Cosmology with Clusters

Alain Blanchard

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Scaling principle

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so that M and z are the only two numbers to characterize a cluster (Δ is set by the cosmology...or by the cosmologist!)

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$$\sigma = \sqrt{\frac{GM}{r}}$$

Velocity dispersion III

Numerically:

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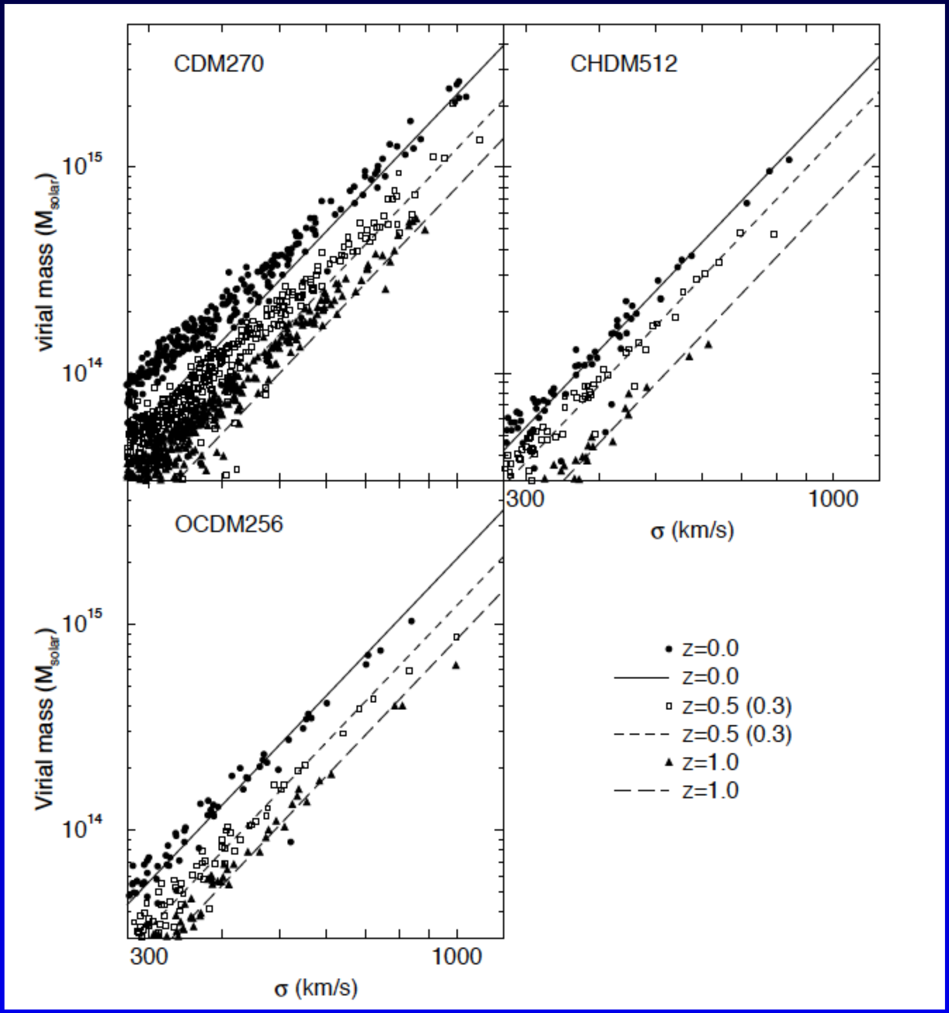
Scaling laws (dependence on mass and redshift).

Velocity dispersion IV

Numerically: good agreement with numerical simulations (Bryan and Norman, 1998):



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This is the scaling of the $M-T$ relation.

Temperature scaling law

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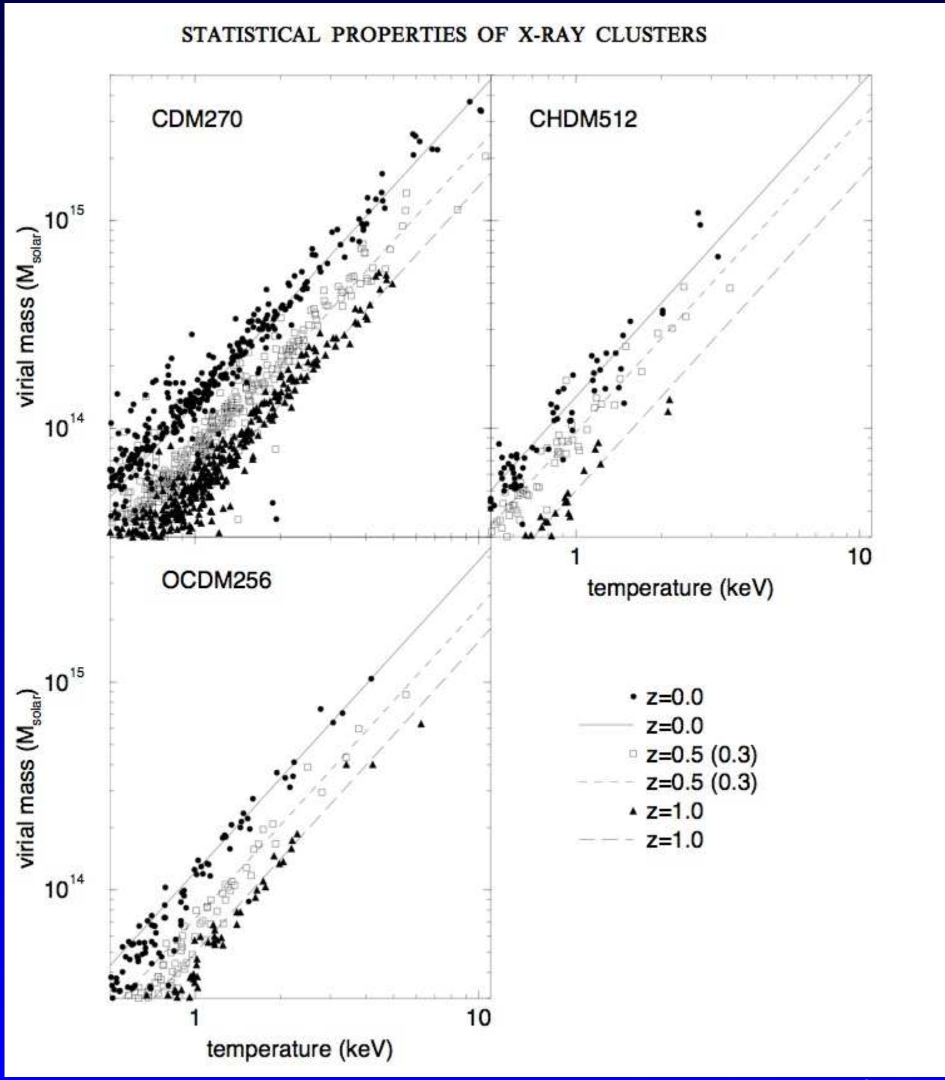

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leading to :

$$Lx \propto M^{4/3}(1+z)^{7/2}(\Omega_m \Delta/178)^{1/6}$$

The mass function

Inspired from Press and Schechter (1974)
The density field $\rho(x)$ has to be smoothed:

$$\tilde{\delta}(x) = \int \delta(x+u) W_R(u) du$$

and

$$\overline{\tilde{\delta}^2(x)} = \sigma^2(R)$$

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For a top hat window (!):

$$M(R) = \frac{4\pi}{3} R^3 \overline{\rho}$$

The mass function

Let's $s(\delta)$ be the probability that a volume element dV will be included in a NL object with mass greater than M given that it is included in a fluctuation of radius $> R$ with a contrast density δ.

$$\int_M^{+\infty} mn(m)dm = \overline{\rho} \int \mathcal{F}_\delta(\delta)s(\delta)d\delta$$

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$$\int_M^{+\infty} mn(m)dm = \overline{\rho} \int \mathcal{F}_\delta(\delta)s(\delta)d\delta$$

for a sharp threshold i.e. $\delta > \delta_{NL}$:

$$\int_M^{+\infty} mn(m)dm = \overline{\rho} \int_{\delta_{NL}}^{+\infty} \mathcal{F}_\delta(\delta)d\delta = \overline{\rho} \int_{\nu_{NL}}^{+\infty} \mathcal{F}(\nu)d\nu$$

The mass function

Following the spherical model:

$$\nu_{NL} = \frac{\delta_{NL}}{\sigma(M)}$$

Just derive against M:

$$n(M) = -\frac{\rho}{M^2\sigma(M)}\delta_{NL}\frac{\ln\sigma}{\ln M}\mathcal{F}(\nu_{NL})$$

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and test it against numerical simulations...

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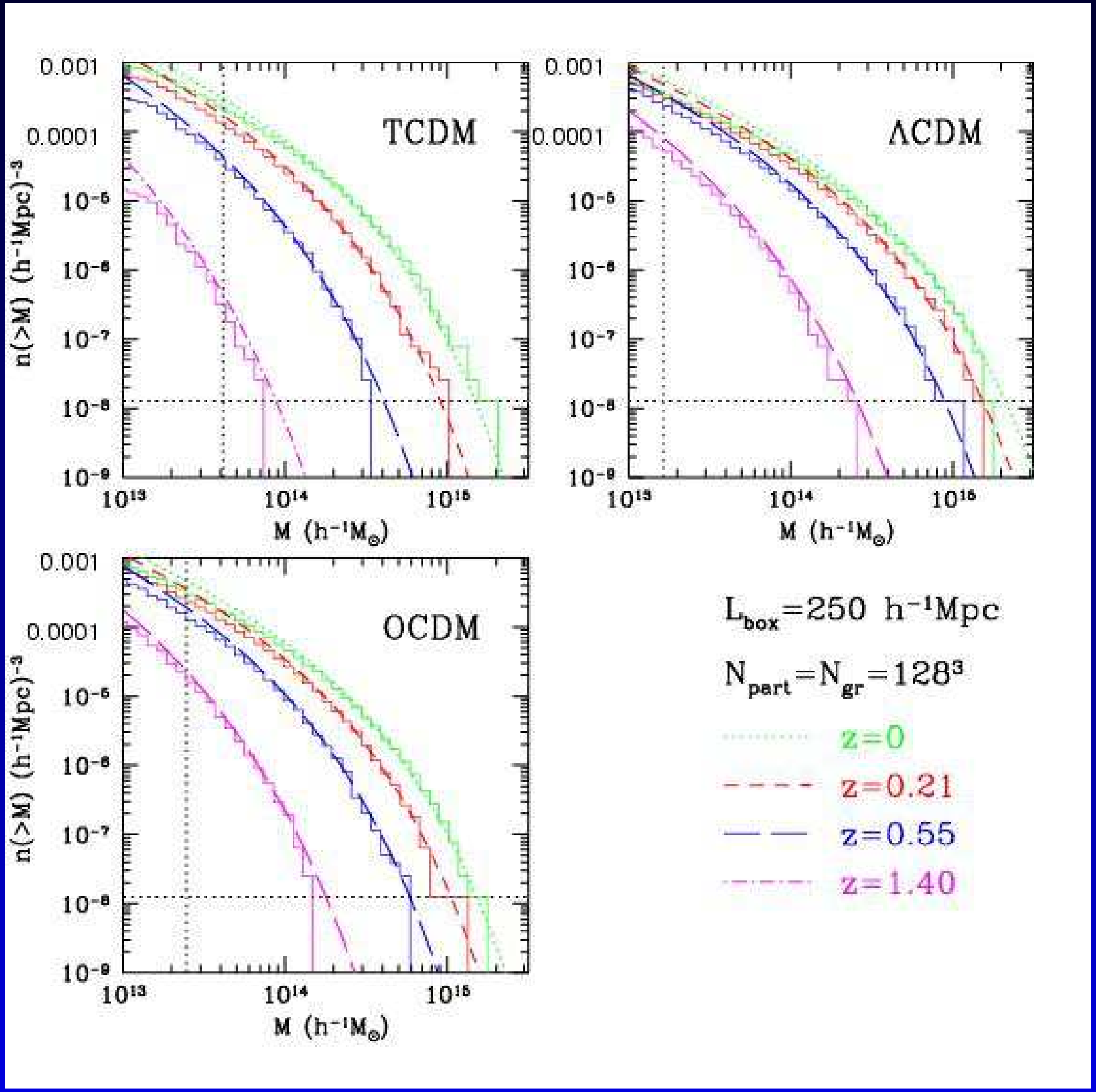

It actually works! (Borgani et al., 2000)

e-PS formula

ST (Sheth & Tormen, 1999) expression for $\mathcal{F}$ (S.O) :

$$\mathcal{F}(\nu) = \sqrt{\frac{2a}{\pi}} A \exp(-0.5a\nu^2)(1. + 1./(a\nu^2)^p)$$

with $a = 0.707$ $A = 0.3222$ $p = 0.3.$

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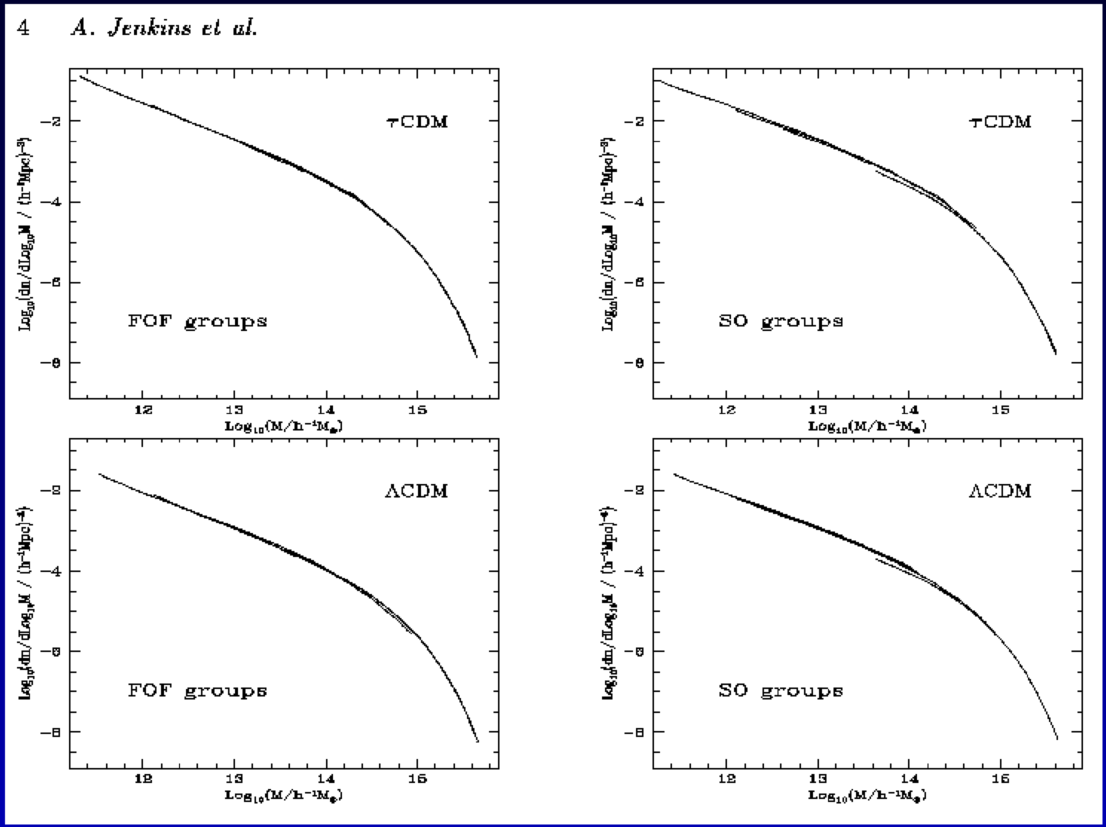

