X-ray Measurement of the Elemental Abundance at the Outskirts of the Perseus Cluster with *Suzaku*

Shutaro Ueda

(shutaro@ess.sci.osaka-u.ac.jp)

&

Kiyoshi Hayashida, Hiroshi Nakajima,

Hiroshi Tsunemi

(Osaka University)

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Talk plan

I. Our purpose

II. A brief introduction to *Suzaku*/XIS and recent studies of the Perseus cluster

III. Spectral study and result

IV. Summary and future prospects

The outskirts era !

To study the chemical evolution of clusters of galaxies, we need to measure elemental abundances of the intracluster medium (ICM) not only the center but also the outskirts.

Recent X-ray observations have clarified:

detailed elemental abundances of the ICM in the center (e.g. O, Ne, Mg, Si, S, Ar, Ca, Cr, Fe, Ni and Mn).

(e.g. Sato+07, Tamura+09, Sakuma+11)

only temperature, density and metallicity at the outskirts.

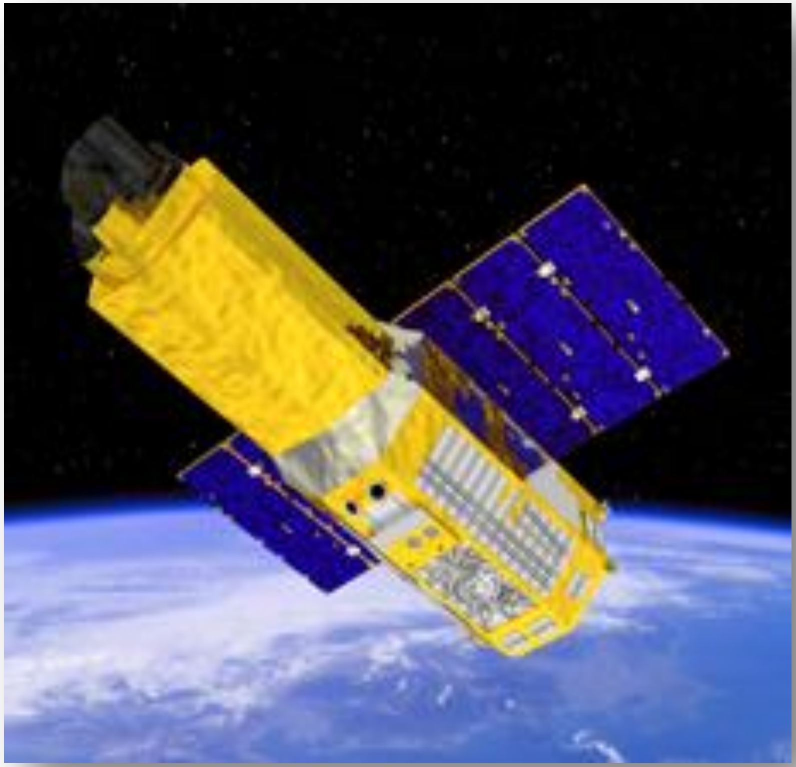
(e.g. Fujita+08, Hoshino+10, Simionsescu+11, Urban+11)

How are the distribution of elemental abundances (especially O, Ne and Mg) at the outskirts ?

Outskirts are the frontier to reveal the chemical evolution of the clusters of galaxies.

Suzaku/XIS and its advantage

XIS (X-ray Imaging Spectrometer) consists of 4 X-ray CCD cameras on board *Suzaku*.
XIS0 and XIS3 are front illuminated CCDs and XIS1 is a back illuminated CCD.



Advantage

- ◆ Energy resolution
- ◆ Linearity (~0.1%@6keV)
- ◆ **Low non X-ray background and its reproducibility**

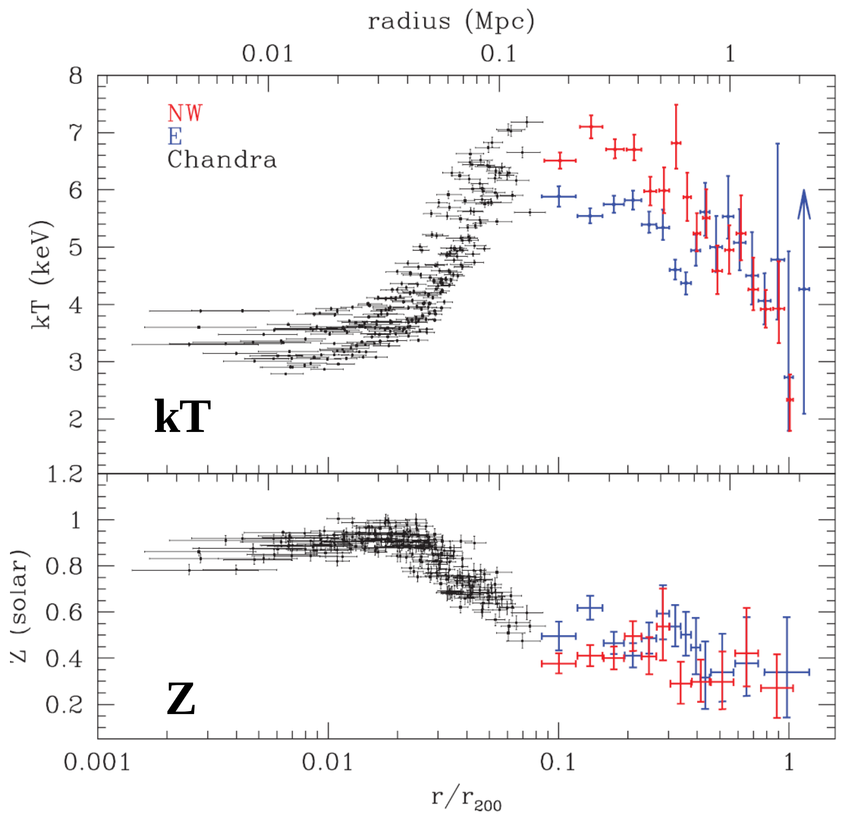
***Suzaku*/XIS is suitable for observing faint and diffuse objects such as outskirts in clusters of galaxies.**

Recent studies of the Perseus cluster

I. For the first time, Dupke & Arnaud 2001 reported Fe abundance at the outskirts (25'~45') using *ASCA*/SIS & GIS.

II. Tamura+09 reported elemental abundances in the center with *Suzaku*/XIS.
$\Rightarrow$ There is a possibility that those are contaminated by cD galaxy.

