# Understanding Galaxy Clusters as Tracers of Cosmic Growth

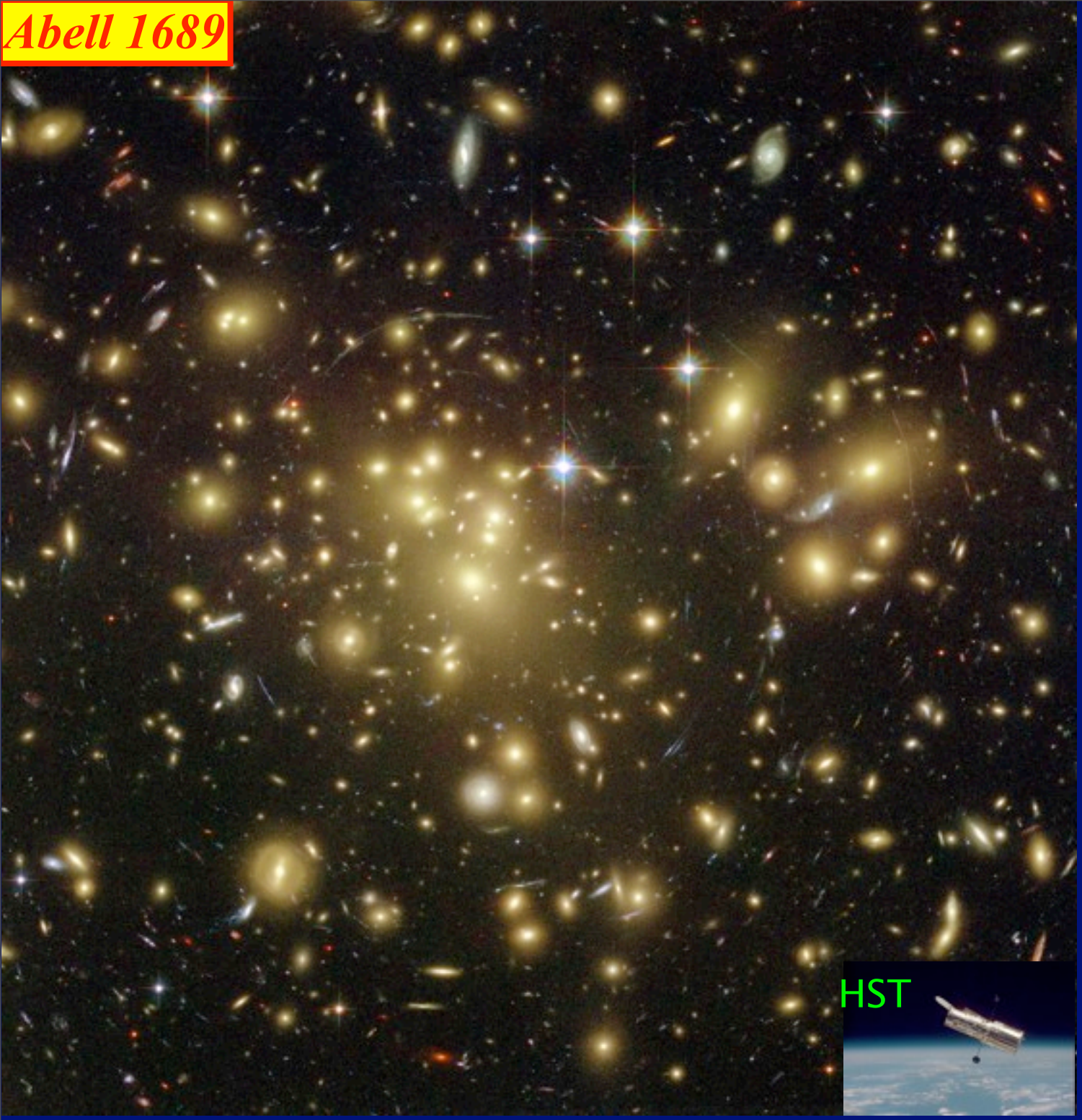
Stefano Borgani
Dept. of Physics
University of Trieste
(also INAF & INFN – Trieste)

An X-ray biased overview…(see Ravi's talk)

(I) Observational progress in the Chandra/XMM era

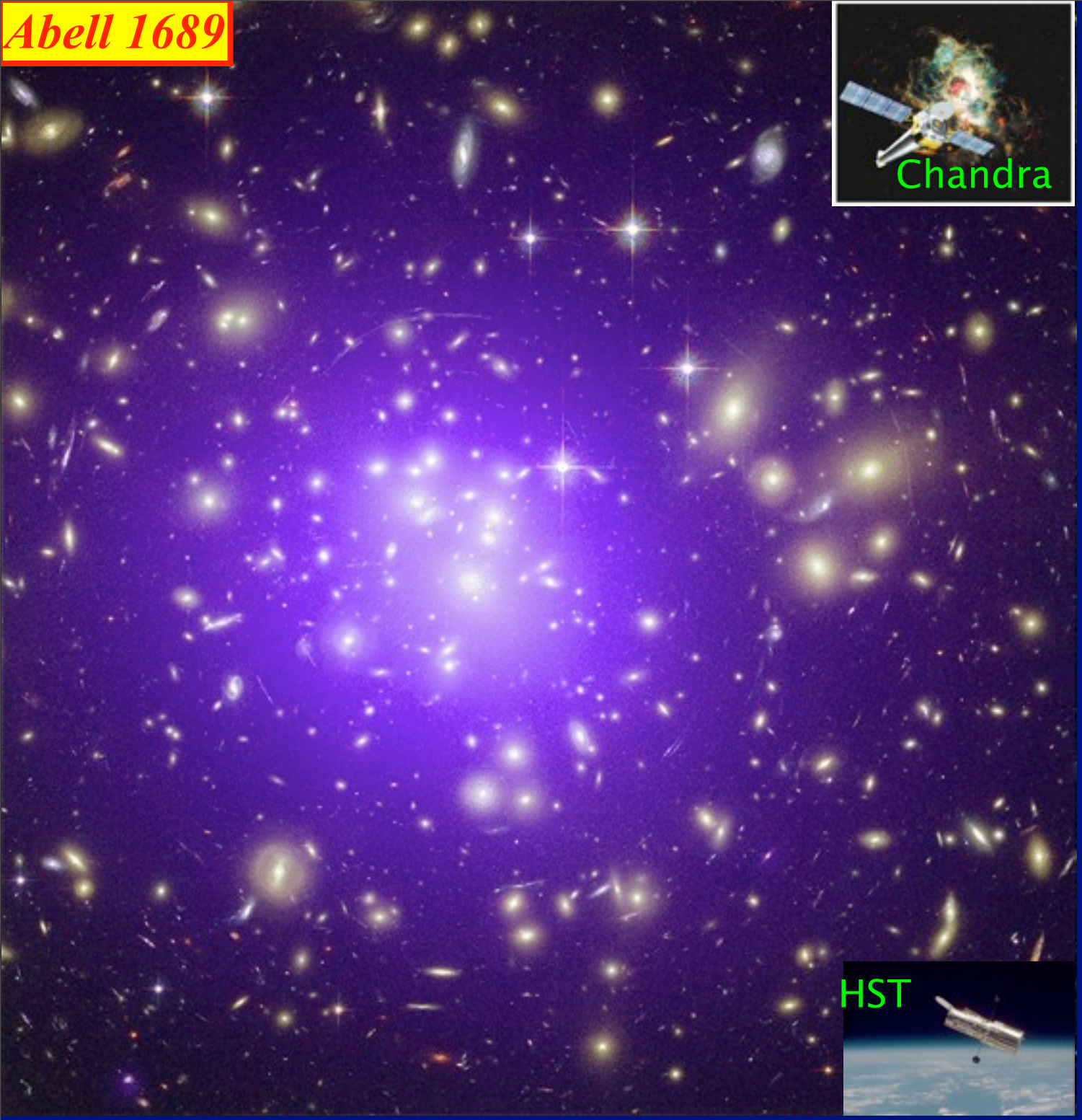
(II) The role of hydrodynamical simulations

(III) Forecasting the future of cluster cosmology




# What is a galaxy cluster ?

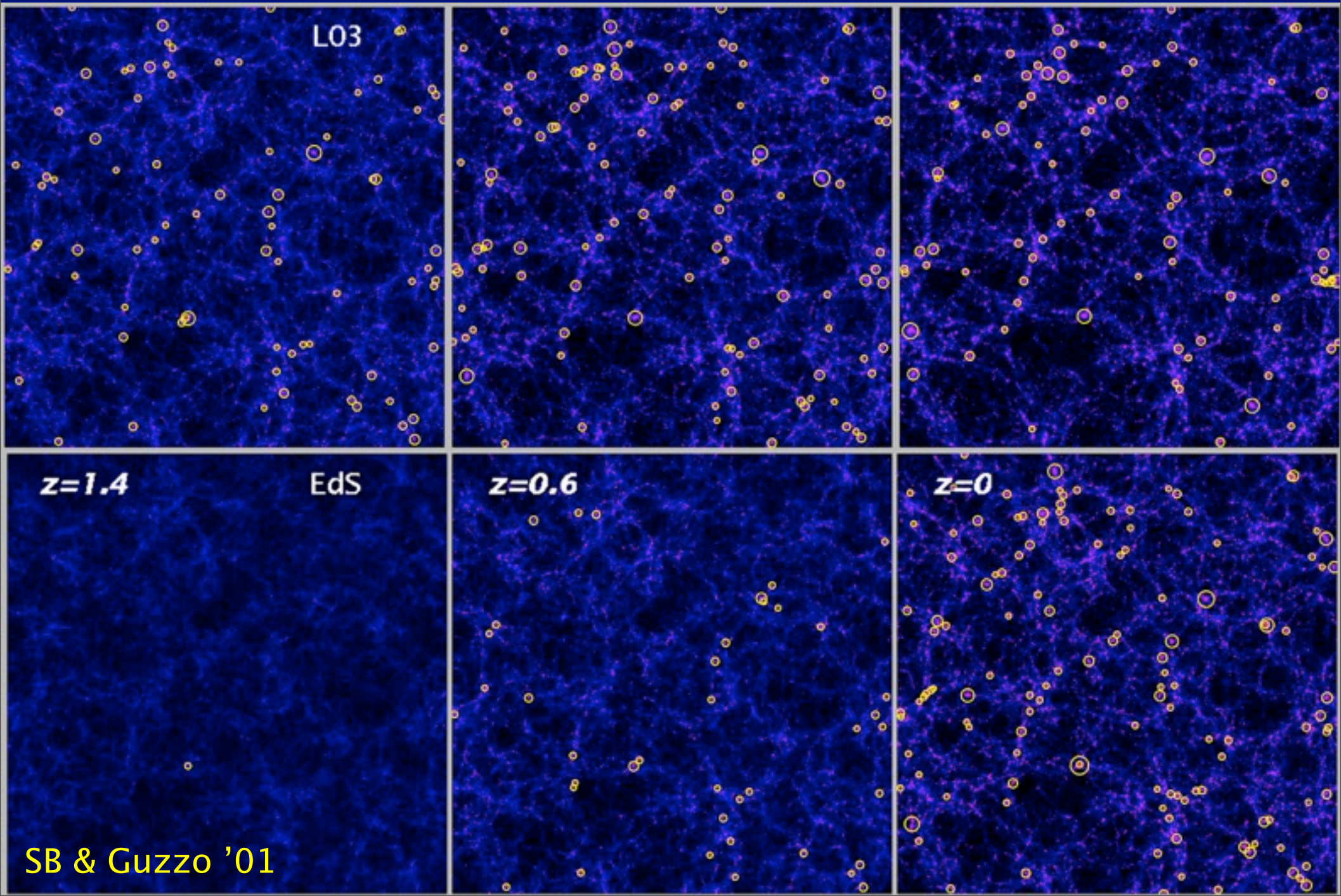
- Concentration of ~$10^3$ galaxies
- $\sigma_v$~500–1000 km $s^{-1}$
- Size: ~1–2 Mpc
- Mass: $10^{15}$ $M_\odot$
  - ➔ $\lambda_i \approx 10$ Mpc




# What is a galaxy cluster ?

- Concentration of ~$10^3$ galaxies
- $\sigma_v$~500–1000 km $s^{-1}$
- Size: ~1–2 Mpc
- Mass: $10^{15}$ $M_\odot$
  - ➔ $\lambda_i \approx 10$ Mpc
- Baryon content:
  - ➔ cosmic share in hydrostatic equilibrium
- ICM temperature:
  - ➔ $T_X$ ~ 2–10 keV
  - ➔ fully ionized plasma;
- Therm bremsstrahlung
  - ➔ $n_e$~$10^{-2}$–$10^{-4}$

# Galaxy clusters as tracers of cosmic growth




SB & Guzzo '01

# What cosmological information from number counts?

➔ No. of clusters of given observable X and z within the survey area

$$\frac{dN(X;z)}{dXdz}$$

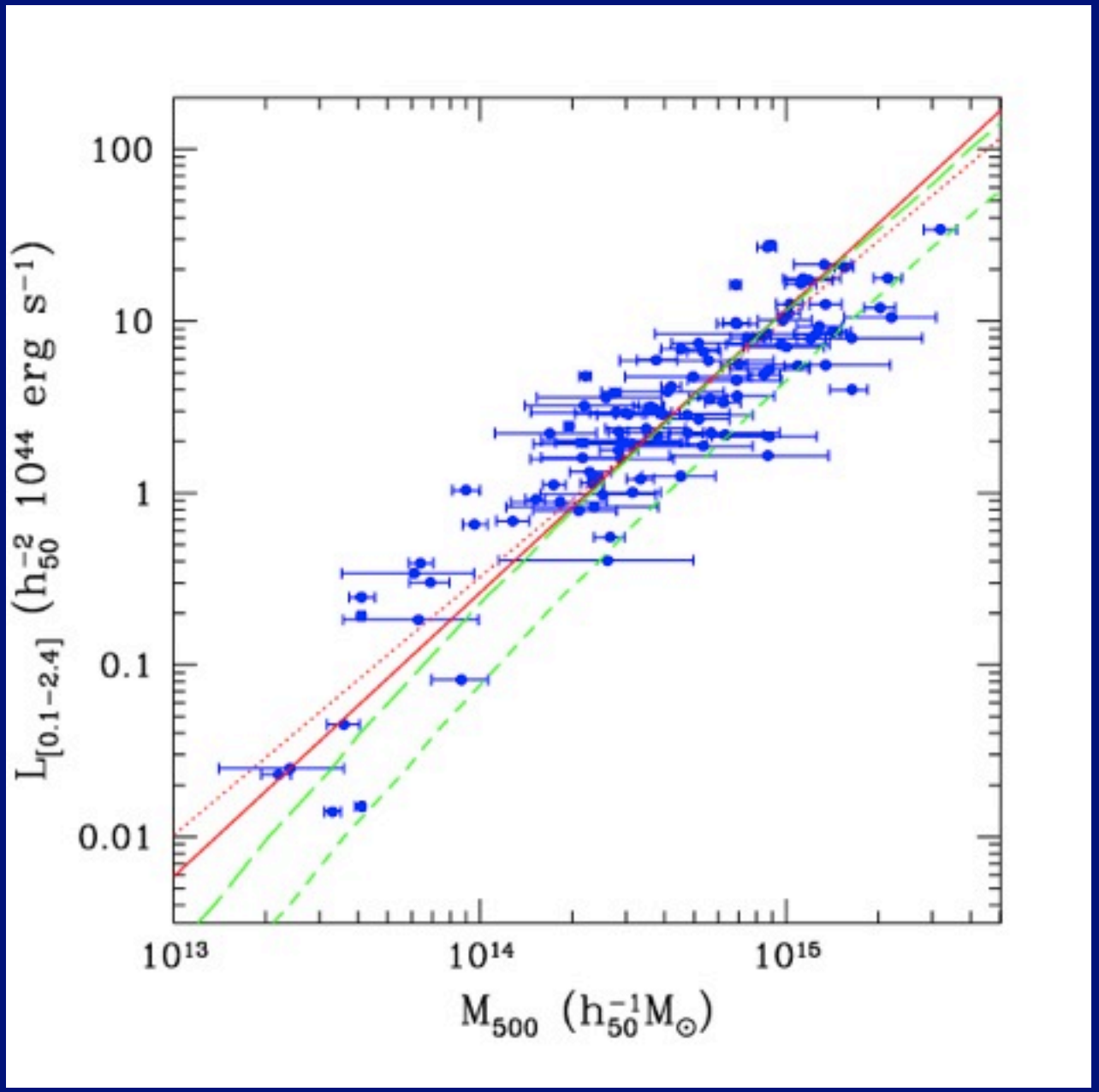
1. Friedmann background: $\frac{dV}{dz}$ ➔ Priors on cosmoloical parameters $\Omega_i$ from CMB, SnIa, $f_{bar}(z)$, ….

