THE OVERDENSITY AND MASSES OF THE FRIENDS-OF-FRIENDS HALOS AND UNIVERSALITY OF HALO MASS FUNCTION

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The friends-of-friends algorithm:

A percolation theory perspective

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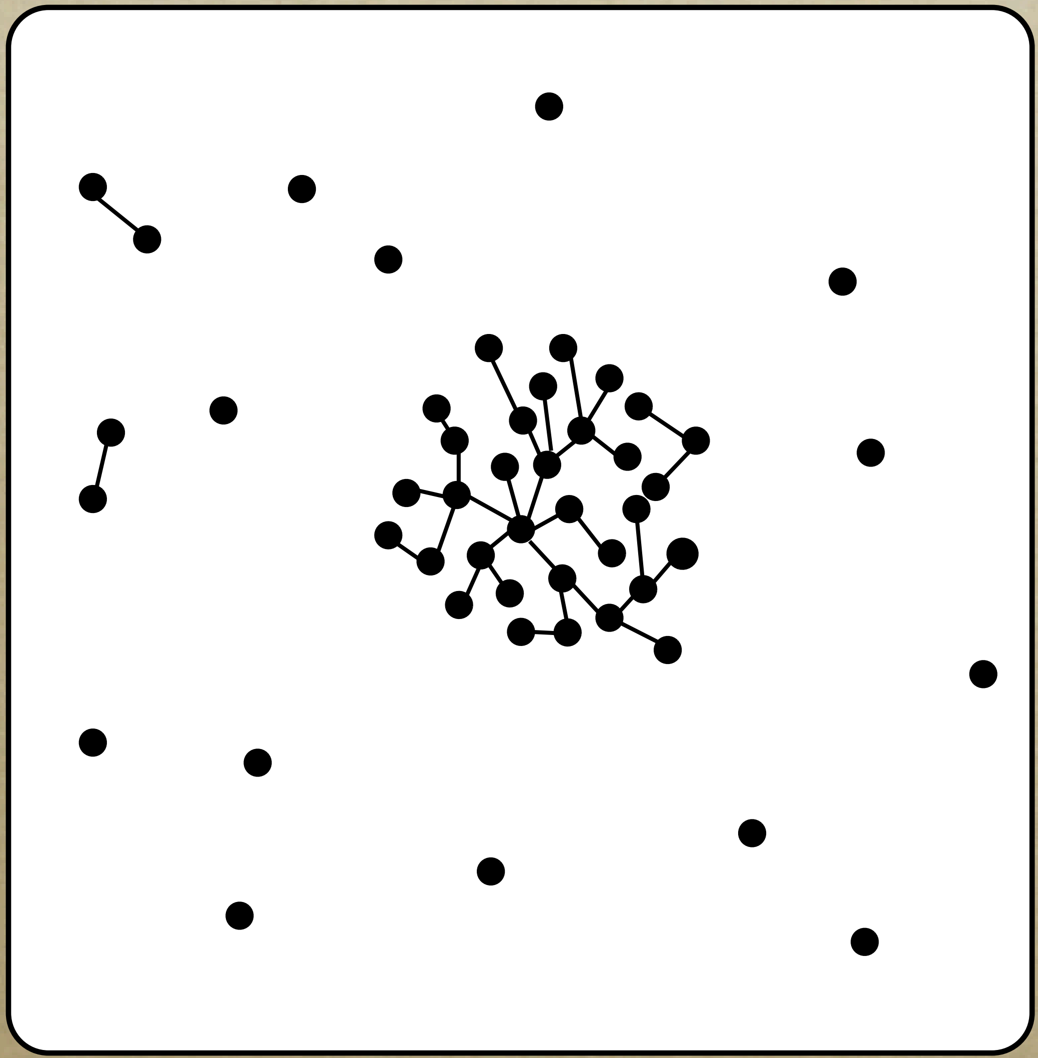
Take home message(s)

- *The properties of FOF halos can be well understood in terms of continuum percolation theory.*
    - *Overdensity of FOF halos : NOT equal to 180, but is dependent on linking length and concentration.*
    - *Resolution dependence of the FOF halo mass.*
    - *Universality of the FOF halo mass function is perhaps a coincidence.*

FOF: A percolation algorithm



- *Used to identify structure in galaxy distribution based on physical proximity*
  - *Huchra and Geller 1982, Press and Davis 1982, Einasto et al. 1984, Eke et al. 2004, Berlind et al. 2006*
- *Useful to identify structures in numerical simulations too.*
  - *See Knebe et al. 2011 for a long list of halo finders using FOF*

Single free parameter:

Linking length, often quoted in terms of the mean inter-particle separation: b

Short introduction to percolation

- *Web applet from:*
  - *R. Gonsalves, University of Buffalo*
- *Terms from percolation theory*
  - *Critical threshold for percolation:* p_c
  - *Infinite cluster*
  - *Strength of infinite cluster:* P_∞

Continuum percolation

- *Swiss cheese model*
  - *Spheres of size R, distributed in a Poisson manner*
  - *Probability of a given point to belong to at least one sphere*
    $$p(x) = 1 - \exp\left[-\frac{4}{3}\pi\, n(x) R^3\right]$$
  - *Overlapping spheres form a network of friends (cluster)*
- *Critical density threshold*

$$n_{\rm crit} = \frac{n_c}{(2R)^3} = \frac{n_c}{(b\bar{l})^3} \qquad n_{\rm c} = 0.652960 \pm 0.000005$$

Lorenz & Ziff 2001

Continuum percolation

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  - *Spher* *son manner*
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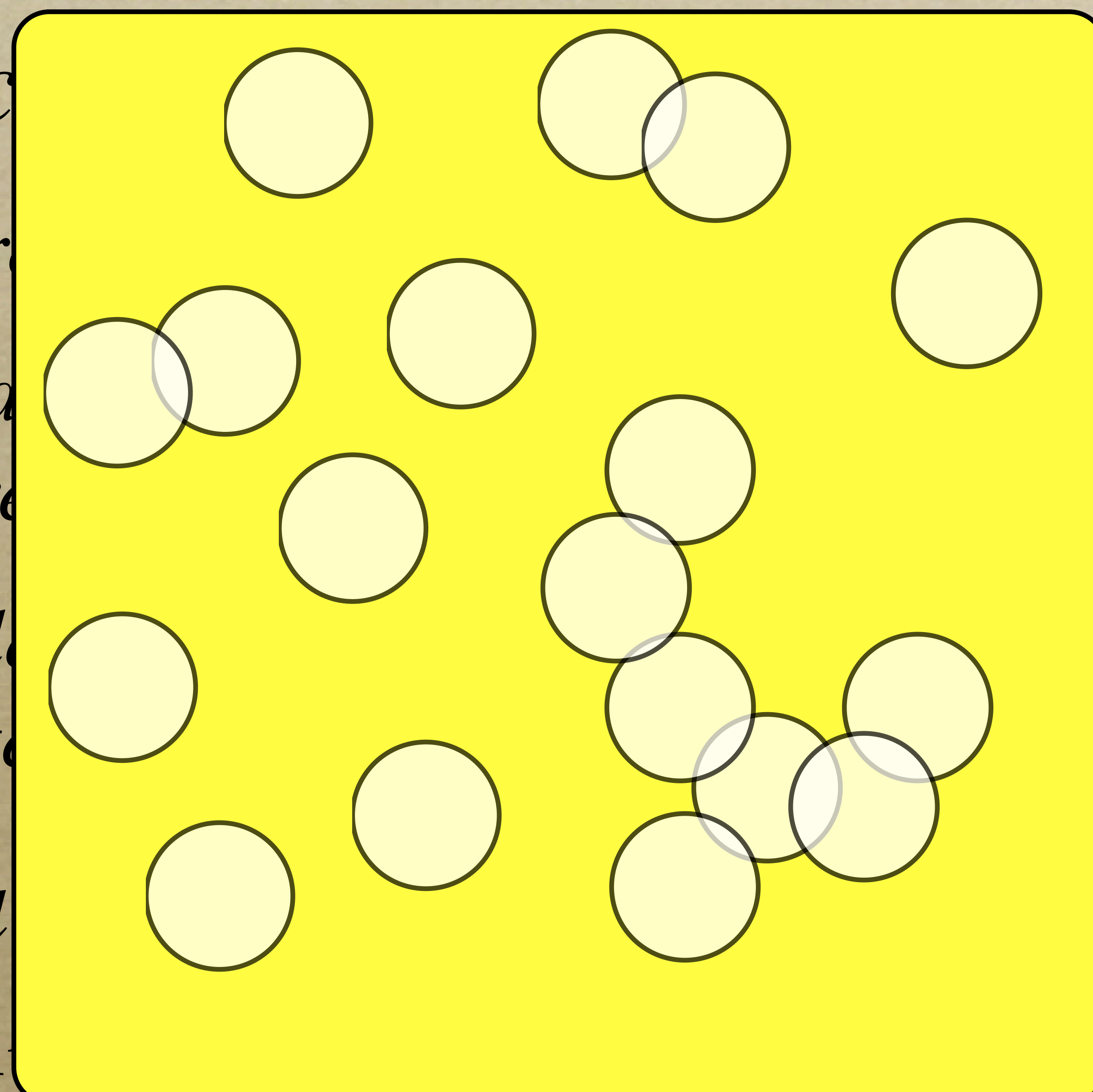

