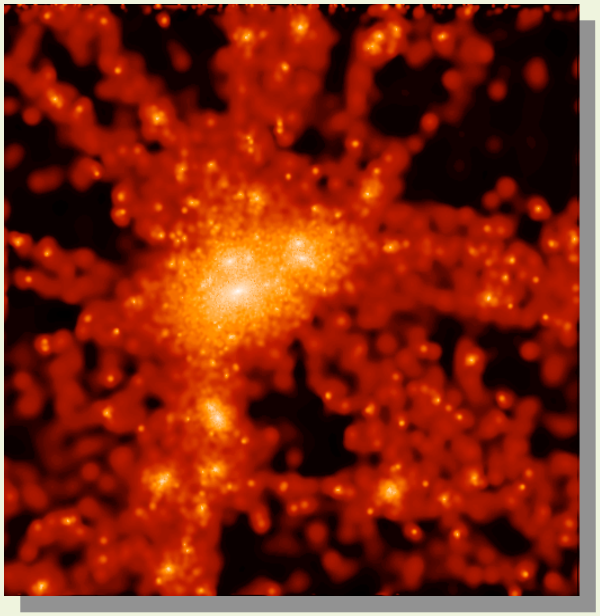
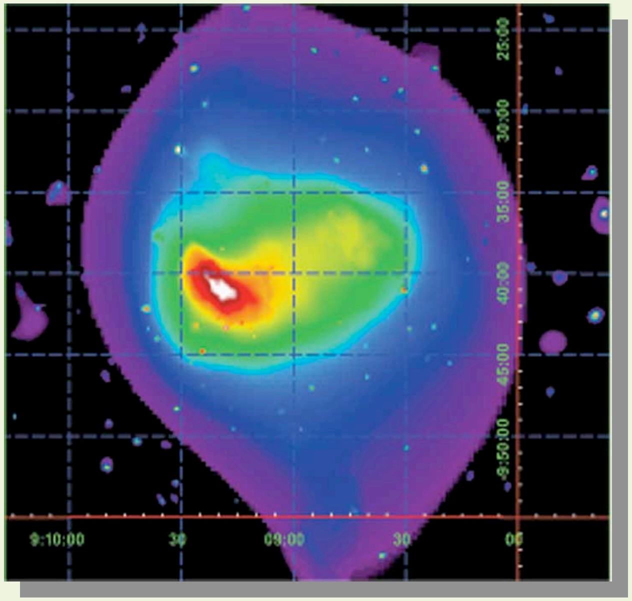
Precise Observable-Mass Relations for Clusters of Galaxies: the case of X-ray Luminosit





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clusters as cosmological probes: reasons for optimism

internal structure

space density

halo clustering

scaling relations

– (real + virtual) clusters display structural regularity

– many independent cluster observables:

T_X , L_X , $\Sigma_X(r)$,

y_0 , $y(r)$

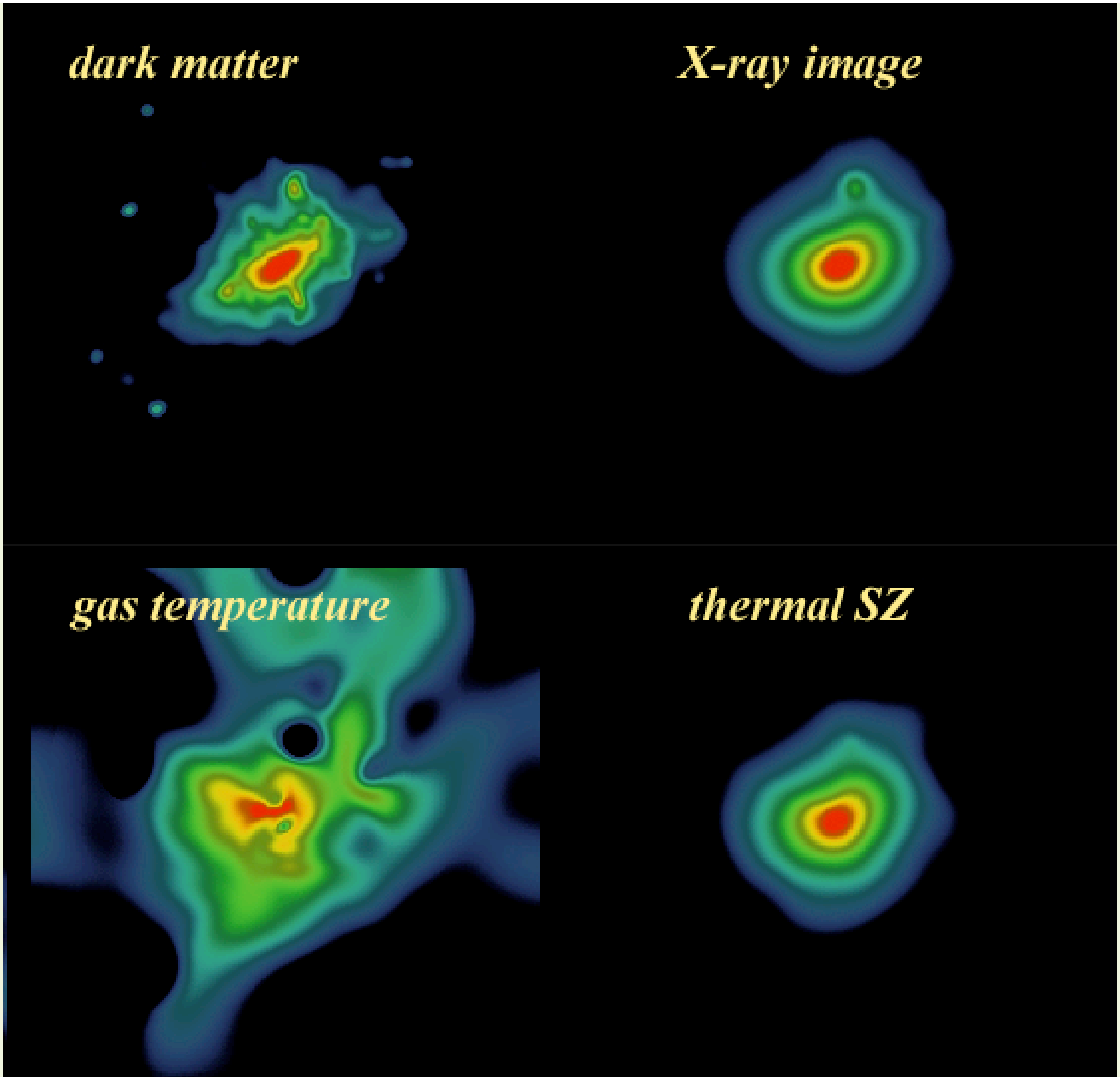
N_{gal} , L_{gal} , $\Sigma_{gal}(r)$, σ_{gal} , lensing $\Sigma_{mass}(r)$

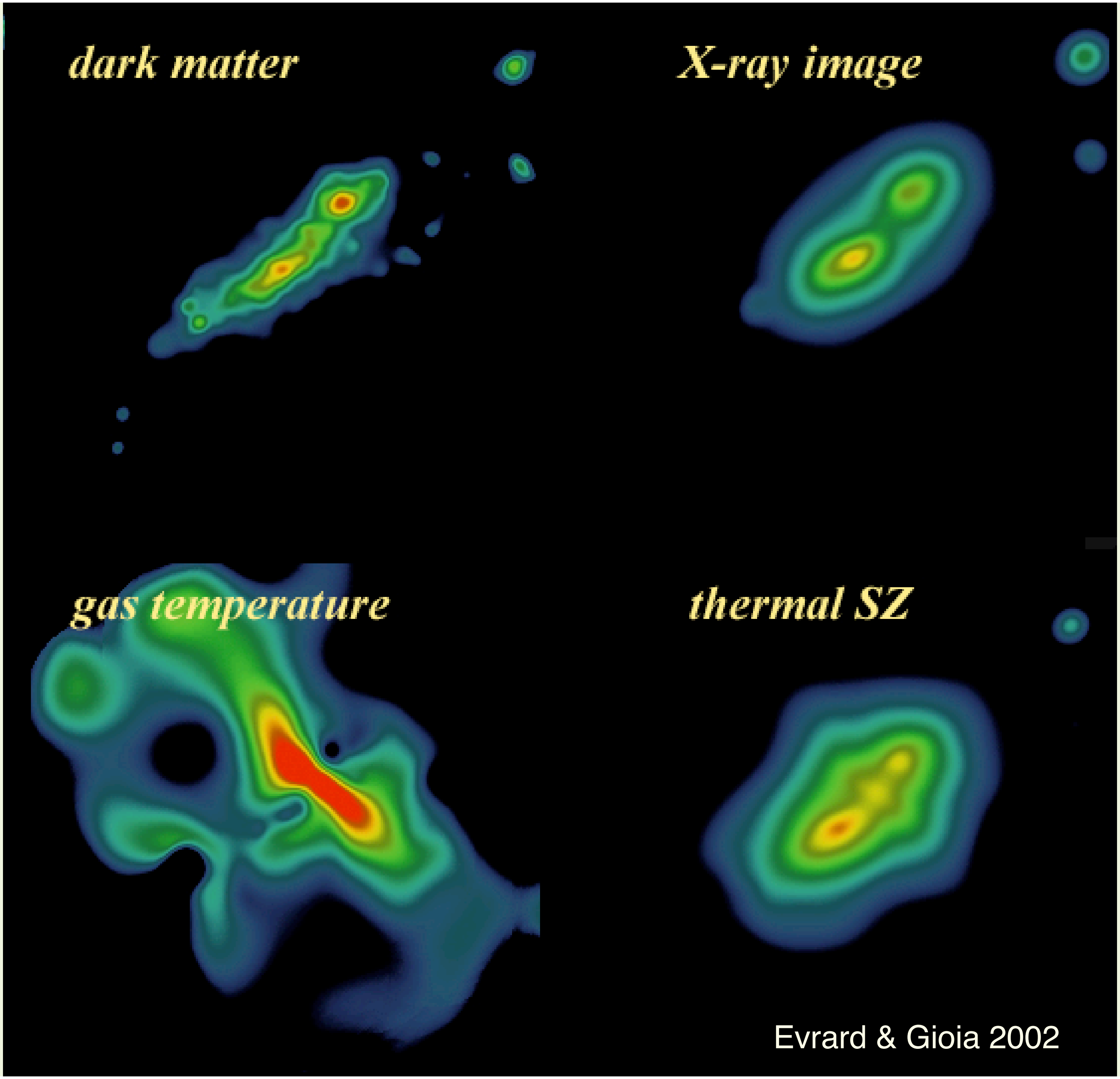
– several independent ways to infer mass:

T_X , σ_{gal} , $\int y$, lensing , bias, counts, ...

