

The Unity of the Universe
Portsmouth, UK
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Dark Matter Astronomy

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Halo assembly for neutralino Λ CDM

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

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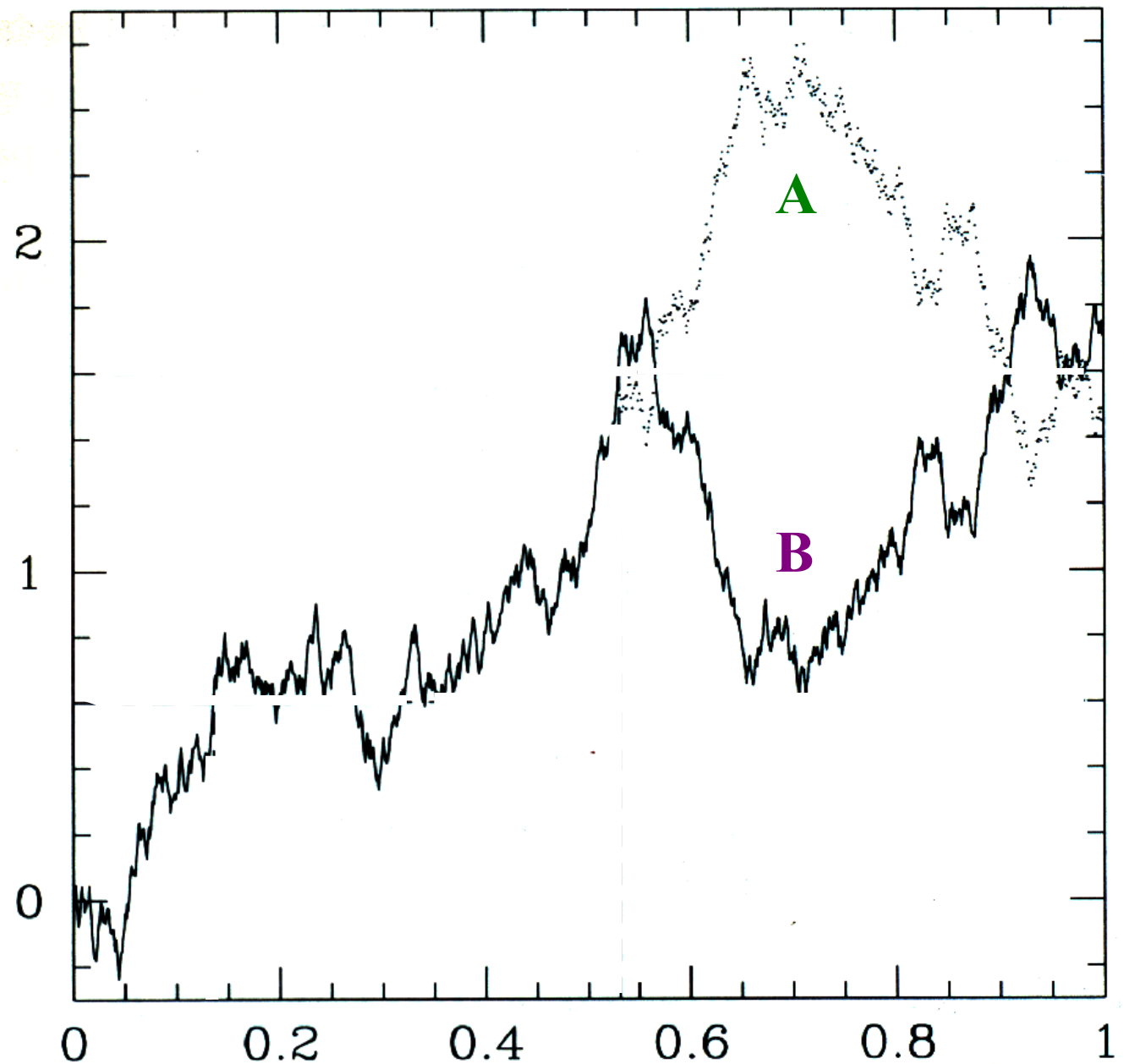
Overdensity vs smoothing at a given position

