Weighing clusters: the X-ray view

Introduction and context

Gabriel W. Pratt

MPE

Measuring masses in X-rays

X-ray mass measurement

Assume spherical symmetry

Hydrostatic equation:

$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM(r)}{r^2}$$

Ideal gas:

$$P = nkT = \frac{\rho}{\mu m_p}kT$$

$$M(r) = -\frac{kT}{\mu m_p}\frac{r}{G}\left[\frac{d\ln\rho}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

X-ray mass measurement

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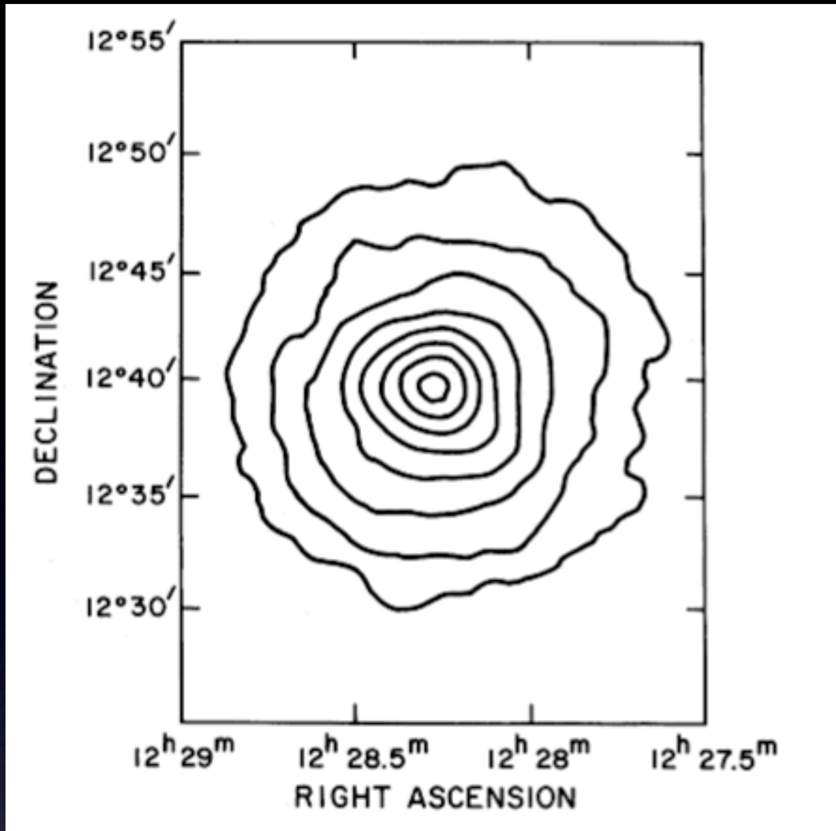
Isothermal

(historical, distant)



Historical

Fabricant et al. 1980
(M87 with *Einstein*, using T profile)

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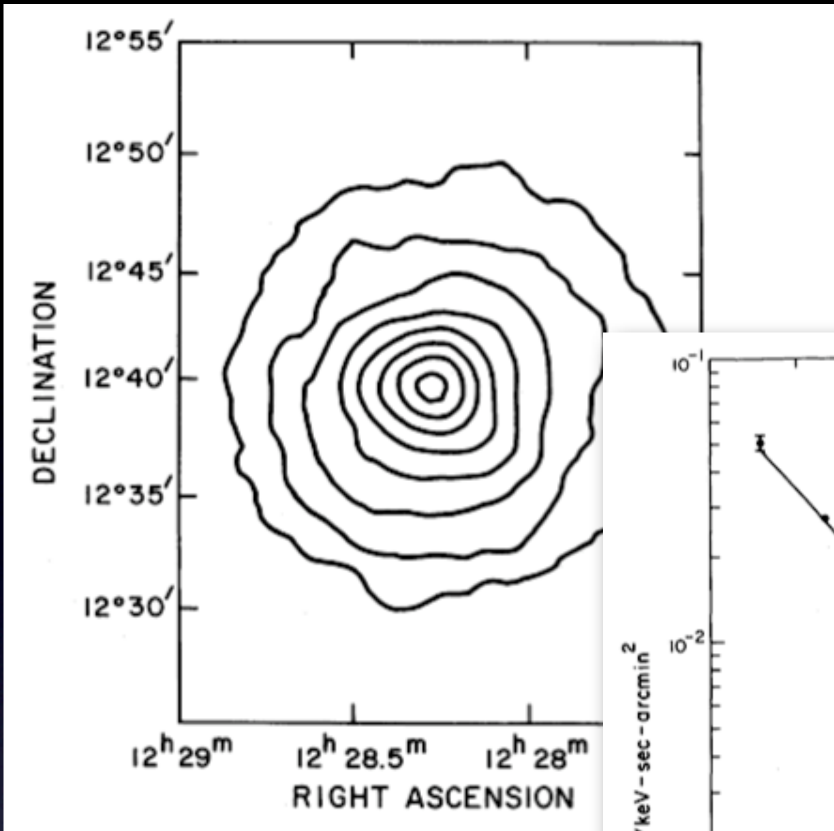

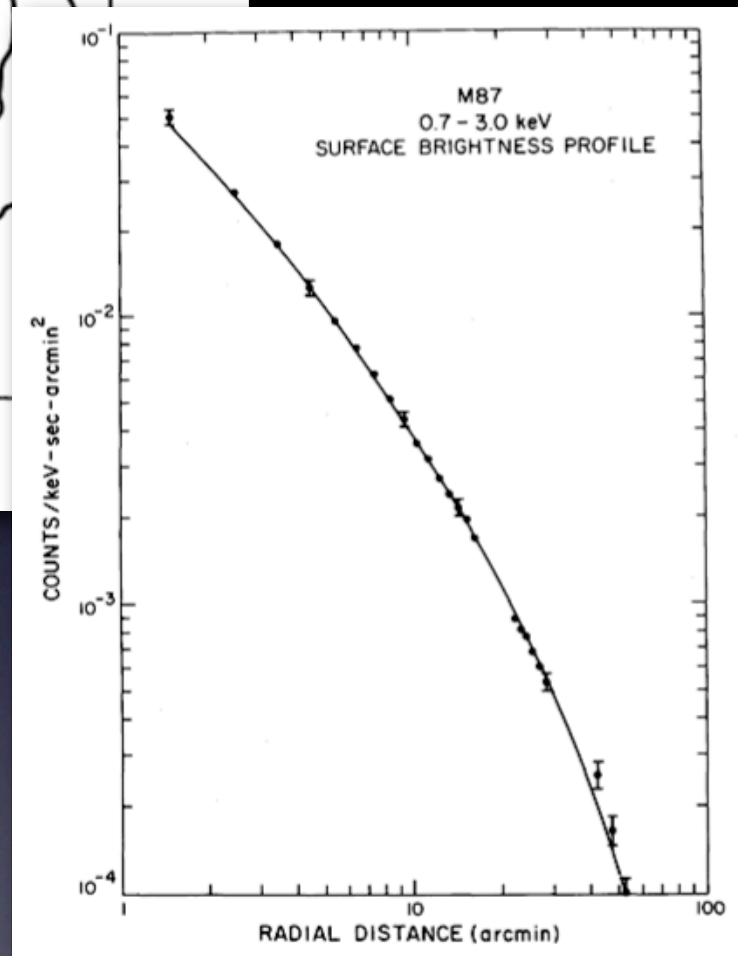

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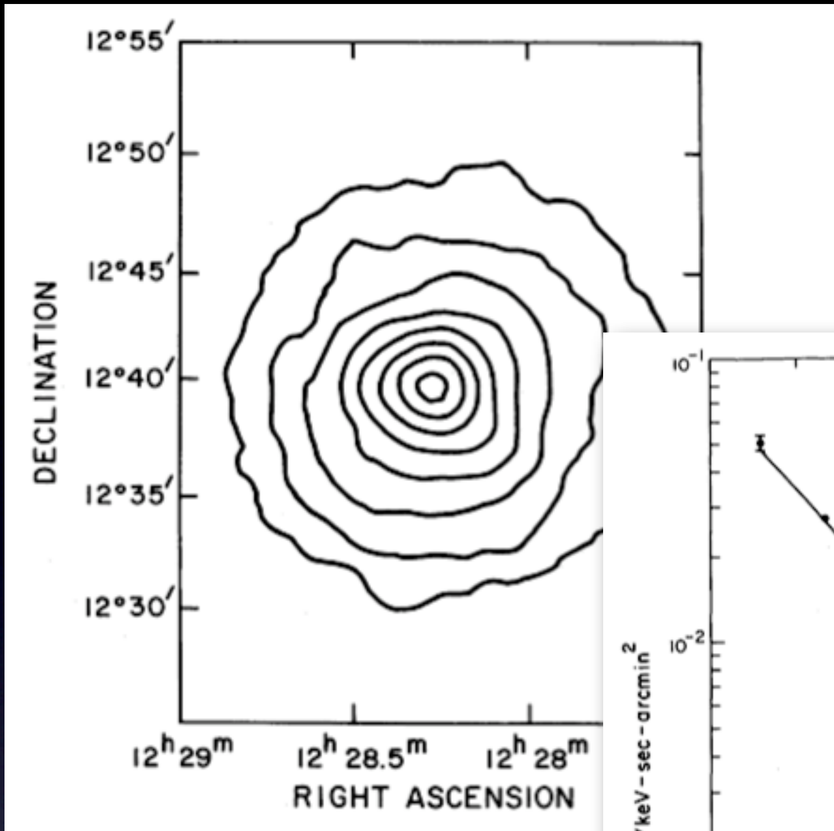
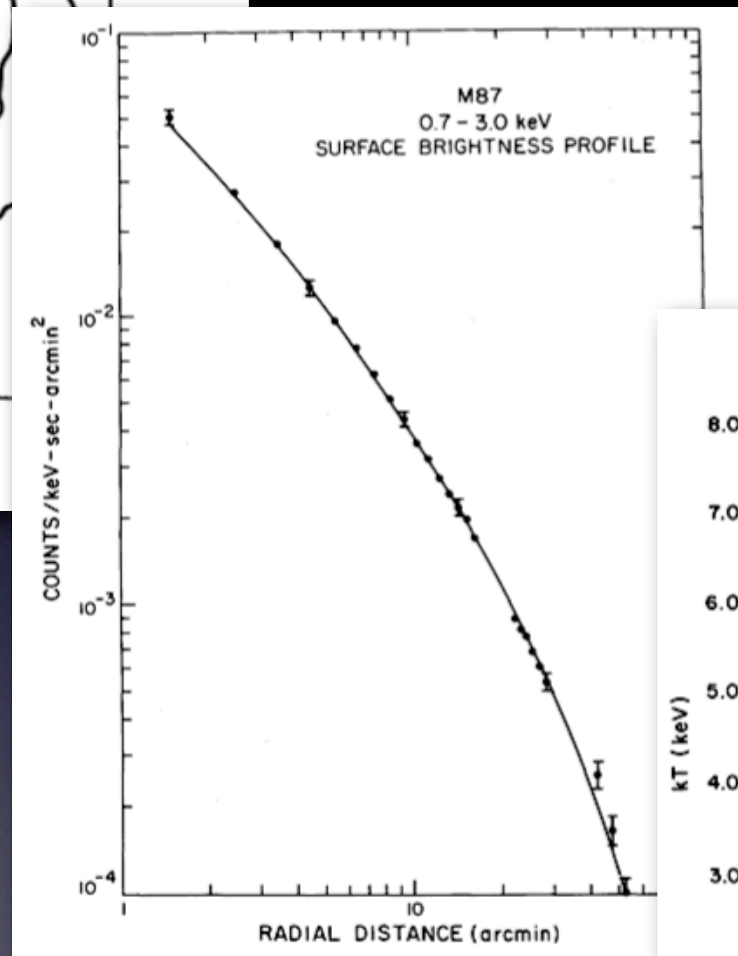
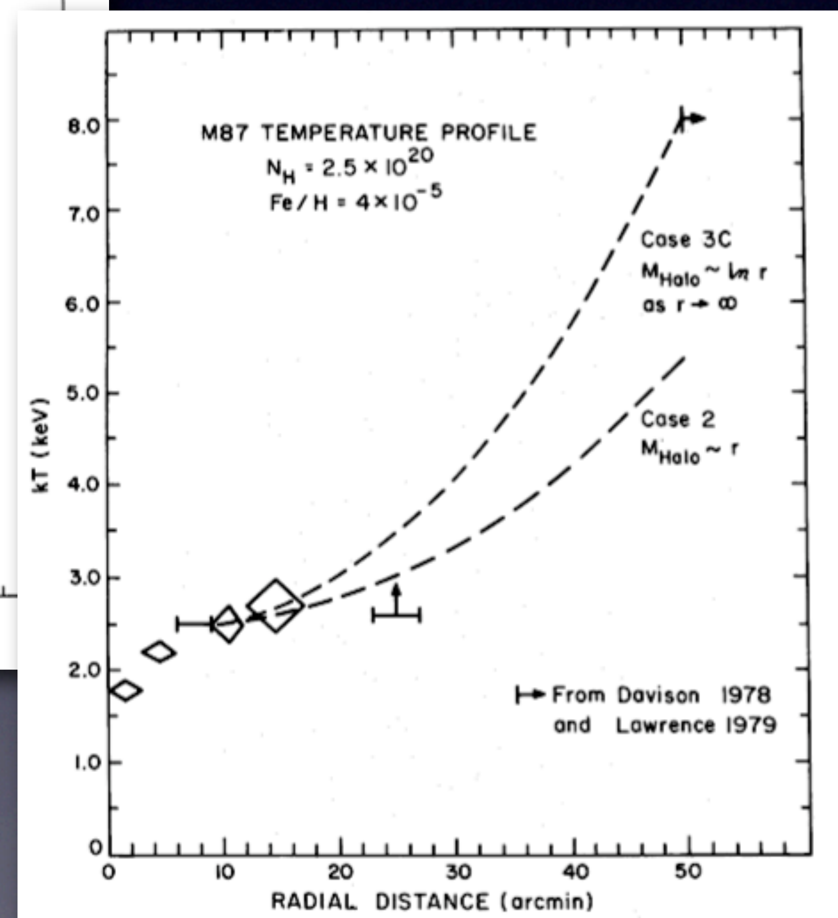
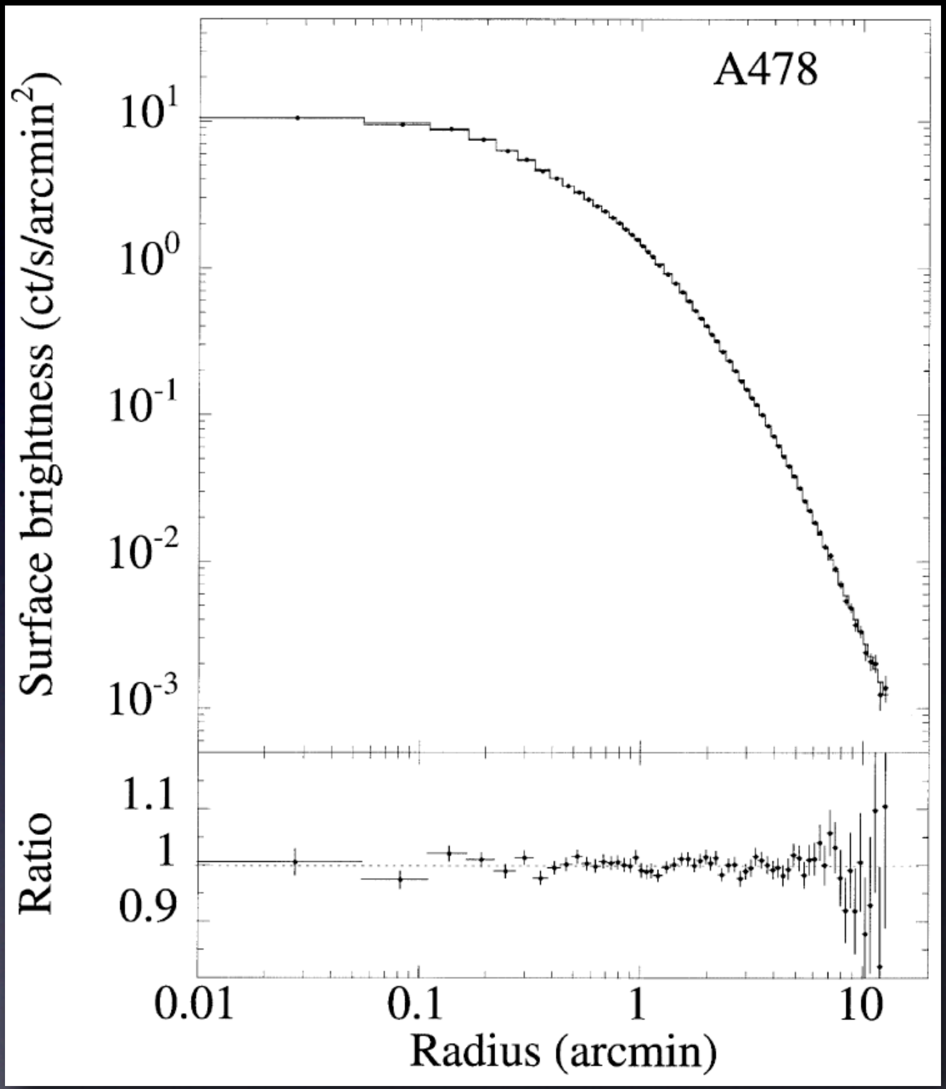
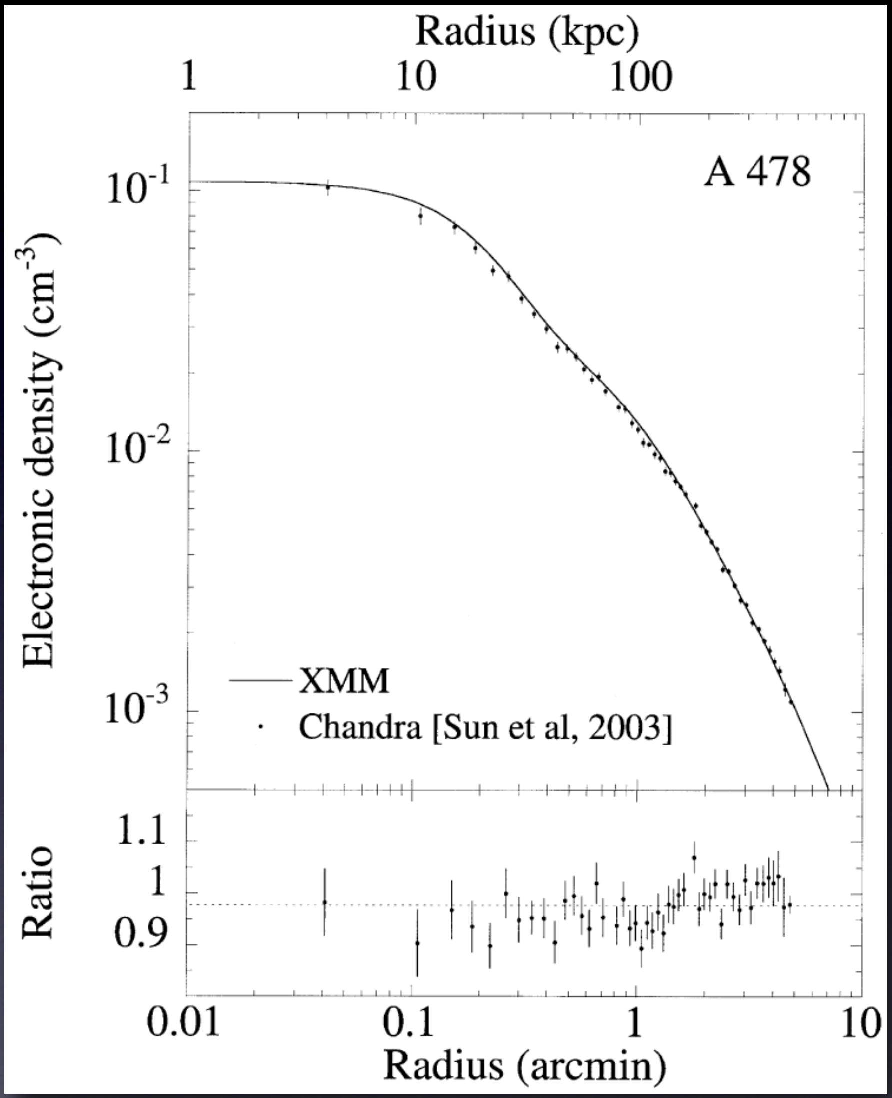






