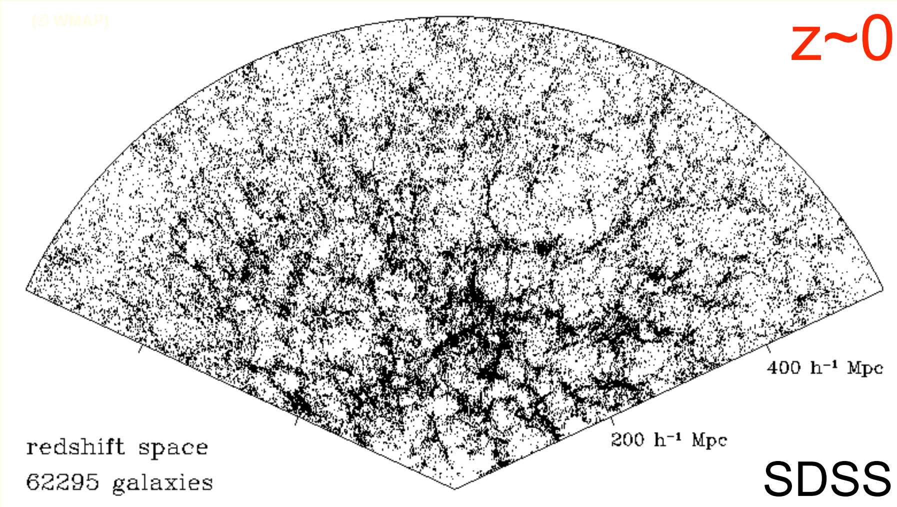
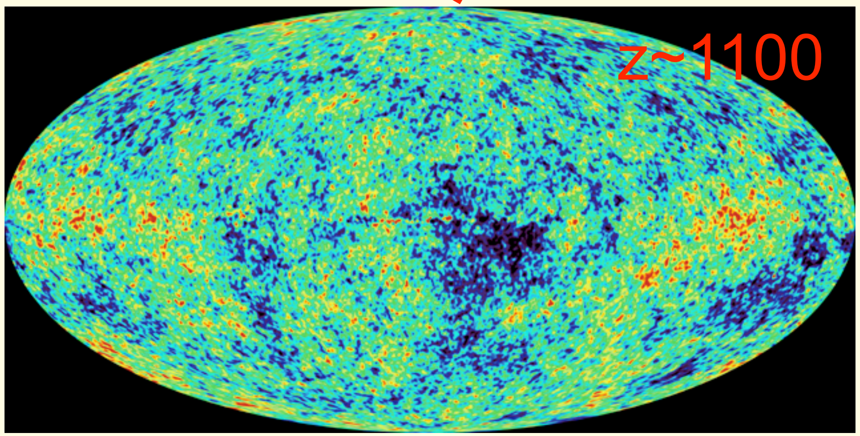
How do galaxy clusters form and evolve over cosmic time ?

M.Arnaud (CEA/Sap)

Structure formation in the Universe



?

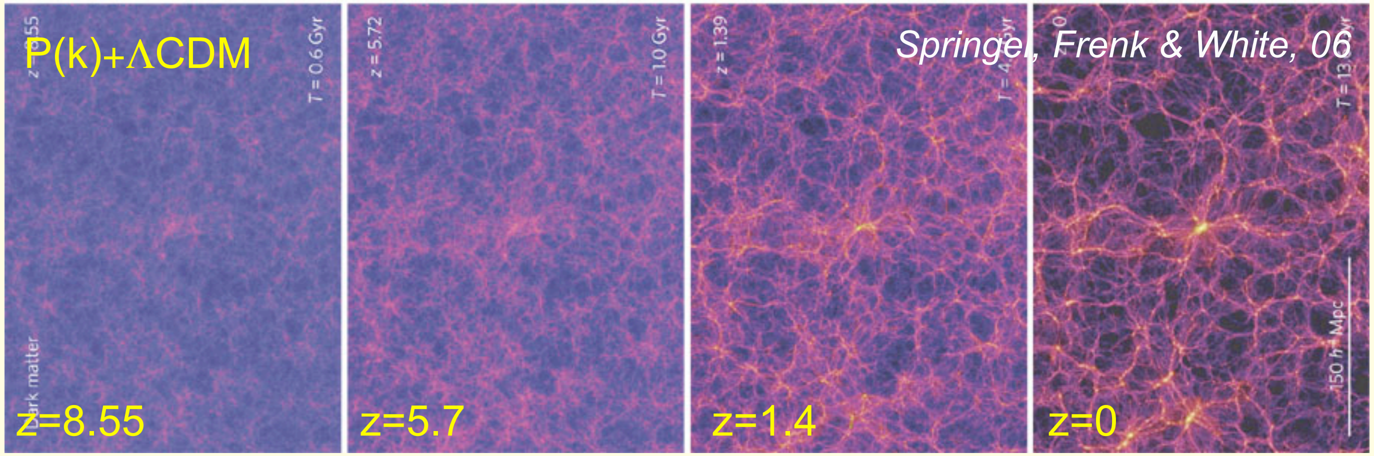


A highly structured Universe
(stars, galaxies, clusters, filaments, voids..)

How did structures form and evolve ?

from initial density fluctuations

Structure formation in the Universe



General scenario: hierarchical formation of structures via gravitation

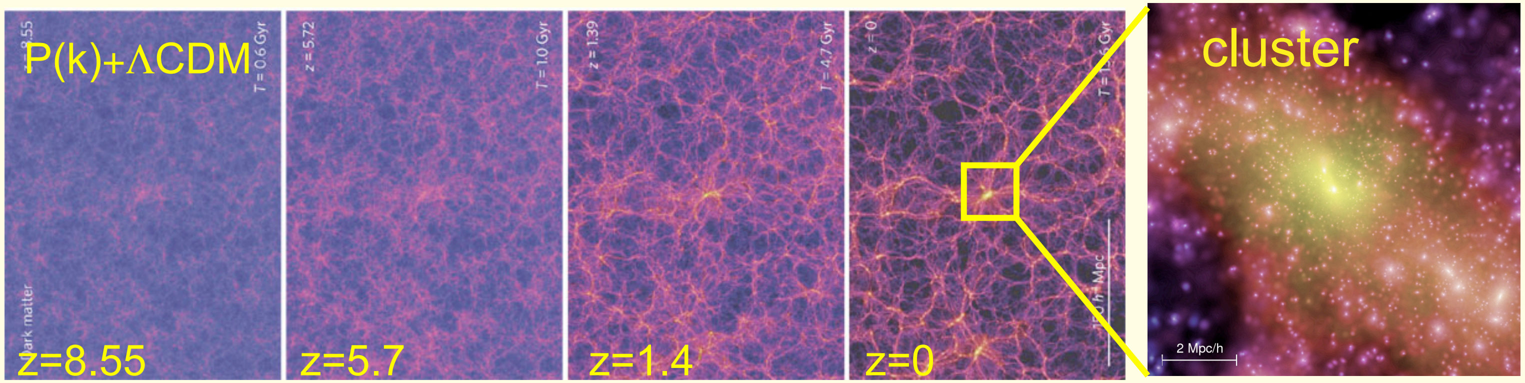
Major Progresses

- Boundary conditions known: P(k) and convergence cosmological model
- Dark matter collapse ~ understood (down to cluster scale)

The history of visible matter (baryons) NOT understood

- gas dynamics much more complex than for DM
- extra physics : cooling, SF, SMBH growth and associated energy &metal release

Structure formation in the Universe



Structure formation at all scales are deeply connected
must simultaneously study the hot and cold components