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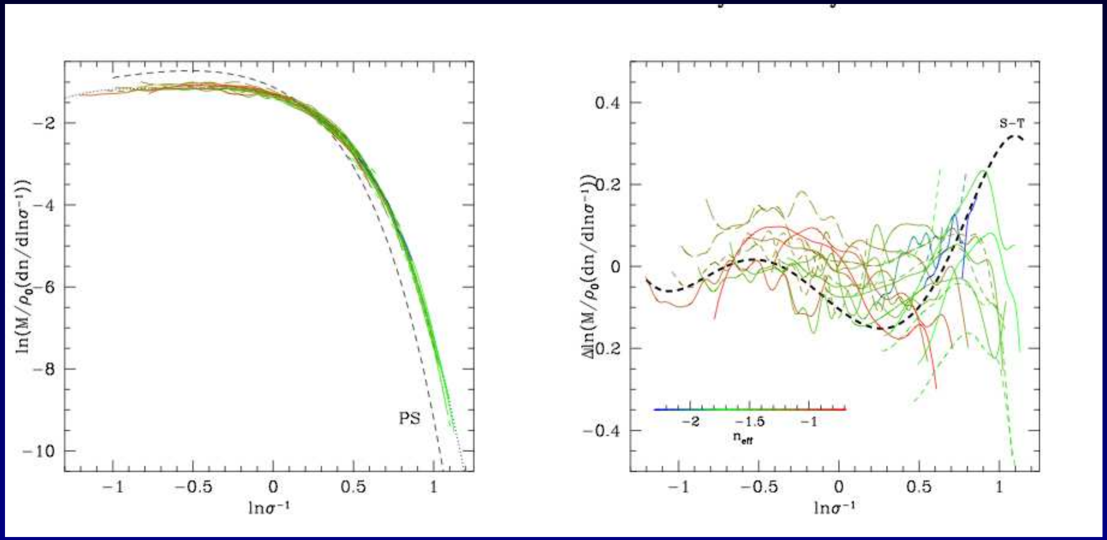

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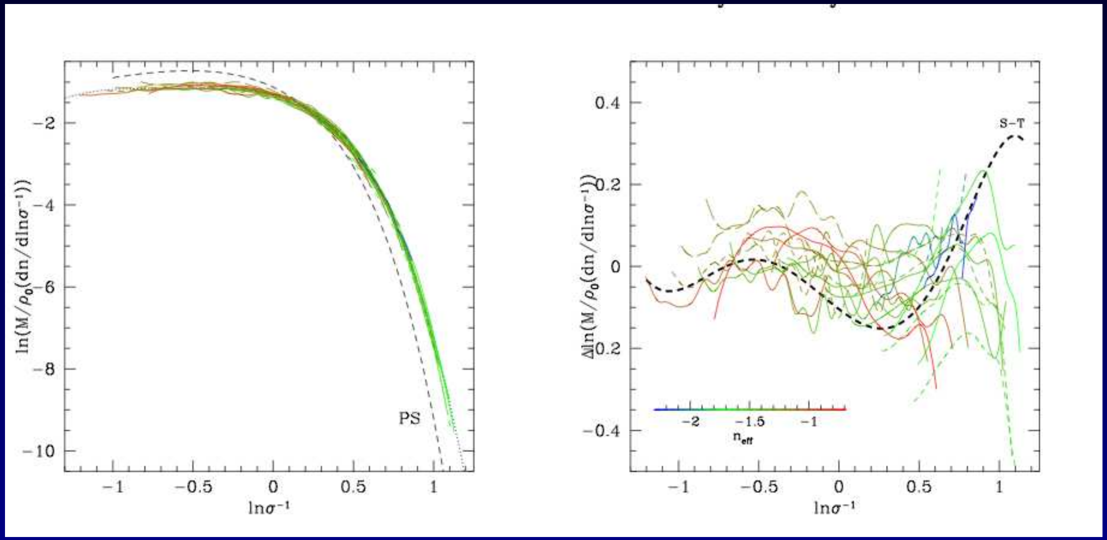

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Different fit:

$$f(M) = \alpha \exp\left(-|\ln(\sigma^{-1}) + \beta|^{\gamma}\right)$$

set constant threshold ($\delta_{NL} = 1.686$) and constant contrast density.

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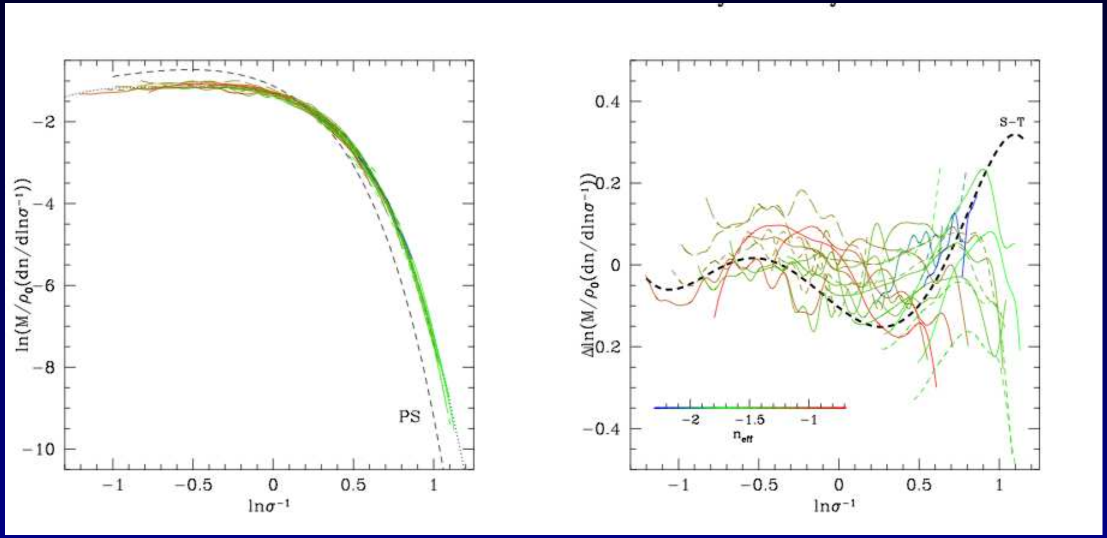

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Universal mass function ?

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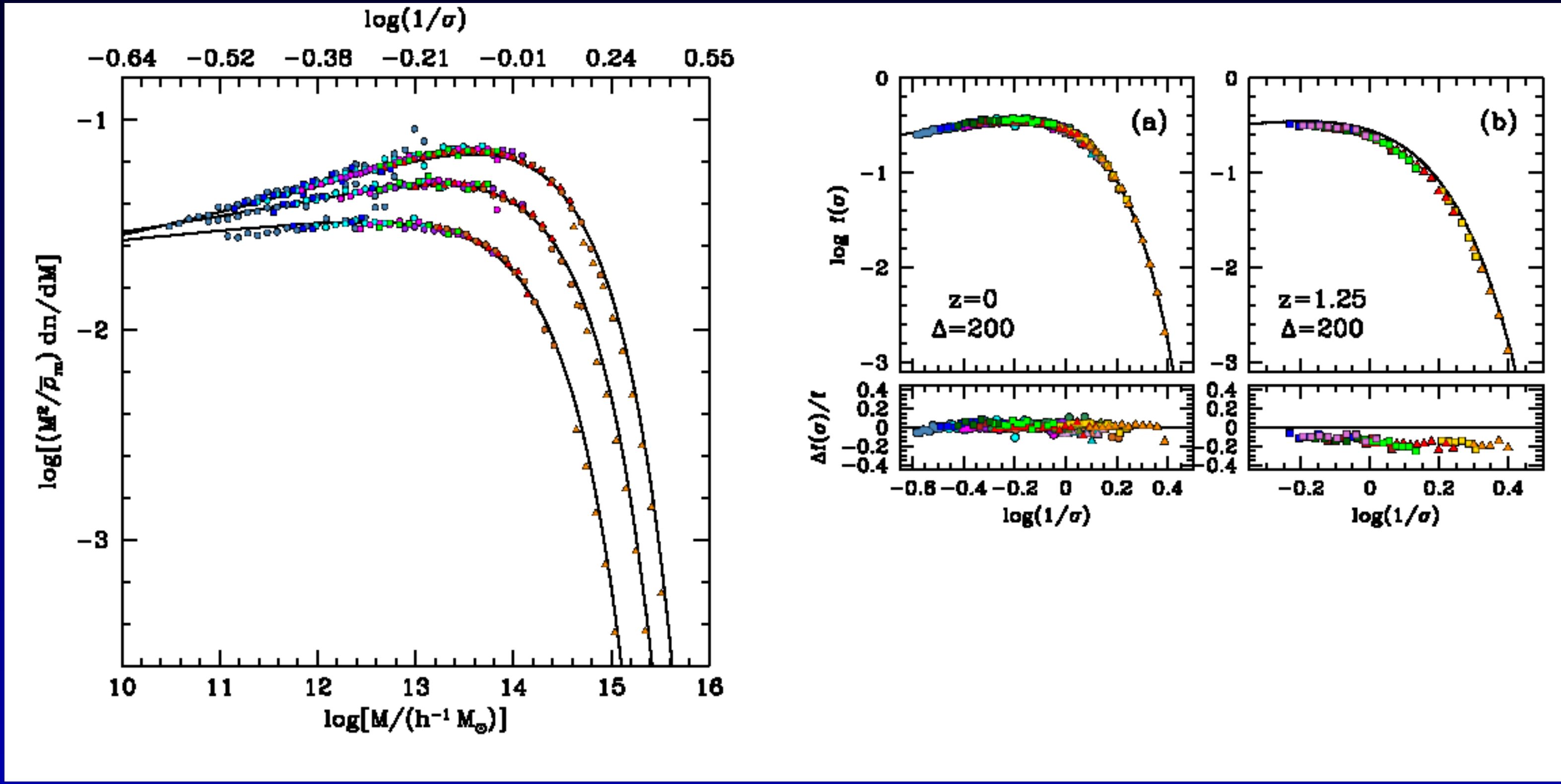

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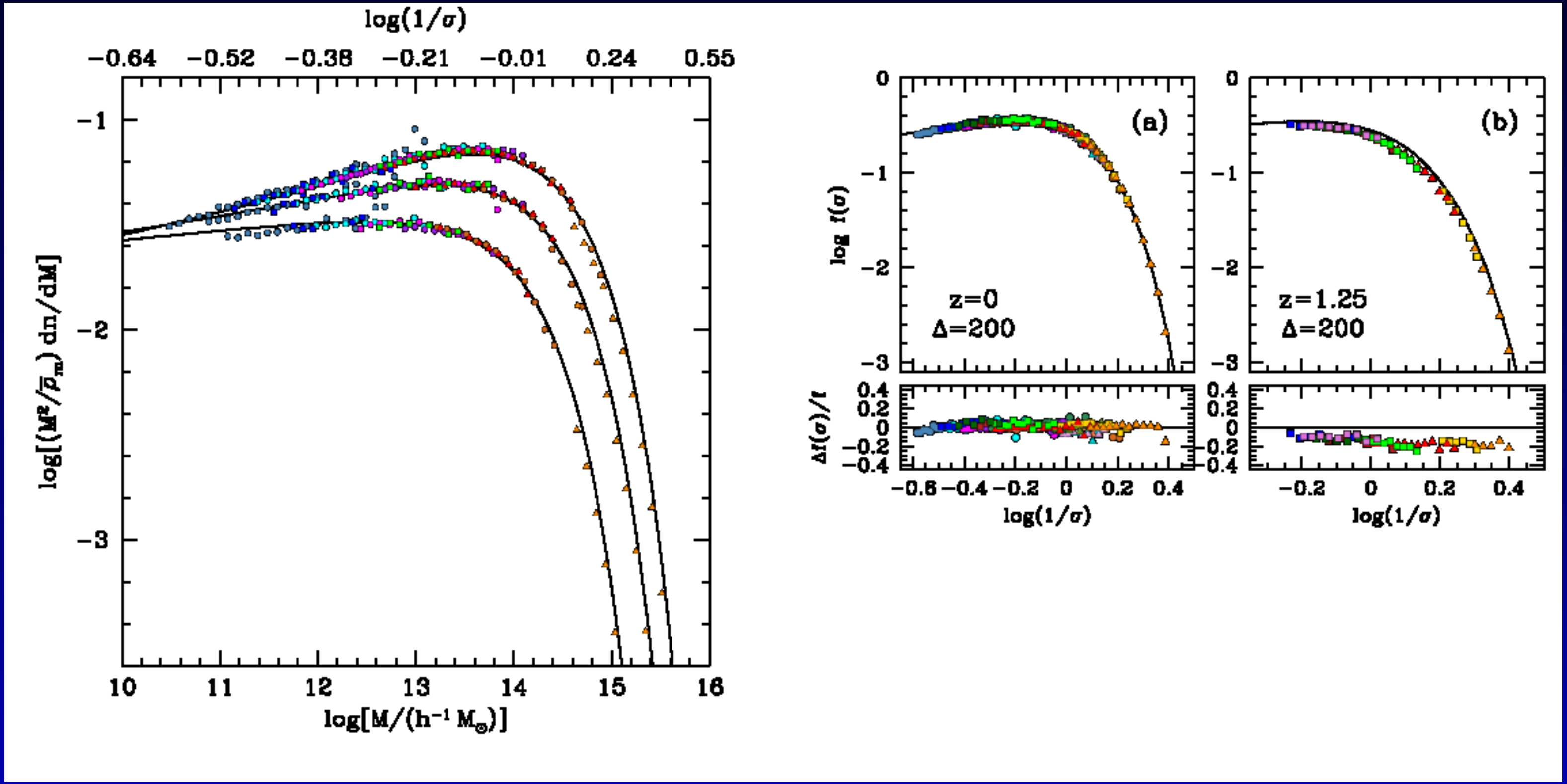