2. Selection function: $f(X,z)$ ➔ Observational strategy

3. Growth history: $\frac{dn(M,z)}{dM}$ ➔ Precisely calibrated with N-body simulations

4. Astrophysics: $p(X|M,z)$ ➔ Priors on "nuisance parameters" $p_j$ from follow-up observations and/or <u>cosmological simulations</u>

# Pre-Chandra/XMM mass proxies



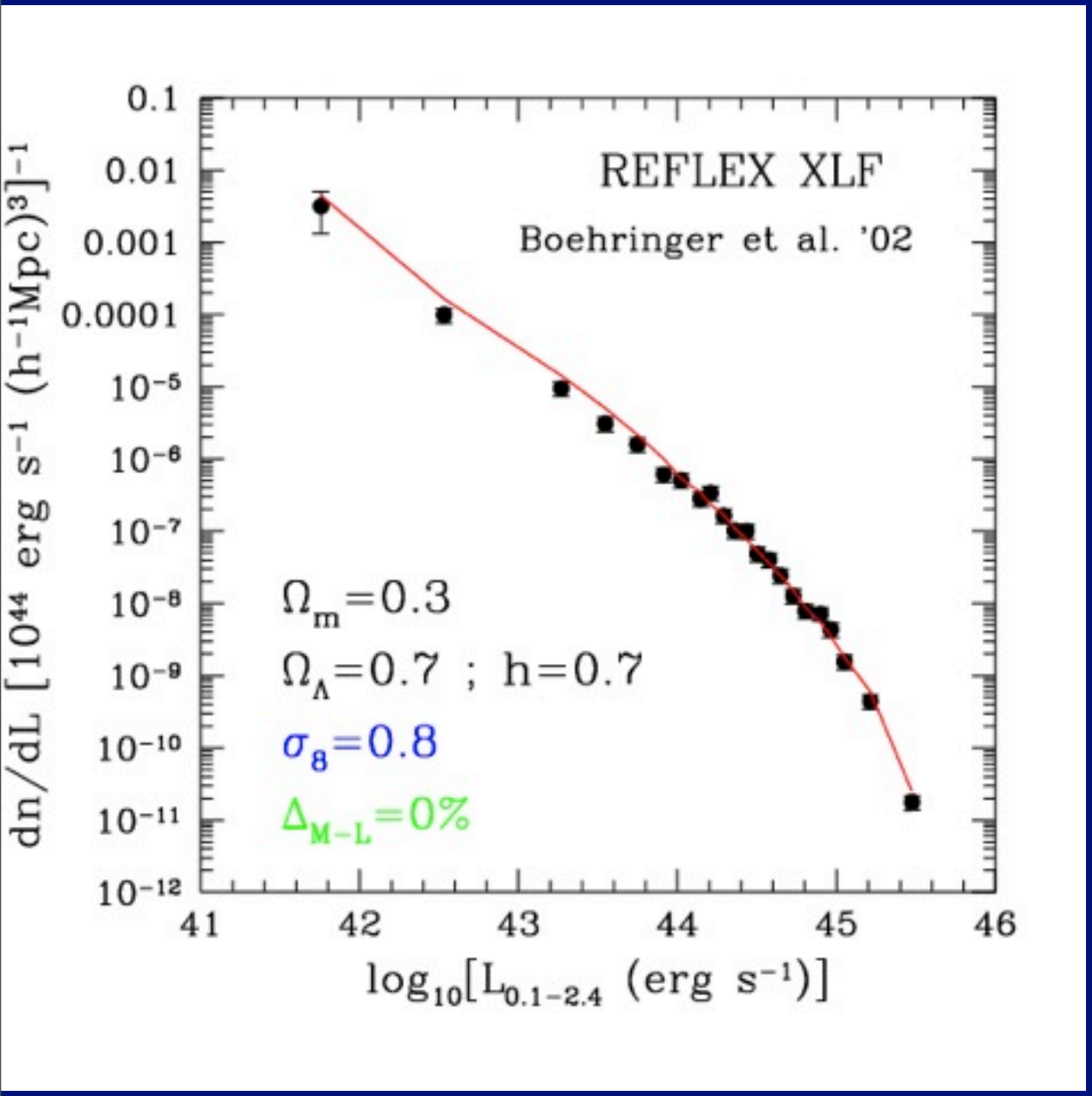

Reiprich & Boehringer 02:

ROSAT imaging
+
ASCA temperatures

Hydrostatic equilibrium
+
isothermal β-model

➔ Well-defined relation with ~40% scatter!

# An example: relevance of scatter in scaling relations



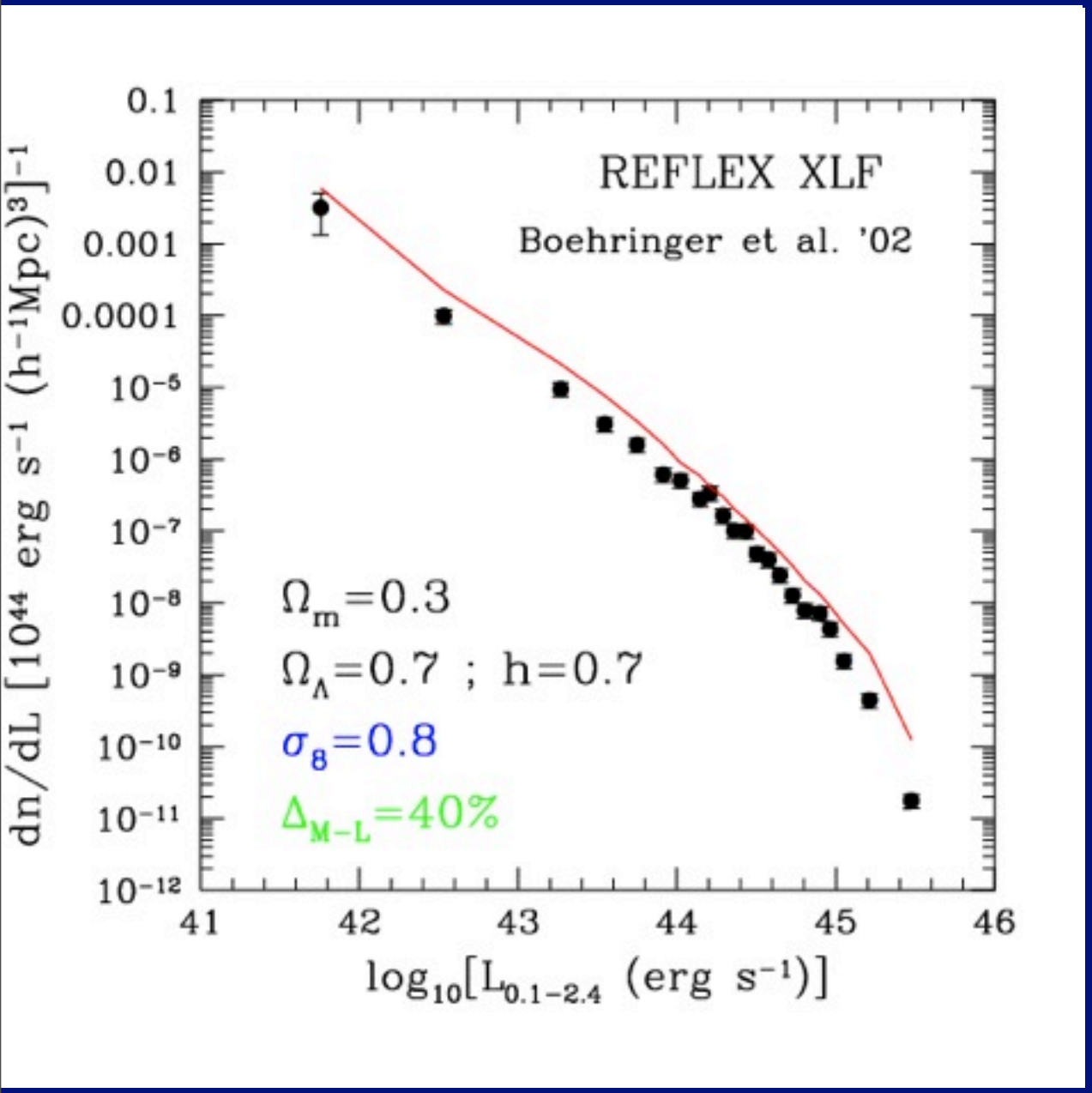

Eke et al. '98, SB et al. '01, Lima & Hu '04

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

➔ Lower $\sigma_8$ required to fit the observed XLF!

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

# An example: relevance of scatter in scaling relations



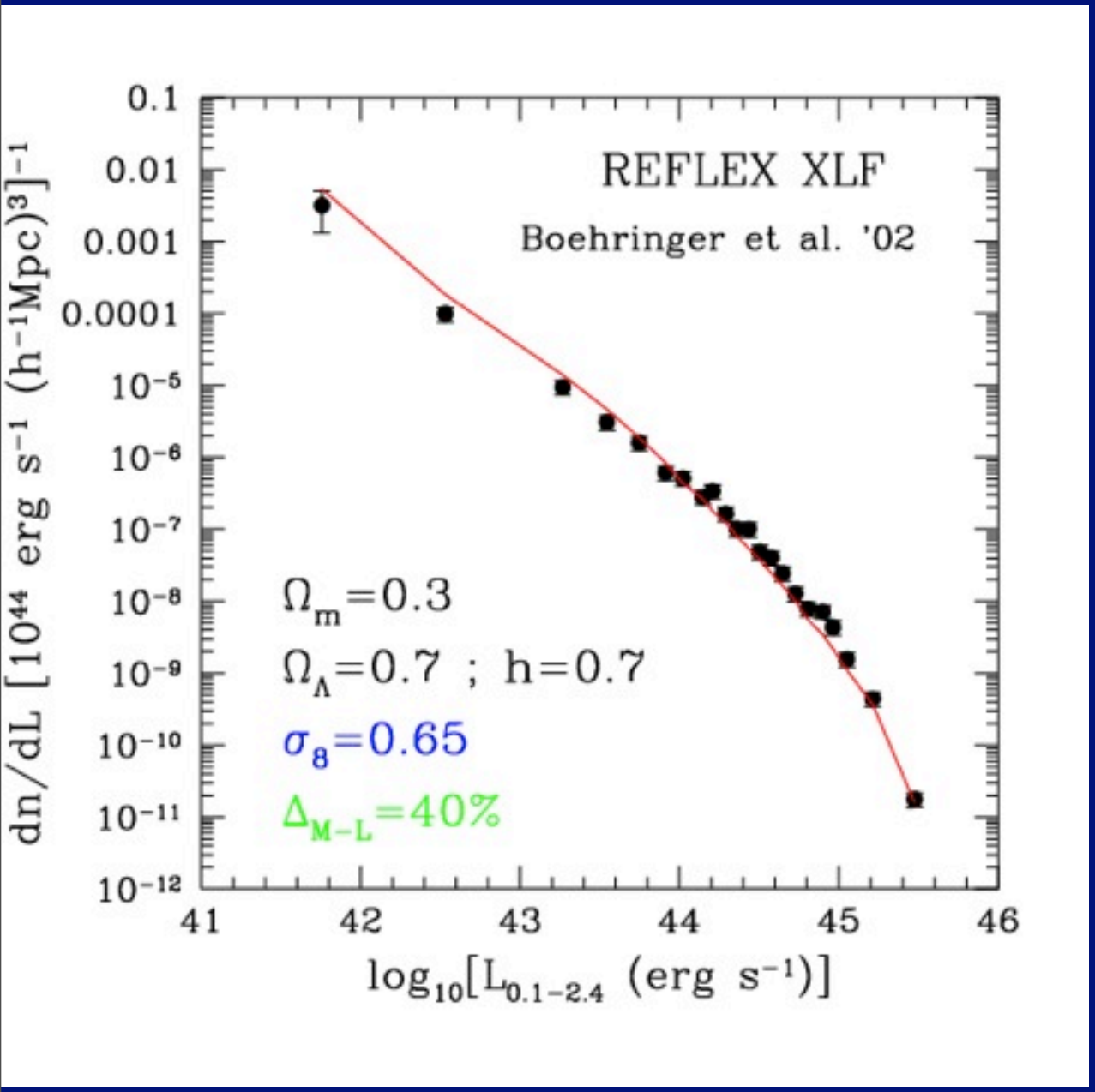

Eke et al. '98, SB et al. '01, Lima & Hu '04

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

➔ Lower $\sigma_8$ required to fit the observed XLF!

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

# An example: relevance of scatter in scaling relations




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

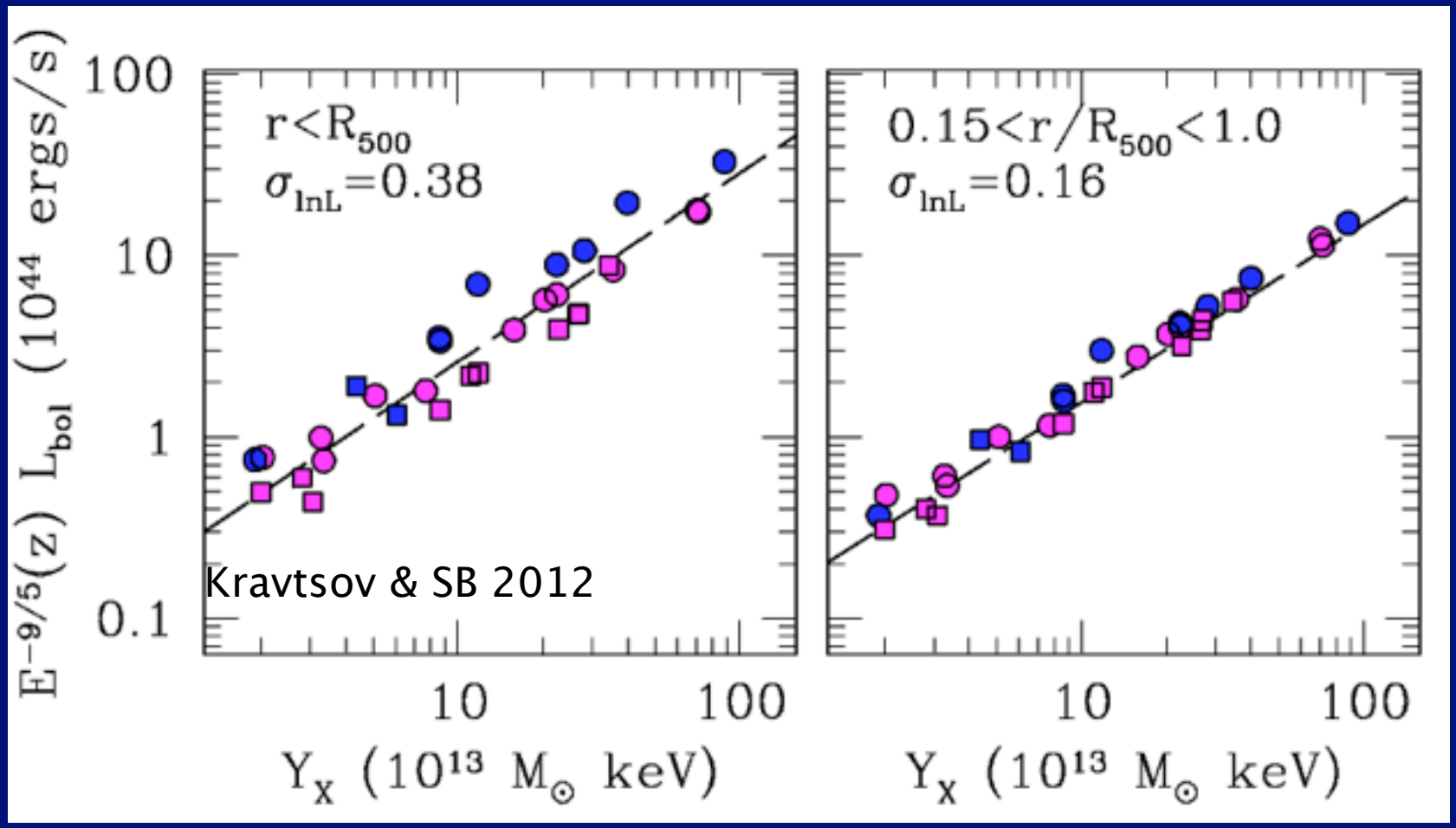
➔ Convolution with intrinsic (log-normal) scatter inflates the predicted XLF

➔ Lower $\sigma_8$ required to fit the observed XLF!

