January 2009

The Los Cabos Lectures

Dark Matter Halos: 3

Simon White
Max Planck Institute for Astrophysics

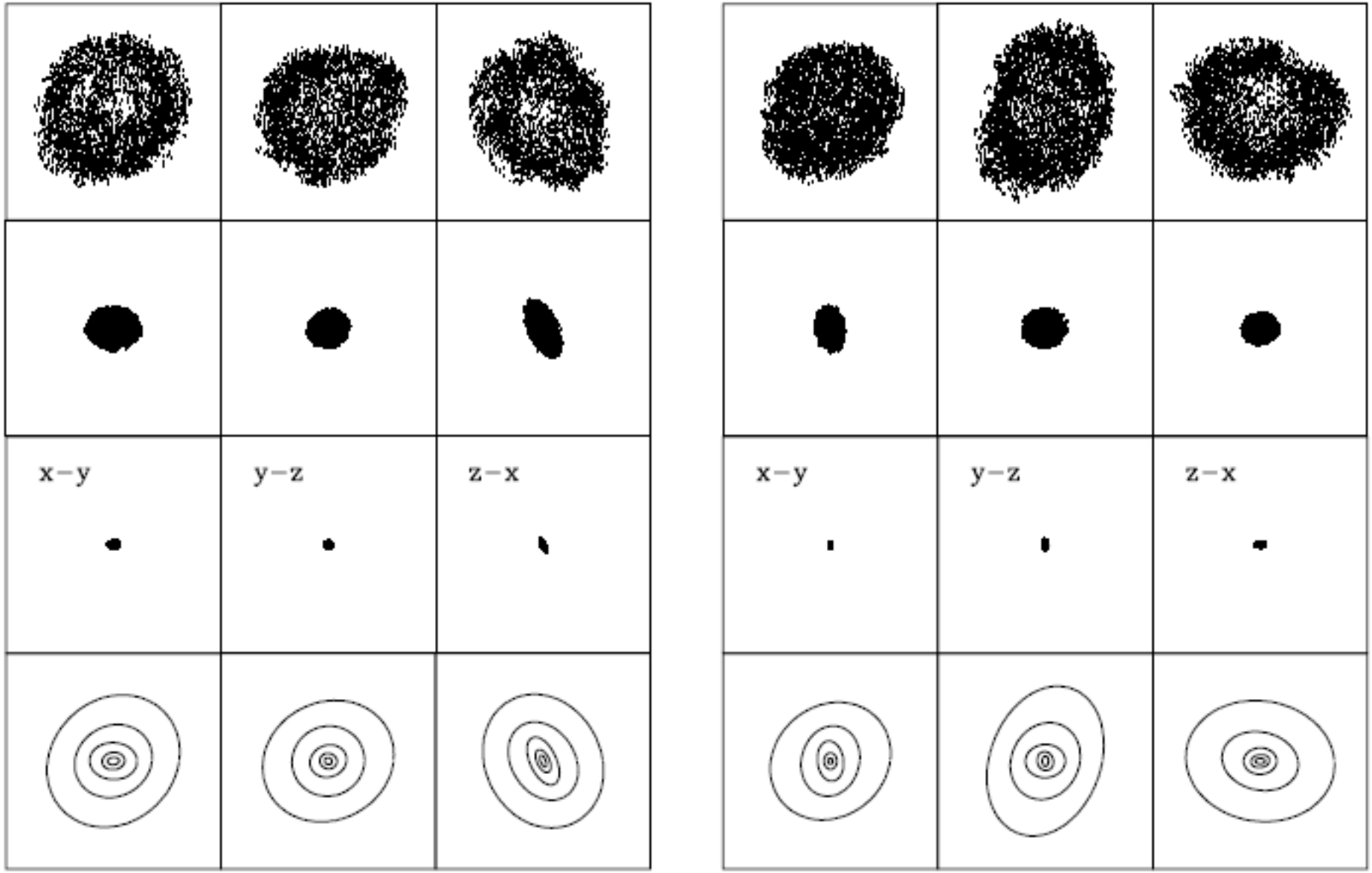
Shapes of halo equidensity surfaces

Group

Jing & Suto 2002

Galaxy

δ

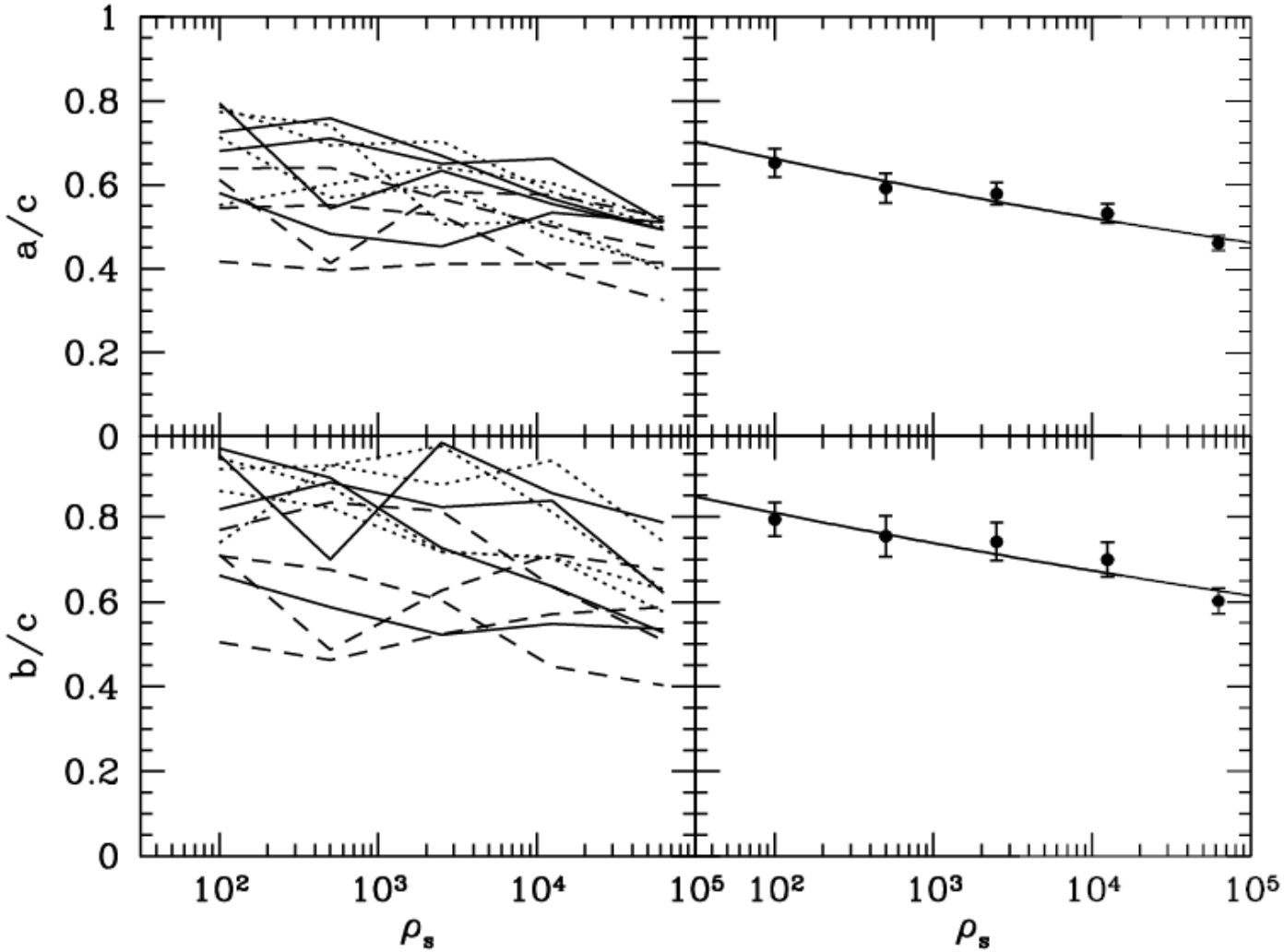


100

2500

6250

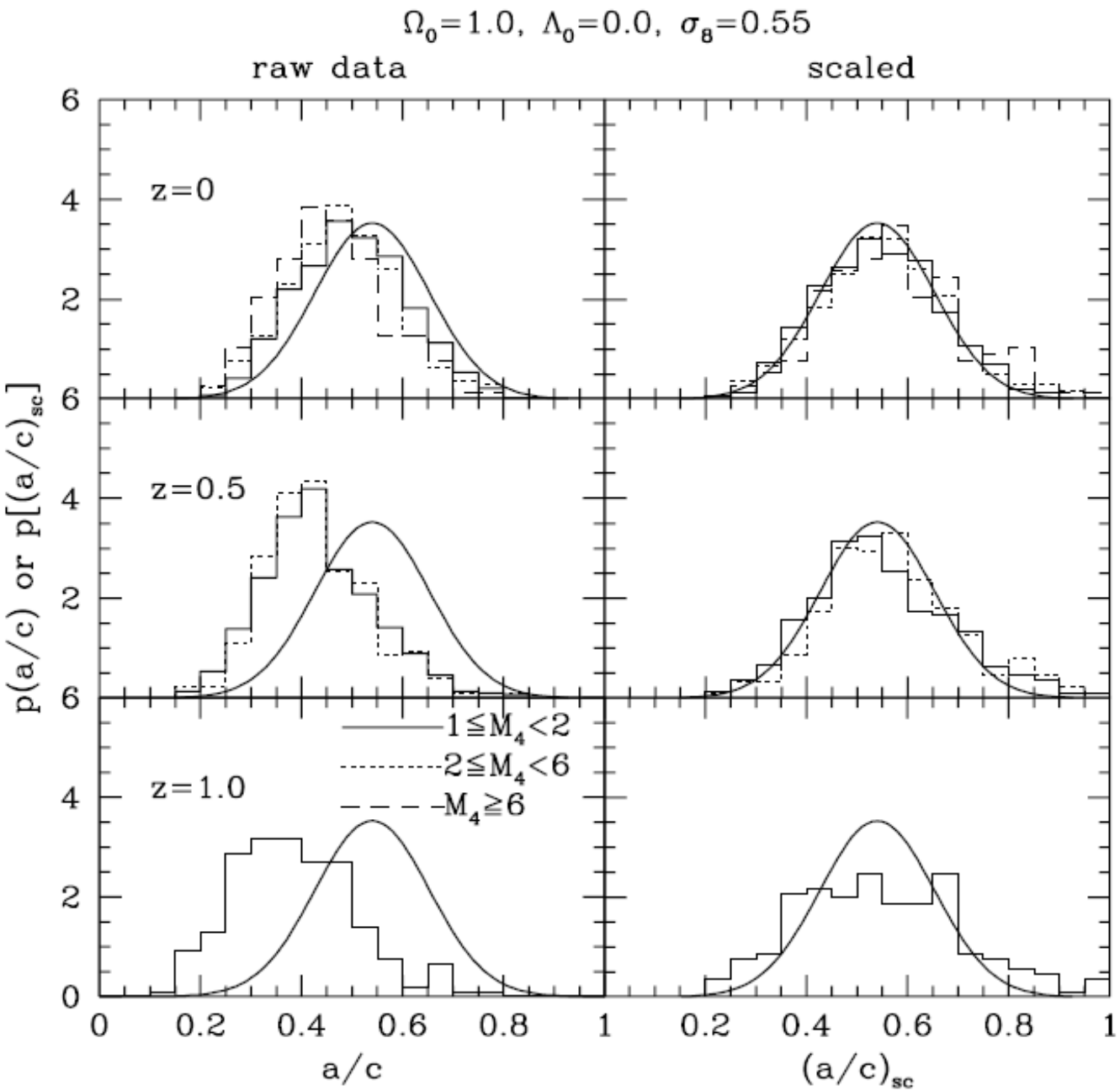
Shapes of halo equidensity surfaces



Jing & Suto 2002

Shapes become systematically less spherical with decreasing radius

Shapes of halo equidensity surfaces



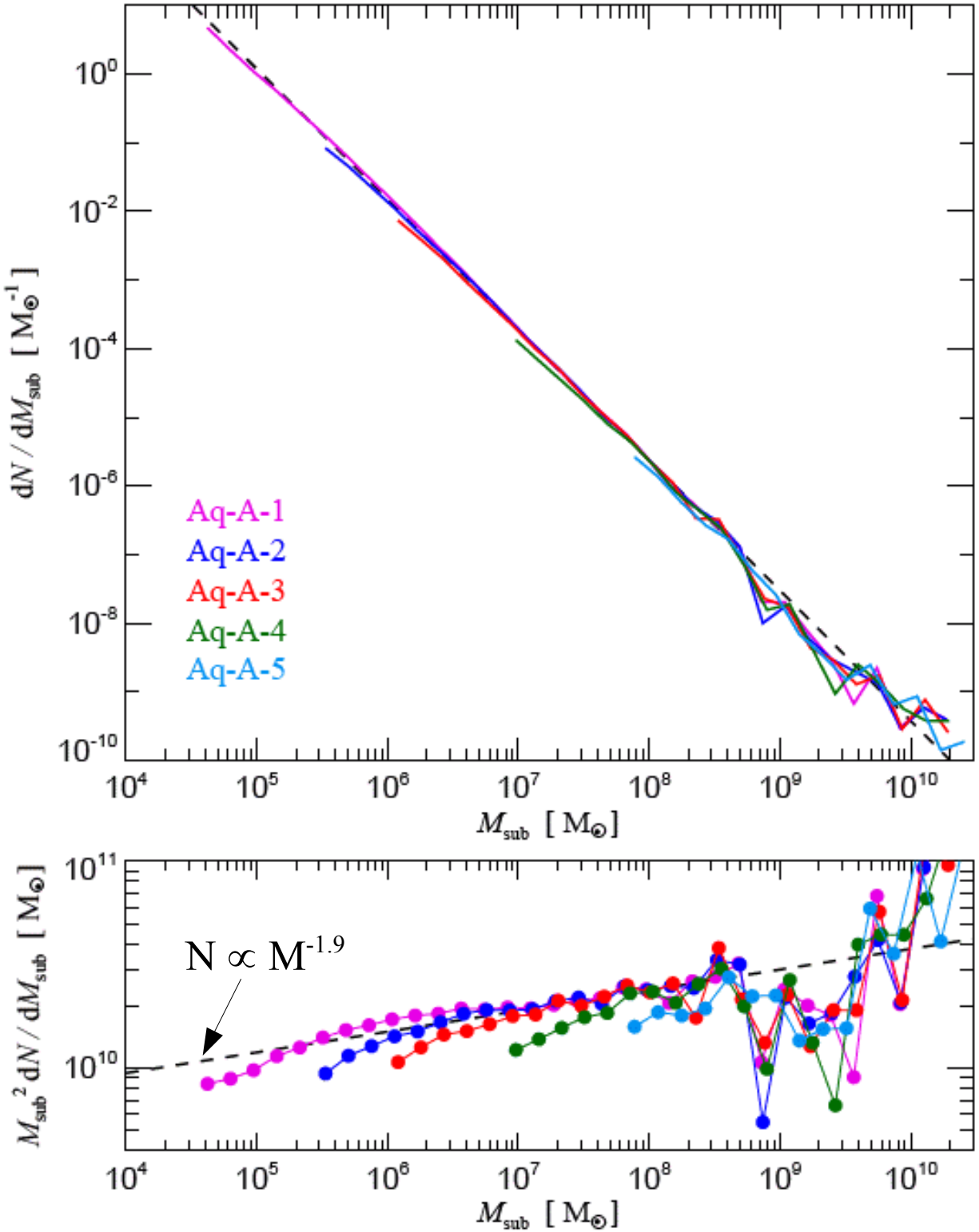
Jing & Suto 2002

Shapes become systematically less spherical with increasing mass

