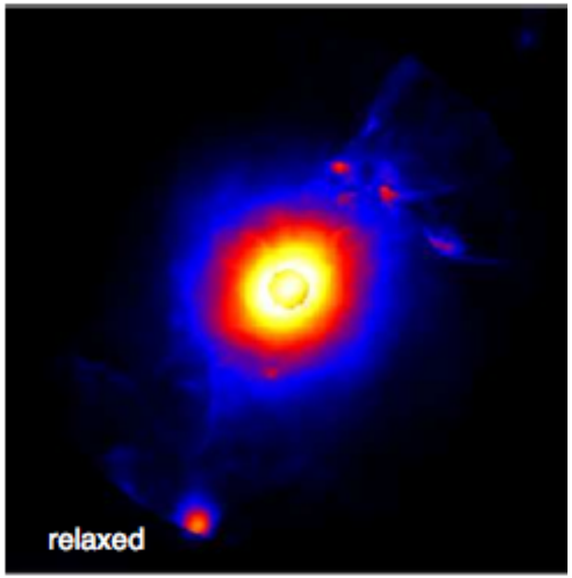
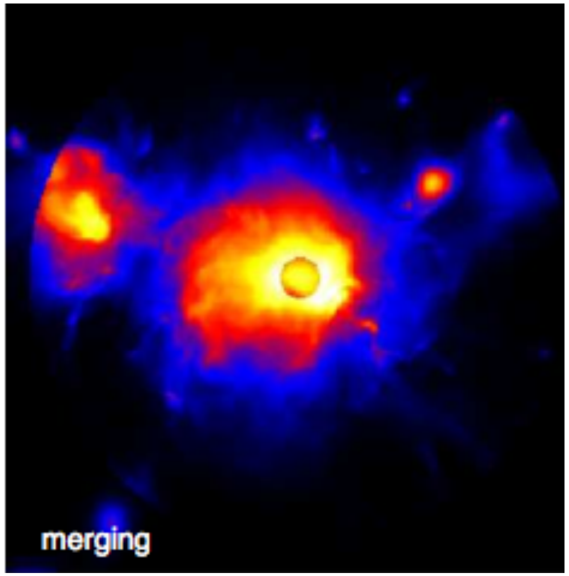
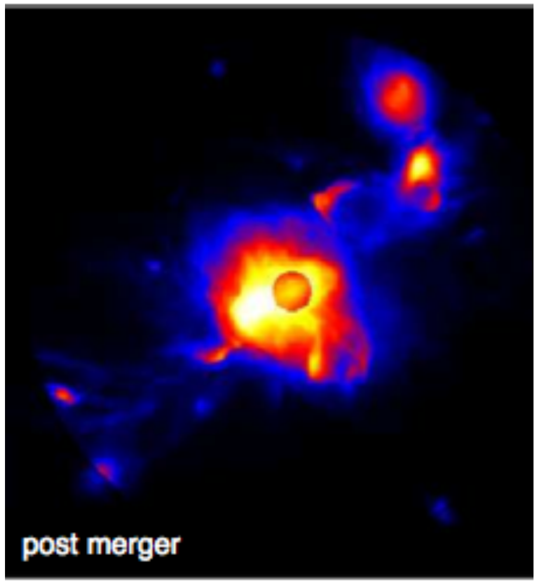
From X-ray observables to M_{tot} in galaxy clusters: *biases & results*

Stefano Ettori (INAF OA Bologna)

Alessandro Baldi, Stefano Borgani, Klaus Dolag, Dominique Eckert, Dunja Fabian, Fabio Gastaldello, Silvano Molendi, Alberto Moretti, Elena Rasia, Susana Planelles, Mauro Roncarelli, Franco Vazza et al.







Total mass from X-rays

- *high counts statistic*: **mass profiles**

(calibration & hydrostatic bias; *~200 out of 1743 obj known*, *Piffaretti et al. 11*)

Ettori et al., 2010, A&A, 524, 68; Baldi, Ettori et al., 2012, A&A, 537, 142; Eckert et al., 2013, A&A, 551, 23; Planelles et al., 2013, MNRAS; Roncarelli et al., 2013, MNRAS;

Ettori et al., 2013, SSRv, arXiv:1303.3530

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

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

Total mass from X-rays

• *high counts statistic*: **mass profiles**

(calibration & hydrostatic bias; *~200 out of 1743 obj known, Piffaretti et al. 11*)

Ettori et al., 2010, A&A, 524, 68; Baldi, Ettori et al., 2012, A&A, 537, 142; Eckert et al., 2013, A&A, 551, 23; Planelles et al., 2013, MNRAS; Roncarelli et al., 2013, MNRAS; Ettori et al., 2013, SSRv, arXiv:1303.3530

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

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

• *low counts statistic*: **scaling relations**

(for galaxy clusters mass function: M_{tot} vs L/T/M_{gas}/Y_X *or* ***a combination of these***…)

Ettori et al., 2012, MNRAS, 420, 2058 - arXiv:1111.1693; Ettori, 2013, MNRAS subm

$$M_{tot} \propto \Delta R_\Delta^3 \Rightarrow \propto T^{3/2} \propto M_g \propto L^{3/4} \propto Y_X^{3/5}$$

Pointing to the minimum scatter: the generalized scaling relations

(Ettori et al. 12)

