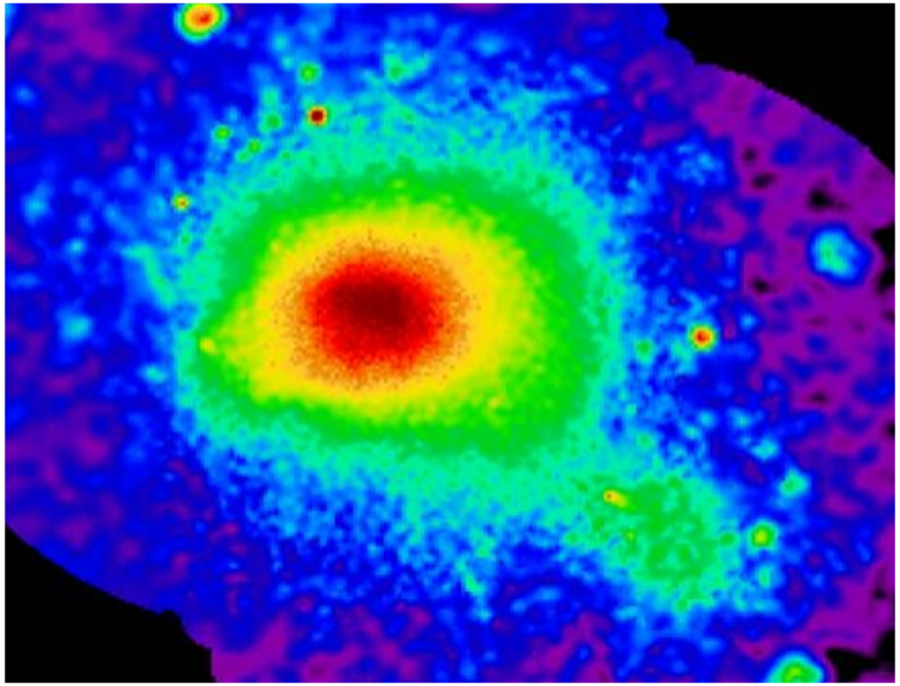
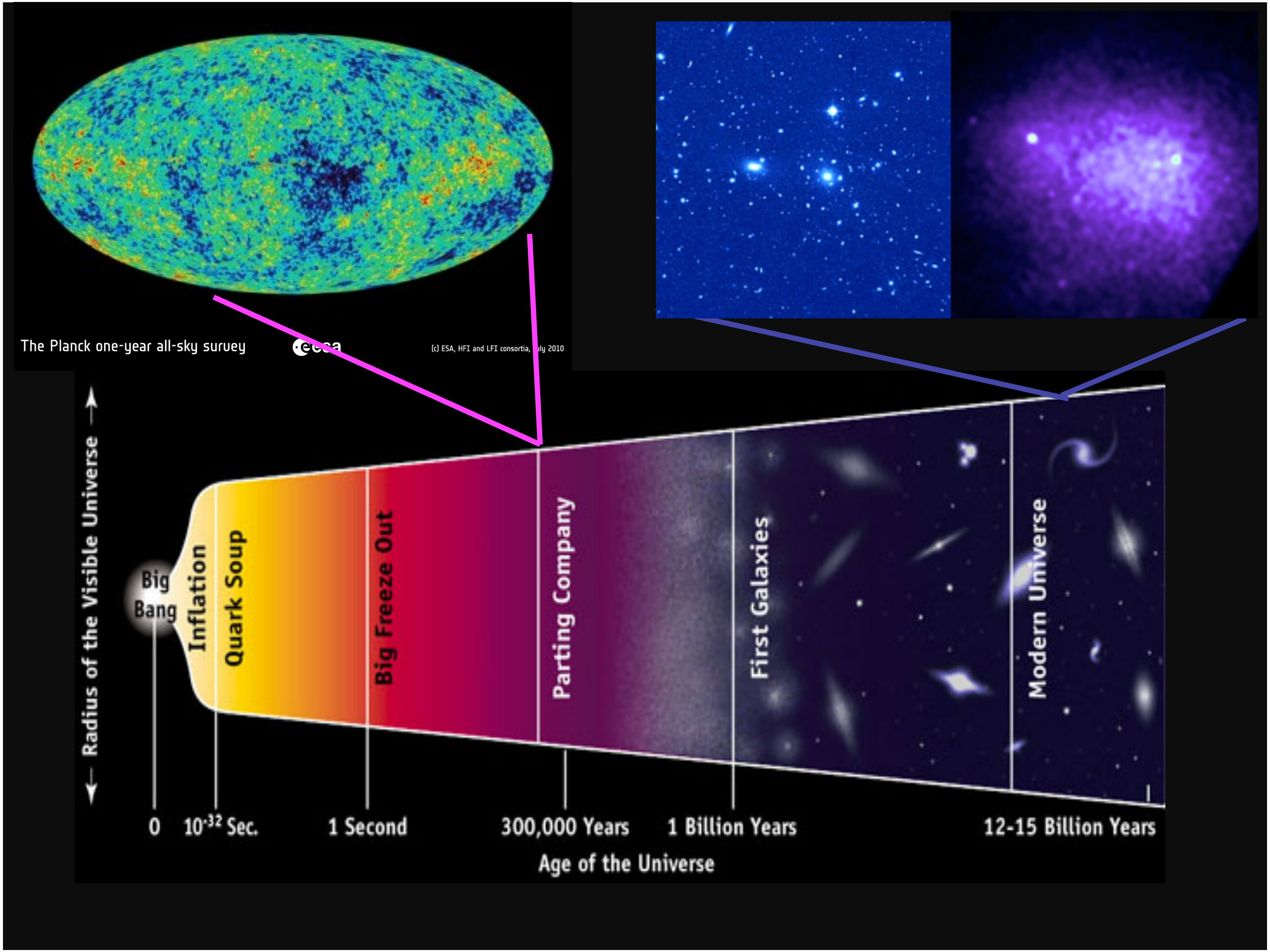
Mass profiles and concentrations in X-ray luminous galaxy clusters



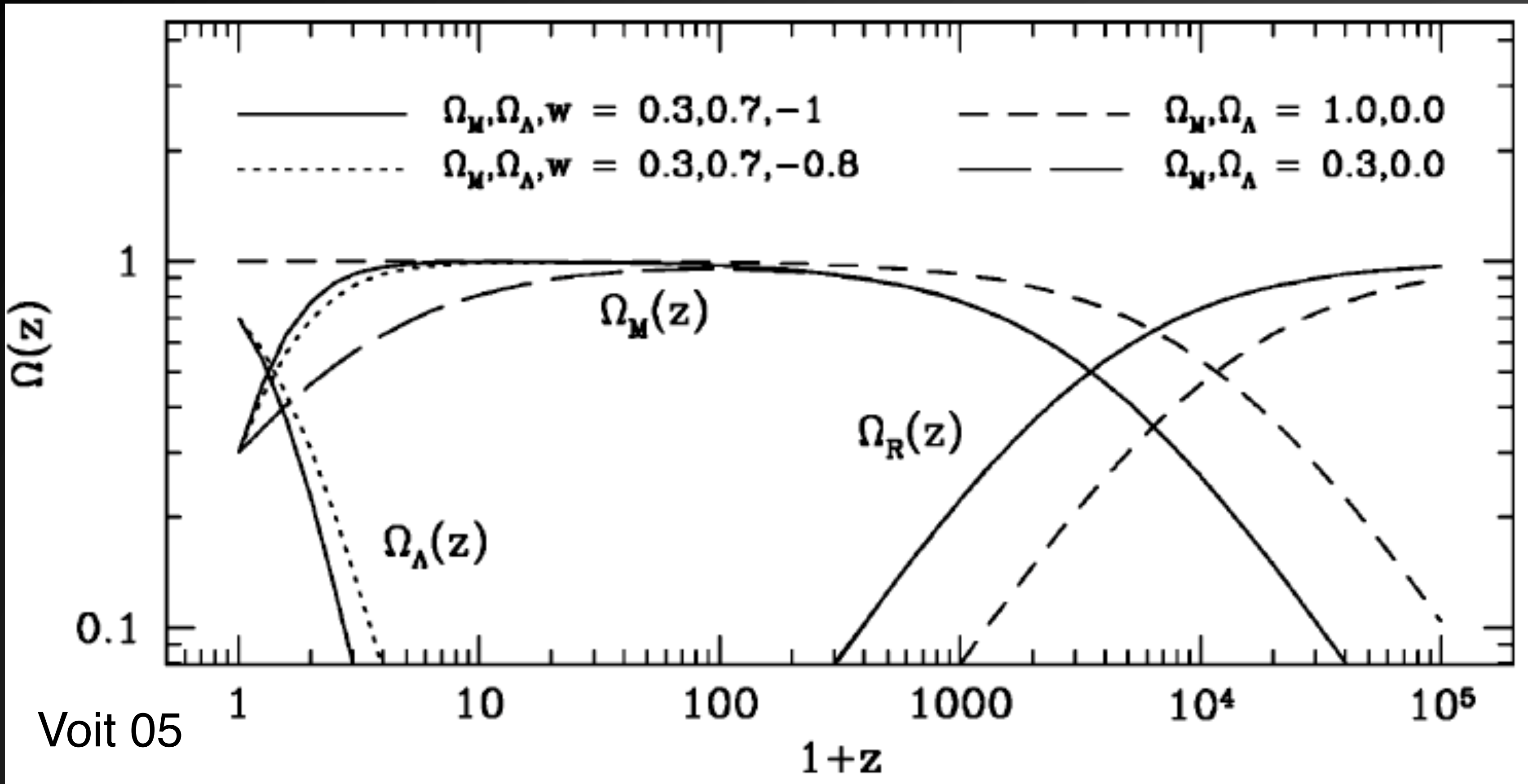
Stefano Ettori

(INAF-OA Bologna)



The Planck one-year all-sky survey
(c) ESA, HFI and LFI consortia, ly 2010
Radius of the Visible Universe
Big Bang
Inflation
Quark Soup
Big Freeze Out
Parting Company
First Galaxies
Modern Universe
0
10^{-32} Sec.
1 Second
300,000 Years
1 Billion Years
12-15 Billion Years
Age of the Universe

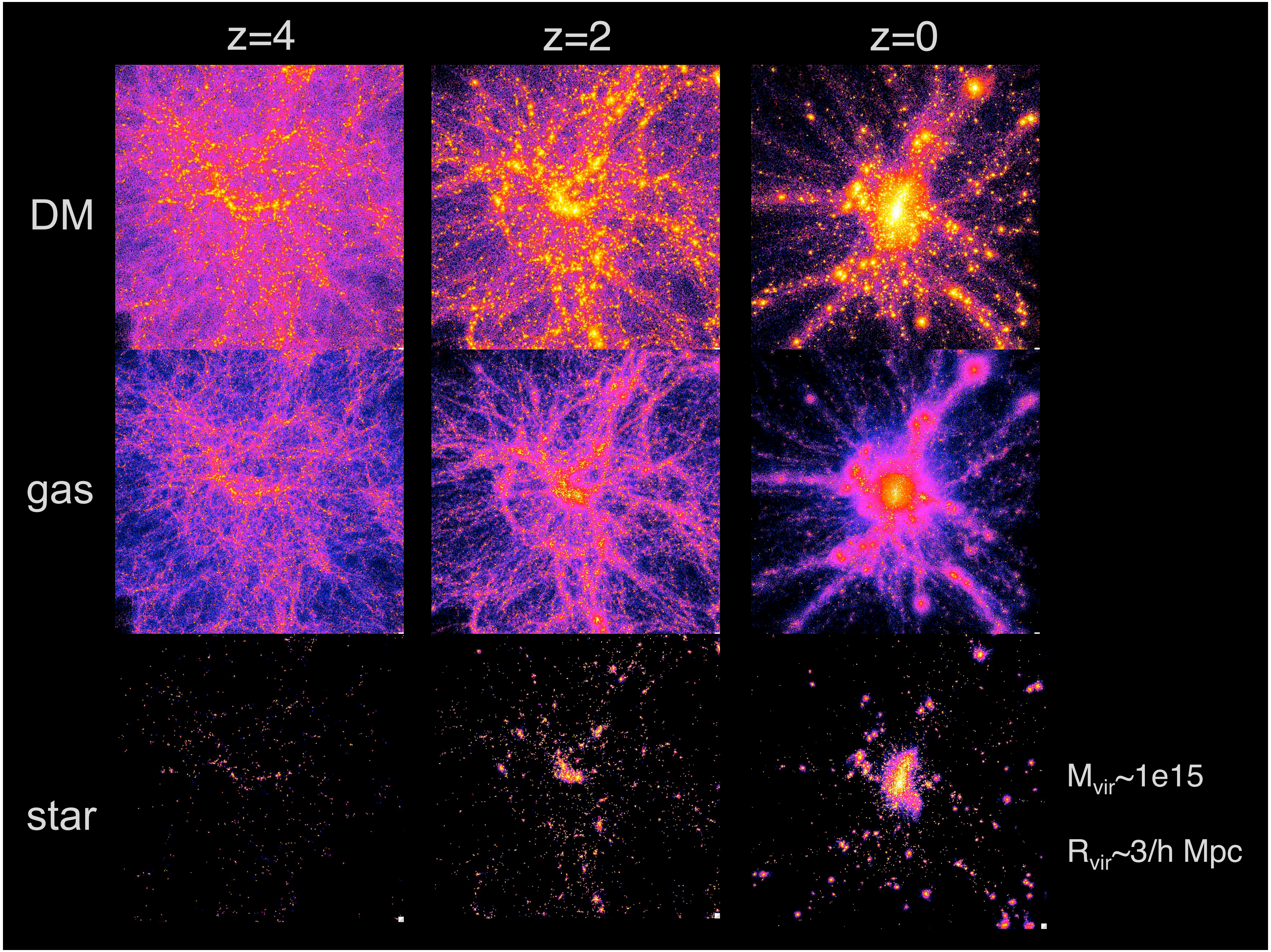
Galaxy clusters & cosmology



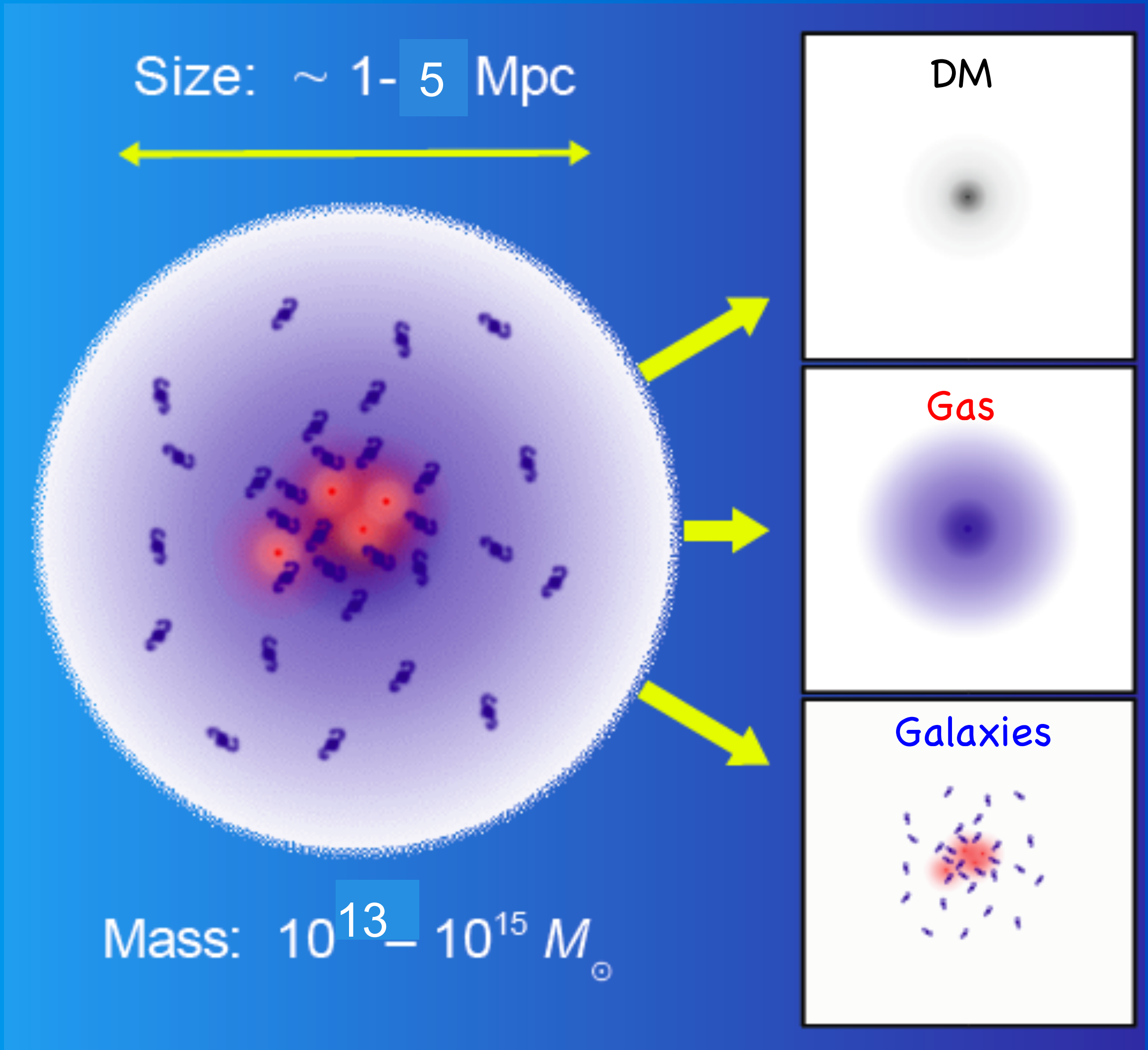
Matter dominates the dynamics at z>1

Dark energy (with equation of state **w=P/ρ**) becomes relevant at z<2

Radiation was the most important component before $z_{eq}=2e4\Omega_m$


z=4
z=2
z=0
DM
gas
star
M_vir~1e15
R_vir~3/h Mpc

Observable Properties of Clusters



Lensing

Mass distrib./profiles
Nature ??