n_{cri} … $\Big(2\pi\Big)$ … $\Big(6\iota\Big)$ … 2960 ± 0.000005

Lorenz & Ziff 2001

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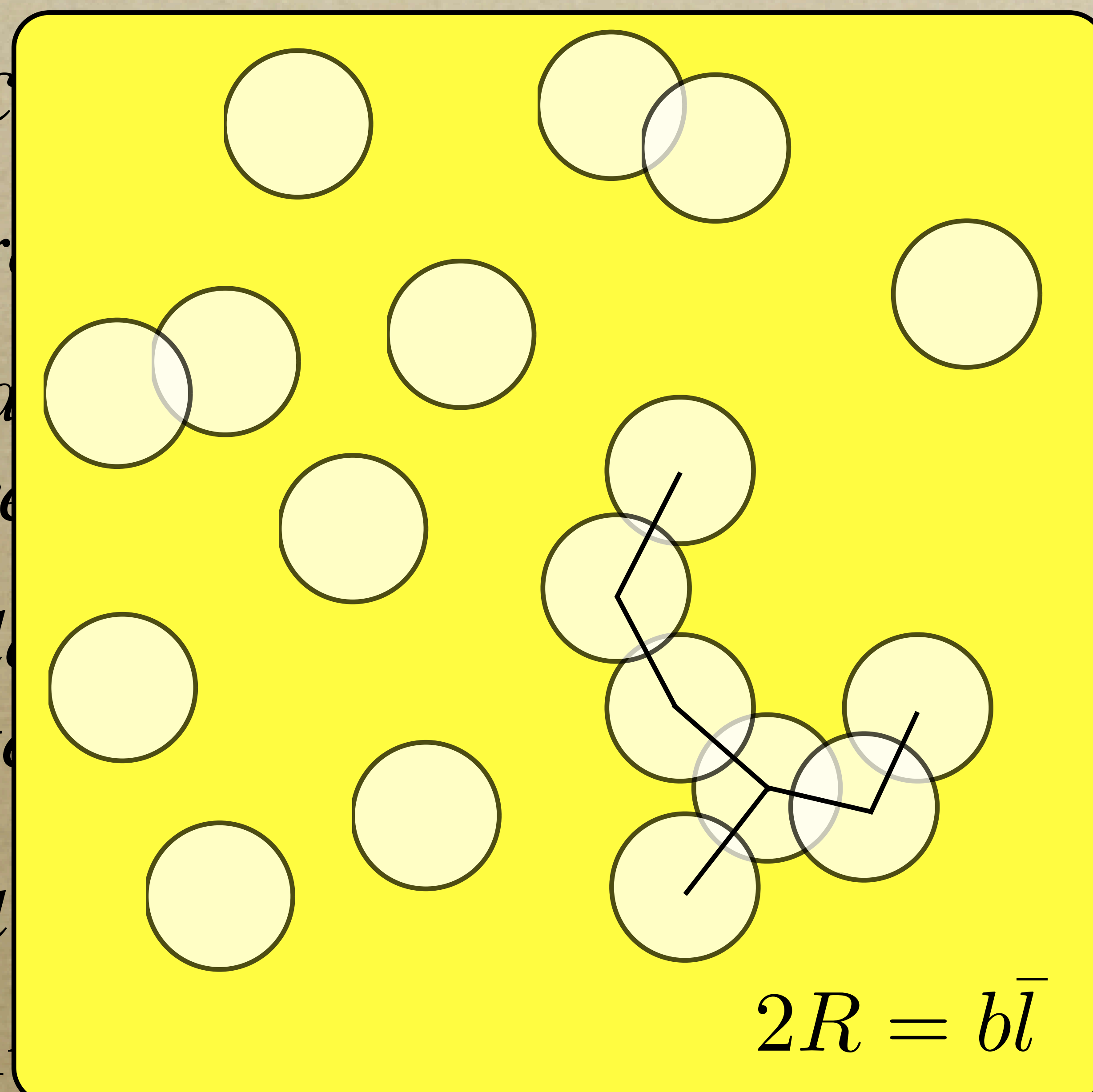

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Simulated FOF halos

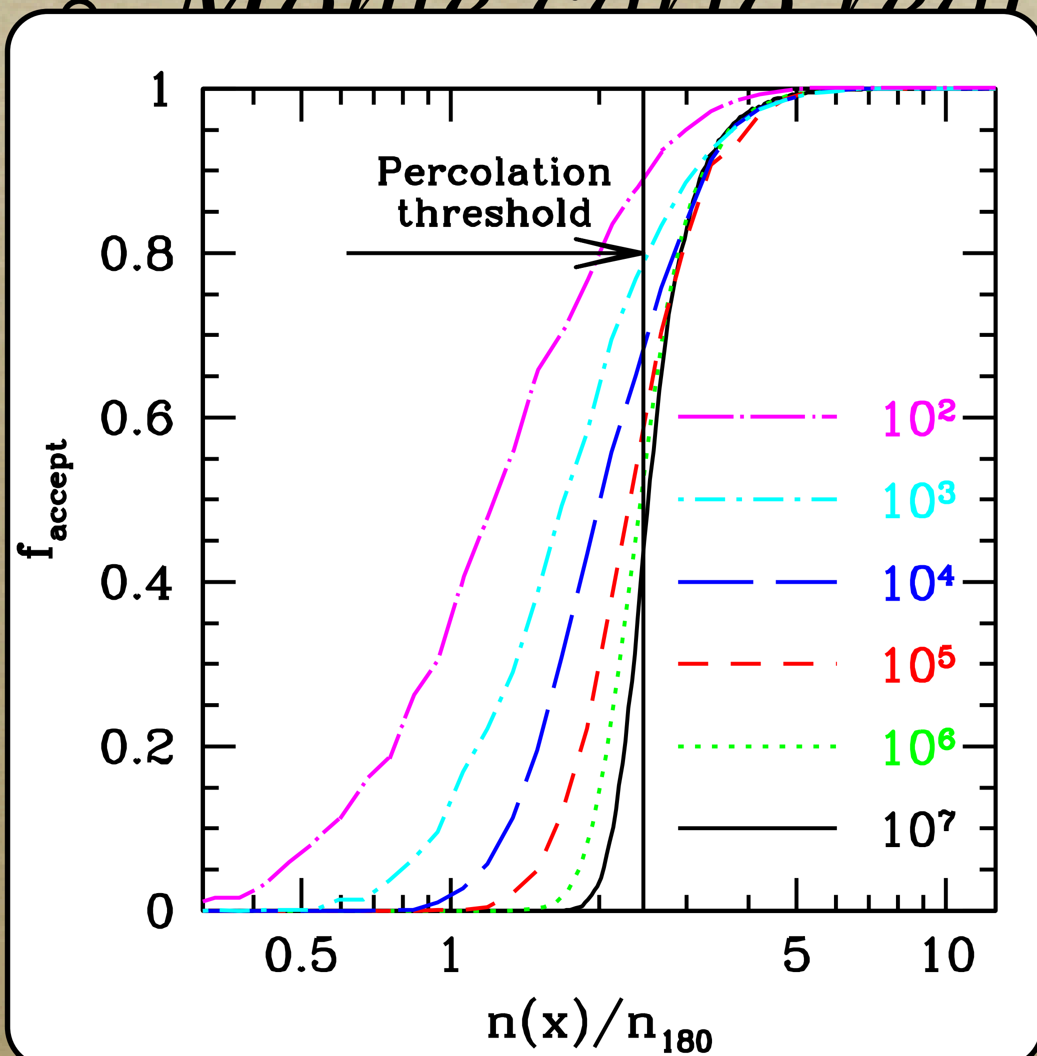
- *Monte carlo realizations of spherically symmetric NFW haloes with varying number of particles*

