Satellites and Tidal Streams
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Structure and substructure in dark matter halos

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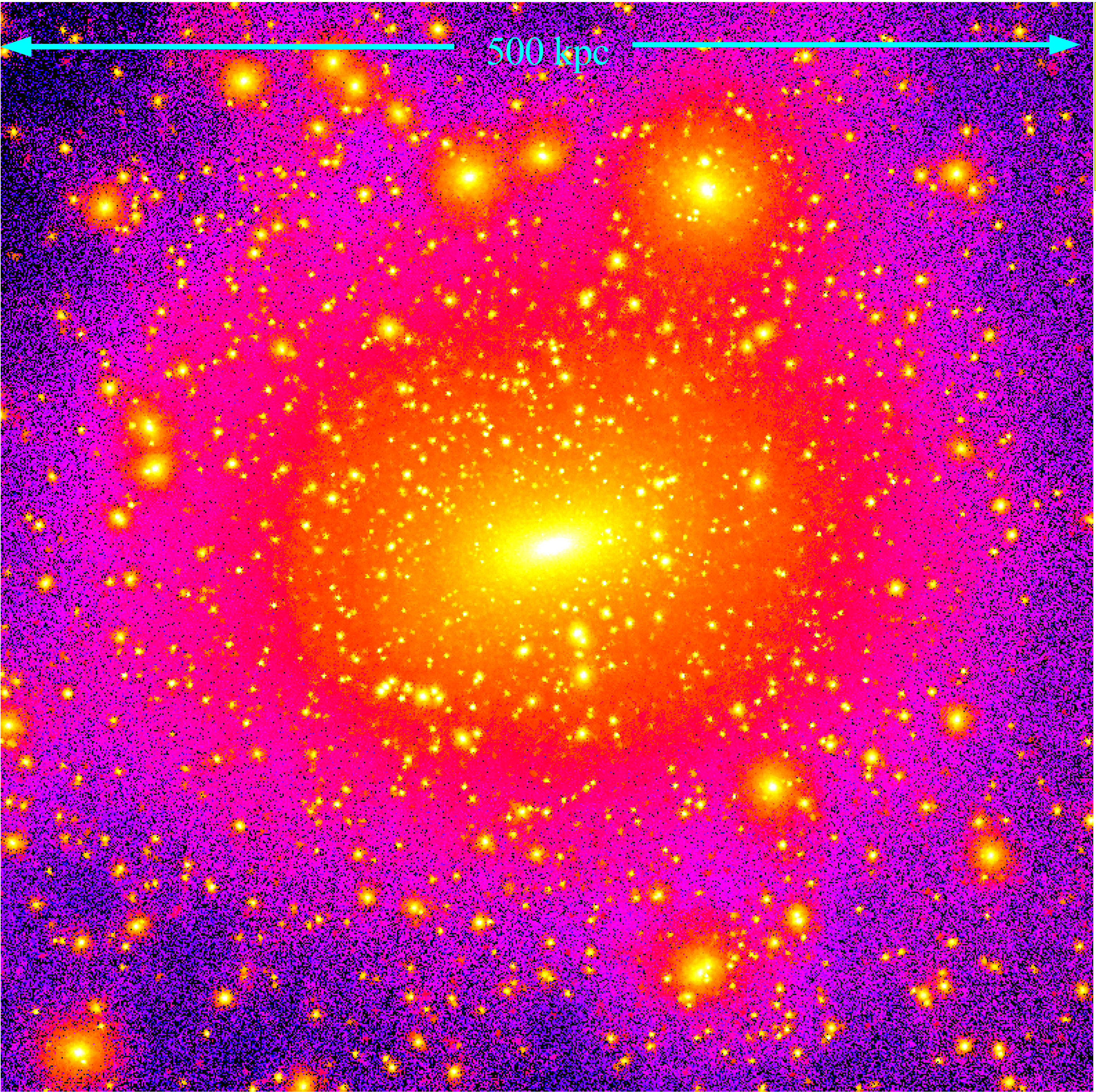
A ΛCDM Milky Way



Does the Milky Way's halo really look like this?

Concentration?

Shape?

Substructure?

Observed velocity dispersion versus potential well depth

Consider a *known* (*i.e.* observed) density distribution of stars $\rho(\mathrm{r})$ in a *given* (*i.e.* simulated) potential well $\Phi(\mathrm{r})$

- For gas in a spherical potential: $\mathrm{d}\,p/\mathrm{d}\,r = -\rho\,\mathrm{d}\Phi/\mathrm{d}\,r = -\rho V_c^2/r$

- For a spherical stellar distribution

$$\mathrm{d}\,(\rho\sigma_{\mathrm{r}}^2)/\,\mathrm{d}\,r + 2\,\rho\,(\sigma_{\mathrm{r}}^2 - \sigma_{\mathrm{t}}^2)/\,r = -\,\rho\,V_c^2/\,r$$

$$\longrightarrow \quad \langle\sigma_{\mathrm{l.o.s.}}^2\rangle = \langle V_c^2\rangle\,/\,3$$

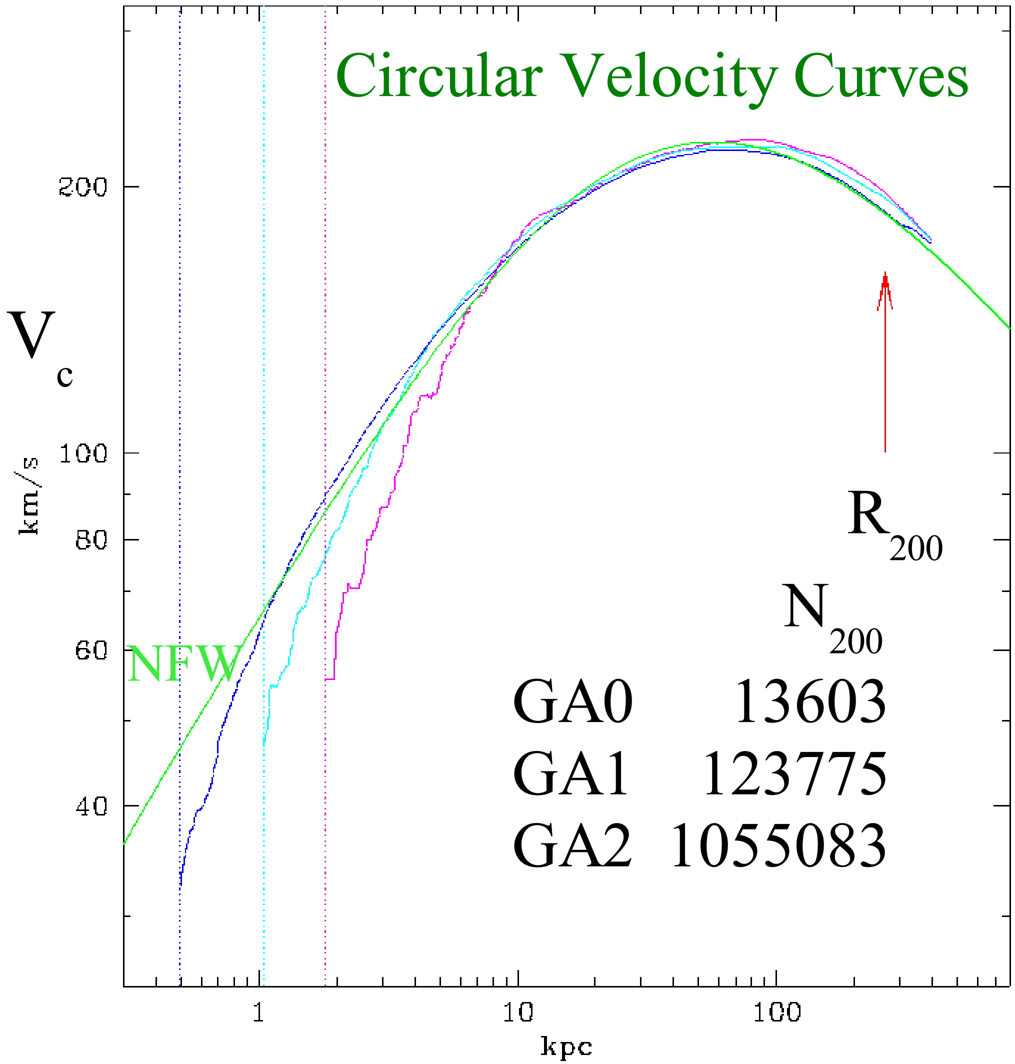
where $\langle....\rangle$ denotes an average over all stars in the dwarf

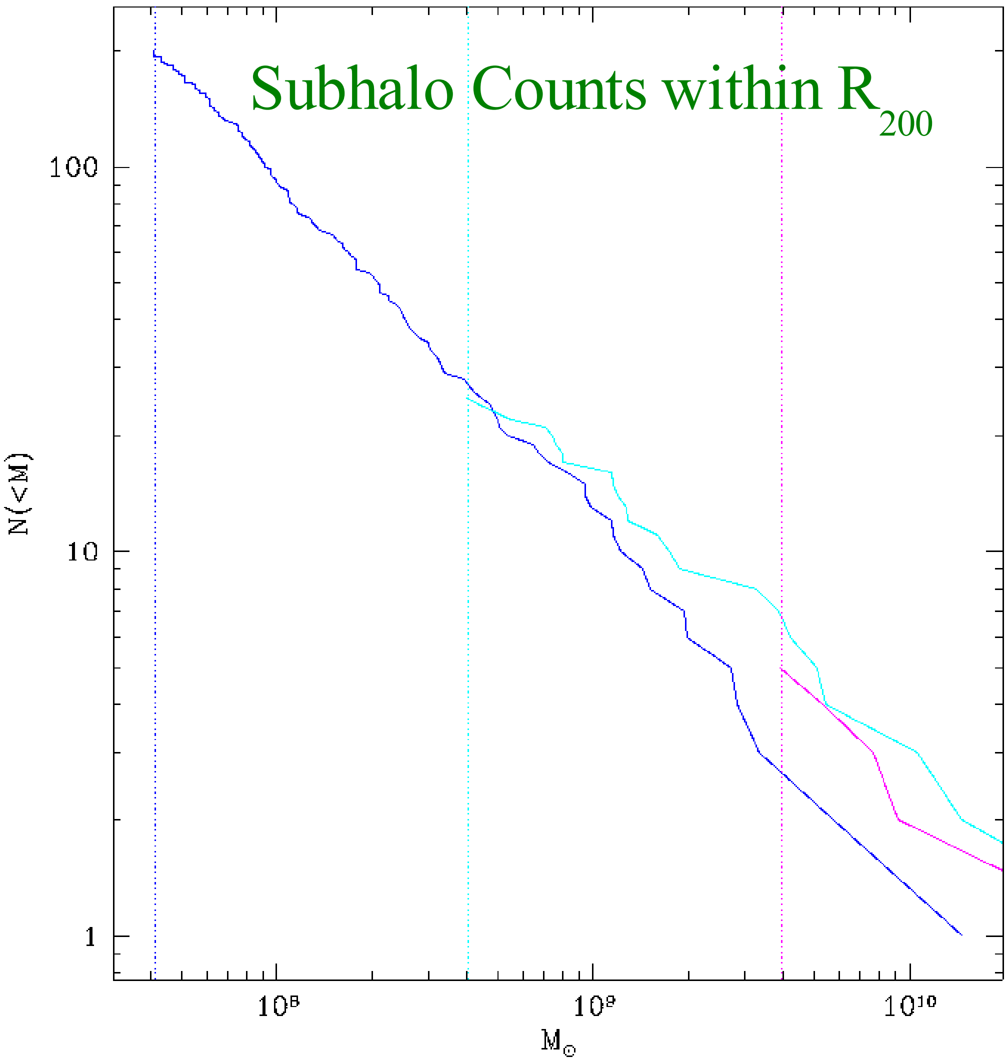
- For an isotropic velocity dispersion ($\sigma_{\mathrm{r}} = \sigma_{\mathrm{t}}$ at all r)

$$\sigma_{\mathrm{l.o.s.}}^2(r_{\mathrm{p}}) = \int \mathrm{d}\,r\;\rho\,V_c^2\,(r^2 - r_p^2)^{1/2}/r \;\Big/\; \int \mathrm{d}\,r\;\rho\,r\,/\,(r^2 - r_p^2)^{1/2}$$

