Cosmology with Galaxy Clusters: an X-ray Perspective

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(I) Tracing cosmic evolution with galaxy clusters

(II) The need to understand clusters as astrophysical objects:

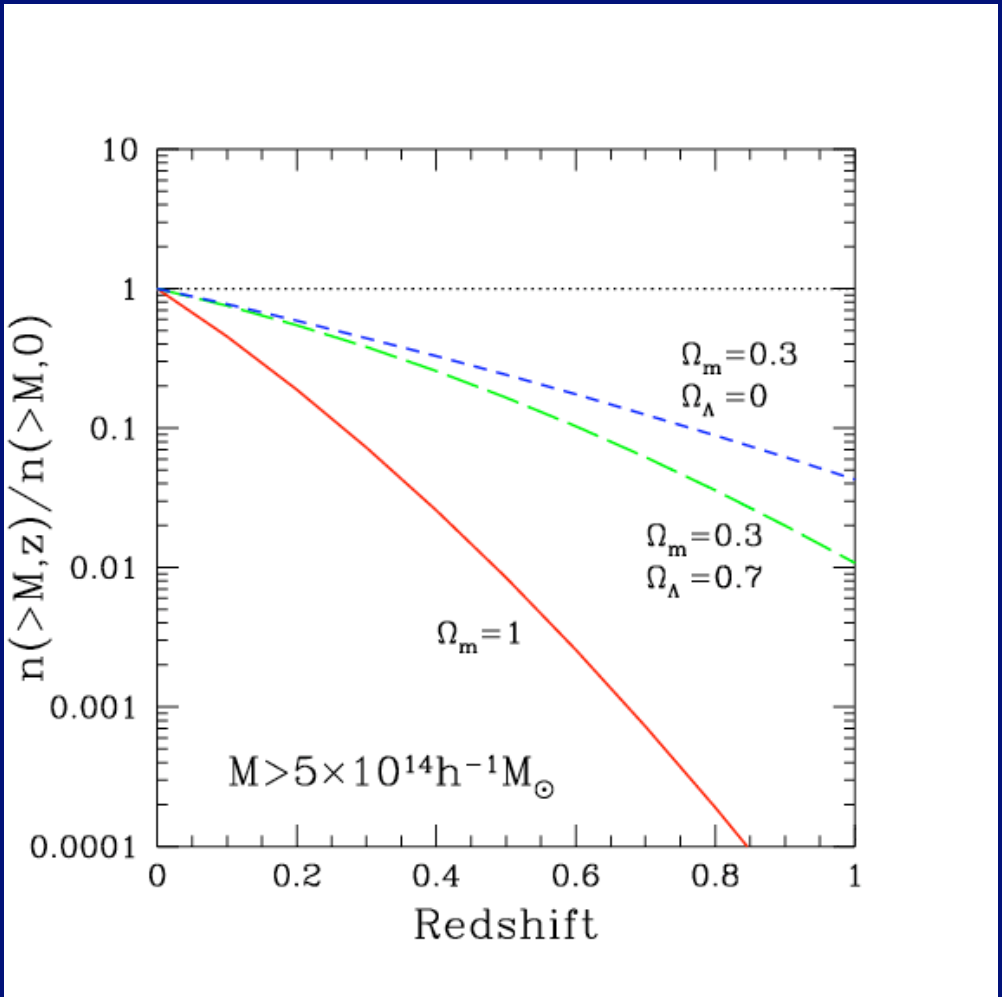
II.a Are clusters in (hydrostatic) equilibrium?

II.b The role of cool cores.

(III) Why then WFXT?

The mass function as a cosmological test

Rosati, SB & Norman '02



Population of massive clusters highly sensitive to the structure growth rate

⇒ Sensitive test for the amount and nature of Dark Matter & Dark Energy

Observables in a flux-limited survey

Volume element:

$$dV(z) = \left(\frac{c}{H_0}\right)^3 \frac{r^2(z)}{E(z)}$$

Radial coordinate of the FLRW metric:

$$r(z) = \begin{cases} \int_0^z dz E^{-1}(z) & \Omega_R = 0 \\ \dfrac{2[\Omega_m z + (2-\Omega_m)(1-\sqrt{1+\Omega_m z})}{\Omega_m{}^2(1+z)} & \Omega_\Lambda = 0 \end{cases}$$

$$E(z) = \left[(1+z)^3\Omega_m + \Omega_R(1+z)^2 + \Omega_\Lambda(1+z)^{3(1+w)}\right]^{1/2}$$

w < -1/3 to have accelerated expansion

L-observable function:

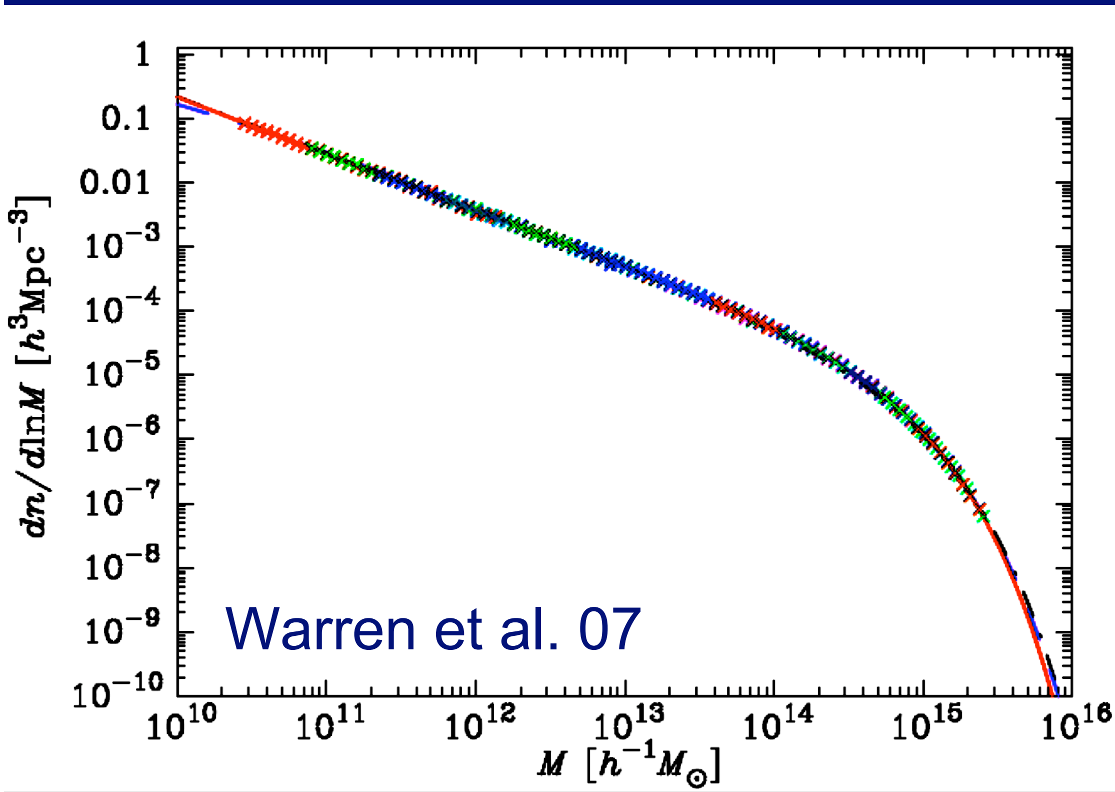
$$\phi(L;z)dL = \frac{dn(M;z)}{dM}\frac{dM}{dL}(z)dL$$

Robust: from PS-like theory

Tricky: depending on cluster physics

Calibrating a ~universal n(M) with simulations

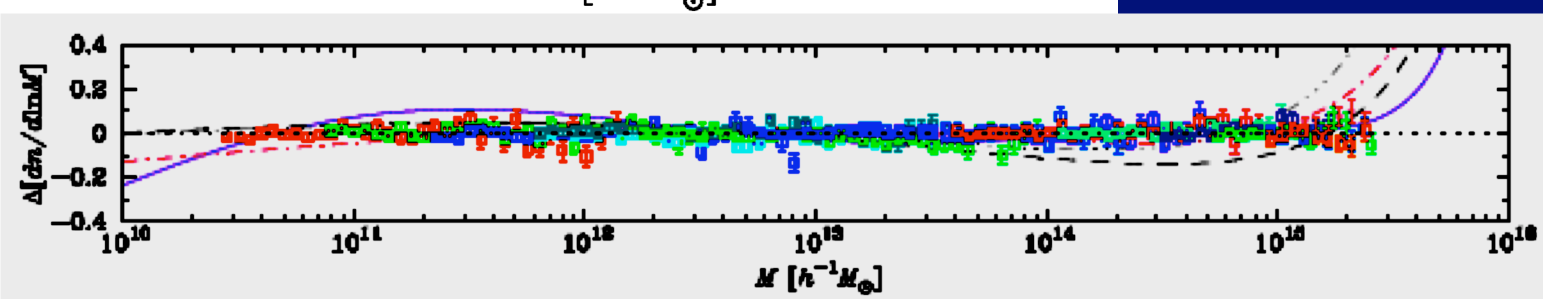
E.g., Sheth & Tormen 2001, Jenkins et al. 2001, Evrard et al. 2002, Springel et al. 2005, Warren et al. 2007, Tinker et al. 2009, Crocce et al. 2009



