Local Galaxy Groups: X-ray Scaling Relations

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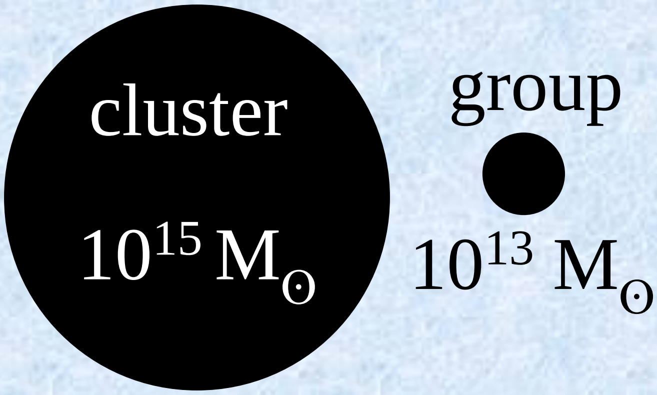
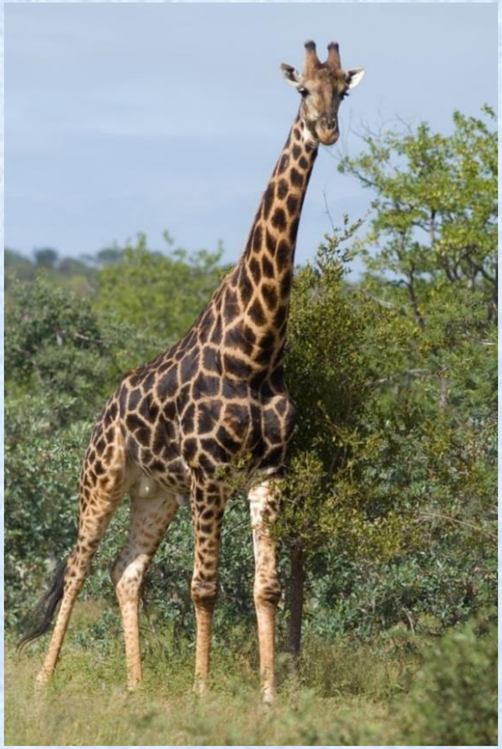




- Galaxy groups are the smallest halos where the bulk of baryons are accounted for, in stars and hot gas.
- Groups are also ideal systems to study baryonic physics (e.g., SN winds, cooling, AGN heating), which dominates the systematic uncertainties for cluster cosmology. The same baryonic physics is important to understand the formation and evolution of galaxies.

Gas + Astronomy
=
Gastronomy

Some cautionary (or boring) notes

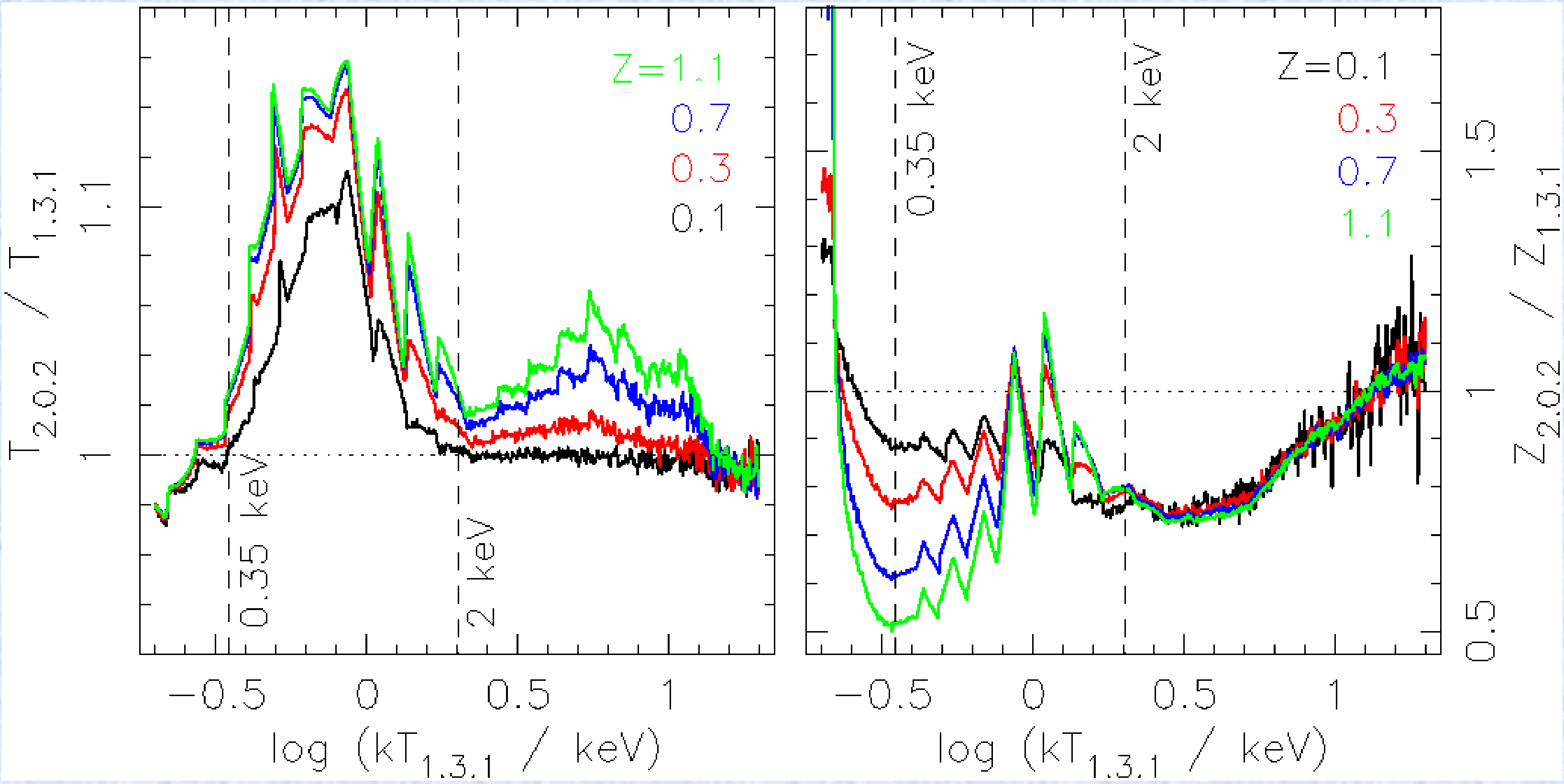
- **Selection biases**: Malmquist bias and Eddington bias (e.g., Stanek+2006; Leauthaud+2011; Teerikorpi 2015)
- Coverage at large radii: $M_{\mathrm{HSE},\,\Delta}$ only depends on T, T / n_e gradient around Δ --- *be careful about extrapolation* !
- Deprojection
- From S_X to density --- 3D abundance profile needed
- Better to use 0.4-2 keV for kT < 0.6 keV groups, but need to have low N_H and low X-ray foreground.
- Absorption (not OK to simply use the HI absorption) --- *extra absorption* at $N_{HI} > 5 - 6 \times 10^{20}$ cm^{-2} (and abundance table matters!)

  (try this for $N_{\mathrm{H,\,total}}$: http://www.swift.ac.uk/analysis/nhtot/index.php)
- *Chandra* / *XMM* cross calibration (also between PN and MOS)

A table in every paper about abundance table, AtomDB, N_H , μ used !

