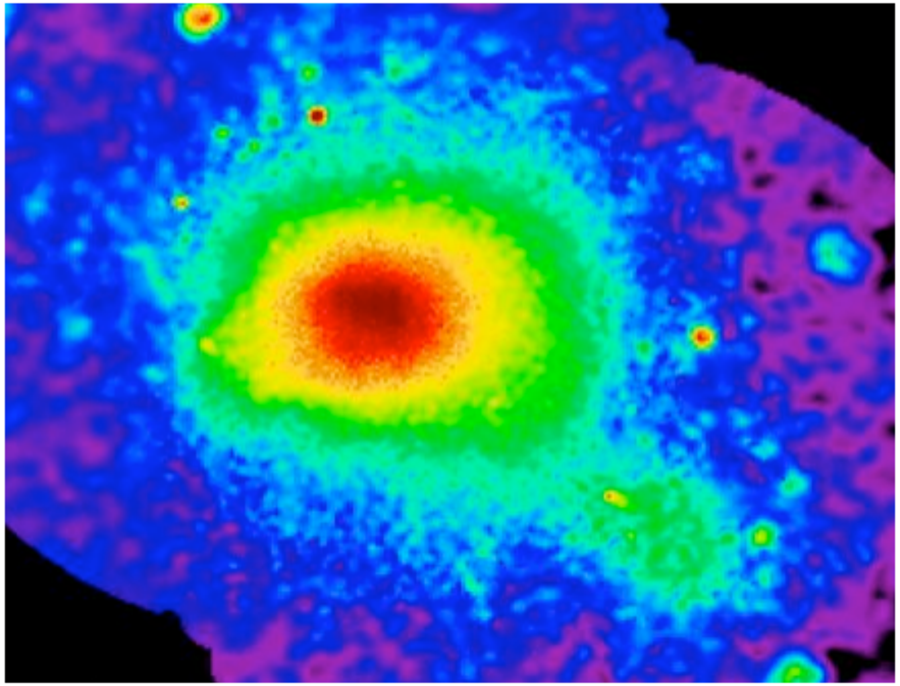
Estimate of the X-ray mass in galaxy clusters



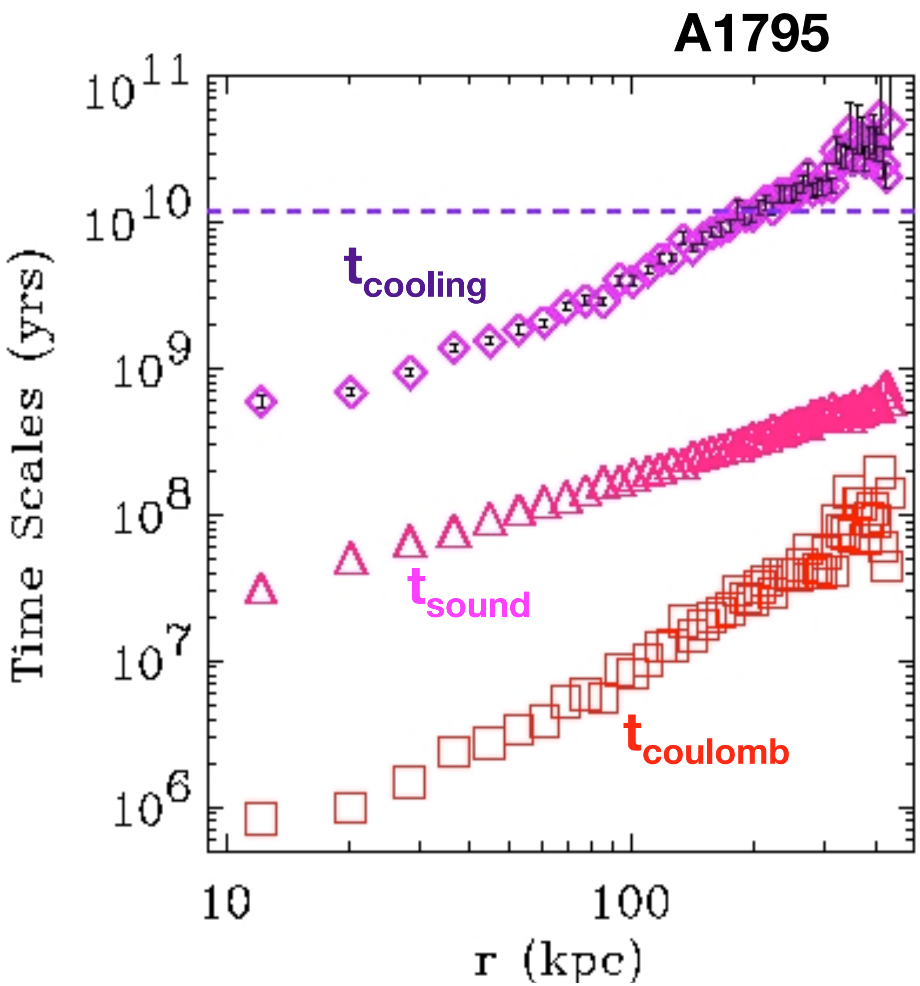
Stefano Ettori

(INAF-OA Bologna)

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

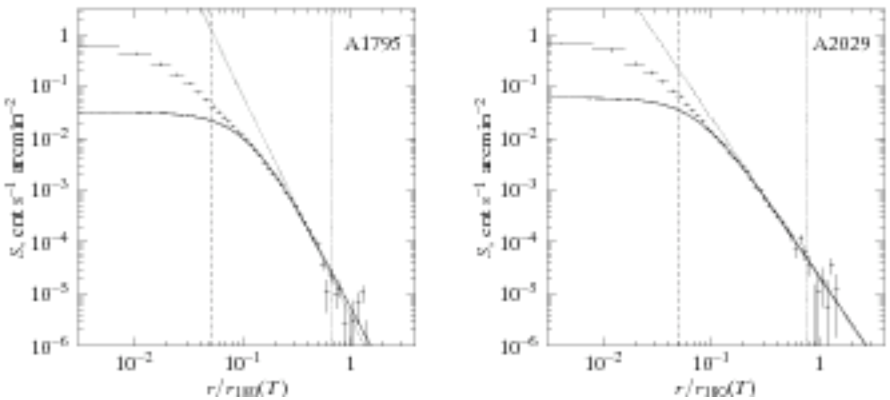
1. spherical symmetry, 2. hydrostatic equilibrium

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

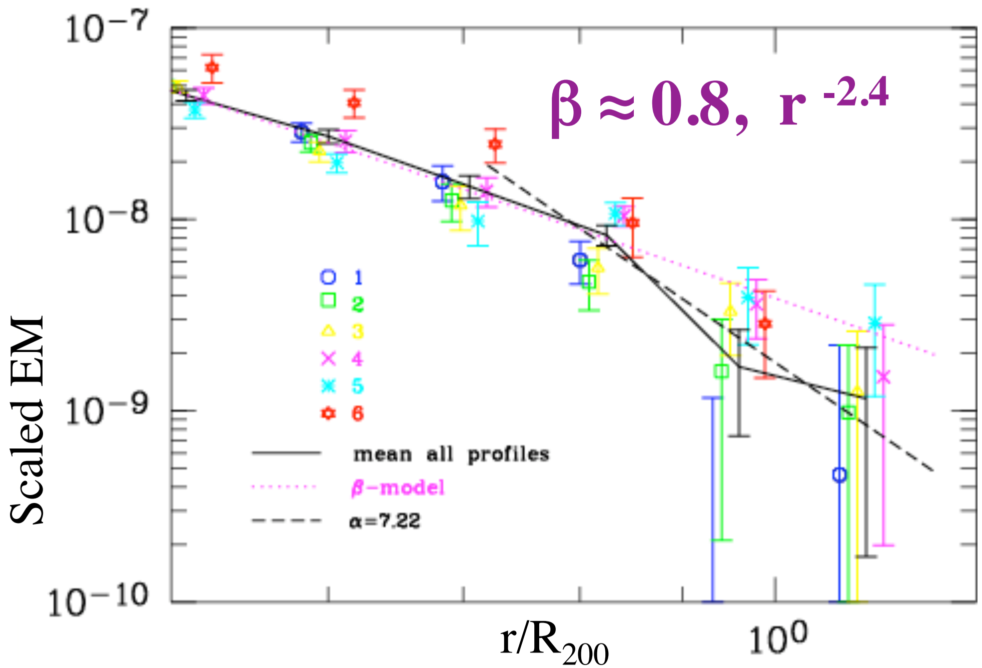
$$M_{tot}(<r) \propto r \times T_{gas}(r) \times (-\alpha_n - \alpha_T)$$

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

ICM at R_{vir}: *Observed clusters*

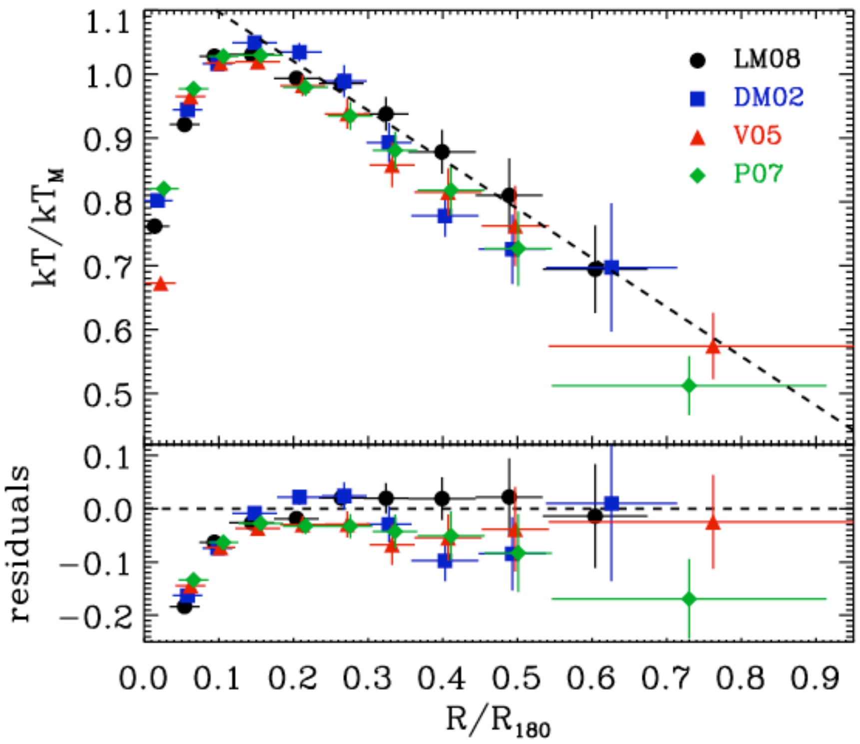


"Outer regions of the cluster gaseous atmosphere" Vikhlinin et al. (99): β~0.8 and larger by ~0.05 of the global fit value

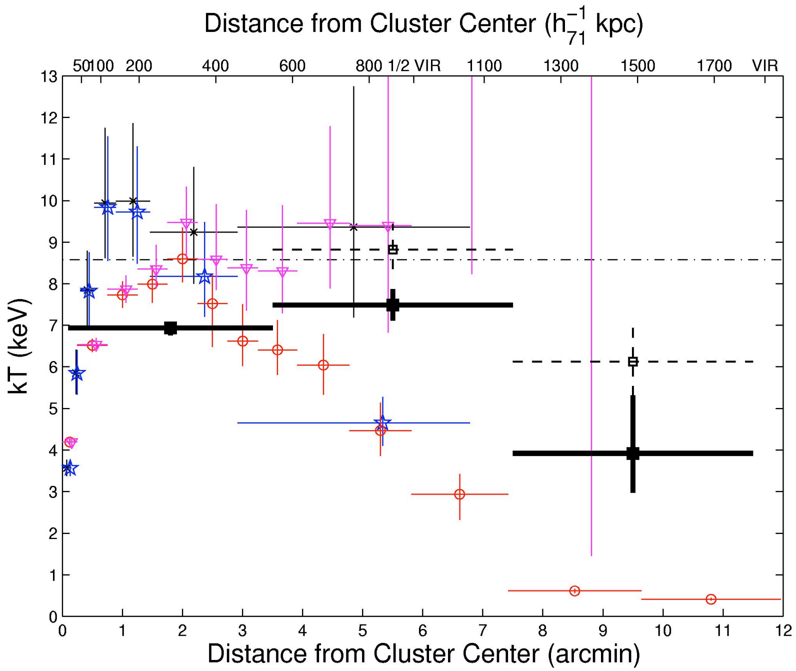


Sample of nearby clusters observed with ROSAT/PSPC (Neumann 2005)