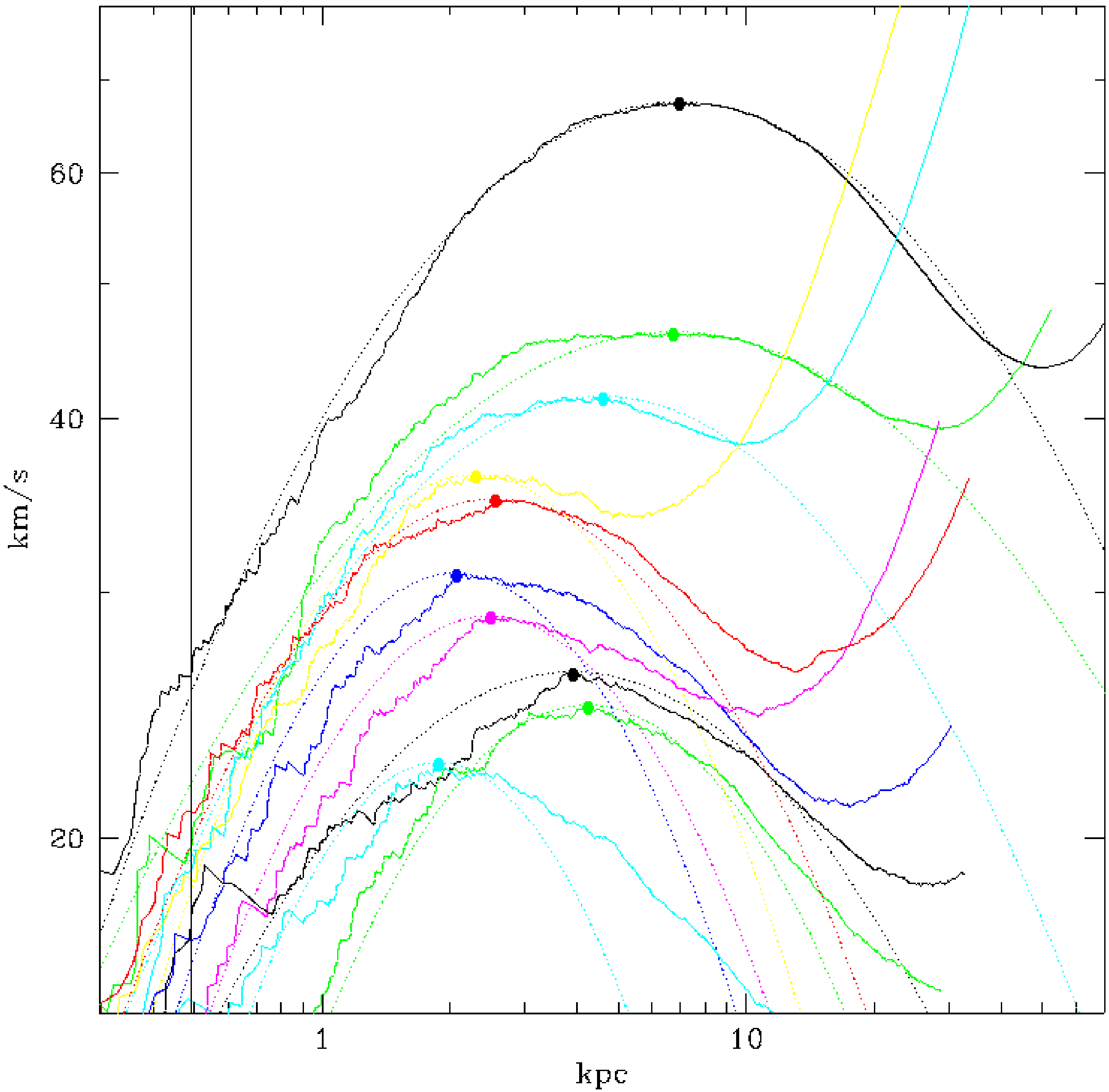
Simulations of ΛCDM Milky Way halos

Stöhr, White, Tormen & Springel 2002





Circular velocity curves for subhalos

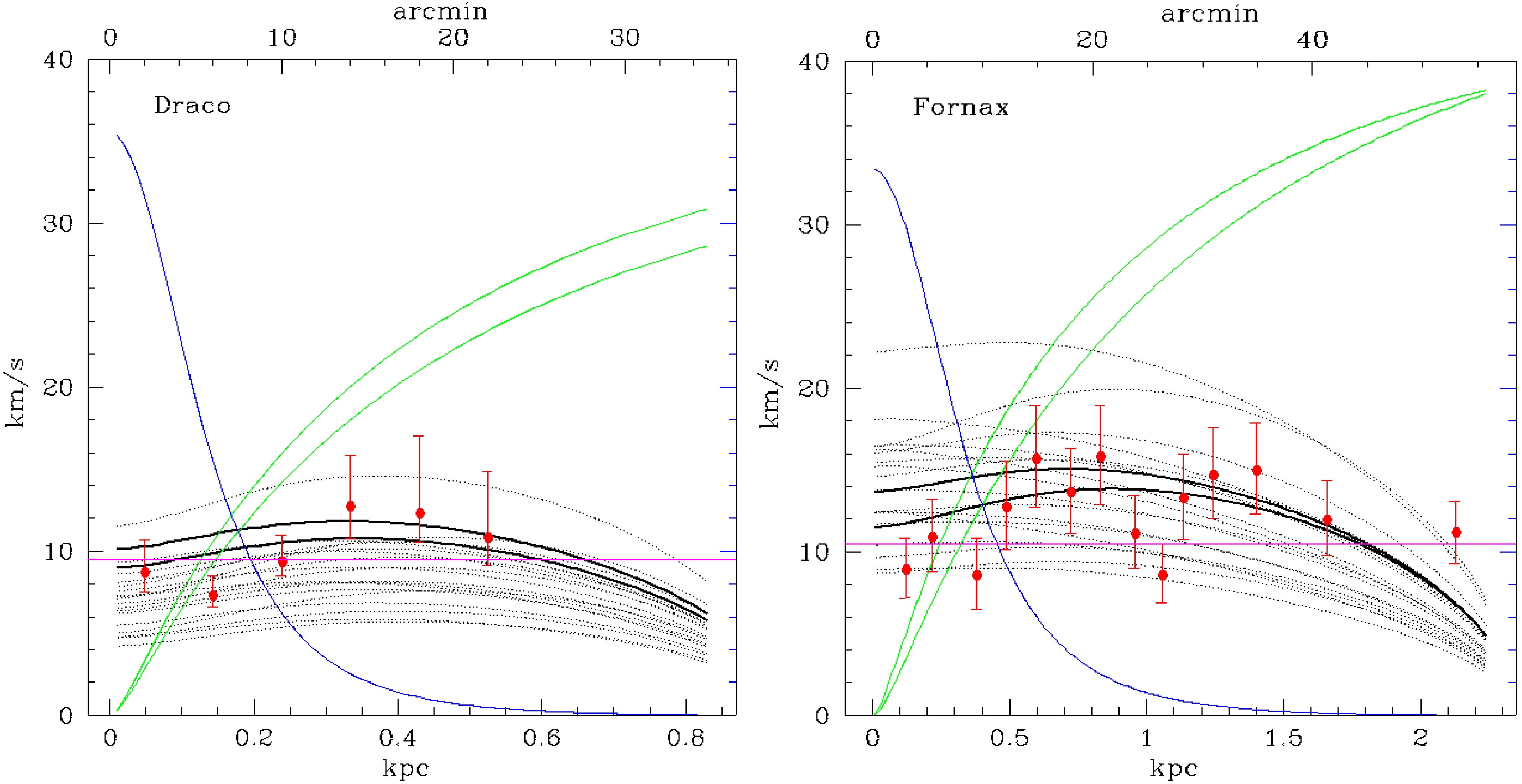


Stöhr et al 2002

$V_c(r)$ for the 20 most massive subhalos in GA2

Predicted velocity dispersion profiles for Draco and Fornax

Putting the observed star distributions in the potentials of the 20 largest ΛCDM subhalos



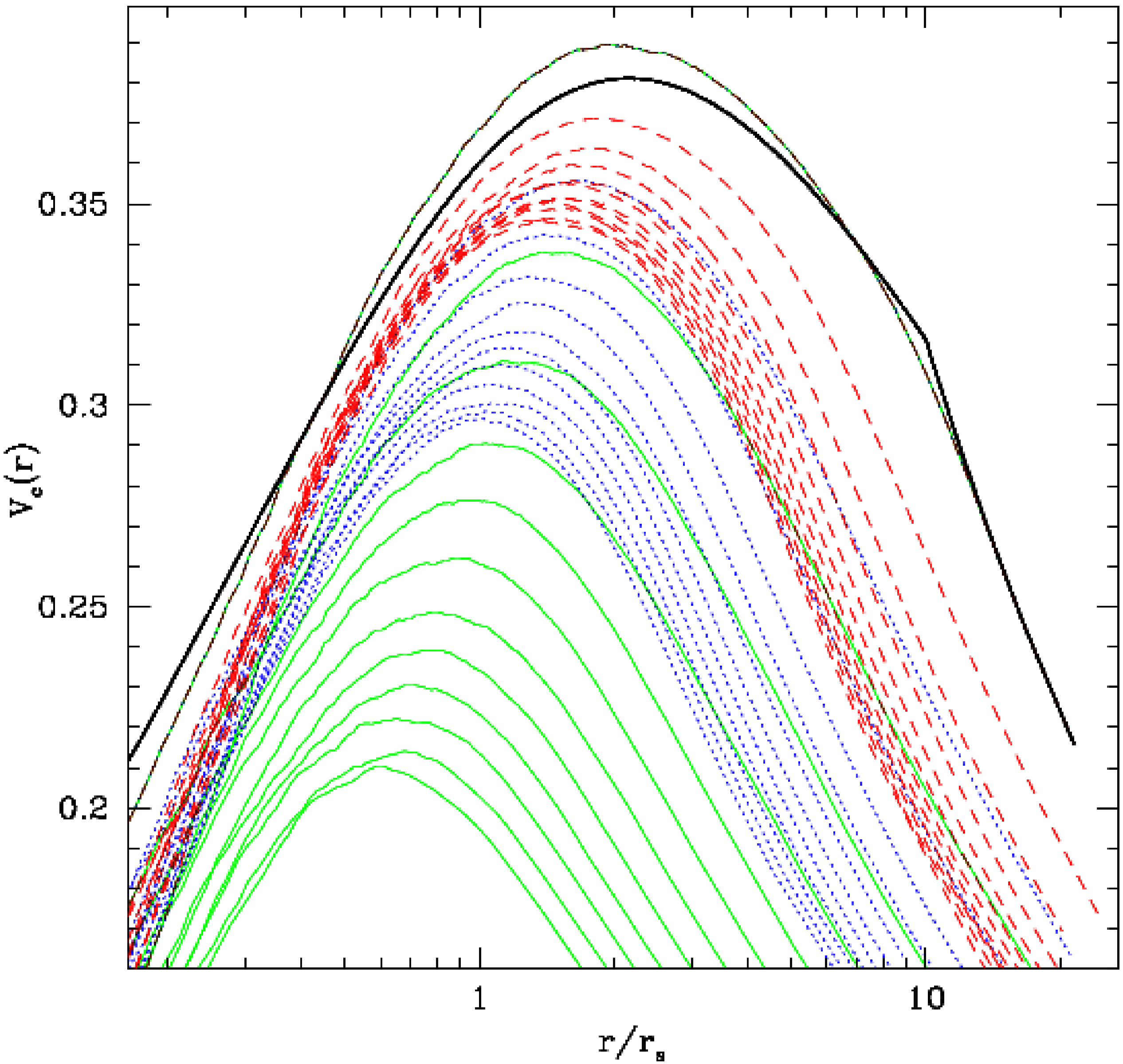
A resolution of the substructure "crisis"?

