Dark Matter Halos, Mass Functions, and Cosmology: a Theorist's View

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Special thanks to Sergei Bashinsky, Salman Habib, Steve Haroz, Zarija Lukic, Kwan-Liu Ma, Pat McCormick, Darren Reed, Paul Ricker

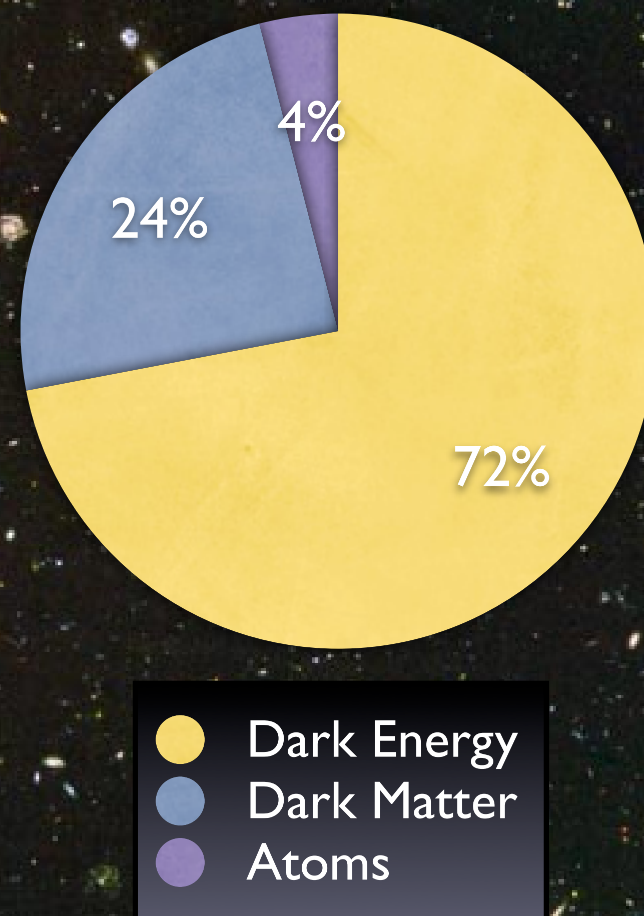
Background: A small section of the first light image obtained by the Sloan Digitial Sky Survey


The Duck Universe

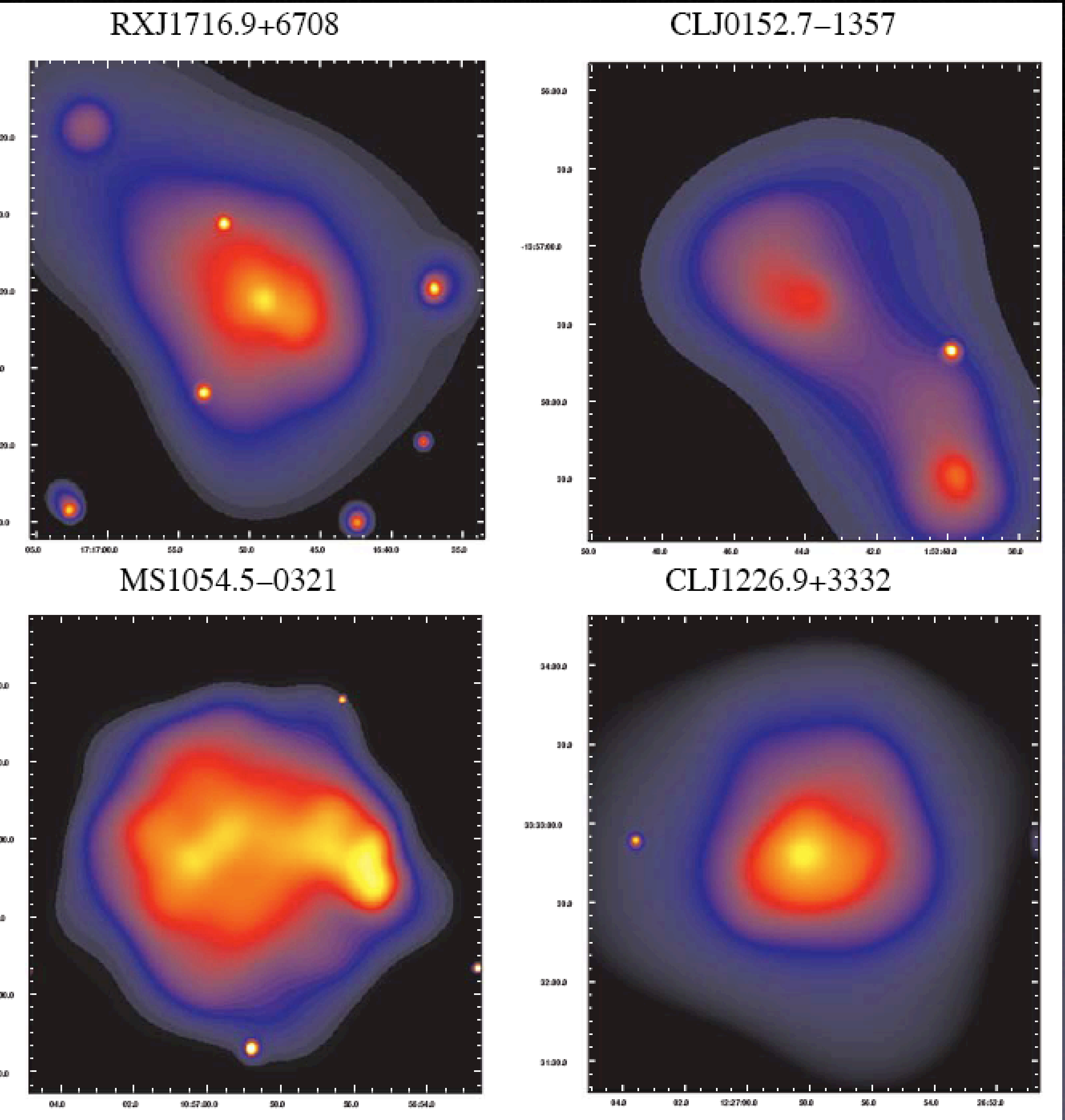
The ~~Duck~~ Dark Universe

Dark Energy Probes:

- Supernovae
- Baryon Acoustic Oscillations
- Weak Lensing
- Clusters of Galaxies



Clusters of Galaxies



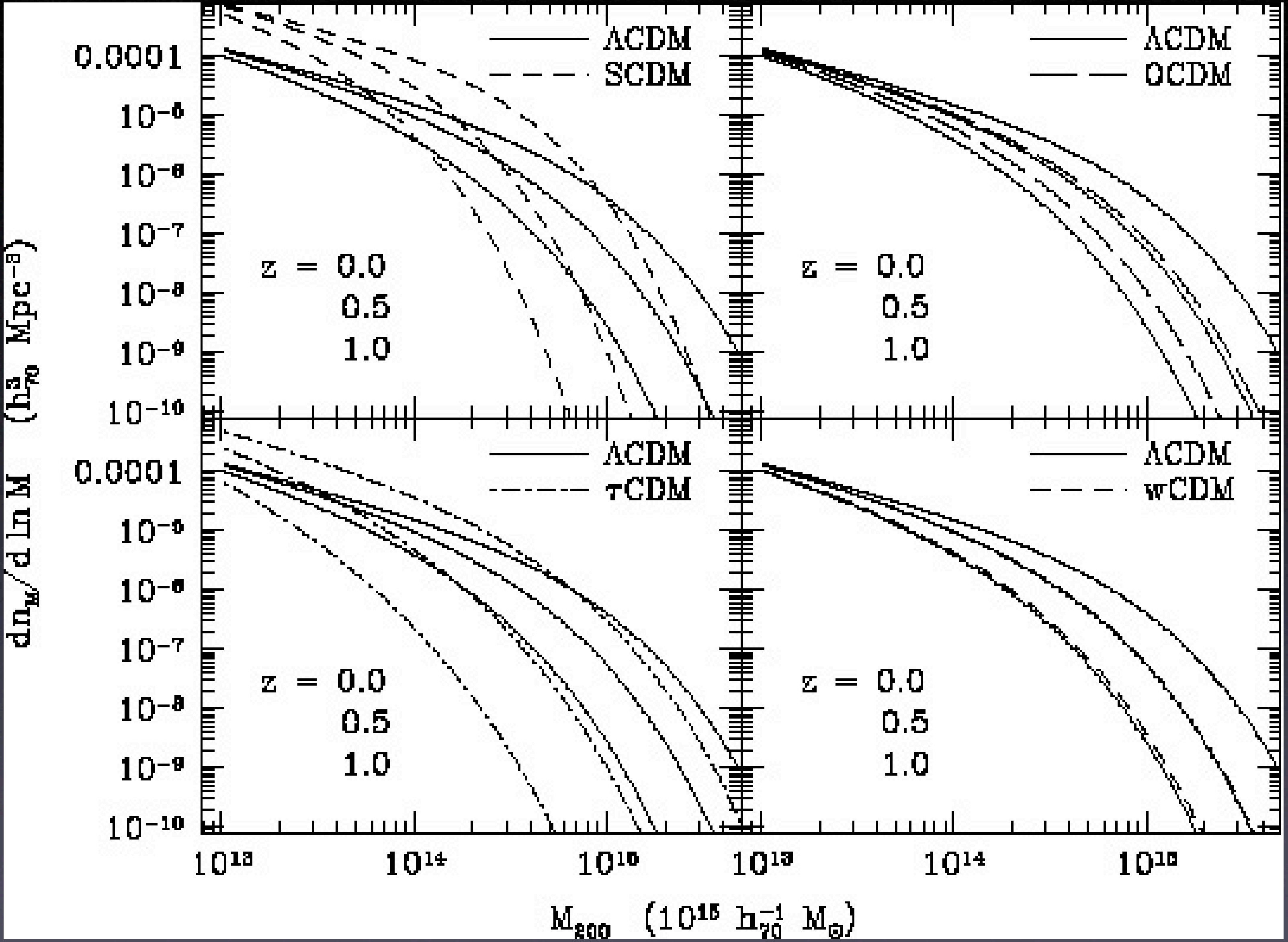
- Chandra X-ray images of clusters from Jeltema et al., ApJ, 2005
- Clusters appear in all forms! Not always nice and friendly round blobs
- Cosmology from clusters? In this talk:
  - Count them! Mass function
  - Merger statistics
- Theorist's Approach: Simulations
  - Precision cosmology
  - What can go wrong?
  - Halo definition?

