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Galaxy Halo Assembly

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Halo assembly for neutralino ΛCDM

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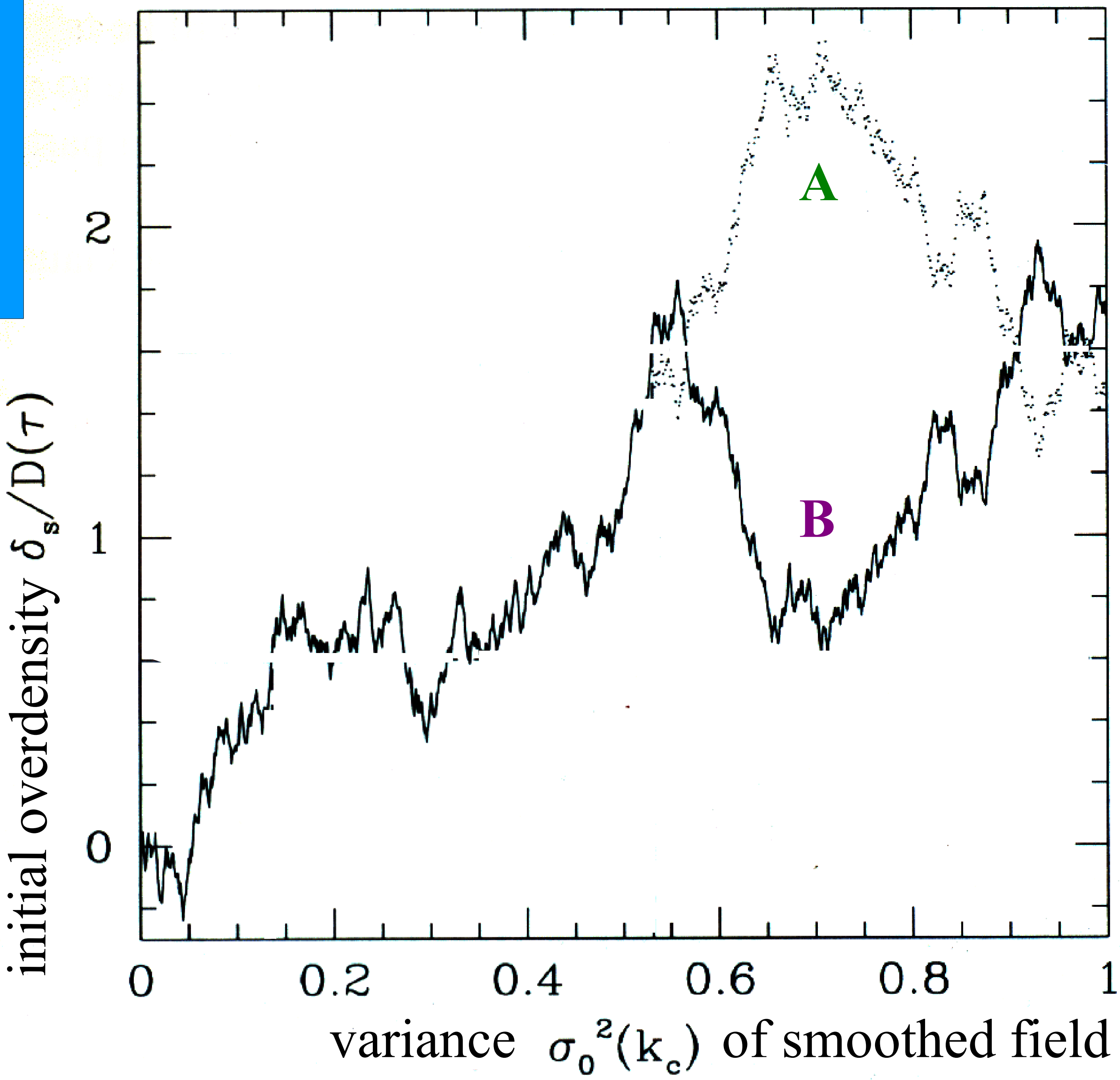
Overdensity vs smoothing at a given position

If the density field is smoothed using a sharp filter in k-space, then each step in the random walk is independent of all earlier steps

A Markov process

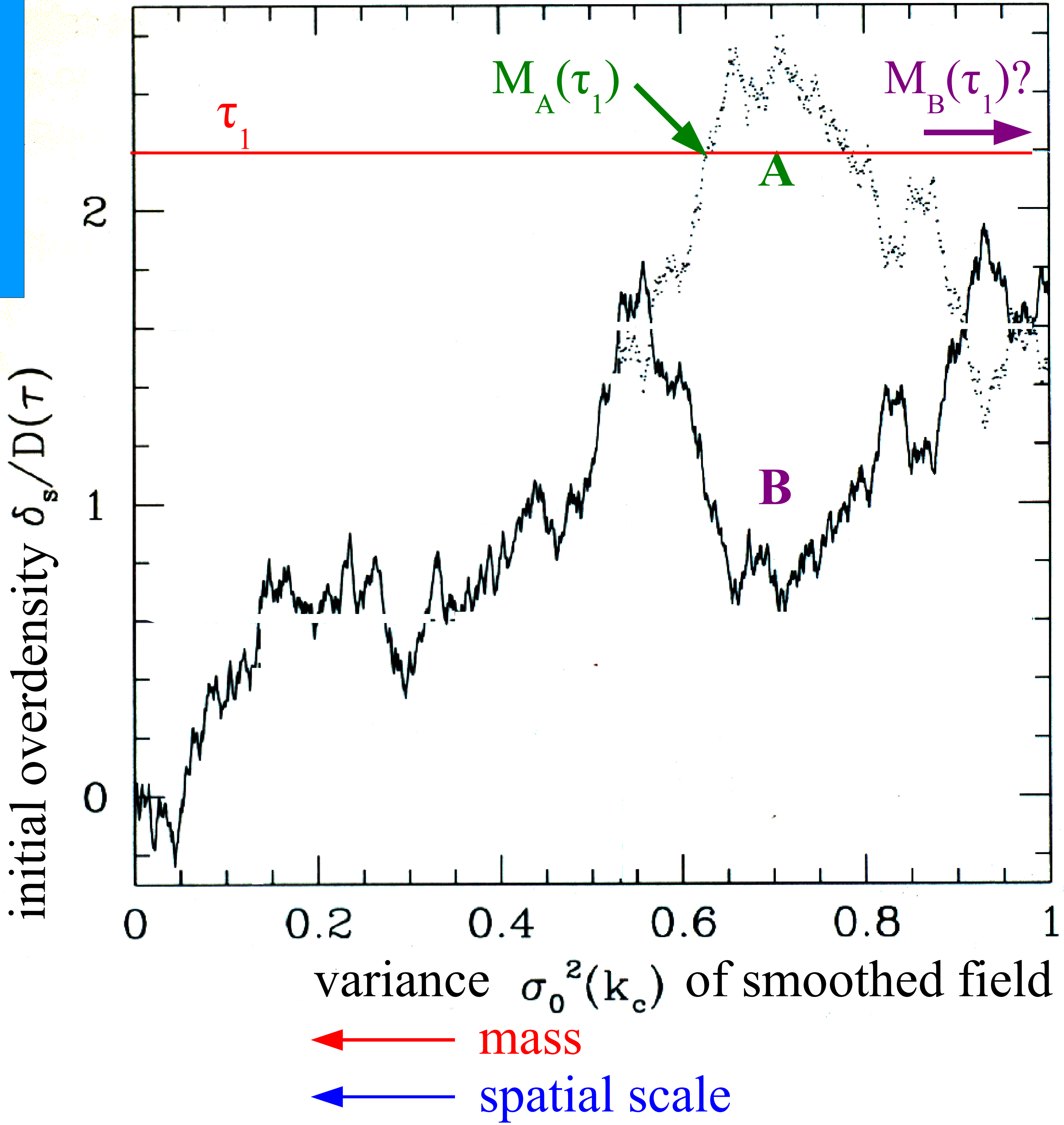
The walks shown at positions **A** and **B** are equally probable



← mass

← spatial scale

Overdensity vs smoothing at a given position



At an early time τ_1

A is part of a quite massive halo

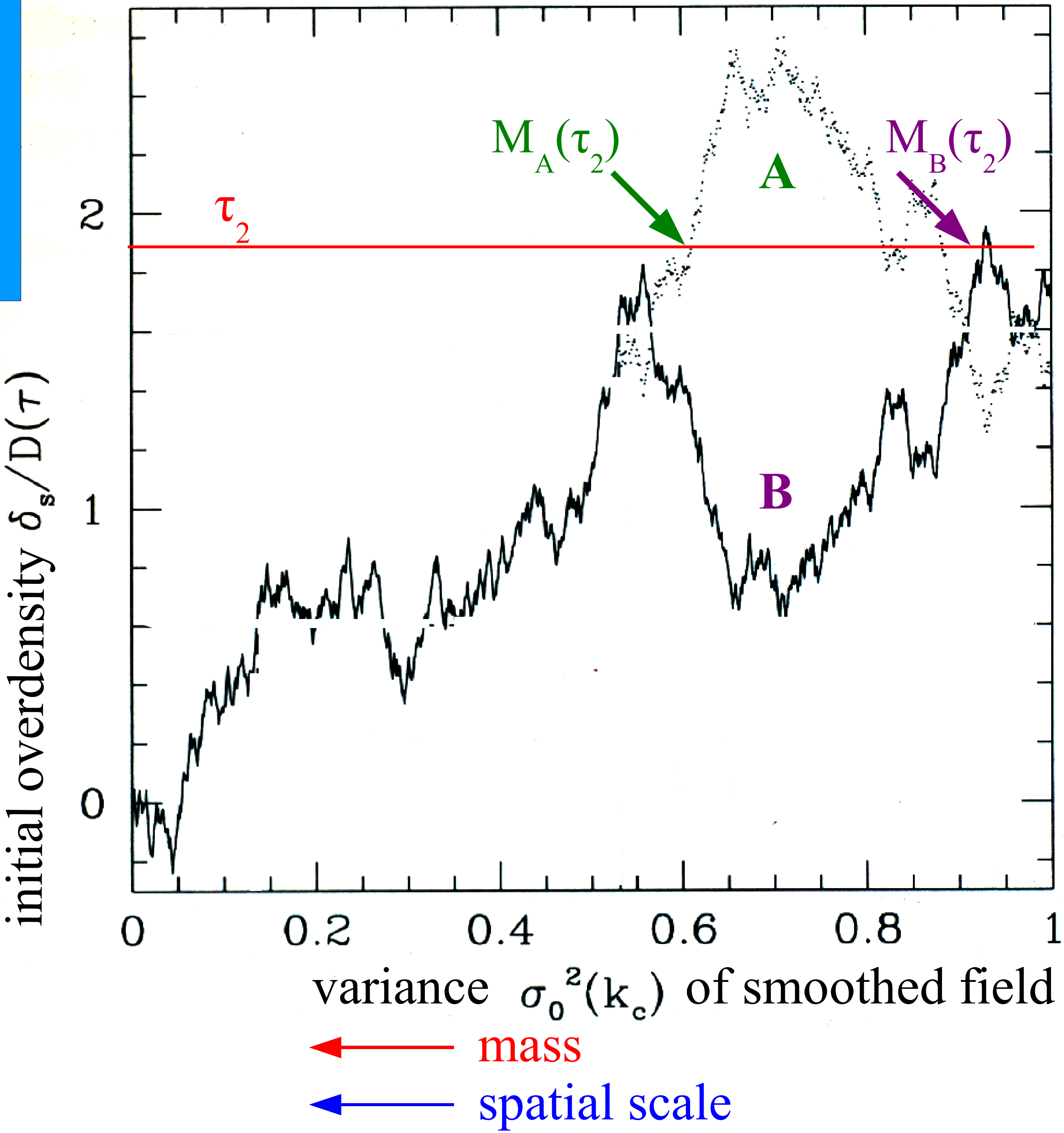
B is part of a very low mass halo or no halo at all