ICM at R_{vir}: *Observed clusters*



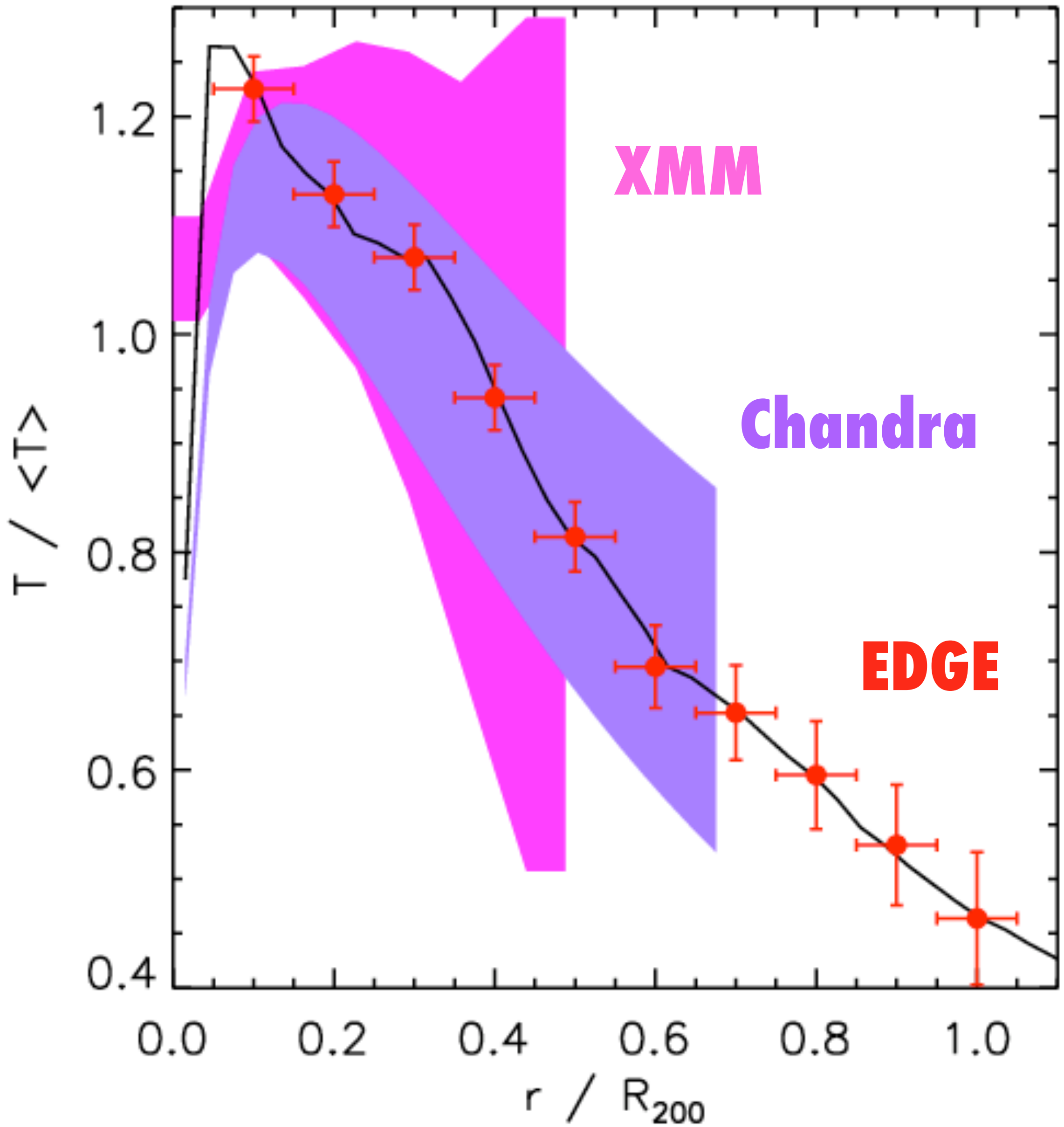
Sample of 60 objects observed with XMM (Leccardi & Molendi 08)



A2204

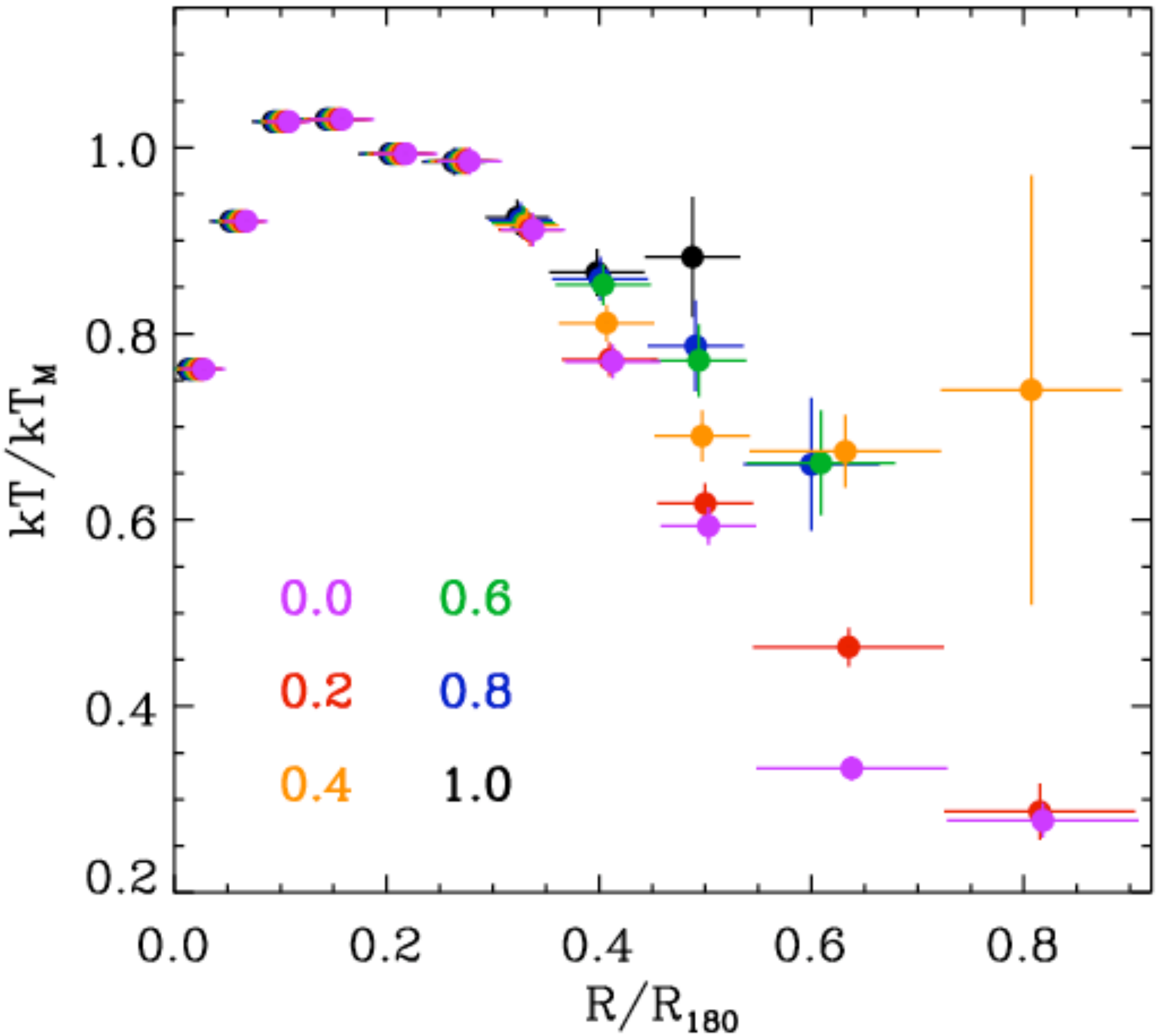
very preliminary results with ***Suzaku*** by T.Reiprich

On the Temperature profile



arXiv:0707.4103

On the Temperature profile



Changing I = Src/Bkg between 0 and 1

(Leccardi & Molendi 2008)

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

$f(x) = \log(x + \sqrt{1+x^2}) - x/\sqrt{1+x^2}$ [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: $P(r) = P_{out} - \mathrm{Sum}(\mathrm{Reverse}(dP))$

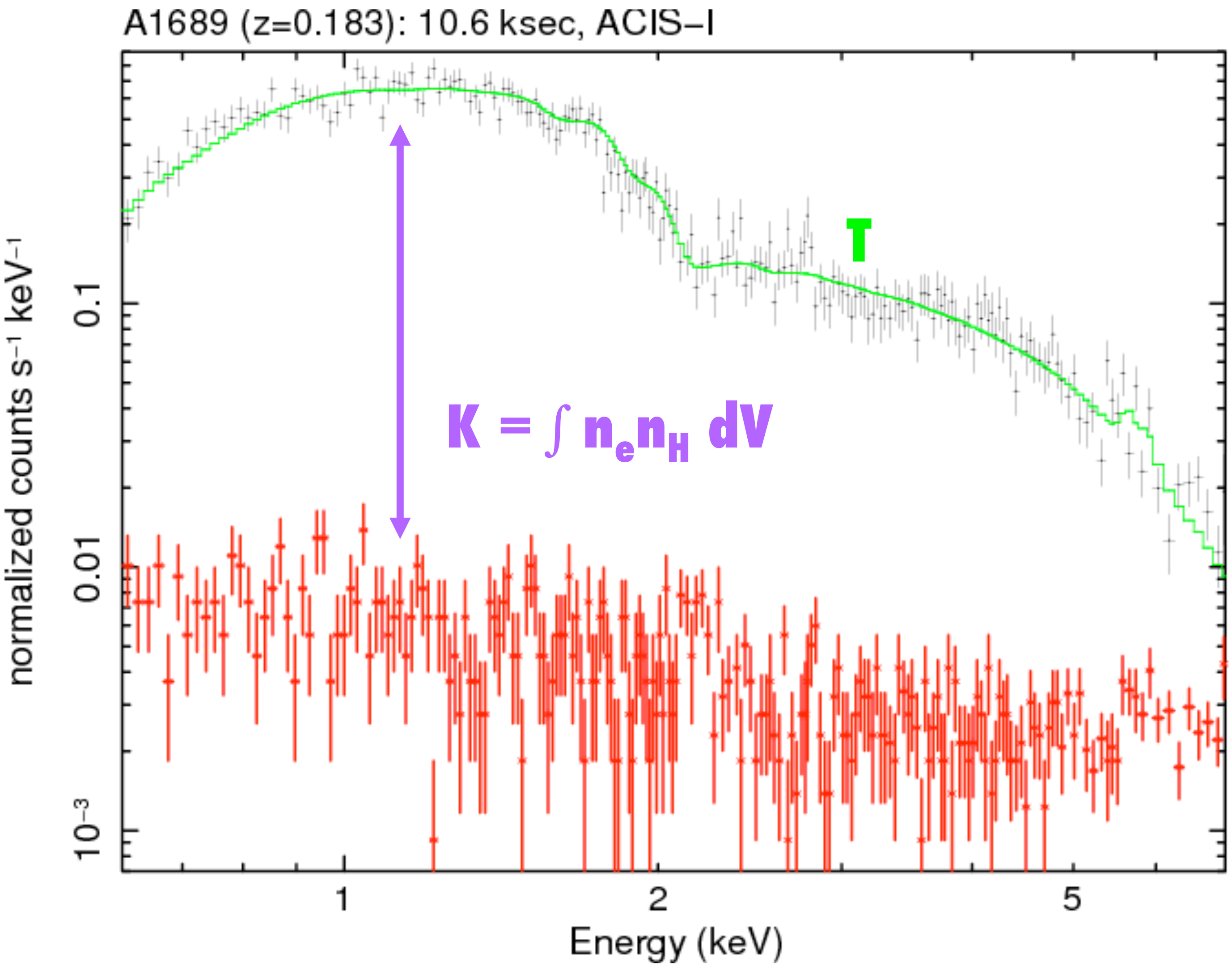
Step 6: $T_{fit} = P(r) / n_e$

Step 6bis: project T_{fit} in the observed annulus

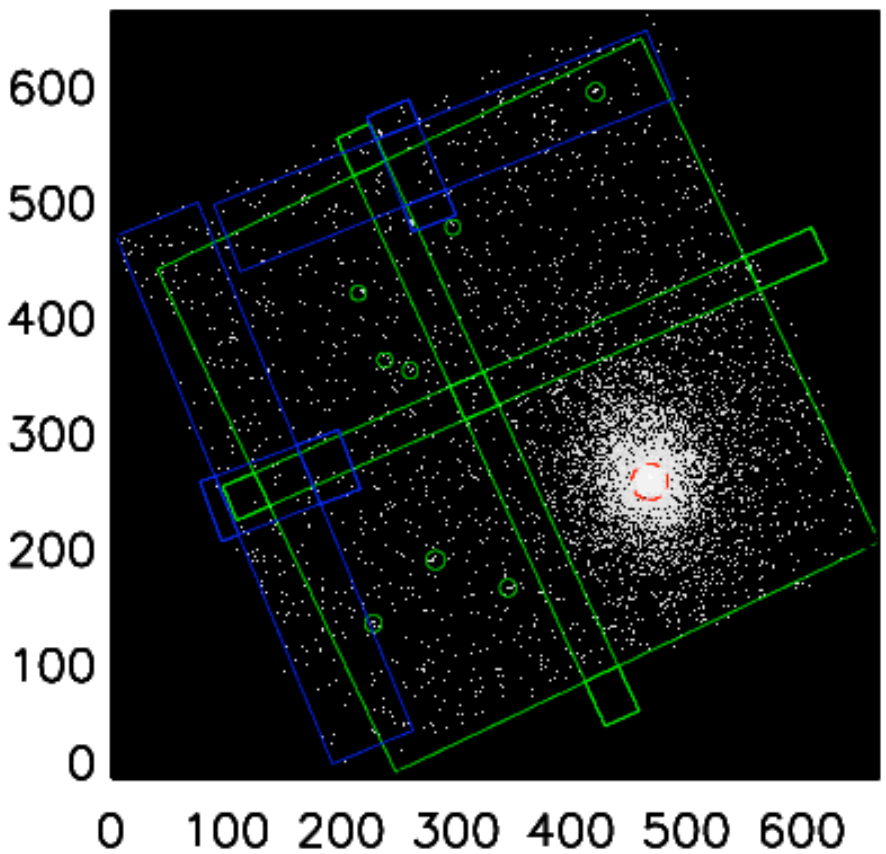
(e.g., with Mazzotta's rule)

