Forefront Observations and Simulations

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- a (brief) look aft
- structural regularity
- Hubble volumes of clusters
- on the real and virtual horizons

1972 : two generations ago…

observation	few thousand optically identified clusters (Abell, Zwicky) Uhuru X-ray detections of three: Coma, Virgo & Perseus (Giacconi etal; Gursky etal; Forman etal; Cavaliere etal)
theory	spherical infall model (Gunn & Gott) CMB photons interacting with thermal gas (Sunyaev & Zel'dovich)
computation	300 particle N-body model of Coma (Peebles)

1986 : one generation ago…

observation — HEAO-1 X-ray detections of 128 clusters (Johnson etal 83)
Einstein imaging of 46 clusters (Jones & Forman 84)
a few reported detections of SZ effect (see Birkinshaw 1999)

theory — peaks in Gaussian random fields (Bardeen etal)

phenomenology — standard CDM model (Blumenthal etal)

computation — 32768 particle N-body models of SCDM (Davis etal)
1D hydro models of ICM evolution (Perrenod)

clusters at Y2K …

what is a cluster? an operational definition (SO algorithm) -

i) filter mass density on Lagrangian scale of 1e13 Msun

ii) center on highest density peak

iii) identify as cluster material within **radius r_D** defined by threshold

$$\rho(< r_\Delta) < \Delta\, \rho_c$$ (note **critical**, not **mean** density)

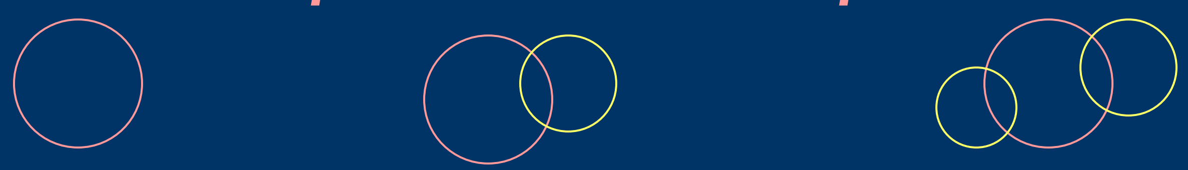
iv) repeat (ii) and (iii) for remaining ungrouped density peaks

particular definitions for this talk

cluster	$hM_{200} > 1e14$ Msun
group	$1e13 < hM_{200} < 1e14$
poor group / galaxy	$hM_{200} < 1e13$

terminology for overlapping groups

parent ***parent - child*** ***parent - children***



the *canonical model* of **clusters** (dissention required !)

gravity acting on a Gaussian initial density field produces an evolving population of massive collapsed structures (clusters defined previously) that

- are structurally regular in dark matter (NFW-like)
- are close to (<~15%) virial/hydrostatic equilibrium (except big mergers)
- retain nearly the cosmic mix of mass components
- have ICM thermodynamics dominated by shock heating and modest additional heating from starburst winds/AGN
- contain intermittent cooling flow cores
- contain galaxies mildly (anti-)biased wrt dark matter

mass hierarchy in Coma : $M_{ICM} \sim 10\ (h/0.65)^{-3/2}\ M_{gal}$

$M_{tot} \sim 10\ (h/0.65)^{-3/2}\ M_{baryon}$

connecting **Light** to **Mass** : Virial Theorem Scalings

- Apply virial theorem within a sphere encompassing a fixed multiple Δ of the critical density ρ_c

$$M_\Delta = (4\pi/3)\,\Delta\,\rho_c\,r_\Delta^{\;3}$$
$$kT/\,\mu m_p = \alpha\; GM_\Delta\,/\,r_\Delta$$

- Leads to expected scalings for characteristic mass and size

$$h(z)\,M_\Delta = (2/\alpha)^{3/2}\,(100/\Delta)^{1/2}\,(kT\,/10\text{ keV})^{3/2}\;\text{x}\;10^{14}\,M_{Sun}$$
$$h(z)\,r_\Delta = (2/\alpha)^{1/2}\,(100/\Delta)^{1/2}\,(kT\,/10\text{ keV})^{1/2}\;\text{Mpc}$$

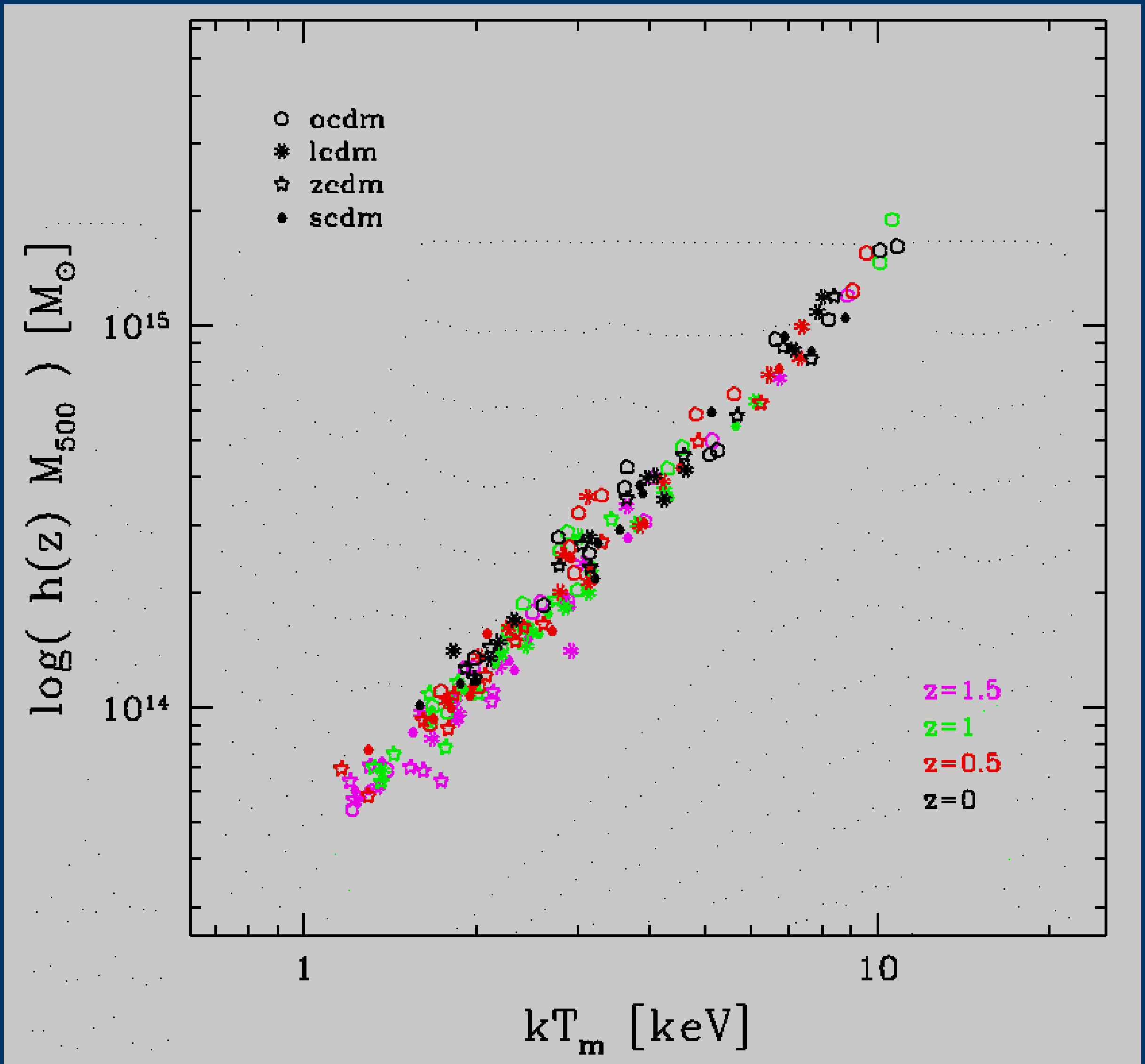
- Cosmology determines `active' scale factor $h(z)$

$$h^2(z) = h^2\,[\,\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\,]$$
$$h = H_0\,/\,(100\text{ km/s/Mpc})$$

Virial Mass-Temp scalings from 48 P3MSPH cluster simulations

~11 % scatter in *h(z)M* at fixed *kT*

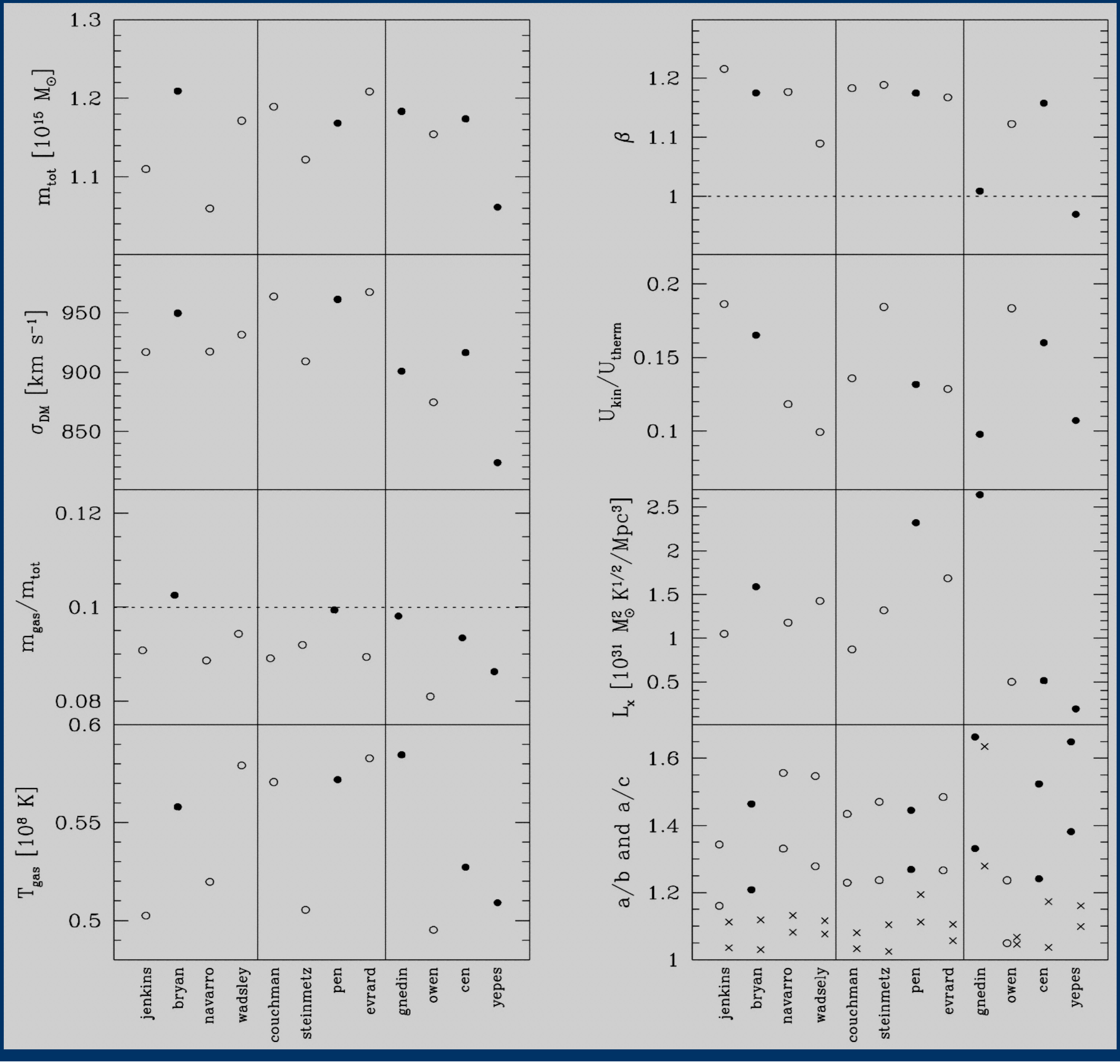
~ independent of cosmology/epoch



Mohr & Evrard 97
Mathiesen, Mohr & Evrard 99
Mathiesen, Evrard & Mohr 99
Mathiesen & Evrard 00

