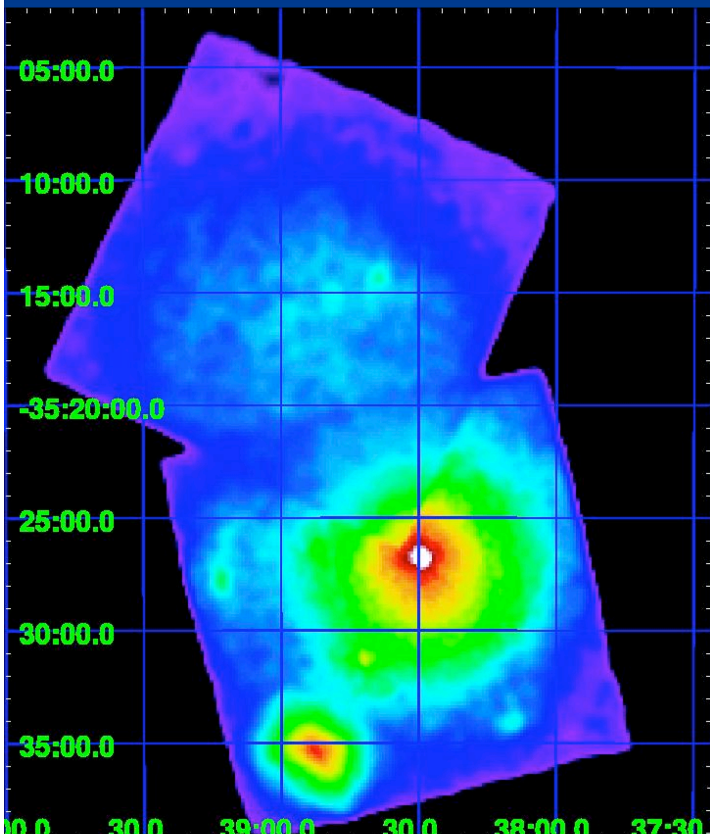
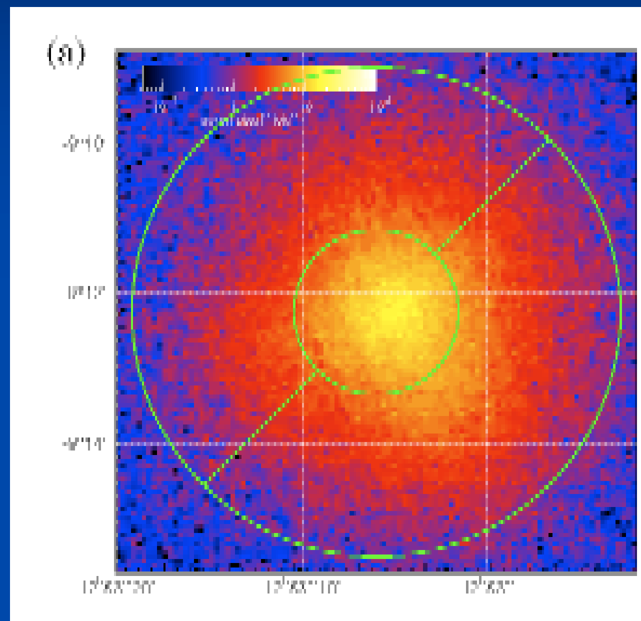
Suzaku Observations of Galaxy Groups (and related systems)

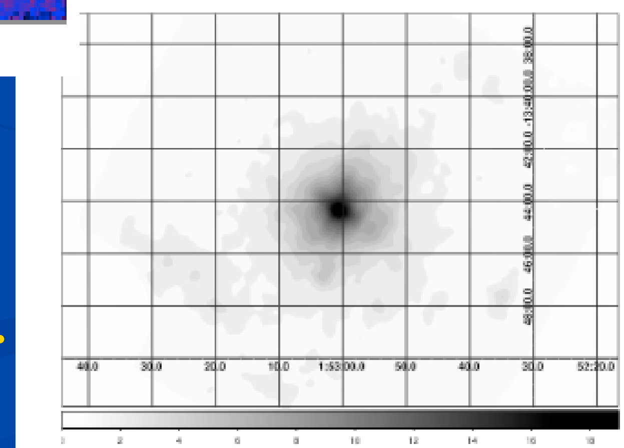


Fornax (Matsushita et al.)



HCG 62
Tokoi et al.

NGC 720
Tawara et al.



Michael Loewenstein, NASA/GSFC-UMD/CP- CRESST

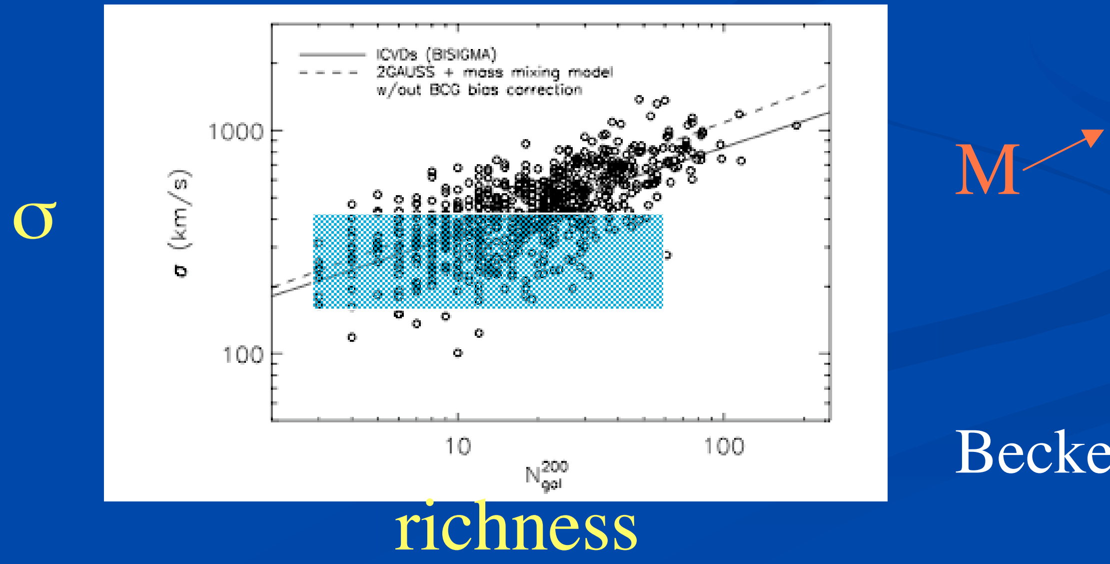
Outline

- Setting the stage: Groups, X-rays, and *Suzaku*
- Early *Suzaku* results -- temperature structure,

  abundance gradients and patterns
- Promise and Priorities

Matter in the Universe (the modern view)

- Most of the matter in the universe is dark matter, collapsed into a hierarchy (10^7-10^{15} $M_\odot$) of halos
- Galaxies are embedded in halos (that may be embedded in larger halos…)
- Larger halos have more galaxies that move faster



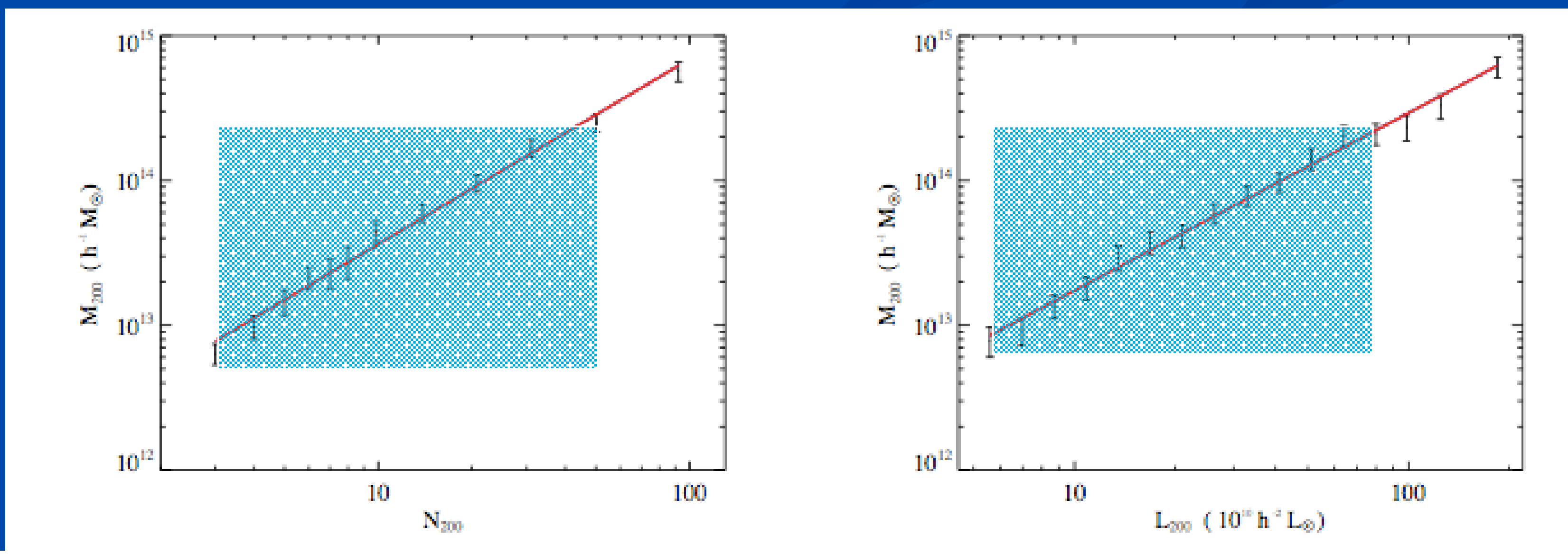
Becker et al. 2007

What is a Galaxy Group? (a personal definition)