– large samples in sub-mm + optical (+ X-ray?) are upcoming

– how `entangled' are astrophysical/cosmological parameters?


dark matter
X-ray image
gas temperature
thermal SZ



dark matter
X-ray image
gas temperature
thermal SZ
Evrard & Gioia 2002

- the exercise -

probing the L_X-M relation in a ΛCDM universe

Exercise: use REFLEX sample luminosity function to characterize the relation between L_X and M within a ΛCDM `concordance' cosmology

$\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$

Approach : convolve mass function with log-normal p(L | M)

$$n(L,z) = \int d\ln M \, n(M,z) \, p(L \mid M,z)$$

$$L_{med}(M,z) = [L_{15,0} M^p](\rho_c(z)/\rho_c(0))^\tau \quad (\tau = 7/6 \; ; \; 0)$$

$$p(L \mid M,z) = \frac{1}{\sqrt{2\pi}\Delta_L} e^{-(\ln L - \ln L_{med}(M,z))^2 / 2\Delta_L^2}$$

p = slope of L-M relation

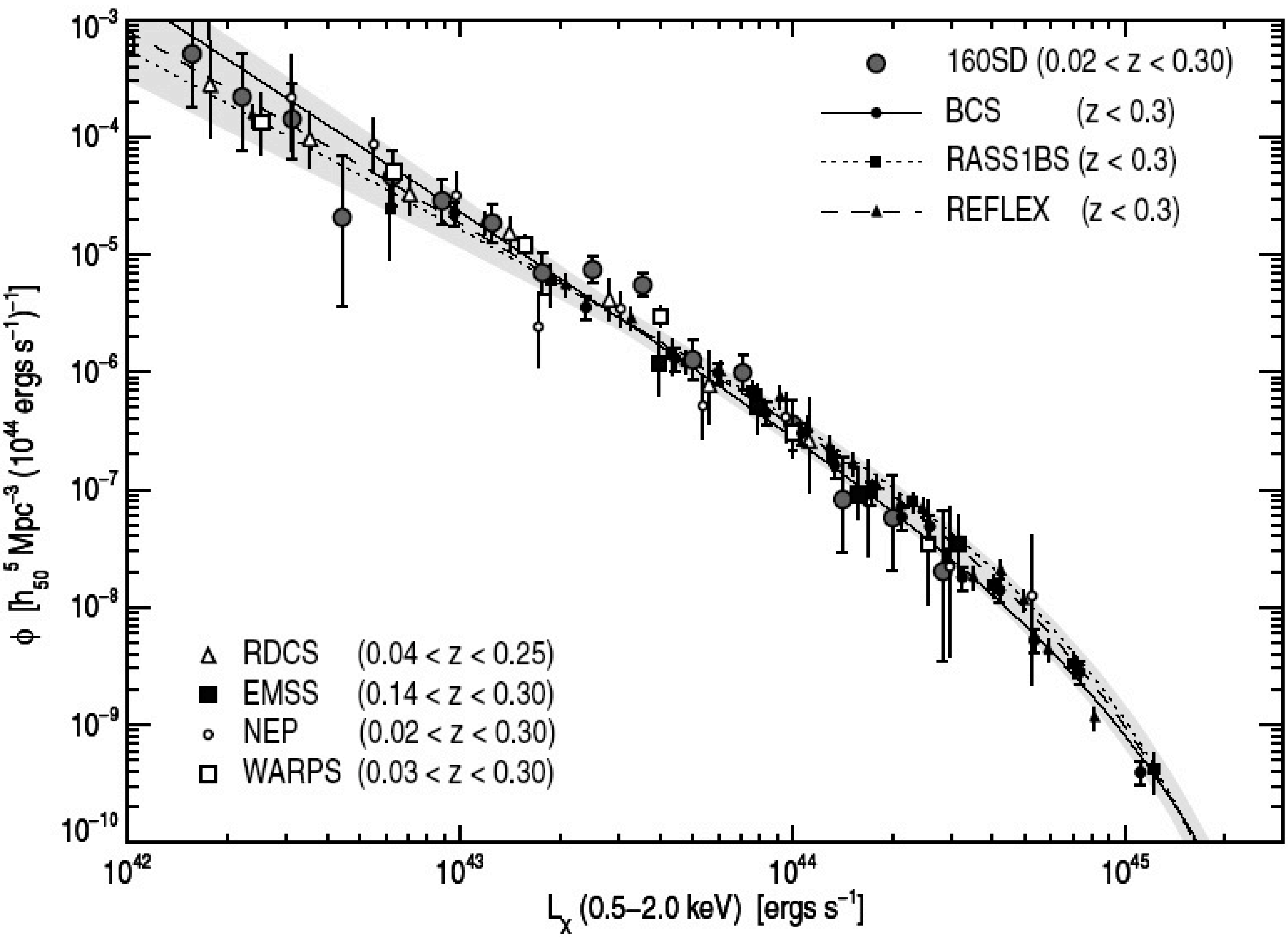
L_{15} = present-epoch normalization (at 10^{15} M_{sun} /h)

Δ_L = scatter in ln(L) ; $\Delta_M = \Delta_L / p$ is scatter in ln(M)

M = mass in units of 10^{15} M_{sun} /h

observed space density in X-rays is well measured

Mullis et al 2004



IG. 5.— Compilation of local XLFs as measured by eight X-ray flux-limited surveys. RDCS: Rosati et al. (1998), EMSS: Henry e 92), NEP: Gioia et al. (2001), and WARPS: Jones et al. (2000b) and the references in Figure 4 (Einstein–de-Sitter universe).

theoretical space density (aka, ***mass function***) is well determined

$$n(\sigma^{-1}(M)) \propto A(\rho_{\mathrm{m}} / M)\exp[-|\ln\sigma^{-1}(M)+B|^{\varepsilon}]$$

(see Abazajian et al poster)

Jenkins et al 2001
Sheth & Tormen 1999

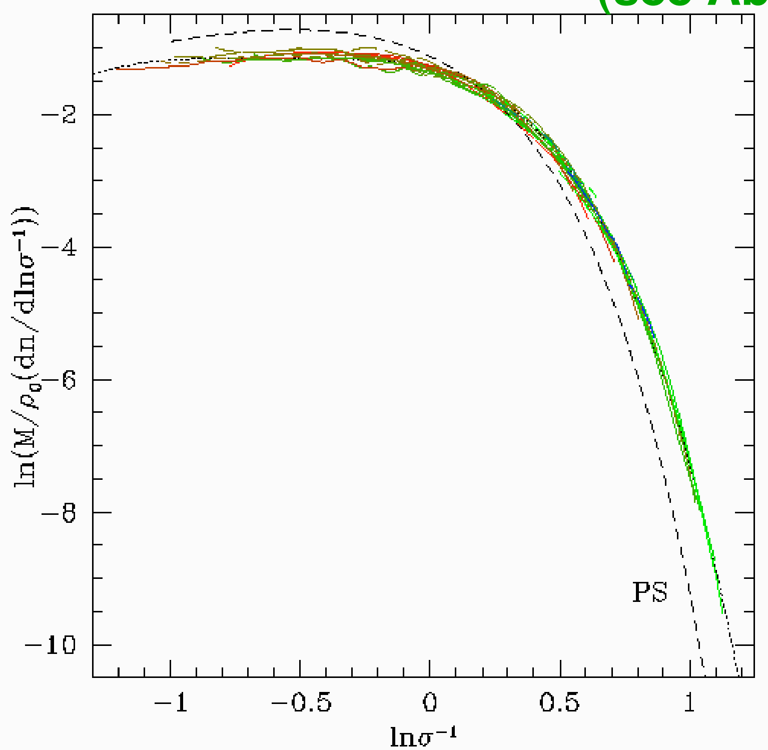
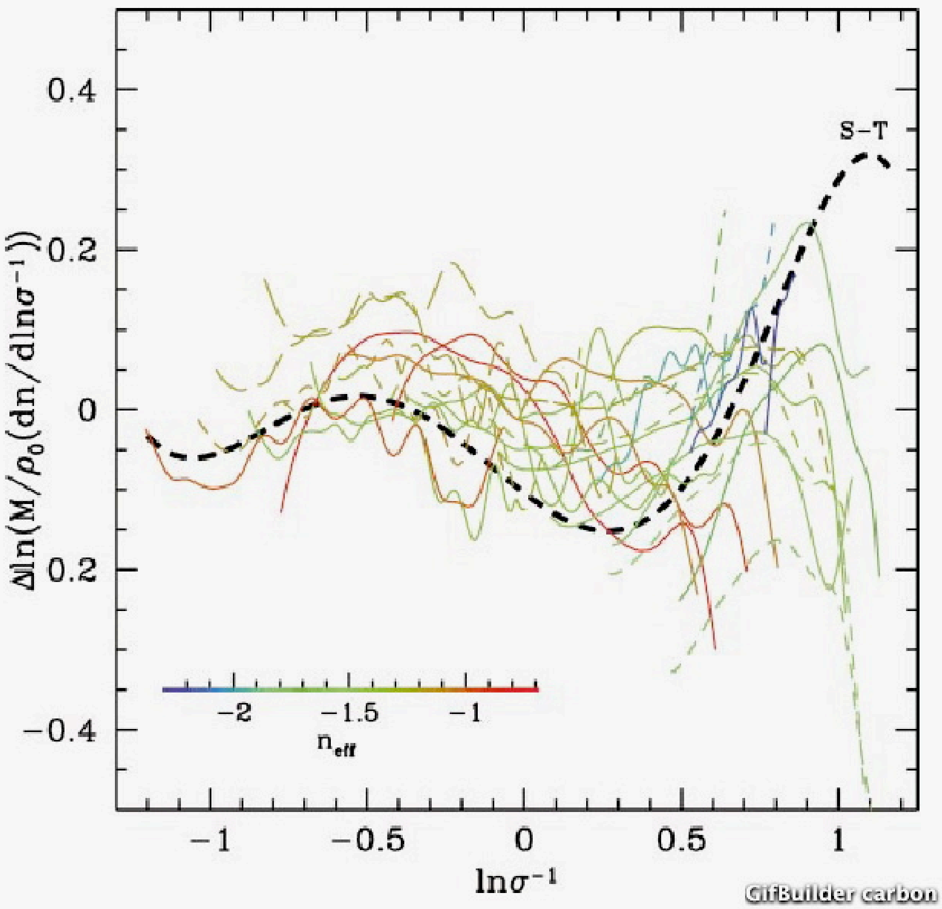
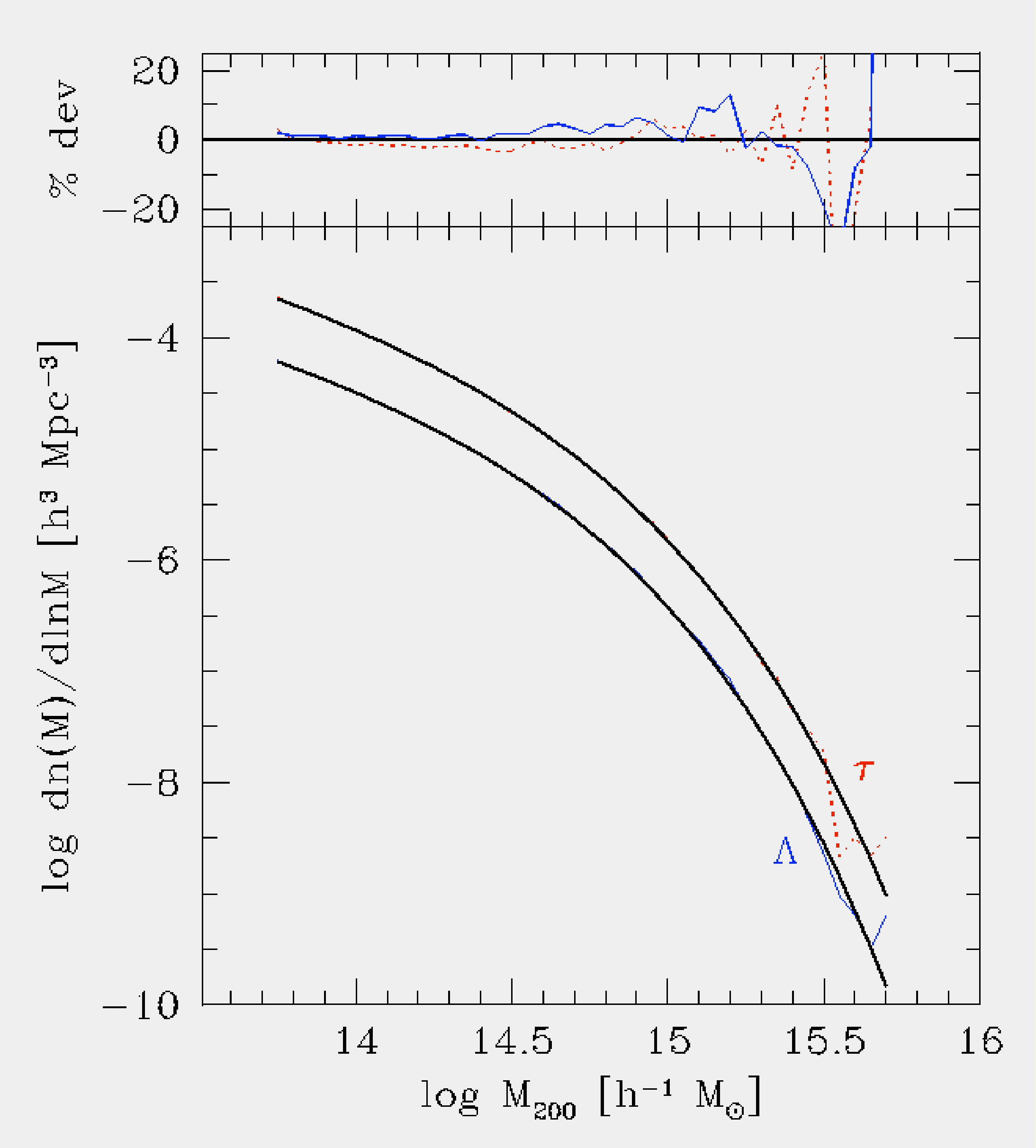


Figure 7. The FOF(0.2) mass functions of all the simulation outputs listed in Table 2. Remarkably, when a single linking length is used to identify halos at all times and in all cosmologies, the mass function appears to be invariant in the $f - \ln\sigma^{-1}$ plane. A single formula (eqn. 9), shown with a dotted line, fits all the mass functions with an accuracy of better than about 20% over the entire range. The dashed curve show the Press-Schechter mass function for comparison.



critical Δ=200 mass function calibration from Hubble Volume sims

Evrard et al 2002



<- rms deviations about fit at <~5% level

fit to functional form of Jenkins et al 2001 using ~1.4M clusters at z=0

fit parameters A, B are now Ω_m dependent

halos/clusters as spherical cows…

`surface' radius r_Δ & enclosed mass $M_\Delta \equiv M$

$$\rho(< r_\Delta) \equiv 3M_\Delta / 4\pi r_\Delta^{\ 3}$$

WARNING!
multiple conventions in literature !

