MIT, October 2005

The Assembly History and substructure of ΛCDM Halos

Simon D.M. White
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- Does the excursion set model describe halo assembly?
  Not all aspects, but it fits many very well
- Is the substructure mass function universal?
  YES -- but *not* when scaled to halo mass
- Is significant mass in low mass substructures?
  NO -- the most massive subhalos dominate
- Is substructure content correlated with other halo properties?
  YES – with halo concentration and formation time
- Are substructures as "old" as their host halos?
  NO -- most fell in at $z<0.5$, *after* typical DM particles
- Do subhalo histories depend on radius within the host?
  YES – mass loss and accretion redshift anticorrelate
- Do satellite galaxies follow the subhalo distribution?
  NO -- they follow the *mass* distribution more closely
- Is the internal structure of subhalos similar to that of halos?
  NO -- their profile slope changes much more rapidly

The phase-space substructure of a dark matter halo

Helmi, White & Springel 2002 Phys.Rev.D. 66, 3502

Dark matter annihilation in the halo of the Milky Way

Stoehr, White, Springel, Tormen, Yoshida 2003 MNRAS 345, 1313

Substructures in cold dark matter haloes

De Lucia, et al. 2004 MNRAS 348, 333

The subhalo populations of ΛCDM dark haloes

Gao, White, Jenkins, Stoehr & Springel 2004b MNRAS 355, 819

Galaxies and subhaloes in ΛCDM galaxy clusters

Gao, De Lucia, White & Jenkins 2004c MNRAS 352, L1

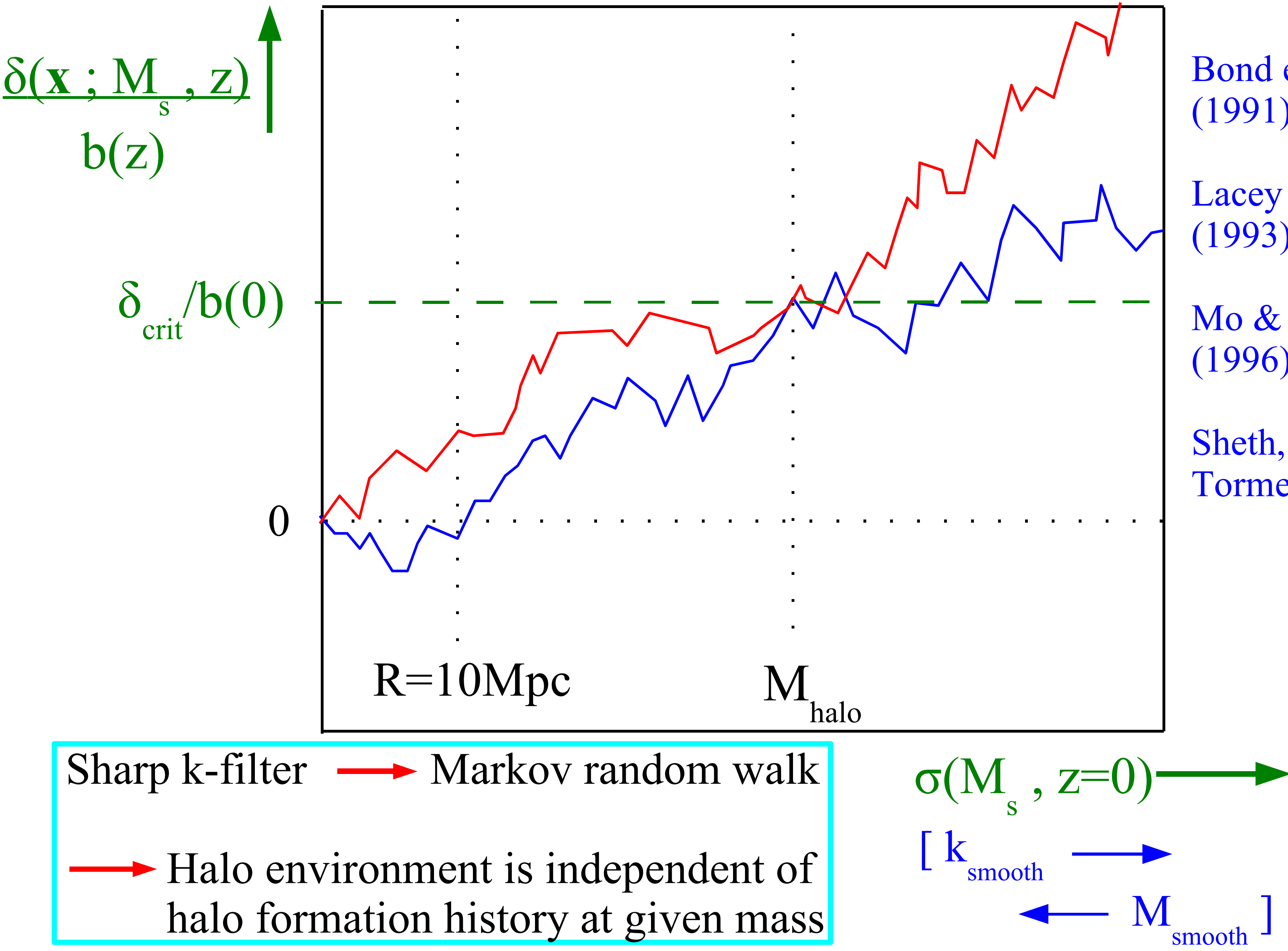
The age dependence of halo clustering

Gao, Springel & White 2005a MNRAS, in press

Early structure in ΛCDM

Gao, White, Jenkins, Frenk, Springel 2005b MNRAS, in press

Excursion-set model for structure evolution



Bond et al (1991)

Lacey & Cole (1993)

Mo & White (1996)

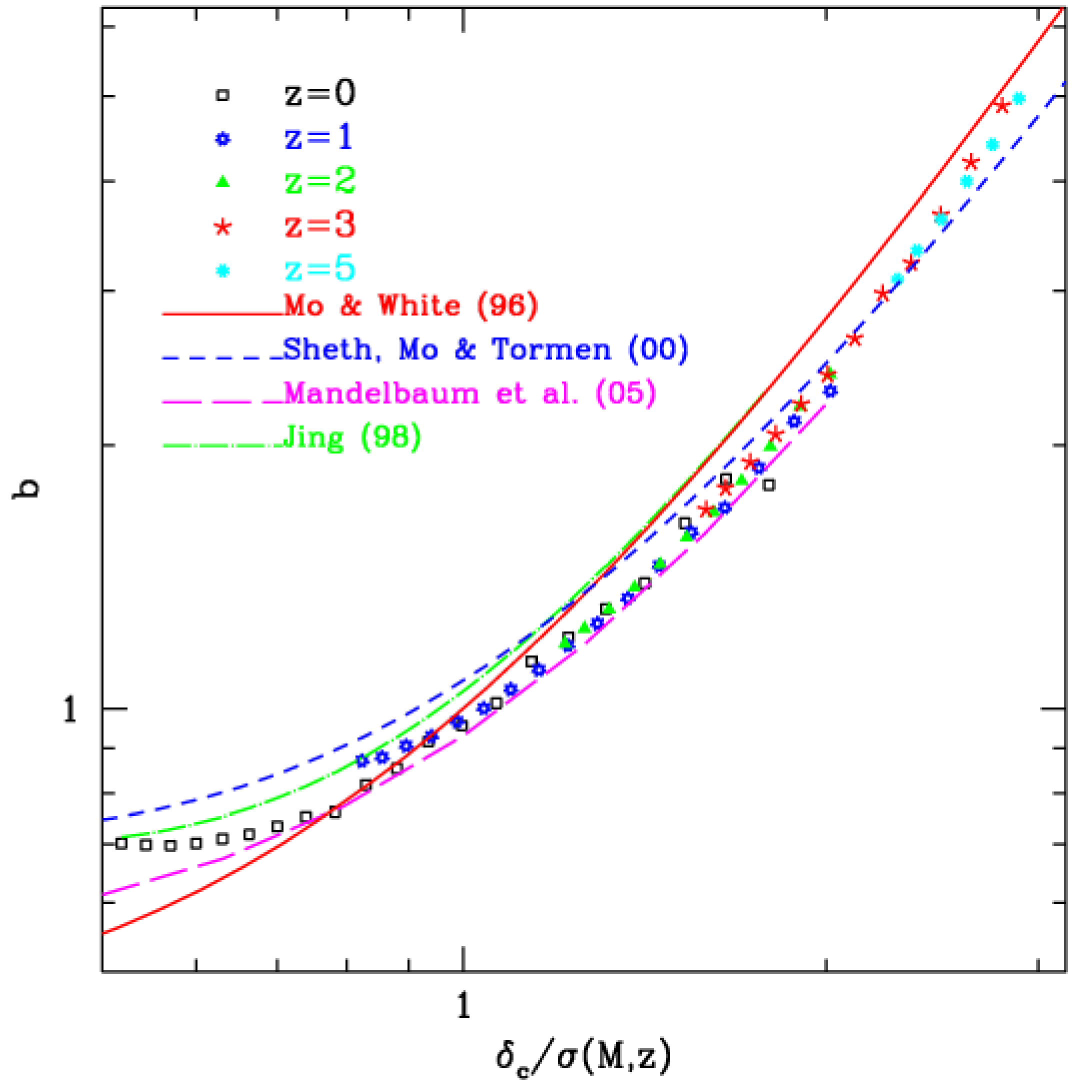
Sheth, Mo & Tormen (2000)

Sharp k-filter → Markov random walk

→ Halo environment is independent of halo formation history at given mass

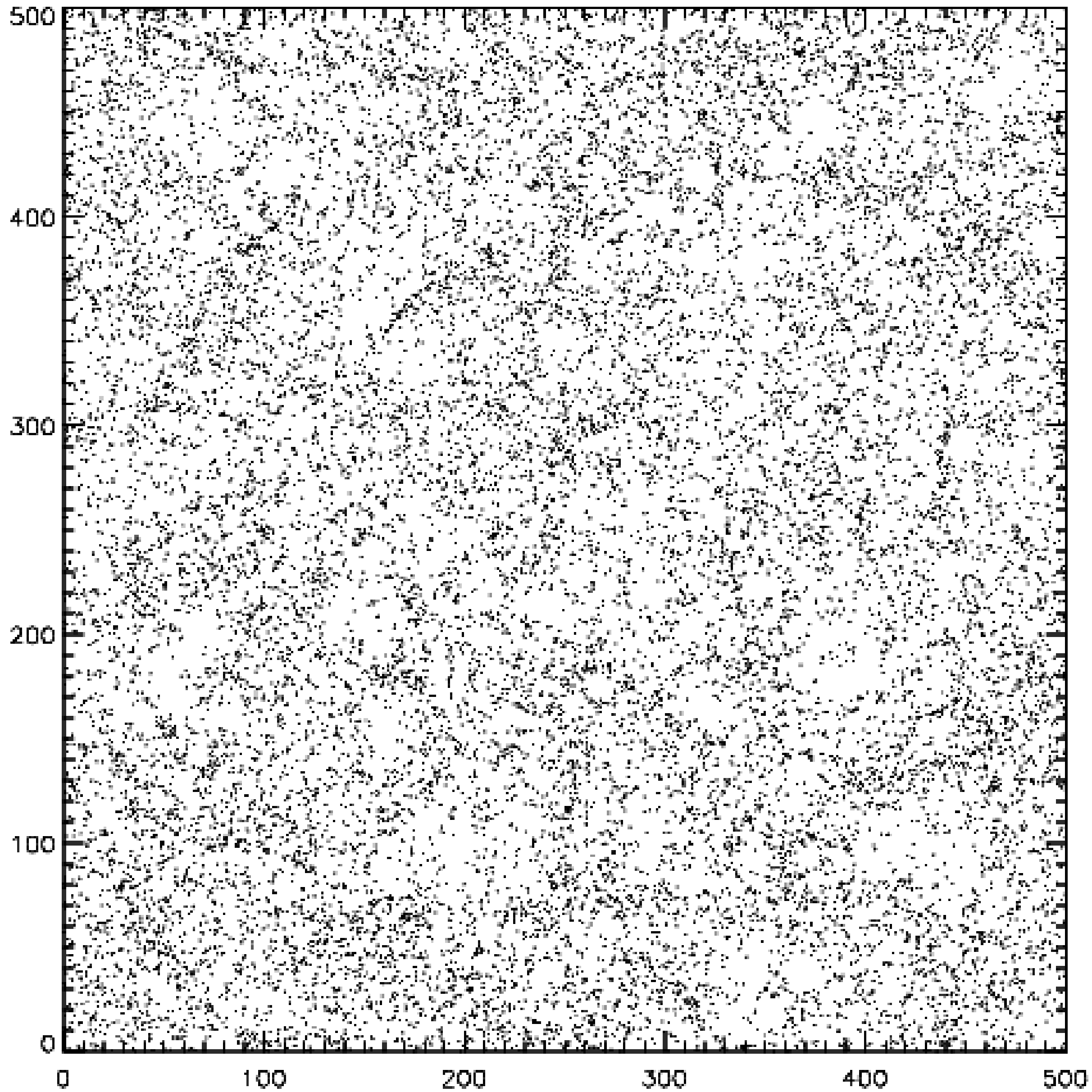
Mean halo bias as a function of mass

Gao, Springel & White 2005



- Massive halos cluster more strongly than low mass halos
- Different simulators agree on the strength of the effect to ~ 10%

Distribution of $10^{11}M_\odot$ halos in the Millennium Run



Gao, Springel & White 2005a

The 20% of halos with the *lowest* formation redshifts in a 30 Mpc/h thick slice

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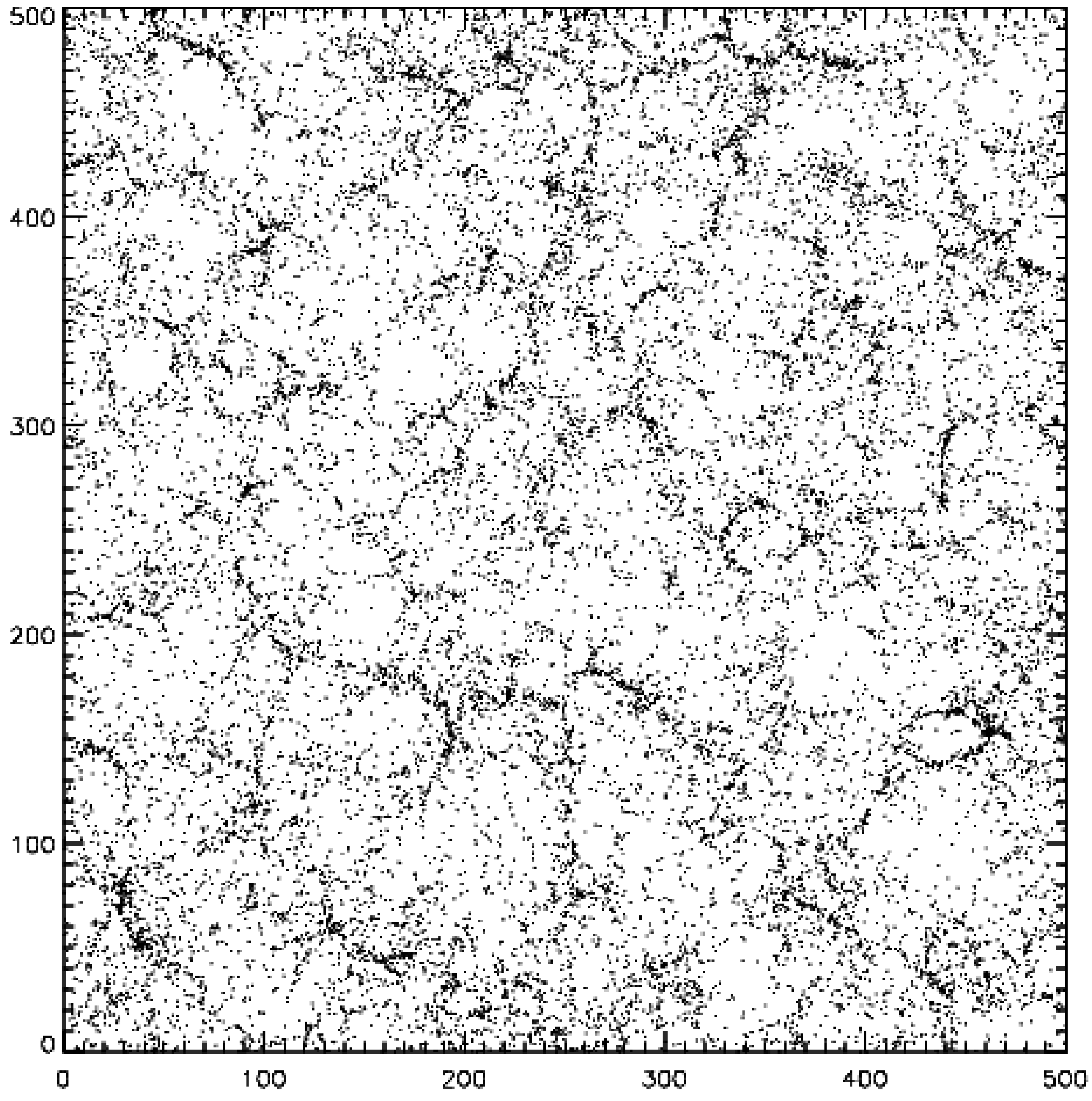

