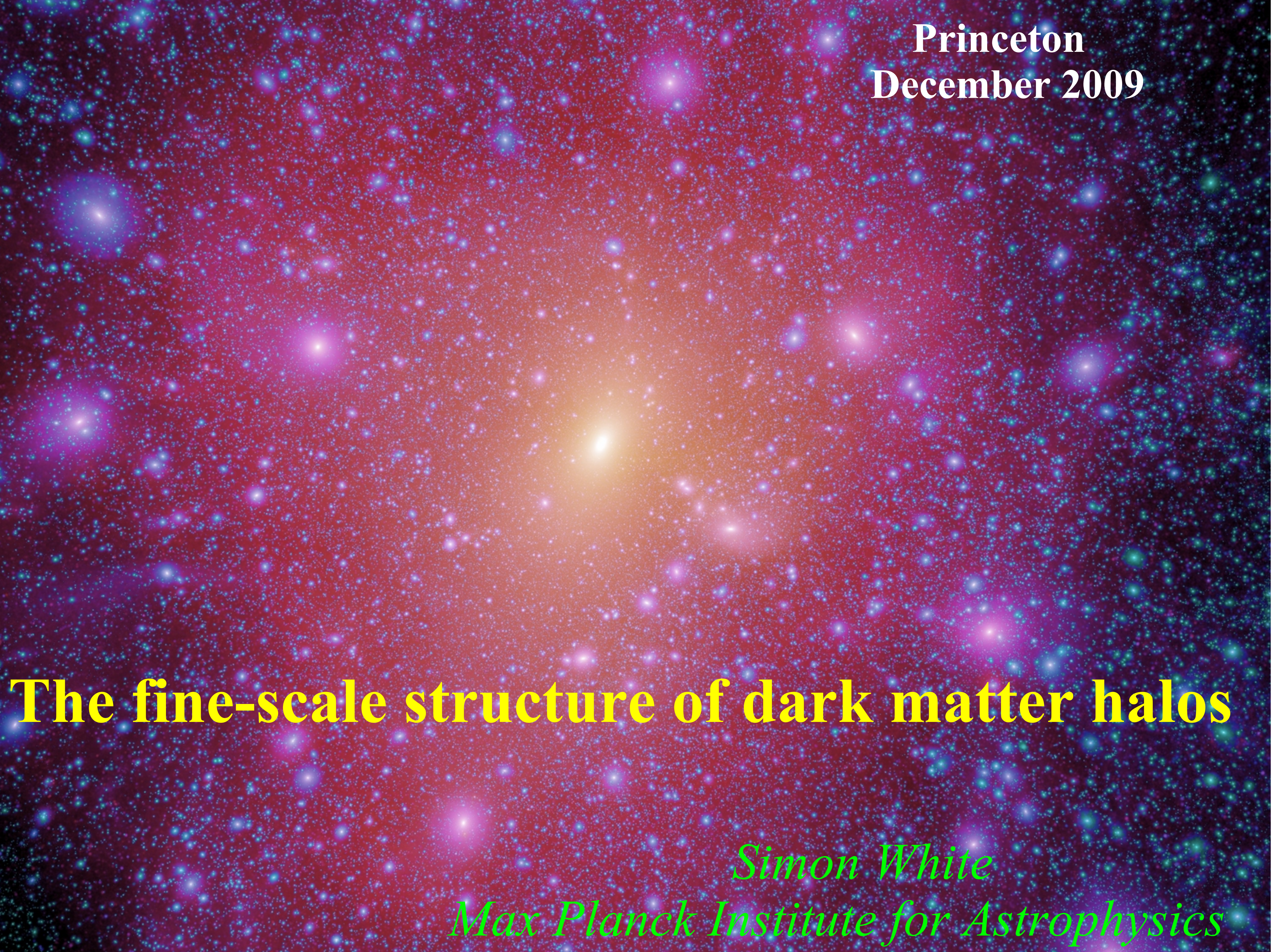


Princeton
December 2009

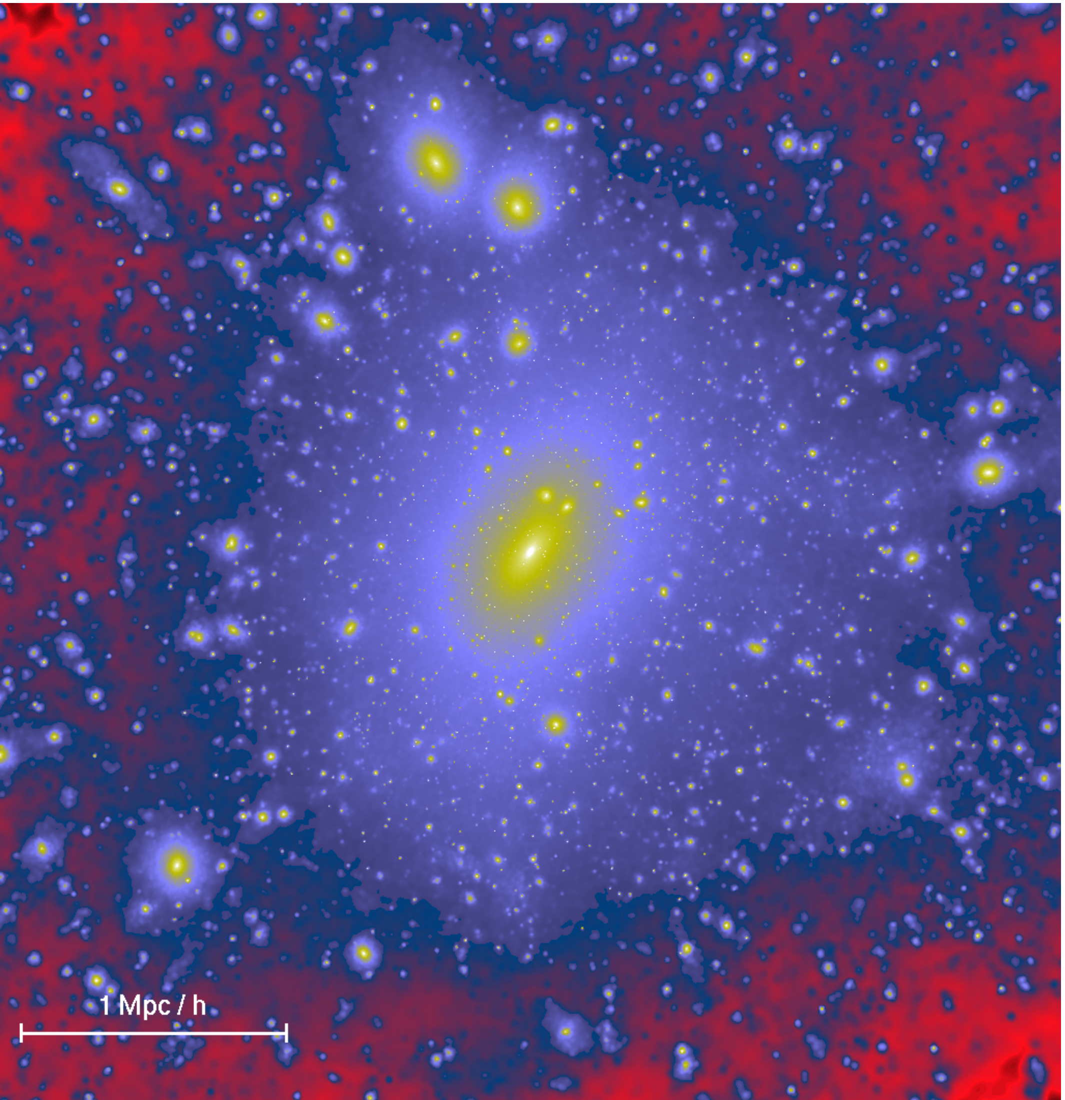
The fine-scale structure of dark matter halos

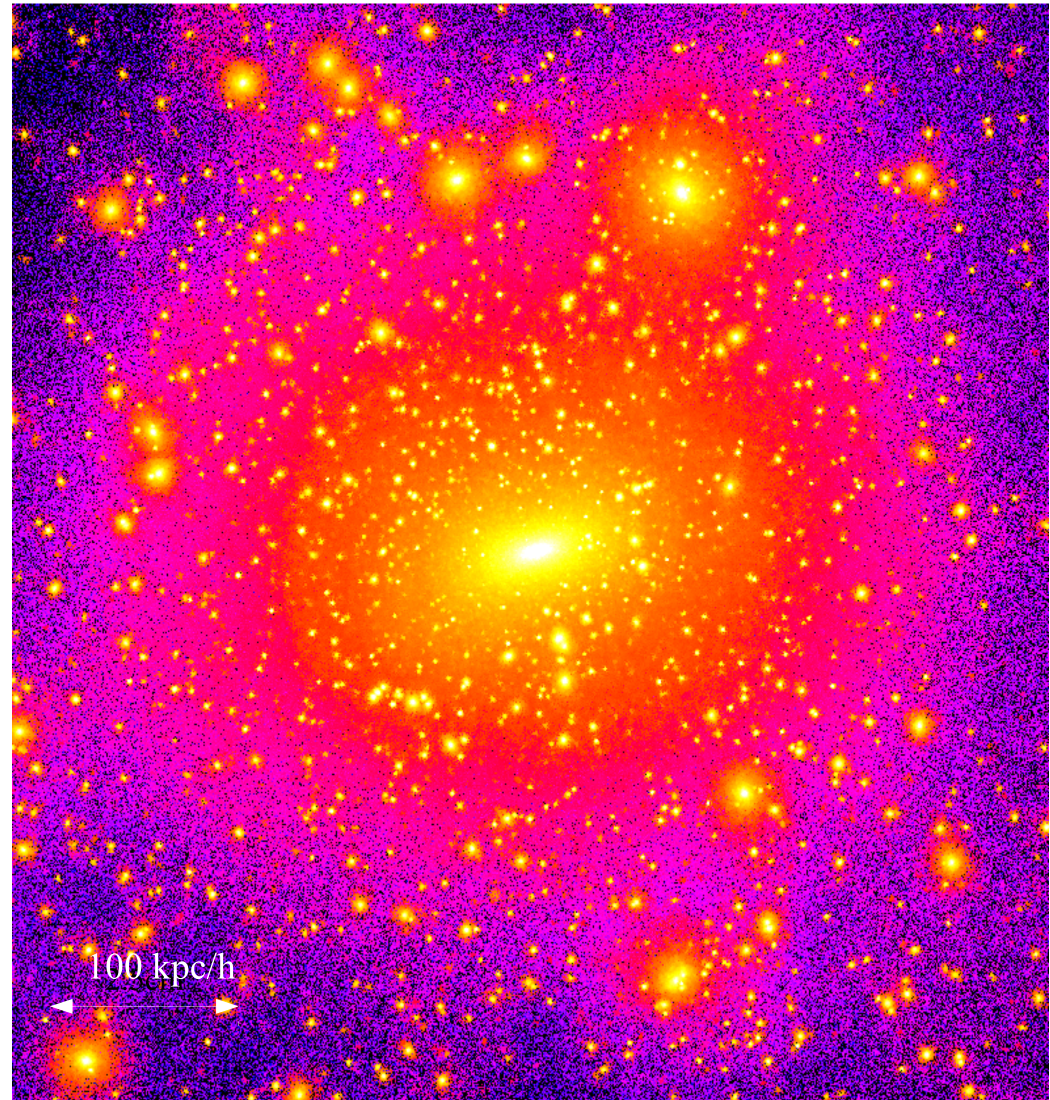
Simon White
Max Planck Institute for Astrophysics

The dark matter structure of ΛCDM halos

A rich galaxy cluster halo
Springel et al 2001

A 'Milky Way' halo
Power et al 2002





ΛCDM galaxy halos (without galaxies!)

- Halos extend to ~10 times the 'visible' radius of galaxies and contain ~10 times the mass in the visible regions

- Halos are not spherical but approximate triaxial ellipsoids
  -- more prolate than oblate
  -- axial ratios greater than two are common

- "Cuspy" density profiles with outwardly increasing slopes
  -- $d\ ln\ \varrho / d\ ln\ r = \gamma$ with $\gamma < -2.5$ at large r
  $\gamma > -1.2$ at small r

- Substantial numbers of self-bound subhalos contain ~10% of the halo's mass and have $d N / d M \sim M^{-1.8}$

→ Most substructure mass is in most massive subhalos

Halo assembly for neutralino ΛCDM

- Typical first generation halos are similar in mass to the free-streaming mass limit – Earth mass or below

Halo assembly for neutralino ΛCDM

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- The mass is primarily in small halos at redshifts $z \geq 15$

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- Structure builds up from small (e.g. Earth mass) to large (e.g. Milky Way halo mass) by a sequence of mergers

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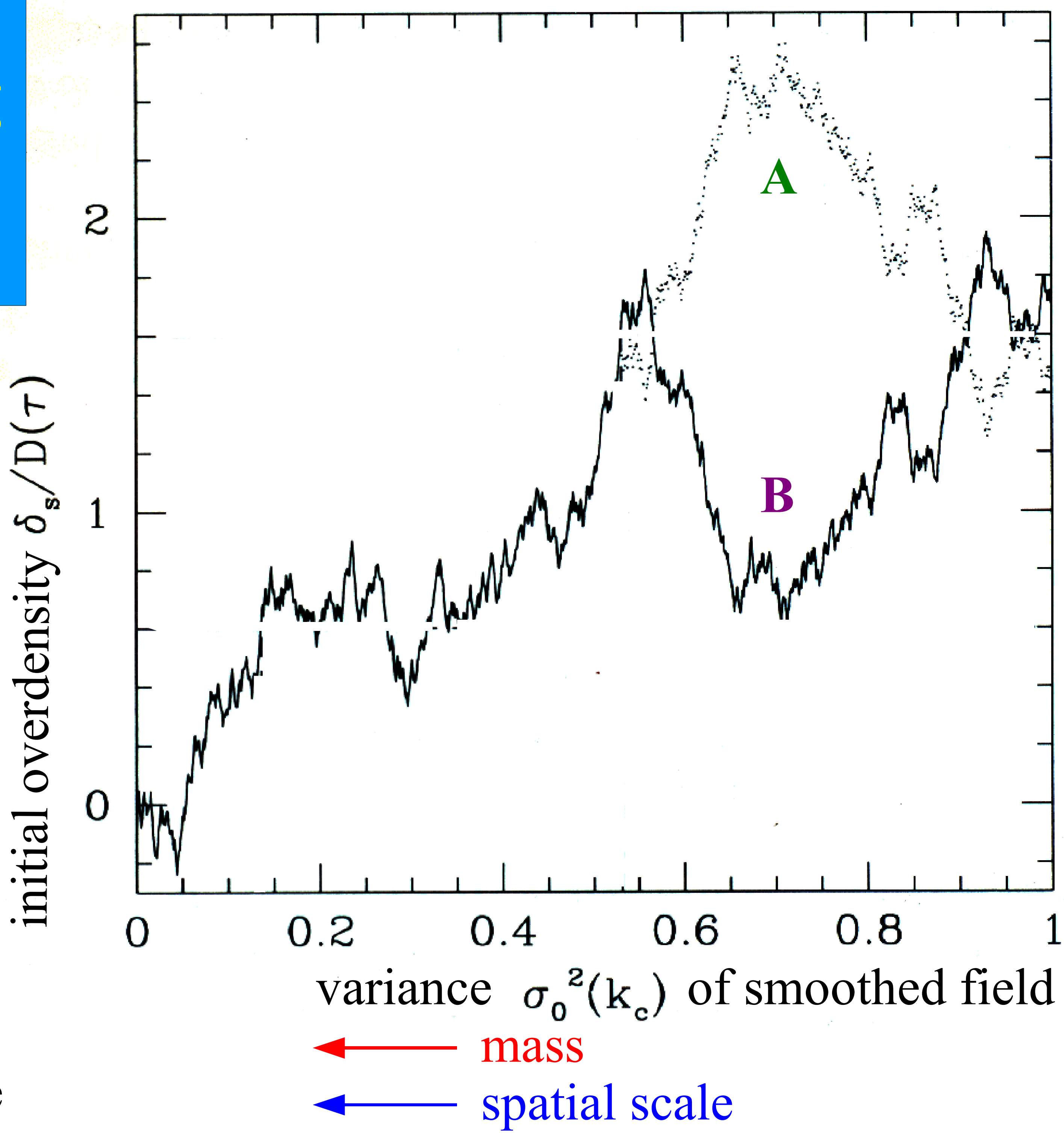
Overdensity vs smoothing at a given position