Gal dynamics

X-ray

Thermodynamics/masses
metallicity

SZ effect

Multi-λ photometry
and spectroscopy

Stellar mass/ stellar pop.
Galaxy evolutions, SF rates

Galaxy clusters & cosmology

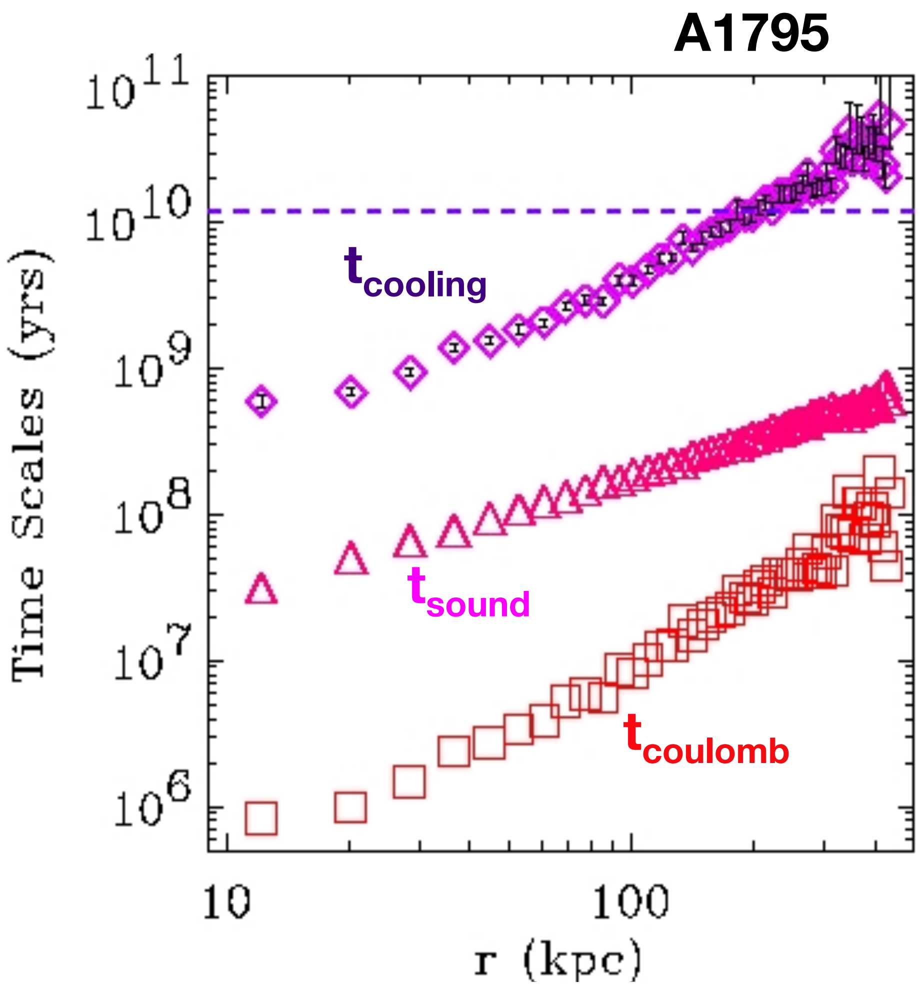
- Concentration of 100-1000 galaxies
- Velocity dispersion (observed): $\sigma_v \sim 1000$ km s^{-1}
- Size: $R \sim 1$ Mpc $\Rightarrow$ the crossing time (lower limit to the relaxation time) is $t_{cross} = R/\sigma_v \sim 1$ Gyr $< t_H = 9.8\ h^{-1}$ Gyr $\Rightarrow$ clusters must be dynamically relaxed at the present
- **Mass:** assuming virial equilibrium $\Rightarrow$ $M \simeq \frac{R\sigma_v^2}{G} \simeq \left(\frac{R}{1}\right)\left(\frac{\sigma_v}{10^3}\right)^2 10^{15}\, h^{-1} M_\odot$
- Mass components: $f_{baryons} \approx 10\text{-}15\%$ ($f_{gas} \approx 10\%$, $f_{gal} \approx$ a few%) $\Rightarrow$ $f_{DM} \approx 80\text{-}90\%$
- Intra-Cluster Gas: $T_X \approx 3\text{-}10$ keV, $n_{gas} \approx 10^{-3}$ atoms/cm^3, $Z \sim 0.3$ solar $\Rightarrow$ **fully ionized plasma,** free-free bremsstrahlung + lines emission: $L_X \sim n_{gas}^2 \Lambda(T)\, V \sim 10^{43}\text{-}10^{45}$ erg/s

$$k_B T \simeq \mu m_p \sigma_v^2 \simeq 6 \left(\frac{\sigma_v}{10^3}\right)^2 \mathrm{keV}$$

X-ray total mass

The ICM is a fluid because the time scale of elastic/ Coulomb collisions between ions & e^- ($t_{coulomb} \propto T^{3/2}/n$) is $\ll$ $t_{cooling}$ ($\propto T^{1/2}/n$) & $t_{heating}$

ICM is in hydrostatic equilibrium:
t_{sound} ($\propto R/T^{1/2}$) $< t_{age} \approx H_0^{-1}$



X-ray total mass

Total mass from X-ray is determined by assuming
1. spherical symmetry, 2. hydrostatic equilibrium

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

X-ray total mass

Total mass from X-ray is determined by assuming

1. spherical symmetry, 2. hydrostatic equilibrium

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

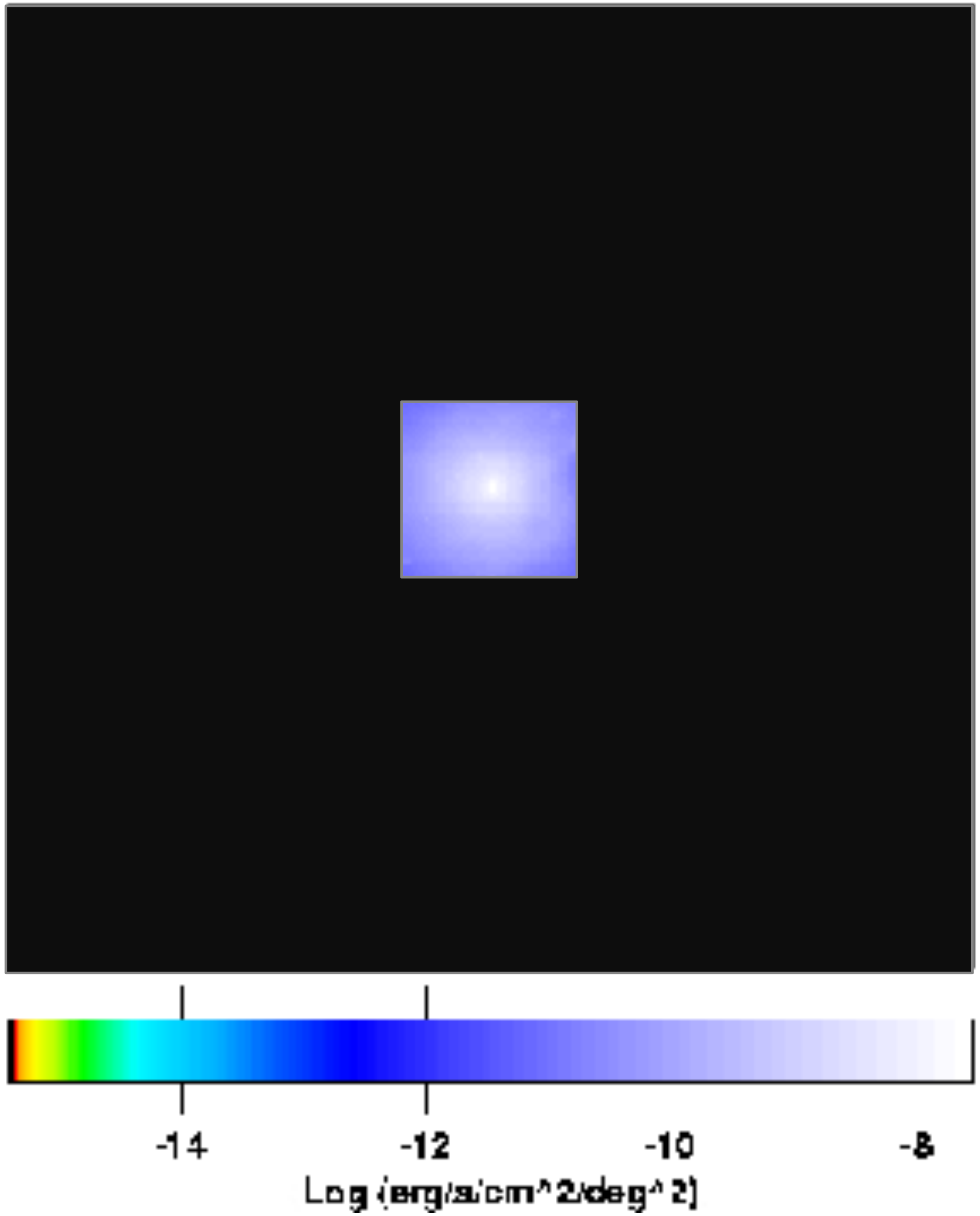
$$M_{tot}(<r) \propto r \times T_{gas}(r) \times (-\alpha_n - \alpha_T)$$

$\alpha_n \sim$ **-2/-2.4** $\alpha_T \sim$ **0/-0.8**

ICM at R_{200}: *S_b of simulated clusters*

R_{2500}

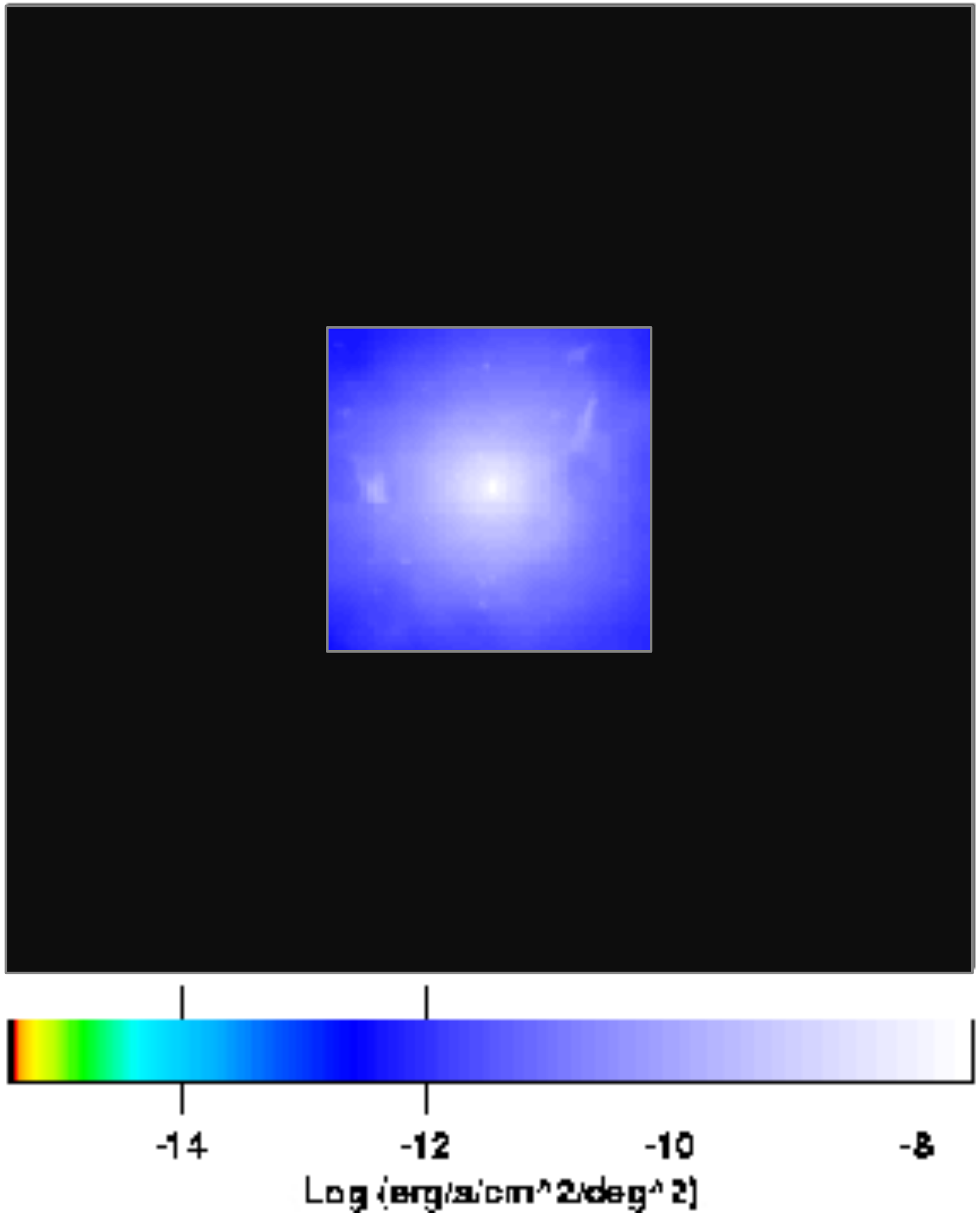
($\sim$0.3 R_{200}
~CXO limit)



ICM at R_{200}: *S_b of simulated clusters*

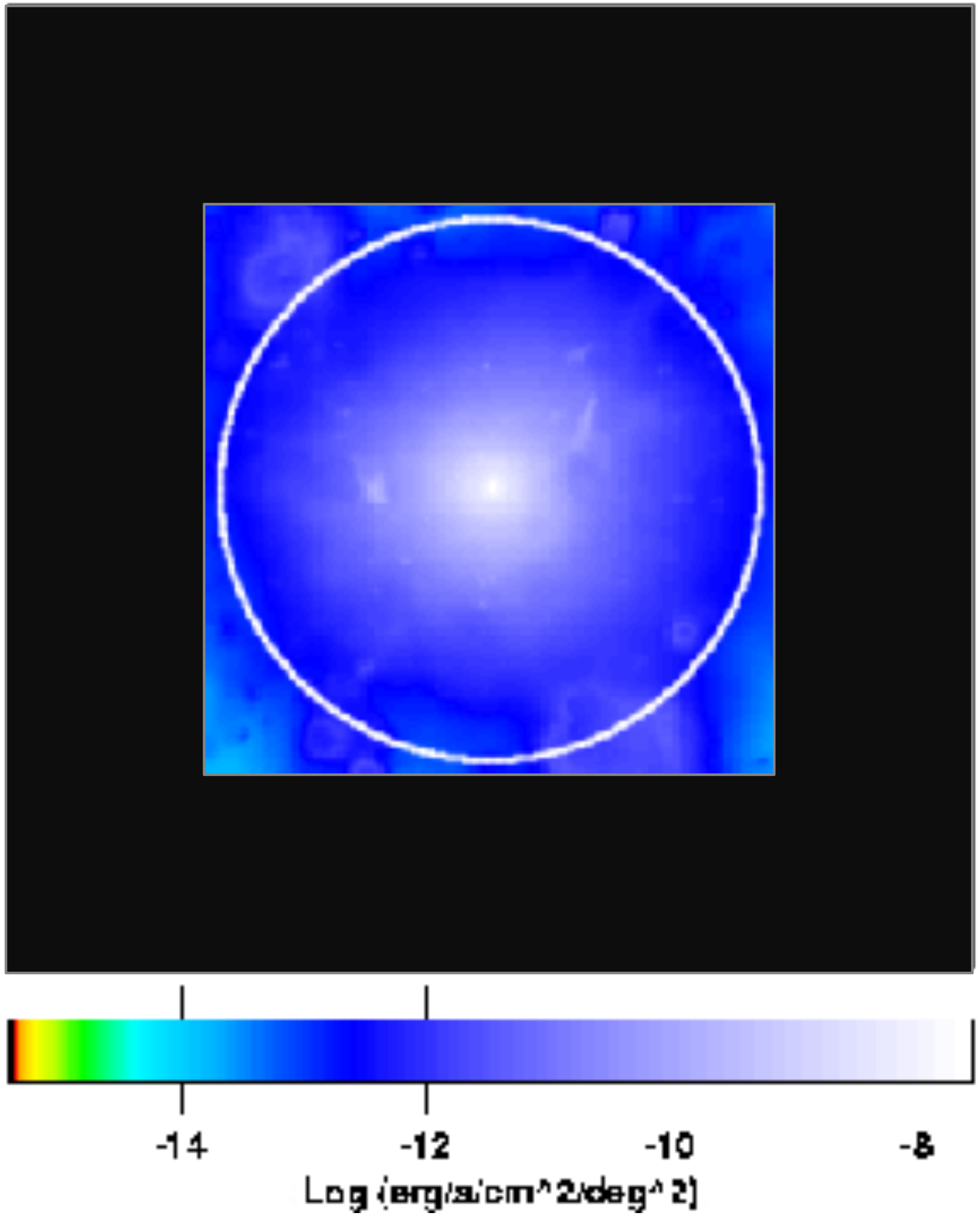
R_{500}

($\sim$0.7 R_{200}
~few best
CXO & XMM
cases)