0-th order statements:

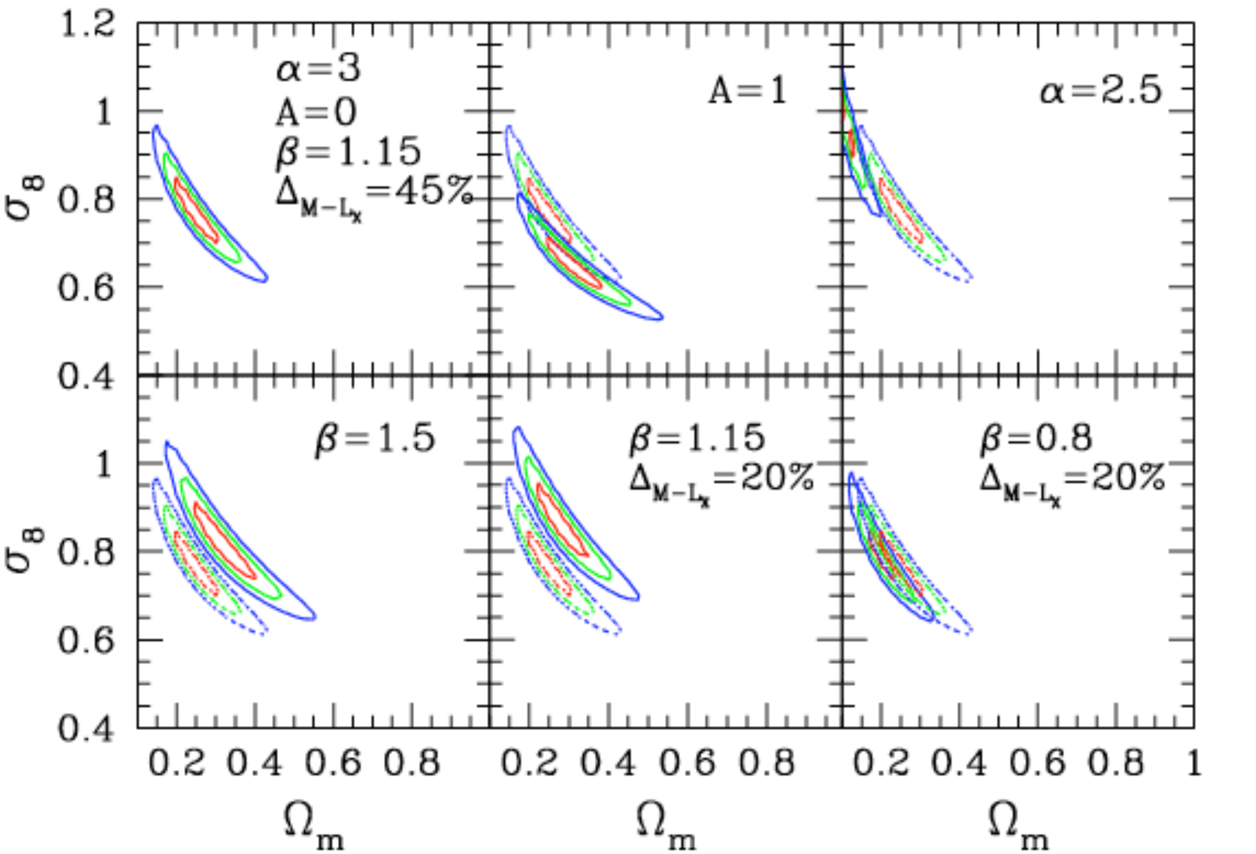
(a) Corrections to the PS MF can be found, which still have an almost universal (i.e. model-independent) shape.

(b) Agreement with the simulated MF always within <10% at the cluster mass-scale.



Cosmology with galaxy clusters as of 2002

SB et al. 01; RBN 02



~100 clusters out to z=0.8 from ROSAT: only L_X available

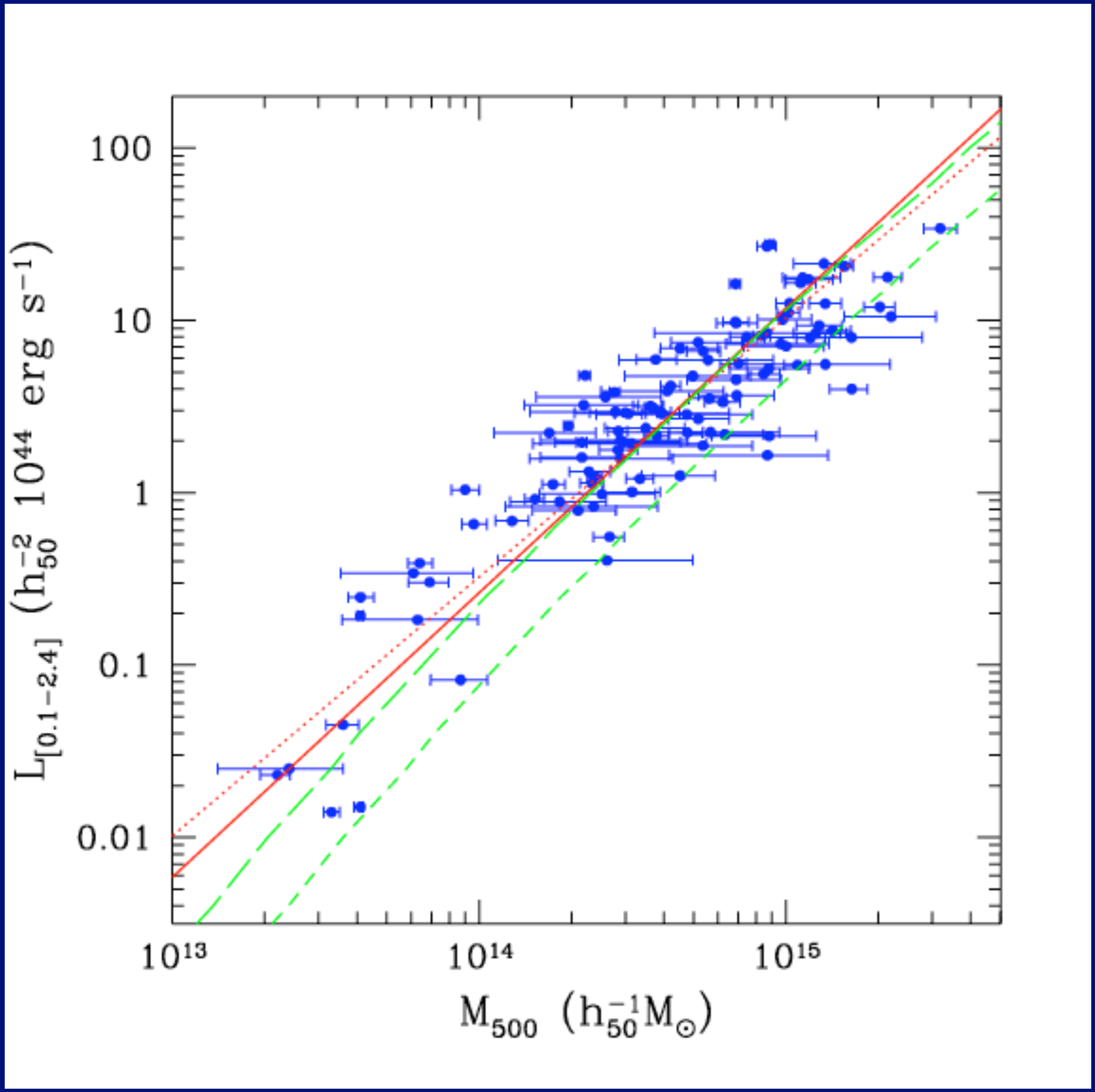
Results dependent on ICM physics....

Ω_m<0.6 at >3σ

σ_8 somewhat small:
$\sigma_8 = 0.80 \pm 0.05$
($\Omega_m = 0.25$)

for the reference analysis.

