Galaxy Cluster Cosmology

1. Clusters as cosmological probes (tracing structure growth and providing distance indicators)
2. Importance of IXO for calibration of underlaying scaling relations
3. Synergy with other missions for cluster cosmology

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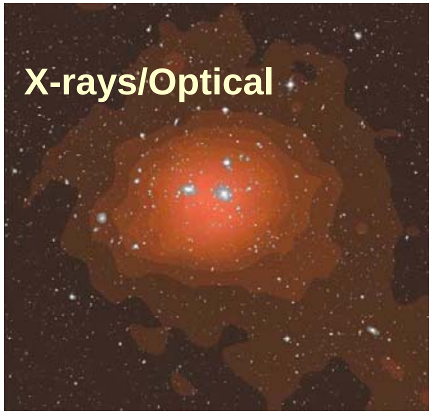
Why X-ray Observations are Mandatory

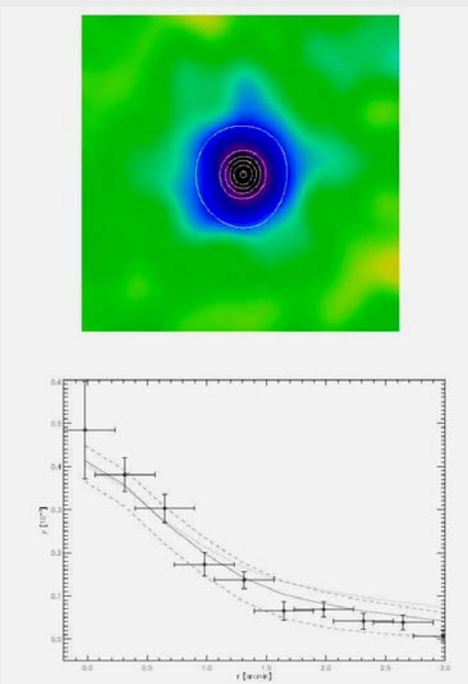


X-ray observations are still the best approach to characterise galaxy clusters!

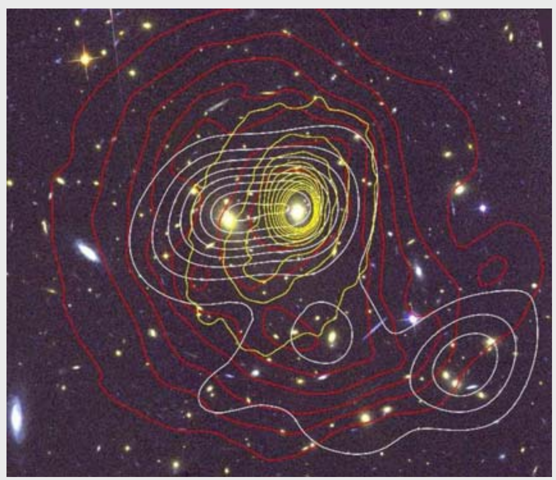
For medium distant clusters: ~ 40 000 cts → 150 – 200 σ Signal!

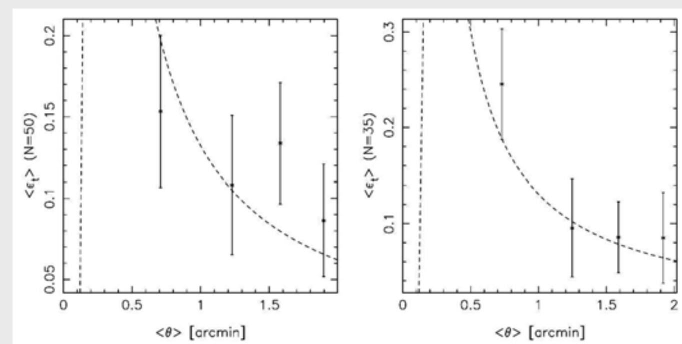
compared to <~ 10 σ for best SZE and Lensing

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

Cosmological Tests with Galaxy Clusters

1. **Evolution of the cluster mass function [tests LSS growth g(z) – and H(z)]**

2. **Evolution of P(k) or ξ(r) of the cluster clustering**

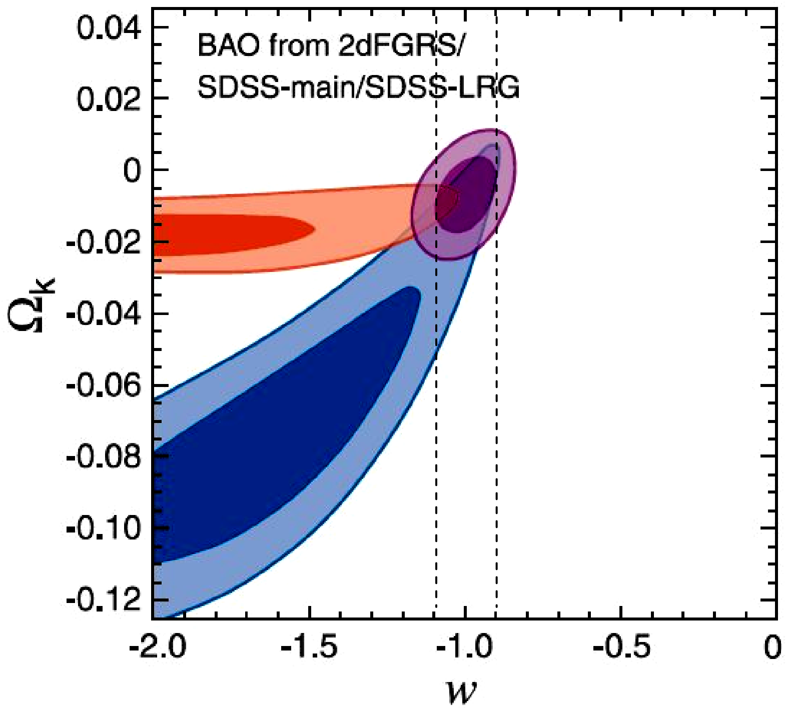
3. **Cluster ICM observations as standard candles**

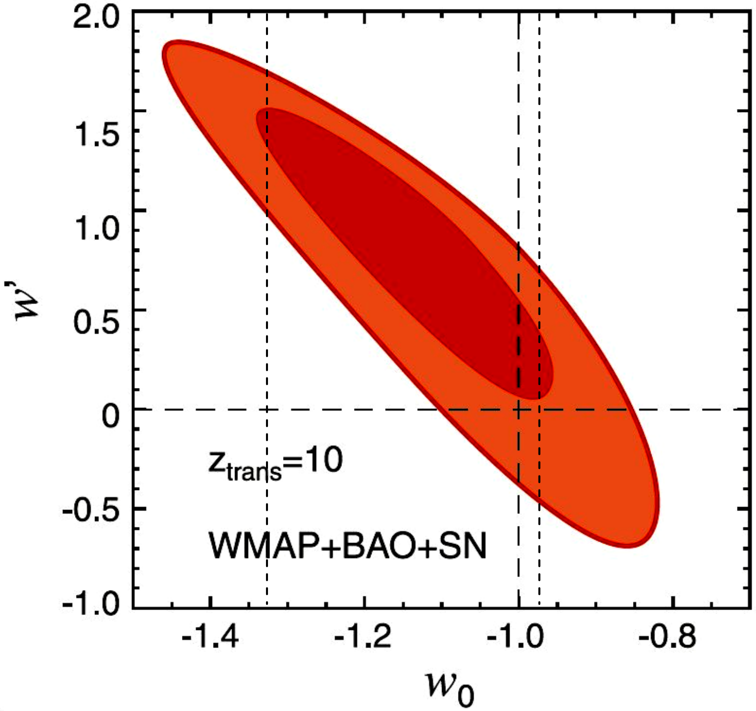
   gas mass fraction or SZE (depend on diameter dist.)