Comparison of 12 gas dynamic cluster simulations

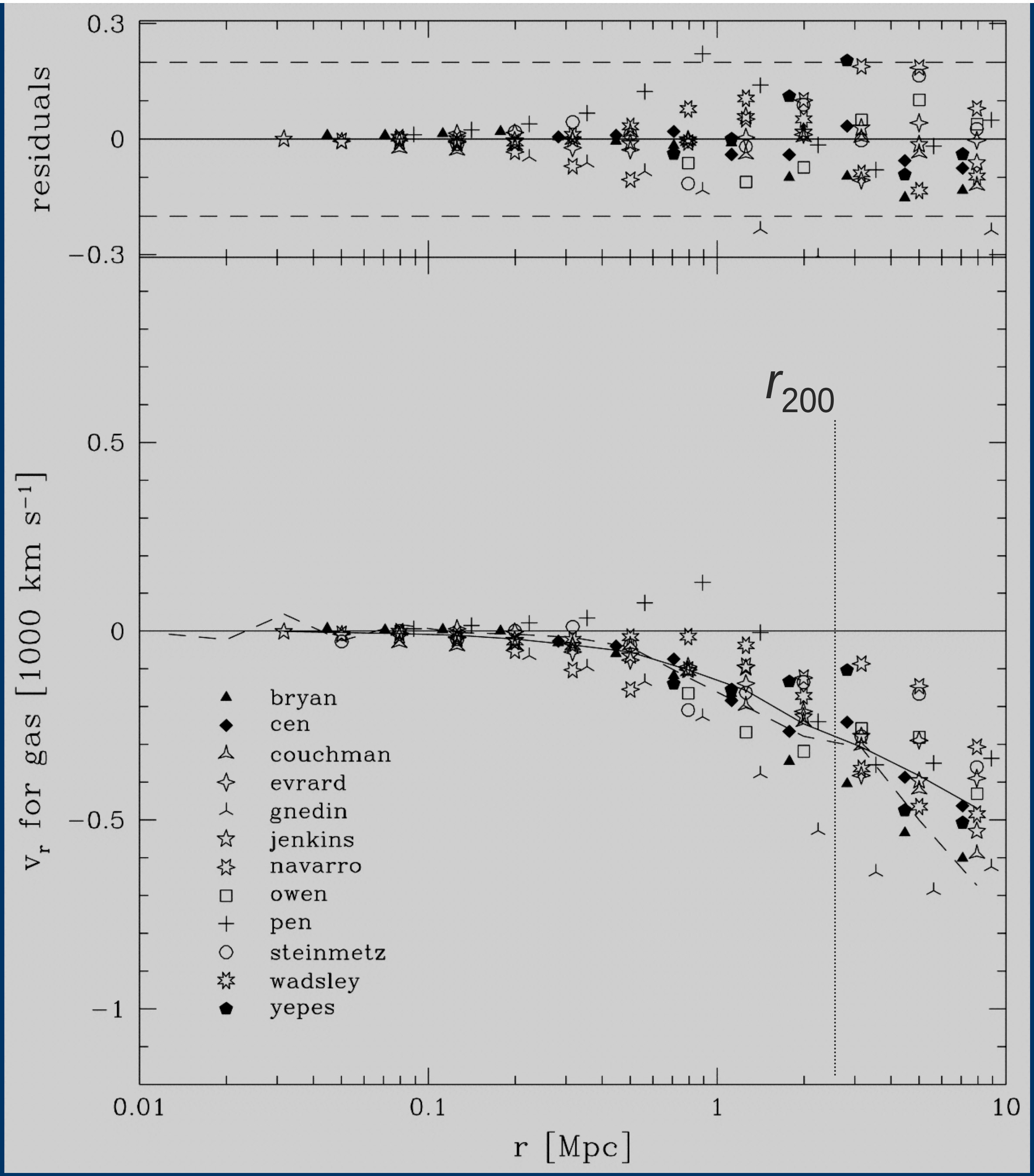
Frenk etal 99



10-20% deviations in bulk measures

correlated deviations partly due to differences in satellite orbits (errors in linear treatment) gas and dark matter still slightly infalling at r_{200}

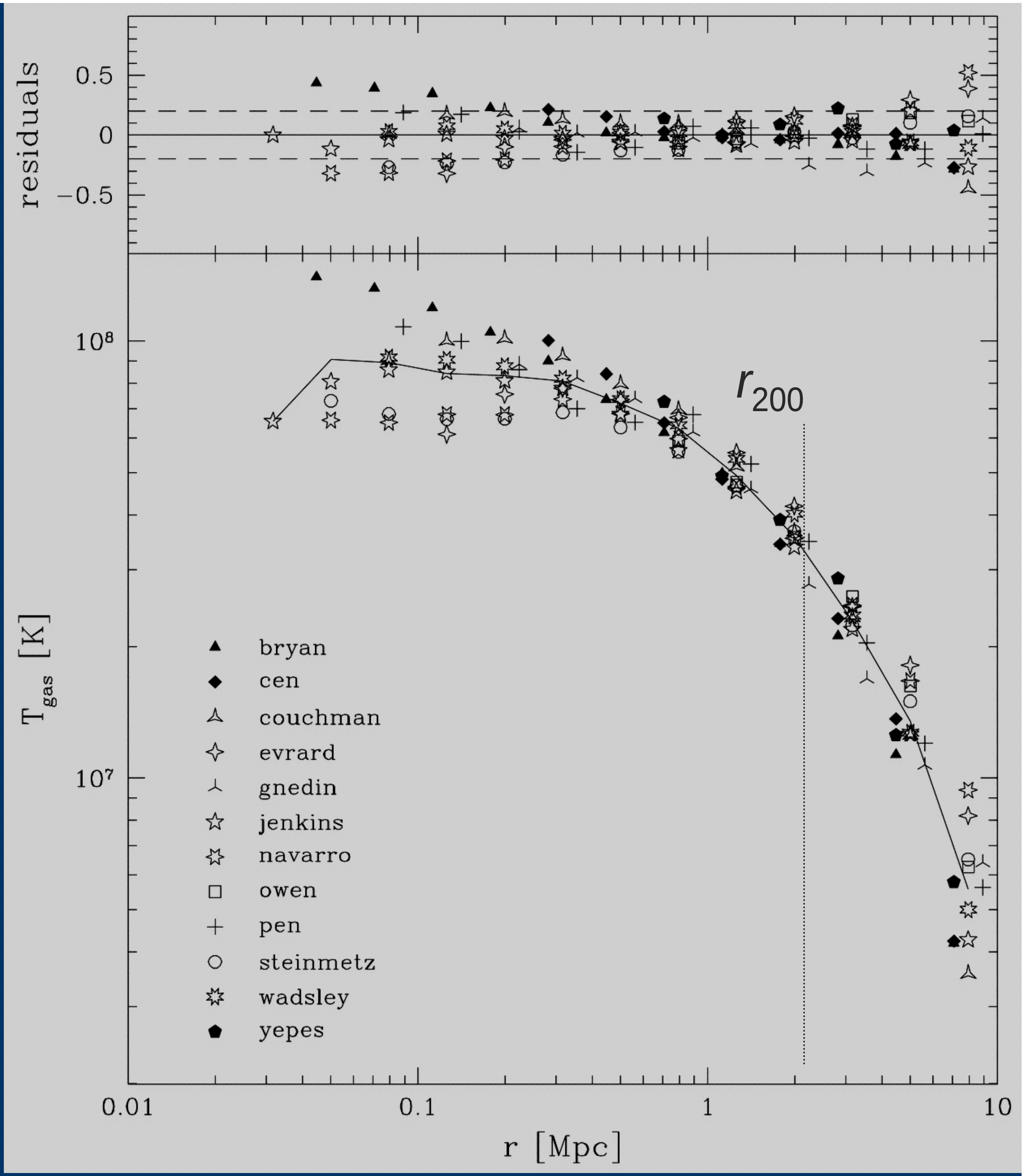
subsonic on average $<v_r^2>/<c_s^2> \sim 0.1$



falling temperature beyond ~0.3 r_{200}

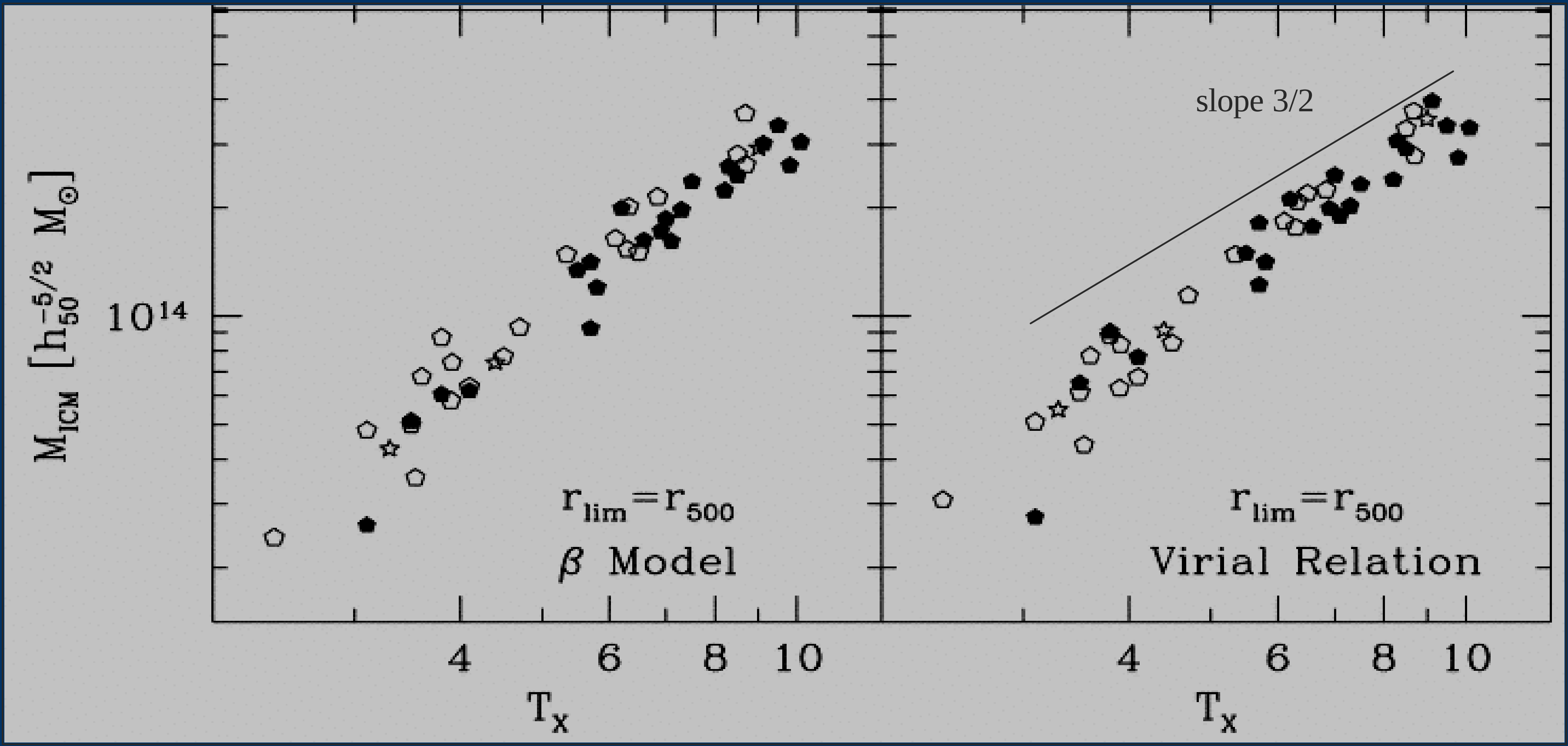
central temperature discrepancy between Eulerian and Lagrangian treatments?