The observed M-L_X relation…

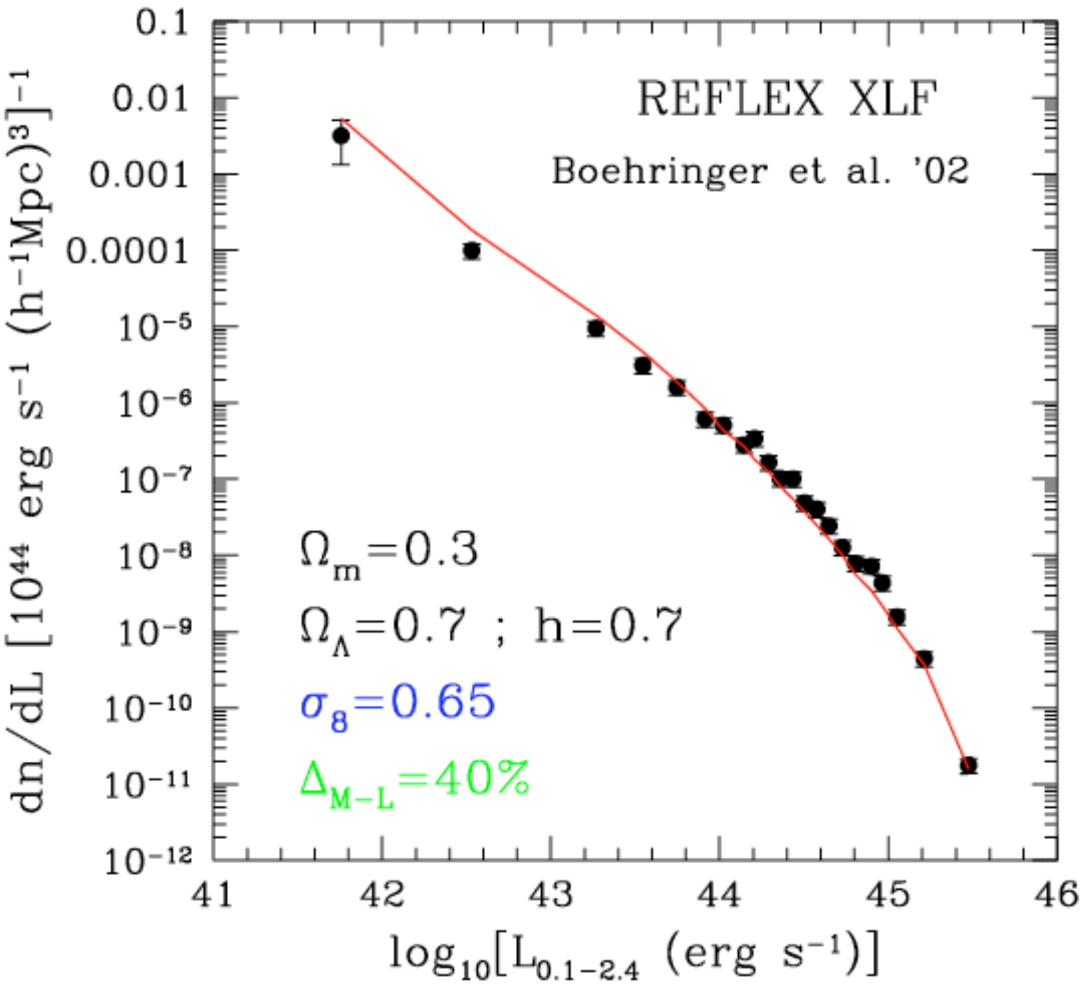


Reiprich & Boehringer 02
ROSAT + ASCA
Hydrostatic equil.
+ isothermal β-model

Resolved T_X profiles with Beppo-SAX
(Ettori et al. '02)

⇒ Well-defined relation with ~40% scatter!

The relevance of calibrating the scatter



Eke et al. '98, SB et al. '01, Lima & Hu '04

⇒ Convolution with intrinsic (log-normal) scatter inflates the predicted XLF

⇒ Lower σ_8 required to fit the observed XLF!

WARNING: what if scatter isn't log-normal? (Shaw et al. '09)

How reliable is the hydrostatic equilibrium?

- Hydrostatic equilibrium (HE):

$$M_{hyd}(<r) = -\frac{rkT}{G\mu m_p}\frac{d\ln(nkT)}{d\ln(r)}$$

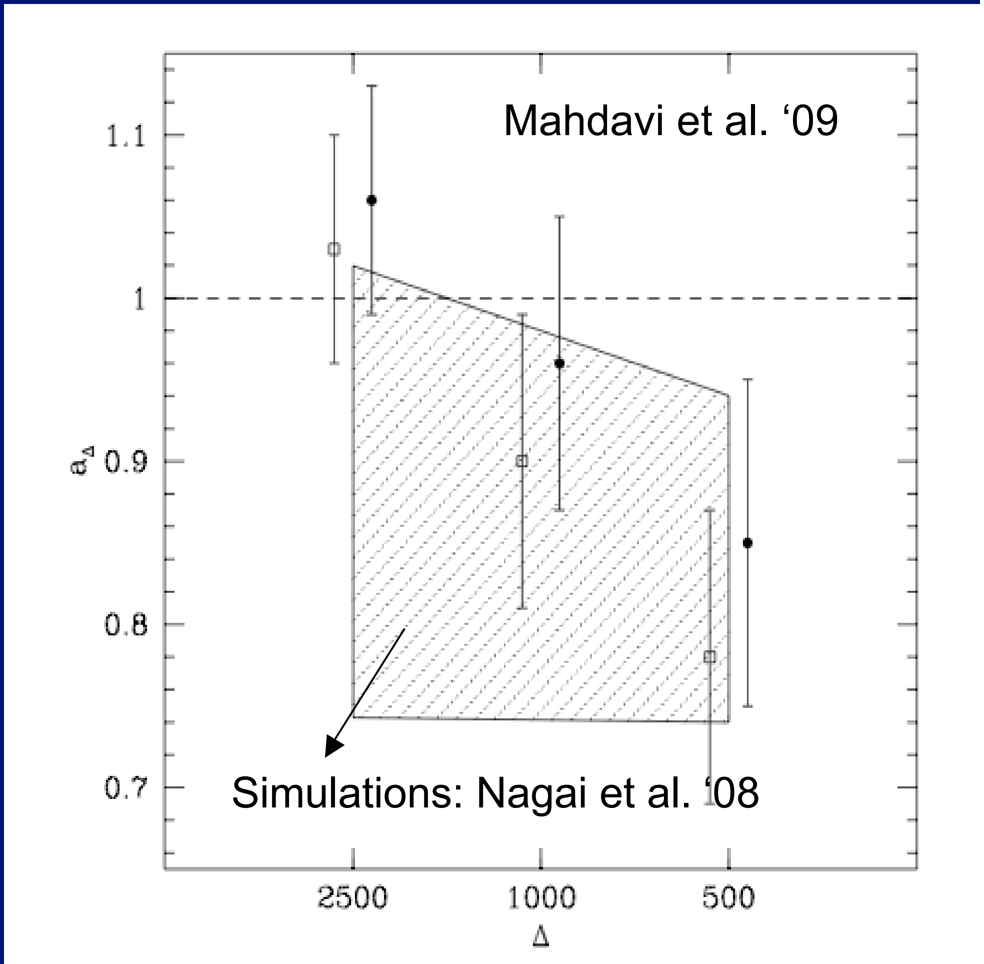
⇒ HE violated at the ~10% level within r_{500}

⇒ Larger deviations at larger radii ($>R_{500}$)

⇒ Larger scatter in the core regions ($<0.15R_{500}$)

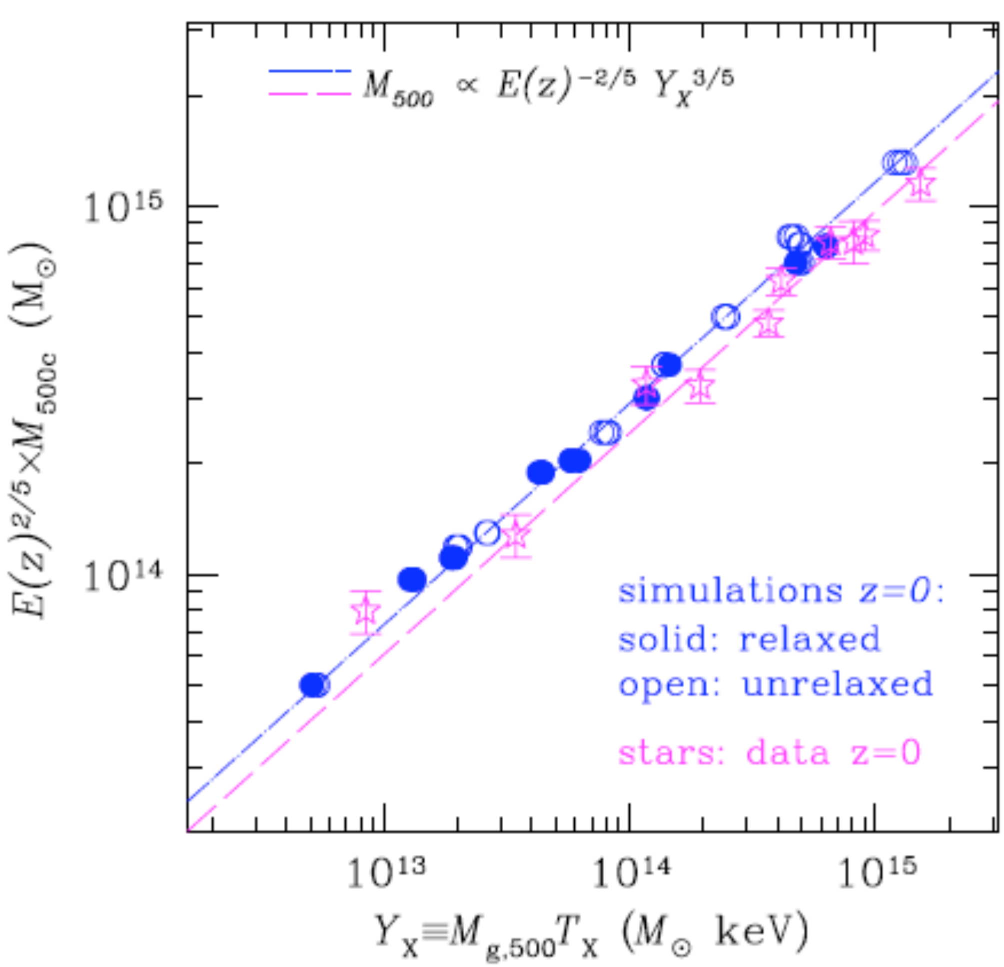
See also Rasia et al. 2006, Nagai et al. 2007, Morandi et al. 2007, Piffaretti & Valdarnini 2008