4. **Shape of DM halos (formation history, details of DM interaction)**

Cosmological Challenge Baseline

WMAP++ Results reported in Komatsu et al. 2008



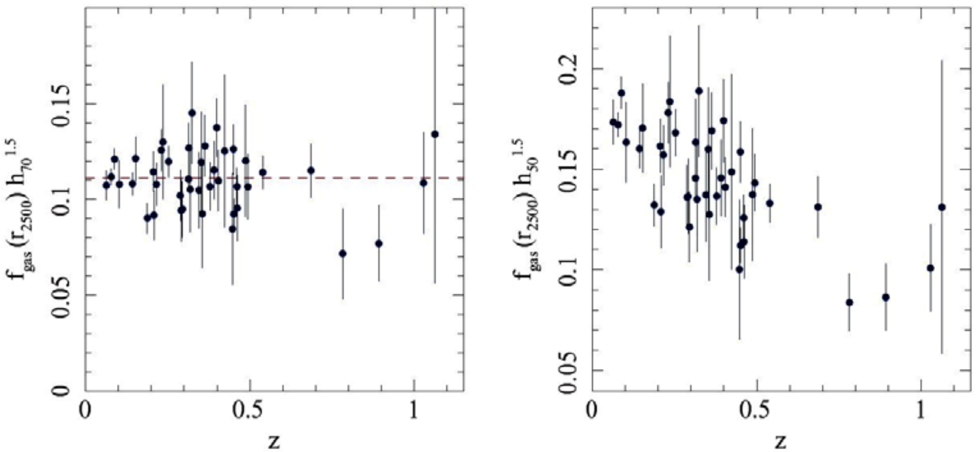


WMAP + BAO + SN : Δw < 15 % (~7% for w const.) Δw' ~ 50 – 70%

eROSITA : Δw ~ 6-7% Δw' ~ 50 %

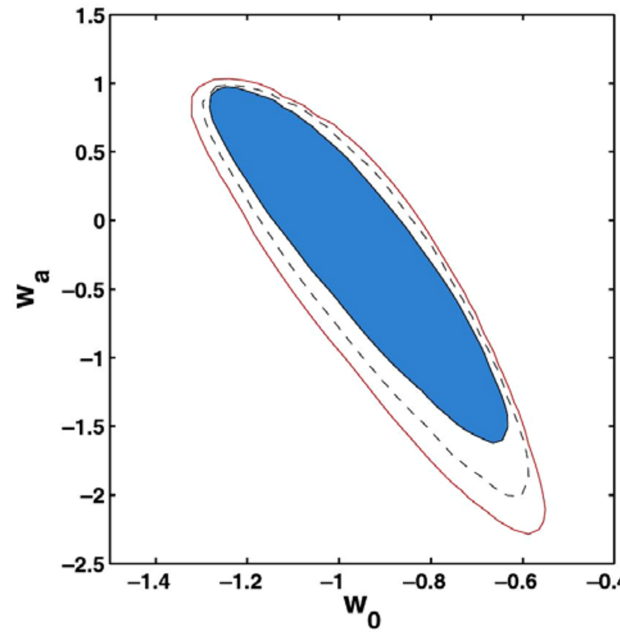
DUNE (EUCLID) : Δw < 5% Δw' ~ 40-50 % (conserv.)

Cosmological Distance Indicators (f_{gas})



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

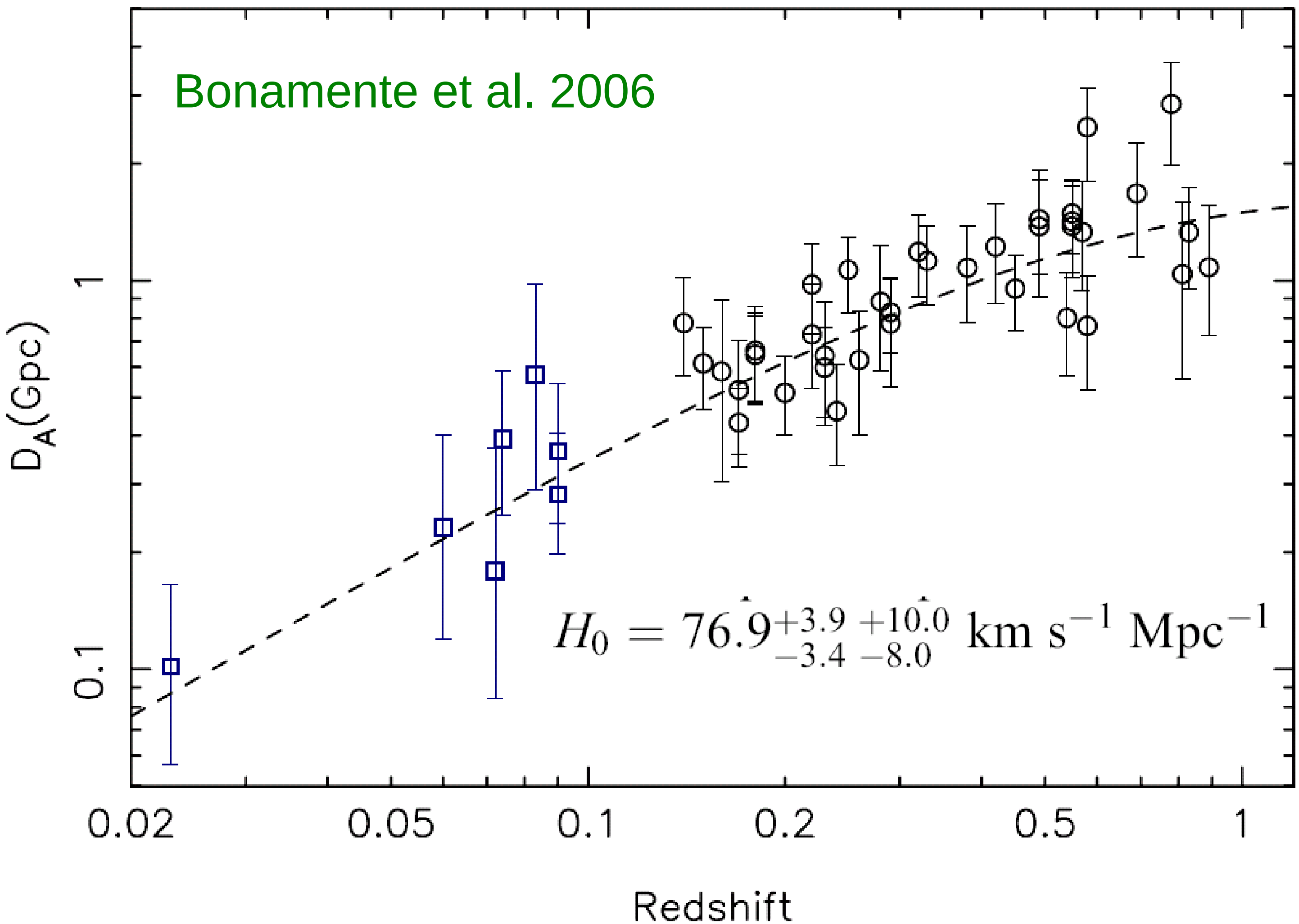
Universal gas mass fraction expected ! (Allen et al. 2008)



