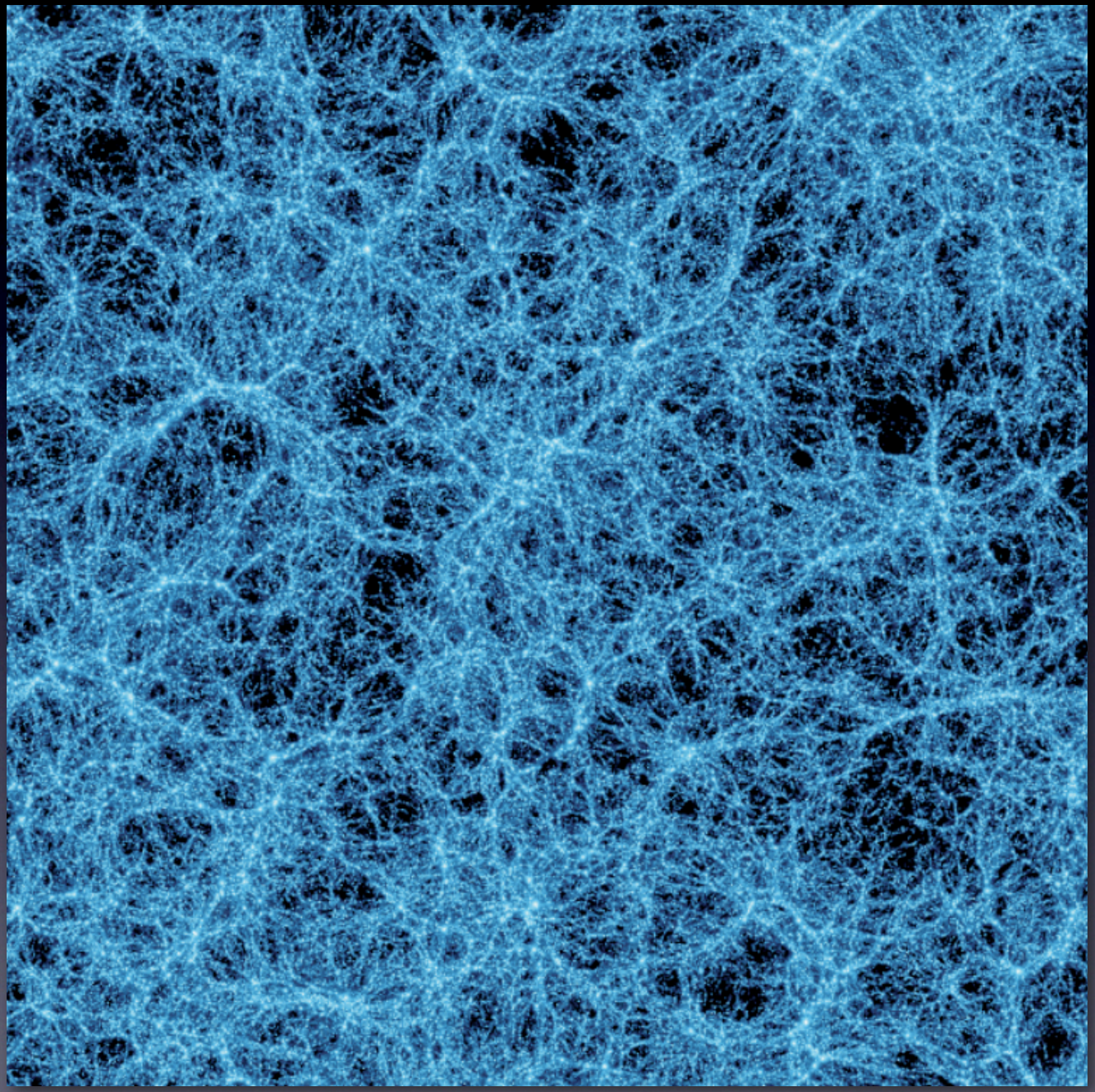
Scalings from Millennium Gas Simulations

Becky Stanek
Elena Rasia
Gus Evrard
Departments of Physics and Astronomy
Michigan Center for Theoretical Physics
University of Michigan

Millennium Gas Simulations



GADGET-2 resimulations of Millennium Sim volume @ Nottingham (F. Pearce)

- 500 Mpc/h
- 1e9 gas+DM particles
- m_p(DM) ~ 1.4e10 Msun
- 25 kpc/h softening
- same cosmology as MS

TWO physical treatments:

GO: gravity only

PH: preheated gas
200 keV-cm2 @z=4

Stanek et al, 0910.1599
2010 ApJ, 715, 1508

Hartley et al. (2008)
Stanek, Rudd, AE (2009)
Short et al., 1002.4539

brief history of preheating...

- introduced in back-to-back ApJ papers almost 20 years ago to solve n(Lx) shape for `standard' CDM model

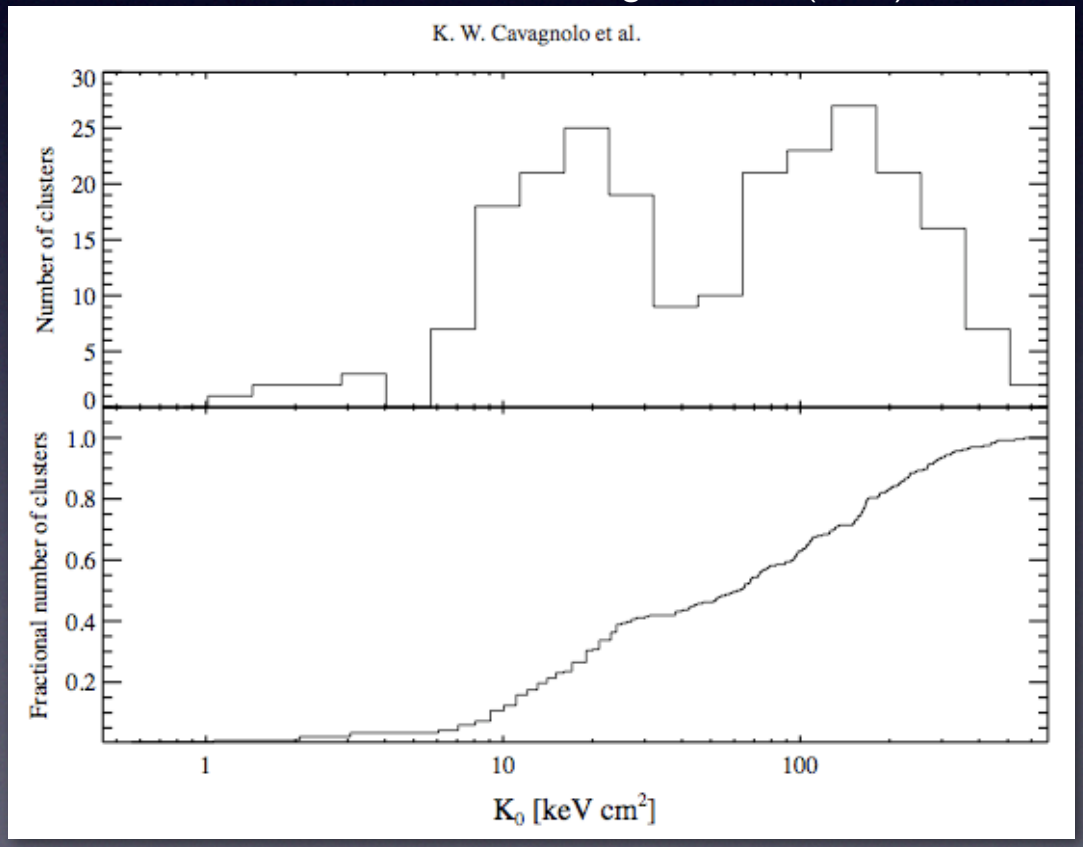
Kaiser (1991)
Evrard & Henry (1991)

- simulations tuned entropy level required to `tilt' L-T relation to match observations

Bialek et al (2001)

- motivated by predominance of `red + dead' galaxies in rich clusters => formed stars and SMBH at early epoch
- empirical support from Chandra analysis of core entropy behavior (ACCEPT sample)

Cavagnolo et al (2009)



your views on preheating? grab your clicker!

What statement best describes your view of preheating?