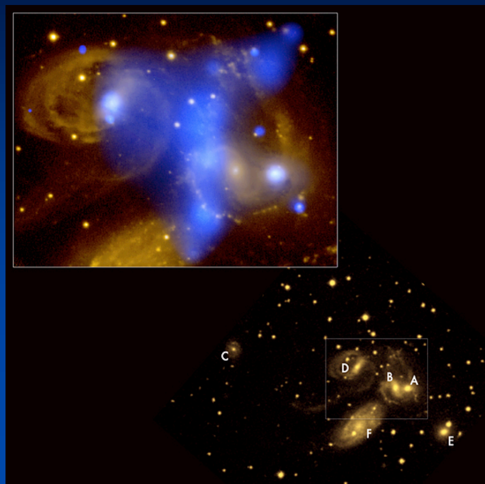
- A dark matter halo with >2 galaxies and $\sigma_{gal} \sim \sigma_{stars}$ (σ~150-400 km/sec), *i.e.* ~ M~ 10^{13} - 10^{14} $M_\odot$
- Optical: 3-50 galaxies, d~Mpc, L~ 10^{11} - 10^{12} $L_\odot$
- X-rays: kT<2.5 keV, L_X <10^{44} erg/sec

Johnston et al. 2007

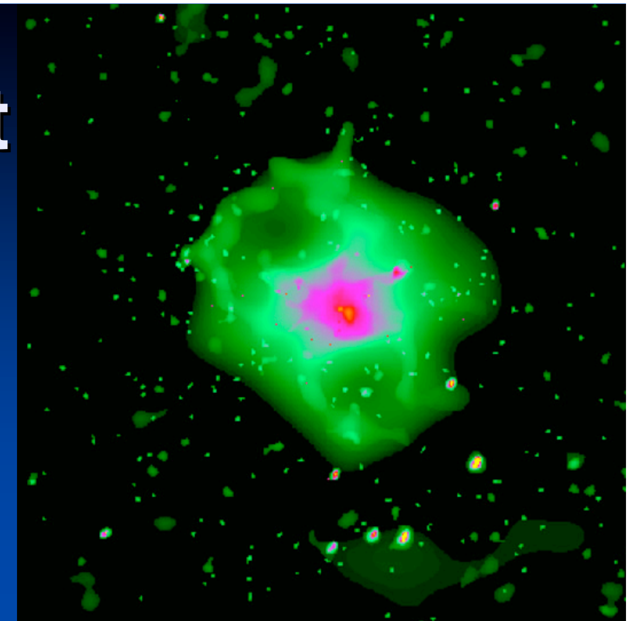
M



Sub-types of interest



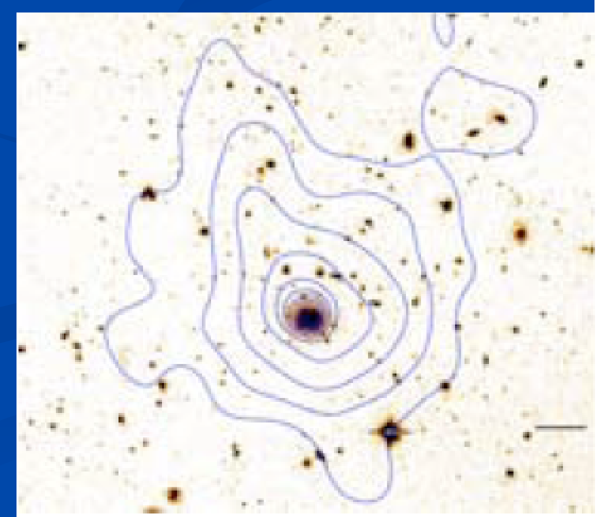
X-ray: NASA/CXC/INAF-Brera/G.Trinchieri et al.;



NASA/CfA/J. Vrtilek et al. Scale

- Compact (HCG) -- short dynamical time
- Fossil -- light dominated by single elliptical

  (complete merging, early formation)
- Cluster subgroup (e.g., NGC 4472)



Khosroshahi et al. 2007

Why Study Groups?

- Groups are where most galaxies live, and are the building blocks of LSS
- A laboratory for galaxy mergers, and merger-induced activity and feedback ($\sigma_{gal} \sim \sigma_{stars}$)
- An incubator for ellipticals: “The centers of massive groups are the preferred environment for the merger-driven assembly of massive ellipticals” (McIntosh et al. 2007)

Why Study Groups in X-rays?

- They're cool: signature of non-thermal emission and feedback more apparent
- The total mass, assembly history, and SFH are reflected in IGM thermal, morphological, and chemical properties and IGM scaling relations
- Compare chemical and thermal properties with clusters: are the cluster abundance anomalies anomalous; are cluster building blocks like present-day groups; are clusters really representative?

ROSAT and *ASCA* Highlights

- Extended ~keV X-ray emission is common, and ubiquitous in massive/elliptical-dominated groups
- (Most) HCGs are bound
- Groups are dark matter dominated
- Groups deviate from cluster scaling relations, and show an excess core entropy
- Discovery of fossil groups

ROSAT and *ASCA* Highlights

- Abundances of Fe and Si

Group	Temperature (keV)	Solar A_α	Solar A_{Fe}
NGC 4325	$1.06^{+0.02}_{-0.06}$	$0.31^{+0.23}_{-0.13}$	$0.42^{+0.14}_{-0.09}$
NGC 5129	$0.87^{+0.02}_{-0.05}$	$0.20^{+0.26}_{-0.14}$	$0.16^{+0.06}_{-0.04}$
NGC 4104	$1.93^{+0.13}_{-0.19}$	$0.80^{+0.24}_{-0.20}$	$0.37^{+0.11}_{-0.12}$
HCG 62	$0.95^{+0.03}_{-0.03}$	$0.23^{+0.08}_{-0.07}$	$0.22^{+0.04}_{-0.04}$
NGC 5044[a]......	1.01	0.30	0.36
RGH 80	$1.02^{+0.05}_{-0.05}$	$0.28^{+0.16}_{-0.08}$	$0.20^{+0.05}_{-0.06}$
MKW 9	$2.18^{+0.11}_{-0.09}$	$0.48^{+0.15}_{-0.13}$	$0.24^{+0.07}_{-0.05}$
Pavo	$0.77^{+0.07}_{-0.05}$	$0.10^{+0.20}_{-0.09}$	$0.17^{+0.88}_{-0.04}$
NGC 6329	$1.32^{+0.04}_{-0.07}$	$0.22^{+0.20}_{-0.13}$	$0.24^{+0.07}_{-0.05}$
Pegasus	$1.04^{+0.03}_{-0.02}$	$0.35^{+0.41}_{-0.09}$	$0.33^{+0.17}_{-0.04}$

Davis et al. 1999

Si (⊙)	Fe (⊙)
0.30 (0.10–0.50)	0.34 (0.27–0.41)
0.49 (0.30–0.71)	0.39 (0.29–0.51)
0.16 (<0.46)	0.22 (0.13–0.31)
0.27 (0.14–0.40)	0.41 (0.34–0.48)
0.50 (0.39–0.63)	0.34 (0.27–0.42)
0.45 (0.28–0.65)	0.27 (0.18–0.34)

Hwang et al. 1999

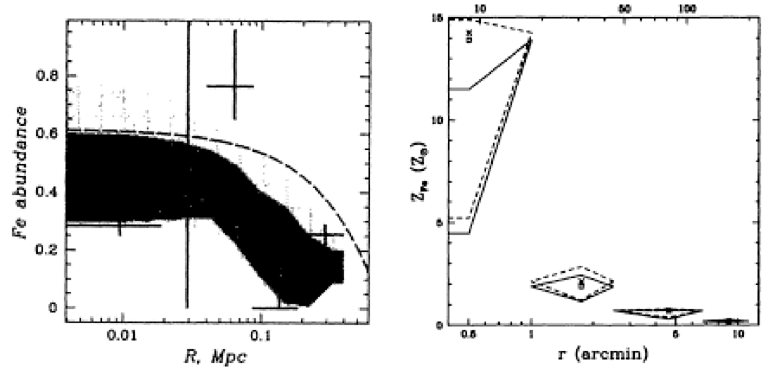


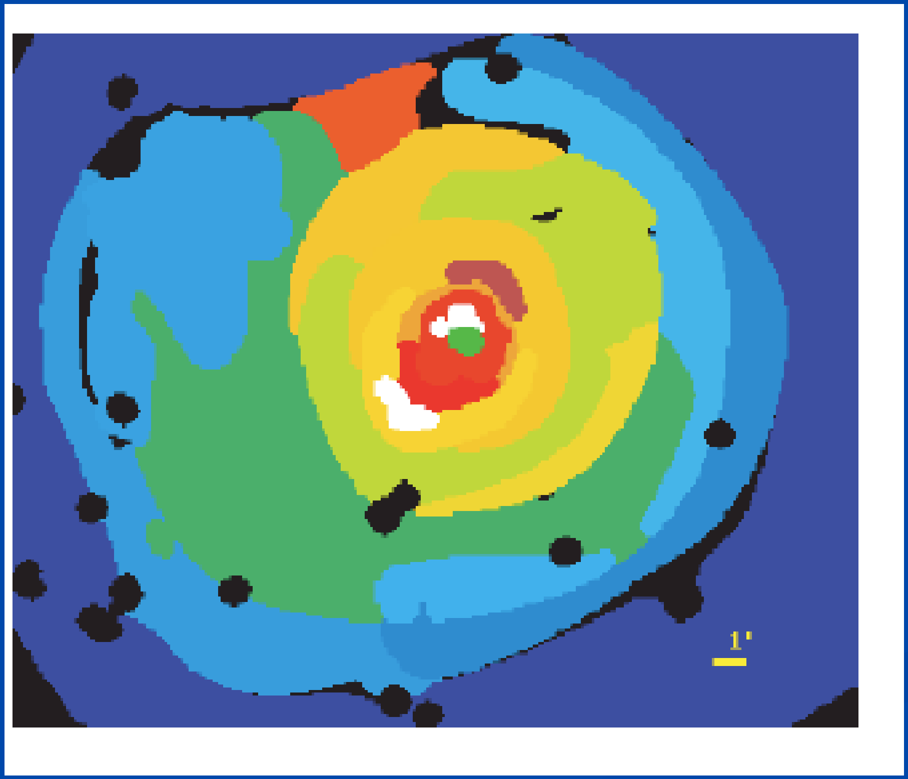
Figure 4. Iron abundance profiles for HCG 62 derived by [left] Finoguenov, David, & Ponman (2000), and [right] Buote (2000a).

