Galaxy Clusters as Cosmological Probes

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Overview

- Galaxy clusters in the cosmic hierarchy

- Cosmology with the ROSAT All-Sky Survey

- Prospects for the eROSITA Survey for galaxy cluster science

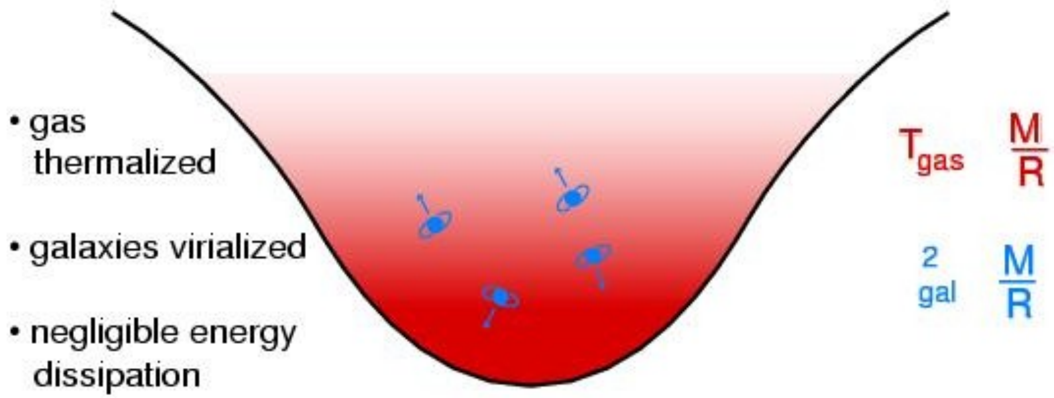
- Conclusions

Comparison of Galaxies and Clusters as Dark Matter Halos

Galaxies

Complex relation between observable stellar population and dark matter halo

Clusters

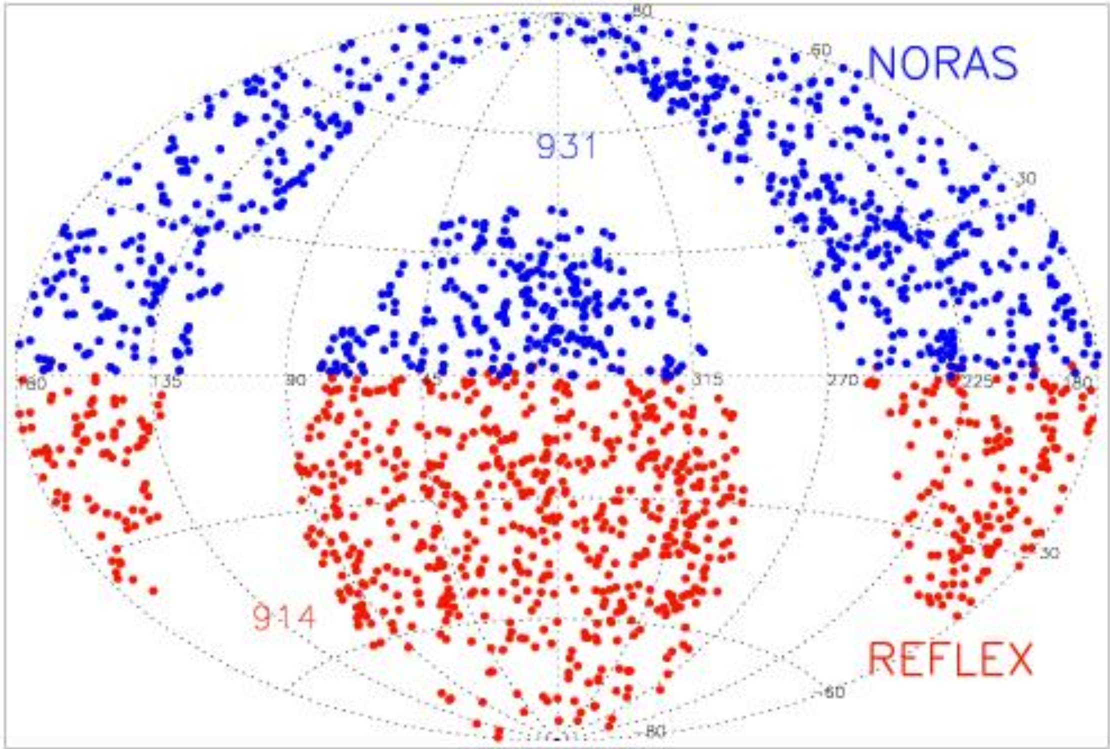


The intracluster gas is heated when the cluster forms and does not cool – it still reflects the potential depth.

Cosmology with Clusters from the ROSAT All-Sky X-ray Survey

Combined REFLEX & NORAS Survey

Extragal. ALL-SKY RASS Survey



REFLEX II 918 clusters

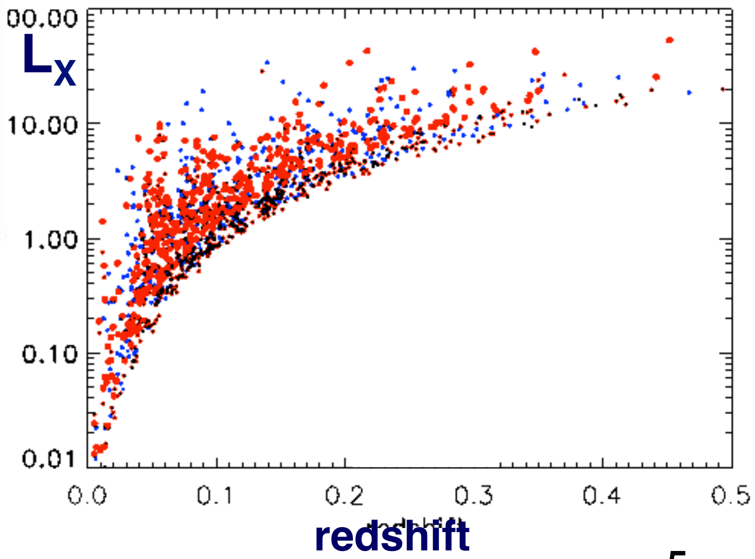
NORAS II 934 clusters

F> 1.8 10^{-12} erg s^{-1} cm^{-2}

REFLEX 1: 18 runs La Silla

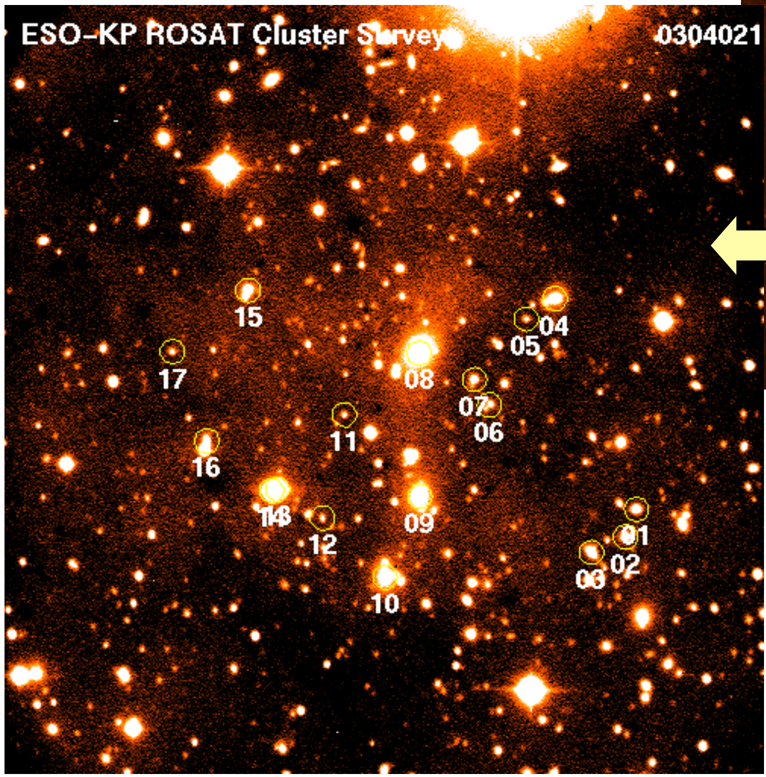
REFLEX 2: 8 runs ESO 3.6m

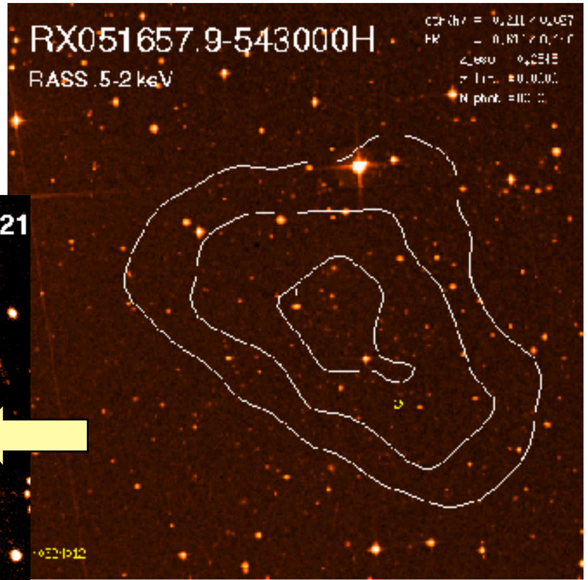
NORAS 10runs C.A. 2 runs K.P.

