Groups/Clusters in Cosmological Context

Stefano Borgani
Dept. of Astronomy & INAF, Trieste

Part 1. Cosmology with galaxy clusters/groups (X-ray biased)

⇒ Why are they useful for cosmology?
Combine nearby and distant systems

⇒ Current status of parameter constraints (σ_8, Ω_m, Ω_Λ, w)

⇒ What's needed to do any better?

Part 2. Astrophysics with groups/clusters

⇒ The IGM / ICM physics with hydro simulations

⇒ Simulations to calibrate groups/clusters as cosmological tools

PART 1:

Cosmology with
galaxy clusters/groups

Different ways of doing cosmology with clusters

(a) The baryon fraction: clusters as fair containers of cosmic baryons

Local clusters: Ω_m once Ω_b known from BBN and/or CMB

Distant clusters:

$$f_{gas}(z)=f_{gas}[d_A(H_0,\Omega_m,\Omega_{DE},w)]=f_{gas}(z=0)$$

(b) The mass function and its evolution:

⇒ Direct probe of σ_8, i.e. P(k) amplitude at the cluster scale;

⇒ Dynamical probe of cosmology, through the linear growth rate of perturbations:

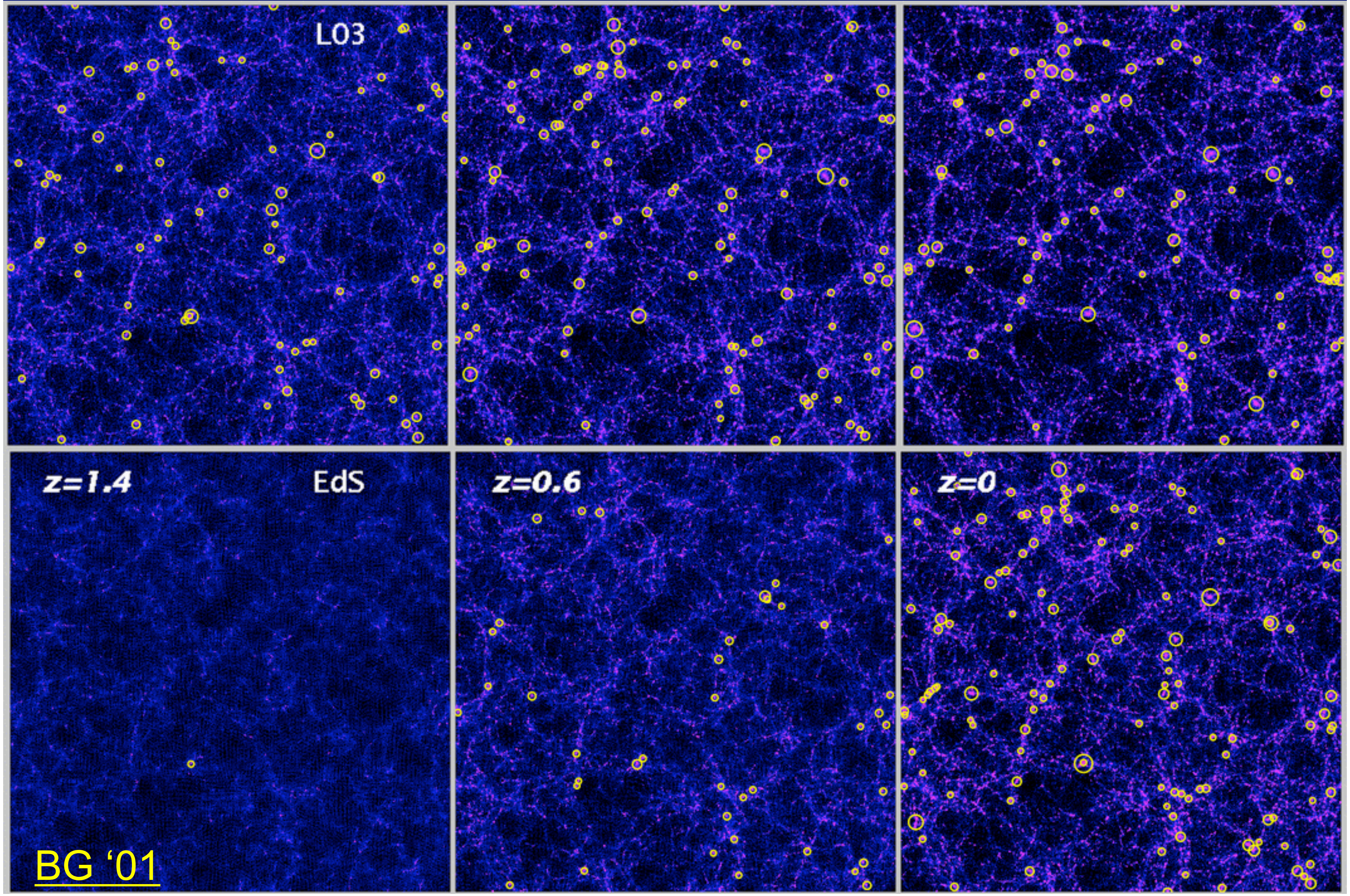
$$D(z) = D(z; \Omega_m,\Omega_{DE},w)$$

(c) Large-scale distribution and clustering of clusters:

⇒ Geometrial probe through the P(k) shape (assuming CDM);

⇒ Cosmology with clustering evolution: **$\xi(r,z)$, P(k,z)**

The evolution of the group/cluster population



What's needed for cosmology with clusters?

(a) A reliable and flexible tool to compute the mass function for a given cosmological model

(b) An efficient method to find clusters:

- sensitivity to detect clusters at high redshift
- negligible impact of false and spurious detections.

(c) A precise knowledge of the selection function

⇒ **searching volume** within which a cluster is found.

$$V_{max} = \int_0^{z_{max}} S[f(L,z)] \left(\frac{d_L(z)}{1+z}\right)^2 \frac{c\,dz}{H(z)}$$

$S(f)$: sky-coverage

$d_L(z)$: luminosity distance

$f = L/(4\pi d_L^2)$: flux

z_{max}: max. z for the given f_{lim}

(d) A reliable method to measure cluster masses

⇒ better if given by the observable on which cluster selection is based.

The Press-Schechter mass function (and beyond)

Assumptions: Spherical collapse + Gaussian perturbations

$$n(M)\,dM = -\frac{2}{V_R}\frac{\partial p(\delta_c, M)}{\partial M}\,dM = \sqrt{\frac{2}{\pi}}\,\frac{\bar{\rho}}{M^2}\,\frac{\delta_c(z)}{\sigma_M}\left|\frac{d\log\sigma_M}{d\log M}\right|\exp\left(-\frac{\delta_c(z)^2}{2\sigma_M^2}\right)dM$$

δ_c: critical density contrast for spherical collapse (=1.69 for EdS)
$p(\delta_c,M)$: Gaussian probability for a perturbation of mass M to exceed δ_c

$$\sigma_M^2(z) = \frac{D^2(z)}{2\pi^2}\int_0^\infty dk\, k^2 P(k) W_M^2(k)$$

⇒ Mass variance at the scale M and redshift z for the filter function $W_M(k)$.

$D(z)=D(z;\,\Omega_m,\Omega_{DE},w)$: linear growth rate of density fluctuations.

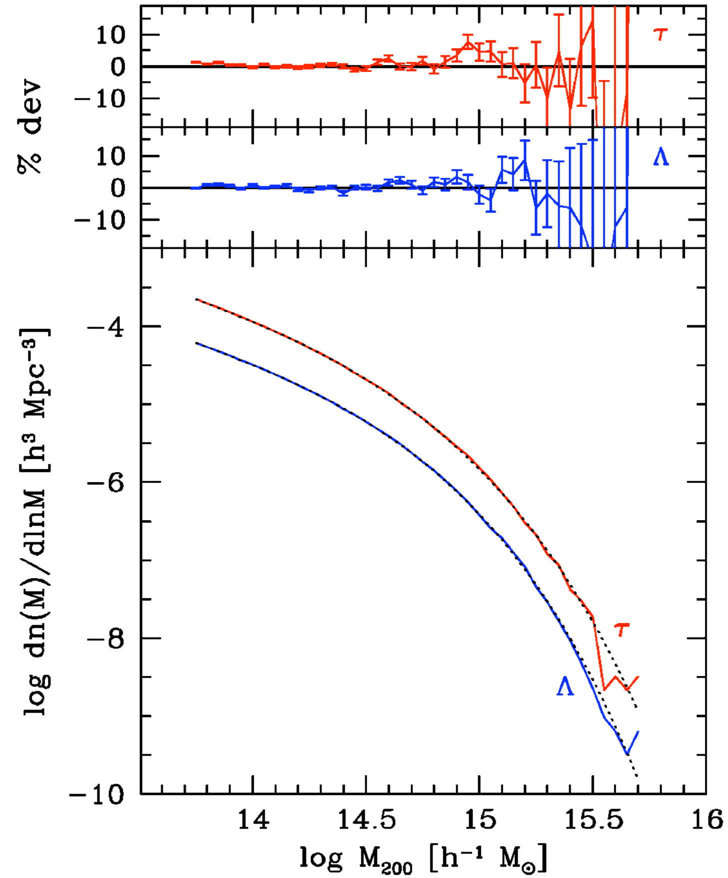
⇒ Too many low-M and too few high-M halos predicted;

⇒ Need to account for the non-spherical nature of collapse (e.g. Sheth & Tormen 1999)

Toward a universal mass function

Testing against N-body over a large dynamical range

Evrard et al. '02

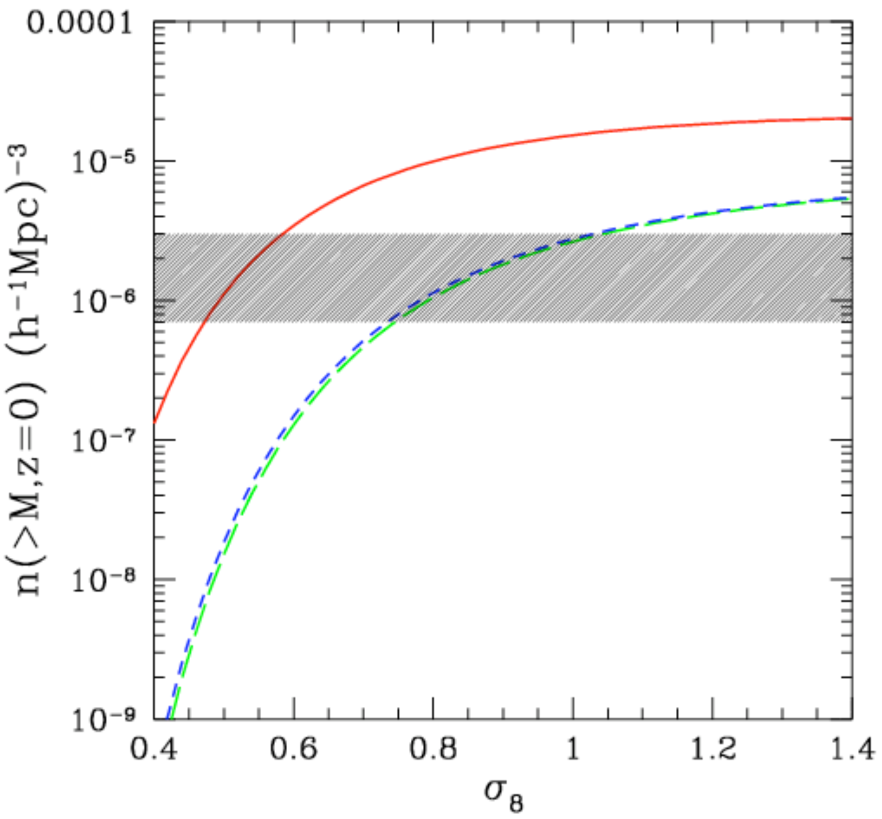


(a) Corrections to the PS MF can be found, which have still a universal (i.e. model-independent) shape.

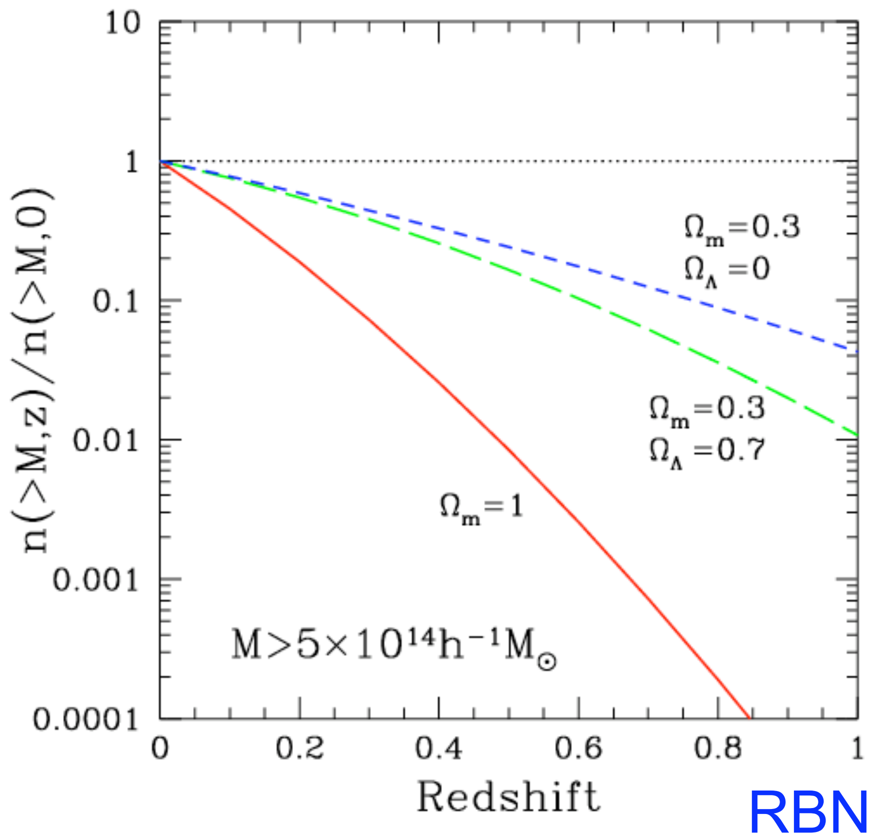
(b) Agreement with the simulated MF always within <10% at the cluster mass-scale.