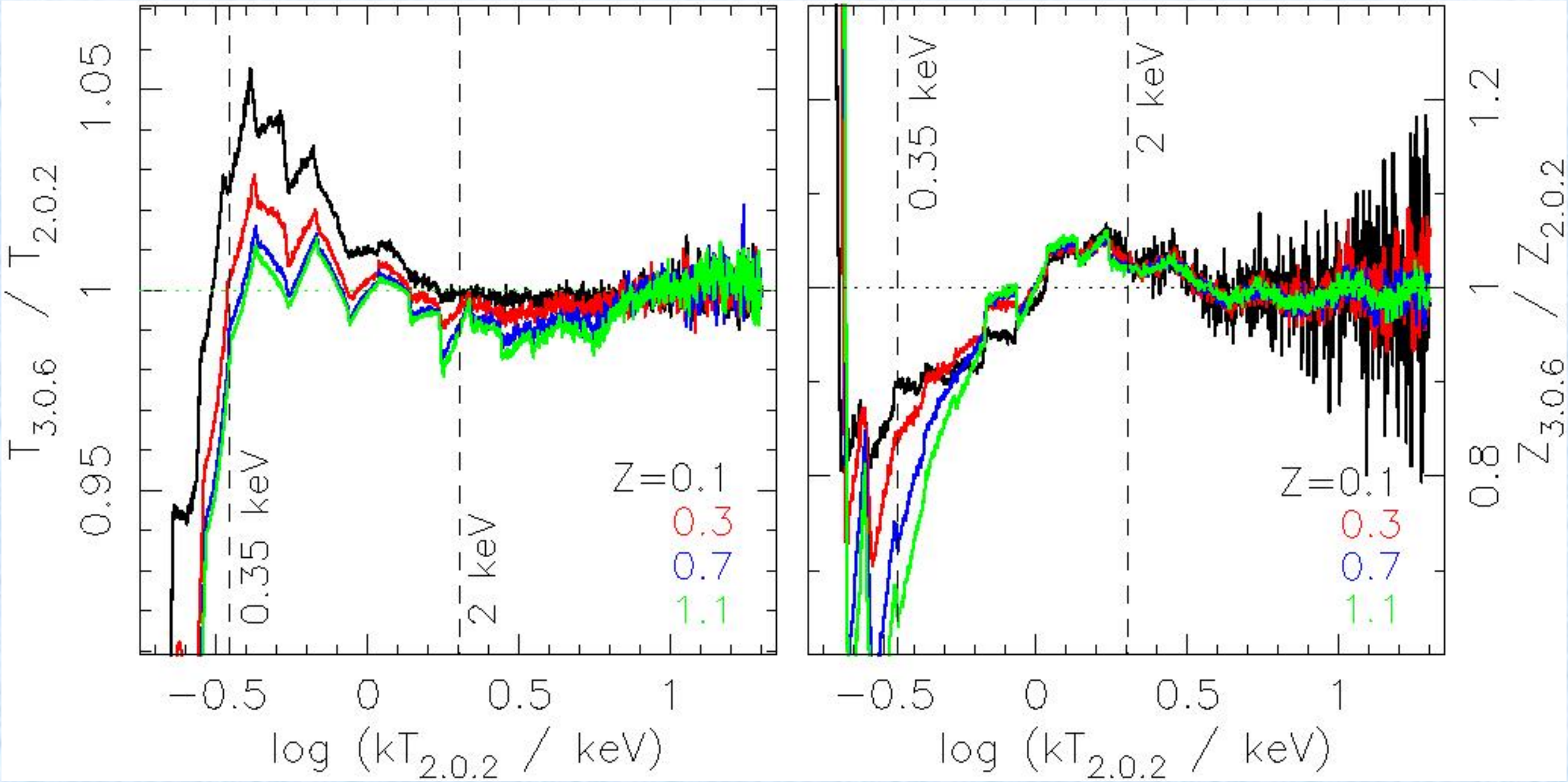
Atomic Database (AtomDB) for X-ray plasma

- AtomDB update from 1.3.1 to 2.0.0 in the summer of 2011, with some significant changes on iron L-shell data
  --- make sure you are comparing apples to apples !
- For groups, T : +10%, Z : -15%, n_e : ±5% (-5% for Z<0.3), L_X (~ 1%) → M_Δ : +10% , $f_{gas,\Delta}$: ~ -10% (e.g., Sun 2012; Lovisari+2015)



AtomDB 3.0.6 released on Nov. 16, 2016

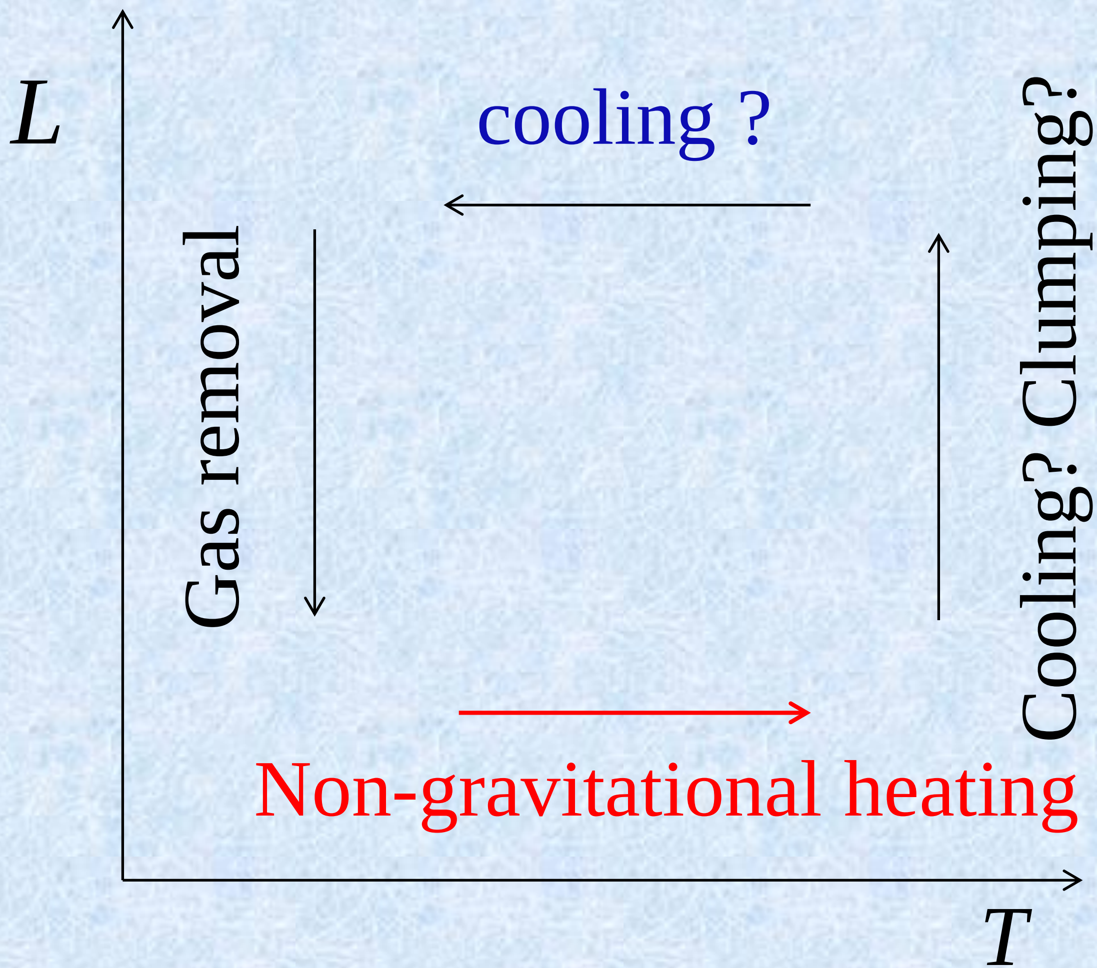
(AtomDB 3.0.7 released on Dec. 8, 2016)



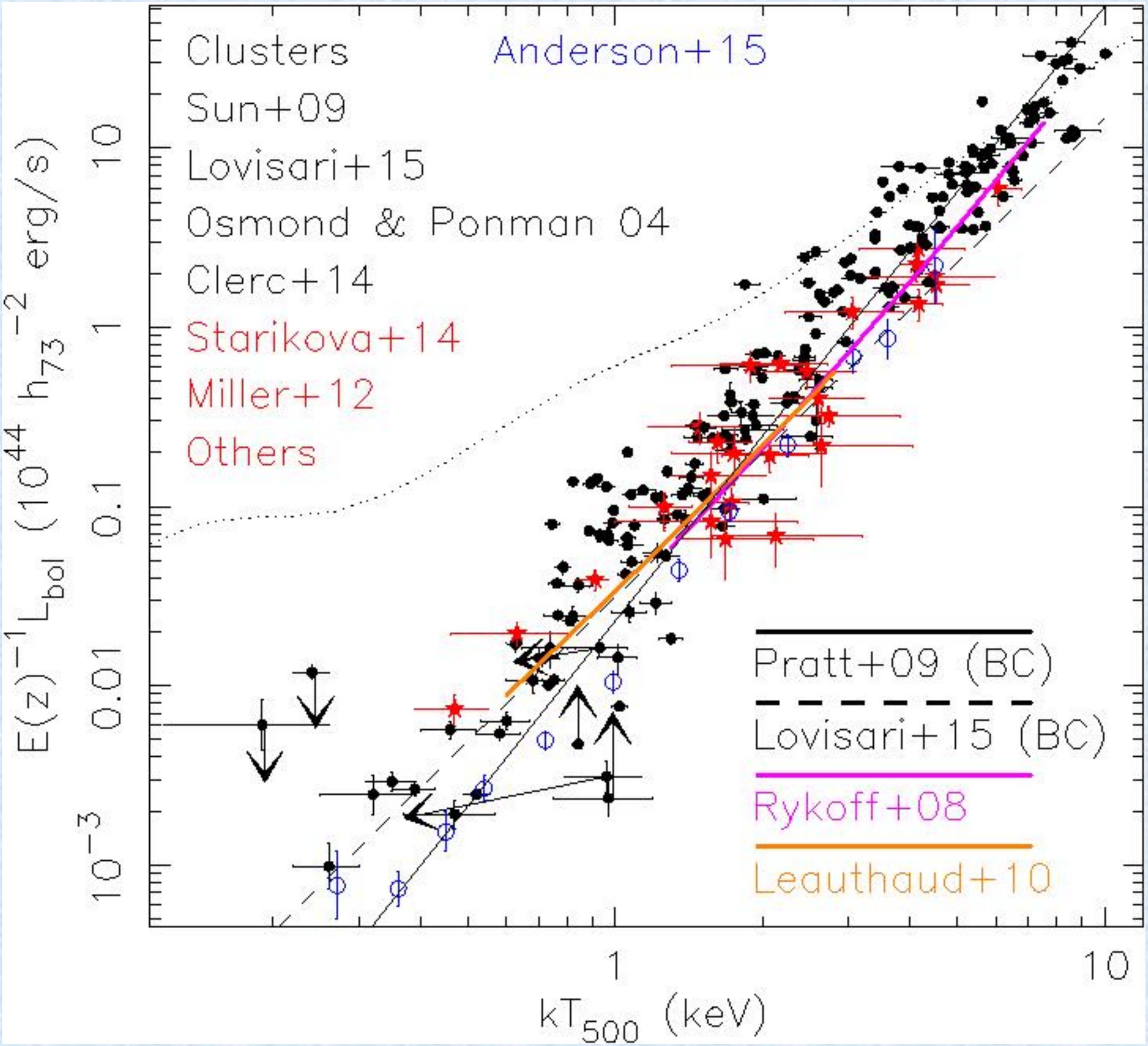
$L_X - T$ relation

$$E(z)^{-1}L(T,r) = f_{gas}{}^2(T,r)[E(z)M(T,r)]\,\overline{\Lambda(T,Z)}\,\hat{Q}(T)$$

