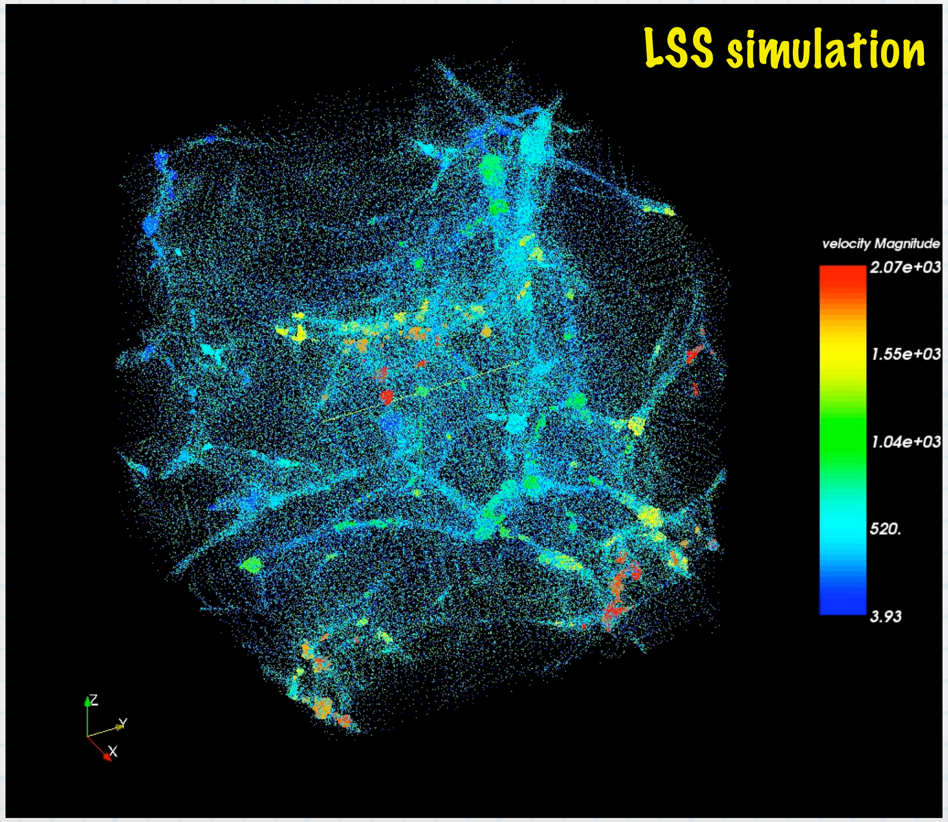
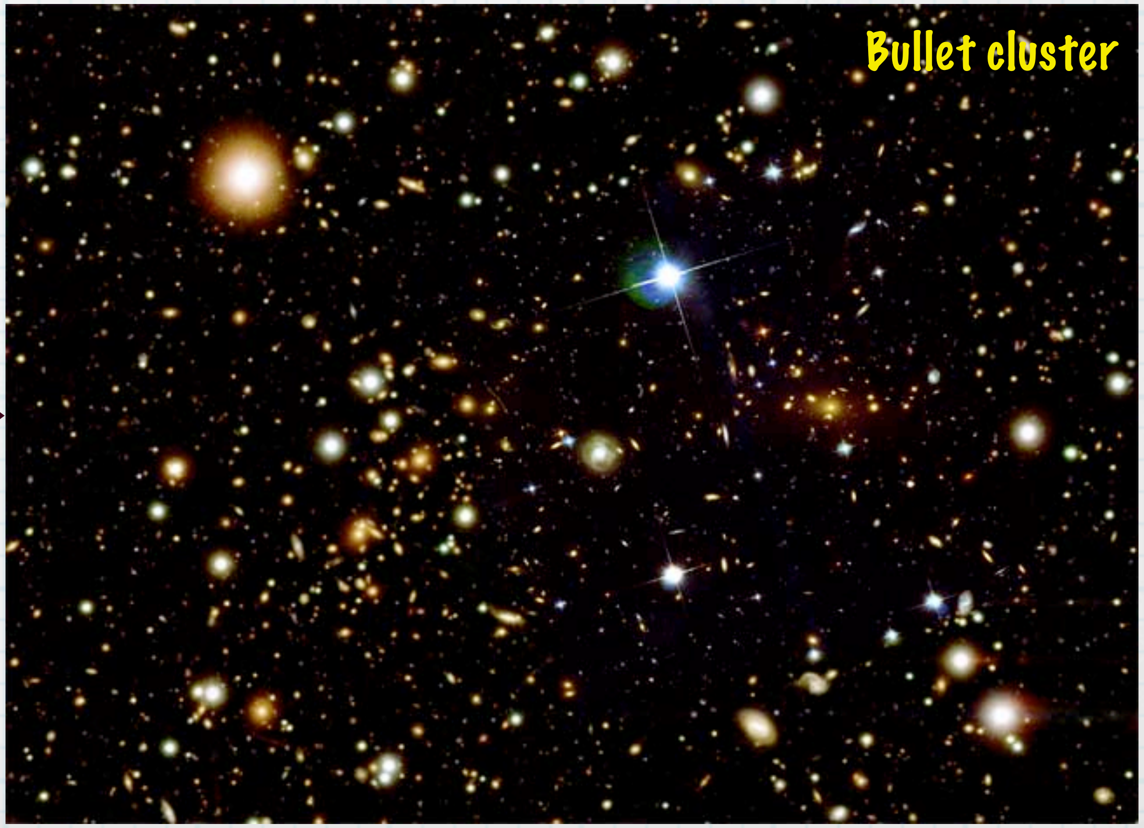
Cluster Cosmology: Opportunities & Challenges

Zarija Lukić (Los Alamos)
with
Ujjaini Alam, Suman Bhattacharya, Konstantin Borozdin, Katrin Heitmann, and Salman Habib

Talk plan

- Cluster cosmology outline
- Worked example: early vs. late dark energy
- Predictions for current and future cluster surveys
- Essential ingredient #1: the mass function
- Essential ingredient #2: mass-observable relations





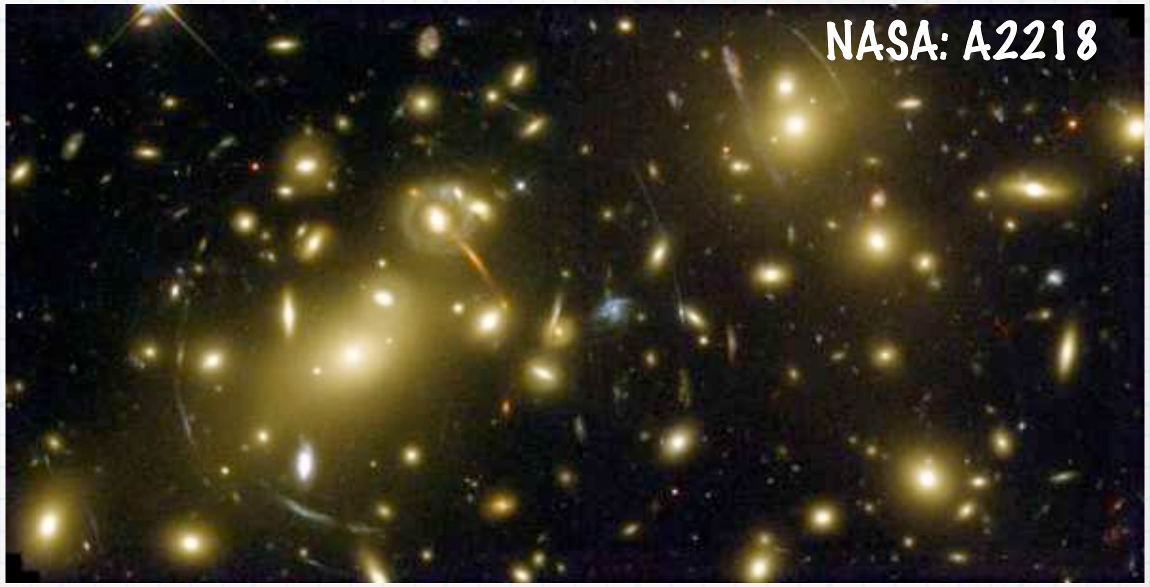
Cosmology & galaxy clusters

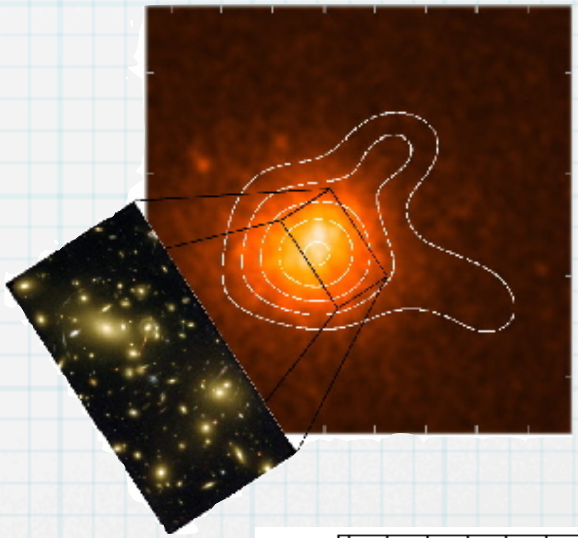
- Galaxy clusters are the heaviest and most recently assembled virialized objects.

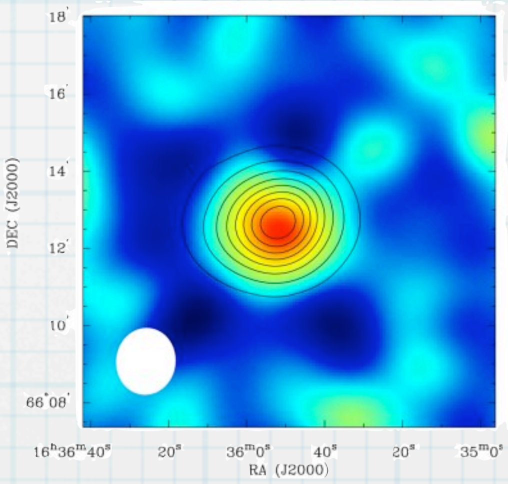
- Their abundance and spatial distribution are sensitive to cosmological parameters, and in particular the amount and properties of dark energy.

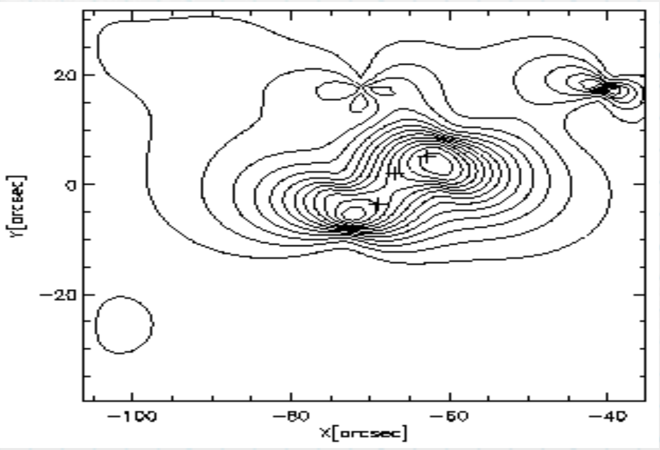
- Clusters can be observed in optical (galaxies), X-ray (diffuse gas), and microwave (SZ effect).

- Observational campaigns have just started, or will start soon (SPT, ACT, Planck, DES, VISTA, LSST, eROSITA).









Two cluster surveys

eROSITA wide survey:

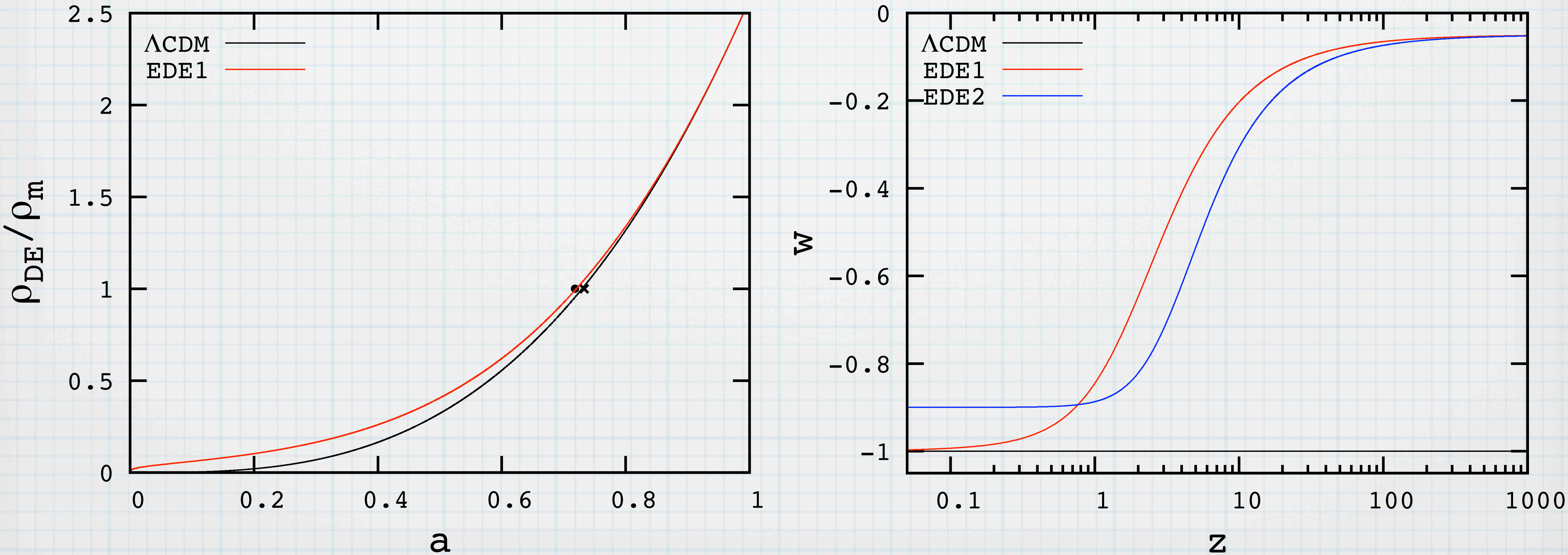
- X-ray emission
- Band: 0.5-5 keV
- Start date: 2012
- Sky coverage: 20,000 deg^2
- S_{min} = 3.3×10^{-14} $erg/cm^2 s$

South Pole Telescope:

- Sunyaev-Zel'dovich effect
- Band: 95/150/220 GHz
- Start date: 2008
- Sky coverage: 4,000 deg^2
- S_{min} = 10 μK

Early vs. late dark energy

- Standard cosmological scenarios imply that dark energy amount is negligible at high redshifts.
- However, if we abandon ΛCDM that need not be the case, and models where DE is 1% level or more of the total density we call EDE.
- Theory is not a good guide for what model is reasonable; observations show $\Omega_{DE} \ll 1$ for $z \gg 1$, and $w_0 \approx -1$.