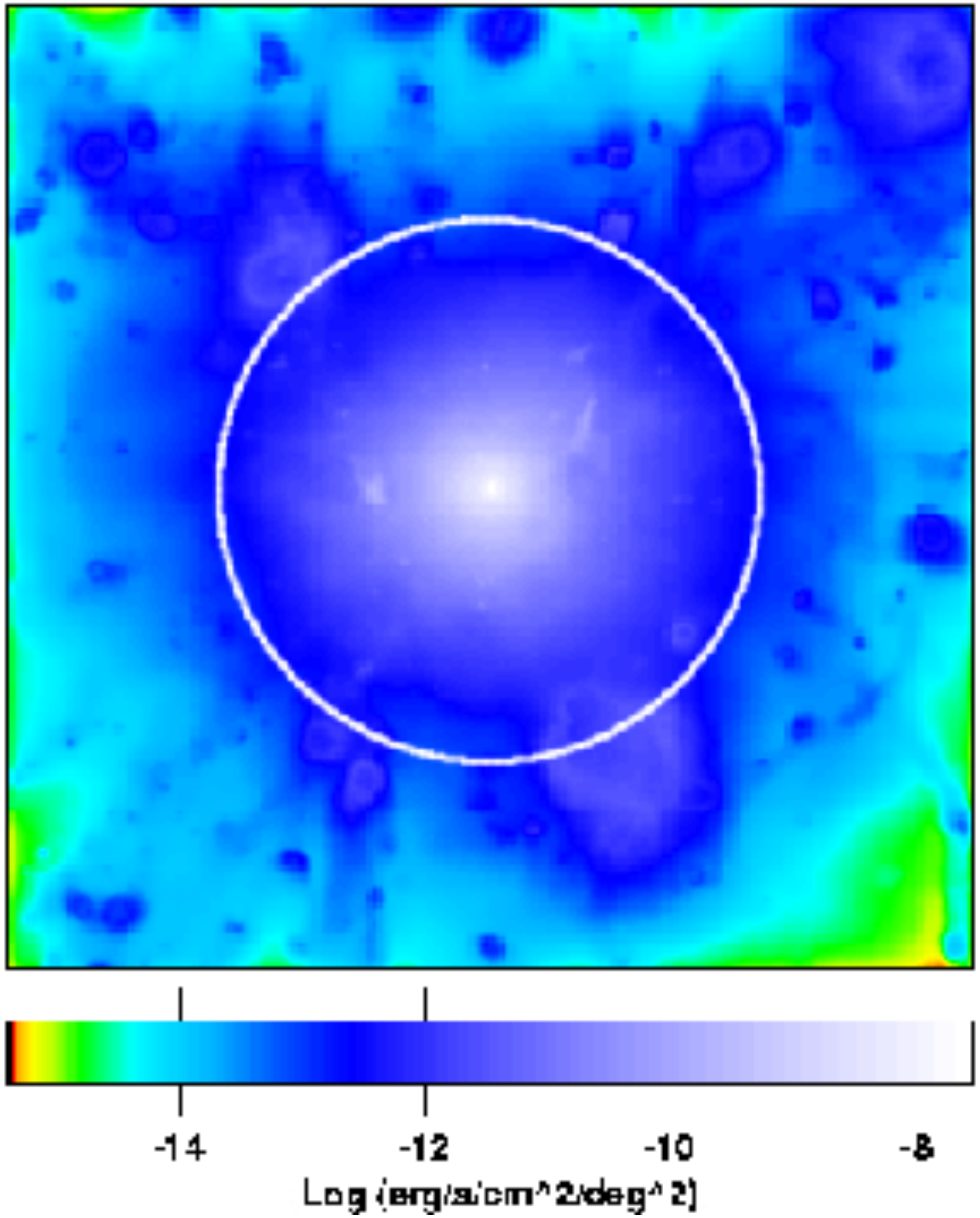


ICM at R_{200}: *S_b of simulated clusters*

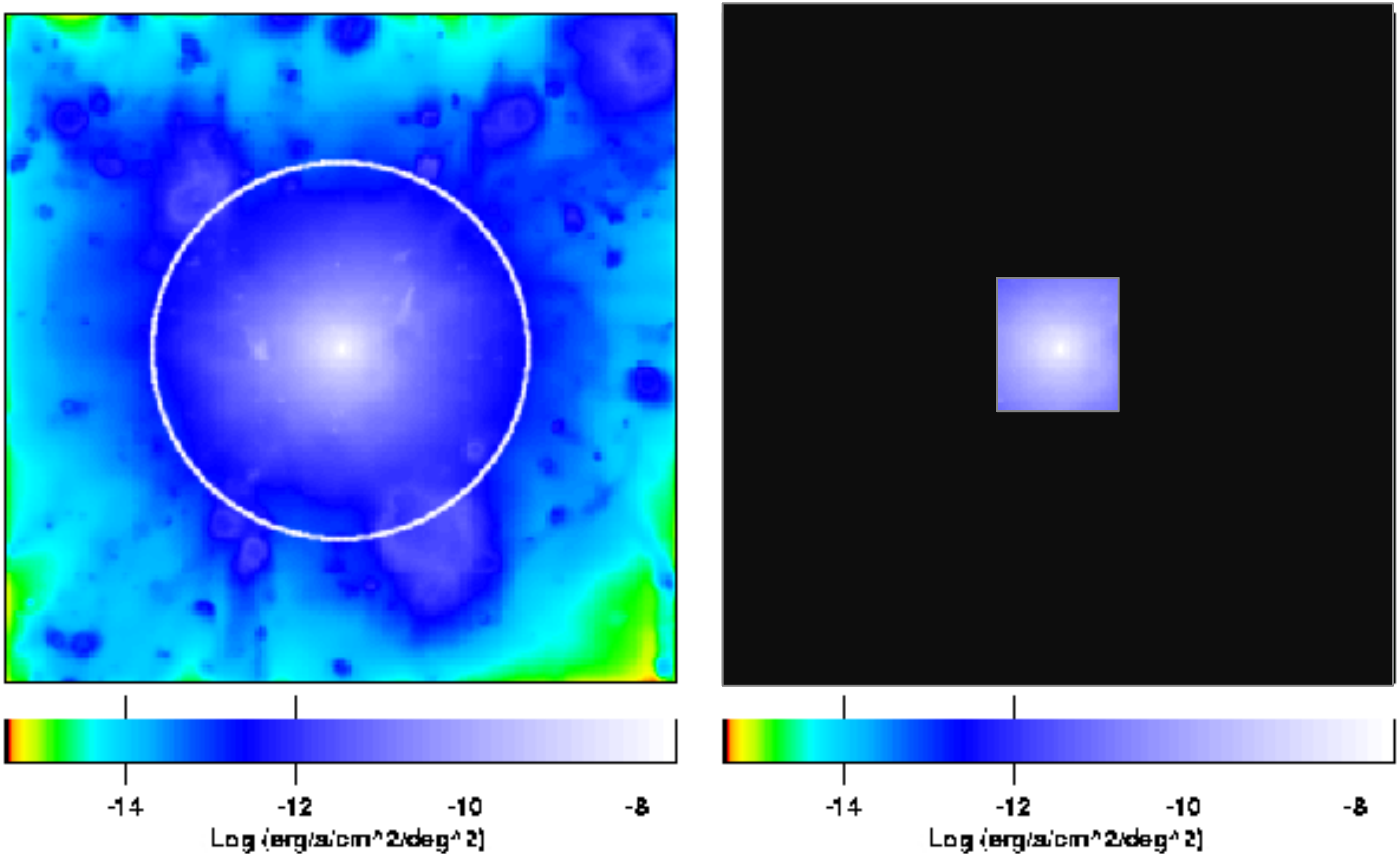
R_{200}



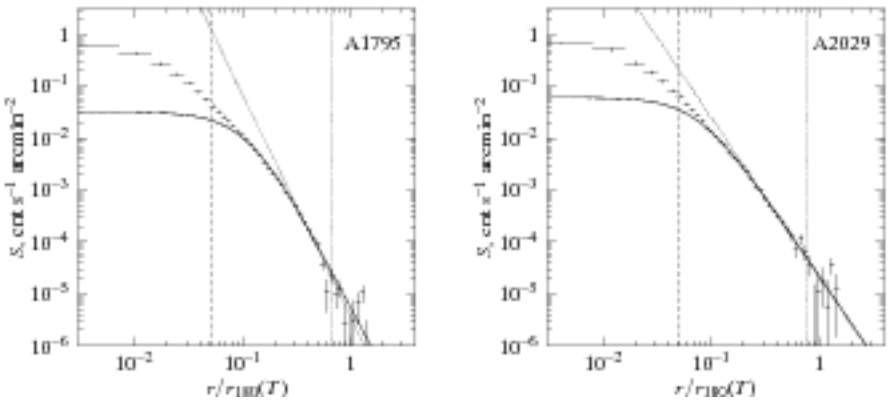
ICM at R_{200}: *S_b of simulated clusters*



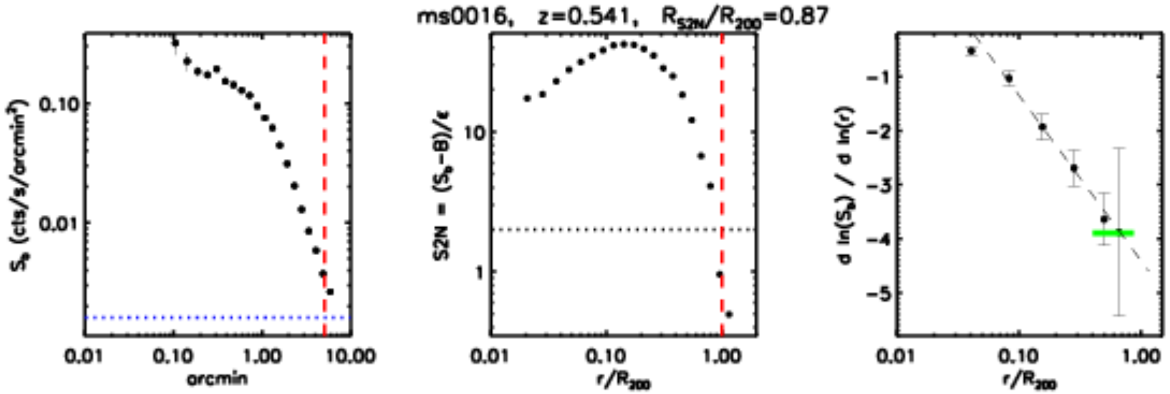
ICM at R_{200}: S_b of simulated clusters



S_b at R_{200}: *Observed clusters*



Vikhlinin et al. (99): β~0.8 and larger by ~0.05 of the global fit value; see also Neumann 2005. Both use a sample of nearby clusters observed with ROSAT/ PSPC



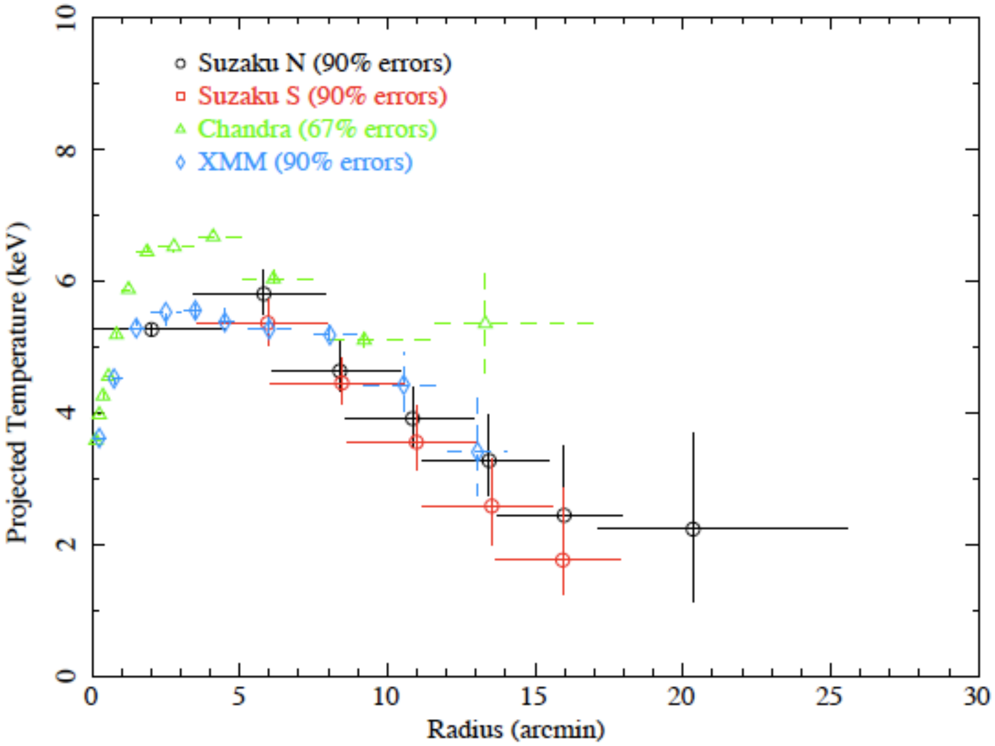
Study of S_b at r >0.7 R_{200} in a sample of high-z (z>0.3) objects with CXO (Ettori & Balestra 09)

Slope of S_b:

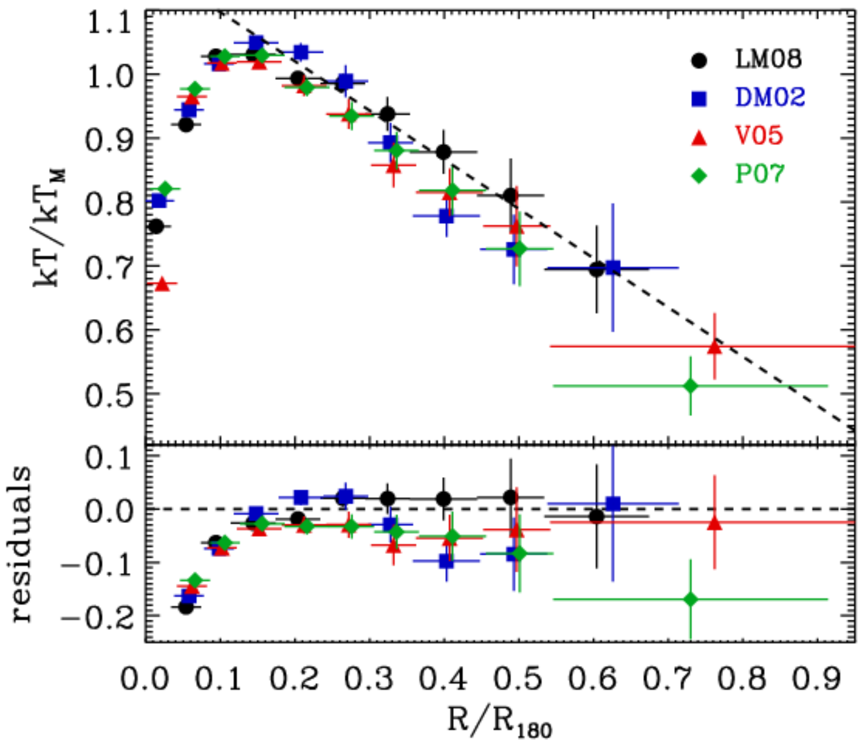
at 0.7 R_{200}: -3.9 ± 0.7, at R_{200}: -4.3 ± 0.9

Note: $S_b \sim r^{1-6\beta}$ … β=0.8/0.9

T_{gas} at R_{200}: *Observed clusters*

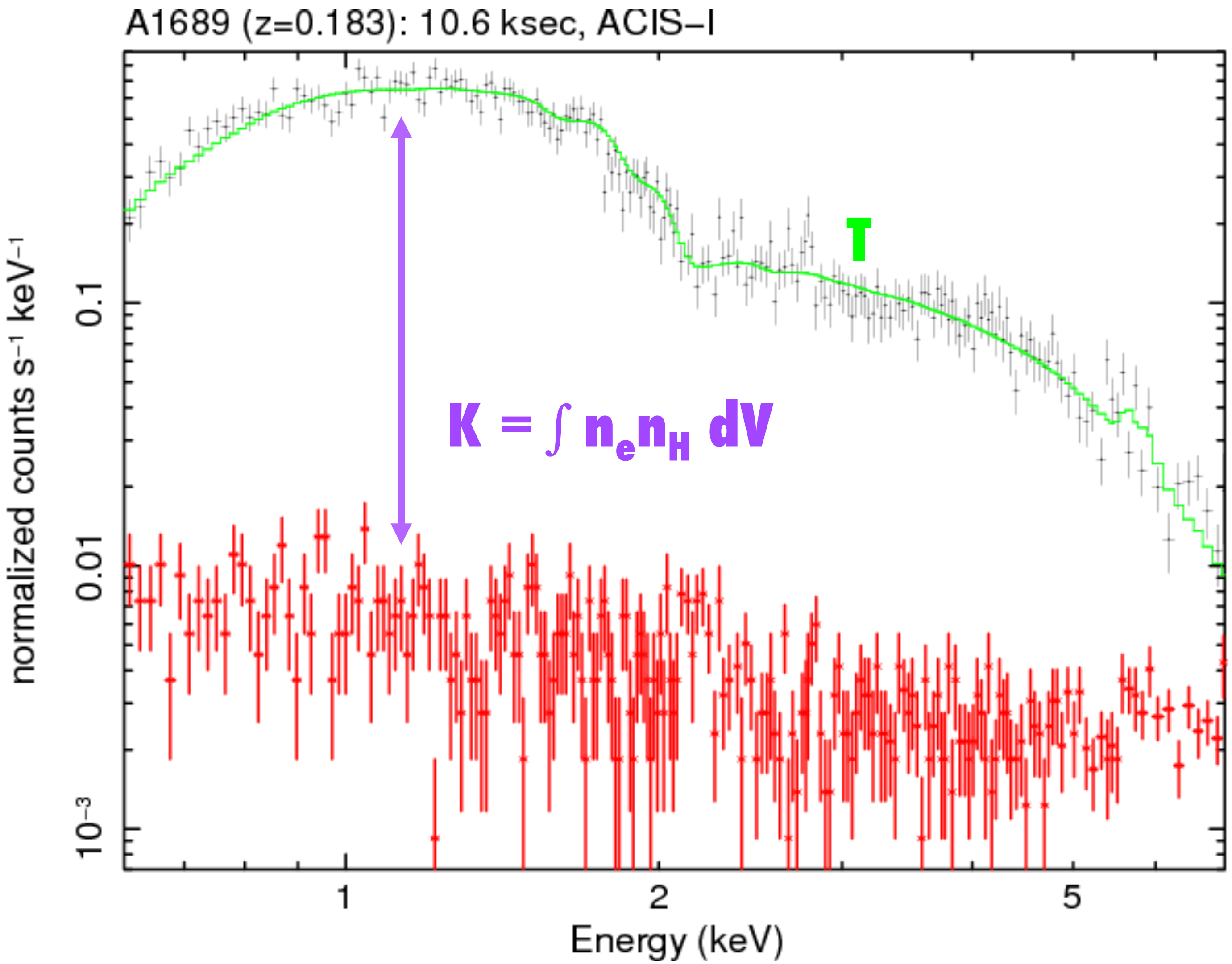


A1795 with ***Suzaku*** by
Bautz et al. (arXiv:0906.3515):
$T \sim r^{-0.9}$, M_{500} ~20-30% < expected

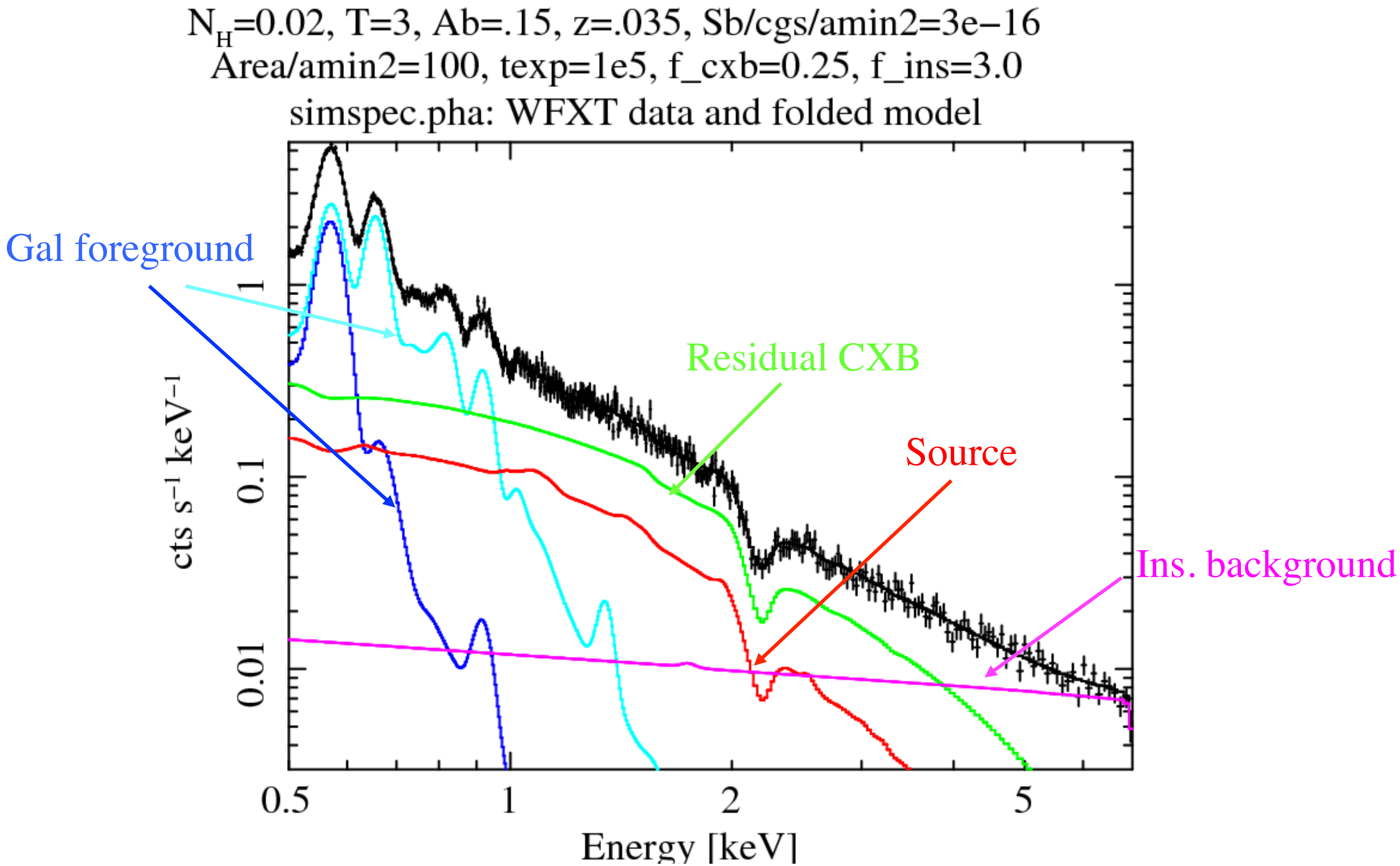


Sample of ~50 objects observed with XMM (Leccardi & Molendi 08)