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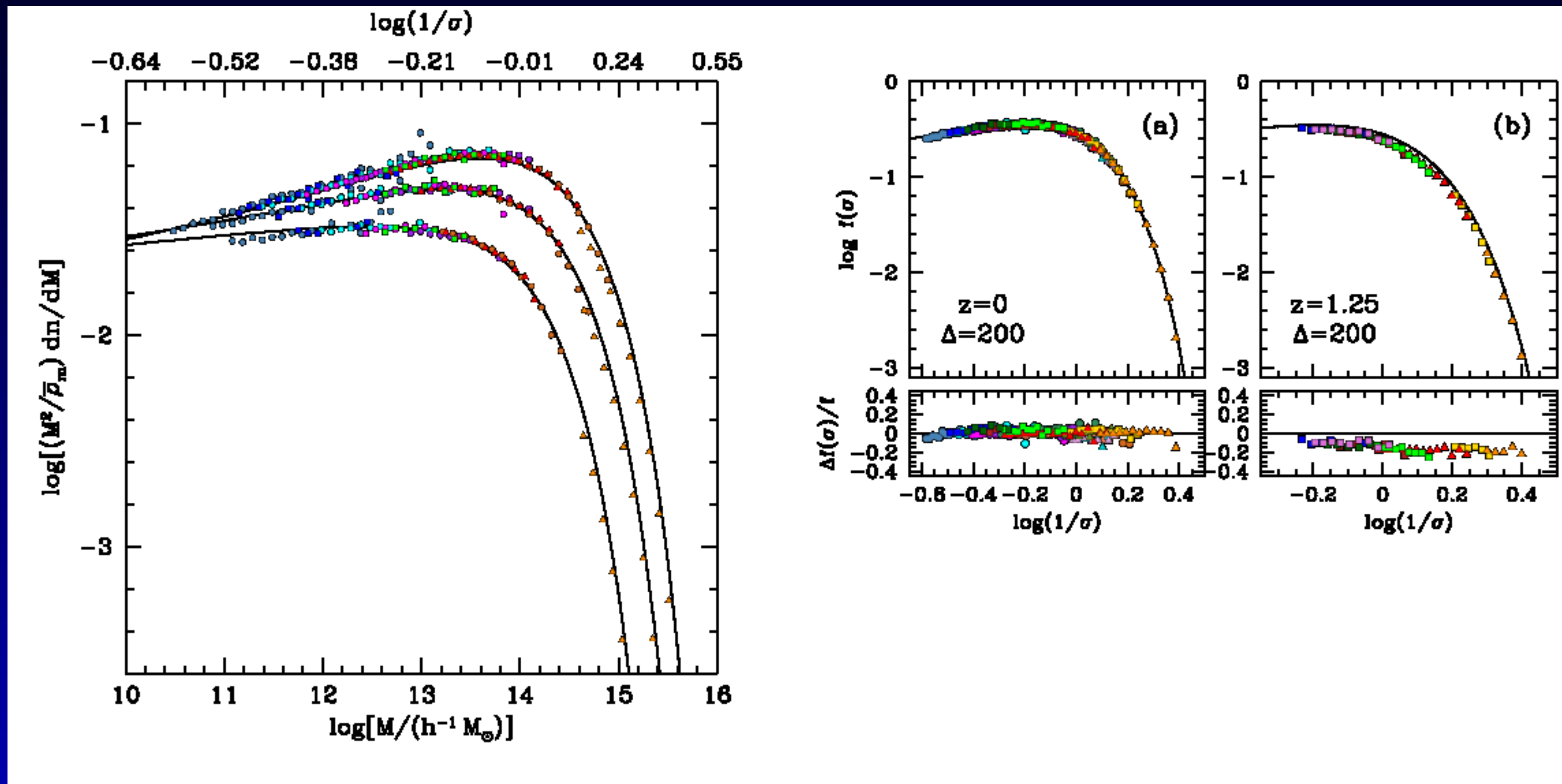

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Non-universal mass function ?

Universality again ?

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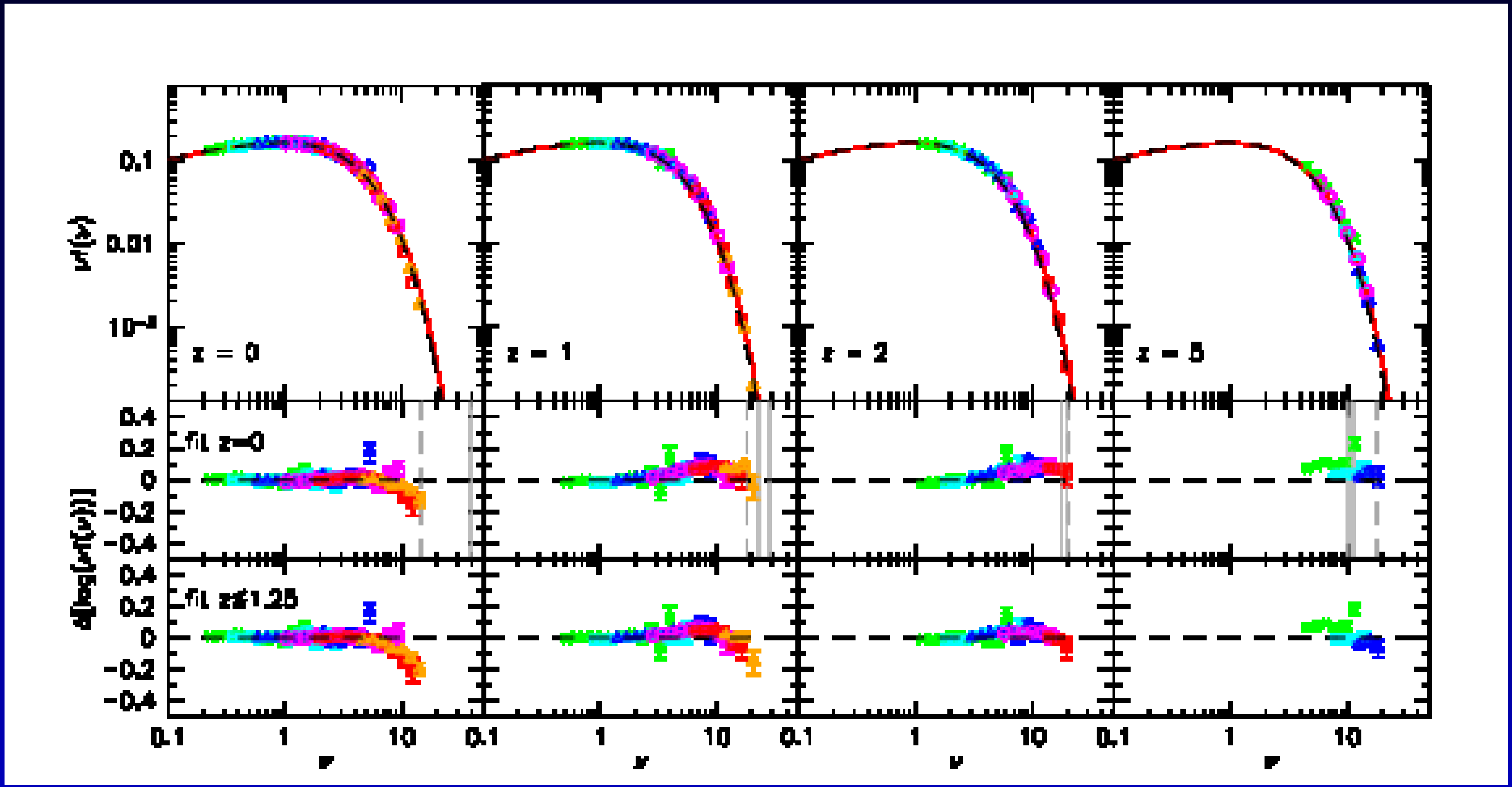

Despali et al. (2015)

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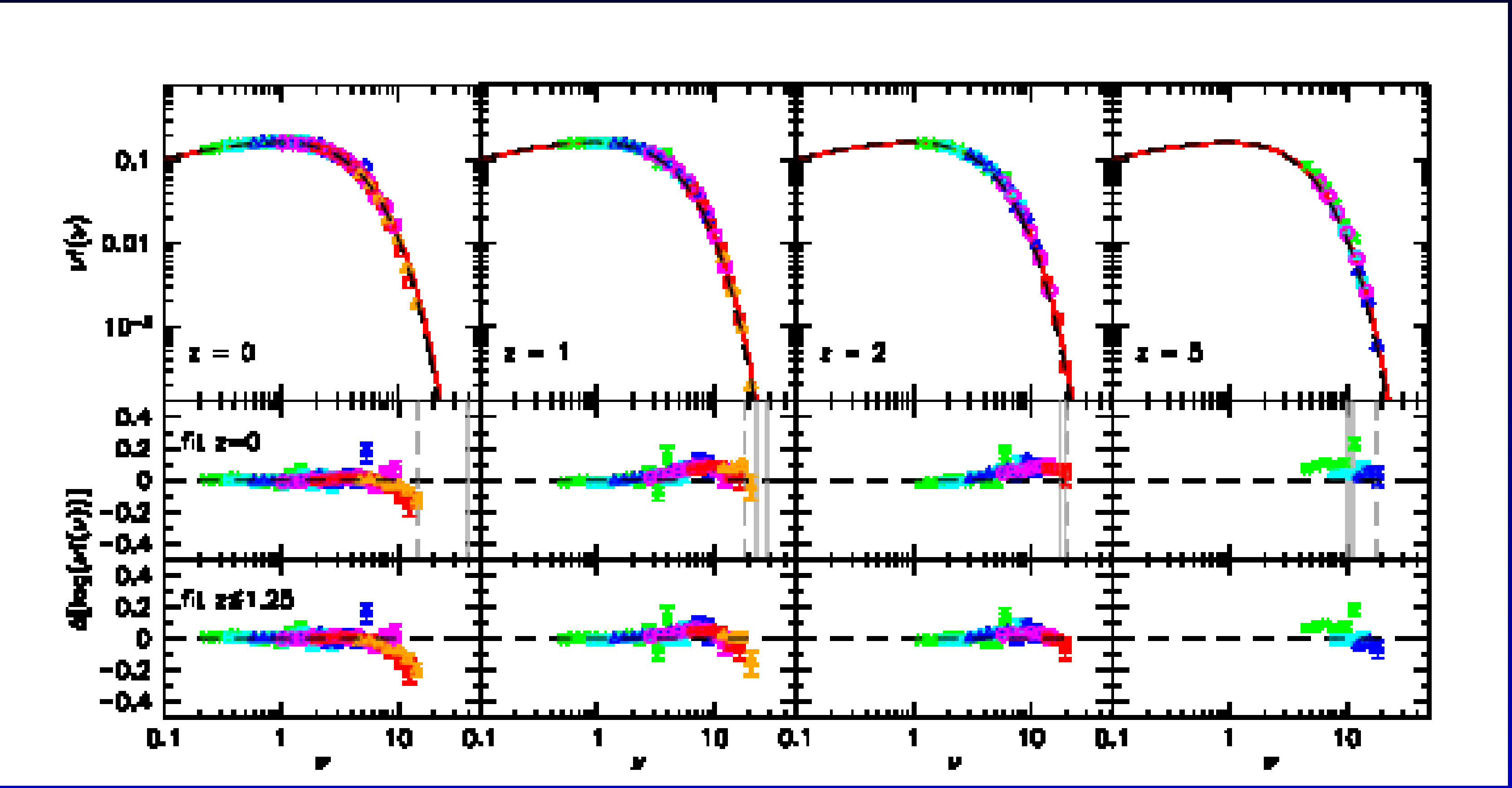

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$a = 0.7689\ A = 0.3222\ p = 0.3$

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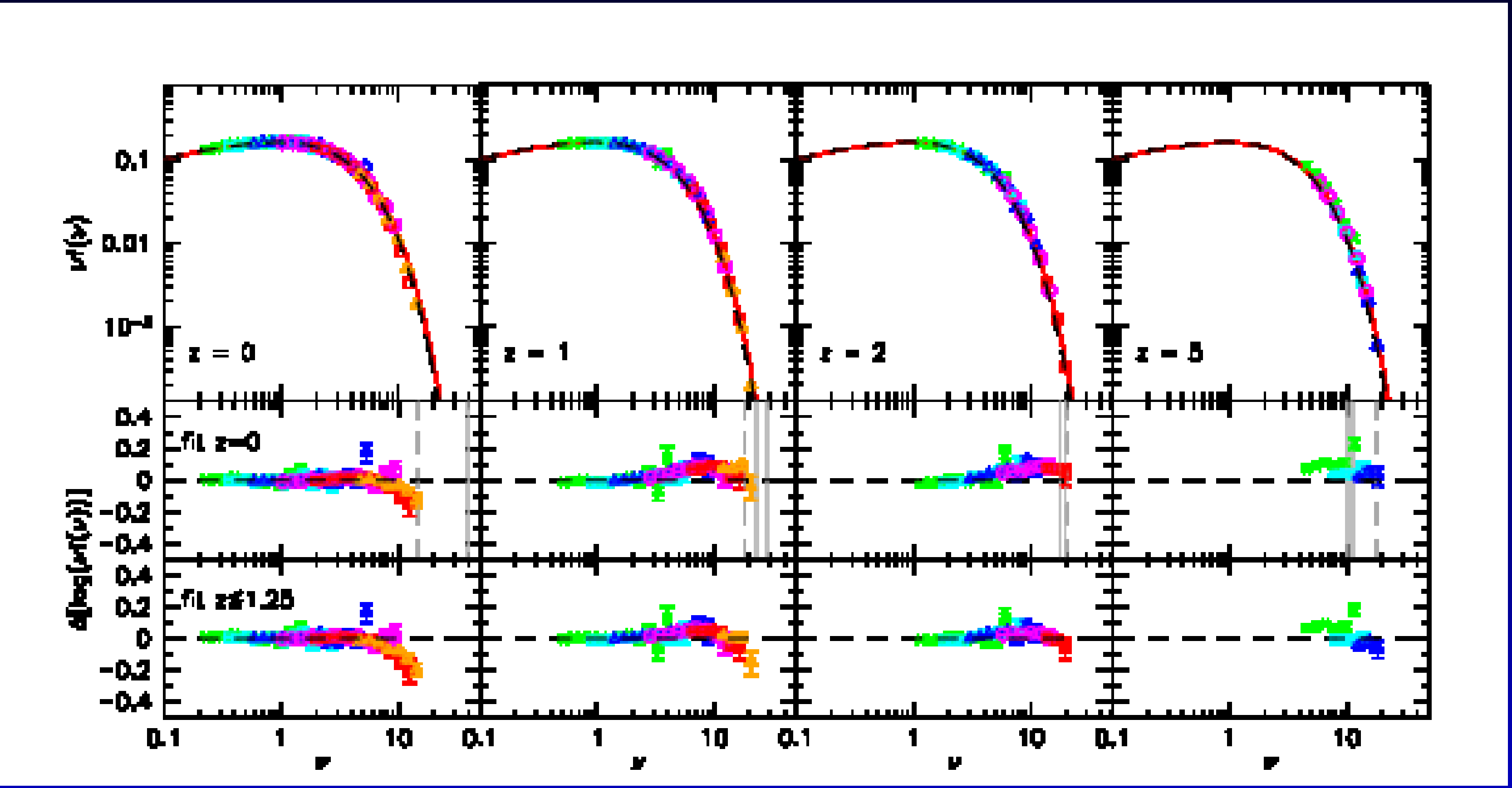

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An other fit on cluster scales...