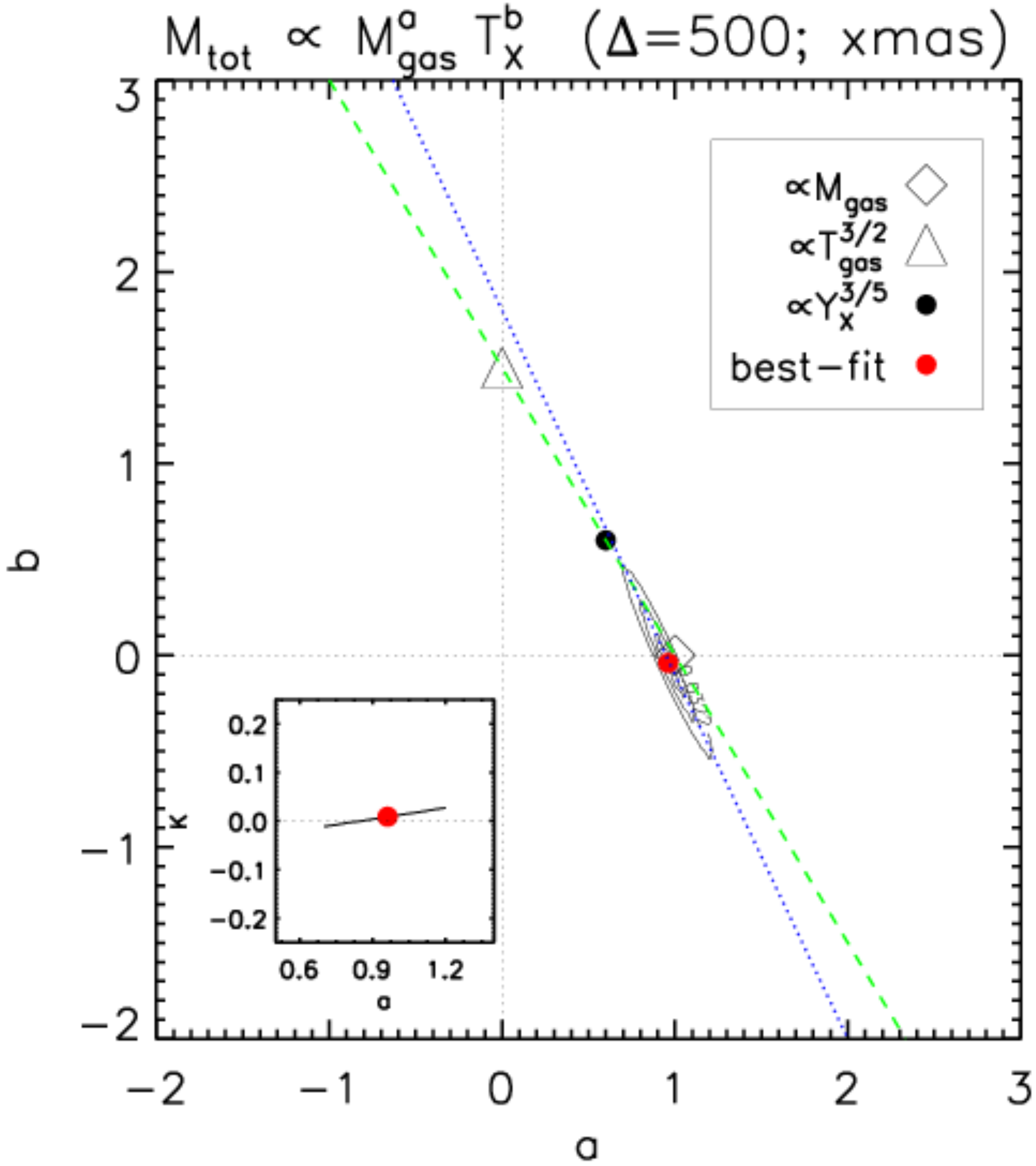
We introduce a generalized scaling law

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

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: $B = T$

The generalized scaling relations



We fit

log $M_{tot} = K + a \log M_{gas} + b \log T$

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

b = −3/2a + 3/2

for A = M_{gas}, B = T

The generalized scaling relations

From *simulations* (Ettori et al. 12)

to *observational data* (Ettori 13):

$$M_{tot} \sim L^{\alpha} M_{gas}^{\beta} T^{\gamma}$$

where the exponents satisfy the eq.

$$\mathbf{4\alpha + 3\beta + 2\gamma = 3}$$

in the self-similar scenario;

$(\alpha=0)\ \gamma = 3/2 - 3/2\ \beta$

$(\beta=0)\ \gamma = 3/2 - 2\ \alpha$

$(\gamma=0)\ \beta = 1 - 4/3\ \alpha$

The generalized scaling relations:

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

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

$\alpha = 0$ … $M_{tot} \sim T^{1.5}$

$\alpha = 3/4$ … $M_{tot} \sim L^{3/4}$

$\alpha = 1/2$ … $M_{tot} \sim (LT)^{1/2}$

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

$\alpha = 0$ … $M_{tot} \sim T^{1.5}$

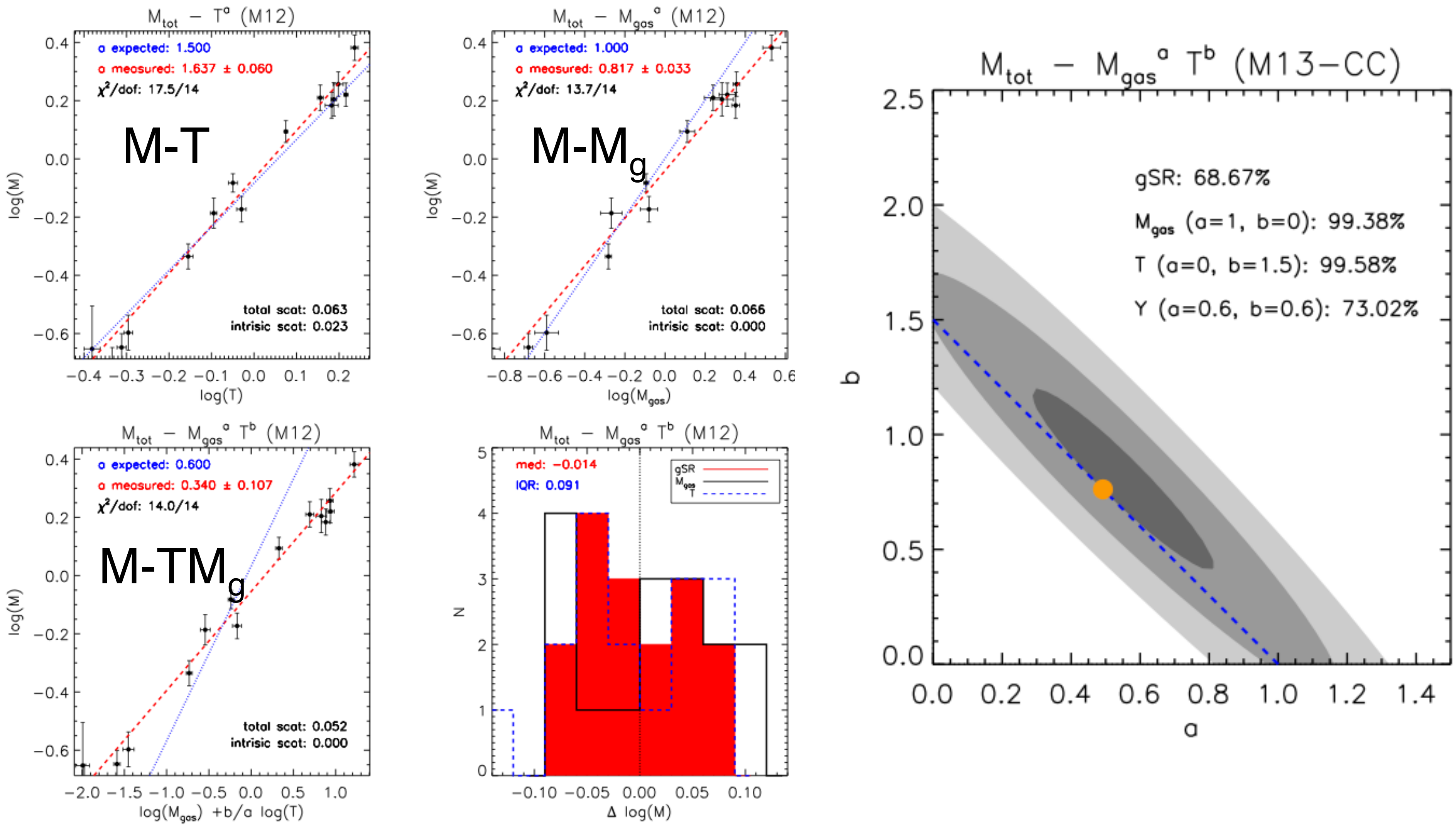
$\alpha = 1$ … $M_{tot} \sim M_{gas}$

$\alpha = 3/5$ … $M_{tot} \sim (M_{gas}\, T)^{3/5}$

$\sim Y^{3/5}$

The generalized scaling relations:

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



The generalized scaling relations:

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

Table 2. Scatter and χ^2 measured in the listed scaling relations by using the data quoted in Mahdavi et al. (2013; M13), Maughan (2012; M12) and Pratt et al. (2009; P09). The degrees of freedom D is just the number of objects in the sample minus 2, the number of free parameters (n, a) used in the fit.

relation	D	χ^2		
$M - T$ (M13)	48	139.8	0.122	$0.085^{+0.017}_{-0.013}$
$M - M_g$ (M13)	48	[illegible]	[illegible]	[illegible]
$M - L$ (M13)	48	[illegible]	0.157	[illegible]
$\boldsymbol{M - M_g\, T}$ (M13)	48	124.6	0.108	[illegible]
$\boldsymbol{M - L\, T}$ (M13)	48	[illegible]	[illegible]	[illegible]
$M - T$ (M13-CC)	14	51.3	0.092	$0.070^{+0.028}_{-0.016}$
$M - M_g$ (M13-CC)	14	50.0	0.115	$0.086^{+0.035}_{-0.021}$
$M - L$ (M13-CC)	14	[illegible]	[illegible]	[illegible]
$M - M_g$ (S09)	21	12.6	0.075	0.000 –
$\boldsymbol{M - M_g\, T}$ (S09)	21	8.7	0.060	0.000 –