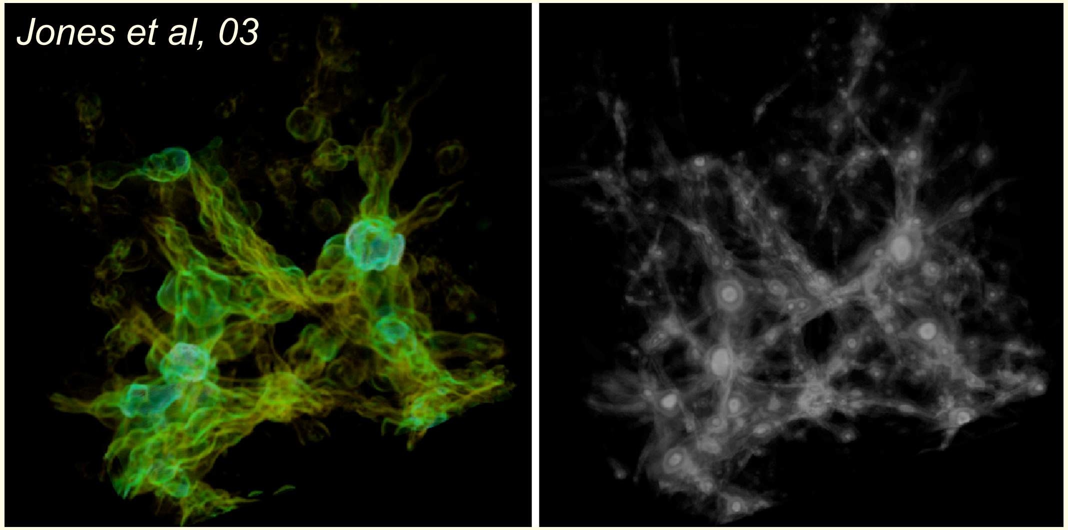
X-ray observations to study

Co evolution of galaxies and their SMBH

Clusters of galaxies (hot gas trapped in dark matter potential)
the largest bound mass concentrations from z ~ 2 till now

Warm/hot filaments
since z ~ 1-2

The physics of hierarchical cluster formation

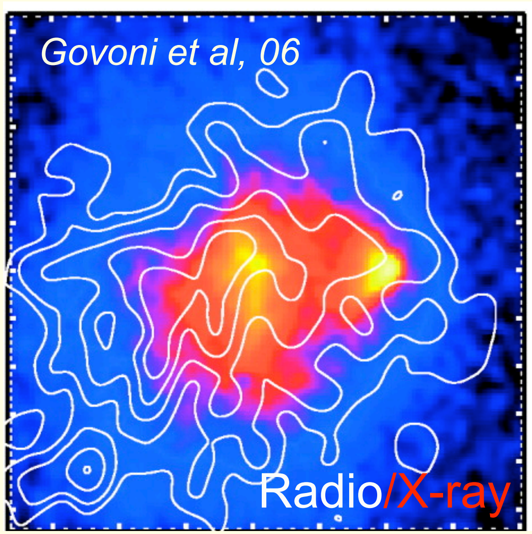


Clusters growth by mergers and matter infalls along filaments

Baryons history: first driven by gravity

Gas “follows” Dark Matter; gravitational heating in potential wells

The physics of hierarchical cluster formation



Open question: energy redistribution during hierarchical formation process

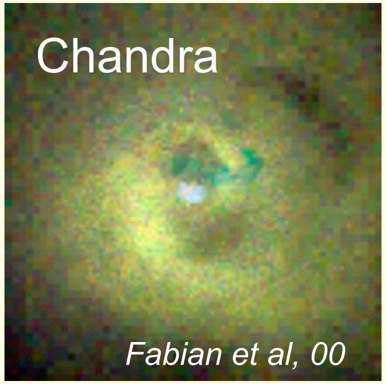
- How the gravitational energy is dissipated into the thermal gas ? shock heating, turbulence; residual kinetic energy
- Origin and acceleration of relativistic particles ?
- What is the amount of ‘non thermal’ energy ? How quiescent clusters are ? *versus time*

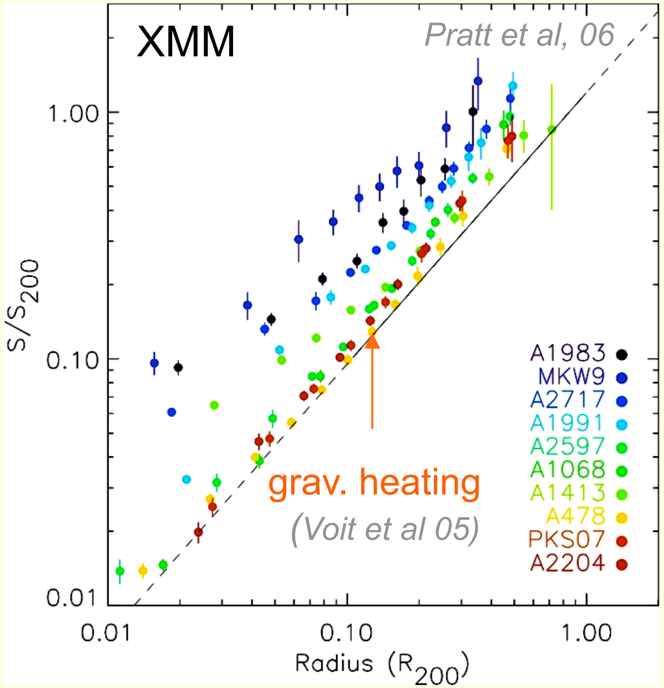
Key observations: spectro-imaging at high spectral resolution + in hard X-ray

- Line shifts (velocity field)
- Line broadening (turbulence)
- IC emission from relativistic plasma

More in H.Bohringer talk

Beyond gravity: cosmic feedback





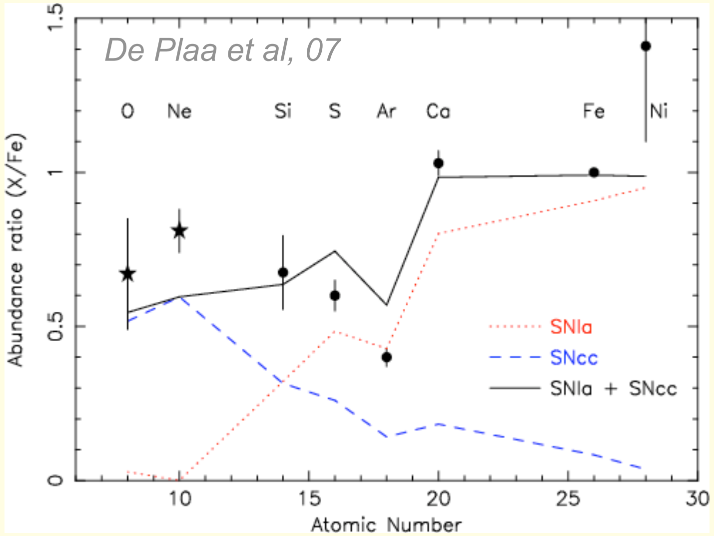
Gravity alone cannot explain:

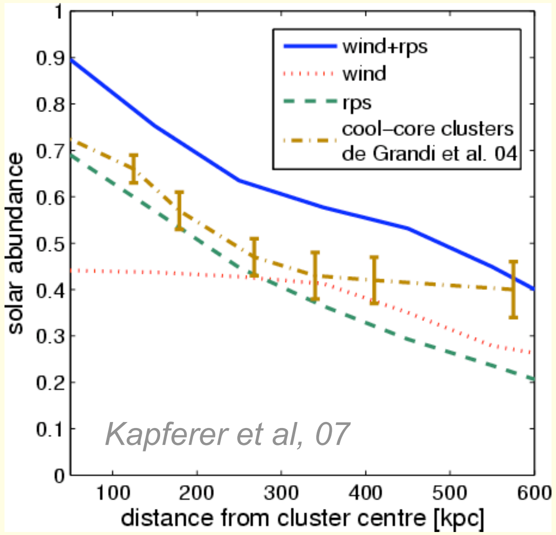
- Star/galaxy formation
  - ⇒ cooling ⇒ over-cooling ⇒ SN/SMBH feedback?
- Thermal regulation in (cooling) cluster cores
- ICM entropy in *present day* clusters

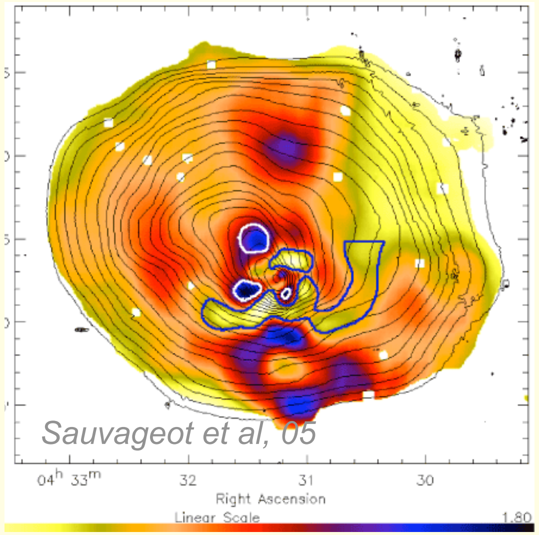
When and how this excess energy was acquired ?