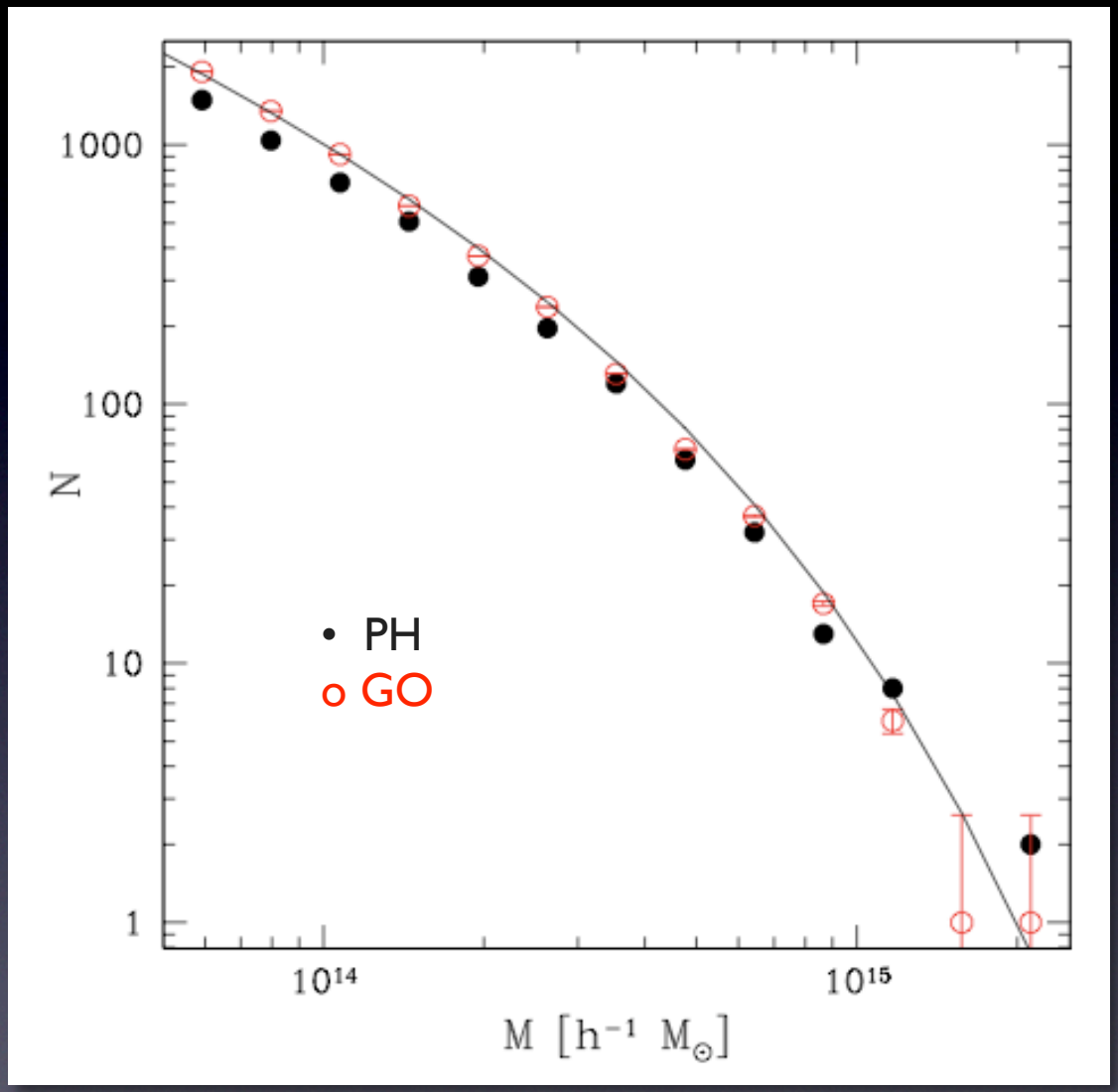
A. It's far too crude to be interesting. Fuggetaboutit.

B. It's a perfect model - only one free parameter!

C. It's an approximate, effective model for ICM behavior outside the core of massive clusters.

D. What's preheating again?

MGS massive halo yield



– halos at z=0 with $M_{200c} \geq$ 5e13 Msun/h:

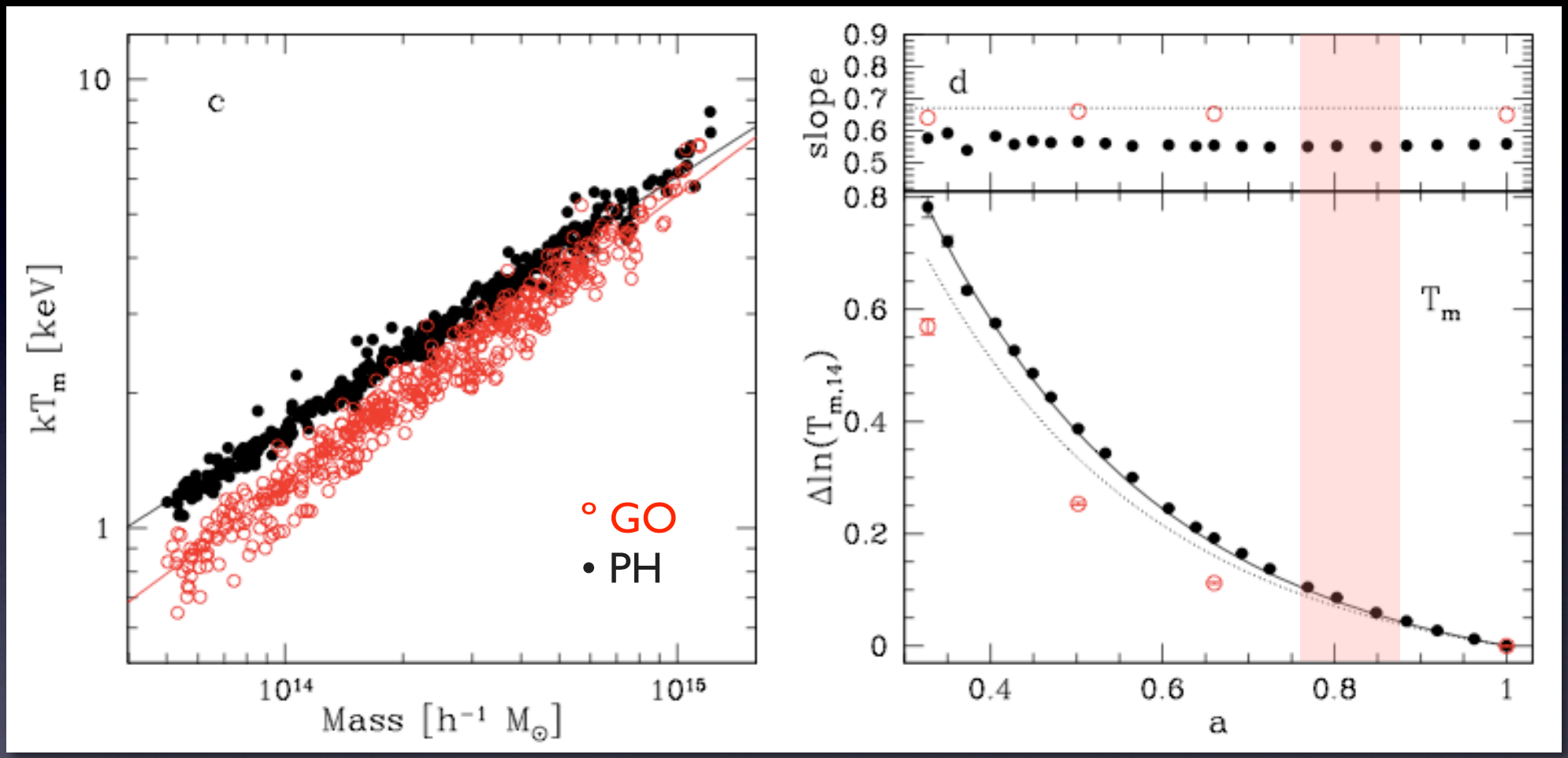
4474 (PH)
5612 (GO)

– 63 output redshifts to z=2 for population evolution, halo formation histories

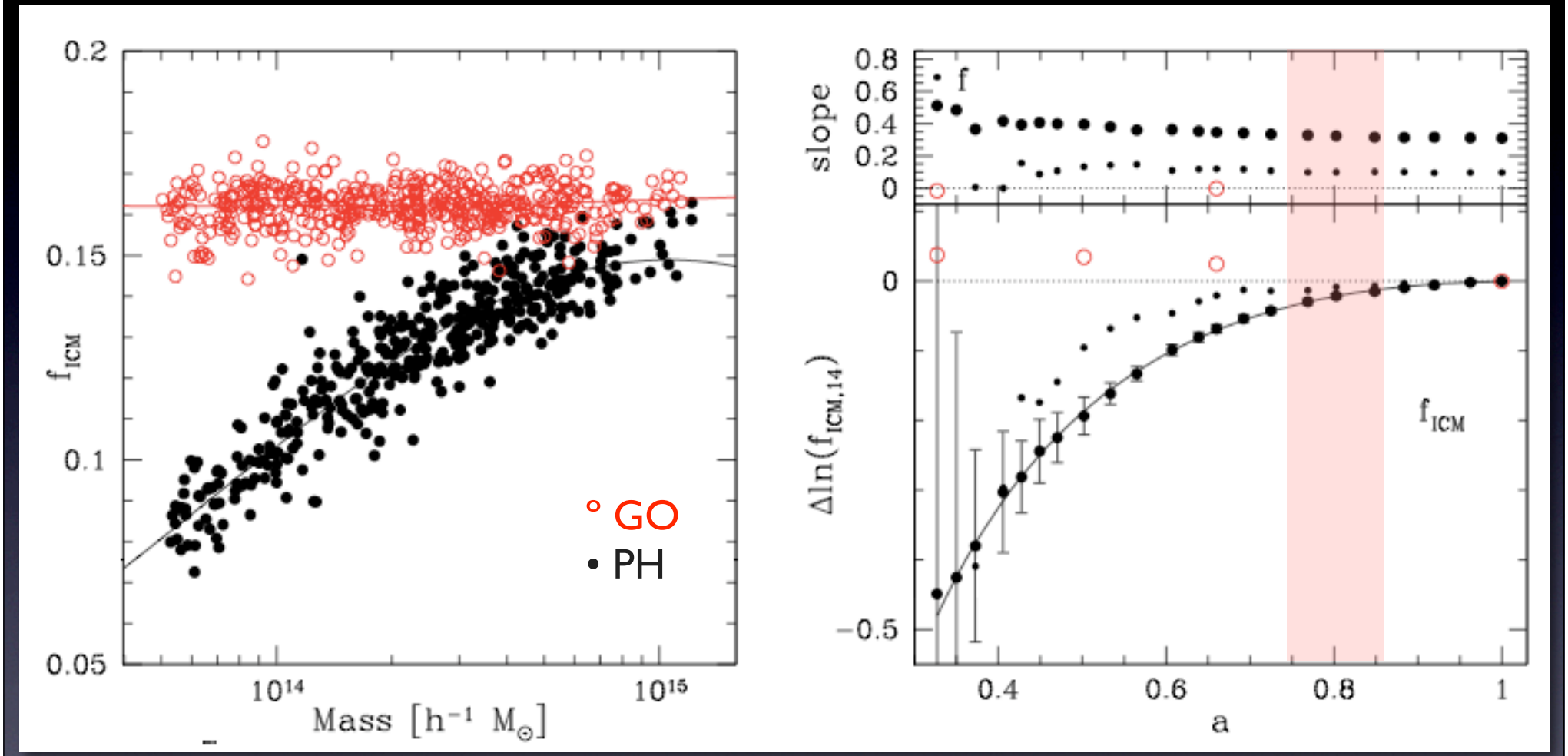
>100,000 halos overall

baryon physics effect on mass function - Stanek, Rudd, AE (2009)