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

initial overdensity $\delta_s/D(\tau)$



variance $\sigma_0^2(k_c)$ of smoothed field

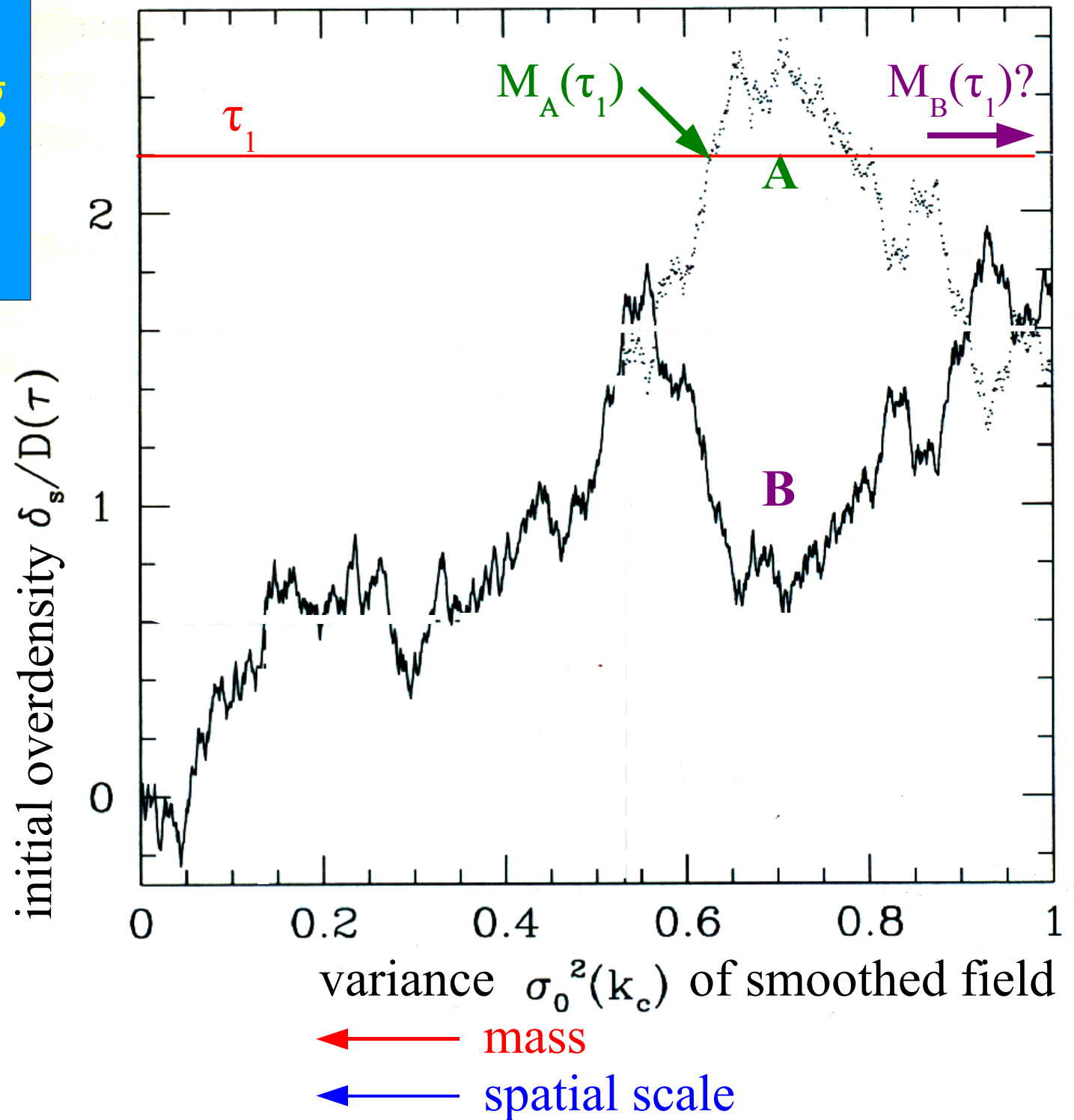
← mass

← 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

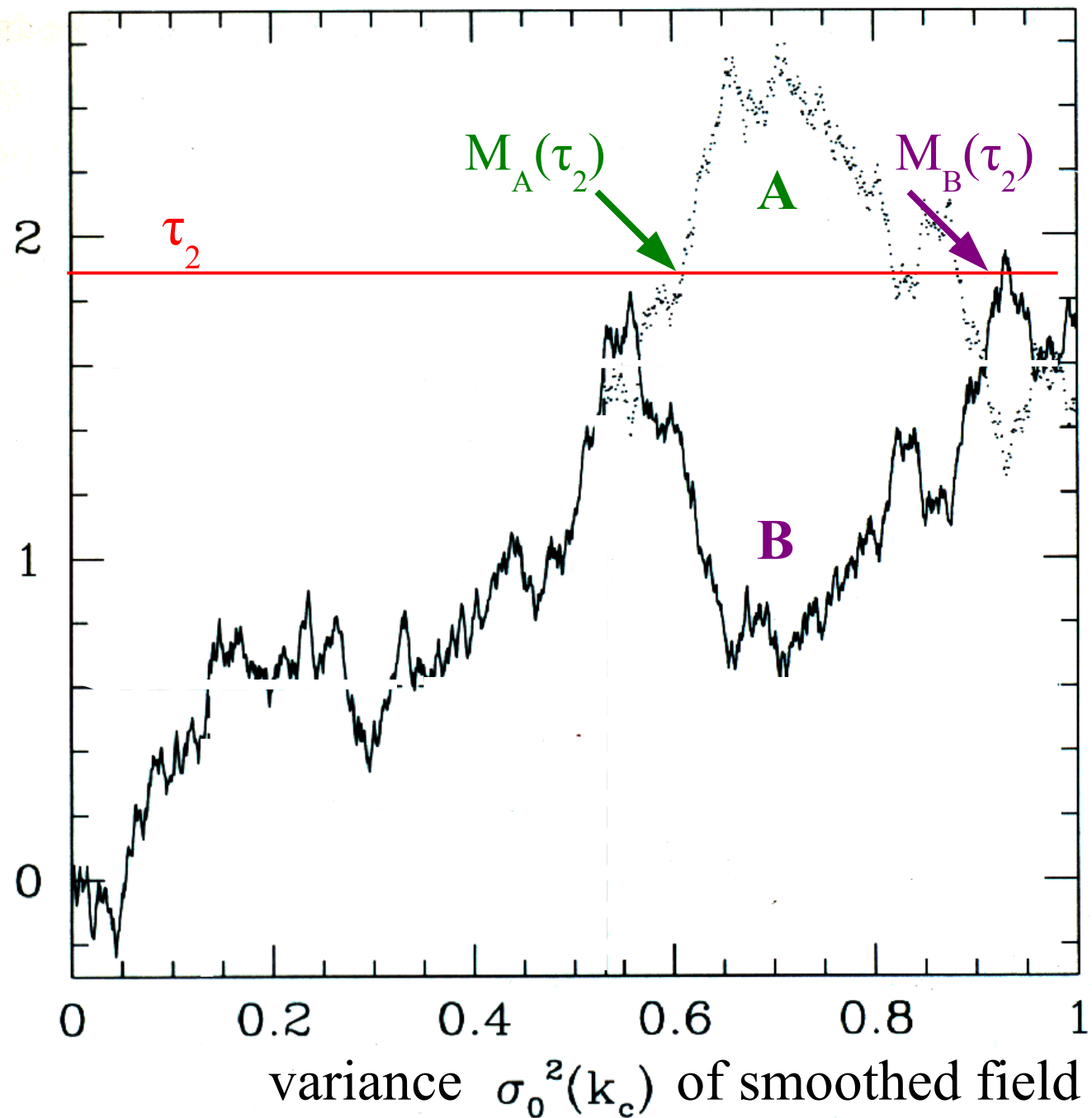


Overdensity vs smoothing at a given position

Later, at time τ_2
A's halo has grown
slightly by accretion

B is now part of a
moderately massive
halo

initial overdensity $\delta_s/D(\tau)$



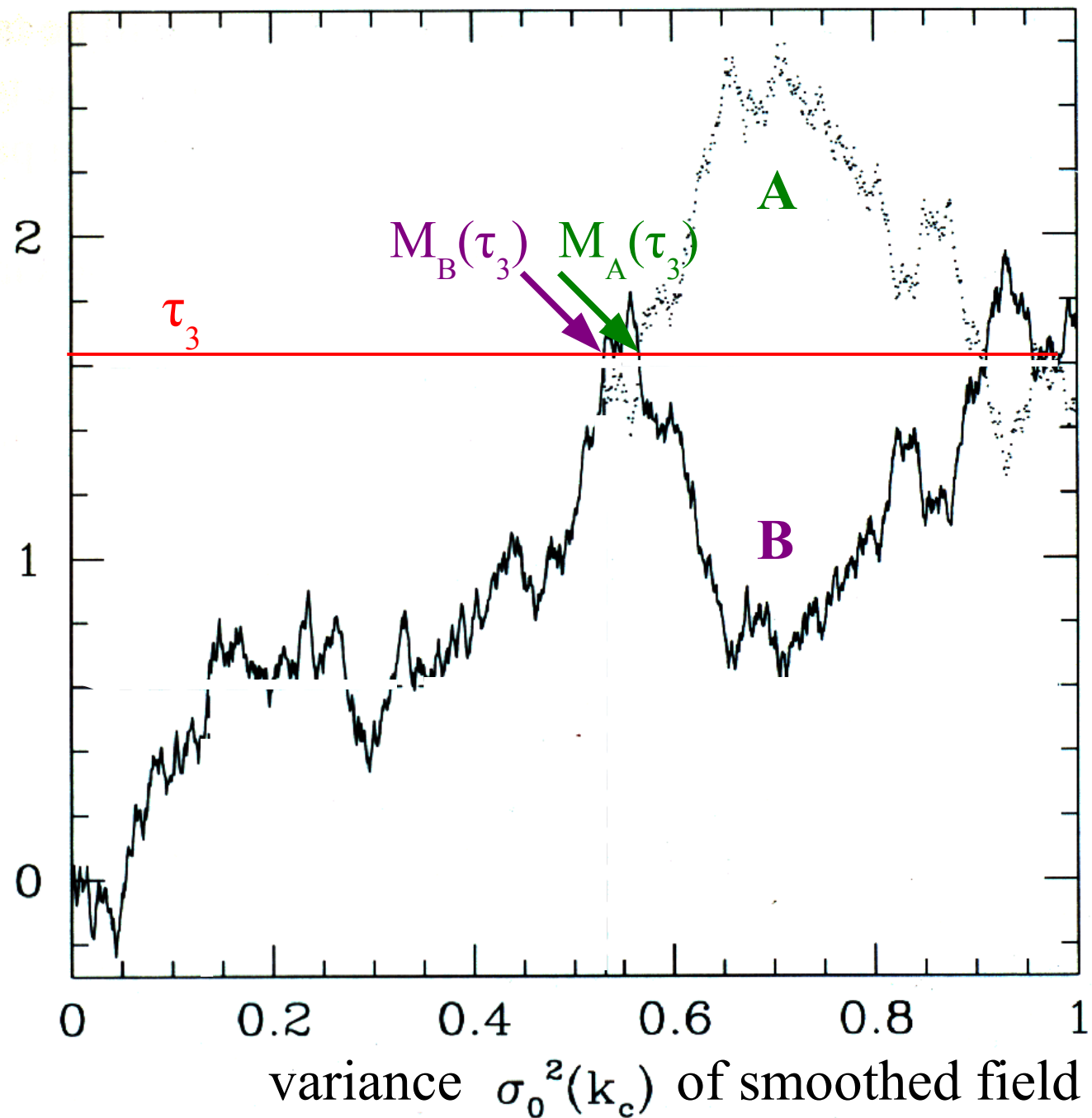
← mass

← spatial scale

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

initial overdensity $\delta_s/D(\tau)$



← mass
← spatial scale

Overdensity vs smoothing at a given position

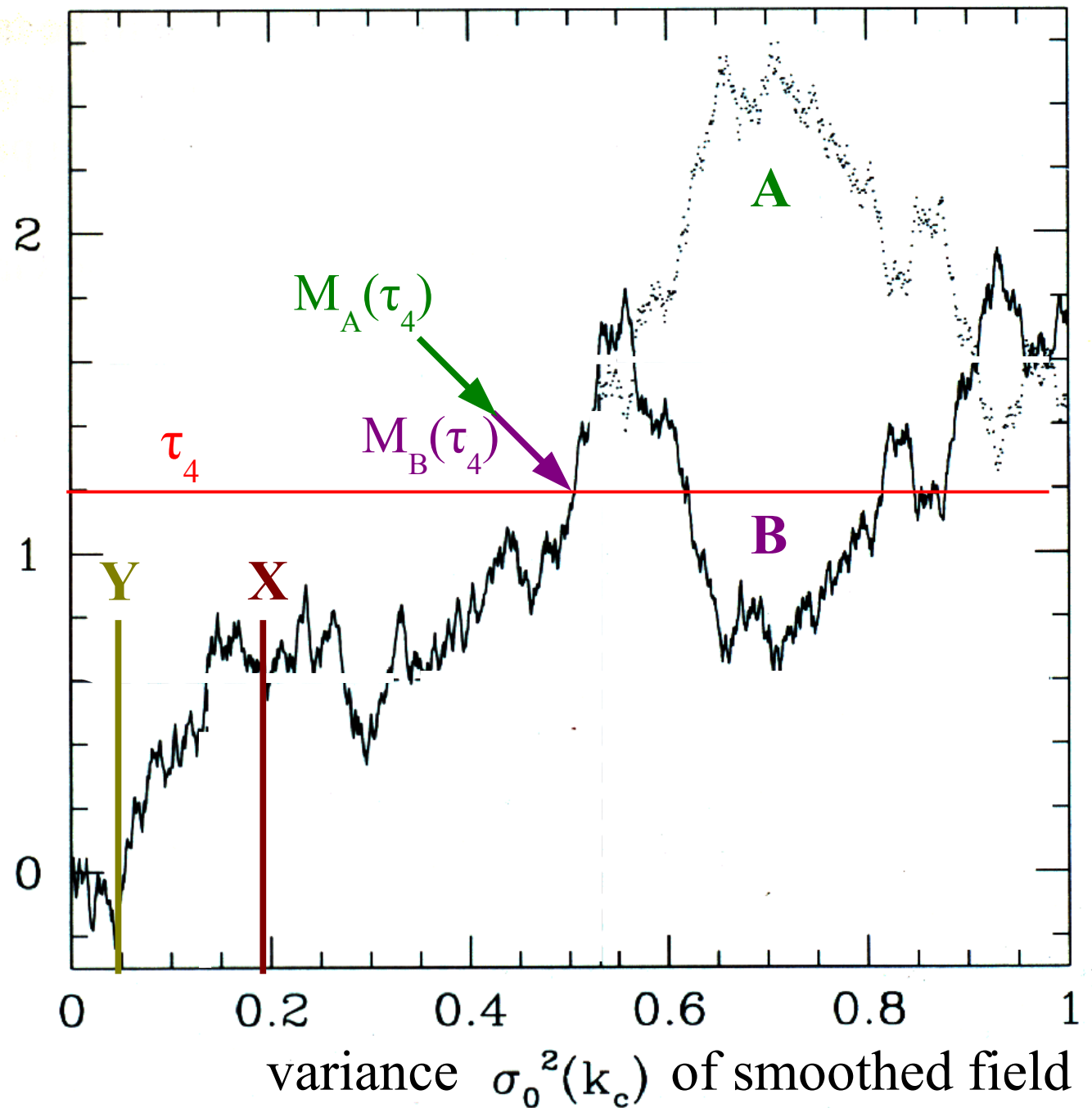
Still later, e.g. τ_4

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

initial overdensity $\delta_s/D(\tau)$



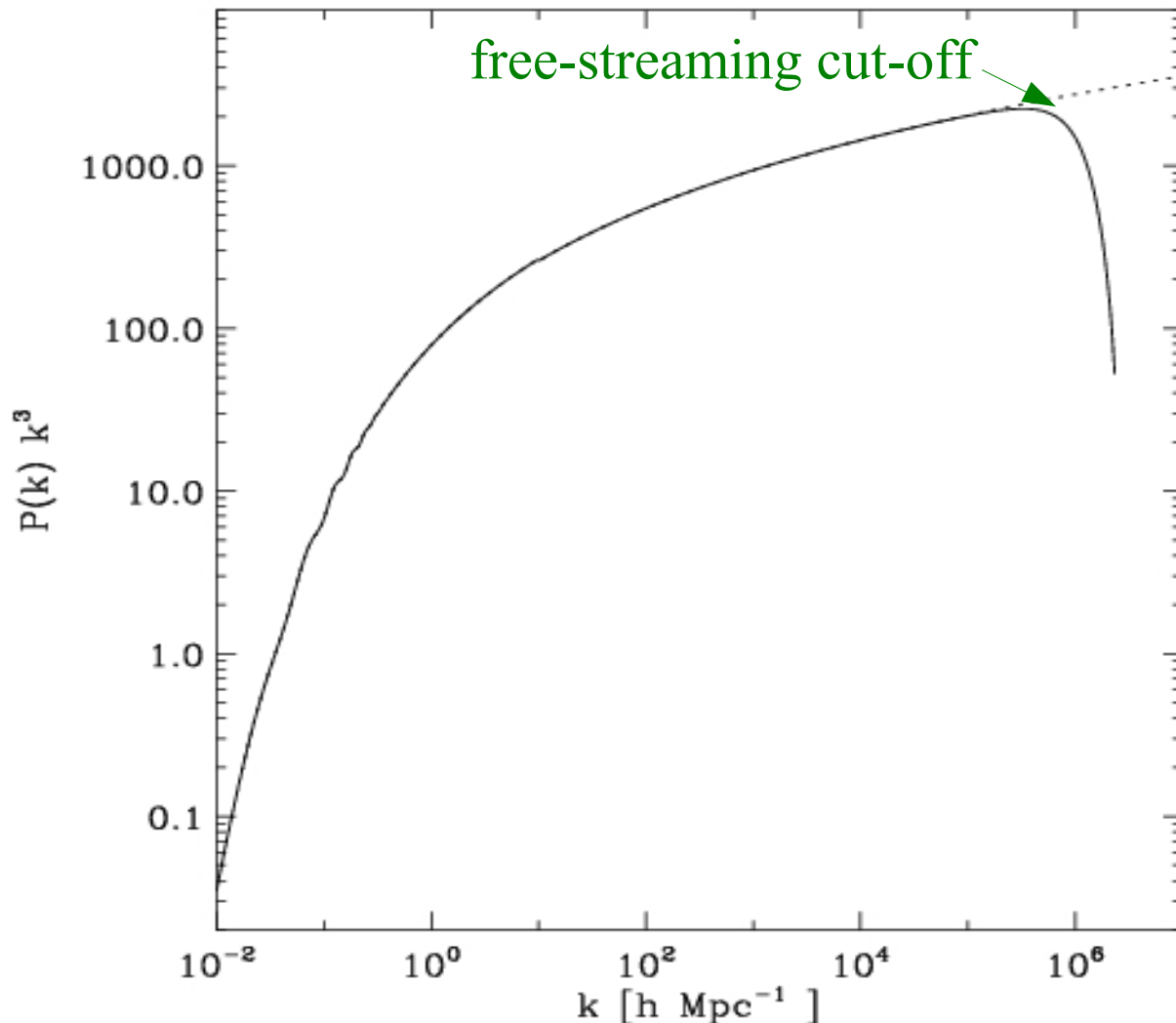
← mass

← spatial scale

EPS statistics for the standard Λ CDM cosmology

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

Angulo & White 2009



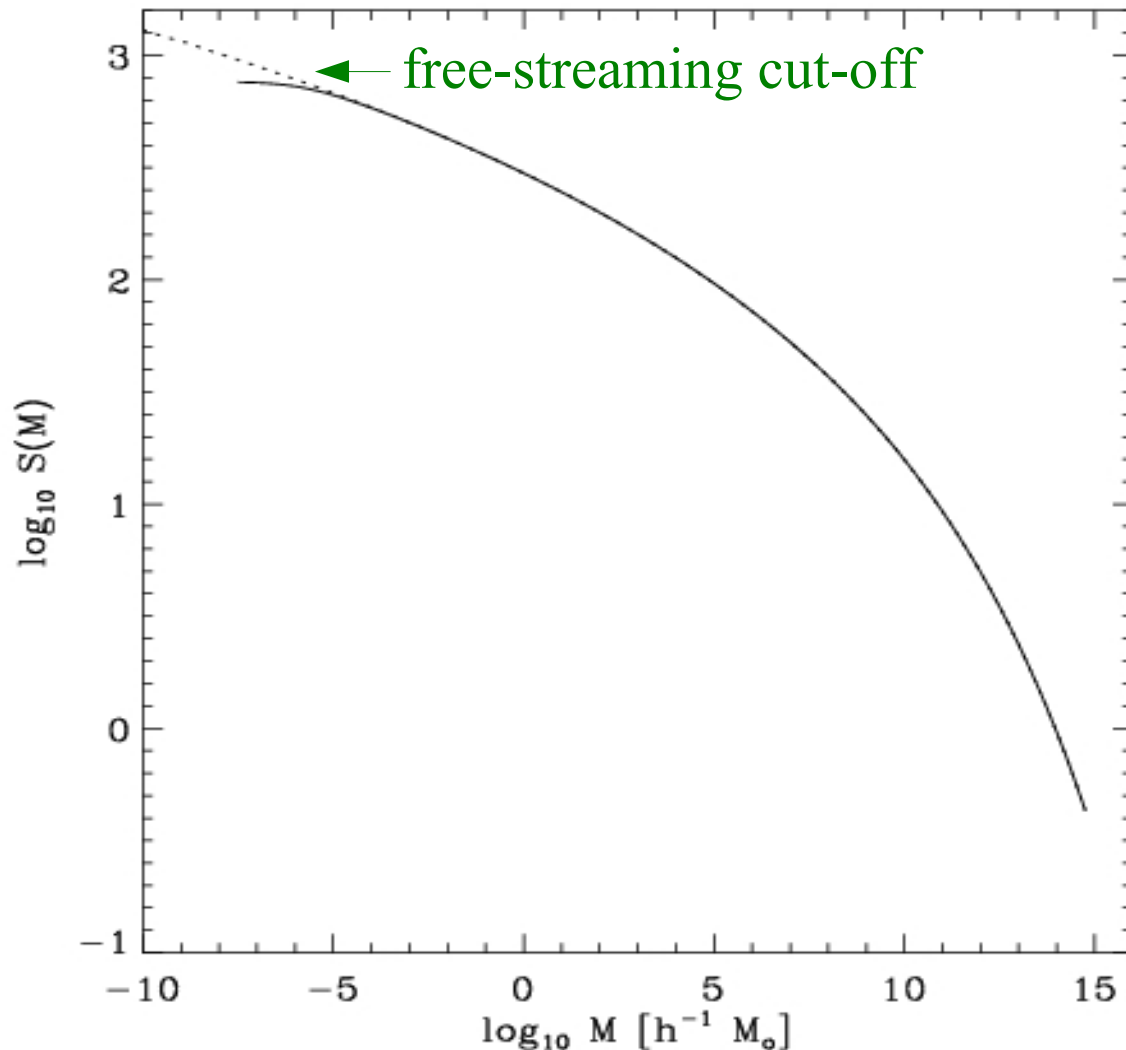
The linear power spectrum in “power per octave” form

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

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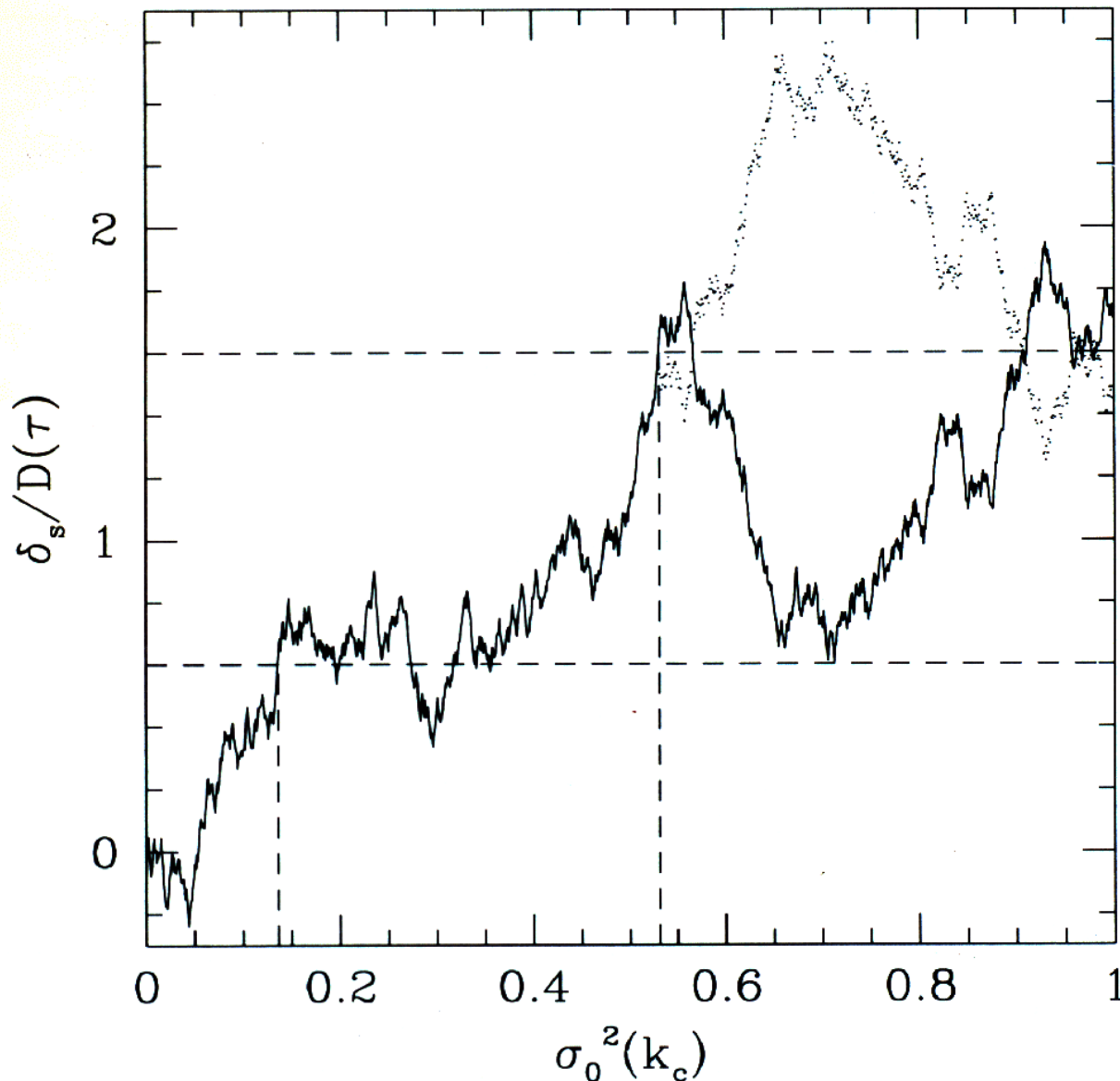


Variance of linear density fluctuation within spheres containing mass M , extrapolated to $z = 0$

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

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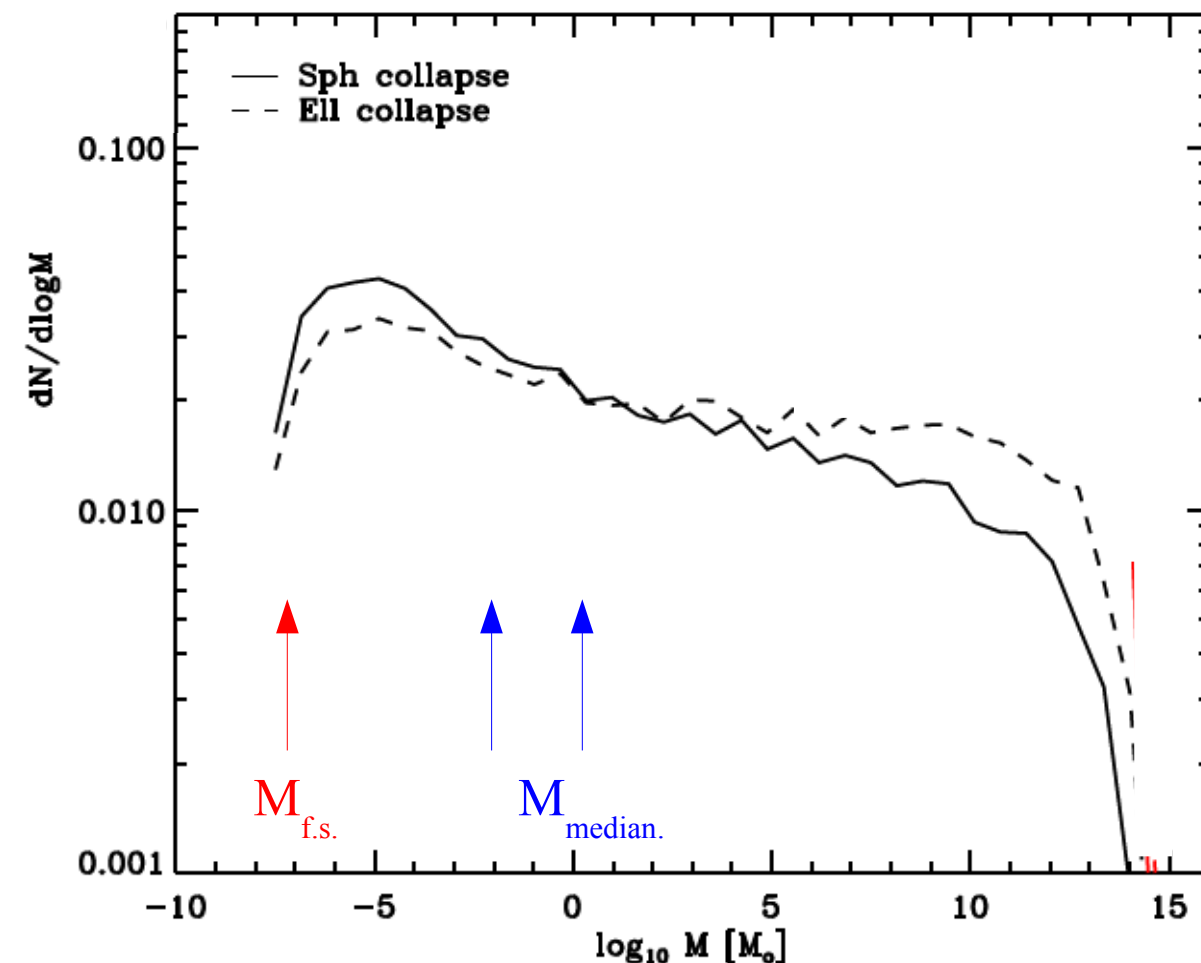
If these Markov random walks are scaled so the maximum variance is 720 and the vertical axis is multiplied by $\sqrt{720}$, then they represent complete halo assembly histories for random CDM particles.