Relative role of cooling, (pre) heating by SN & SMBH, others?

Cosmic feedback: history of metal production and circulation





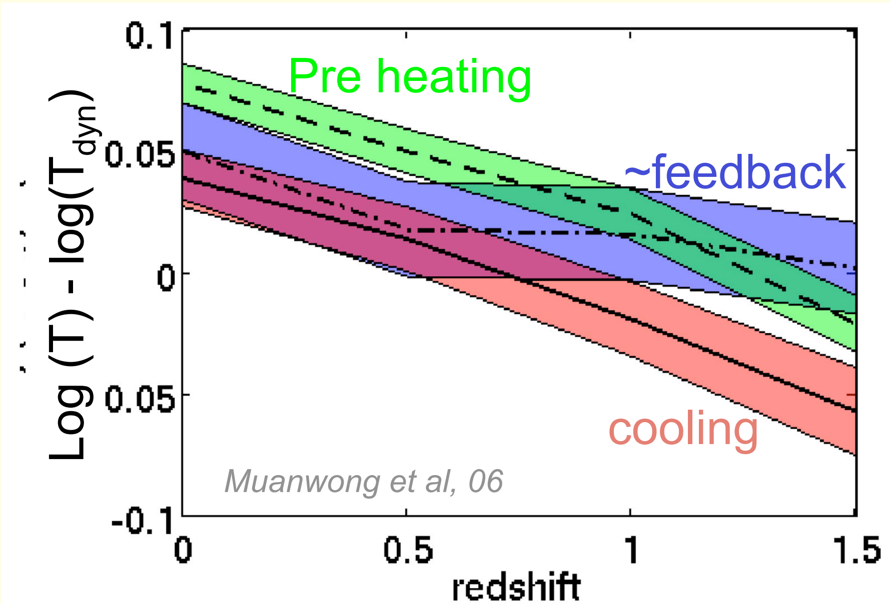


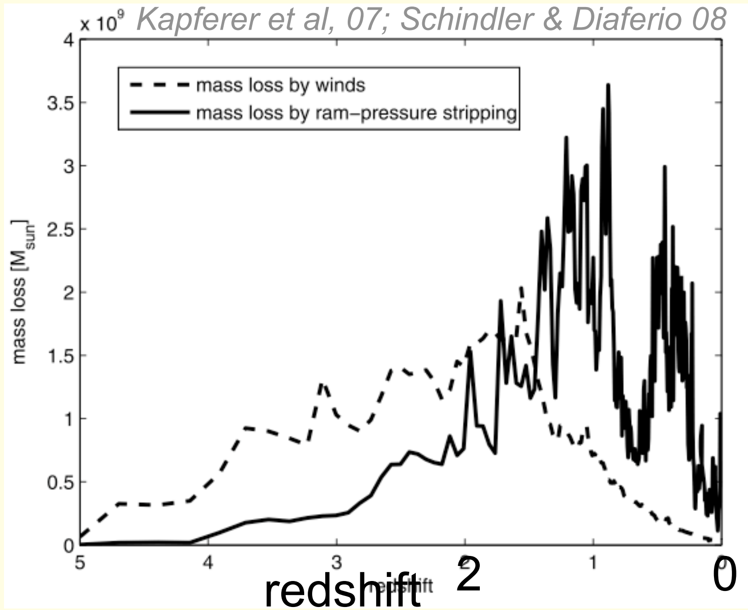
ICM : unique laboratory to study nucleosynthesis history.

X-ray observations provide direct information on :

- When the various metals are produced ?
- What are the source of the metals ?
- How the metals produced in the galaxies are ejected (by SN winds, ram-pressure stripping, AGN outflows etc..?) and redistributed (during gas infalls or mergers) in the ICM?

The key information: cluster evolution

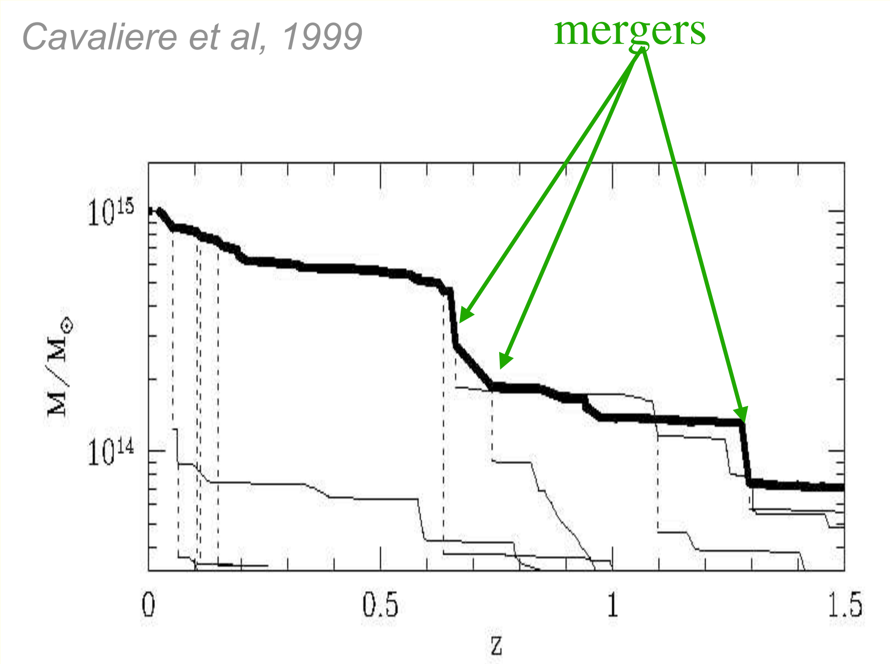


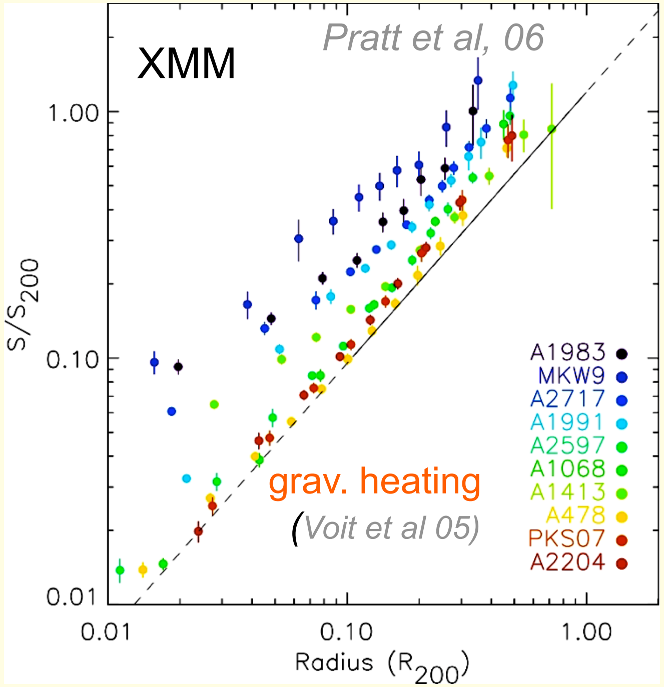


⇒ Present cluster population: fossil record of formation history
⇒ Various processes (cooling, feedbacks ..) have different time dependence
⇒ To disentangle and understand the role of each process:

study the first clusters which appear at z~2 and
directly trace their evolution to the current epoch