Overdensity vs smoothing at a given position

Later, at time τ_2

A's halo has grown slightly by accretion

B is now part of a moderately massive halo

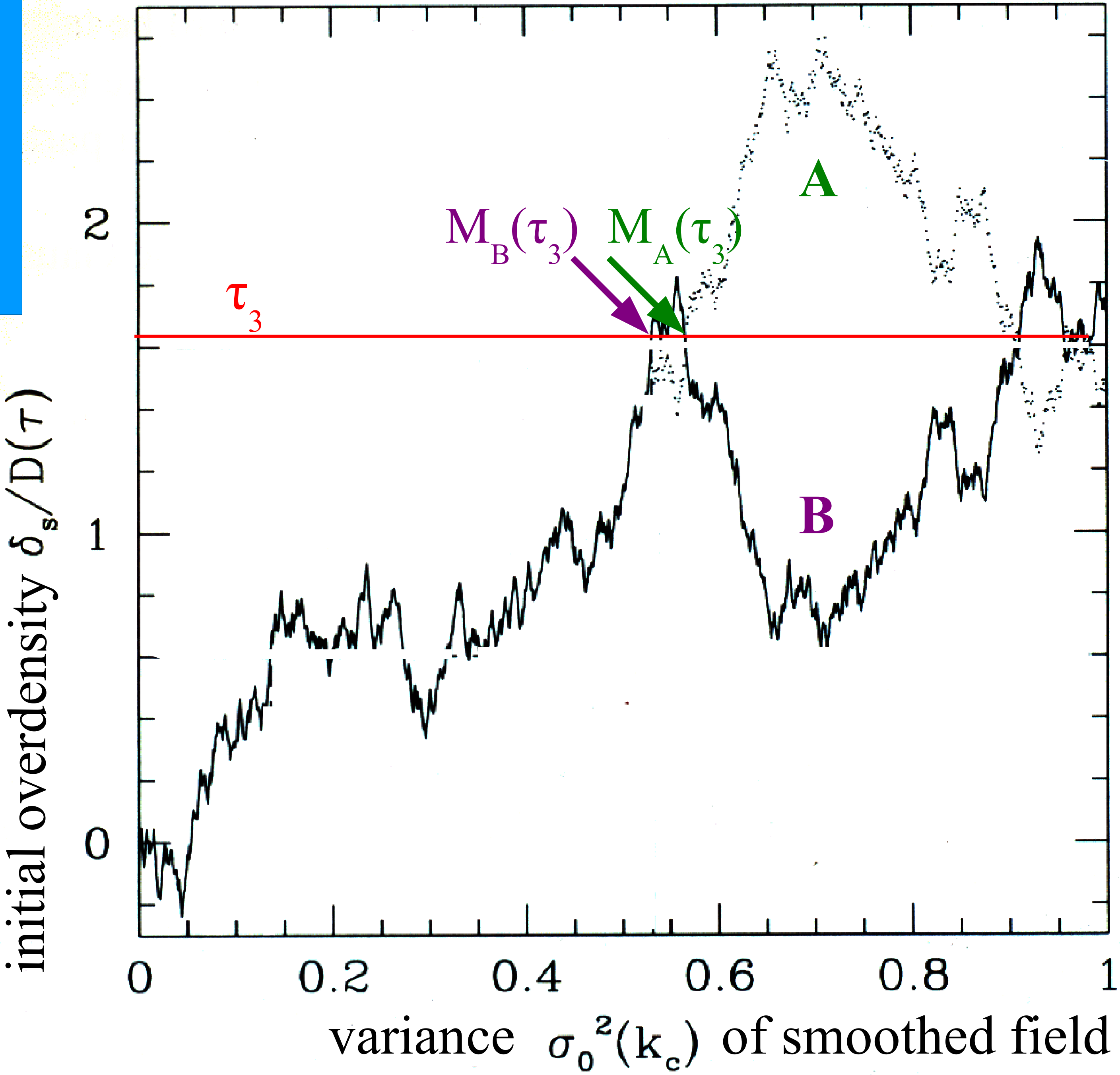


Overdensity vs smoothing at a given position

A bit later, time τ_3

A's halo has grown further by accretion

B's halo has merged again and is now more massive than **A**'s halo



← mass

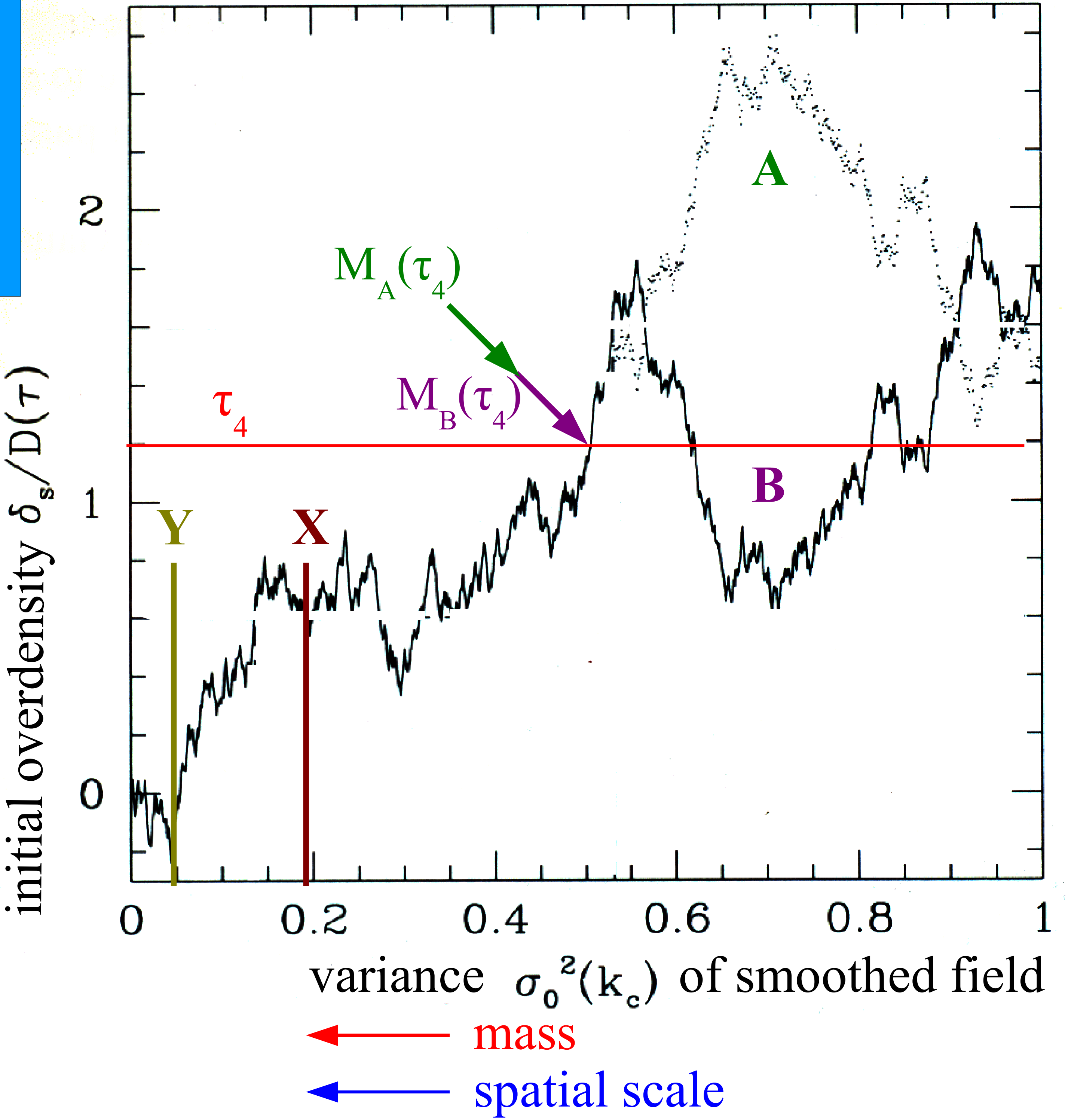
← spatial scale

Overdensity vs smoothing at a given position

Still later, e.g. τ_4

A and **B** are part of halos which follow identical merging/ accretion histories

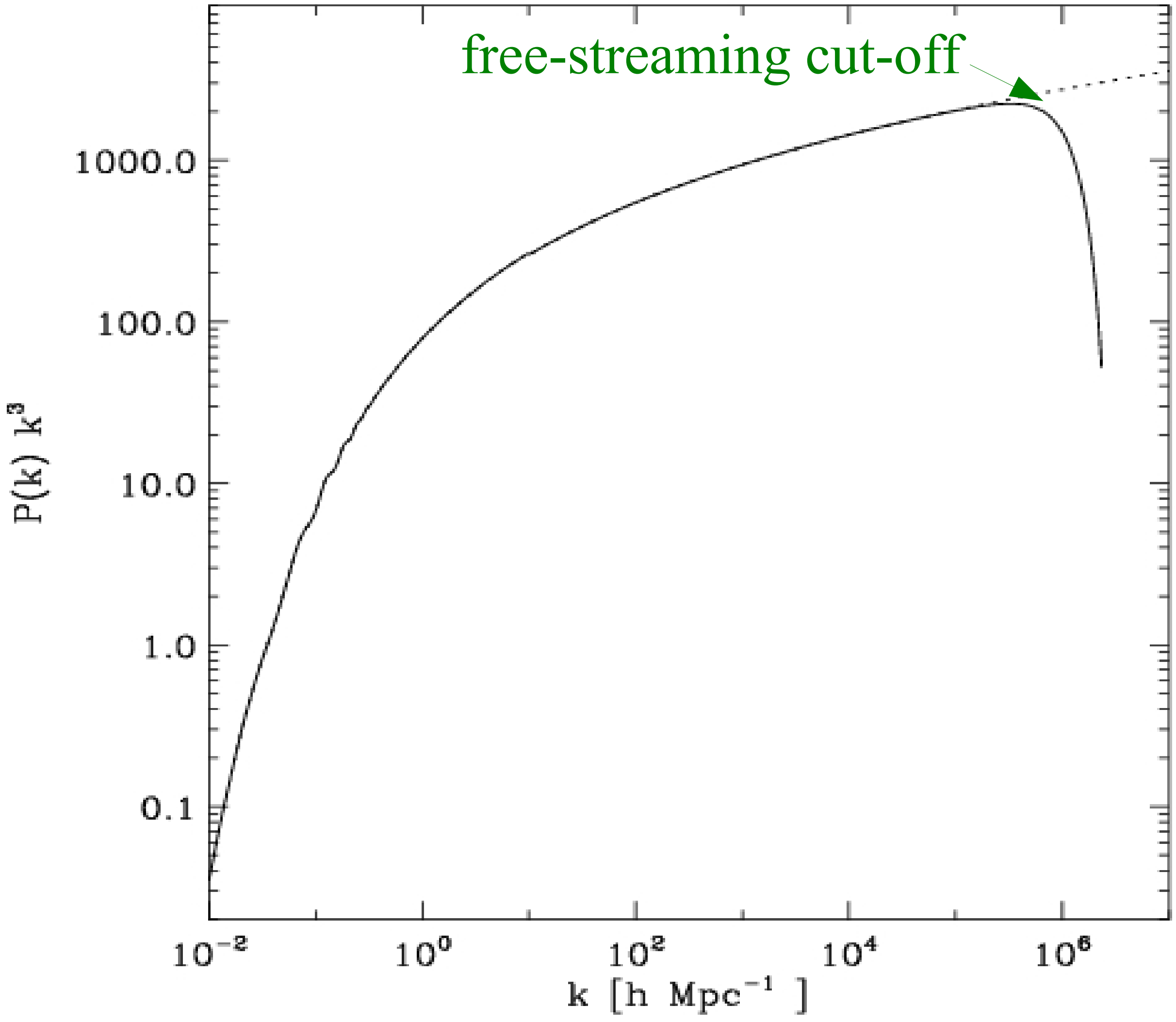
On scale **X** they are embedded in a high density region.
On larger scale **Y** in a low density region



EPS statistics for the standard ΛCDM cosmology

Millennium Simulation cosmology: $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, $n=1$, $\sigma_8 = 0.9$

Angulo et al 2009



The linear power spectrum in "power per octave" form

Assumes a 100GeV wimp following Green et al (2004)

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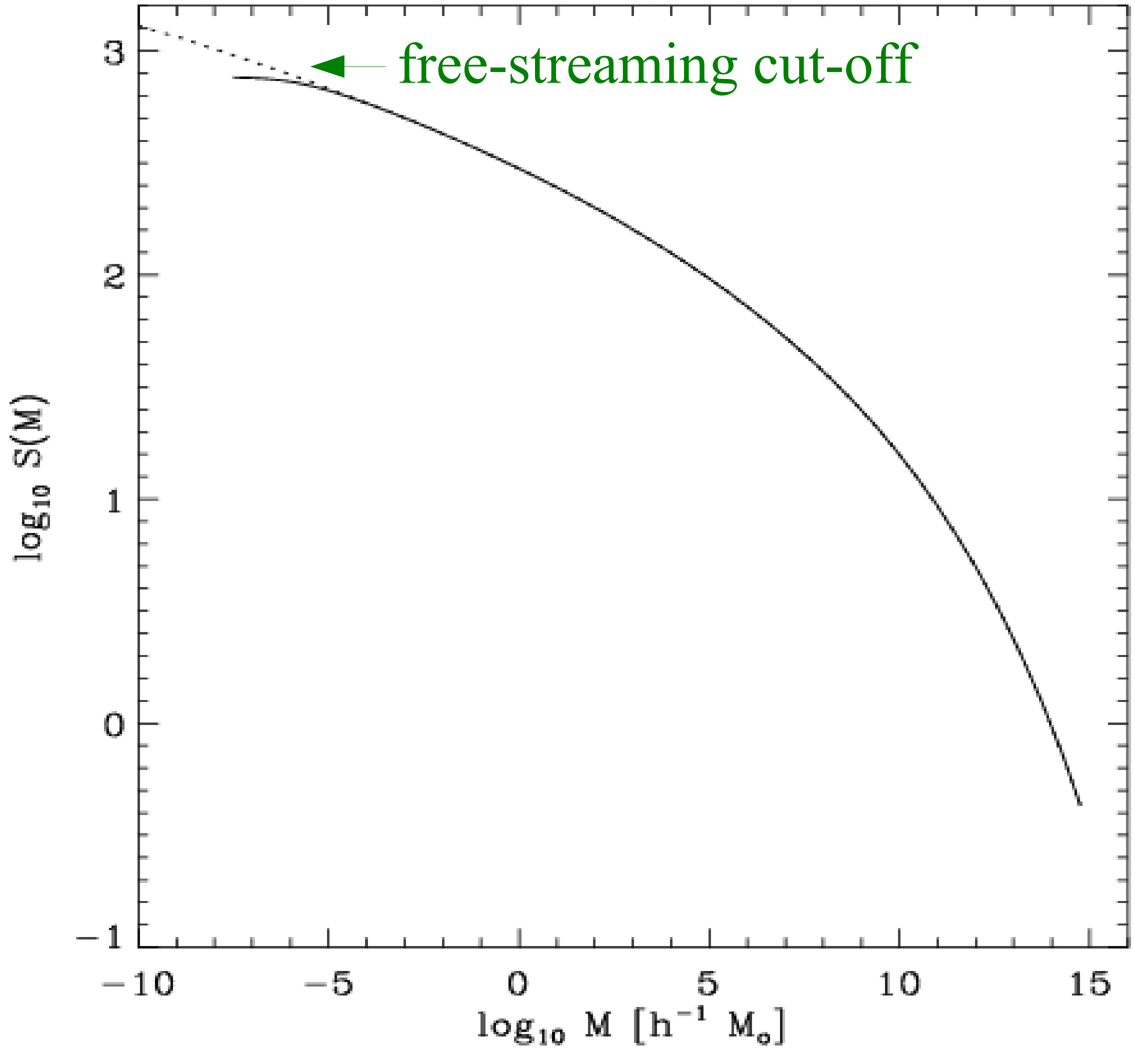

Variance of linear density fluctuation within spheres containing mass M, extrapolated to z = 0

As $M \rightarrow 0$, $S(M) \rightarrow 720$

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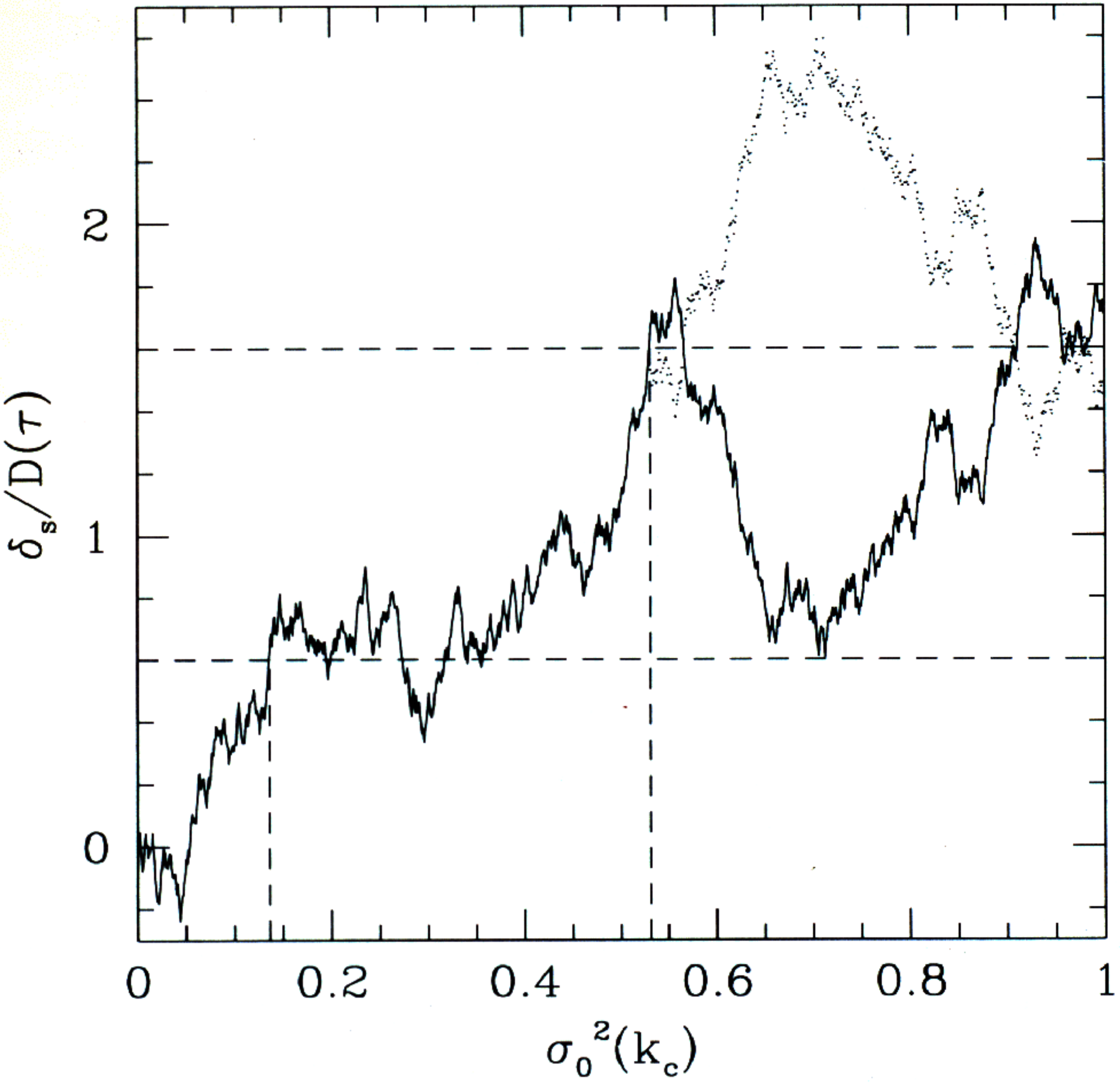

If these Markov random walks are scaled so the maximum variance is 720 and the vertical axis is multiplied by √720, then they represent complete halo assembly histories for random CDM particles.