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

EPS statistics for the standard Λ CDM cosmology

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Angulo & White 2009



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

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

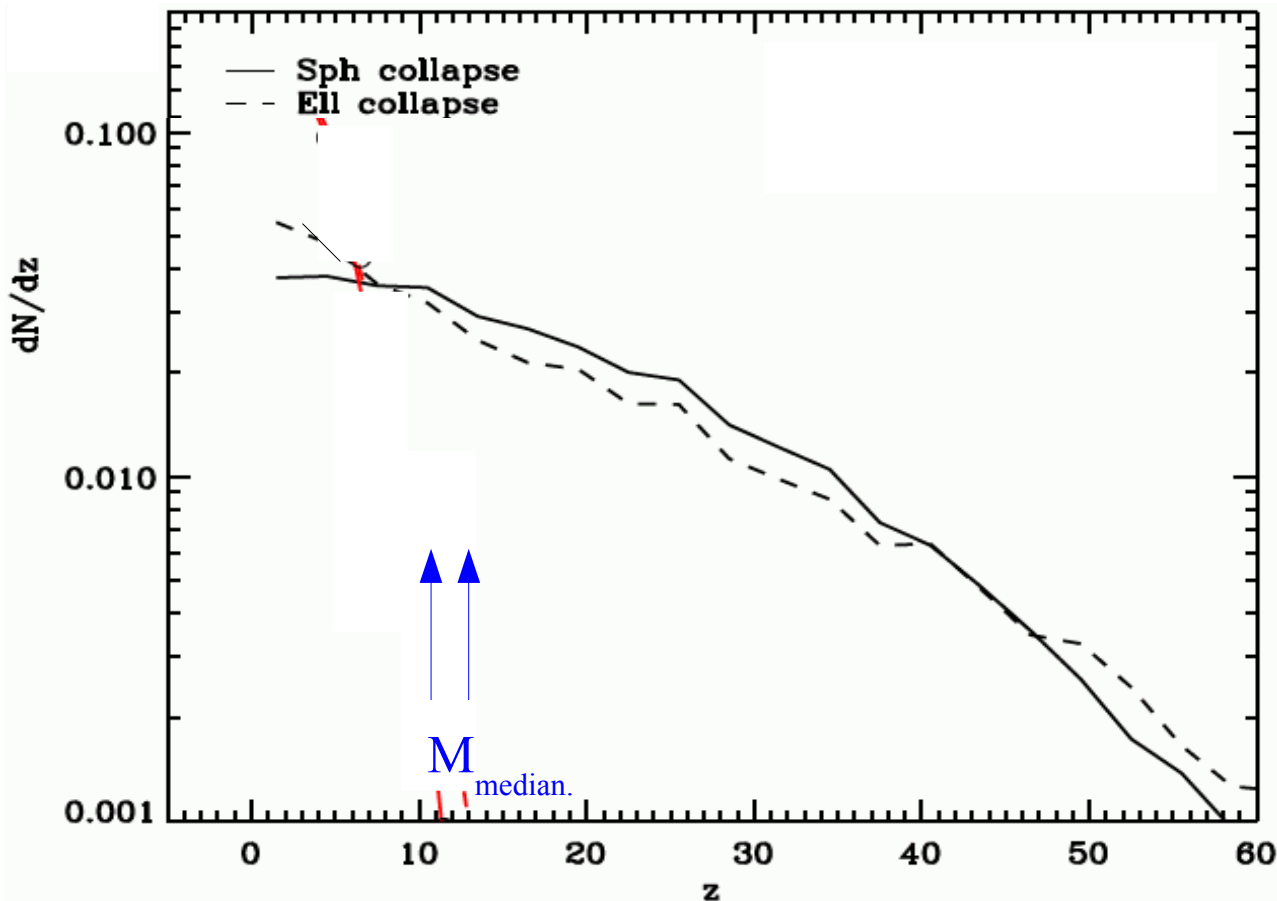
For 10% of the mass the first halo has $M > 10^7 M_\odot$

Direct simulation will become possible around 2035

EPS statistics for the standard Λ CDM cosmology

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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

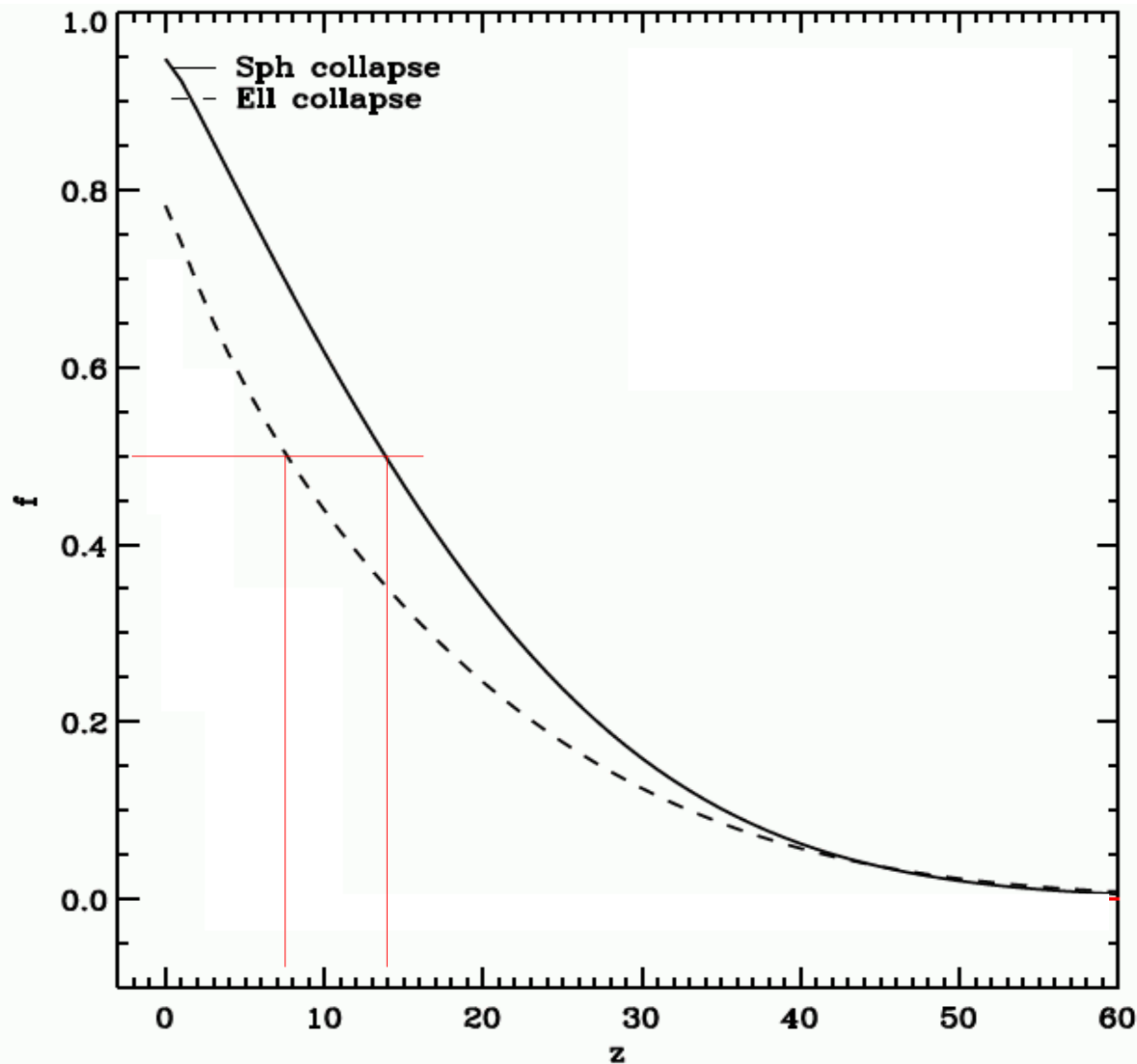
For 10% of the mass the first halo collapses at $z > 34$

For 1% at $z > 55$

EPS statistics for the standard Λ CDM 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

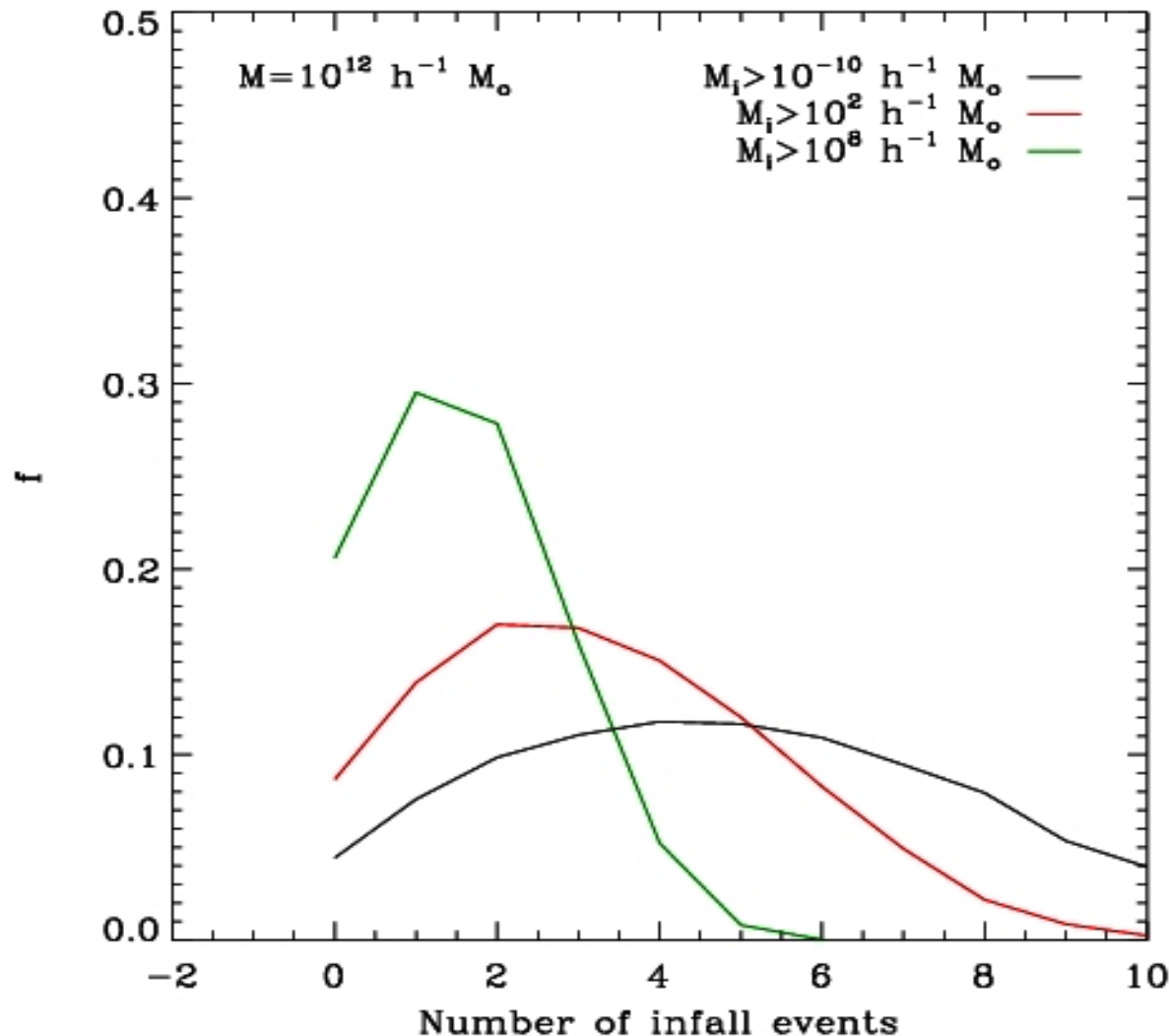
Beyond $z = 50$ almost all the mass is diffuse

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

EPS statistics for the standard Λ CDM 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 $M > 10^8 M_\odot$

