Clusters of Galaxies

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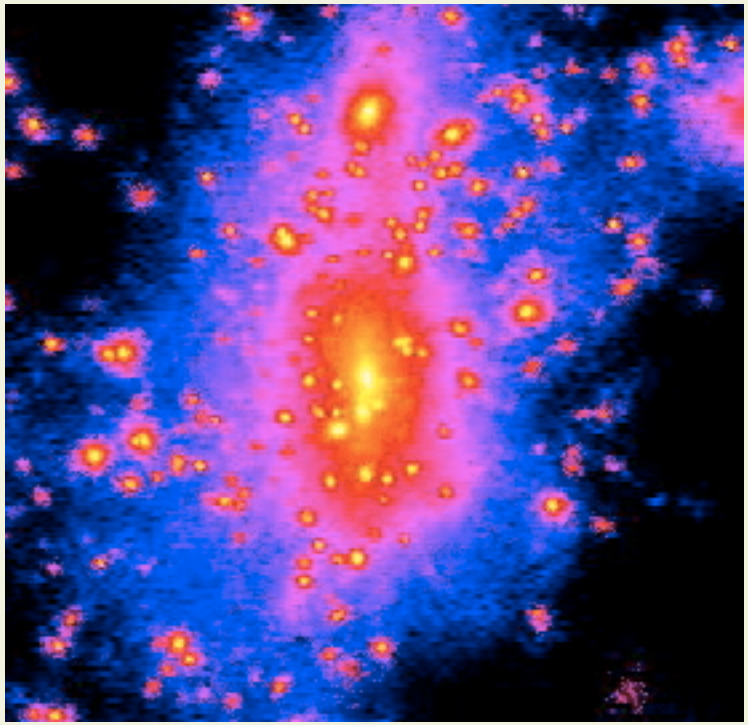
what is a galaxy cluster?

"A large knot of quasi-equilibrium, self-gravitating matter embedded within an evolving filamentary network (the `cosmic web') of growing density perturbations."



B. Moore, http://www.nbody.net

rough characteristics -

$N_{gal} \sim 10$ or larger (fewer is a `galaxy group' or lone galaxy)

$k_B T_X \sim 1\text{-}15$ keV

$R \sim 0.3\text{-}2\ h^{-1}$ Mpc

$M \sim 10^{13} - 10^{15.5}\ h^{-1}\ M_{sun}$

see Sarazin, C. 1986, Rev Modern Physics, 58, 1

content hierarchy of clusters

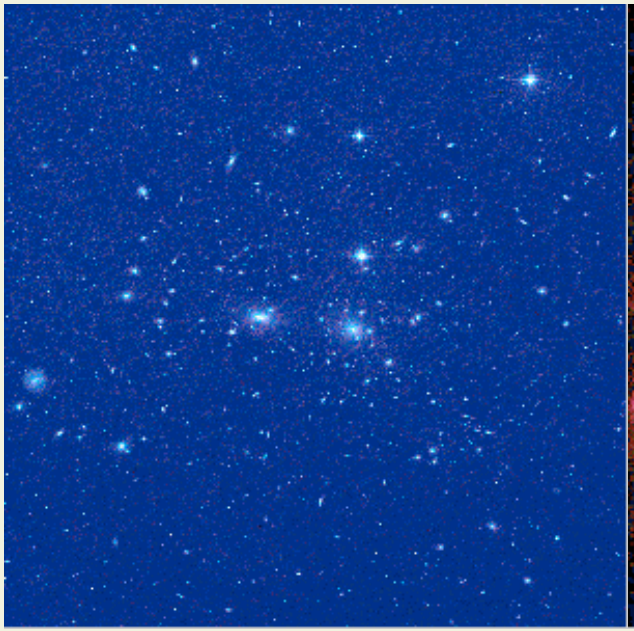
galaxies

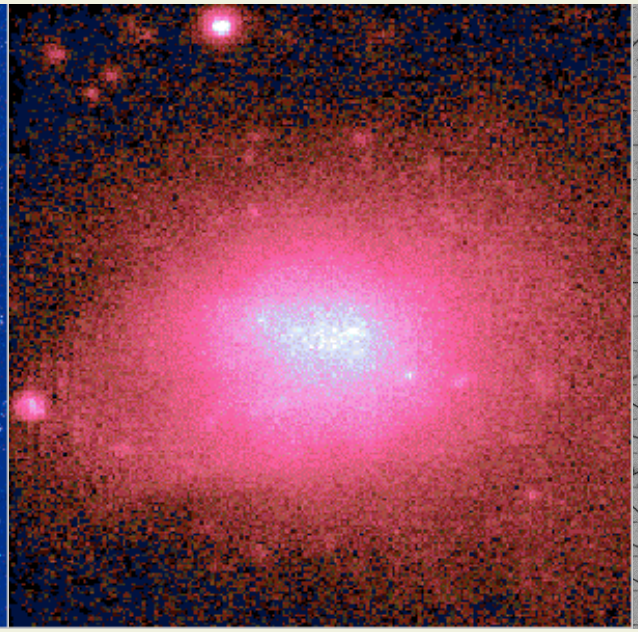
hot intracluster medium (ICM)

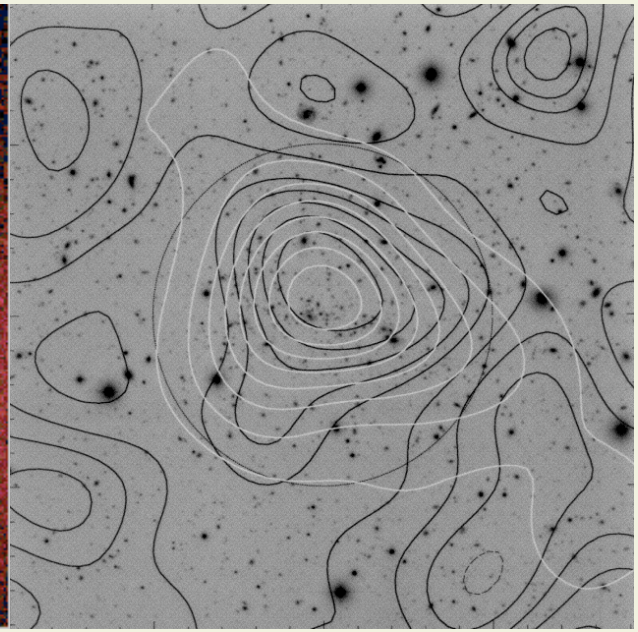
$M_{ICM} \sim 10\ (h/0.65)^{-3/2}\ M_{gal}$

dark matter

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







$$M_{gal} = 1.0 \pm 0.2 \times 10^{13}\, h^{-1} M_{\odot}$$

$$M_{tot} = 1.10 \pm 0.18 \times 10^{15}\, h^{-1} M_{\odot}$$

estimates for Coma:

$$M_{ICM} = 5.5 \pm 1.0 \times 10^{13}\, h^{-5/2} M_{\odot}$$

Luppino & Kaiser 1997

White et al 1993

more precise measurements needed, and for more clusters

(*to come from SDSS and XMM/Chandra*)