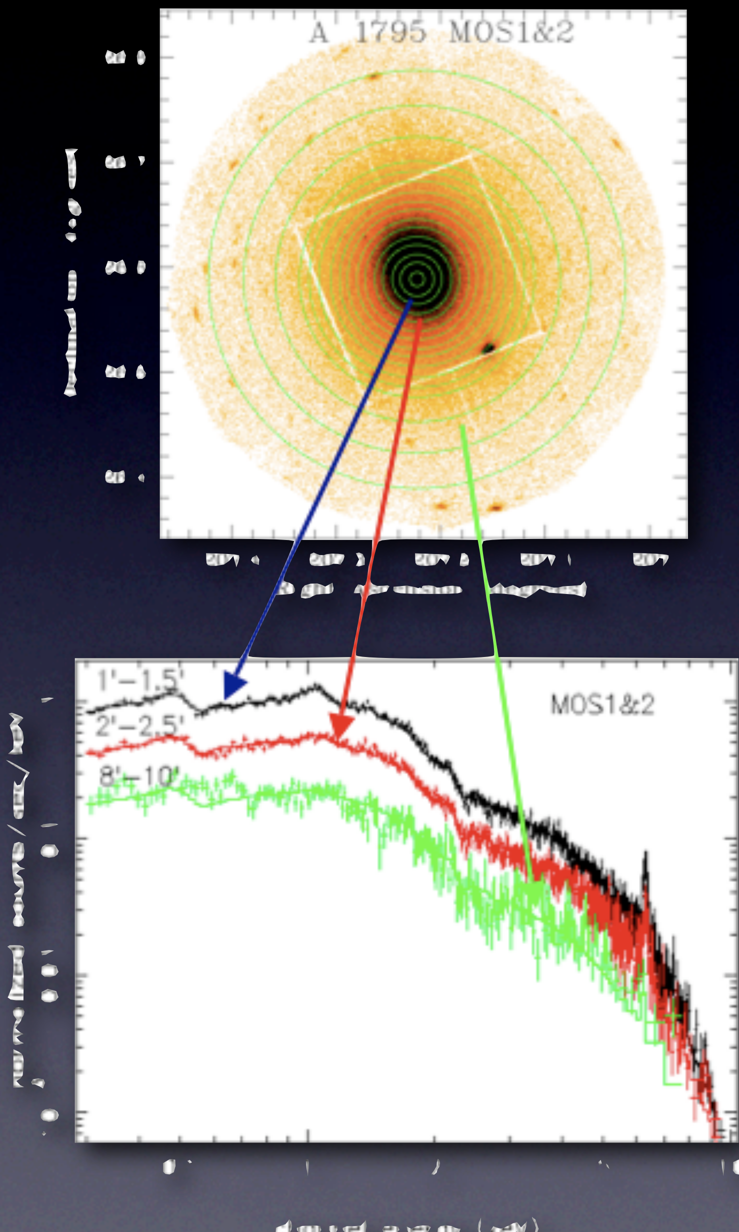
Density profile



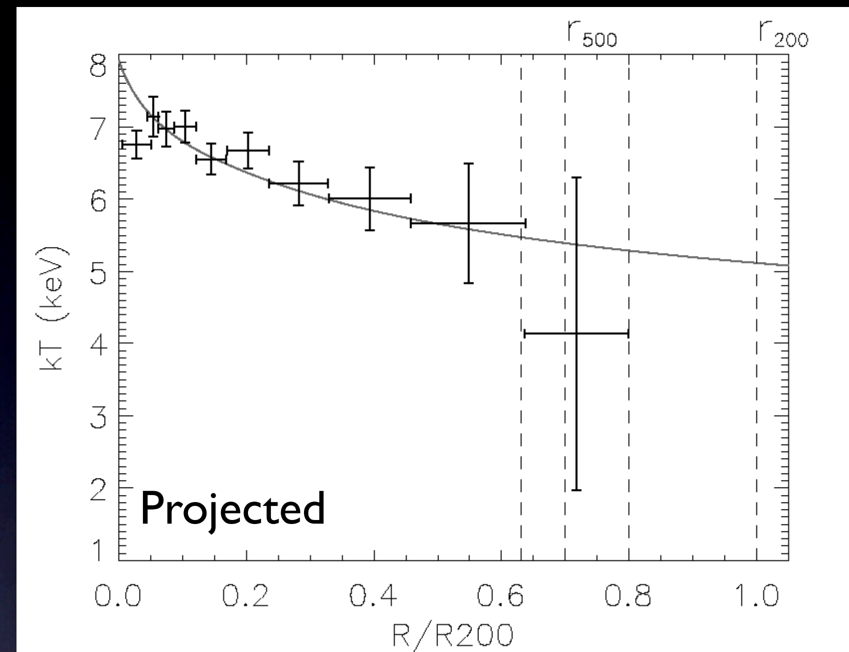


Pointecouteau et al. 2004 (Abell 478)

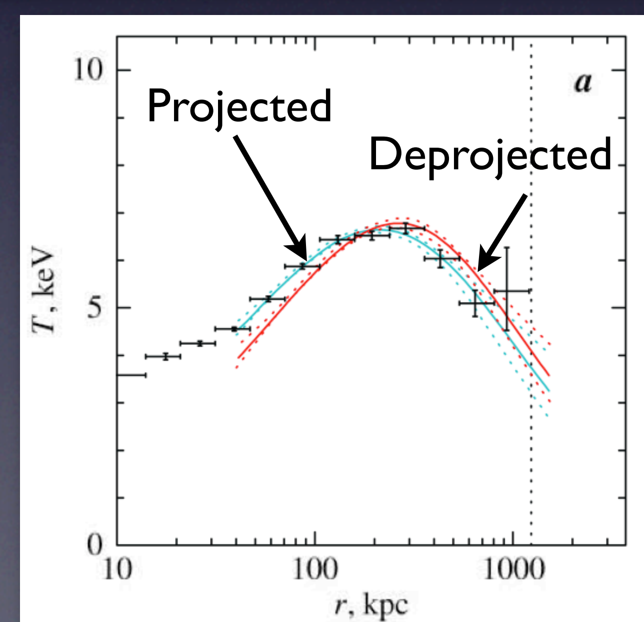
Temperature profile



Arnaud et al. 2001 (Abell 1795)

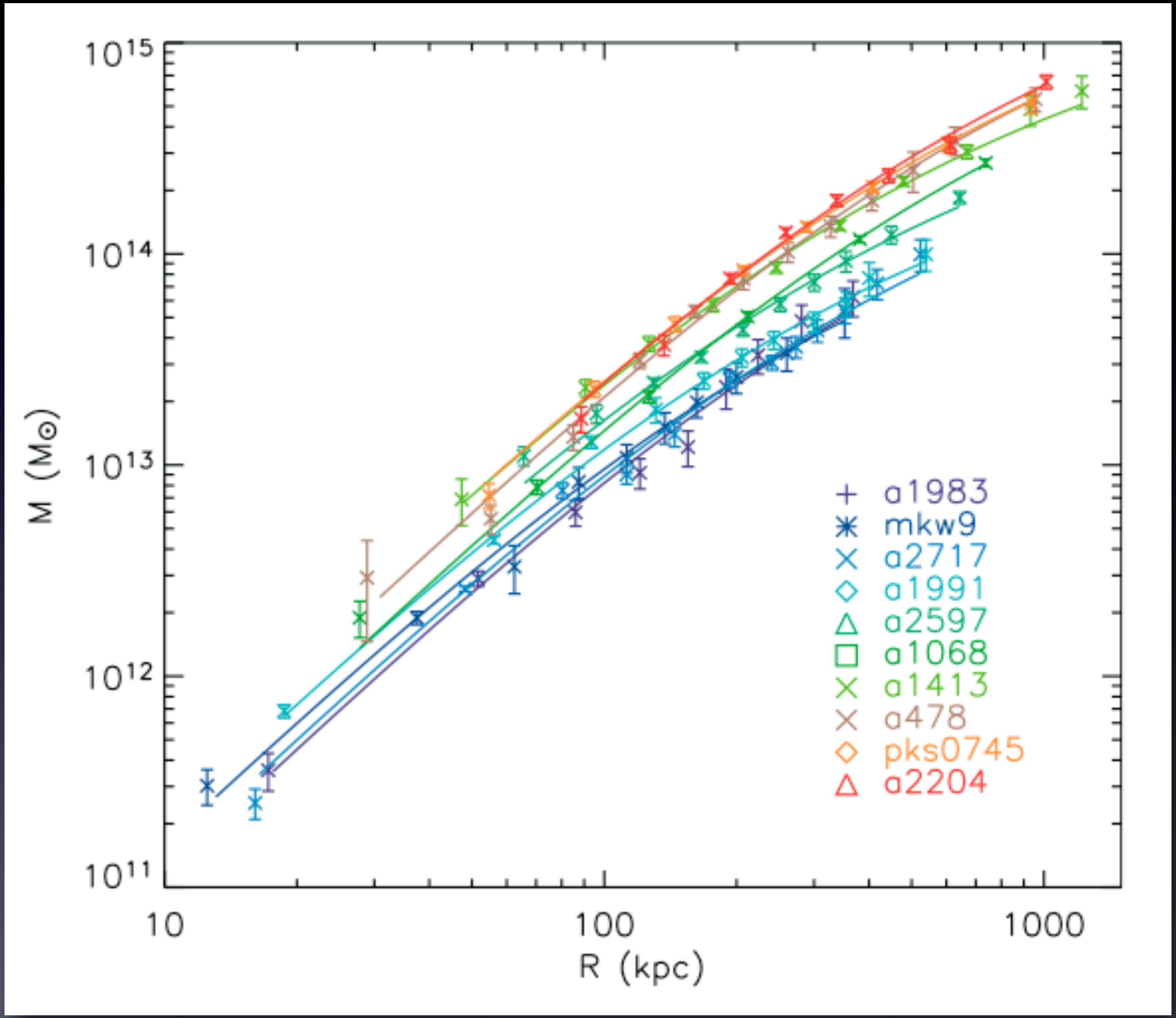


Pratt & Arnaud 2002 (Abell 1413)