not yet understood



ICM Mass - Temp relation for 45 clusters of the Edge sample

Mohr, Mathiesen & Evrard 99



14 % scatter in M_{ICM} at fixed T_X supports canonical model

also Neumann & Arnaud 99, Ellingson+CNOC scalings of X-ray/optical profiles

combination of L_X , R_I and M_{ICM} test different moments of the gas density distribution -> constraints on multiphase models

preheated ICM : P3MSPH simulatons

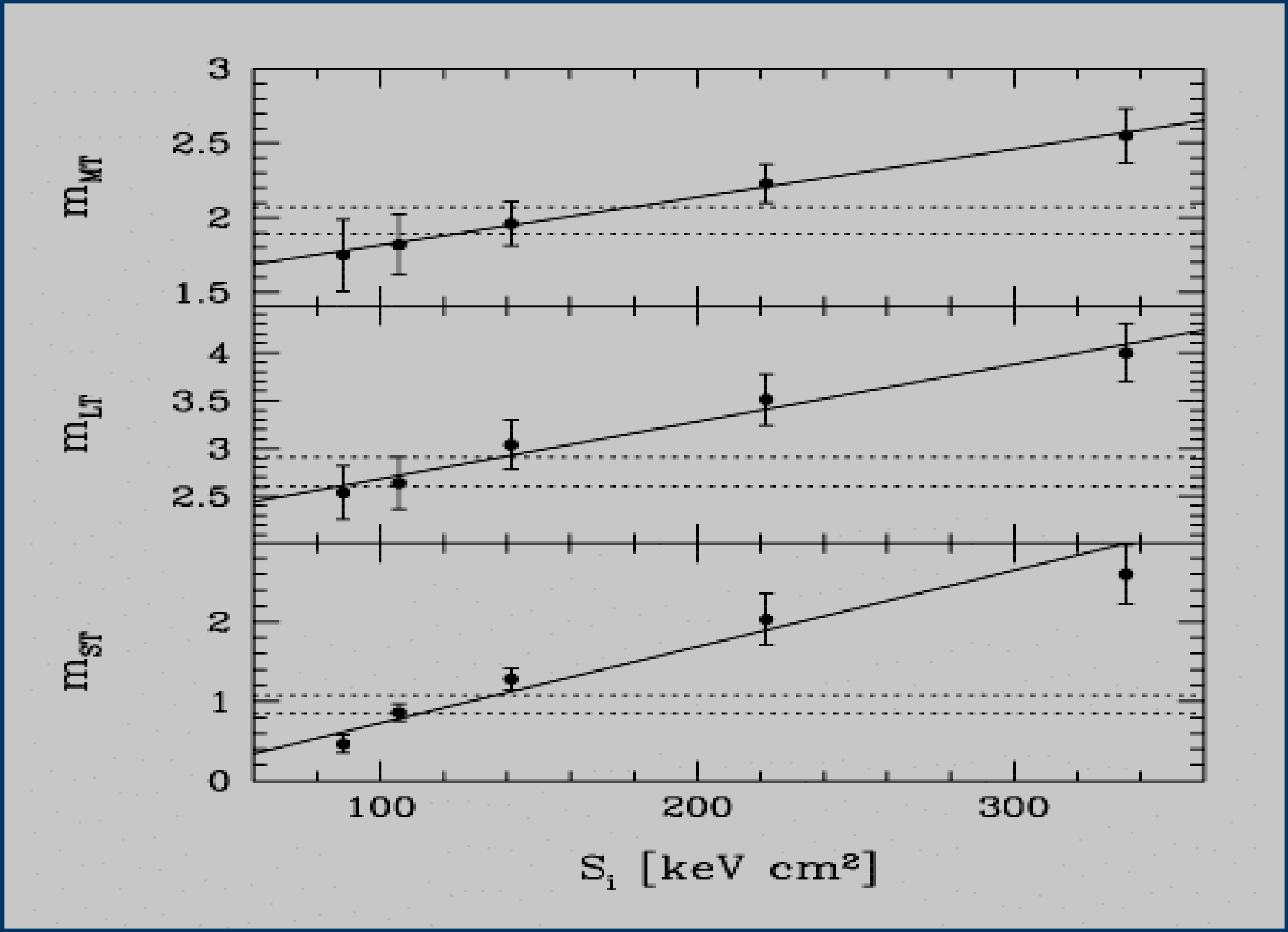
Bialek, Mohr & Evrard, in prep

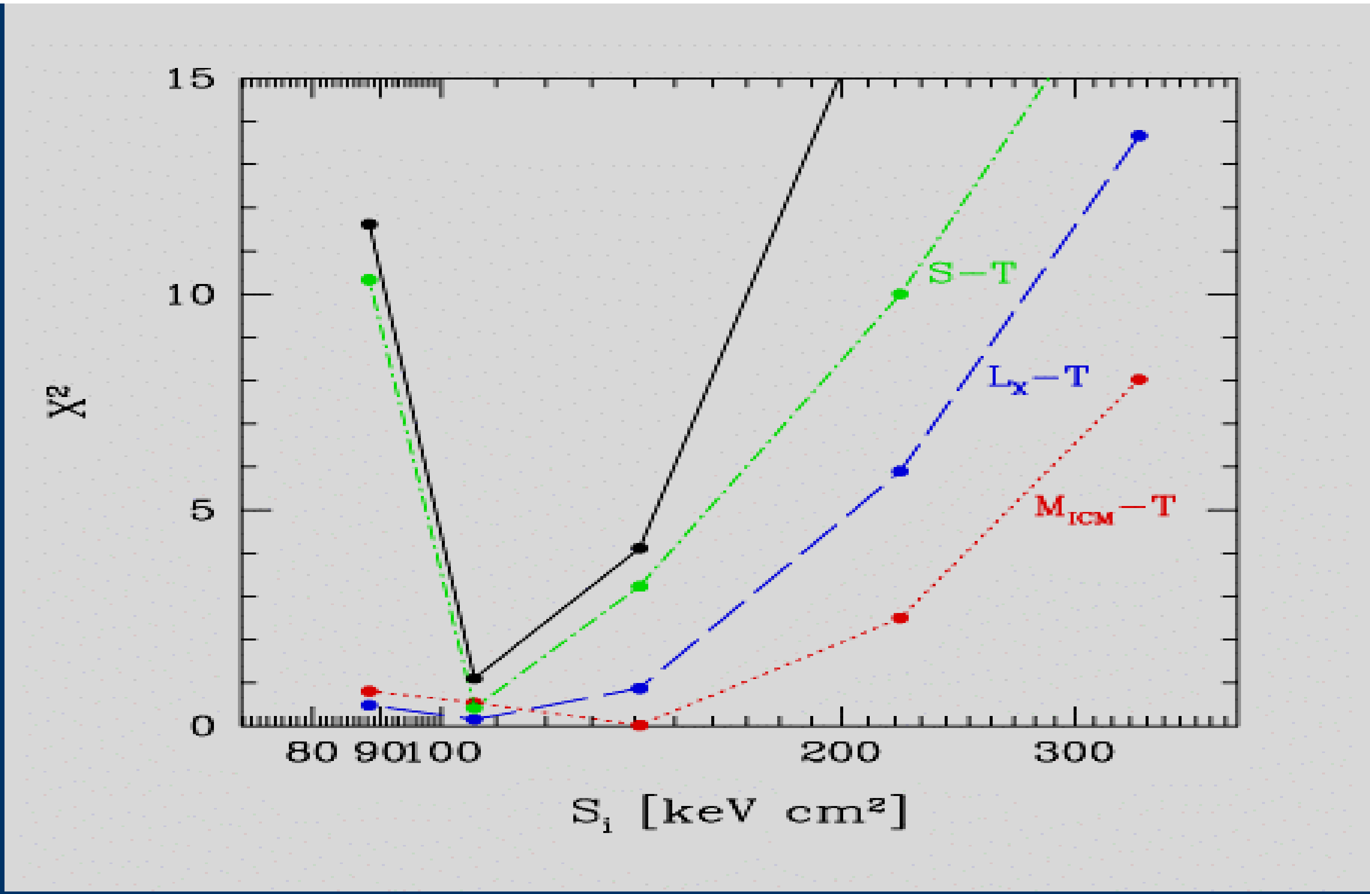
12 ΛCDM clusters evolved from different initial temperatures
phrase in terms of initial entropy $S_i = \ln (T_i / \rho_i^{2/3})$
mekal emission model with 0.3 solar spectral T's used in fitting relations

M_{ICM} - T_X

L_X - T_X

R_I - T_X





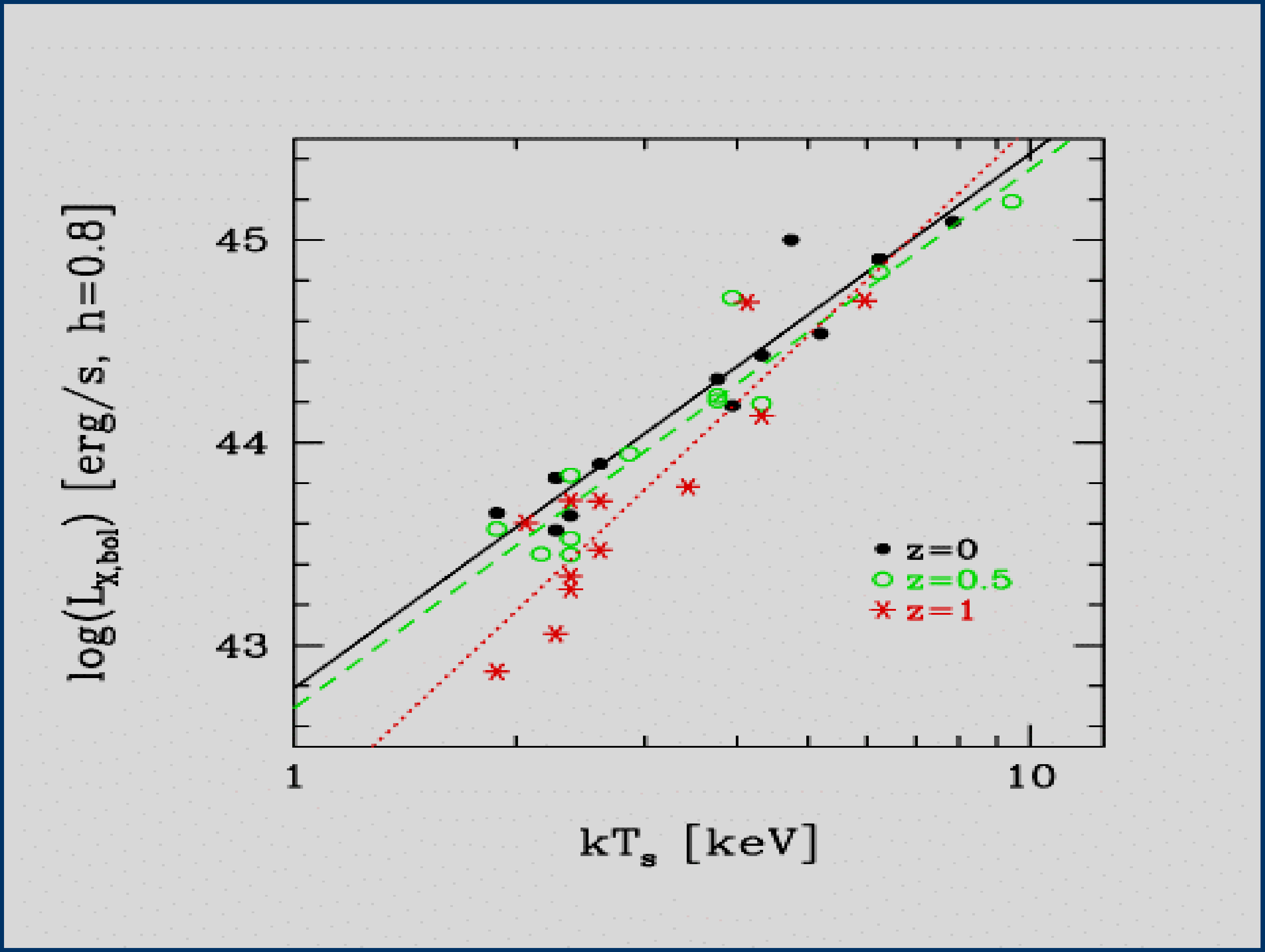
initial entropy S_i ~ 100 keV cm^2 provides good matches to observations
agrees with empirical determination of entropy `floor'