Carlstrom et al 2001

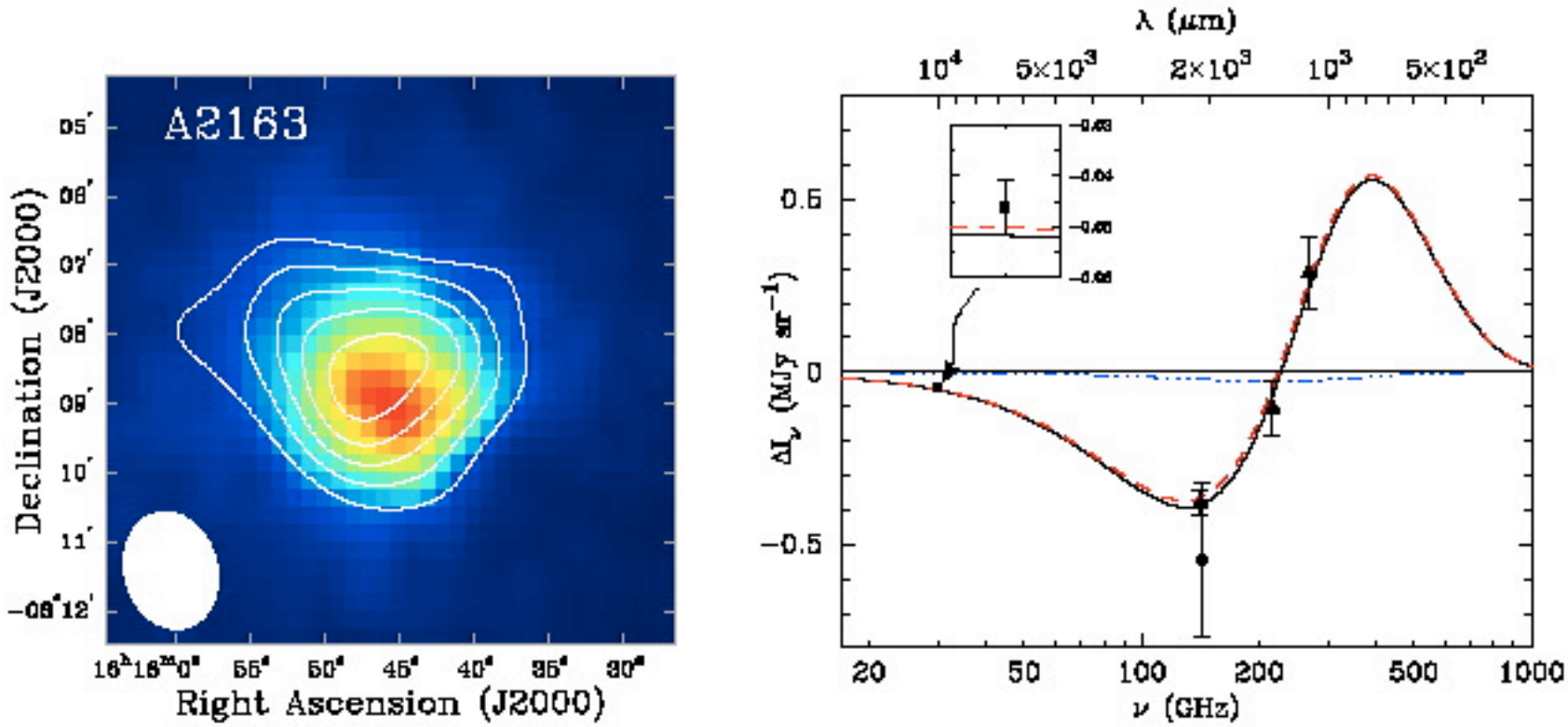
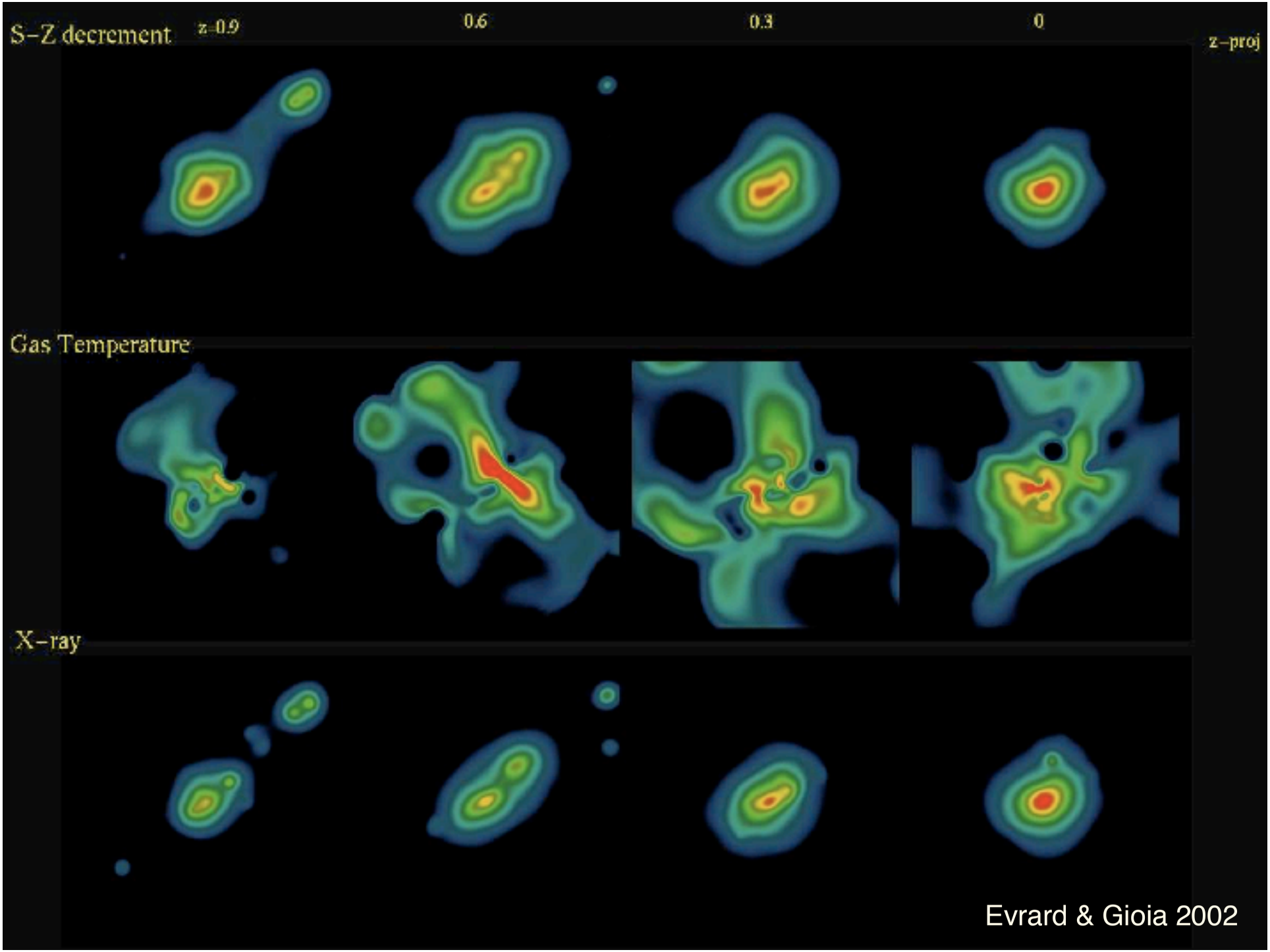
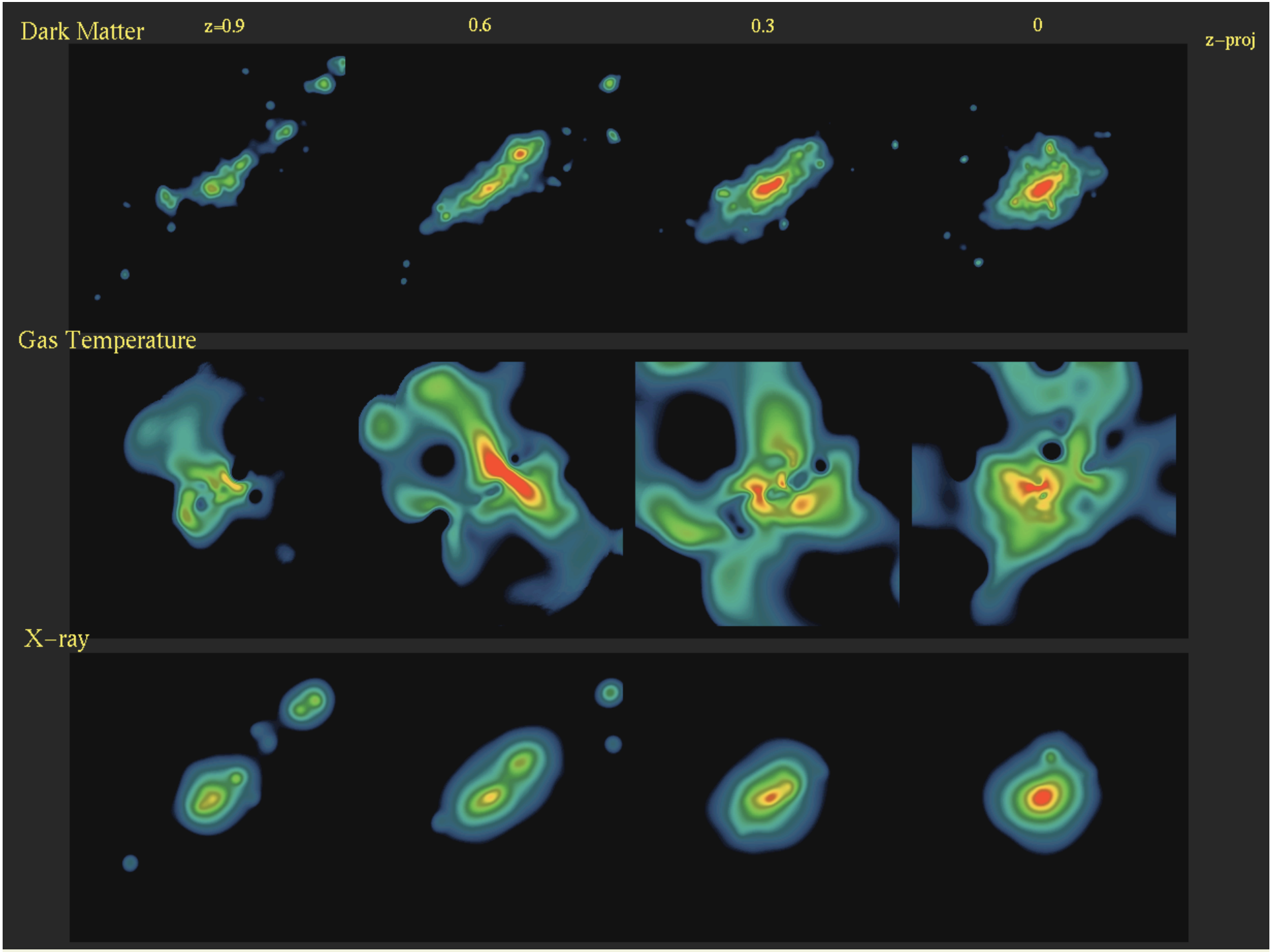