Dark energy perturbations

- Self-consistent treatment of dark energy perturbations
  - Consider DE as an additional fluid:

$$ds^2 = a^2(\eta)\left[(1+2\Psi(\mathbf{x},\eta))d\eta^2 - (1+2\Phi(\mathbf{x},\eta))\delta_{\alpha\beta}dx^\alpha dx^\beta\right]$$

$$\delta_i' = -3\mathcal{H}(c_{s,i}^2 - w_i)\delta_i - \left[1+3\mathcal{H}(c_{s,i}^2 - c_{a,i}^2)\right](1+w_i)\frac{v_i}{k} - 3(1+w_i)\Psi'$$

w≠-1 perturbations!

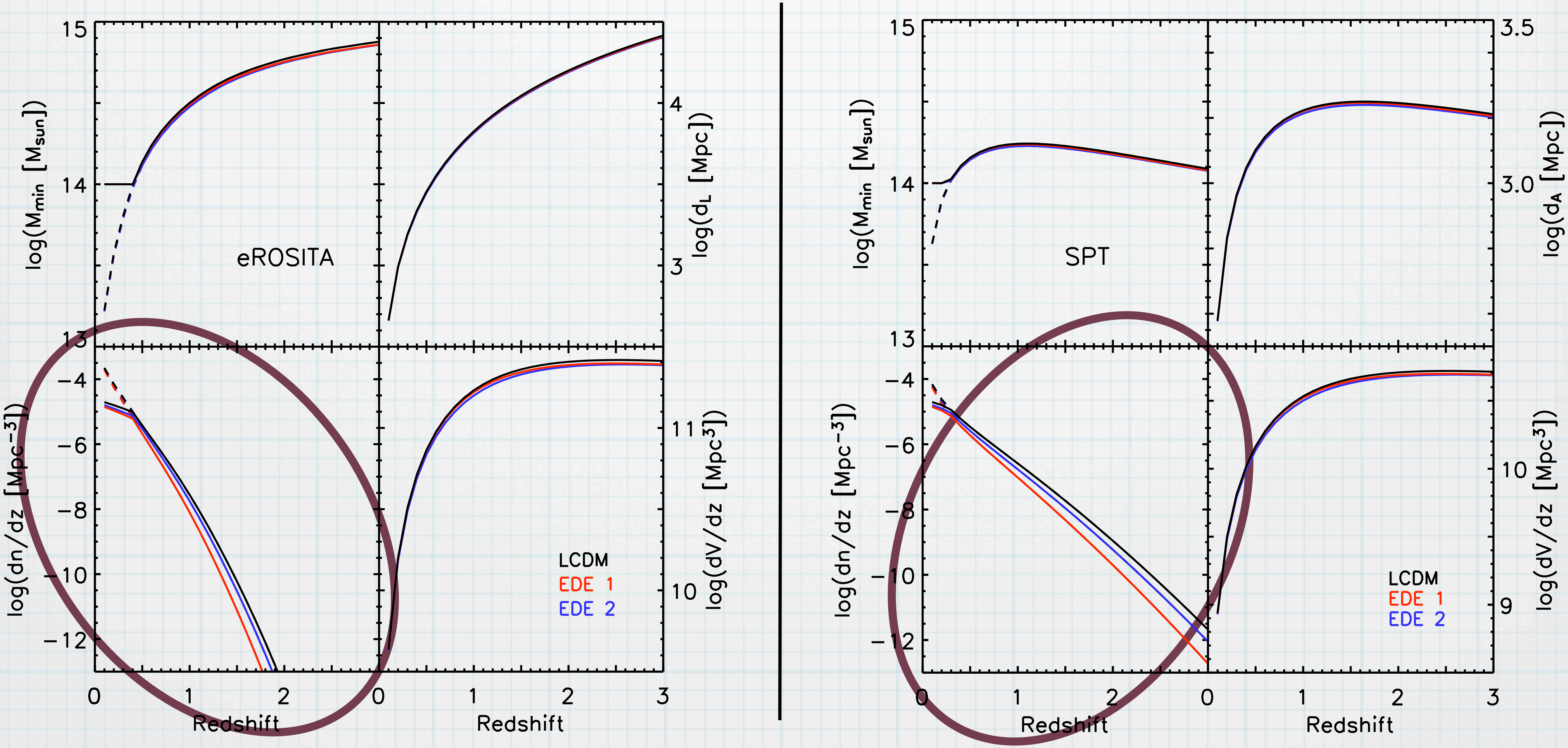
$$v_i' = -\mathcal{H}(1-3c_{s,i}^2)v_i + \frac{kc_{s,i}^2}{(1+w_i)}\delta_i - kA$$

$$\eta = \int_0^t \frac{dt'}{a(t')} \; ; \qquad \mathcal{H} = \frac{a'}{a} \; ; \qquad c_{a,i}^2 = \frac{\partial p_i}{\partial \rho_i}$$

X-ray vs. SZ survey

ΛCDM: WMAP7+BAO+H_0 (Komatsu et al. 2009)

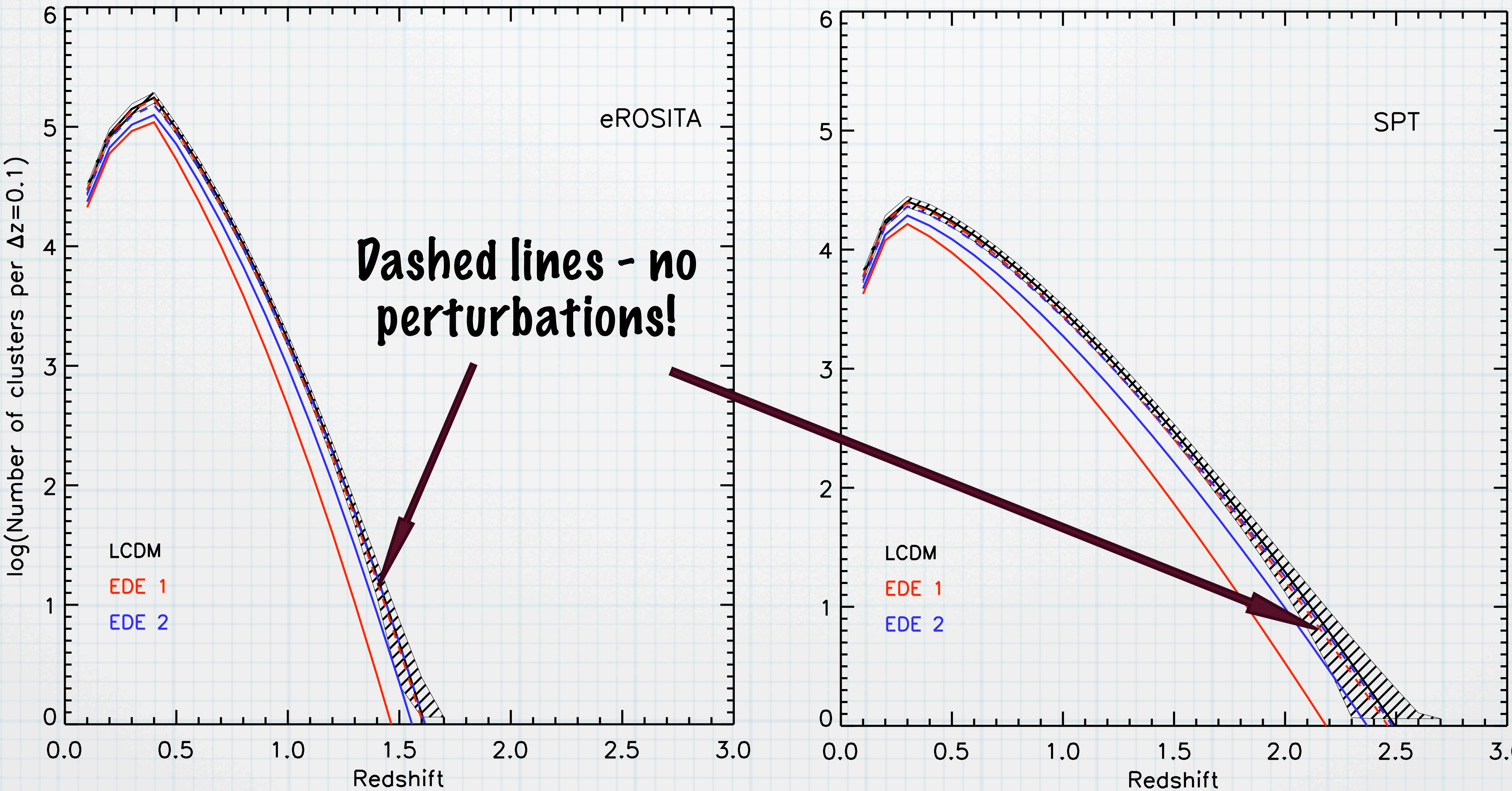
EDE1: w_0=-1, EDE2: w_0=-0.9 edge of current EDE constraints (Alam 2010)



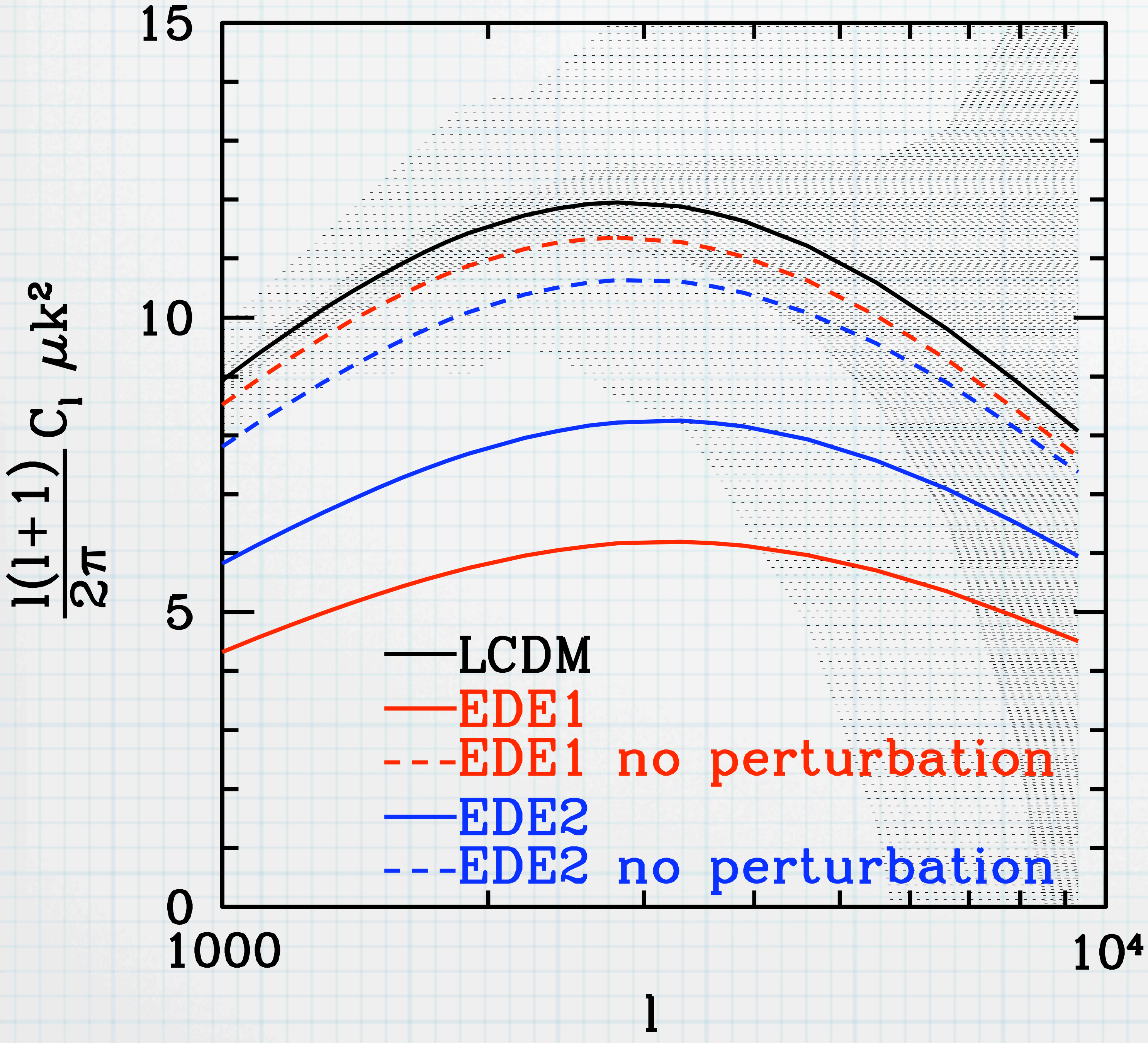
Cosmological sensitivity comes mostly from comoving abundance!