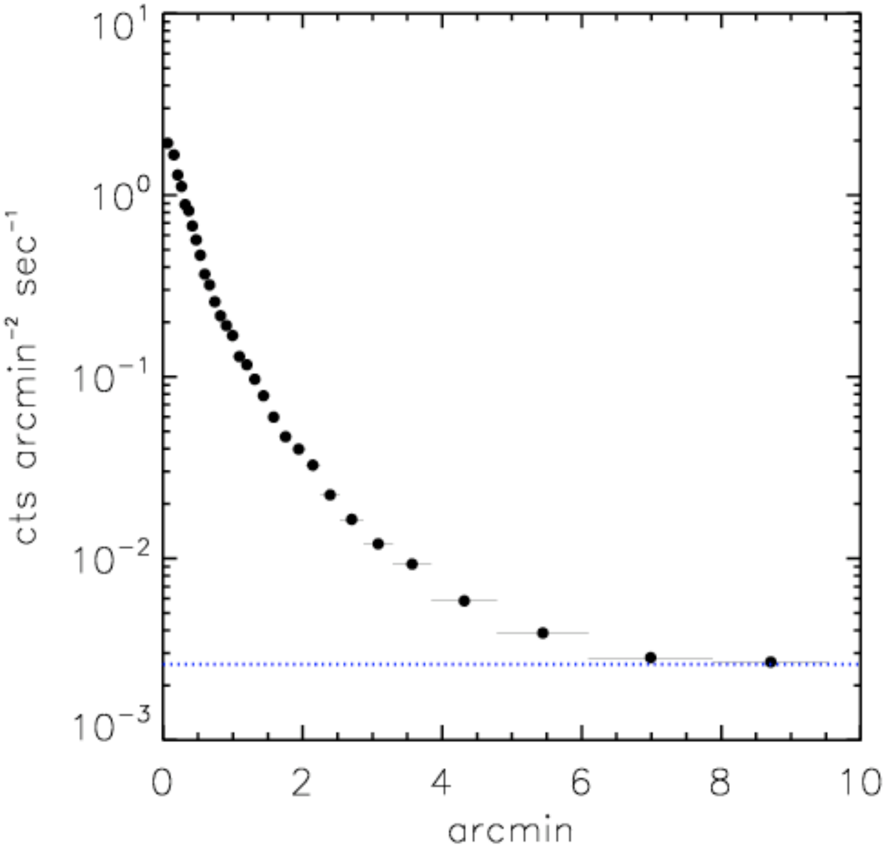
Step 7: $\chi^2(c, rs) = \mathrm{Sum}((T_{fit} - T_{xspec})^2 / err^2)$

X-ray total mass: *the observables*



X-ray total mass: *the observables*

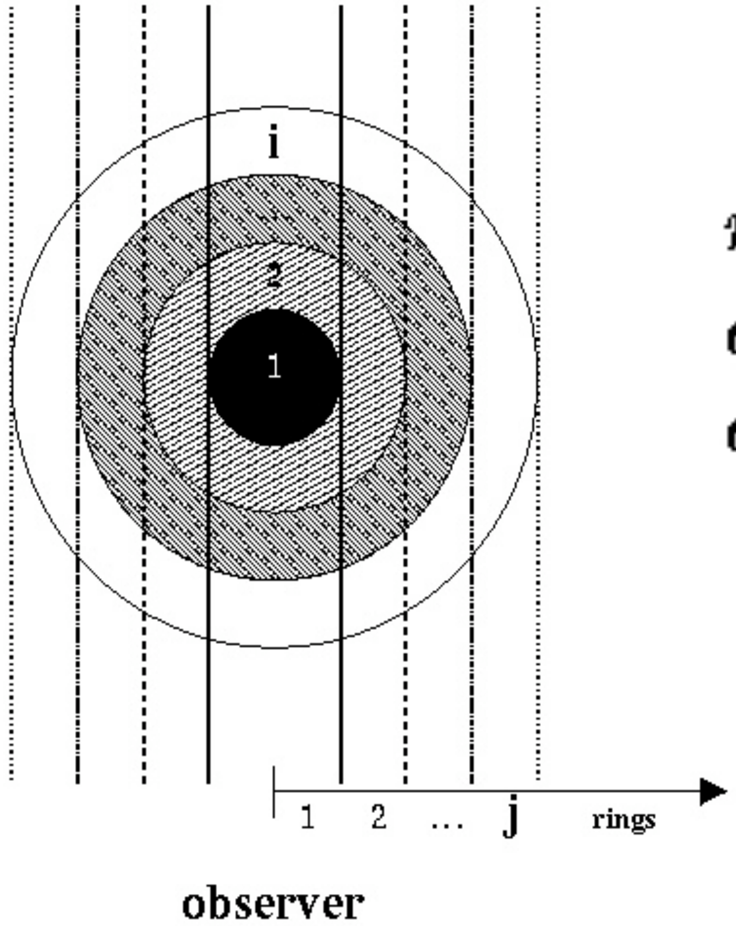




A1689: z=0.183, t_{exp}=10.8 ksec, total cts=32,500

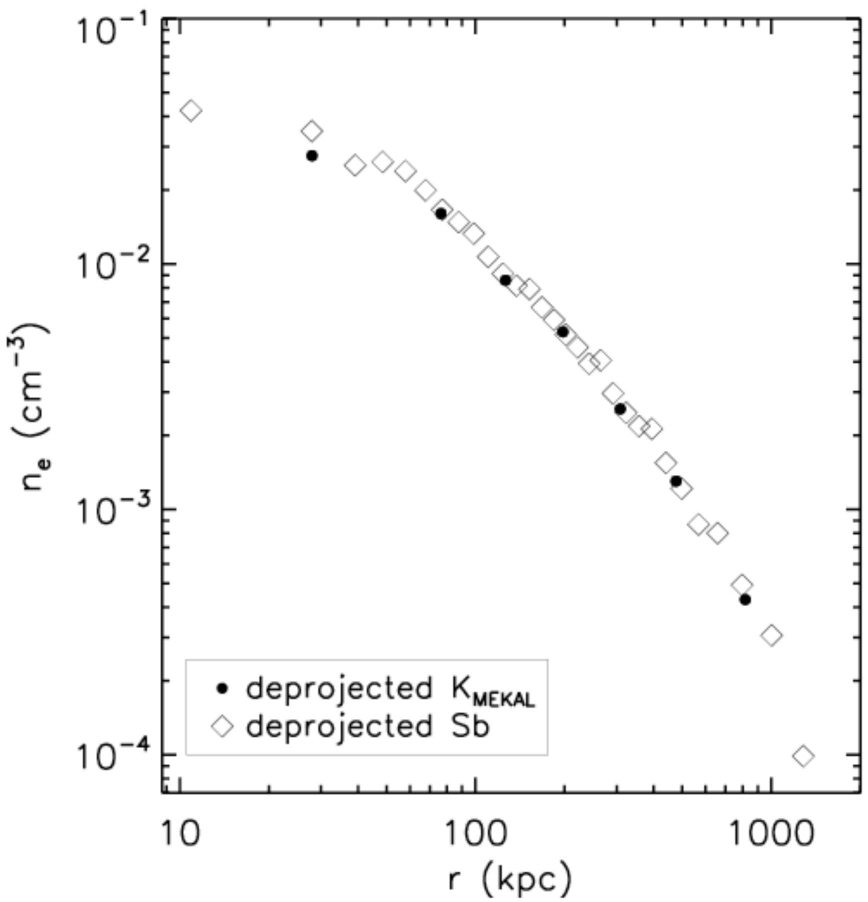
X-ray total mass: *the deprojection*

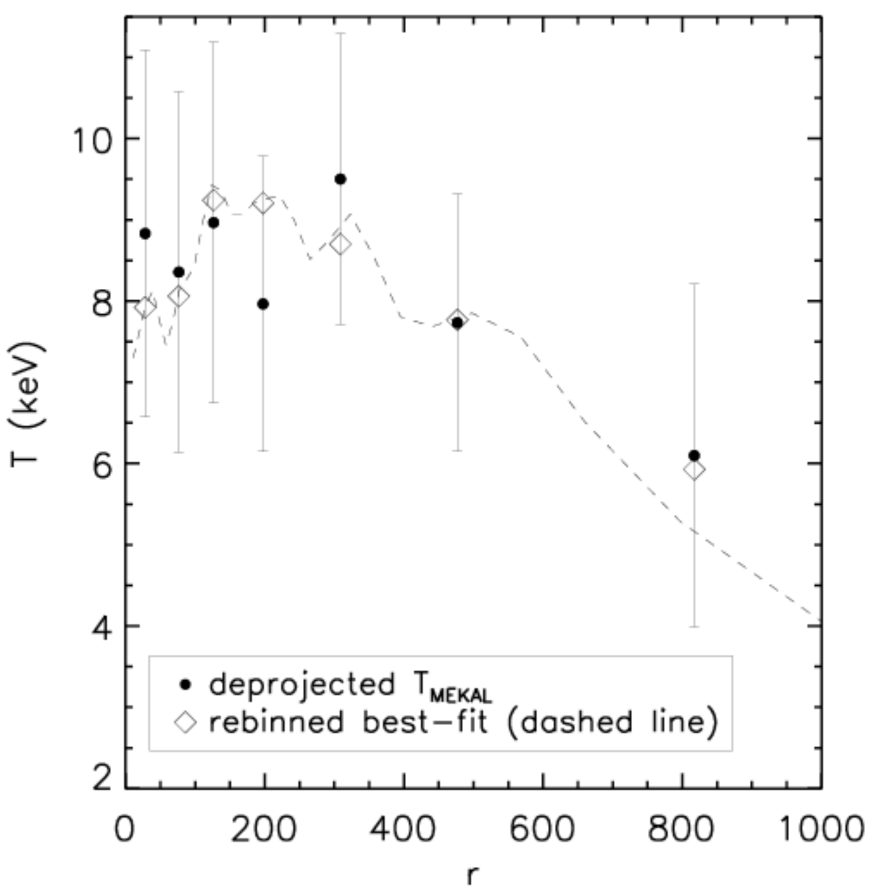
(Fabian & Cambridge group, Nulsen, Buote, Ettori, Arabadjis, Peterson et al.,Vikhlinin, Pratt, Pizzolato, Croston,...)



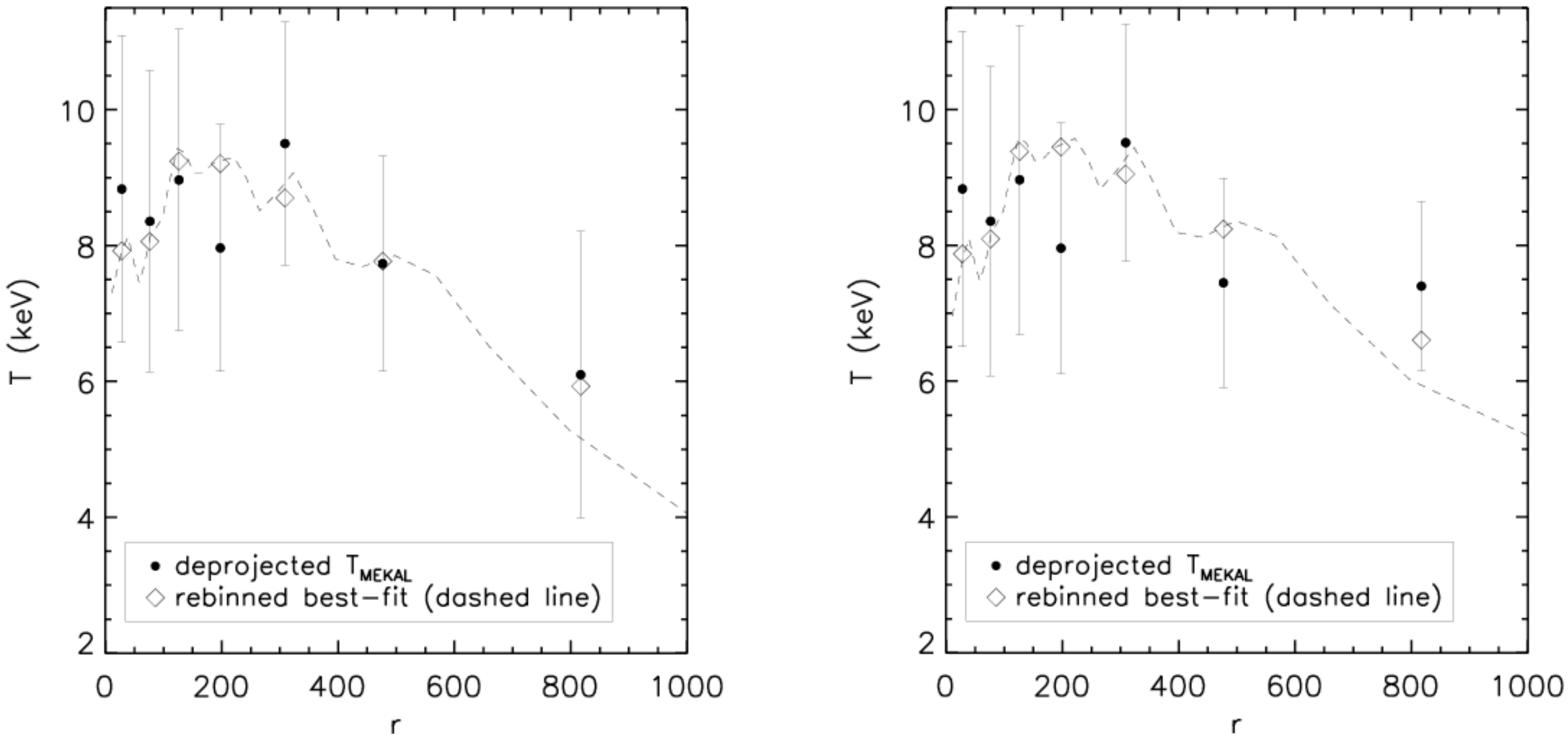
$$n_e = \left[(\mathbf{Vol}^T)^{-1} \#(EI/0.82) \right]^{1/2}$$
$$\epsilon = (\mathbf{Vol}^T)^{-1} \# L_{\mathrm{ring}}$$
$$\epsilon T_{\mathrm{shell}} = (\mathbf{Vol}^T)^{-1} \#(L_{\mathrm{ring}} T_{\mathrm{ring}}).$$