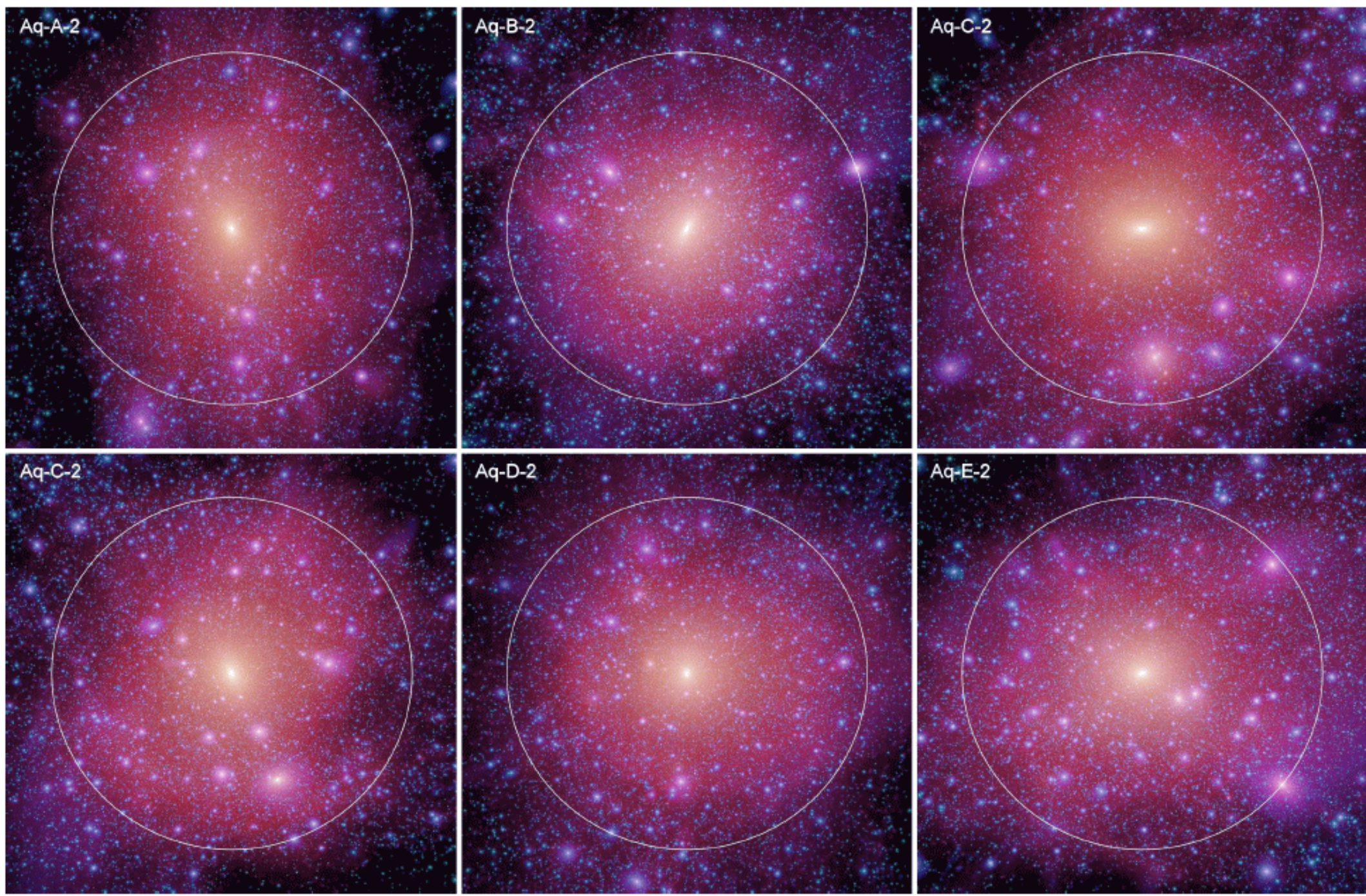
EPS halo assembly: conclusions

- 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

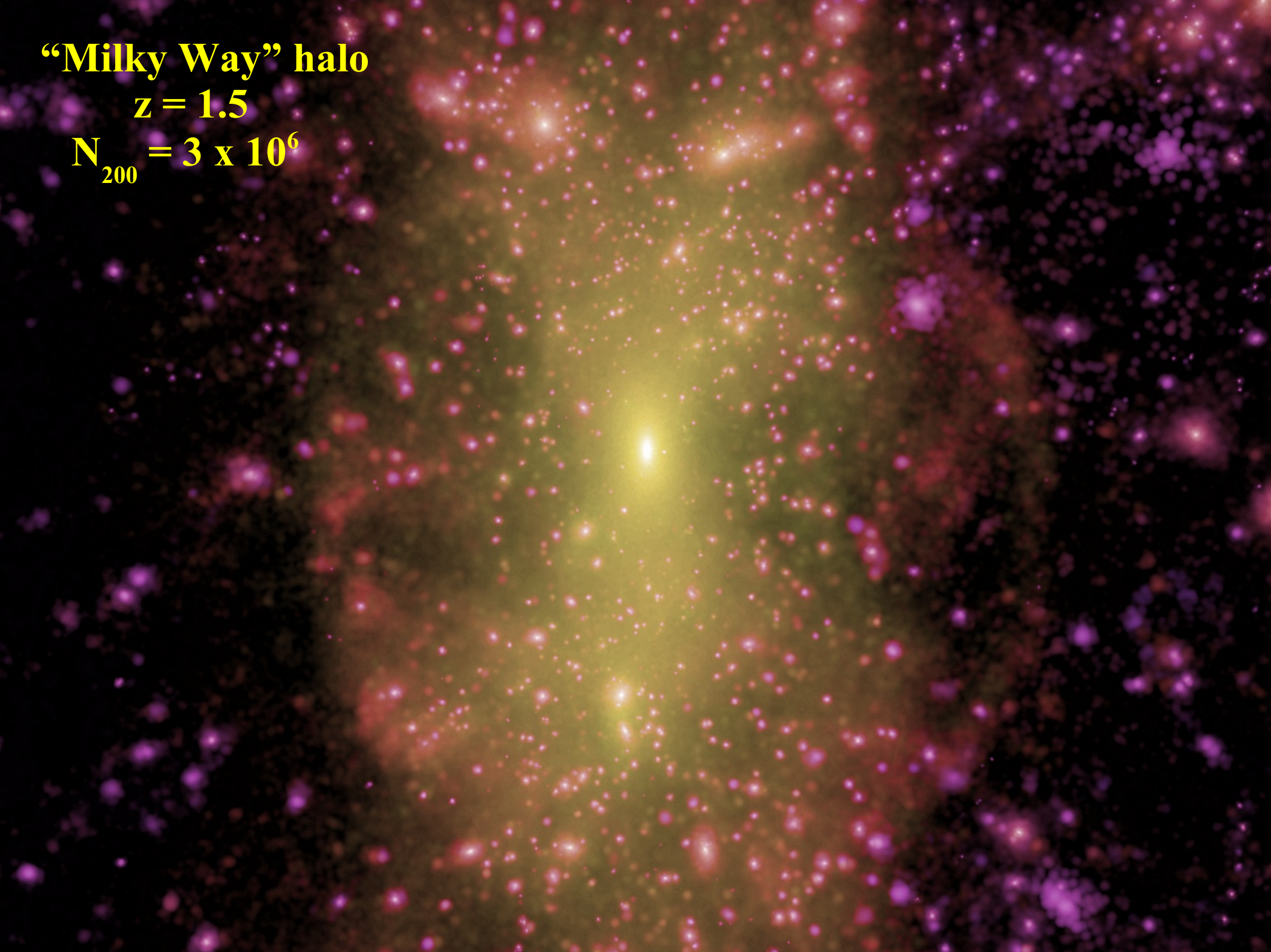
Springel et al 2008



“Milky Way” halo

$z = 1.5$

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



“Milky Way” halo

$z = 1.5$

$N_{200} = 94 \times 10^6$



“Milky Way” halo

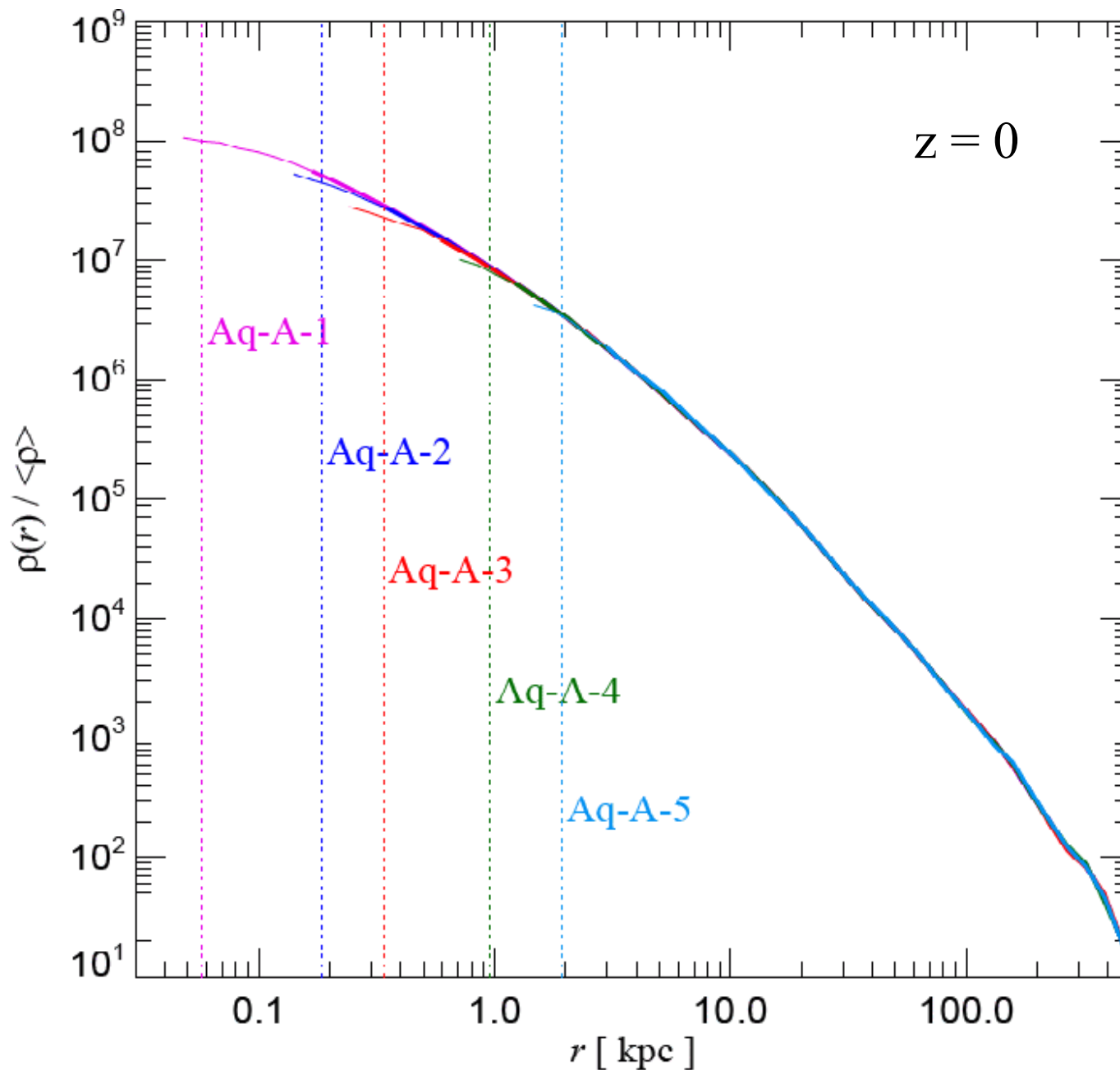
$z = 1.5$

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



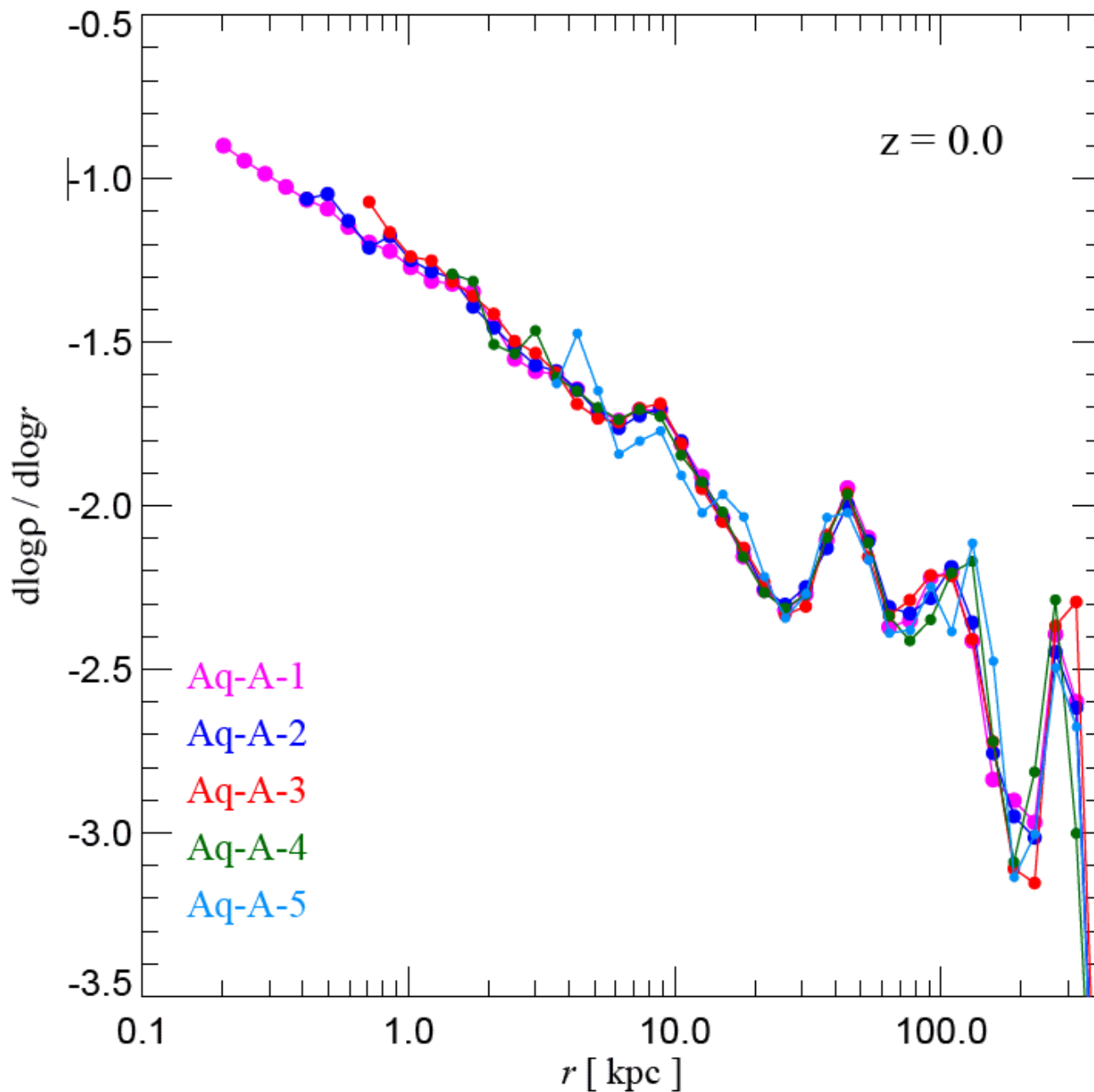
How well do density profiles converge?

Aquarius Project: Springel et al 2008



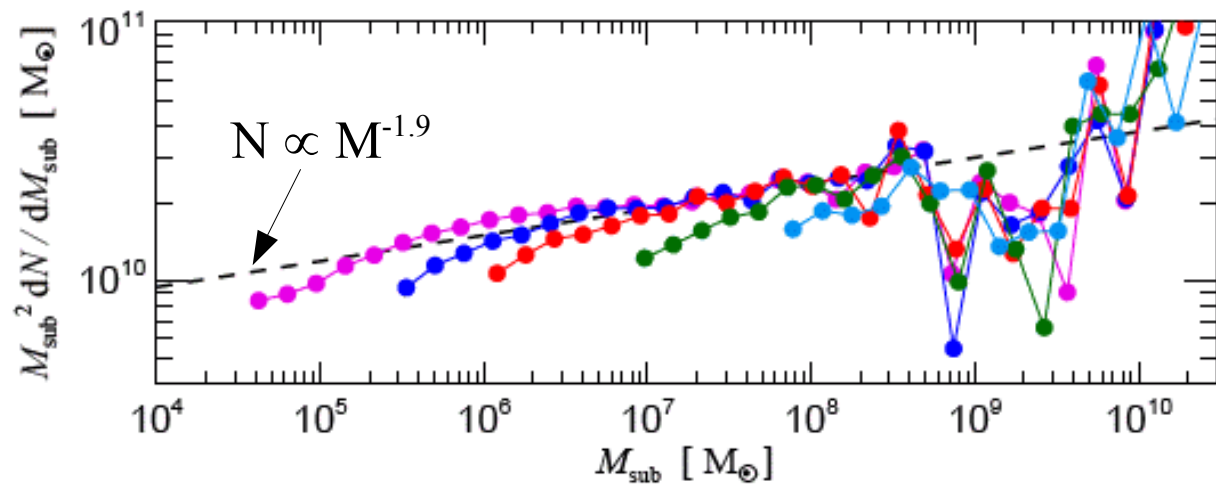
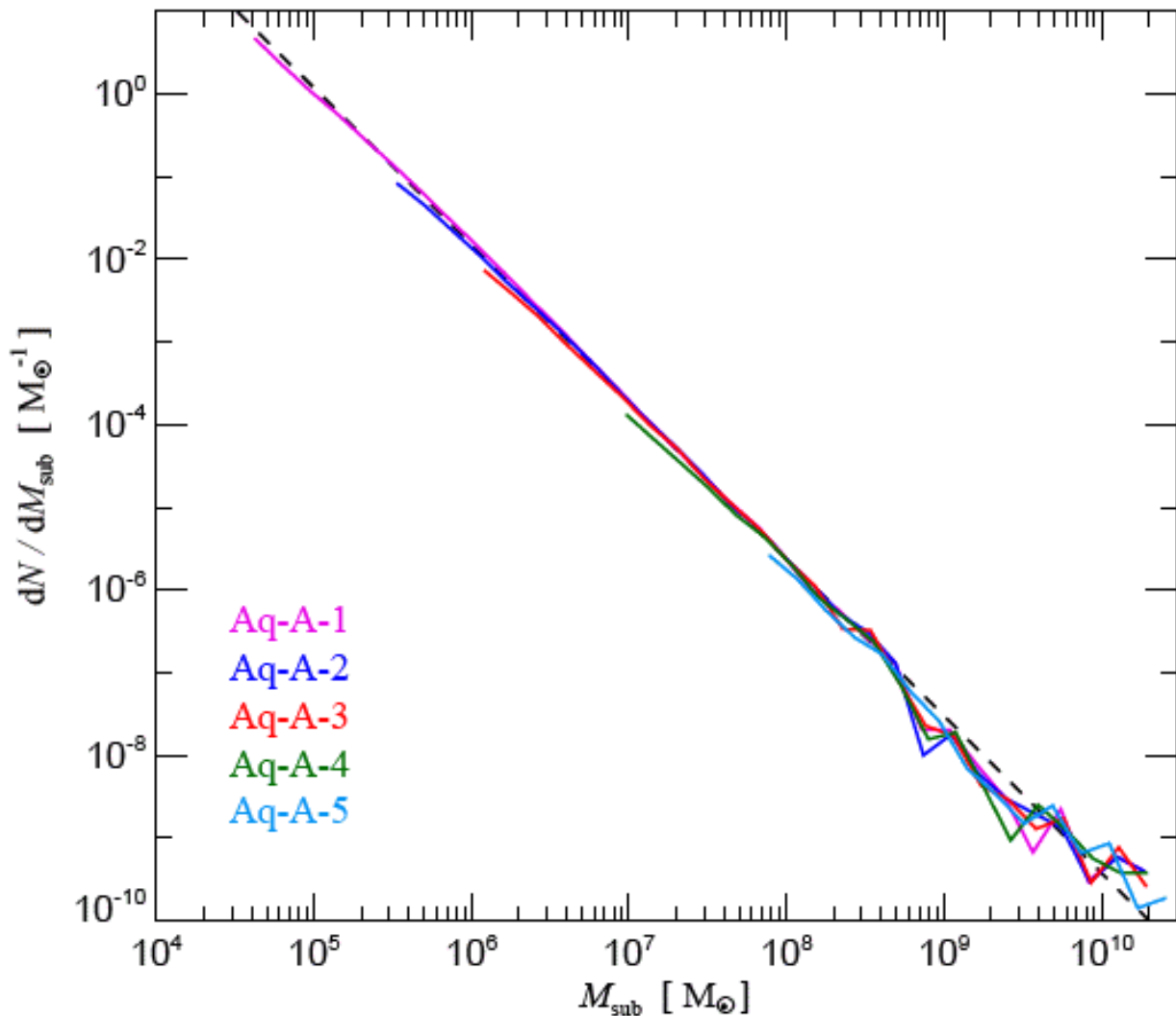
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Aquarius Project: Springel et al 2008



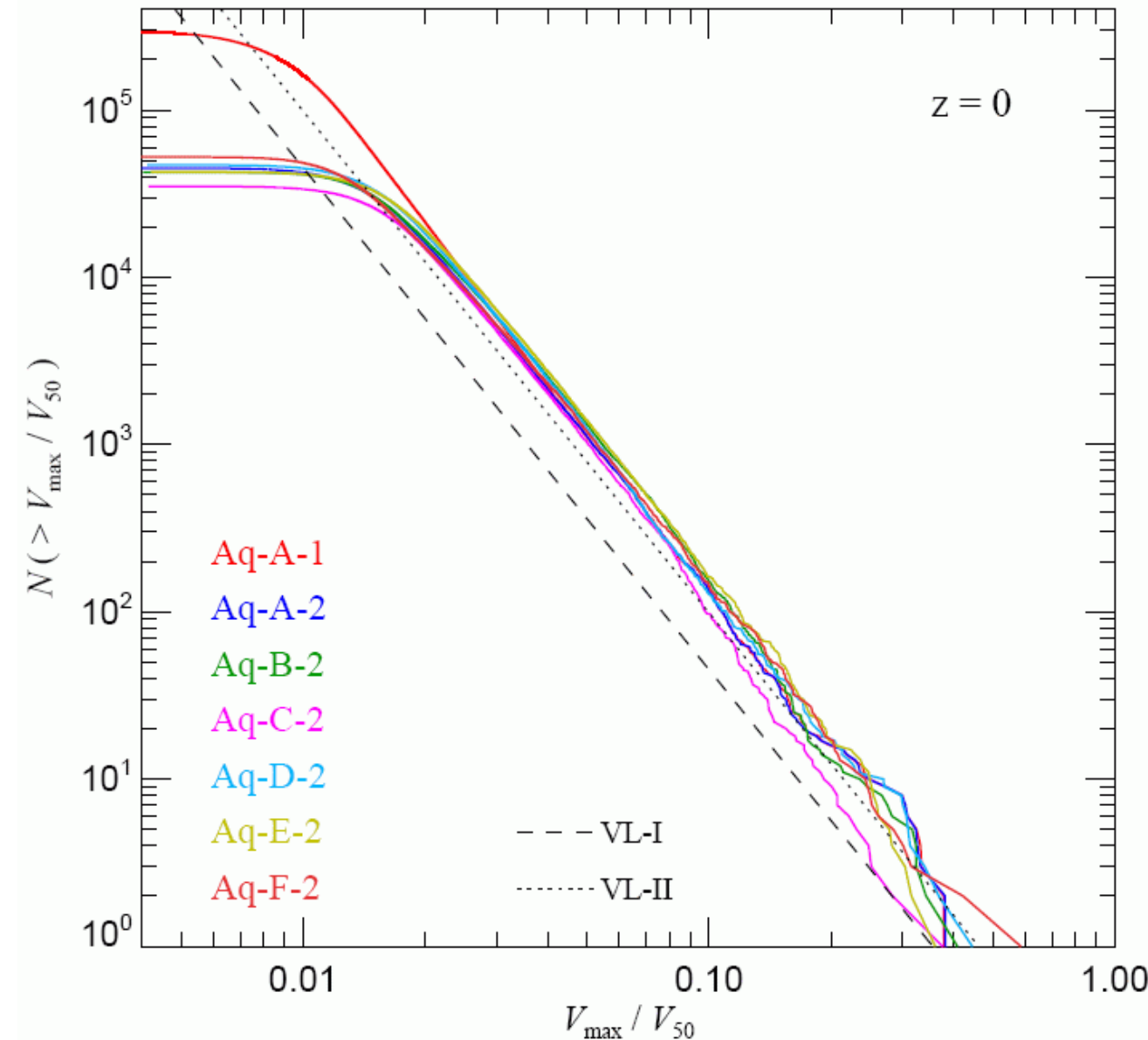
How well does substructure converge?