Lloyd-Davies, Ponman & Cannon 99

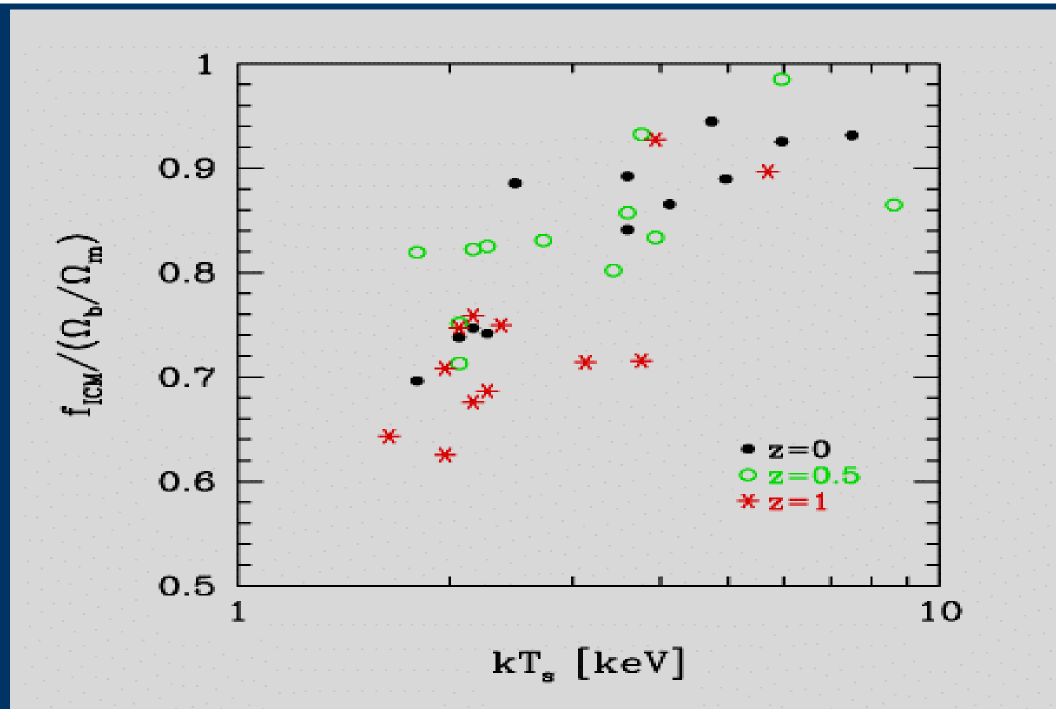
mild disagreement(?) among theoretical approaches

Tozzi, Cavaliere & Menzi 98
Balogh, Babul & Patton 98
Wu, Fabian & Nulsen 99
Bower etal 00

models show little or no shift in L-T relation out to *z*~1

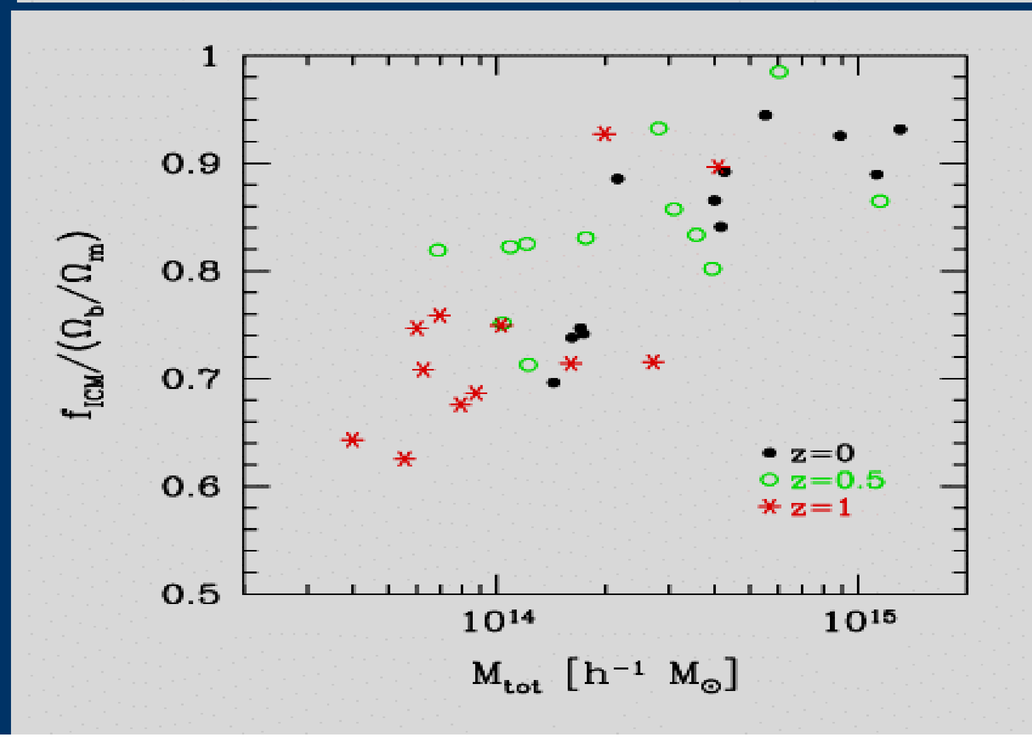


moderate ICM gas loss within r_{200} for T<~4 keV clusters



limited to <~30% depletion for hM_{200} > 1e14 Msun

`fair sample' of cosmic mix hypothesis is ok for clusters to z~1

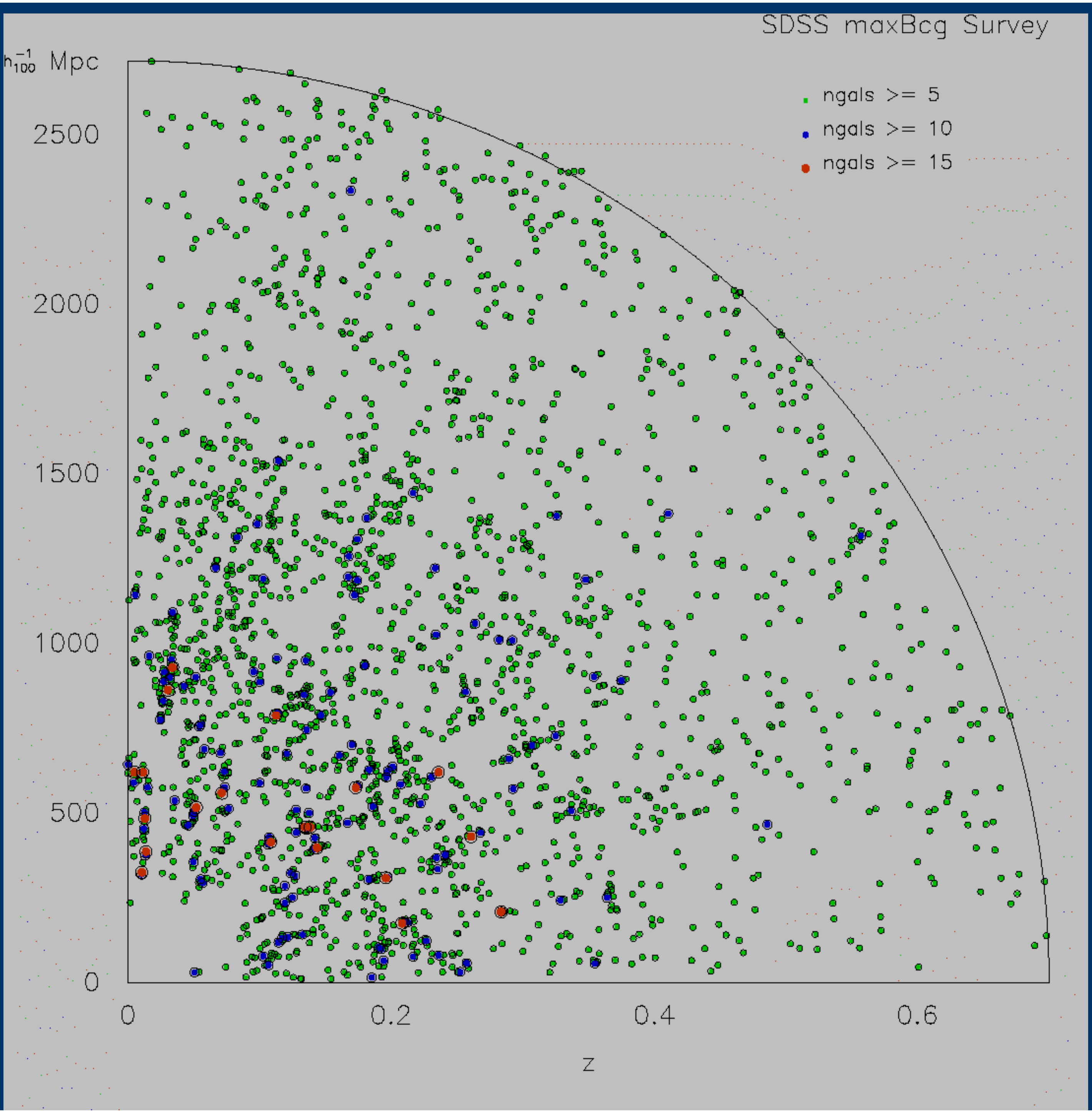


preliminary
Sloan Survey cluster catalogue

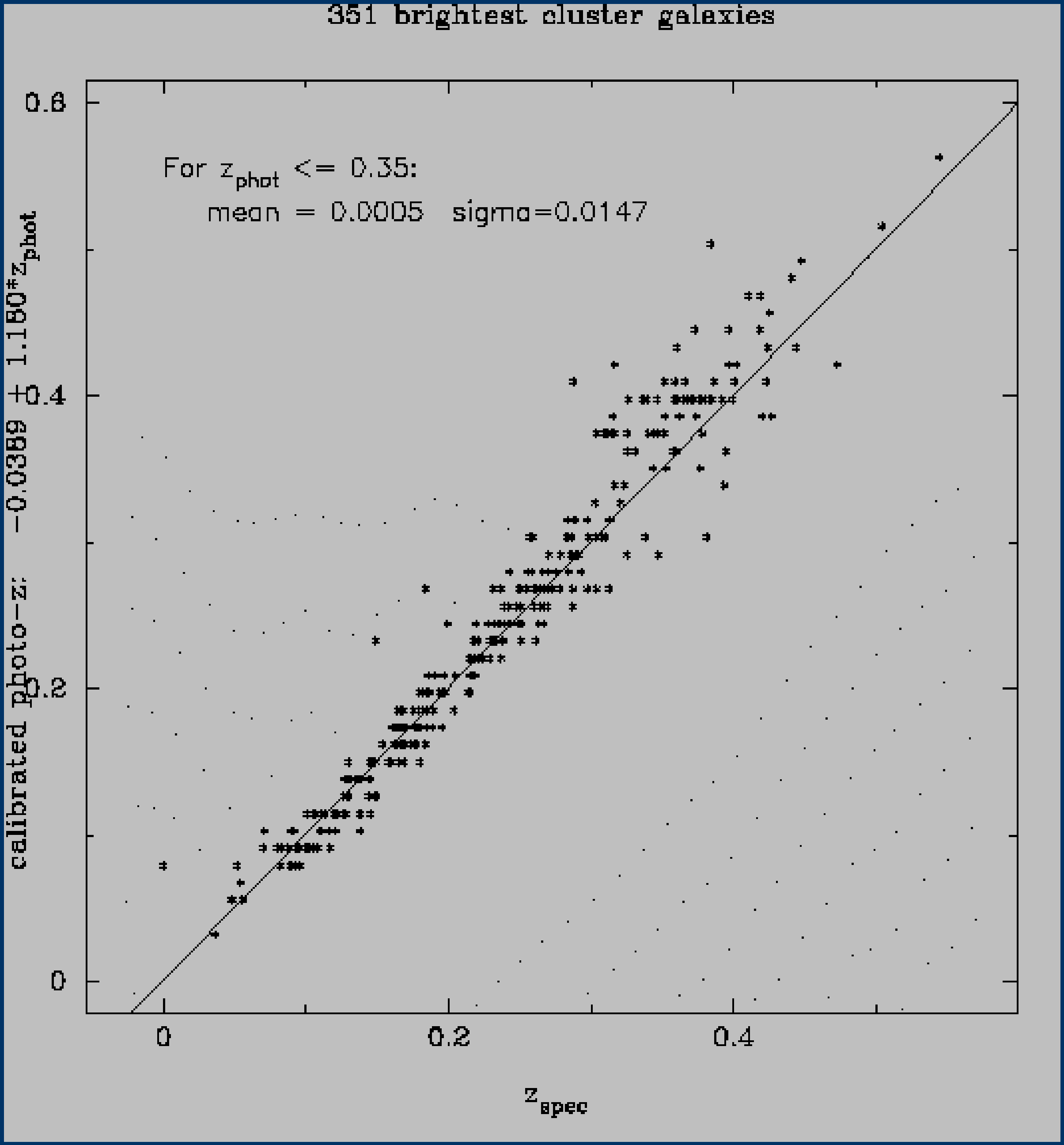
J. Annis (Chicago)
& SDSS conortium

Adaptive color selection centered on bright red galaxies

lots o' clusters!