X-ray total mass: n_{gas} & T_{gas}

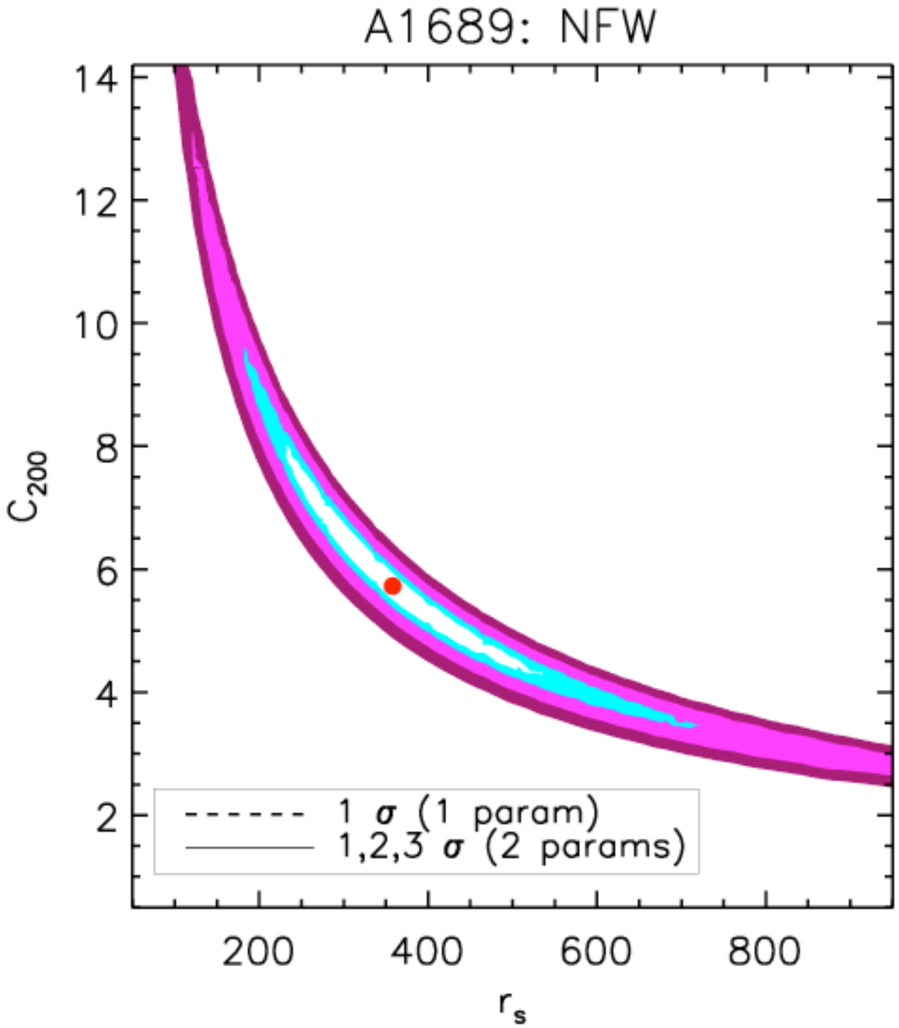


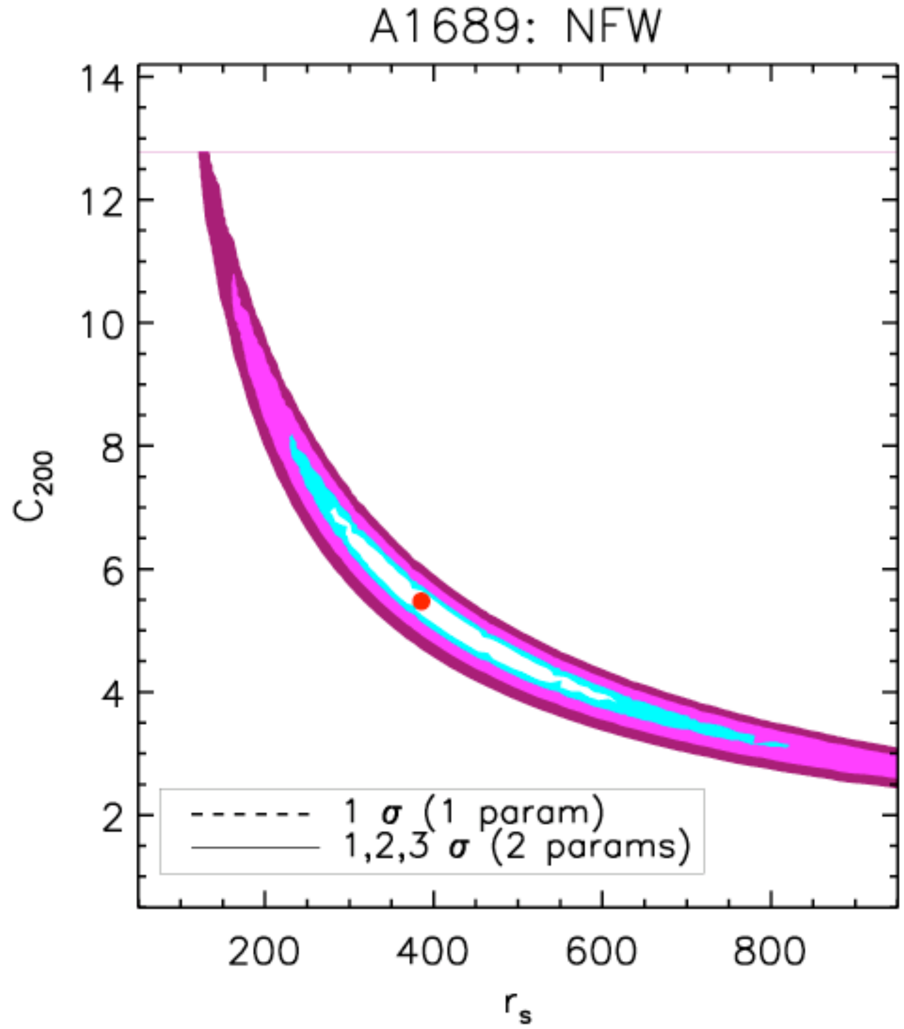


X-ray total mass: *changing T(r)*



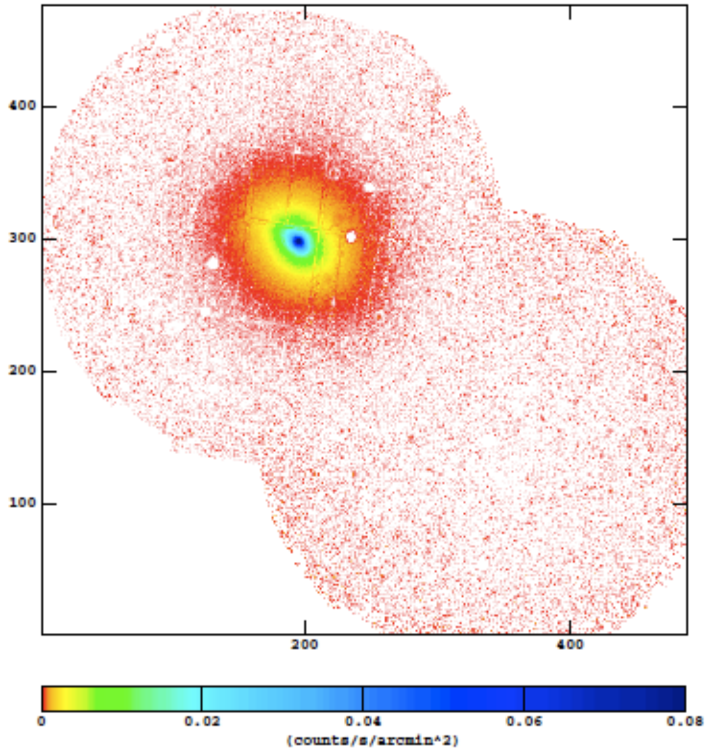
X-ray total mass: *changing T(r)*

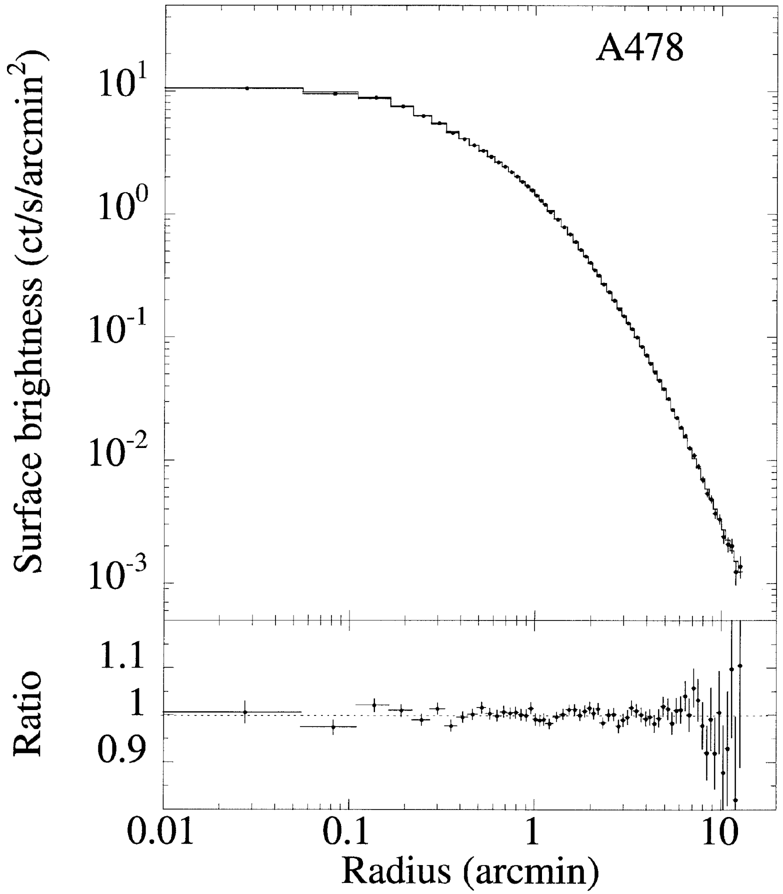


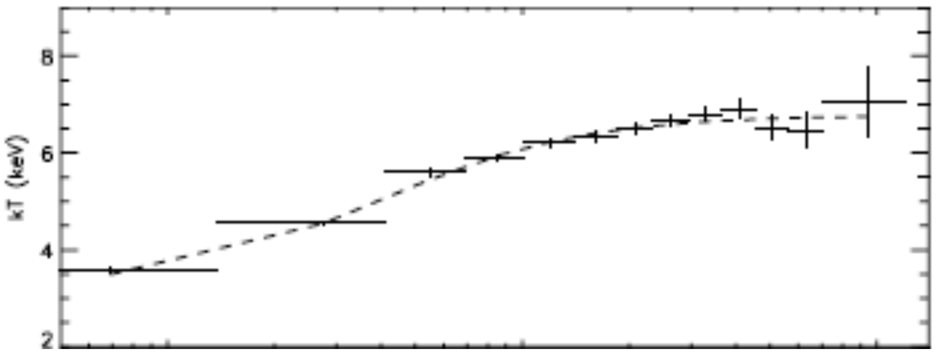


X-ray total mass: *other methods*

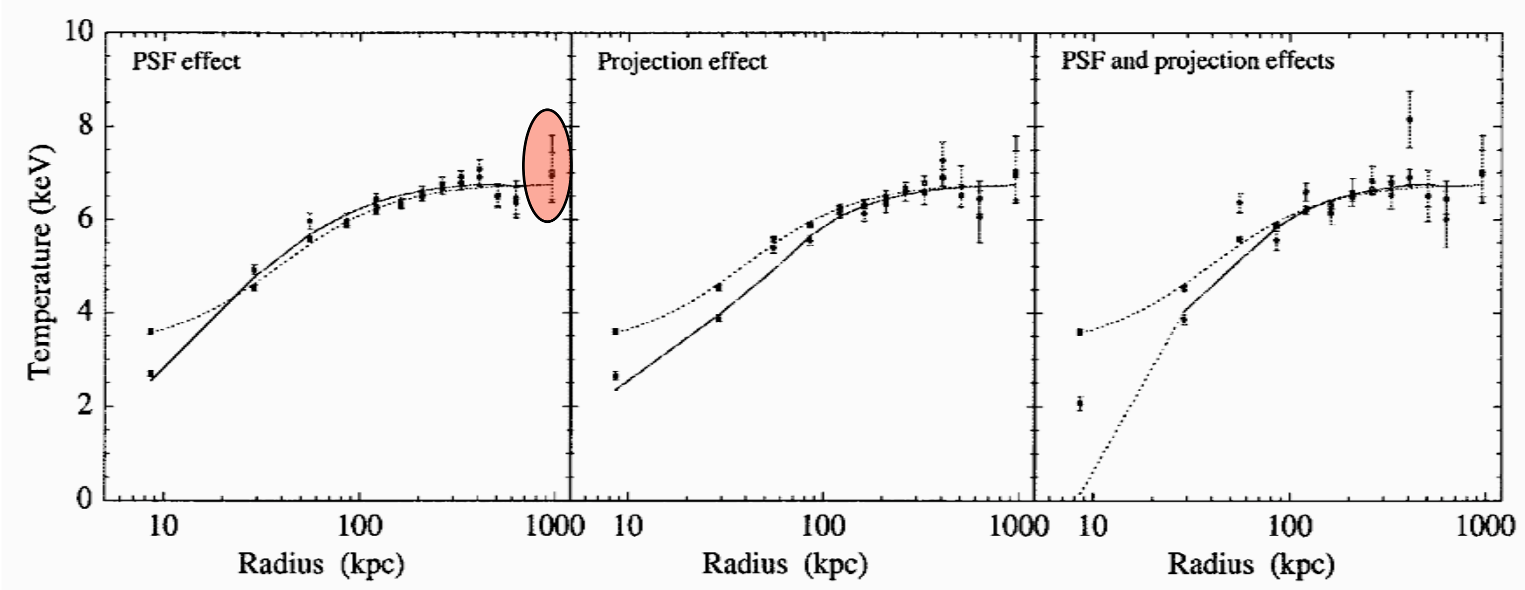
eg. Buote, **Pointecouteau**, Vikhlinin

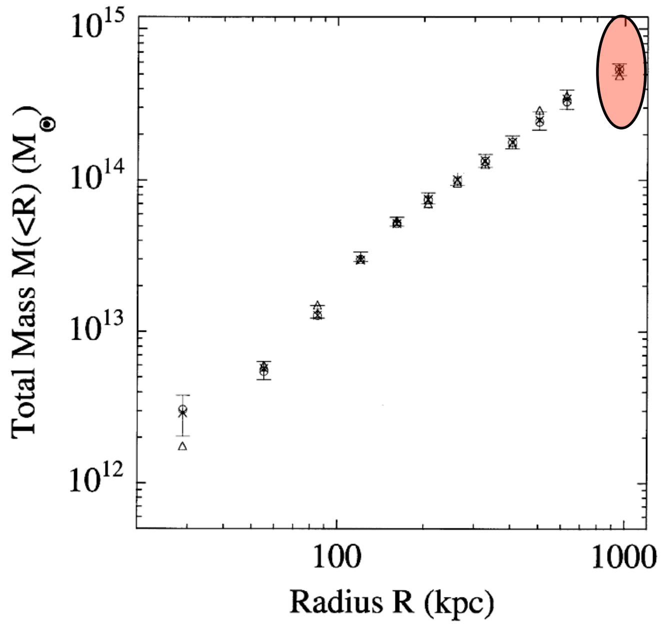






X-ray total mass: *other methods*





X-ray total mass: *other methods*

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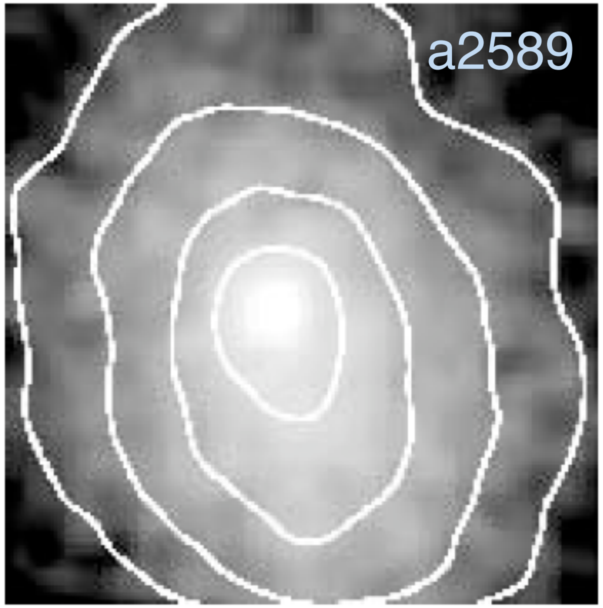
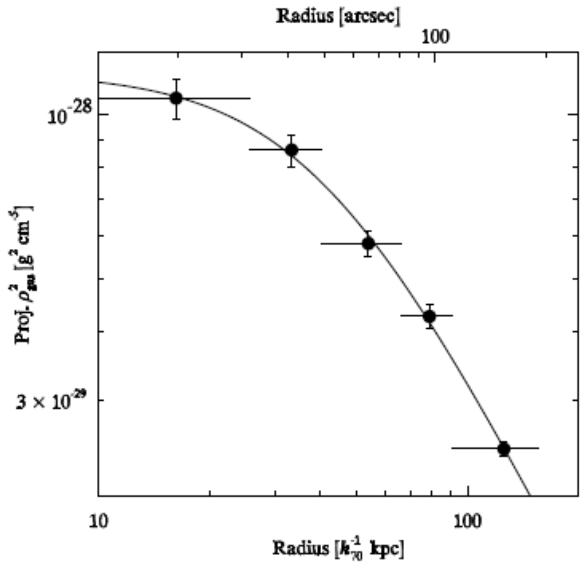
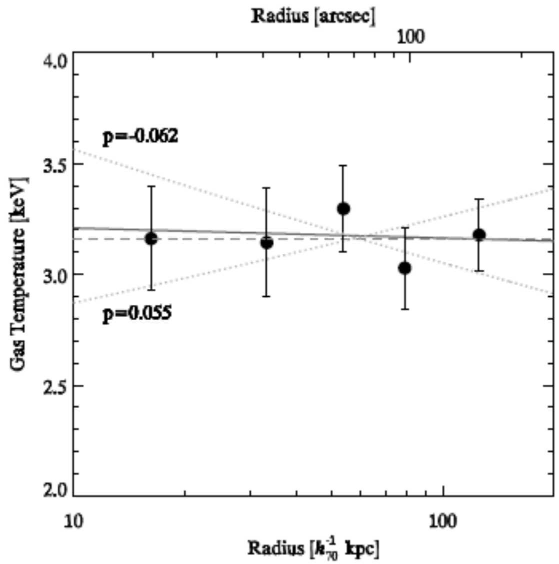






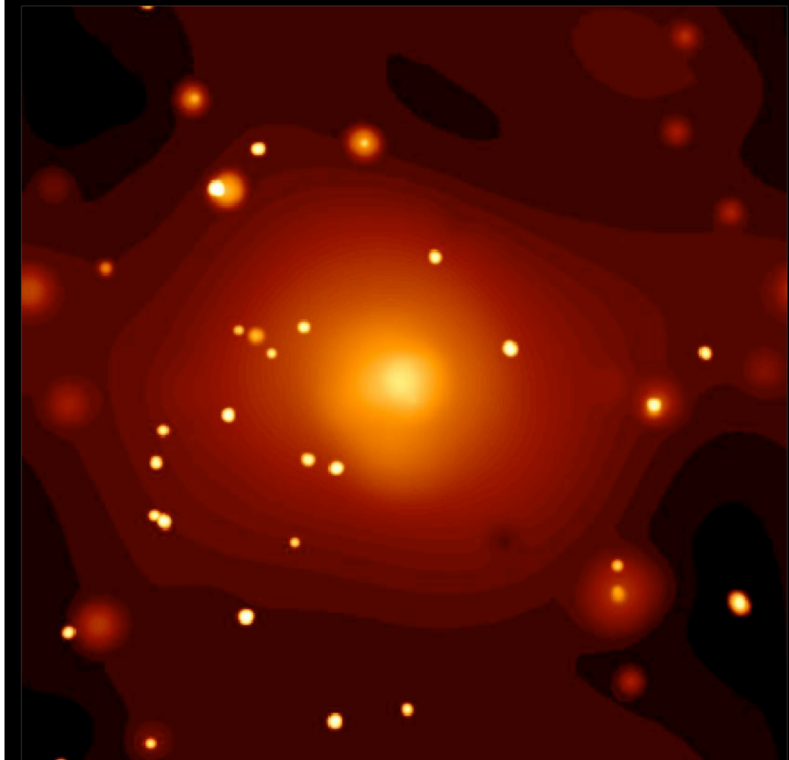
Error Budget for Dark Matter Fits