X-ray total mass: *the observables*

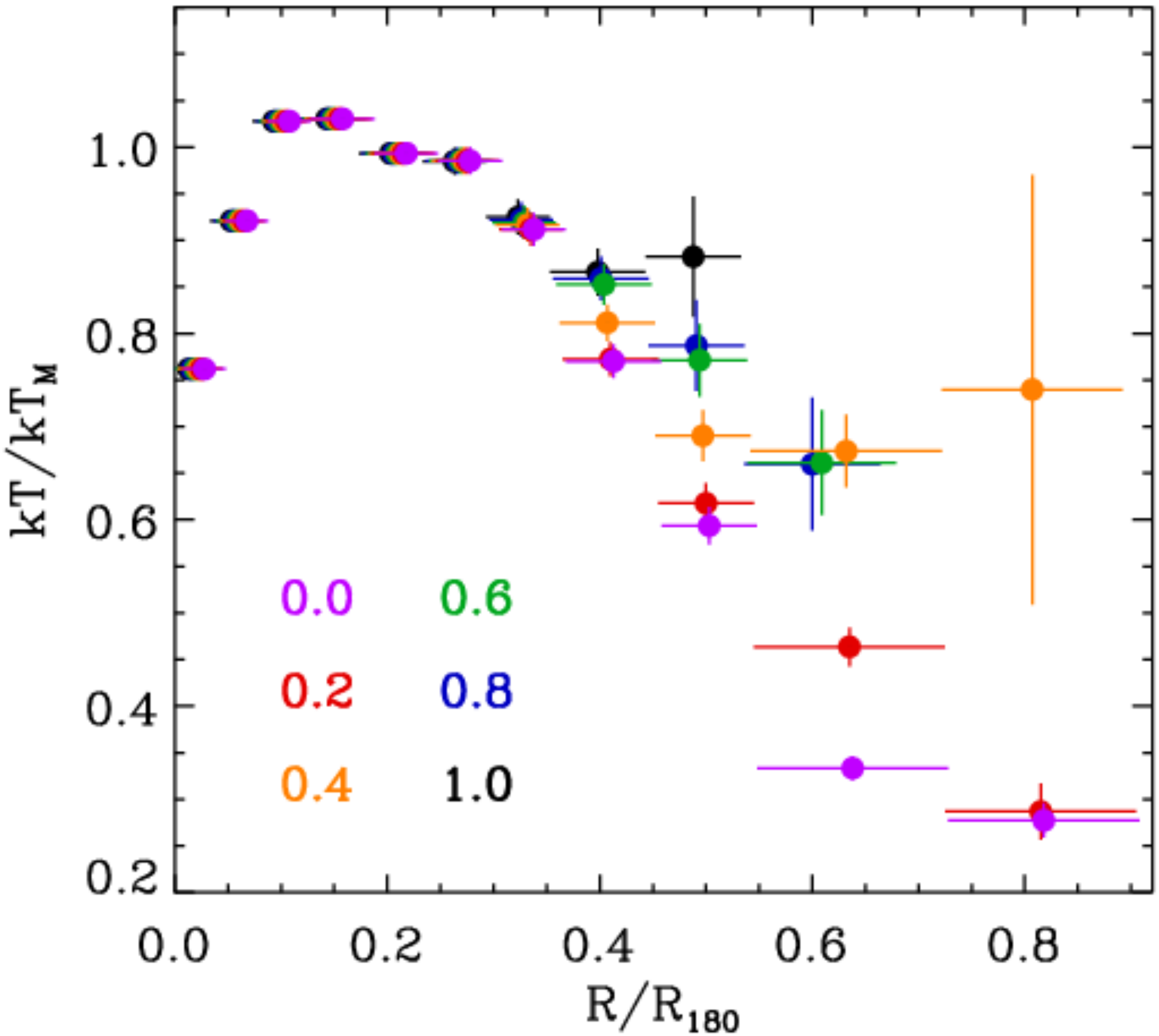


Bkg: dominant in GCs outskirts



Simulation for 3keV cluster @ R200

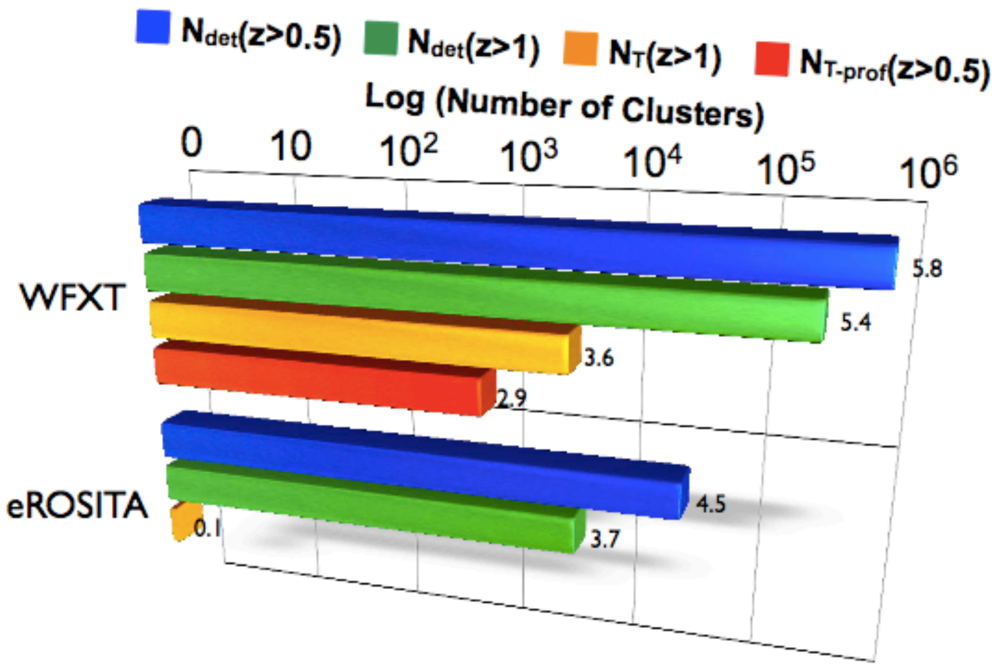
On the Temperature profile

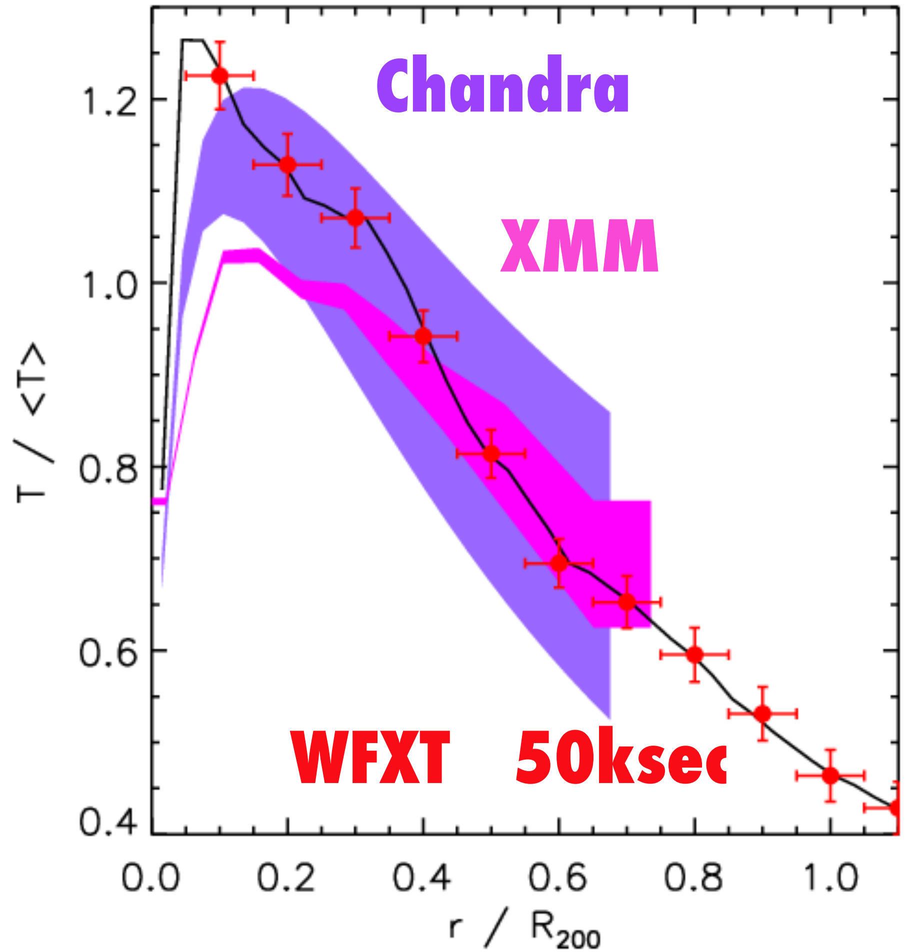


Changing I = Src/Bkg between 0 and 1

(Leccardi & Molendi 2008)

T_{gas} profile: *future prospects*





T(r) will be available for 0.1% (~1000) of the detected clusters @z>0.5 (Giacconi et al., arXiv:0902.4857)

Ettori & Molendi (arXiv:1005.0382)

Estimate of the X-ray M_{tot}

✓HEE with functional forms of T and n_{gas} (e.g. β-model) & then fit with mass models (e.g. NFW)

Buote, Pointecouteau, Vikhlinin (& high-z obj with T=const)

✓ Use of mass models (e.g. NFW) by fitting **either** T_{deproj} **or** T_{xspec} from inversion of HE

Fabian/Allen, Ettori

✓ direct application of HEE on deprojected T and n_{gas}

Ettori (and others…)

✓ Integral of HEE from deprojected spectra

Nulsen (pioneering work in 1995 with Hans on Virgo)

Estimate of the X-ray M_{tot}

To summarize: two methods

model-dependent	model-independent
forward	**backward**

Pro

smooth profiles derivable	not need for parameters

Contra

radial shape imposed need many parameters (e.g. Vikhlinin 05: 10 in n_{gas}, 9 in T_{gas}) degenaracy	radial profiles often not smooth enough, derivatives problematic

X-ray total mass in 7 steps

Step 1: define a grid in {c, rs}

Step 2: define a functional form for

$M(<r) = K * f(x) * r_s^3 * m(c)$

where $m(c) = \delta/3 * c^3 / (\log(1+c) - c/(1+c))$

$f(x) = \log(x + \mathrm{sqrt}(1+x^2)) - x/\mathrm{sqrt}(1+x^2)$ [Isothermal]

$= \log(1+x) - x/(1+x)$ [NFW]

$= \ldots$

Step 3: at each resolved r, estimate $dP = -M/r^2 * n_e * dr$

Step 4: define P_{out}

Step 5: $P(r) = P_{out}$ - Sum(Reverse(dP))

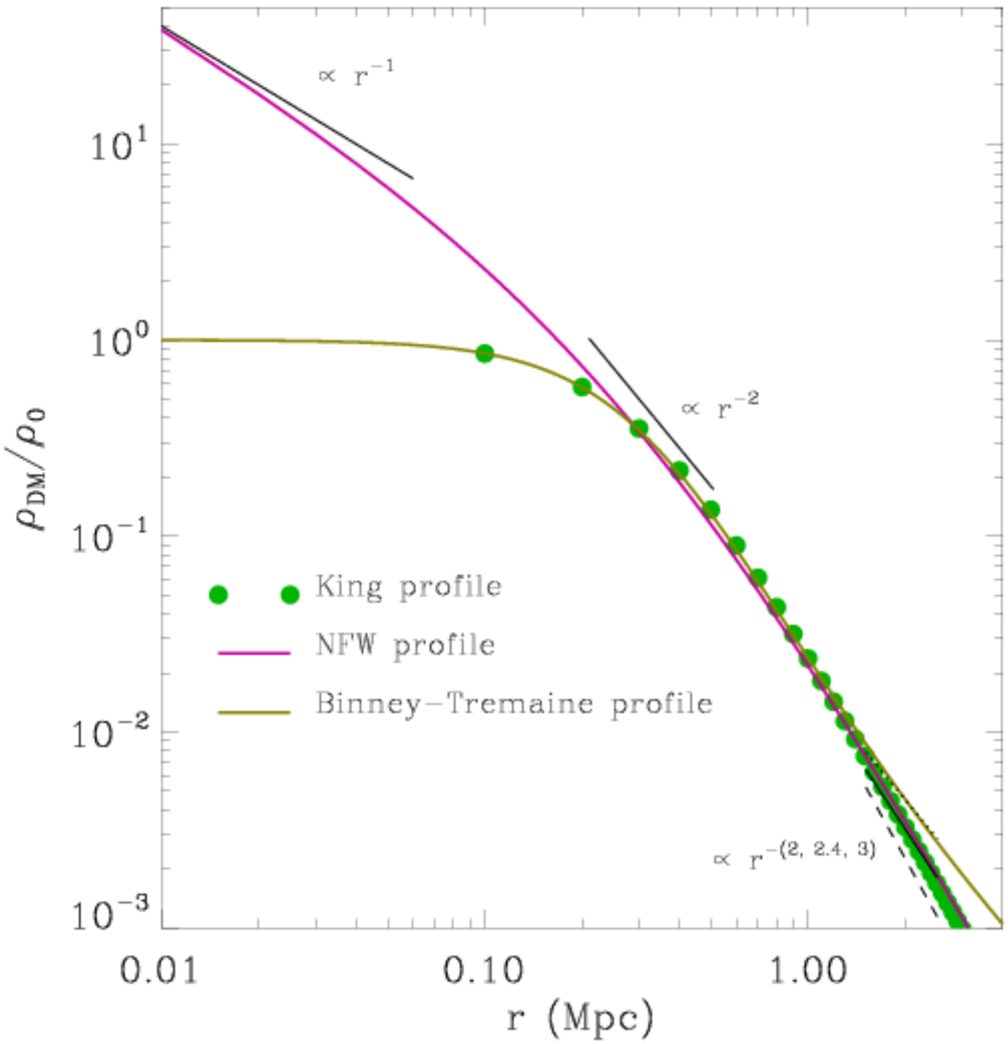
Step 6: $T_{fit} = P(r) / n_e$

Step 6bis: project T_{fit} in the observed annulus (e.g., with Mazzotta's rule)

Step 7: $\chi^2 (c, rs)$ = Sum($(T_{fit} - T_{xspec})^2 / err^2$)

Structure of CDM halos

(Navarro, Frenk, White 1996, 1997)



The **NFW profile** is an approximation to the equilibrium configuration produced in simulations of collisionless DM particles

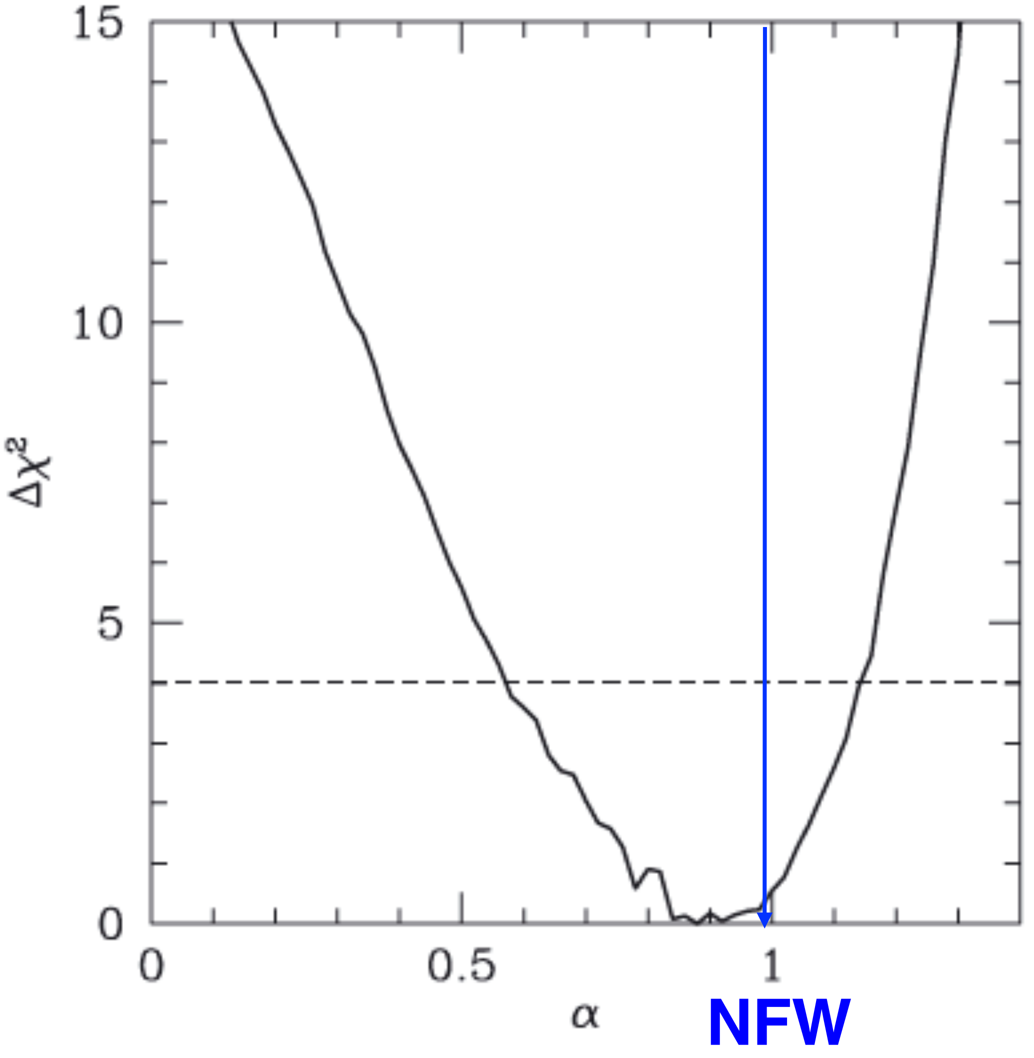
$$\frac{\rho_{DM}}{\rho_0} = \left(\frac{r}{r_s}\right)^{-1}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\rho_0 = \rho_c \delta_c$$

$$\delta_c = \frac{200}{3}\frac{c^3}{\ln(1+c) - c/(1+c)}$$

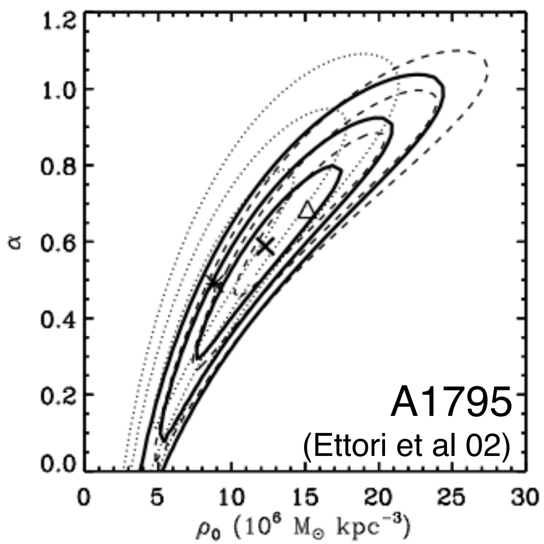
$$R_{200} = M_{200} / \ (\rho_c V_{200}) = c \times r_s$$

