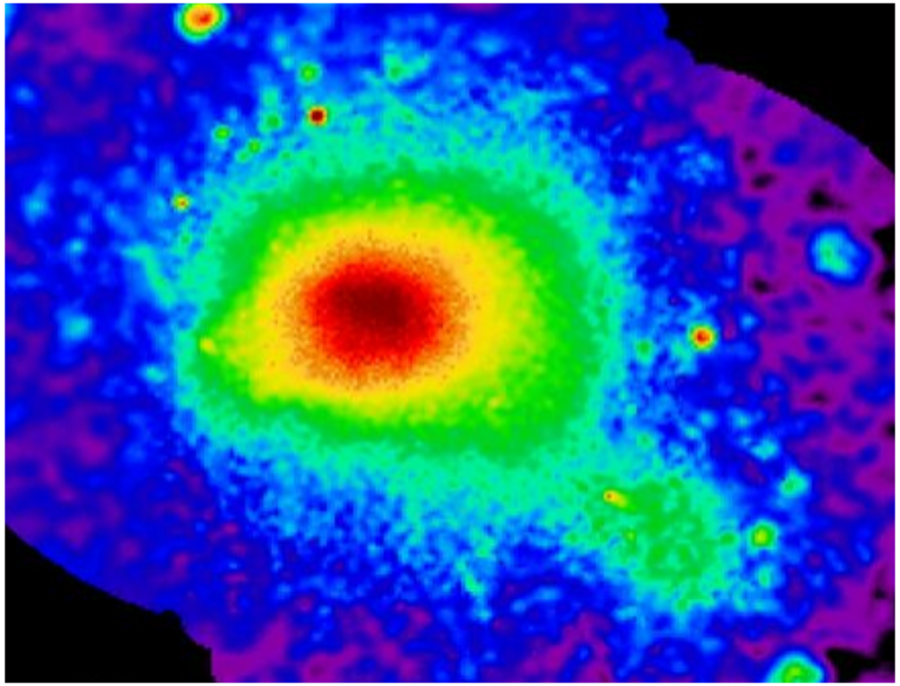
X-ray Galaxy Cluster mass profiles:

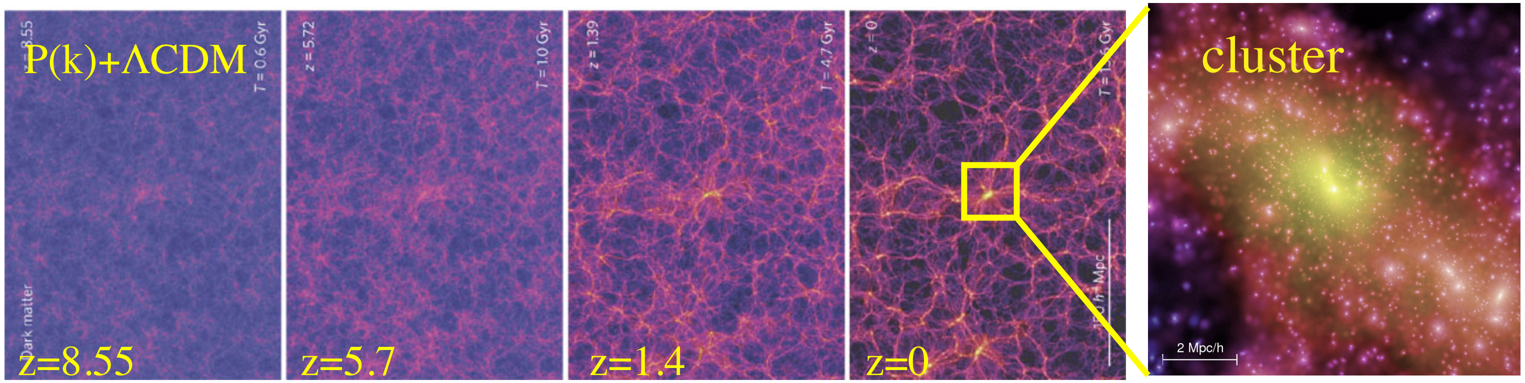
present constraints & limitations



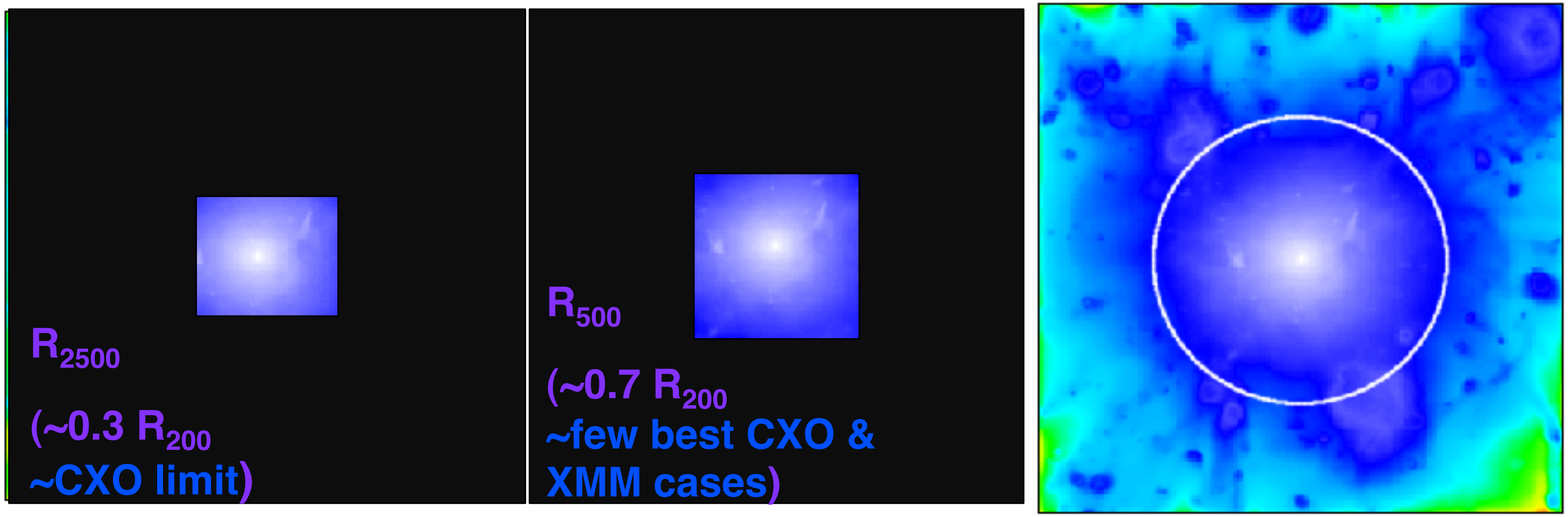
Stefano Ettori

(INAF-OA Bologna)

Structure formation in the Universe



We know how the gravity forms structures on cluster scales.
X-rays provide a direct probe of the thermalized gas
in a cluster's potential.



Total mass from X-rays

- *low counts statistic*: scaling relations

(M_{tot} vs L/T/M_{gas}/Y_X or a combination of these…)

- *high counts statistic*: mass profiles

(~200 out of 1743 obj known, *Piffaretti et al. 10*) by assuming

1. spherical symmetry, 2. hydrostatic equilibrium

$$\boxed{\frac{d\Phi}{dr} = \frac{G\,M_{tot}(<r)}{r^2} = -\frac{1}{\rho_{gas}}\frac{dP_{gas}}{dr}}$$

- **mass profiles as cosmological probes**

(calibration for scaling laws; ***f_{gas} & cMz*** as diagnostic of the baryonic and CDM distribution)

Total mass from X-rays

Total mass from X-ray is determined by assuming

1. spherical symmetry, 2. hydrostatic equilibrium

$$M_{tot}(<r) = -\frac{kT_{gas}(r)\ r}{G\mu m_p}\left(\frac{\partial \ln n_{gas}}{\partial \ln r} + \frac{\partial \ln T_{gas}}{\partial \ln r}\right)$$