1. critical contrast $\quad \rho(< r_\Delta) \equiv \Delta\rho_c(z) \ \ ; \ \ \rho_c(z) \equiv 3H(z)^2/8\pi G$

   1a. fixed Δ $\quad \Delta = const \approx 10^2$

   1b. variable Δ: $\quad \Delta(\Omega_m) = 18\pi^2 + 82x - 39x^2 \ \ ; \ \ x \equiv \Omega_m(z) - 1$

2. mean contrast $\quad \rho(< r_\Delta) \equiv \Delta\bar{\rho}_m(z) \ \ ; \ \ \bar{\rho}_m(z) = \Omega_m(z)\rho_c(z)$

Gunn & Gott 1972 ; Bertschinger 1985

Evrard, Metzler & Navarro 1996

spherical cows? where's the hide?

M. White 2002

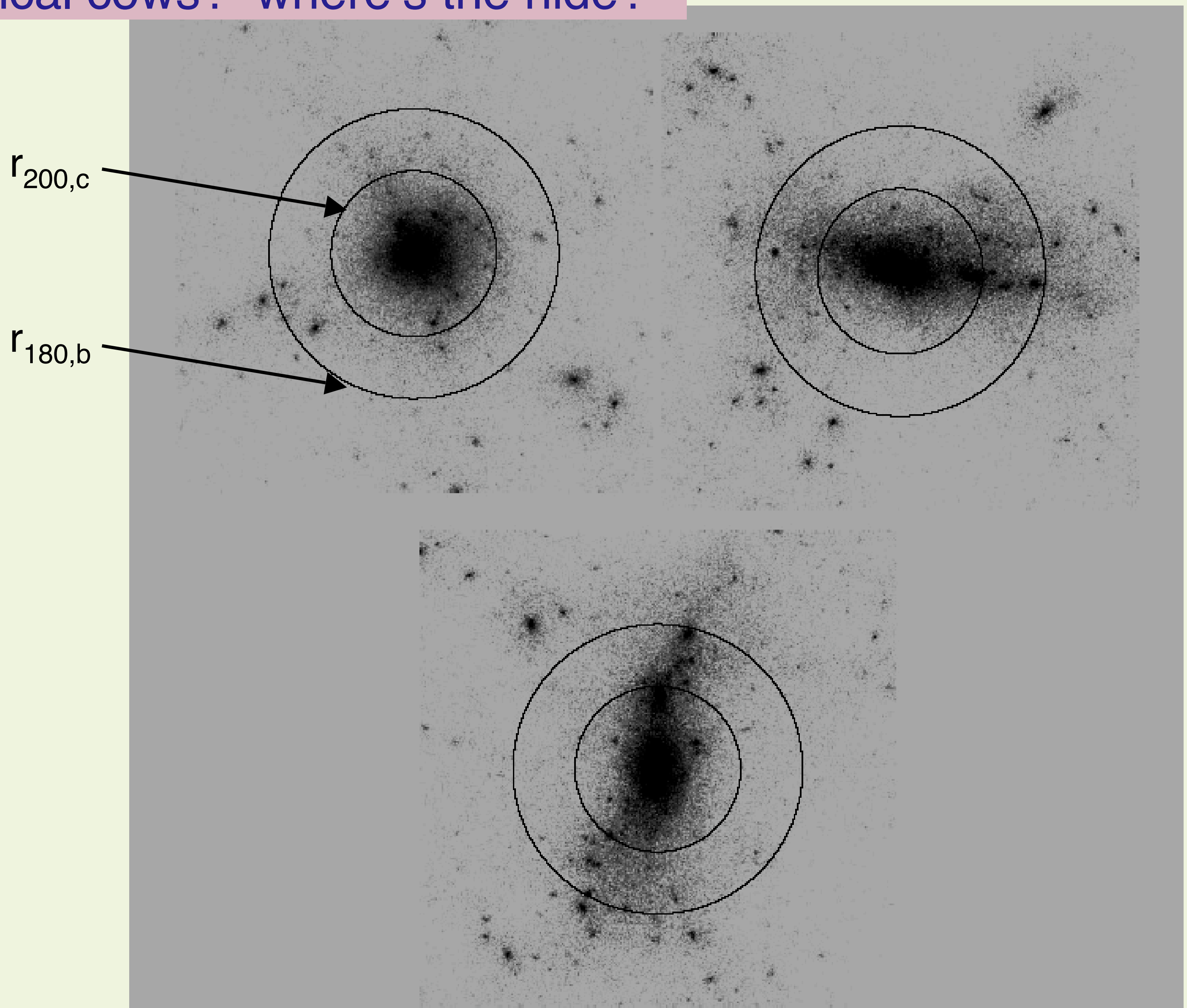
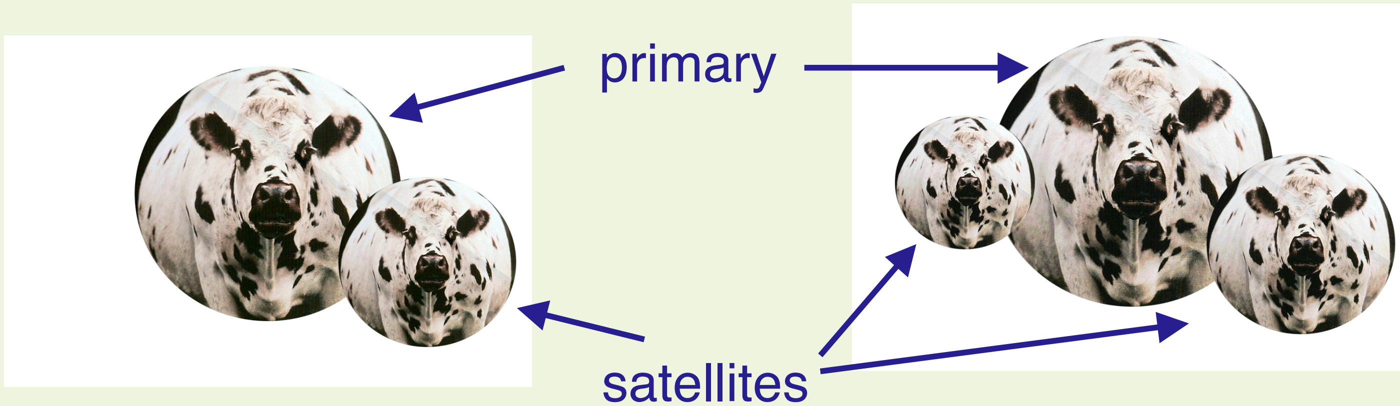
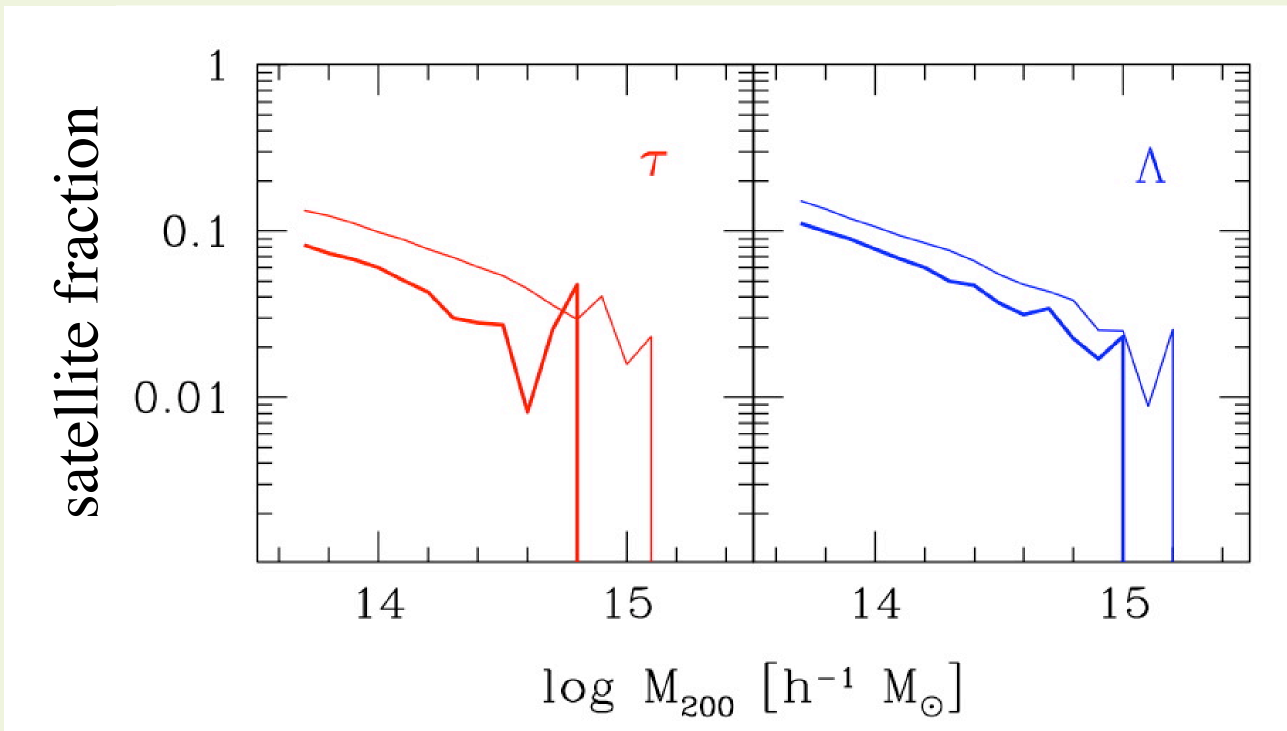


FIG. 2.—Projected density in a cube 10 h^{-1} Mpc on a side centered on the second most massive halo in the 512^3 particle simulation. The three panels are projections down the x-, y-, and z-axes of the box. The gray scale is logarithmic, running from 10^2 to 10^5 times the mean density. The solid circles show $r_{200c} \simeq 1.74\ h^{-1}$ Mpc (*inner*) and $r_{180b} = r_{54c} \simeq 3.04\ h^{-1}$ Mpc (*outer*). Within r_{180b} the material exhibits a wide range of density contrasts. Note that the halo is neither isolated nor spherical and has quite a bit of substructure.

so spherical cows can overlap?





self-similar scaling expectations

Kaiser 1986

- bolometric luminosity from bremsstrahlung (at high T)

$$L_{bol} \propto \int dV \rho_{\rm gas}^2 \Lambda(T) \propto f_{\rm gas}^2 \rho_{\rm c}(z) M T^{1/2}$$

(*M* is total mass)

$$T \propto \rho_c^{1/3}(z) M^{2/3}$$

$$L_{bol} \propto f_{\rm gas}^2 \rho_{\rm c}^{7/6}(z) M^{4/3}$$

$$\propto f_{\rm gas}^2 \rho_{\rm c}^{1/2}(z) T^2$$

- soft, band-limited (0.1-2.4 keV) luminosity somewhat shallower

$$L_{soft} \propto f_{\rm gas}^2 \rho_{\rm c}(z) M$$

X-ray luminosity-temperature relation => more complex model

self-similar model:
purely gravitational heating + constant ICM gas fraction

additional physics…
– gas cooling
– gas heating from winds/AGN
– other `ISM-like' processes?