Photometric redshifts to z=0.35 accurate to ~ 0.015




FRANK AND ERNEST
IF YOU THINK THE UNIVERSE IS BIG YOU SHOULD SEE THE SOURCE CODE!
2-5
THAVES

Hubble Volume Simulations

C. Frenk, F. Pearce, A. Jenkins (Durham)
S. White J. Colberg, N. Yoshida (MPA-Garching)
T. MacFarland (Rechenzentrum Garching)
H. Couchman (McMaster)   P. Thomas (Sussex)
G. Efstathiou (Cambridge)   J. Peacock (Edinburgh)
A. Evrard (Michigan)

Science goals

- character of rare LSS objects
- mock galaxy surveys, cluster catalogs
- public database

Two billion particle N-body simulations (m_p = 2.2e12 h^{-1} M_o)

LCDM $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$, L=3000 h^{-1} Mpc

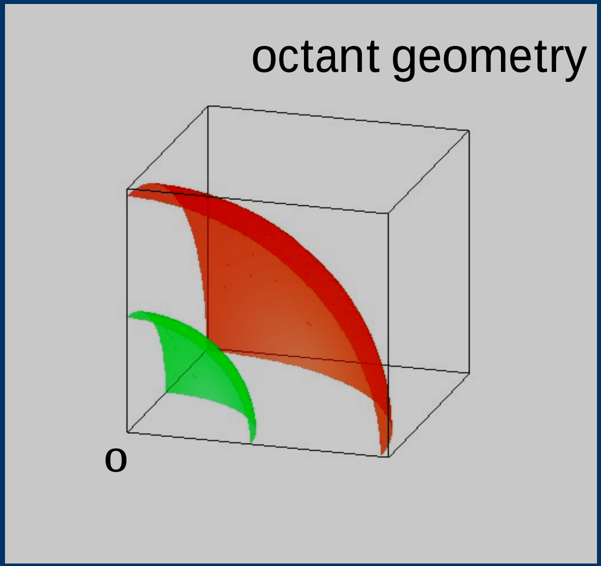
tCDM $\Omega_m = 1$, $\Omega_\Lambda = 0$, $\sigma_8 = 0.6$, L=2000 h^{-1} Mpc

artificial `sky' surveys

view structure along past light-cone of a virtual observer

to max redshifts z_{max} set by L (octants) and $L/2$ (spheres)

	octants	spheres
area coverage	π	8π
z_{max} (**L**CDM)	1.45	0.58
z_{max} (**t**CDM)	1.25	0.45



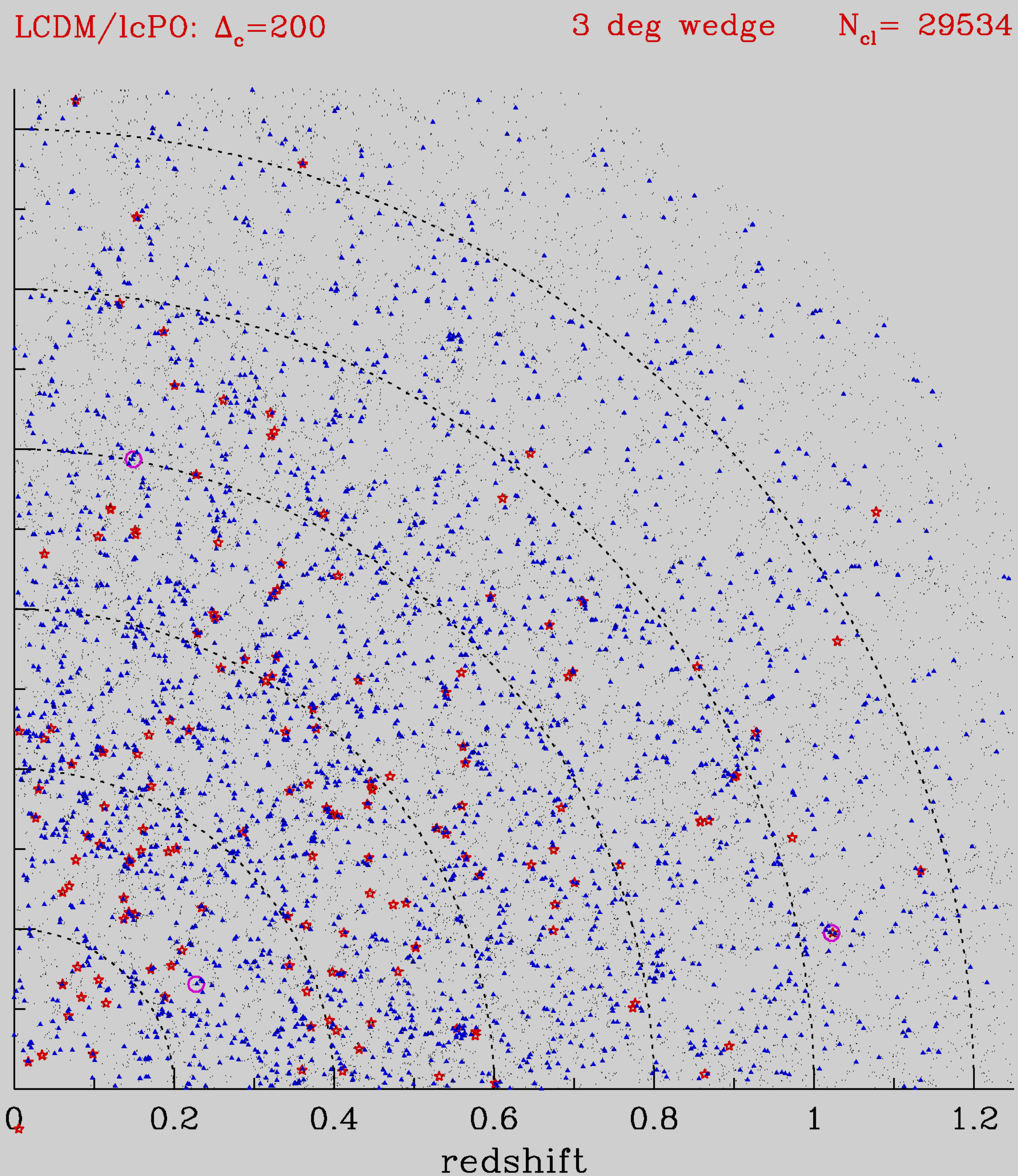
simulations yield big, deep cluster samples

Numbers in combined surveys

M_{200}	>1e15	>1e14
LCDM	582	397,595
tCDM	233	216,346

clusters in 3x 90 deg^2 slice of a virtual ΛCDM sky (extracted from octant survey)

symbol color indicates mass-
black >3e13
blue >1e14
red >3e14
circles >1e15



a *unified* form for the mass function of collapsed objects (Jenkins etal /0005260)

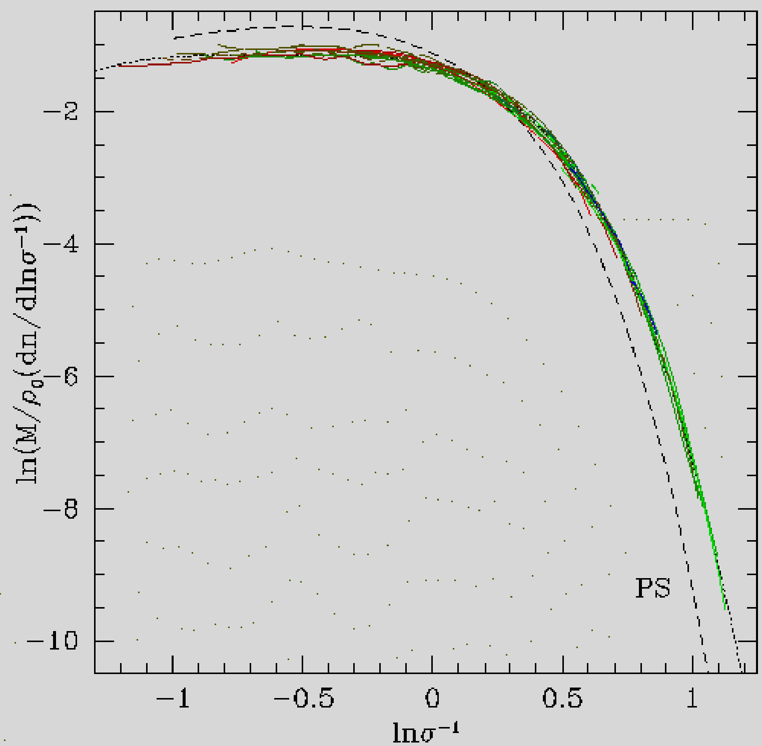


Figure 7. The FOF(0.2) mass functions of all the simulation outputs listed in Table 2. Remarkably, when a single linking length is used to identify halos at all times and in all cosmologies, the mass function appears to be invariant in the $f - \ln\sigma^{-1}$ plane. A single formula (eqn. 9), shown 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.