Springel et al 2008



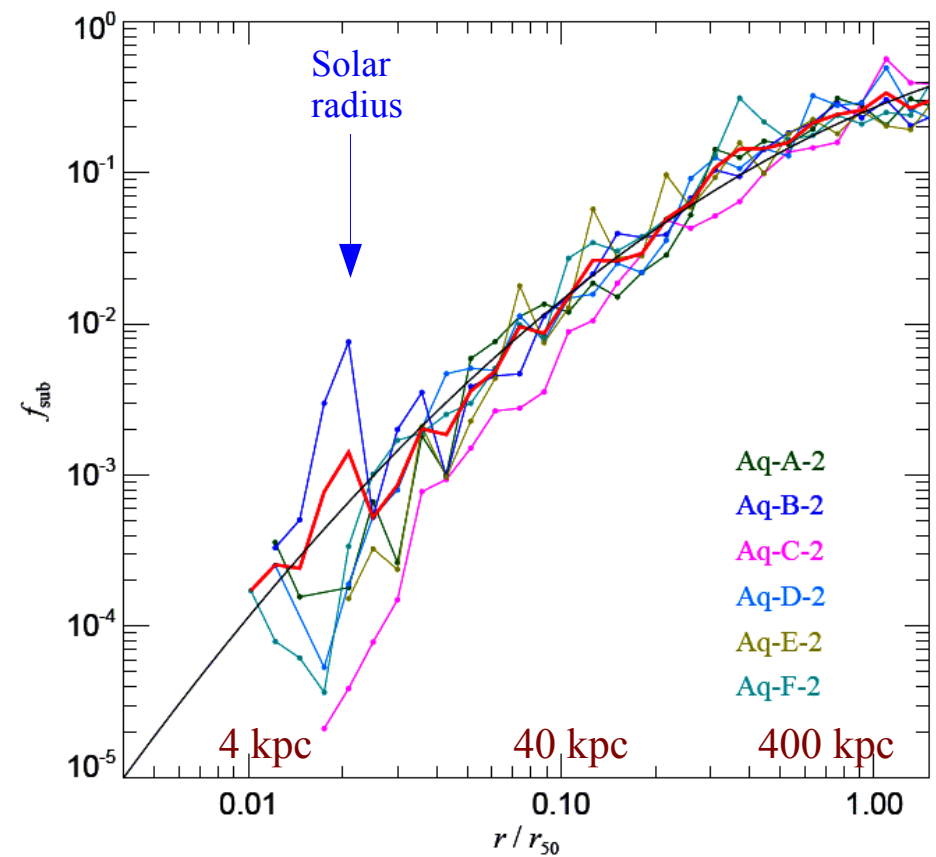
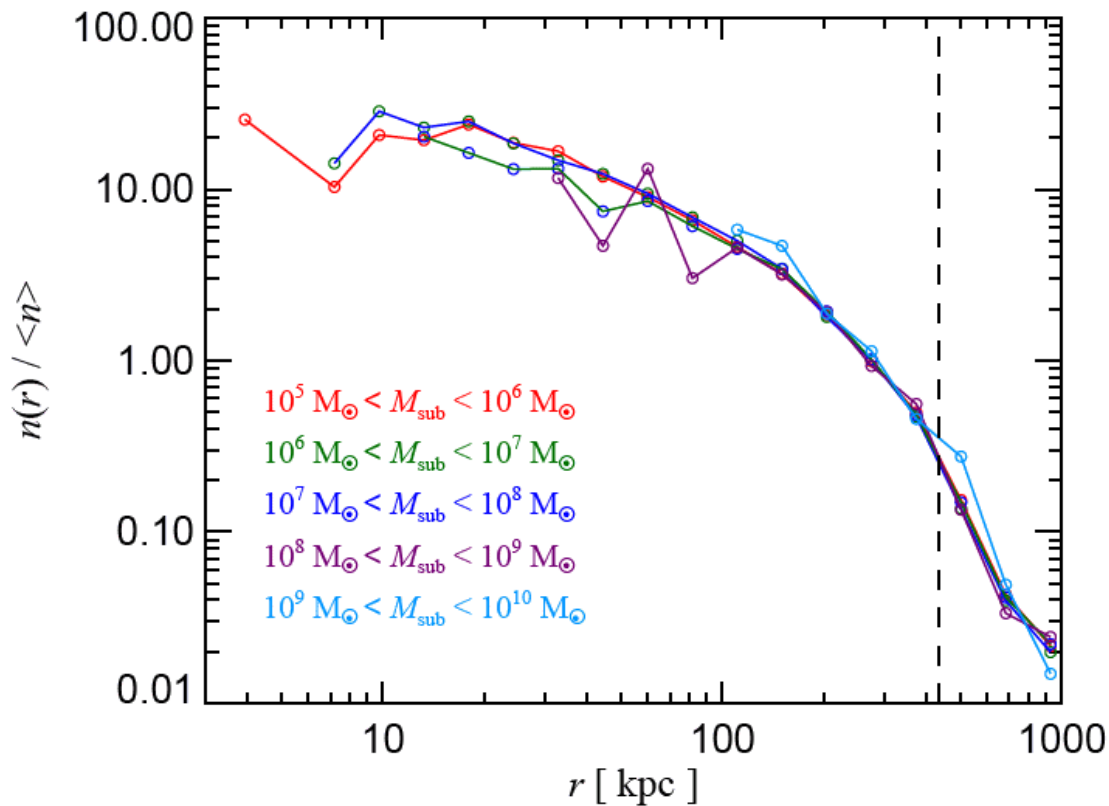
How uniform are subhalo populations?

Springel et al 2008

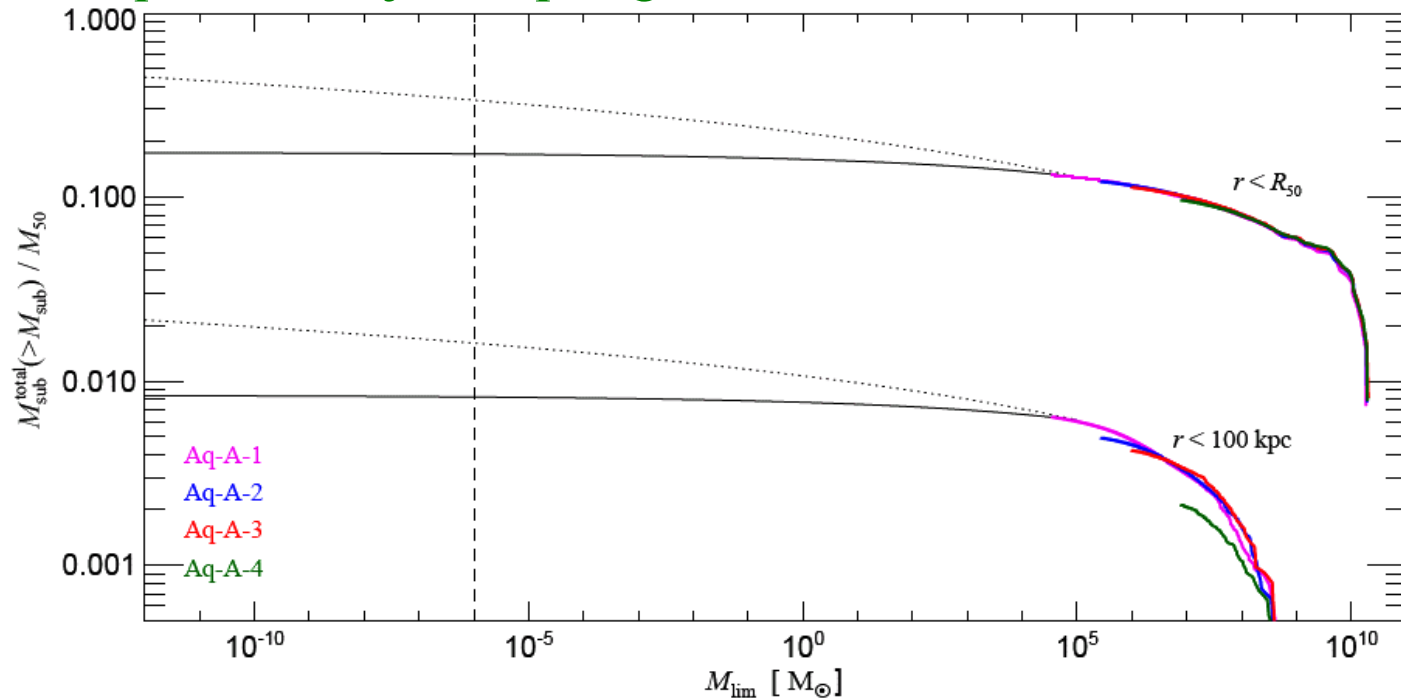


For the six Aquarius halos, the scatter in subhalo abundance is Poisson at high mass and $\sim 20\%$ at low mass

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



Aquarius Project: Springel et al 2008



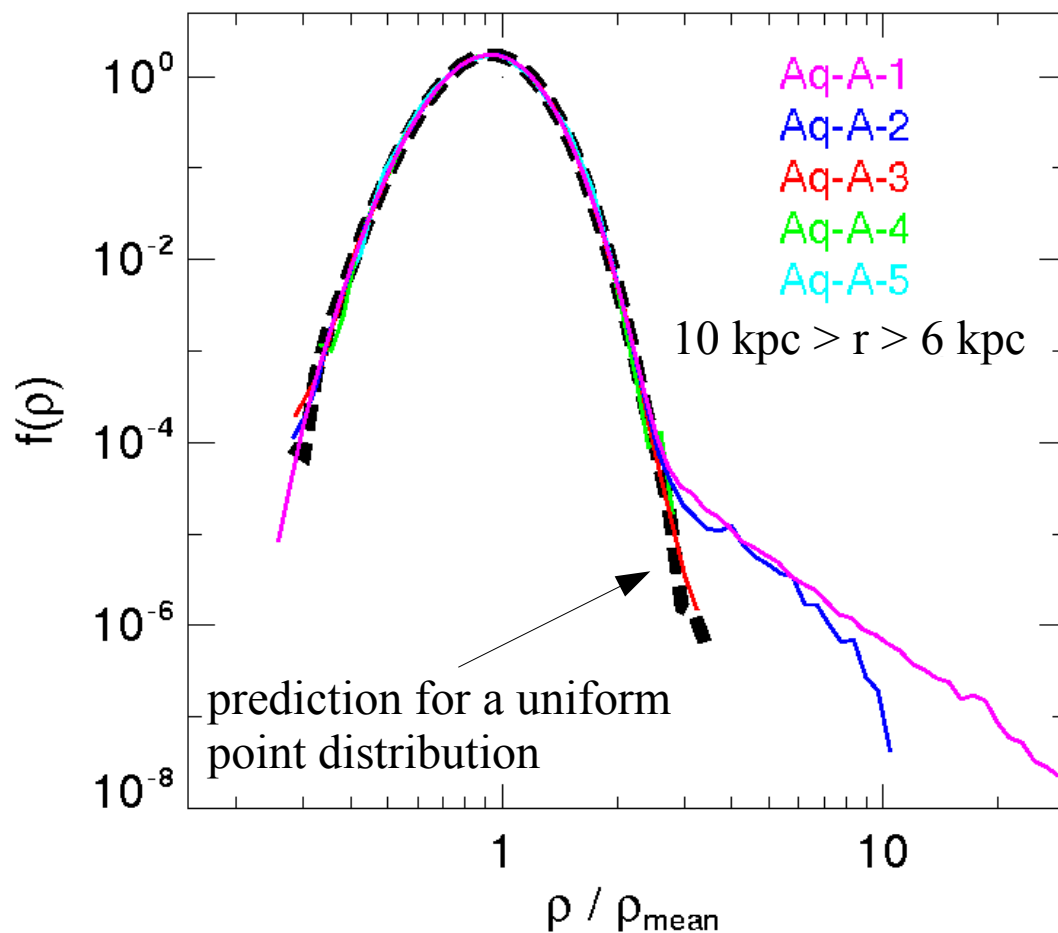
- All mass subhalos are similarly distributed
- A small fraction of the inner mass in subhalos
- $\ll 1\%$ of the mass near the Sun is in subhalos

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

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

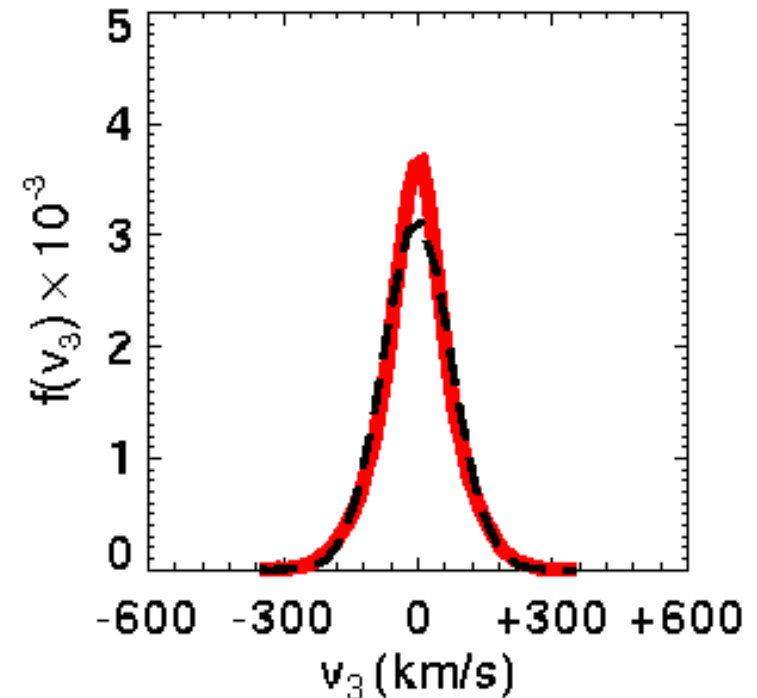
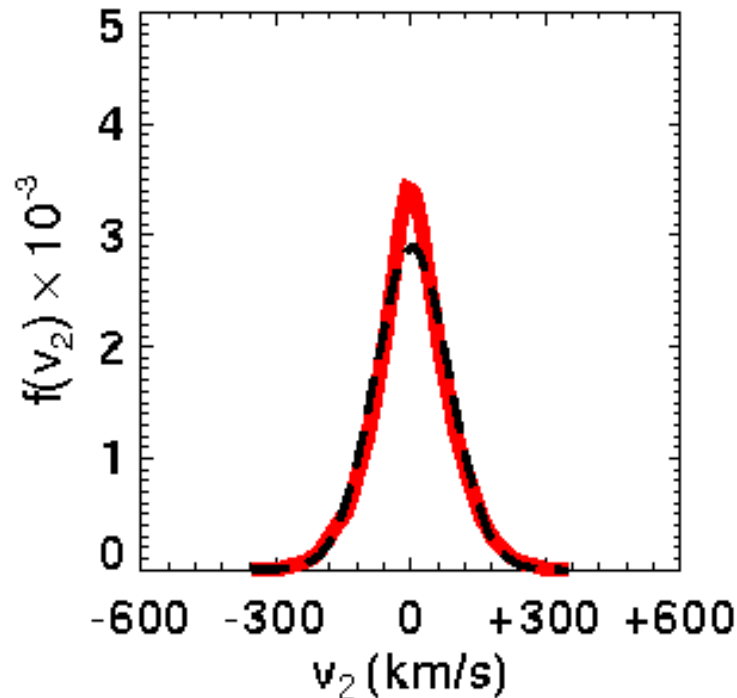
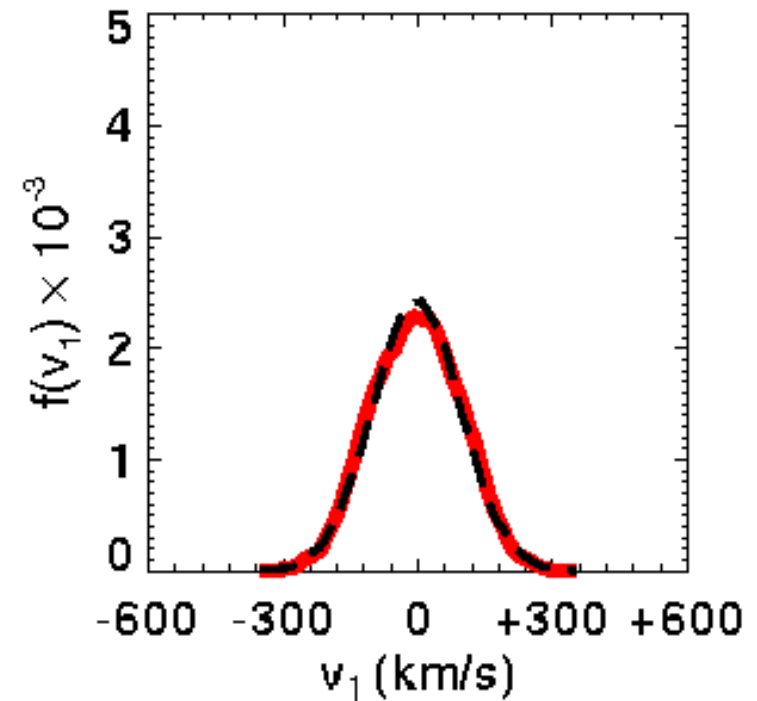
Vogelsberger et al 2008



