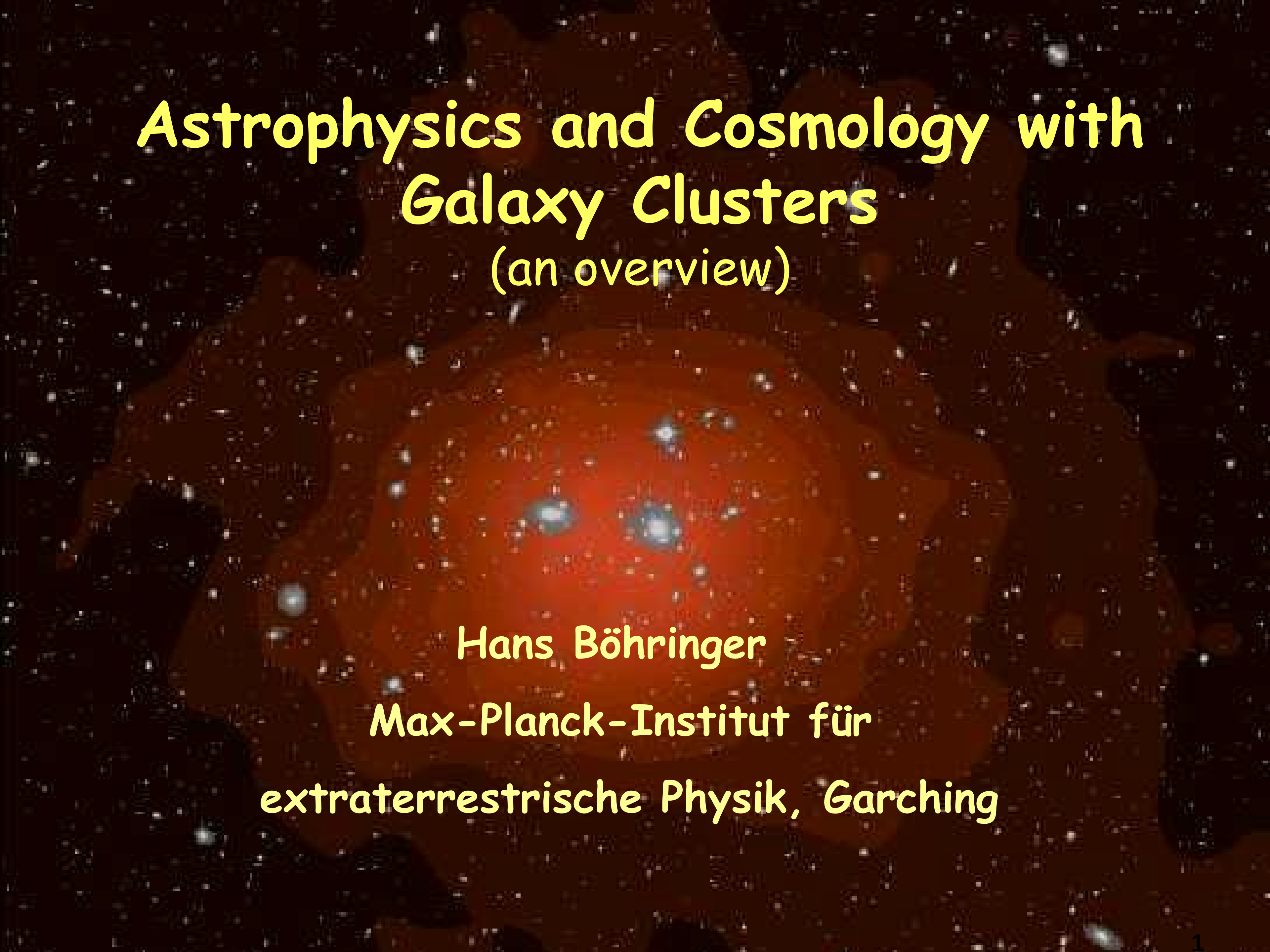


Astrophysics and Cosmology with Galaxy Clusters

(an overview)

Hans Böhringer

Max-Planck-Institut für

extraterrestrische Physik, Garching


What box should we open ?

Overview

- Galaxy Cluster Structure and Scaling Relations
- Weighing Clusters
- Chemical Abundances
- Assessing Large-Scale Structure
- Testing Cosmological Models
- Prospects of future Galaxy Cluster Surveys (e,g. eROSITA, IXO)

Why are we interested in Clusters ?

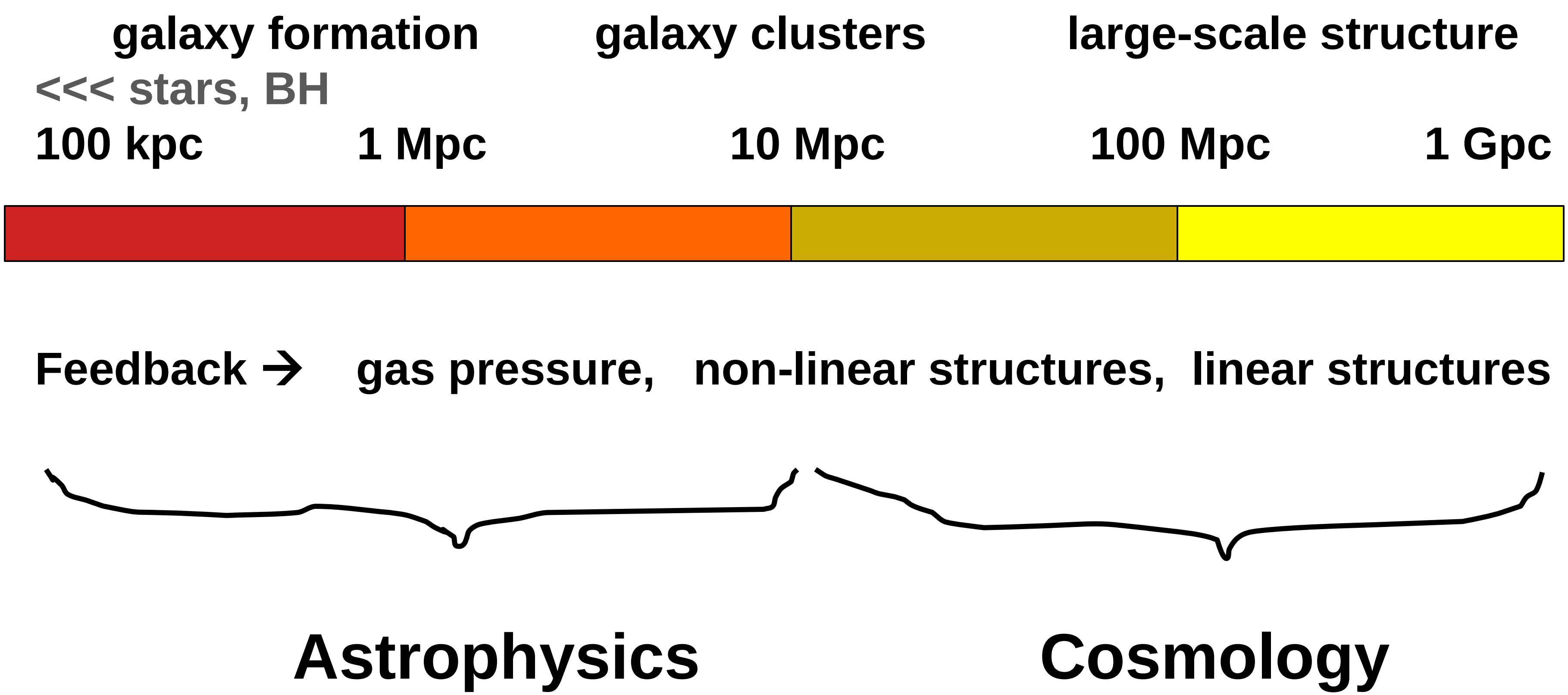
The are the largest, well defined building blocks in the Universe, which are characterized by their own proper equilibrium state.

They are as fundamental astrophysical laboratories as stars and galaxies

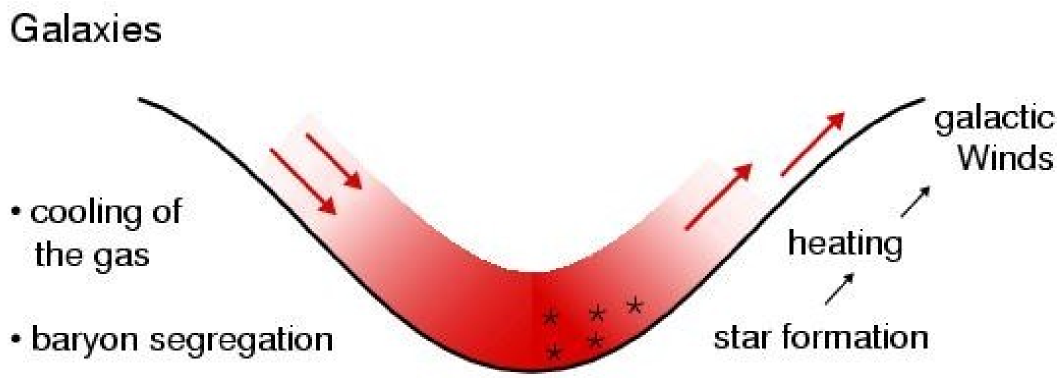
Their astrophysical exploration has started about 3 decades ago (except for Zwicky's special work on missing matter)

The are laboratories for the study of: large-scale structure formation – gravitational collapse equilibrium configurations – dark matter properties - coeval galaxy populations as function of environment – plasma and atomic physics – chemical enrichment history – feedback processes – gravitational lensing – shock wave thermalization – cosmic ray acceleration - ….

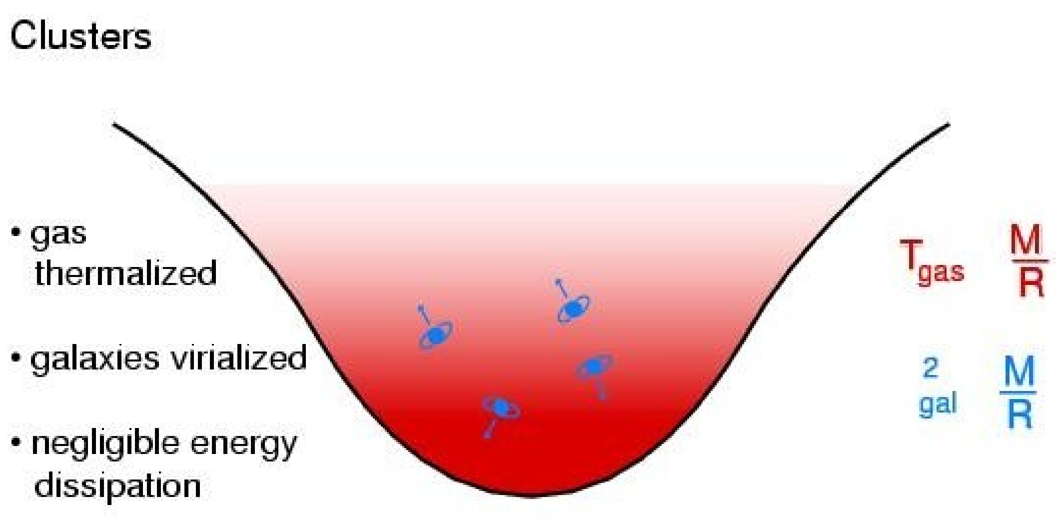
Galaxy Clusters within Cosmic Structures



Comparison of Galaxy and Cluster Dark Matter Halos



Complex relation between observable stellar population and dark matter halo



For galaxy clusters we can see the entire Dark Matter Halo in X-rays directly.

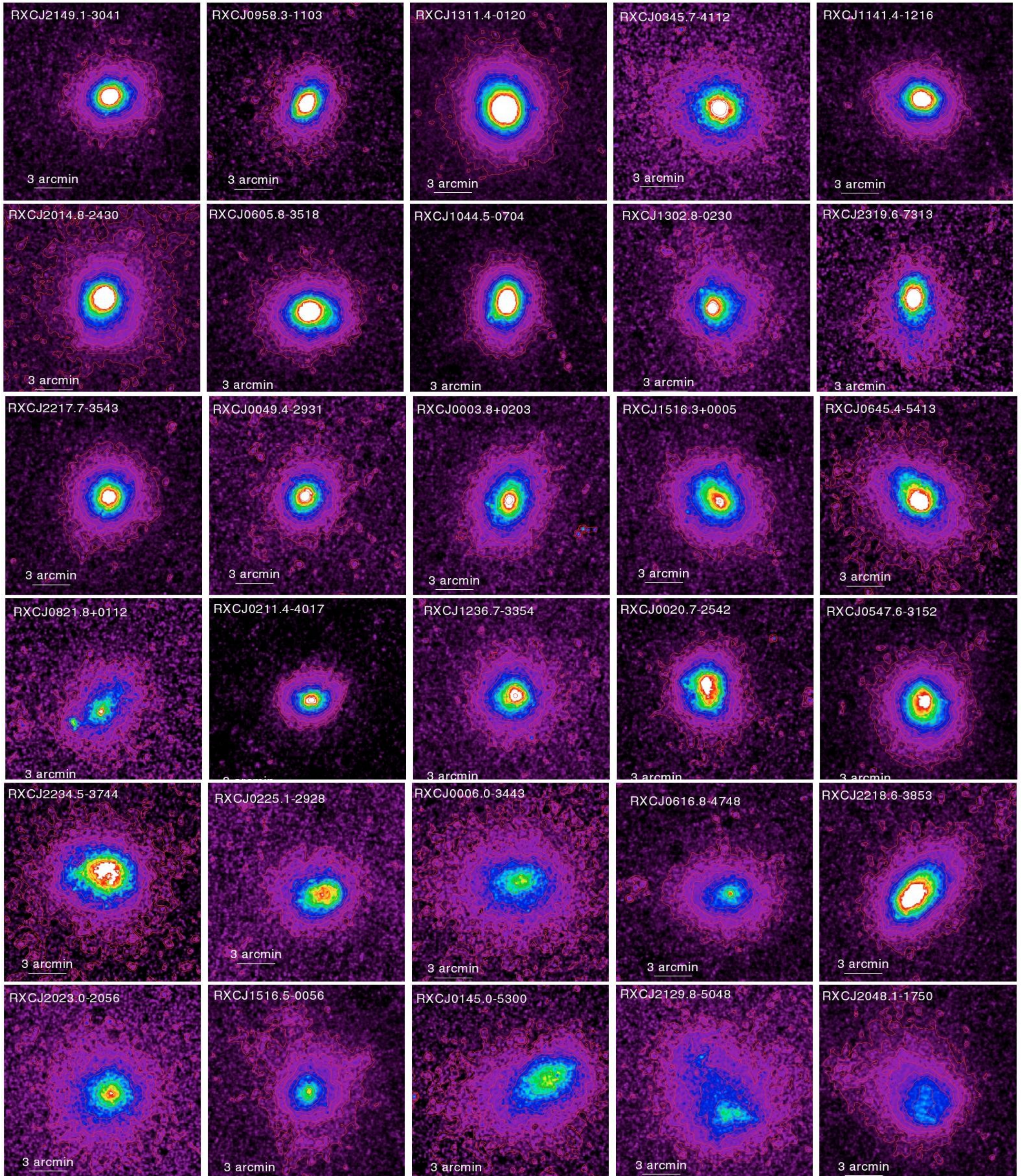
Disadvantage: cluster are dynamically young !

How well do we understand how to interpret observations of galaxy clusters?

