XMM-Newton Observations of Central Regions of Cluster Galaxy

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3. Results and Discussion
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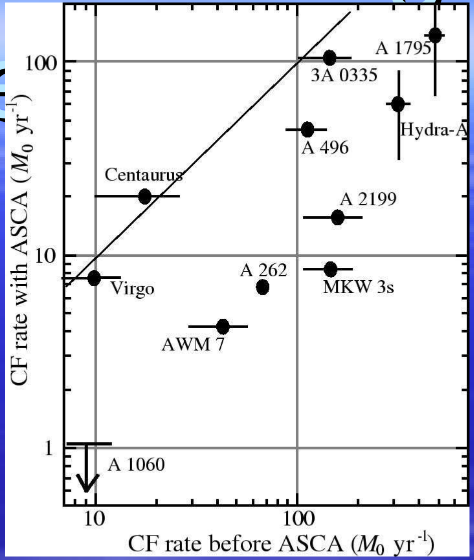
4. Summary

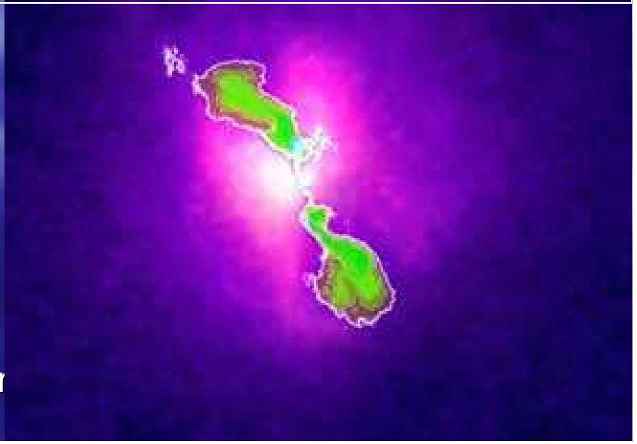
Motivation (1) Cooling and Heating of the central core

- At the cores of X-ray clusters, the gas is cooling via X-ray radiation.
  - $T_{cool} < H^{-1}$
- A cooling flow, unless some heat sources balances with the radiation dynamically.
- However, no direct evidence of the cooled material.
- ASCA spectra shows a lack of low-temperature emission.
- AGN-ICM interactions.



From Makishima et al. 2001

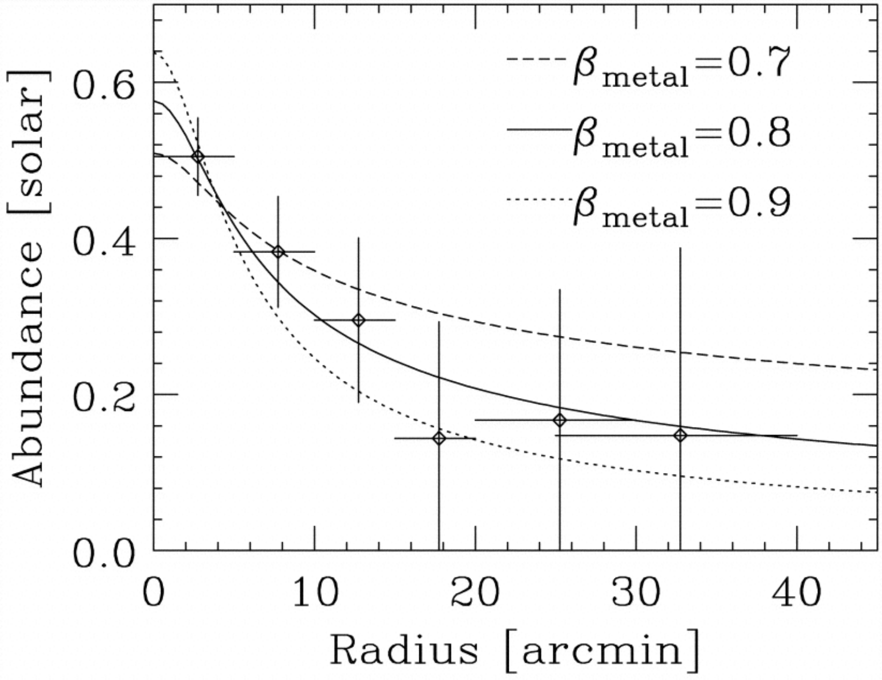
From McNamara et al. 2000



Unknown, but one of the most energetic physics mechanism (heat source, mass transfer).

Motivation (2) Metal production and circulation

- M_{Fe}(ICM) > M_{Fe}(stars)
  - Production and circulation of the ICM metal has not fully understood.
- Metal origins in galaxies
  - Normal stars -> SN Ia
  - Massive stars -> SN II
- The most direct evidence would be found around cD galaxies.



From Ezawa et al. 1997

Limitations before XMM/Chandra

Spatial and spectral resolution of previous instruments are limited.

1. Poor spatial resolution along with the projection effect.
2. Fe-L line complex could not resolved (Coupling of absorption and temperature).
3. Thermal structure depends on the assumed model.
4. → severe errors in the abundances of Fe and other elements.
5. In most cases these measurements are limited to the Fe, Si and S abundances (Not O).