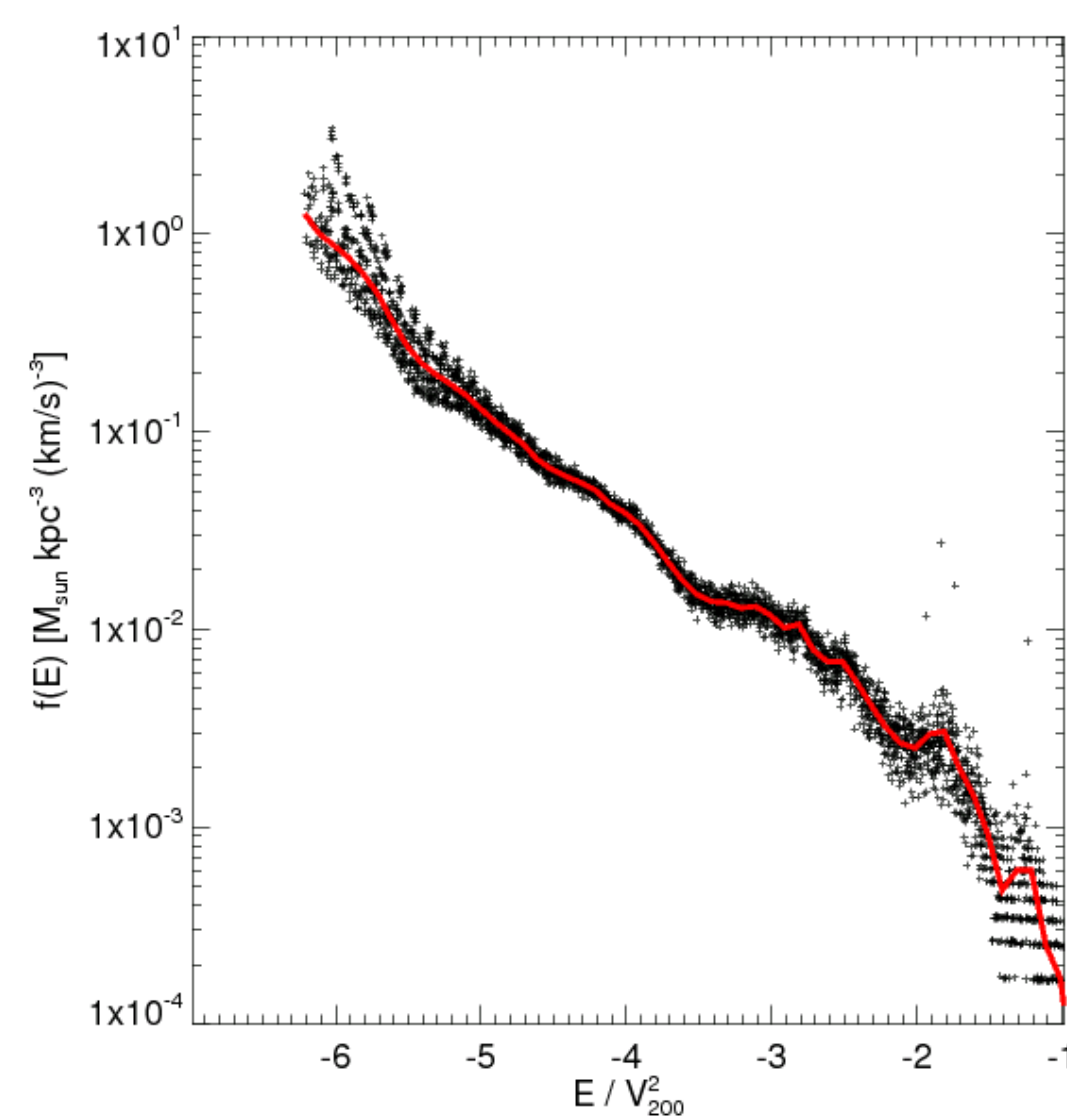
- Estimate a density ρ at each point by adaptively smoothing using the 64 nearest particles
- Fit to a smooth density profile stratified on similar ellipsoids
- The chance of a random point lying in a substructure is $< 10^{-4}$
- The *rms* scatter about the smooth model for the remaining points is only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

Local velocity distribution

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

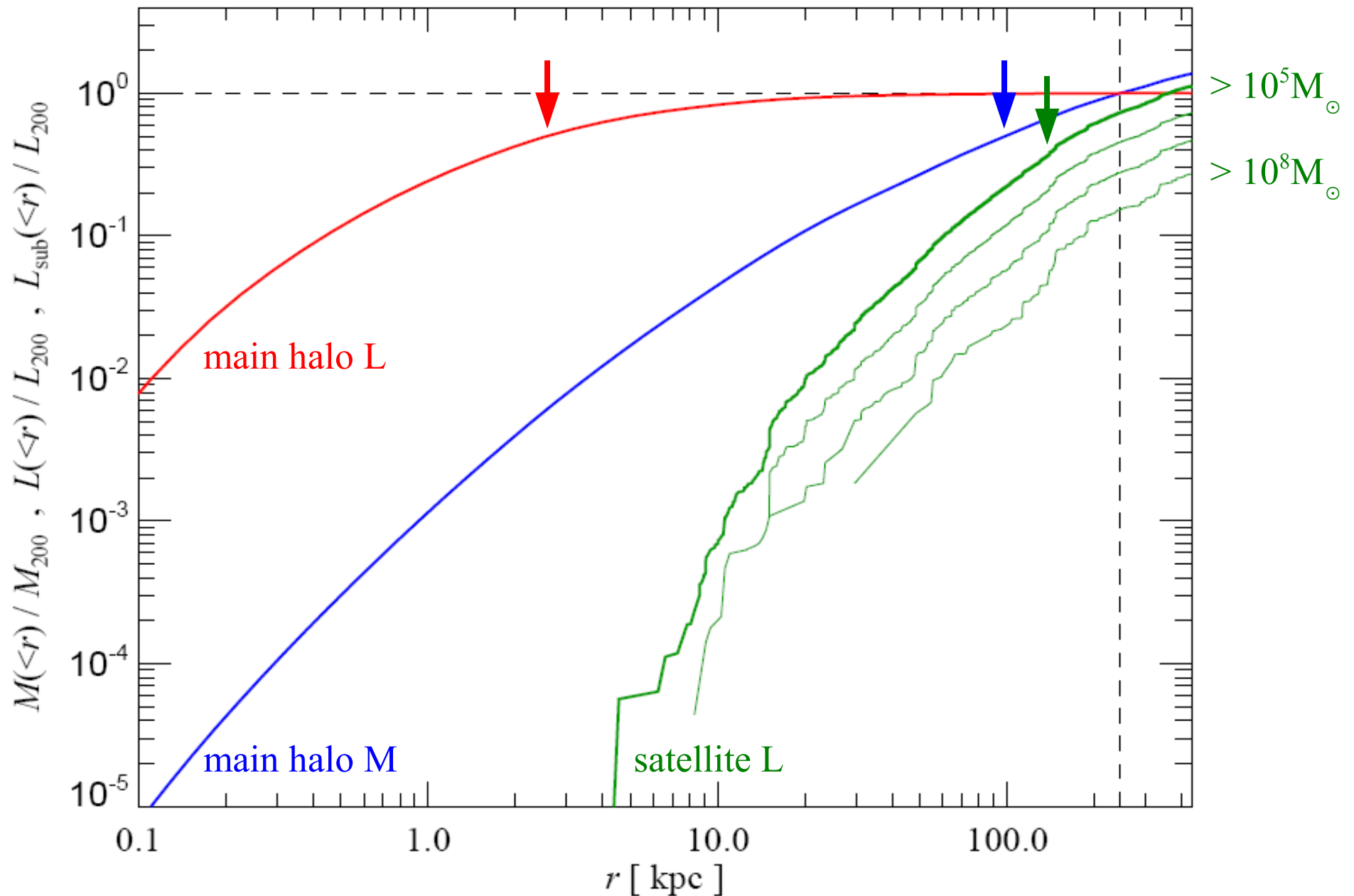
Conclusions for direct detection experiments

- 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 $\sim 20\%$ amplitude which are the fossils of the detailed assembly history of the Milky Way's dark halo

————→ Dark matter astronomy

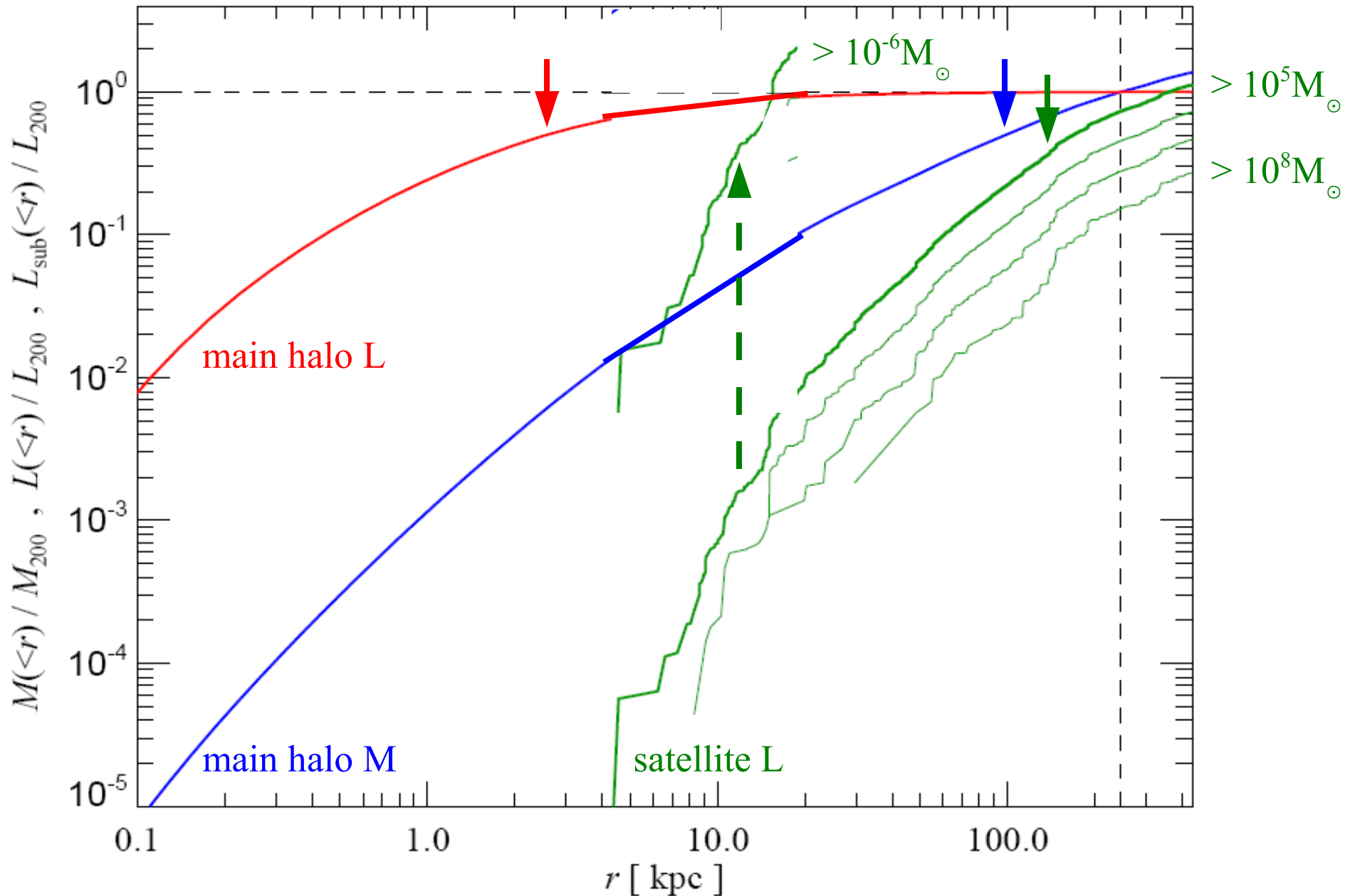
Mass and annihilation radiation profiles of a MW halo

Springel et al 2008



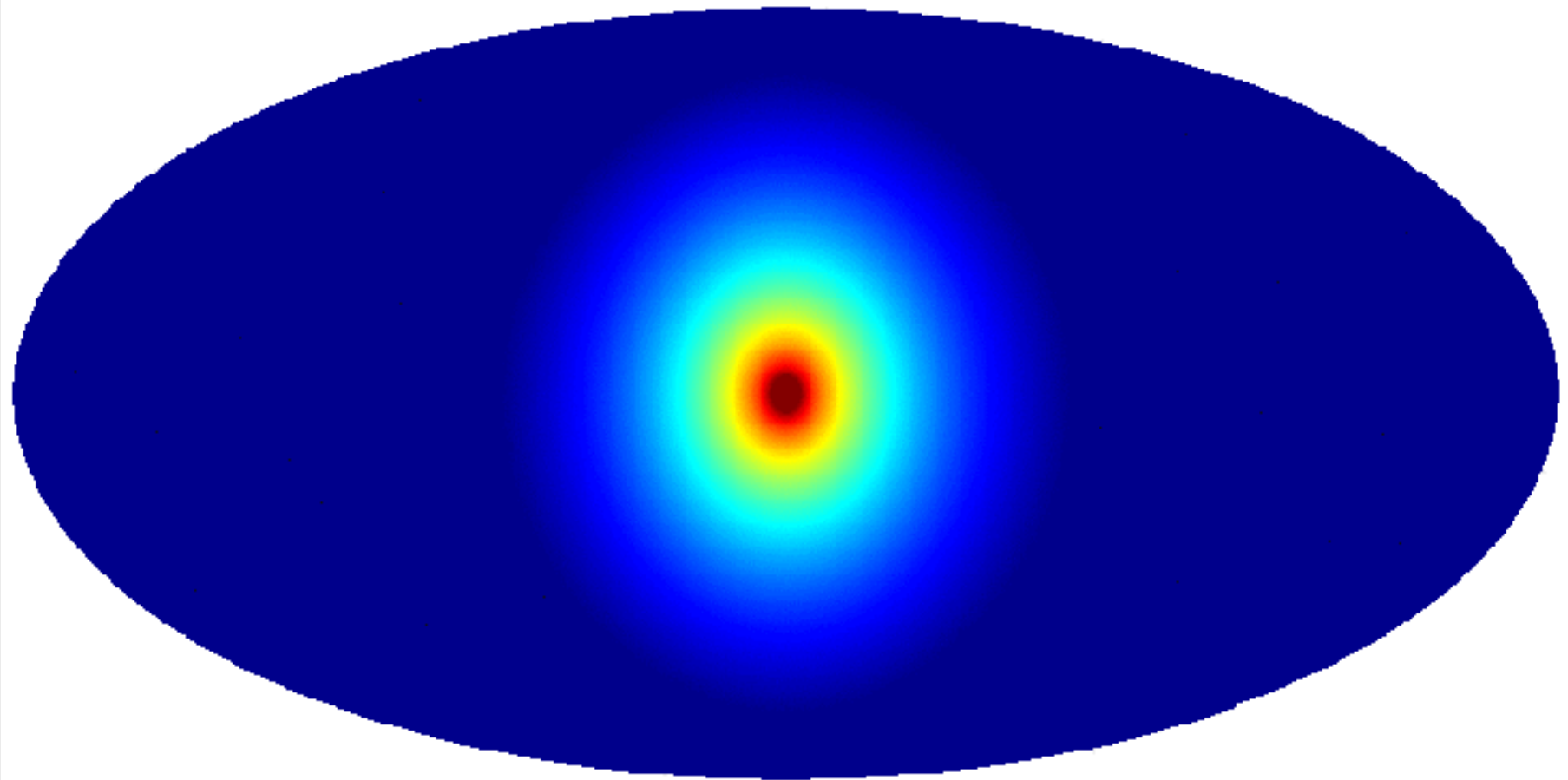
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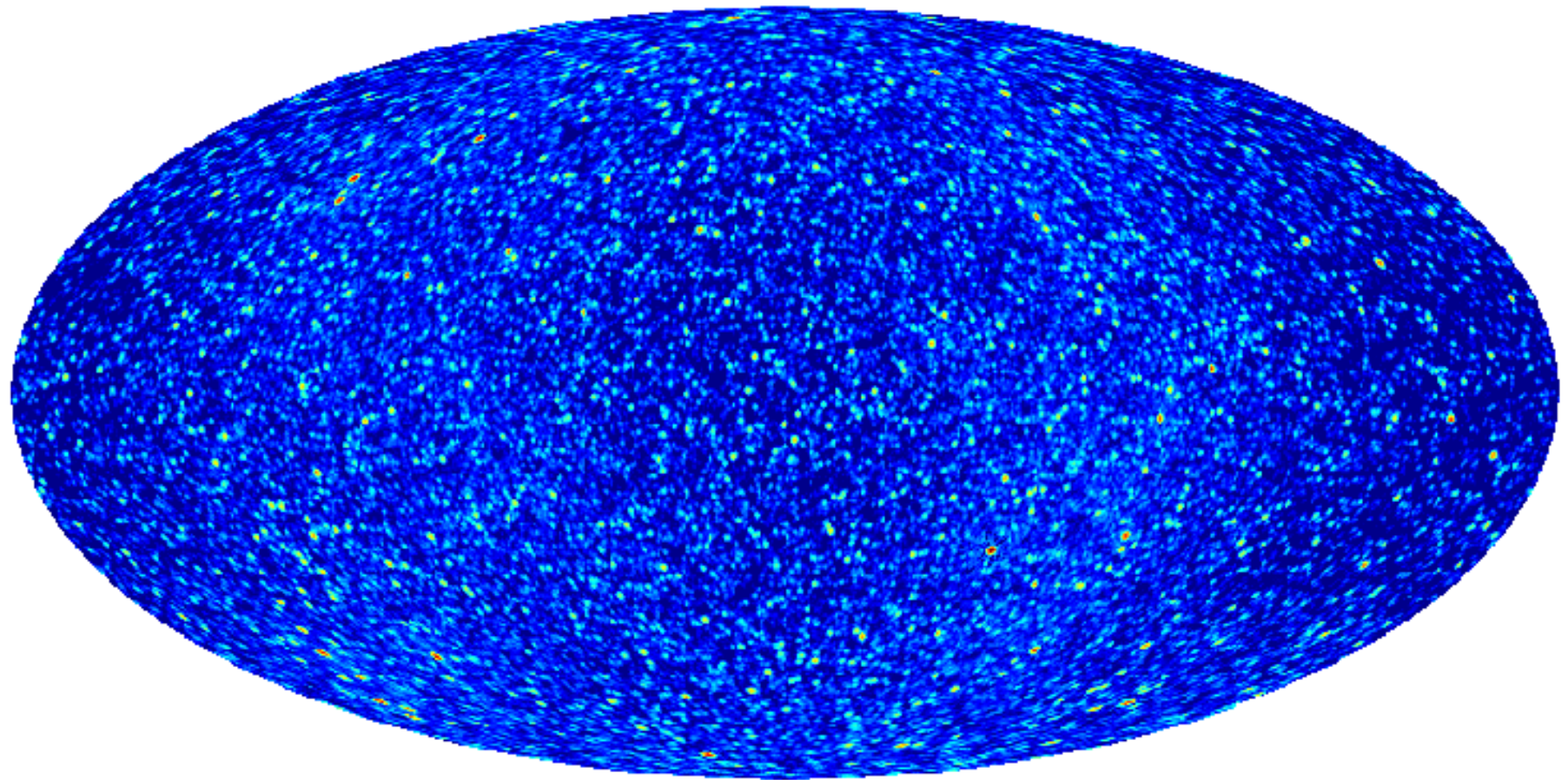
Milky Way halo seen in DM annihilation radiation

smooth main halo emission (MainSm)