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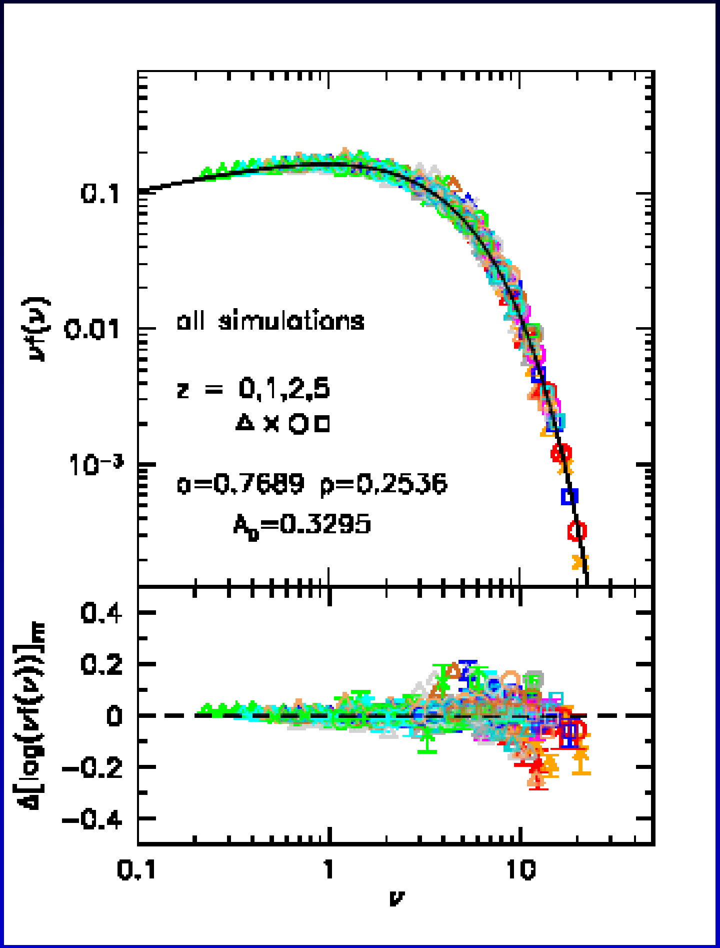

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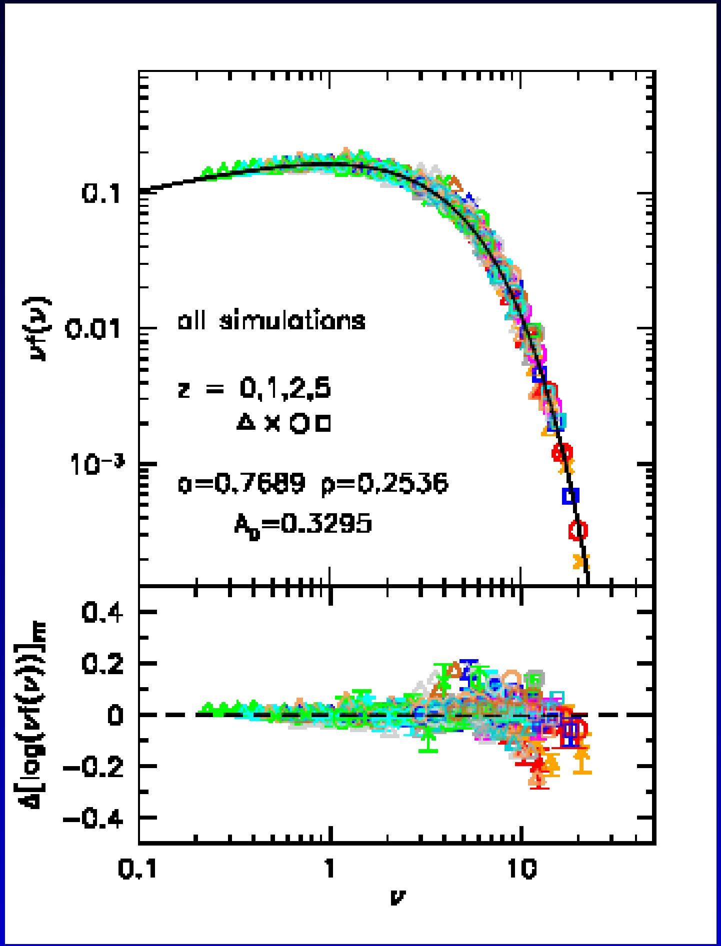

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Universal mass function 5-7%.

Conclusions

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Conclusions

- There is a convincing modeling of dark matter distribution and evolution in both linear and non-linear regimes to constrain cosmological scenario.
- Allows to investigate structure formation. History of individual structure is missing: merging tree $\rightarrow$ semi-analytical method “SAM” in order to model galaxy formation : assembly/evolution.
- Warning: data come through “light” which is coming from baryons and this was almost not discussed in these lectures...

Cluster as cosmological tools

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Important progresses are due to numerical simulations:

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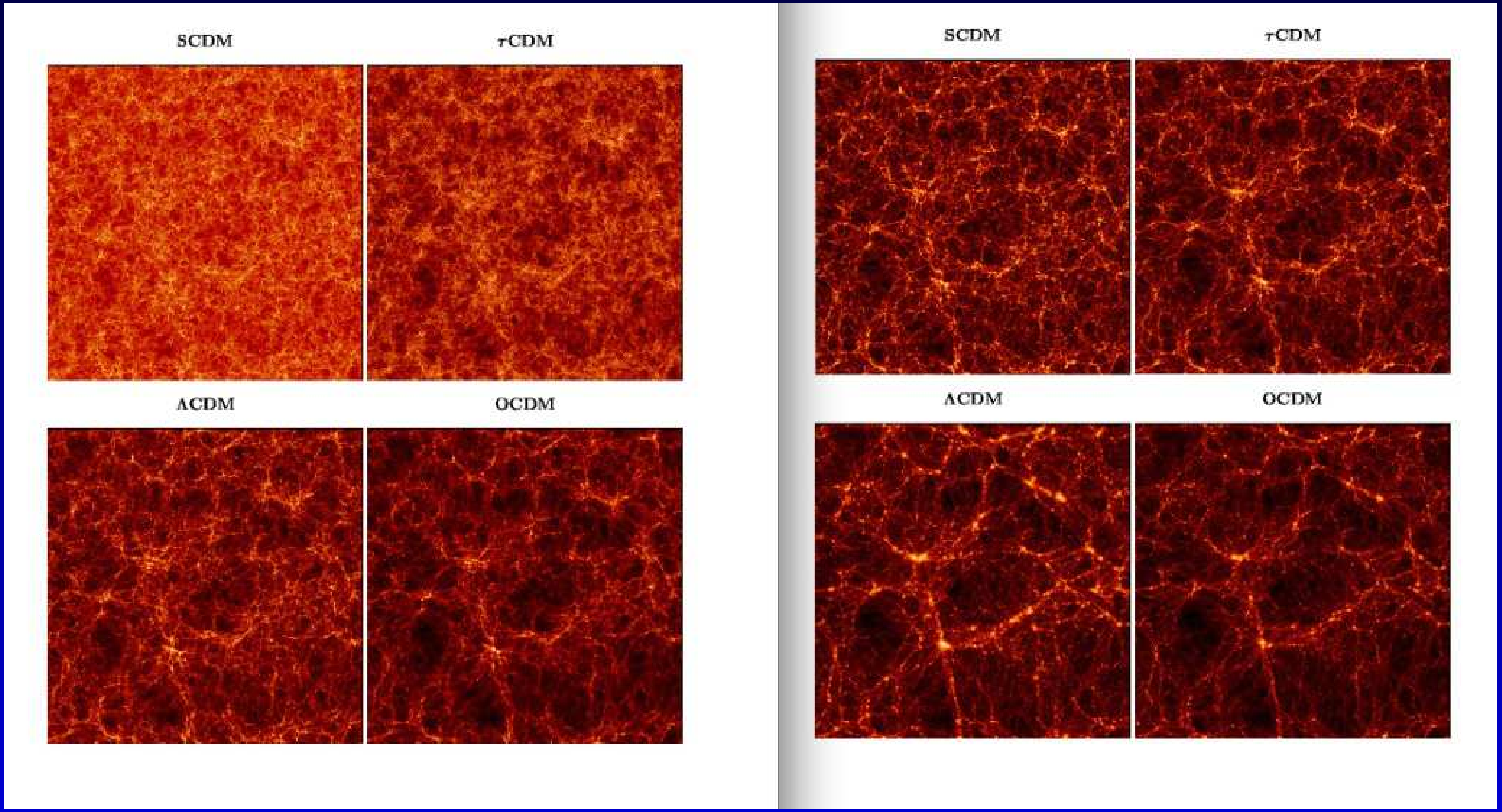

Numerical simulations

20 years ago...

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TABLE 1

SIMULATION PARAMETERS

Designation	Ω_{cold}	Ω_{hot}	Ω_{baryon}	h	m_ν (eV)	σ_8	N_{cell}	N_{part}	L_{box} (h^{-1} Mpc)
CDM270........	0.94	0.0	0.06	0.5	0	1.05	270^3	135^3	85
CHDM512......	0.725	0.2	0.075	0.5	2×2.3	0.7	512^3	3×256^3	50
OCDM256......	0.34	0.0	0.06	0.65	0	0.75	256^3	128^3	85
CHDM256......	0.6	0.3	0.1	0.5	7.0	0.67	256^3	3×128^3	85

Numerical simulations

2015...

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Main set of simulations							
name	box [h^{-1}Mpc]	z_i	$m_p[M_\odot h^{-1}]$	soft [kpc h^{-1}]	$N_{h-tot}(z=0)$	$N_{h>300}(z=0)$	colour
Ada	62.5	124	1.94×10^7	1.5	2264847	103852	green
Bice	125	99	1.55×10^8	3	2750411	129674	cyan
Cloe	250	99	1.24×10^9	6	3300880	161580	blue
Dora	500	99	9.92×10^9	12	3997898	191793	magenta
Emma	1000	99	7.94×10^{10}	24	4739379	176633	red
Flora	2000	99	6.35×10^{11}	48	5046663	75513	orange

Table 1. Features of Le SBARBINE simulations run with Planck13 parameters $\Omega_m = 0.307$, $\Omega_\Lambda = 0.693$, $\sigma_8 = 0.829$ and $h = 0.677$ and containing 1024^3 dark matter particles. The last two columns report the total number of haloes identified with the Spherical Overdensity at redshift $z = 0$ that are resolved with more than 10 and 300 particles, respectively.

Secondary set of simulations						
name	Ω_m	Ω_Λ	σ_8	box [h^{-1}Mpc]	$m_p[M_\odot h^{-1}]$	colour
Tea	0.2	0.8	0.7	150	1.396×10^9	gray-square
Tea-big	0.2	0.8	0.7	1000	4.135×10^{11}	gray-square
Tina	0.2	0.8	0.9	150	1.396×10^9	gray-triangle
Tina-big	0.2	0.8	0.9	1000	4.135×10^{11}	gray-triangle
Vera	0.4	0.6	0.7	150	2.791×10^9	brown-square
Vera-big	0.4	0.6	0.7	1000	8.271×10^{11}	brown-square
Viola	0.4	0.6	0.9	150	2.791×10^9	brown-triangle
Viola-big	0.4	0.6	0.9	1000	8.271×10^{11}	brown-triangle
Wanda (wmap7)	0.272	0.728	0.81	150	1.898×10^9	blue-circle
Wanda-big (wmap7)	0.272	0.728	0.81	1000	5.624×10^{11}	blue-circle

Table 2. Details of the small set of 10 simulations with different cosmological parameters. Each contains 512^3 dark matter particles with initial conditions generated at redshift $z = 99$. For all the models the Hubble parameter is $h = 0.6777$, apart from the WMAP7 cosmology for which $h = 0.704$.