On the importance of low mass systems

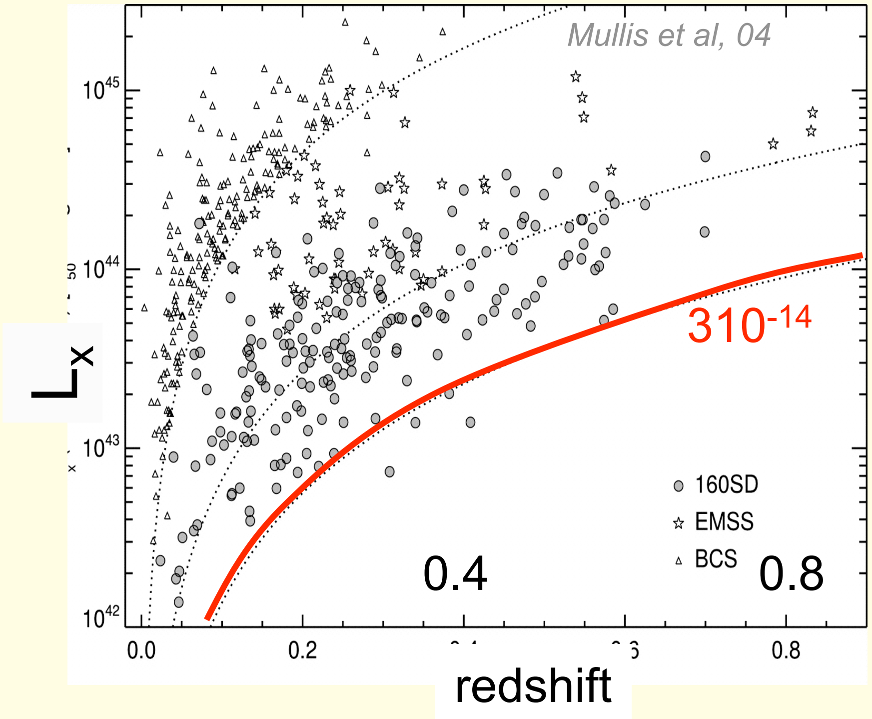




seeds and building blocks of today massive clusters

Cosmic feedback vs gravity more important at low mass

Present-day evolution studies

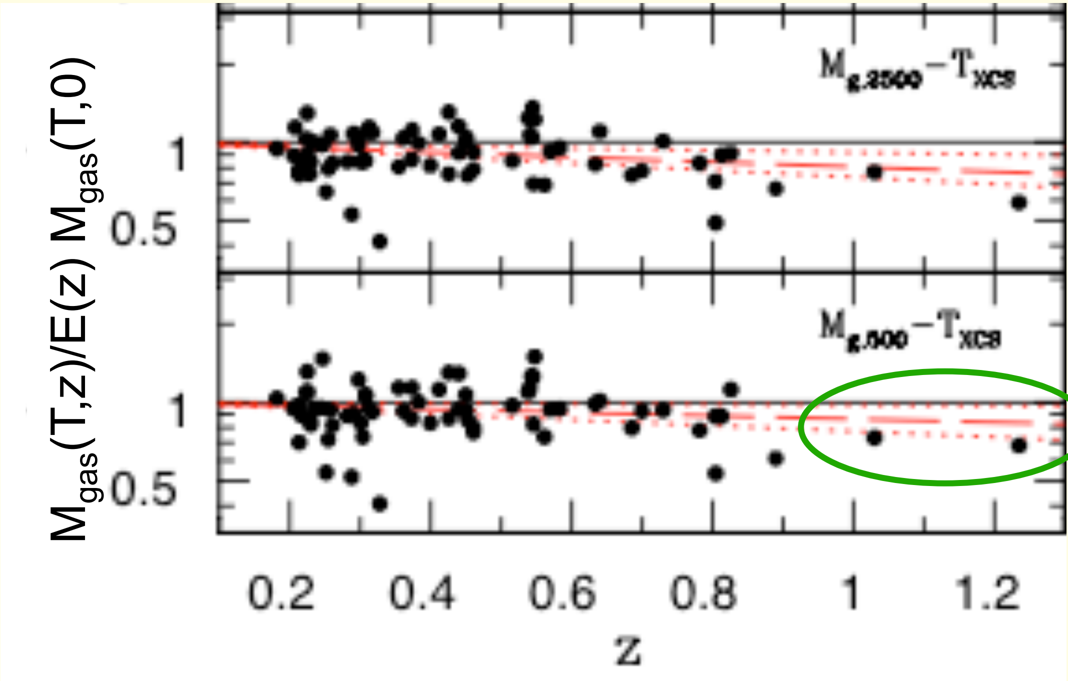


Chandra/XMM
follow-up observations at flux limit of Rosat surveys

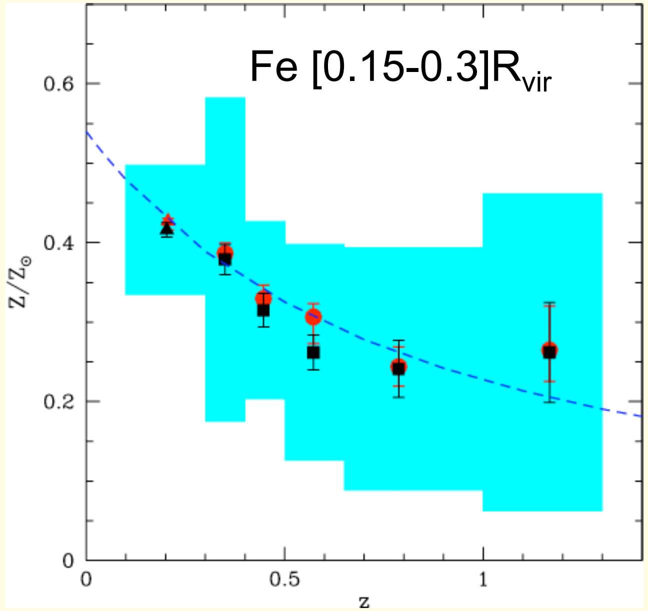
mass limit increases with z

Present-day evolution studies

O'Hara, Mohr & Sanderson,08



Balestra et al, 07; see also Maughan et al, 08



XMM/Chandra stacking analysis

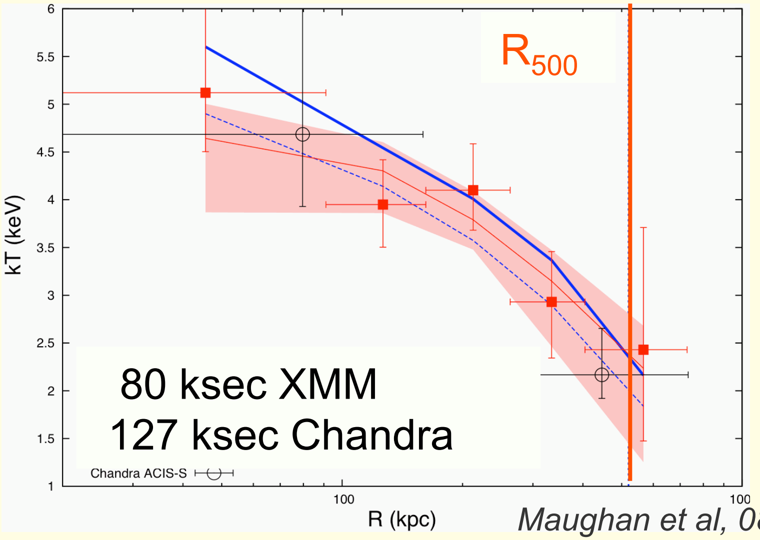
Global scaling properties up to z~1

but kT > 4-5 keV @ z > 0.6 and precision decreases

z > 1 basically unexplored

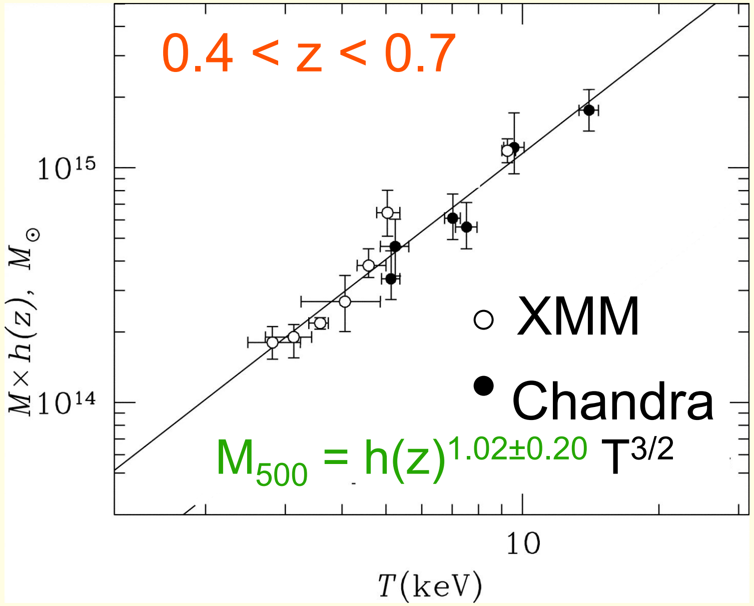
Present-day evolution studies

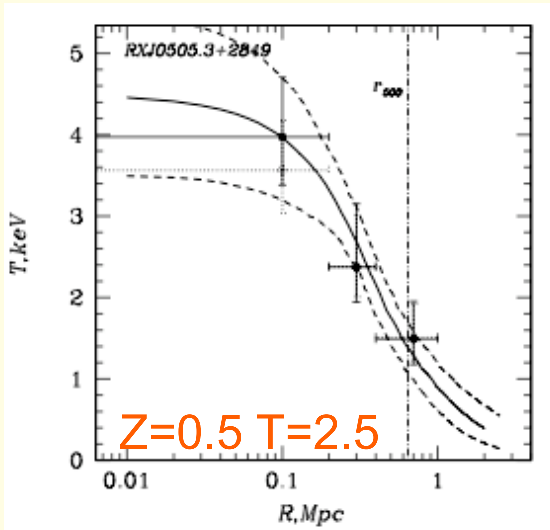
XLSSJ022403.9 z=1.05



Maughan et al, 08

Kotov & Vikhlinin,05, 06

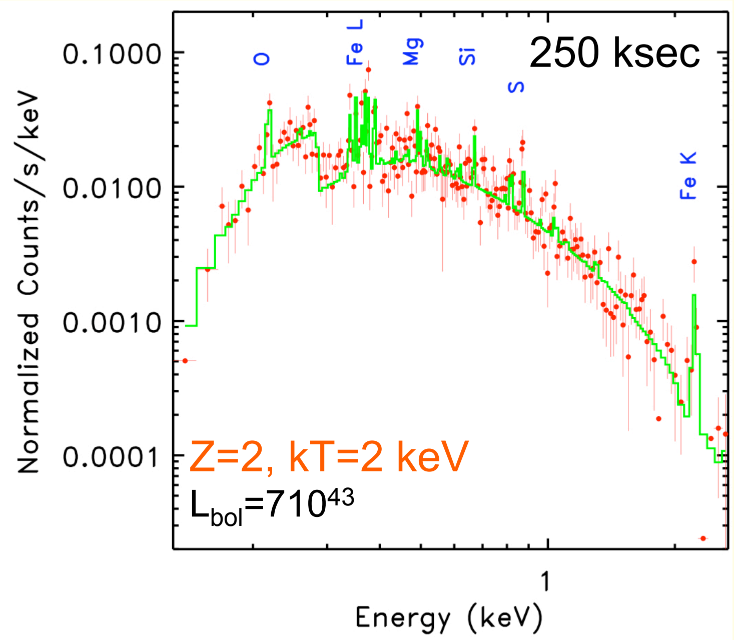


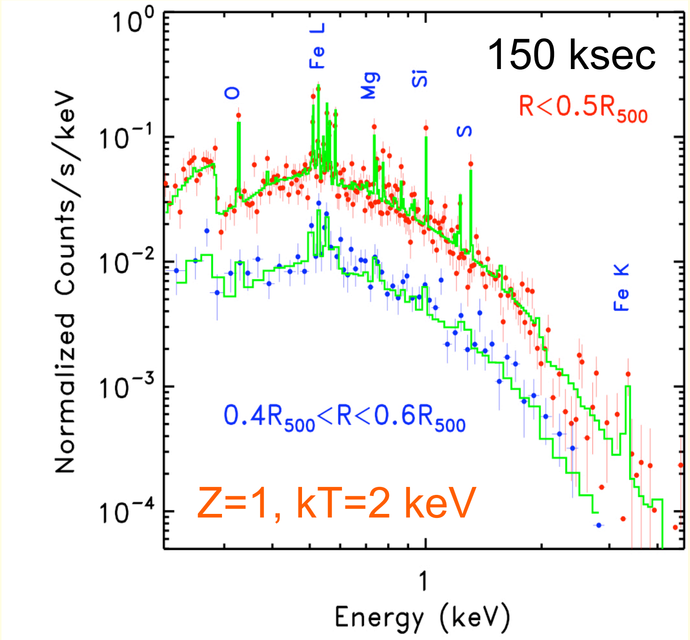


Profiles up to z ~ 1. for
