Galaxy Cluster Astrophysics & Cosmology with IXO

1 Tracing the Evolution of the Baryonic Component in the Visible Structure of the Universe
(Cluster and IGM Astrophysics)

2 Galaxy Clusters as Cosmological Probes

Allen, Arnaud M., Böhringer, Bonamente, Burns, Evrard, Henry, Jones, McNamara, Ohashi, Patnaude, Vikhlinin,
Arnaud K., Bautz, Blanchard,Bregman, Chartas, Croston, David, Donahue, Fabian, Finoguenov, Furuzawa, Gallagher, Habe, Hornschemeier, Heinz, Kaastra, Kapferer, Lamer, Mahdavi, Makishima, Matsushita, Nagai, Nakazawa, Nulsen, Ogle, Perlman, Ponman, Proga, Pratt, Randall, Rapetti, Reiprich, Richards, Romer, Ruszkowski, Schmidt, Smith, Tananbaum, Vrtilek, Worrall

Tracing the Buildup of the Visible (Baryonic) Cosmic Structure with Galaxy Clusters

1. Evolution of the baryons in the hierarchically forming Dark Matter halos (mergers, shock heating, cosmic rays and magnetic fields)

2. Thermal evolution of the baryons in the presence of star and black hole formation (cooling, feedback heating, preheating, etc.)

3. Chemical enrichment of the ICM (incl. transport processes)

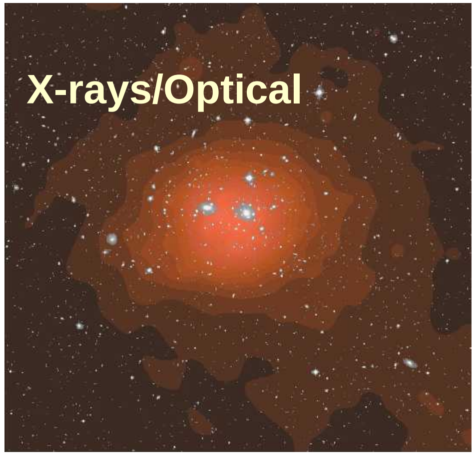
4. Growing Black Holes in the cluster centers (cool cores and BH feedback)

5. Tracing the DM halo structure and mass distribution with the ICM

With spatially resolved line spectroscopy - up to redshift ~ 2

- only possible with IXO !! (IXO or never in our generation)

Why X-ray Observations are Mandatory

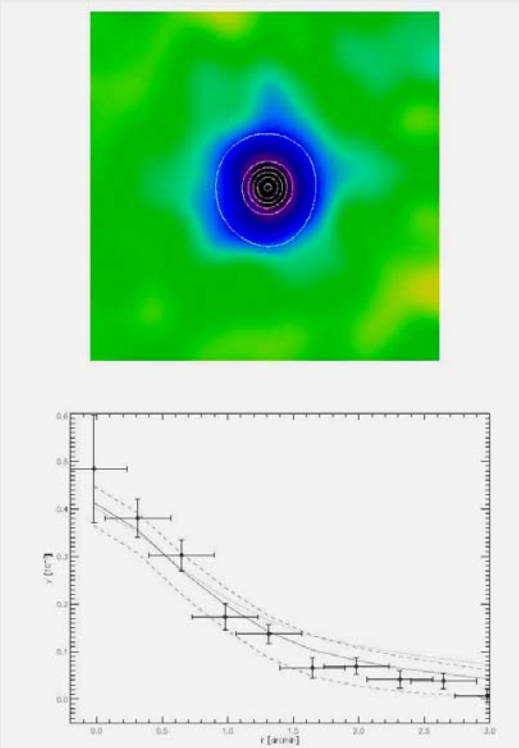


X-ray observations are still the best approach to characterise galaxy clusters!

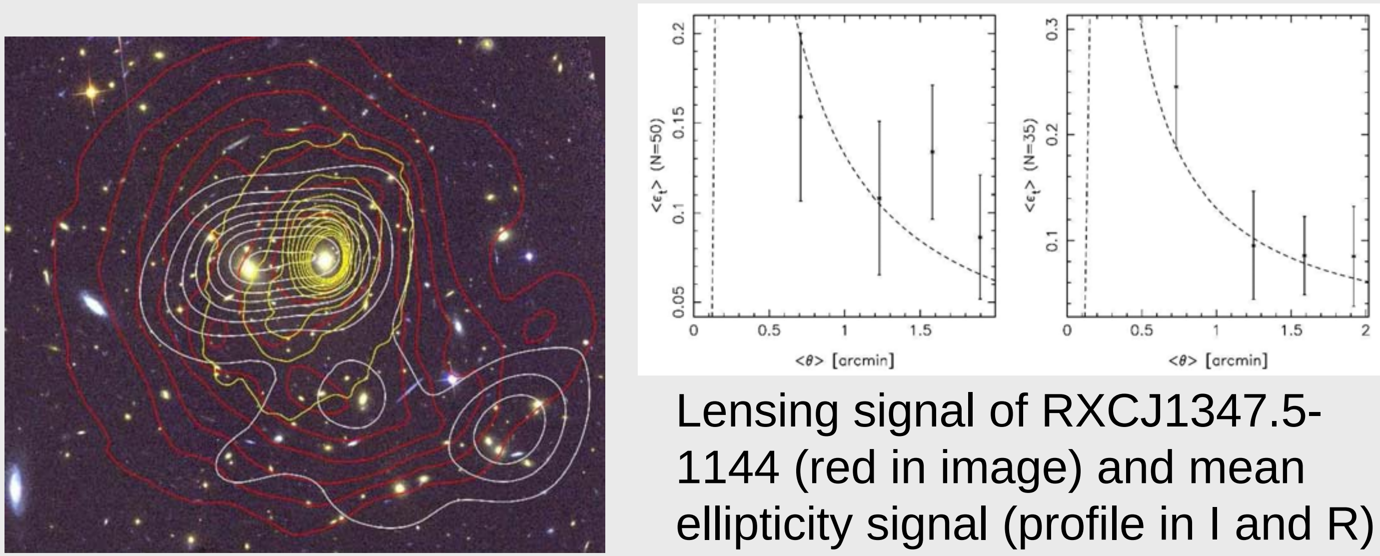
For medium distant clusters: ~ 40 000 cts → 150 – 200 σ Signal!

compared to <~ 10 σ for best SZE and Lensing

We are interested in exploring and understanding the physics in its original complexity before making simplifying generalizations !