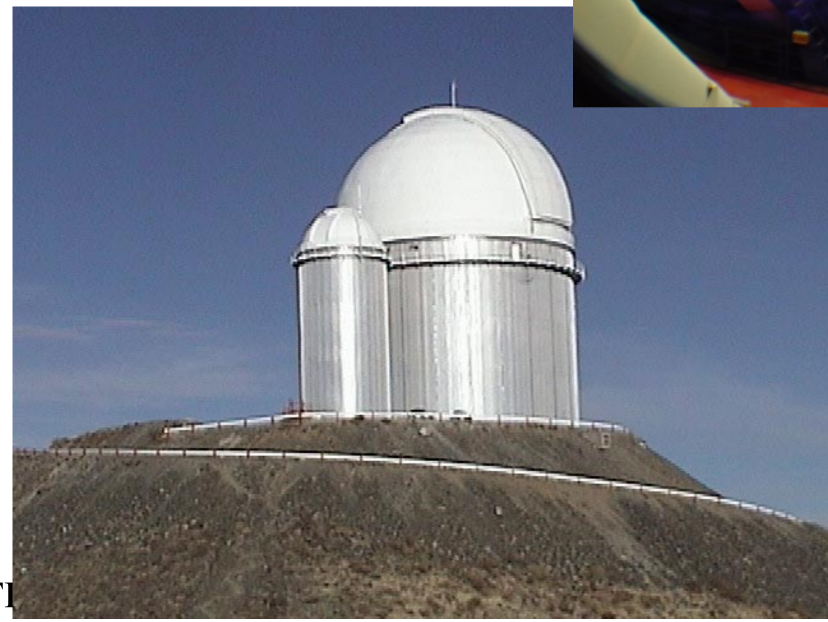


Böhringer et al. 2000, 2001, 2004, 2012

ESO – Key Program
conducted at La Silla 1992 - 99 (II) - 2011

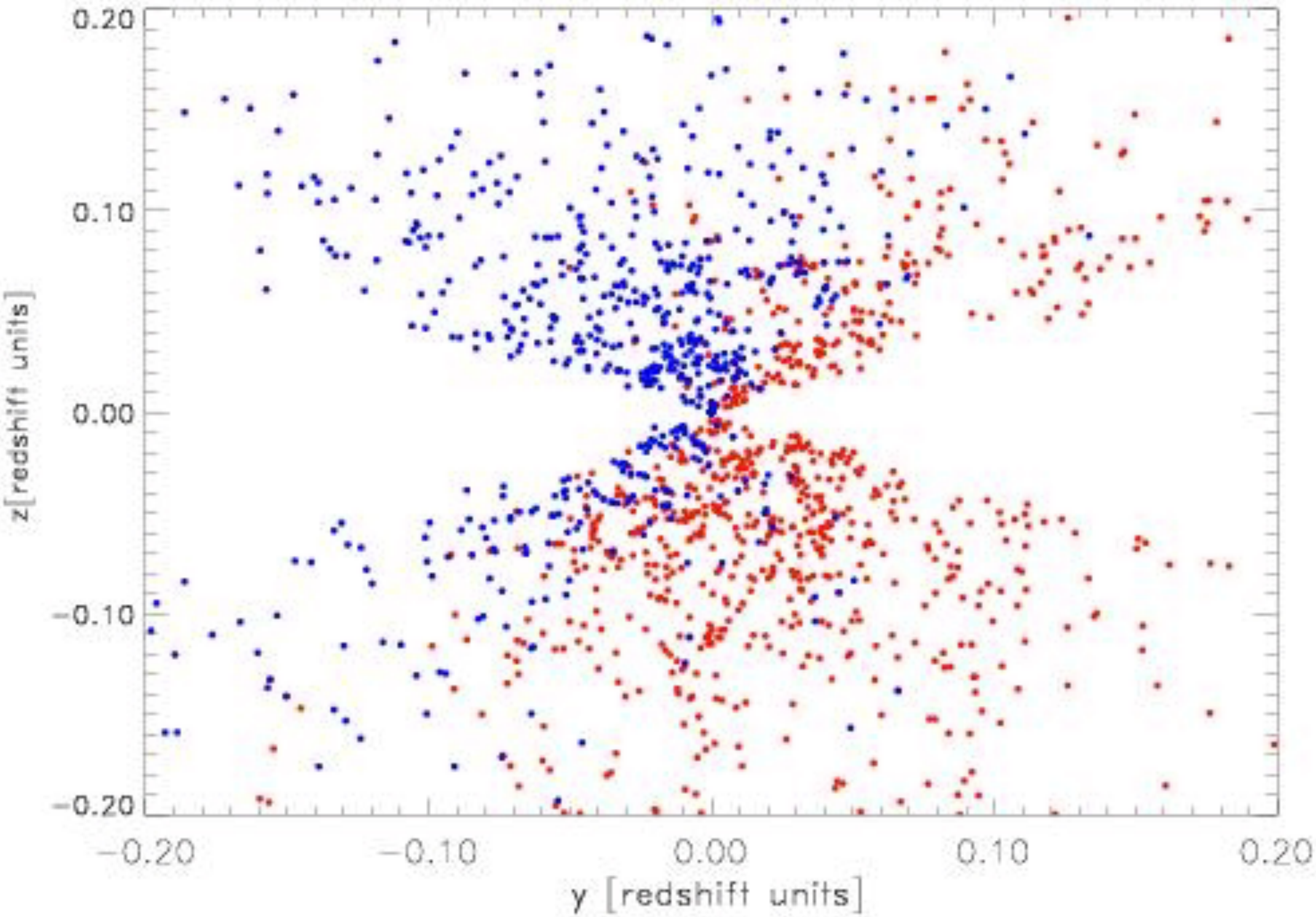




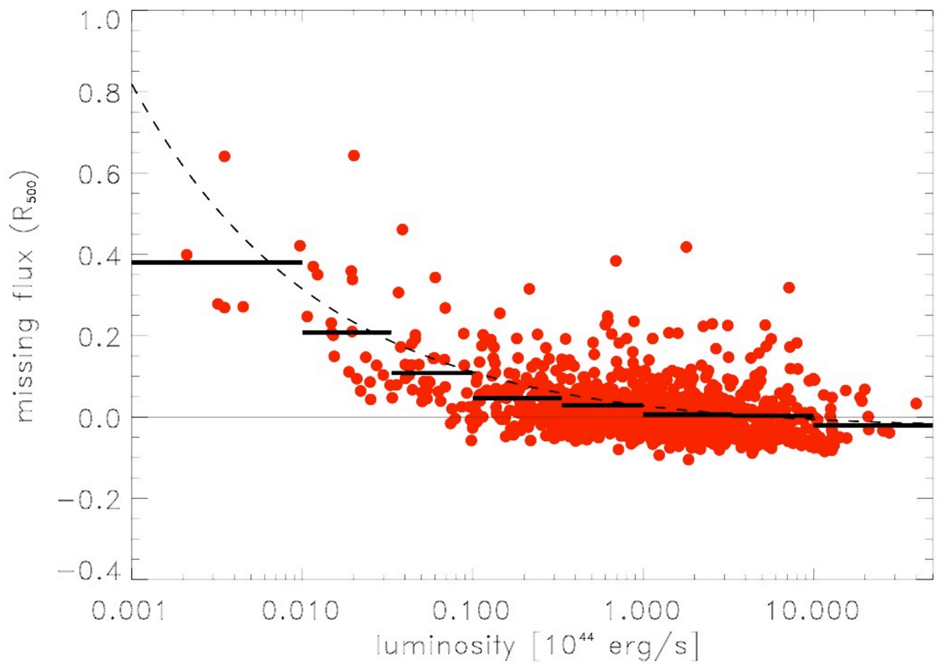


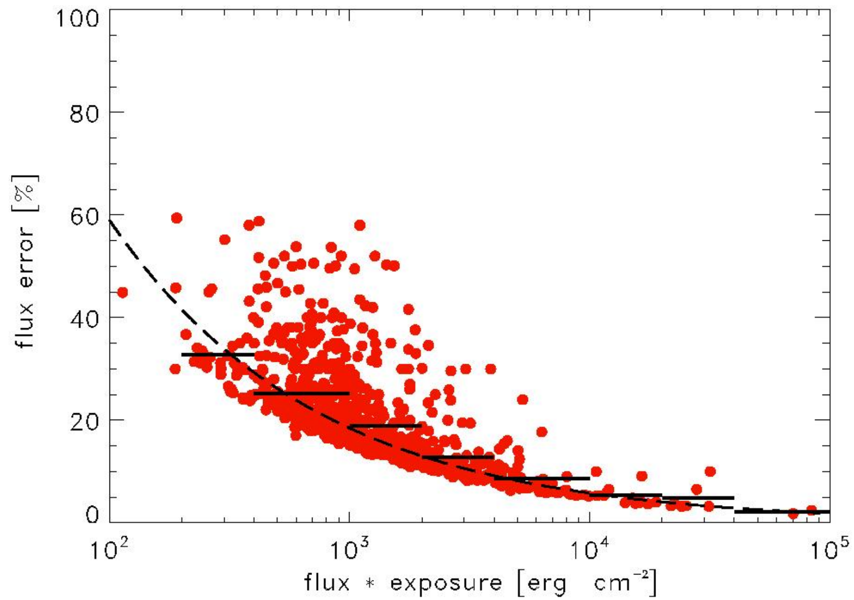
ESO
3.6m
Telesko
p

3-Dimensional Distribution of the ROSAT Clusters



Missing Flux and Flux Error



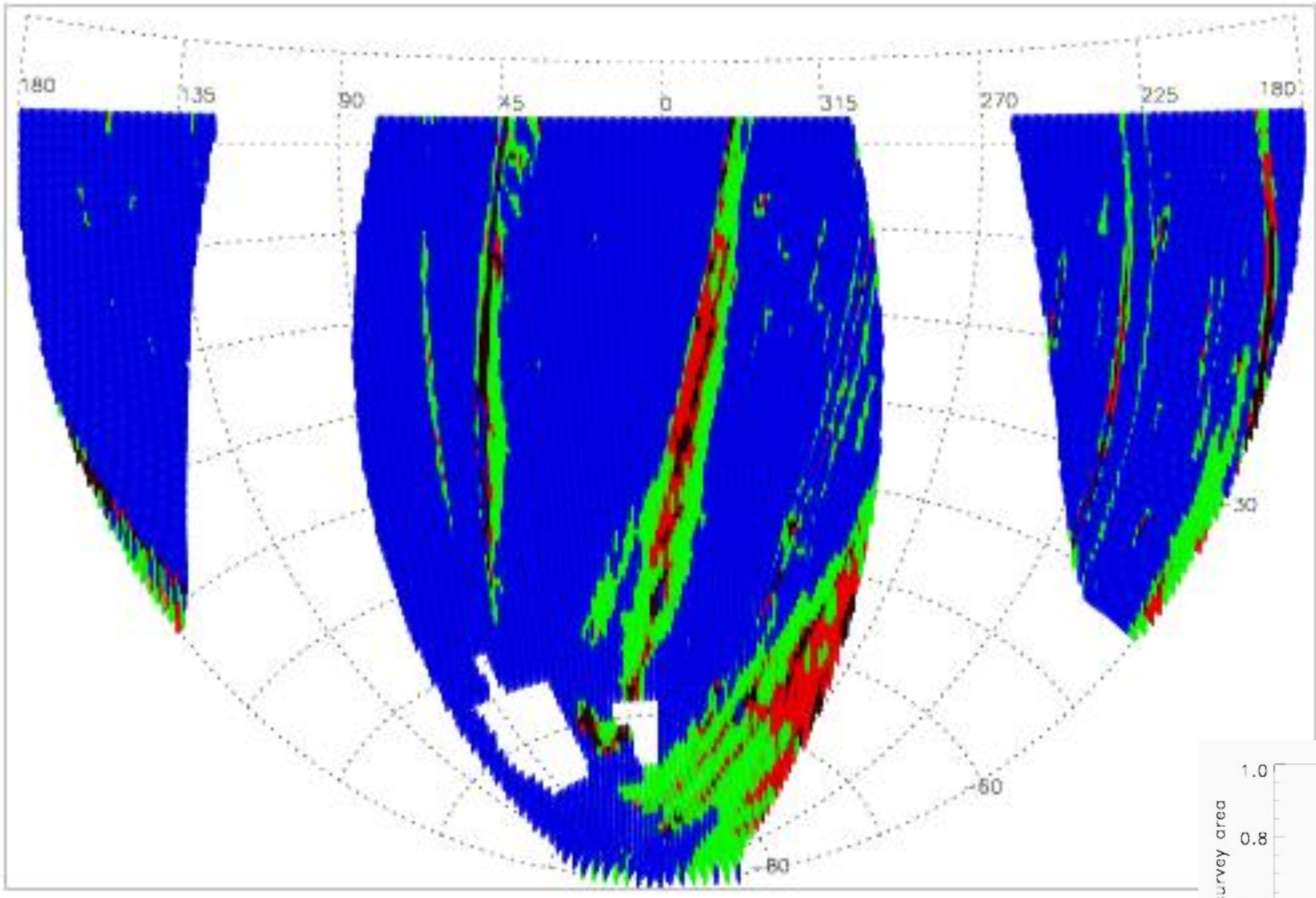


Missing flux with respect to r_{500} in the detection aperture - modeled as a function of X-ray luminosity