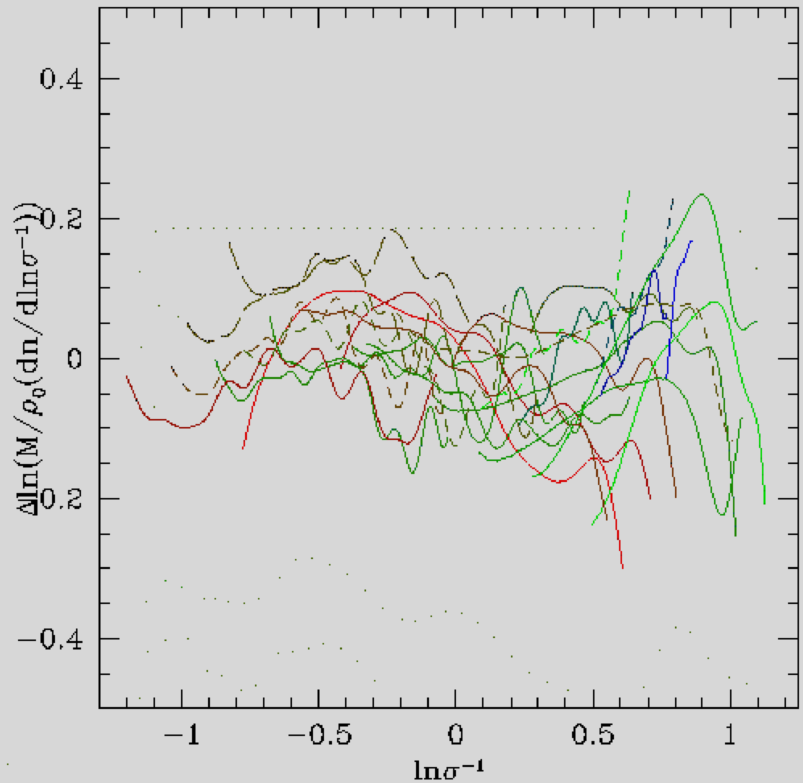
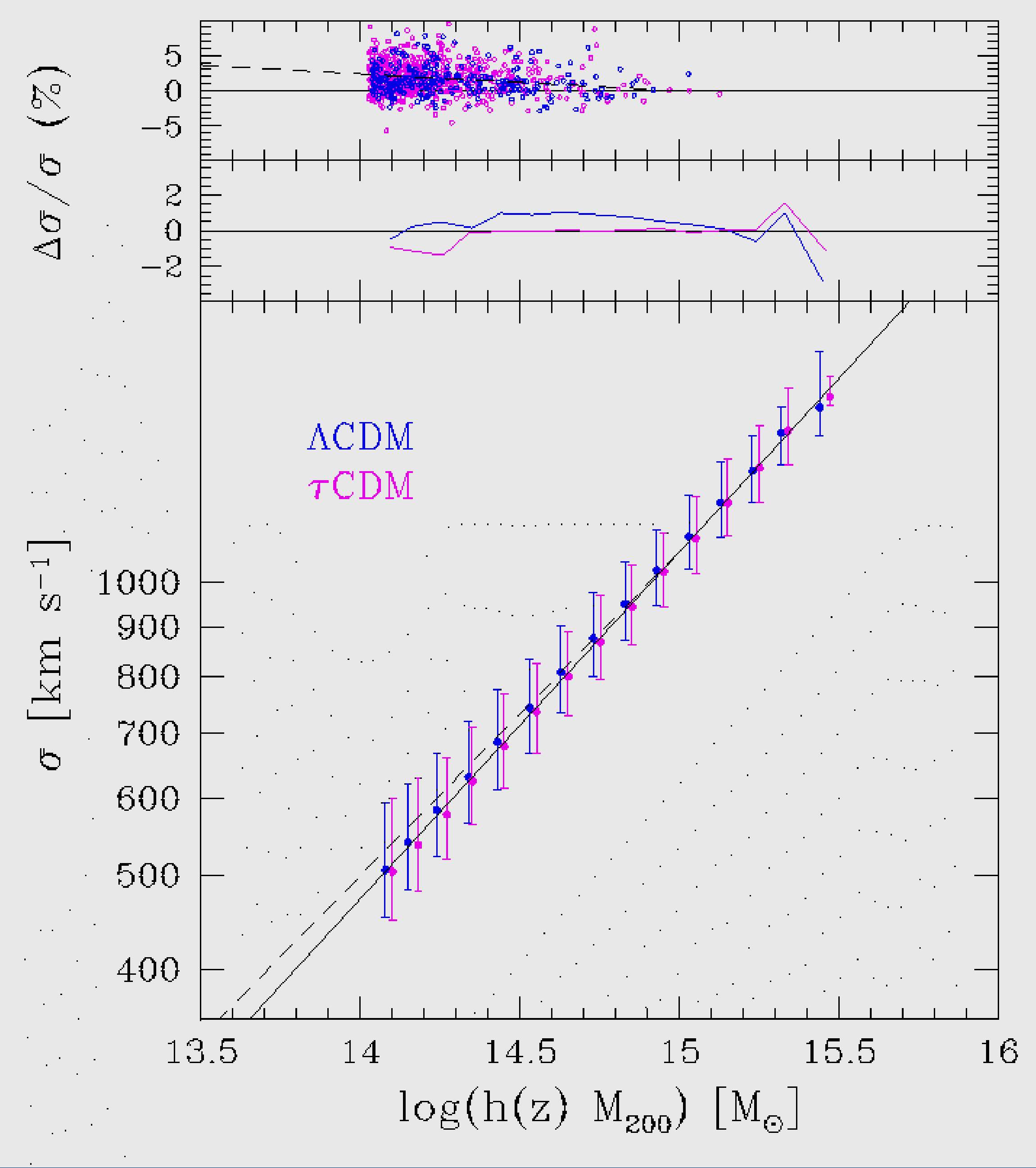


Figure 8. The residual between the fitting formula, eqn. 9, and the FOF(0.2) mass functions for all the simulation outputs listed in Table 2. Solid lines correspond to simulations with $\Omega = 1$, short dashed lines to flat, low Ω_0 models, and long dashed lines to open models.



<- comparison to higher resolution experiments

slope consistent with 1/3

<- residuals at few % level

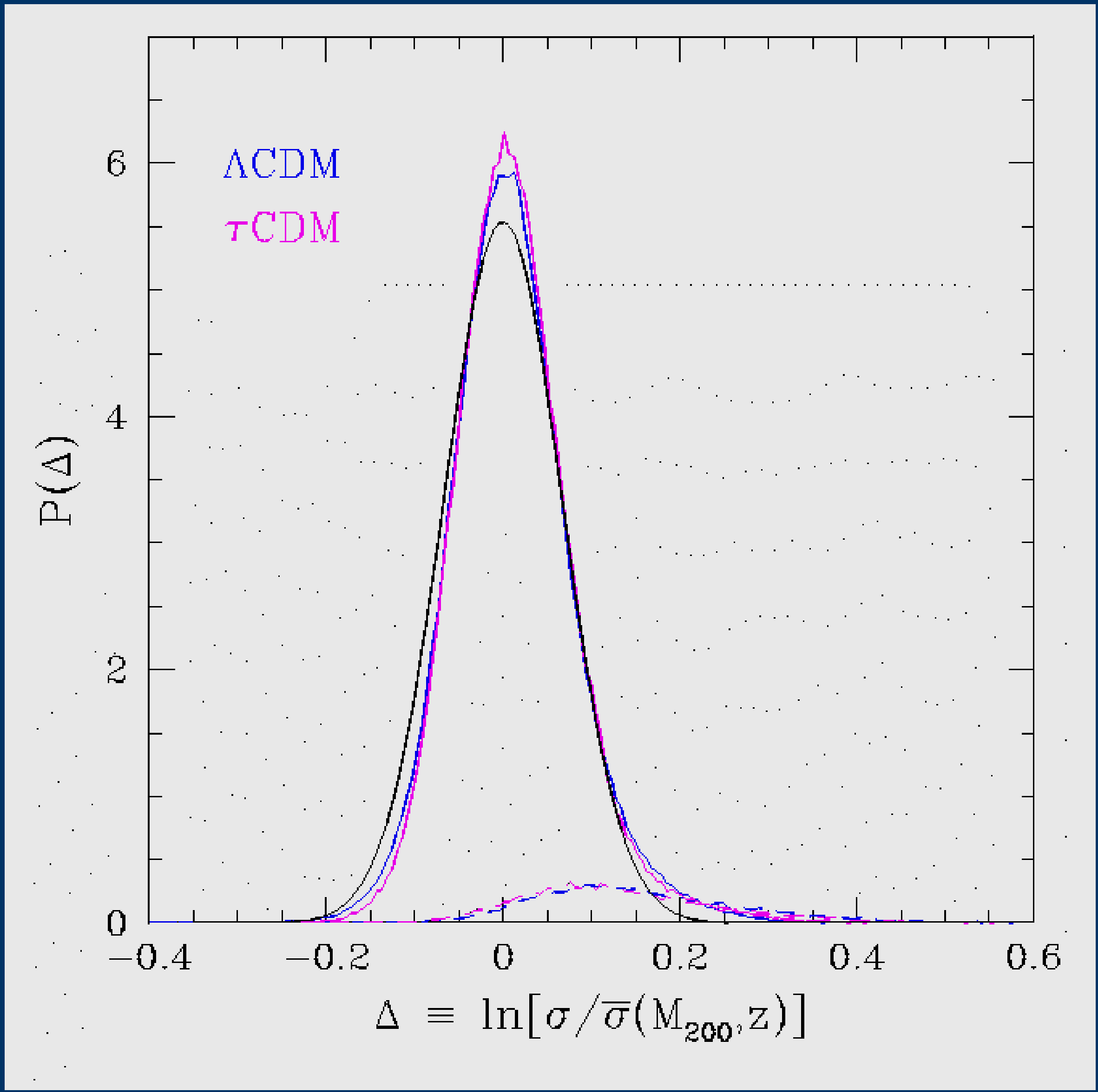
`unified' and precise form for median velocity - mass relation

points : median

error bars : 5 - 95 % range

solid line : best fit

dashed line : slope 1/3



Parent population:
approximately lognormal scatter about median relation

rms(Δ) ~ 0.07

child population (dashed)
fraction by number: 7.5%
displaced to high **s**
likely merger debris
not yet dissolved by parent

Table 1: **Parent cluster population** : $\sigma = \sigma_{15}\ [h(z)M_{200}/10^{15}\ \mathrm{M}_\odot]^\alpha$

model	N^a	σ_{15}	α	rms(Δ)
ΛCDM – HV	367424	1080.9 ± 0.5	0.35533 ± 0.00028	0.070
τCDM – HV	200049	1080.0 ± 0.6	0.35816 ± 0.00038	0.068
ΛCDM – J98[b]	280	1087 ± 10	0.3432 ± 0.0056	0.046
τCDM – J98[c]	594	1091 ± 9	0.3406 ± 0.0046	0.050

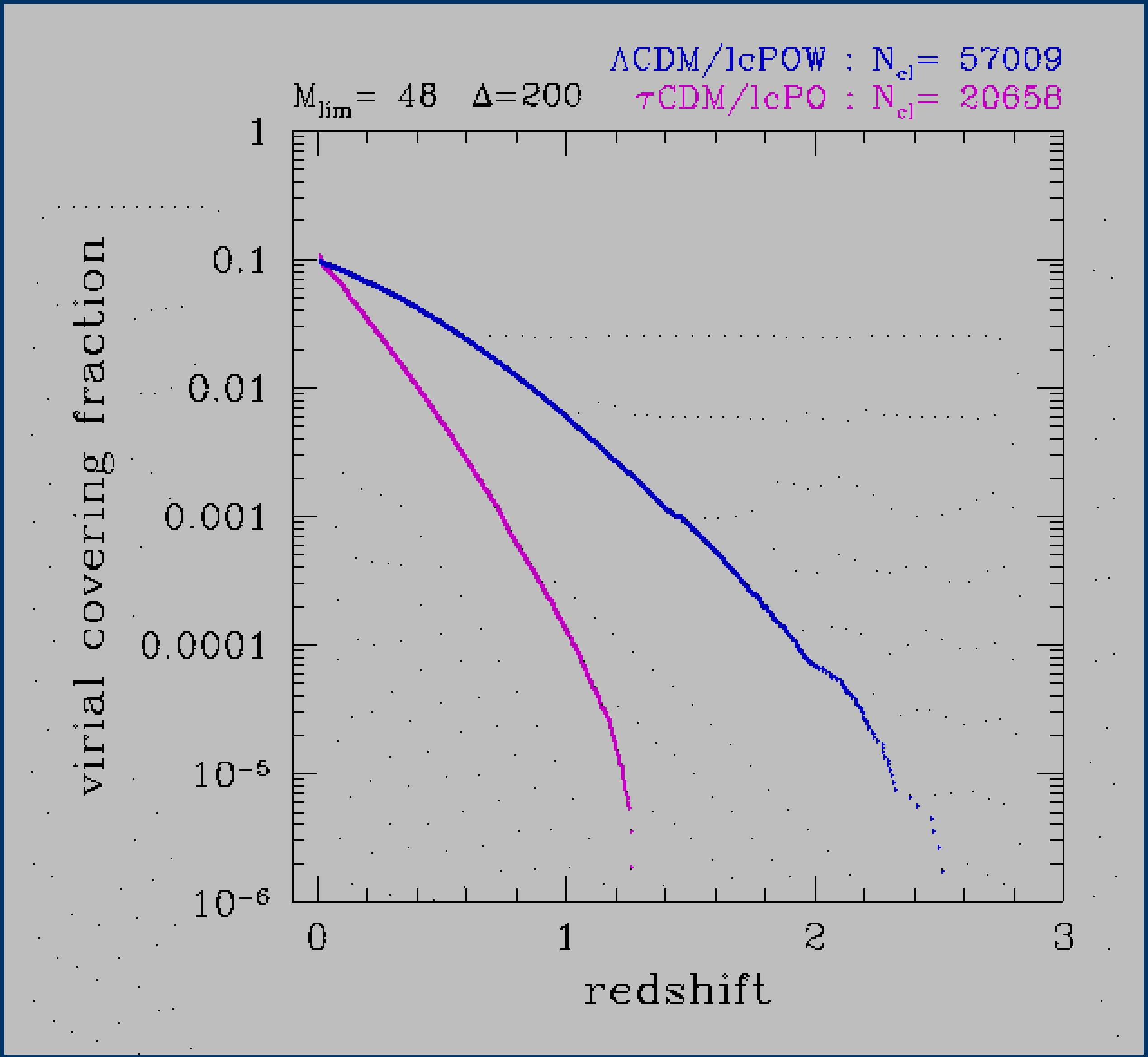
[a] $M_{200} > 10^{14} h^{-1}\,\mathrm{M}_\odot$ ($\geq$ 48 particles)
[b] Jenkins *et al.* (1998), $m_{part} = 6.8 \times 10^{10} h^{-1}\,\mathrm{M}_\odot$ ($N >$ 1584 particles)
[c] Jenkins *et al.* (1998), $m_{part} = 2.3 \times 10^{11} h^{-1}\,\mathrm{M}_\odot$ ($N >$ 468 particles)

zero-point well determined : $\mathbf{s}_{15}$ = 1085 +- 10 km/s
slope affected by resolution: converging to .333 ?