- The observed kinematics of *all eleven* of the Milky Way's satellites are consistent with them being embedded in one of the 15 most massive subhalos in the ΛCDM Milky Way
  There is no contradiction but an excellent agreement!

- The potential wells of the less massive substructures are too shallow to harbour the observed satellites

- The outstanding question is *why* the formation of stars has been so inefficient in these substructure potentials
  e.g. Draco and Fornax have similar potentials but differ by a factor 60 in luminosity

High resolution simulations of subhalo stripping

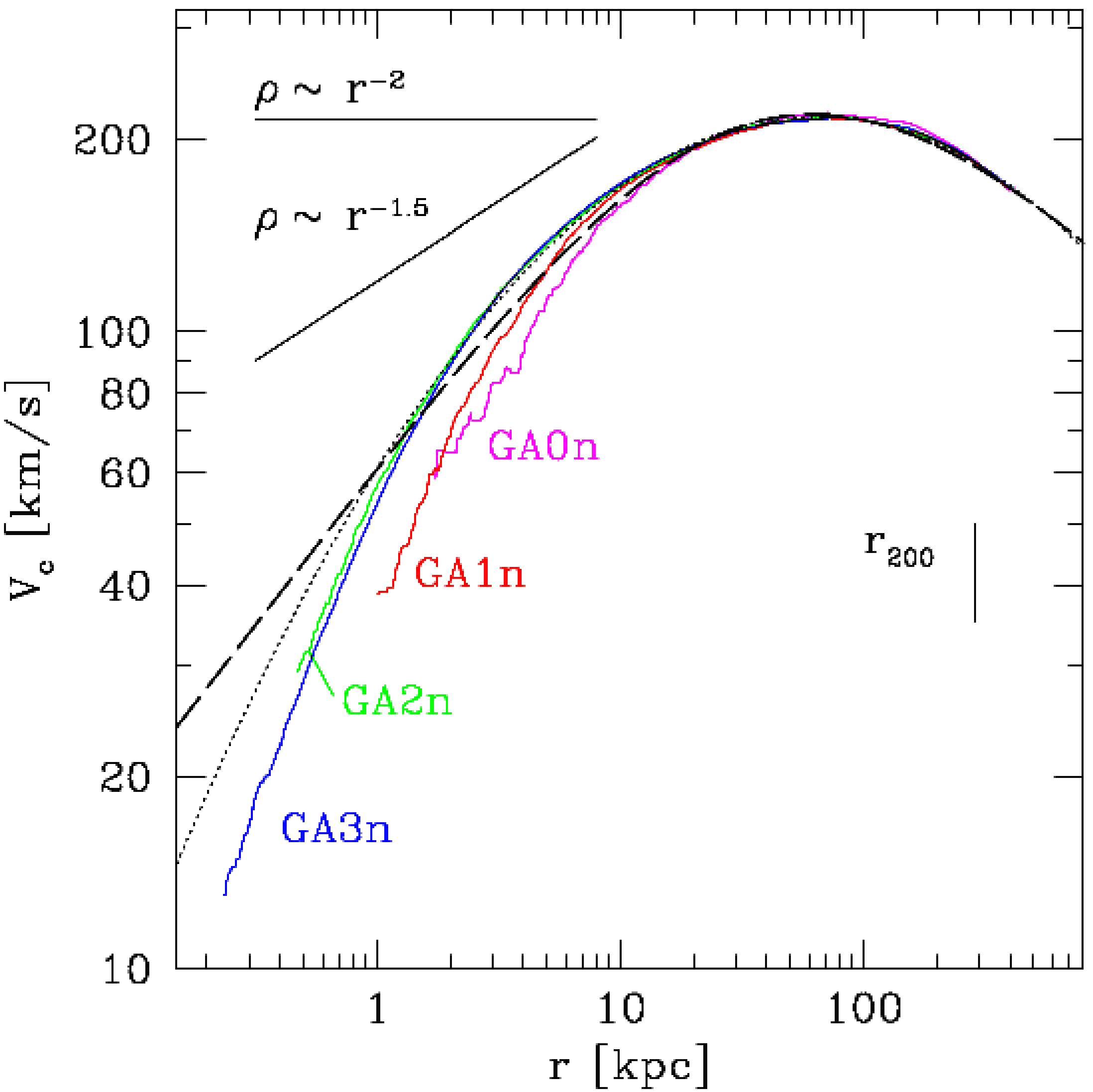


Hayashi et al 2002

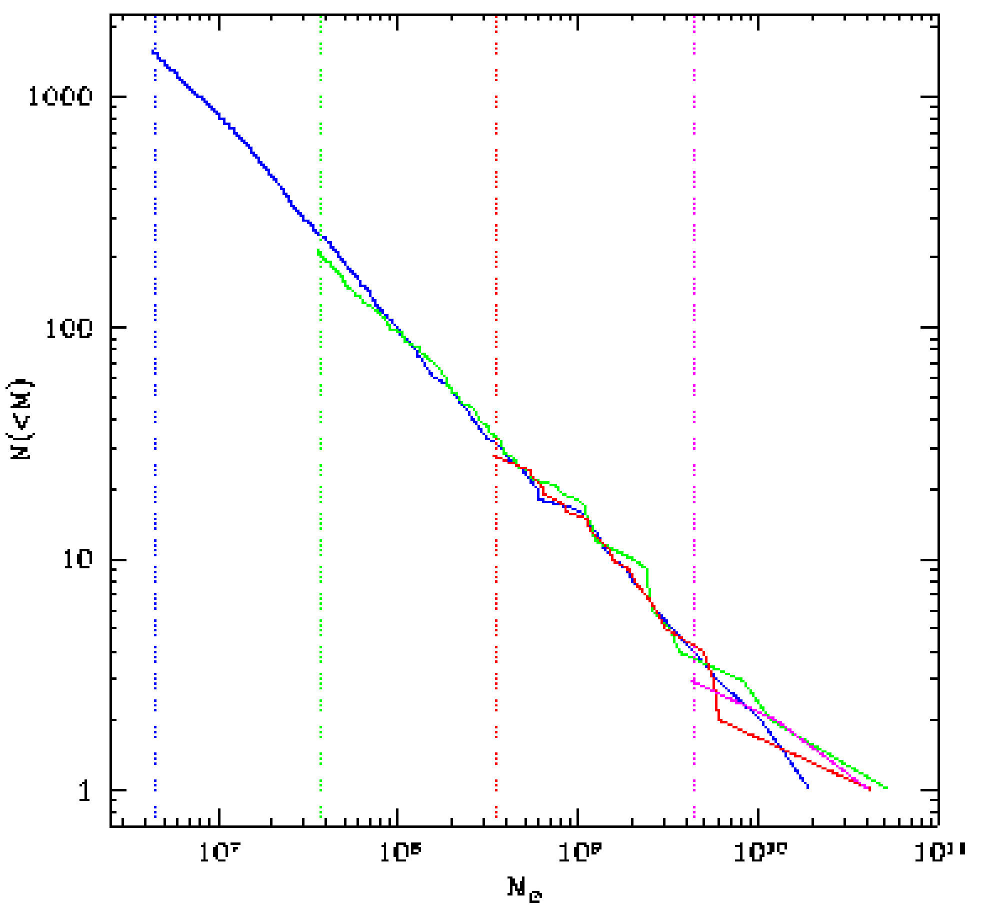
Simulations of the tidal stripping of a single NFW subhalo with N ~ 100,000 falling into a rigid NFW Milky Way halo