XMM-Newton (1999-)

- EPIC (CCD; PN+MOS)
  - Larger effective area in 0.3-10 keV.
  - Better spatial resolution (15” in PSF HPD).
  - Better spectroscopic capability in low X-ray energy band.
  - *(high background)*

- RGS (Reflection Grating Spectrometer)
  - High resolution spectroscopy in 0.3-2 keV (O and Fe-L resolved spectrum)
  - Only for peaked X-ray core of clusters.
  - *(Only one dimensional spatial resolution).*

XMM Observations

	z	T(ICM; keV)
NGC 533	.018	1.3
A 262	.016	2.2
Ser 159 *	.057	2.4
MKW 9	.040	2.6
2A 0335	.034	3.0
A 2052 *	.036	3.1
Hyd-A	.055	3.4
MKW 3s *	.046	3.5
A 4059	.047	4.0
A 1837	.071	4.4

	z	T(ICM; keV)
A 496	.032	4.4
A 3112 *	.077	4.5
A 1795 *	.064	5.8
A 399	.071	6.2
Perseus	.018	6.5
A 1835	.254	7.2
Coma *	.024	7.5
A 754	.056	8.0
A 3226	.061	8.7

Cool, med-T, hot clusters

Soft excess (<0.5 keV) clusters (*)

Analysis: Basic Assumption

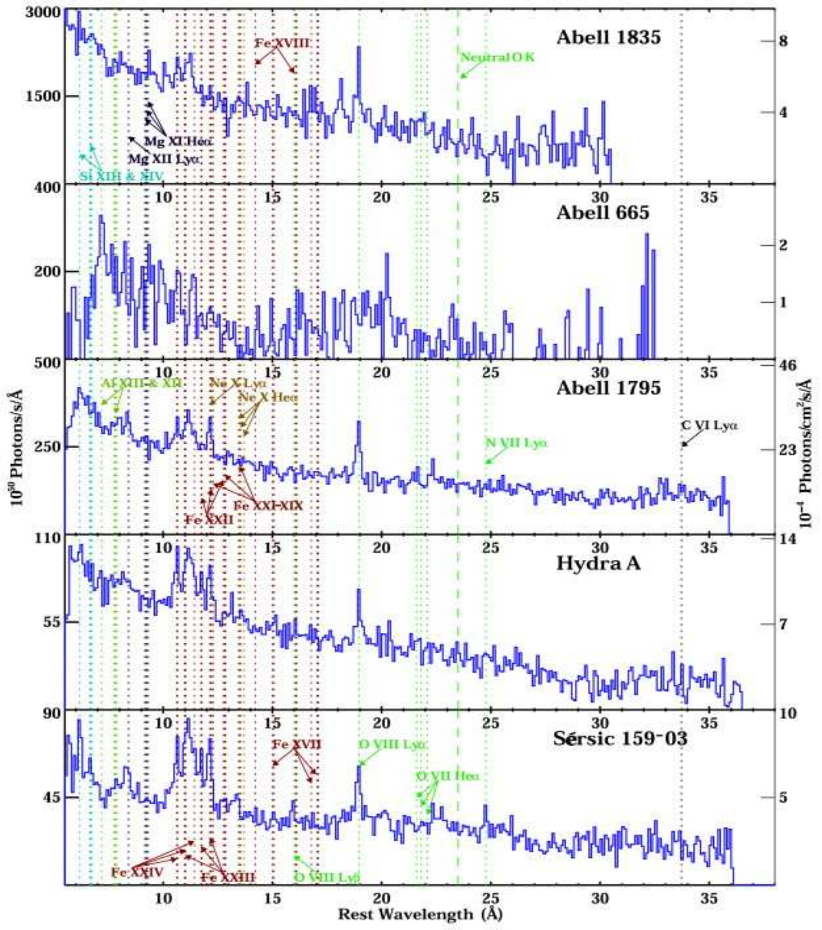
- X-ray spectral distribution is assumed to be spherically symmetric.
- Using a set of concentric spectra, 3D-spectra for each shell is derived.

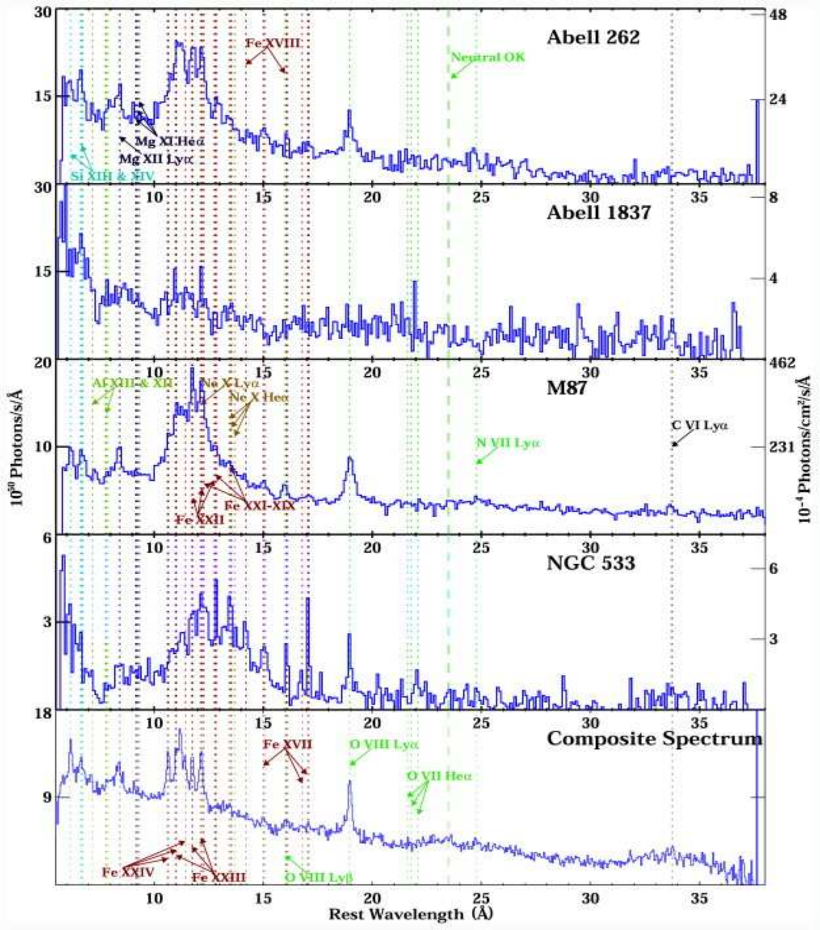
- Spectral models:

1. Single-Phase, collisional ionization equilibrium: 1T
2. Multi-temperature
3. Isobaric cooling flow: CF
   - Isolated plasma at constant pressure cooling via X-ray radiation.
   - $dEM(T)/dT \propto 1/\Lambda(T)$, $\Lambda(T)$ is the cooling function.