Relation	n	a	cov_{na}
$M - M_g\, T$			
M13	-0.095 ± 0.009	0.417 ± 0.061	-3.355×10^{-4}
M13-CC	-0.070 ± 0.019	0.492 ± 0.140	-2.234×10^{-3}
[illegible]	[illegible]	0.340 ± 0.107	3.610×10^{-4}
P09	-0.077 ± 0.003	0.419 ± 0.027	-1.223×10^{-5}
S09	[illegible]	[illegible]	6.046×10^{-3}
[illegible]			
M13	-0.112 ± 0.014	0.159 ± 0.030	-3.280×10^{-4}
[illegible]	[illegible]	[illegible]	-1.092×10^{-3}
[illegible]	[illegible]	[illegible]	-2.548×10^{-5}

The best-fit relations are:

$M_{tot} \propto M_g^{\,a} T^{1.5-1.5a}$, **with** $a \approx 0.4$

$M_{tot} \propto L^{a} T^{1.5-2a}$, **with** $a \approx 0.15$

gSR are the most efficient relations, holding among observed physical quantities in the X-ray band, to recover M_{tot}

(*i.e. they provide the lower χ^2, the lower total scatter and the lower intrinsic scatter among the studied SL*)

Total mass from X-rays

- *high counts statistic*: **mass profiles**

(calibration & hydrostatic bias; *~200 out of 1743 obj known*, *Piffaretti et al. 11*)

Ettori et al., 2010, A&A, 524, 68; Baldi, Ettori et al., 2012, A&A, 537, 142; Eckert et al., 2013, A&A, 551, 23; Planelles et al., 2013, MNRAS; Roncarelli et al., 2013, MNRAS;

Ettori et al., 2013, SSRv, arXiv:1303.3530

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

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

- *low counts statistic*: **scaling relations**

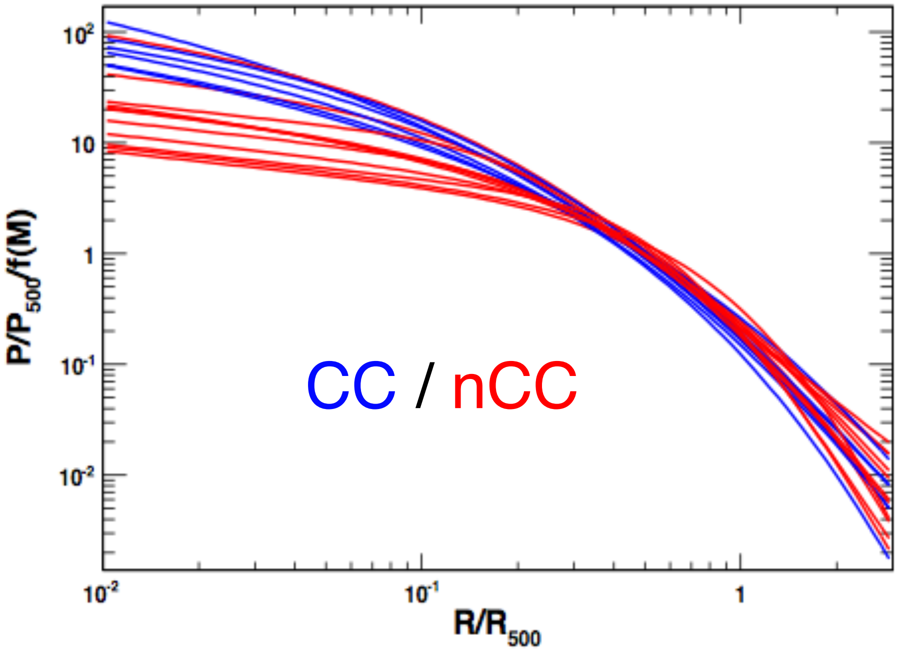
(for galaxy clusters mass function: M_{tot} vs L/T/M_{gas}/Y_X *or* ***a combination of these***…)

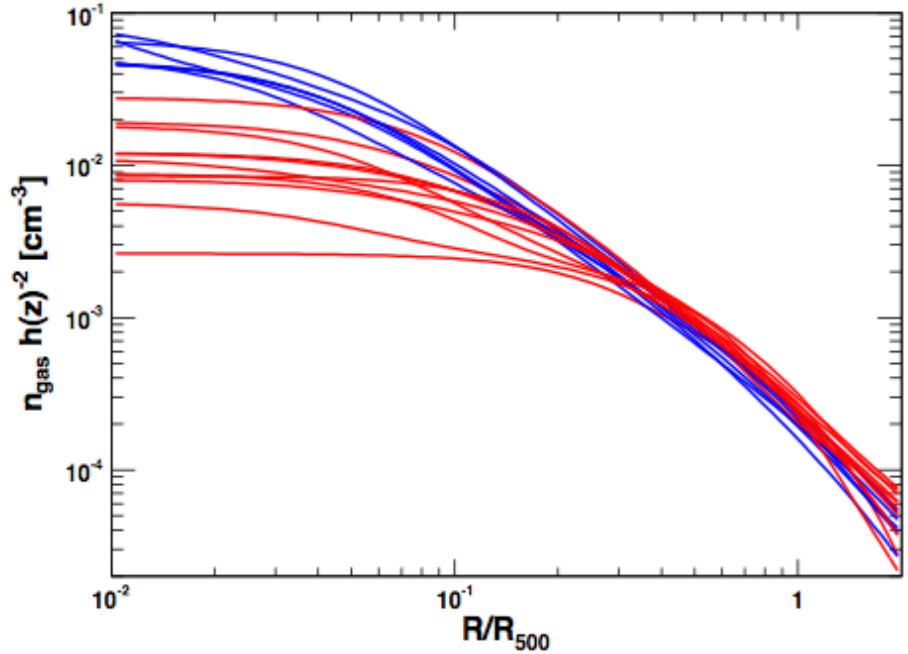
Ettori et al., 2012, MNRAS, 420, 2058 - arXiv:1111.1693; Ettori, 2013, MNRAS subm

$$M_{tot} \propto \Delta R_\Delta^3 \Rightarrow \propto T^{3/2} \propto M_g \propto L^{3/4} \propto Y_X^{3/5}$$

The X-ray/SZ view out to R_{200}

Thermodynamic properties of the ICM for 18 objects in common with Planck SZ thermal pressure and the ROSAT X-ray gas density profiles (Eckert et al. 13a & 13b –see Molendi's talk)