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

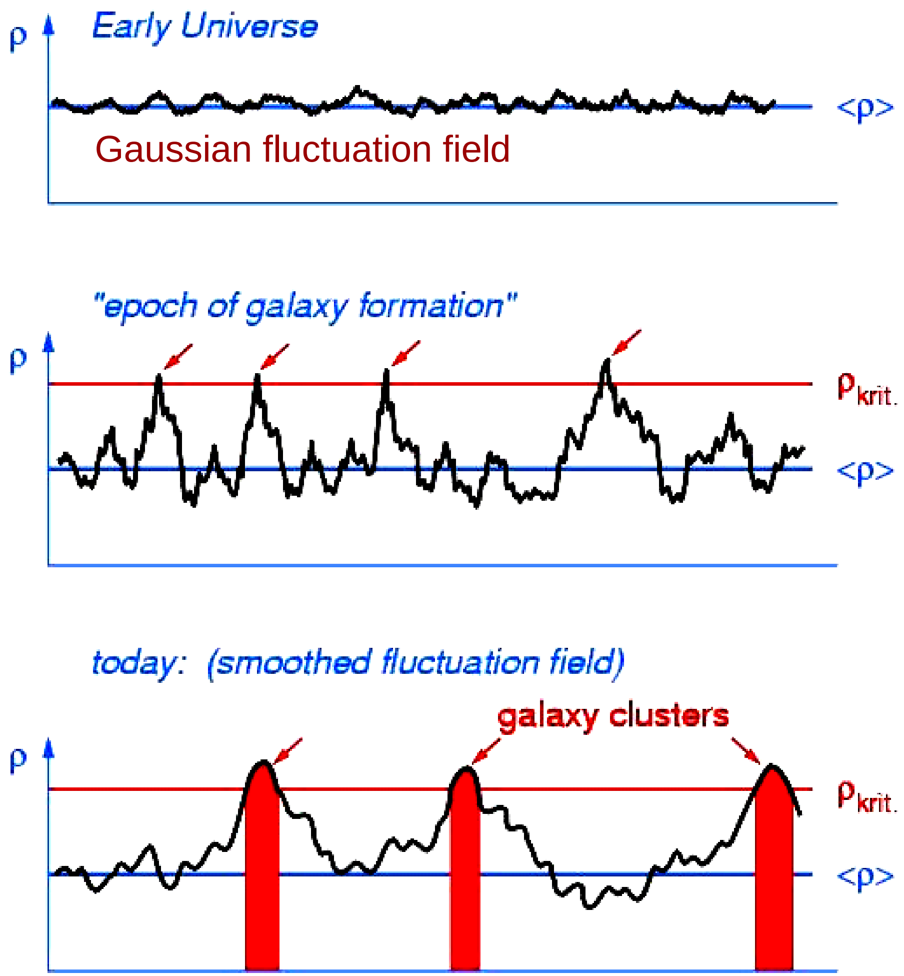
(Rapetti et al. 2008)

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

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



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

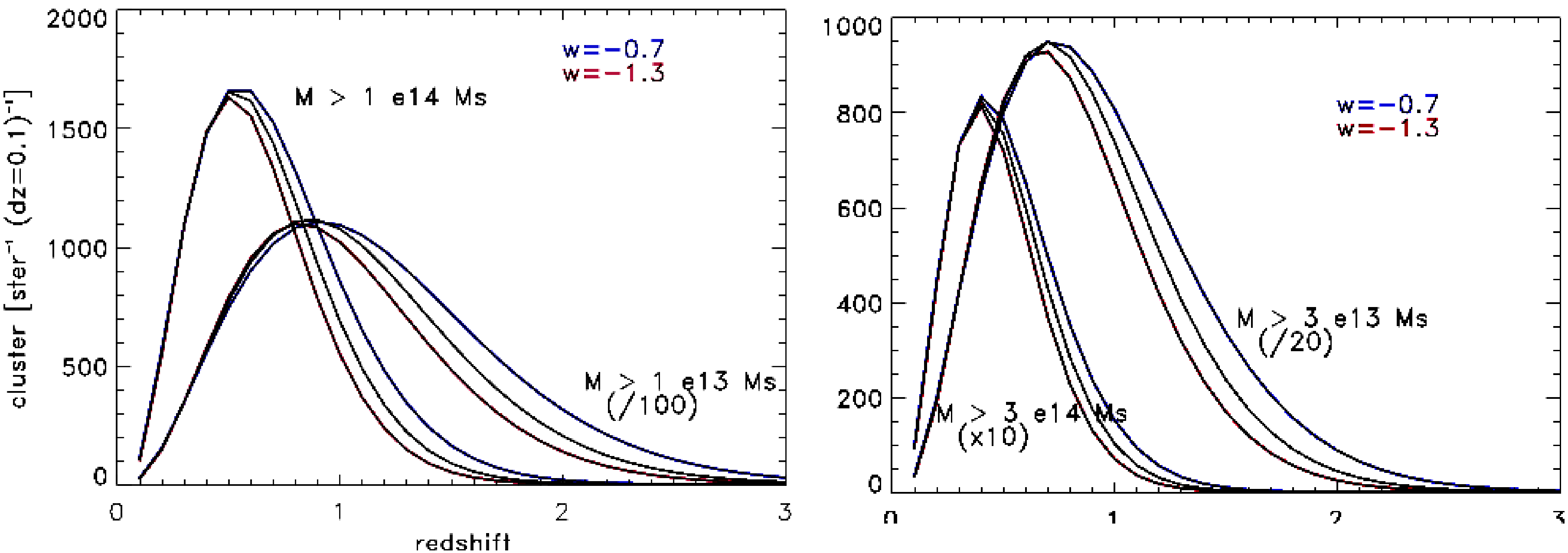
Statistics of the peaks (Cluster Population) is closely connected to the statistical properties of the fluctuation field, P(k) or ξ(r)