The mass function as a cosmological test

Changing the P(k) normalization

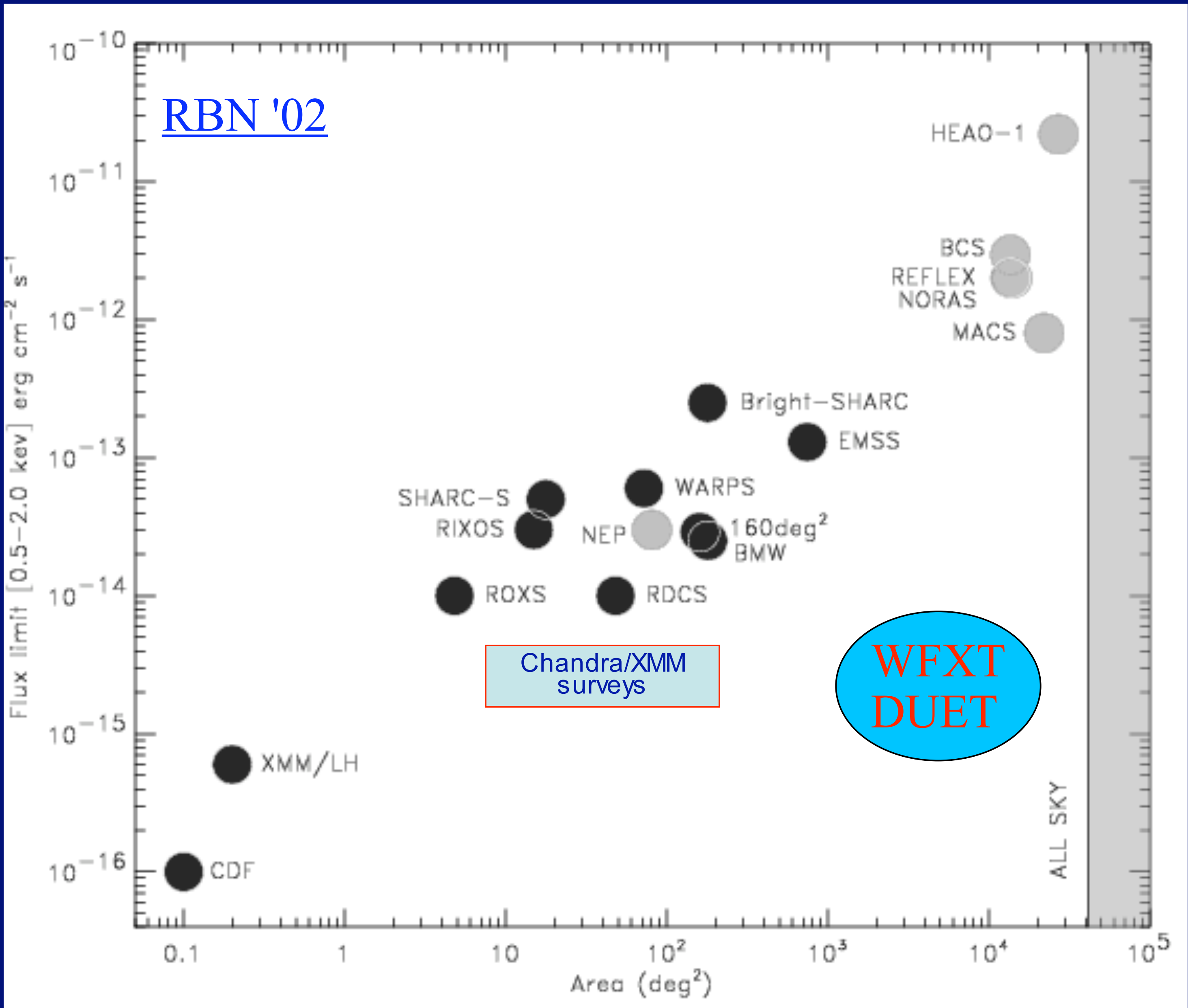


Changing the density parameter



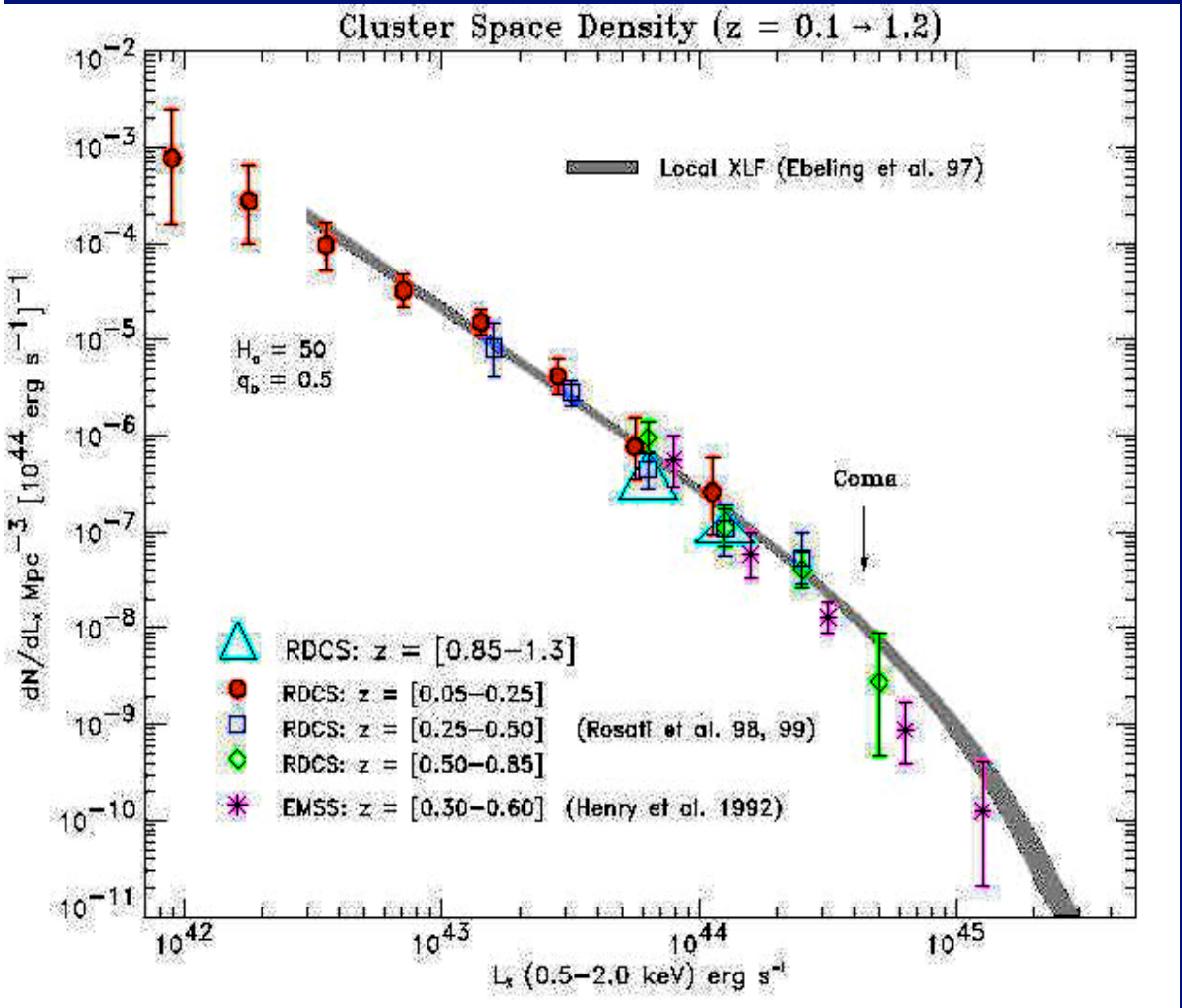
RBN '02

Current status of X-ray surveys



The cluster X-ray luminosity function

Rosati, SB & Norman '02; Mullis et al. '04



Excellent agreement among all the local XLF!

Bulk of the cluster population already in place at z ~ 1!

Groups and clusters as a unique (X-ray) family.

How to estimate cluster masses?

(a) Dynamics as traced by member galaxies

Assuming virialization of a spherical system:

$$M \approx \frac{\sigma_v^{\,2} R_v}{G}$$

σ_V: velocity dispersion of member galaxies.

R_V: virial radius.

Applied to: ENACS, CNOC, 2dFGRS, SDSS

(b) Dynamics of the collisional component (gas)

Hydrostatic equilibrium:

$$M \approx \frac{k_B T R_v}{G \mu m_p}$$

$k_B T$ from X-ray or SZ observations.

μ : mean molecular weight

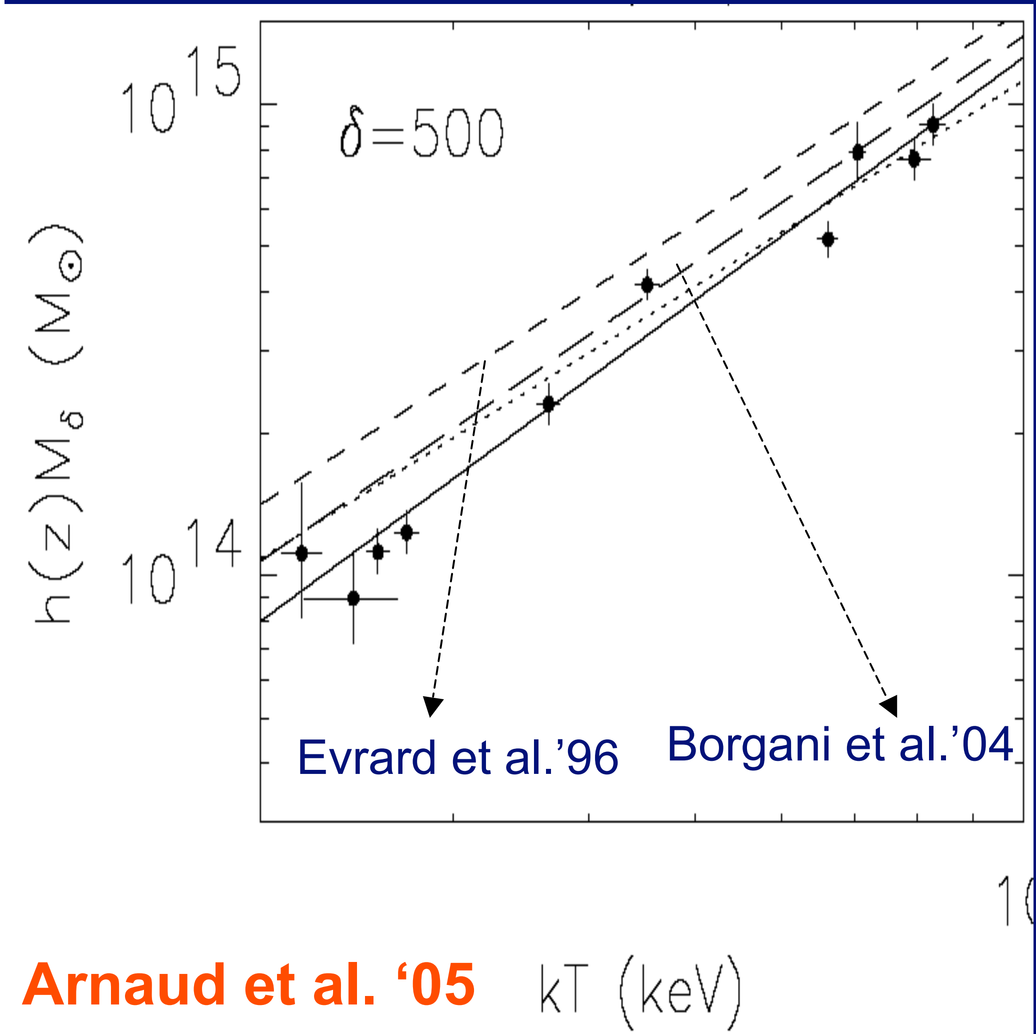
m_p: proton mass

(c) Phenomenological scaling relations

$$L_X \sim T^{\alpha} (1+z)^{A} \quad ; \quad L_X \sim M^{\gamma} (1+z)^{\Gamma}$$