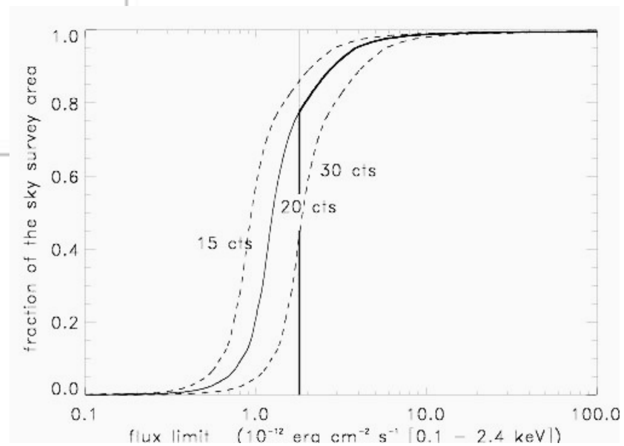
Flux error as a function of exposure x flux (~photon number) – the fit is very close to a square root function

Böhringer et al. 2012 in prep

REFLEX II Selection Function



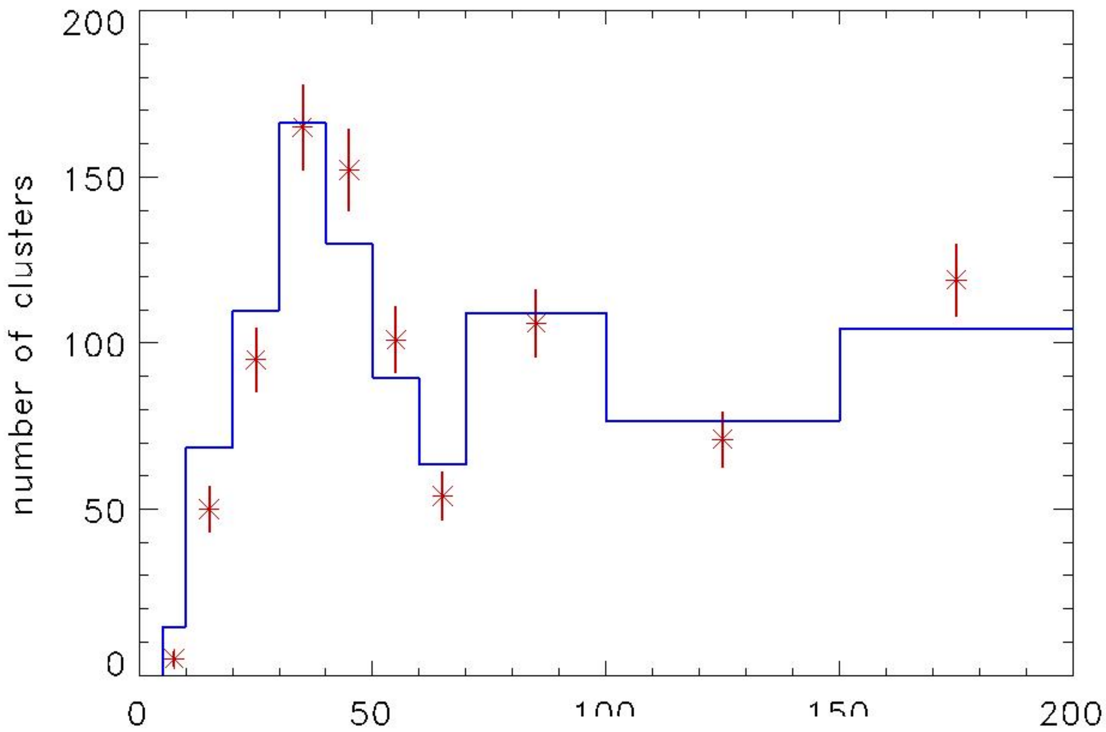
effective flux limit



Blue = flux limit of 1.8 10^{-12} erg/s/cm^2 for > 20 source counts, other color higher flux limit

Böhringer et al. 2012 in prep

Completeness Test with Photon Number Statistics

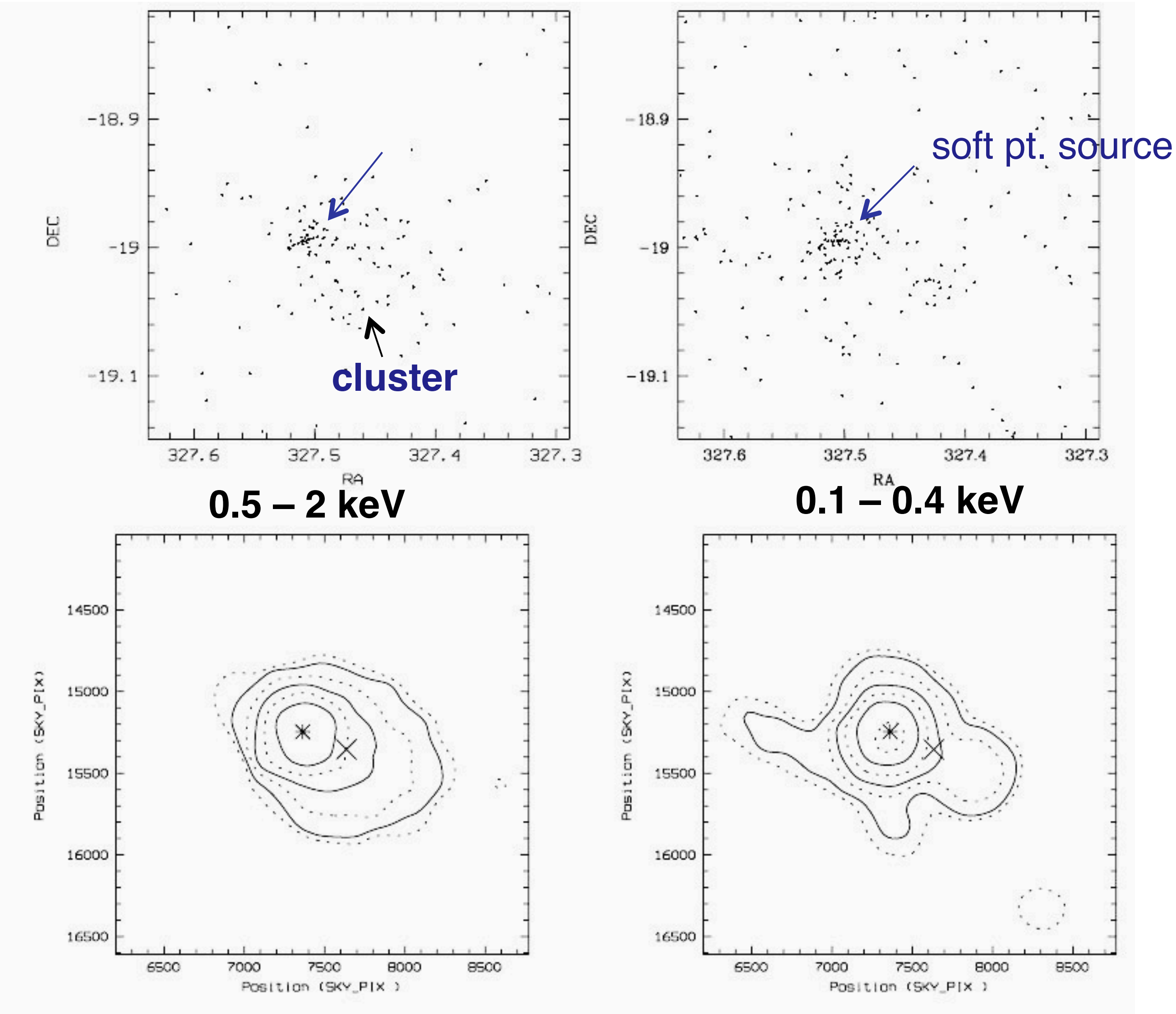


Statistics of the clusters detected with a certain number of source photons compared to the prediction from the logNlogS and REFLEX II sensitivity map