Cluster counts

- EDE models not ruled out by current data can be ruled out using cluster counts. Constraints on transition redshift!



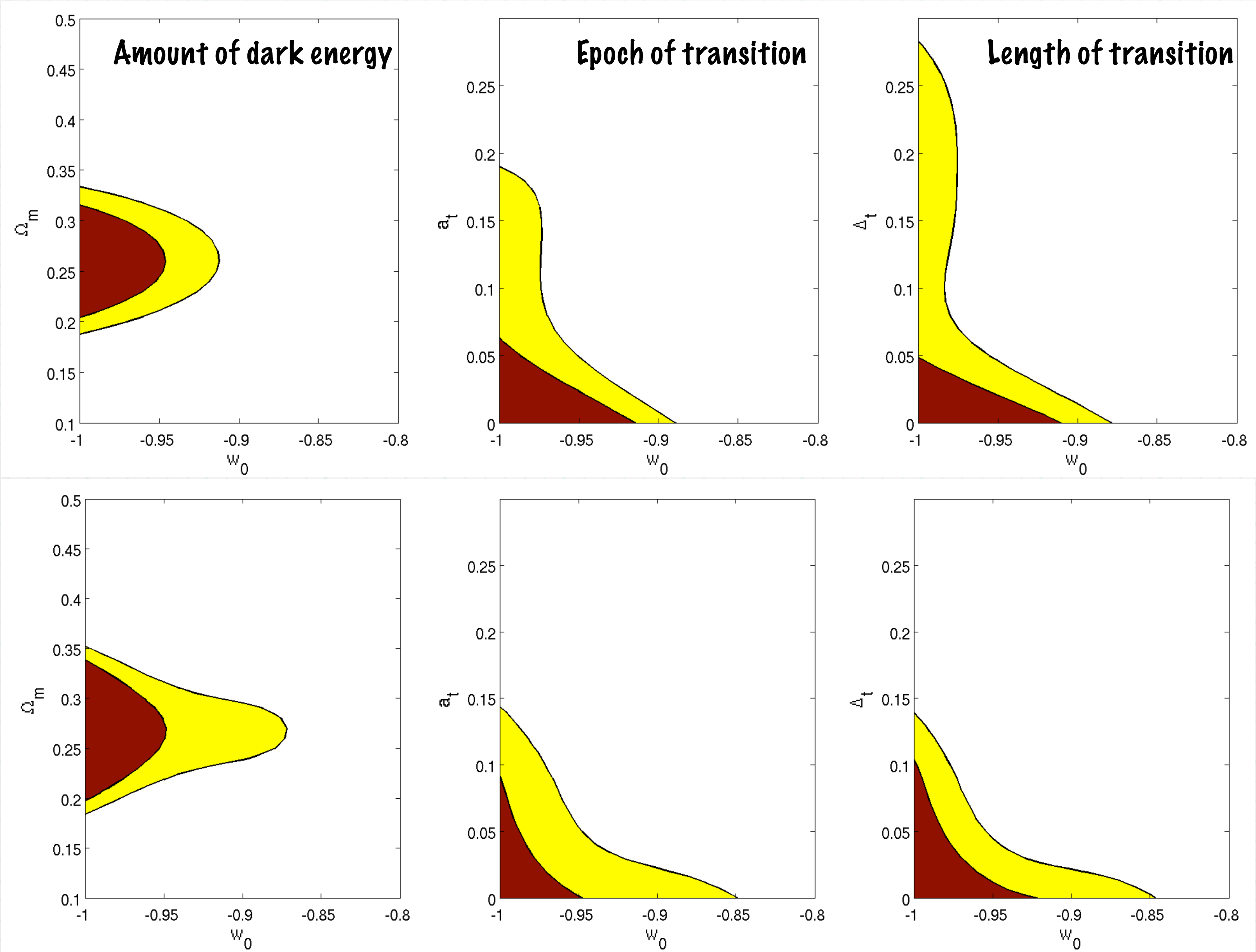
SZ power spectrum



- CMB signal at few arcminutes scales.
- At high-l, most sensitive to group of galaxies mass range ($M<10^{14}\ M_{sun}$).
- Planck full sky survey and SPT/ACT.
- Perfect removal of contaminants (e.g. radio loud galaxies), as well as perfect removal of primary CMB.

Alam, Lukić and Bhattacharya 2011

MCMC analysis



Cluster counts
+
CMB

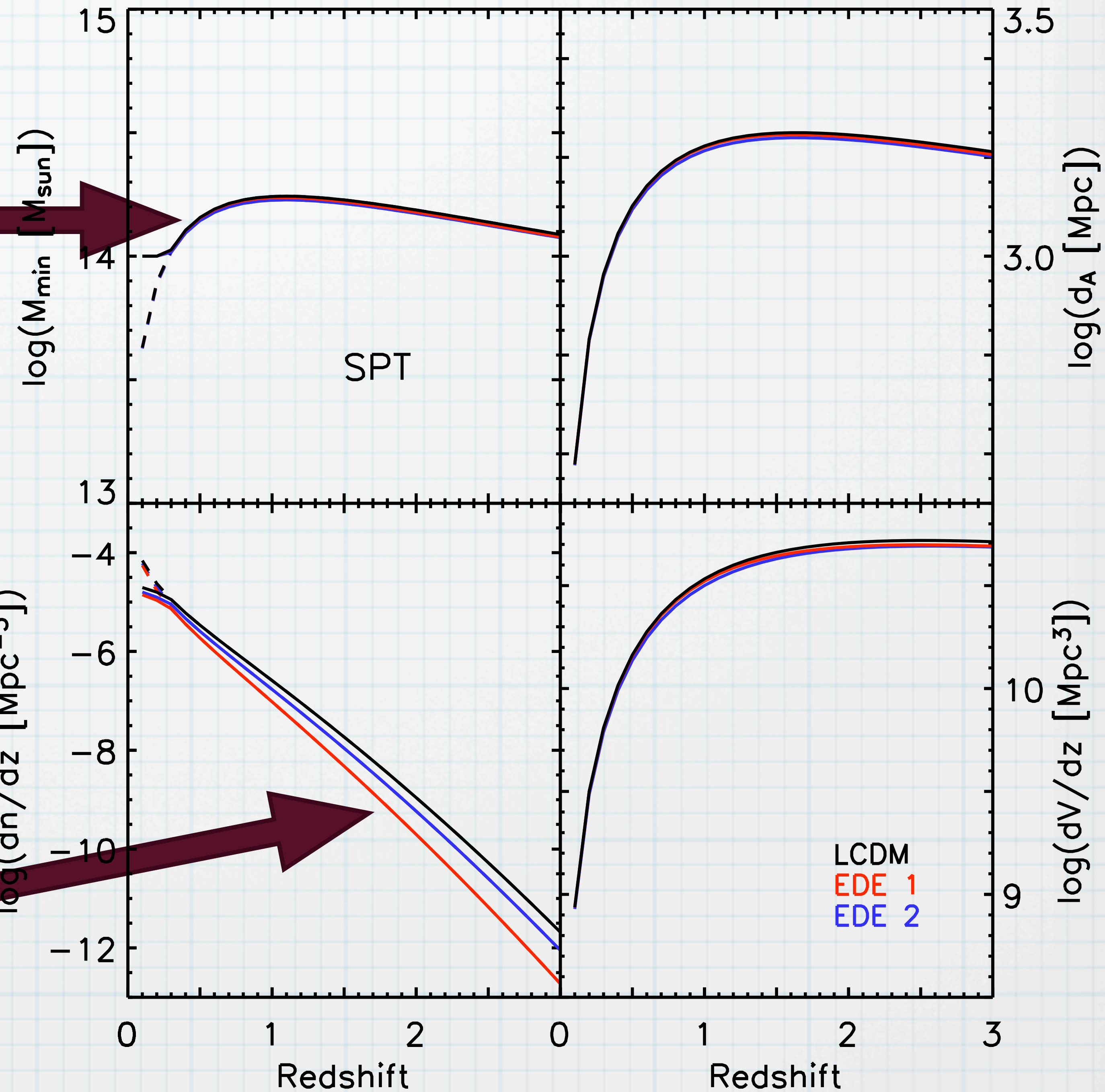
SZ P(k)
+
CMB

Alam, Lukić and Bhattacharya 2011

Theoretical components

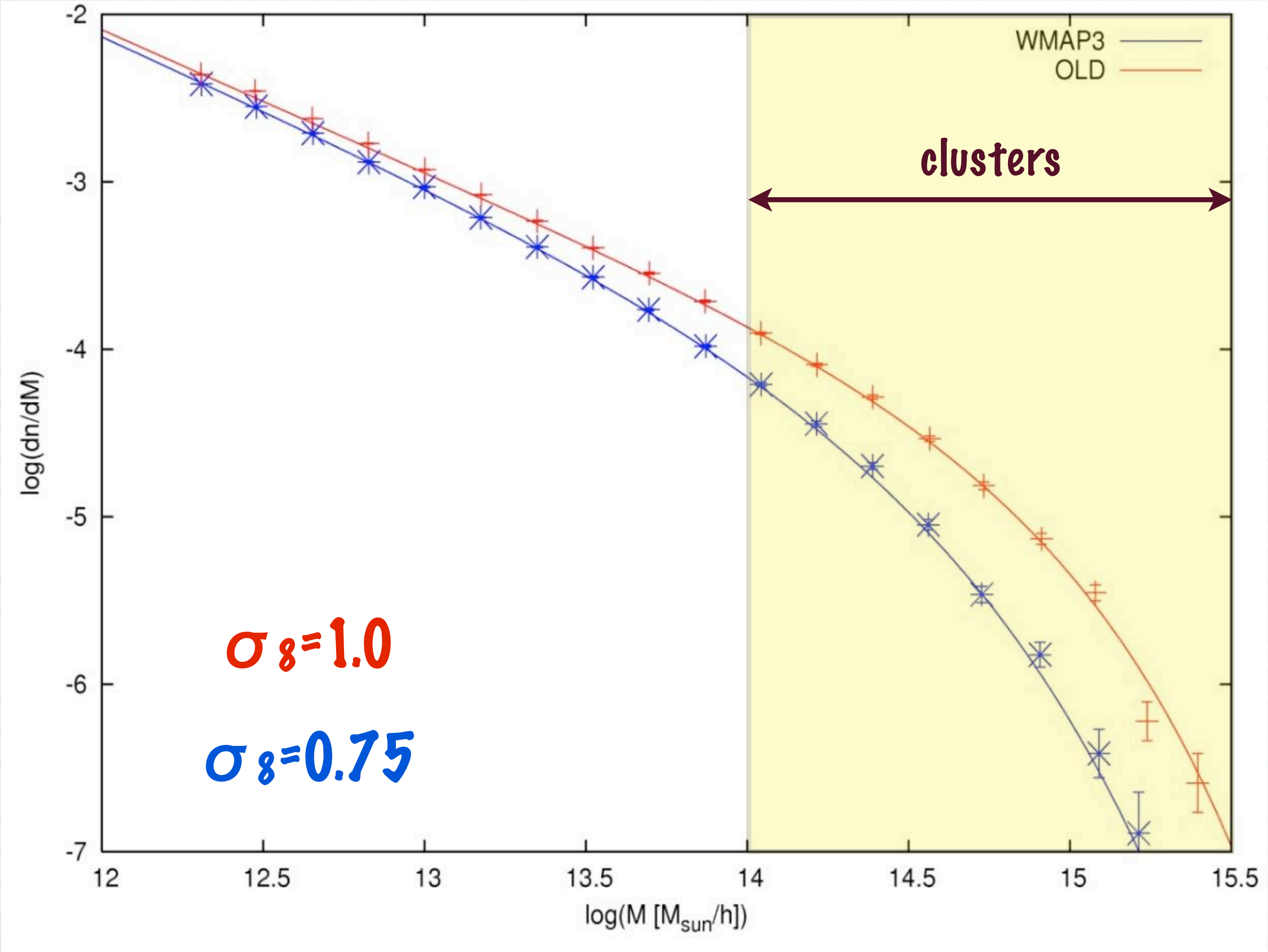
- To determine M_{min} we need to know how to calculate mass from a given observable.

- We need theoretical prediction for comoving abundance of clusters for any cosmology of interest.