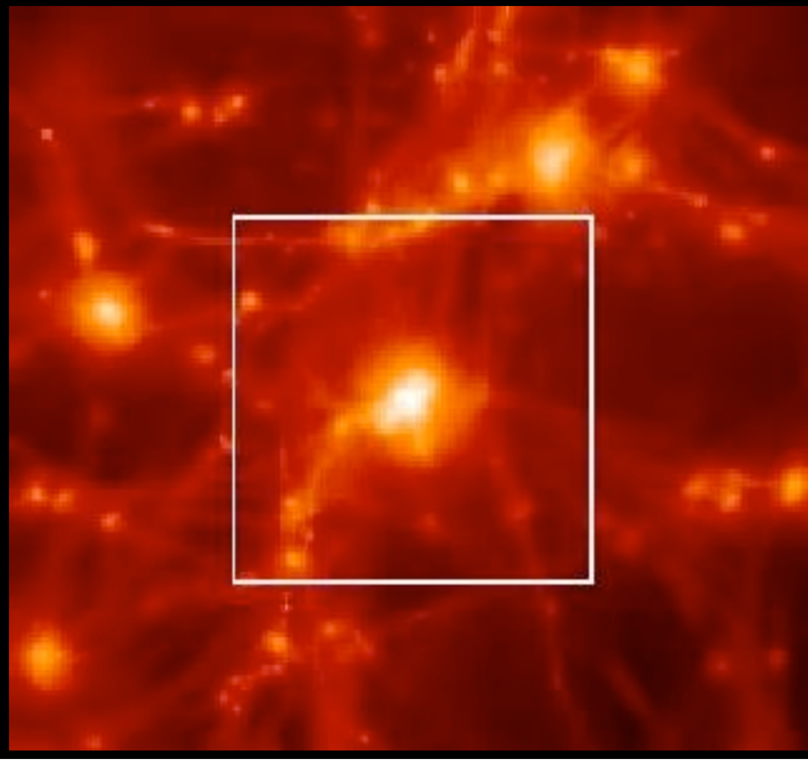
Parameter	Best Fit	$\Delta_{\rm Statistical}$	$\Delta_{\rm Background}$	$\Delta_{M_{\rm stars}}$	$\Delta_{\rm Deproj}$
Power-law model:					
γ	1.65	± 0.21	(+0.17, −0.16)	(+0.06, −0.00)	+0.35
NFW model:					
c	4.9	± 2.4	(+1.9, −1.7)	(+1.2, −0.6)	−3.8
$r_{\rm vir}$ (Mpc)	1.0	± 0.5	(+0.3, −0.2)	(+0.06, −0.05)	+1.9

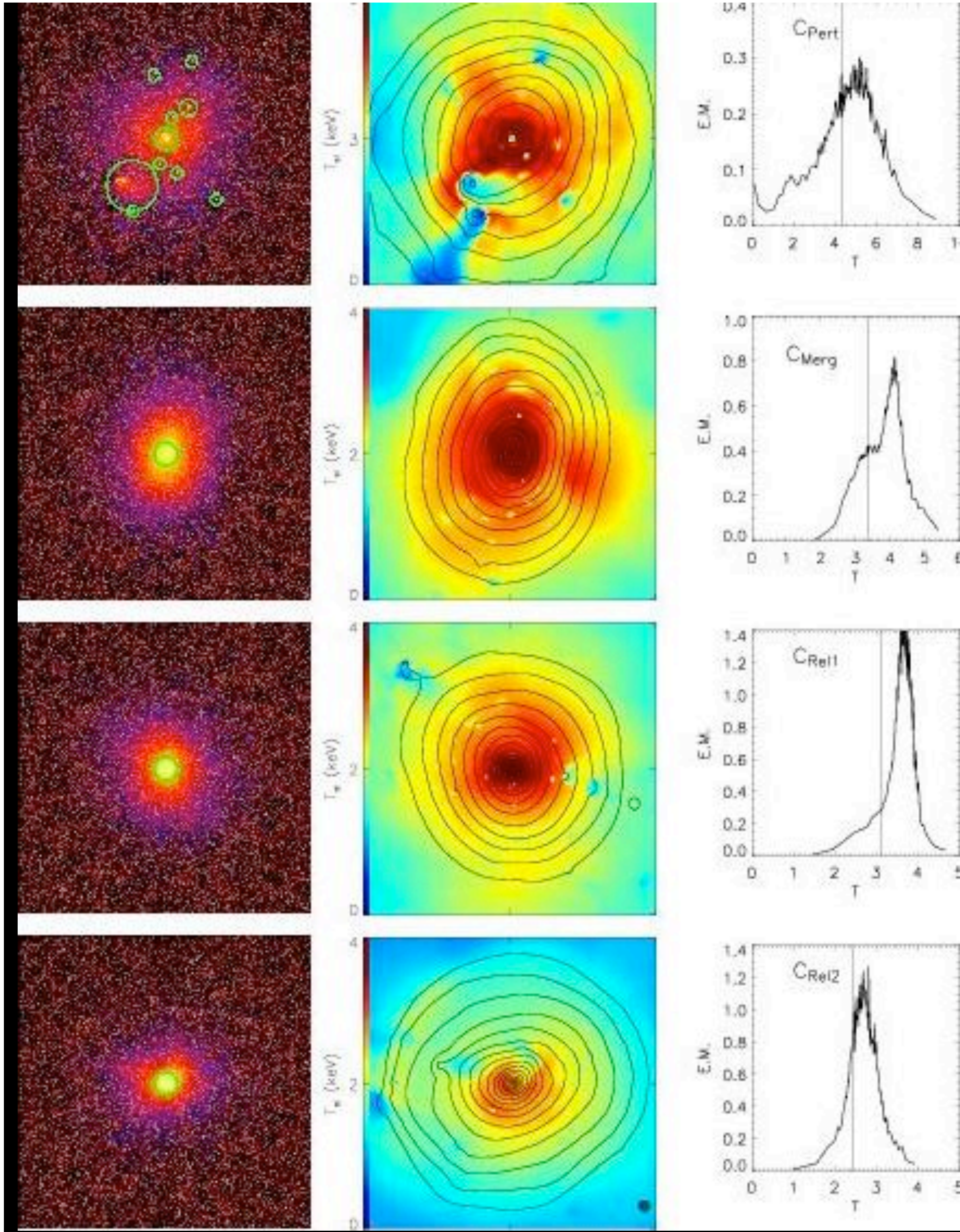
Notes.—The "Best Fit" column indicates the best-fit value and $\Delta_{\rm Statistical}$ the 1 σ statistical error from Table 3. The quantity $\Delta_{\rm Background}$ gives the results when the X-ray background level is set to ±20% of nominal. $\Delta M_{\rm stars}$ represents the uncertainty associated with the stellar mass-to-light ratio. The quantity $\Delta_{\rm Deproj}$ provides an estimate of the error associated with the deprojection procedure.