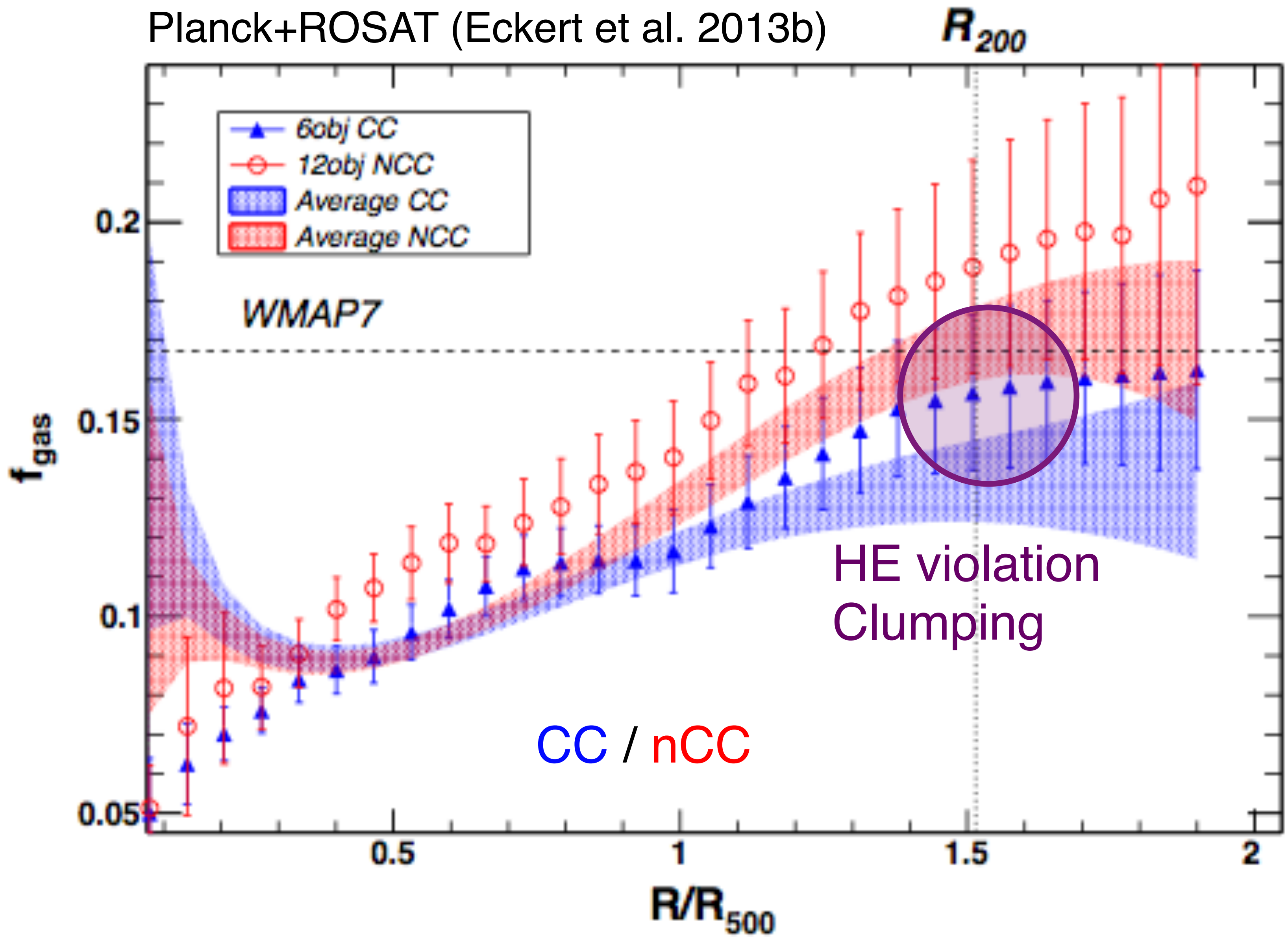




$T = P/n$ $\quad K = P/n^{5/3}$ $\quad M = -r^2/(G\ \mu\ m\ n)\ dP/dr$

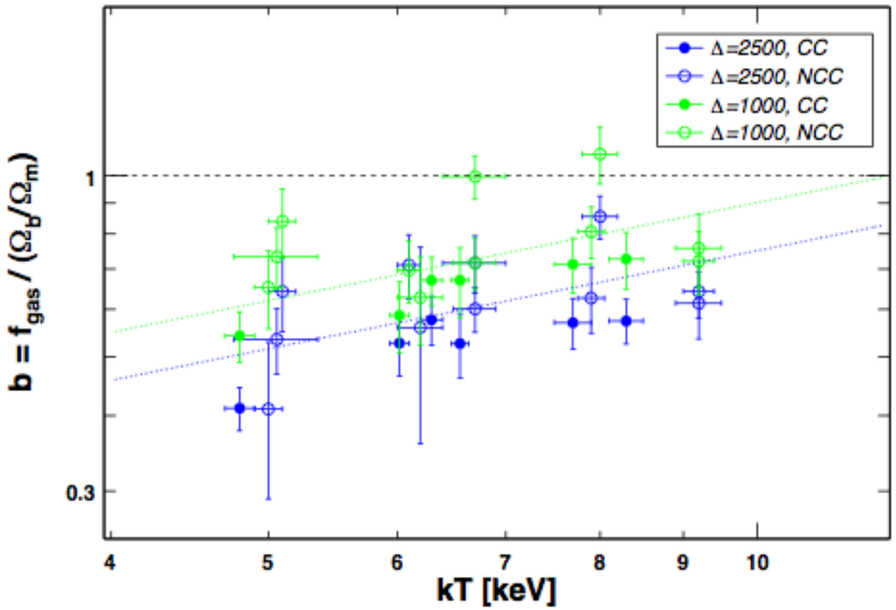
The X-ray/SZ view out to R_{200}

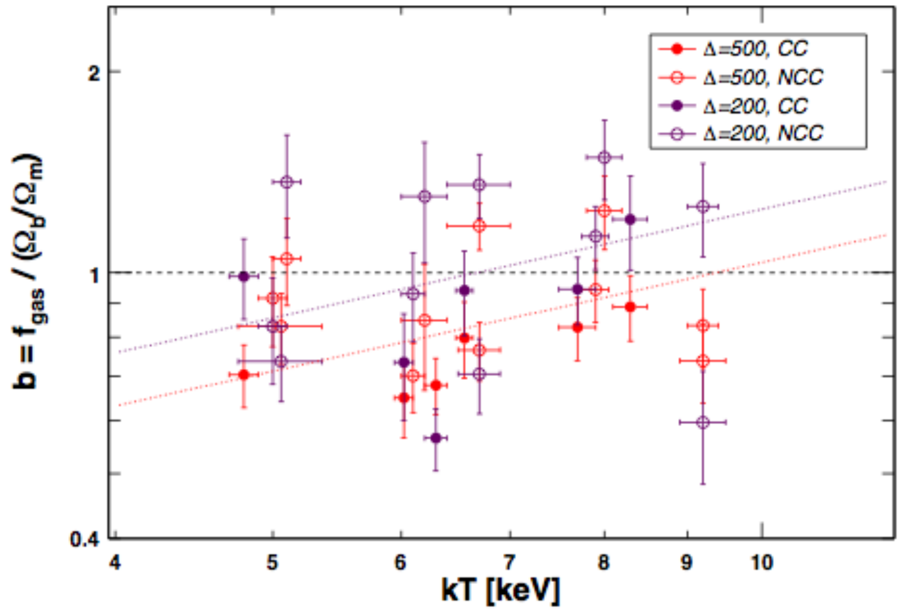
Planck+ROSAT (Eckert et al. 2013b)



The X-ray/SZ view out to R_{200}

In Eckert et al. (13b), we study f_{gas} distribution
by combining P_{SZ} from Planck and n_{gas} from ROSAT





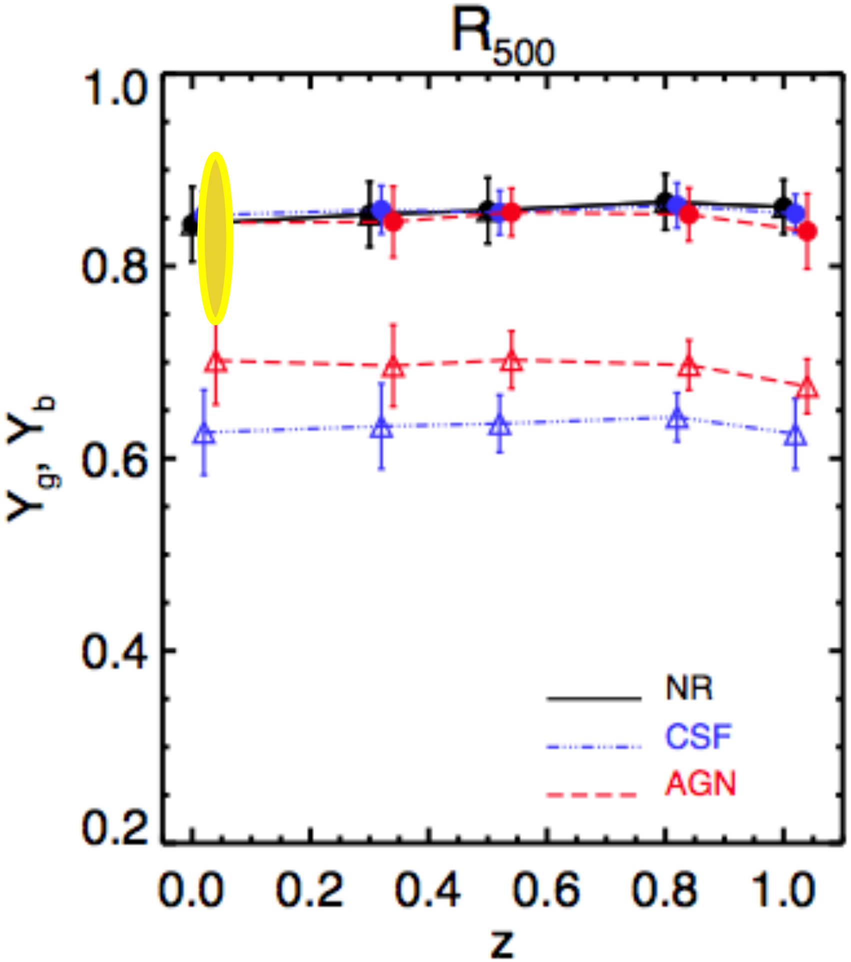
$$f_{gas} / f_{b,WMAP7} = b_{500} (\Delta/500)^{\alpha} (T_{gas} / 7 keV)^{\beta}$$