Vikhlinin et al. 2006

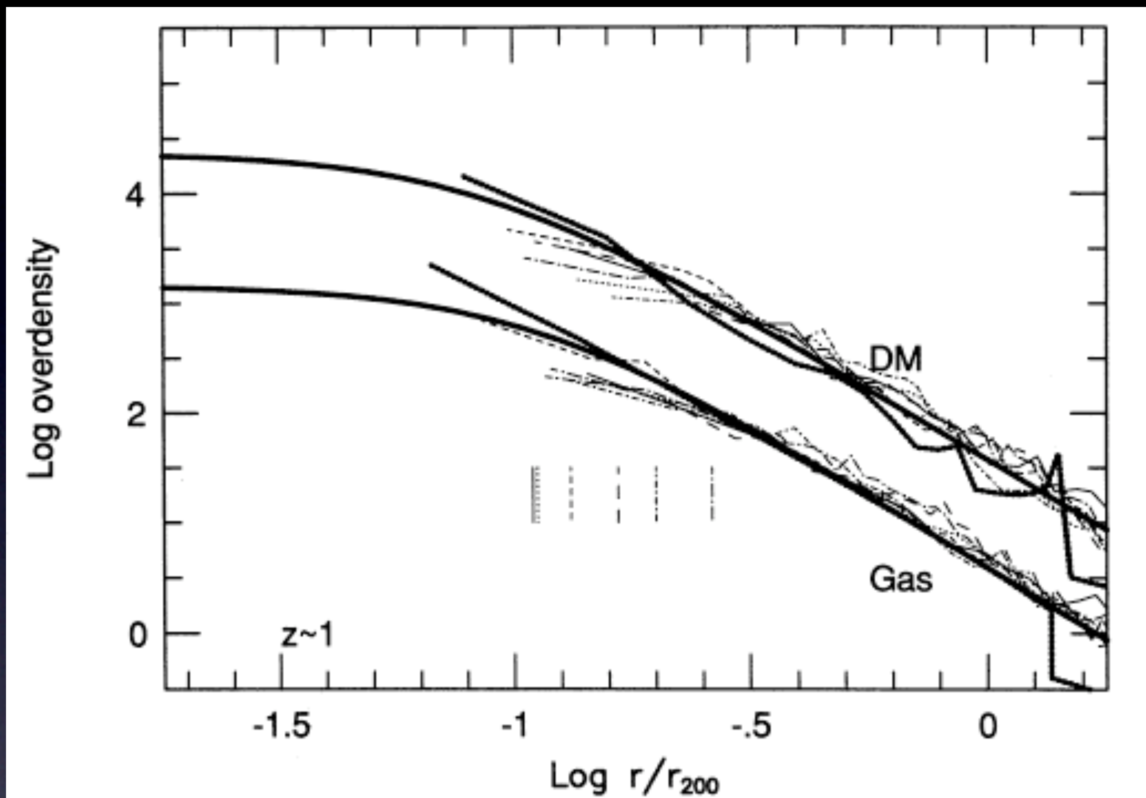
Mass profile



Pointecouteau et al. 2005

Mass profile modelling

Mass profile modelling



$$\rho_r = \frac{\rho_c(z)\delta_c}{(r/r_s)(1+r/r_s)^2}$$

$$r_\delta = c_\delta r_s$$

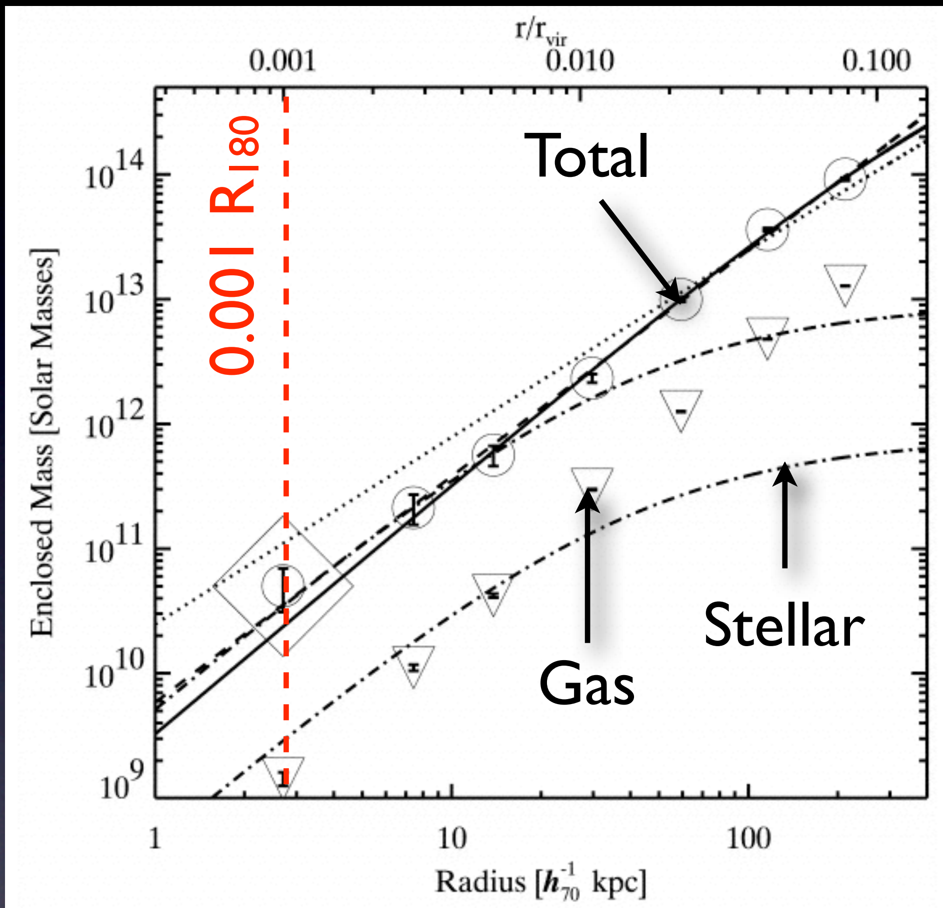
Navarro et al. 1997

$$M(r) = 4\pi\rho_c(z)\delta_c r_s^3 m(r/r_s)$$

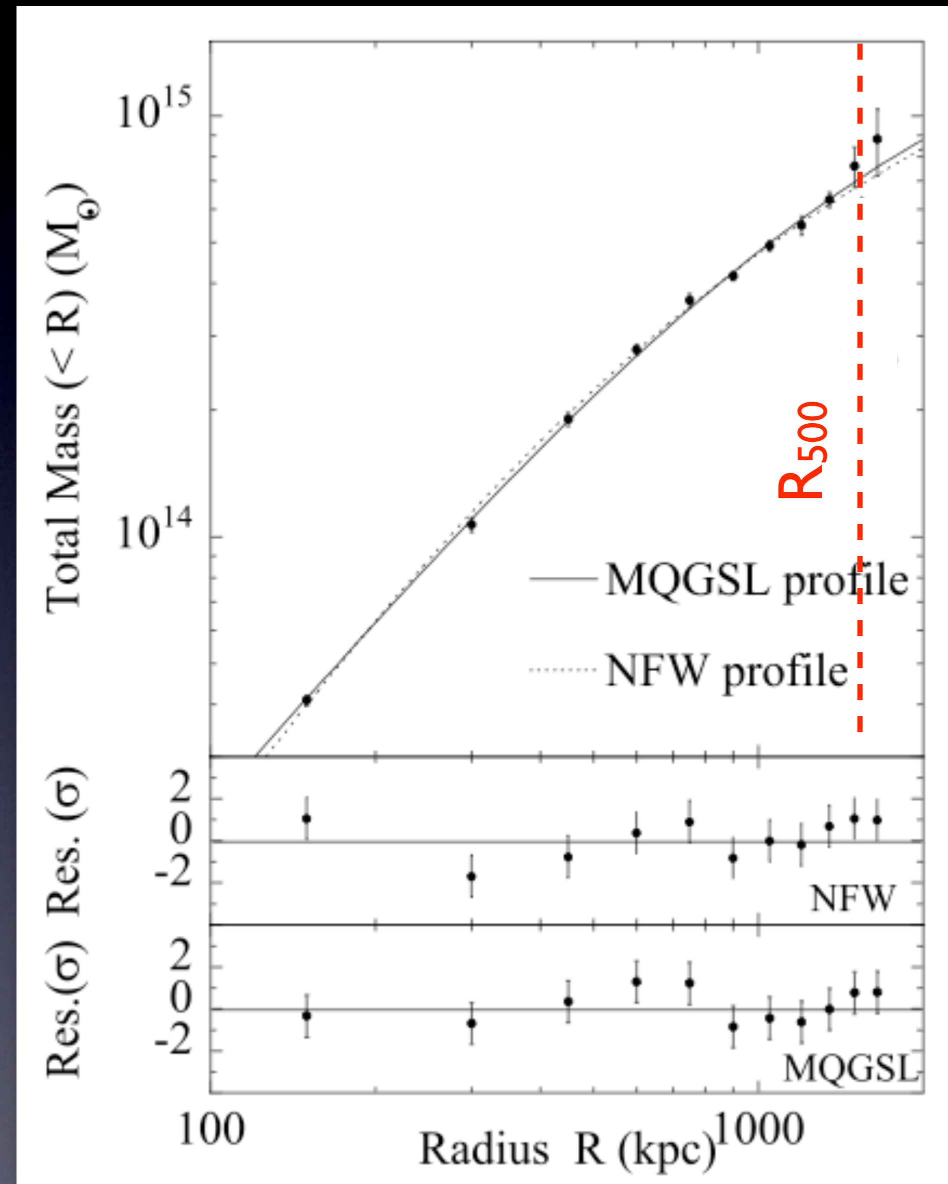
$$m(x) = \ln(1+x) - x/(1+x)$$

Suto et al. 1998

Mass profile modelling



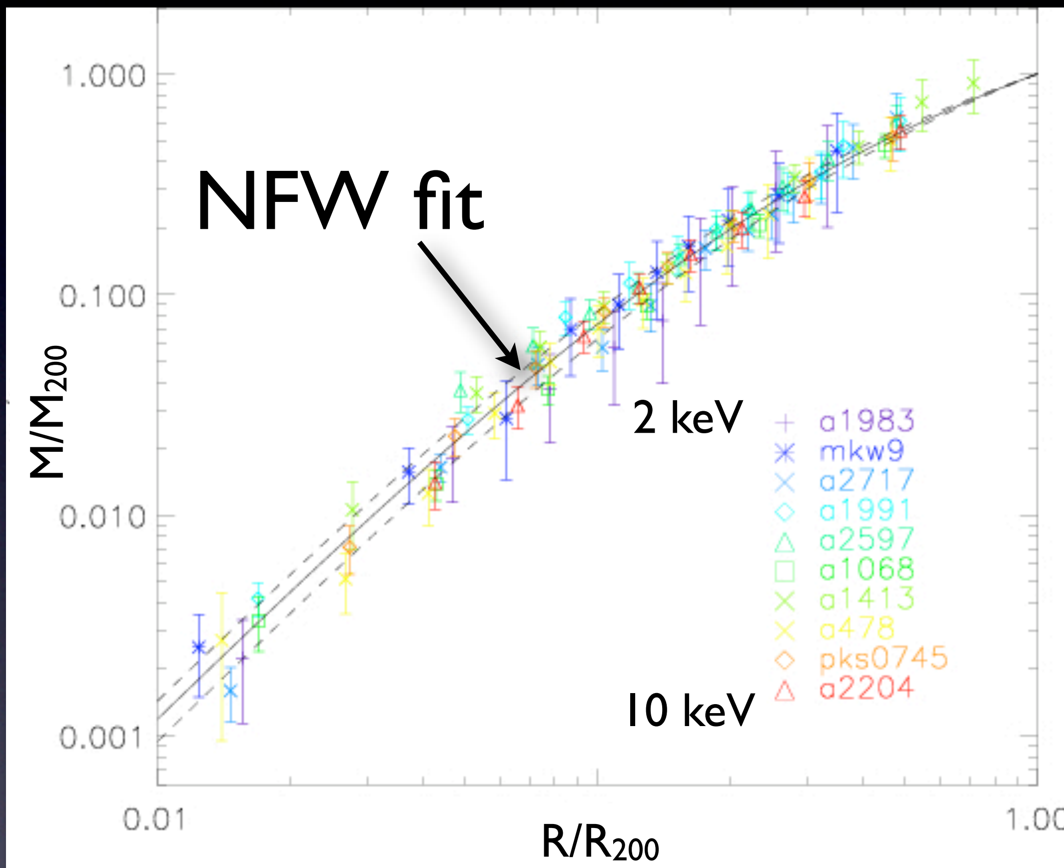
Lewis & Buote 2003 (Abell 2029)



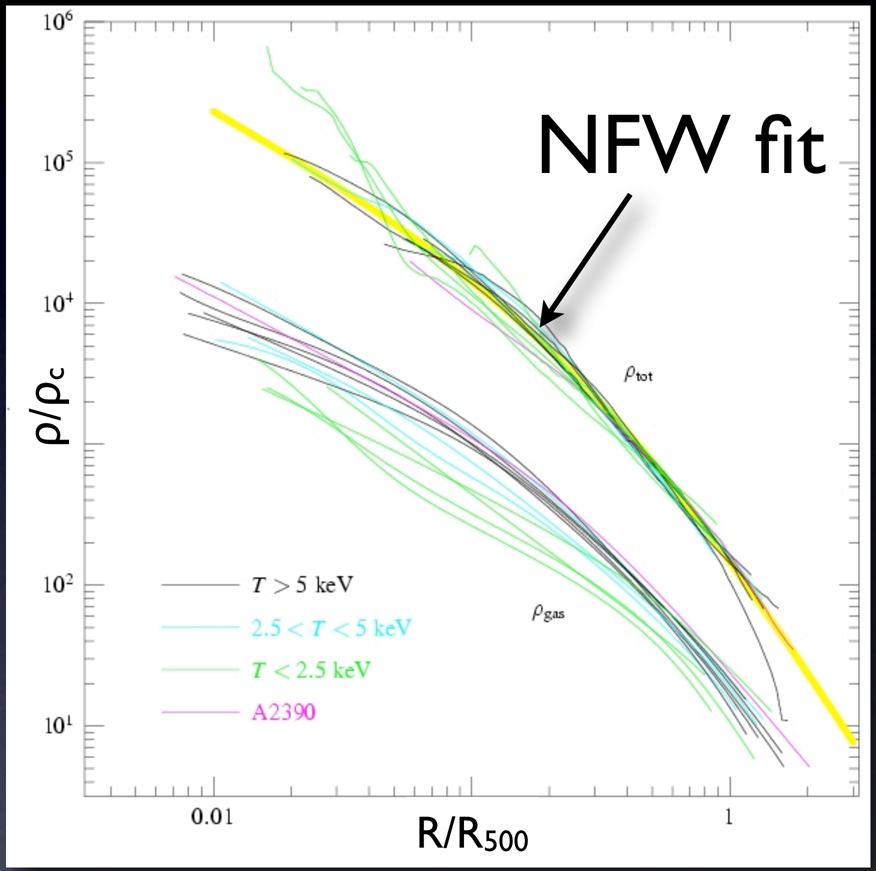
Pratt & Arnaud 2002 (Abell 1413)

Scaled total mass/density profiles

Regular systems, assume spherical symmetry, HE



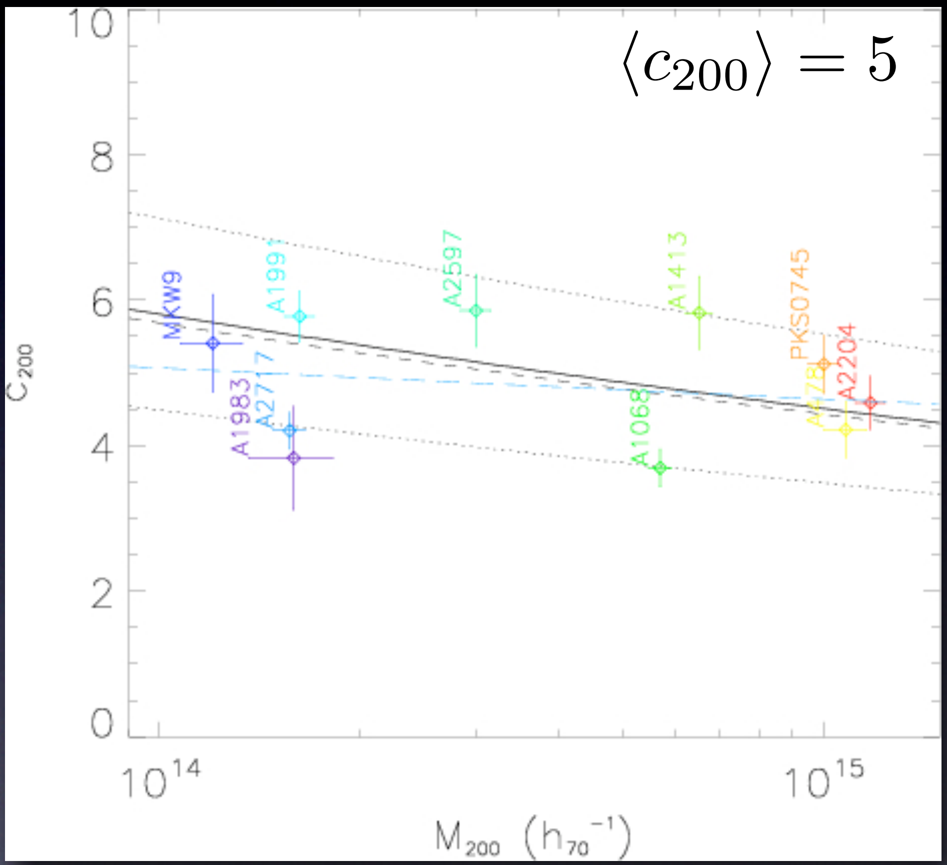
Pratt & Arnaud 2005;
Pointecouteau, Arnaud & Pratt 2005
(XMM, regular)



