The oxygen abundance from X-rays : methods and prospects

K. Matsushita

Where are oxygen synthesized in stars?

- Hot intracluster medium (ICM)
- Warm-hot intergalactic medium?
- Hot interstellar medium in early-type galaxies

O Synthesis in our Galaxy

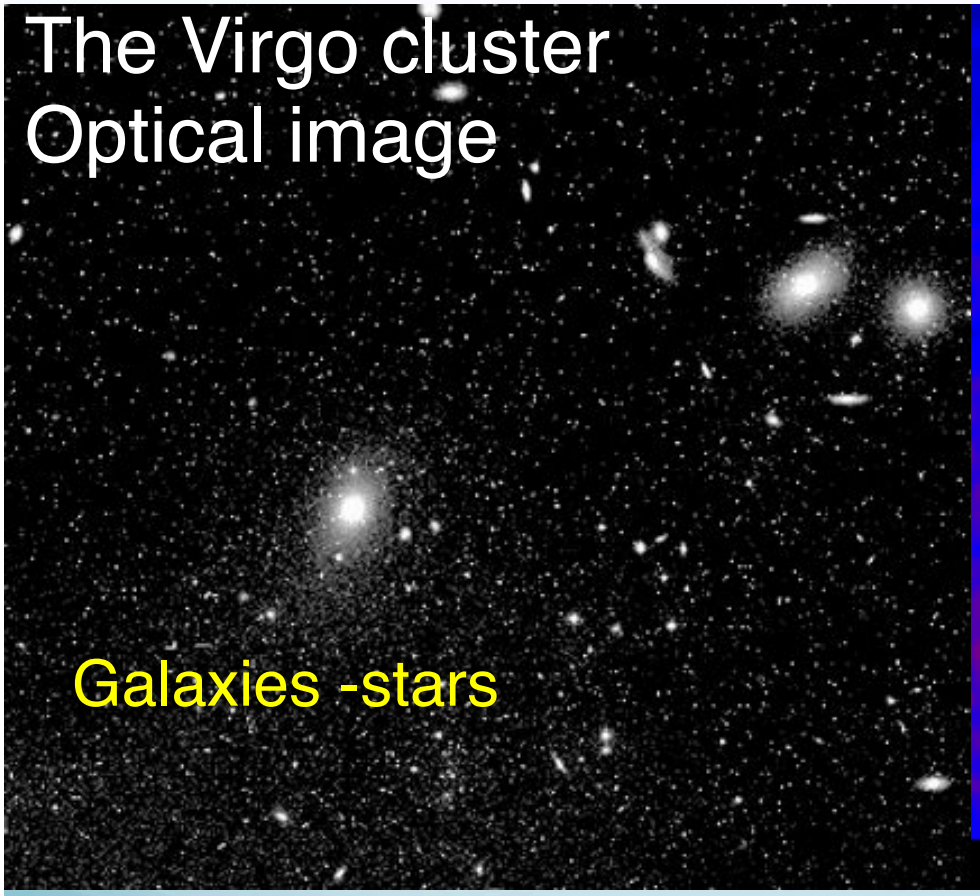
- Planetary nebulae
- Supernova remnant

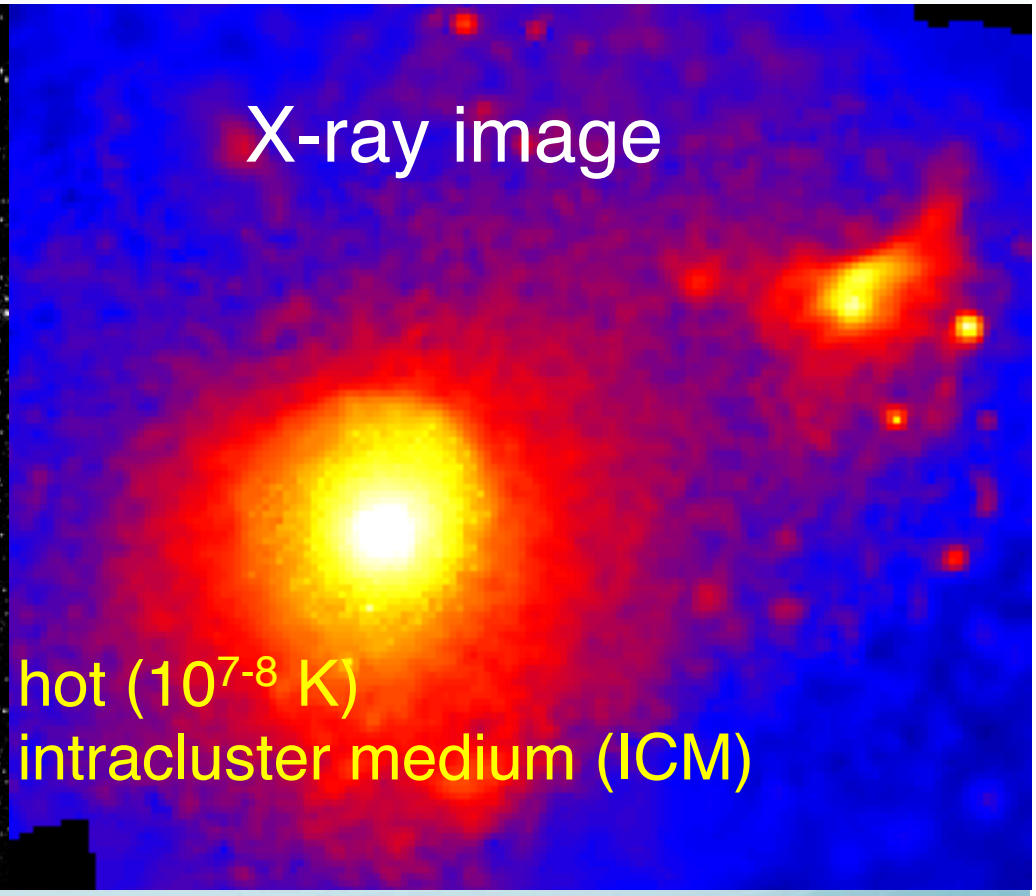
O in the intracluster medium (ICM)

- Metals in the intracluster medium
- Detection of O lines from intracluster medium
- O mass to light ratio and initial mass function
- Abundance pattern of O, Mg, Si, S and Fe
- Systematic uncertainties in O abundance measurements
- next Japanese X-ray satellite, Astro-H

Unless otherwise specified, we use APEC plasma code (Smith et al. 2001), Solar abundance table by Lodders (2003), errors are quoted at 90% confidence.

Metals in the intracluster medium





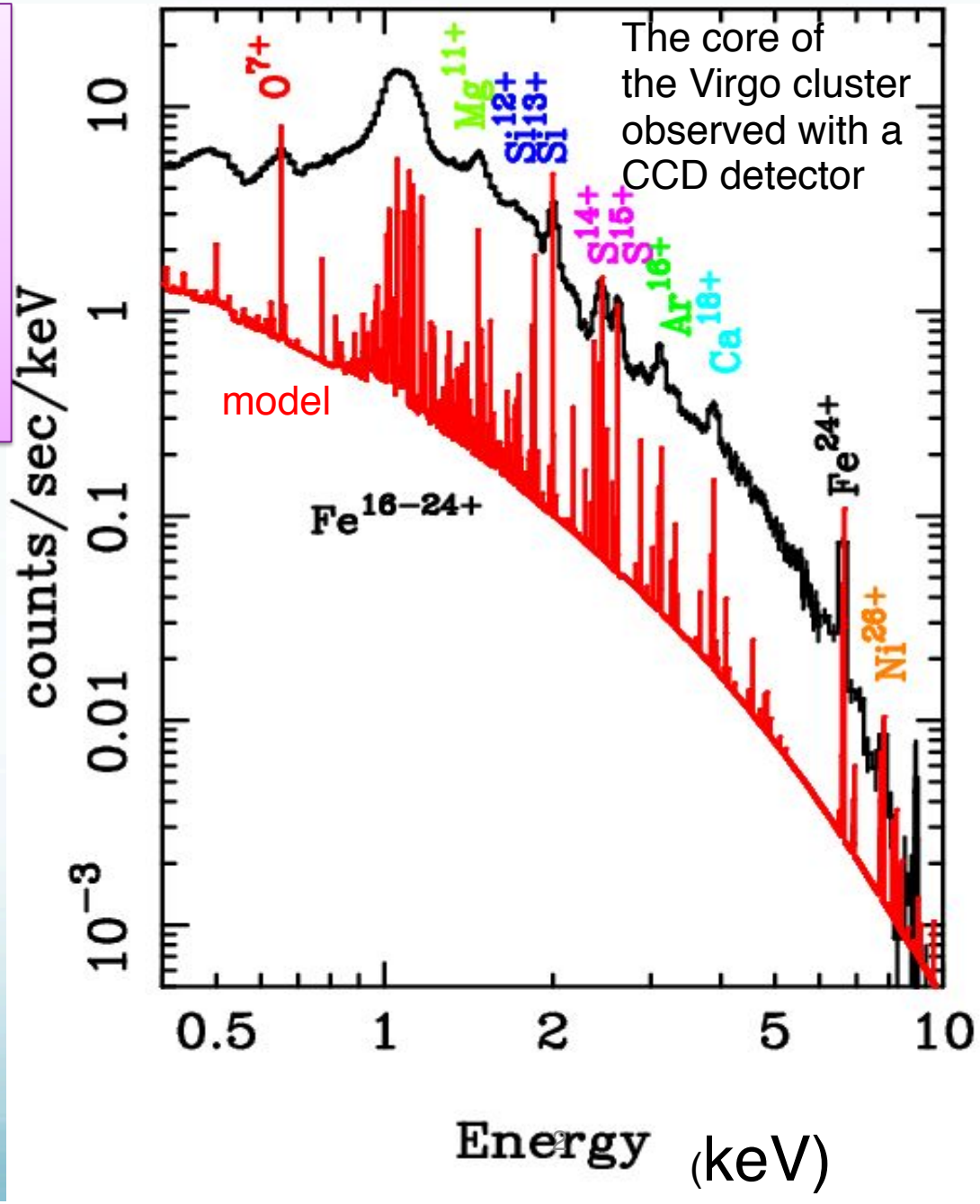
In clusters of galaxies,
most of the baryons are in the form of ICM

A representative spectrum of ICM

The ICM contains a large amount of metals synthesized by supernovae (SNe) in galaxies

From X-ray spectra of ICM, we can derive amount of metals in ICM

Fe-K lines are the most prominent in the X-ray spectra of ICM, and Fe abundance has been studied in detail.



Fe mass in the ICM vs. Luminosity of early-type galaxies

- Using the Ginga satellite

(Ginga was not able to spatially resolve ICM)

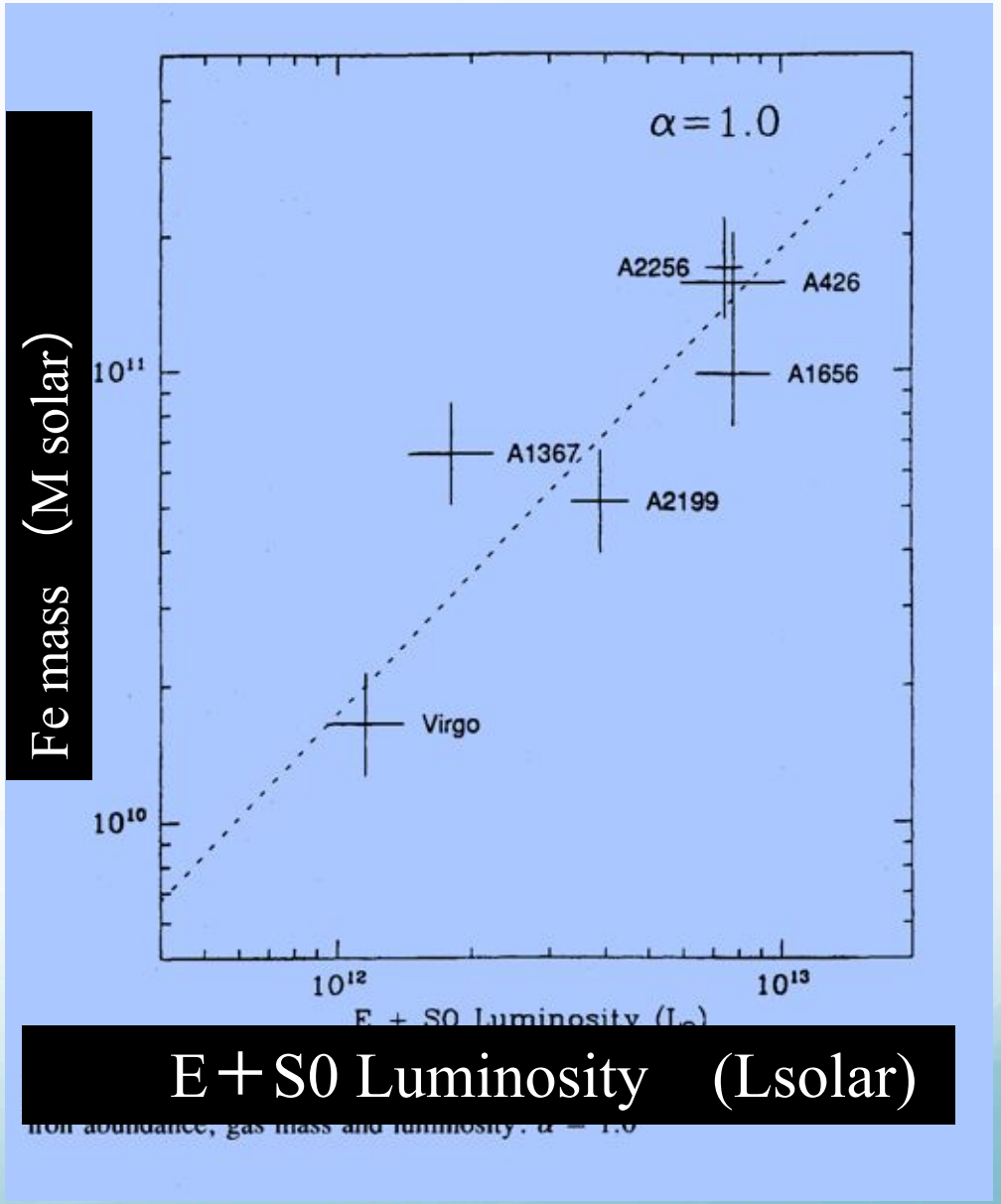
- Fe mass in ICM ∝ Luminosity of E, S0

  (Arnaud et al. 1992)

  – Fe in ICM are synthesized by E and S0 galaxies?

- Fe mass in the ICM is comparable to that in stars in galaxies

  – Galaxies lost significant amount of of Fe into the ICM

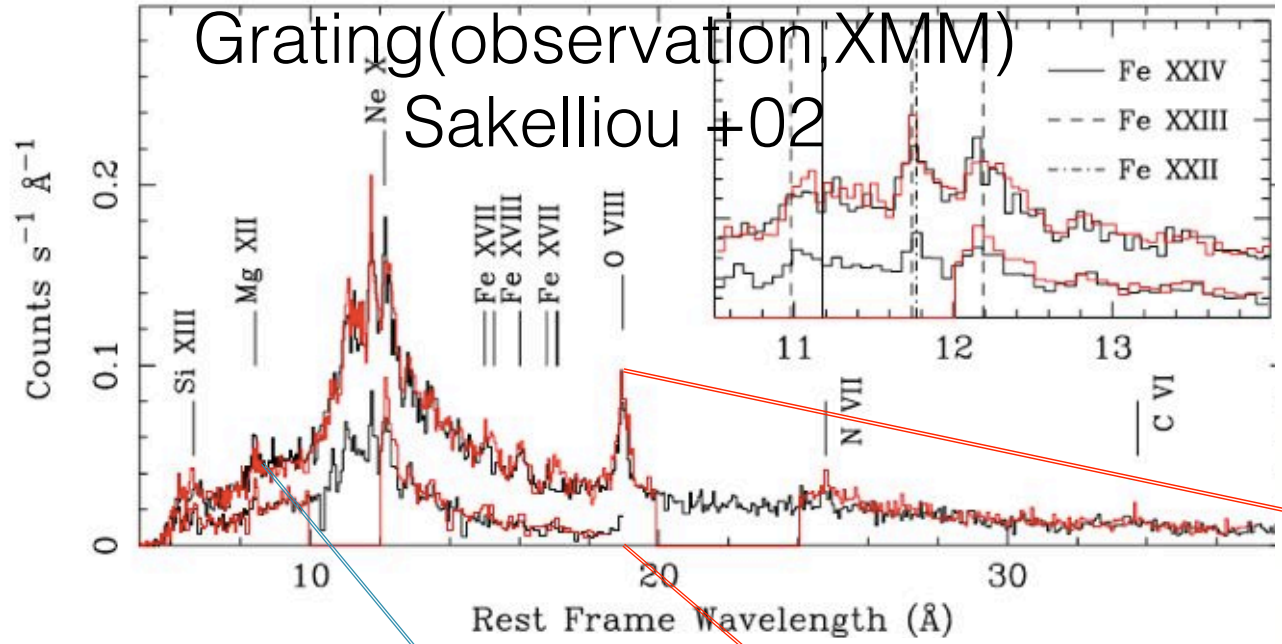


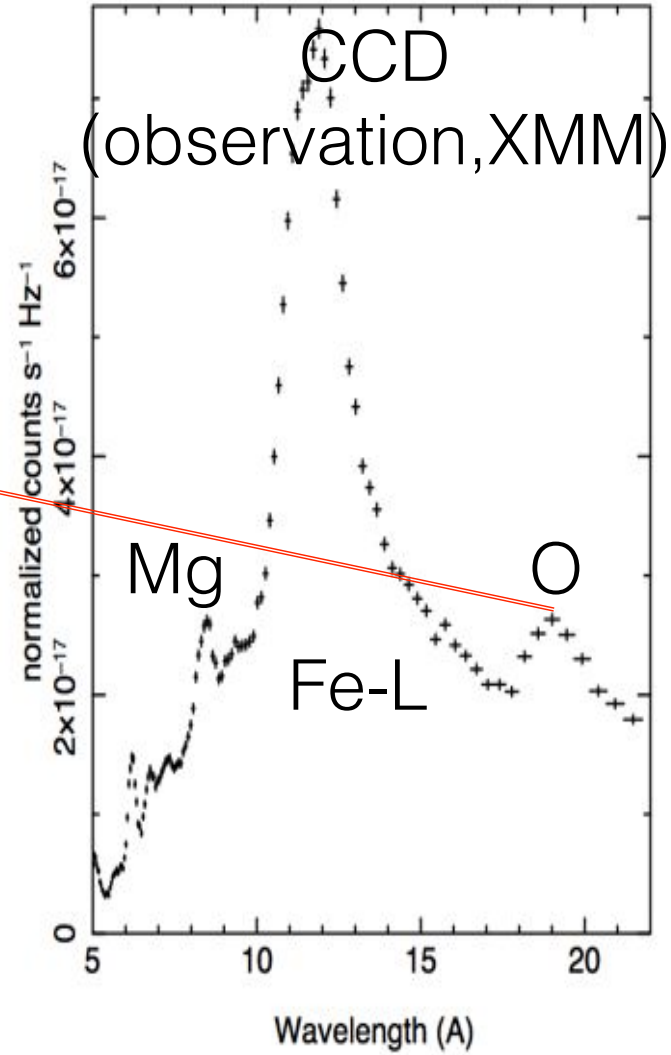
X-ray detectors

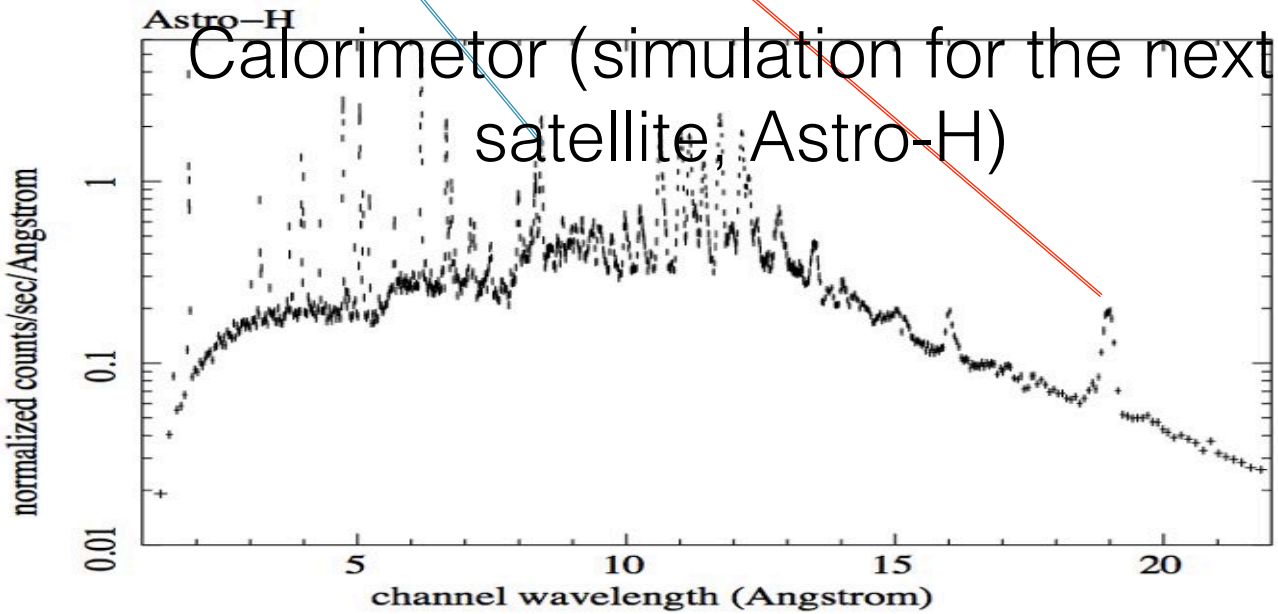
CCD detectors	Gratings	Calorimetors

• Moderate energy resolution
  • Contamination from O lines from our Galaxy
  • Contamination from Fe-L lines
• Large effective area, large field of view
  • Suitable for diffuse emission
	• Good energy resolution
	• Only for point like sources (including very bright cluster core)
	• Low effective area
		• Good energy resolution
		• Suitable for diffuse emission
		• Larger effective area than gratings
		• The field of view and effective area of SXS onboard Astro-H (2014--)are not large