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Clusters Self-similarity from simulations:

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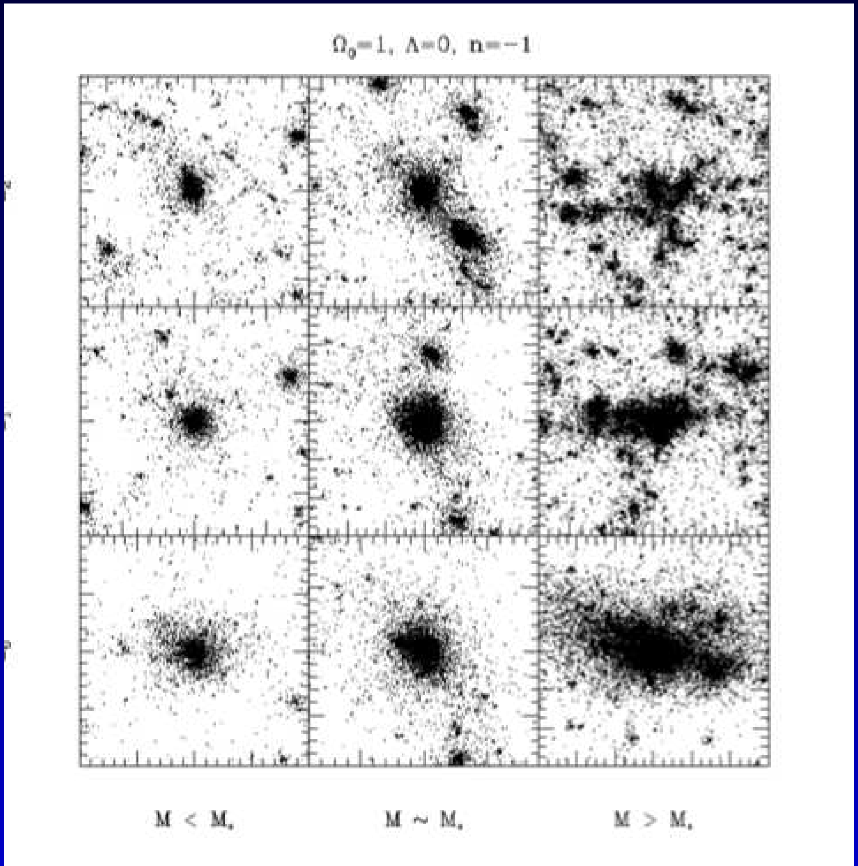

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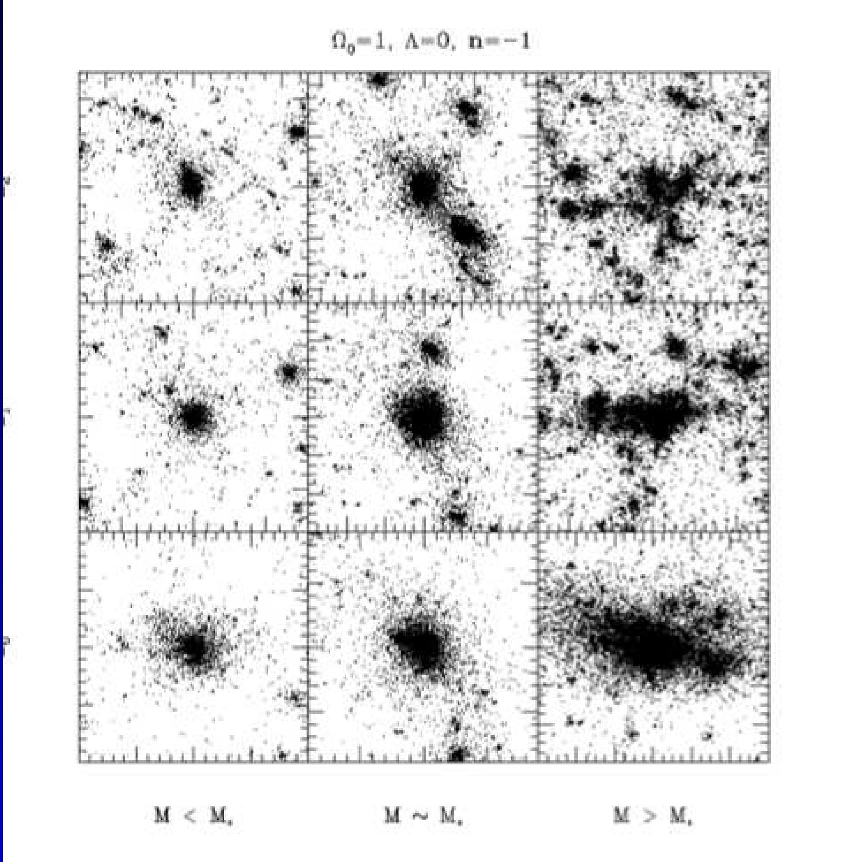

$\sigma(M_*) \sim 1$

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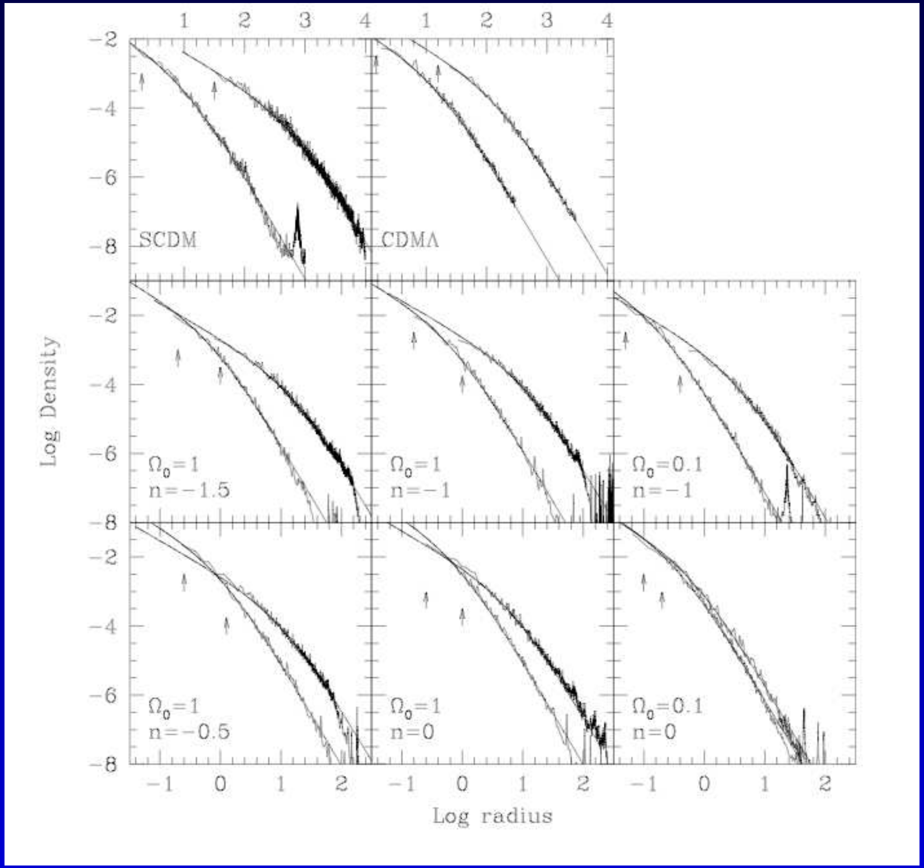

NFW profiles

From numerical simulations DM halo appear to be well fitted by the so-called NFW profile:

$$\frac{\rho(r)}{\rho_c} = \frac{\delta_c}{(r/r_c)(1. + r/r_c)^2}$$

Two parameters: mass in some radius (for instance $\Delta = 200$) and one parameter: the concentration c : $r_c = r_{200}/c$

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allows analytical $M(r)$

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Recent simulations of Clusters:

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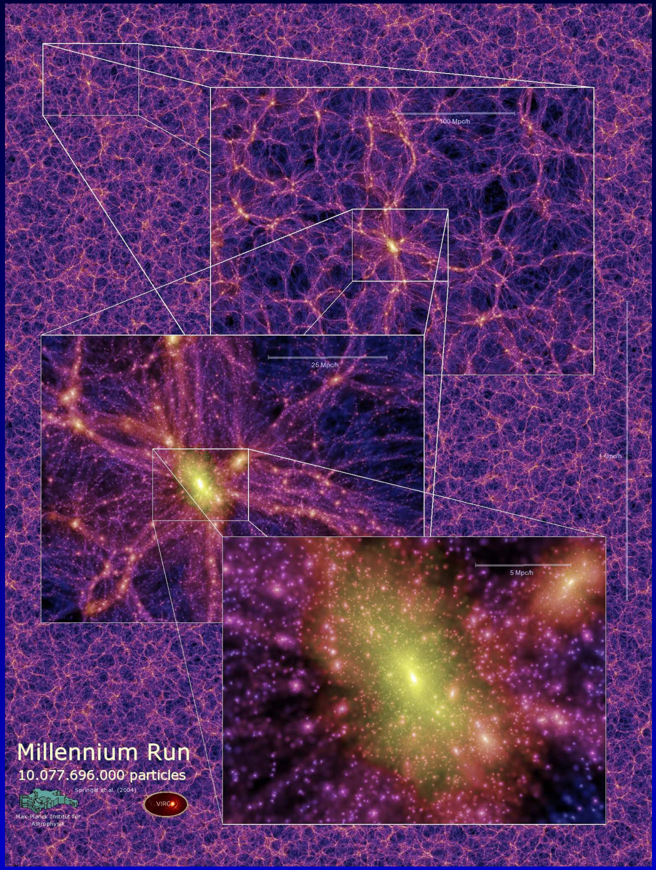

Millenium simulation: much more detailled pictures...

Cluster as cosmological tools

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More from millenium simulation:

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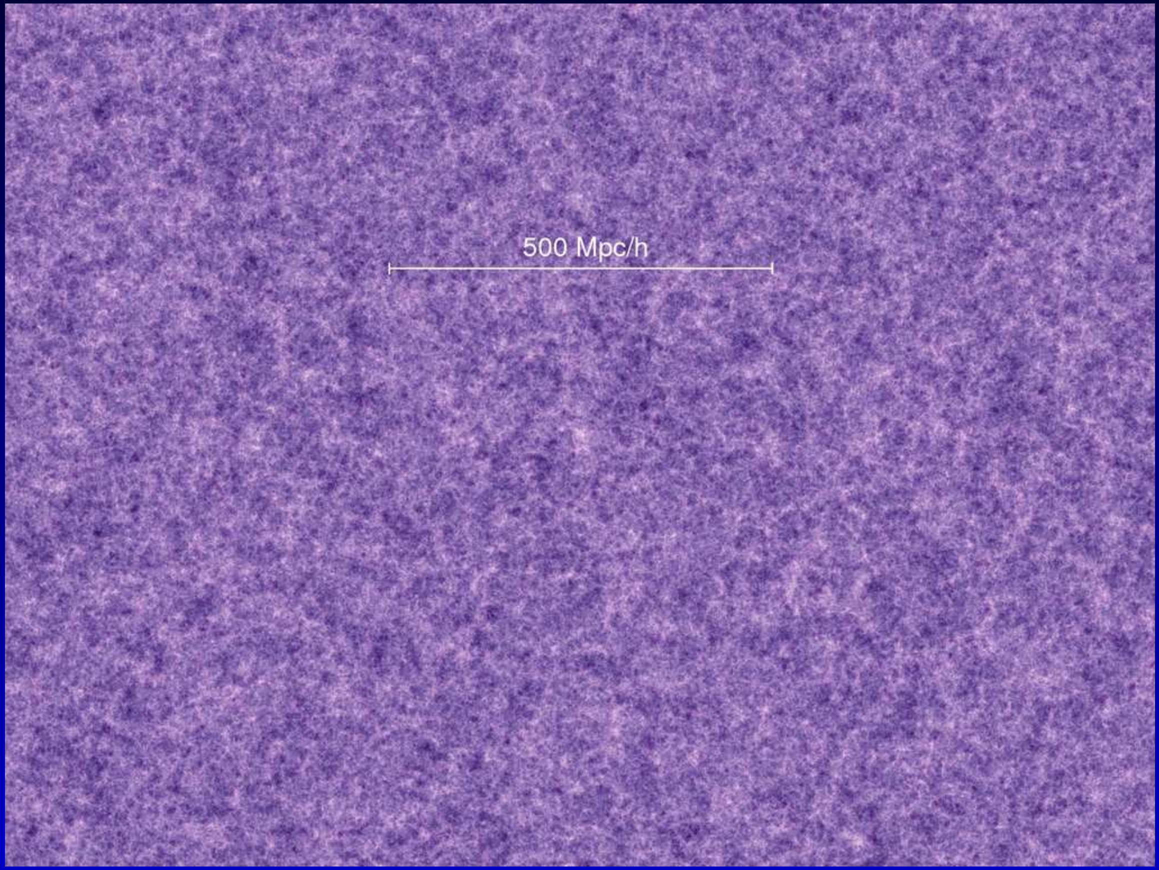

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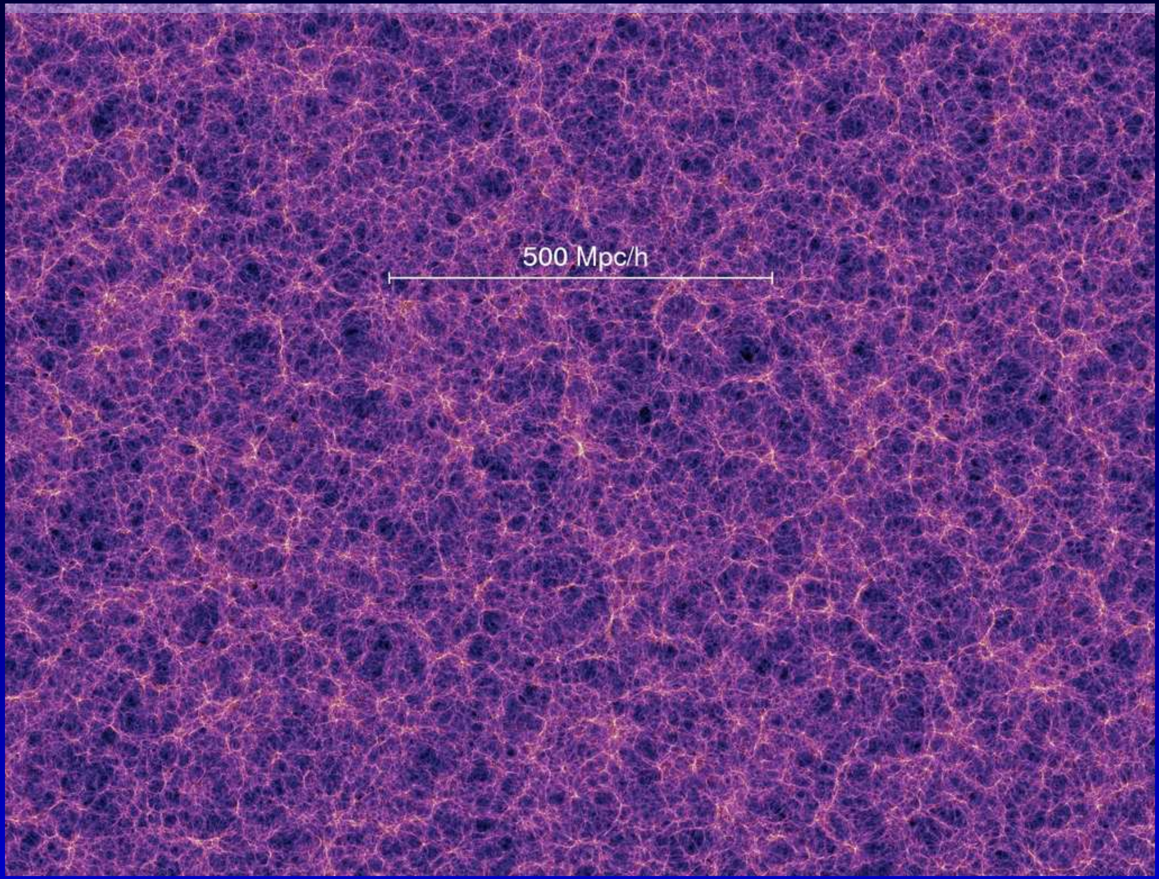