Mass function: definitions

- Distribution of masses in the Universe: dn/dM



- Or in cosmology (and redshift) "independent" way (Jenkins et al. 2001, ≈20% accurate):

$$f(\sigma, z) \equiv \frac{d\rho/\rho_b}{d\ln\sigma^{-1}} = \frac{M}{\rho_b(z)} \frac{dn(M,z)}{d\ln[\sigma^{-1}(M,z)]}$$

$$\sigma^2(M,z) = \frac{d^2(z)}{2\pi^2}\int_0^\infty k^2 P_{\rm lin}(k) W^2(k,M) dk$$

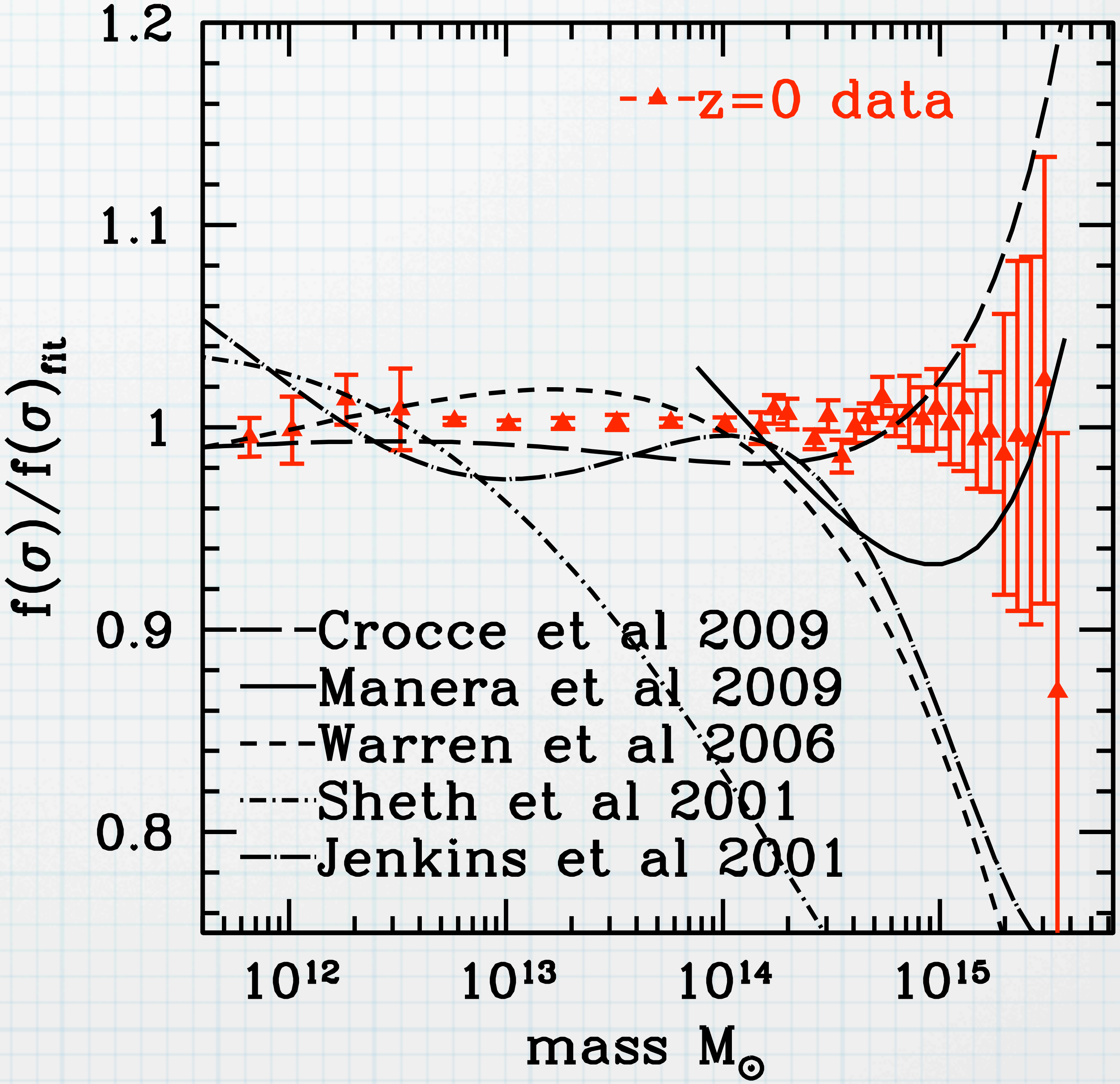
$$W(r) = \begin{cases} \frac{3}{4\pi R^3}, & r < R \\ 0, & r > R \end{cases}$$

$$W(k) = \frac{3}{(kR)^3}\left[\sin(kR) - kR\cos(kR)\right]$$

Precision issue

- In previous considerations we were looking for relative difference between cosmologies. But we do need to have absolute predictions to best-fit observations.

- To make it subdominant source of error MF has to be calibrated to about 1% (Wu et al. '10, Cunha & Evrard '10).

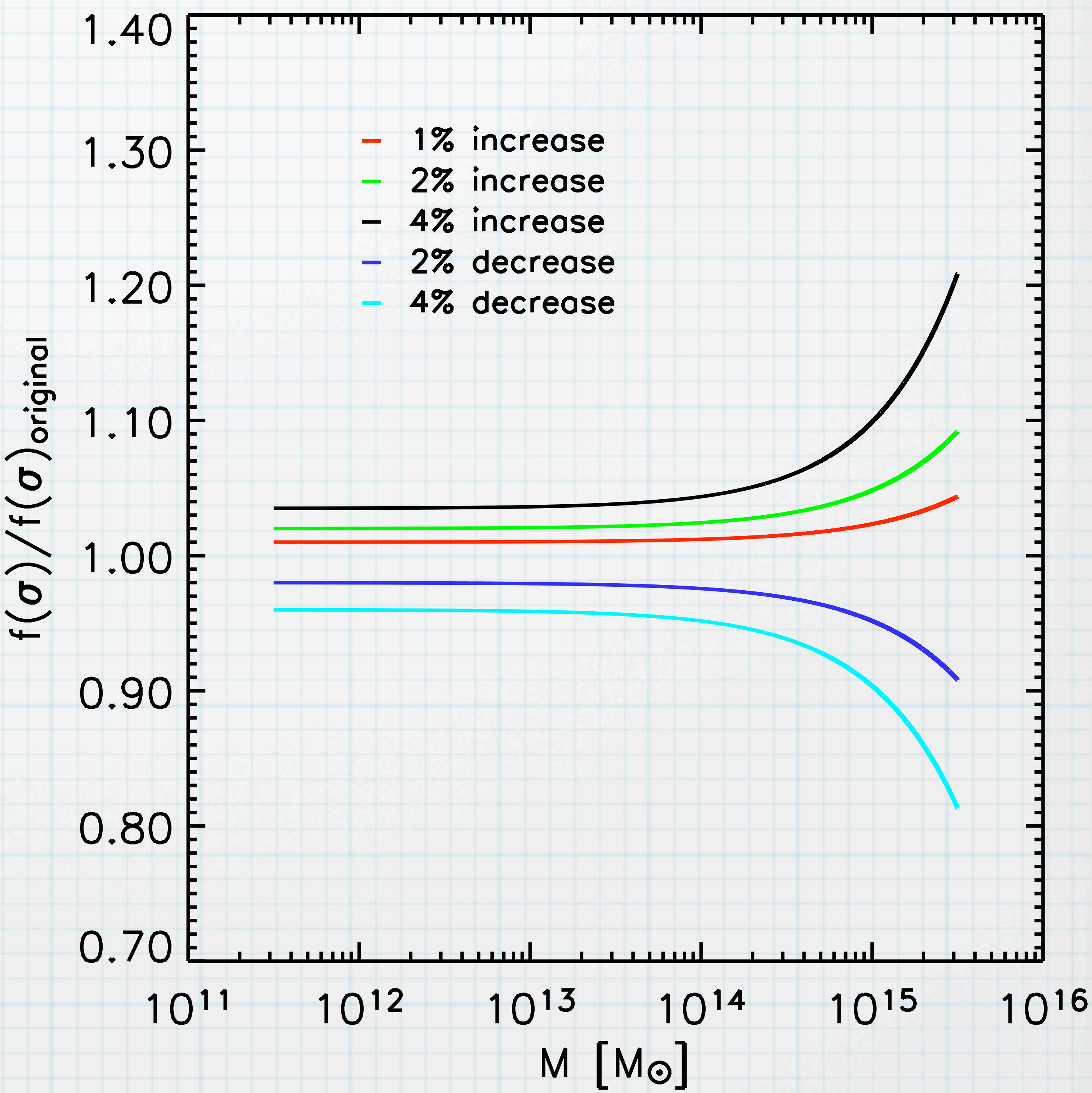


Precision issue

- In previous considerations we were looking for relative difference between cosmologies. But we do need to have absolute predictions to best-fit observations.

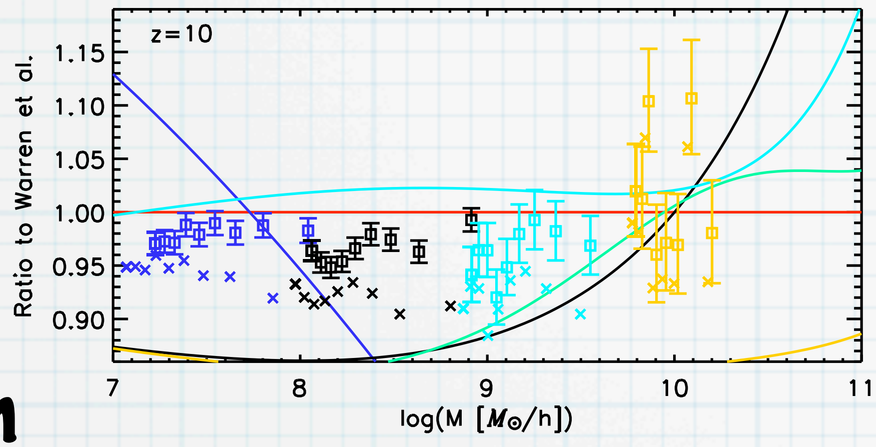
- To make it subdominant source of error MF has to be calibrated to about 1% (Wu et al. '10, Cunha & Evrard '10).

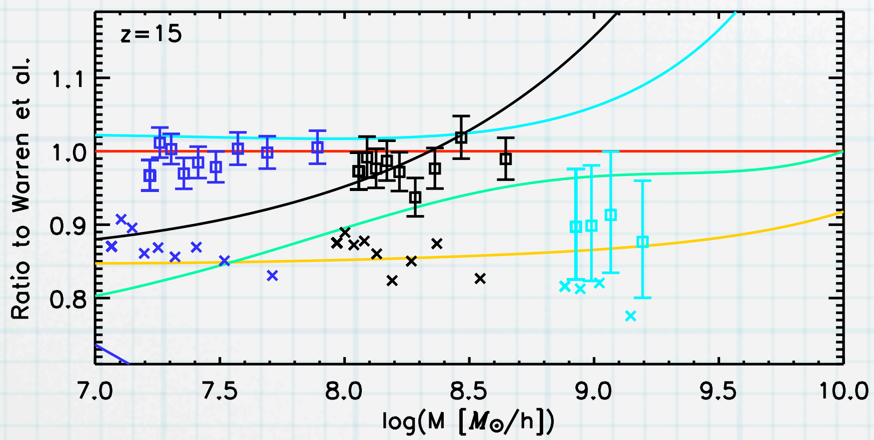
- Achieving that goal is difficult for the same reason that makes cluster counts a good cosmological probe: exponential sensitivity!