Figure 14: Left panel: An image of the SZE effect toward Abell 2163 obtained with the BIMA interferometer overlaid on a ROSAT image of the X-ray emission. Right panel: the SZE spectrum of Abell 2163 using data from BIMA at 28.5 GHz,[34] DIABOLO at 140 GHz [72] (filled circle) and SuZIE at 140 GHz, 218 GHz and 270 GHz [33] (filled triangles). The best fit thermal and kinetic SZE spectra are shown by the dot-dashed line and the dashed lines, respectively, with the spectra of the combined effect shown by the solid line. The limits on the Compton y-parameter and the peculiar velocity are $y_0 = 3.65 \pm 0.40 \times 10^{-4}$ and $v_p = 415^{+920}_{-765}$ km s^{-1}.[33,34]

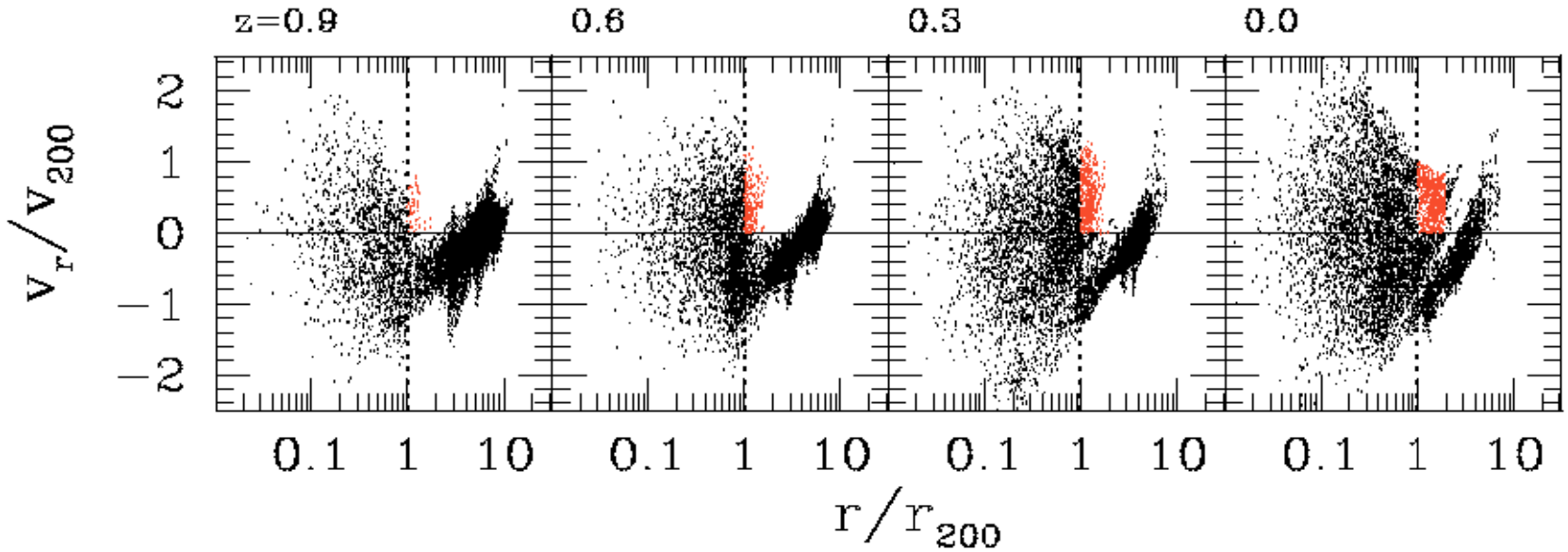


Evrard & Gioia 2002

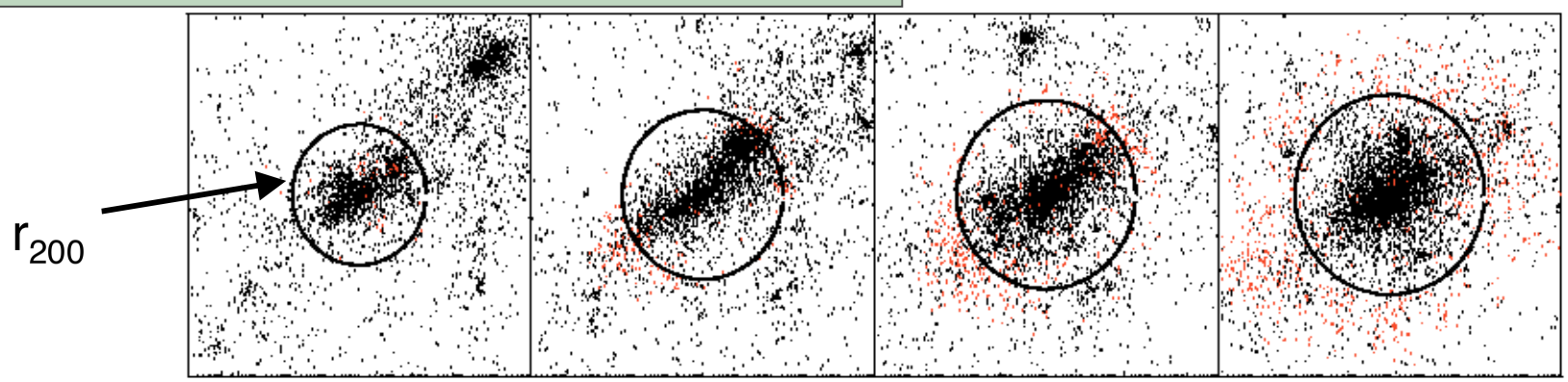

Dark Matter
z=0.9
0.6
0.3
0
z−proj
Gas Temperature
X−ray

dark matter structure in a P3MSPH simulation

Evrard & Gioia 2002



r_{200} defined by *critical density threshold*



3D infall is complex - boundary is not sharp…

virial theorem expectations

link between cluster mass and observables (gas T or galaxy velocities)

$$\sigma^2 \propto \frac{kT_X}{m_p} \propto \frac{GM_\Delta}{r_\Delta}$$

for the mass within a critical density threshold one obtains

$$H(z)M_\Delta \propto T^{3/2} \propto \sigma^3$$

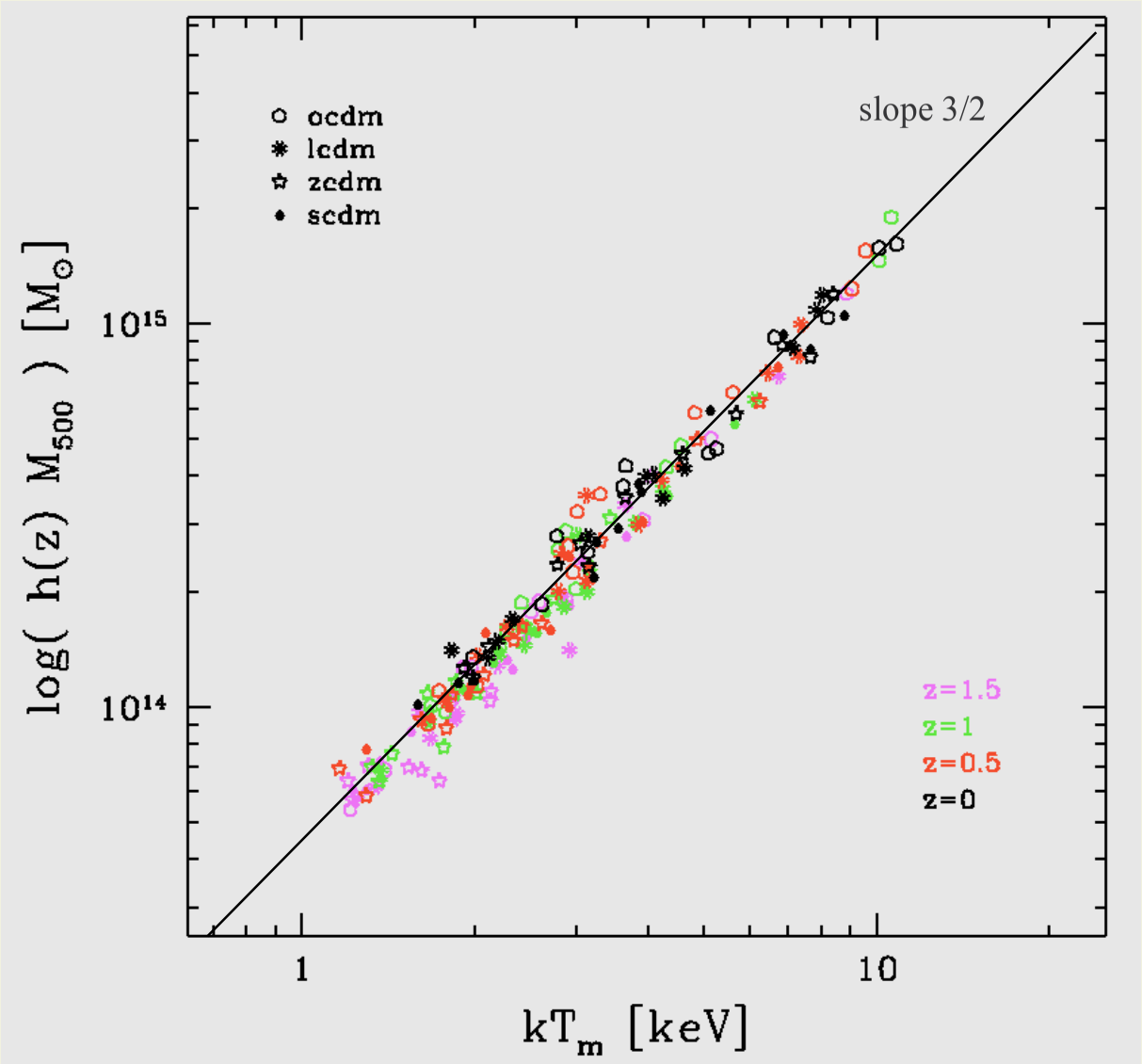
$$H(z)r_\Delta \propto T^{1/2} \propto \sigma$$