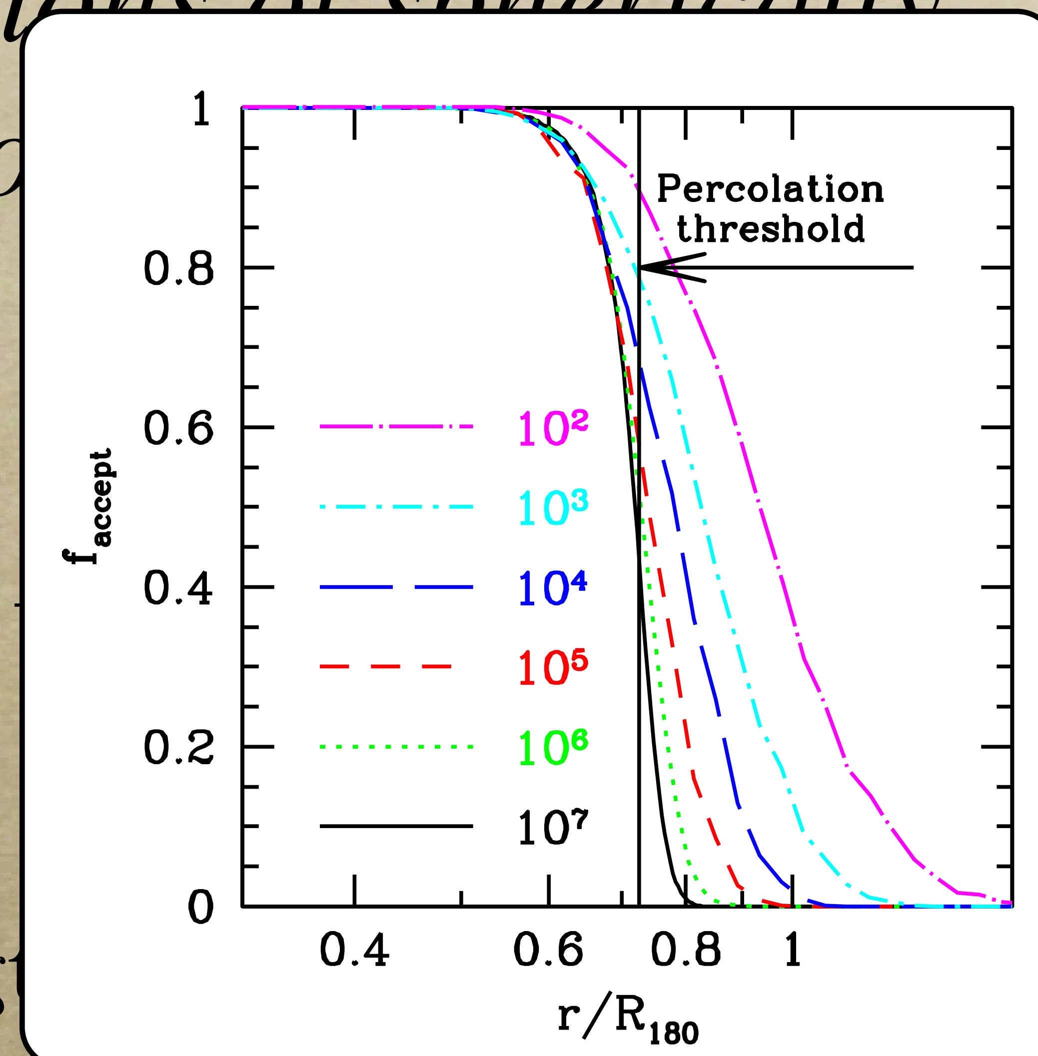
$$N_{180} = \frac{4}{3}\pi r_s^3 \left[\log(1+c_{180}) - \frac{c_{180}}{1+c_{180}}\right] = \frac{4}{3}\pi \frac{R_{180}}{\bar{l}}^3 180$$