An ensemble of walks thus represents the probability distribution of assembly histories

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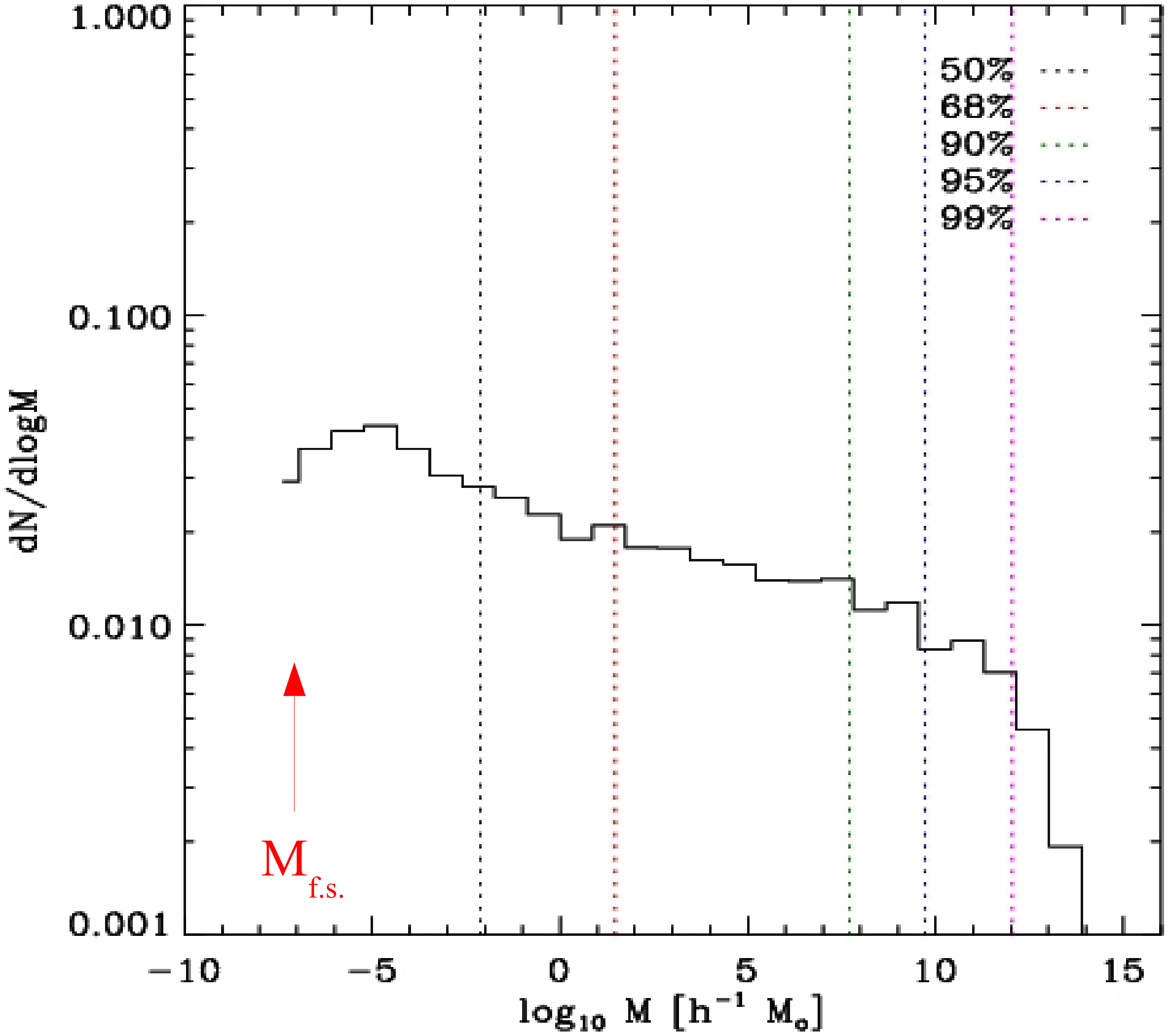

Distribution of the masses of the <u>first generation</u> halos for a random set of dark matter particles

The median is $10^{-2}M_\odot$

For 10% of the mass the first halo has $M > 10^7 M_\odot$

Direct simulation will become possible around 2035

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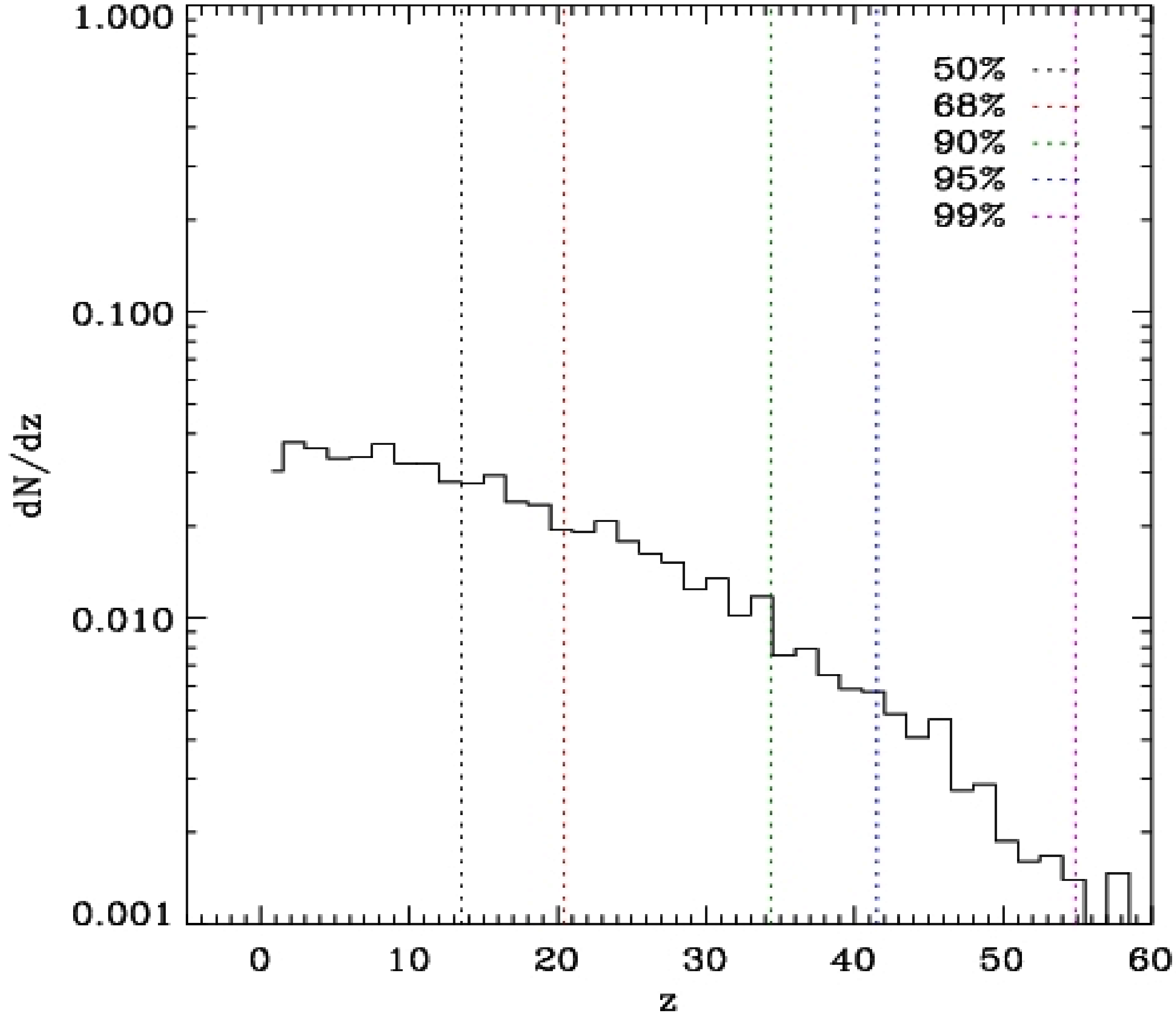

Collapse redshift distribution of the first generation halos for a random set of dark matter particles

The median is z = 13

For 10% of the mass the first halo collapses at z > 34

For 1% at z > 55

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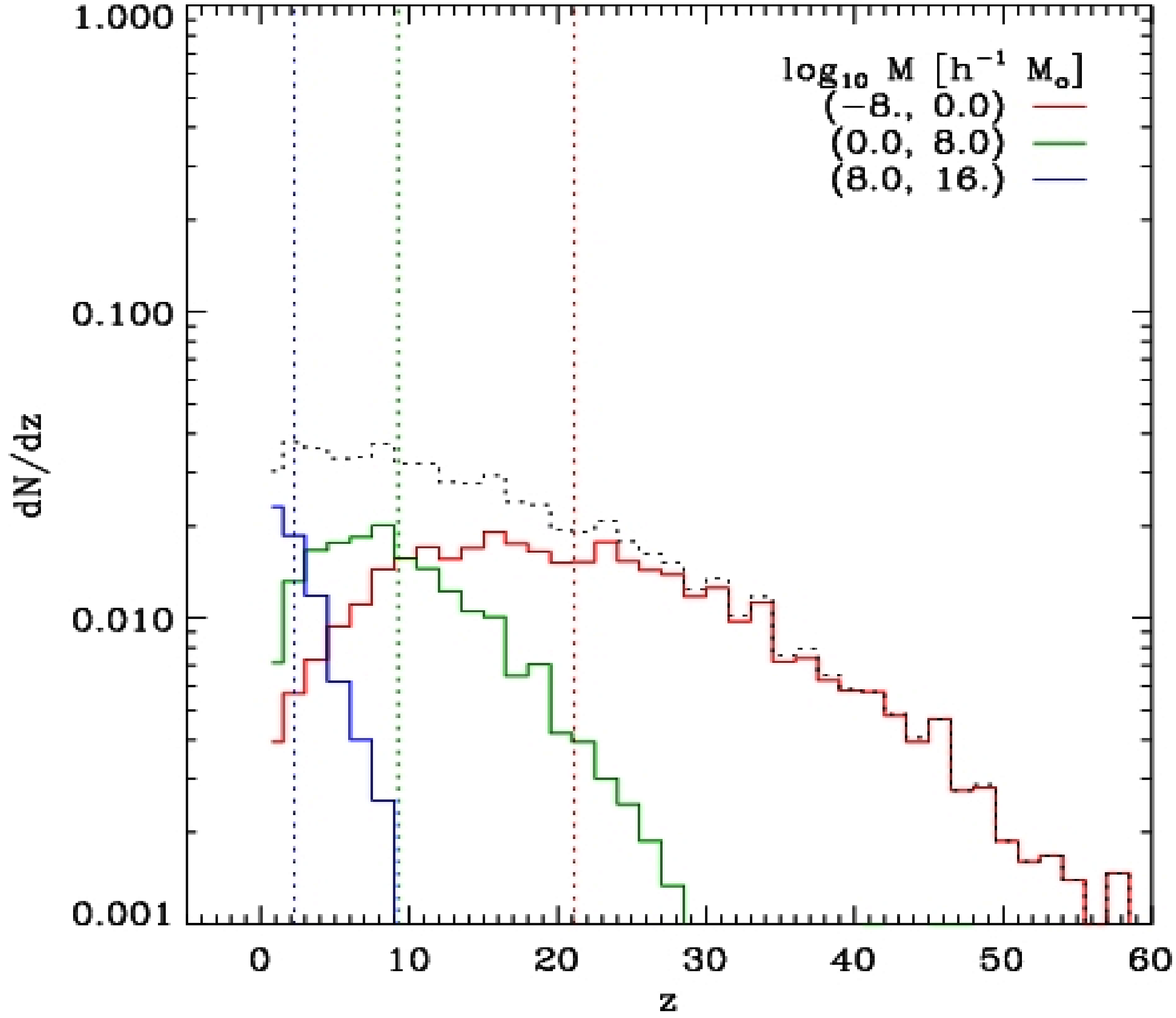

Collapse redshift distribution for <u>first generation</u> halos split by their mass

The high redshift tail is entirely due to matter in small mass halos

For first halo masses below a solar mass, the median collapse redshift is z = 21

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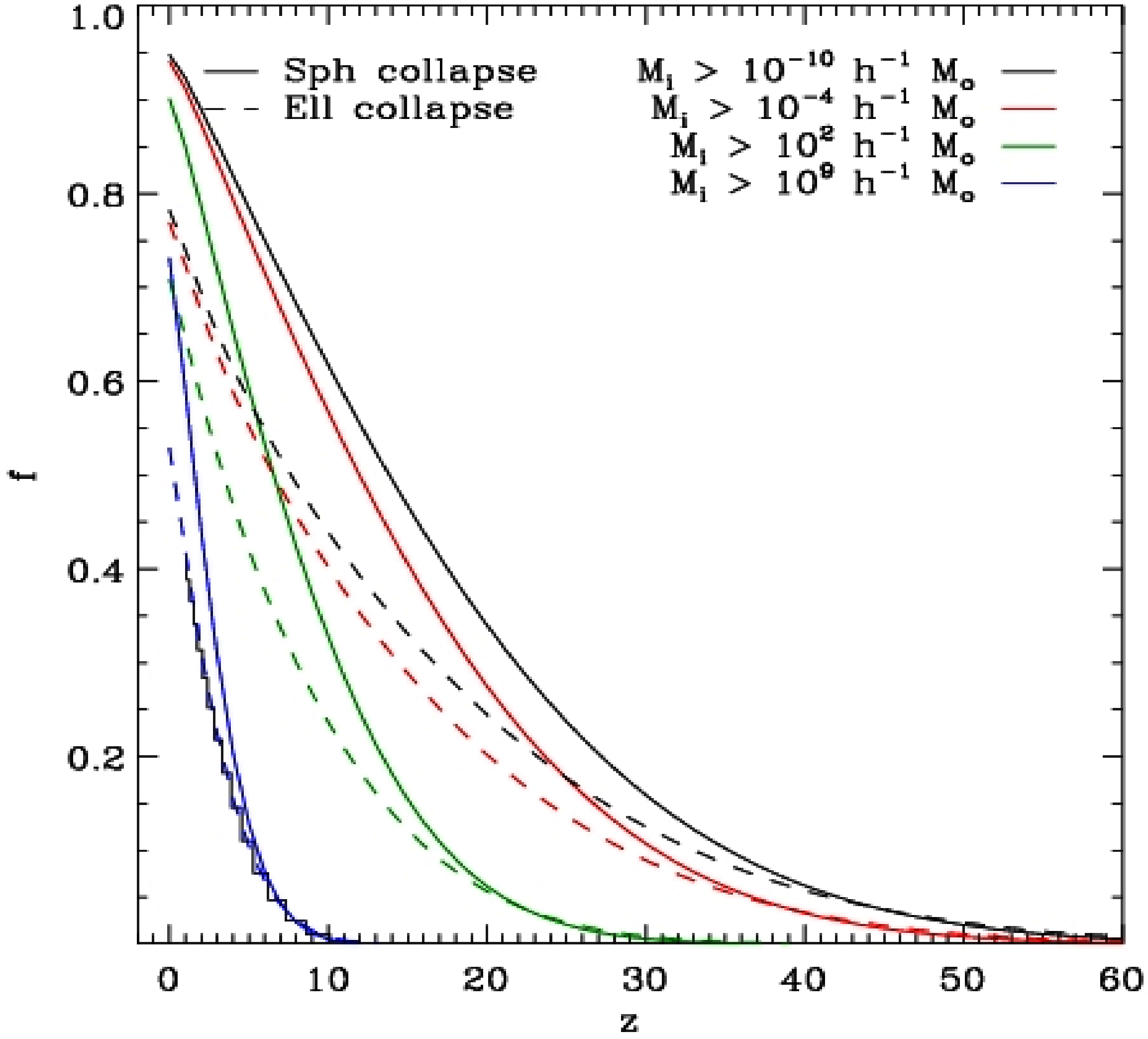

Total mass fraction in halos

At $z = 0$ about 5% (Sph) or 20% (Ell) of the mass is still diffuse

Beyond $z = 50$ almost all the mass is diffuse

Only at $z < 2$ (Sph) or $z<0.5$ (Ell) is most mass in halos with $M > 10^8 M_\odot$ The "Ell" curve agrees with simulations

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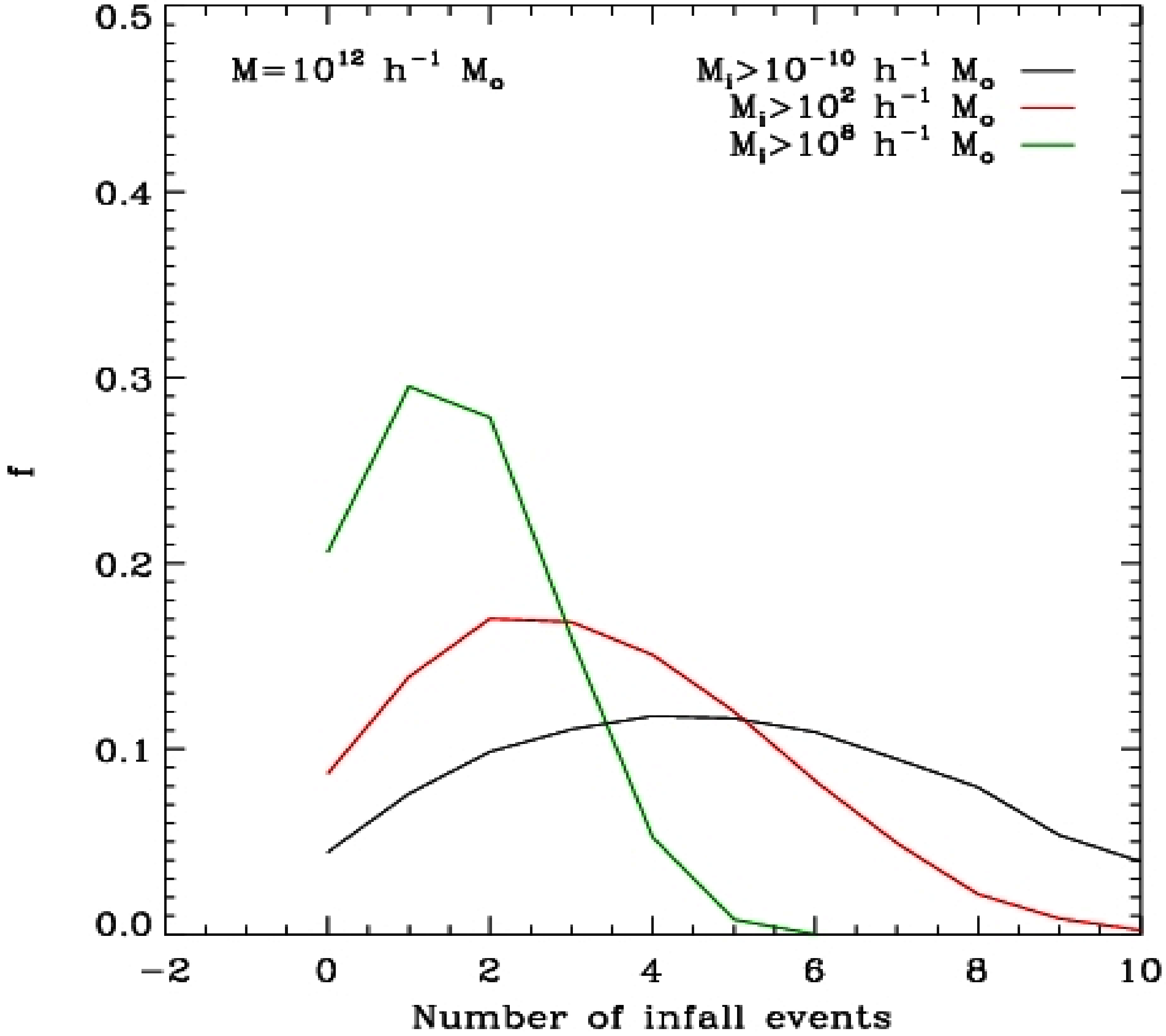


The typical mass element in a "Milky Way" halo goes through ~5 "infall events" where its halo falls into a halo bigger than itself.