Böhringer et al. 2012 in prep

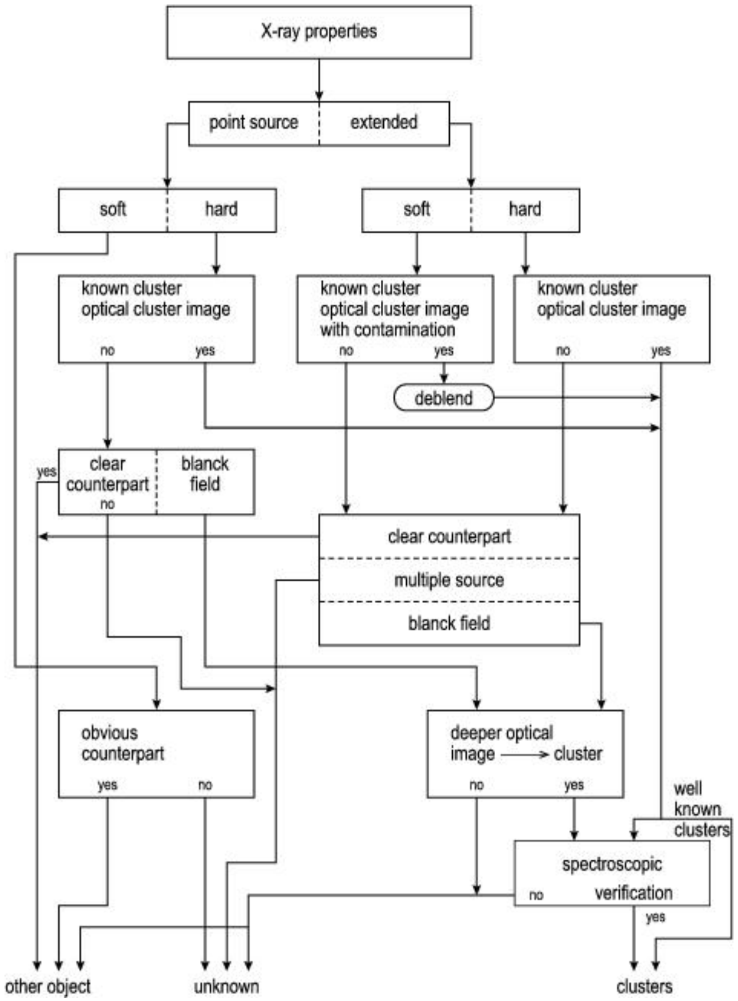
Details of Source Evaluation

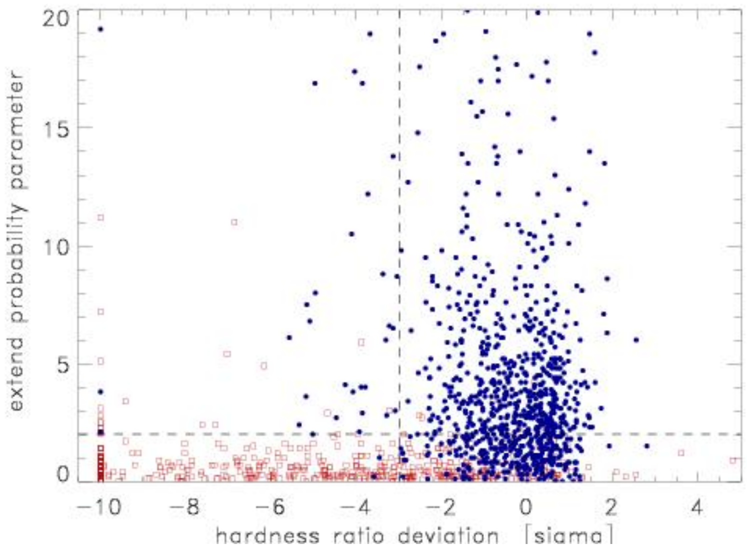
Galaxy cluster and soft point source



Chon & Böhringer 2012

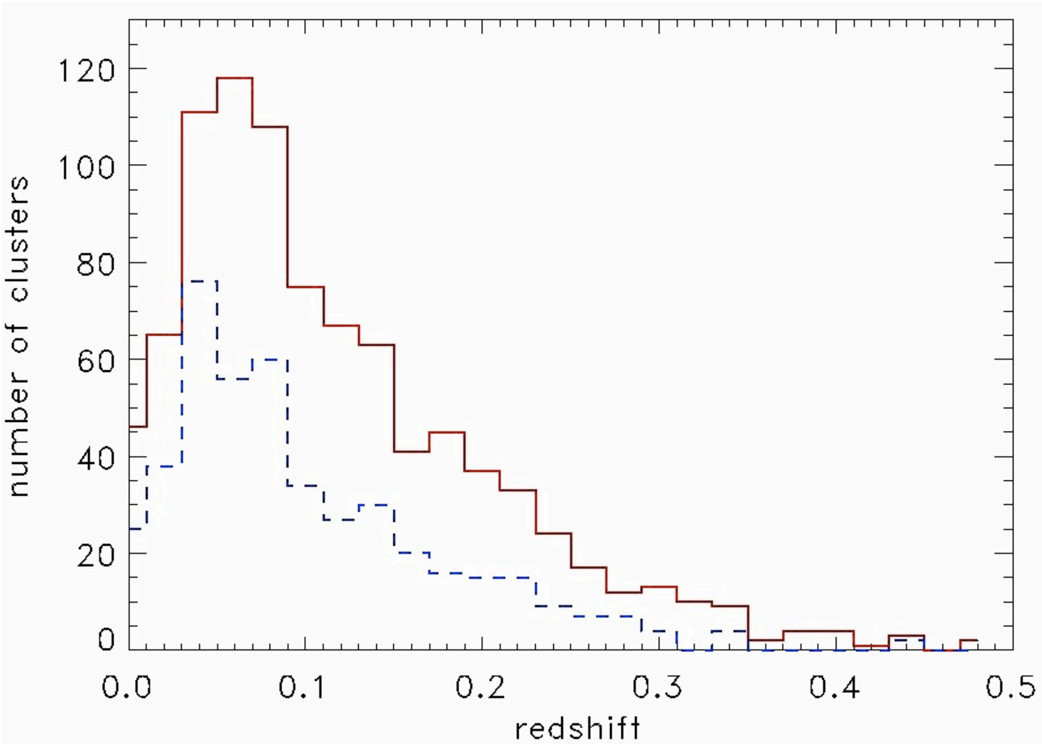
Cluster Identification Based on X-ray and Optical Data



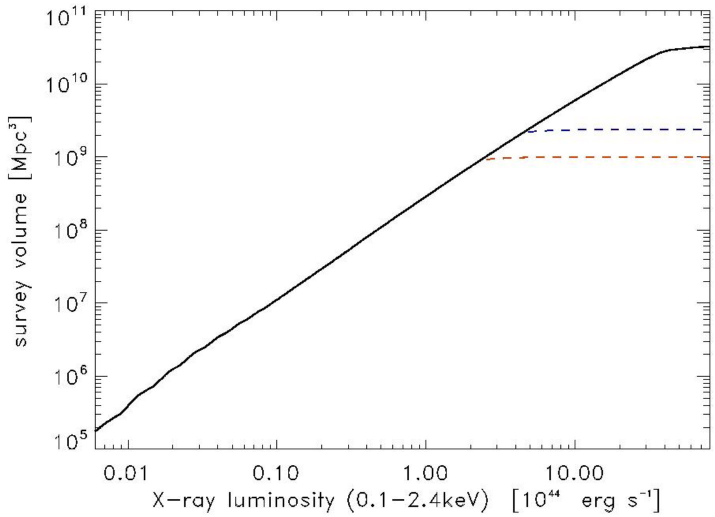


Böhringer et al. 2012 in prep

Redshift Distribution and Survey Volume



Redshift distribution of REFLEX II clusters (red) compared to REFLEX I (blue dashed)



Survey volume of REFLEX II for redshift limits of z = 0.8 (black) 0.3 (blue) 0.22 (red)

Böhringer et al. 2012 in prep

Cosmological model
$H_0 \quad \Omega_m \quad \Omega_\Lambda \quad \Omega_B$ (w)

← **cosmological parameters**

↓

Generation of density fluctuations
$\sigma_8 \quad P_0(k)$

← **primordial P(k)**
Test of inflation

↓

Nature of the Dark Matter
CDM (HDM) ? (transfer fct.)

← **form of DM (e.g. neutrinos)**

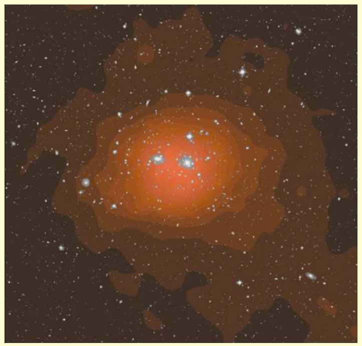
↓

Structure evolution
(gravitational effect)

← **effect of Dark Energy**

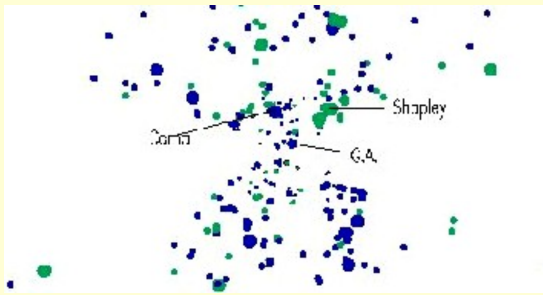
↓

Galaxy clusters mass function



$$\frac{d^2N}{dMdz}$$

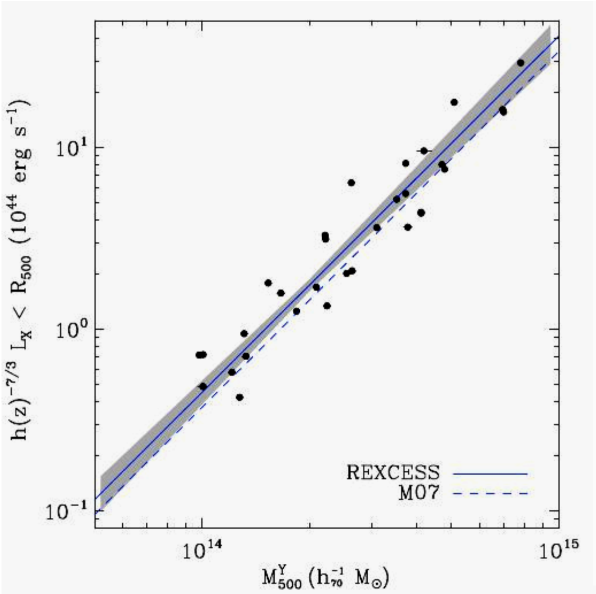
Large-scale galaxy/cluster distribution



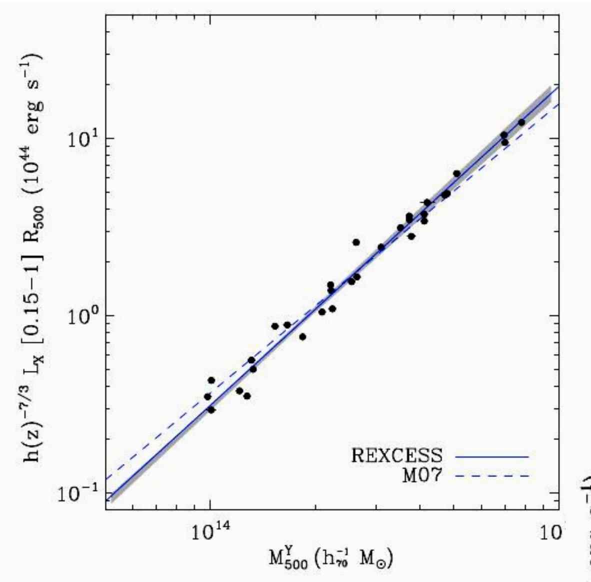
$P(k)_{clus}$

L_X – M Relation (bolometric)

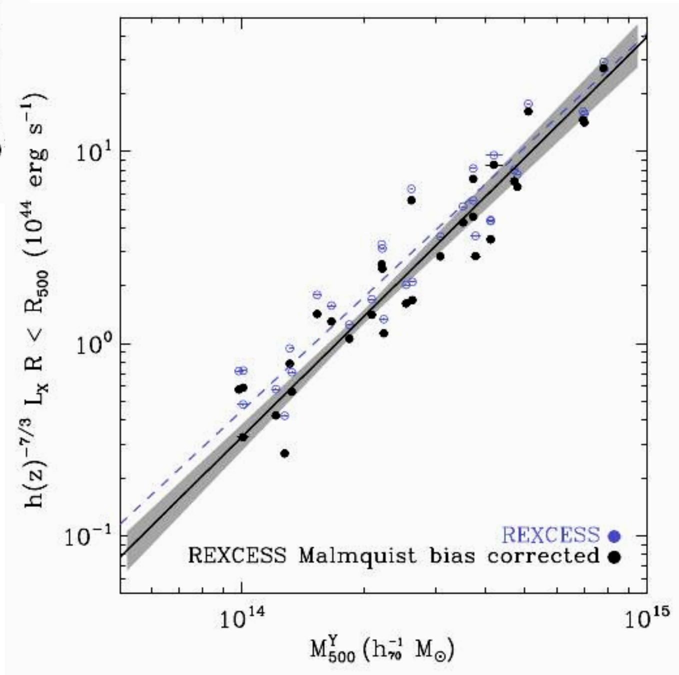
total luminosity



core excised luminosty



One has to correct for a small Malmquist bias, because the more luminous clusters have a slightly larger detection volume.