(d) Weak and strong gravitational lensing

The M-T relation of nearby clusters



Arnaud et al. '05

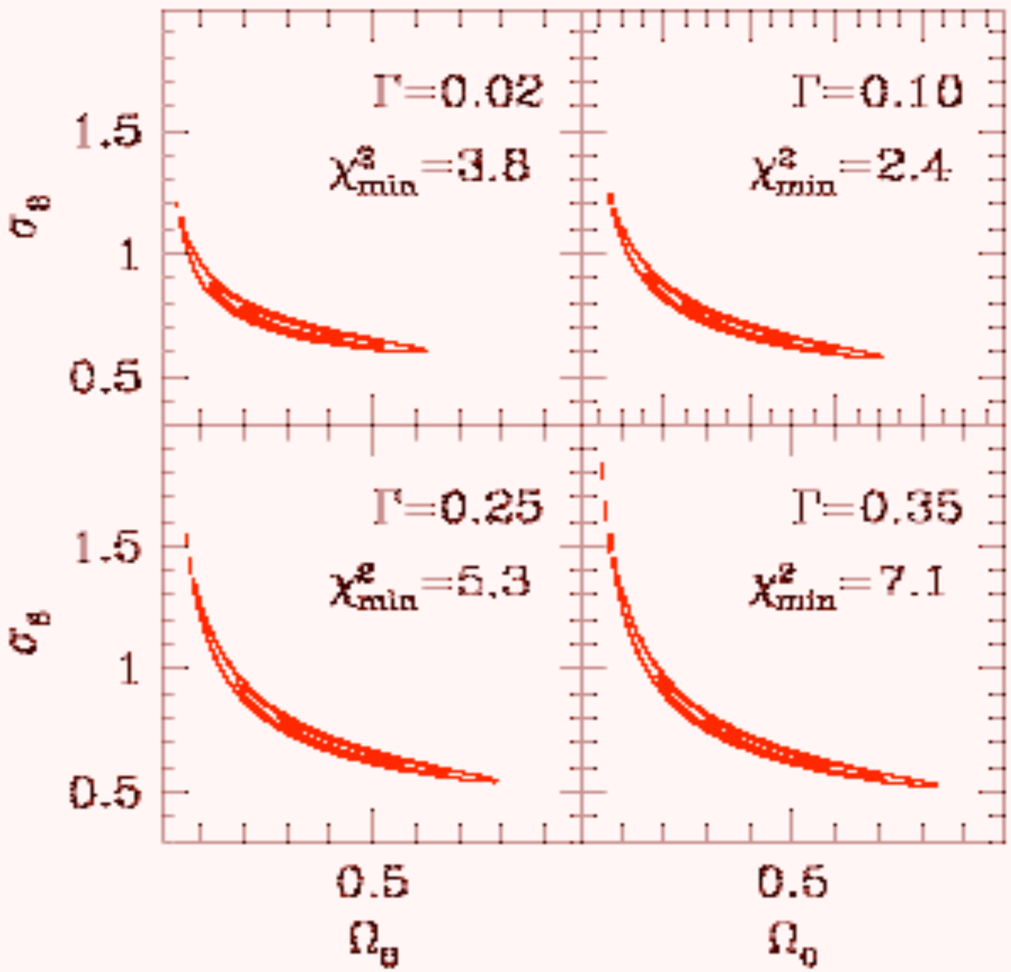
ASCA: isothermal gas + β-model
(Nevalainen et al. '00)

ASCA: politropic gas + β-model
(Finoguenov et al. '01)

<u>Resolved T_X profiles:</u>

Beppo-SAX
(Ettori et al. '02)
Chandra
(Allen et al. '01)
XMM-Newton
(Arnaud et al. 2005)

Constraints from the X-ray temperature function



Eke et al. (1998)

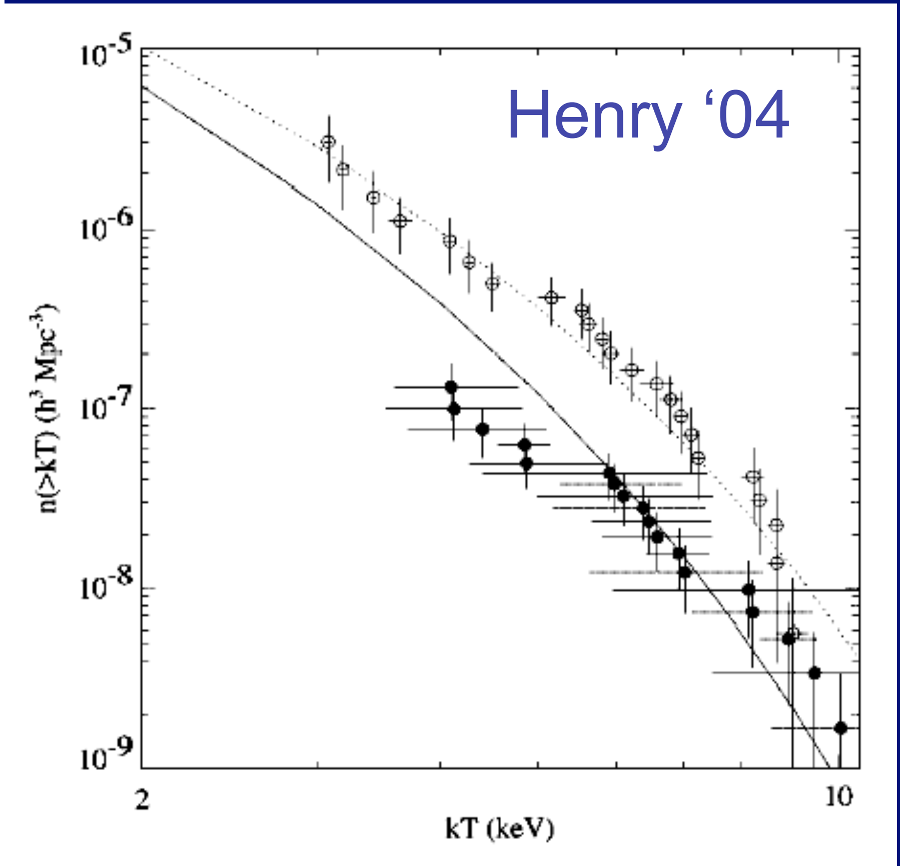
25 clusters at z<0.1 (Henry & Arnaud ’91)

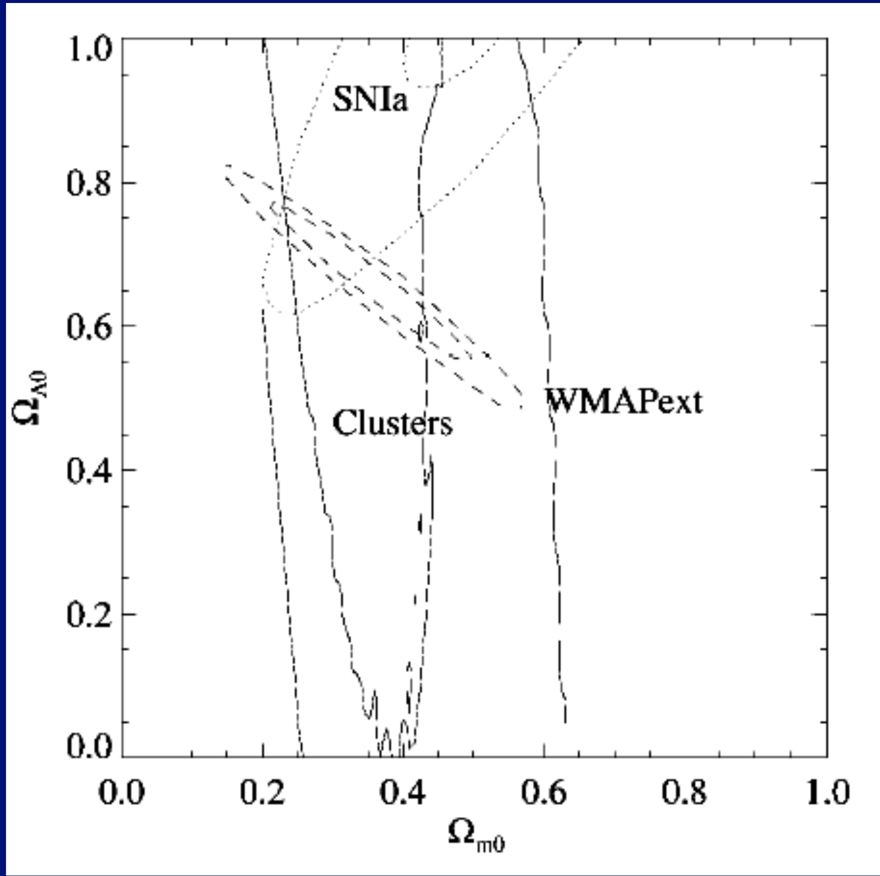
10 EMSS clusters with 0.3 < z < 0.4 (Henry ’97)