III. Simionescu+11 reported the large scale structure of the ICM beyond virial radius with *Suzaku*/XIS.



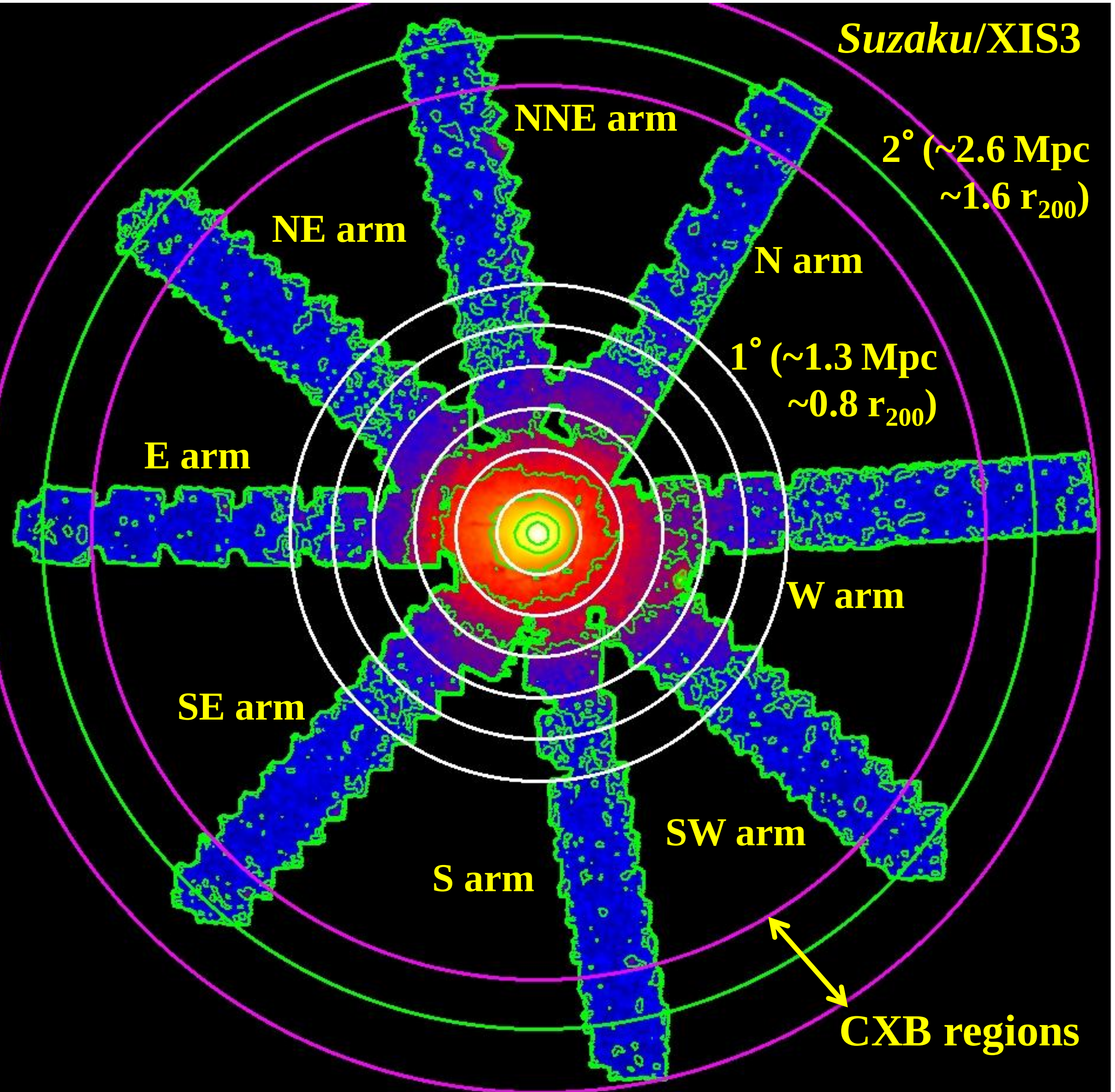
Simionescu+11

Simionescu+11 measured temperature, density and metallicity of the ICM.
$\Rightarrow$ Metallicity is ~0.3 solar at the outskirts

The Perseus cluster is the best target for our purpose.

We measured elemental abundances at the outskirts ($0.2r_{200}$ ~ $0.8\ r_{200}$).

Suzaku Observations



Suzaku **observations of the large scale structure of the ICM in the Perseus cluster**

We extracted X-ray spectra from 5 annular regions from 10' to 60' (white circles).

60' corresponds to ~1.3 Mpc or ~0.8 r_{200}.
(r_{200} = 1.79 Mpc, Simionescu+11.)

We estimated cosmic X-ray background (CXB) and the Galactic emission spectra using data of outermost regions (beyond ~2.3 Mpc).

We included systematic errors owing to CXB fluctuations.

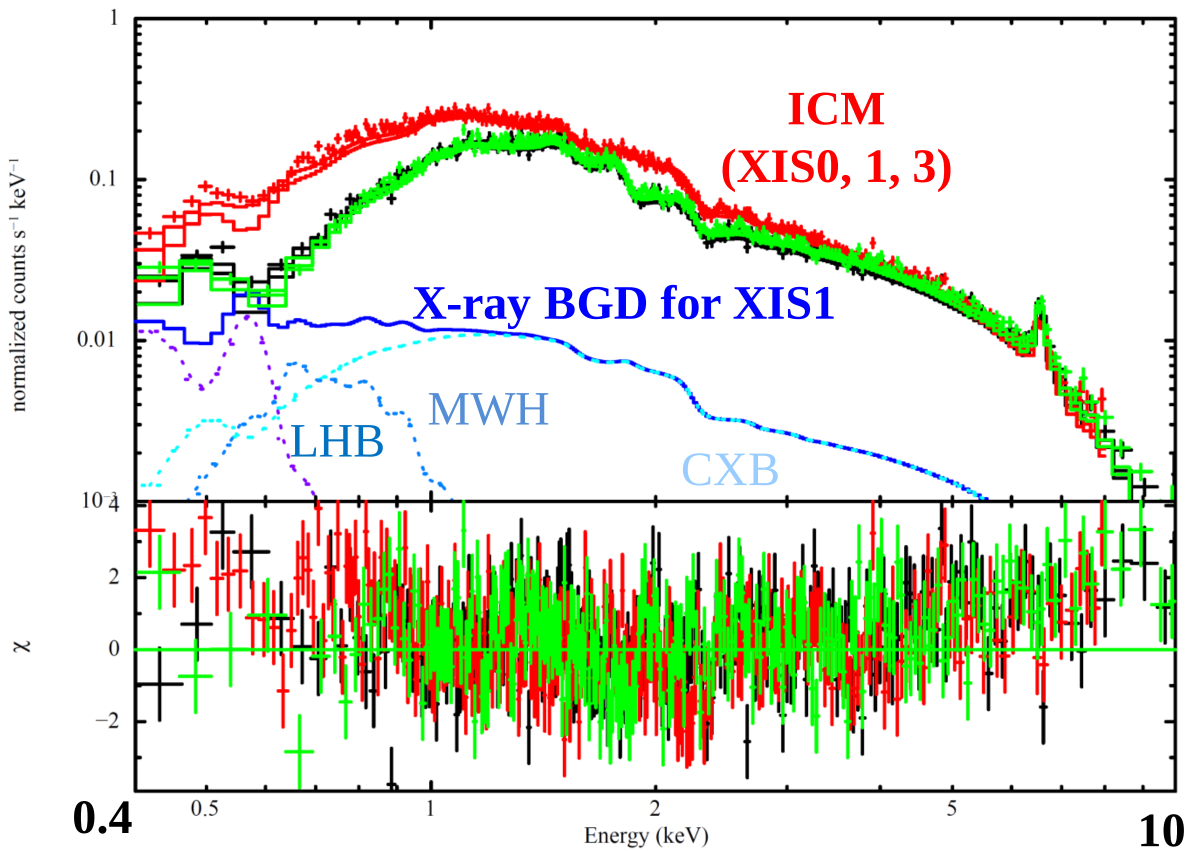
Fitting method

CXB model: more detail as shown in Boldt 1987 and Nishino et al. 2012.