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

New Diagnostic Tools and Capabilities

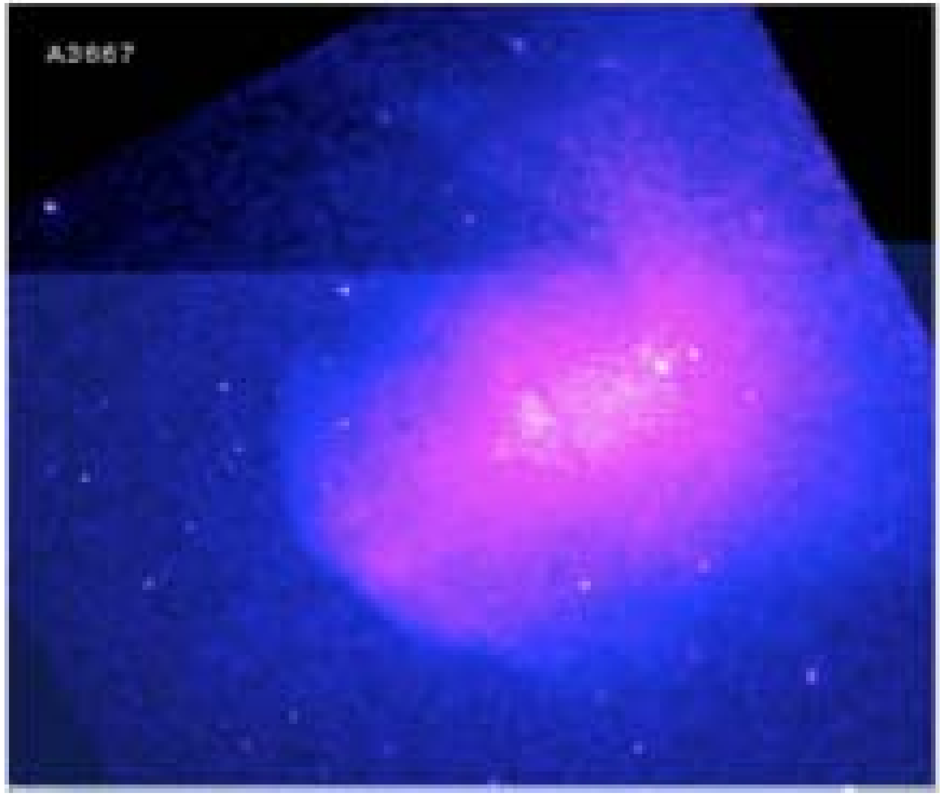
Line Spectroscopy:

1. Line shifts and line broadening: velocity diagnostics

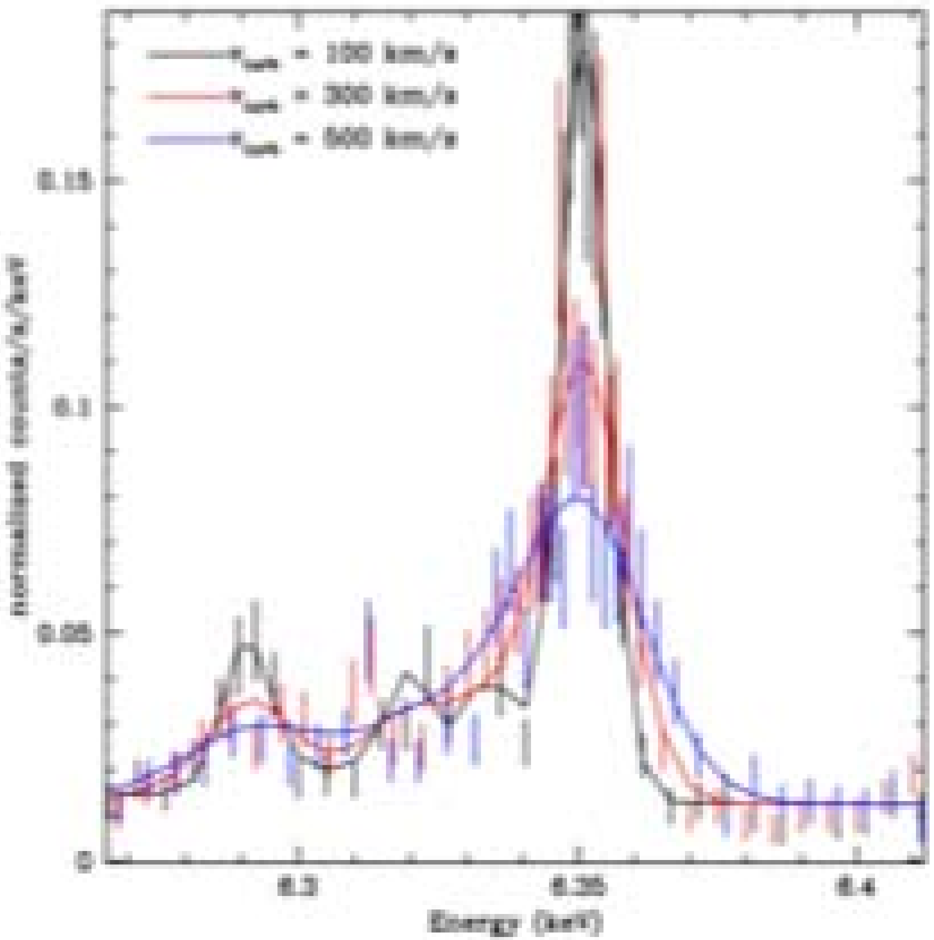
2. Detailed abundances (detailed heavy element production history)