$$M_{tot}(<r) \propto r \times T_{gas}(r) \times (-\alpha_n - \alpha_T)$$

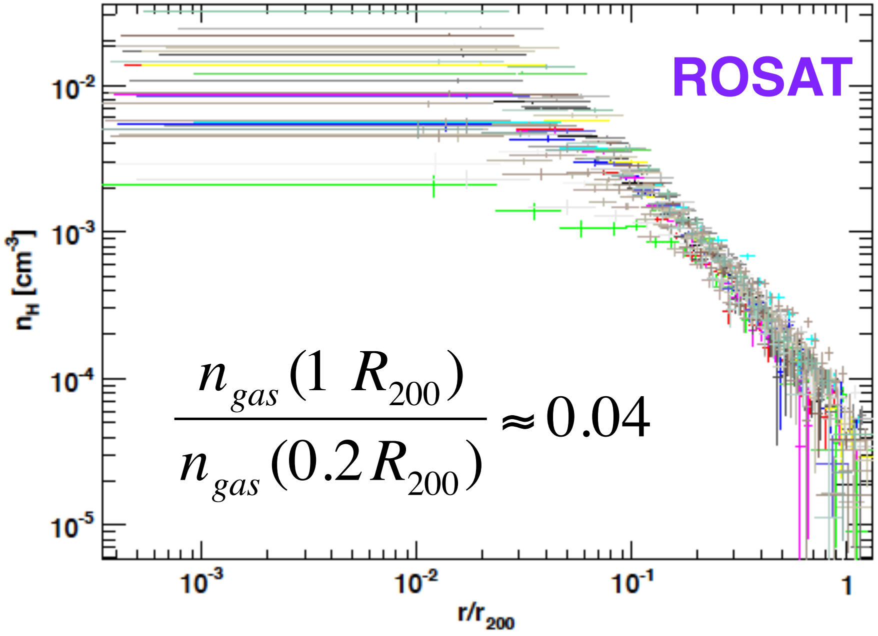
α_n~ **-2/-2.4** α_T~ **0/-0.8**

On the gas density profile

local

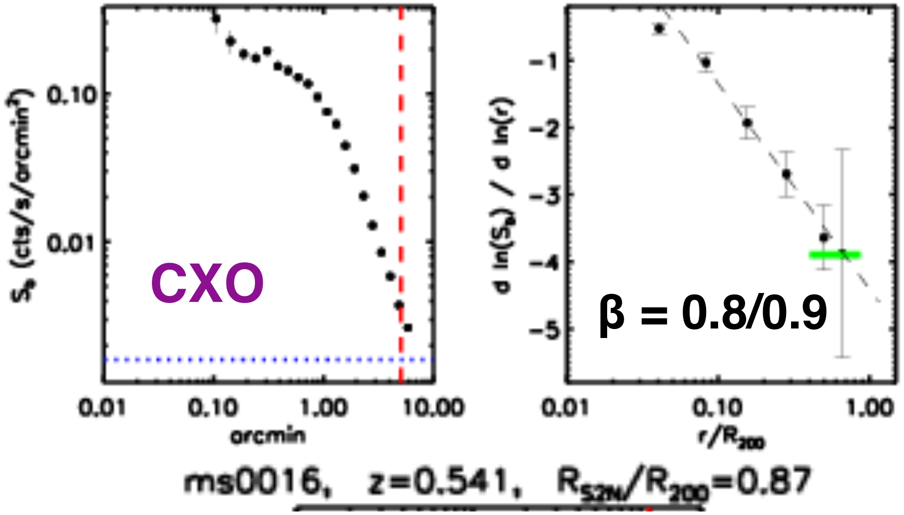
@z>0.3

Eckert, Vazza, SE, et al. 11



$$\frac{n_{gas}(1\ R_{200})}{n_{gas}(0.2\,R_{200})} \approx 0.04$$

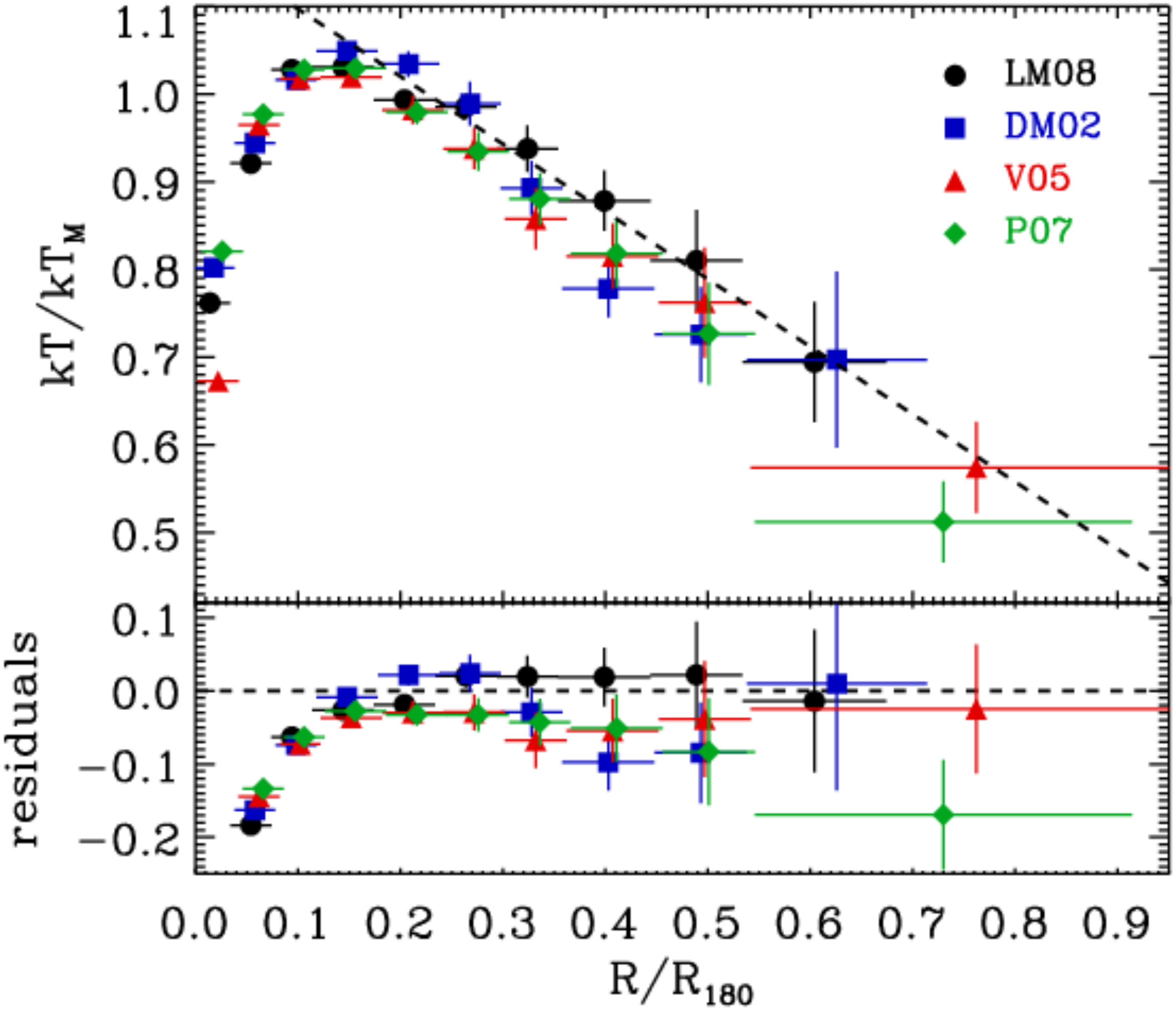
Ettori & Balestra 09



$$f_{gas}(R_{200}) \approx (0.15 \pm 0.01)\,(T/10\,keV)^{0.48}$$

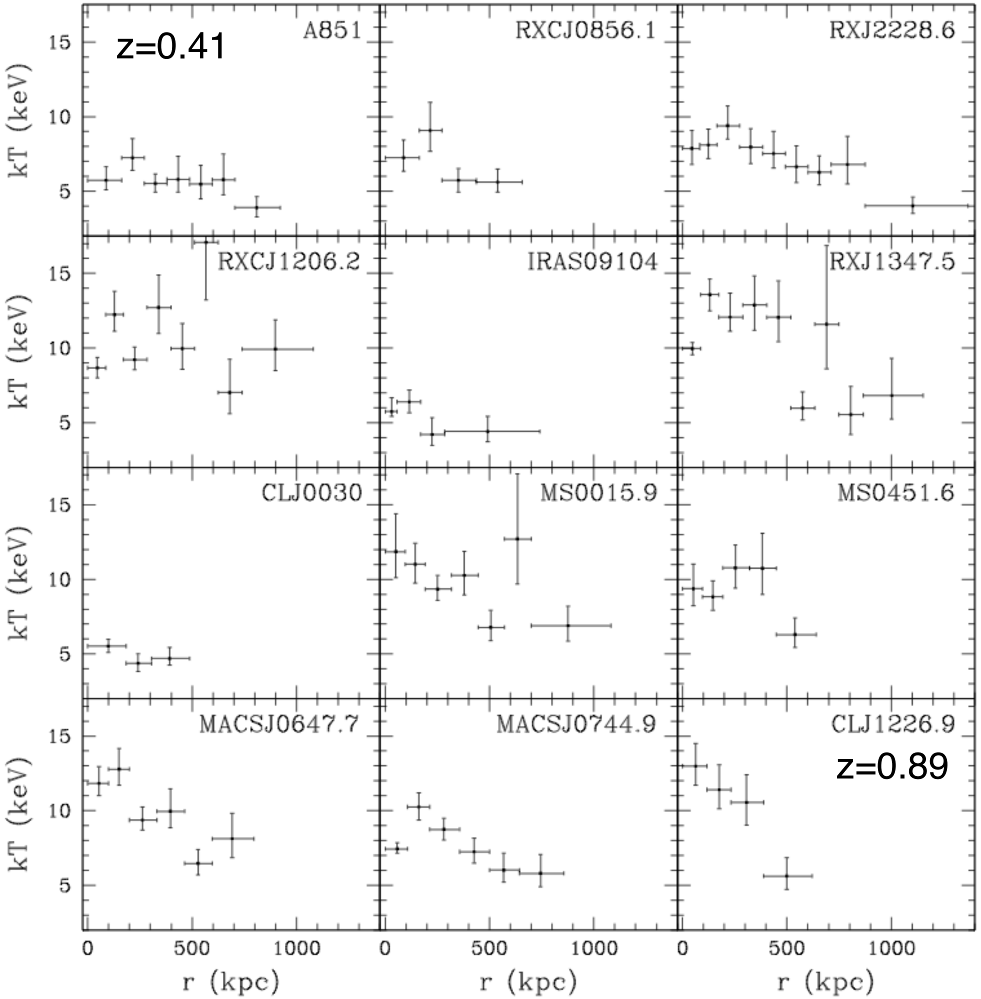
$$f_{gas}(R_{200}) \approx 0.89\,(\Omega_b/\Omega_m)_{WMAP7}$$

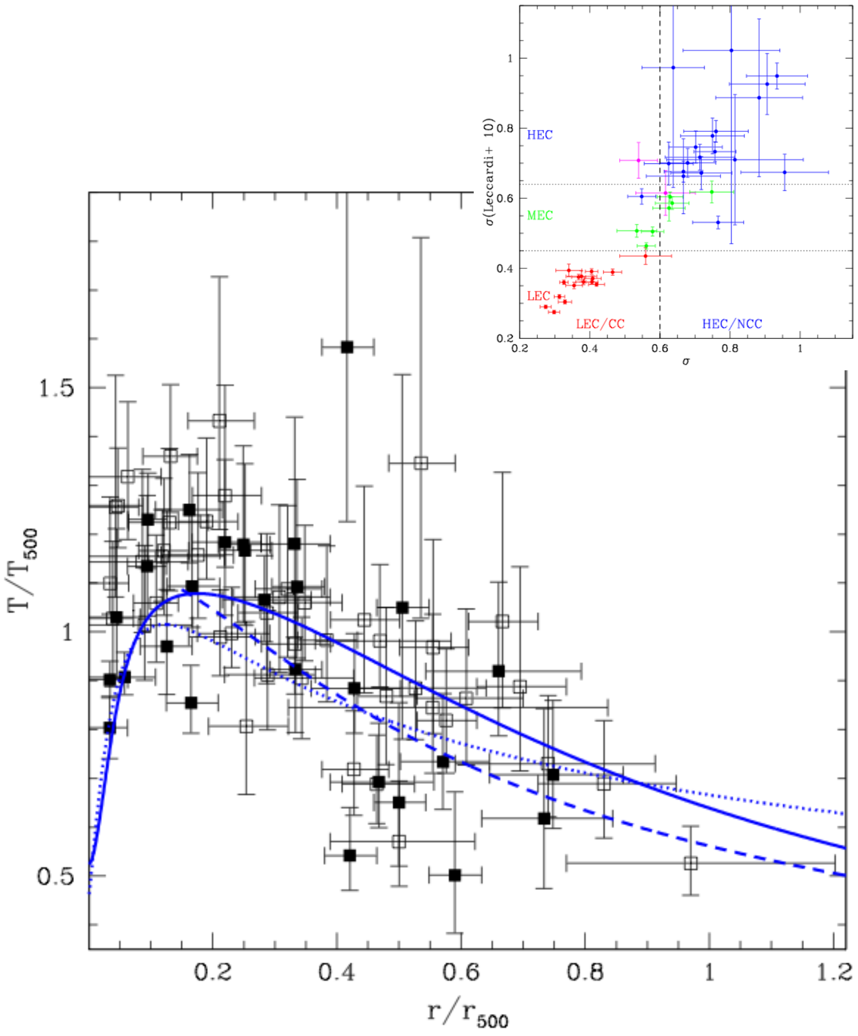
On the Temperature profile



An universal* T(r)

*as function of {***radius, z, dynamical state***}





An universal* T(r)