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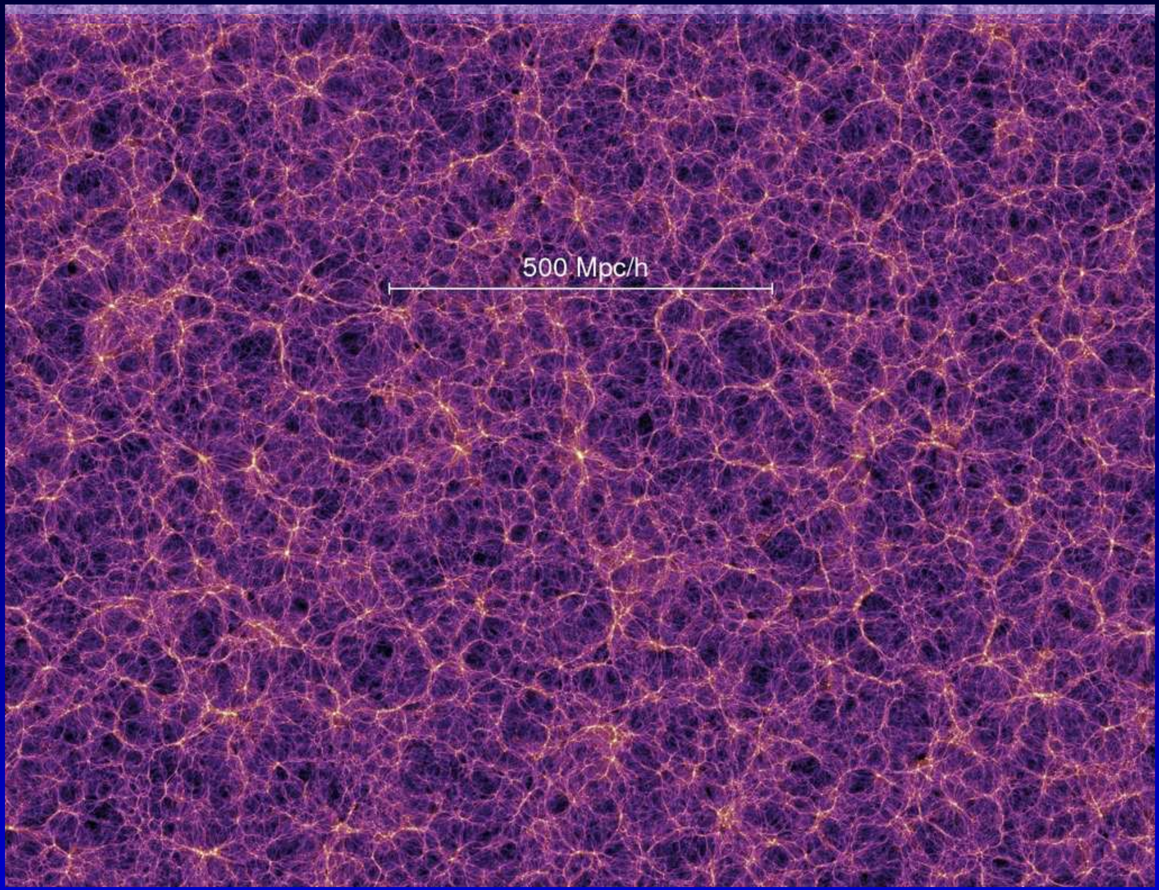

Movies

Movies

here

https://www.youtube.com/watch?v=xfgDoExbu_Q

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Which reference contrast (Δ_{th})? Δ_v, 178, 200, 500, 2000...

Different halo finders

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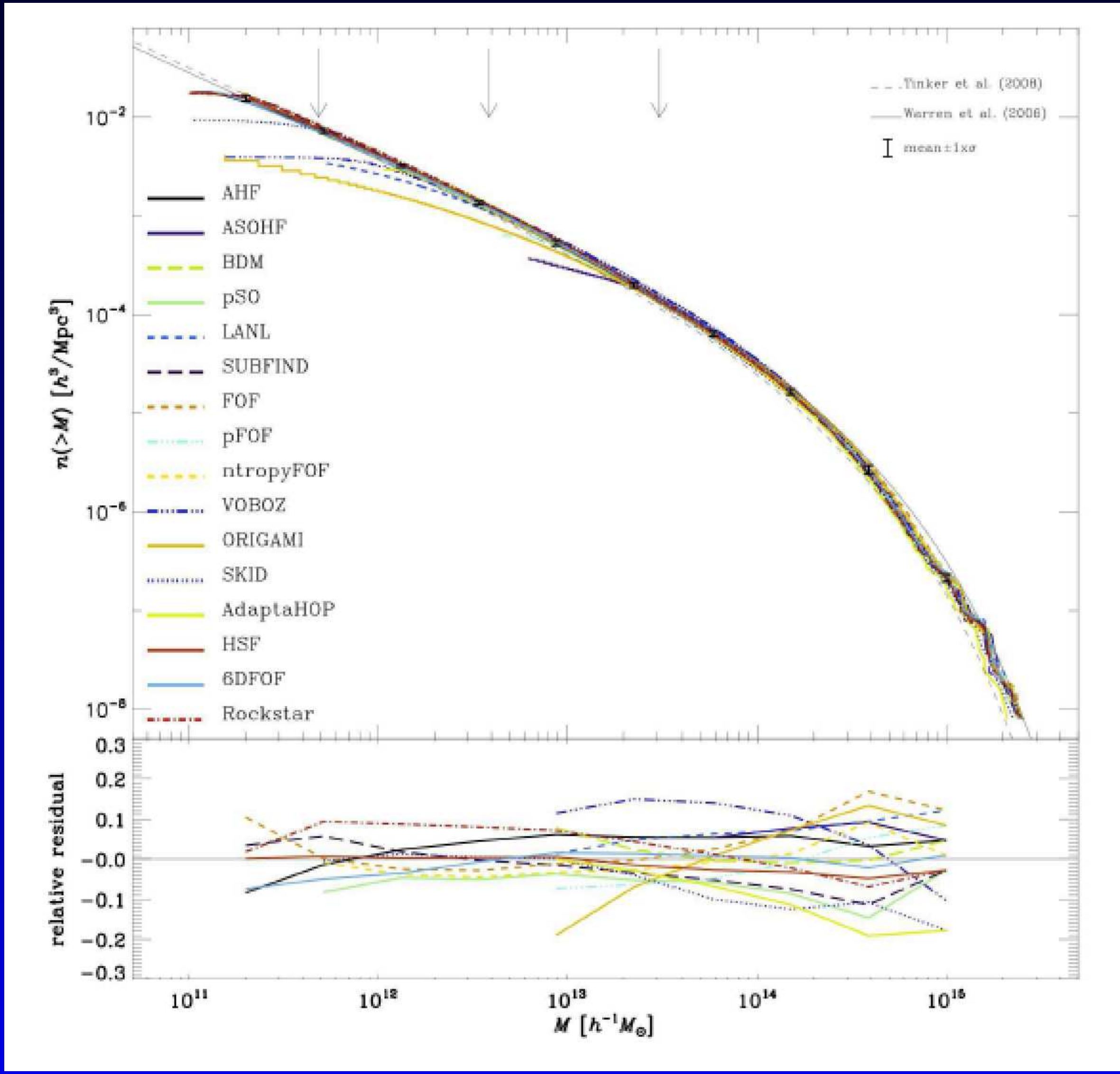

Knebe et al. (2013)

The spherical model (reminder)

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Transition into the non linear regime is extremely rapid.
Can be generalized to other models:

$$\delta_{NL}(z,C), \Delta_{NL}(z,C)$$

Plus profile(M,z,C)...

Cluster mass function

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$$N(M,z) = -\frac{\rho}{m^2\sigma(M)}\delta_s\frac{d\log\sigma}{d\log M}\mathcal{F}(\frac{\delta_s}{\sigma(M)})$$

Cluster mass function

$$N(M,z) = -\frac{\rho}{m^2\sigma(M)}\delta_s\frac{d\log\sigma}{d\log M}\mathcal{F}(\frac{\delta_s}{\sigma(M)})$$

estimation of $\sigma(M) \leftrightarrow P(k)$:

$$\sigma^2(R) = \int P(k)\hat{W}(kR)d^3k$$

with :

$$\hat{W}(kR) = \frac{3\sin(kR)/kR - \cos(kr)}{(kR)^2}$$

Cluster mass function evolution

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$$\sigma(R, z) = D(z)\sigma(R, 0)$$

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So $\sigma(M, z))$ contains the **growing rate** of fluctuations.

From mass to observables

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Needs a flux limited survey...

From mass to observables

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Each cluster as a luminosity s_x, a redshift z and a T_x

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Unbiased estimator...

From mass to observables

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Application to the x-ray temperature:

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$$T_x \propto \frac{GM_\Delta}{R_\Delta}$$

From mass to observables

Application to the x-ray temperature:

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so that:

$$T_x = A_{TM} M^{2/3} (1+z) (\Omega_m \Delta / 178)^{1/3}$$

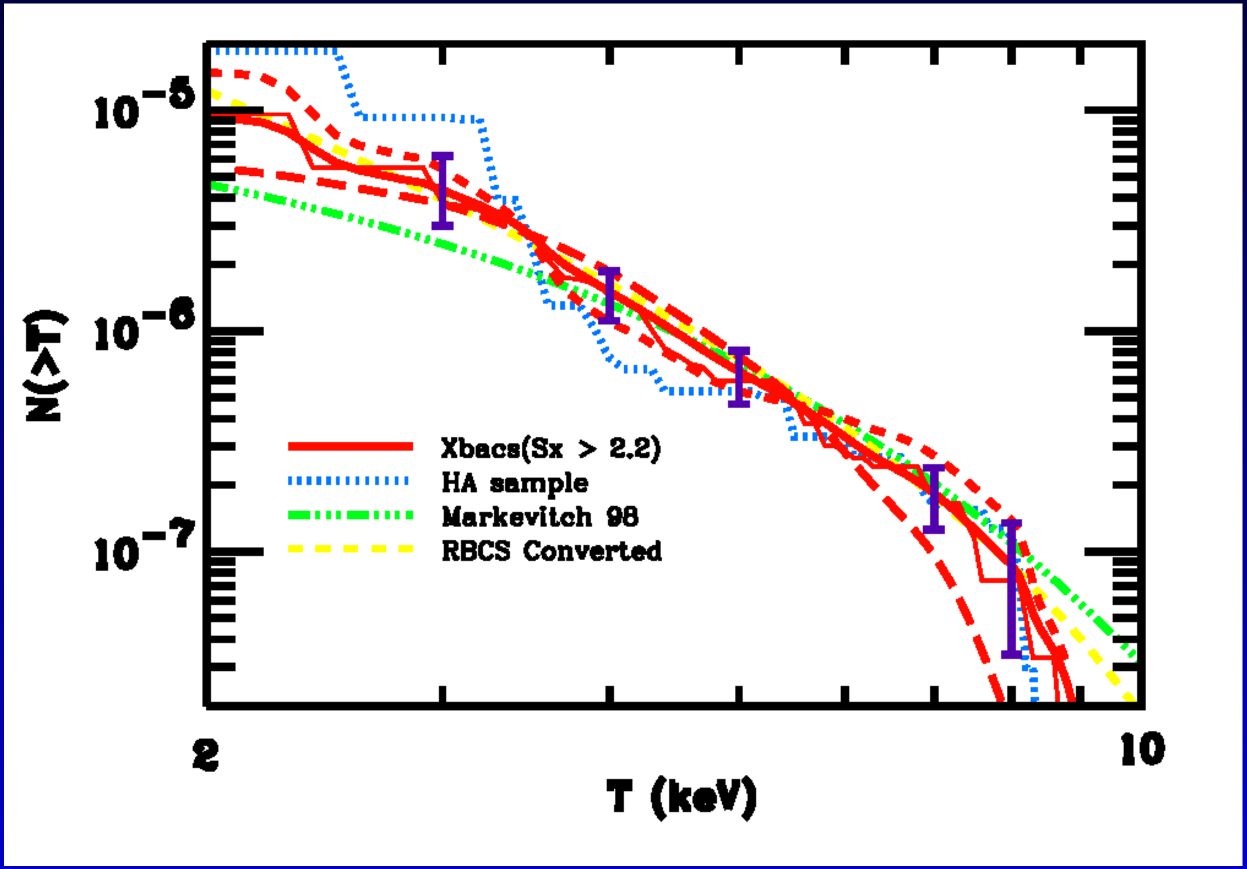
From mass to observables

From mass to observables

Fitting $N(T_x)$

From mass to observables

Fitting $N(T_x)$



From 50 X-ray cluters (2000)