aim is to invert and recover $L(M_\Delta \,|\, \sigma_{gal})$

clusters' virial regions cover 10% of sky

see M. Voit's poster



expected counts
above 2e14 Msun/h
in 100 sq deg

~ 260 Λ

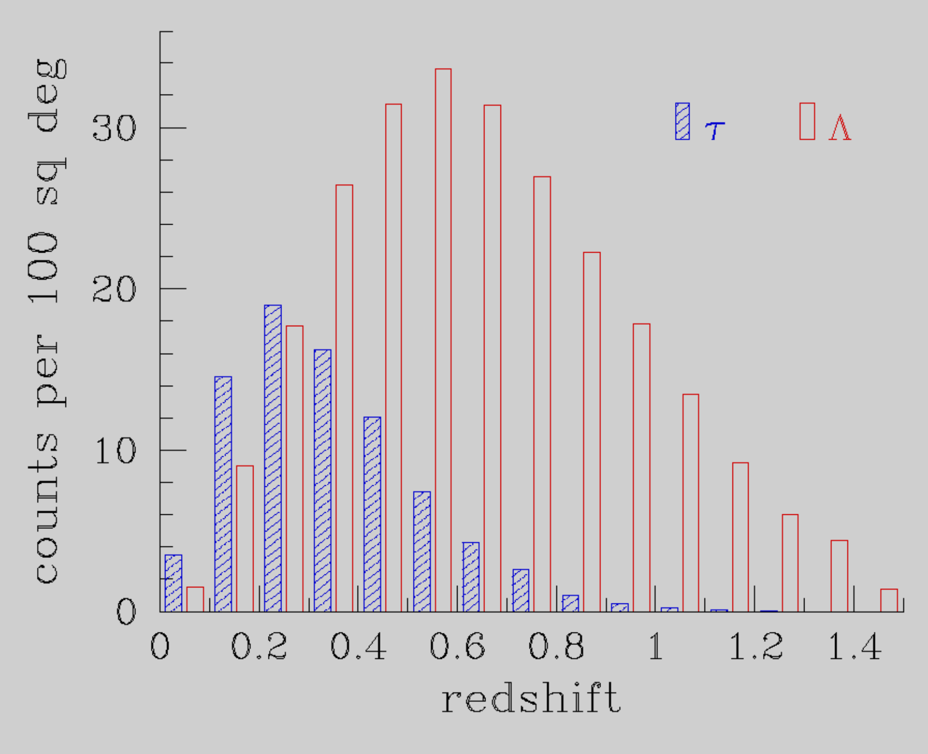
~ 80 τ

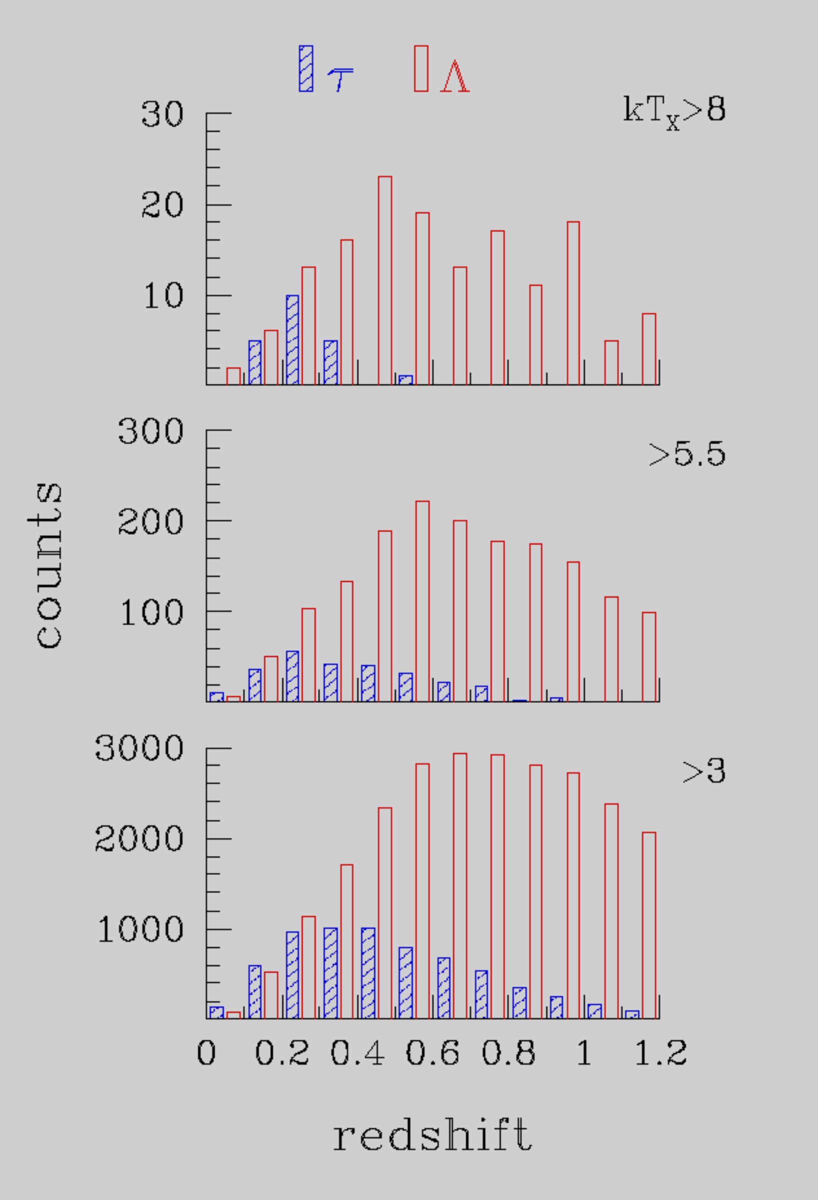
need SZ searches !

