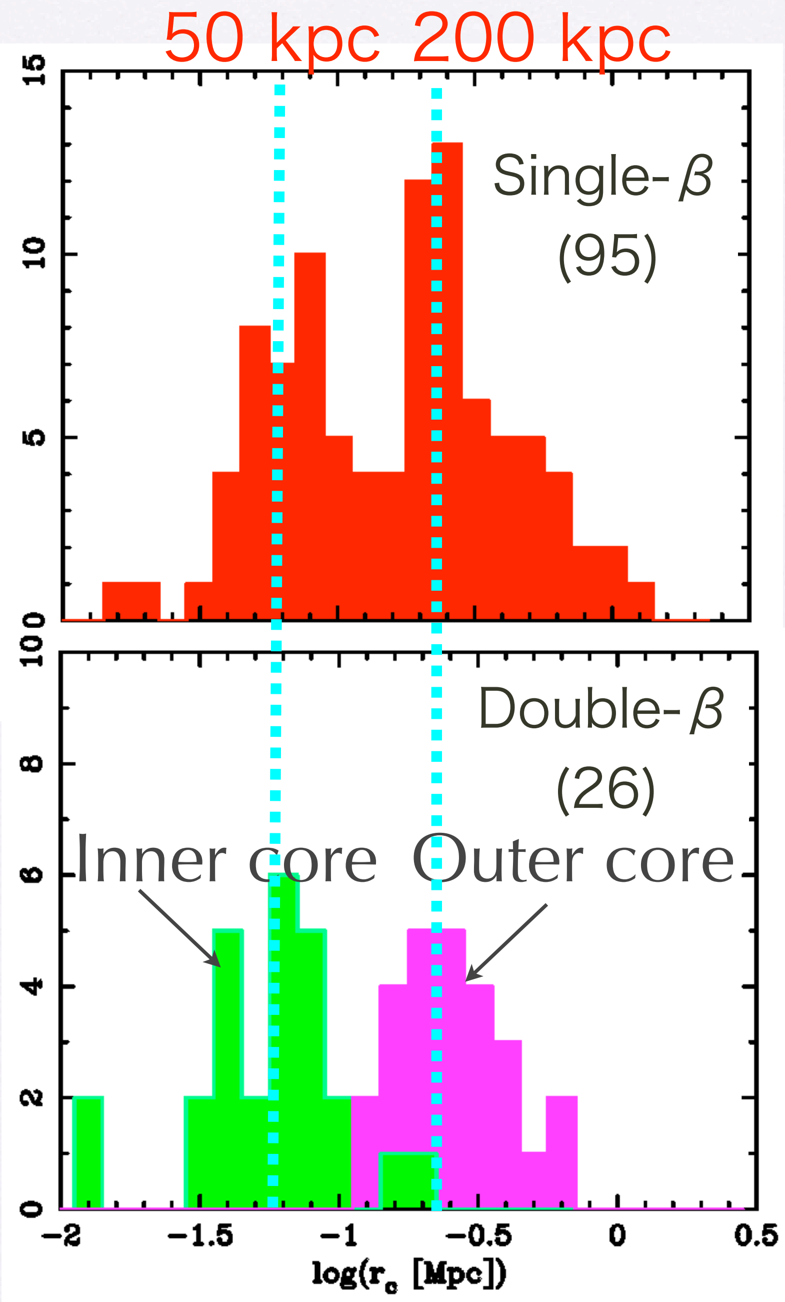


Fig. 4. $L-T$ relation without (*left*) and with (*right*) correction by E_z. (*Upper panels*) Dotted line: slope fixed to the predicted value of 2. Dashed line: slope free. The solid lines represent the local best-fit results (from thinnest to thickest line): Markevitch (1998; with core excised in cooling flows clusters), Arnaud & Evrard (1999), Novicki et al. (2002; for objects at $z < 0.3$) and Novicki et al. (2002; for objects at $0.6 > z > 0.3$). Solid line: Ettori et al. (2002; thinest line), Allen et al. (2001c). (*Bottom panels*) Plot of the $\Delta\chi^2$ distribution for the one interesting parameter $B(B_z)$ given in Eq. (7). Each solid line corresponds to a local scaling relation plotted with the same thickness in the upper panel and compared to all the 28 objects with $z \geq 0.4$ in our sample. The 2 and 3σ limits are shown as dot-dashed lines.

Histograms of r_c

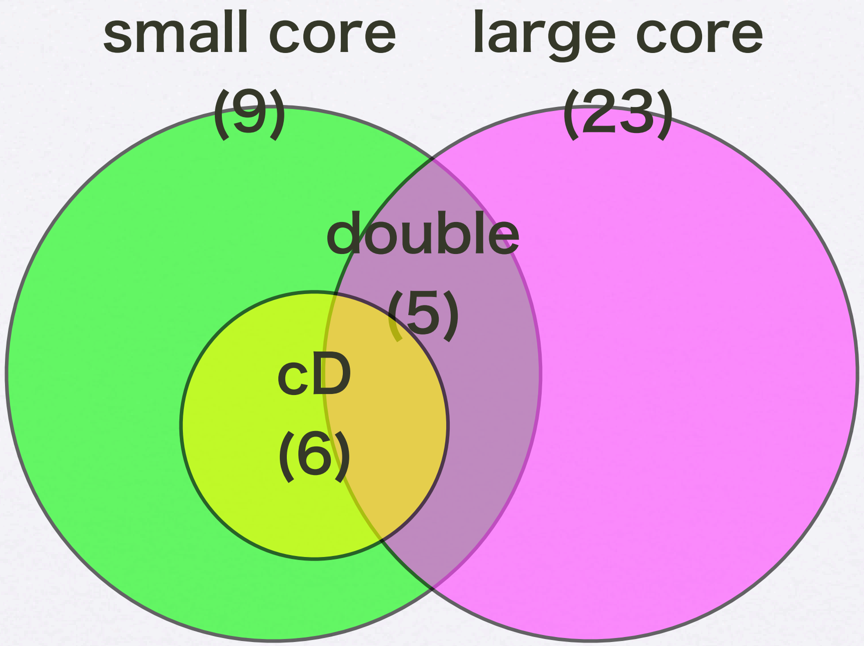
Ota & Mitsuda 2002 ApJL



45 nearby clusters (Mohr et al. 1999) were added together.

cf. Ettori et al. 2004
rc ~100kpc, no significant double for high-z

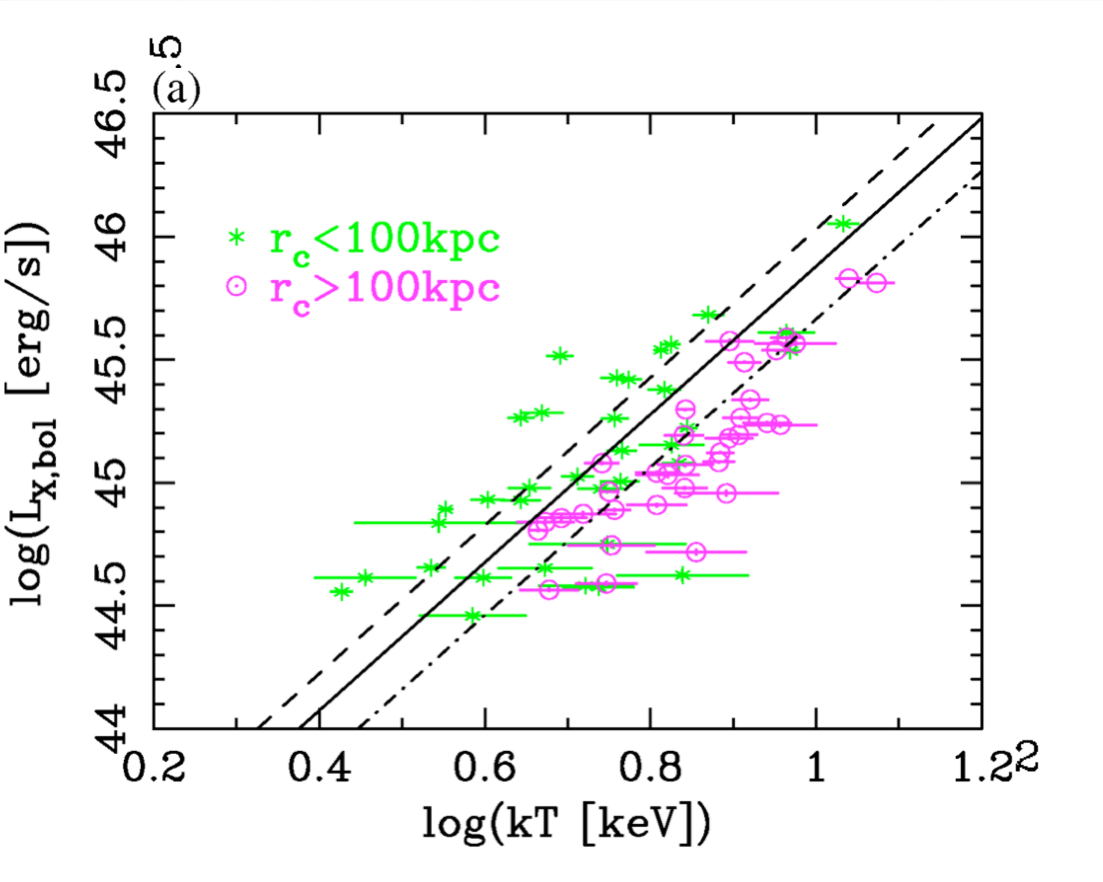
cD galaxy and core radius



cDs appear in clusters with small core or double-β clusters.