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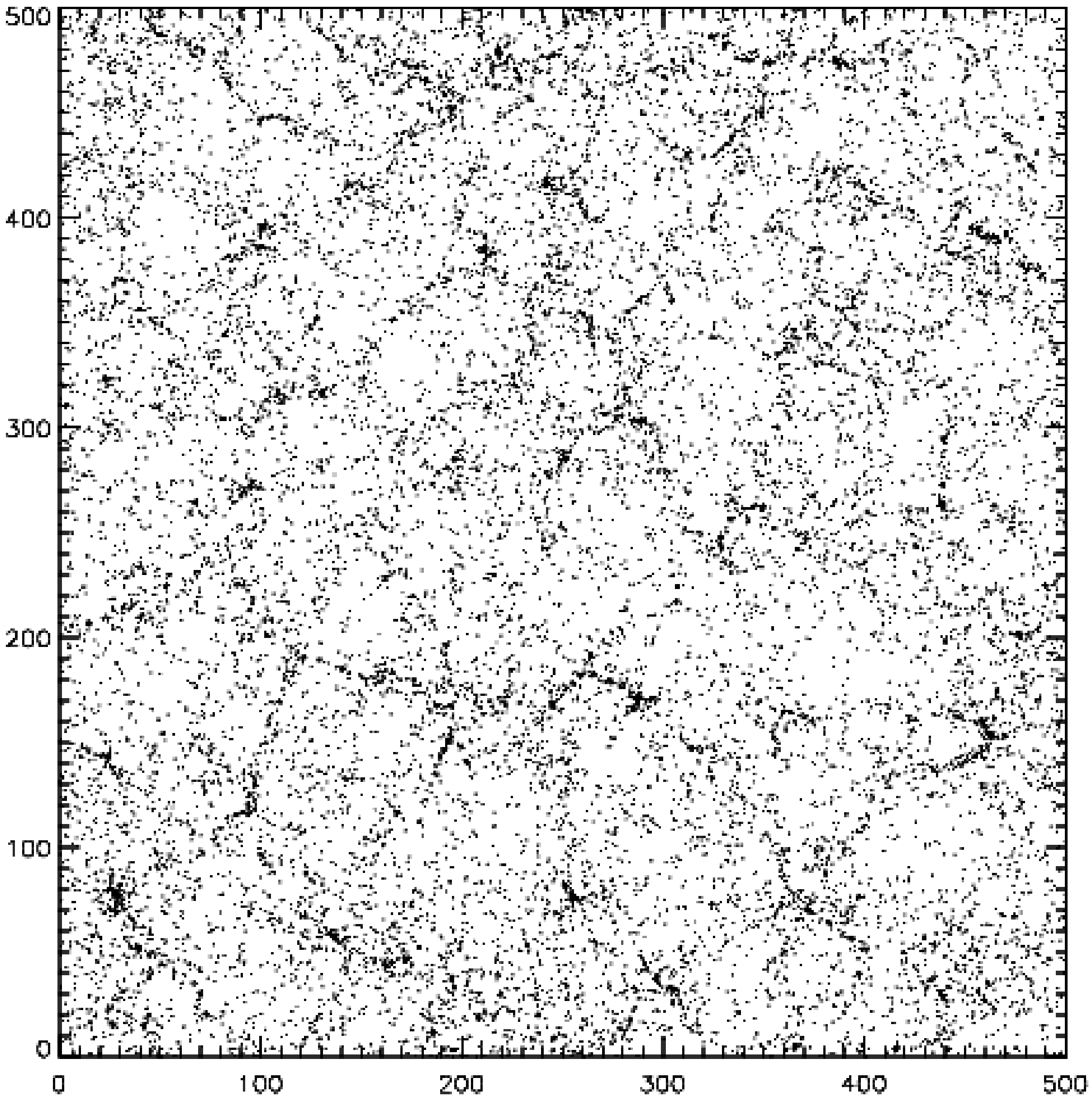
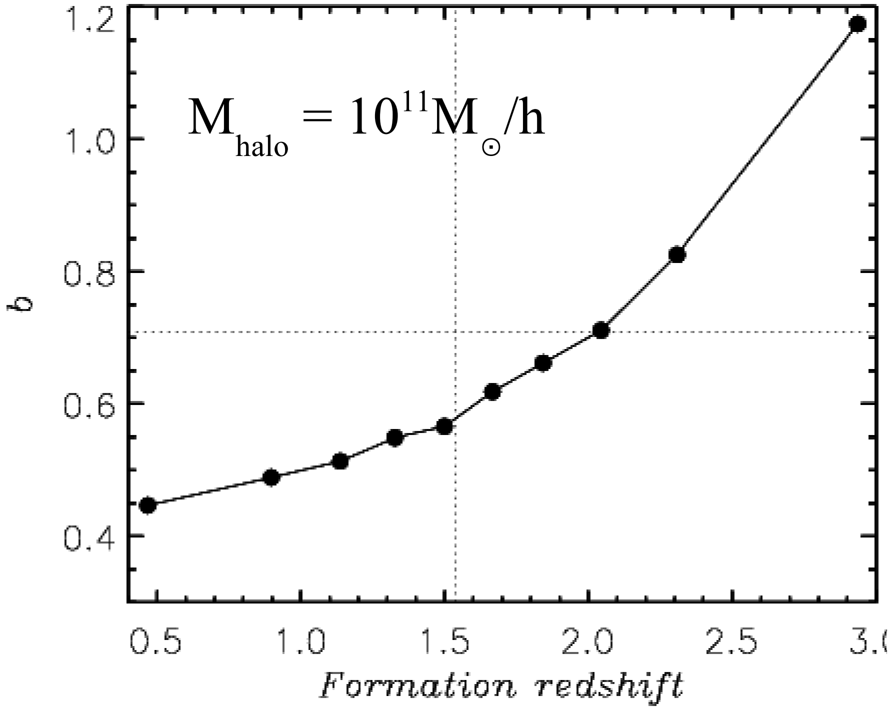


Gao, Springel & White 2005a

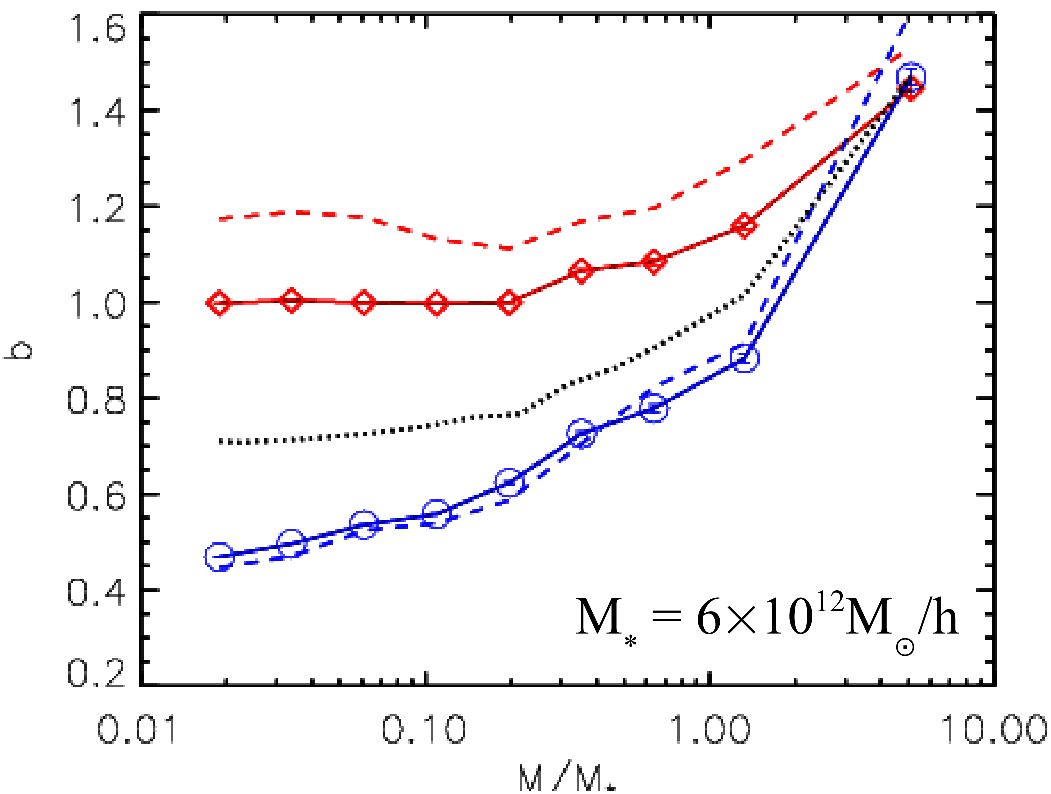
An equal number of randomly chosen DM particles

Halo bias as a function of mass and formation time

Gao, Springel & White 2005a



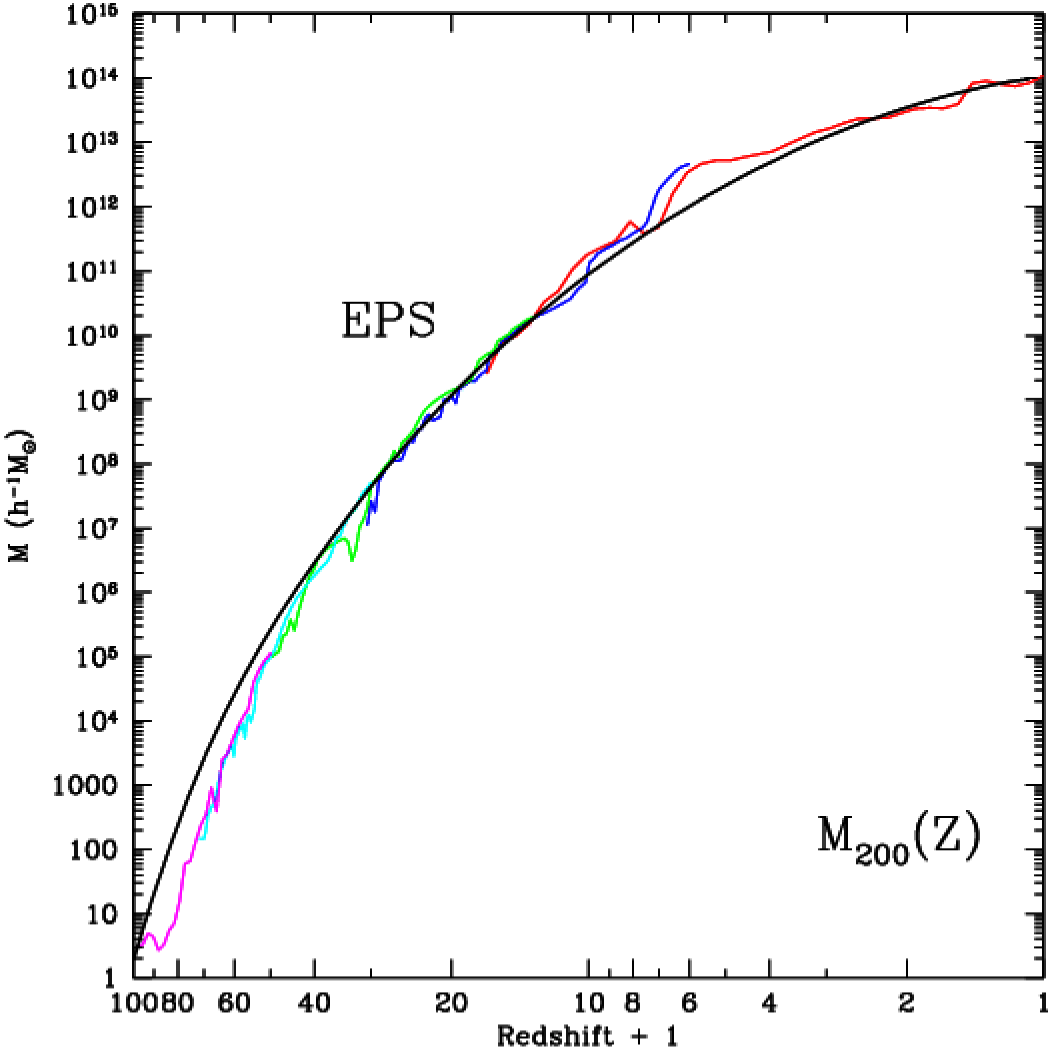
- Bias increases smoothly with formation redshift



- The dependence on formation redshift is strongest at low mass
- This dependence is consistent *neither* with excursion set models *nor* with HOD models

EPS theory and massive halo growth

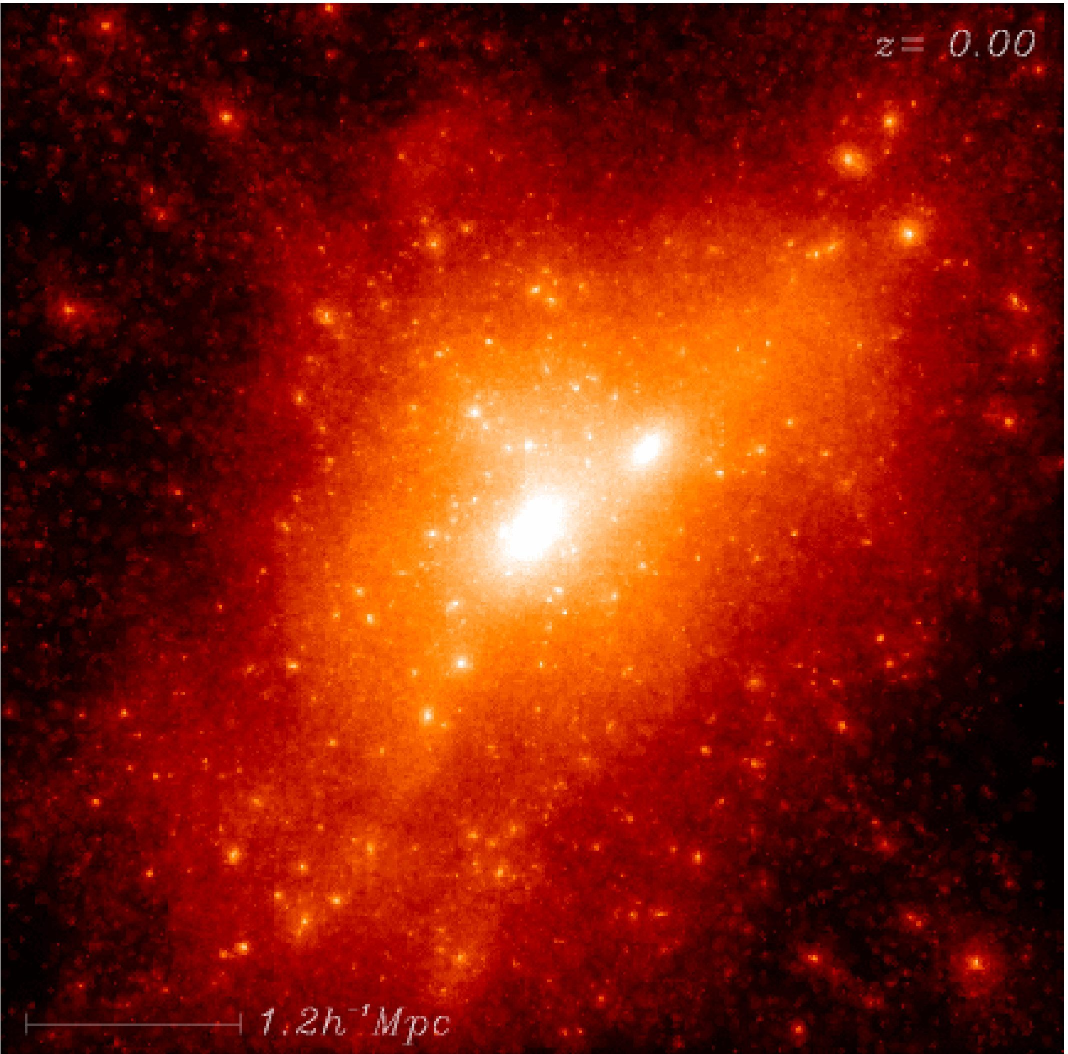
Gao et al 2005b

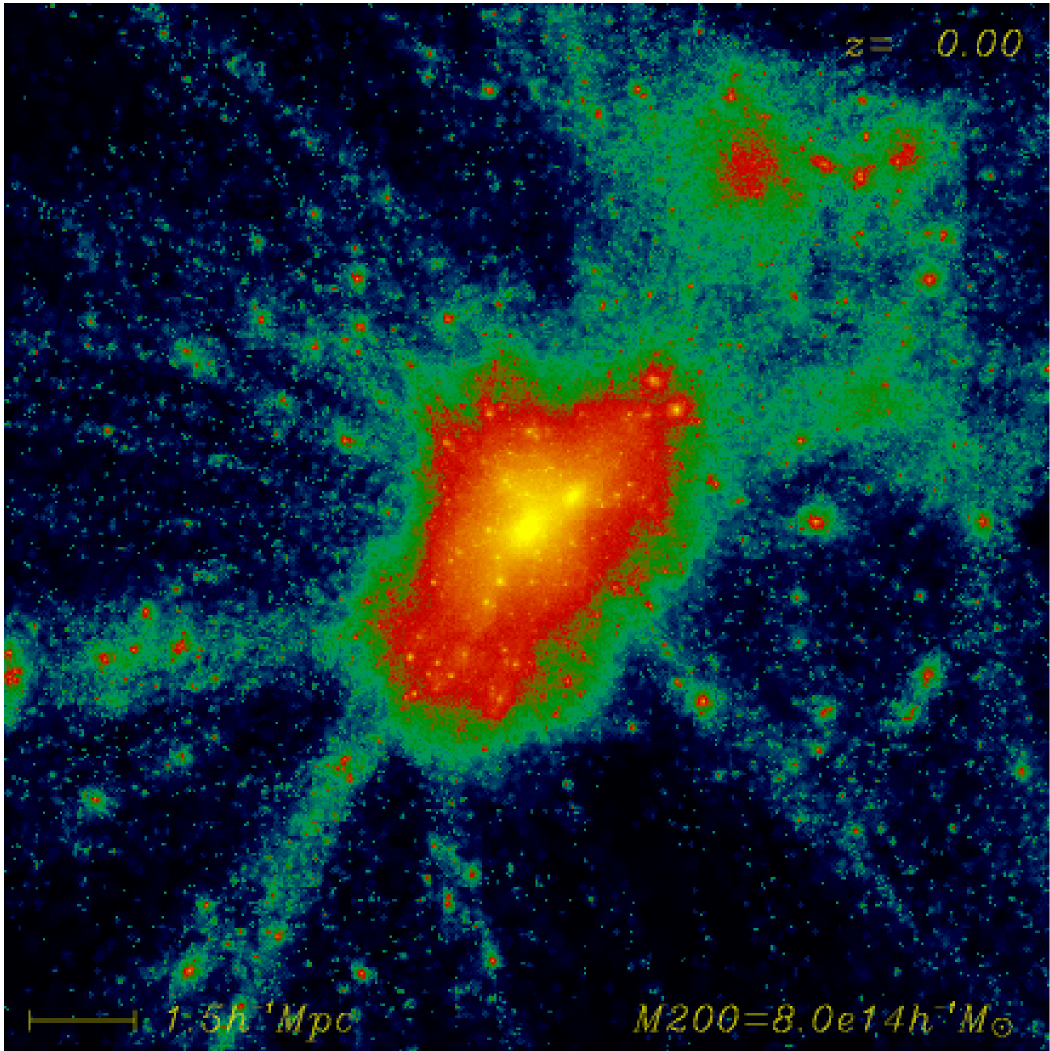


- Most massive progenitor of a $10^{14}M_\odot$ halo was traced back to z = 5
- Its most massive progenitor was traced back to z = 12
- Then back to z = 29
- Then back to z = 49
- Then back to z = 100