We fitted all X-ray spectra with single temperature models (vAPEC).

Model: wabs * (vAPEC + pow * highecut + $APEC_{MWH}$) + $APEC_{LHB}$

ICM emission — CXB and Galactic emissions (fixed all regions)



The best fit result of 20’ ~ 30’ region (red-χ^2=4353/4137)

We set each parameter for all annular regions as below.

- N_H : 0.132 x10^{22} cm^{-2} (fixed)
- Redshift : 0.0183 (fixed)
- He : 1 solar (fixed)
- kT : free
- O(=C=N), Ne, Mg(=Al), Si, S(=Ar=Ca) and Fe(=Ni) : free.
- Solar abundance table : Anders & Grevesse 1989

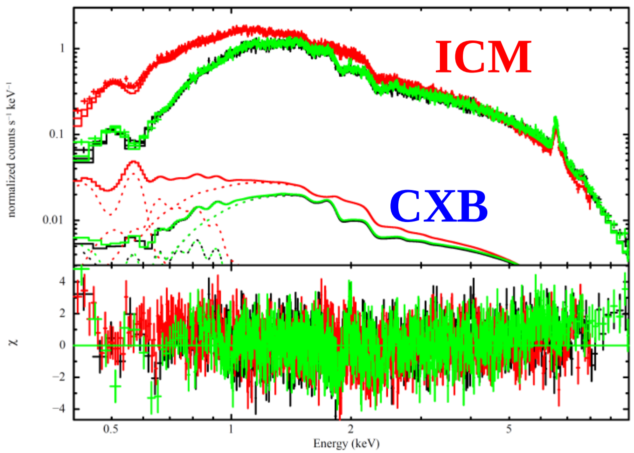
A single temperature model well reproduces the X-ray spectrum.

Spectral analyses of 5 annular regions

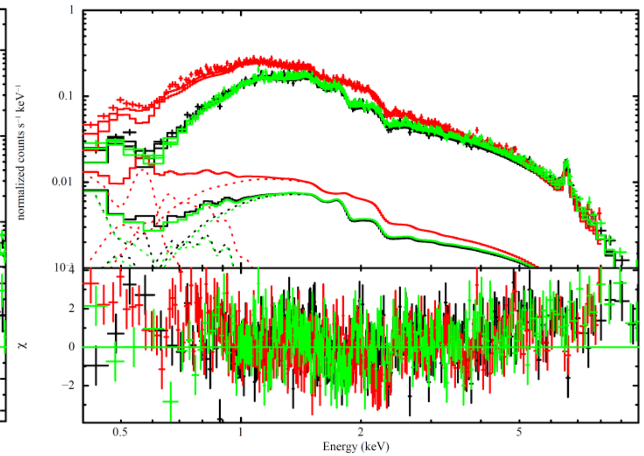
We fitted all X-ray spectra with single temperature models (vAPEC).

Model: wabs * (vAPEC + pow * highecut + $APEC_{MWH}$) + $APEC_{LHB}$

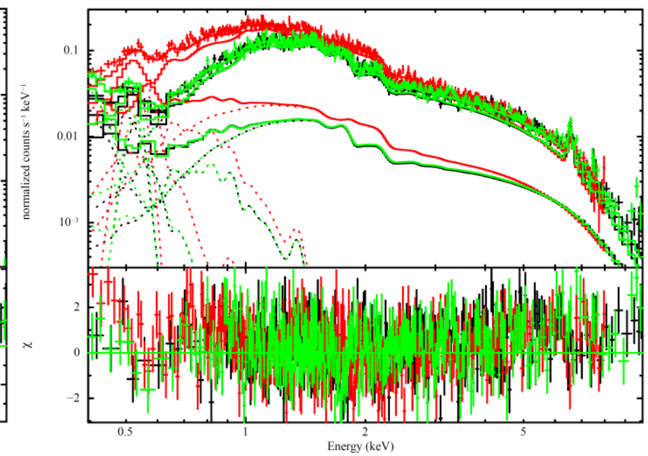
ICM emission — CXB and Galactic emissions (fixed all regions)



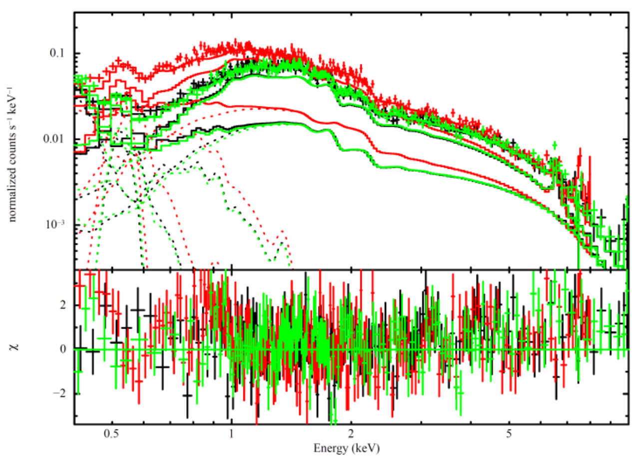
10’ ~ 20’ (red-χ^2=6326/5950)



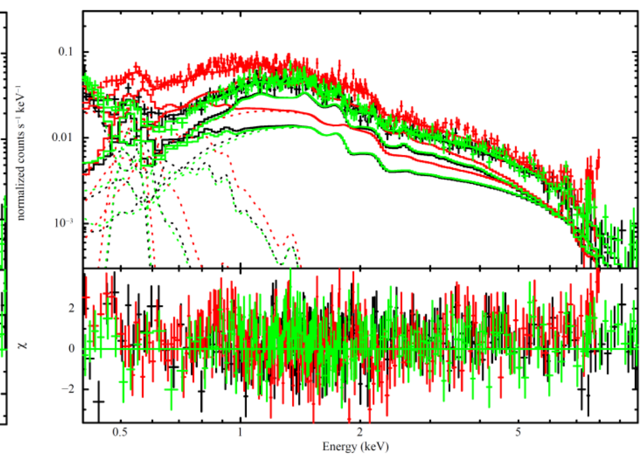
20’ ~ 30’ (red-χ^2=4353/4137)



30’ ~ 40’ (red-χ^2=3550/3456)