b_{500} = 0.76±0.02 (CC) 0.92±0.02 (NCC), $\alpha = -0.2$, $\beta = 0.5$

f_{gas} : *Observed vs sims clusters*

$$f_{gas}/f_{b,WMAP7} = b_{500}(\Delta/500)^{\alpha}(T_{gas}/7keV)^{\beta}$$

b_{500} = 0.76±0.02 (CC) 0.92±0.02 (NCC), $\alpha = -0.2$, $\beta = 0.5$



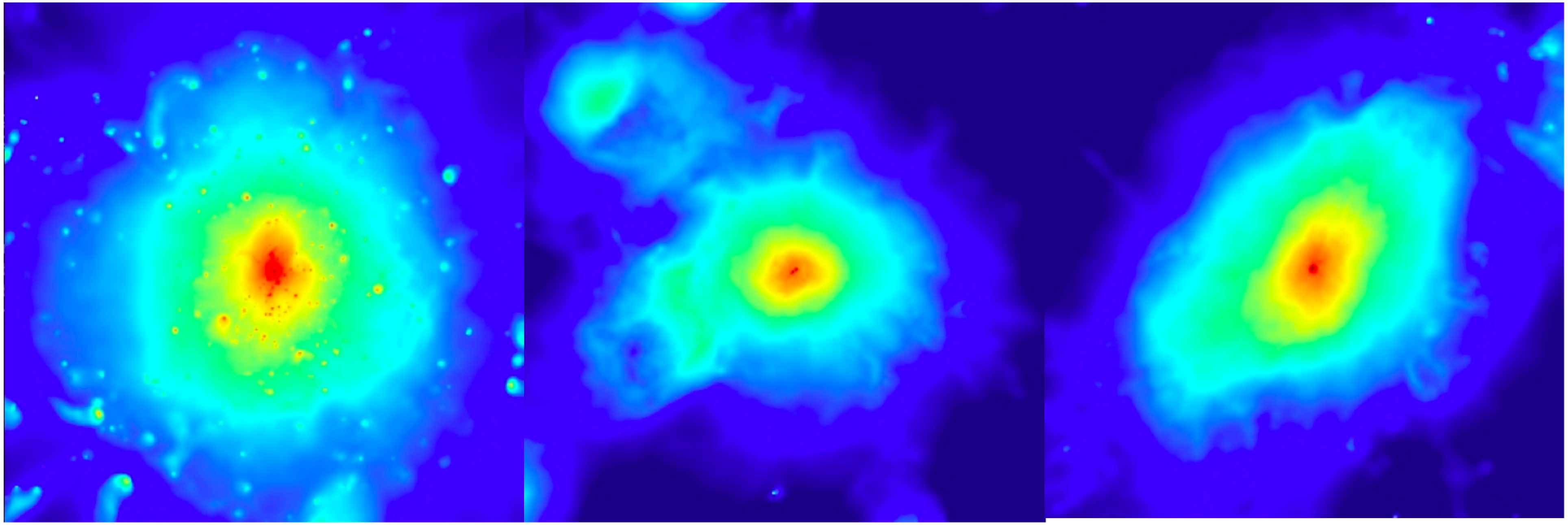
WMAP7: f_b=0.167±0.008

Planck13: f_b=0.155±0.004

… **0.81** / **0.98**

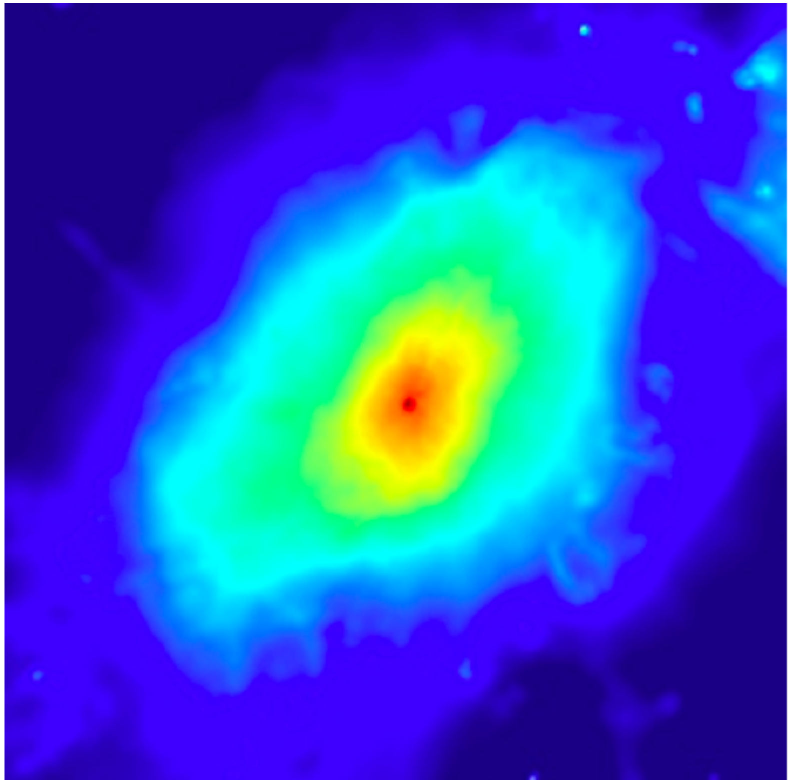
Planelles et al. 13