From mass to observables

From mass to observables

Fitting $N(T_x)$

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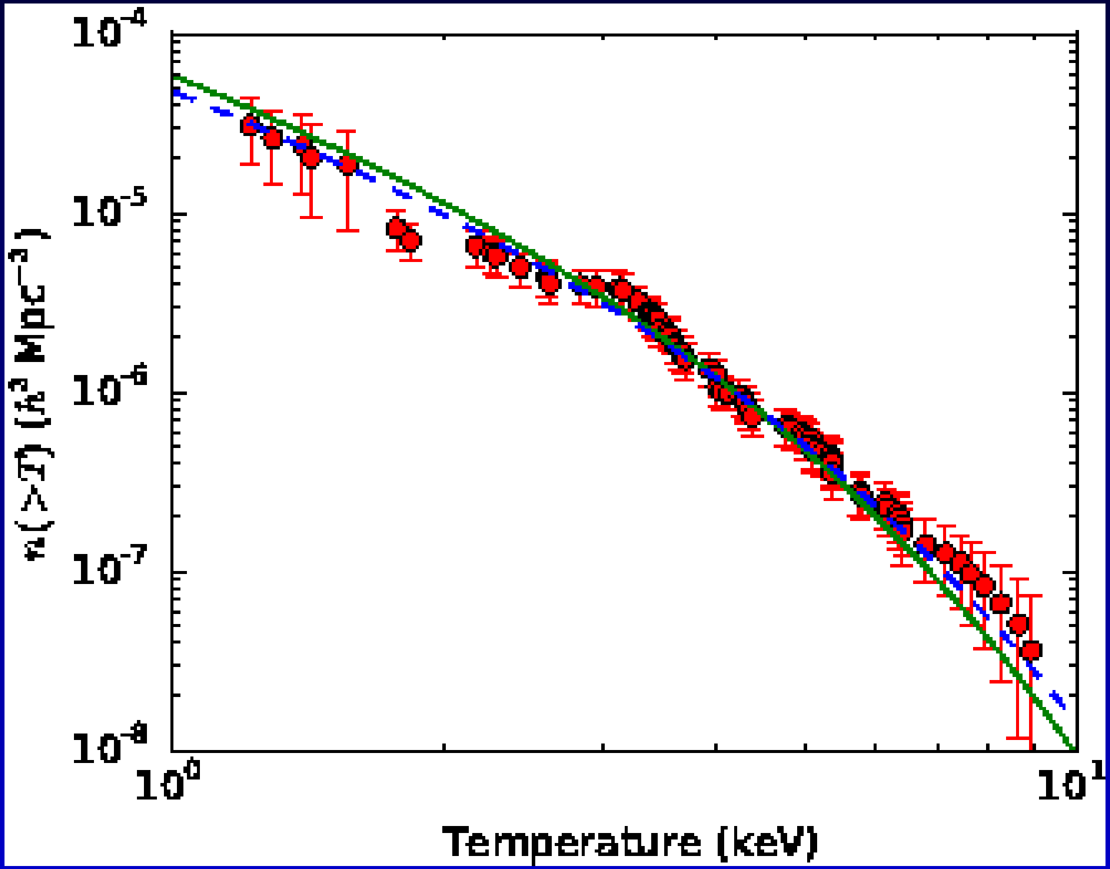

From 72 X-ray cluters (2015)

Applications

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Measuring local matter fluctuations:

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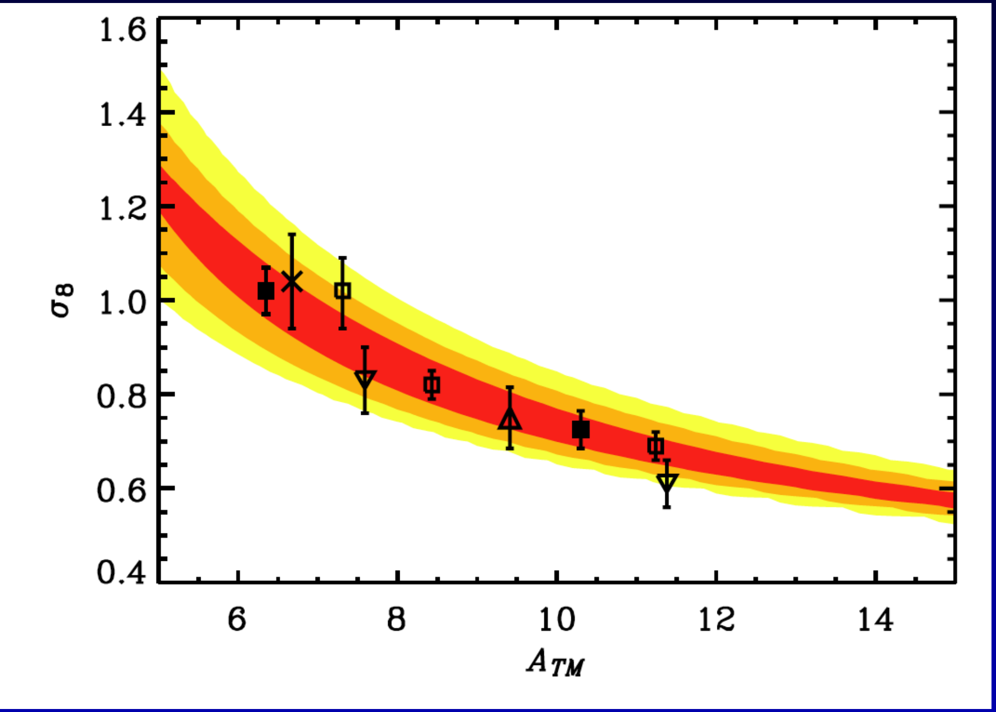

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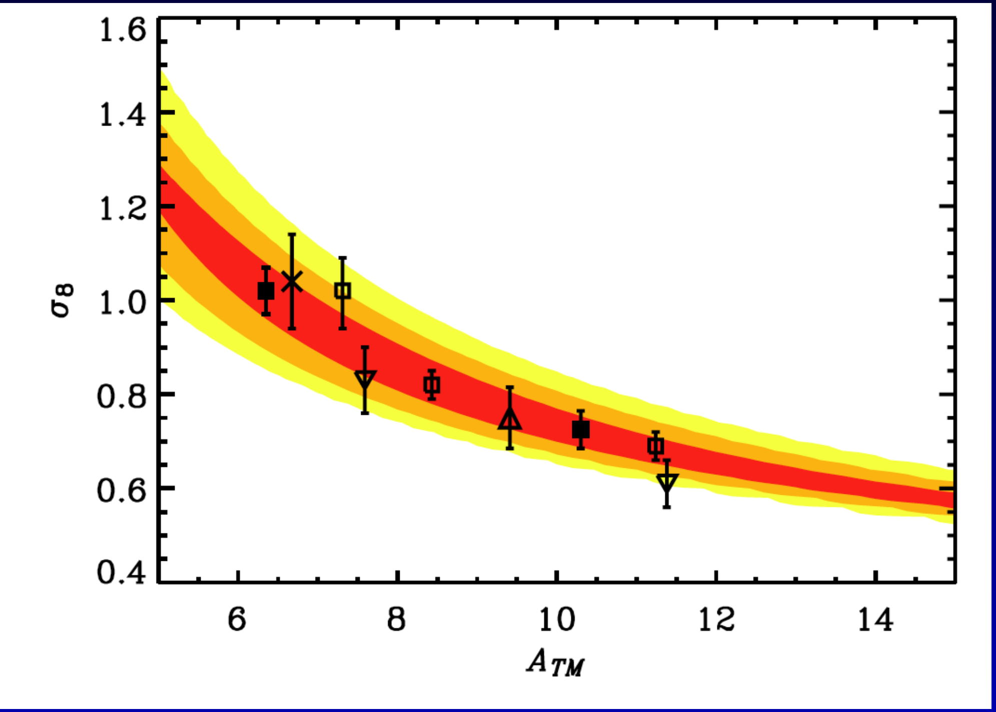

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Consistency and degeneracy...

From mass to observables: troubles...

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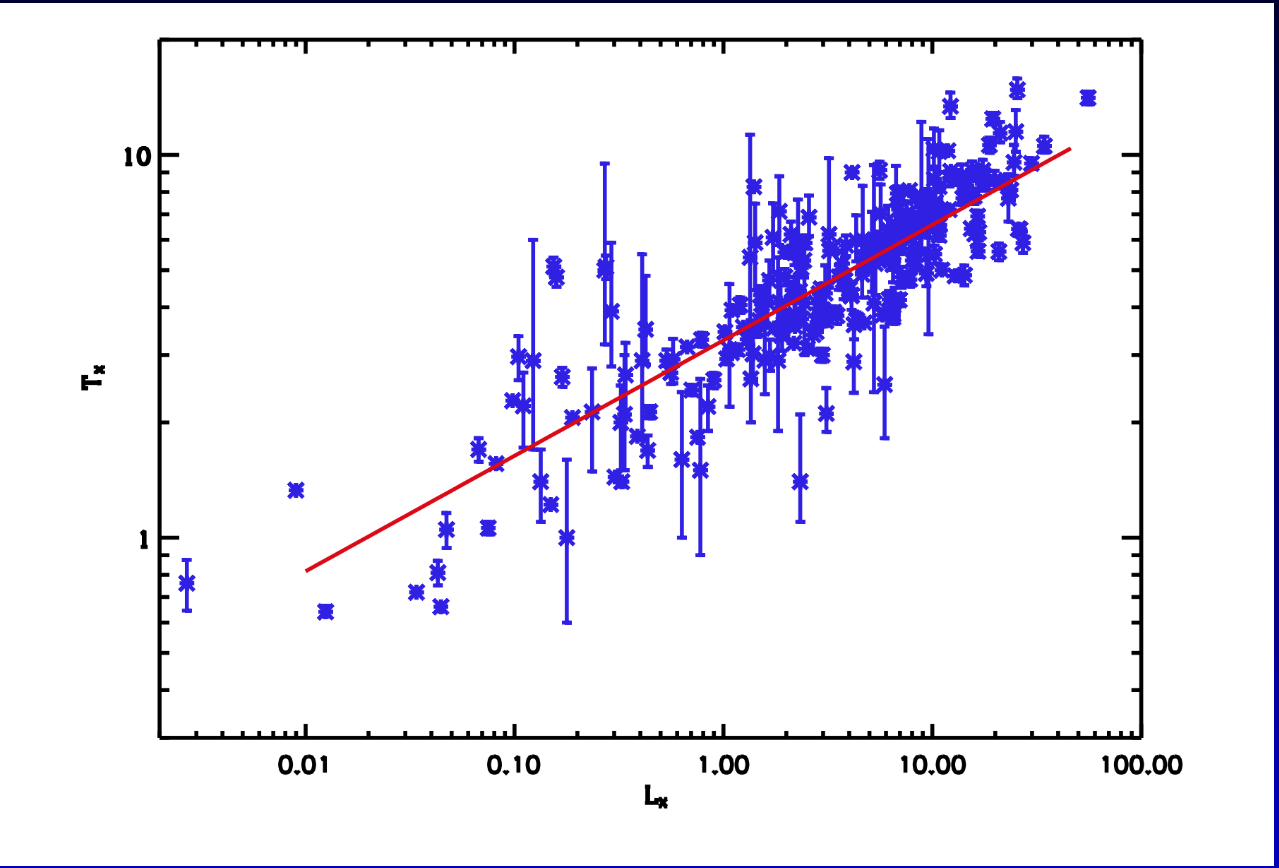
Gas in clusters needs extra heating and scaling law is not expected to hold for L_x (not with M and thereby not with z).

From mass to observables: troubles...



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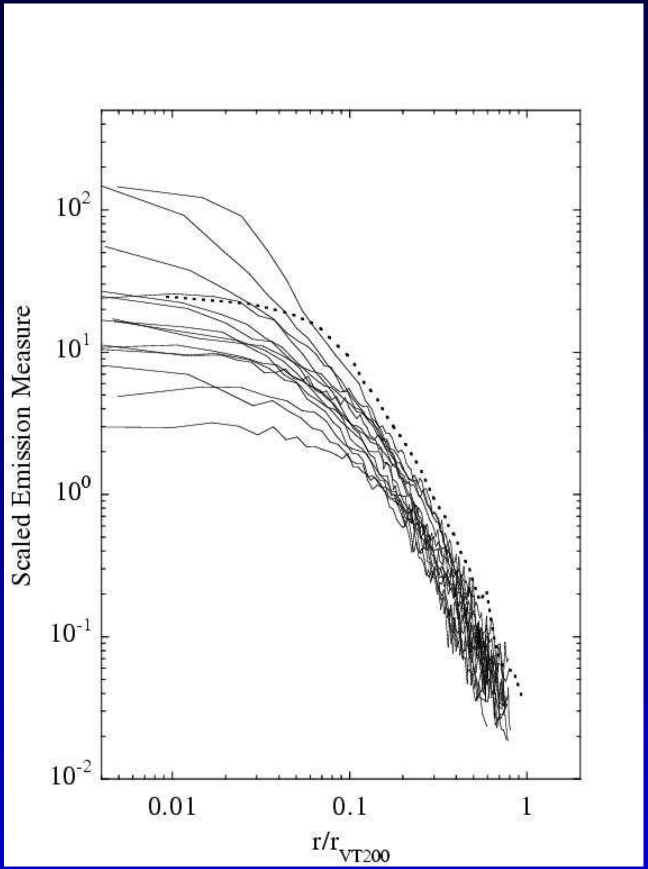

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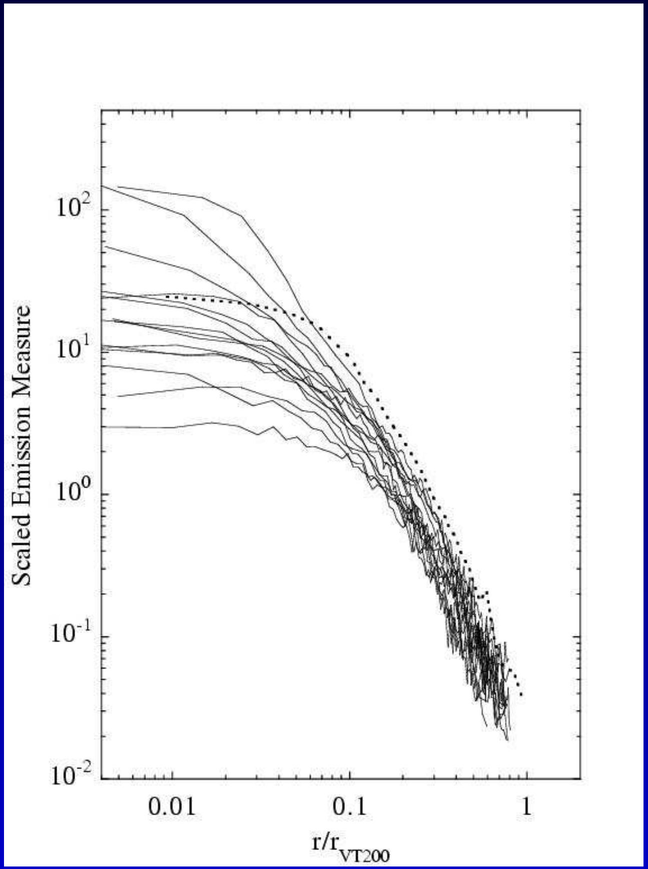

So clusters may be self-similar after all...