MGS scaling : mass-weighted temperature



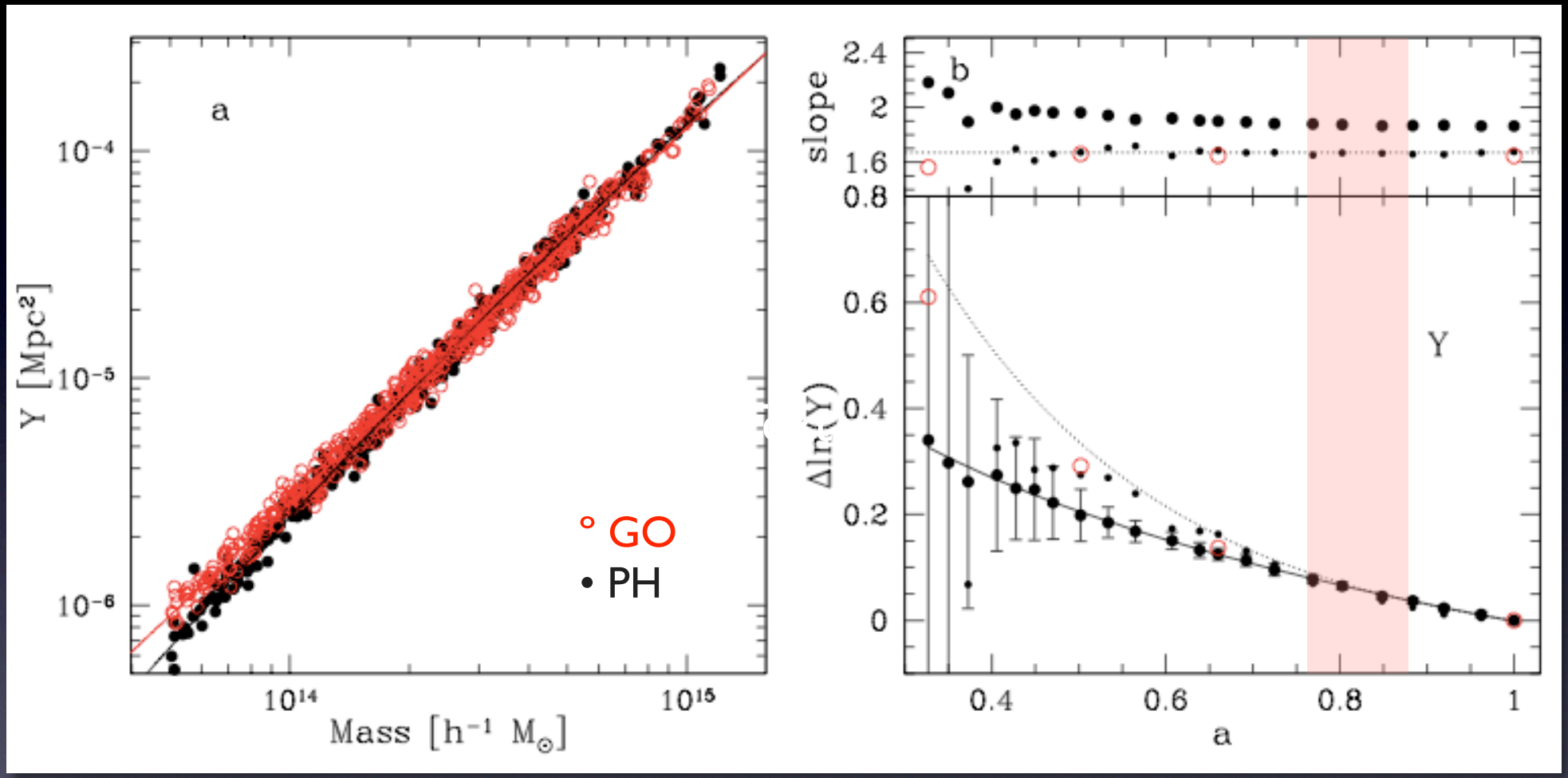
MGS scaling : ICM mass fraction



solid: quadratic fit in ln(M)

large dots: values at 1e14 Msun/h
small dots: values at 5e14 Msun/h

MGS scaling : SZ Y-parameter



solid: quadratic fit in ln(M)

large dots: values at 1e14 Msun/h
small dots: values at 5e14 Msun/h
solid: quadratic fit in ln(a)

MGS with SAM feedback (FO) : SZ Y

Te

° GO
• PH

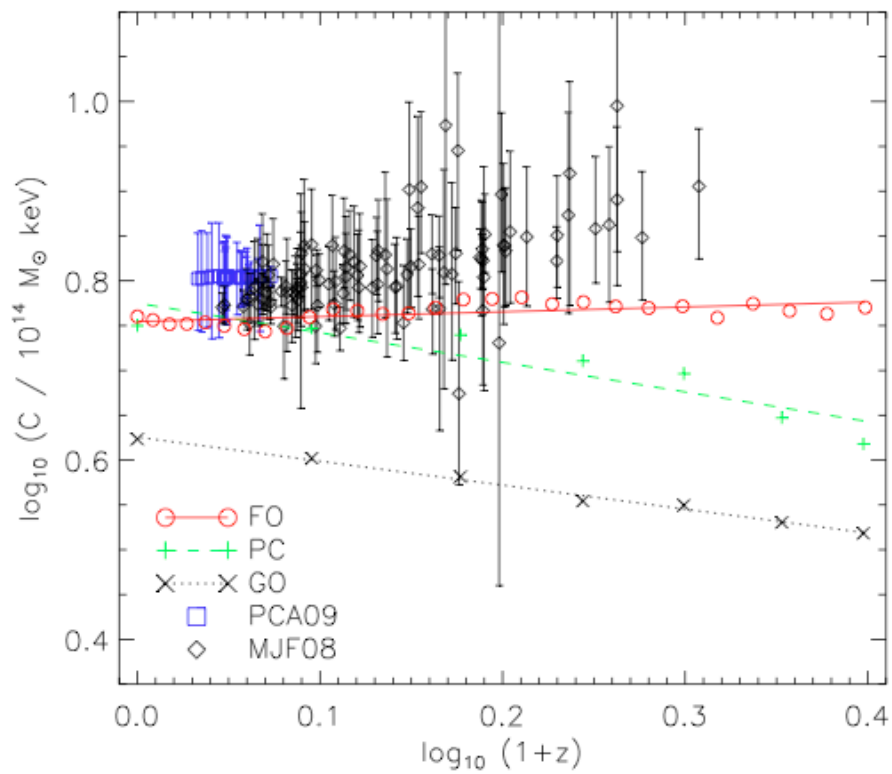
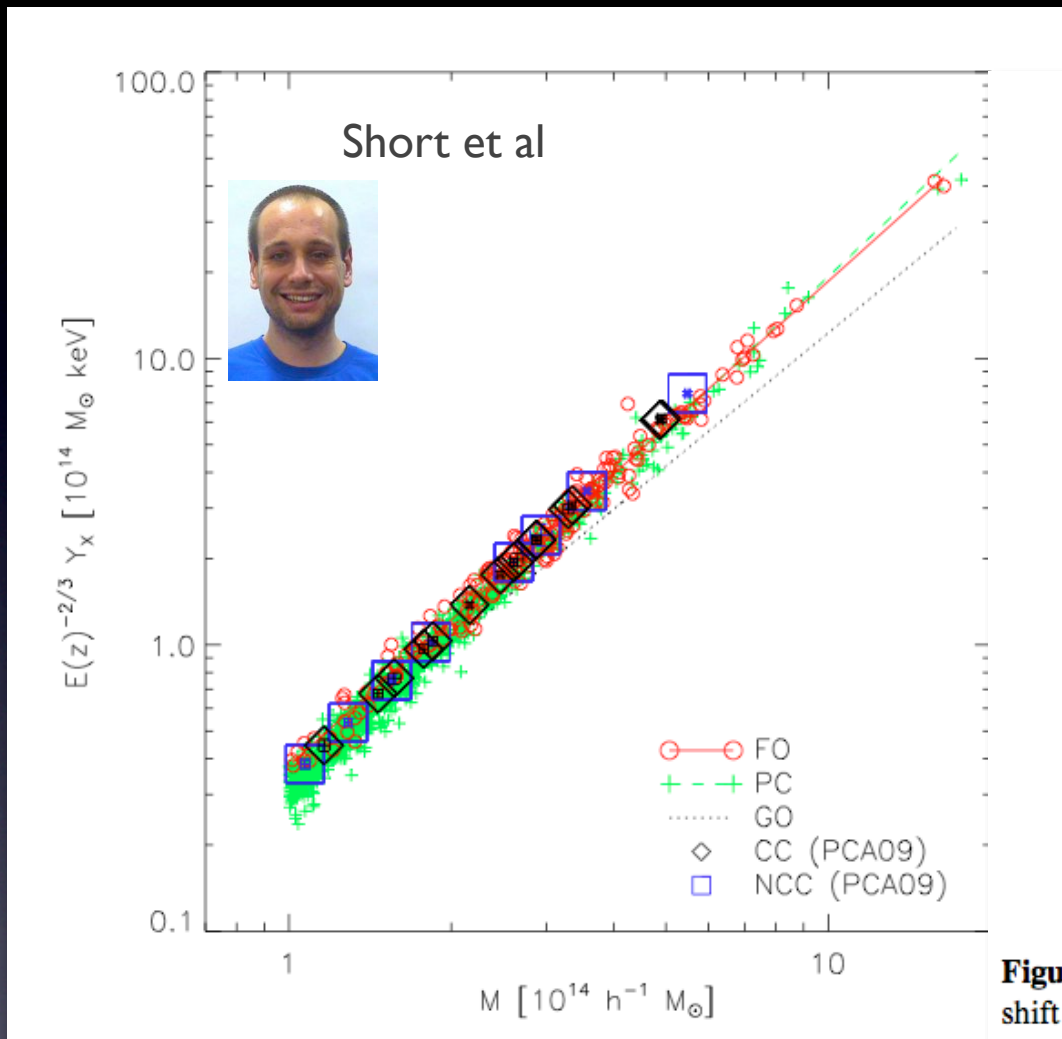


Figure 9. Normalisation of the Y_X-M scaling relation as a function of redshift for each of the Millennium Gas simulations. Low-redshift observational data from REXCESS (PCA09) and the high-redshift data of MJF08 is shown for comparison. 1σ error bars are also plotted for the observational data.