Therefore the increase of the cluster abundance with time measures the structure growth function, g(z)

where: $P(k,z) = g(z)/g(0)\ P_0(k)$

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

Differential comoving cluster abundance (> $Mass_{limit}$) $ster^{-1}$ $dz=0.1^{-1}$

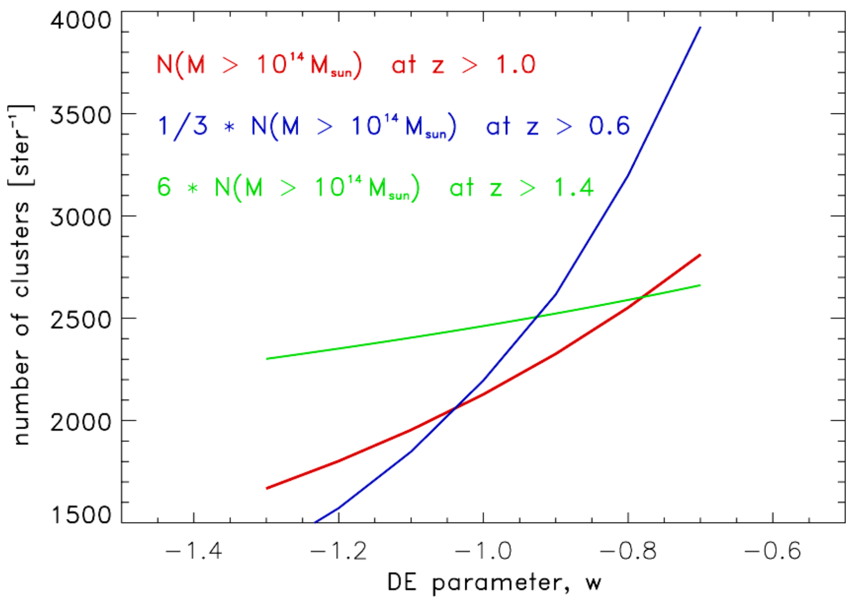


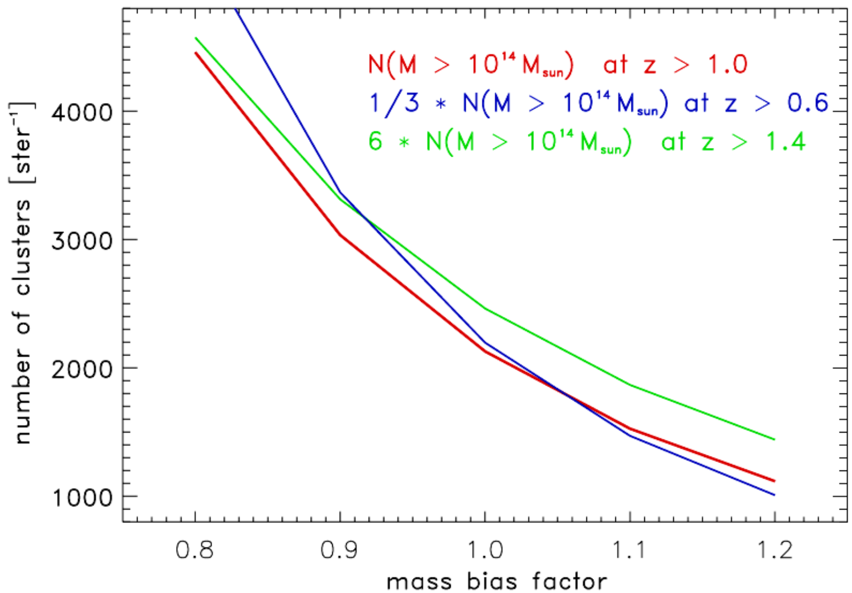
→ There are more distant clusters for small (negative) w !

Requires mass calibration to few % !

see also Haiman et al. 2001

Details Cluster Evolution I





Approximately :

$$\frac{d \log N}{d \log w} = 0.85 \ (z > 1) = 1.75 \ (z > 1.4)$$

ΔN 10% → Δw 10%

$$\frac{d \log N}{d \log m} = -3 \quad (z > 1) = -3.5 \quad (z > 1.4)$$

Δm_{cal} 3% → Δw 10%

→ Scatter in M is less of a problem than bias (calibration of the mean)

Details of Cluster Evolution II

ΔN 10% → Δw 10%

one needs **few hundred clusters** in the critical M – z regime

Δm_{cal} 3% → Δw 10%

calibration should be **better than 2%**

Scatter in m has to be known for the mass proxy used (e.g. Lx, Tx, Yx)

few hundred clusters help to reduce shot and scatter in similar way

How many Test Objects Do We Find ?