⇒ Level of HE violation in simulations comparable to the X-ray/lensing mass ratio.



A new cluster mass proxy

Kravtsov, Nagai & Vikhlinin ‘06

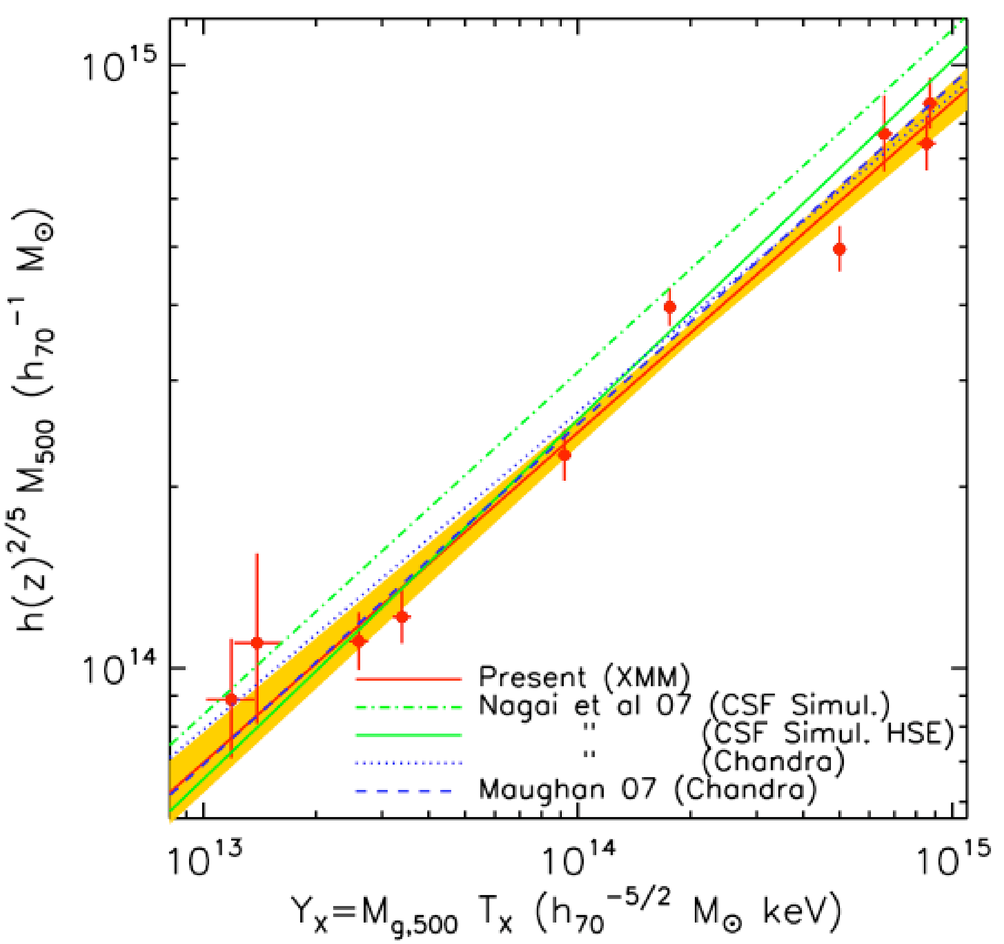


X-ray “pressure”:

$$Y_X = M_{gas} T_X$$

1. Similar to Compton-y from SZ observations.
2. Very small intrinsic scatter: ~ 5-7 % !
3. About 15 % offset wrt Chandra results.

A new cluster mass proxy



Vikhlinin et al. 08: 16 clusters observed with Chandra

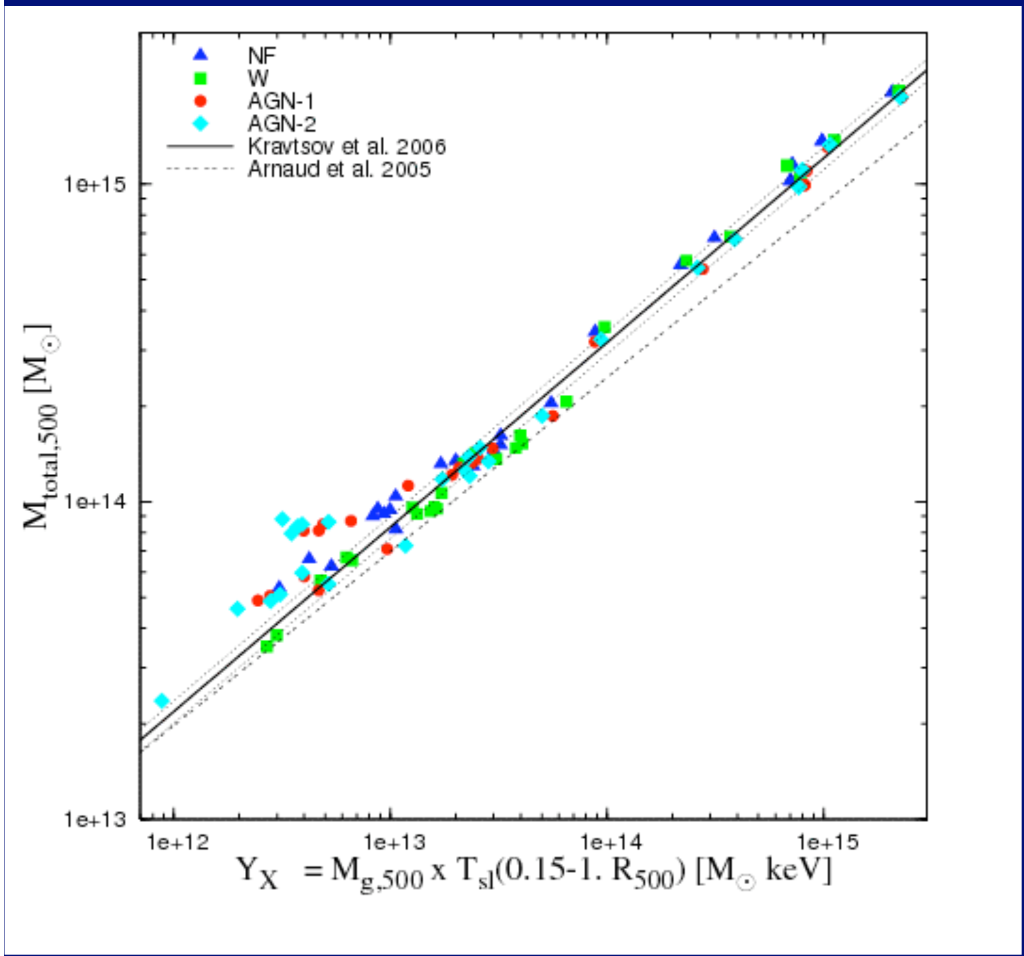
⇒ Reassuring agreement with weak-lensing masses (Hoekstra 07).