A Theorist's Universe (Dark Matter only)

The Mass Function

- **Statistics describing the halo mass distribution in the Universe**
- **n(M): number density of clusters/halos with mass > M in comoving volume element**
- **Evolution of mass function is highly sensitive to cosmology because matter density controls rate at which structure grows**
- **After Press/Schechter: semi-analytic fits by Sheth &Tormen (1999), Jenkins et al. (2001), and Warren et al. (2006) (and many more...) using simulations**
- **Fits and their evolution are controlled by growth function D(z), which itself is a function of Ω_m, Ω_Λ, and ω**

Evolution of the Mass Function for Different Cosmologies



from G.M. Voit, astro-ph/0410173, SCDM: Standard-CDM, Ω_m=1.0,

OCDM: Open-CDM, Ω_m=0.3, Ω_Λ=0

τCDM: ad hoc power spectrum, adjust shape

ωCDM: ΛCDM with ω=-0.8

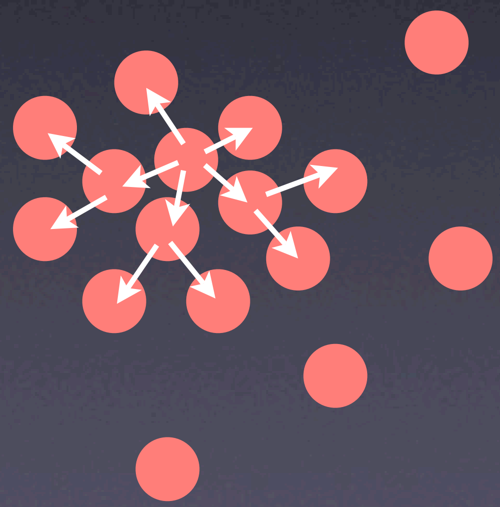
What is a Halo?

M. White A&A, 2001
Z. Lukic, D. Reed, S. Habib, K.H., arXiv:0803.3624, ApJ subm.

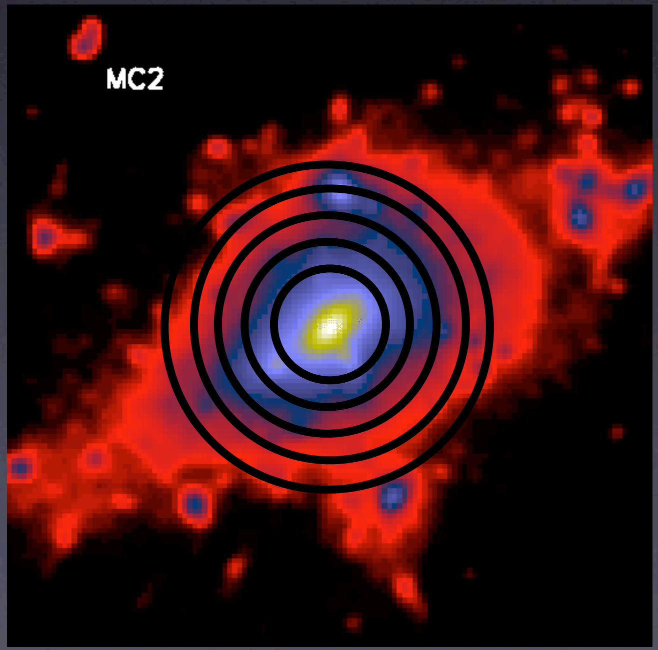
- **How can we find a halo in a simulation?**
  (i) group finder (ii) density finder
- **How can we compare the results?**
- **How do we compare to observations?**

} **will get back to this**

- **Until further notice: FOF with linking length b=0.2**



Friends-of-Friends halo finder



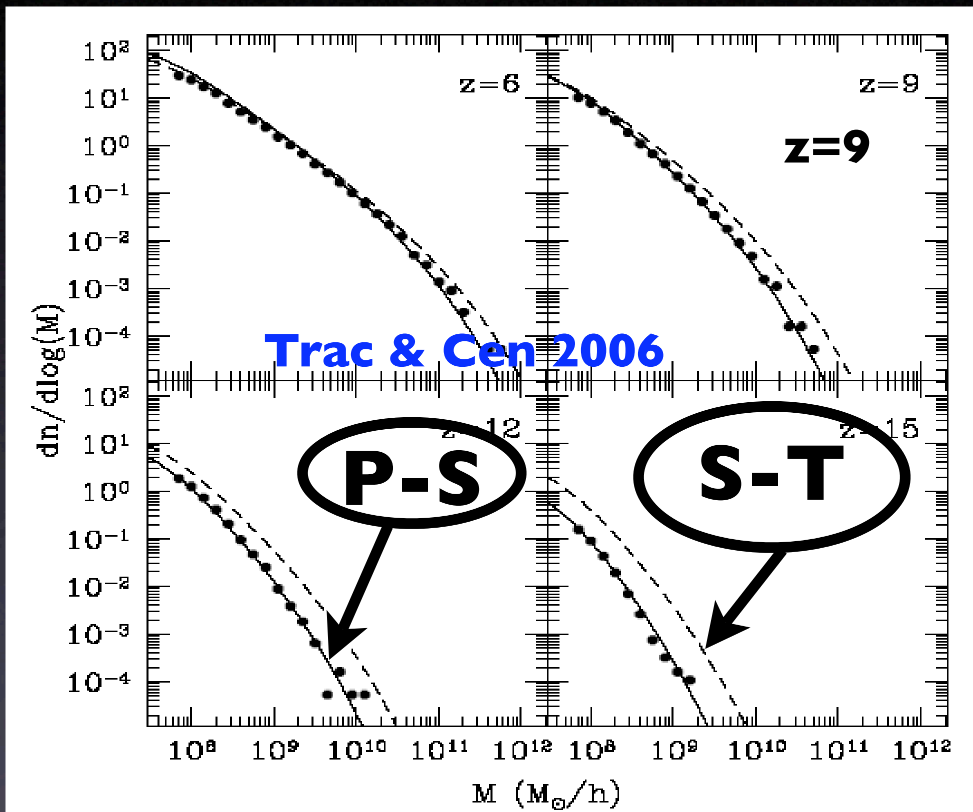
Overdensity finder

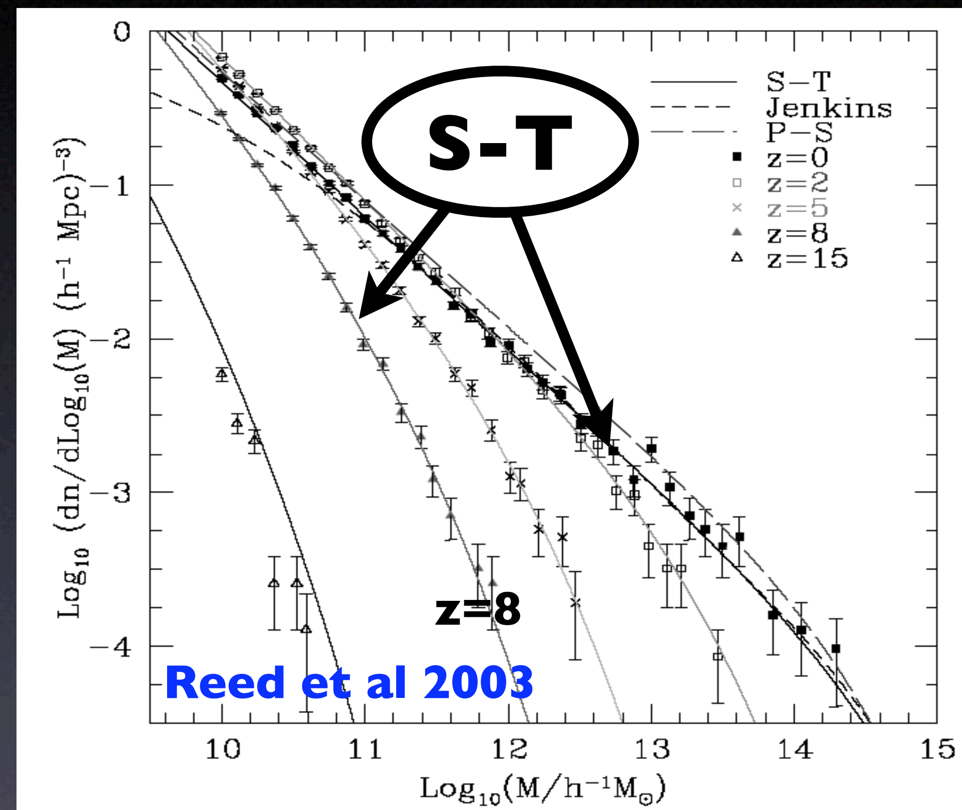
Challenges for the Simulation of the Mass Function and its Evolution

K. H., Z. Lukic, S. Habib, P.M. Ricker ApJ 642, L85 (2006)
Z. Lukic, K.H., S. Habib, S. Bashinsky, P.M. Ricker ApJ 671, 1160 (2007)

- ✓ **First halos at high redshift very small: need very high mass resolution (difficult because lots of particles are needed) or small boxes (not very good statistics)**
- ✓ **Very high starting redshift: small halos form early, initial conditions in simulation don't have halos, enough time for halo formation to take place is required**
- ✓ **Number of time steps: high starting redshift and enough time for halo formation lead to time step criteria**
- ✓ **Force resolution: in order to be able to resolve small halos, force resolution needs to be sufficient**

Contradictory Results on the Form of the Mass Function at High Redshift? Press-Schechter or Sheth-Tormen like?