n_{gas} : *clumpiness*

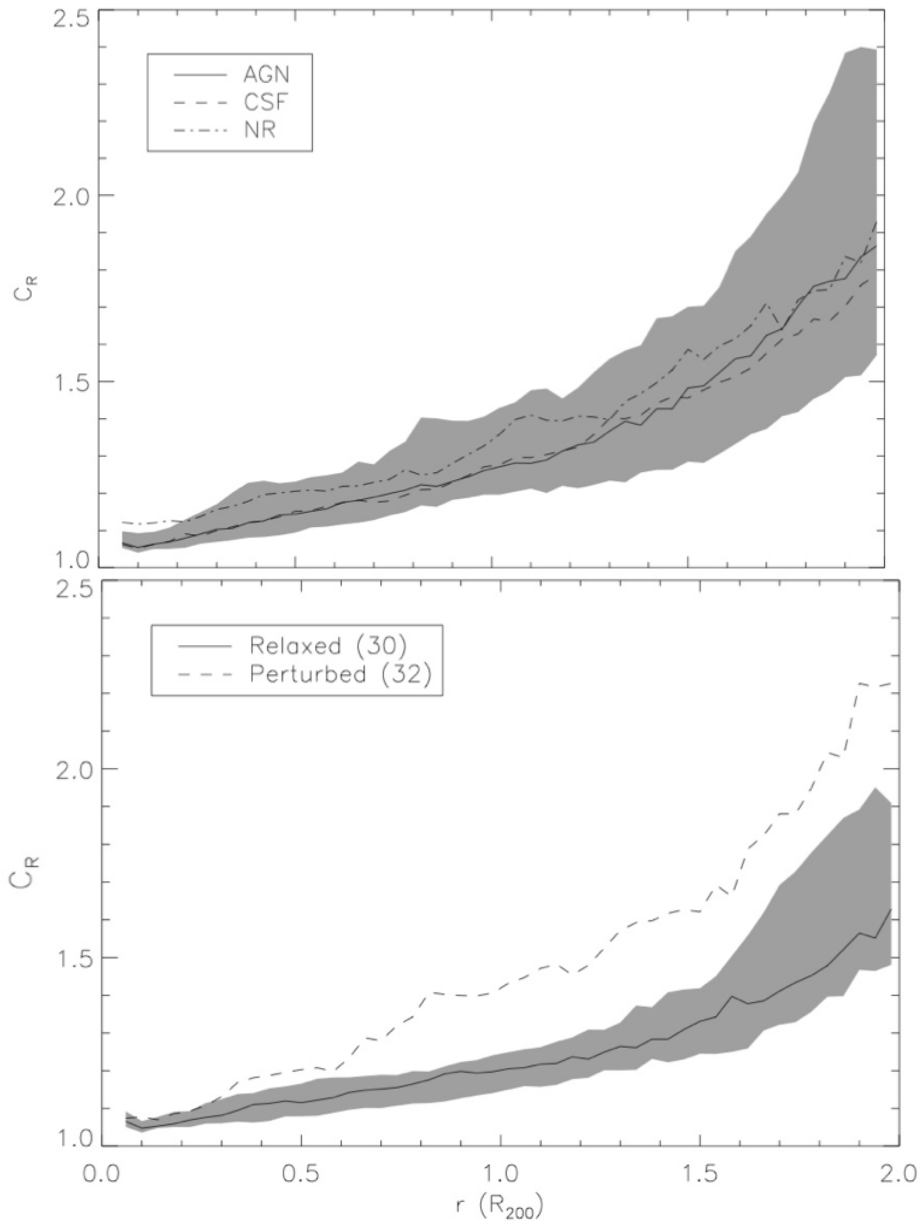


Clumps Sub-halos Asymmetries

n_{gas} : *clumpiness*



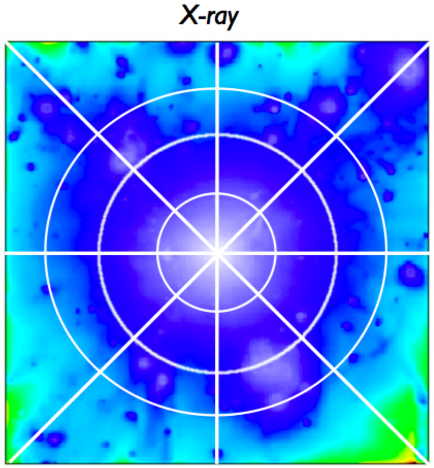
Asymmetries

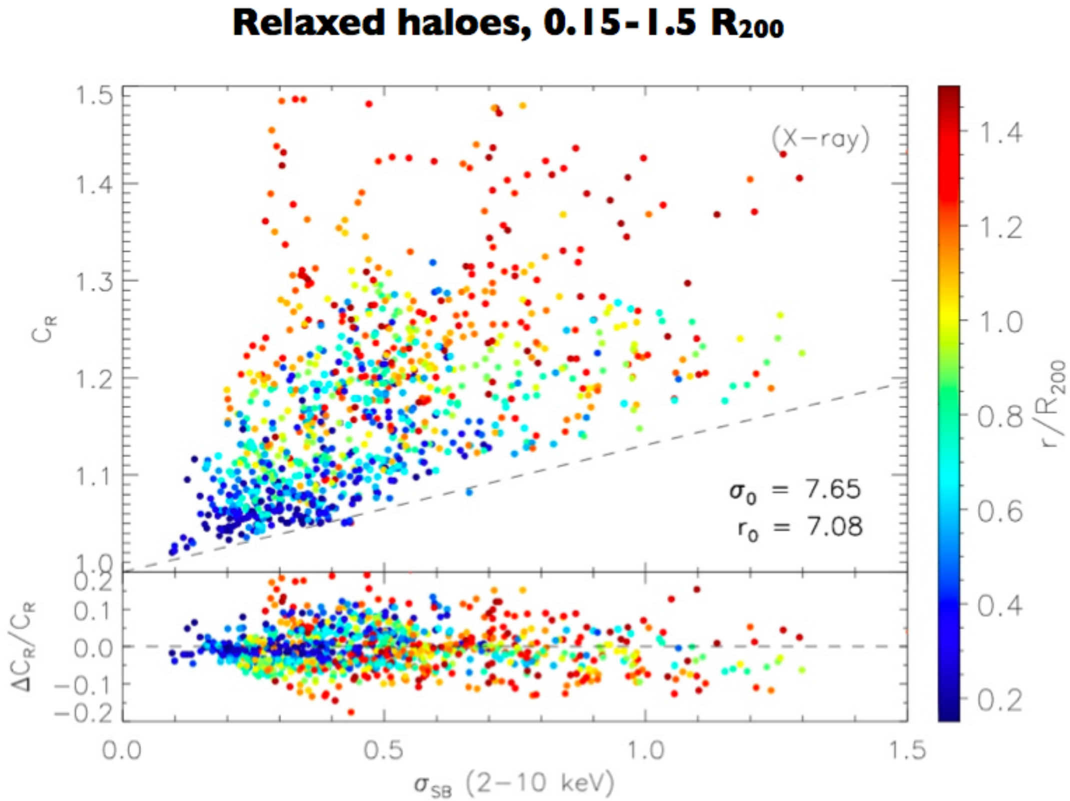


n_{gas} : *clumpiness*

$$\sigma_X(r) = \sqrt{\frac{1}{N}\sum_i^N \frac{[x_i(r)-X(r)]^2}{[X(r)]^2}}$$

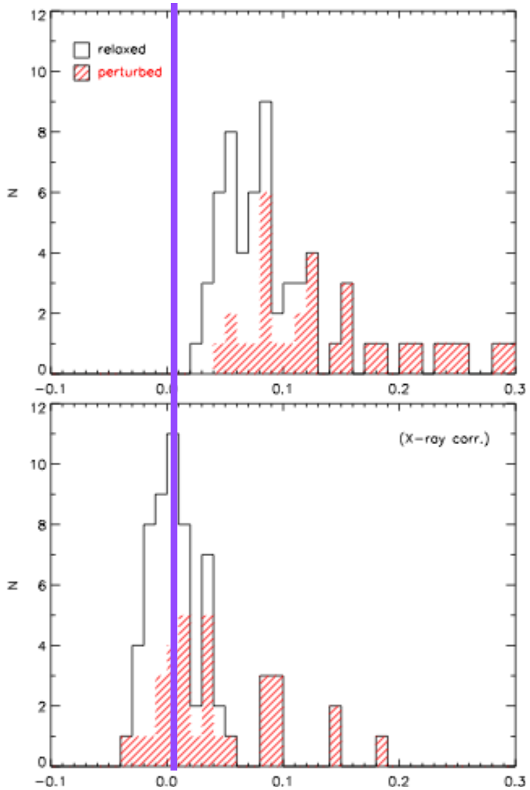
x_i: SB in a given sector
X: average over the N sectors