Arnaud et al. 07: 10 nearby relaxed clusters observed with Chandra

⇒ Close agreement with Chandra results

Testing the robustness of the Y_X mass proxy

Fabjan, SB, et al. in preparation



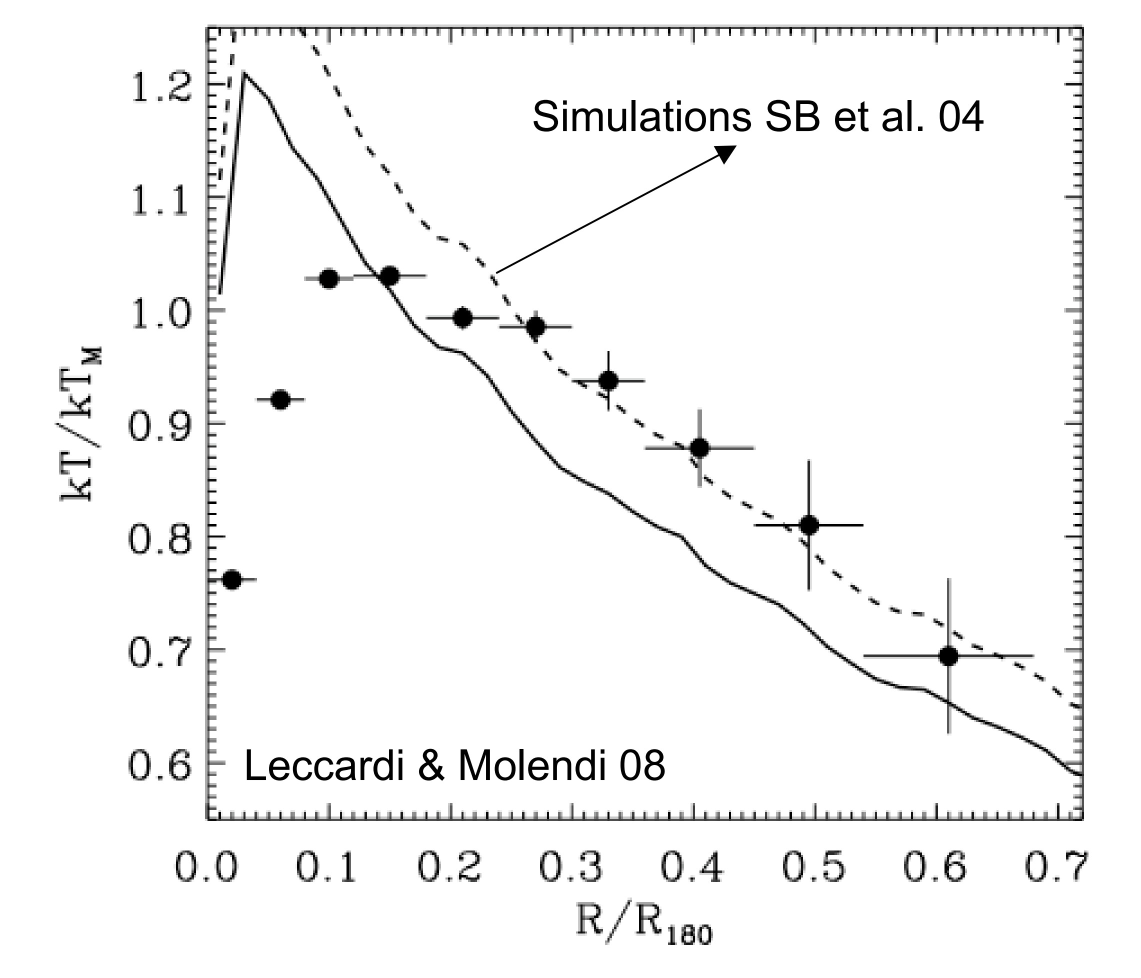
Y_X scaling calibrated with simulations only for

- Limited number of clusters (11)
- Non-radiative and Cooling+SF model

⇒Expand the range of physical models: different feedback (SN & AGN), viscosity schemes, thermal conduction.

⇒Calibrate scatter over a much larger number of clusters within a 300 h^{-1}Mpc box

What happens in cluster cores?



$R < (0.1\text{-}0.15)\ R_{500}$: Increased scatter in surface brightness and temperature profiles

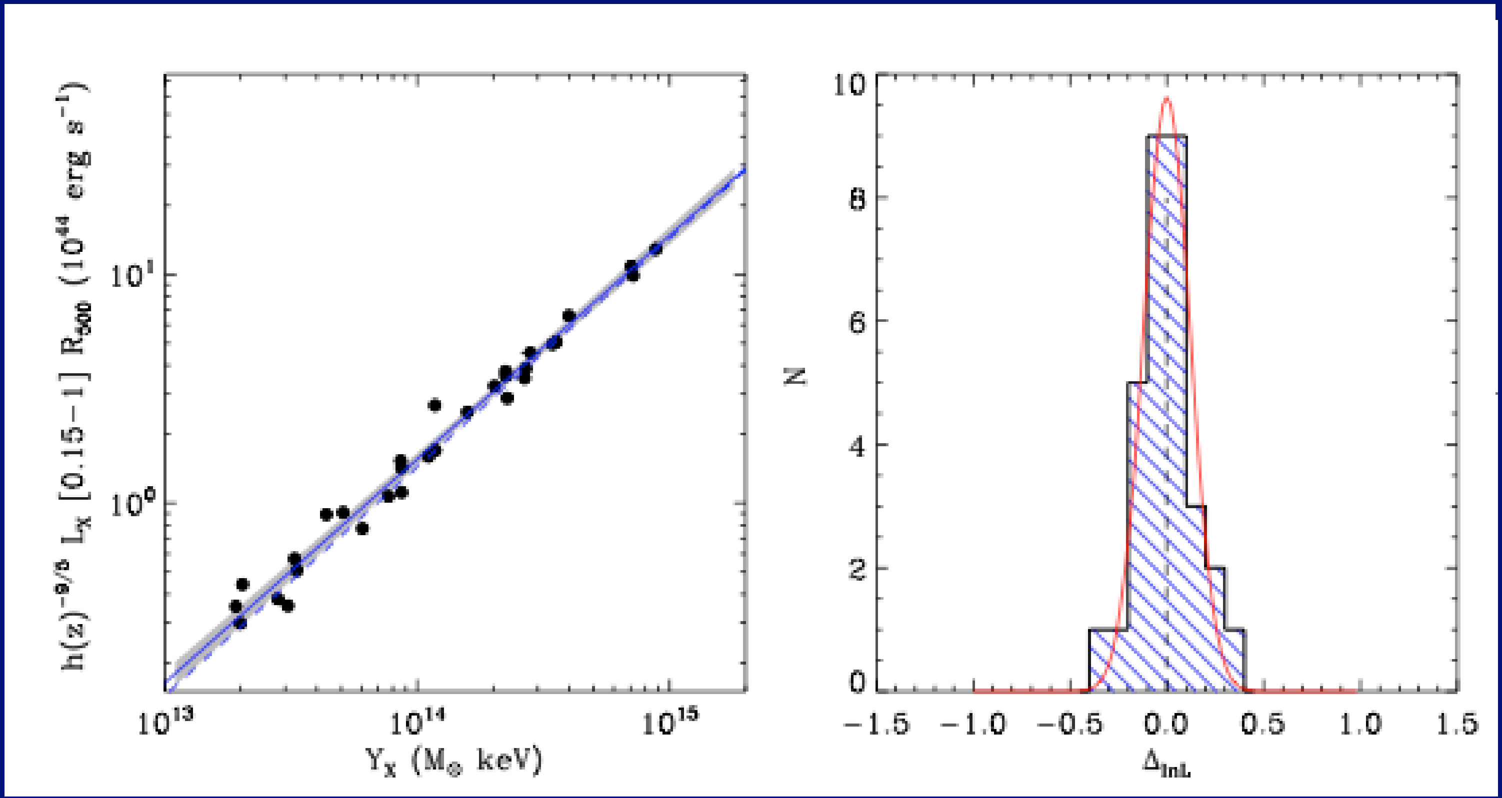
⇒ Diversity introduced by complex astrophysical processes establishing the cool-core structure.

$0.15 < R/R_{500} < 1$: Much better agreement with simulations

⇒ Simpler dynamics dominated by gravity and condition of pressure equilibrium.