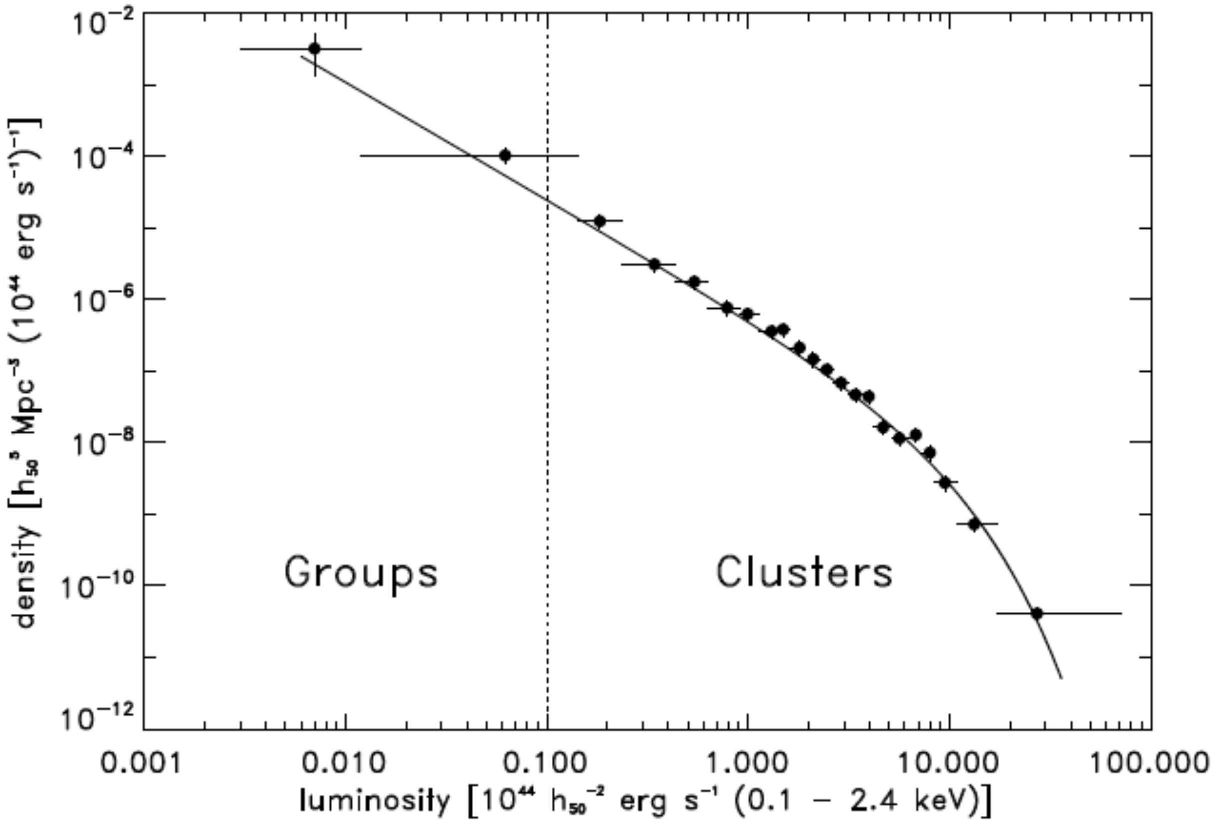
slope : ~ 1.8
scatter ~ 40%

slope : ~ 1.7
scatter ~ 18%

[Pratt et al. 2009a] M estimated from Y_X

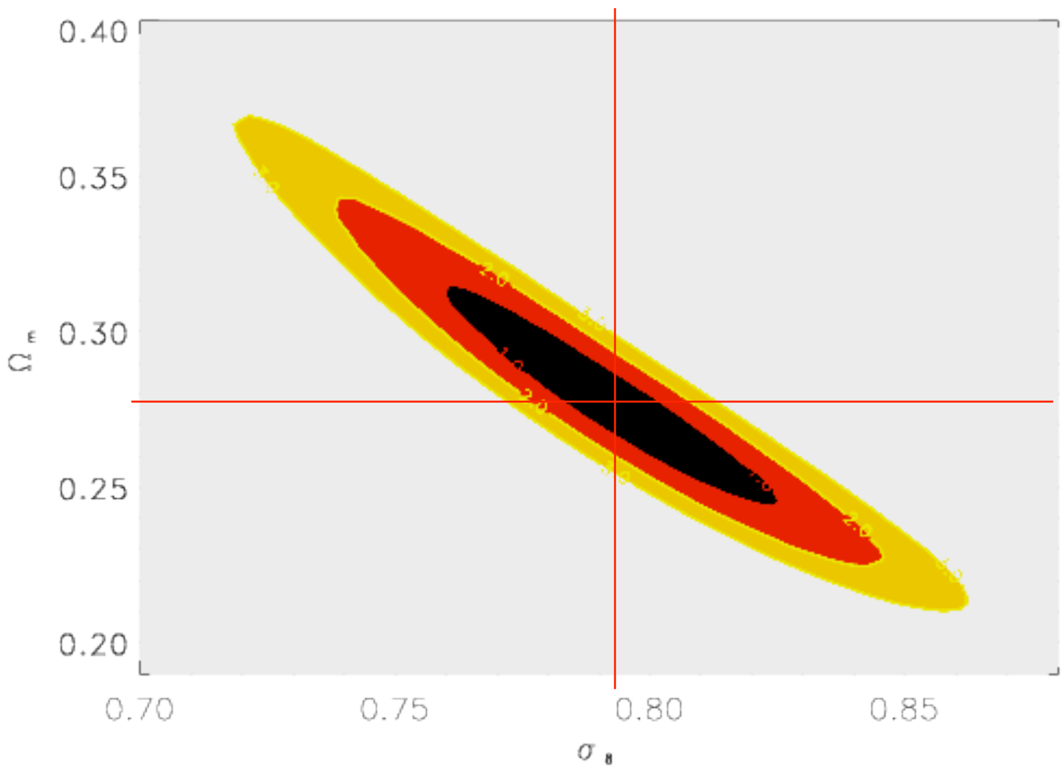
Observed and Predicted X-ray Luminosity Function

REFLEX I survey (Böhringer et al. 2002) fit of the prediction from a concordance model $\Omega_m = 0.29$, $\sigma_8 = 0.79$ to the REFLEX I XLF



Constraints from cosmological model predicted and observed X-ray luminosity function

REFLEX I survey (Böhringer et al. 2002, 2010)

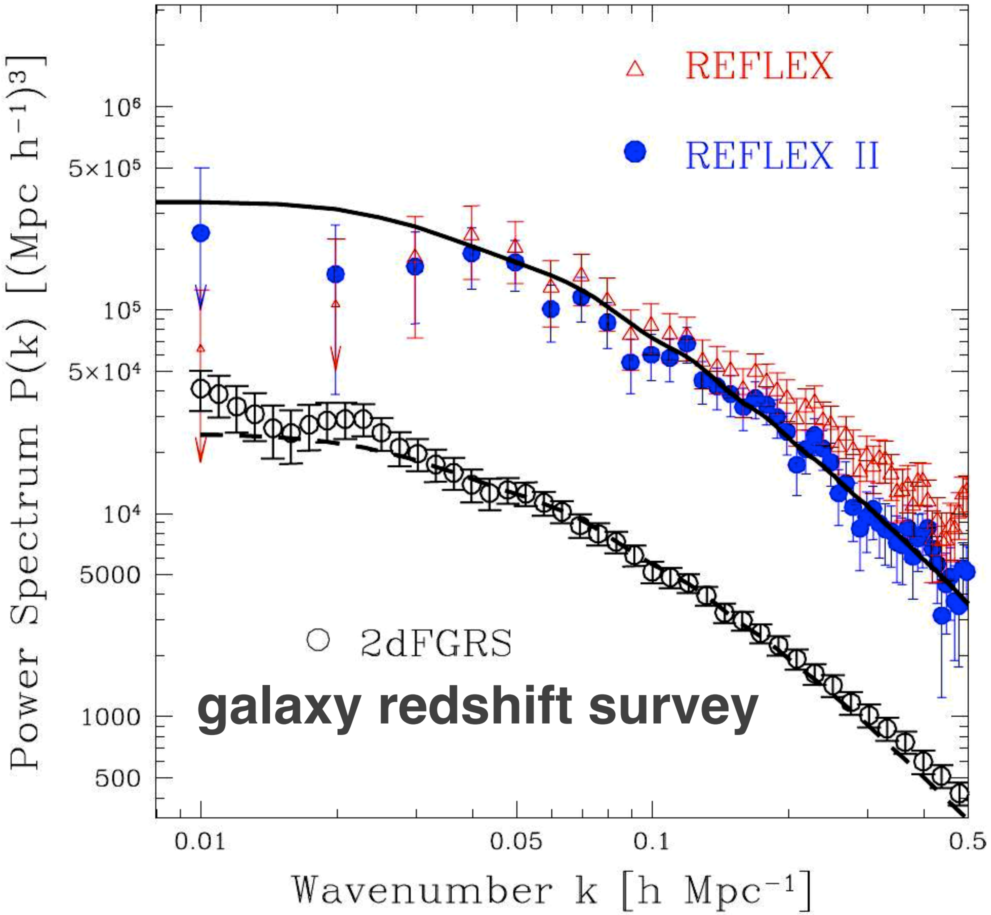


Ω_m = 0.28 +- 0.05
σ_8 = 0.79 +- 0.04

statistical errors

+- 0.05 for systematics

REFLEX II Power Spectrum (LCDM-Cosmology)

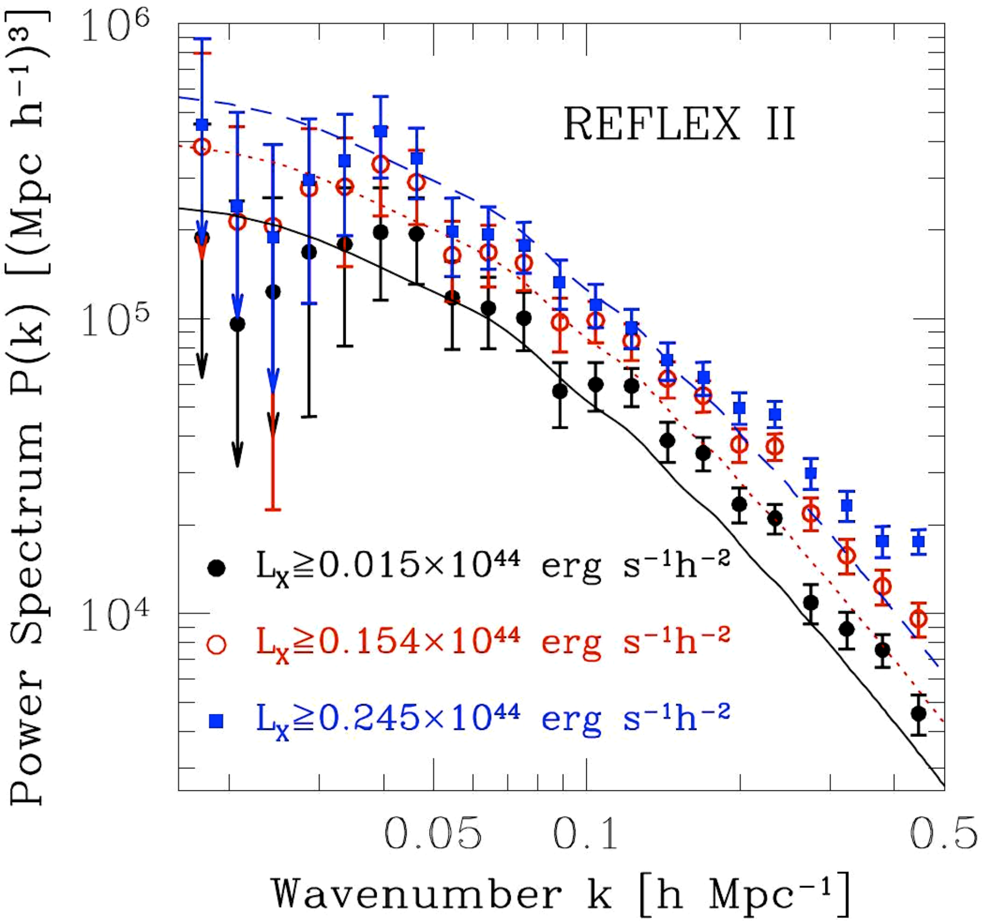


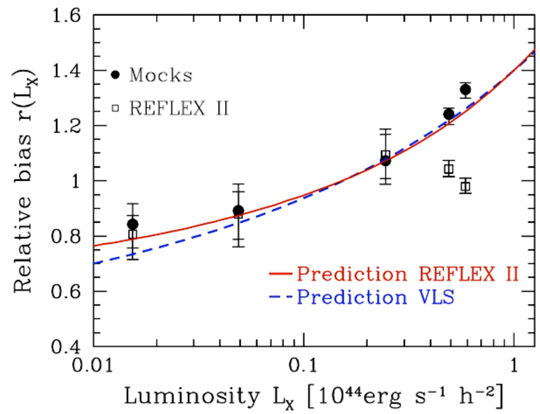
The lines give the prediction of the Concordance Cosmological Model with WMAP 5yr parameters

Balaguera-Antolinez et al. 2010

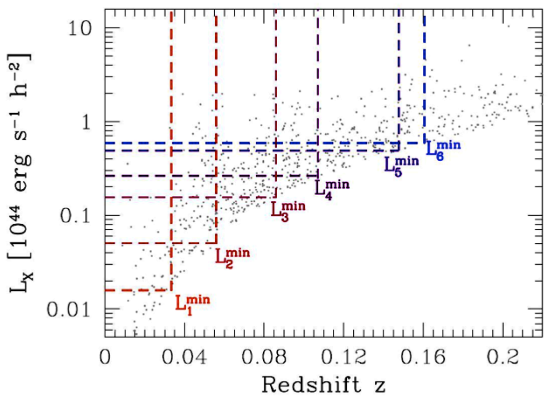
REFLEX II Power Spectrum (biasing)