X-ray mass: *central density slope*



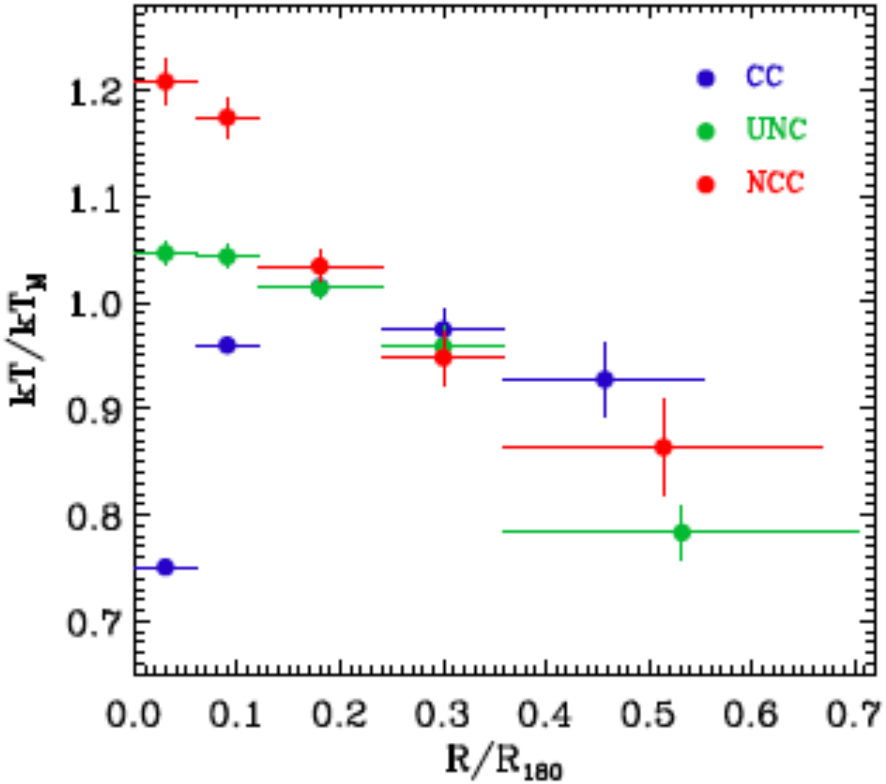
Schmidt & Allen 07: 27 out of 34 clusters observed with Chandra prefer NFW vs isothermal sphere.

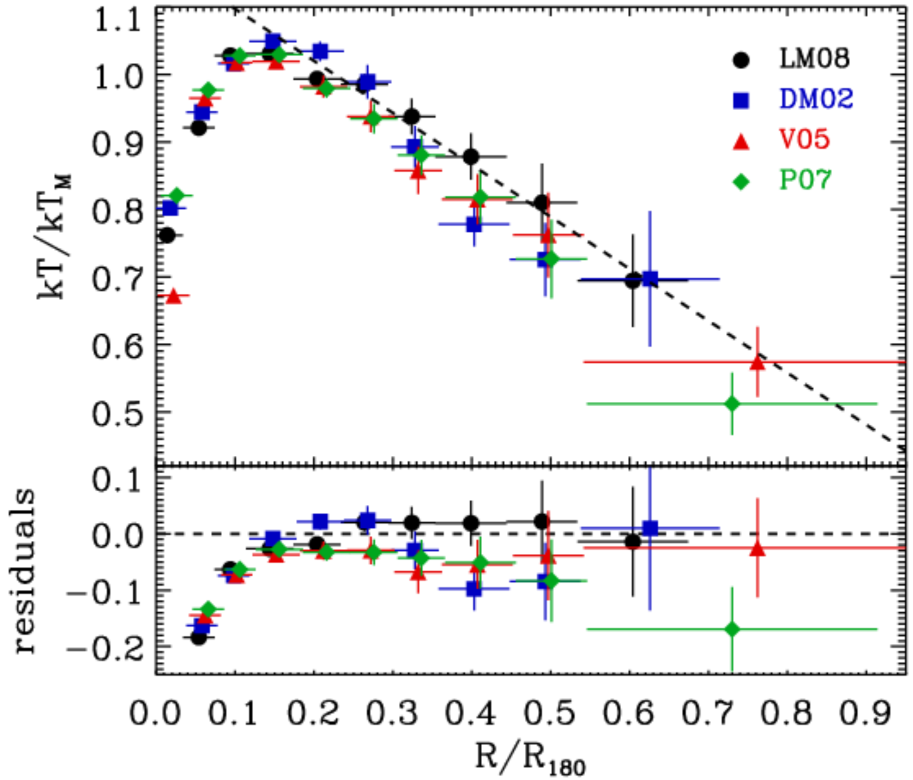
Combining the χ^2:
$\alpha = 0.88 \pm 0.3$ (95% c.l.)



The sample for c-M_{DM}

(from Leccardi & Molendi 2008)

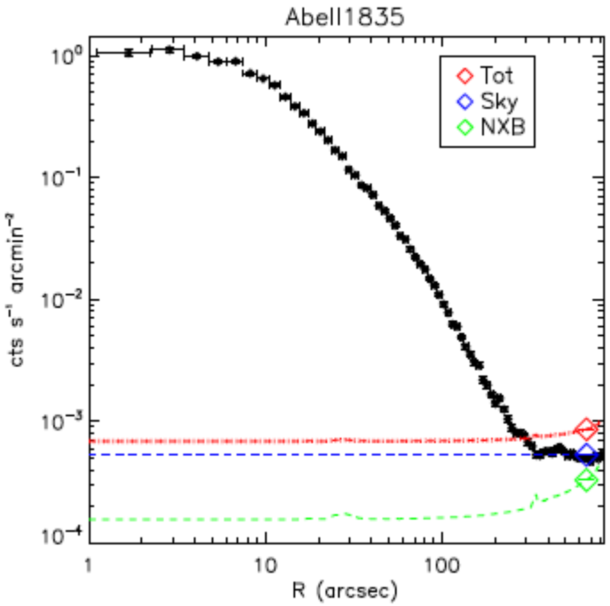


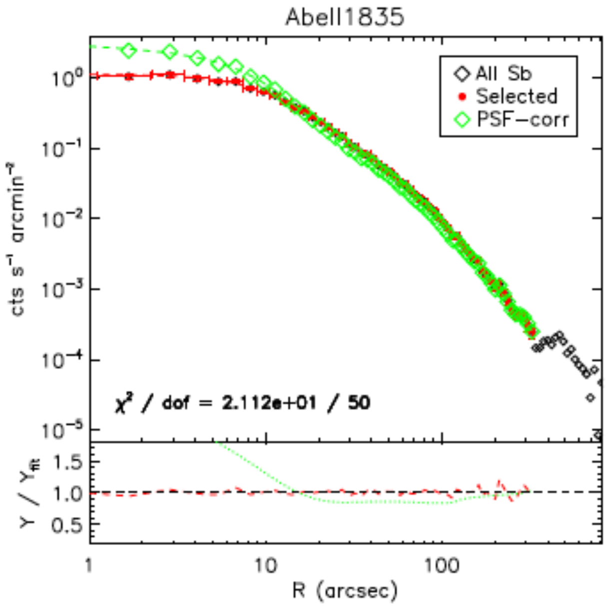


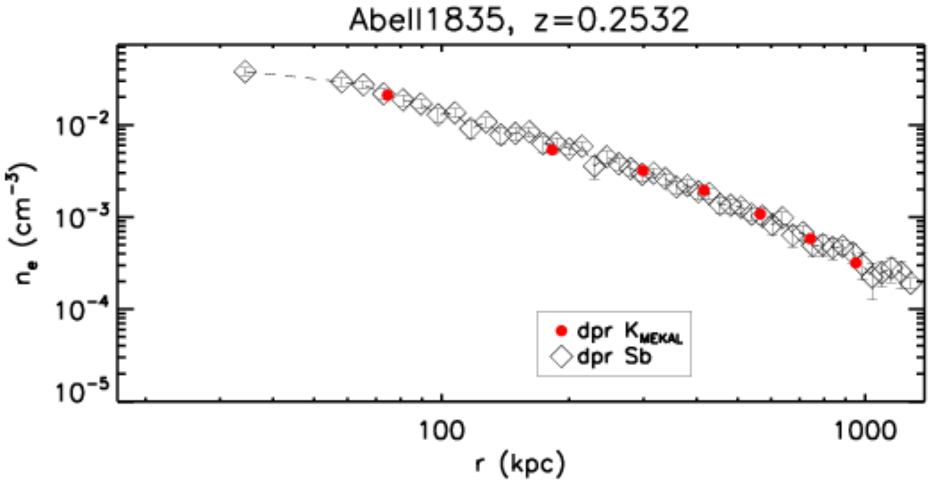
44 X-ray luminous galaxy clusters, relaxed (=CC) & not (=NCC), observed with *XMM-Newton* in the z-range 0.1–0.3

The sample

We have extended the LM08 spectral analysis with an analysis of the XMM S_b to recover n_{gas}



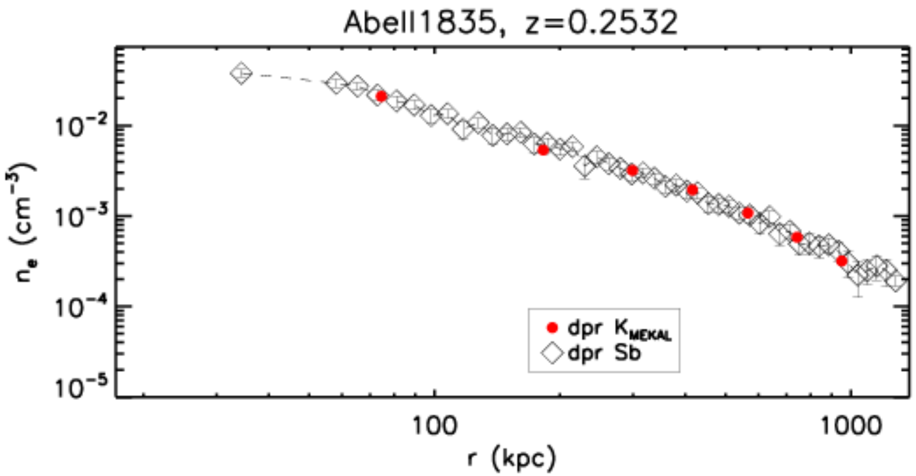




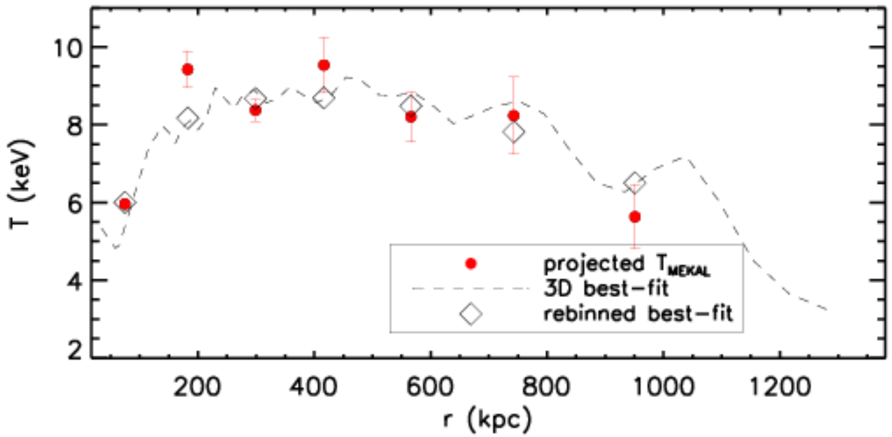
The analysis

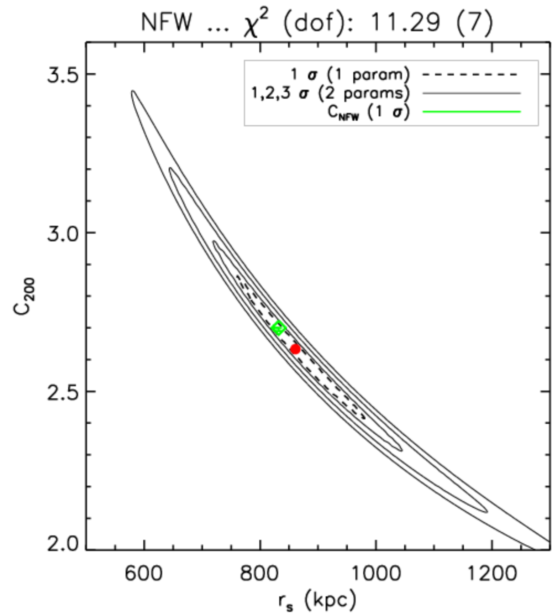
We have extended the LM08 spectral analysis with an analysis of the XMM S_b to recover n_{gas}

We use n_{gas} & T_{gas} +NFW to constrain $\{r_s, c\}$



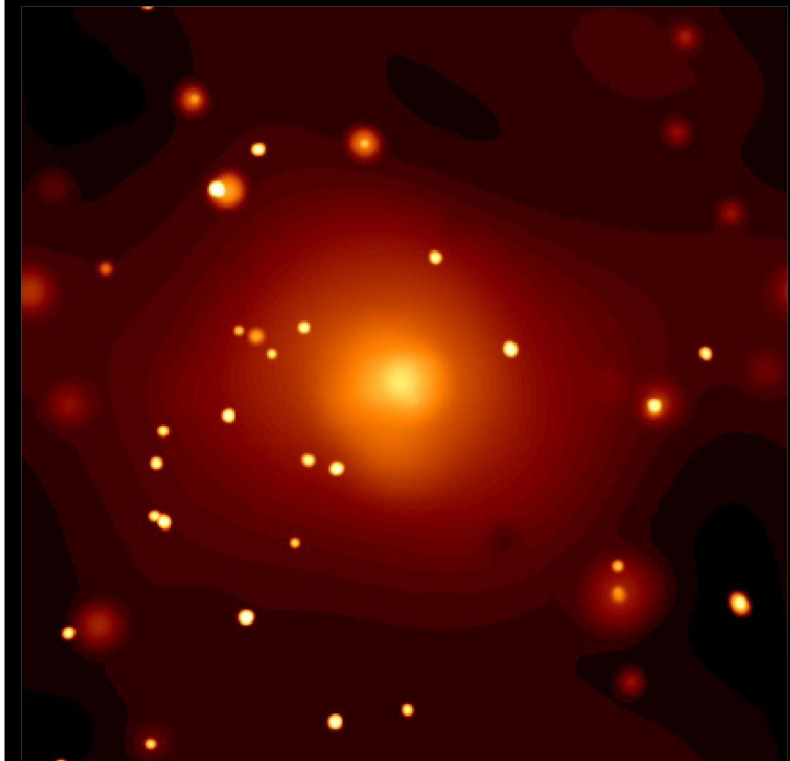
$$
\begin{aligned}
&M_{\rm DM}(<r) = M_{\rm tot}(<r) - M_{\rm gas}(<r) = 4\pi\, r_{\rm s}^3\, \rho_{\rm s}\, f(x), \\
&\rho_{\rm s} = \rho_{c,z} \frac{200}{3} \frac{c^3}{\ln(1+c) - c/(1+c)} \\
&f(x) = \ln(1+x) - \frac{x}{1+x} \qquad (1)
\end{aligned}
$$

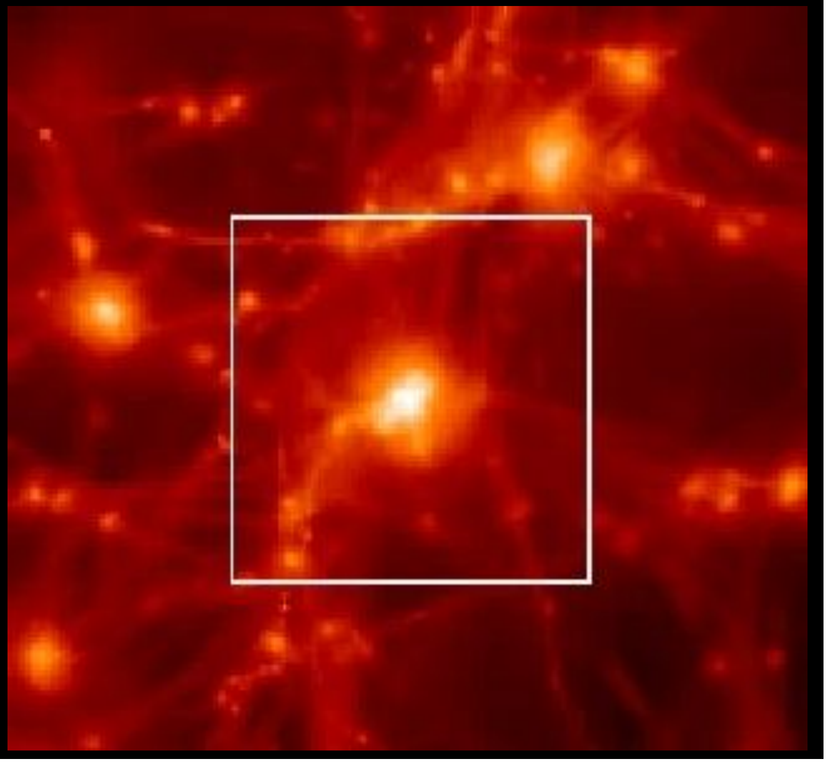




But do we know the systematics in the estimates of M_{tot} in X-ray galaxy clusters ?