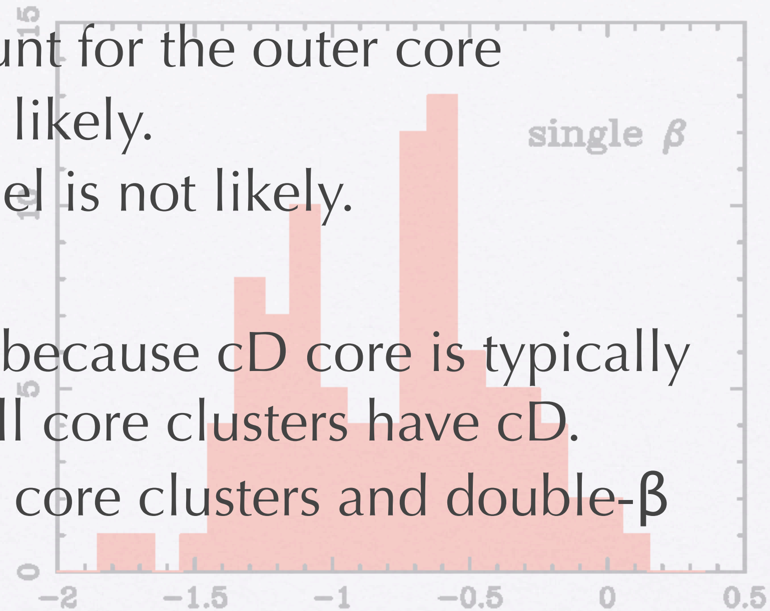
But difficult to explain the small core scale ~50kpc because the typical core radius of cD galaxy ~10kpc.

Lx–T and core radius



The normalization factors are significantly different between two subgroups.

FAQs on the origin of two r_c scales



- ICM origin
  - Abundance gradient ? -- may account for the outer core dominant double-β cluster, but not likely.
  - Cooling flow ? -- The standard model is not likely.
- Dark matter origin
  - cD galaxy potential ? -- Not likely because cD core is typically 10 kpc as well as only 50% of small core clusters have cD.
  - Merging ? -- Possible but that small core clusters and double-β clusters are ~regular clusters...
  - DM has two preferable scales? -- Yes as long as we rely on hydrostatic equation and isothermal β-model.
- Other origin
  - MOND ?

In this talk, I focus on the effect of cooling on L_X-T

2. Impact of cooling on the L_X–T relation

i) L_X–T and gas density profile

ii) L_X–T and cooling

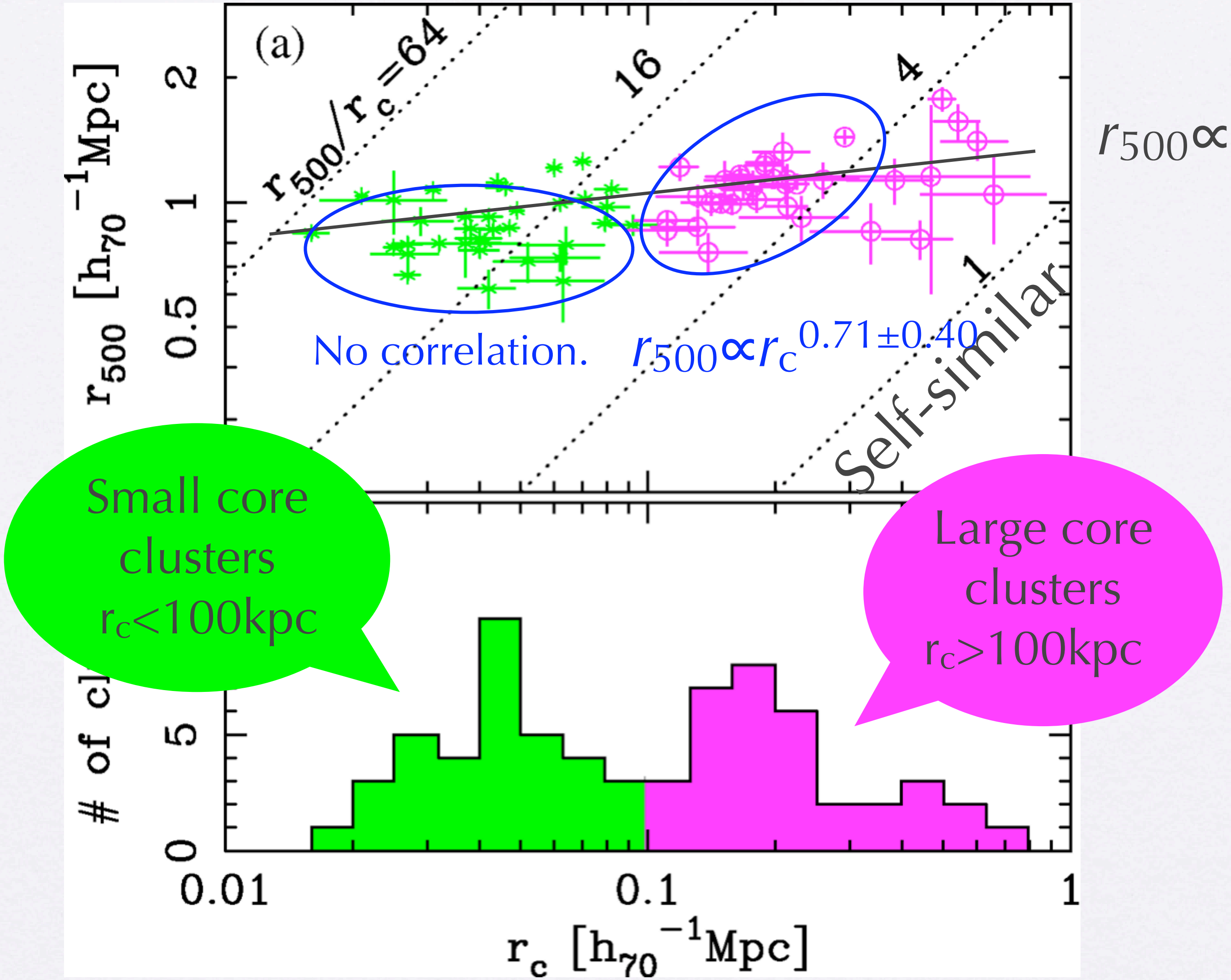
iii) L_X–T β and X-ray morphology

In this analysis, we use the parameters from single-β model.

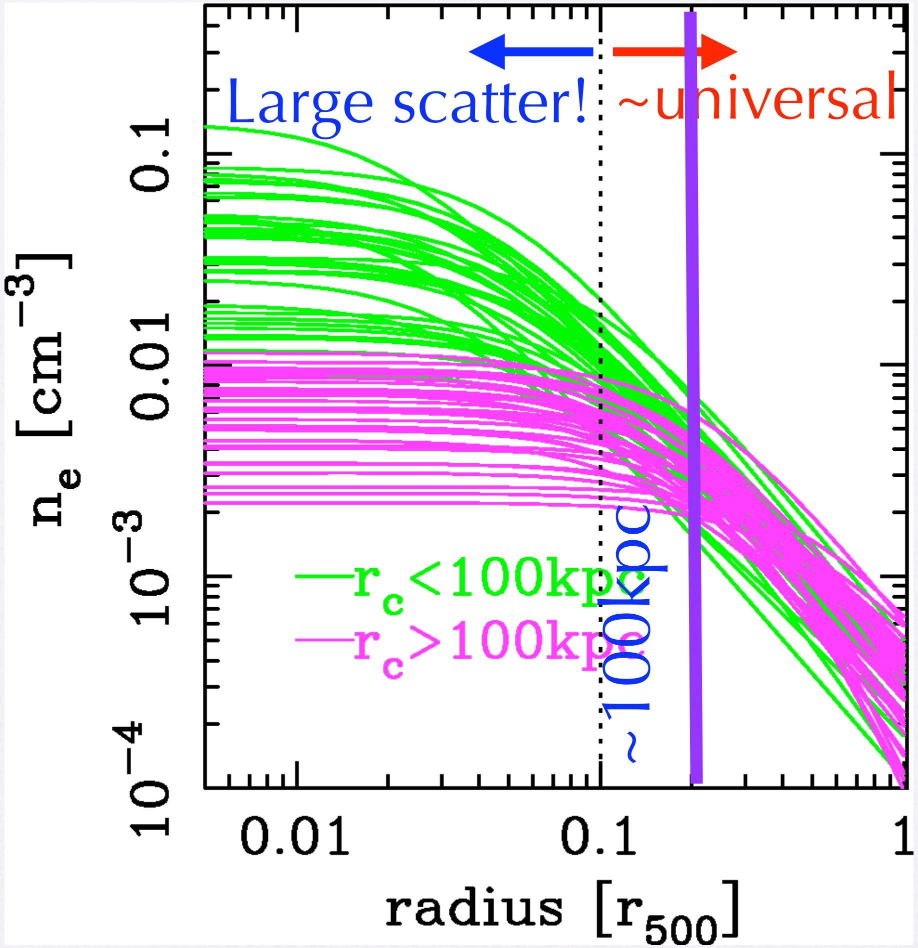
Ota et al. in prep.