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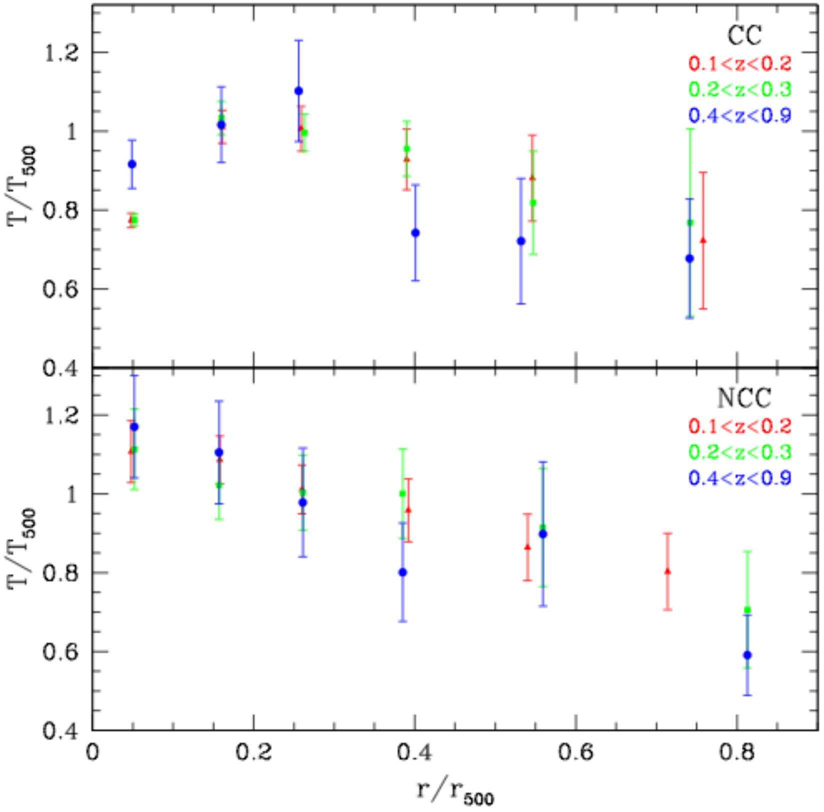


$$\left\{\begin{array}{l} \boxed{\dfrac{T}{T_{500}}(r,\sigma,z) = 1.14\pm0.05\,\dfrac{(x/0.045)^{\alpha}+\xi}{(x/0.045)^{\alpha}+1}\cdot\dfrac{1}{(1+(x/0.4)^2)^{\beta}},} \\ \xi = 0.33\pm0.06\cdot\phi_{+}(\sigma,\zeta=0), \\ \alpha = 3.85\pm1.79\cdot\phi_{-}(\sigma,z), \\ \beta = 0.16\pm0.04\cdot\phi_{+}(\sigma,z), \\ \boxed{\phi_{\pm}(\sigma,z)=1+0.23\pm0.11\cdot(1+\sigma)+0.17\pm0.09\cdot(1+z)} \end{array}\right.$$

- higher z clusters are at less advanced stage of their evolution:

CC clusters have less pronounced central temperature dip;
NCC clusters have steeper profiles (*Baldi, Ettori, et al. subm.*)

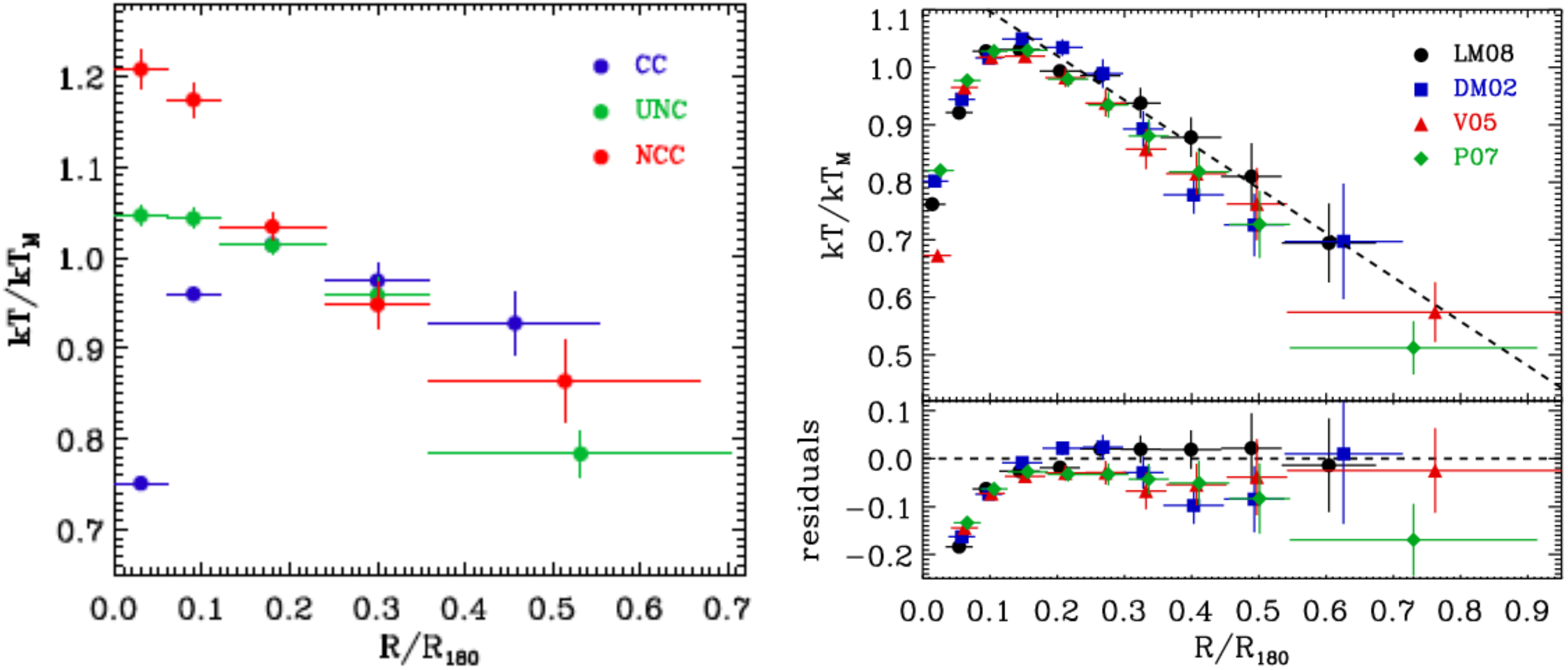
Estimate of the X-ray M_{tot}

$$M_{tot}(<r) = -\frac{kT_{gas}(r)\ r}{G\mu m_p}\left(\frac{\partial \ln n_{gas}}{\partial \ln r} + \frac{\partial \ln T_{gas}}{\partial \ln r}\right)$$

	model-dependent ***forward***	**model-independent** ***backward***
Pros	derivable smooth profiles	not need for parameters
Cons	radial shape imposed / add priors (see Mantz & Allen 11) need many parameters / degenaracy (e.g. Vikhlinin 05: 10 in n_{gas}, 9 in T_{gas})	radial profiles often not smooth enough, derivatives problematic

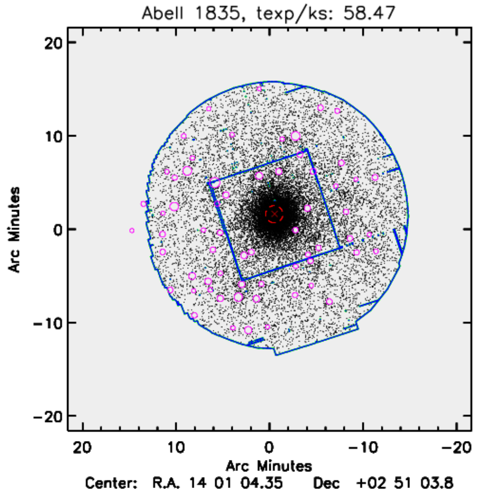
To be considered: model-independent smooth profiles (e.g. Gaussian processes)

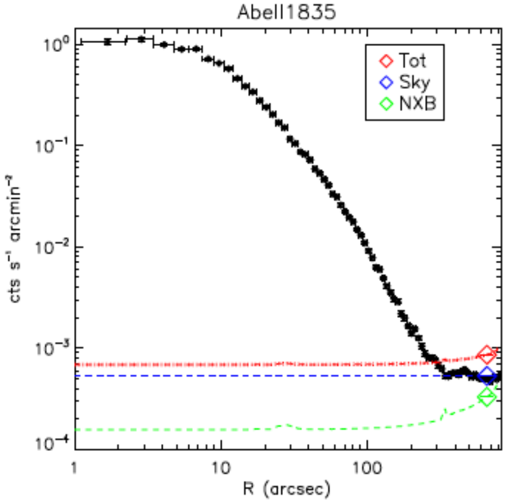
Mass profiles: c-M relation

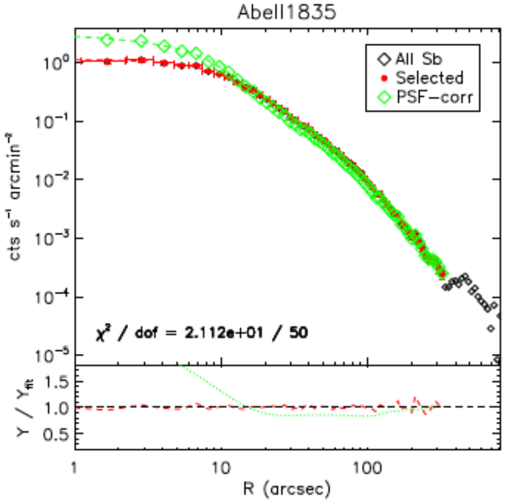


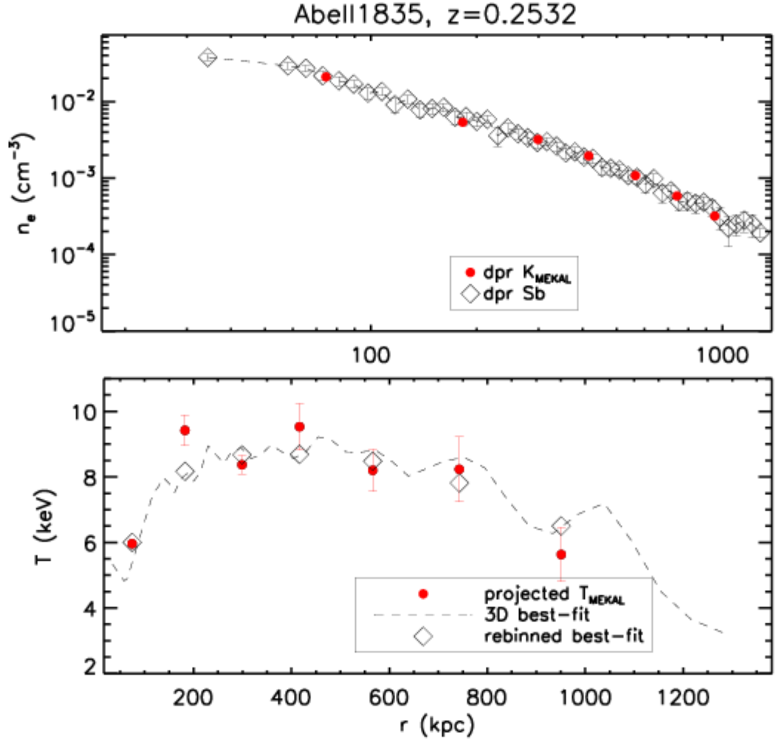
44 X-ray luminous galaxy clusters, relaxed (=CC) & not (=NCC), observed with *XMM-Newton* in the z-range 0.1–0.3