Ω_m=0.45 ± 0.20

σ_8=0.7 ± 0.1

Constraints from the X-ray temperature function

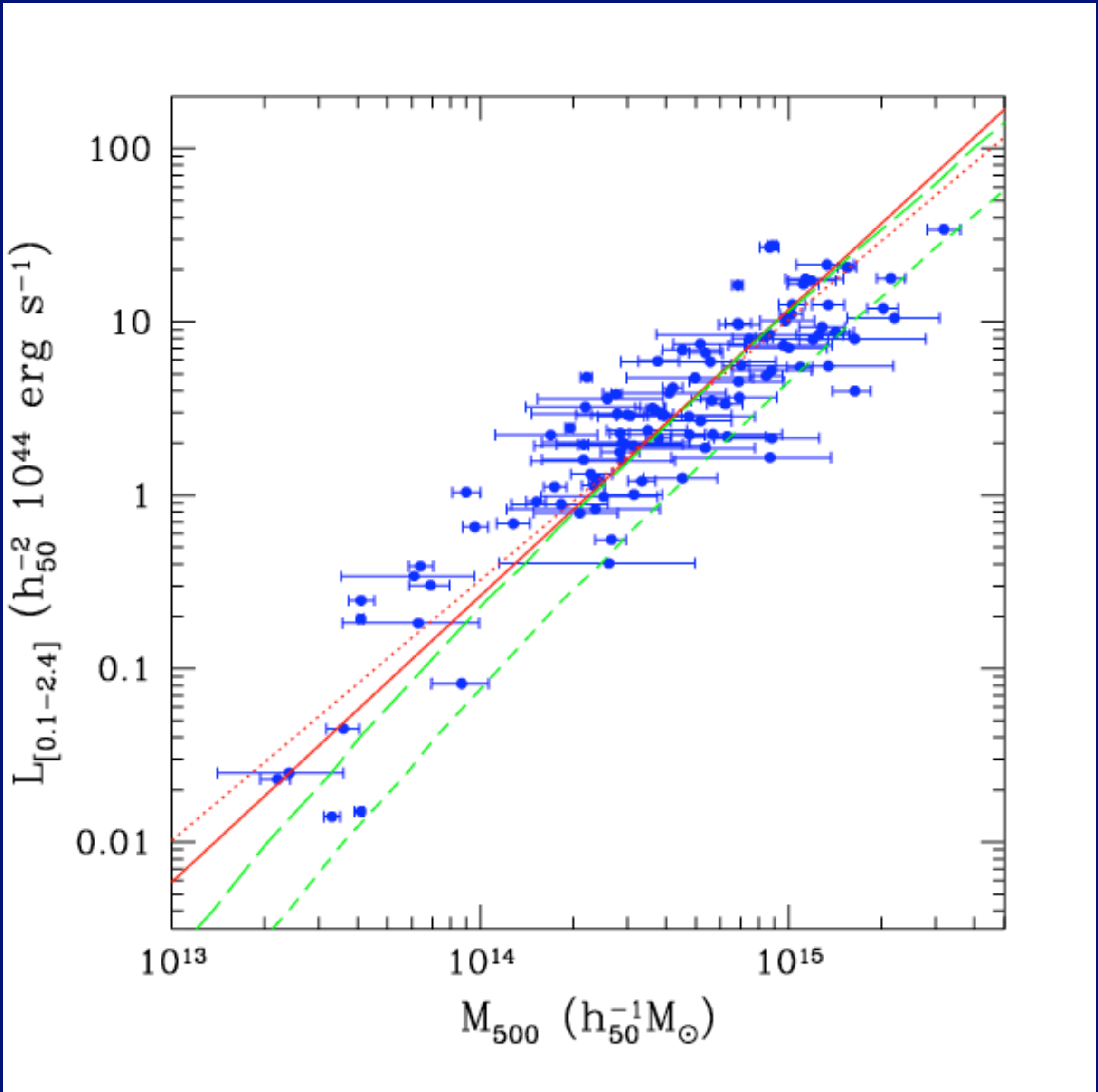




25 clusters at z<0.1 + 23 EMSS clusters with 0.3 < z < 0.8

Evidence for low Ω_m, consistent with SNIa and WMAP constraints

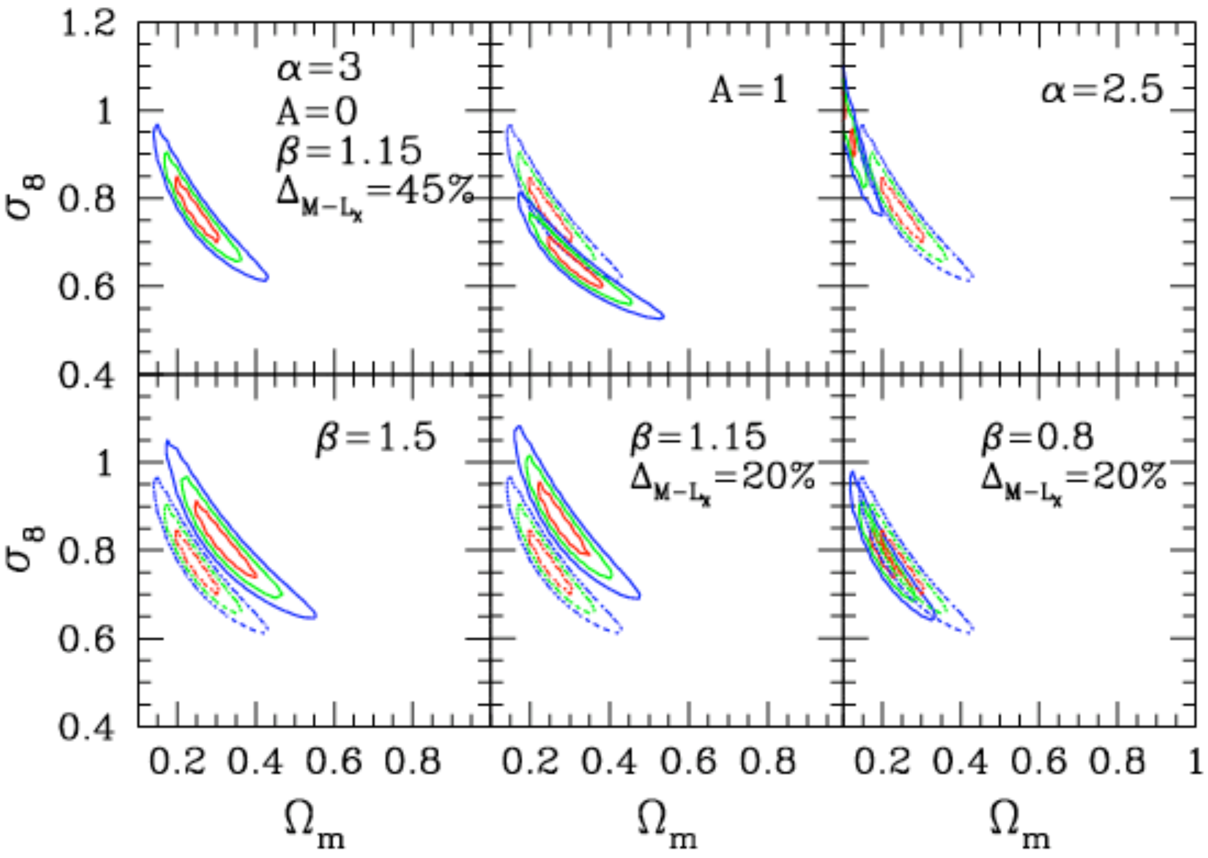
The observed M-L_X relation…



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

Resolved T_X profiles with Beppo-SAX
(Ettori, De Grandi & Molendi '02)
⇒ Well-defined relation with ~30-40% scatter!

Cosmological constraints from the XLF



Results dependent on ICM physics....

Ω_m<0.6 at >3σ

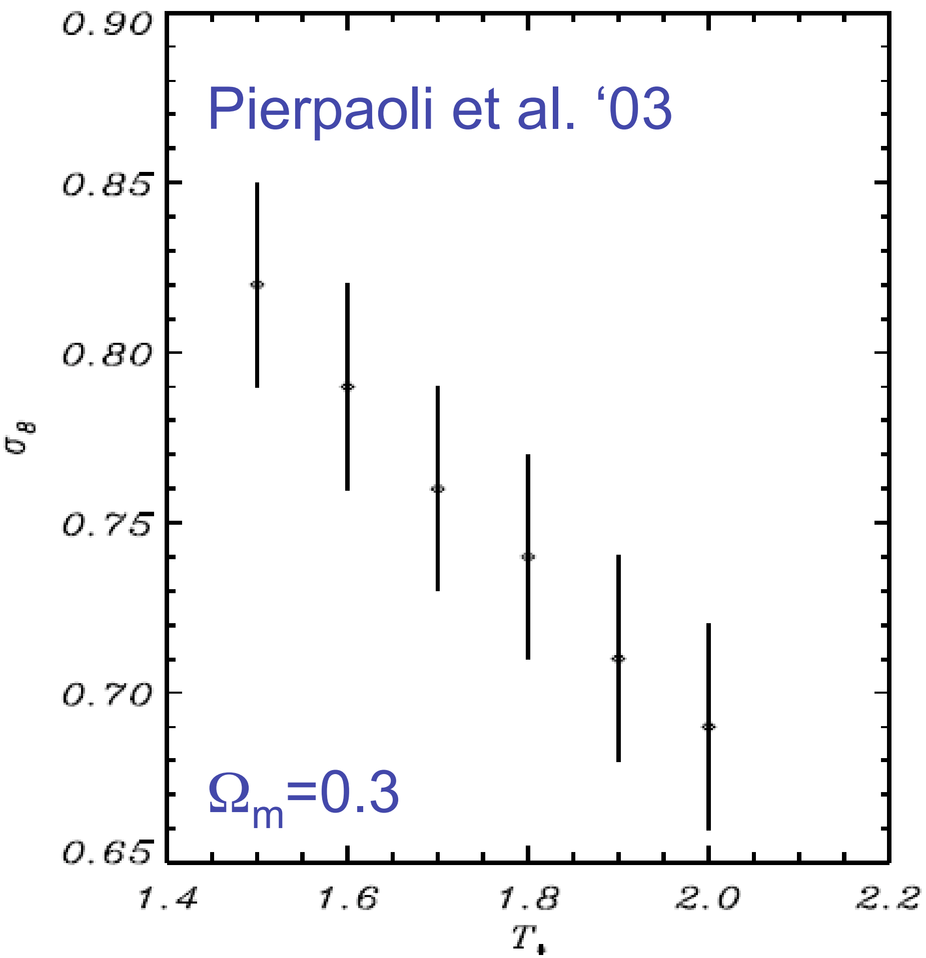
σ_8 somewhat small:
σ_8 = 0.70 ± 0.05 (Ω_m = 0.3)

for the reference analysis.

Effect of the M-T normalization on σ_8

From hydrostatic equil.:

$$\left(\frac{M(T,z)}{10^{15}\,h^{-1}\,\mathrm{M}_\odot}\right) = \left(\frac{T}{T_*}\right)^{3/2}\left(\Delta_c E^2\right)^{-1/2}$$



$T_* \approx 1.6$ for $\beta_{spec}=1$

Larger T* ⇒ Smaller M at fixed T

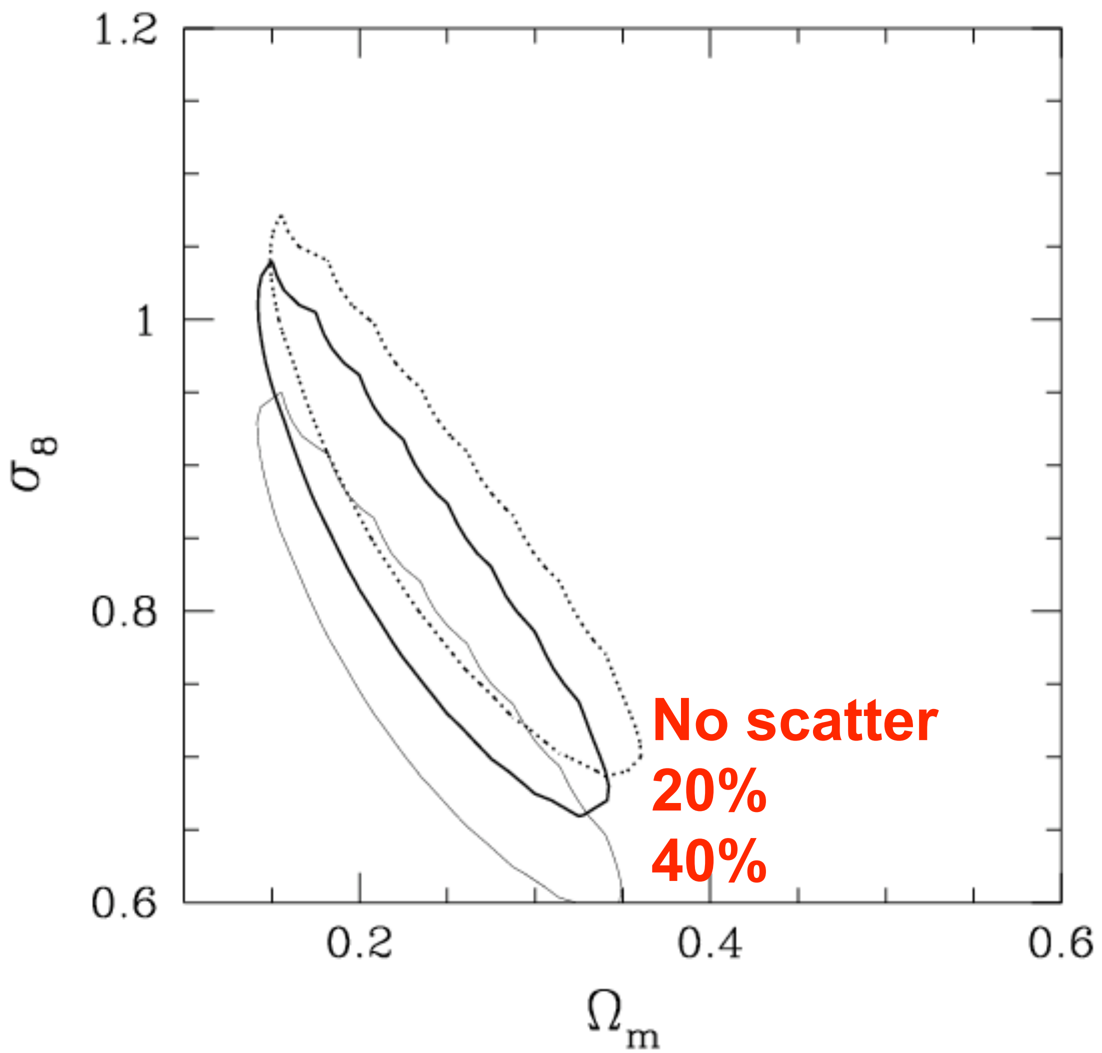
⇒ Higher mass function from the observed XTF

⇒ Larger σ_8 required

$$\Omega_{\mathrm{m}}^{0.6}\sigma_8 \propto (T_*)^{-0.8}$$

Huterer & White '02

Intrinsic scatter in the M-L_X relation



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

⇒ Lower σ_8 required to fit the observed XLF!

Expectations for the future

Several 1000 clusters over several 100 sq.deg. mapped with SZ from already planned surveys.

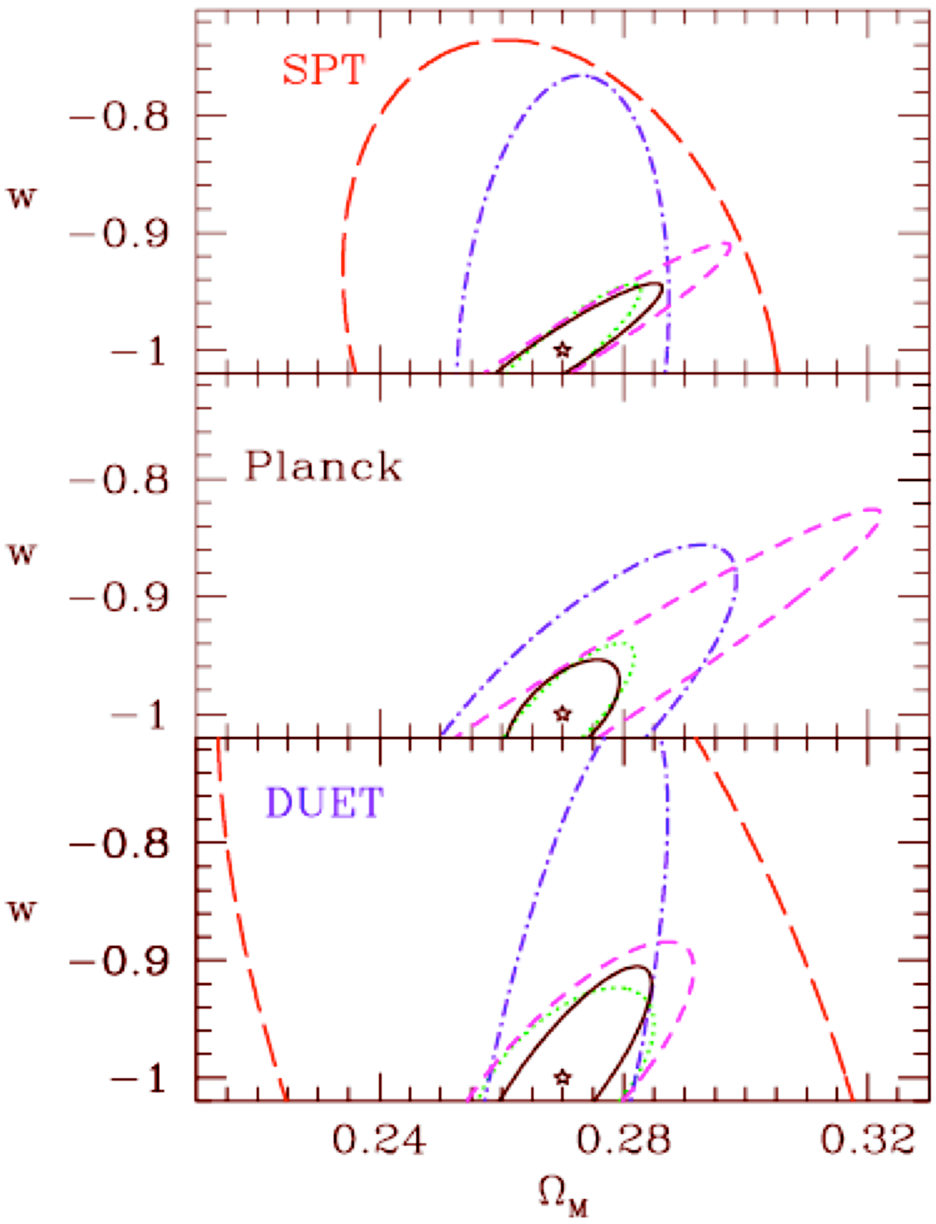
Several 10^4 clusters over several 1000 sq.deg. from possible wide-field X-ray telescopes (none approved so far....).