$$(\ \hat{Q}(T) = \langle\rho^2\rangle\ /\ \langle\rho\rangle^2\ )$$



$L_X - T$ relation



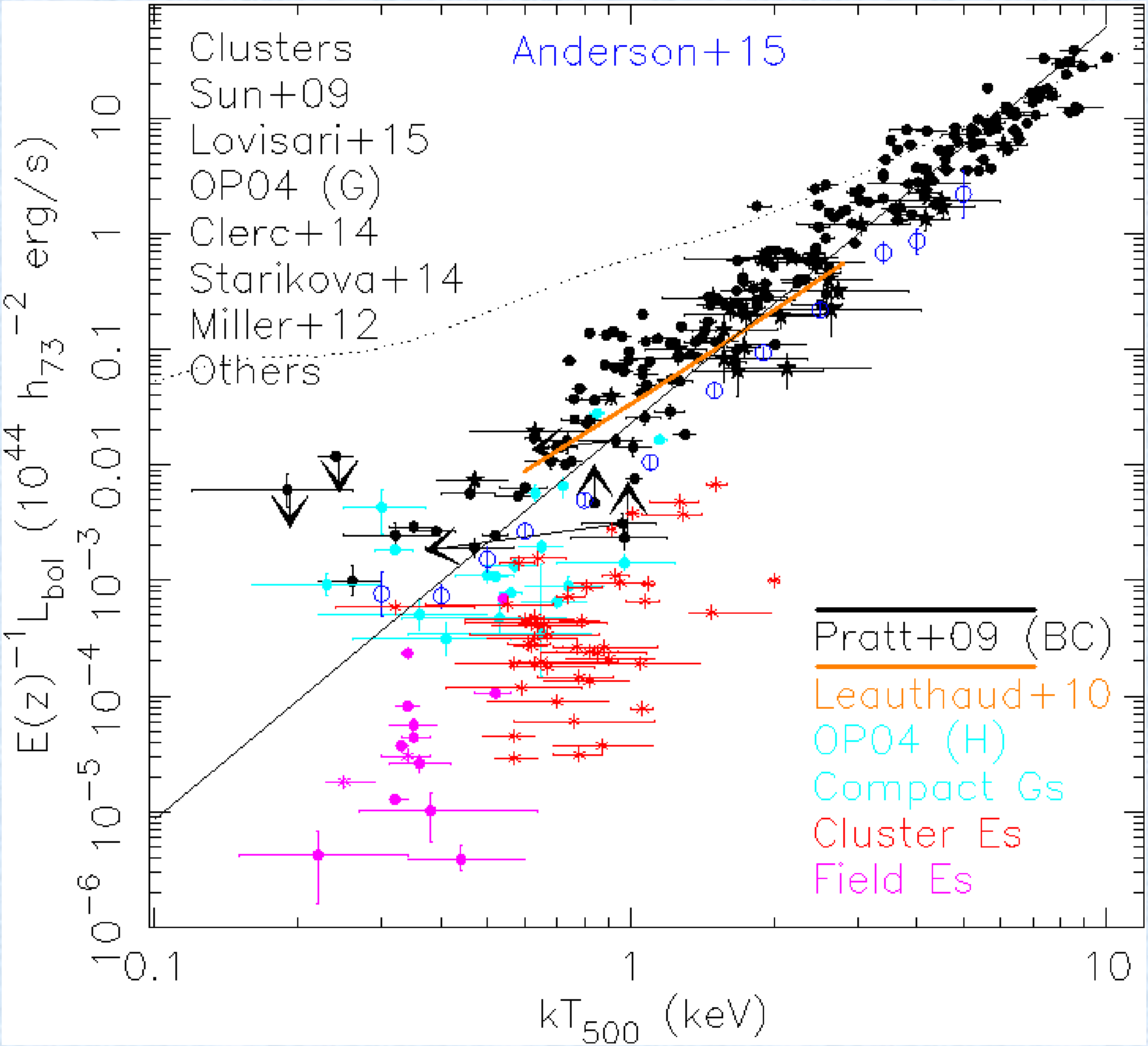
Non-X-ray selected

X-ray selected

(BC: bias corrected)

Pratt+2009: 3.39
Lovisari+15: 2.86
Zou+2016: 3.29

$L_X - T$ relation



Compact groups:
Desjardins+12,
Desjardins+13,
O'Sullivan+14

Cluster Es:
Sun+07, 09

Field Es:
Boroson+2011
Li+2012

Now clearly see non-gravitational heating & likely more gas loss …

$L_X - T$ relation

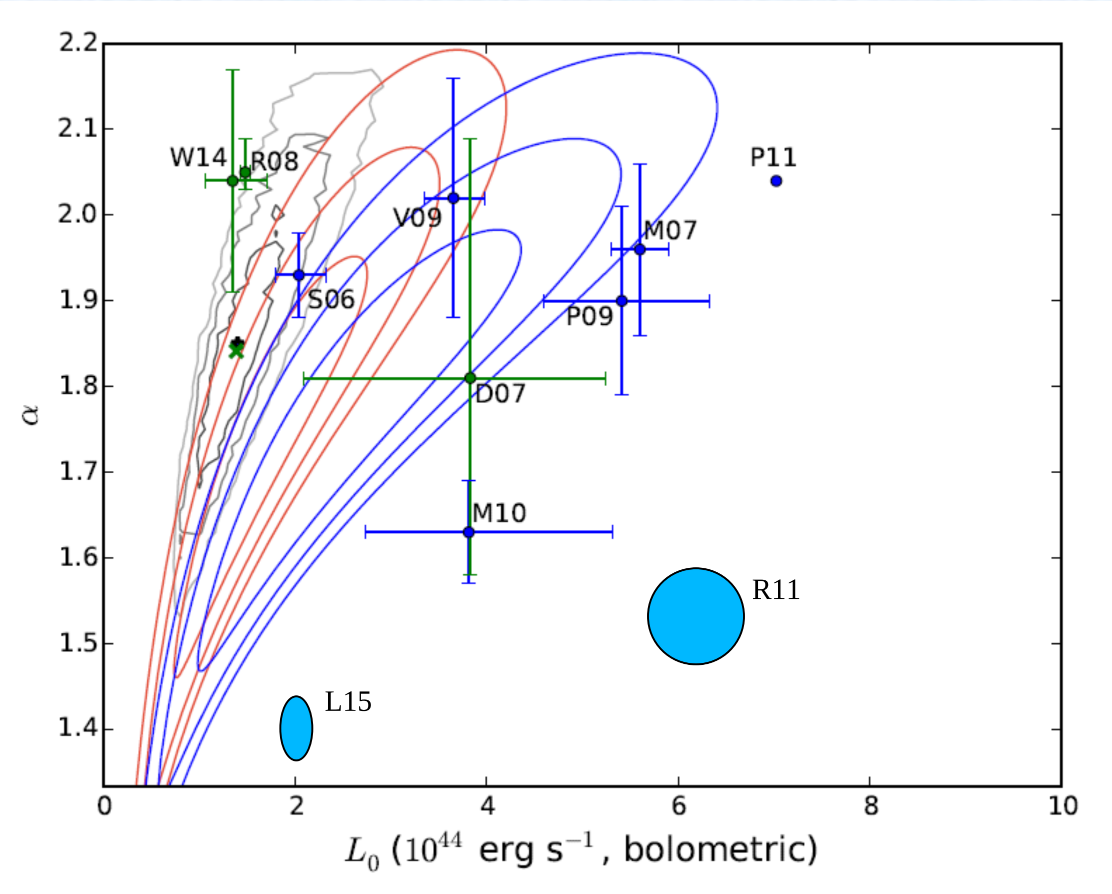
- A slope of ~ 3 with no significant sign of steepening for E dominated groups
- Likely steepening from spiral rich groups ?
- Eventually steepening as T is not a good measure of the underlying mass because of extra heating
- At $L_{bol} < 10^{42}$ erg/s , what about X-ray thermal halos of individual galaxies?

