Metals in clusters of galaxies observed with Suzaku and XMM-Newton

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Radial profiles of metals outside cool cores

- Abundance pattern of O, Mg, Si, and Fe
- O mass in the ICM/luminsotiy of galaxies
- Fe mass in the ICM/luminosity of galaxies
- Radial profiles of Fe abundances in the ICM
- Groups vs. clusters

Astro-H

Unless otherwise specified, we use APEC plasma code v1.3.1,
solar abundance table by Lodders (2003), and
errors are quoted at 90% confidence.

O mass to light ratio in the Universe

Half of metals in the solar system : O.

- Chemical evolution of the Universe
- ≒history of synthesis of O

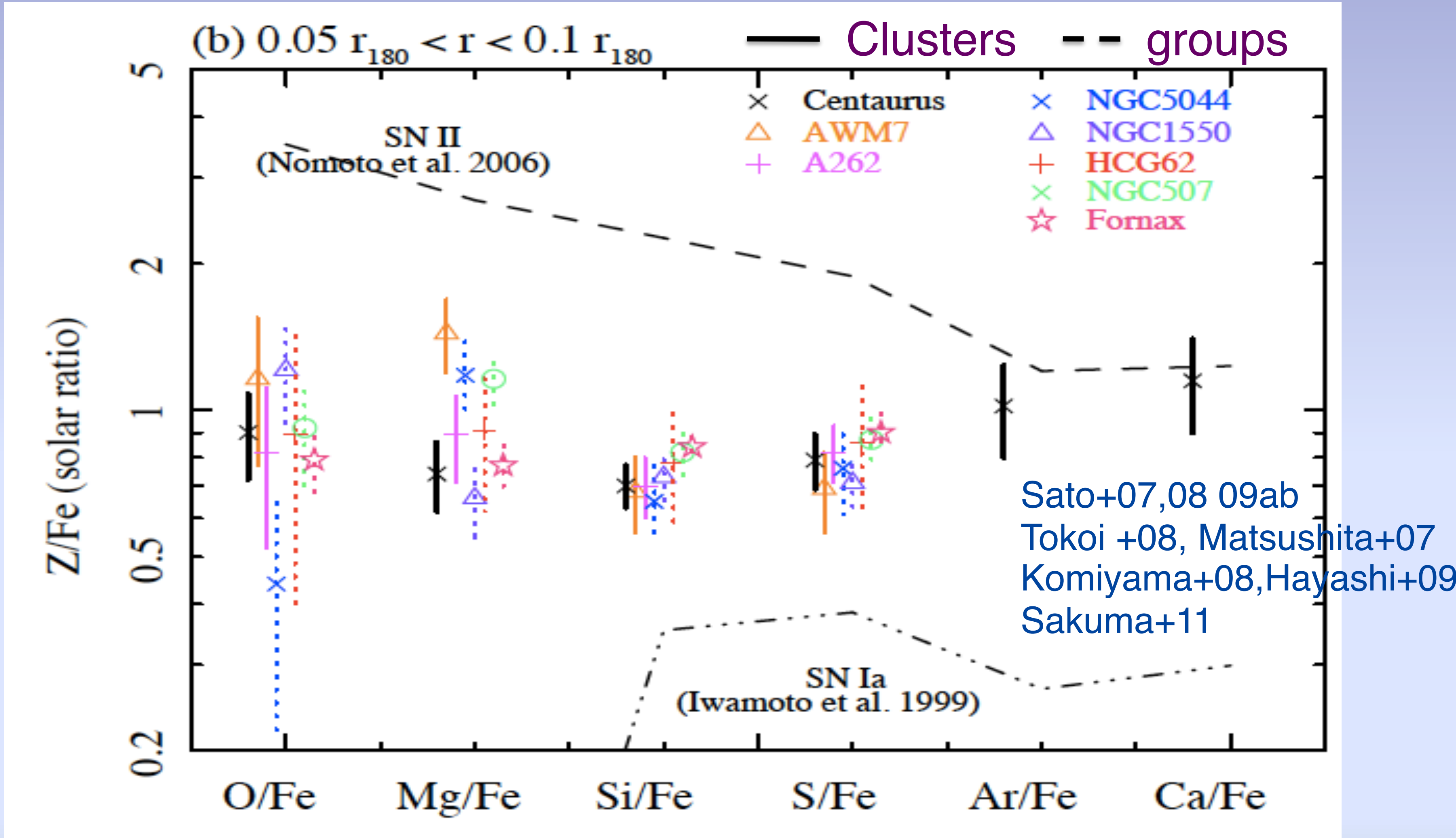
O (Mg) -- synthesized by SN II

- O and Mg mass reflect total amount of massive stars in the past
- Fe and Si are synthesized by both SN Ia and SN II
- α/Fe ratios are indicators for contributions from SN Ia and SN II

Future Goals:O mass-to-light ratio in the Universe

- Galaxies, groups, clusters of galaxies out to the virial radius and WHIM
- Initial mass function of stars vs. environment
- Feedback from SN II

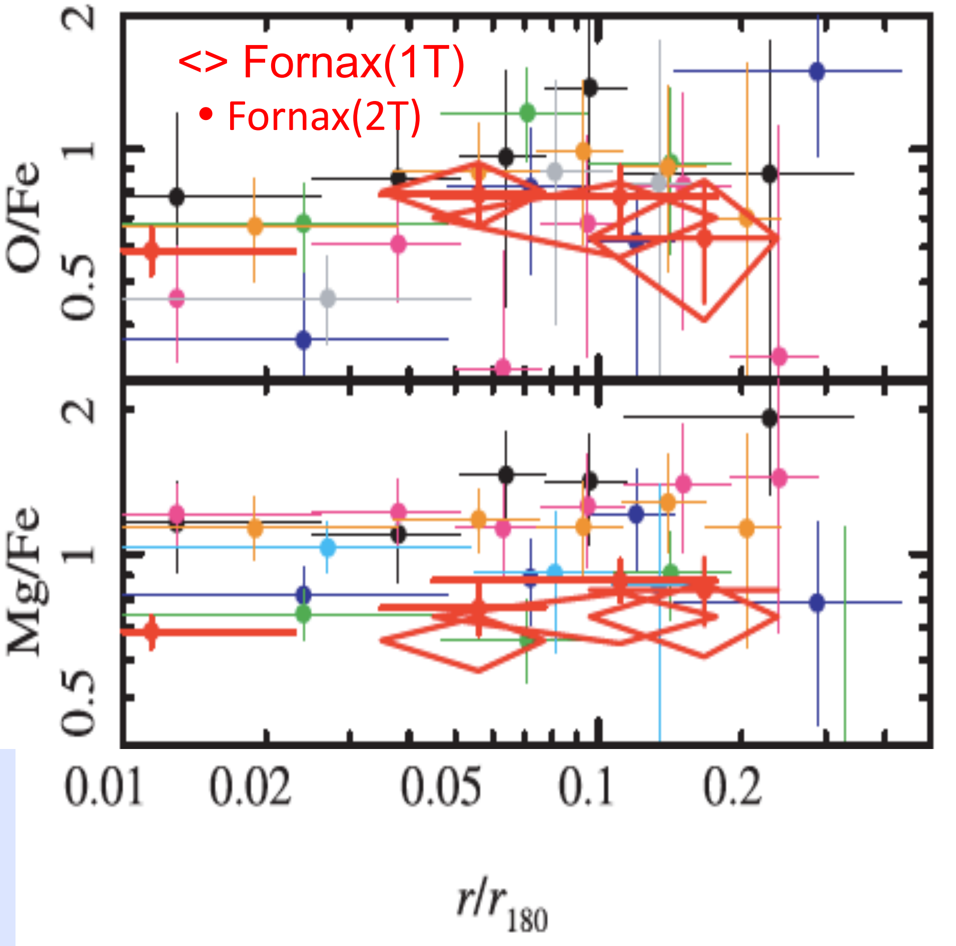
Abundance Pattern of the ICM outside core regions (0.05-0.1r_{180}) observed with Suzaku

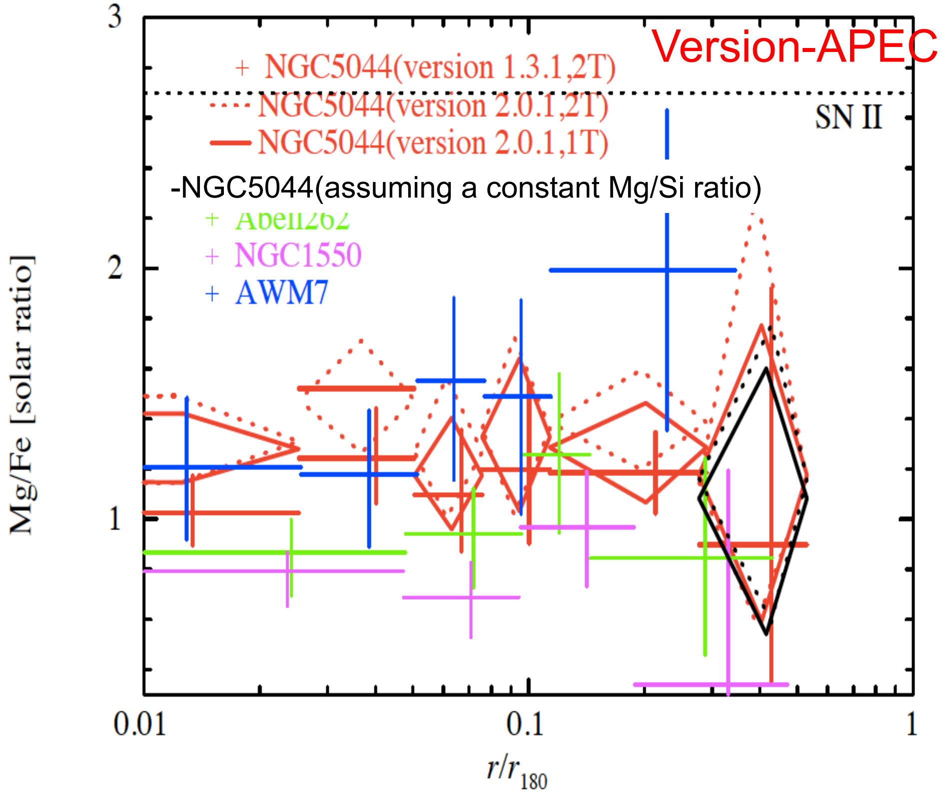


O, Mg, Si, S, Ar, Ca, and Fe ratios are close to the solar ratio within a few tens of %. -> contribution of both SN Ia and SN II

- Using solar abundance table by Lodders (2003)

The radial profiles of O/Fe and Mg/Fe ratios



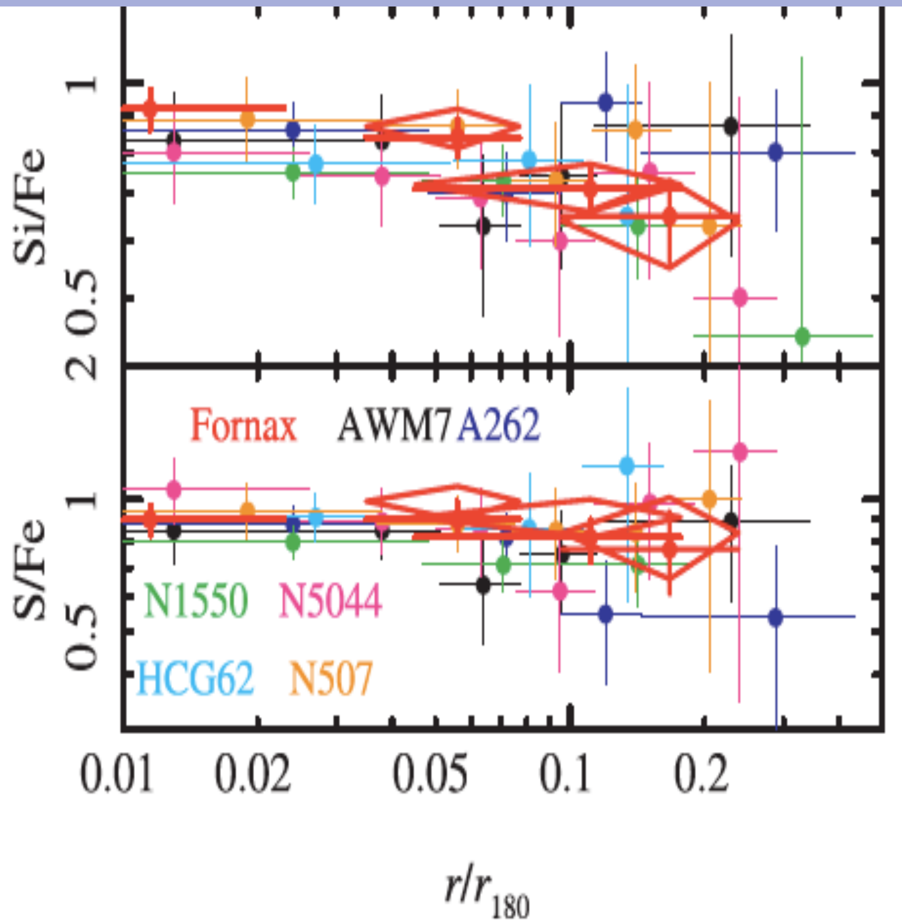


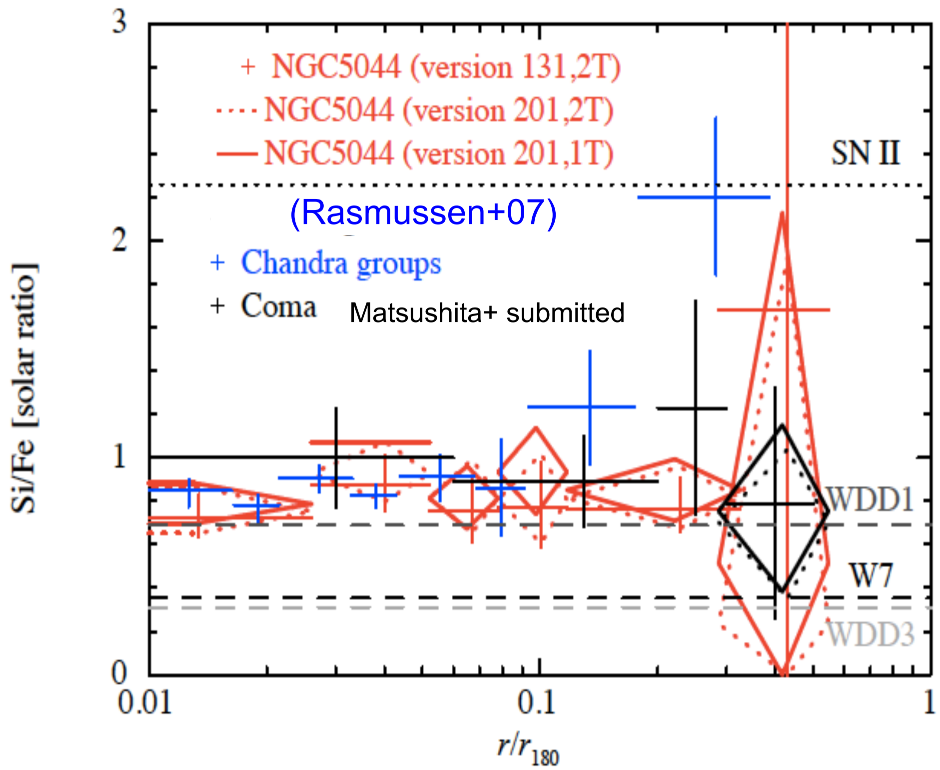
Murakami+11
Sasaki+ submitted

- Outside cool cores, the O/Fe and Mg/Fe ratios show no significant radial dependence
- The scatter in the Mg/Fe ratios – caused by systematic uncertainties in the Fe-L atomic data? Or real dependence on cluster properties?

The radial profiles of the Si/Fe and S/Fe ratios

Murakami+11
Sasaki+ submitted



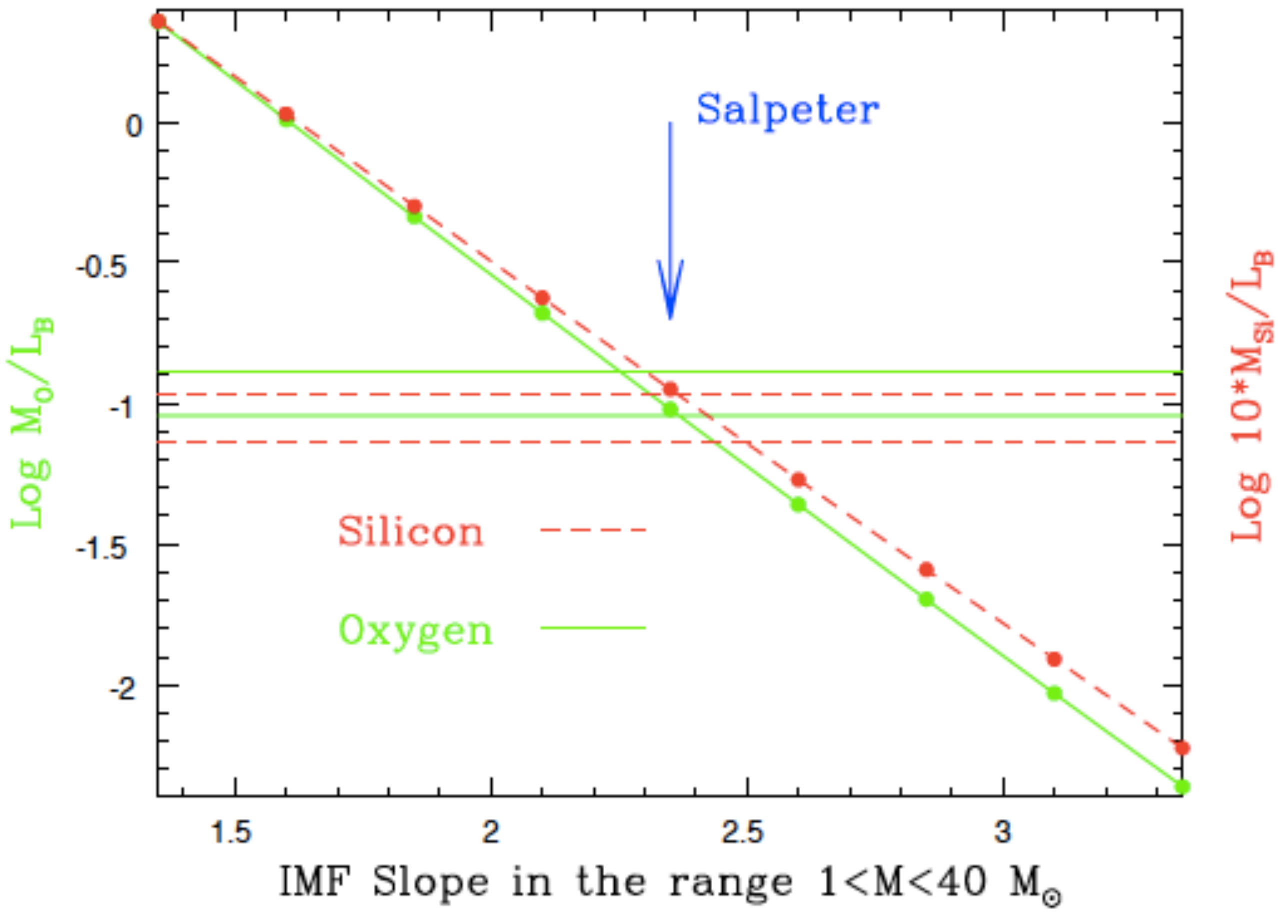


- The Si/Fe and S/Fe ratios do not increase with radius
- The NGC 5044 group (an X-ray luminous group) and the Coma cluster show similar radial profiles of Si/Fe ratio.