X-ray spectra of M 87 (kT=2 keV)



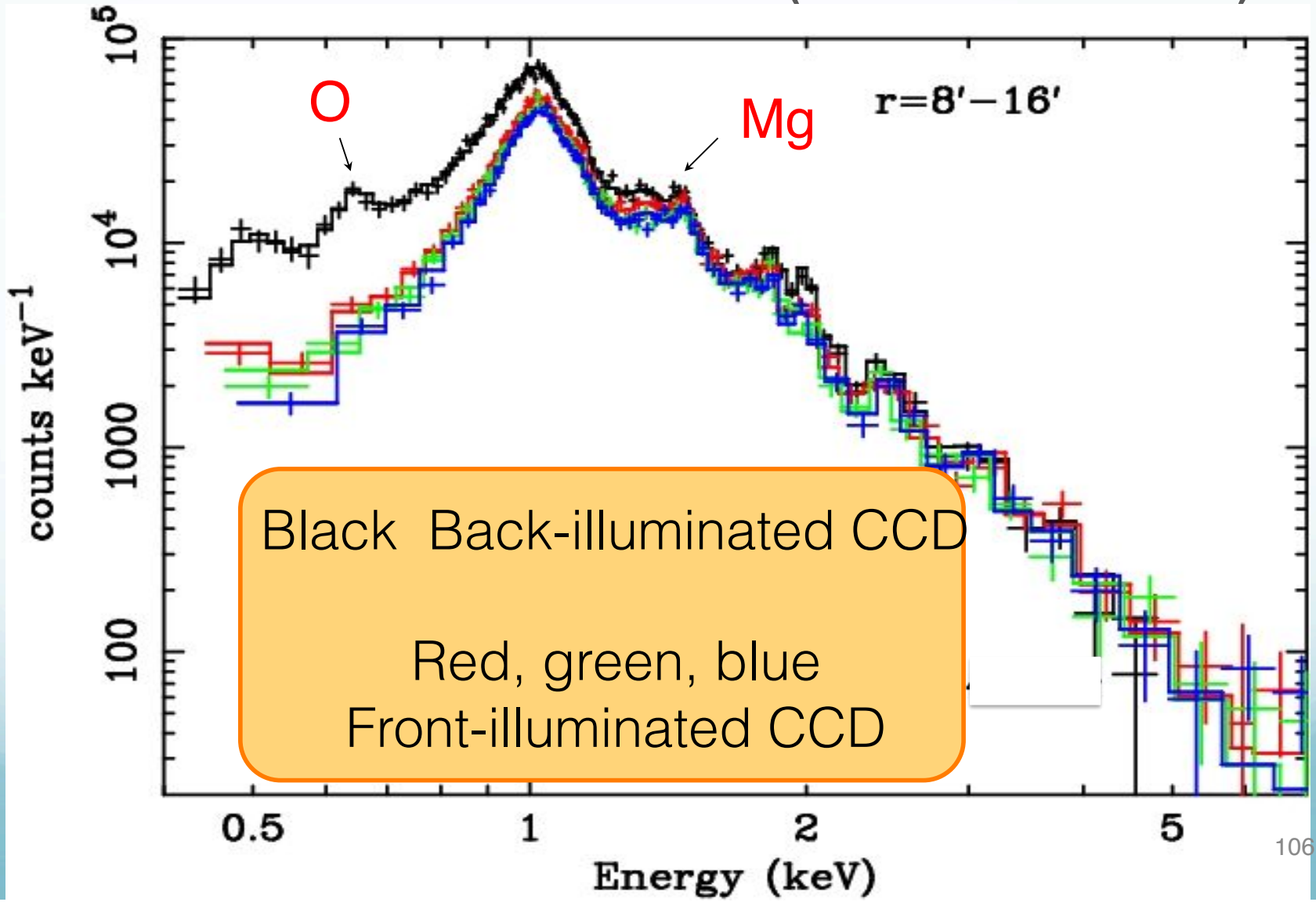




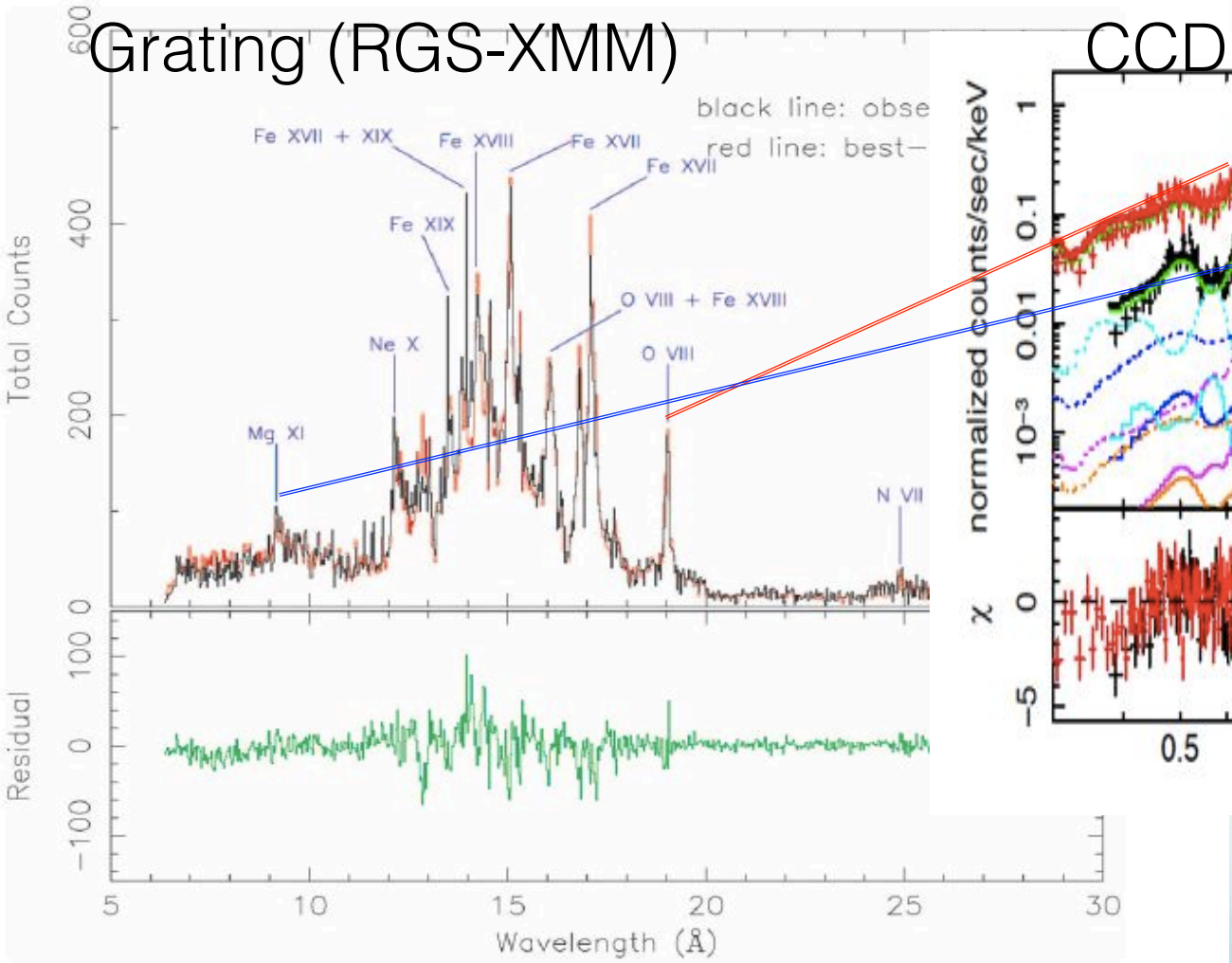
Kα line of O VIII

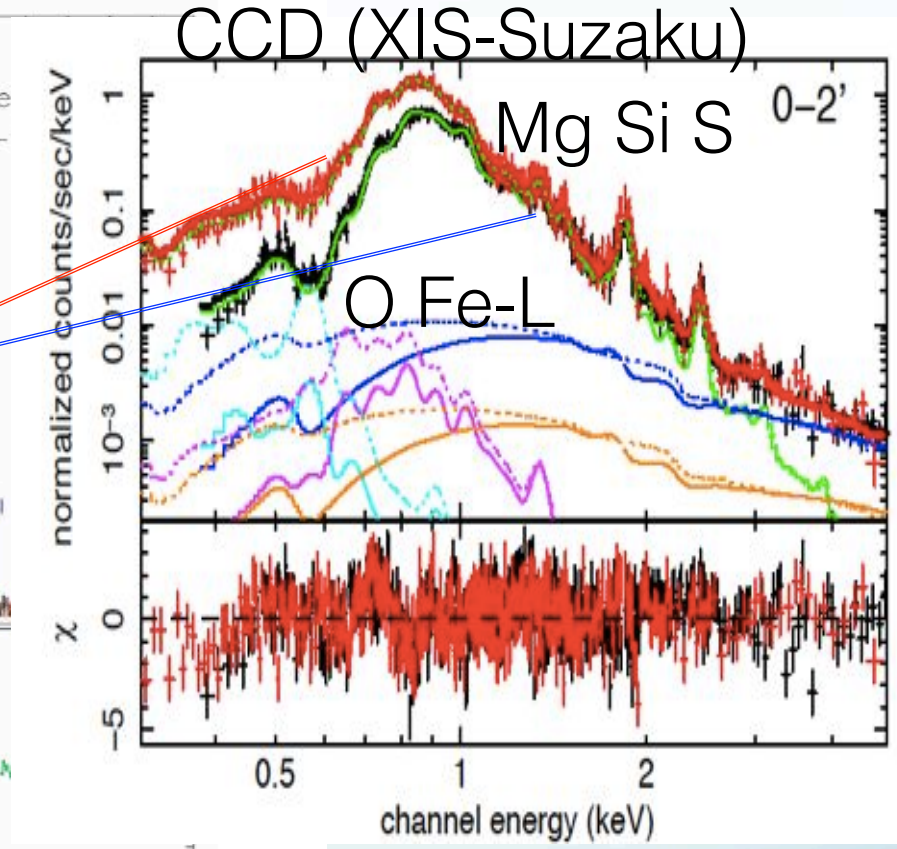
Detection of O and Mg lines with Suzaku satellite outside core regions

Spectra of the Fornax cluster (Matsushita+07)



X-ray spectra of NGC 4636 (X-ray luminous E gal) 0.6 keV





Xu et al. (2002), Hayashi et al.(2009)

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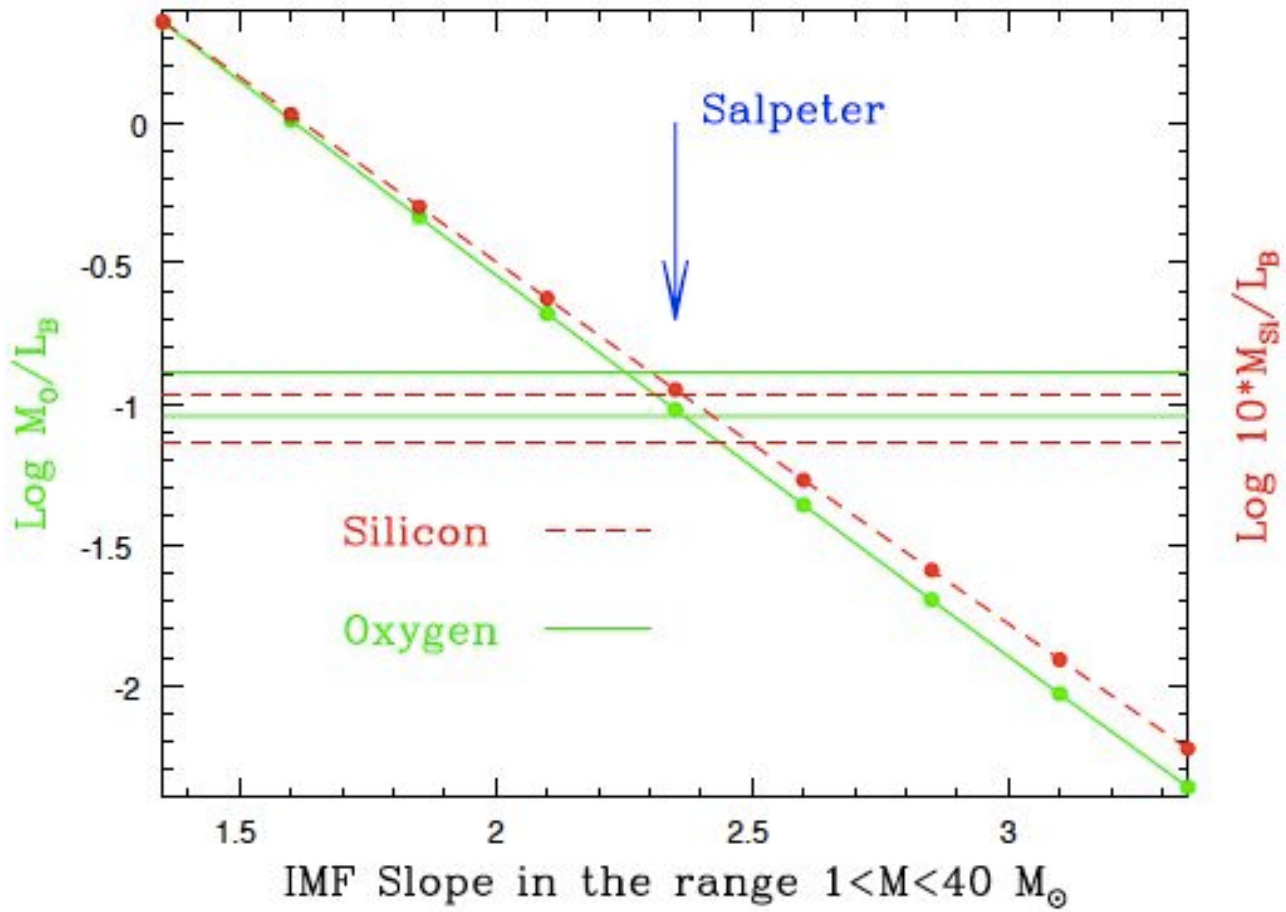
O-mass/stellar light vs. initial mass function of stars

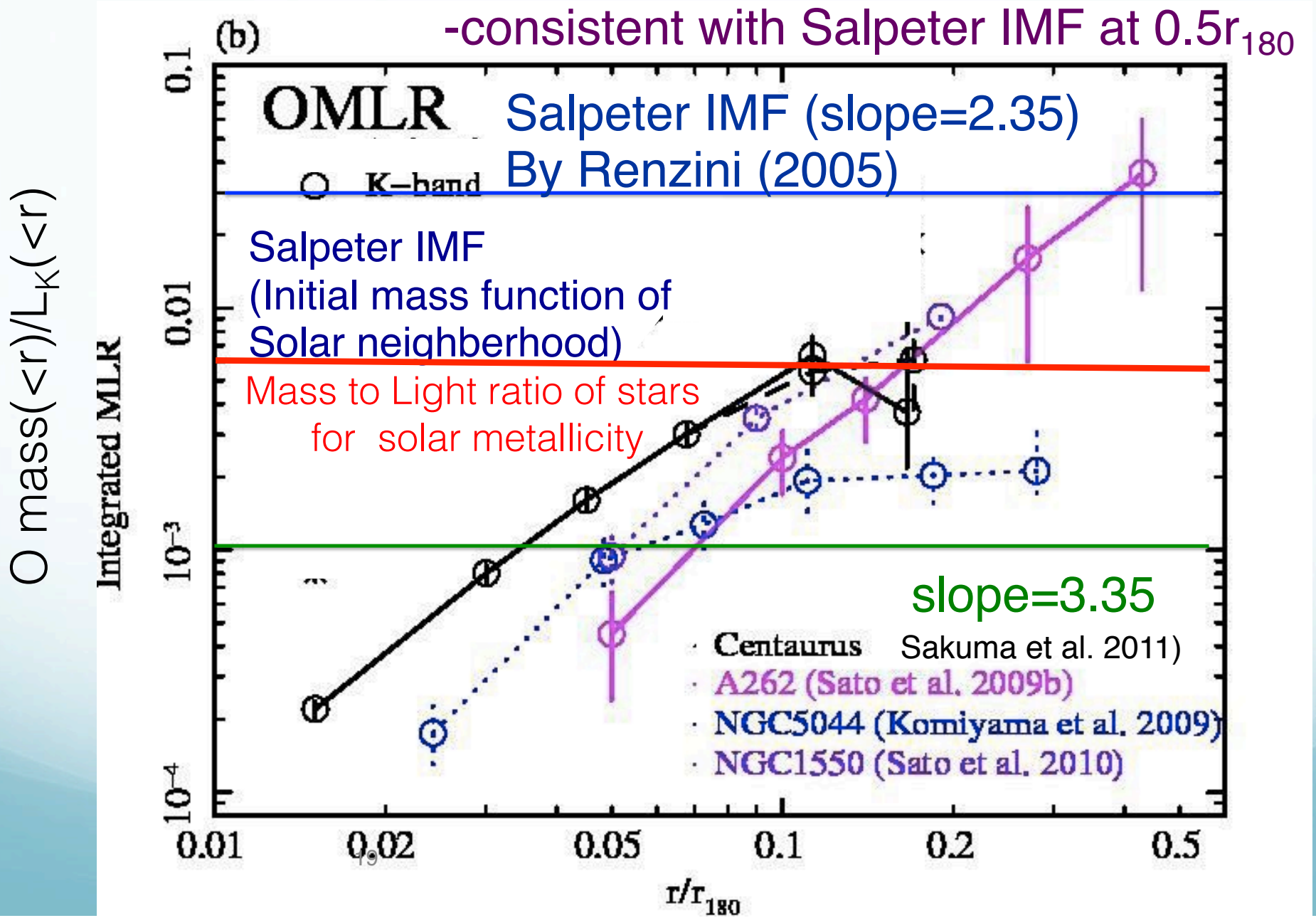
Oxygen mass (in ICM and in stars) in a cluster /stellar light in a cluster is a steep function on the slope of IMF (Renzini 2005)



O Mass to light ratio – sensitive to IMF

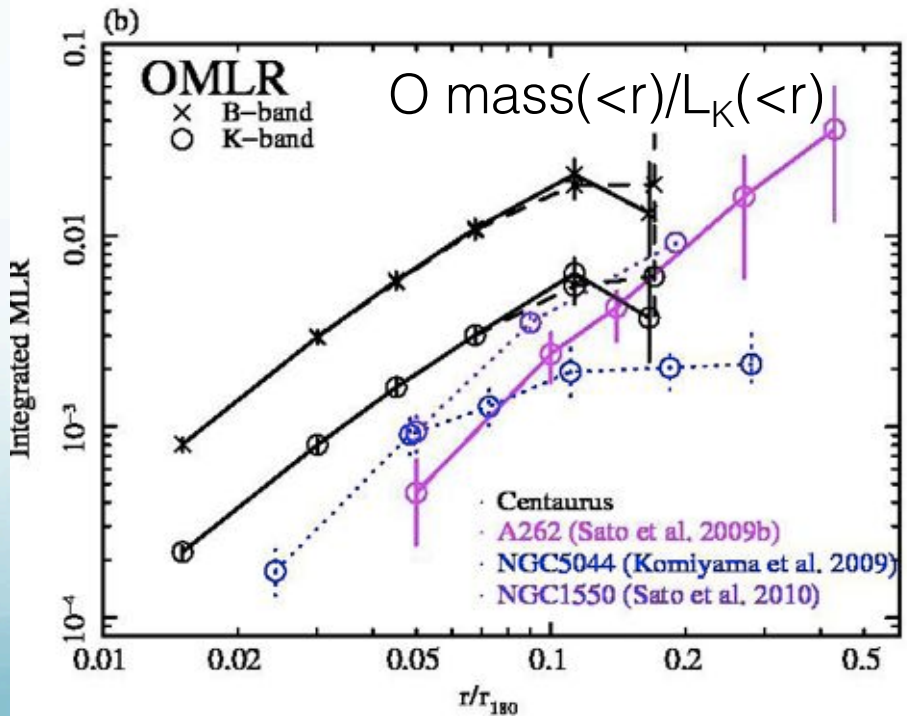
Massive stars to low mass stars

-consistent with Salpeter IMF at $0.5r_{180}$



O Mass in the ICM

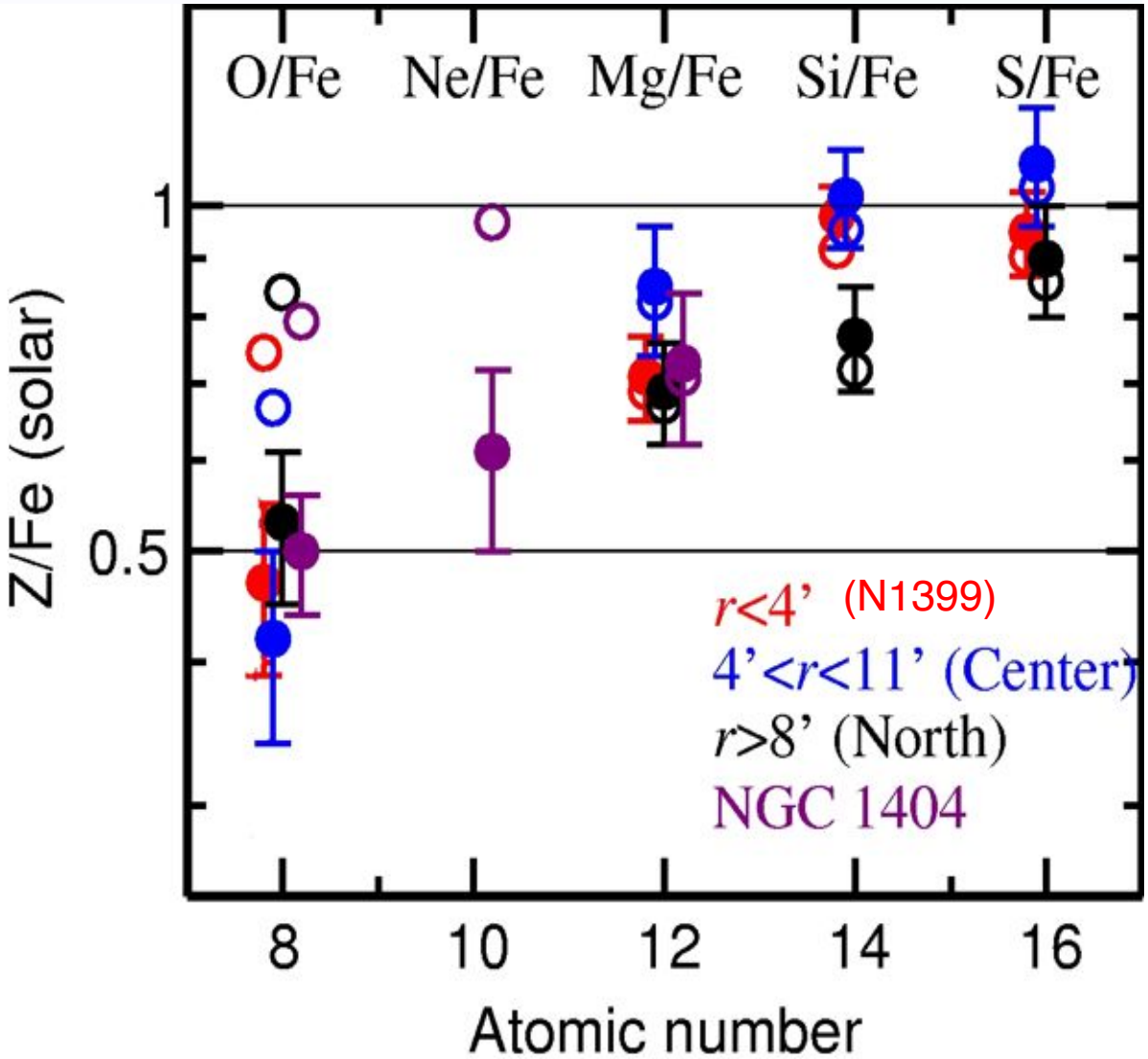
- O mass in the ICM is comparable or even larger than the O mass in stars
- O mass to the light ratio within 0.5 r_{180} is consistent with a Salpeter IMF
  - *r_{180} is the virial radius defines the boundary in which matter at ~ 180 times the critical density of the universe*
  - Since O mass in the ICM increases with radius, we need O detection out to the virial radius to total amount of O in each cluster