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. in prep*





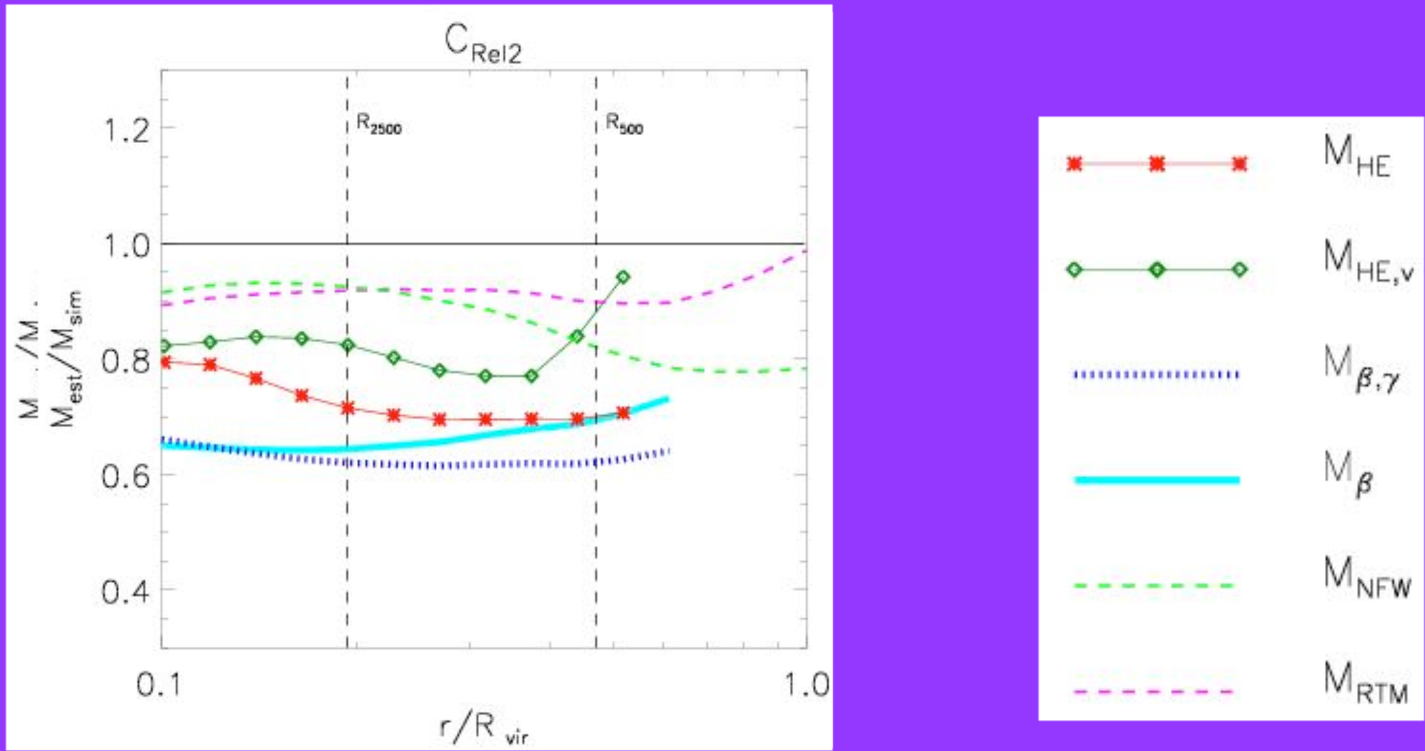


Rasia, SE et al. 06:

5 clusters in different dynamical state (T_{gas}~3.9, 3.6, 3.3, 2.7 keV) have been extracted from the simulation and processed with X-MAS to obtain moch Chandra ACIS-S3 1 Ms observations

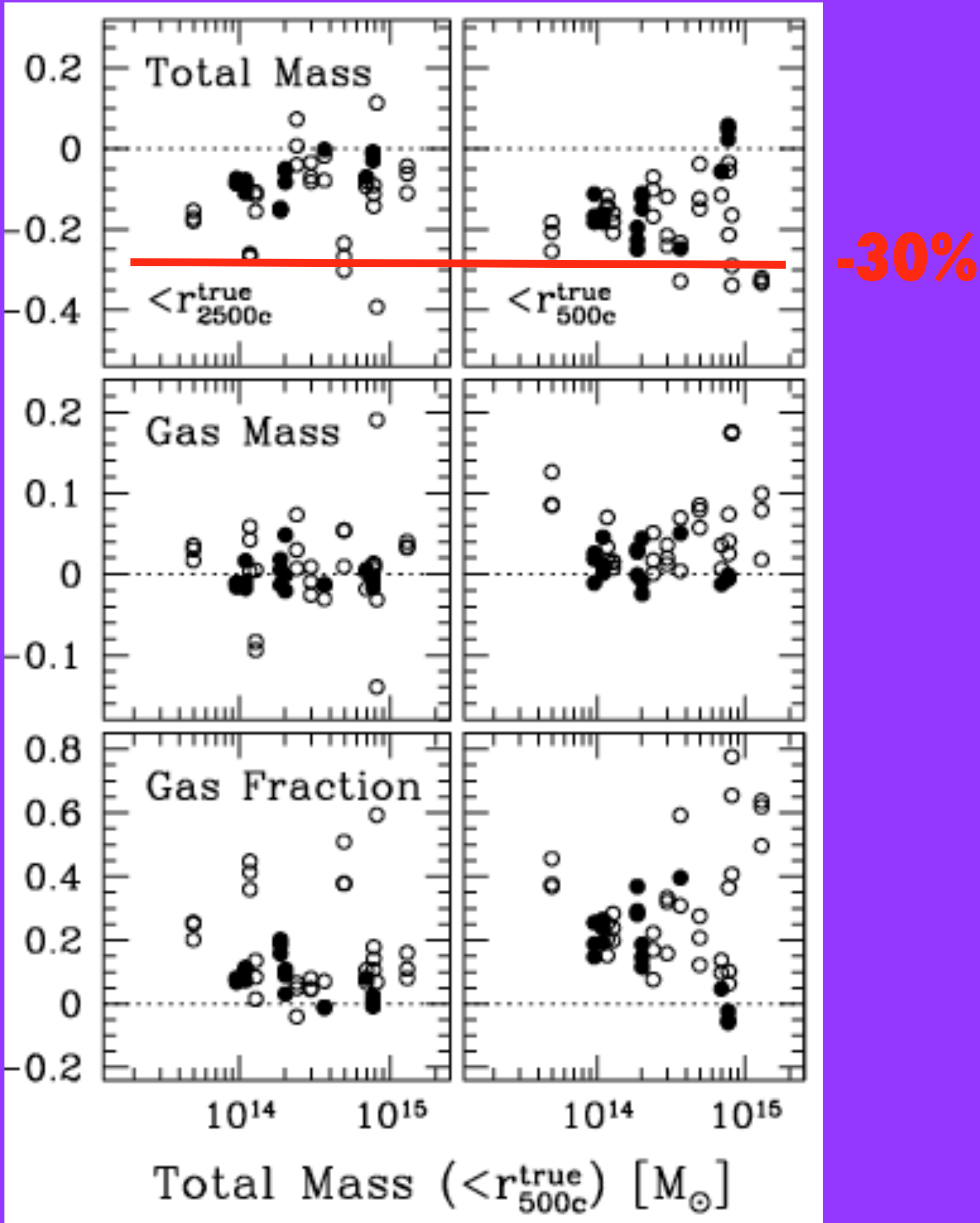
X-ray total mass: results

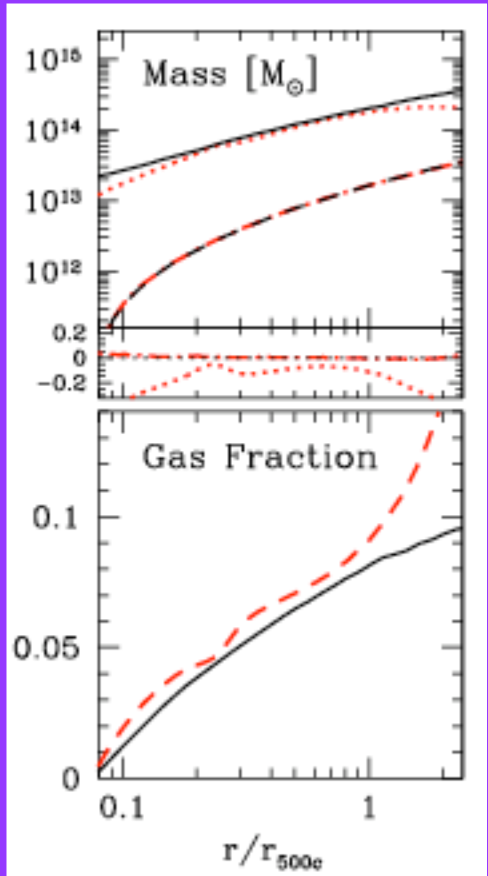
X-ray M_{est} underestimates M_{true} by 10-45 %