O-mass/stellar light vs. initial mass function of stars

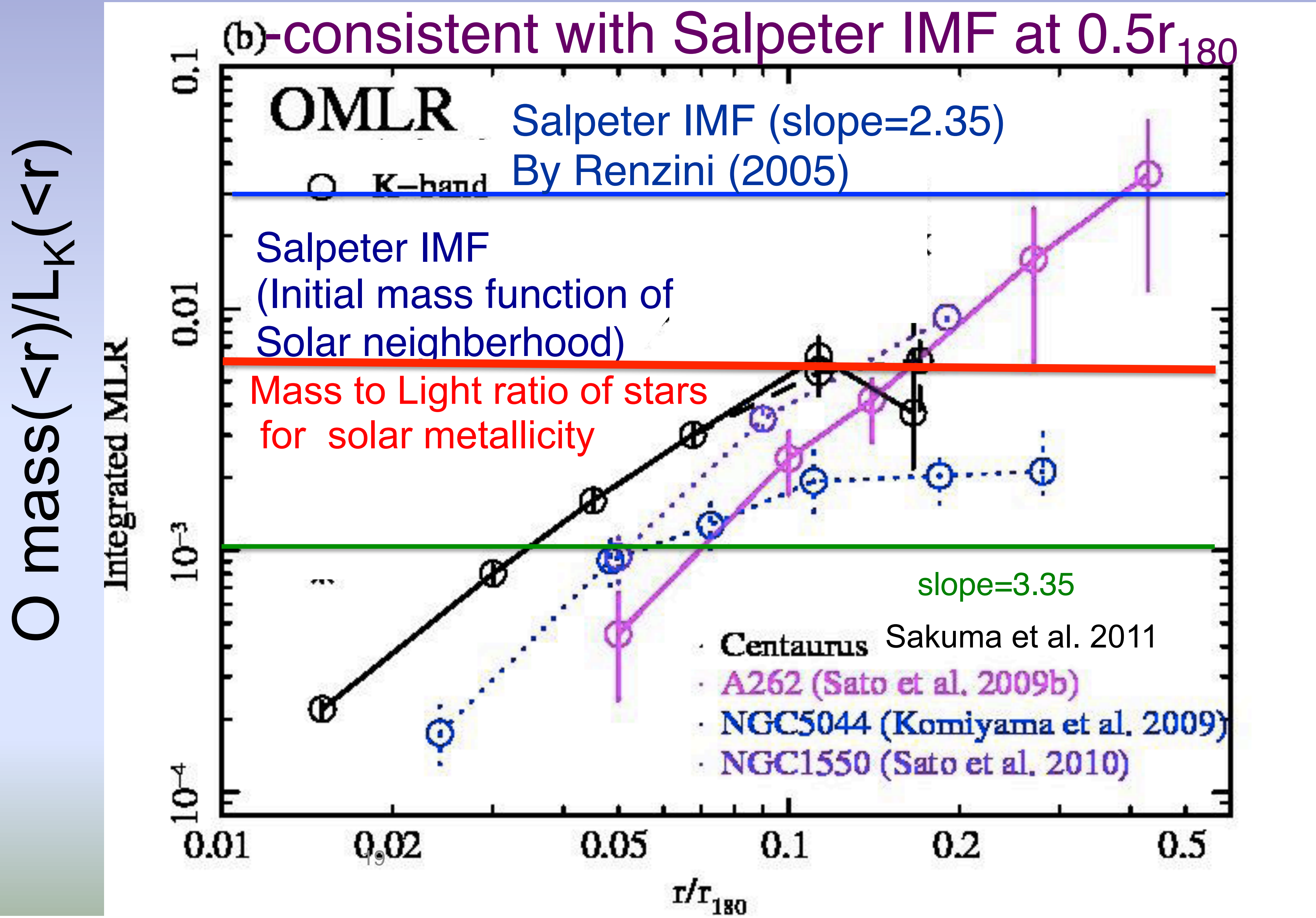
Oxygen mass (in ICM and in stars) in a cluster /stellar light in a cluster is a steep function on the slope of IMF (Renzini 2005)

Stellar light reflect mass of low mass stars because most of stars in cluster galaxies are old



O Mass to light ratio – sensitive to IMF

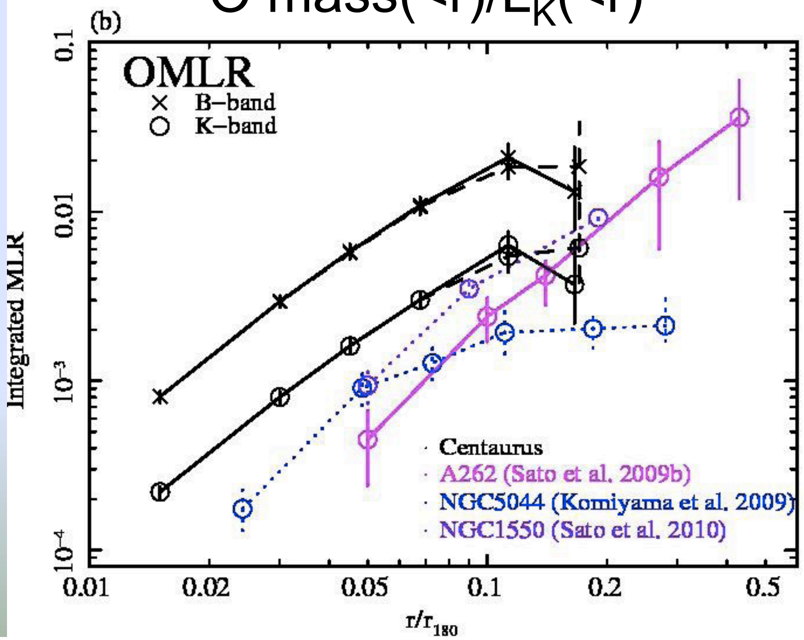
Massive stars to low mass stars



O Mass in the ICM

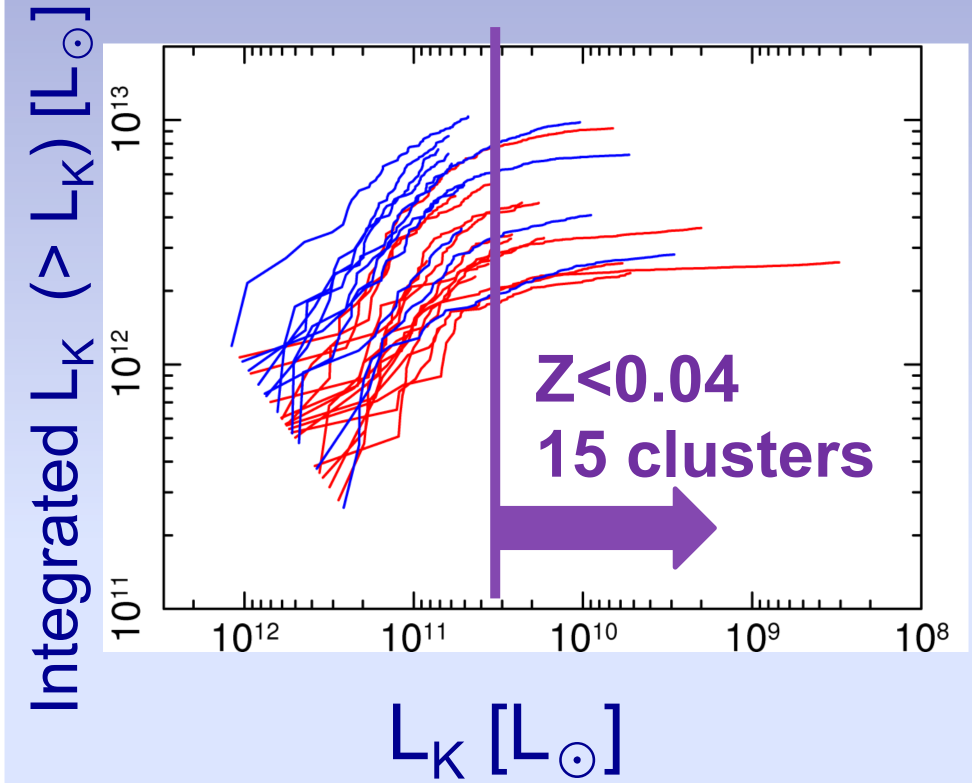
- The α/Fe ratios are close to the solar ratio and show no significant radial gradient
  - Most of Fe are synthesized by SN Ia
- O mass in the ICM is comparable or even larger than the O mass in stars
- O mass to the light ratio within 0.5 r_{180} of Abell 262 is consistent with the Salpeter IMF
  - Since O mass in the ICM to stellar light ratio increases with radius, to derive total amount of O, we need O observations out to the virial radius (with DIOS?)
  - We can derive the Fe mass in the ICM out to the virial radius with Suzaku

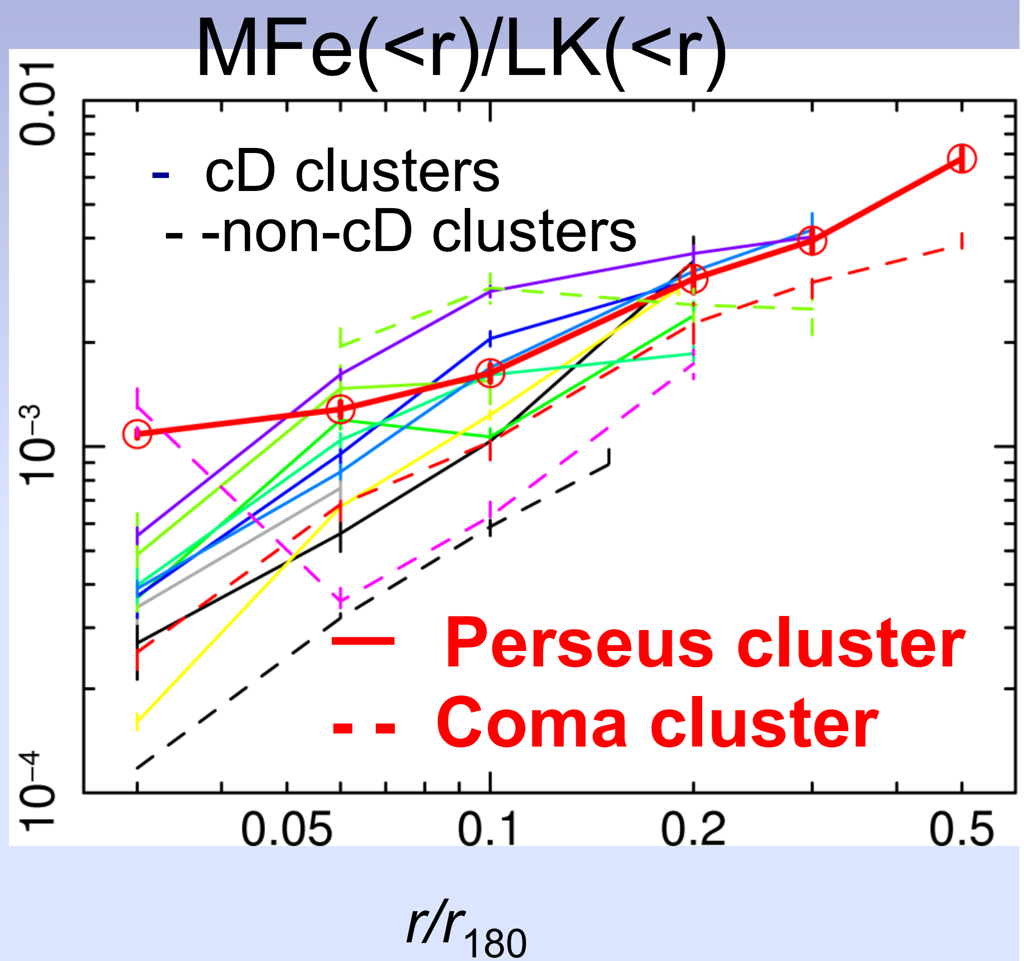
O mass(<r)/L_K(<r)



Integrated Fe-mass-to-light ratio (IMLR)

15 clusters at z<0.04 observed with XMM and 2MASS





A large scatter in core regions

Sakuma et al. in prep

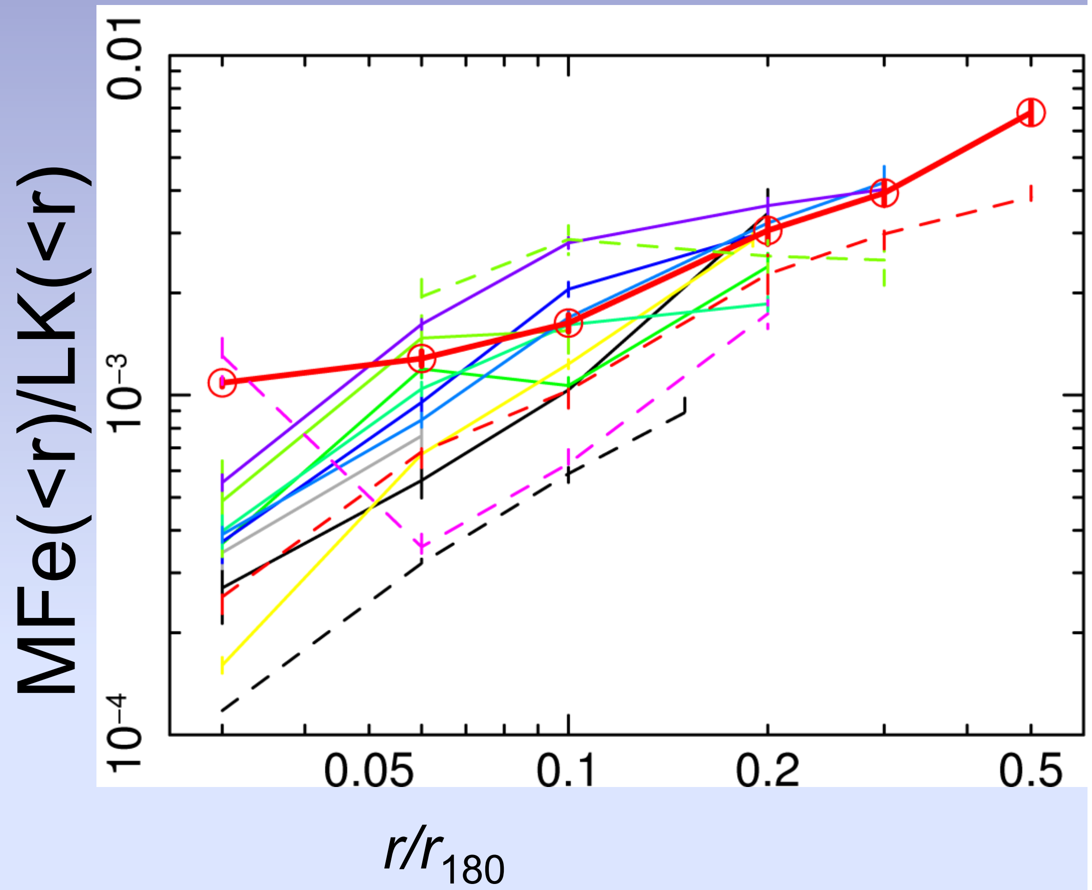
Integrated Iron mass to light ratios: $M_{Fe}(<r)/L_K(<r)$

MFe(<r)/LK(<r) increases with a radius at least up to 0.5r180

-- Fe in the ICM is more extended than stars

-- If galaxies synthesized Fe after cluster formation, the MFe(<r)/LK(<r) should be flat

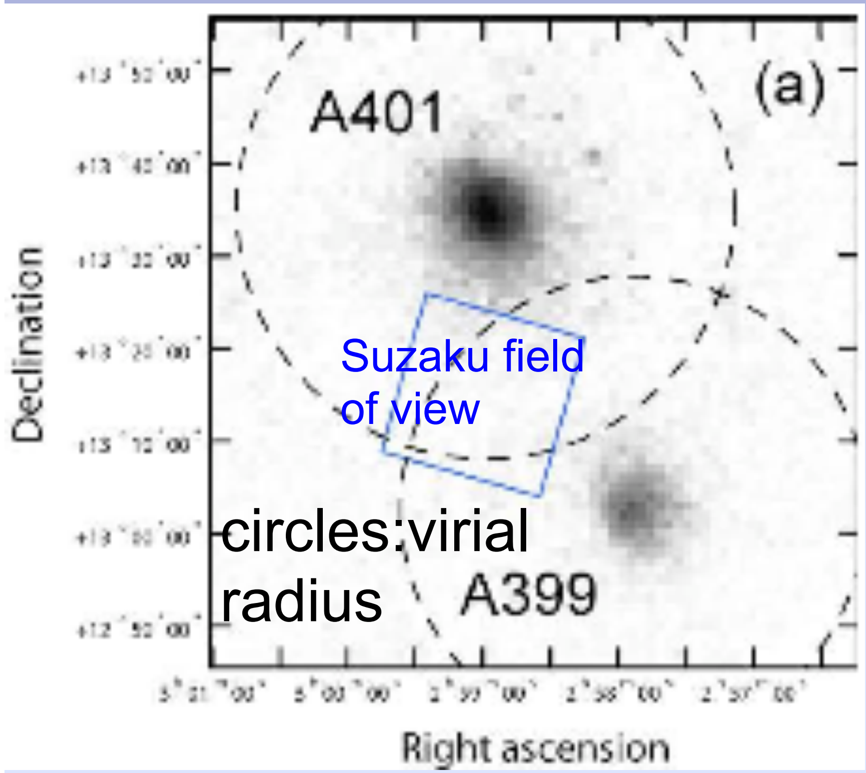
-- Early synthesis of Fe?