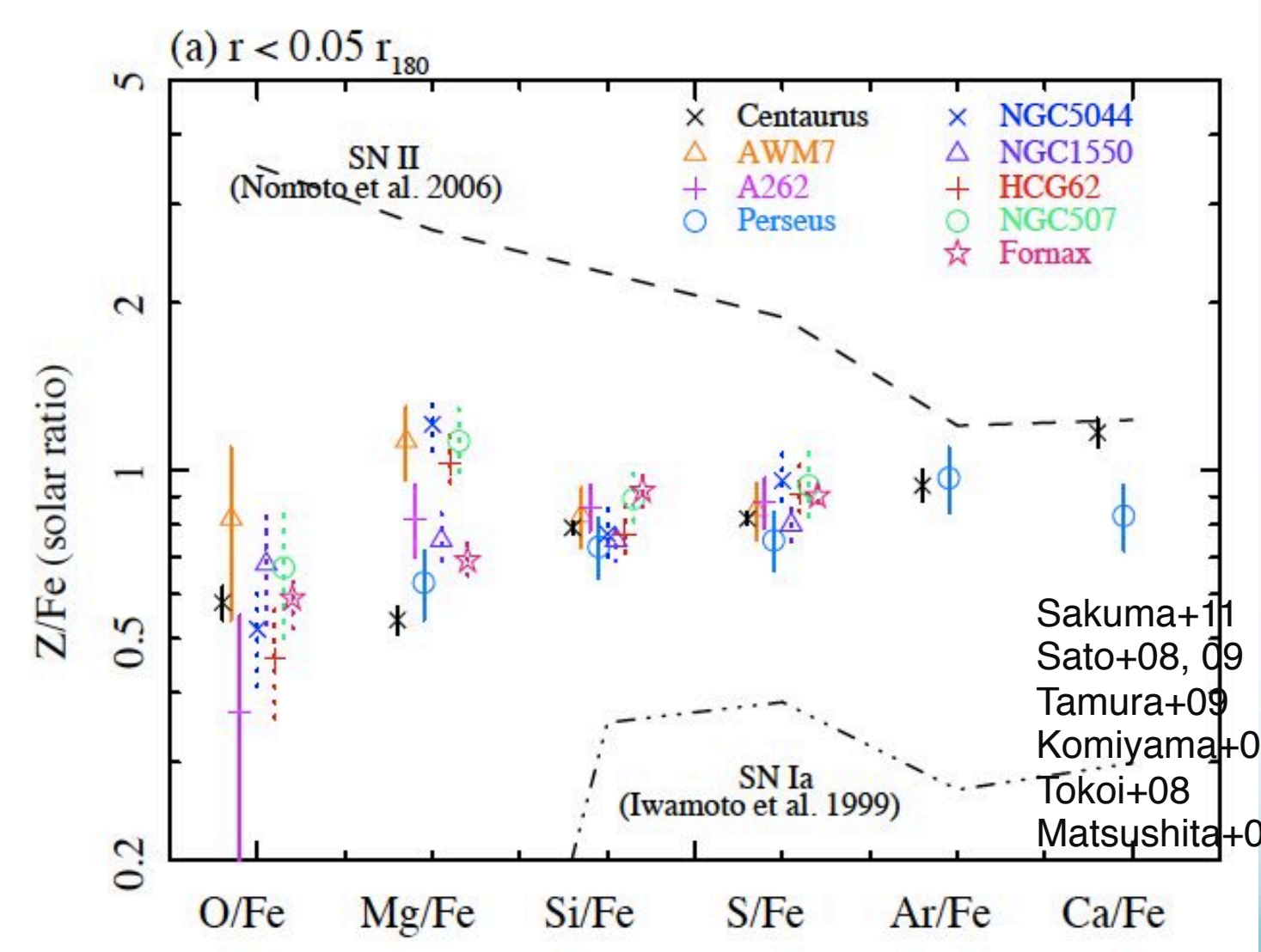
Abundance pattern of the Fornax cluster using new solar abundance

● : solar abundance by Feldman (1992)
low O/Fe ratios

○ : new solar abundance by Loddars (2003)
abundance pattern of O, Ne, Mg, Si, S, and Fe become close to the solar ratio



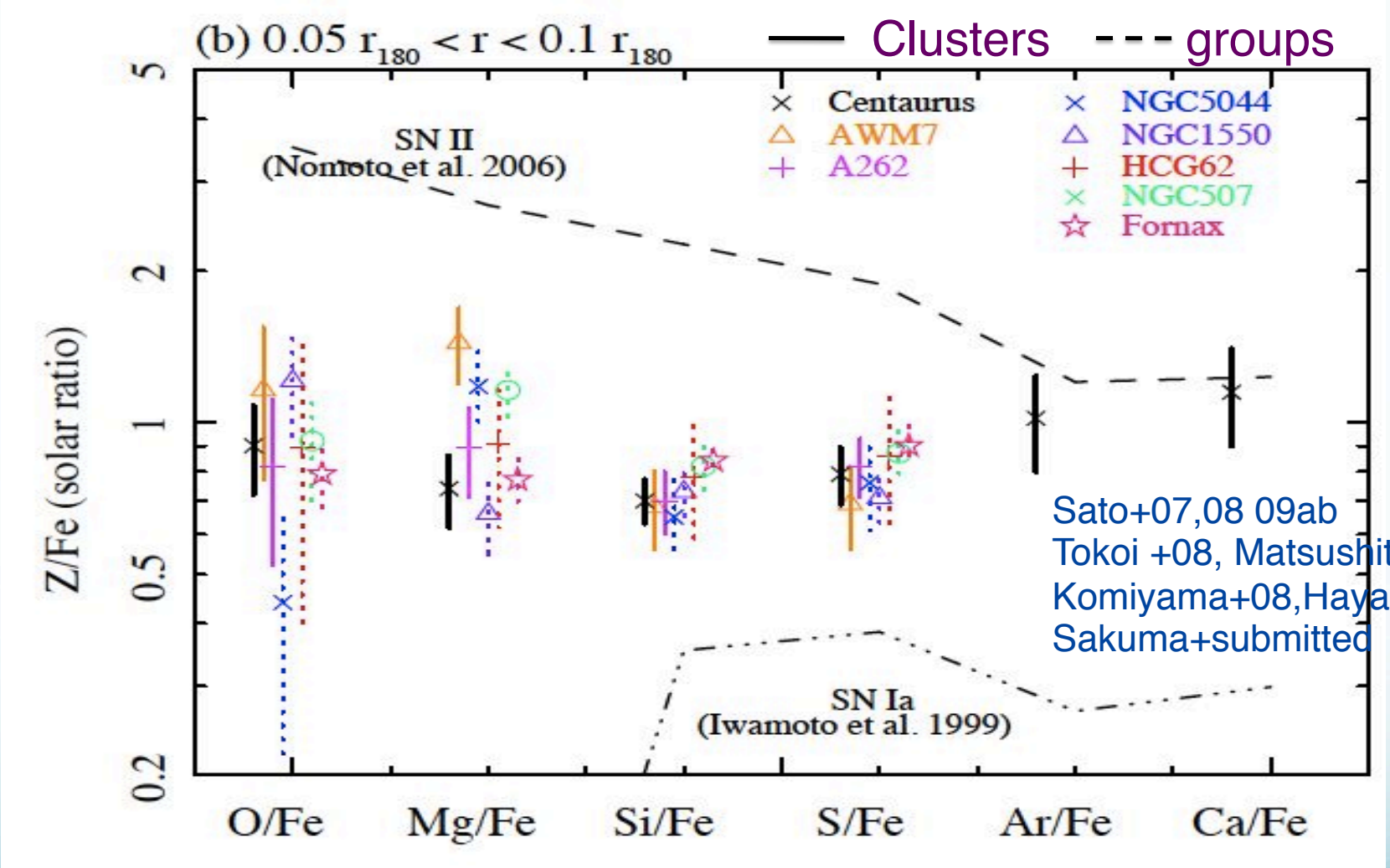
Abundance pattern of the central regions of clusters and groups of galaxies



Sakuma+11
Sato+08, 09
Tamura+09
Komiyama+09
Tokoi+08
Matsushita+07

- Using solar abundance table by Lodders (2003)

Abundance Pattern of the ICM outside core regions observed with Suzaku

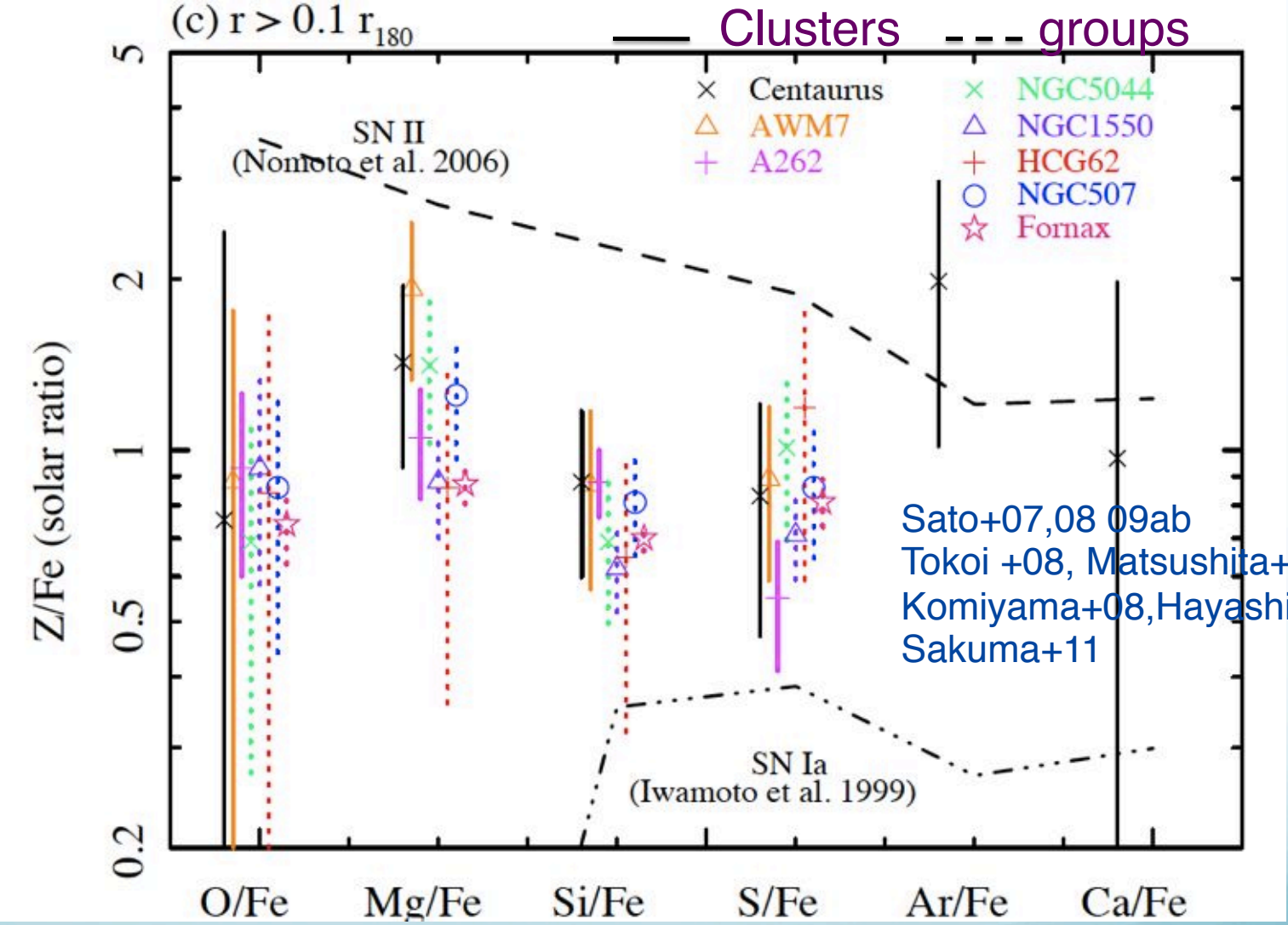


Sato+07,08 09ab
Tokoi +08, Matsushita+07
Komiyama+08,Hayashi+09
Sakuma+submitted

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)

Abundance Pattern outside cool cores observed with Suzaku

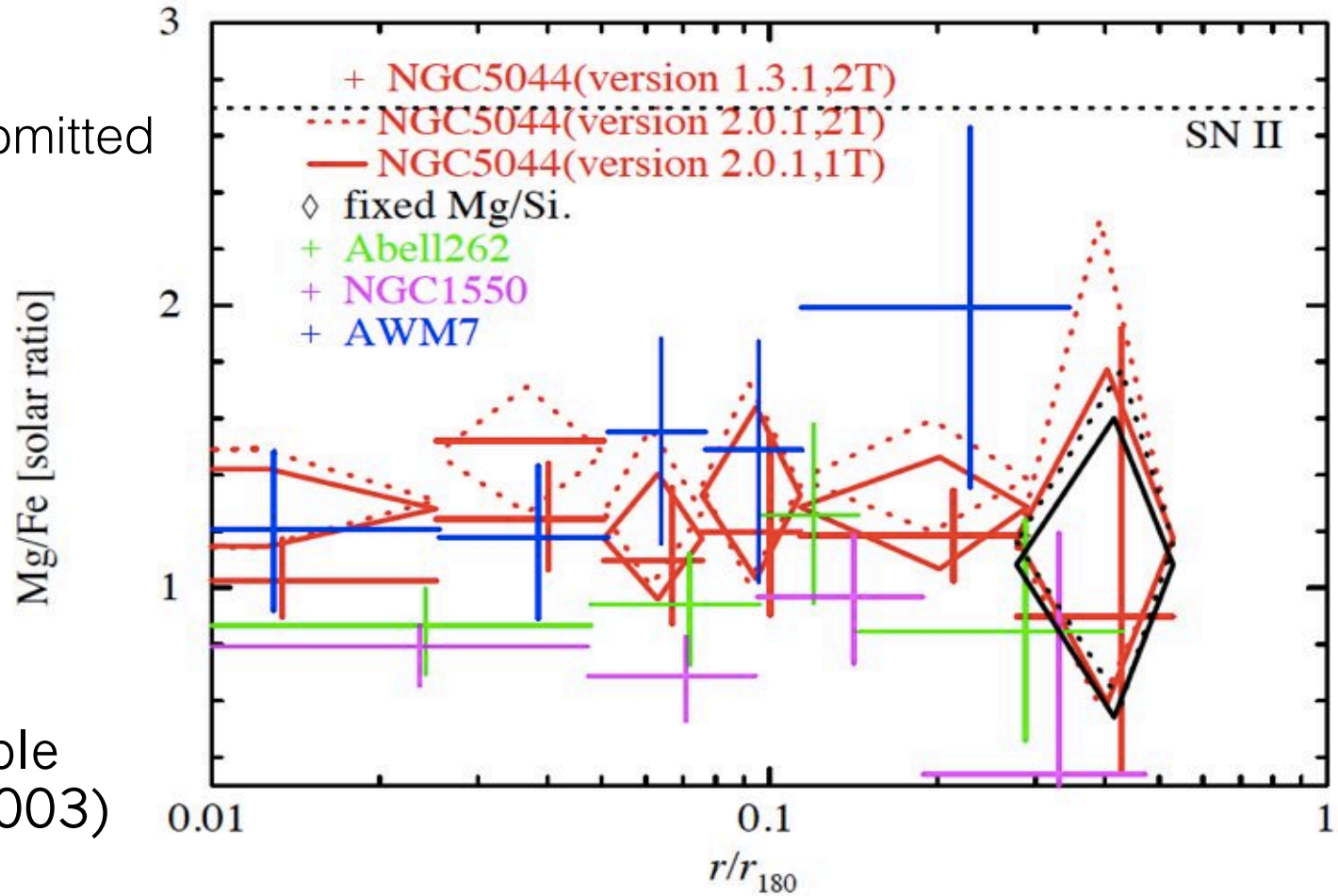


Sato+07,08 09ab
Tokoi +08, Matsushita+07
Komiyama+08,Hayashi+09
Sakuma+11

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

Mg/Fe ratio out to 0.5r180 of poor clusters and groups of galaxies

Sasaki et al. submitted



- Using solar abundance table by Lodders (2003)

- Three kinds of data for the NGC 5044 group indicate the systematic uncertainties in the Mg/Fe ratio

Abundance pattern of O/Mg/Si/S/Fe in the ICM

- With the solar abundance table by Lodders (2003), the observed O/Fe ratios outside cool core regions are close to the solar ratio
- Beyond 0.1—0.2 r_{180}, the uncertainties of the observed O abundances increase caused by the contamination of the Galactic emission.
- The Mg/Fe ratios of poor clusters and groups of galaxies are consistent with the solar ratio out to 0.5 r_{180}

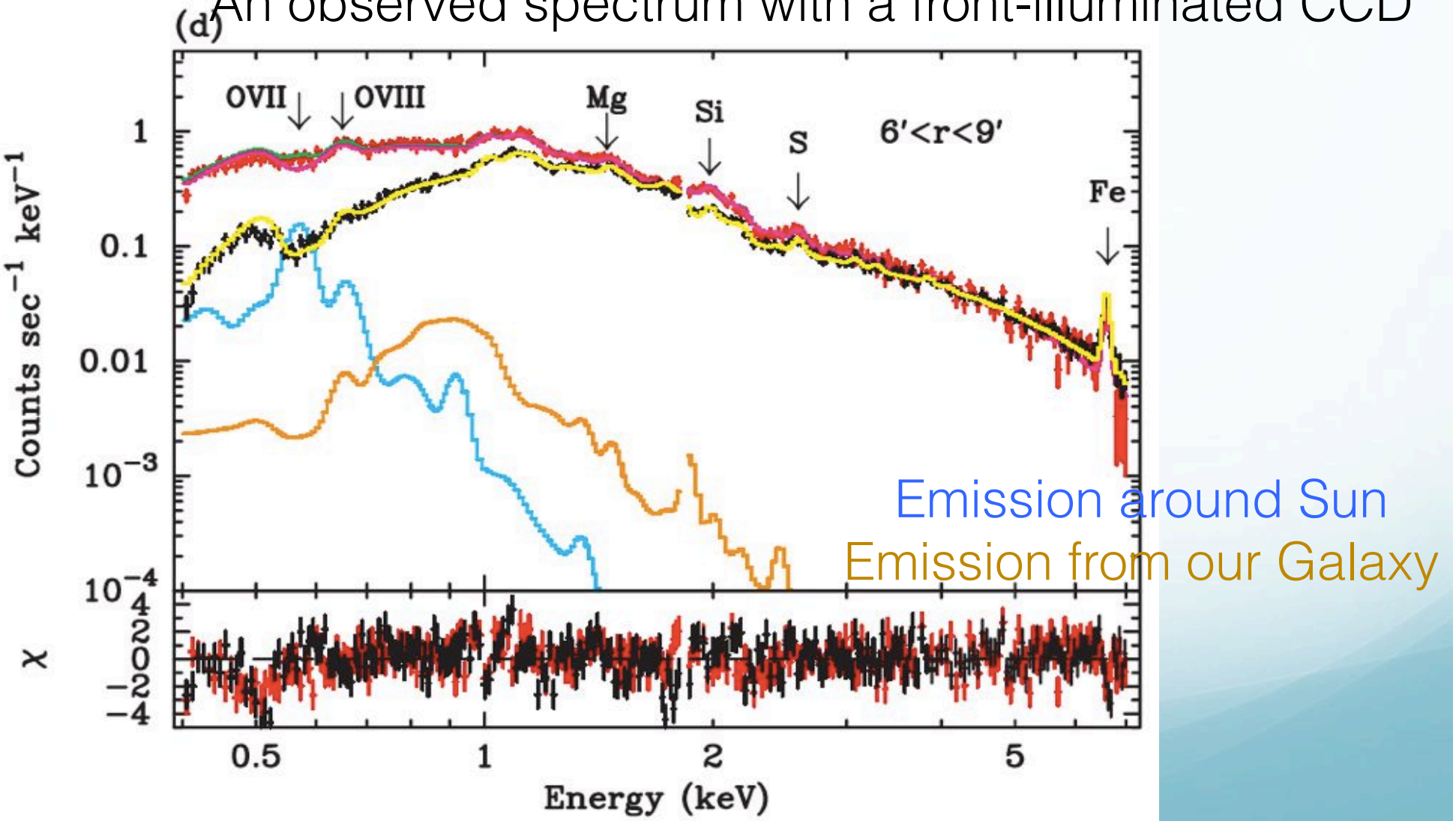
Systematic uncertainties in O abundance

- Contribution of the emission from our Galaxy
- Systematic uncertainties in atomic data
- Systematic uncertainties in the response matrix of the detector
- Contamination of Fe-L lines
- Simple temperature structure outside cool core regions
  - Even in the cool cores, the temperature range is not wide
- Timescale is enough to reach ionization equilibrium, ion-electron equilibrium, for dust sputtering
- Cooling time scale is longer than the Hubble time outside cool core regions