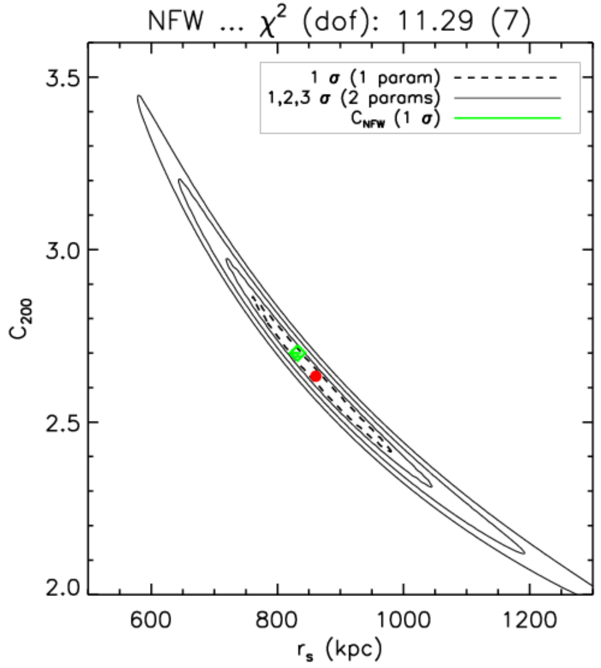
Mass profiles: c-M relation



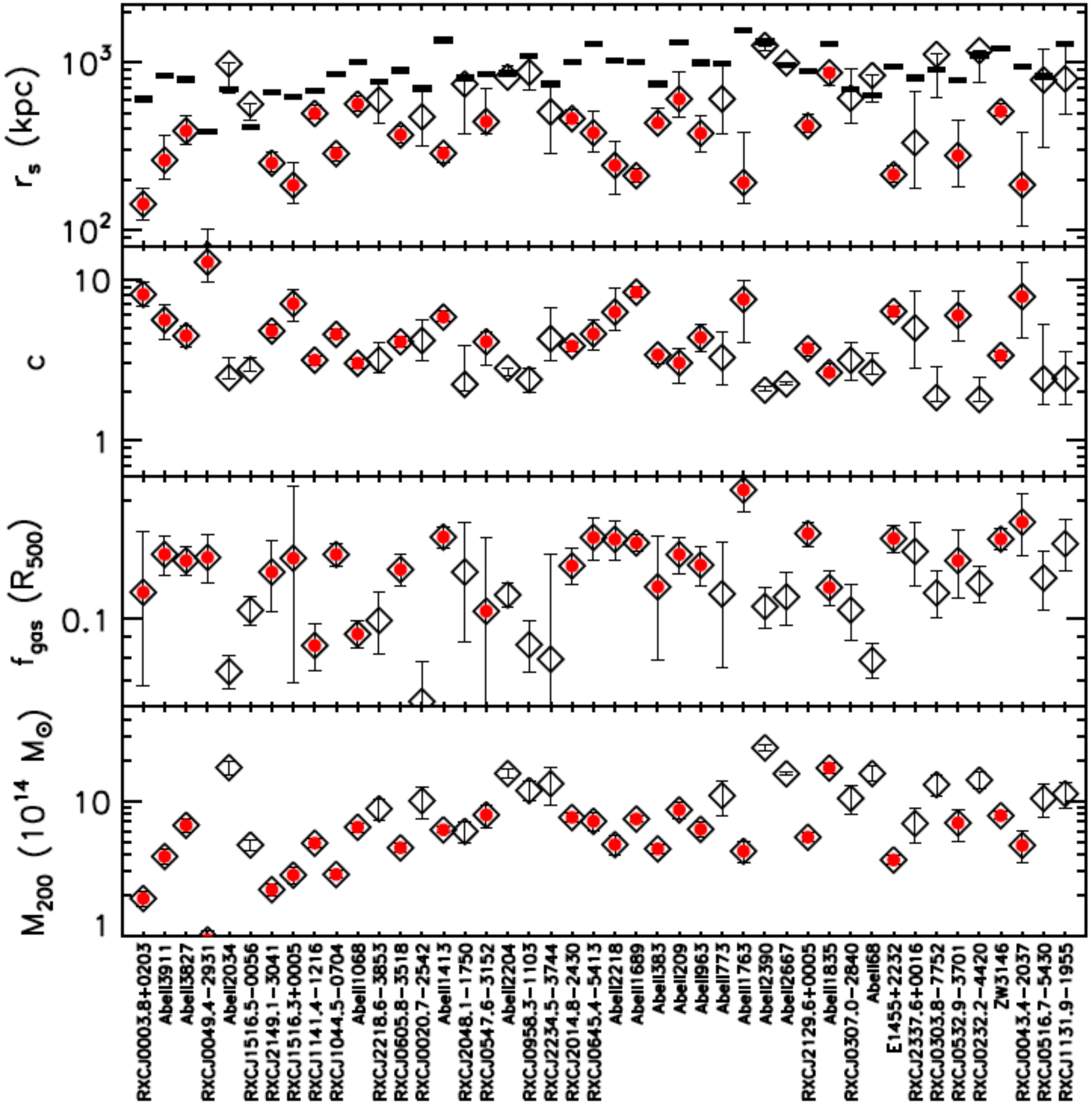








Results on {c, M, f_{gas}}



$c = R_{200}/r_s$

$f_{gas} = M_{gas}/M_{tot}$

$M_{200} = 200 \rho_c(z)\ V$

$V = 4/3 \pi R_{200}^3$

Gas mass fraction

To constrain the cosmological model

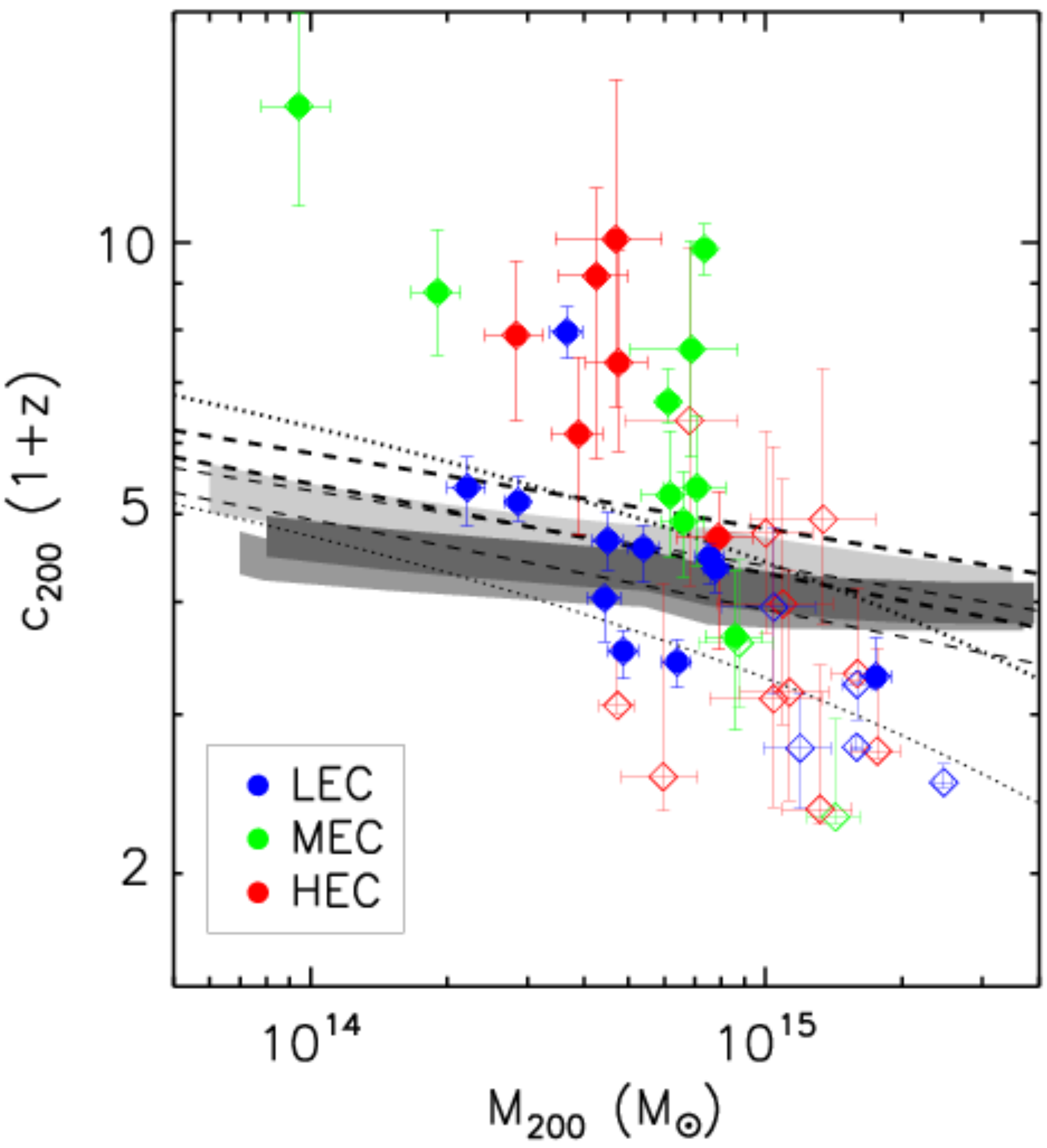
$$\Omega_m + \Omega_\Lambda + \Omega_k = 1$$

We combine a **dynamical** and a **geometrical** method (see also Allen et al, Blanchard et al., Ettori et al, Mohr et al) :

1. baryonic content of galaxy clusters is representative of the cosmic baryon fraction Ω_b / Ω_m (White et al. 93)

2. f_{gas} is assumed constant in cosmic time in very massive systems (Sasaki 96, Pen 97)

c-M relation: $\sigma_8-\Omega_m$



Dotted lines: Eke et al. (01) for a given ΛCDM at z=0 (from top to bottom: σ_8=0.9 and 0.7).

Shaded regions: Maccio' et al. (08, see Bullock et al. 01) for WMAP-1, 5 and 3 years (from the top to the bottom, respectively).