Milky Way halo seen in DM annihilation radiation

emission from resolved subhalos (SubSm+SubSub)



-3.0 2.0 Log(Intensity)

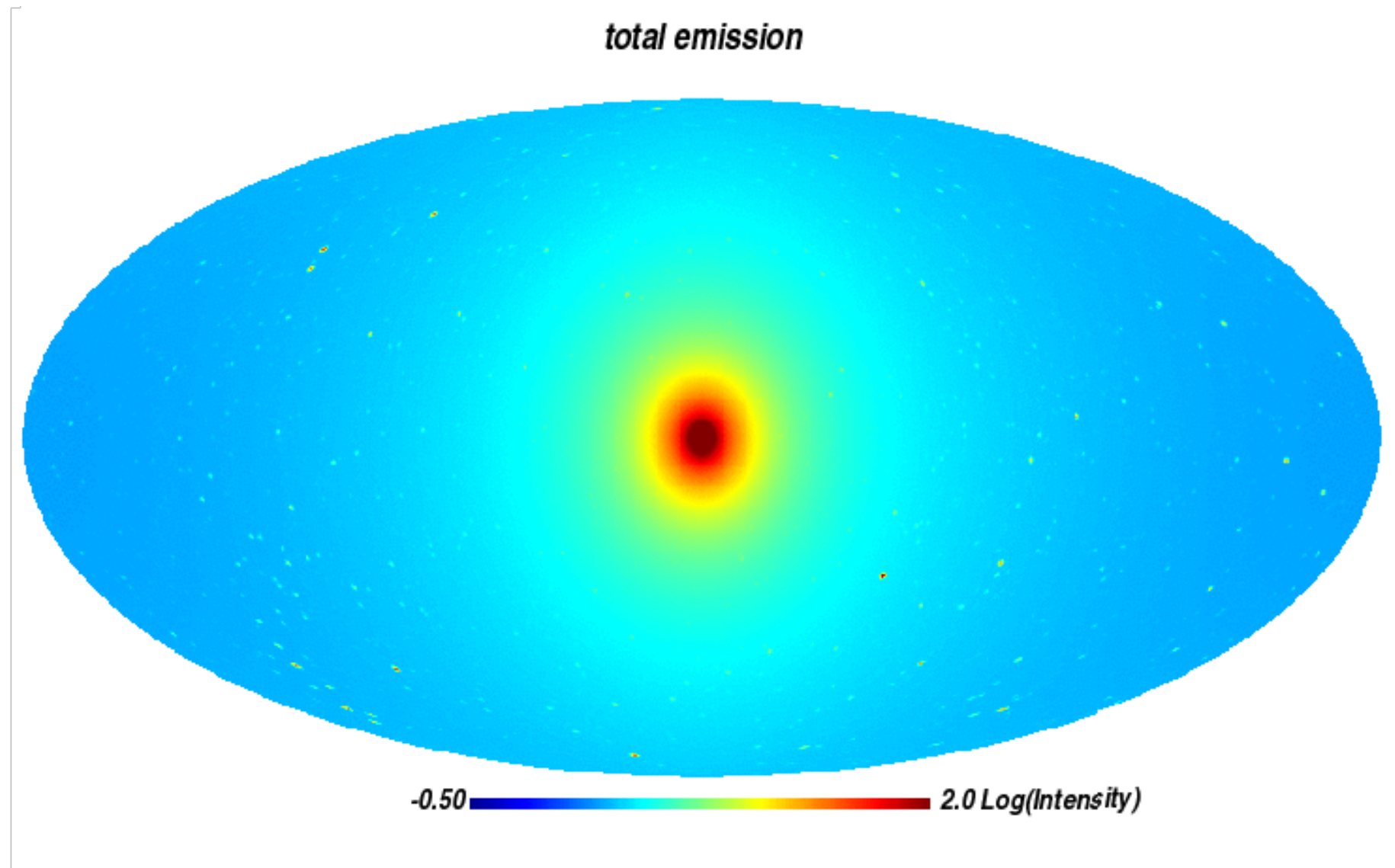
Milky Way halo seen in DM annihilation radiation

unresolved subhalo emission (MainUn)

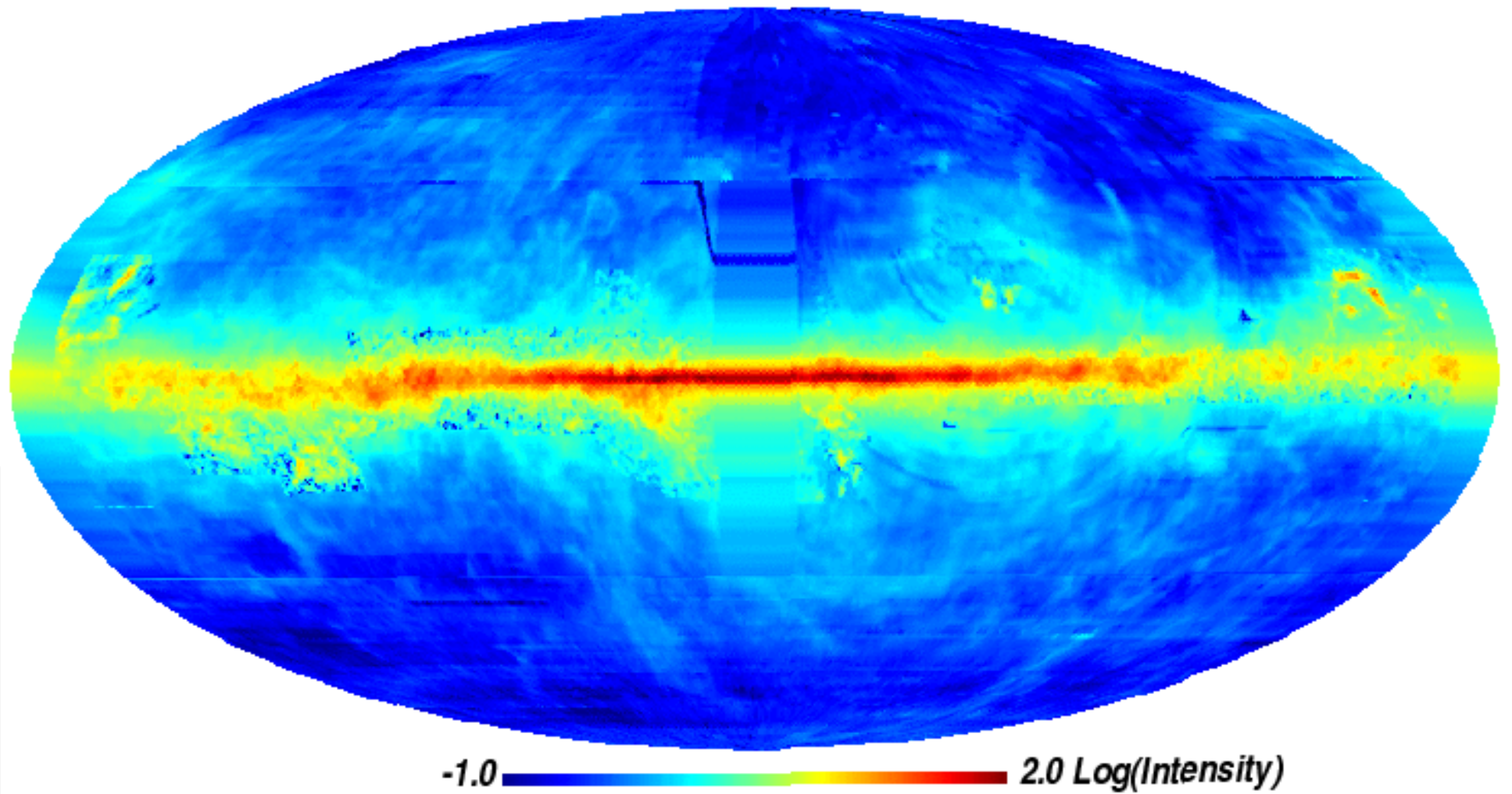


-0.50  2.0 Log(Intensity)

Milky Way halo seen in DM annihilation radiation



GALPROP, optimized

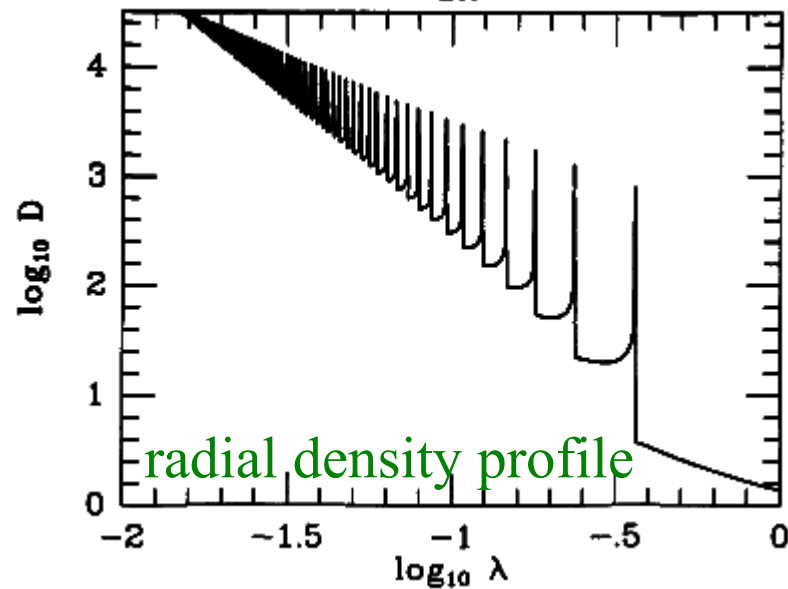
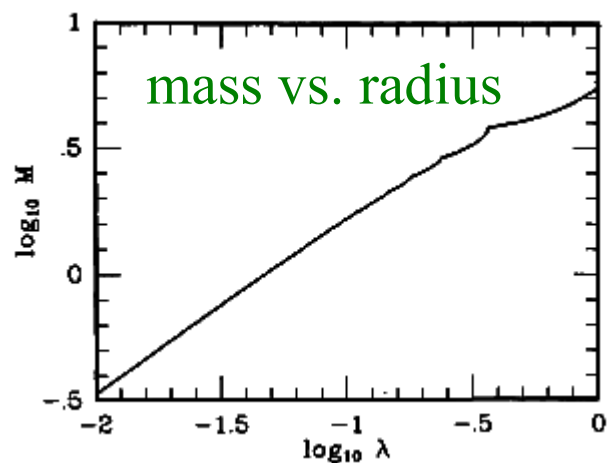
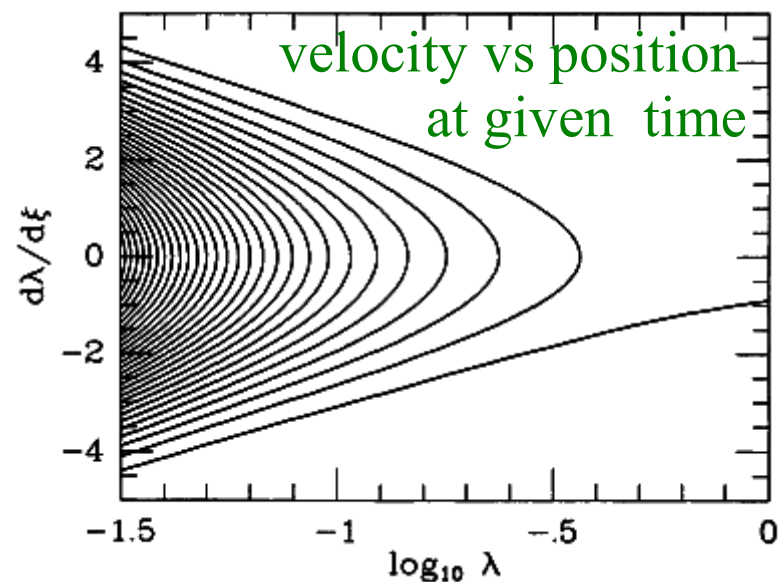
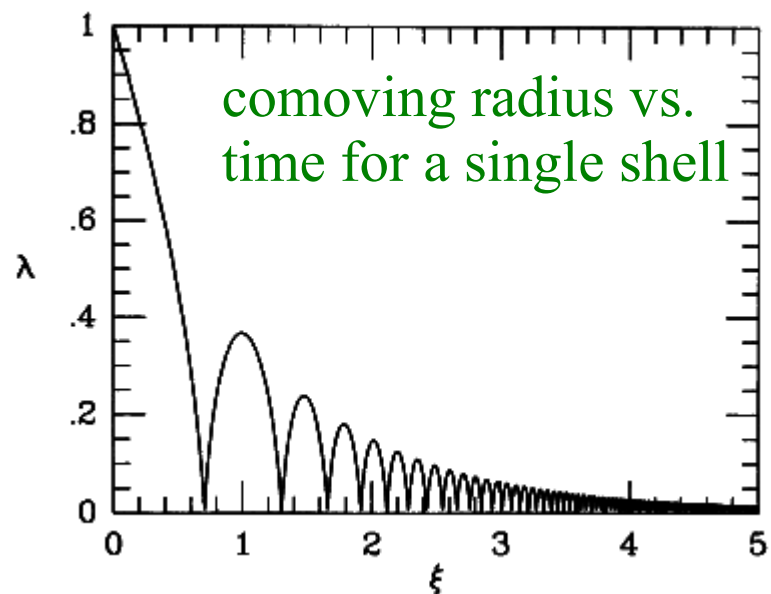


Conclusions about clumping and annihilation

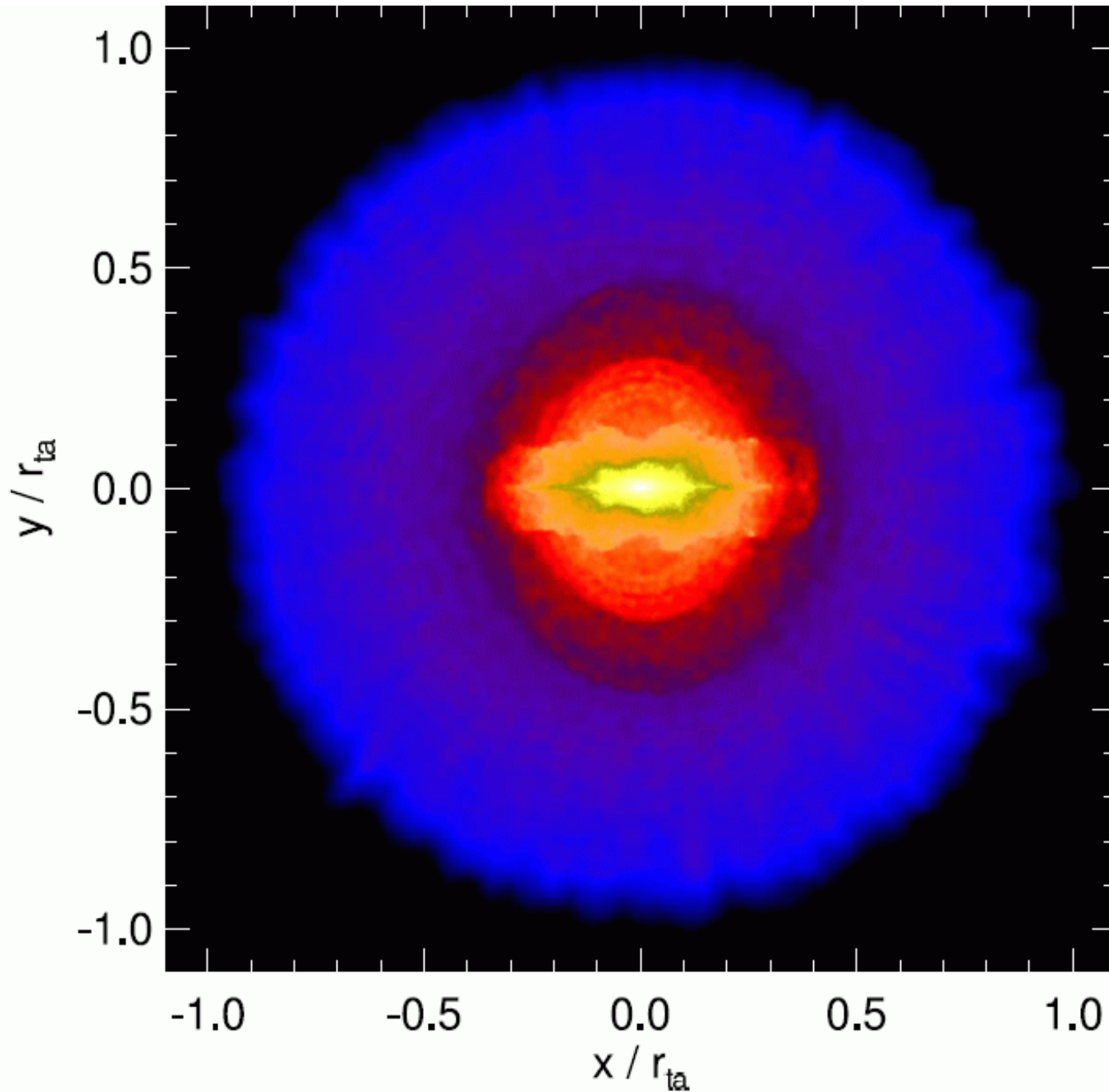
- Subhalos increase the MW's total flux within 250 kpc by a factor of 230 as seen by a distant observer, but its flux on the sky by a factor of only 2.9 as seen from the Sun
- The luminosity from subhalos is dominated by small objects and is nearly uniform across the sky (contrast is a factor of ~ 1.5)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