$$\text{Linking length} : 0.2\,\bar{l}$$

Simulated FOF halos

- *Monte carlo realizations of spherically*





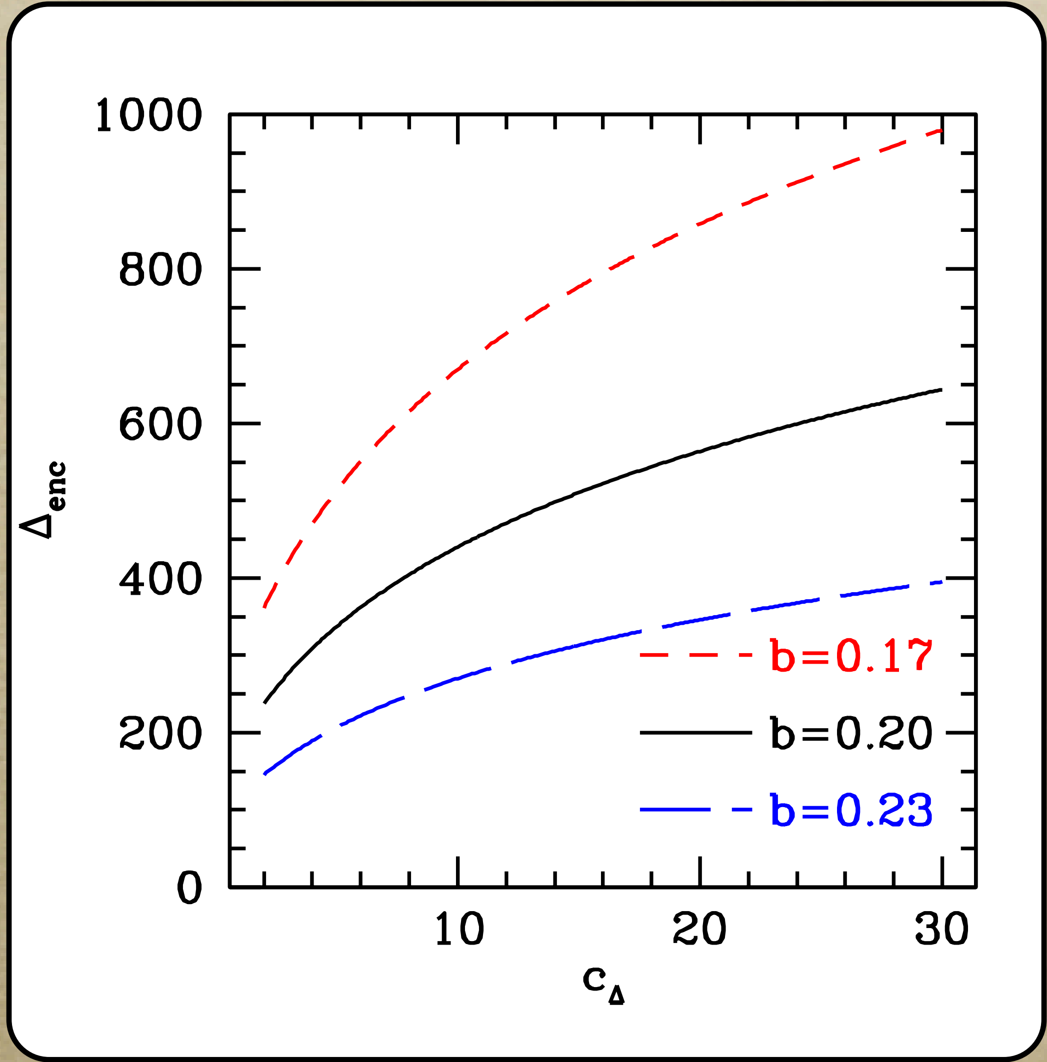
Concentration dependence of overdensity

- *Percolation predicted boundary of the FOF halo*

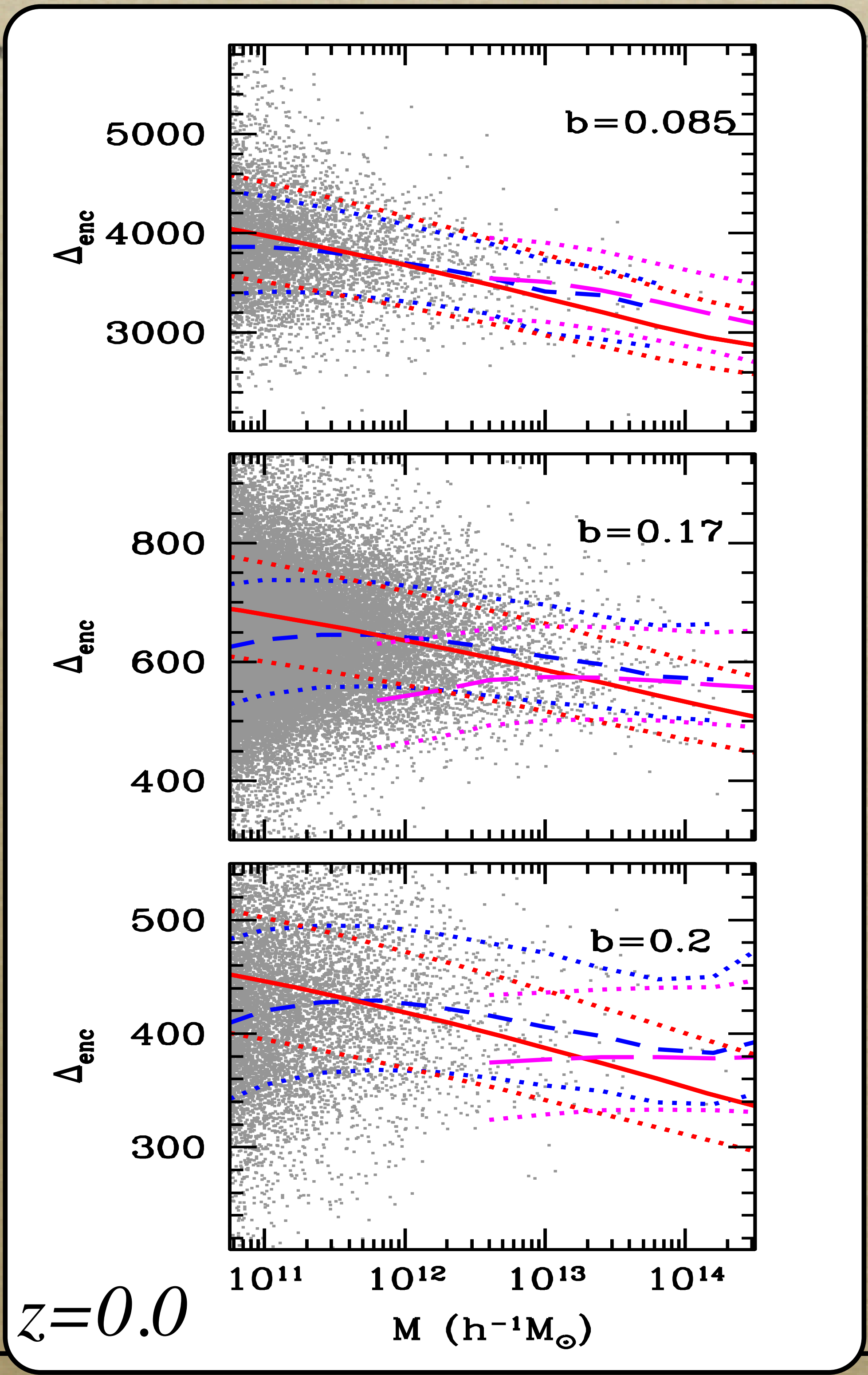
$$n(r_\Delta) = n_{\rm crit} = \frac{n_c}{(b\bar{l})^3}$$

- *Overdensity:*

$$\Delta = \frac{\int_0^{r_\Delta} n(r) 4\pi r^2 {\rm d}r}{\frac{4}{3}\pi r_\Delta^3} - 1$$