$$C^{est}(\sigma,r) = 1 + \frac{\sigma}{\sigma_0} + \frac{r}{r_0}$$

n_{gas} : *clumpiness*



$M_{gas} \sim C(r)^{0.5}$

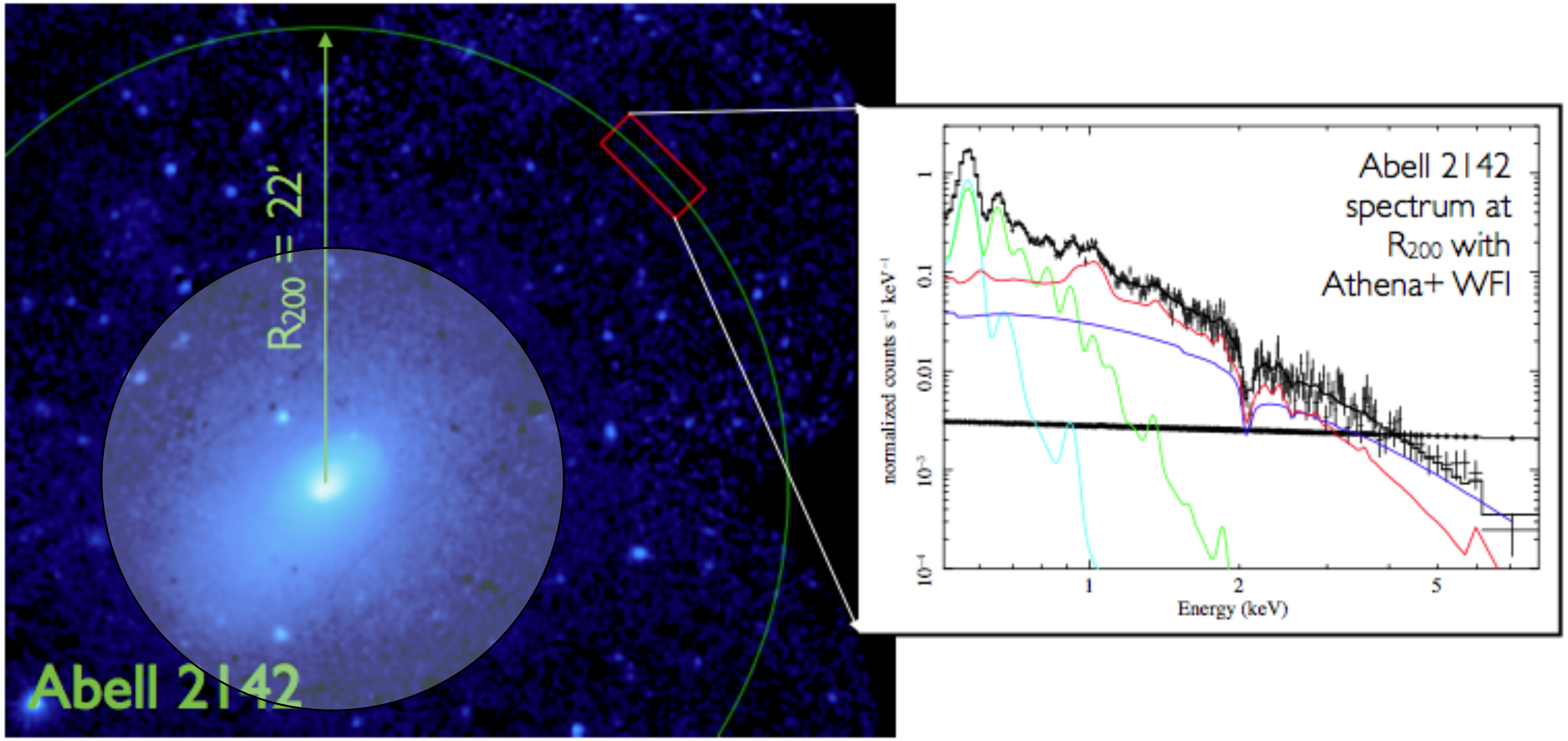
$$M_{HE} \sim \frac{\partial \ln T + \partial \ln n + 0.5\,\partial \ln C(r)}{\partial \ln r}$$

Roncarelli, Ettori et al. 13

	M_{gas}	M_{he}	f_{gas}
C_R bias	$+6.11^{+1.73}_{-1.51}$	$-2.22^{+1.52}_{-2.02}$	$+8.45^{+2.57}_{-2.11}$
Corrected	$-0.08^{+1.22}_{-0.94}$	$-0.38^{+1.69}_{-1.19}$	$+0.06^{+2.38}_{-0.98}$

Future on X-ray galaxy clusters: *Athena+*

(see Nandra et al. arXiv:1306.2307; Ettori-Pratt et al. arXiv:1306.2322)

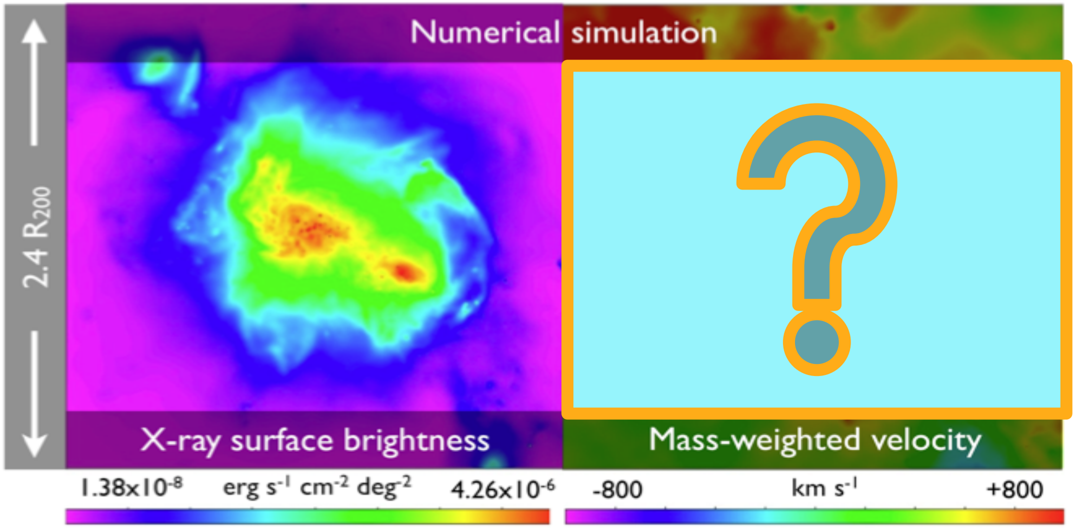


Cluster outskirts

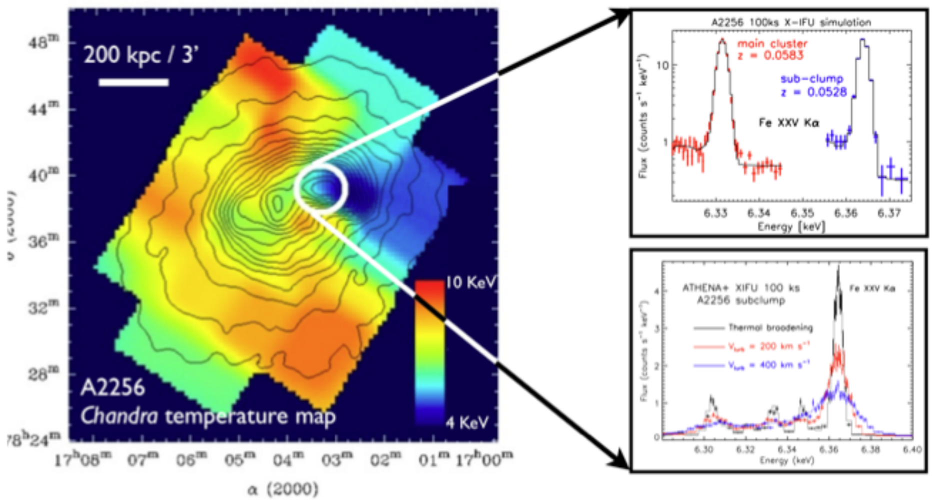
With 100k-sec WFI exposure, gas emissivity, T, Z with 2, 3, 18% (90% c.l.) can be measured at R_{200}.