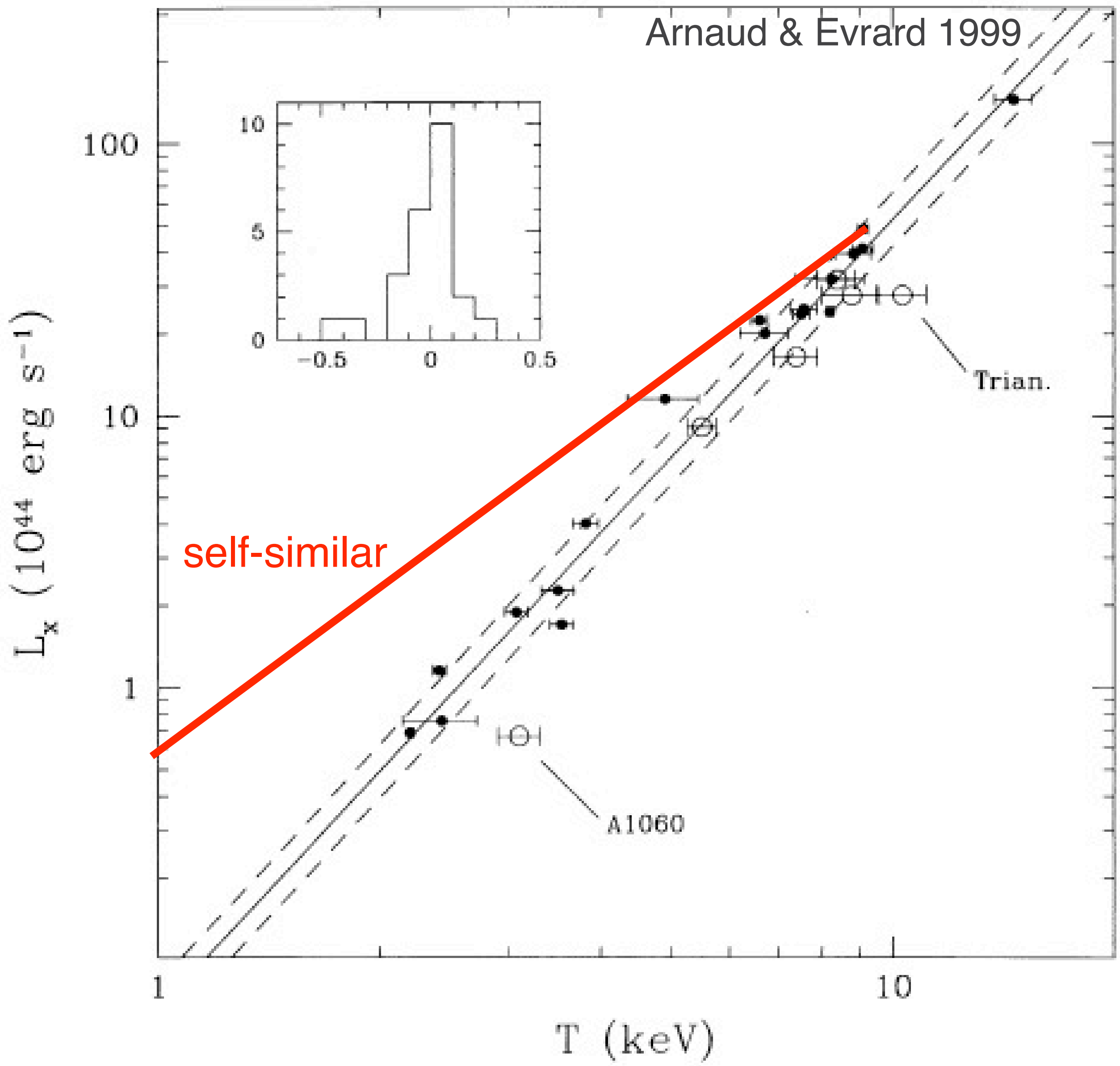
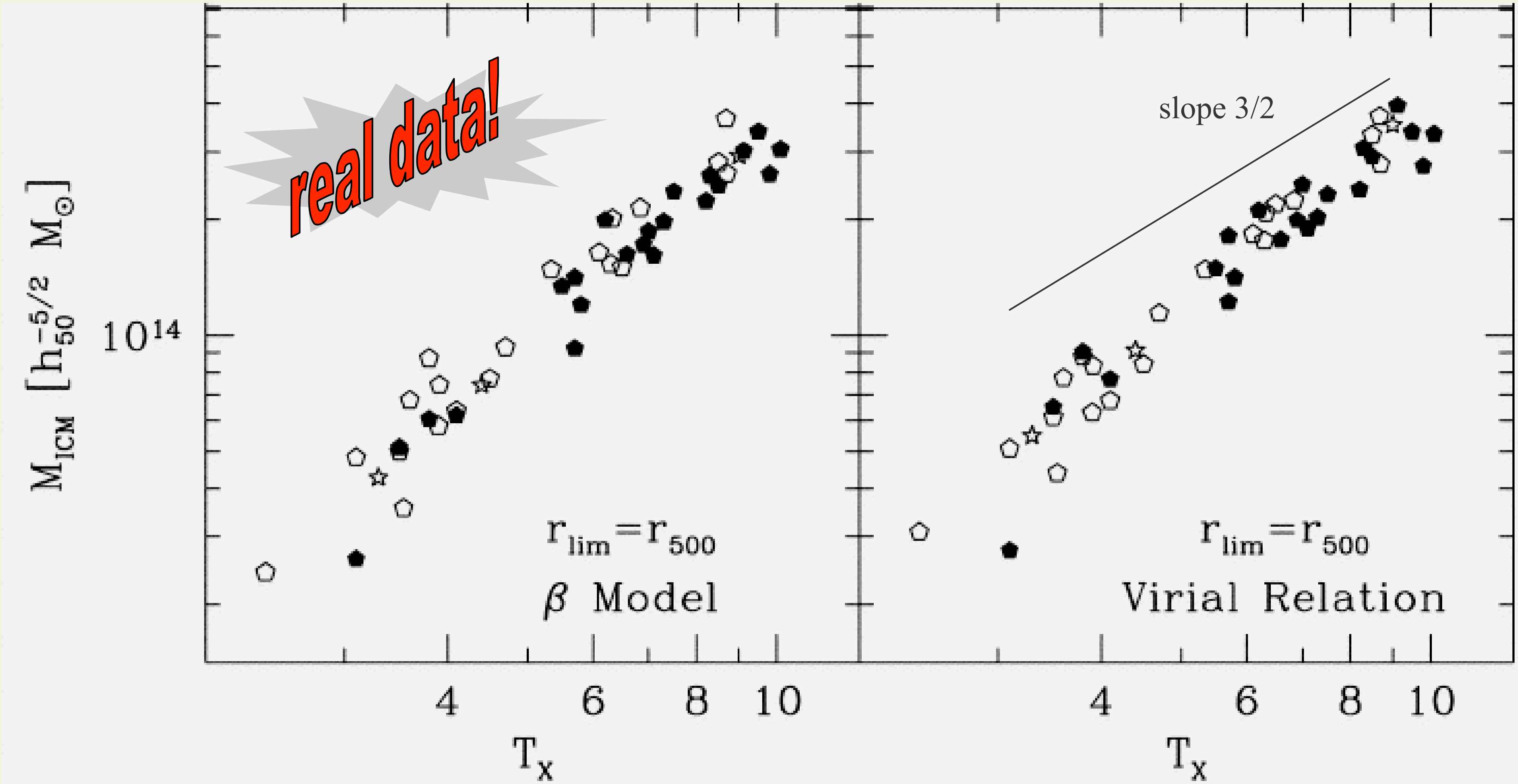


Figure 1. The luminosity–temperature relation for the 24 clusters used in

ICM mass-temperature relation for X-ray flux-limited sample

Mohr, Mathiesen & Evrard 99



14 % scatter in M_{ICM} at fixed T_X

K-band stellar mass-temperature relation

Lin, Mohr, & Stanford 2004

$$\frac{L_{500}}{10^{12}\,h_{70}^{-2}\,L_\odot} = 3.95 \pm 0.11 \left(\frac{M_{500}}{2\times10^{14}\,h_{70}^{-1}\,M_\odot}\right)^{0.69\pm0.04}$$

~25% scatter in L_{500} at fixed T_X

assumes binding masses -

$$M_{500} = 2.55^{+0.29}_{-0.25}\times10^{13}\,\frac{M_\odot}{h_{70}}\left(\frac{T_X}{1\ \mathrm{keV}}\right)^{1.58^{+0.06}_{-0.07}},$$