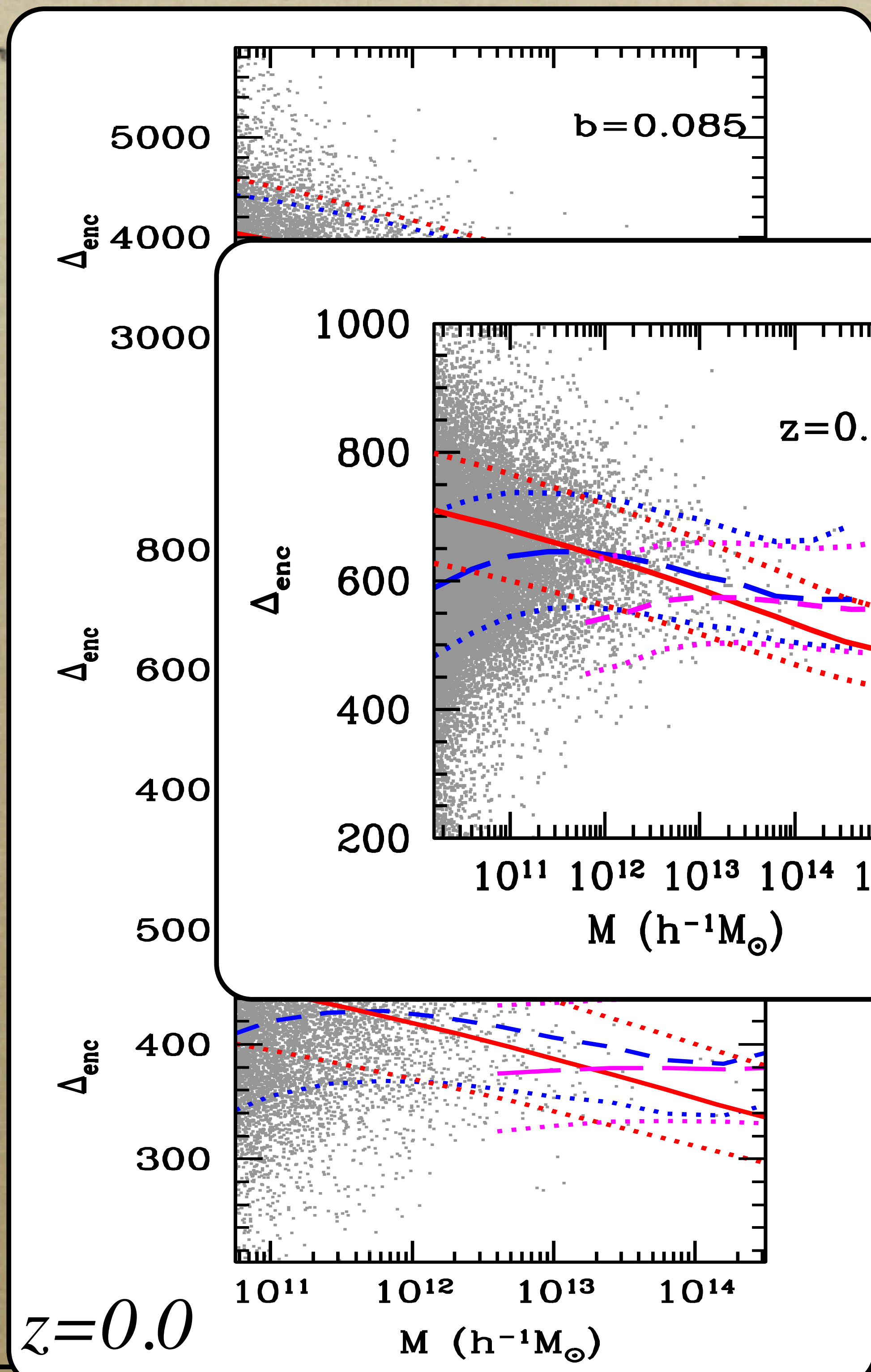
Overdensity of real FOF halos

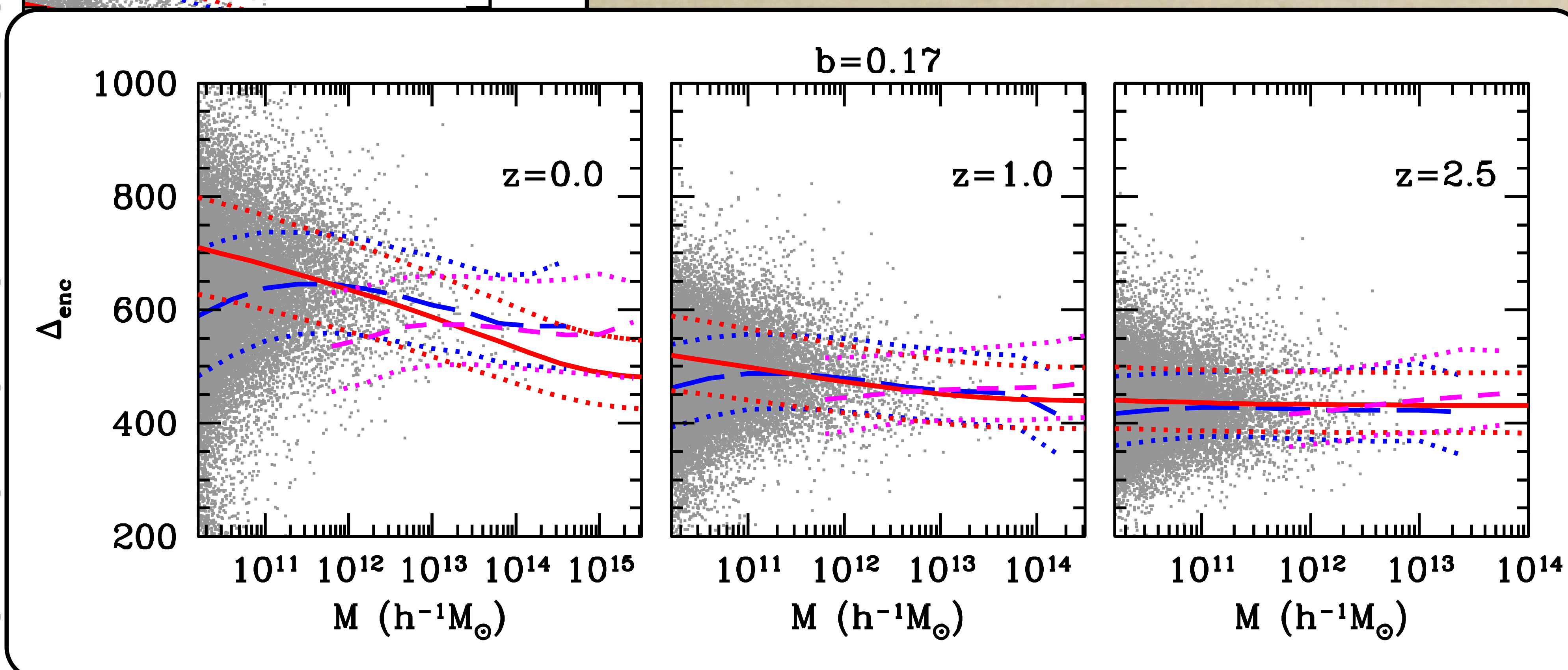


- *Predictions work remarkably well for different linking lengths.*
- *Scatter in overdensities due to scatter in concentration.*