Getting rid of cool cores…

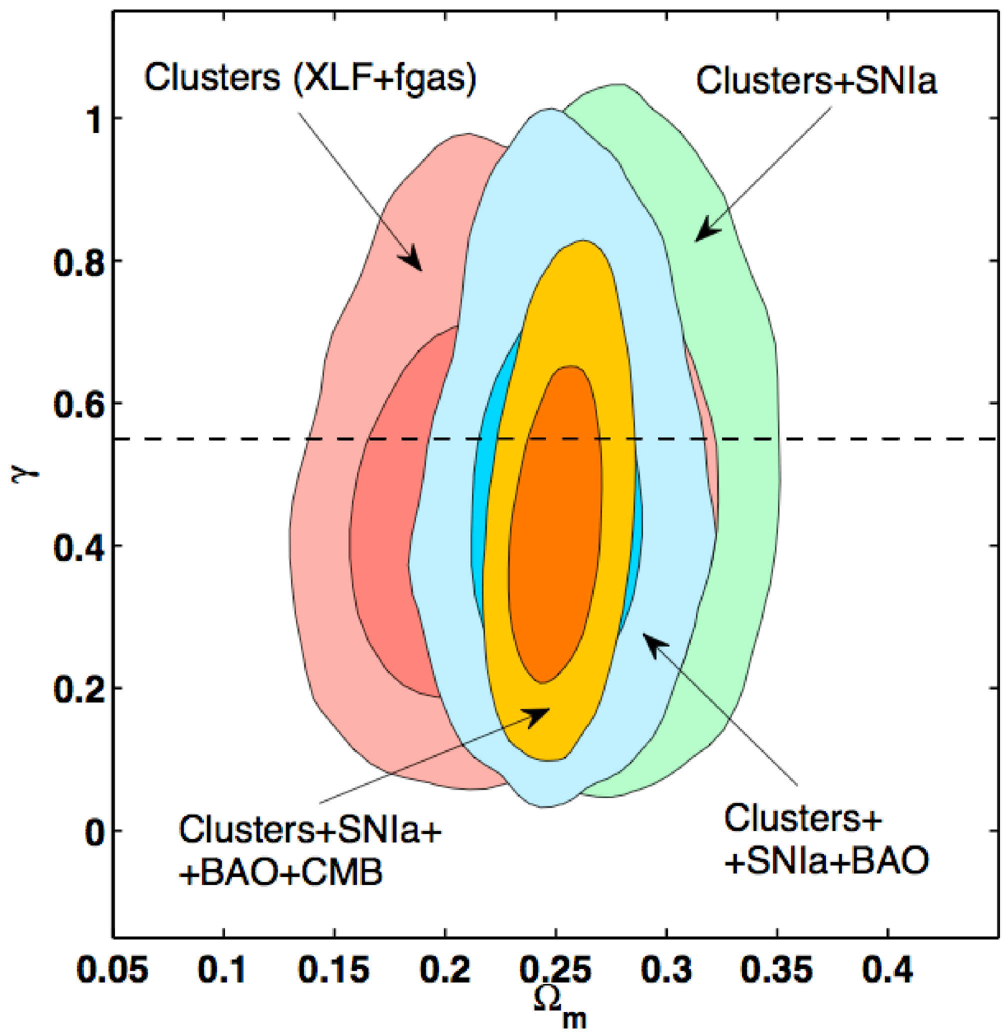
Pratt et al. '09: representative sample of 31 nearby clusters observed with XMM



⇒ With cool cores: $\sigma_{\ln L} \sim 0.4$

⇒ After excising cool cores: $\sigma_{\ln L} \sim 0.16$

Cluster cosmology as of today



Vikhlinin et al. '09

~90 ROSAT clusters, followed-up with Chandra, out to z~0.9

⇒Constraints on the DE EoS

Rapetti et al. '09

ROSAT BCS (78) + REFLEX (126) + MACS (34) clusters out to z~0.9, followed-up with Chandra

⇒Constraints on deviations from GR:

$$\frac{d\delta}{da} = \frac{\Omega_m(a)^\gamma}{a}\,\delta$$

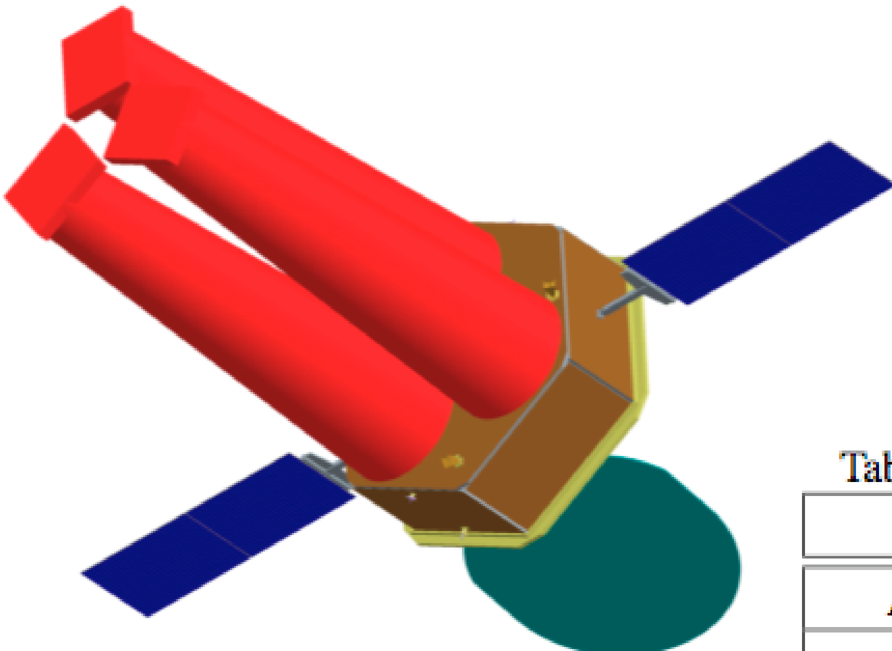
γ=0.55 : standard GR

γ=0.68 : DGP brane-world model

The Wide Field X-Ray Telescope (WFXT)

US: JHU, Marshall, CfA - Italy: ASI/INAF (Milano, Trieste, Bologna, Napoli) - ESO

http://wfxt.pha.jhu.edu/



Whitepaper on Cluster Science submitted to the Decadal Survey:

R. Giacconi et al.: Galaxy Clusters and the Cosmic Cycle of Baryons across Cosmic Times (arXiv:0902.4857)

Table 1: WFXT Mission Performance Requirements

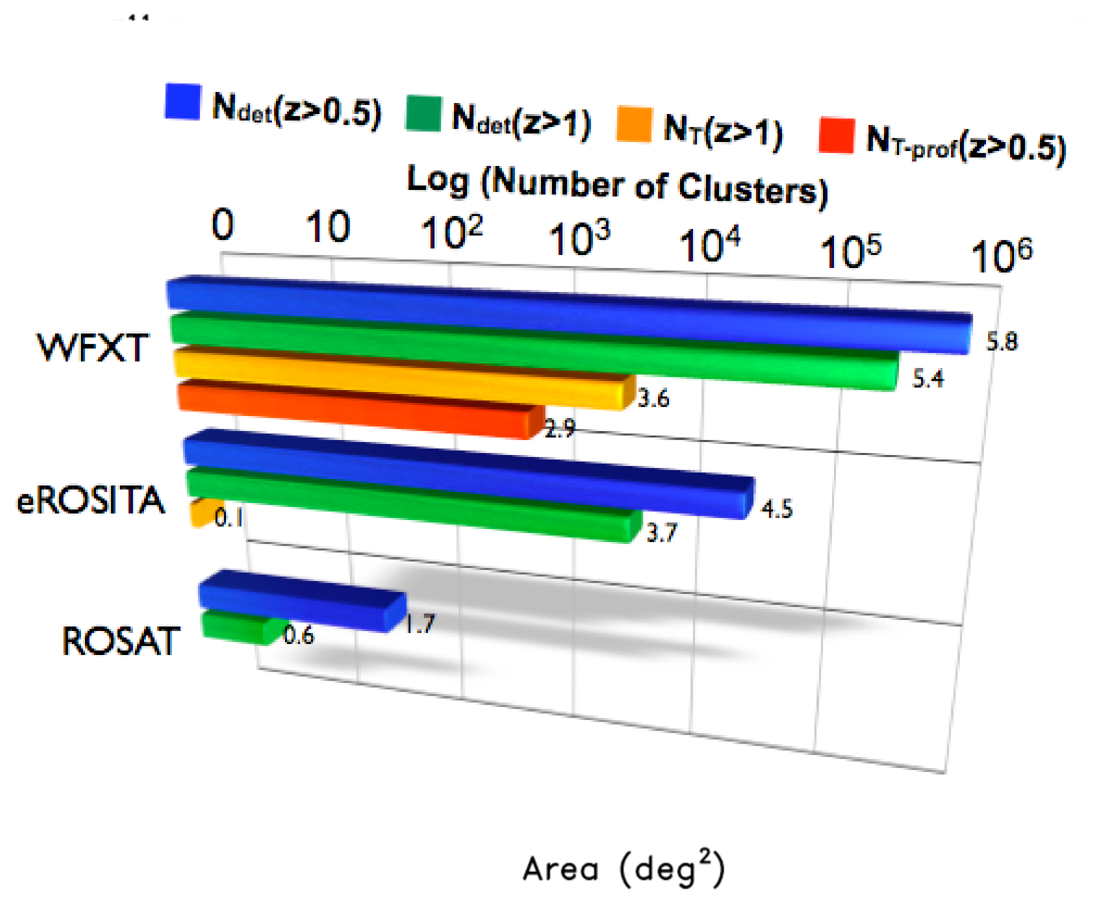
Parameter	Requirement	Goal
Area (1 keV)	$6,000\,cm^2$	$10,000\,cm^2$
Area (4 keV)	$2,000\,cm^2$	$3,000\,cm^2$
Field of View	1^o diameter	1.25^o diameter
Angular Resolution	$< 10''$ HEW	$\leq 5''$ HEW
Energy Band	0.2 - 4 keV	0.1 - 6 keV
Energy Resolution	$\frac{E}{\Delta E} > 10$	$\frac{E}{\Delta E} > 20$
Time Resolution	$<$ 3 seconds	$<$ 1 second

RFI Whitepaper submitted to the Decadal Survey:

S. Murray et al.: Wide Field X-Ray Telescope Mission

WFXT cluster surveys

Detection: 50-100 counts
T_X measurements: 1500 counts
T_X profiles: 15.000 counts



The ultimate cluster survey

WFXT improves wrt eROSITA by about as much as eROSITA improves wrt RASS!