Representative X-ray spectra of the ICM

An observed spectrum with a back-illuminated CCD

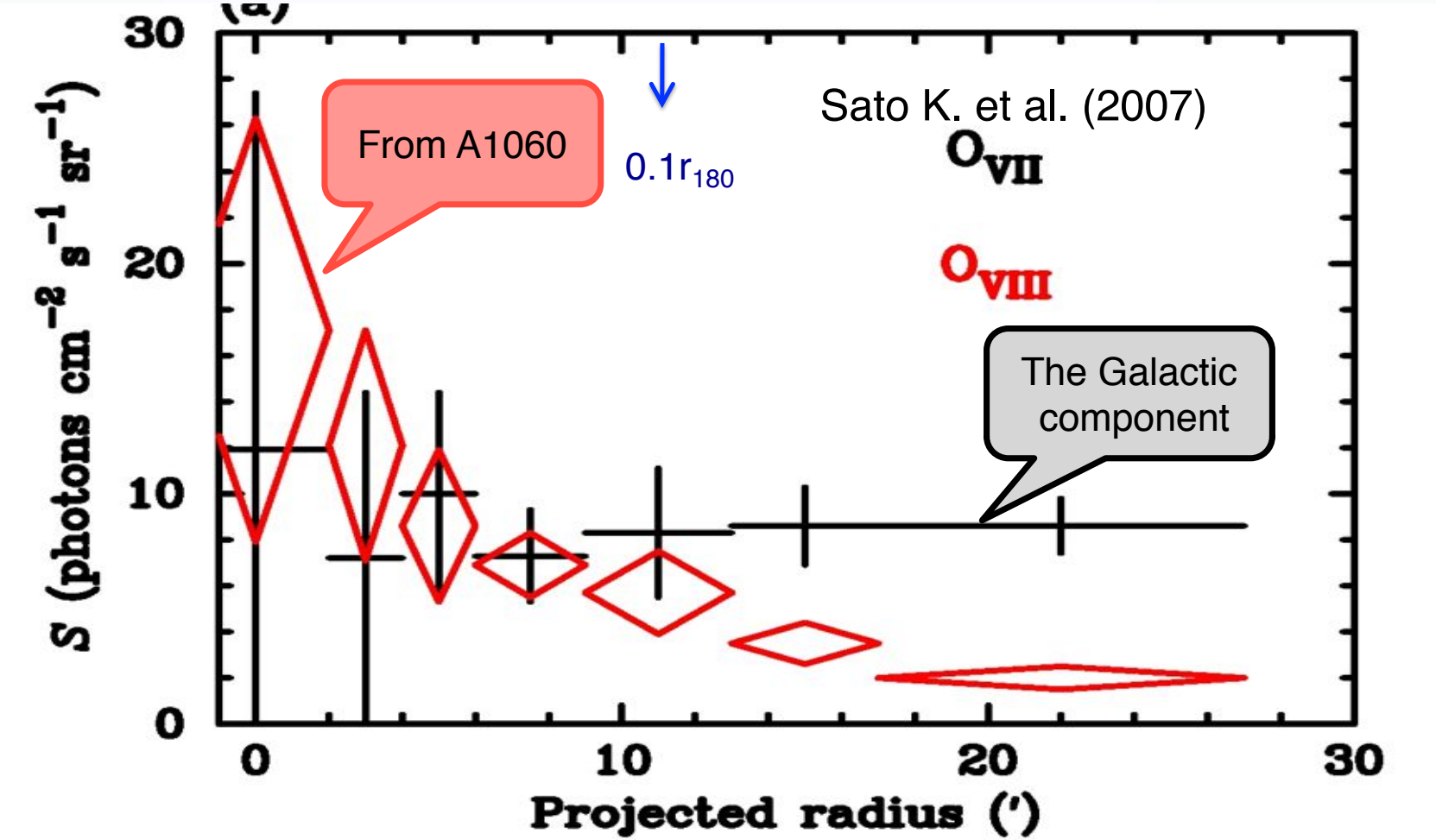
An observed spectrum with a front-illuminated CCD



The effect of the Galactic emission

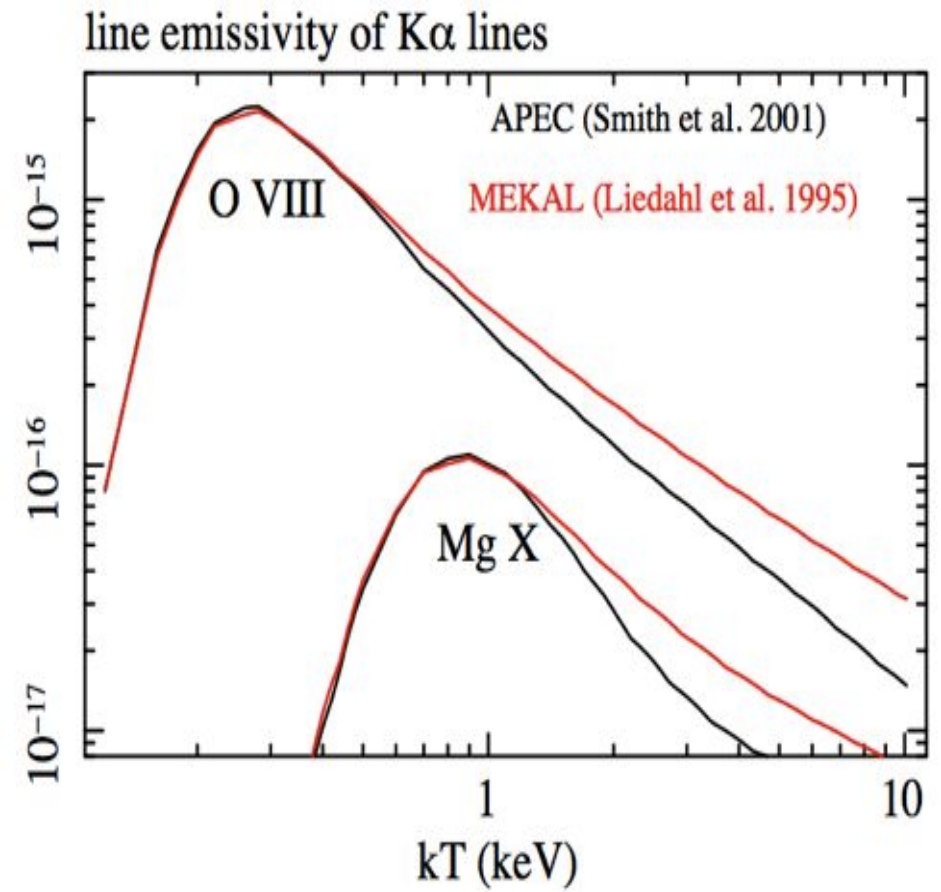
Surface brightness of OVII, OVII lines of A1060 cluster

A sum of the cluster emission and the Galactic emission

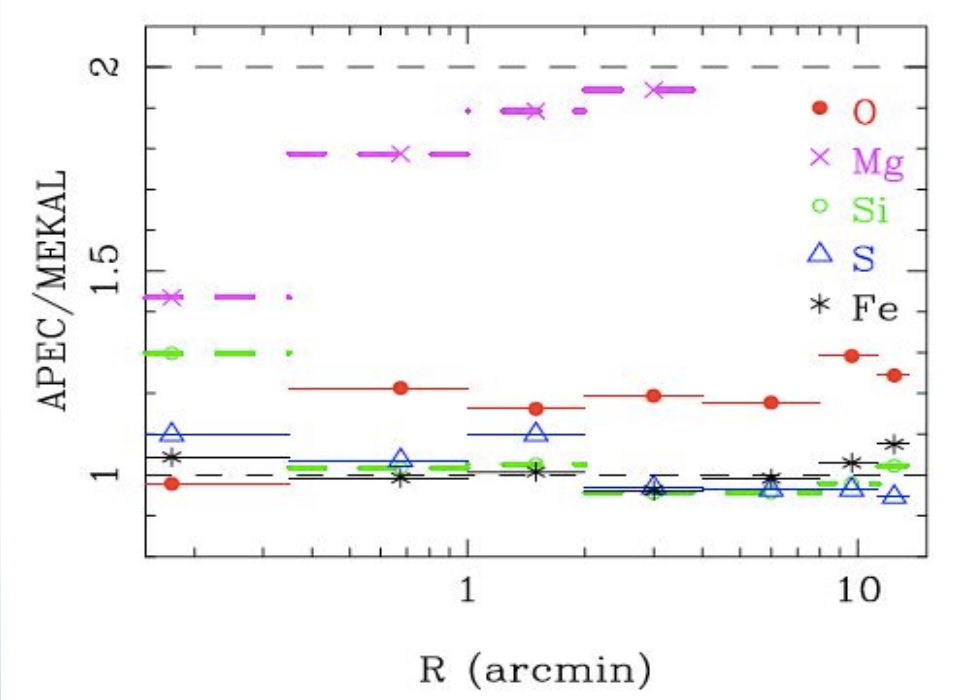


CCD detectors cannot resolve O lines from nearby clusters and our Galaxy

Systematic uncertainty in atomic data



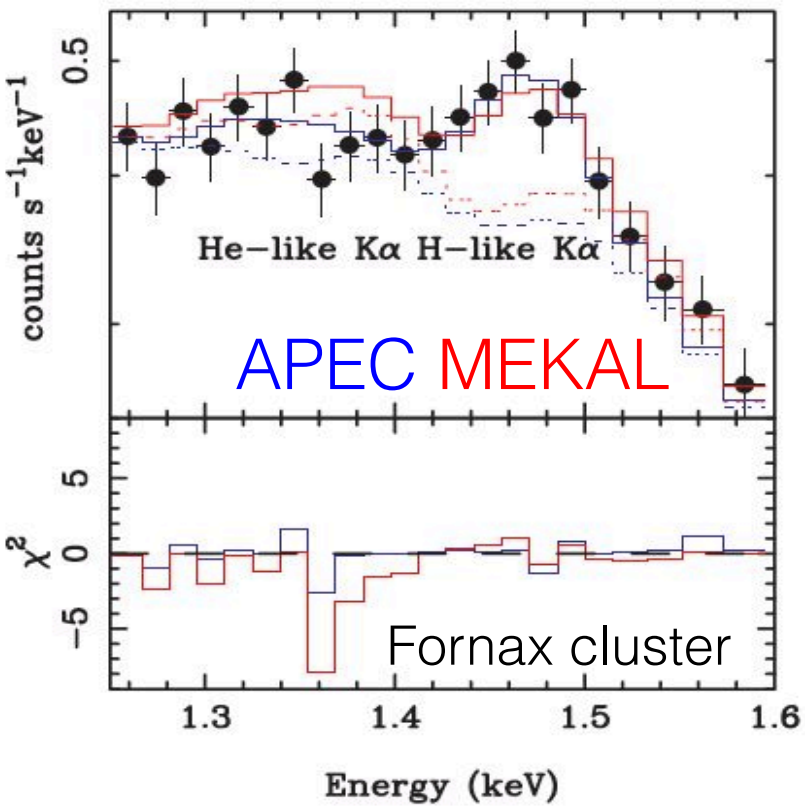
Ratio of derived abundances with APEC and MEKAL codes of M 87 (Matsushita+03)



- Hot ISM in E gals: 0.3—0.8 keV group: 0.5—2 keV
- Cool cores: 0.5—2 keV; outside cool core:2—10 keV

Systematic uncertainty in atomic data

Mg-K lines



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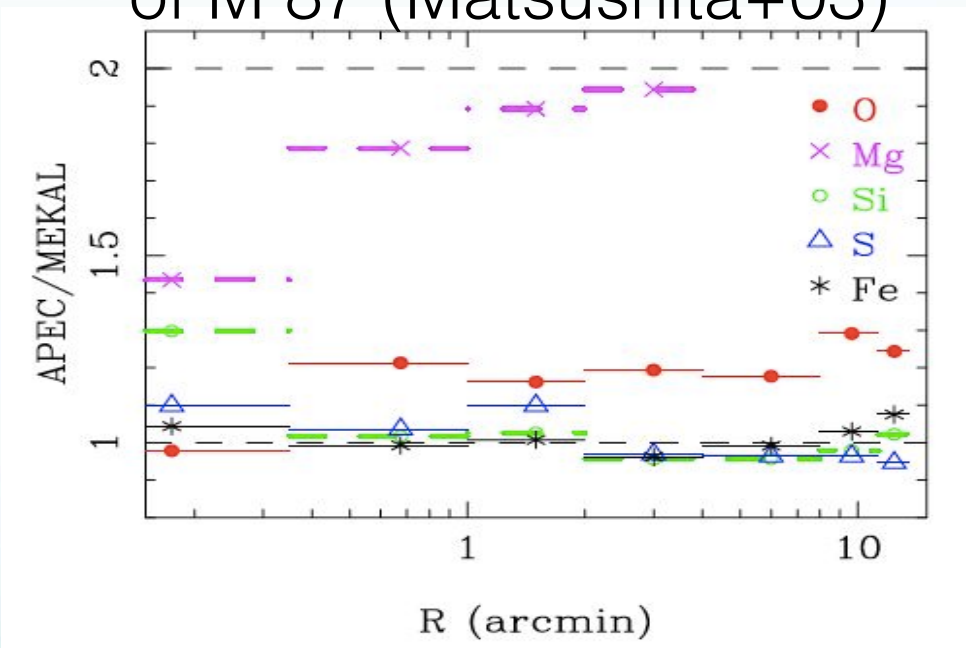
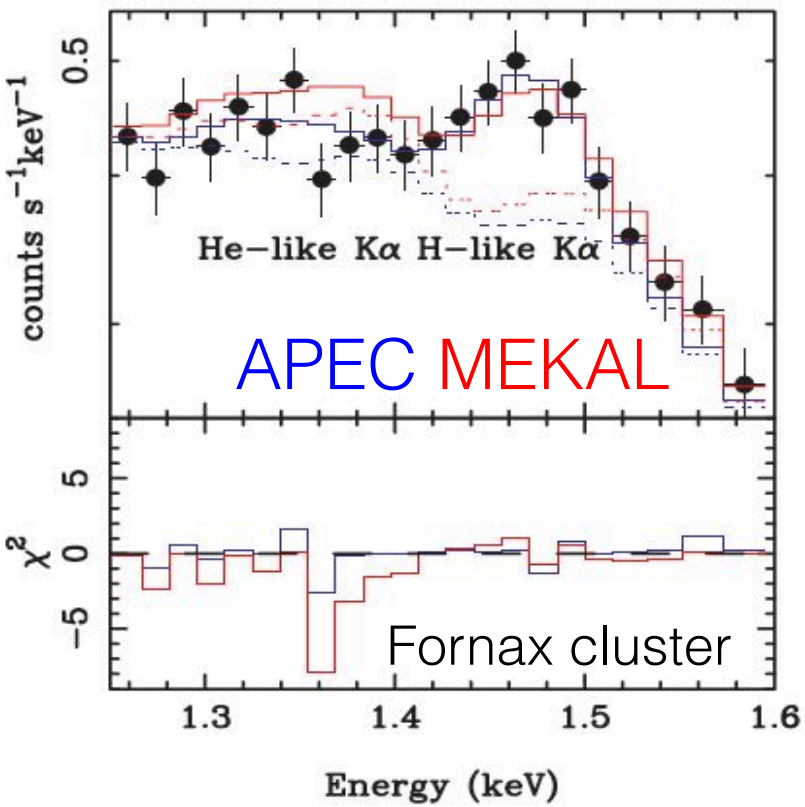


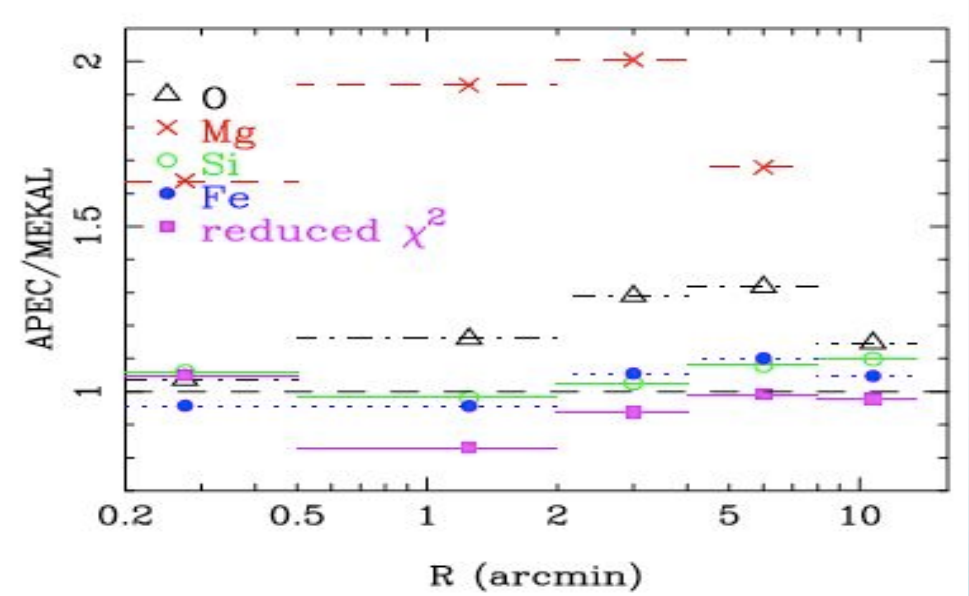
- Discrepancy of Mg abundances are caused by difference in the Fe-L model around the Mg lines
- The APEC model gives better fits around the Mg lines

Systematic uncertainty in atomic data

Mg-K lines



Ratio of derived abundances with APEC and MEKAL codes of the Centaurus (Matsushita+07)



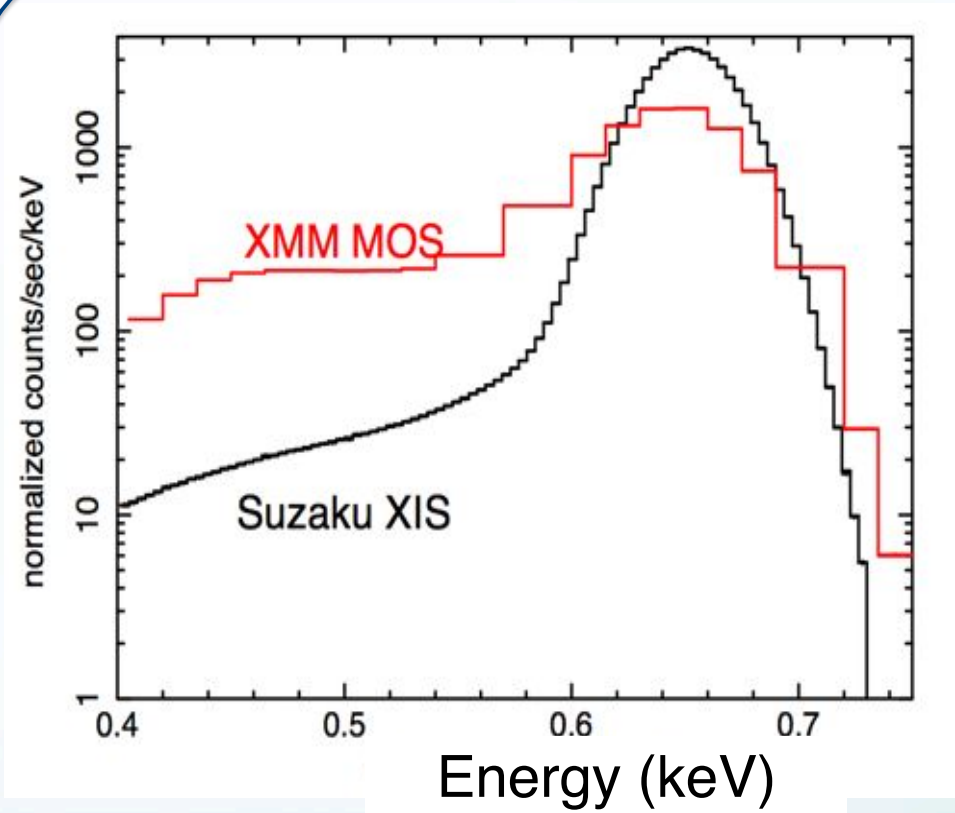
- Discrepancy of Mg abundances are caused by difference in the Fe-L model around the Mg lines
- The APEC model gives better fits around the Mg lines