Kill the systematics with statistics?

Self-calibration (e.g. Majumdhar & Mohr ’03; Lima & Wu ’05):

1. Parametrize the M-X scaling, its scatter and the corresponding evolutions.
2. Fit such parameters along with the cosmological ones.

Expectations for the future



Majumdar & Mohr '04: self-calibration by combining:

1. Number counts dN/dz
2. Power spectrum of clusters
3. Follow-up observations to measure masses for 100 clusters.

See also Lima & Hu '05

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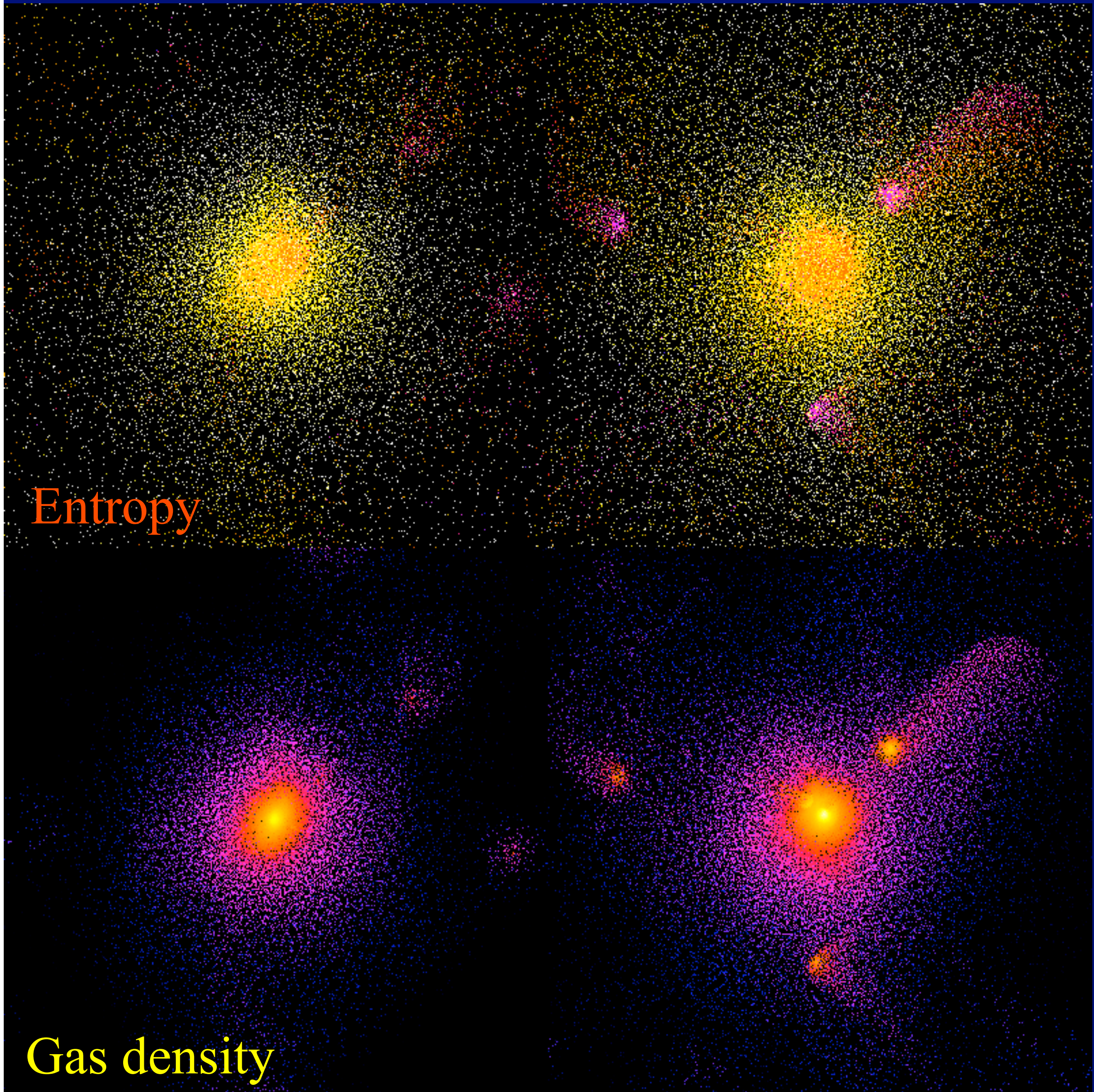
Open issue: are the functional forms unique to account for the complexities of clusters?
Precision cosmology requires precision knowledge of the cluster physics and dynamics!

PART 2:

Astrophysics with groups/clusters:
The role of hydro simulations



Self-similar ICM:

gravity only at work

(Kaiser 1986)

Hydrostatic eq.

$T(M,z) \propto M^{2/3}\, E(z)^{2/3}$

Bremss emiss.:

$L_X \propto M \rho_g T^{1/2}$

$\Rightarrow$

$L_X \propto M^{4/3} E(z)^{7/3}$
$\propto T^2\, E(z)$

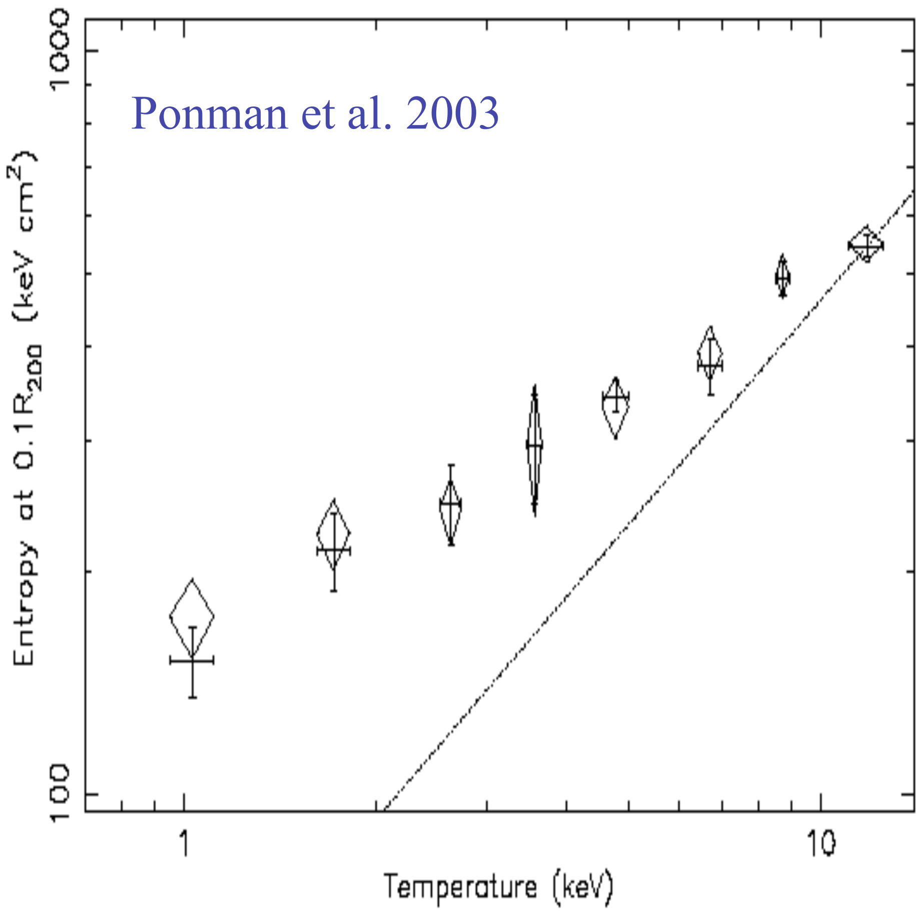
$S \propto (T/\rho_g^{\,2/3})$
$\propto T\, E(z)^{-4/3}$

$S = e^{(s/c_V)}/R$

$y_0 \propto T^{3/2}\, E(z)$

Facts against a self-similar ICM

Also talks by T. Ponman and S. Roychowdhury



The L_X-T_X relation:

- $L_X \propto T^{\sim 3}$ for $T > 2$ keV.
- Steepening below T~1keV?

  But see Osmond & Ponman 04; Mulchaey & Zabludoff '98
- Degree of evolution (?)

  Vikhlinin et al. '01, Ettori et al. '04

Entropy excess in groups:

$$S = T/n_e^{2/3}$$

- Entropy ramp at $0.1R_{200}$.

  Ponman et al. 2003
- Entropy profiles relatively enhanced in groups:

  $$S \propto T^{2/3}\, E(z)^{-4/3}$$

  Pratt & Arnaud '04

How to break self-similarity

(1) Non gravitational heating

- Introduce a characteristic T_X scale
- Place the gas on a higher adiabat

⇒ Prevent it from reaching high density

⇒ Suppress the X-ray luminosity

Sources: **SN energy feedback, AGN activity**

Evrard & Henry '91
Bower '96
Cavaliere et al. '98
Tozzi & Norman '01
Bialek et al. '01
SB et al. '02
Babul et al. '02
……

(2) Radiative cooling

- **Introduce a characteristic entropy scale**
- Selectively remove low-S gas with $t_{cool}<t_H$

⇒ Increase gas entropy in the hot phase

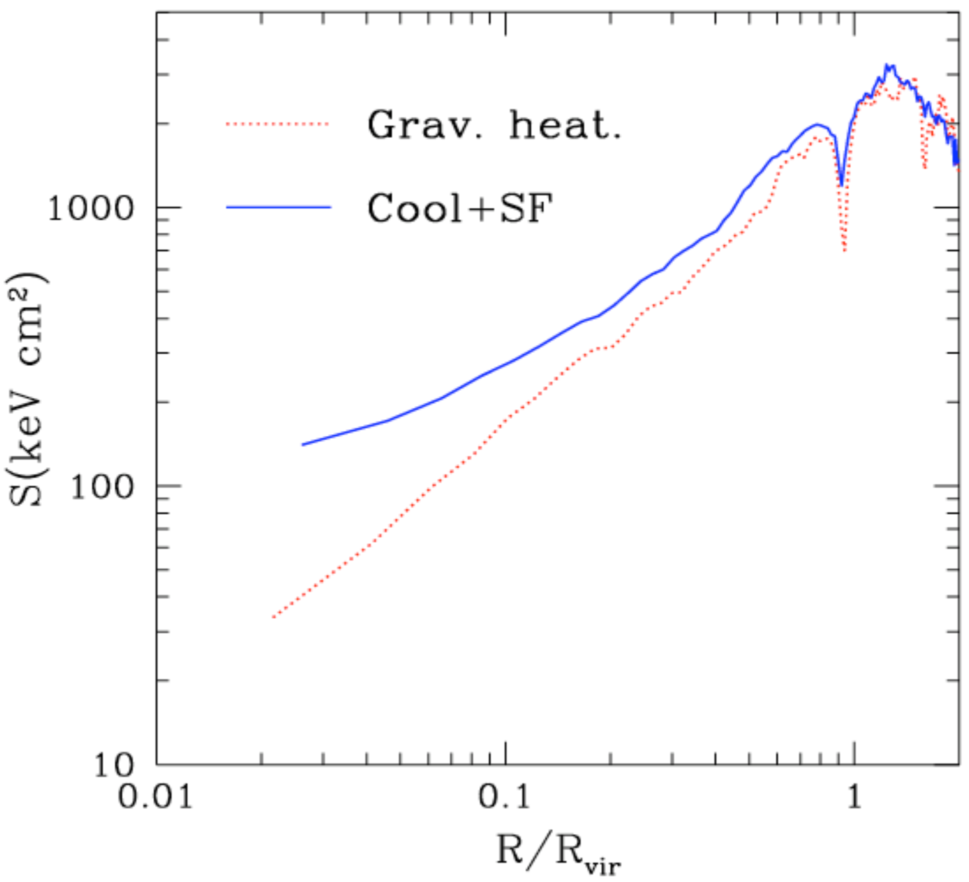
⇒ Decrease the X-ray luminosity

Pearce et al. '99
Bryan '00
Muanwong et al. '01
Bryan & Voit '01
Wu & Xue '02
Voit et al. '02
Dave` et al. '02
Tornatore et al. '03
…..

The Role of Cooling

⇒ Take gas out of the hot diffuse phase.