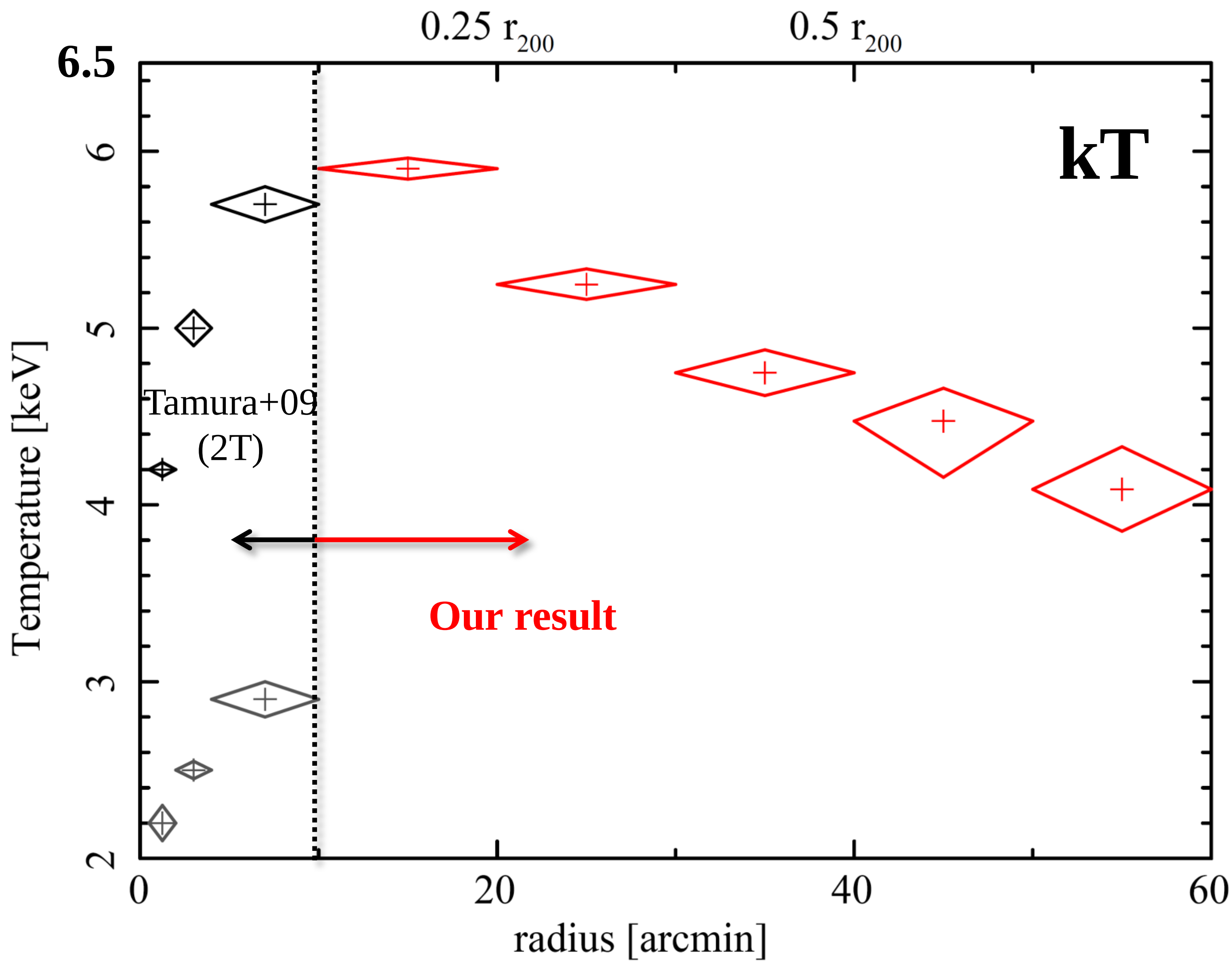
40’ ~ 50’ (red-χ^2=2874/2732)



50’ ~ 60’ (red-χ^2=2275/2210)

The single temperature models well reproduce the X-ray spectra in all 5 annular regions.

Radial profile of the ICM temperature

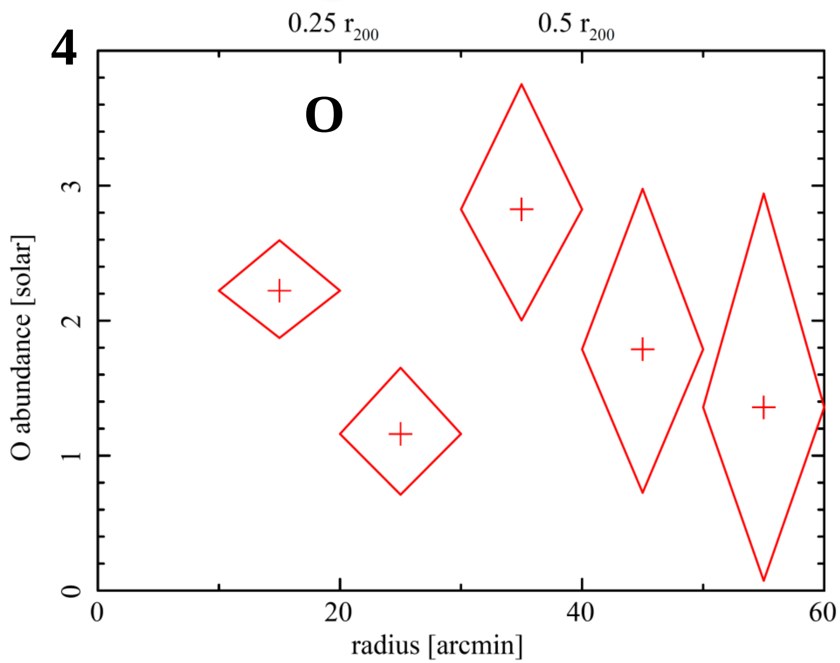


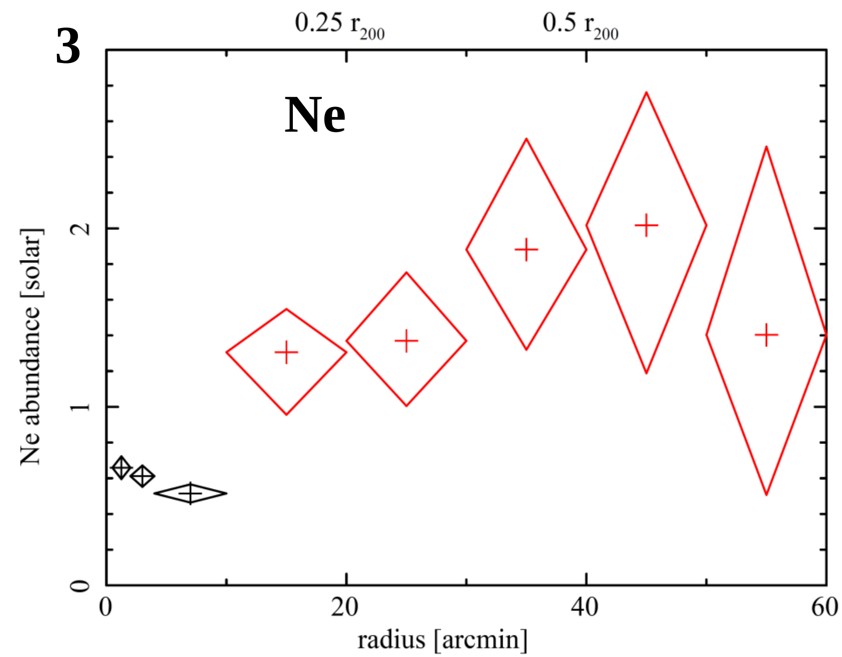
The ICM temperature decreases smoothly from 6 keV to 4 keV at 10’ to 60’.