A simple scaling leaves a "universal" result for the axis ratio distributions

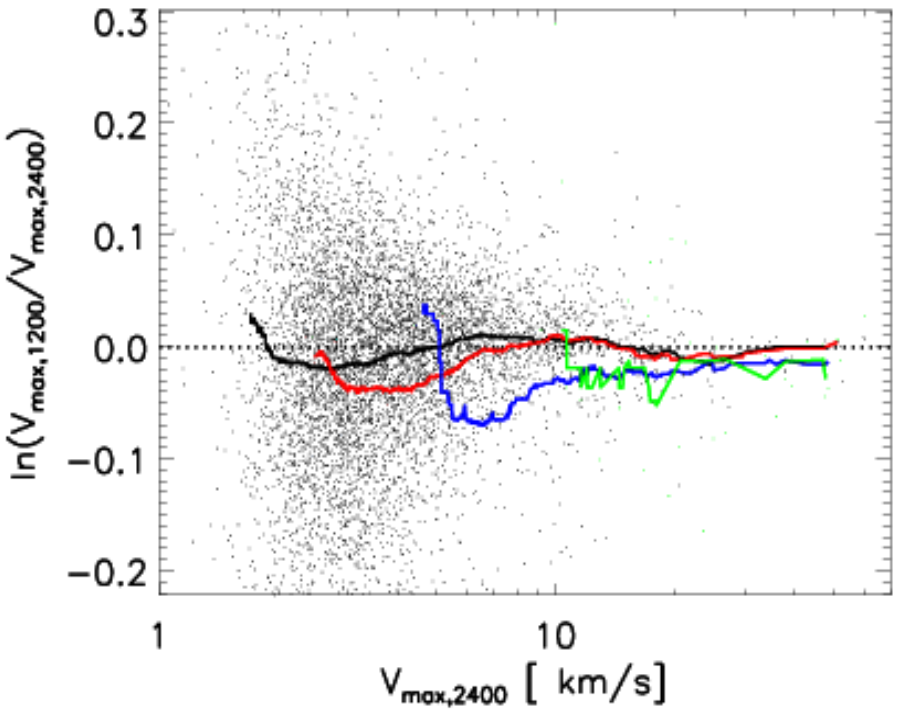
How well does substructure converge?

Springel et al 2008

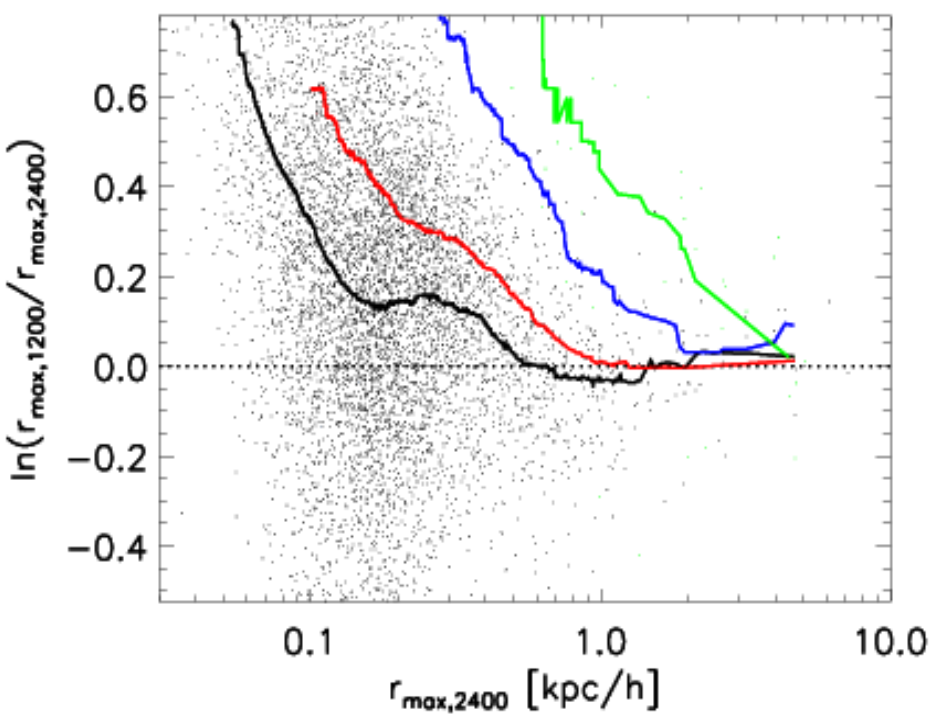


How well does substructure converge?

Aquarius Project: Springel et al 2008



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



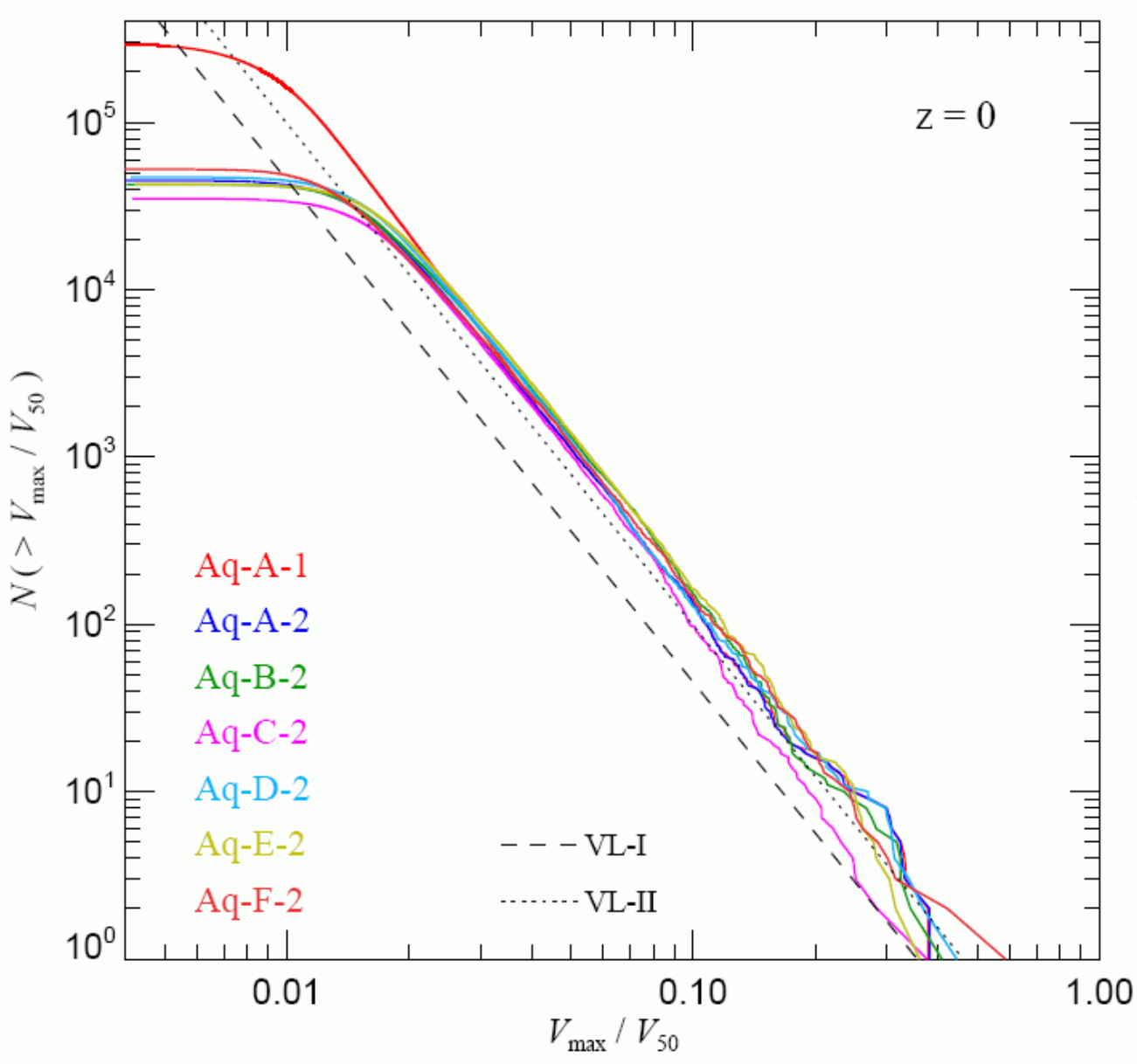
Biggest simulation gives convergent results for

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

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

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

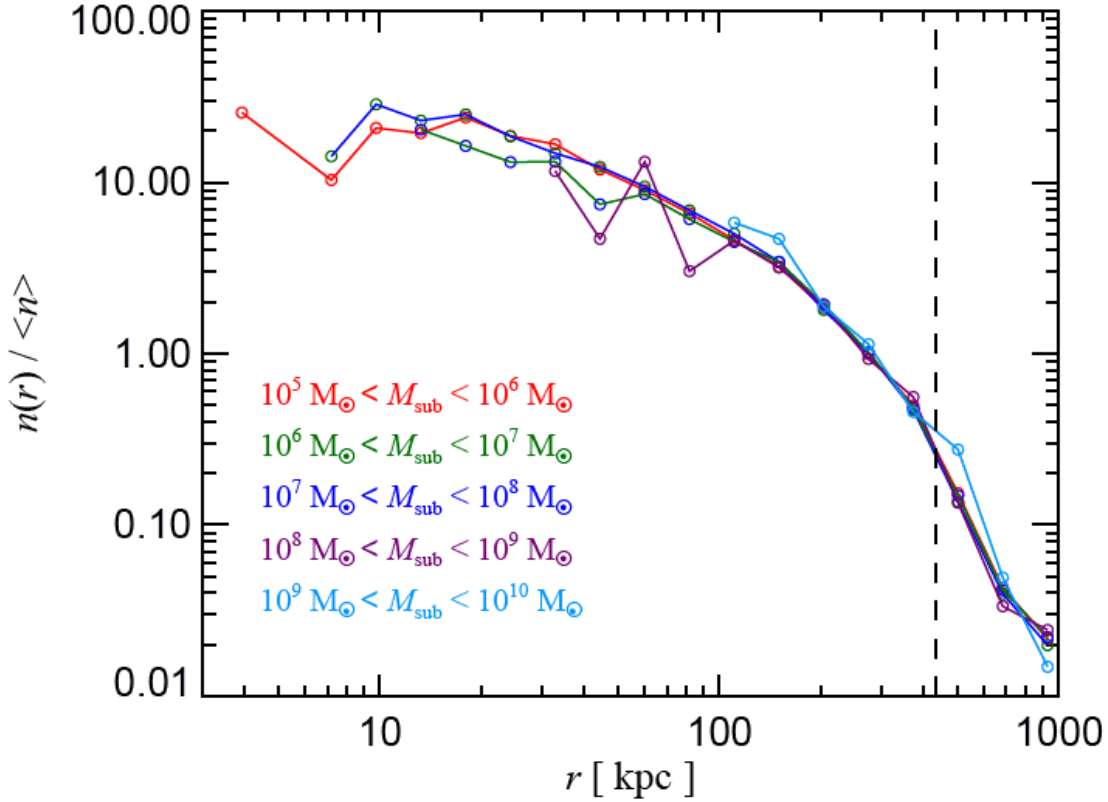
How uniform are subhalo populations?