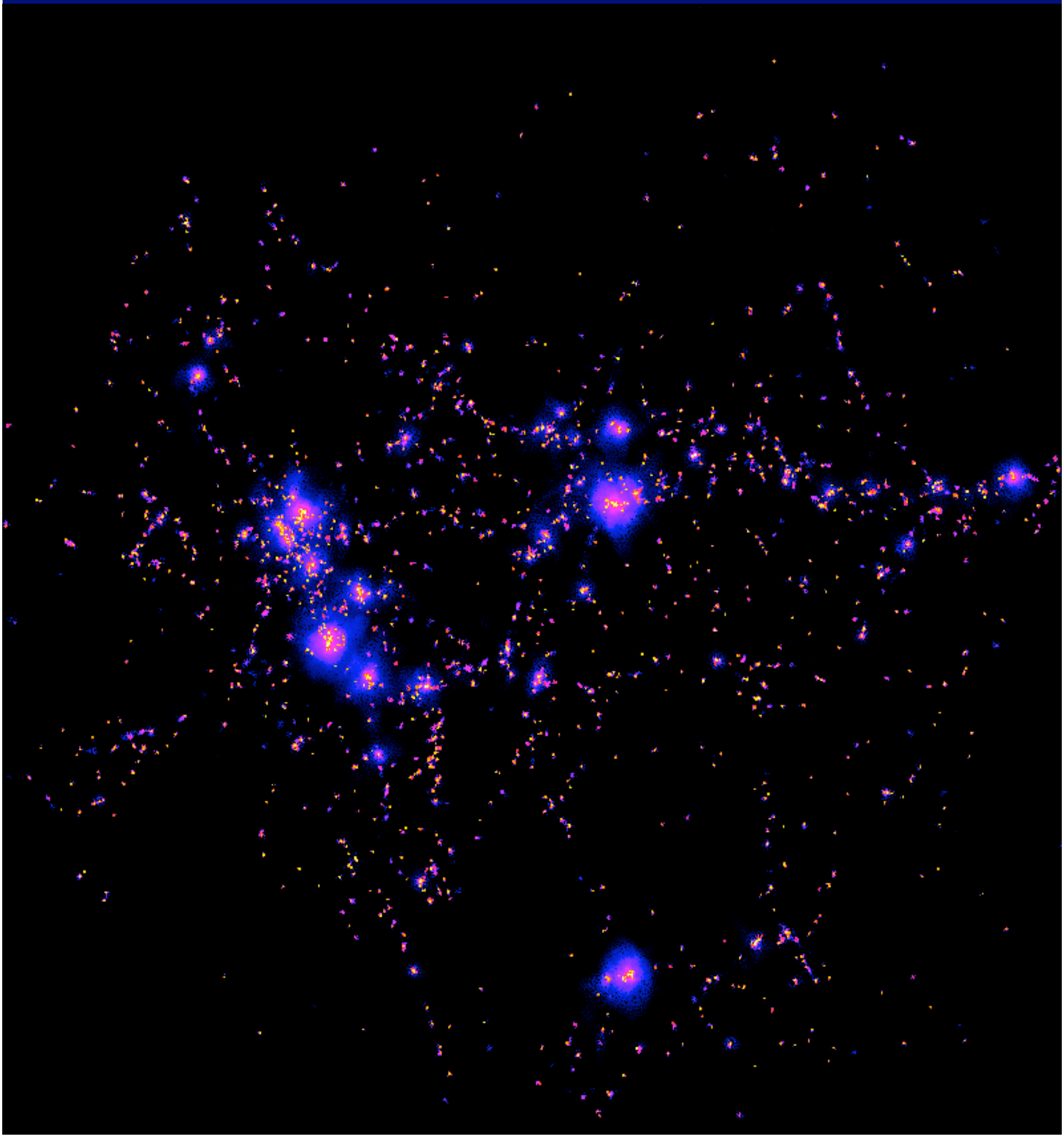
Pearce et al. '99
Bryan '00
Muanwong et al. '01
Bryan & Voit '01
Wu & Xue '02
Voit et al. '02
Dave` et al. '02



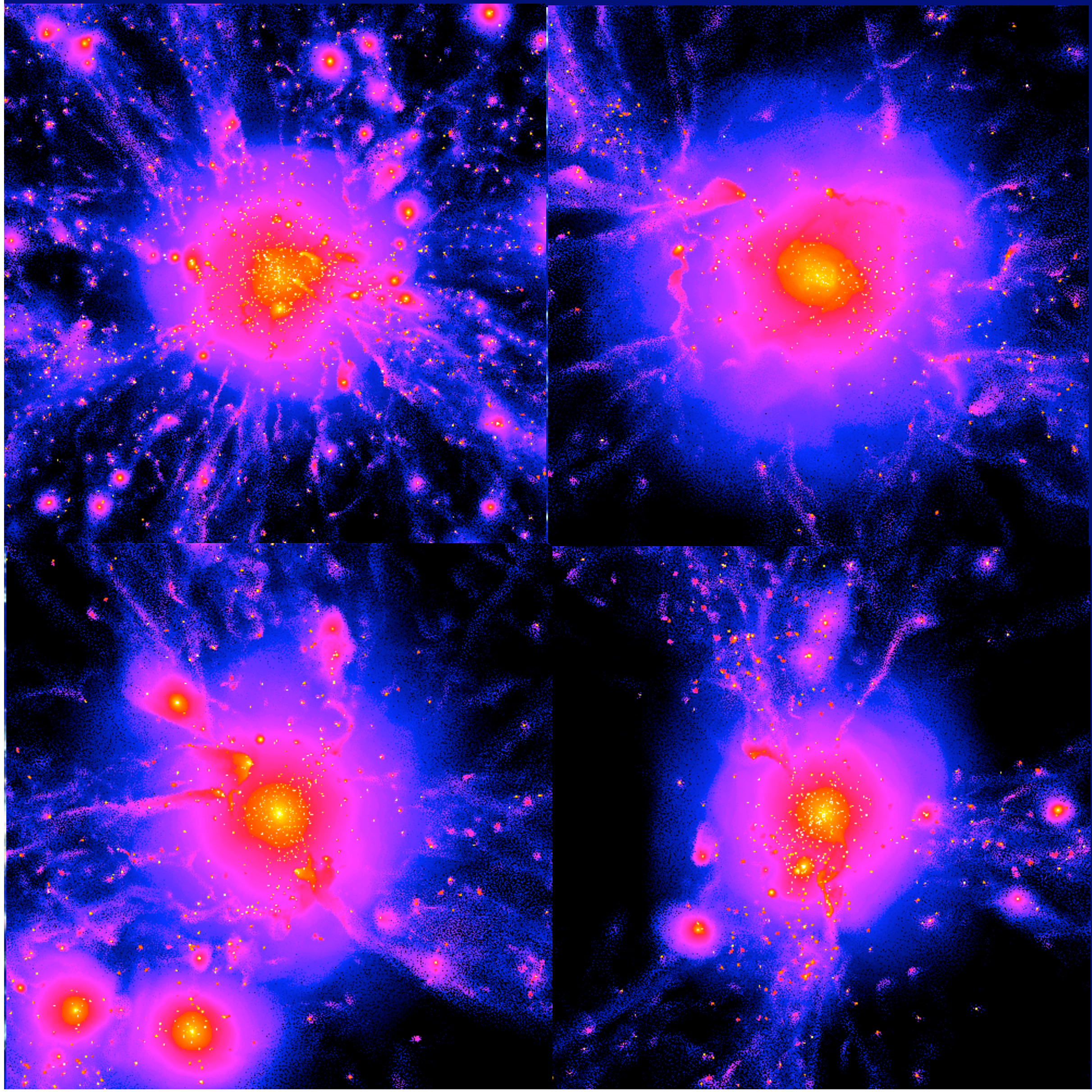
- Selectively remove low-entropy gas, with short t_{cool}.
- Bring high-entropy gas from external to internal cluster regions (Bryan 2000).

⇒ But cooling runaway….
⇒ Pre-heating to regulate the amount of gas below the cooling threshold

A proto-cluster region at z=2



Group/Clusters Hydro Simulations



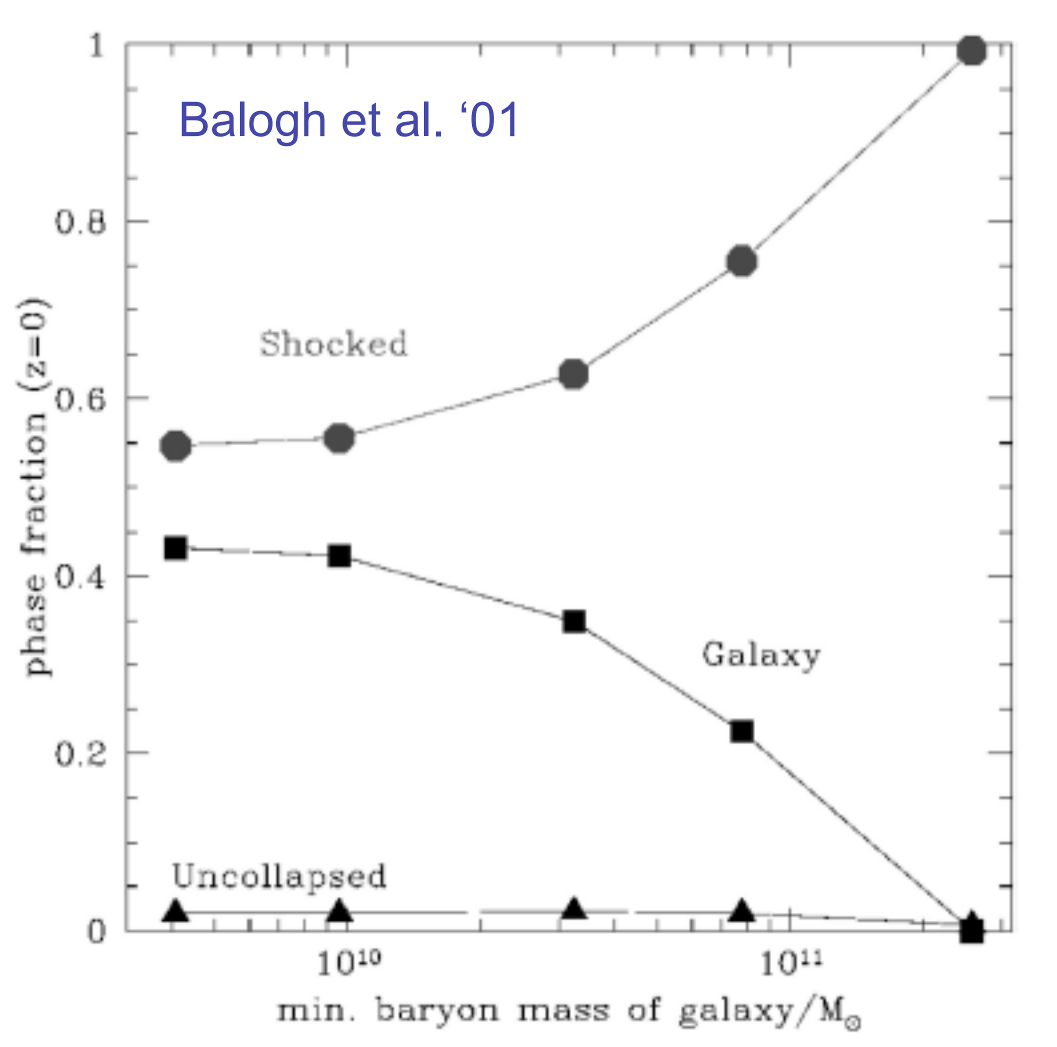
Tree + SPH
GADGET-2

SB et al. '04
L= 192 h^{-1} Mpc
$N_{gas}=N_{DM}=480^3$
ε_{Pl} = 7.5 h^{-1}kpc
Cooling + SF +
galactic winds

Resimulate
clusters at
high resolution

The fraction of cold gas in clusters

SB et al. 2004



From observations:

$f_{cold} \sim 10\%$

- No trend with T_X
  Balogh et al. '01
- Larger f_{cold} for groups
  Lin, Mohr & Stanford '03

From simulations:

$f_{cold} \sim$ 15-20% for clusters

$f_{cold} \sim$ 20-25% for groups

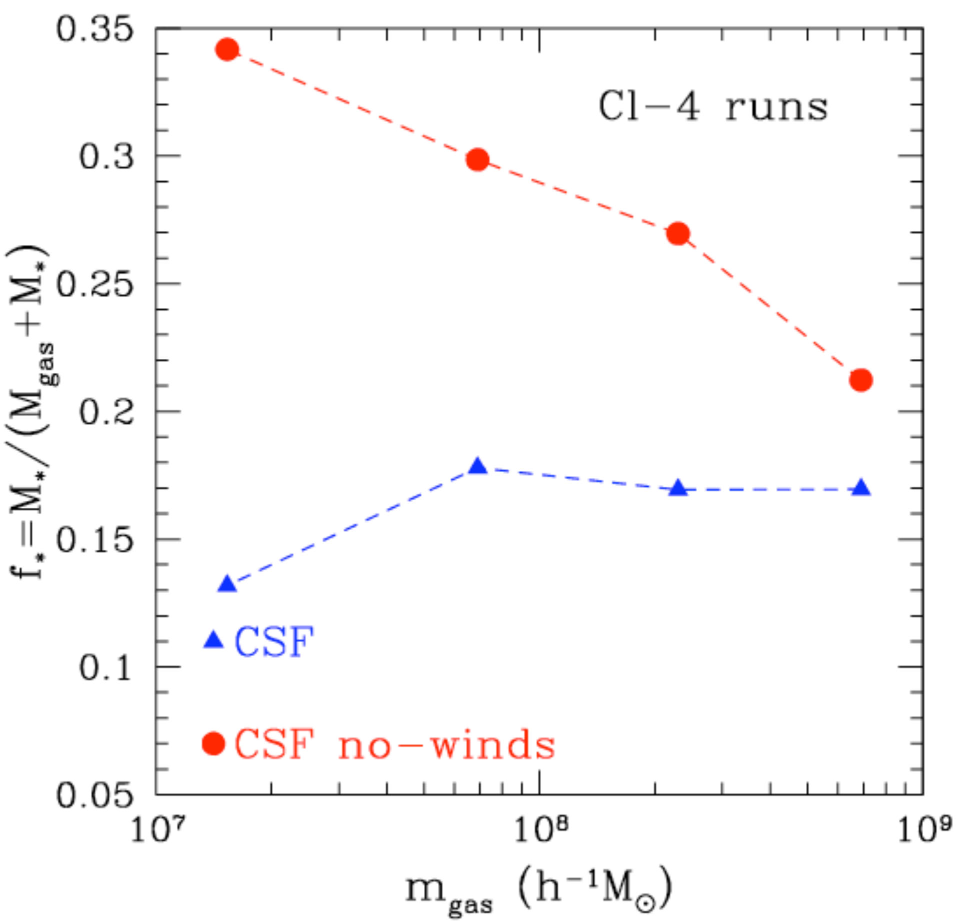
⇒ Feedback not strong enough to prevent overcooling!