Are cluster profiles self-similar?

⭐ r_{500}–r_c relation



Gas density profiles of 69 clusters



$r<0.1r_{500}$

The small core clusters show higher central density.

$r>0.1r_{500}$

The profiles are consistent with "similarity" in outer profiles of nearby clusters (Neuman & Arnaud 1999)

Neumann & Arnaud (1999)

26 clusters (0.04<z<0.06)

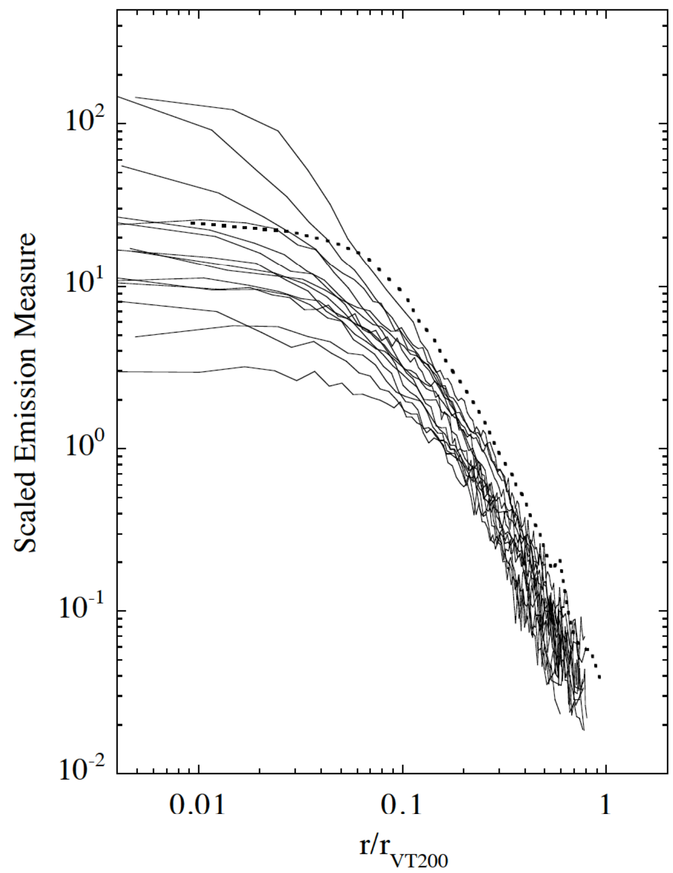
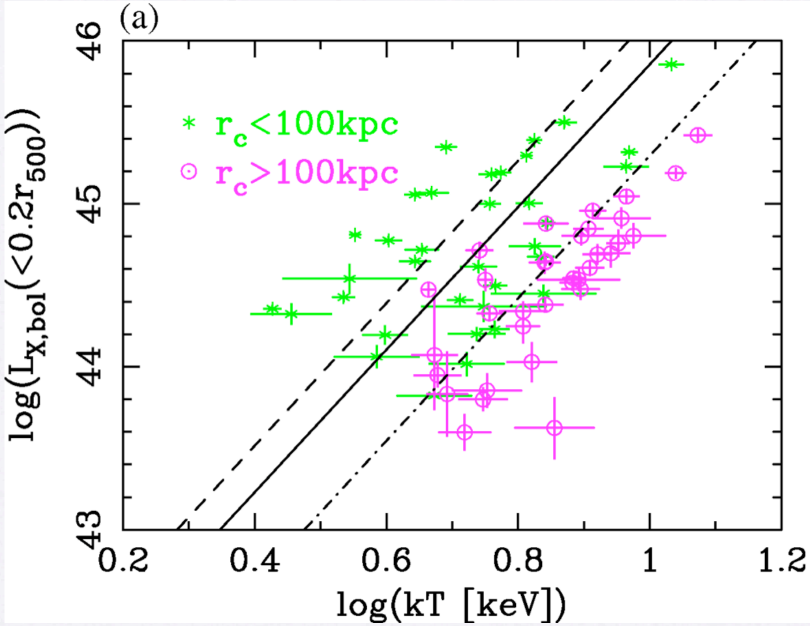
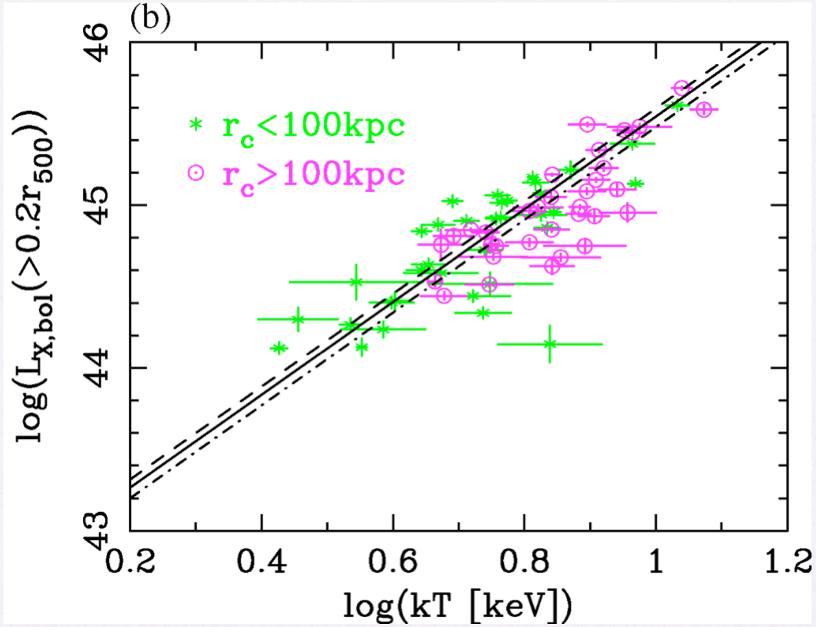


Fig. 2. The scaled emission measure profile (Eq. 7) of the clusters in the spectroscopic sub sample. The radius is normalised to r_{VT200} (Eq. 9). The dotted line shows, for comparison, the emission measure profile of Abell 2163 (z=0.201, kT=14.6 keV, Elbaz et al. 1995). Beyond $r/r_{\mathrm{VT200}} \sim 0.1$ the profiles look remarkably similar.

L_X–T inside/outside $0.2r_{500}$





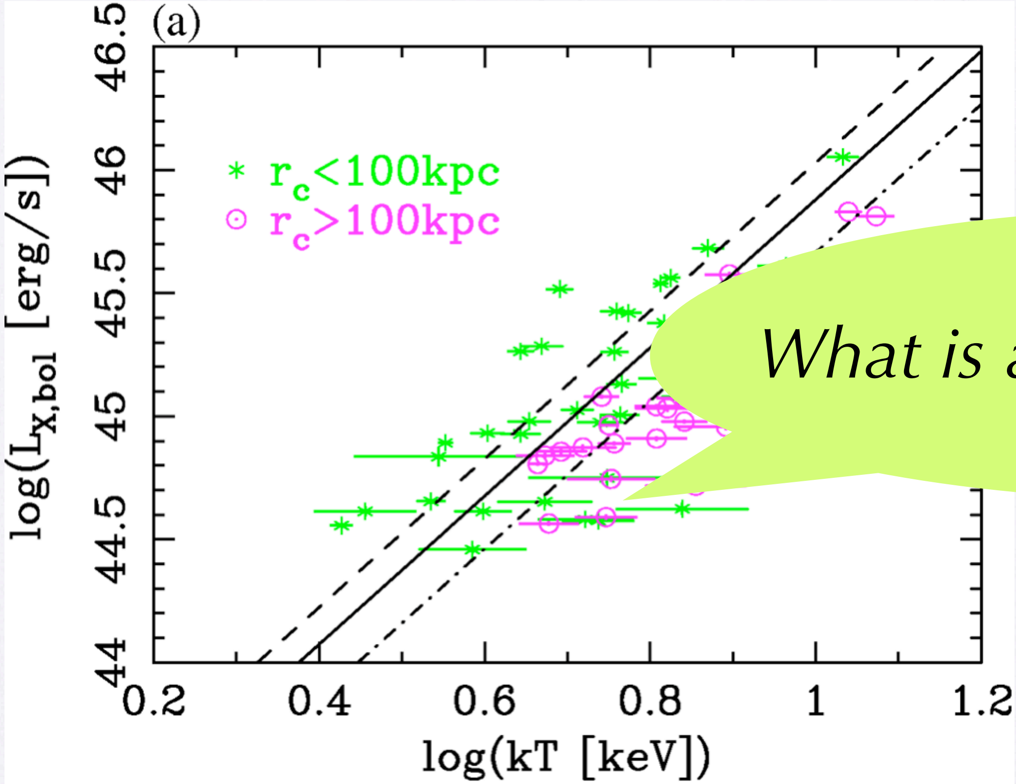
$$L_X(< 0.2r_{500}) \propto T^{4.37^{+1.54}_{-1.50}}$$

$$L_X(> 0.2r_{500}) \propto T^{2.85^{+0.30}_{-0.27}}$$

Very large scatter
Systematic difference between two groups

Surprisingly small scatter
Significantly steeper than T^2
cf. Allen & Fabian 1998