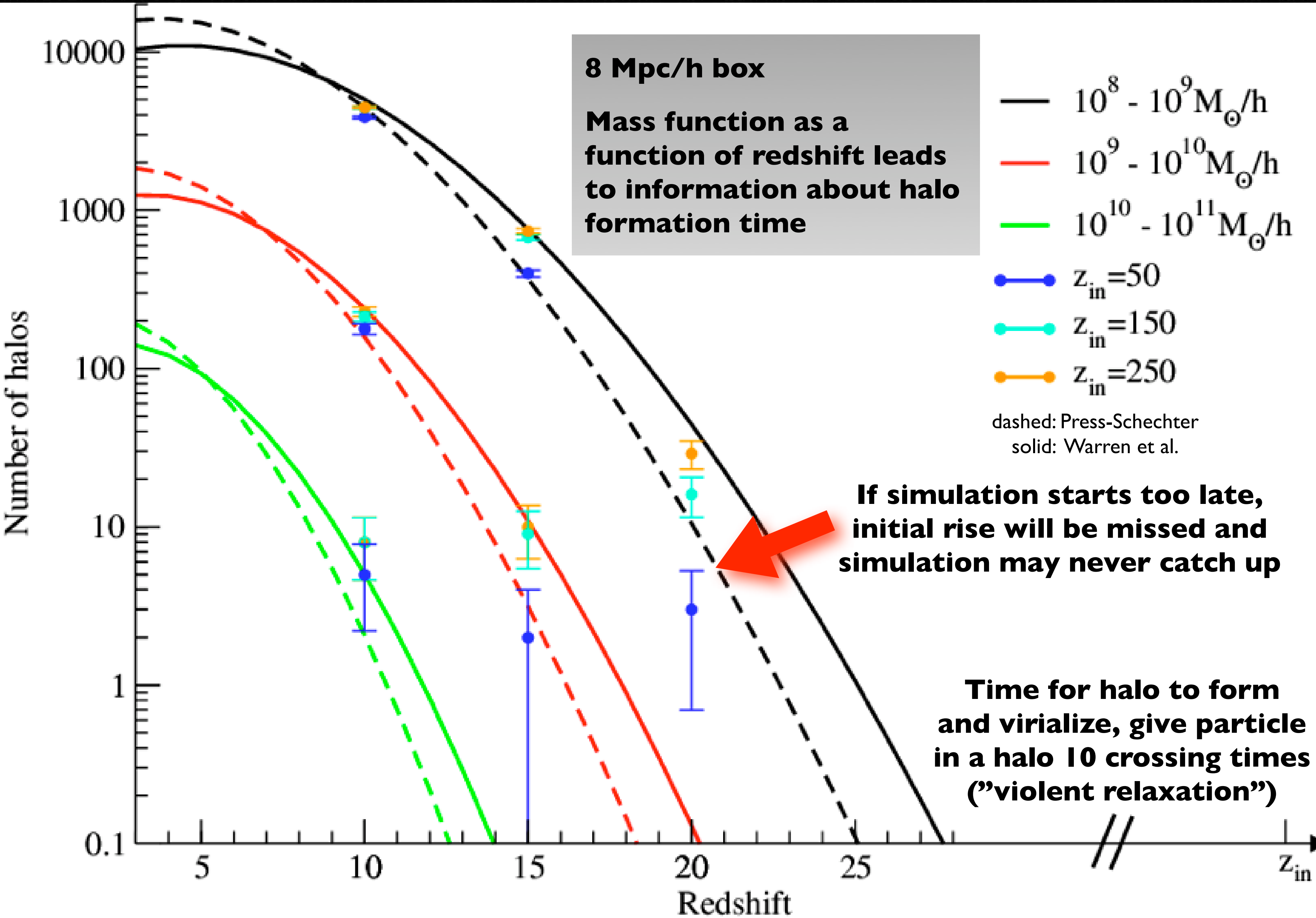


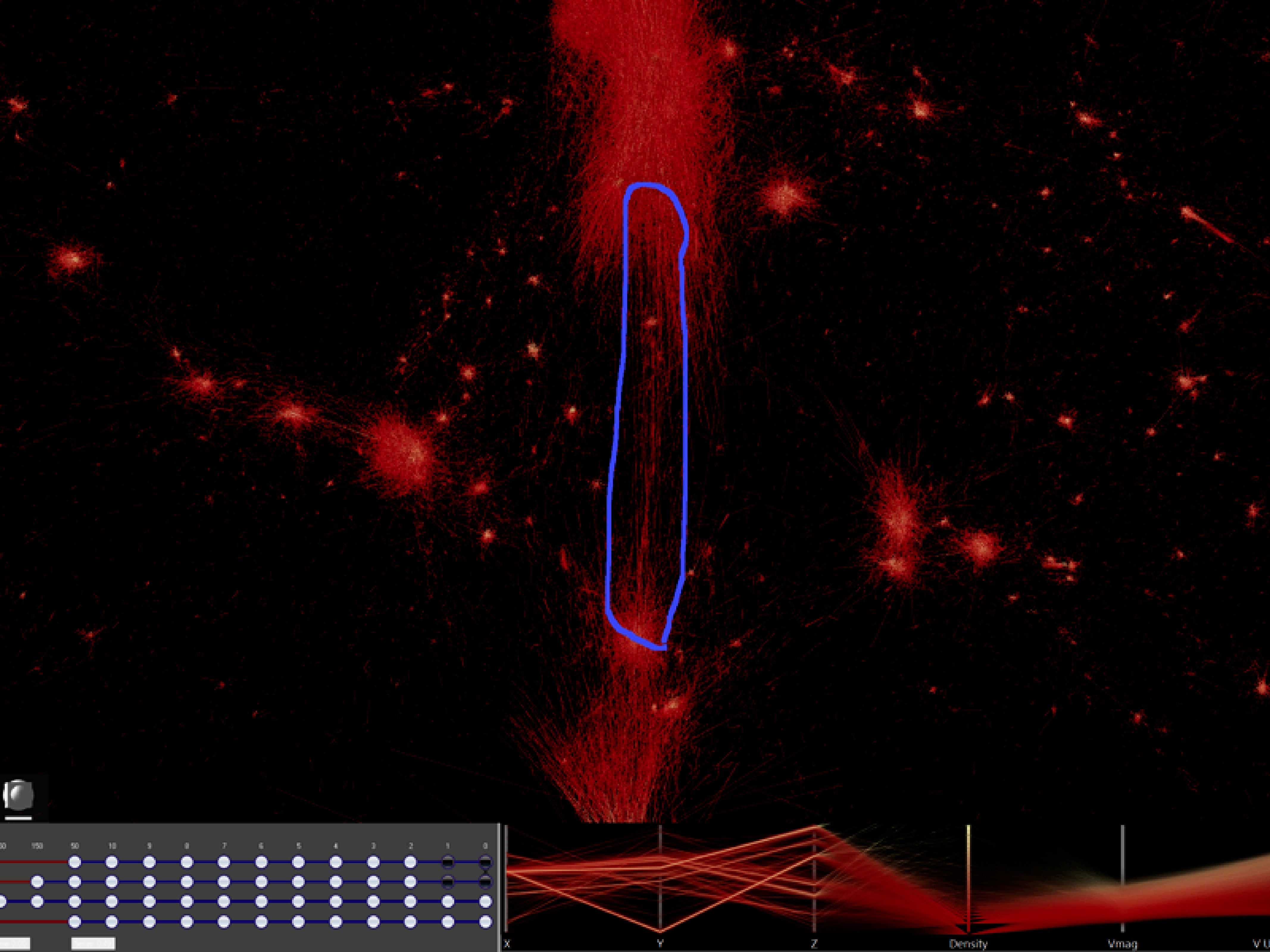
Particle Mesh Code PMM
50Mpc/h box,
initial redshift z=60

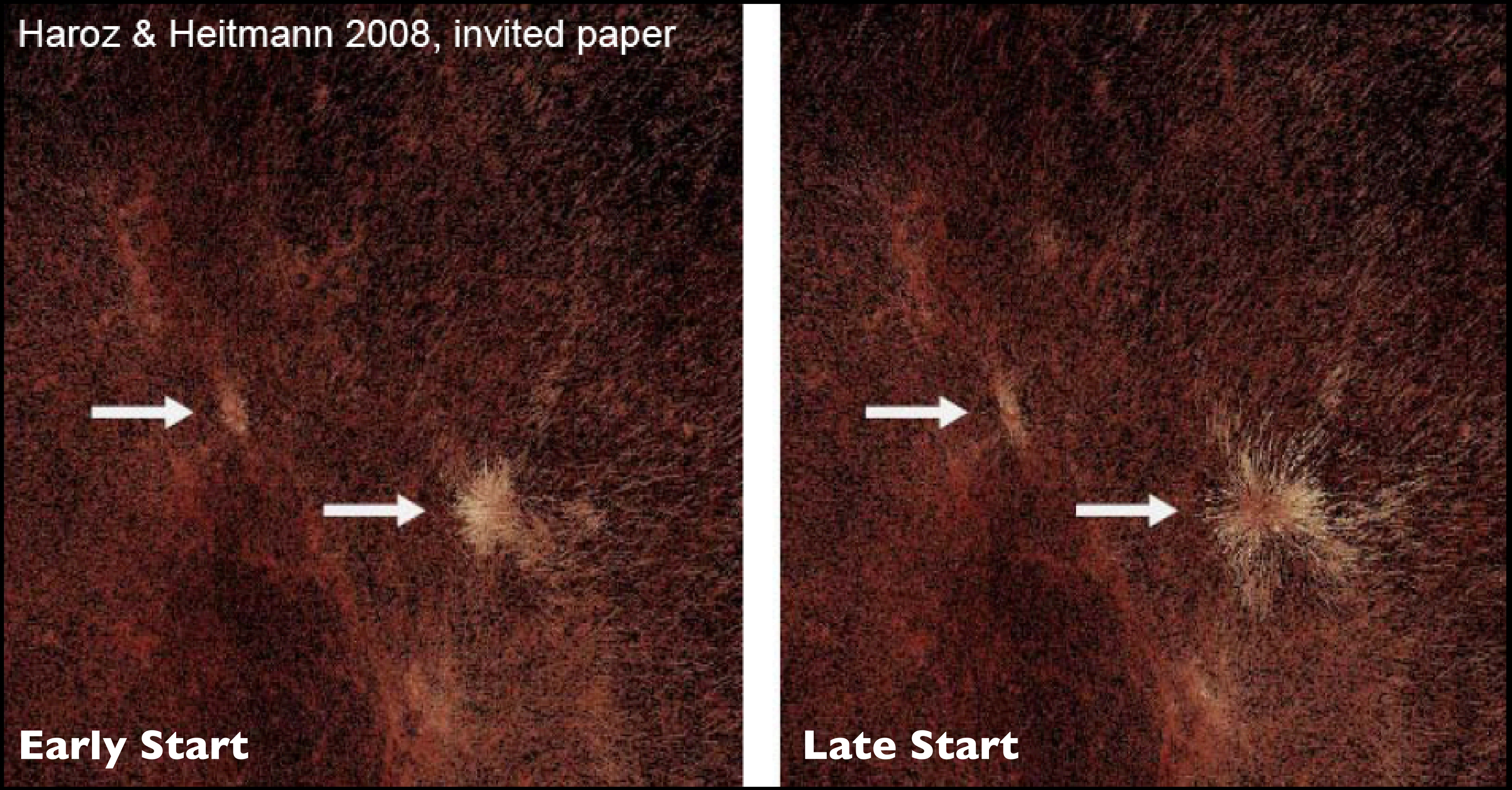
Tree Code PKDGRAV
50Mpc/h box,
initial redshift z=130

Both code participated in code comparison, good agreement!