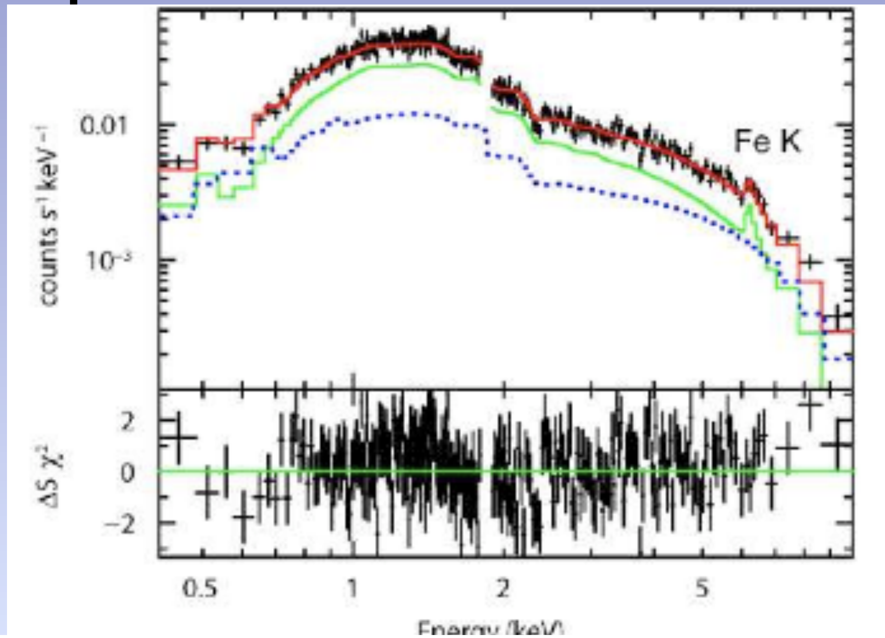


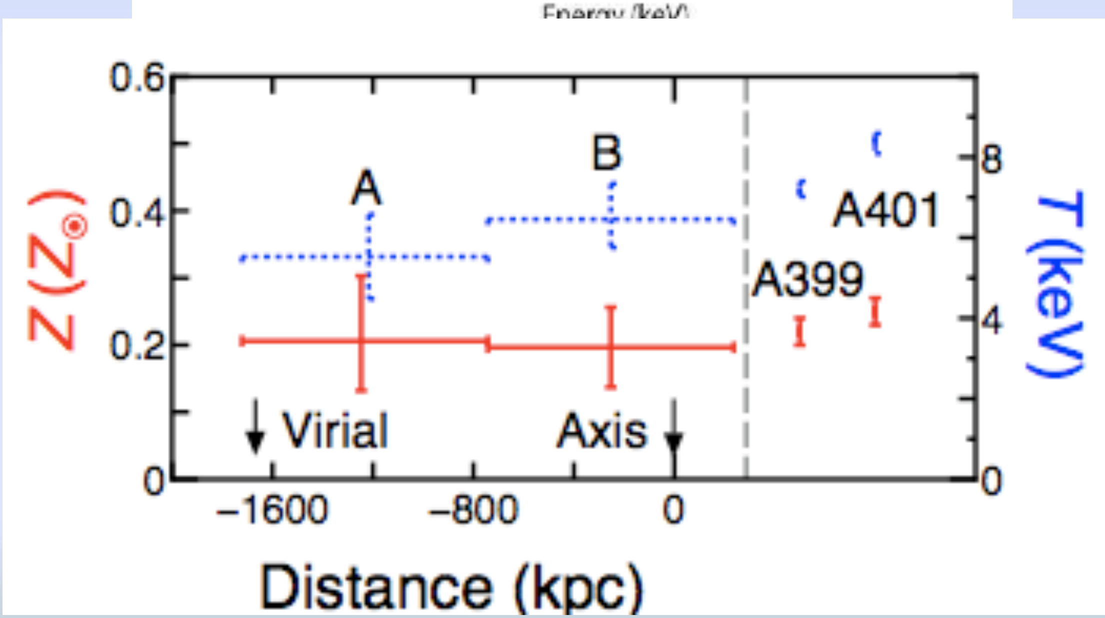
To derive total Fe mass to light ratio, we need to go beyond 0.5r180

Suzaku detection of Fe line up to the virial radius

Fujita et al. (2008)





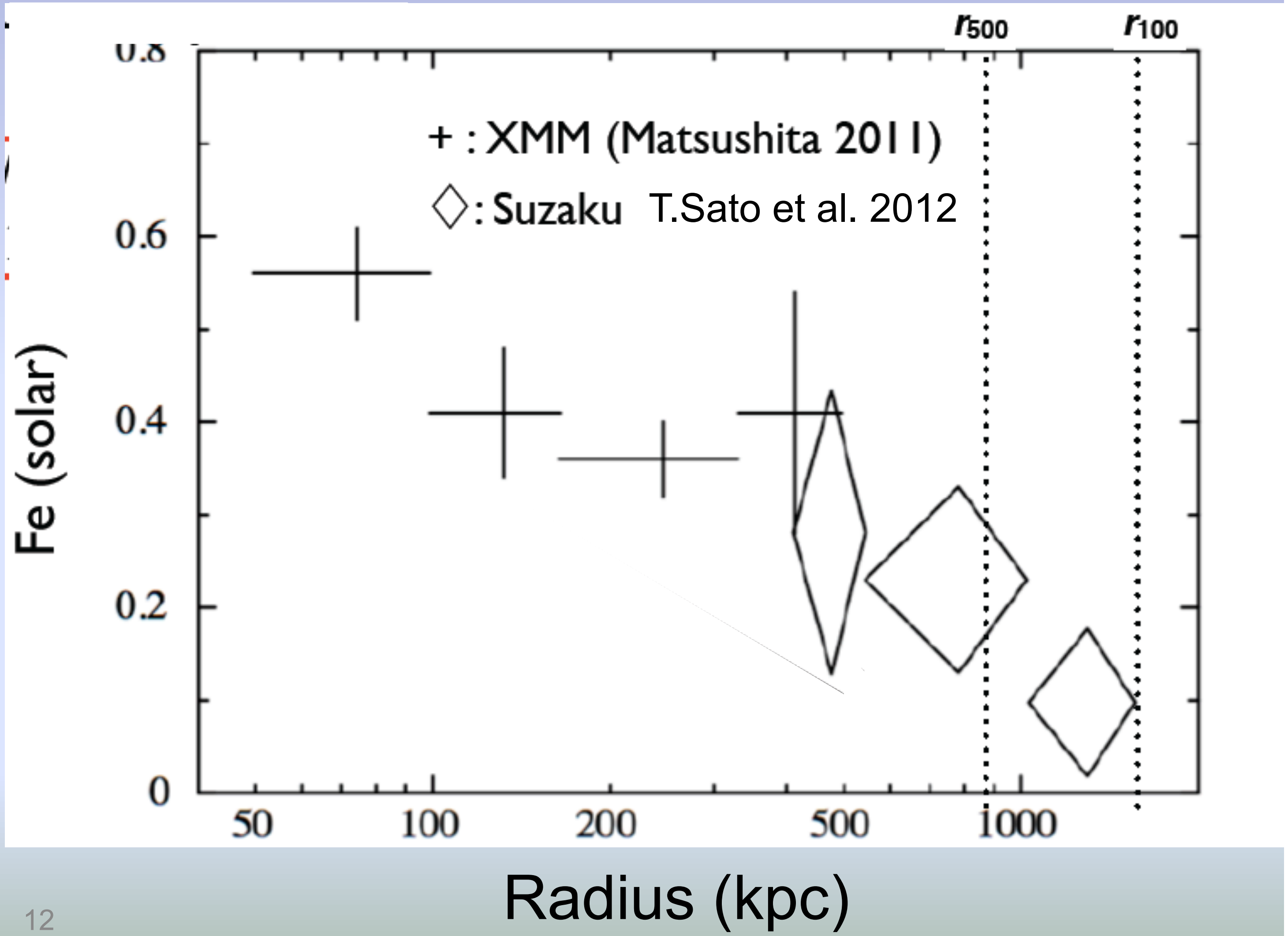


High Fe abundance

@ 0.5-1.0 r_{180}

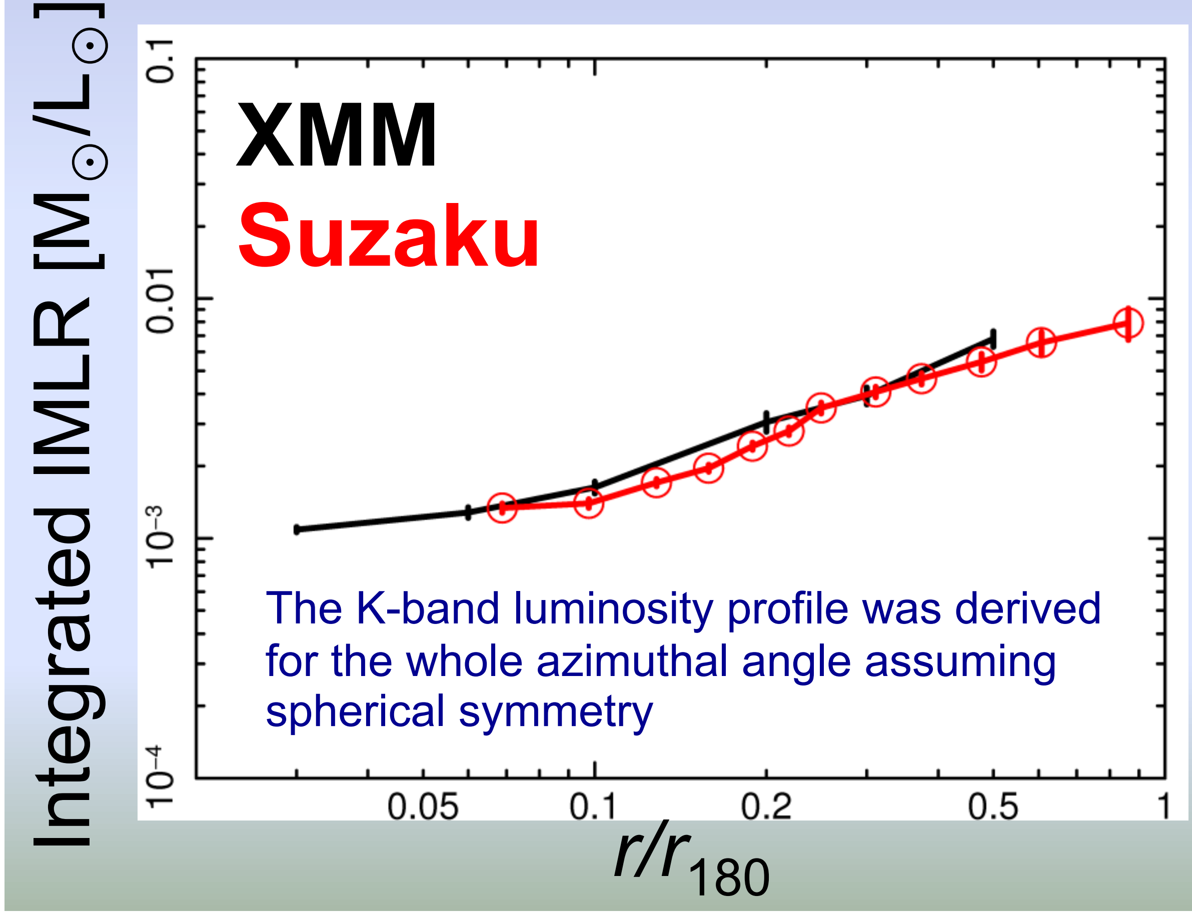
solar abundance: Anders&Grevesse(1989)

Radial profile of Fe abundances out to the virial radius of the Hydra A cluster

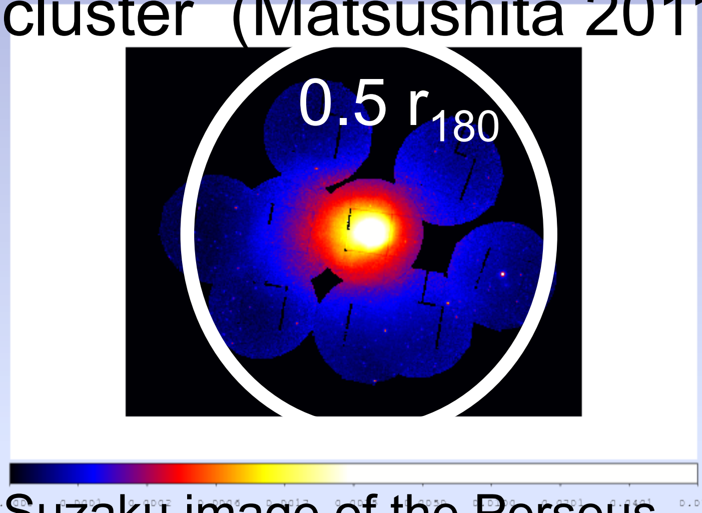


IMLR (M_{Fe}/L_K) of the Perseus clusters out to the virial radius (Sakuma et al. in prep)

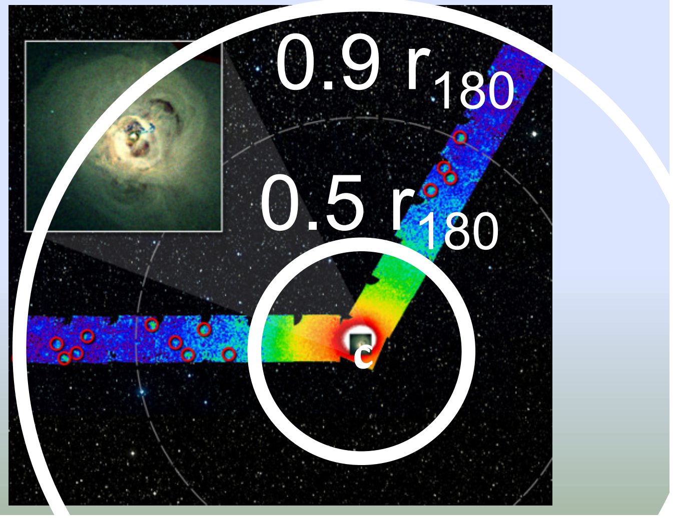
- We calculated the IMLR of the Perseus cluster up to 0.9 r_{180} using XMM and Suzaku results (Matsushita 2011,Simionescu+2011).



XMM image of the Perseus cluster (Matsushita 2011)

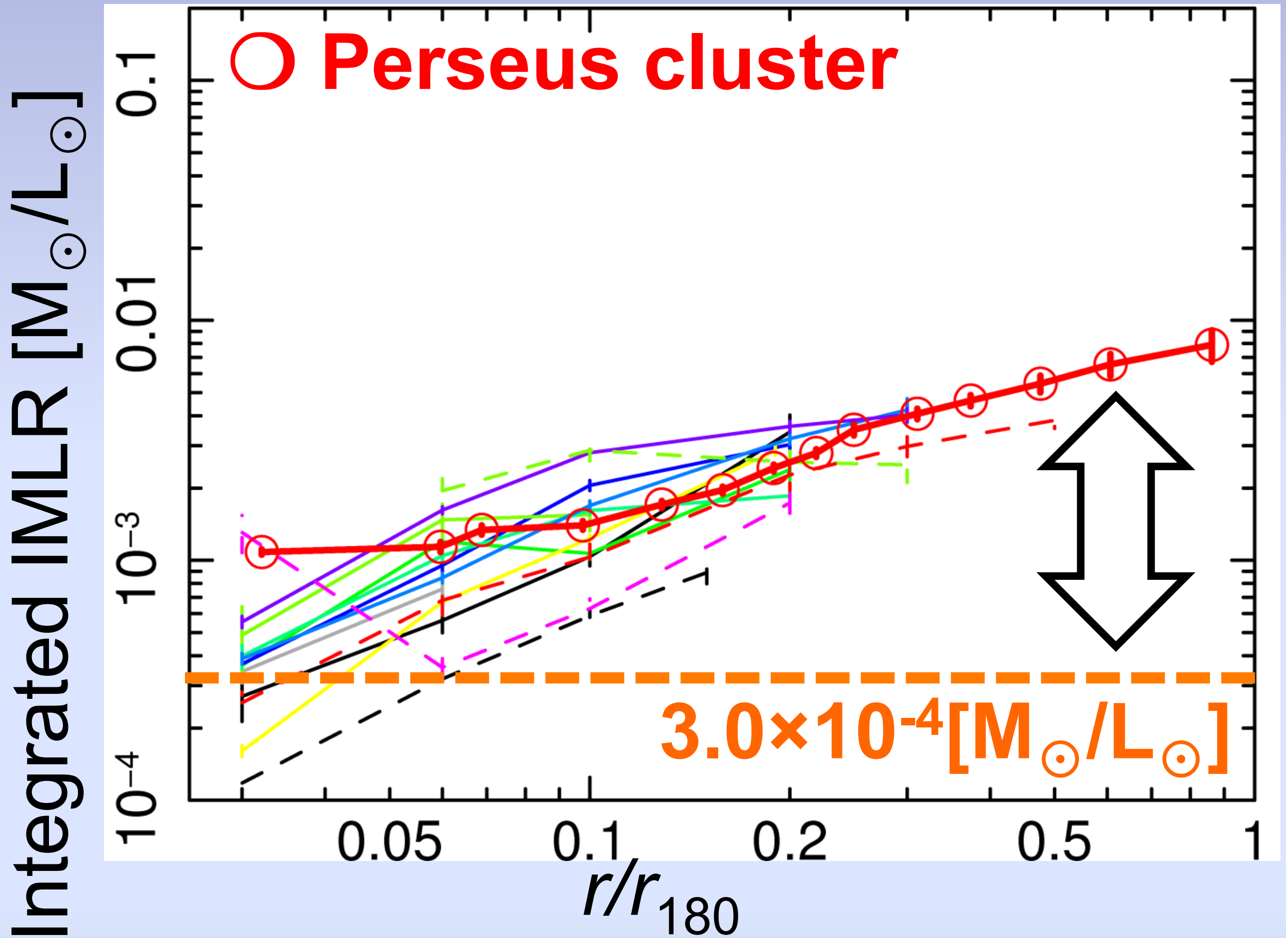


Suzaku image of the Perseus cluster (Simionescu+2011)



Iron supplied by SN Ia over the Hubble time

We estimated the iron mass supplied by SN Ia over the Hubble time with the present SN Ia rate.