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

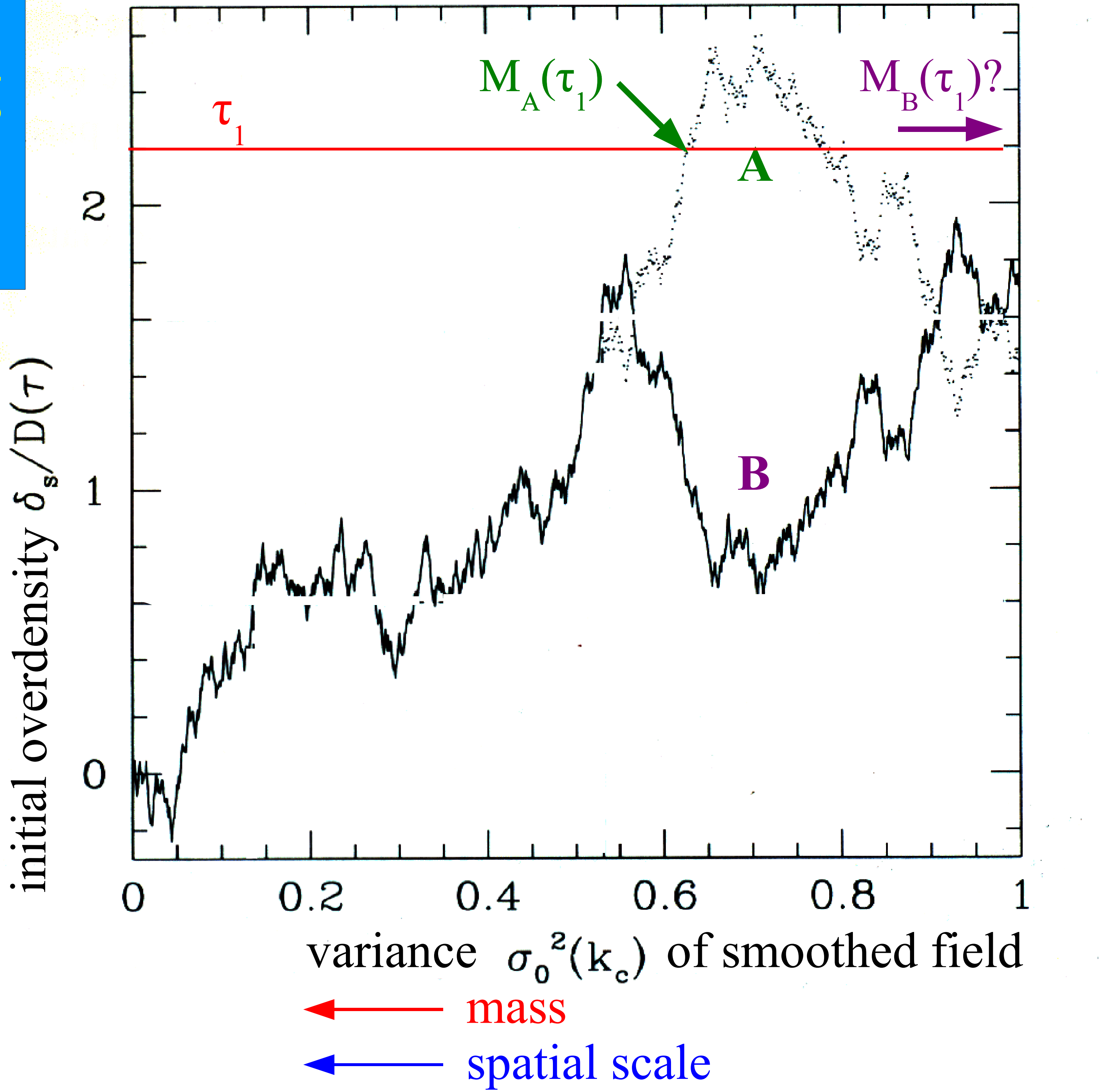


Overdensity vs smoothing at a given position

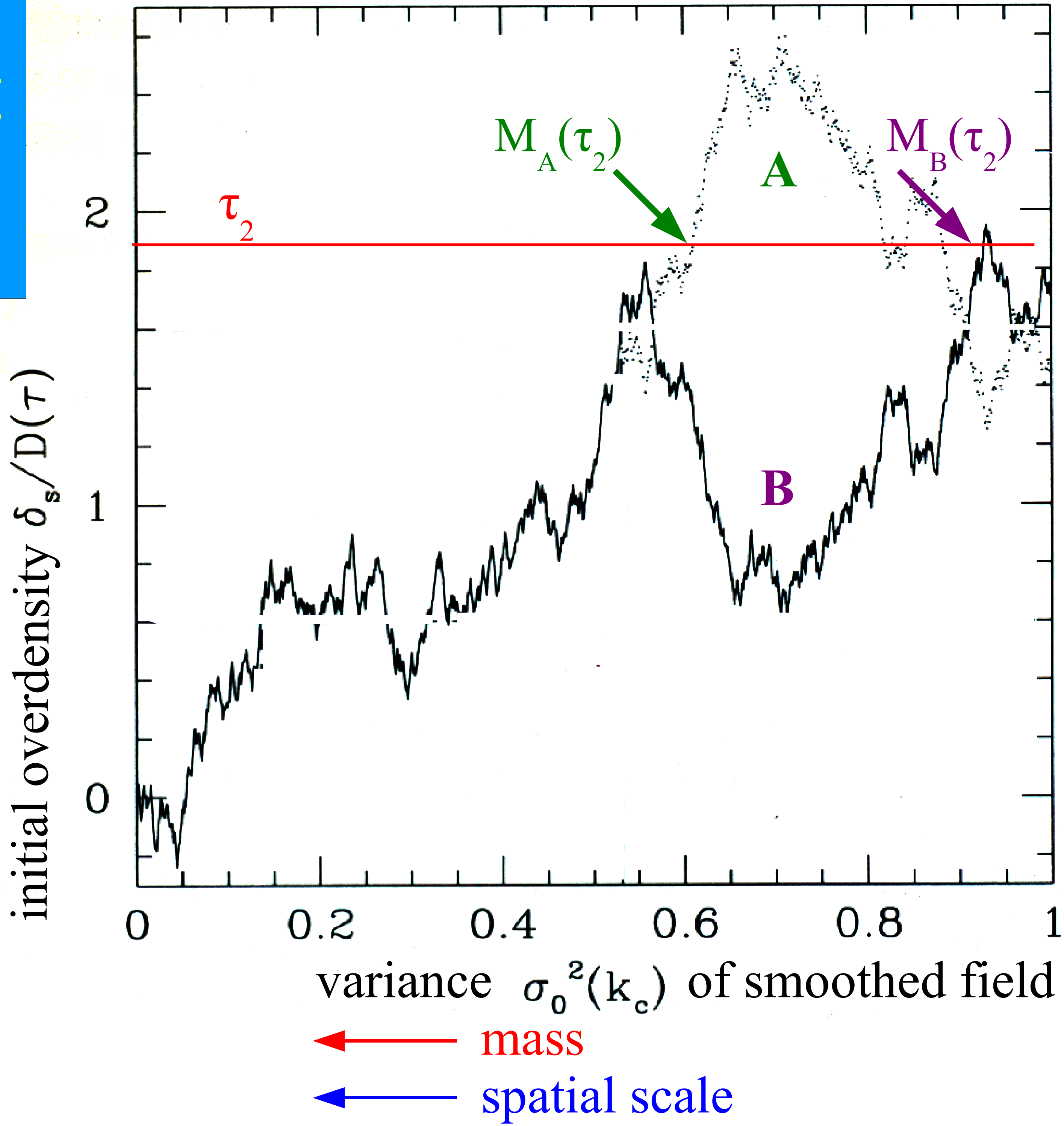
At an early time τ_1

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

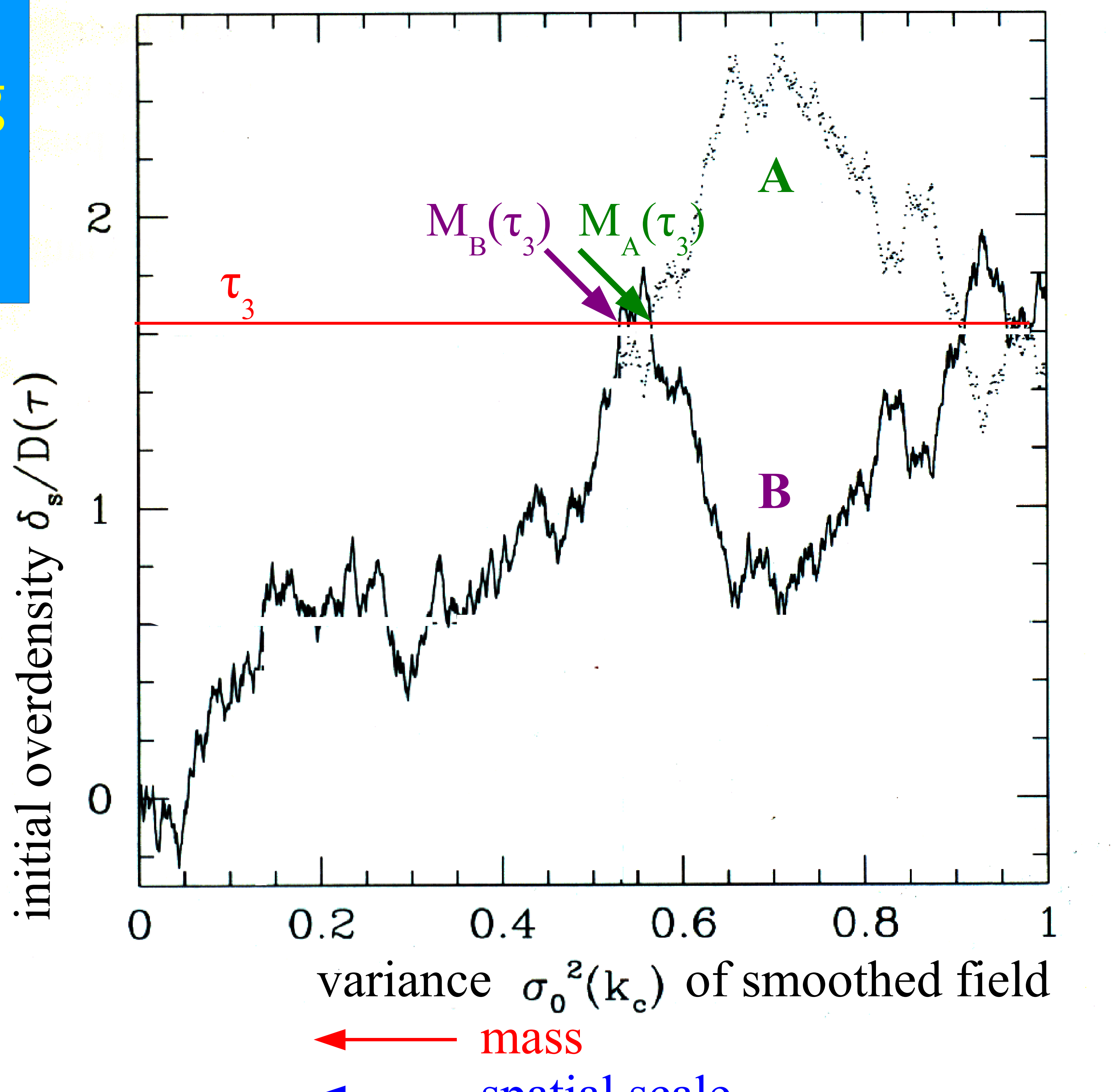
B is now part of a moderately massive halo

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

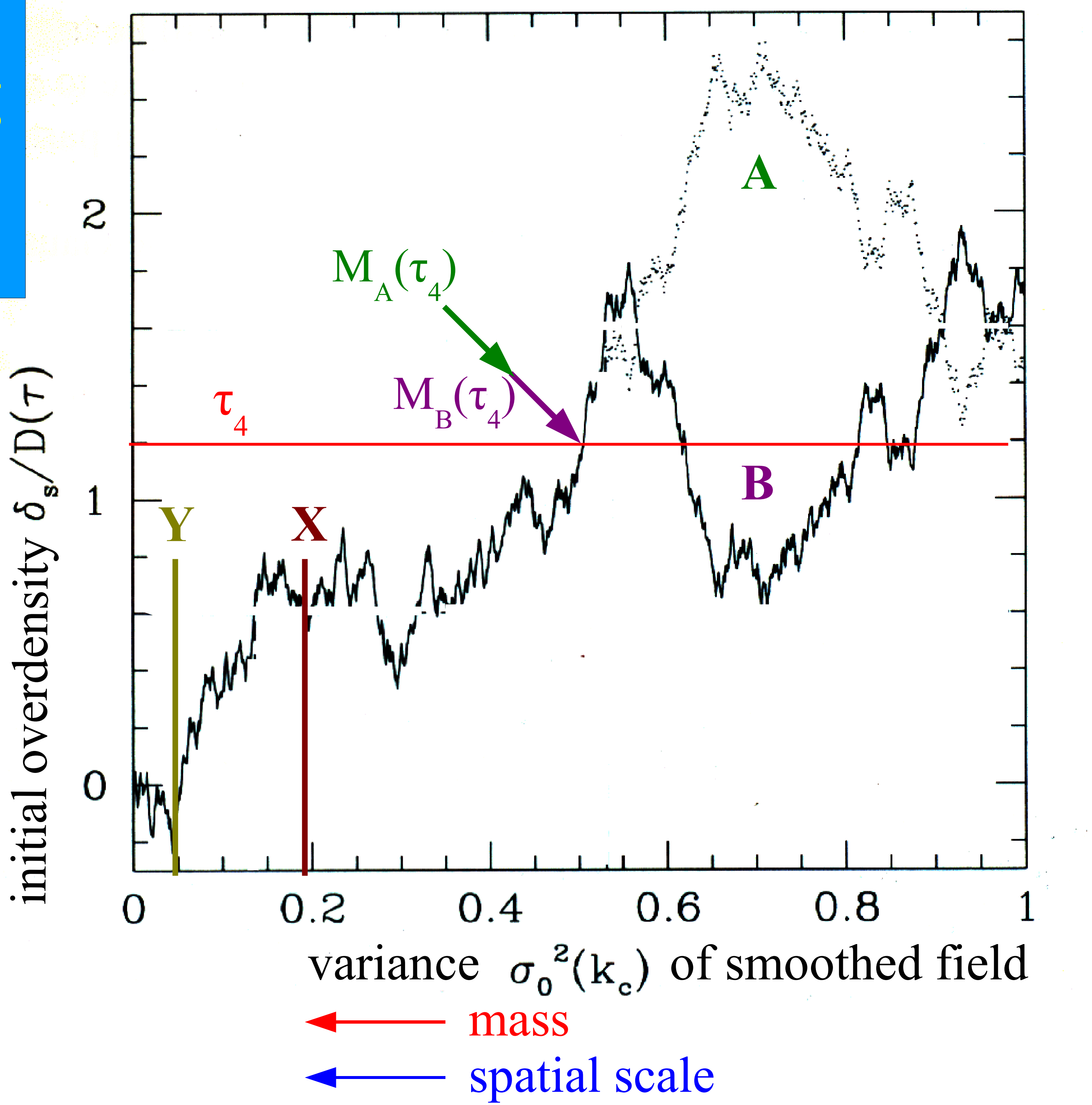


Overdensity vs smoothing at a given position

Still later, e.g. τ_4

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

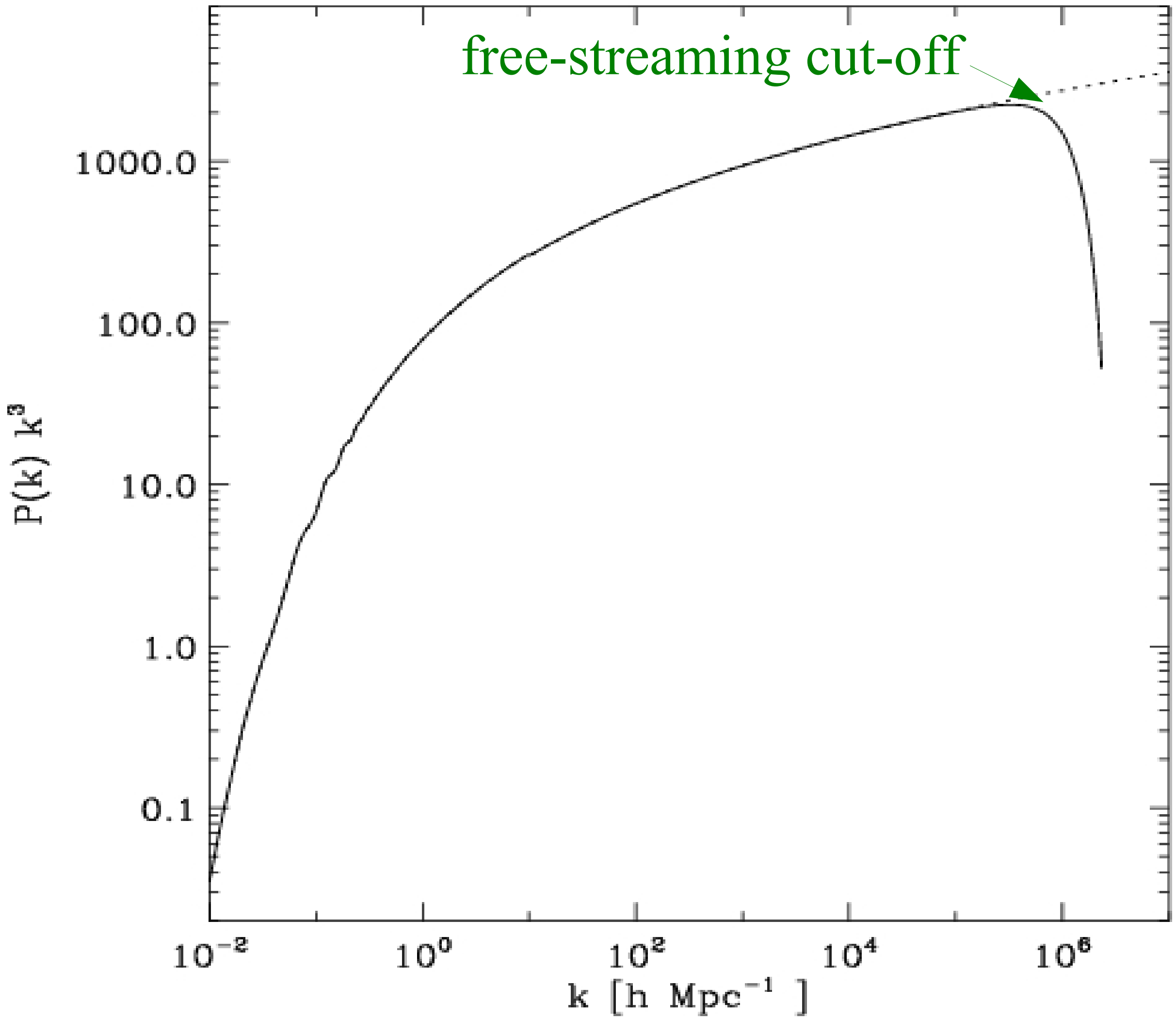
On scale X they are embedded in a high density region.
On larger scale Y in a low density region



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 & White 2009



The linear power spectrum in "power per octave" form

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

EPS statistics for the standard ΛCDM cosmology

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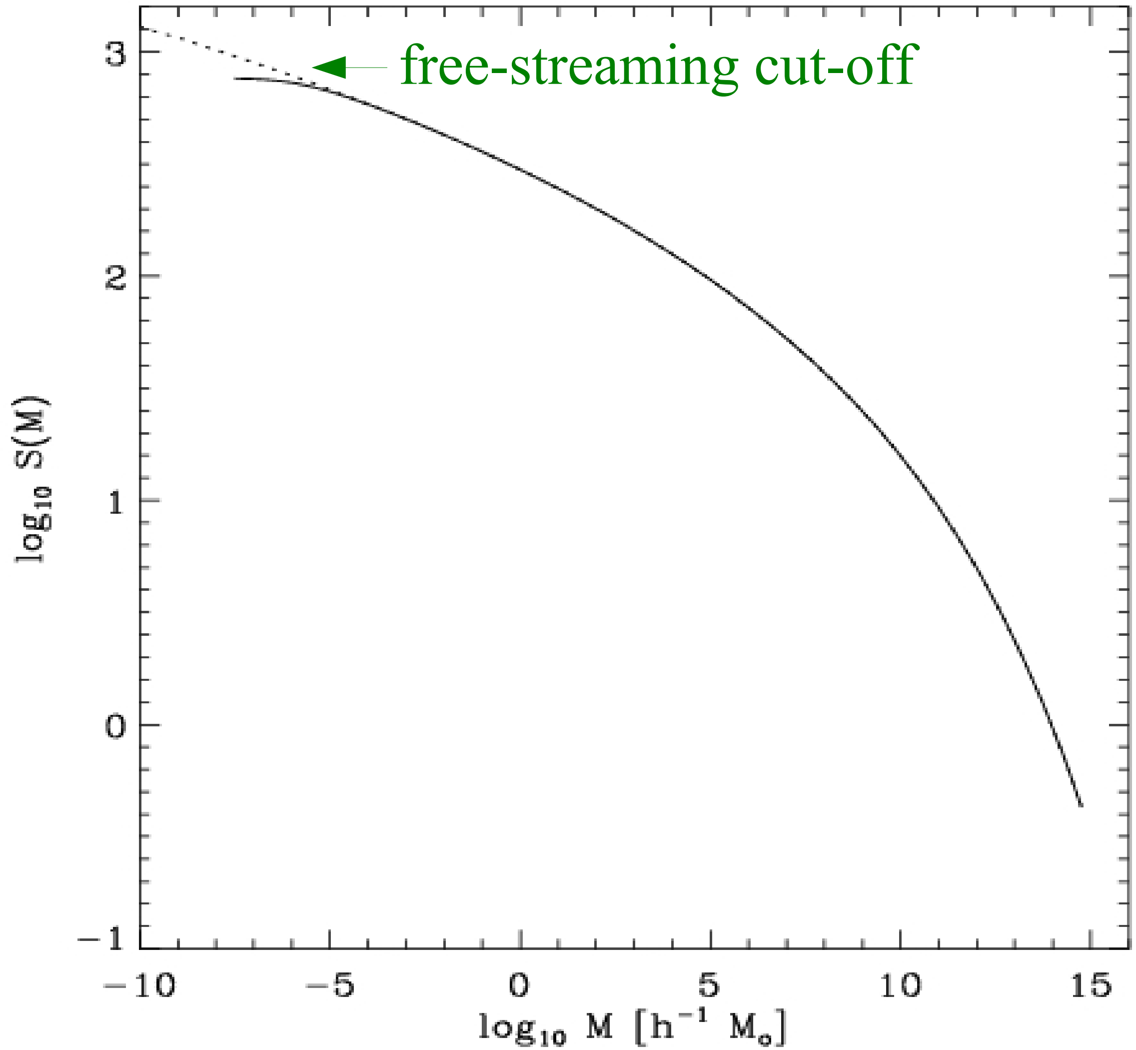

Variance of linear density fluctuation within spheres containing mass M, extrapolated to z = 0

As M → 0, S(M) → 720

EPS statistics for the standard ΛCDM cosmology

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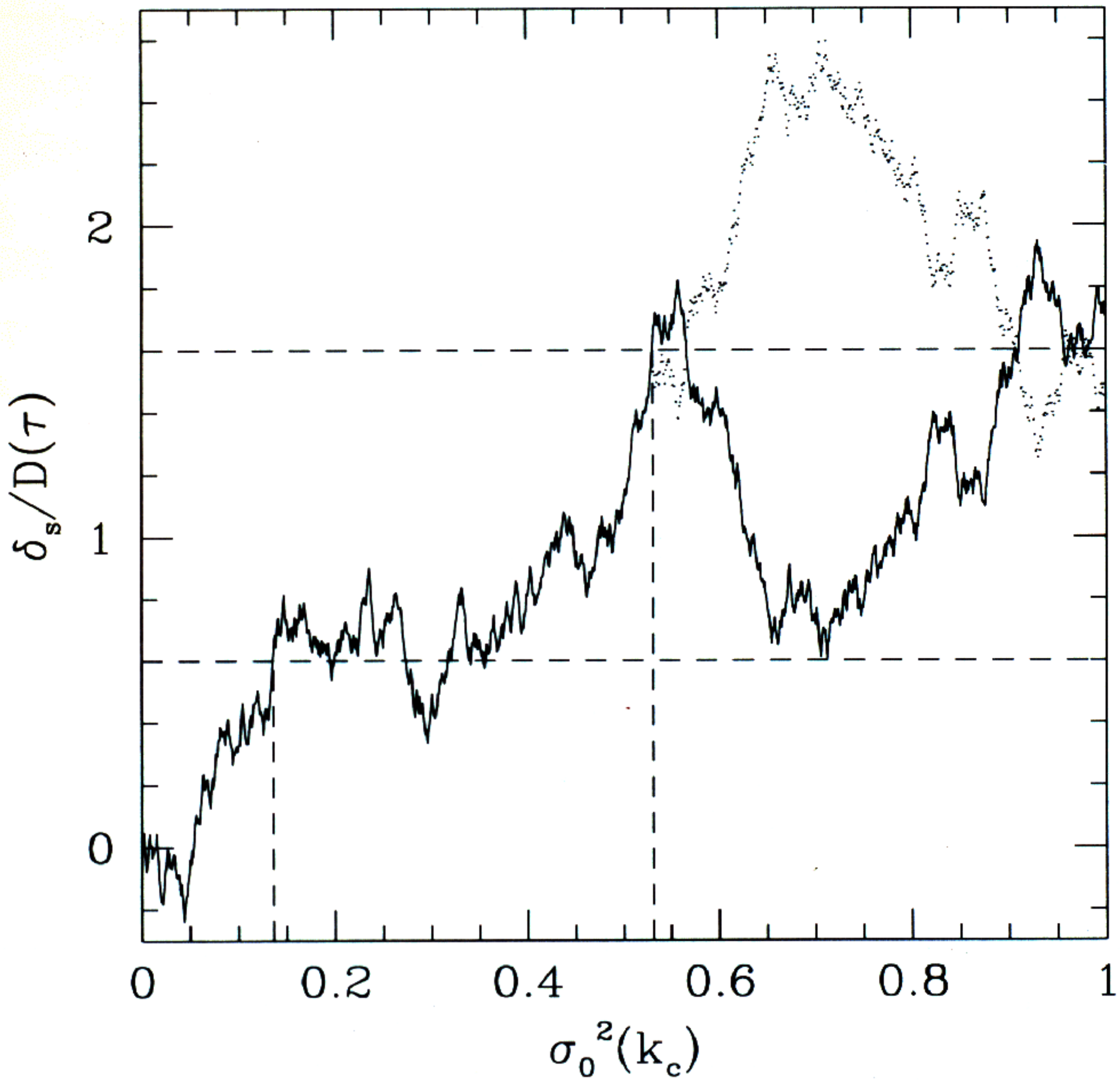

If these Markov random walks are scaled so the maximum variance is 720 and the vertical axis is multiplied by √720, then they represent complete halo assembly histories for random CDM particles.