massive (Planck like) clusters

but poor at low mass

Evolution studies with IXO





kT: ± 3% ; Redshift !
O, Mg: ±35%; Si : ±25%; Fe: ±14%

annulus: kT : ± 5% ; Fe: ±23%

Global properties up to z=2

Ab, kT profiles⇒ S (r) and M(r)
as in local Universe
with XMM/Chandra

Serendipitous search of ‘first’ groups (with WFI)

Summary

How structures formed and evolved?

- Boundary conditions ~ known
- General scenario and Dark matter collapse ~ understood
- Visible matter (baryons) physics NOT understood.

fondamentally a multi-scale problem:

history of galaxies and hot/warm diffuse gas linked

probably a complex interplay between grav. and non grav physics

A major goal for IXO:

Understand the thermo-dynamical history of the hot intergalactic medium

- How gravitational energy is converted during hierarchical formation?
- What produces the ICM entropy and what limits (regulate) cooling ?
- How and when galaxy feedback worked ?

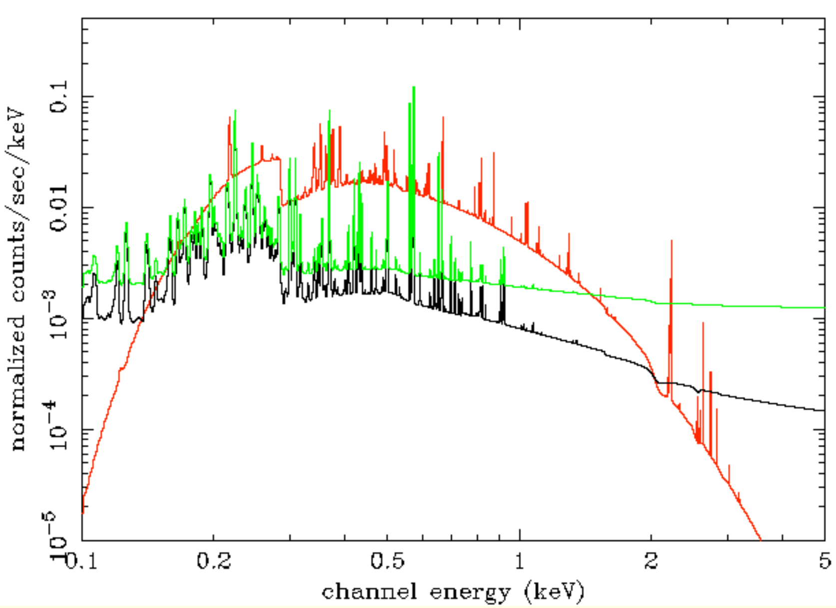
and the production and circulation of metals