Ponman et al. 2003

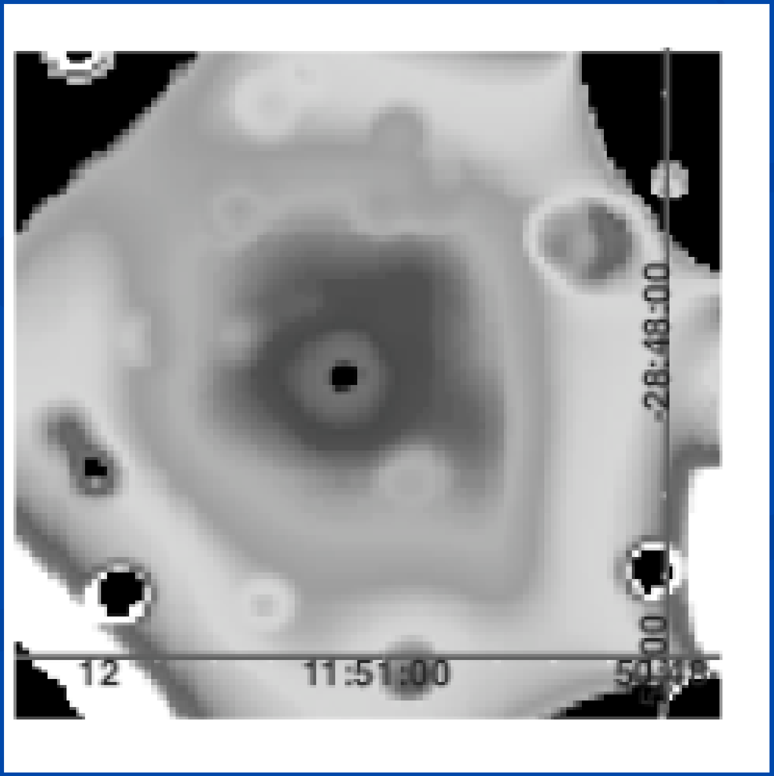
XMM-Newton and Chandra

- Detailed profiles, maps of abundance, entropy… (e.g., Finoguenov et al.)

NGC 5044 abundances

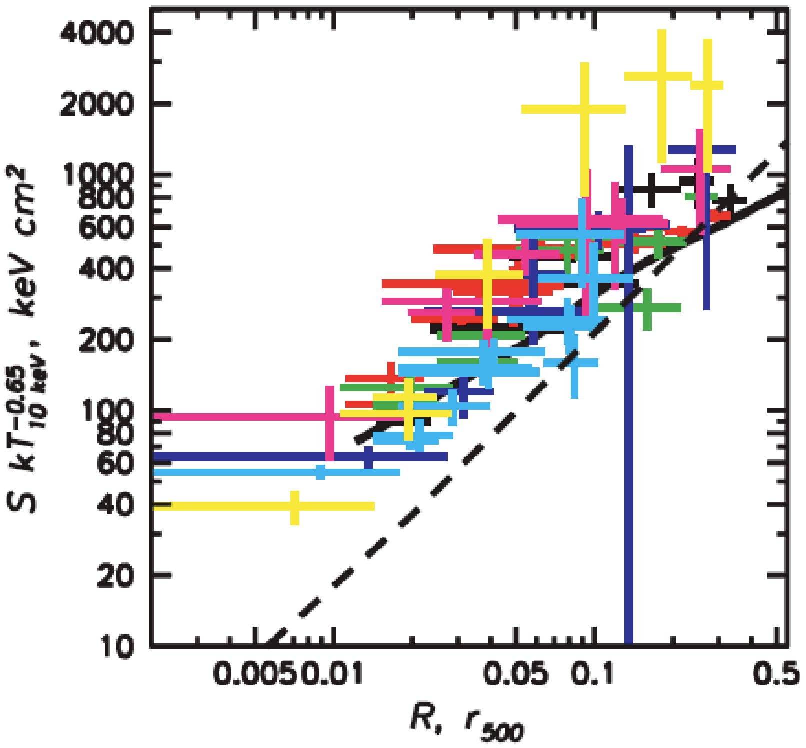


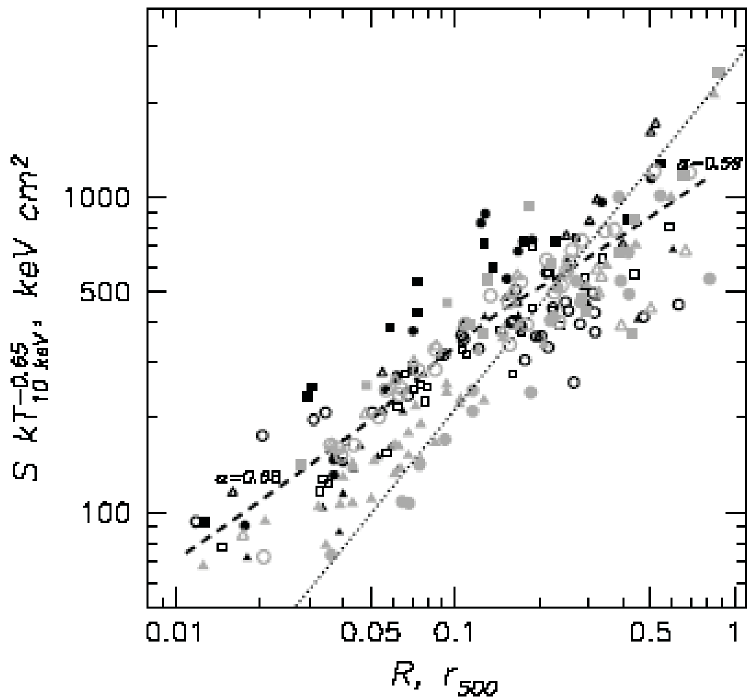
NGC 3923 entropy



XMM-Newton and Chandra

More heating evidence, less clarity on how and when



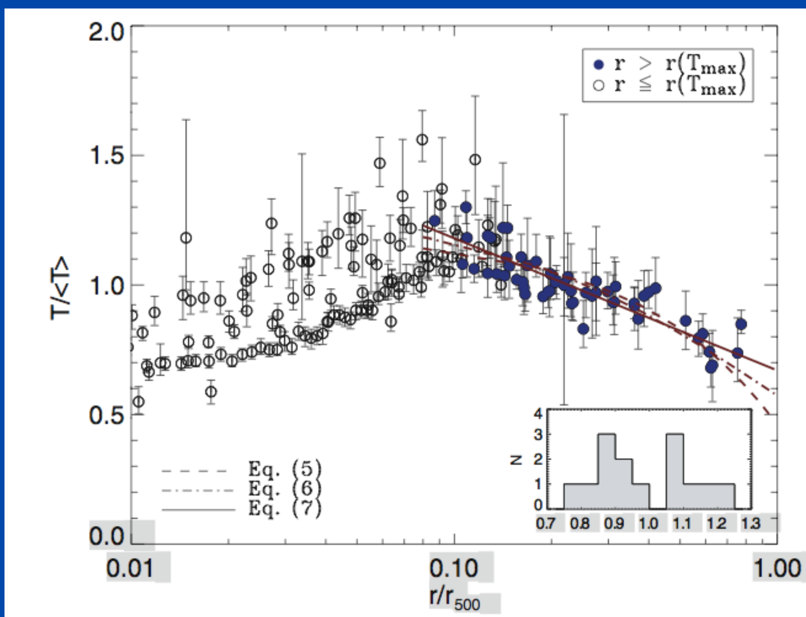


Finogueonov et al.

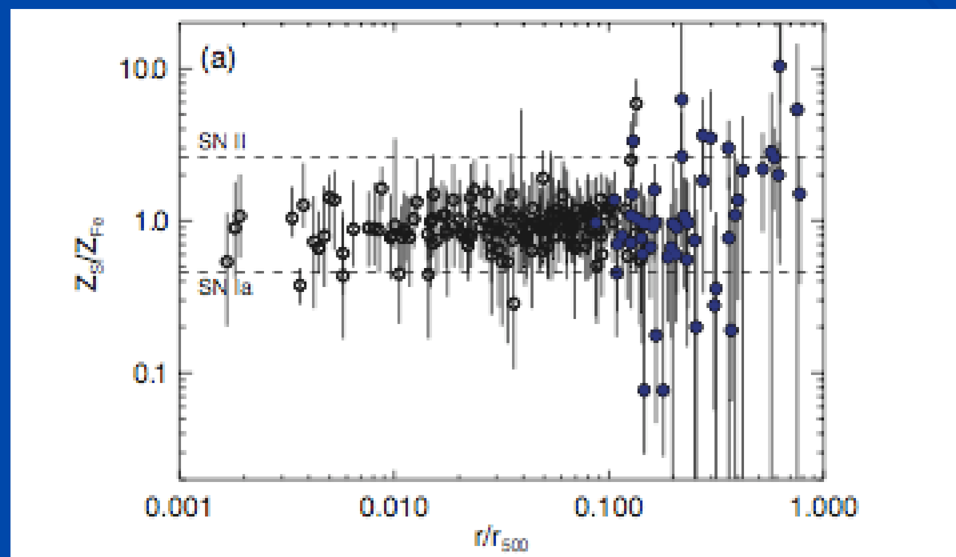
XMM-Newton and Chandra

- To higher redshift, more detail, and larger radius
  GEMS --Chandra (Rasmussen and Ponman 2007)

scaled temperature



Si/Fe (grsa)