A $10^{14}M_{\odot}$ halo at redshift z =0

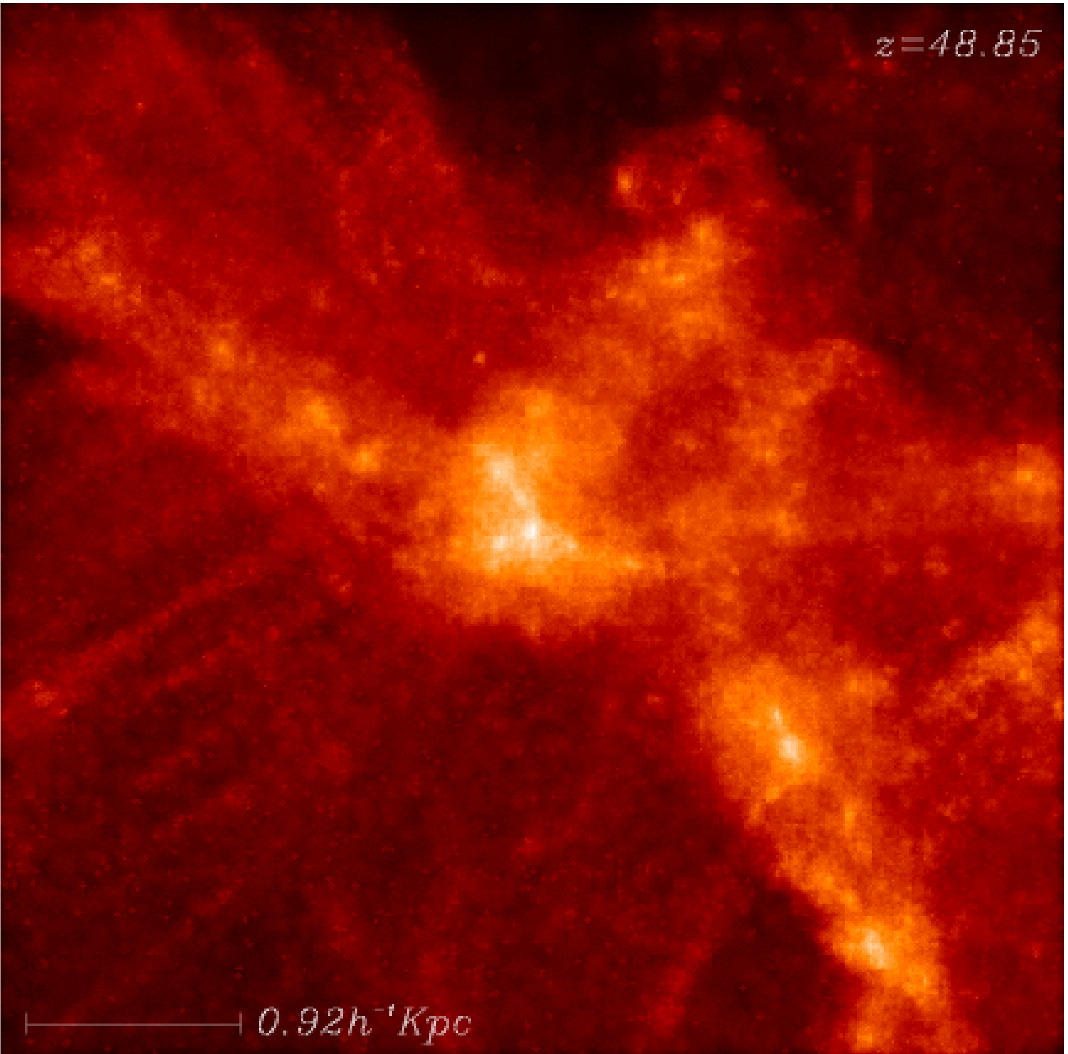
Gao et al 2005b

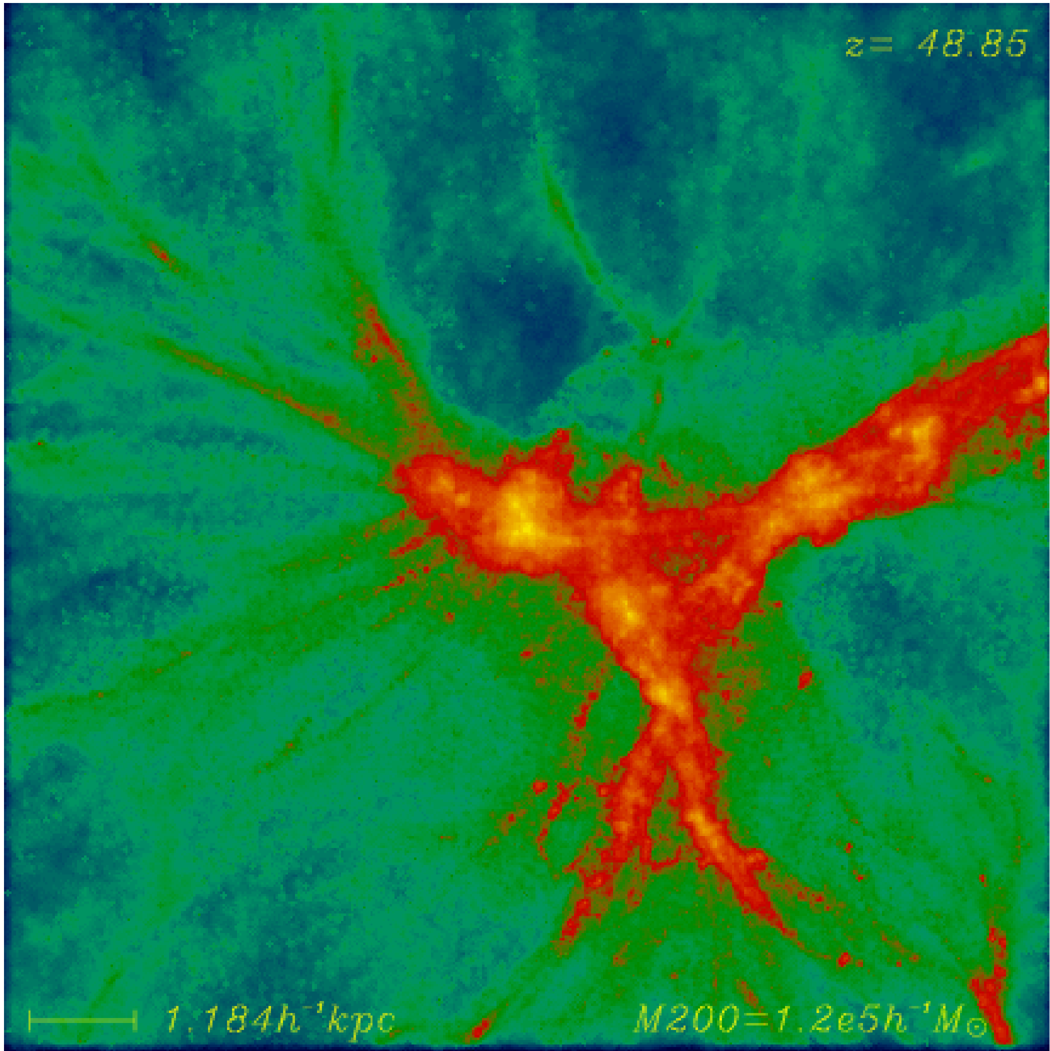


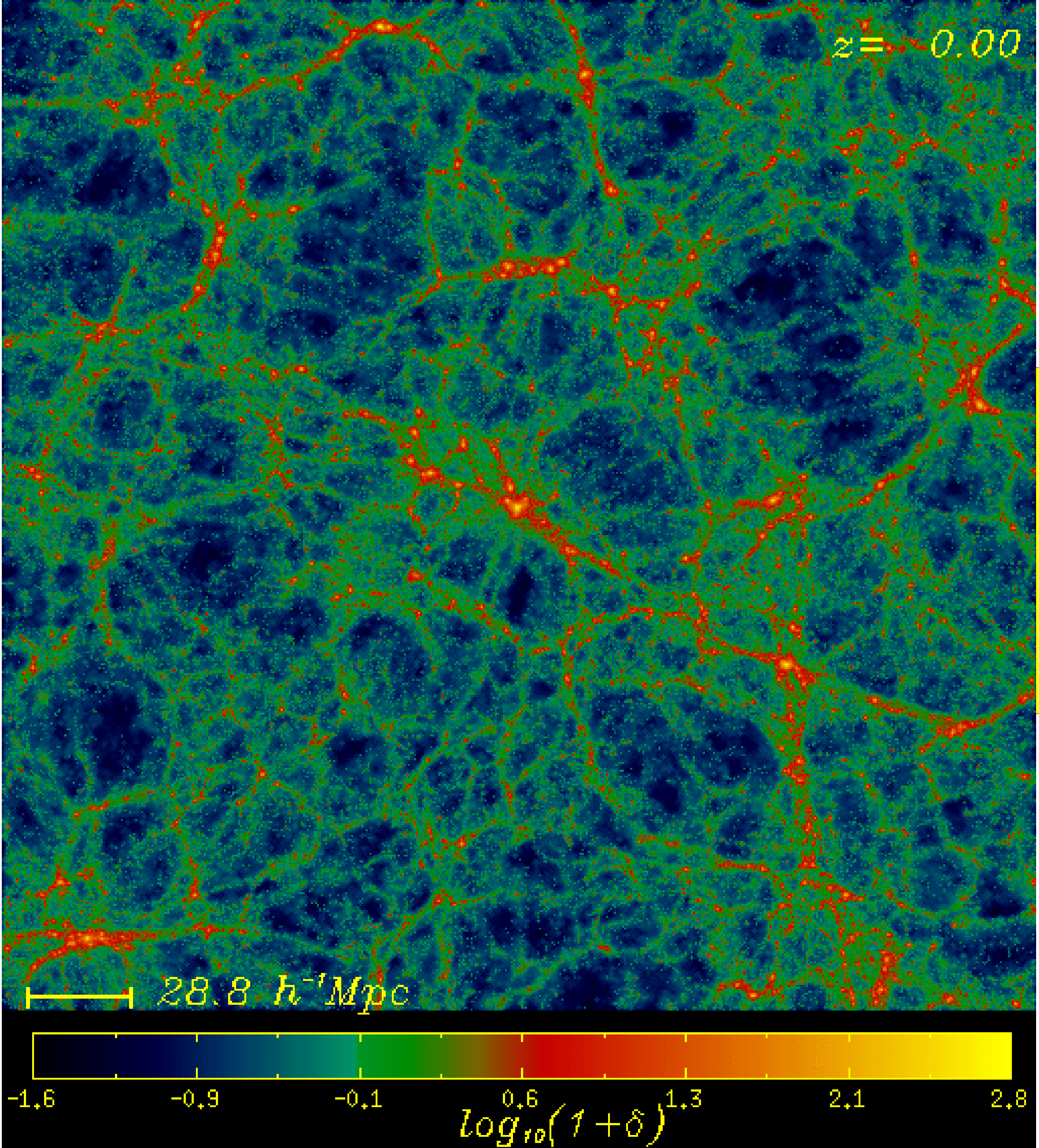


A $10^5 M_\odot$ halo at redshift z =49

Gao et al 2005b

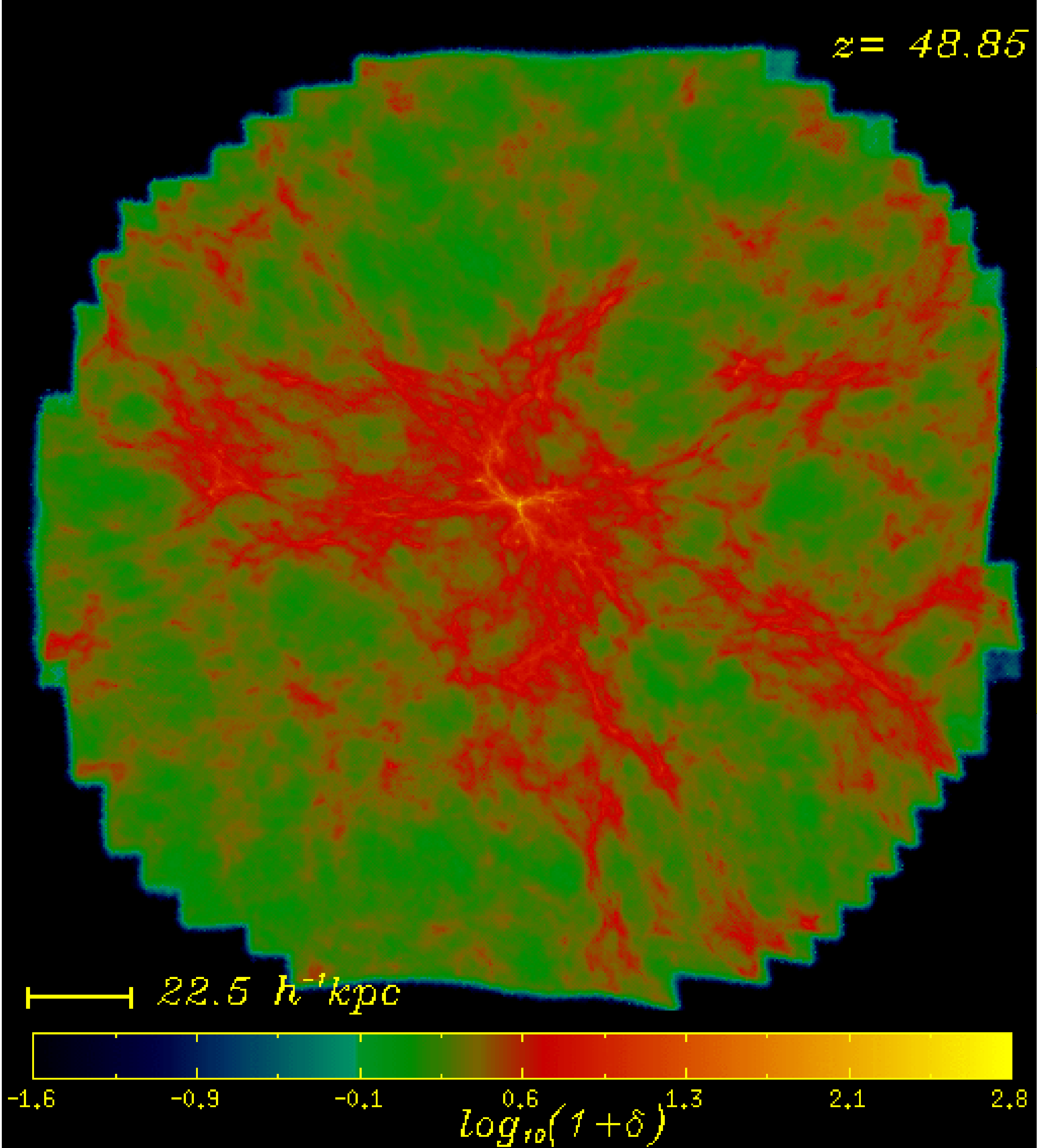






Gao et al 2005b

Environment of a $10^{14}M_\odot$ halo at redshift z =0



Gao et al 2005b

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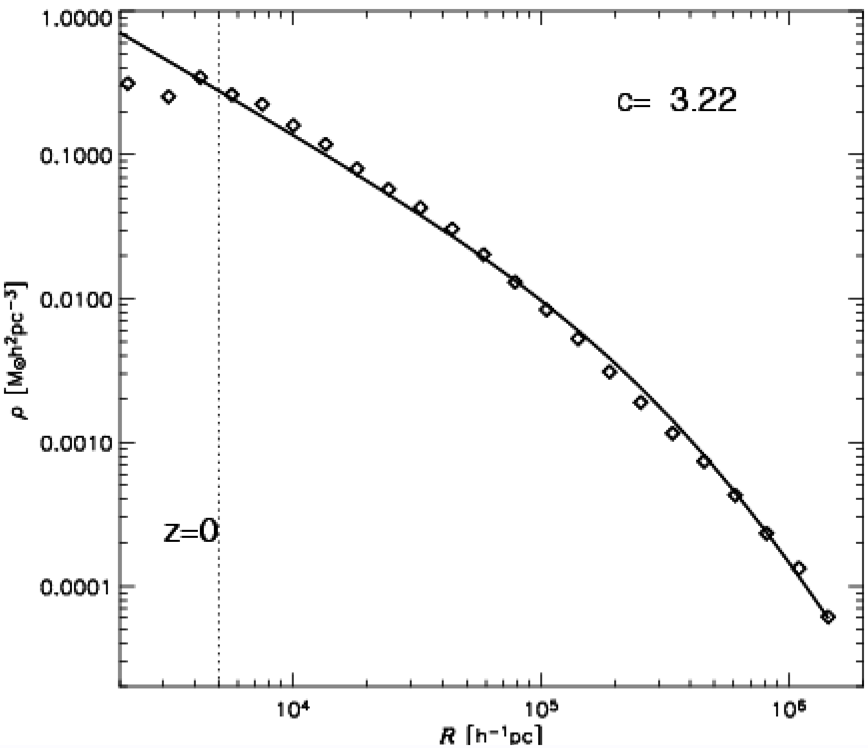
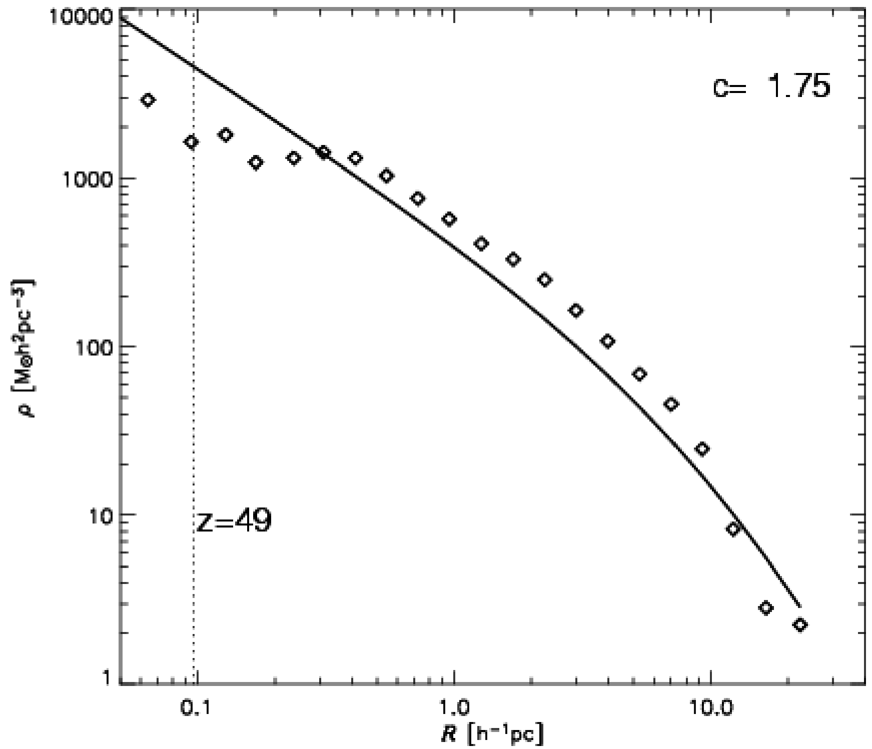
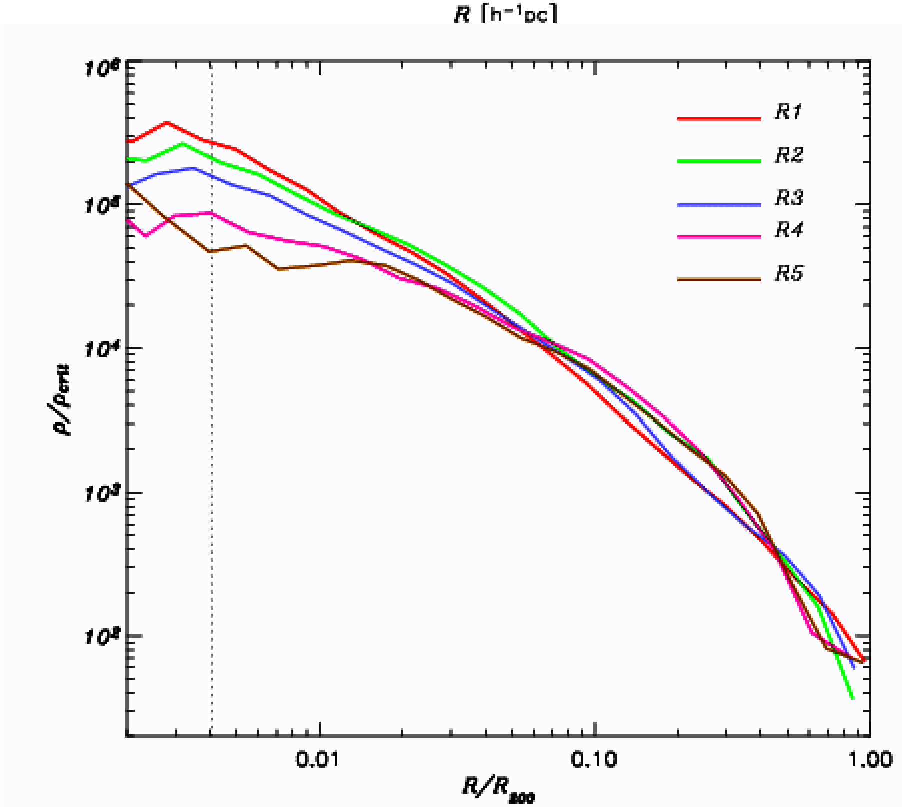