3. Multi-temperature structure

Velocity Diagnostics in Abell 3667

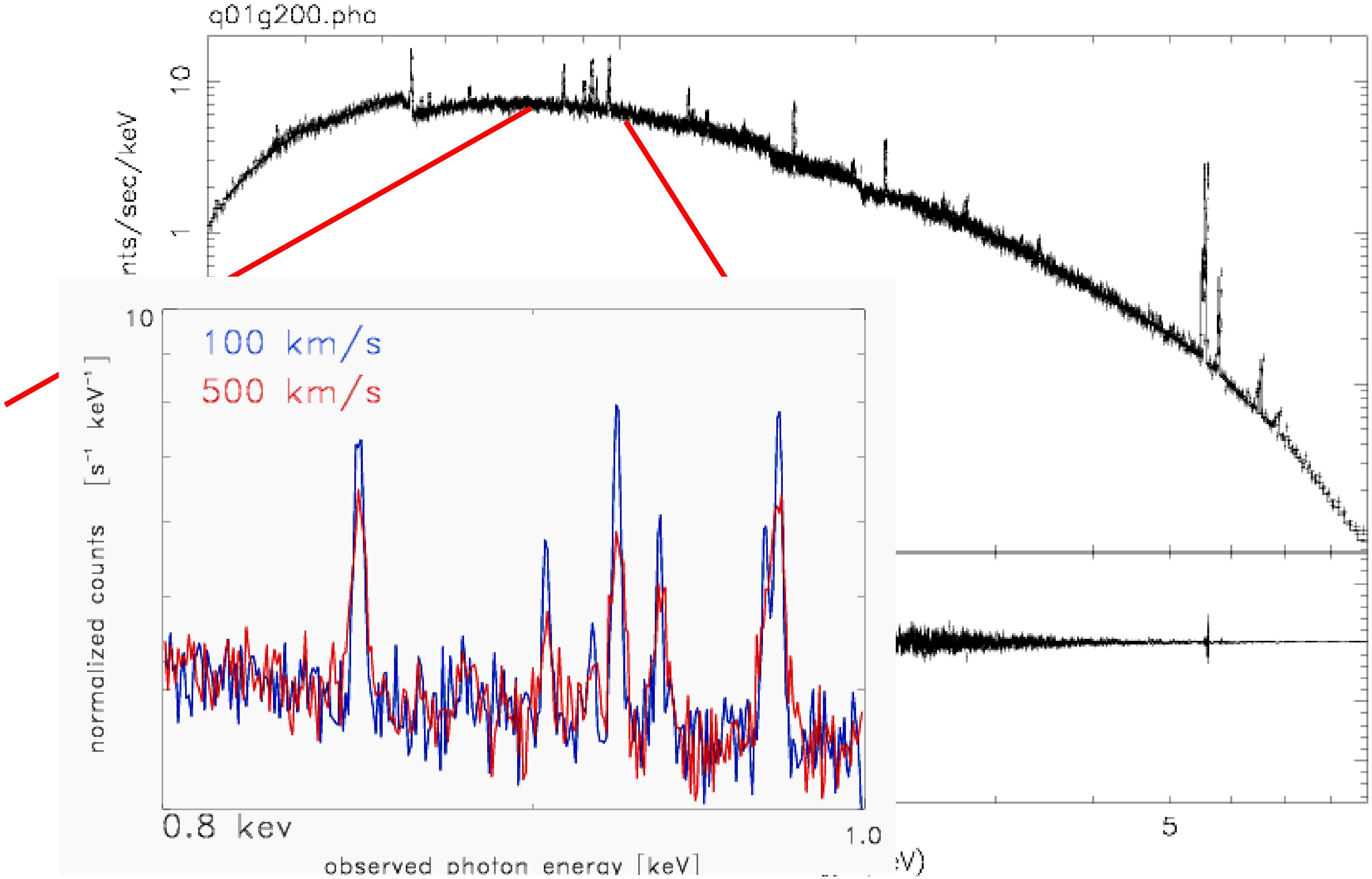


500 ksec Chandra observation of the merging cluster A3667



Simulated 200 ksec observation with IXO assuming a velocity broadening of 100, 200 and 500 km/s - one would also see line shifts !

Diagnostics of Velocity Line Broadening I



5 keV spectrum, velocity broadening 100 (blue) 500 (red) km/s (Gaussian)
uncertainty of velocity measurement in 100 ks observation: $\Delta v <= +-20$ 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**