Not just a cluster-counting machine:

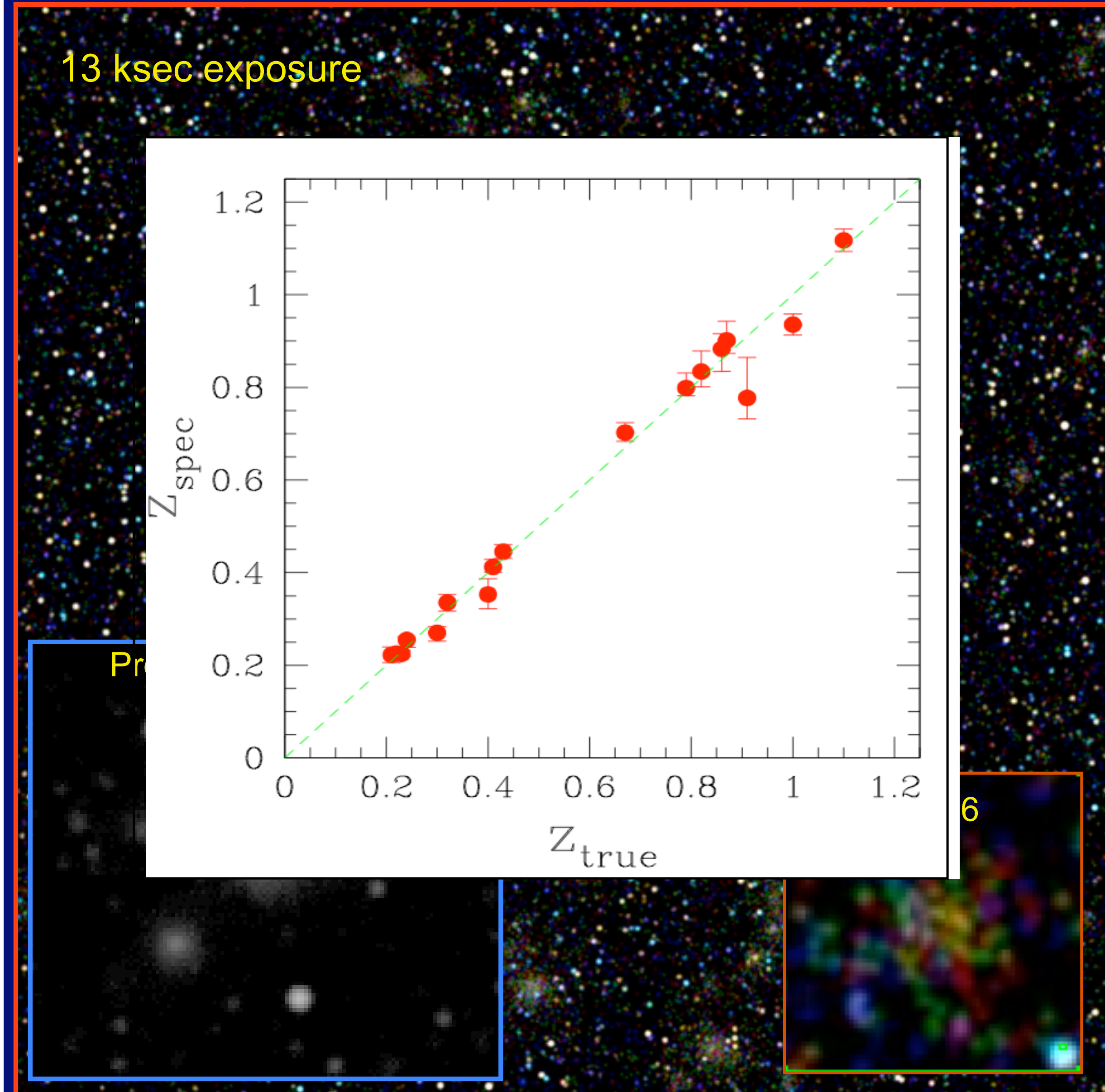
Lifetime: 5 years - 3 surveys

Deep: 100 deg^2 (400 ksec): CDF depth over 1000x area!

Medium: 3,000 deg^2 (13 ksec) to deep Chandra/XMM sens.

Wide: 20,000 deg^2 (4 ksec) to $3\text{-}5\times10^{-15}$ erg/cm^2/s

The potential of a WFXT survey



With 13 ks: ~L_* clusters at z=1.6 detected with ~ 500 counts.

With 400 ks: the simulated Spiderweb cluster detected with > 10^4 counts.

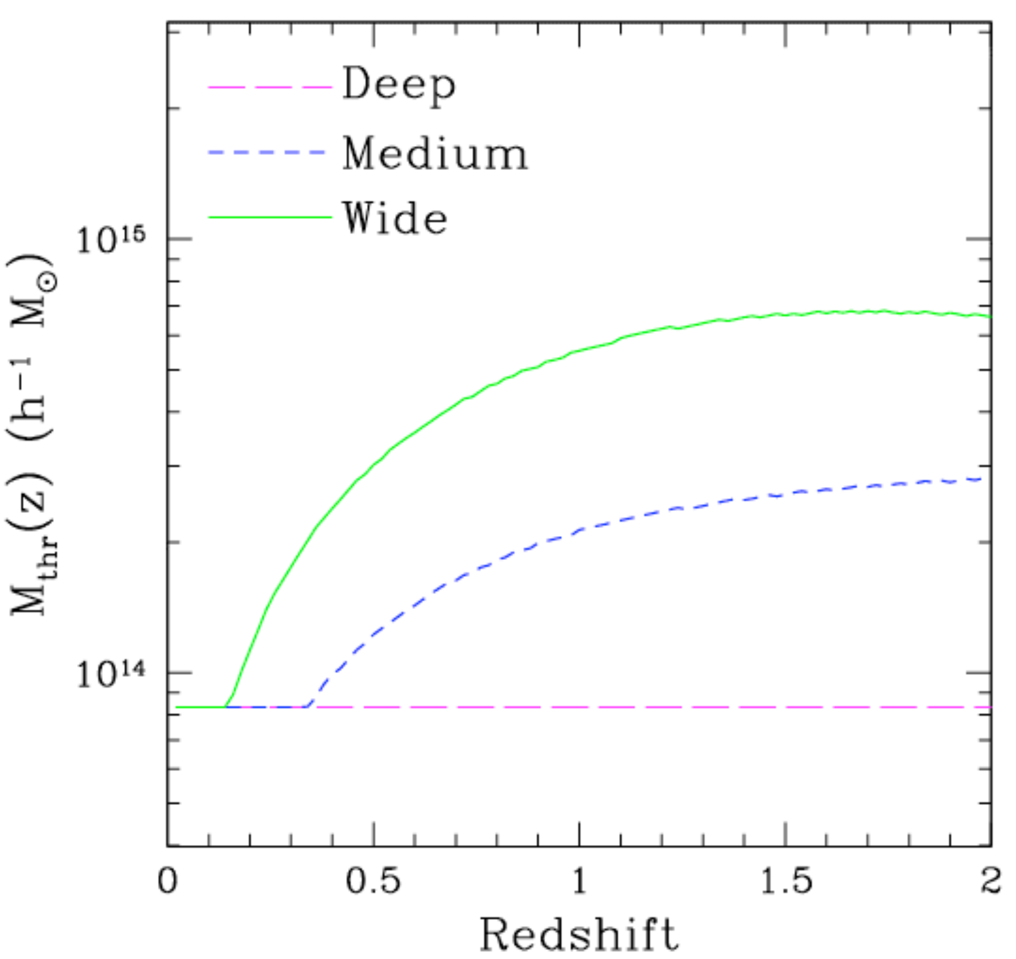
Redshift ,easured with ~500 counts for the 17 brightest clusters in this field

⇒ Completely X-ray based cluster redshift survey!