Halo Growth Function




X
Y
Z
Density
Vmag


Haroz & Heitmann 2008, invited paper
Early Start
Late Start

Force Resolution Criteria

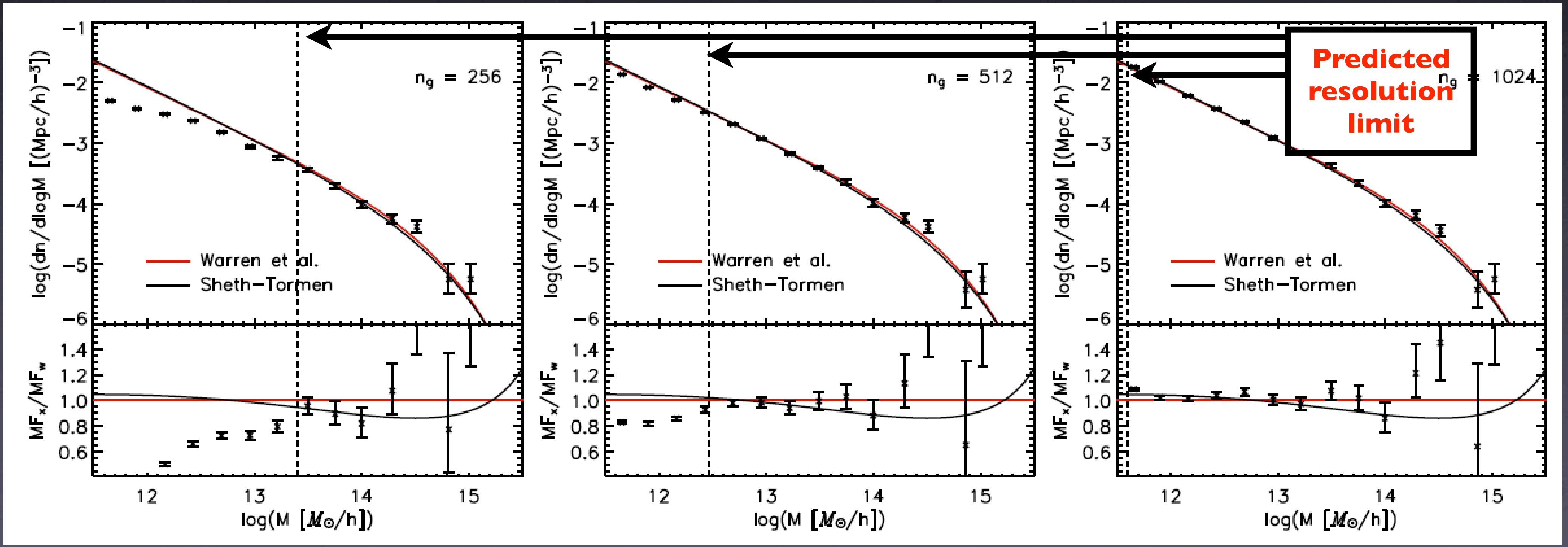
- **Force resolution δ_f should be smaller than R_{200}**
- **We do not need to resolve the inner part of the halo!**

# of particles in halo

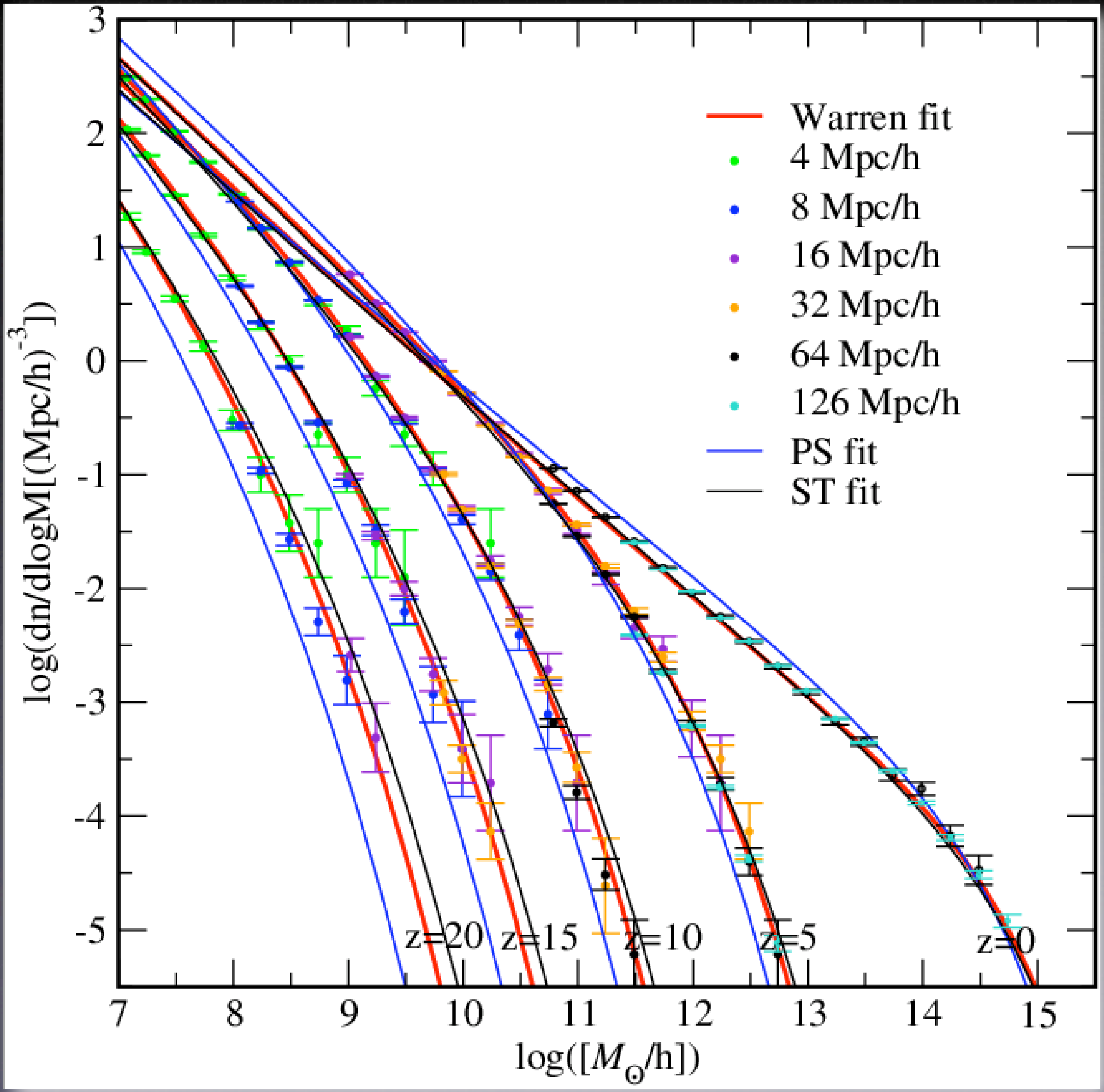
$$\frac{\delta_f}{\Delta_p} < 0.62 \left[\frac{n_h \Omega(z)}{\Delta}\right]^{1/3}$$