Ratios btw estimated and true mass profile of the simulated cluster

X-ray total mass: results





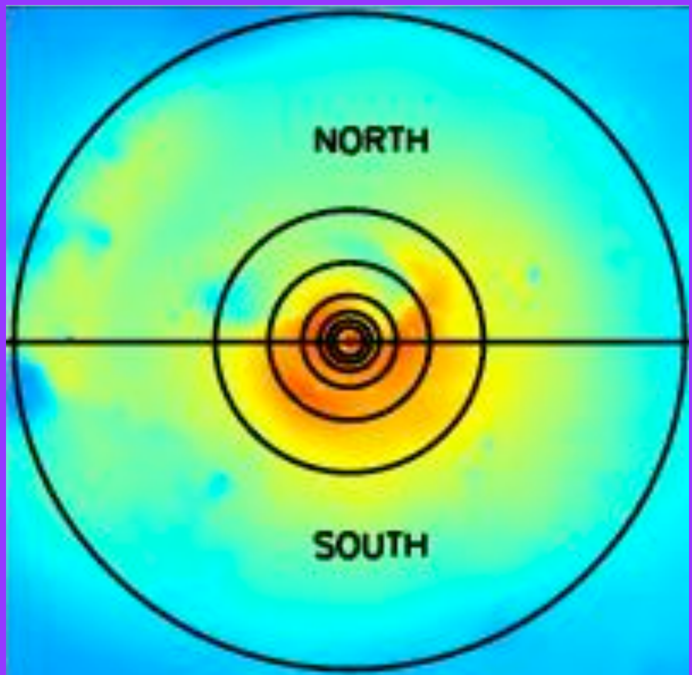
Nagai et al. 07

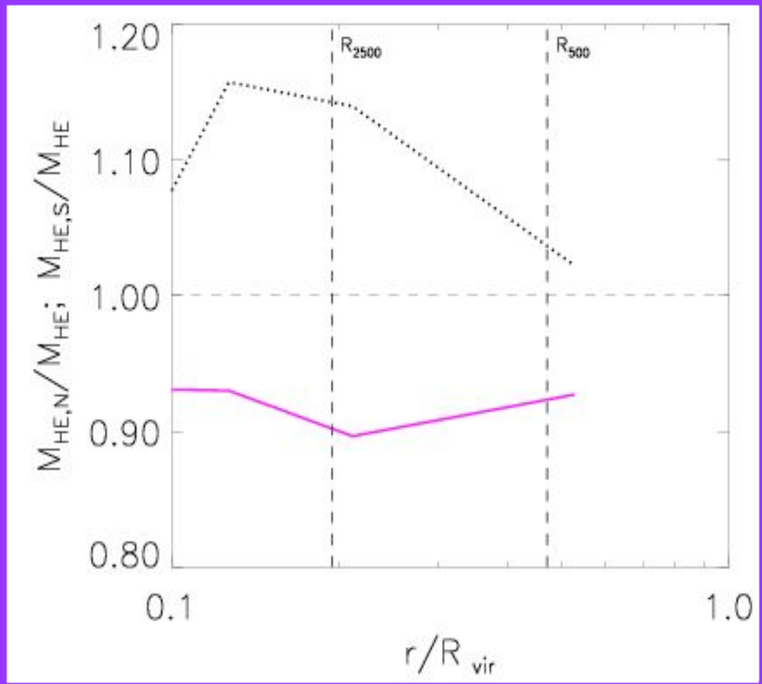
X-ray total mass: results

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 %

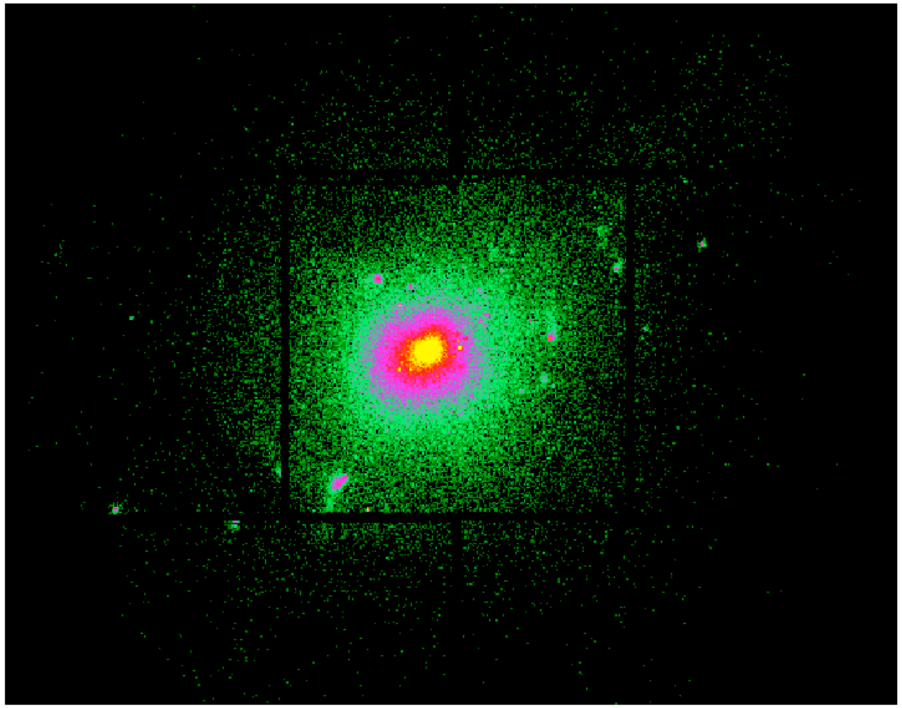
➔ poor contraints on n_{gas} from β-model;
due to the limited radial interval over which the fit is done, β / c_{NFW} are always lower / higher than the values measured from fit of ρ_{gas} up to R_{200}

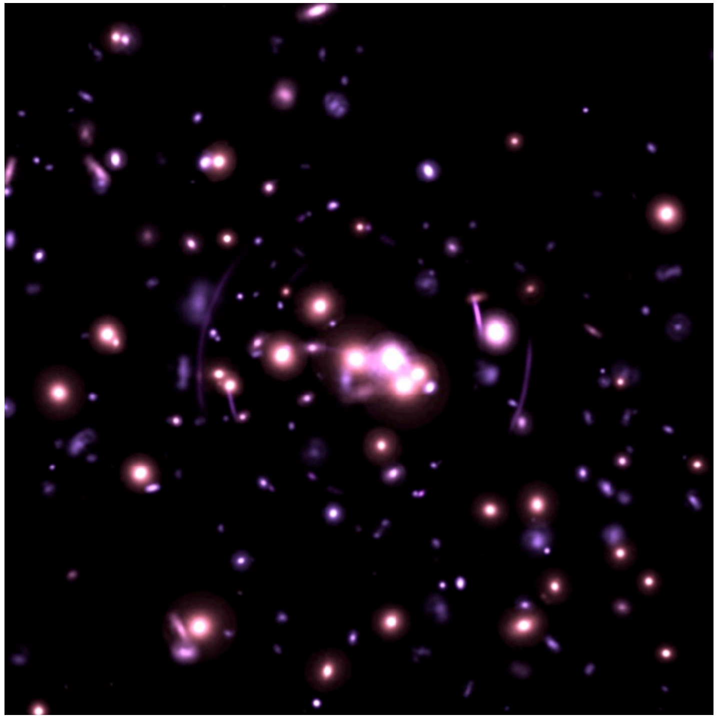
X-ray vs lensing mass: *simulations*

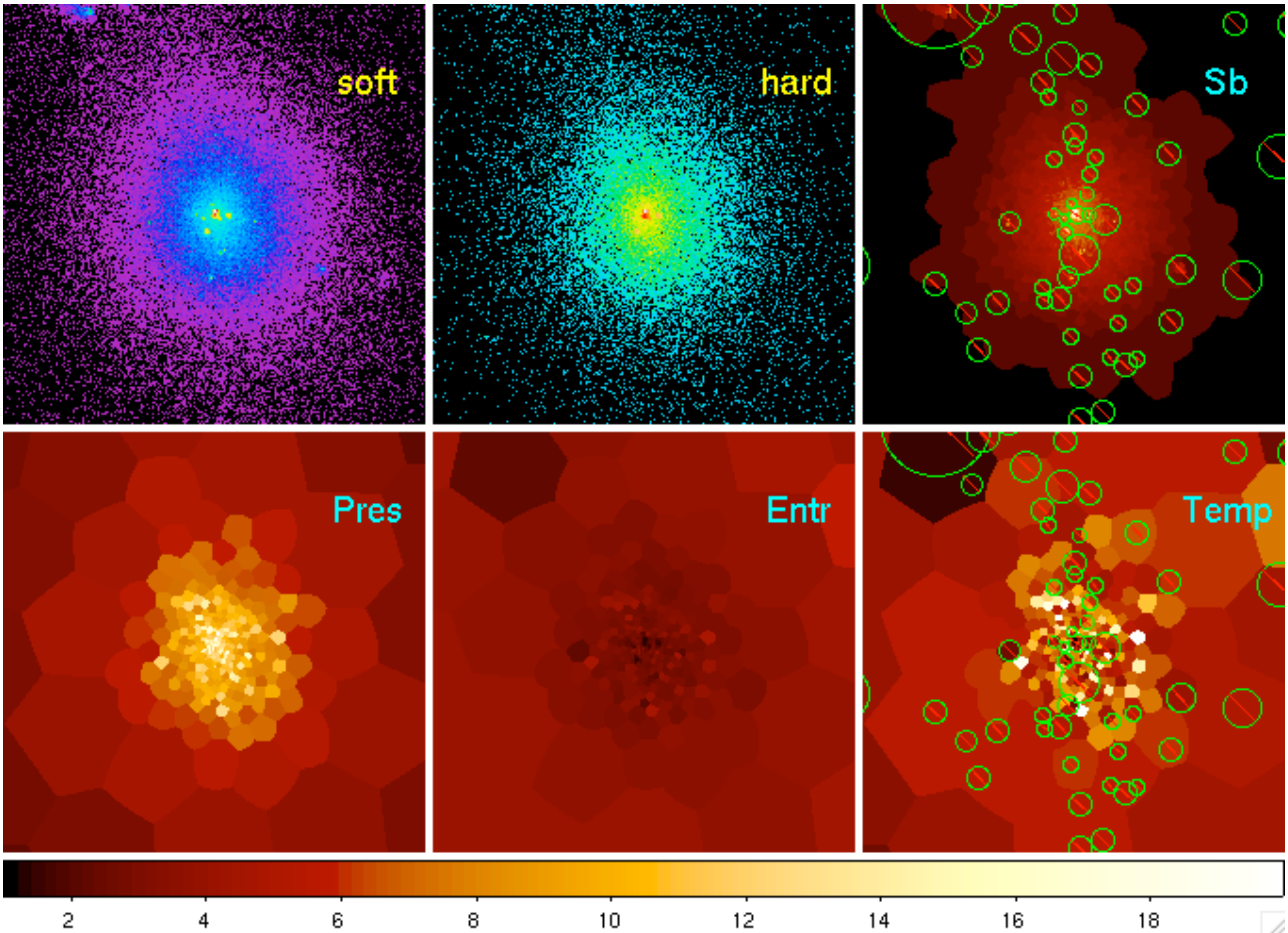
M_X / X-MAS vs $M_{lensing}$ / ray tracing

both from hydrodynamical simulated clusters

(work in progress with E. Rasia & M. Meneghetti)






soft
hard
Sb
Pres
Entr
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2
4
6
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10
12
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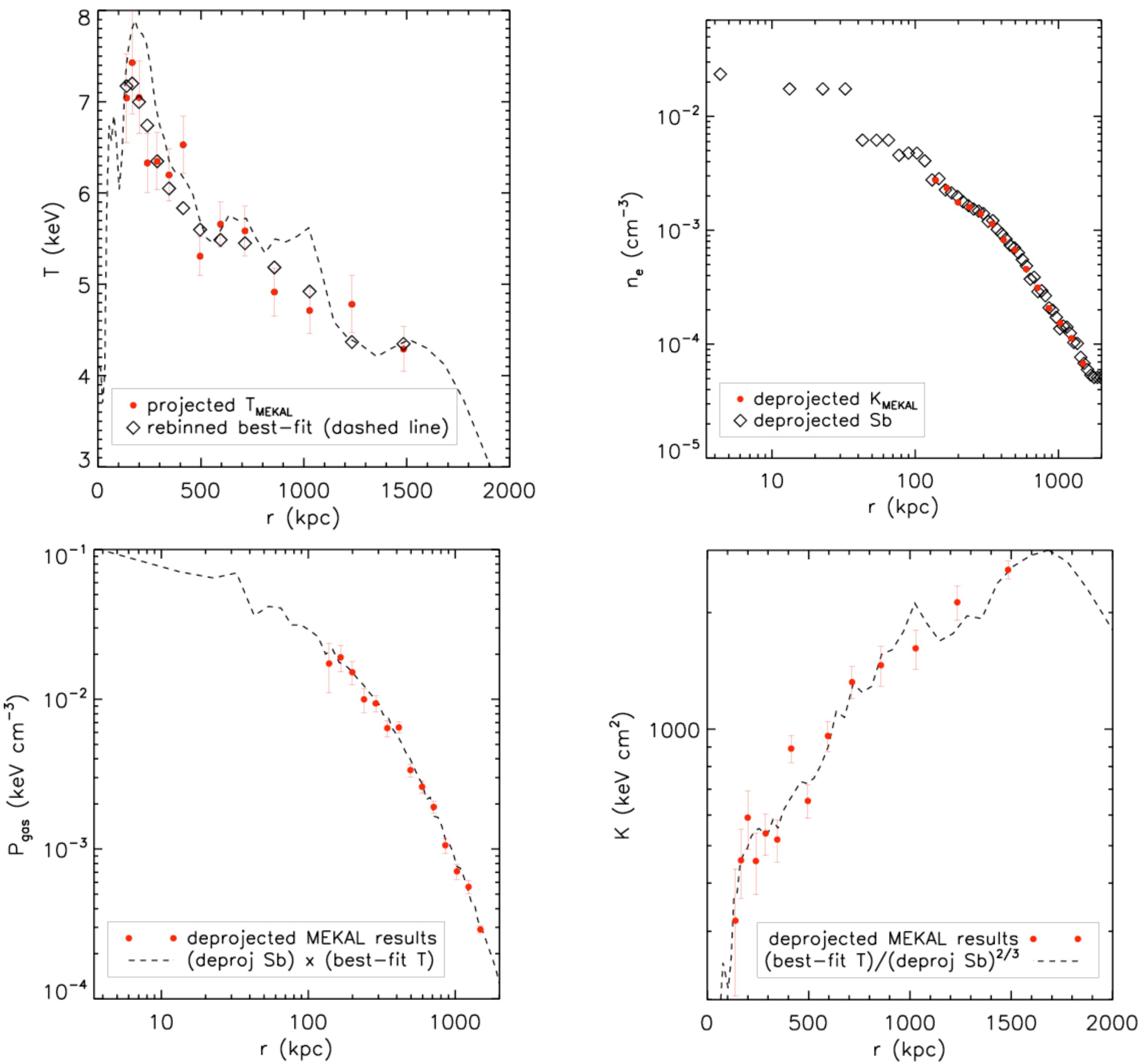
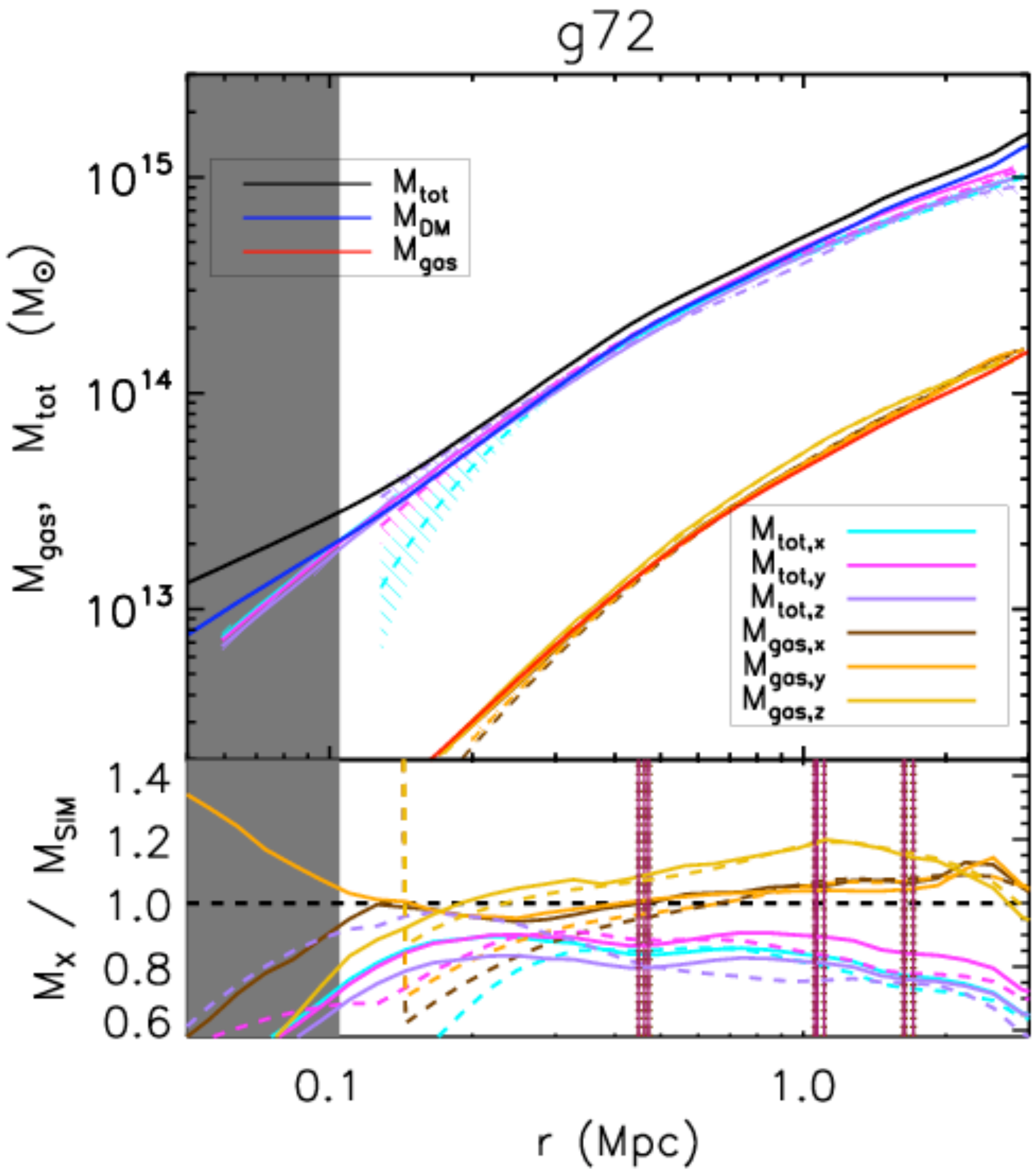
16
18