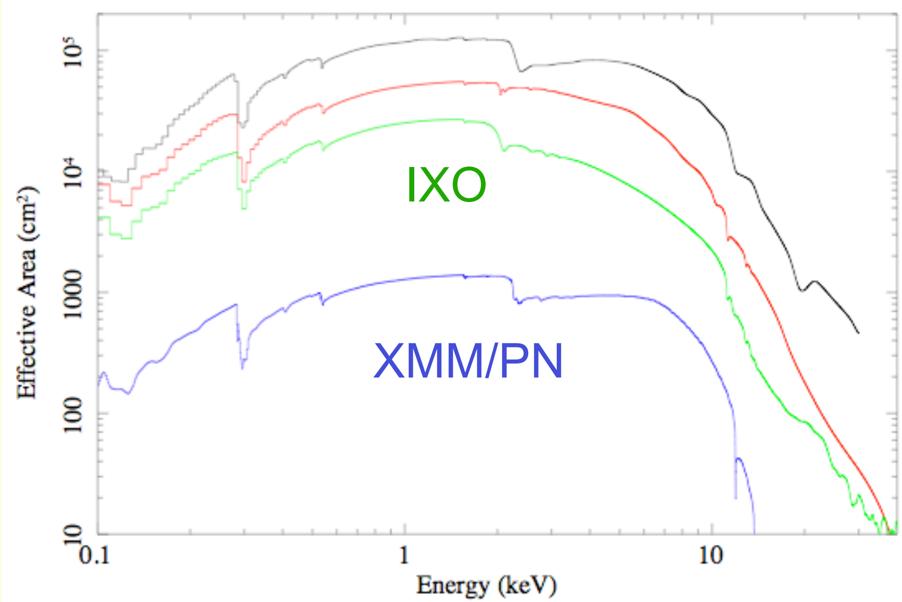
Mission Requirements:

mesure v, turbulence in local clusters

study the first clusters which appear at z~2 and trace their evolution to now

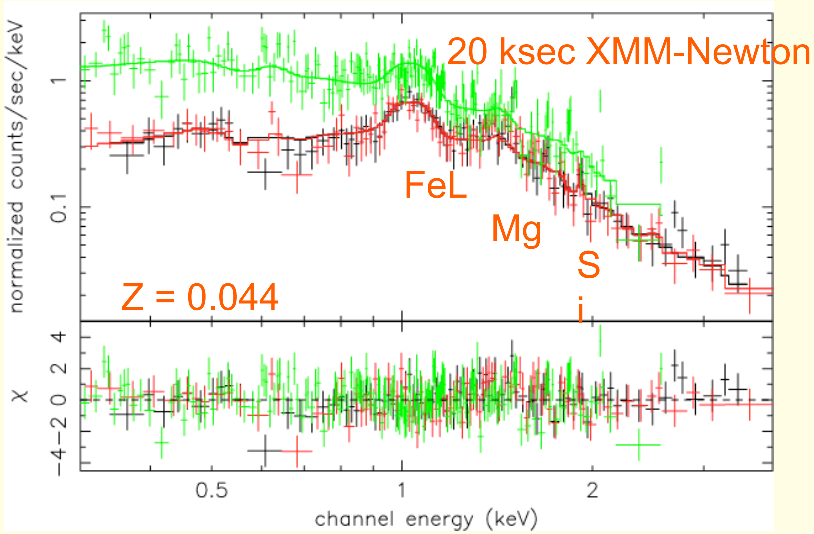
need spectral resolution AND effective area AND low background


normalized counts/sec/keV
0.1
0.01
10^{-3}
10^{-4}
10^{-5}
0.1
0.2
0.5
1
2
5
channel energy (keV)

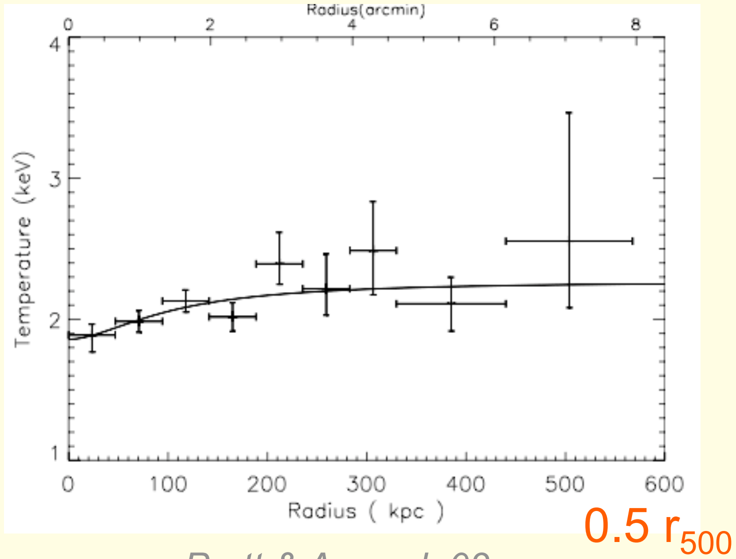

IXO
XMM/PN
Effective Area (cm²)
10^5
10^4
1000
100
10
0.1
1
10
Energy (keV)