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*



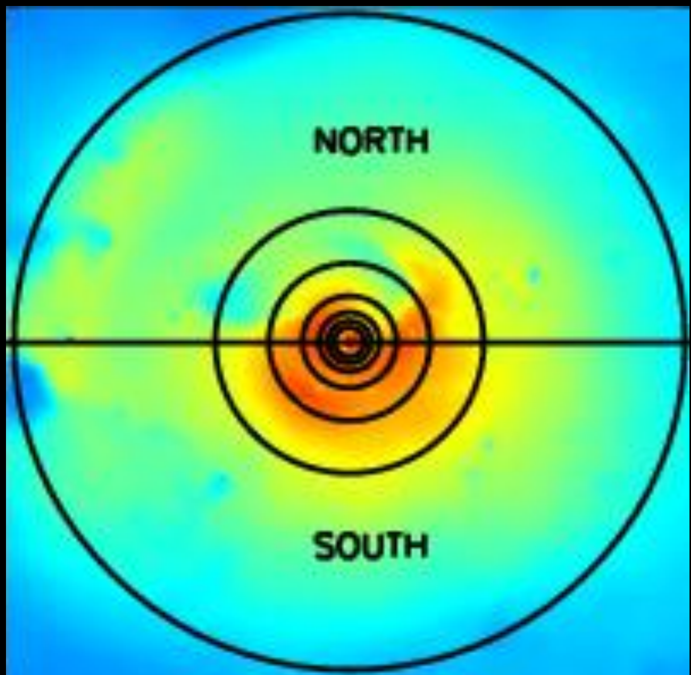


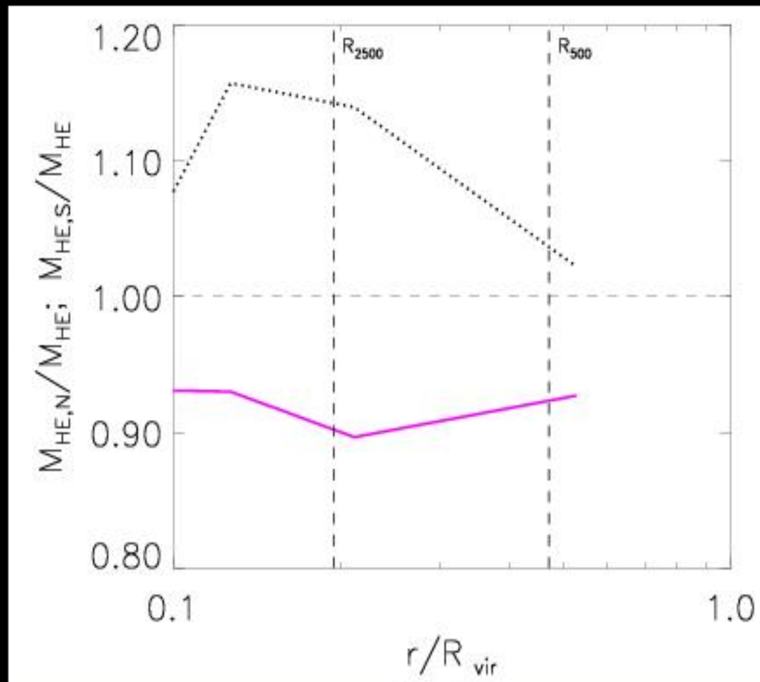
X-ray total mass: results

X-ray M_{est} underestimates M_{true} by 10-45 %

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

➔ inhomogeneities in T map affect M_{tot} by 10-15 %





X-ray total mass: results

X-ray M_{est} underestimates M_{true} by 10-45 %

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

➔ inhomogeneities in T map affect M_{tot} by 10-15 %

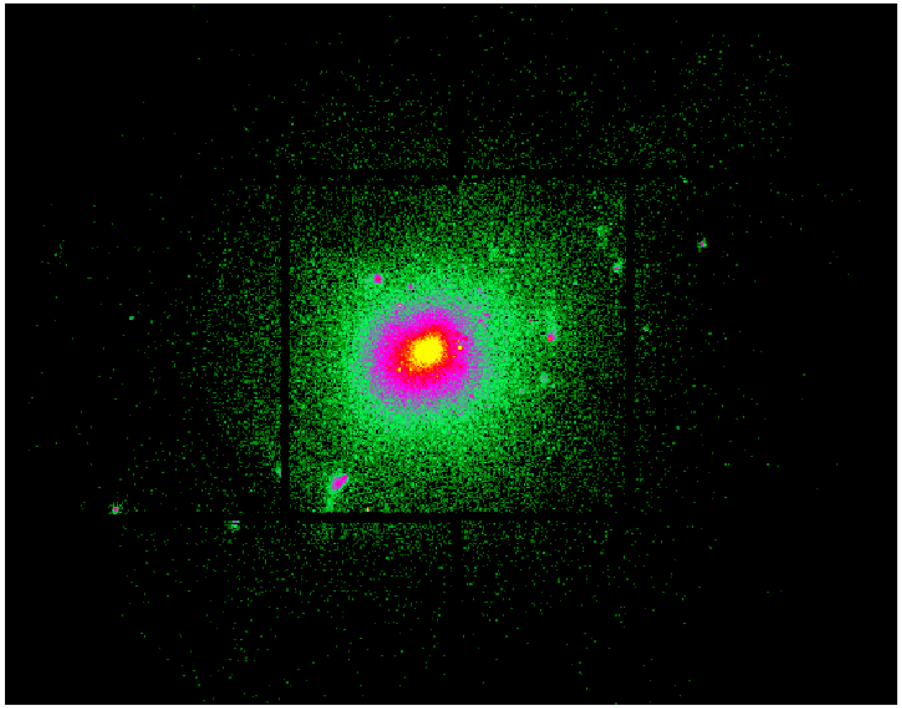
➔ poor contraints on n_{gas} from β-model; due to the limited radial interval over which the fit is done, β / c_{NFW} are always lower / higher than the values measured from fit of ρ_{gas} up to R_{200}

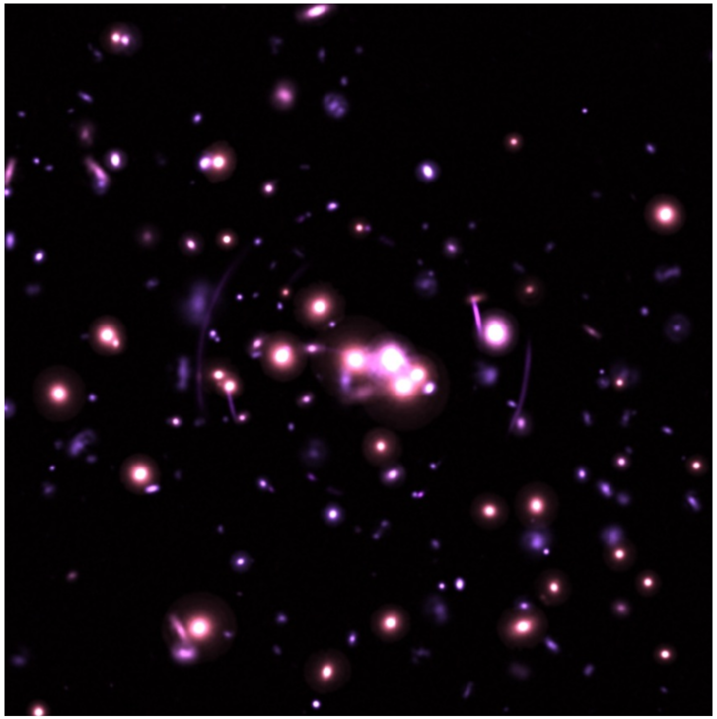
X-ray vs lensing mass: *simulations*

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

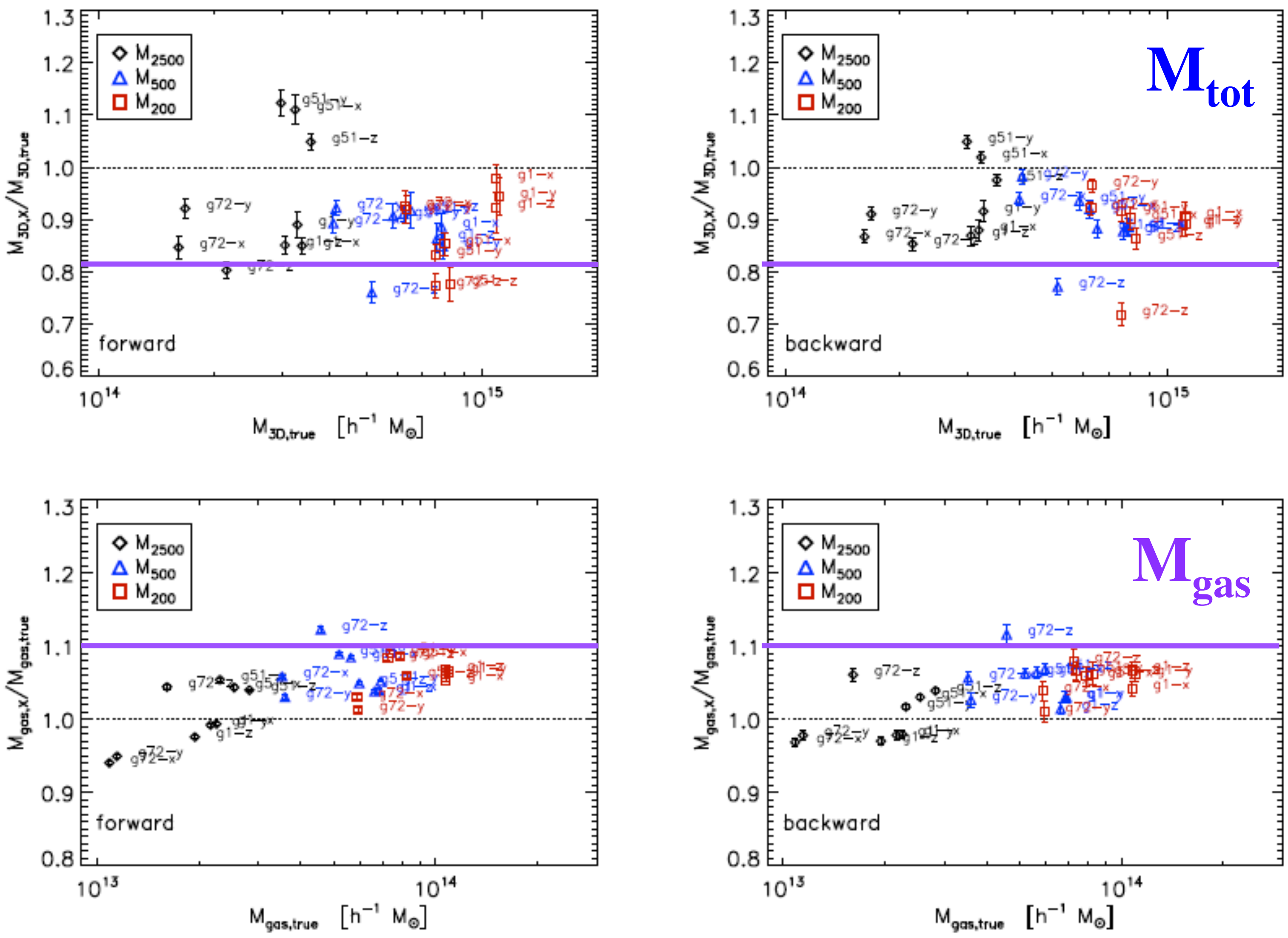
both convolve hydro simulations with observational setup

(work with E. Rasia & M. Meneghetti;
see also Nagai, Kravtsov, et al.)

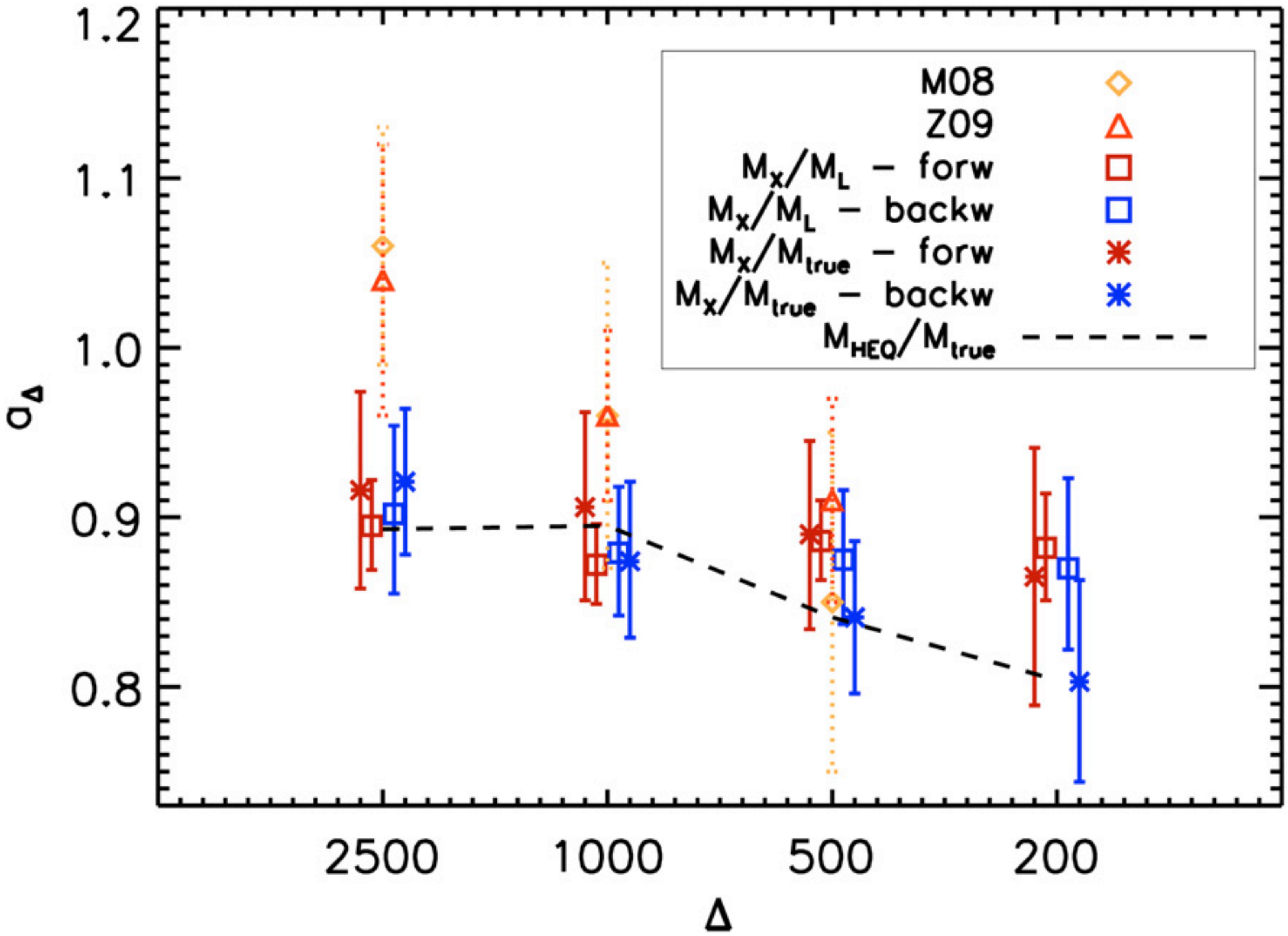




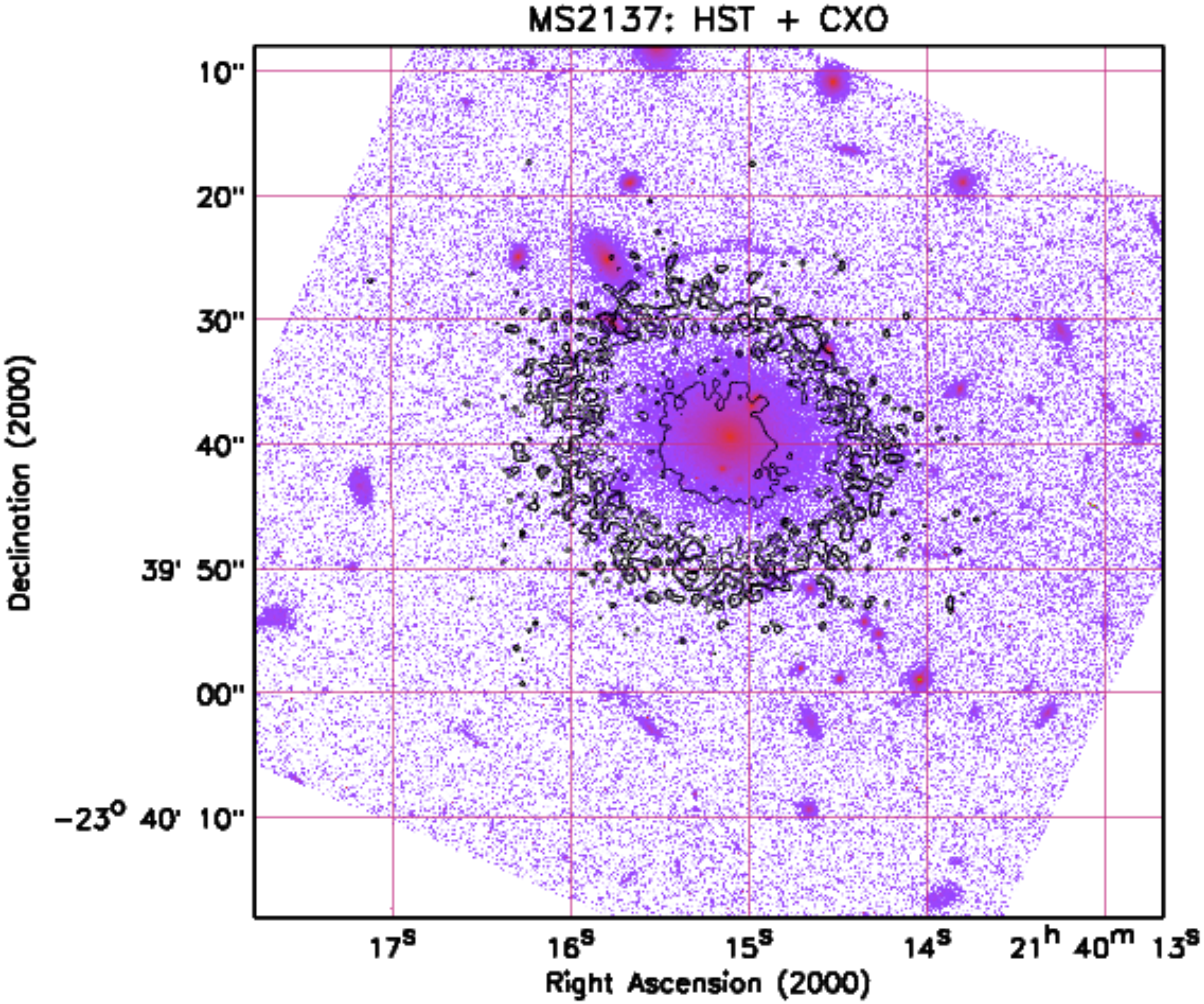
X-ray vs lensing mass: *simulations*



X-ray vs lensing mass: *simulations*

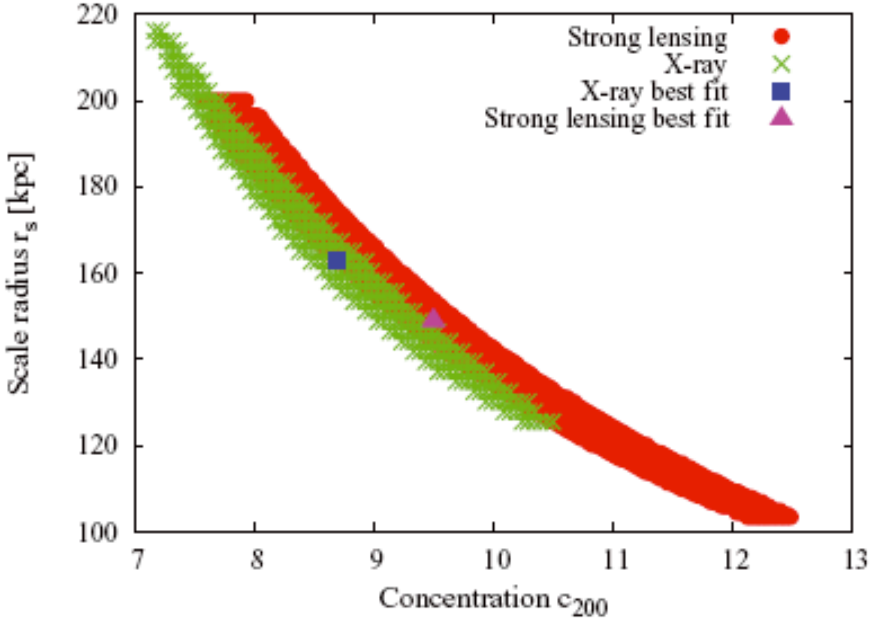


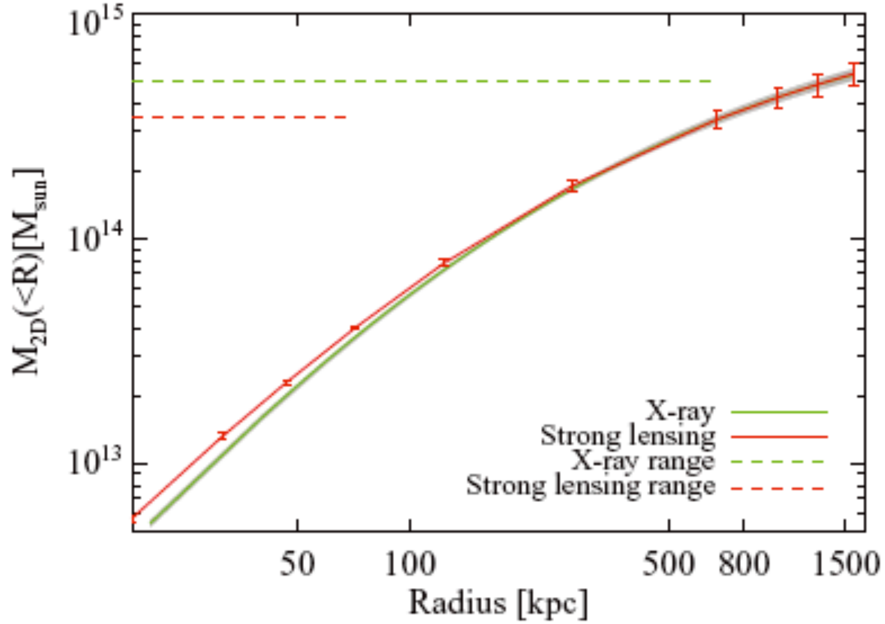
X-ray total mass: *MS2137*



The case of MS2137

(Donnarumma et al. 2008)