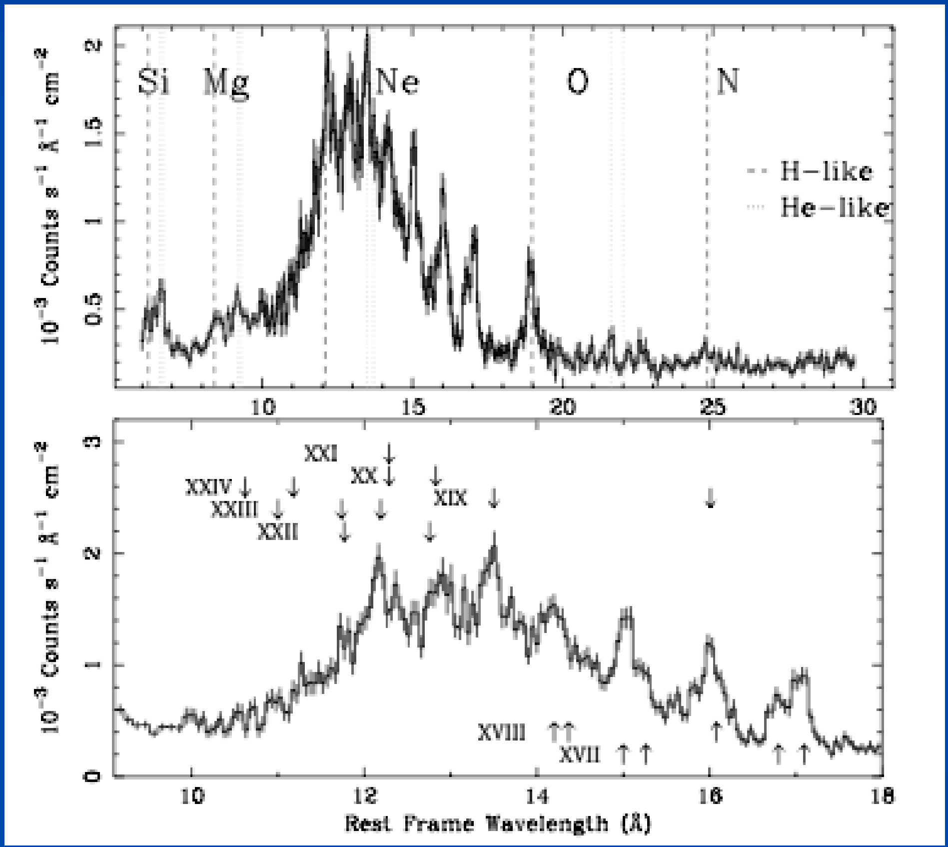


r/r_{500}

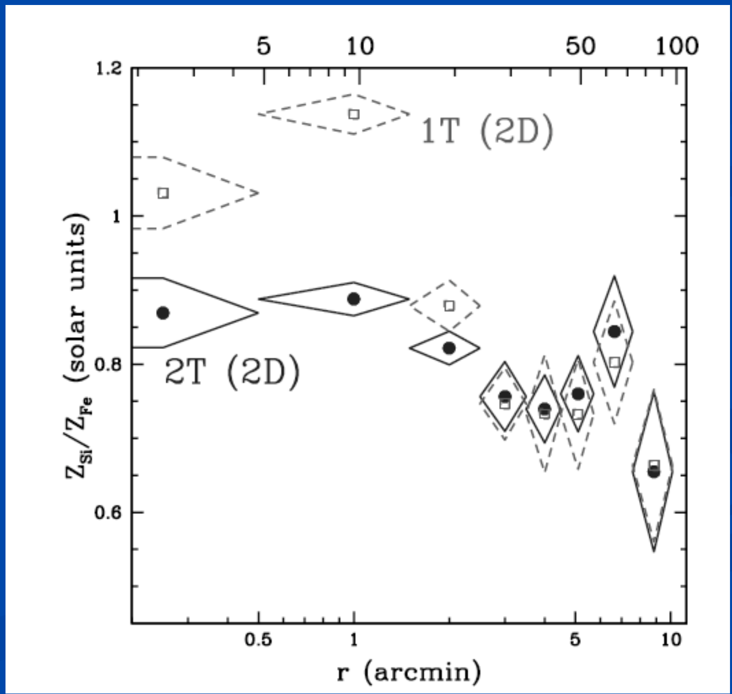
XMM-Newton and Chandra

- High resolution spectra, multi-phase models

NGC 5044



Si/Fe profile



Tamura et al. 2003

Buote et al. 2003

Why Study Groups with *Suzaku*?

Lower background plus better (CCD) spectral resolution

- push to the virial radius
- more emission lines

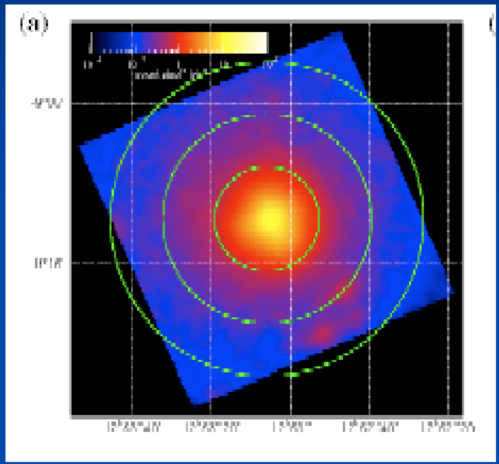
  -- correct spectral model (multi-temperature and optical depth signatures)

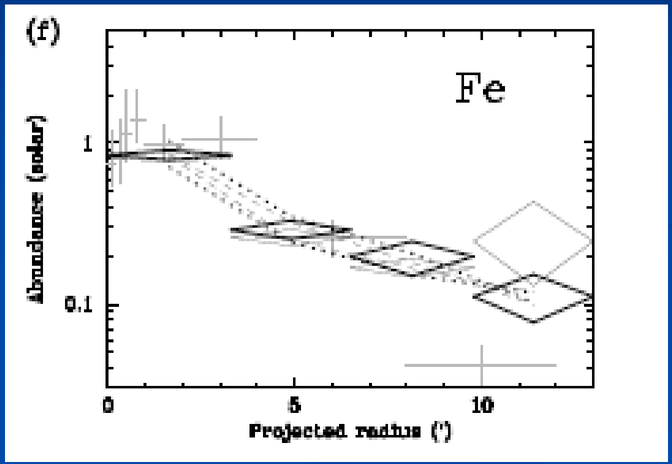
  -- more accurate abundances and abundance gradients of more elements
- good synergy with Chandra ACIS, XMM MOS/pn (better imaging) and RGS (better spectral resolution)
- signature of non-thermal emission in HXD (Fukazawa)

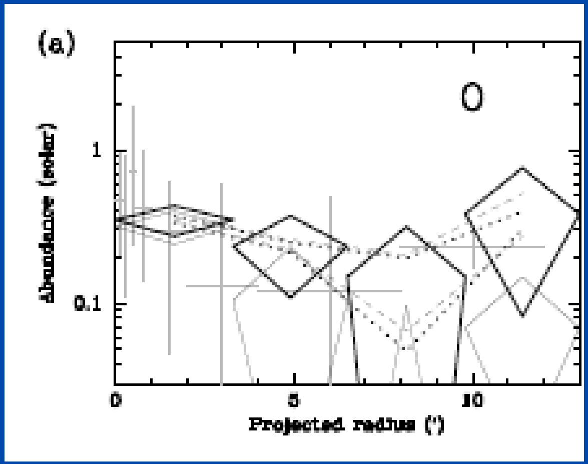
Cool (<2 keV) Systems Observed with *Suzaku*

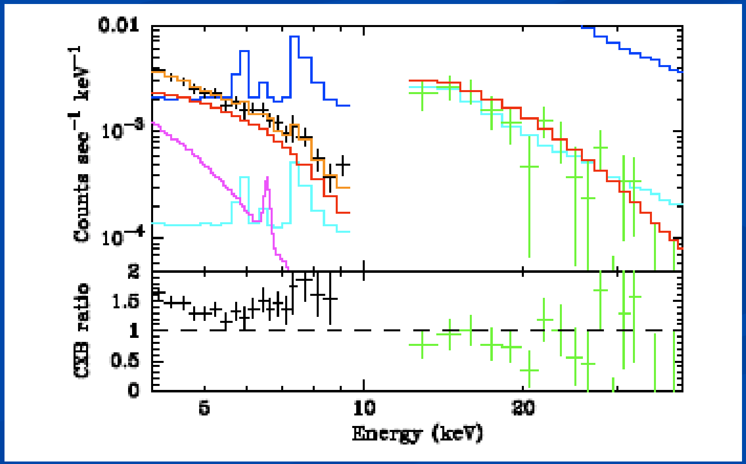
Fornax/N1399	SWG	poor cluster
HCG 62	SWG	compact group
NGC 720	SWG	isolated elliptical
NGC 4636	SWG	Virgo elliptical
Virgo/M87	AO-1	poor cluster
NGC 507	AO-1	group
NGC 5044	AO-1	group
NGC 3923	AO-1	isolated elliptical
NGC 4472	AO-1	Virgo elliptical
NGC 4649	AO-1	Virgo elliptical

Case Study: HCG 62









See Tokoi-san's poster (A23) and preprint (0711.1454)

Temperature Structure

XIS requires 2-T model in NGC 1399, HCG 62, NGC 4472

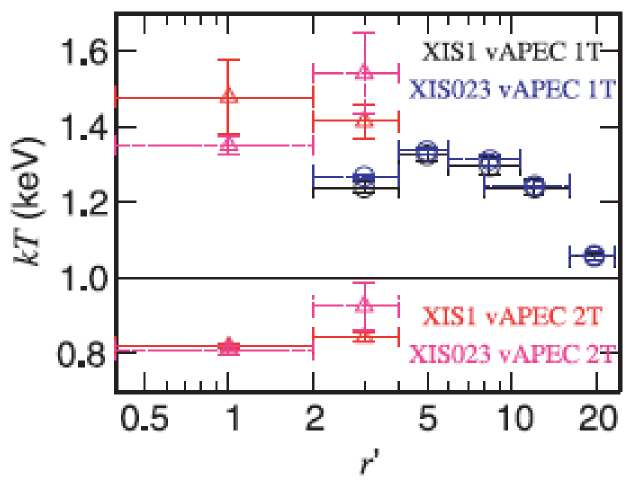
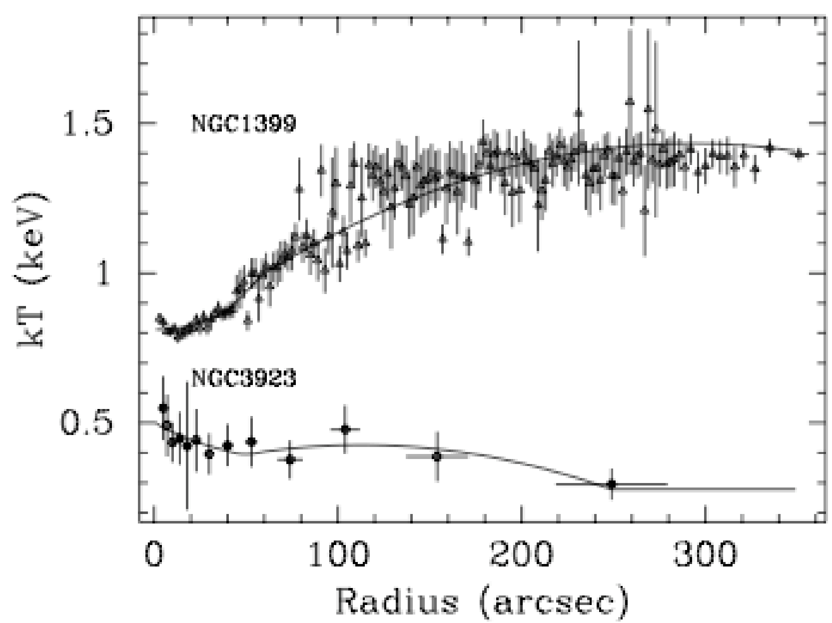