– Abundances of O, Ne, Mg, Si, S, and Fe are free parameters.

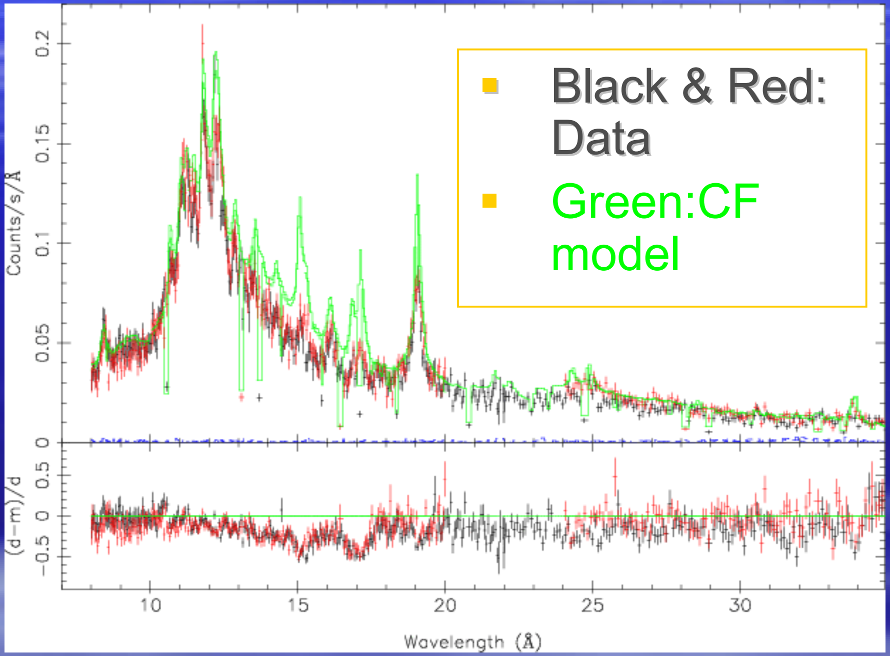
XMM/RGS spectroscopy of the cluster cores (r<50-100 kpc)