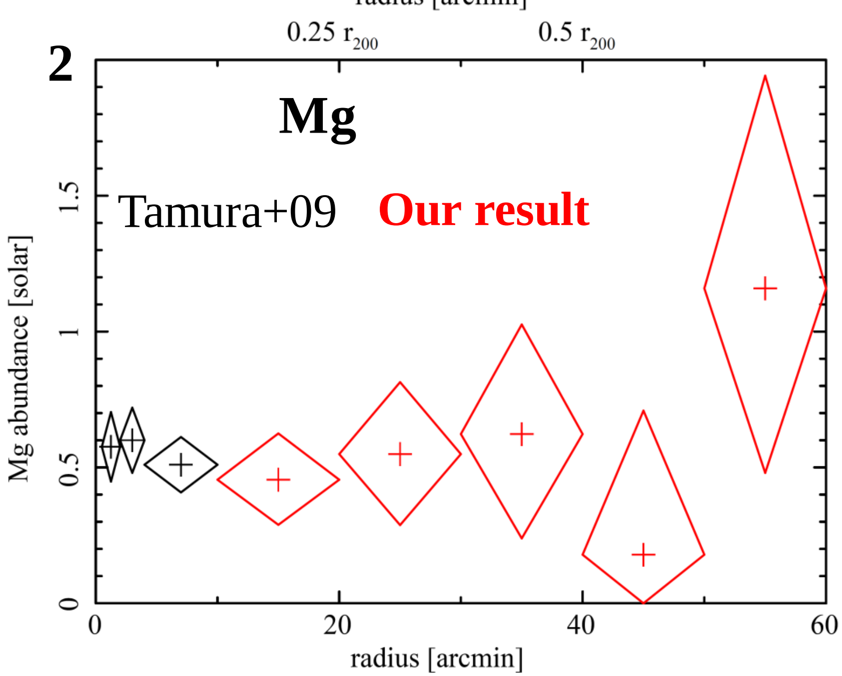
⇒ Consistent with that obtained by Simionescu+11.

Note that error bar shows 90% CL hereafter.

