Galaxy Clusters as Cosmological Probes

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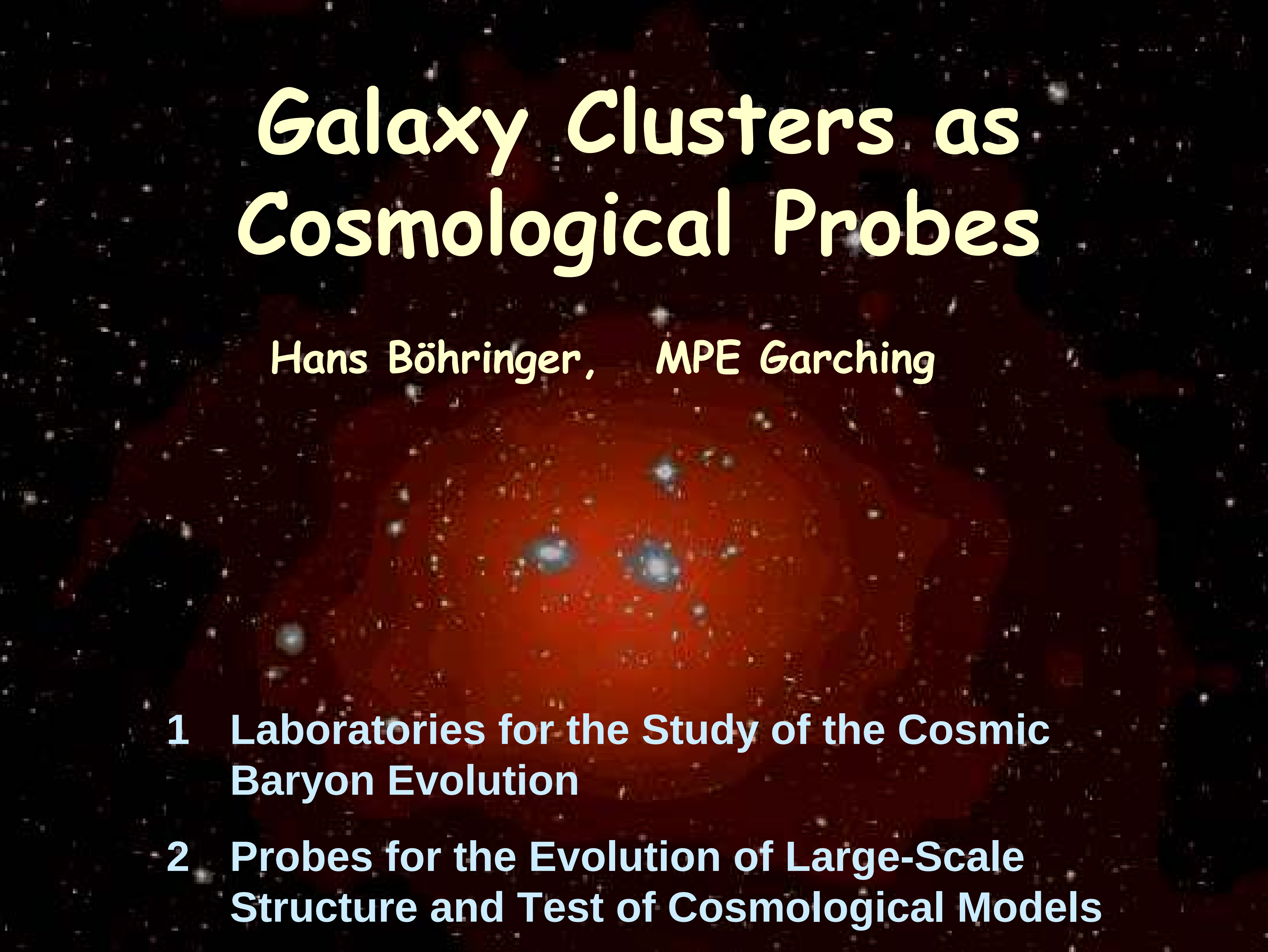
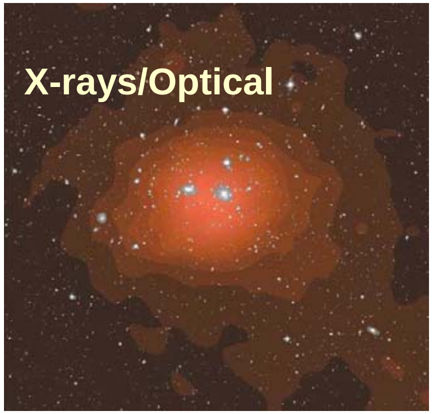


1. Laboratories for the Study of the Cosmic Baryon Evolution
2. Probes for the Evolution of Large-Scale Structure and Test of Cosmological Models

Why X-ray Observations are Mandatory



X-ray observations are still the best approach to characterise galaxy clusters!

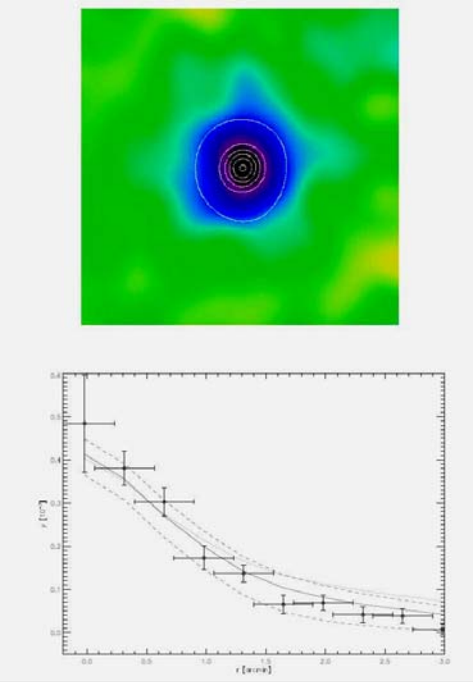
i) Compared to optical images:

- Cluster as one continuous entity

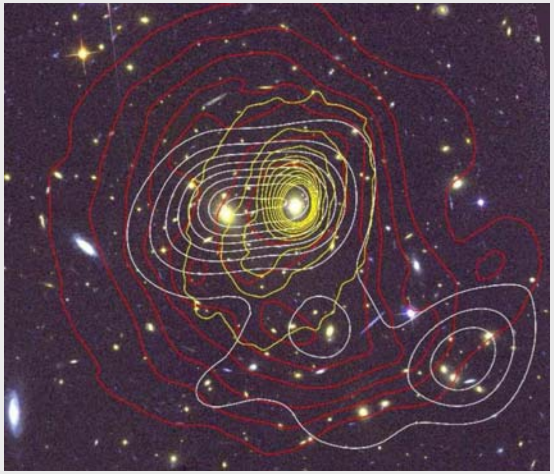
- Good statistics for projected structure, ICM temperature closely correlated to cluster mass

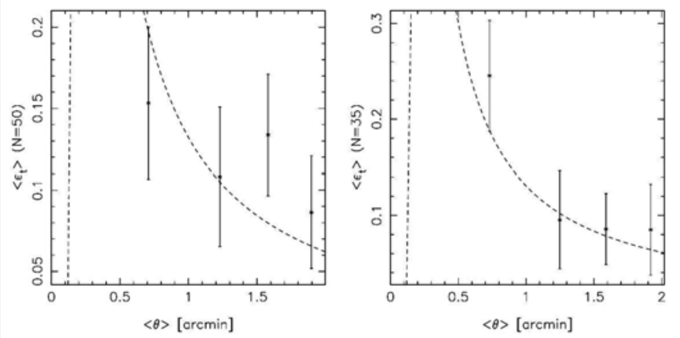
ii) For medium distant clusters: ~ 40 000 cts → 150 – 200 σ Signal!

compared to <~ 10 σ for best SZE and Lensing



APEX SZE observation of RXCJ1347-1144 (Kneissl in prep.)

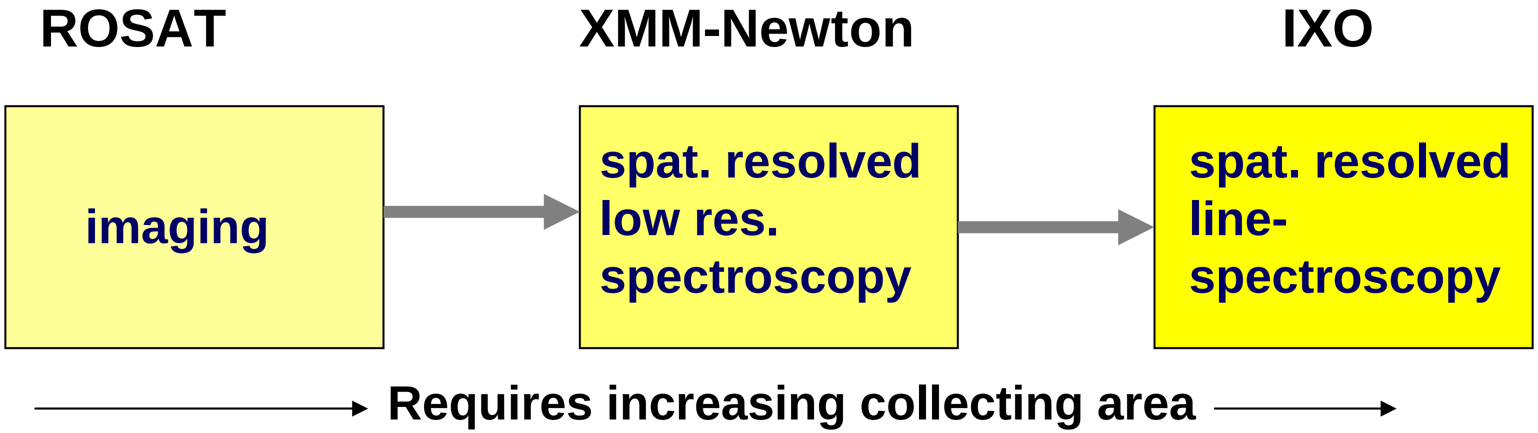




Lensing signal of RXCJ1347.5-1144 (red in image) and mean ellipticity signal (profile in I and R) Bradac et al. 05,08

Expected Progress with IXO

1. **Precise Astrophysics of clusters ($z < 1$) allowed by line spectroscopy**



ROSAT

imaging

XMM-Newton

spat. resolved low res. spectroscopy

IXO

spat. resolved line-spectroscopy

Requires increasing collecting area

2. **Detailed Astrophysics of clusters in the range $z = 1 \ldots 2$**

   in similar detail as currently performed for medium z (0.3 .. 0.5) clusters with XMM-Newtion

This provides the means for cosmology and cosmic evolution studies !