Interparticle spacing

Overdensity

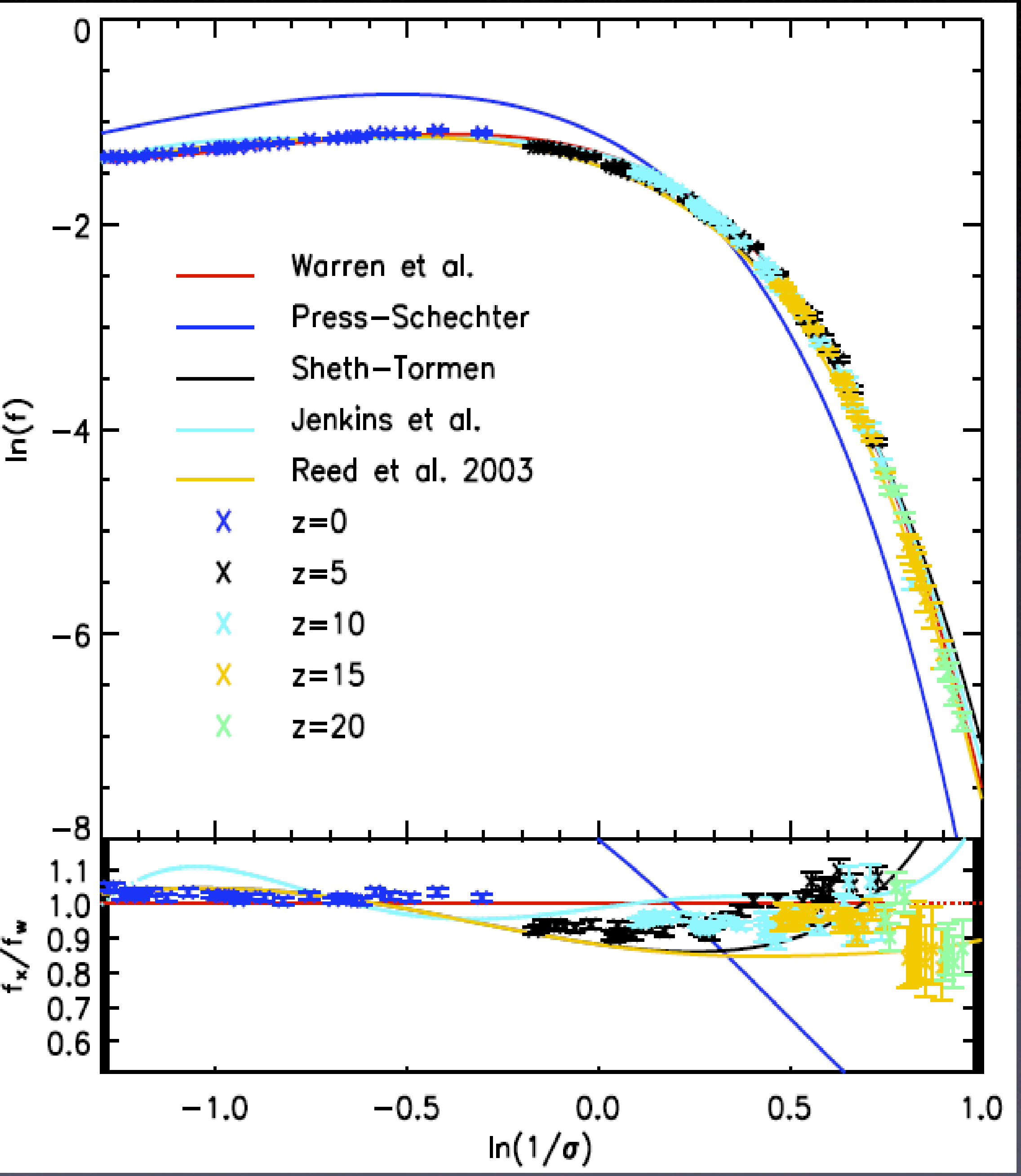


Mass Function Summary I



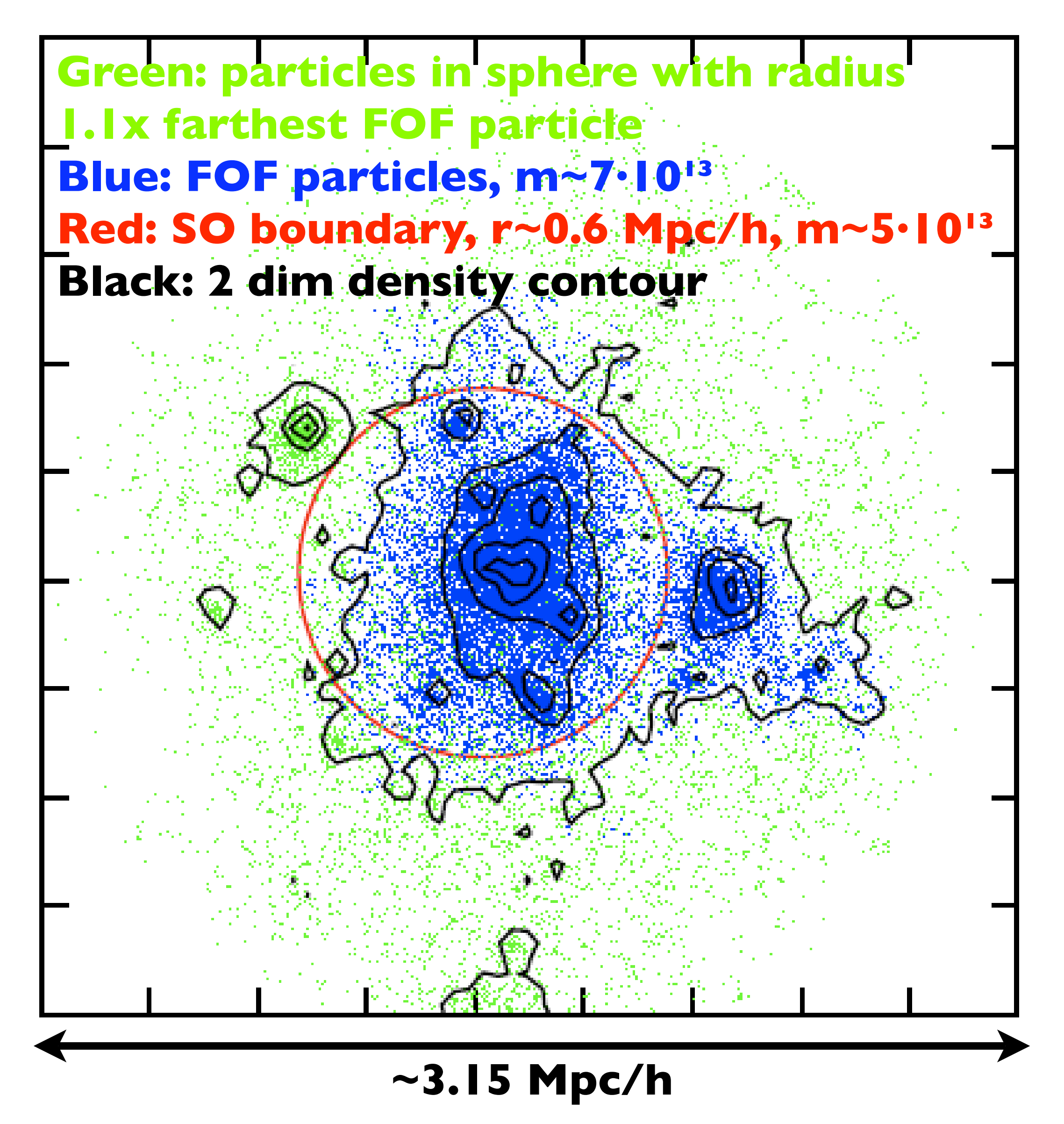
- 64 simulations of varying box size, covering large mass range
- Good agreement with Warren et al. (2006) down to z=20
- Press-Schechter is off by an order of magnitude at high z
- Careful study of: resolution and time step criteria, starting z, box size effects

Mass Function Summary II: Universality

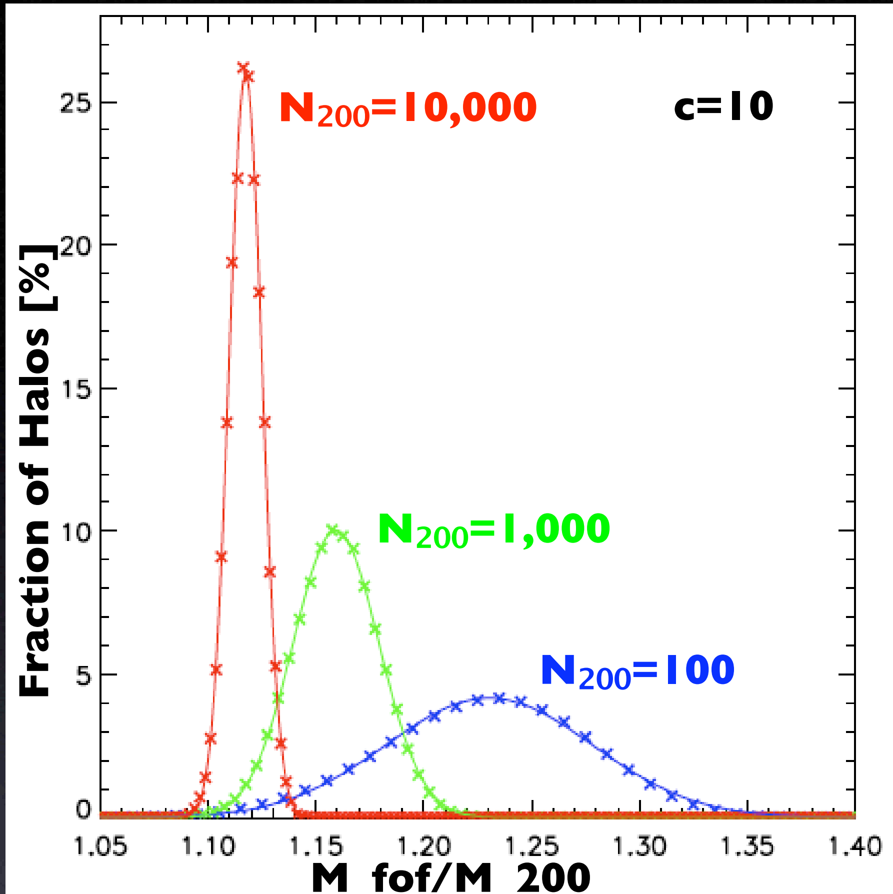


- Mass function in terms of σ(M)
- Universality holds at the 10% level over wide redshift range
- Advantage: no need to run a simulation for each cosmology
- Can we accurately connect FOF halo mass to SO and give simple translation between mass functions? (earlier work: White 2001)

Halo Masses



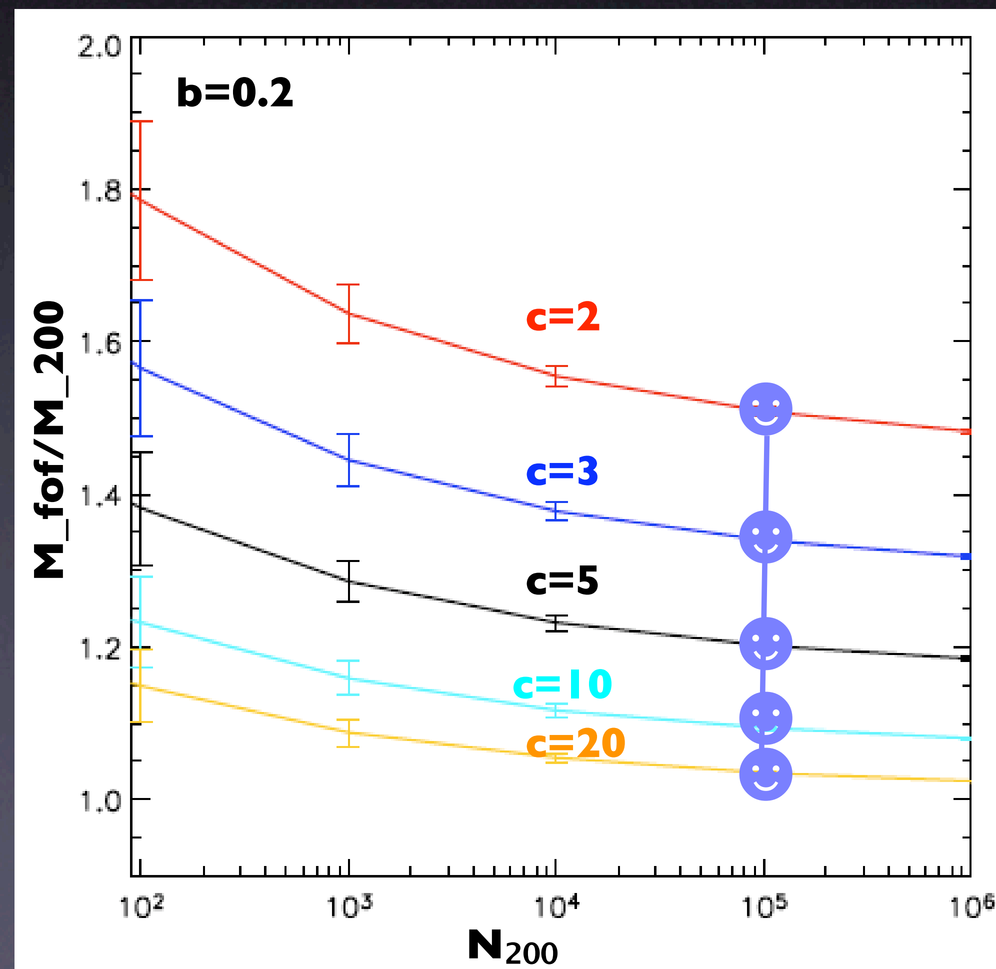
- FOF mass: follows iso-density contours, hence tracks shapes of bound objects faithfully
- SO mass: builds spheres around density peaks, easier to relate to e.g. X-ray gas, which is measured in 2-d projection
- Not all halos are round! Neither in observations nor in simulations!
- Choose halo definition with observational probe in mind, none is prefect...
- Easy translation between them would be very helpful!