Vikhlinin et al 2006 (Chandra, regular)

Dark matter constraints: *c* - *M* relation

Quantitative test of CDM scenario



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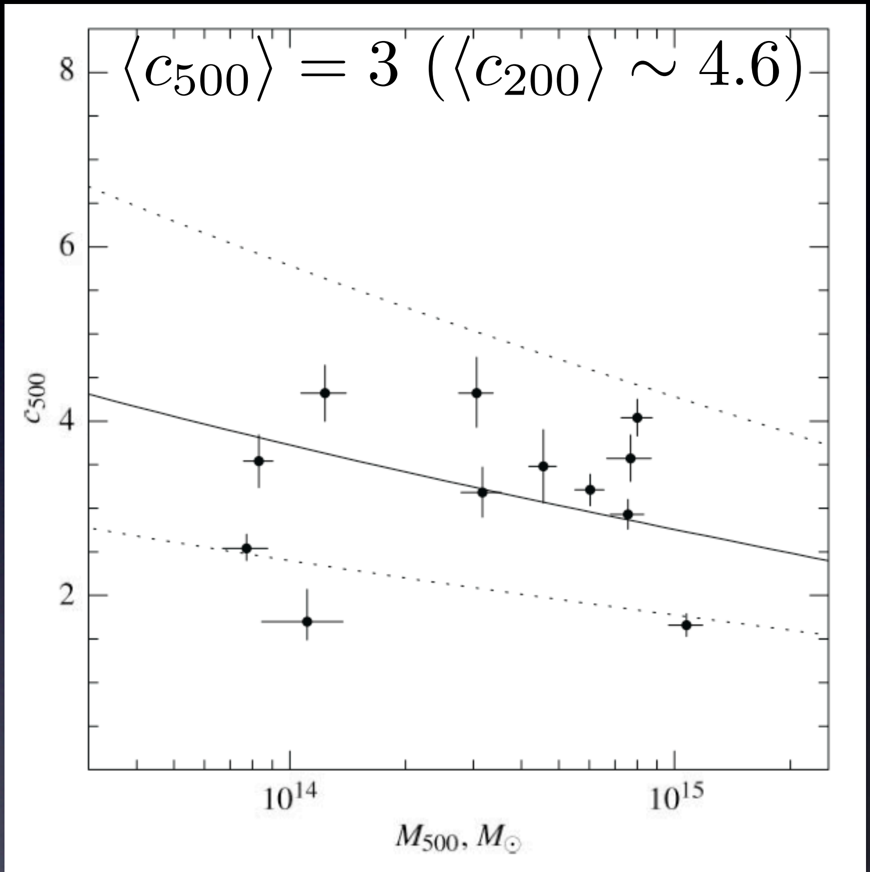


Vikhlinin et al 2006 (Chandra, relaxed)
see also: Sato et al 2000, Gastaldello et al. 2007, Buote et al. 2007, Humphrey et al. 2006, Schmidt & Allen 2007

Mass proxy relations

X-ray scaling laws in self-similar scenario

Virial theorem

$$\frac{GM_\delta}{R_\delta} \propto kT$$

Constant gas mass *fraction*

$$f_{\rm gas} = M_{{\rm gas},\delta}/M_\delta = {\rm const.}$$

X-ray scaling laws for global properties

$$T \propto M/R \propto R^2 \propto M^{2/3}$$

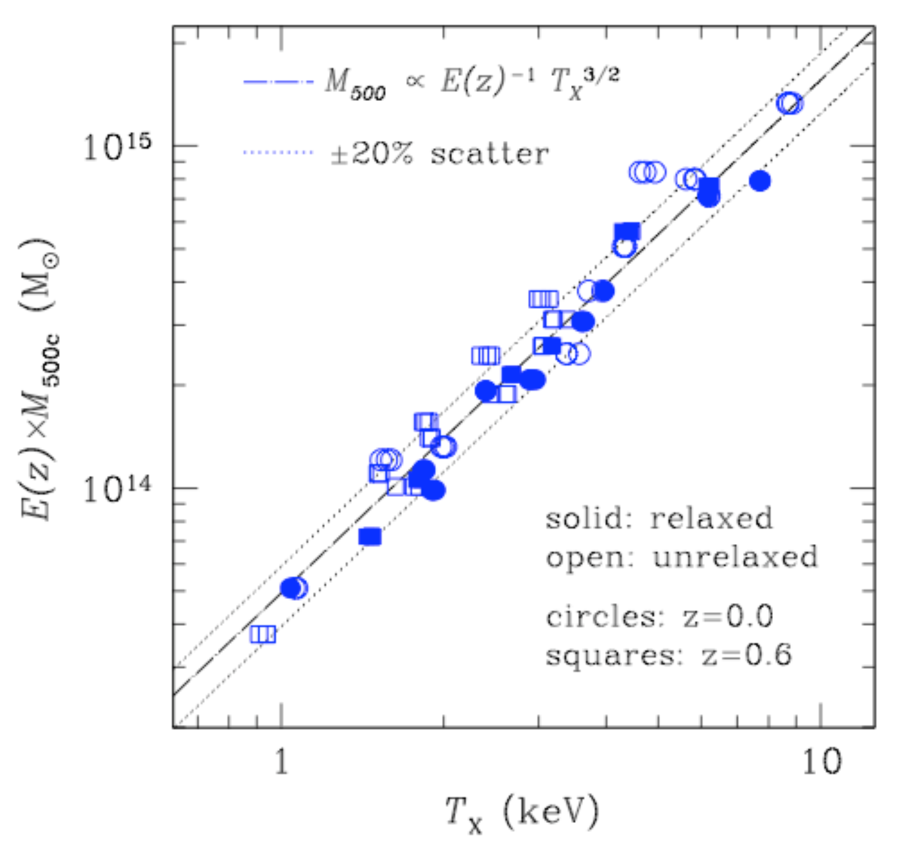
$M \propto T^{3/2}$ (interesting for cosmo)

$$R \propto T^{1/2}$$

(assuming Bremsstrahlung)

$$L \propto T^2$$

$L \propto M^{4/3}$ (interesting for cosmo)



Mass proxy relations

Kravtsov et al. 2006
(cosmological numerical simulations)

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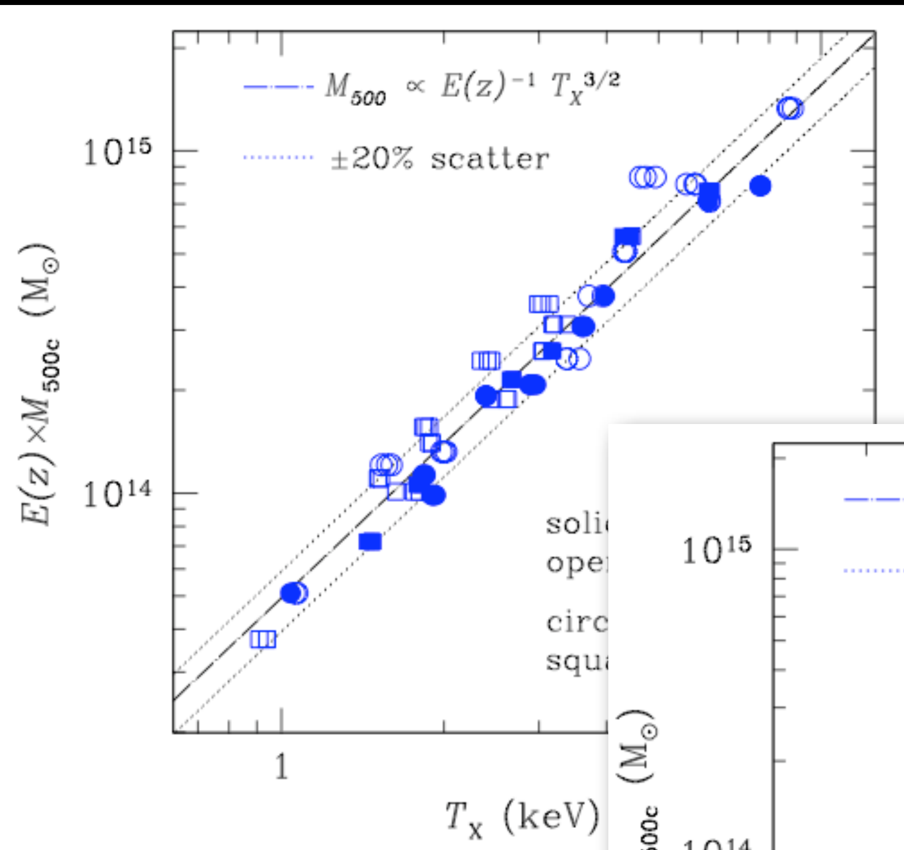