Dashed lines (thin: z=0.1, thick: z=0.3) indicate the best-fit range at 1σ in a WMAP-5 yrs cosmology from Duffy et al. (08)

Scatter in the sample
σ_{tot}~0.14 (σ_{stat}~0.09)
LEC: σ_{tot}~0.08 (σ_{stat}~0.03)

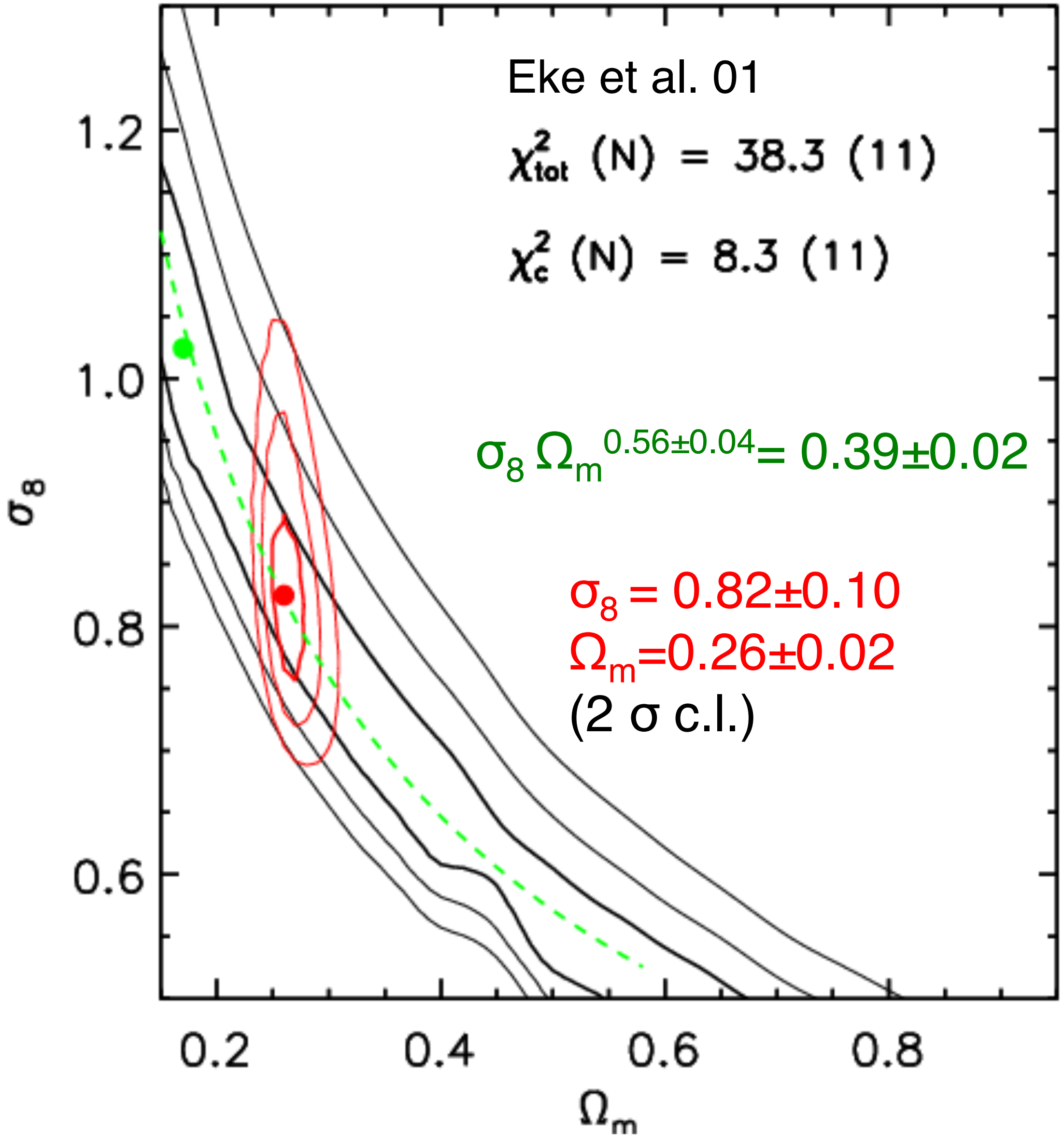
NOTE: LEC≈CC … HEC≈mergers
(see e.g. Leccardi et al. 2010)

Combining {c, M, f_{gas}}: $\sigma_8-\Omega_m$

- We constrain (σ_8, Ω_m) by comparing our estimates of (c_{200}, M_{200}) to the predictions tuned from CDM simulations (*black contours*)

- We consider both **systematics** (e.g. different T profiles; fitted n_{gas}; two methods: ~5%) in our measurements & **scatter** from numerical predictions (~20%, e.g. Neto et al. 07)

- We add constraints from f_{bar} (*red contours*).



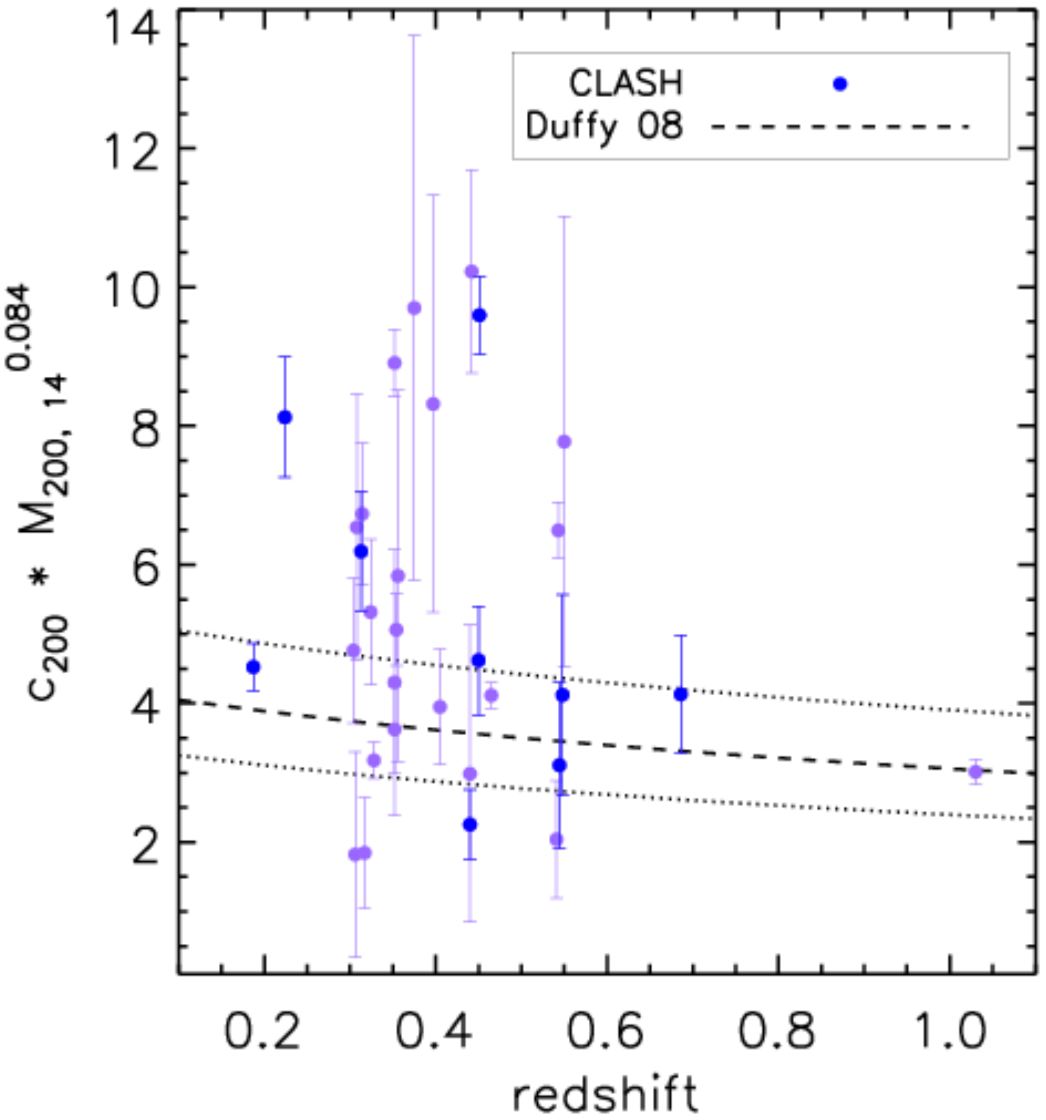
Eke et al. 01

$\sigma_8\,\Omega_m^{0.56\pm0.04} = 0.39\pm0.02$

$\sigma_8 = 0.82\pm0.10$
$\Omega_m = 0.26\pm0.02$
(2 σ c.l.)