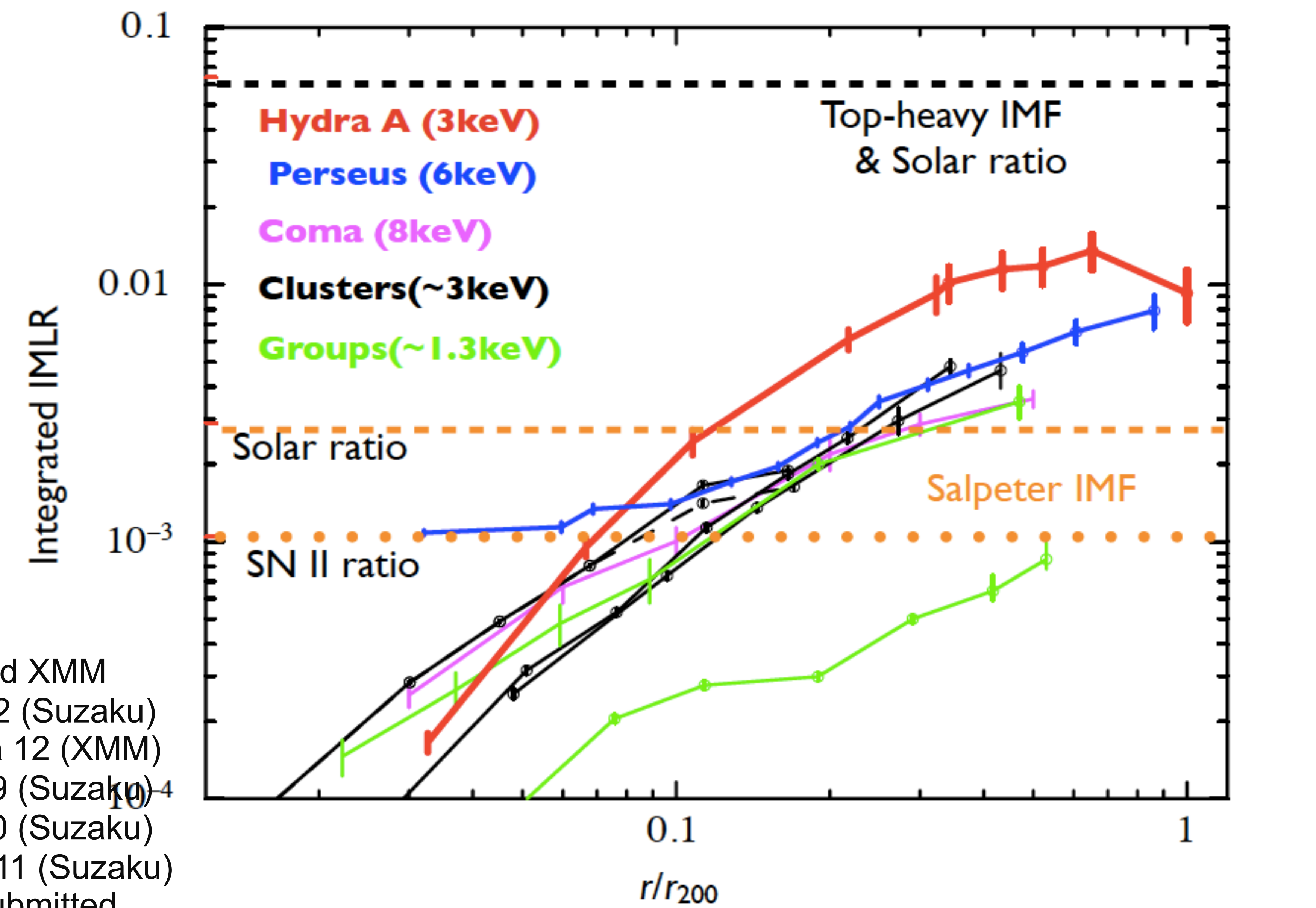


(present SN Ia rate) ×(Iron yield per SN Ia) ×(Hubble time)

⇒ **3.0×10^{-4} [$M_\odot$/$L_{K,\odot}$]**

The lack of iron indicates that Fe production rate was higher in the past.

Iron-Mass-to-light ratio out to the virial radius



Suzaku and XMM
Sato T. +12 (Suzaku)
Matsushita 12 (XMM)
Sato K+ 09 (Suzaku)
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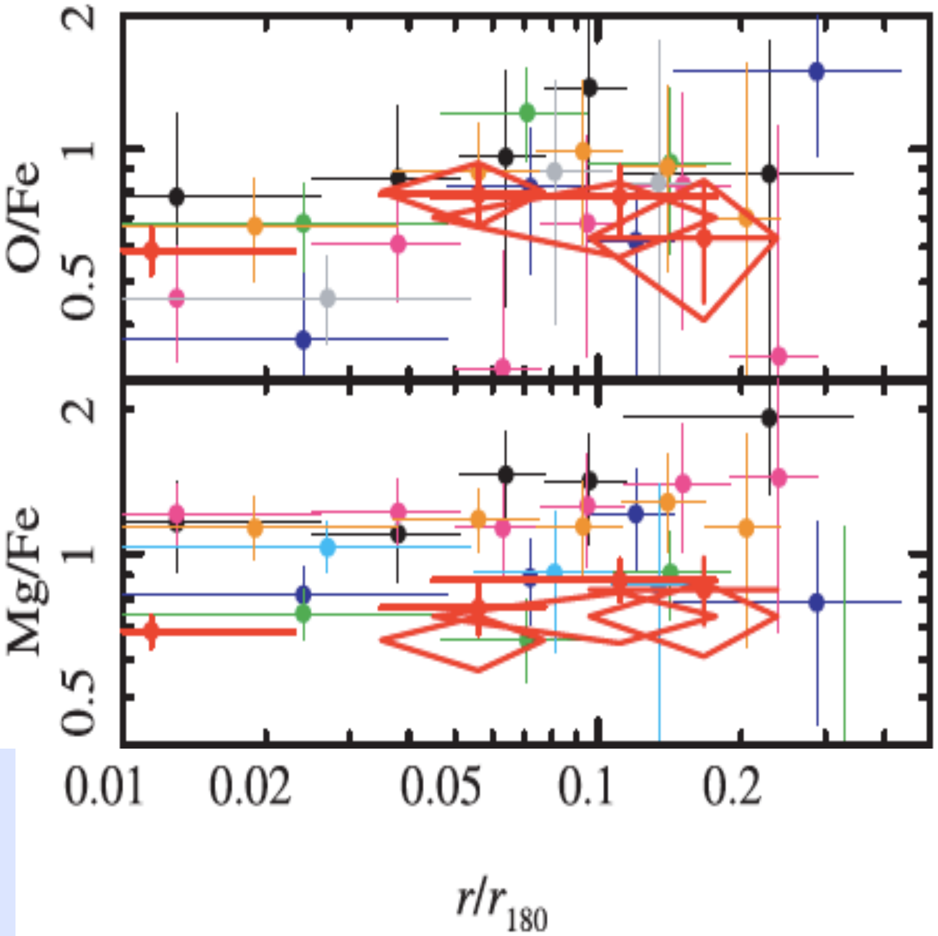
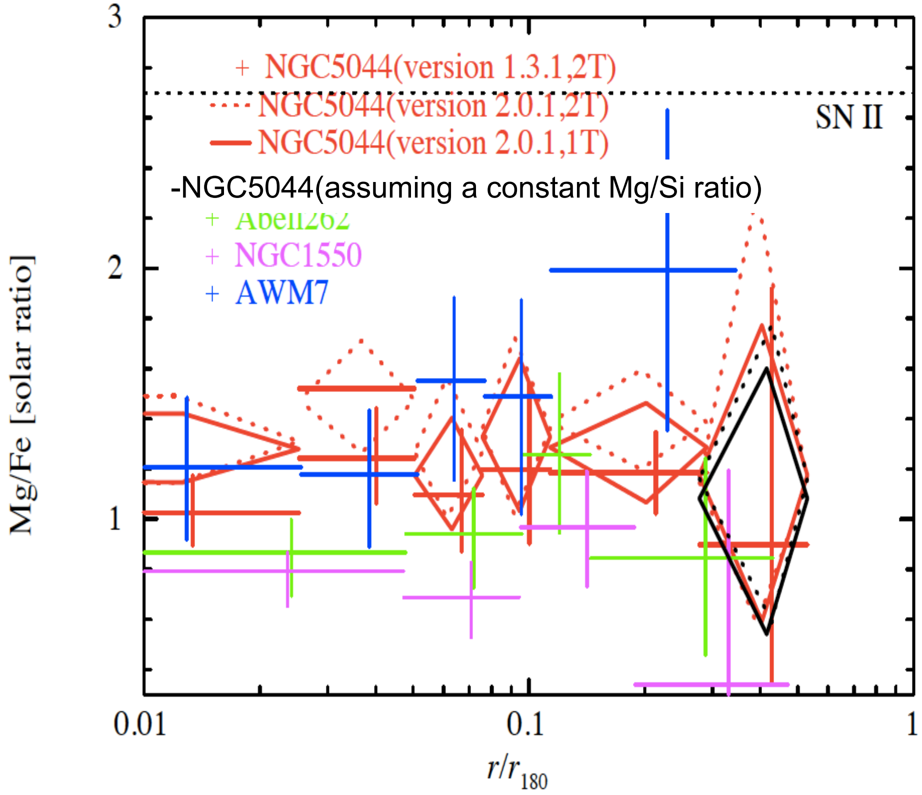
Sakuma +11 (Suzaku)
Sasaki+ submitted (Suzaku)

The radial profiles of O/Fe and Mg/Fe ratios





Murakami+11
Sasaki+ submitted

The α/Fe ratios are close to the solar ratio and show no significant radial gradient

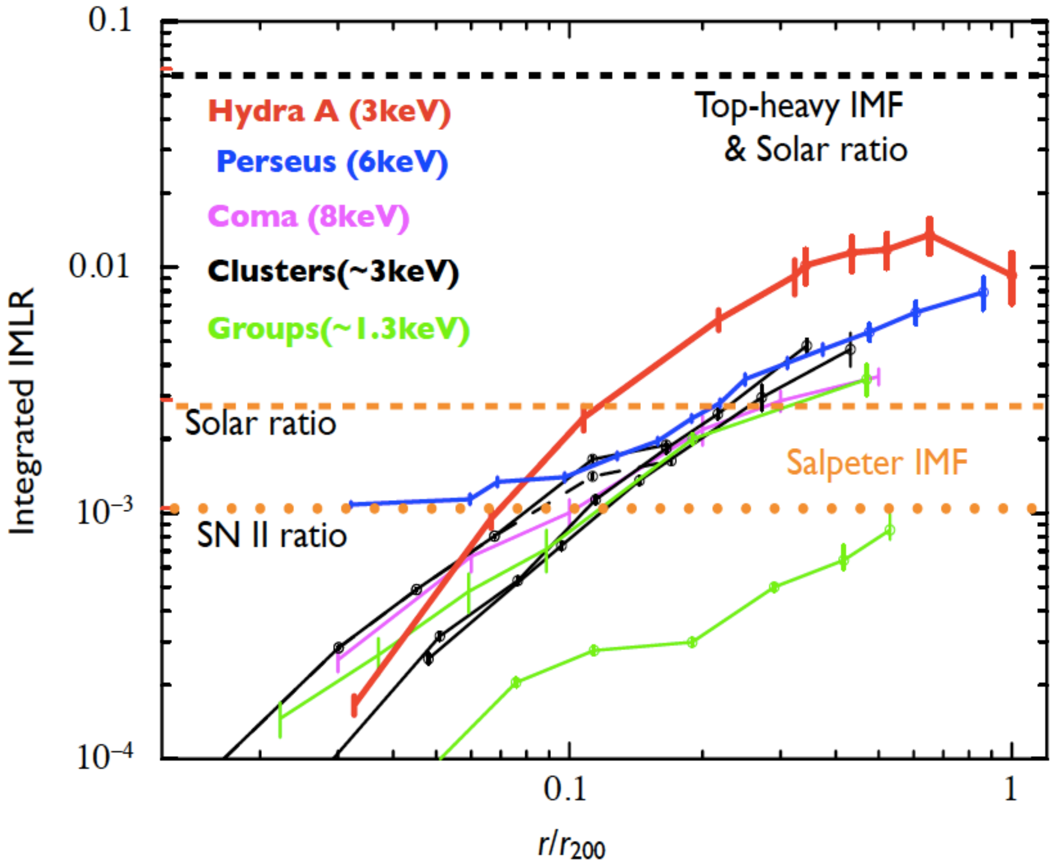
➔ Most of Fe are synthesized by SN Ia

Iron-mass-to-light ratio out to the virial radius

Assuming the solar O/Fe ratio up to r180, 10-30% of Fe come from SN II

Then, the IMLR out to r180 of the two clusters are smaller than the expectation by top-heavy IMF

If cluster outskirts have SN II like abundance pattern, the IMF should be flatter