Finoguenov et al 2001

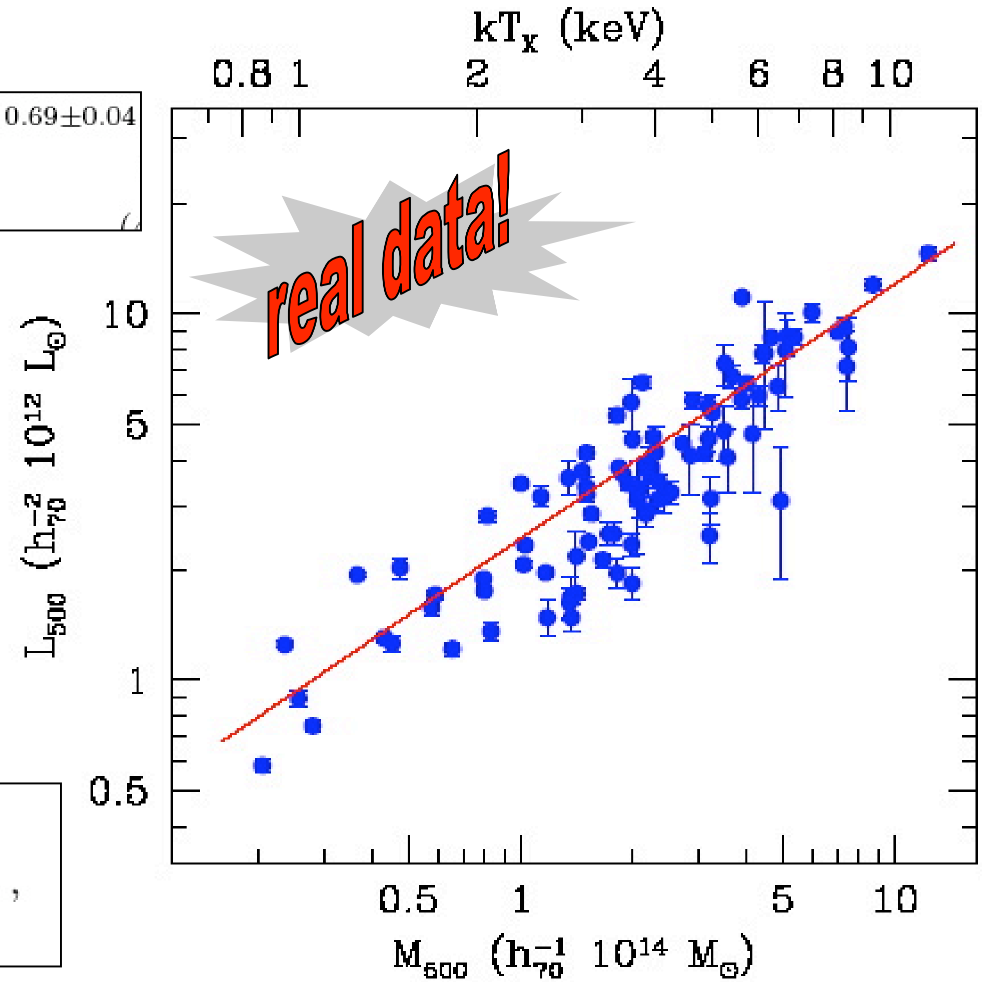
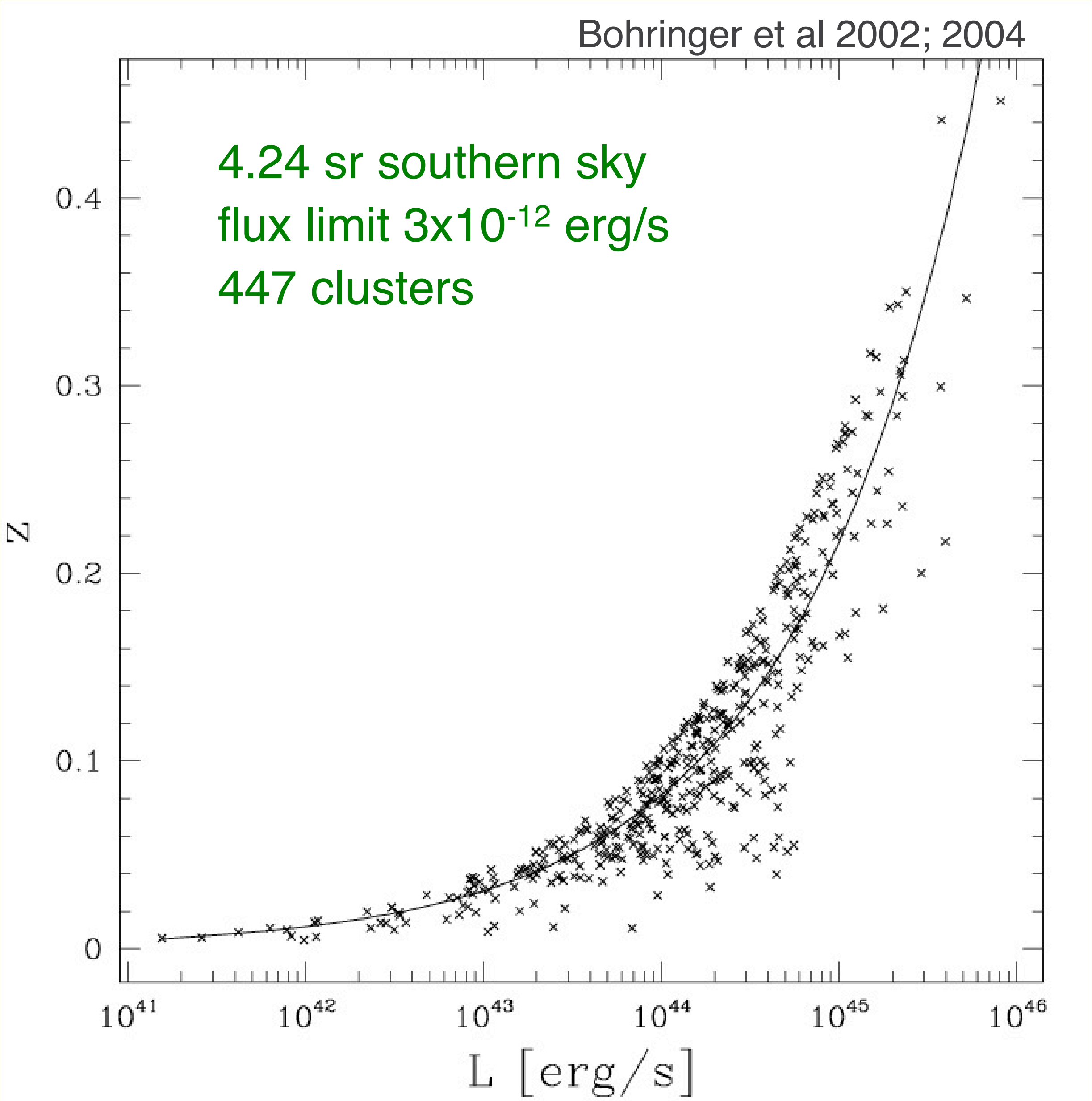


FIG. 3.— *K*-band luminosity–mass correlation within r_{500}. The best-fit relation has a slope of 0.69 ± 0.04. The scatter about the best-fit is 32%. For most of the clusters the uncertainties in light is smaller than the size of the points. For clarity we do not show the uncertainty in cluster mass (see Fig 5). At the top is the X–ray temperature, from which M_{500} is estimated (see Eqn 1).

- back to the task… -

the REFLEX sample

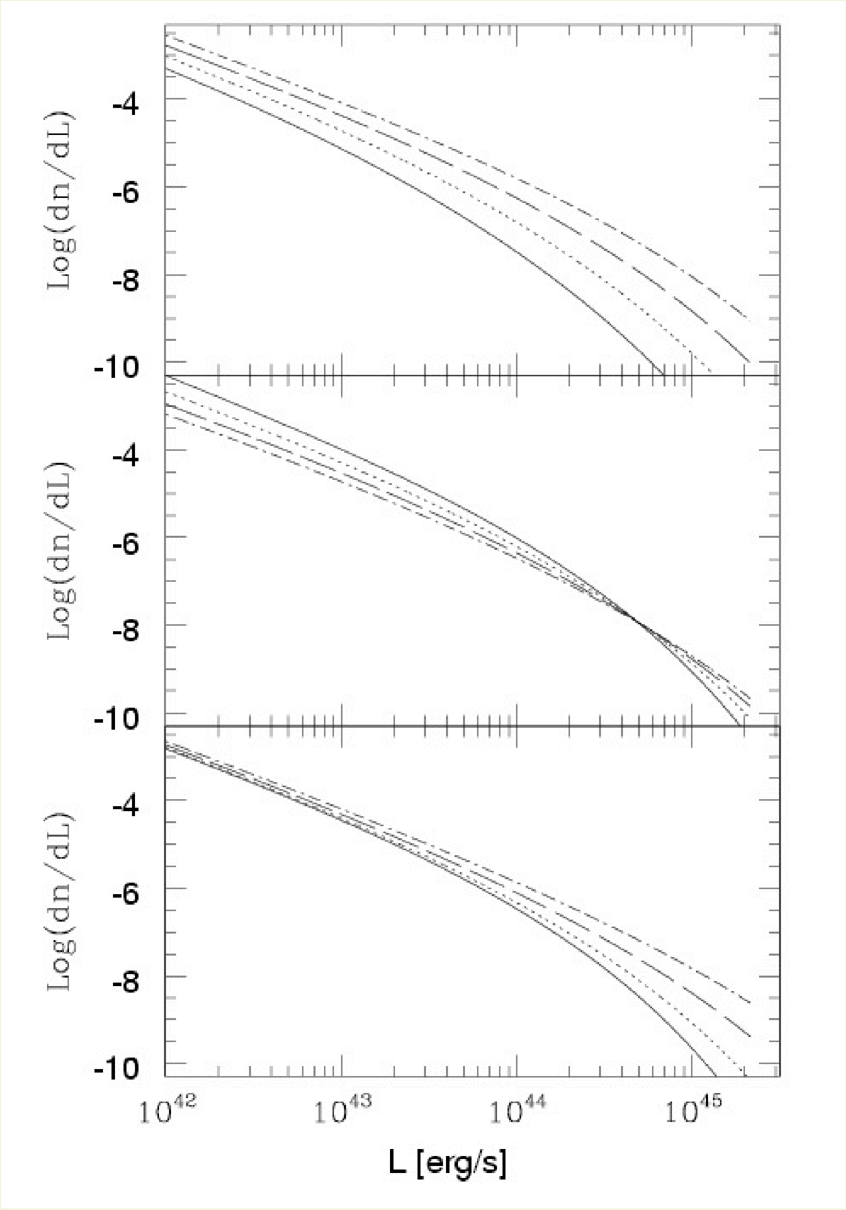


model modifications to accommodate flux limited nature:

evaluate n(M,z) at median z at each L

make small (self-similar) z-corrections to align individual L values to median z

expect parameter degeneracies



vary L_{15}

vary p

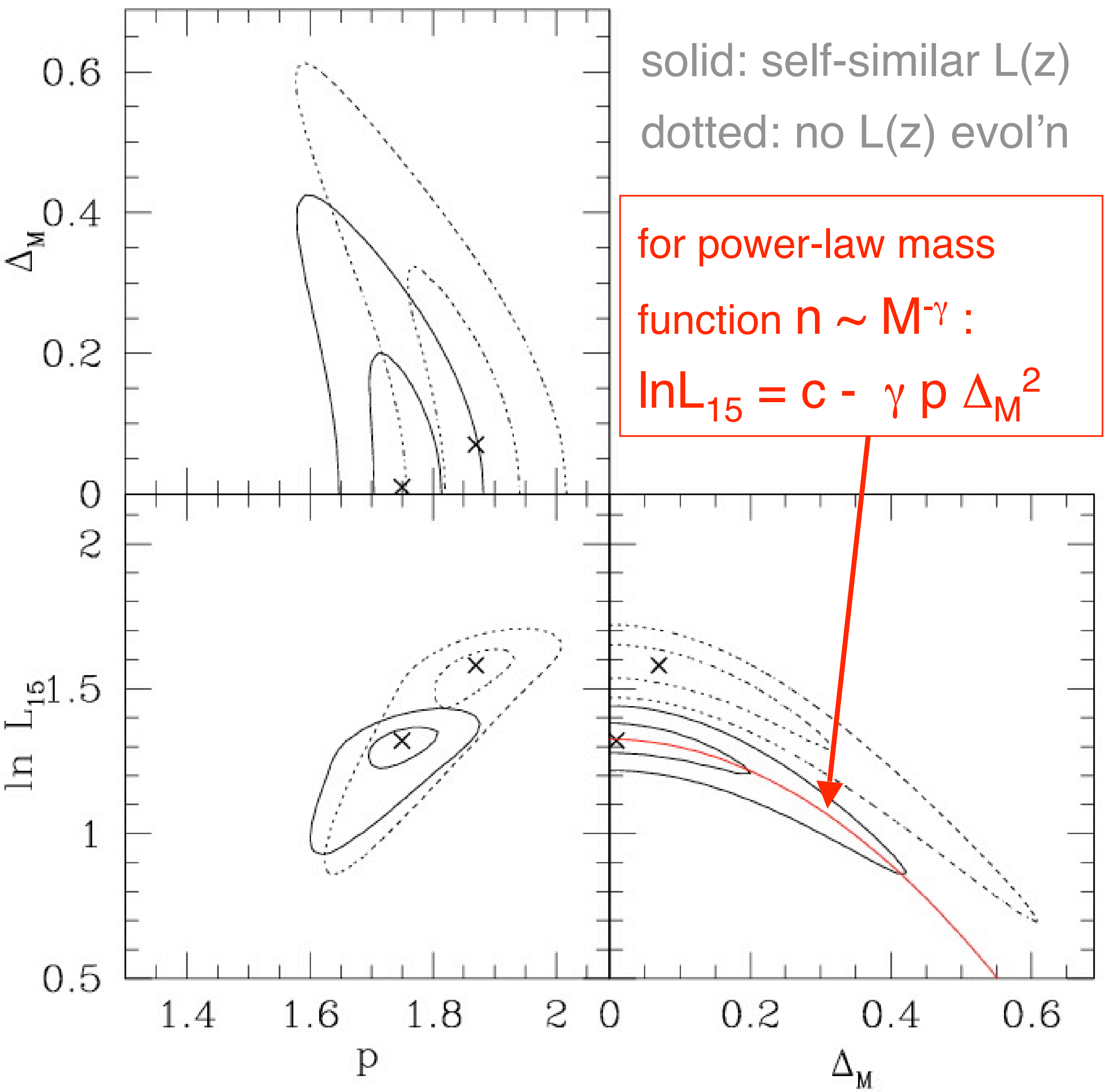
vary Δ_M

results from matching REFLEX luminosity function

moderate range of allowed scatter (up to ~50%), ML value near zero

dramatically wider range in median scaling relation (L_{15} , p) compared to Δ_M=0 case

i.e., range of allowed ICM physics!