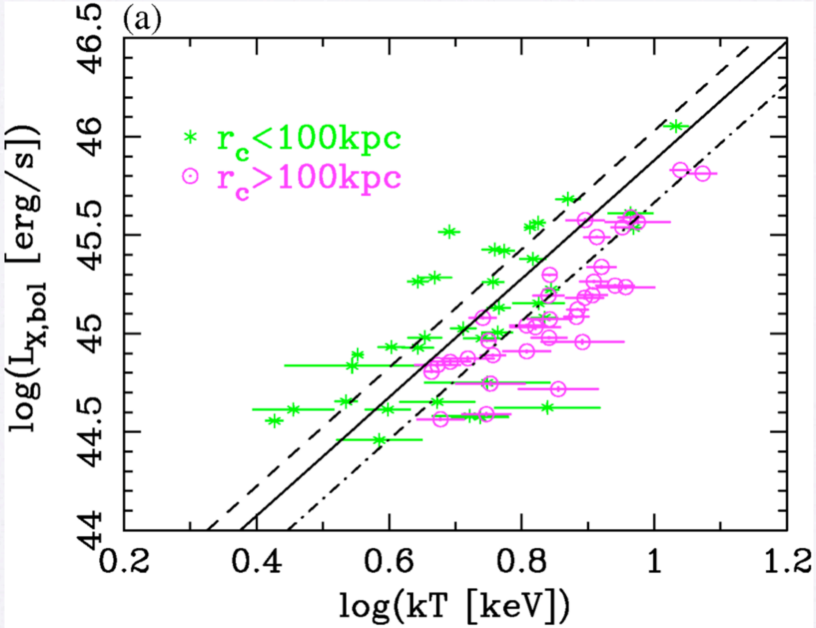
Lx–T and core radius

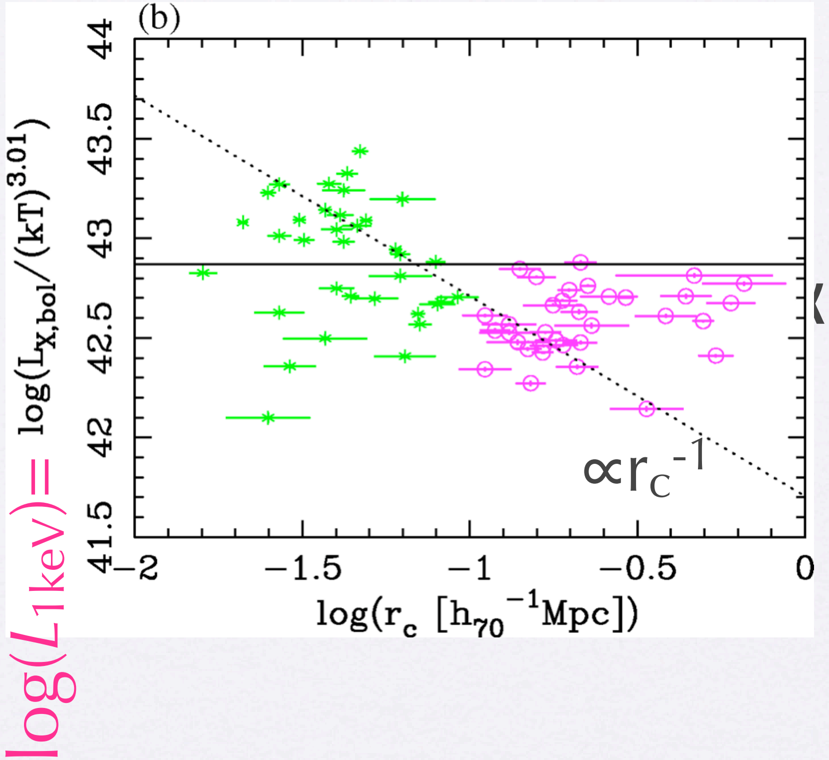


What is a control parameter?

The normalization factors are significantly different between two subgroups.

L_X–T and core radius





$$L_X \propto T^{3.01^{+0.49}_{-0.44}}$$

Systematic difference between two groups

Approximately $L_X \propto T^3 r_c^{-1}$

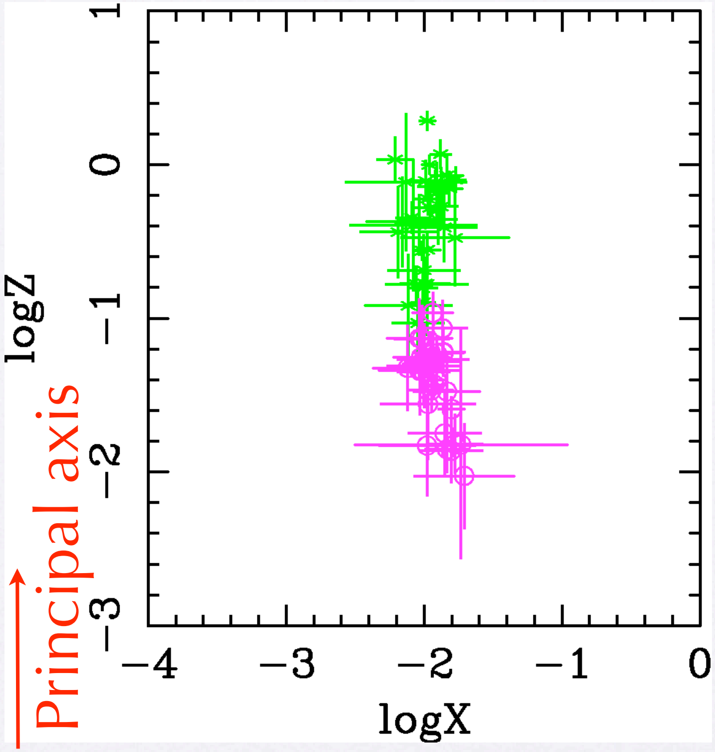
c.f. Fabian et al. 1994

$L_X \propto T^{3.3}\ Mdot^{0.4}$

X-ray fundamental plane analysis

- Planar fitting in the (n_{e0}, T, r_c) space
  - Fundamental plane for the distant sample is consistent with that obtained for nearby clusters (Fujita & Takahara 1999)
  - The principal axis

$$Z \propto {n_{e0}}^{1.20} T^{-0.69}$$
$$\propto {t_{cool}}^{-1.2} \quad \because t_{cool} \propto T^{1/2}/n_{e0}$$



t_{cool} is likely to be a control parameter!

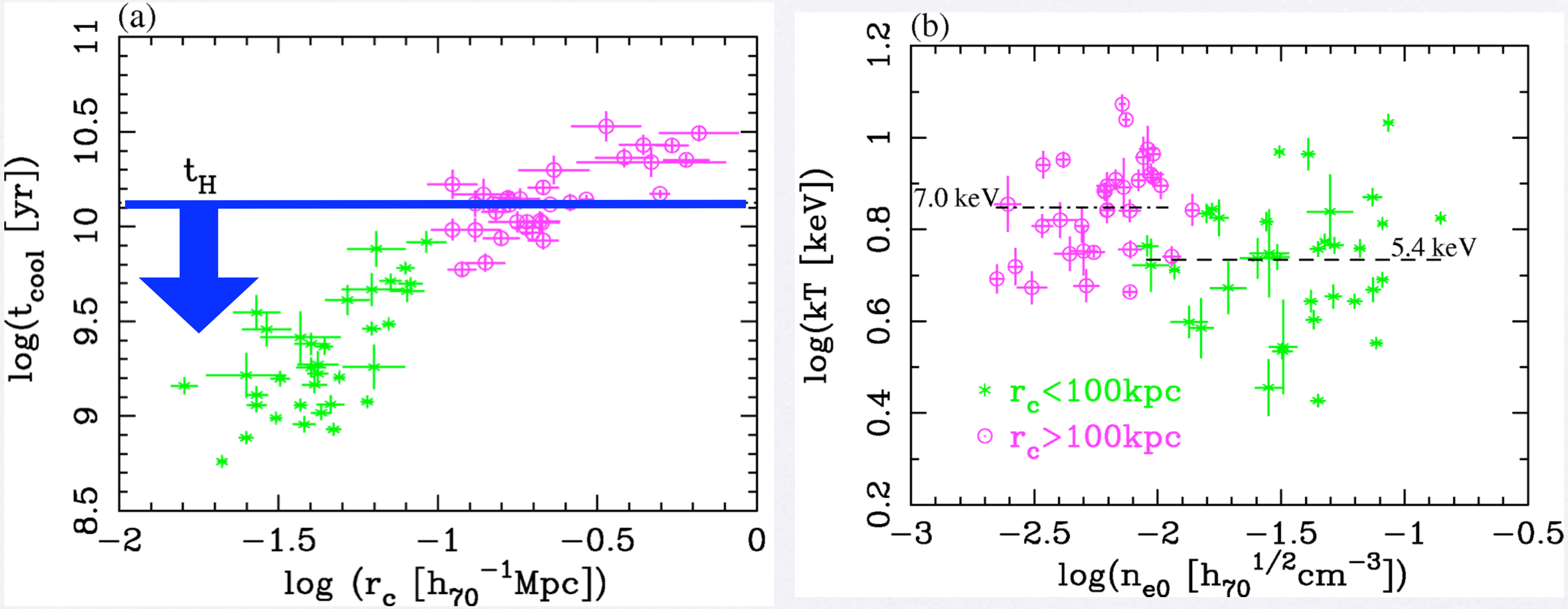
2. Impact of cooling on the L_X–T relation