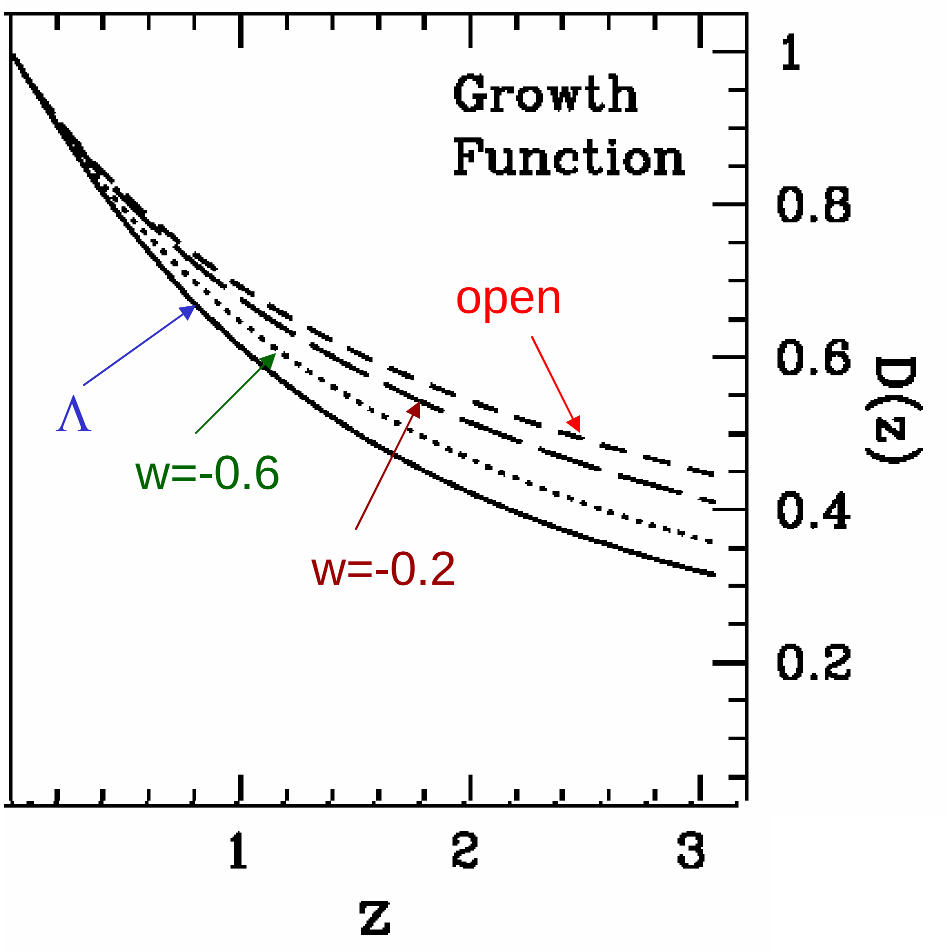
Testing Cosmological Models & Tracing Cosmic Evolution with Galaxy Clusters

The new terretory for XEUS cluster physics is the redshift

range of $z = 1$ 2

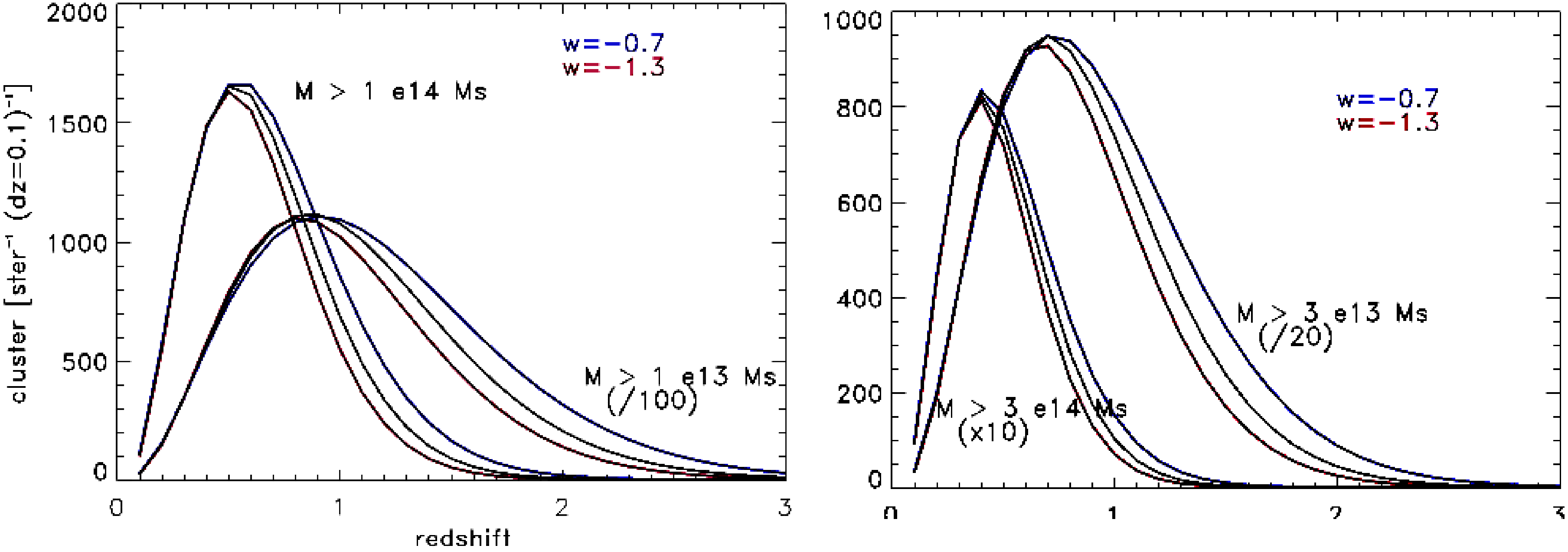
The Influence of *w* on Cosmic Evolution

Density fluctuation growth:



Evolution of the Cluster Mass Function
as a test for the cosmological model

Differential comoving cluster abundance (> Mass$_{\mathrm{limit}}$) ster^{-1} dz=0.1^{-1}

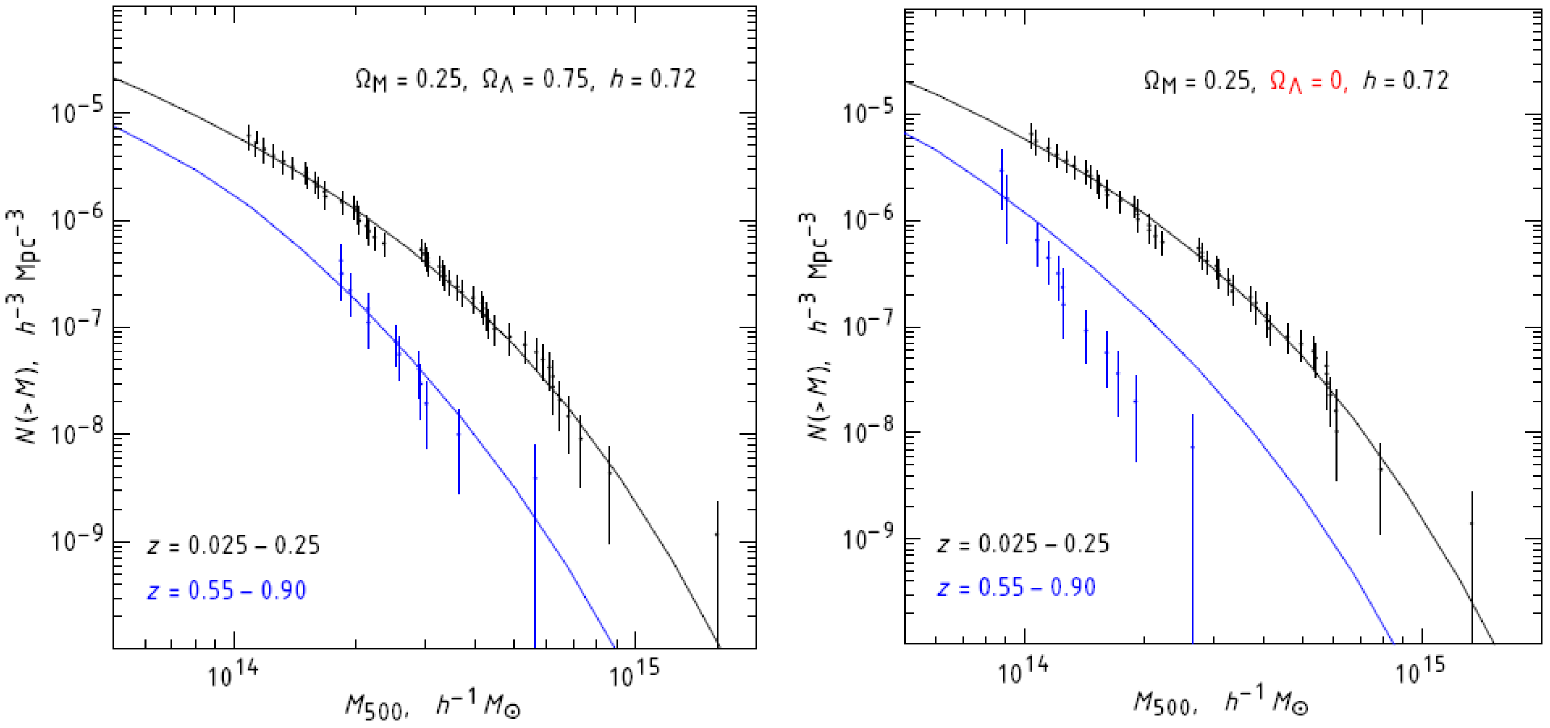


→ There are more distant clusters for small (negative) w !