Sunyaev-Zeldovich

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$$Y = K M_g T_g D_a^{-2} \tag{1}$$

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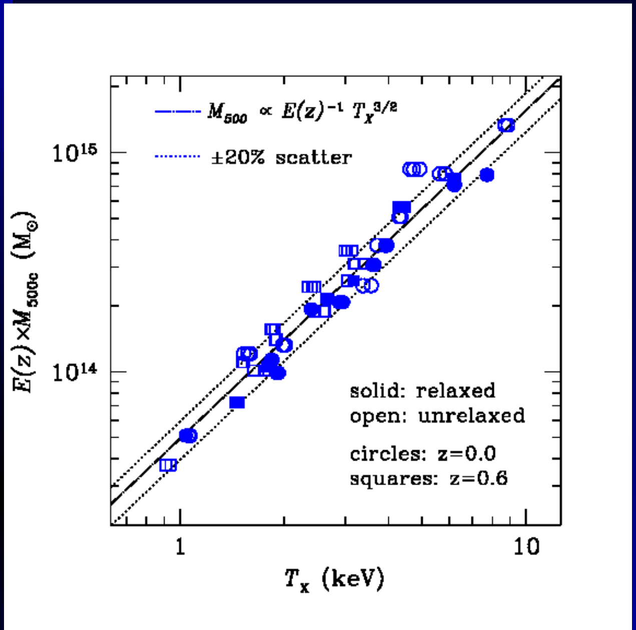
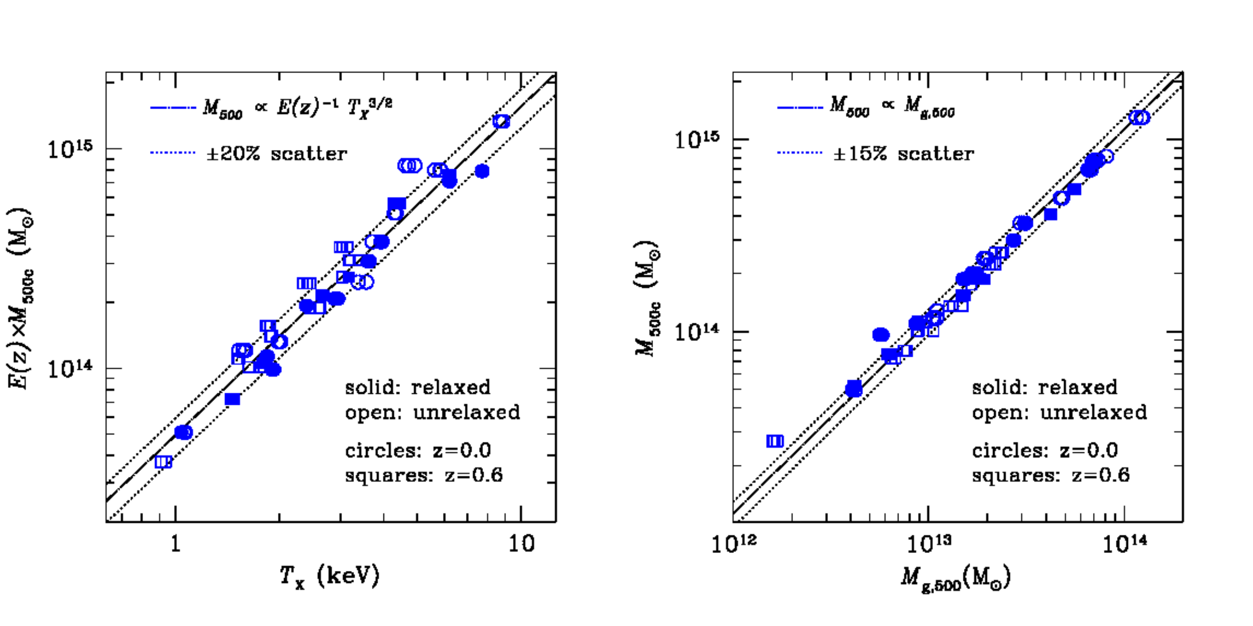
Better mass proxy (Barbosa al., 1997)

Sunyaev-Zeldovich



(Kravtsov, Vikhlinin, Nagai 2006)

Sunyaev-Zeldovich



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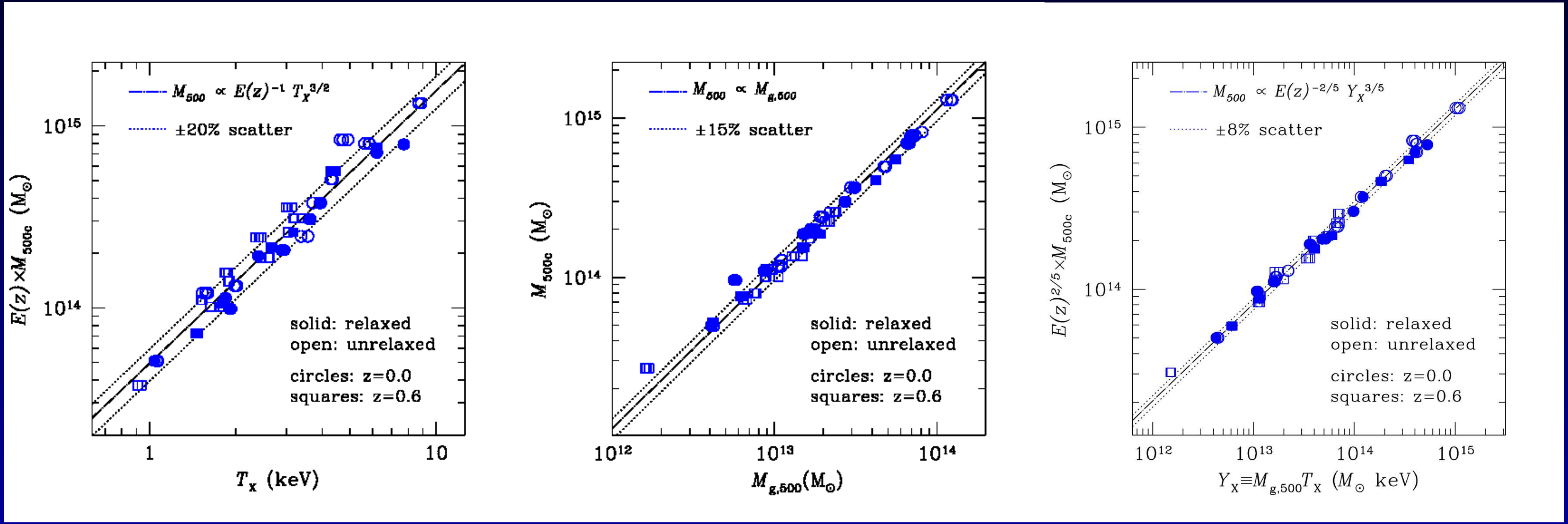

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Sunyaev-Zeldovich

$$Y = K M_g T_g D_a^{-2} \quad (2)$$

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Sunyaev-Zeldovich

(2)
$$Y = K M_g T_g D_a^{-2}$$

Independent of the gas geometry, clumping, ...
Better mass proxy (Barbosa al., 1997)
Leading to the scaling law

$$Y = \kappa \xi A_{TM} f_B M^{5/3} h^{8/3} \left(\Omega_M \frac{\Delta(z, \Omega_M)}{178} \right)^{1/3} (1+z) D^{-2}$$

where $\kappa = 1.816.10^{-4}$ and ξ accounts for the difference between T_x and T_g.

Sunyaev Zeldovich

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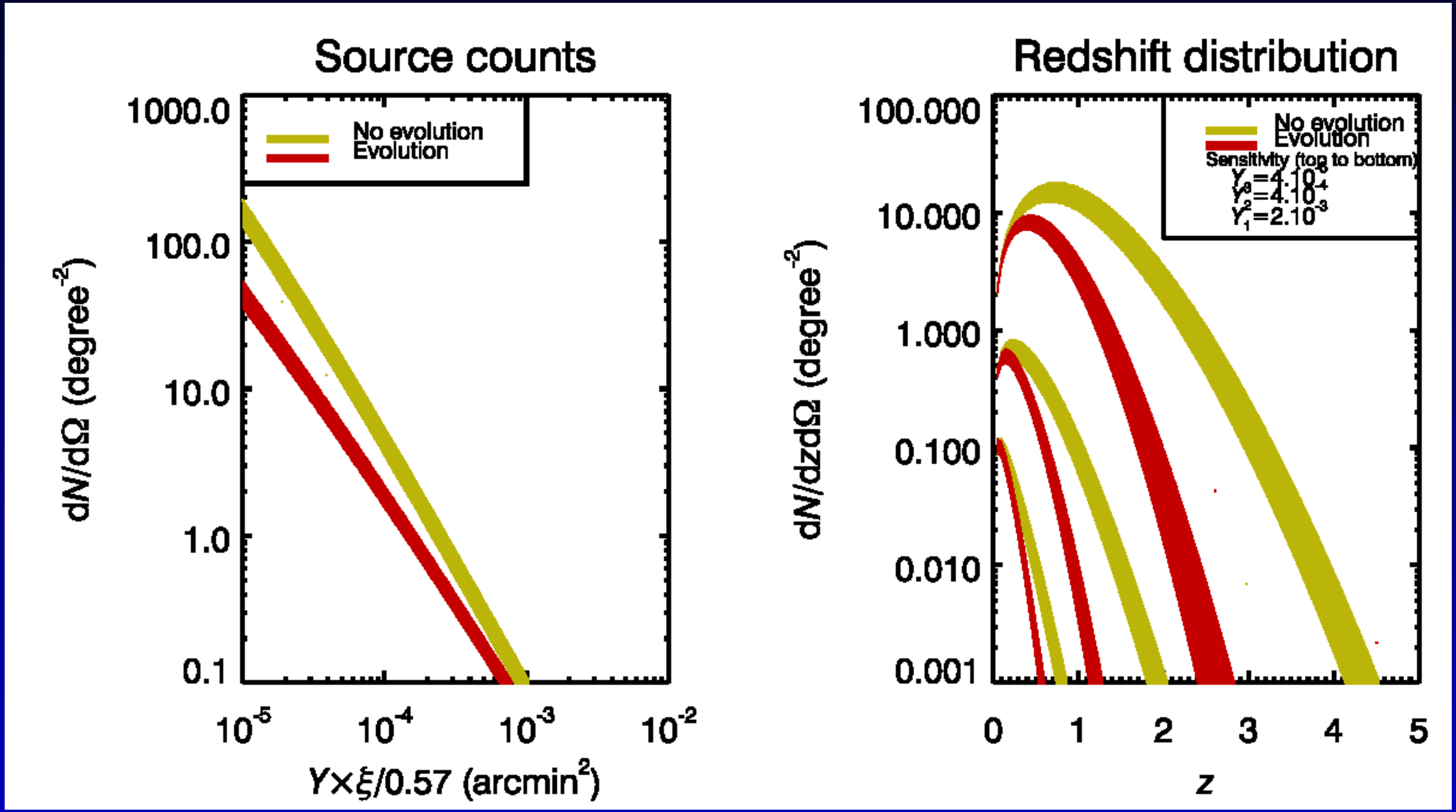

Planck cluster-CMB tension

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The analysis of Planck CMB data provides high precision constraints on (most) cosmological parameters.

Planck cluster-CMB tension

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Table 4. Parameter 68 % confidence limits for the base ΛCDM model from *Planck* CMB power spectra, in combination with lensing reconstruction ("lensing") and external data ("ext," BAO+JLA+H_0). Nuisance parameters are not listed for brevity (they can be found in the *Planck Legacy Archive* tables), but the last three parameters give a summary measure of the total foreground amplitude (in μK^2) at $\ell = 2000$ for the three high-ℓ temperature spectra used by the likelihood. In all cases the helium mass fraction used is predicted by BBN (posterior mean $Y_P \approx 0.2453$, with theoretical uncertainties in the BBN predictions dominating over the *Planck* error on $\Omega_b h^2$).

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086

...

Table 5. Constraints on 1-parameter extensions to the base ΛCDM model for combinations of *Planck* power spectra, *Planck* lensing, and external data (BAO+JLA+H_0, denoted "ext"). Note that we quote 95 % limits here.

Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	< 0.492	< 0.589	< 0.194
N_{eff}	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
Y_P	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$	$0.250^{+0.026}_{-0.027}$	$0.247^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.114	< 0.114	< 0.0987	< 0.112	< 0.113
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$

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Take the hydrostatic mass estimates for $M - T$

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Add an offset to the mass : $M_{HE} = (1 - b)M_{true}$
with $1 - b = 0.8$

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Compute the number of clusters expected in the ΛCDM model with the Planck selection function.

Planck SZ counts

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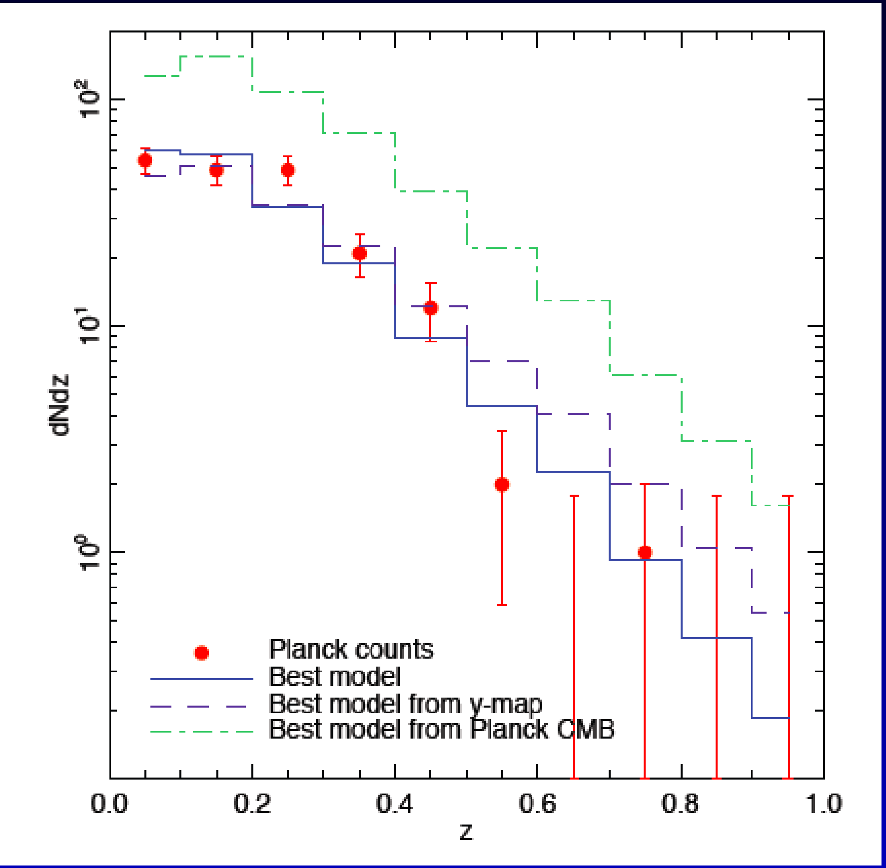

Planck CMB-cluster tension

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Clusters are not selected exactly as expected (selection function issue).

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This is the indication of new physics...