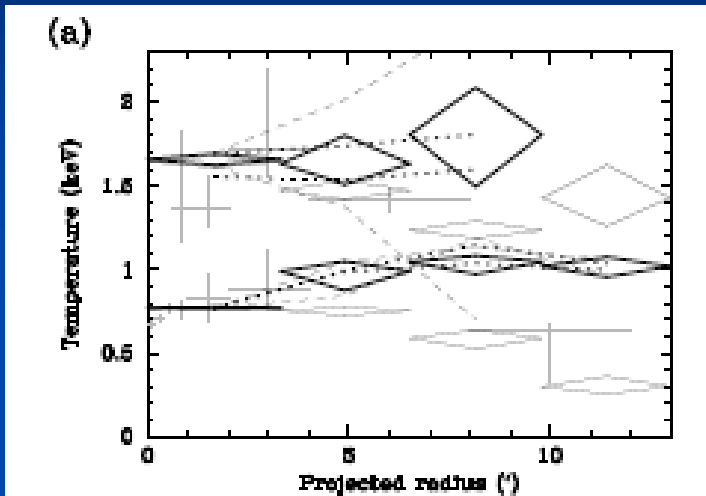
Fig. 4. Temperature profile of the ICM using the single-temperature vAPEC model (open circles) and the two-temperature vAPEC model (open triangles) derived from XIS 1 (solid lines) and XIS 0, 2, 3 (dotted lines).



Matsushita et al. 2007 Fukazawa et al. 2006 (Chandra)

multi-phase or gradient? implications for heating and mass profile? implications for abundances? same for NGC 4472

Temperature Structure in HCG 62



Suzaku (Tokoi et al. 2007)

(1’~18 kpc, r_{virial}~1°)

Chandra/XMM (Morita et al. 2006)

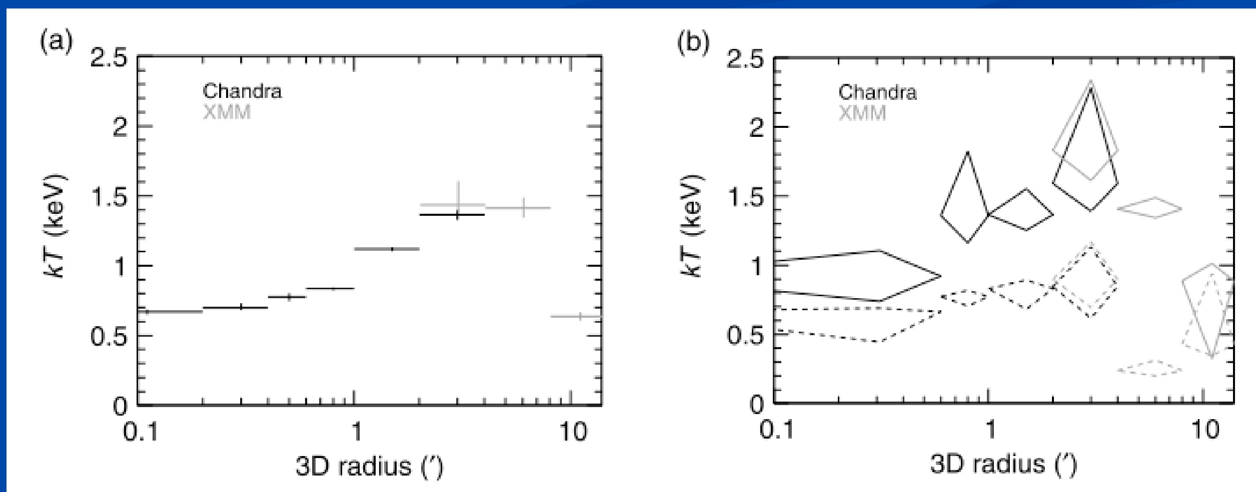


Fig. 9. (a) Temperature profiles with the 1-T vMekal models based on the deprojected spectral fit. ACIS-S3 (black) was used for $r < 4'$, and MOS1, MOS2, and pn (gray) were used for $2' < r < 14'$. (b) Same as (a), but with the 2-T vMekal models.

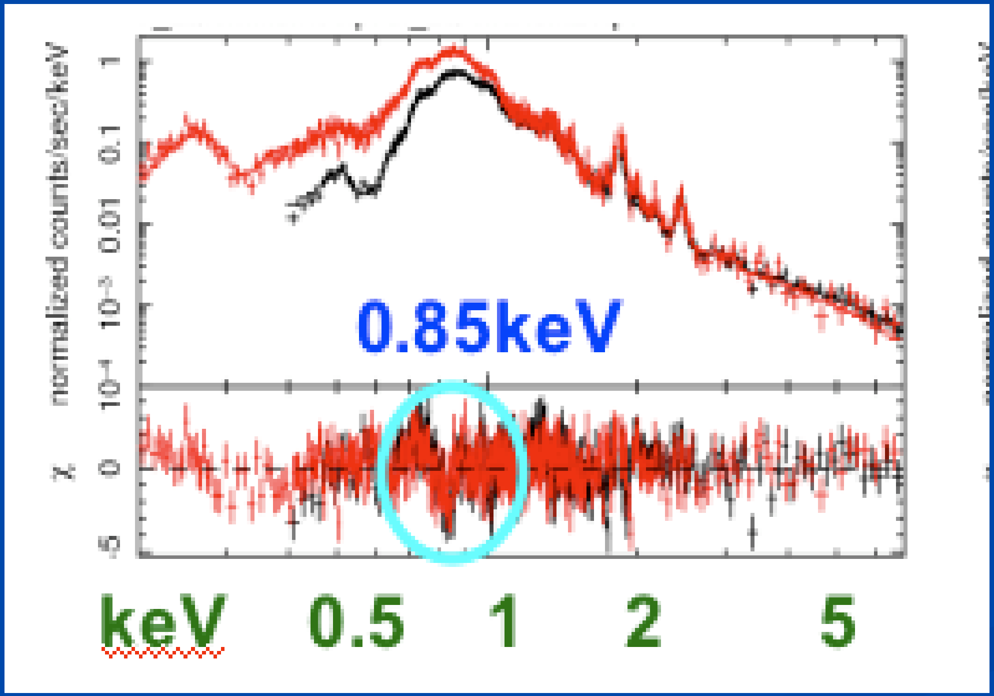
Abundances

RGS: N(?), O, Ne, Mg, Fe

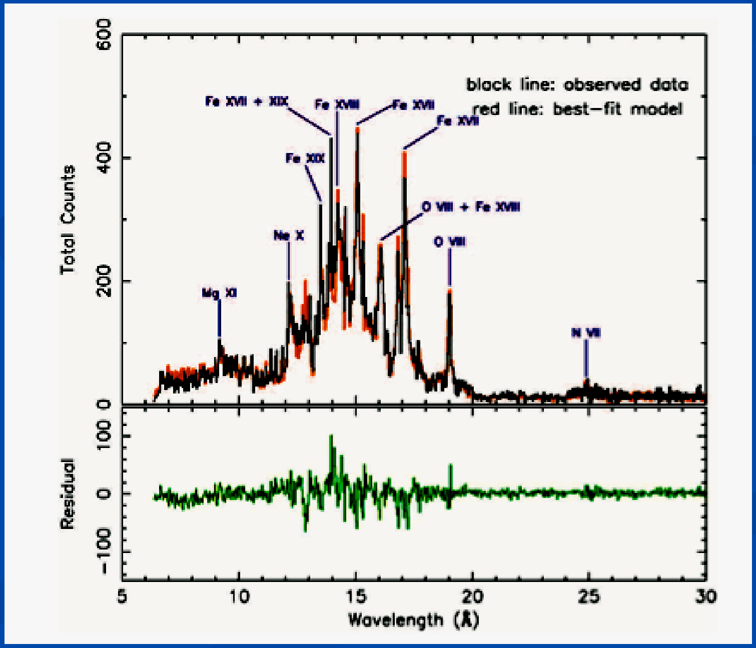
EPIC/Chandra: O(?), Ne(?), Mg(?), Si, S(?), Fe