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

EPS statistics for the standard ΛCDM cosmology

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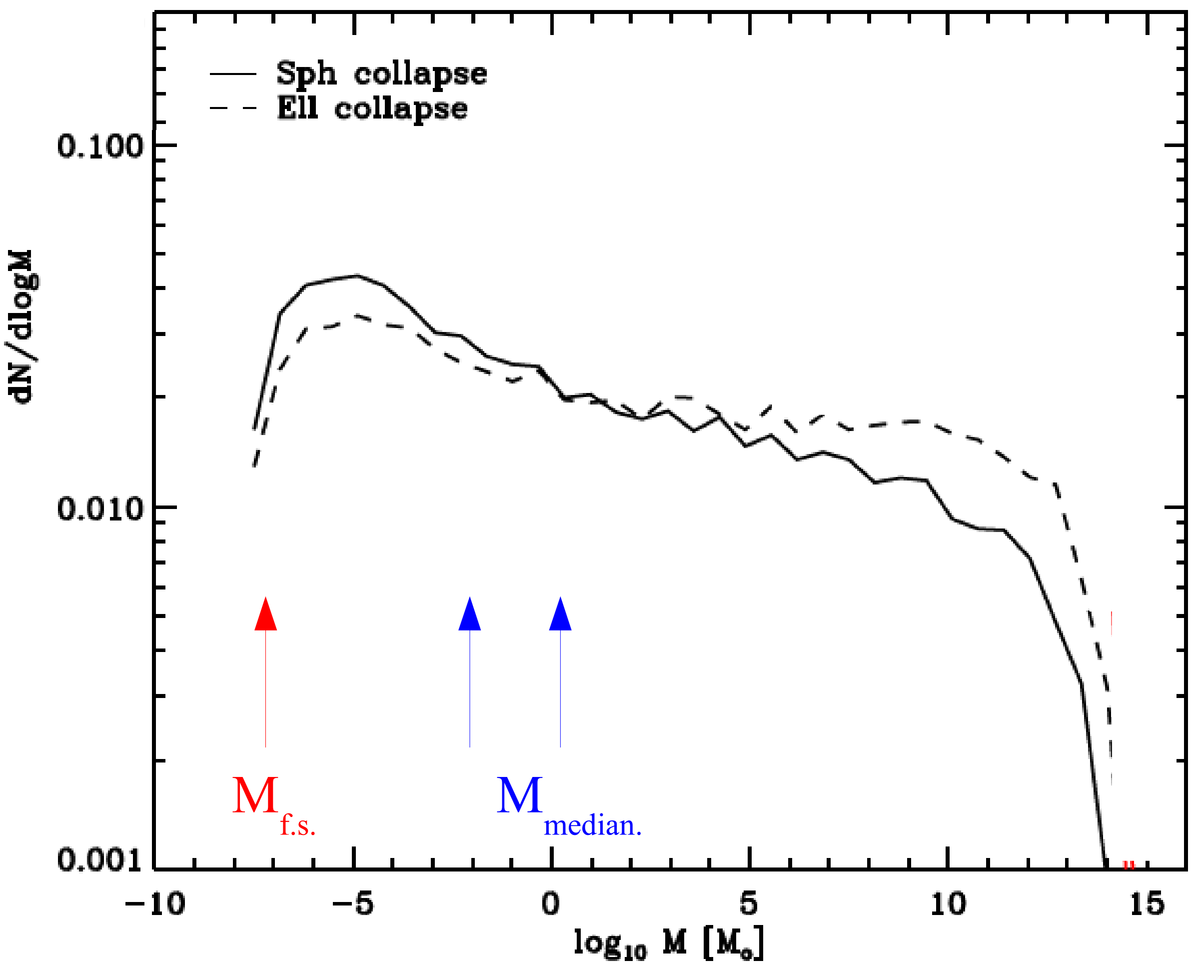


Distribution of the masses of the first generation halos for a random set of dark matter particles

The median is 10^{-2} to 1.0 $M_\odot$

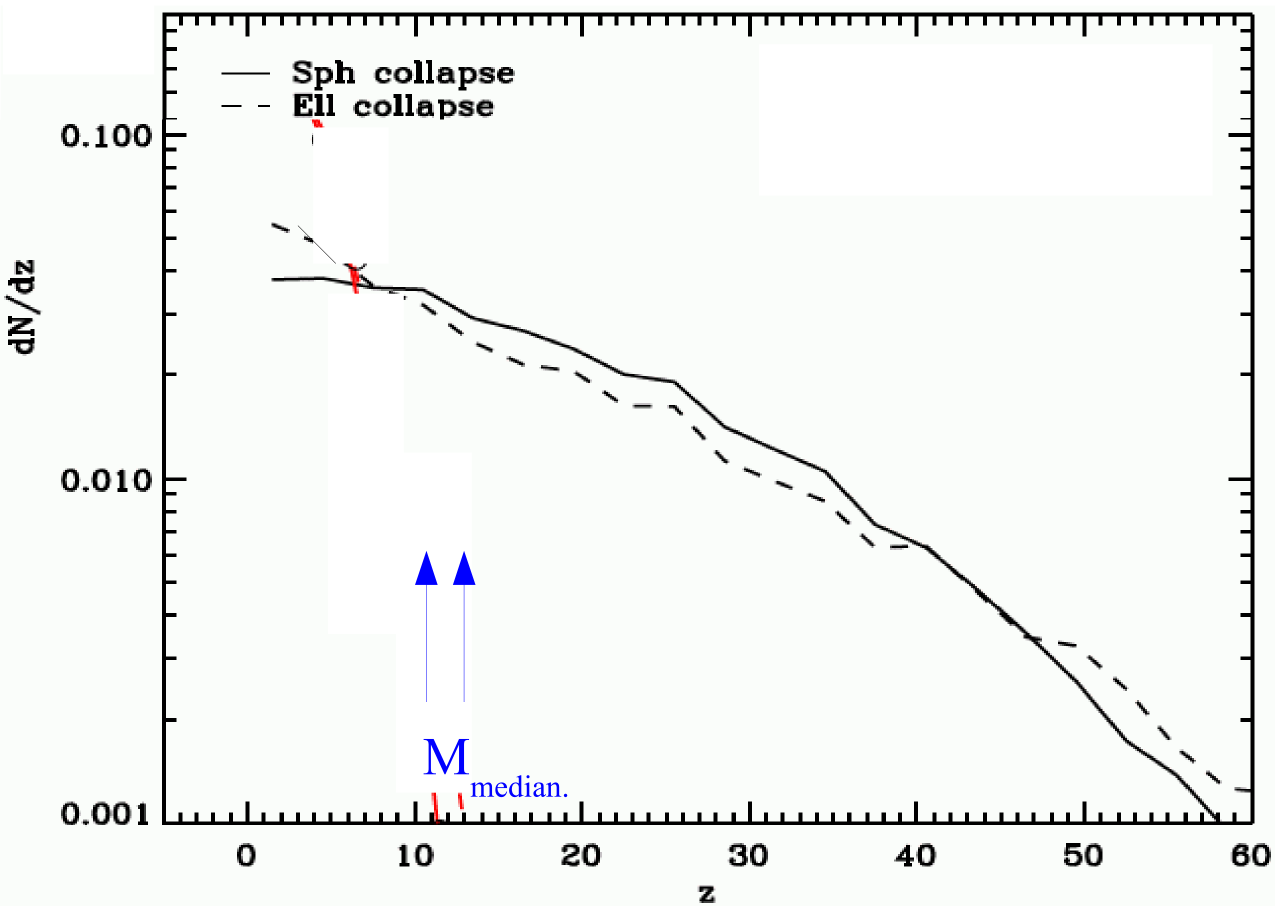
For 10% of the mass the first halo has $M > 10^7 M_\odot$

Direct simulation will become possible around 2035

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 & White 2009



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

The median is z = 10 to 13

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

For 1% at z > 55

EPS statistics for the standard ΛCDM cosmology

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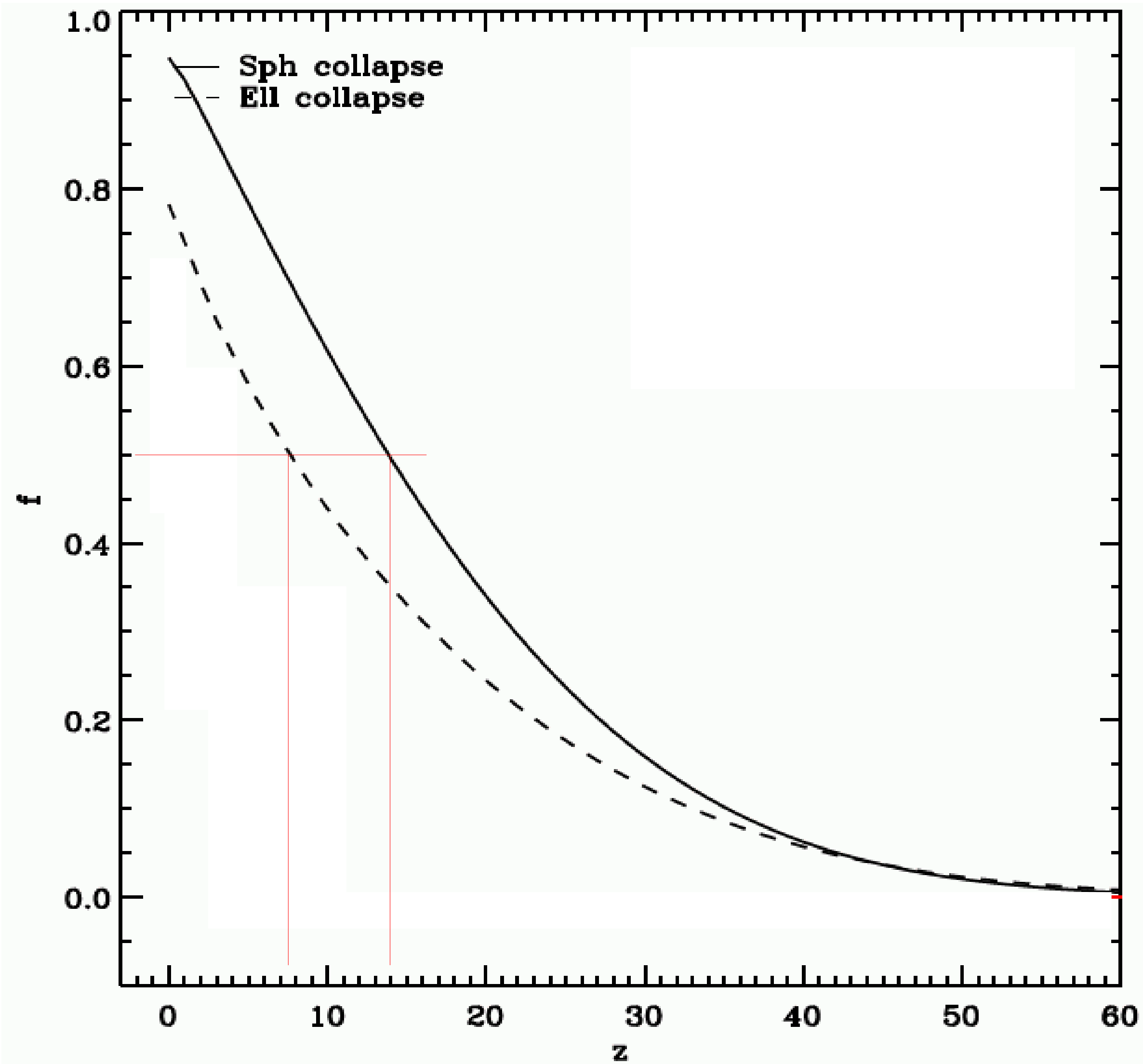
Angulo & White 2009



Total mass fraction in halos

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

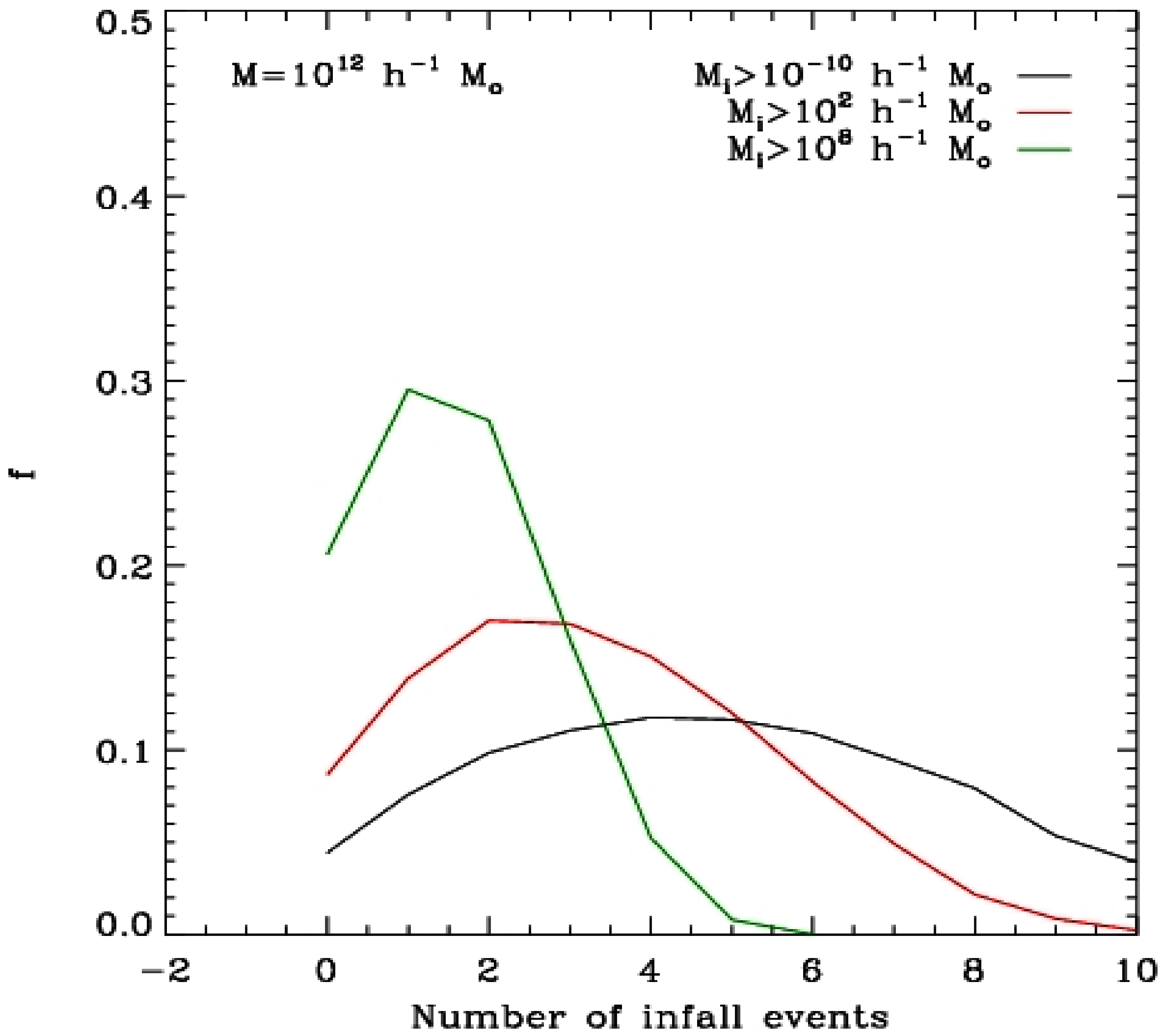
Beyond z = 50 almost all the mass is diffuse

Only at z < 13 (Sph) or z<8 (Ell) is most of the dark matter in halos

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 & White 2009



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 $z = 13$

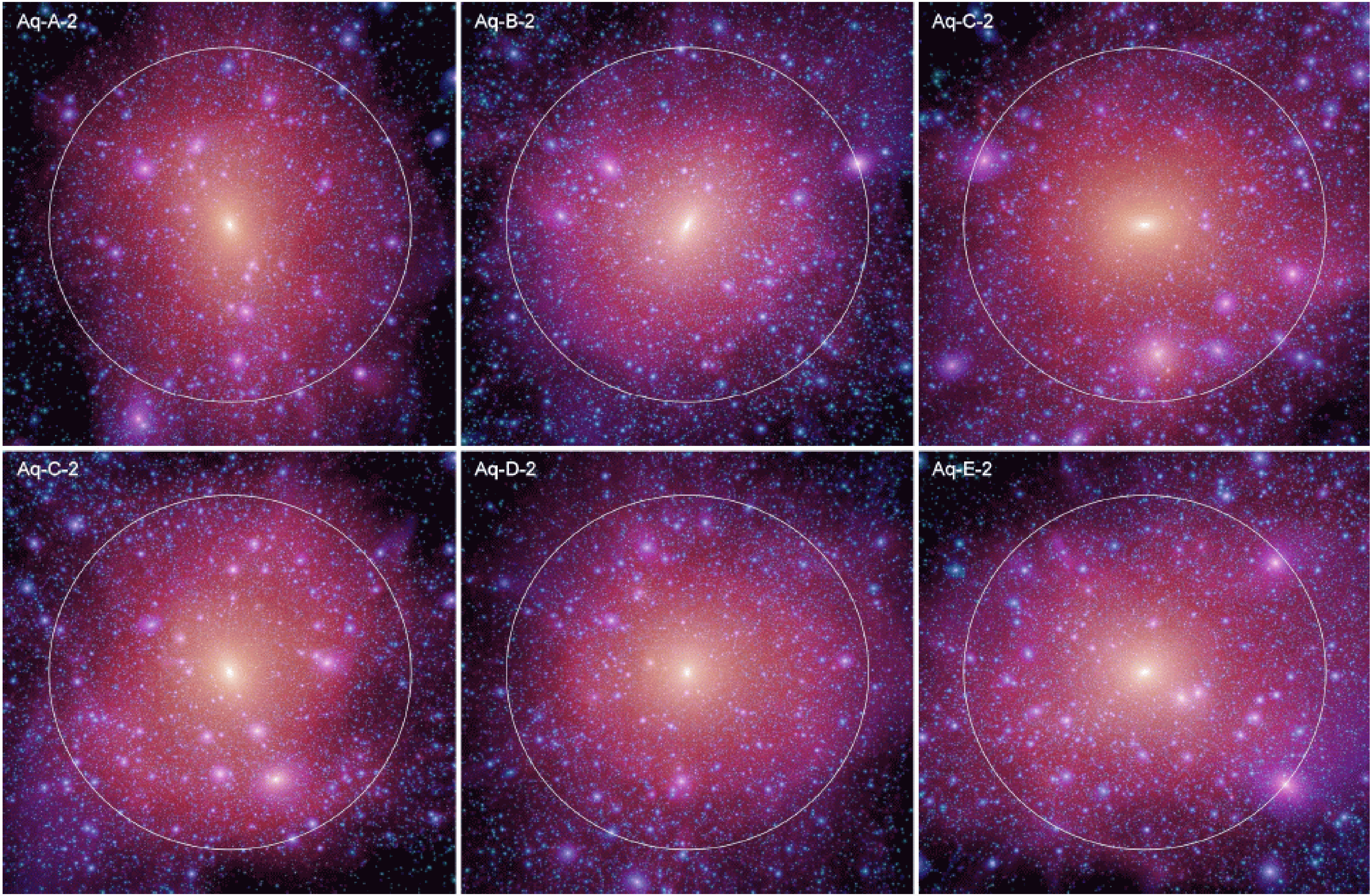
- Halo growth occurs mainly by accretion of much smaller halos

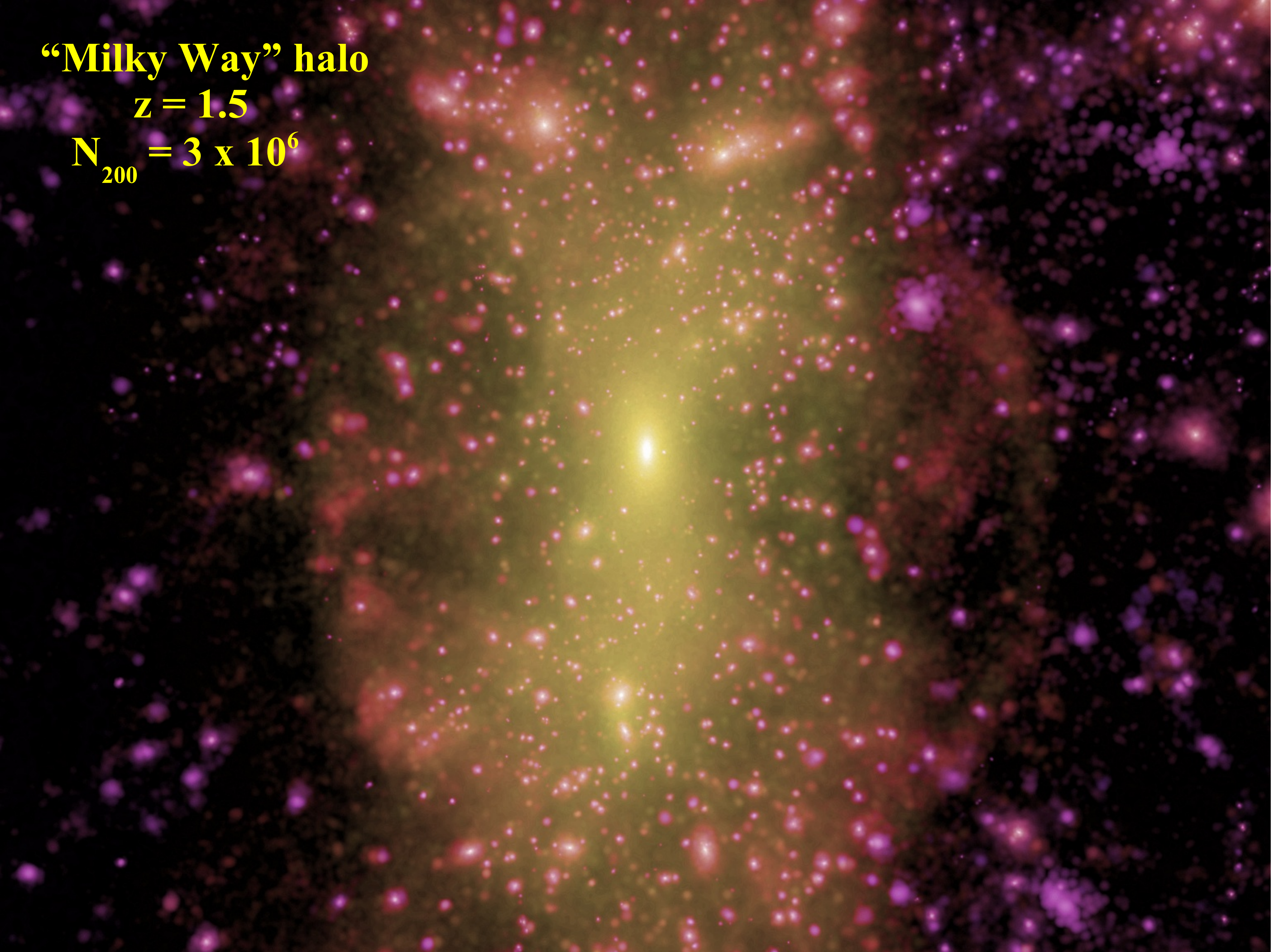
- There are typically few (~5) “generations” of halos, only 1 or 0 predecessors with $M > 10^8 M_\odot$ for most particles in a “MW” halo