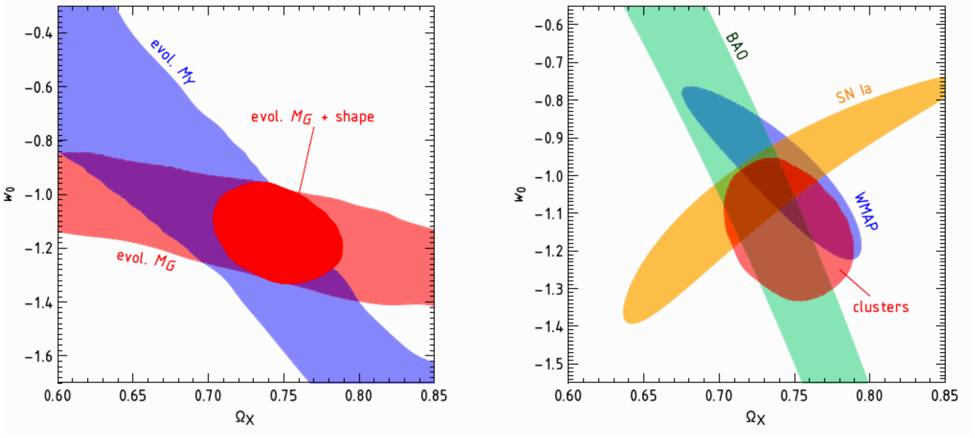
Requires mass calibration to few % !

see also Haiman et al. 2001

Evolution of the Cluster Mass Function

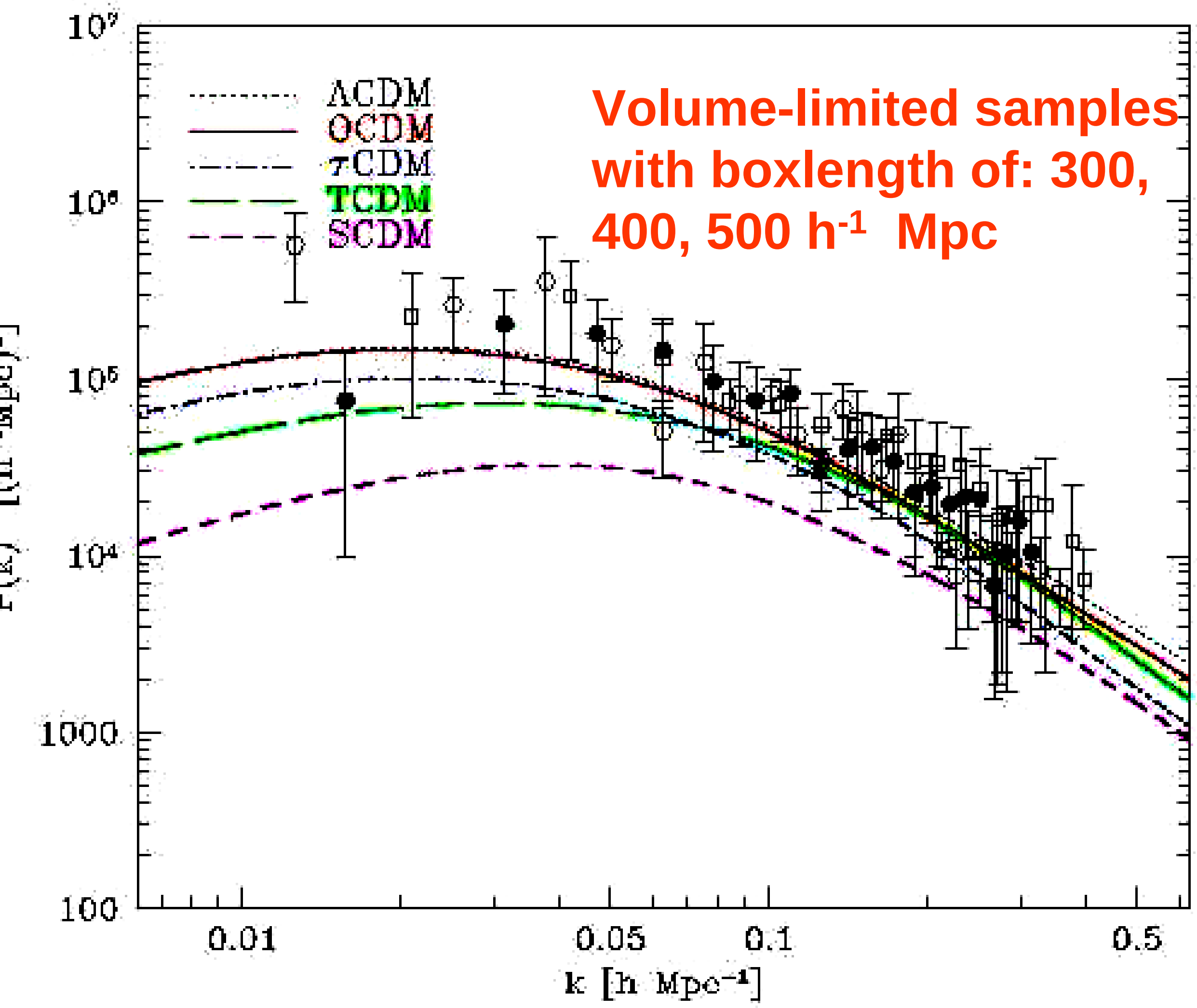


Model constraints from the observation of the cluster mass function evolution: gas mass and Yx parameter as alternative observables (proxies)

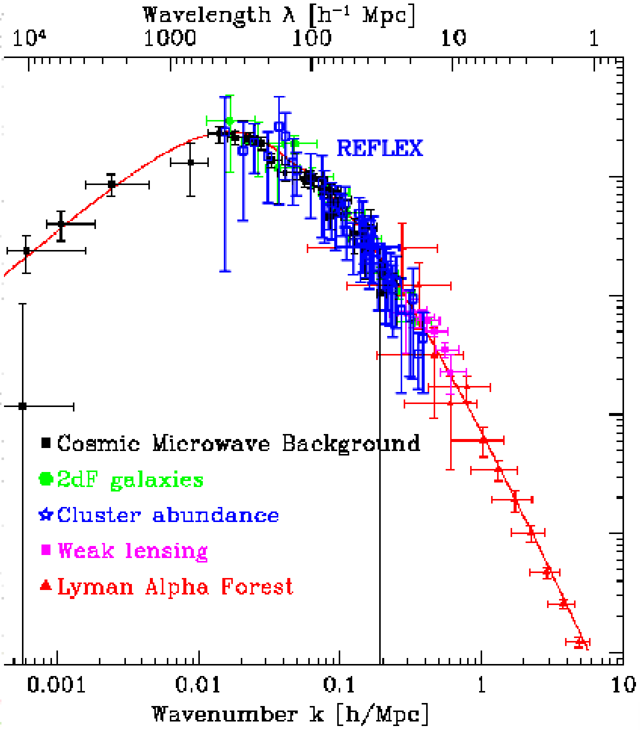


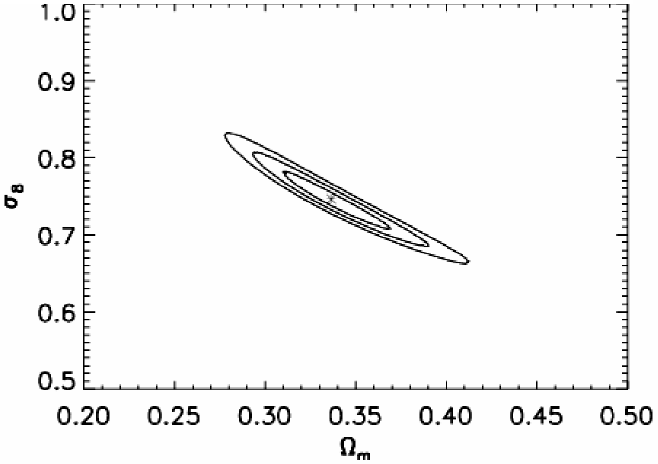
Vikhlinin et al. , Astro-ph 2008

Spatial Distribution Characterized by P(K)