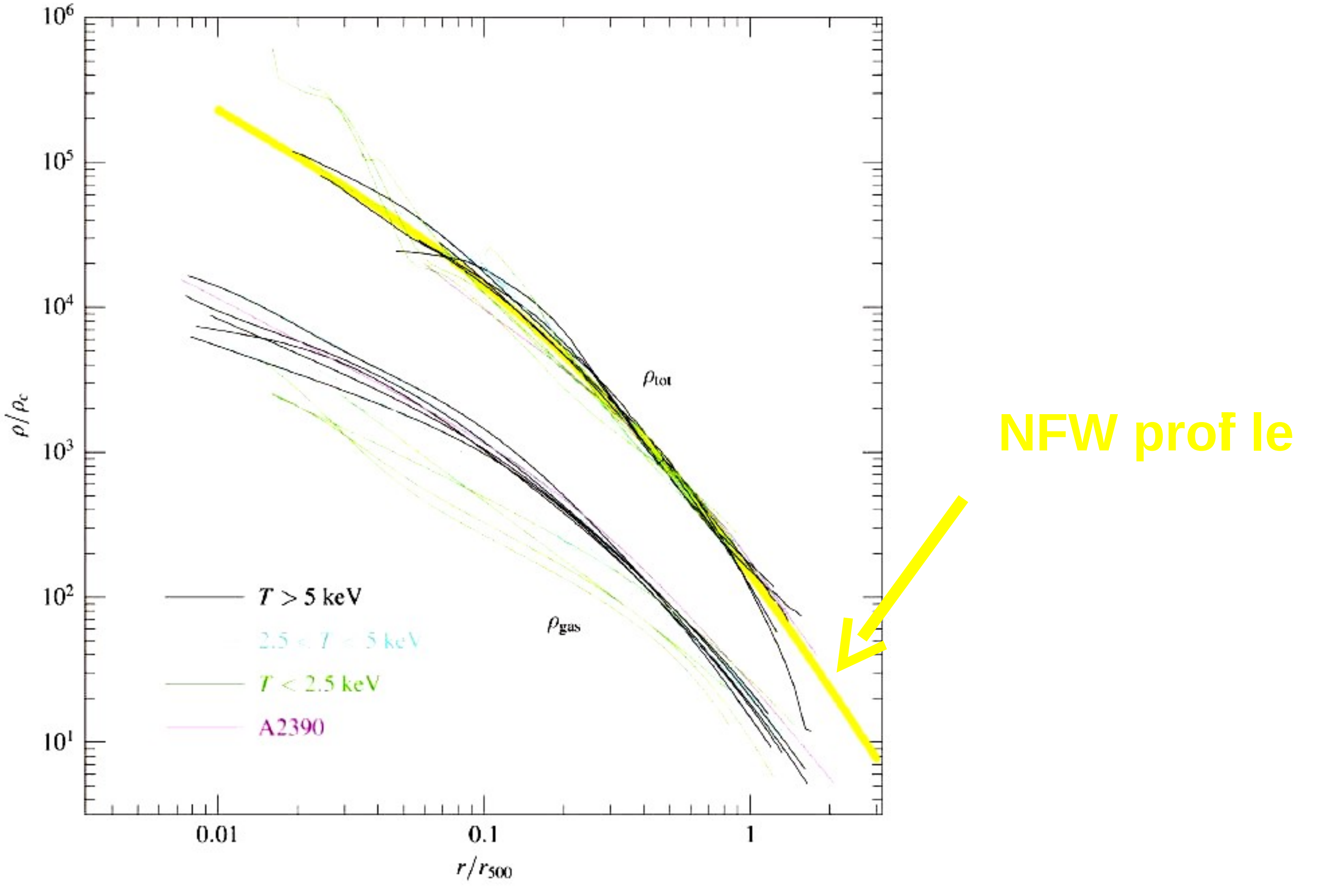
Concept of Scaling Relations

Concept of Self-Similarity

Self-Similarity of Galaxy Cluster Morphology

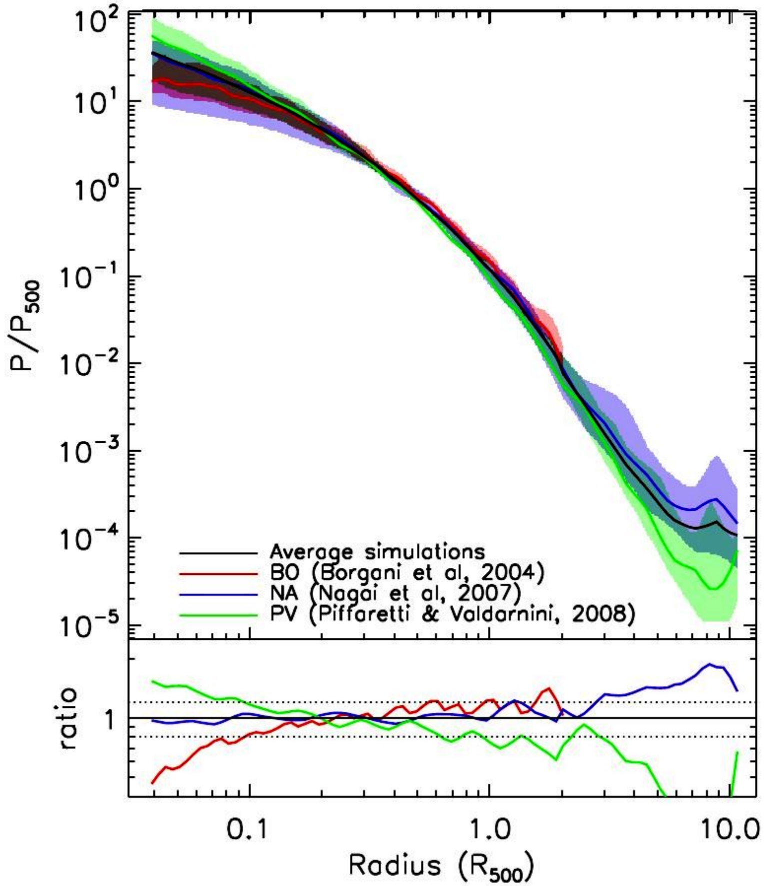

RXCJ2149.1-3041
RXCJ0958.3-1103
RXCJ1311.4-0120
RXCJ0345.7-4112
RXCJ1141.4-1216
RXCJ2014.8-2430
RXCJ0605.8-3518
RXCJ1044.5-0704
RXCJ1302.8-0230
RXCJ2319.6-7313
RXCJ2217.7-3543
RXCJ0049.4-2931
RXCJ0003.8+0203
RXCJ1516.3+0005
RXCJ0645.4-5413
RXCJ0821.8+0112
RXCJ0211.4-4017
RXCJ1236.7-3354
RXCJ0020.7-2542
RXCJ0547.6-3152
RXCJ2234.5-3744
RXCJ0225.1-2928
RXCJ0006.0-3443
RXCJ0616.8-4748
RXCJ2218.6-3853
RXCJ2023.0-2056
RXCJ1516.5-0056
RXCJ0145.0-5300
RXCJ2129.8-5048
RXCJ2048.1-1750
3 arcmin

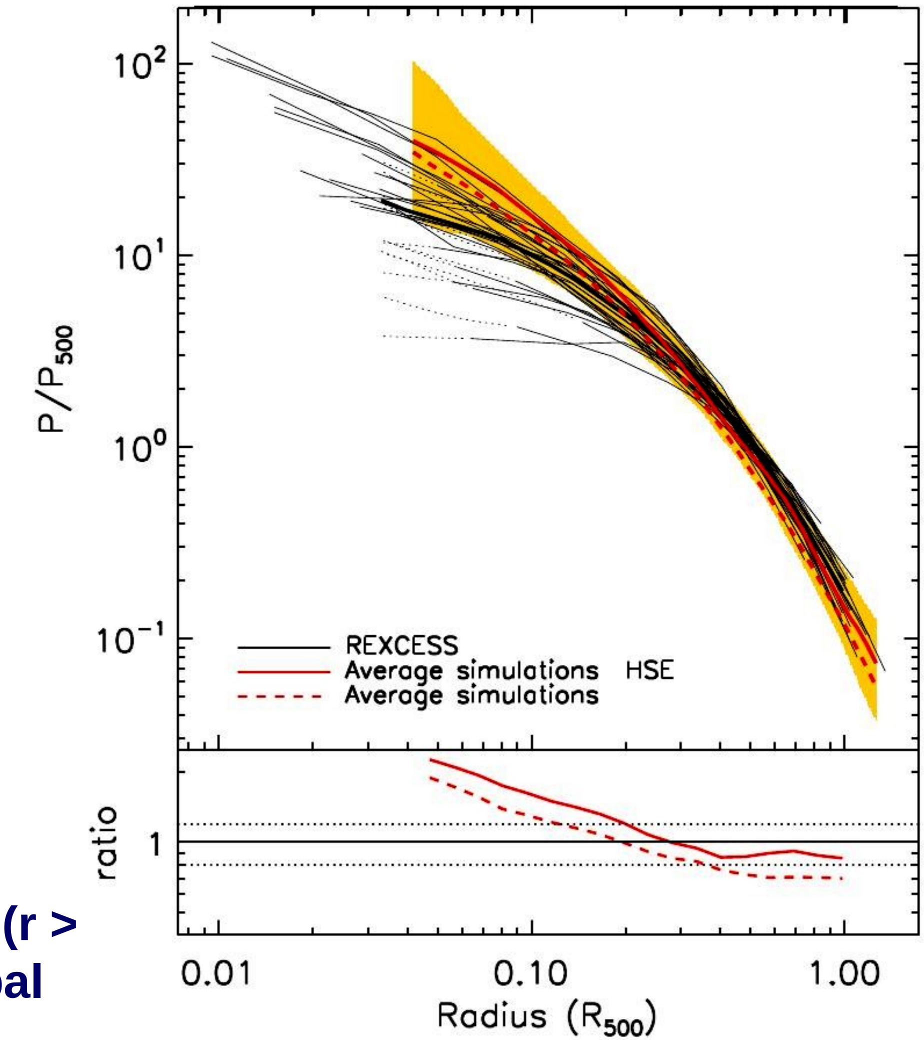
X-ray Determined Mass Profiles of Relaxed Galaxy Clusters



Results by Vikhlinin et al. (2006) fro CHANDRA X-ray observations

Pressure Profile in Simulations and Observations





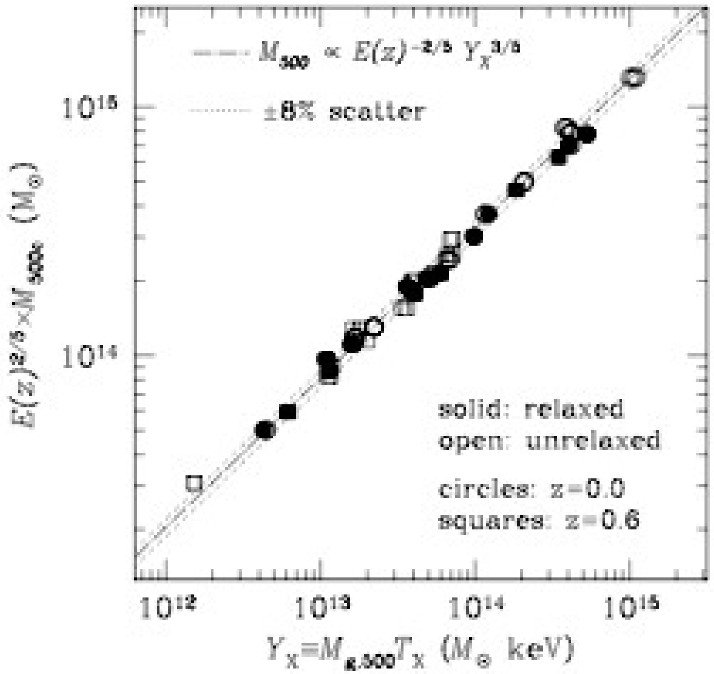
Agreement of different simulations (r > 0.1 R_{500}) is better than 20%. On global scales: 10% low bias compared to simulations – plus mass underestimate due to dynamical pressure.

[Arnaud et al. 2009]

Details of Pressure Profile Scaling

Y_X – M Relation (relaxed clusters)

same Y_X – M Relation (also unrelaxed clusters)



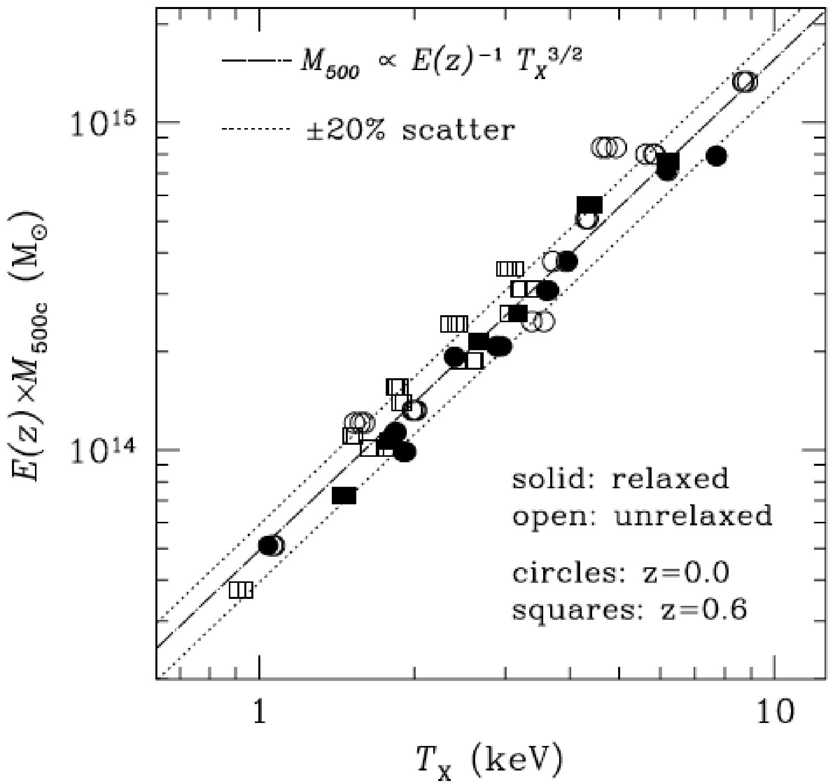
Kravtsov et al. 2006

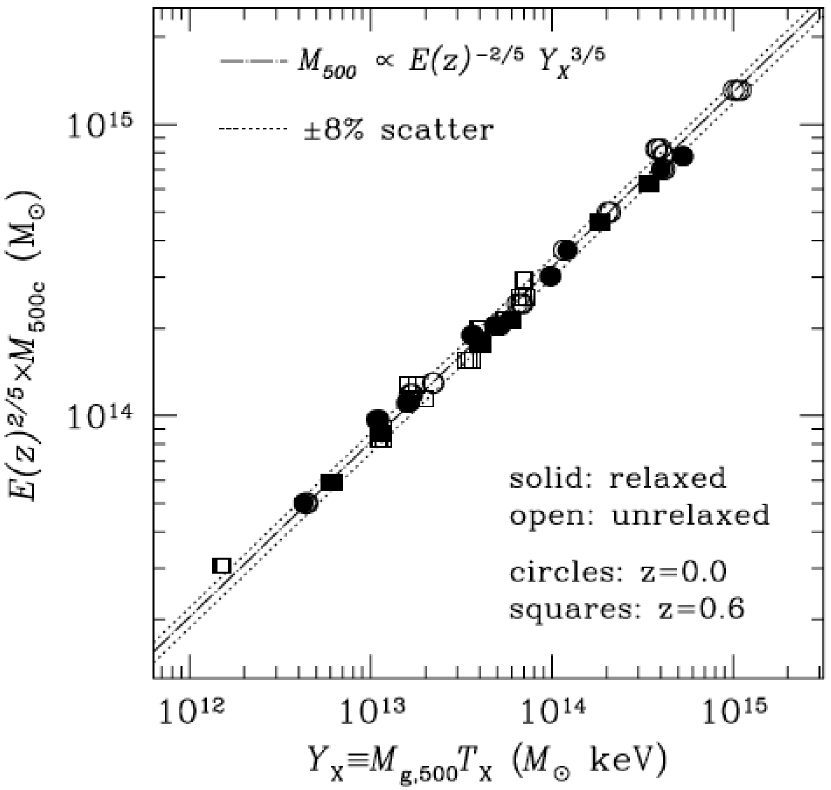
M_Y

P_{500}

P/P_{500}

Improved mass estimator combining T_X and M_{gas} = Y_X

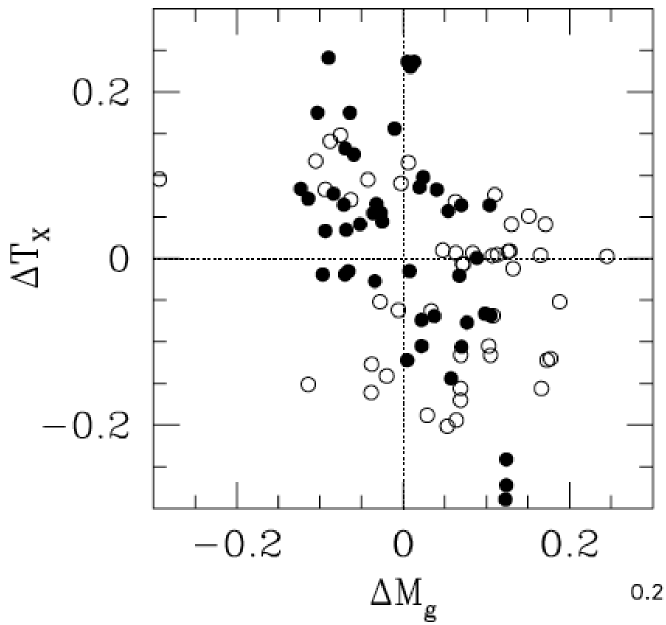




Y_X is better than M_{gas} and T_X because these two mass proxies are anti-correlated and their combination reduces the scatter. [Kravtsov et al. 2006]

0

Anti-correlation of T_X and M_{gas} as Mass Proxies

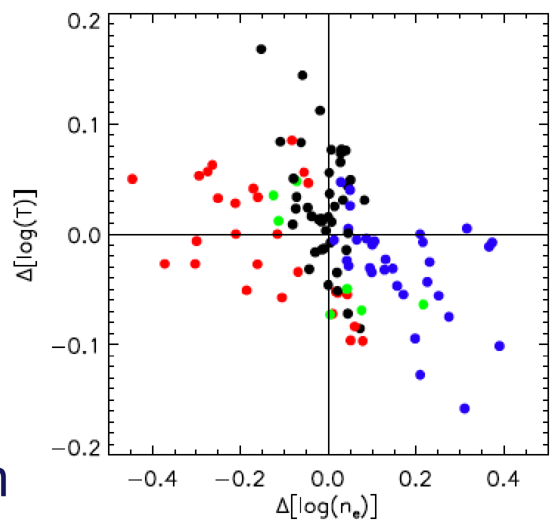


Simulations by Kravtsov et al. (2006) showing the anti-correlation

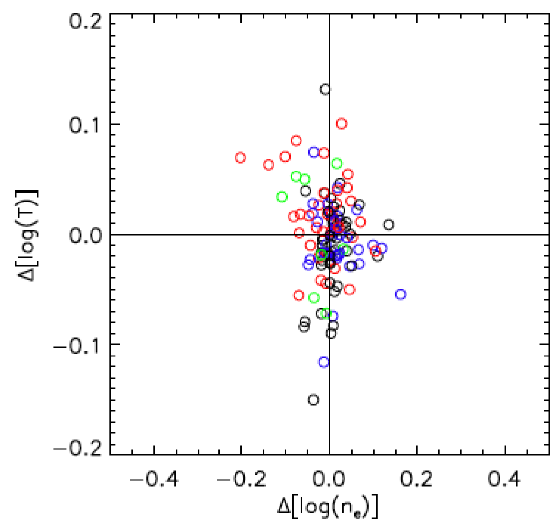
Observations: REXCESS sample [Arnaud et al. 2010]

The observations show the strong anti-correlation only in the cool-core region

There are less cold clumps in observed than in simulated clusters outside the core



$r < 0.2\ r_{500}$

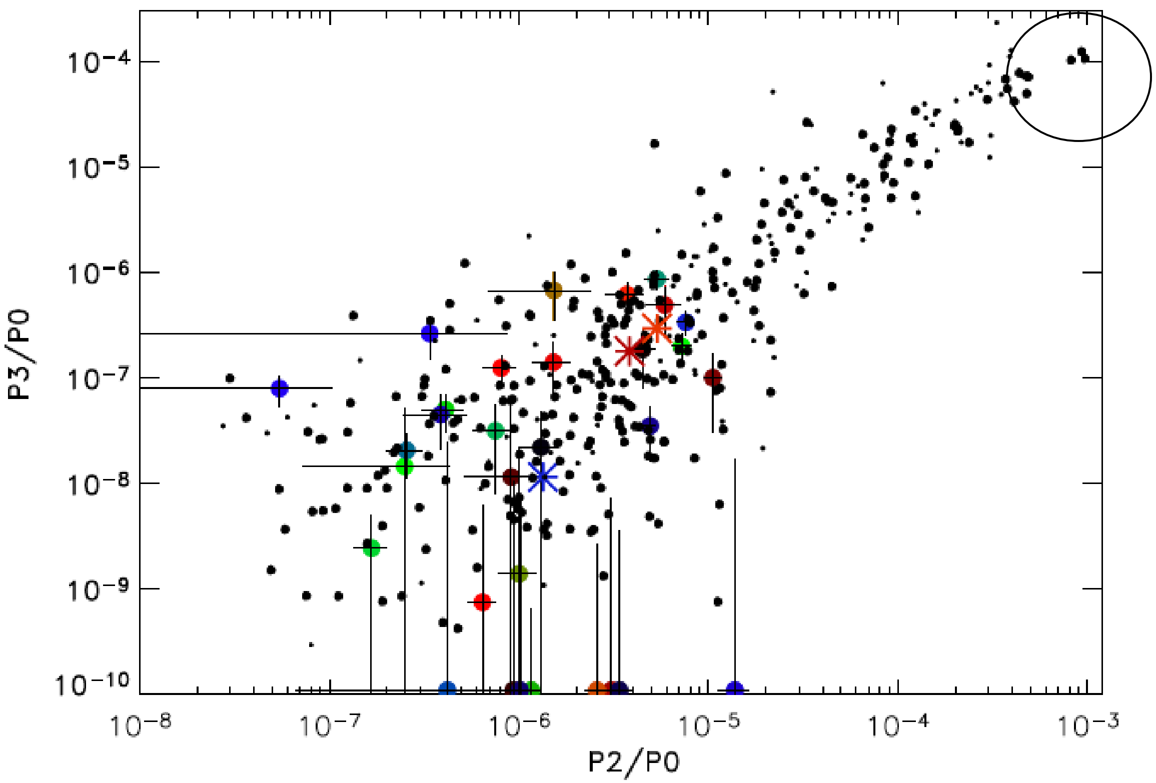


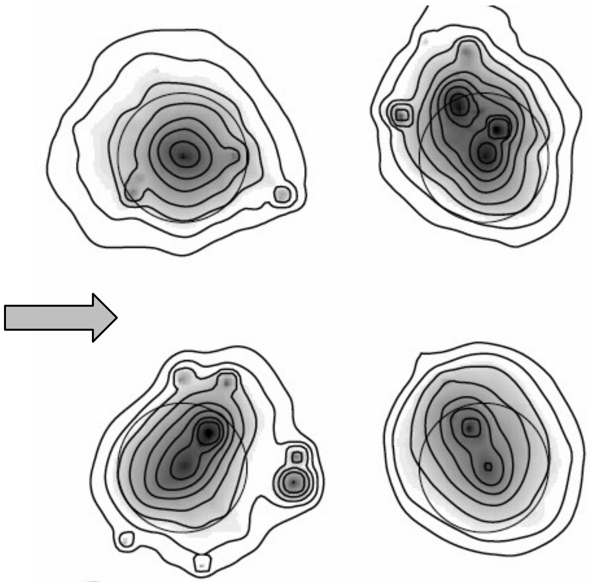
$r > 0.2\ r_{500}$

H. Böhringer

X-ray Surface Brightness Substructure in Observed vs. Simulated Clusters (Borgani et al. 2004 – no feedback)