MGS with SAM feedback (FO) : SZ Y



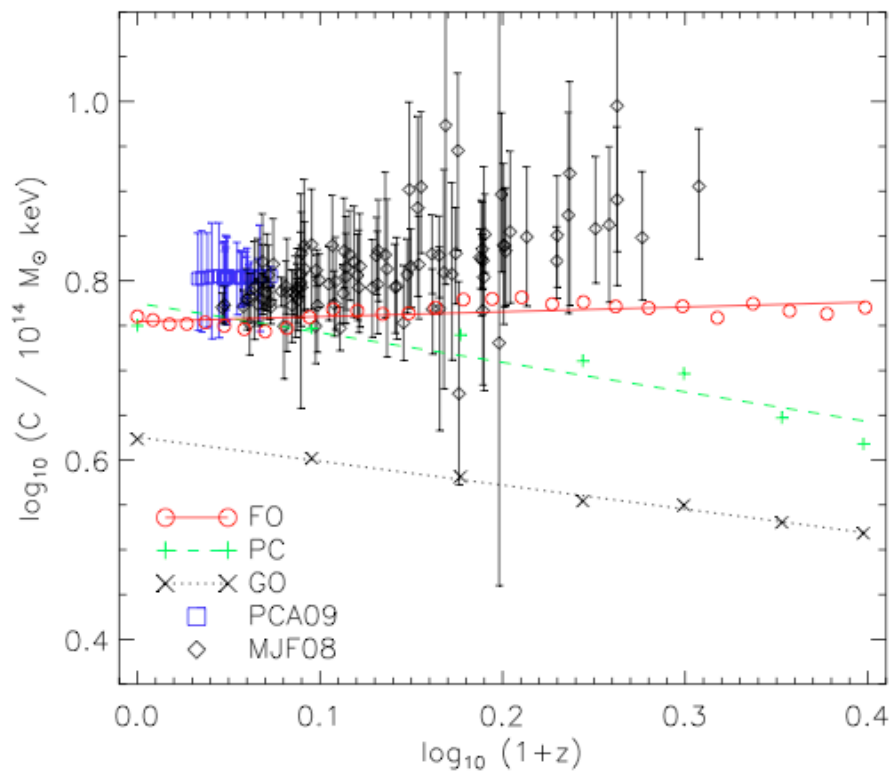
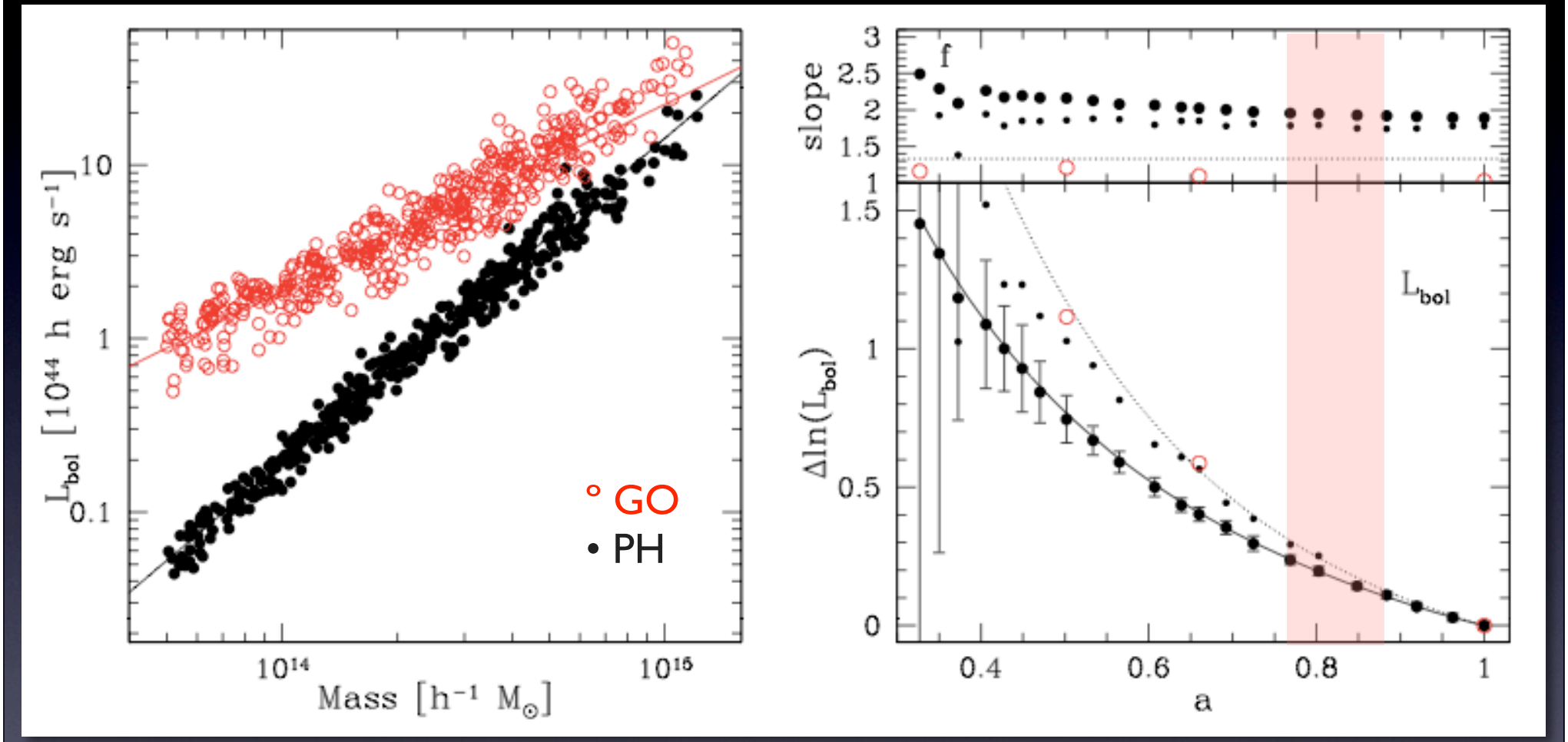


Figure 9. Normalisation of the Y_X-M scaling relation as a function of redshift for each of the Millennium Gas simulations. Low-redshift observational data from REXCESS (PCA09) and the high-redshift data of MJF08 is shown for comparison. 1σ error bars are also plotted for the observational data.