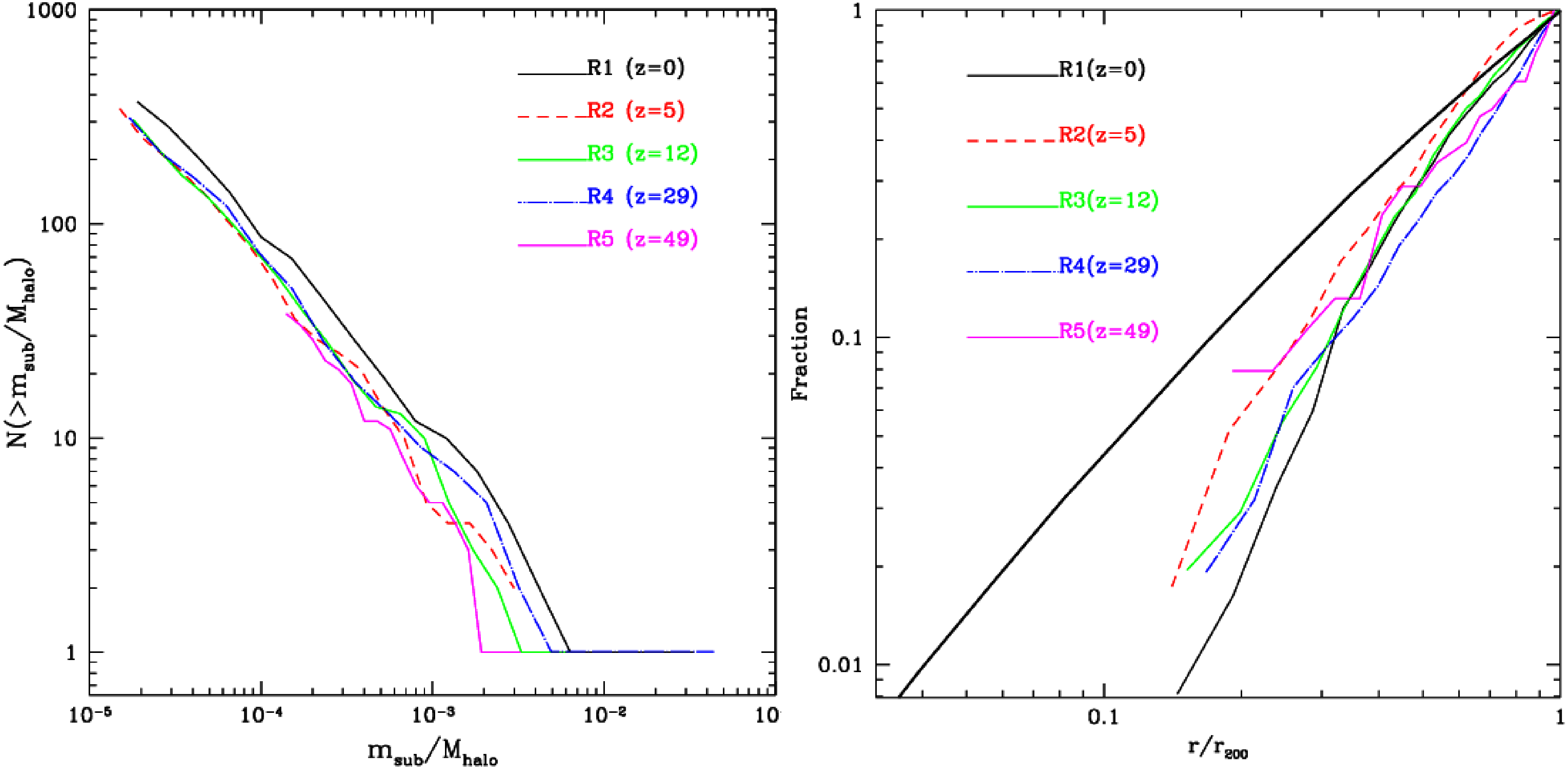


Density profiles of massive halos at various redshifts

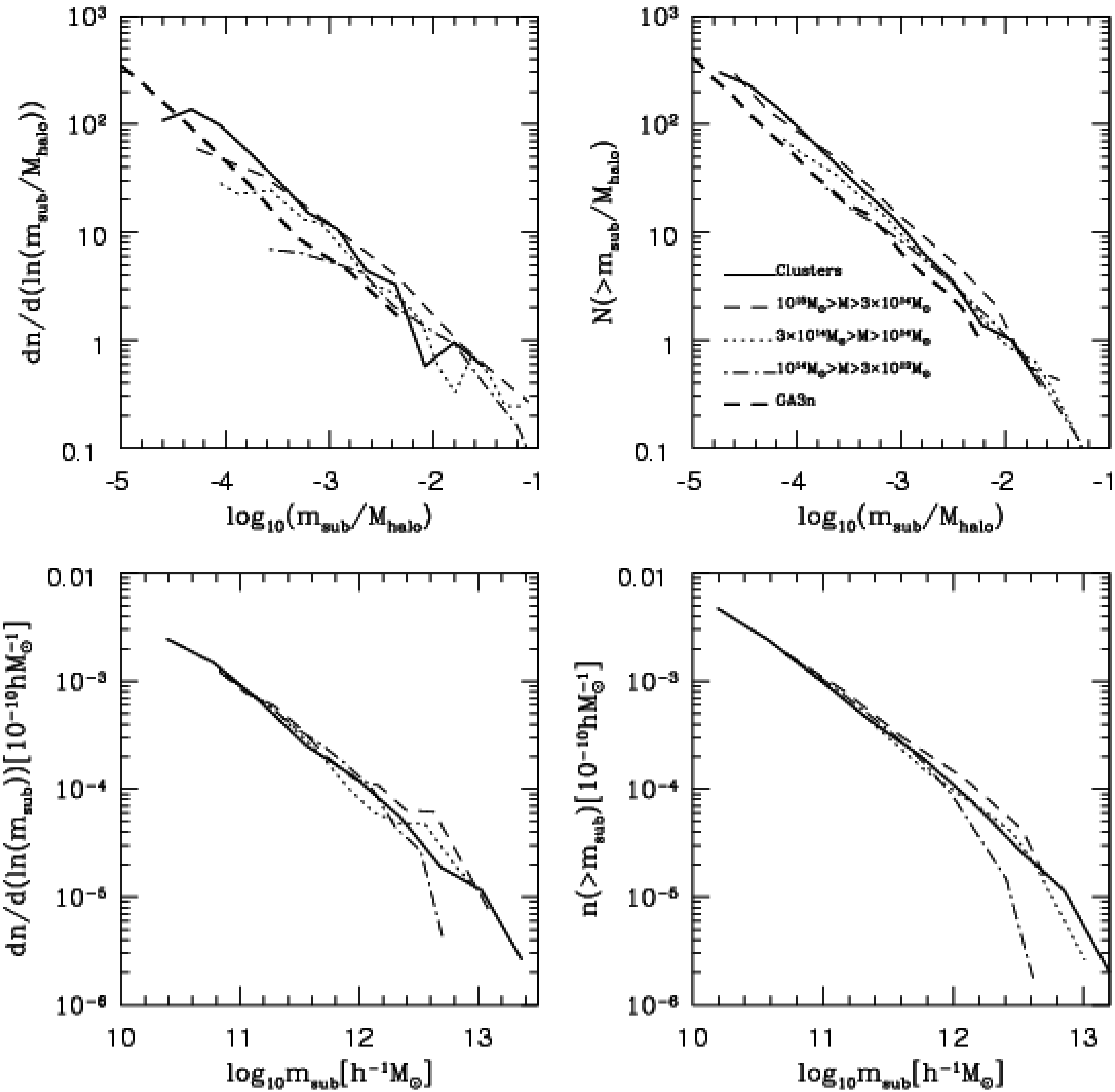
Gao et al 2005b

Internal structure of massive halos at various redshifts

Gao et al 2005b



Gao et al 2004b



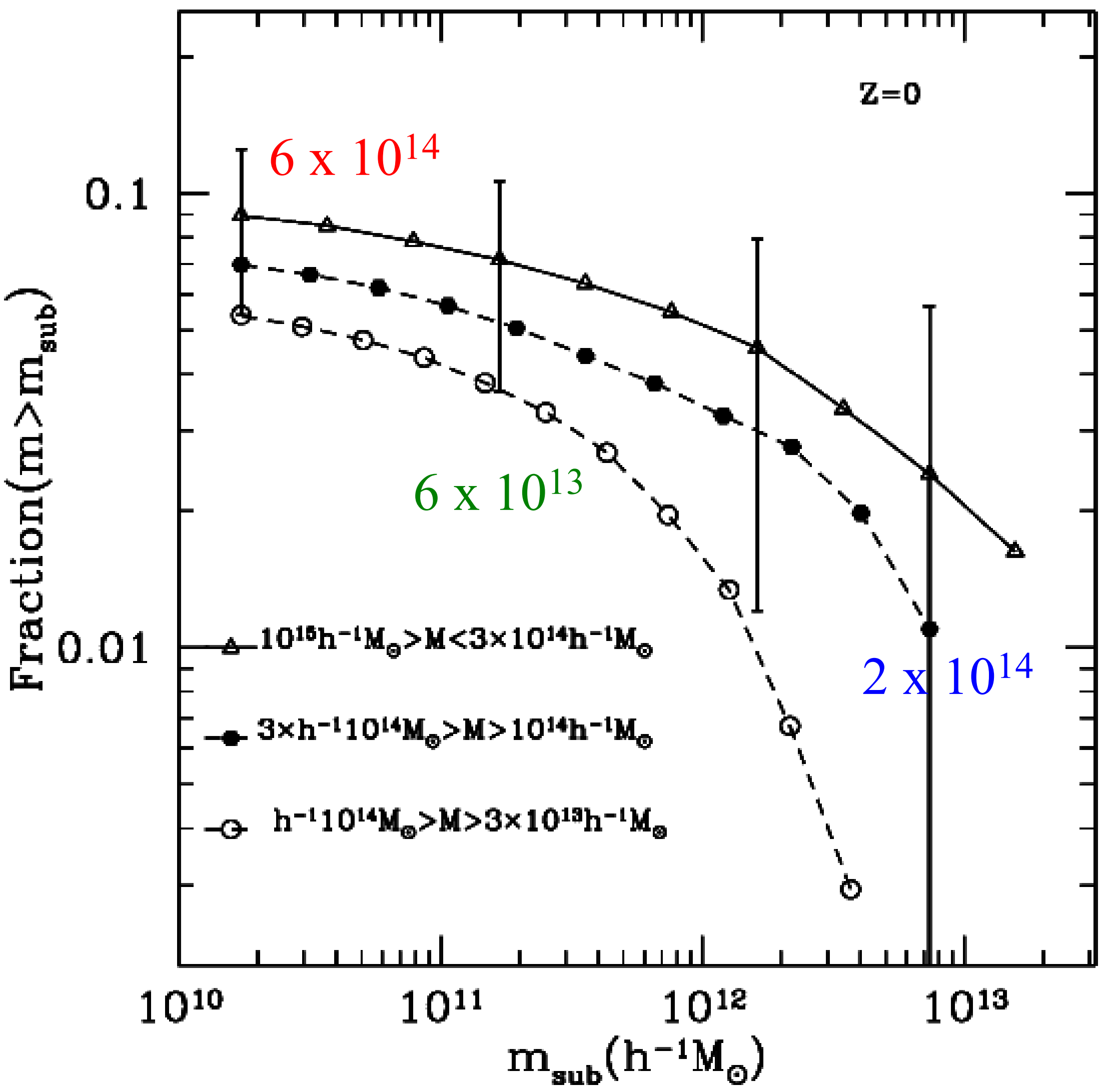
Universal substructure mass functions?

Scaling subhalo mass functions to the mass of the parent halo gives systematics with M_{halo}

Counting subhalos per unit parent halo mass *without* scaling gives much better agreement at low mass + a cut-off at high m_{sub}/M_{halo}

Mass fraction in substructure

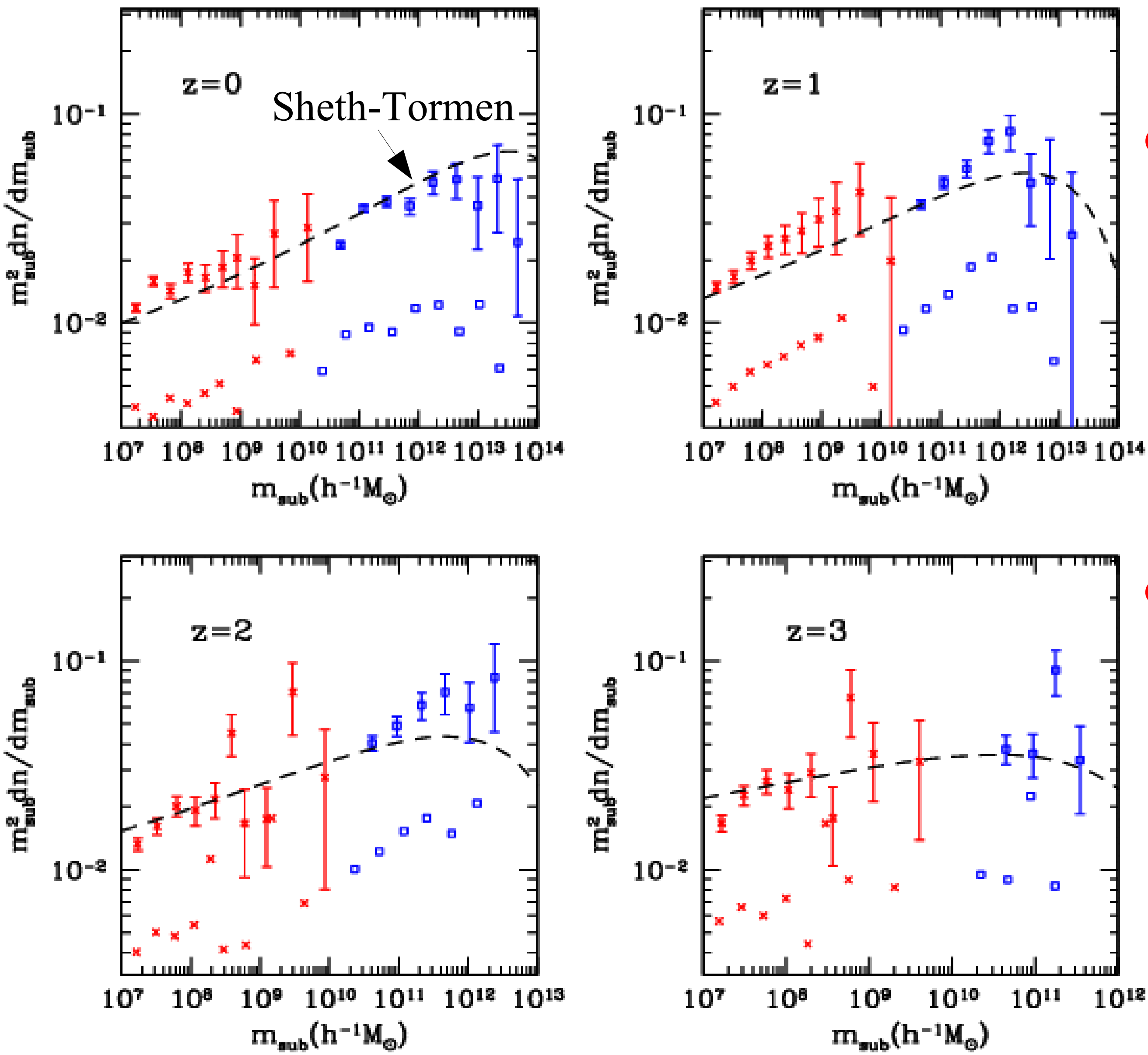
Gao et al 2004b



- Dispersion is <u>large</u>
- Most of subhalo mass is in the most massive subhalos
- More massive halos have a larger fraction of their mass in substructure
- Fraction of halo mass in subhalos less massive than ~ 2 x 10^{11} is the same in all the mass groups