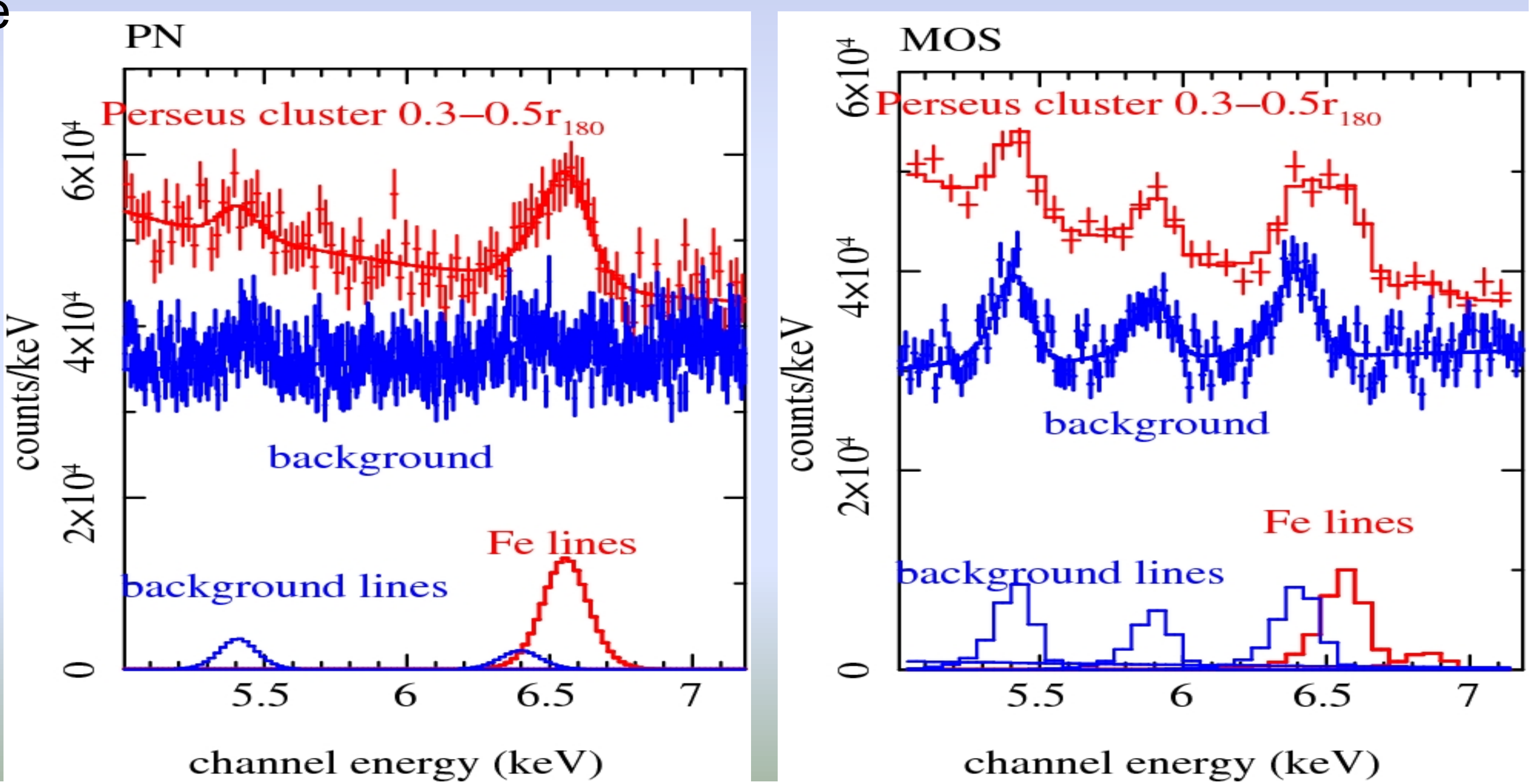


To detect O lines from ICM up to virial radius, we need Dios

Fe abundance of the ICM in 28 nearby clusters with XMM z<0.08

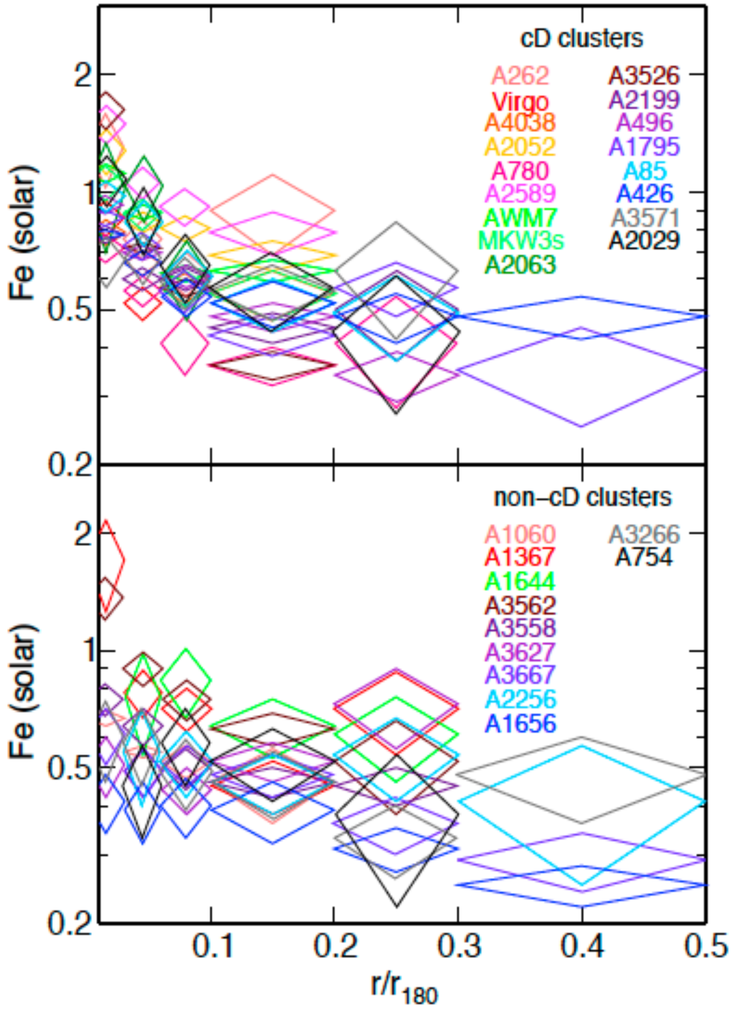
Matsushita 2011

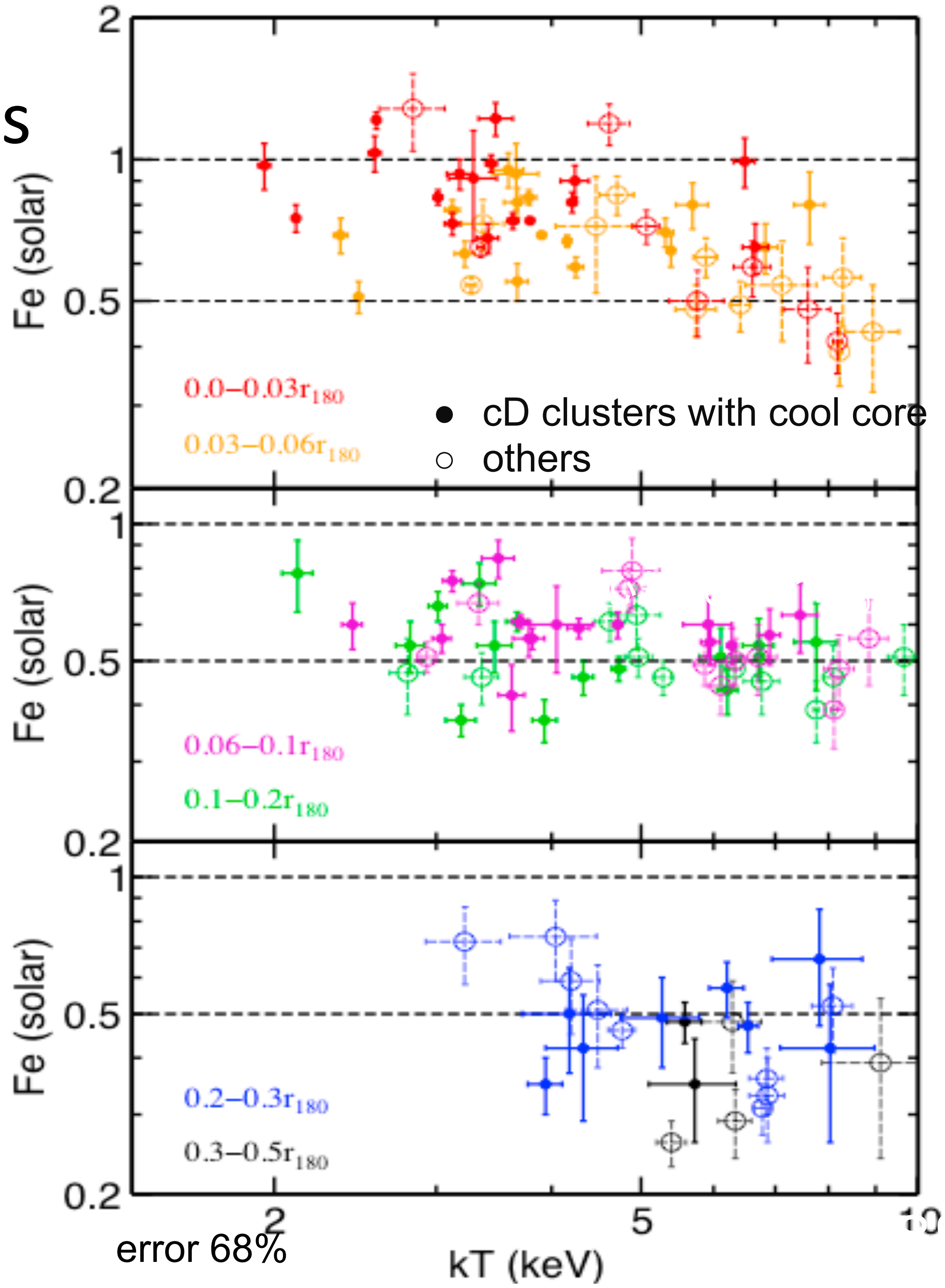
We derived Fe abundances from the flux ratios of Fe lines to the continuum within an energy range of 3.5–6 keV to minimize and evaluate systematic uncertainties due to background and temperature structure



Radial dependence of the Fe abundances

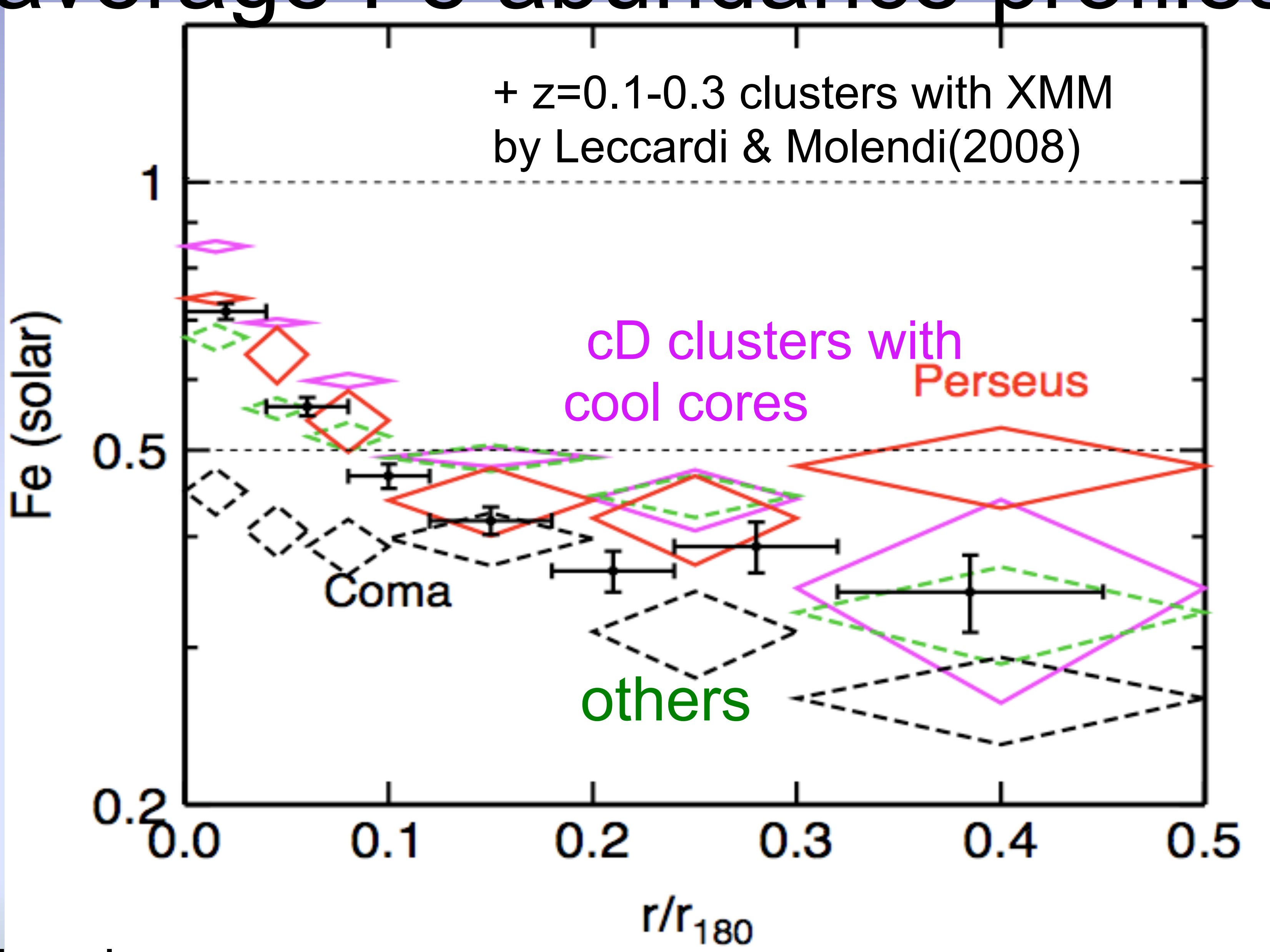
Fe abundances are derived from the flux ratios of He-like Fe line and the continuum





error 68%

The average Fe abundance profiles

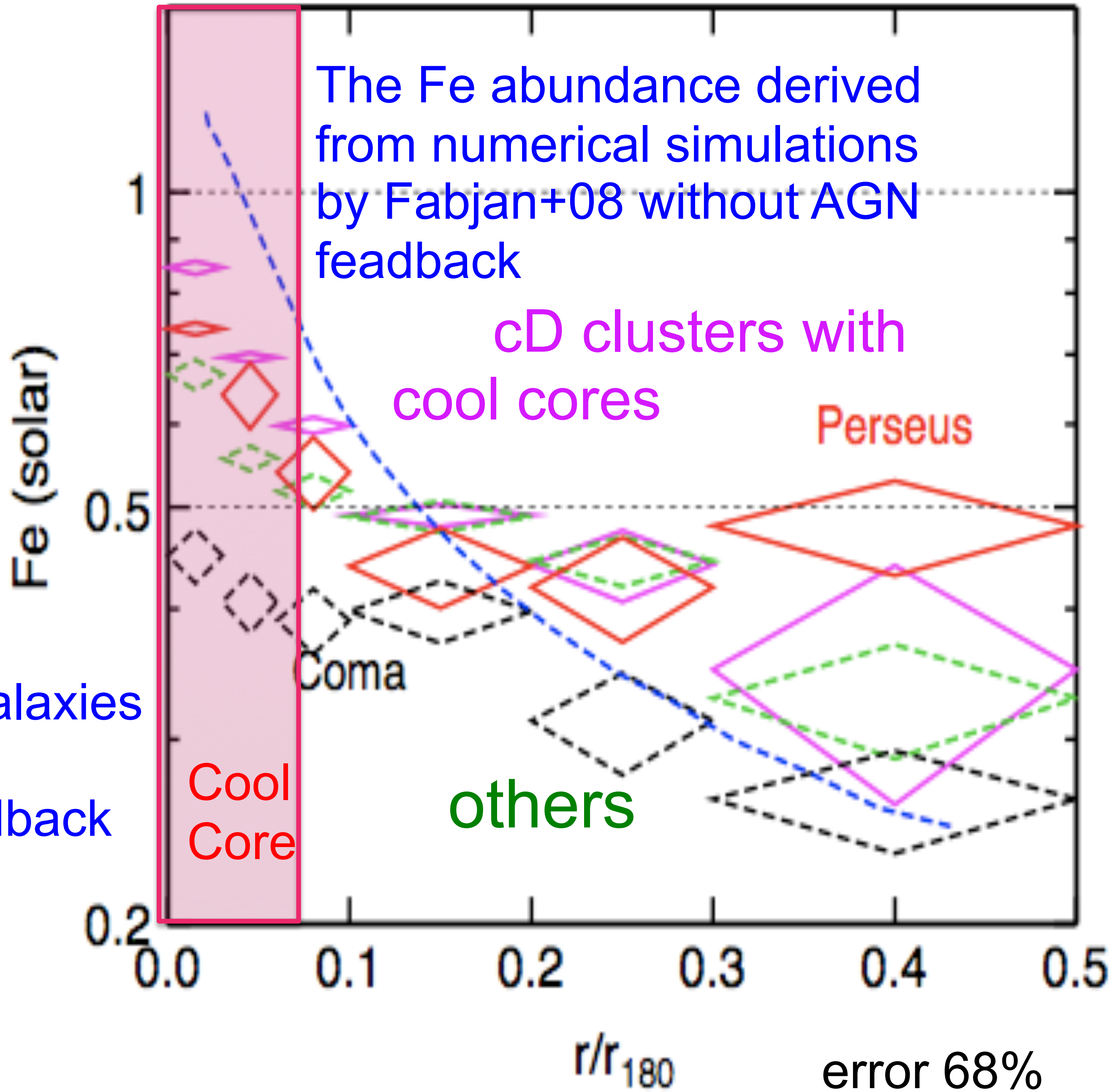


solar abundance:
Ioddars (2003)

error 68%

The average Fe abundance profiles

The observed flatter radial profile of the Fe abundance at 0.1-0.5r_{180} indicates early metal enrichment than numerical simulation



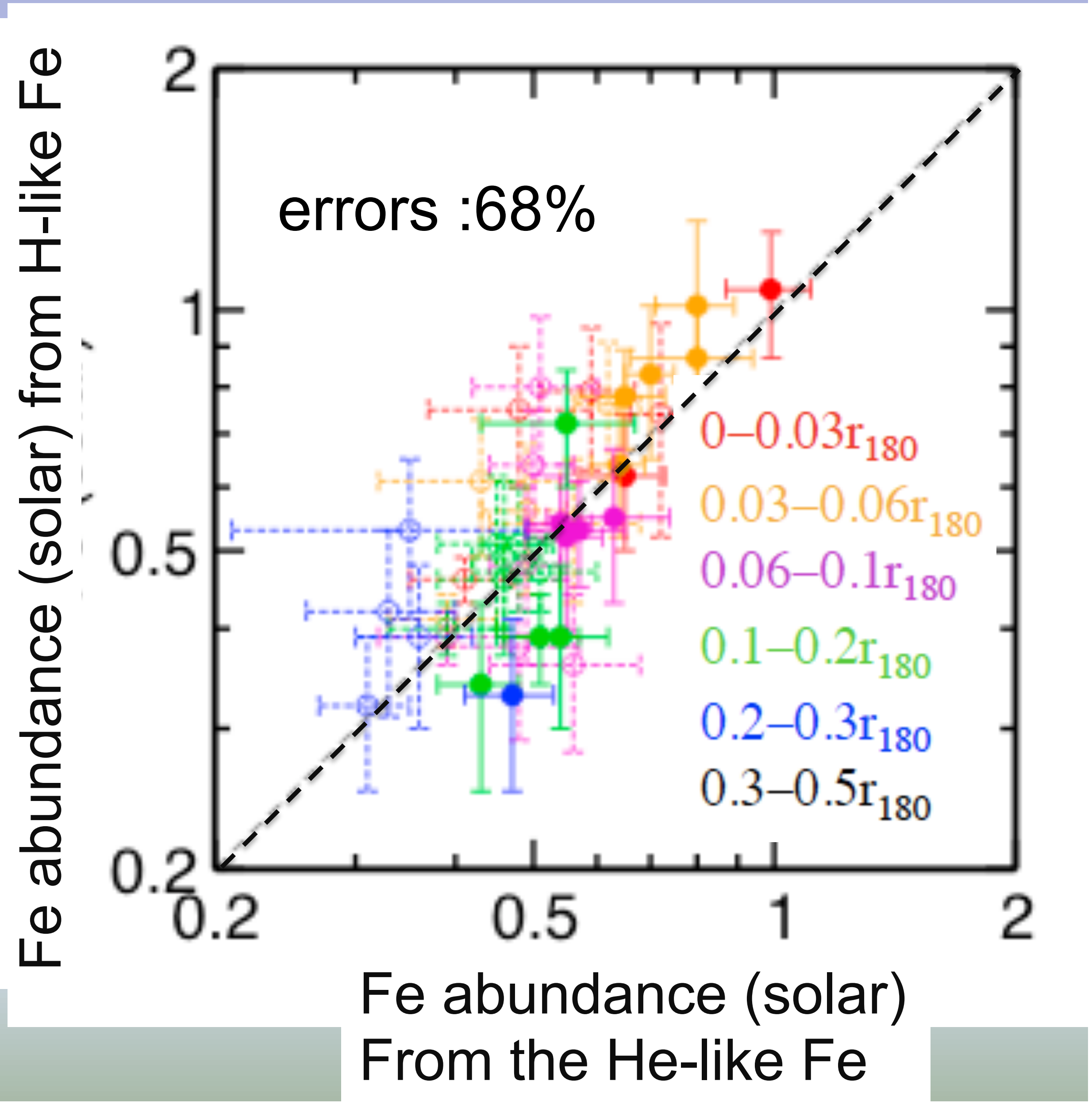
Within the cool cores, where metals from cD galaxies are important, processes like AGN feadback should be important

solar abundance: loddars (2003)

Systematic uncertainty in the Fe abundance He-like vs. H-like

He-like and H-like Fe lines give consistent Fe abundances

Small systematic uncertainty, since temperature dependences of the two lines are different



Metals outside core regions (0.05-0.5r_{180})

Metals mostly come from galaxies via past galactic wind at starburst and SN Ia When and how metals ejected into ICM?