MGS scaling : bolometric X-ray luminosity

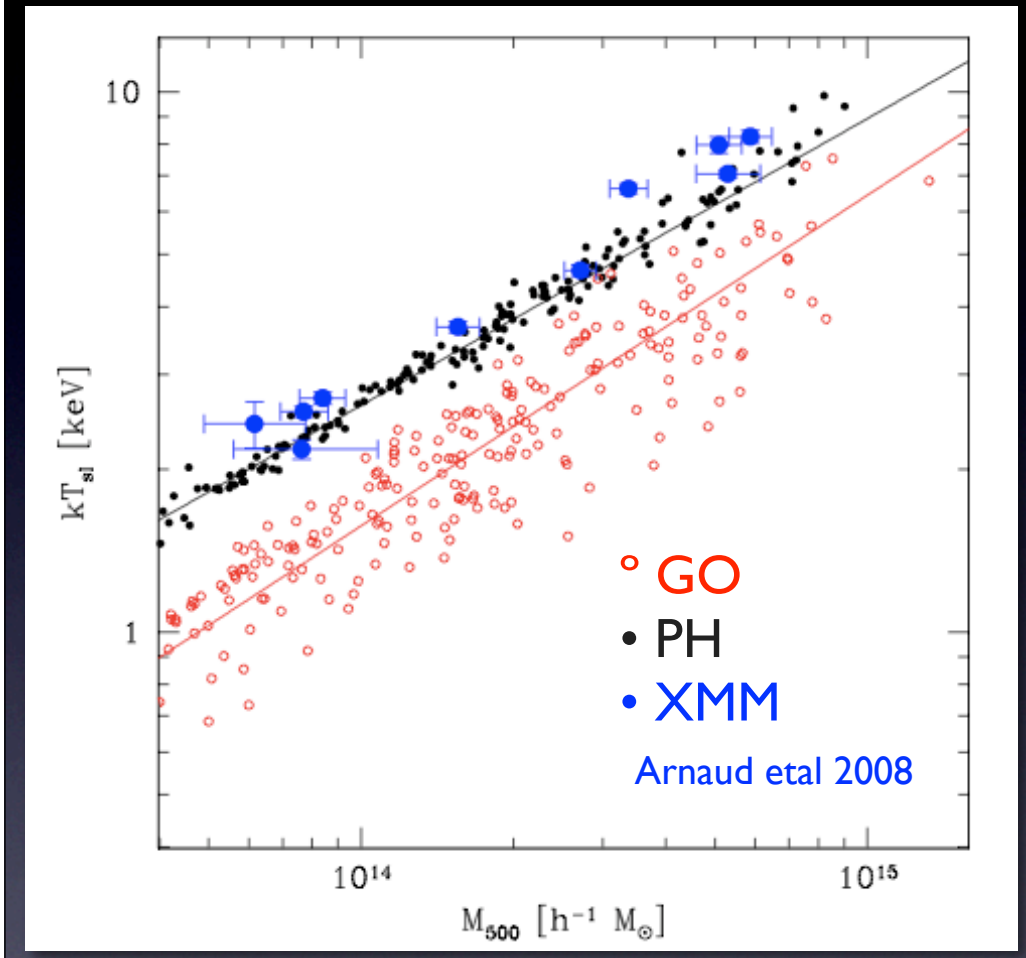


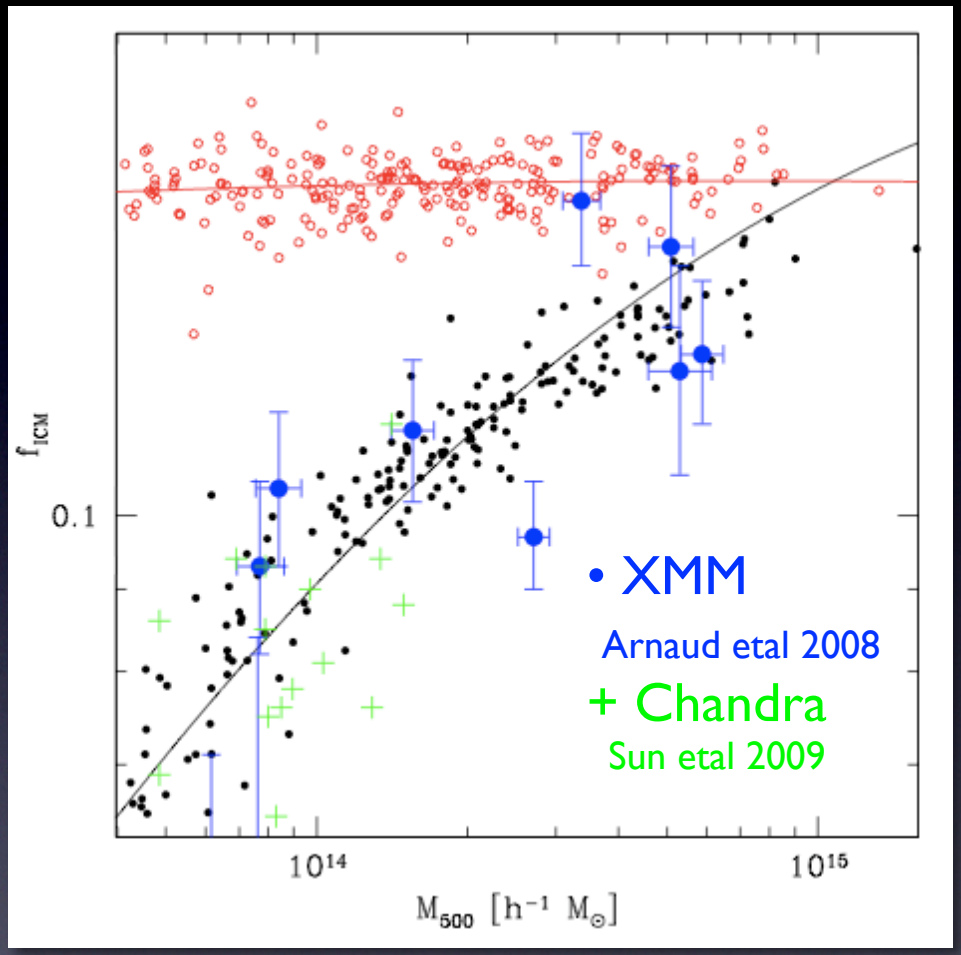
solid: quadratic fit in ln(M)

large dots: values at 1e14 Msun/h
small dots: values at 5e14 Msun/h
solid: quadratic fit in ln(a)