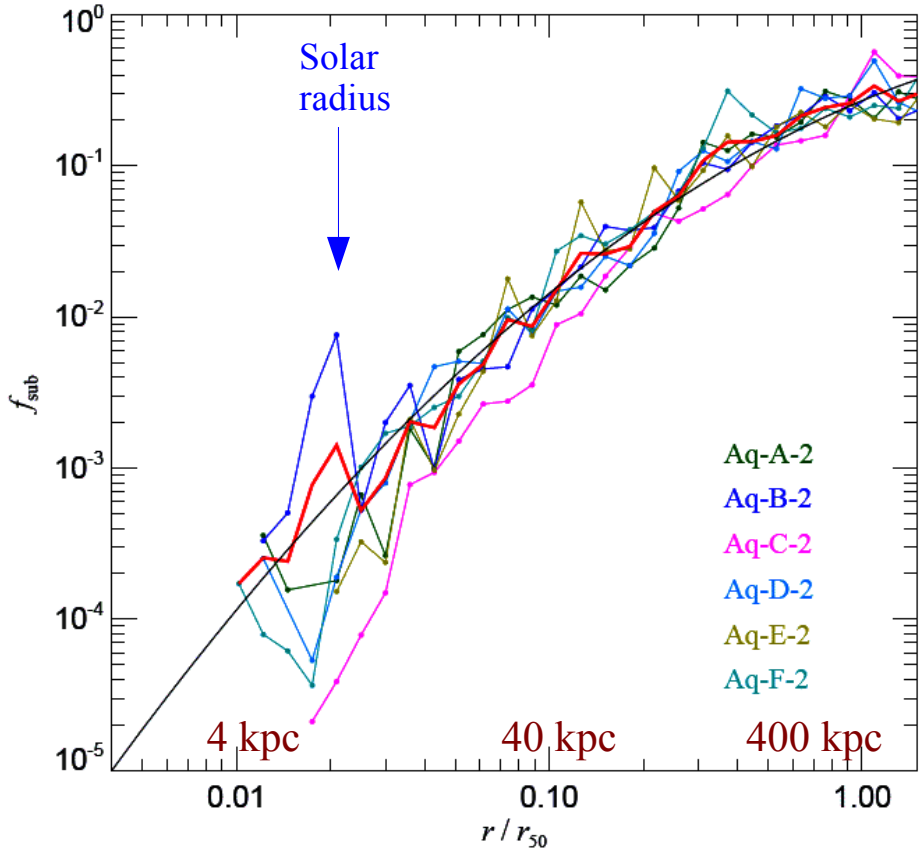


Springel et al 2008

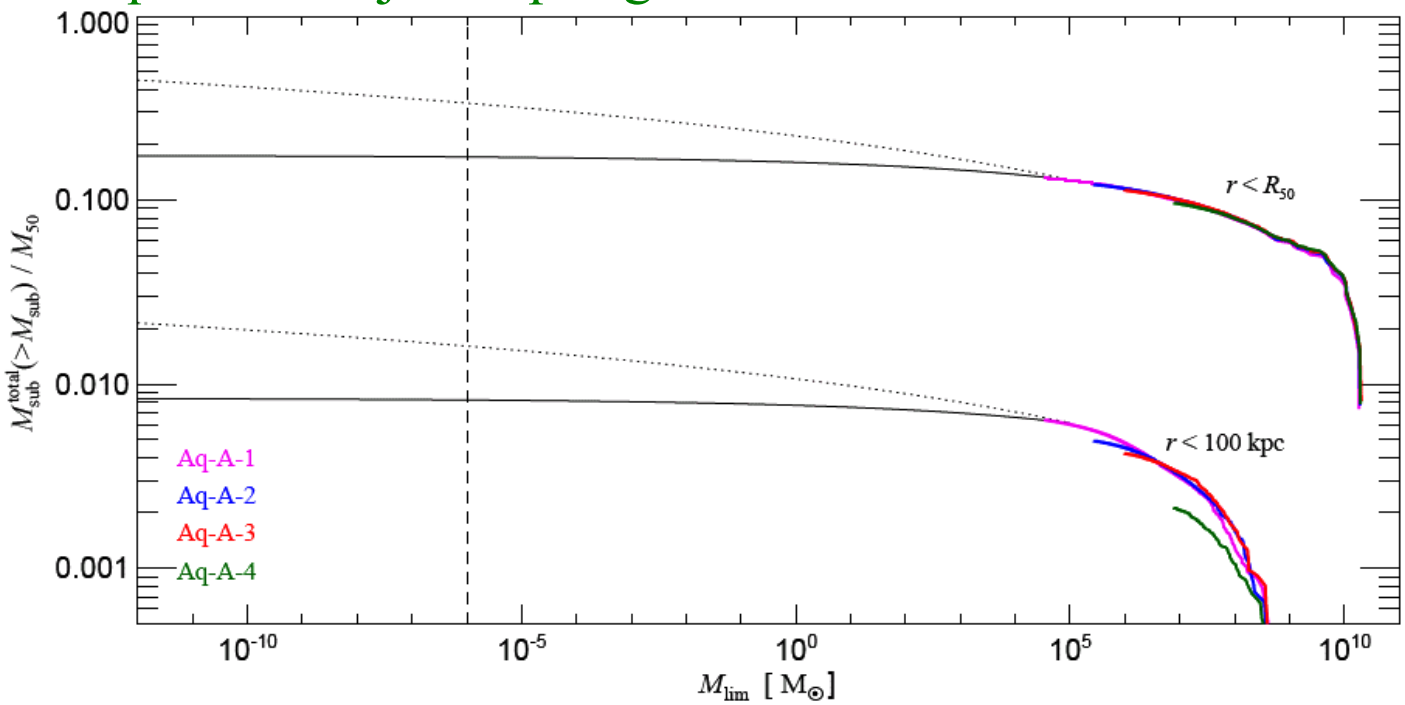
For the six Aquarius halos, the scatter in subhalo abundance is Poisson at high mass and ~20% at low mass

The Via Lactea simulations differ significantly





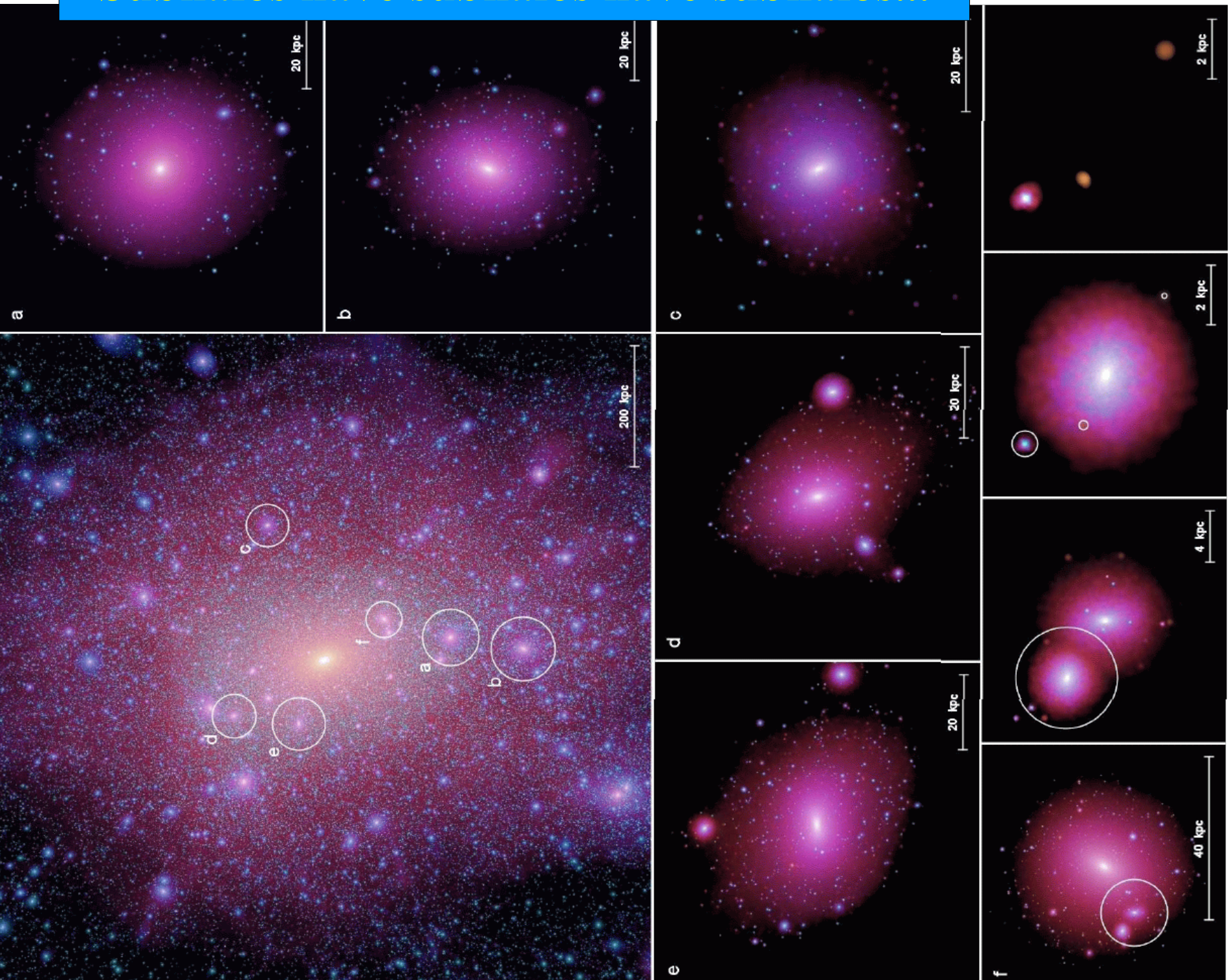
Aquarius Project: Springel et al 2008



- 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

Subhalos have subhalos have subhalos...

Springel et al 2008



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 small fraction of the mass in the inner halo

Small-scale structure of the CDM distribution

- Direct detection involves bolometers/cavities of meter scale which are sensitive to particle momentum
  - -- what is the density structure between m and kpc scales?
  - -- how many streams intersect the detector at any time?

- Intensity of annihilation radiation depends on

$$\int \rho^2(\boldsymbol{x}) \langle \sigma v \rangle \, dV$$

  - -- what is the density distribution around individual CDM particles on the annihilation interaction scale?

Predictions for detection experiments depend on the CDM distribution on scales <u>far</u> below those accessible to simulation

→ We require a good theoretical understanding of mixing and small-scale structure

Dectectability issues for the CDM distribution

- Laboratory experiments
  What is the expected CDM distribution in space and in velocity on the scale of the apparatus?

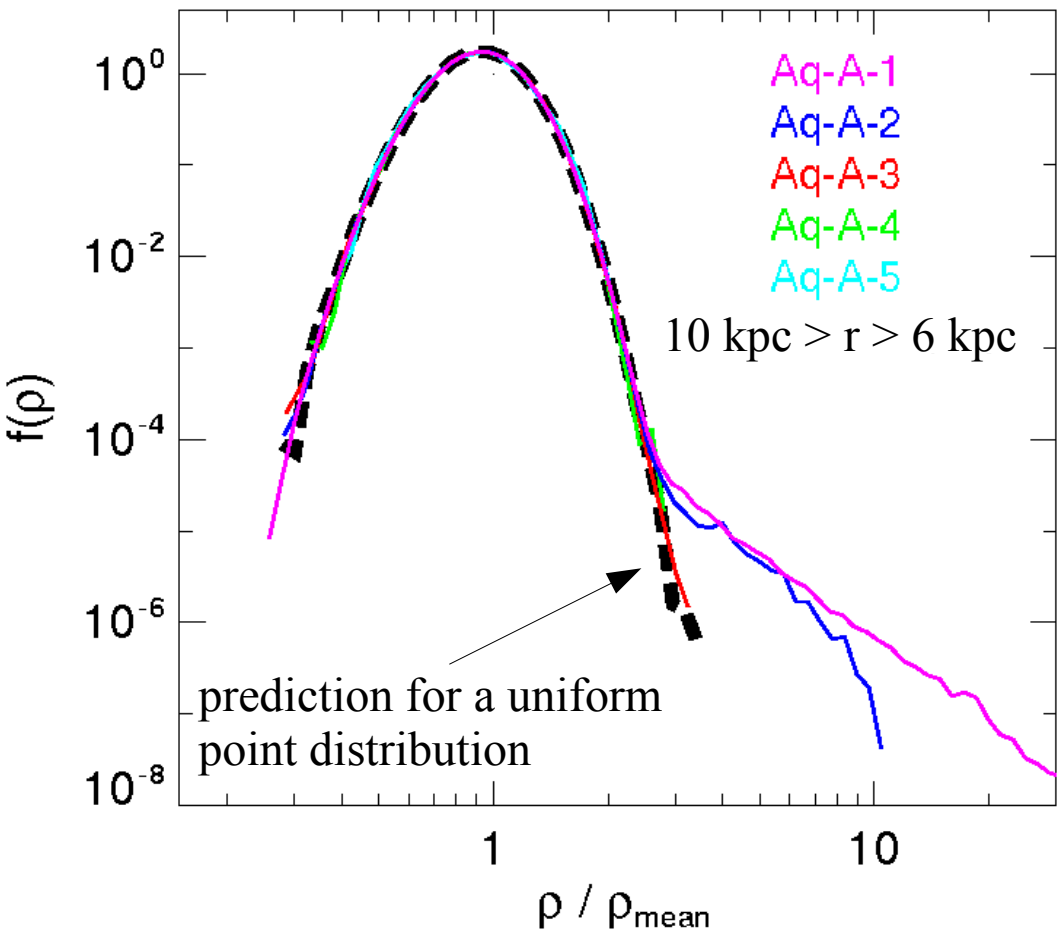
- Small-scale clumping
  How much γ-emission comes from small clumps?
  Which structures should be most easily detected?

- Unbound phase-space structure
  How much γ-emission comes from caustics?

- Galactic Centre
  How much γ-emission comes from the black hole's cusp?