Extended distribution of Fe than stars

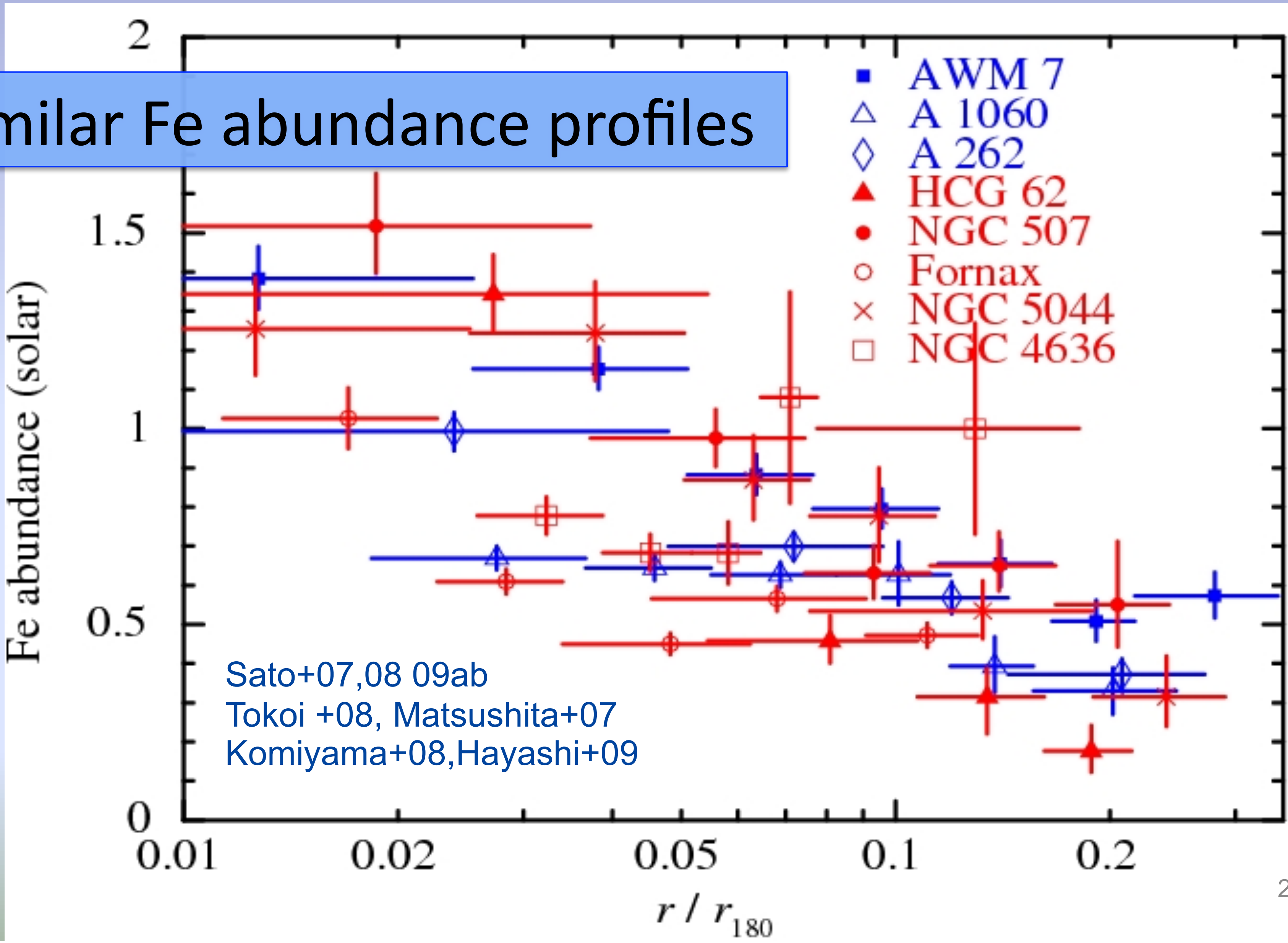
flatter Fe abundance profile at 0.1—0.5r_{180} than expected

O/Fe and Mg/Fe ratios are 1—1.5 solar ratio (<0.3r180)

- These results indicate that galaxies synthesized Fe in early phase in cluster formation and pollute the ICM before distributions of galaxies became more centrally peaked than ICM (at present ICM is more extended than stars)
- O Mass to light ratio is sensitive to IMF of stars
- Fe mass to light ratio out to r_{180}

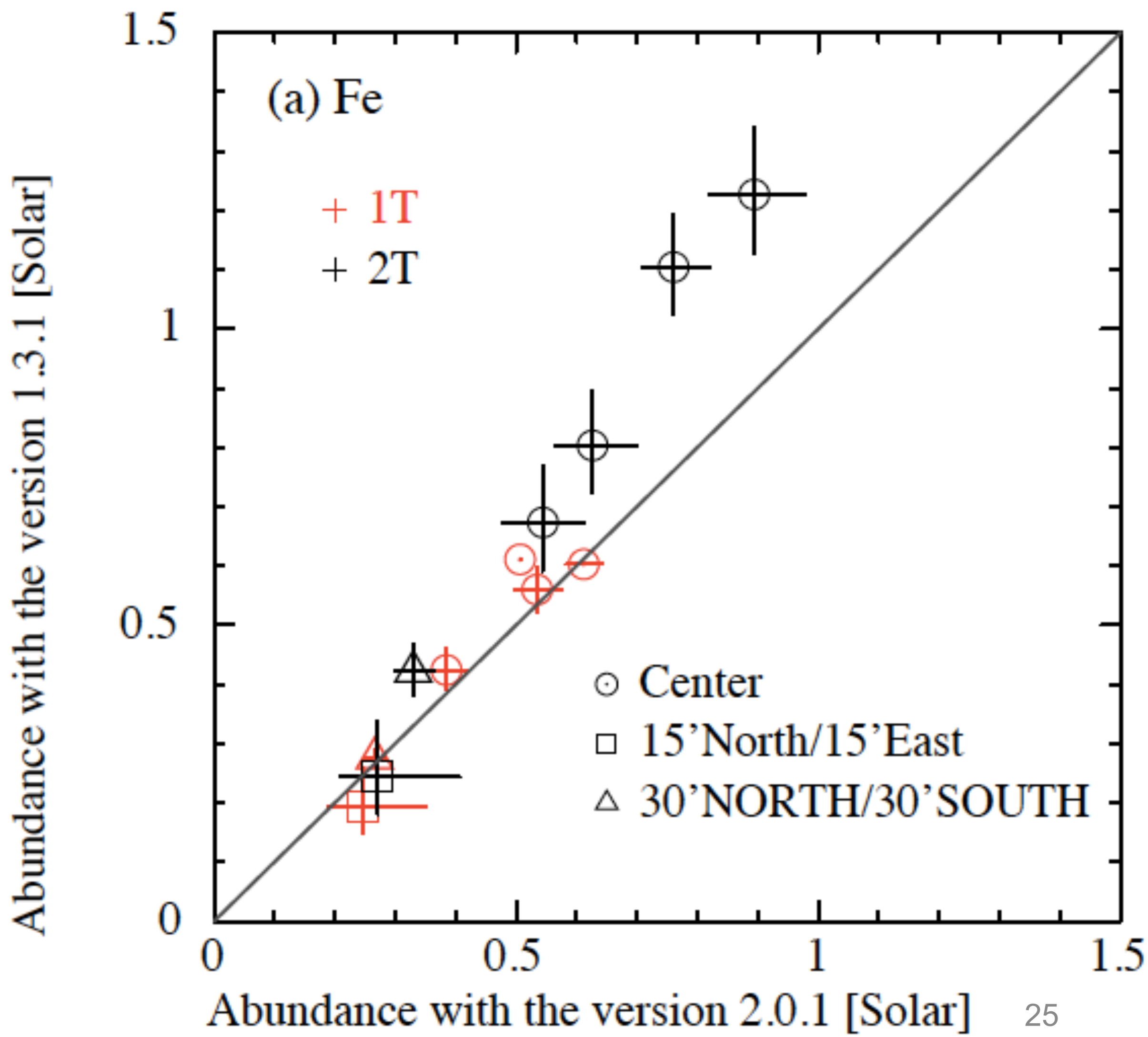
Suzaku observations of Fe abundance profiles of ICM in clusters and groups

similar Fe abundance profiles



Comparison of the derived Fe abundances with APEC v1.3.1 and v2.0.1

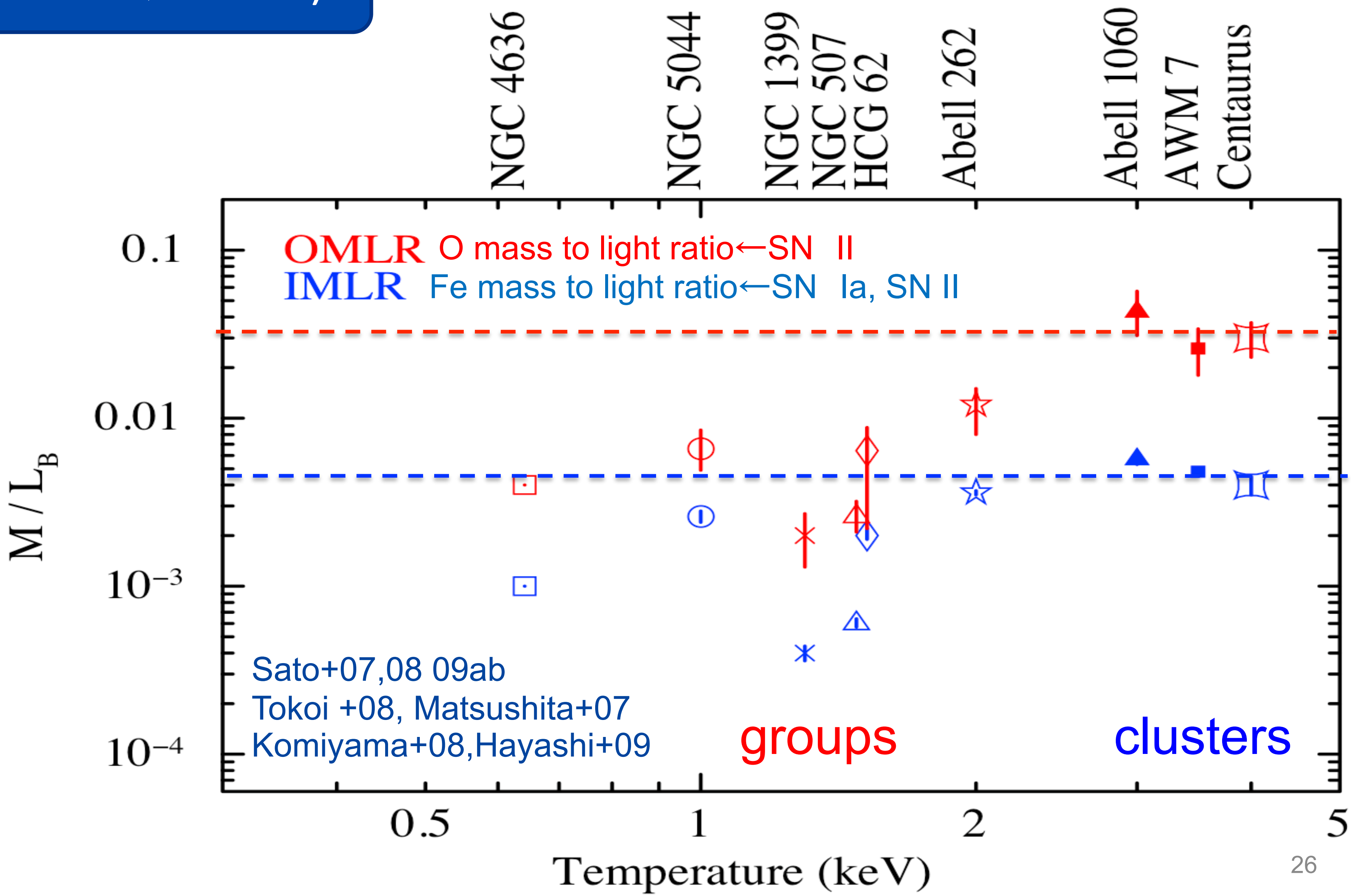
- The NGC 5044 group (Sasaki + submitted)
- The Fe abundances were derived from Fe-L lines
- Using 2T model fits, the Fe abundances strongly depend on the atomic data



Metal mass to light ratio

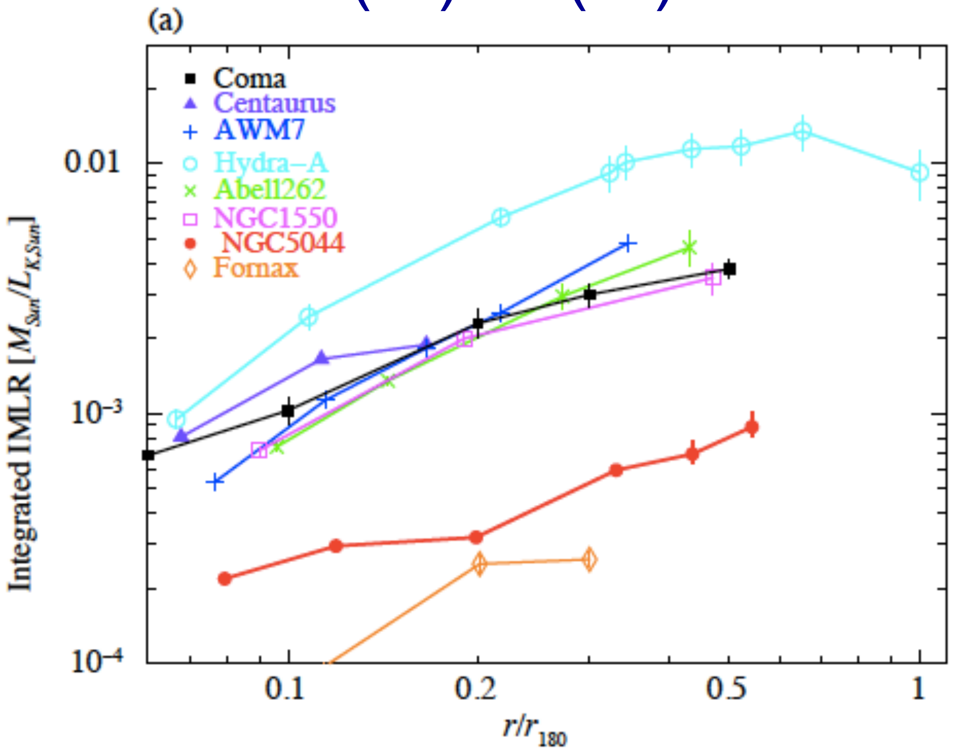
Mainly low mass stars

Suzaku (<0.1r180)

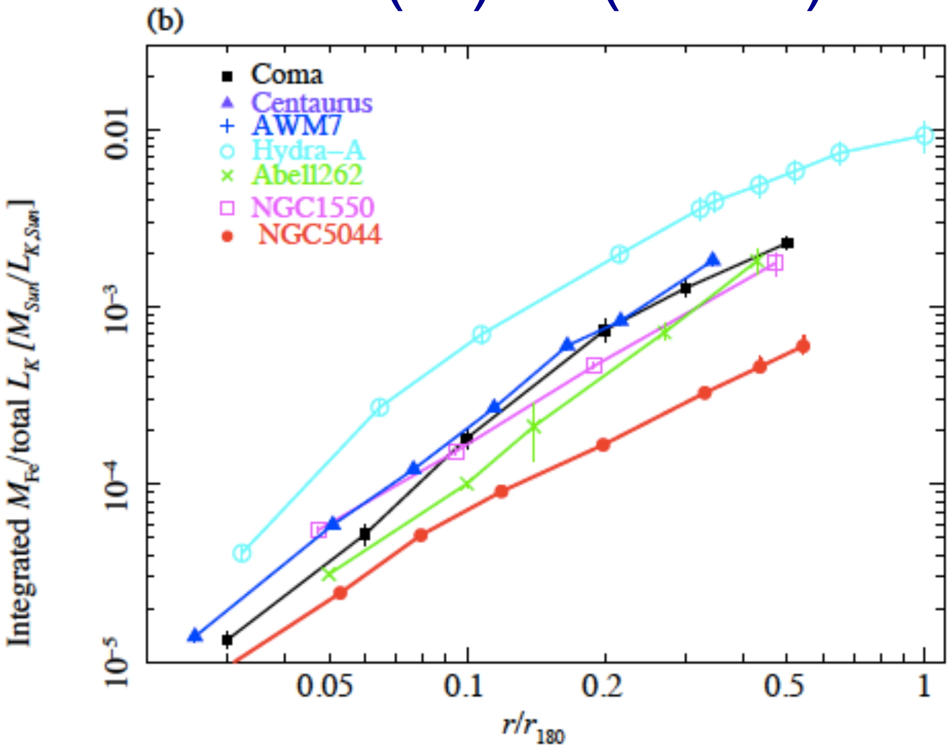


Iron-Mass-to-light ratio out to the virial radius

MFe(<r)/LK(<r)



MFe(<r)/LK(<r180)



Suzaku and XMM
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Sakuma +11 (Suzaku)
Sasaki+ submitted (Suzaku)

- Smaller scatter

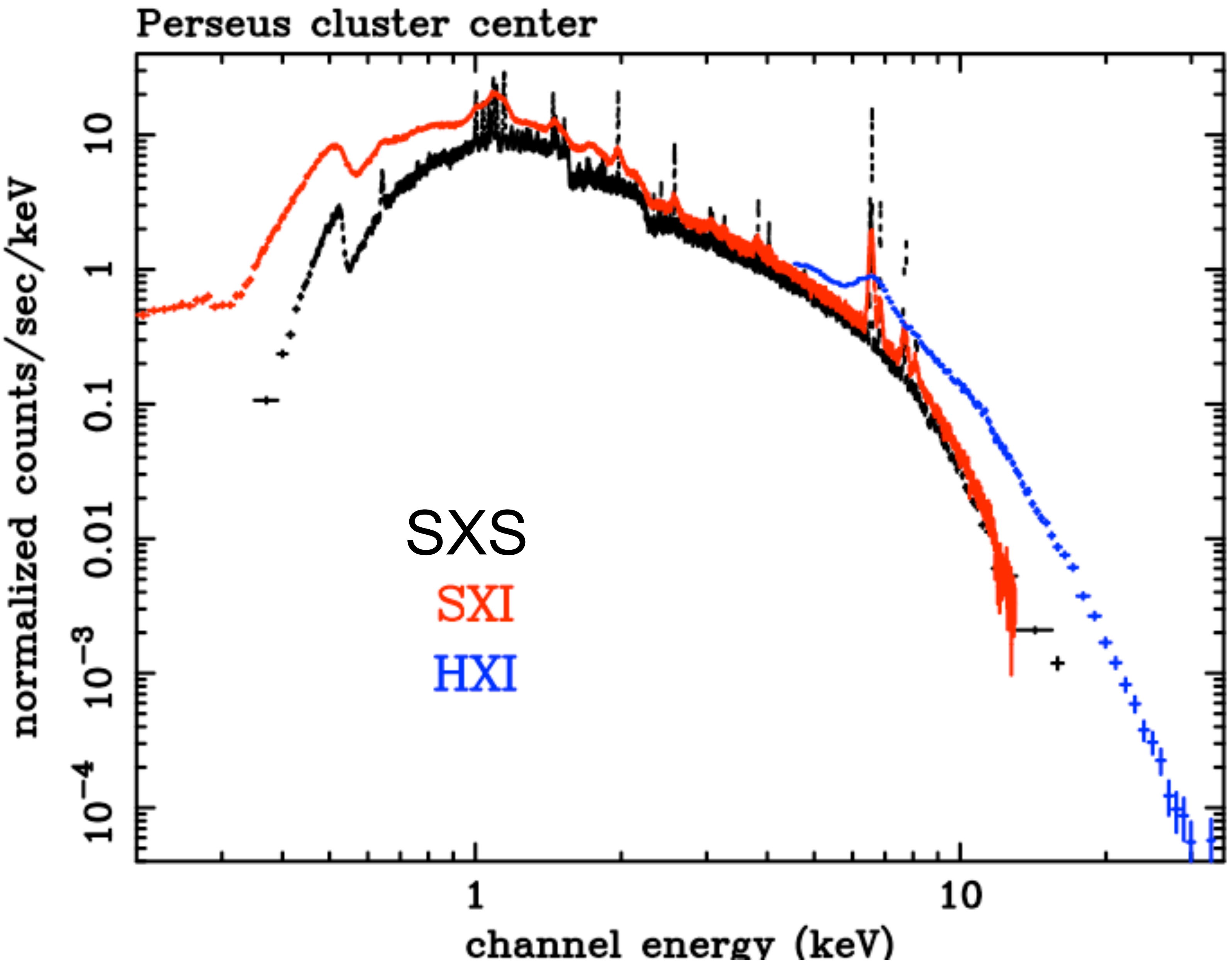
Groups vs. clusters

similar Fe abundance profiles up to $0.3r_{180}$

The observed metal mass-to-ratio are smaller in groups and poor clusters reflecting that gas fraction is smaller in groups

- difference in star formation history?
- same star formation history but difference in the effect of feedback?