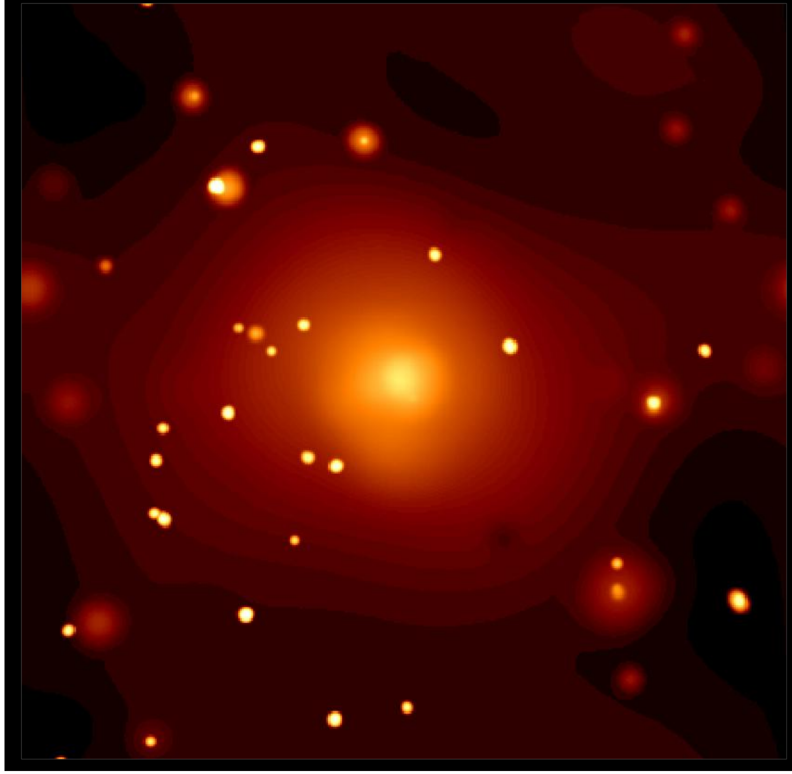
Evolution in {c-M}

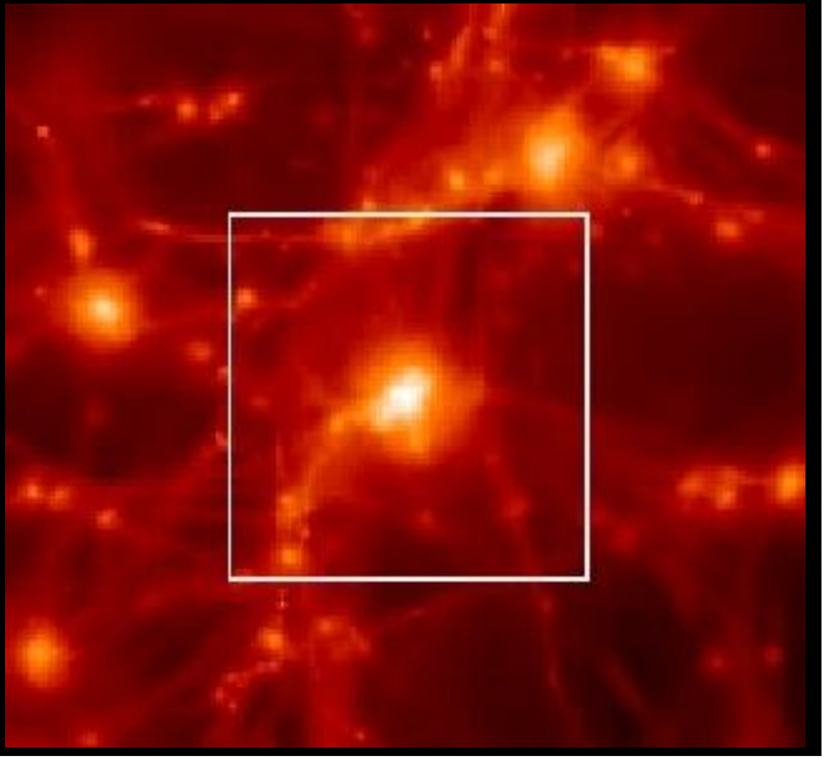
moving @z>0.3 with *Chandra*



But do we know the systematics in the estimates of M_{tot} in X-ray galaxy clusters ?

Evrard, Metzler, Navarro 96; Schindler 96; Bartelmann & Steinmetz 96;
Balland & Blanchard 97; Kay et al. 04; Rasia, SE et al. 06; Hallman et al. 06;
Nagai, Vikhlinin, Kravtsov 07; *Meneghetti, Rasia, SE et al. 2010; Rasia et al. 12*



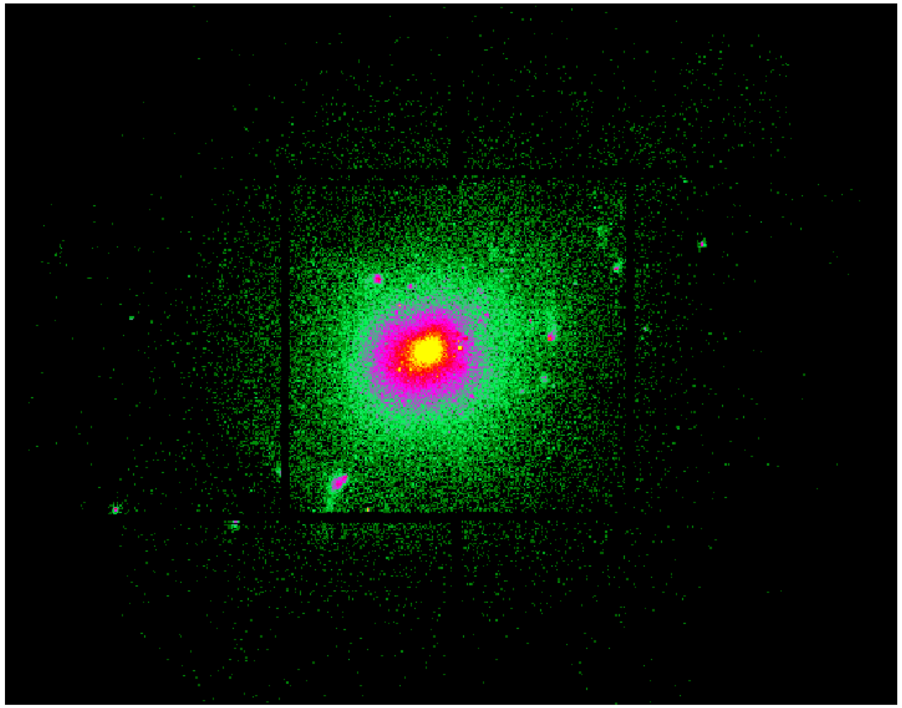


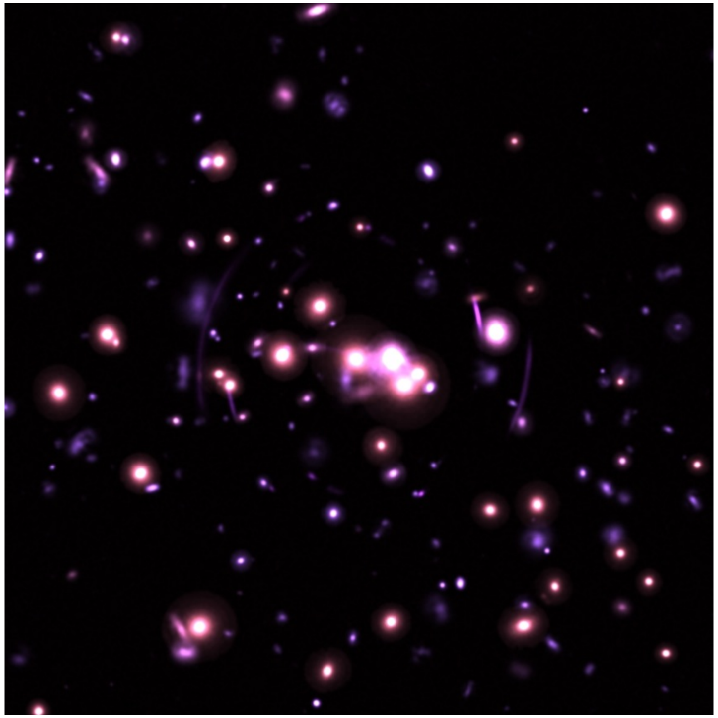
X-ray & lensing mass: *simulations*

M_X / X-MAS & **M_{lens}** / SkyLens

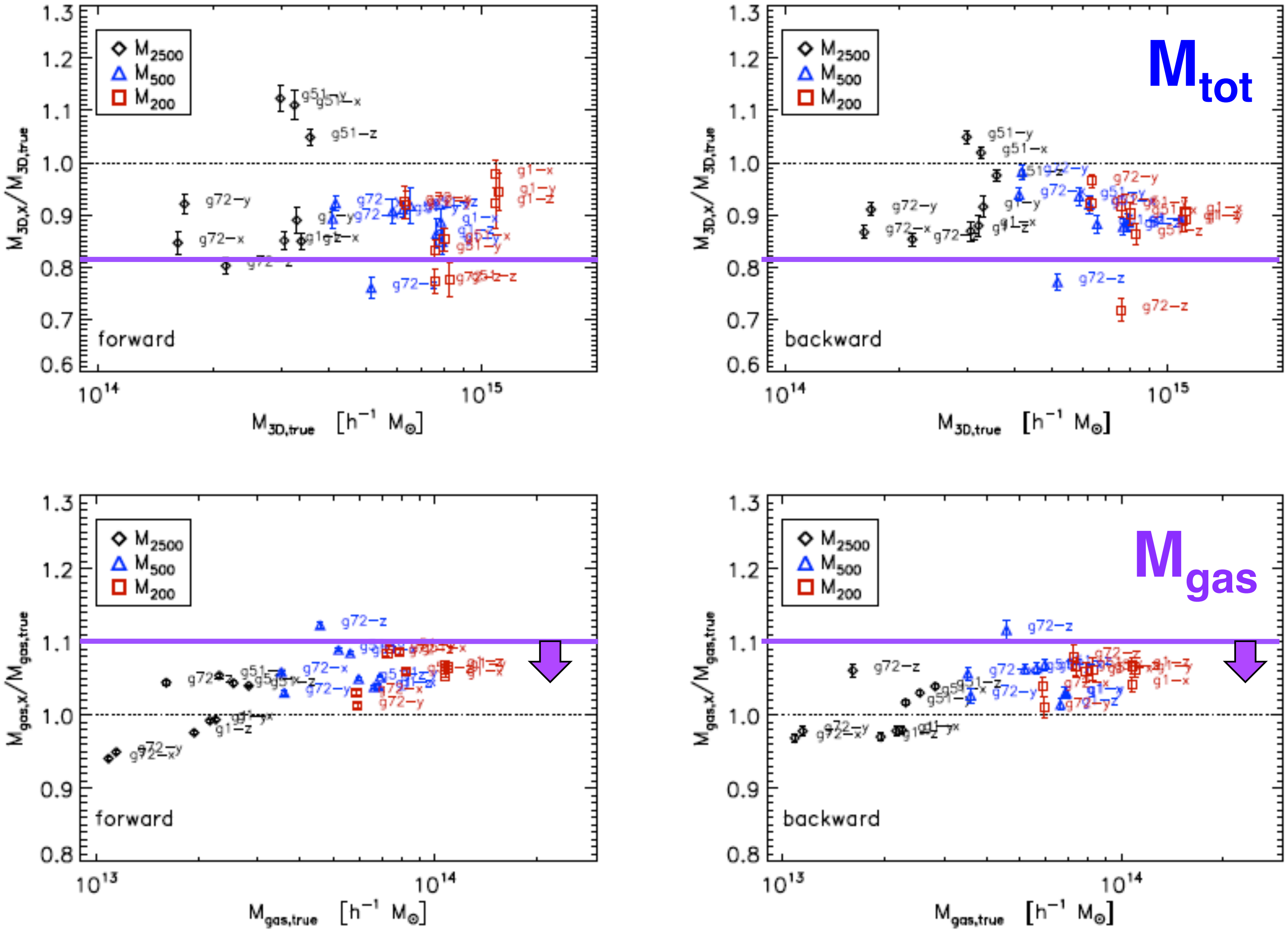
both convolve hydro simulations of 20 massive (~1e15 $M_\odot$) objects with observational setup

(work with E. Rasia & M. Meneghetti)