i) L_X–T and gas density profile

ii) L_X–T and cooling

iii) L_X–T β and X-ray morphology

$t_{\rm cool} - r_{\rm c}$ and $T - n_{\rm e0}$



$t_{\rm cool}$ is tightly correlated with $r_{\rm c}$

For all small core clusters,

$t_{\rm cool} < t_{\rm H}$ →cooling is effective

$n_{\rm e0}$ is higher for smaller $r_{\rm c}$

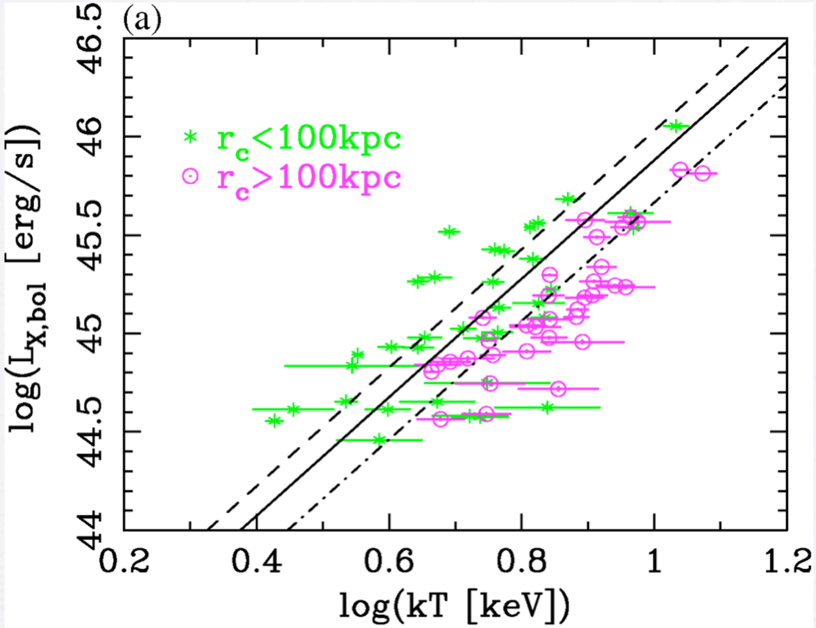
→ central concentration as gas cools

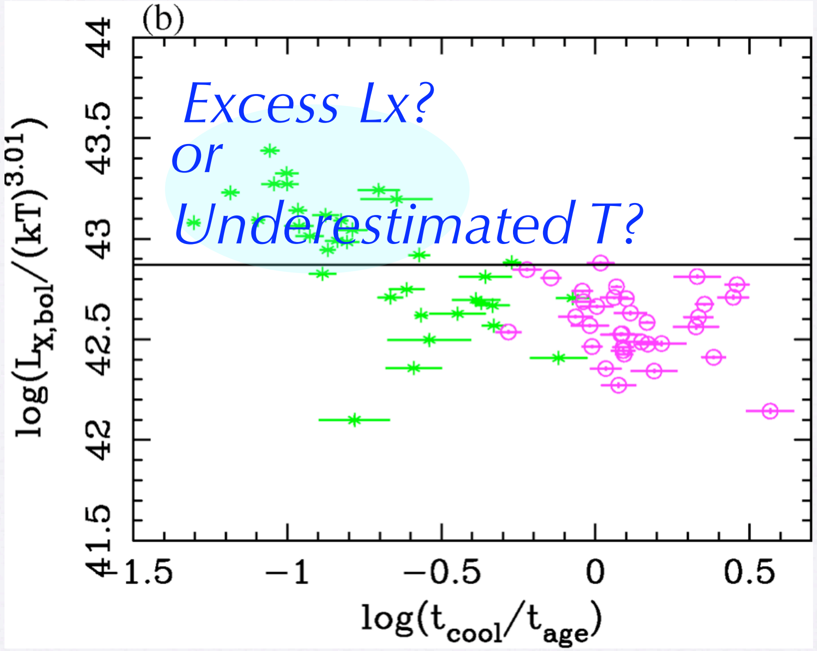
No clear difference in T ranges

→evidence against the standard CF.

The average T is 30% smaller → mild temperature decrease in small core clusters.

L_X–T and cooling time





For $\log(t_{cool}/t_{age})<-0.5$, L_{1keV} is systematically higher.

Estimation of ambient temperature, T'

Assumptions:

- Universal temperature profile; $T(r) \propto r^{0.2}$ (Tamura et al. 2001)
- β-model; β=0.7, r_c=50 kpc

$\rightarrow T' \sim 1.3\ T$

T underestimates T' by 30% ~ comparable to the difference in average T between two r_c groups.

Apply T'=1.3T for 26 clusters with $\log(t_{cool}/t_{age})<-0.5$!

Tamura et al. (2000)

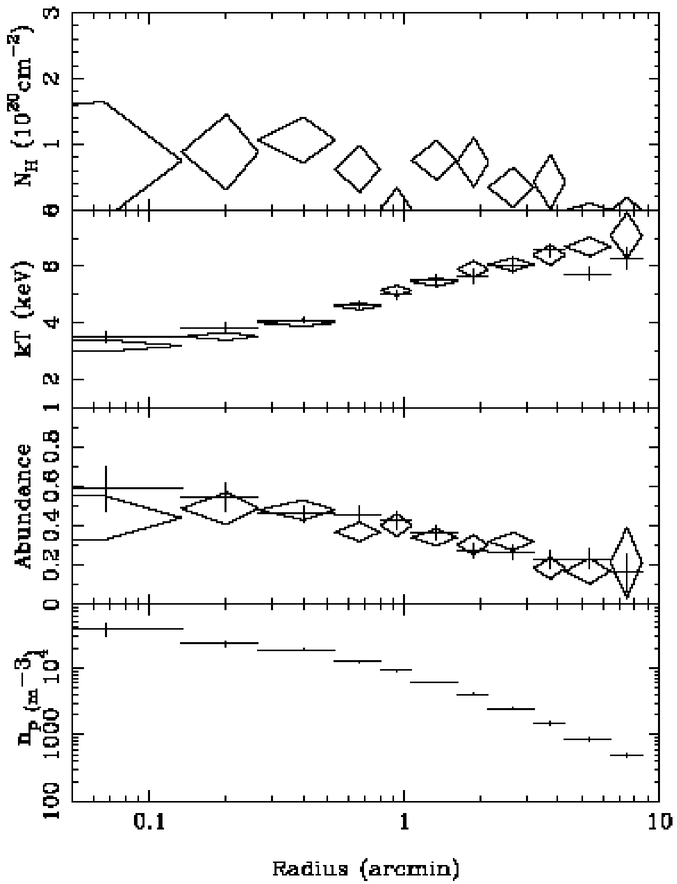
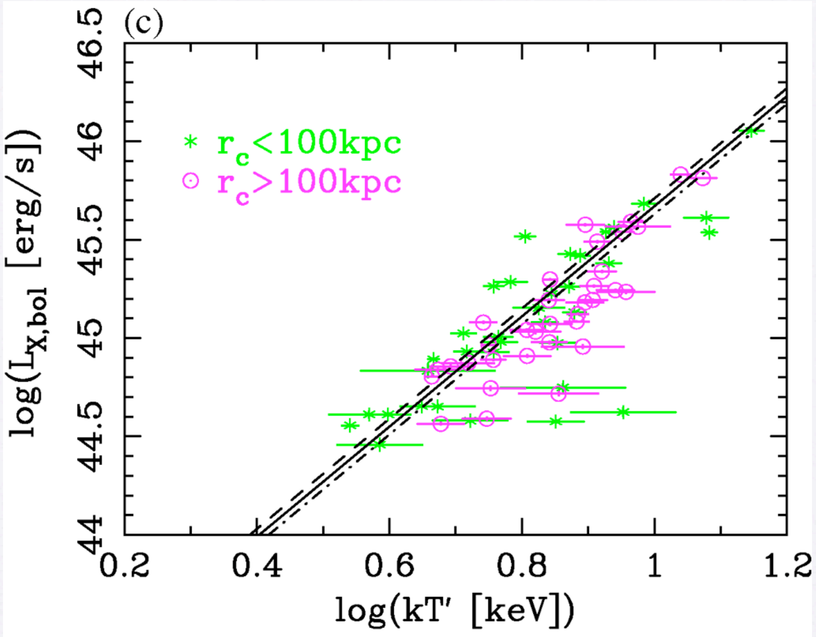
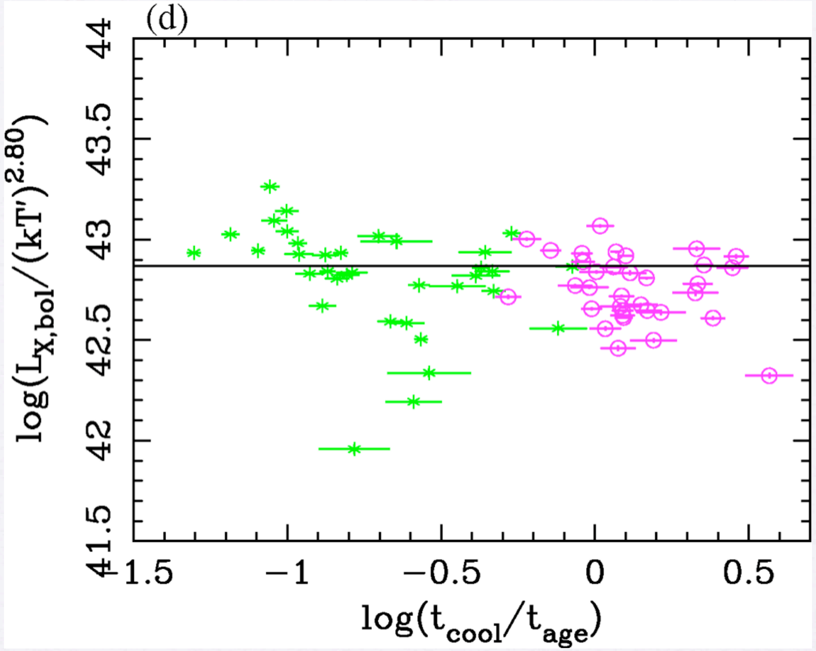


Fig. 1. Properties of the ICM as a function of projected radius derived from the PN and MOS spectra based on a single temperature model. From top to bottom, absorbing column density, temperature, metal abundance, and the deprojected hydrogen density were shown, respectively. The PN and MOS results were shown by diamonds and crosses, respectively.