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





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



X-ray Galaxy Cluster Scaling Relations

The REXCESS Cluster Sample
(The Representative XMM-Newton Cluster Structure Survey)

Cluster selection:

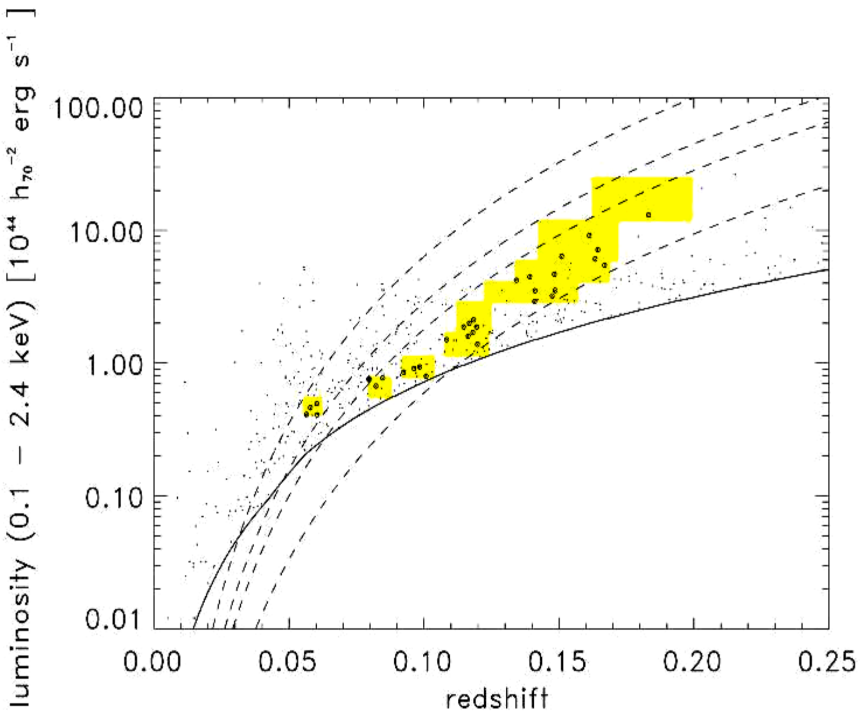
- only by L_X (and z)

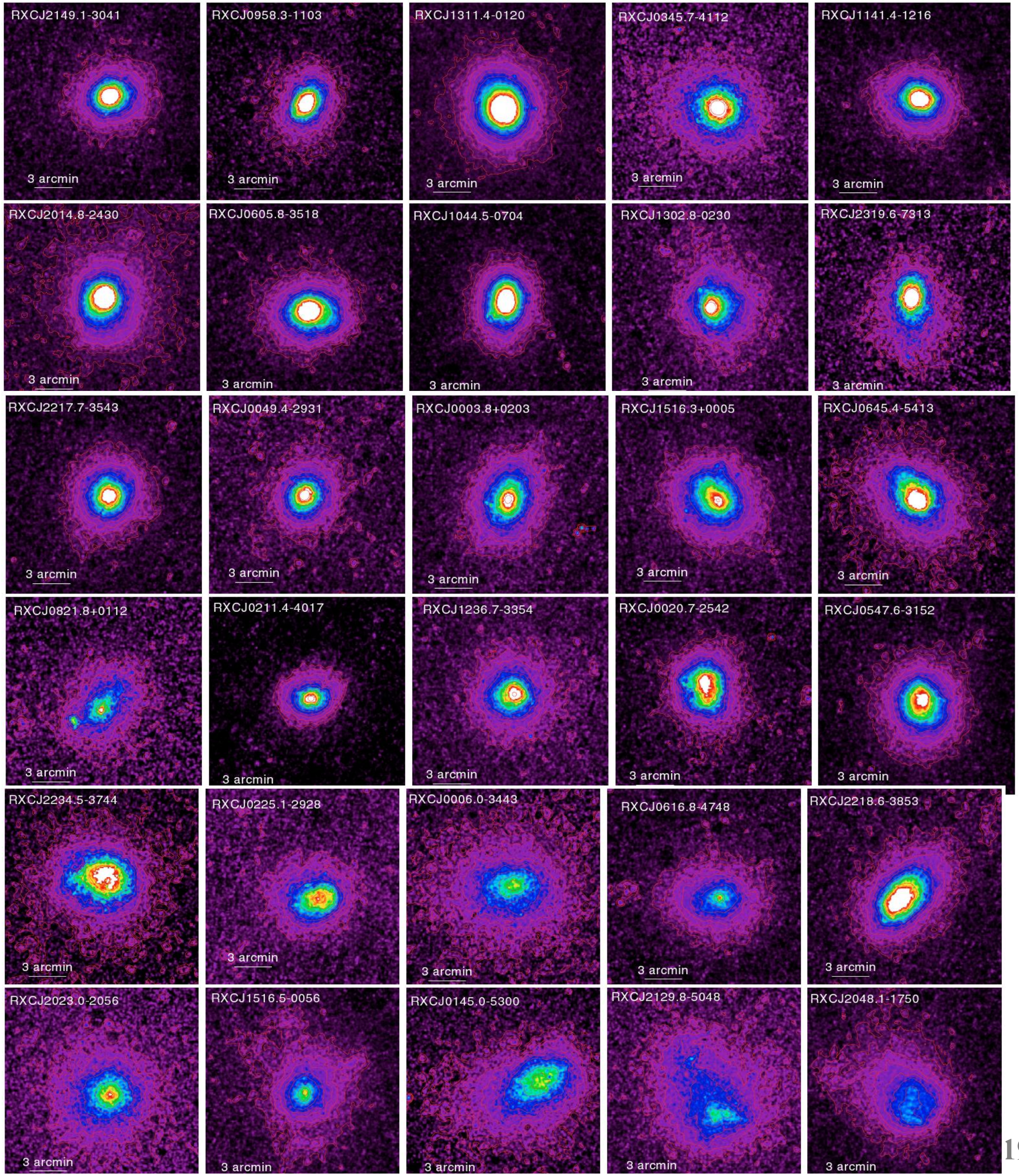
- ~ homogeneous L_X coverage
  0.4 – 20 10^{44} erg/s (0.1–2.4 keV)
  → 9 luminosity bins

- → clusters with $T_X > 2$keV

- z = 0.055 – 0.18
  to not completely fill the XMM camera $r_{500} < 9$-11 arcmin

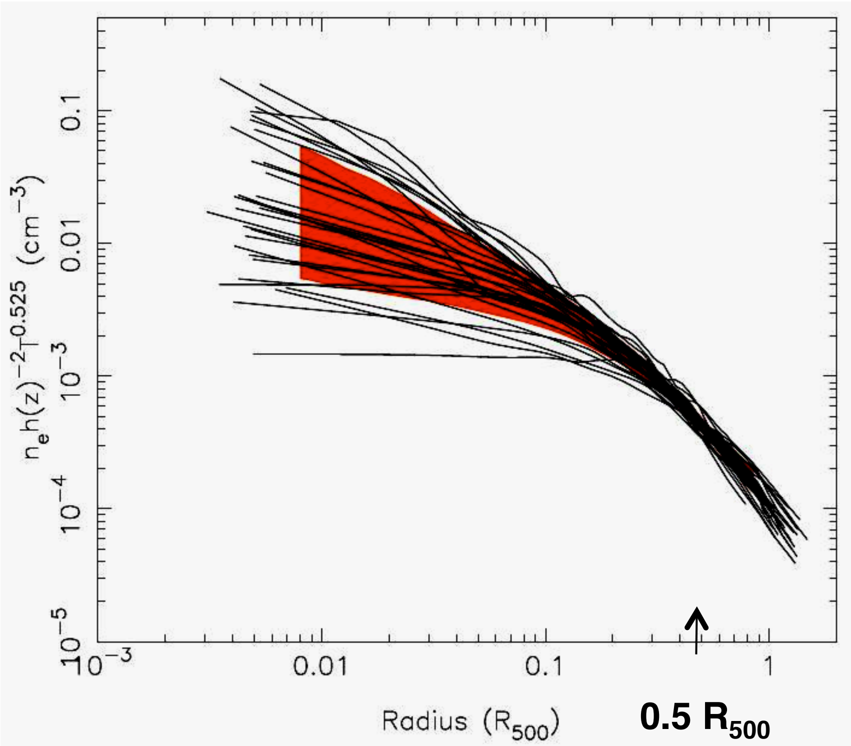
33 clusters – 2 multiple clusters




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

Gas Density Profiles

density scaled (by T_X)

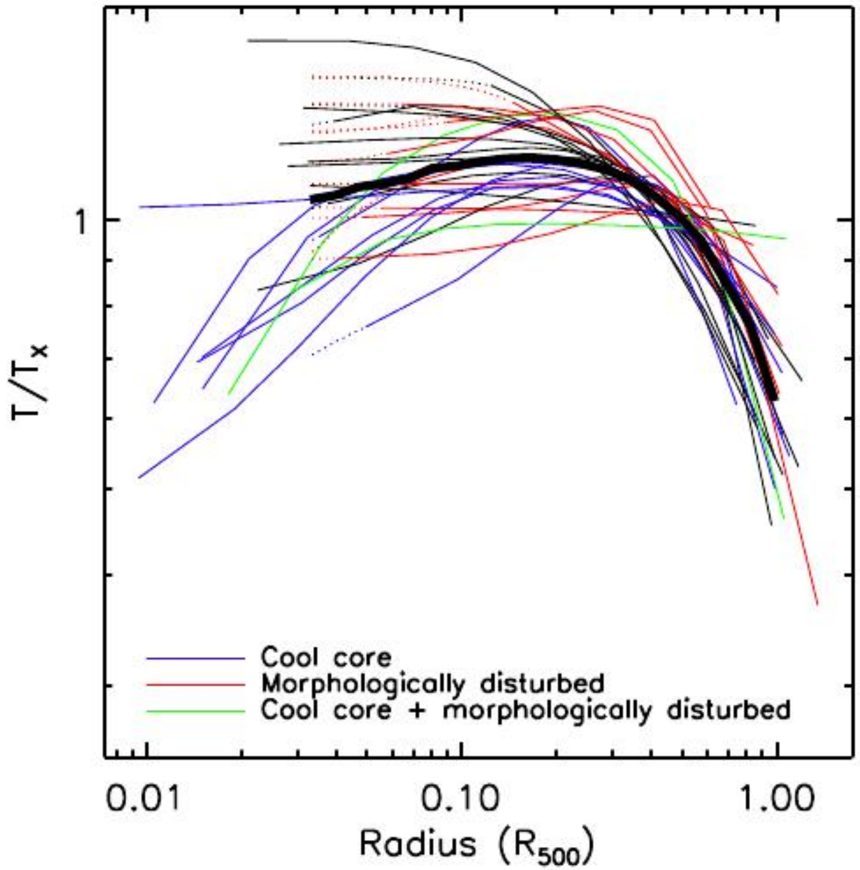


$$S_x = (1+z)^{-4} \int n_e^2 \; \Lambda(T_X) \; dl$$

Scatter at 0.5 R_{500} : 13%
- implies ~ f_{gas} propto $M^{-0.3}$

[Croston et al. 2008]

temperature scaled

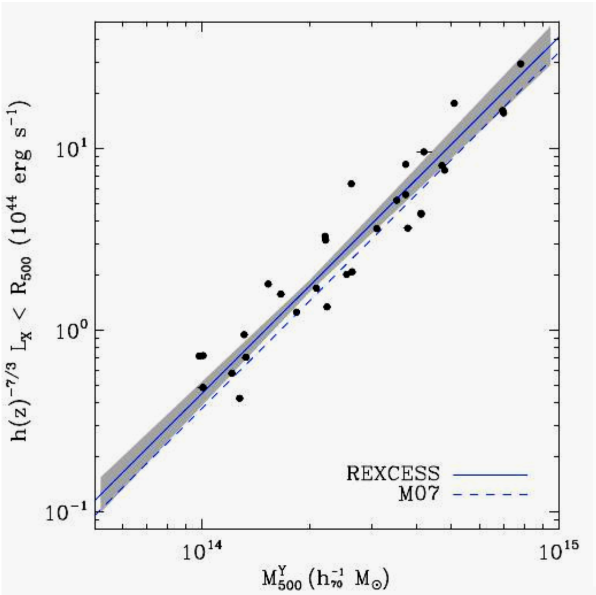


Scaling by R_{500} and mean temperature (0.15 – 0.75 R_{500})