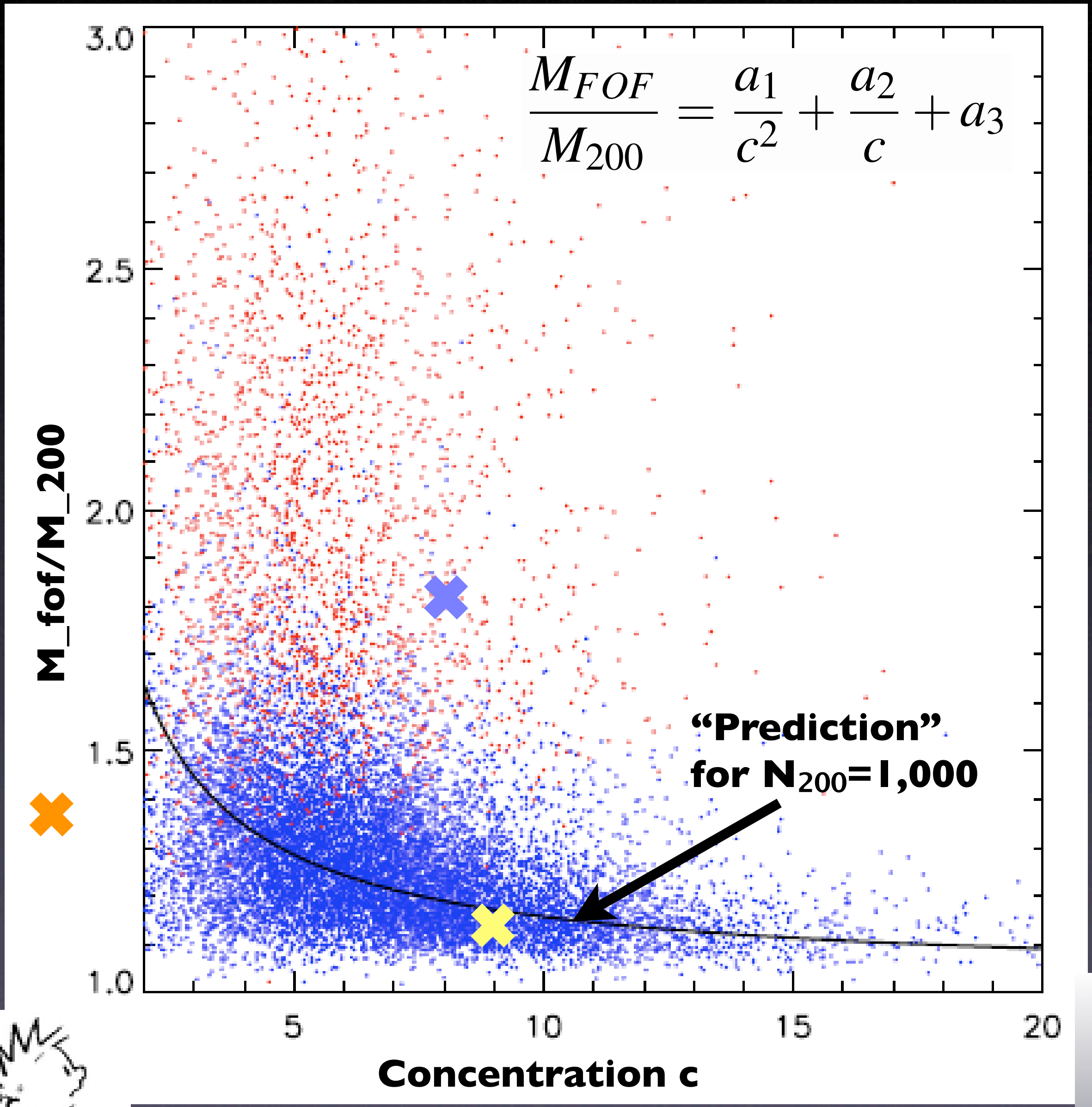
Mock Halos

- Assume density profile for halo, here: Navarro-Frenk-White (NFW, 1996) profile, empirically found to fit dark matter halo profiles in simulation
- Populate halo with particles according to profile and given overdensity mass, add additional particles in the tail

- Generate millions of FOF mock halos and measure SO mass (here: M_{200} wrt. critical)
- Relation between SO and FOF mass depends on concentration c, particle sampling, linking length, code resolution (changes c)

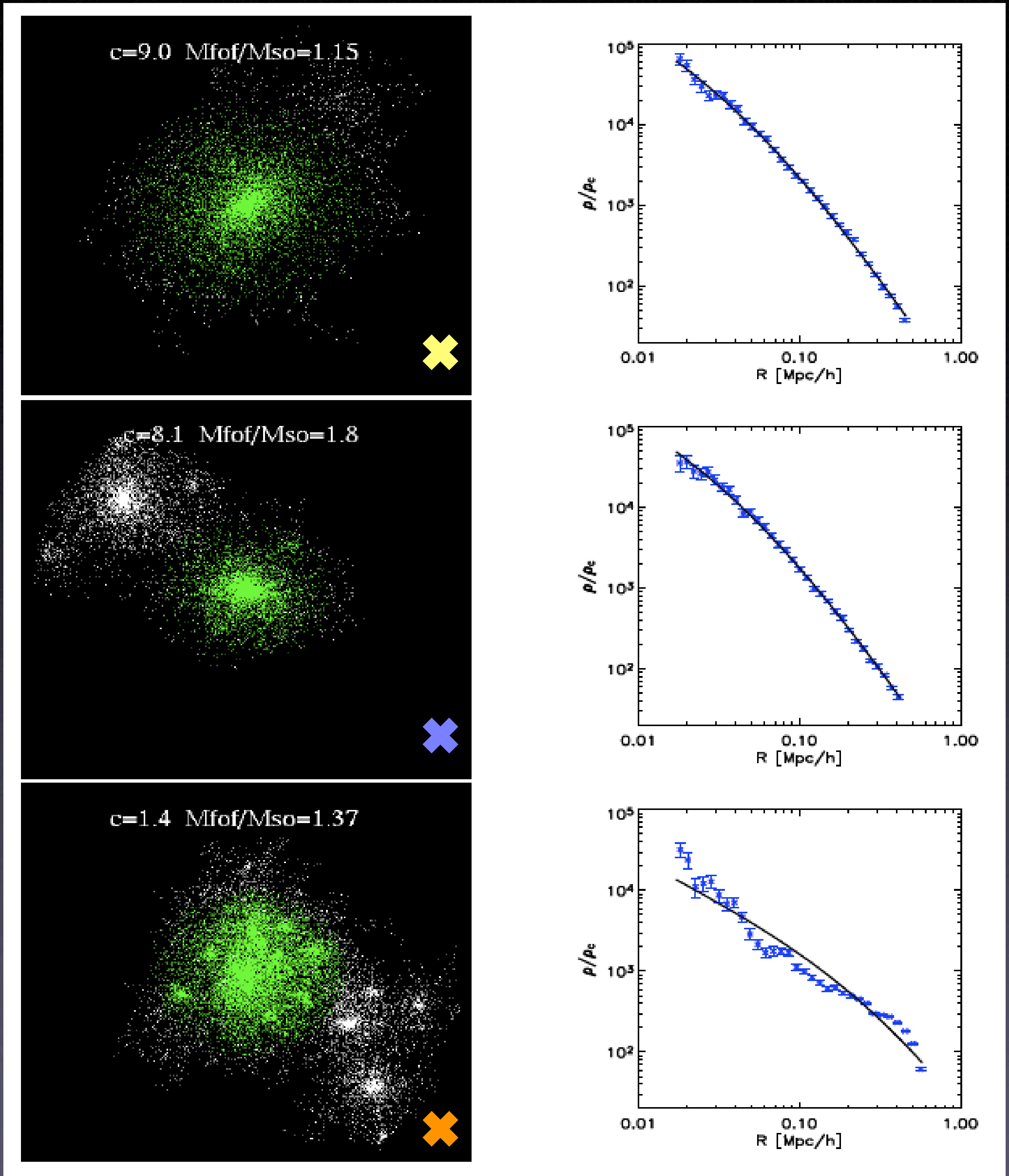


Comparison with Simulated Halos



- Measure FOF and SO from simulation, SO is found from FOF centers
- Halos with more than 1,000 particles
- For some halos: mass ratio much too high, for some halos concentration very low
- Take a "look" at halos from above the prediction, below the prediction, following the prediction

4 Gadget-2 runs: 512³ particles each, two 174Mpc/h and 512Mpc/h boxes each, two cosmologies, main difference: σ_8=0.75 and σ_8=1.0