Perseus cluster (r<2') with Astro-H
vapec (0.6keV, 2.6keV, 6.1keV)



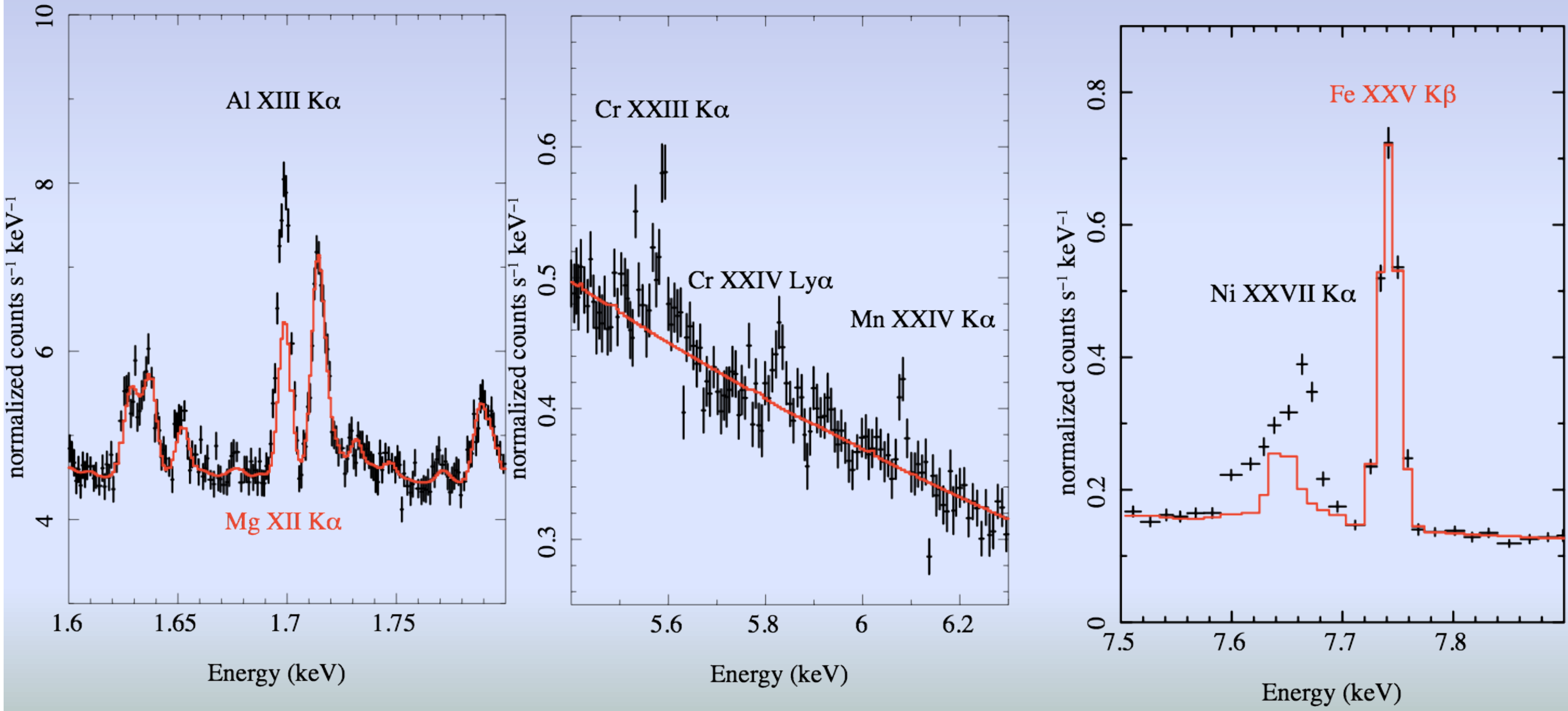
The center of the Perseus cluster with ASTRO-H

200 ks, assuming 300km/s turbulence

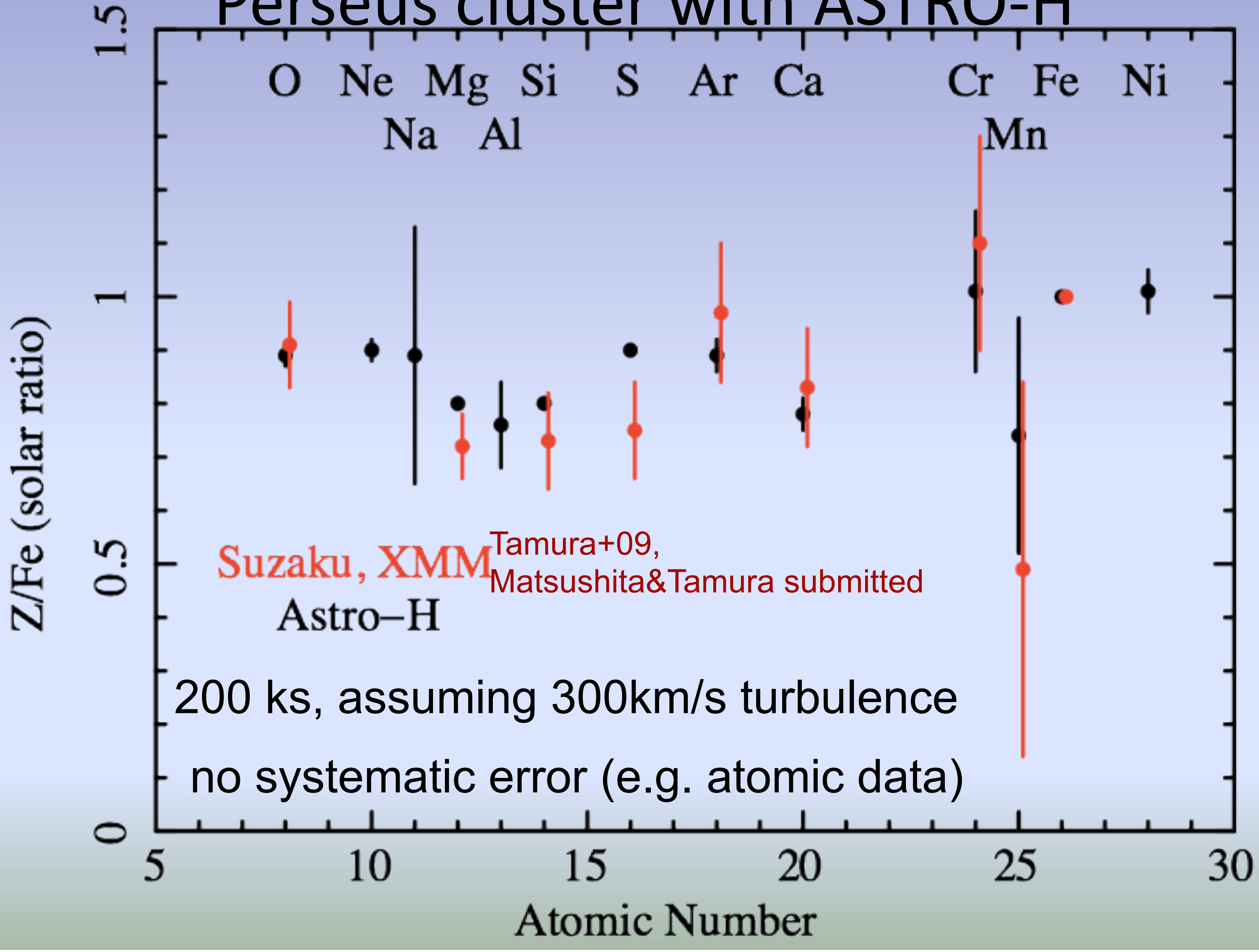
Al

Cr, Mn

Ni, Fe Kβ



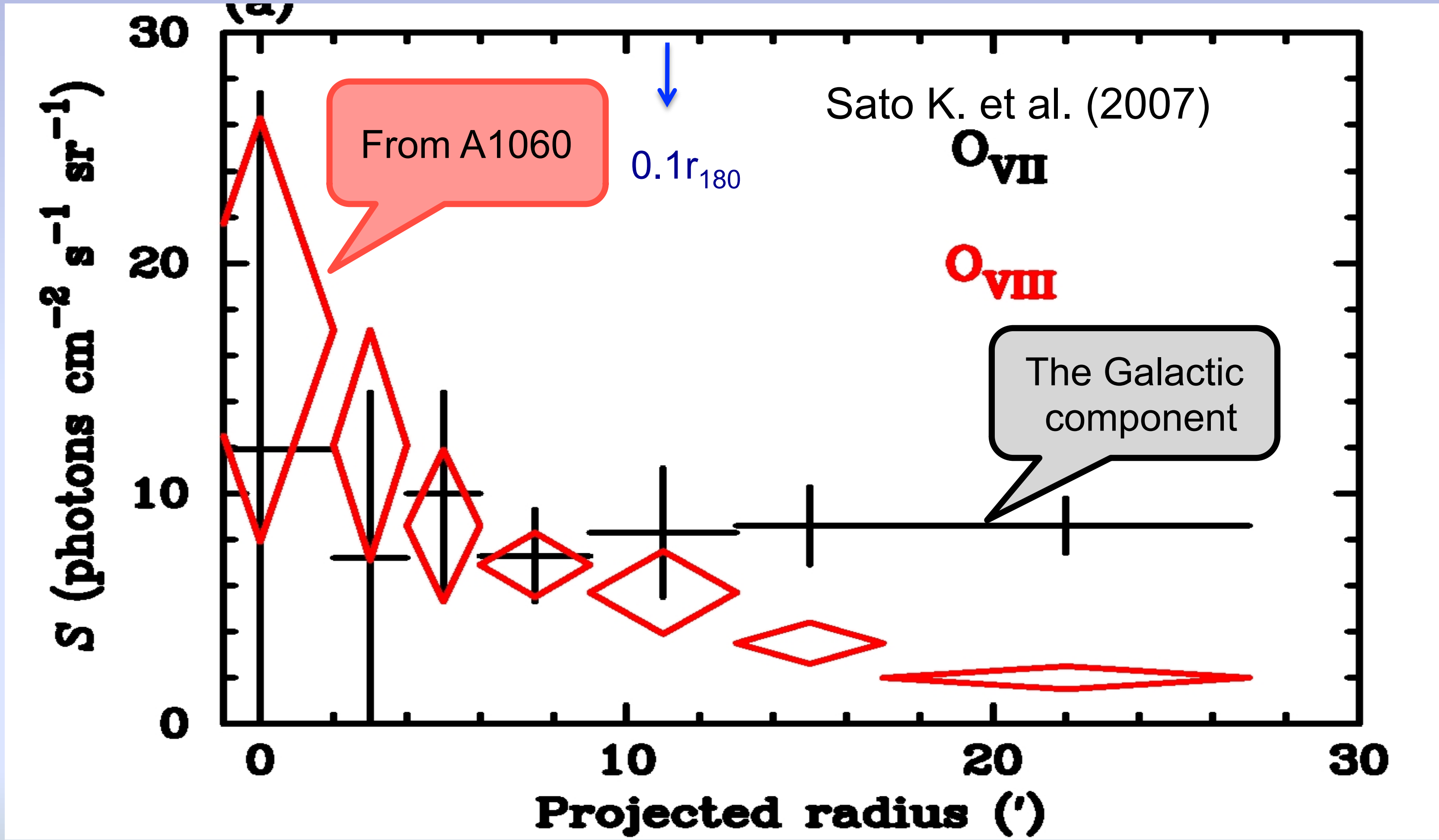
Abundance pattern of the center of the Perseus cluster with ASTRO-H



The effect of the Galactic emission

Surface brightness of OVII, OVII lines of A1060 cluster

A sum of the cluster emission and the Galactic emission

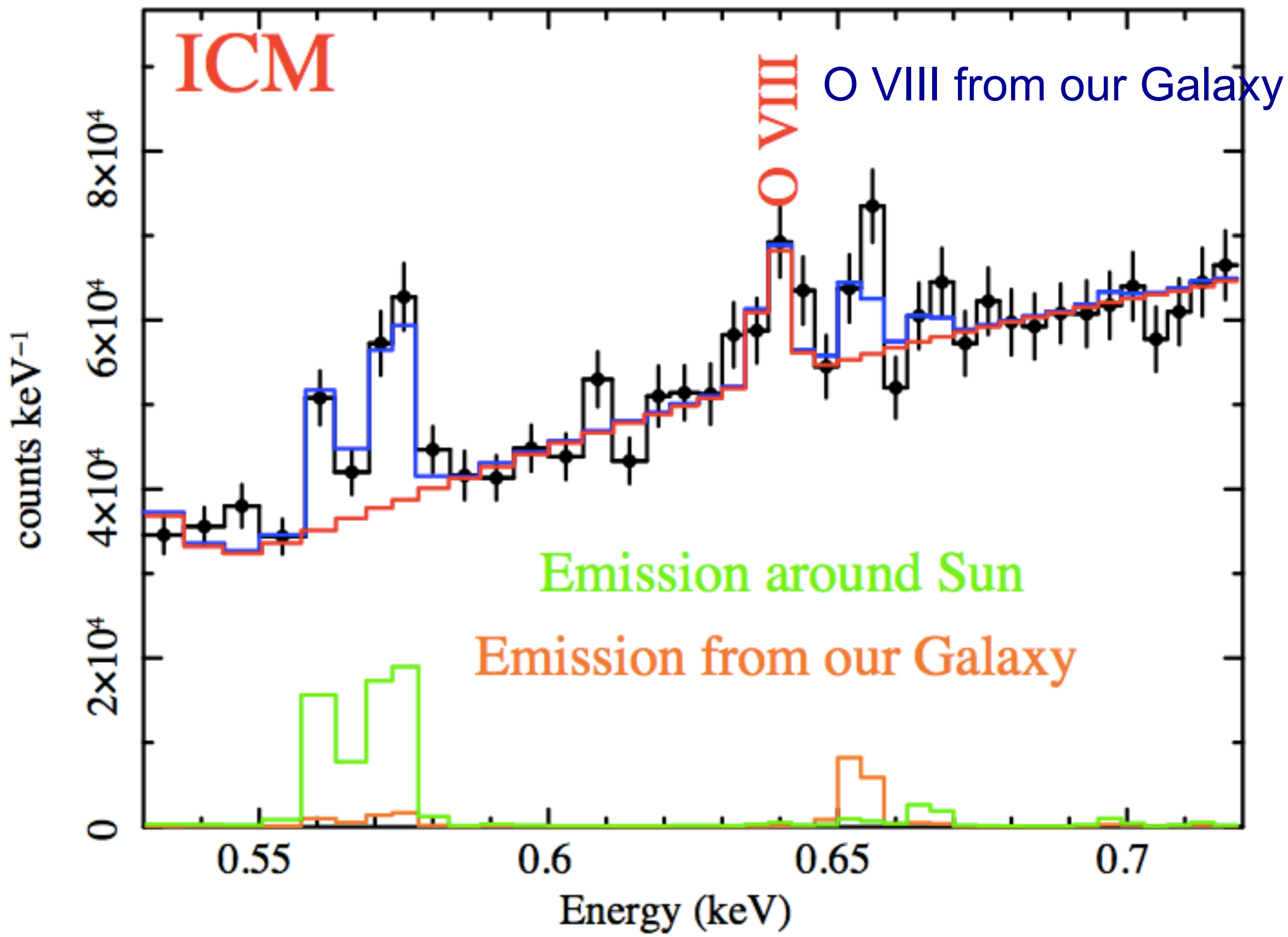


The next japanese X-ray satellite, ASTRO-H or DIOS will be able to distinguish O lines from clusters using redshift information