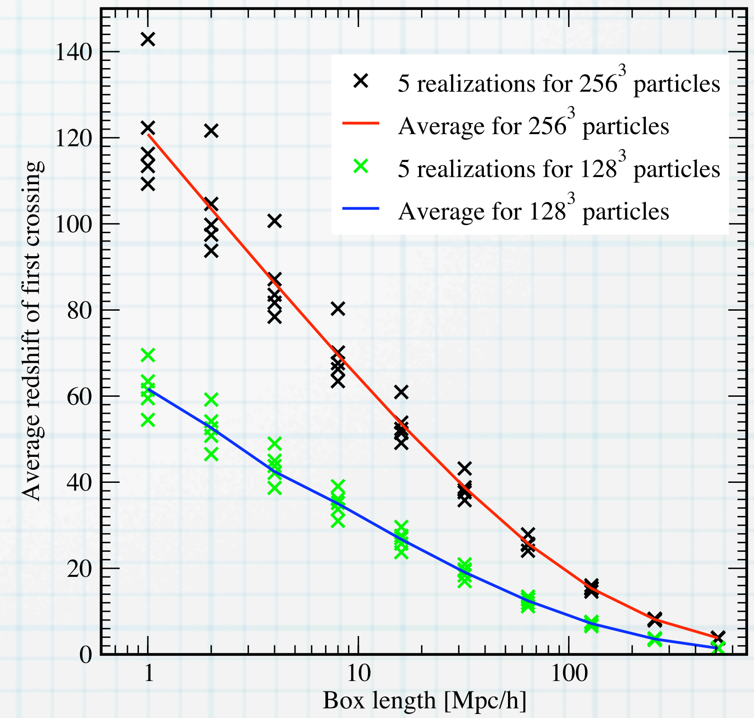
1% simulation challenge

- Finite simulation volume

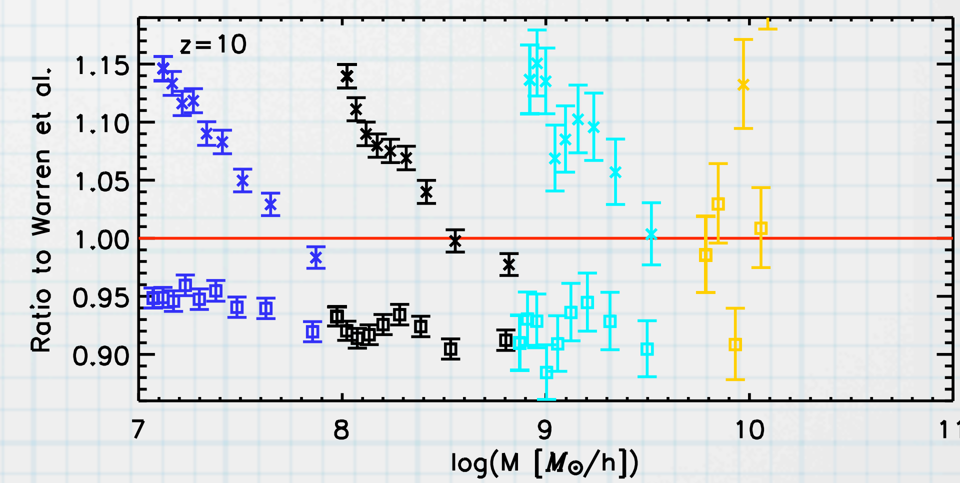


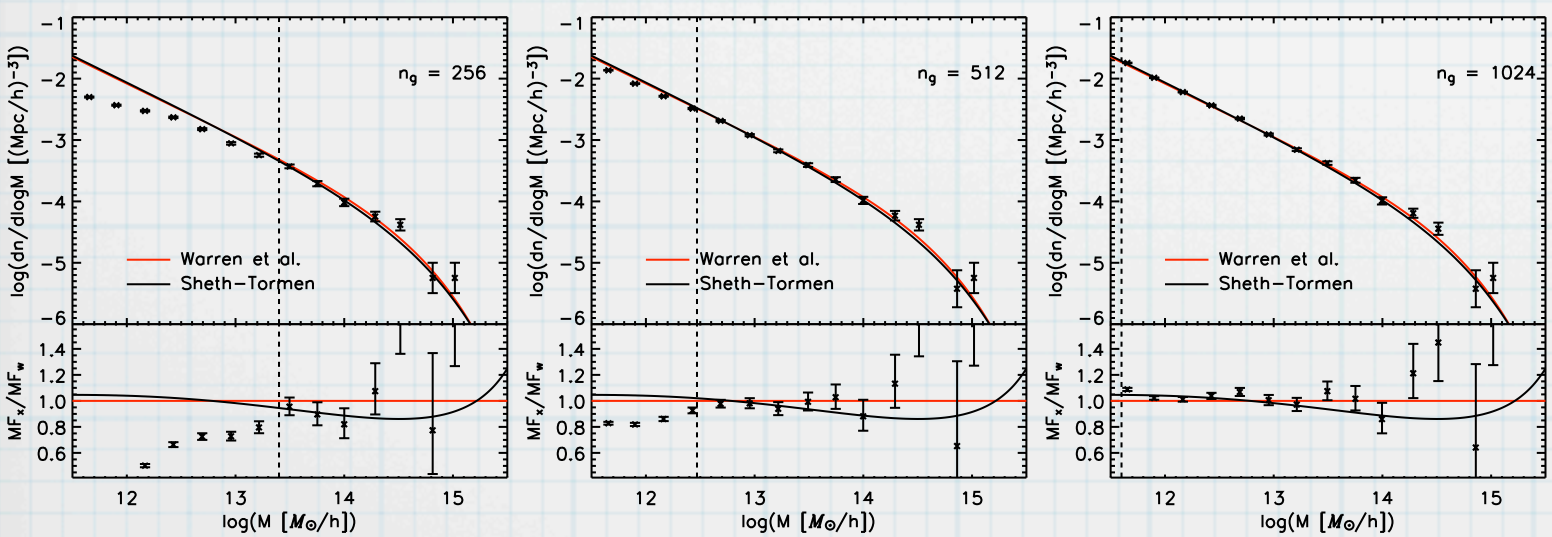


- Starting redshift



- Mass resolution

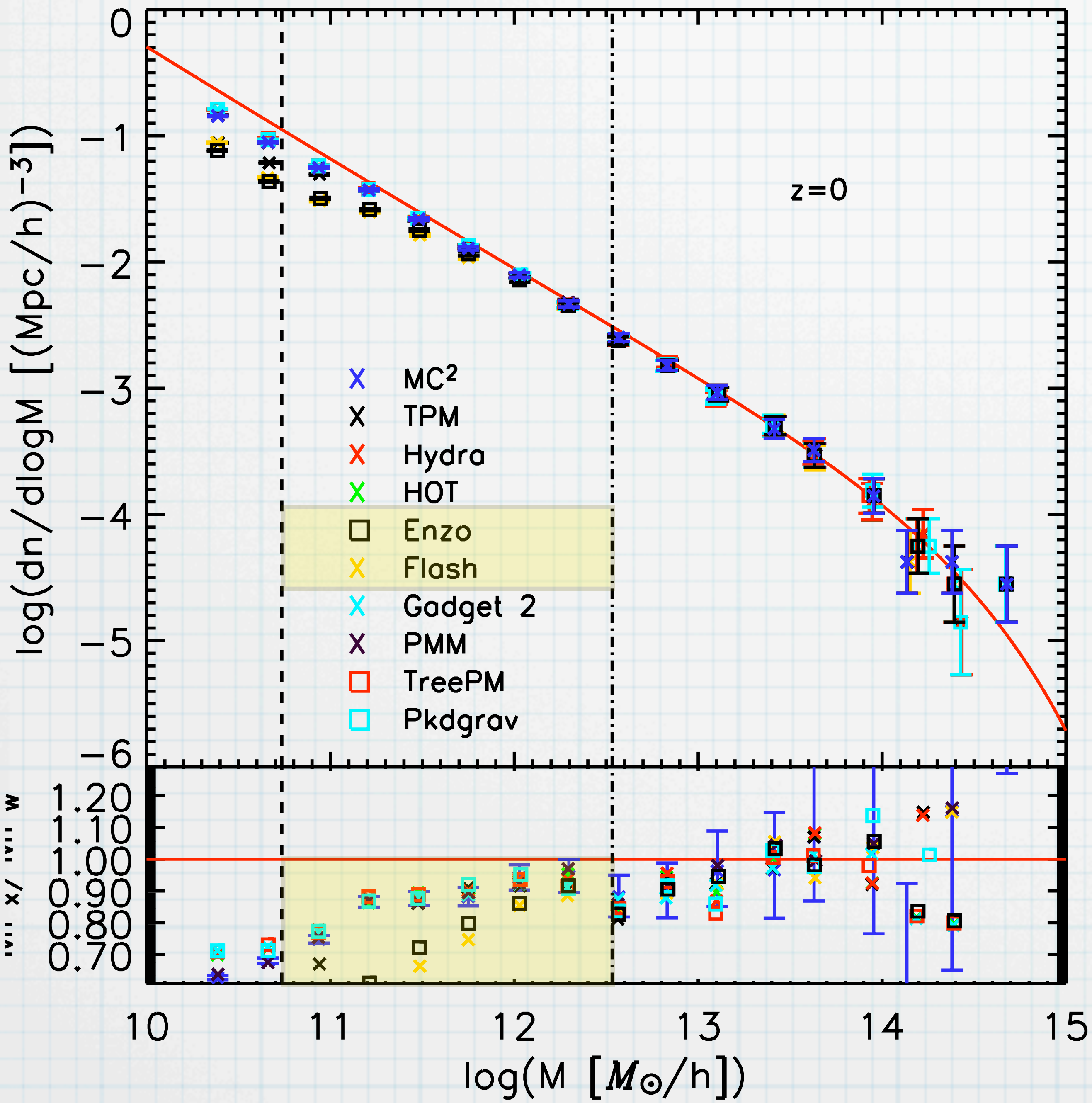




- Force resolution

(Lukić et al. 2007)

Force resolution & AMR



Heitmann et al. 2009

- Criterion from Lukić et al. 2007:

$$\frac{\delta_f}{\Delta_p} < 0.62 \left[\frac{n_h \Omega(z)}{\Delta}\right]^{1/3}$$

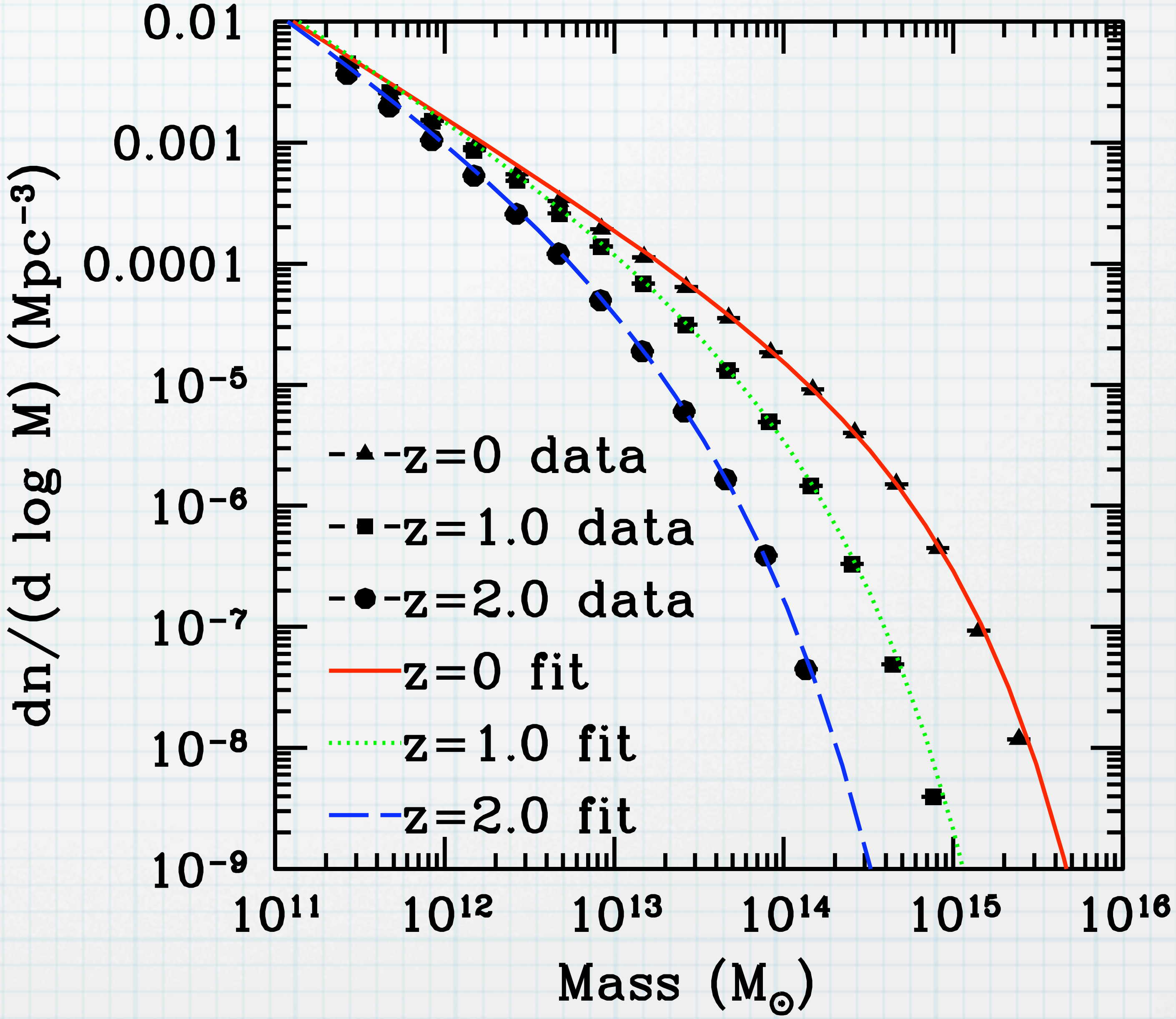
- Ability to capture all objects of certain mass is determined by the base grid, not amount of subsequent refinements!

- (Ability to resolve inner structure of halos depends on refinements.)

Halo mass function

Bhattacharya et al. 2010:

- 30 ΛCDM (close to WMAP) simulations
- TreePM codes (high-res)
- 5 different box sizes
- Total volume 220 Gpc^3
- Halos with 500+ particles



Best fit:
(4 parameters)

$$f(\sigma, z) = A\sqrt{\frac{2}{\pi}} \exp\left[-\frac{a\delta_c^2}{2\sigma^2}\right]\left[1 + \left(\frac{\sigma^2}{a\delta_c^2}\right)^p\right]\left(\frac{\sqrt{a}\delta_c}{\sigma}\right)^q$$

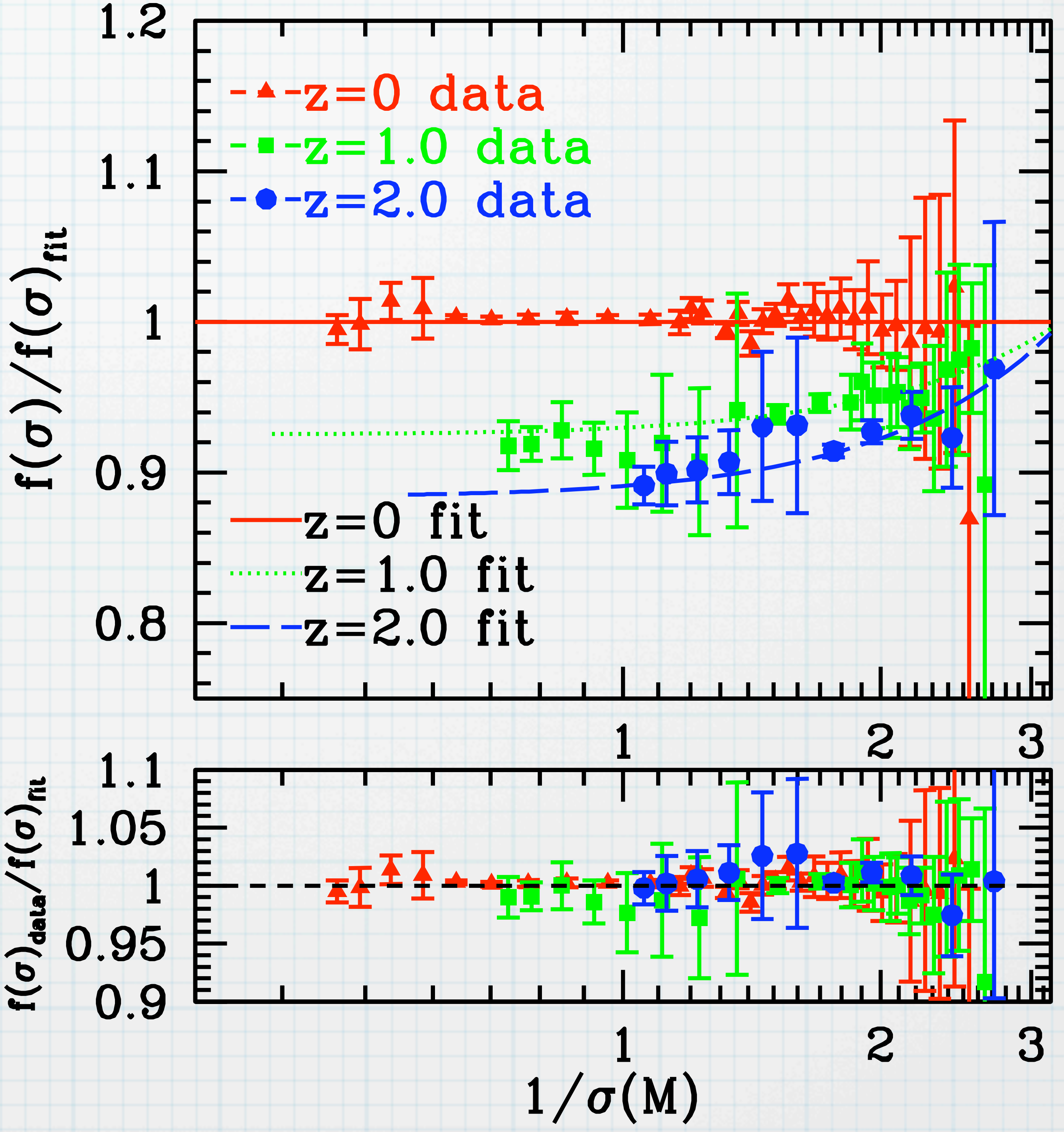
Redshift evolution

- For practical applications, it is actually more important to have accurate mass function prediction for 0.2<z<2.5, rather than z=0.