solid: self-similar L(z)

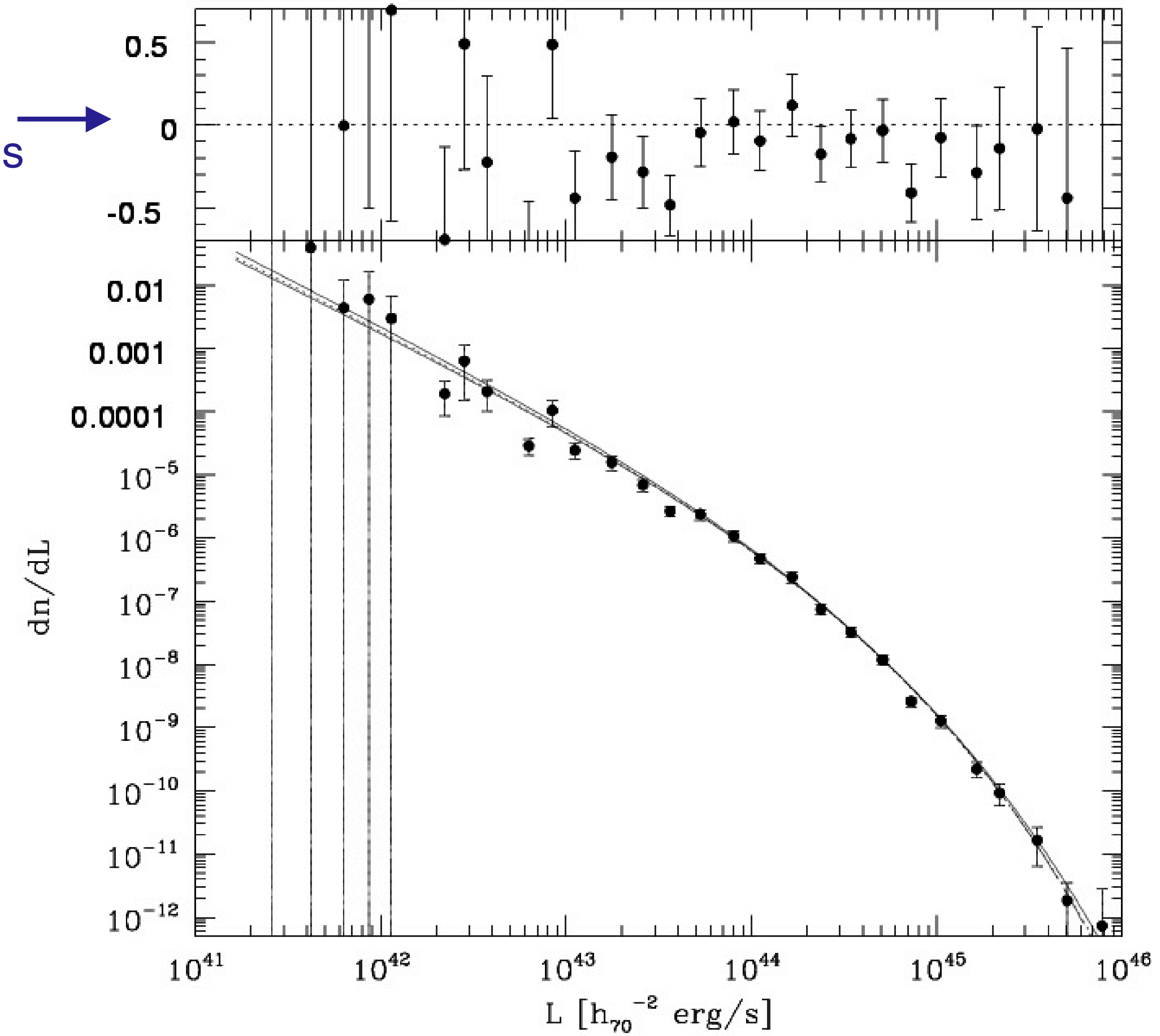
dotted: no L(z) evol'n

for power-law mass function $n \sim M^{-\gamma}$:

$\ln L_{15} = c - \gamma p \Delta_M^2$

best fit is a good fit

ln(*n*) residuals

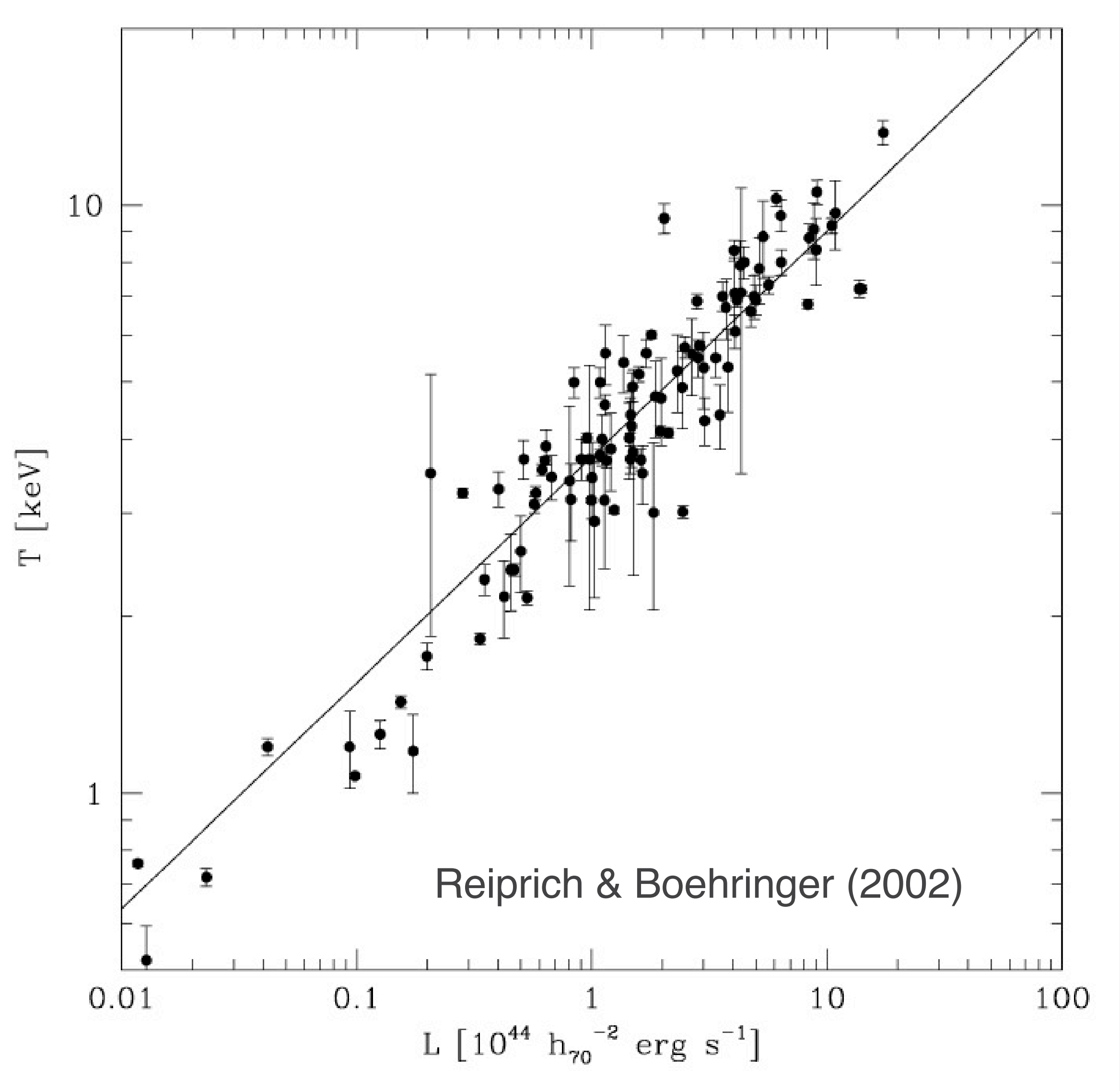


- is that all? -

scatter in X-ray L-T relation offers extra information

scatter in ln(T):
$\Delta_{T|L} = 0.25 \pm 0.01$

$$\Delta_{T|L} = \left\langle \ln(T/\overline{T}(L))^2 \right\rangle^{1/2}$$



incorporating observed T-L scatter

- the i^th cluster lies somewhat off the mean M-L and M-T scalings

$$\ln M_i = \frac{1}{q} \ln\left(\frac{T_i}{T_{15}}\right) + \delta_{M|T,i},$$
$$\ln M_i = \frac{1}{p} \ln\left(\frac{L_i}{L_{15}}\right) + \delta_{M|L,i}.$$

- subtracting these shows that q/p is the slope of the T-L relation

$$\ln\left(\frac{T}{T_{15}}\right) - \frac{q}{p} \ln\left(\frac{L}{L_{15}}\right) = q(\delta_{M|L,i} - \delta_{M|T,i}).$$

- the second moment holds the key…

$$\Delta^2_{M|L} = \frac{\Delta^2_{T|L}}{q^2} - \Delta^2_{M|T} + 2 < \delta_{M|L,i}\delta_{M|T,i} >$$

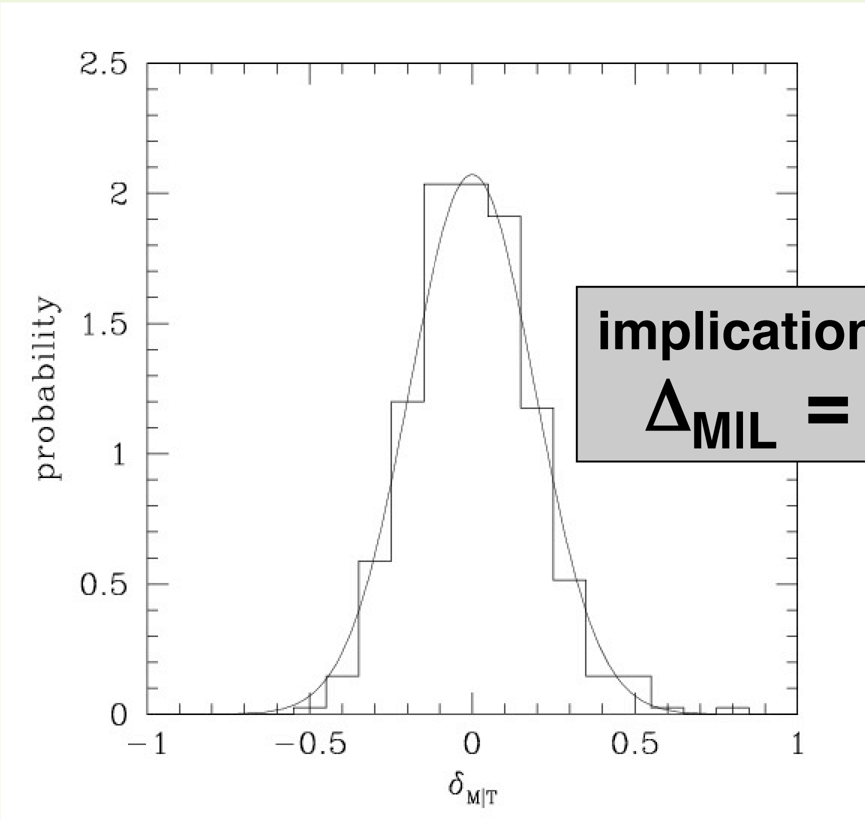
observed!