Blue: Bolshoi
Magenta: MultiDARK
Red: Predictions

Overdensity of real FOF halos

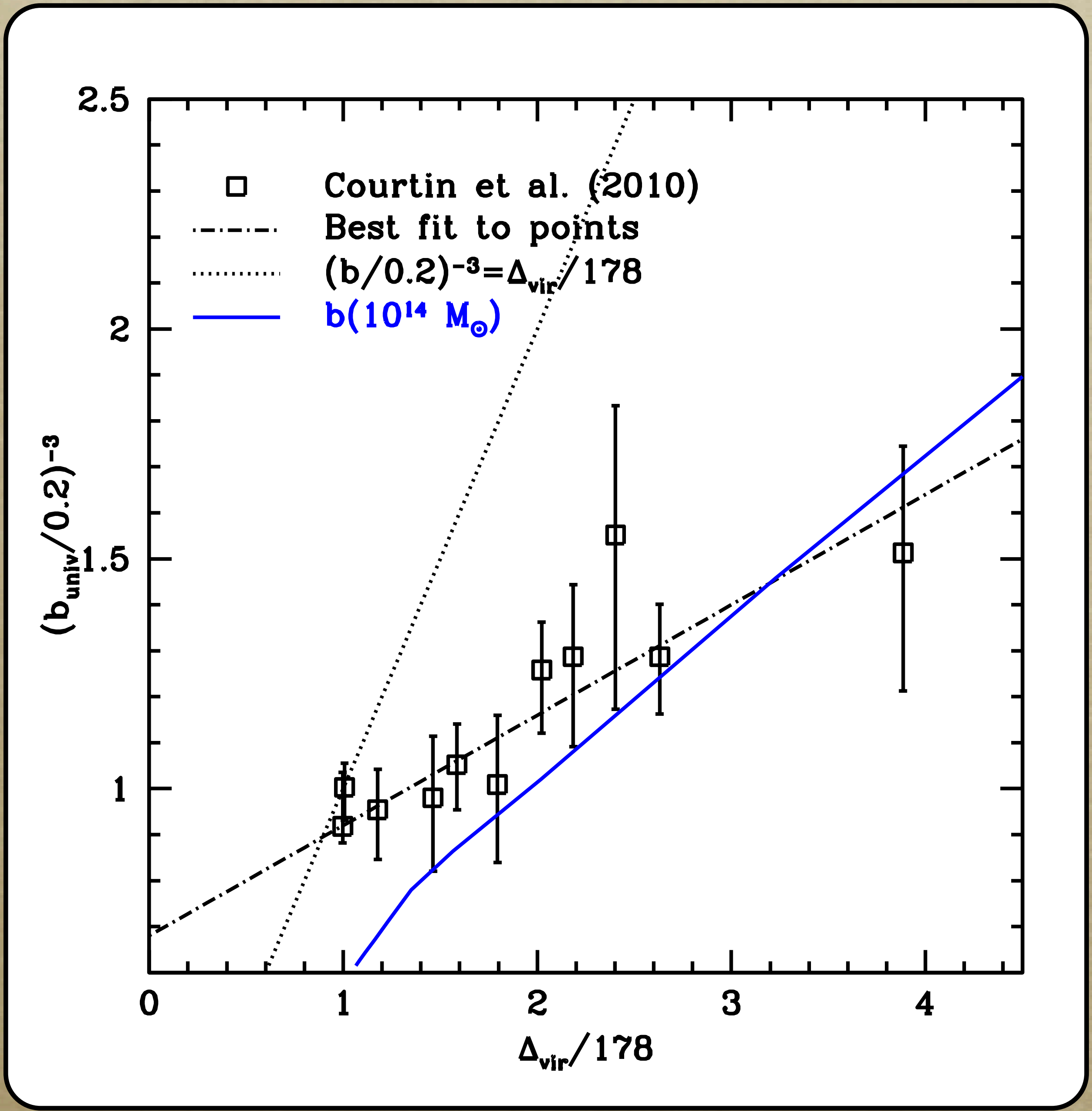




- *And at high redshift*

Blue: Bolshoi
Magenta: MultiDARK
Red: Predictions

Universality of the mass function



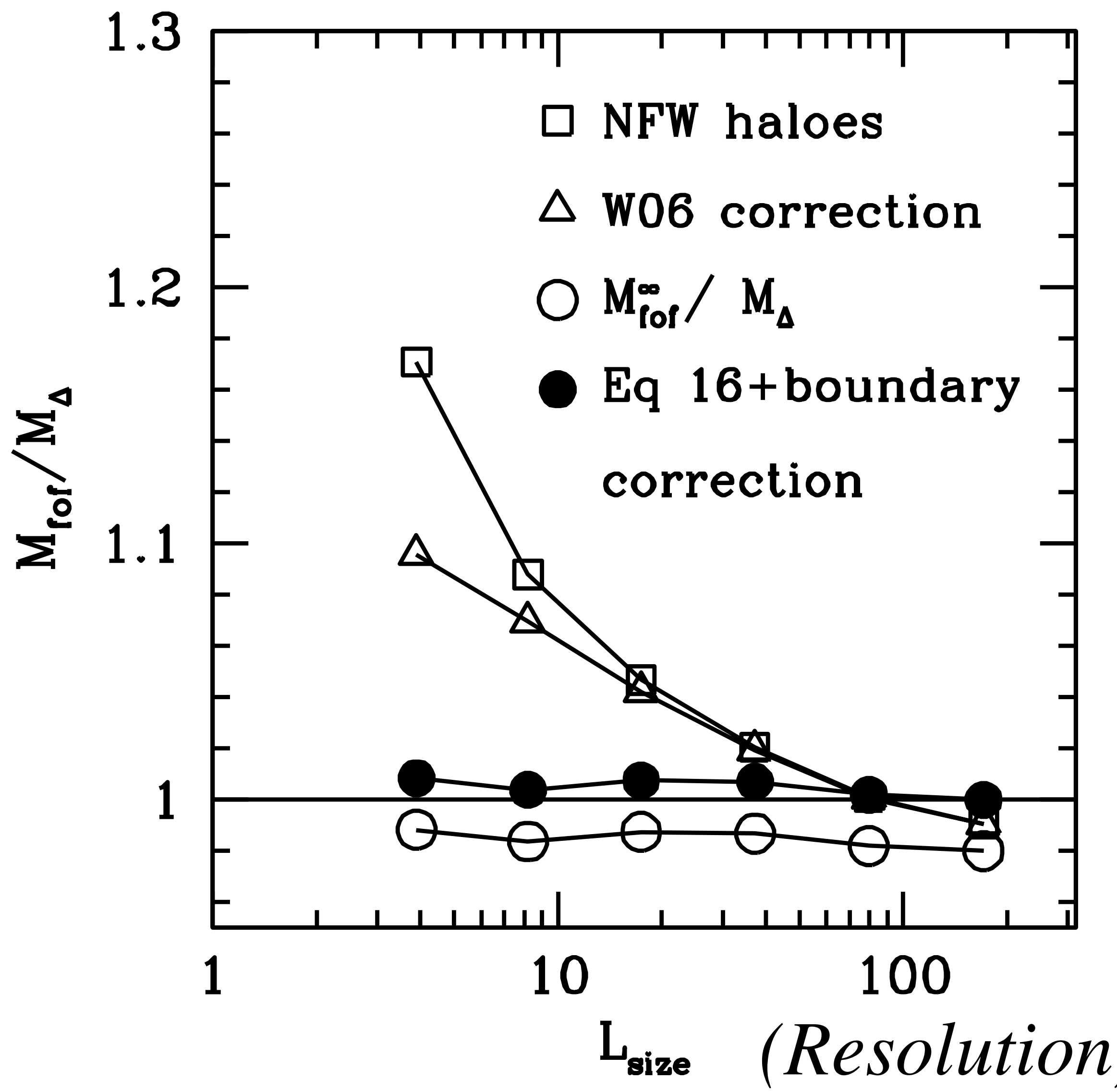
- *The FOF mass function is universal for different cosmologies at different redshifts if b is adjusted.*

Courtin et al. 2010

- *Blue line: Percolation theory prediction*

$$\left(\frac{b}{0.2}\right)^{-3} = \left(\frac{\Delta+1}{244.86}\right)\frac{c_\Delta^2}{\mu(c_\Delta)(1+c_\Delta)^2}$$

Resolution dependence of FOF mass



(Resolution)

- *First observed by Warren et al. (2006) using idealized experiments of isothermal haloes*
- *Proposed a correction based upon the number of particles in the FOF halo*
- *Lukic et al. (2009) subsequently carried out tests with idealized NFW halos with varying concentration*

Percolation on finite lattices

- *Threshold for percolation changes on finite size lattices*

$$\tilde{p}_c - p_c \propto L_{\rm size}^{-1/\nu} \qquad L_{\rm size} = \frac{2R_\Delta}{b\bar{l}}$$

- *Mass selected by FOF changes*

$$\Delta M \propto \frac{\partial M}{\partial p}(\tilde{p}_c - p_c) \propto \left|\frac{\partial M}{\partial p}\right| L_{\rm size}^{-1/\nu}$$