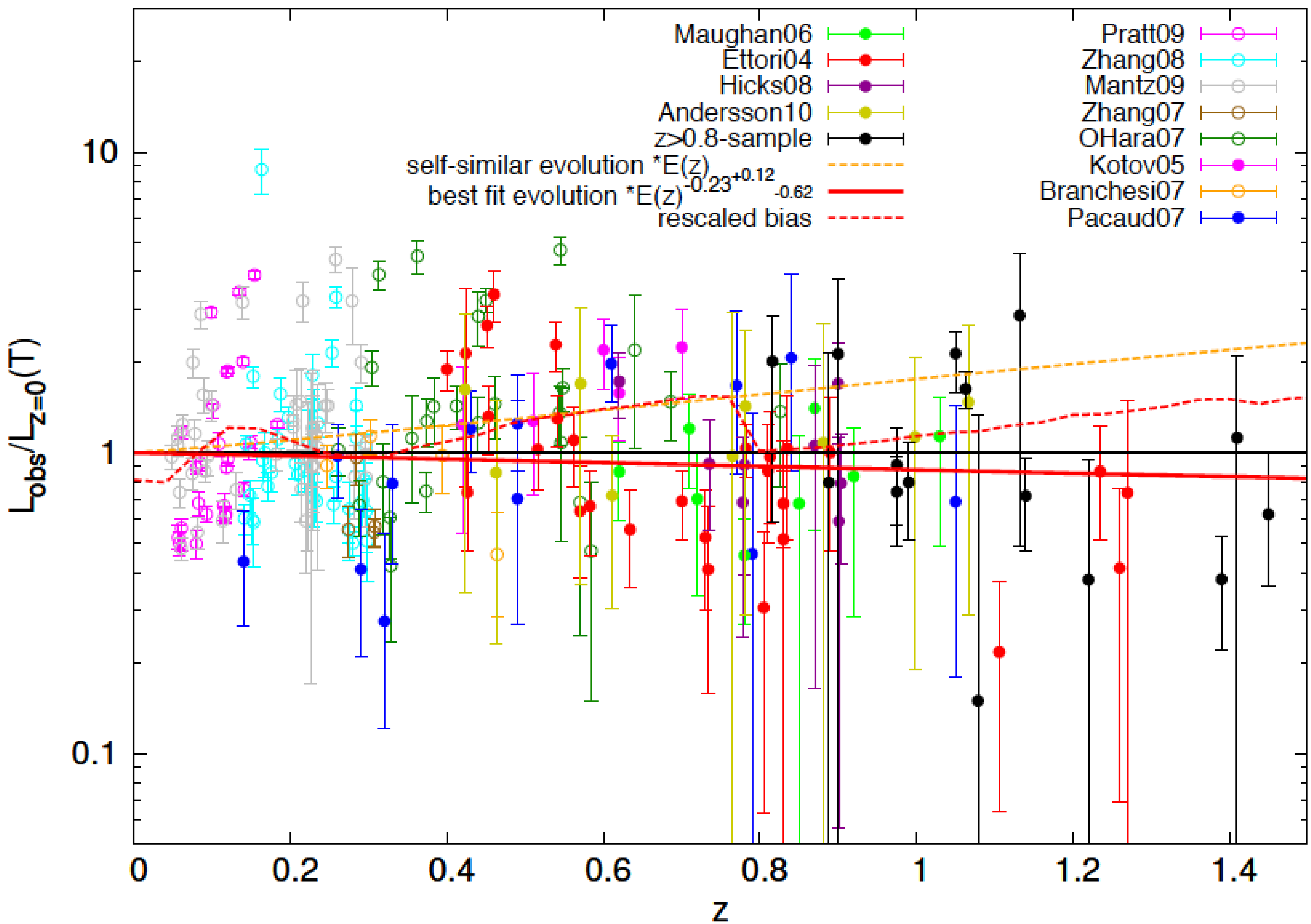
Observed clusters = colored symbols
Simulated clusters = black dots





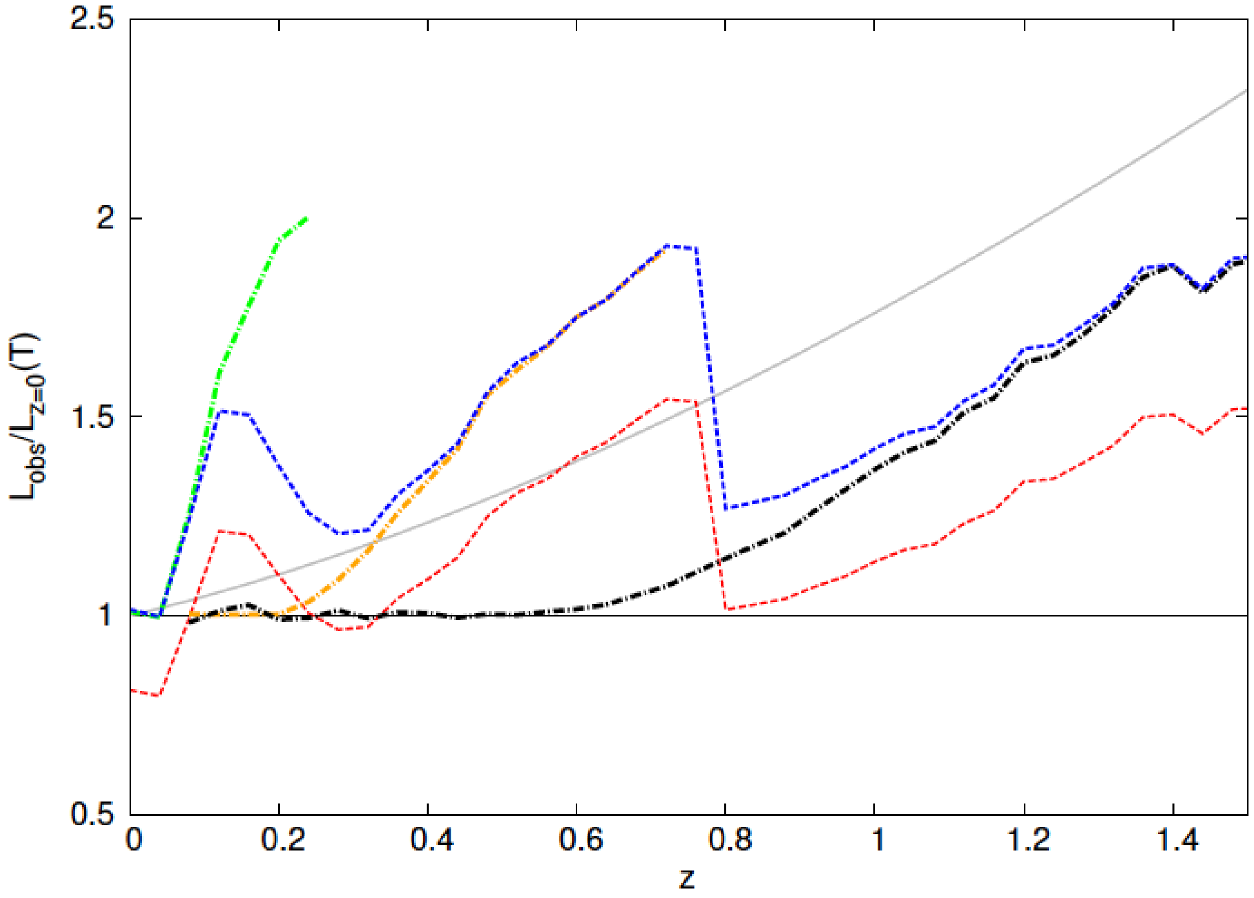
A large fraction of simulated clusters has more substructure: due to cool clumps embedded in the hotter ICM

Evolution of the L_X – T_X Relation



Reichert et al. 2011 (submitted)

Toy model for the Selection bias of a set of flux limited surveys for the L-T Relation

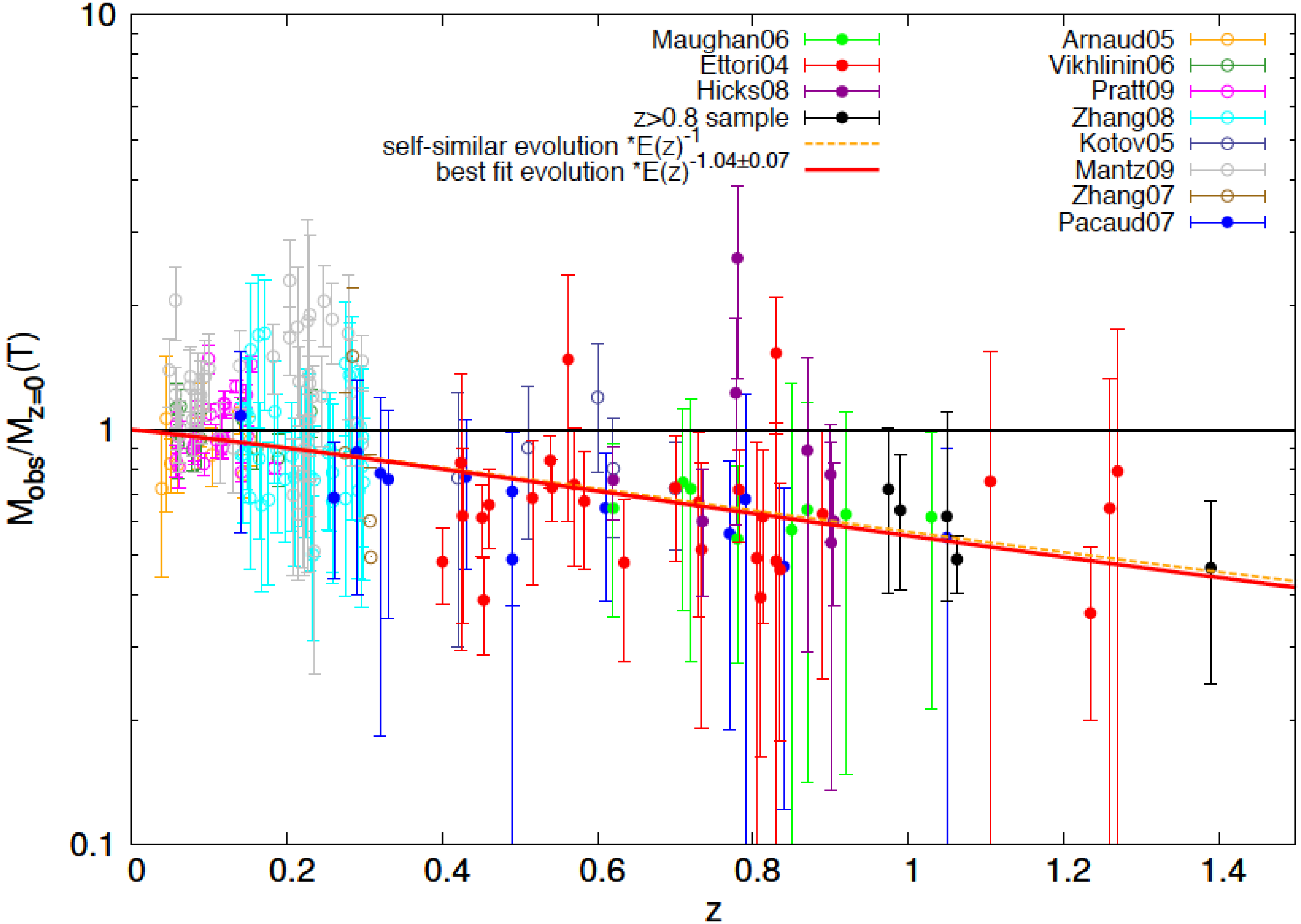


Simulation with 3 surveys types:

3 10^{-12} erg/s/cm^2 (REFLEX area)
10^{-13} erg/s/cm^2 (400 deg^2)
10^{-14} erg/s/cm^2 (80 deg^2)