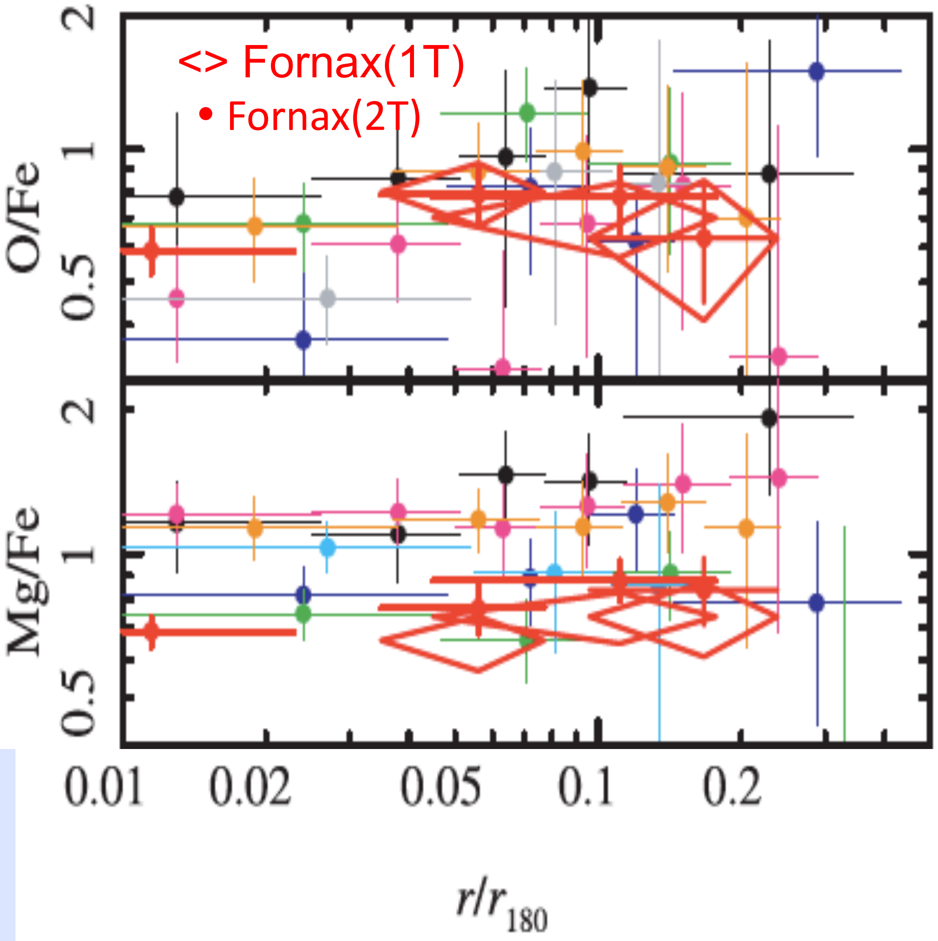
O measurement with Astro-H

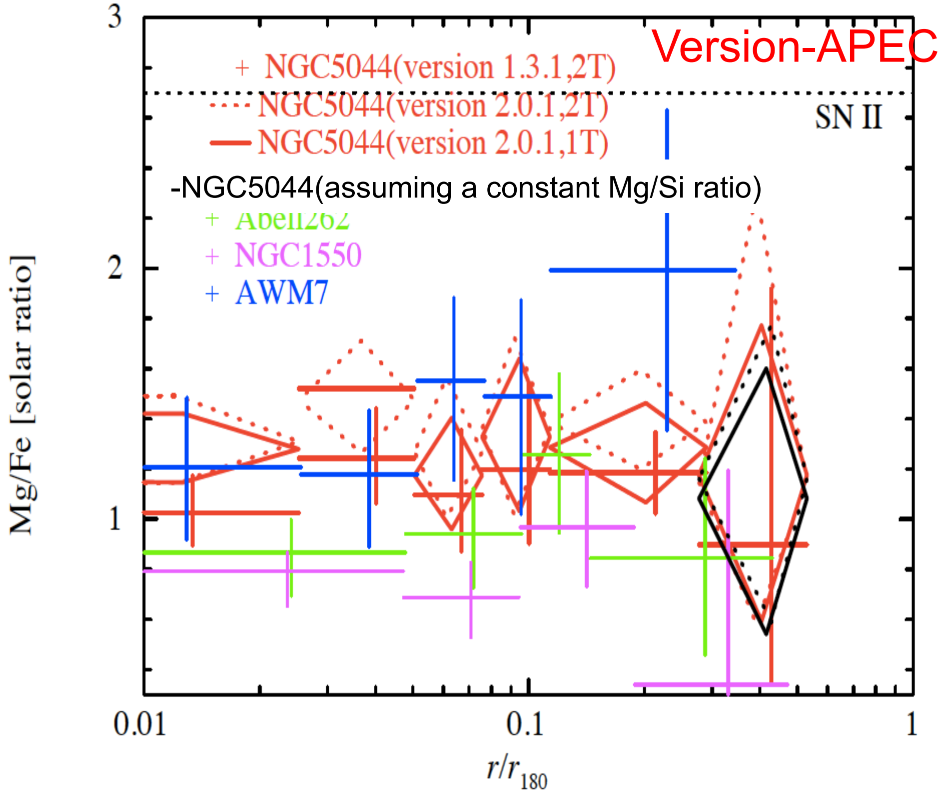
- We will be able to detect the O VIII line from the Coma cluster (kT=8 keV, redshift=0.02), one of the hottest cluster.

An expected spectrum of the central region of the Coma cluster (with an 200 ks exposure)



The radial profiles of O/Fe and Mg/Fe ratios





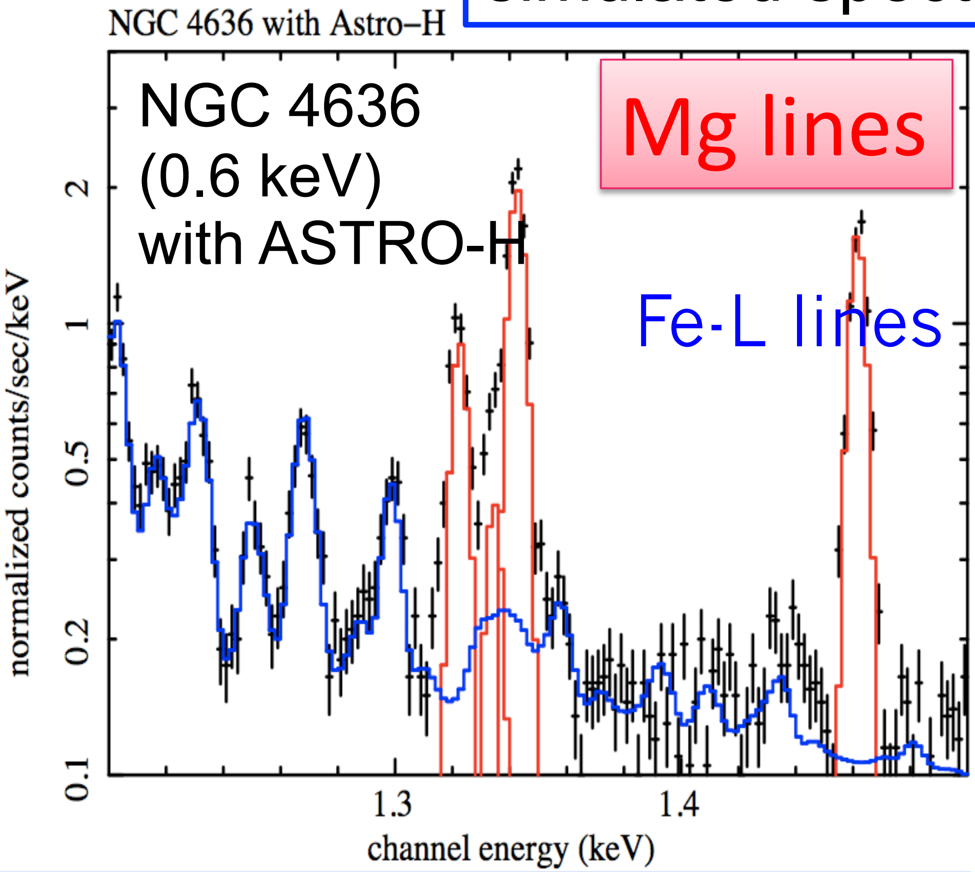
Murakami+11
Sasaki+ submitted

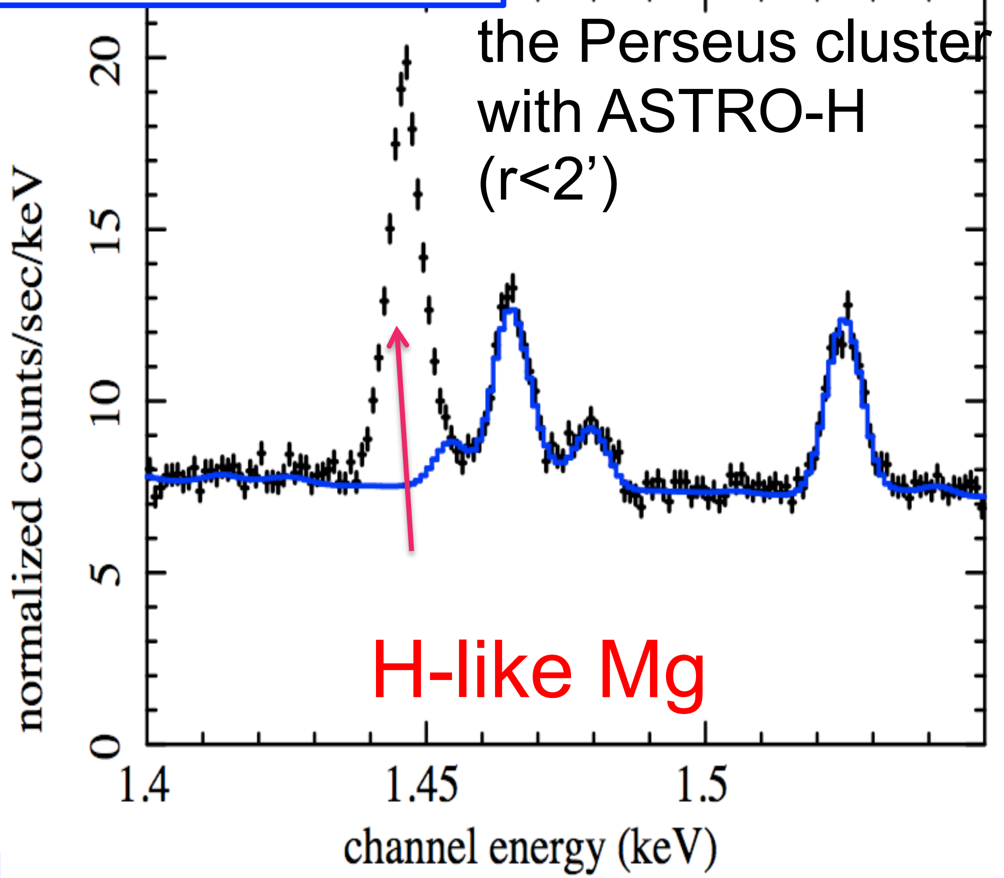
- Outside cool cores, the O/Fe and Mg/Fe ratios show no significant radial dependence
- The scatter in the Mg/Fe ratios – caused by systematic uncertainties in the Fe-L atomic data? Or real dependence on cluster properties?

Systematic uncertainty in determining the Mg abundance

Fe-L lines around Mg lines – ASTRO-H

simulated spectra with Astro_H





Mg Kα lines are free from Fe-L lines

Triplets of He-like Kα will be detected

Summary

Abundance pattern from O to Fe of the ICM outside cool core is close to that of the new solar abundance by Loddars (2003)

- 80% of Fe come from SN Ia

Early formation of metals in Intracluster Medium (ICM)

- Fe is more extended than stars
- Relatively flat Fe abundance profiles

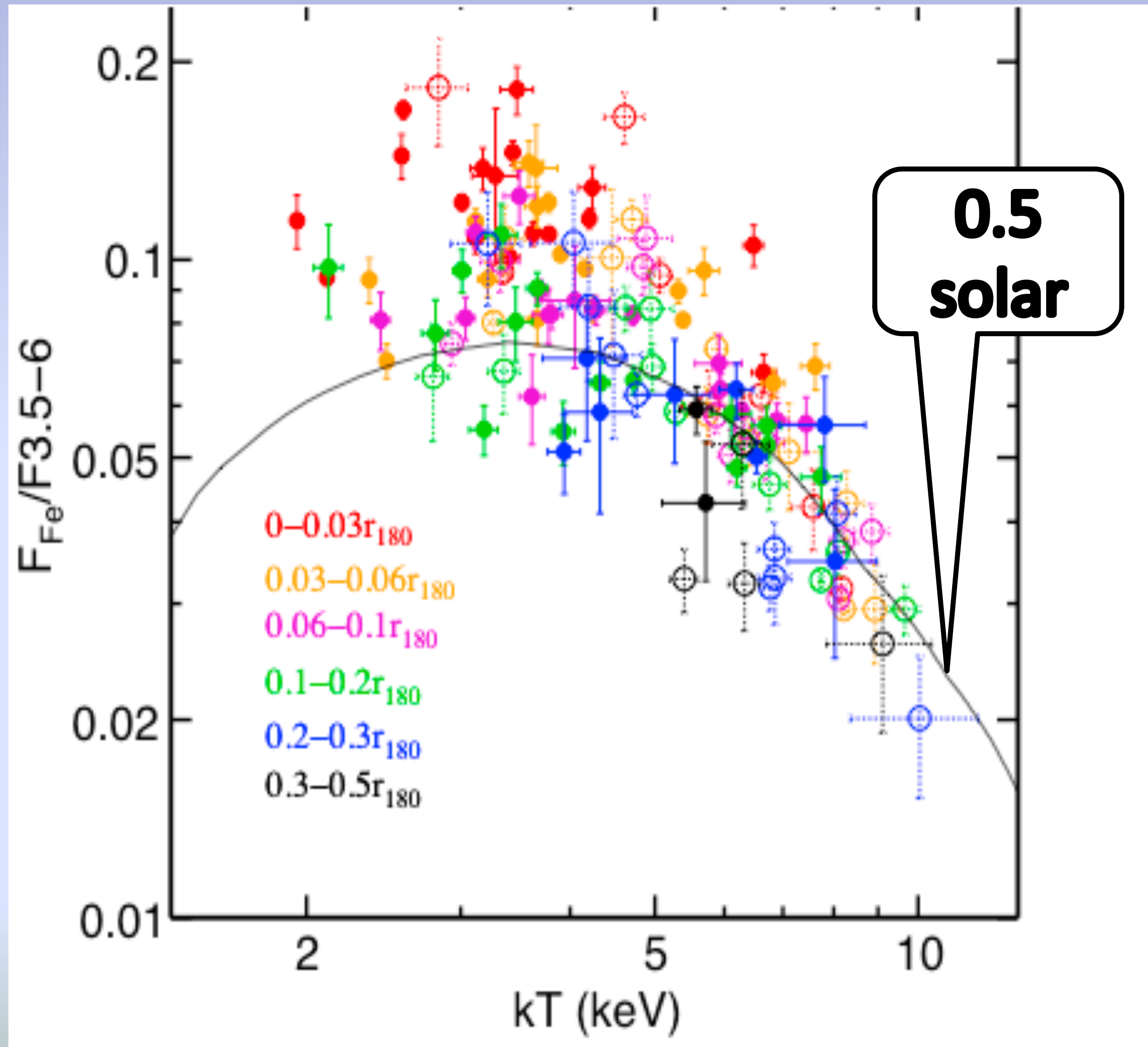
Future missions

- rare metals with Astro-H
- metals in clusters up to the virial radius with DIOS or another satellite for WHIM detection

Flux ratio of the He-like Fe line and continuum(3.5-6keV)

Dependence of the ratio on the plasma temperature is rather weak within 20% of 2-6 keV.

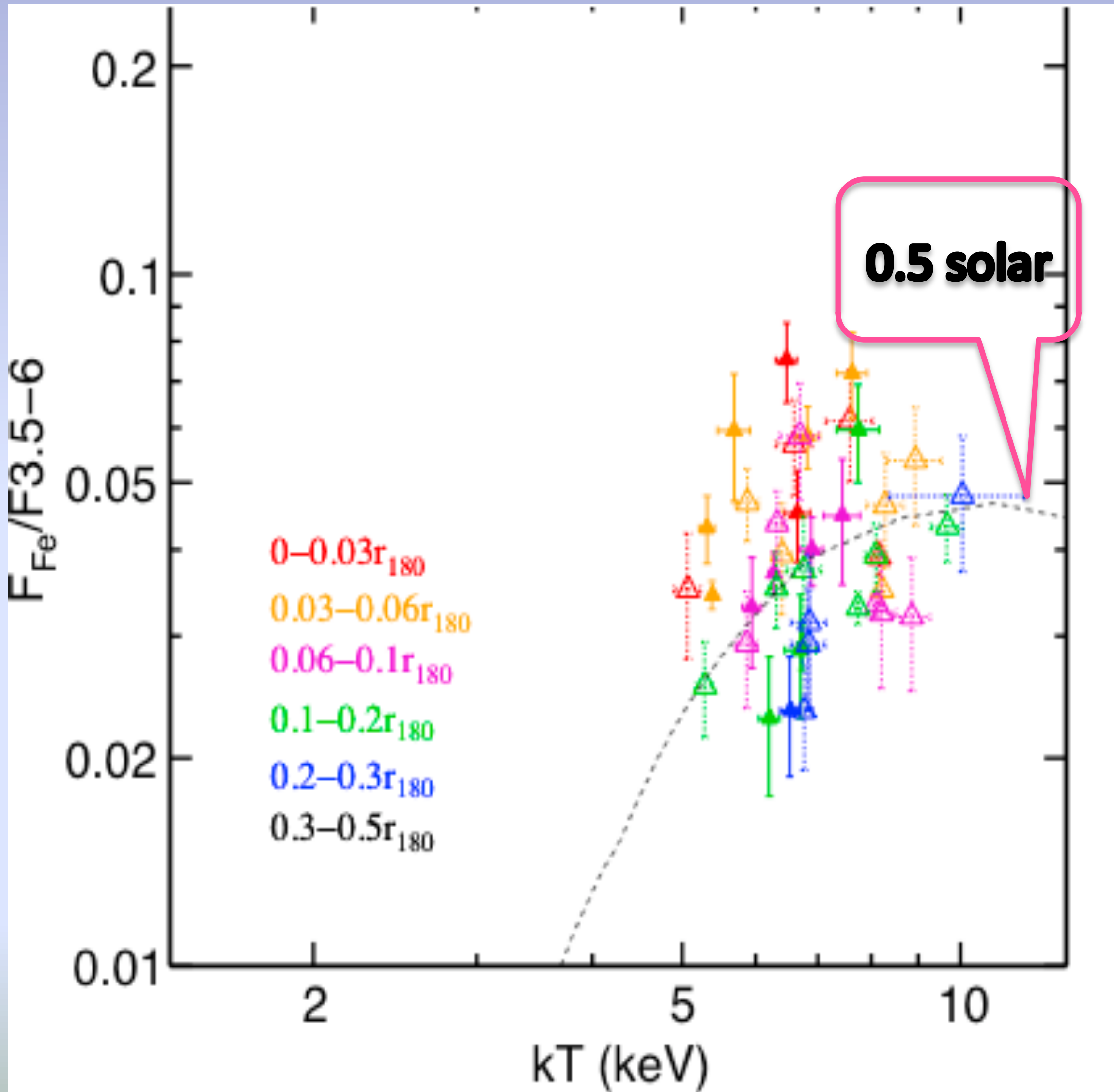
Below 6 kev, the uncertainty in the Fe abundance due to temperature structure is small



Flux ratio of the H-like Fe line and continuum(3.5-6keV)

Weak temperature dependence within 20% of 7-17 keV

The systematic uncertainty in the Fe abundance is smaller above 6 keV



systematic uncertainty in the Fe abundance: multi kT vs. single kT

Fe abundance derived from the flux ratio of the Fe lines and the continuum using best-fit multi-temperature model

$\Delta Fe = (Fe_{multi\ kT} - Fe_{singlekT})/Fe_{singlekT}$

≤10-20%

He-like < 5keV

H-like > 5keV

systematic uncertainty due to temperature sturcture is small