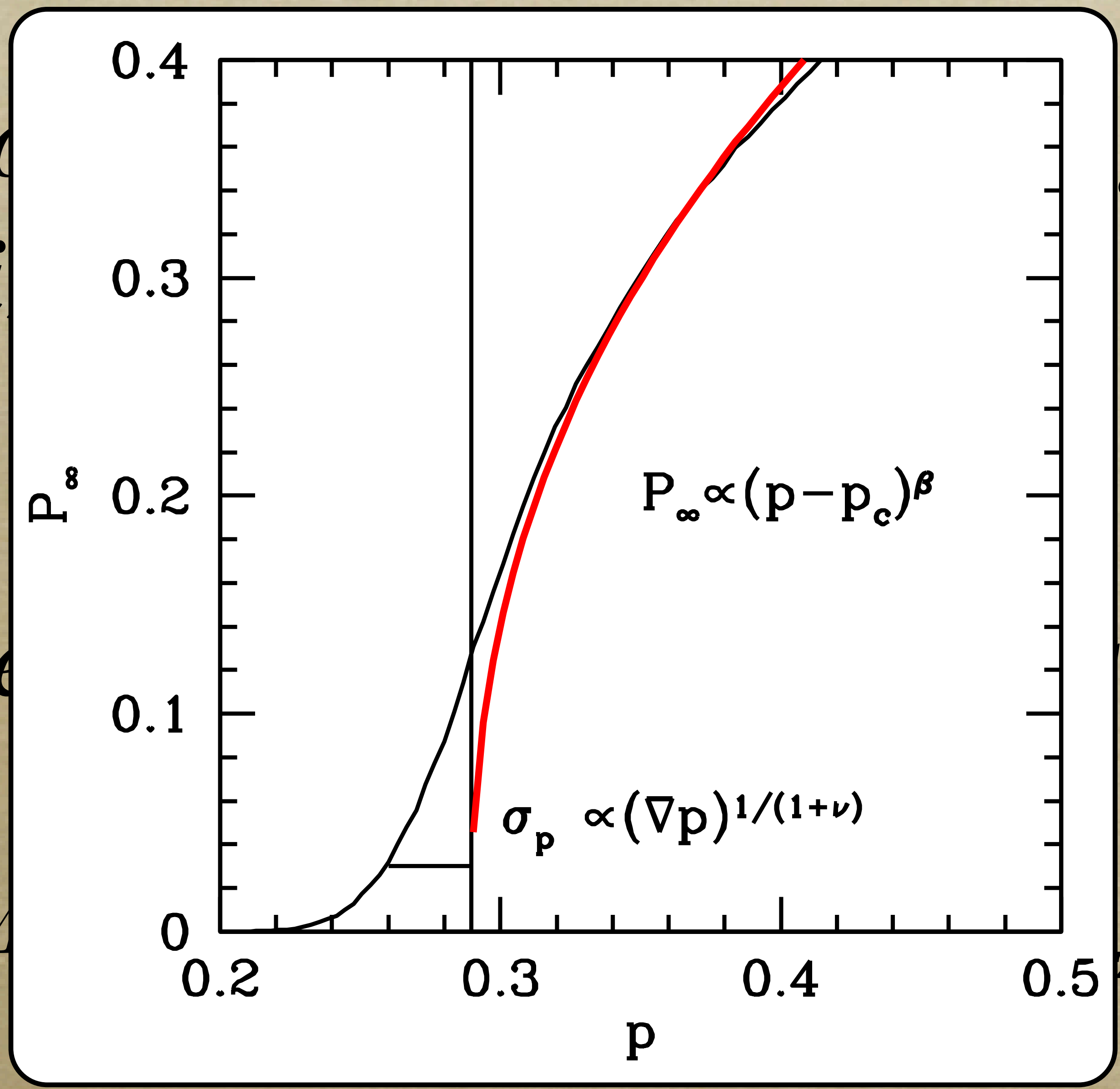
Percolation on finite lattices

- *Thresh*... ...*ges on finite si*...

$$L_{\text{size}} = \frac{2R_\Delta}{b\bar{l}}$$

- *Mass se*...

ΔM ... $^{1/\nu}$ ... ze



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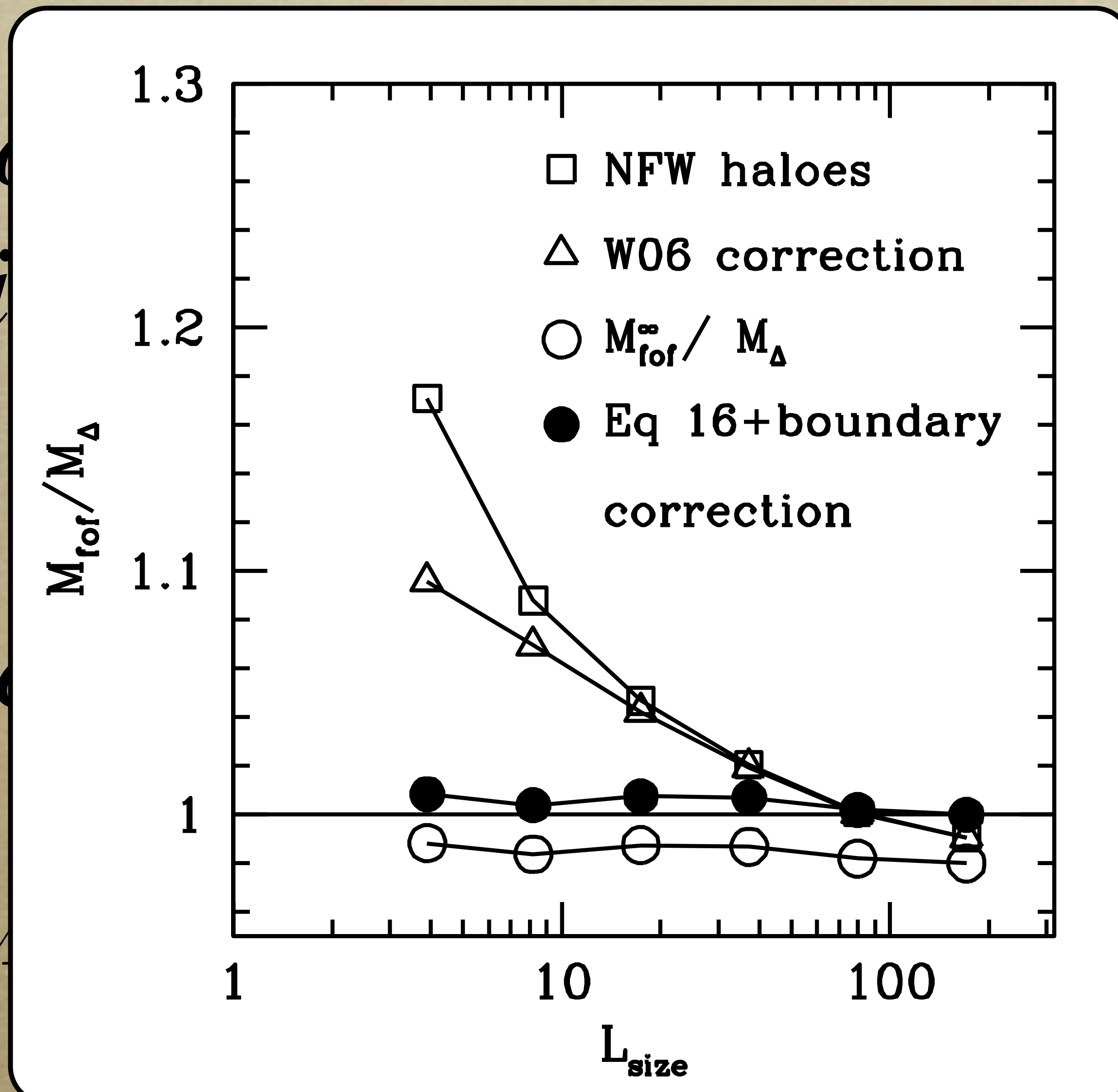