Future on X-ray galaxy clusters: *Athena+*

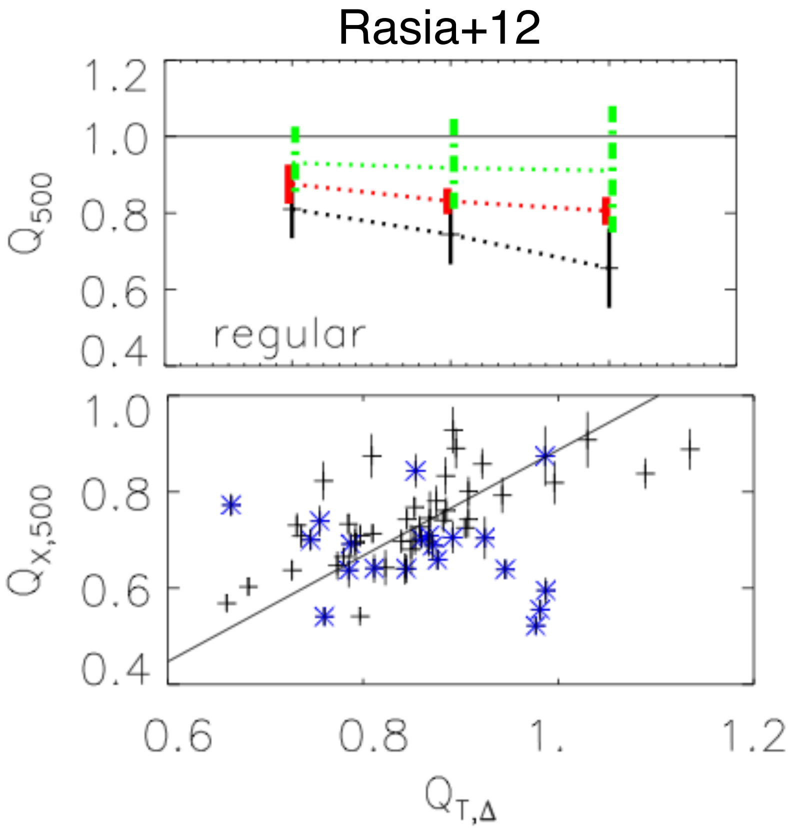
(see Nandra et al. arXiv:1306.2307; Ettori-Pratt et al. arXiv:1306.2322)

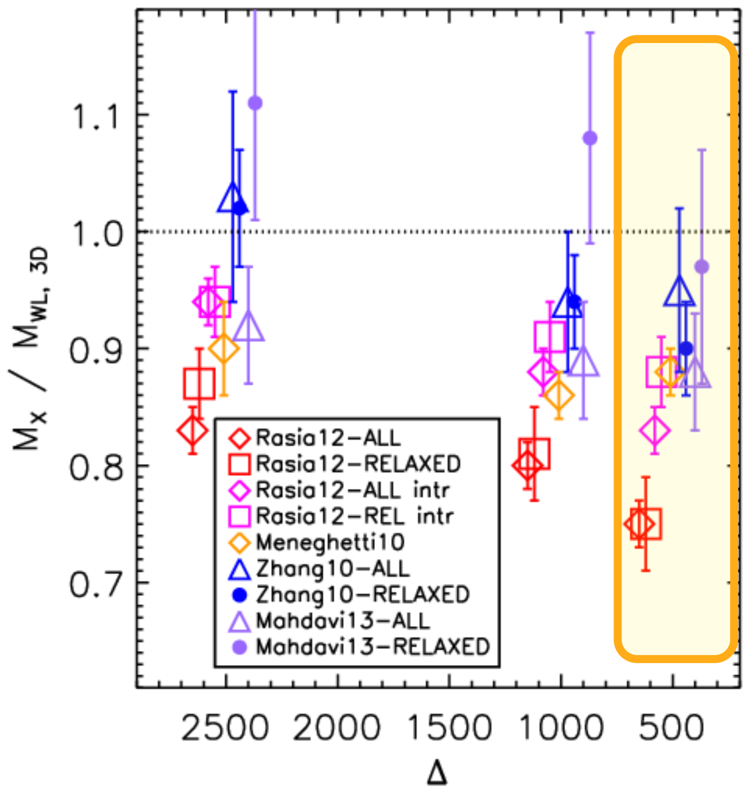


Bulk motion and turbulent broadening of FeXXV Ka line. With 100k-sec X-IFU exposure, 0^{+20} 200±5, 400±10 km/s can be resolved.



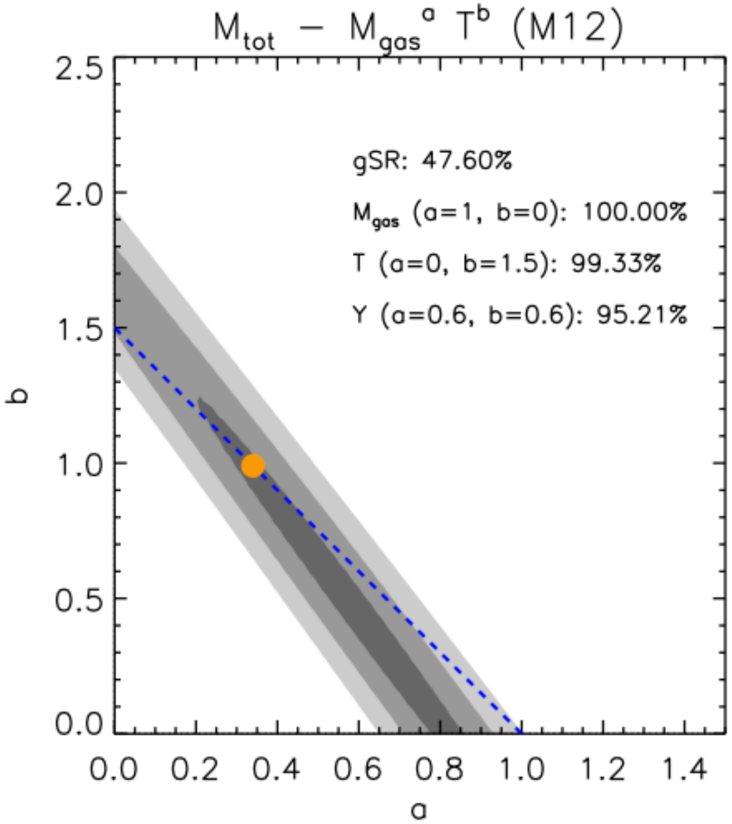
Biases on M_{hyd}





- **hydrostatic bias** is function of R, M, dynamical state ($M_{hyd} \sim M_{tot}$ in CC objs). **HE holds locally**: we need objective methods to characterize the dynamical state & localize disturbed regions. ***CLASH results soon…***

gSR & M_{hyd}



gSR:

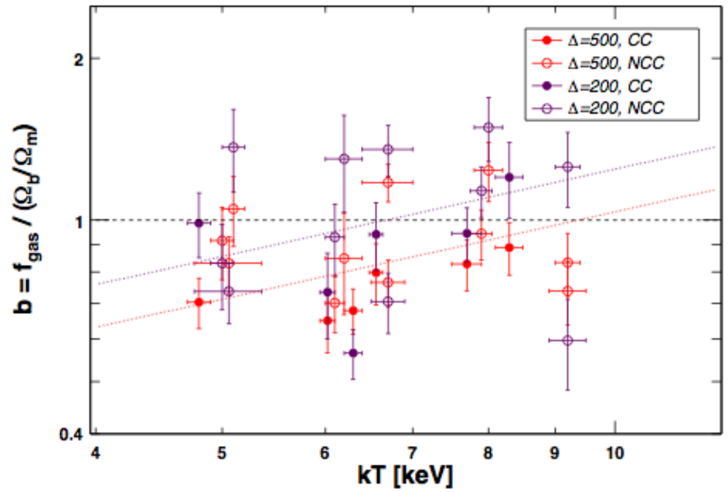
$M_{tot} \propto M_g^{\alpha} T^{1.5-1.5\alpha}$, with $\alpha \approx 0.4$

$M_{tot} \propto L^{\alpha} T^{1.5-2\alpha}$, with $\alpha \approx 0.15$

gSR are the most efficient relations, *holding among observed physical quantities in the X-ray band*, to recover M_{tot} (i.e. they provide the lower χ^2, the lower total scatter and the lower intrinsic scatter among the studied SL)

Some considerations on f_{gas}

Eckert+13b



• we have the first direct constraints on the **depletion factor & evidence of difference btw CC/NCC @R_{200} in f_{gas}** (HE/ clumps by ~1.23; residual clumpiness due to asymmetries: b_{gas}~8±2 %)

• **f_{bar} is in agreement with Ω_b/Ω_m** (if M_{hyd} is underestimated, "missing baryons" problem appears –see Ettori 2003)