Density relative to a smooth ellipsoidal model

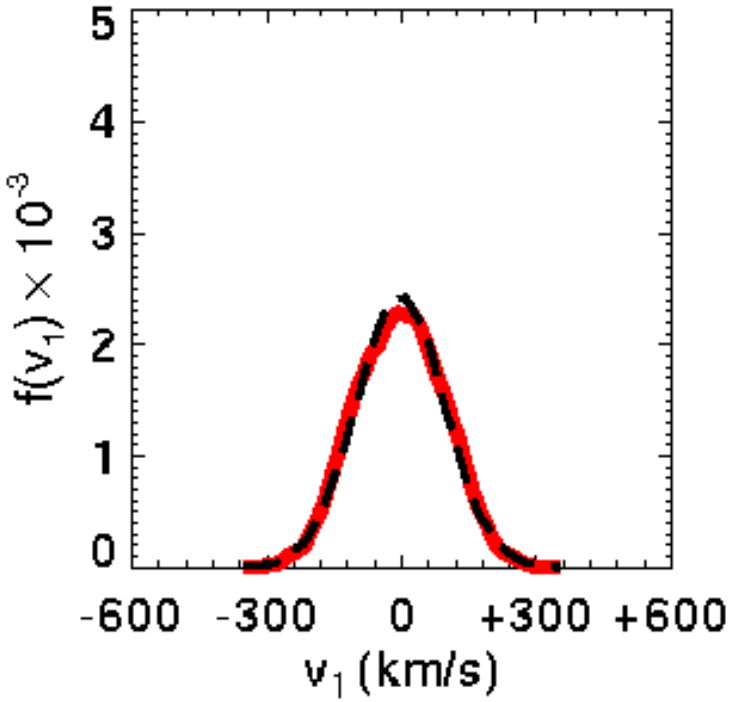
Vogelsberger et al 2008

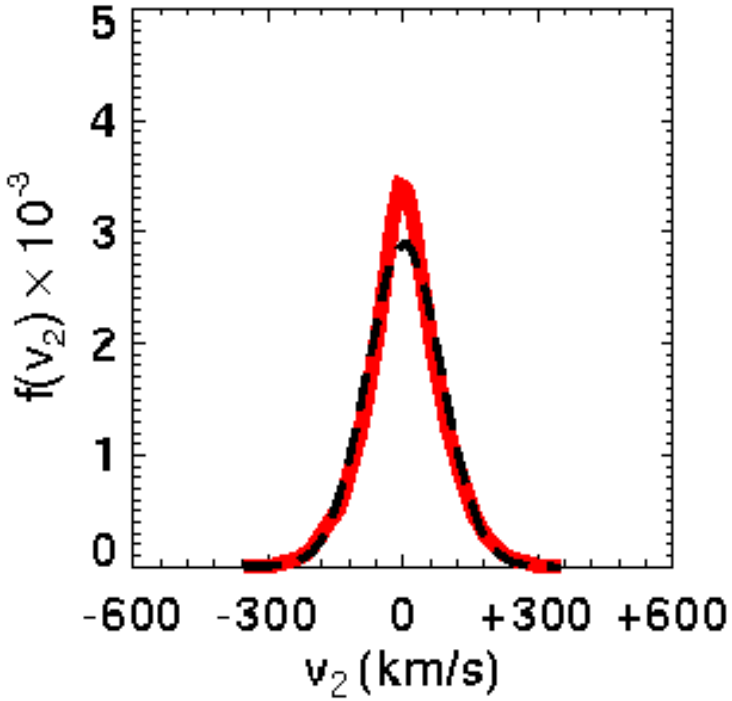


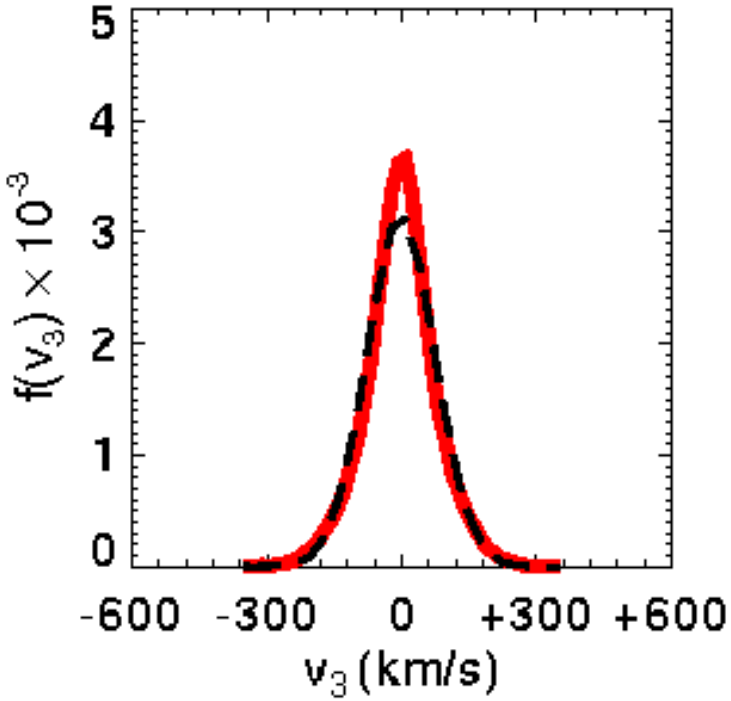
- Estimate a density ρ at each point by adaptively smoothing using the 64 nearest particles
- Fit to a smooth density profile stratified on similar ellipsoids
- The chance of a random point lying in a substructure is $< 10^{-4}$
- The *rms* scatter about the smooth model for the remaining points is only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

Local velocity distribution

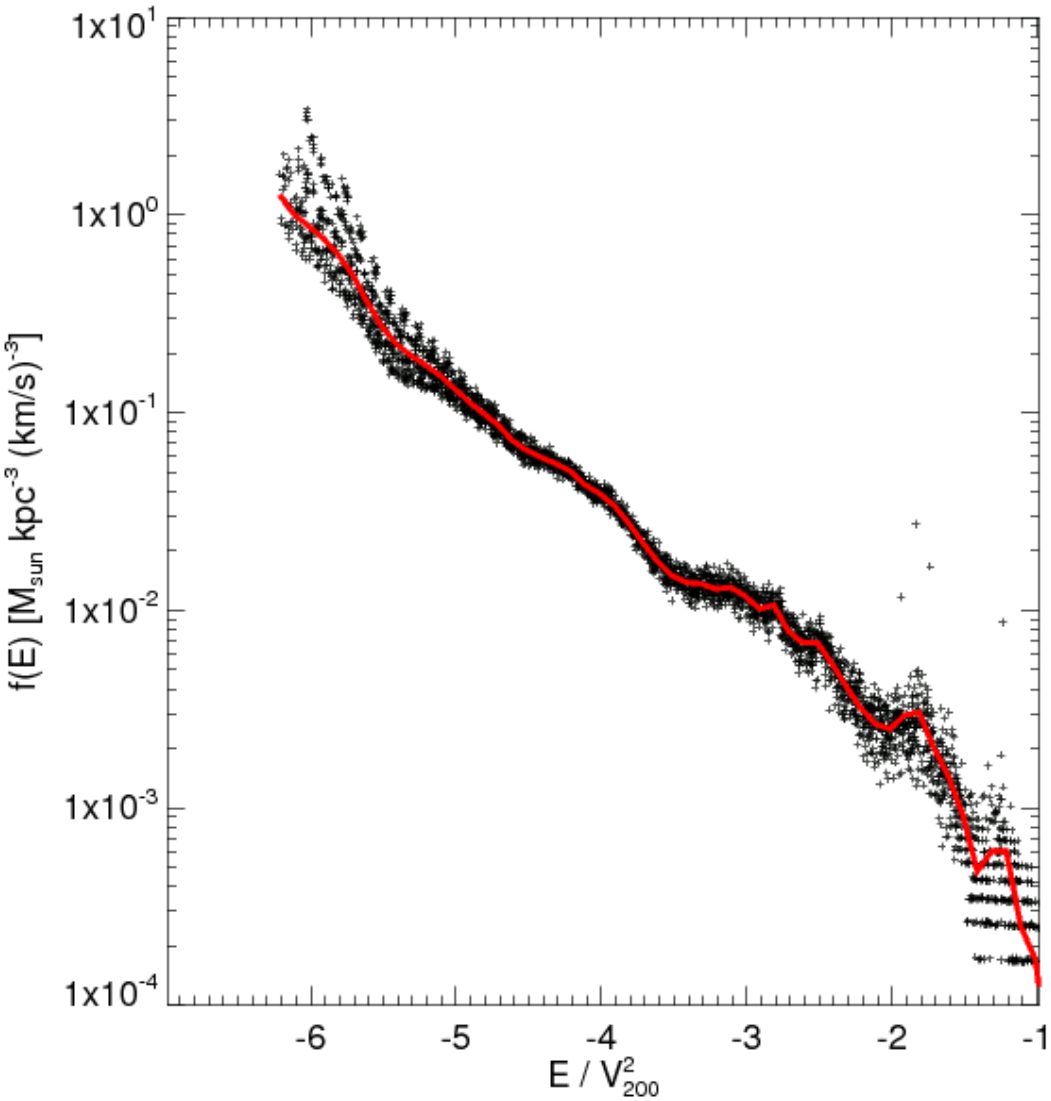
- Velocity histograms for particles in a typical $(2\text{kpc})^3$ box at R = 8 kpc
- Distributions are smooth, near-Gaussian and different in different directions
- No individual streams are visible







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

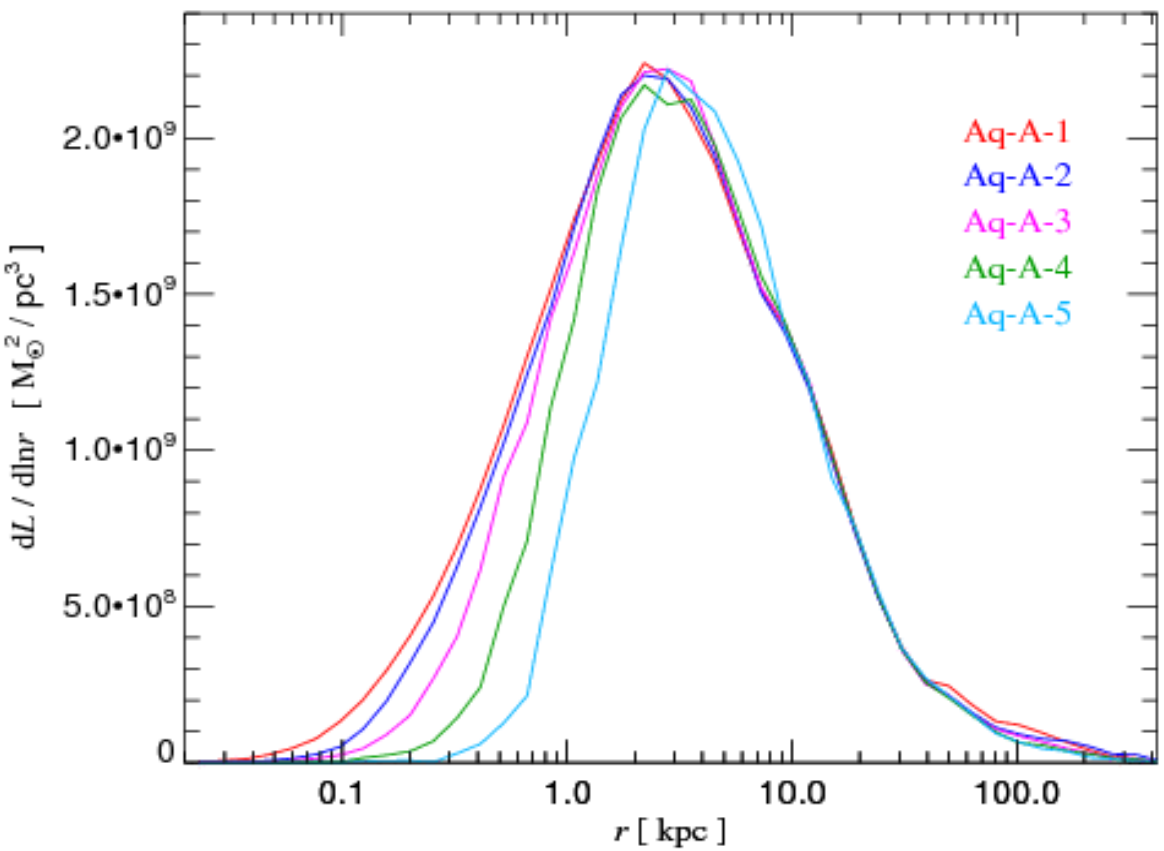
- With more than 99.9% confidence the Sun lies in a region where the DM density differs from the smooth mean value by < 20%

- 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

Convergence of annihilation luminosity of main halo

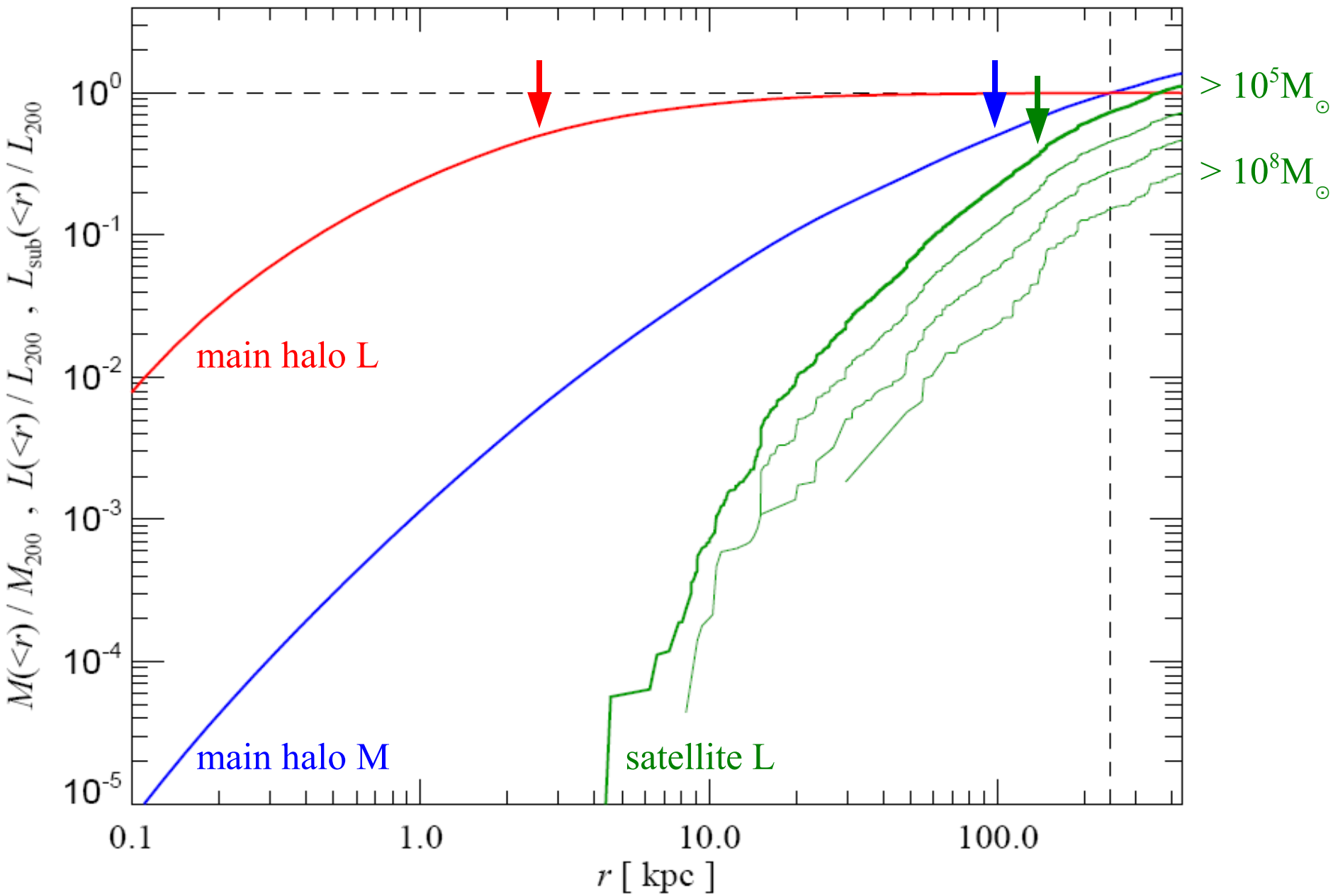
Springel et al 2008



- Distribution has converged at the percent level for the main halo
- Most emission comes from 0.5 kpc < r < 20 kpc
- Emission is not converged for most subhalos but should scale as V^4_{max} / r_{max}
- This estimate is converged for $V_{max} > 1.5$ km/s
  $r_{max} > 165$ pc