XIS: O, Ne (?), Mg, Si, S, Ar, Fe

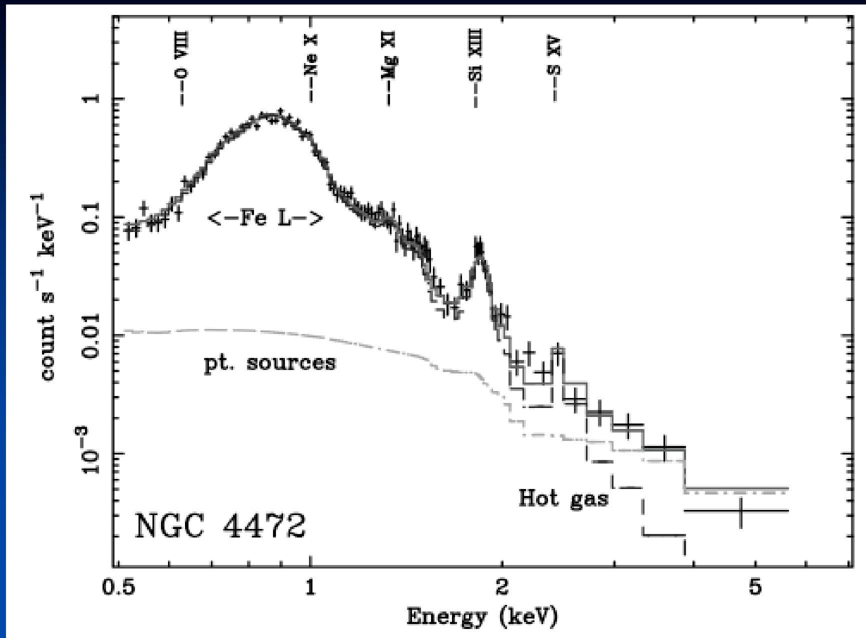
NGC 4636



XIS: Hayashi et al. 2008

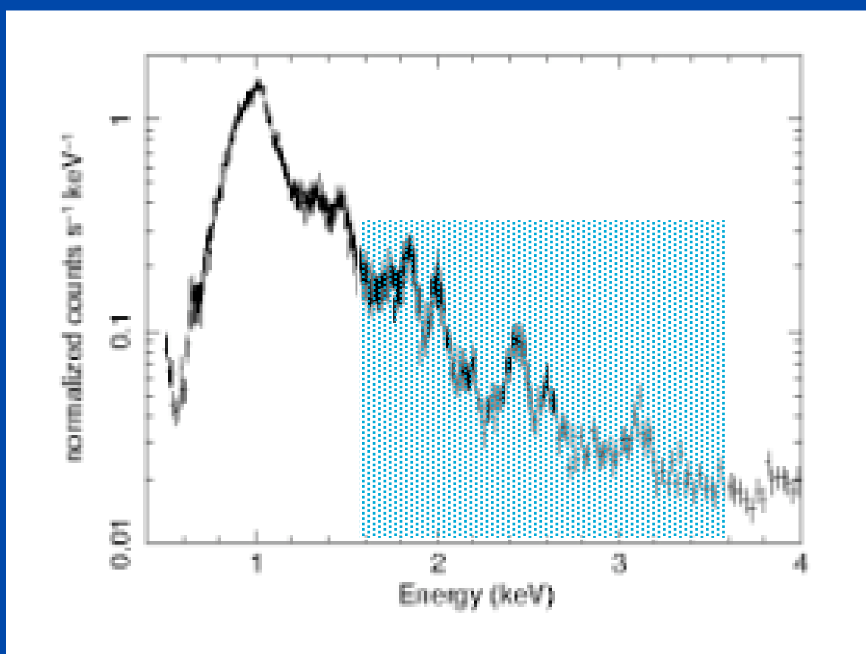


RGS: Xu et al. 2002

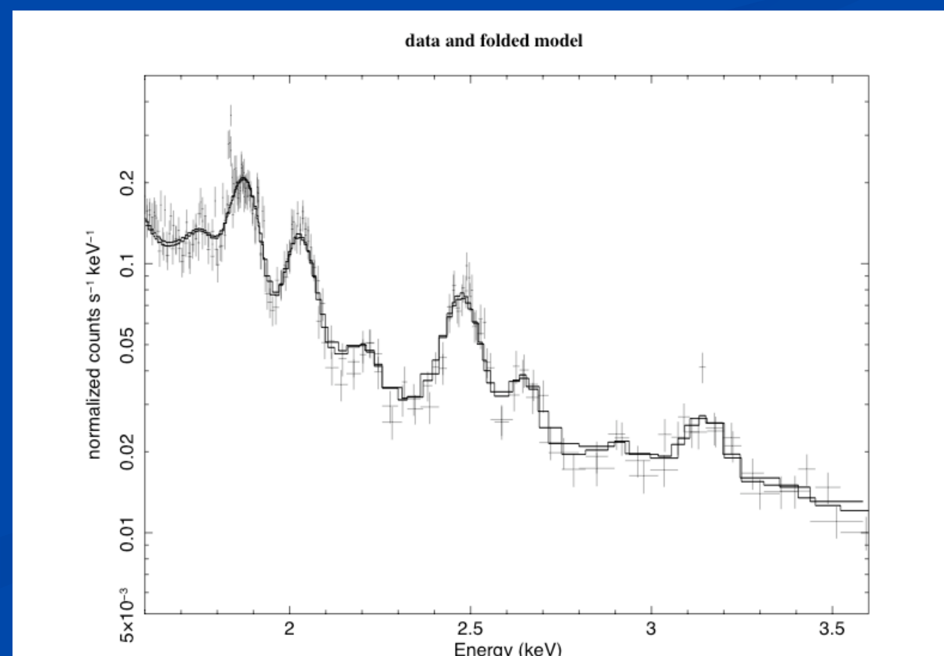


Chandra (Humphrey and Buote 2006)

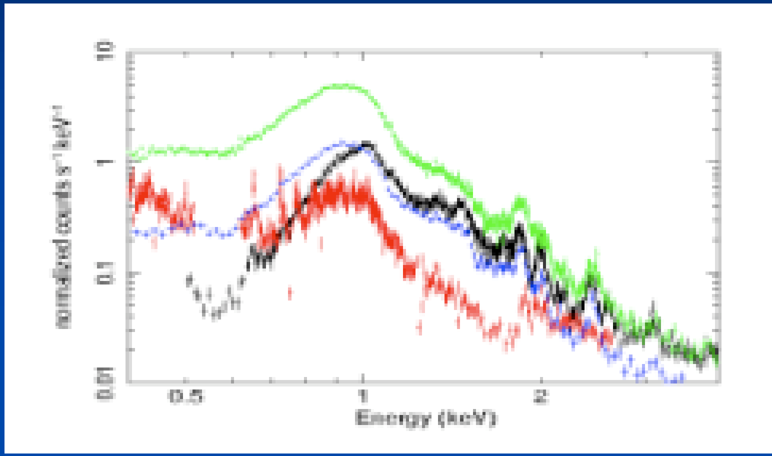
NGC 4472

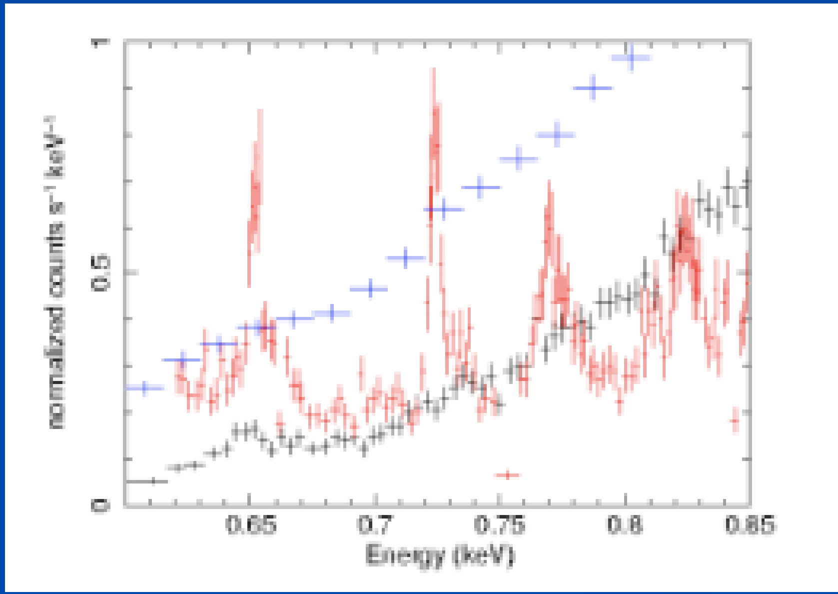


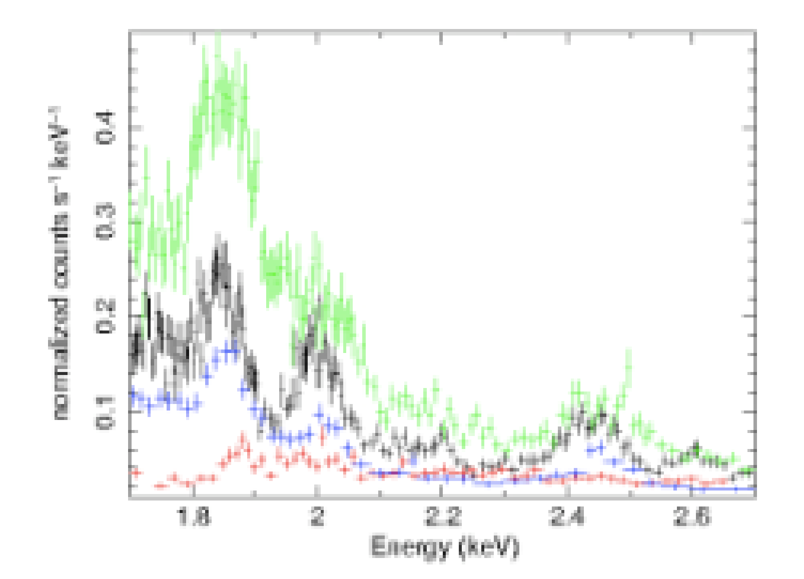
Mg XII, Si XIII, SiXIV, SXV, SXVI, Ar XVII