MGS: comparison to observations

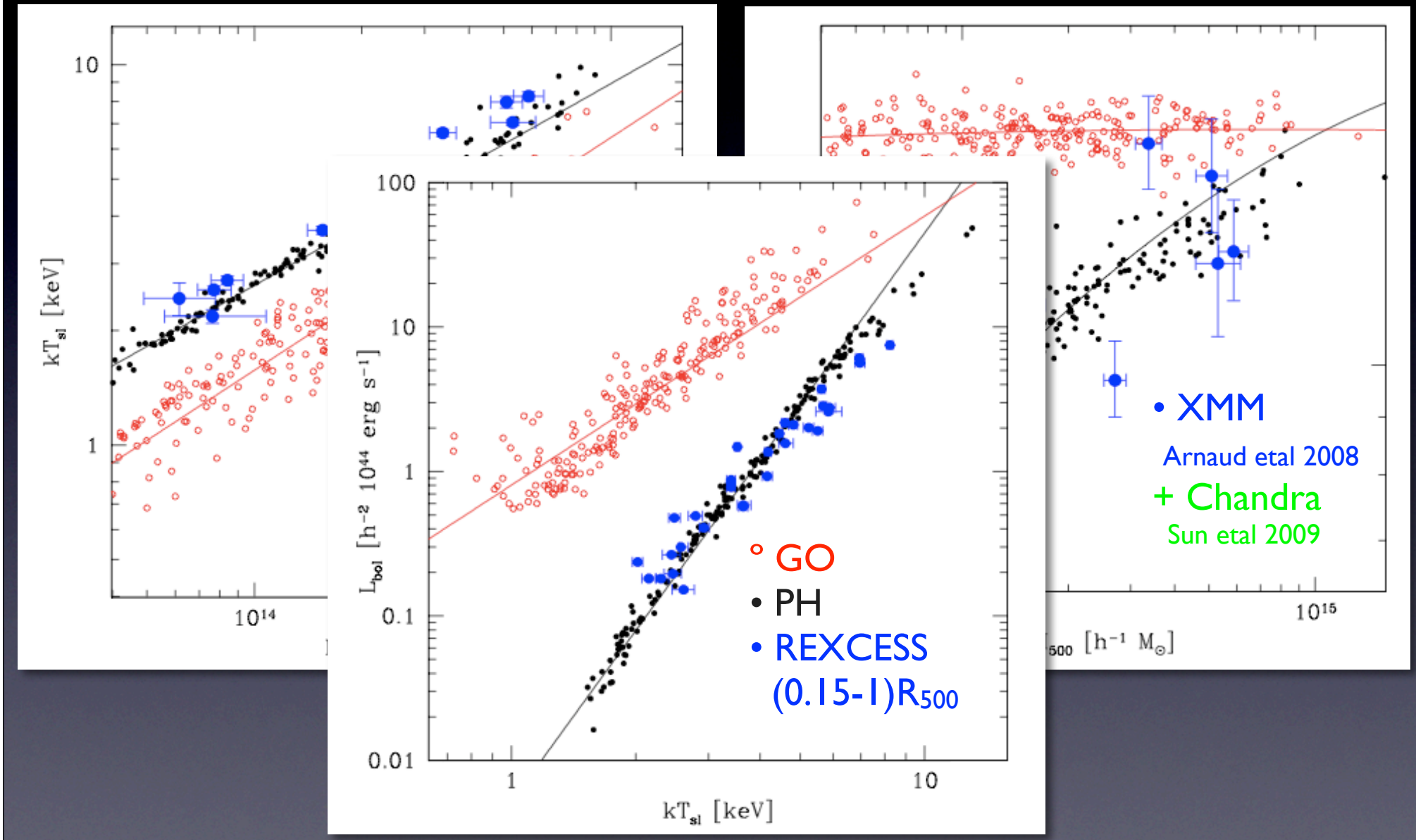
Stanek et al, 0910.1599





MGS: comparison to observations

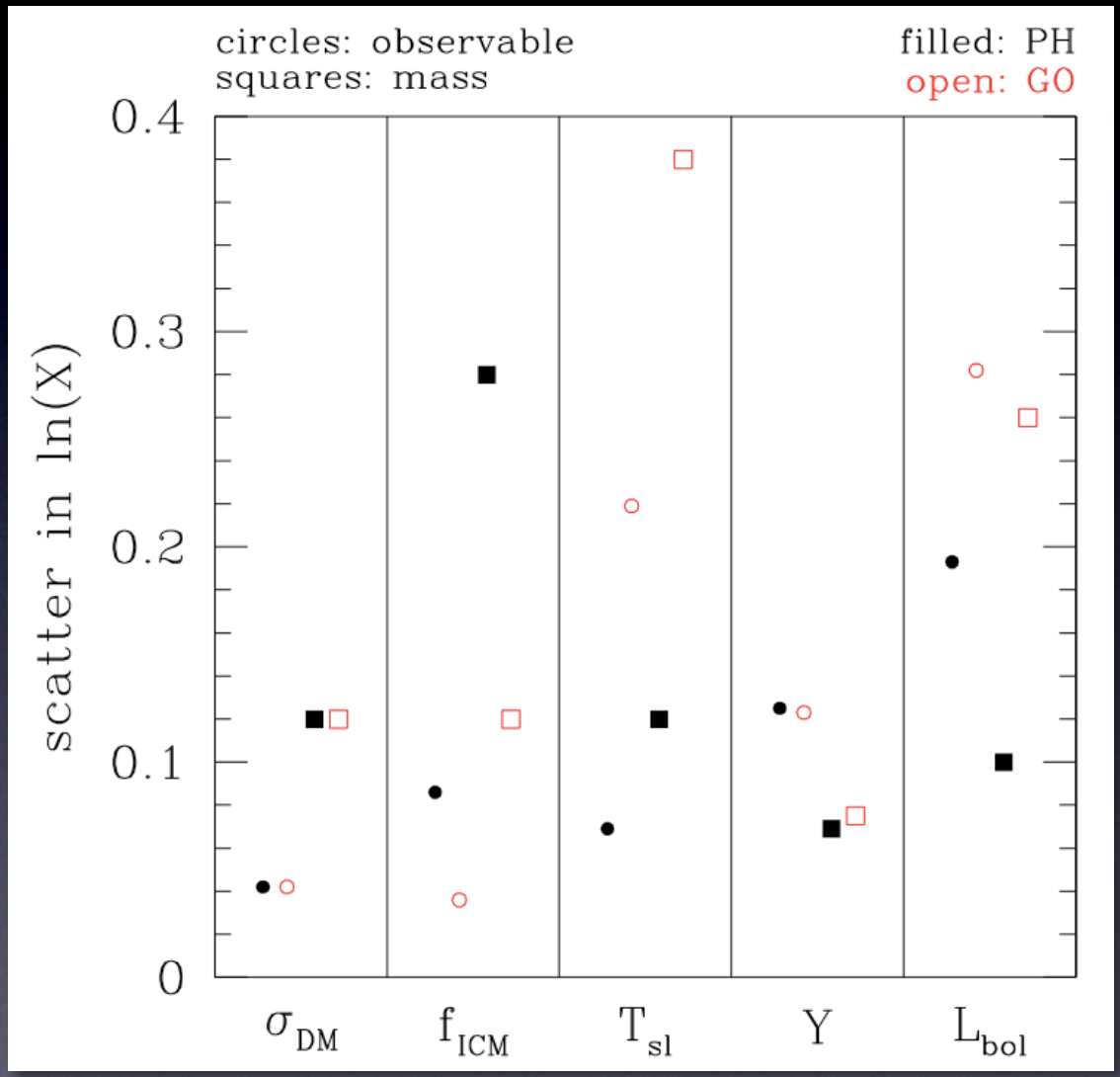
Stanek et al, 0910.1599



MGS scaling : variance about mean scalings

$\sigma_{\mu i} = \sigma_i / m_i$ mass scatter in ith observable

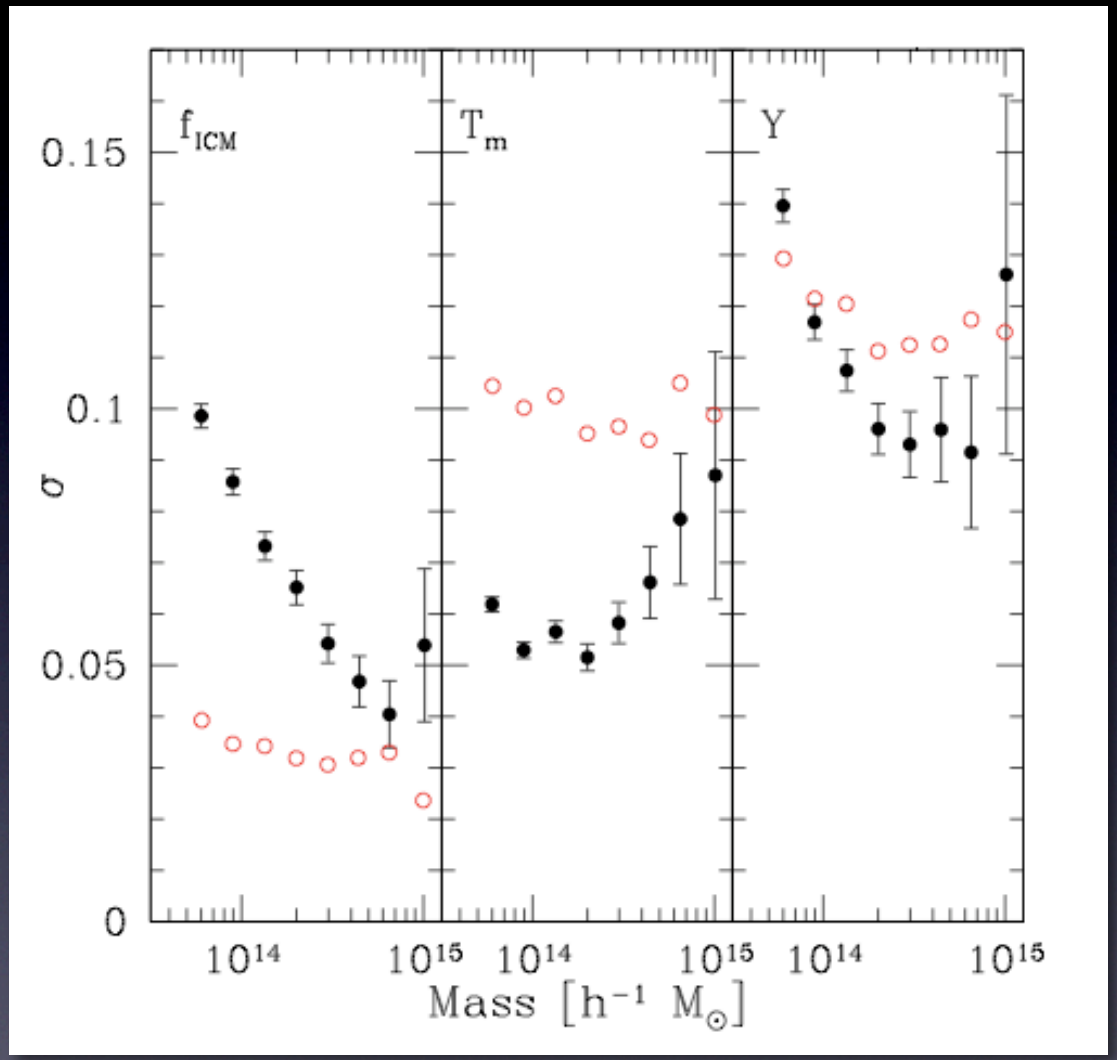
For ICM, Y has smallest mass scatter and is stable across PH/GO treatments



MGS scaling : mass dependence

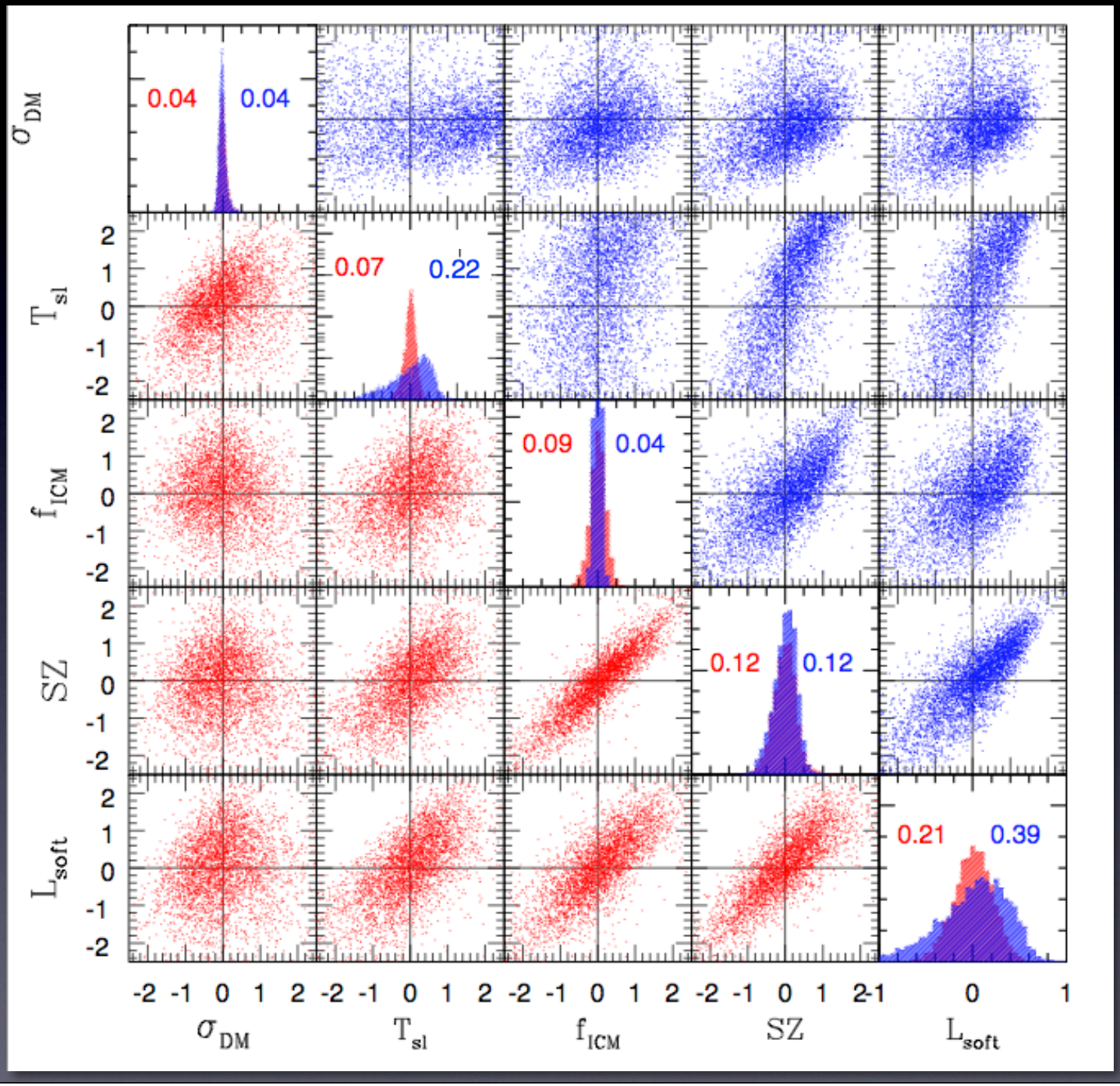
Strong mass dependence of scatter in ICM mass fraction <~3e14 Msun/h.