Typically only one of these is as part of a halo with $M > 10^8 M_\odot$

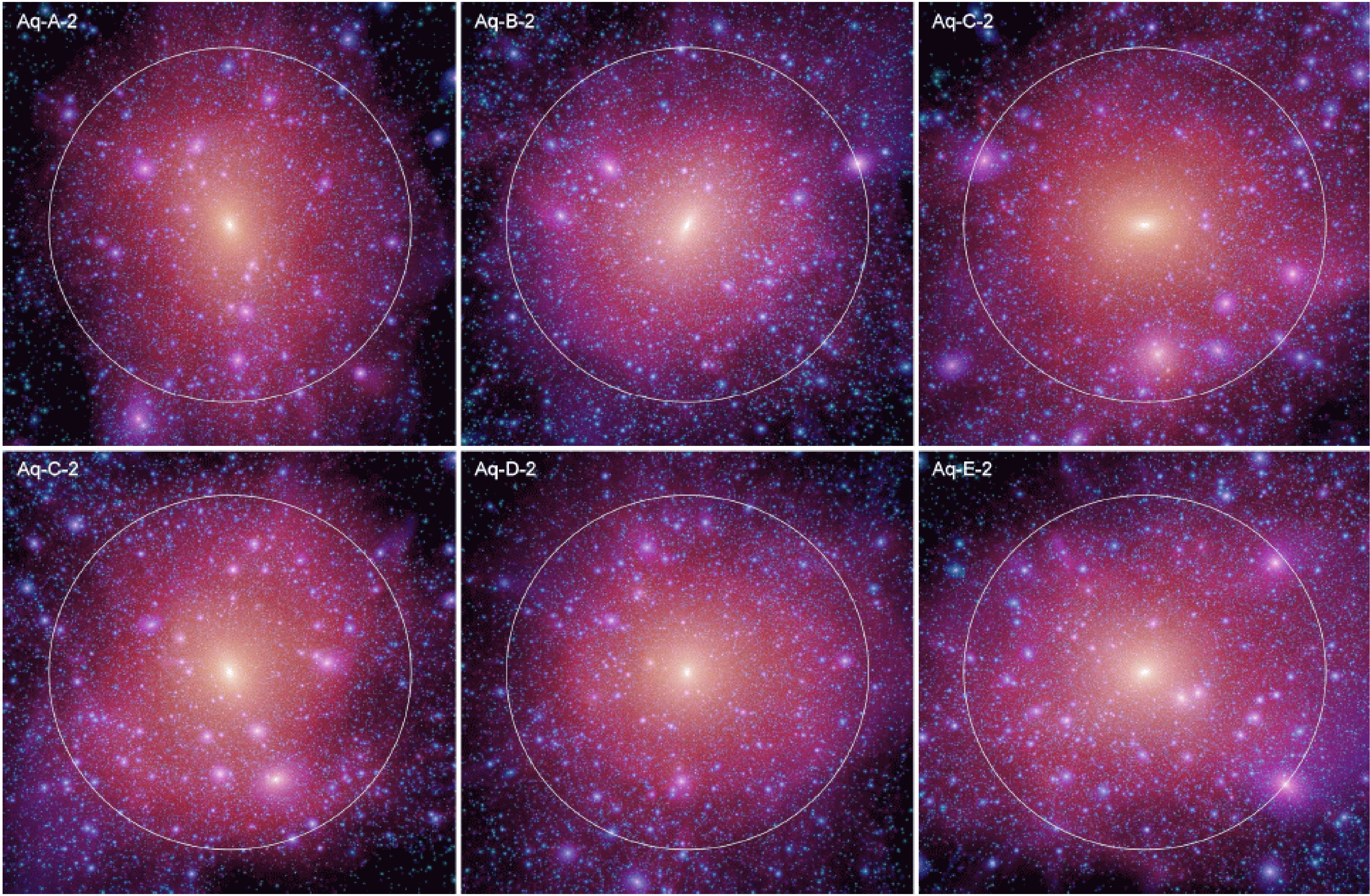
EPS halo assembly: conclusions

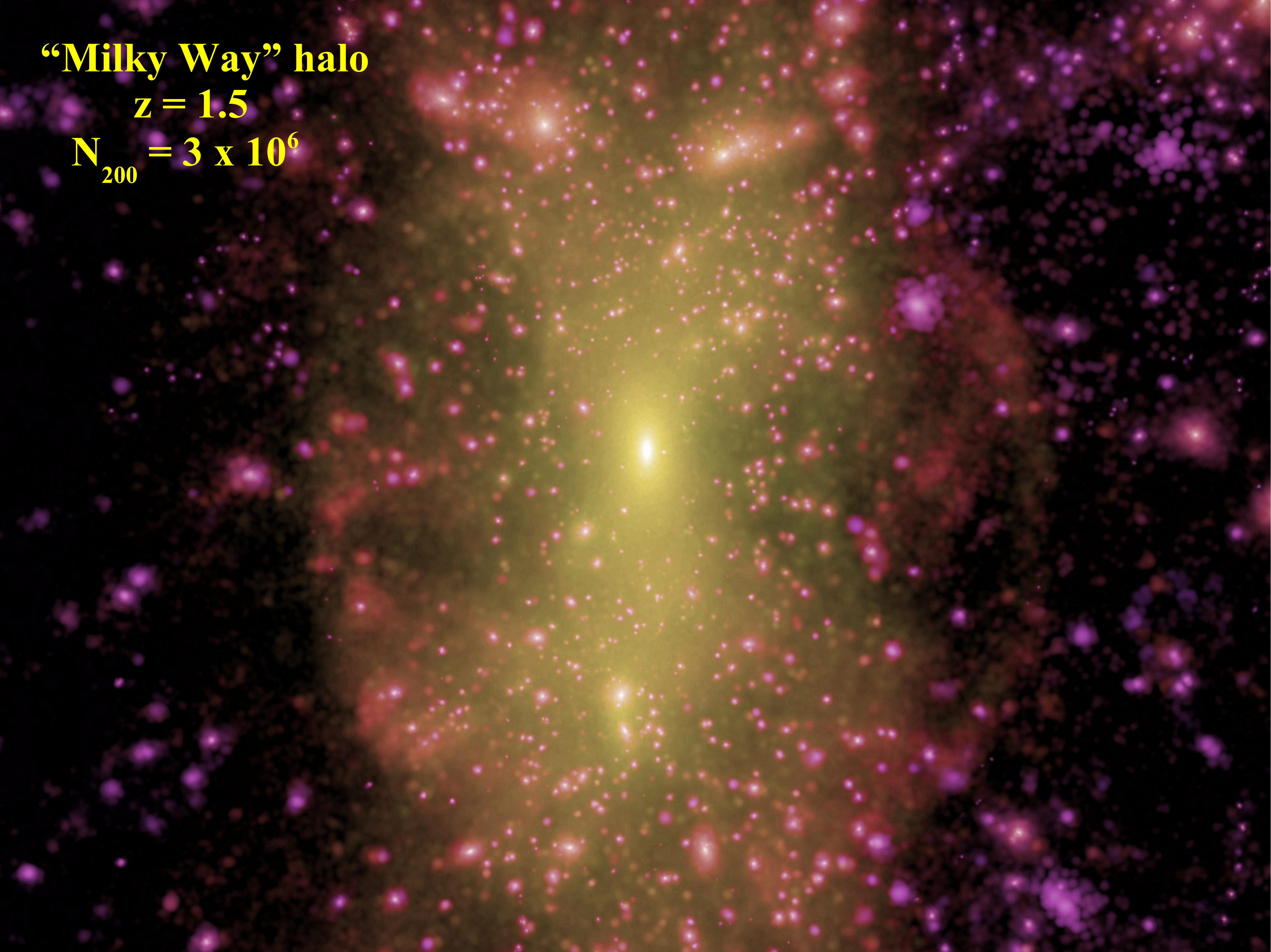
- The typical first generation halo is much more massive than the free-streaming mass limit
- First generation halos typically form quite late $z \lesssim 13$
- Most mass is diffuse (part of no halo) beyond $z = 20$
- Halo growth occurs mainly by accretion of much smaller halos
- There are typically few (~5) “generations” of halos

→ Low mass “first” halos are little denser, and so not much more resistant to tidal destruction than more massive “first” halos

The Aquarius halos

Springel et al 2008





“Milky Way” halo

$z = 1.5$

$N_{200} = 3 \times 10^6$

“Milky Way” halo
$z = 1.5$
$N_{200} = 94 \times 10^6$

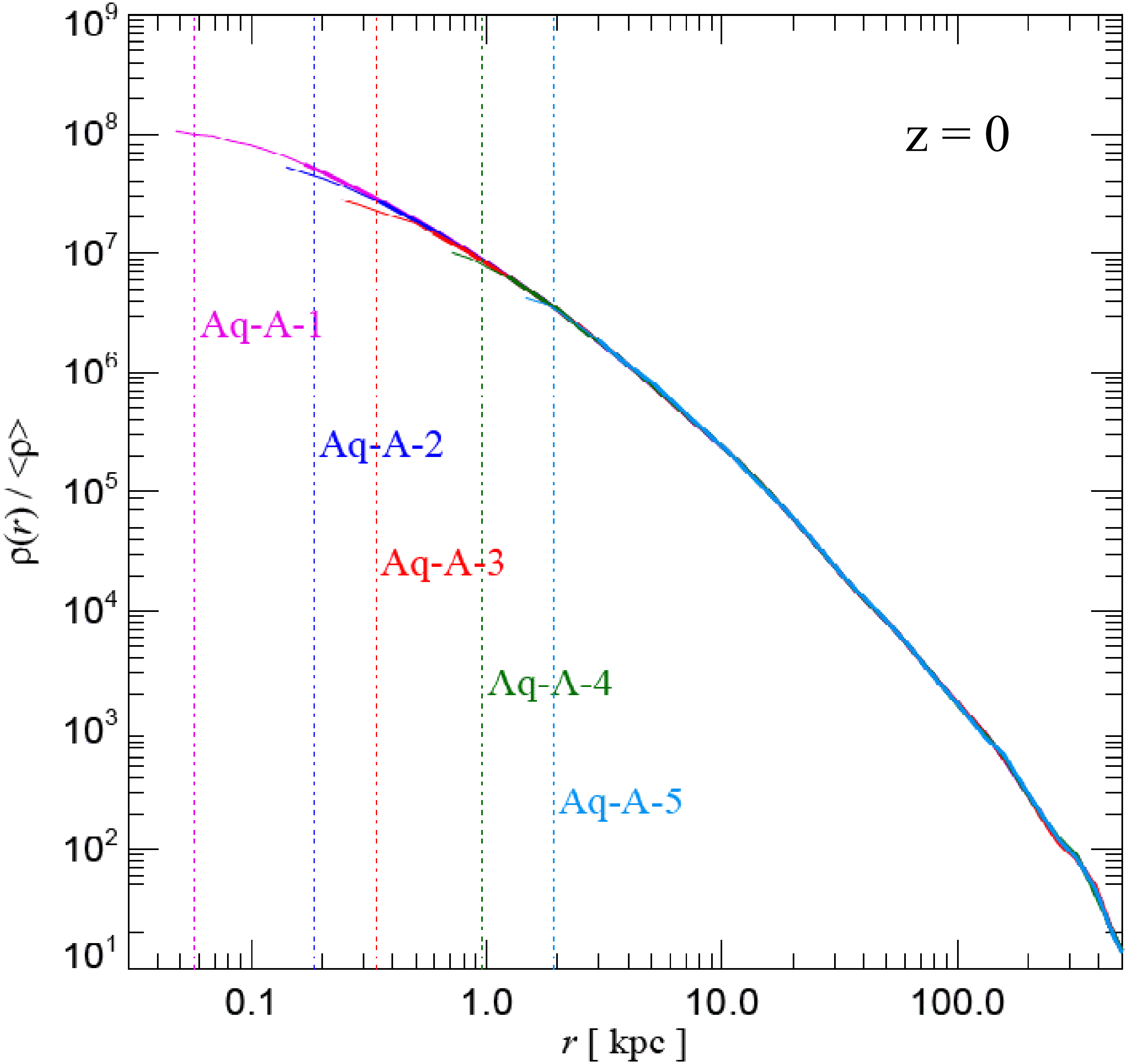
"Milky Way" halo

$z = 1.5$

$N_{200} = 750 \times 10^6$

How well do density profiles converge?

Aquarius Project: Springel et al 2008



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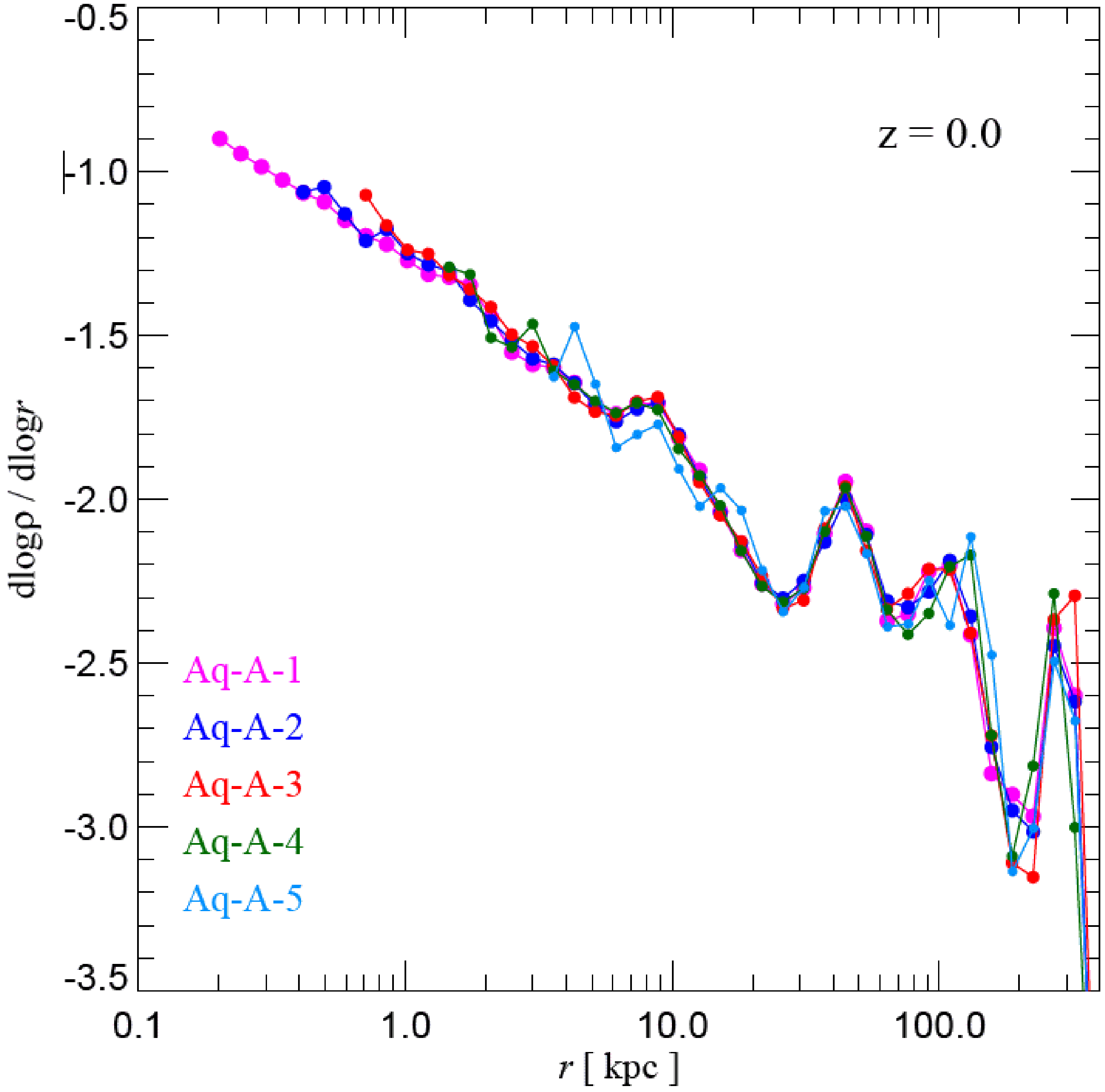