From XMM to IXO spectroscopy

A1983



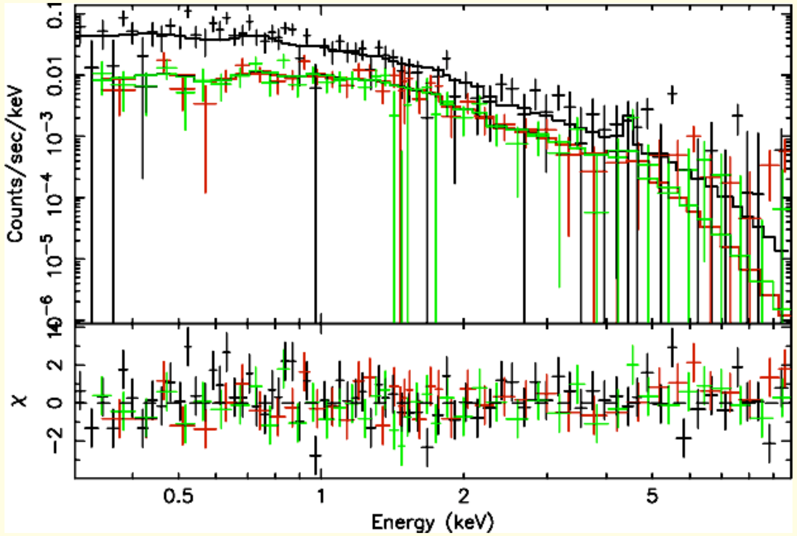
kT = 2.13 ± 0.04 keV

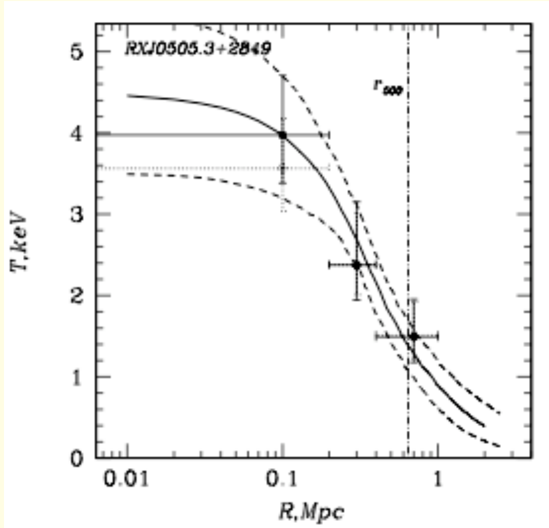


Pratt & Arnaud, 03

Nearby low mass cluster:
Detailed profiles and abundance measurements

RXJ 0505.3+2849 Z = 0.51 XMM-Newton





Kotov & Vikhlinin , 05

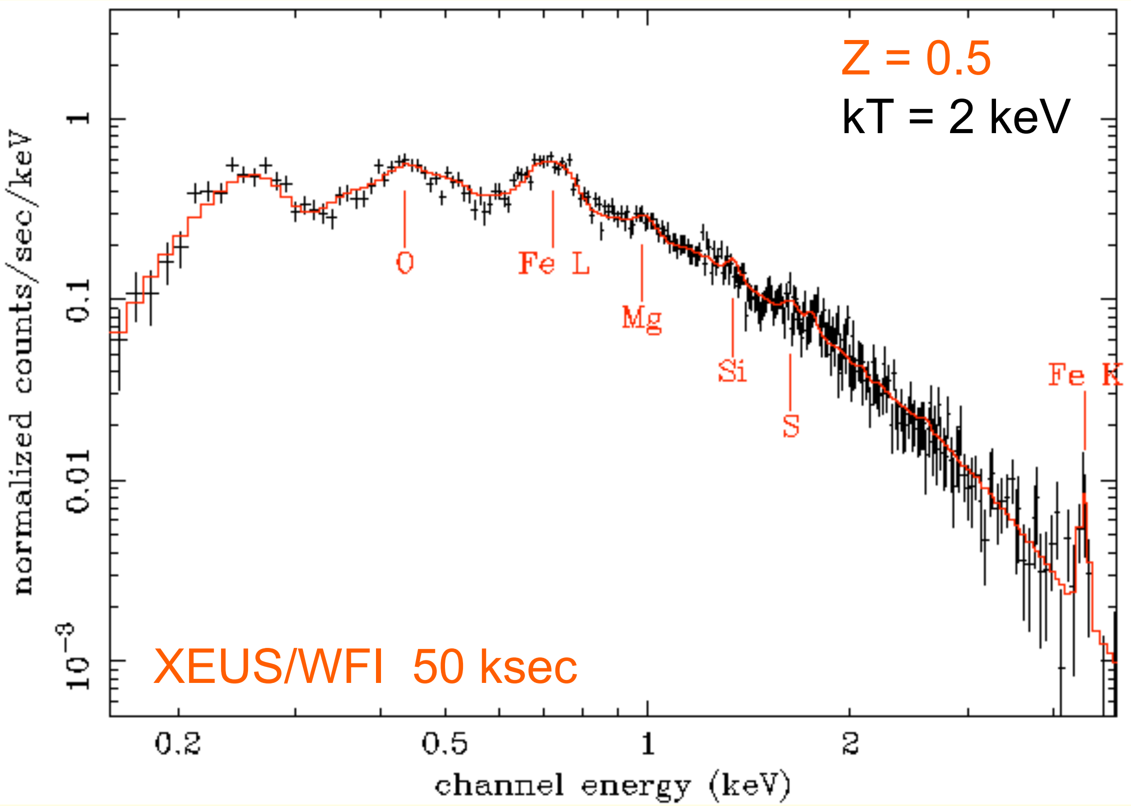
Lumb et al , 04

kT_{spec} = 2.5 ± 0.5 keV

at z=0.5

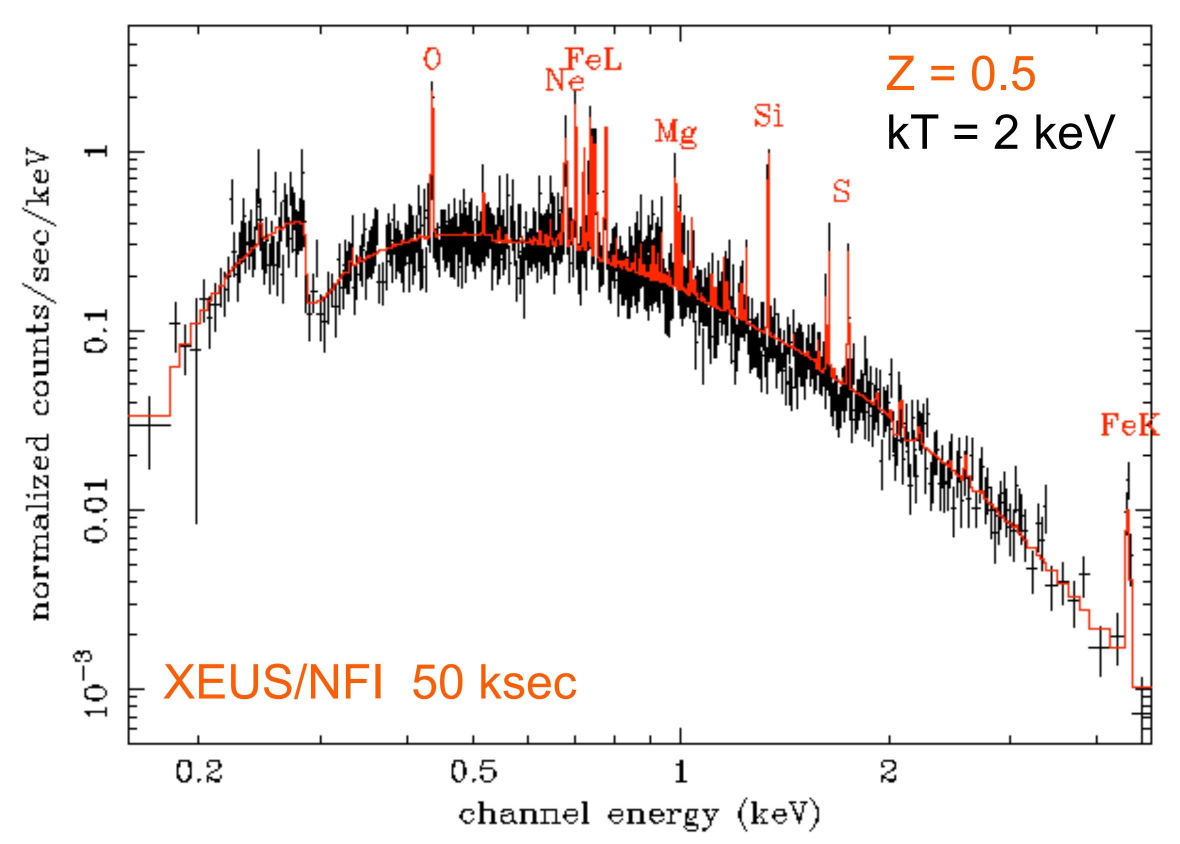
only Fe abundance and crude kT profile

A1983 put at z =0.5 r < $0.5r_{500}$ integration region



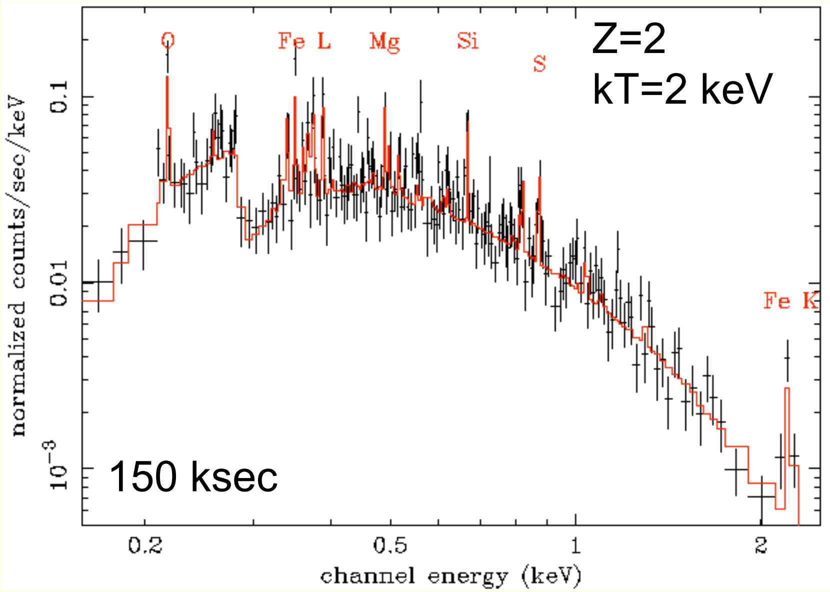
kT ± 1.4% (1σ)
O ±24%
Mg ±50%
Si ±20%;
Fe ±10%

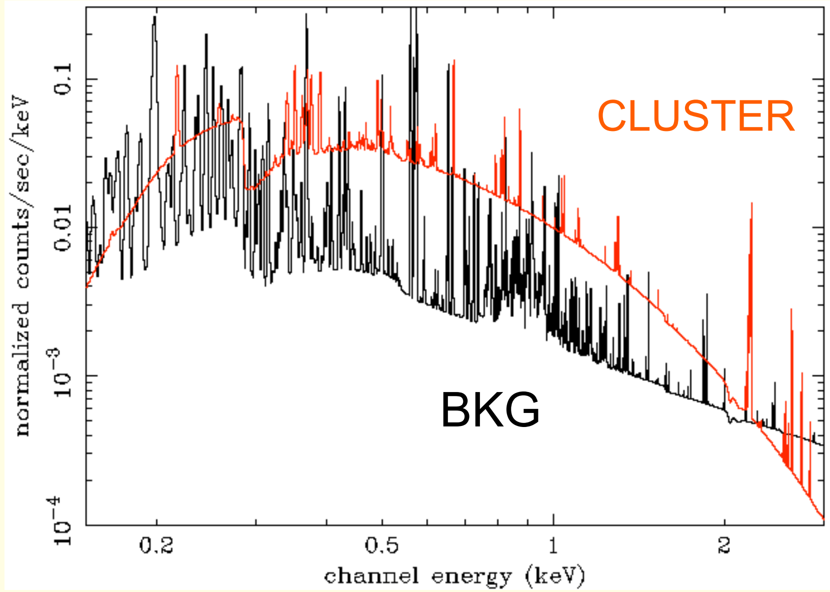
XEUS/WFI at z =0.5 ~ XMM at z =0.044
but α elements precision still ‘poor’