Radial profiles of O, Ne, Mg abundances



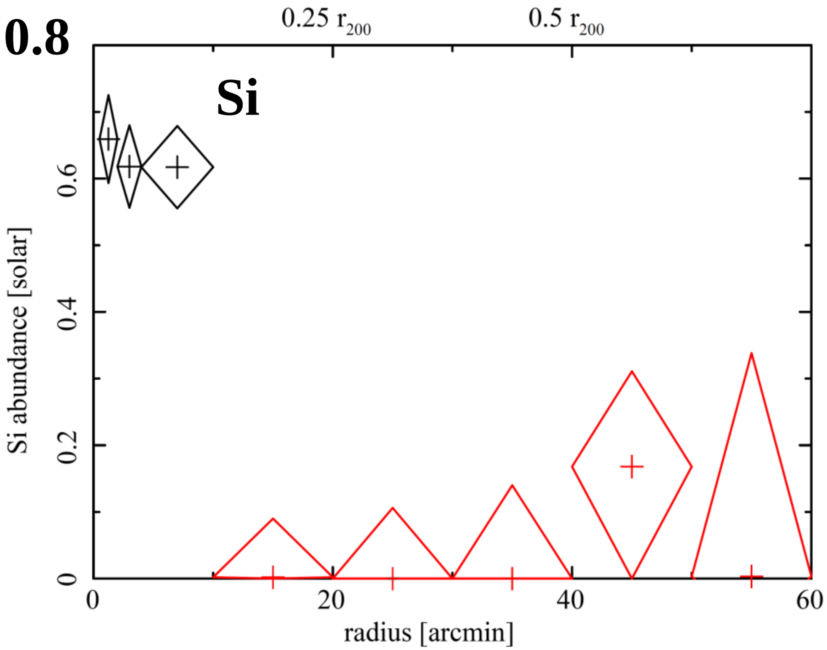


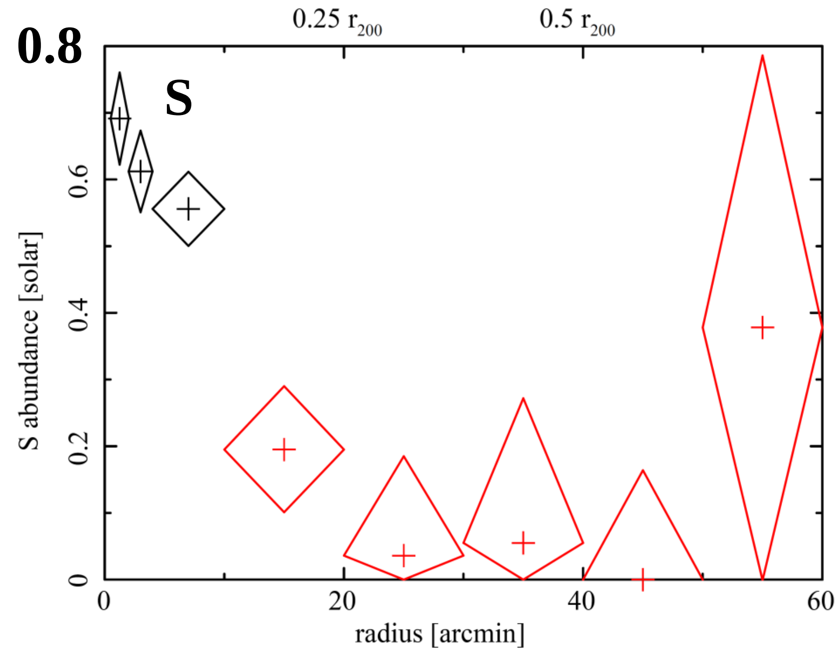


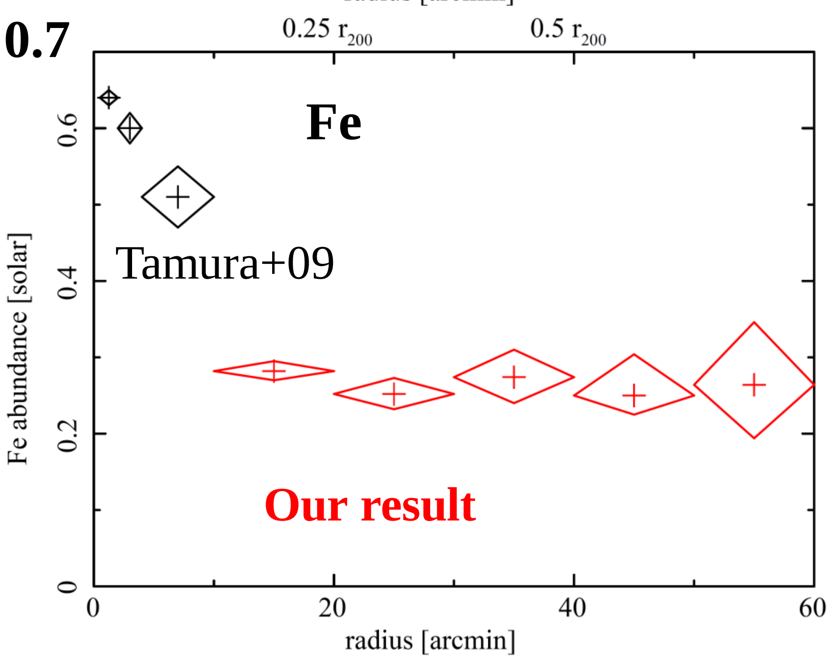
- **We obtained O, Ne and Mg abundances at the outskirts.**

- **O, Ne and Mg are almost constant at 10’ to 60’ (0.2 r_{200} ~ 0.8 r_{200}).**
  ⇒ In particular, Mg is ~0.6 solar with better statistics.

Radial profiles of Si, S, Fe abundances



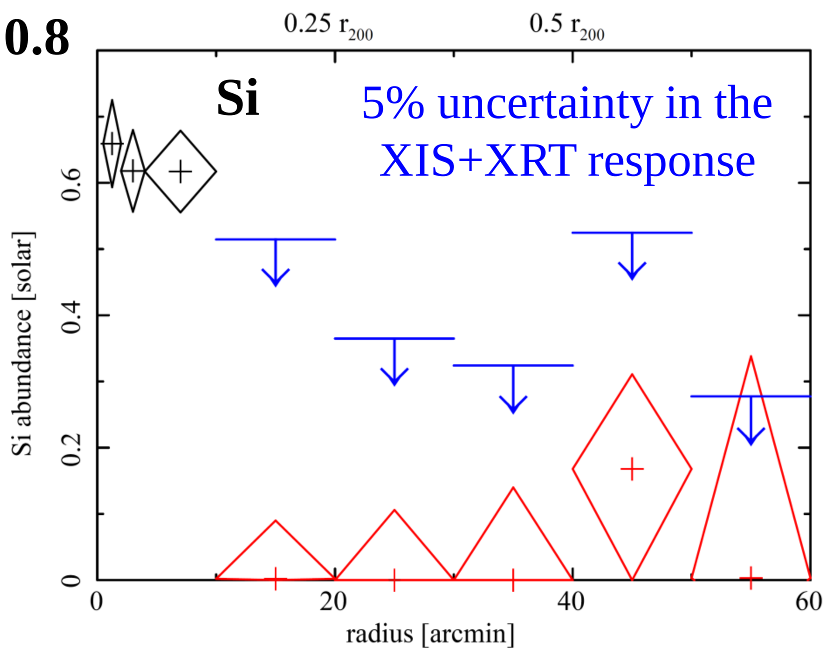


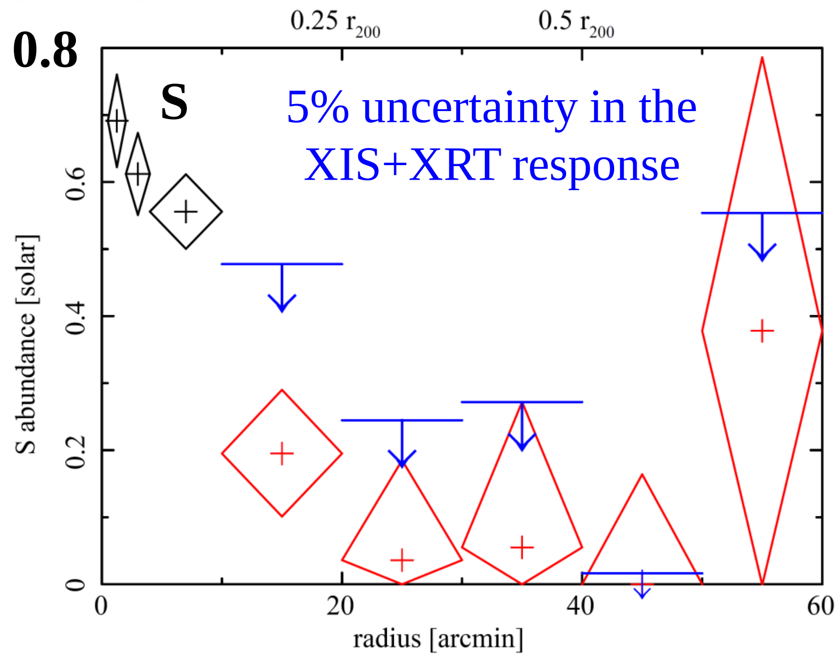


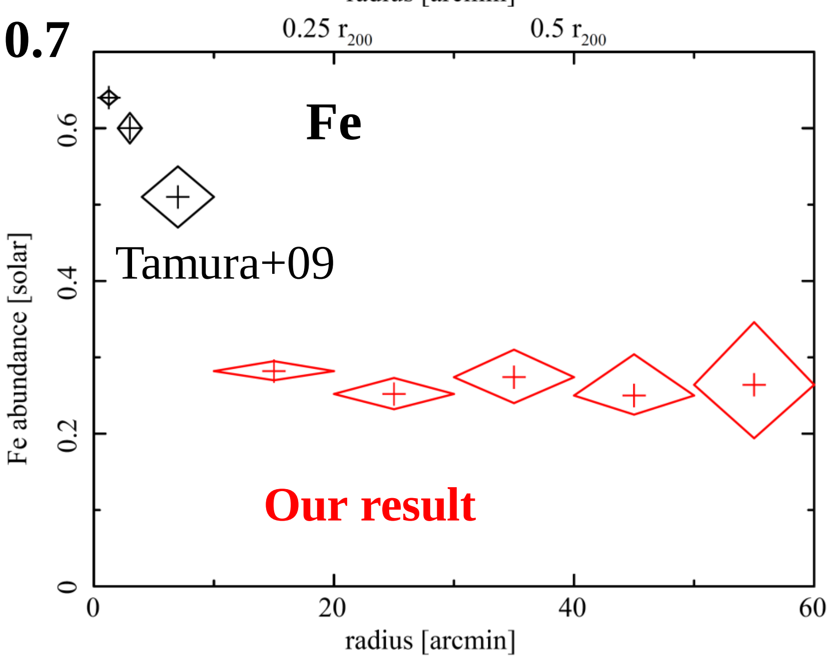
- **Fe is almost constant of ~0.3 solar at 10' to 60' (0.2 r_{200} ~ 0.8 r_{200}) with better statistics.**

Si and S abundances are less than that of Fe.
We need further consideration on this point.