$$C_i(z) = \frac{C_i(0)}{(1+z)^{\alpha_i}}$$

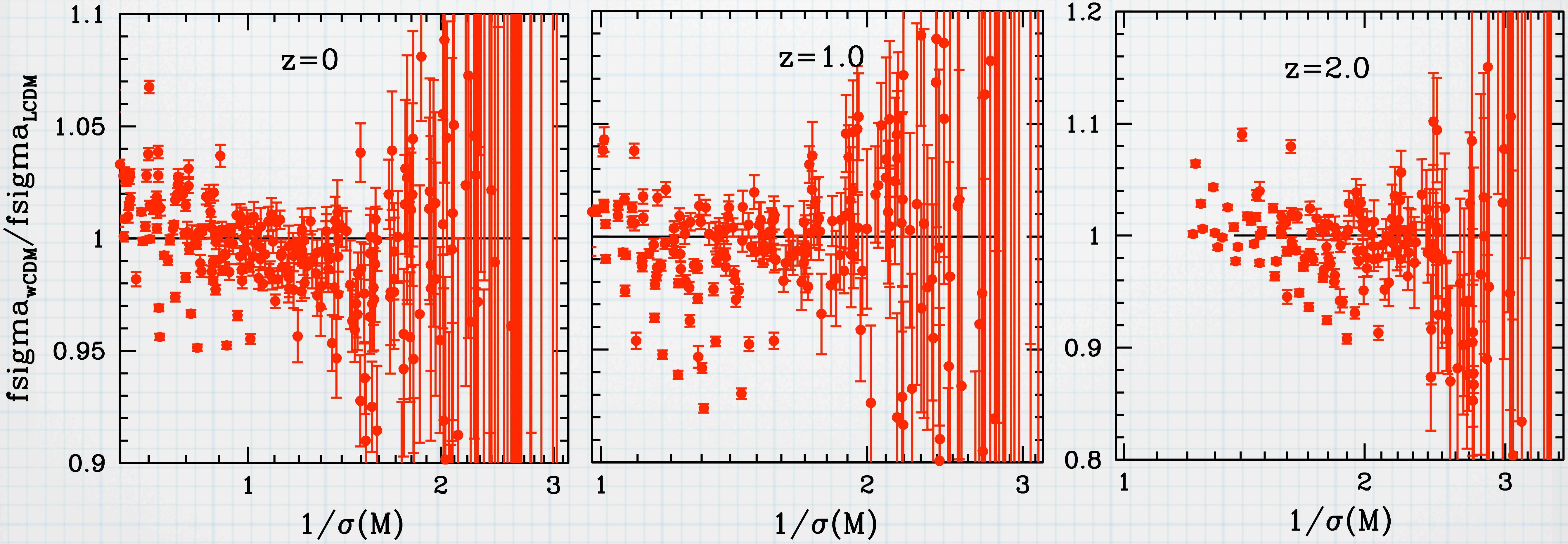
- 2 out of 4 parameters do not show time evolution.

- See also Tinker et al. 2008 in context of SO halos.



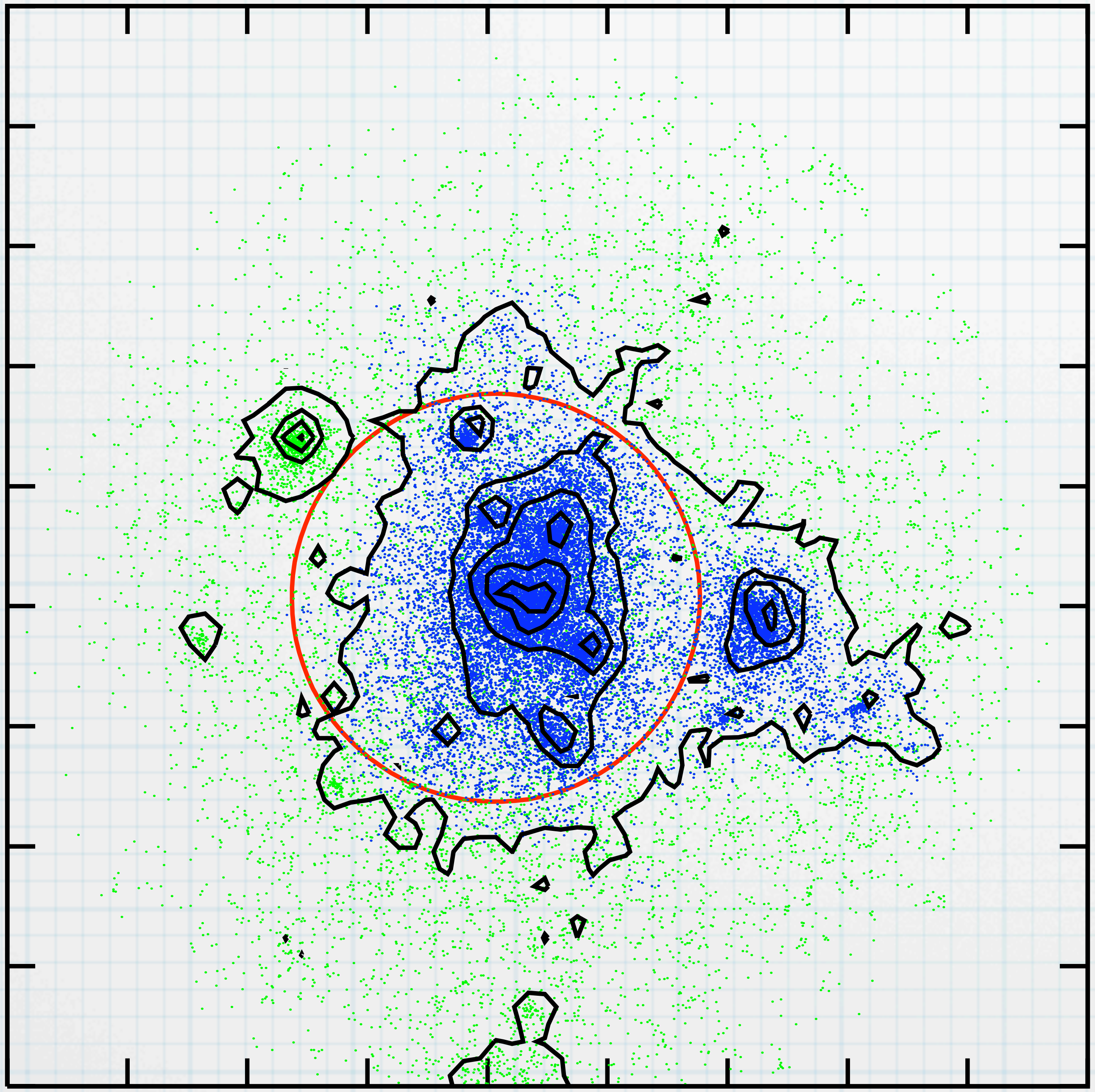
wCDM cosmologies

- 36 wCDM cosmologies sampling 5 parameters of interest: Ω_M, Ω_B, σ_8, w, n_s (Heitmann et al. 2009).
- Gadget-2, 1.3Gpc on a side, ≈$5 \times 10^{10} M_{sun}$ particle mass, 50kpc softening



Bhattacharya et al. 2010

Halo definitions



From simulation:

GREEN: all extracted particles

BLUE: particles in FoF halo

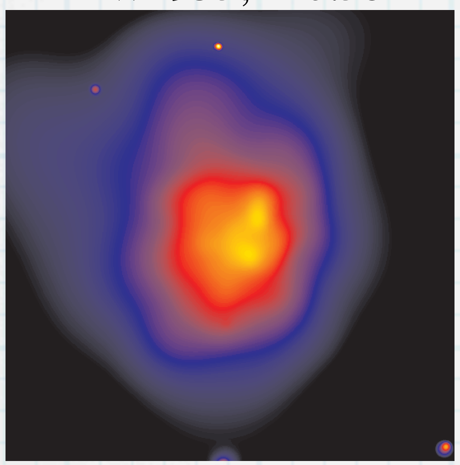
CIRCLE: overdensity radius R_{200}

CONTOURS: isodensity

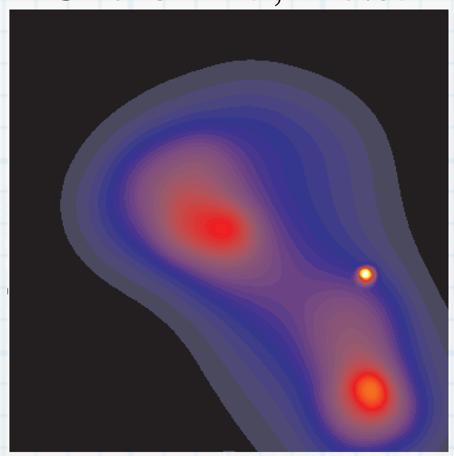
(Lukić et al. 2009)

Are clusters spheres?