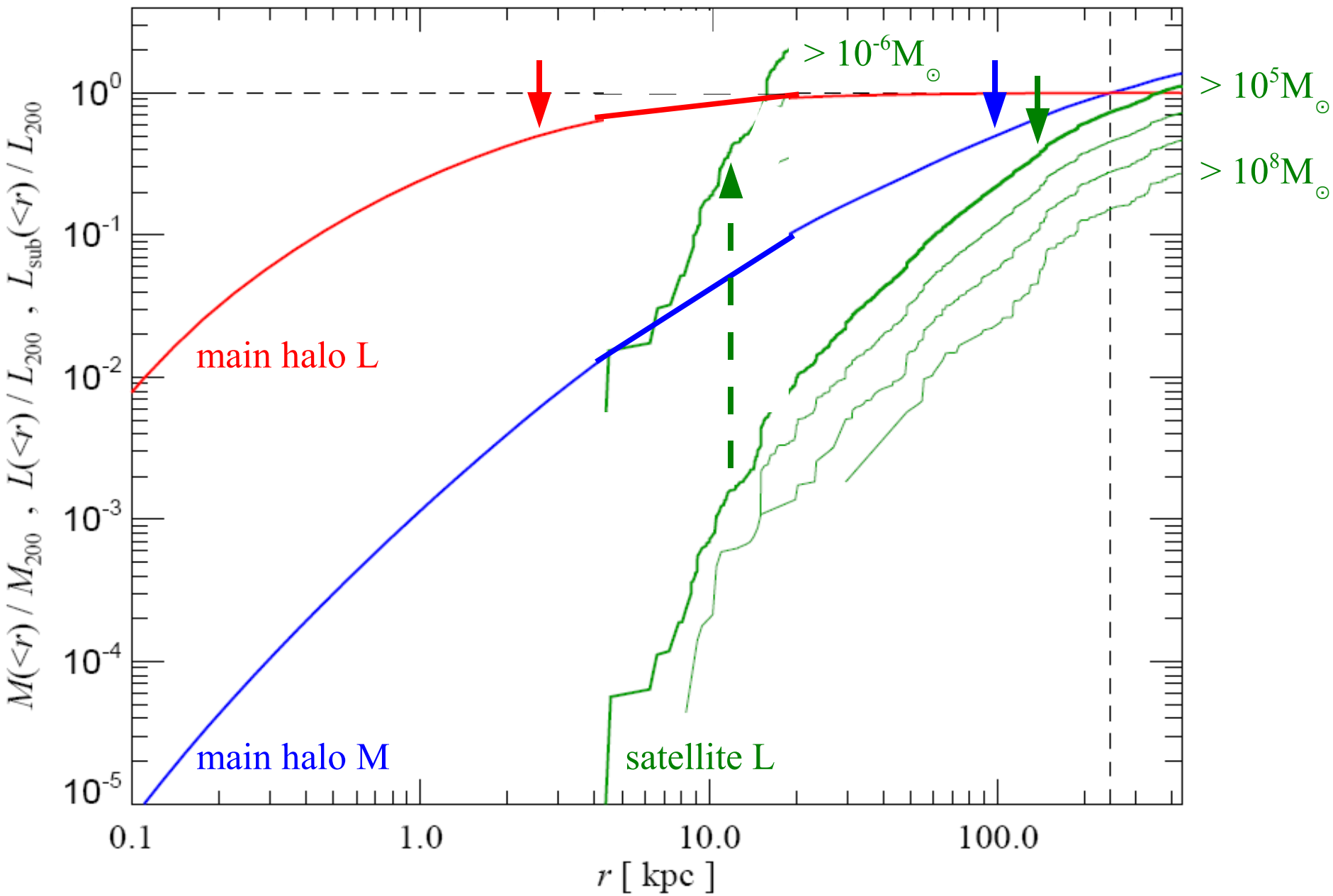
Mass and annihilation radiation profiles of a MW halo

Springel et al 2008



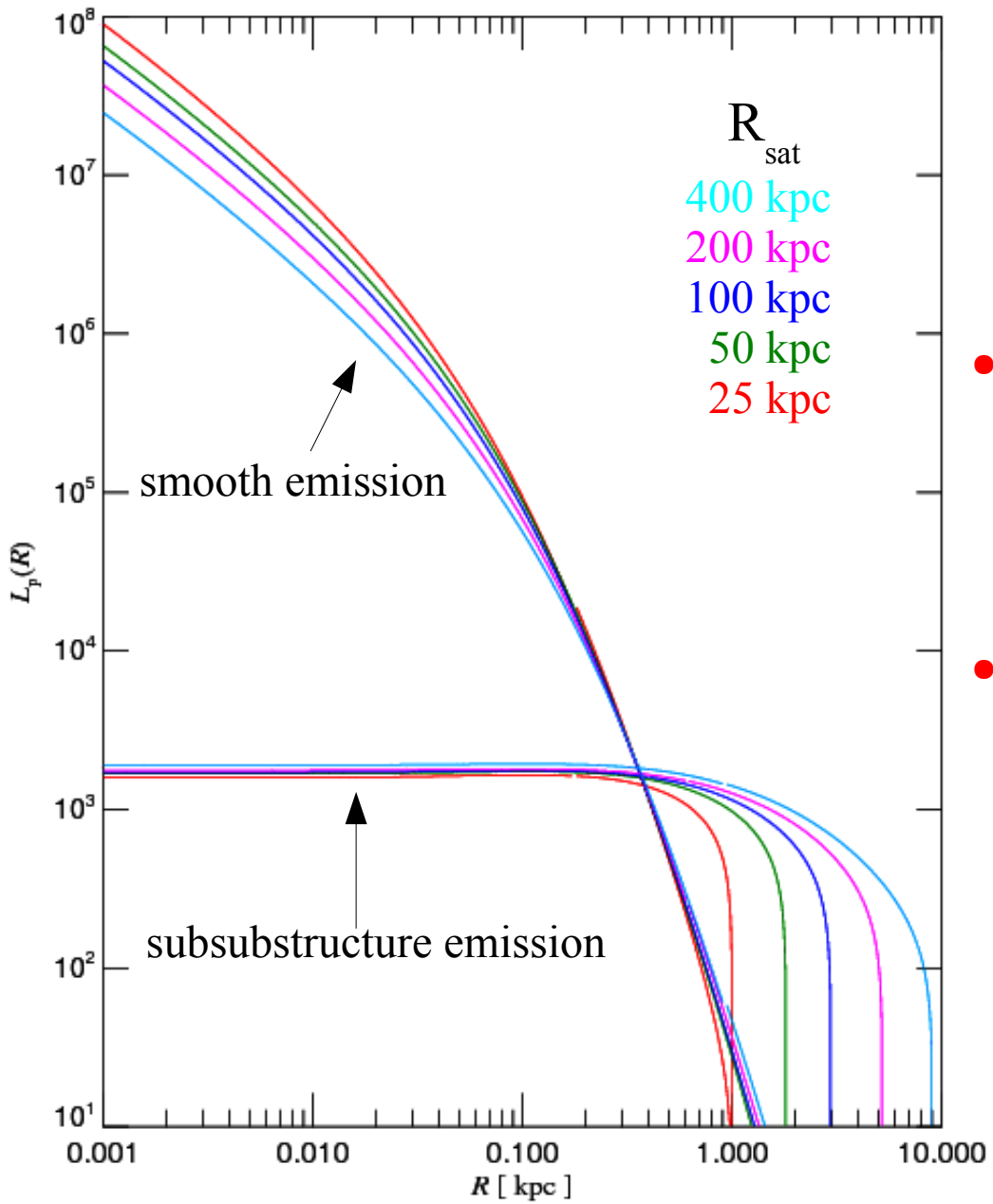
Mass and annihilation radiation profiles of a MW halo

Springel et al 2008



Subhalo annihilation luminosity profiles: V_{max} = 10 km/s

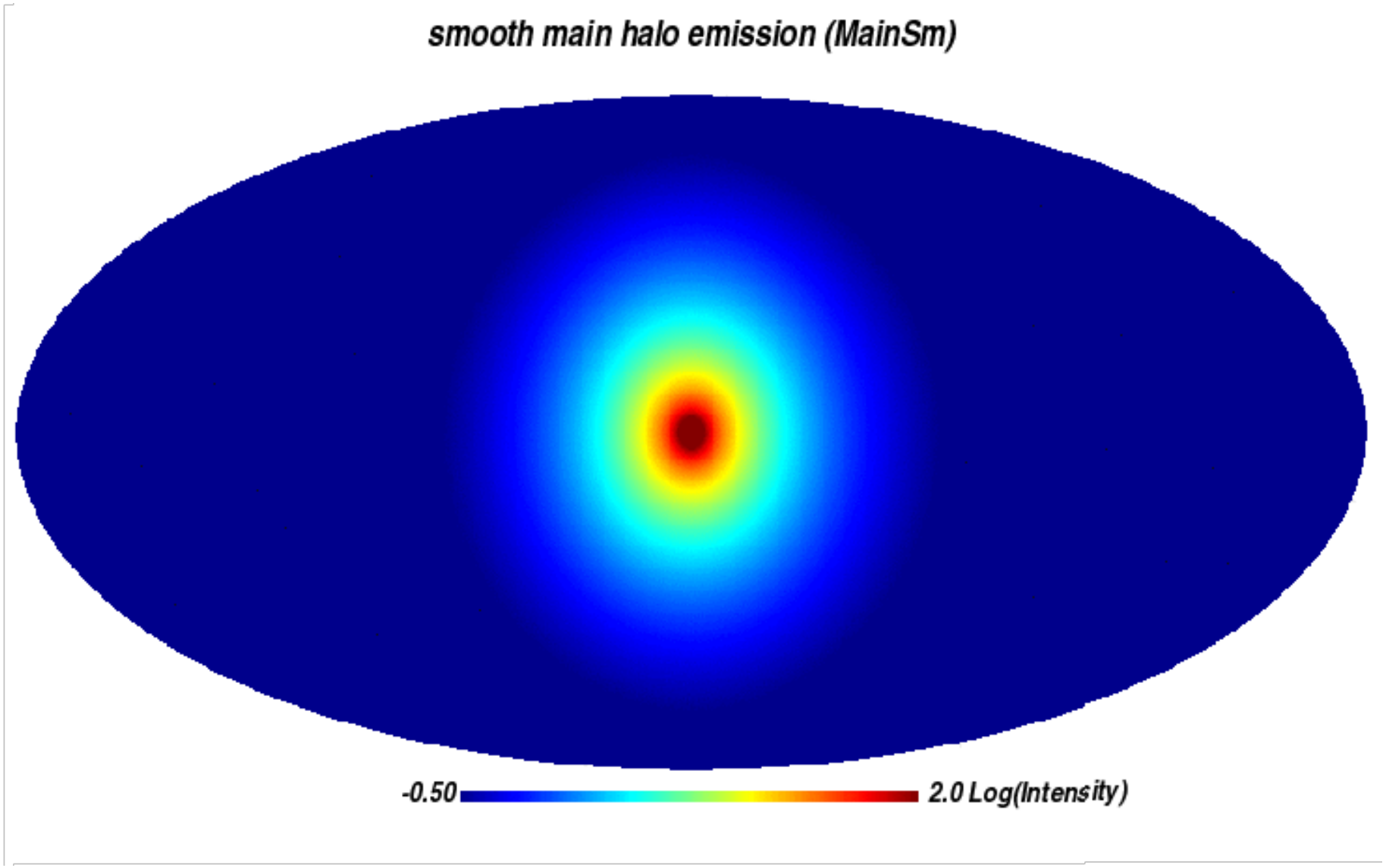
Springel et al 2008



- MW subhalos above Earth mass contribute 230 times as much luminosity within 250 kpc as the smooth halo mass distribution
- The projected surface brightness of the subhalo population is almost uniform
- When a small object falls into the MW, tides remove its subhalos but don't affect its smooth emission

→ subsubstructure does not much boost subhalo luminosities in the inner Galaxy (r < 30 kpc)