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

# The relevance of resolving cluster cores

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



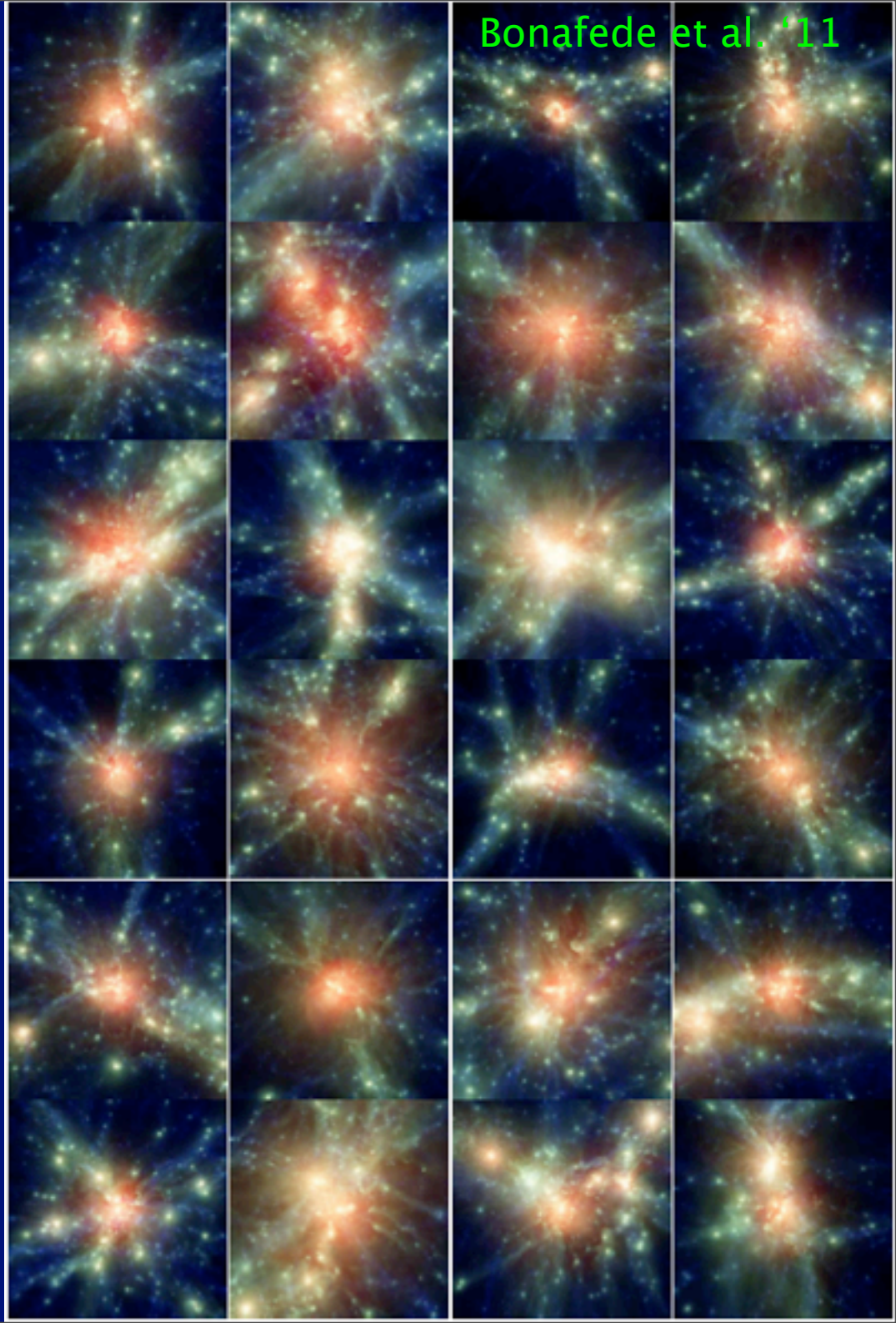

Excising cores ➔ Decrease of scatter by factor >2

➔ No diversity between CC and NCC clusters

# The role of simulations

- ➔Calibrate the Halo Mass Function
- ➔Define what's the regime where clusters are best modeled (and understood)
- ➔Understand and calibrate systematics and biases in mass measurements
- ➔Define and test "mass proxies": robustness and intrinsic scatter in their scaling with true mass

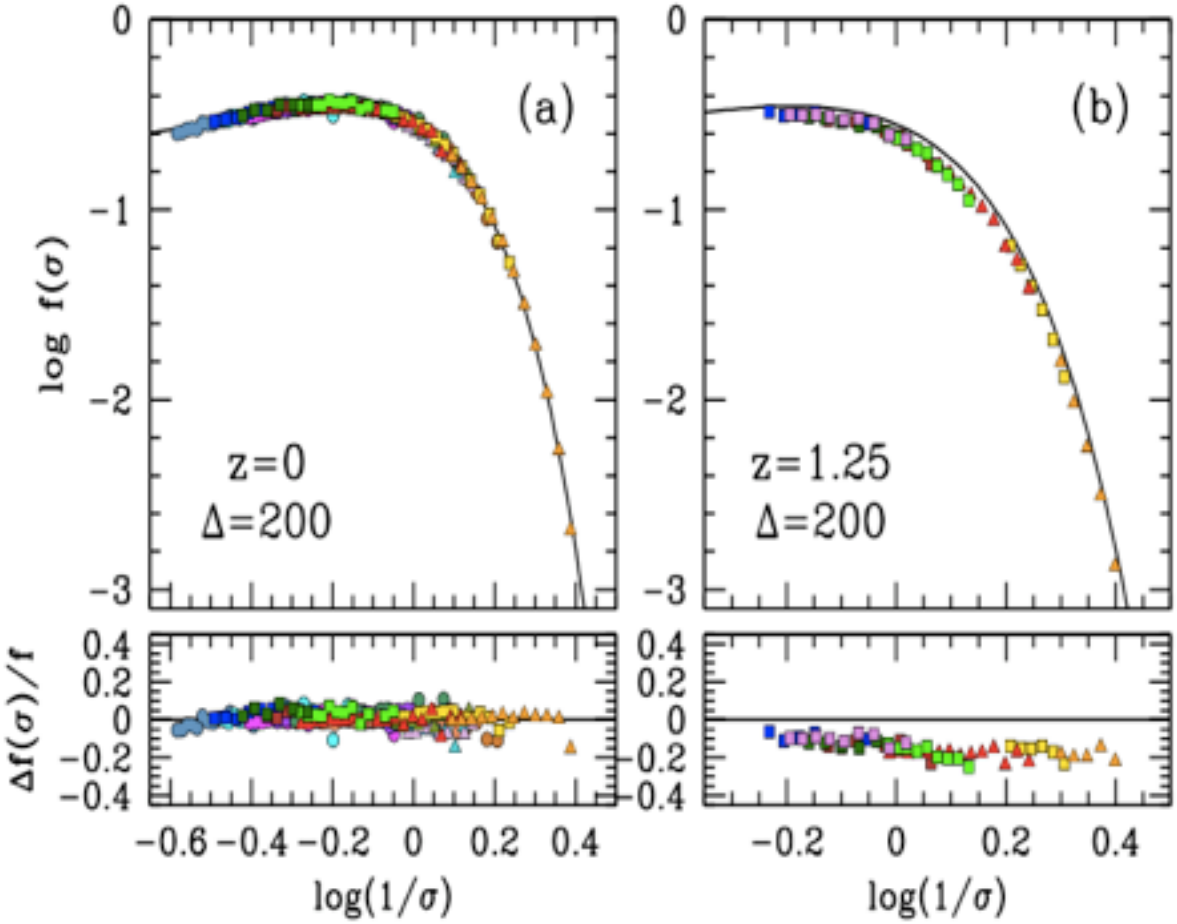
(e.g. SB & Kravtsov 09)



# Calibrating a ~universal HMF with DM simulations

E.g., Sheth & Tormen 2001, Jenkins et al. 2001, Evrard et al. 2002, Springel et al. 2005, Warren et al. 2007, Reed et al. 2008, Tinker et al. 2009, Crocce et al. 2009

Tinker et al. 09




<u>0-th order statements:</u>

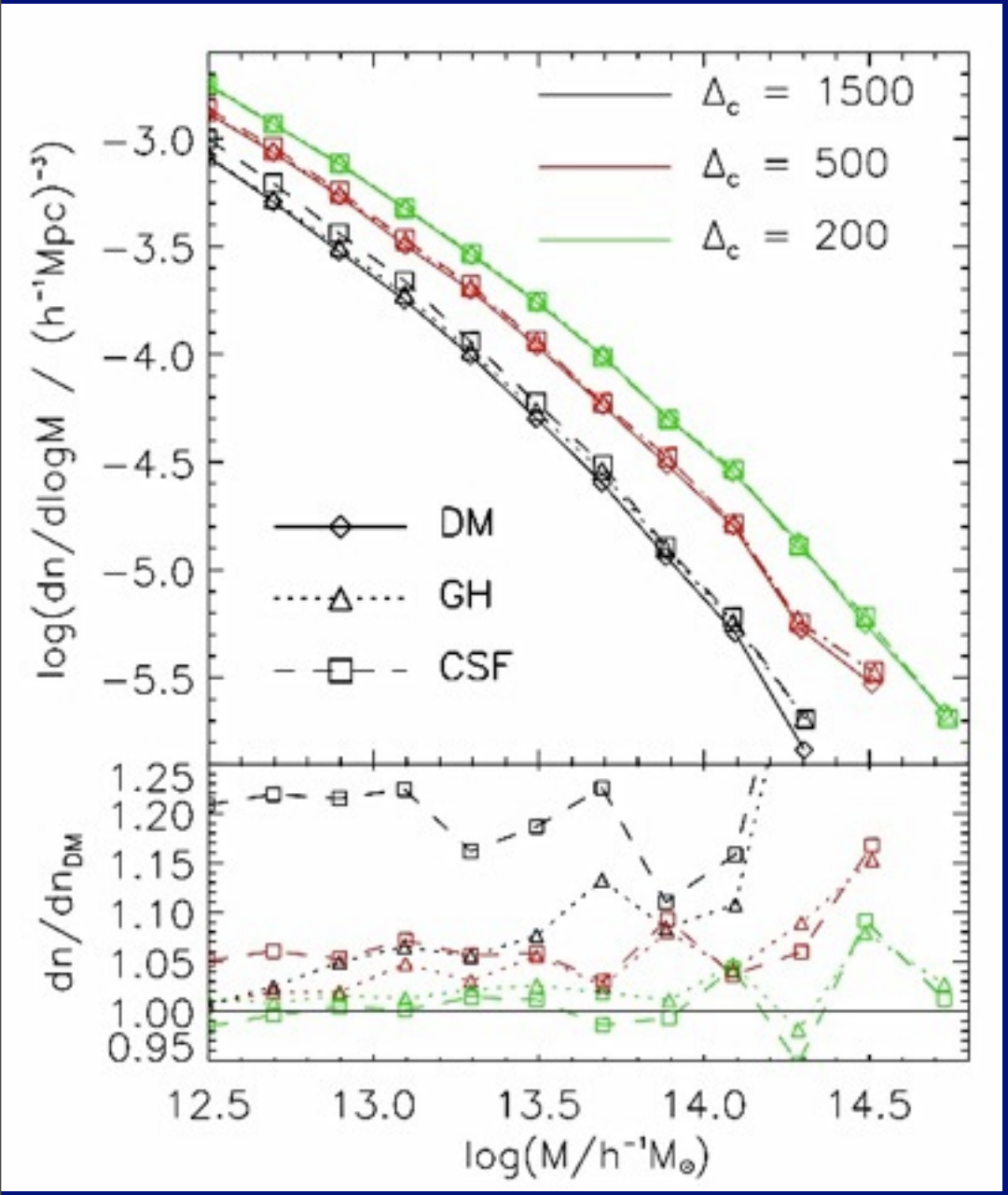
(a) N-body simulations provide the DM halo MF to any required precision.

(b) Corrections to the Press-Schechter HMF still almost universal (i.e. independent of cosmology and reshift).

(c) Residuals <10% at the cluster mass-scale.

# Effect of gas-dynamics on the MF

Cui et al. '11a




➔ Homogeneous set of large simulations, from the same ICs

L = 410 $h^{-1}$ Mpc ; $N_{DM}=N_{gas}=1024^3$

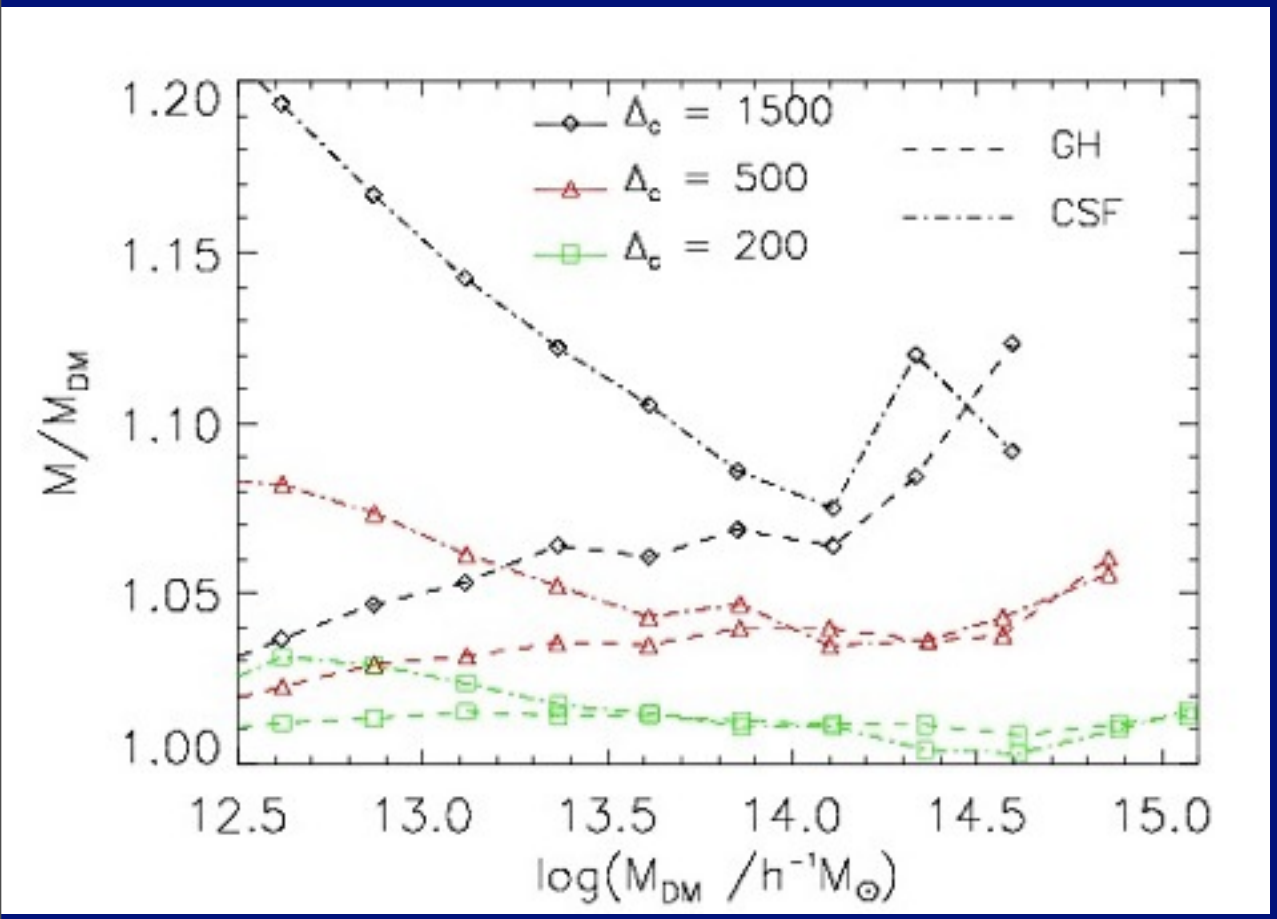
➔ Using Gadget-3 (Springel '05)