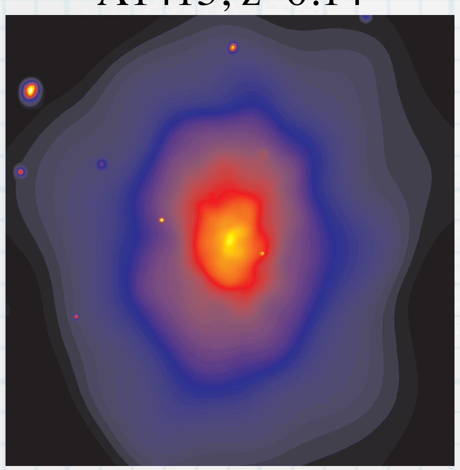
ZW1953, z=0.38



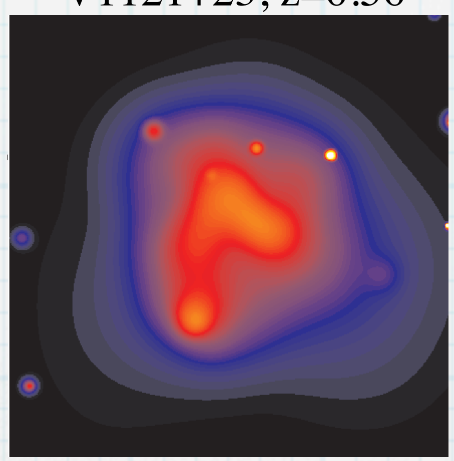
CL0152−13, z=0.83



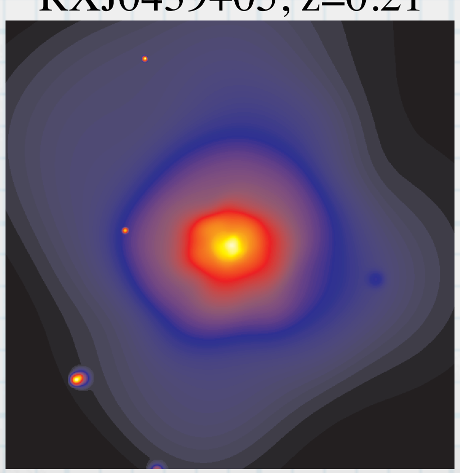
A1413, z=0.14



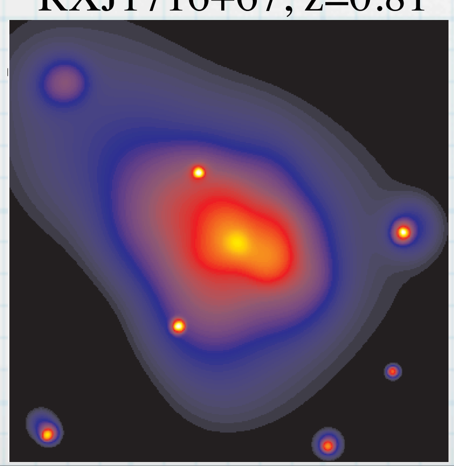
V1121+23, z=0.56



RXJ0439+05, z=0.21

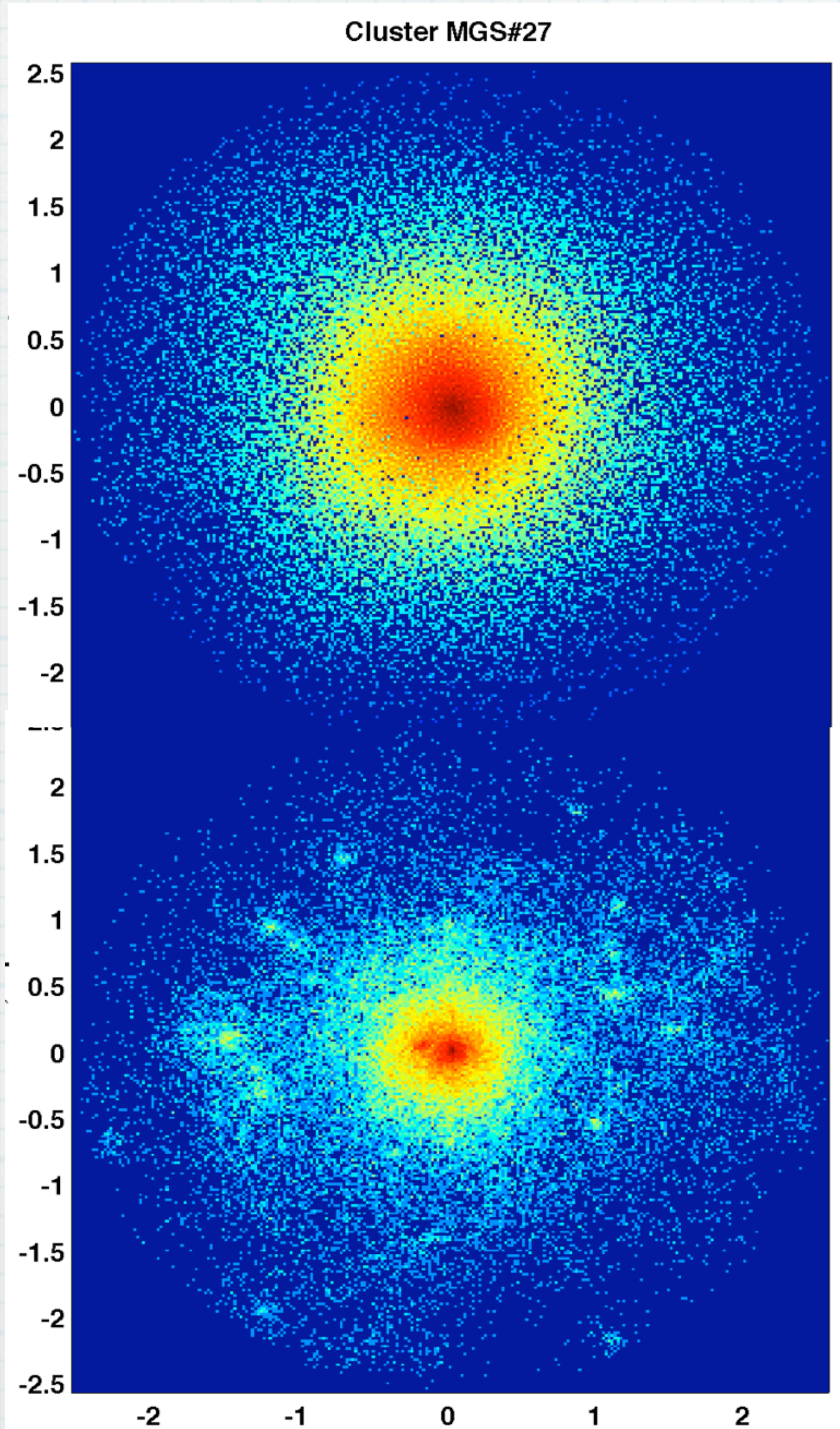


RXJ1716+67, z=0.81

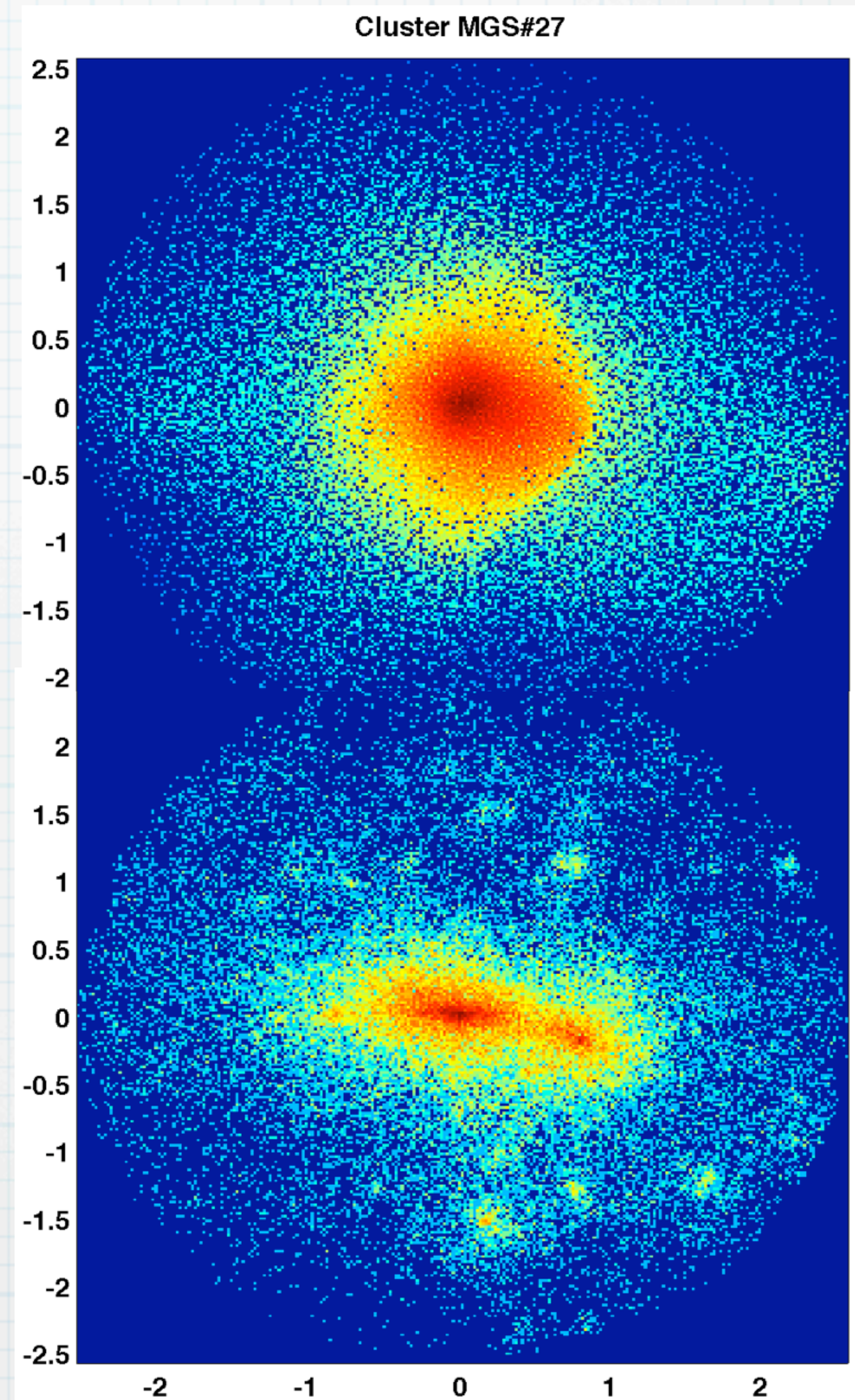


- Chandra observations, published in Jeltema et al. 2005.
- Clearly, clusters are not always round and relaxed.
- This is without even accounting for projection effects.