Milky Way halo seen in DM annihilation radiation



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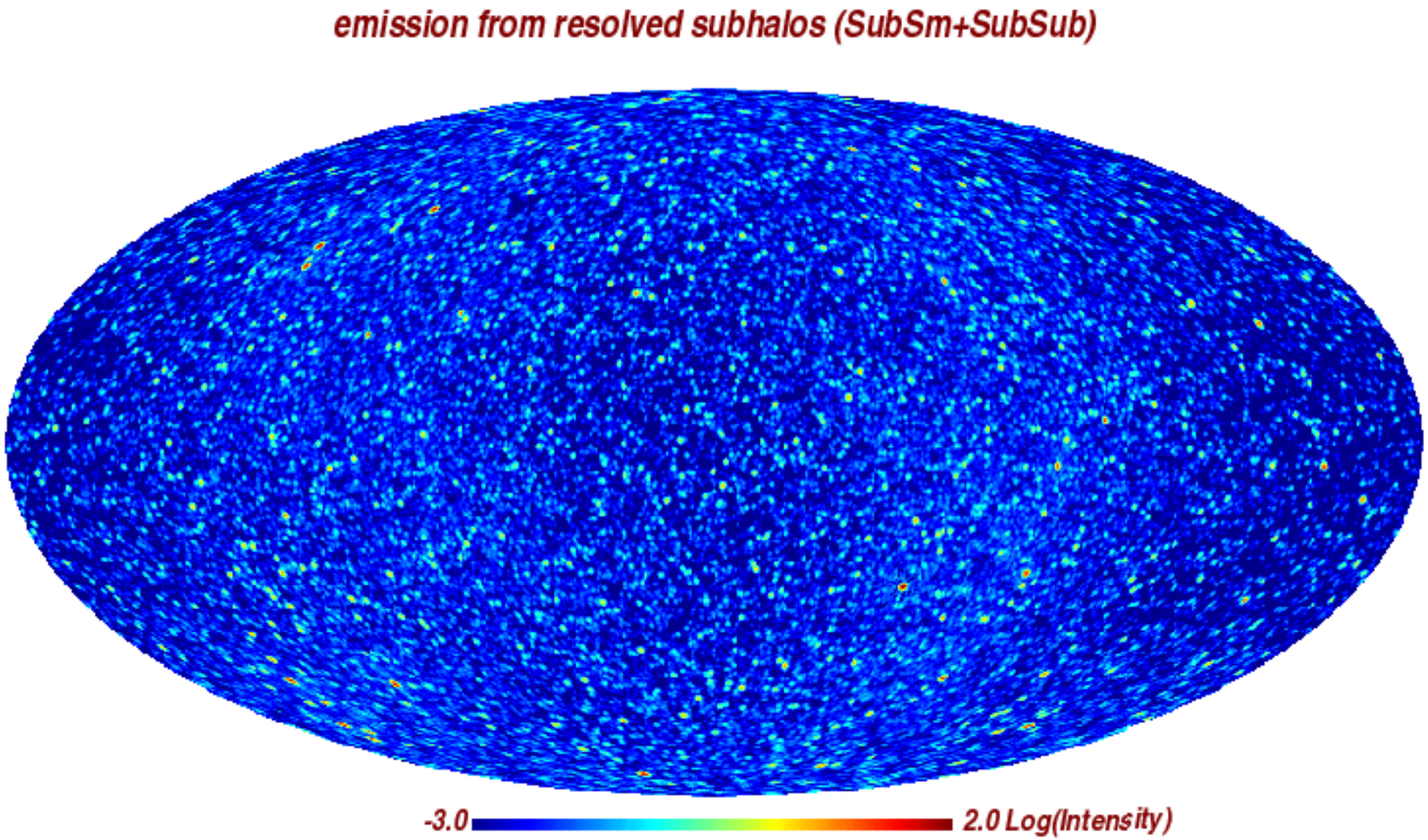

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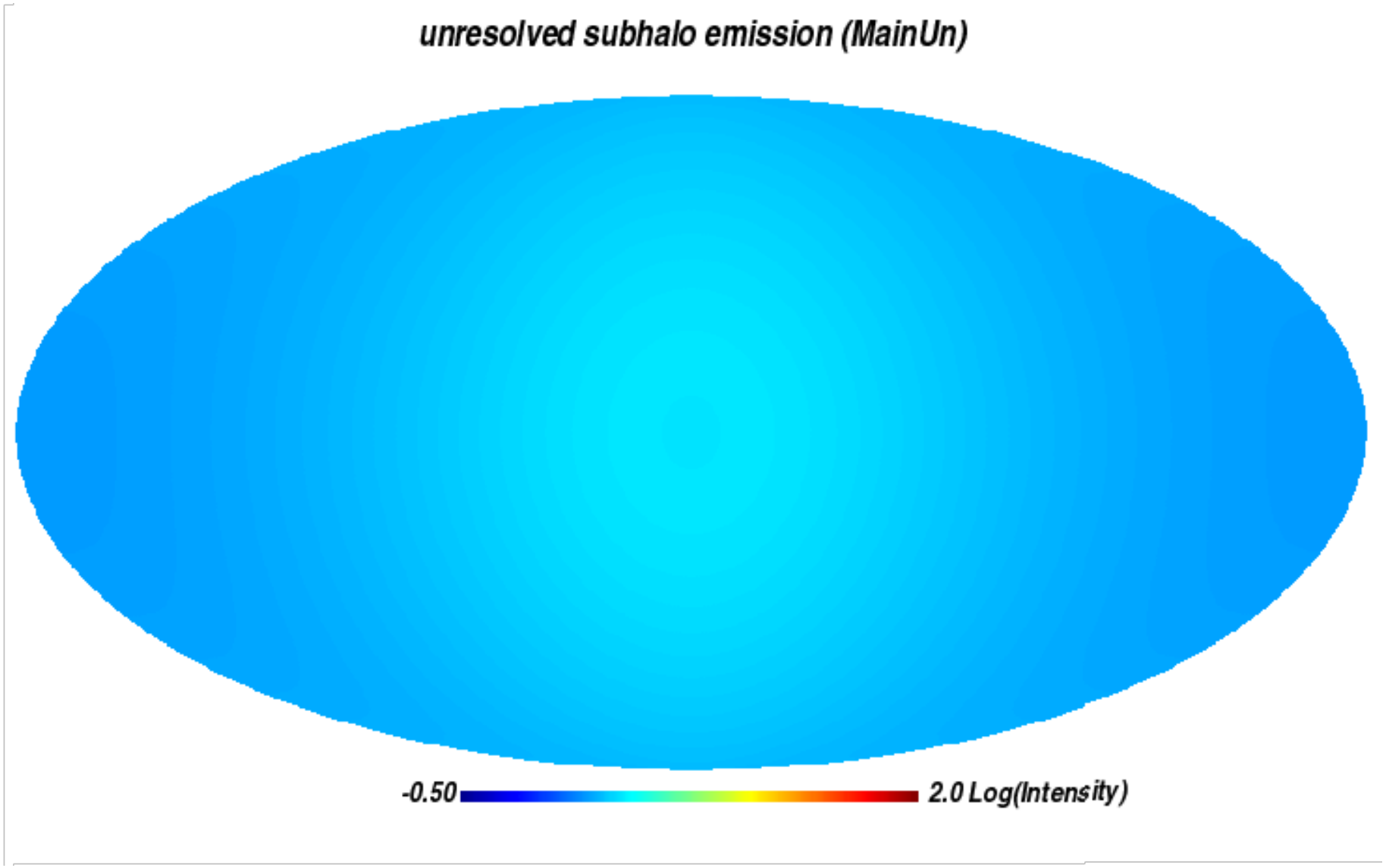

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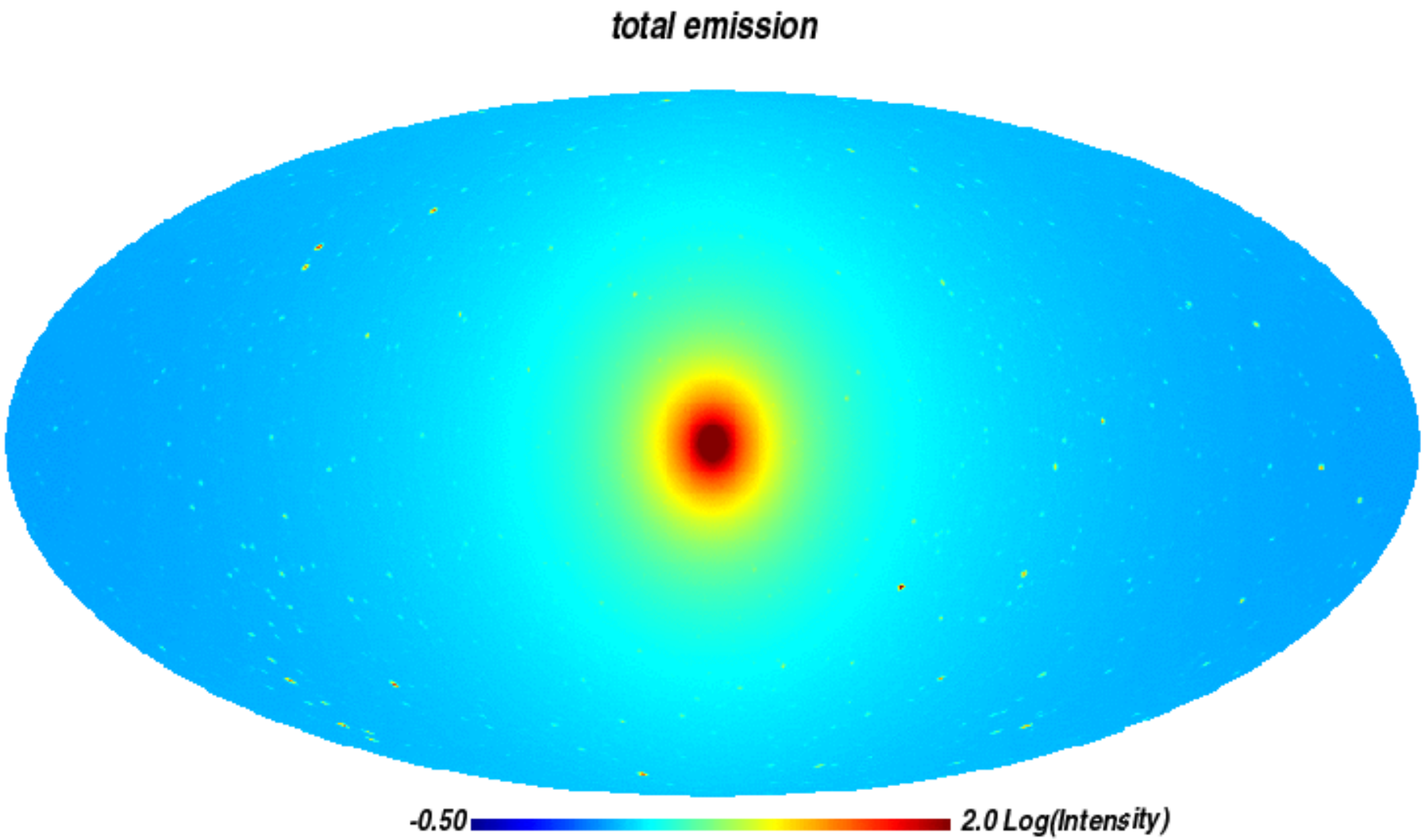
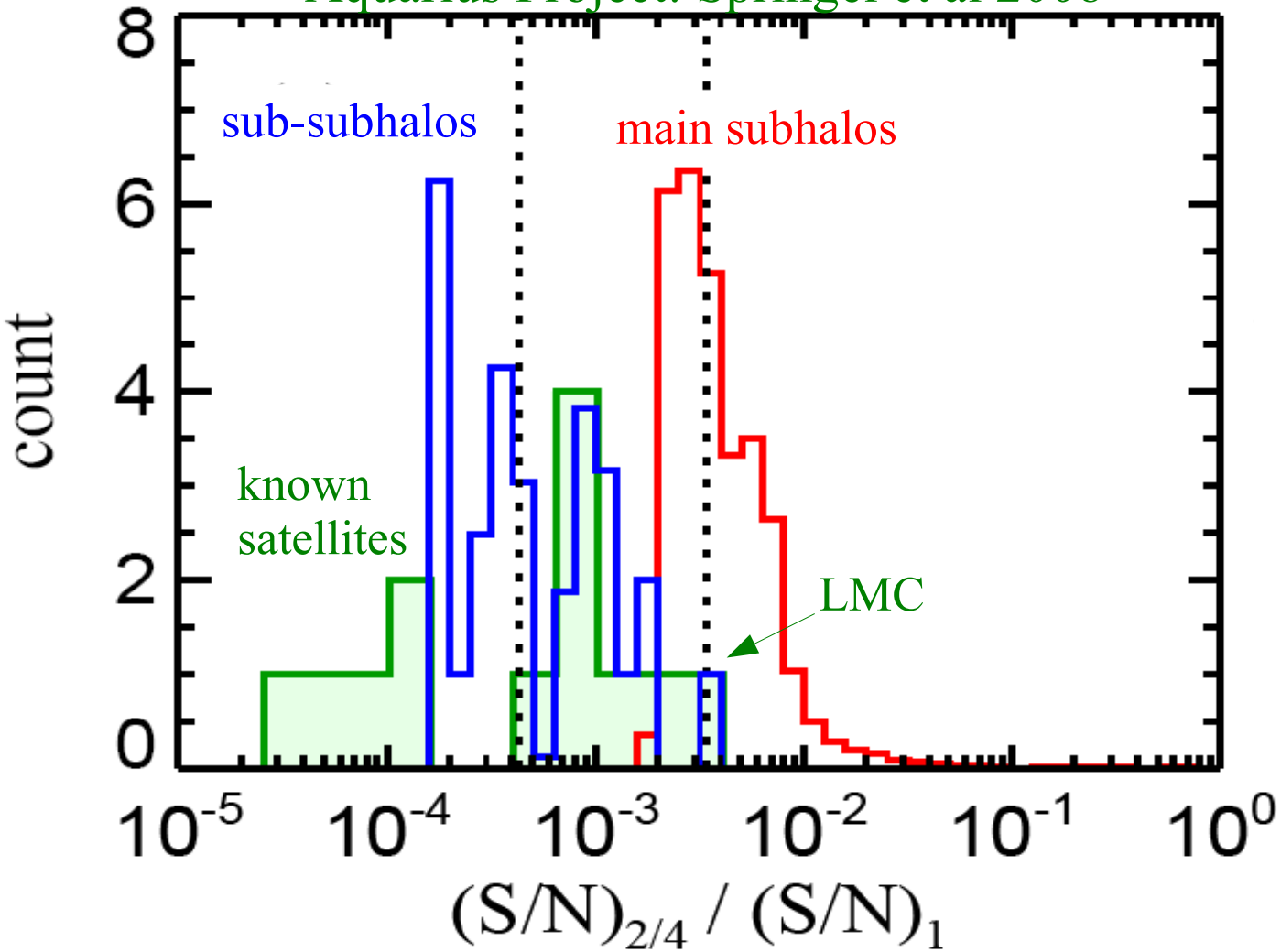
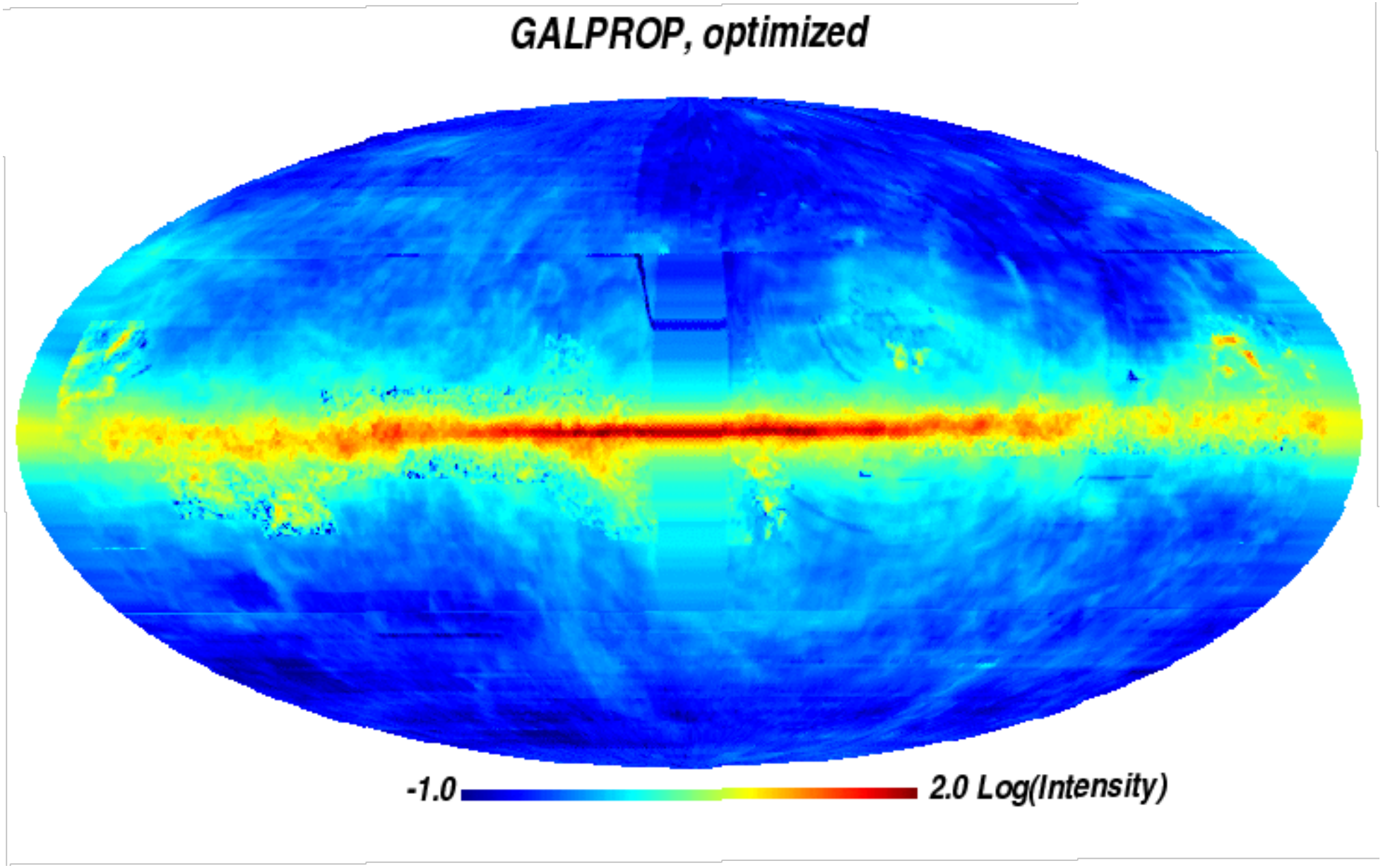