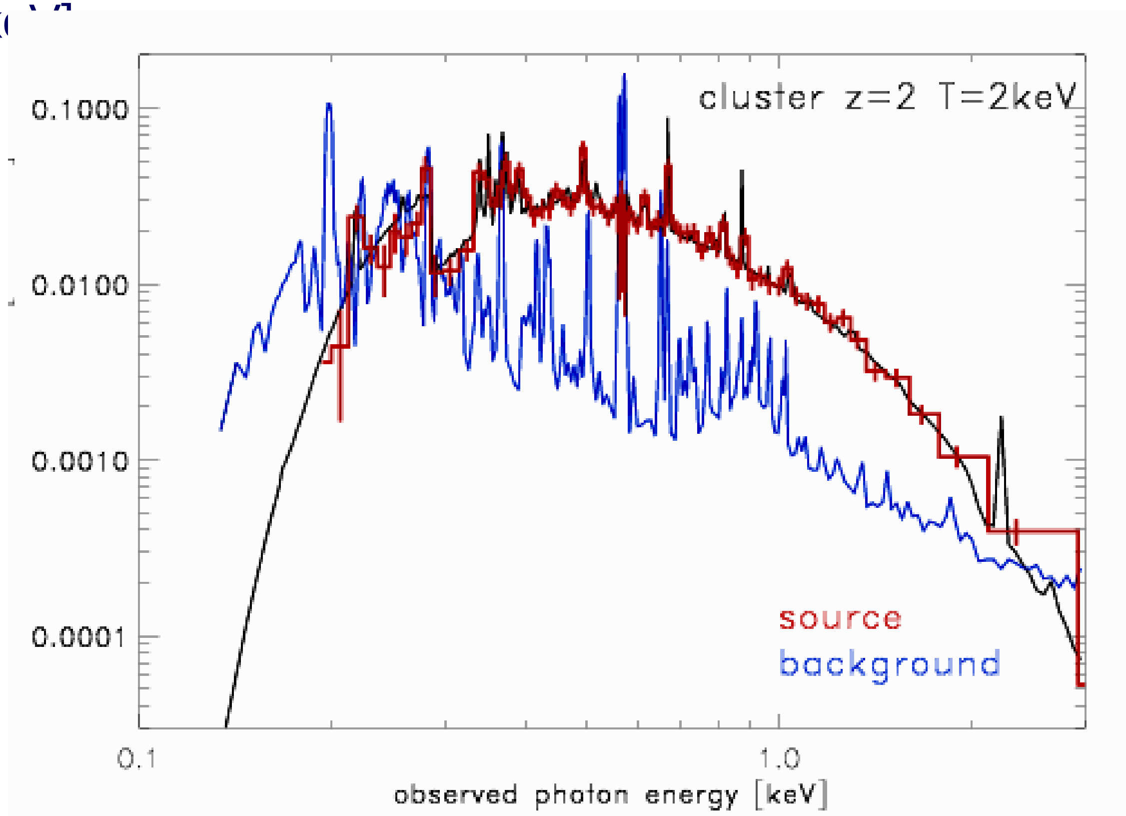
Redshift	mass	clusters /20000 deg2 (half of the sky)	X-ray luminosity
$z > 2$	$> 10^{14} M_{sun}$	100	10^{44} erg/s
	$> 3\ 10^{13} M_{sun}$	20000	$2\ 10^{43}$ erg/s
	$> 10^{13} M_{sun}$	$4\ 10^{5}$	$3\text{-}5\ 10^{42}$ erg/s
$z > 2.5$	$> 3\ 10^{13} M_{sun}$	3000	$2\ 10^{43}$ erg/s
	$> 10^{13} M_{sun}$	$1\ 10^{5}$	$3\text{-}5\ 10^{42}$ 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**

Galaxcy Group at z = 2

High z extreme: Group at z = 2

- F_X = 5 10^{-16} – 1 10^{-15} erg s^{-1} cm^{-2}
- L_X = 3 10^{43} erg $s^{-1,}$ [0.5 -2 k
- centr. Sfb. ~ 3-6 x bkg
- core radius ~ 40 kpc = 5"



Spectroscopy:

-Temperature +- 5%

- Abundance $\Delta <$ 0..05

- [Fe] +- 11%

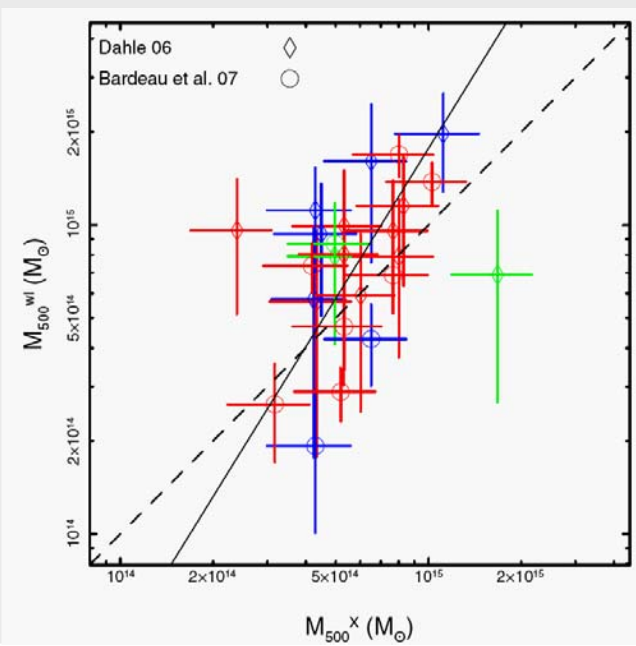
- [Si] +- 18%

- [O], [Mg] +- 30%

External Calibration of the Cluster Masses

To be better than 10% in Δw requires:

- **Mean mass calibration better than 2%** [> 500 – 1000 lensing cl.]
- **Abundances better 5 - 7% > 400 strategically strong clusters**
- **Mass scatter < 20 - 30% (uncritical)**
- **M $> 10^{14}$ M_{sun} (z > ~1) or e.g. M > 3 10^{13} M_{sun} (z >~ 1.4)**