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

A resimulation with 10x better mass resolution



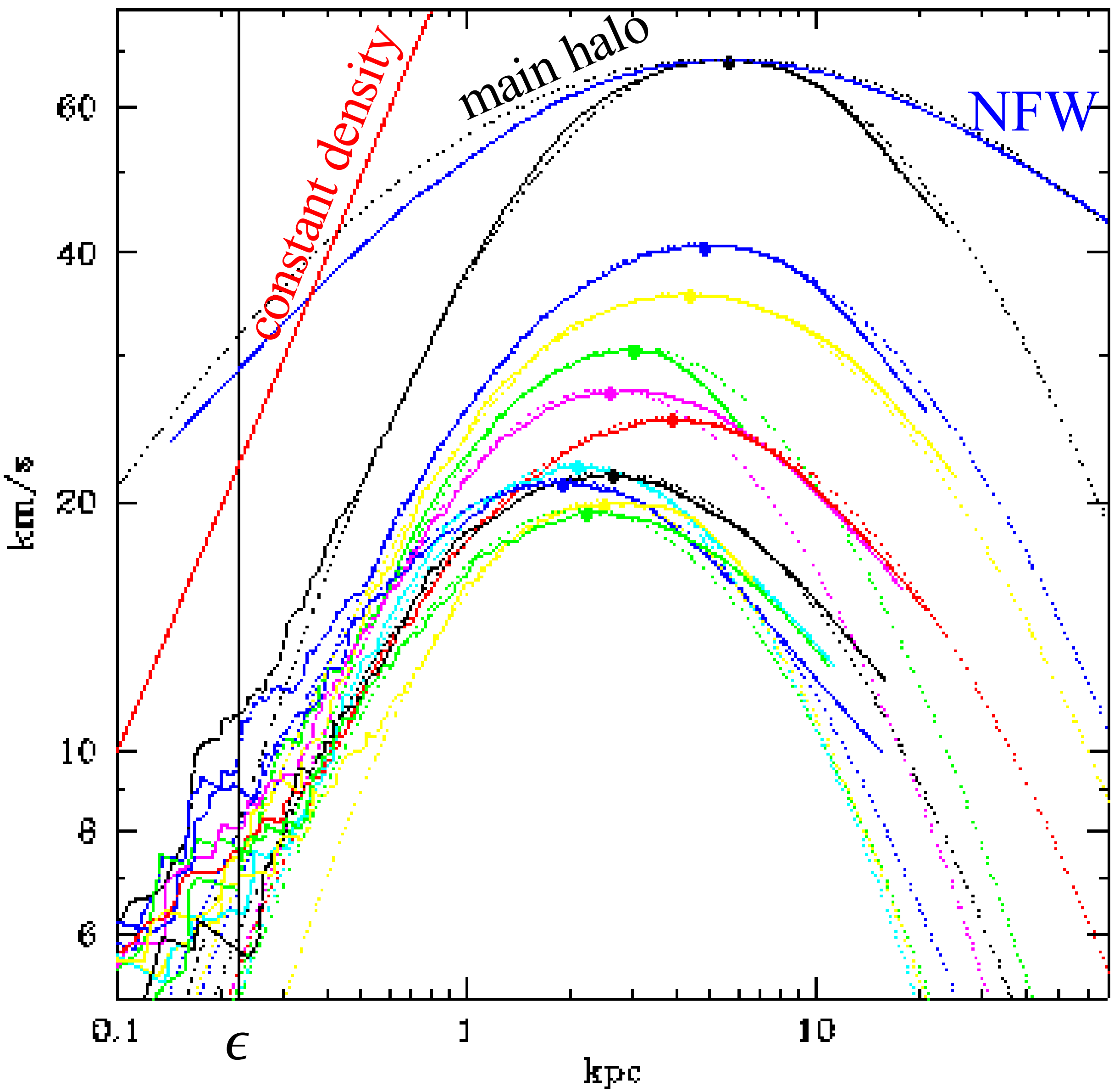
Stoehr et al 2003



New simulation with N_{200} = 10,089,396, ϵ = 240 pc, improved integration for all simulations

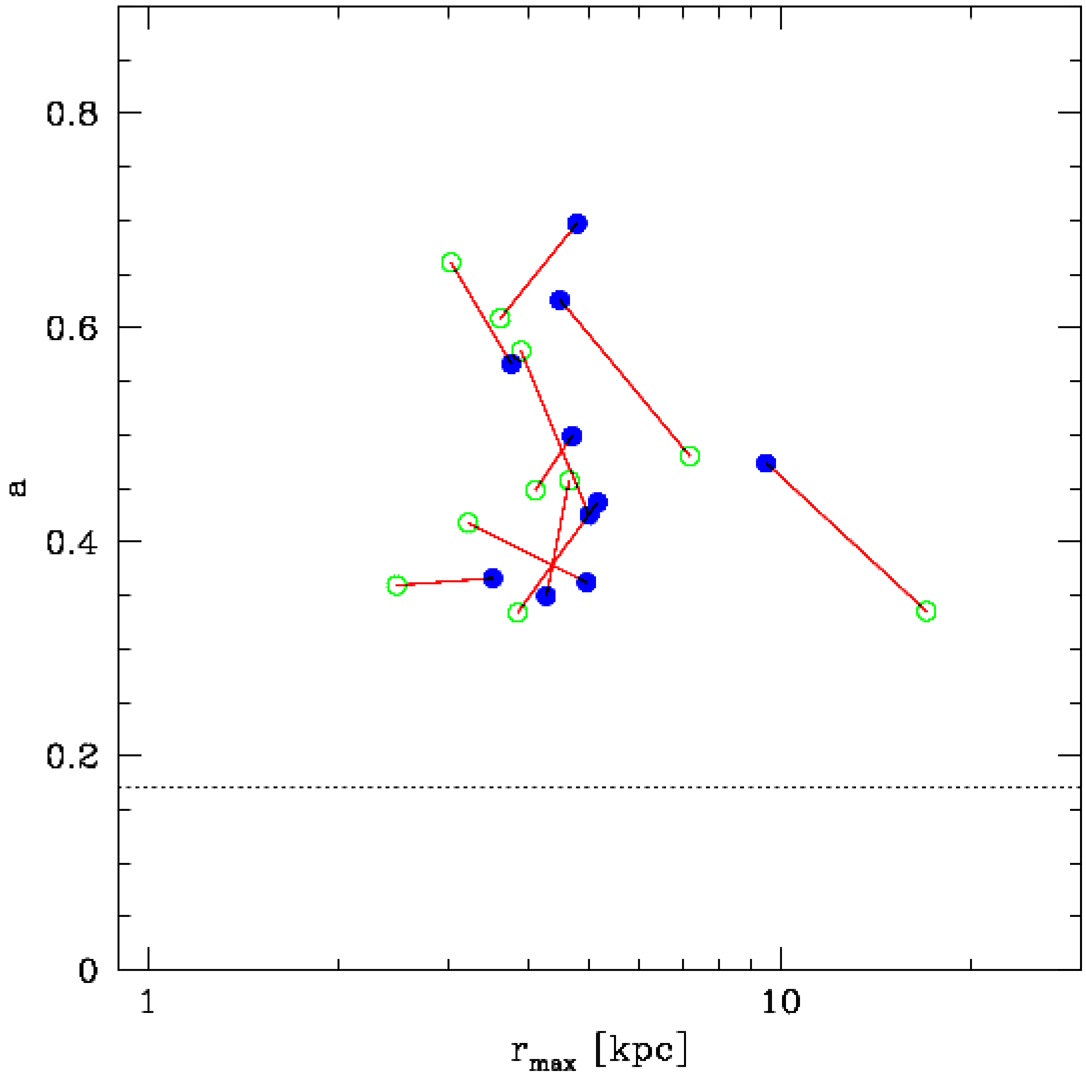
Satellite circular velocity curves

Stoehr et al 2003



- Circular velocity curves for 11 of the 30 most massive subhalos in GA3n
- Only bound particles used
- 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'
- Subhalo profiles approach a constant density core in the inner regions

Convergence test for subhalo structure



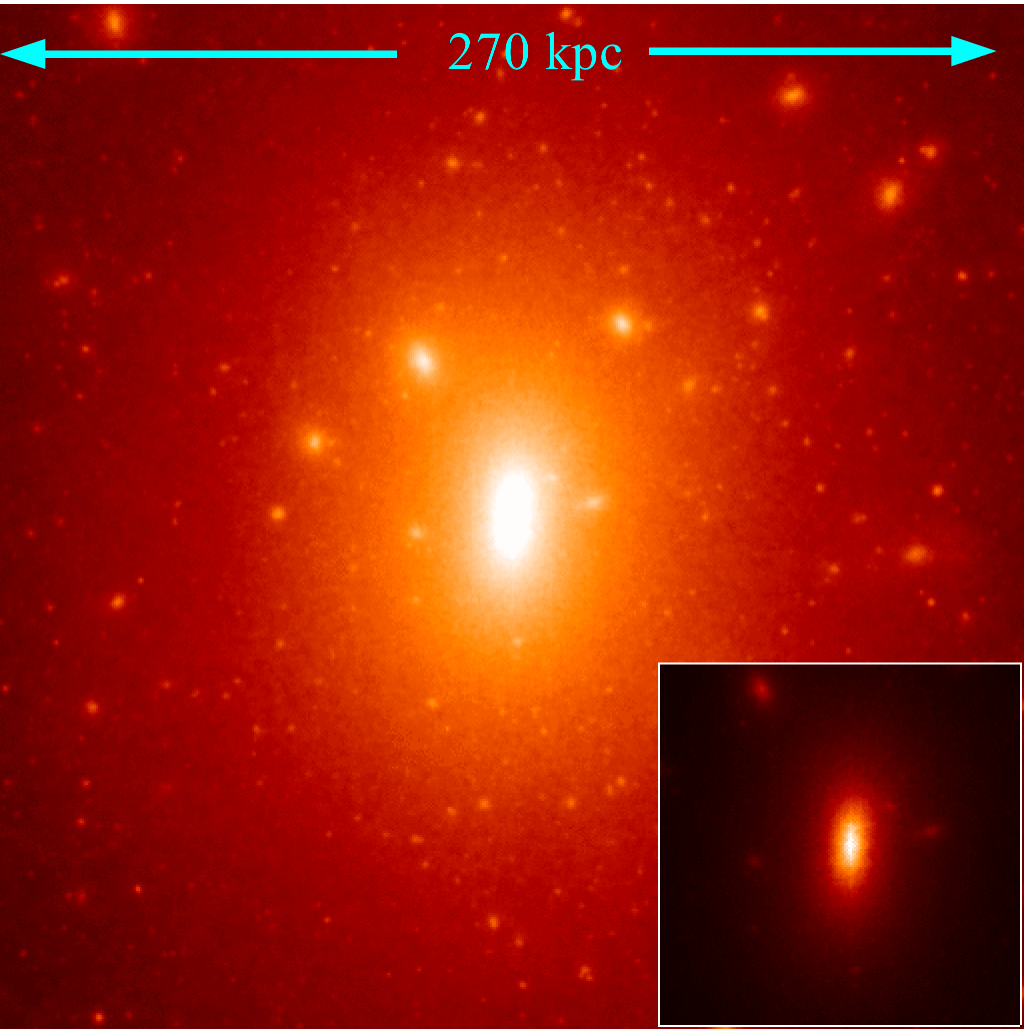
- 10 of the 14 most massive subhalos in GA3n can be matched to subhalos in GA2n
- Structural parameters of the circular velocity curves match well with no systematic trend despite 10 times better resolution

$$\log (V_c/V_{max}) = - a\, [\log(r/r_{max})]^2$$

- a values are much larger than the a = 0.17 found for the main halo in both GA2n and GA3n