virial Mass-Temp scaling from P3MSPH simulations

Mathiesen & Evrard `01

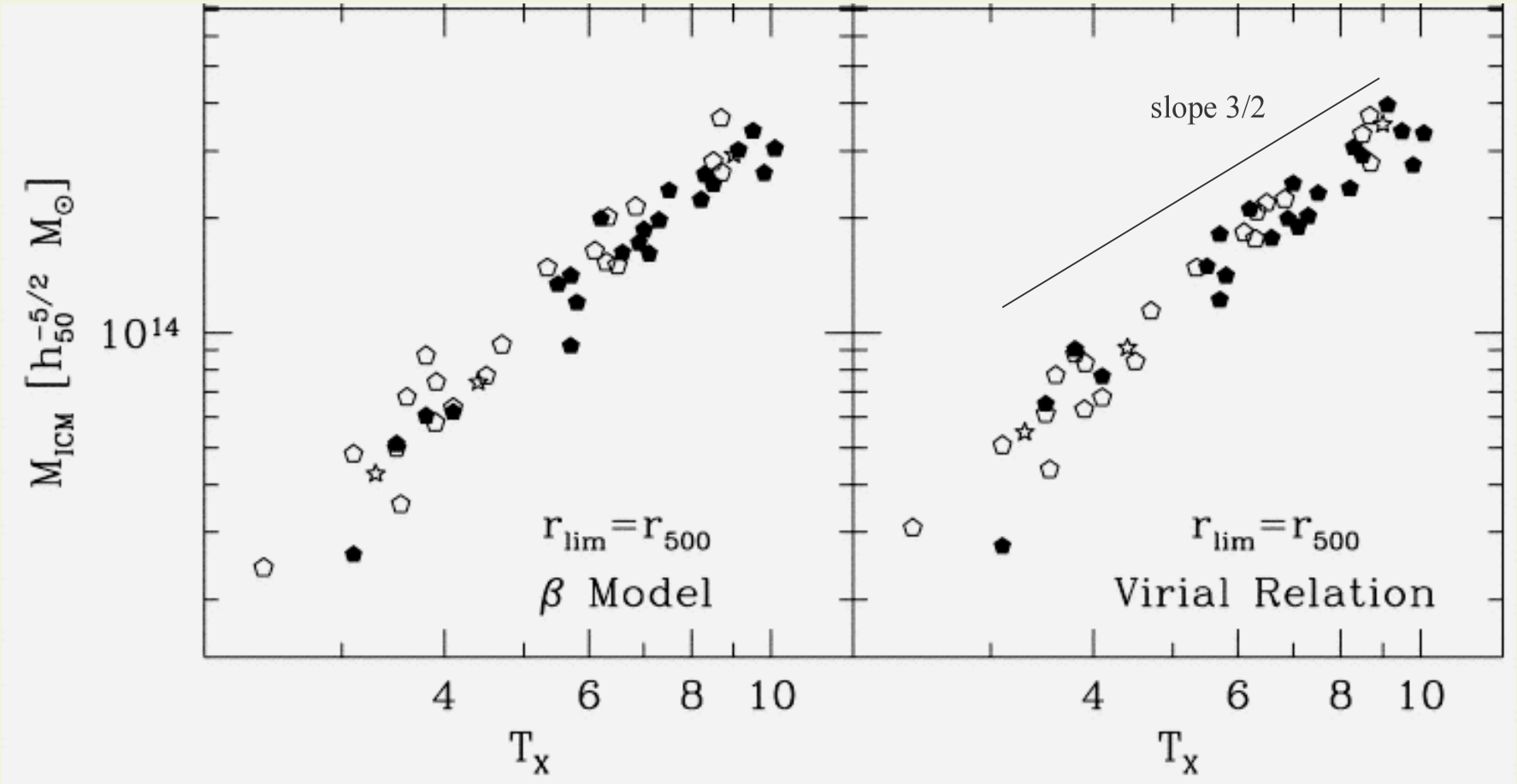
~11 % scatter in
h(z)M at fixed *kT*

independent of
cosmology/epoch



observed ICM mass-temperature relation for 45 local clusters

Mohr, Mathiesen & Evrard 99



14 % scatter in M_{ICM} at fixed T_X

hierarchical clustering from a Gaussian random density field

define fluctuation amplitude on mass scale M by filtering high-k modes of power spectrum

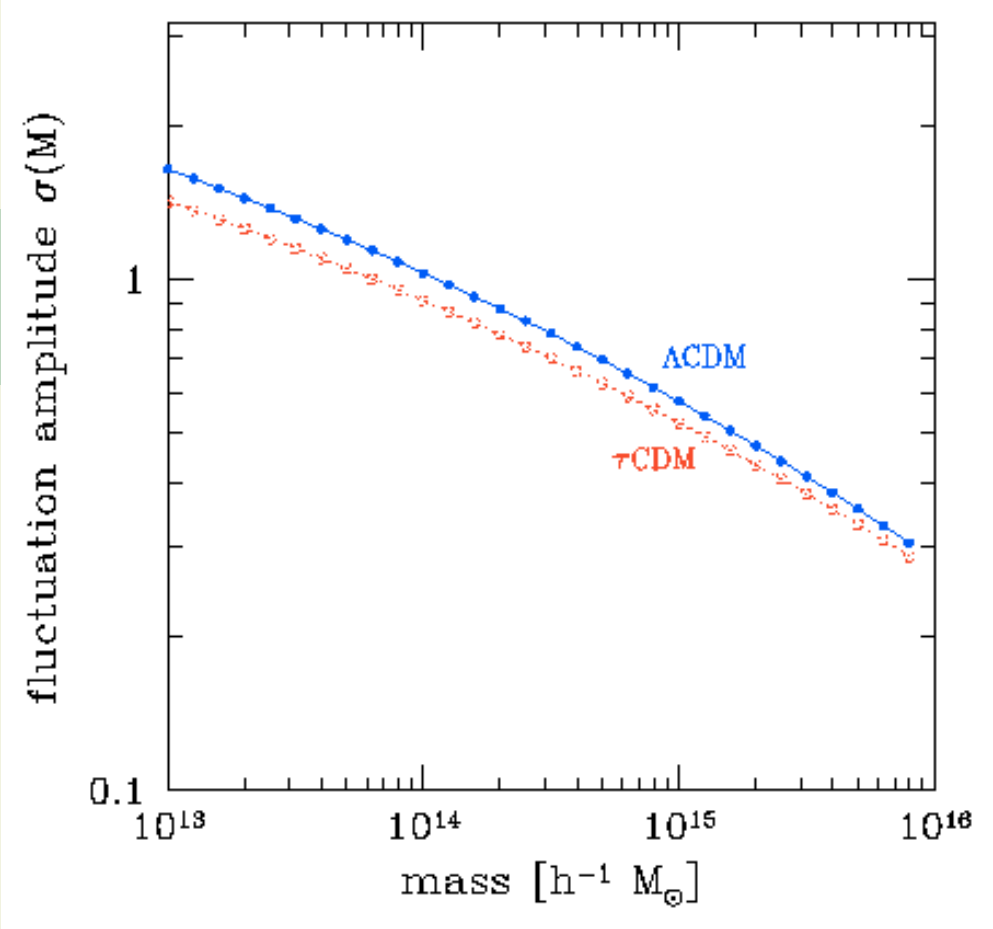
Peebles 1980; 1993; Peacock 1999
Bardeen et al 1984, ApJ
Davis, Efstathiou, Frenk & White 1985, ApJ

$$\sigma^2(M) = \int d^3k\, W(kM^{1/3})P(k)$$

for power-law $P(k) \sim k^n$

$\sigma \sim M^{-\alpha}$; $\alpha = (n+3)/6$

Model	Ω_m	Ω_Λ	σ_8
ΛCDM	0.3	0.7	0.90
τCDM	1.0	0	0.60



most CDM models locally have

$\sigma(M) \sim 0.5\, M^{-1/4}$; $n_{eff} \sim -1.5$

(M in units of $10^{15}\, h^{-1}\, M_{sun}$)