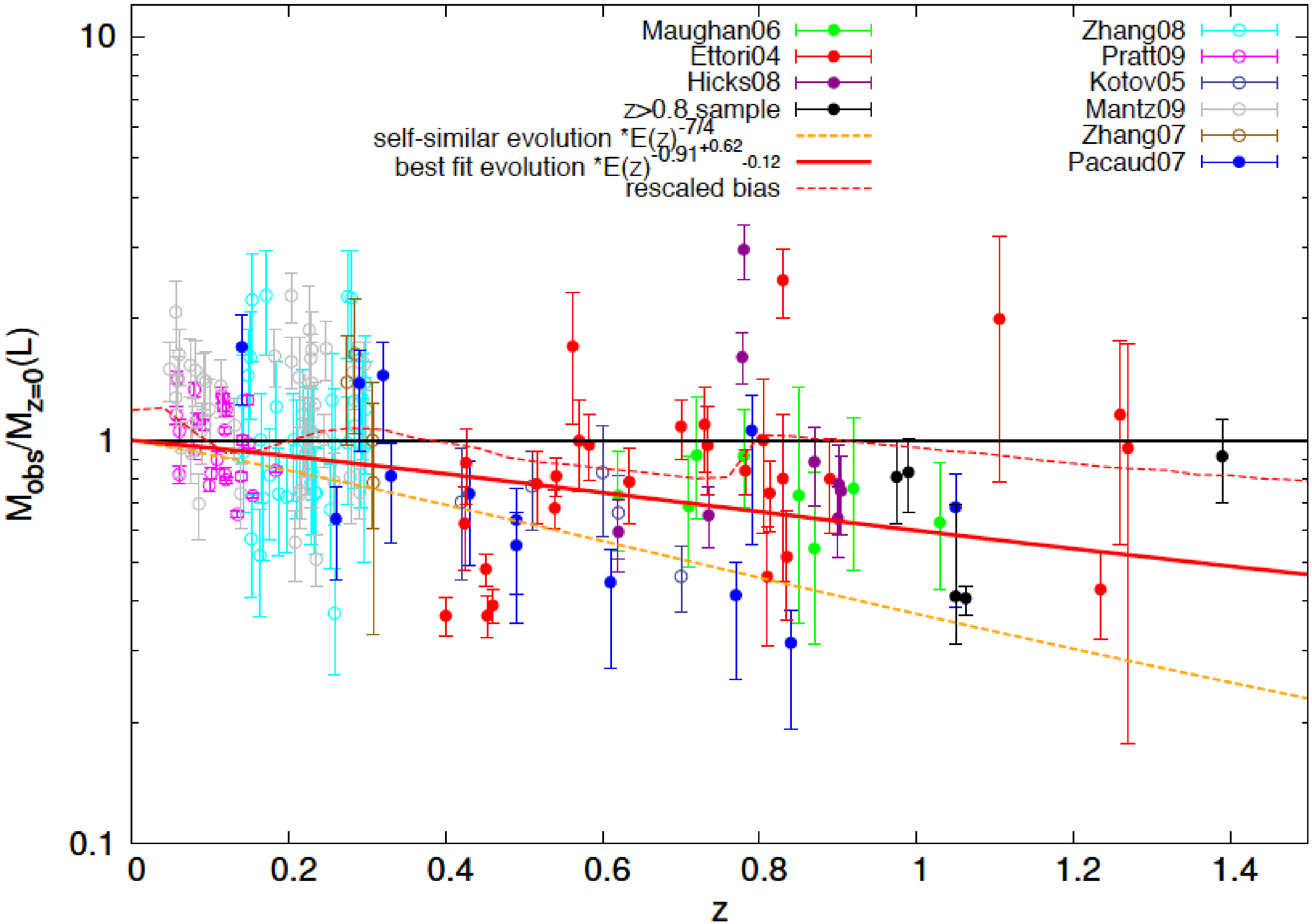
Reichert et al. 2011

Evolution of the M-T Relation



Reichert et al. 2011

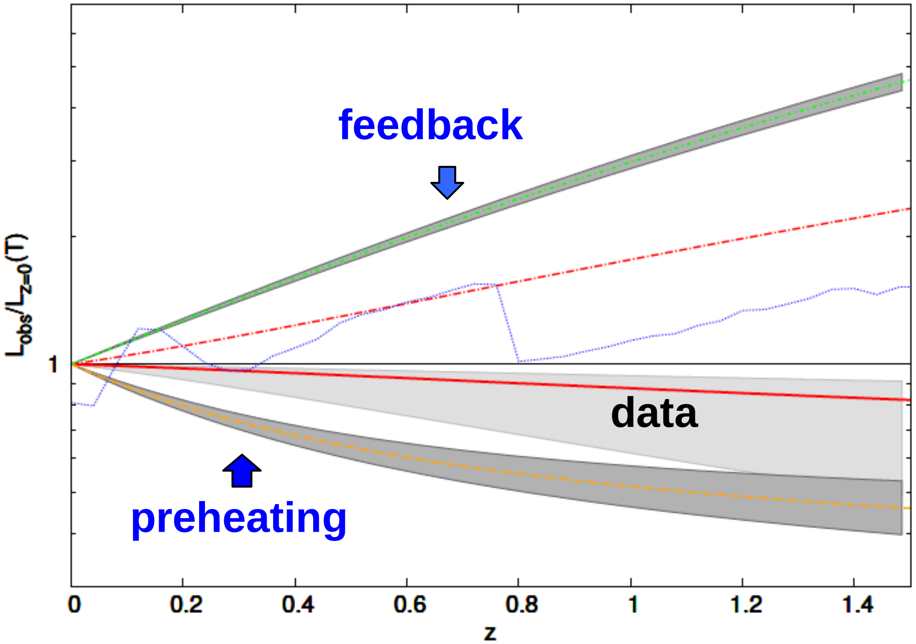
Evolution of the L_{bol}-M Relation



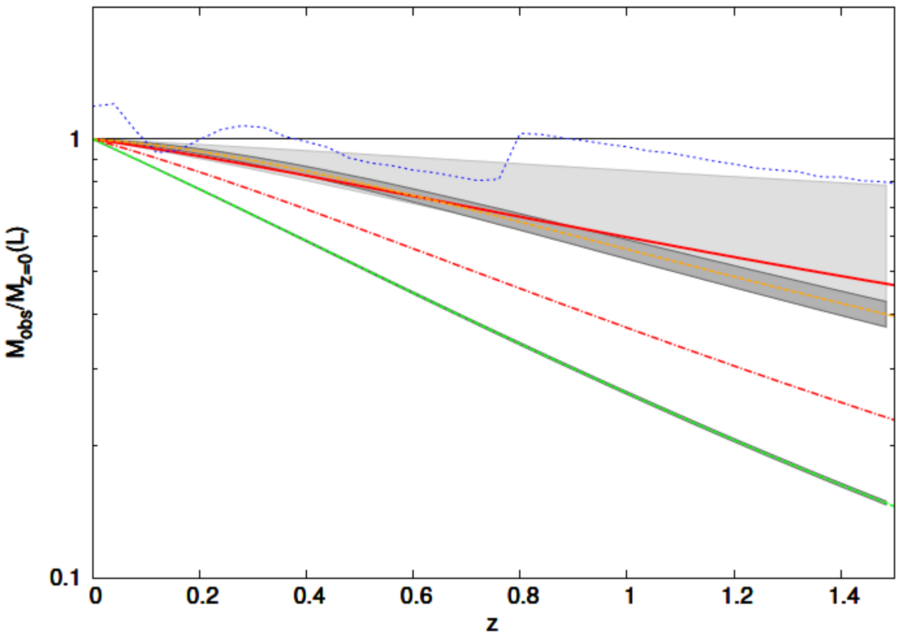
Reichert et al. 2011

Comparison to Simulations of Short et al. 2010

L – T Relation



M – L Relation

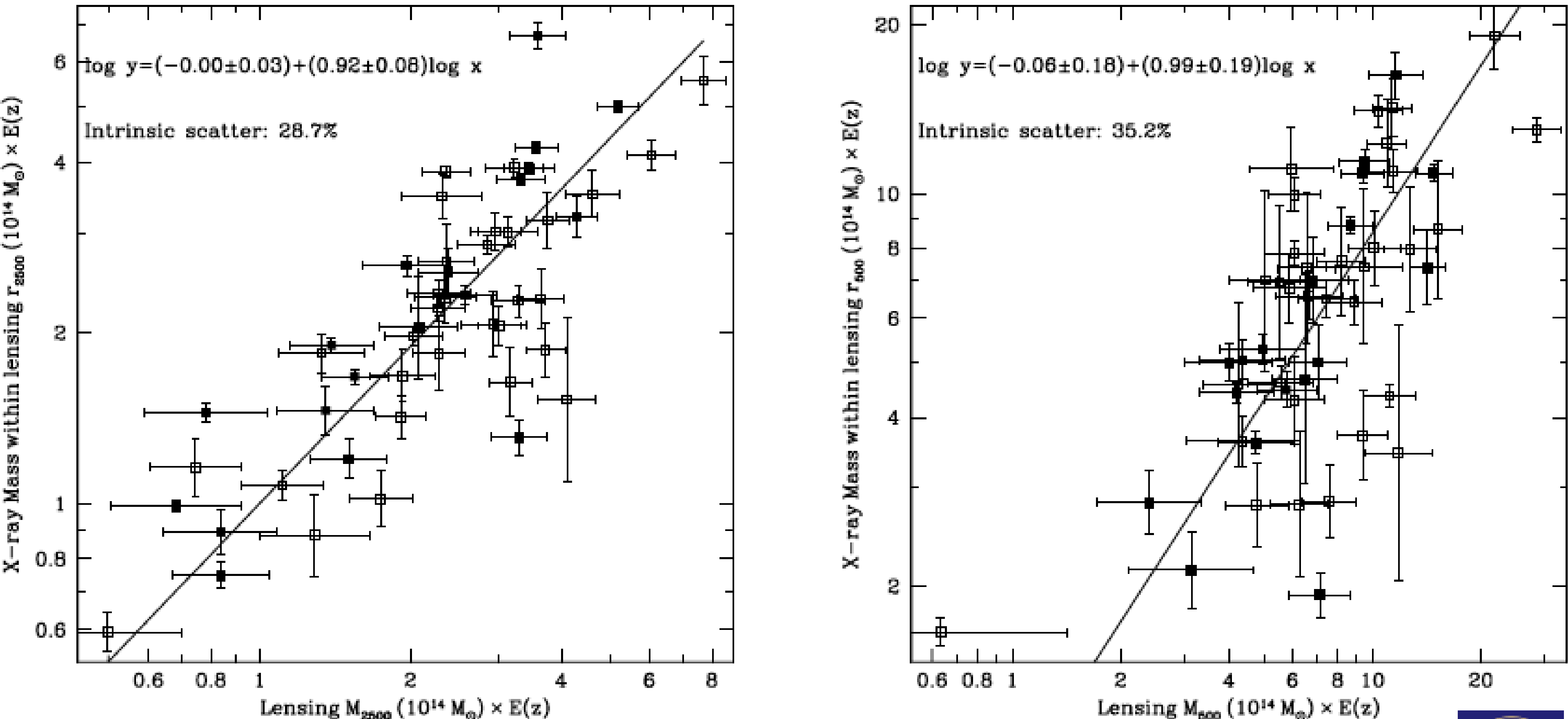


The preheating scenario fi ts much better to the observations

Reichert et al. 2011

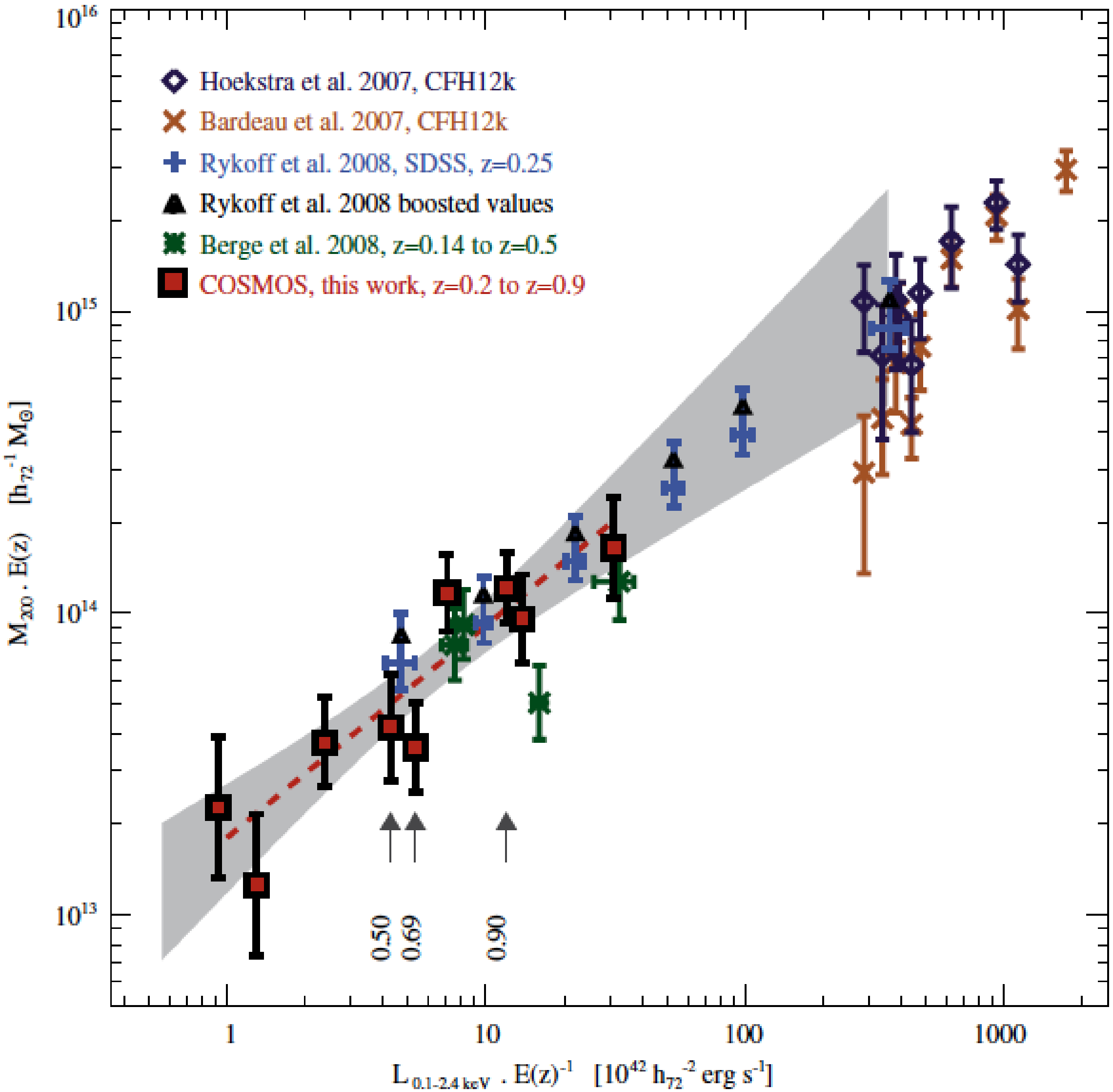
X-ray mass underestimate

Linearity of $M_x - M_L$ relation



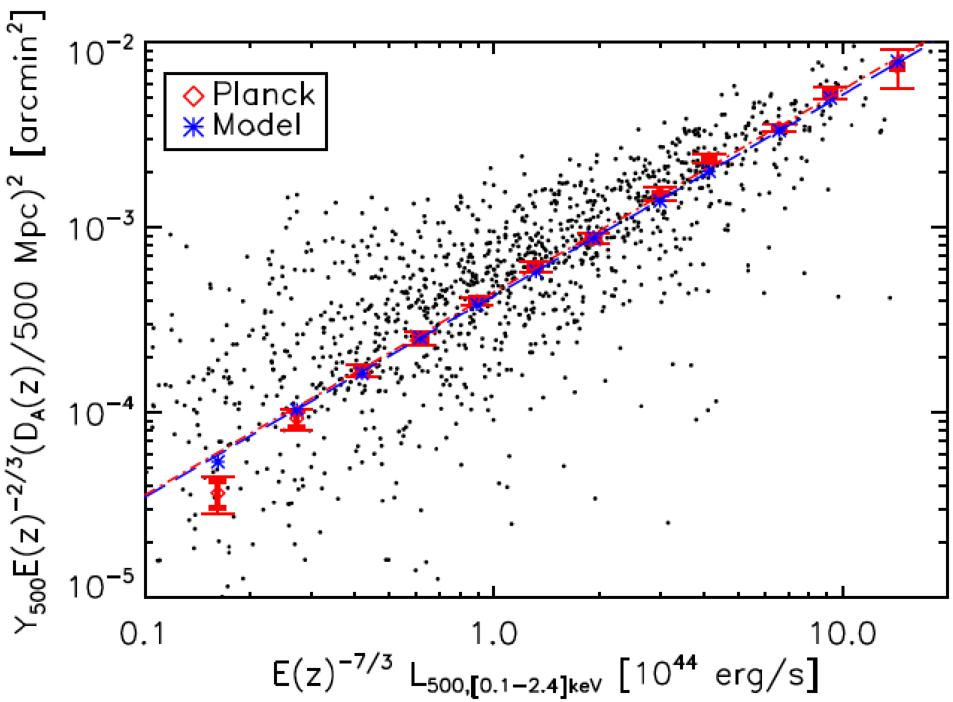
SF STATE

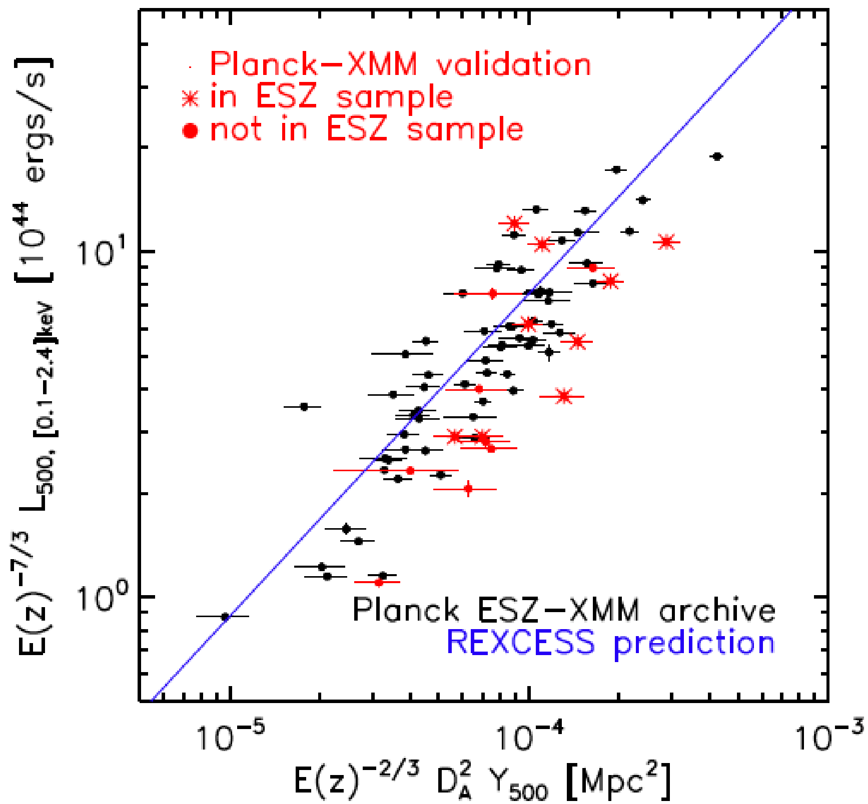
Calibration of the L-M Relation by Lensing



From Leauthaud et al. 2010

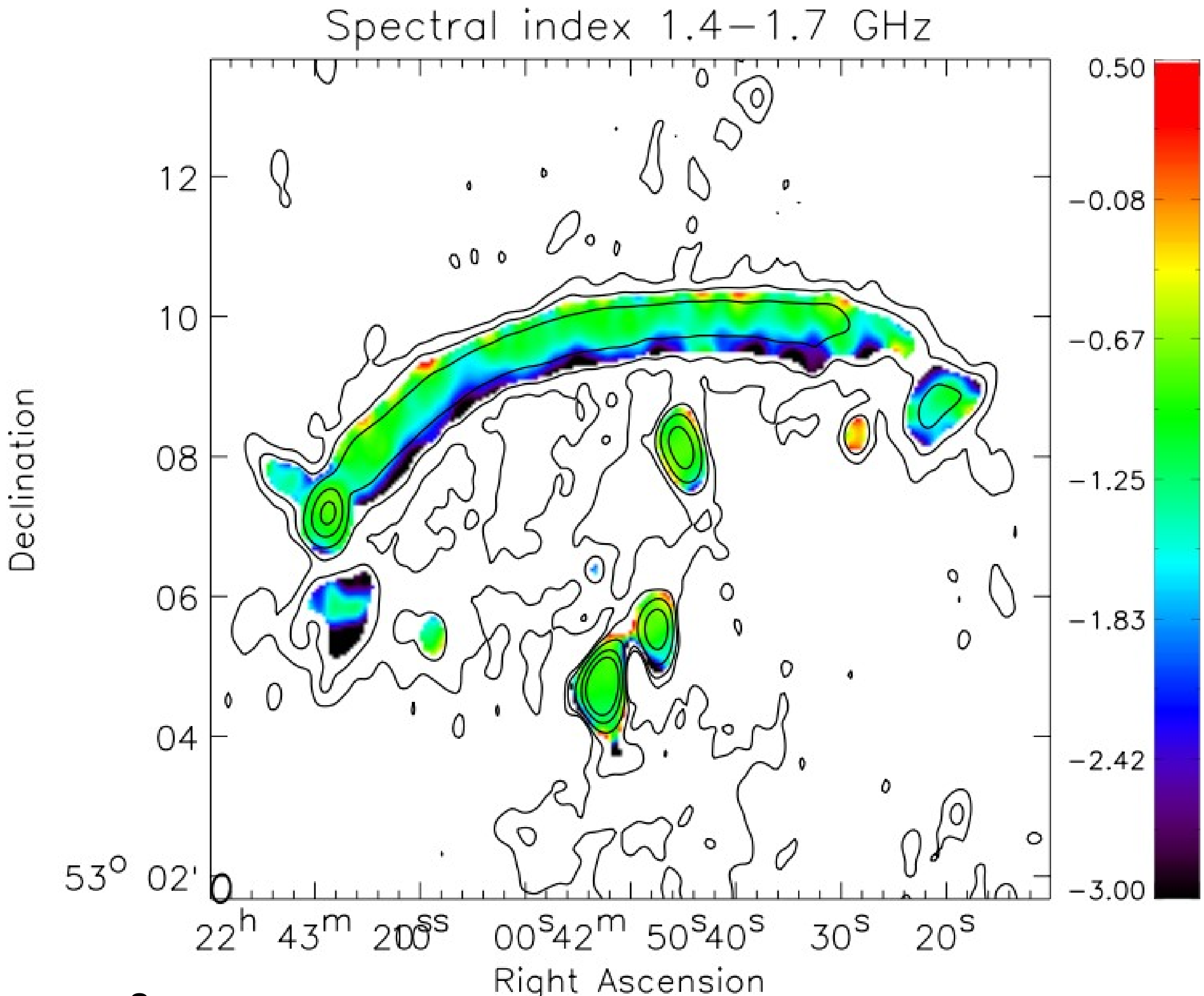
Very Comforting Consistency of Planck SZ and X-ray Observations





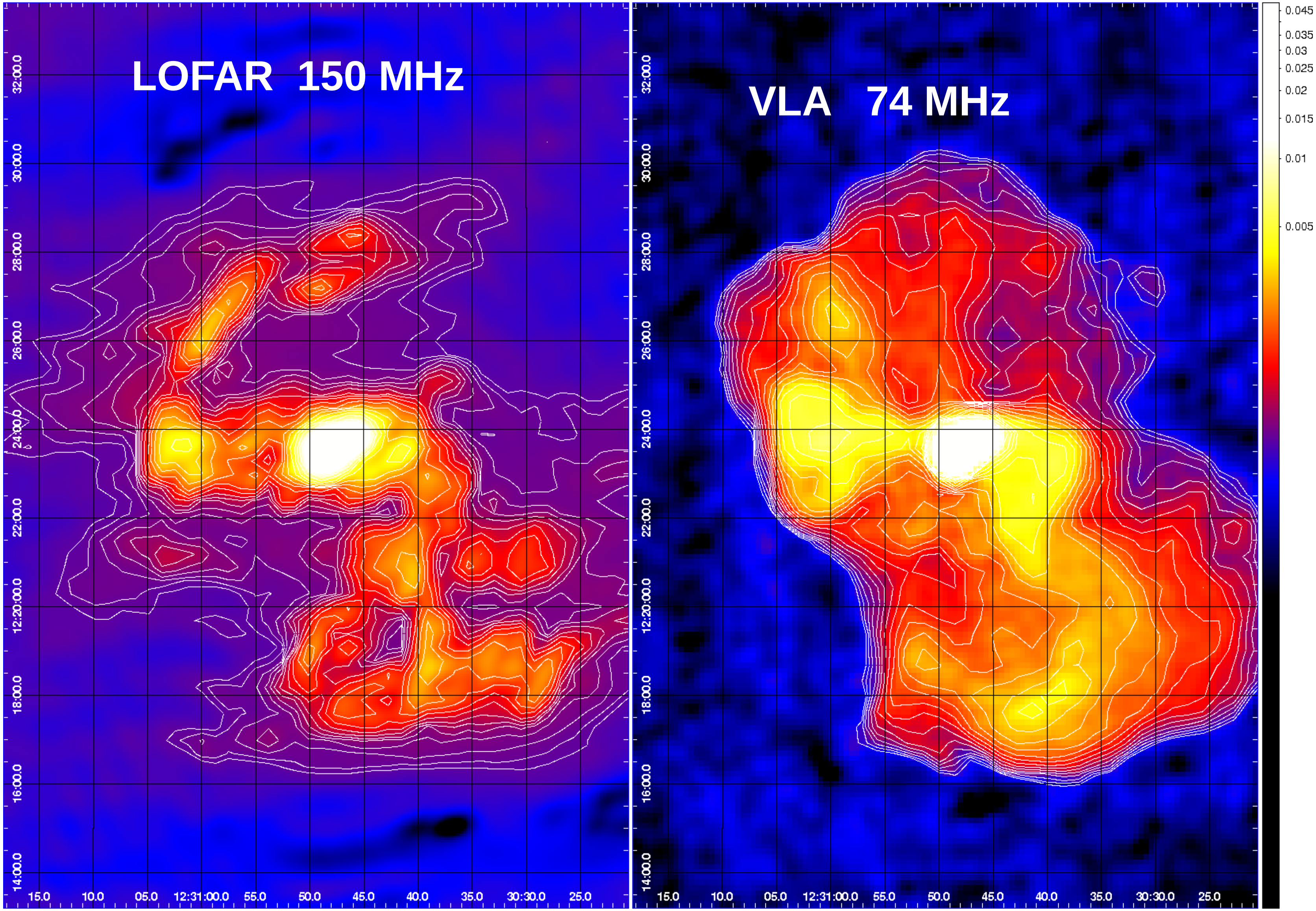
Planck Collaboration 2011
See Monique's talk