Advantages of CCD detectors onboard Suzaku

The XIS instrument onboard Suzaku (2005-) has

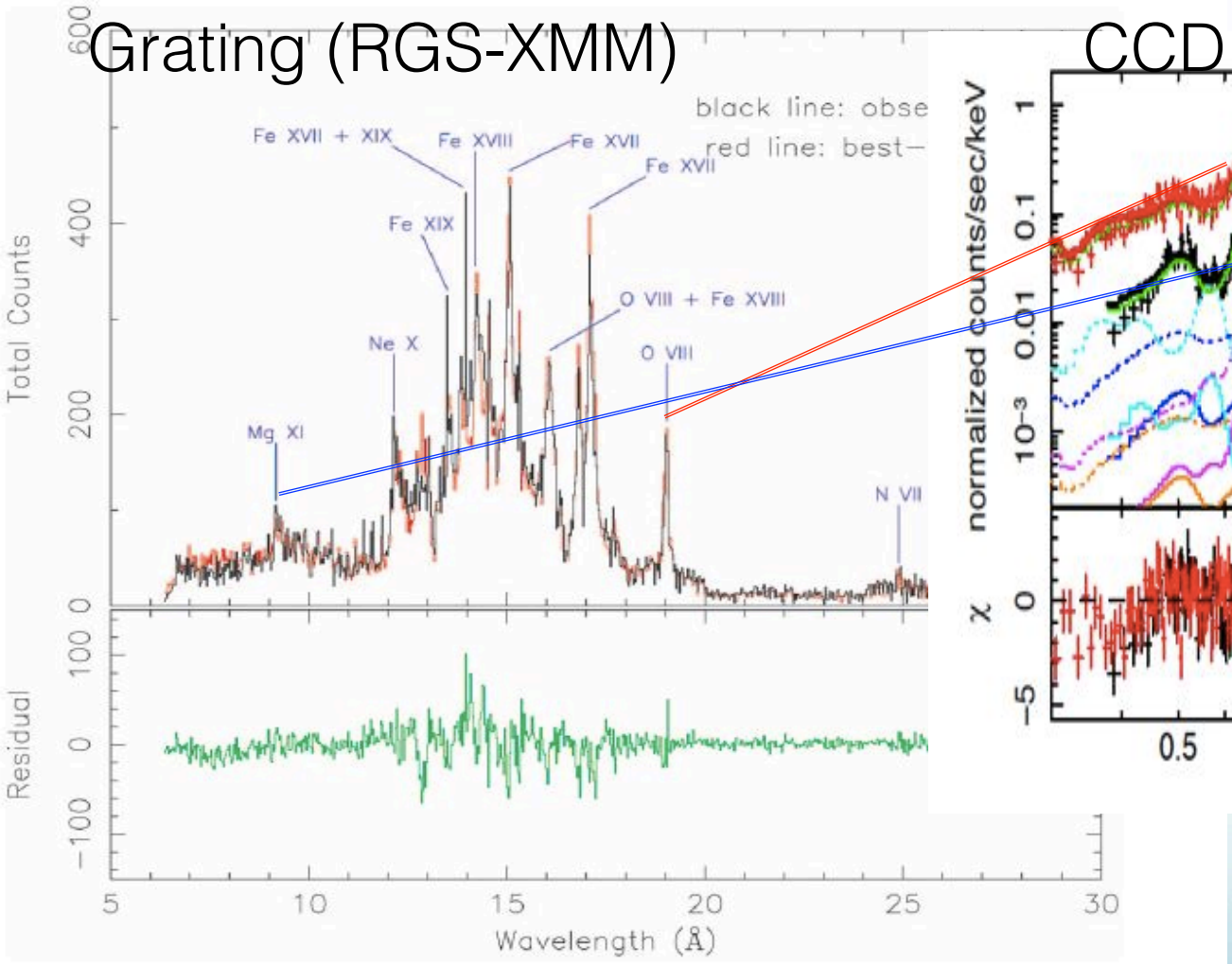
- an better line spread function due to a very small low-pulse-height tail below 1 keV

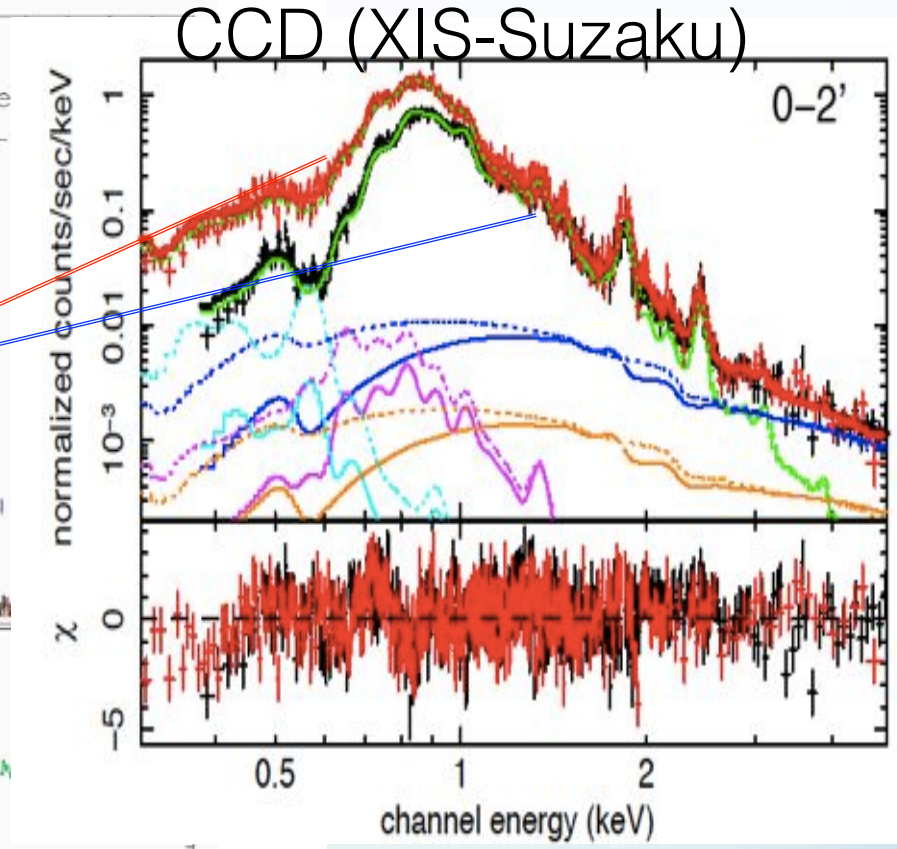
  energy range around O lines is not suffered by strong Fe-L lines
- a very low background.



Response of a line at 0.65 keV (Kα line of H-like O) of XMM-MOS and Suzaku XIS detectors

X-ray spectra of NGC 4636 (X-ray luminous E gal) 0.6 keV





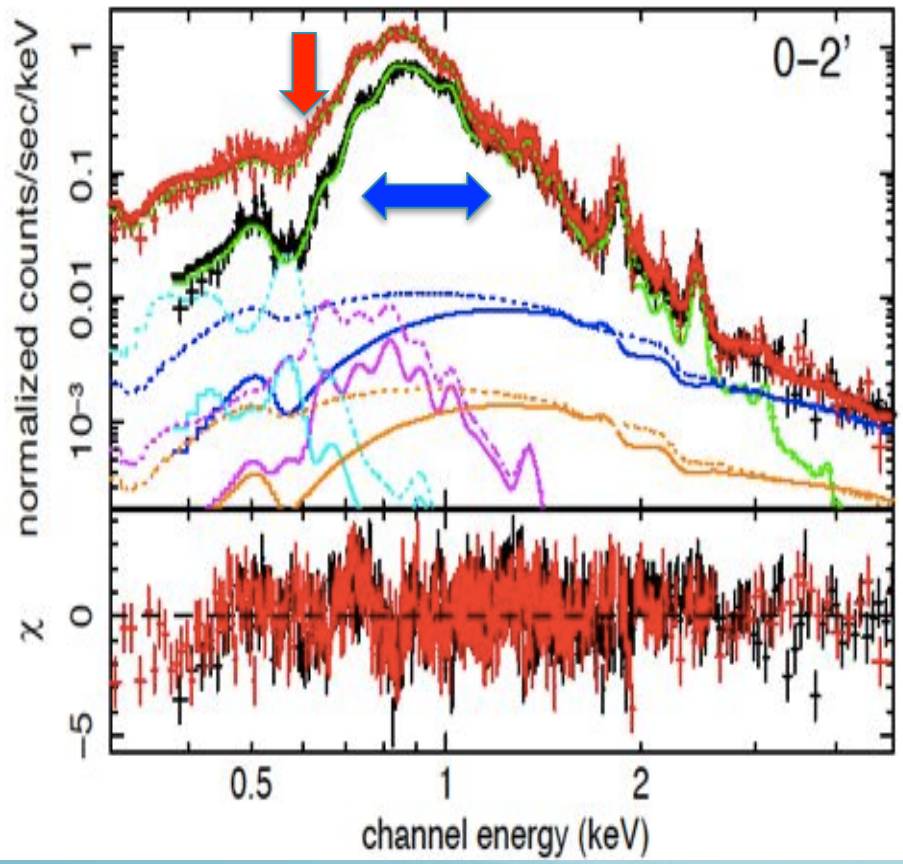
Xu et al. (2002), Hayashi et al.(2009)

X-ray spectra of NGC 4636 (X-ray luminous E gal) 0.6 keV

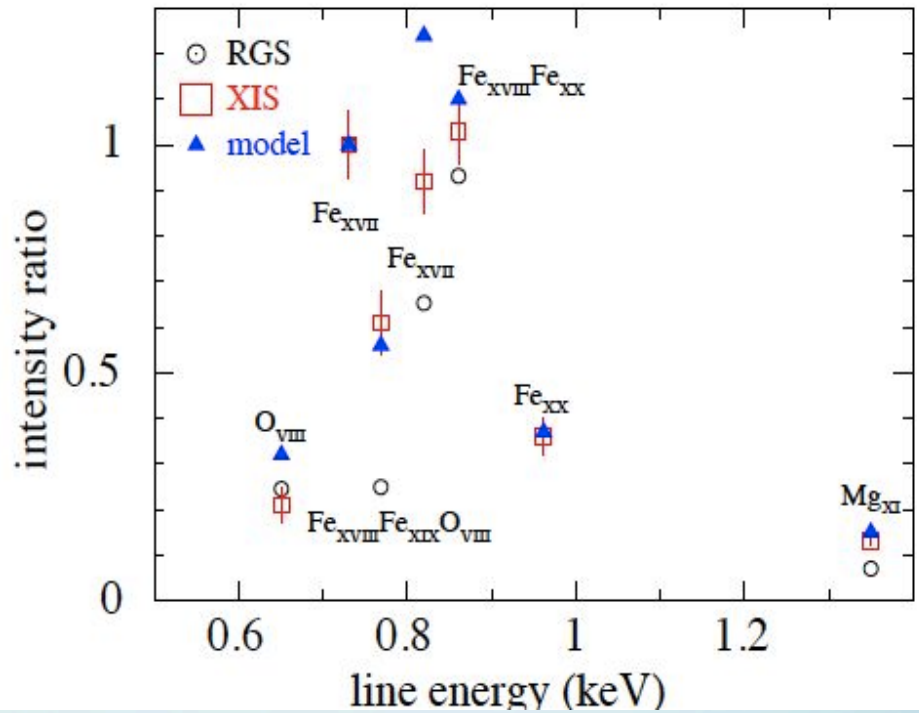
XIS(CCD) spectra

OVIII

Fe-L



RGS(grating) and CCD(XIS) gave mostly consistent line ratios

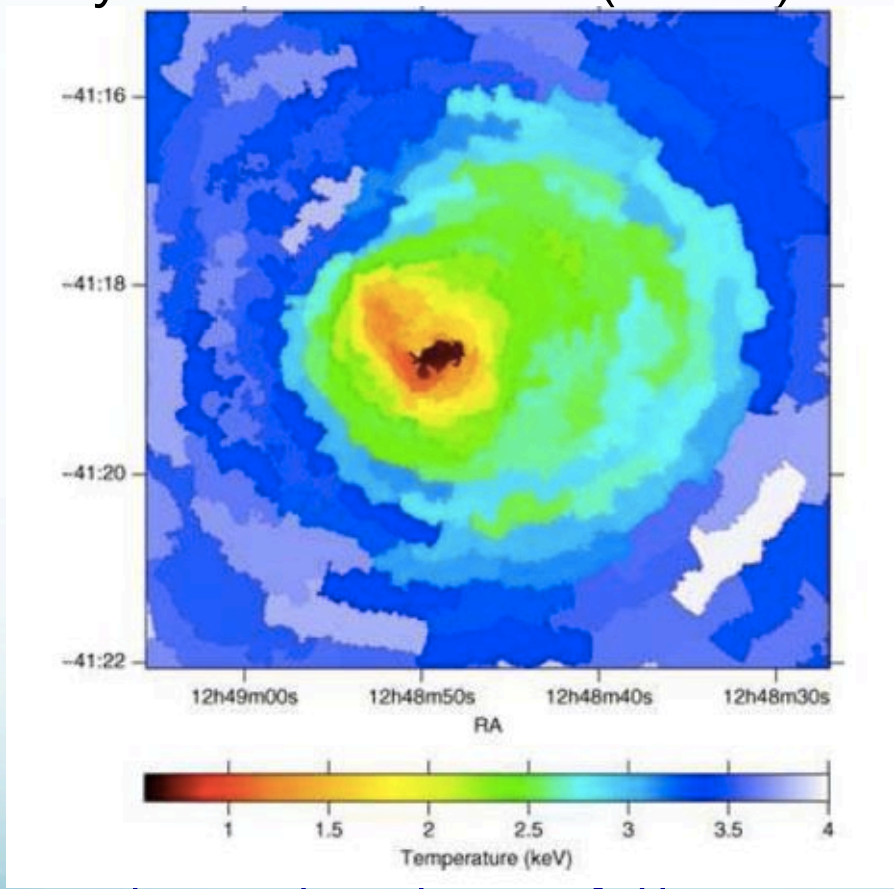


We need accurate response of detectors and Fe-L modeling

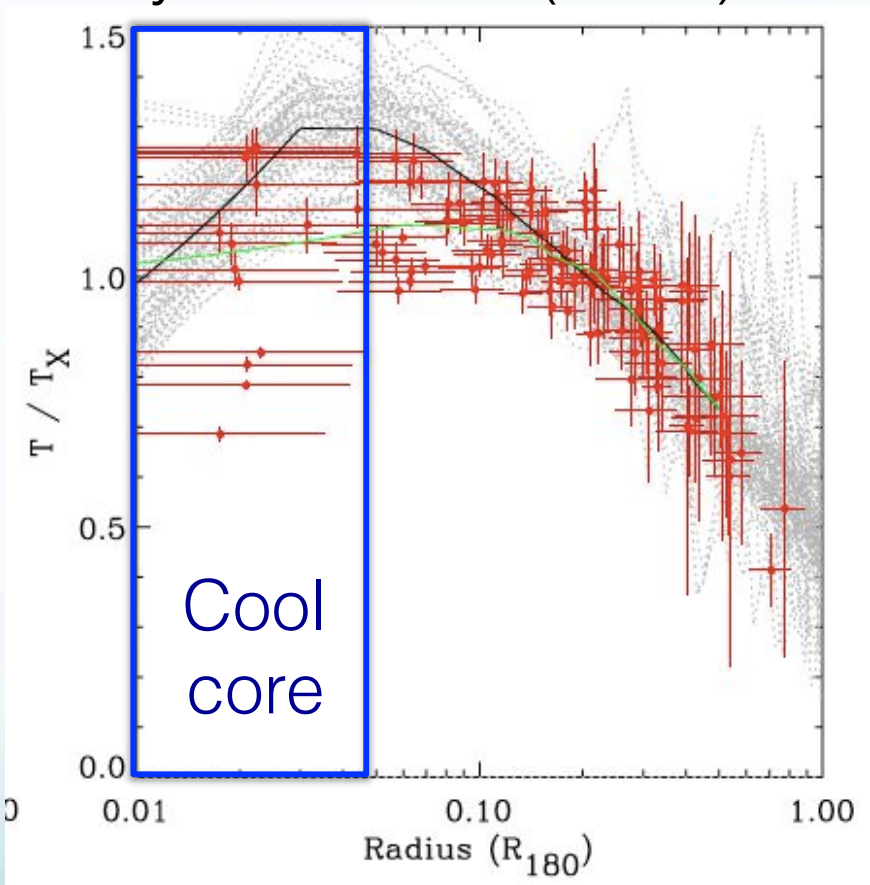
Xu et al. (2002), Hayashi et al.(2009)

Temperature structure of the ICM

Temperature map of the core of the Centaurus cluster by Sanders et al. (2006)



Scaled temperature profiles by Pratt et al. (2007)

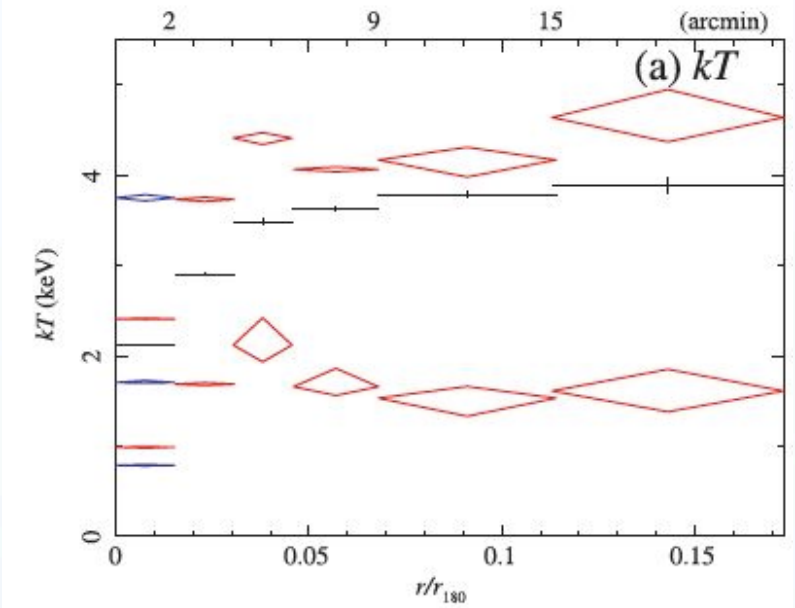


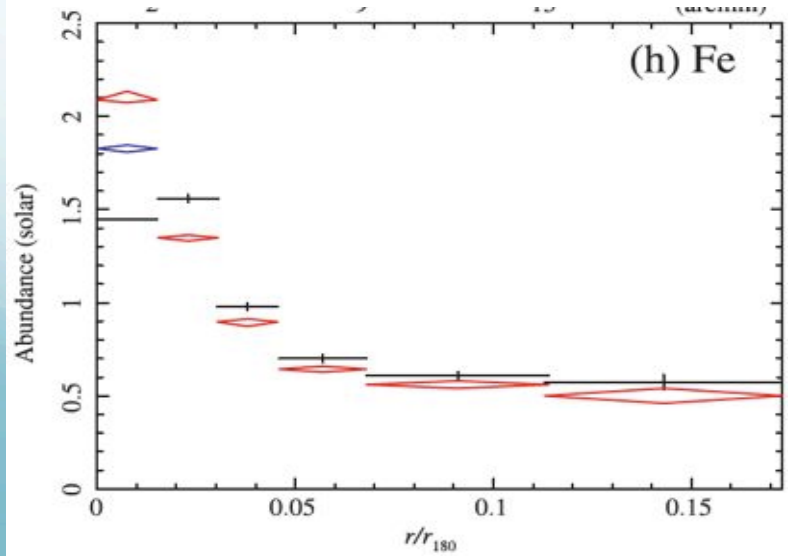
Temperature structure of the core regions is rather complicated

Relatively simple temperature structure outside cool core regions

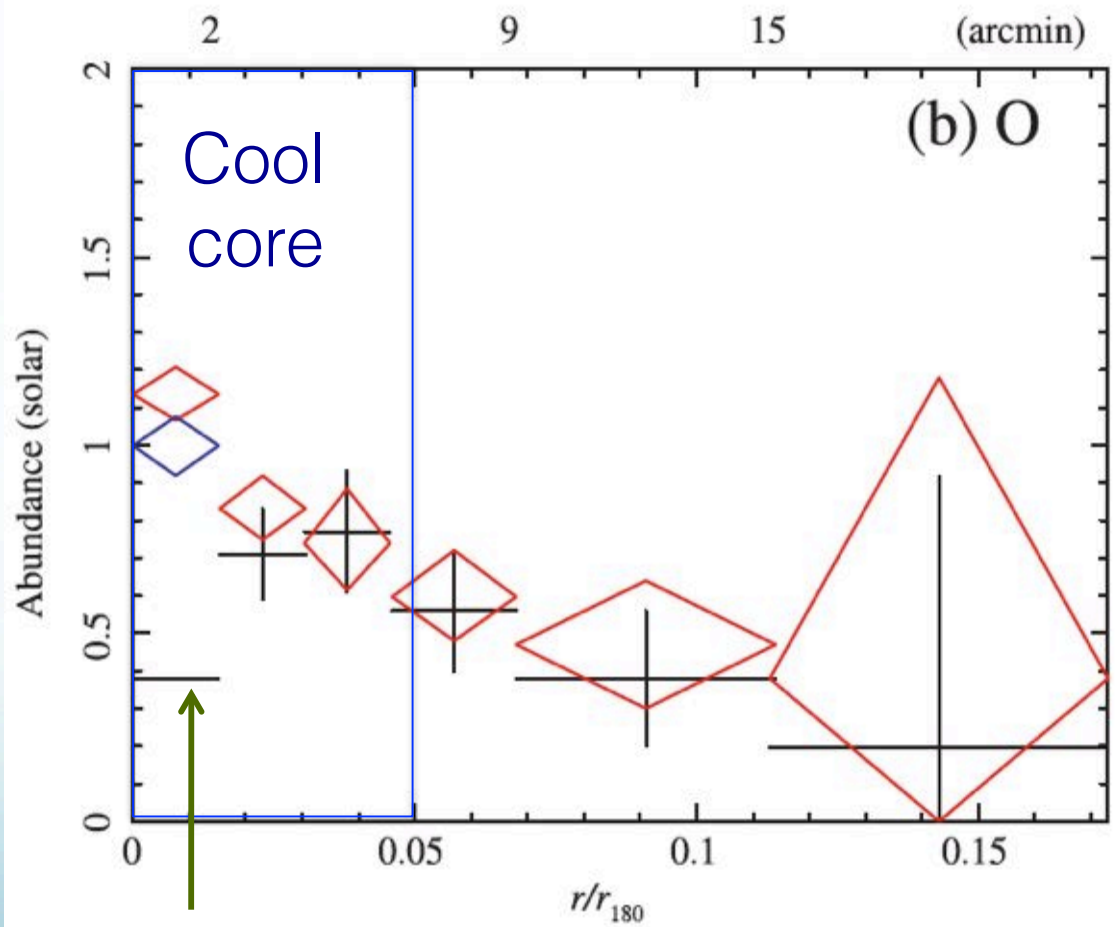
Effect of temperature structure

Radial profiles of temperature, O and Fe abundances in the ICM of the Centaurus cluster (Sakuma et al. 2011)