L_X–T' and cooling time





$$L_X \propto T'^{2.80^{+0.28}_{-0.24}}$$

Small scatter!

No difference between two groups.

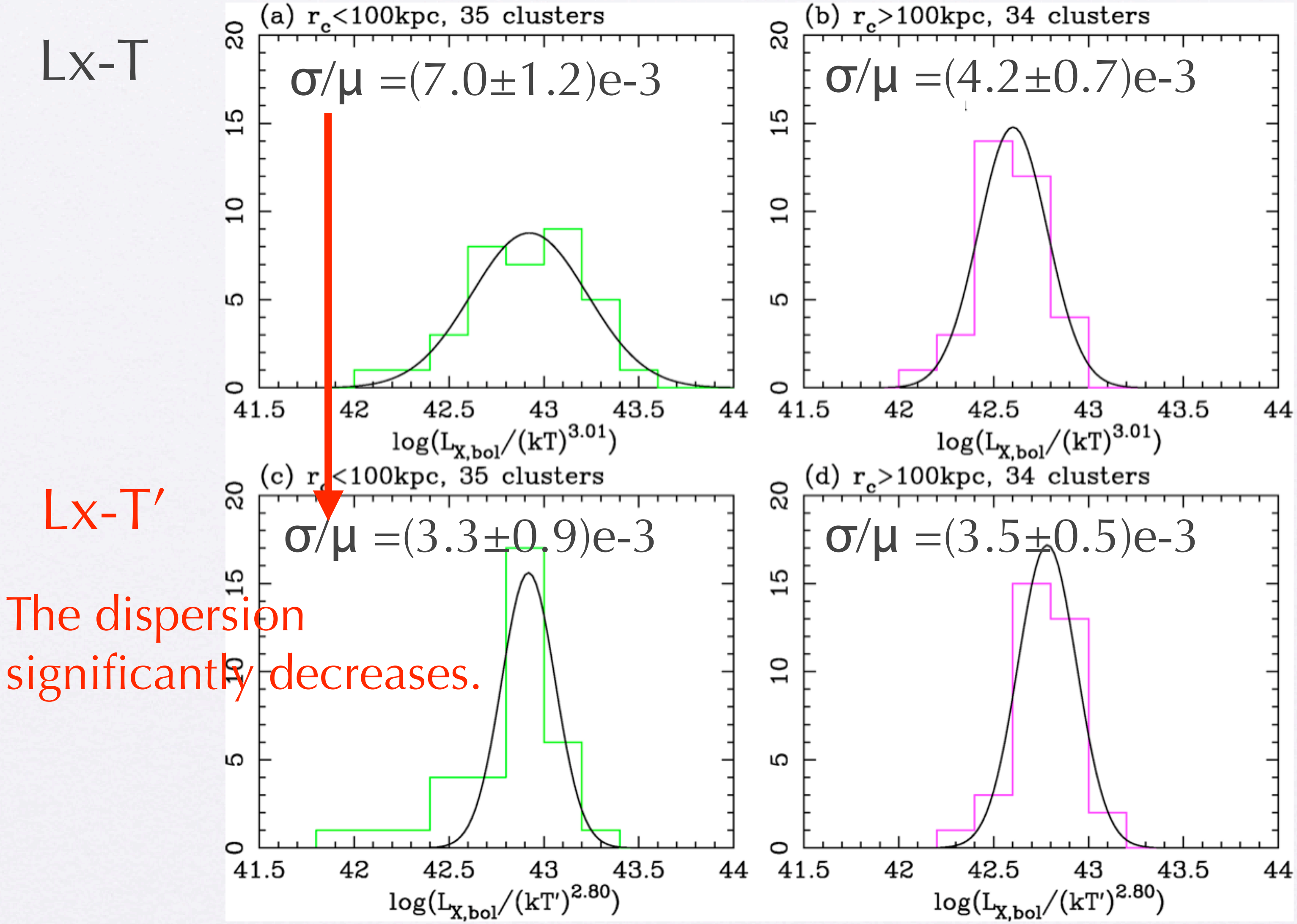
cf. Fukazawa et al. 2004

α=2.34±0.29

$L_{1\mathrm{keV}}$~constant

for a wide range of t_{cool}!

Comparison of $L_{1\mathrm{keV}}$ distribution



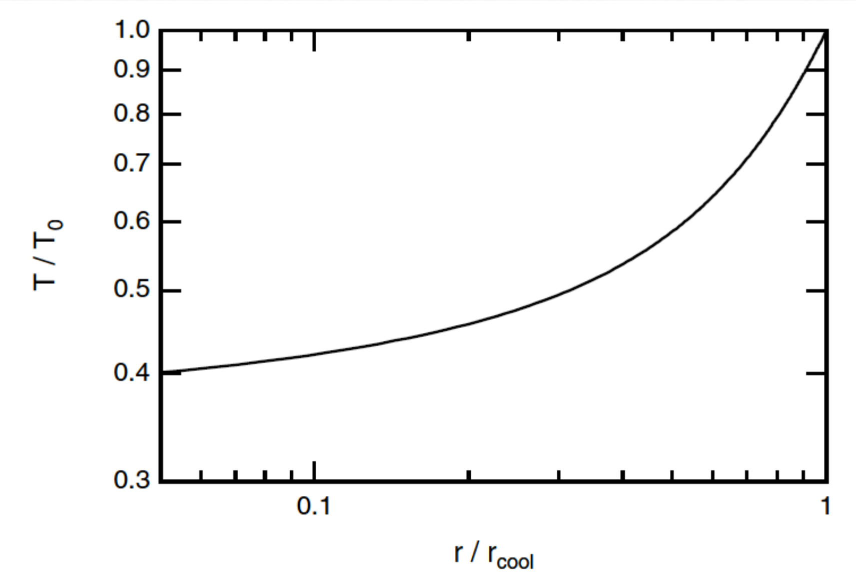
Gas cools but ...

- $L_{1\mathrm{keV}}$ ~ constant for a wide range of t_{cool}
  - The standard CF model predicts cooling that accelerates as time
  - Our result showed luminosity ~ a rate of thermal energy loss is kept nearly constant even after the onset of cooling

→ *This suggests some steady-state of gas is realized in small core clusters.*

Possibility of quasi-hydrostatic state

- Quasi-hydrostatic model (Masai & Kitayama 2004)
  - describes gas under radiative cooling supposing a moderate and smooth gas inflow so as to compensate the thermal pressure loss and keep local hydrostatic balance.
  - Predicted temperature profile
    - central temperature ~1/3 the ambient temperature
  - Mass inflow is expected not vary very much



→Our results can be consistently understood within a framework of the quasi-hydrostatic model.