FOF(0.2) and mean SO(200) mass functions take `universal' form in $\sigma(M)$

$$n(\sigma^{-1}(M)) = A\exp[\alpha\,|\ln\sigma^{-1}(M) + B\,|^{\beta}]$$

Jenkins etal 2001

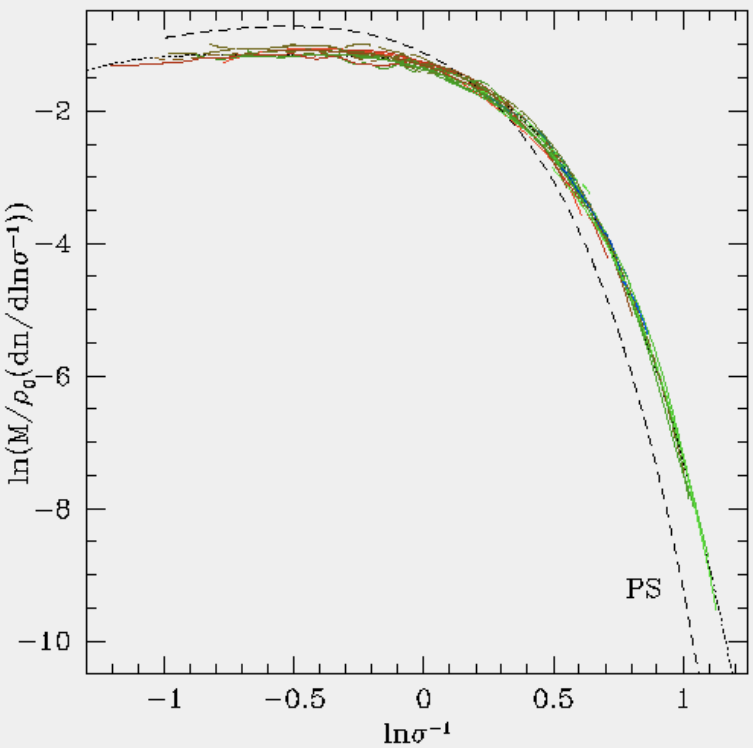


Figure 7. The FOF(0.2) mass functions of all the simulation outputs listed in Table 2. Remarkably, when a single linking length is used to identify halos at all times and in all cosmologies, the mass function appears to be invariant in the $f - \ln\sigma^{-1}$ plane. A single formula (eqn. 9), shown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

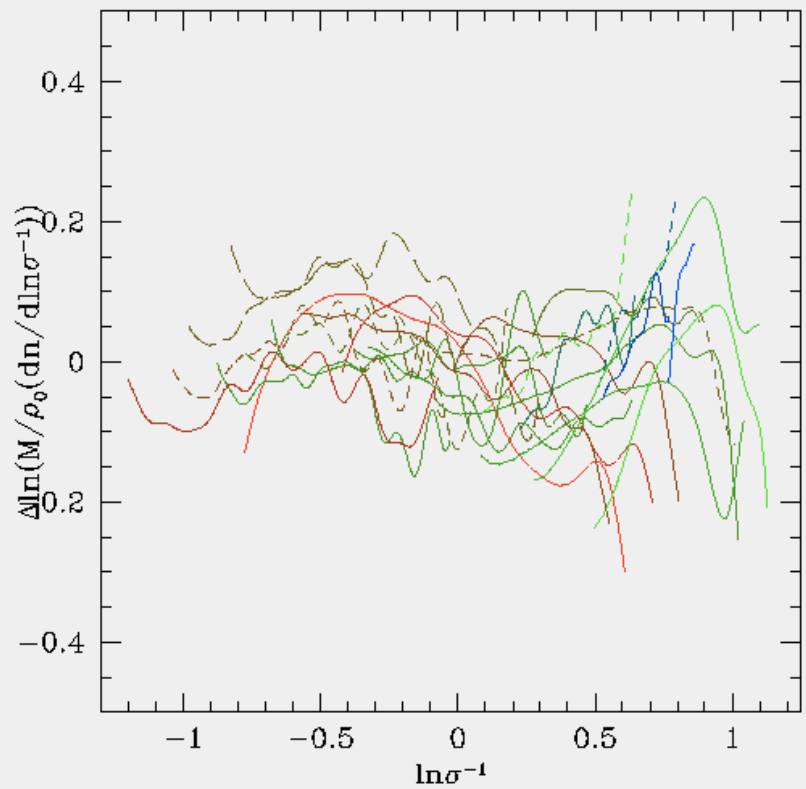
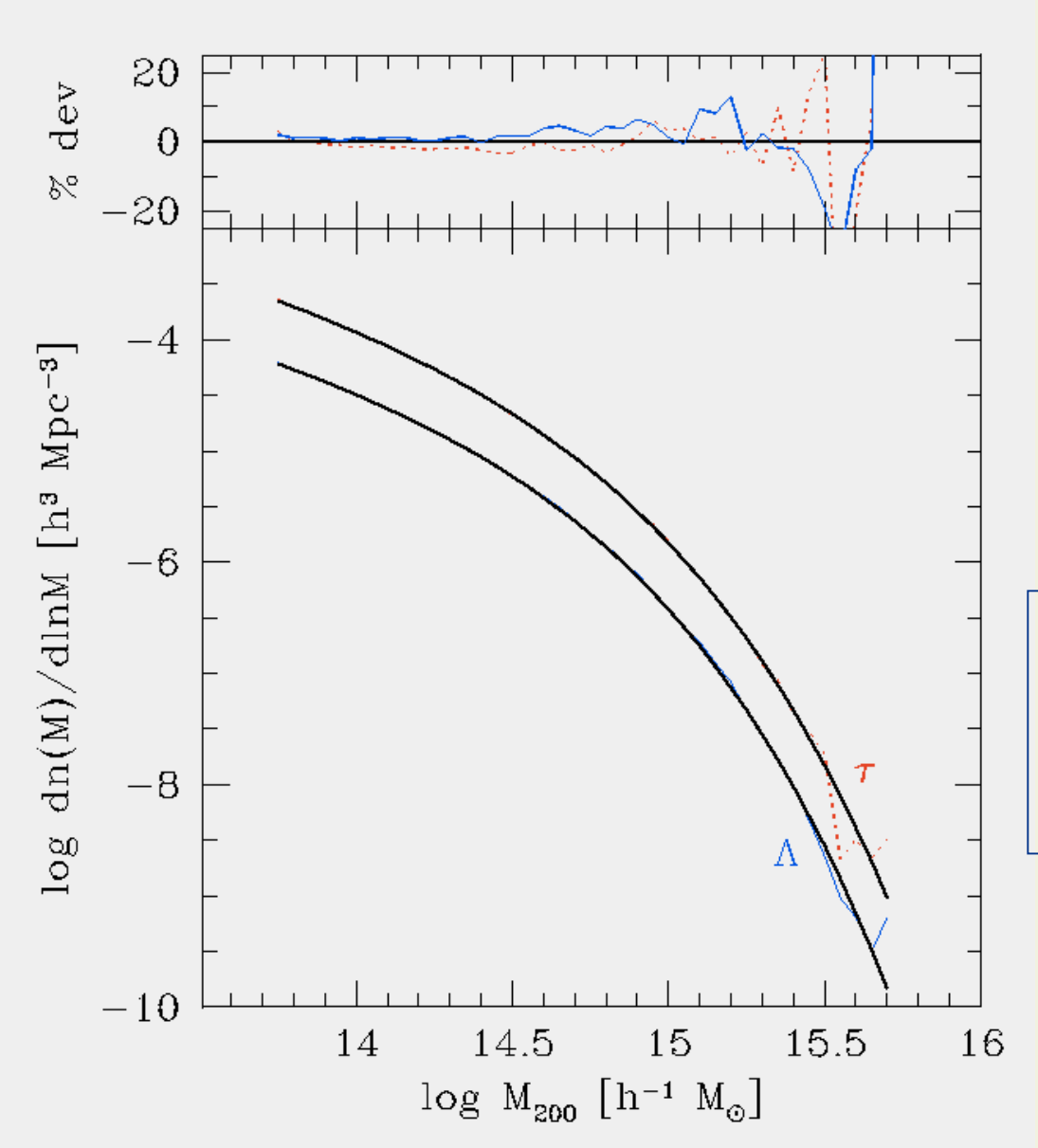


Figure 8. The residual between the fitting formula, eqn. 9, and the FOF(0.2) mass functions for all the simulation outputs listed in Table 2. Solid lines correspond to simulations with $\Omega = 1$, short dashed lines to flat, low Ω_0 models, and long dashed lines to open models.