1T 2T 3T models for the ICM



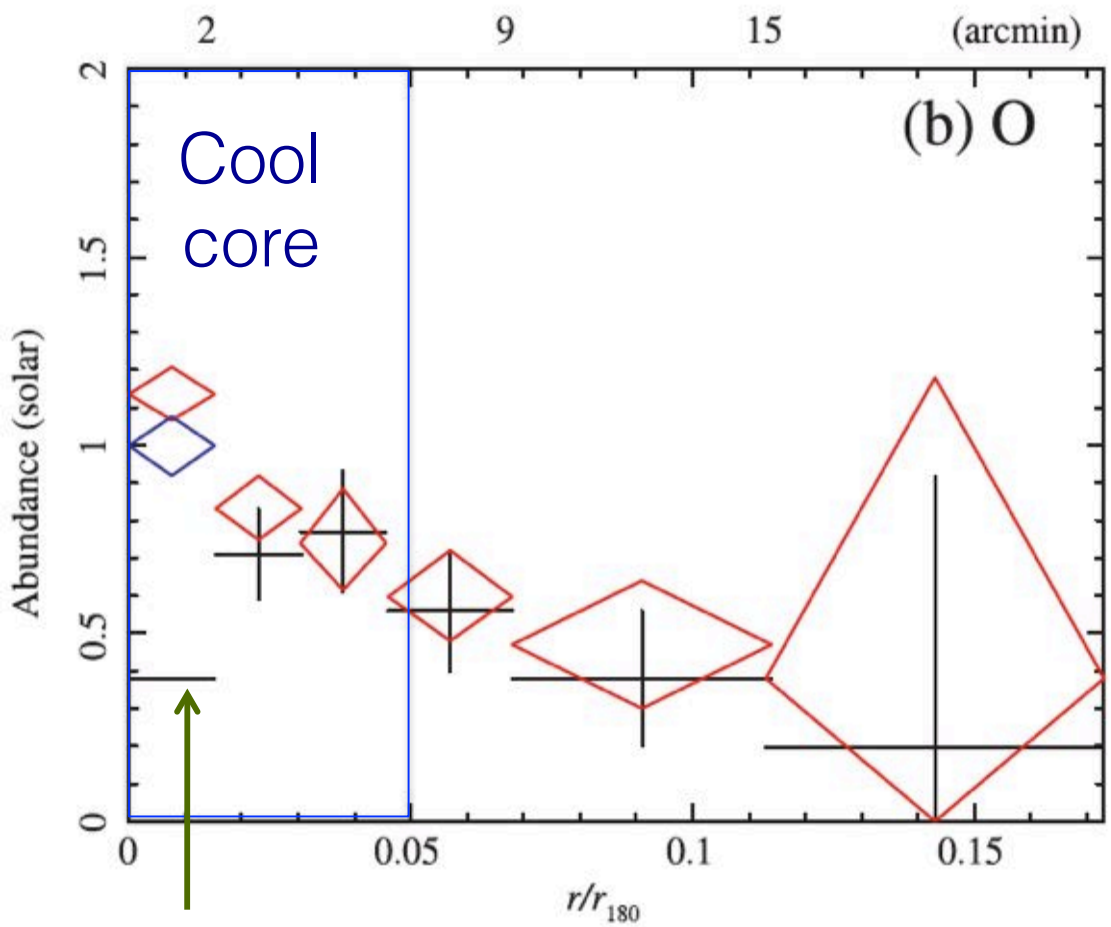
An unacceptable fit with large χ2

Effect of temperature structure

Radial profiles of temperature, O and Fe abundances in the ICM of the Centaurus cluster (Sakuma et al. 2011)

1T 2T 3T models for the ICM

- For data with poor statistics, be careful to the results of the 1T model fits especially in cool core regions where temperature structure is rather complicated



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Astro-H satellite

- Next japanese X-ray satellite (2014--) with a calorimetor detetor

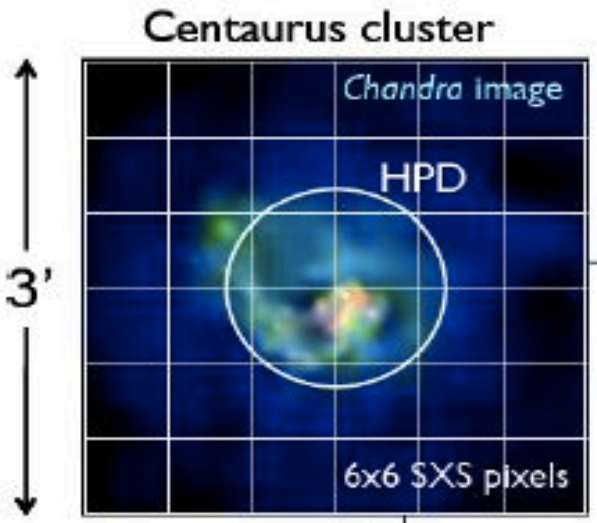
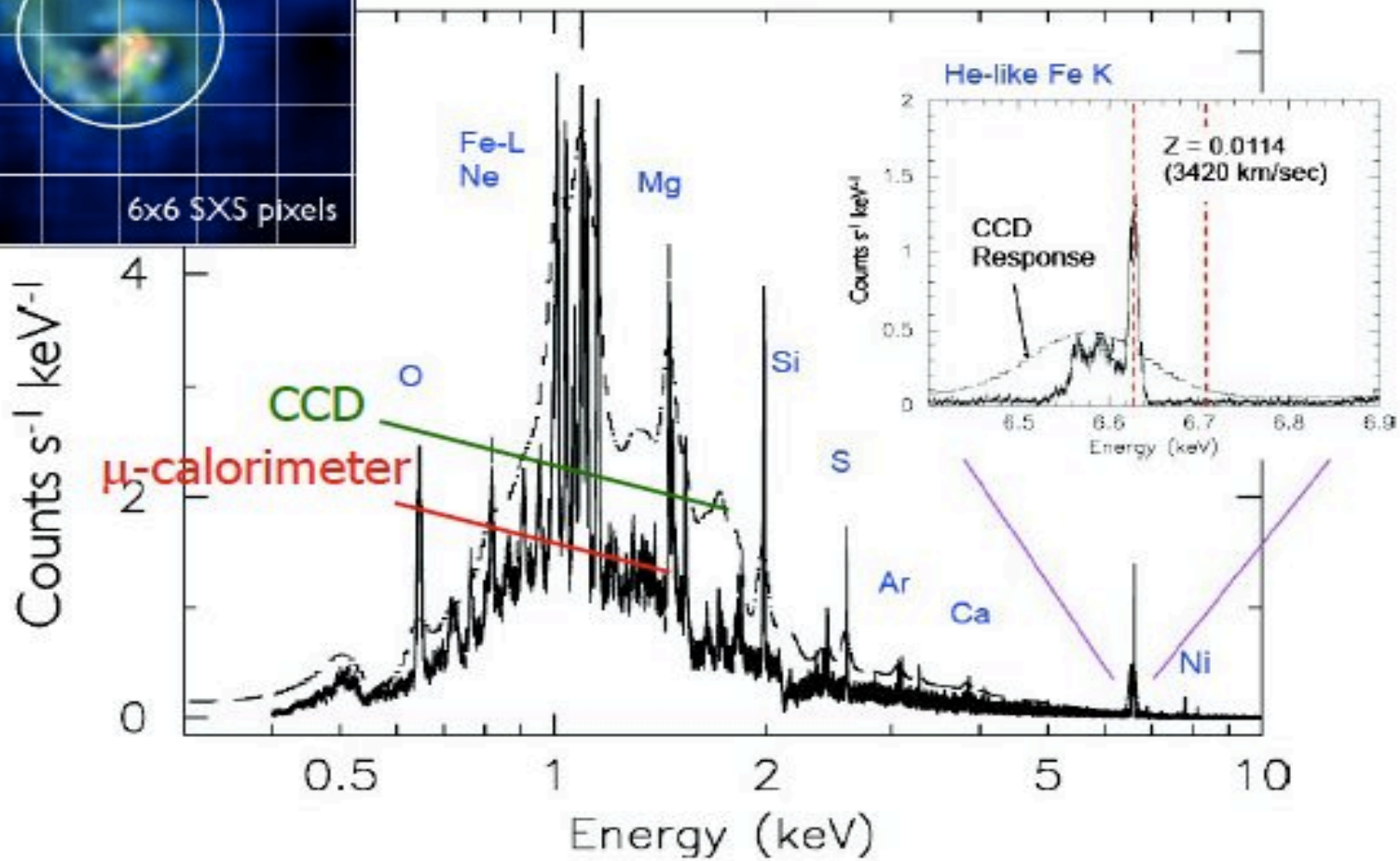
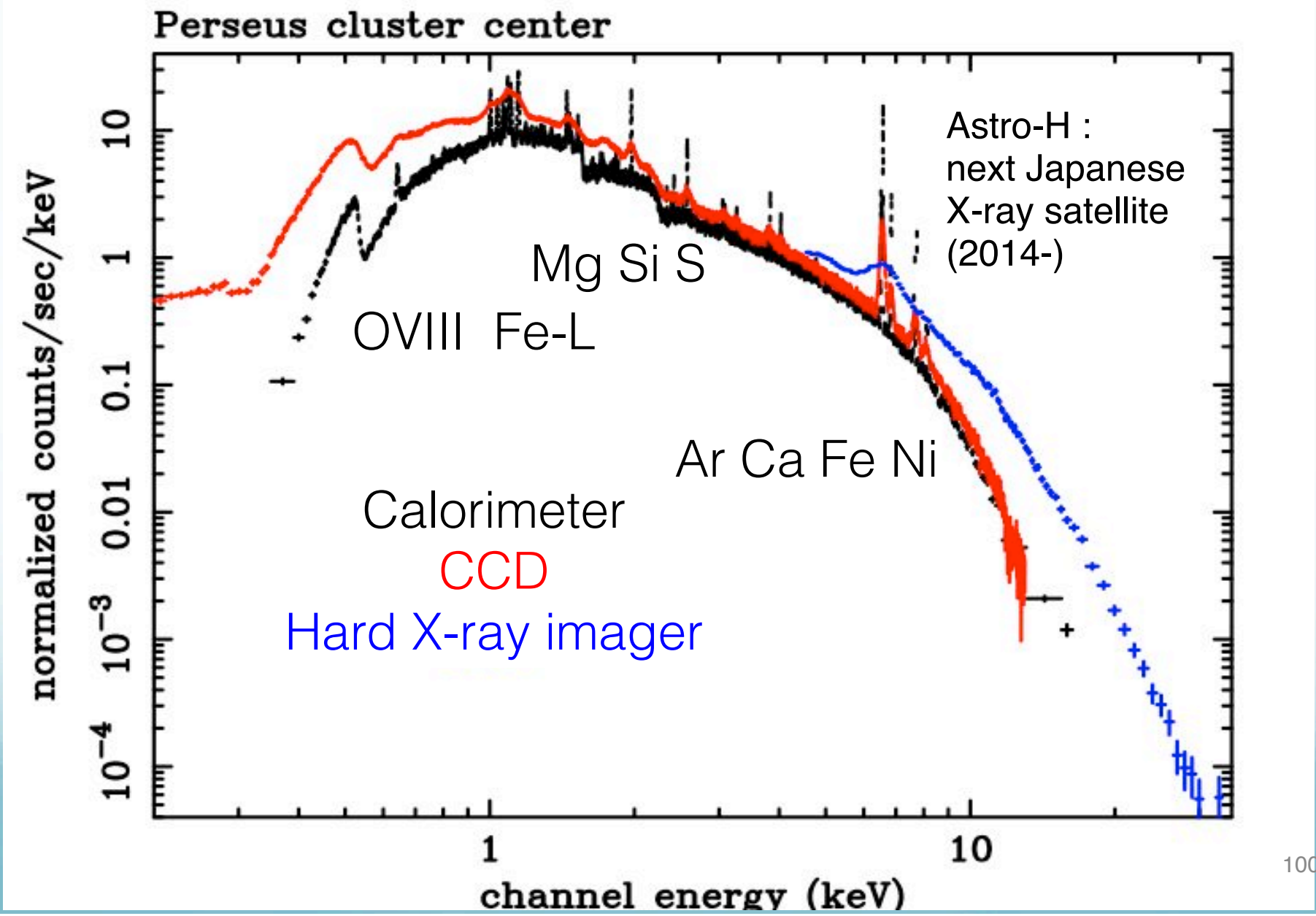


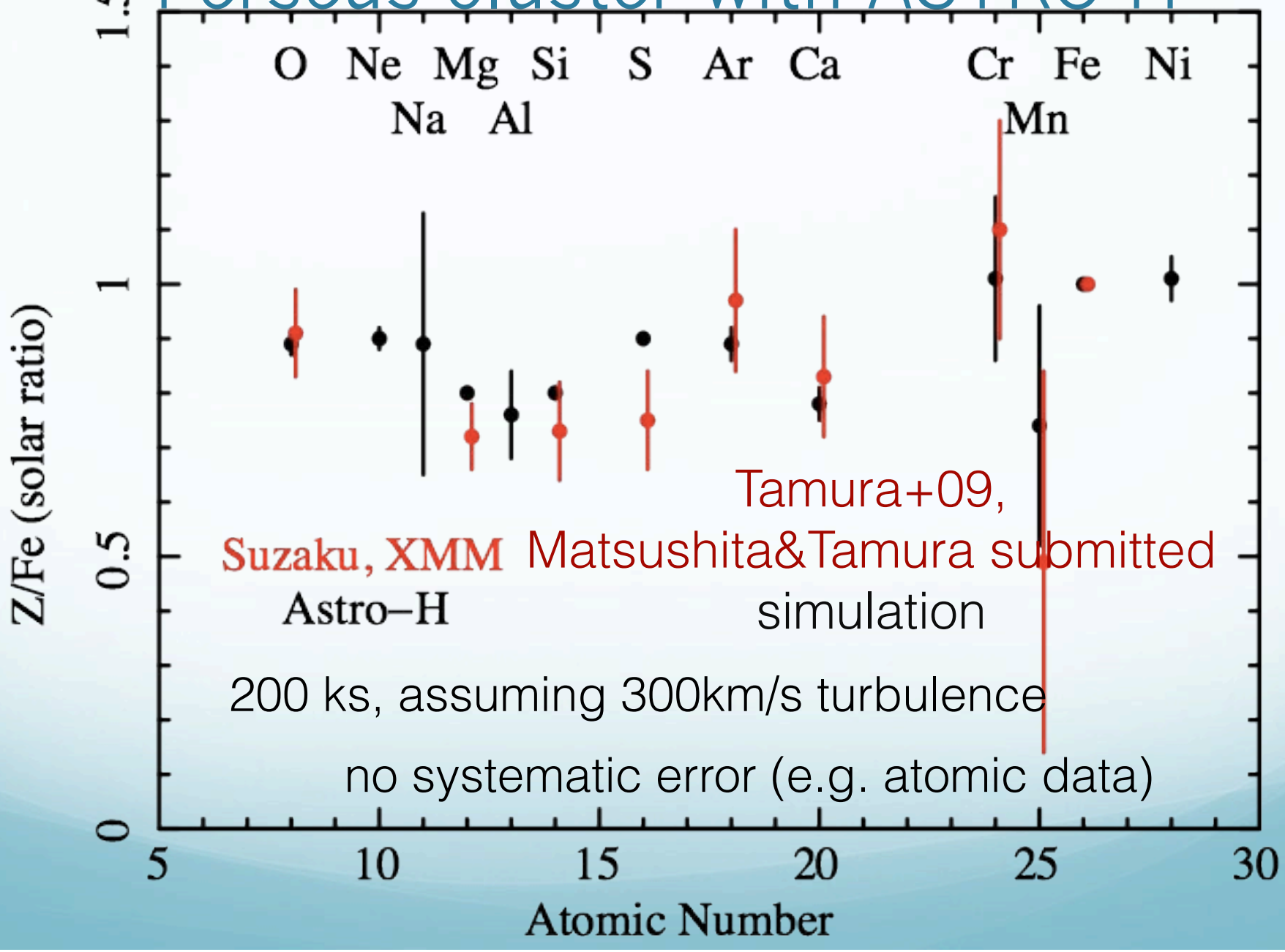
Fig. 3 *Simulated spectrum of Centaurus cluster.*



Simulated spectra from the Perseus cluster with Astro-H



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

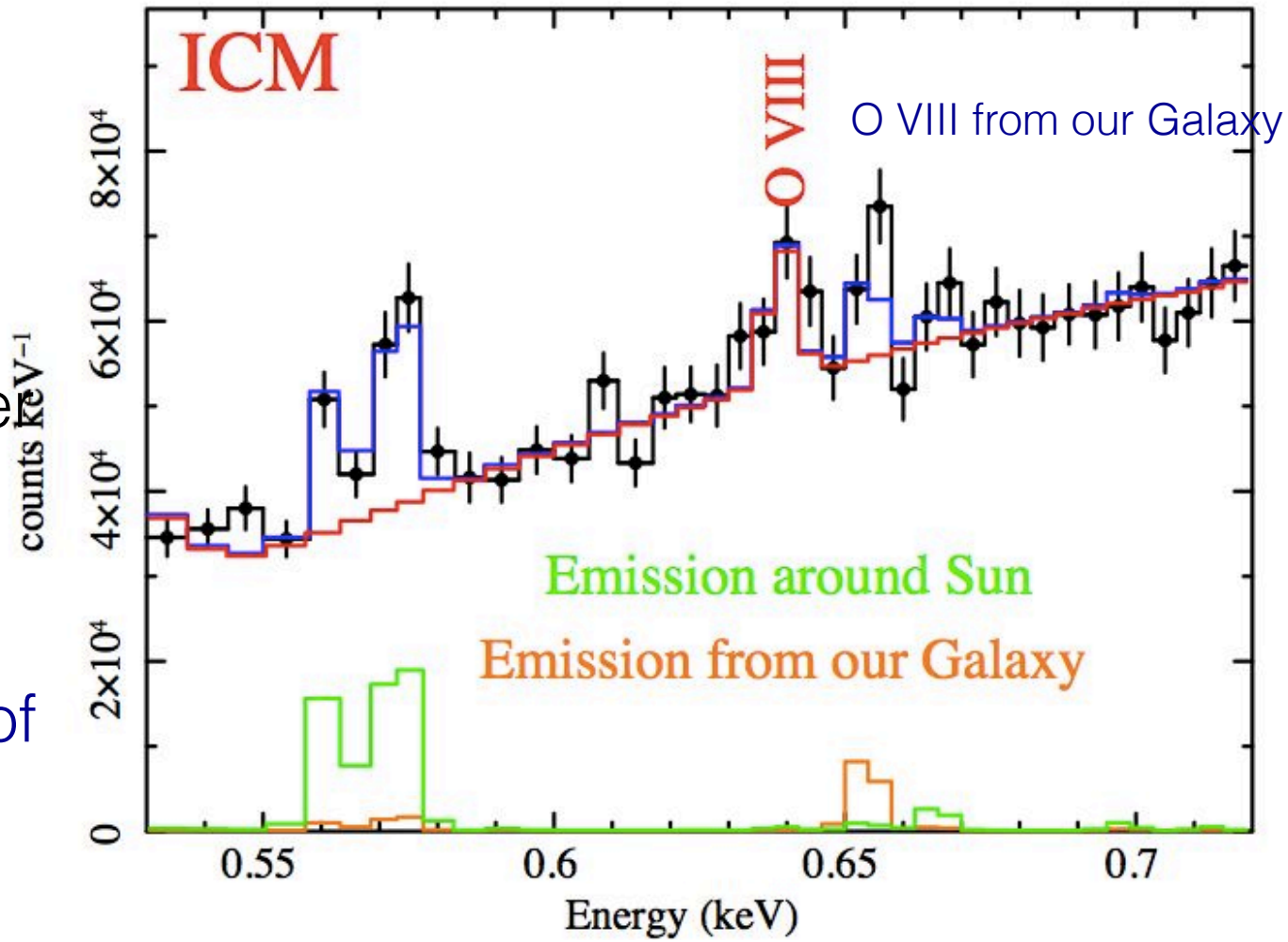


O measurement with Astro-H

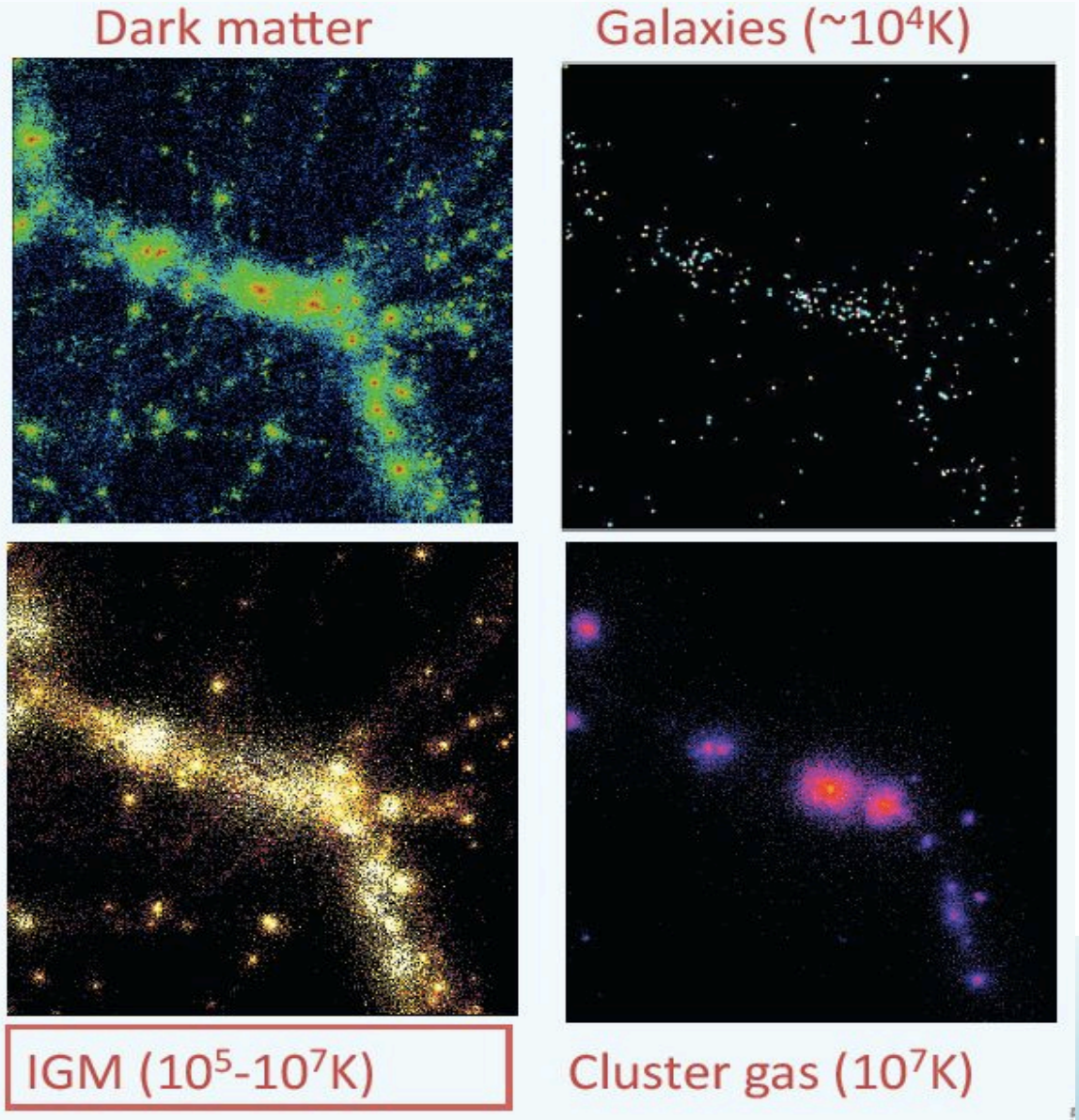
- We will be able to detect the O VIII line from the Coma cluster (kT=8 keV, redshift=0.02), one of the hottest cluster.