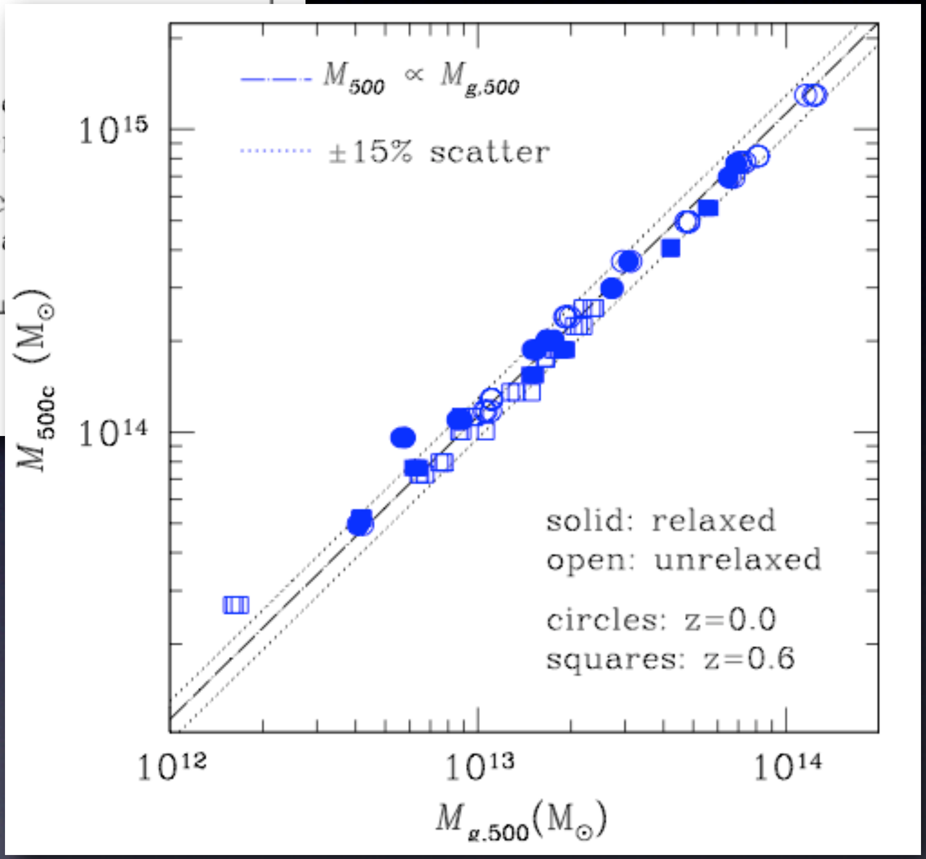

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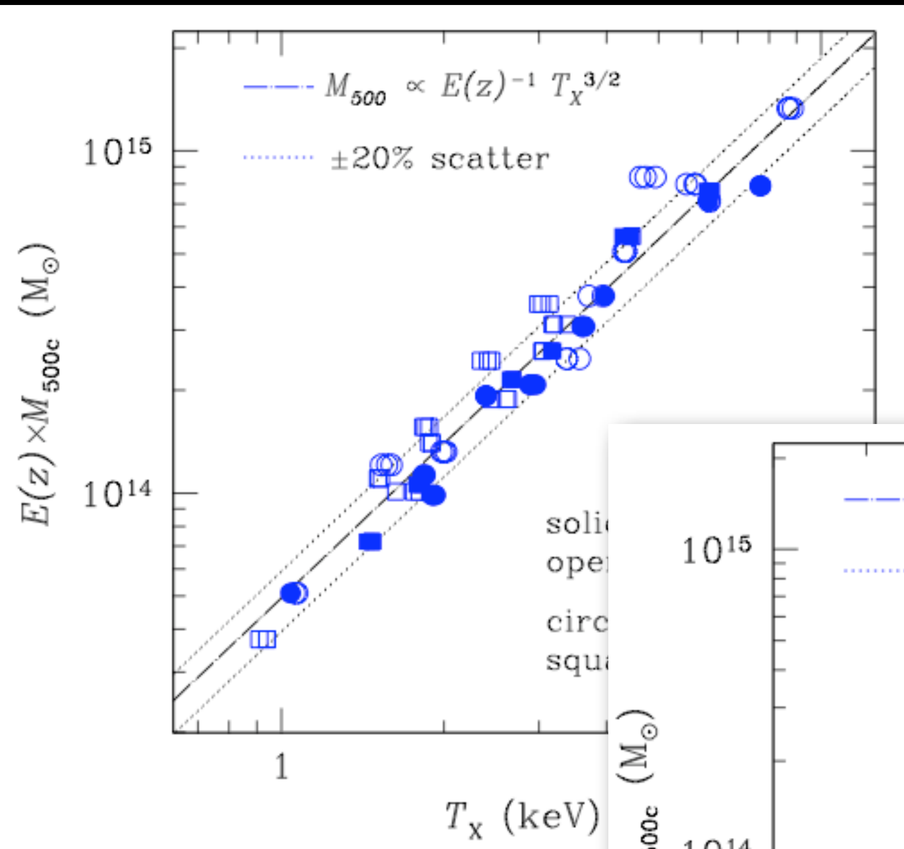
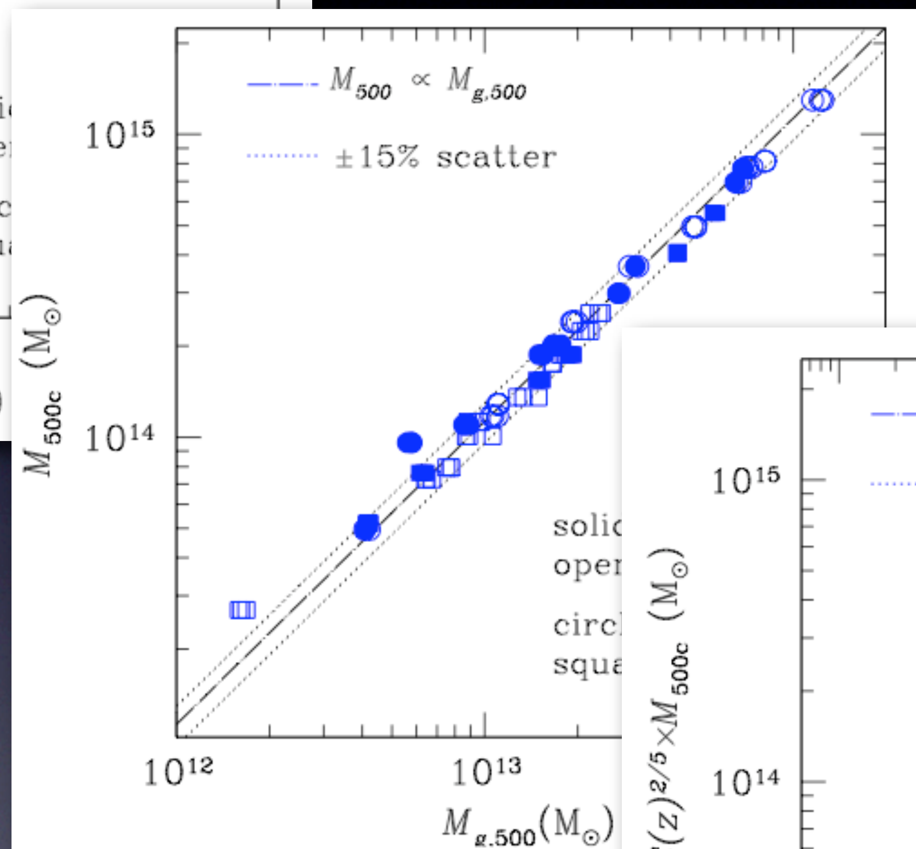
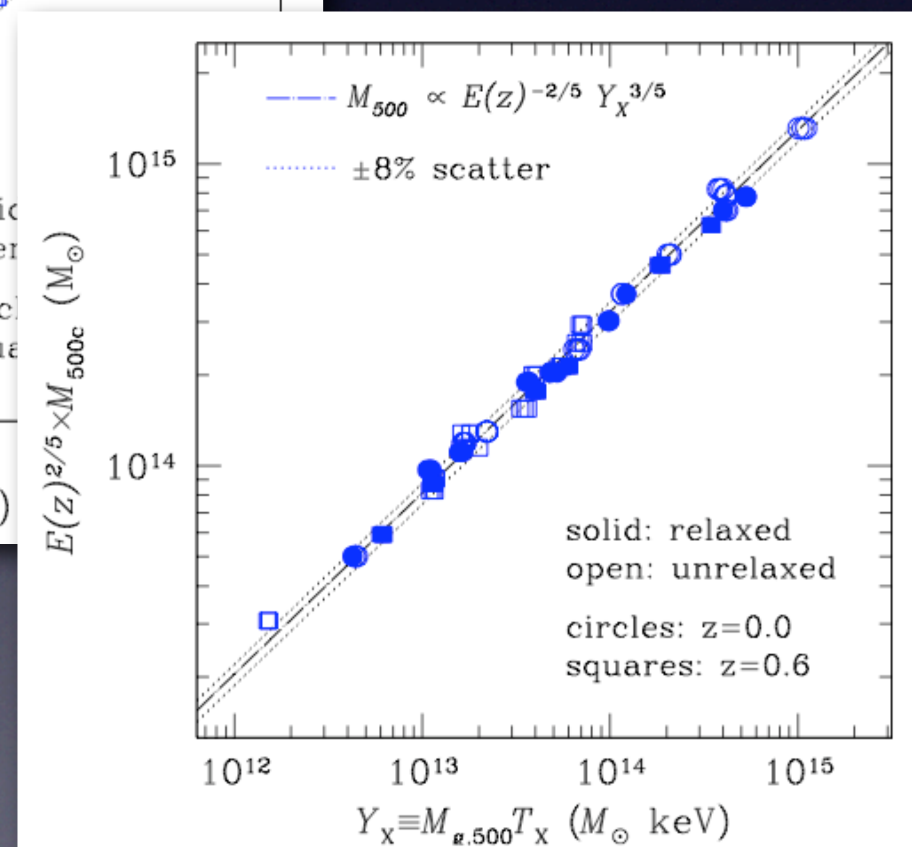
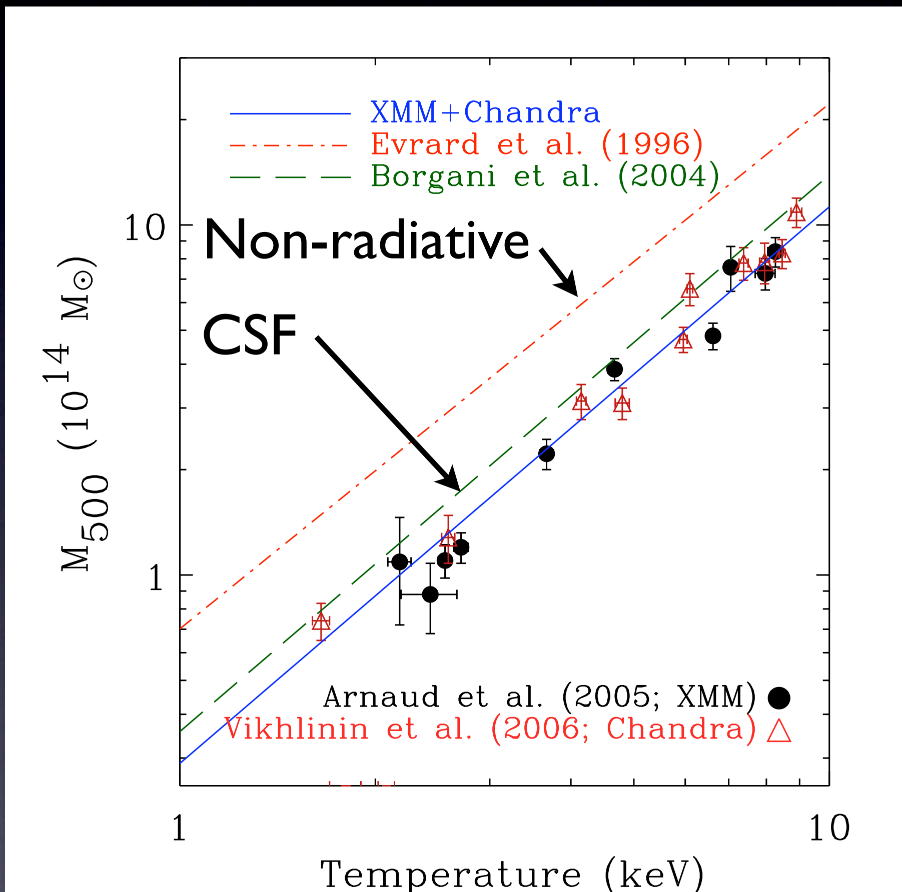




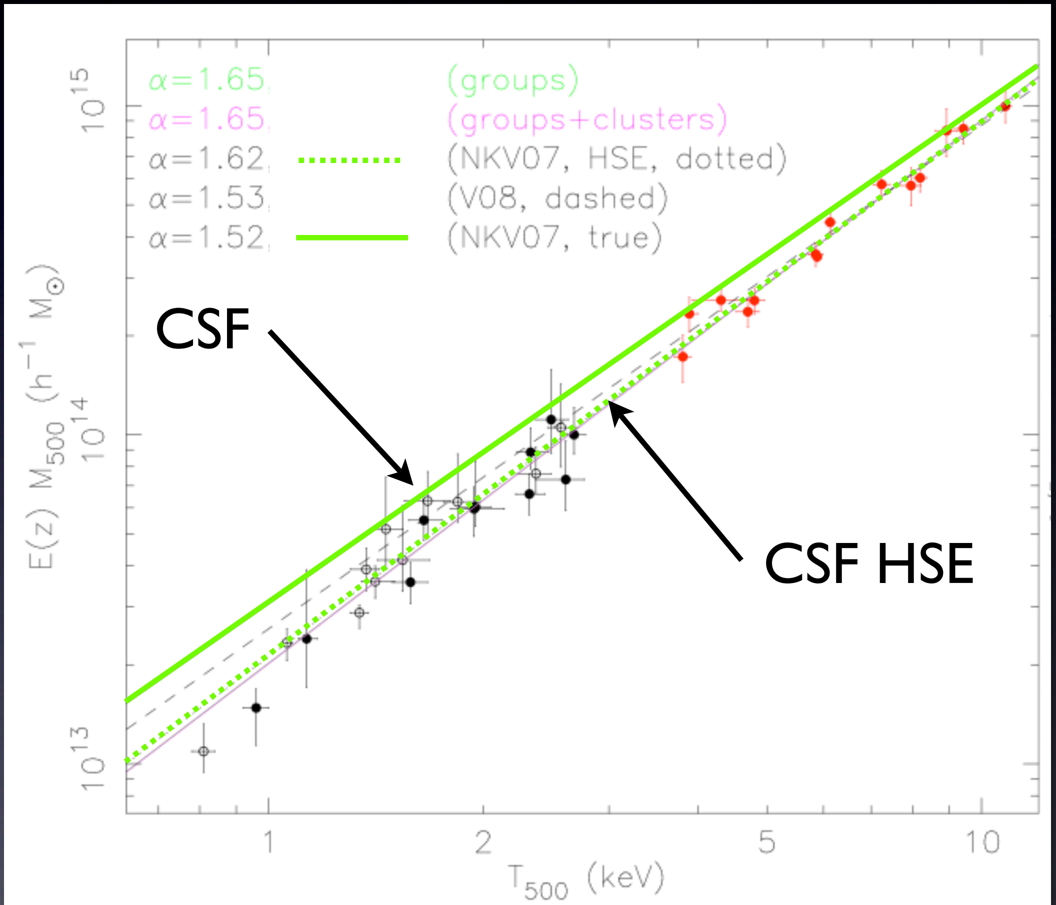


$M - T$ relation

Assume spherical symmetry, HE, regular systems

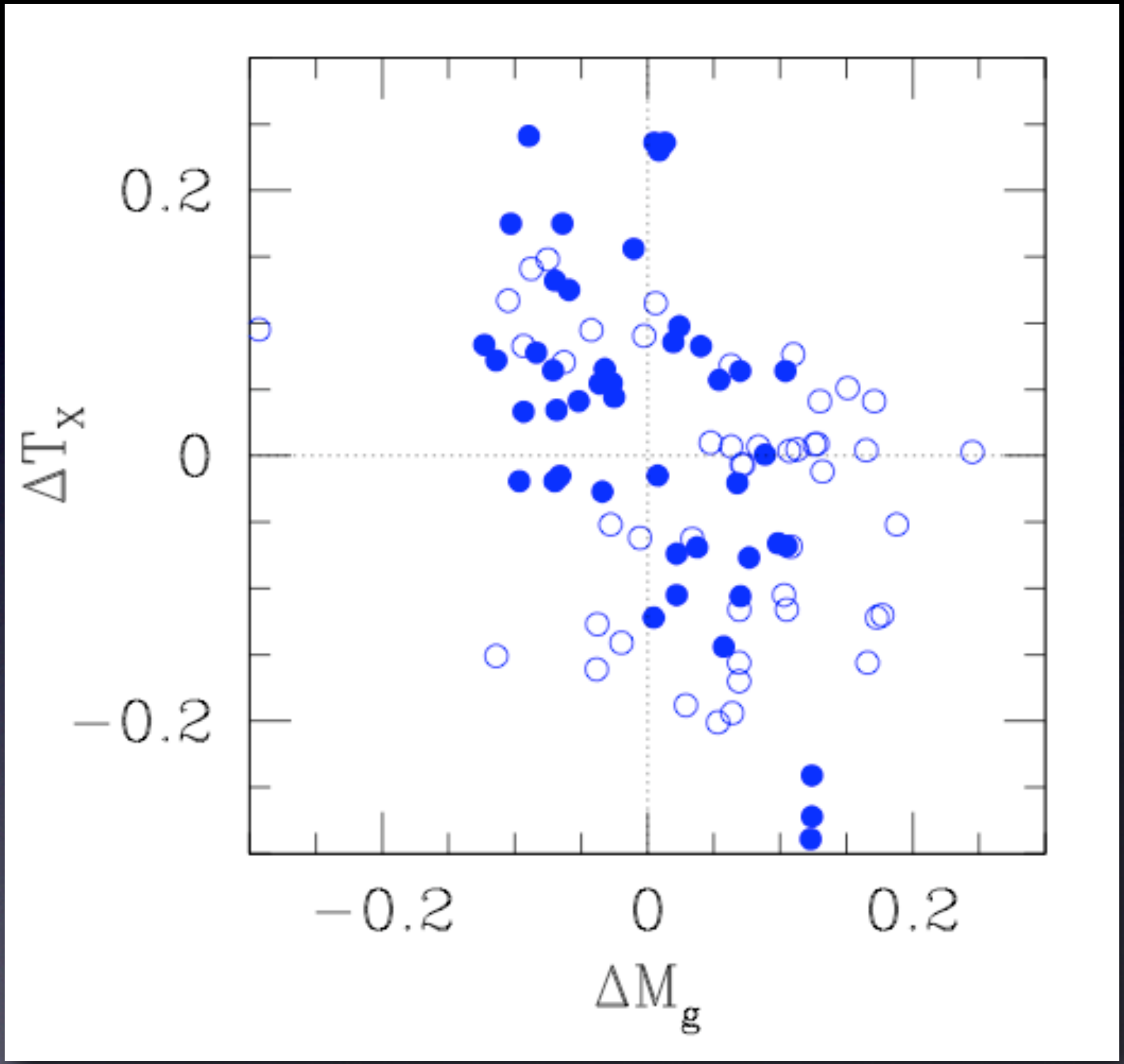


Pratt 2006



Sun et al. 2008

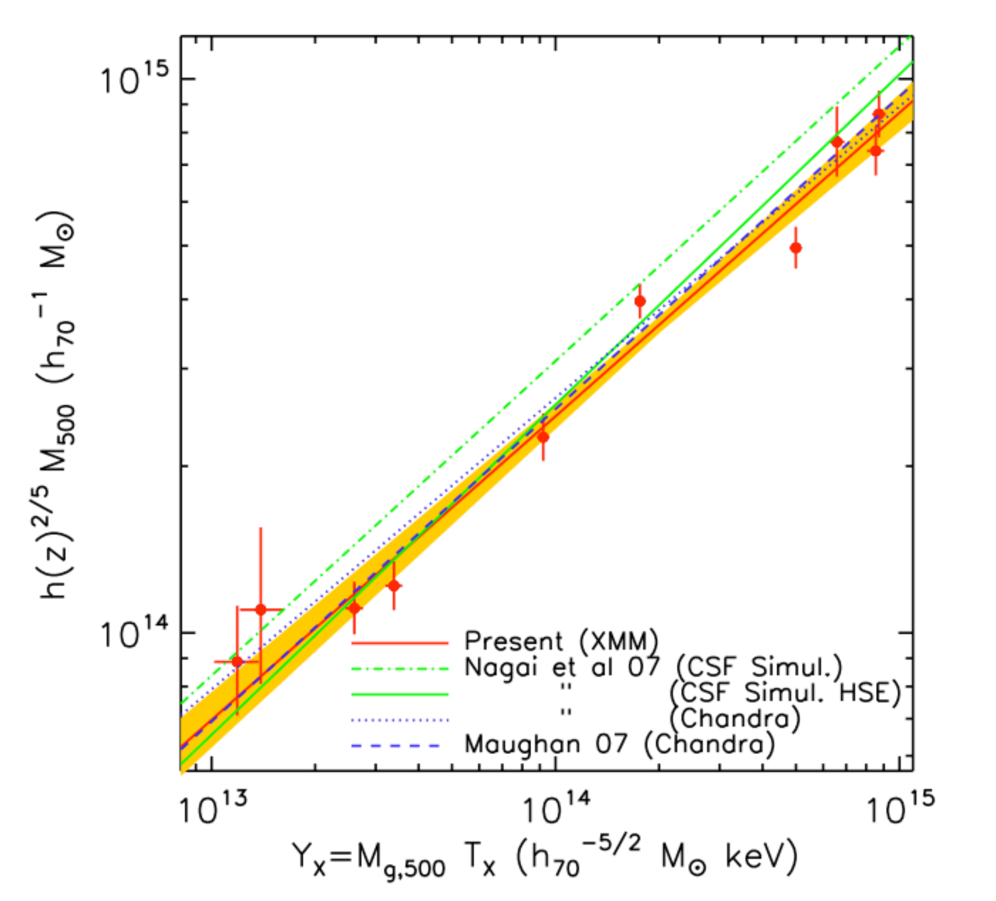
Fractional deviations (wrt self-similar relation)