Subhalo and halo abundance/mass are parallel

Gao et al 2004b

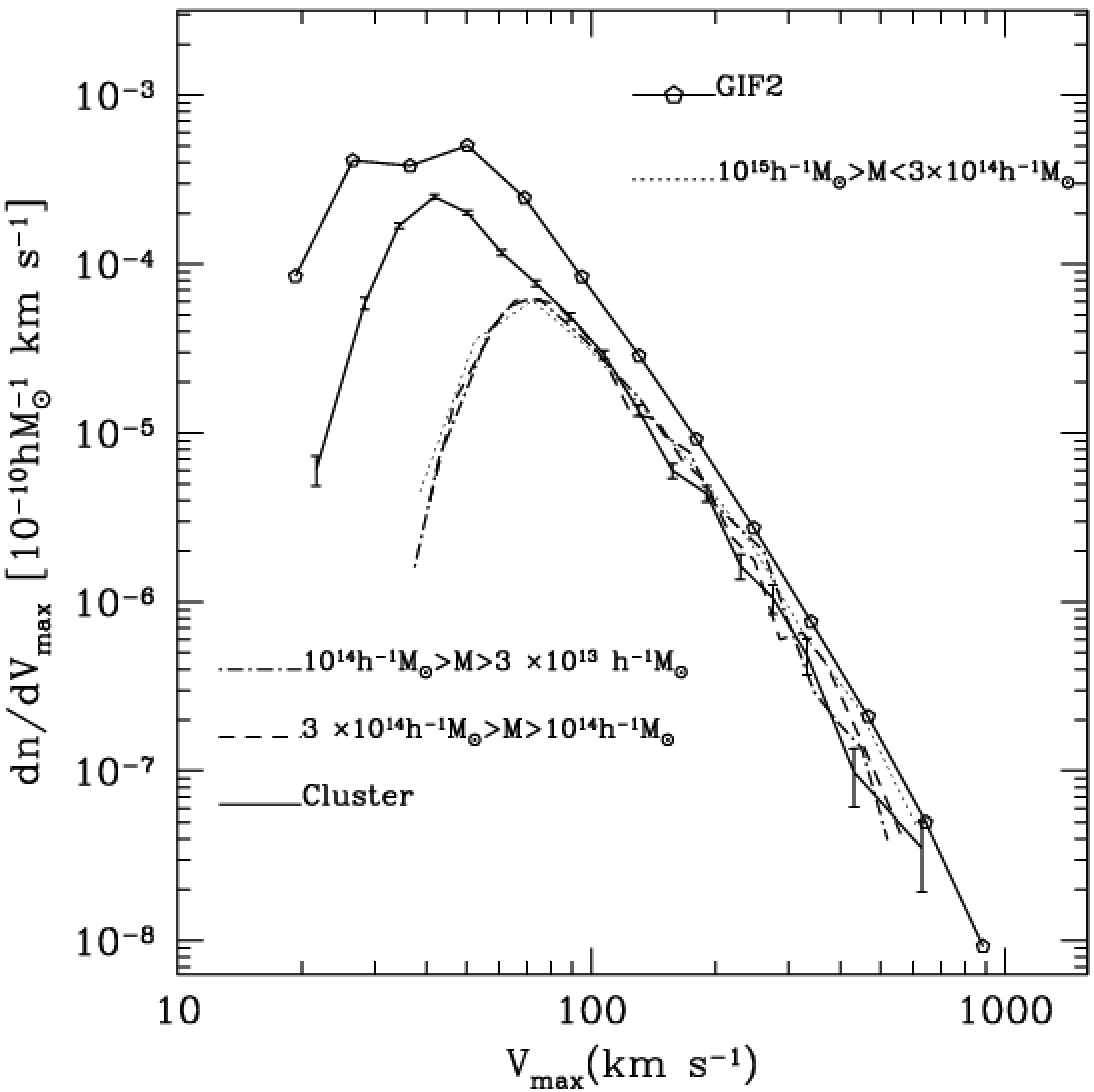


- Subhalos are bounded at higher density than halos

  → ~ half the mass for similar structure

- Doubling the masses we estimate for subhalos

  → subhalo abundance per unit mass in halos is the same as halo abundance per unit mass in the Cosmos

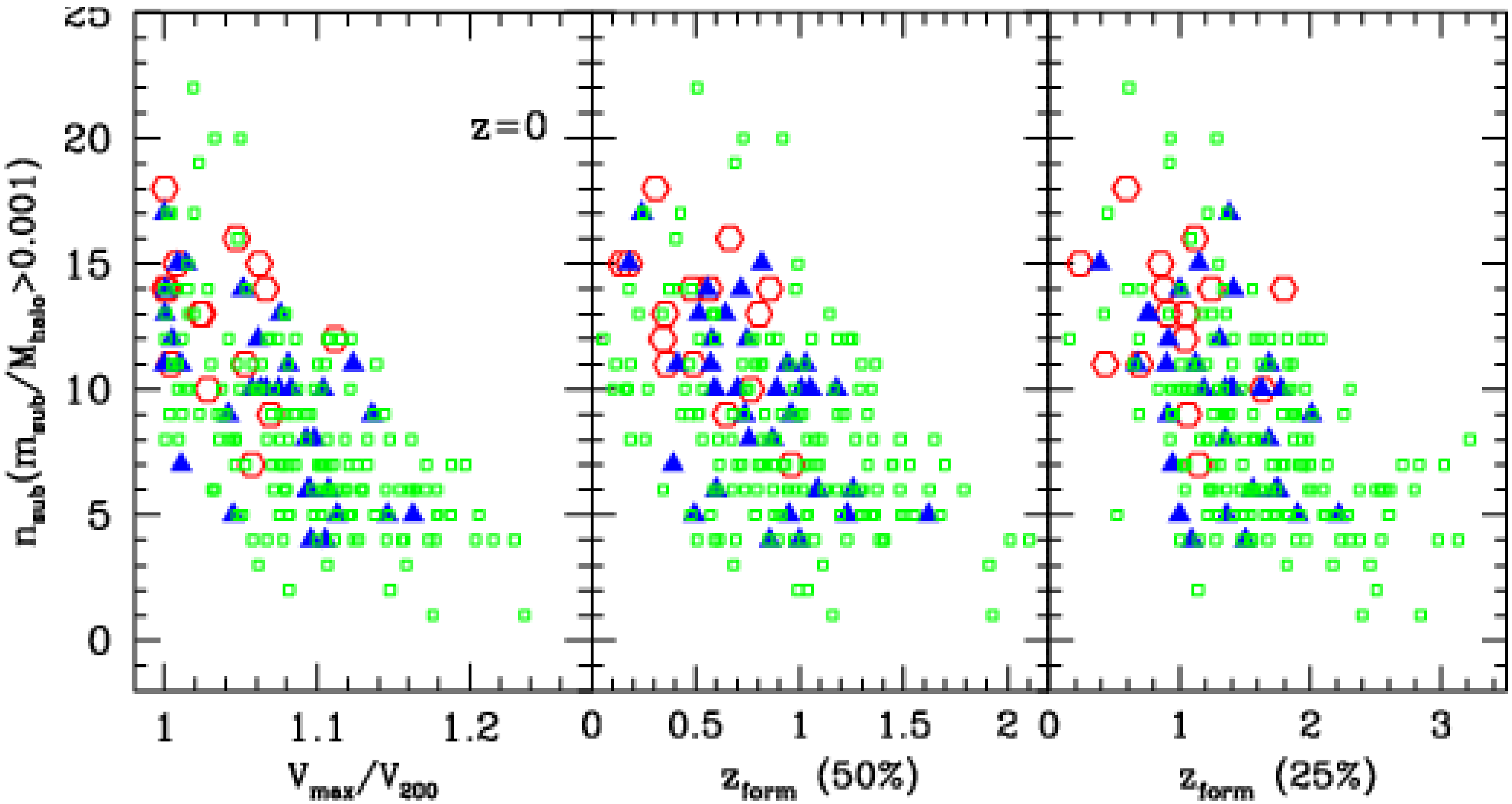


Gao et al 2004b

- The differential abundance per unit mass of subhalos counted as a function of maximum circular velocity is very similar in halos of different mass
- It is similar to the abundance per unit mass of main halos in the Universe as a whole
- At given abundance/unit mass subhalos have 20% lower V_{max} than halos

Substructure as a function of other halo properties

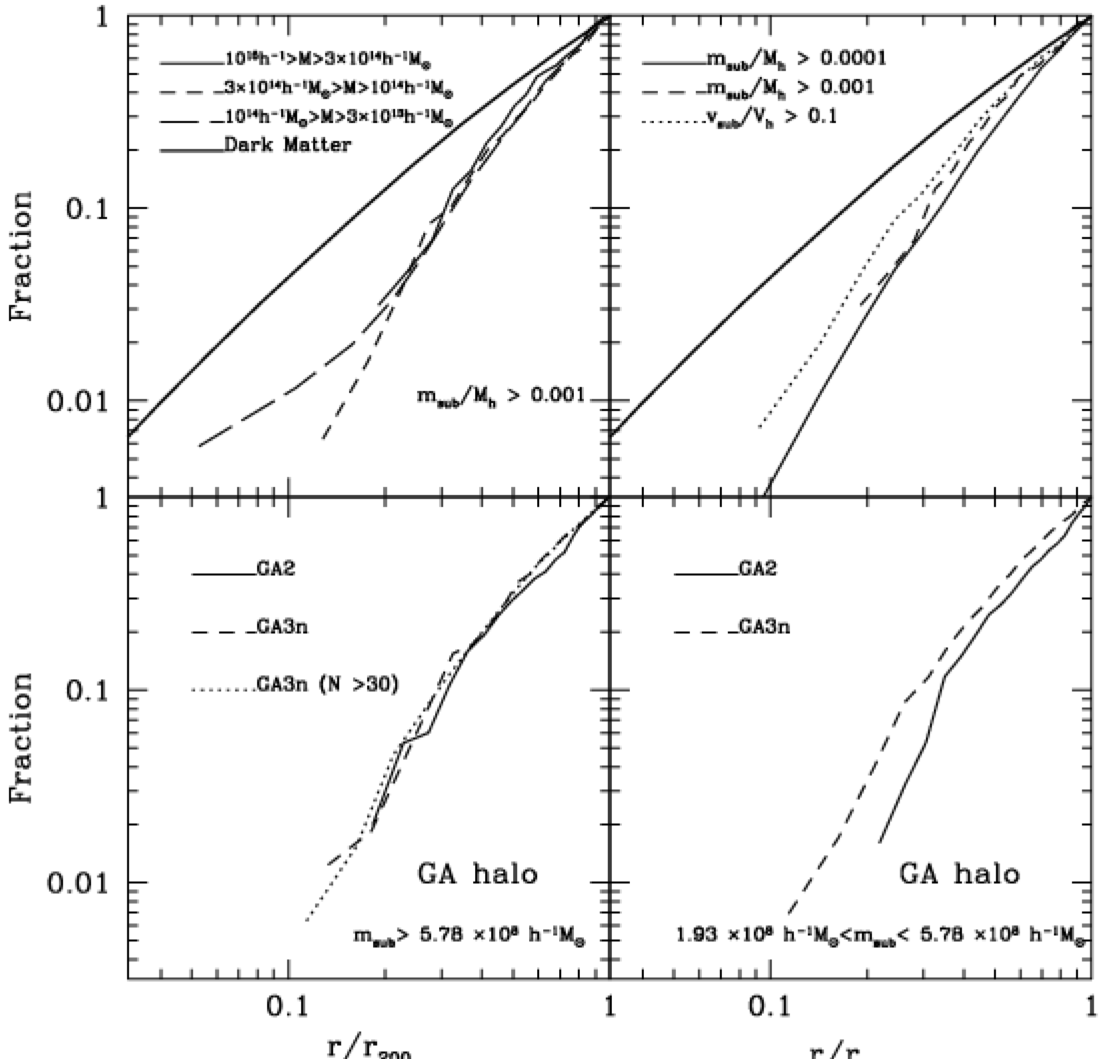
Gao et al 2004b



At every mass, halos with lower concentration (V_{max}/ V_{200}) or with later formation times have more substructure

Radial distribution of subhalos

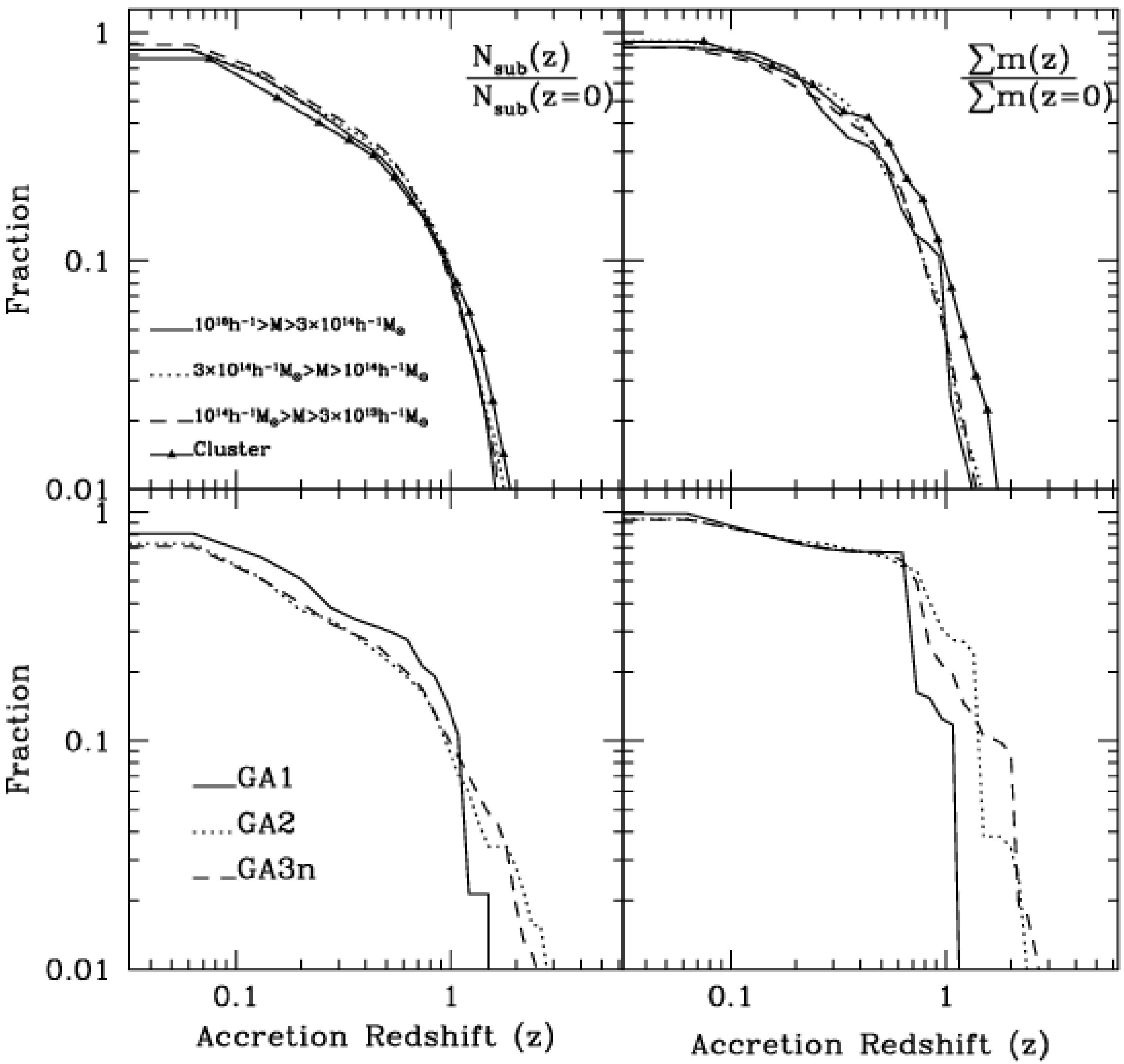
Gao et al 2004b



- Plots show the fraction of all subhalos within r_{200} above a given mass or circular velocity threshold which lie in $r < r_{200}$
- Convergence for thresholds larger than 30 particles
- Profile depends little on the mass of the main halo or on the mass threshold, M_h or m_{sub}/M_h
- Profile much *less* concentrated than that of the mass
- Profiles are more concentrated for a V_{max} threshold than for a mass threshold

When are sub-halos accreted?

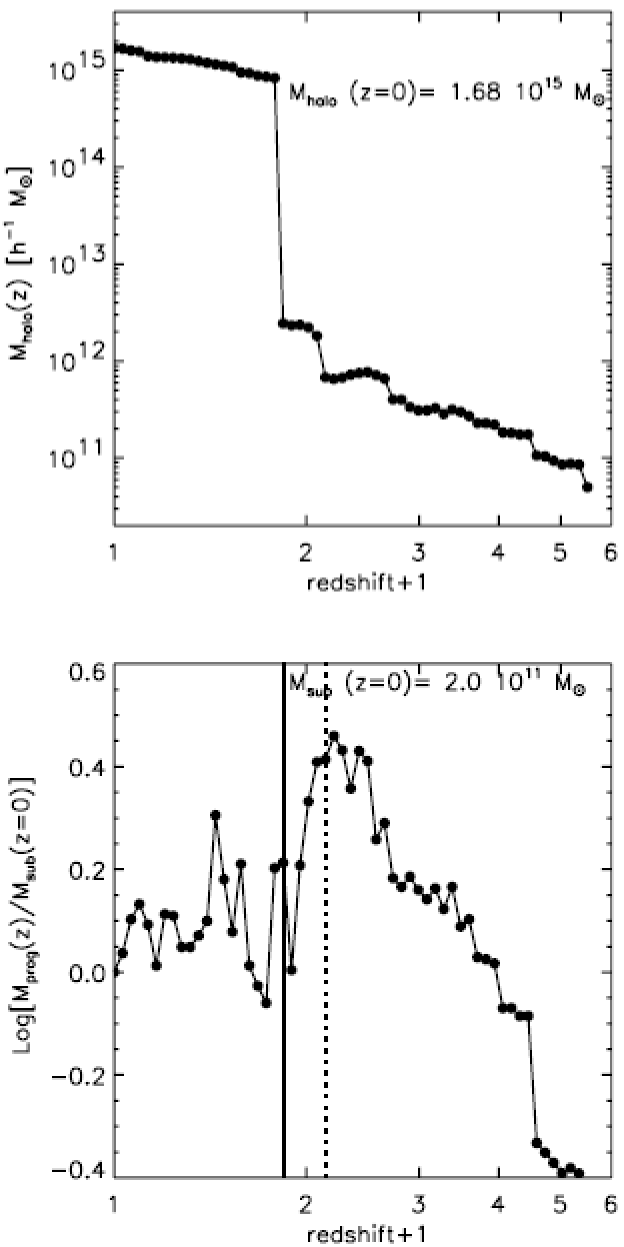
Gao et al 2004b



Most of the subhalos (and most of the mass in subhalos) first became a subhalo at *late* times