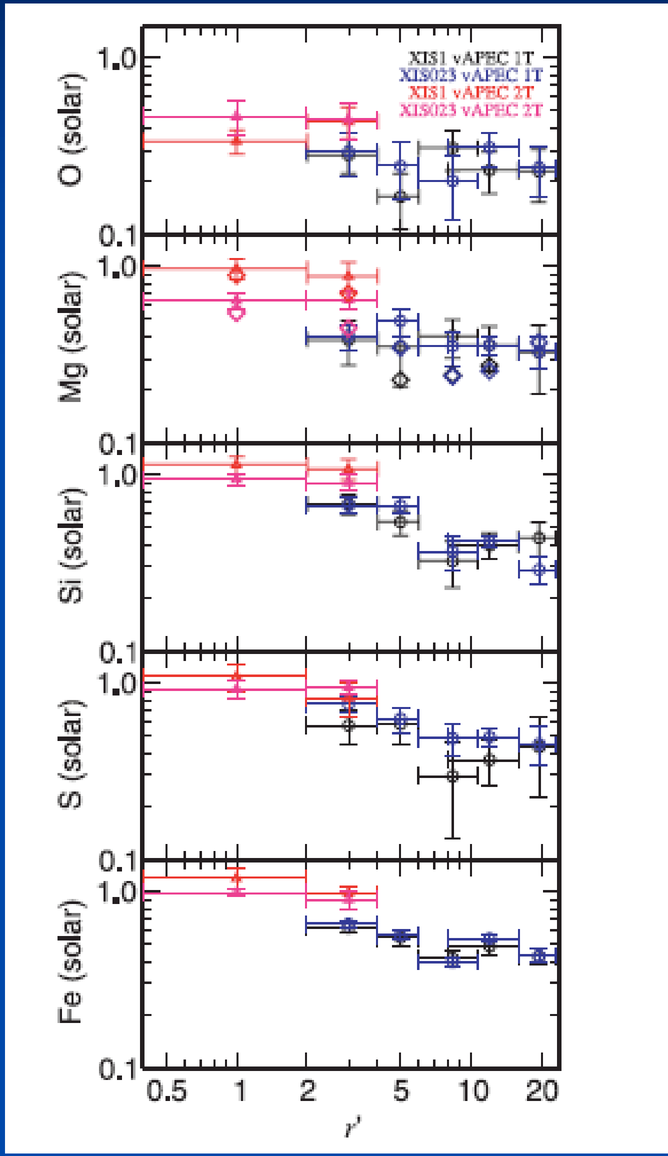
Complementarity, e.g. NGC 4472

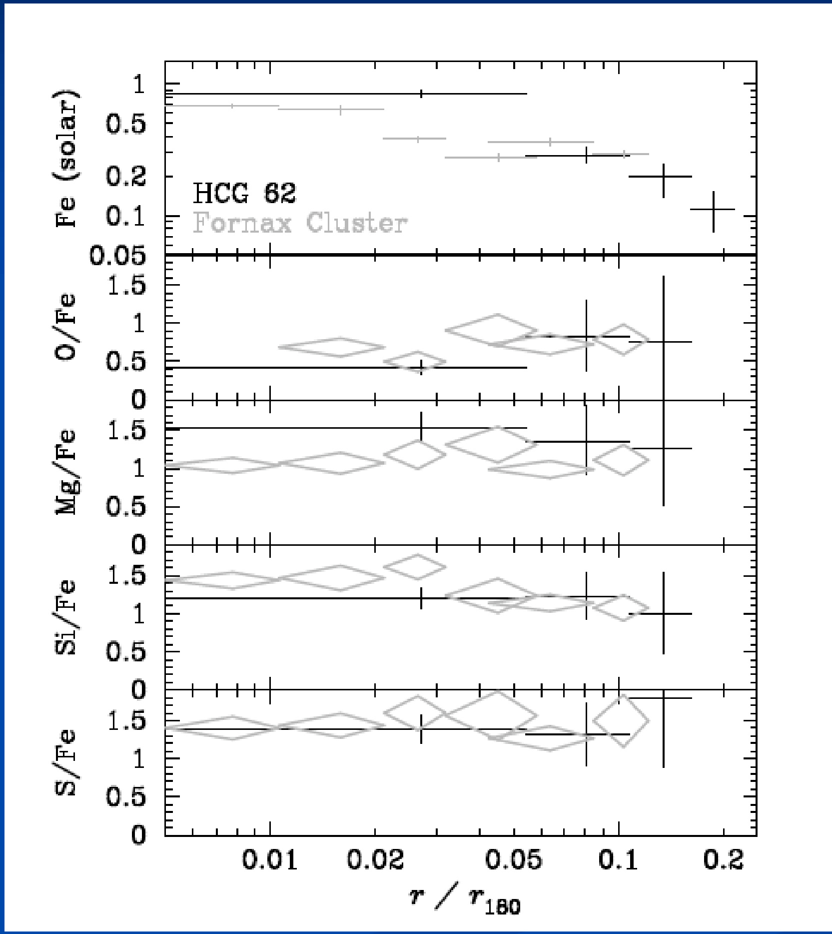






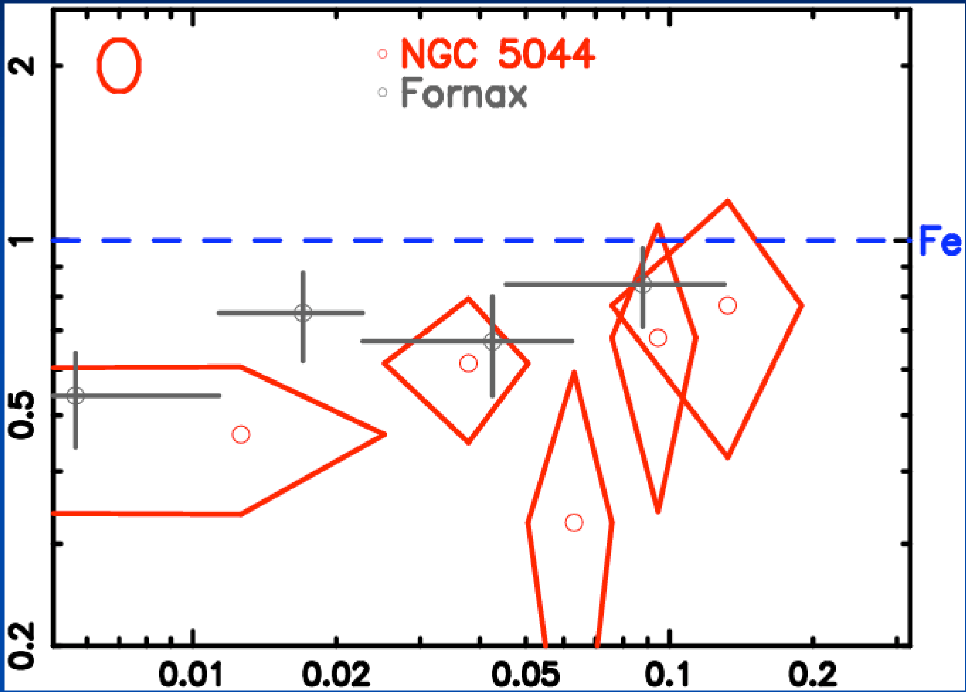
Abundance Profiles

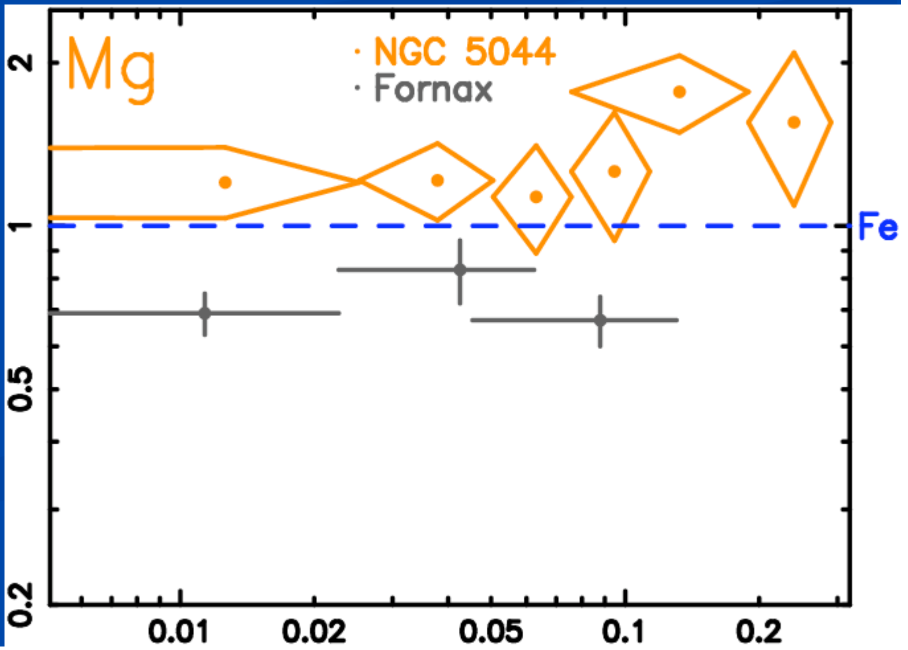




Matsushita et al., Tokoi et al.