precise calibration of critical □=200 mass function

Evrard etal 2002, ApJ



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

fit to functional form of Jenkins etal 01 using ~1.4M clusters at z=0

independent agreement with Bode at al `01 and Hu & Kratsov `02 at ~10% level

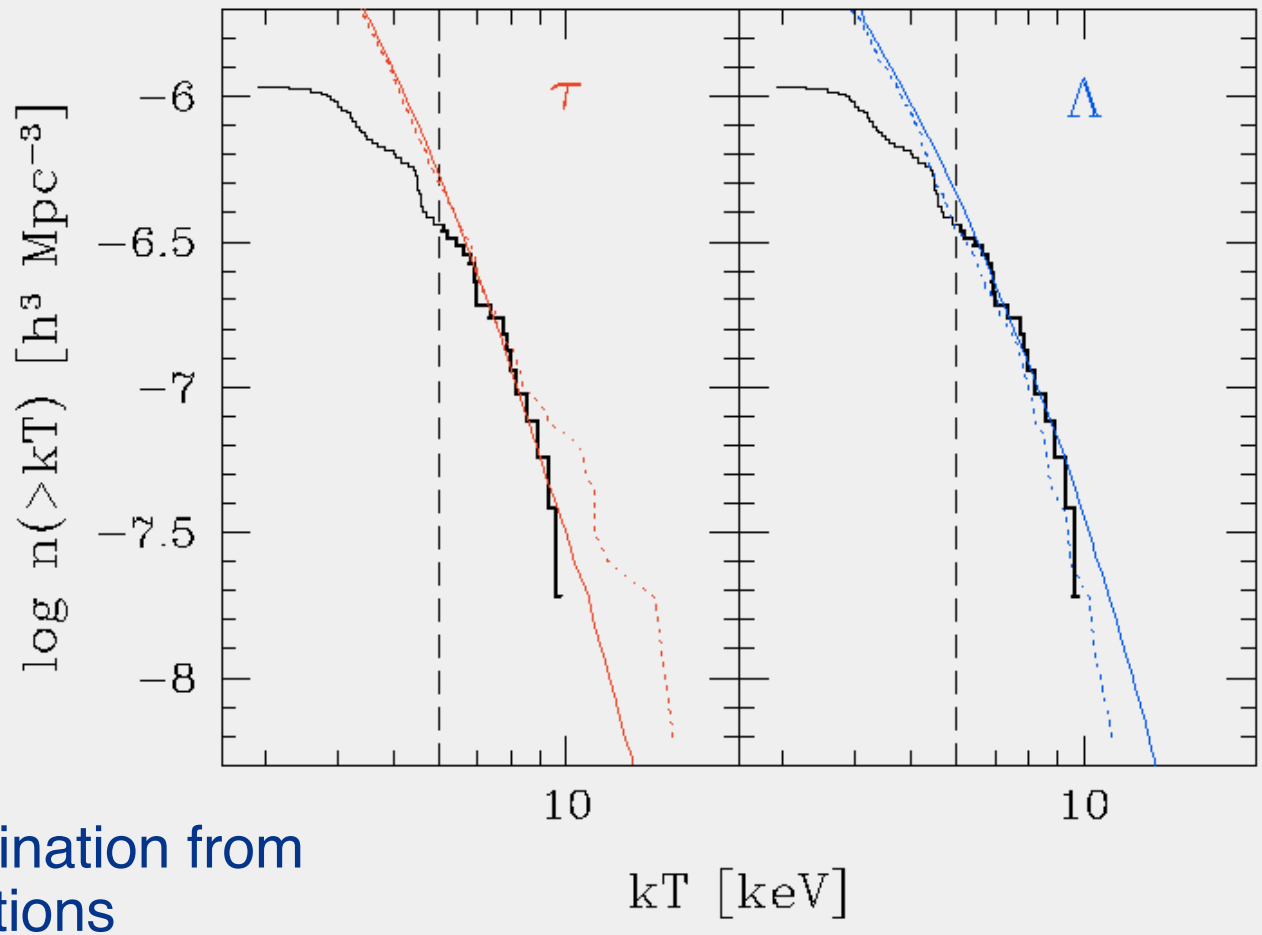
fit to local `temperature function'

$\square = \square_{DM}{}^2 / (kT_X/\square m_p)$

$\square_\square$ = 1.10 +- 0.06 $\square_\square$ = 0.92 +- 0.06

degenerate with power spectrum normalization

$\square \sim \square_8{}^{5/3}$



observational data :

Markevitch `98
White `00
Pierpaoli, Scott & White `01

independent determination from gas dynamic simulations

$\square$ =1.15, implies $\square_8$=1.04 for $\square$CDM

Evrard et al 02

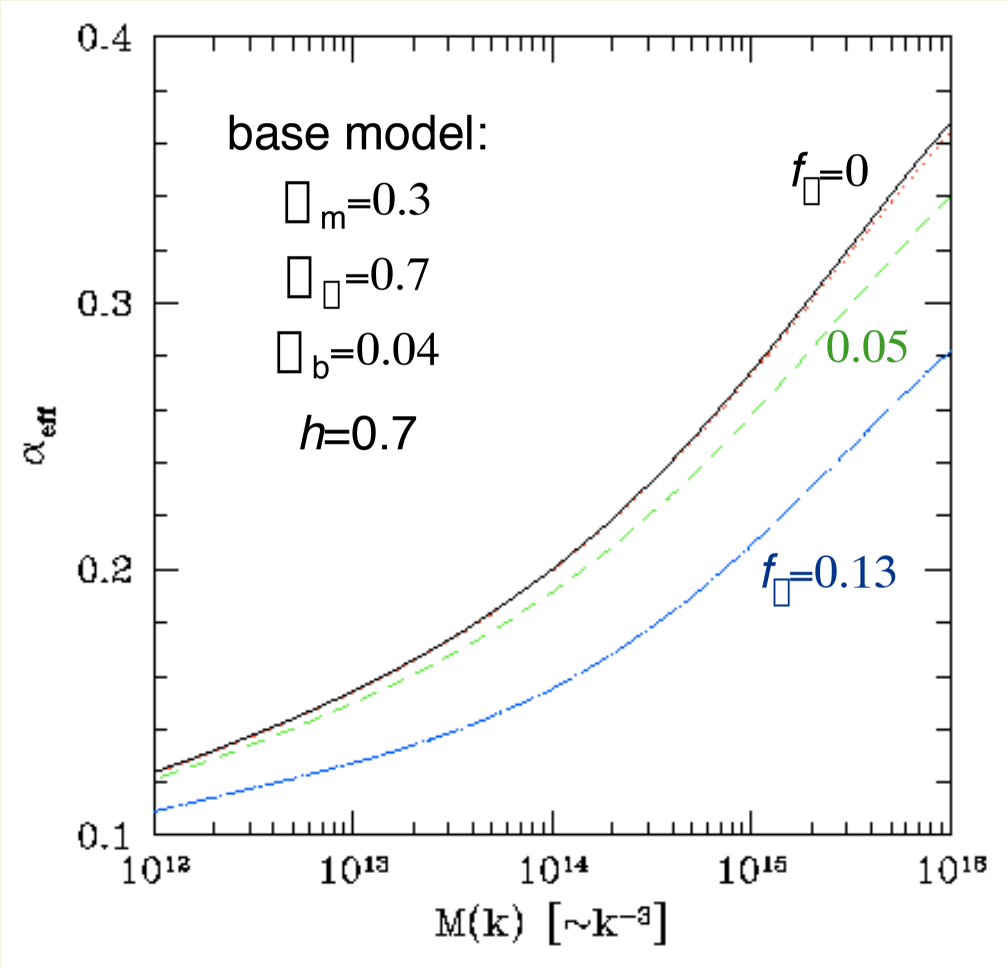
Frenk et al 1999

the absolute mass scale of clusters remains uncertain

Reference	M_{500} at 6 keV (1e15 M_{sun}/h)	Comments
Evrard, Metzler & Navarro 96	0.52	Lagrangian hydro
Bryan & Norman 98	0.78	Eulerian hydro
Mathiesen & Evrard 01	**0.87** 0.83	spectral T, 0.5-9.5 keV bandpass spectral T, 2-9.5 keV bandpass
Bialek, Evrard & Mohr 01	0.65	preheated ICM, spectral T, 0.5-9.5 keV
Mohr, Mathiesen & Evrard 99	0.47	from beta-model fit to A1795
Nevalainen, Markevitch & Forman 00	**0.17**	ASCA radial T gradients
Finoguenov, Reiprich & Bohringer 01	0.30	ASCA radial T gradients (larger sample)
Henry 00	0.66	$\sigma_8 = 0.9$ ($\Omega_m = 0.3$)
Pierpaoli, Scott & White 01	0.58	$\sigma_8 = 1.0$ ($\Omega_m = 0.3$)
Ikebe et al 02	0.59	$\sigma_8 = 0.9$ ($\Omega_m = 0.3$)
Seljak 02	0.23	$\sigma_8 = 0.7$ ($\Omega_m = 0.35$)
	$\mathbf{0.48(\sigma_8/0.9)^{5/2}}$	Jenkins MF, HV fit to local T-ftn (σ)

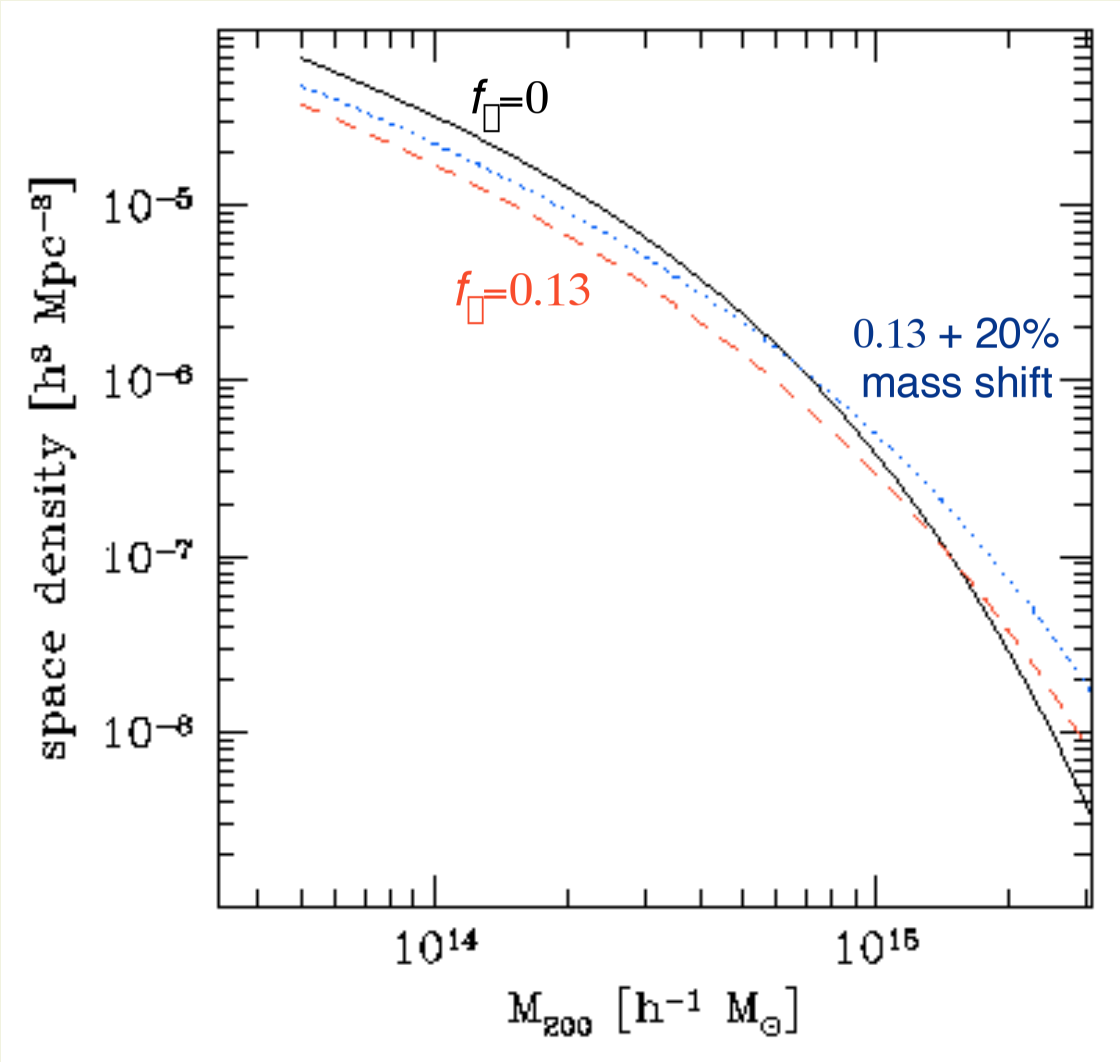
25% uncertainty in mass scale implies 10% uncertainty in σ_8