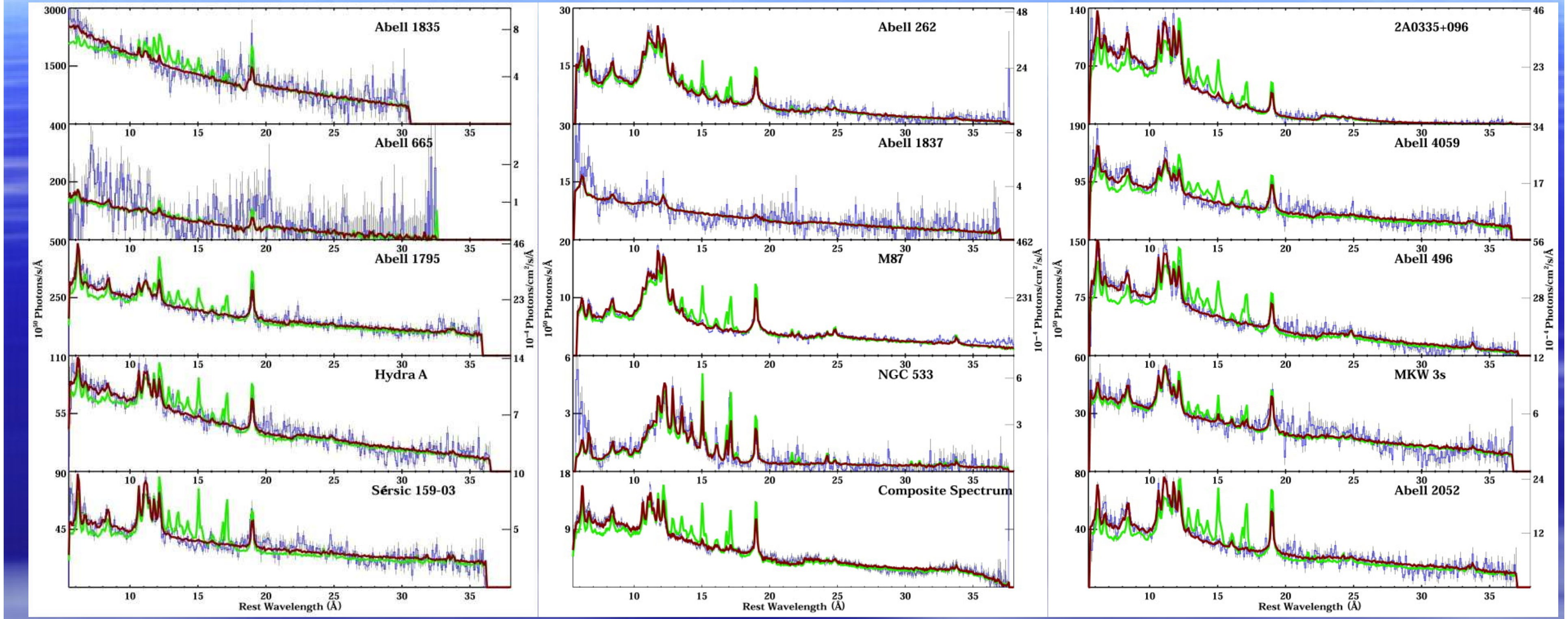
From Peterson et al. 2003

RGS results: Best example M87



From Sekelliou et al. 2002

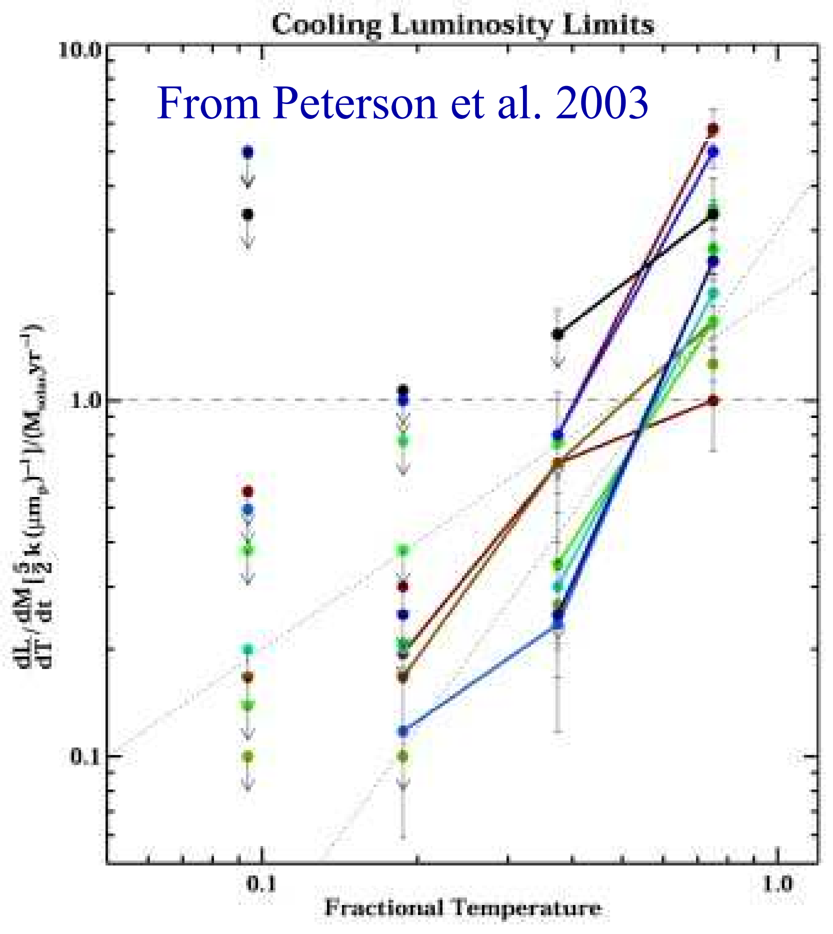
- Fe-L emission from a range of ionization stages, Fe XVII, XVIII.. XXIII. → Not isothermal.
- The CF model over-produces some of Fe-L emissions. → plasma cooler than ~ 600 eV should be cut-off or cooling-flow is very small.



- Blue: Data
- Green: CF model
- Red: Multi-Temperature model

From Peterson et al. 2003

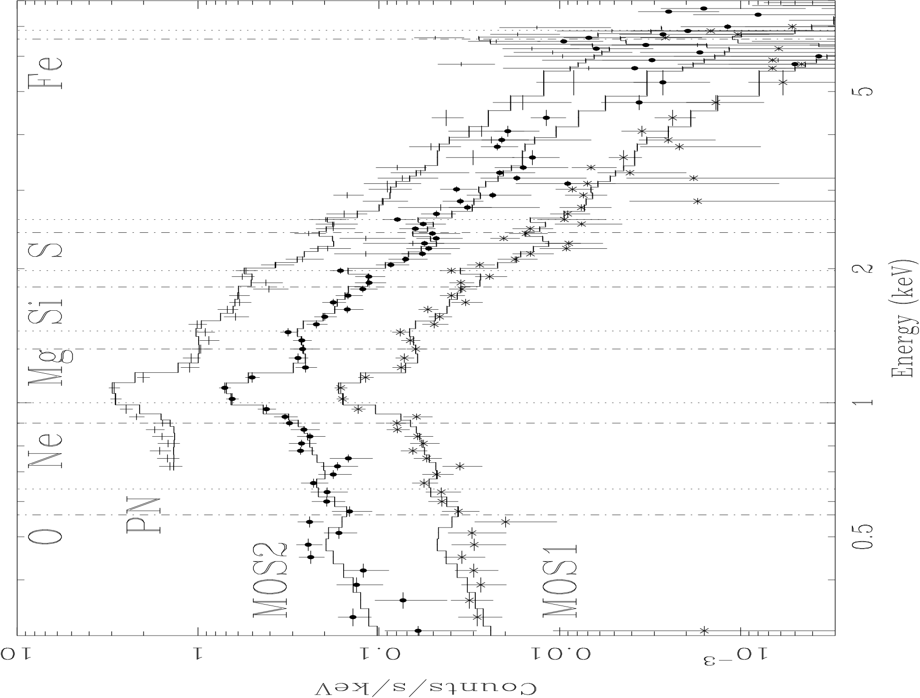
RGS constrains on the thermal structure



From Peterson et al. 2003

- Detection of line emission from plasma down to TICM/2 (TICM is the ambient ICM temperature).
- The isobaric cooling flow model can be rejected in almost all cases: a sever lack of emission from lower temperature plasma.
- No evidence of X-ray absorption by cold material.