2. Impact of cooling on the L_X–T relation

i) L_X–T and gas density profile

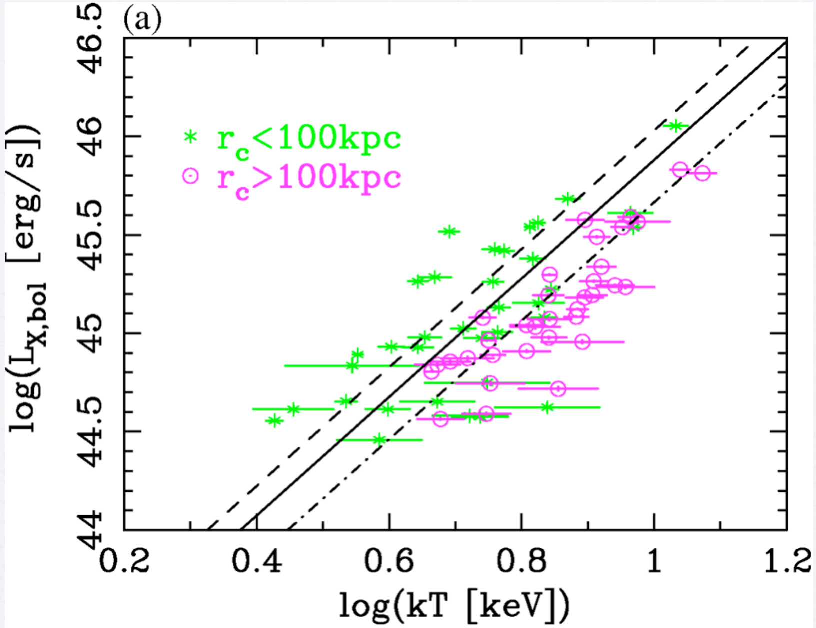
ii) L_X–T and cooling

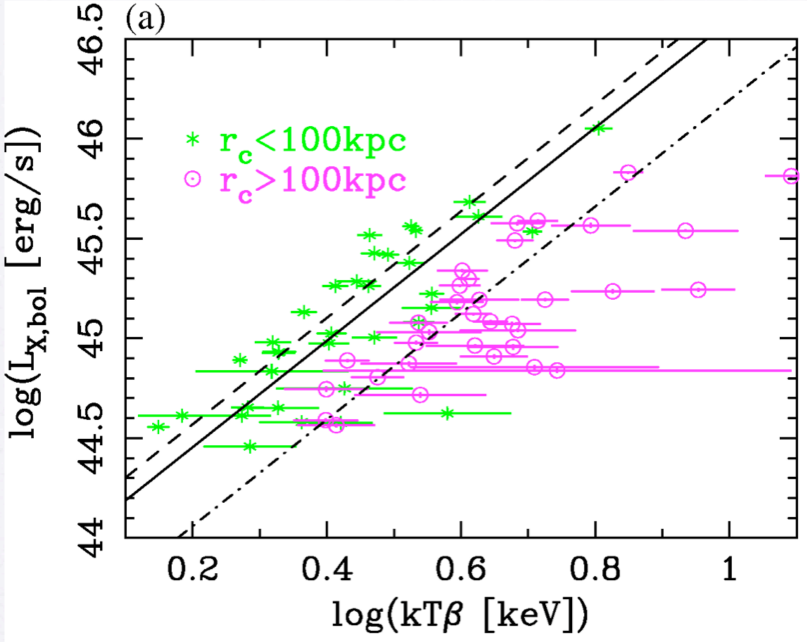
iii) L_X–T β and X-ray morphology

Virial temperature under β-model

- Under the virial theorem and the β-model,
  - $T_{\rm vir} = T_{\rm gas}\beta\ x^2/(1+x^2) \sim T_{\rm gas}\beta\ \ (x \equiv r_{\rm vir}/r_{\rm c} \gg 1)$
- We examine L_X–$T\beta$ and L_X–$T'\beta$ and discuss the relevance to X-ray morphology
  - β; slope parameter determined from the ROSAT radial profile fitting

L_X–T and L_X–Tβ





$$L_X \propto T^{3.01^{+0.49}_{-0.44}}$$

$$L_X \propto (T\beta)^{2.67^{+0.44}_{-0.44}}$$

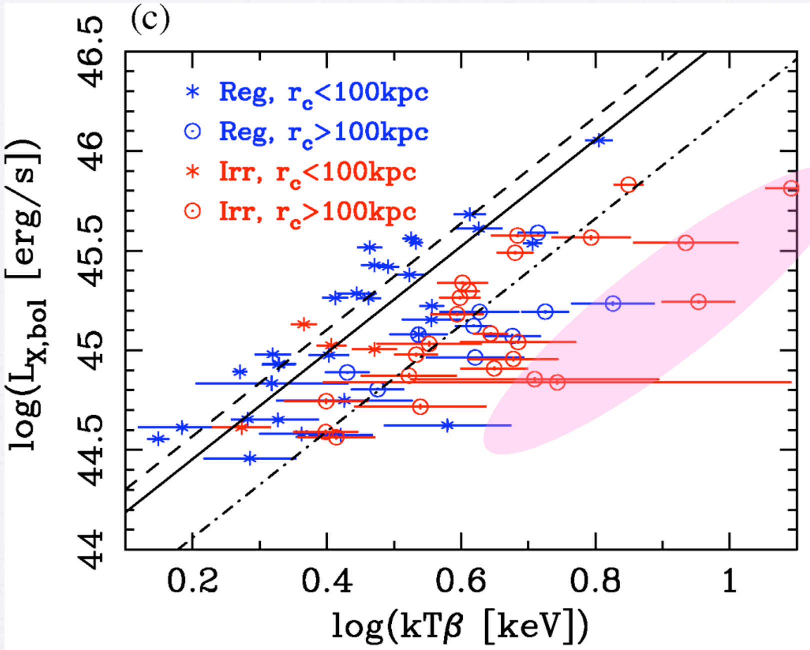
σ/μ =(7.0±1.2)e-3

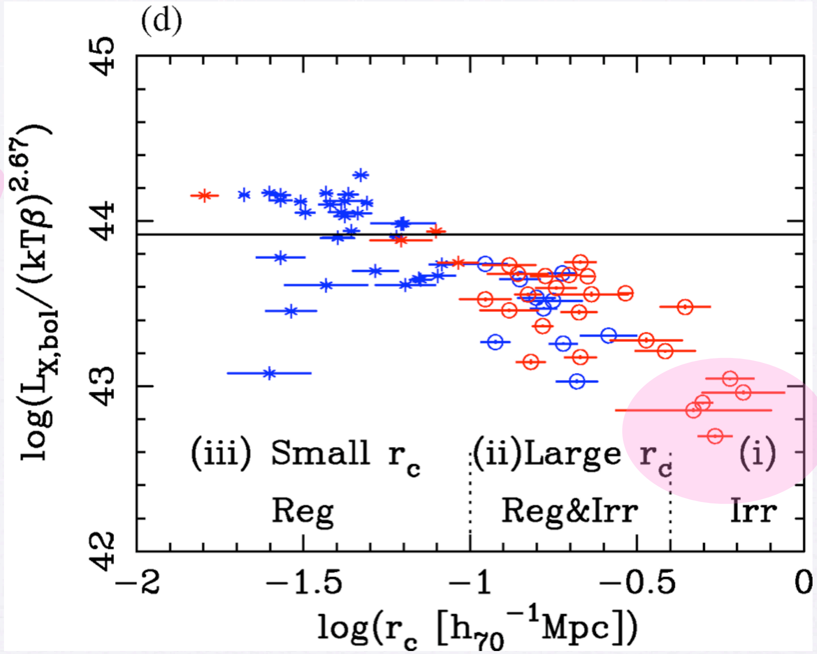
σ/μ =(4.2±0.7)e-3

σ/μ =(4.6±0.7)e-3 ↓

σ/μ =(10.8±7.8)e-3 ↑

L_X–$T\beta$ and X-ray morphology



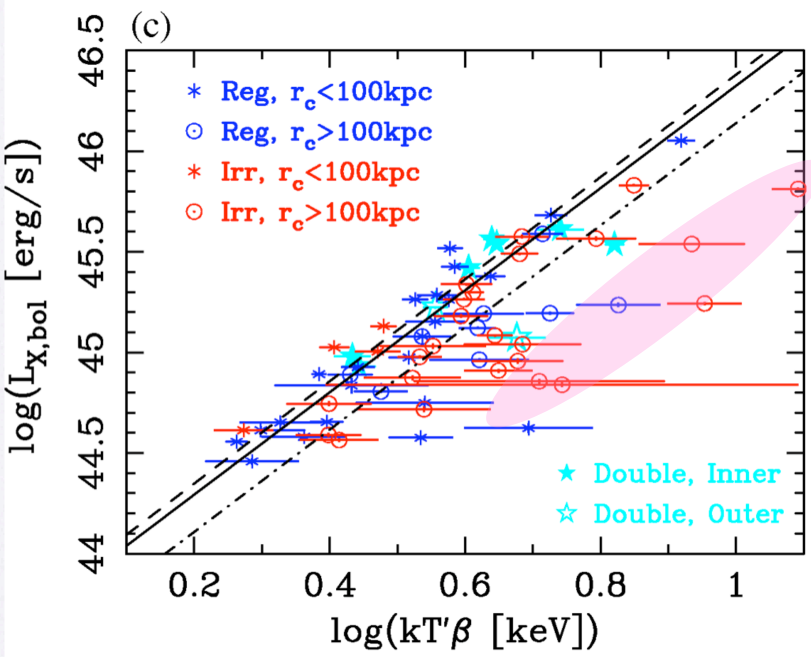


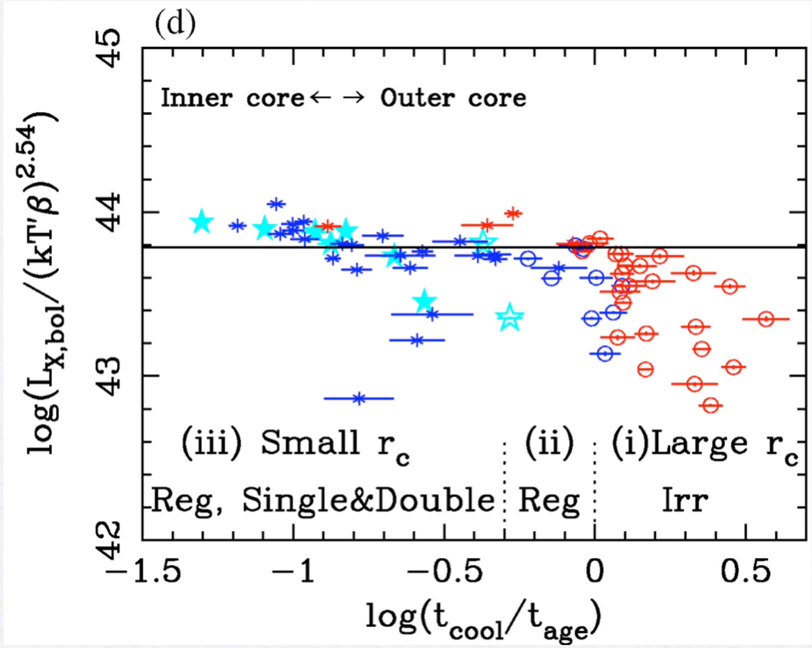
5 clusters with very large core >400kpc show signatures of merging or cold front in the surface brightness

Merging clusters segregate from the regular clusters on the L_X–$T\beta$ plane.