[Arnaud et al. 2009]

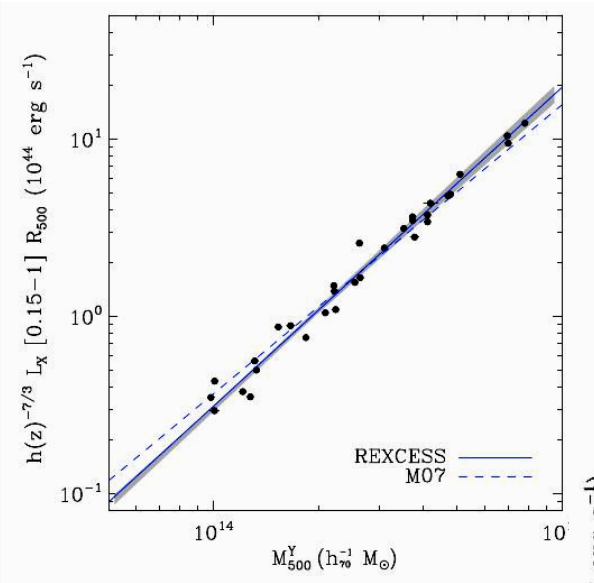
L_X – M Relation (bolometric)

total luminosity



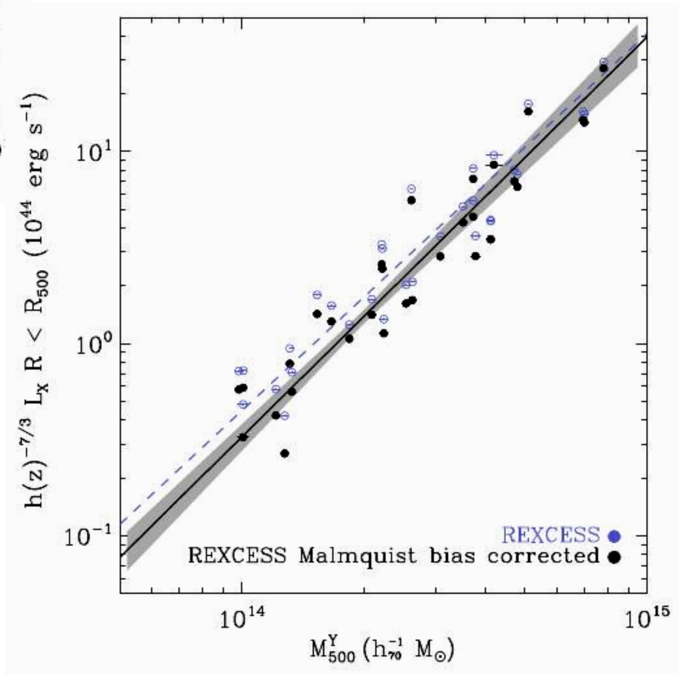
slope : ~ 1.8
scatter ~ 40%

core excised luminosty



slope : ~ 1.7
scatter ~ 18%

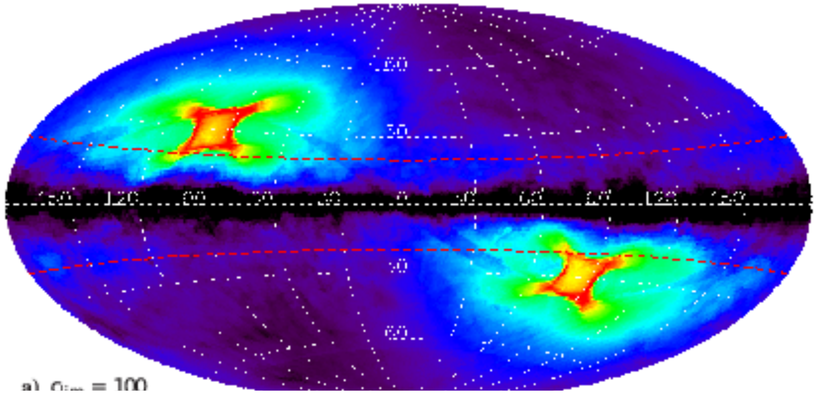
One has to correct for a small Malmquist bias, because the more luminous clusters have a slightly larger detection volume.



[Pratt et al. 2009a] M estimated from Y_X

Prospects for the eROSITA Survey

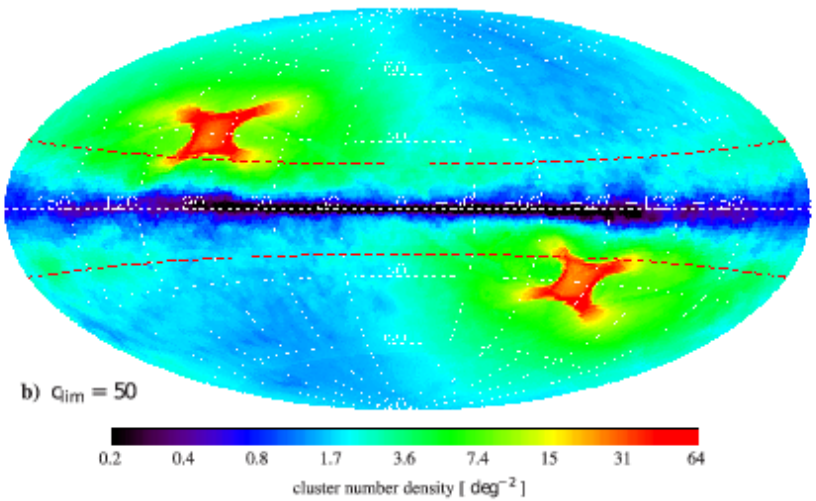
Galaxy Cluster Number Counts in the eROSITA Survey



$N_{phot.}$	all sky	extragal. Sky
50	~300 000	~240 000
100	~140 000	~105 000
500	~ 20 000	~ 15 000
1000	~ 9 000	~ 6 700

M. Mühlegger Ph.D. Thesis

Redshift	extragal. Sky > 100 cts
> 0.3	~ 50 000
> 0.6	~ 10 000
> 0.8	~ 3 500
> 1.0	~ 900



M. Mühlegger, G. Chon,
H. Böhringer

Assumptions for the Modelling for eROSITA

- Cosmological parameters: H_0 = 70 km/s/Mpc Ω_b = 4.5%
  Ω_m = 0.30 Ω_Λ = 0.70 σ_8 = 0.80   + standard P(k)

- M – L relation used – see later

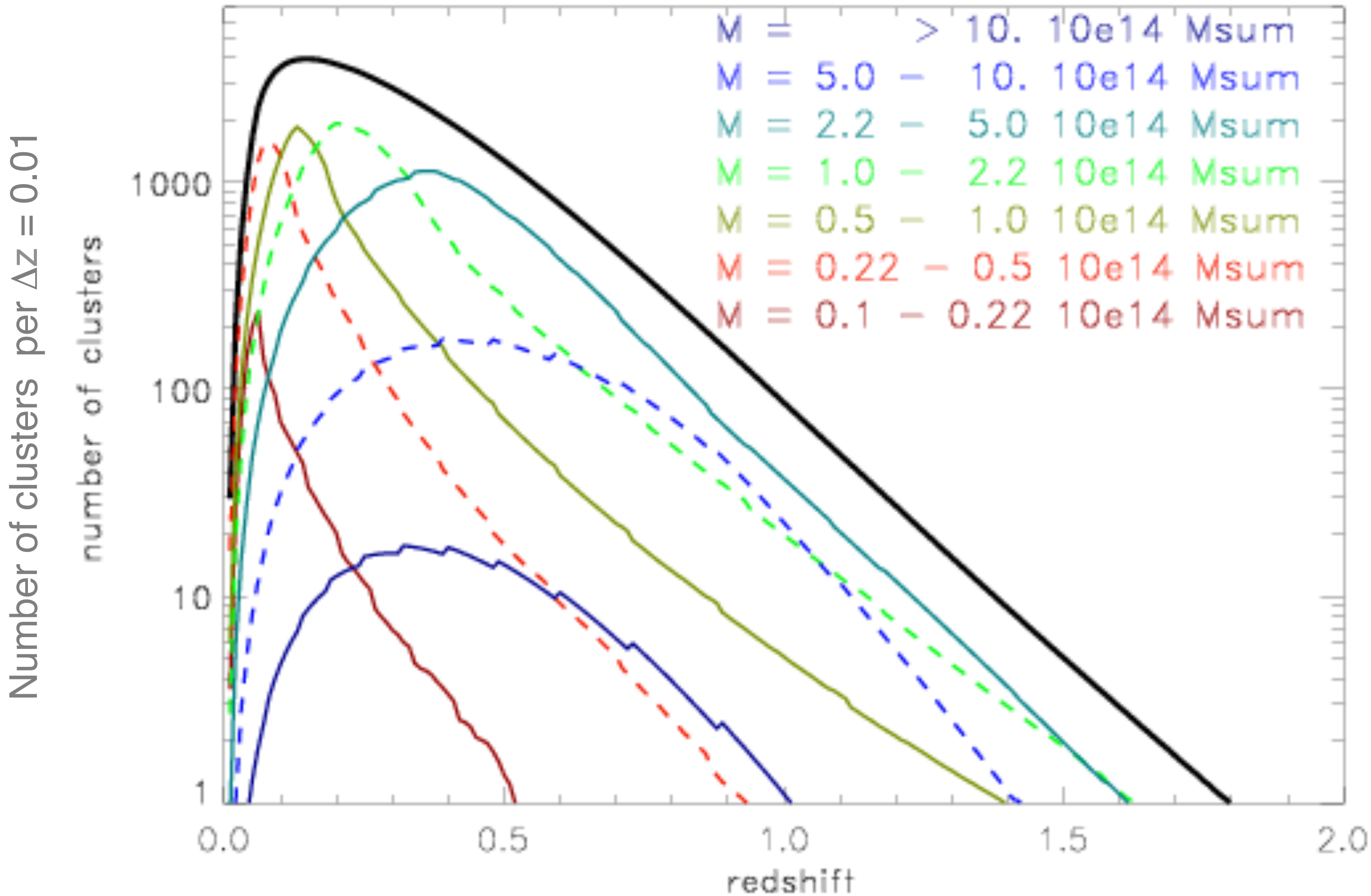
- Exposure maps for eROSITA Survey (from Robrade)

- Minimal count limit of 100 source counts
  (ROSAT >20-30 cts   XMM-Surveys > 100 cts)