--- X-ray coronae known in groups and clusters (*Chandra* : Vikhlinin+2001; Sun+02; Sun+07; Jeltema+08)

--- Some works indeed included X-ray emission from member galaxies

--- in the stacked X-ray signal

$L - M$ relation

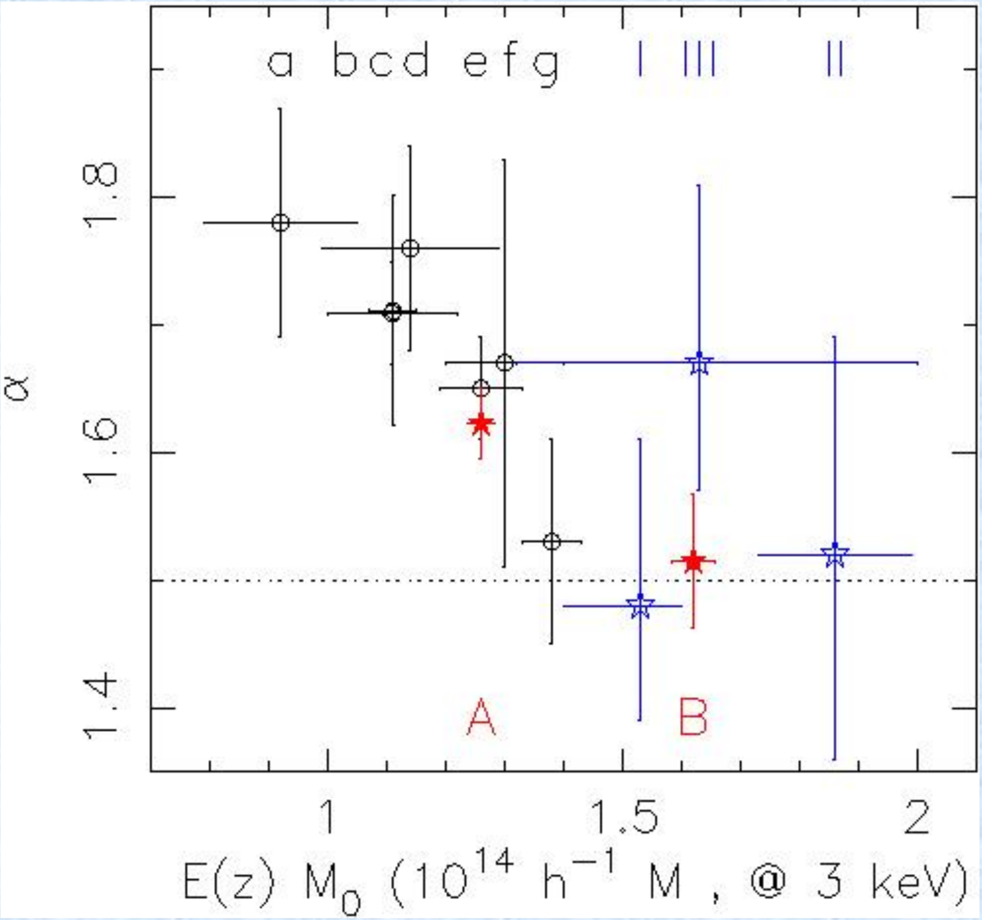


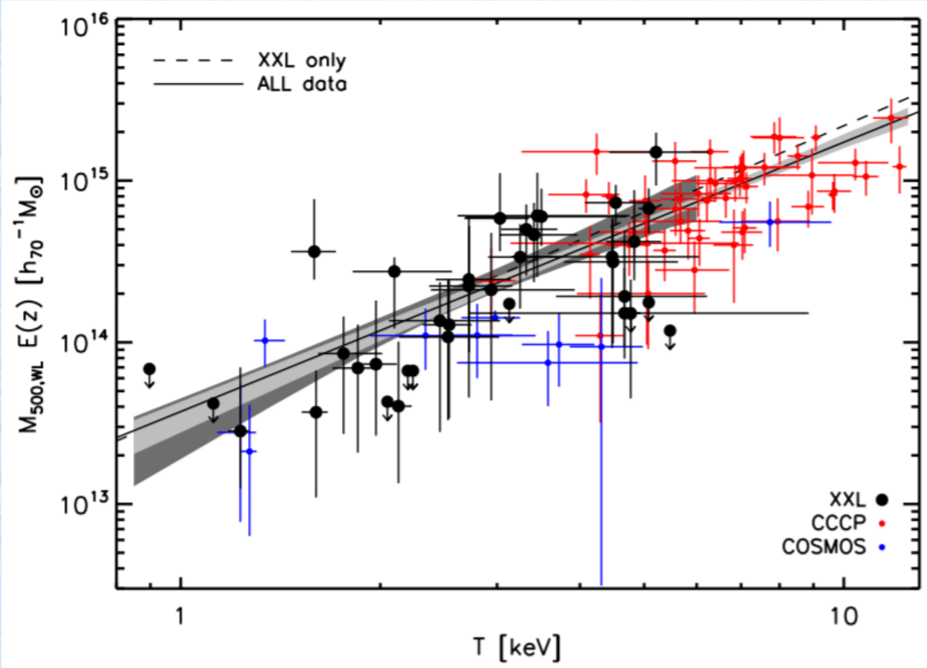
(S06: Stanek+06; D07: Dai+07; R08: Rykoff+08; M07: Maughan+08; V09: Vikhlinin+09; P09: Pratt+09; M10: Mantz+10; P11: Planck+11; R11: Reichert+11; W14: Wang, Yang+14; L15: Lovisari+15)

Anderson+ 2015 **with update (Thanks to Mike Anderson !)**

- Most results show slopes steeper than the self-similar relation (4/3)
- Selection bias? Mass calibration? HSE mass bias ?