Textbook example of an aging shock accelerated cosmic ray electron population



Van Weeren & Brueggen

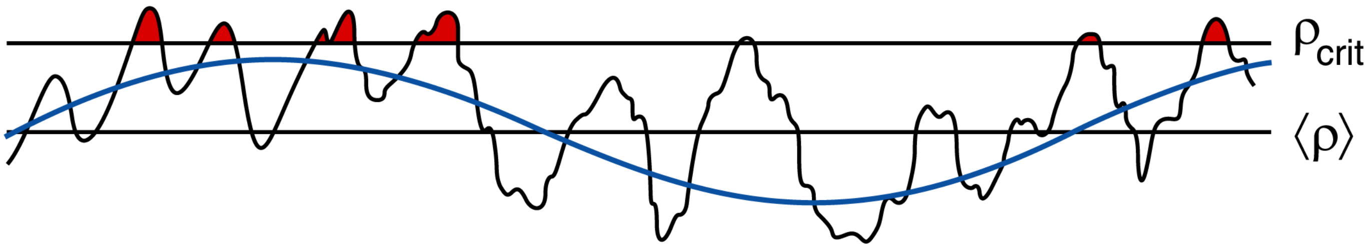
First Lofar Observations of a Cluster (Virgo)



Probing the large-scale matter distribution with galaxy clusters

Spatial modulation of the density of peaks (clustering) :

simplified fluctuation field with
short + long wavelength comp.



→ The cluster distribution traces the matter distribution in a „biased“ (amplified) way

[Mo & White 1996,

Sheth & Tormen 1999]

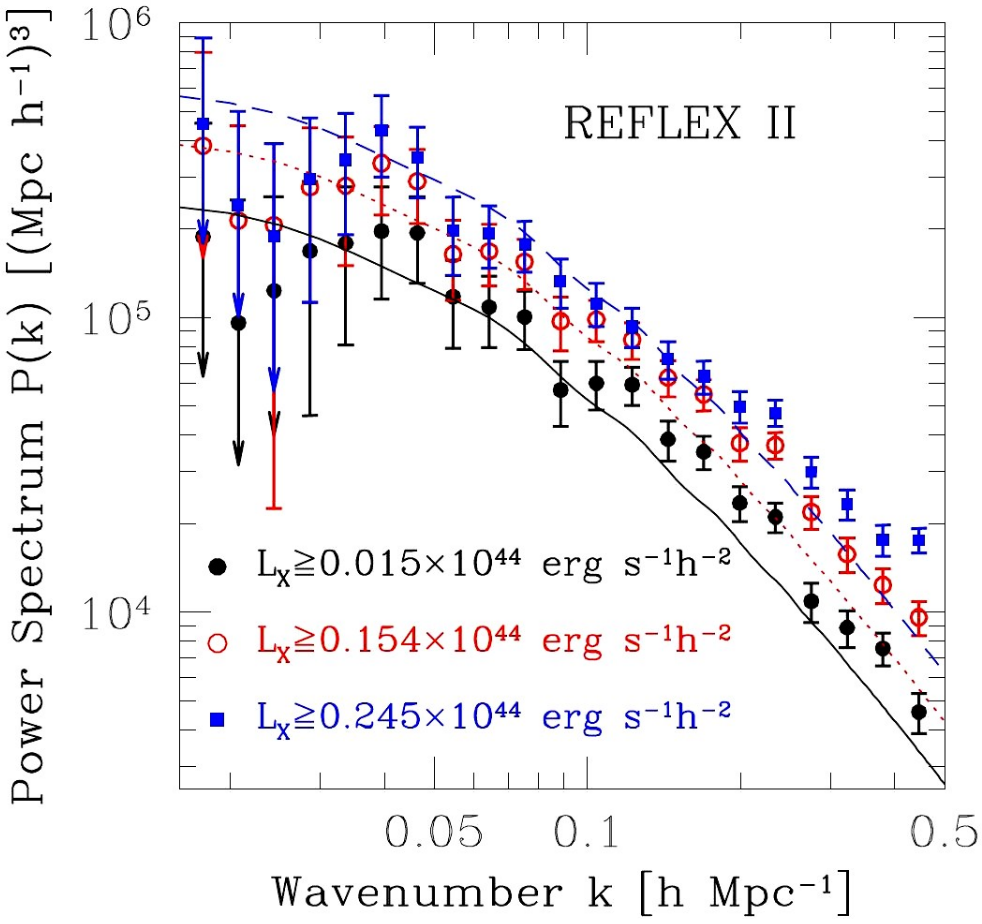
Biasing :

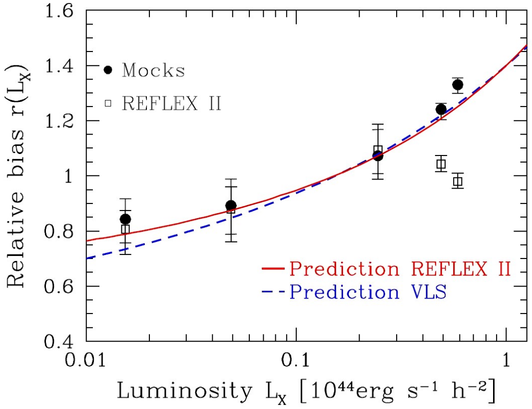
$$\widetilde{P}(k) = b^2 \cdot P_{DM}(k)$$

$$b(M,z) = 1 + \frac{\Delta_*}{\sigma^2(M,z)} - \frac{1}{\Delta_*}$$

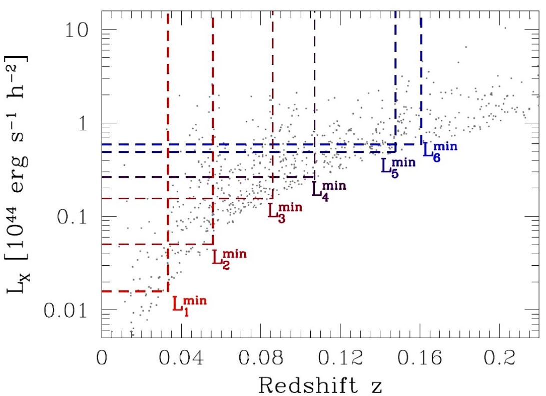
REFLEX II Power Spectrum (biasing)

The amplitude of the P(k) increases with increasing lower mass limit



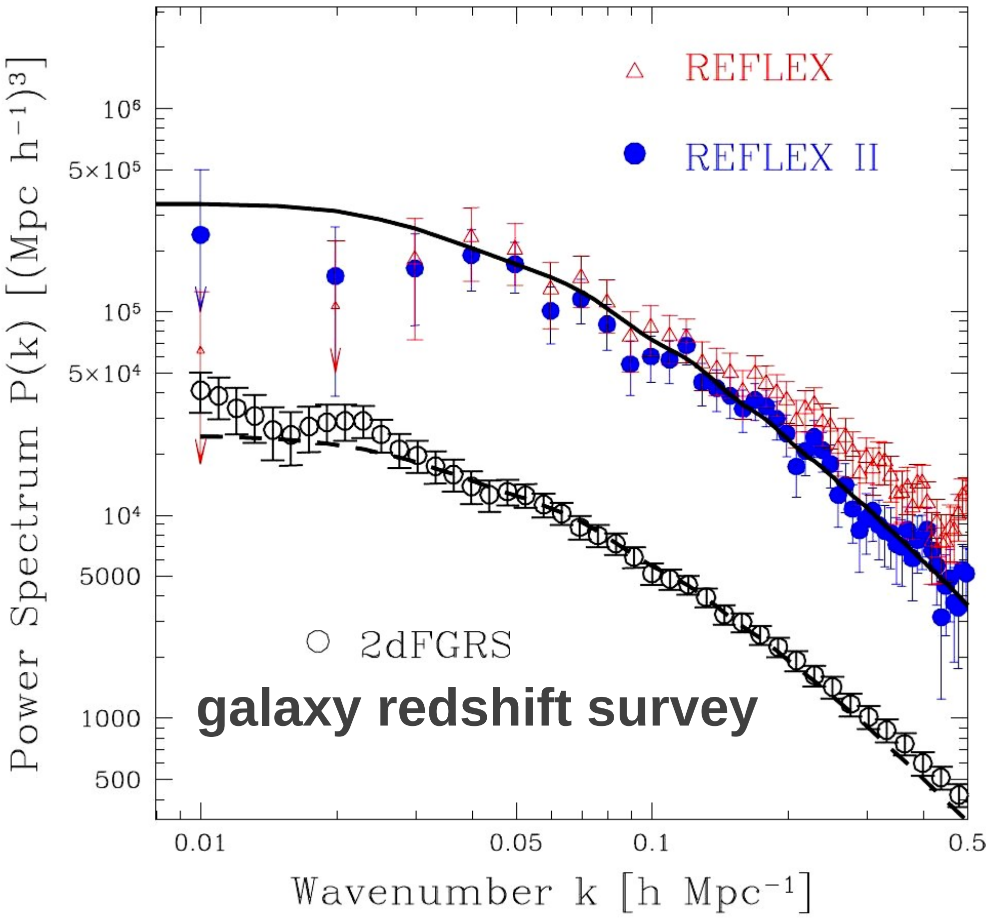


Increase of the amplitude (above) for 6 volume limited subsamples



Balaguera-Antolinez et al. 2010

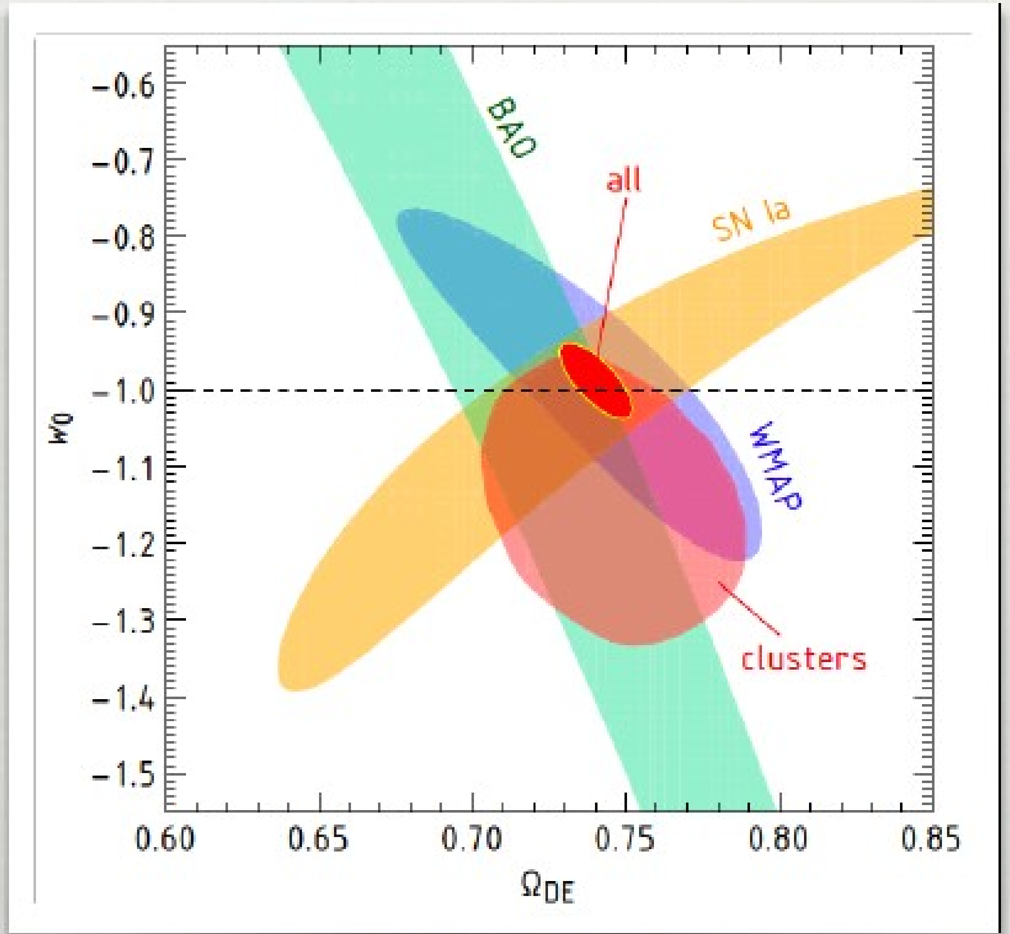
REFLEX II Power Spectrum (ΛCDM-Cosmology)



The lines give the prediction of the Concordance Cosmological Model with WMAP 5yr parameters

Balaguera-Antolinez et al. 2010

W_0 FROM COMBINATION OF METHODS



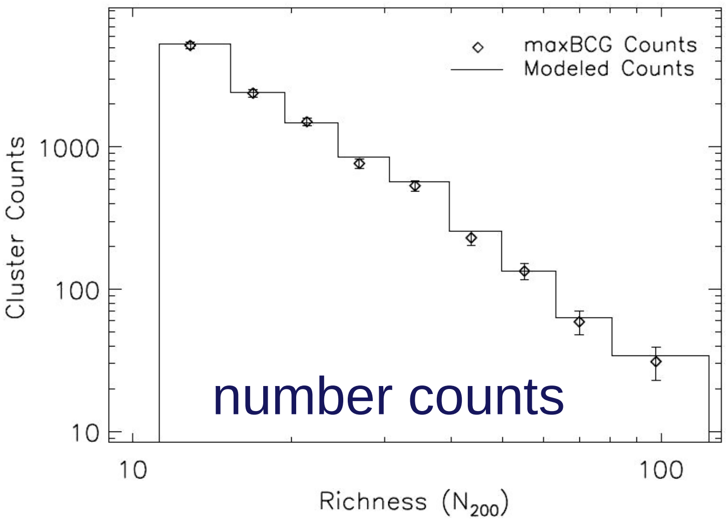
$w_0 = -0.99 \quad \pm 0.045$ (stat) $\quad$ ($\pm$ 0.067 without clusters)

± 0.039 (sys) $\quad$ ($\pm$ 0.076)

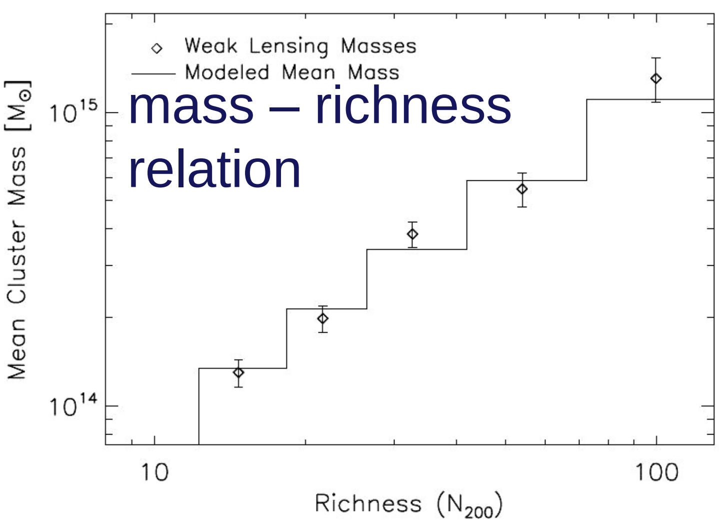
2009 ApJ 692 1060

Constraints from Optical work with SDSS

cluster richness (galaxy number) used as mass proxy



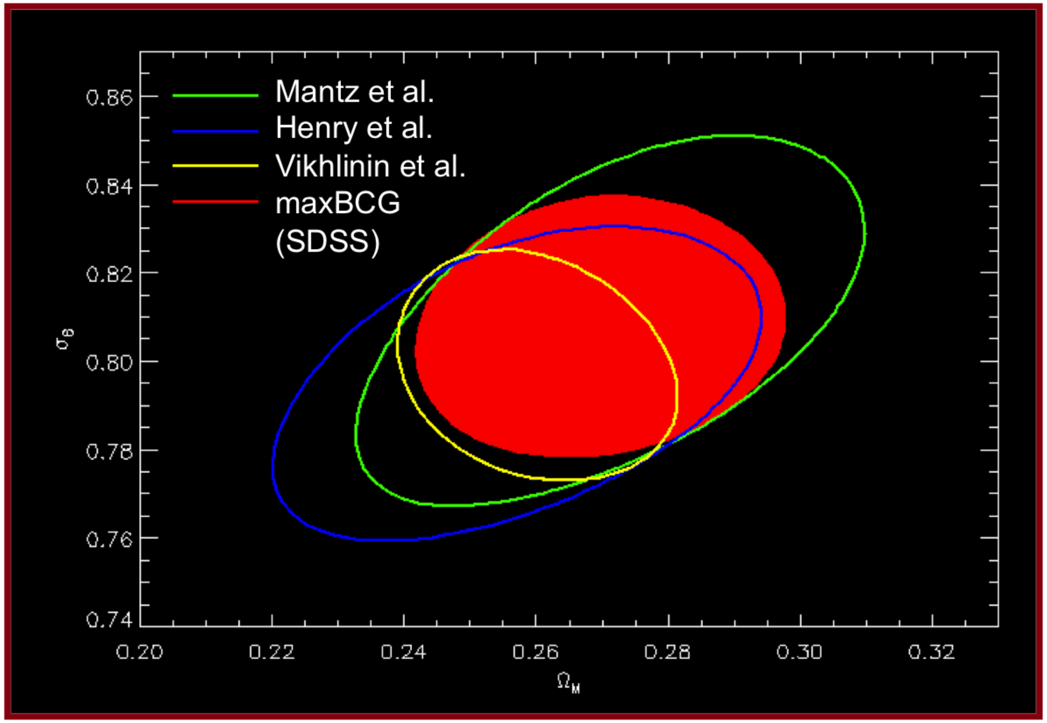
number counts



mass – richness relation

9349 clusters at z = 0.1 … 0.3

M ~ 10^{14} – 4 10^{15} M_{sun}



Similar constraints as for X-rays with much more clusters due to large scatter of mass proxy.