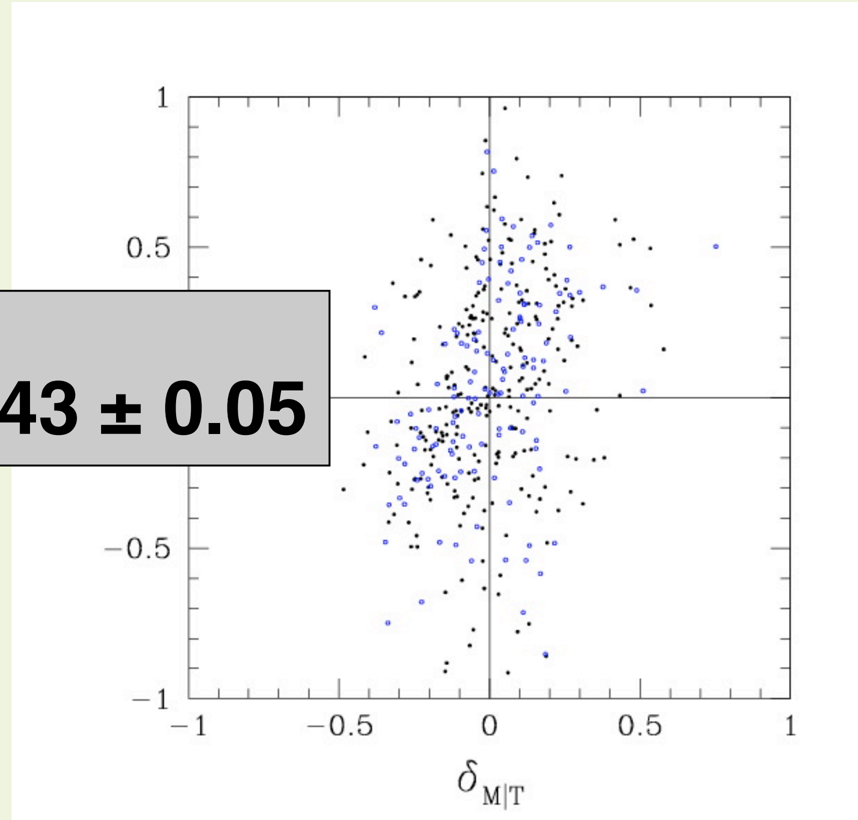
but what about these?

simulations to the rescue!

68 `preheated' cluster models @ z<0.5

Bialek et al 2005





implication:

Δ_{MIL} = 0.43 ± 0.05

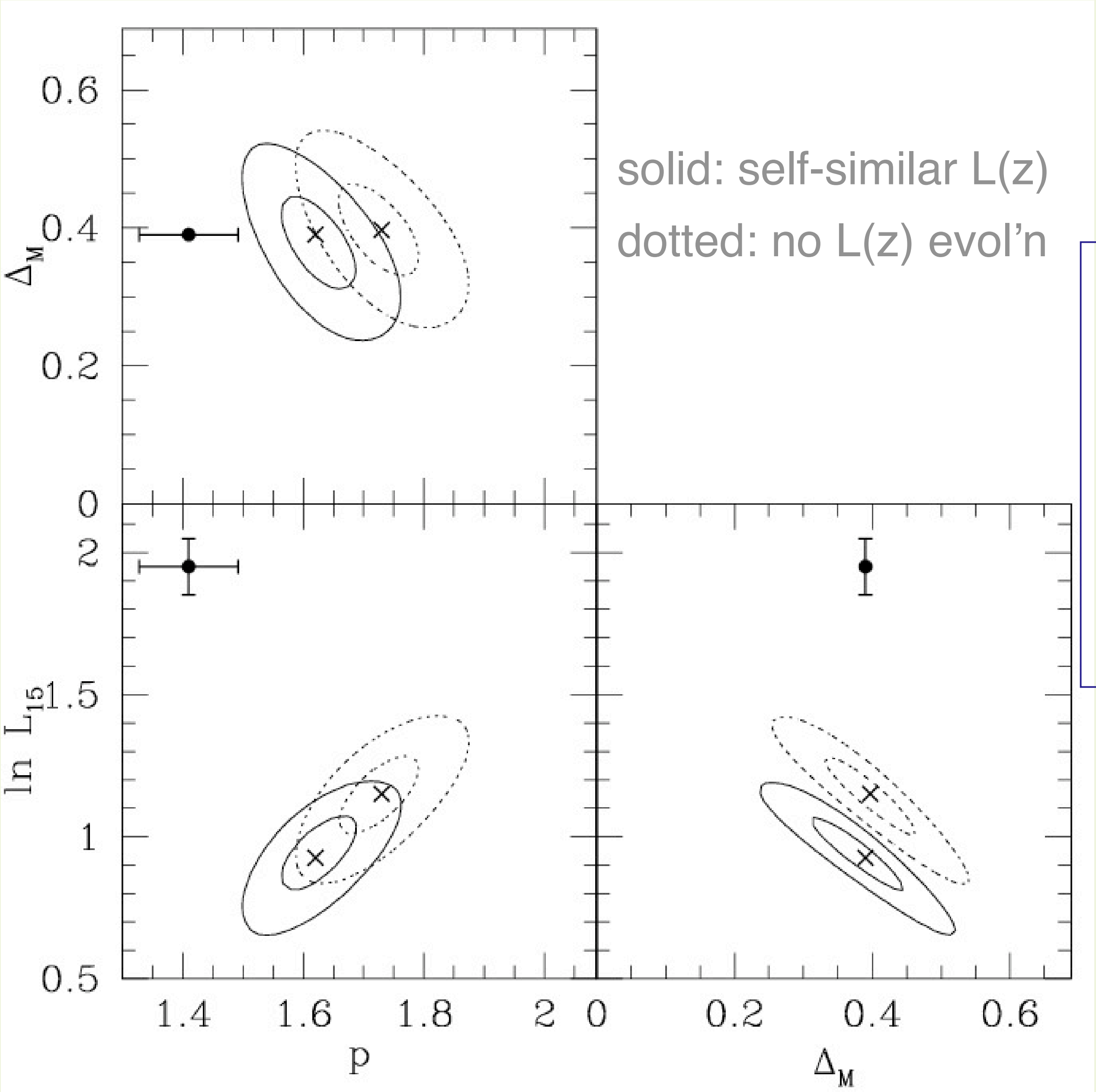
variance in M at fixed T:

Δ^2_{MIT} = 0.036

covariance:

$< \delta_{MIL}\, \delta_{MIT} >$ = 0.017

addition of scatter constraint is powerful

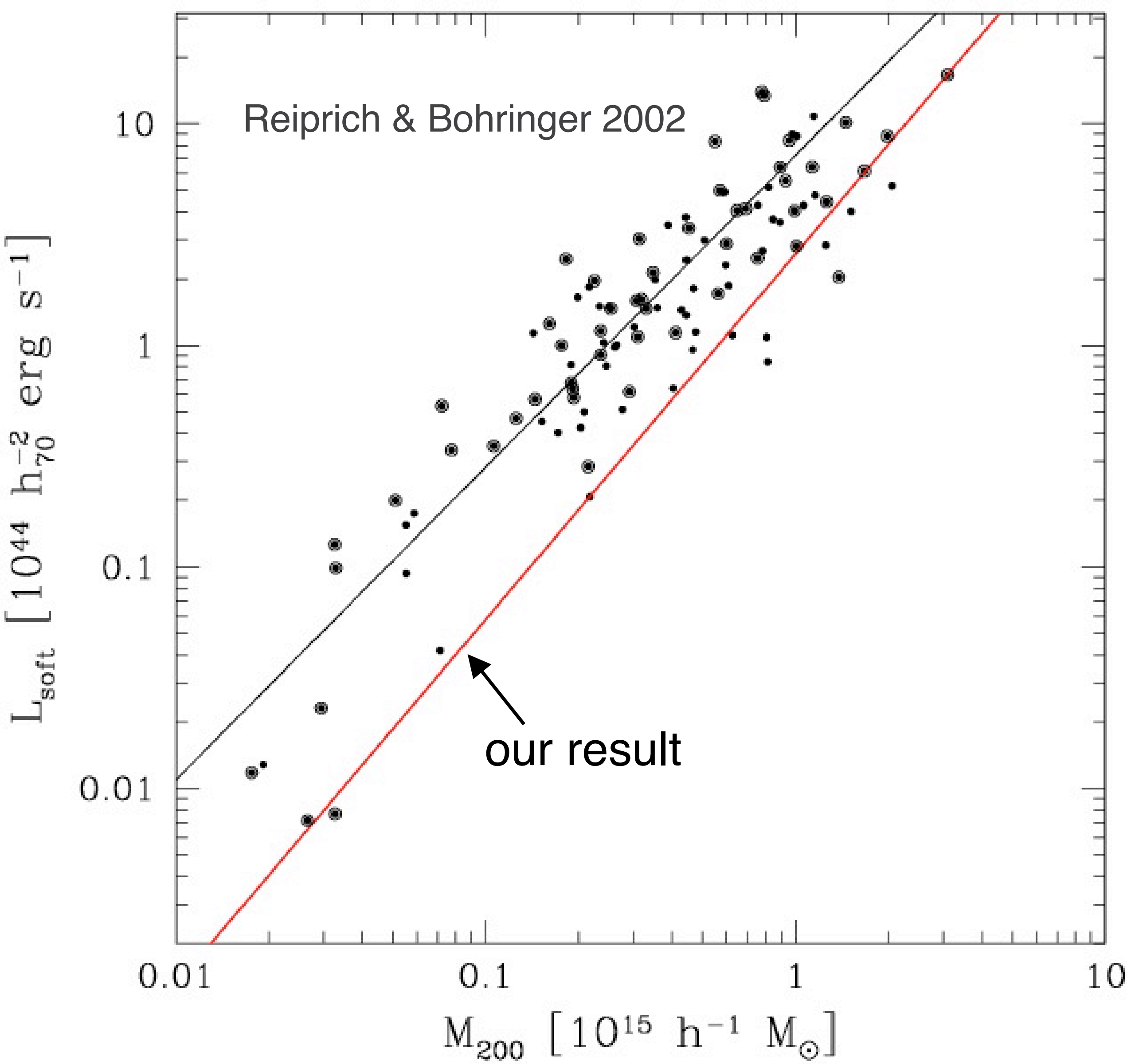


solid: self-similar L(z)

dotted: no L(z) evol'n

disagreement w/ Reiprich & Bohringer (2002) estimate using hydrostatic masses (dot w/ 90% c.l. errors)

discrepancy with previous work using hydrostatic masses



"isothermal beta-model" estimates

$$M \sim \beta_{fit} T r$$

dependence on cosmology

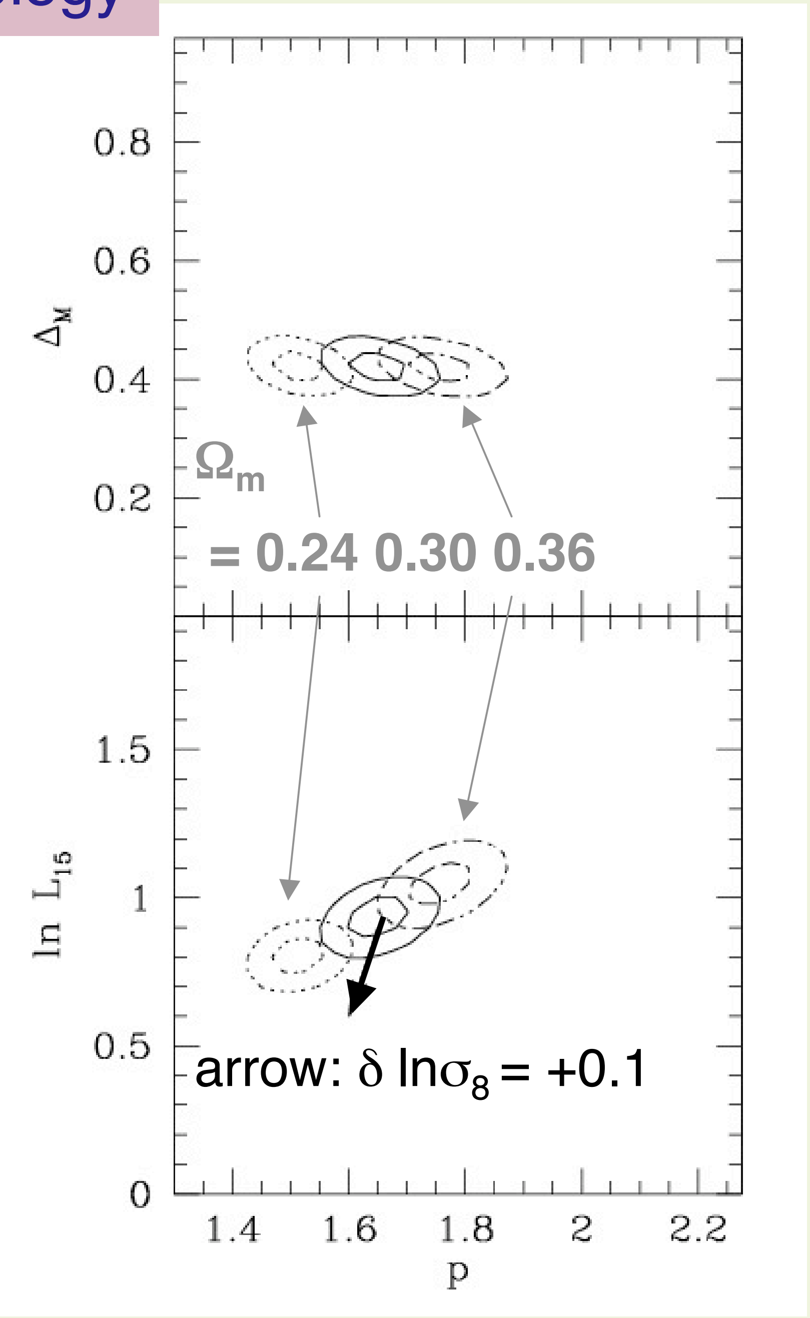
vary matter density keeping

$\Omega_m \sigma_8^2$ =const

(~ fixed space density)