EPIC Spectra and best-fit models

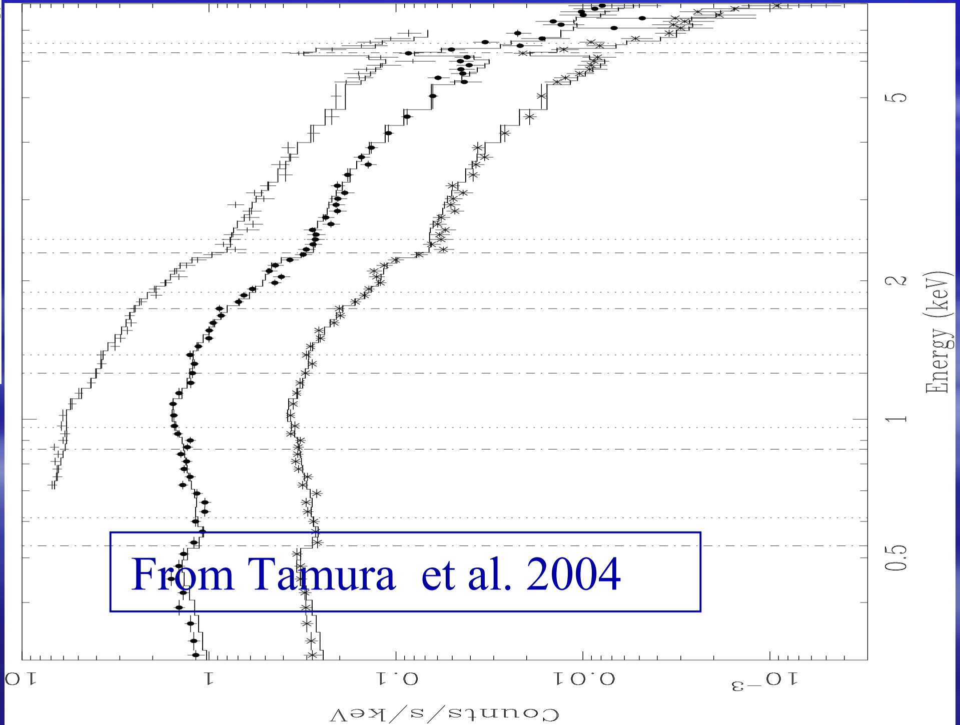


A 262 (2 keV)

1’<R<2’

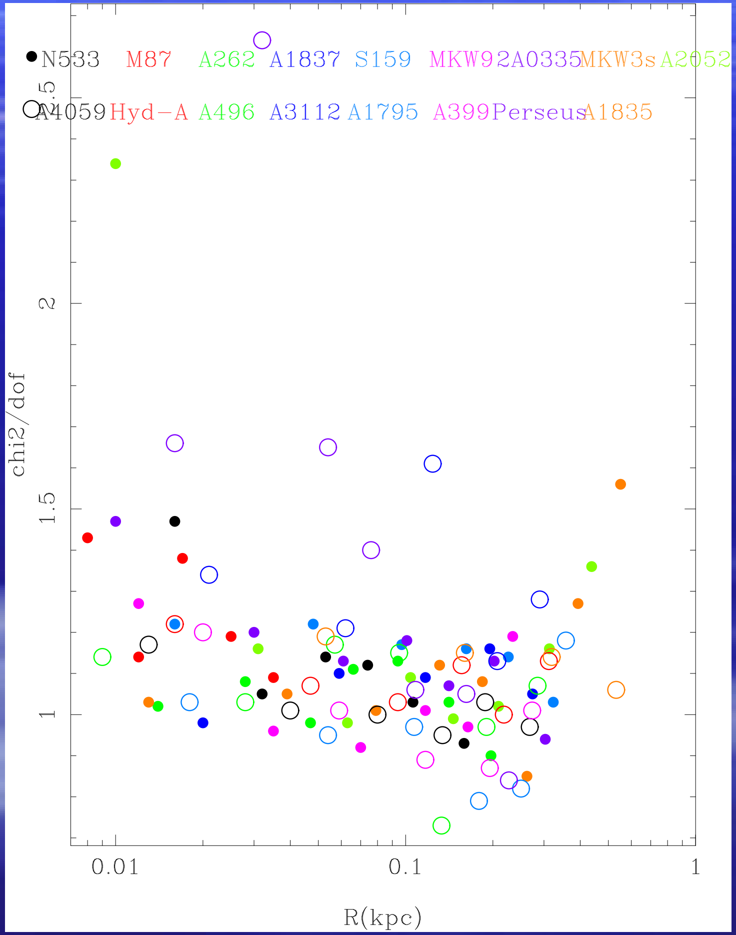
A1795 (6 keV)

1’<R<2’



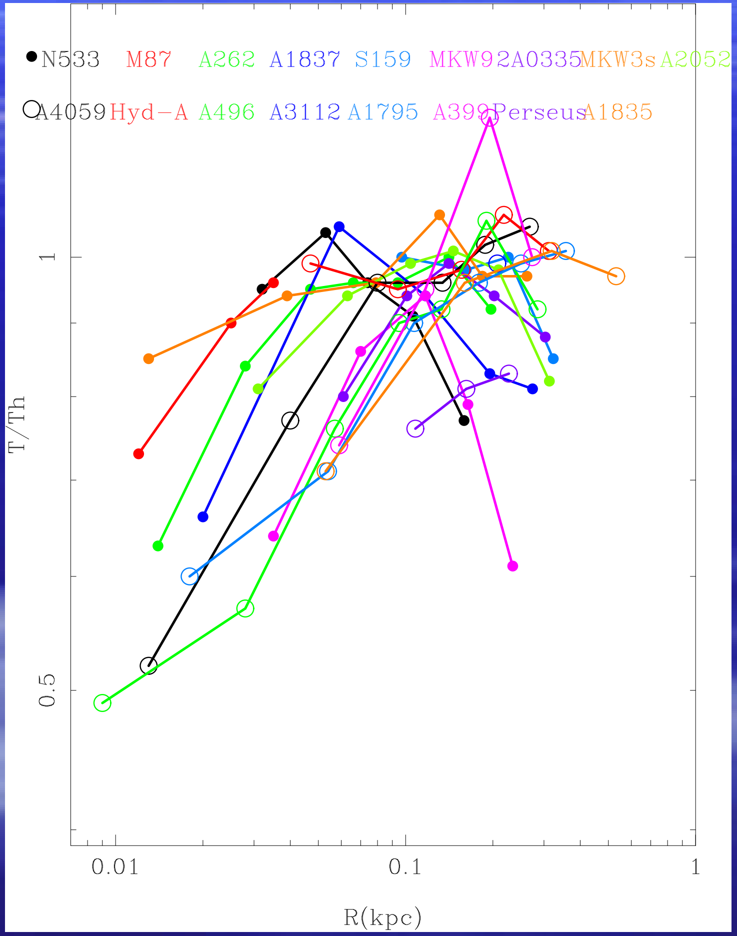
From Tamura et al. 2004

Results from the Spatially Resolved Spectroscopy (EPIC)