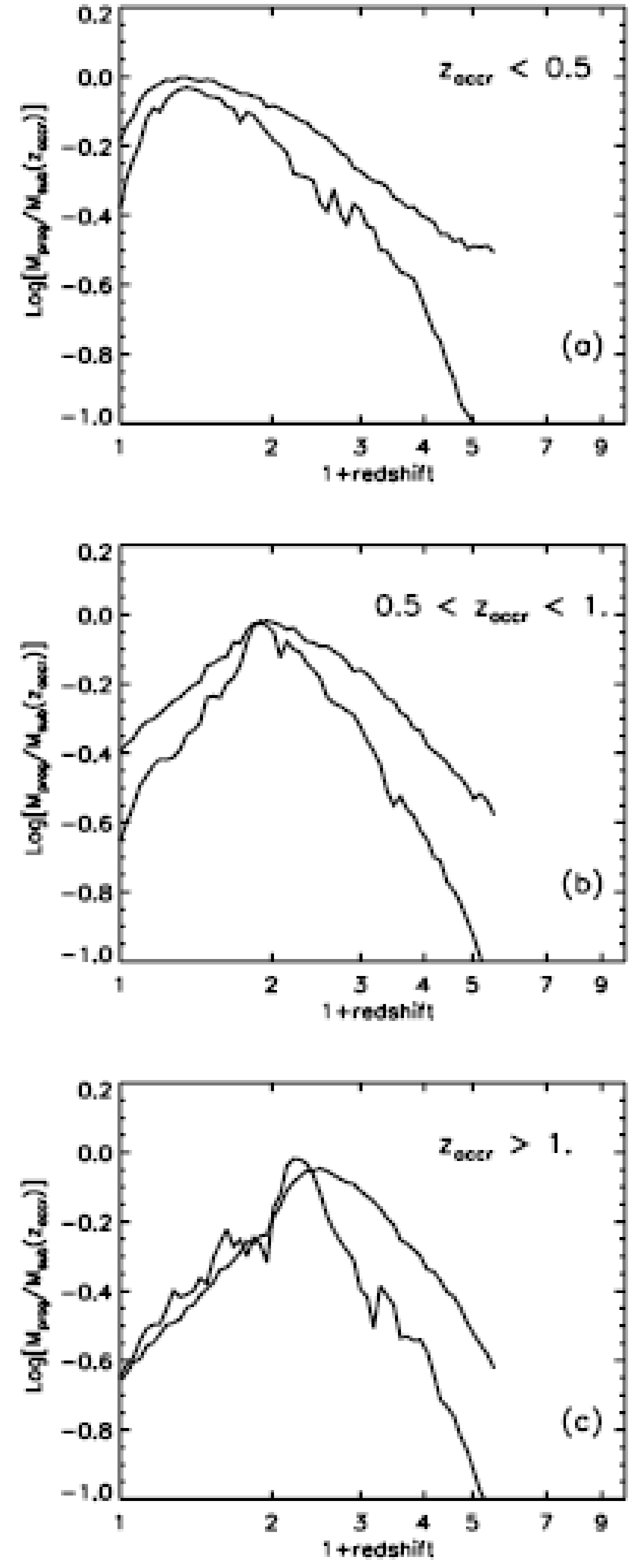
70% after z = 0.5
90% after z = 1.0

This is much *later* than the accretion time of typical DM particles



Subhalos grow while independent objects but are stripped once part of a bigger halo

De Lucia et al 2004



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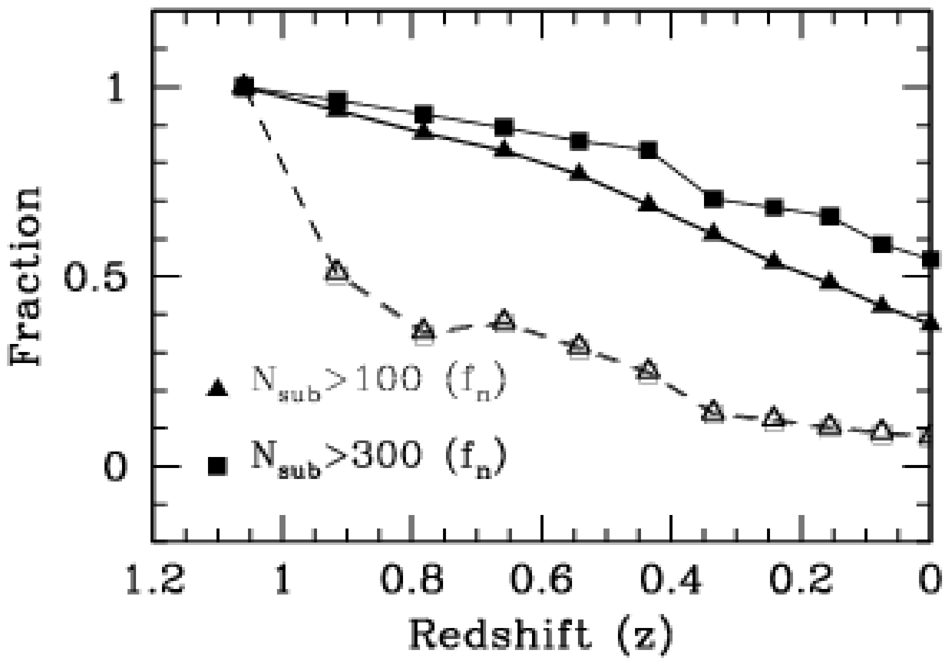
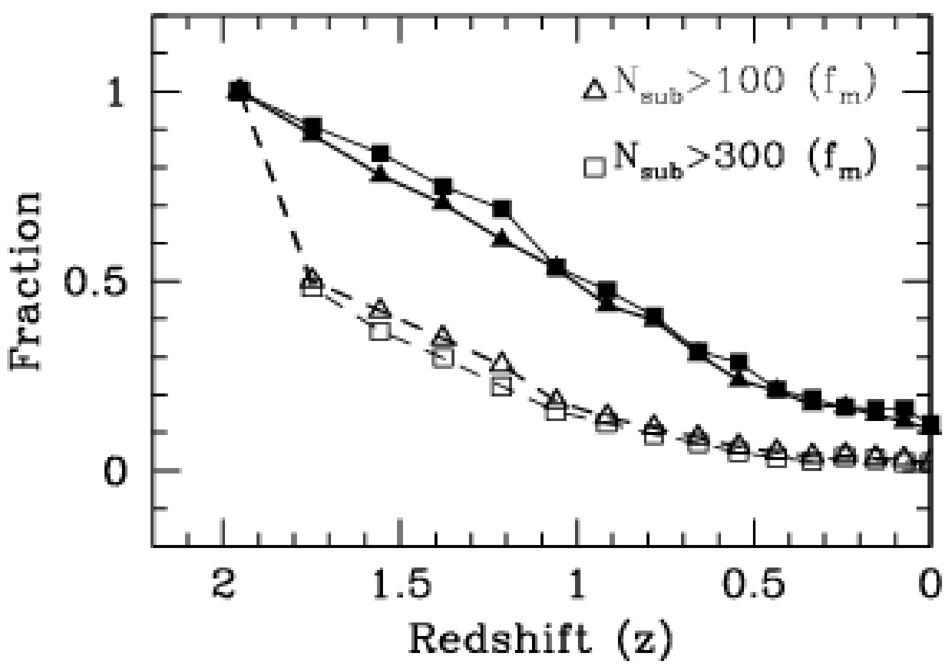




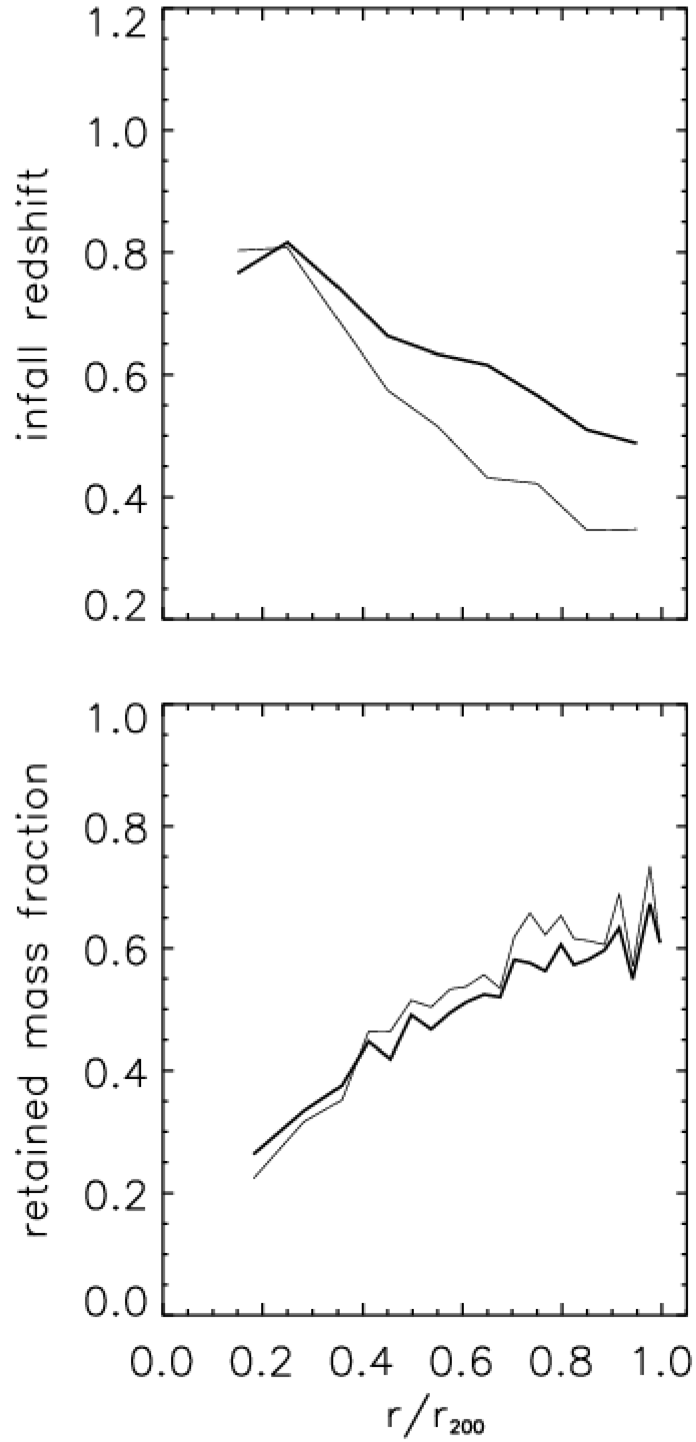
How rapidly do infalling halos lose mass or disrupt

Subhalos accreted at z = 1 lose a factor 2 in number and a factor 12 in mass by z = 0

Subhalos accreted at z = 2 lose a factor 8 in number and a factor 50 in mass by z = 0

Although the number reduction is affected by resolution the mass reduction is not

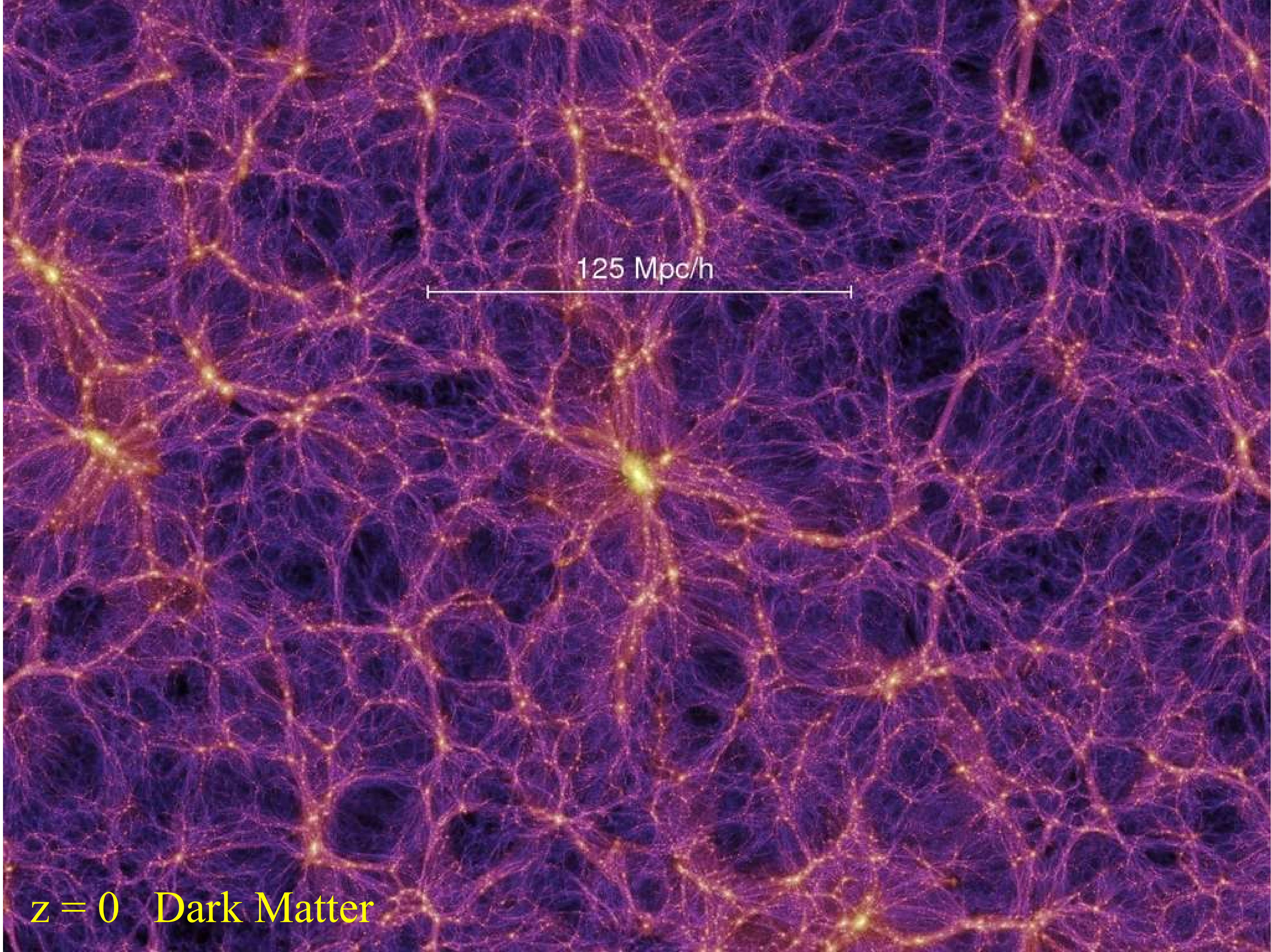
Gao et al 2004b

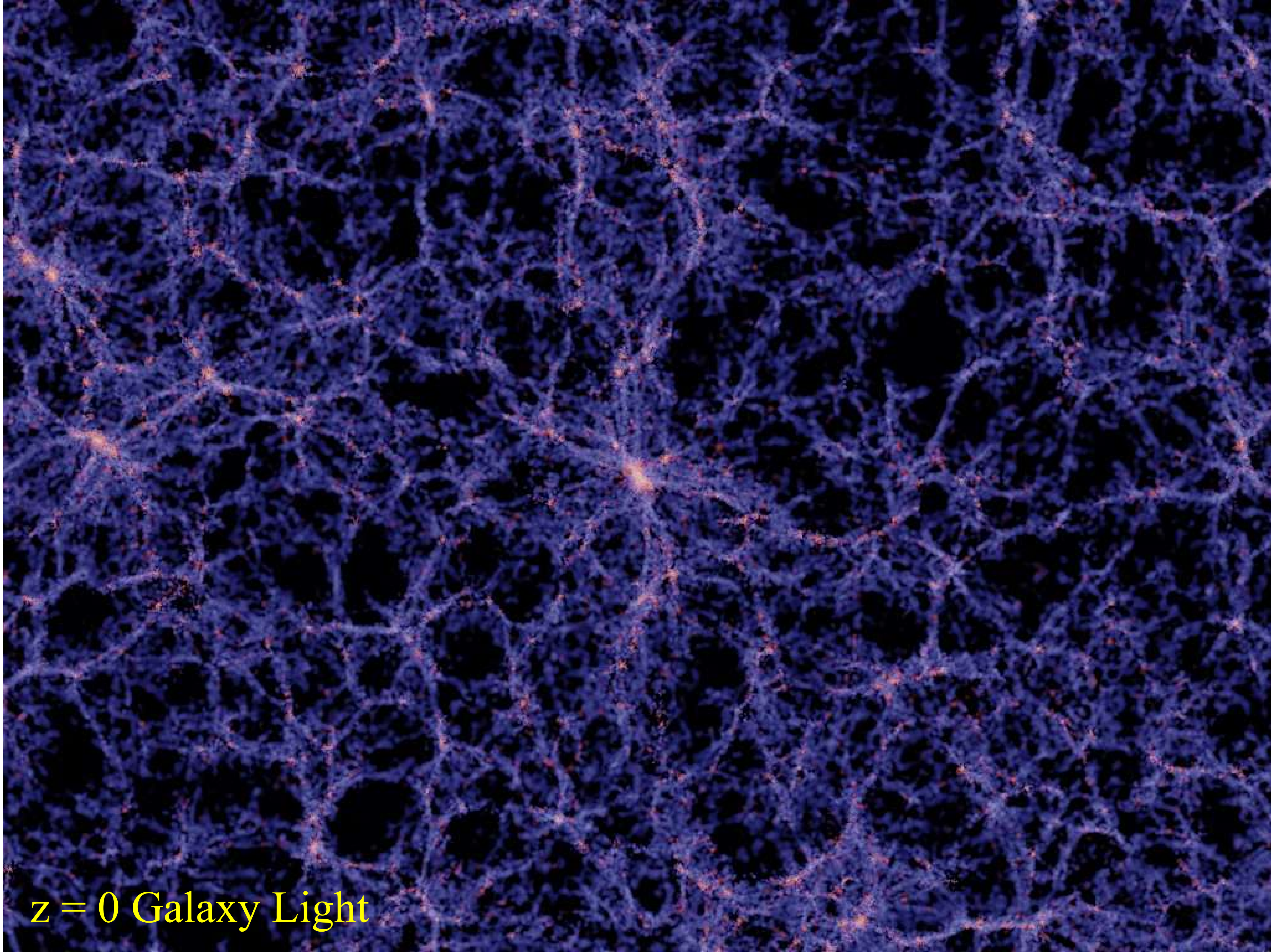


Surviving subhalos near the centre of a halo have higher typical infall redshifts than those near the edge

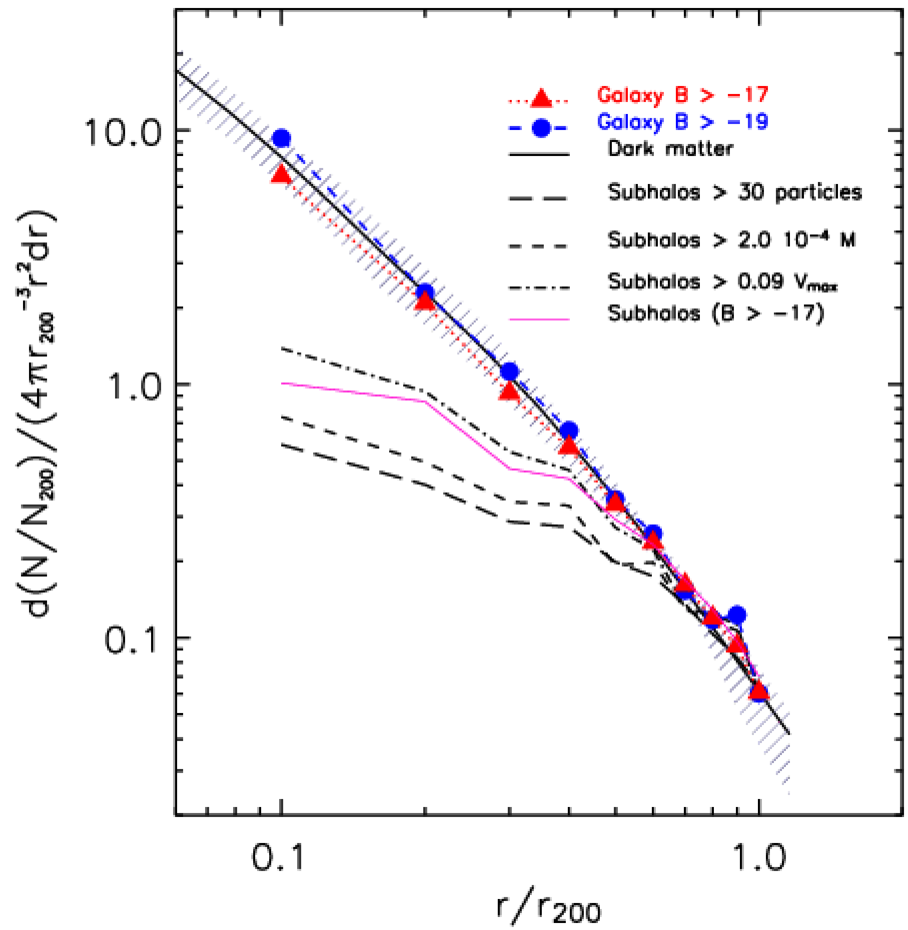
Surviving subhalos near the centre of a halo have typically lost more mass since infall than those near the edge