1. DM-only (2 particle populations)
2. Non-radiative hydro
3. Hydro with cooling + SF + SN feedback

➔ Slight increase in the MF in hydro simulations

➔ As a fctn. of $\Delta_c$: <5% @ $\Delta_c$=200

# The impact on halo masses




For $\Delta_c$=200, 500 and $M>10^{13.5}M_\odot$

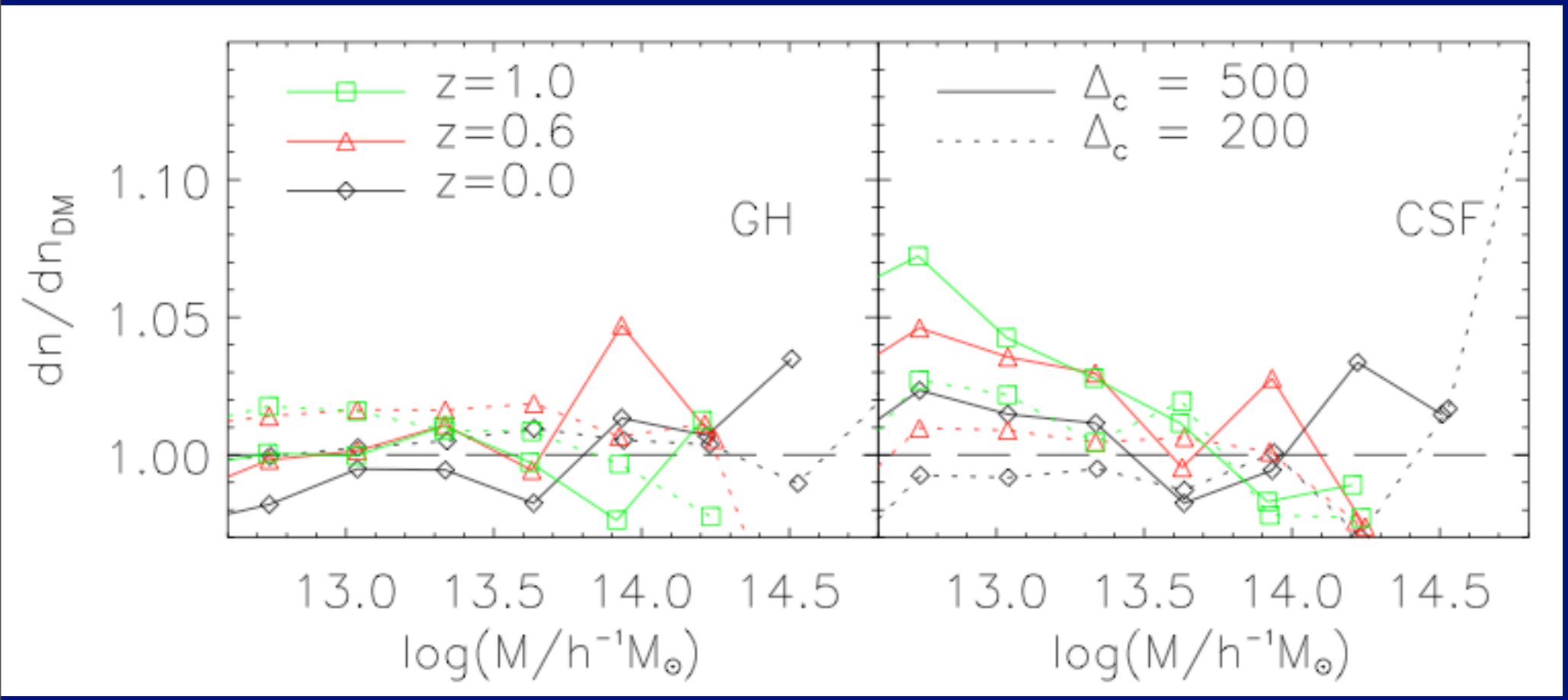
➔ Nearly constant mass variation

➔ Increase by ~1% in for $M_{200}$

➔ Increase by ~4% for $M_{500}$

➔ Effect of cooling+SF smaller than overall effect of gas

# The impact on halo masses



# How reliable is hydrostatic equilibrium?

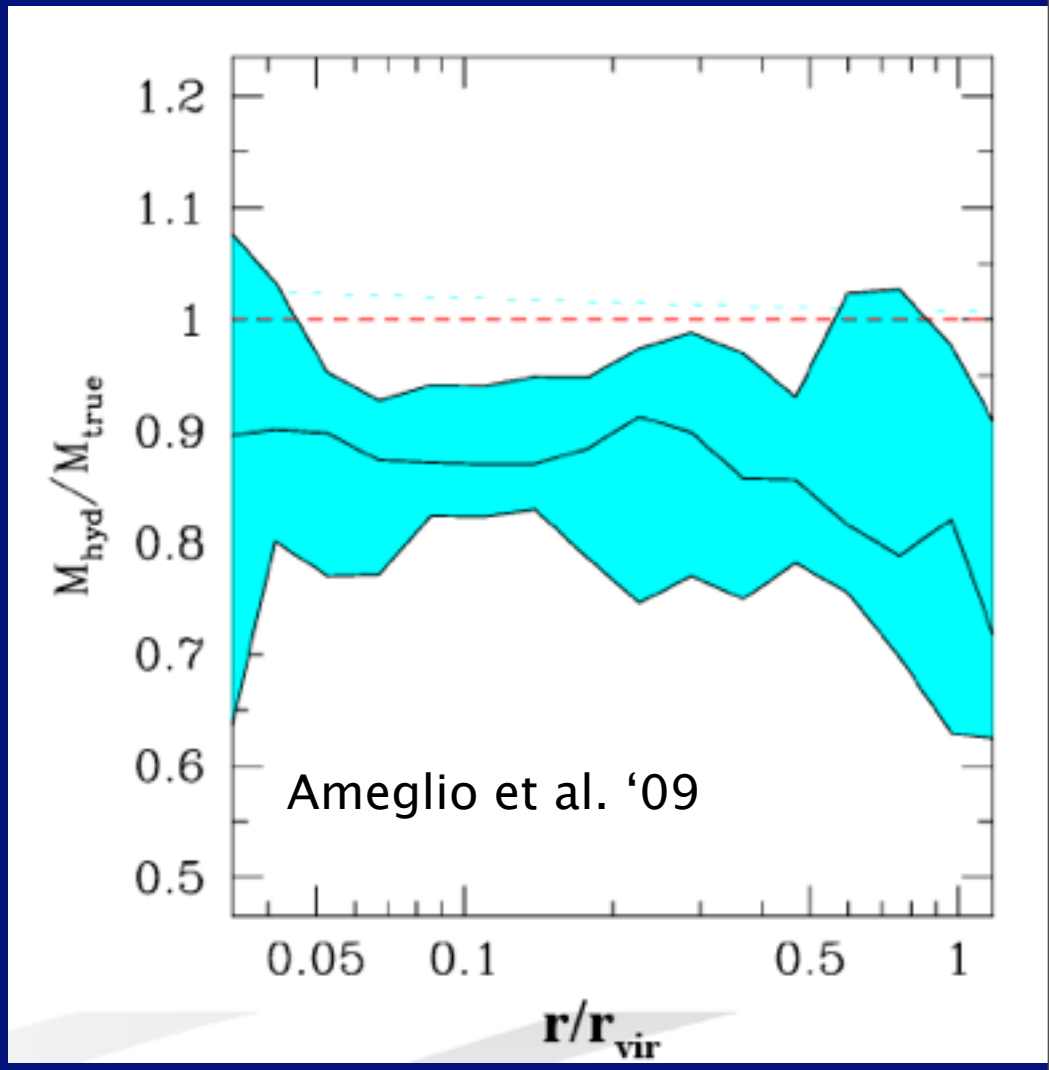
- Hydrostatic equilibrium (HE):

➔ 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



# How reliable is hydrostatic equilibrium?

- Hydrostatic equilibrium (HE):

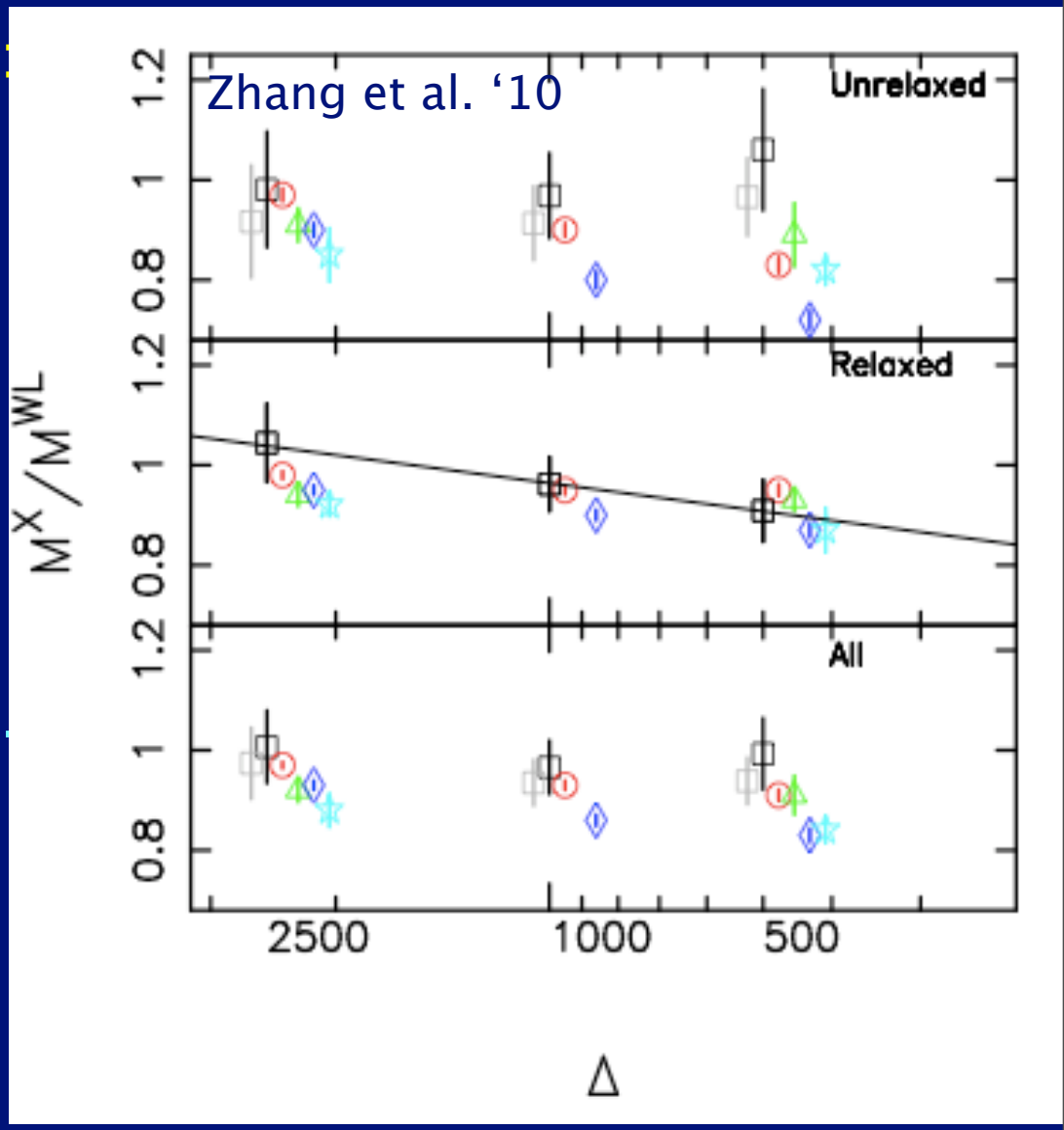
➔ HE violated at the ~10% level within $r_{500}$

➔ 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 (e.g. Zhang et al. '10)

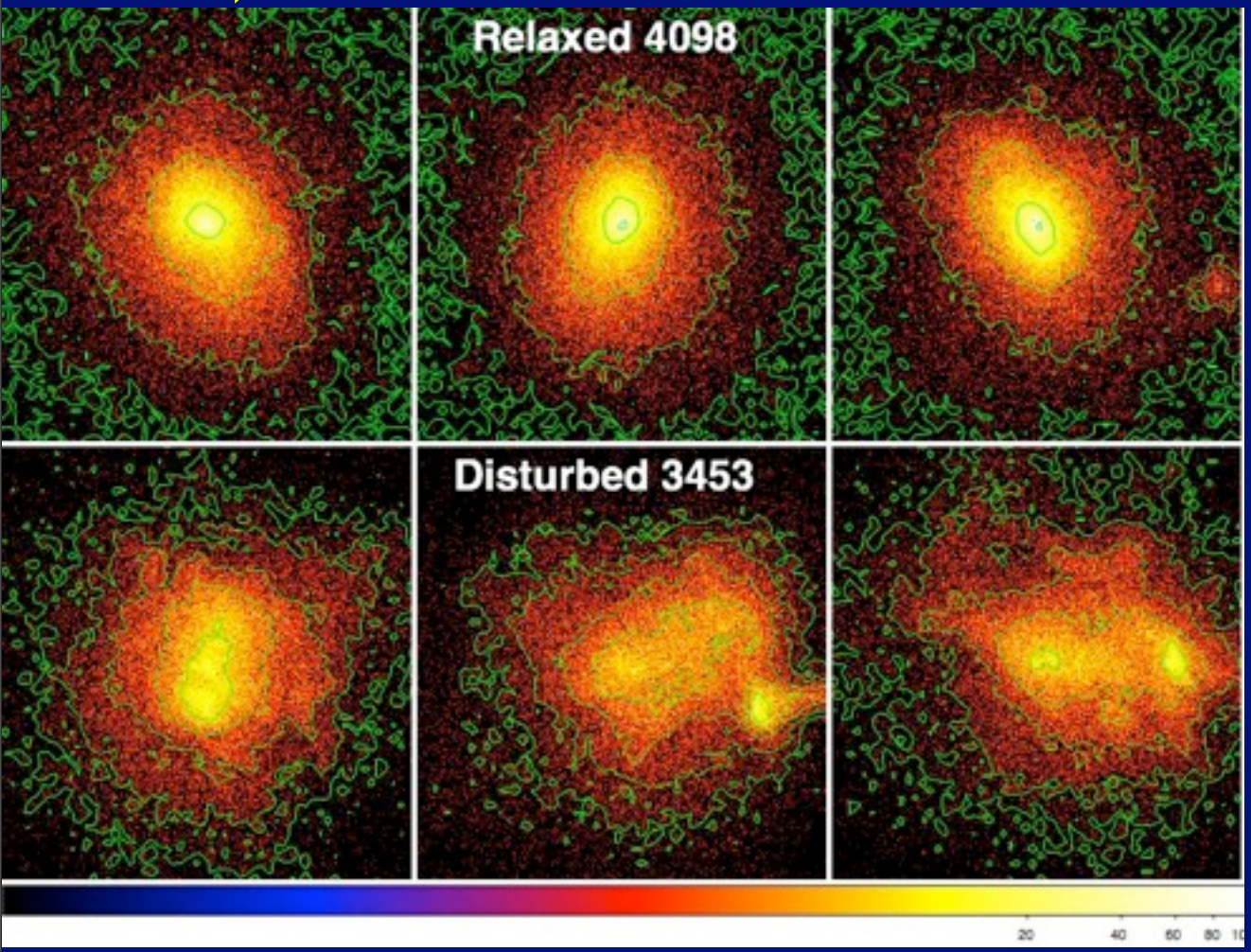


# Mimicking X-ray observations

Rasia et al. '11

➔ Event files from X-MAS Chandra simulator with 100 ks exp. time

➔ [0.7-2] keV X-ray image (16 x 16 arcmin$^2$)




➔ 20 clusters @ z=0.25 with $M_{200} > 5 \times 10^{14}\ M_\odot$

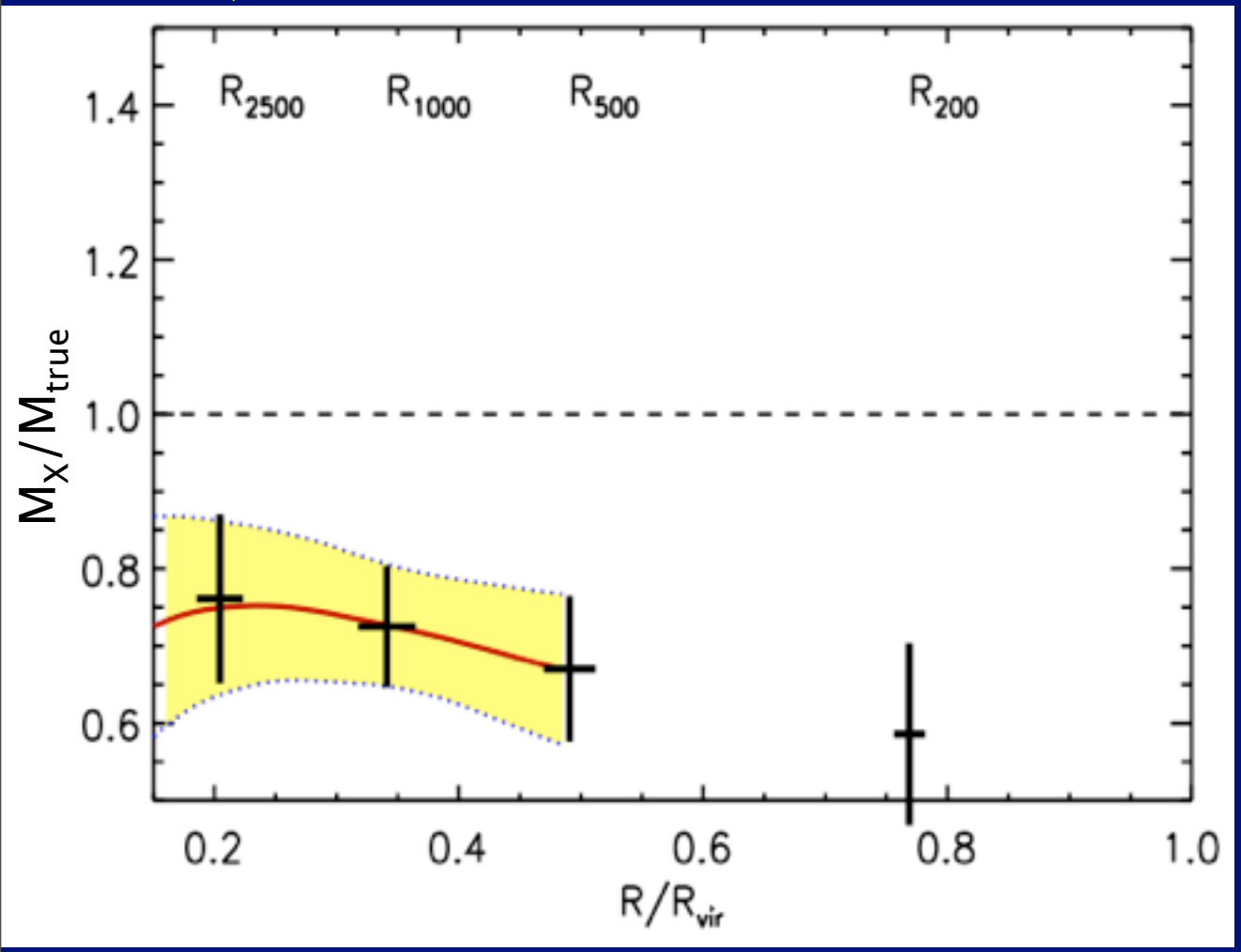
➔ 3 projections for each cluster

# Mimicking X-ray observations

Rasia et al. '11

➔ Event files from X-MAS Chandra simulator with 100 ks exp. time

➔ [0.7-2] keV X-ray image (16 x 16 arcmin$^2$)