1. Runaway with resolution?
2. Amount of diffuse stars?

Preventing the cooling catastrophe with feedback?

SB, Dolag, Murante et al. ‘05

Star fraction vs. resolution

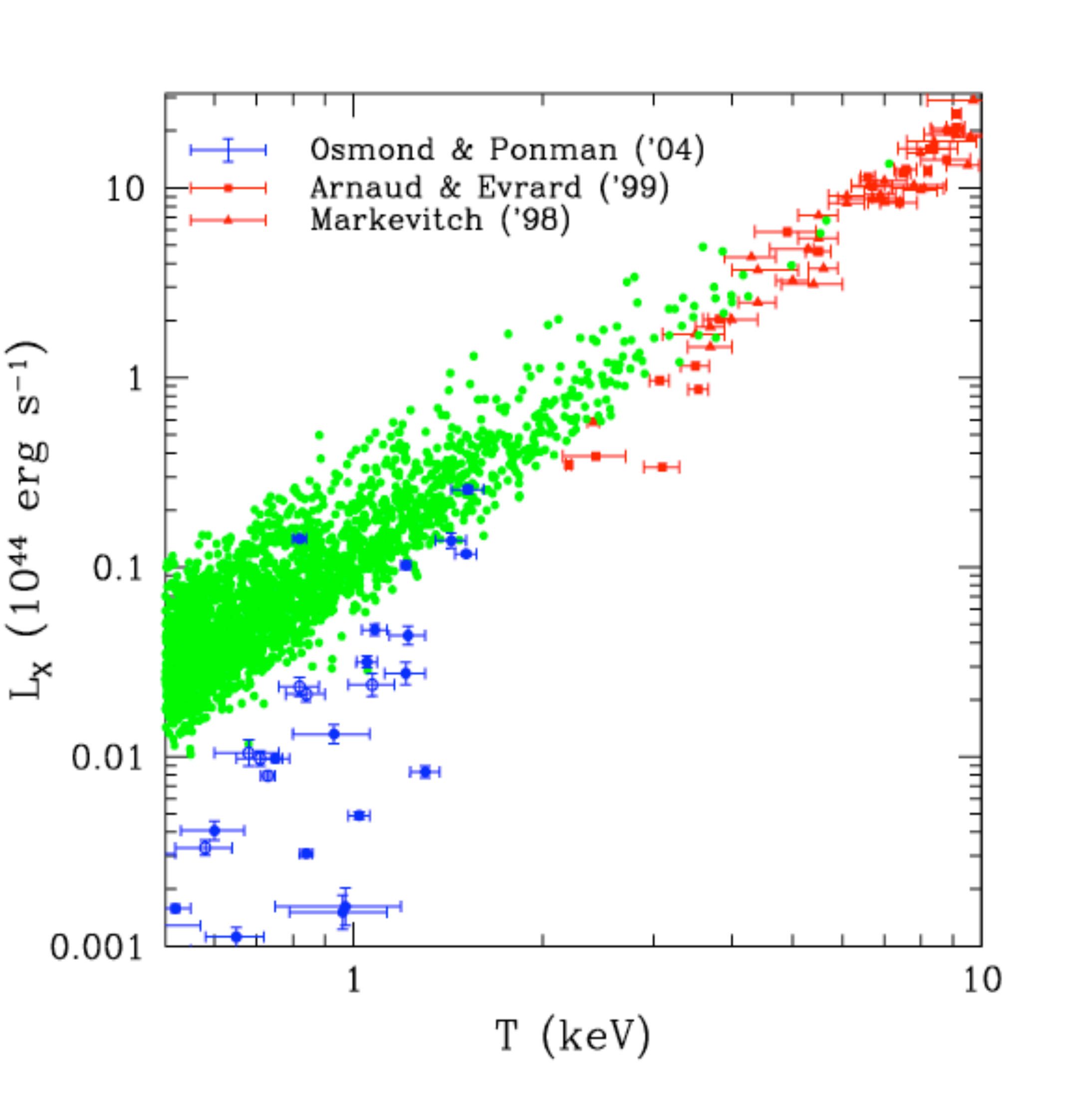


- Feedback with galactic winds prevents the cooling runaway.
- f* even decreasing at the highest resolution.

Effect of pre-heating: earlier winds from smaller halos forming at higher redshift.

Getting closer to the observed f*...

The L_X-T relation



Dave et al. '02: cooling only

L_X-T relation reasonable, but up to 80% of baryons in stars for groups!

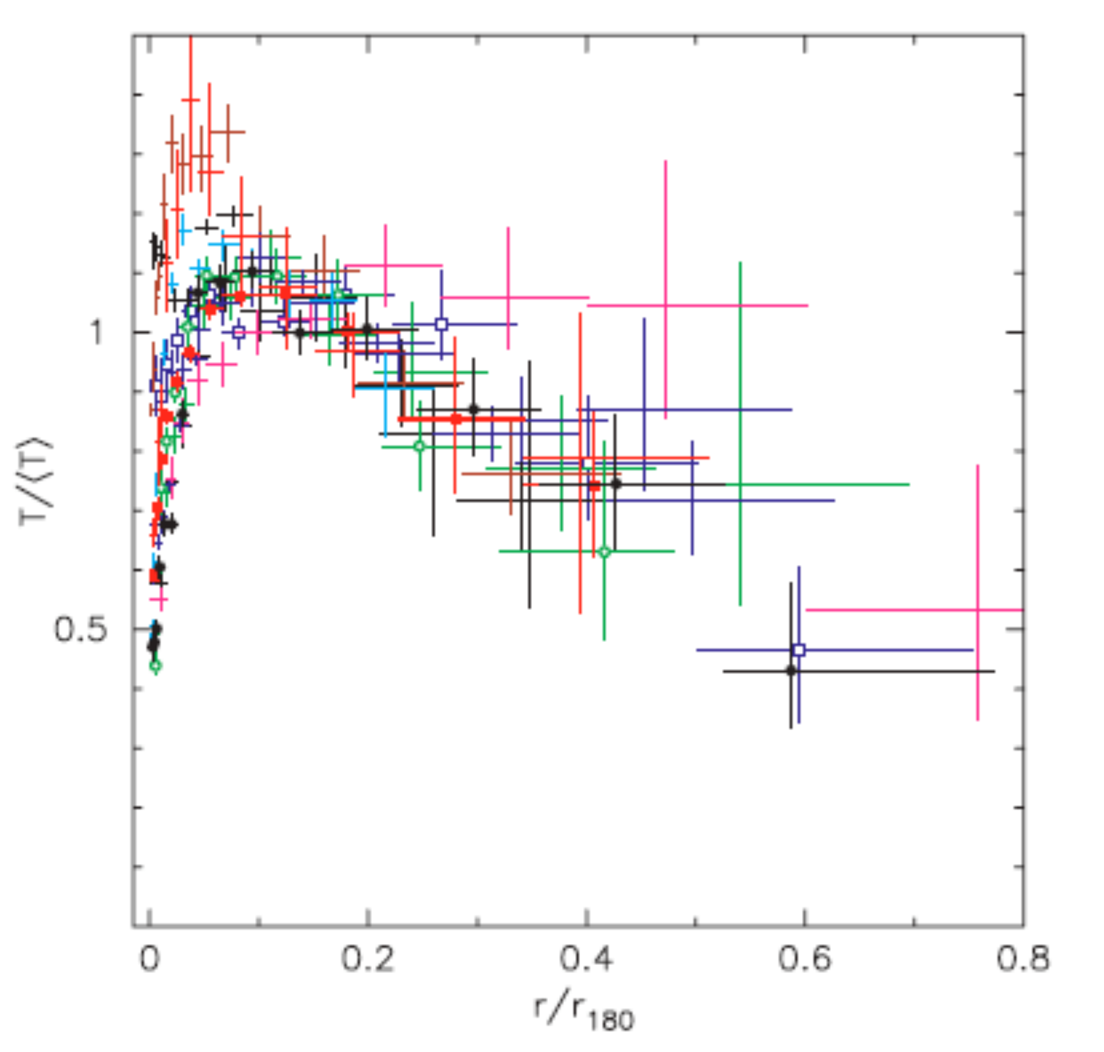
Muanwong et al '03: cooling + pre-heating

No much bending at the scale of groups.

SB et al '04: cooling + SF + galactic winds

Again, wrong shape and small scatter for groups.

The observed temperature profiles



Molendi 2004:

Open circles: Beppo-SAX non cool cores.

Filled circles: Beppo-SAX cool cores.

Squares: XMM compilation.

Polytropic eq. of state:

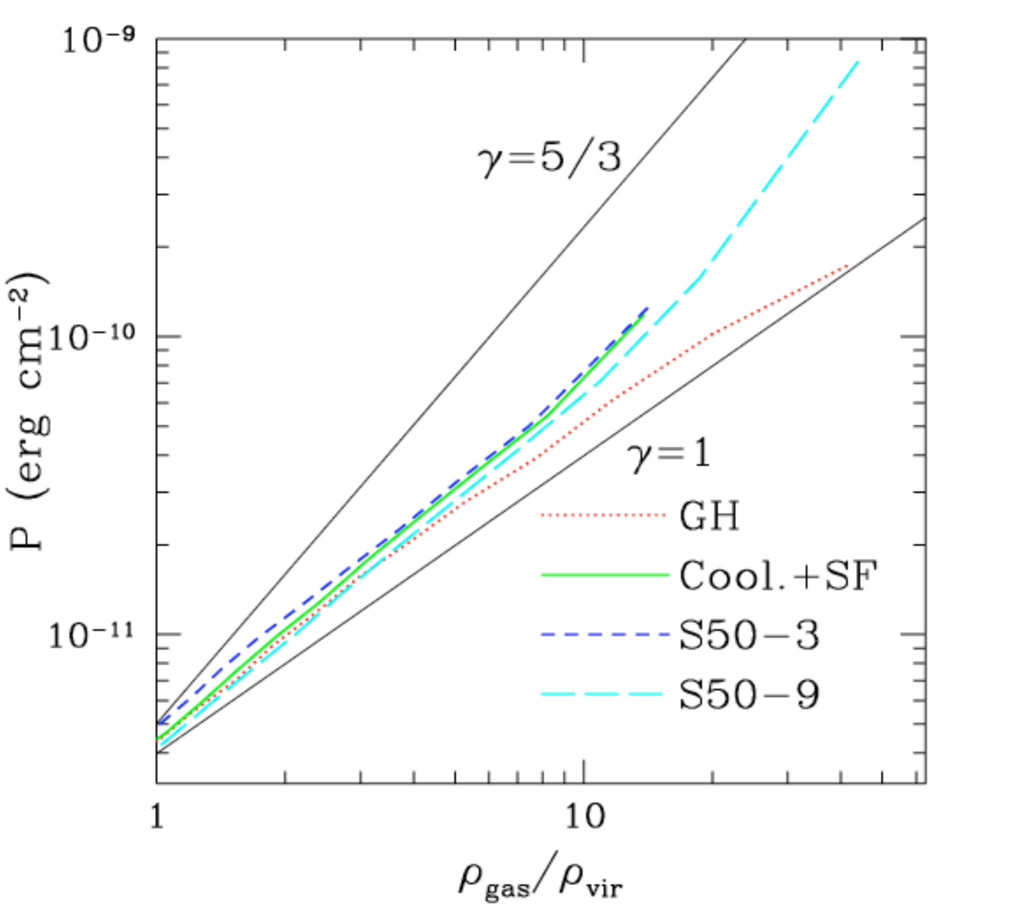
$$T \propto \rho_{gas}^{\ \gamma - 1}$$

$$\gamma \approx 1.15 - 1.20$$

Vikhlinin 2004:

Chandra observ. of 13 relaxed clusters.