from shape of mass function at rare tail (at fixed Ω_m)

$$L_{15} \propto \sigma_8^{\sim -4}$$

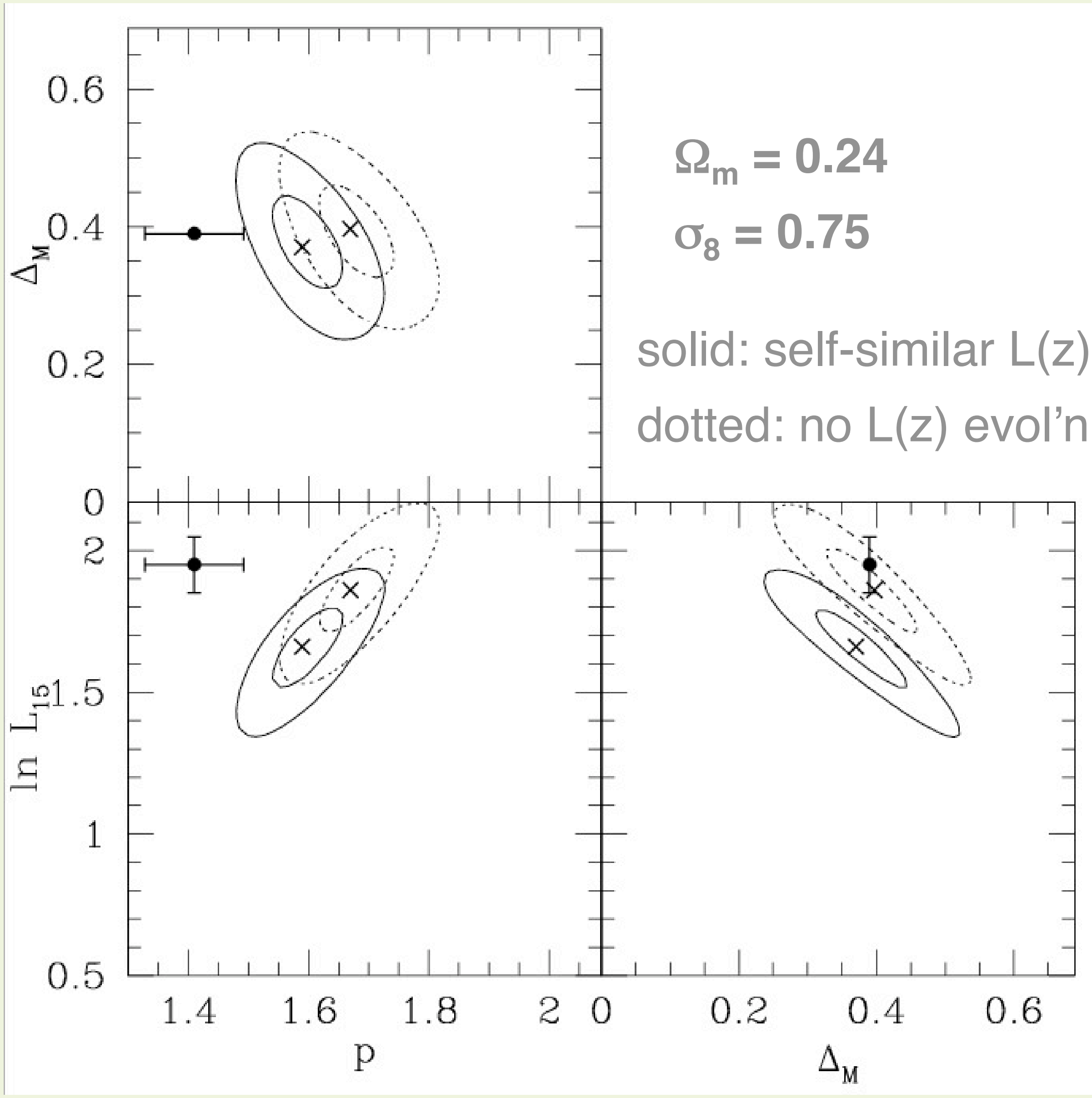


want
lower Ω_m
AND
lower σ_8

explicit example that closes in on RB02

requires only ~20% mass underestimates

see E. Rasia's poster



$\Omega_m = 0.24$

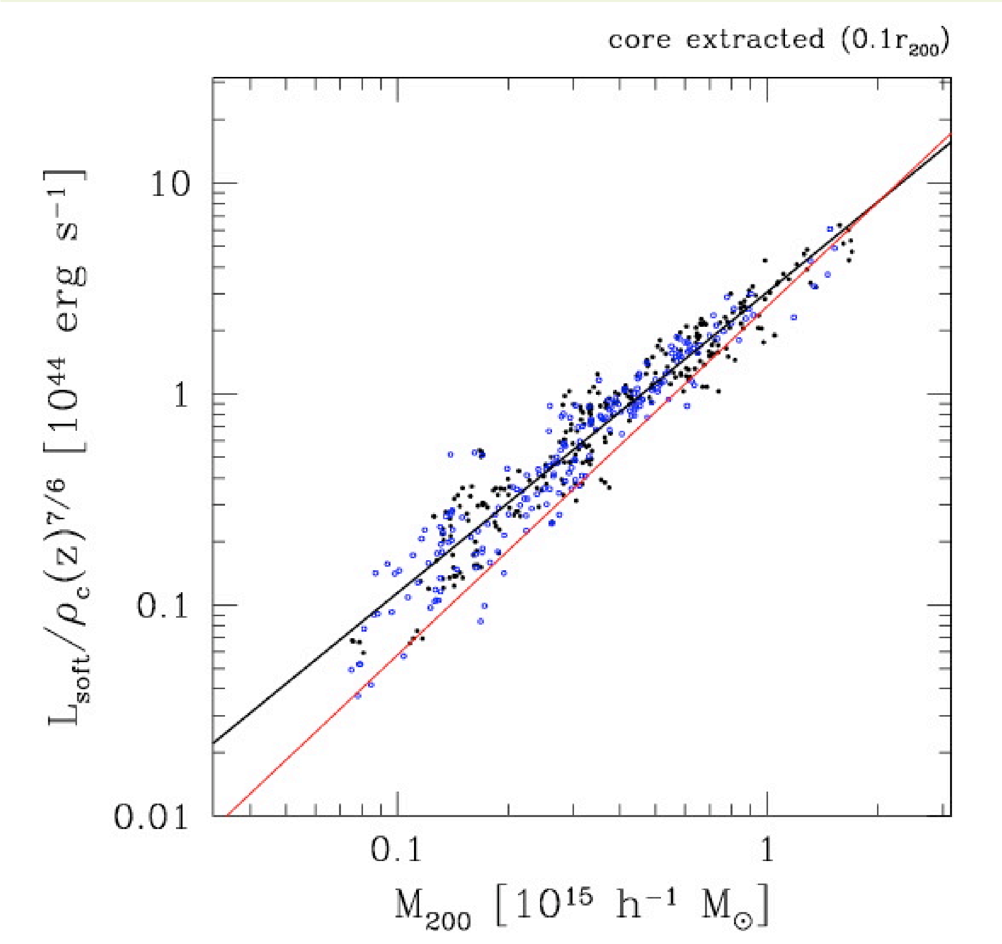
$\sigma_8 = 0.75$

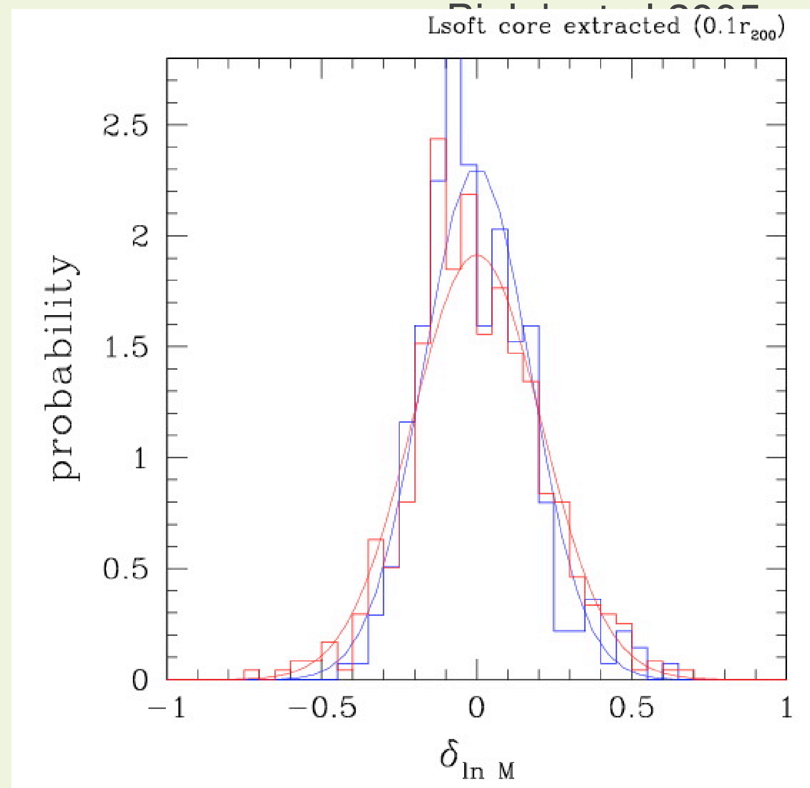
solid: self-similar L(z)

dotted: no L(z) evol'n

what do simulations say?

68 `preheated' cluster models @ z<0.36





slope: p=1.42 ± 0.02

Δ_{MIL} = 0.21 (all)
0.17 (M>3e14)

conclusions

REFLEX sample luminosity function is well fit by convolving the mass function in a ΛCDM cosmology with p(L | M) described as a power-law with log-normal scatter, but

- model is degenerate, need additional constraints
- T-L scatter (+ sim input) implies $\Delta_M = 0.43 \pm 0.06$
- resultant mean relation for SS evol's is then

$$p = 1.62 \pm 0.08 \; ; \ln L_{15} = 0.95 \pm 0.15 \; ; \Delta_M = 0.37 \pm 0.15$$

- discrepancy (in intercept) with hydrostatic mass estimates:

beta model masses biased low (factor 1.8 in concordance model!)

need lower σ_8 (+ Ω_m?) to reduce bias to ~30%

- `preheated' hydro models: $\Delta_{M|L} = 0.2$ (for core-extracted L)

independent mass estimates (via weak lensing) are critically needed!