Morphological change along r_c-axis

LX–T′β and cooling time





$$L_X \propto (T'\beta)^{2.54^{+0.29}_{-0.26}}$$

Morphological change along t_{cool}!

σ/μ =(2.7±0.5)e-3 for Reg.

σ/μ =(6.7±1.6)e-3 for Irr.

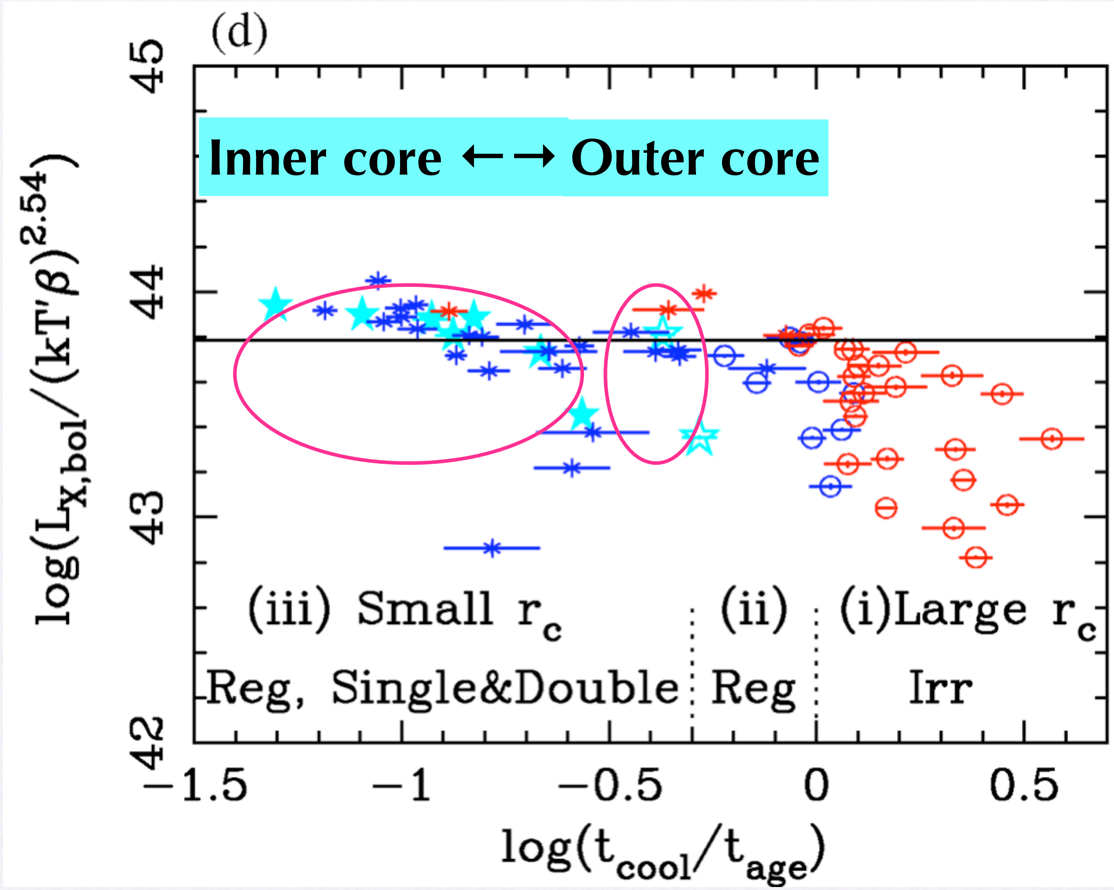
Discussion

Three phases of ICM evolution

(i) $t_{cool}<t_{age}$ Irregular, Large r_c

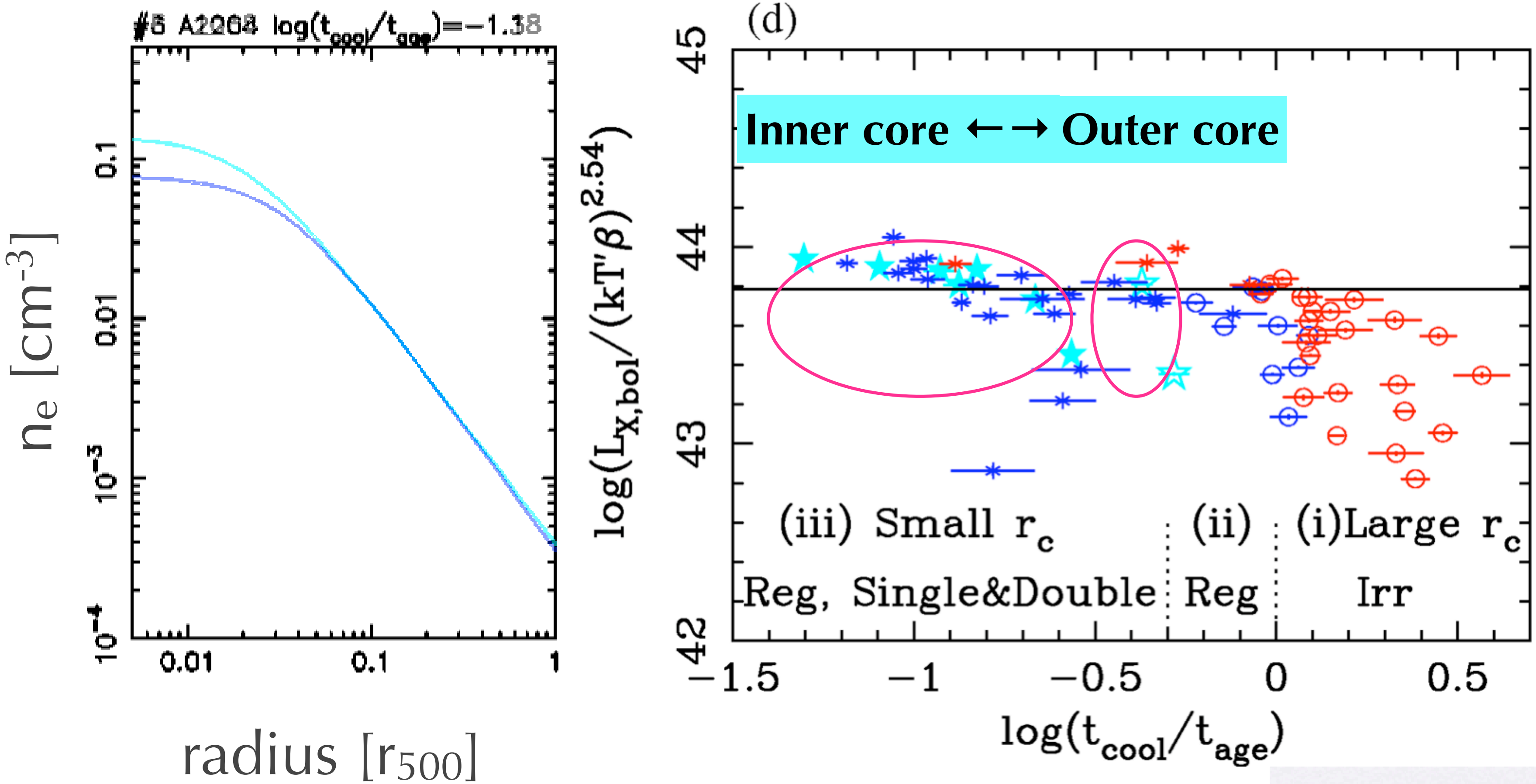
(ii) $t_{age}/3<t_{cool}<t_{age}$ Regular, Large r_c

(iii) $t_{cool}<t_{age}/3$ Regular, Small r_c, Double-β appears!



Evolution of density structure: a *phenomenological picture*

sorted by t_{cool}



After cluster collapses, t_{cool} falls below t_{age}, core is radiatively cooled with keeping quasi-hydrostatic balancing, and the central density becomes higher to evolve from an outer-core-dominant cluster to inner-core dominant cluster

Summary

Summary and future observations

⭐ Based on the ROSAT & ASCA distant sample, we showed:

1. L_X–T and gas density profile
2. L_X–T, L_X–T′ and t_{cool}
3. L_X–Tβ, L_X–T′β and X-ray morphology

→Cooling has a significant impact on the Lx-T. The results can be consistently understood within a framework of quasi-hydrostatic model.

⭐ Things to be further studied

1. Temperature profiles are not directly constrained
2. Detailed calc. on density profile under quasi-static model
3. Heating

⭐ Future observations

1. High-resolution SZ+X
2. Astro-E2