Radial profiles of Si, S, Fe abundances





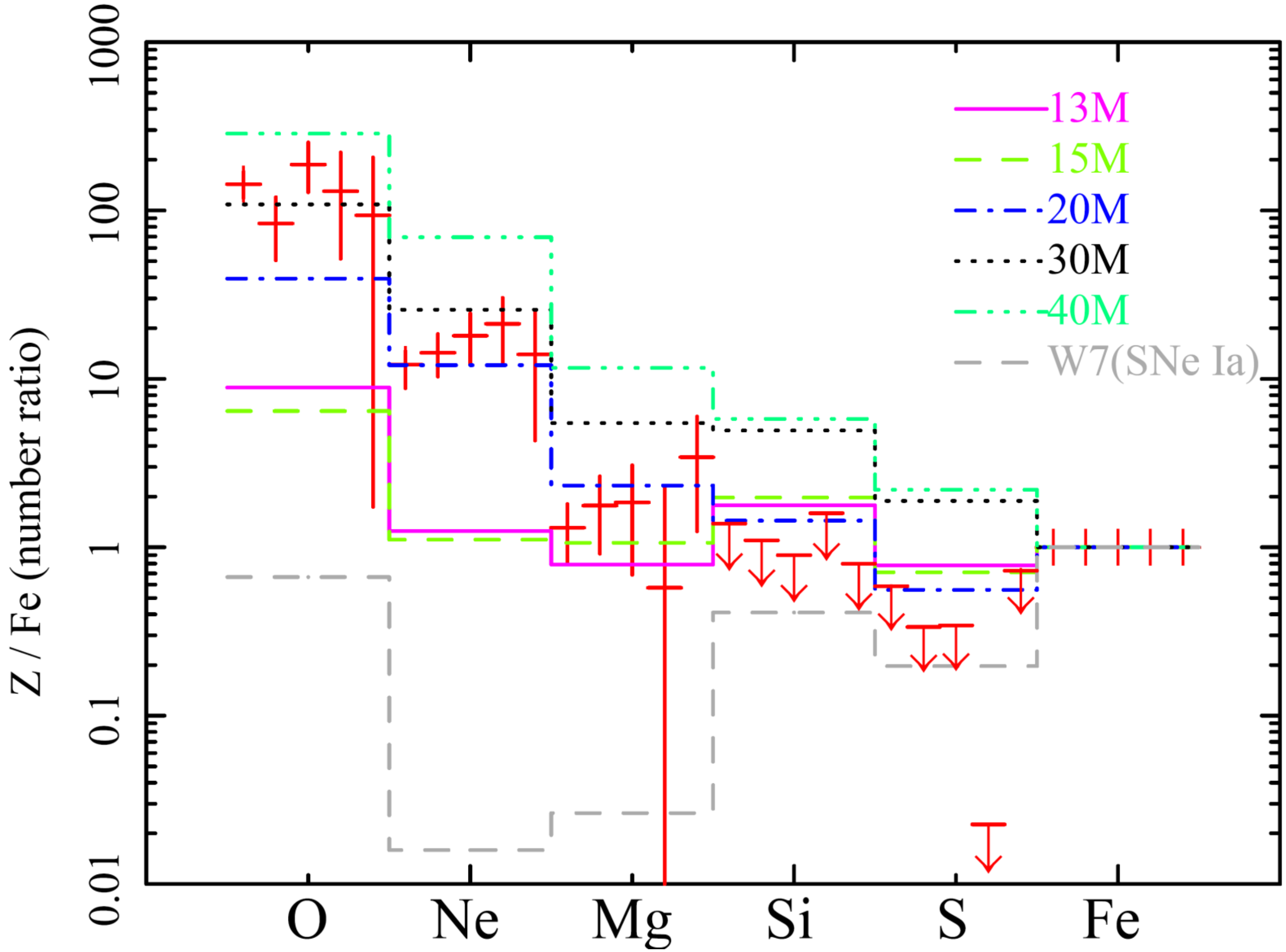


The X-ray energies of Si K-lines and S K-lines from the ICM are close to those of Si K-edge and Au M-edge where the XIS+XRT response has large (~5%) uncertainty.

Si is < 0.6 solar and S is < 0.6 solar with taking into account this systematic uncertainty.

Number ratios of Z/Fe

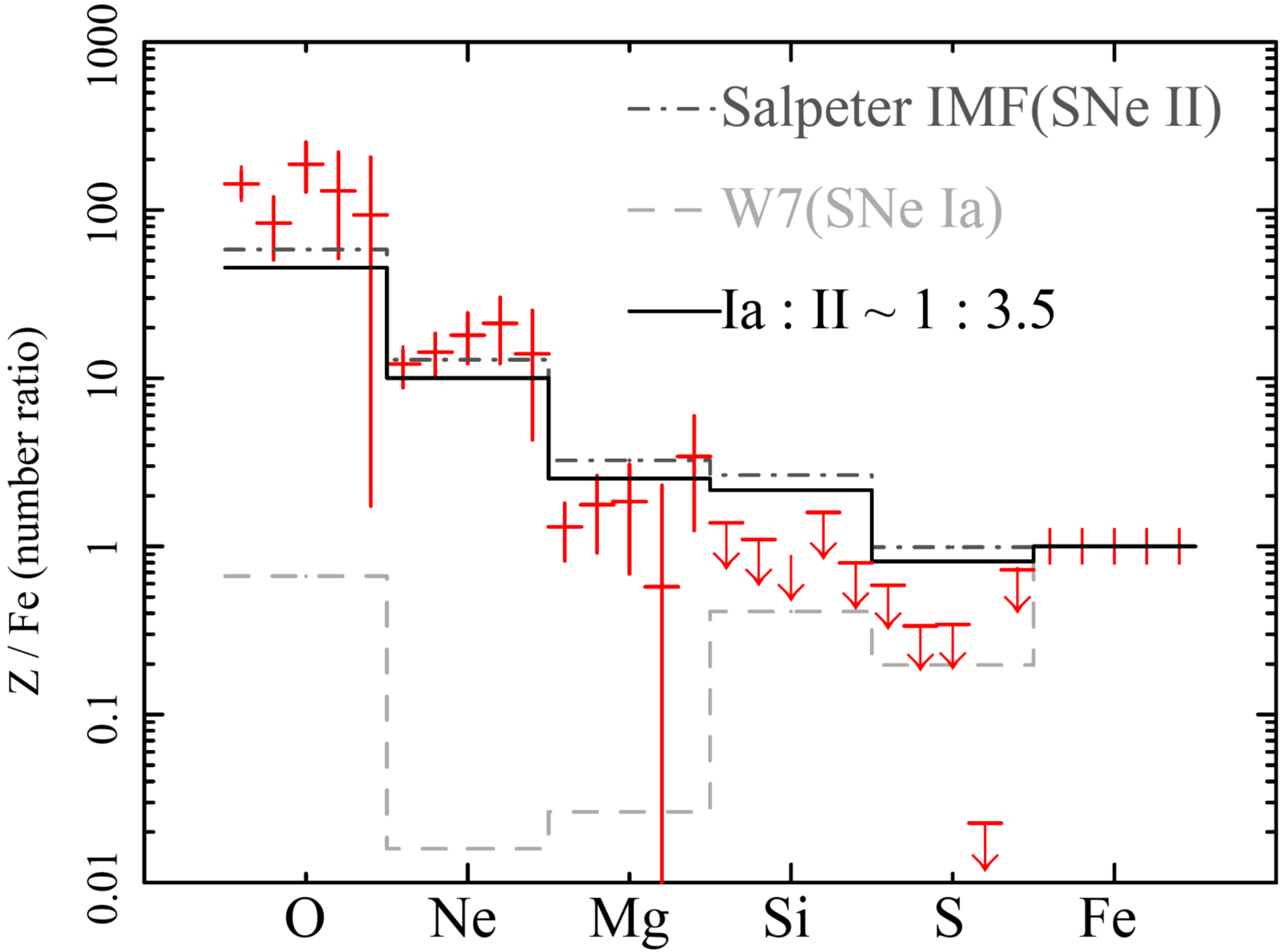
We plot number ratios of elemental abundances (Z/Fe) and models.
SNe II : Nomoto+06 (Z=0.02), SNe Ia : W7 model (Iwamoto+99) .