X-ray vs Optical mass

$M_X \approx M_{lensing}$ within 15% implies

$$\frac{G\,M_X}{r^2} = -\frac{d(P_{therm} + P_{NO-therm})}{dr}\frac{1}{\rho_{gas}}$$

$P_{NO\text{-}therm} \approx 0$

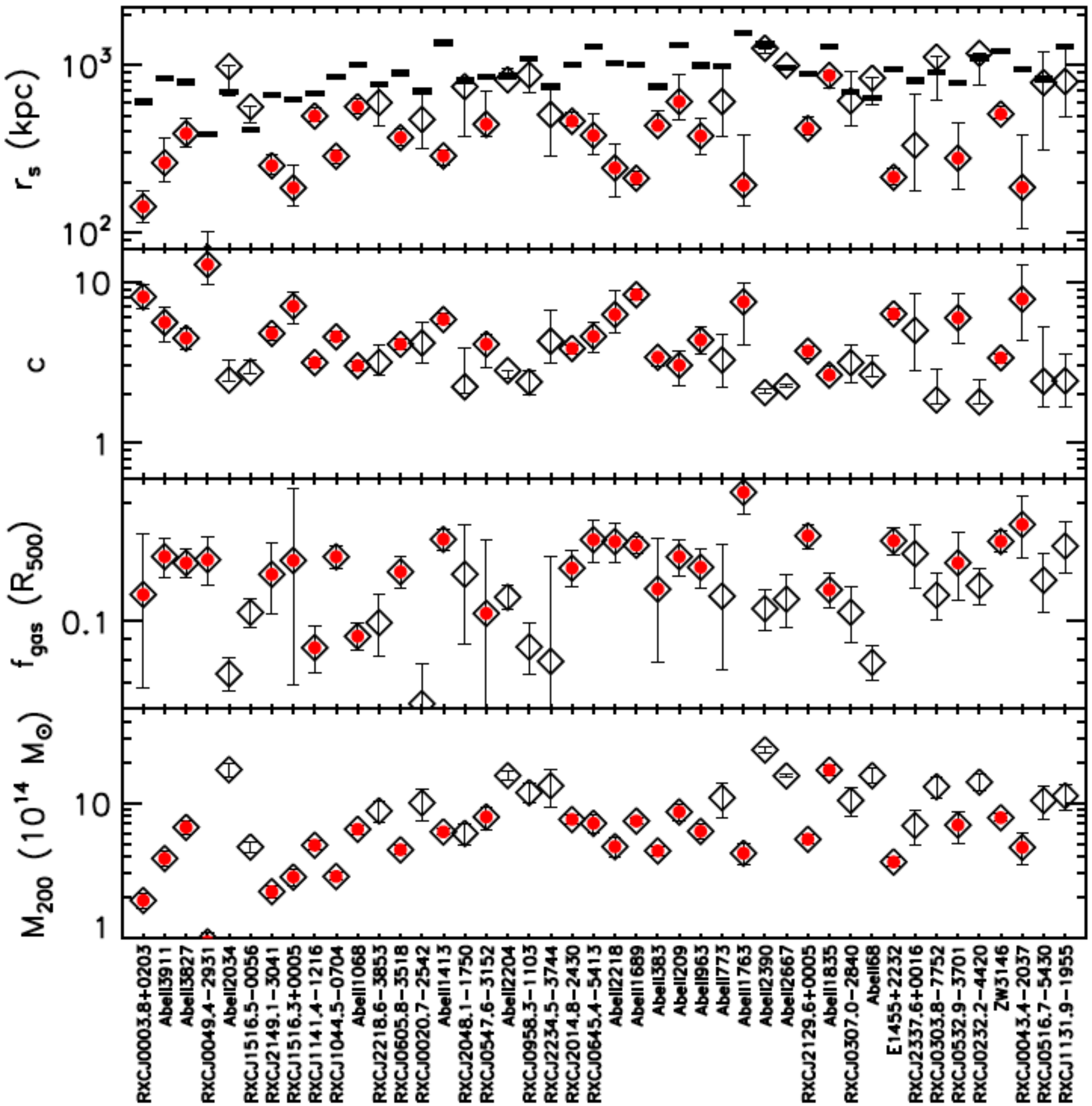
Moreover, the difference btw M_X and true Mass **cannot be larger than ~20%** as proved in cosmological studies [e.g. $f_{bar} = (M_{gas}+M_{star})/M_{tot} = \Omega_b / \Omega_m$] & hydrodynamical simulations…

Conclusions on estimate of the X-ray M_{tot}

• Hydrostatic equilibrium holds locally: look for relaxed regions also in merging systems

• At least two main ways (one ***forward***, one ***backward***) to apply HEE: pro/contra, no systematic is evident btw them, not thermalized ICM is missed *(but see good agreement btw X-ray/lensing data)*

Results on $\{c, M_{DM}, f_{gas}\}$



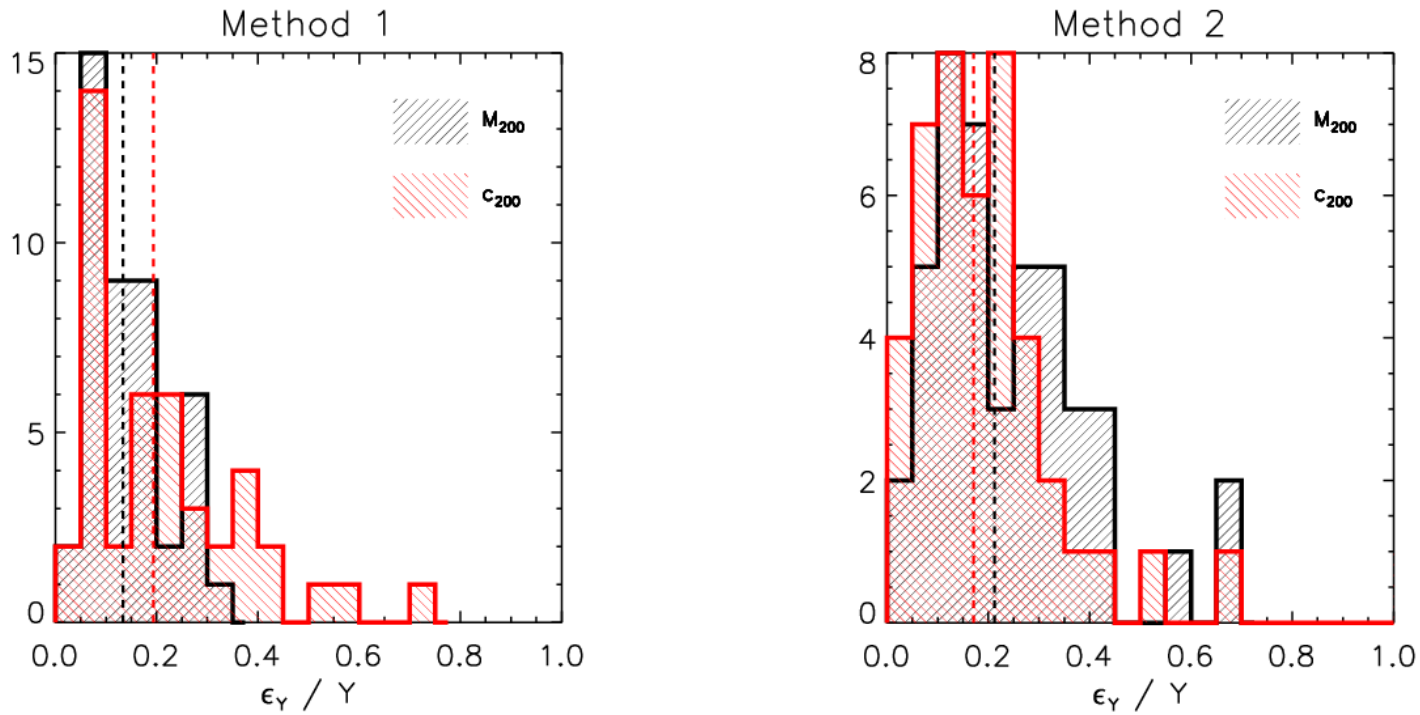
$c = R_{200}/r_s$

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

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

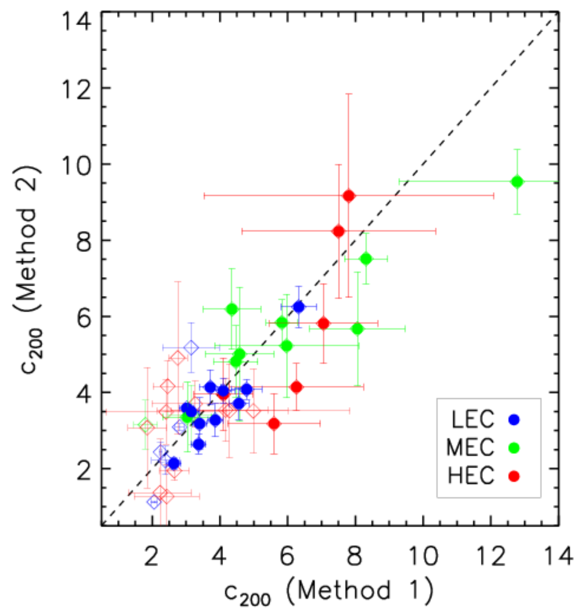
$V = 4/3\pi R_{200}^3$

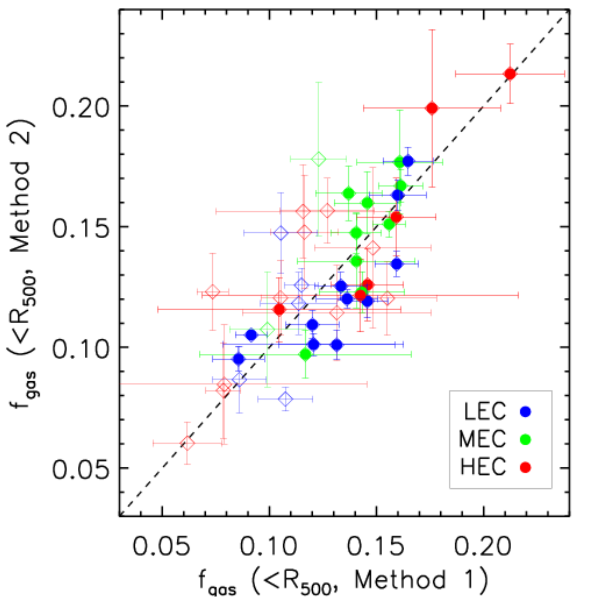
The c-M_{DM} relation: statistical



- (*Method 1*) (de)projected data +HEE +NFW +fit T(r):
  ~15-20% relative errors on c_{200} & M_{200}
- (*Method 2*) … +functional form for $n_{gas}(r)$ +T_0:
  ~20% relative errors

The c-M_{DM} relation: systematics

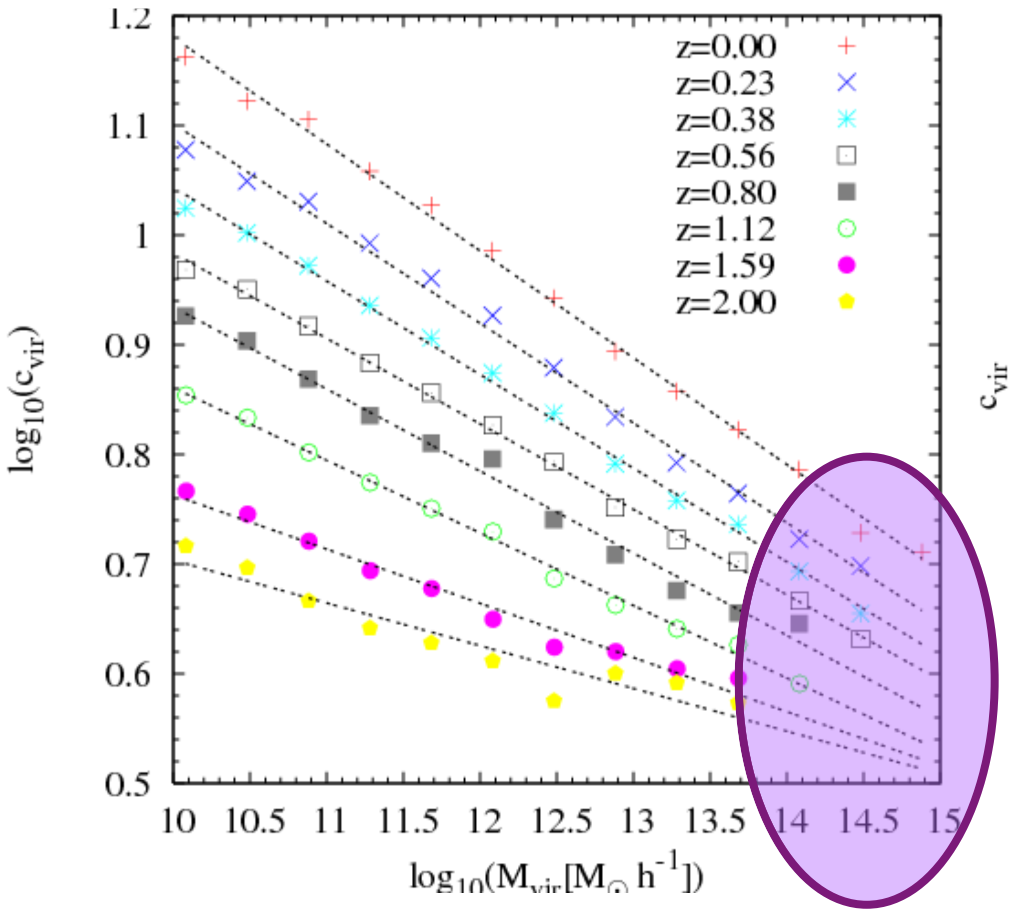


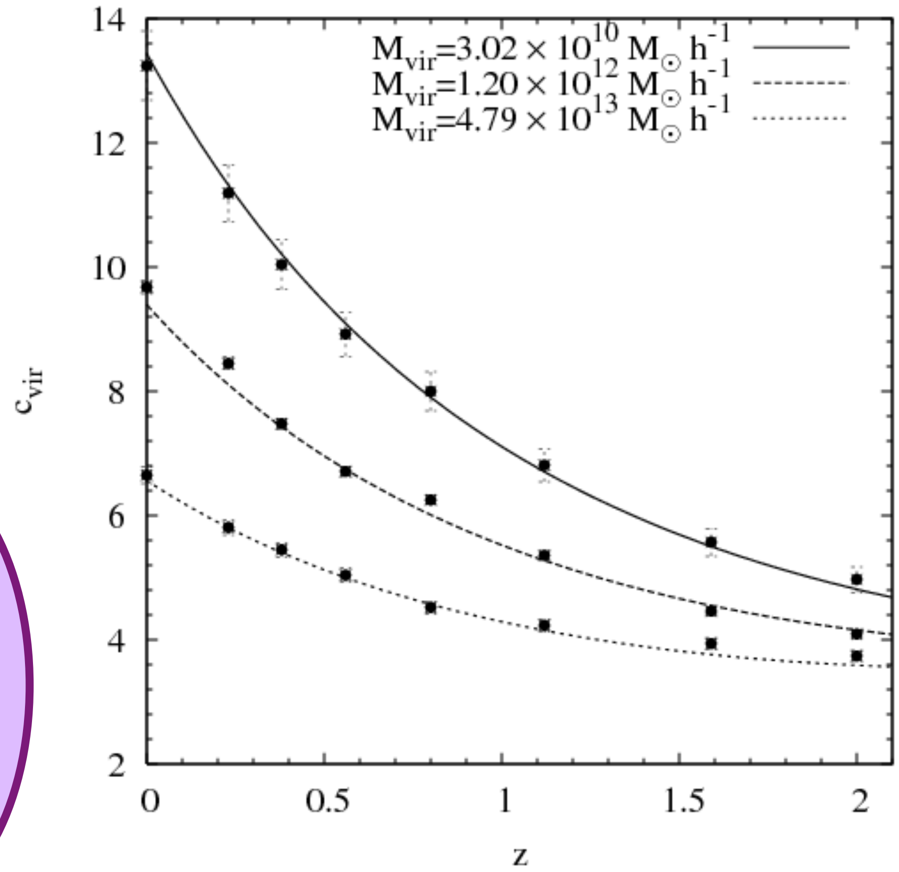


Dataset	$(\hat{c}_{200} - c_{200})/c_{200}$	$(\hat{M}_{\rm DM} - M_{\rm DM})/M_{\rm DM}$	$(\hat{f}_{\rm gas} - f_{\rm gas})/f_{\rm gas}$
Method 2	−0.013	+0.008	+0.036
M2	+0.010	−0.017	+0.009
$T_{\rm 3D}$	−0.048	−0.036	+0.024
fit $n_{\rm gas}$	+0.001	+0.011	+0.000
$P_{\rm out}$	−0.011	+0.030	−0.014
at R_{200}	(−0.048, +0.010)	(−0.036, +0.030)	(−0.014, +0.036)
Method 2	–	−0.015	+0.035
M2	–	−0.018	+0.010
$T_{\rm 3D}$	–	−0.046	+0.025
fit $n_{\rm gas}$	–	+0.012	−0.008
$P_{\rm out}$	–	+0.028	−0.013
at R_{500}	–	(−0.046, +0.028)	(−0.013, +0.035)
Method 2	–	−0.073	+0.032
M2	–	−0.013	+0.008
$T_{\rm 3D}$	–	−0.059	+0.028
fit $n_{\rm gas}$	–	+0.004	+0.000
$P_{\rm out}$	–	+0.020	−0.009
at R_{2500}	–	(−0.073, +0.020)	(−0.009, +0.032)