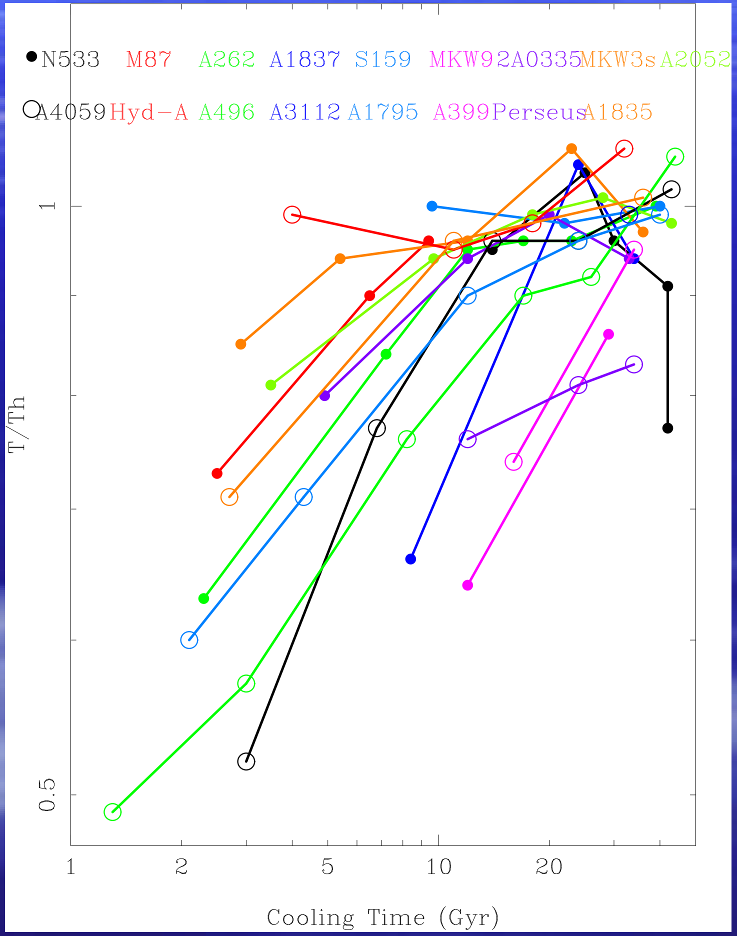
- Model: Spherically symmetric single-phase.
- At R<20 kpc, can be rejected.
  - – Complex thermal structure. Large scale AGN/ICM interaction, or ISM in cD galaxy, or else.
- 20<R<100 (kpc), describe most of the data.
  - – Exceptions are Perseus (the brightest) and A3112 (Soft excess).

Radial distribution of temperature



- In all region with Tcool < 10 Gyr, we resolved temperature drop.
- Some clusters show strong drop, but some show weak one.