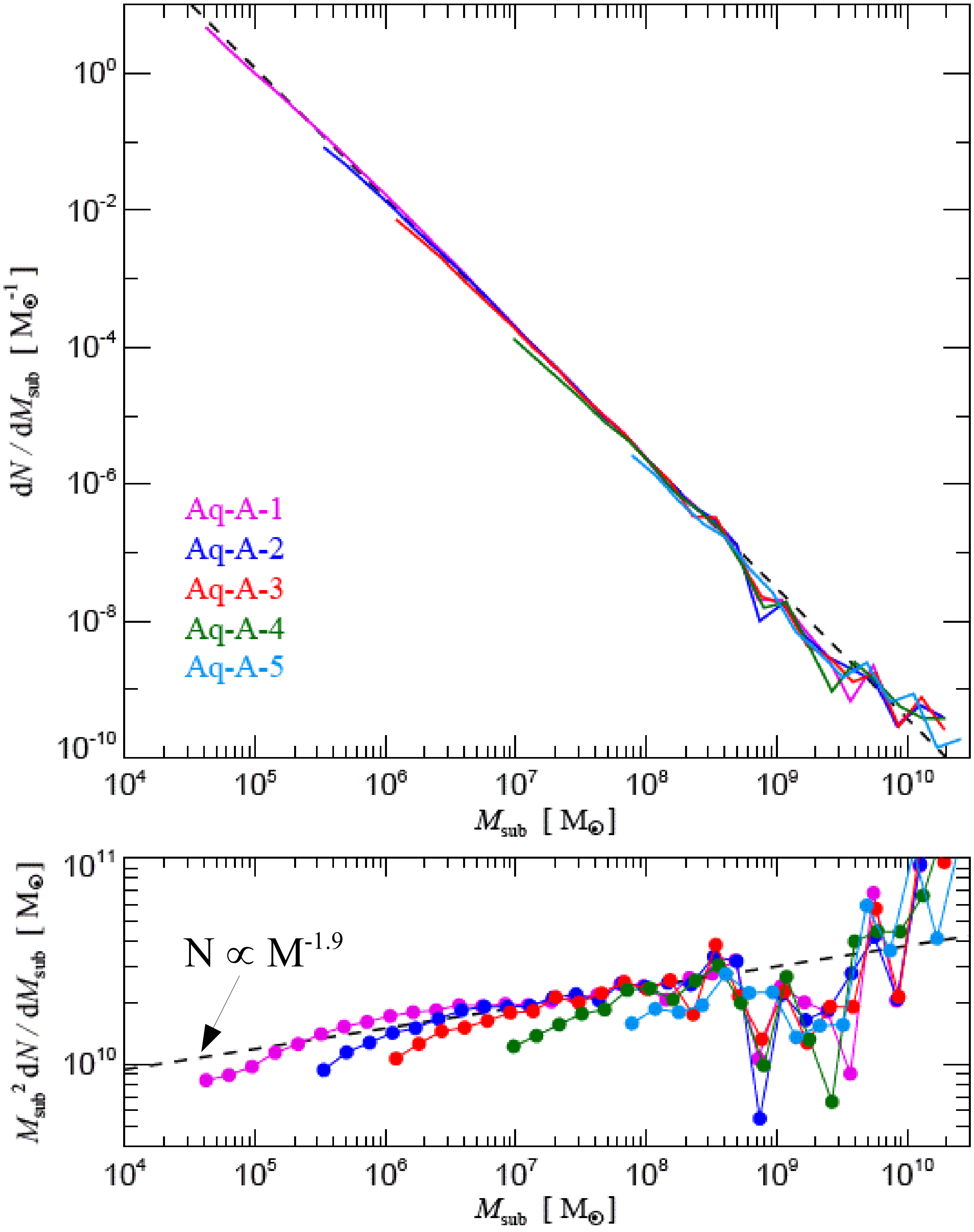

How well does substructure converge?

Springel et al 2008

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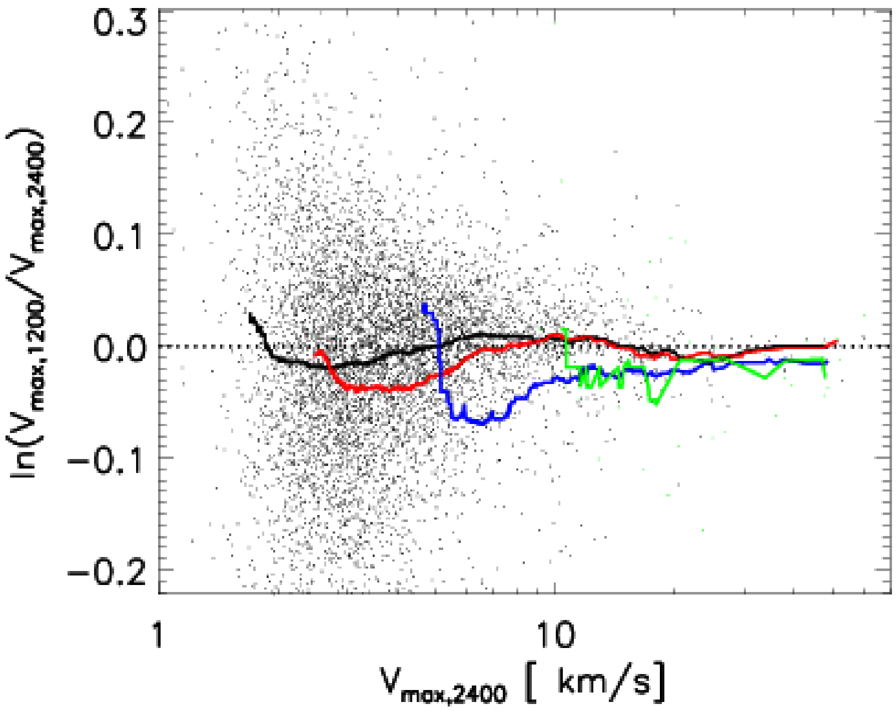
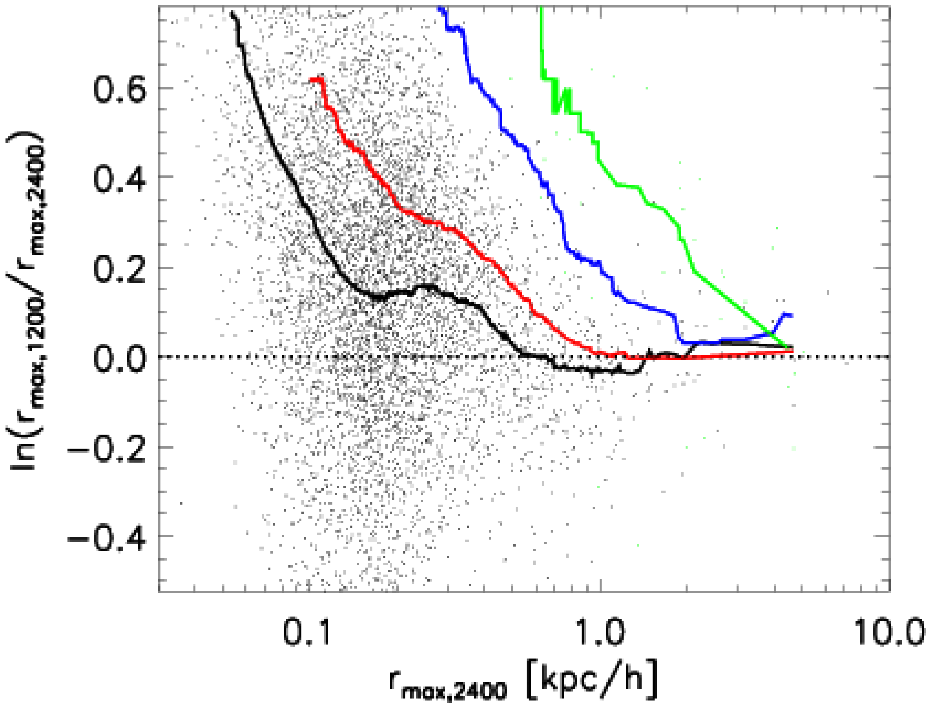
Aquarius Project: Springel et al 2008



Convergence in the size and maximum circular velocity for individual subhalos cross-matched between simulation pairs.



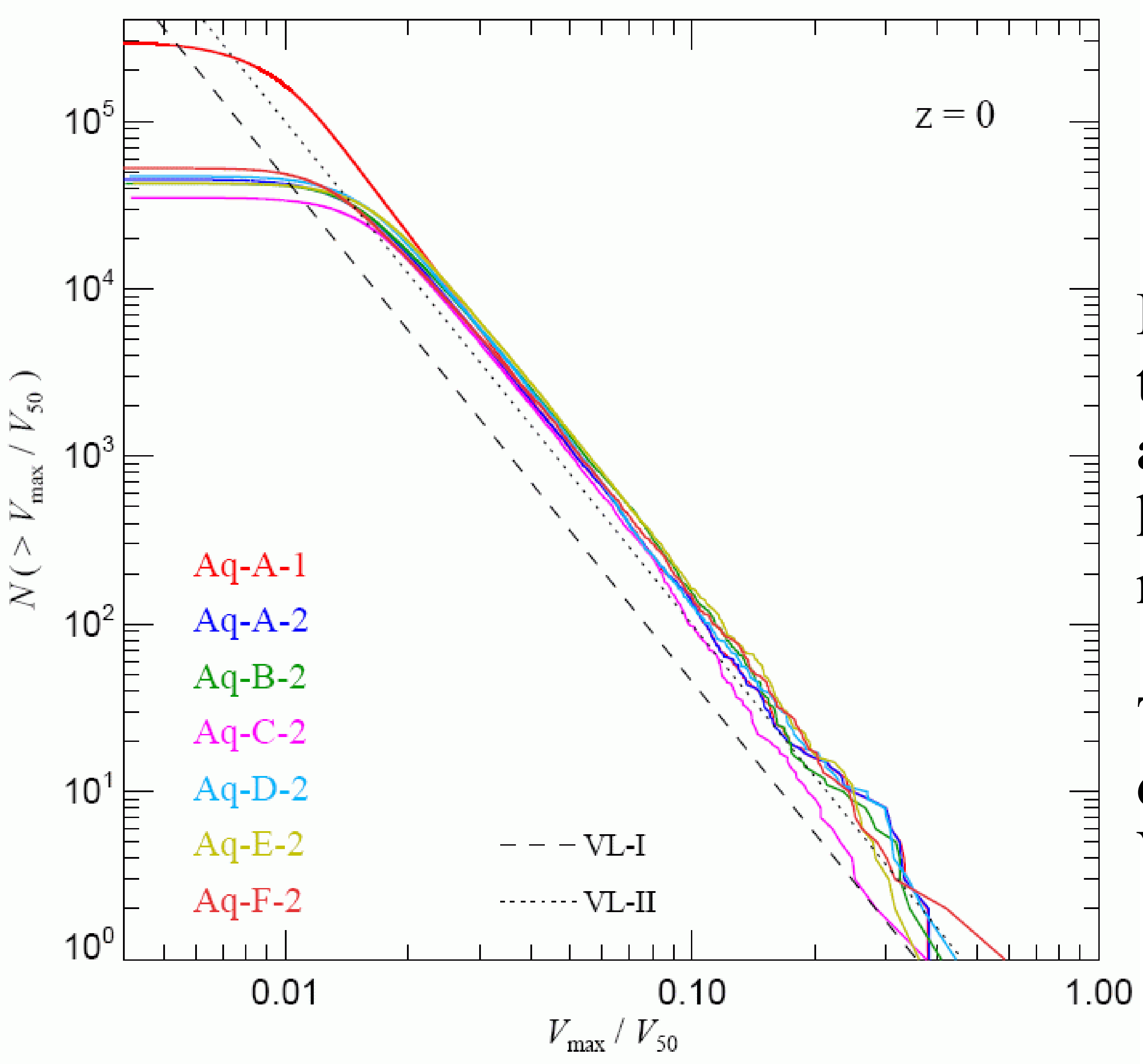
Biggest simulation gives convergent results for

$$V_{max} > 1.5 \text{ km/s}$$

$$r_{max} > 165 \text{ pc}$$

<u>Much</u> smaller than the halos inferred for even the faintest dwarf galaxies

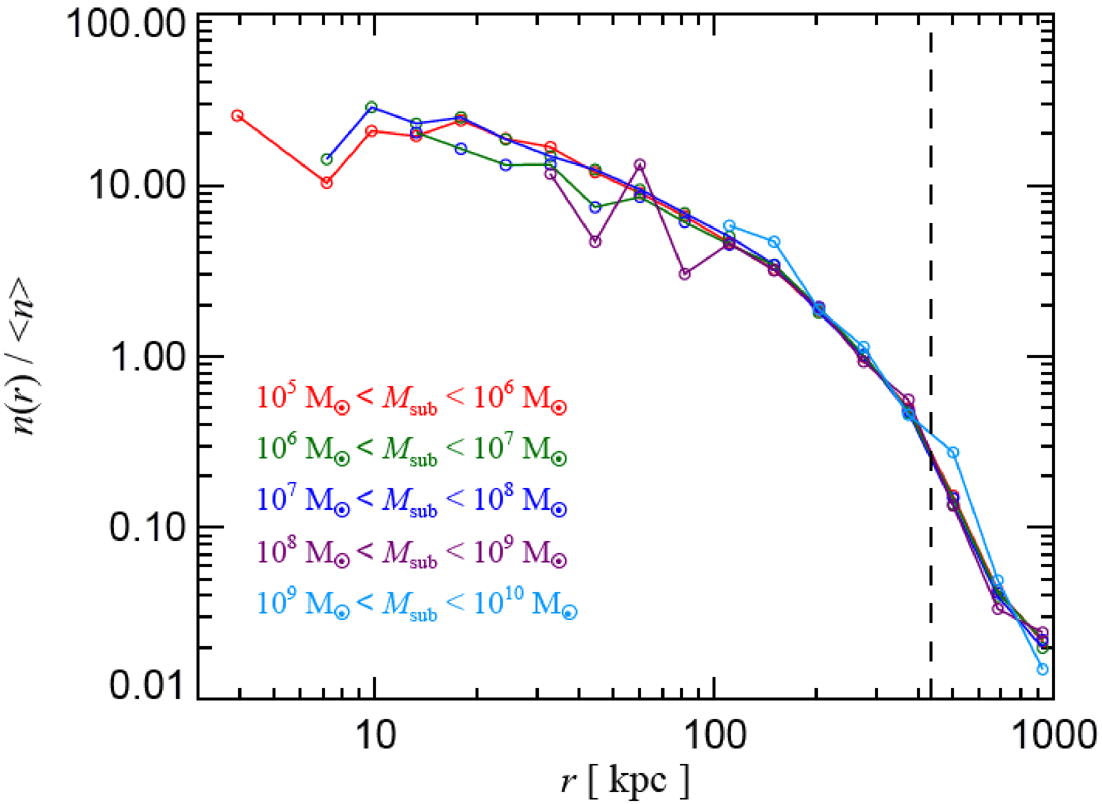
How uniform are subhalo populations?