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

The Aquarius halos

Springel et al 2008



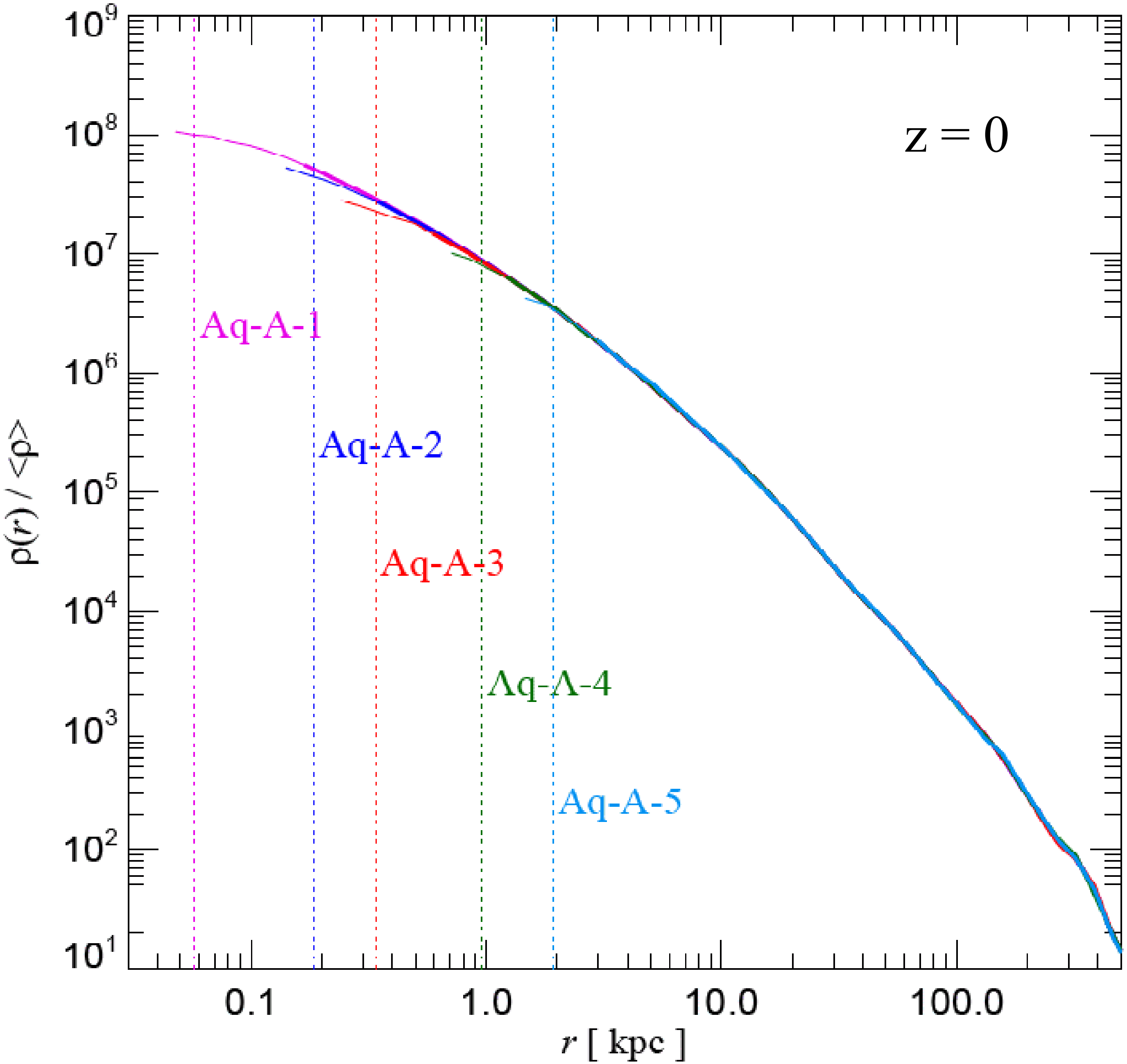

"Milky Way" halo
z = 1.5
$N_{200} = 3 \times 10^6$


"Milky Way" halo
z = 1.5
N200 = 94 x 10^6


"Milky Way" halo
z = 1.5
N200 = 750 x 10^6

How well do density profiles converge?

Aquarius Project: Springel et al 2008



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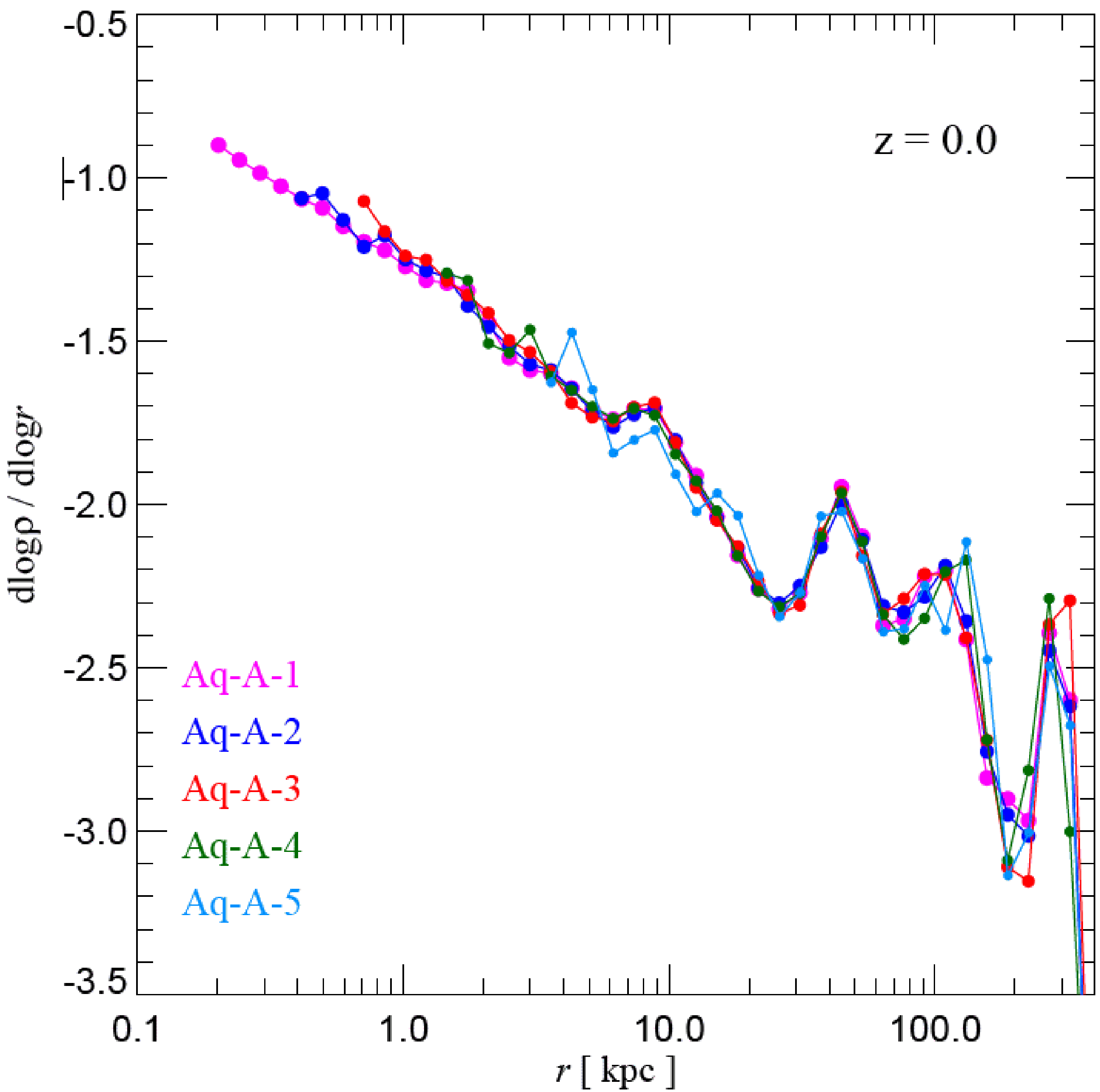
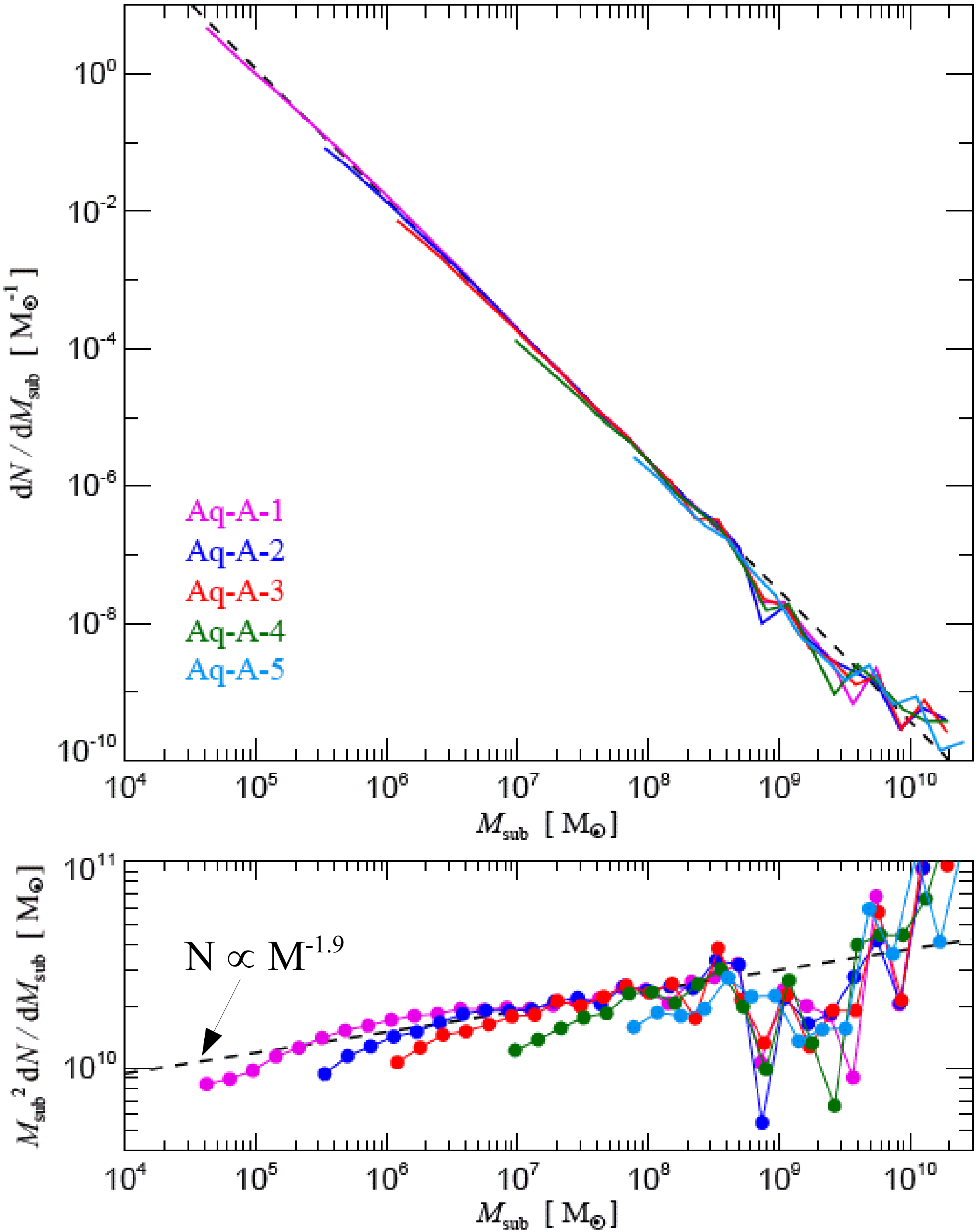
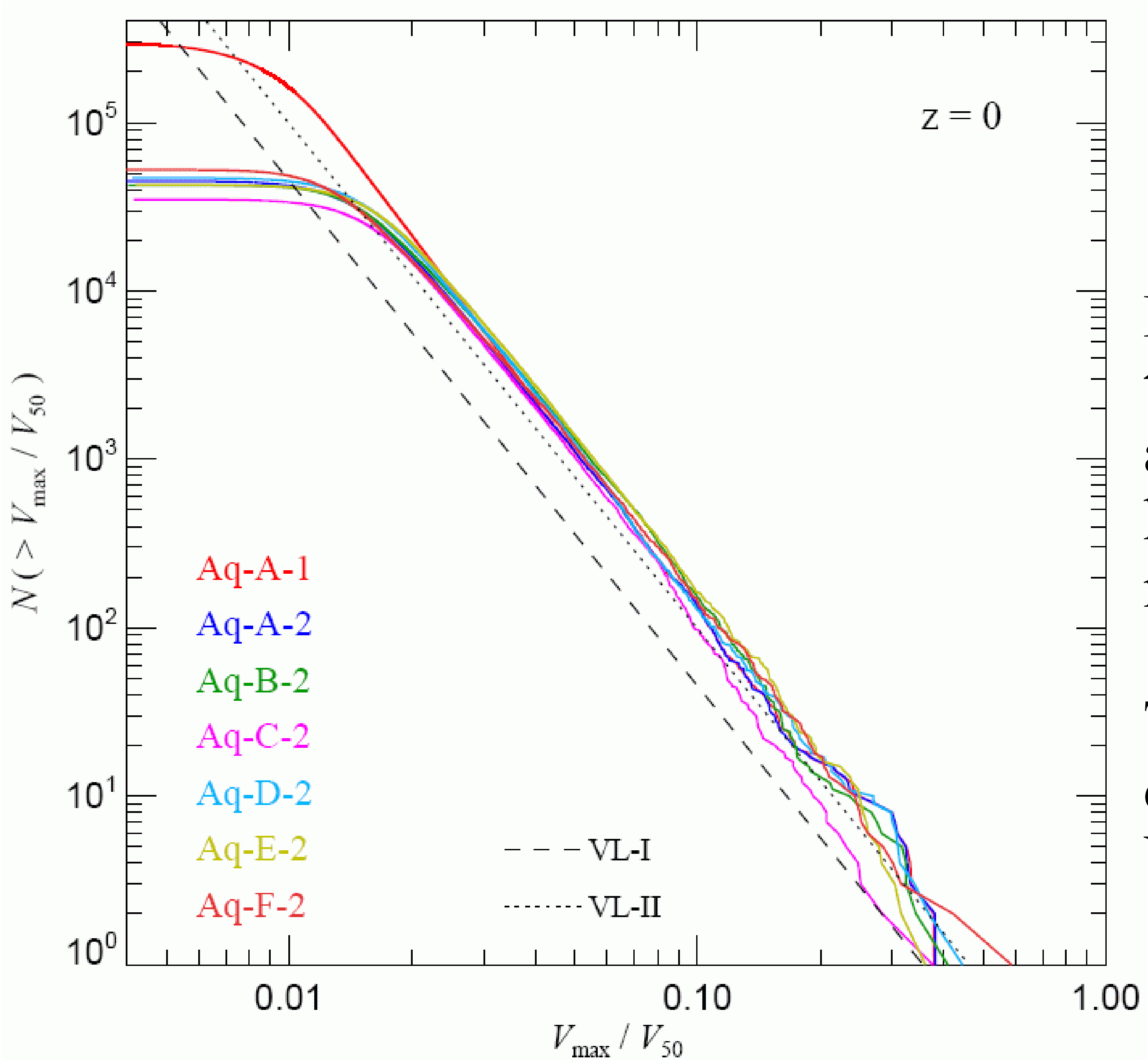




How well does substructure converge?

Springel et al 2008

How uniform are subhalo populations?

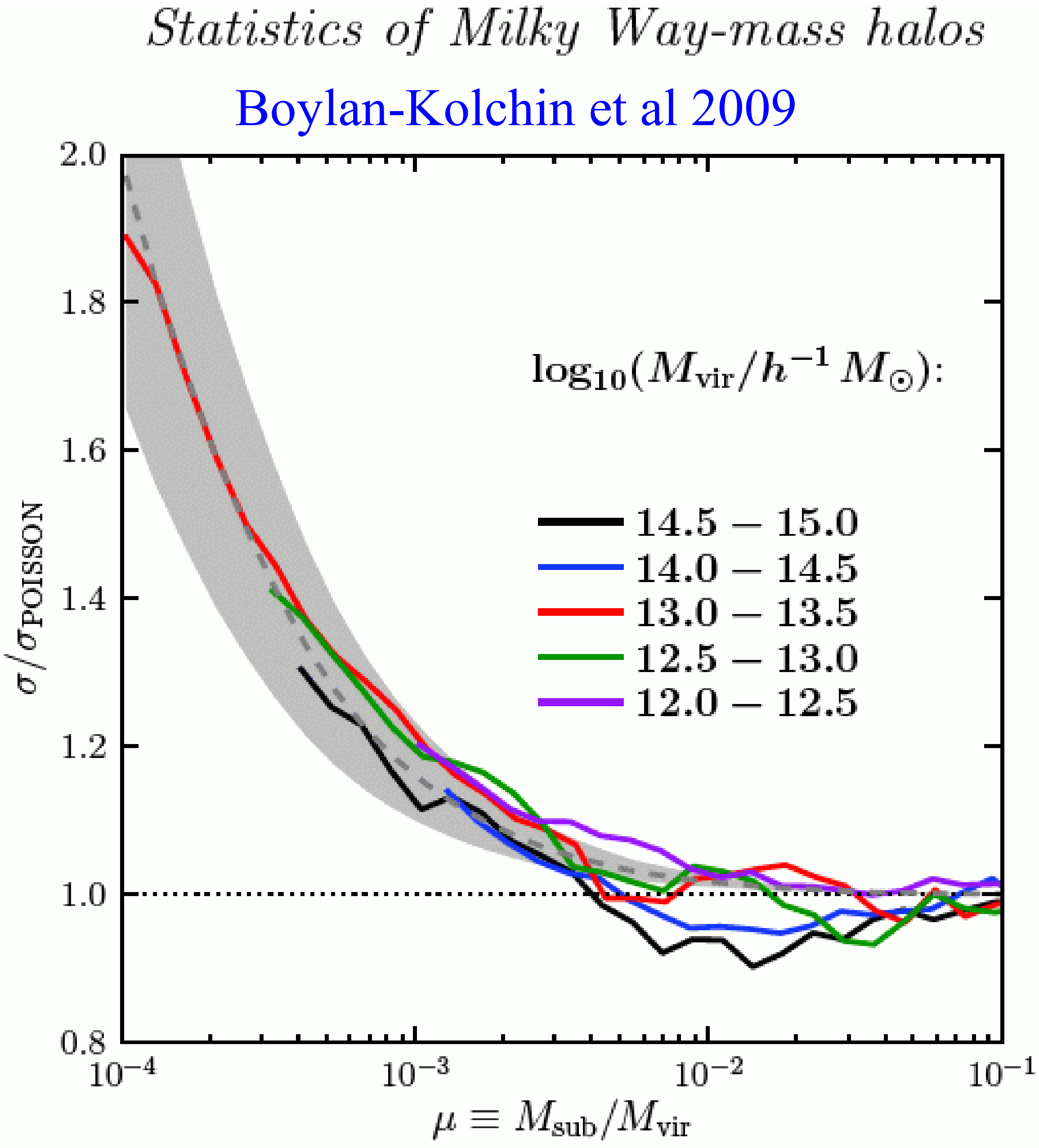


Springel et al 2008

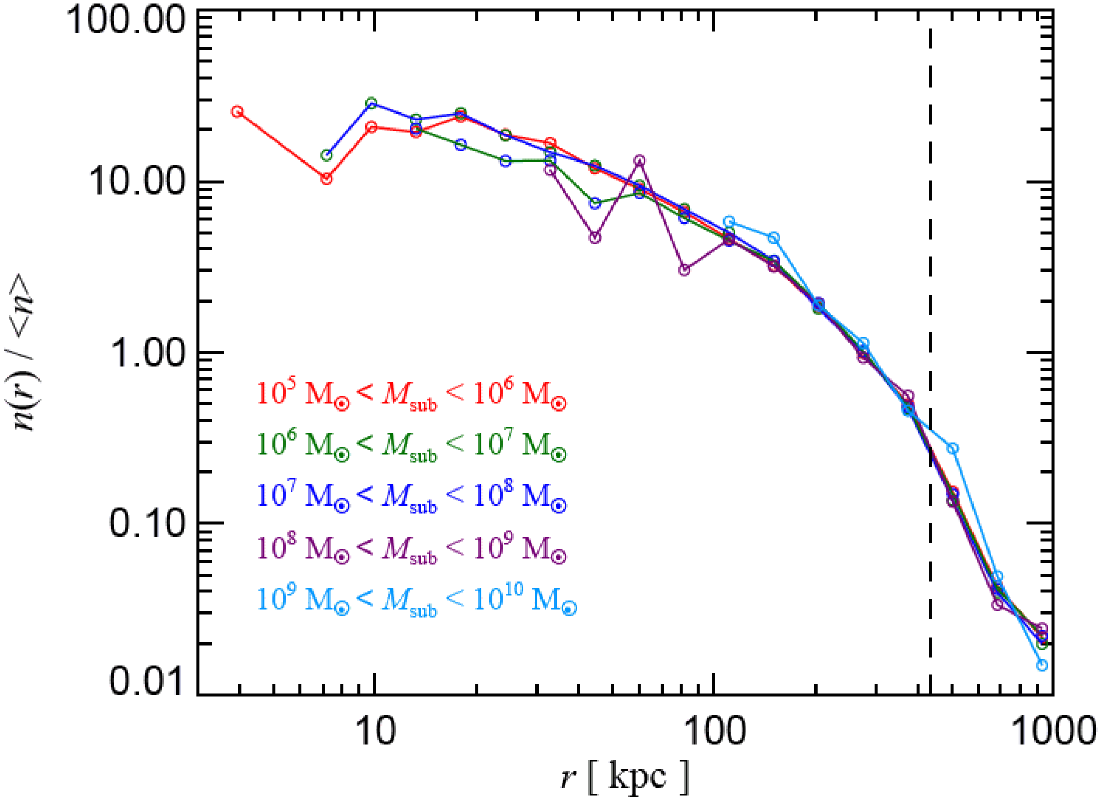
For the six Aquarius halos, the scatter in subhalo abundance is Poisson at high mass and ~20% at low mass