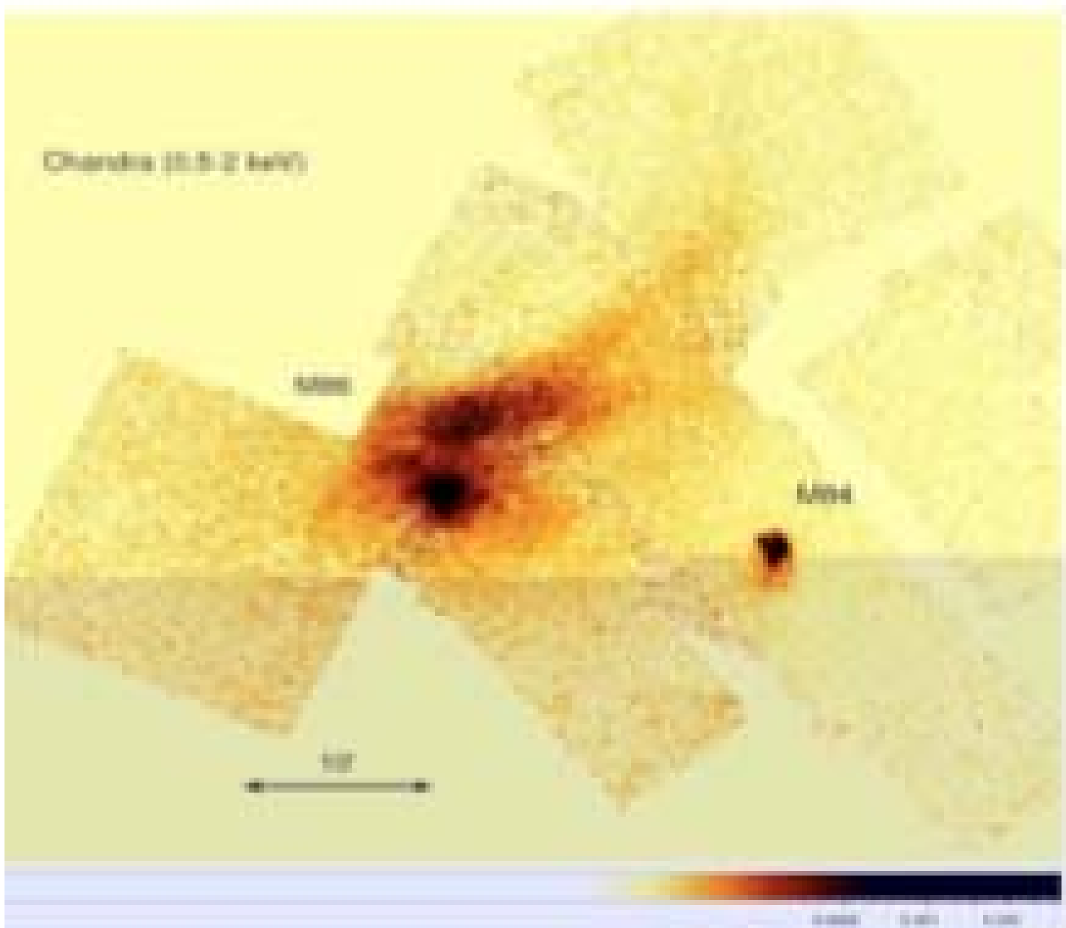
2 keV, exp.= 100 ks **Δv ~ 5-7 km/s**

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

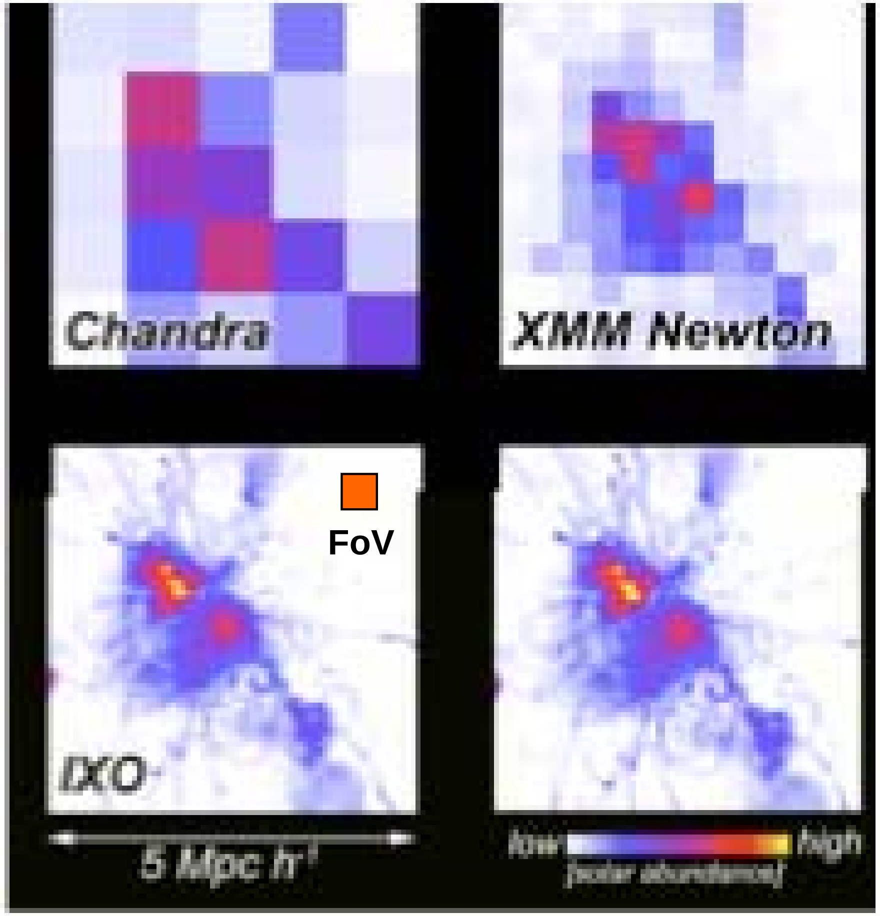
5 keV, exp. = 100 ks **Δv ~ 70 km/s**

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

Detailed Abundance Distribution



Chandra X-ray image of M86 in the Virgo cluster and its ram-pressure stripped tail



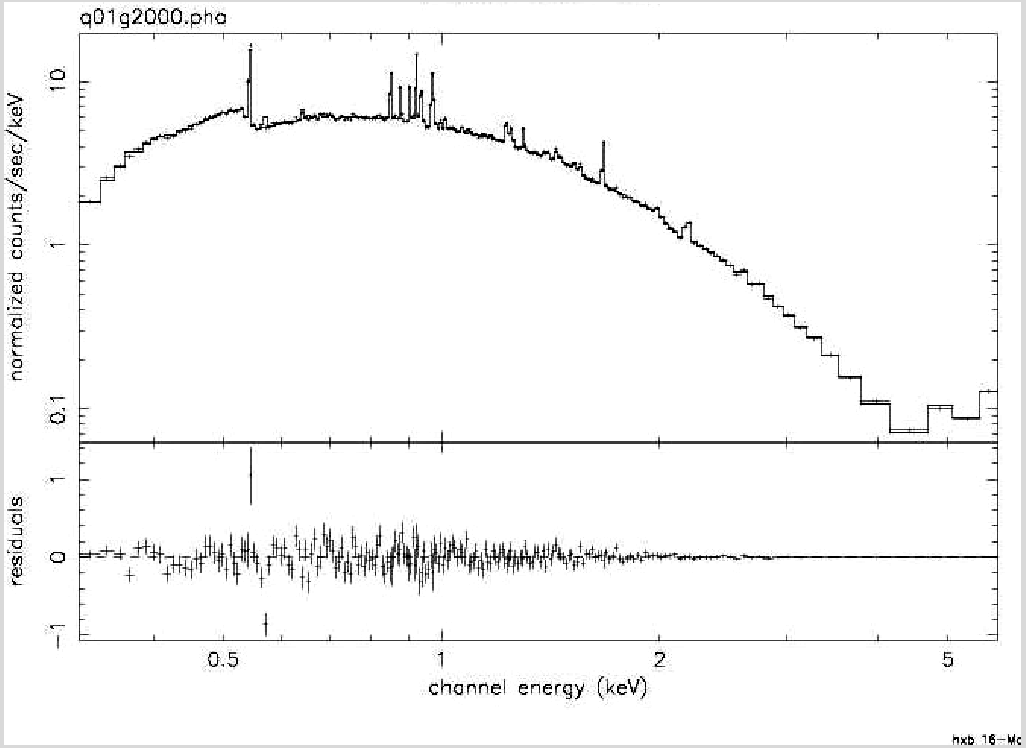
Simulated cluster with metal abundance distribution seen by (Chandra, XMM, IXO)