The number ratios of O, Ne and Mg at the outskirts are similar to those of SNe II nucleosynthesis.

SNe II + SNe Ia model

We evaluated the contribution ratio of SNe II to SNe Ia in the ICM at the outskirts.
(SNe Ia: W7, SNe II: the Salpeter IMF from 10 to 50 $M_{\odot}$, ratio of II to Ia: 3.5 (Sato+07).



A factor of 2 excess is found in the number ratio of O.

Summary

◆ The ICM temperatures at the outskirts are consistent with those obtained by Simionescu+11.

◆ We obtained O, Ne, Mg, Si, S and Fe abundances at the outskirts.

⇒ Mg is ~0.6 solar up to ~0.8 r_{200} with better statistics.

⇒ Fe is almost constant of 0.3 solar at 0.2 r_{200} to 0.8 r_{200}.

◆ The number ratios of O, Ne and Mg are similar to those of SNe II nucleosynthesis.

⇒ The number ratio of O/Fe is ~100.

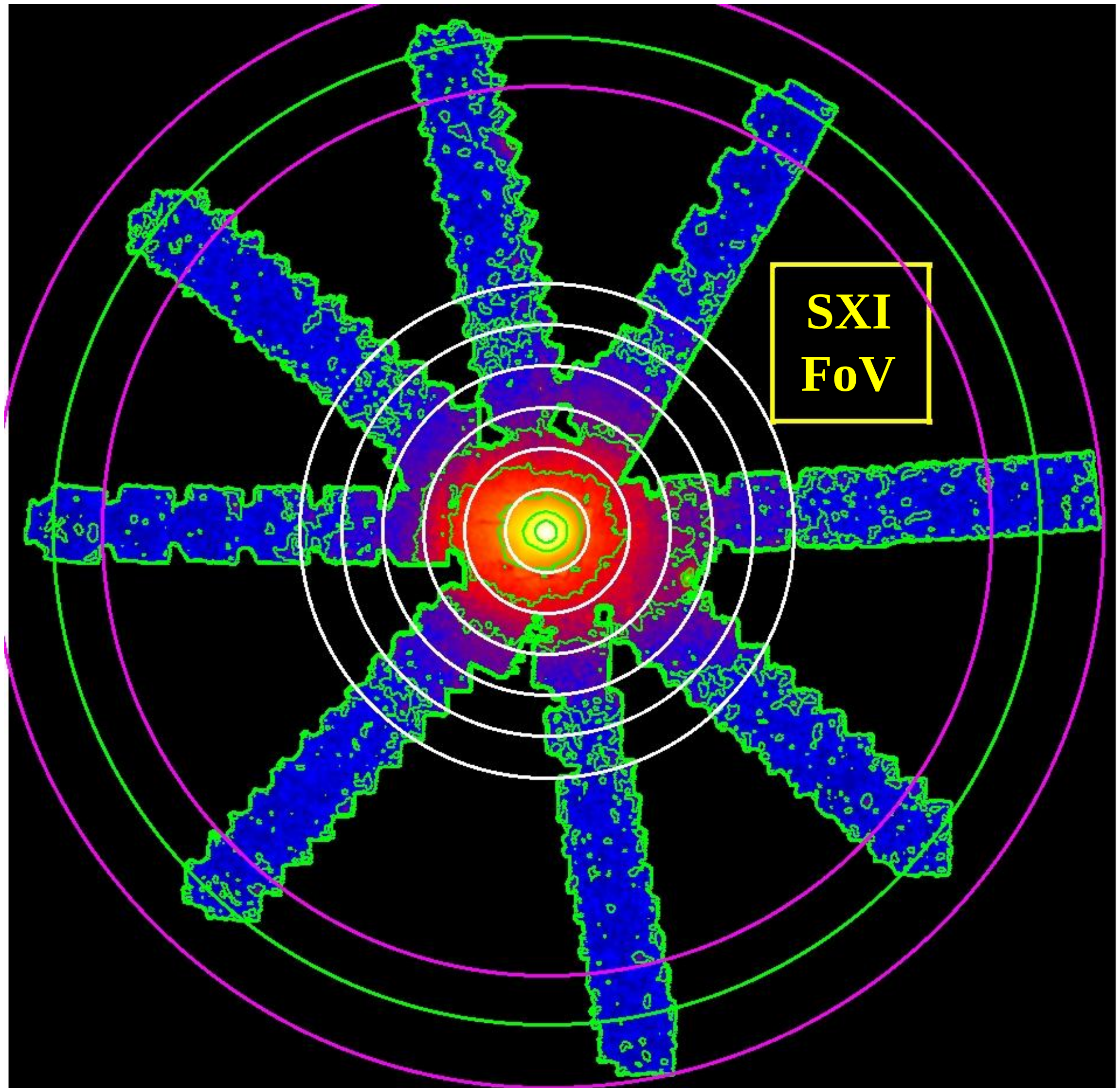
⇒ That of Ne/Fe is ~10. (That of Ne/Fe in the center is ~3)

⇒ That of Mg/Fe is ~2. (That of Mg/Fe in the center is ~1)

◆ The number ratio of O is a factor of 2 excess from Salpeter IMF.

Future prospects

We will have a powerful tool to measure elemental abundances at the outskirts of clusters of galaxies: it is an X-ray CCD camera (SXI: Soft X-ray Imager) on board ASTRO-H (2014).



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