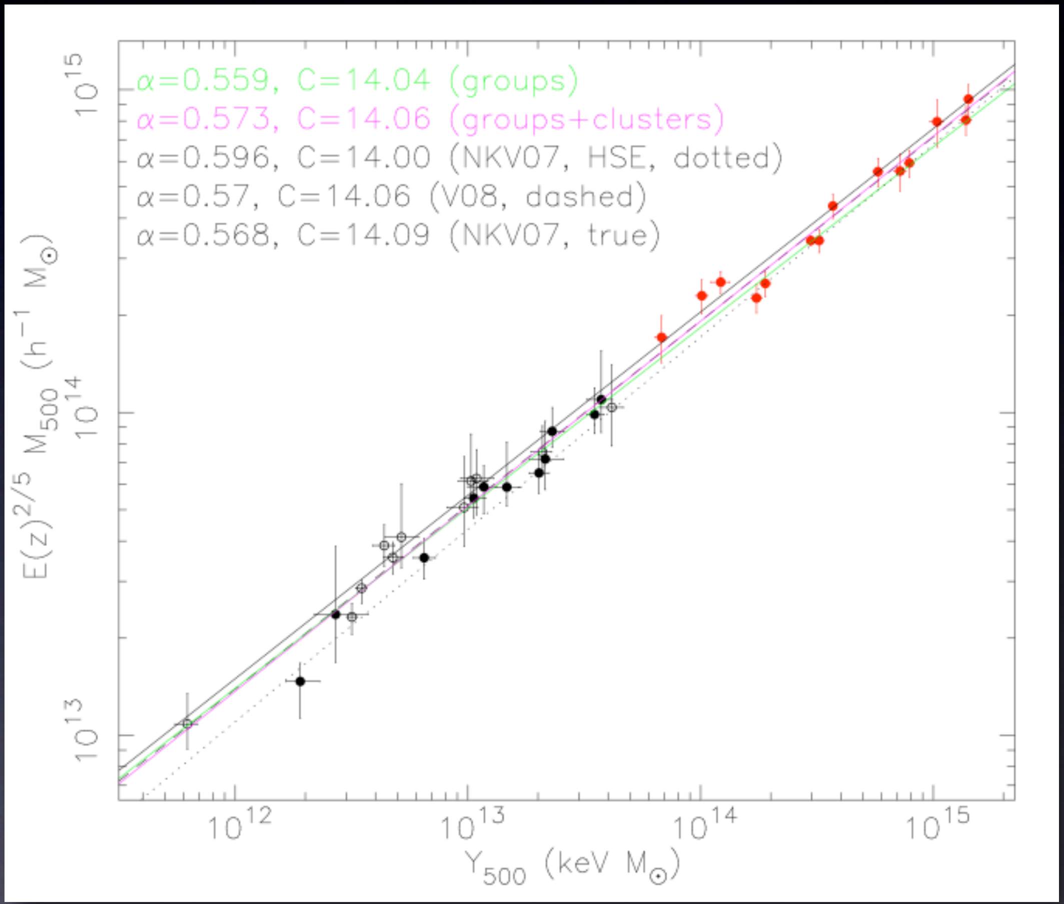
Kravtsov et al. 2006

$M - Y_X$ relation

$$Y_X = M_{g,500}\,T$$



Arnaud et al. 2007

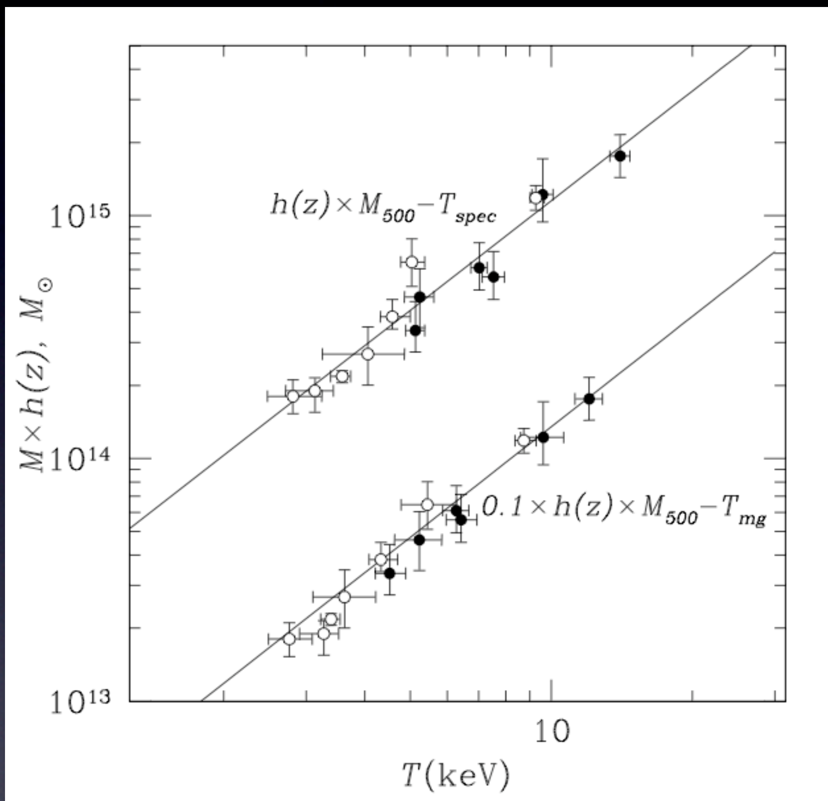


Sun et al. 2008

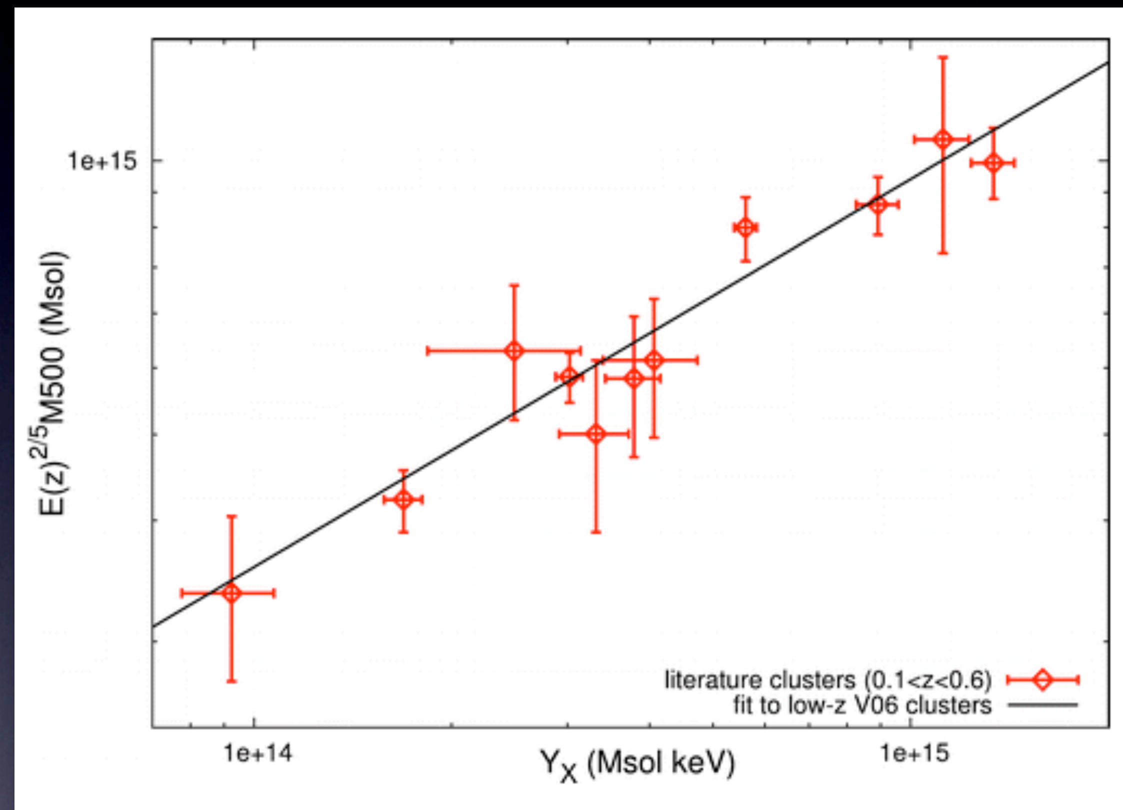
Evolution

$M - T;\ 0.4 < z < 0.7$

$M - Y_X;\ 0.1 < z < 0.8$



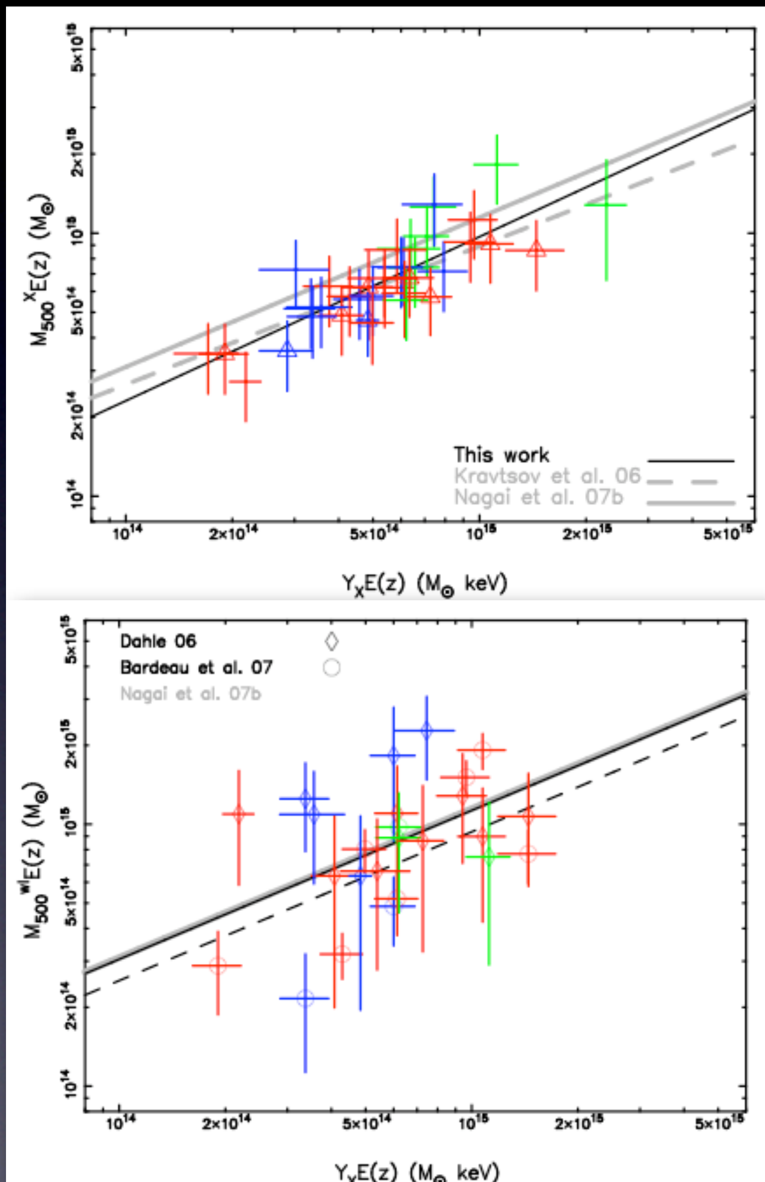
Kotov & Vikhlinin 2006



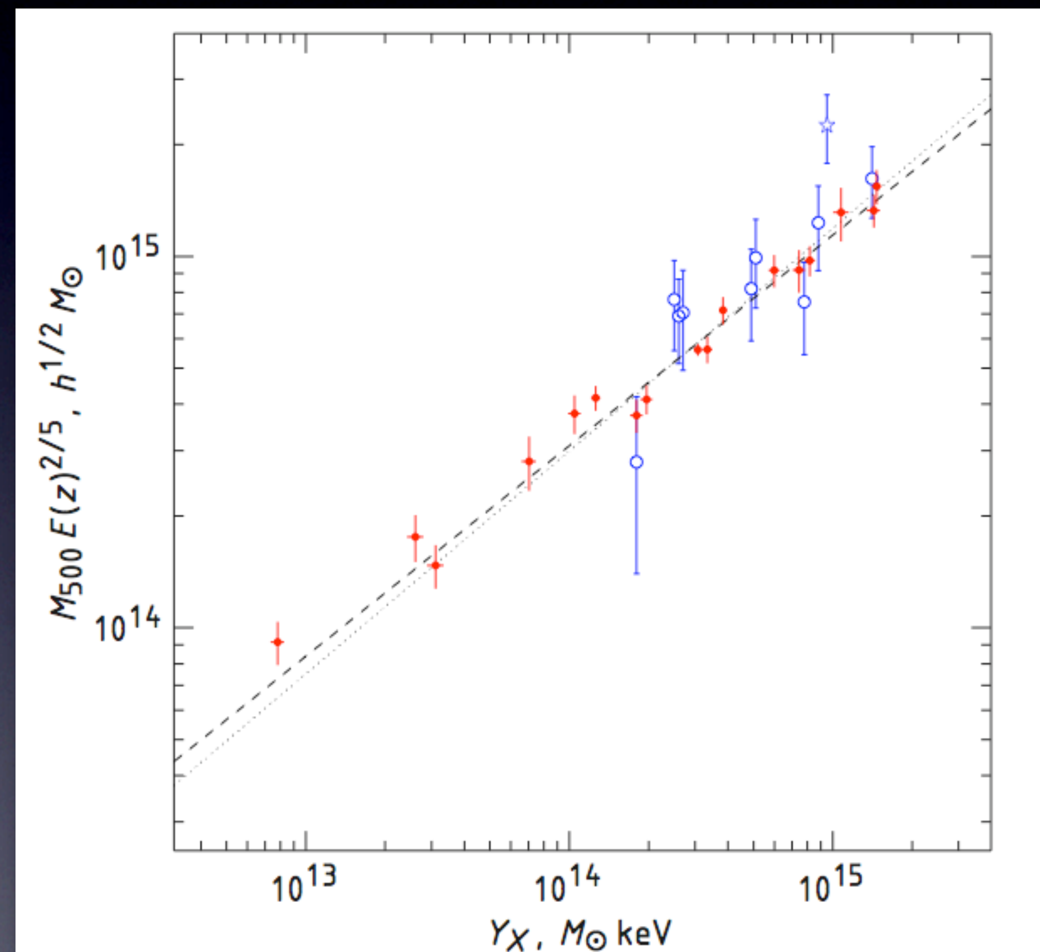
Maughan 2007

$$M_{500} = h(z)^{1.02\pm0.20}\ T^{3/2}$$

X-ray vs weak lensing

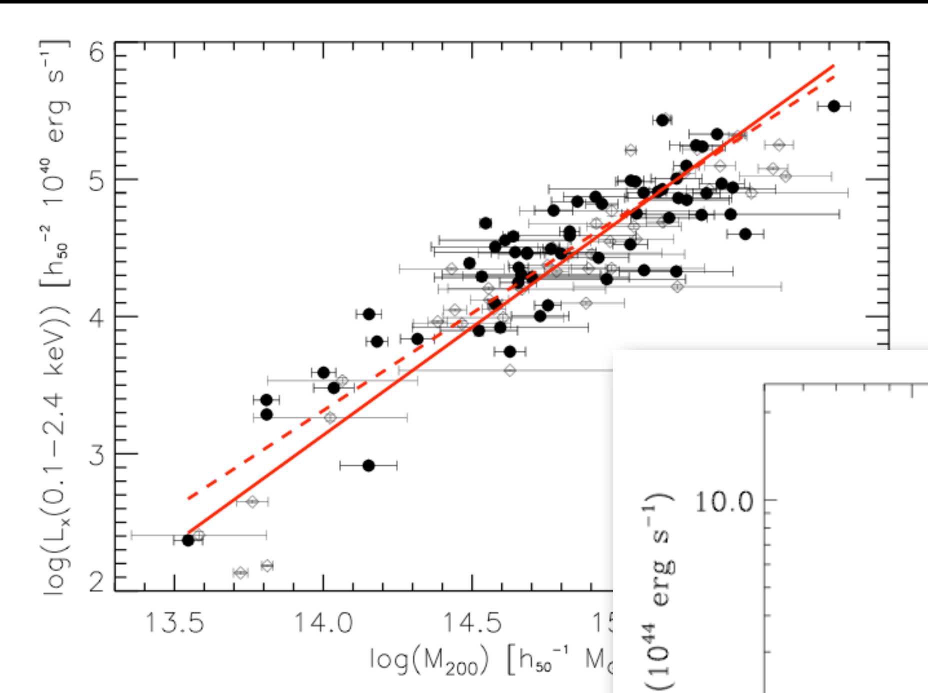


Zhang et al. 2008

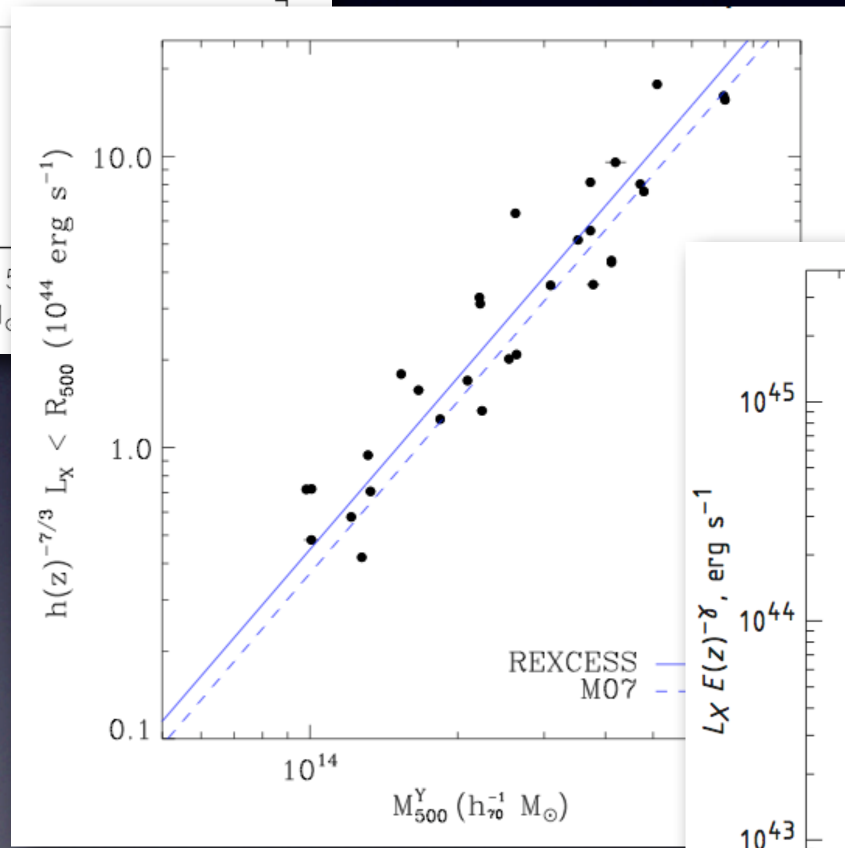


Vikhlinin et al. 2008
(+Hoekstra 2007)