➔ 20 clusters @ z=0.25 with $M_{200} > 5 \times 10^{14}\ M_\odot$

➔ 3 projections for each cluster

➔ ~30% mass underestimate at $R_{500}$

➔ 10-15% from HE violation

➔ ~15-20% from bias in X-ray temperature estimate

$T_X \sim 0.8\ T_{mw}$

# … and X-ray/lensing mass comparison

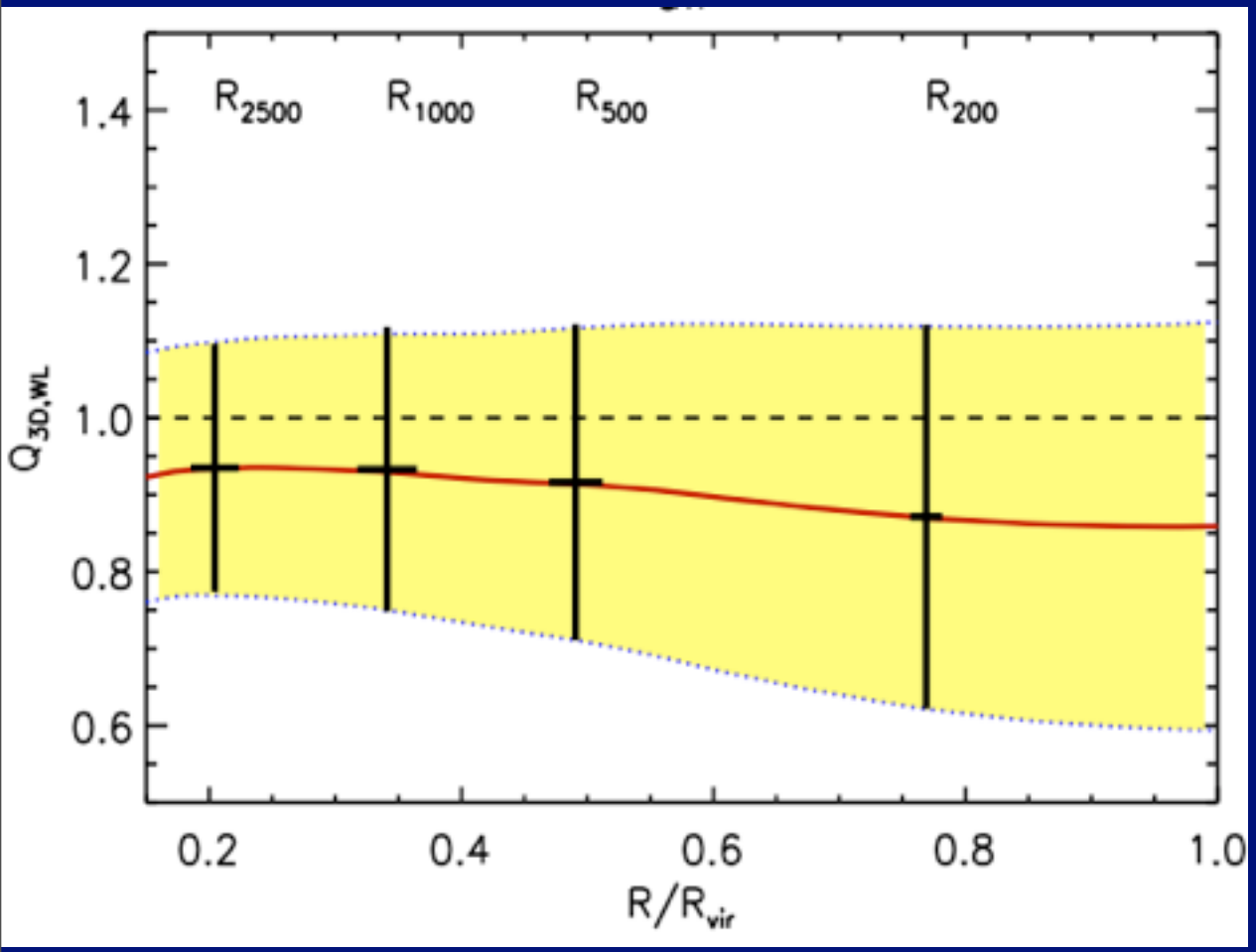
Rasia et al. '11

WFC3 lensing of a massive simulated cluster at z=0.25

Based on the SkyLens tool

# … and X-ray/lensing mass comparison

Rasia et al. '11




WFC3 lensing of a massive simulated cluster at z=0.25

Based on the SkyLens tool

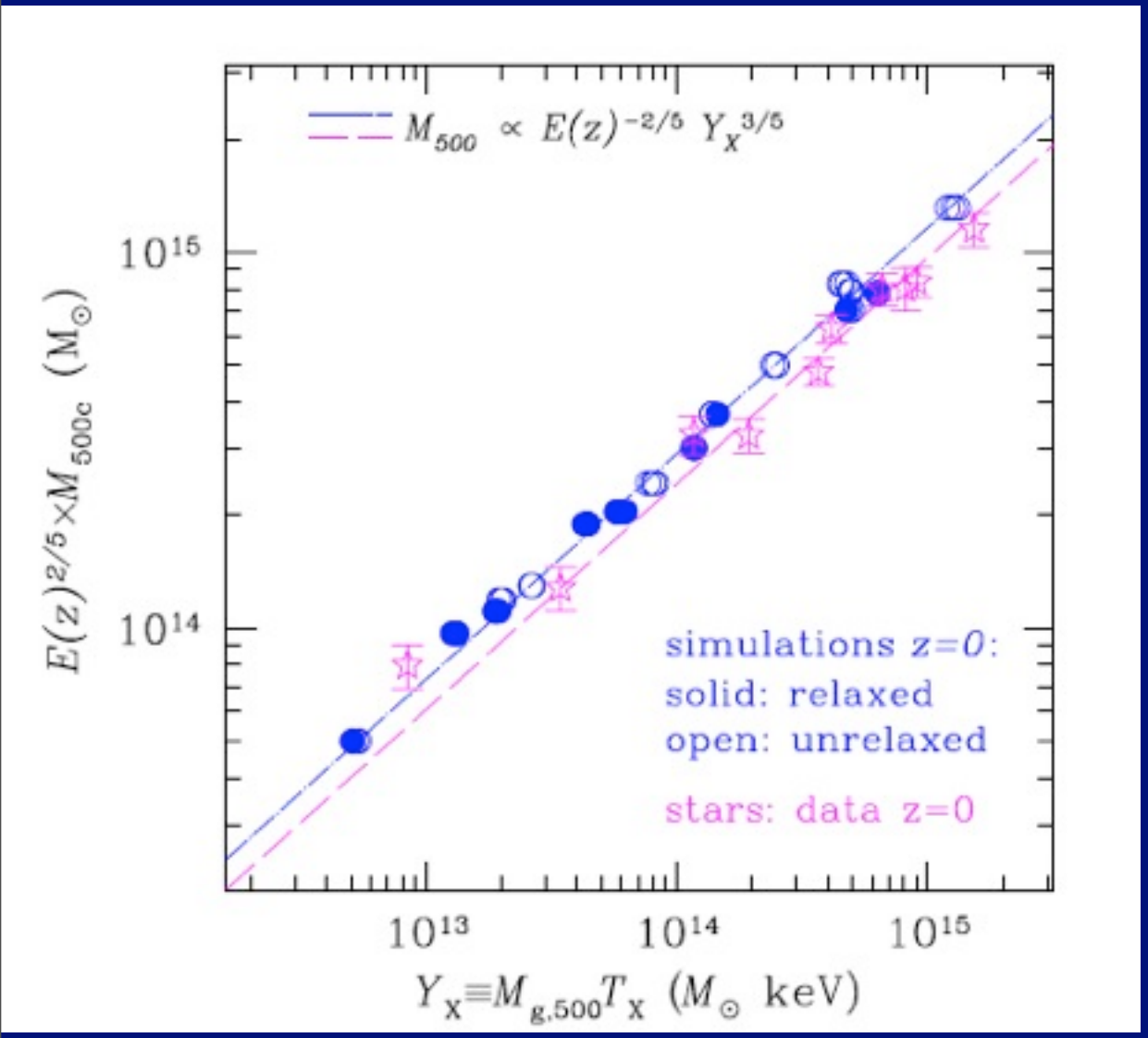
➔ ~10% mass underestimate

at $R_{500}$

➔ ~20% intrinsic scatter

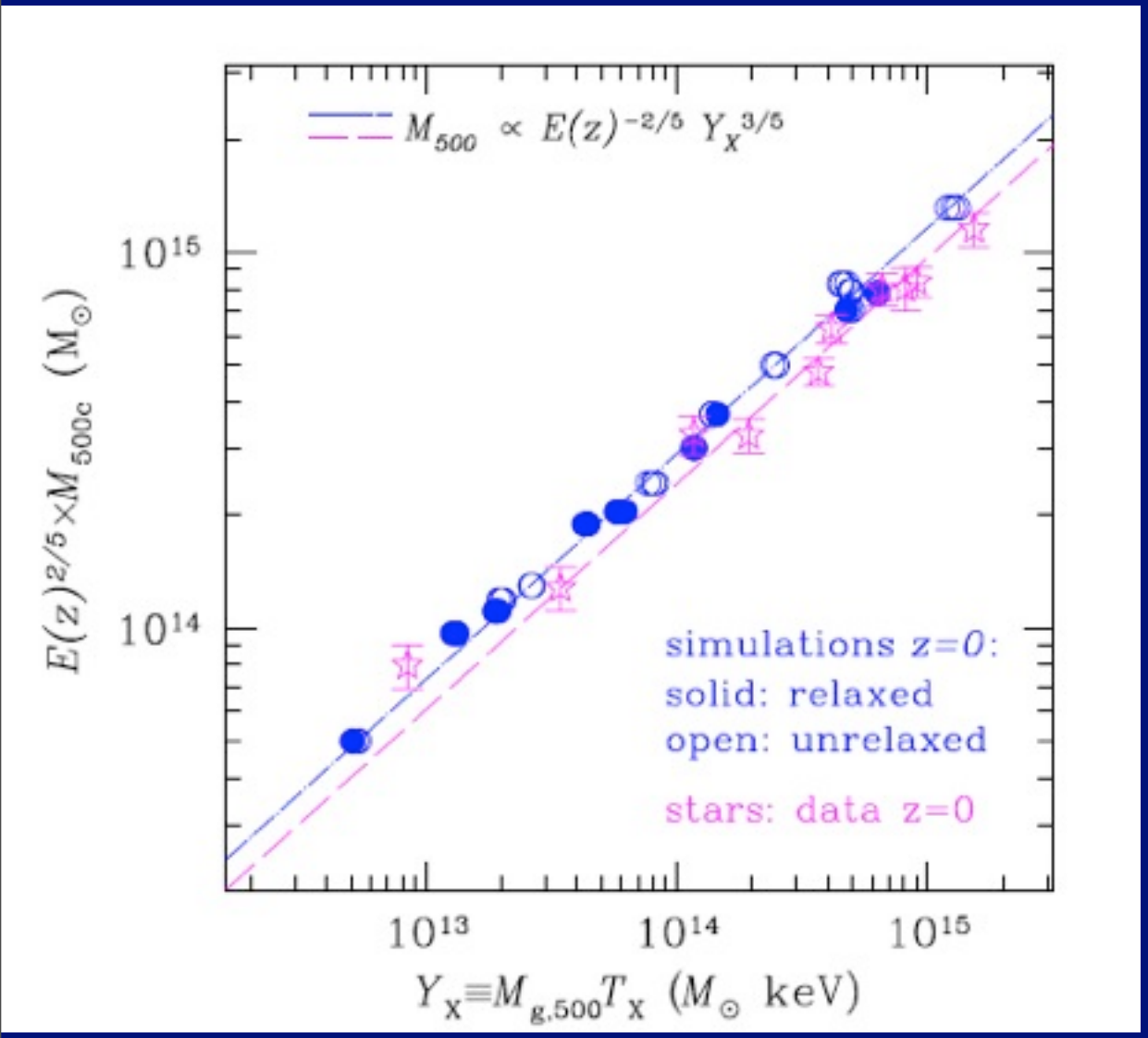
# Mass proxies: X-ray "pressure"

Kravtsov, Nagai & Vikhlinin '06



# Mass proxies: X-ray "pressure"

Kravtsov, Nagai & Vikhlinin '06




X-ray "pressure":