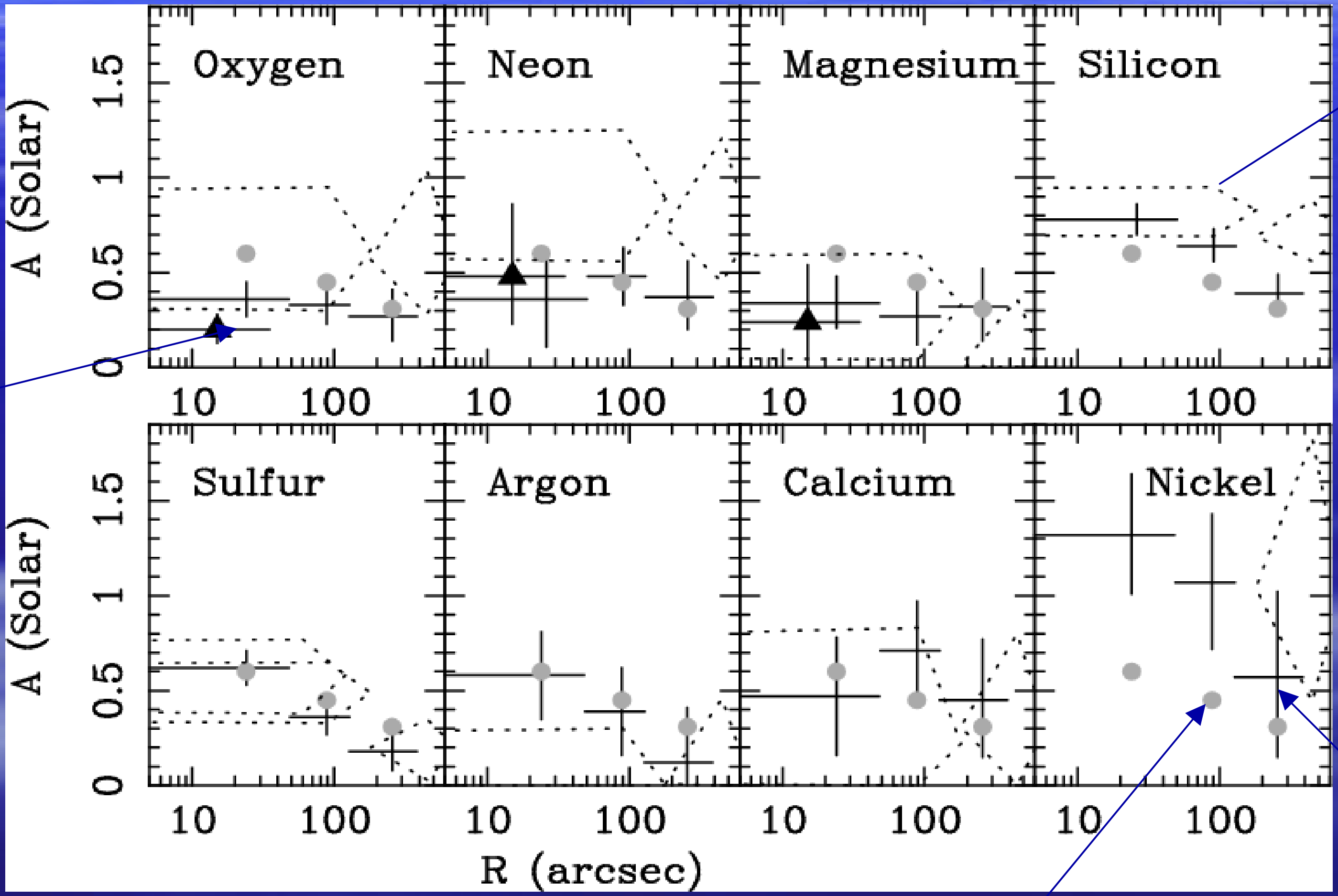
Radial distribution of temperature



- No universal scaling law in T vs. R with cooling time. Some clusters (Ser159-3, MKW 3s, Hyd-A) show weak temperature gradient, some (A496) shows steep one.
- A range of evolutionary stages. Why ?

Metal Distribution: Best example (A496)

From Tamura et al. 2001

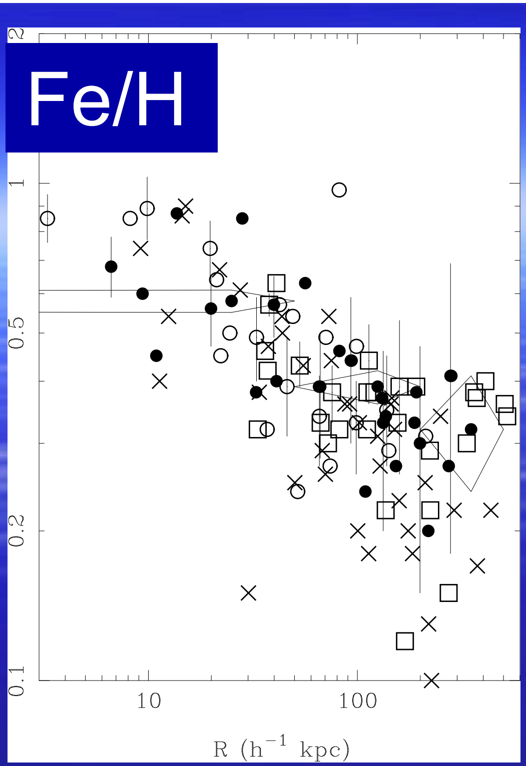


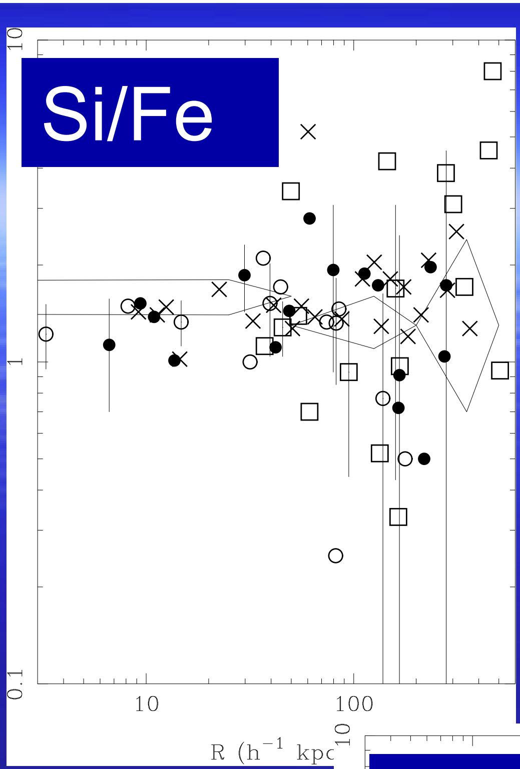
ASCA

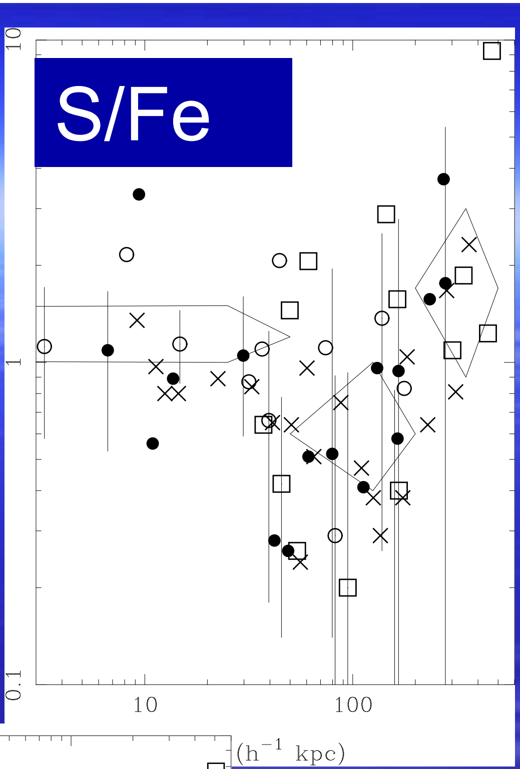
X(RGS)