M – *T* relation



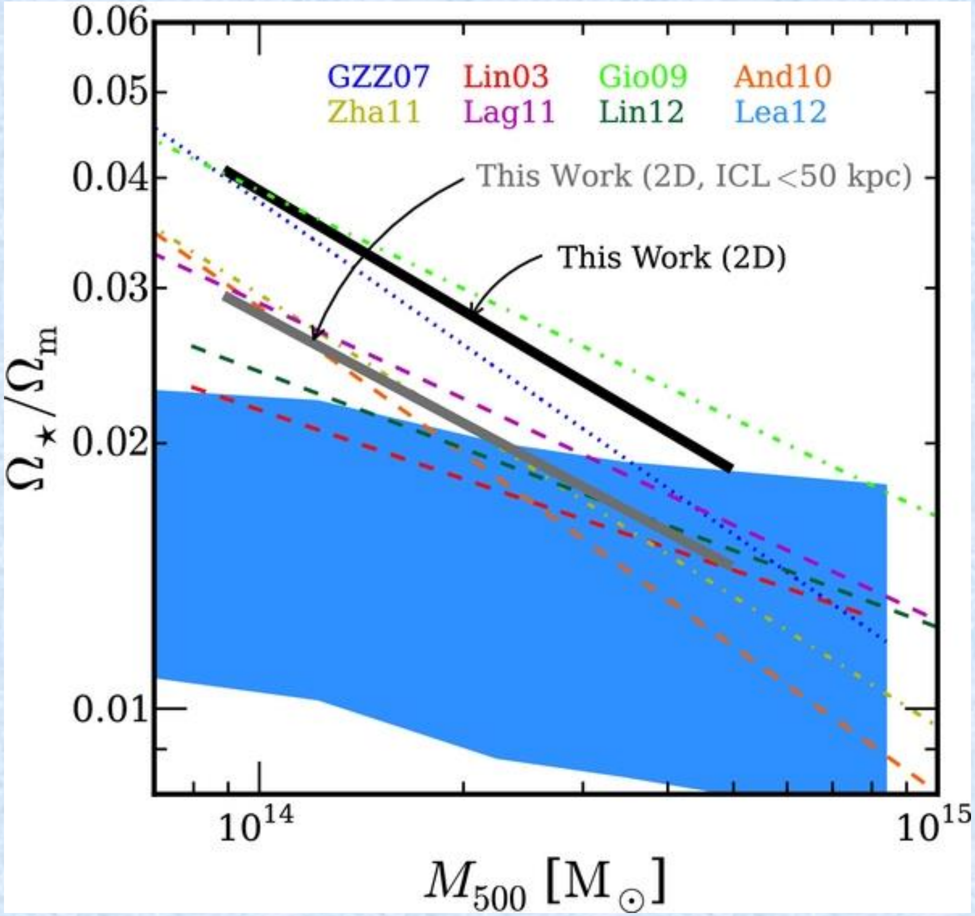


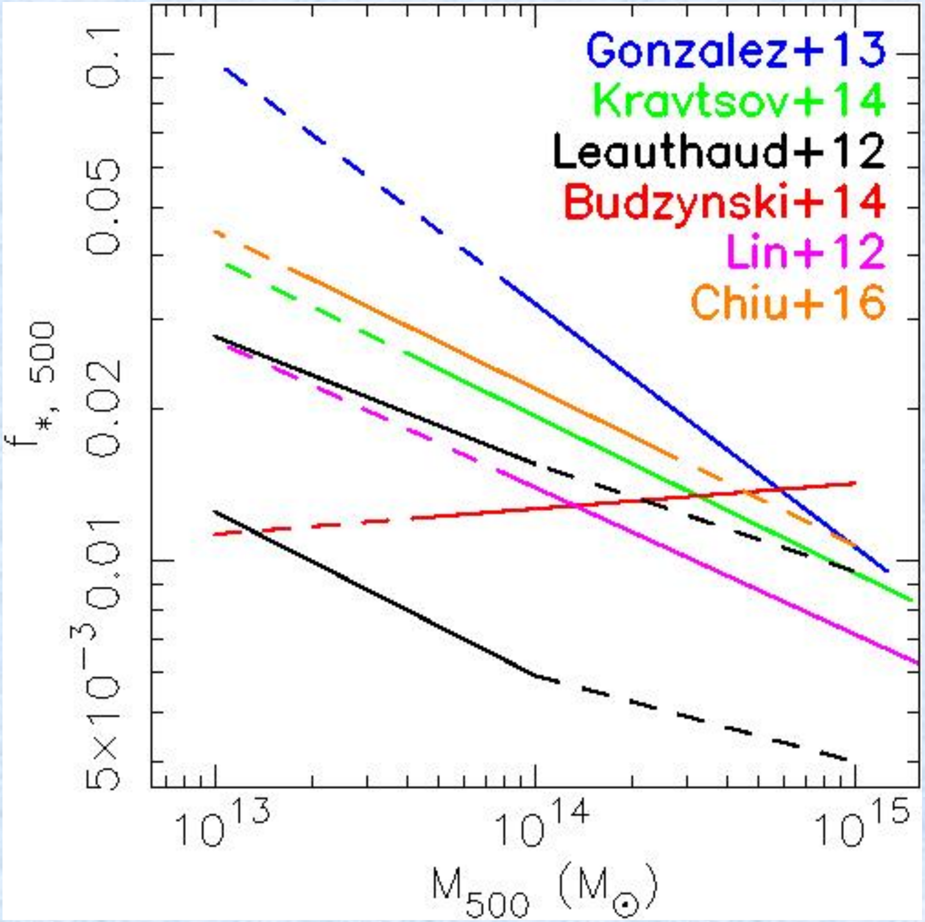
Lieu+ 2016 (XXL)

(~ 25% - 30 % mass bias)

a: Finoguenov+01; b: Lovisari+15; c: Arnaud+07; d: Reichert+11
e: Sun+09; f: Juett+10; g: Vikhlinin+09 A: Nagai+07 (HSE)
B: Nagai+07 (true) I: Kettula+13; II: Kettula+15; III: Lieu+16

Stellar mass fraction in groups / clusters





Left Fig. from Gonzalez+2013, including Lin+2003; Gonzalez+2007; Giodini+2009 (revised in Giodini+2012); Andreon 2010; Zhang+2011; Lagana+2011; Leauthaud+2012; Lin+2012
Right Fig., adds Budzynski+2014; Kravtsov+2014; Chiu+2016)

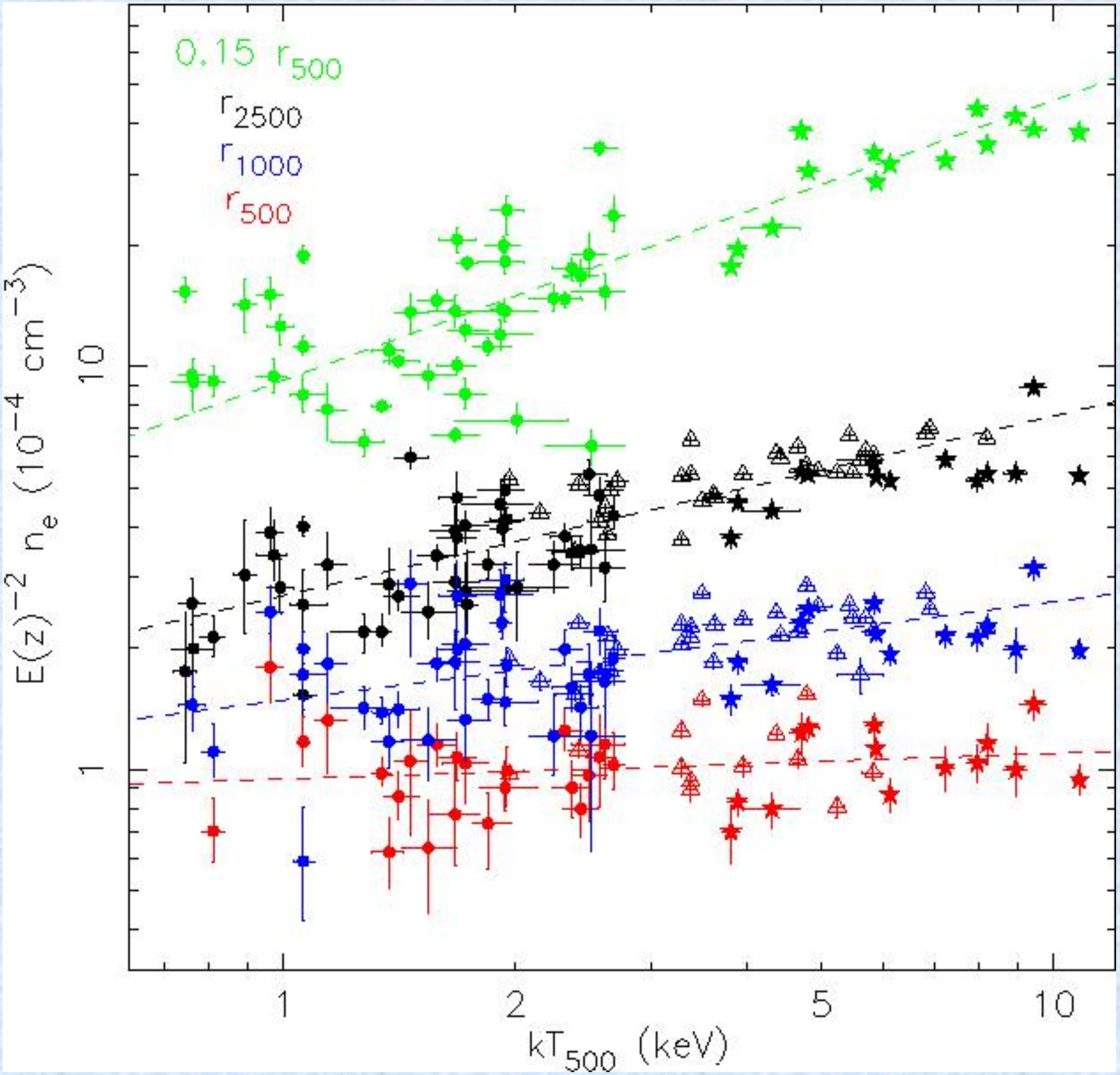
1) ICL contribution
2) Single *M* / *L* ratio ? (optical or NIR)
3) IMF (including variation, radial or galaxy-to-galaxy) ?
4) Others: different ways to estimate the halo mass; deprojection? LF correction (low-surface brightness galaxies)?

(See recent discussions in Leauthaud et al. 2012; Gonzalez et al. 2013; Budzynski et al. 2014; Kravtsov et al. 2014)

The ICL in groups ?

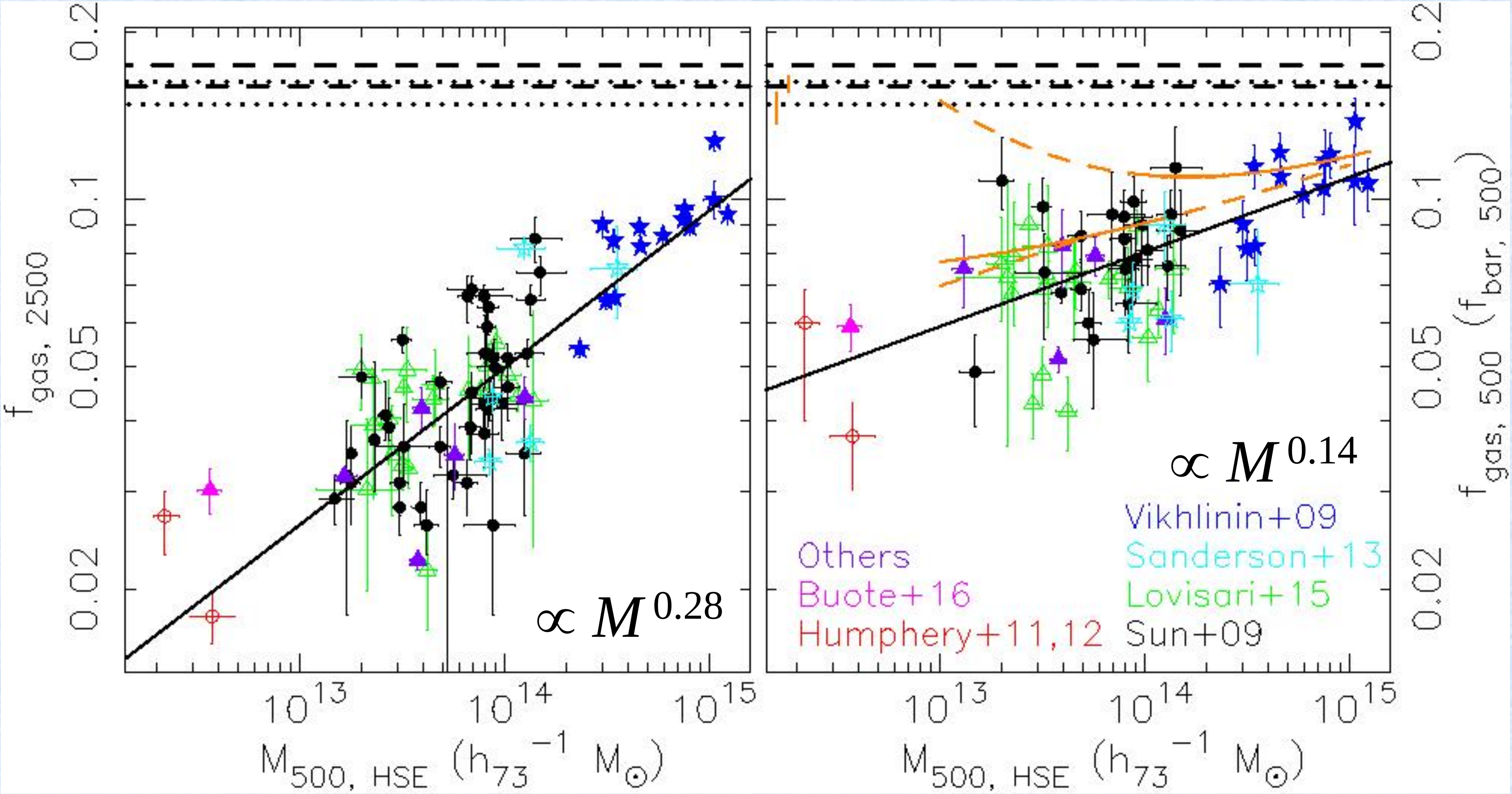
1) Stacking data (e.g., Budzynski et al. 2014 with SDSS)
2) Indirect tracers (e.g., McGee & Balogh 2010 --- SN; LMXB ?)
3) Direct NIR/optical imaging? (e.g., with low focal ratio telescopes like Dragonfly and LBC/LBT)