γ-rays from the annihilation of DM particles

Stoehr et al 2003



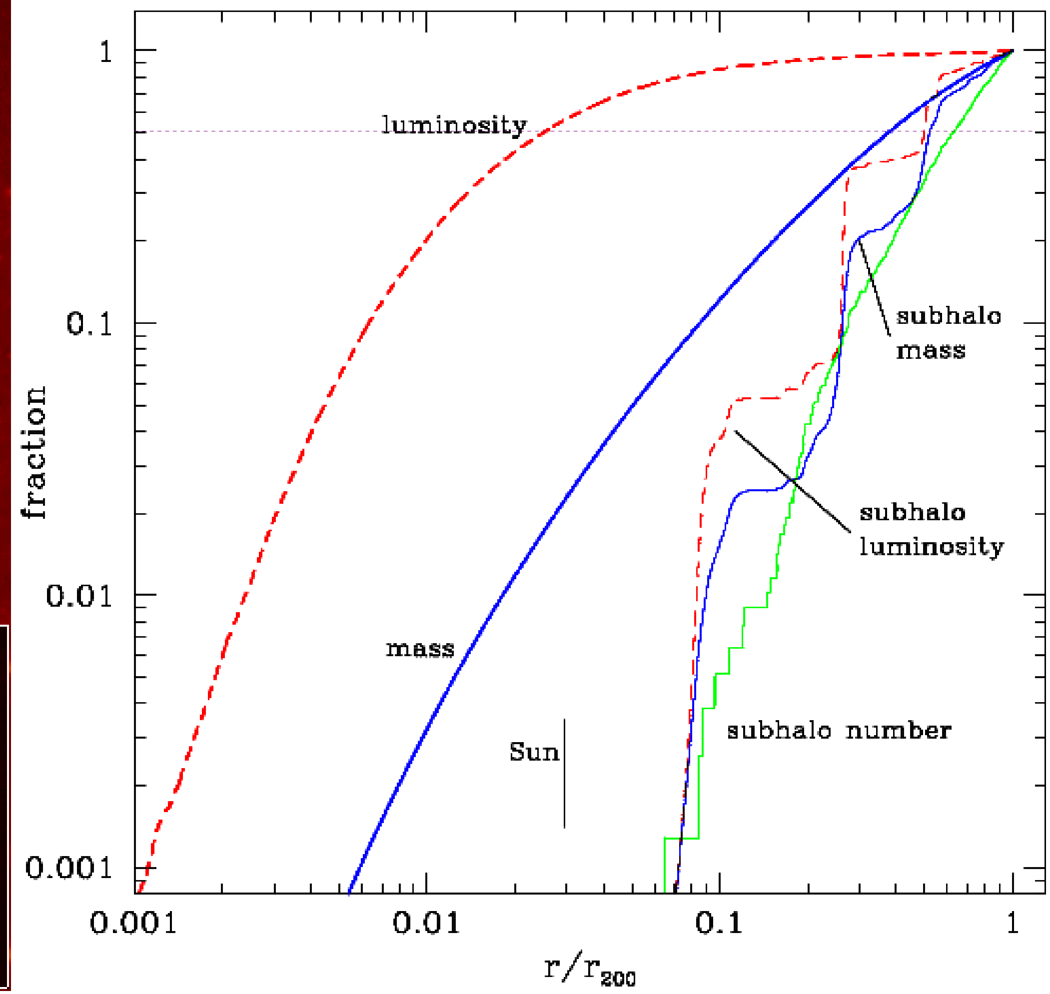
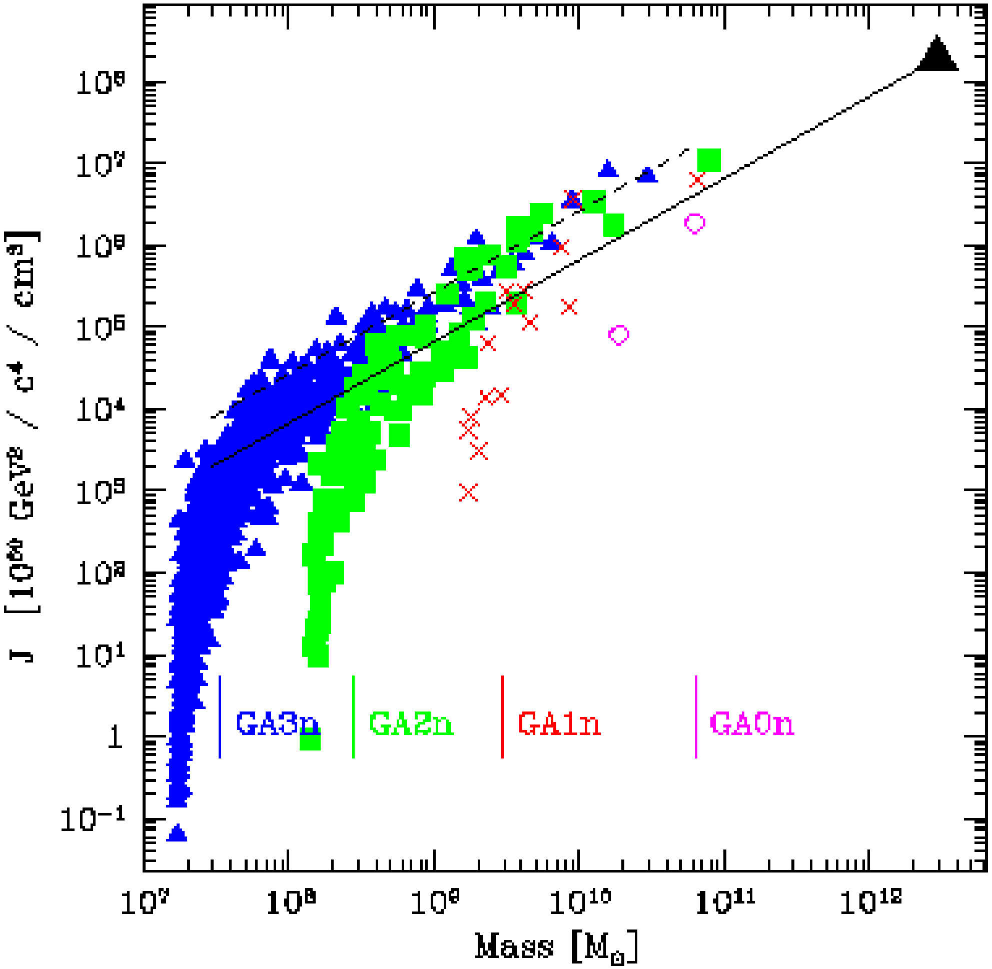


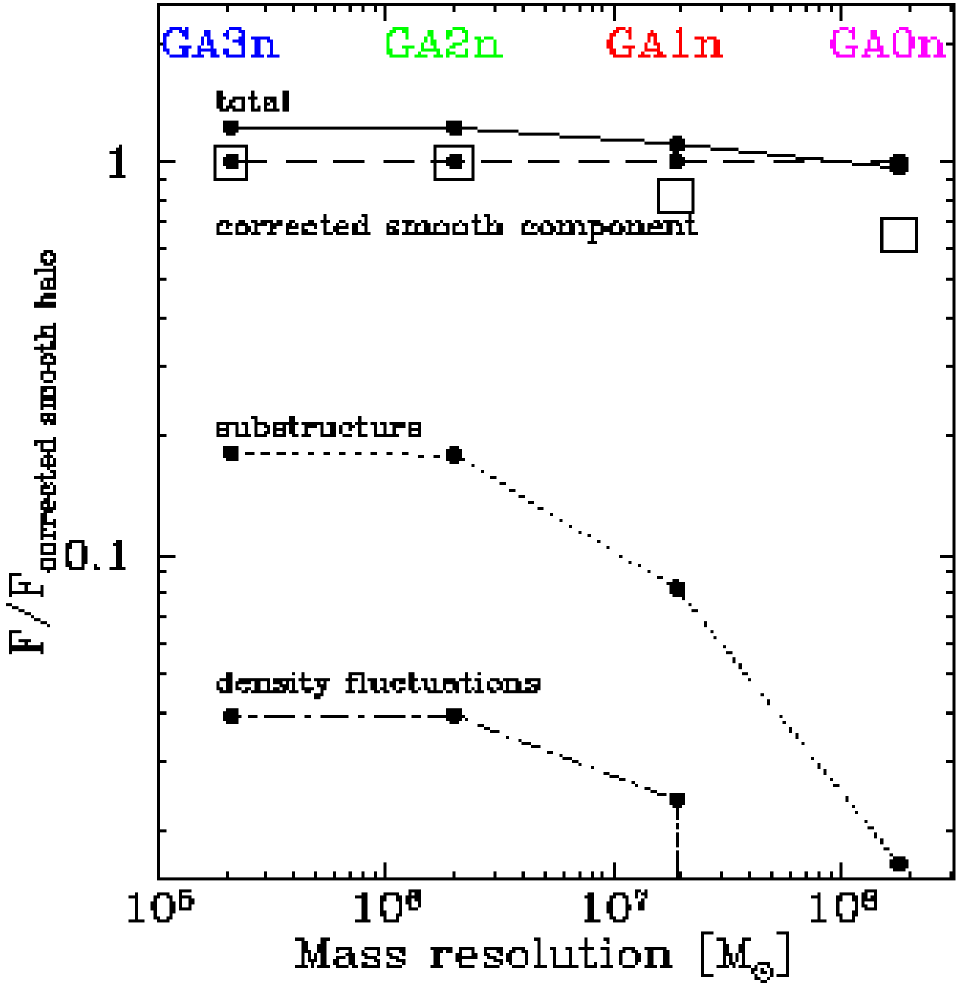
Image of a 'Milky Way' halo in annihilation radiation

Distributions of mass and of smooth and subhalo luminosity

γ-rays from the annihilation of DM particles

Stoehr et al 2003





$J = \sum_i m_i \, \rho_i$ summed over all particles in a (sub)halo is $\propto L_i$

Convergence of contributions to luminosity with increasing mass resolution in simulation

γ-rays from the annihilation of DM particles

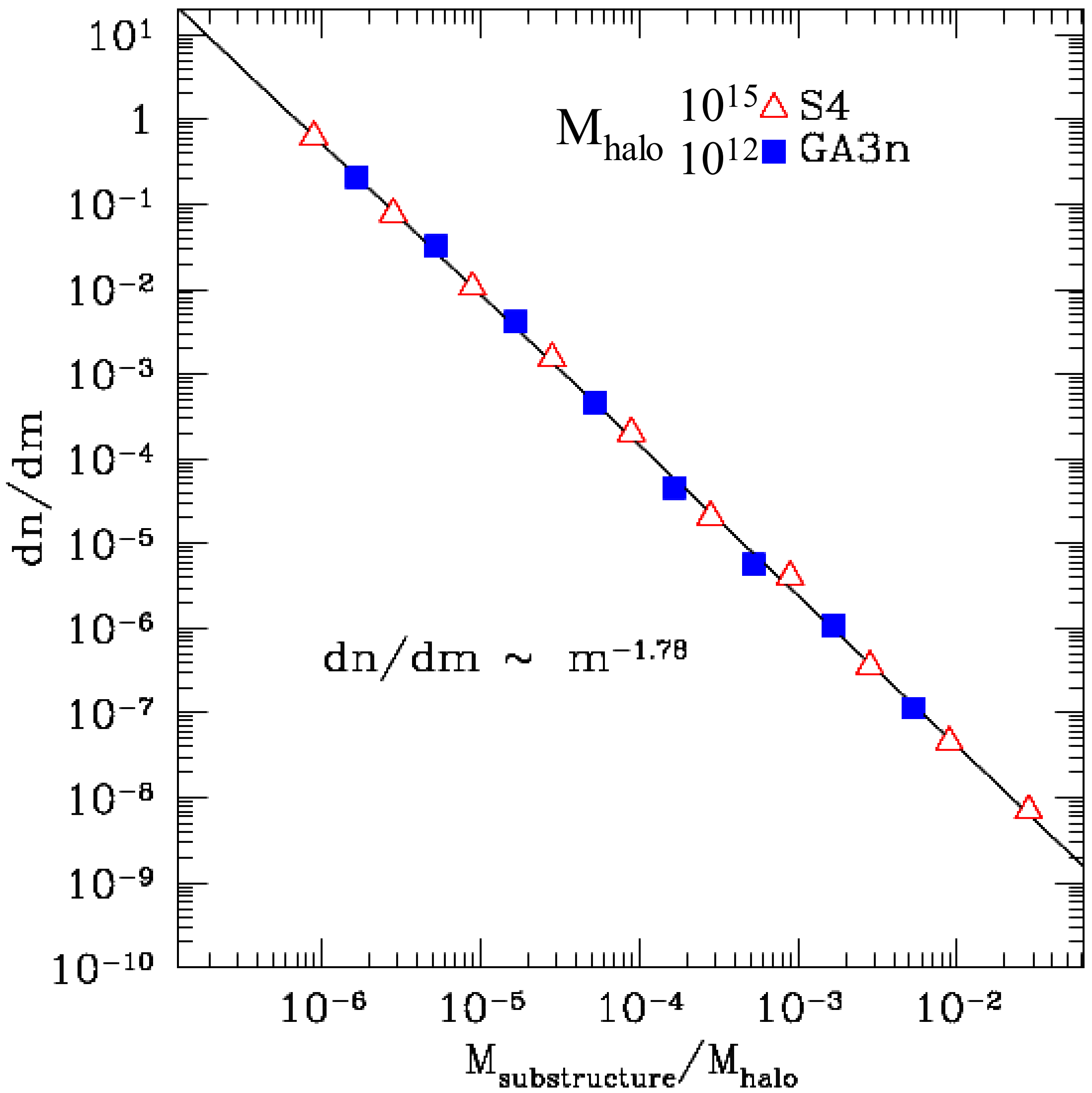
- The annihilation luminosity is $L \propto \int \rho^2 \, dV \propto \int \rho^2 r^2 \, dr$ for a spherical system → the dominant contribution comes from regions where $\rho \propto r^{-1.5}$
- The simulated ΛCDM Milky Way halo has half its luminosity coming from within 8.6 kpc of the centre
- The luminosity/mass of substructures is independent of mass → extra luminosity comes from most massive substructures
- The total luminosity exceeds that of a smooth spherical halo with the same $V_{circ}(r)$ by:

  +25% due to substructure
  +15% due to flattening
  + 8% due to unbound substructure

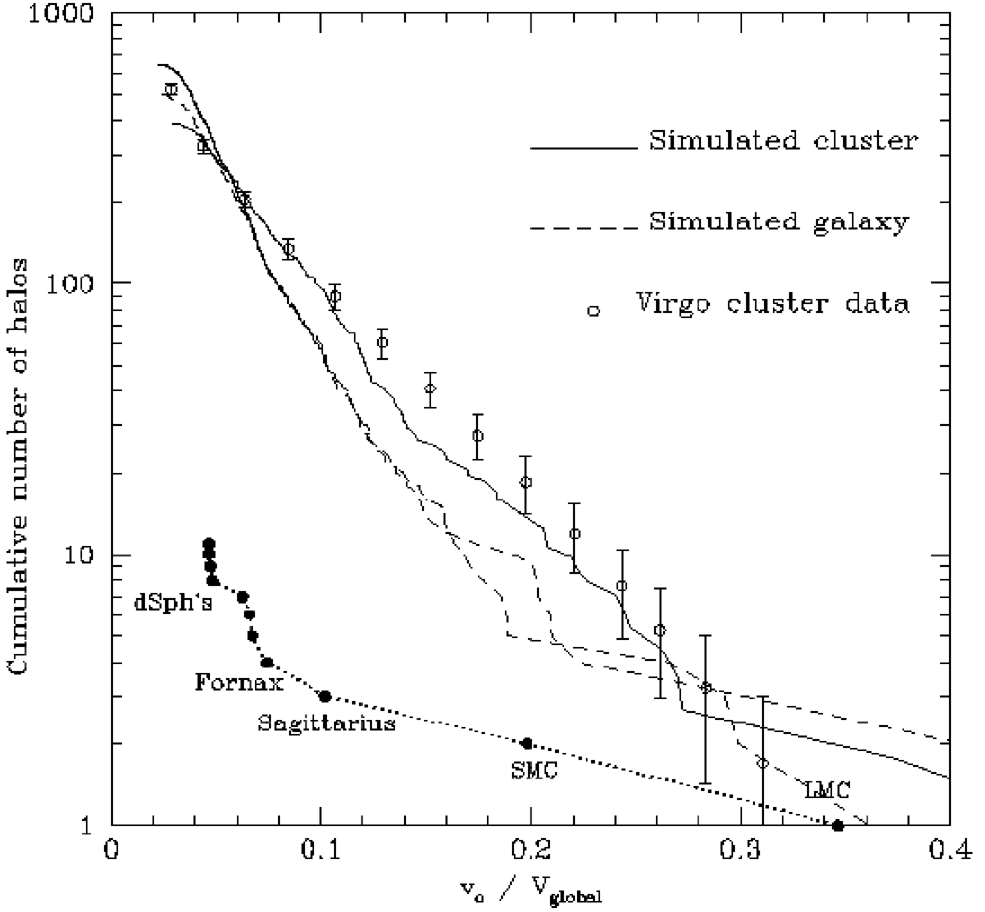
- Annihilation radiation from $R < R_{sun}$ may be detectable with next generation γ-ray telescopes

Are galaxy halos scaled copies of clusters?

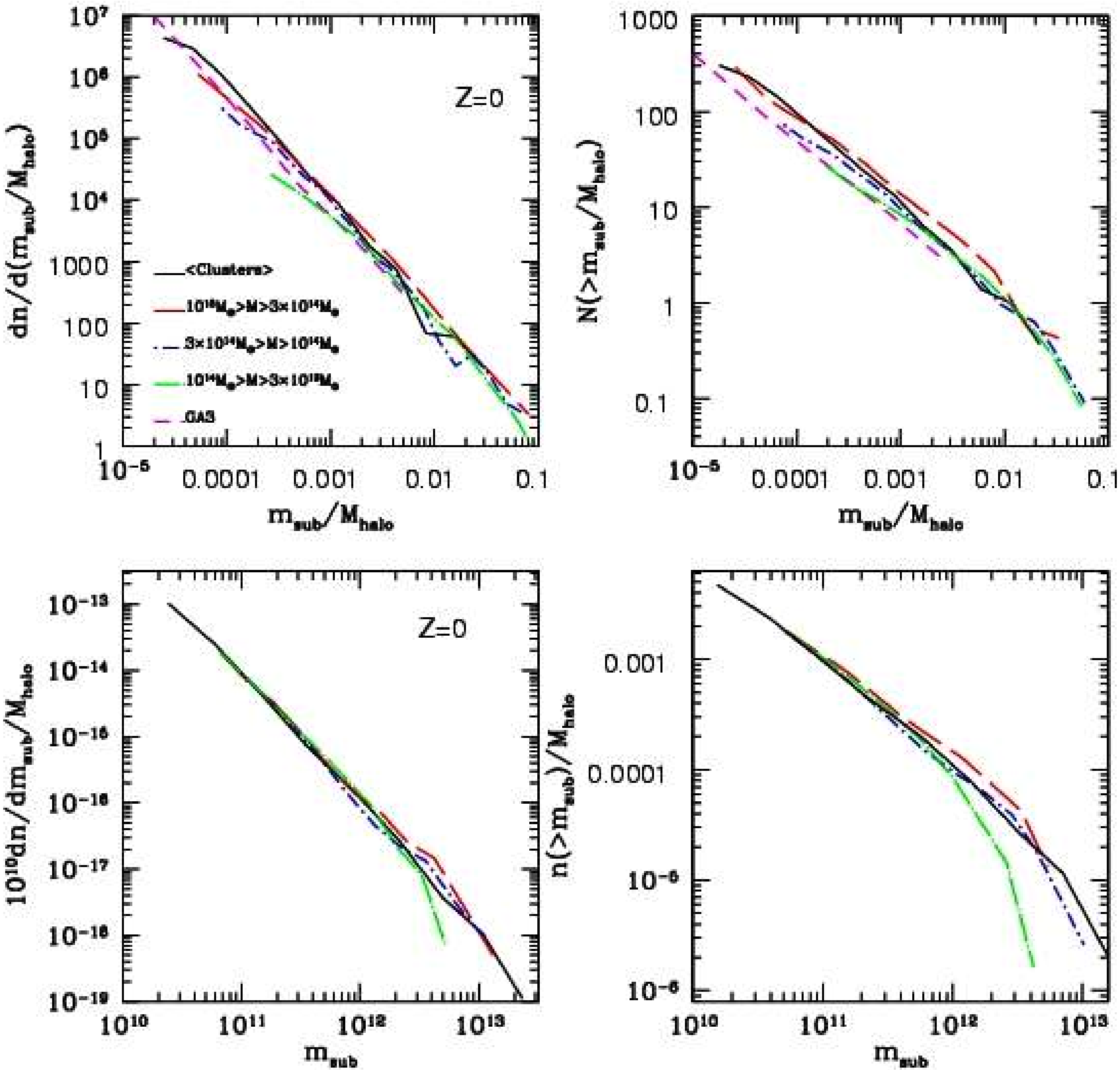
Stoehr et al 2003



Moore et al 1999



Gao Liang et al 2003



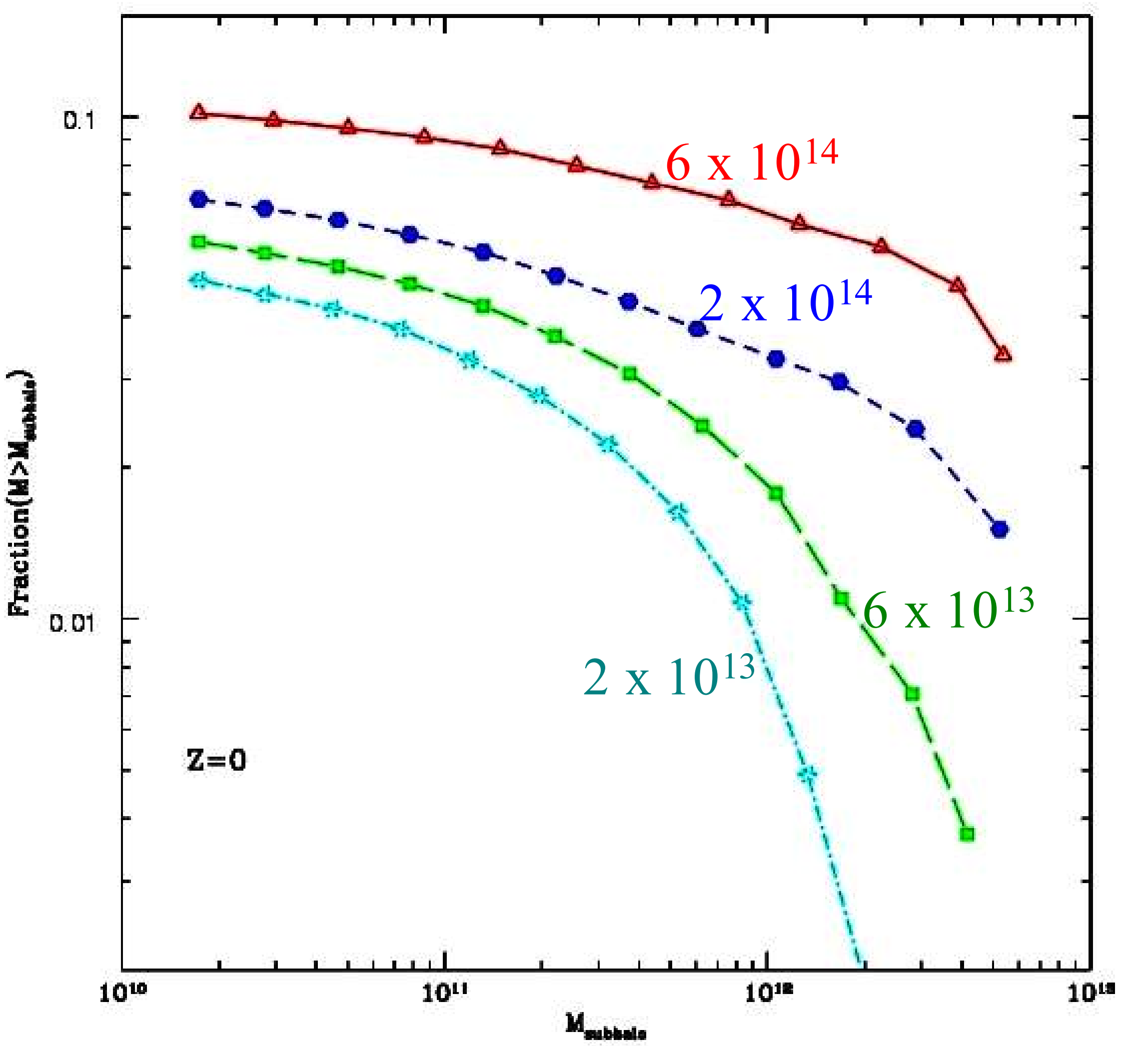
Universal substructure mass functions?