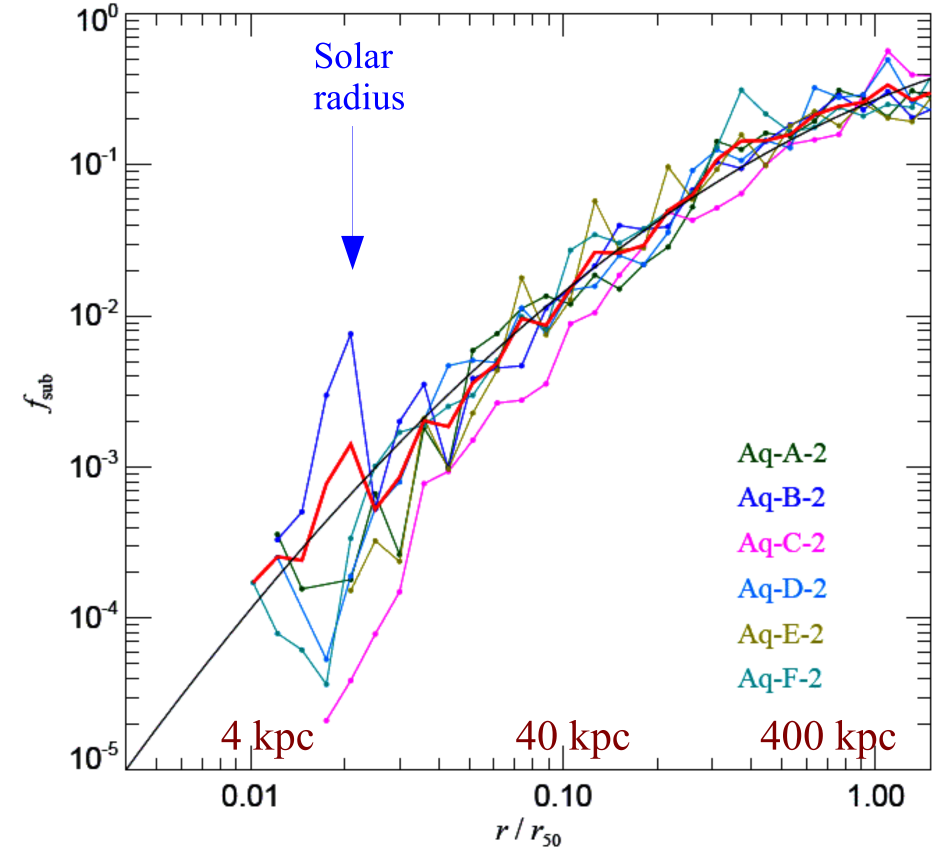
The Via Lactea simulations differ significantly, at least VL-I

Intrinsic scatter in halo occupation numbers

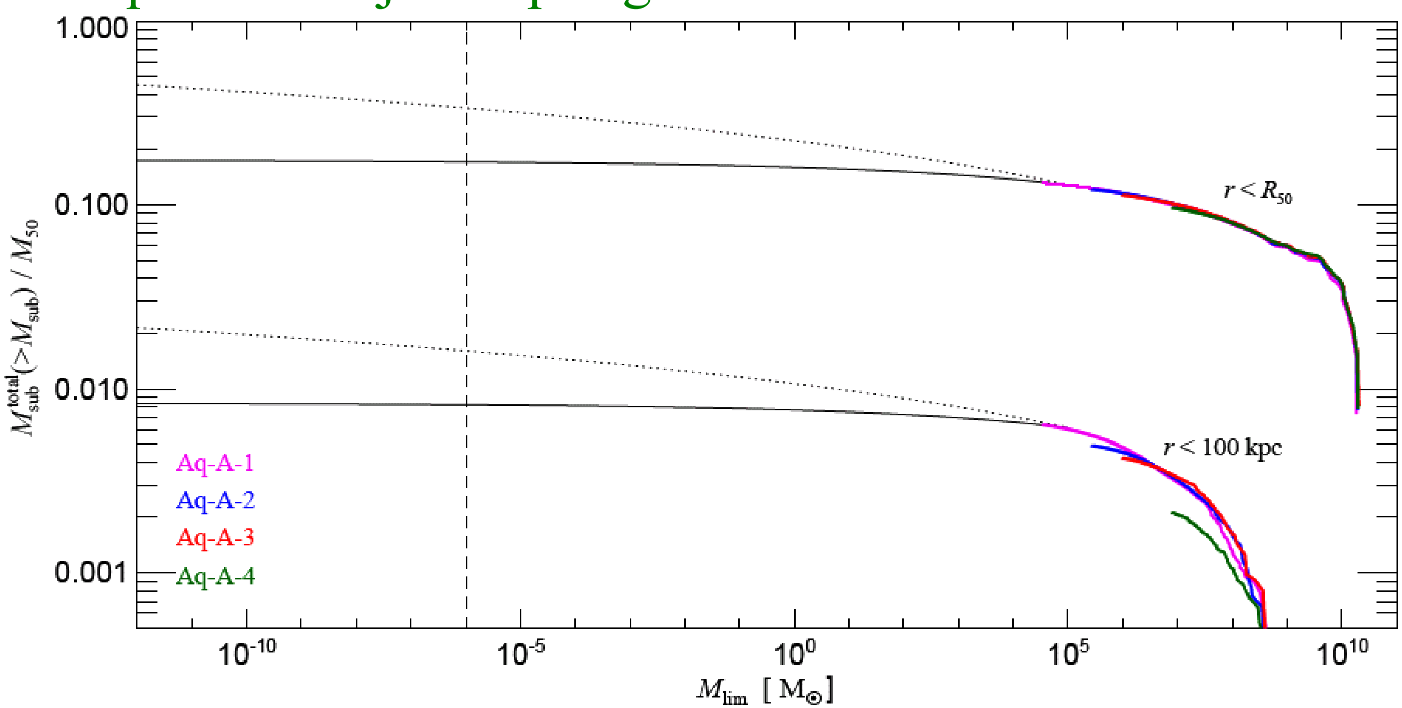


Scatter in the number of subhalos with $M_{sub} > \mu\, M_{halo}$ is Poisson for $\mu > 0.005$ but is ~18% for $\mu < 0.001$





Aquarius Project: Springel et al 2008

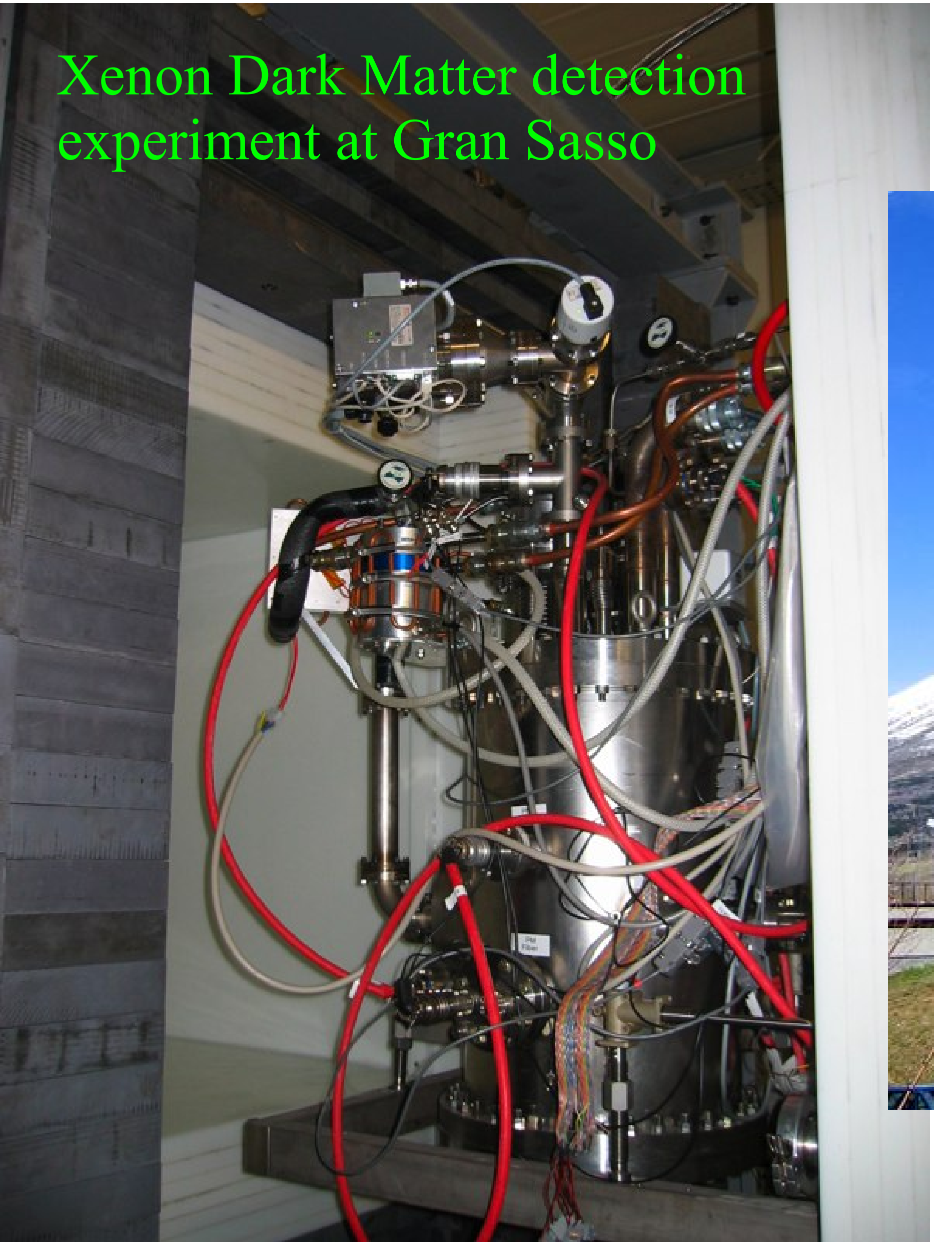


- All mass subhalos are similarly distributed
- A small fraction of the inner mass in subhalos
- <<1% of the mass near the Sun is in subhalos

Substructure: conclusions

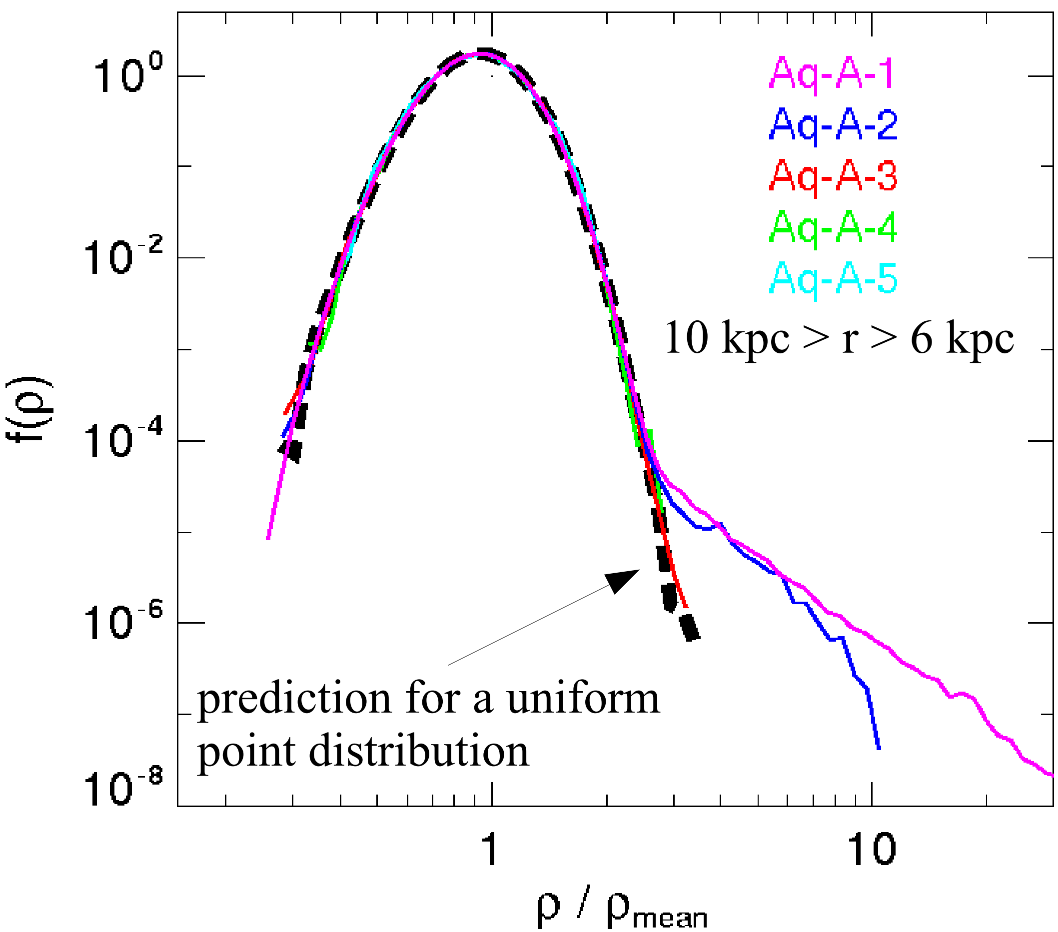
- Substructure is primarily in the outermost parts of halos
- The radial distribution of subhalos is almost mass-independent
- Subhalo populations scale (almost) with the mass of the host
- The total mass in subhalos converges only weakly at small m
- Subhalos contain a very small mass fraction in the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

Maybe Dark Matter can be detected in a laboratory



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

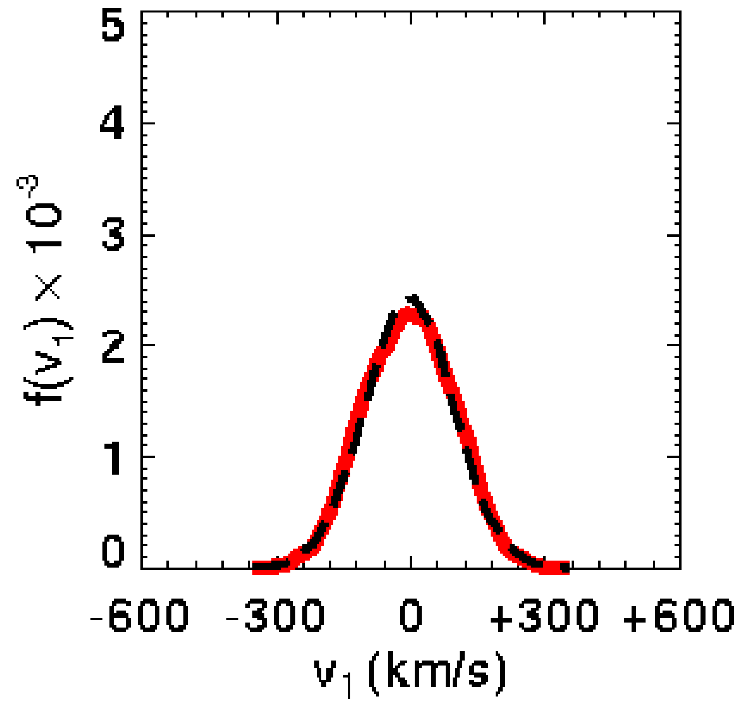
Vogelsberger et al 2008

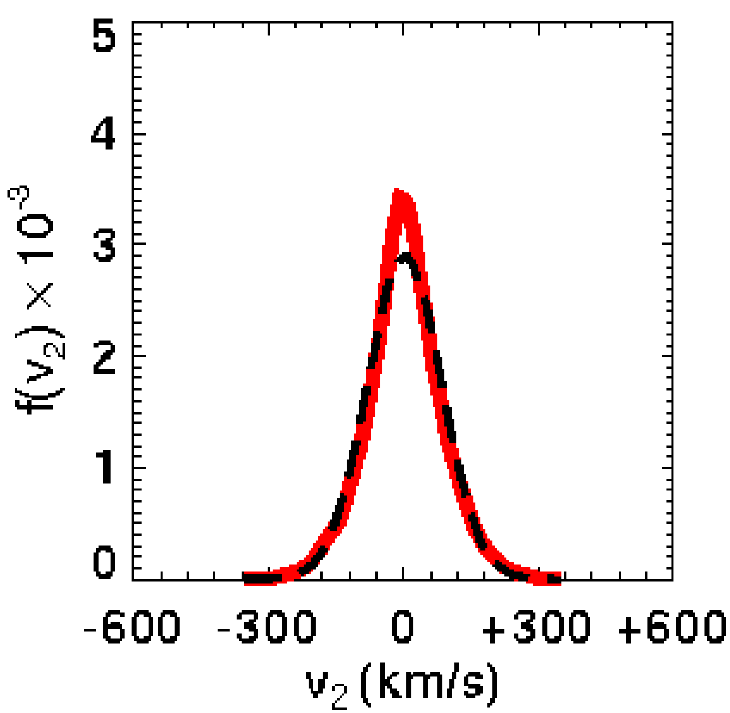


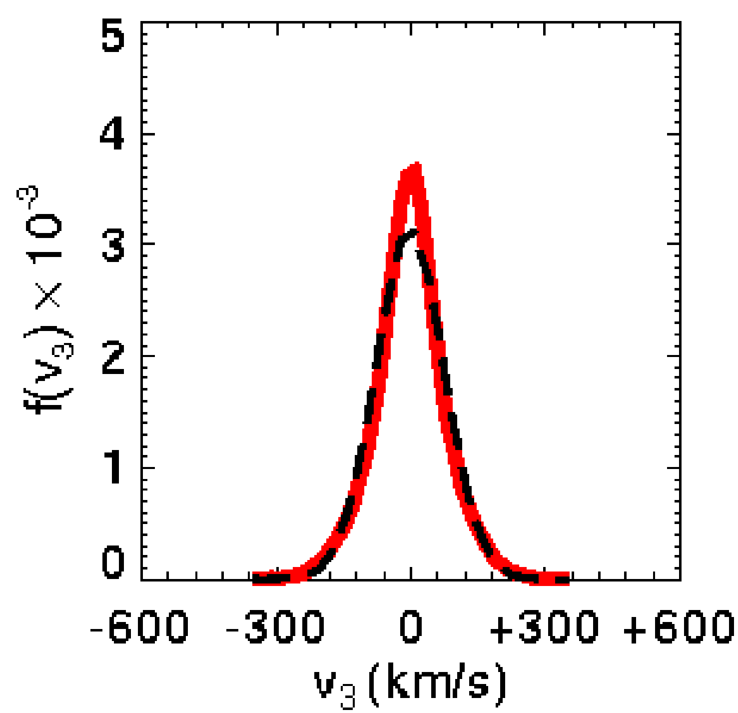
- Estimate a density ρ at each point by adaptively smoothing using the 64 nearest particles
- Fit to a smooth density profile stratified on similar ellipsoids
- The chance of a random point lying in a substructure is $< 10^{-4}$
- The *rms* scatter about the smooth model for the remaining points is only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

Local velocity distribution

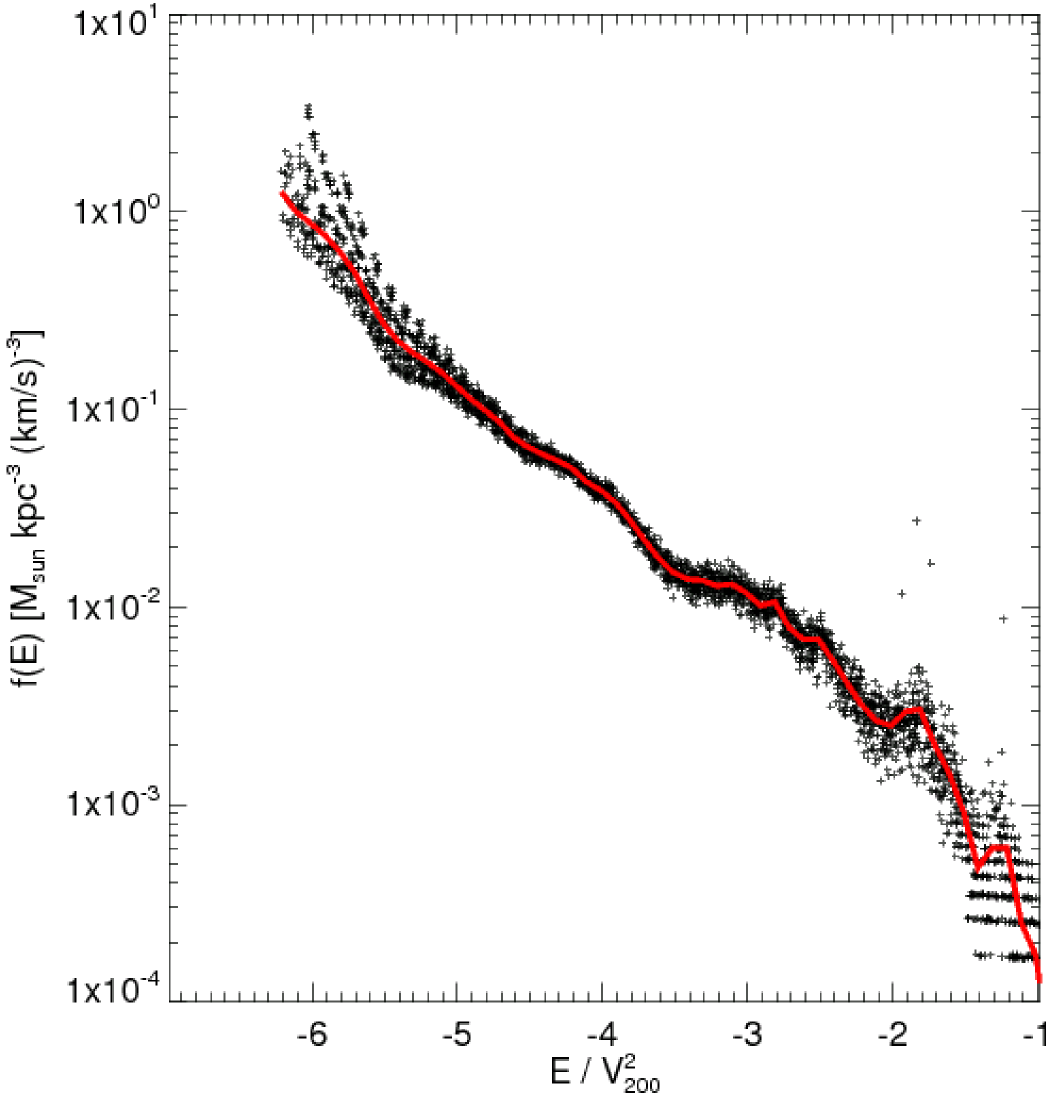
- Velocity histograms for particles in a typical $(2\text{kpc})^3$ box at R = 8 kpc
- Distributions are smooth, near-Gaussian and different in different directions
- No individual streams are visible