Averages over 15 halos with M > 3 x 10^{14} and for subhalos with m > 2 x 10^{10}


125 Mpc/h
z = 0 Dark Matter

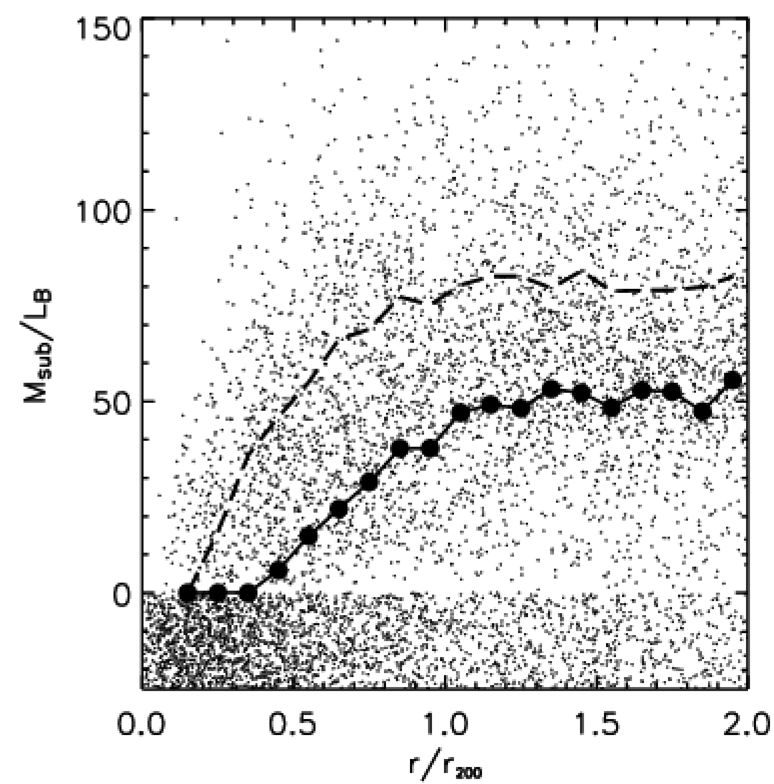

z = 0 Galaxy Light

Gao et al 2004c



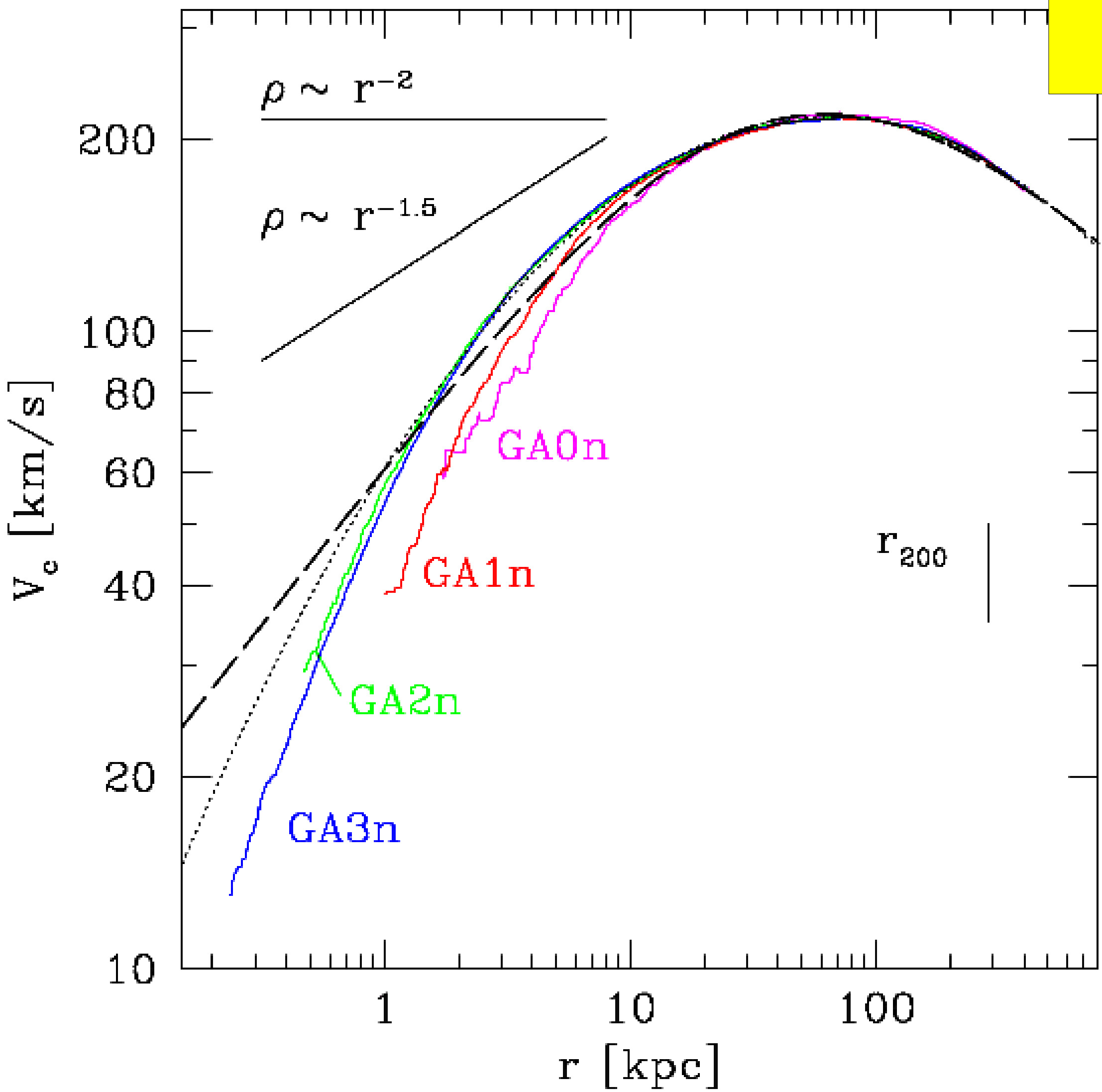
Do galaxies follow the subhalo distribution?

The galaxy population to a magnitude limit is predicted to follow the radial mass profile *not* the subhalo profile to a mass or circular velocity limit



This is because the galaxy M/L is a strong function of r within a halo as a consequence of stripping effects

Stoehr et al 2003

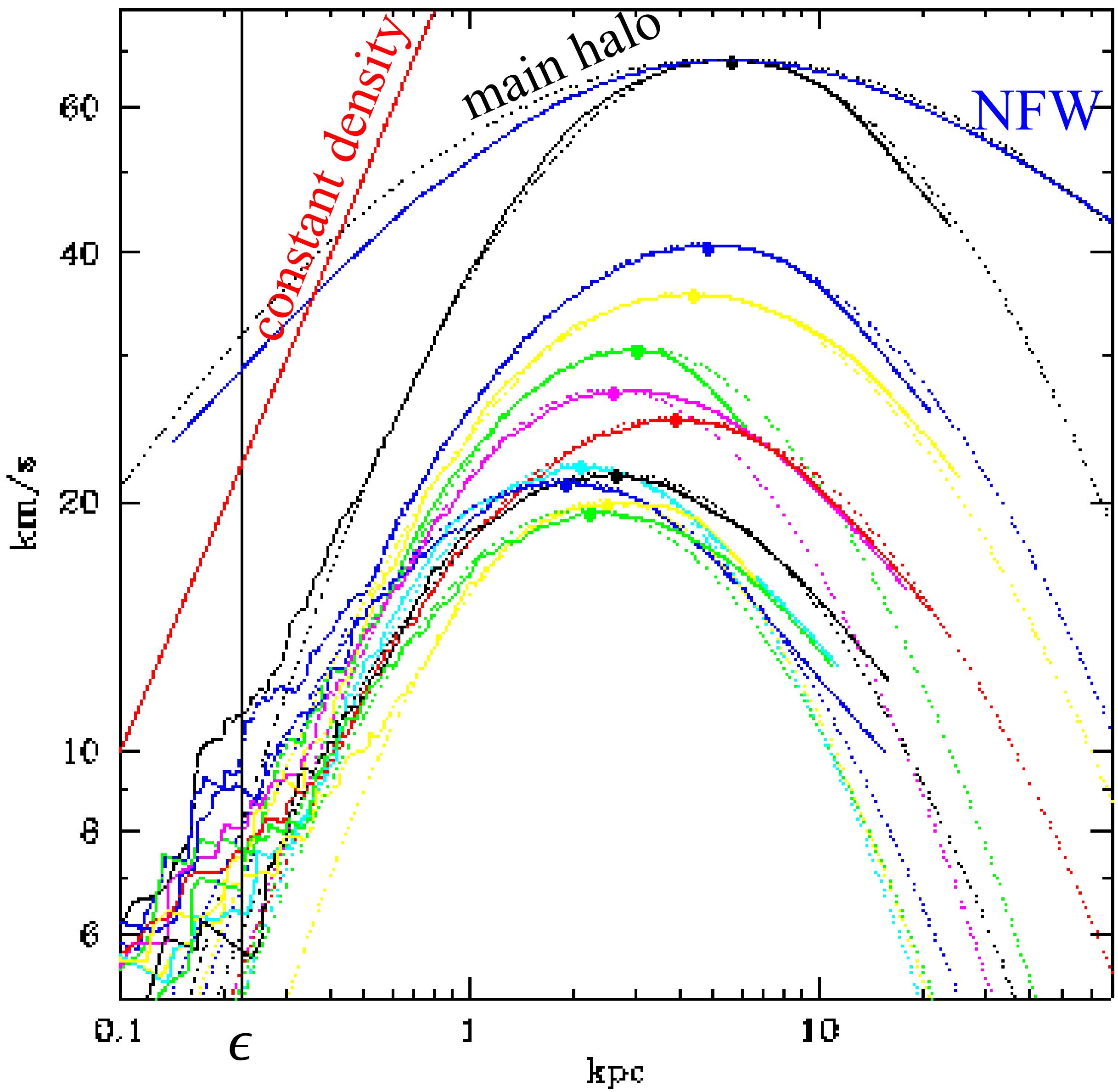


Inner density structure of a Milky Way halo

- Four simulations from the same initial conditions but with differing resolution
  N_{200} = 14,000, 130,000, 1,200,000, 10,100,000
- Inner structure converges down to about 1 kpc
- Slope is $\rho \propto r^{-1.5}$ at 7 kpc

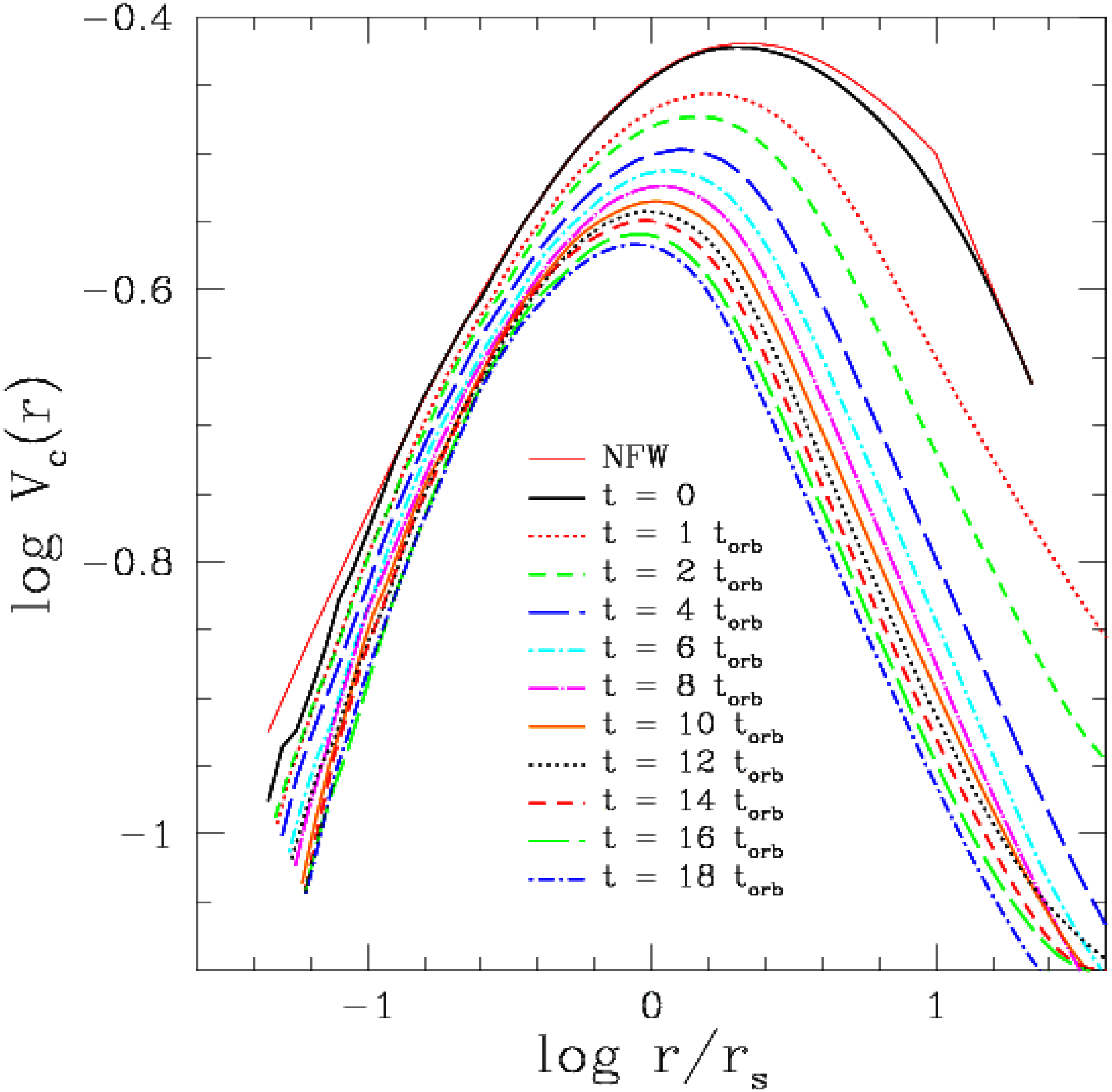
Satellite circular velocity curves

Stoehr et al 2003



- Circular velocity curves for 11 of the 30 most massive subhalos in a 10^7 particle 'Milky Way' halo
- The NFW and 'main halo' curves are scaled to the (r_m, V_m) of largest subhalo
- All curves are narrower than NFW or 'main halo'
- Many profiles approach a constant density core in their inner regions
- ***The MOST MASSIVE of these potentials could host the observed satellites***

High resolution simulations of subhalo stripping



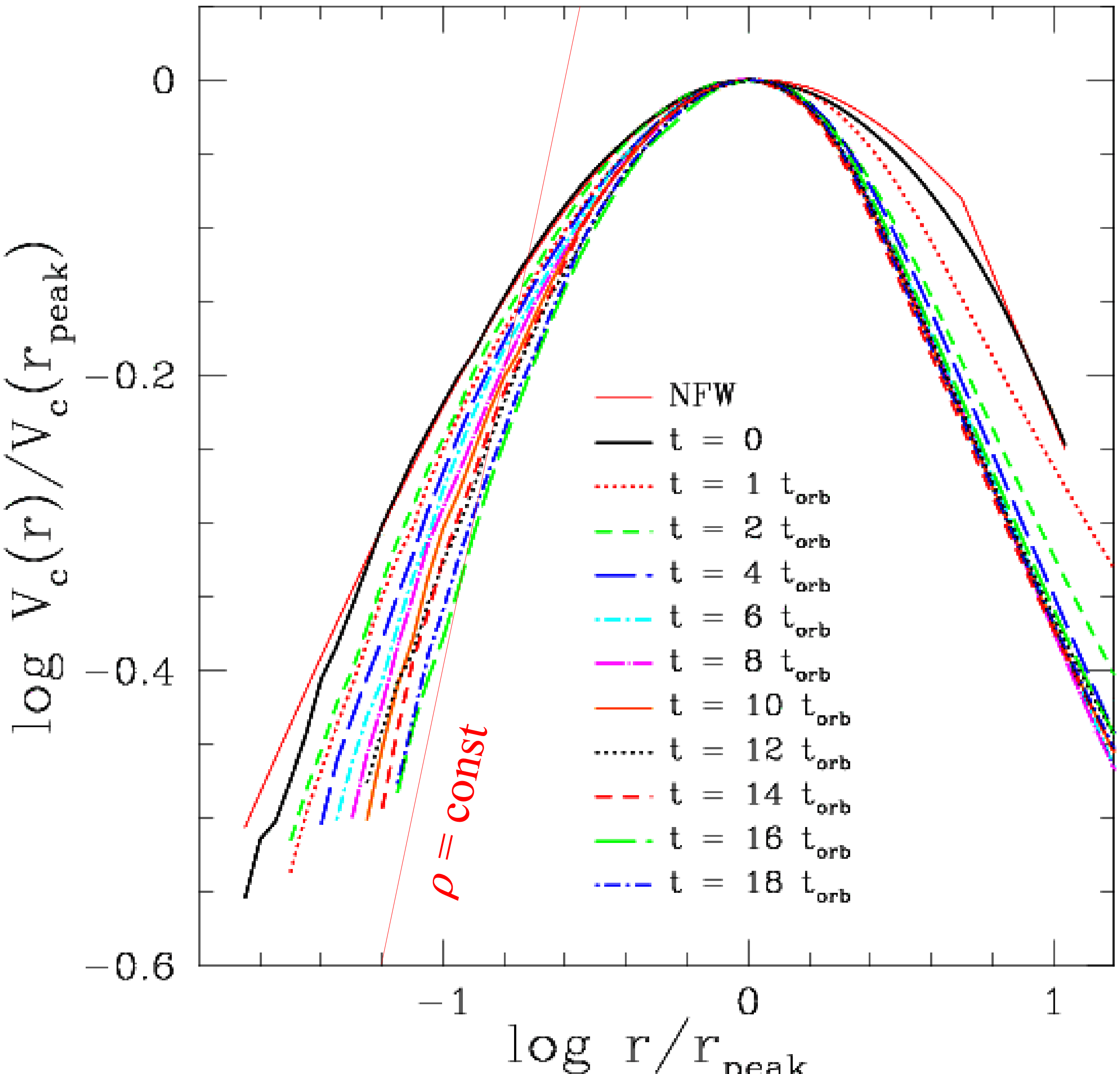
Hayashi et al 2003

Tidal stripping of an equilibrium NFW subhalo with N ~ 400,000 falling into a rigid NFW Milky Way.