S/N for detecting subhalos in units of that for detecting the main halo
30 highest S/N objects, assuming use of optimal filters

Aquarius Project: Springel et al 2008



- 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
-1.0
2.0 Log(Intensity)

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

Cold Dark Matter at high redshift (e.g. $z \sim 10^5$)

Well *after* CDM particles become nonrelativistic, but *before* they dominate the cosmic density, their distribution function is

$$f(\boldsymbol{x}, \boldsymbol{v}, t) = \rho(t)\,[1 + \delta(\boldsymbol{x})]\,N\,[\{\boldsymbol{v} - \boldsymbol{V}(\boldsymbol{x})\}/\sigma]$$

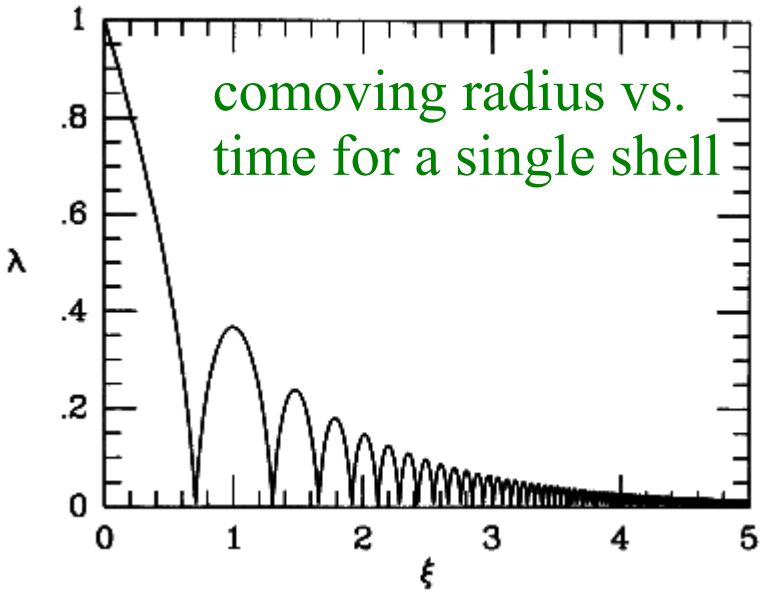
where $\rho(t)$ is the mean mass density of CDM,
$\delta(\boldsymbol{x})$ is a Gaussian random field with finite variance $\ll 1$,
$\boldsymbol{V}(\boldsymbol{x}) = \nabla\psi(\boldsymbol{x})$ where $\nabla^2\psi(\boldsymbol{x}) \propto \delta(\boldsymbol{x})$
and N is standard normal with $\sigma^2 \ll \langle|\mathbf{V}|^2\rangle$

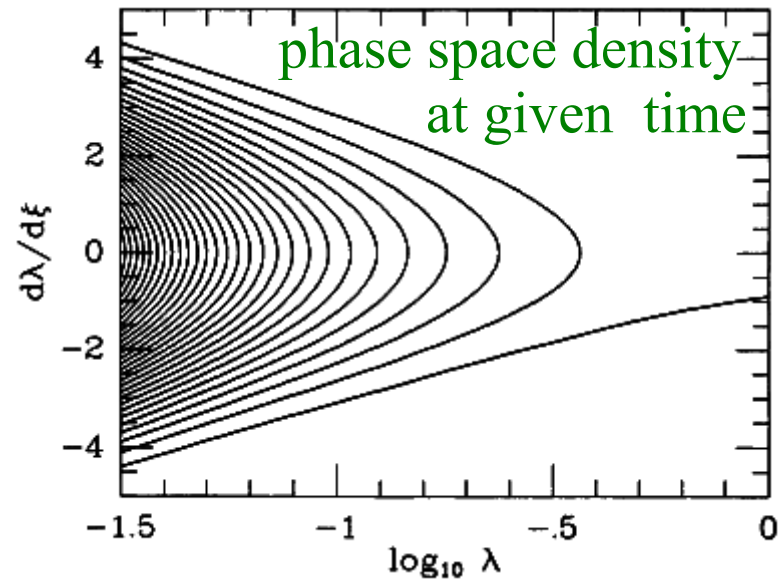
CDM occupies a thin 3-D 'sheet' within the full 6-D phase-space and its projection onto **x**-space is near-uniform.

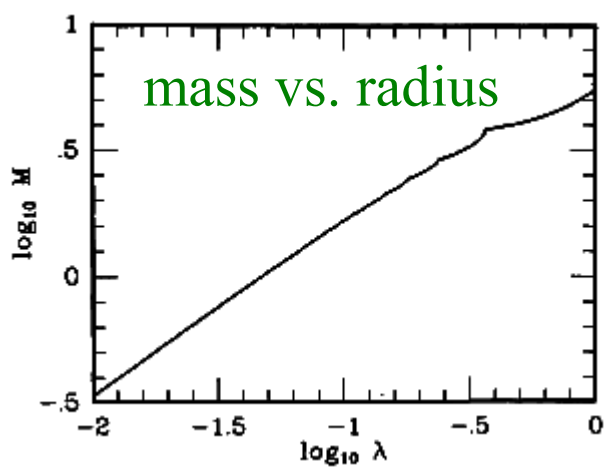
$Df/Dt = 0$ → only a 3-D subspace is occupied at later times. Nonlinear evolution leads to a complex, multi-stream structure.

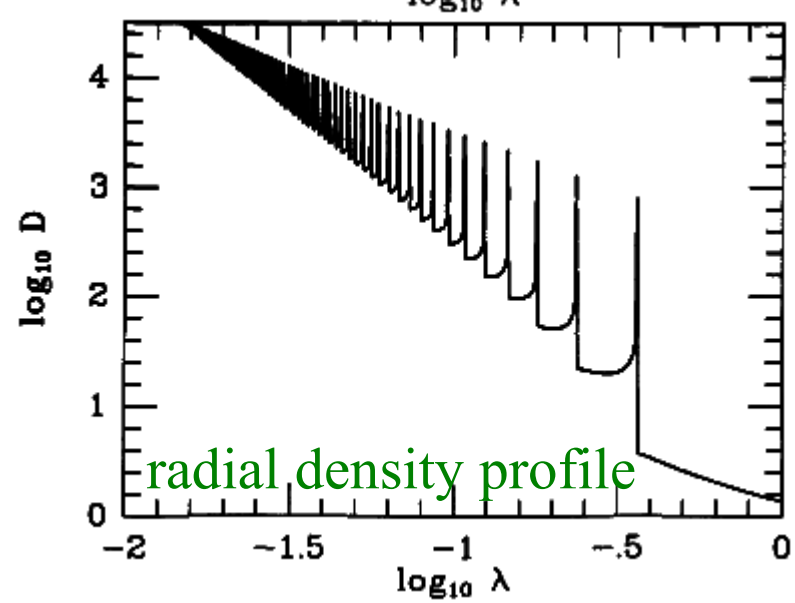
Similarity solution for spherical collapse in CDM

Bertschinger 1985









Evolution of CDM structure

Consequences of $Df/Dt = 0$

- The 3-D phase sheet can be stretched and folded but not torn
- At least 1 sheet must pass through every point **x**
- In nonlinear objects there are typically many sheets at each **x**
- Stretching which reduces a sheet's density must also reduce its velocity dispersions to maintain f = const.
- At a caustic, at least one velocity dispersion must $\longrightarrow \infty$
- All these processes can be followed in fully general simulations by tracking the phase-sheet local to each simulation particle

The geodesic deviation equation

Particle equation of motion: $\dot{X} = \begin{bmatrix} \dot{\mathbf{x}} \\ \dot{\mathbf{v}} \end{bmatrix} = \begin{bmatrix} \mathbf{v} \\ -\nabla\phi \end{bmatrix}$

Offset to a neighbor: $\delta\dot{X} = \begin{bmatrix} \delta\mathbf{v} \\ T \cdot \delta\mathbf{x} \end{bmatrix} = \begin{bmatrix} 0 & I \\ T & 0 \end{bmatrix} \cdot \delta X \; ; \; T = -\nabla(\nabla\phi)$

Write $\delta X(t) = D(X_0, t) \cdot \delta X_0$, then differentiating w.r.t. time gives,

$$\boxed{\dot{D} = \begin{bmatrix} 0 & I \\ T & 0 \end{bmatrix} \cdot D \quad \text{with } D_0 = I}$$