The c-M_{DM} relation: $\sigma_8 - \Omega_m$

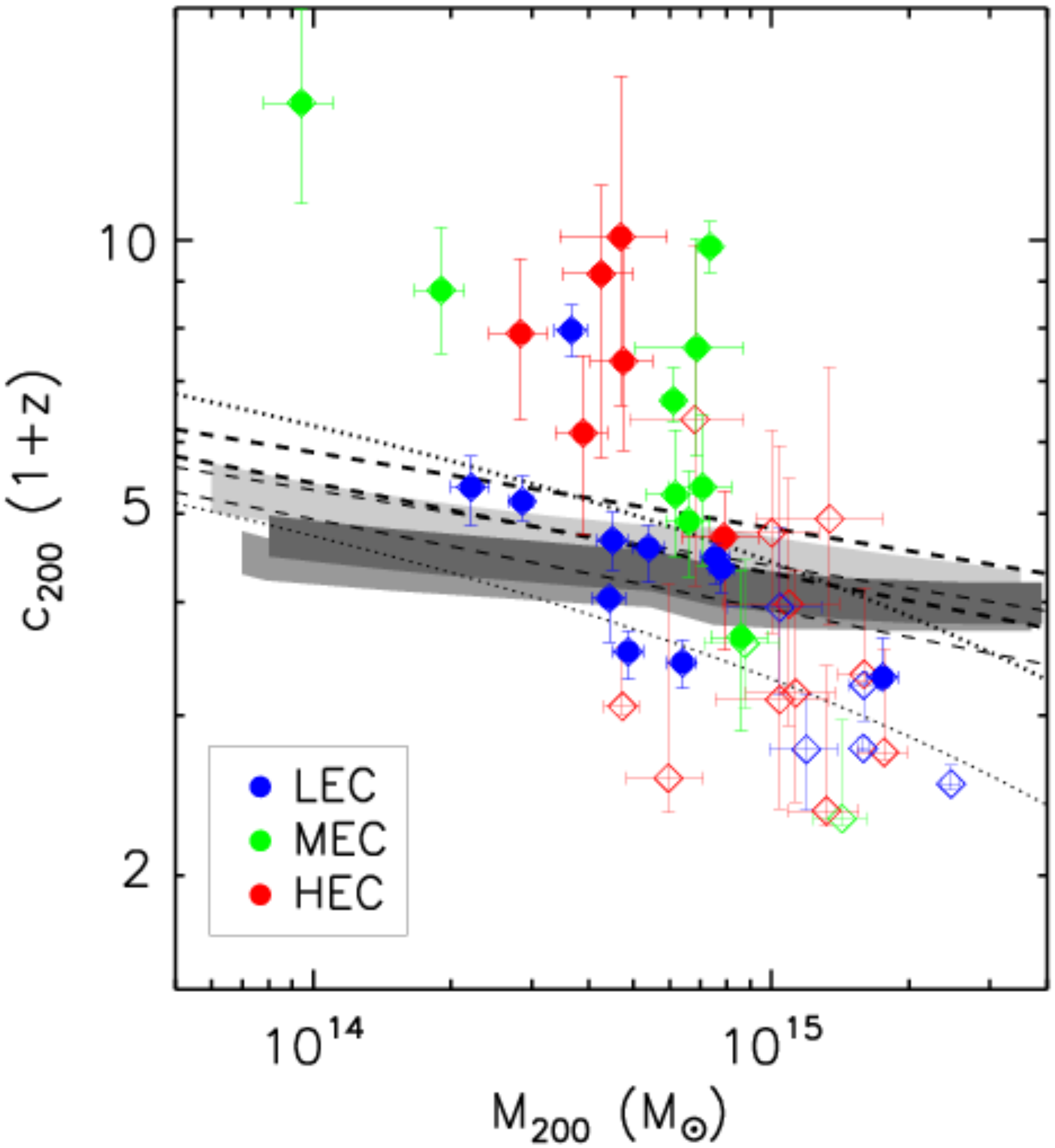
Concentration [$\sim M_{200}^{1/3}/(r_s\ \rho_{c,z}^{1/3})$] depends on the halo mass growth history (function of σ_8 & $\rho_{c,z}$) and needs N-body simulations to be described as function of (M,z)





(Munoz-Cuartas et al. 2010)

The c-M_{DM} 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)

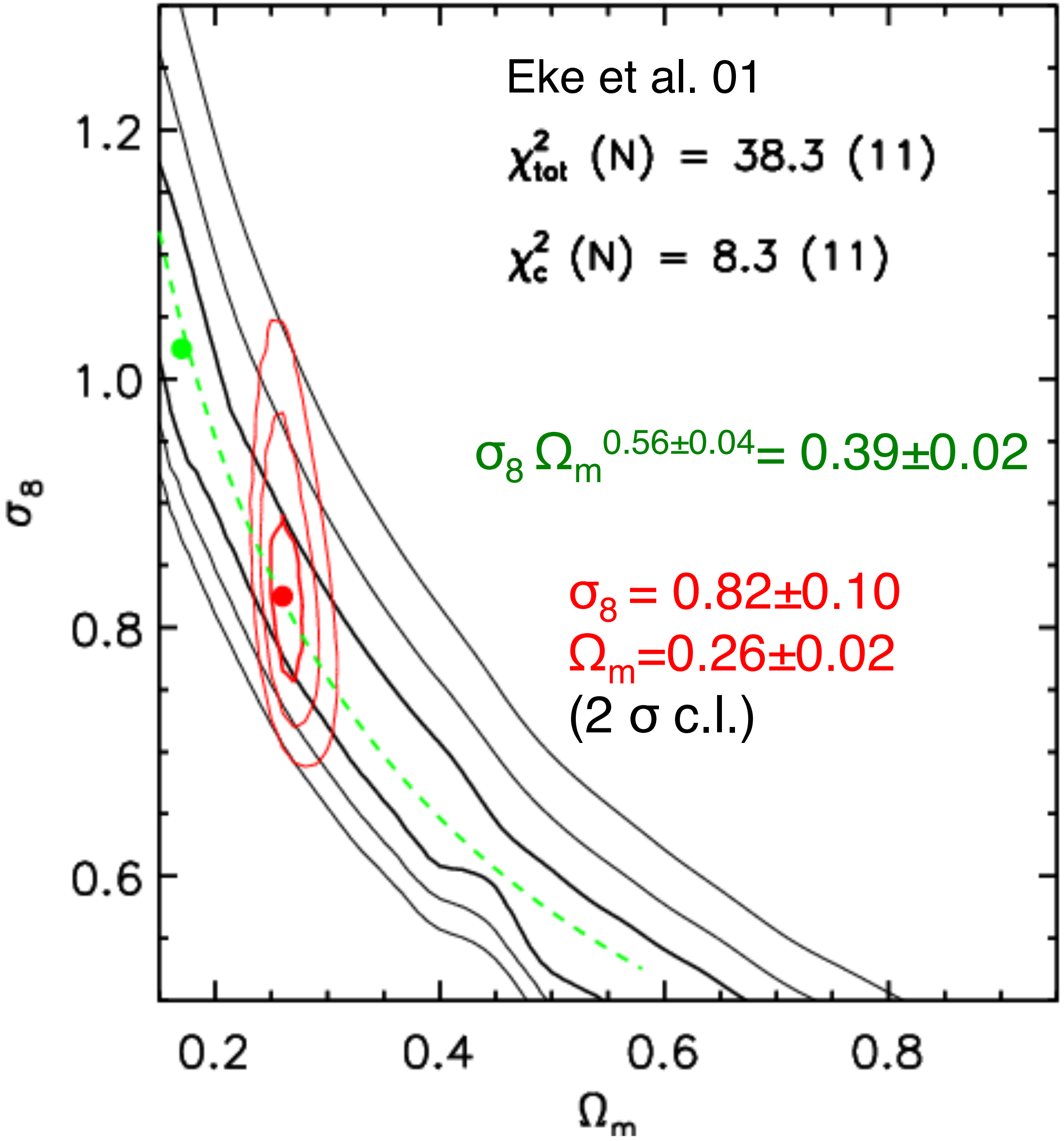
NOTE: LEC≈CC … HEC≈mergers (see e.g. Leccardi et al. 2010)

Combining {c, M_{DM}, 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*).



Gas mass fraction

To constrain the cosmological model

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

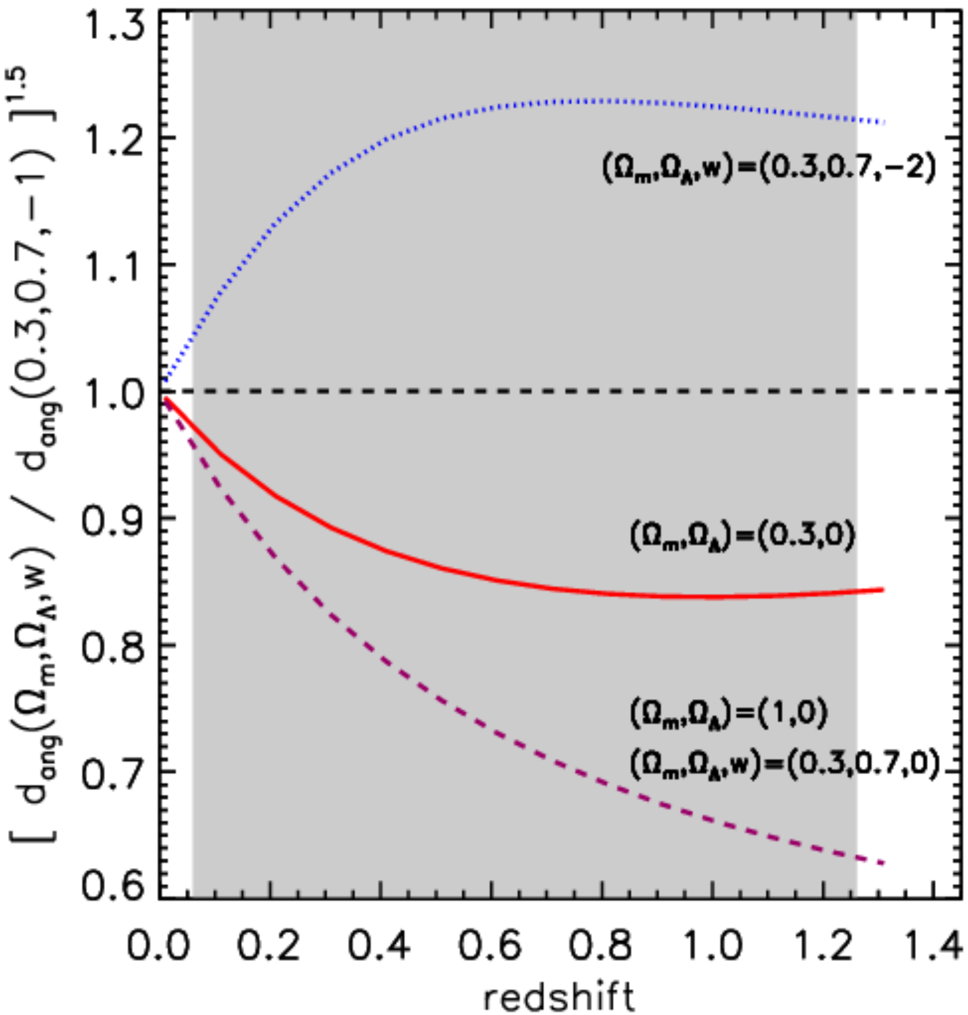
We combine a **dynamical** and a **geometrical** method

(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)

The cosmological dependence

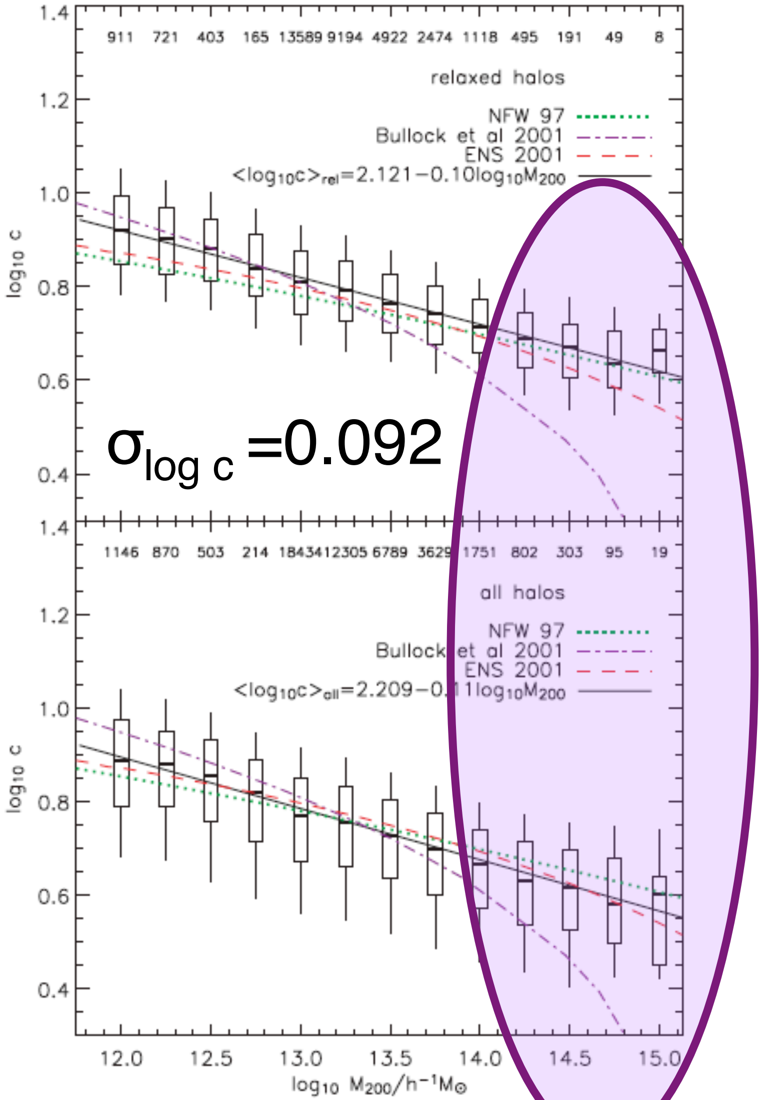
$$f_{gas}(<R_{500}) = M_{gas}/ M_{tot} \propto n_{gas}R^3/R \propto d_{ang}(\Omega_m, \Omega_\Lambda, w)^{3/2}$$



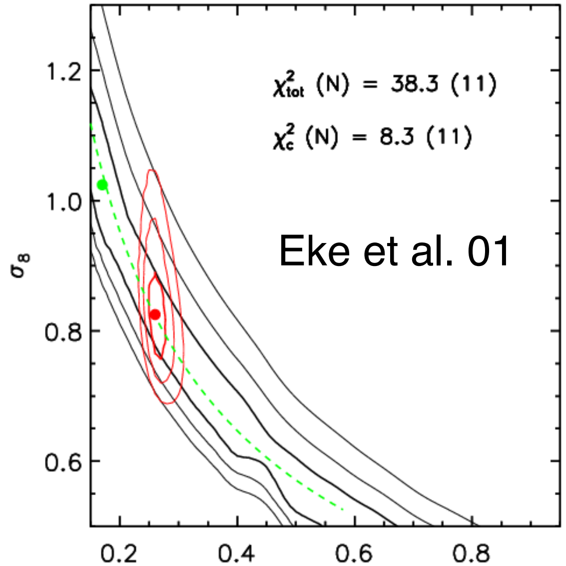
500 relaxed hot (T>5 keV) obj with f_{gas} estimate precise at 5% level provides a FoM_{DETF} [~1/ (σ_{w0} σ_{wa}), $w=w_0+w_a(1-a)$] ~**15-40** *(Rapetti et al. 08)*, comparable to:

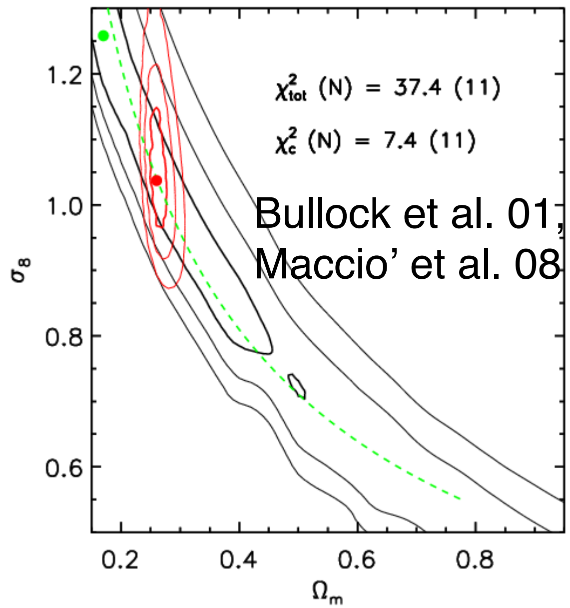
ground-based SNIa … 8-22
Space-based SNIa … 19-27
Ground-based BAO … 5-55
Space-based BAO … 20-42
Space-based clusters cts … 6-39

The c-M_{tot} relation: $\sigma_8 - \Omega_m$



Neto et al. 07





Combining $\{c, M_{DM}, f_{gas}\}$: conclusions

• We demonstrate that analysis in the **$\{c, M_{DM}, f_{gas}\}$** plane represent a mature & competitive technique to constrain **$\{\sigma_8, \Omega_{m,} (w)\}$**

• *Our results depend (~20%) on the models adopted to relate the properties of the DM halos to the background cosmology*. A more detailed analysis of the output of larger sets of cosmological numerical simulations is requested to provide the needed calibration of massive (>1e14 Msun) DM halos as function of $\{\sigma_8, \Omega_{m,} z\}$ for more definitive & robust results

Combining {c, M_{DM}, f_{gas}}: conclusions

- **Impact of WDM**:

(1) the change in core density and concentration due to the lower formation redshift in WDM models;
(2) the suppression of density cusps due to relic thermal velocities of the WDM particles.

Smith & Markovic (2011) found that the former effect is the most important. Relic velocities only affect the density structure on scales r<1 kpc/h