R_{apo}=10 R_s R_{peri}= 3 R_s

Note that the amplitude of the $V_c(r)$ curve drops even in the inner regions

High resolution simulations of subhalo stripping

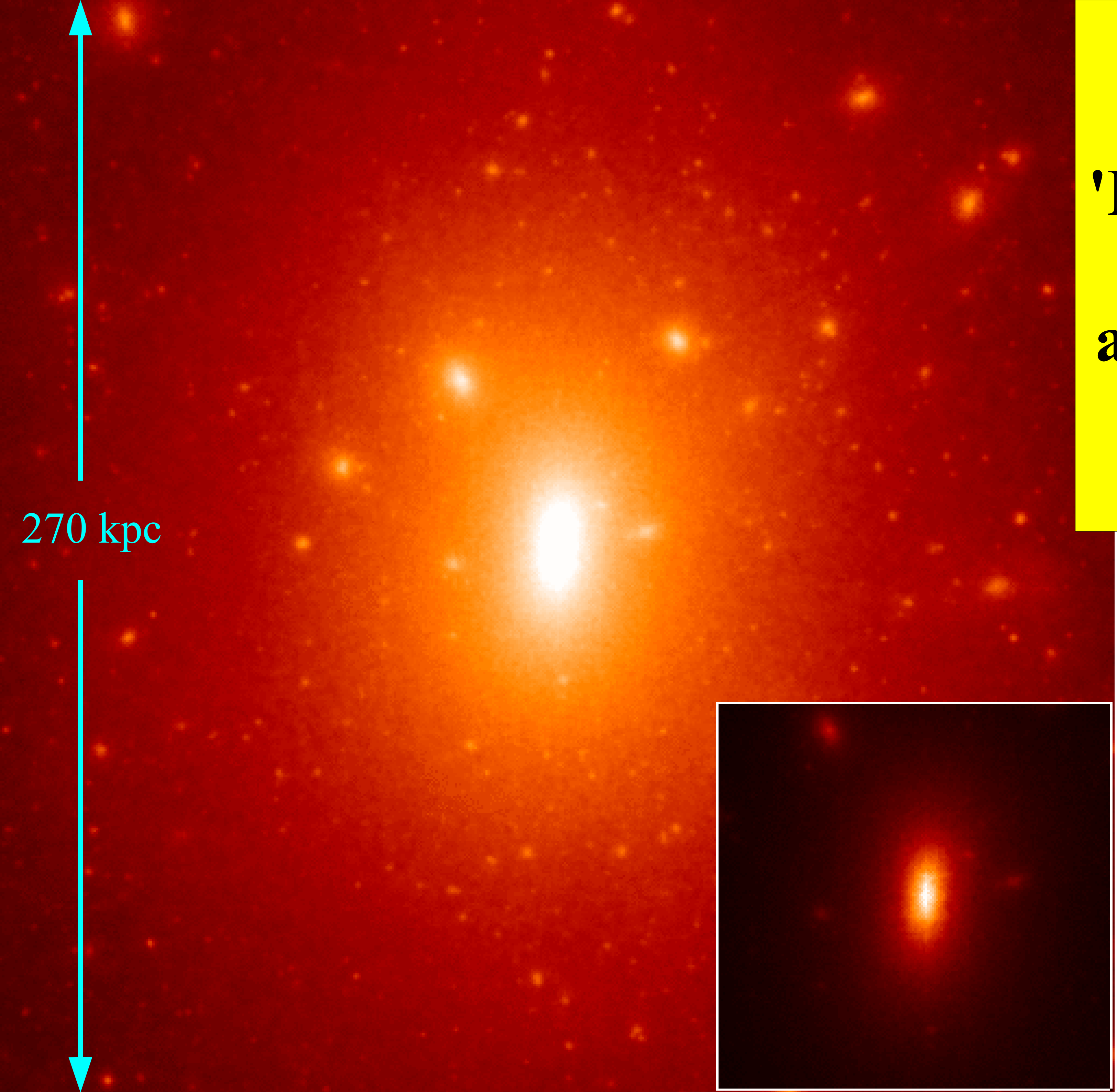


Hayashi et al 2003

Tidal stripping of a single NFW subhalo with N ~ 400,000 falling into a rigid NFW Milky Way

Note the steepening of the inner $V_c(r)$ curve

Image of a 'Milky Way' halo in annihilation radiation

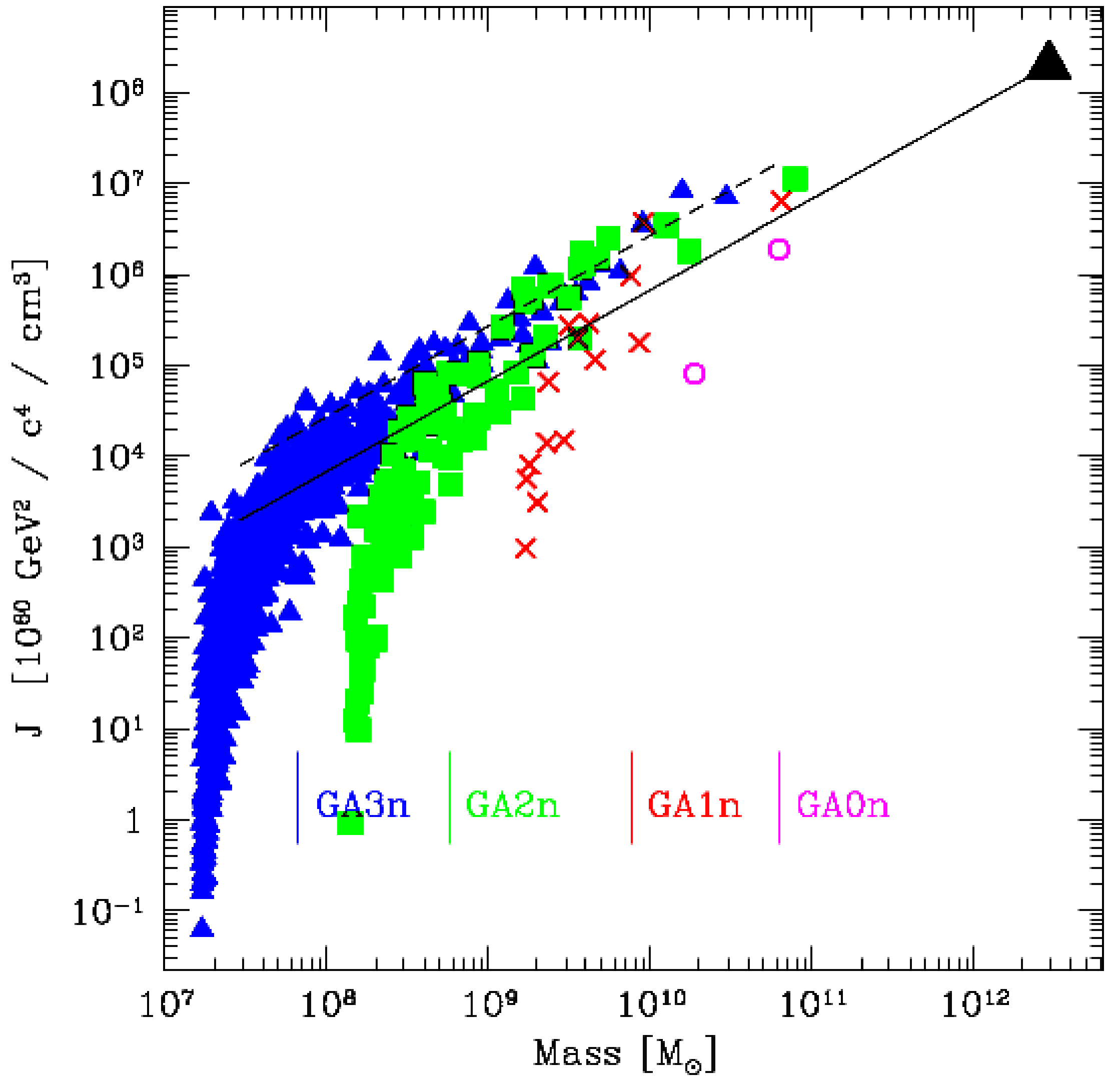


$$S(\boldsymbol{\theta}) \propto \int \rho^2 \, \mathrm{d}l$$

Stoehr et al 2003

Stoehr et al 2003

Substructure luminosity

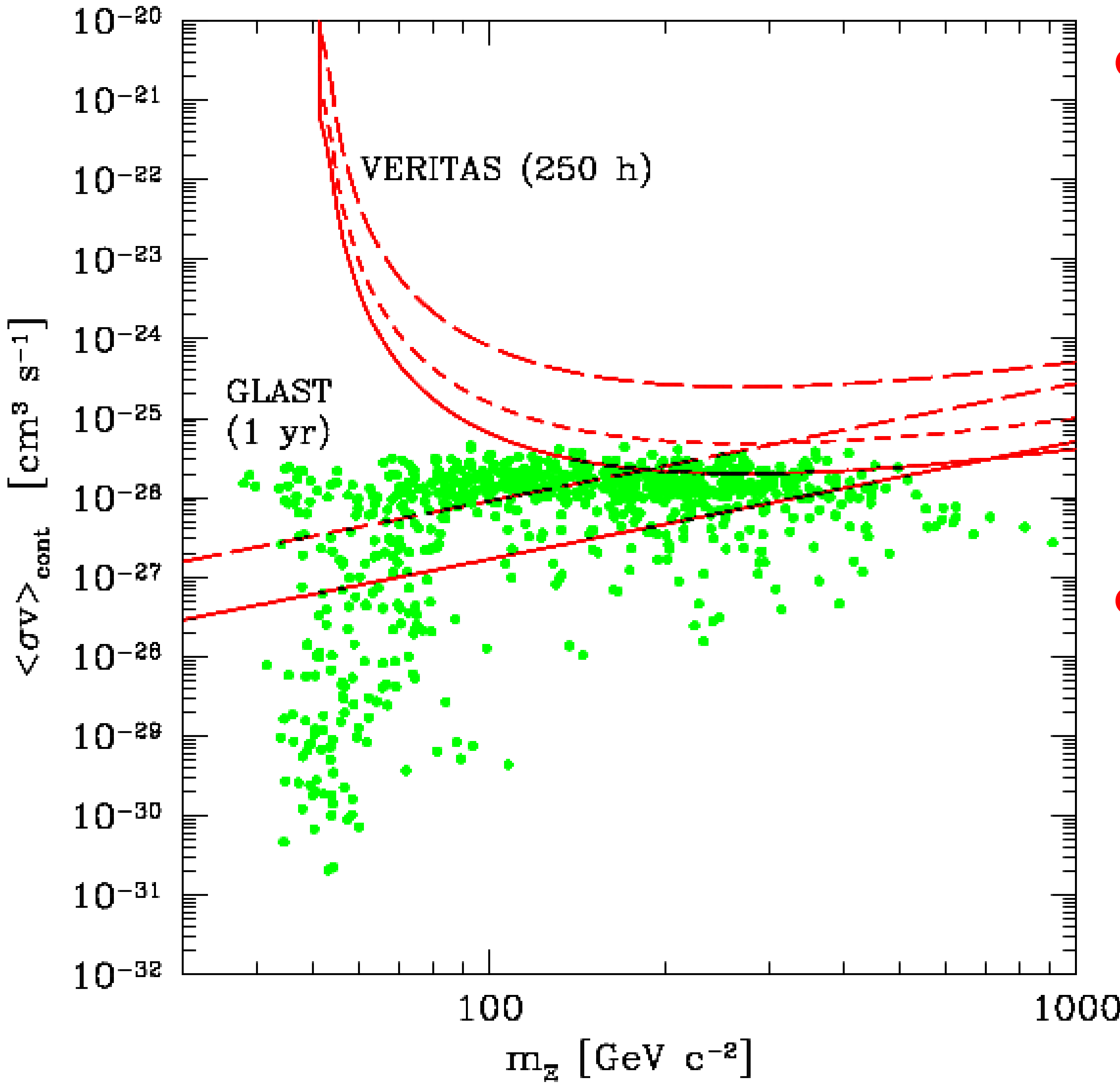


- $J = \sum \rho_i m_i$ is proportional to the annihilation luminosity of an object
- J appears to have converged for the higher resolution models
- $J \propto M$ for subhaloes

→ total subhalo luminosity dominated by most massive objects

Could GLAST or VERITAS see the Signal?

Stoehr et al 2003

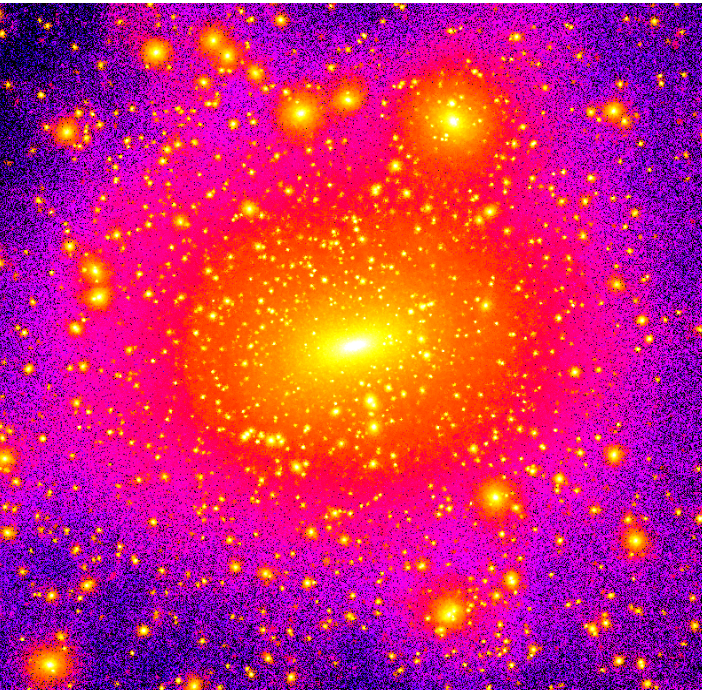


Possible MSSM params from Darksusy

- For VERITAS (a Cerenkov detector with 1.75° FOV) the detectability of the G.C. depends on poorly resolved regions of the simulation and is marginal

- For GLAST (a satellite with 3 sterad. FOV) detection should be possible 20° to 30° from the G.C. in a very long integration and for most MSSM parameters. This does *not* depend on poorly resolved regions of the simulation

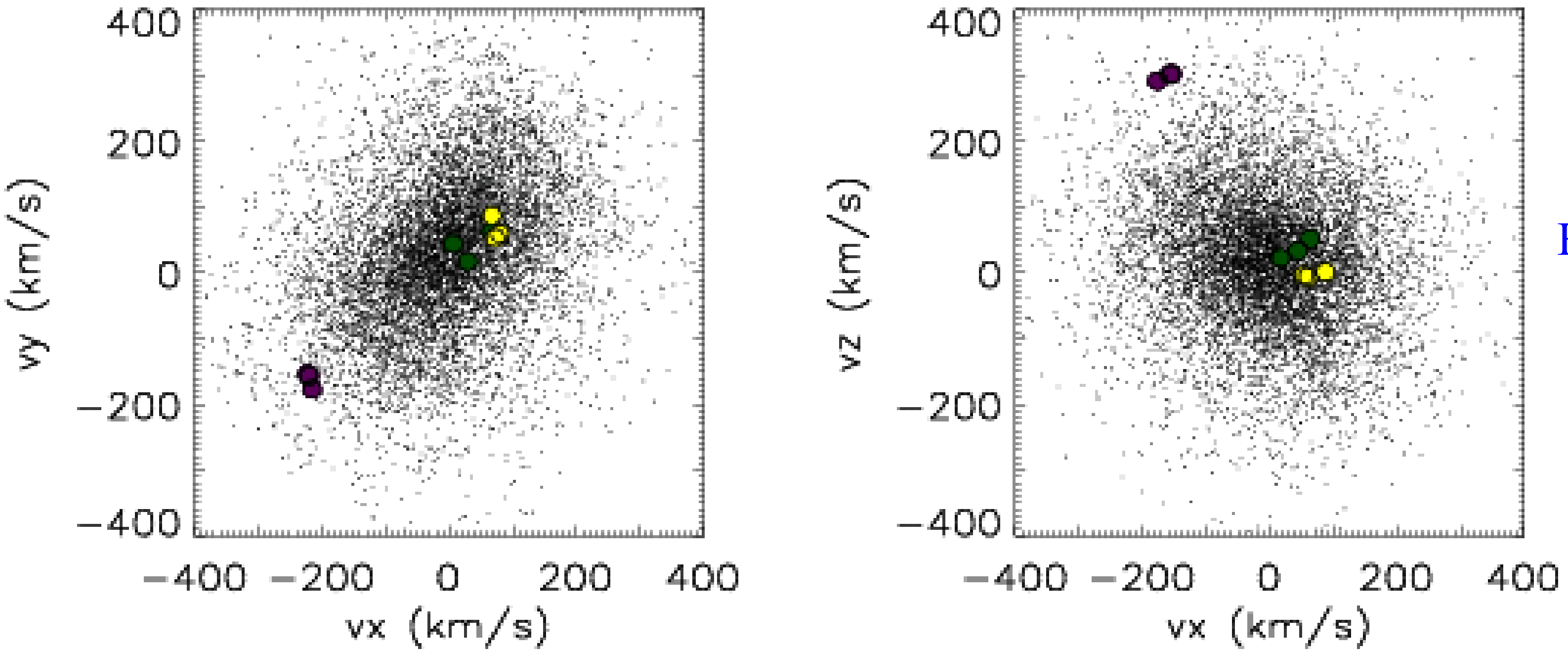
Dark Matter structure in the Solar Neighborhood



- ΛCDM ⟶ Galactic halo made by mergers
- Cores of progenitors survive as substructure
- Remainder present as phase-wrapped streams

What should DM detectors on Earth see?

- Local DM consists of many 1000's of streams
- Most come from a few massive progenitors
- These merged early with the Milky Way
- Distribution is almost multivariate gaussian



Helmi, White & Springel 2003

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