Simulated cluster with 7 keV, Lx = 2 10^{44} erg/s z = 0.05 (20 arcmin ~ 0.3 Mpc)
30ksec exposure

Diagnostics of Multi-Temperature Structure

Spectrum of 3 & 5 keV plasma

(Em = 1:1) 50 ksec exposure:



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

Exp.= 100ks 7 +- 0.2 keV

3 +- 0.3 keV

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

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

exp = 200ks → ΔT ~ 0.2 keV

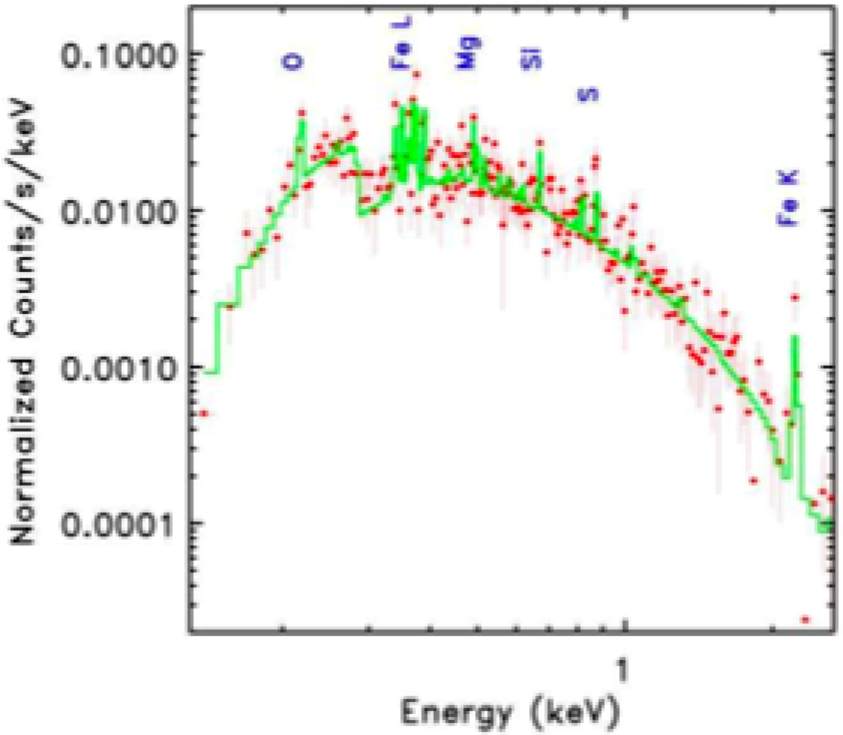
= 100ks ΔT ~ 0.4 keV „

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

exp = 50 ks → DT ~ 0.3/2 keV

At lower temperatures things are much easier !

General Spectroscopic Diagnostics
out to z ~ 2

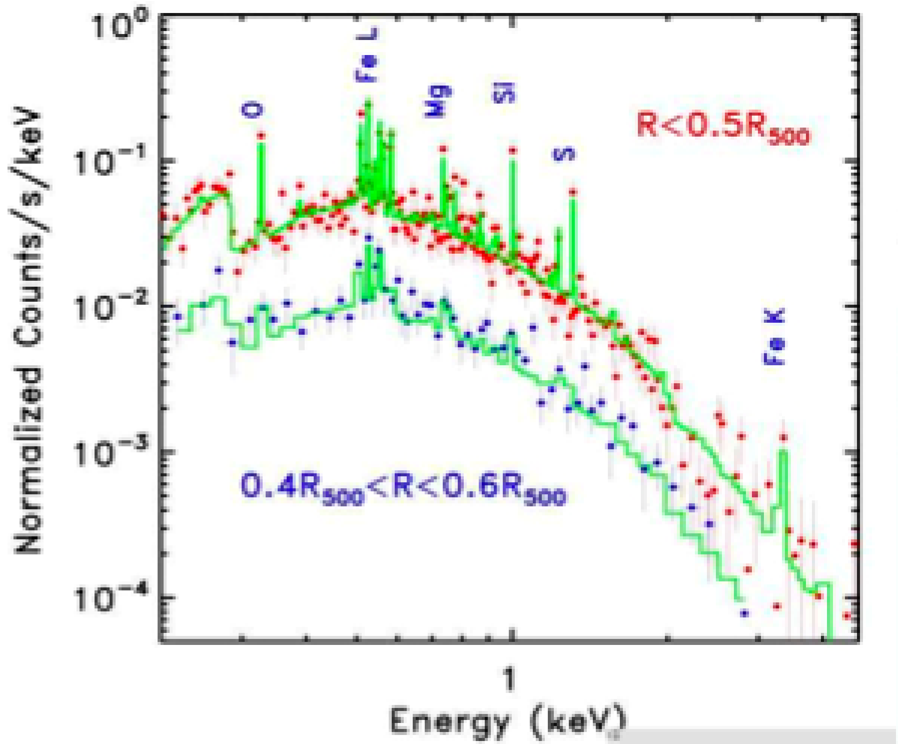


250 ks IXO (NFI) observation of a low mass system (2 keV, Lx = 7.7 10^{43}erg/s) at z = 2

Measurements: ΔT ~ 3.5%

Δ[O],[Mg] ~ 35% Δ[Si],[S] ~ 25%

Δ[Fe] ~ 15%



z = 1 cluster exposure = 150ks

inner and outer region

Measurements: ΔT ~ 5%

Δ[Fe] ~ 20%

How many Test Objects Do We Find ?

Redshift	mass	clusters /20000 deg2 half of the sky	X-ray luminosity
$z > 2$	$> 10^{14}\,M_{sun}$	100	10^{44} erg/s
	$> 3\ 10^{13}\,M_{sun}$	20000	$2\ 10^{43}$ erg/s
	$> 10^{13}\,M_{sun}$	$4\ 10^{5}$	$3\text{-}5\ 10^{42}$ 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**

Serendipitous Discoveries @ High z

For a 20 x 20 arcmin^2 FoV for WFI

1 year of observations (50% eff.) = 300 x 50 ks obs.

assuming a ration of 1.5 : 1 for NFI and WFI observations

→ 5 year archive (30% useful obs.) 20 deg^2

10 year „ " 40 deg^2

We expect about 1-2 cluster T>= 2 keV z>~ 2 per deg^2

which can be identified in 50 ks exposures (300 – 1000) cts

This will provide a new terretory for follow-up studies in confirmed-evolved distant clusters ! (Unless SZE experiments make an enormous progress, there is no other way to find these groups/clusters !