kT ± 1.4% (1σ)
O ±10%
Ne ±15%
Mg ±15%
Si ±11%;
Fe ±5 %

(Much) better abundance estimates with XEUS/NFI

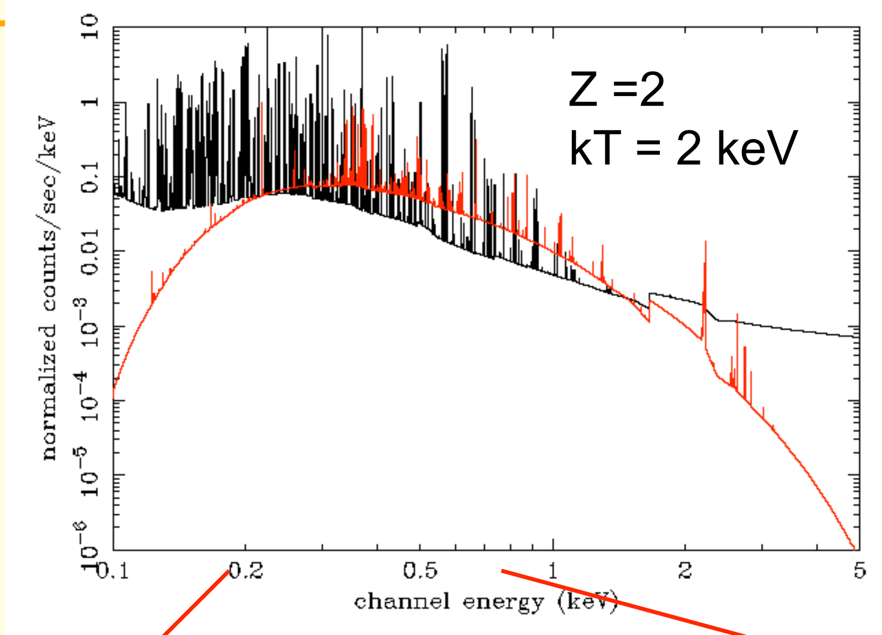


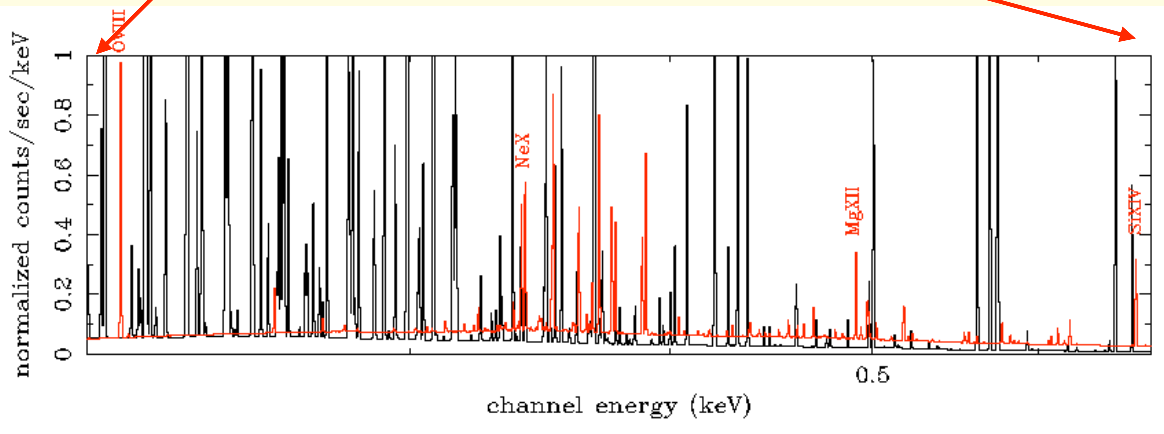


Can extend global properties study to z=2 with NFI

Need the spectral resolution to separate cluster from ‘sky’ lines

Mission Requirements





Energy range: 0.2 - 10 keV

- detect OVII up to z=2 (0.218 keV)
- 10 keV for kT estimates
- *80 keV for hard tail study (rel part/B)*

Spectral resolution: 2 eV below 1 keV

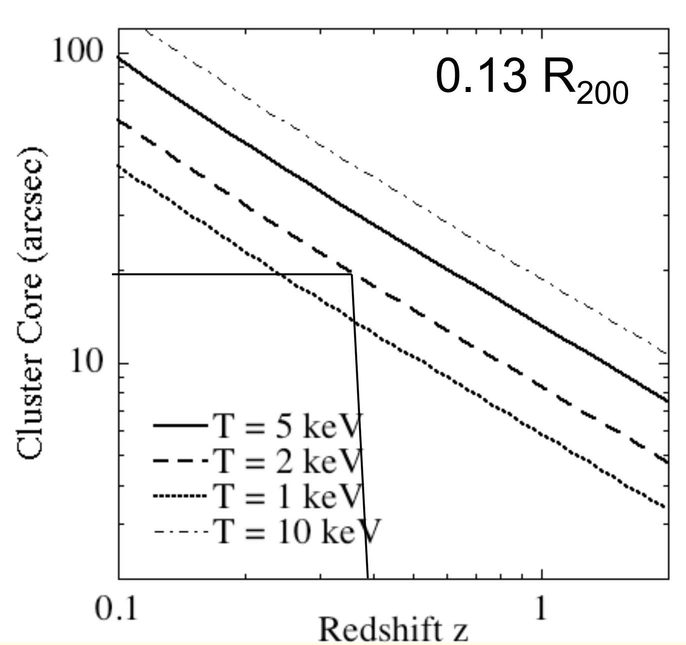
- separate cluster lines and sky line and be photon limited for α elements line z=0.5 - 2
- *turbulence study*

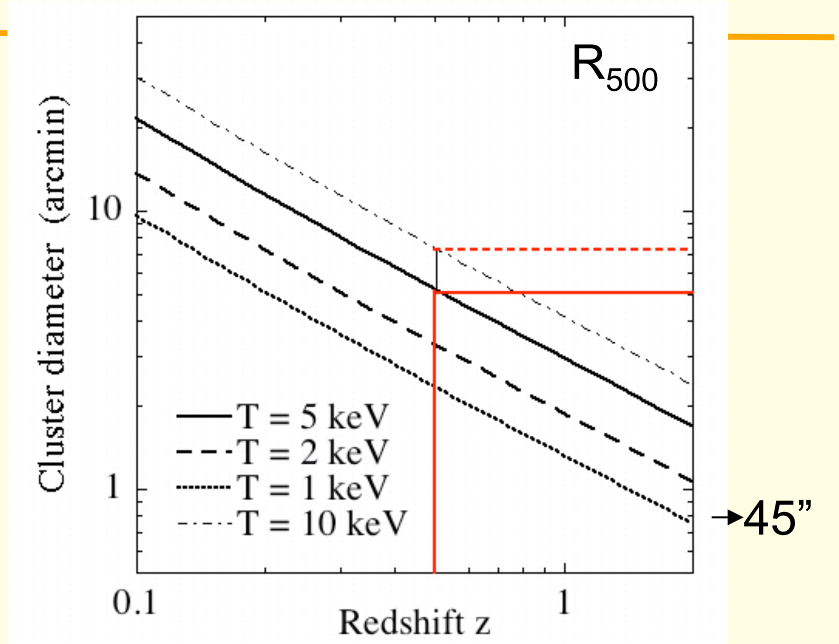
Effective area: 10m^2@ 1 keV

5 σ detection in 100 ksec of Mg line kT > 2 keV z <2

L_{bol} = 5.3 10^{43} ergs/s ; 50% flux in extraction region (r<15")

Mission Requirements (Cont.)





Core size kT=2 keV; z=2 : 5”
But: to limit AGN confusion : 2”

Fine mapping of CF at z~0.4-0.5

Resolve 1 keV , z=2 cluster:
20” in CCD outer FOV

Spatial resolution : requirement ~ 5” ; 20” outer FOV
Goal ~ 2”