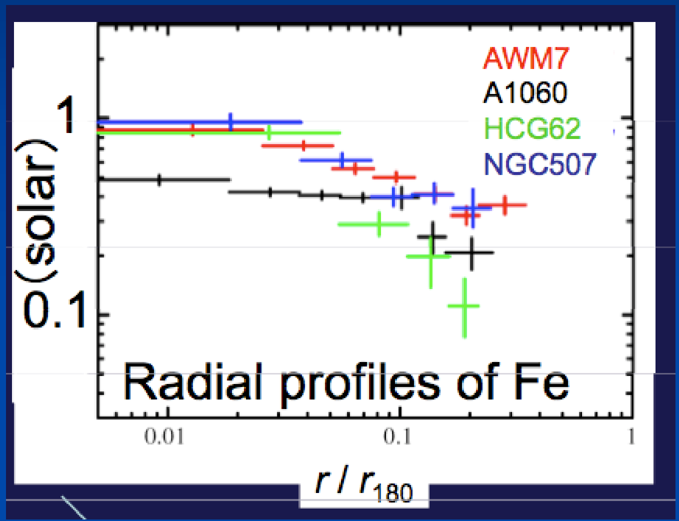
Abundance Profiles



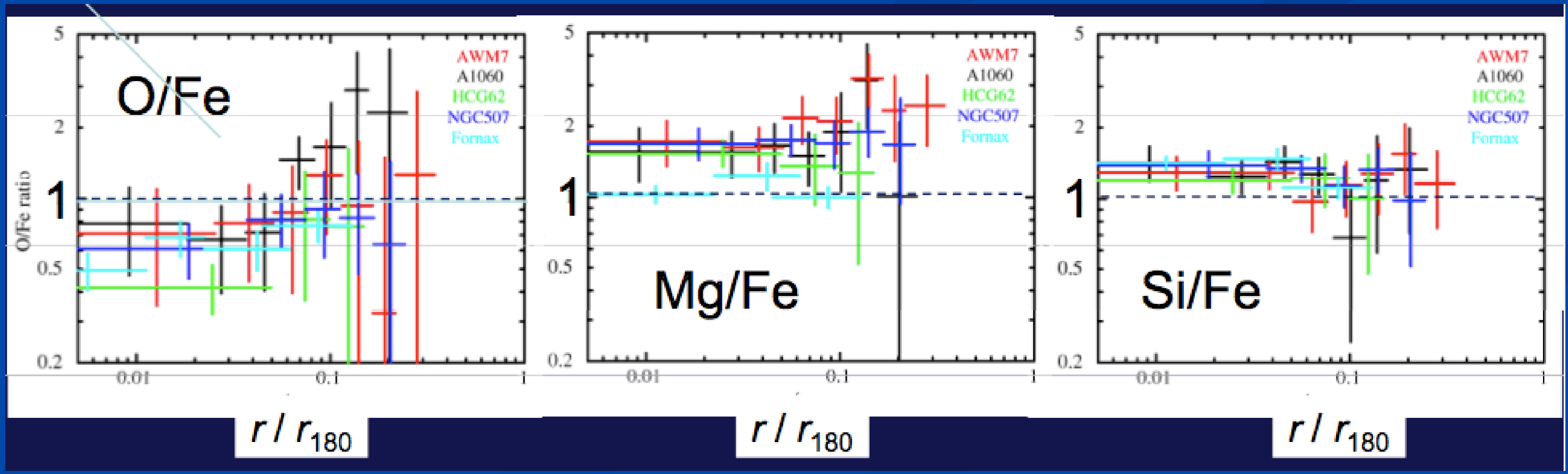


courtesy K. Matsushita

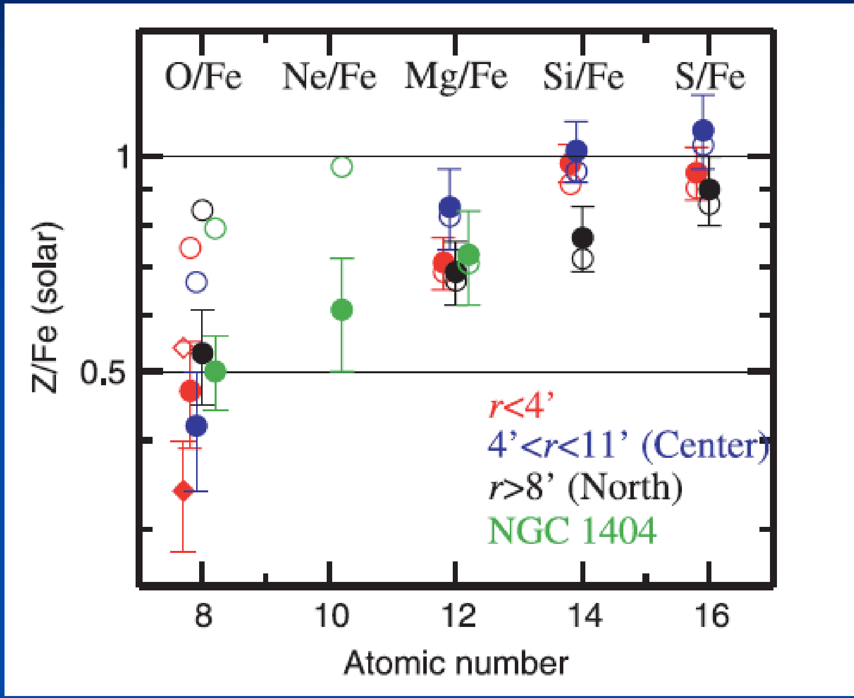
Abundance Profiles



courtesy K. Sato

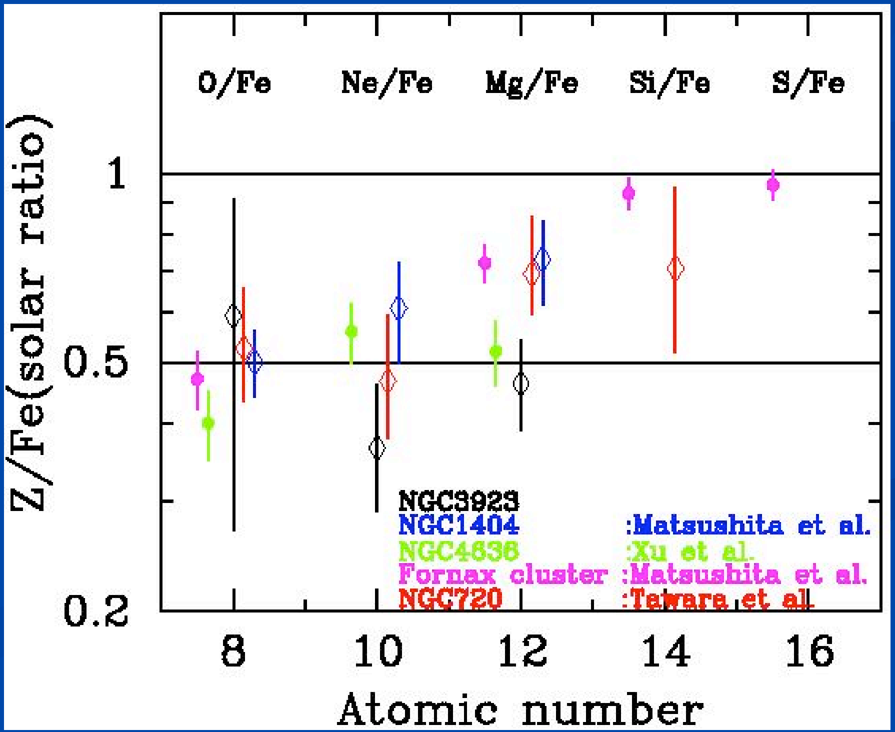


Abundance Patterns



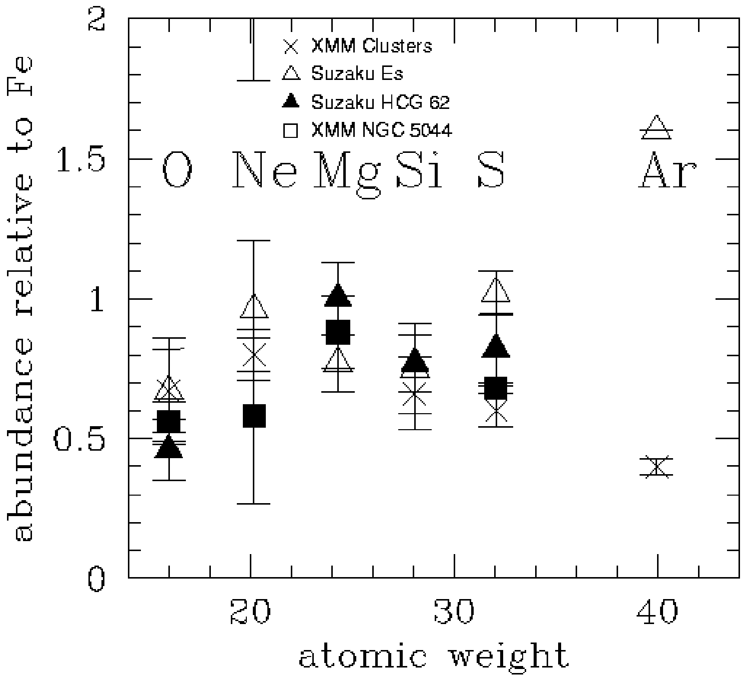
Matsushita et al. 2007

Similar pattern within systems, and from system to system -- Fe/α≥1



courtesy Y. Fukazawa

Abundance Patterns



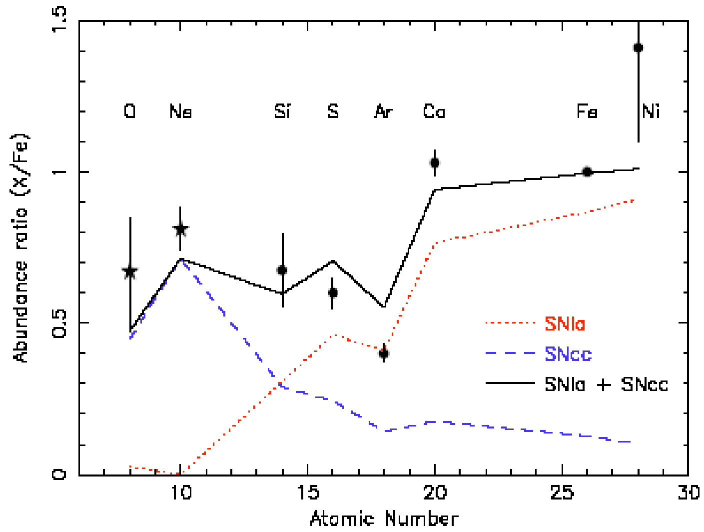


Fig. 8. Fit using the *SNIa* yields by Badenes et al. (2006), but now with additional oxygen and neon data points (stars) obtained from the RGS spectra of Sérsic 159-03 and 2A 0335+096. Here, the core-collapse model with $Z = 0.02$ and Salpeter IMF is used.

Abundances in Groups with *Suzaku*: Promise

- Abundances in IGM are diagnostics of heavy element synthesis (SFH, SNIa) and transport (galactic winds, feedback) -- fundamental galaxy formation processes
- Groups are important because (compared to clusters) they are typical, and their low kT provides access to more elements -- we need to understand groups in order to understand clusters
- Early *Suzaku* results demonstrate that a wide range of elements -- and their distribution -- can be measured to a new level of accuracy, precision, and detail

Abundances in Groups with *Suzaku*: Priorities

- More observations of a wide range of groups!
- Do with SCI (resolution matters)
  - -- need good background tools to go to r_{virial}
- Find groups where we can measure Ne (?) and Ca (?)
- Combine with higher angular resolution observations

Abundances in Groups with *Suzaku*: Priorities

- Connect to cosmological context
  SDSS statistical M/L *vs*. Suzaku individual,
  star formation/halo connection -- an X-ray analog?
- Go to higher redshift (see Miller et al. Poster A22)

Balestra et al. 2007 clusters