Conclusions for Astrophysics Part

The envisioned detailed cluster studies will answer many important questions that arise today quite precisely:

1)Physics of cluster build-up by mergers and matter accretion

2)Thermal evolution due to cooling, star formation and BH feedback

3)Detailed history and composition of chemical enrichment (sources and transport processes)

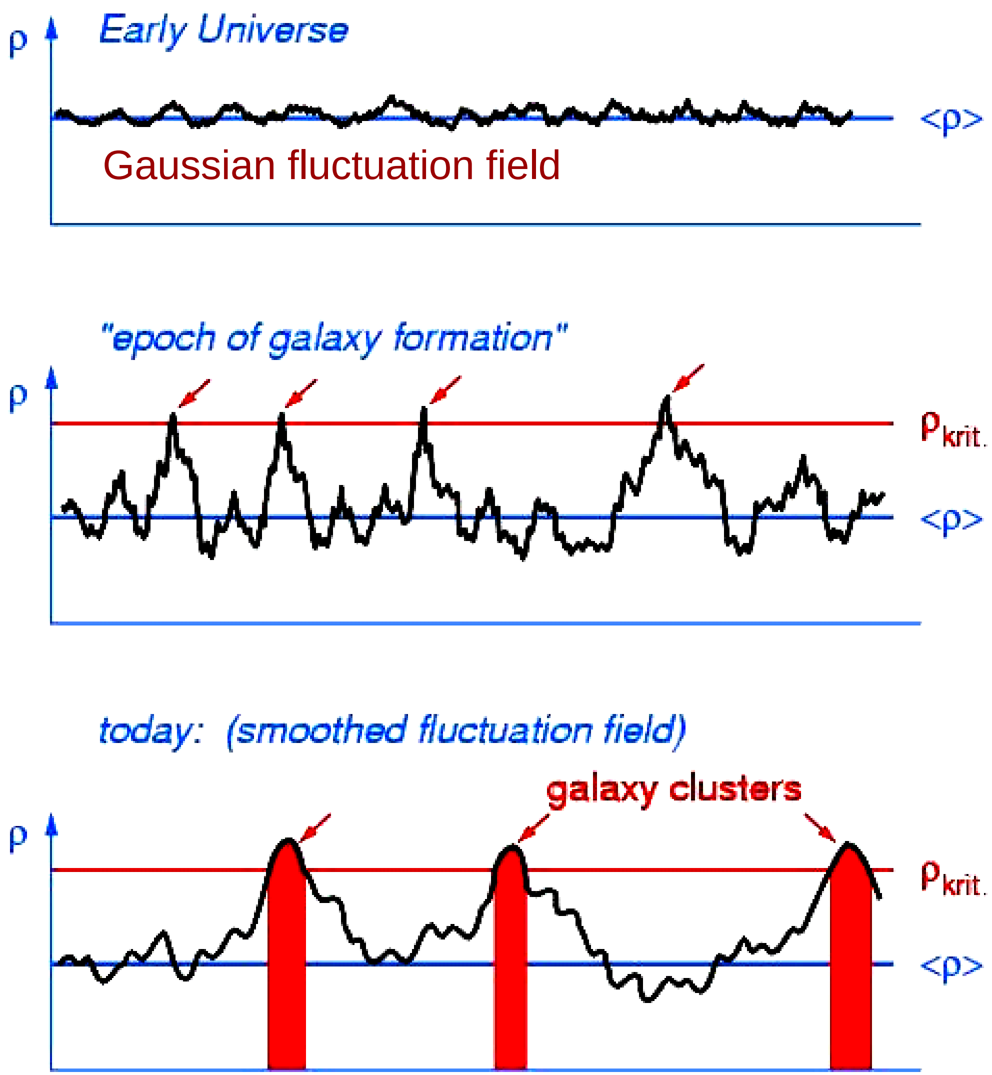
4)Black hole growth in cluster centers

5)Details of the physics of the ICM (e.g. turbulence, heat cond., etc)

Possible Observing Program

Detailed cluster studies for all mentioned apects:		total
33 clusters at z < 0.3 (average 4 sightlines with 30ks)		4 Msec
40 clusters z = 0.3 – 0.8	50 – 70 ksec	2.4 Msec
36 clusters z = 0.8 – 1.4	100 – 120 ksec	4 Msec
23 clusters z = 1.4 – 2	150 – 250 ksec	4.6 Msec
132 clusters		15 Msec

The Role of Galaxy Clusters in the Hierarchy of Large-Scale Structure



mass of galaxy clusters ~ 10^{14} – 10^{15} M_{sun}

The evolution of the cluster population is tightly connected to the evolution of the large-scale of the matter-density field

The statistics of the cosmological model and the matter composition determine the statistics (power spectrum) of the large-scale structure.

The cosmology determines the number density of clusters (peaks in density field) as a function of mass and redshift.

Cosmology

3 types of cosmological tests:

(i)Early Universe (CMB) geometry, matter-energy budget)