$$Y_X = M_{gas} T_X$$

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

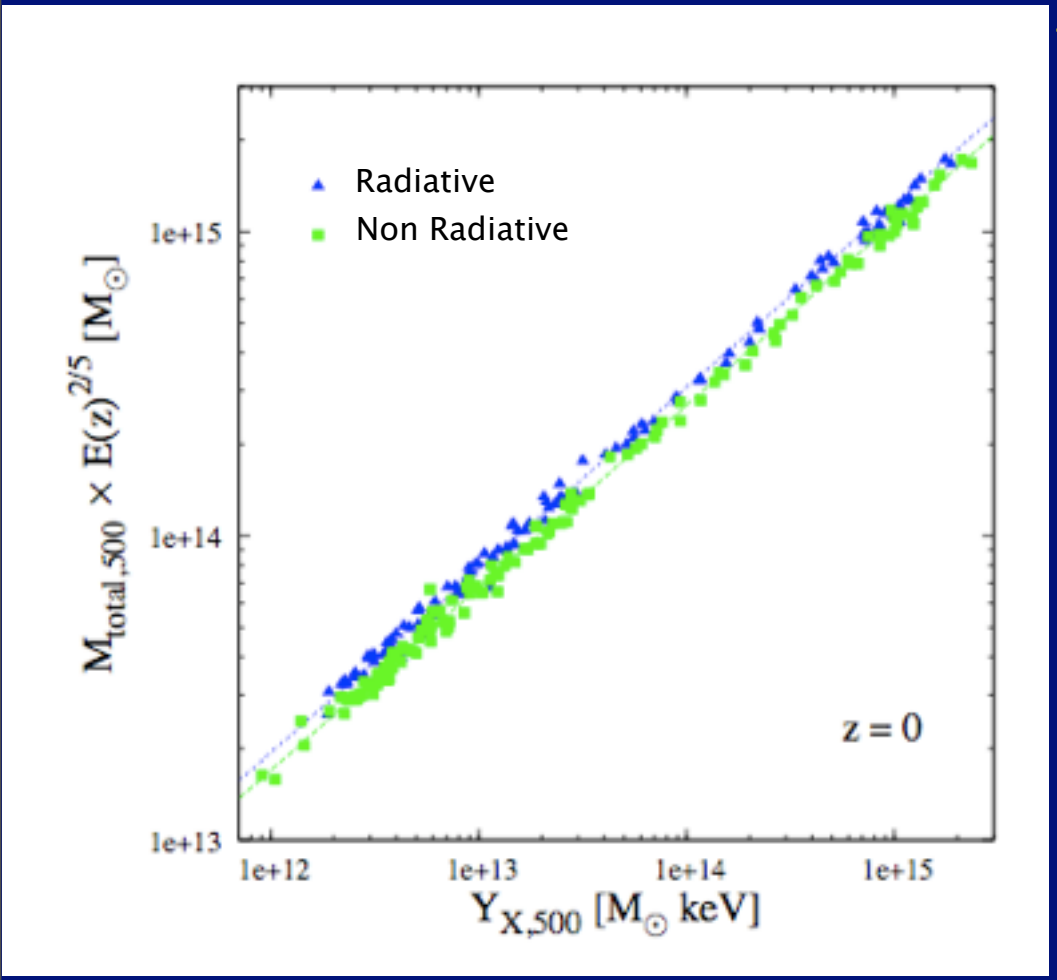
➔ Exclude core regions with R < 0.15 R

# Scaling relations @ z=0

Fabjan et al. '11

$Y_X$

Self-similar: $M_{tot,500} = C_Y E(z)^{-2/3} Y_X^{3/5}$



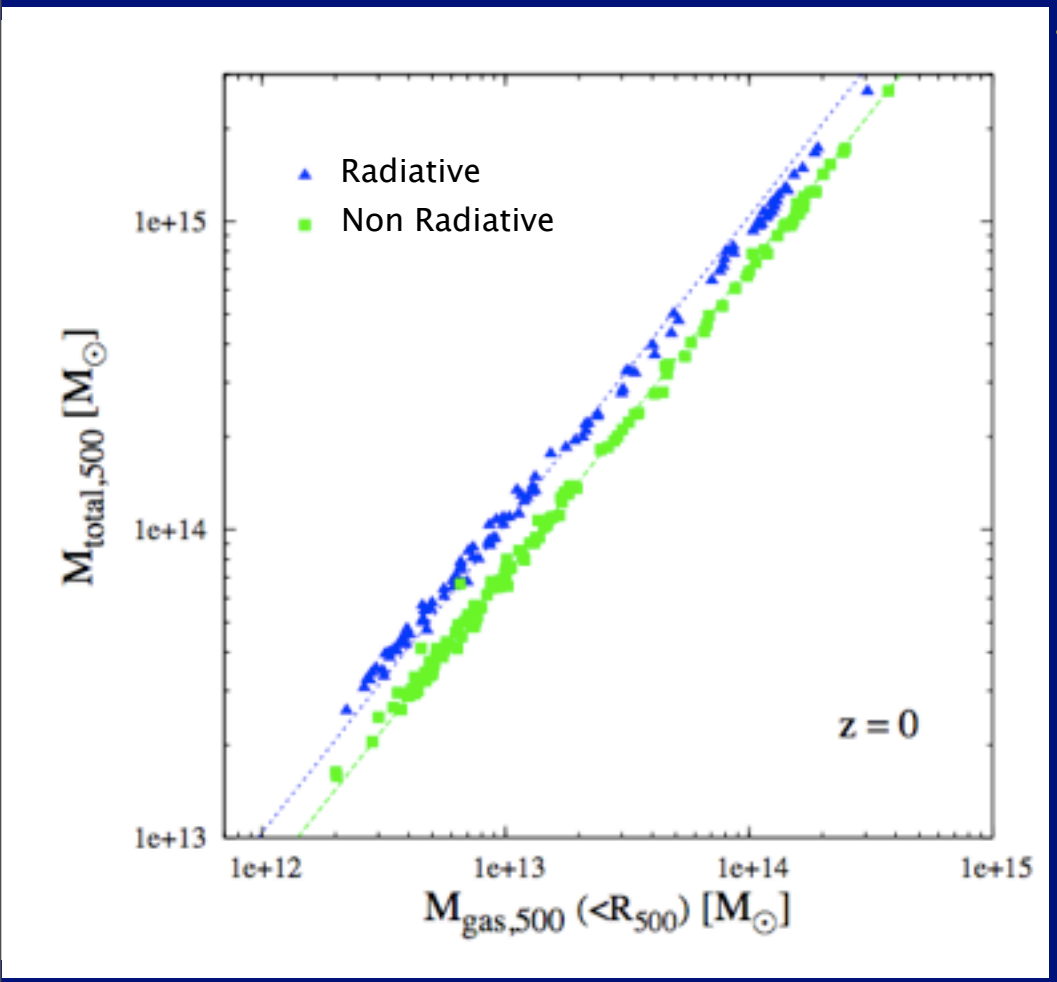

➔Weak (but sizeable) sensitivity to ICM physics

➔Always close to self-similar prediction

(see also Stanek et al. 09)

# Scaling relations @ z=0

Fabjan et al. '11




(see also Stanek et al. 09)

$Y_X$

Self-similar: $M_{tot,500} = C_Y E(z)^{-2/3} Y_X^{3/5}$

➔Weak (but sizeable) sensitivity to ICM physics

➔Always close to self-similar prediction

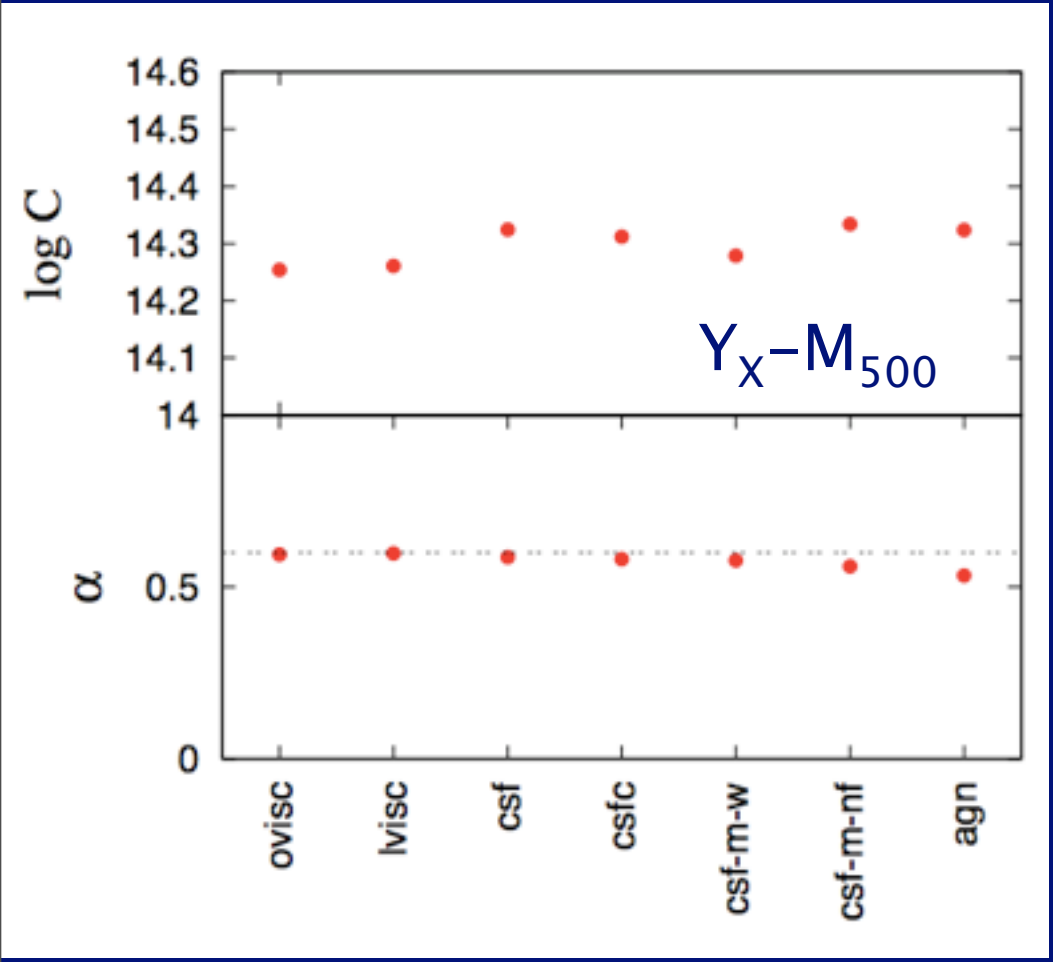
$M_{gas}$

Self-similar: $M_{tot,500} = C_{Mg} M_{gas,500}$

➔More sensitive to ICM physics

➔Larger deviations from self-similar slope for the radiative runs

# Stability against changing the ICM physics




$Y_X$

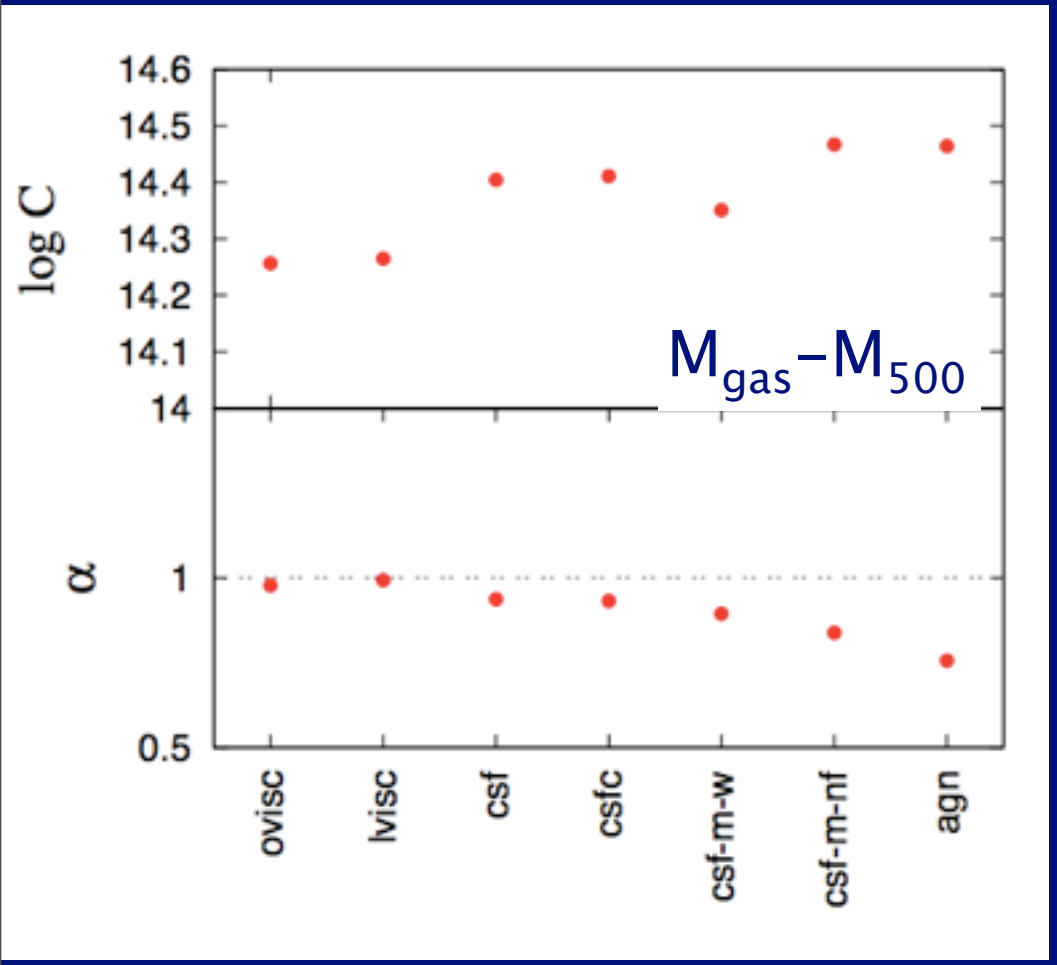
$$M_{tot,500} = C_Y E(z)^{-2/3} Y_X^{\alpha}$$

➔Weak dependence of normalization on ICM physics

➔Slope always very close to self-similar

ovisc: nr-standard viscosity
lvisc: nr-reduced viscosity
csf: cooling+SF
csfc: cooling+SF+conduction
csf-m-nf: chemical enrichment
csf-m-w: chemical enrichment+winds
csf-m-agn: chemical enrichment+AGN

# Stability against changing the ICM physics




ovisc: nr-standard viscosity
lvisc: nr-reduced viscosity
csf: cooling+SF
csfc: cooling+SF+conduction
csf-m-nf: chemical enrichment
csf-m-w: chemical enrichment+winds
csf-m-agn: chemical enrichment+AGN

**$Y_X$**

$$M_{tot,500} = C_Y E(z)^{-2/3} Y_X^{\alpha}$$

➔Weak dependence of normalization on ICM physics

➔Slope always very close to self-similar

**$M_{gas}$**

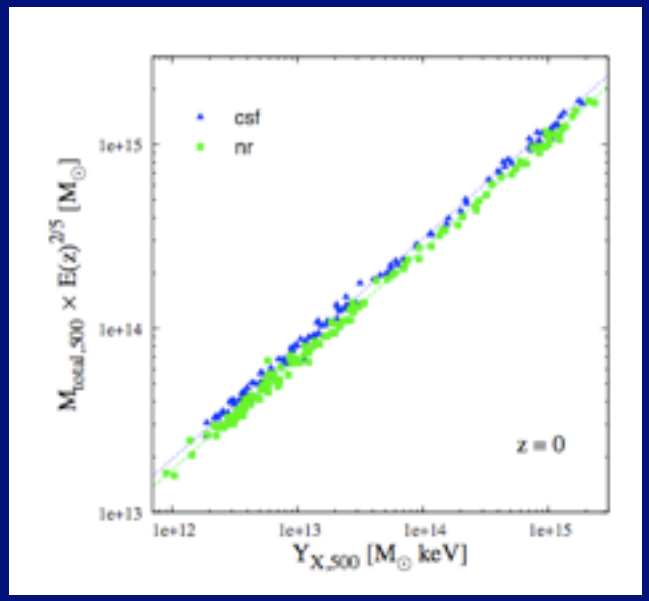
$$M_{tot,500} = C_{Mg} M_{gas,500}^{\alpha}$$

➔More sensitive dependence of amplitude on ICM physics

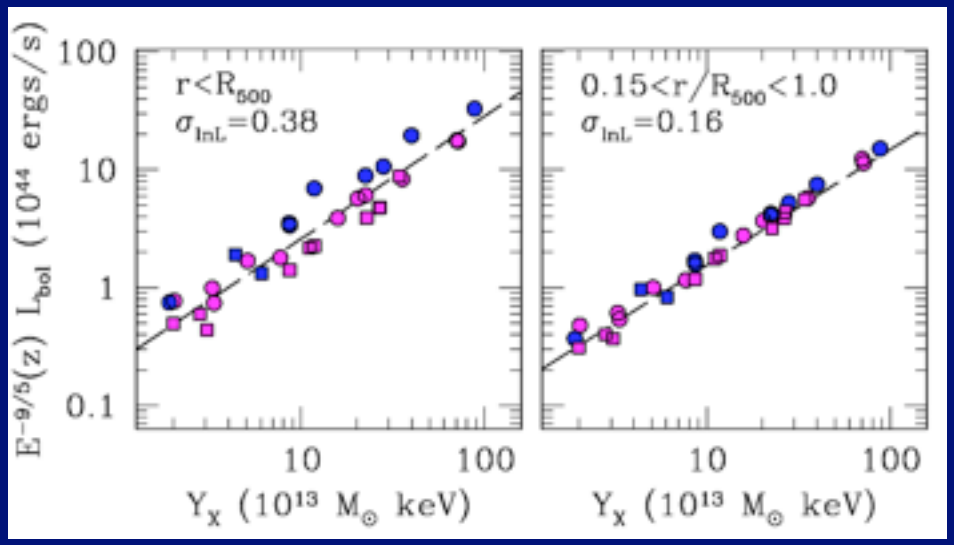
➔Larger deviations from self-similar slope in radiative runs