- Calculation of the detection limit per sky pixel & redshift shell

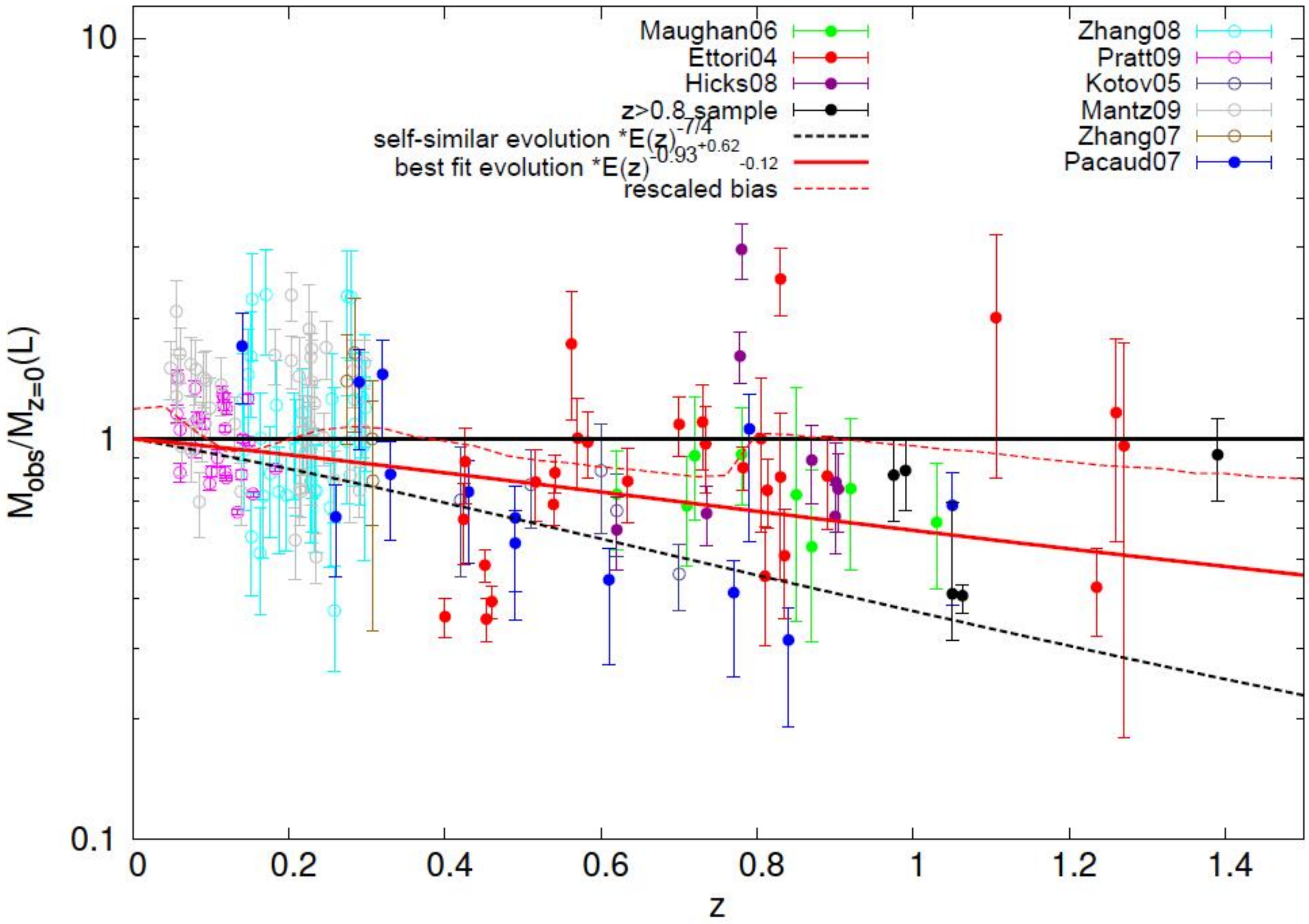
- For Galaxies: richness – L_X relation (SDSS)
  - cluster galaxy luminosity function
  - evolution of L* involving mostly passive evol.

Mass and Redshift Distribution of the Clusters



eROSITA WB

Observed Evolution of the M - L Relation

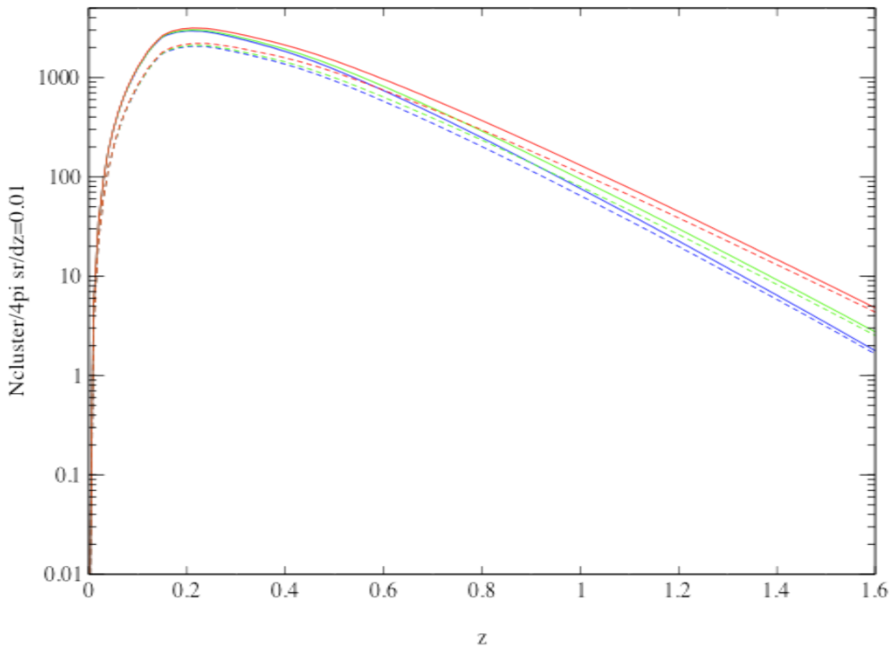


X-ray luminosity for given cluster mass does not increase as fast with redshift as assumed in self-similar models ! **Reichert, Böhringer, et al. 2012**

Change of Number of Predicted Distant X-ray Cluster Number Counts

Ratio of clusters above redshift 1 seen by eROSITA:

	ratio to self-similar
Self-similar:	1
no L-T rel. evol.:	0.55
New relation:	0.27



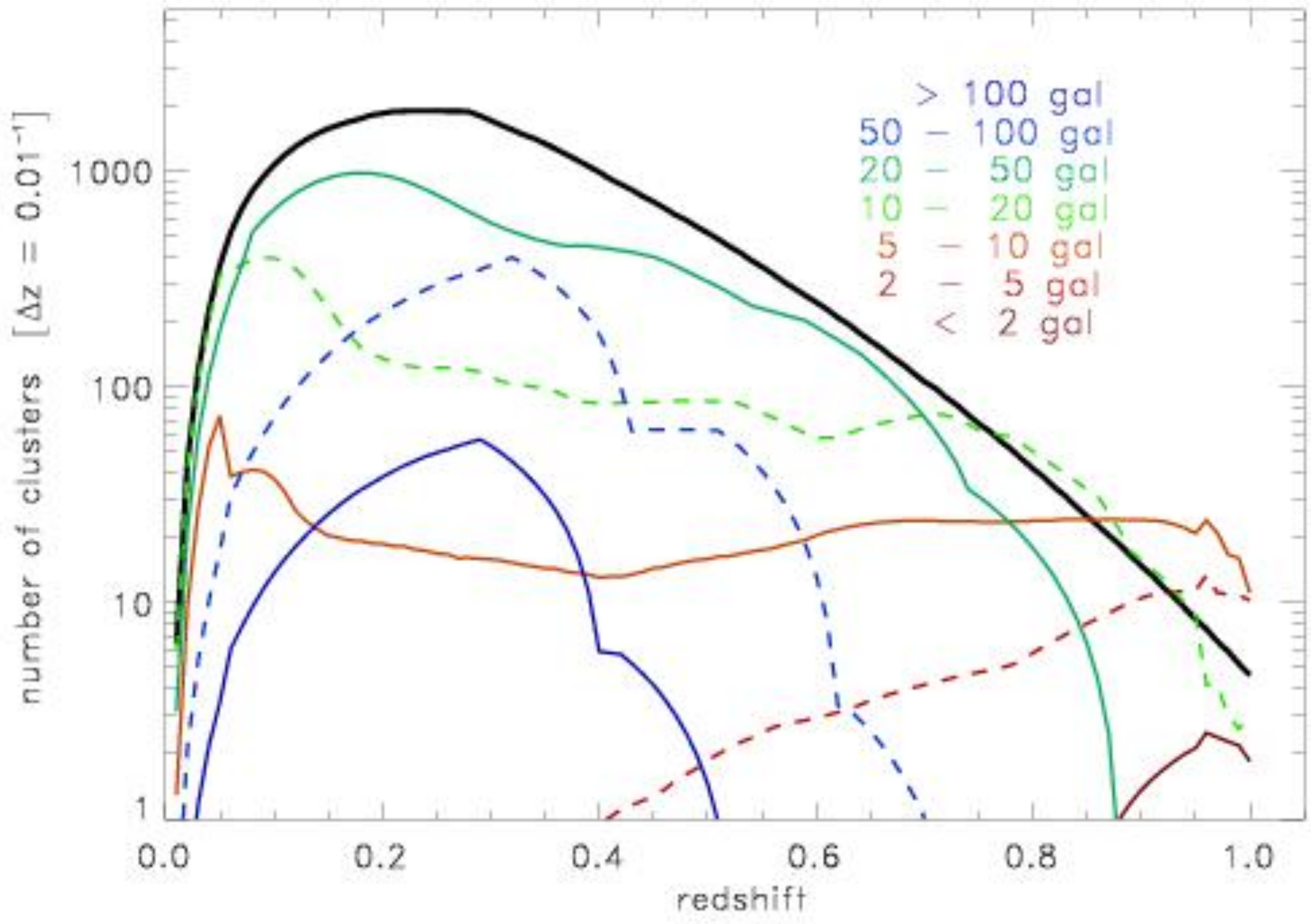
Reichert, Böhringer et al. 2011

Results of cluster number forecast for different cosmological models

	refer.	σ_8=0.83	Ω_m=0.25	w = -1.3	w = -0.7
z > 0.4	41600	52600	27600	42300	43600
z > 0.8	4800	6900	3200	3900	6300
z > 1.2	490	760	315	327	830

Observable Galaxies per Clusters

Magnitude range = 18.5 to 20.5 in i-band (< 22 in r-band)



Summary on the Number of Observable Galaxies

For a 15 000 deg² Survey (e.g. 4MOST):

~ 50 000 galaxy clusters

on average 50 galaxies/cluster = 2.5 Million galaxies
visible for a spectroscopic limit of r = 22 / I = 20.5

Science goal:	# clusters	redshift	
	34 000	0 – 0.2	
	30 000	0.2 – 0.4	
	11 000	0.4 – 0.6	
	3000	0.6 – 0.8	
	800	0.8 – 1.0	
	250	1.0 – 1.2	achievable 70 – 90%

Conclusions

- eROSITA is about 30 times more sensitive for the detection of clusters
  → ~ 100 000 cluster will be detected with > 100 cts

- ~ 7000 cluster with > 1000 cts → temperature, morphology, ..
  wide range of astrophysical studies (e.g. scaling relations and feedback)

- LSS statistics (P(k) for > 10 000 clusters in ten redshift shells out to z = 0.6 (10x more precise than for REFLEX)

- Large potential for constraining cosmological model parameters also for Dark Energy equation of state – and testing more exotic models