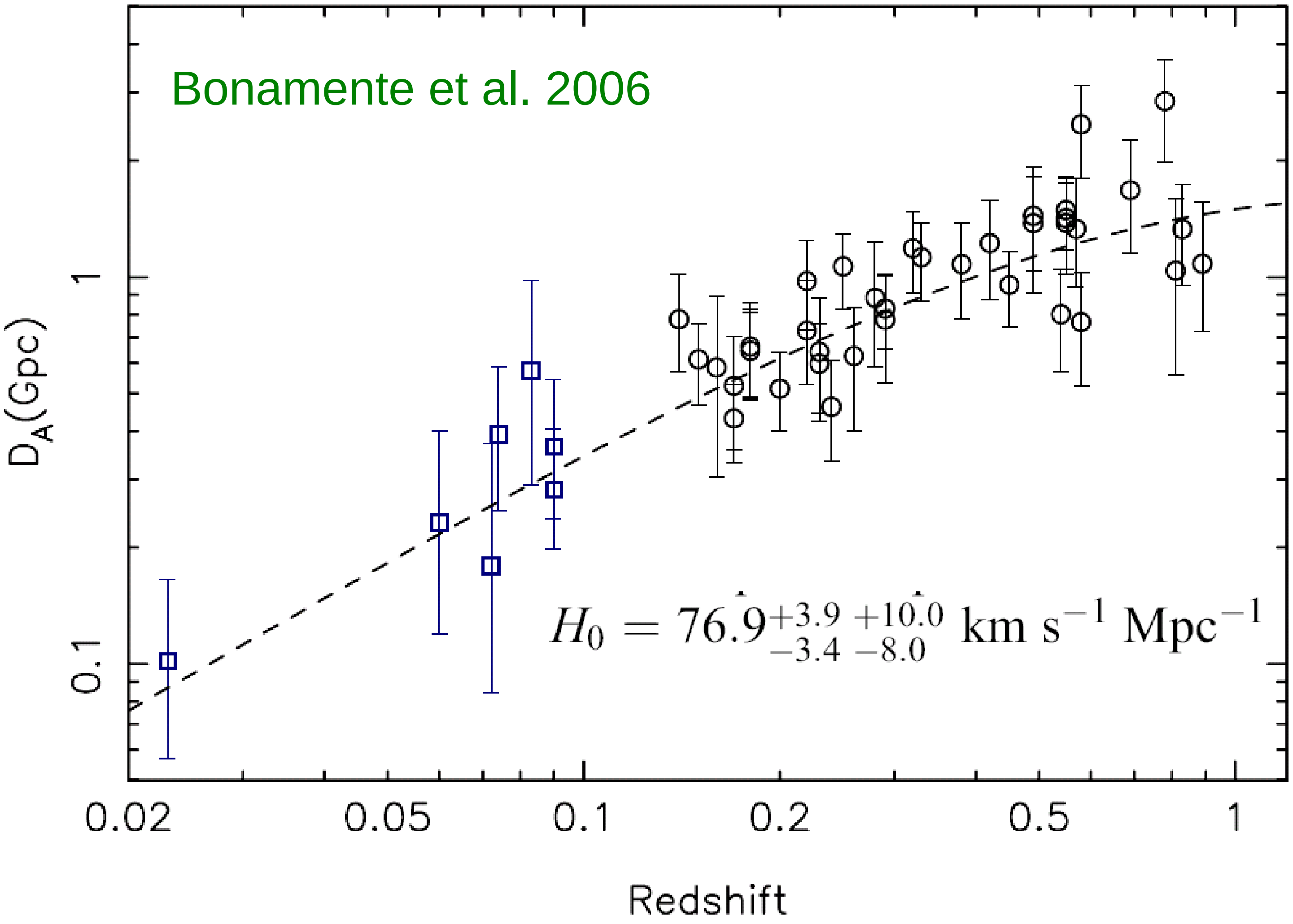
Volume-limited samples with boxlength of: 300, 400, 500 h^{-1} Mpc





Schuecker et al. 2001 - REFLEX Survey

H_0 Determination from X-ray and SZ-Effect



Current redshift leverage gets only good constraints on H_0 - larger redshift range necessary to constrain the matter/energy composition

Scientific Quests for Distant Cluster Observations

To Study the evoluton of:

- **Cluster Structure (dyn. State, halo shape,...)**

2. **Cluster Mass Function**
3. **Spatial Correlation (P(k) or $\xi(r)$ normalization)**
4. **Evolution of the cluster ICM (entropy) and galaxy population (mass to light ratio)**
5. **Heavy element abudances in the ICM**

X. Clusters as distance indicators: X-ray/SZ observatioms
- baryon fraction

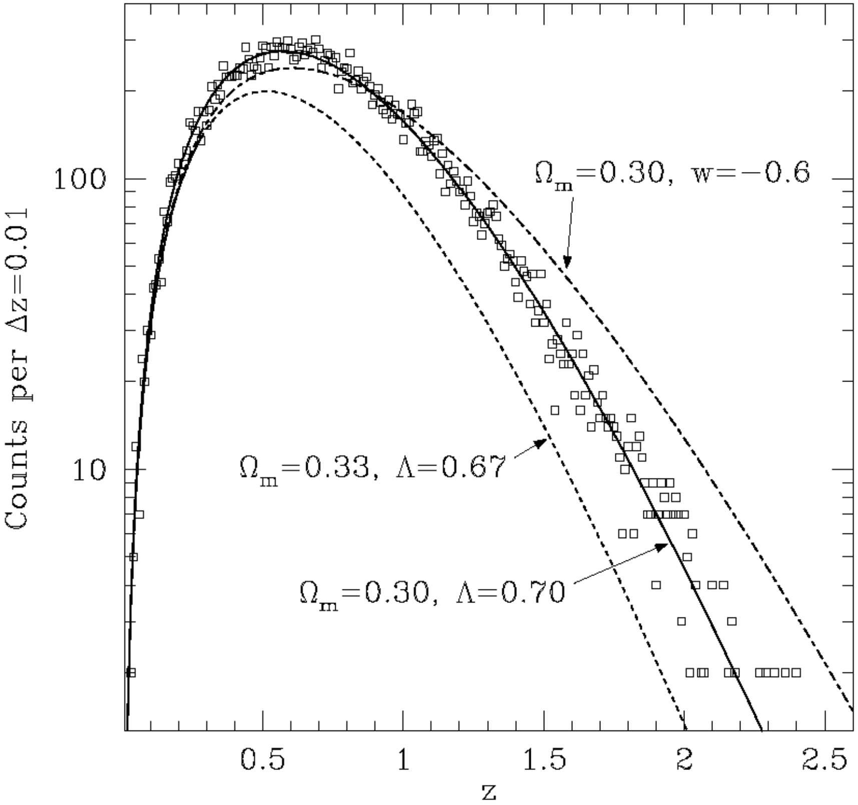
How many Test Objects Do We Find ?

Redshift	mass	clusters /20000 deg2	X-ray luminosity
$z > 2$	$> 10^{14} M_{sun}$	100	10^{44} erg/s
	$> 3\ 10^{13} M_{sun}$	20000	$1.5\ 10^{43}$ erg/s
	$> 10^{13} M_{sun}$	$4\ 10^{5}$	$3\text{-}4\ 10^{42}$ erg/s
$z > 2.5$	$> 3\ 10^{13} M_{sun}$	3000	$2\ 10^{43}$ erg/s
	$> 10^{13} M_{sun}$	$1\ 10^{5}$	$3\text{-}5\ 10^{42}$ erg/s
$z > 3$	$> 3\ 10^{13} M_{sun}$	200	$2.7\ 10^{43}$ erg/s
	$> 10^{13} M_{sun}$	$2\ 10^{4}$	$4\text{-}6\ 10^{42}$ erg/s

→ **Clusters** ($>10^{14}M_{sun}$) **exist up to z ~ 2, massive groups up to z ~ 2.5**

New SZE-Cluster Surveys

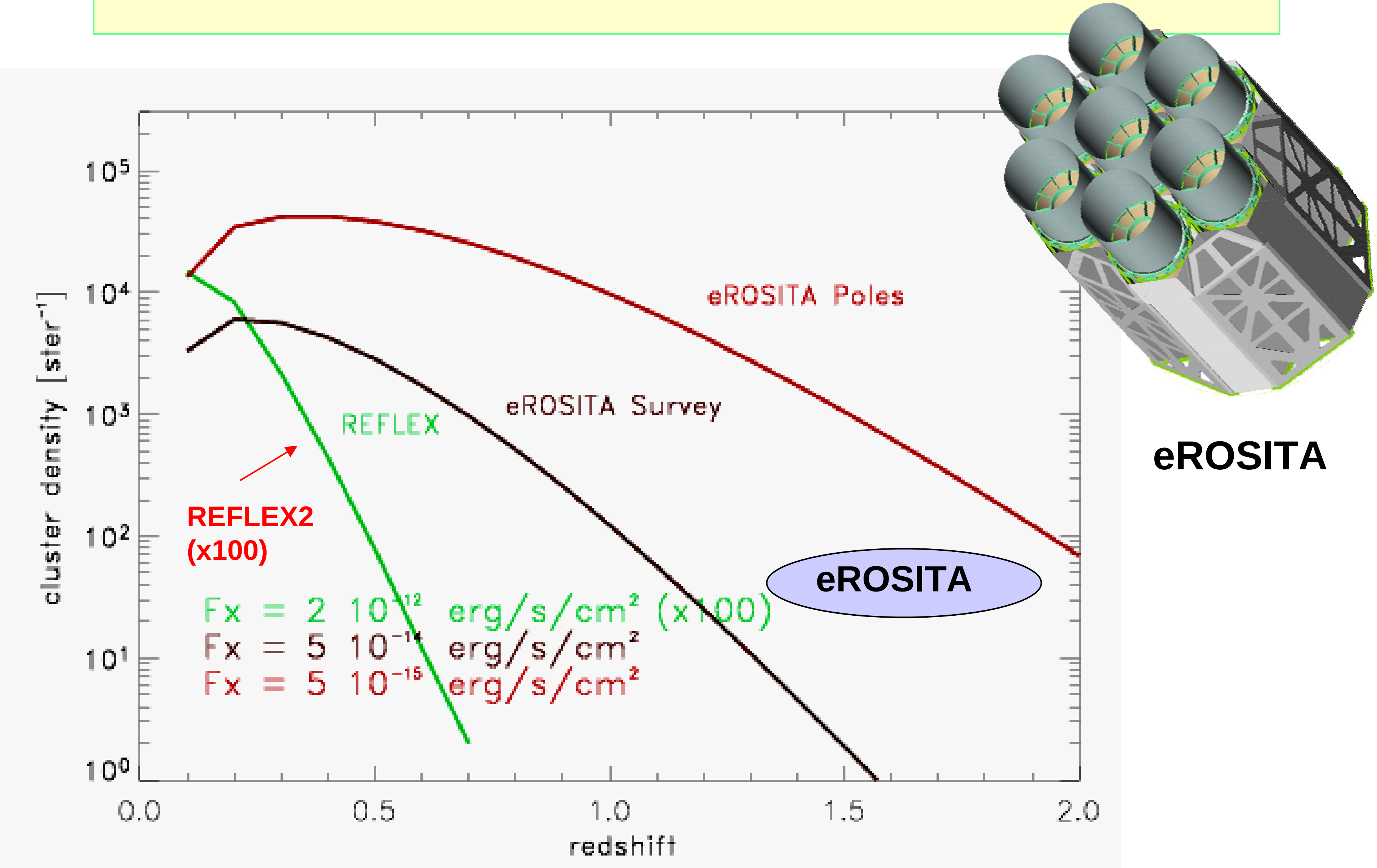
SZE Survey with
SPT (South Pole Telescope) in 4000 deg2 SZ survey]