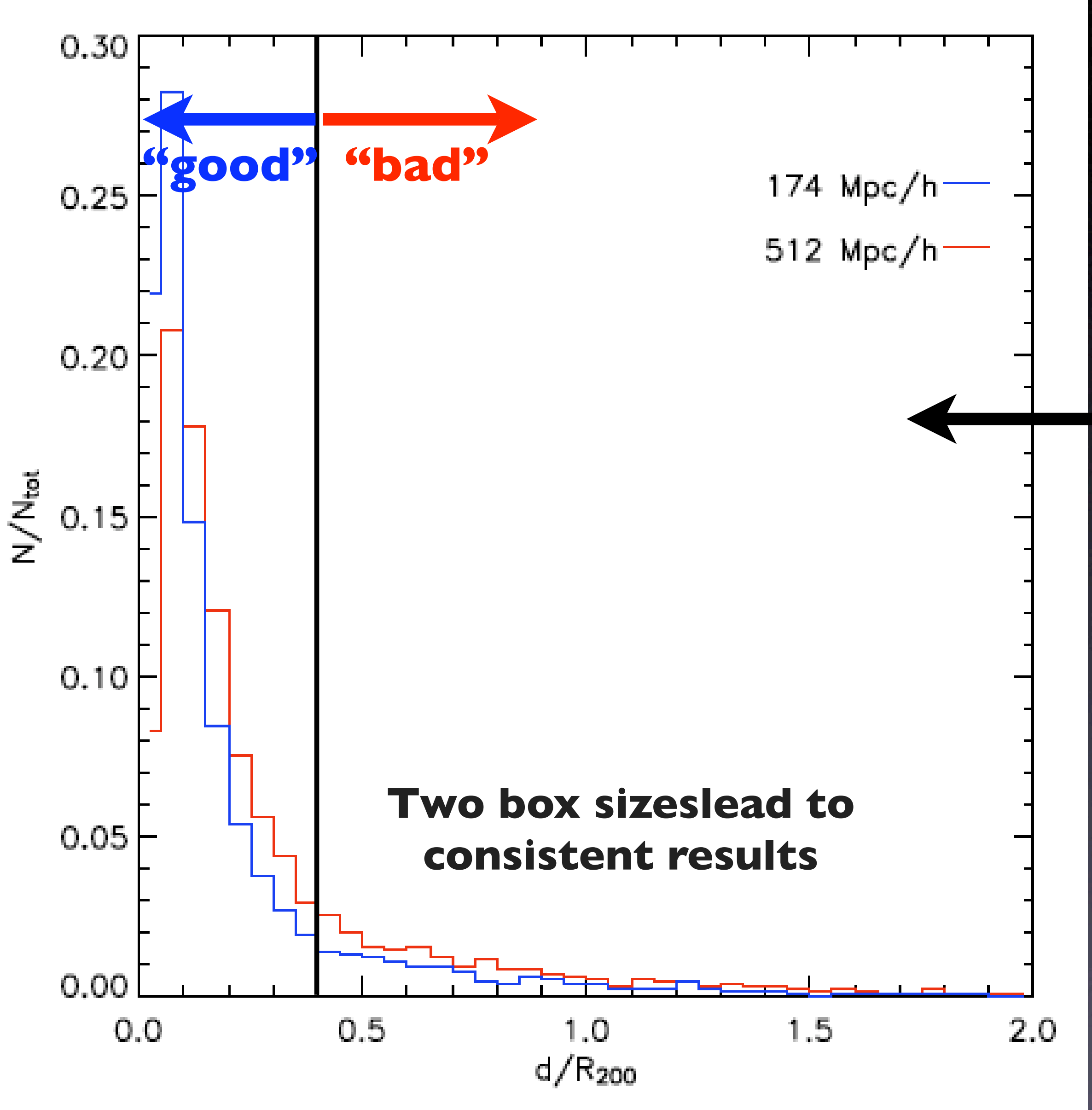


**c=9, M_fof/M_200=1.15
NFW profile fits well,
Clear center around
which SO is determined,
Prediction works well**

**c=8.1, M_fof/M_200=1.8
“Bridged halo”, center
is not well defined,
NFW profile fits well
for main halo, but mass
prediction ignores
second componnet**

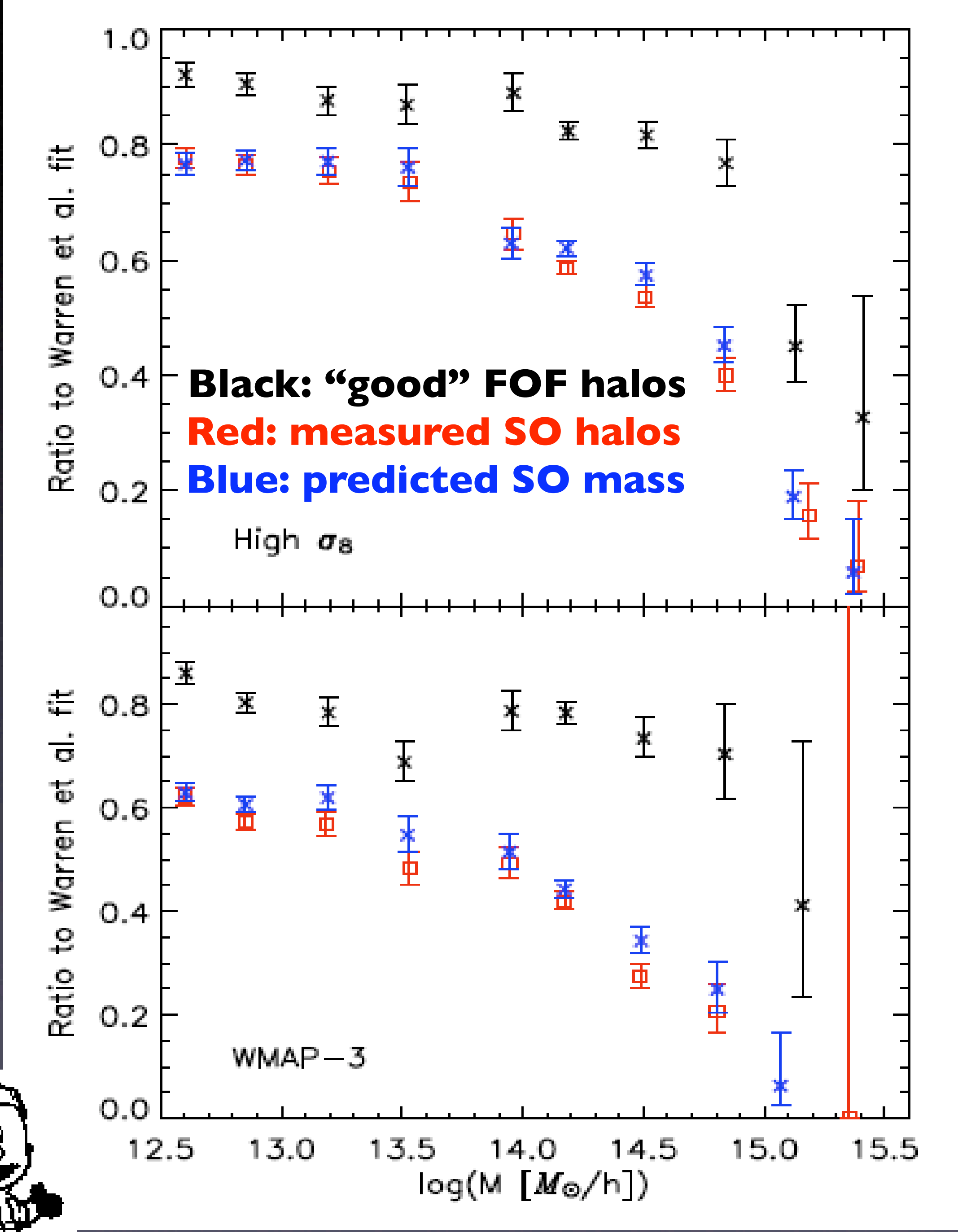
**c=1.4, M_fof/M_200=1.37
Lots of substructure,
NFW profile off,
concentration wrong**

The “good” and the “bad” Halos



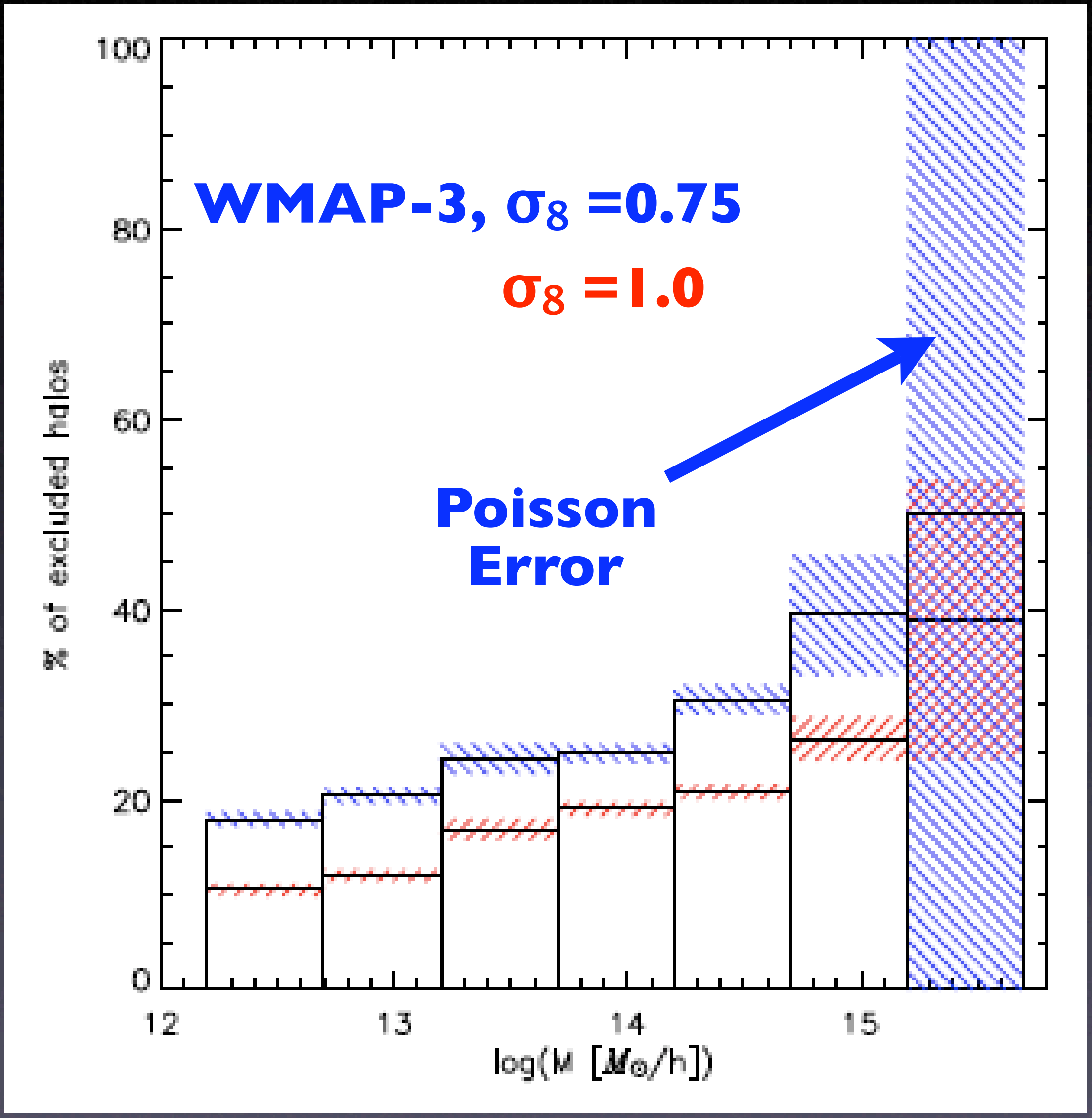
- Three different methods explored to identify “bad” halos:
  1. Exclude every halo with ratio > 2
  2. Measure potential minimum and center of mass for FOF halo, if their distance > 0.4/R$_{200}$, exlude
  3. Find deepest potential minimum and get SO halo, look for second deepest minimum and grow next SO halo, if second mass is > 20% of first, exclude
- Consistent results for all methods, ~15% exclusion