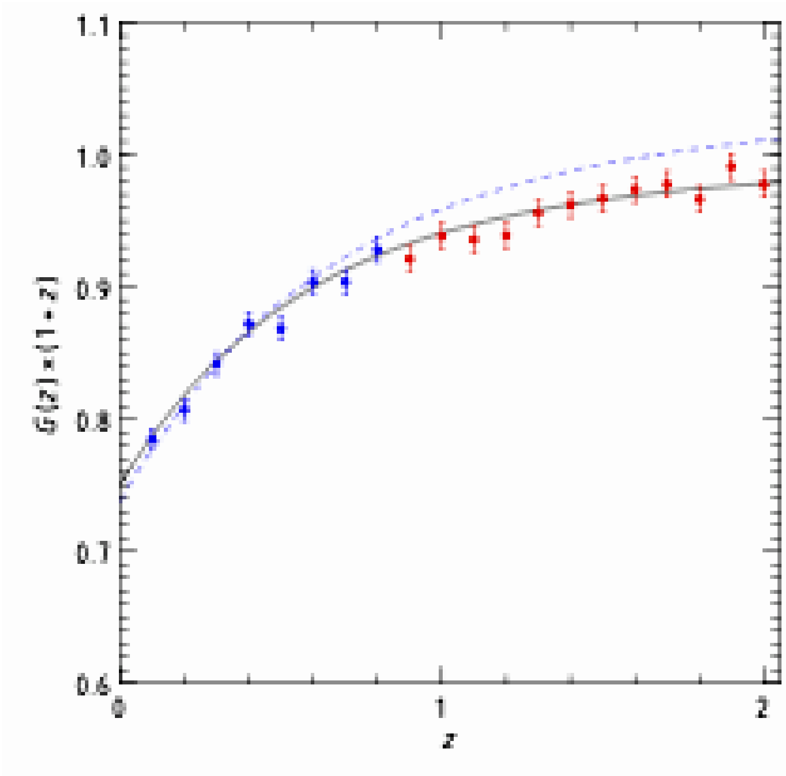
(ii)Global geometry tests (SN, BAOs, cluster F_{bar} or X-ray/SZE)

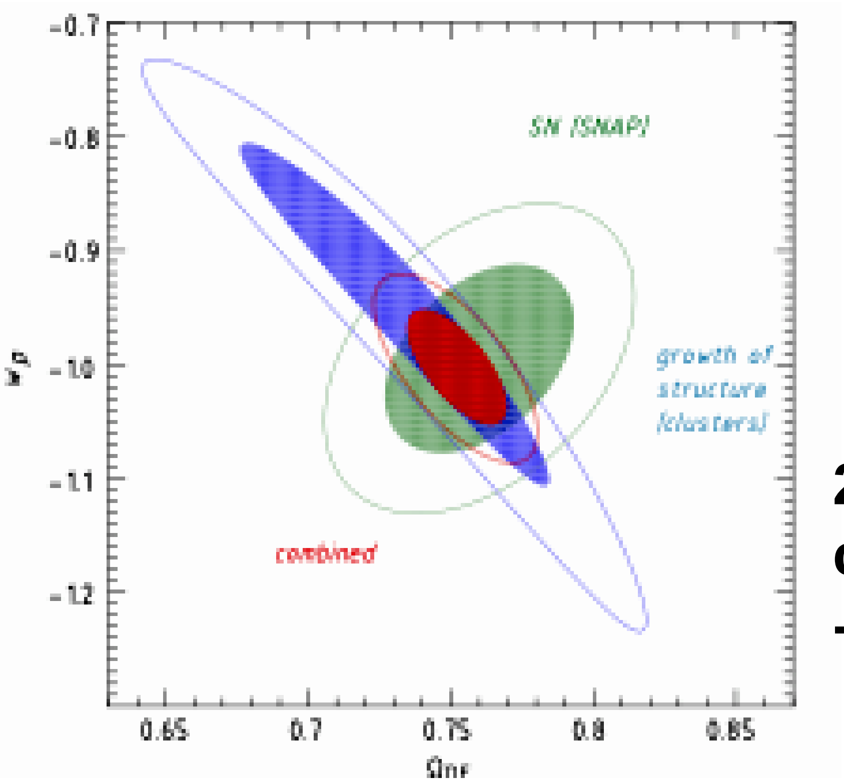
(iii)Structure growth tests (cluster abund. evol., lensing, redshift space distortions of galaxy surveys)

Test (ii) and (iii) reveal difference for quintessense type and modified gravity (e.g. brane world) models

- Both tests can be realized with clusters !