→ to determine *w* to about ~5% time variations to about 10-20%

See also ACT and APEX Surveys

Prospects of the eROSITA Survey

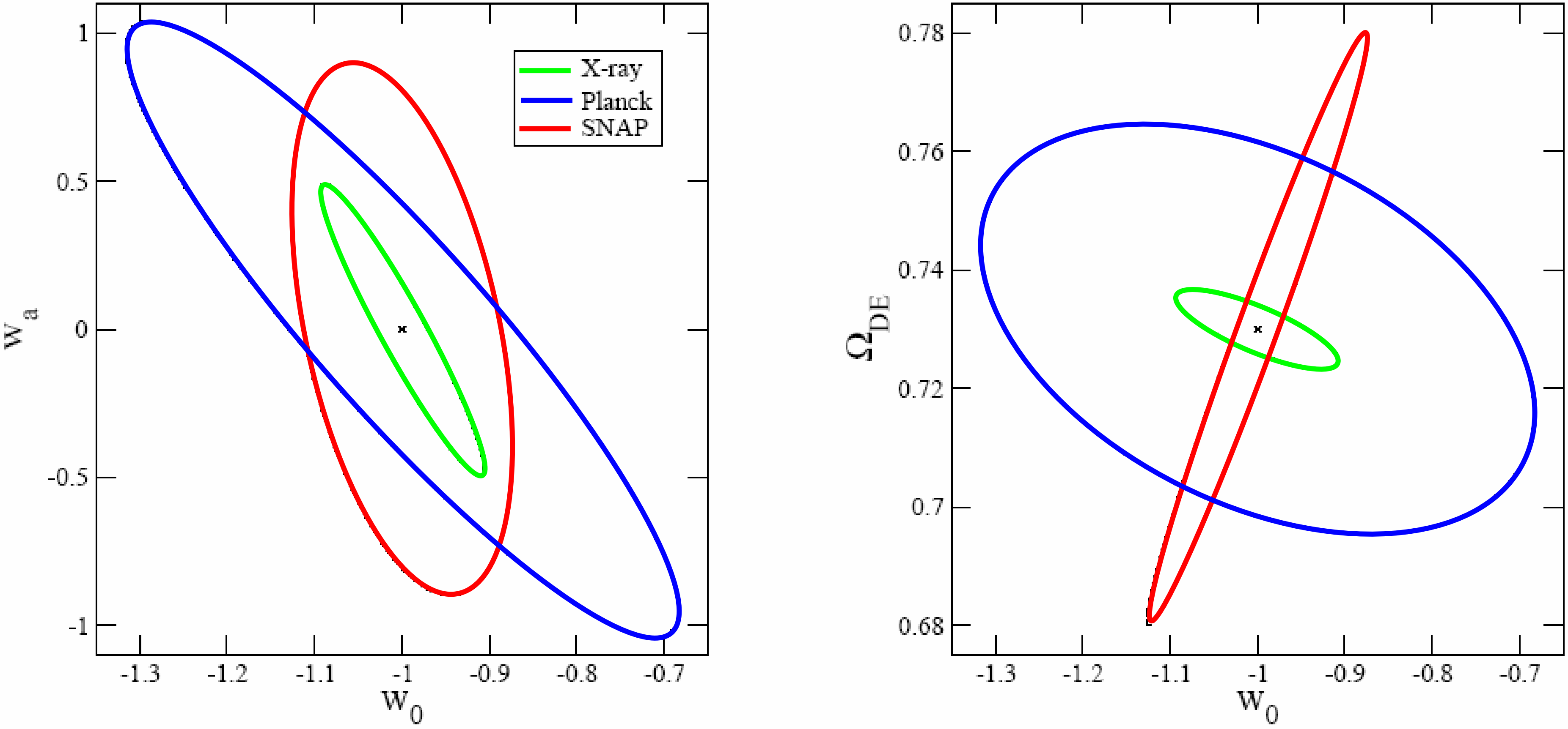


Constraints from 100K Cluster Survey

Time dependence of w_x

$w_{x(z)} = w_0 + w_a z$

$p(z) = w_x(z) * \rho(z)$



Results from the White Paper submitted to the NASA/DOE Dark Energy Task Force: Haiman, … , G.H. et al., 2005, astro-ph/0507013

Limitations

Already now the implications for cosmology from X-ray surveys are systematics limited:

- **We need better mass measurements**

- **We need a better characterization of the scaling relations of cluster mass with various observables**

1. Precise Astrophysics of Nearby Clusters

1. **Understanding the heating of cool cores**
2. **Studying the structure of mergers, diagnostics of shocks, assessing turbulence**
3. **Precison studies of the ICM temperature structure**
4. **Detailed heavy element abundance measurements**
5. **Precise mass profiles (Dark Matter Halo evolution study)**
6. **Non-thermal plasma contribution to pressure (IC detect.)**

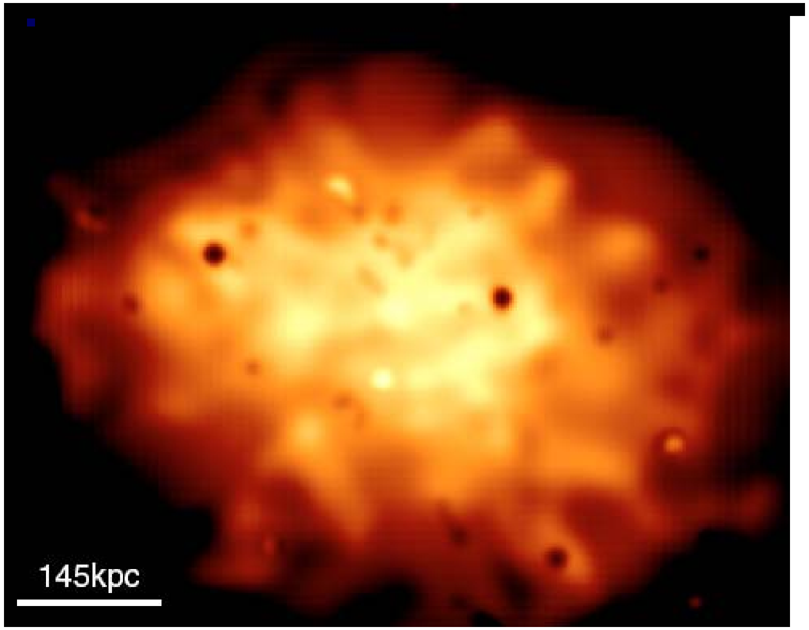
Methods:

- **Velocity diagnostics with (STJ and TES)**
- **Unvailing multi-temperature components**
- **Special line ratio diagnostics**
- **temperature, pressure, entropy, metallicity maps**

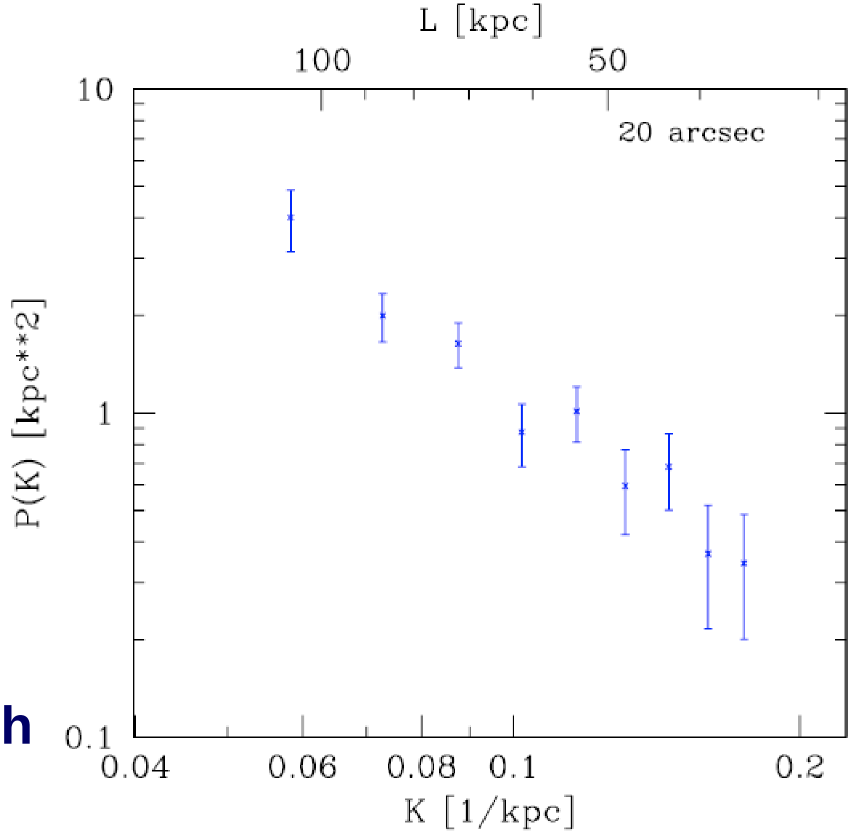
Detection Turbulent or Infall Velocity Structure

Turbulence detected in the image (pressure map) of the Coma cluster with XMM-Newton (Schuecker et al. 2004). ~ 10 – 20% turbulent energy density versus thermal energy density.