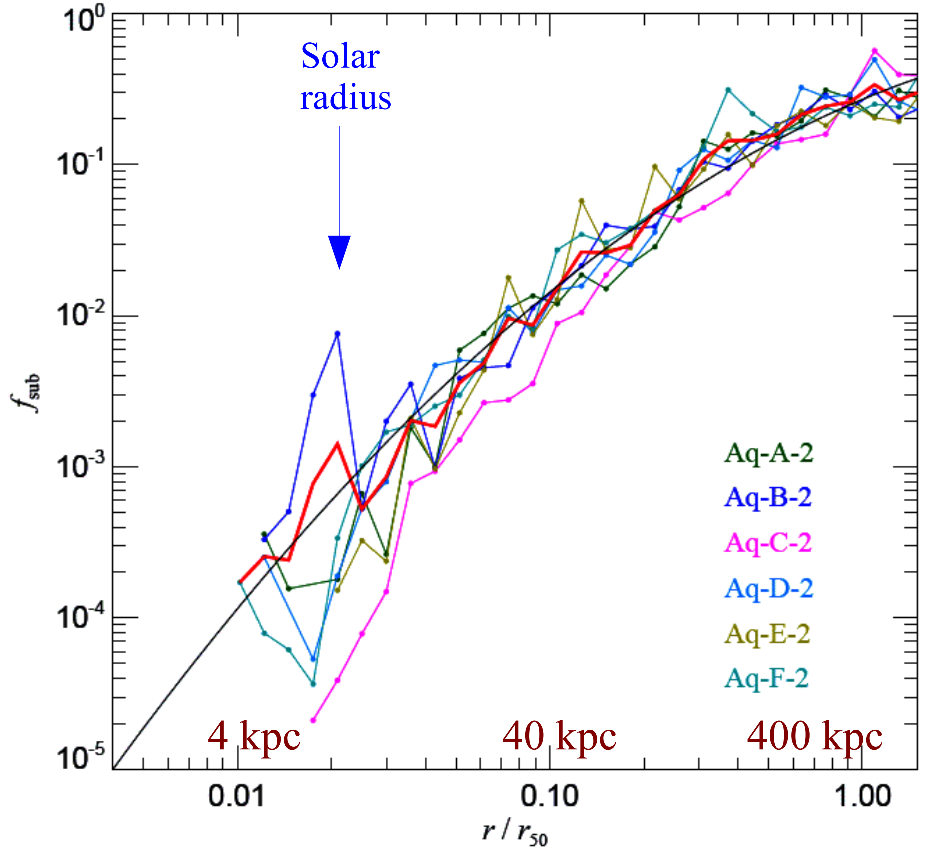


Springel et al 2008

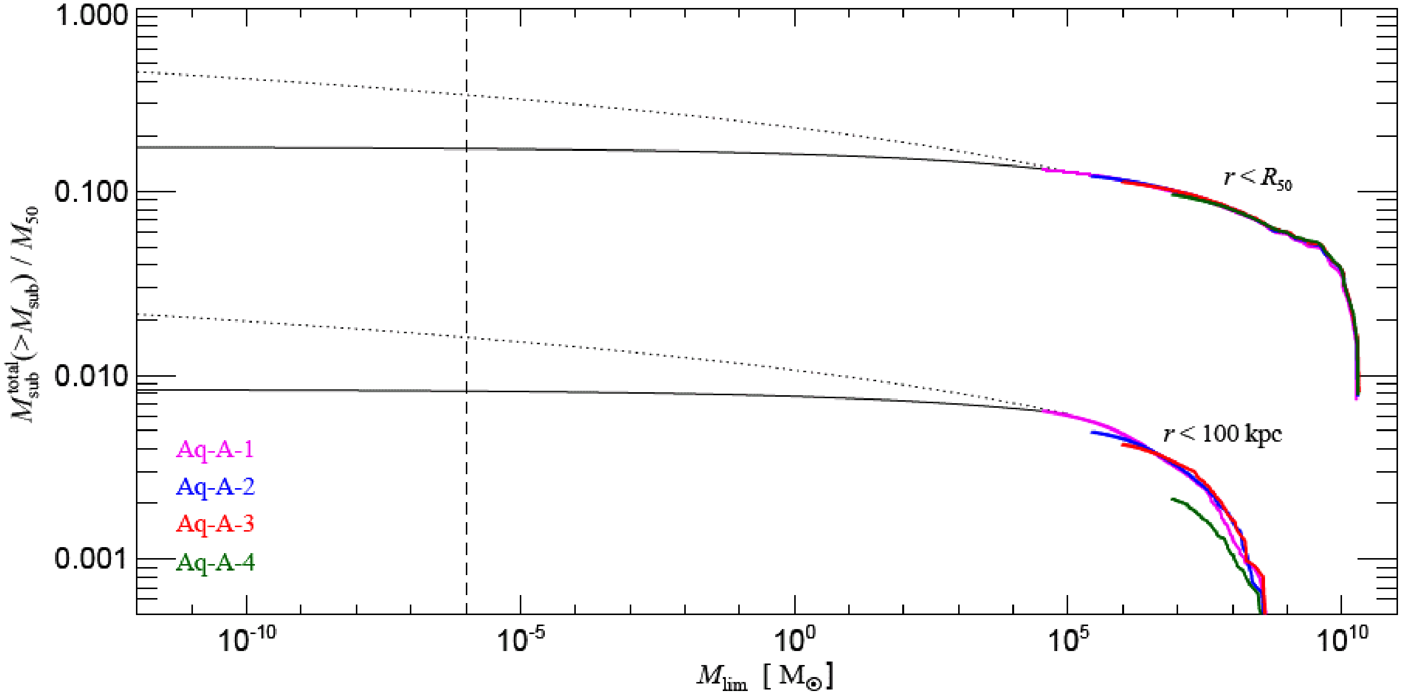
For the six Aquarius halos, the scatter in subhalo abundance is Poisson at high mass and ~20% at low mass

The Via Lactea simulations differ significantly, at least VL-I





Aquarius Project: Springel et al 2008



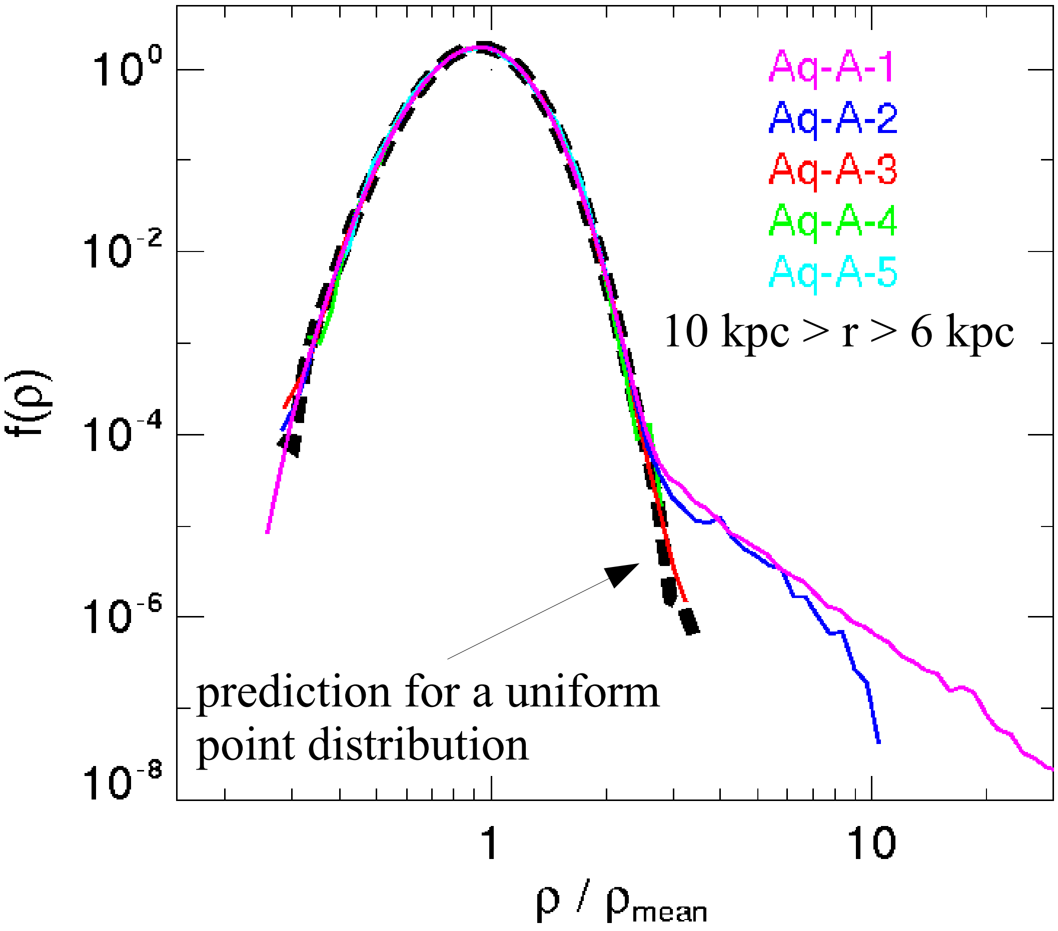
- All mass subhalos are similarly distributed
- A small fraction of the inner mass in subhalos
- <<1% of the mass near the Sun is in subhalos

Substructure: conclusions

- Substructure is primarily in the outermost parts of halos
- The radial distribution of subhalos is almost mass-independent
- Subhalo populations scale (almost) with the mass of the host
- The subhalo mass distribution converges only weakly at small m
- Subhalos contain a very small mass fraction in the inner halo

Local density in the inner halo compared to a smooth ellipsoidal model

Vogelsberger et al 2008



prediction for a uniform point distribution

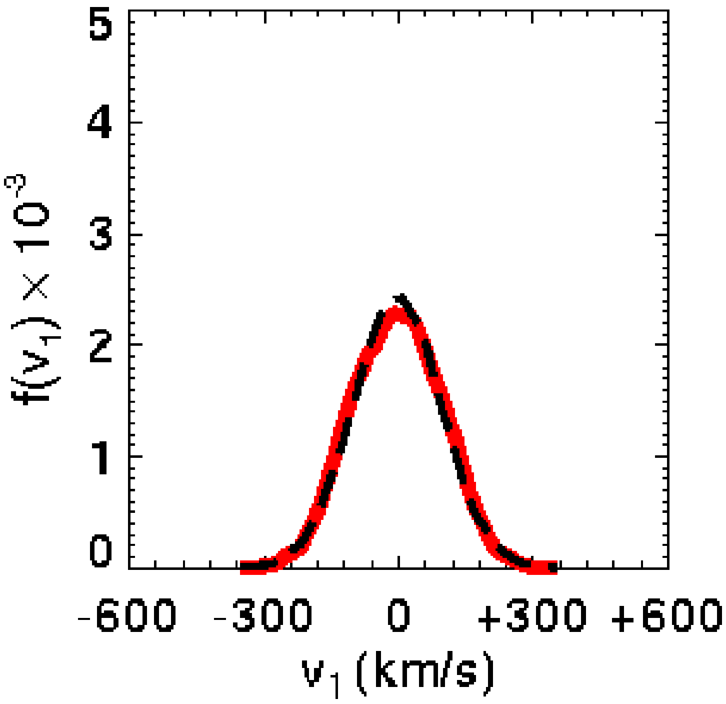
- Estimate a density ρ at each point by adaptively smoothing using the 64 nearest particles
- Fit to a smooth density profile stratified on similar ellipsoids
- The chance of a random point lying in a substructure is $< 10^{-4}$
- The *rms* scatter about the smooth model for the remaining points is only about 4%

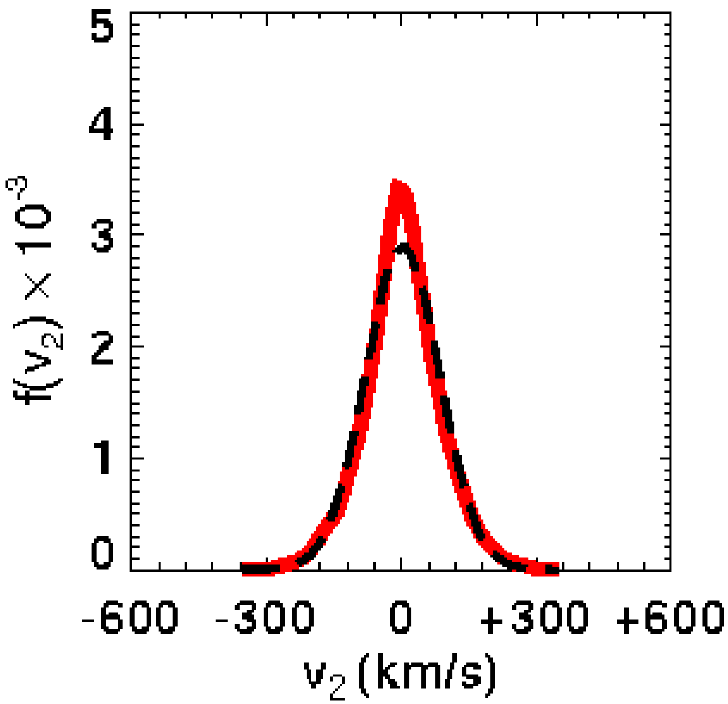
Local velocity distribution

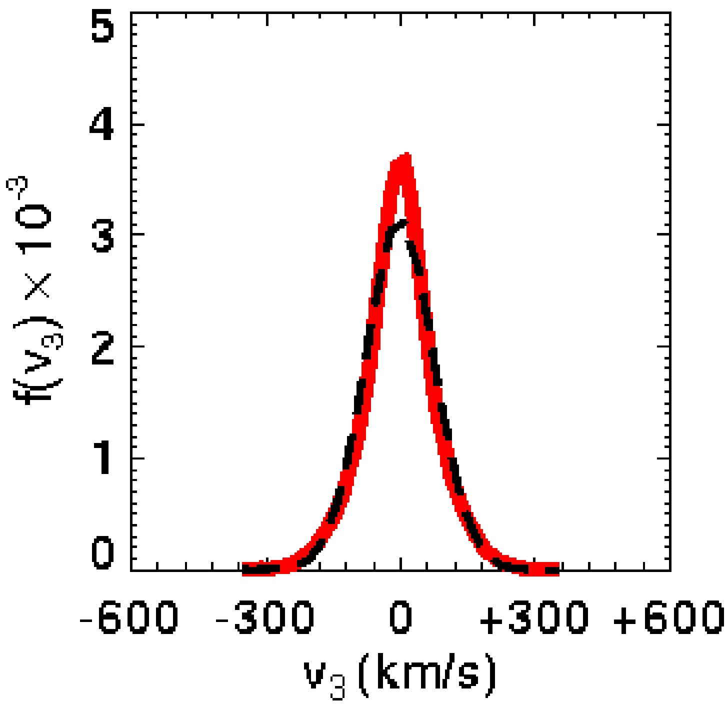
- Velocity histograms for particles in a typical $(2\text{kpc})^3$ box at R = 8 kpc