P. Tozzi, A. Bignamini, J. Santos (Trieste)
and the WFXT Team

Selection functions of WFXT surveys

Sartoris, SB et al. ‘09 in prep.



- Take F_{lim} corresponding to 1500 photons:

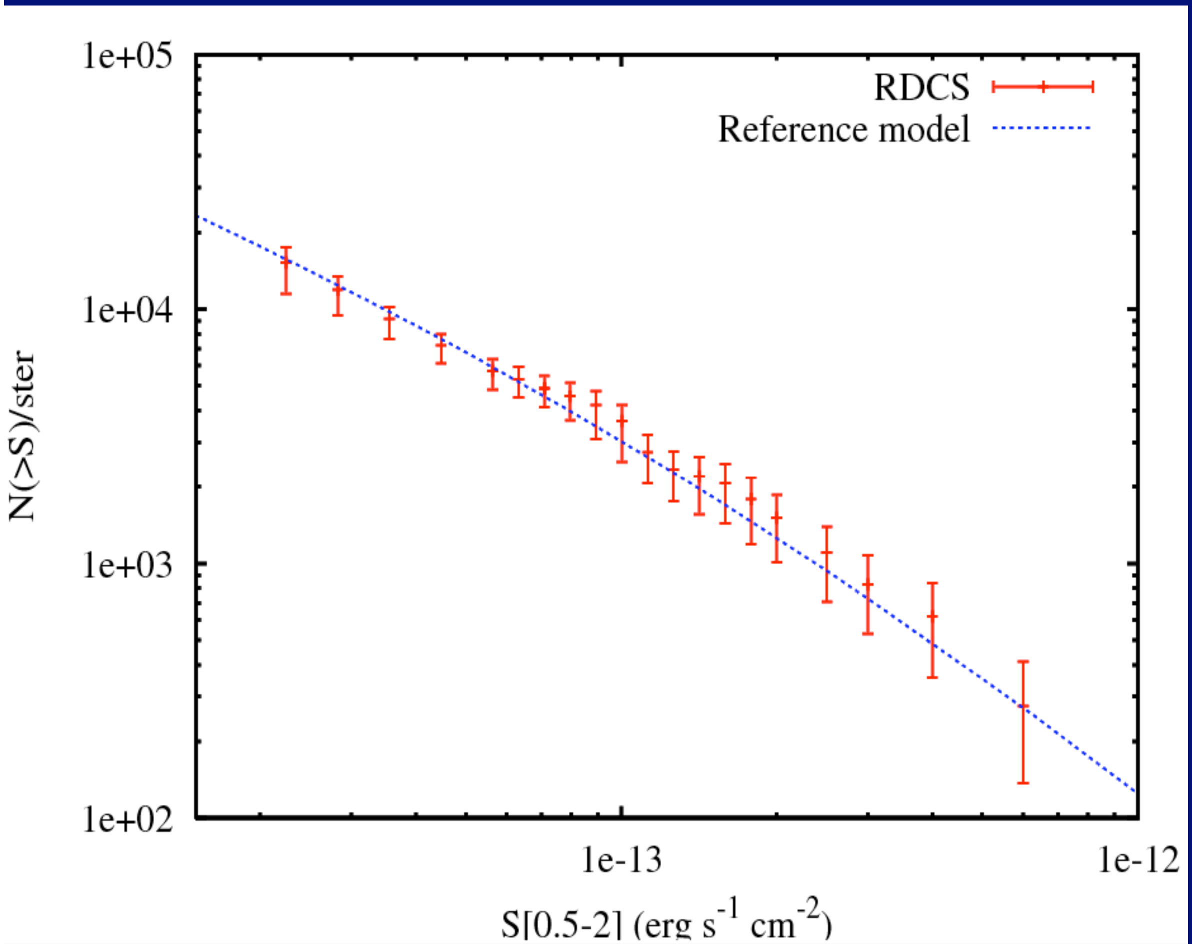
⇒ Precise determination of redshift

⇒ Robust mass proxy (e.g. $Y_X=T_{500}M_{gas}$; Kravtsov et al. 06)

- Use the observed L_X-M_{500} relation (Maughan et al. 07)

- Deep survey to calibrate the Y_X-M_{500} relation down to F_{lim} for detection in the Wide Survey

Calibrating the reference model



<u>Cosmological parameters:</u>

Ω_m=0.26 (flat) , Ω_{bar}=0.046

σ_8=0.80 , n_s=0.96 , h=0.72

w_0=-1 , w_a=0

Halo mass function from Jenkins et al. (2001)

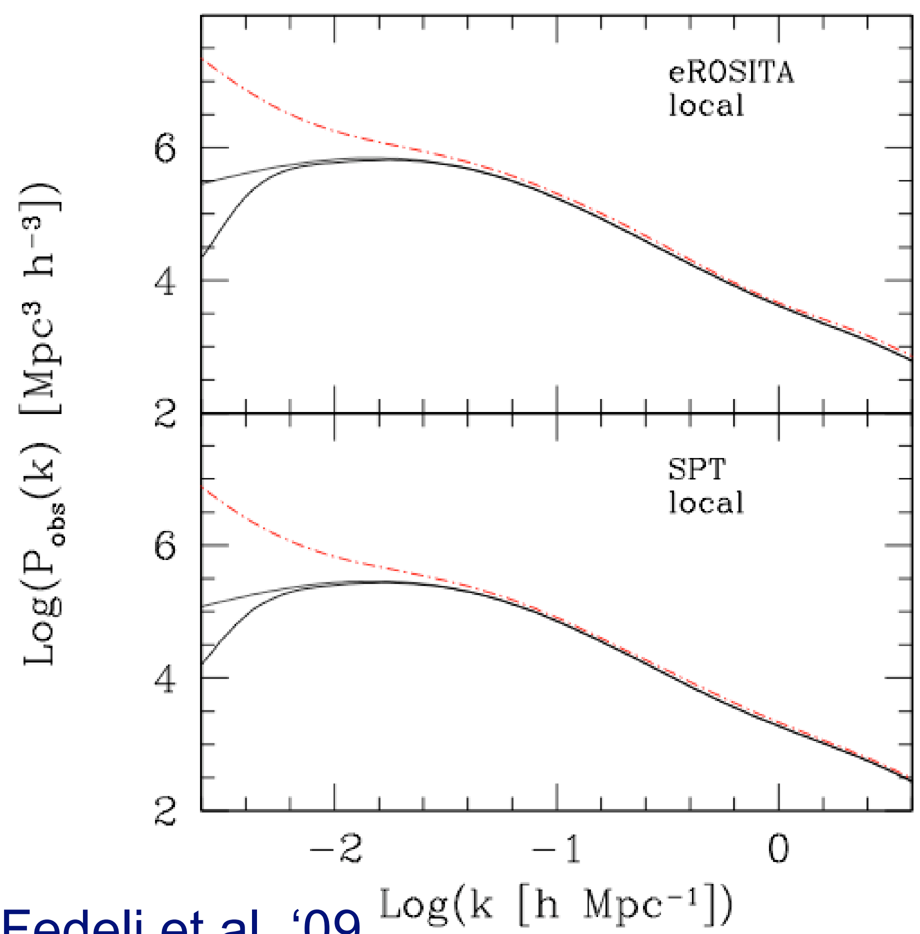
<u>Nuisance parameters:</u>

Mass bias: -15% evolving as $(1+z)^\alpha$, α=1

Intrinsic scatter in L_X-M conversion: 30% evolving as $(1+z)^\beta$, β=1

Constraining non-Gaussian models

Collab. with C. Fedeli & L. Moscardini



Fedeli et al. '09

Non-Gaussian perturbations:

$$\Phi(\mathbf{x}) = \Phi_{\mathrm{L}}(\mathbf{x}) + f_{\mathrm{NL}}\left[\Phi_{\mathrm{L}}^2(\mathbf{x}) - \left\langle \Phi_{\mathrm{L}}^2(\mathbf{x})\right\rangle\right]$$

WMAP5: $-9 < f_{NL}^{CMB} < 111$ (95% C.L.) (Komatsu et al. 09)

LSS: $-29 < f_{NL}^{CMB} < 69$ (95% C.L.) (Slosar et al. 08)

Positive skewness: collapse of halos at higher z, for fixed σ_8.

CONCLUSIONS

1. Galaxy clusters ARE powerful probes of cosmic growth!!

2. $0.1 < R/R_{500} < 1$: Gas dynamics much simpler and already well described by simulations

⇒ Regime where clusters can be robustly calibrated as tools for cosmology!

Sensitivity (grasp & PSF) of WFXT crucial to:

a. Robust mass proxies (e.g. Y_X, M_{gas}) for $\sim 10^5$ clusters out to $z \sim 1.5$

b. Characterize emission from cool cores in the measure of mass proxies: 10” subtends a scale of ~80 kpc @ z=1

Lots of highly interesting astrophysics
while doing “cluster cosmology”….