Scatter above this mass (esp. in Y) is constant.



MGS: covariance of multiple INTRINSIC signals at fixed halo mass

Stanek et al 2010



preheating
gravity only

MGS: covariance of multiple intrinsic signals at fixed halo mass

Stanek et al 2010

TABLE 6
CORRELATION COEFFICIENTS AT REDSHIFT ZERO [a]

Signal	$\sigma_{\rm DM}$	T_m	$T_{\rm sl}$	$f_{\rm ICM}$	Y	$L_{\rm bol}$	$\hat{Q}$	c
$\sigma_{\rm DM}$	–	0.55	0.81	0.28	0.54	0.51	0.17	0.19
T_m	0.35	–	0.85	0.48	0.97	0.67	0.38	0.49
$T_{\rm sl}$	0.86	0.5	–	0.42	0.83	0.67	0.47	0.64
$f_{\rm ICM}$	-0.10	0.42	0.37	–	0.69	0.60	0.32	0.37
Y	0.079	0.74	0.62	0.88	–	0.73	0.40	0.51
$L_{\rm bol}$	0.26	0.50	0.73	0.76	0.78	–	0.65	0.70
$\hat{Q}$	0.32	0.029	0.56	0.15	0.12	0.59	–	0.71
c	0.15	0.053	0.39	0.29	0.26	0.51	0.64	–

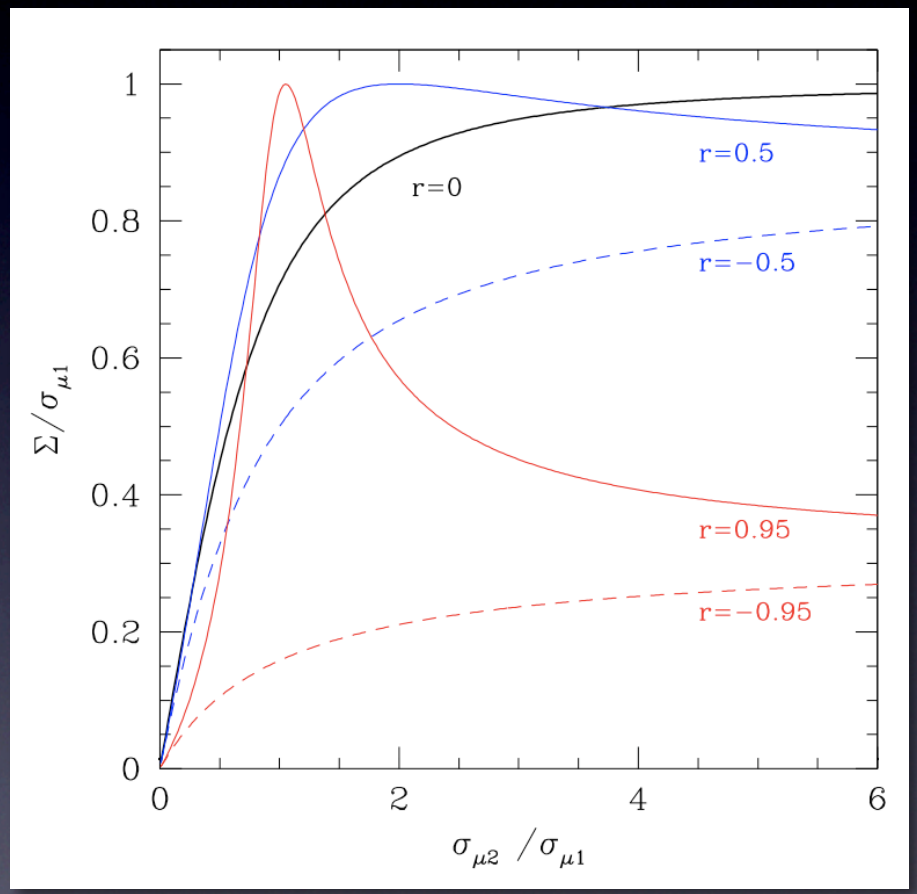
[a] The redshift zero correlation coefficients, with the results from the PH simulation in the lower triangle and the results from the GO simulation in the upper, as in Figure 8. Uncertainties from bootstrapping resampling are on the order of 0.01 and are not shown.

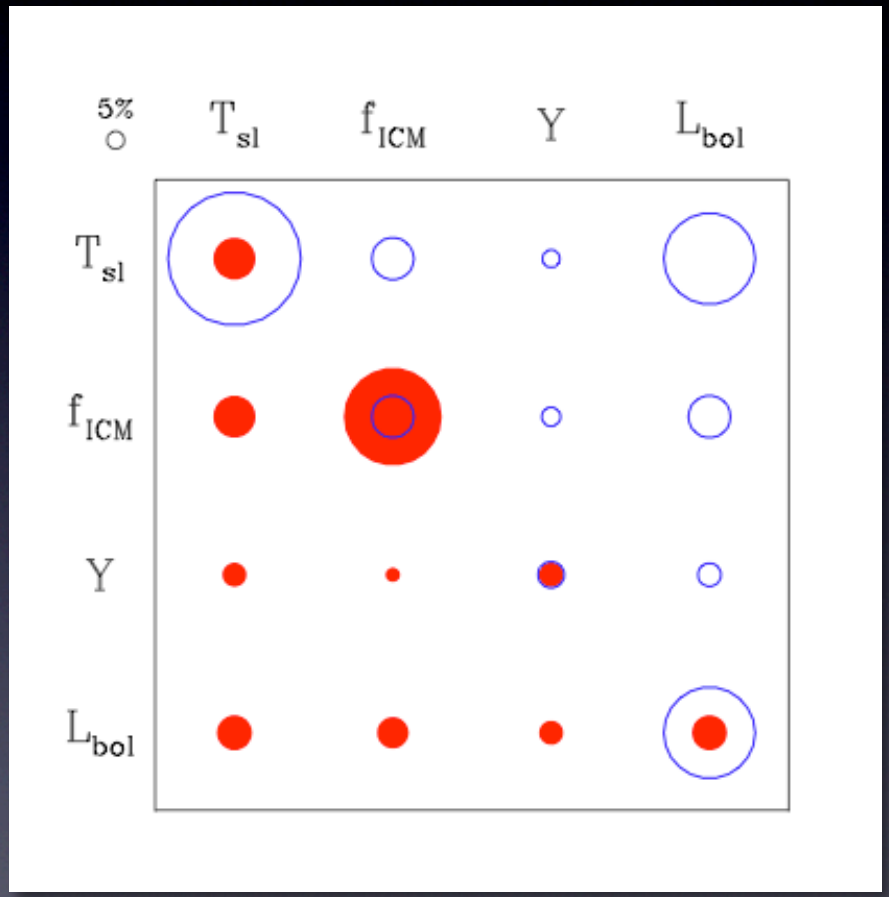
GO

PH

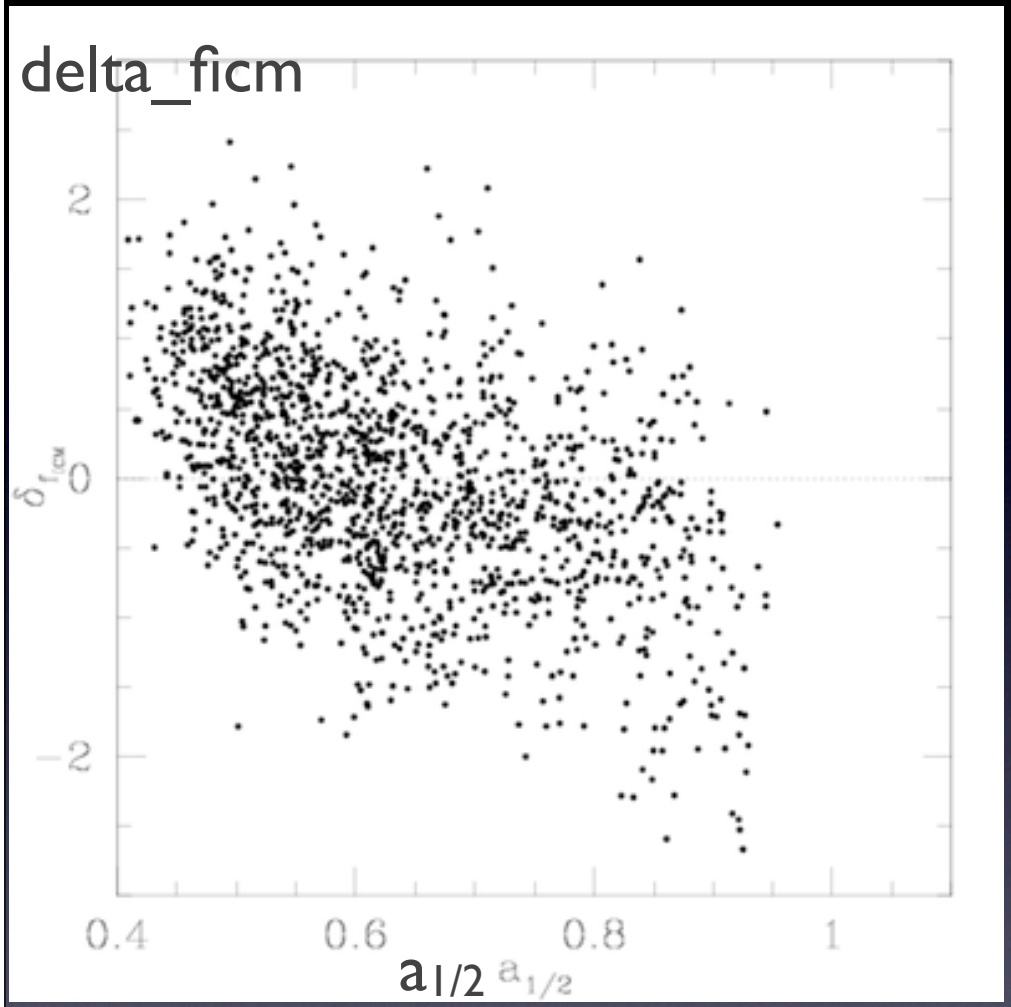
effective mass scatter using pairs of signals