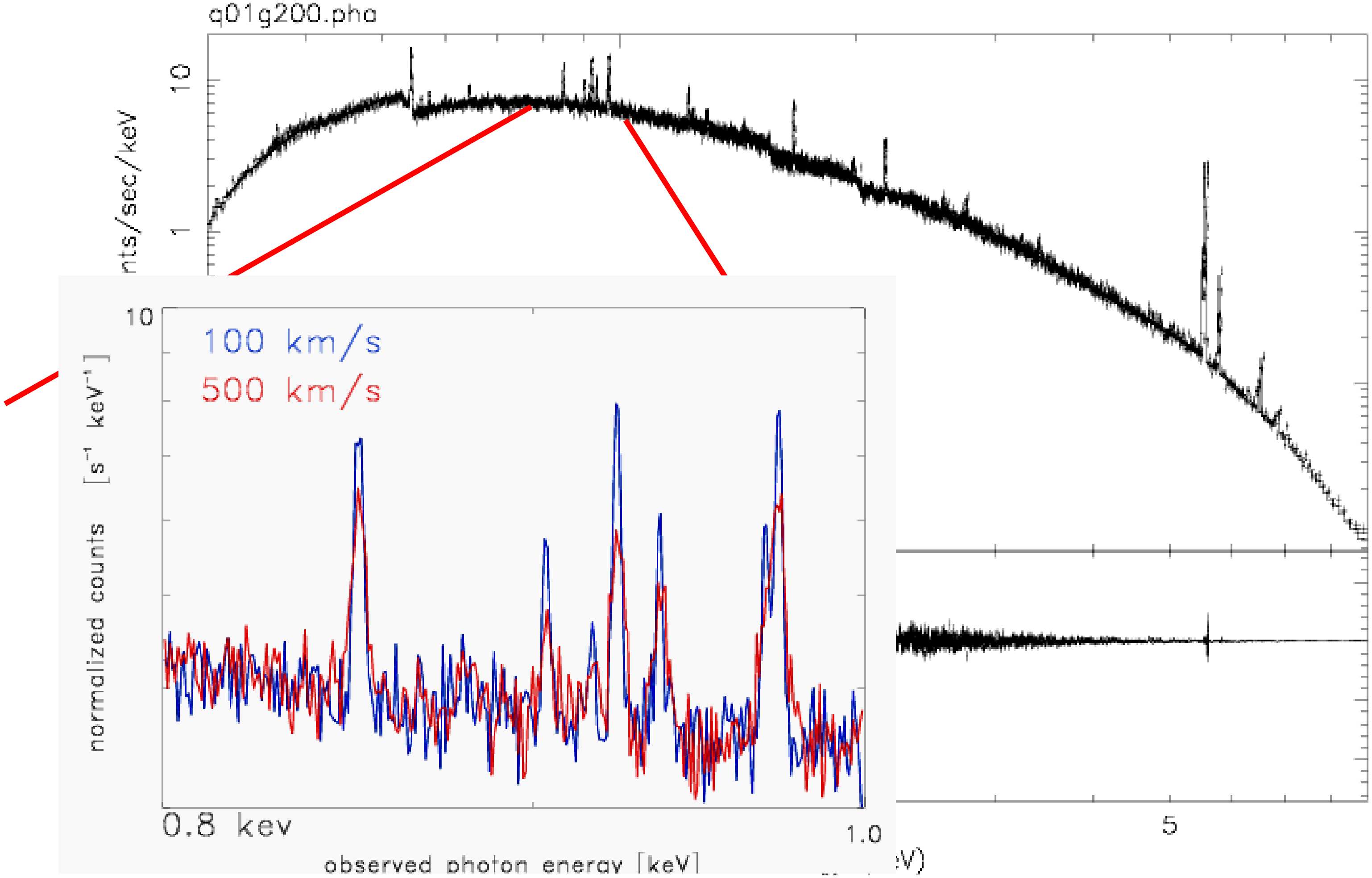
Mass bias for X-rays :
~ - 12% +- 12%

Zhang et al. 2008
(LoCuSS project G. Smith ea.)

Precise Diagnostics

1. Studying the structure of mergers, diagnostics of shocks, assessing turbulence
2. Precison studies of the ICM temperature structure
3. Velocity Broadening as a third parameter for observable mass relations

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: Δv <= +-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 $\Delta v \sim$ **20 km/s (0 – 600 km/s)**

exp.= 40 ks $\Delta v \sim$ **50 km/s**

8 keV, exp.= 100 ks $\Delta v \sim$ **40 km/s**

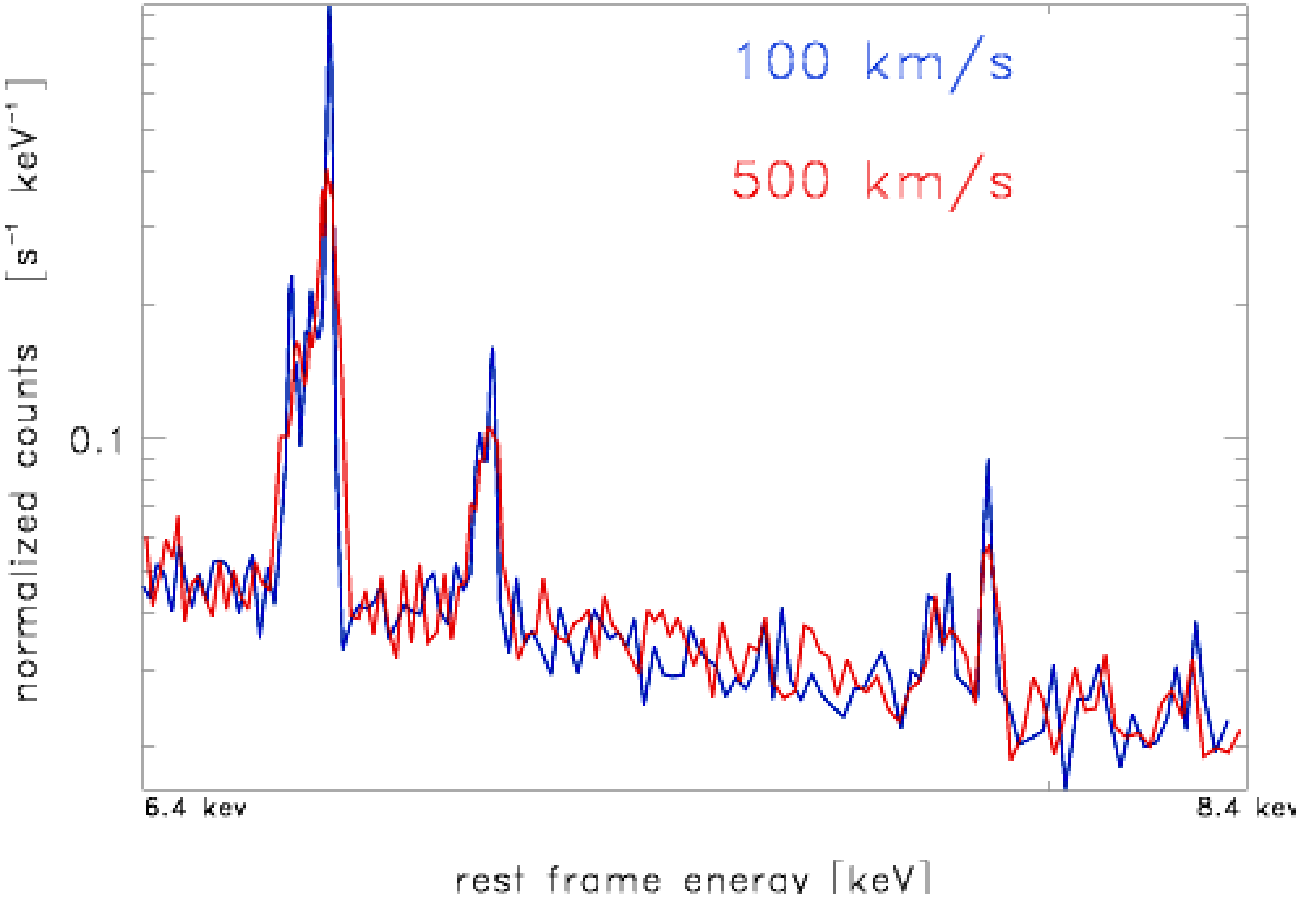
2 keV, exp.= 100 ks $\Delta v \sim$ **5-7 km/s**