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

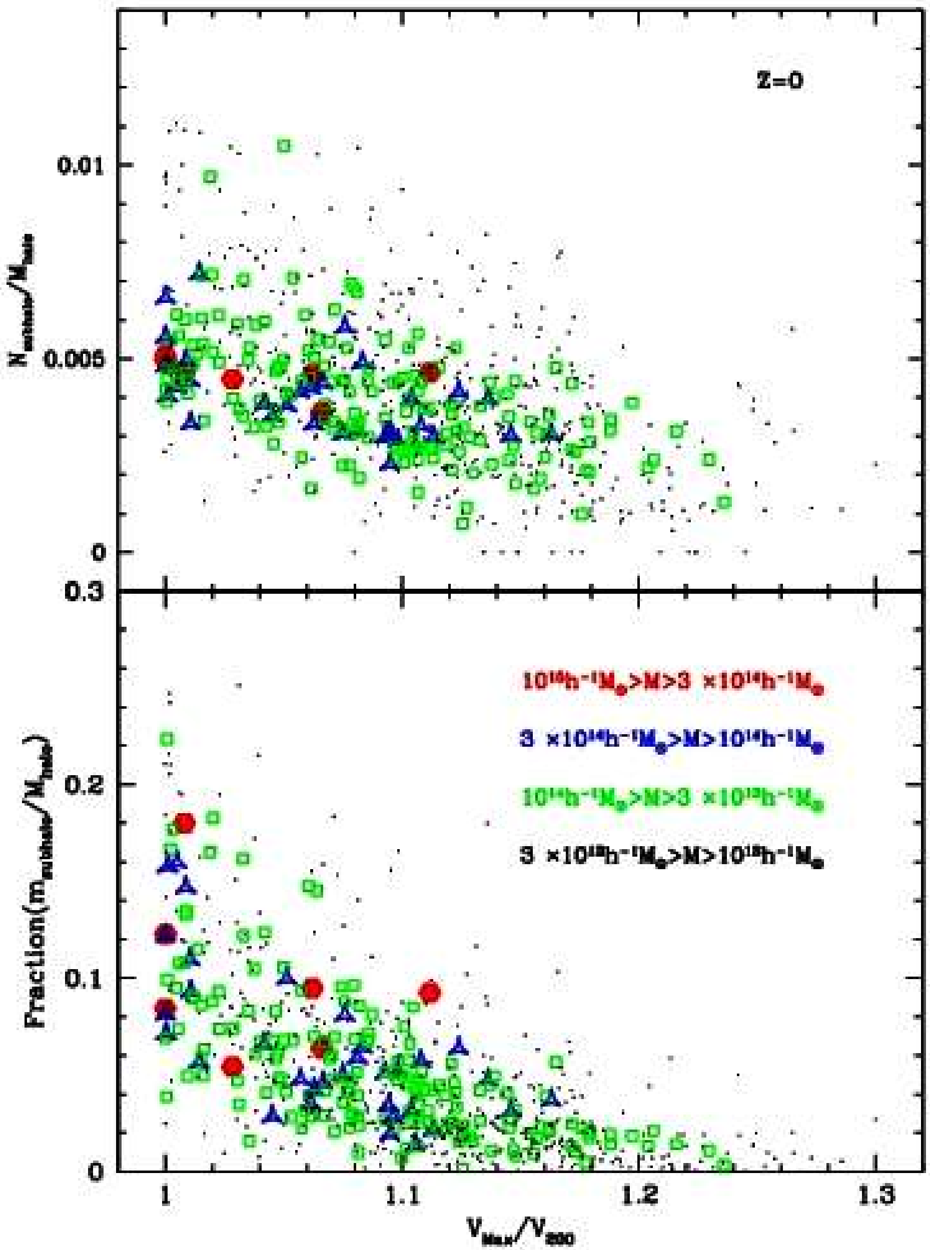
Gao Liang et al 2003



- 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

The concentration--substructure relation

Gao Liang et al 2003

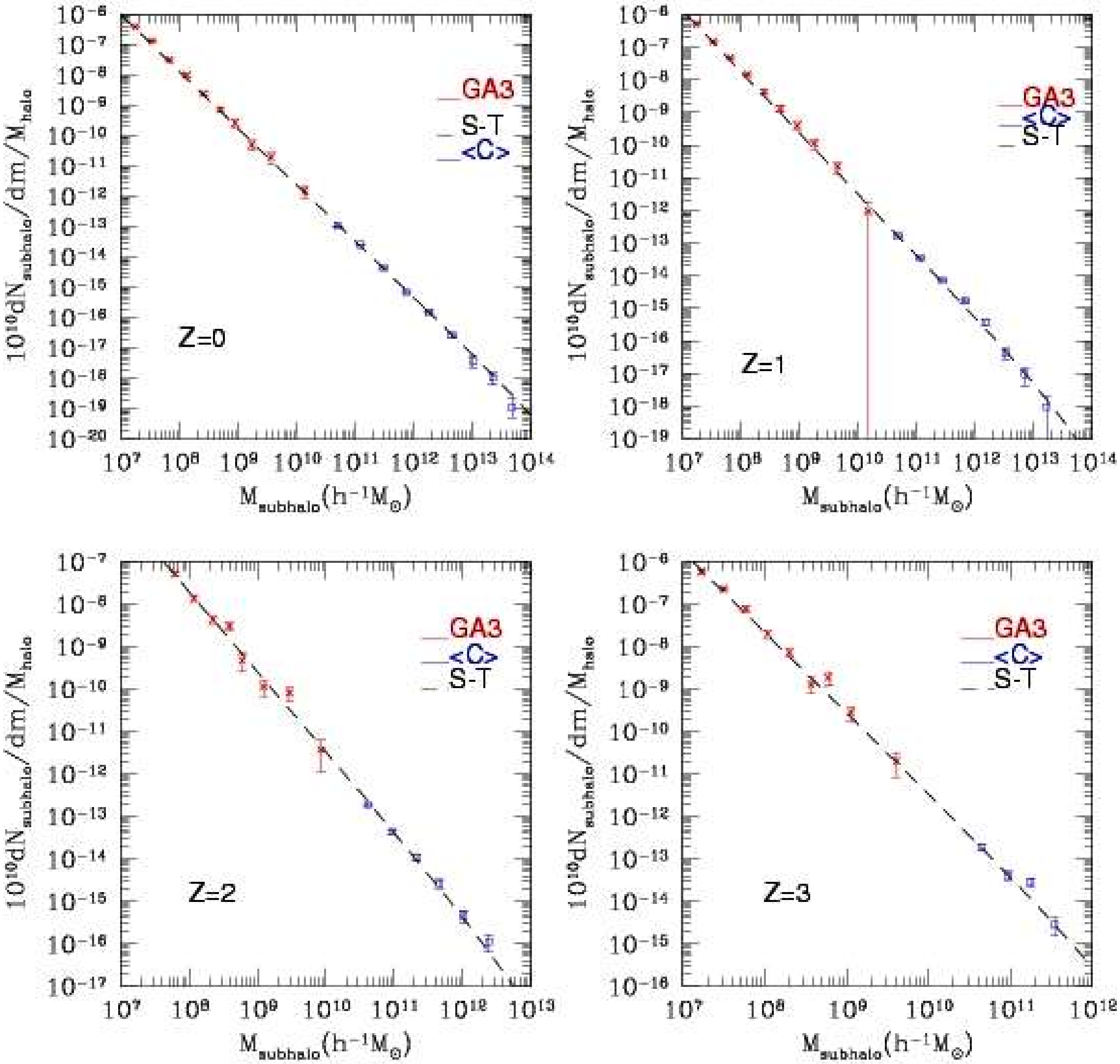


The concentration of a halo, as measured by V_{max}/V_{200}, is anticorrelated with the fraction of its mass in substructure.