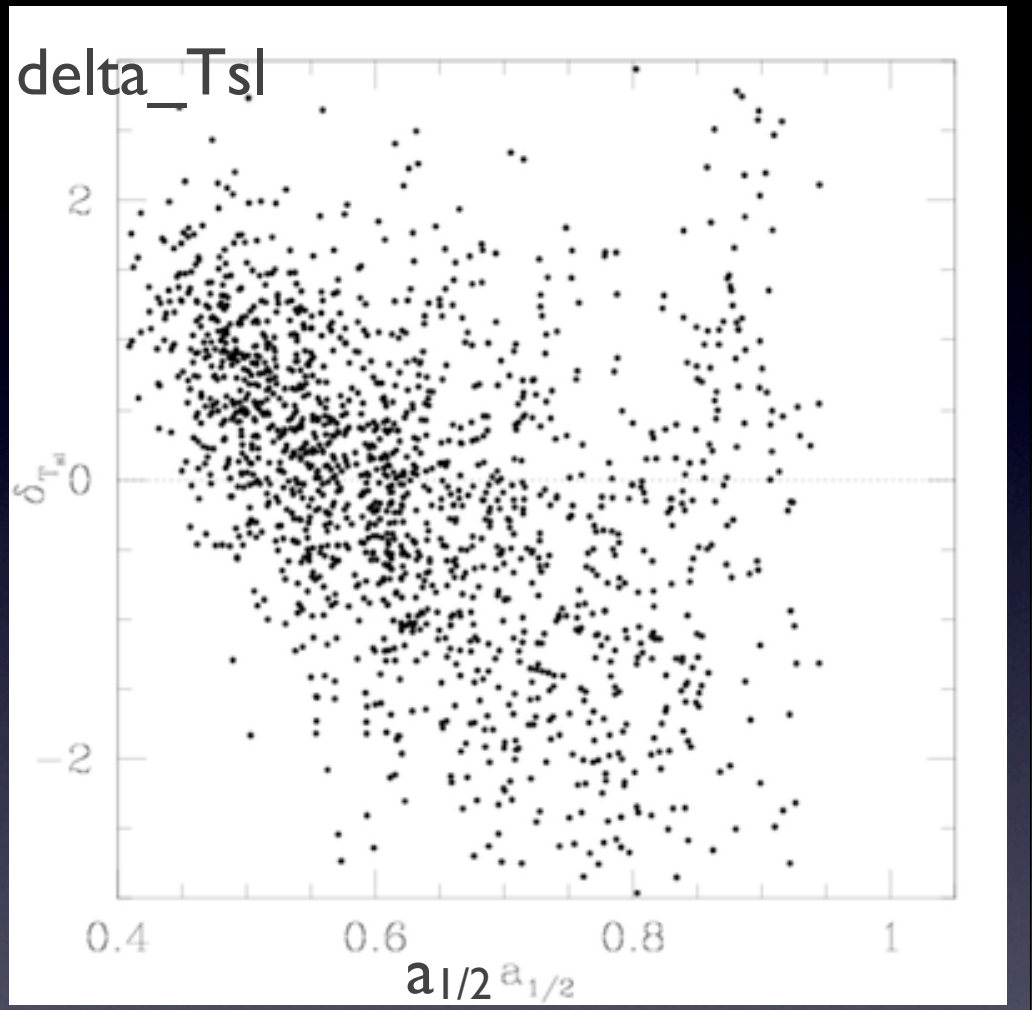
$$\Sigma^{-2} = (1-r^2)^{-1}(\sigma_{\mu 1}^{-2} + \sigma_{\mu 2}^{-2} - 2r\sigma_{\mu 1}^{-1}\sigma_{\mu 2}^{-1}).$$





deviations correlate with formation history

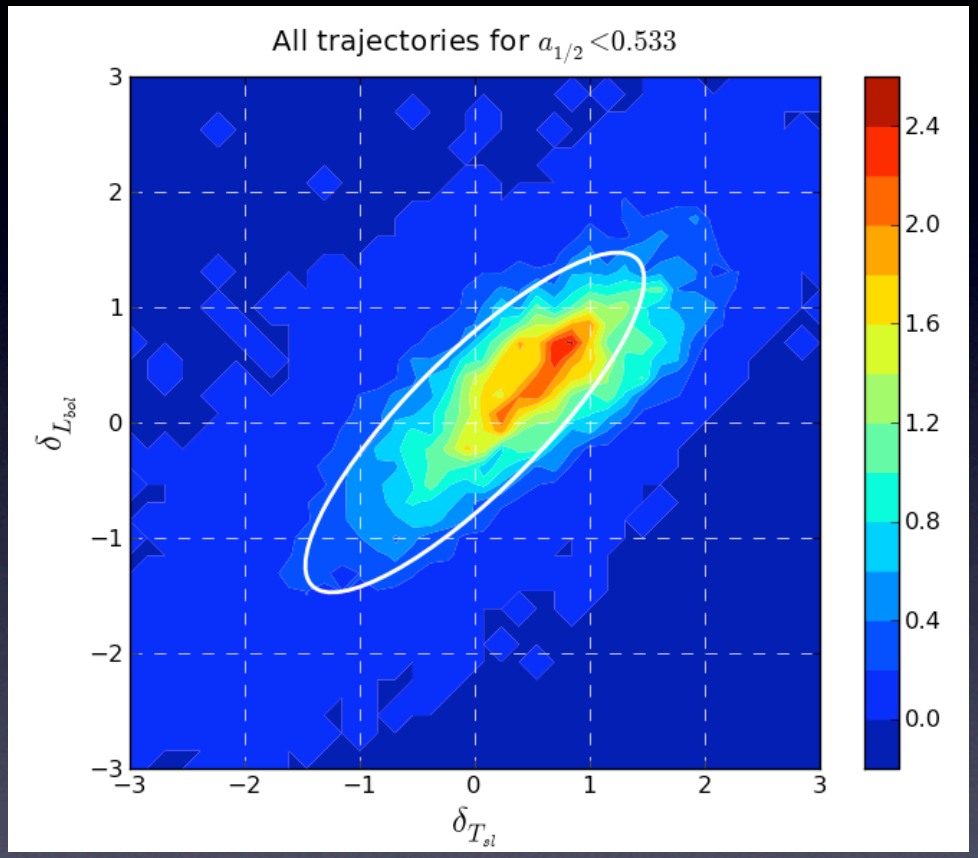




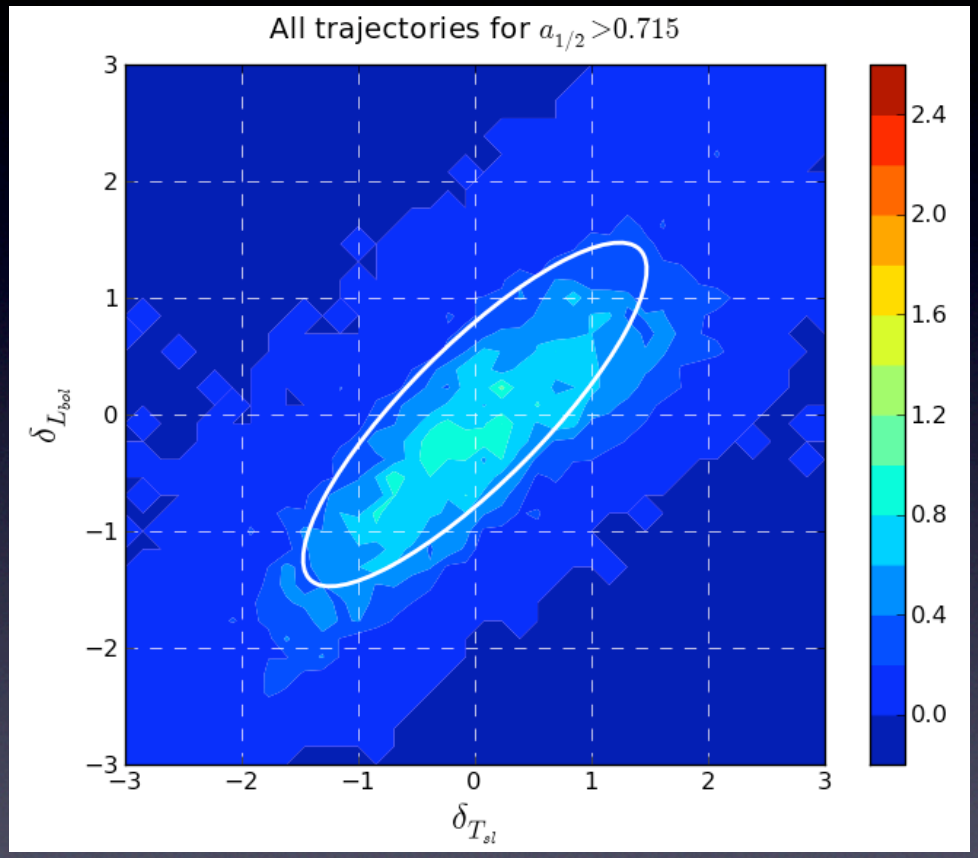
Stanek et al. , in prep

deviations correlate with formation history

early formed quartile (~400 halos)



late formed quartile (~400 halos)



Stanek et al. , in prep

Chandra Msec images of 400 halos at z~0.4