Holder etal 00

median redshift
is sensitive
cosmological
diagnositic

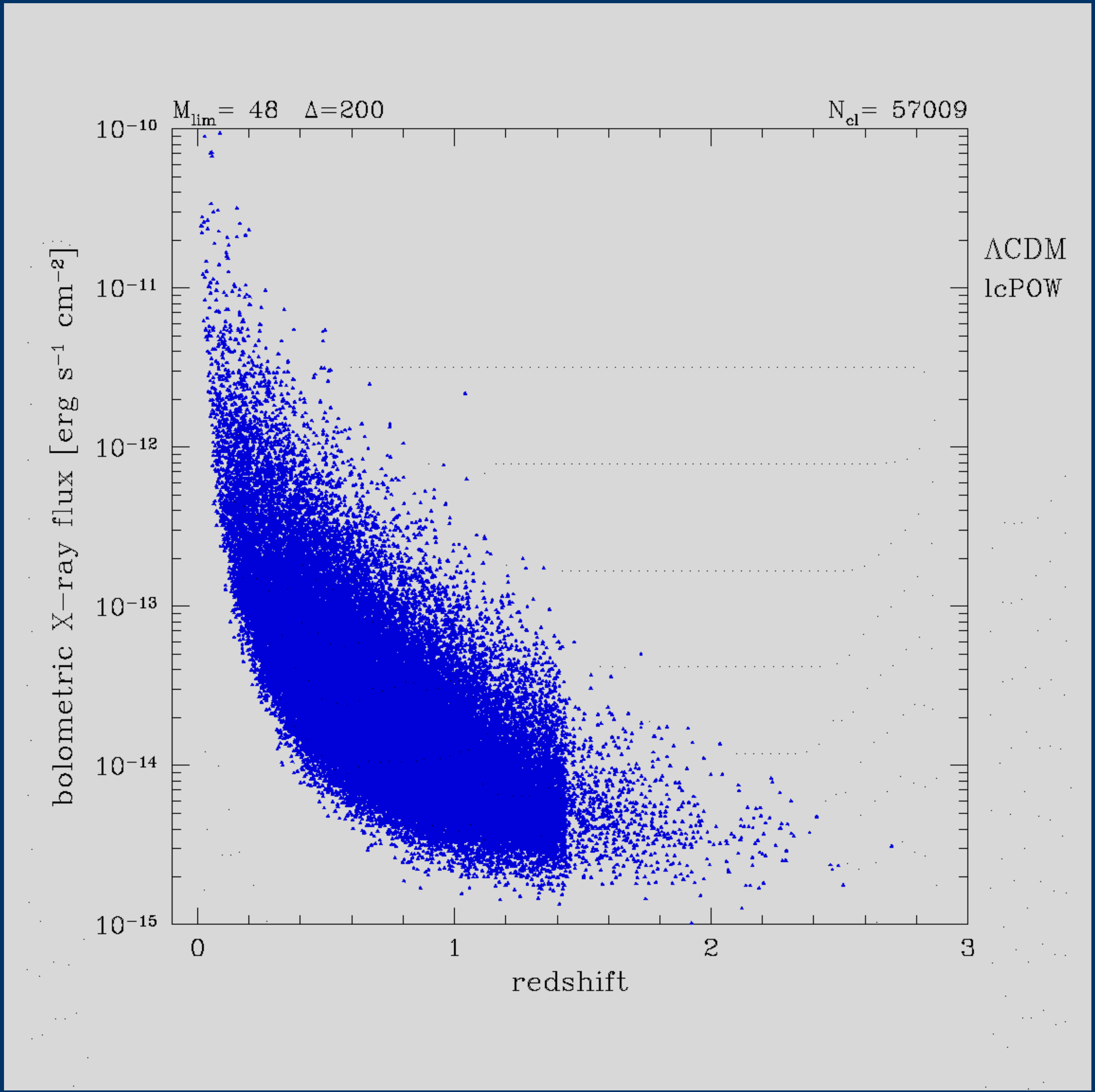
Oukbir & Blanchard 92



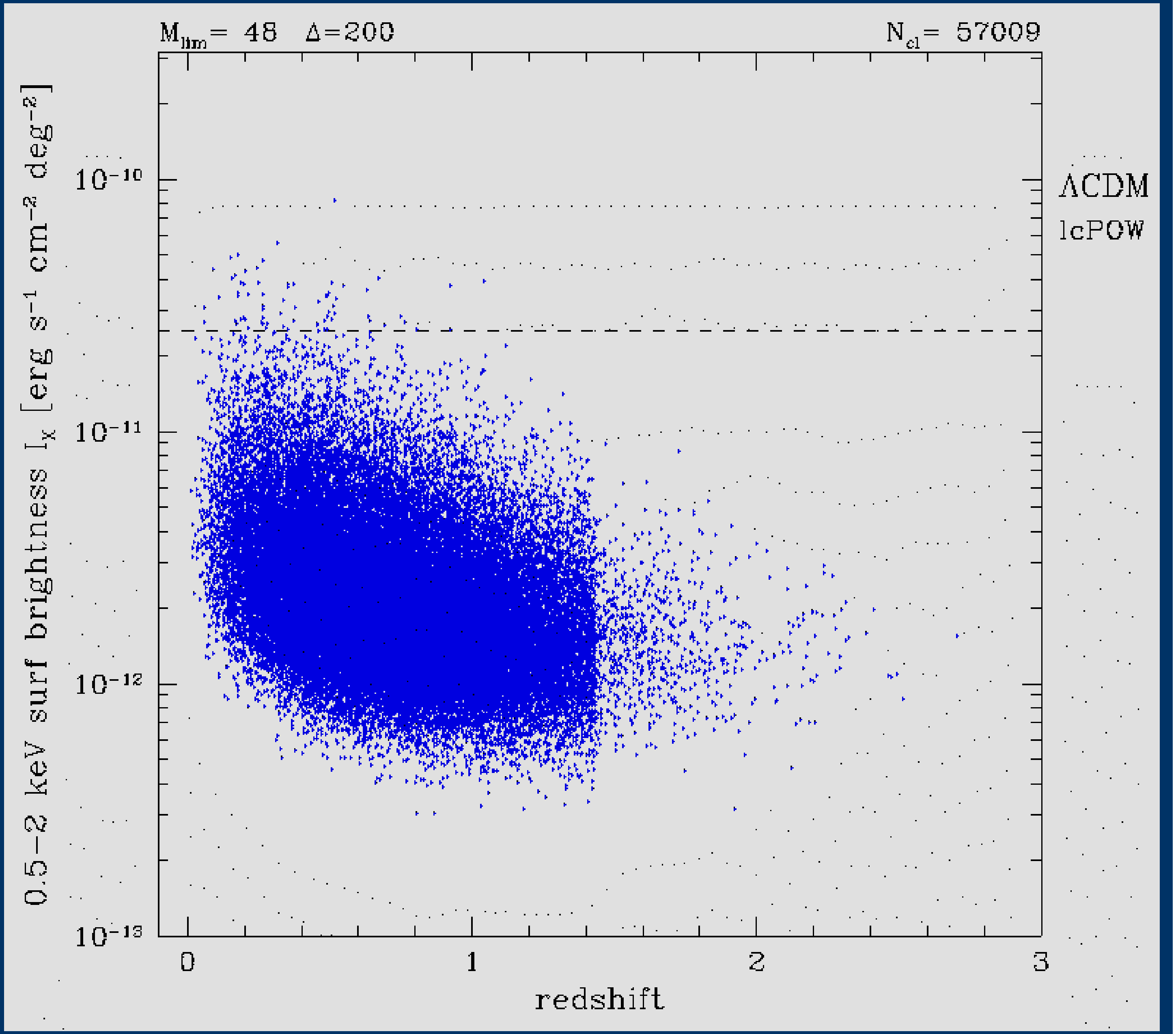


expected flux of entire cluster population is above detectable limits

(see P. Vianna's poster)



Mean 0.5-2 keV surface brightness of mass limited sample is nearly independent of redshift

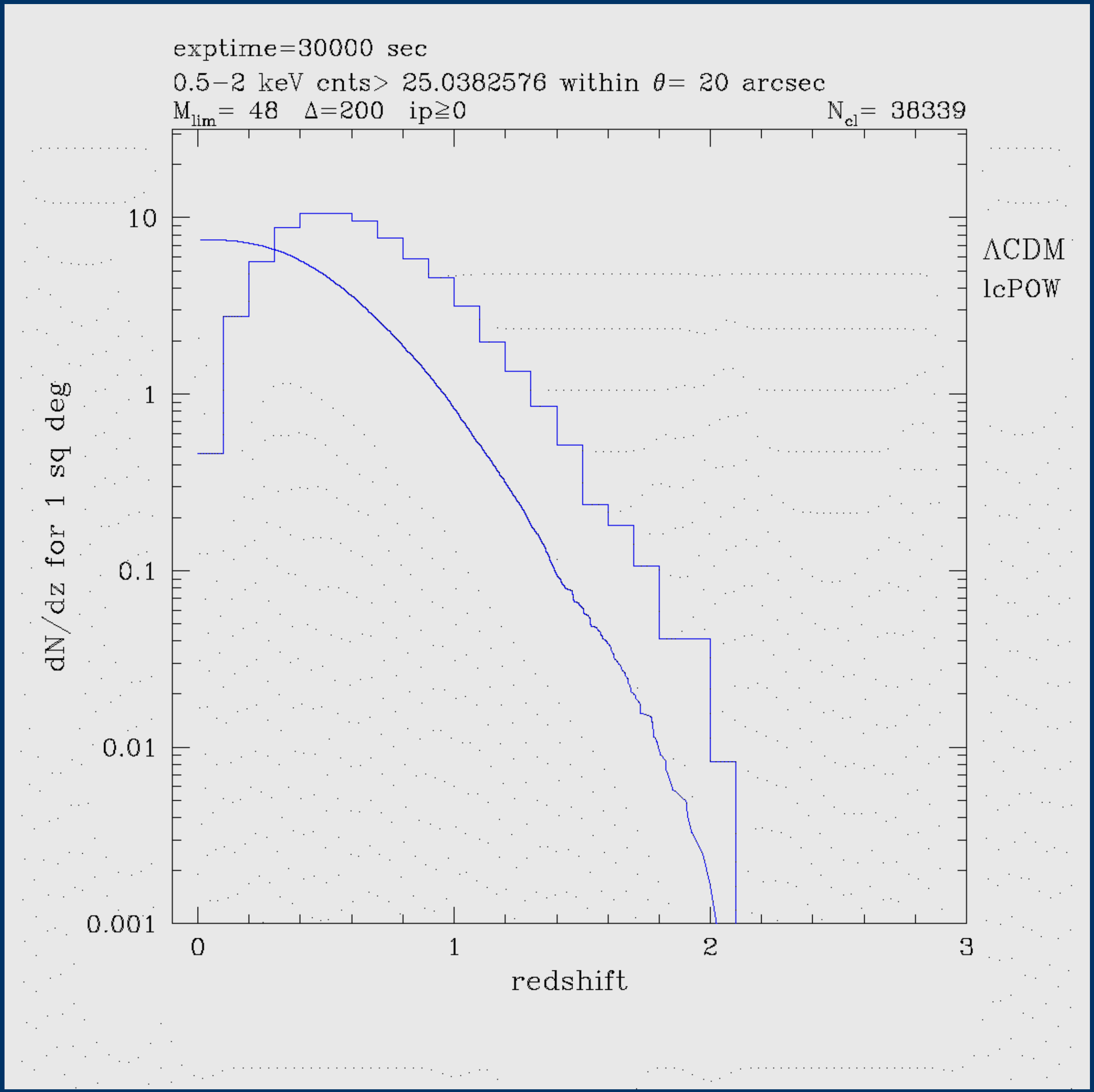


serendipitous searches in deep pointings should find them

ΛCDM
constant β
non-evolving L-T

Chandra S3
8.3x8.3 arcmin^2
30000 sec exposure
10 arsec filtering
5 sigma detection

expect
~ 10 per sq deq
~ 15% w/ $z>1$



but how far does regularity hold?

Jones etal 00

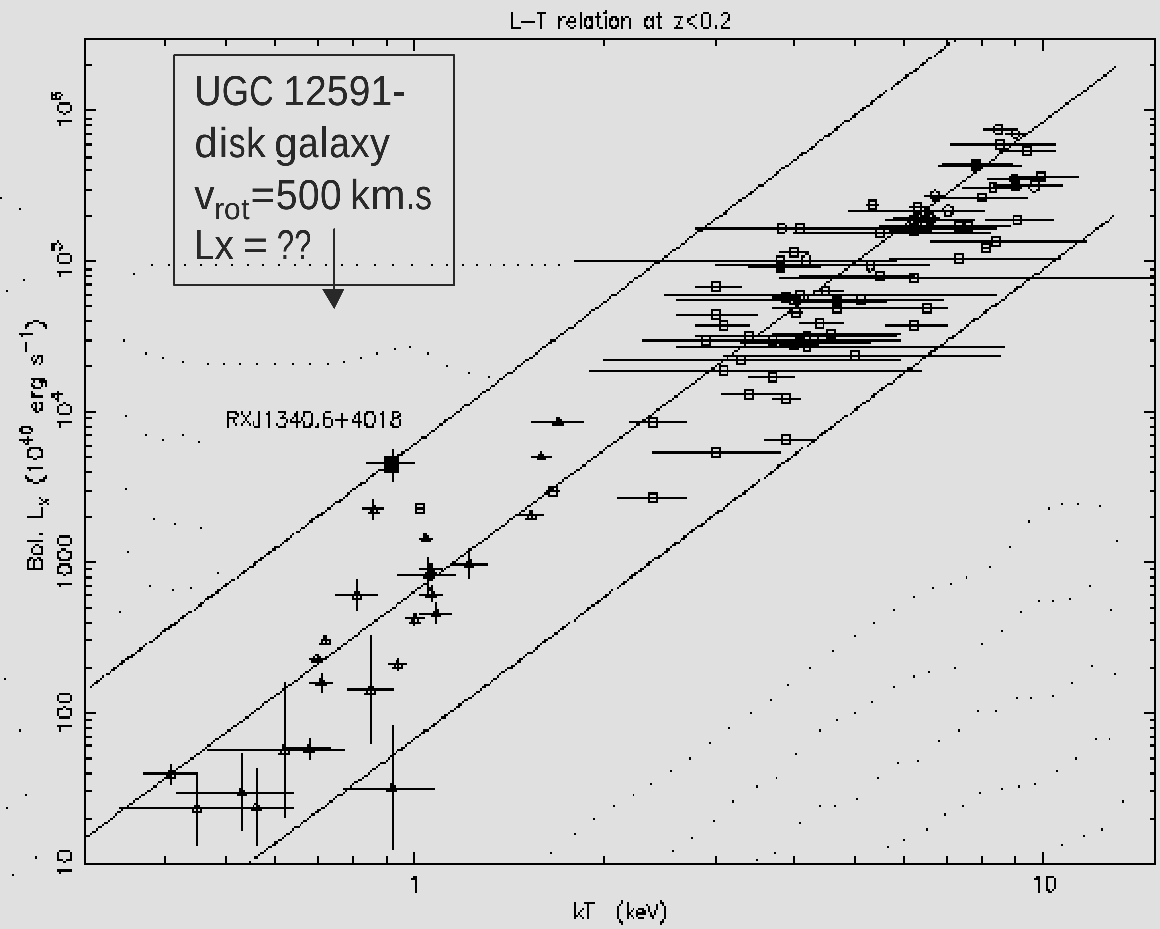


Figure 12. X-ray luminosity–temperature relation for clusters and groups. RXJ1340.6+4018 is the most deviant point above the best fit (solid) line. Dotted lines are parallel to the best fit line and are merely to guide the eye. Open squares are from David et al (1993), circles from Mushotzky & Scharf (1997) and triangles from Helsdon & Ponman (1999).

at the forefront…

simulations

expanded use of combined SAM + dynamical simulation approaches
improved contact between theory and observation
more realistic dynamical models with galaxy formation/feedback
bigger bigger **bigger !**

progress will be steady but slow (?)

Is canonical model correct?

- when/where are B-field, non-thernal effects large?
- degree of multiphase structure?

at the forefront…

observations

optical : deep searches + SDSS

X-ray follow-up : serendipitous searches

proposed wide-field medium deep missions in SDSS area

SZ searches

lobby for $$$ *for building new telescopes !*

detailed spectroscopy (coming from Chandra/XMM)

-> multiphase constraints

more sensitive radio / HE X-ray / EUVE observations

-> non-thermal component

Needed :

- better census of baryons in groups/clusters
- calibration of virial M-T relation via weak lensing

THE END