Halo gas / baryon fraction



Vikhlinin + 09; REXCESS (Pratt + 09); Sun + 09

Halo gas / baryon fraction



(Others: Gastaldello+2007; Democles+2010; Rasmussen+2010; Wong+2016; Morandi, Sun+2016)

Looks nice, but systematic uncertainty …

- ICM clumping:

 clumping factor, $C = \frac{\langle n_e^2 \rangle}{\langle n_e \rangle^2}$, generally around 1.5 – 2 at r_{200} (C = 1.8 → f_{gas} decreases by 25%)

- HSE mass bias:

 recent WL works suggest 40% to 10%, the mass dependence is still unclear; 40 % mass bias at M_{500} → 18% lower on $f_{gas,\,500}$ for $\beta = 0.5$

- Sample bias:

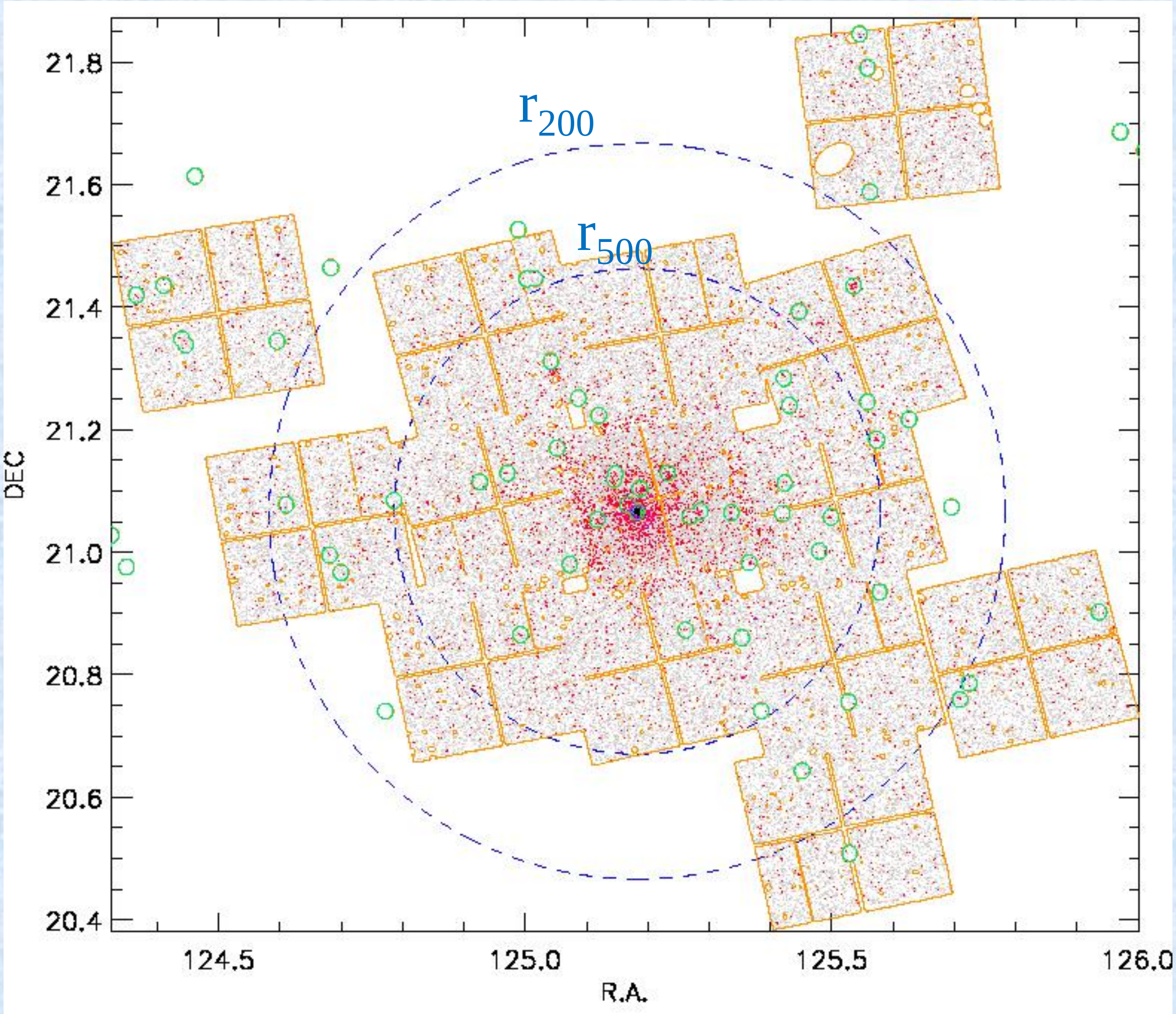
 Malmquist bias and X-ray selection bias

- And beyond r_{500} !

 f_{gas} ↑ at $r > r_{500}$ (NFW, $\beta = 0.5$, ~ 80% ↑ from r_{500} to r_{101})

NGC 2563 at z = 0.0157

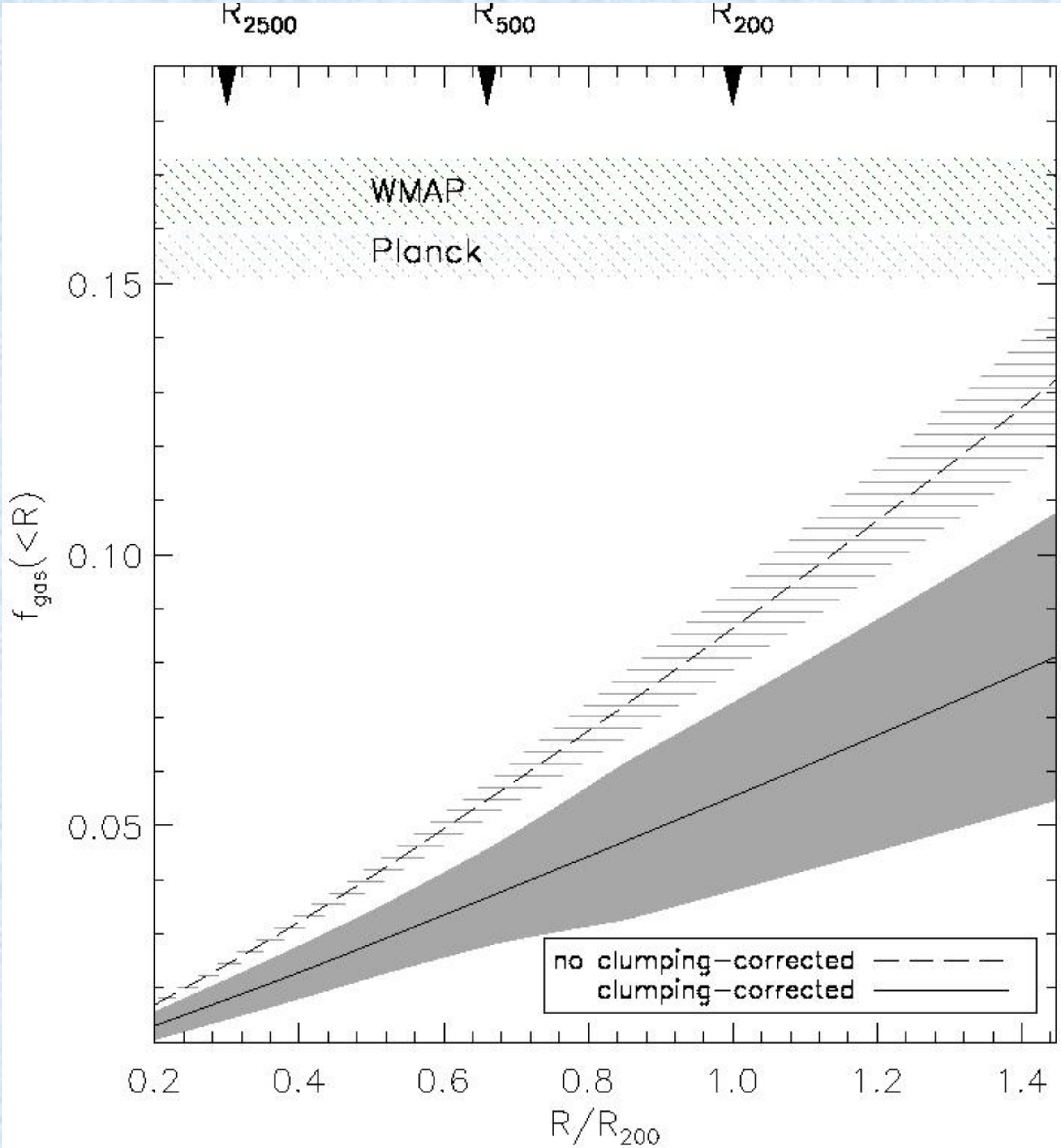
15 ACIS-I observations with a total clean exposure of 430 ks (PI: Mulchaey)!