Coma pseudo-pressure map

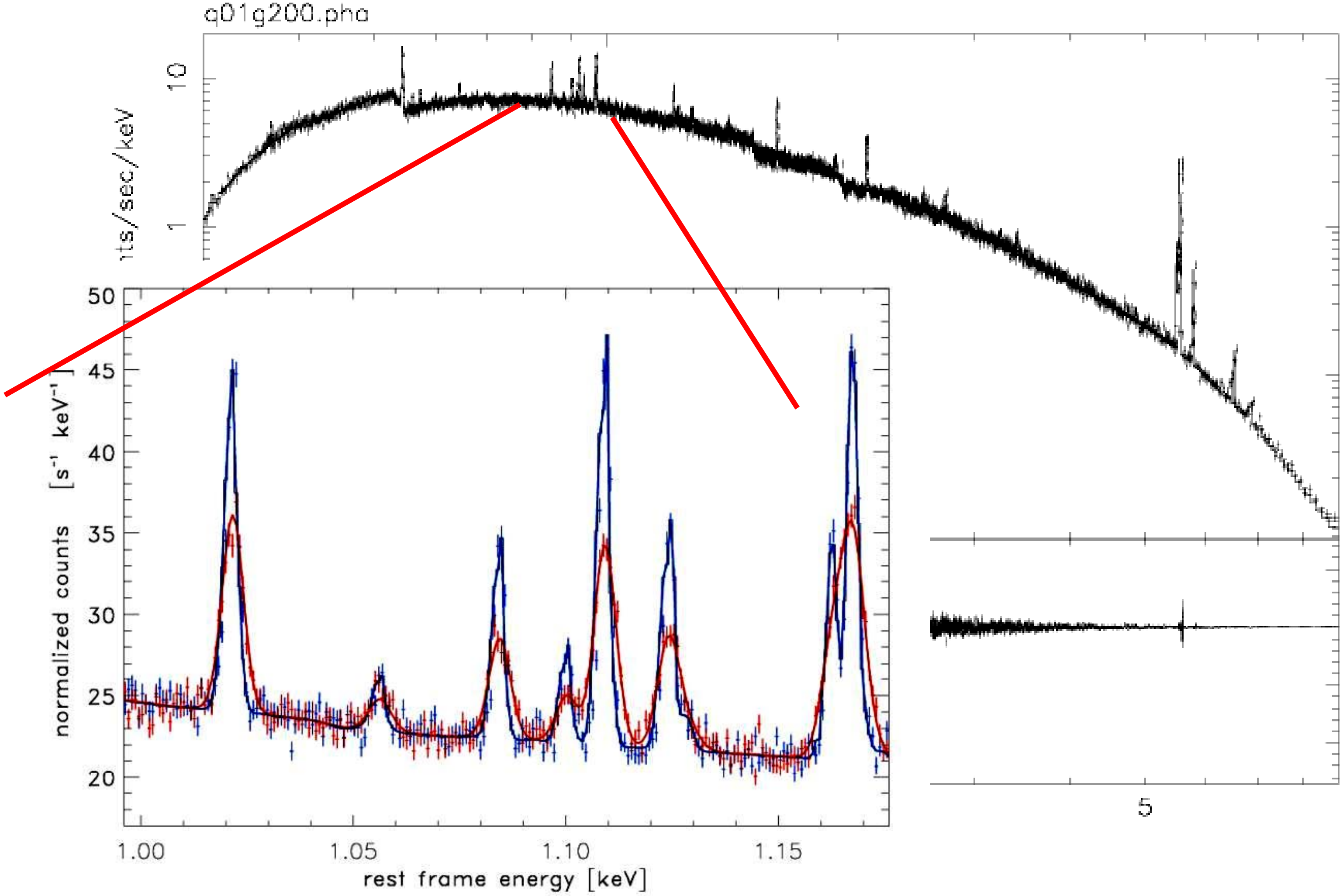


power spectrum of pressure fluctuations



This amount of turbulence (~ 300 km/s) should also be visible in high resolution spectra !

Diagnostics of Velocity Line Broadening I



5 keV spectrum, velocity broadening 100 (blue) 600 (red) km/s (Gaussian)
uncertainty of velocity measurement in 100 ks observation: $\Delta v = \pm 20$ km/s

Diagnostics of Velocity Line Broadening II

Summary (simulations with TES detector) :

[cluster z = 0.2, $F_X = 3\ 10^{-13}$ erg s^{-1} cm^{-2} abund.= 0.3]

5 keV, exp.= 100 ks **Δv ~ 20 km/s (0 – 600 km/s)**

exp.= 40 ks **Δv ~ 50 km/s**

8 keV, exp.= 100 ks **Δv ~ 40 km/s**

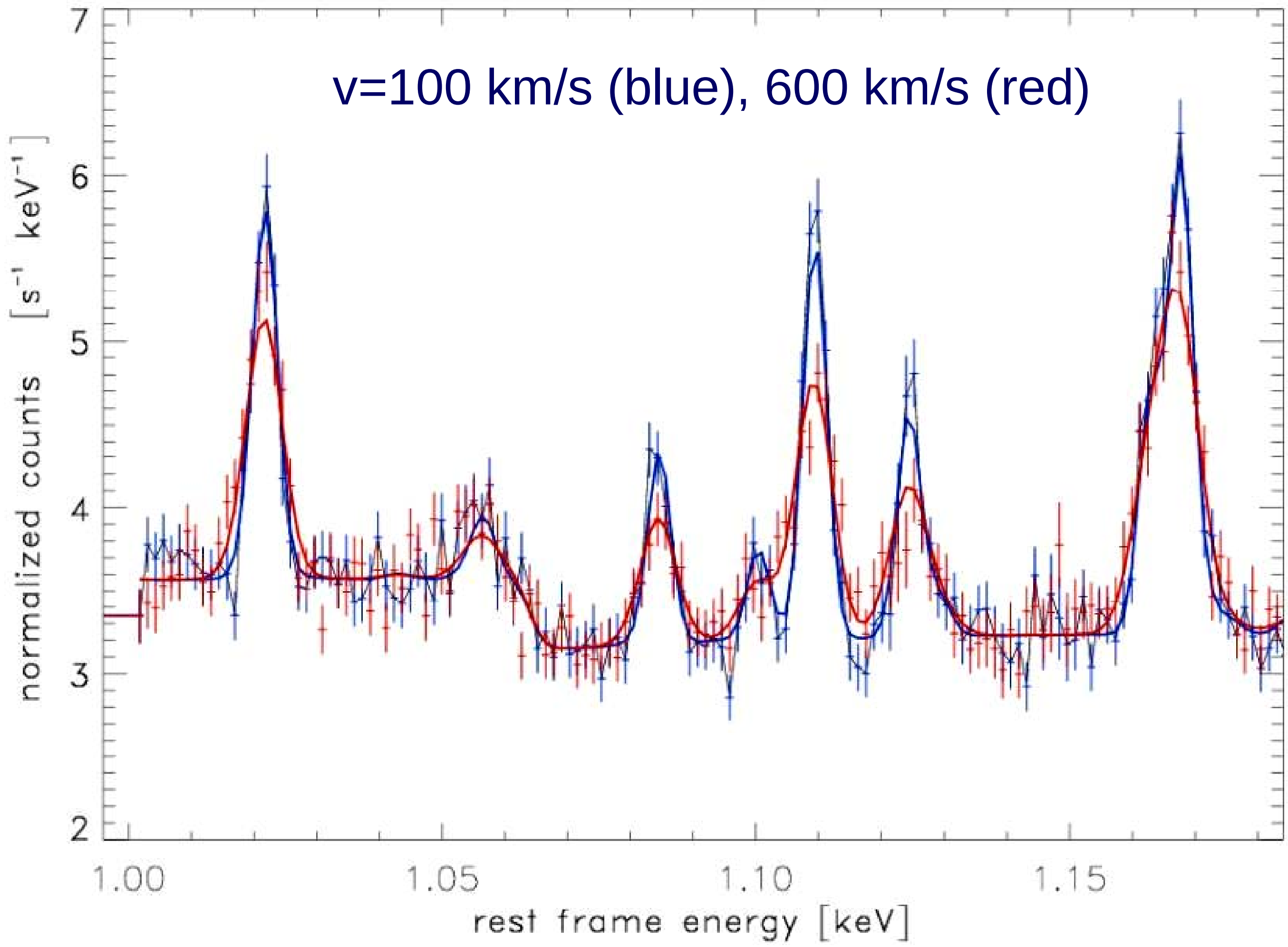
2 keV, exp.= 100 ks **Δv ~ 5-7 km/s**

[distant cluster z = 1, $F_X = 10^{-14}$ erg s^{-1} cm^{-2}, ab=0.3]

5 keV, exp. = 100 ks **Δv ~ 70 km/s**

→ Velocity structure is observable even for distant clusters !
spectral fitting can be complex (to find the true minimum)