$L - M$ relation

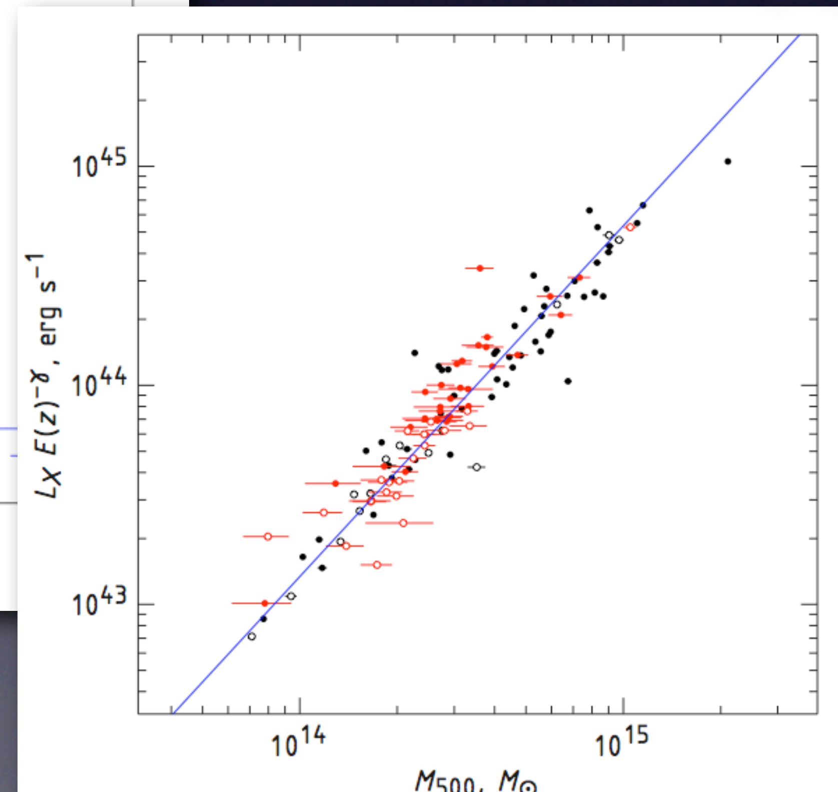


Reiprich & Böhringer 2002 (isothermal β)



REXCESS (Y_X)

Vikhlinin et al. 2008 (Y_X)