Projection effects



XY plane

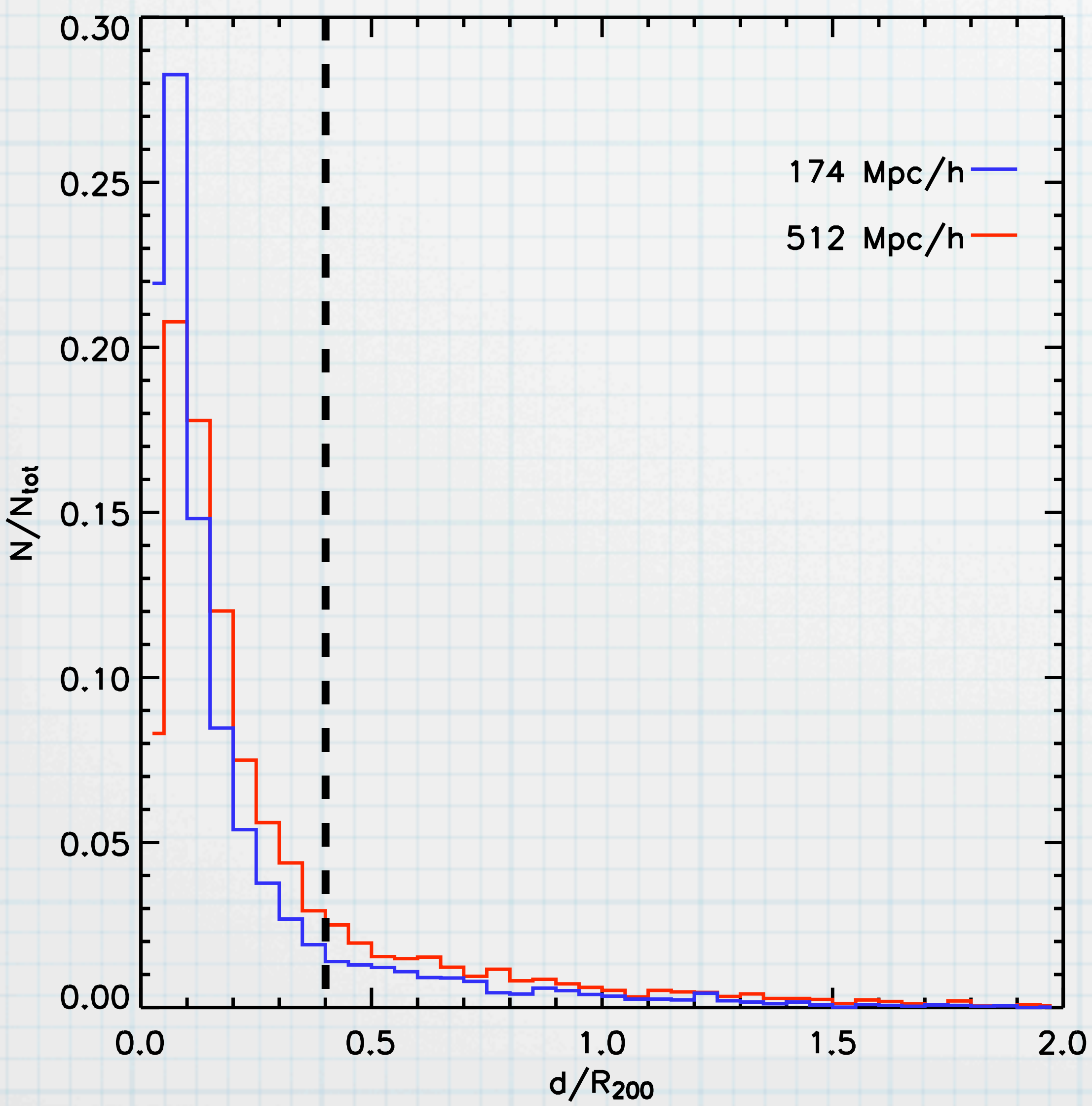


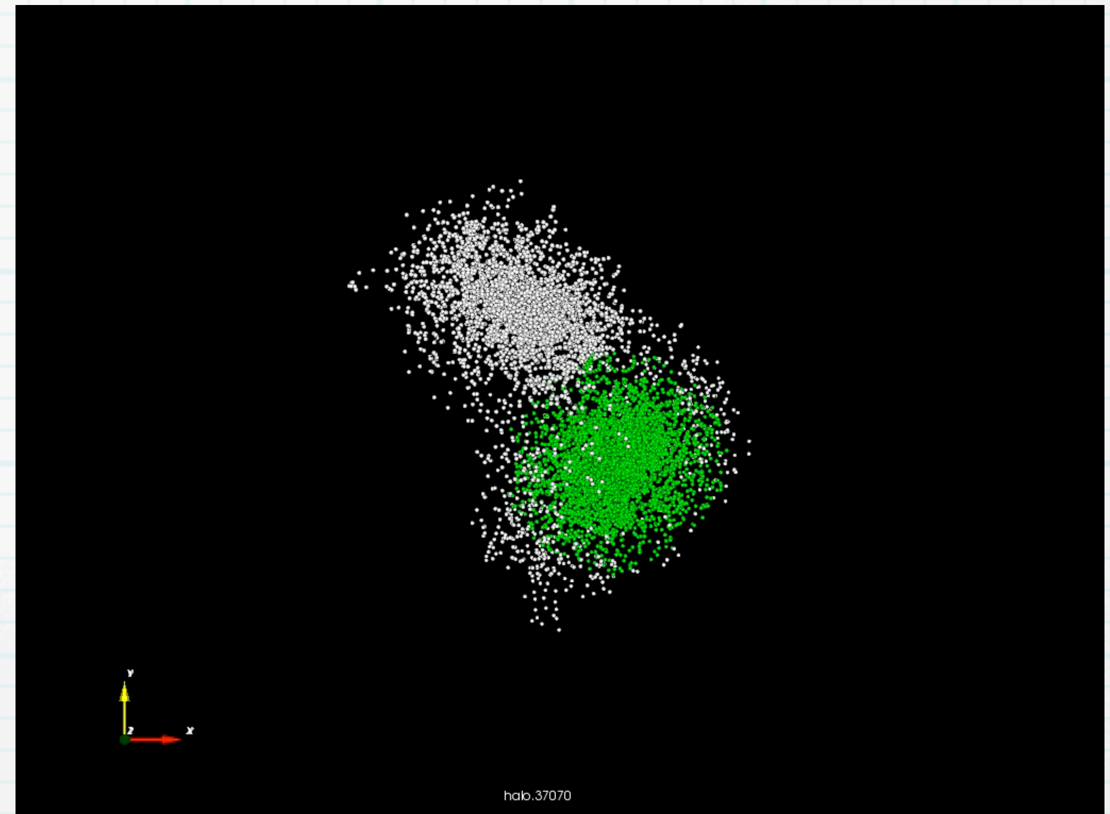
YZ plane

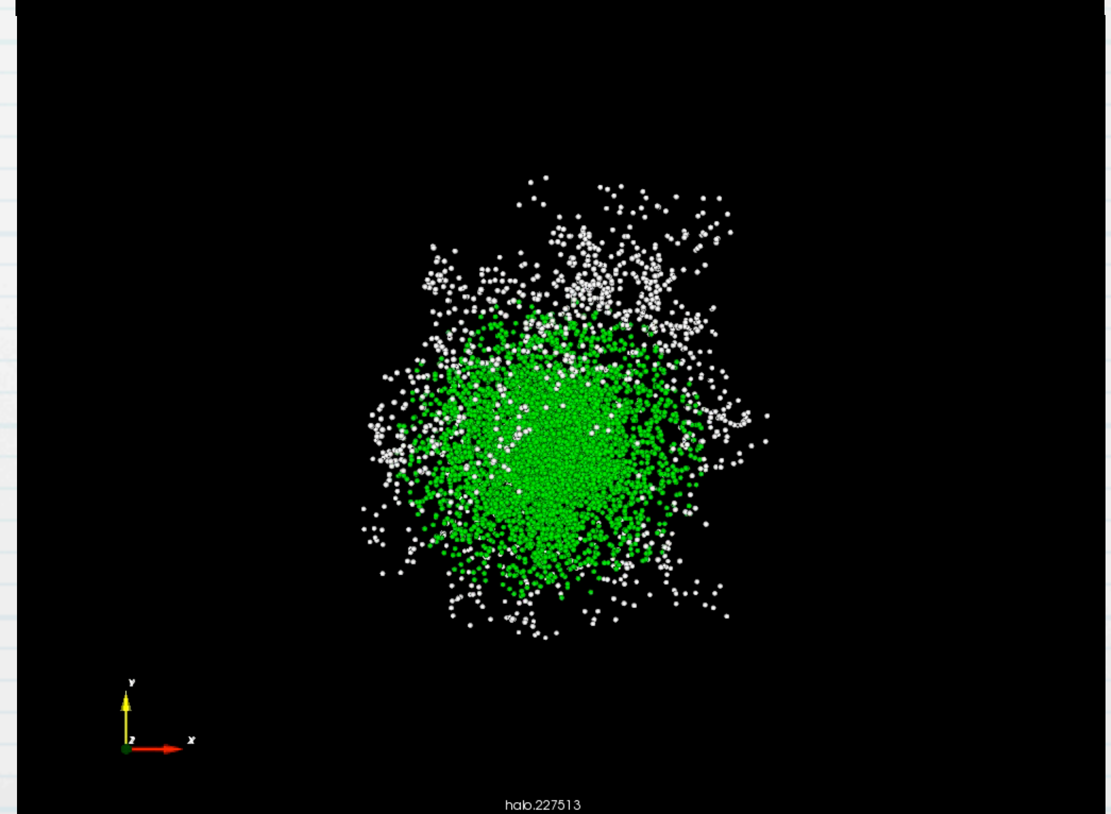
Lukić et al. 2011, in prep.

Merging vs. isolated halos

- Halos form hierarchically in CDM cosmologies - smaller mass halos form first and then merge to form heavier halos.

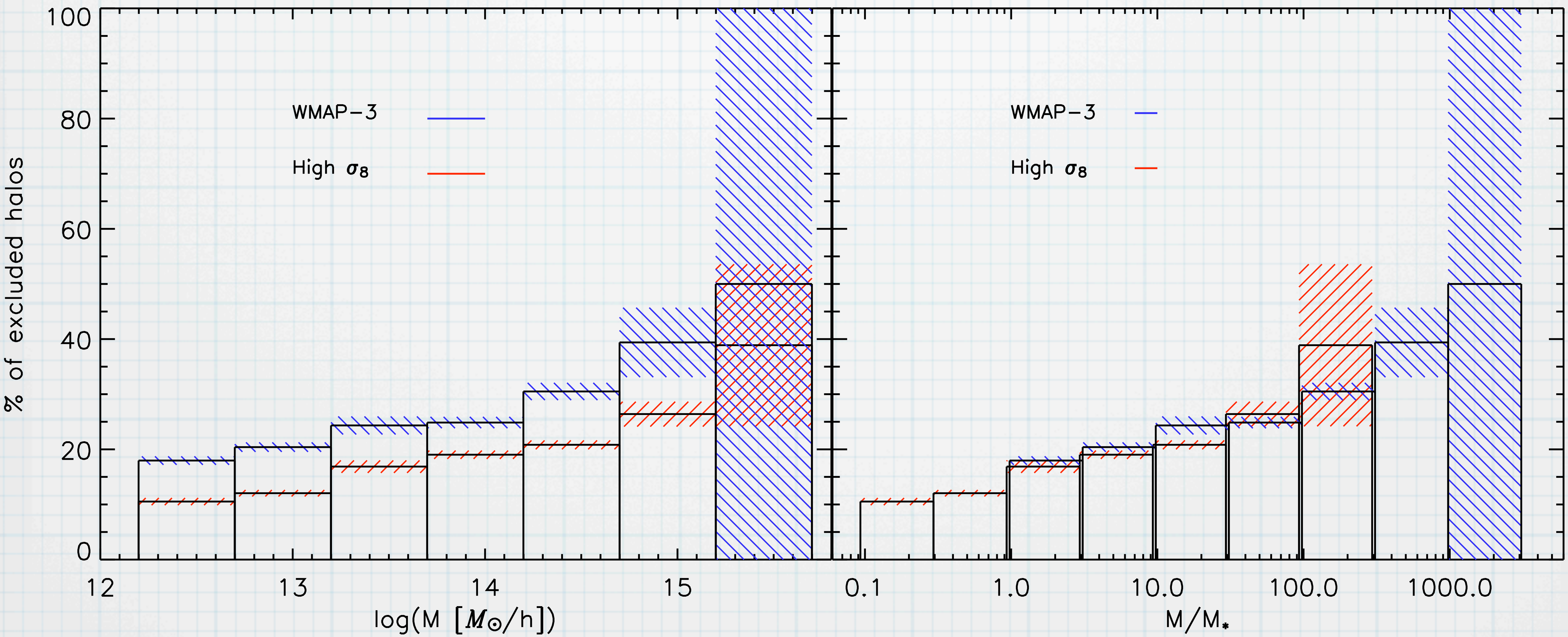






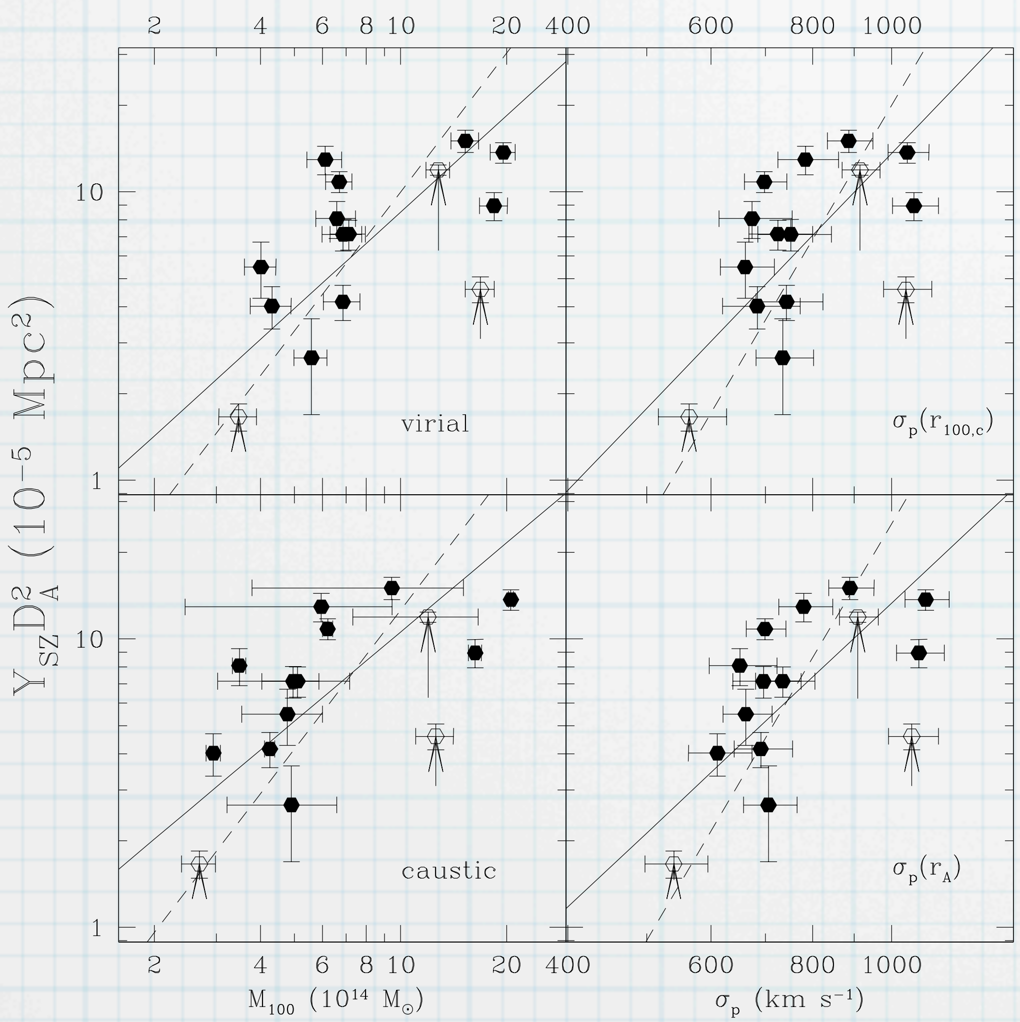
Fraction of merging halos

- Fraction of halos we classify as being in some phase of merger, based on how displaced is center of mass from gravitational potential minimum.



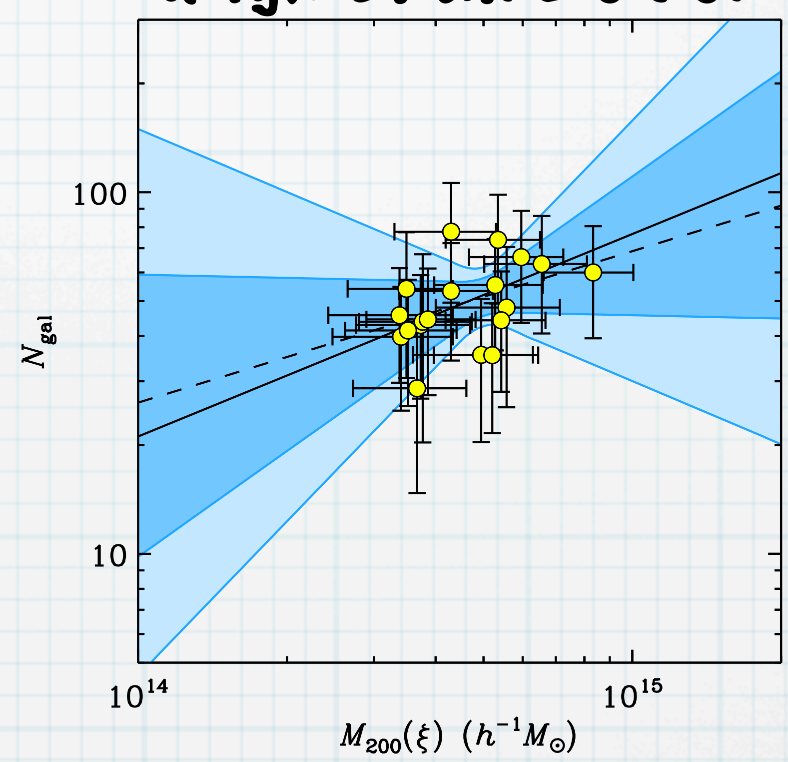
(Lukić et al. 2009)

Mass-observable relations

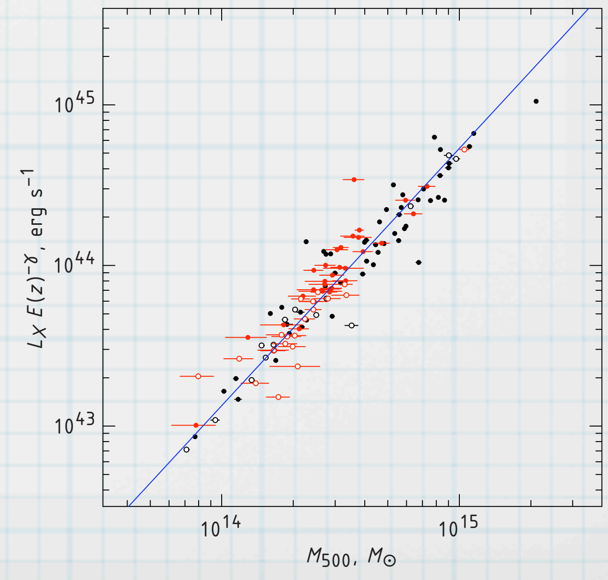


- σ-mass; Y_{sz}-mass (Rines et al. 2010)

- Richness-mass (High et al. 2010)



- X-ray luminosity-mass (Vikhlinin et al. 2009)



SEVERAL SLIDES WITH UNPUBLISHED WORK HAVE BEEN REMOVED

Summary

- Perturbations in dark energy sector cannot simply be neglected, especially if w is allowed to evolve.

- Cluster redshift distribution data will significantly improve constraints on early dark energy.

- We have a 5% accurate fit for the mass function (FoF b=0.2 halos).

- Redshift dependence matters in Λ-dominated phase, and has to be explicitly accounted for.

- wCDM cosmologies are within 5-10% of ΛCDM fit throughout mass & redshift range relevant for cluster surveys.

- Fraction of merging halos can be a good test of cosmology, as it does not suffer completeness issue.

- We provide observationally motivated way to define clusters as "merging" and "relaxed". It leads to improvement of mass-observable scatter for "relaxed" sample.

The End