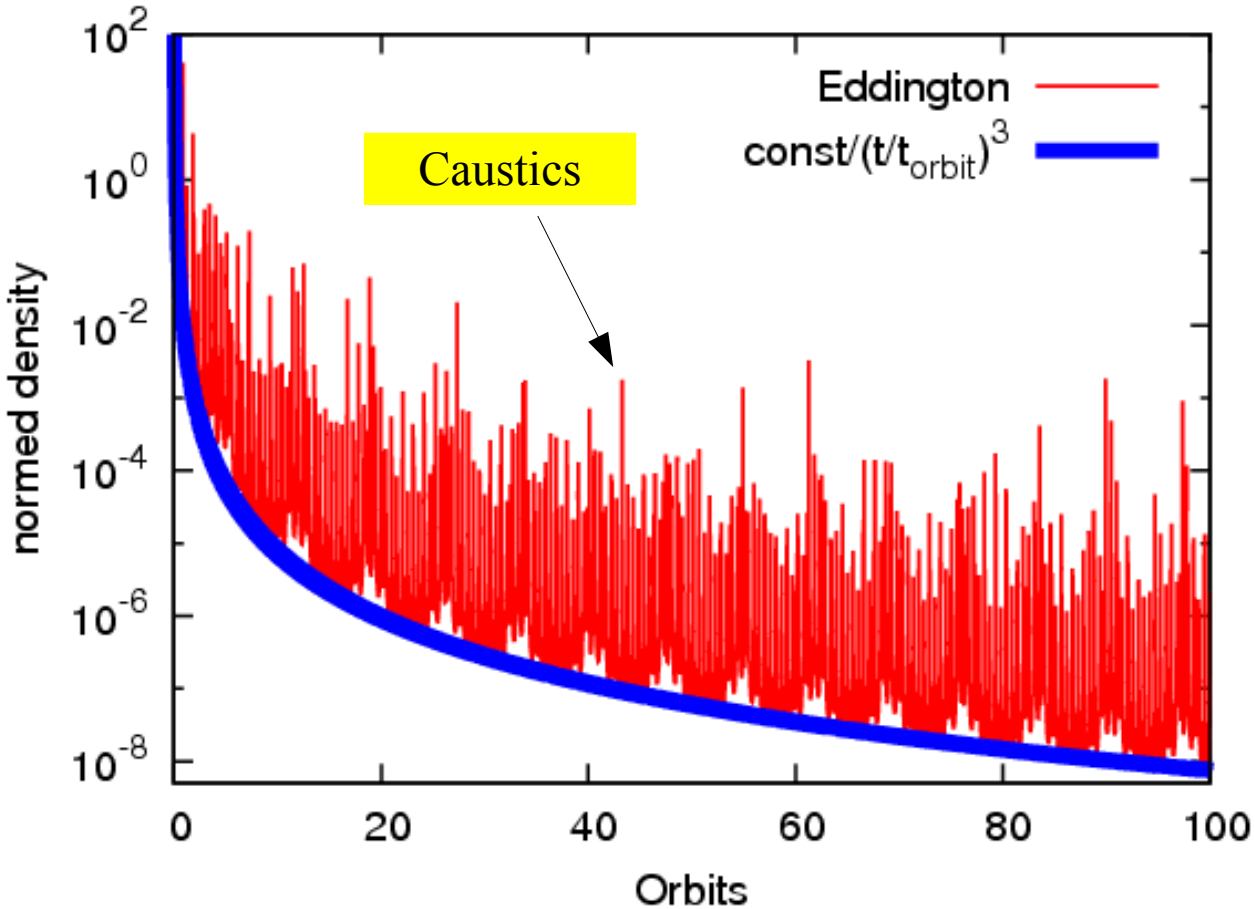
- Integrating this equation together with each particle's trajectory gives the evolution of its local phase-space distribution
- No symmetry or stationarity assumptions are required
- det(D) = 1 at all times by Liouville's theorem
- For CDM, $1/|\det(D_{\mathbf{xx}})|$ gives the decrease in local 3D space density of each particle's phase sheet. Switches sign and is infinite at caustics.

Static symmetric potentials

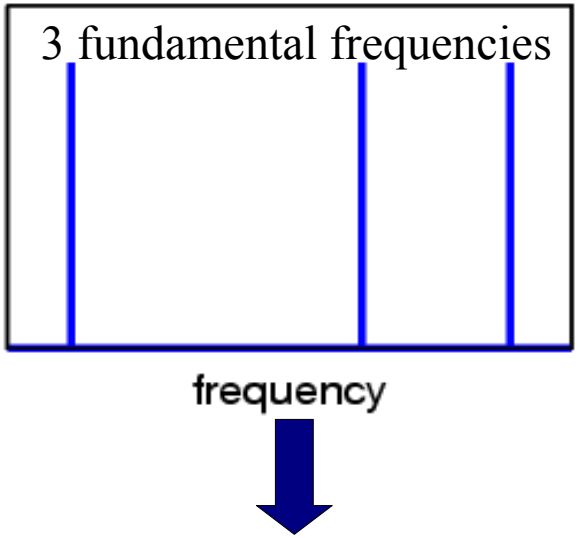
Mark Vogelsberger, Amina Helmi, Volker Springel

Axisymmetric Eddington potential

$$\Phi(r,\theta) = v_{\rm h}^2 \log\left(r^2 + d^2\right) + \frac{\beta^2 \cos^2\theta}{r^2}$$



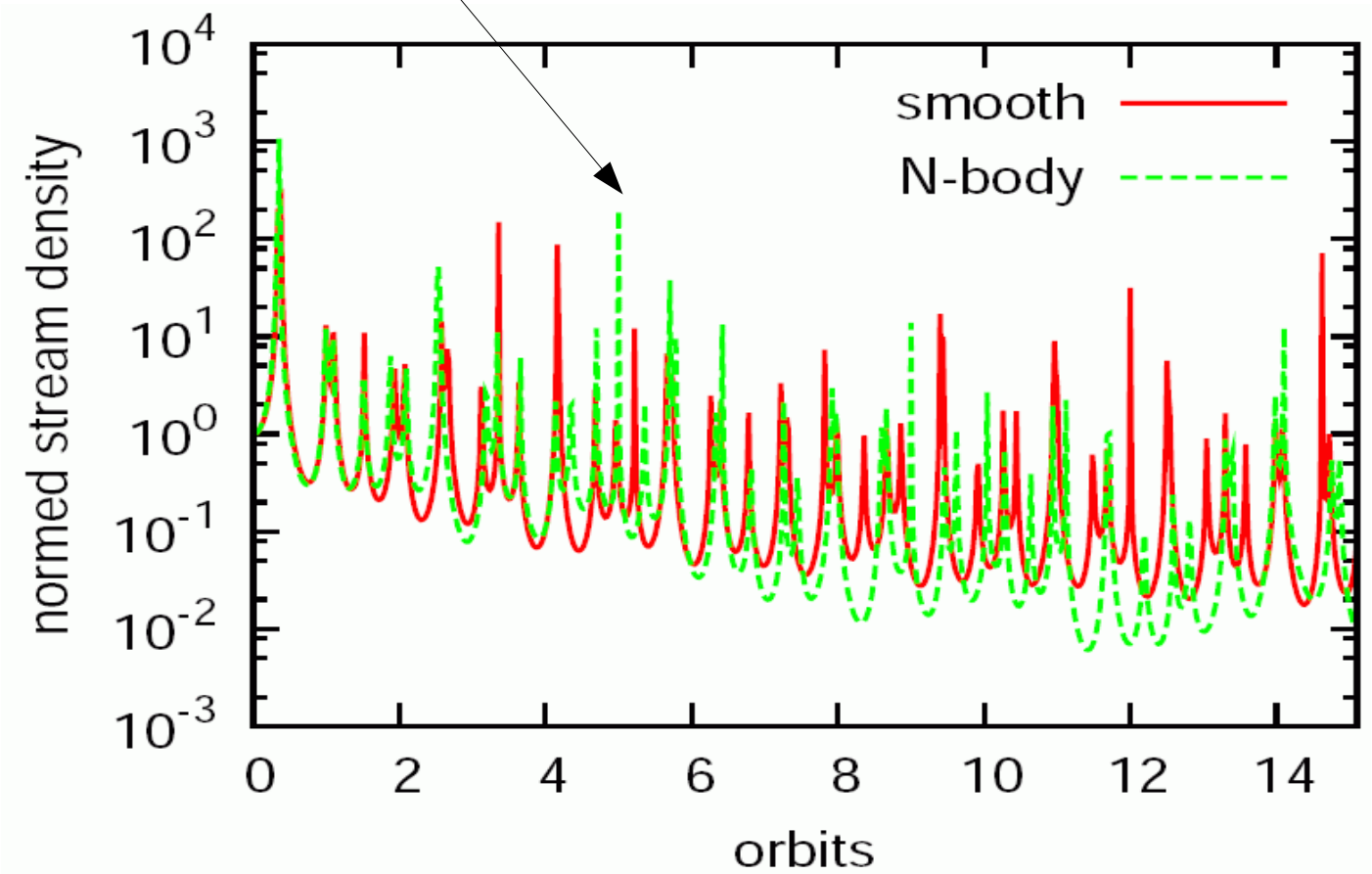
Spectral analysis of orbit:



density decreases like $1/t^3$

A particle orbit in a live Halo

caustics resolved in N-body live halo!



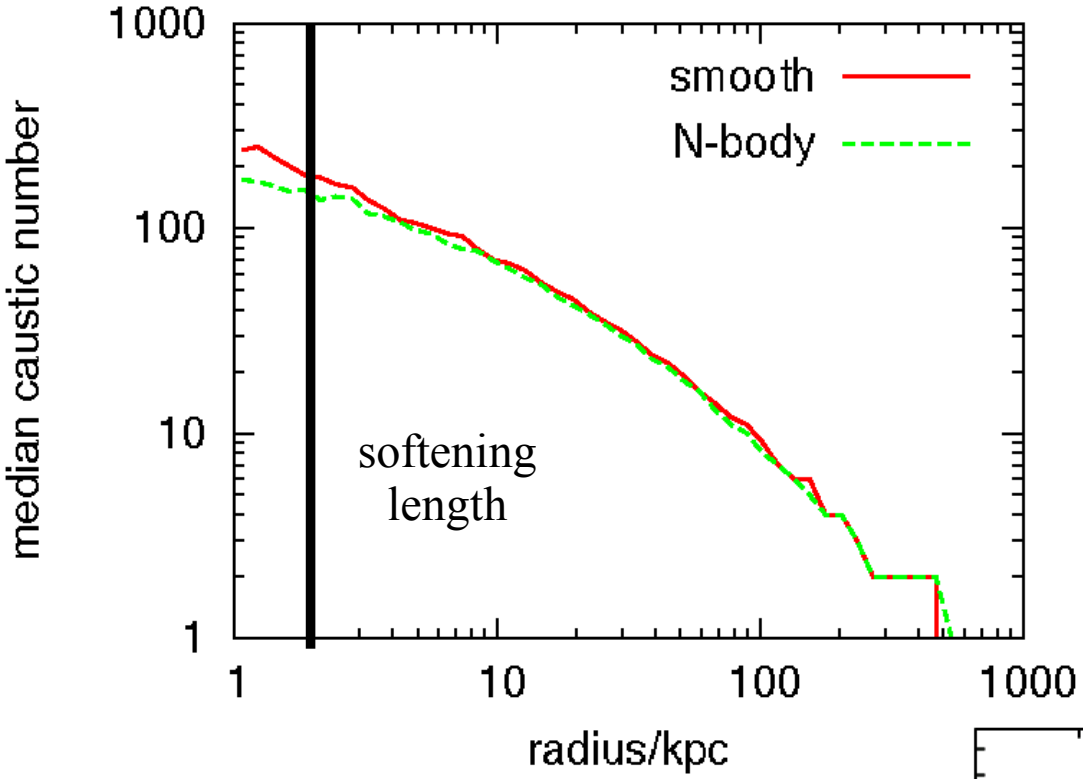
spherical Hernquist density profile

$$\rho(r) = \frac{M}{2\pi}\frac{a}{r}\frac{1}{(r+a)^3}$$

general shape and caustic spacing/number very similiar!

phase-space density conservation: 10^{-8}

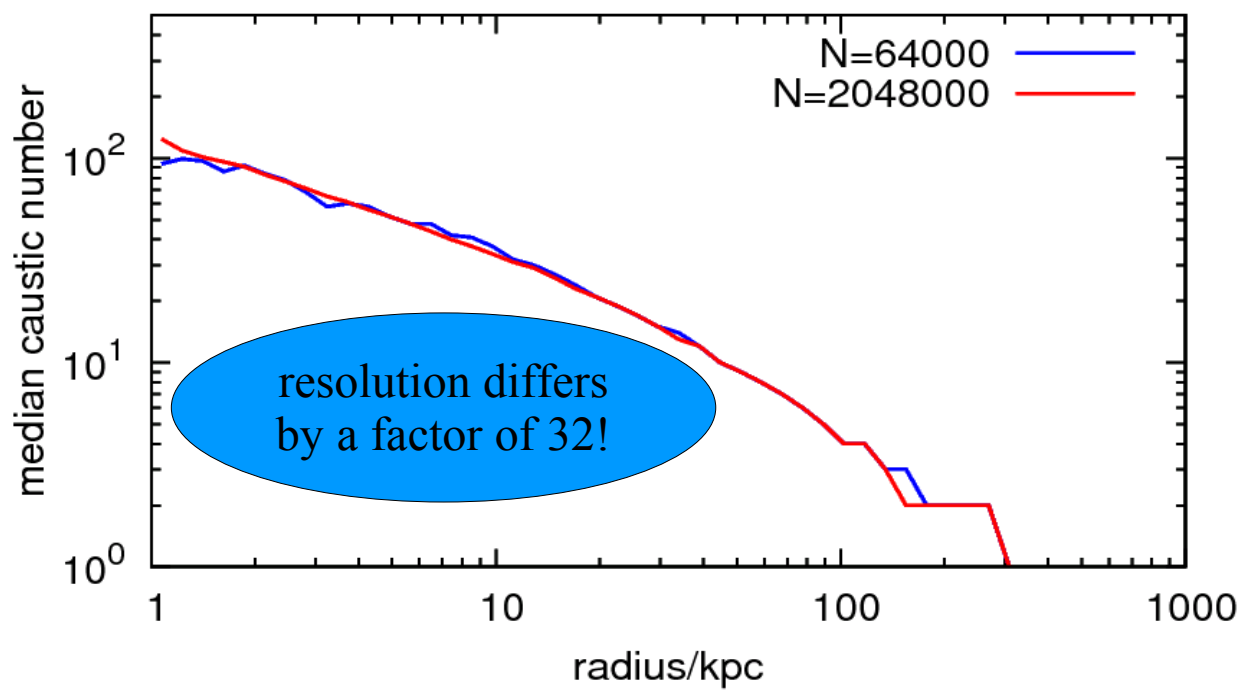
Number of Caustic Passages



analytic and N-body results nearly the same!

Annihilation boost factor estimates due to caustics should be very robust!

Very stable against particle number and softening length!



Conclusions about streams and caustics

- GDE robustly identifies caustic passages and gives fair stream density estimates for particles in fully 3-D CDM simulations

- Many streams are present at each point well inside a CDM halo (at least 100,000 at the Sun's position)

  → quasi-Gaussian signal in direct detection experiments

- Caustic structure is more complex in realistic 3-D situations than in matched 1-D models but the caustics are weaker

  → negligible boosting of annihilation signal due to caustics

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 energy 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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