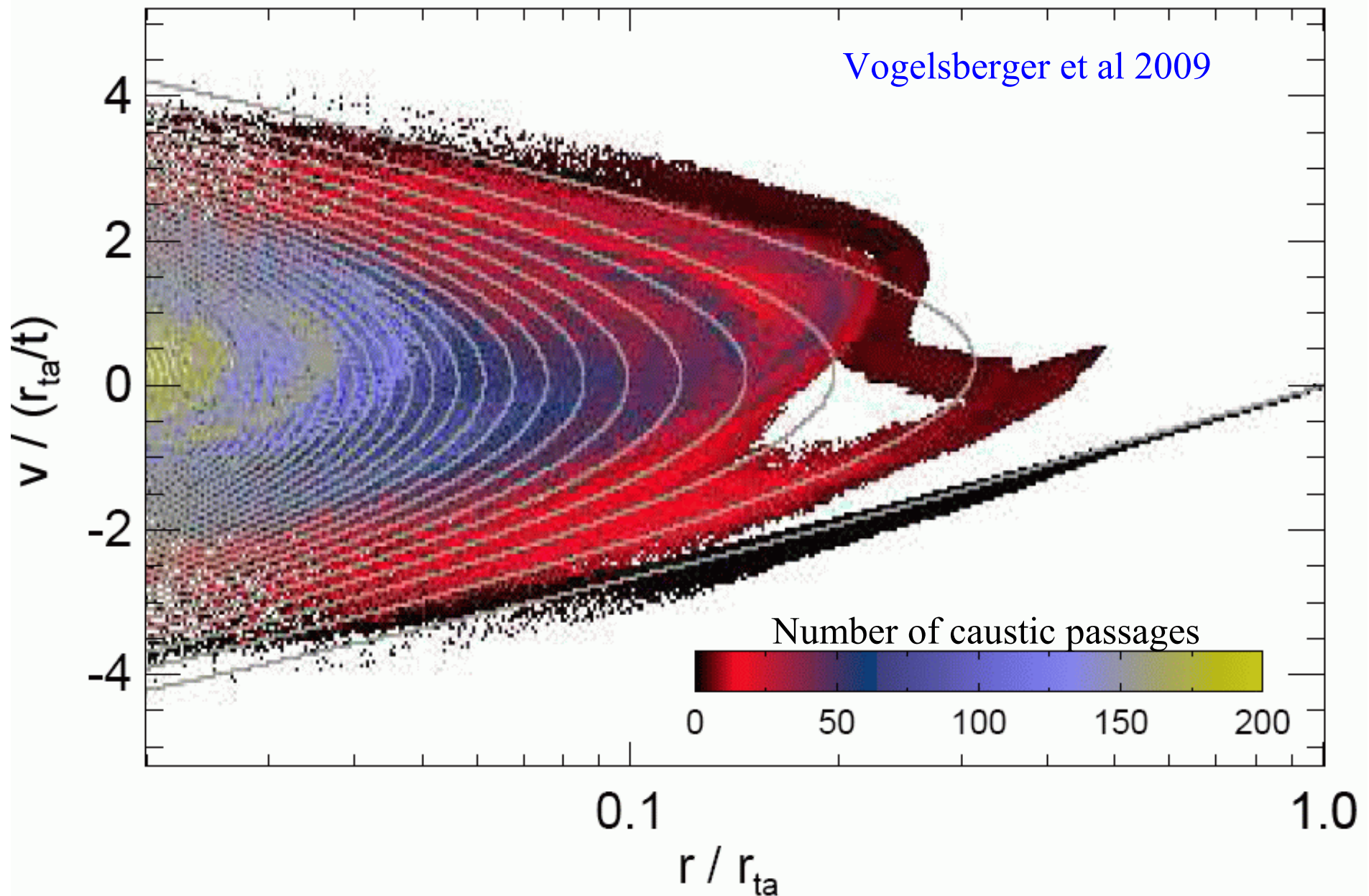


Vogelsberger et al 2009

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

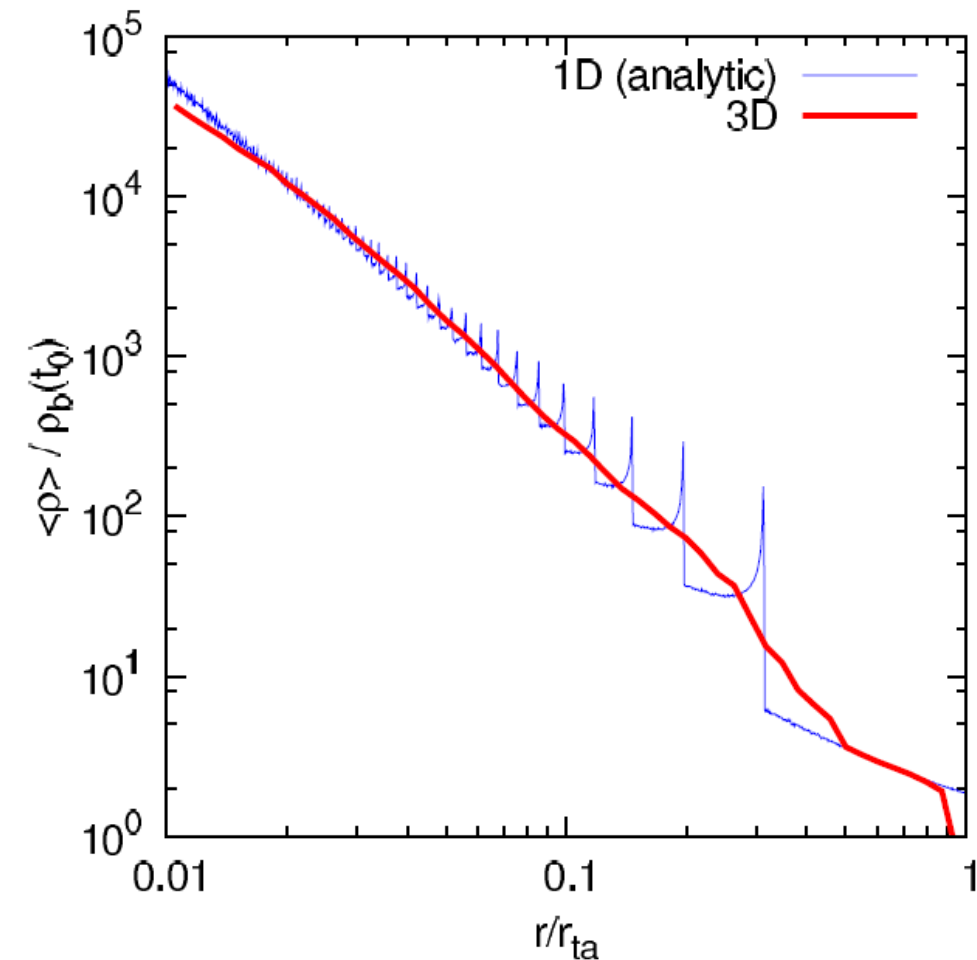
Simulation from self-similar spherical initial conditions

Geodesic deviation equation \longrightarrow phase-space structure local to each particle

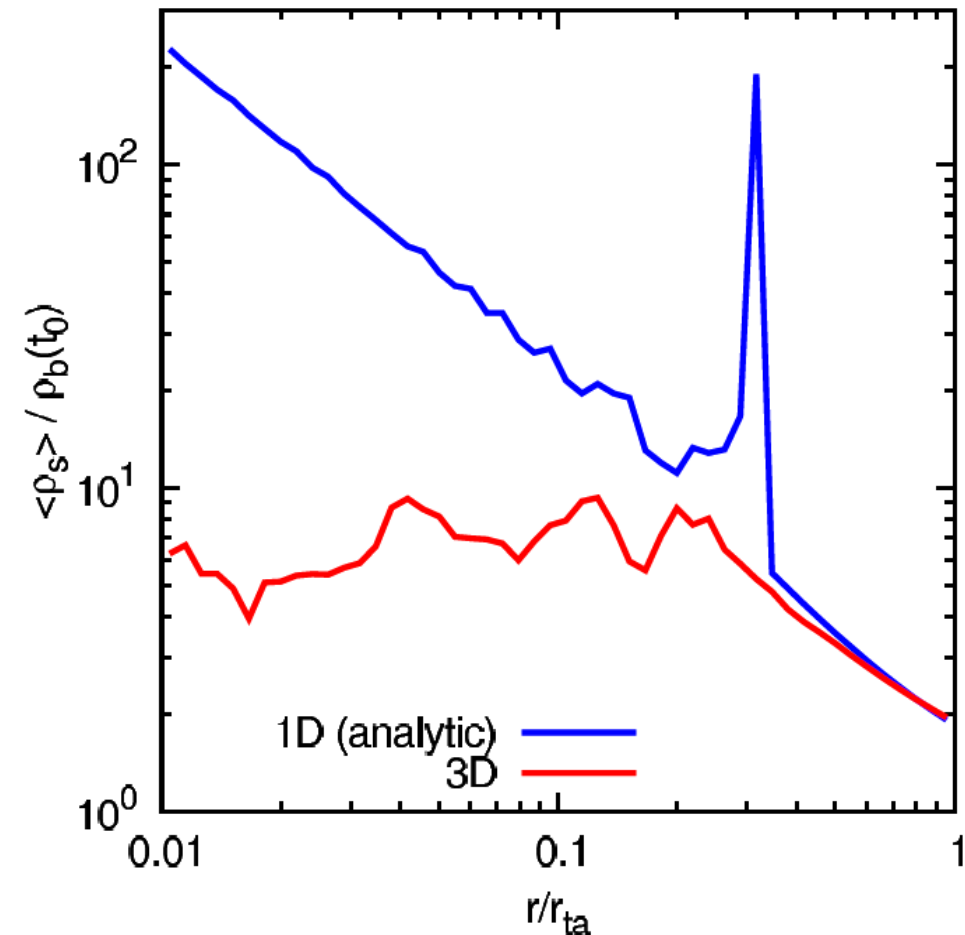


Simulation from self-similar spherical initial conditions

Vogelsberger et al 2009



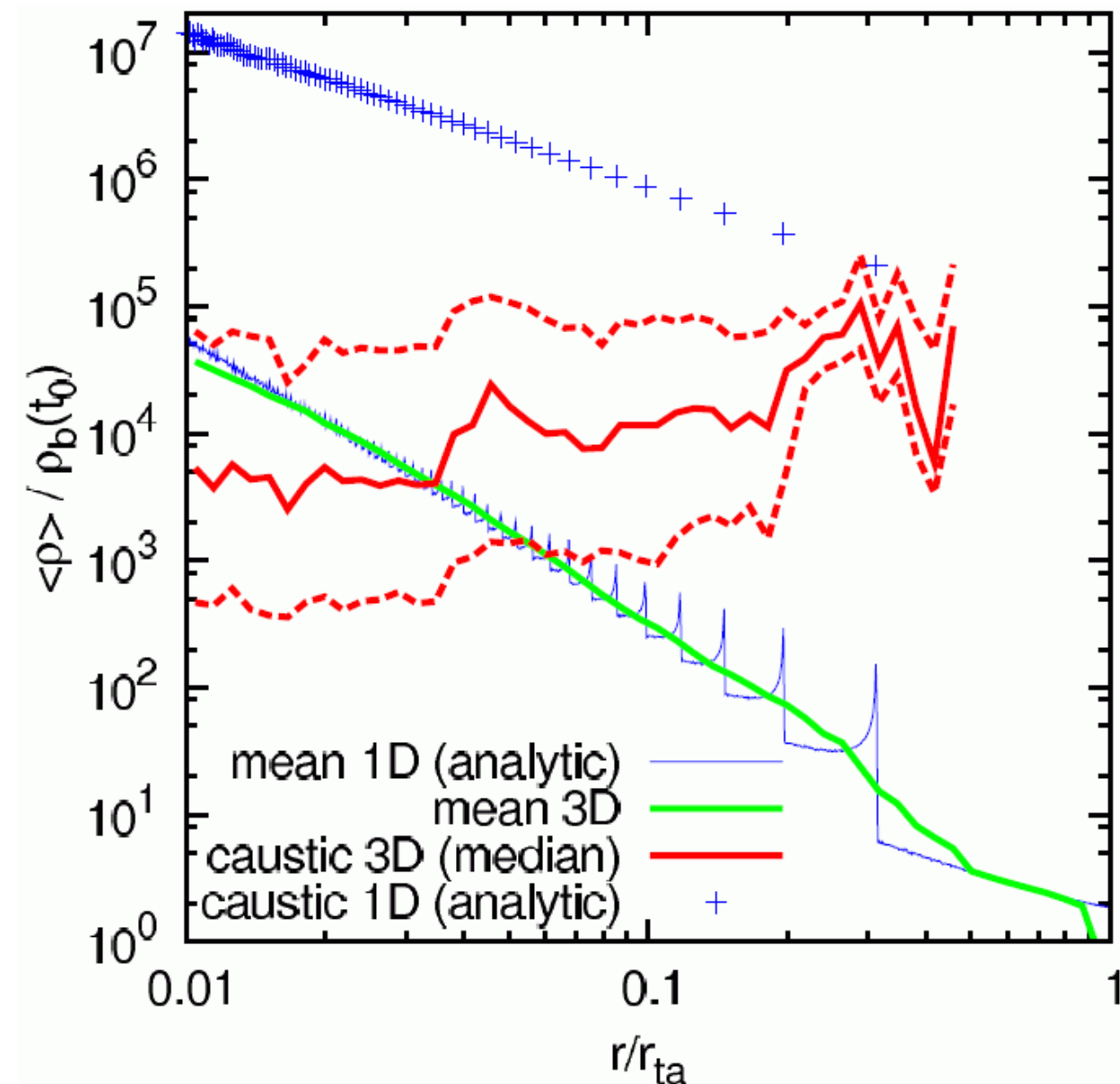
Radial density profile



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

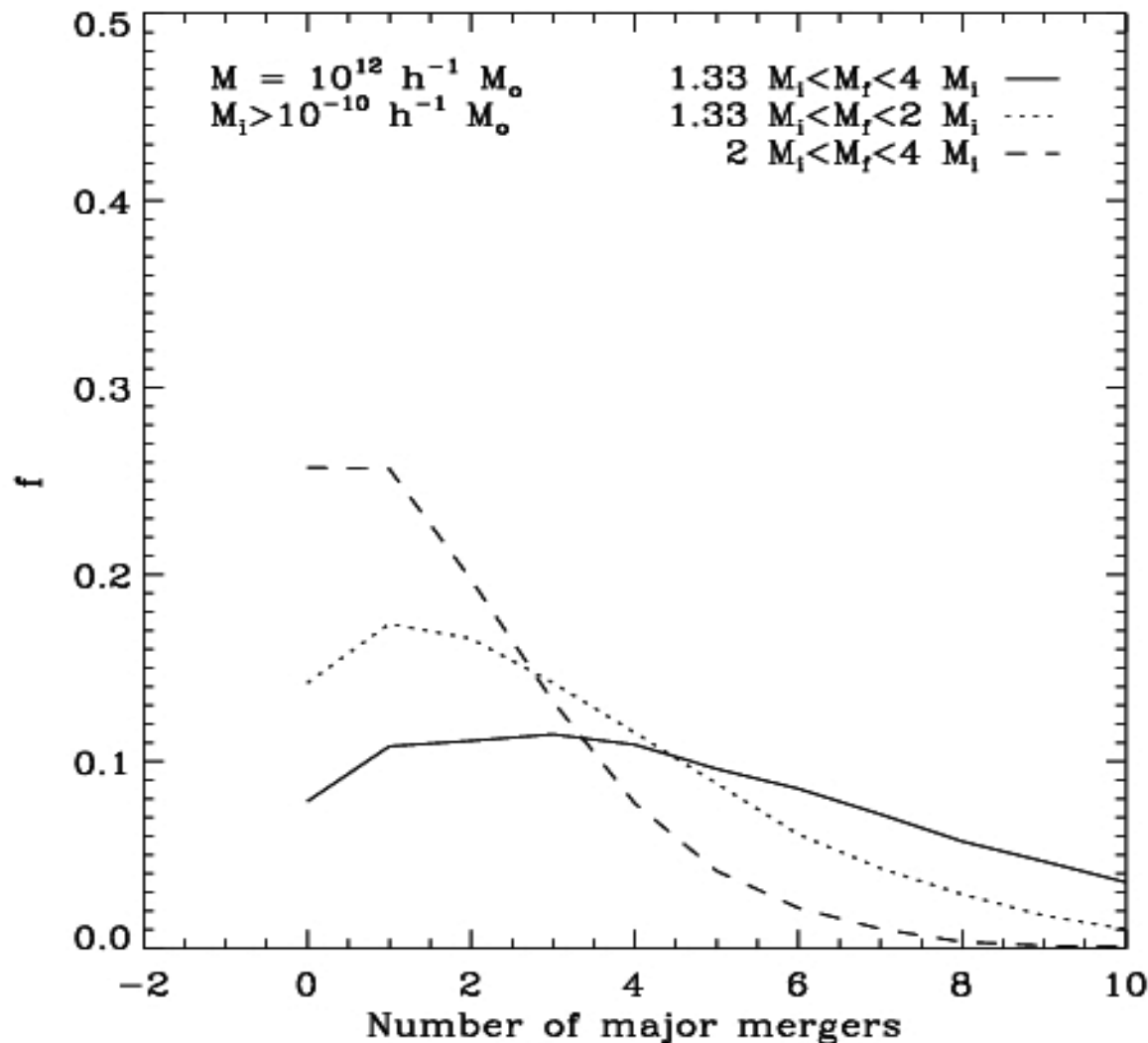
Conclusions about caustics and annihilation

- Caustics are less significant in realistic three-dimensional situations than in one-dimensional similarity solutions
- The annihilation luminosity from caustics is a small fraction of the total (e.g. $\sim 4\%$ of that outside 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

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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