X-ray & lensing mass: *simulations*



M_{tot}

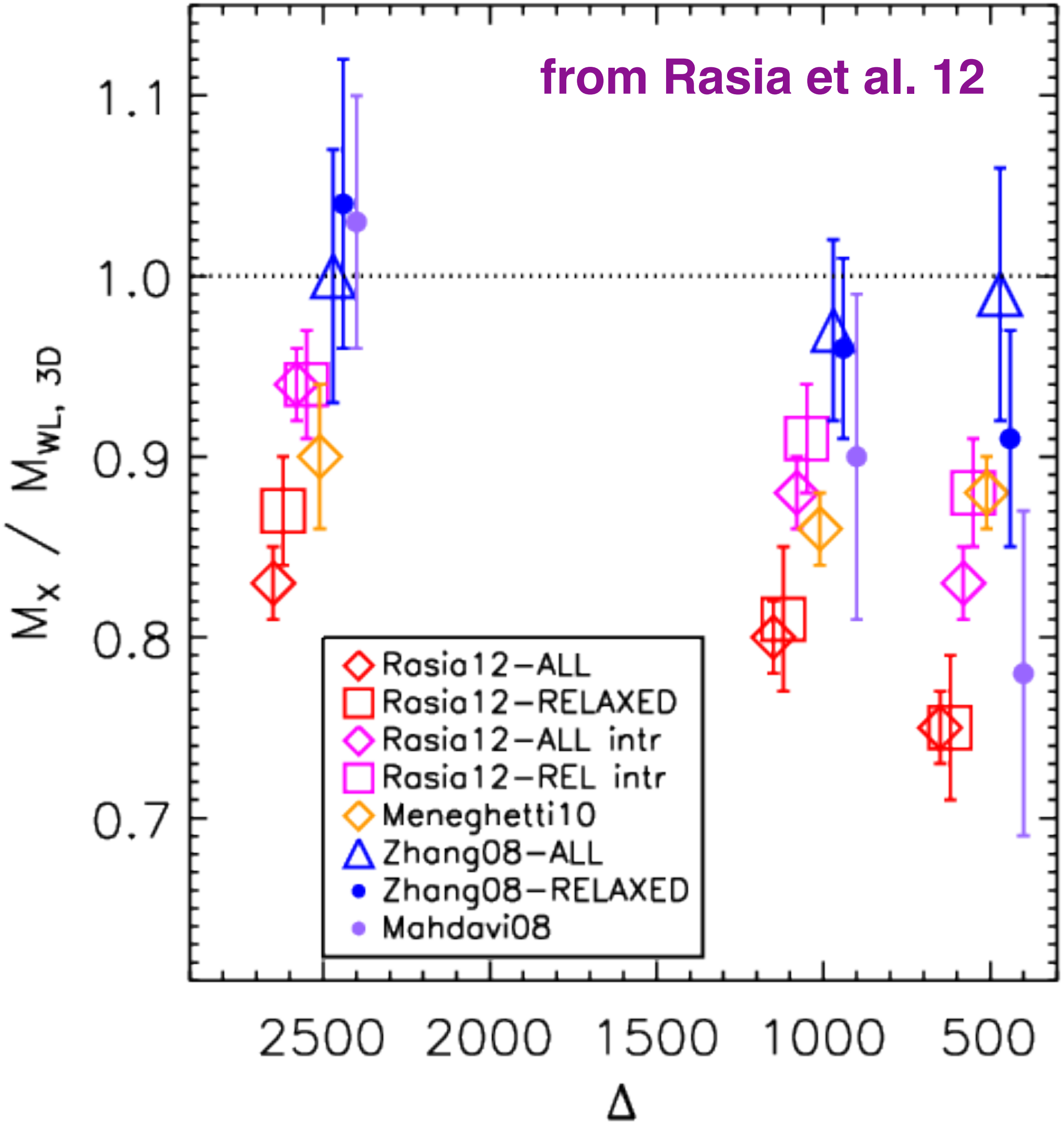
Nagai et al. 07

M_{gas}

Nagai et al. 07

Meneghetti et al. 10

X-ray & lensing mass: *simulations*



X-ray total mass: results from simulations

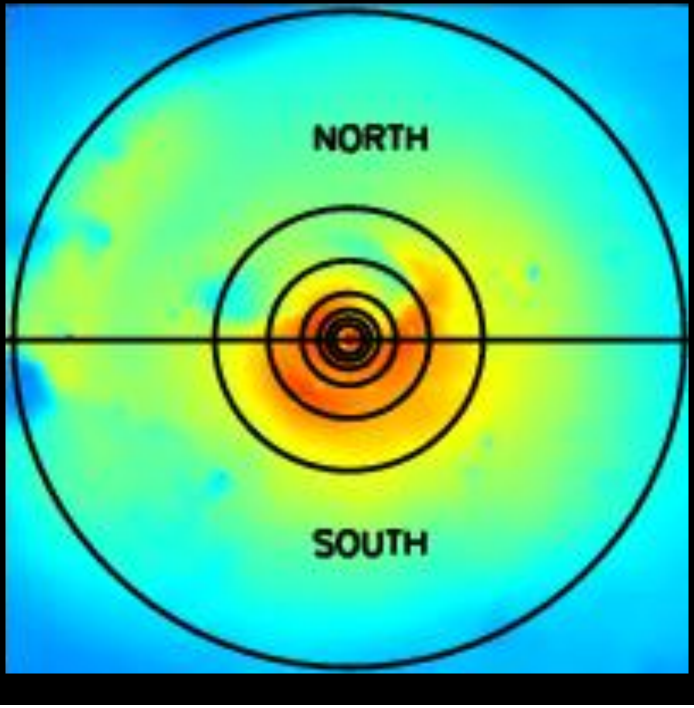
M_X underestimates M_{true} by 10-35 %

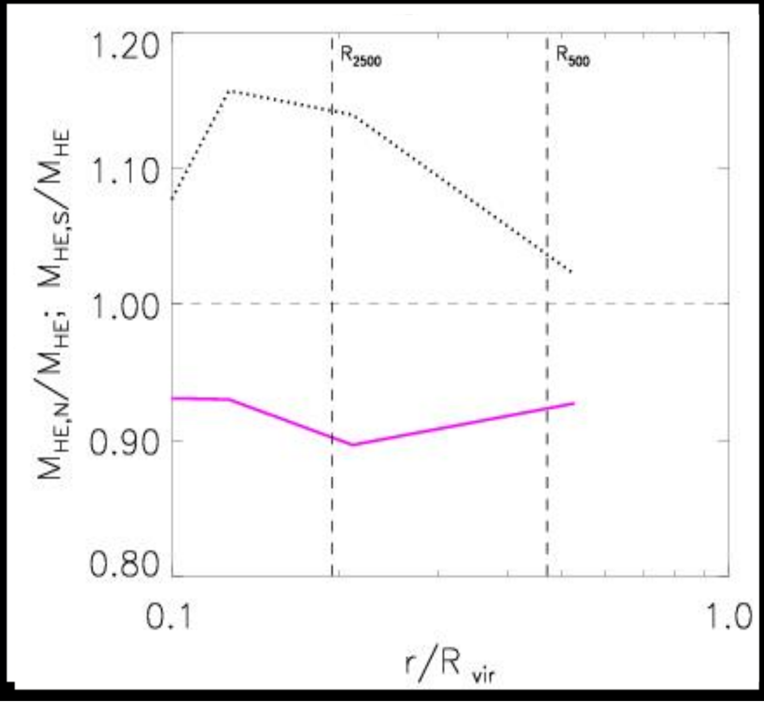
(depending on, e.g., the thermal conduction in the sims)

➔~half of the error budget comes from neglecting gas motions

(see e.g. Nagai et al., Lau et al. 09)

➔ ~half from inhomogeneities in T map





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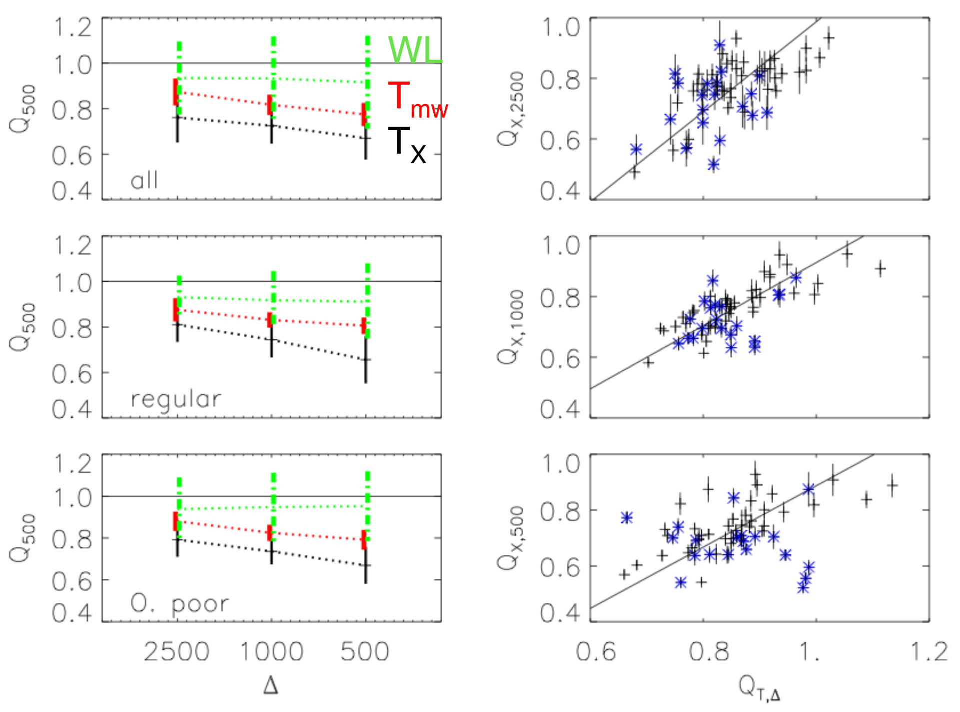


X-ray total mass:
results from simulations

M_X underestimates M_{true} by 10-35 %

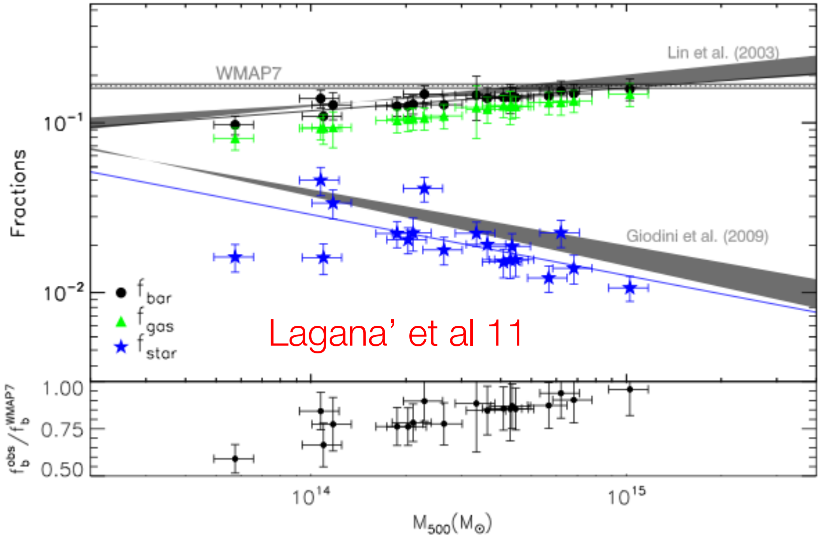
➔ Bias in M_X has low scatter (<10%; weak-lensing-derived masses obtained from the fit of the cluster tangential shear profiles with NFW functionals are biased low by ~5-10% with a large scatter ~ 10-25%)