Energy space features – fossils of formation



The energy distribution within $(2\ \mathrm{kpc})^3$ 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

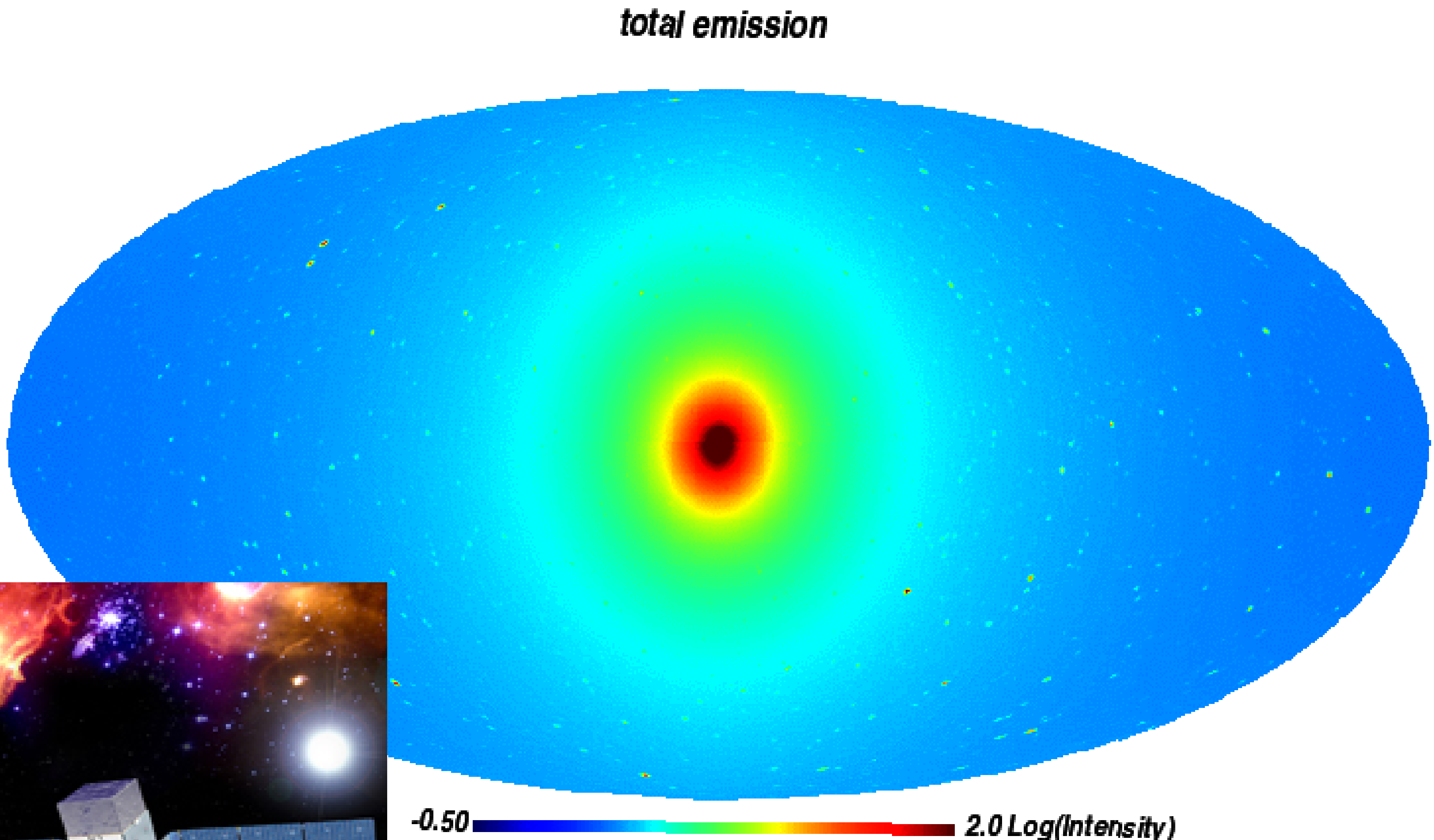
Conclusions for direct detection experiments

- 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

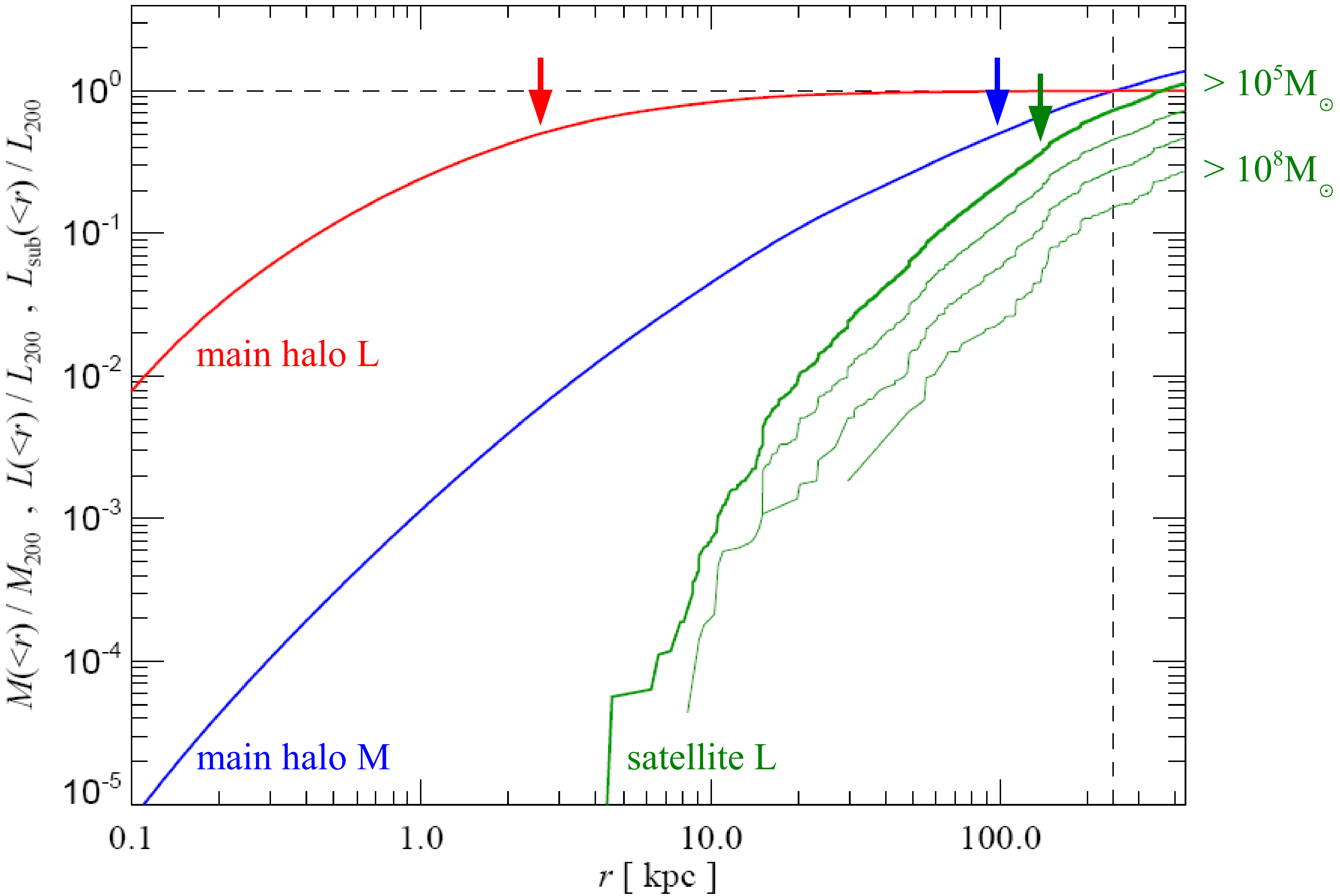
→ Dark matter astronomy



Maybe the annihilation of Dark Matter will be seen by Fermi?

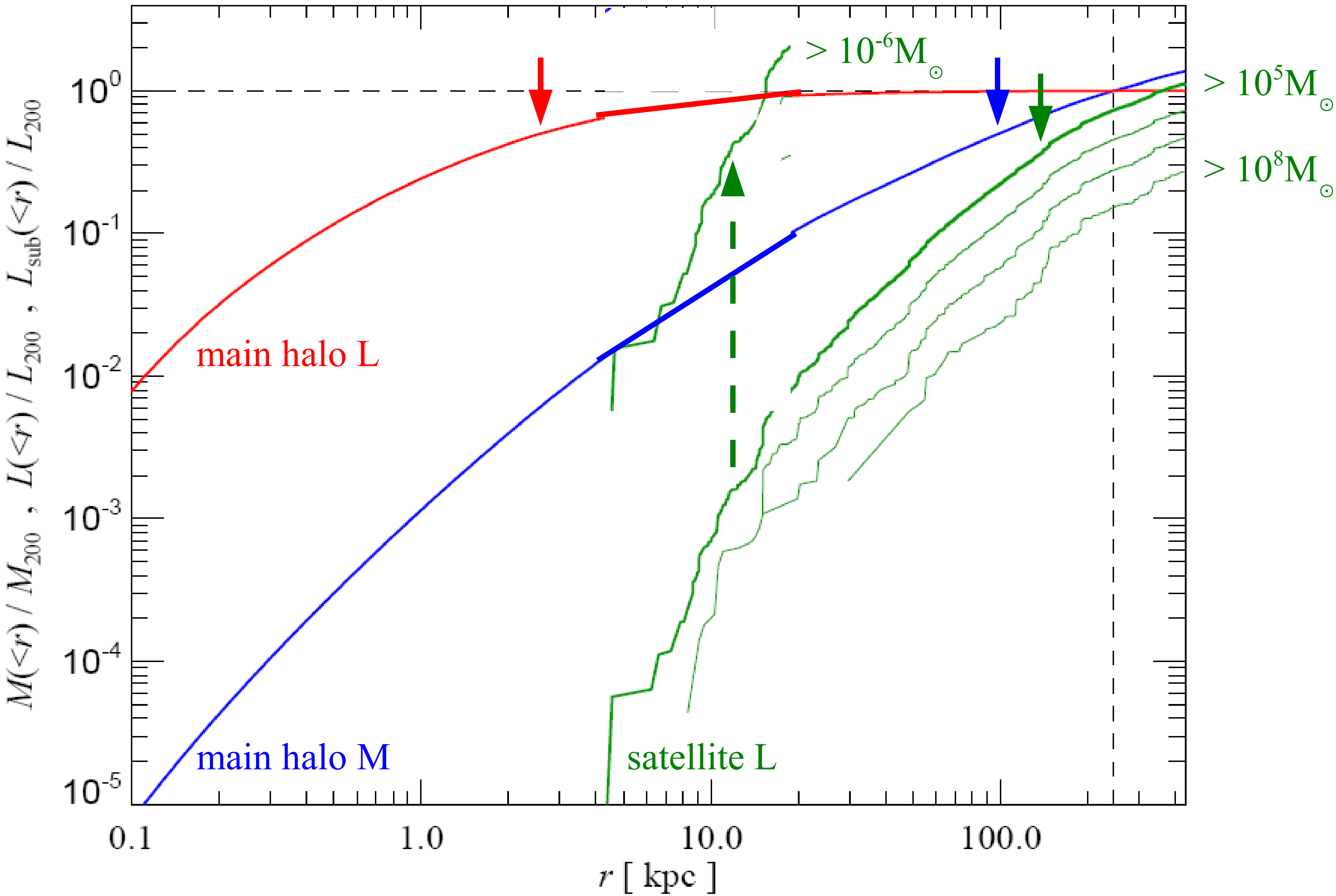
Mass and annihilation radiation profiles of a MW halo

Springel et al 2008

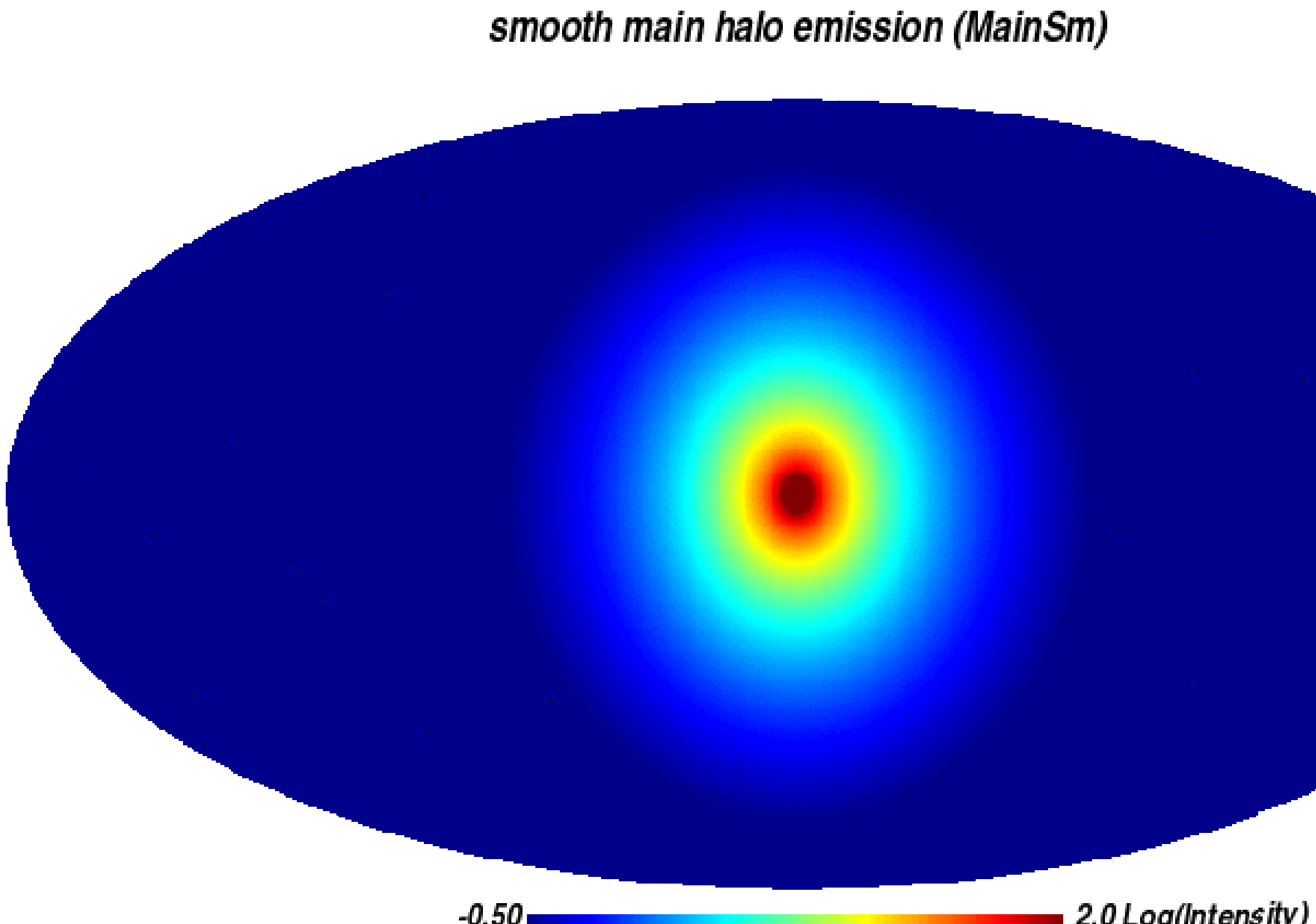


Mass and annihilation radiation profiles of a MW halo

Springel et al 2008



Milky Way halo seen in DM annihilation radiation



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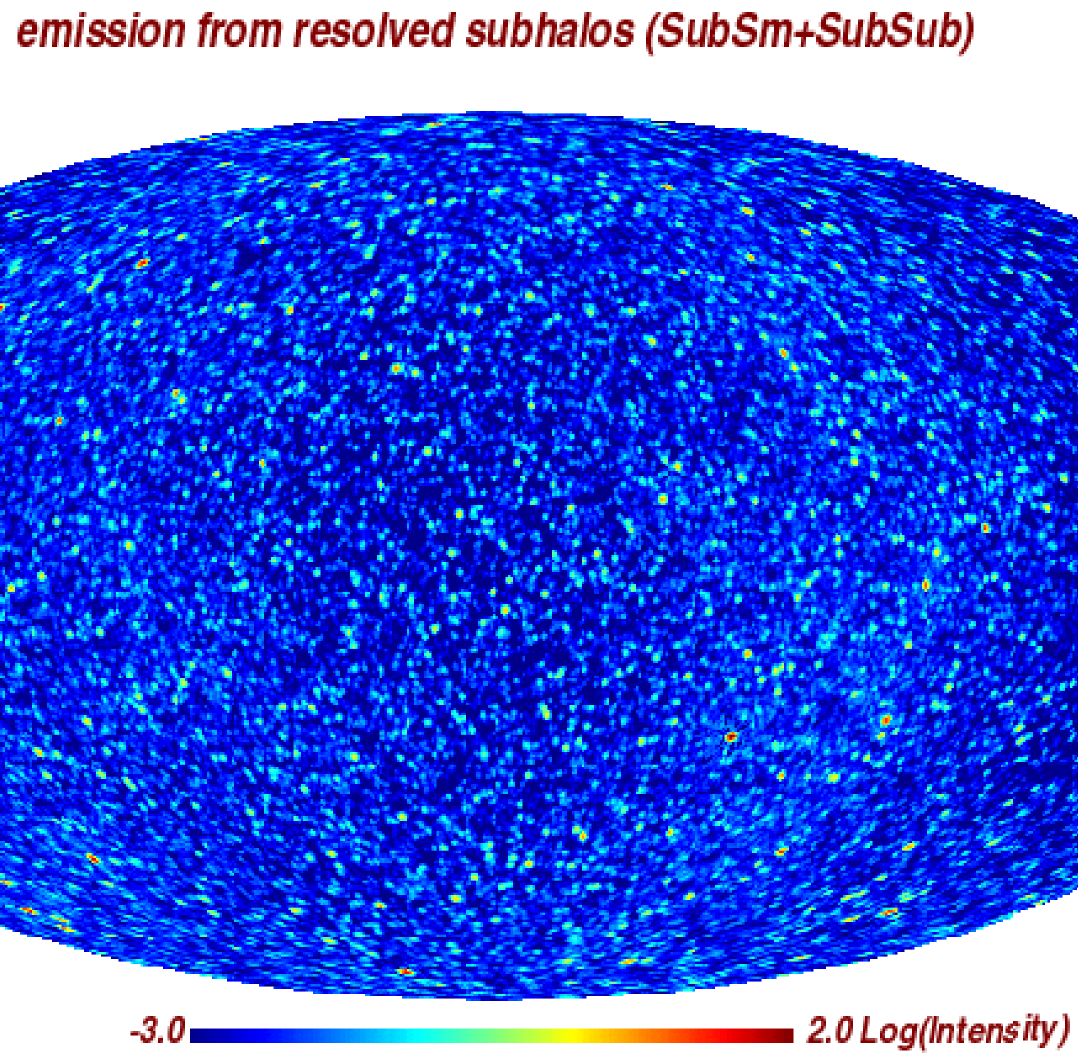

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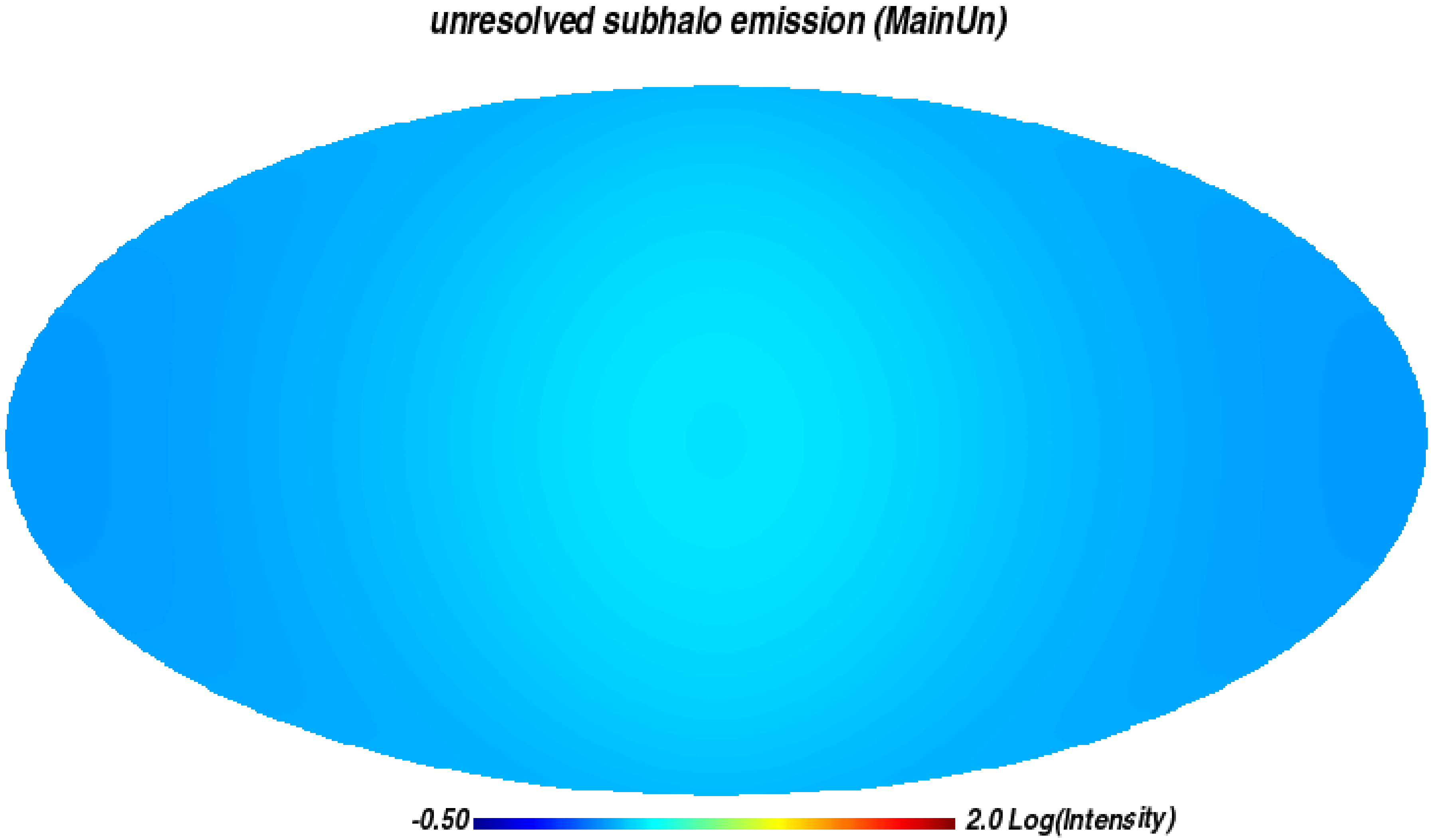