- Distributions are smooth, near-Gaussian and different in different directions

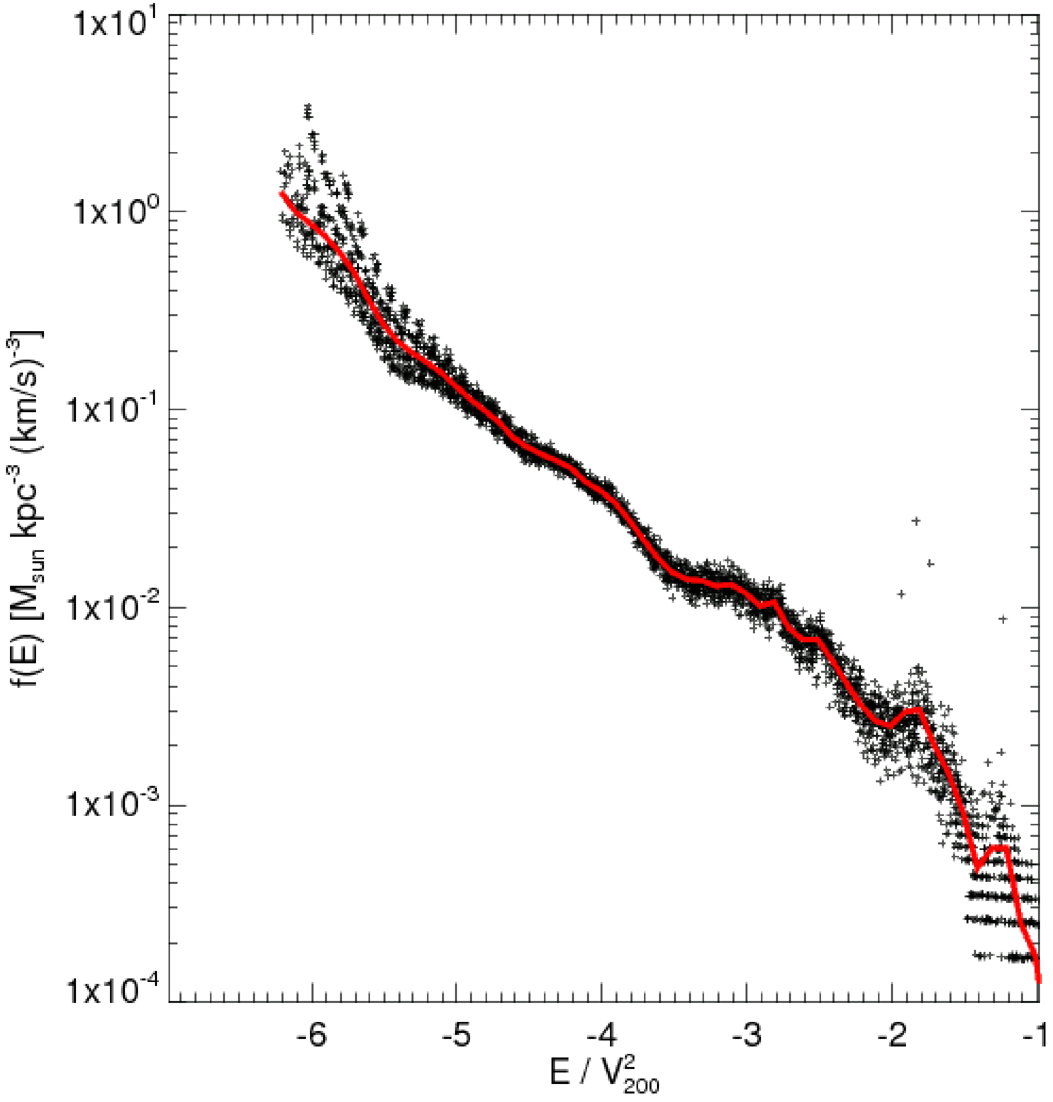
- No individual streams are visible







Energy space features – fossils of formation



The energy distribution within (2 kpc)^3 boxes shows bumps which

-- repeat from box to box

-- are stable over Gyr timescales

-- repeat in simulations of the same object at varying resolution

-- are different in simulations of different objects

These are potentially observable fossils of the formation process

Conclusions for direct detection experiments

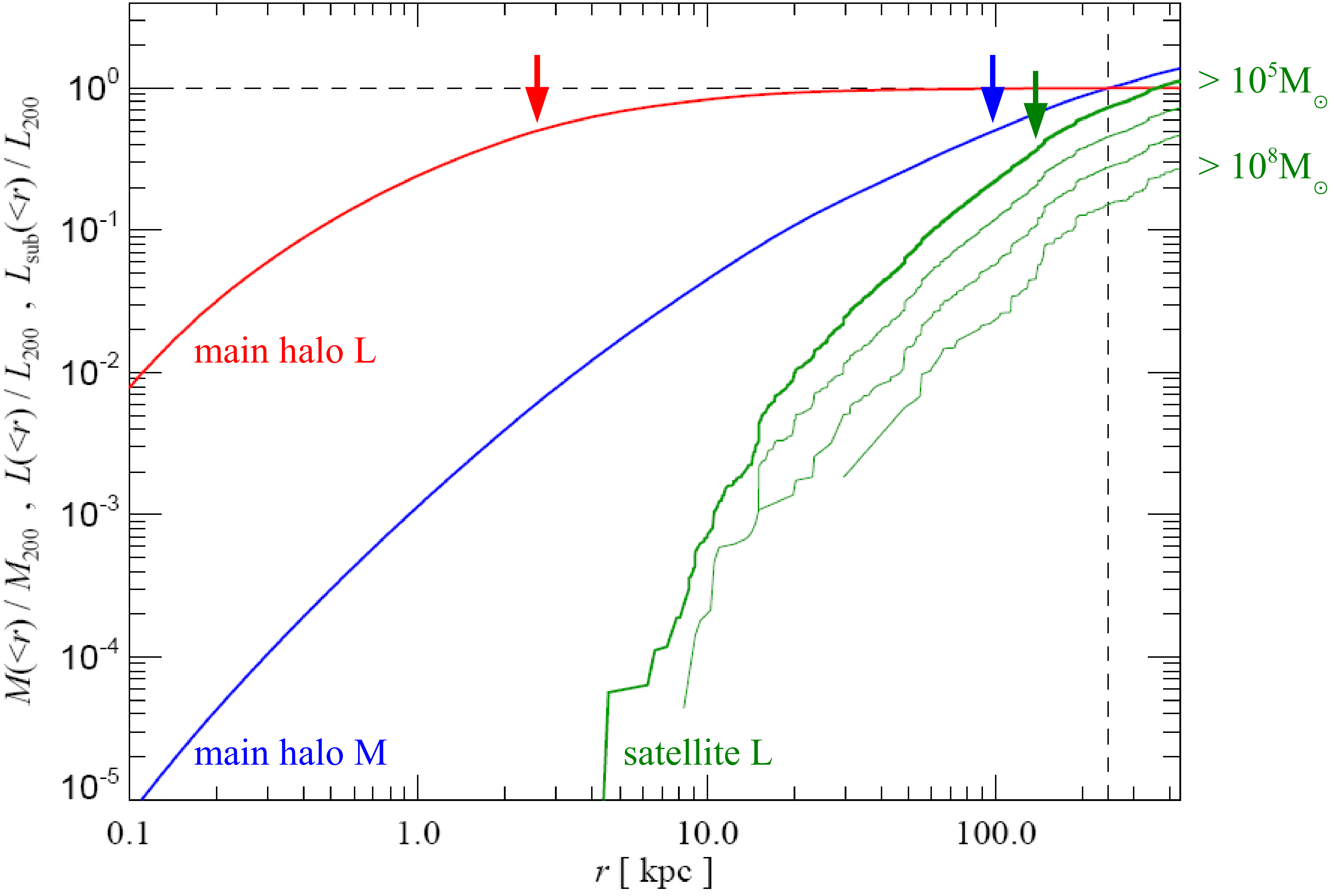
- With more than 99.9% confidence the Sun lies in a region where the DM density differs from the smooth mean value by < 20%

- The local velocity distribution of DM particles is similar to a trivariate Gaussian with no measurable "lumpiness" due to individual DM streams

- The energy distribution of DM particles should contain broad features with ~20% amplitude which are the fossils of the detailed assembly history of the Milky Way's dark halo

Mass and annihilation radiation profiles of a MW halo

Springel et al 2008



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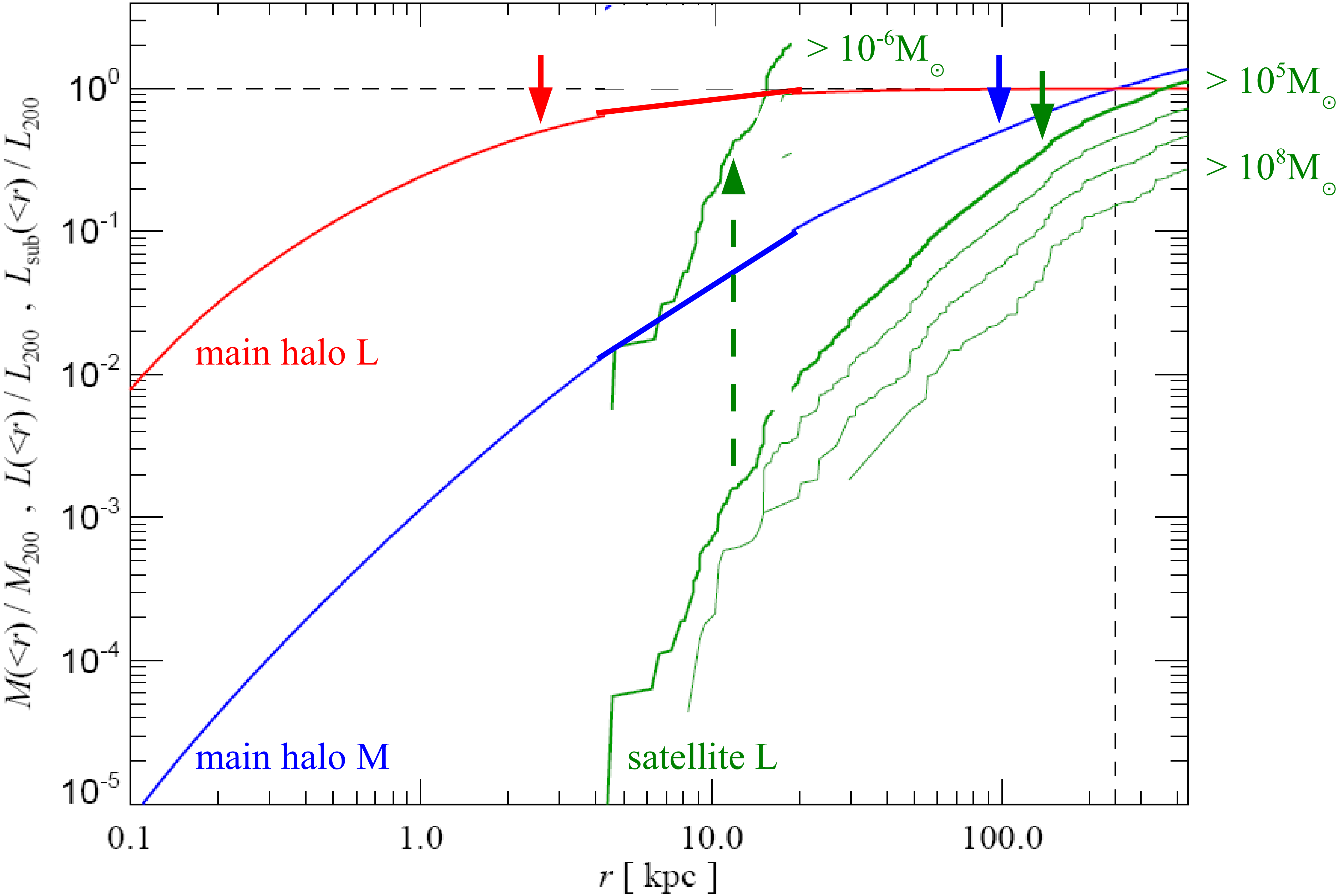
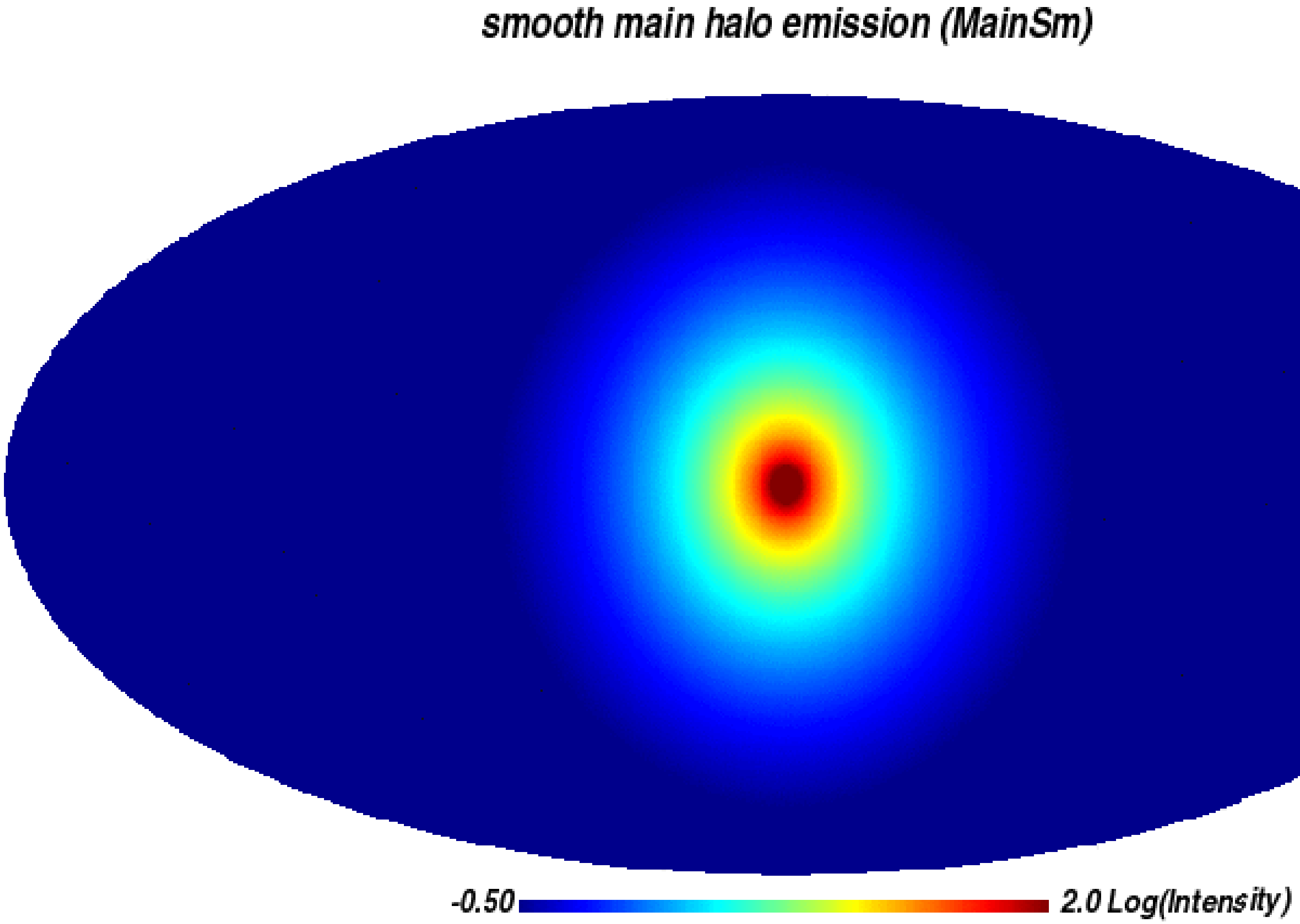


Milky Way halo seen in DM annihilation radiation



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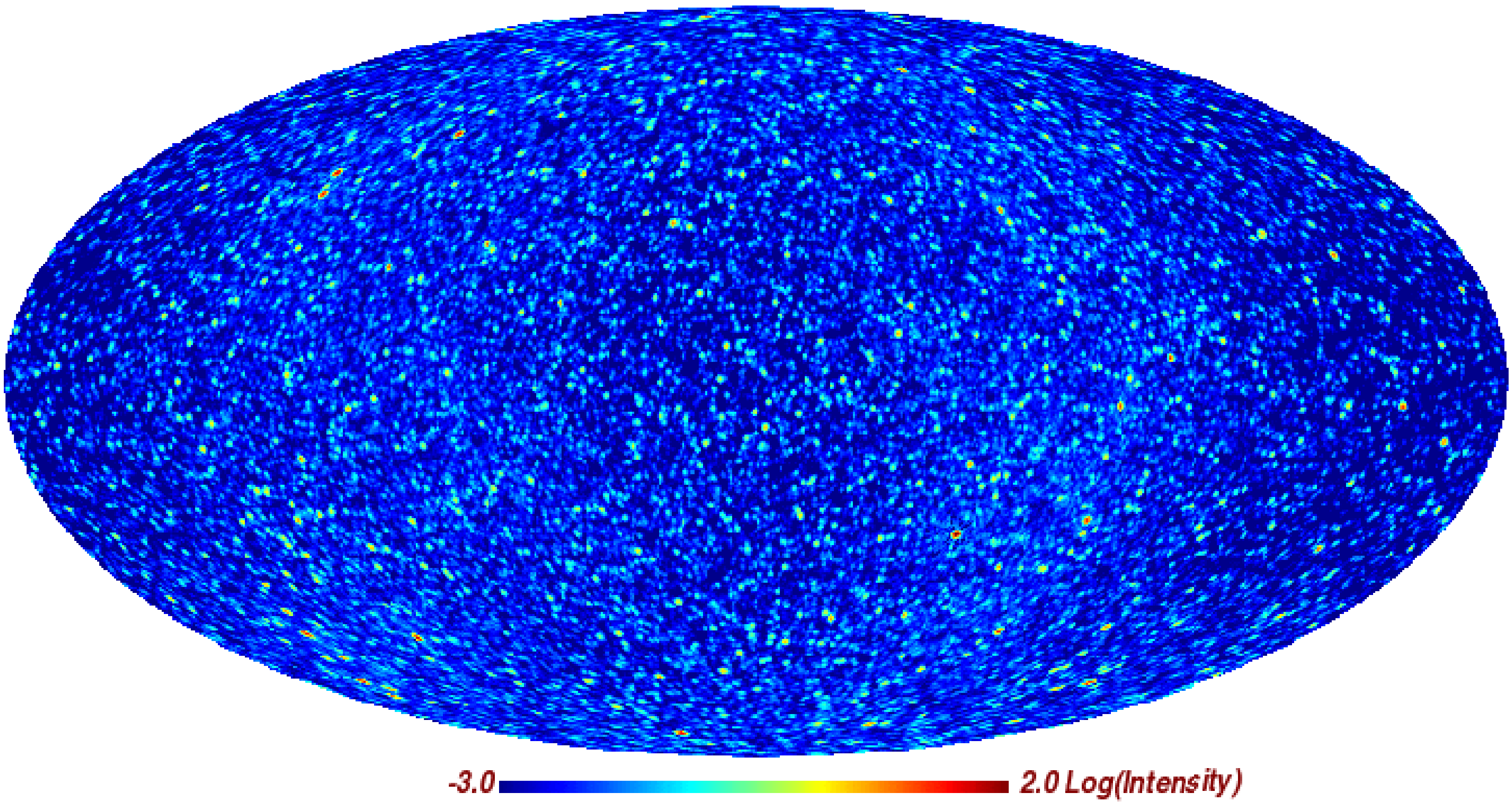
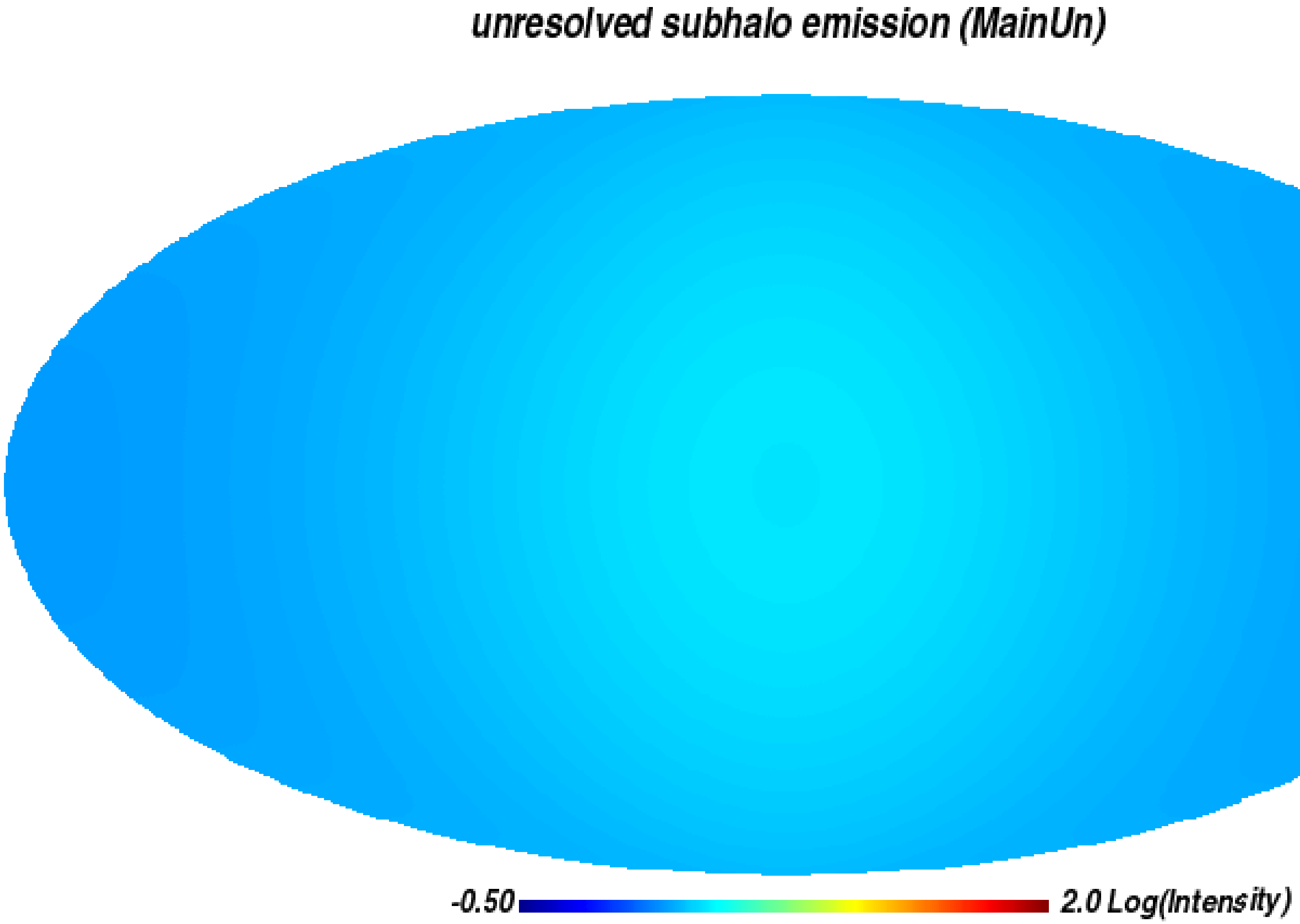

emission from resolved subhalos (SubSm+SubSub)