T (keV)
r (kpc)
projected T_{MEKAL}
rebinned best−fit (dashed line)
n_e (cm^{-3})
r (kpc)
deprojected K_{MEKAL}
deprojected Sb
P_{gas} (keV cm^{-3})
r (kpc)
deprojected MEKAL results
(deproj Sb) x (best−fit T)
K (keV cm^2)
r (kpc)
deprojected MEKAL results
(best−fit T)/(deproj Sb)$^{2/3}$

X-ray total & gas mass: *projection*

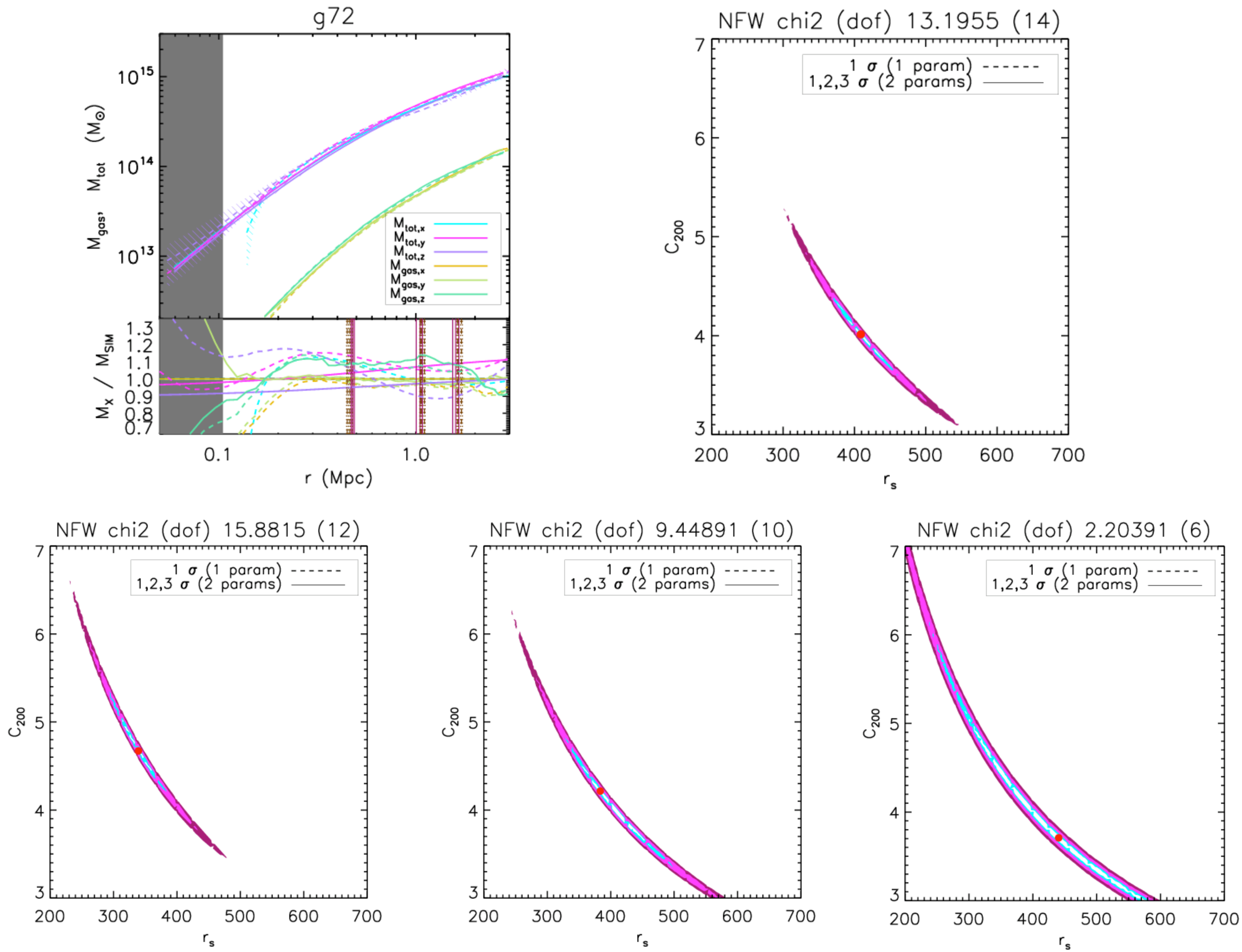


NOTE:

1. whatever the projection/method is M_{gas} is recovered within few (~5) %

2. **forward/backward** methods (solid/dashed lines) are consistent within 10-15%

3. Errors on M_{tot} too optimistic ?



g72
M_{gas}, M_{tot} ($M_\odot$)
M_X / M_{SIM}
r (Mpc)
$M_{tot,x}$
$M_{tot,y}$
$M_{tot,z}$
$M_{gas,x}$
$M_{gas,y}$
$M_{gas,z}$
NFW chi2 (dof) 13.1955 (14)
NFW chi2 (dof) 15.8815 (12)
NFW chi2 (dof) 9.44891 (10)
NFW chi2 (dof) 2.20391 (6)
1 σ (1 param)
1,2,3 σ (2 params)
C_{200}
r_s

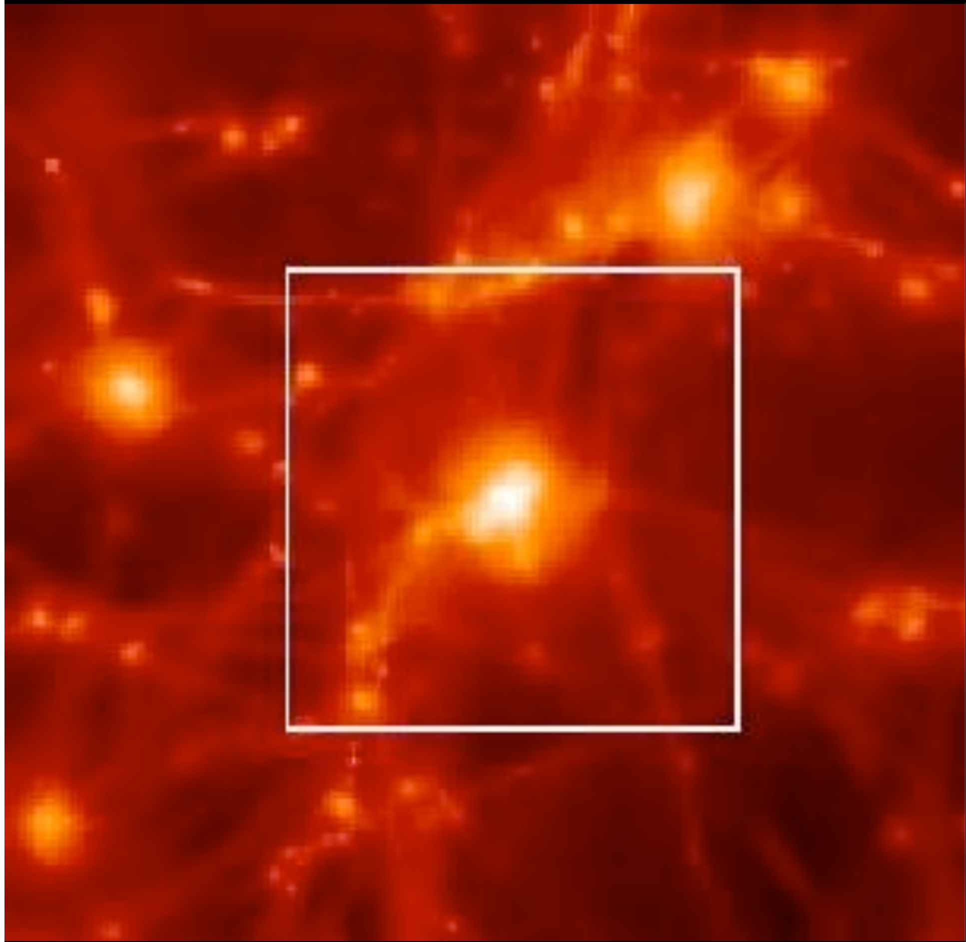
Conclusions on estimate of the X-ray M_{tot}

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

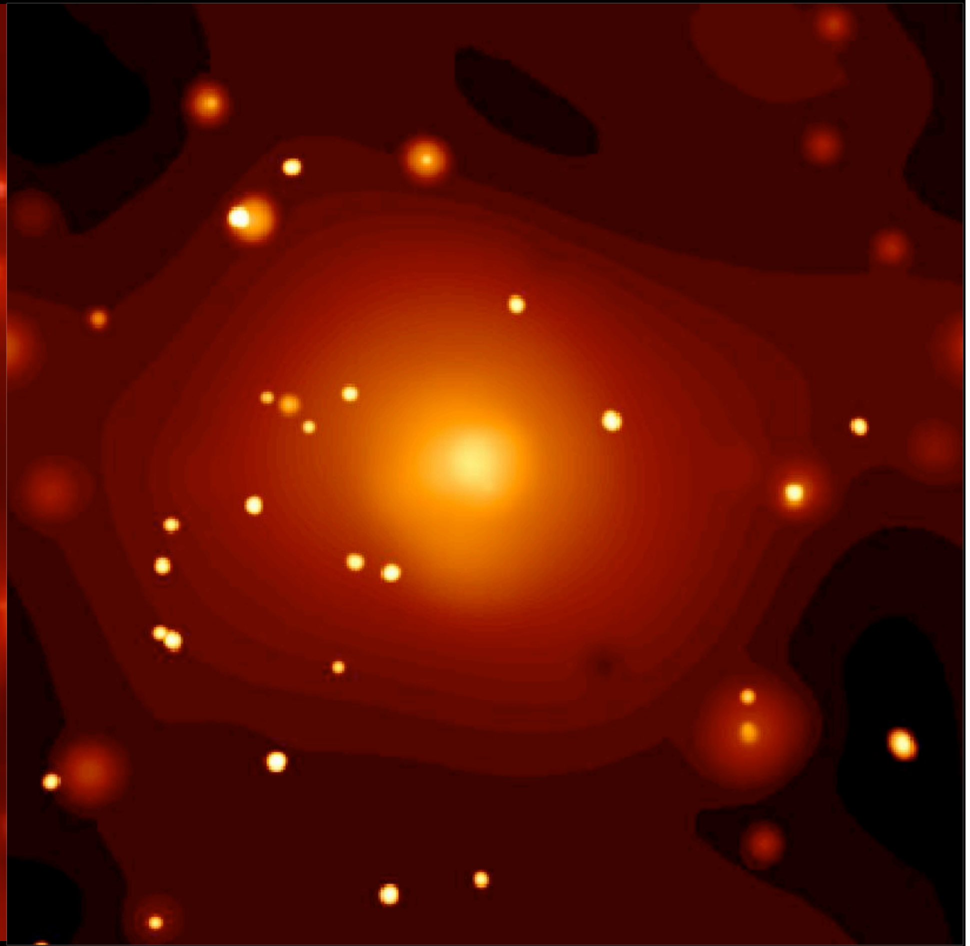
- At least two main ways (one ***forward***, one ***backward***) to apply HEE: pro/contra, no systematic is evident btw them, not thermalized ICM is missed

- Are errors on M_{tot} too optimistic ?

Baryons in simulated 6 keV @z=1
(© Norman et al)



Rxj1252 @z=1.23
(© Rosati et al.)



Simulators & Observers: towards an unique view of galaxy clusters