[Rozo et al. 2010, ApJ 708, 645]

Non-Quintessence Cosmological Models

e.g. Modifi ed Gravity Models

Braneworld models

Non-Gaussianiy Models

They need a separate assessment of cosmic geometry and structure growth

Among the probes for structure growth galaxy clusters have been and are very competitive !

Cosmological probes for the growth of structure

Needed in addition to geometry probes to tests for non-trivial (non Quintessence type) Dark Energy Cosmologies

1. **Galaxies: uncertain link to halo mass**

2. **Clusters: uncertainty due to non-virialized objects**

   - mass function very sensitive - LSS highly biased !

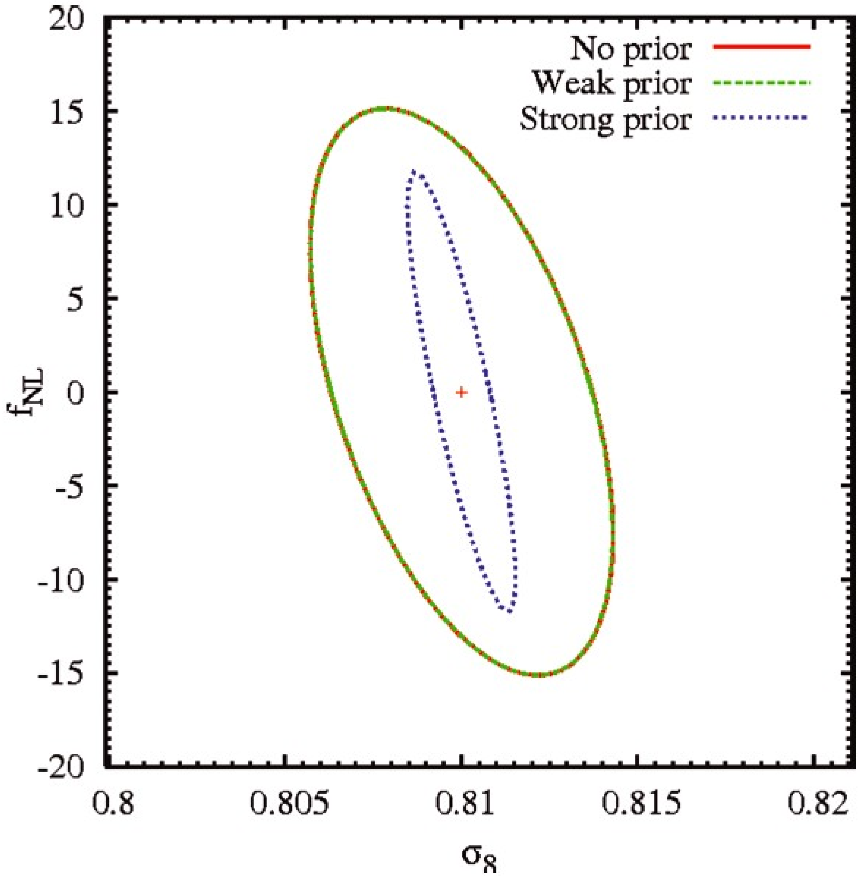
3. **Lensing: seen in projection = only cumulative effect**

4. **Ly-α forest: limited statistics**

→ **Galaxy clusters have an important role in the game !!**

Constraints on non-Gaussianities for a WFXT type mission

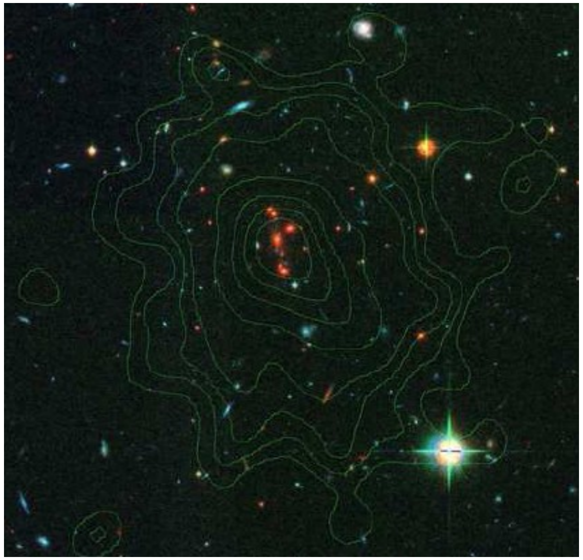
250 000 clusters , 20 000 with precise mass proxies
- Using number counts and the power spectrum



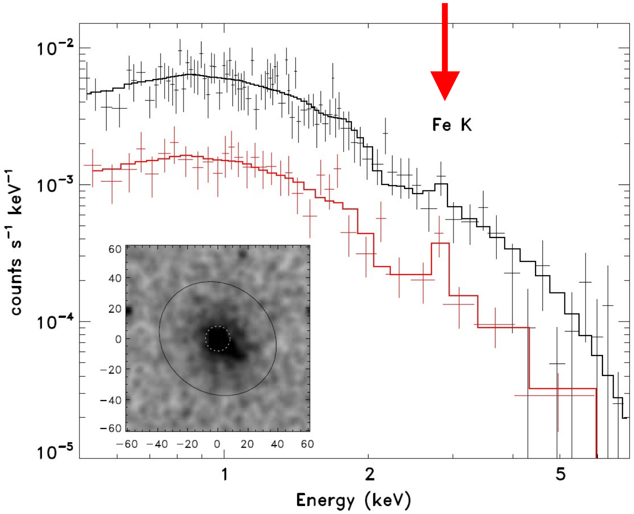
Current constraint of the CMB $f_{NL} < O(100)$

[Sartoris et al. 2010]

Puzzle (?): XMMU J2235.3-2557 at z=1.39



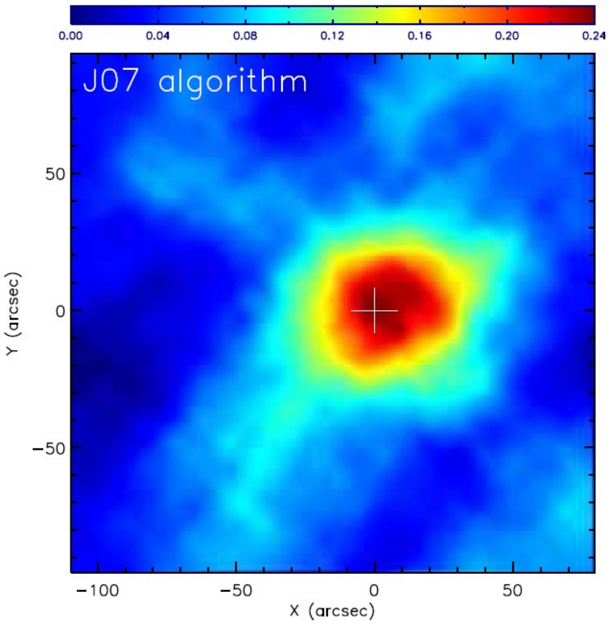
HST/ACS i+z & VLT/ISAAC K_s
with Chandra X-ray contours



200 ksec Chandra Spectrum

T_X=8.6 keV (+-1.3)

M_{200}= 6 (+-1.3) 10^{14} M_{sun}



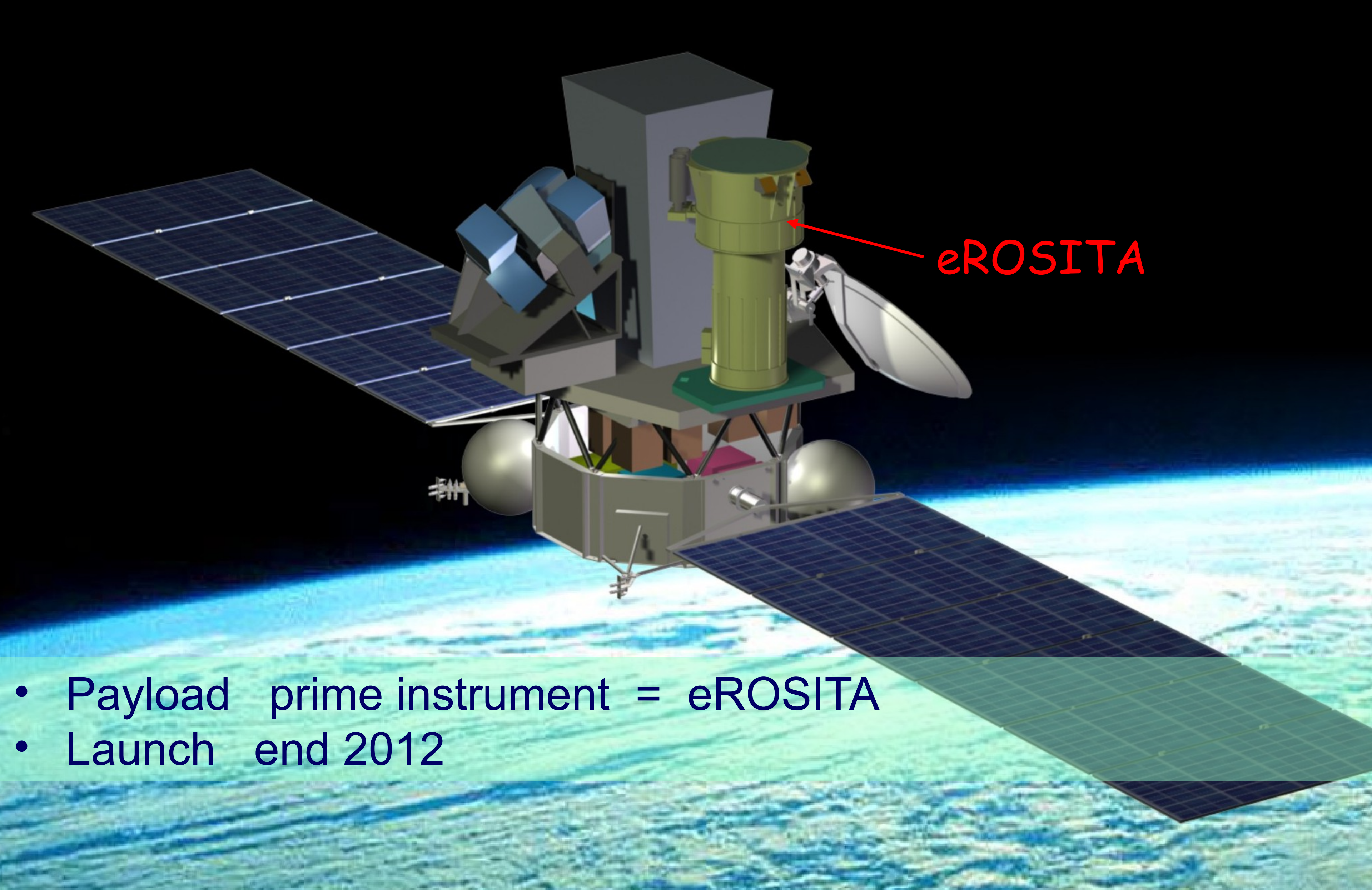
HST Weak Lensing Map (8σ)

M_{200}= 7.3 (+-1.3) 10^{14} M_{sun}

XMMU J2235.3-2557 is the
hottest and most massive cluster known at z>1
expected surface density: 1 in >1000 deg²

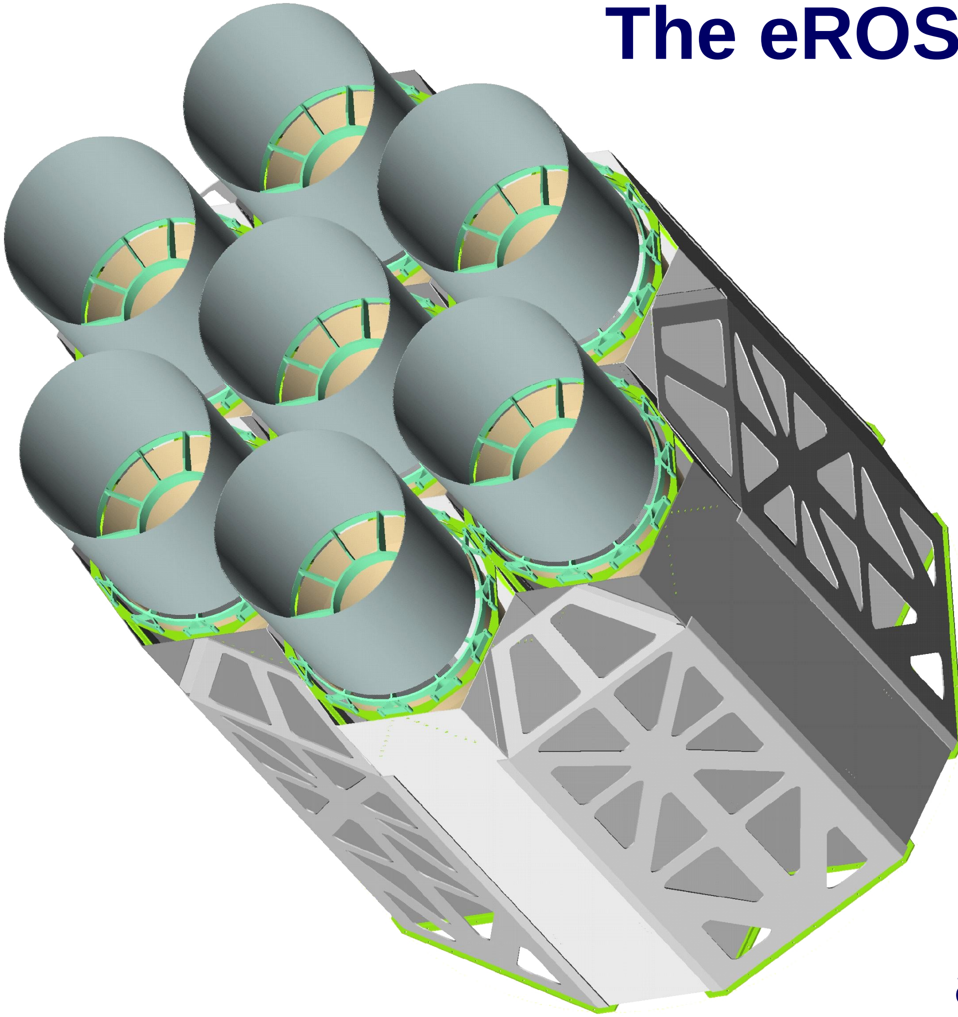
P. Rosati et al., in print, A&A, arXiv:0910.1716
M.J. Jee et al., 2009, ApJ, 704

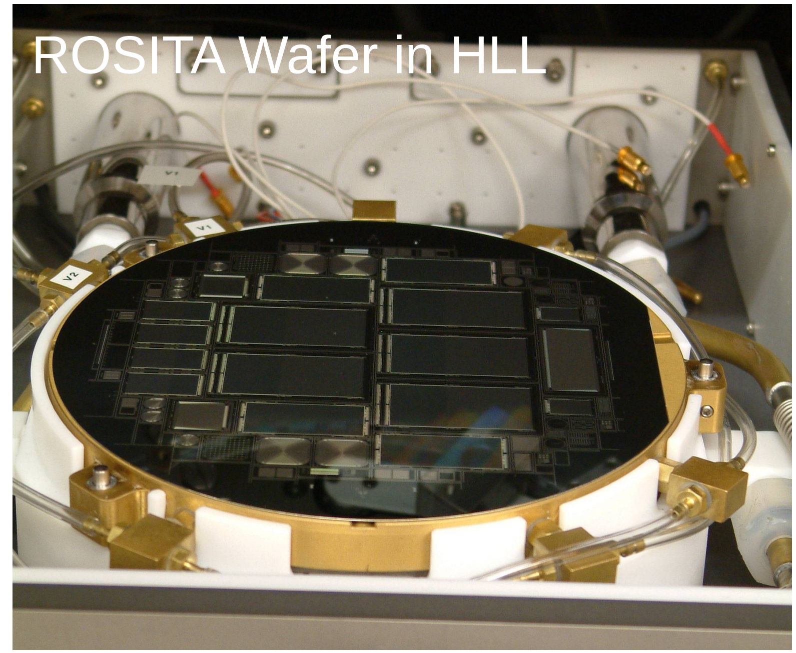
eROSITA on SpektrumX-Gamma



- Payload prime instrument = eROSITA
- Launch end 2012

The eROSITA Survey





Main goal: Study of Dark Matter and Dark Energy using a sample of ~100 000 galaxy clusters out to redshifts of $z \sim 1.5$

Mirror Modules

Mirror Module qualified (Thermal Vacuum, Vibration, X-ray

8 Mirror Structures finished (manuf., heaters, metrol., clean., alignm.)

2/3 of all mirror mandrels finished (rest until end of 2011)

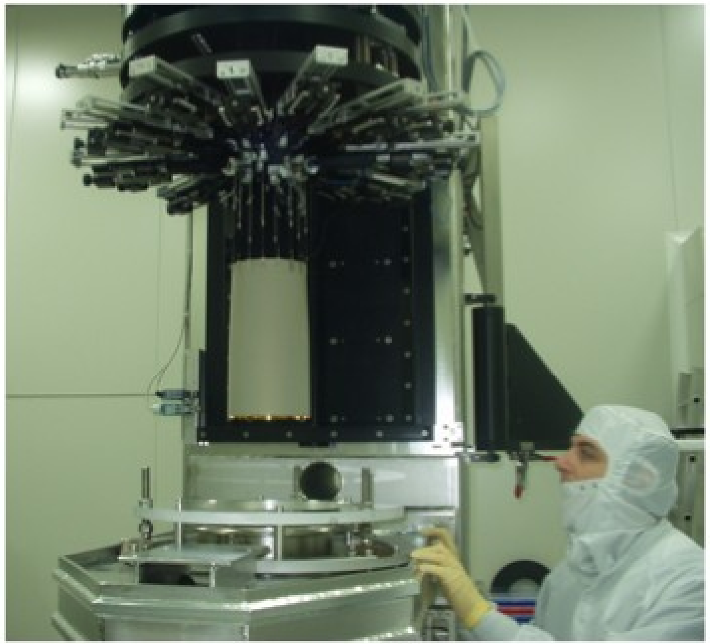
Equipment at MLT completed (e-form baths, 2VOBs, releas., metrol., etc.)