constraints on the cosmic neutrino mass fraction from cluster mass function



slope of power spectrum on cluster scales is sensitive to neutrino mass fraction

constraints on the cosmic neutrino mass fraction from cluster mass function



shape of mass function contains information on neutrino mass fraction that is non-degenerate with shifts in the cluster mass scale

clusters as cosmological tools? need astrophysics!

$$P\,(\text{cosm} \mid \text{obs}) = P_{\text{prior}}\,(\text{cosm})\; P\,(\text{obs} \mid \text{cosm}) \,/\, P\,(\text{obs})$$

theoretical effort (& uncertainty) lies here

for galaxy clusters, problem is <u>separable</u>

$$P\,(\text{obs} \mid \text{cosm}) \sim P\,(\text{M,z} \mid \text{cosm})\;\; P\,(\text{obs} \mid \text{M,z})$$

- space density $n\,(\text{M, z} \mid \text{cosm})$ **<u>solved</u>**
- how do clusters `light up' ? $P\,(\text{obs} \mid \text{M,z})$ **<u>needs work!</u>**

mock SDSS analysis using ΛCDM Hubble Volume sky survey realizations

T. McKay, R. Wechsler, AE (Michigan)
J. Annis (FNAL)
C. Miller, R. Nichol (CMU)

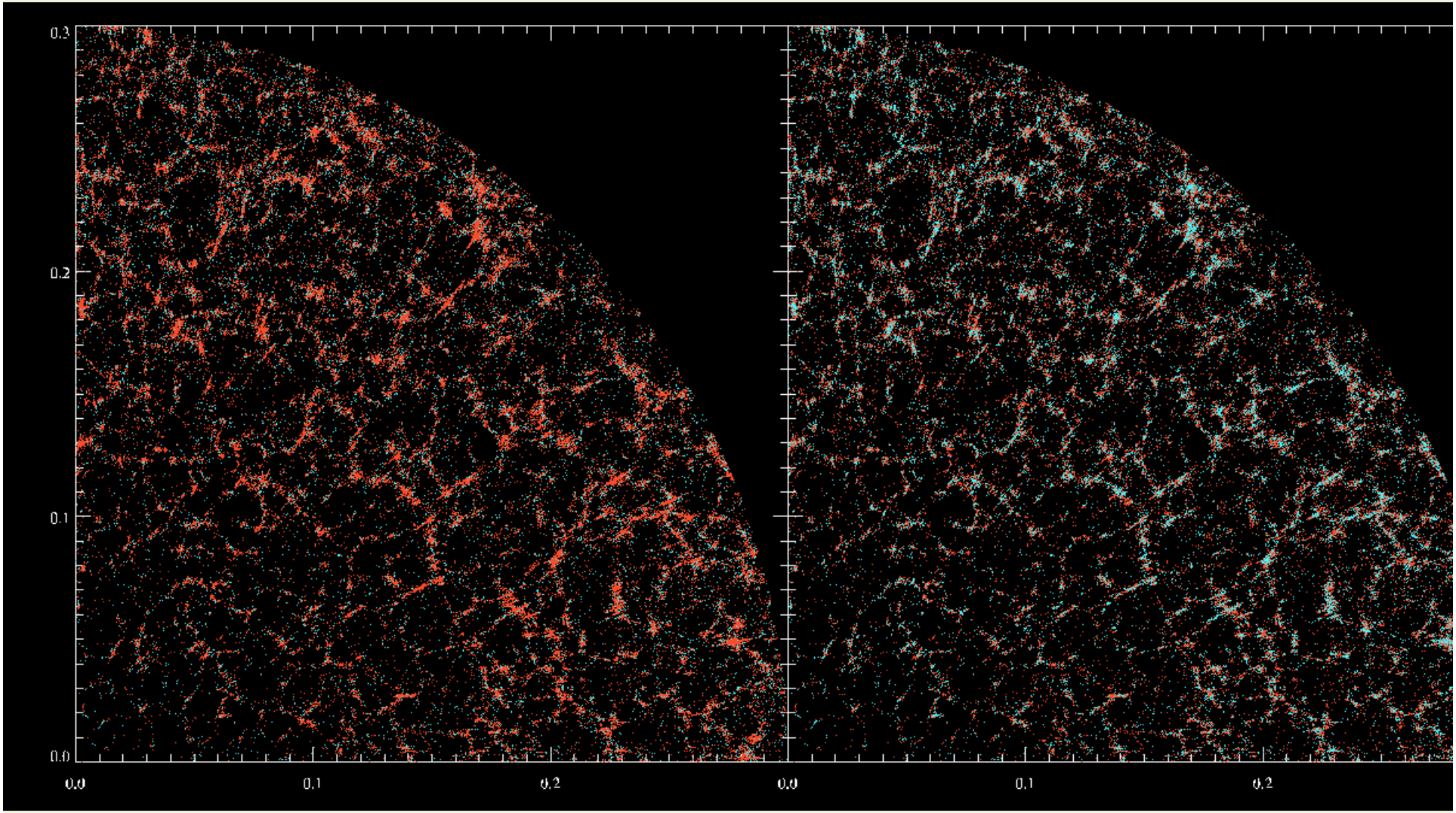
Aims:

- understand systematic (astrophysical) uncertainty in estimates of cosmological parameters from SDSS clusters
- constrain models of galaxy formation in cluster environments

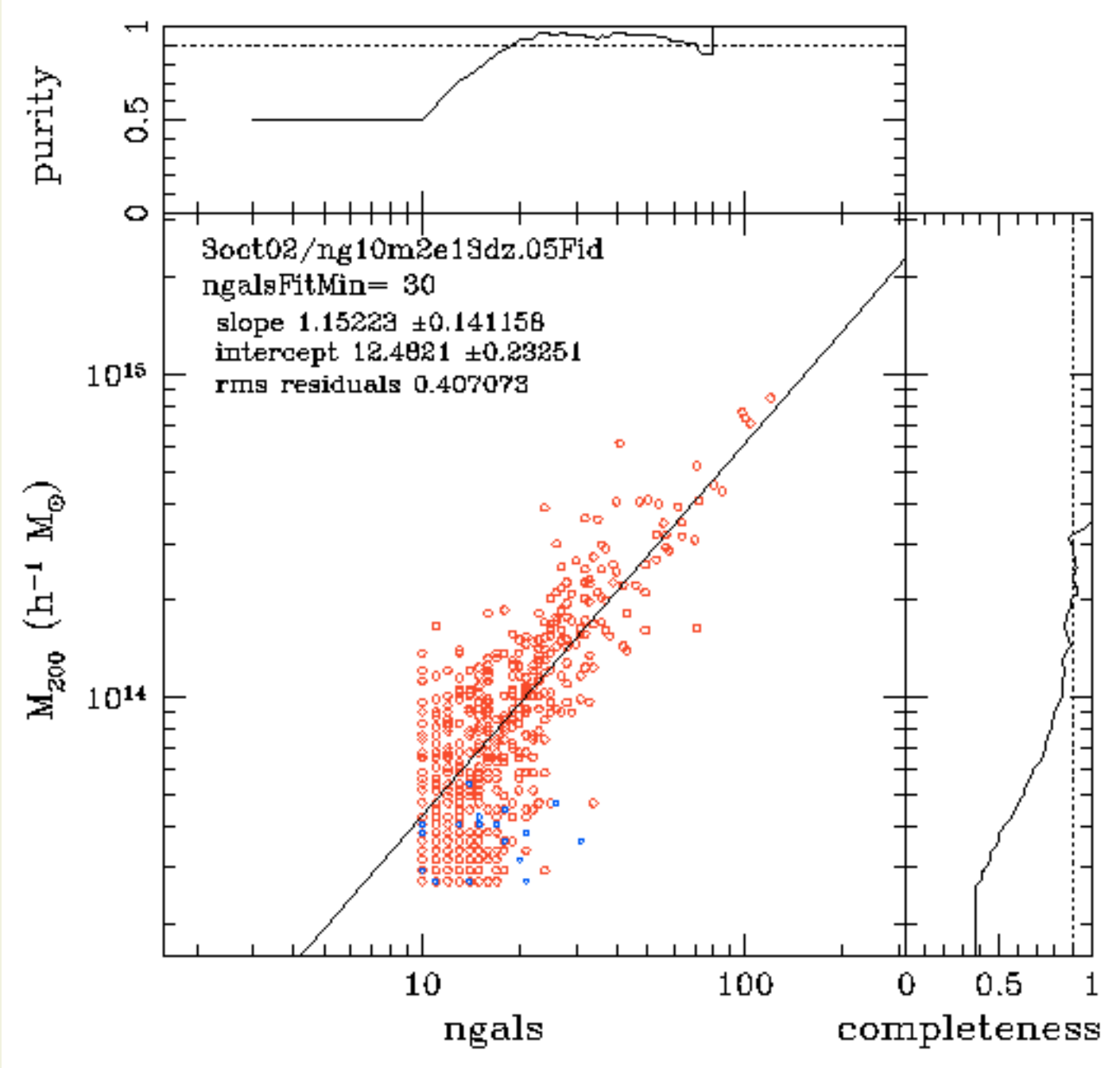
$$P(M_{200} \mid ngals) \propto P(ngals \mid M_{200})$$