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

5 keV, exp. = 100 ks $\Delta v \sim$ **70 km/s**

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

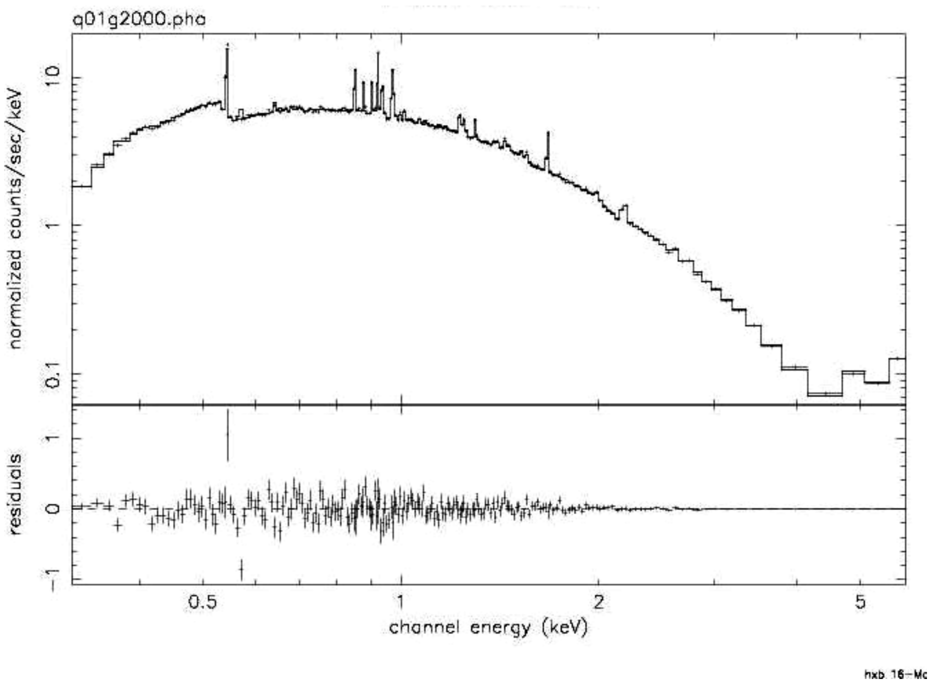
Line Broadening in Distant Clusters



Cluster: z=1, F_X ~ 1.0 10^{-14} erg $s^{-1}cm^{-2}$ (0.5-2 keV) → Δv ~30 - 40 km/s for 200 ks obs. - (50 - 70 km/s in 100 ks)

Diagnostics of Multi-Temperature Structure II

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



3(10%) & 7(90%) keV plasma:

Exp.= 100ks 7 +- 0.2 keV

3 +- 0.3 keV

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

4 & 8 keV plasma:

exp = 200ks → ΔT ~ 0.2 keV

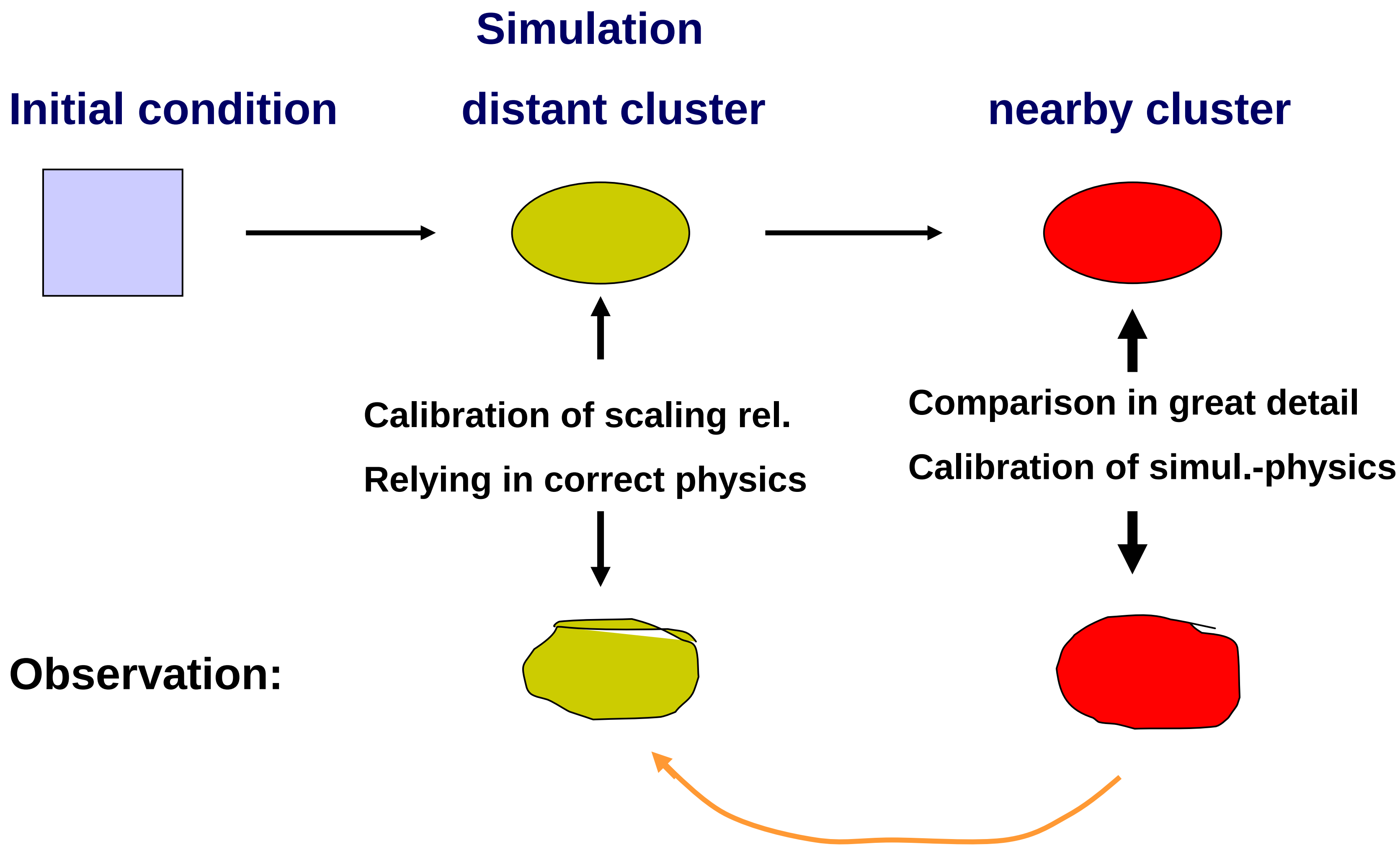
= 100ks ΔT ~ 0.4 keV „

3 & 5 keV plasma:

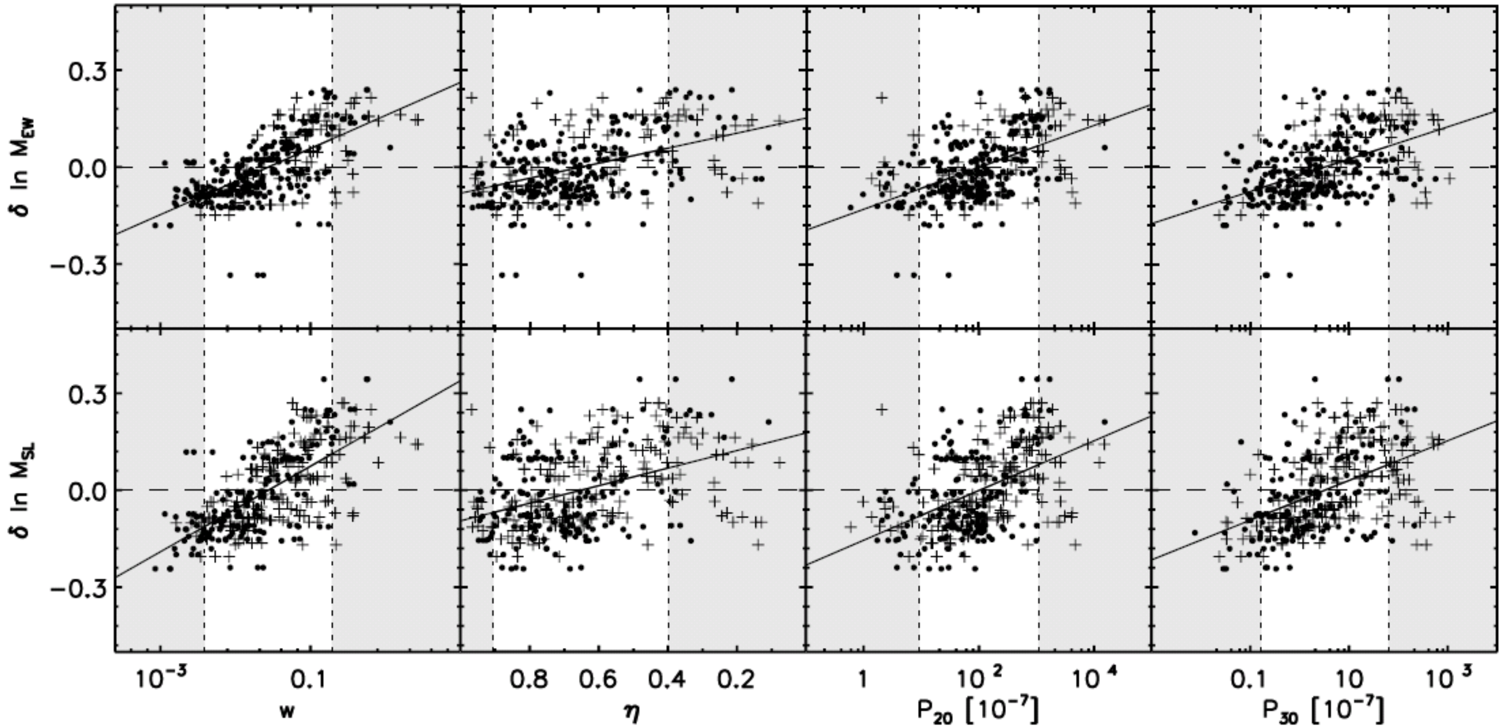
exp = 50 ks → DT ~ 0.3/2 keV

At lower temperatures things are much easier !

Comparison to Simulations
Calibration of Scaling Relations



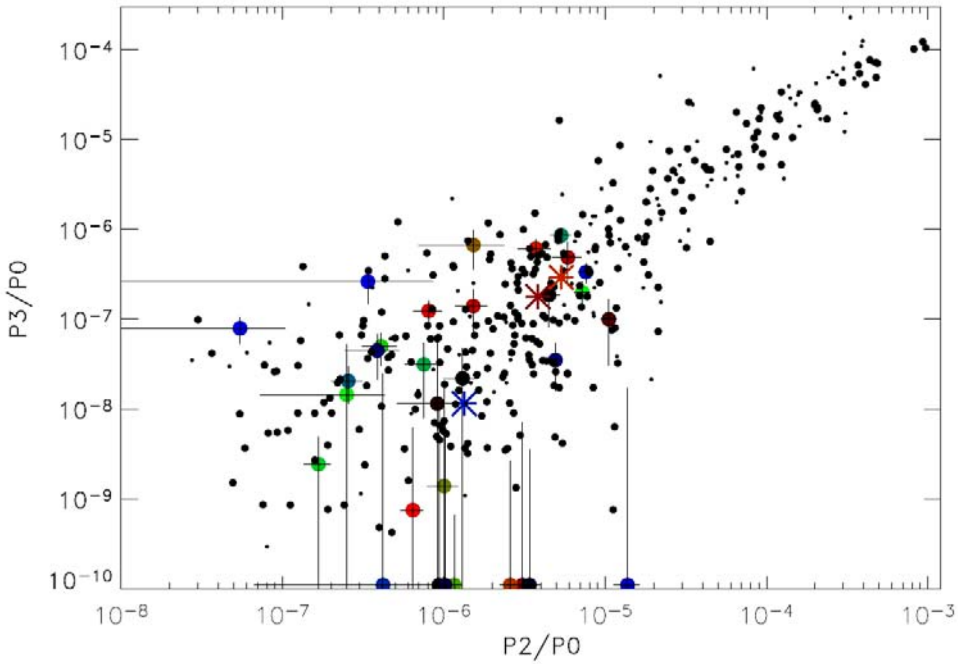
Narrowing Down the M-T Relation with Structure Parameters (example)

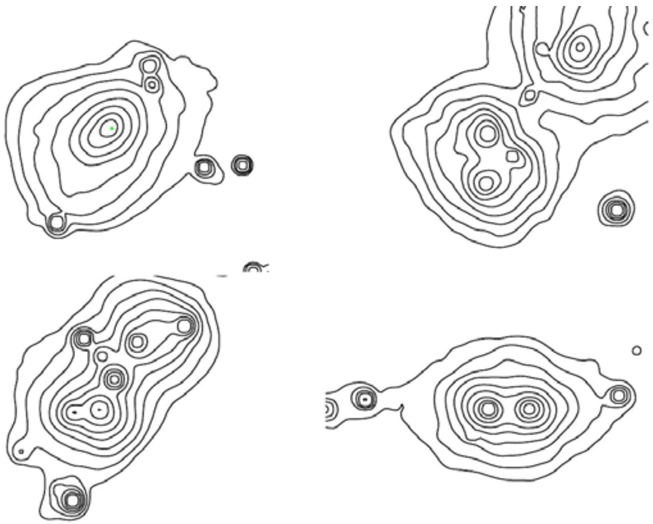


Ventimiglia et al. 2008 : deviation, ΔM, from the mean M-T_X relation for simulated clusters (Borgani et al. 2004). The fitted trend with substructure parameters can be used to produce a correction factor which reduces the scatter of the relation.

I believe that the velocity broadening of X-ray lines is an even better diagnostics !

Differences Between Simulations and Observations (in Substructure Measures)





Distribution of **power ratios P2/P0 and P3/P0** for the representative cluster sample **REXCESS (colored points)** and **simulated clusters** (Borgani et al. 2004). There are **more extremely substructured clusters in the simulations** – they have more extreme cool cores. The right panel gives a few expamles (X-ray surf. brightn.) of extremely structured clusters. (Böhringer et al. 2009).

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 experiements make an enormous progress, there is no other way to find these groups/clusters !

Conclusion

IXO will provide the detailed insight into cluster structure and evolution 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