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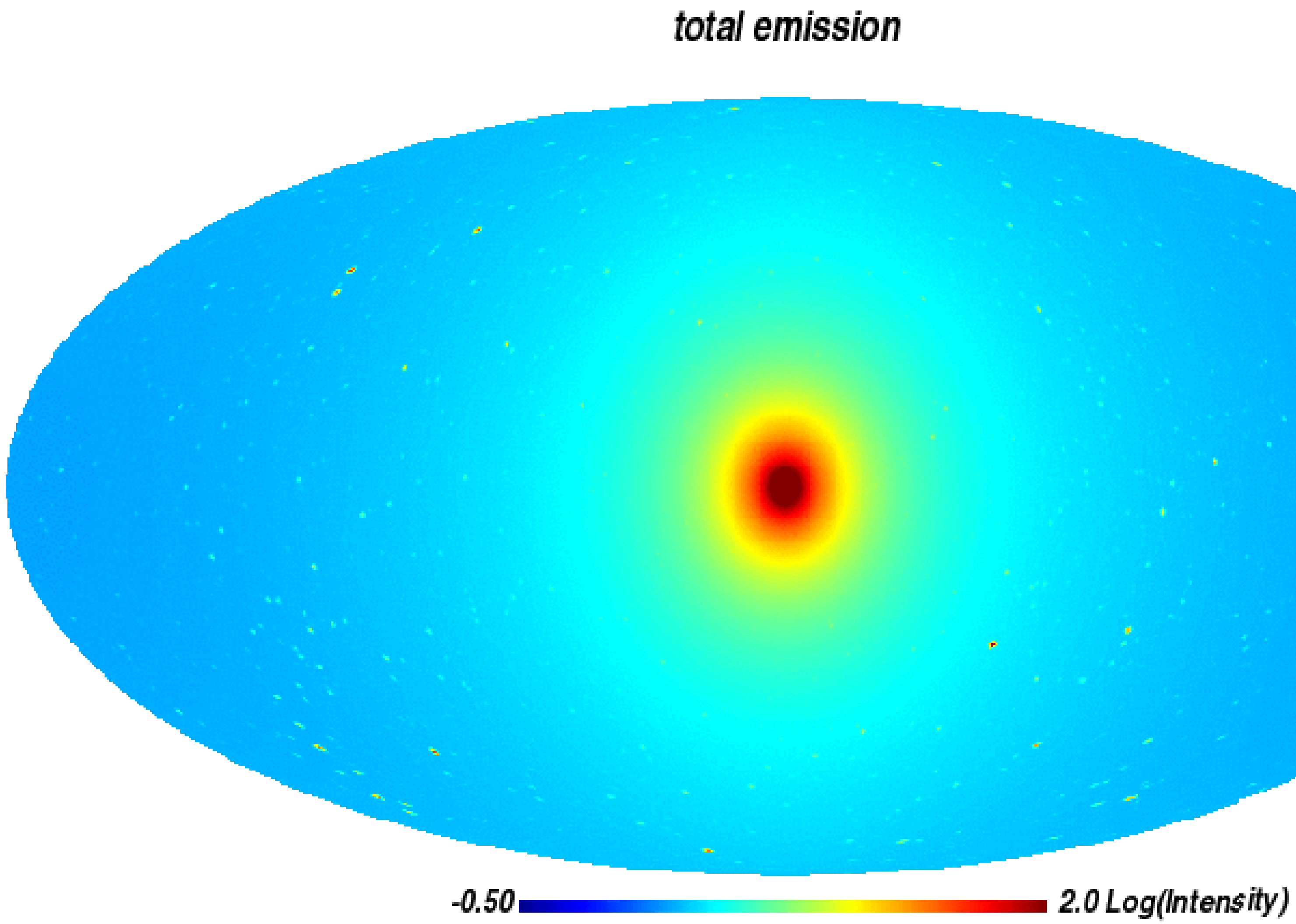
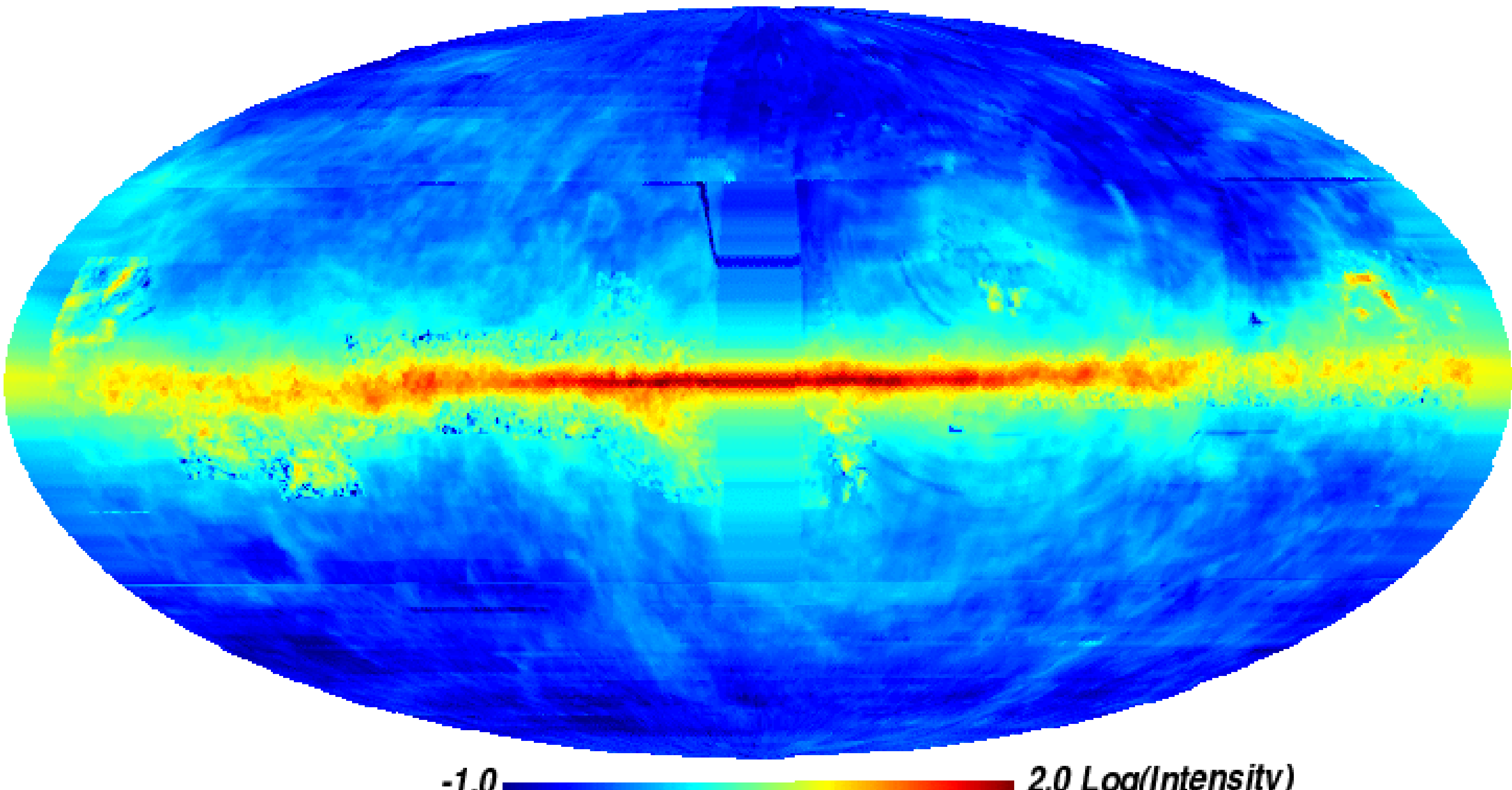


GALPROP, optimized

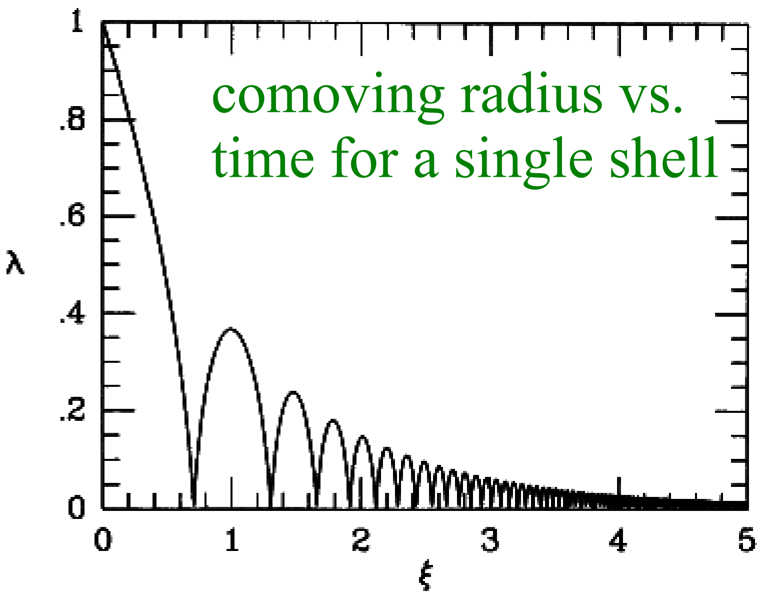


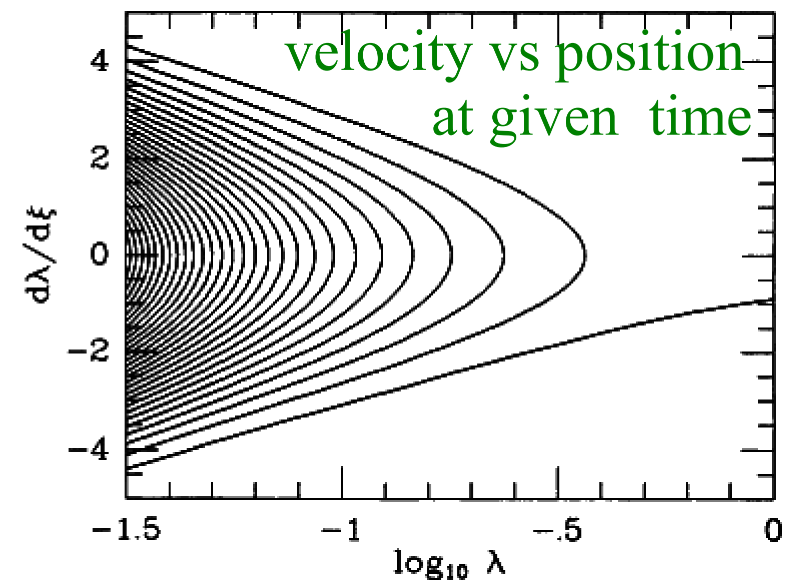
Conclusions about clumping and annihilation

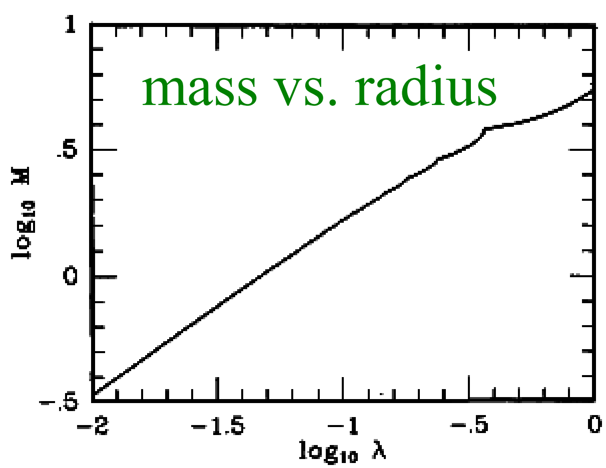
- Subhalos increase the MW's total flux within 250 kpc by a factor of 230 as seen by a distant observer, but its flux on the sky by a factor of only 2.9 as seen from the Sun
- The luminosity from subhalos is dominated by small objects and is nearly uniform across the sky (contrast is a factor of ~1.5)
- 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

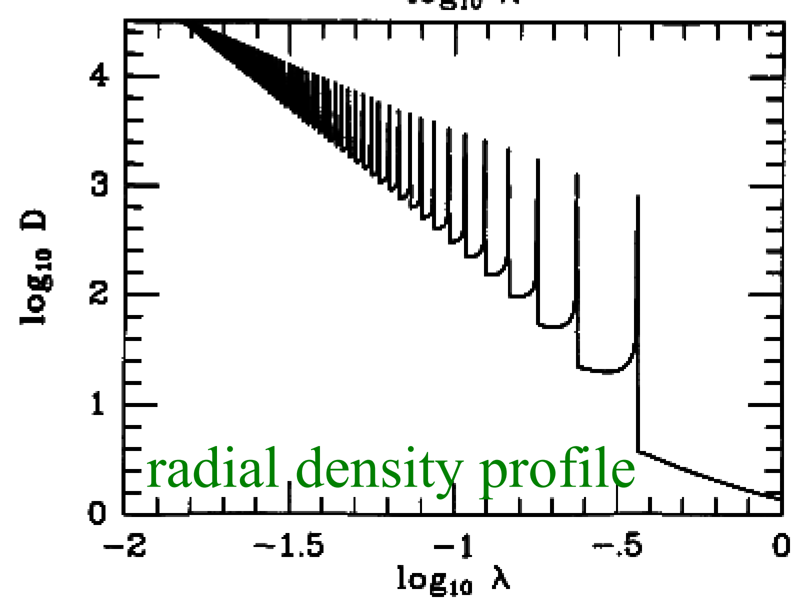
Caustics in self-similar spherical halo growth

Bertschinger 1985

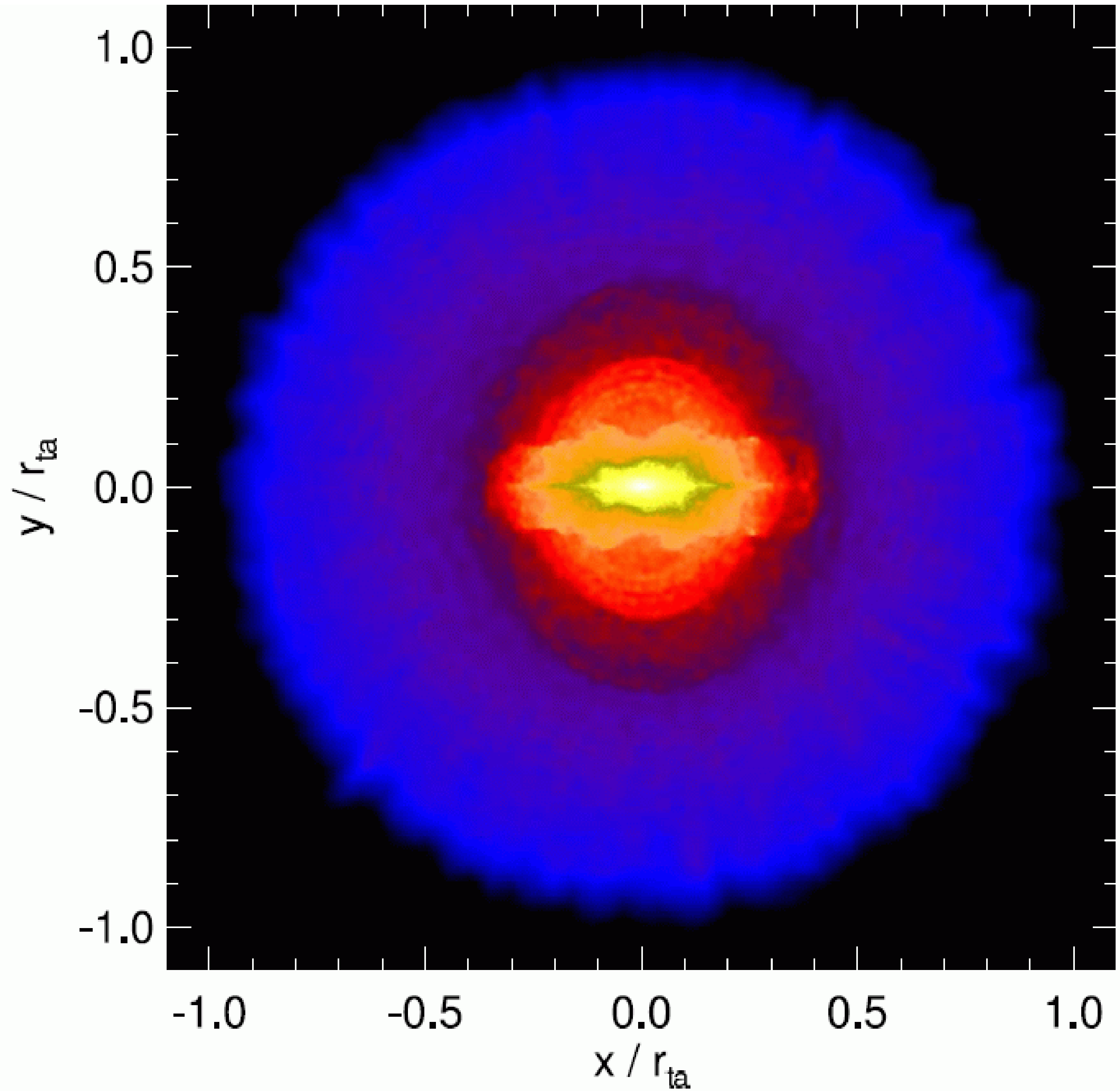








Simulation from self-similar spherical initial conditions

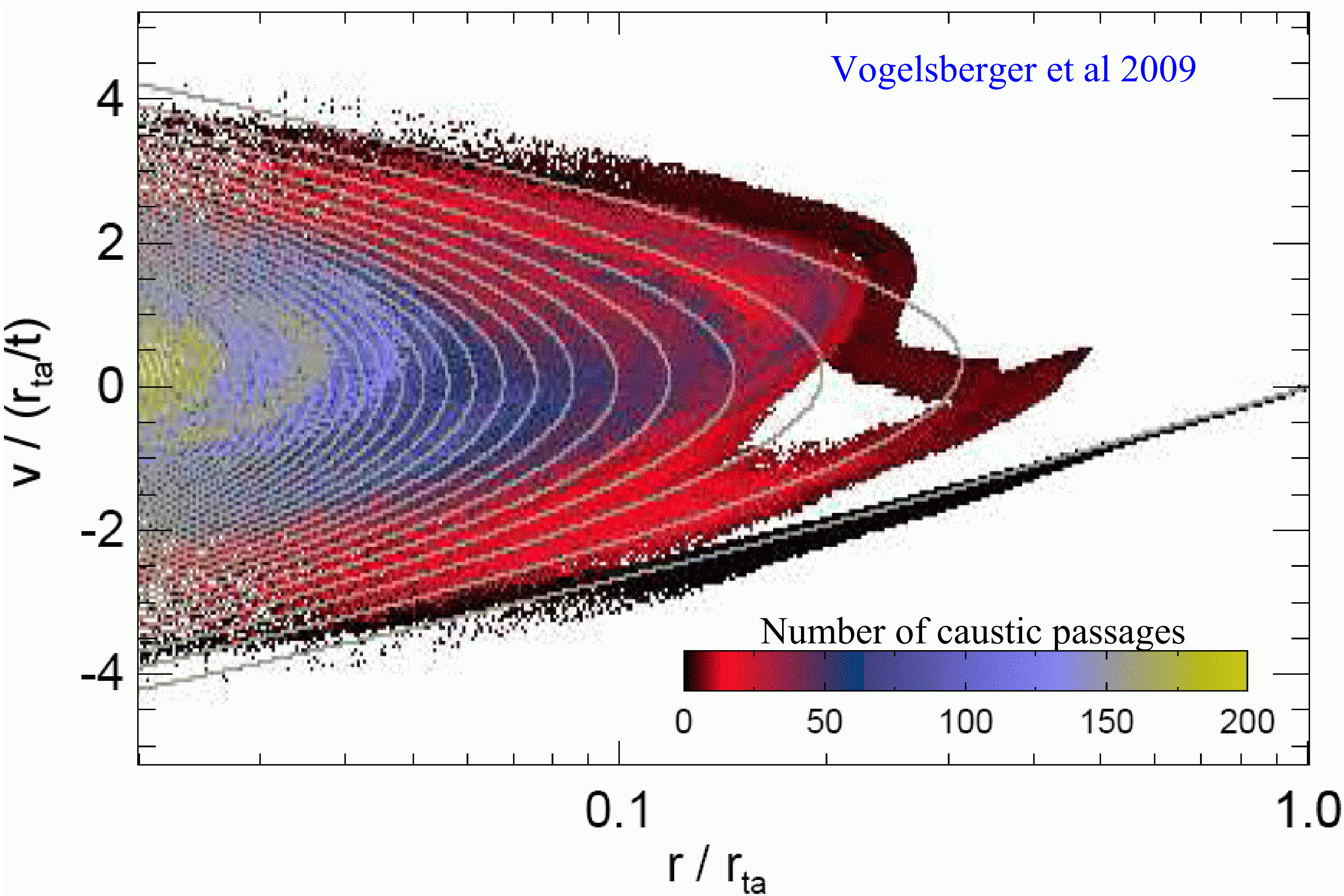


Vogelsberger et al 2009

The radial orbit instability leads to a system which is strongly prolate in the inner nonlinear regions