(r_{500} = 456 kpc)

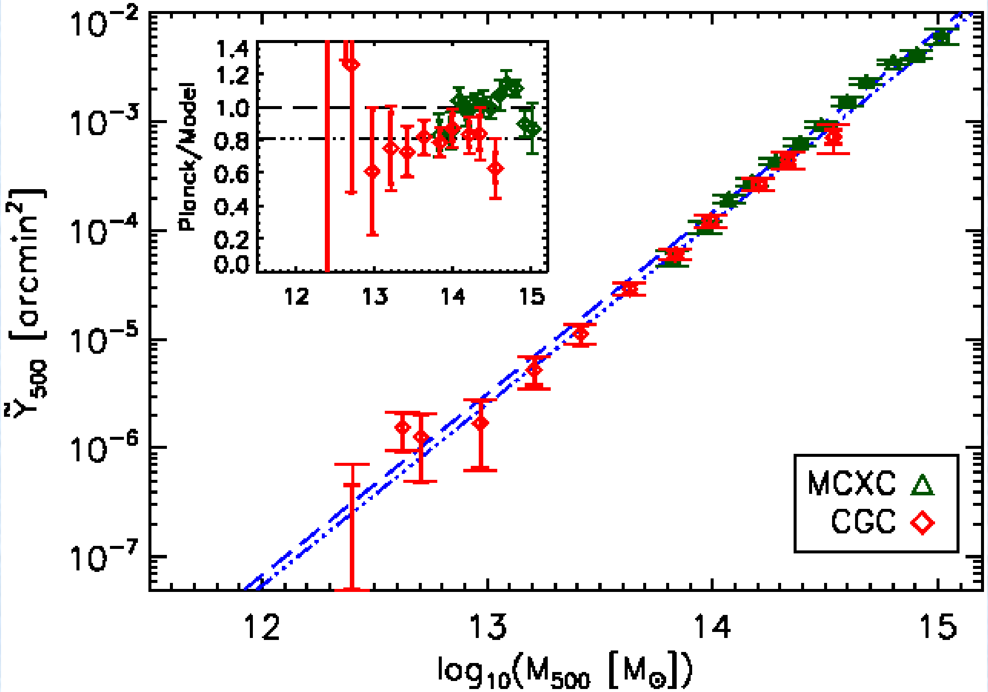
Morandi, Sun et al. 2017

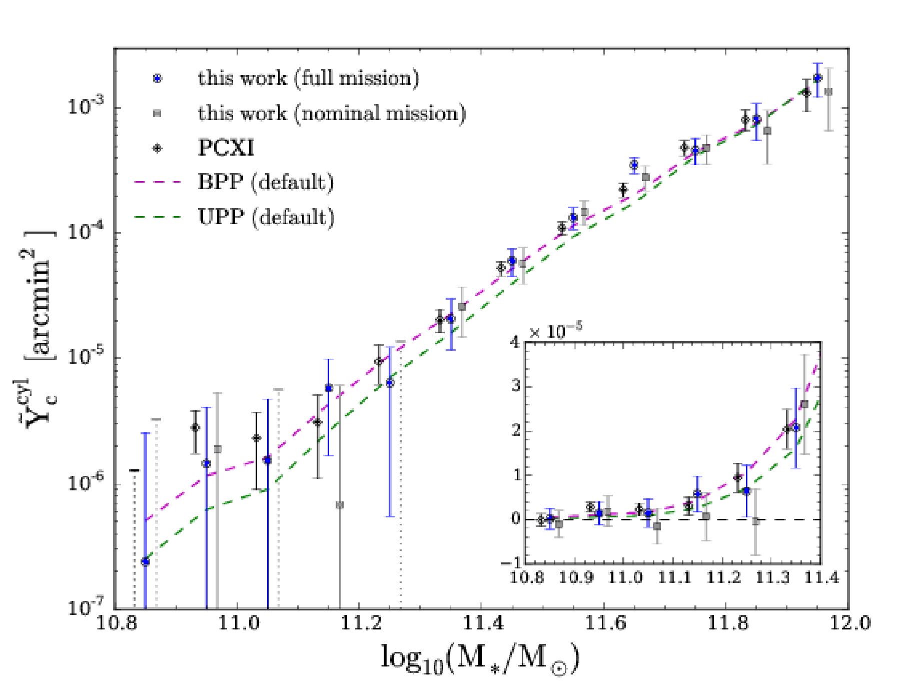
Results to be posted soon …



Morandi, Sun et al. 2017

Self-similar to $M_{500} \sim 4 \times 10^{12}$ M_{Sun} ?