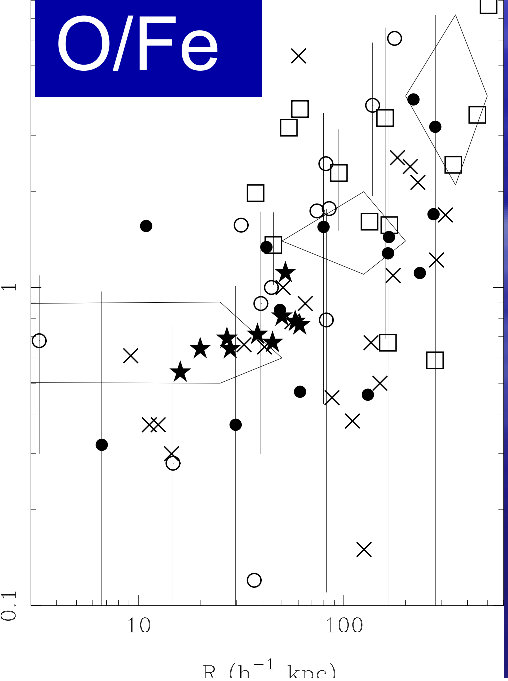
X(EPIC)

Fe (EPIC)









→

Radius (kpc)

○ cool clusters (T<3keV)

● med-T clusters

□ hot clusters (T > 6keV)

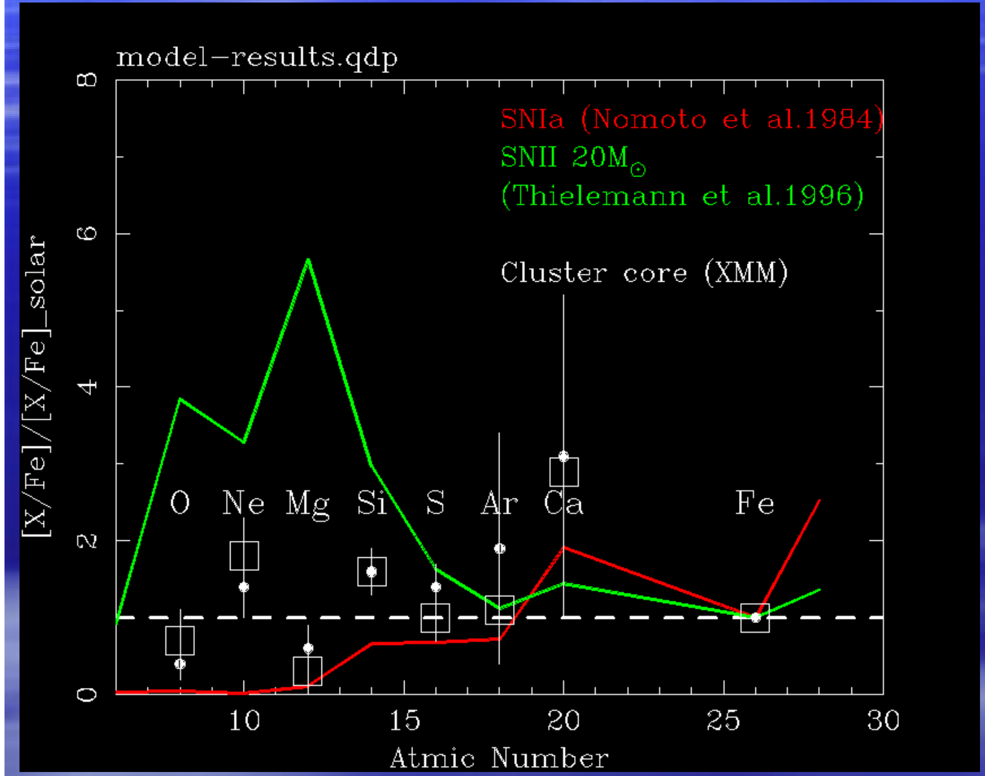
× “Soft excess”

◇ average (cool+med-T)

★ RGS results

2005-3 T.Tamura

Discussion I: SN ratio in the cluster centers (accurate measure of O)



- The observed metal ratios (e.g., O/Fe) are between SNIa and SNII predictions.
- The cluster center gas could be produced by SNIa+SNII.
- N_{Ia}/N_{II} ∼0.6, $M^{Fe}{}_{Ia}/M^{Fe}{}_{total}$ ∼ 0.8, $M^{O}{}_{Ia}/M^{O}{}_{total}$ ∼0.05

Discussion II : total Oxygen mass and total number of SNII at the cluster core

Measurement

Observed O mass within 50h^{-1} kpc :

10^8-2×10^9 $h^{-2.5}$ Msun

Theoretical assumption :

1. All O was originated from SNII.
2. One SNII produces 2 Msun Oxygen (Tsujimoto et al. 1995).

→ 10^8-2.5×10^9 of SN II .

→ 10^7 year (a typical life time of a 20 Msun star) x (10-200) SN IIe/year.

(cf. a typical starburst galaxy ~ a few SNII/year)

Discussion III :
Origins of the ICM metals

- Si, S, Fe show similar central increase, but O shows no spatial variations.
- Consistent with that Si-S-Fe for a large part have a common origin, while the O has a different origin.
- One possibility:
  - Outer region (Cluster as a whole): Past SN II and SN Ia metal has been mixed.
  - Central region : recent SNIa metal causes an excess in Si-S-Fe.

Summary

- We have analyzed the XMM data of ～20 X-ray bright cD clusters.
- The high-spectral spectroscopy with the RGS provided strong limits on the cooling plasma.
- The spatially resolved spectra from the EPIC were used to derived accurate thermal and chemical structure of the central region of the ICM.
- The central plasma is cooling, but not as expected from the cooling flow model, suggesting some unknown heat source and/or energy transfer mechanism.
- In most cases, the Fe abundances along with the Si and S increase towards the cluster center. The O abundance, in contrast, show uniform distribution. Different origins between Fe-Si-S and O.

References

- Tamura et al. 2001, A&A 379, 107
- Sakelliou et al. 2002, A&A, 391, 903
- Peterson et al. 2003, ApJ, 590, 207
- Kaastra et al. 2004, A&A, 413, 415
- Tamura et al. 2004, A&A, 420, 135