The temperature profiles in simulations



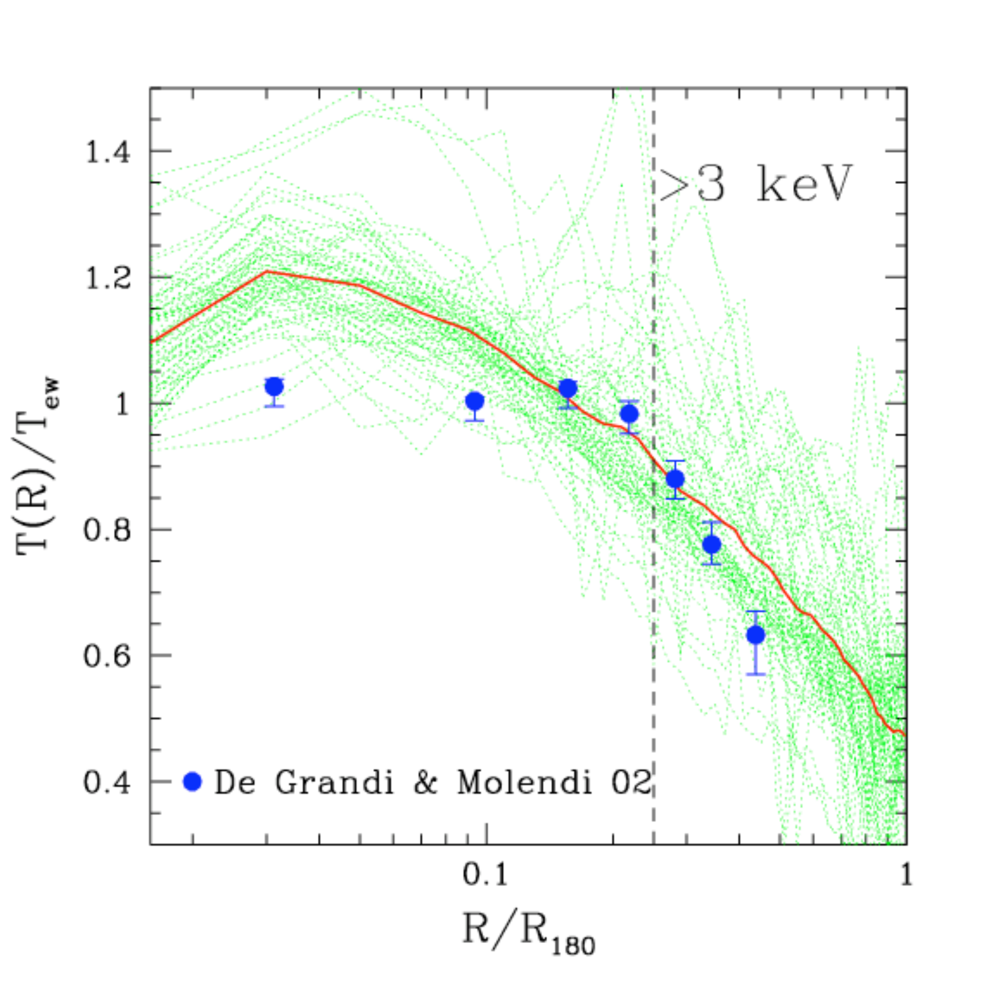
Tornatore et al. '03: cooling +SF + pre-heating

Steepening with radiative cooling

Central profiles quite sensitive to the included physics

Steepening of T-profiles from adiabatic compression of infalling gas.

The temperature profiles in simulations



Loken et al. '03: non-radiative and radiative runs

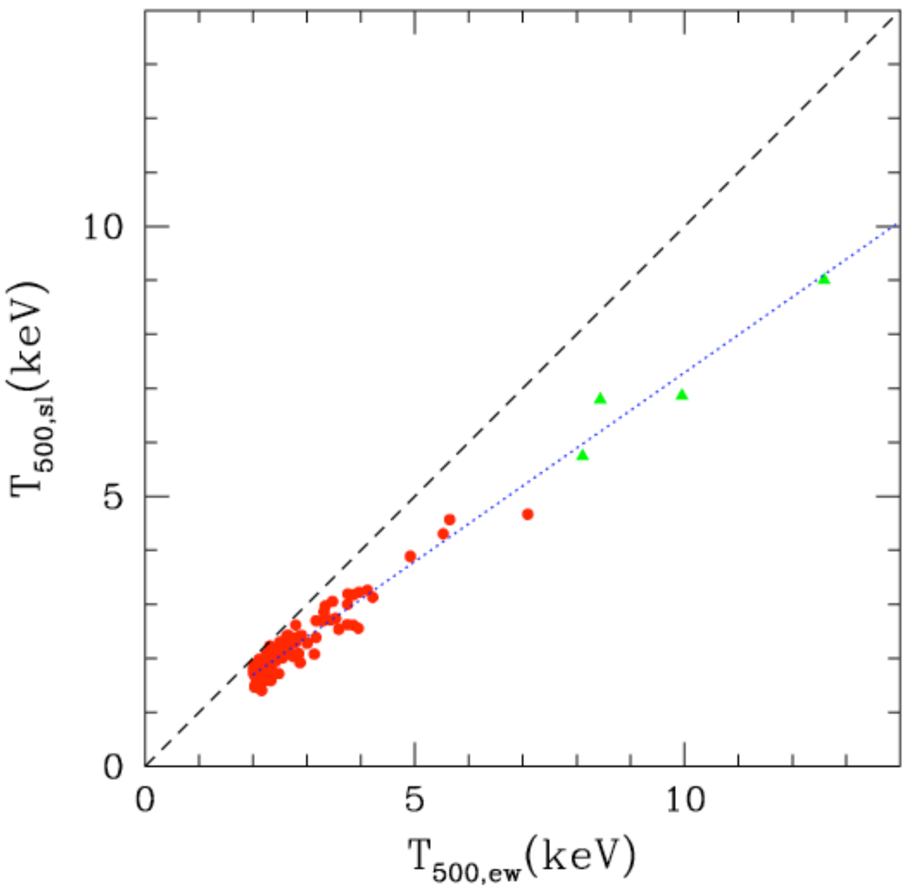
Reasonable profiles in the outside the cool-core regions.

SB et al. '04: cooling + SF + galactic winds

Too steep profiles in the central regions.

Calibrating clusters as cosmological tools

SB et al. 2004; Rasia et al. 2005, 2006



Emission-weighted temperature:

$$T_{ew} \equiv \frac{\int \Lambda(T) n^2 T\, dV}{\int \Lambda(T) n^2 dV}$$

Not a fair representation of the spectroscopic temperature (Mathiesen & Evrard '01)

Spectroscopic-like temperature (Mazzotta et al. '04; Vikhlinin '05)

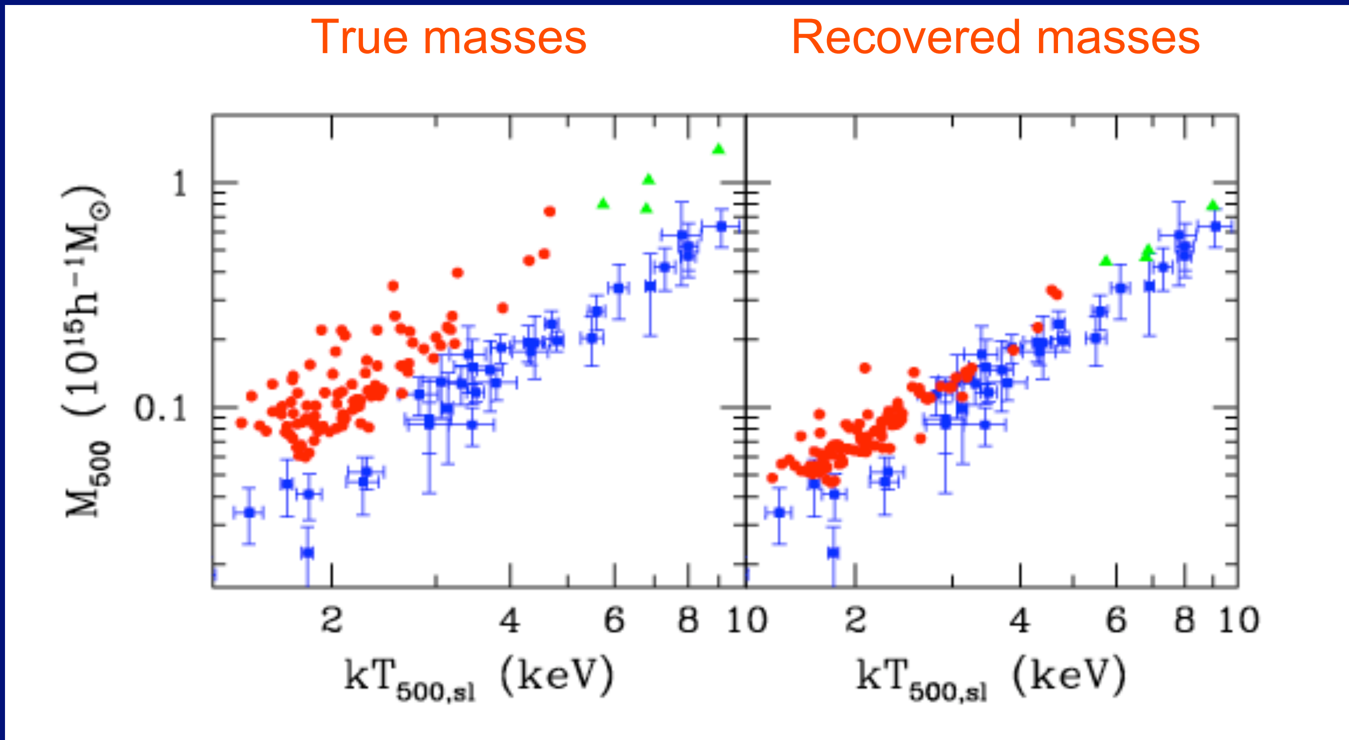
$$T_{sl} \equiv \frac{\int n^2 T^a / T^{1/2} dV}{\int n^2 T^a / T^{3/2} dV}$$

$a = 0.75$

Calibrating clusters as cosmological tools

Use the βγ-model for the ICM + hydrostatic equilibrium: (Finoguenov et al. '01; Ettori et al. '03)

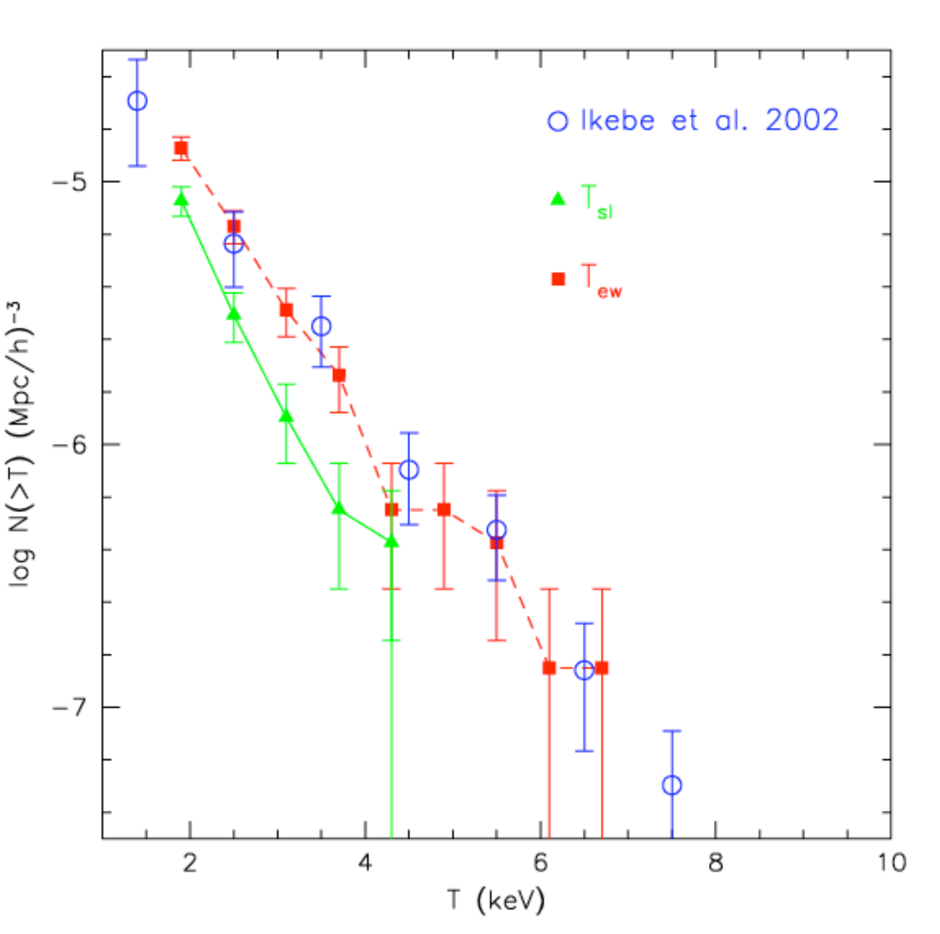
$$M_{tot}(<r) = 3.70 \times 10^{13} M_\odot T(r) r \frac{3\beta\gamma x^2}{1+x^2}$$



Recovered masses biased low by ~30-40%

Calibrating clusters as cosmological tools

Mass underestimate ⇒ σ_8 from the XTF underestimated by ~15%



Good agreement with σ_8=0.8 when using T_{ew};

Simulated XTF lower than the observed one when using T_{sl}

⇒ Need $\sigma_8 \approx 0.9$ to recover agreement with the observed XTF.

⇒ Alleviate tension with WMAP+SDSS constraints? (Tegmark et al. 2004)

Conclusions (?)

Cosmology with the evolution of groups/clusters ?

Already done !! $\Omega_m \approx 0.3 \pm 0.2$; $\sigma_8 \approx 0.8 \pm 0.1$

1. Local XTF and XLF (assuming CDM);
2. XTF and XLF evolution.

Precision cosmology requires having systematics under exquisite control !!

Can simulations help to understand systematics?

Quite possible, but a good knowledge of IGM/ICM physics required.

1. Temperature structure in the cool cores
2. Entropy amplification in the outskirts (talk by T. Ponman)
3. Produce reasonable galaxies and metal enrichment (poster by S. Cora)

Better for simulators to go hand by hand with observes!!