Line Broadening in Distant Clusters



Cluster: z=1, $F_X \sim 1.5\ 10^{-14}$ erg $s^{-1}cm^{-2}$ (0.5-2 keV) → Δv = 20 – 50 km/s for 250 ks obs. - 70-80 km/s in 100 ks

The Influence of Multi-Temperature Structue and Turbulence on the Cluster Mass Determinatioon

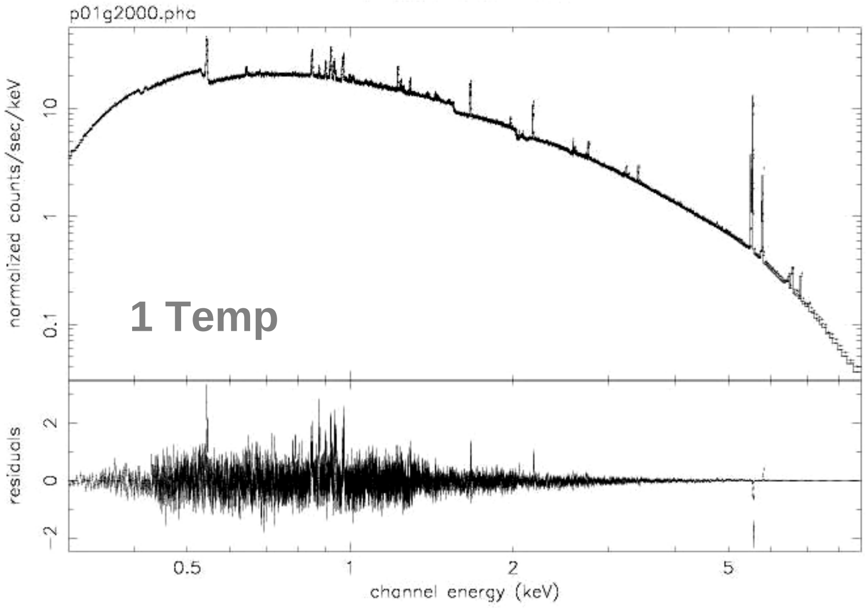
Simulations show two sources of mass underestimation (for the assumption of hydrostatic equilibrium and spherical symmetry):

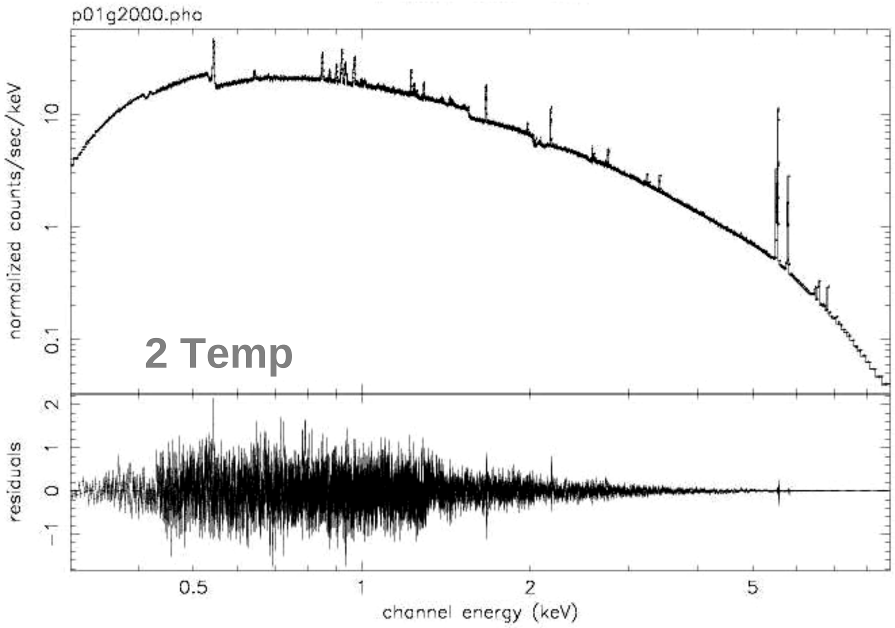
1) If there is additional kinetic pressure in the ICM (turbulence) this adds to the overall ICM pressure → higher mass
2) If the plasma has locally a range of temperatures, the temperature will be biased low with respect to a mass weighted mean temperature (the weighting to estimate the overall pressure)

E.g. Rasia et al. 2006 find on average an underestimate of the mass of about 20% - half due to turbulence, half due to temperature structure. This depends on the physics used in the simulations and needs to be tested by observations !!

Diagnostics of Multi-Temperature Structure I

Half & half mixture of 4keV and 8keV (F_X=10^{-12} erg s^{-1} cm^{-2}), analysed as 1 temperature and 2 temperature model 200 ks exposure (TES detector):

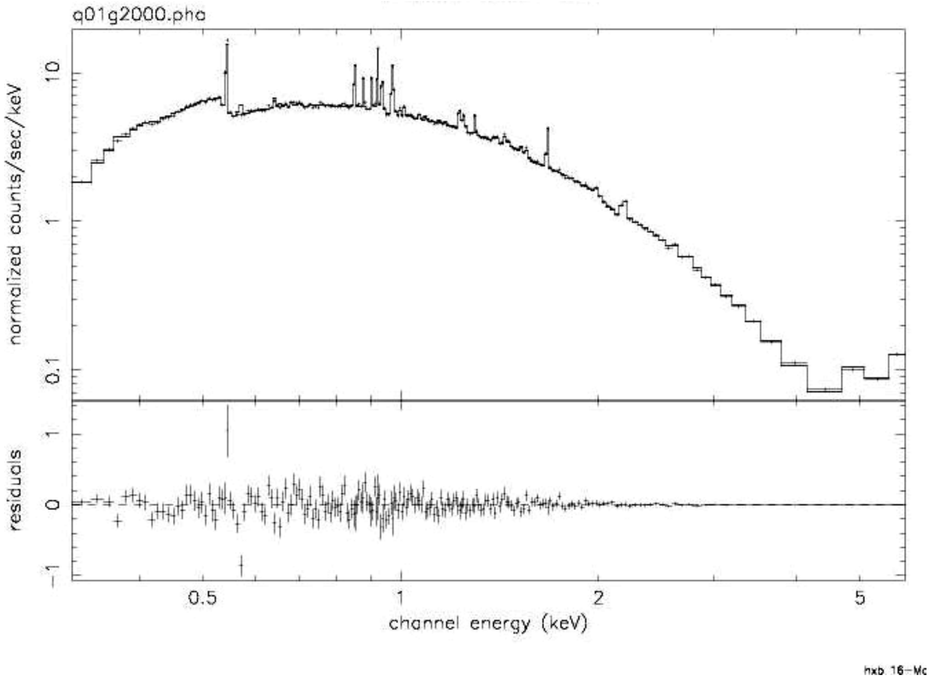




In the 200 ks exposure the two temperatures can be determined with an accuracy better than 5%, they can still be clearly distinguished in a 50 ks exposure (F_X ~ 5 10^{-13} erg s^{-1} cm^{-2}) at ΔT ~ 0.6 keV.

Diagnostics of Multi-Temperature Structure II

STJ spectrum of 3 & 5 keV plasma (Em = 1:1) 50 ksec exposure:



Feasibility ($F_X = 5\ 10^{-13}$ erg s^{-1} cm^{-2}):

<u>4 & 8 keV plasma:</u>

exp = 200ks → ΔT ~ 0.2 keV (TES)

= 100ks ΔT ~ 0.4 keV „

= 100ks ΔT ~ 0.3/1 keV (STJ)

<u>3 & 5 keV plasma:</u>

exp = 50 ks → DT ~ 0.3/2 keV (TES)

50 ks DT ~ 0.4/2 keV (STJ)

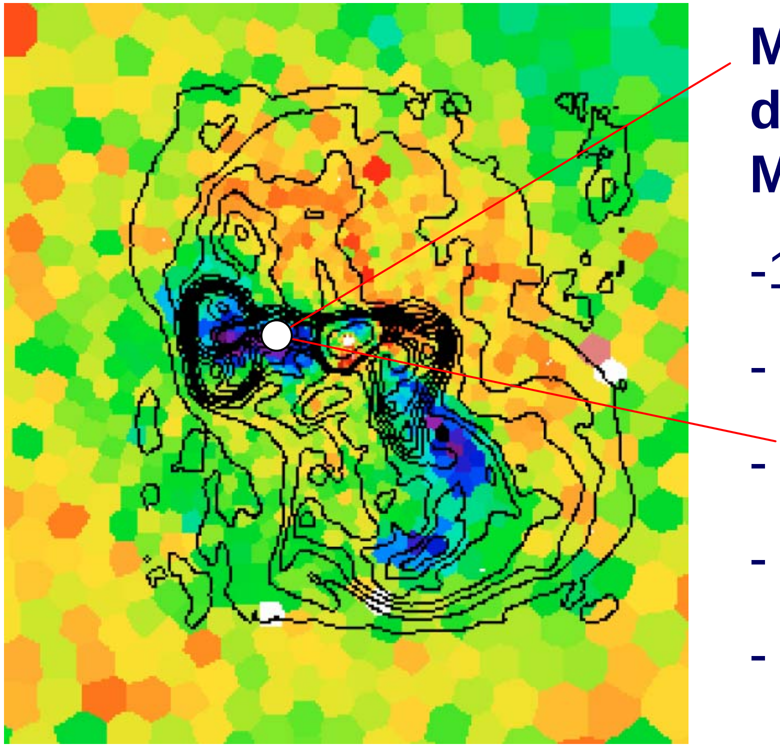
<u>3(10%) & 7(90%) keV plasma:</u>

Exp.= 100ks 7 +- 0.2 keV

3 +- 0.3 keV

At lower temperatures things are much easier !