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

The effective area of the calorimeter is relatively small

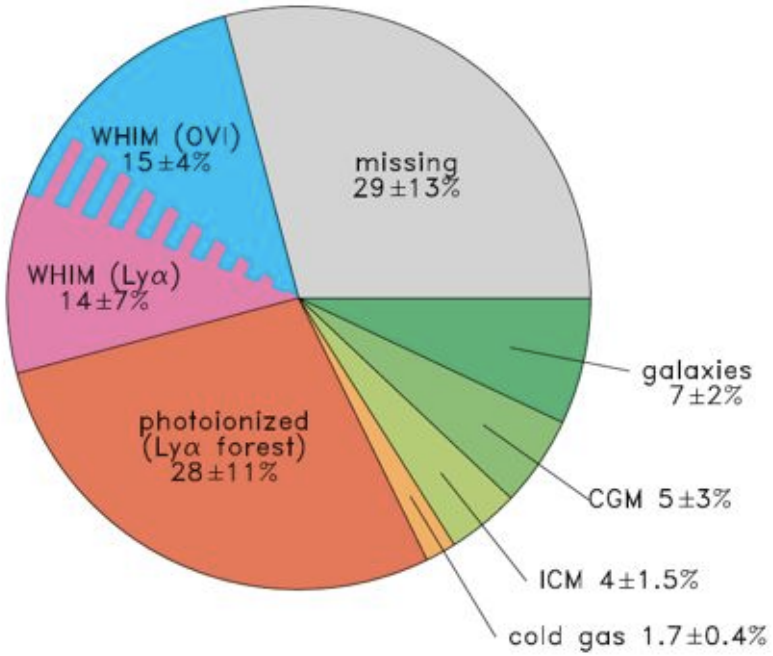


Warm-hot intergalactic medium



Shull et al. (2011)

Baryon census of low-redshift Universe

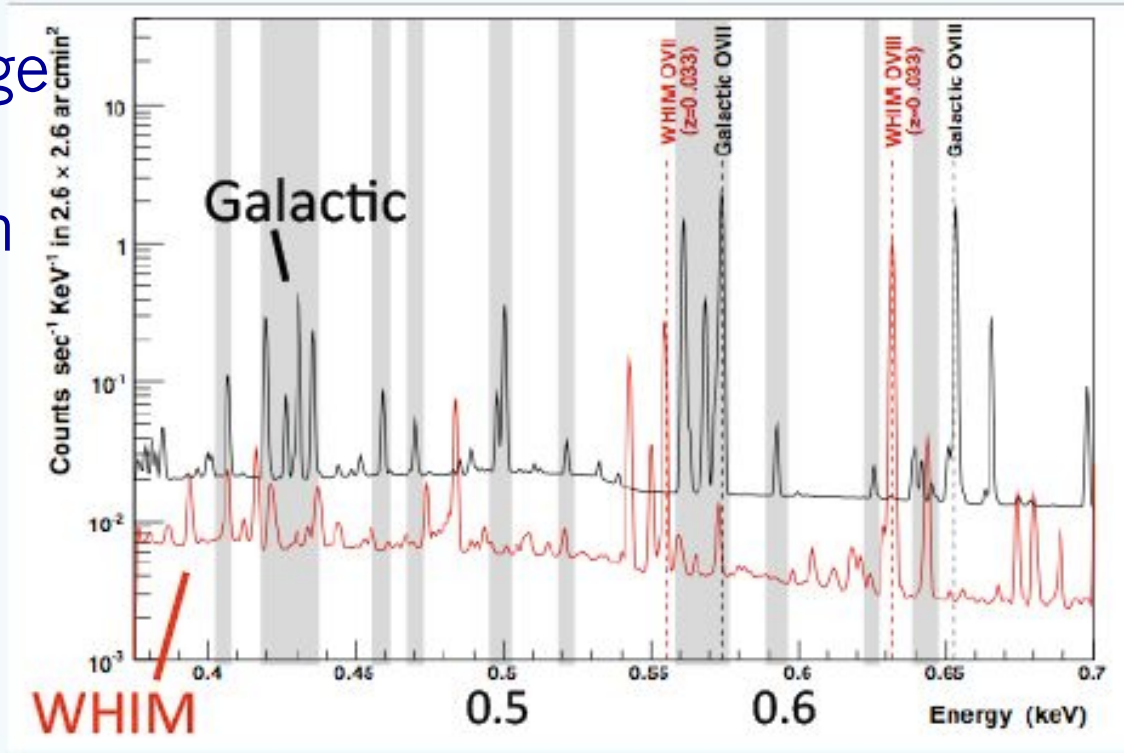


WHIM is the most likely candidate for missing baryon

Numerical simulations by Yoshikawa et al. (2001)

Search for Warm-Hot-Intergalactic Medium

- Several satellites to search WHIM with O VII and O VIII emission lines are proposed
- To derive total amount of Oxygen in the Universe, we need observations of WHIM
- These satellites have large field of views and also suitable to derive Oxygen mass of ICM of clusters and groups of galaxies



Simulated spectra with an X-ray satellite for WHIM

Metals within core regions and in early-type galaxies

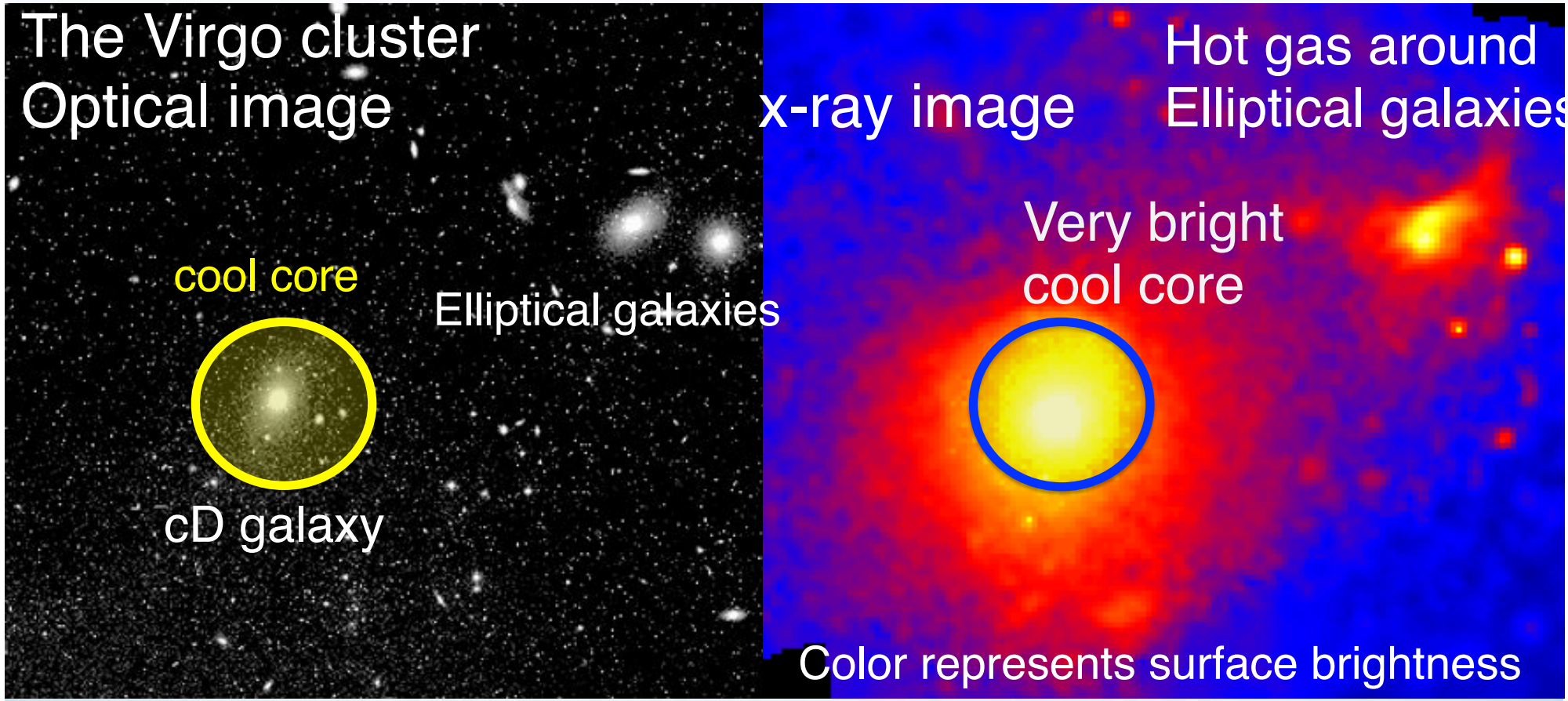
cD galaxies eject metals via SN Ia and stellar mass loss

SN II?

Abundance pattern of O/Mg/Fe within cool cores

Comparison with abundance pattern of elliptical galaxies – present supply of metals into ICM

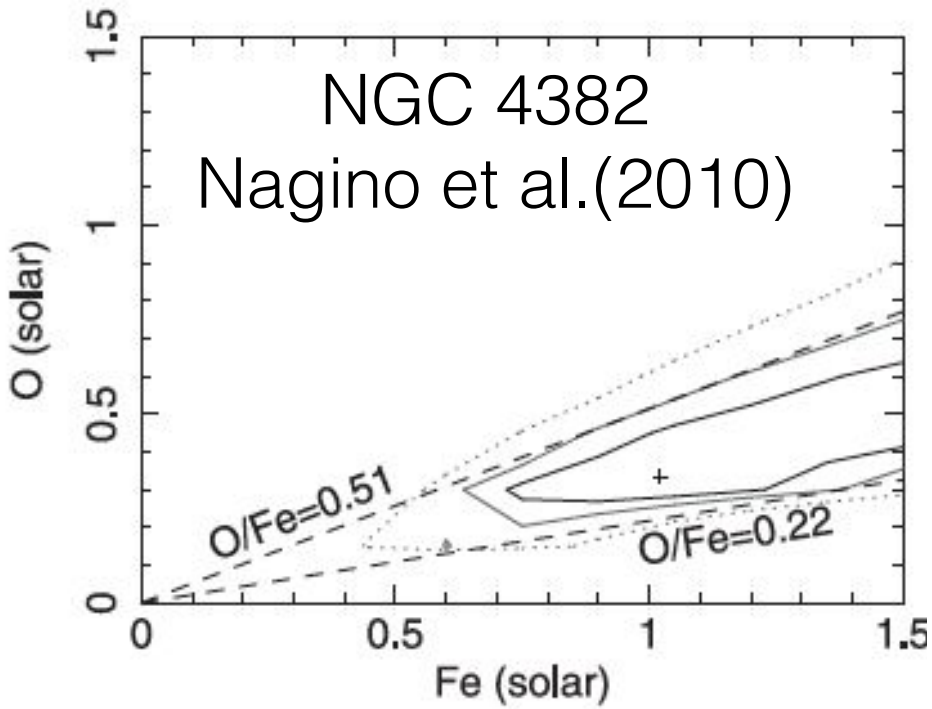
Metals in hot gas in cD galaxies and elliptical galaxies



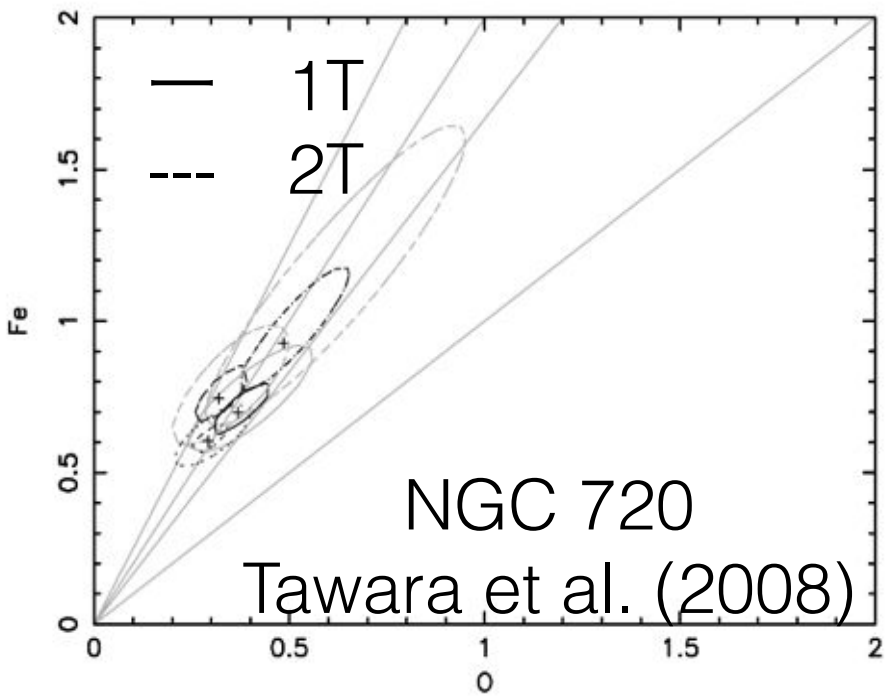
Metal supply from the cD galaxy is important in cluster core regions.

Metals in hot gas in elliptical galaxies -- those synthesized by recent SN Ia and those come from stellar mass loss

Confidence contours of O and Fe abundances in the ISM



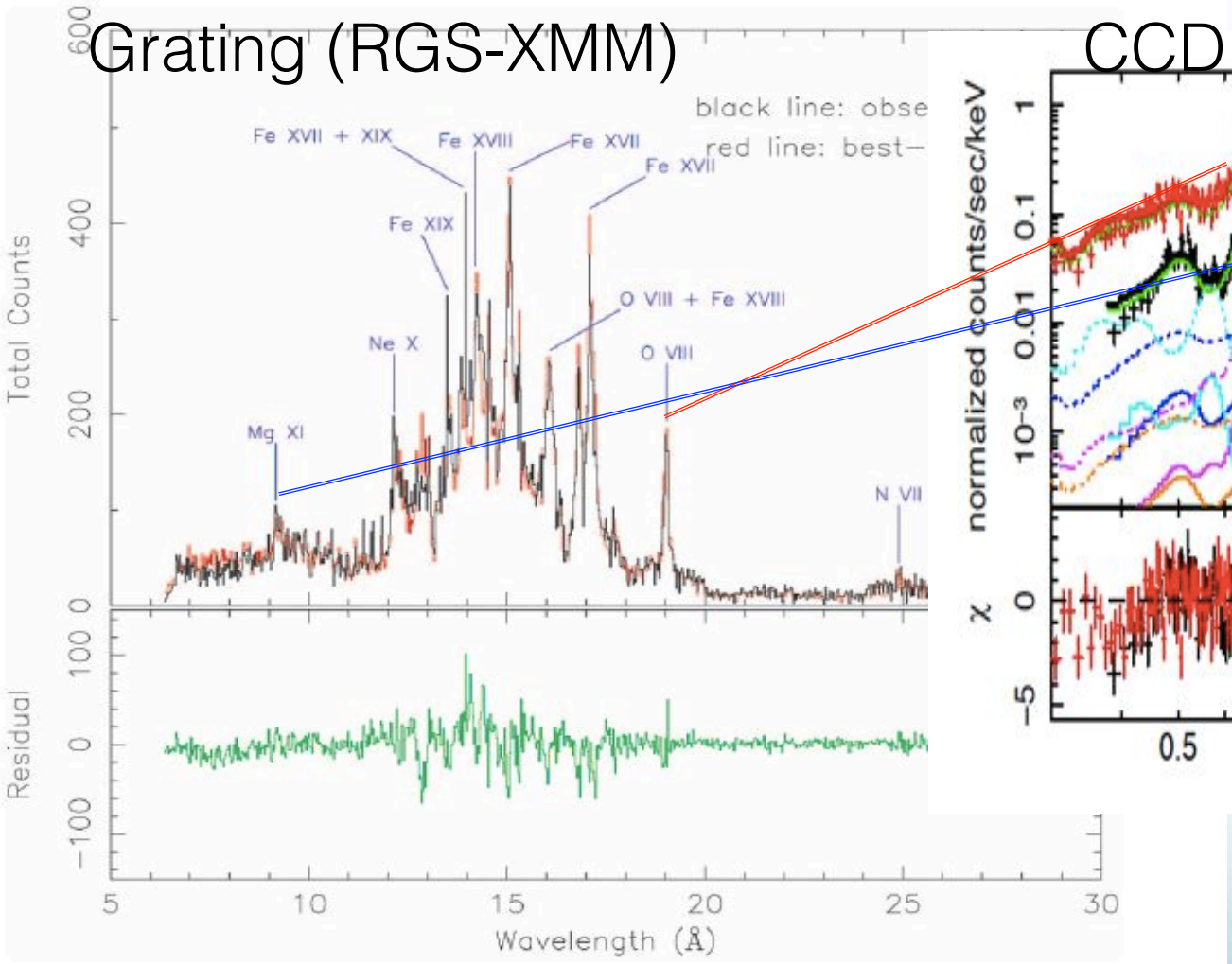
Solar abundance table Lodders (2003)

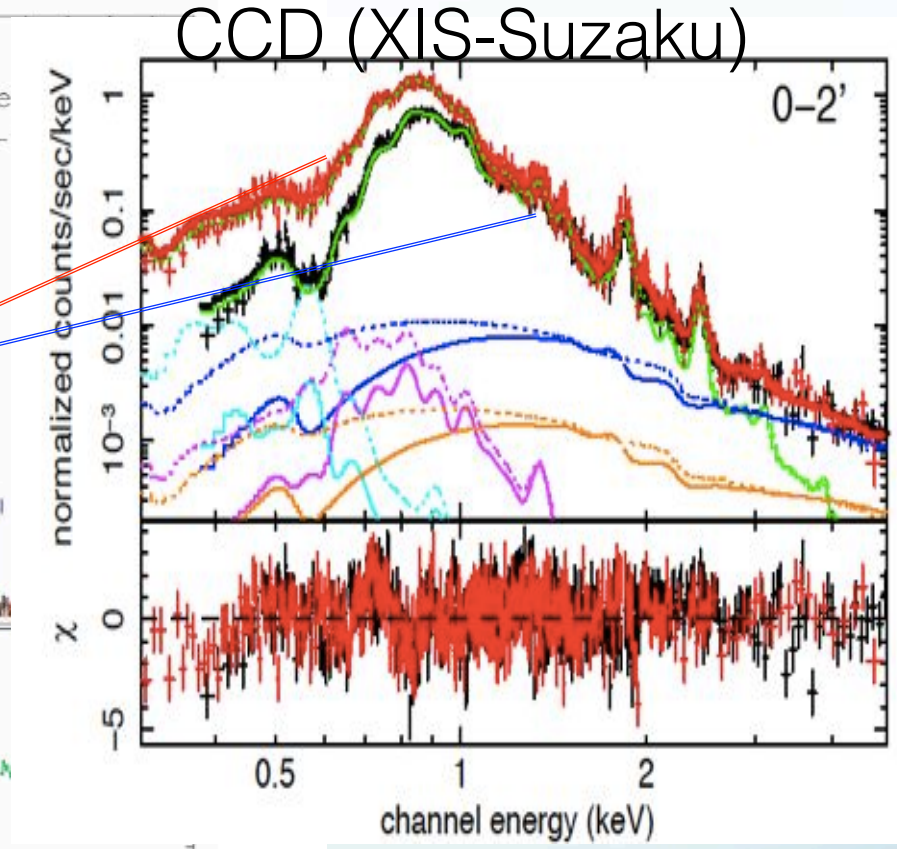


Feldman (1992)