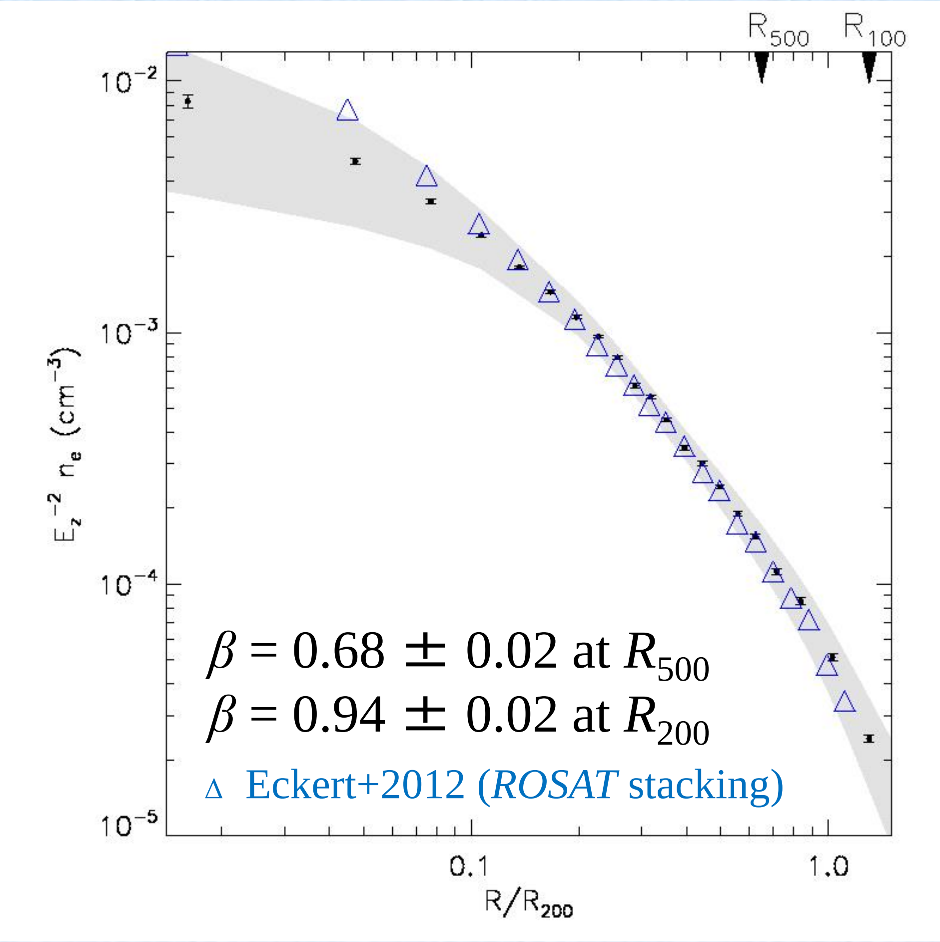


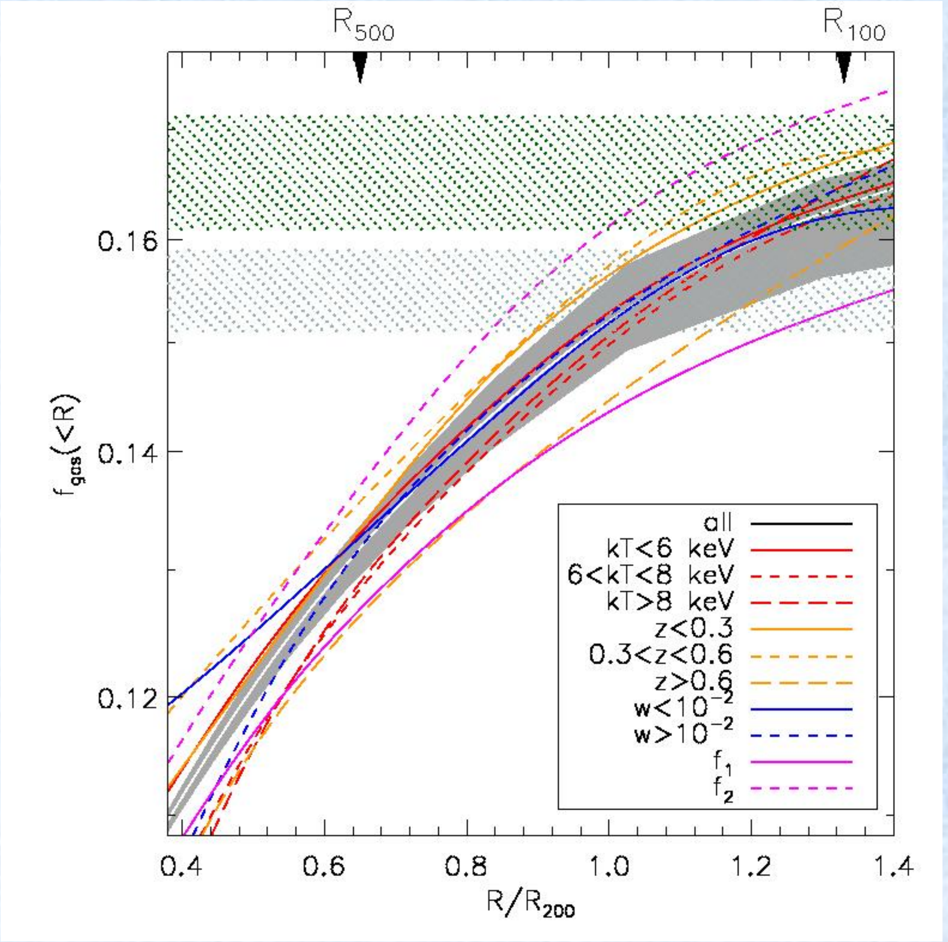
Planck Intermediate Result XI (2013) Greco+2014

Le Brun+2015 suggested that the apparent conflict between Planck stacking and the known gas fraction of groups is from the inappropriate spatial template in the Planck analysis. However, fluxes measured within 5 r_{500} would only have ~ 10% bias

--- gas ejection beyond r_{500} in low-mass halos ?

The cluster outskirts probed by *Chandra* “stacking”





320 clusters at $0.056 < z < 1.24$ with $kT > 3$ keV (~ 7 keV median)

20 Ms data !

Morandi, Sun + 2015

Outskirts of groups via stacking:

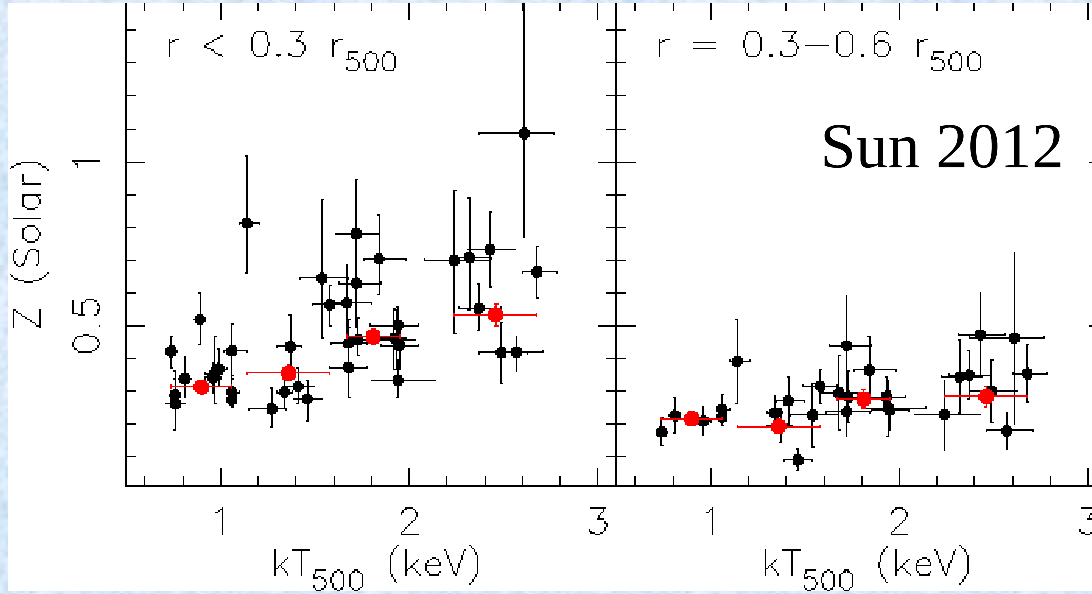
- 71+ groups (kT = 0.8 - 2.8 keV, z < 0.15), 4.2 Ms+ *Chandra* observations
- Use abundance template from a small sample of best-studied groups
- Initial results (only weighted average) on a subsample of 12 groups:

$\beta \sim 0.55$ between r_{500} and r_{200} (consistent with some *Suzaku* results on 3 groups, e.g., Wong+2016; Nugent+2017)

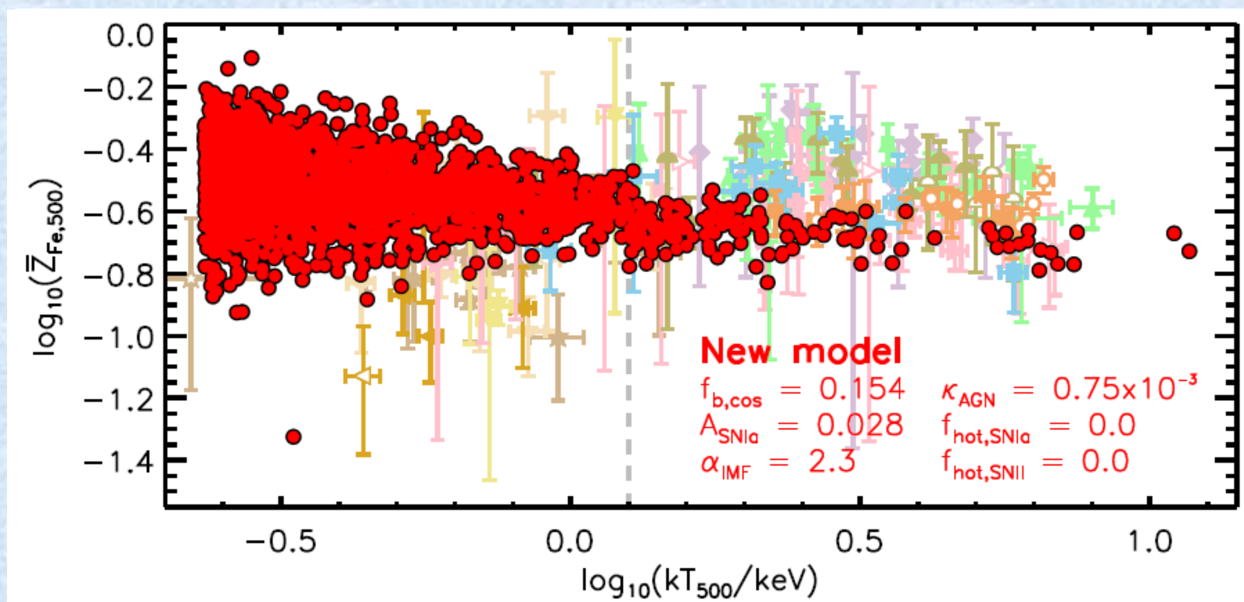
more to come …

Hot gas metal content

Hot gas becomes progressively iron poor around the center with decreasing mass. *How to remove metal-rich gas in groups? Where are the metals? Too much metal in clusters (e.g., Loewenstein 2013; Renzini & Andreon 2014)*



(also see Rasmussen & Ponman 2009)



Yates+2017

Conclusions

1) Hot gas, star and metal content of galaxies to clusters puts strong constraints on our models of baryon physics.

2) Groups are hot gas poor compared to clusters but the contrast is smaller at r_{500}. Will we find a lot of gas and metals beyond r_{500} or even r_{200} in groups?

3) Important to study systematic uncertainty and selection effects of scaling relations.

Looking forward …

1) It is more and more expensive to observe groups and galaxies with *Chandra* now (0.97 keV: count rate decreases by 40% from cy14 to cy18; 50% for 0.54 keV: during the same period!). *XMM* becomes more important now. We are all waiting for *eRosita*, *Athena+* (2028) and likely *X-ray surveyor / Lynx* (hopefully 2034) !
2) How to move forward now for groups?
   a) WL mass calibration
   b) stacking short exposures of a large optically selected sample