Results for the Mass Function



- Consider only "good" halos, 85% of all halos
- Measure FOF mass and SO mass
- Predict SO mass from FOF mass and concentration halo by halo
- Agreement better than 5%!
- Next step: replace halo-by-halo mapping by using M-c relation and scatter (in prep.)
- Got sidetracked on that because....

Perhaps the “bad” ones are also good??



- Measure fraction of excluded halos as a function of their mass: clear cosmology dependence!
- As function of M_* (characteristic collapse mass): universal (?)
- For $M_{200} \geq 10^{14}$ Msun: fraction of halos with major satellite as function of satellite mass fraction cosmology dependent
- Advantage over mass function: relative measure

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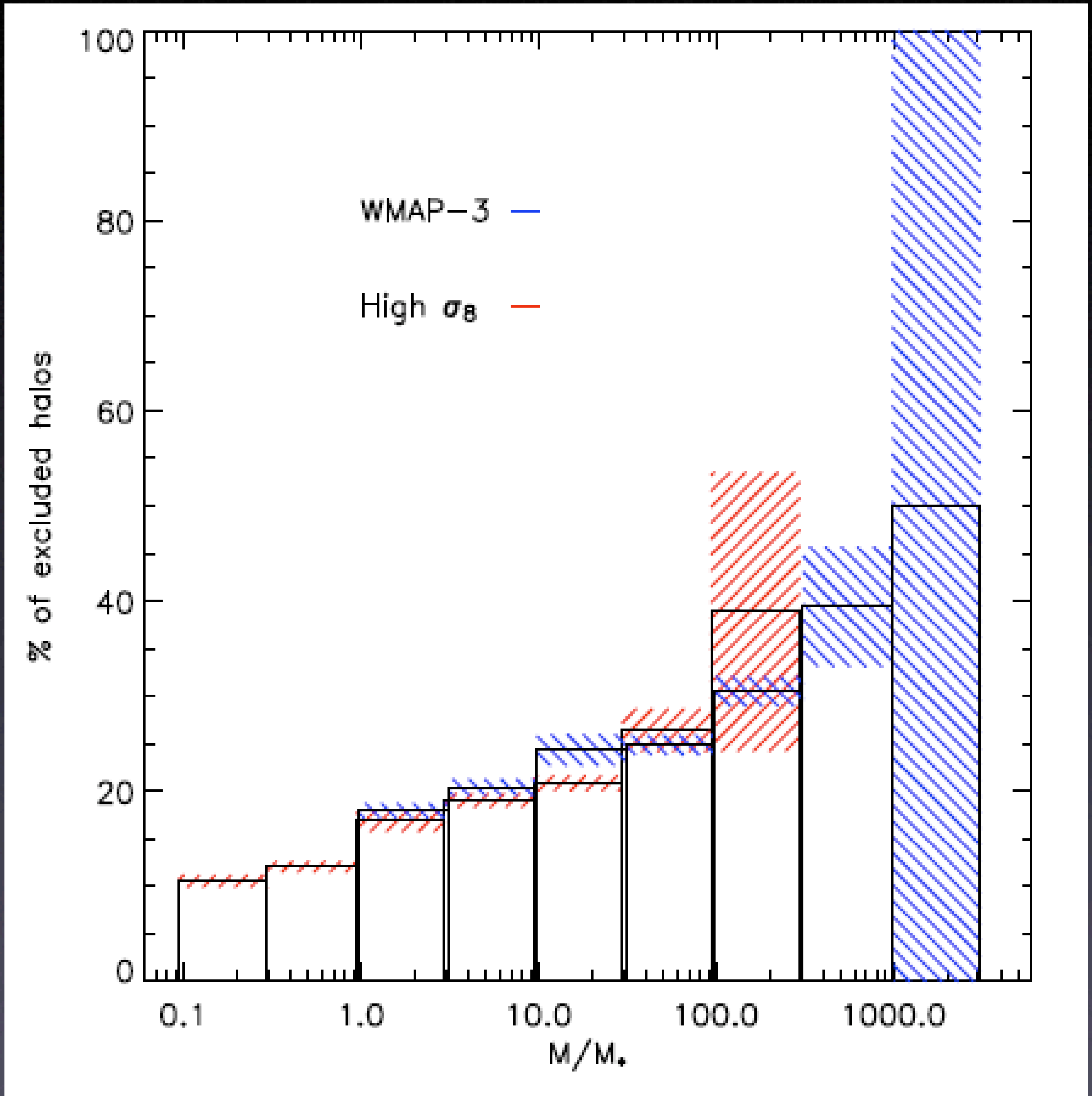

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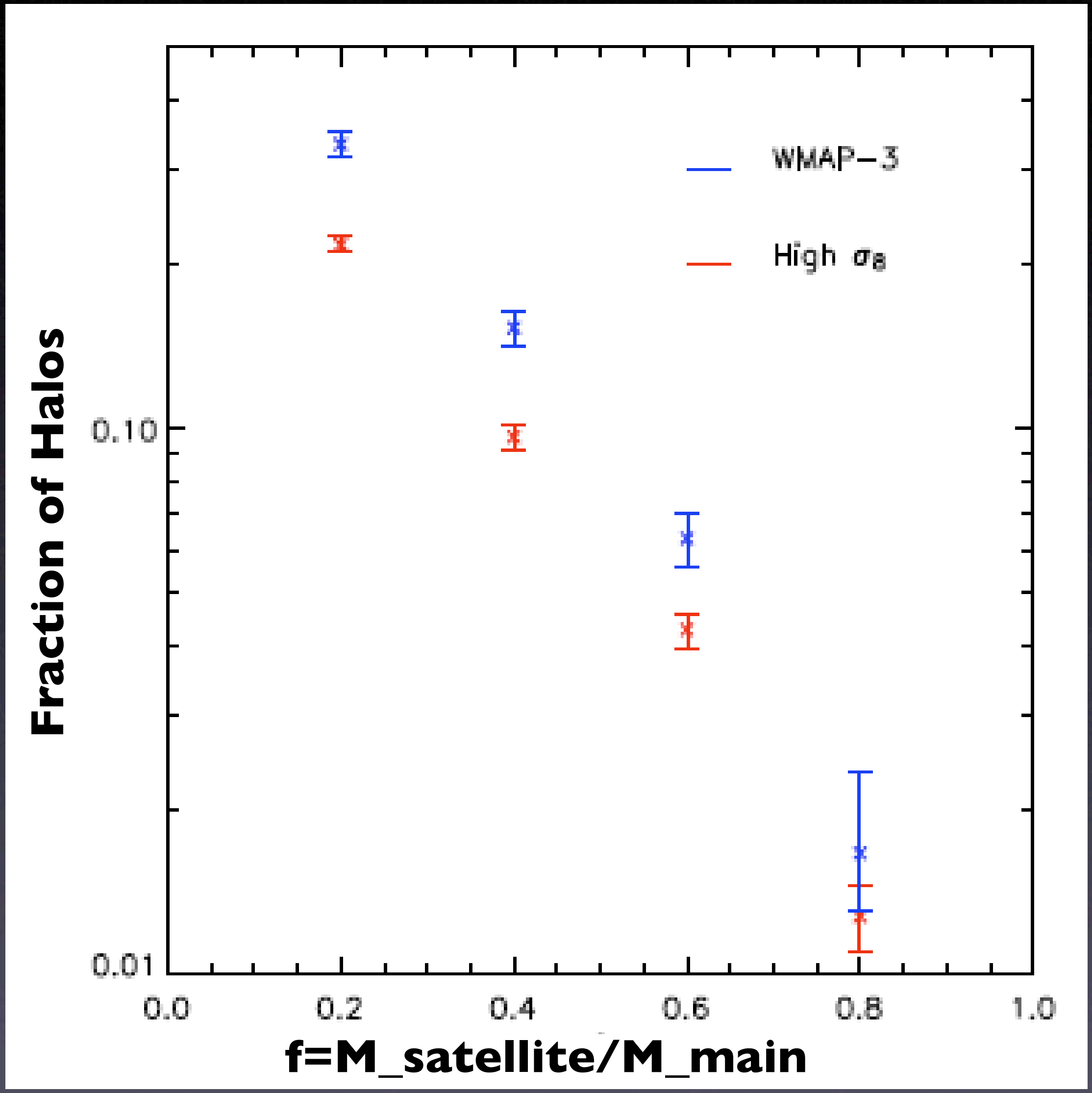

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Conclusion and Summary

- FOF mass function carefully characterized out to z=20
- Extremely robust: we derived conditions for starting redshift, force resolution, number of time to get mass function at 5% accuracy
- Universality holds at 5% level for b=0.2
- SO mass: much more difficult to measure, sufficient mass resolution important
- Derived connection between FOF mass and SO mass for “nice” halos, depending on c and N
- Fraction of halos in merging state contains information about cosmology, advantage: relative measure, volume selection is mitigated