FM-production started (speed ~ 1 shell/day/VOB)

Next: FM-1 with first 15 shells to be tested in PANTER on march 3rd

Mirror Modules

2-forming baths for eROSITA
→ 8 mandrels/shells simultaneously

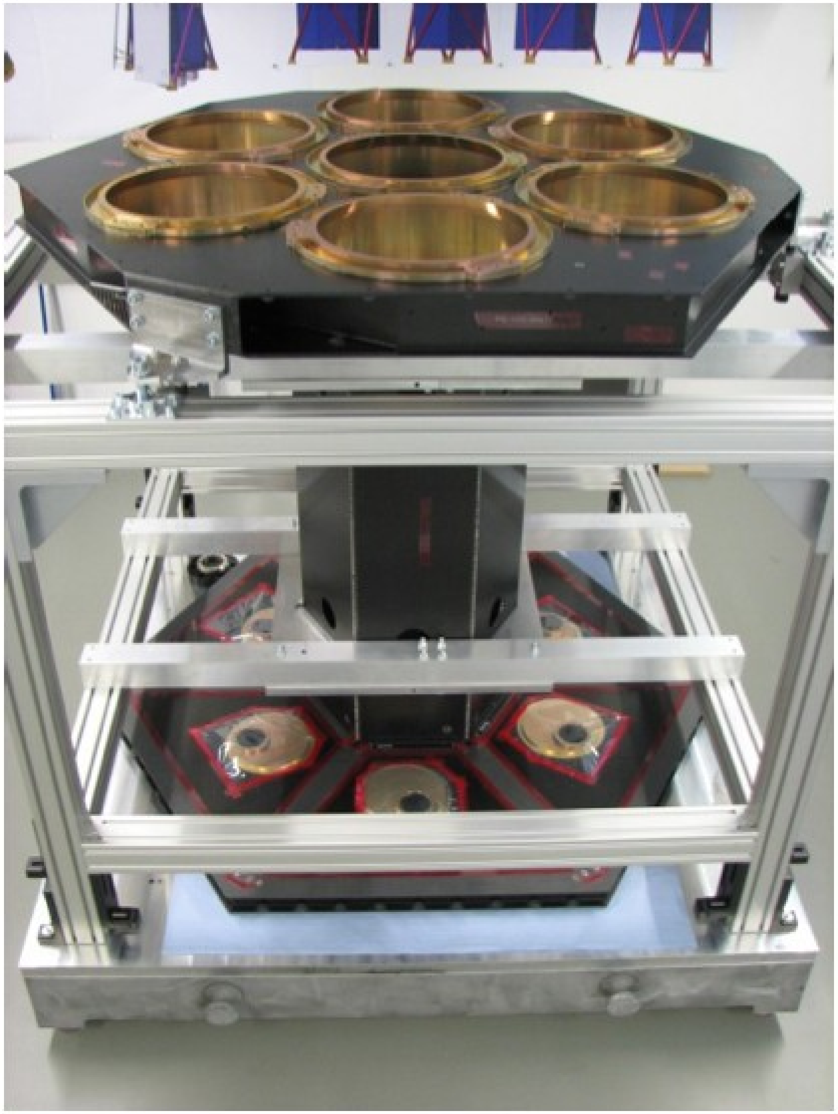


2 "Vertical Optical Benchs"
for alignment and integration

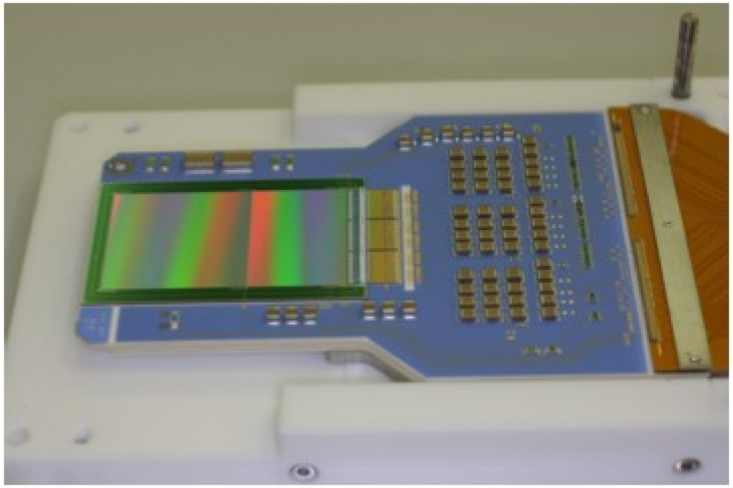
Integration of Shells
step by step from inside to outside

Telescope Structure

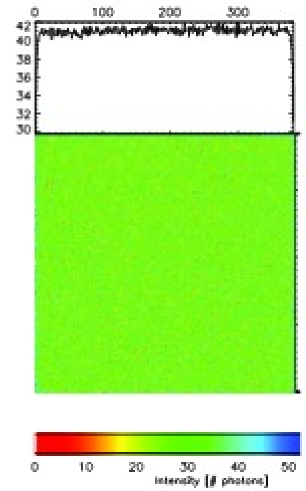
growing...



CCD - Cam



CCD-Module: CCD (left) on ceramic PCB



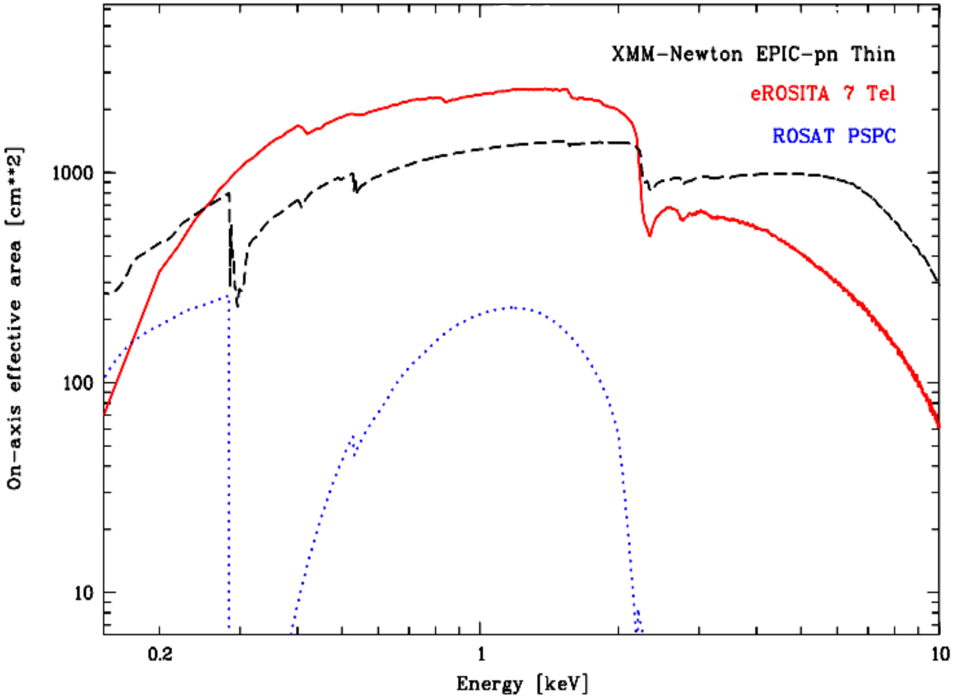
CCDs are fully within specification!

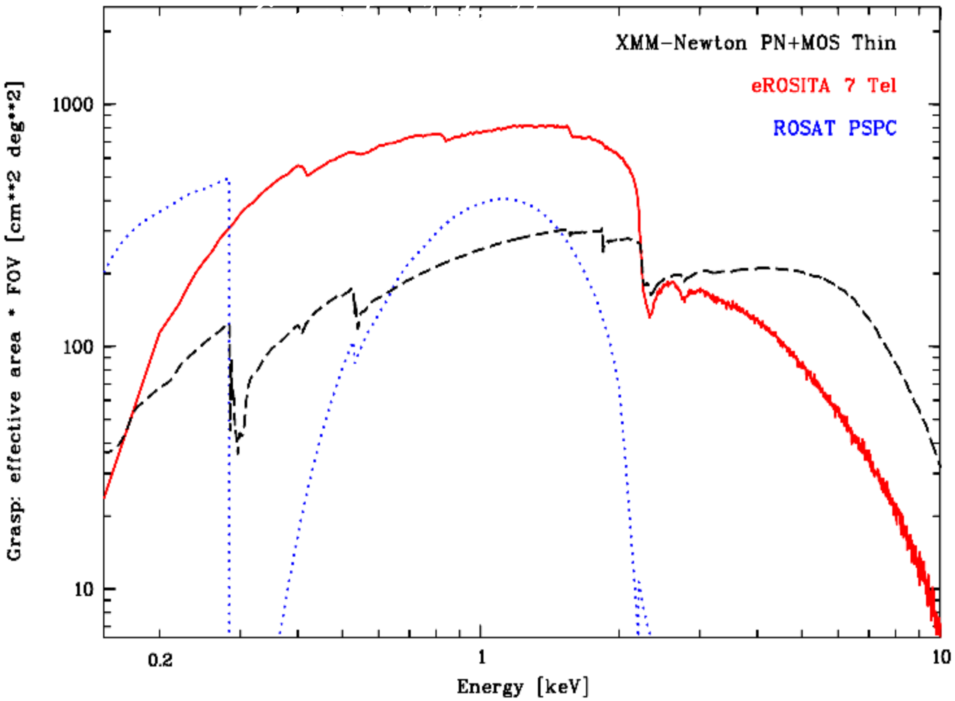
"TRoPIC" camera working since 3,5 years
EM camera working since 1/2 year

Next: STM-Camera goes next week into PUMA

Proton Shield: gold coated copper

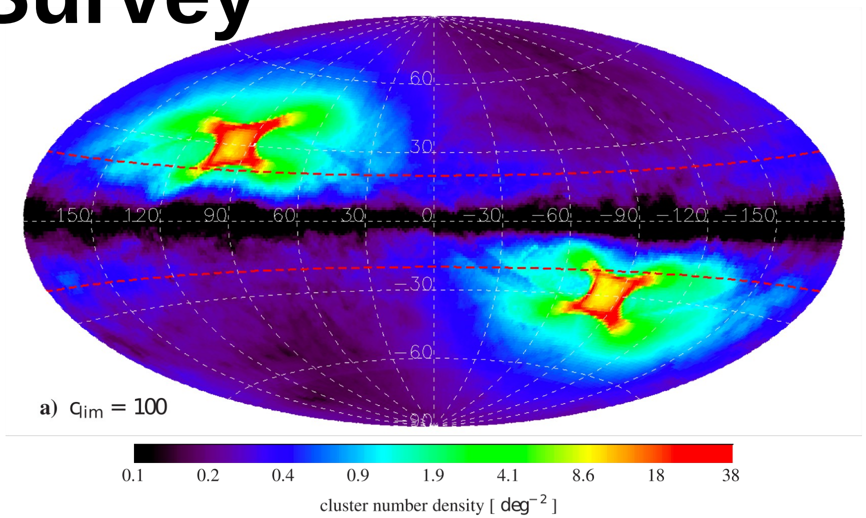
Effective Area and Grasp of eROSITA

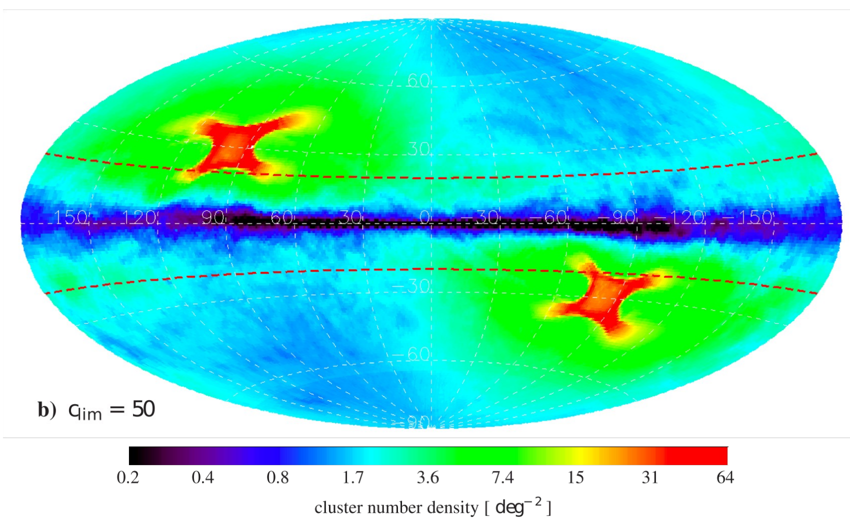




Grasp of 7 eROSITA telescopes is 3-4 x higher than 3 XMM-Newton telescopes in the energy range 0.3-2 keV!
(At energies 5-15 keV, the Russian ART-XC is taking over.)

Galaxy Cluster Detections in the eROSITA Survey

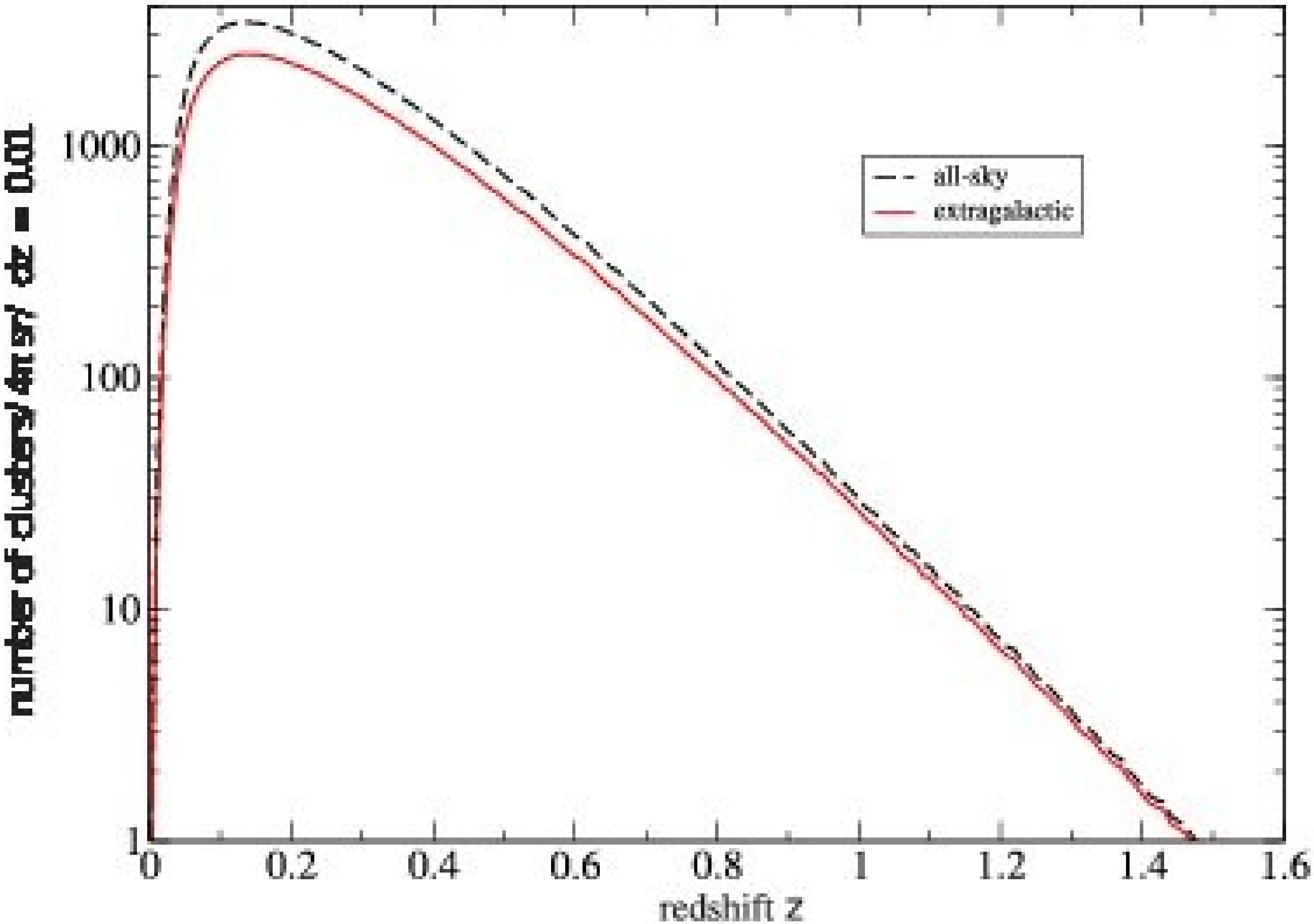




Nphot.	all sky	extragal sky
30	393810	293767
50	236503	176946
100	113227	85139
500	17272	13159
1000	7191	5514

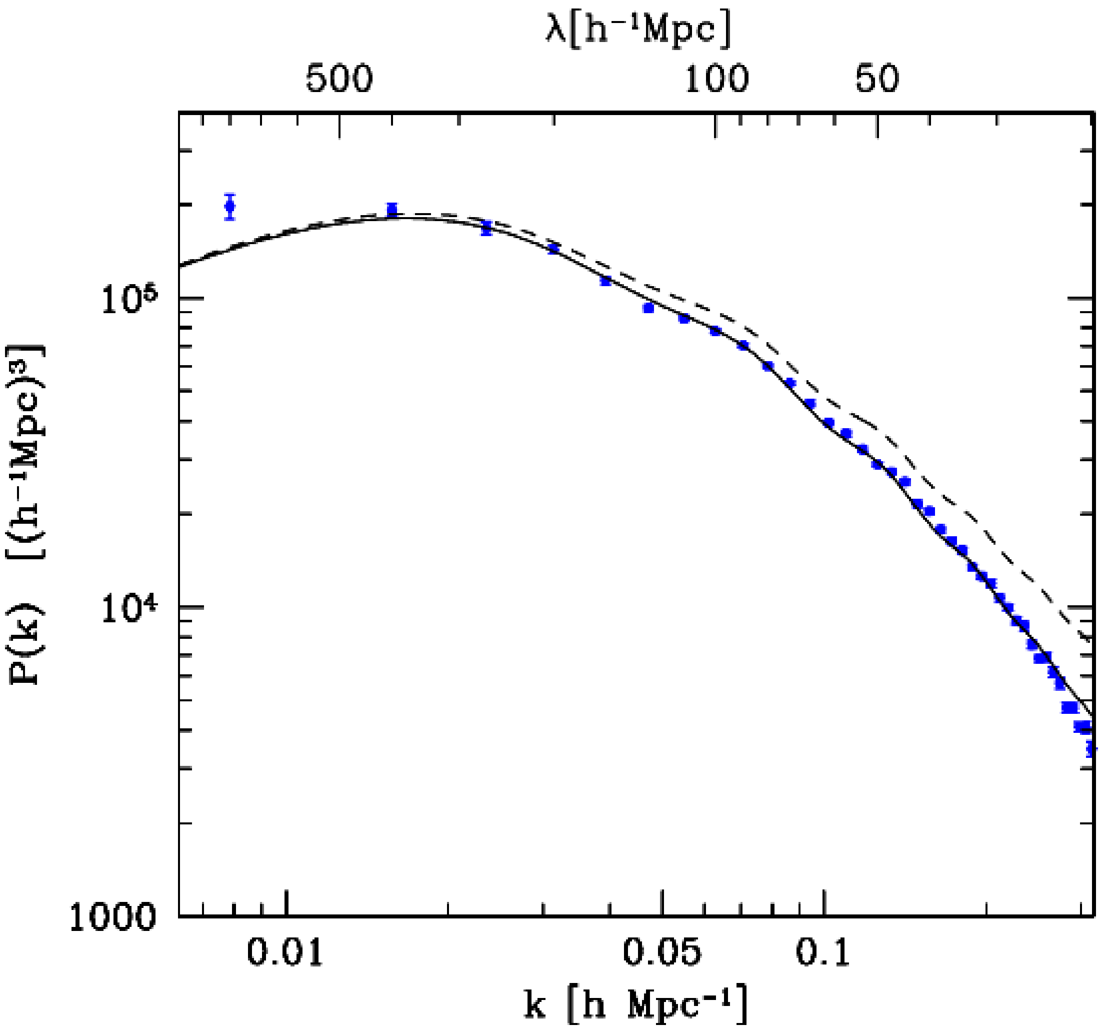
M. Mühlegger Ph.D. thesis

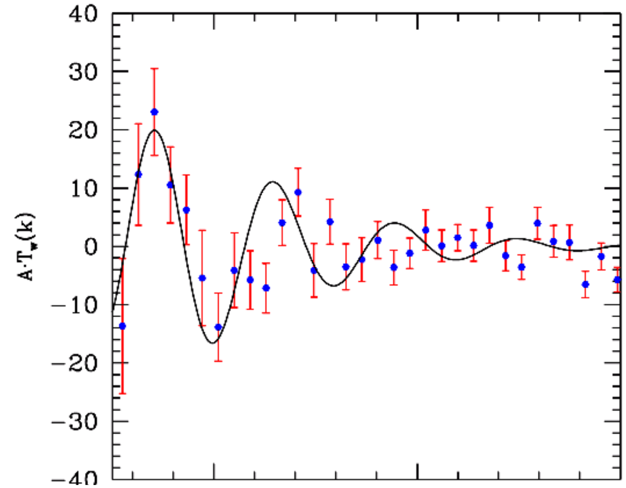
Redshift Distribution of the Galaxy Cluster Detections