Cool Core Diagnostics: M87 halo



Multi-temperature-Abundance diagnostics in the radio lobe region of M87 (50ks observation TES):

-10% cool plasma 1keV, hot Pl. 2.3 keV

- $T_1 = 0.99$ +- 0.002 T2 = 2.27 +- 0.01
- Fe, Si, S (1) = 2.3 +- 0.14
- O, Mg (1) = 0.9 +- 0.24 (0.07)
- Fe, Si, S (2) = 0.7 +- 0.01
- O, Mg (2) = 0.3 +- 0.05 (0.01)

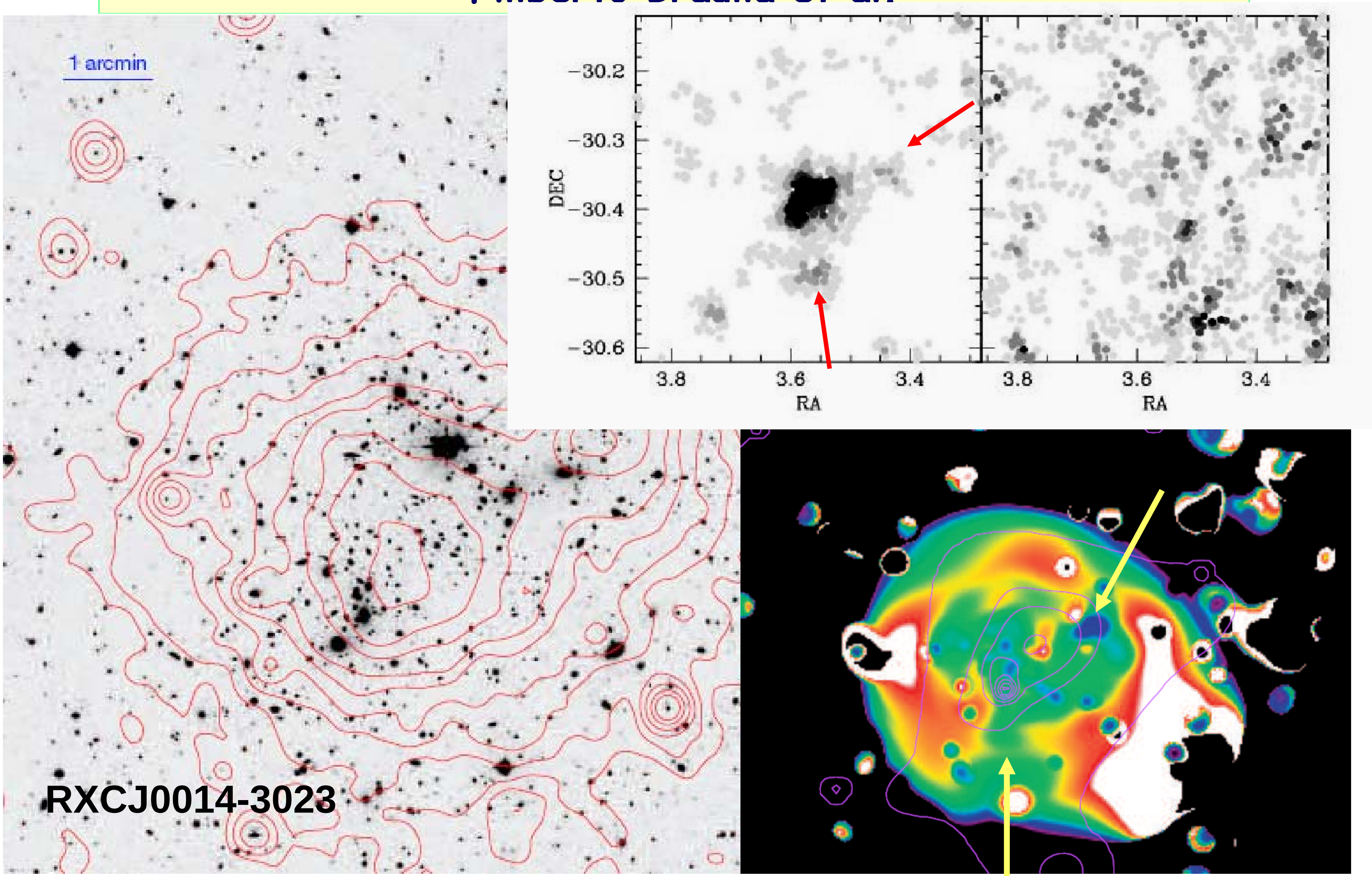
1 arcmin^2 test region with

Fx (0.5-2) = 4.3 10^{-12} erg s^{-1} cm^{-2}

With XMM-Newton we can barely distinguish 2 temp., but not different abundances

Connection Between Clusters and LSS

Filiberto Braglia et al.



Temperature, Pressure and Entropy Maps at z ~ 1 ... 1.5

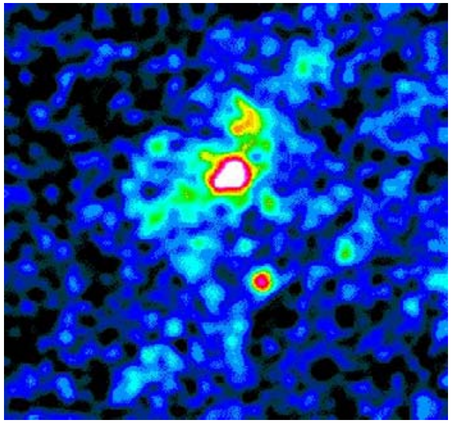
Feasibility for a cluster with $F_X = 10^{-14}$ erg s^{-1} cm^{-2}
z = 1-1.4 , 5 keV, abund. = 0.3 solar

XEUS count rate ~ 0.2 s^{-1} 200ks → 40 000 cts

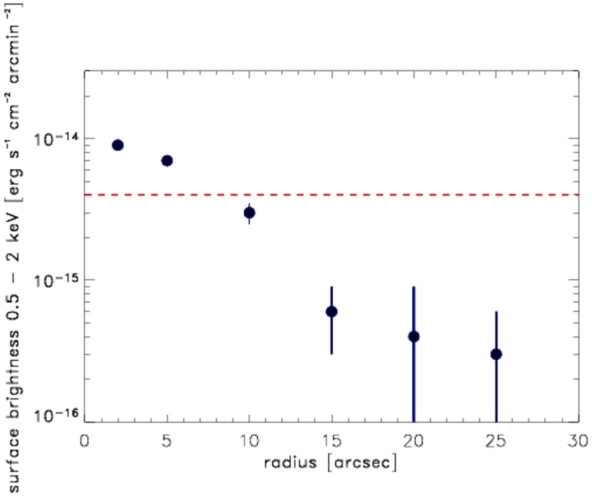
This will provide similar temperature, entropy, pressure maps as shown for the REFLEX DXL clusters (the temperature maps would even be better, due to the better spectral resolution !)

The flux limit ($F_X = 10^{-14}$ erg s^{-1} cm^{-2}) used above corresponds to the sensitivity limit of our XMM-Newton Distant Cluster Project (XDCP) where we find about one z>1 cluster per deg^2
→ we will have enough study objects of with the assumed properties !

Galaxcy Group at z = 2

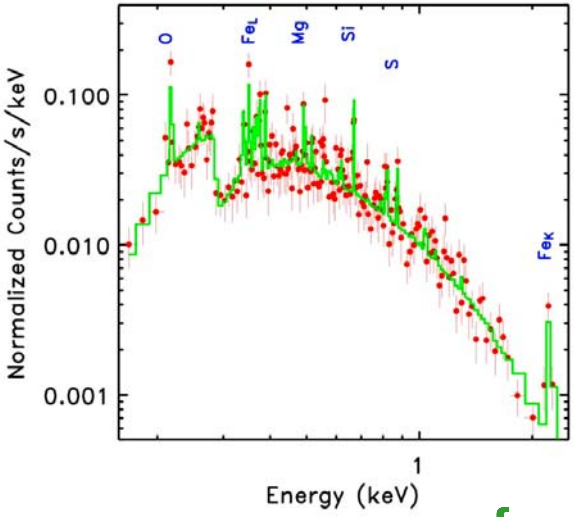


Surface brightness still determined to about 3.5 core radii (140 kpc)



High z extreme: Group at z = 2

- $F_X = 5\ 10^{-16}$ erg s^{-1} cm^{-2}
- $L_X = 7\ 10^{43}$ erg $s^{-1,}$ [0.5 -2 keV]
- centr. Sfb. ~ 2x bkg
- core radius 40 kpc = 5“



Spectroscopy:

-Temperature +- 3%

- [Fe] +- 11%
- [Si] +- 18%
- [O], [Mg] +- 30%

from M. Arnaud

Requirements for XEUS

To explore distant clusters (z = 1 .. 2.5) in detail we need:

-- large collecting area > 3 m^2 is good

-- at minimum 5“ resolution

-- energy resolution of current response matrices

(2.5 ev at Fe L-lines)

-- large FoV of NFI

& WFI is great to detect groups z > 2

-- low background and well assesed background

(new approaches should be tried - e.g. out-of- field bkg
. monitor CCD)

Conclusion

XEUS will provide new insight in detailed astrophysics of nearby clusters

Really new terretory: cluster astrophysics and cosmology with cluster at $z = 1 \ldots 2\ (2.5)$

1. Precise meassurements of cluster structure, thermal history, chemical evolution, formation history, mass-to-light ratio (=stellar vs total mass)
2. Precise measurements of cluster masses → required for cosmology + issues above
3. Basis for testing cosmological models with
   (i) cluster evolution and spacial distribution and
   (ii) SZE/X-ray standard candles (and baryon fraction)