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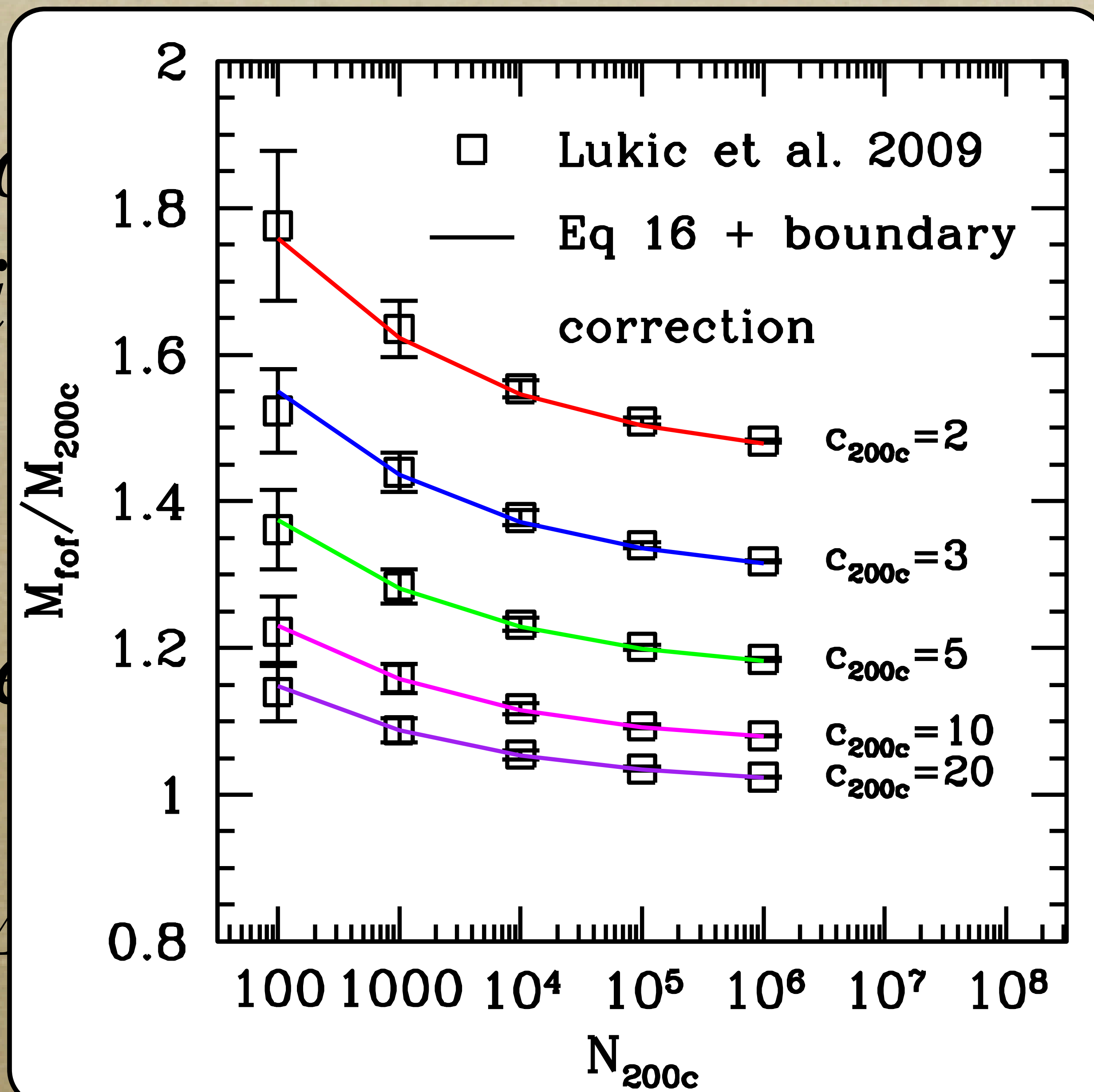
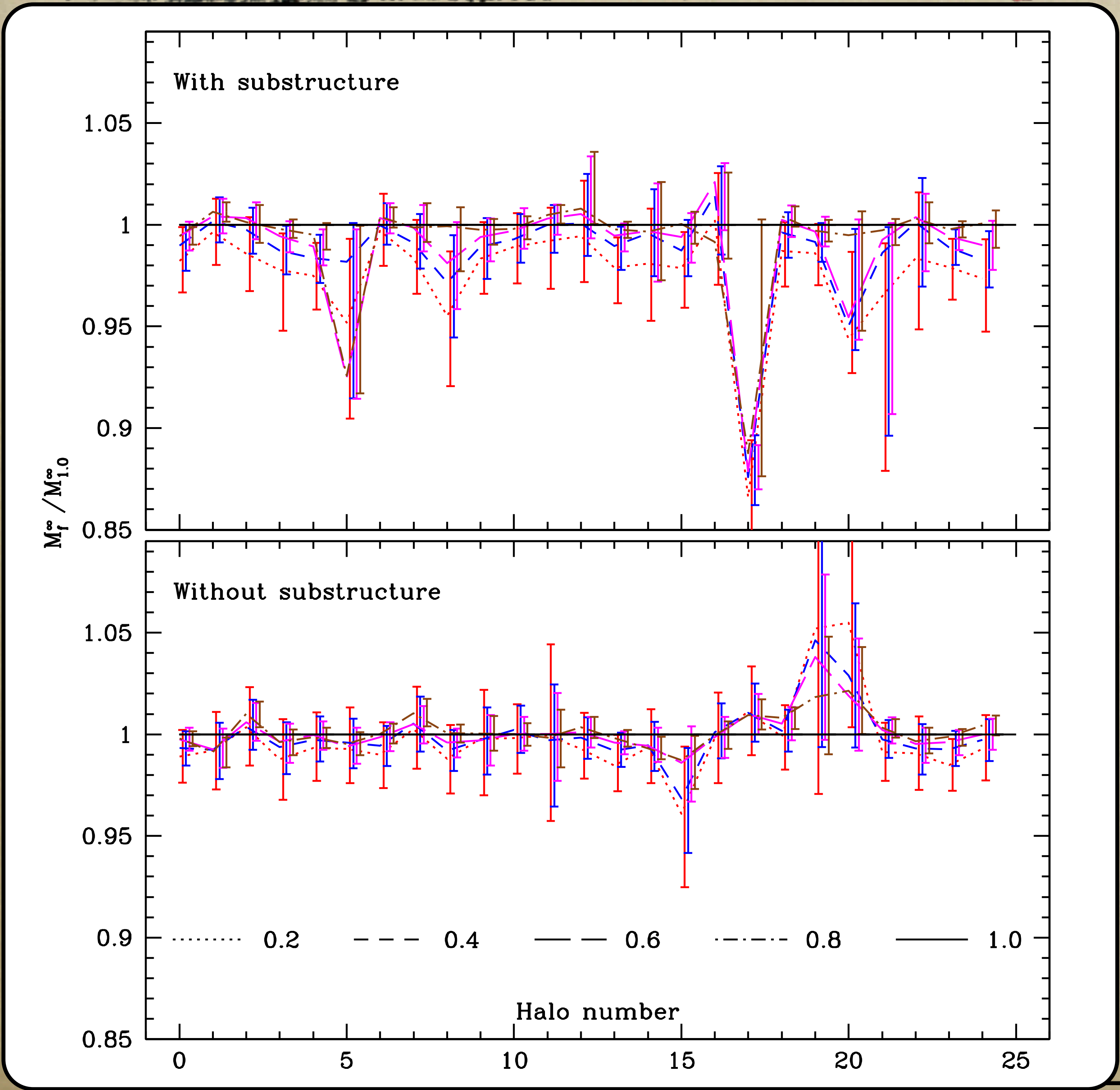


What about real FOF halos?



- *25 most massive haloes from Bolshoi simulation.*
- *Run FOF on a fraction of particles.*
- *Correct the halo mass using the percolation theory prescription.*

Triaxiality not a big issue, but substructure is a huge problem!!!

Take home message(s)

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    - *Overdensity of FOF halos : NOT equal to 180, but is dependent on linking length and concentration.*
    - *Resolution dependence of the FOF halo mass, **difficult to correct because of substructure**.*
    - *Universality of the FOF halo mass function is perhaps a coincidence.*