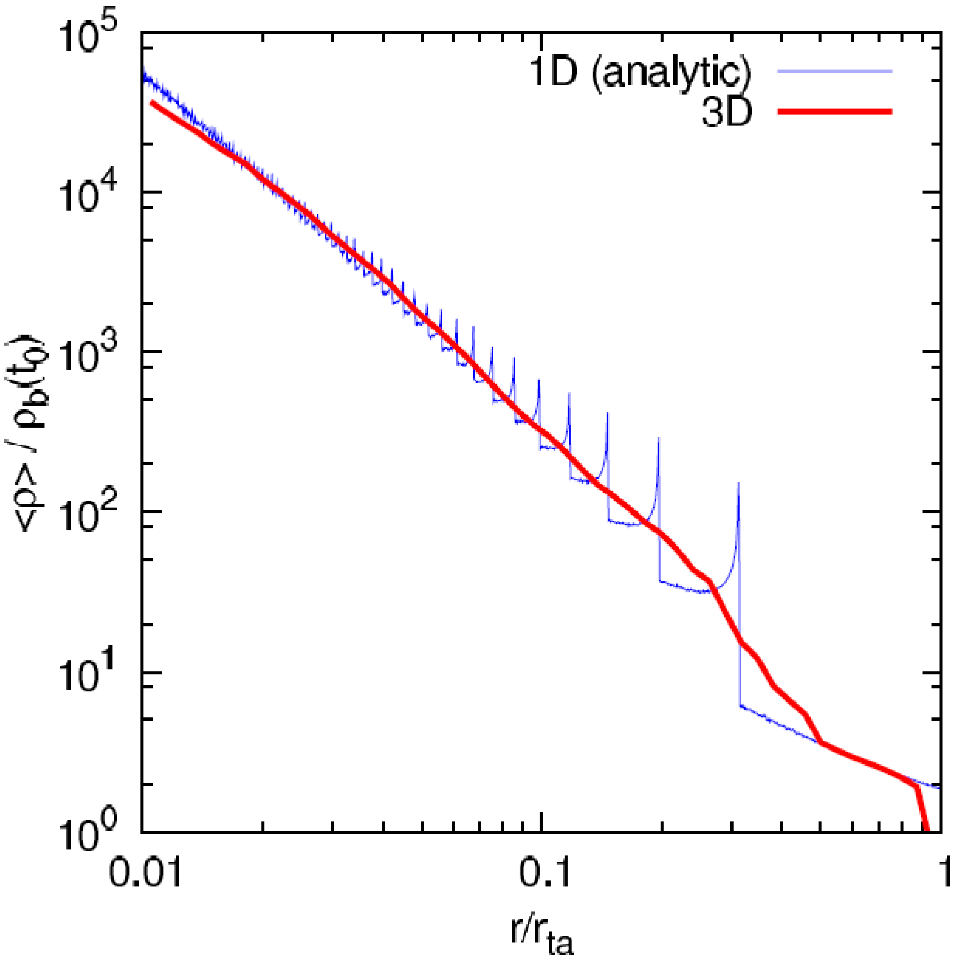
Simulation from self-similar spherical initial conditions

Geodesic deviation equation → phase-space structure local to each particle

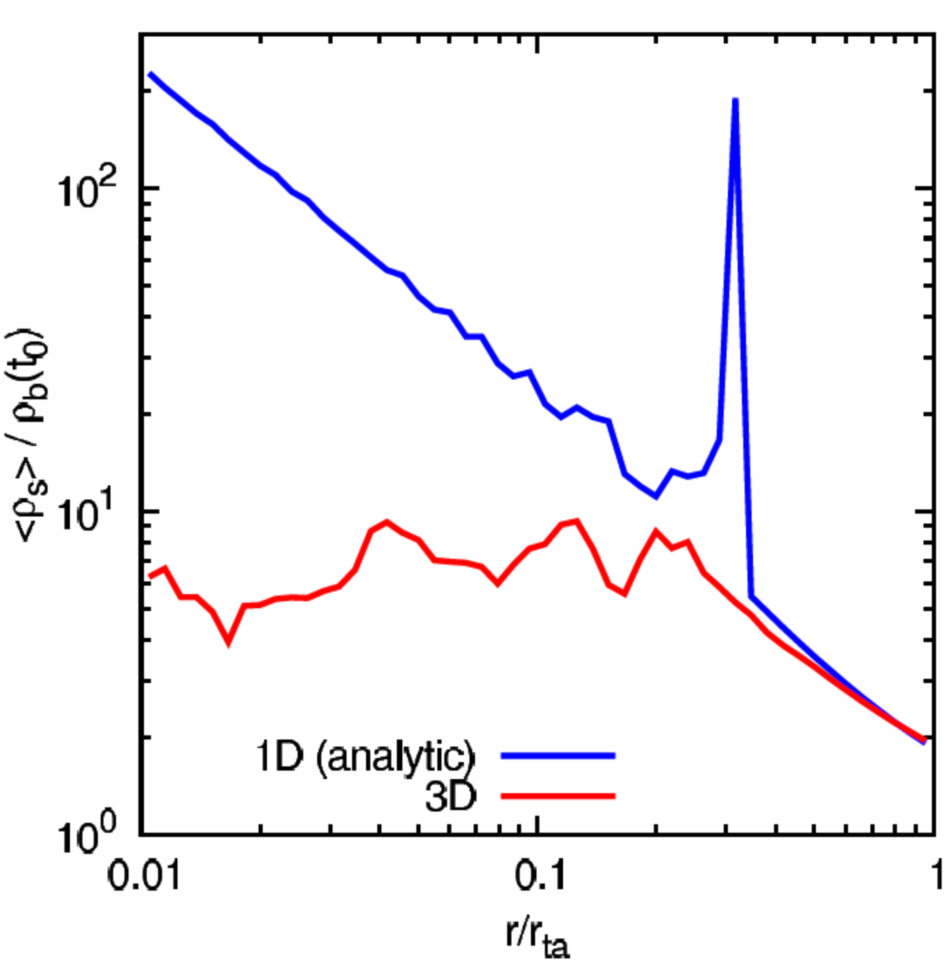


Simulation from self-similar spherical initial conditions

Vogelsberger et al 2009



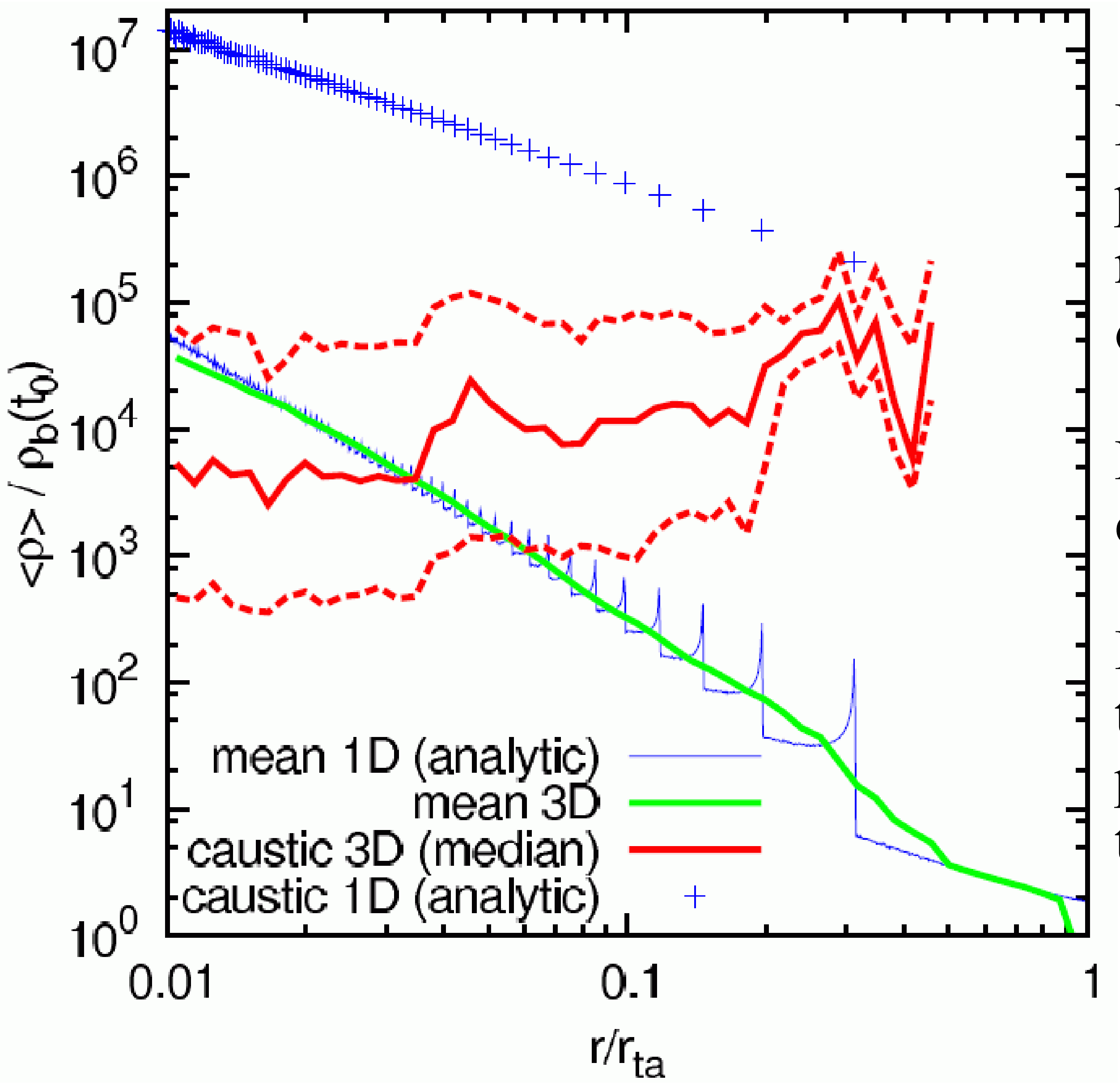
Radial density profile



Median density of streams associated with individual particles

Simulation from self-similar spherical initial conditions

Vogelsberger et al 2009

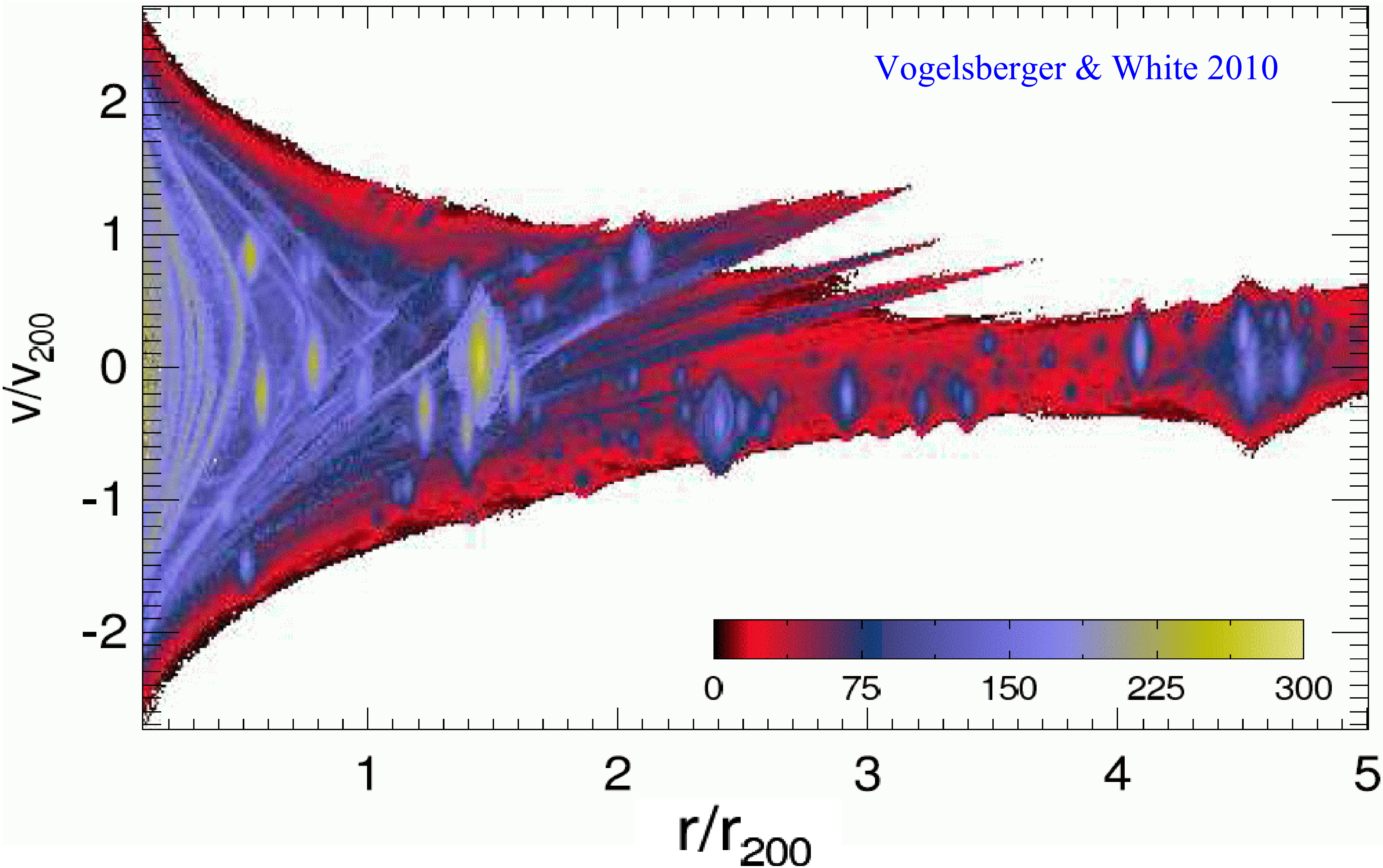


Maximum density at caustic passage assuming a standard neutralino WIMP with a mass of 100 GeV

Median and quartiles plotted at each radius for the simulation

Except for the outermost caustic the maximum density at caustic passage is lower in 3d than in the similarity solution

Caustic crossing counts in a ΛCDM Milky Way halo



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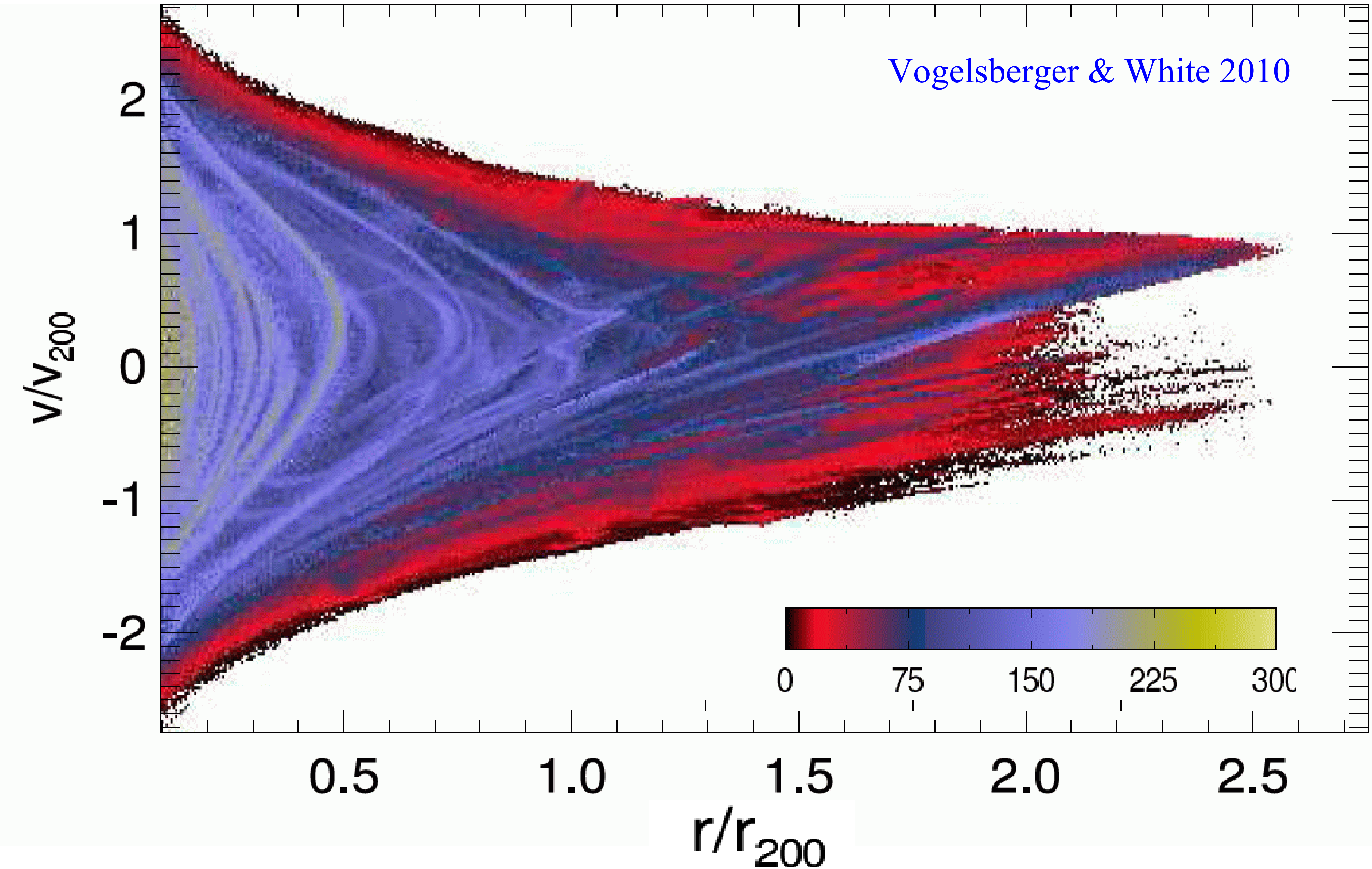

Conclusions about caustics and annihilation

- Caustics are less significant in realistic three-dimensional situations than in one-dimensional similarity solutions

- Particles in the inner regions of halos (e.g. r ~ 10kpc in the MW) have typically passed through several hundred caustics
  → low stream densities and weak caustics

- The annihilation luminosity from caustics is a small fraction of the total (e.g. ~4% of that beyond 10 kpc for a MW model)

- If annihilation radiation is detected from external galaxies (e.g. M31) only the outermost caustic is likely to be visible

Myths about small-scale structure and DM detection

- Halo DM is mostly in small (e.g. Earth mass?) clumps
  → direct detectors typically live in low density regions

- DM streams → non-Maxwellian, “clumpy” $f(\mathbf{v})$
  → direct detectors will see an irregular velocity distribution

- Small (Earth-mass?) clumps dominate observable annihilation signal

- Dwarf Spheroidals/subhalos are best targets for detecting annihilation
  (and are boosted by sub-substructure)

- Smooth halo annihilation emission is dominated by caustics

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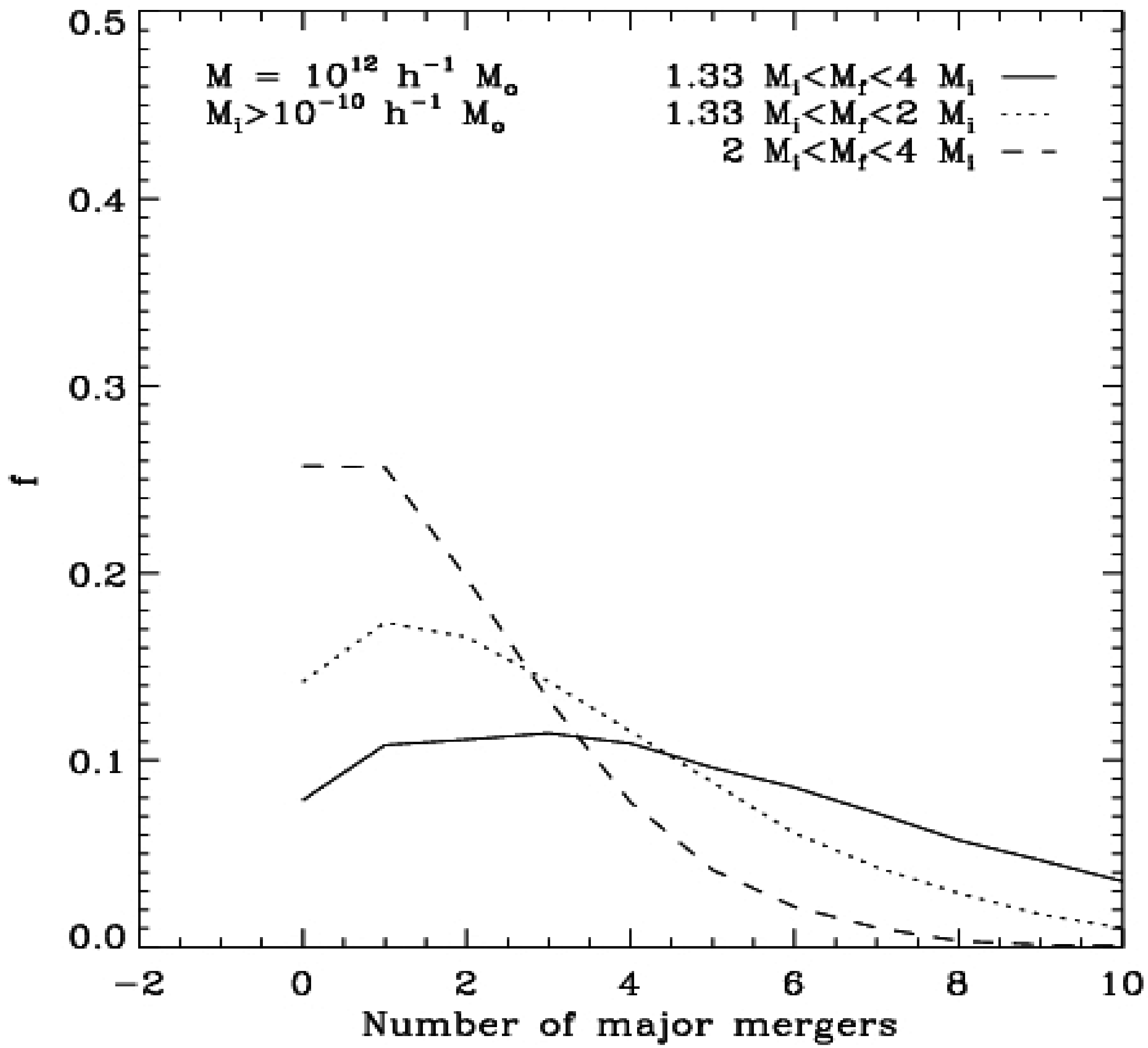
EPS statistics for the standard ΛCDM cosmology

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

Angulo et al 2009



The 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