# Two lessons for future surveys:

# Two lessons for future surveys:



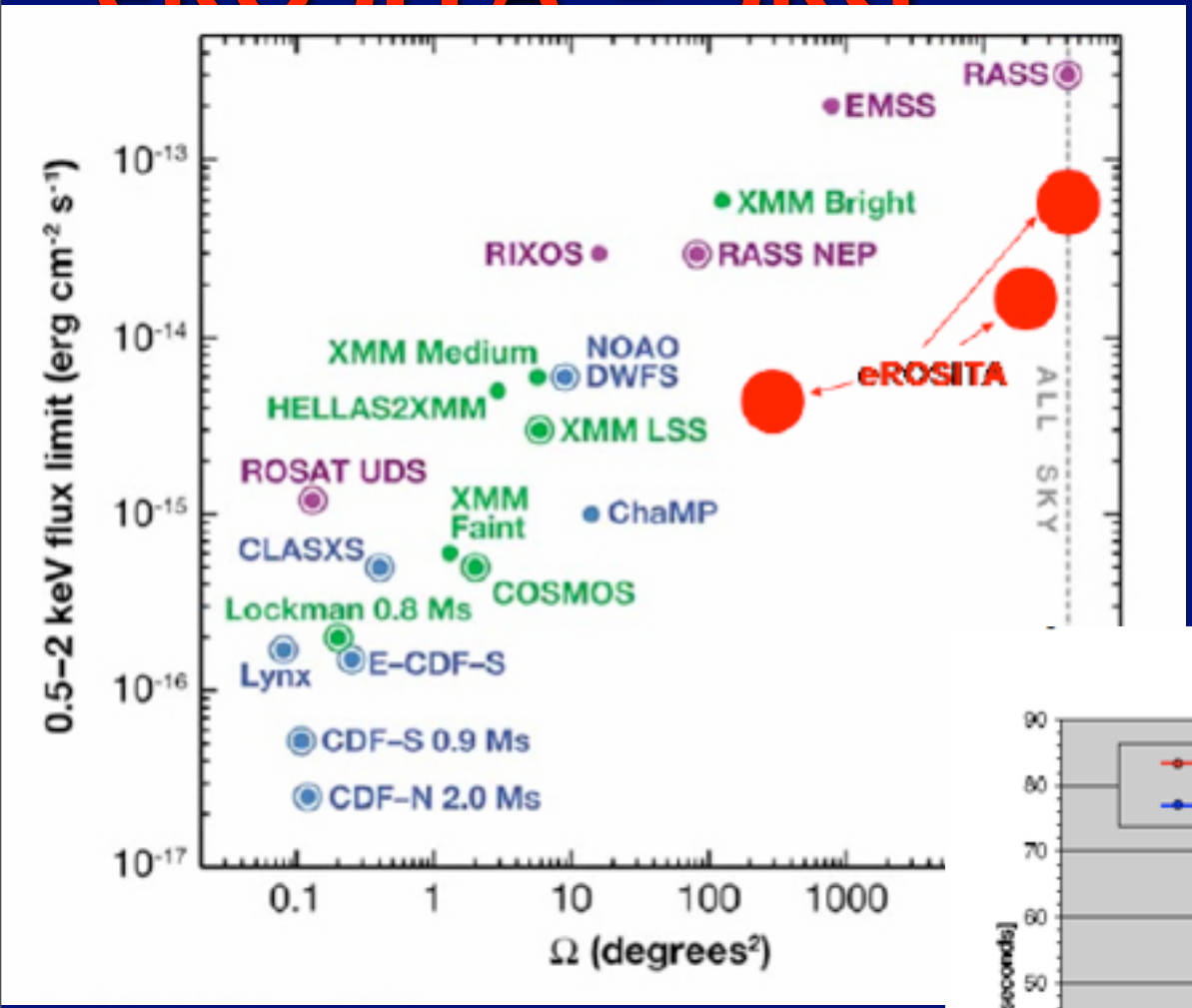

➔ Detect ~$10^3$ net photon counts per cluster to measure robust mass proxies

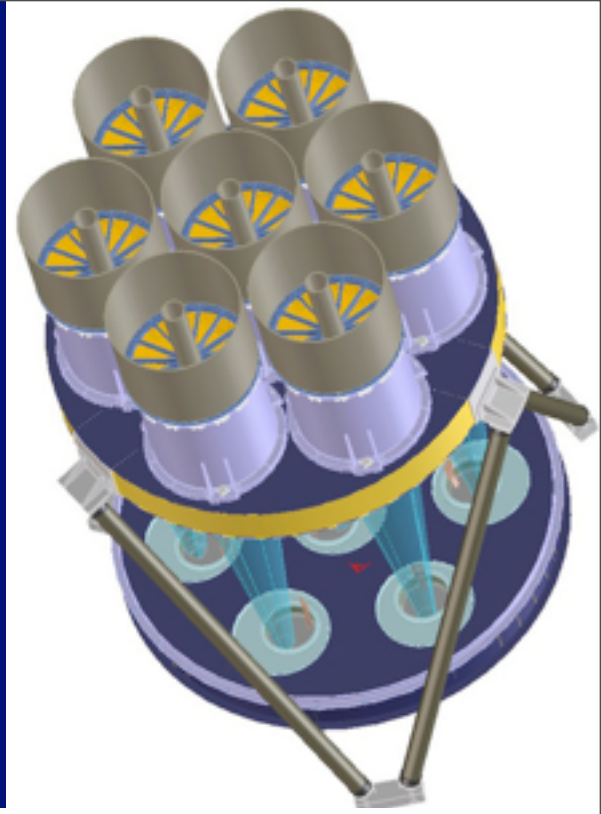


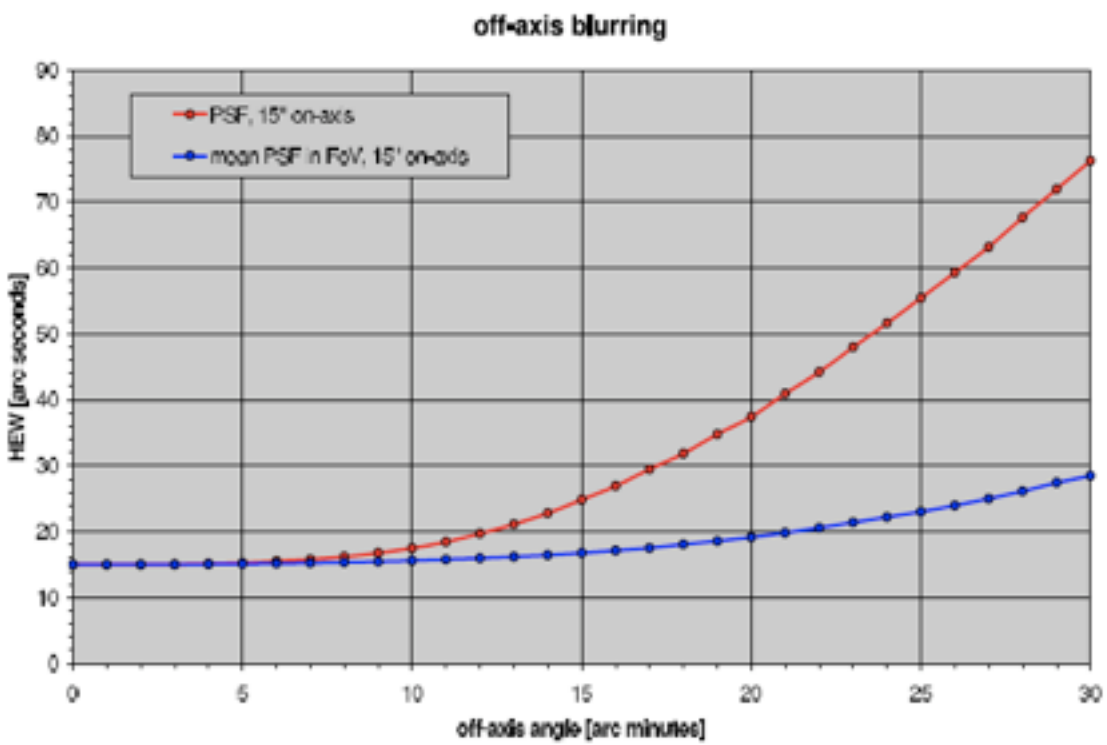

➔ Resolve cluster cores at high redshift to reduce scatter in the M–X calibration

10 arcsec @ z=1
➔ 110 $h^{-1}$ kpc comoving

# eROSITA – SRG






Will detect all $>10^{15} M_\odot$ halos

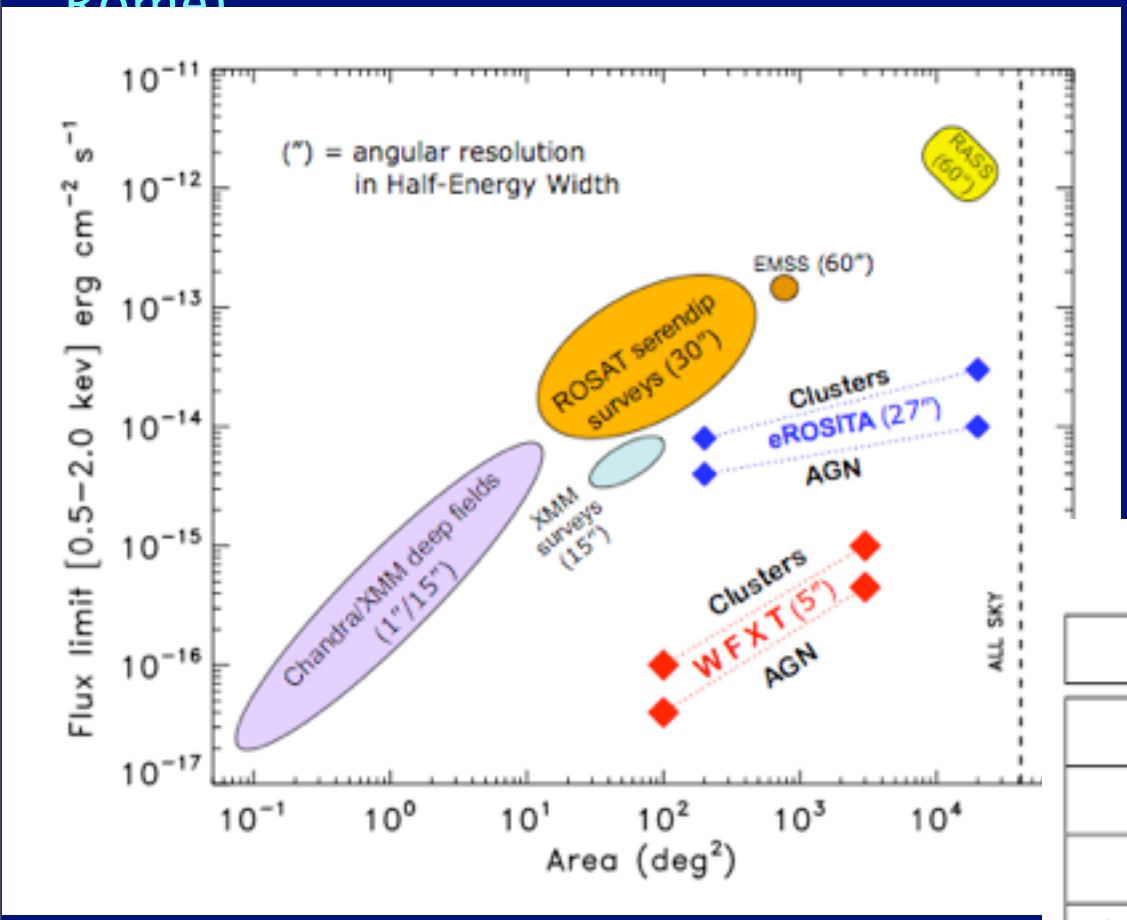
Predehl et al. arXiv:1001.2502

Cappelluti et al. arXiv:1004.5219

# The Wide Field X-Ray Telescope (WFXT

http://www.wfxt.eu

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




Giacconi et al. arXiv:0902.4857

SB et al. arXiv:1010.6213

Rosati et al. arXiv:1010.6252

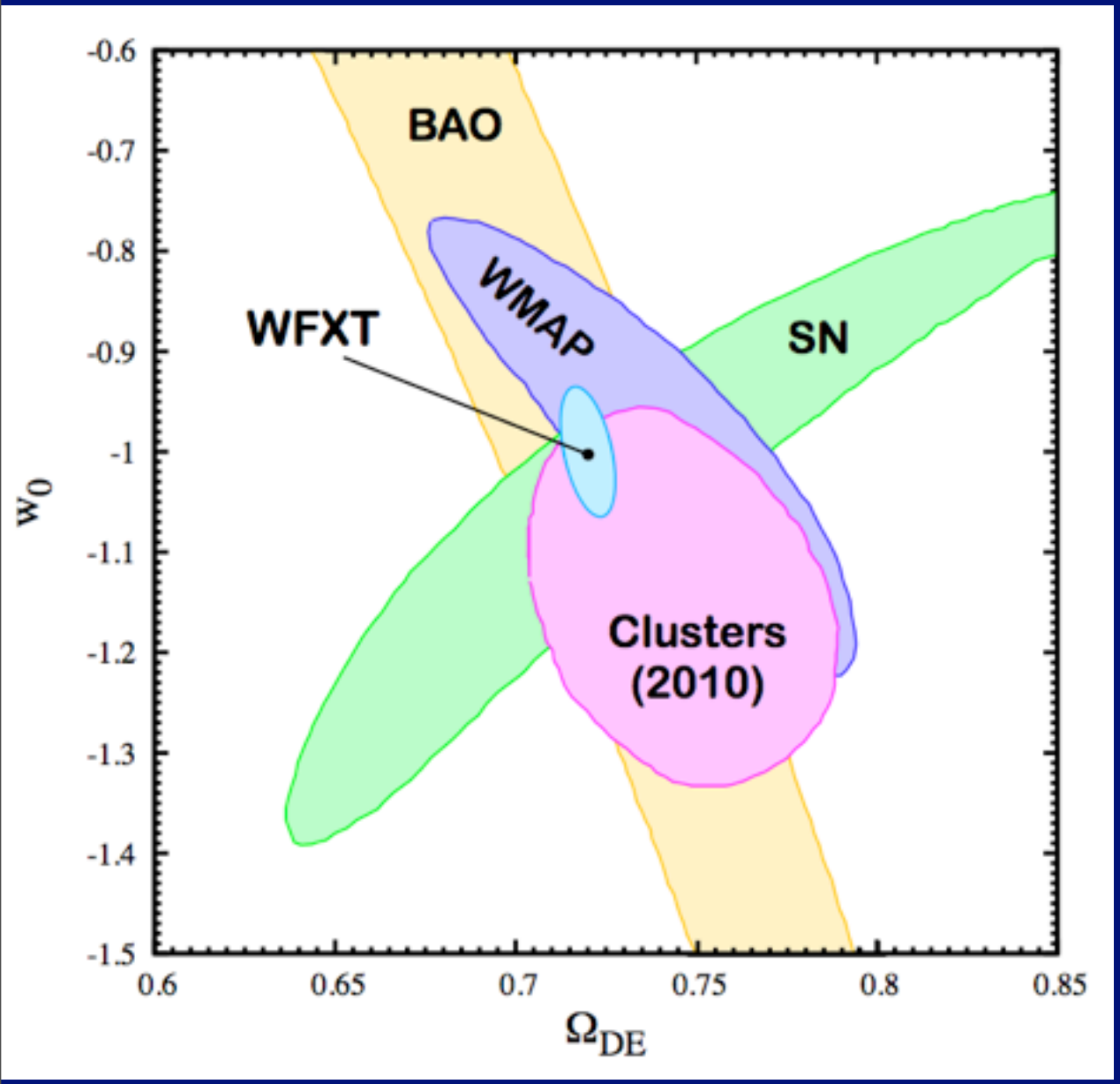
Table 2: WFXT Mission Performance Requirements

| Parameter | Requirement | Goal |
|---|---|---|
| Area (1 keV)$^{(*)}$ | $7,000\,cm^2$ | $10,000\,cm^2$ |
| Area (4 keV) | $2,000\,cm^2$ | $4,000\,cm^2$ |
| Field of View | $1^o$x $1^o$ | $1^o$x $1^o$ |
| Angular Resolution (1 keV) | $5''$ HEW | $\leq 5''$ HEW |
| Pixel Size | $\sim 1''$ | $\sim 1''$ |
| 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 |

Whitepaper submitted to the NASA RFI 2011 Call for X-ray missions:

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

# DE constraints from next-generation X-ray surveys

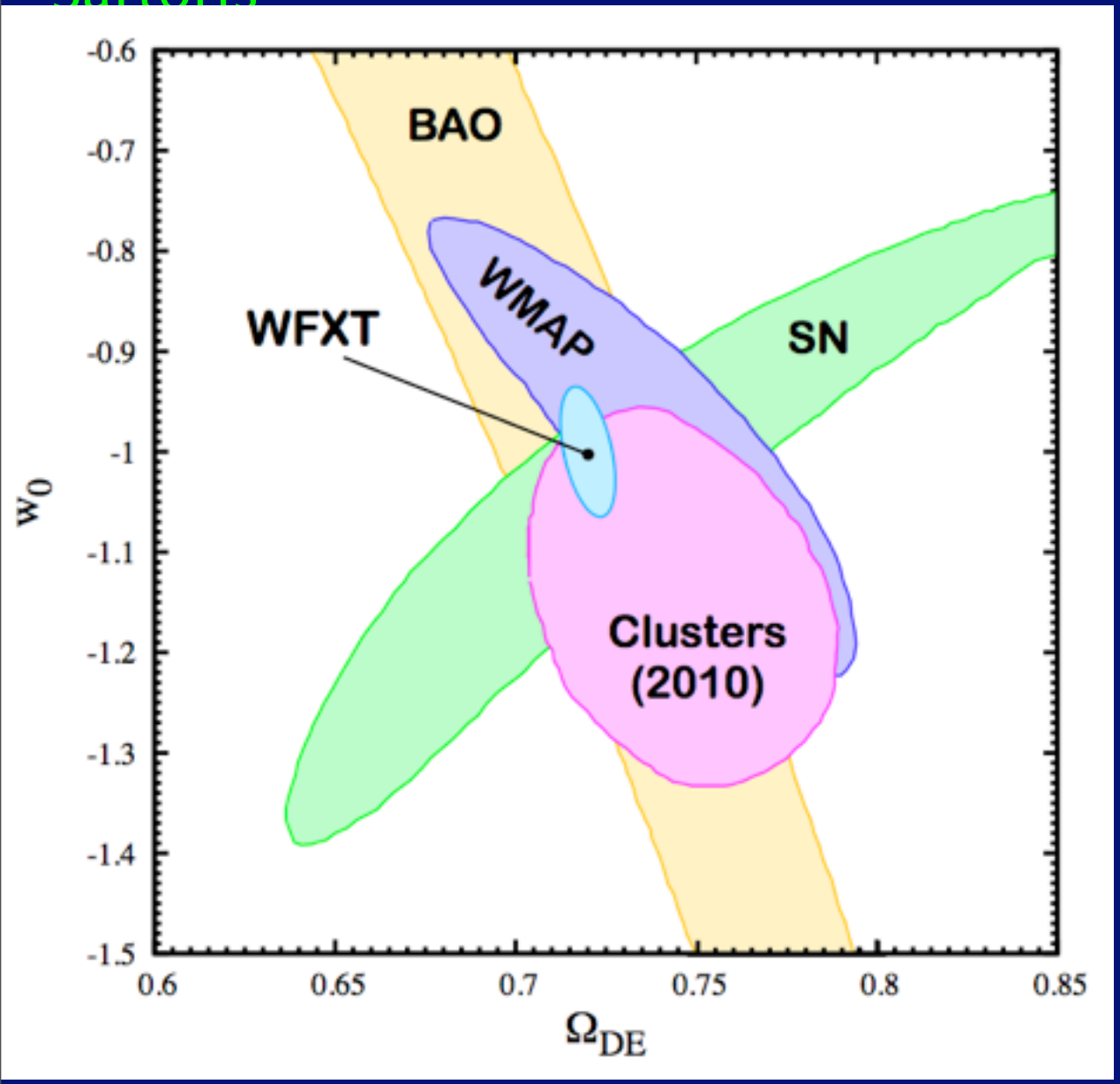



As of today:

~100 ROSAT clusters at <z>~0.5 followed-up with Chandra (Vikhlinin et al. 09, Mantz et al. 10)

# DE constraints from next-generation X-ray surveys

Courtesy of B. Sartoris

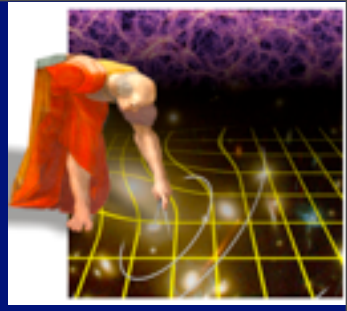


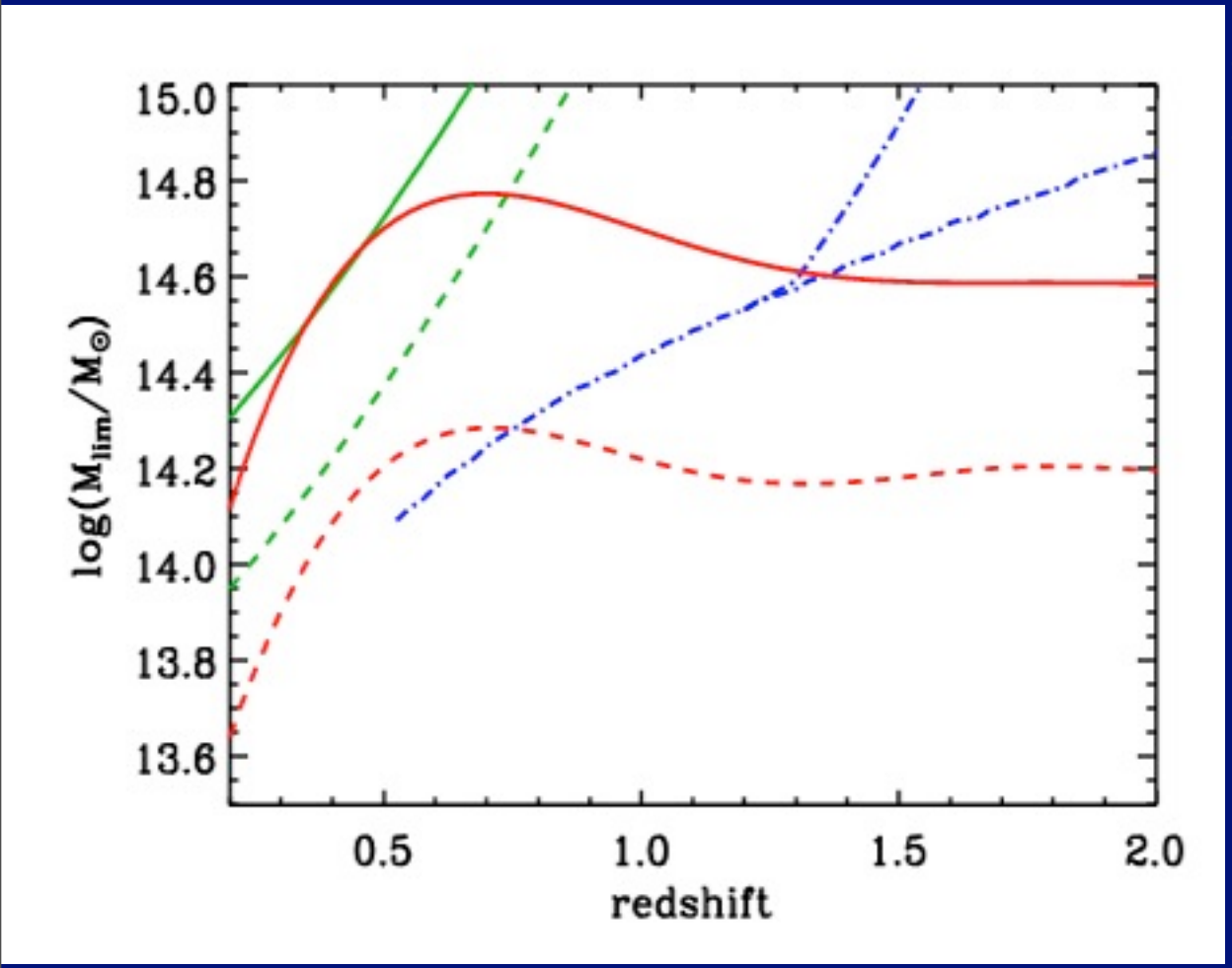

As of today:
~100 ROSAT clusters at <z>~0.5 followed-up with Chandra (Vikhlinin et al. 09, Mantz et al. 10)

WFXT (i.e. beyond eROSITA):
~$10^4$ clusters to be observed with Chandra quality data

Much more than DE EoS:
➔ Scale-dependence of growth
➔ Scale-dependence of bias
➔ …

# EUCLID






Cluster identification in the photometric survey

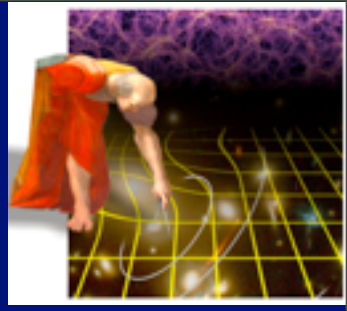
Internal follow-up from:

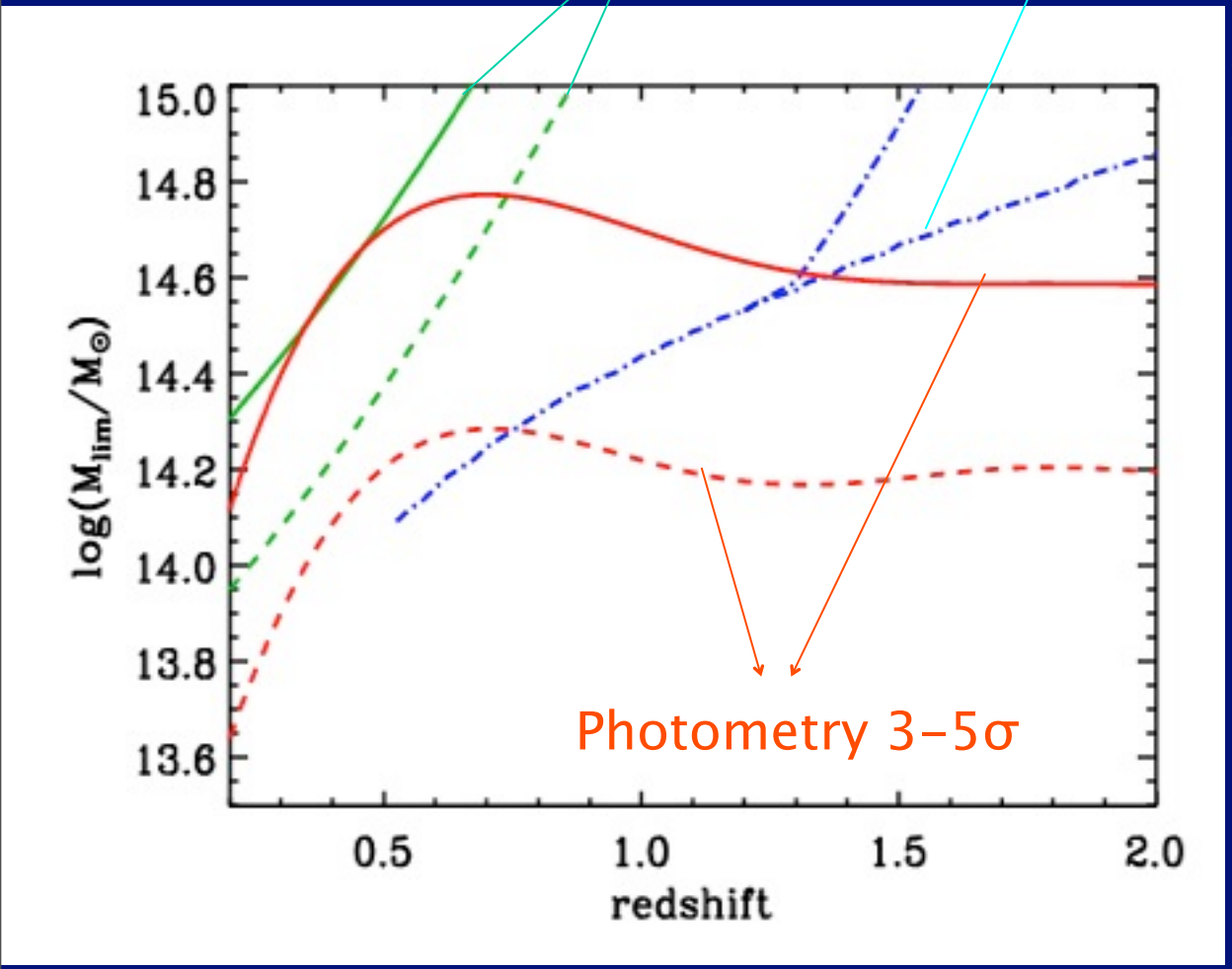
➔ Spectroscopic survey: increase purity and precise redshift measurements

➔ Imaging survey: masses from weak lensing

On behalf of the EUCLID Clusters of Galaxies SWG

# EUCLID






Cluster identification in the photometric survey

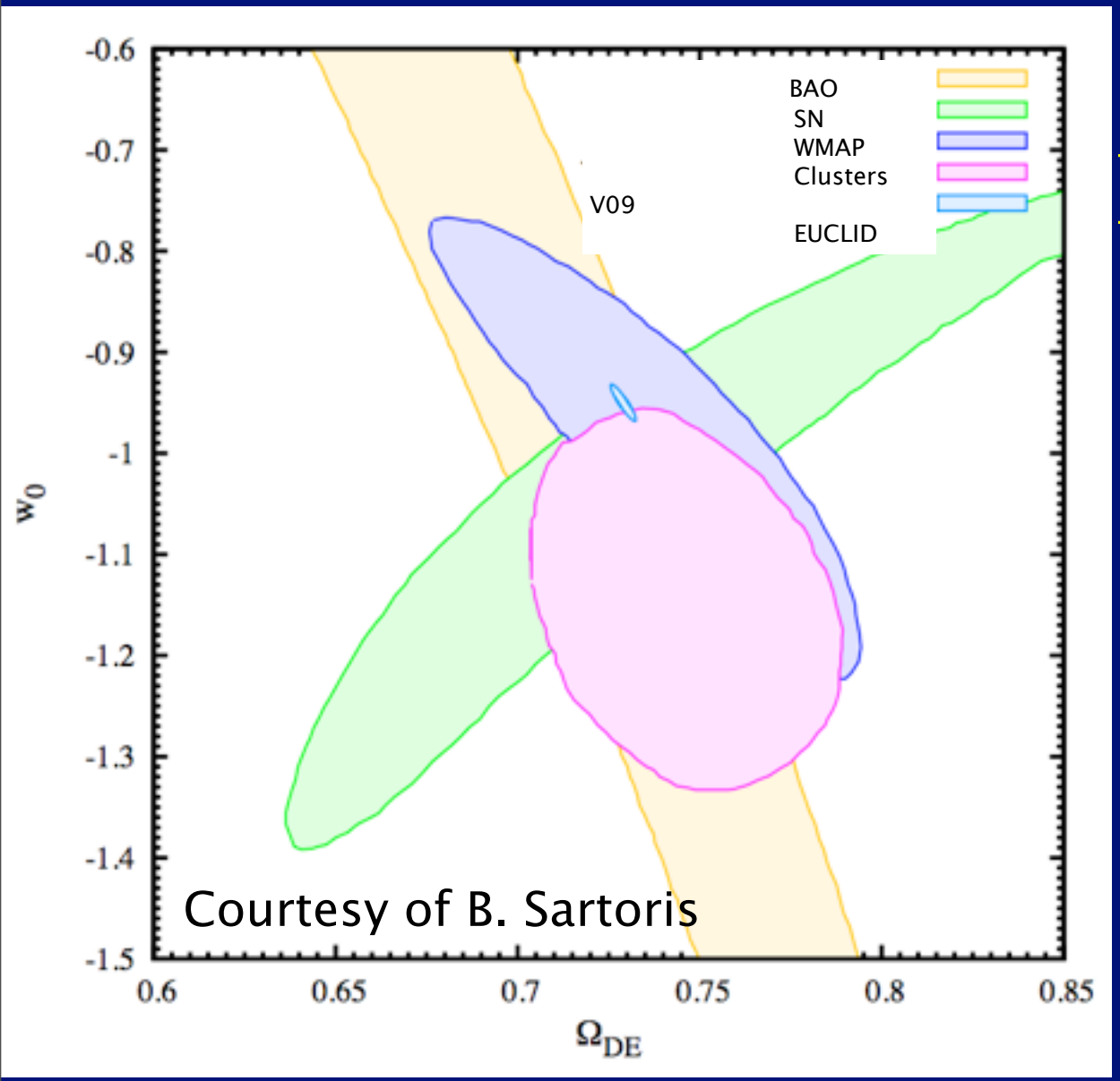
Internal follow-up from:

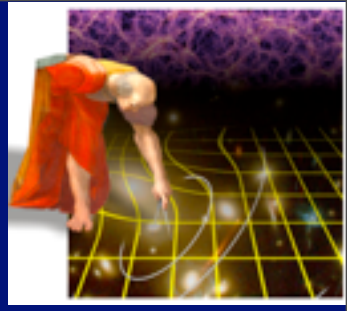
➔ Spectroscopic survey: increase purity and precise redshift measurements

➔ Imaging survey: masses from weak lensing

On behalf of the EUCLID Clusters of Galaxies SWG

# EUCLID



Cluster identification in the photometric survey

Internal follow-up from:

➔ Spectroscopic survey: increase purity and precise redshift measurements

➔ Imaging survey: masses from weak lensing

On behalf of the EUCLID Clusters of Galaxies SWG

# Summary

Advances in cluster cosmology driven by:

1. Quality of observational data

- ➔ Spatial resolution to excise core regions;
- ➔ Collecting area to measure mass proxies

2. Use of cosmological simulations to calibrate

- ➔ Robust and stable mass proxies;
- ➔ Biases in mass measurements

# Summary

Advances in cluster cosmology driven by:

1. Quality of observational data

➔ Spatial resolution to excise core regions;

➔ Collecting area to measure mass proxies

2. Use of cosmological simulations to calibrate

➔ Robust and stable mass proxies;

➔ Biases in mass measurements

➔ Immense synergies between future high-sensitivity X-ray, SZ (e.g. CCAT) and EUCLID surveys!

➔ Calibration of mass function (and bias) could become the limiting factor