➔ Bias in M_X grows moving outwards

➔ Bias is correlated (weakly with P30, more with centroid shift) with parameters of X-ray morphology

Some considerations on M_{hyd}

- **HE holds locally**: we need objective methods to characterize the dynamical status of a cluster
- if $M_{hyd} < M_{tot}$ (but M_{hyd} is in agreement with M_{lens} for many individual relaxed objects), **the bias** (with low scatter) **is function of R, M, dynamical state**
- **f_{bar} in agreement with Ω_b/Ω_m** once some depletion is accounted for (if M_{hyd} is underestimated, “missing baryons” problem appears –see Ettori 2003)



Lagana’ et al 11

Pointing to the minimum scatter: the generalized scaling relations

(Ettori et al. 12)

We introduce a generalized scaling law

$$M_{tot} = K A^a B^b$$

to look for the minimum scatter in reconstructing the total mass of hydrodynamically simulated X-ray galaxy clusters, considering ***two independent observables***:

- one accounting for the gas density distribution: $A = M_{gas}$ or L
- the other tracing the ICM temperature: $B = T$

Pointing to the minimum scatter:

$M_{tot} = K A^a B^b$

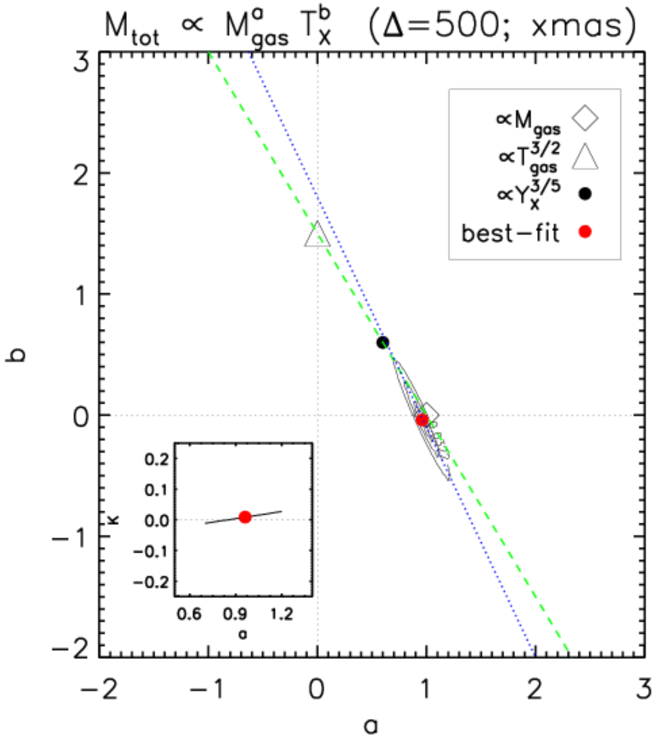
We find **a locus in the plane of the logarithmic slopes** ***a*** & ***b*** where *the scatter in mass is minimized*:

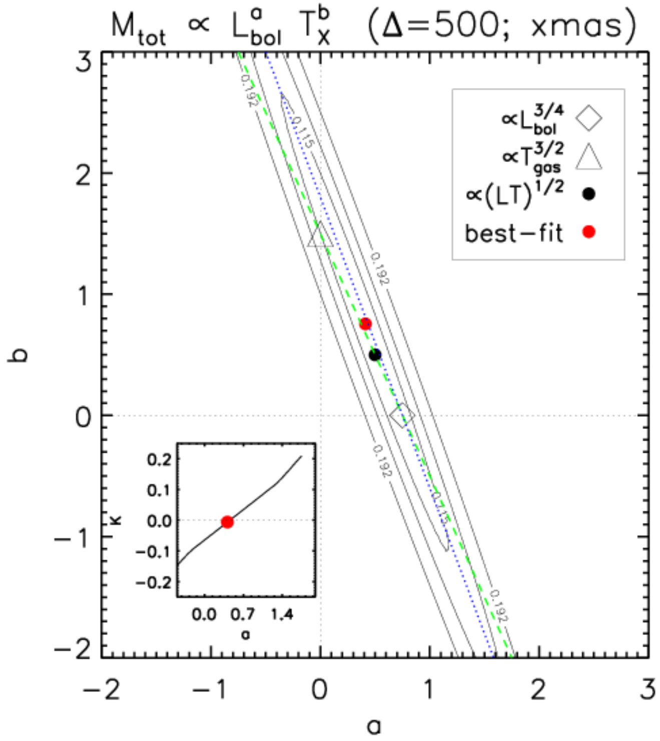
$b_M = -3/2 a_M + 3/2$

for A = M_{gas}, B=T

$b_L = -2 a_L + 3/2$

for A = L, B = T





Pointing to the minimum scatter:
$M_{tot} = K\, A^{a}\, B^{b}$

$M_{tot} \sim L^{\alpha}\ T^{-2\alpha+1.5}$

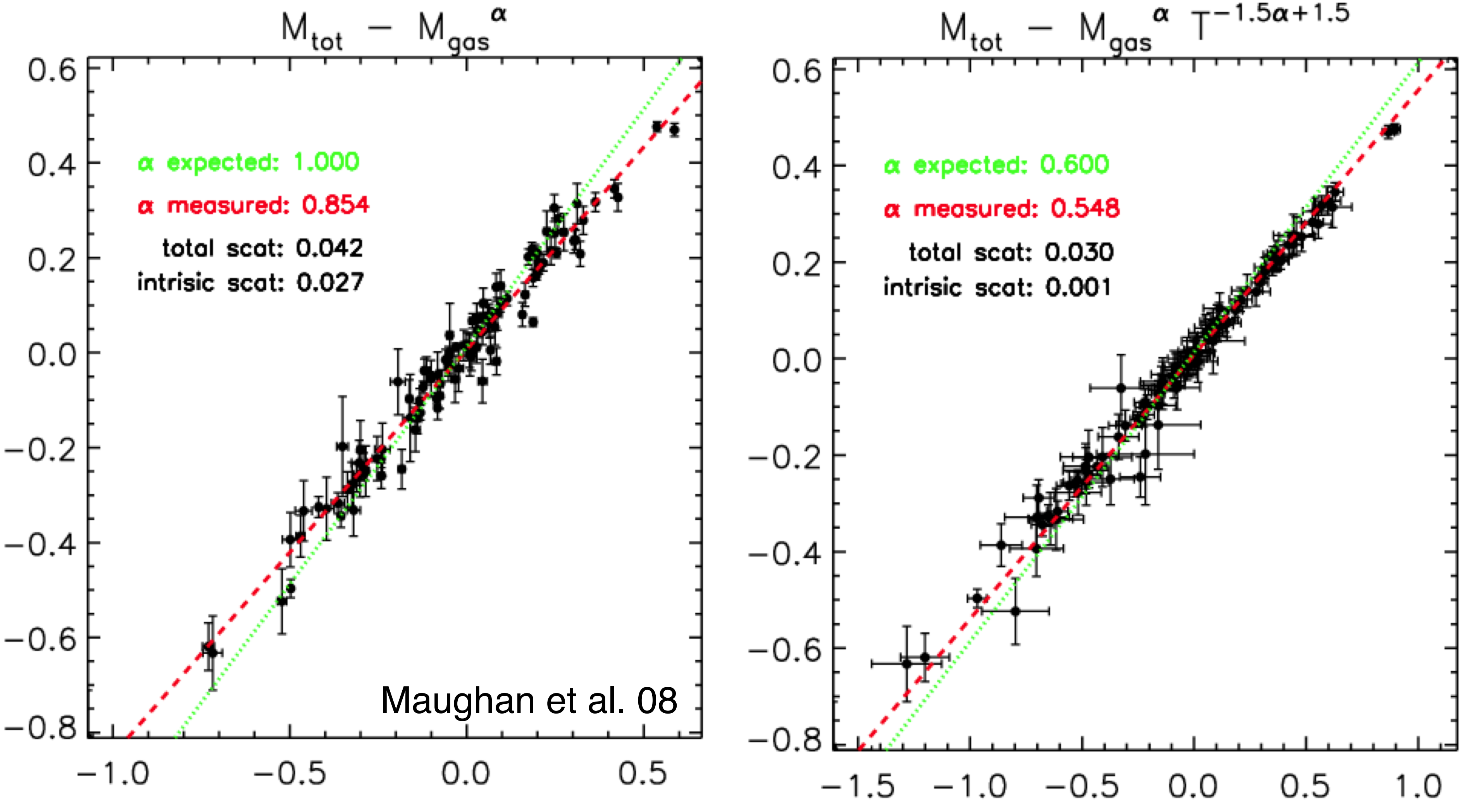
$a = 0$ … $M_{tot} \sim T^{1.5}$
$a = 3/4$ … $M_{tot} \sim L^{3/4}$
$a = 1/2$ … $M_{tot} \sim (LT)^{1/2}$

$M_{tot} \sim M_{gas}^{\ \alpha}\ T^{-1.5\alpha+1.5}$

$a = 0$ … $M_{tot} \sim T^{1.5}$
$a = 1$ … $M_{tot} \sim M_{gas}$
$a = 3/5$ … $M_{tot} \sim (M_{gas}\, T)^{3/5}$
$\sim Y^{3/5}$

Pointing to the minimum scatter:

$$M_{tot} = K\, A^{a}\, B^{b}$$



Maughan et al. 08

Summary

- ***Galaxy clusters as cosmological probes:*** *mass function* & **mass profiles** (***f_{gas} & cMz*** as diagnostic of the baryonic and CDM distribution; Ettori et al. 2010)

- ***Hydro simulations suggest that $M_{hyd} < M_{tot}$ with a low scatter*** (Meneghetti et al. 2010; Rasia et al. 2012) but ***observed*** X-ray and lensing M profiles agree well when compared over the same radial range for not disturbed objects

- *Scaling relations*: lower scatter on M_{tot} by combing more observables, like L / T / M_{gas} (Ettori et al. 2012)

- *Thanks to*: Baldi, Eckert, Gastaldello, Meneghetti, Molendi, Rasia, Rossetti, Leccardi, Borgani, Fabjan, Dolag, Vazza et al.

Conference
on Galaxy Cluster Masses
Madonna di Campiglio, 17-22 March 2013

We are organizing an international conference in Madonna di Campiglio (ski resort at ~170 km north of Verona, ~200 km NE of Milano) on the topic of:

Galaxy cluster masses from the core to the outskirts:
the need for a multi-wavelength approach

The distribution of the gravitating and baryonic mass in galaxy clusters is the key ingredient to use galaxy clusters as astrophysical laboratories and cosmological probes. We propose to discuss this issue in a conference that will be focused mainly on the following items: (1) the reconstruction of the cluster mass profiles through X-ray, SZ, strong and weak lensing techniques; (2) the use of X-ray, SZ and lensing derived quantities as proxies of the gravitating mass; (3) mapping of the cluster outskirts with X-ray, SZ and weak lensing methods; (4) estimates of the systematics affecting mass reconstruction and cosmological implications of these measurements.