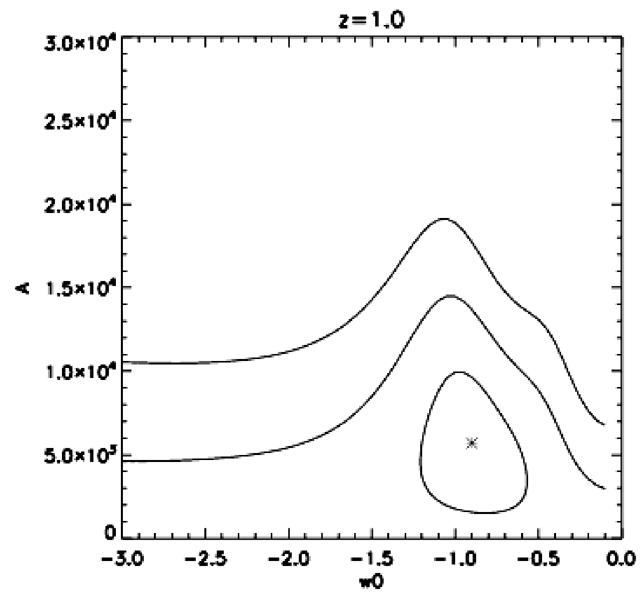


M. Mühlegger 2010

Constraints from Baryon Oscillations







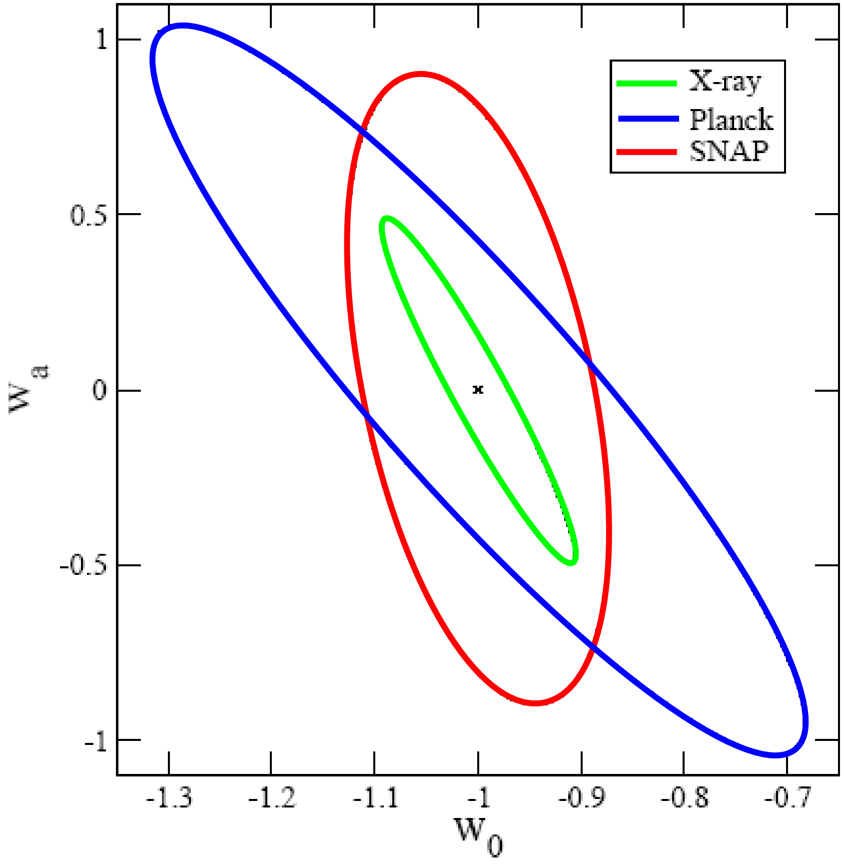
100 000 clusters in survey required !

Schücker 2005, priv. comm.

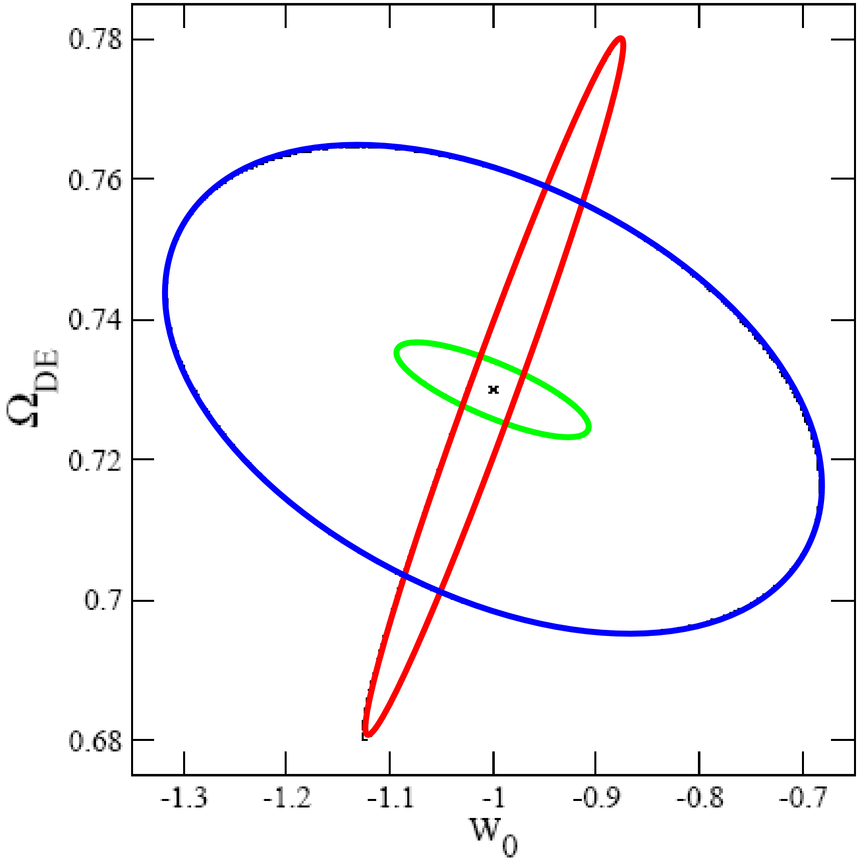
Constraints from 100K Cluster Survey

Time dependence of w_x

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



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



Haiman, et al., 2005, astro-ph/0507013

What is needed to fully exploit the results

eROSITA   X-ray detections and characterizations

Photometric Survey: SDSS, PanSTARRS, DES, KIDS, VIKING, HSC

EUCLID   weak lensing mass calibration

IXO - XMM-Newton/Chandra: detailed X-ray parameters

BigBOSS & ESO Survey (e.g. 4mMOSST etc.)   galaxy spectroscopy

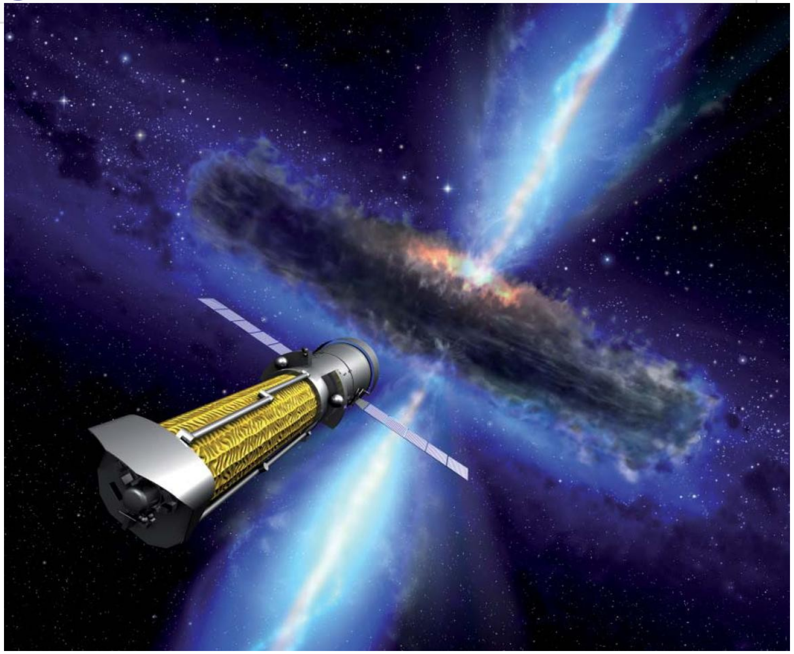
International X-ray Observatory - IXO

What we need:
- **Large collecting area**
- **Good angualr resolution <5”**
- **Good spectral resolution few eV**

This is the IXO mission:

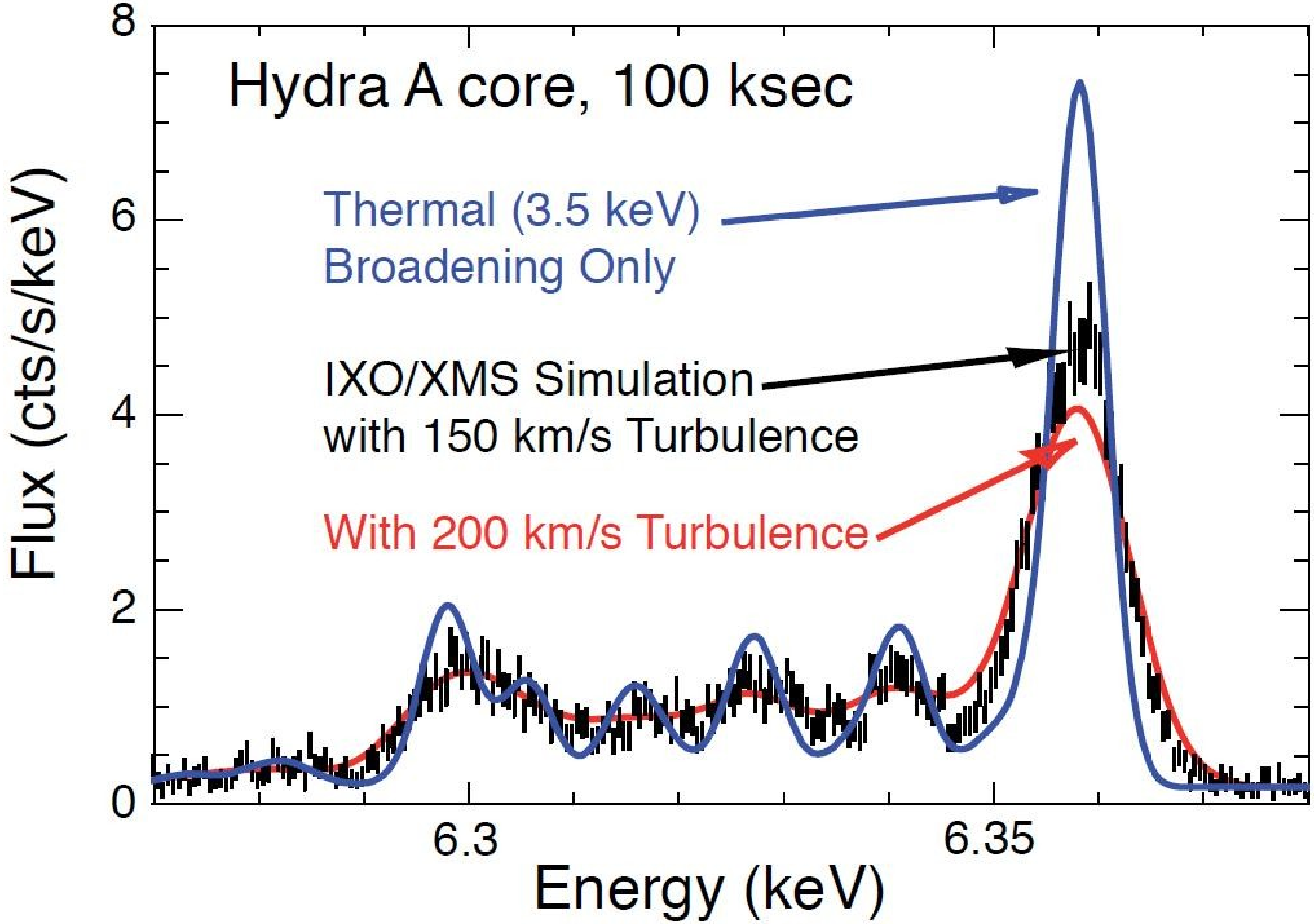
NASA is not supporting it any more
ESA wants to have a selection of one of 3 missions in Feb 2012 (possibly with increased budget)

We have to organize ourselves to all support this unique chance to have the next generation X-ray observatory !!!



20 m focal length
6450 kg - launcher: Atlas V/551
Mirror 2.8 m^2 effective area (1keV)
PSF 5 arcsec
Mirror: silicon pore optics or glass shells l
Orbit: L2 800 000 km amplitude
Lifetime: design 5yr, expect. 10yr

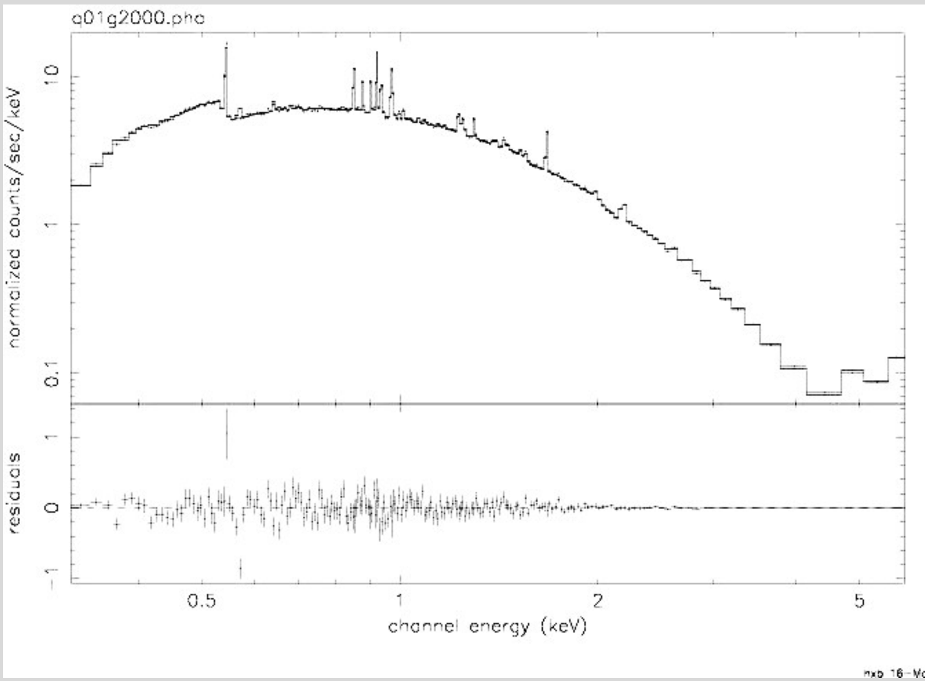
Velocity Diagnostics of the Cluster ICM



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

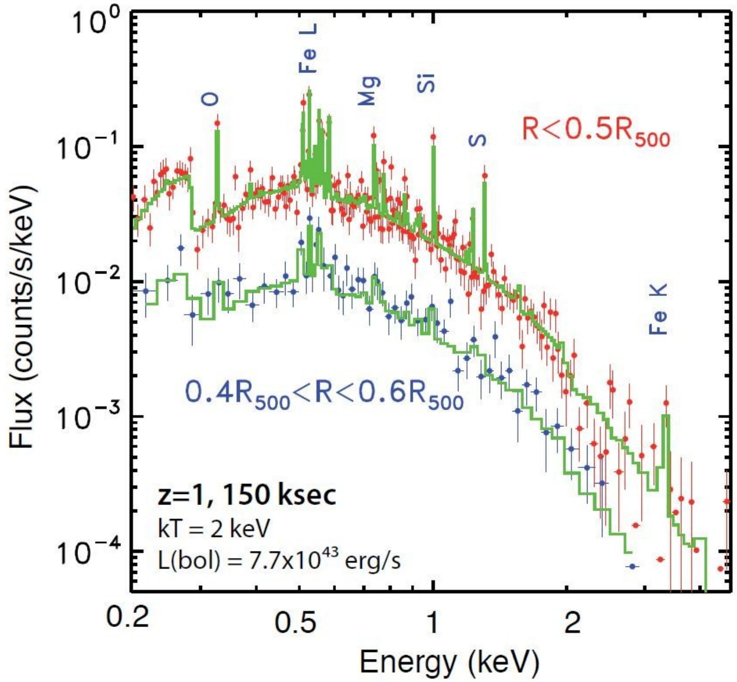
= 100ks ΔT ~ 0.4 keV „

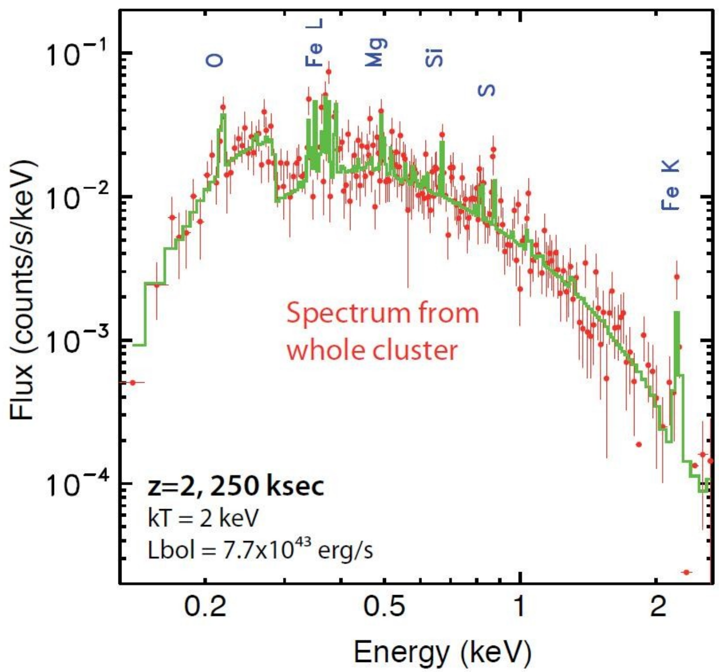
<u>3 & 5 keV plasma:</u>

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%

Conclusions

Thanks to the Organizers for this wonderful workshop

We learned many new things and saw an enormous progress

... and we had an interesting outlook on many new projects to come

Thus, a lot of hard work lays in front of us ...

... but also surely exciting new scientific results!