- The elongated shape of the confidence contours indicates that the relative values are determined more accurately than the absolute values.
- Line emission dominates the spectra and abundances affect the confidence level

X-ray spectra of NGC 4636 (X-ray luminous E gal) 0.6 keV



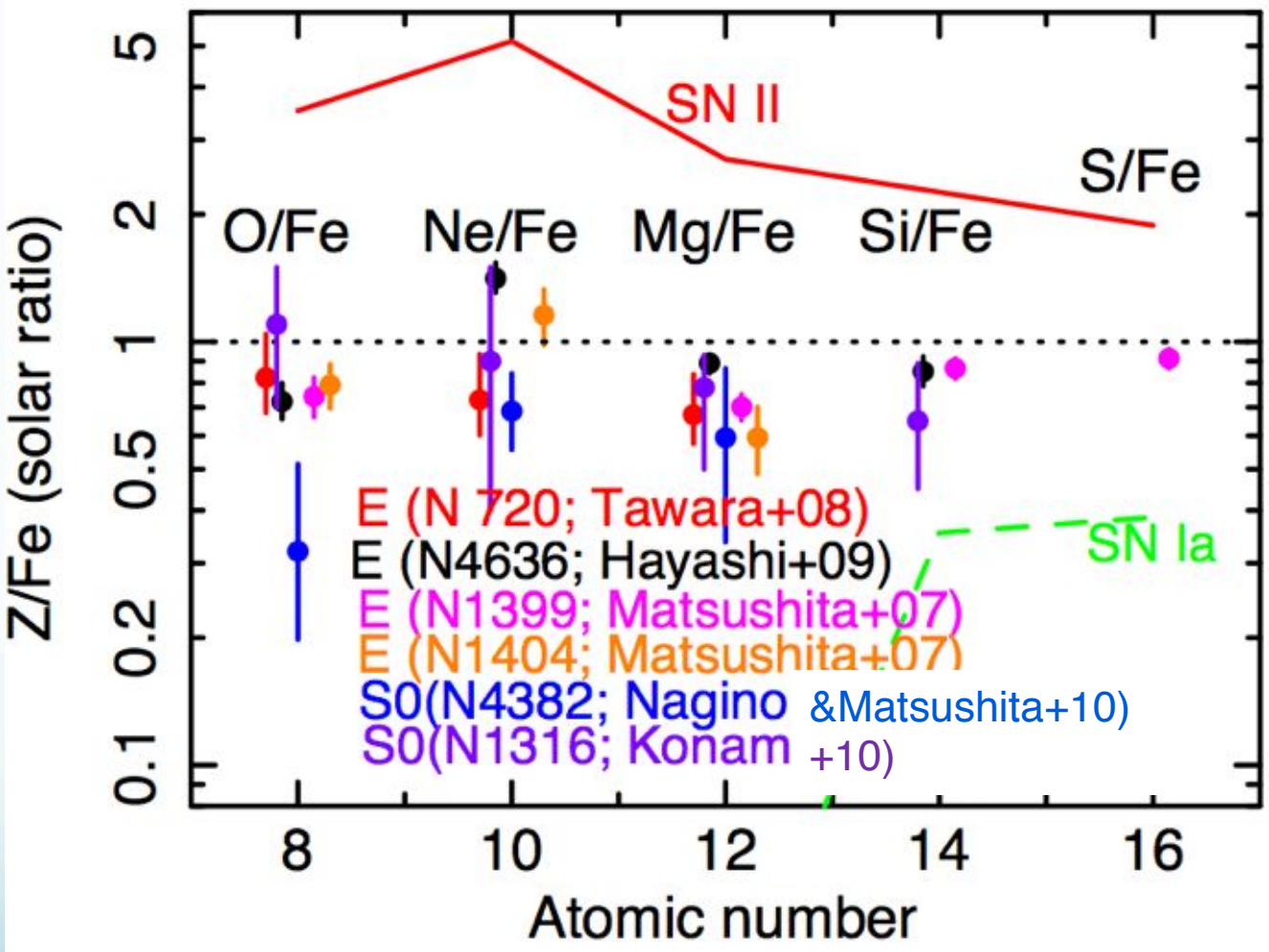


Xu et al. (2002), Hayashi et al.(2009)

Abundance pattern of ISM in Es and S0s observed with SUZAKU

Solar abundance pattern! (except a S0)

most of Fe come from SNe Ia



using the solar abundance by Loddars (2003)

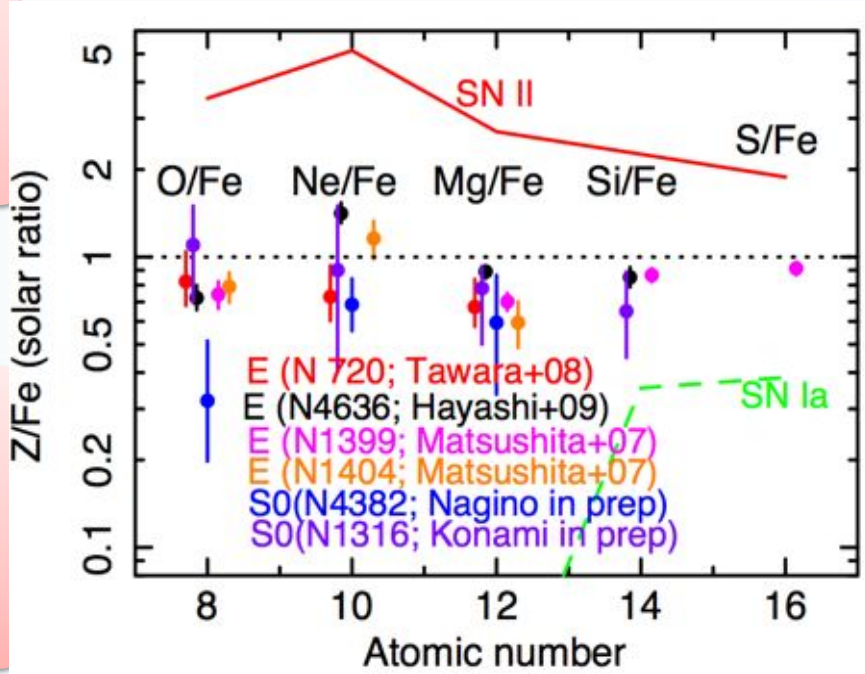
Abundance pattern of ISM in E and S0 observed with SUZAKU

abundance pattern of O, Ne, Mg, Si, Fe is nearly solar except N 4382

Mixture of metals from recent SNe Ia and mass loss

- significant fraction of Fe should come from recent SN Ia

supports enhancement of [α/Fe] of stars in these giant ET galaxies



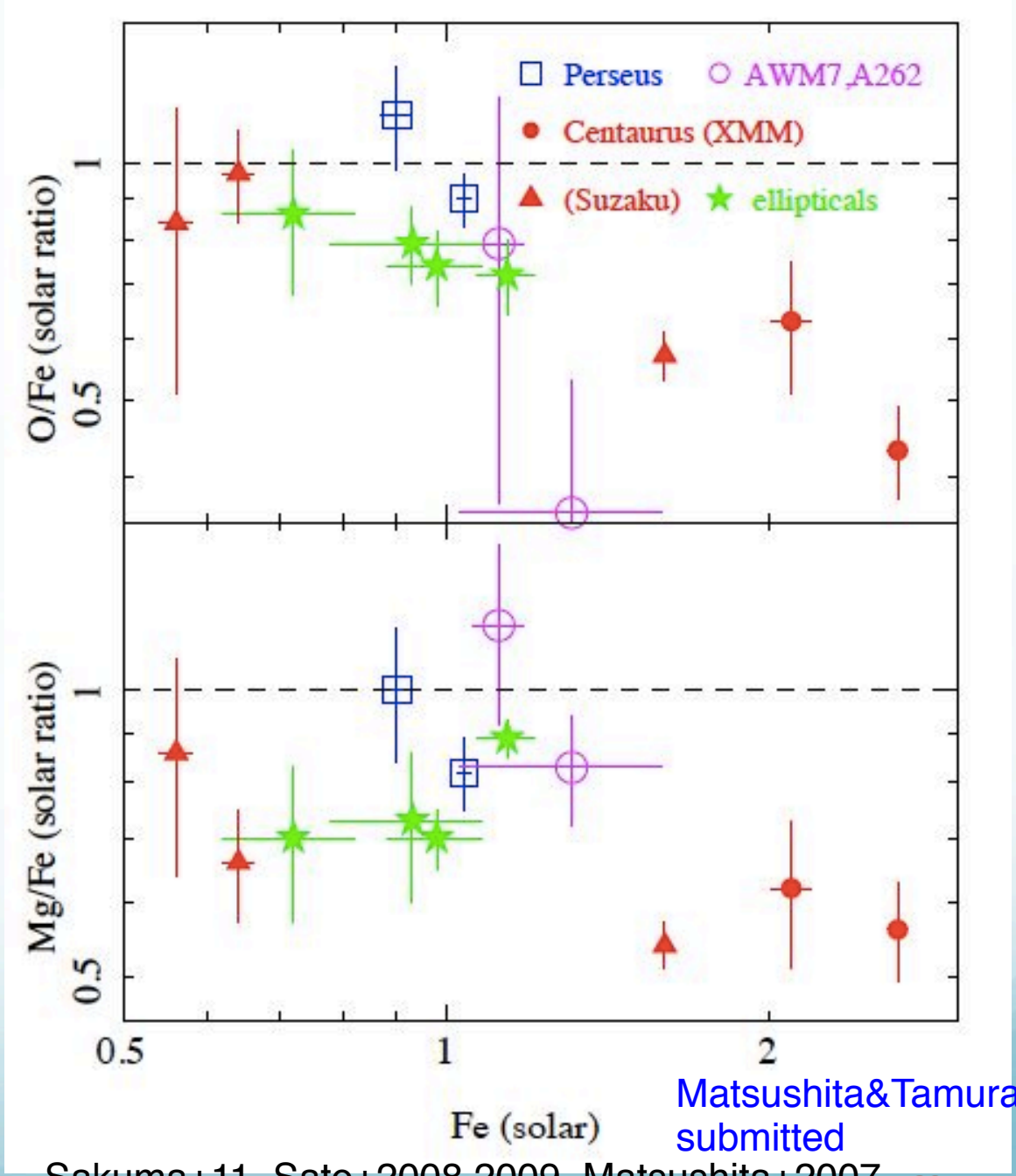
using the solar abundance by Lodders (2003)

O/Fe, Mg/Fe vs. Fe abundance in cool cores and ellipticals

The cool core of the Centaurus cluster has a very high central Fe abundance and lower O/Fe and Mg/Fe ratios

Contribution of SN Ia is higher

Not a simple accumulation of hot ISM in ellipticals



Matsushita&Tamura submitted

Sakuma+11, Sato+2008,2009, Matsushita+2007
Tawara+08, Hayashi+09

Stellar metallicity in E and S0 galaxies

The observed O and Mg abundances of ISM in ellipticals are 0.5-1 solar

- These metals come from stellar mass loss
- The O and Mg abundances of ISM are consistent with stellar metallicity observed with optical Mg2 index

The solar abundance pattern of ISM indicates supersolar α/Fe considering the contribution from SN Ia

reflecting star formation history in Ellipticals.

The oxygen abundance from X-rays : methods and prospects

K. Matsushita

Where are oxygen synthesized in stars?

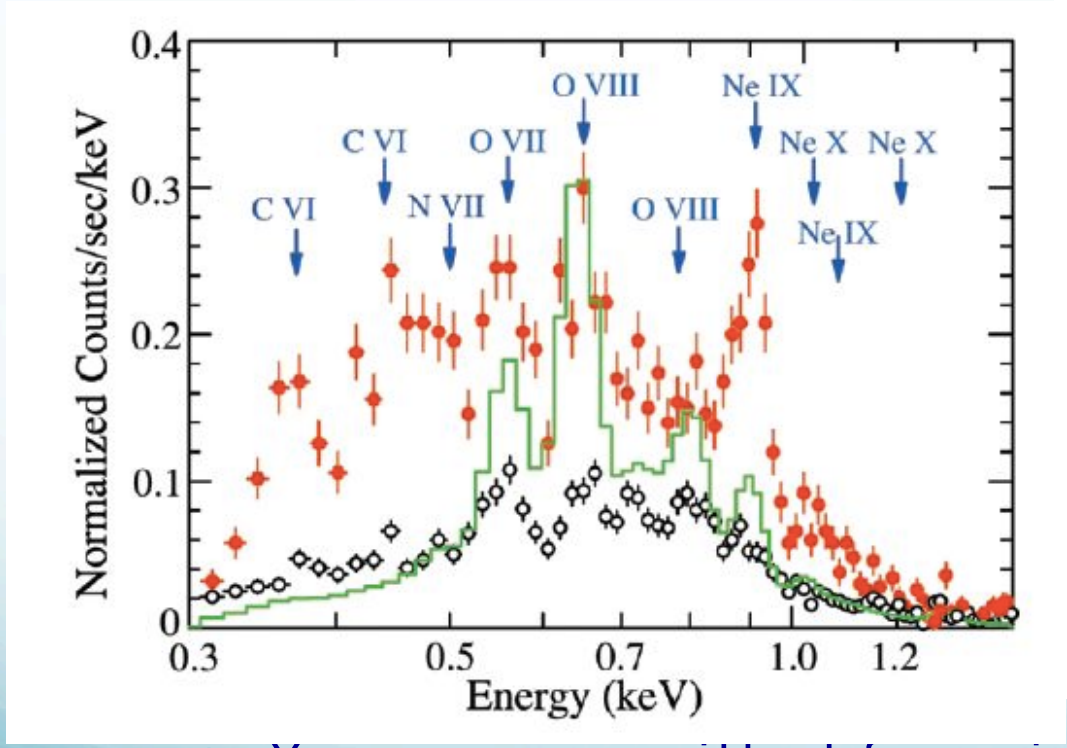
- Hot intracluster medium,
- warm hot intergalactic medium?
- Hot interstellar medium in early-type galaxies

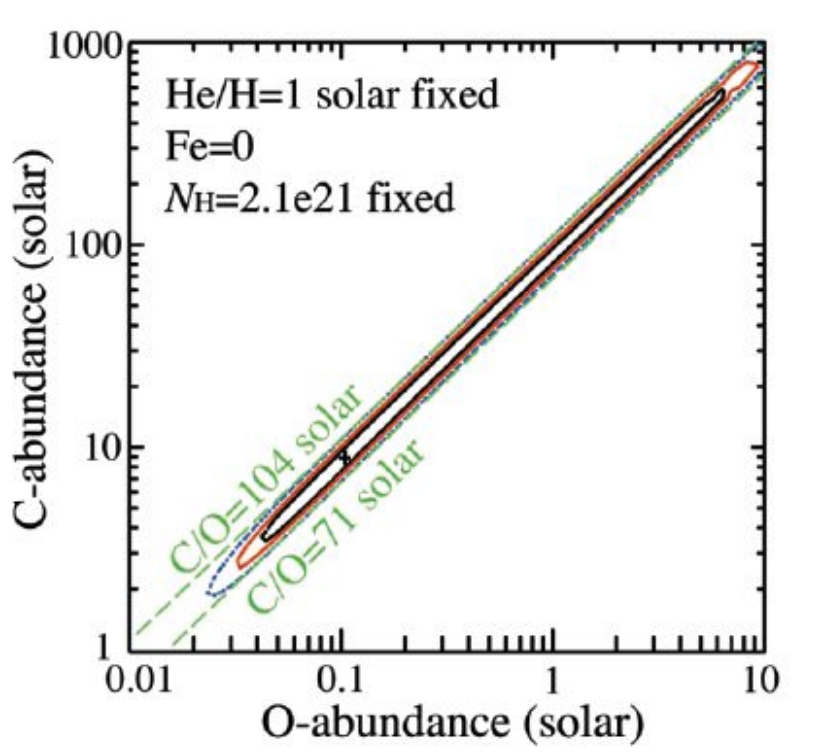
O Synthesis in our Galaxy

- Planetary nebulae
- Suparnova remnant

High C/O ratio of the X-ray emitting planetary nebula BD 30 3639 with Suzaku X-ray satellite (Murashima +2006)

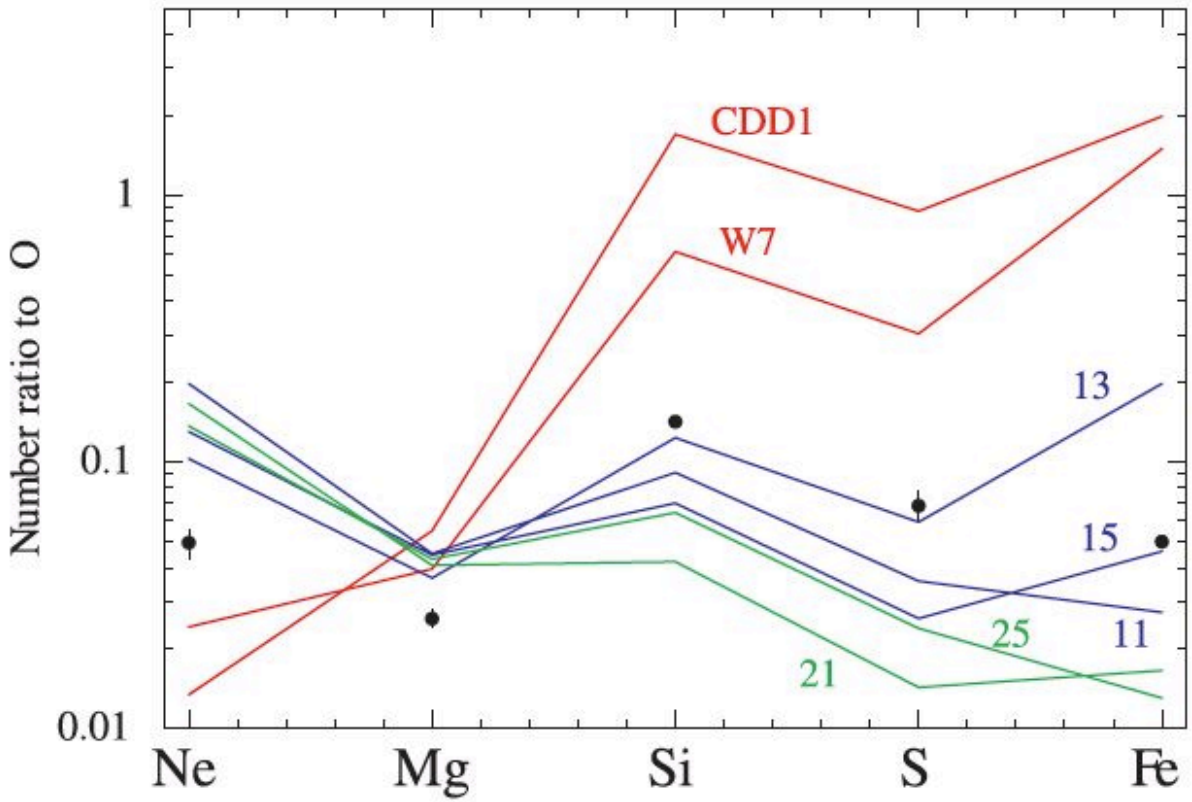
- observed o background
  - old solar abundance ratio

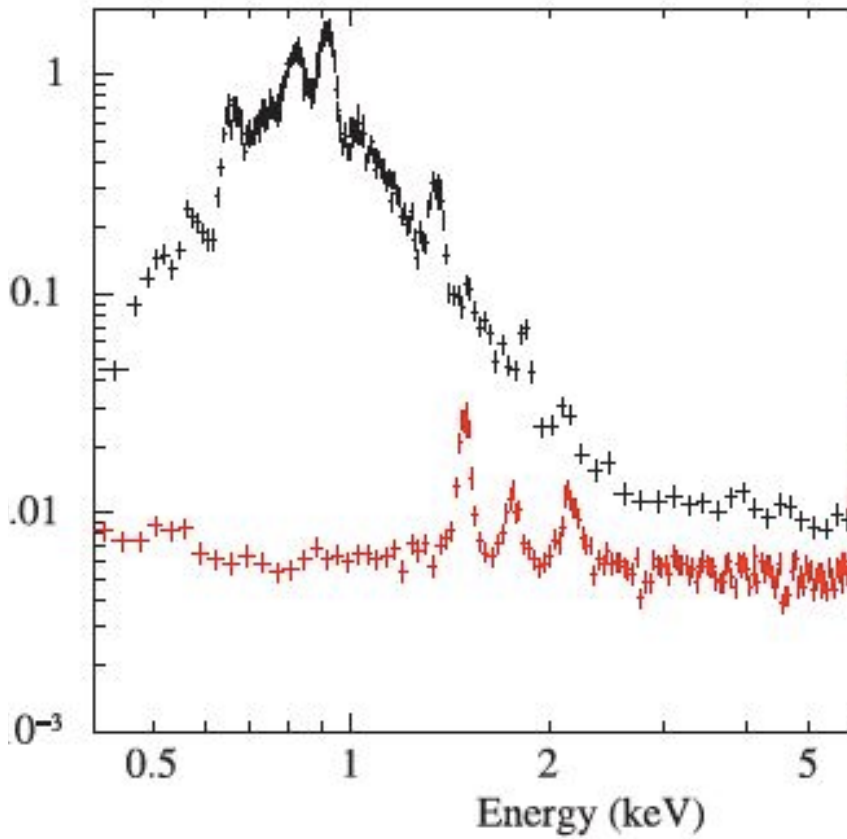




- X-rays are emitted from innermost region of the PN, mainly by helium-shell-burning products

Suzaku Observations of Thermal and Non-Thermal X-Ray Emission from the Middle-Aged Supernova Remnant G156.2 (Katsuda et al. 2009)





- Plasma of SNR is much more complicated than that in clusters because of shorter timescale
- Time scale is not enough to reach ionization equilibrium