This is true for both cluster and galaxy mass halos

Subhalo and halo mass functions

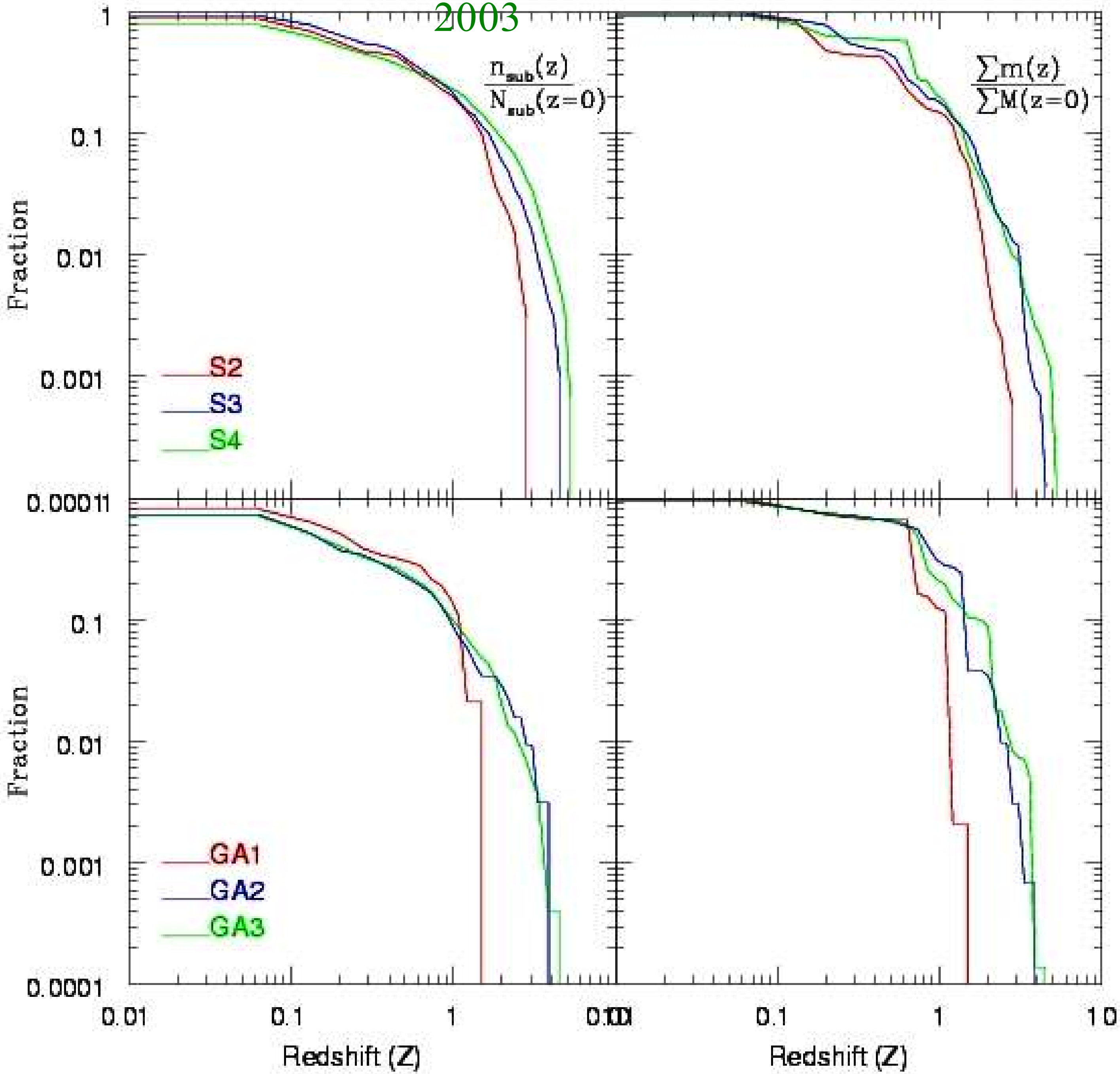
Gao Liang et al 2003



The abundance of sub- halos per unit mass within collapsed halos is very similar to the abundance of halos per unit mass in the Universe as a whole, once a correction is made for the differing density at the edge

When are sub-halos accreted?

Gao Liang et al 2003

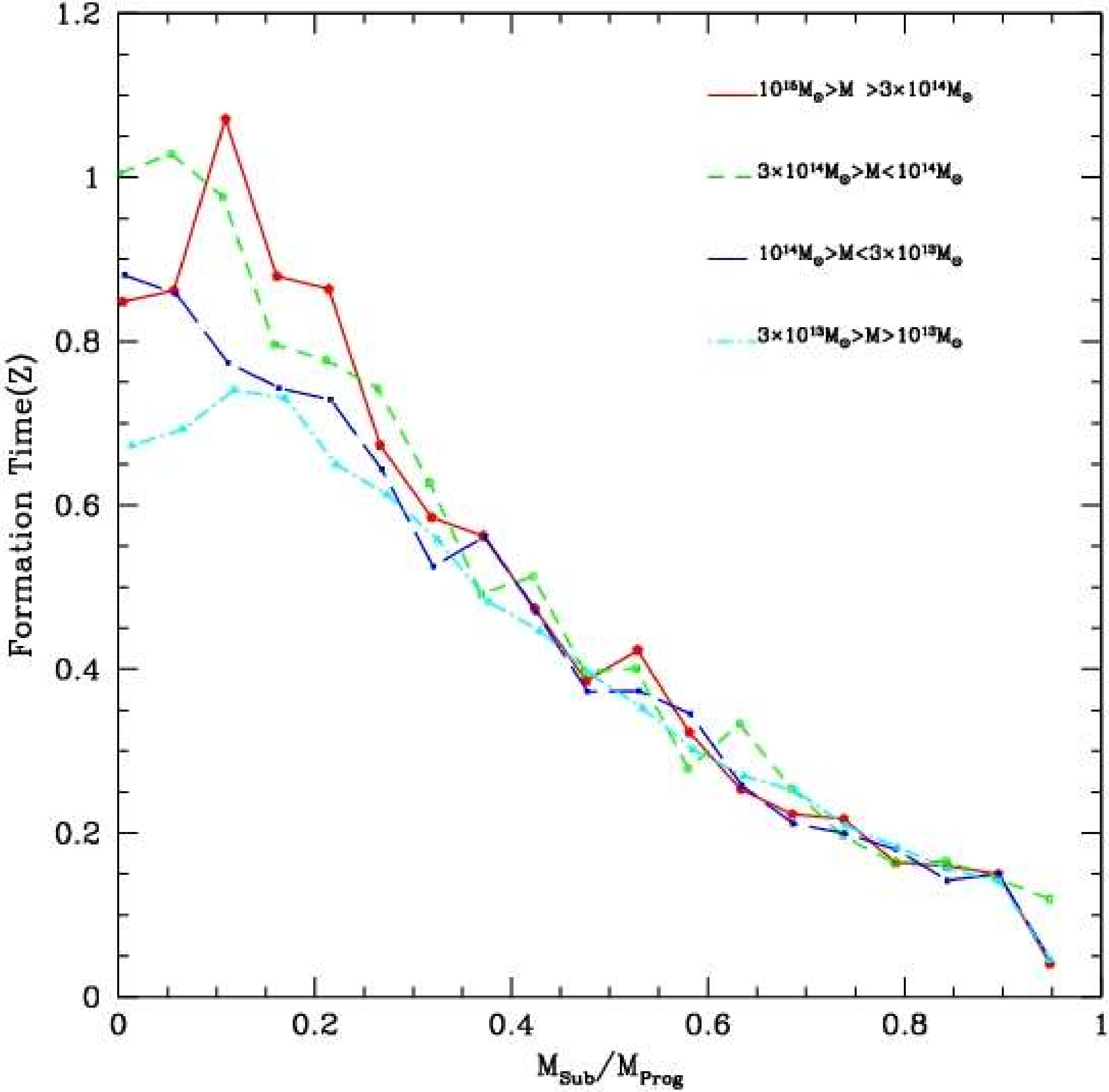


Most of the subhalos (and most of the mass in subhalos) first became a subhalo at *late* times

60% after z = 0.5
80% after z = 1.0

Mass loss vs Accretion time

Gao Liang et al 2003



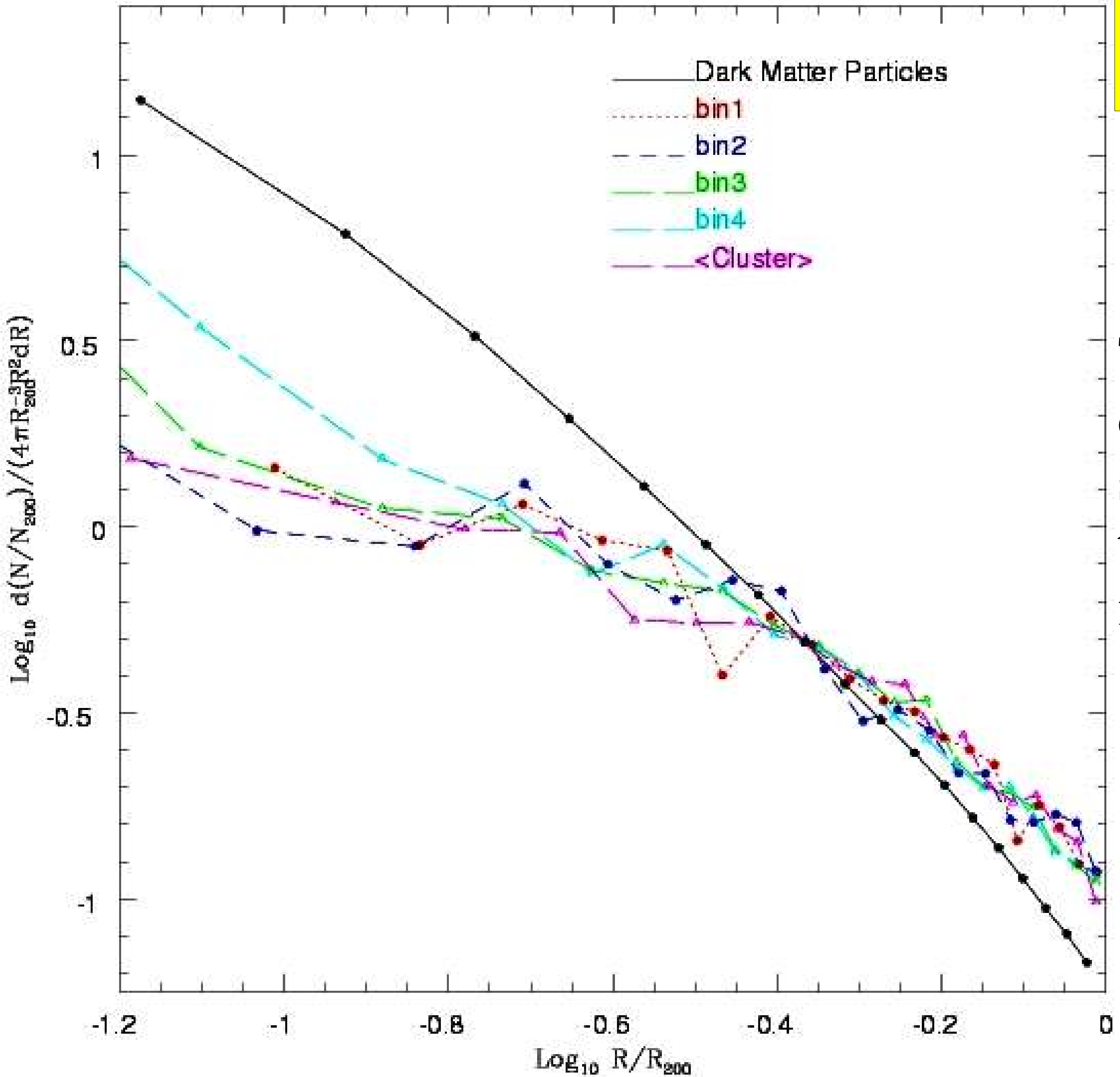
Subhalos which have lost little mass were accreted recently

Subhalos retaining more than half their mass have $\langle z_{acc} \rangle \sim 0.3$

Subhalos retaining <0.1 of their mass have $\langle z_{acc} \rangle \sim 0.9$

Gao Liang et al 2003

Density profiles for subhalos



The mean radial density profiles of subhalos are shallower than those of the mass in halos of all masses

Conclusions

- Satellite subhalos appear to have softer cores both than their progenitor halos and than isolated halos of similar mass
- The normalised halo mass function $(1/M_{halo})\ dN(m_{sub})/dm_{sub}$ appears to be universal for $m_{sub} \ll M_{halo}$
- After correction for the differing definitions of (sub)halo edge, this function is close to the Sheth-Tormen halo mass function
- The concentration of a halo is anticorrelated with the amount of substructure it contains
- Most z=0 subhalos first became subhalos at *low* redshift ($z < 1$)
- Subhalos with less mass loss were accreted at lower redshift
- The density profiles for subhalos are shallower than NFW