Milky Way halo seen in DM annihilation radiation



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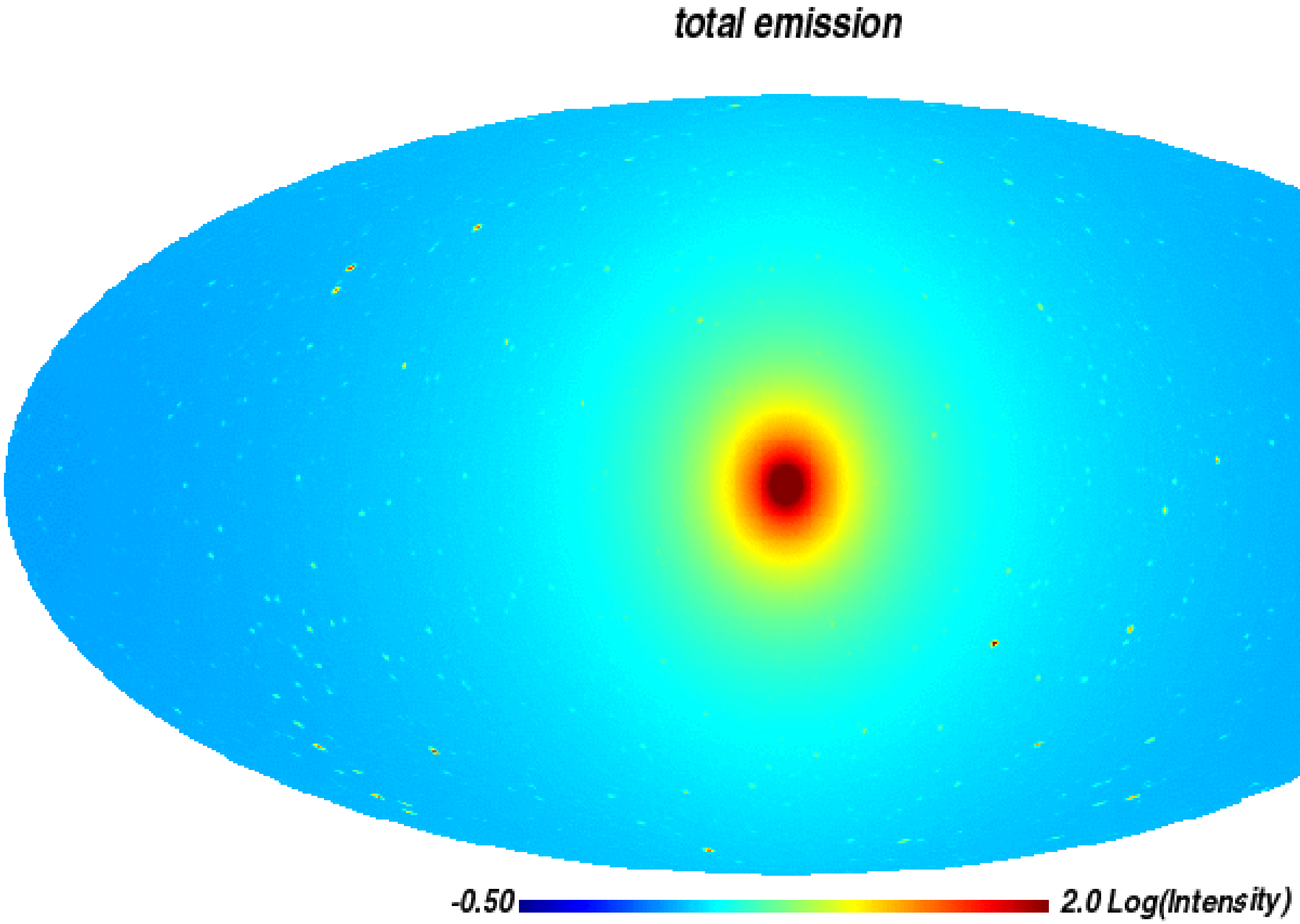
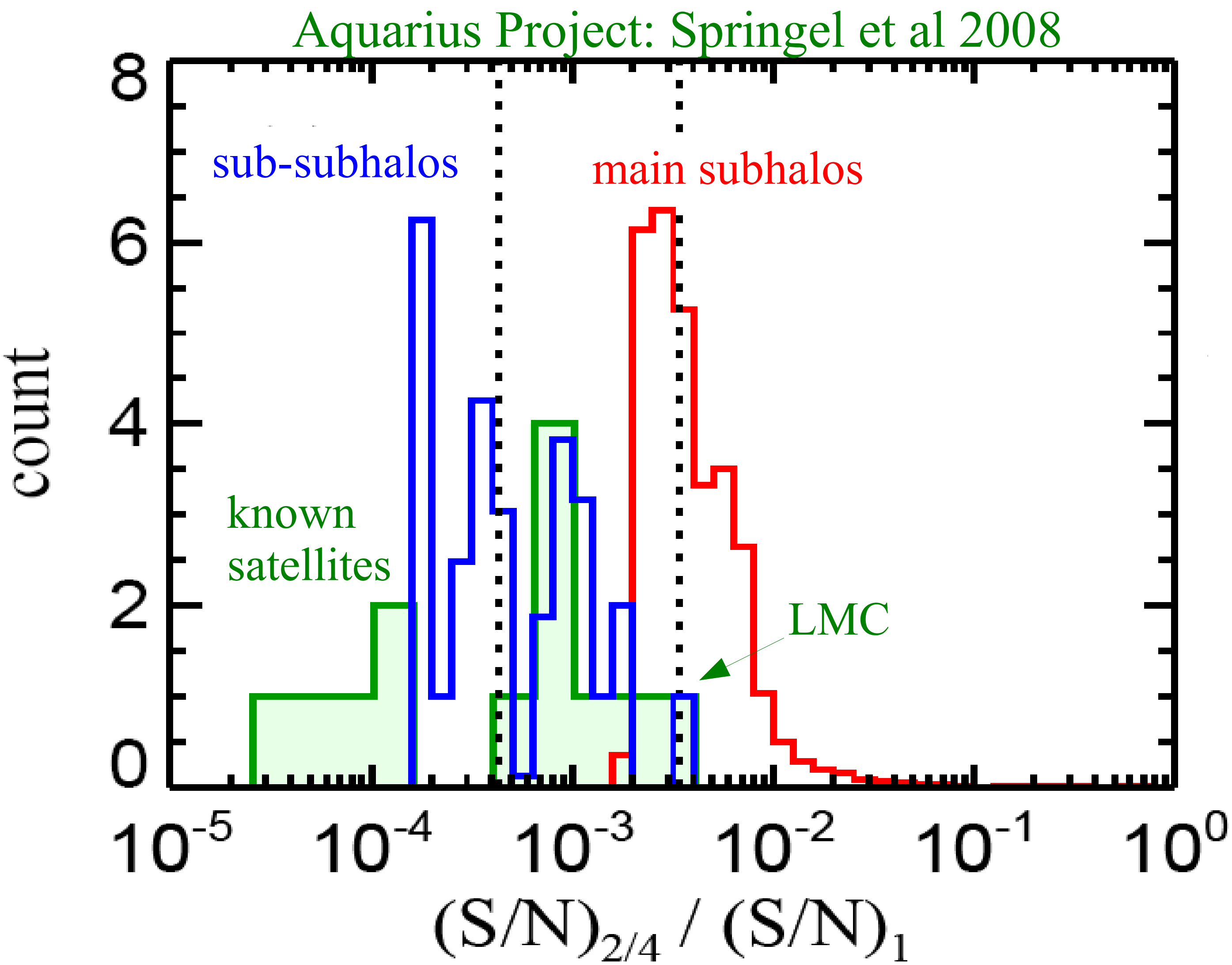
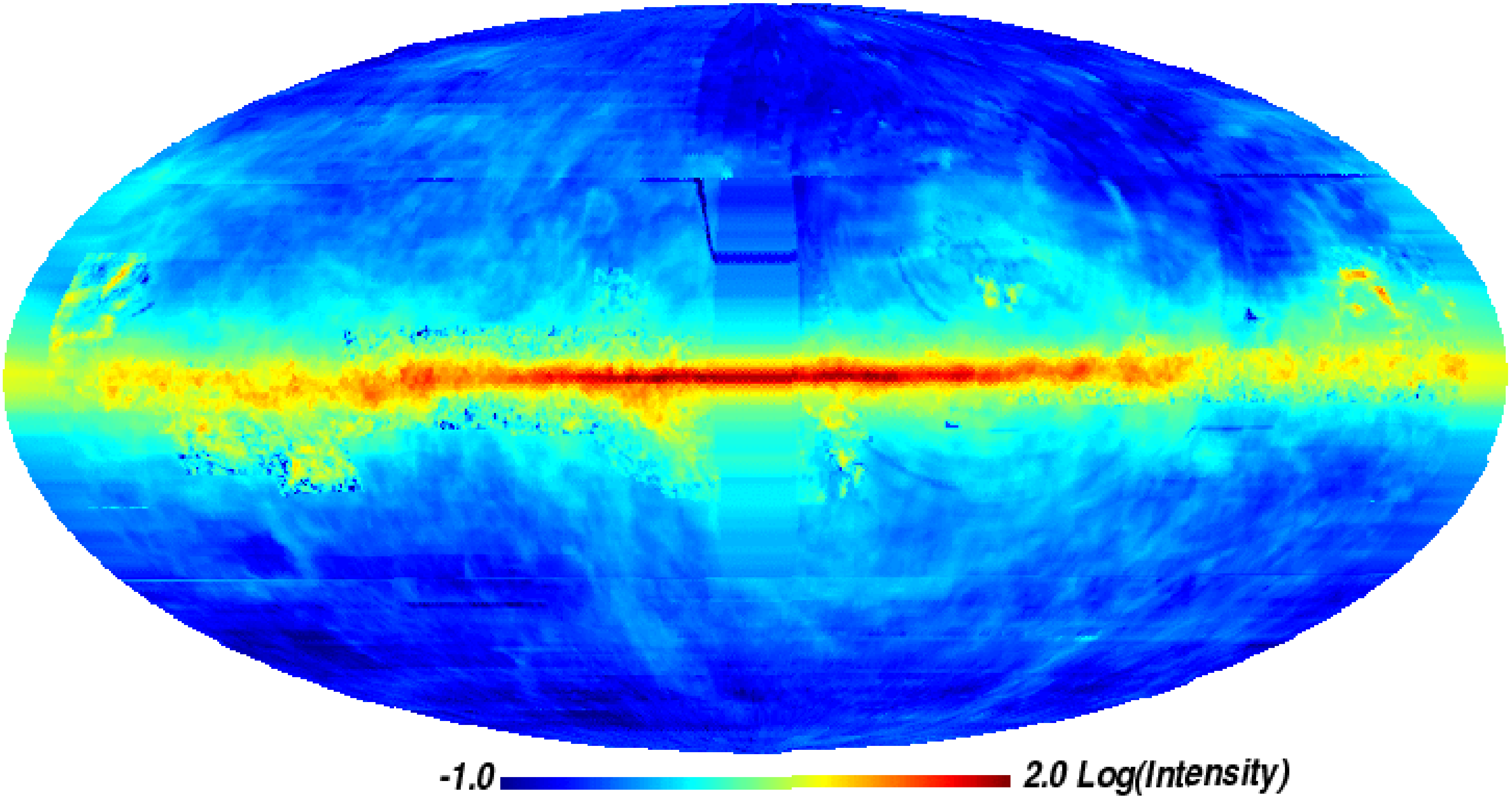


S/N for detecting subhalos in units of that for detecting the main halo
30 highest S/N objects, assuming use of optimal filters



- Highest S/N subhalos have 1% of S/N of main halo
- Highest S/N subhalos have 10 times S/N of known satellites
- Substructure of subhalos has no influence on detectability

GALPROP, optimized



Conclusions about clumping and annihilation

- Subhalos increase the MW's total flux within 250 kpc by a factor of 230 as seen by a distant observer, but its flux on the sky by a factor of only 2.9 as seen from the Sun
- The luminosity from subhalos is dominated by small objects and is nearly uniform across the sky (contrast is a factor of ~1.5)
- Individual subhalos have lower S/N for detection than the main halo
- The highest S/N *known* subhalo should be the LMC, but smaller subhalos without stars are likely to have higher S/N

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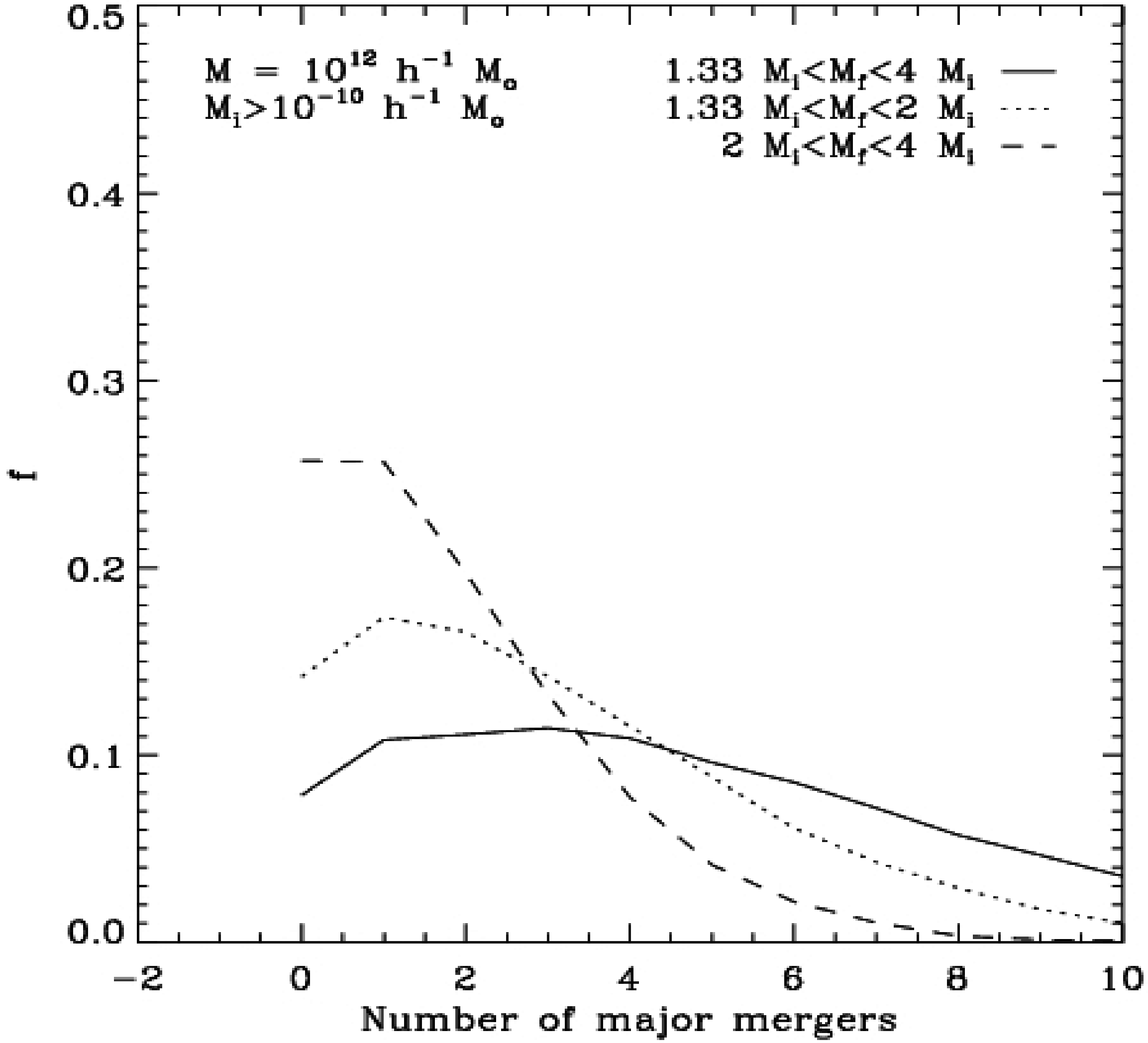

The typical mass element in a “Milky Way” halo goes through 3.5 “major mergers” where the two halos are within a factor of 3 in mass

The majority of these occur when the element is part of the larger halo