Process:

- assign SDSS galaxies to DM particles in manner that reproduces
  clustering length dependence on *r*-luminosity
  dependence of color in (z-space) density
- run cluster finding algorithms + match outputs to real-space input

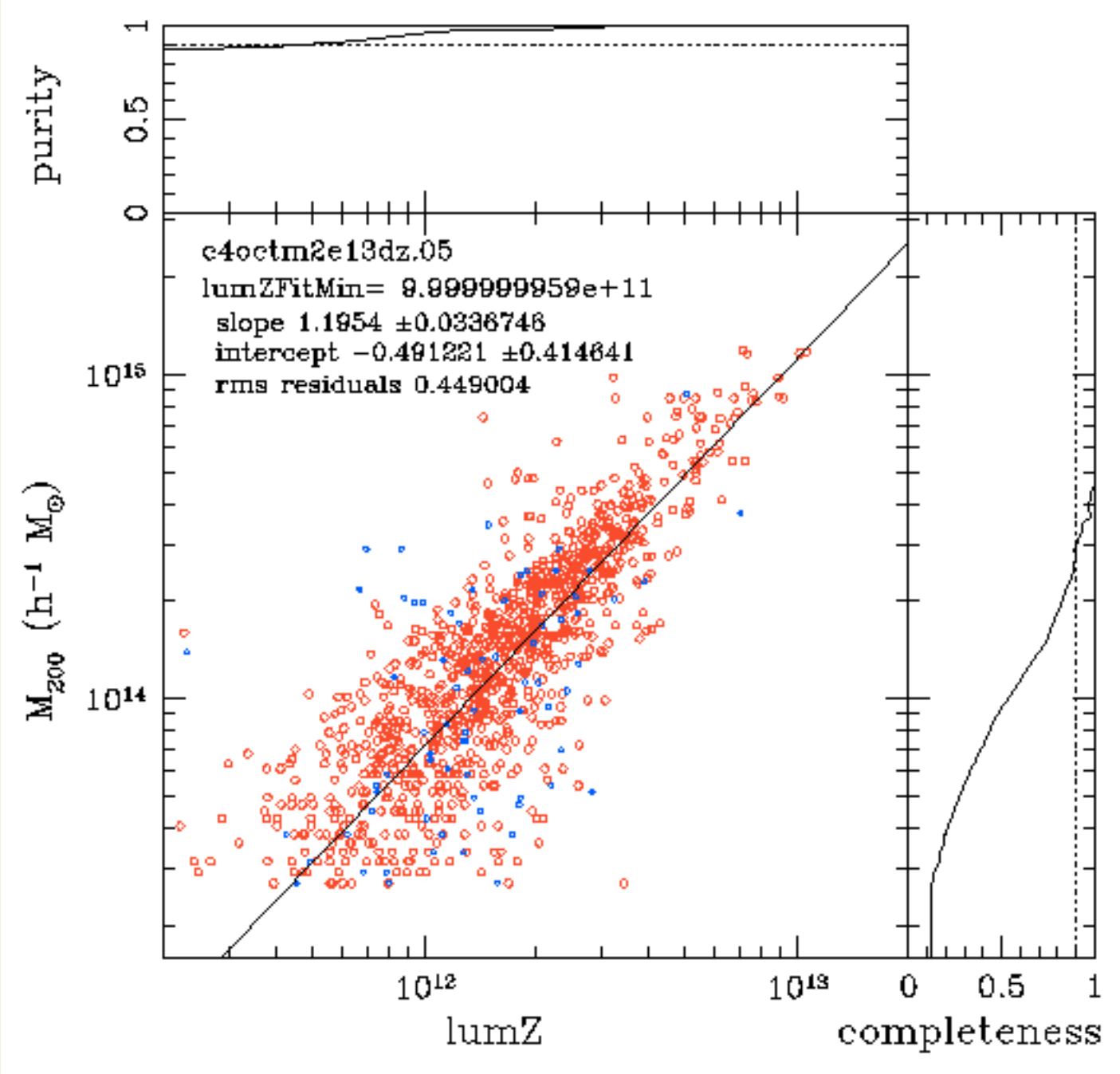

0.3
0.2
0.1
0.0
0.0
0.1
0.2
0.0
0.1
0.2

maxbcg finder



C4

finder

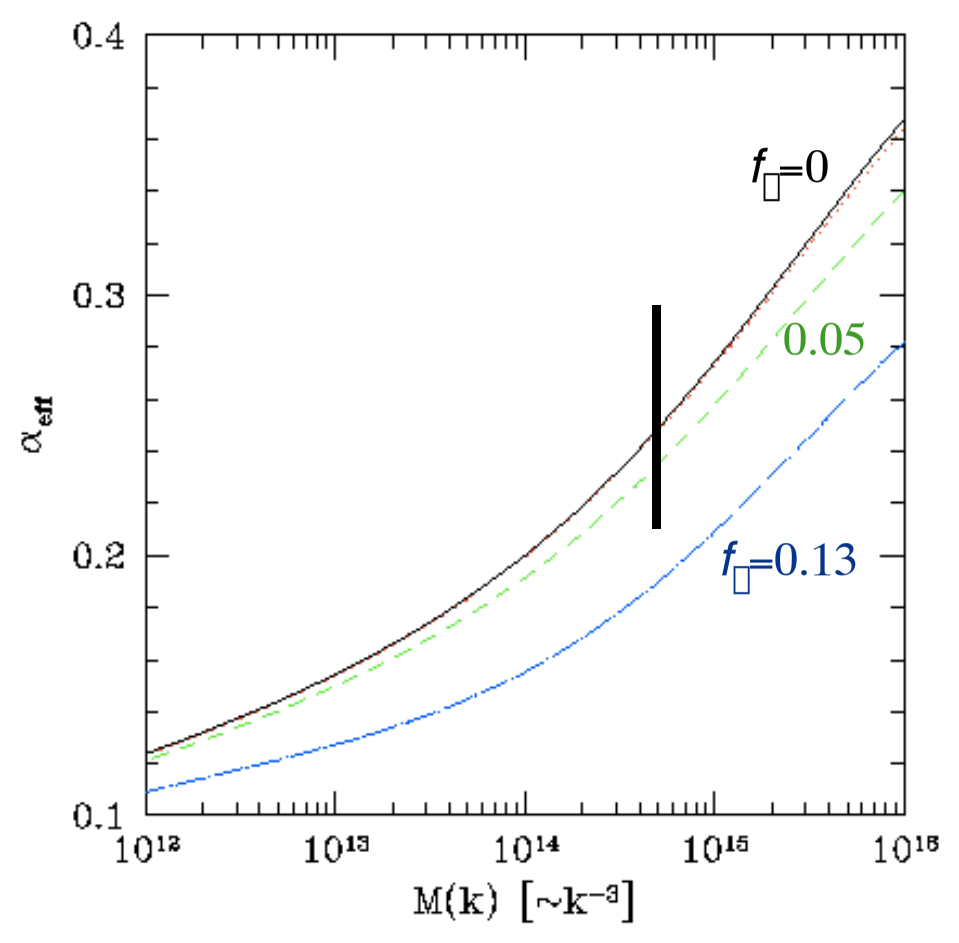

purity
0
0.5
1
c4octm2e13dz.05
lumZFitMin= 9.999999959e+11
slope 1.1954 ±0.0336746
intercept −0.491221 ±0.414641
rms residuals 0.449004
10^{15}
10^{14}
M_{200} (h^{-1} $M_\odot$)
10^{12}
10^{13}
lumZ
0
0.5
1
completeness

How well will we do?

expect ~10,000 clusters with $M > 10^{14} M_{sun}$ and $z < 0.3$ in full SDSS, so systematics will dominate

if characterization P(M | n or L) results in 10% mass uncertainty, then error in ln□(M) is ~.04.

independence check from maxbcg/C4 cluster finders



watch this space!