Measuring Cluster Abundance Evolution





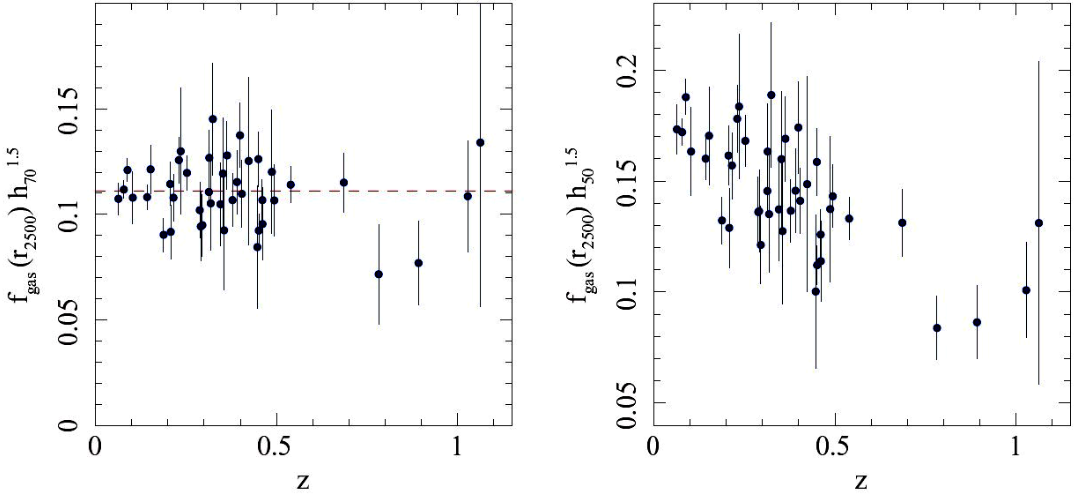
2000 clusters - 10 Msec

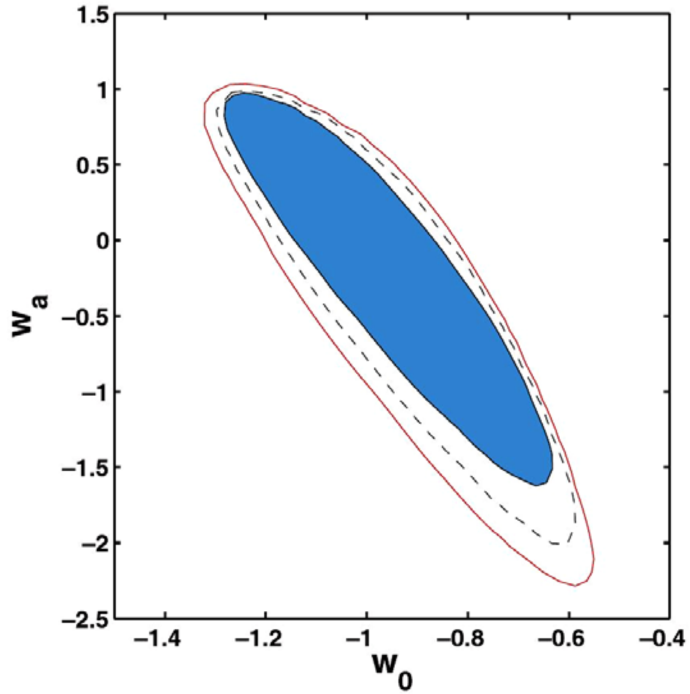
IXO observation of 100 clusters per $\Delta z = 0.1$ out to $z = 2$ → 2000 cl.

$\Delta\sigma_8$ ~ 1% per redshift interval - data: Yx = (T*gas mass) - requires mass calibration by lensing to 2-3%

→Structure growth parameter $\Delta\gamma$ ~ 0.022 (0.045) {0.018(0.034) with PLANCK}
e.g. Standard model $\gamma = 0.55$ DGP brane-wold model $\gamma = 0.68$

Cosmological Distance Indicators (f_{gas})





Gas mass fraction as function of redshift - deduced for different cosmologies (Concordance model, Einstein-deSitter model)

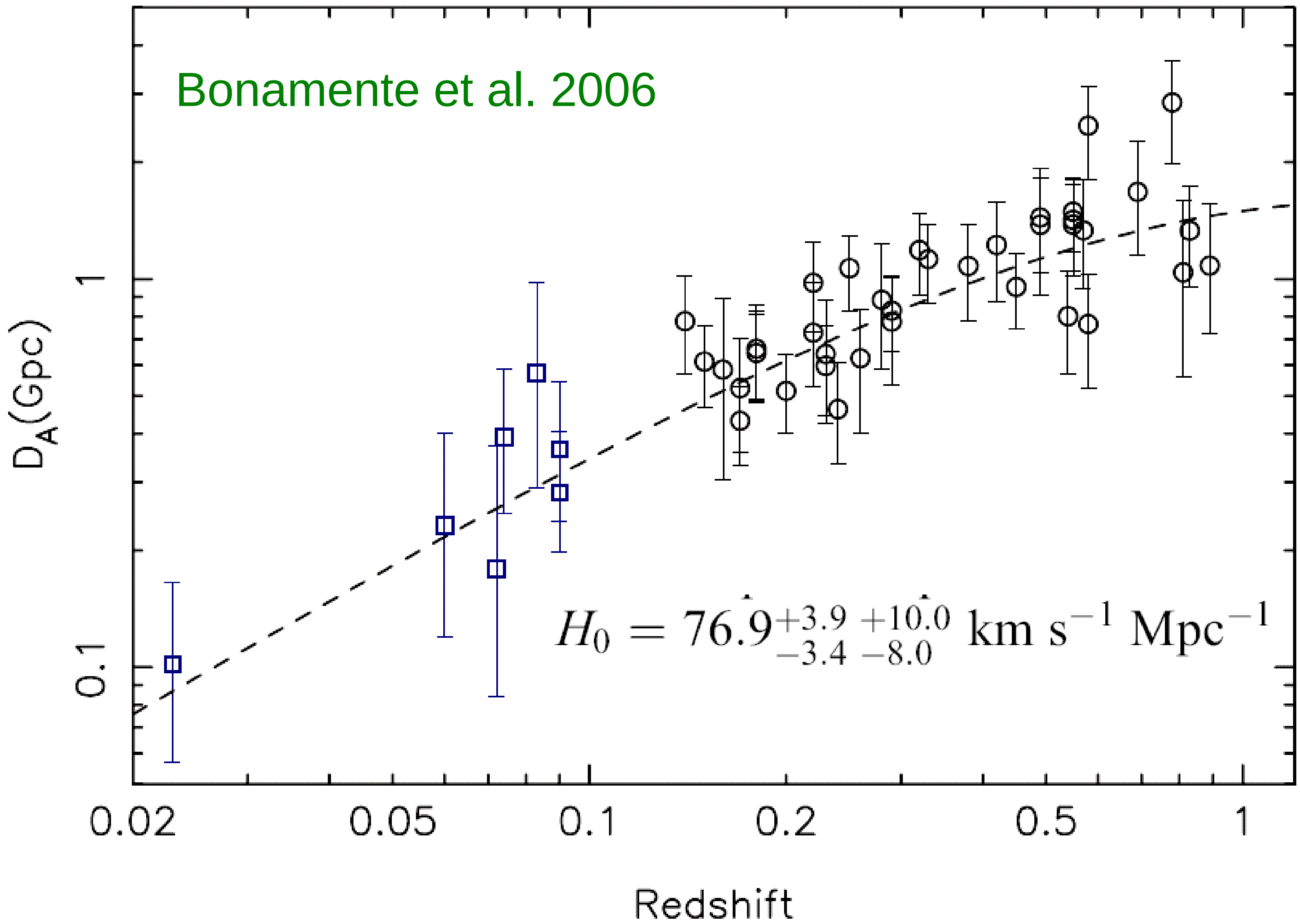
Universal gas mass fraction expected ! (Allen et al. 2008)

Prospected cosm. Constraints from 500 hot (> 5keV) clusters (z = 0..2) with 2%, 5% or 10% mass measurement accuracy

(Rapetti et al. 2008)

500 hottest, regular clusters observed in 10 Msec

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

Conclusion

IXO will provide the detailed insight into cluster structure and evolution – comprehensive picture of the evolution of baryons in large DM potentials including star formation, chemical enrichment and SMBH evolution ---- also necessary to put the results from forerunning cluster surveys on precise footing to allow stringent cosmological tests

Cluster cosmological tests provide complementary information on cosmology by probing the growth of structure in the Universe (which depends on DM + DE)

We will reach a new terretory for cluster astrophysics and cosmology with cluster at z >= 1.5 – 2 (... 2.5)
→ IXO has a discovery potential for clusters/groups at redshifts >~ 2