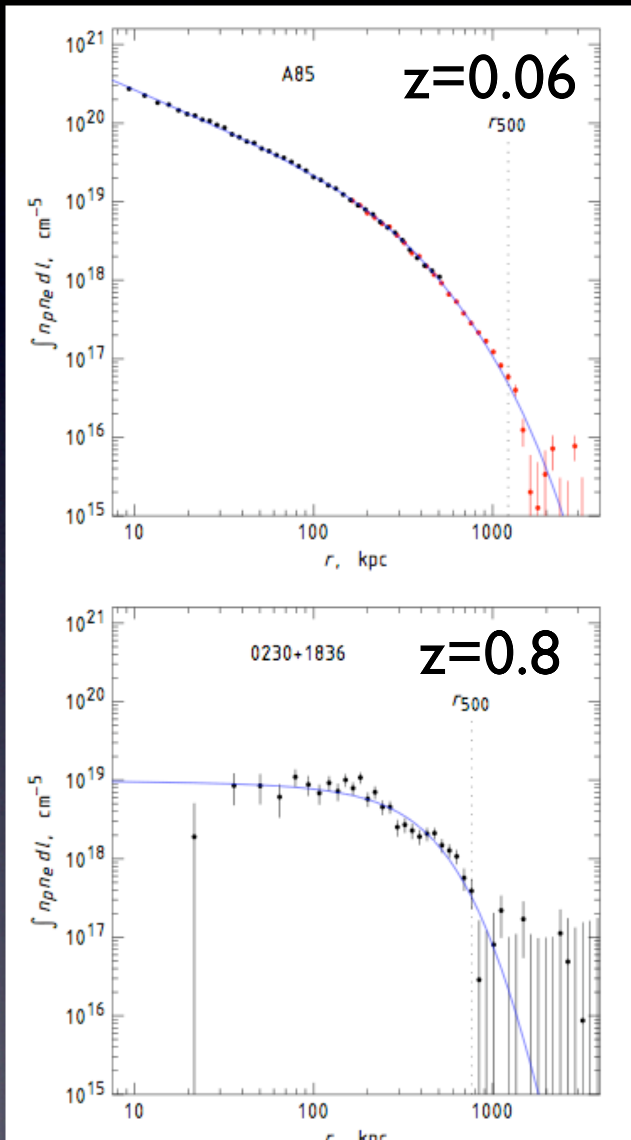


NB Large samples needed

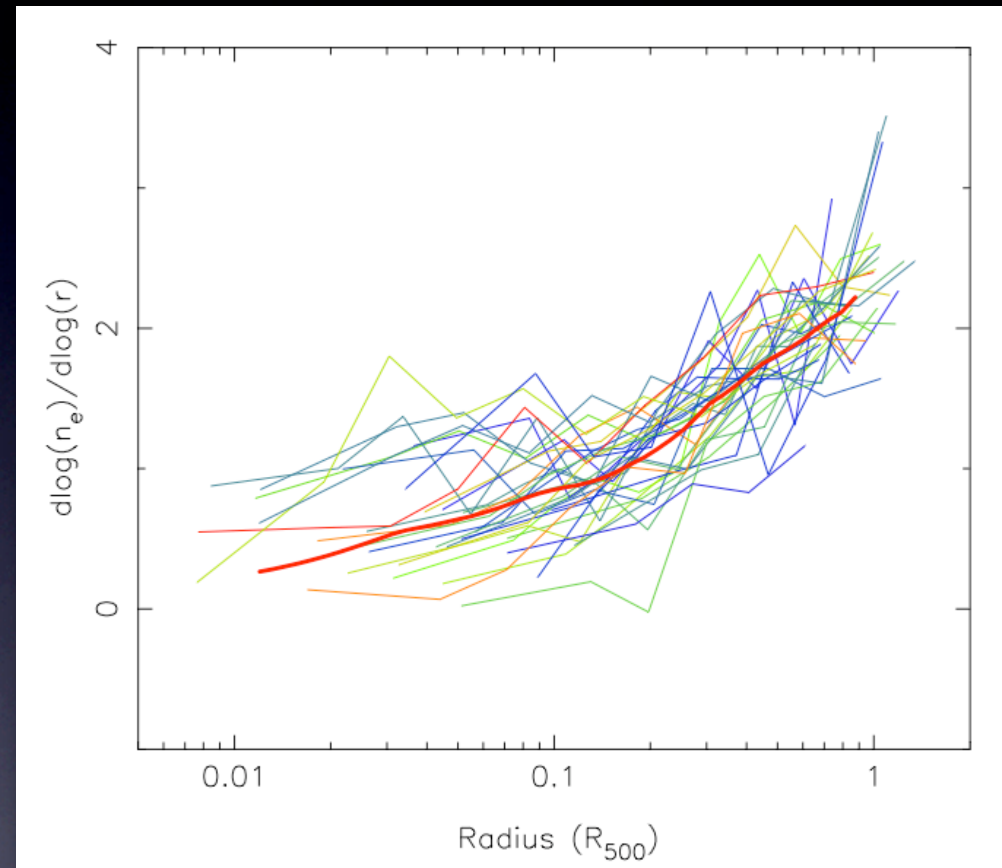
(Some) Points of concern

Data quality issues

Surface brightness/density profiles



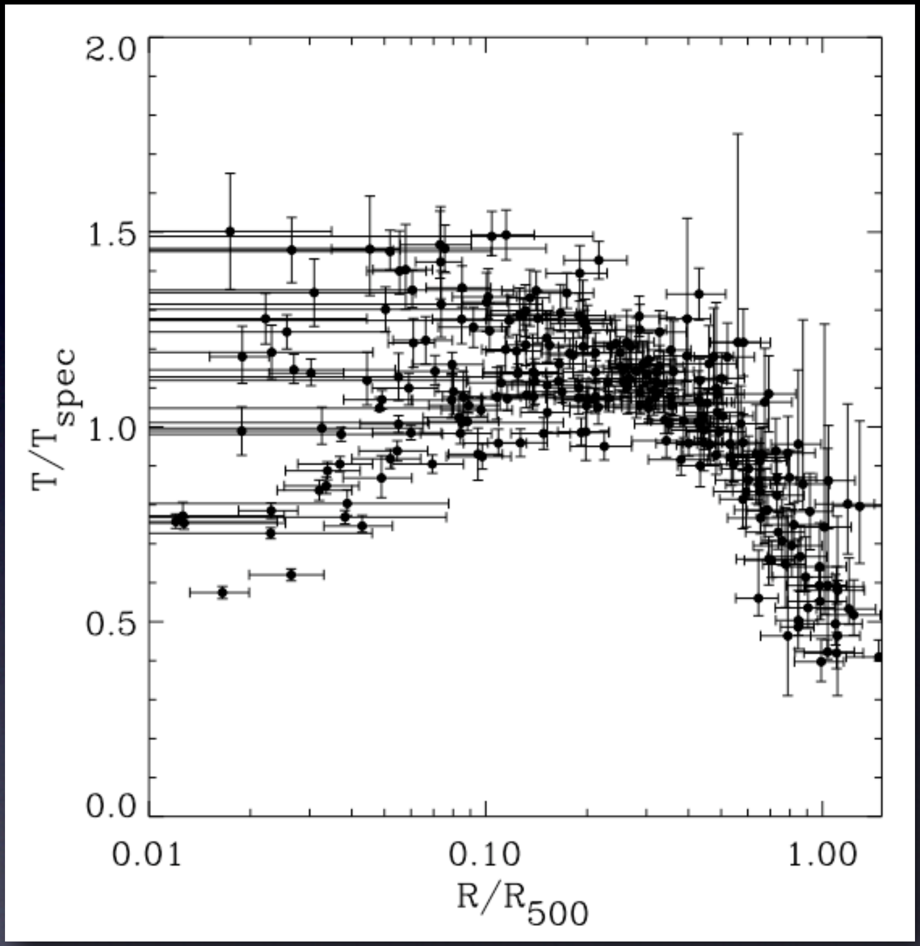
Vikhlinin et al. 2008



Croston et al. 2008

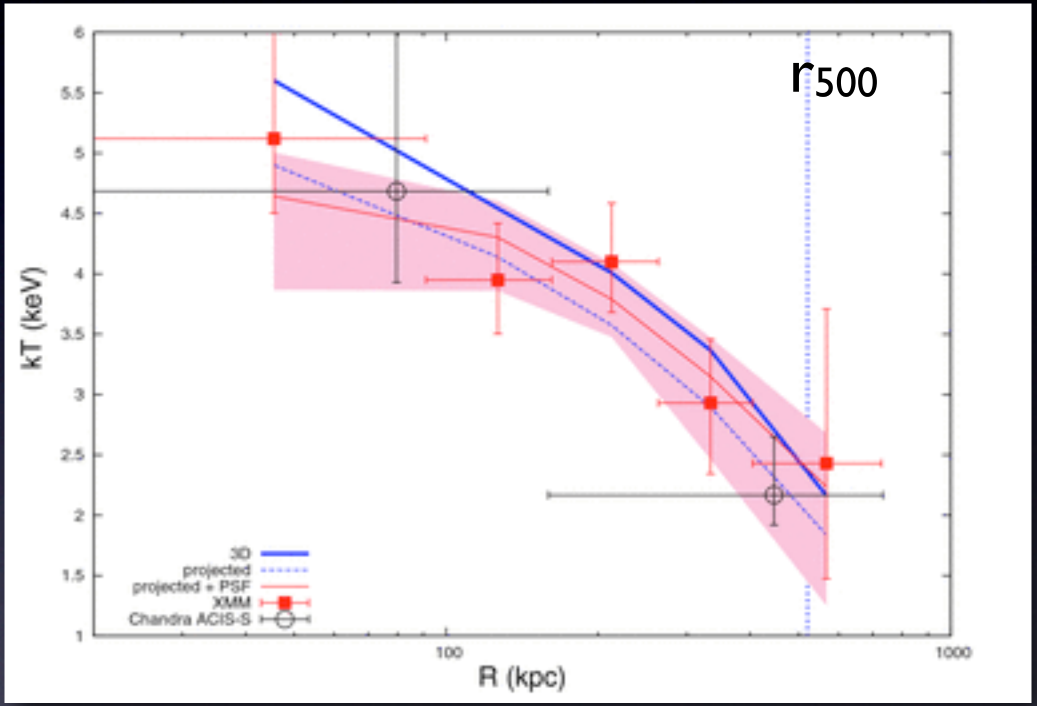
Data quality issues

Temperature profiles



REXCESS

$z < 0.2;\ \mathrm{T_{exp}} \sim 20\mathrm{ks}$

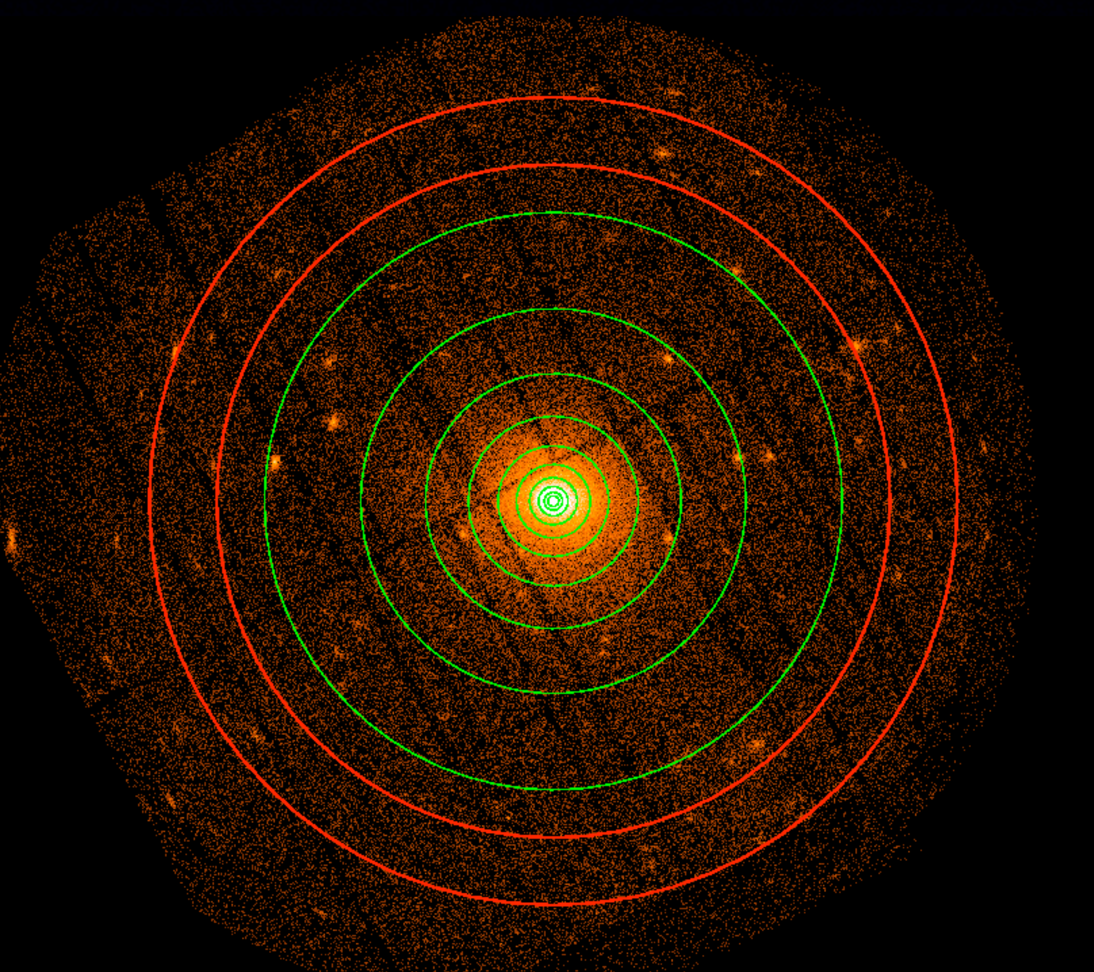


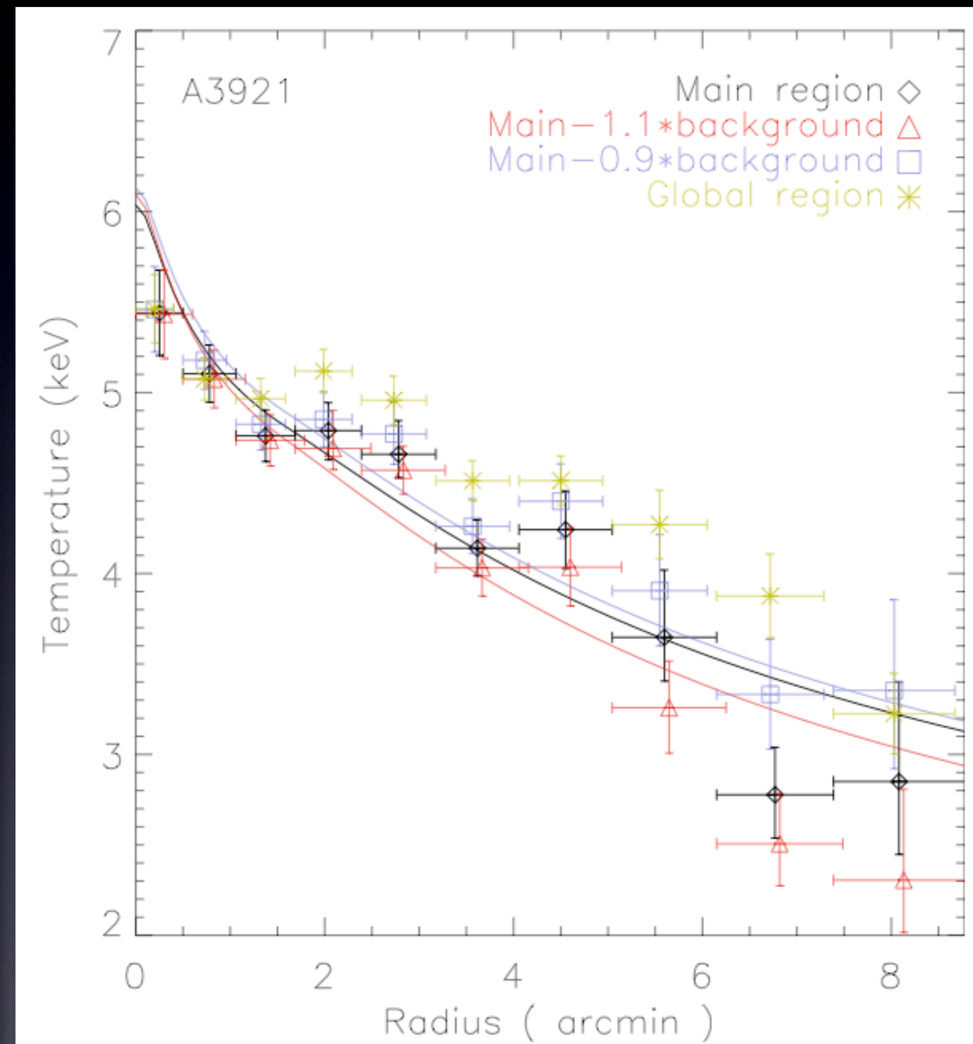
Maughan et al. 2008

$z \sim 1;\ \mathrm{T_{exp}} \sim 80\mathrm{ks\ (XMM)},$
$130\mathrm{ks\ (Chandra)}$

Data analysis issues

Background subtraction

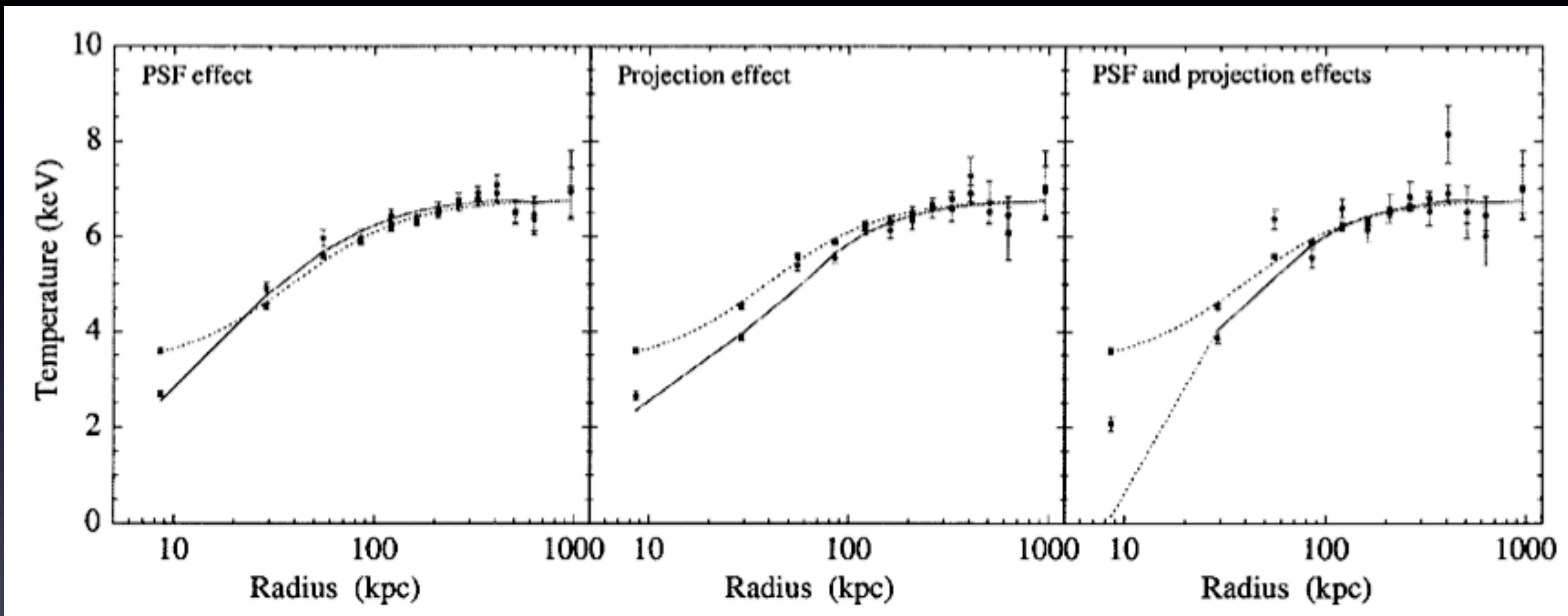




Belsole et al. 2005

Data analysis issues

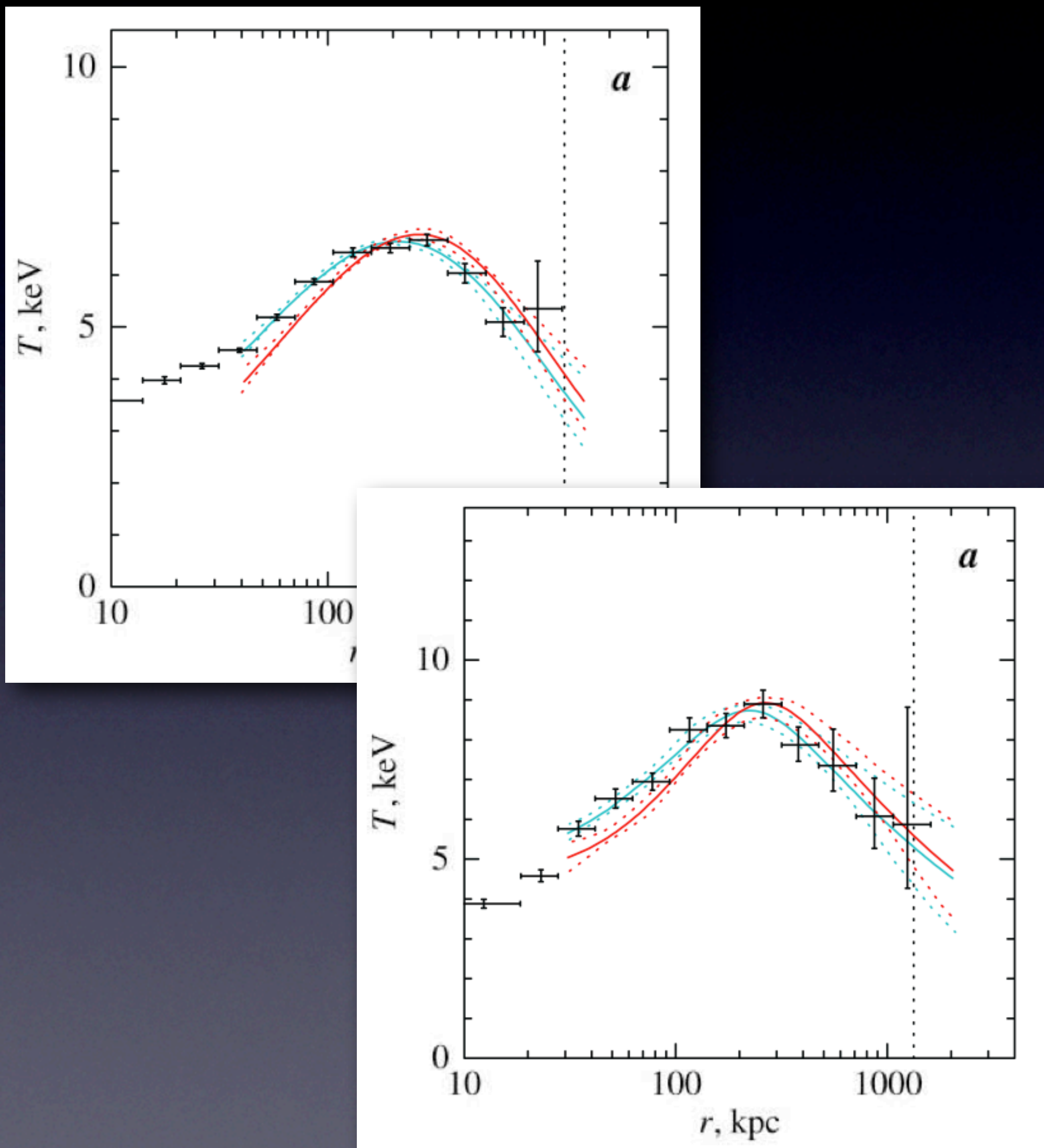
Noise amplification due to deconvolution

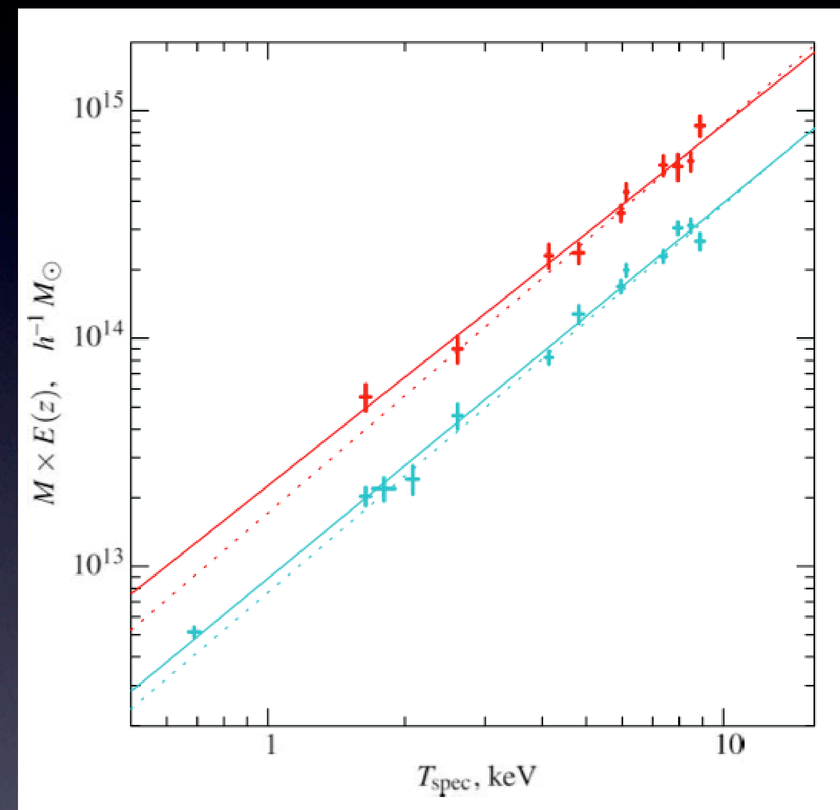


Pointecouteau et al. 2008

Data analysis issues

Parametric models may over-constrain and limit uncertainties





Vikhlinin et al. 2006

Conclusions

X-ray mass estimation method well established

General support for CDM model

- mass profiles, c-M relation for regular systems

Work ongoing for X-ray mass proxy relations

- per cent level agreement of *observed* local X-ray mass proxy relations (normalisation and slope)

- normalisation disagreement (<10 per cent) wrt state of the art simulations (possible evidence for non-thermal pressure support?)

- cross-calibration with lensing still in infancy & inconclusive re: non-thermal pressure; also, how to compare at low masses?

- evolution of relations relatively untested (calibration of isothermal assumption needed?)

Future progress - current data

X-ray data quality should be strictly controlled

- need to detect out to R_{500} in SB *and* temperature for precise log gradients
- significant mass/temperature *and* redshift range needed
- background subtraction requires local estimate (nearby systems fill FoV)

⇒ longer exposures for distant systems, offset pointings for nearby objects

Deconvolution

- unstable even if PSF effects negligible
- parametric models may underestimate errors by forcing smooth functions

Application of HE to unrelaxed systems

- must understand the consequences (simulations?)

Future progress (X-ray)

What instrument?

- Chandra
  + PSF not an issue (at centre), point source subtraction at high-z
  - ACIS-S FoV is small, ACIS low energy response suspect, throughput

- Suzaku
  + Lower background cf Chandra or XMM
  - PSF 100x Chandra, 10x XMM

- XMM
  + FoV, throughput
  - PSF, background variability

Proposing

- Pressure factor of 7-8 (1-2 proposals accepted in priority A, 3-4 in B)

- < 1.5 Msec available for Topic F (A+B+C, A07)

- < 6 Msec available for ALL Large Programmes (AO-7)

End