Séminaire IAP
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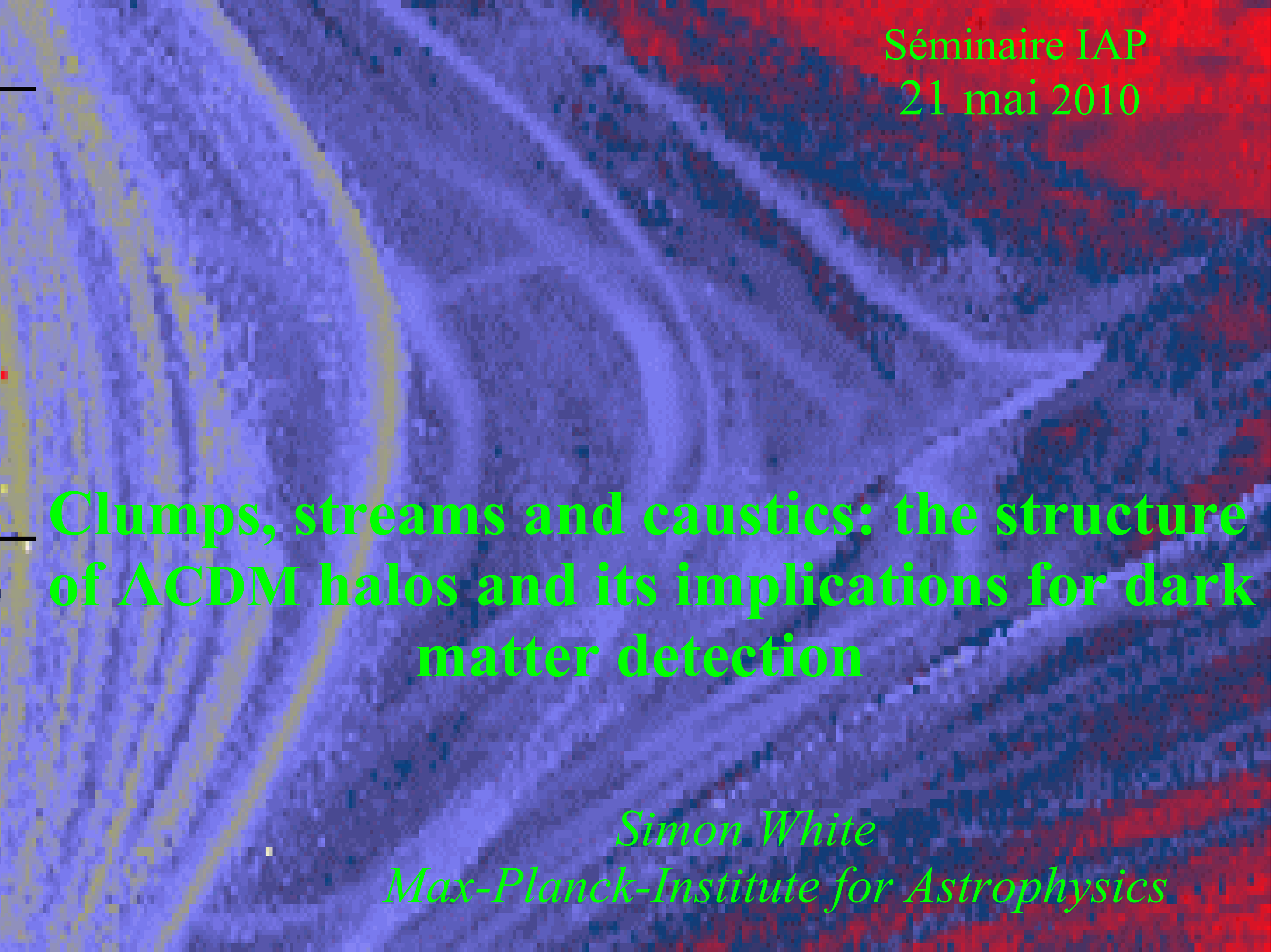

Clumps, streams and caustics: the structure of ΛCDM halos and its implications for dark matter detection

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MPA Hausseminar,
April 2010

Clumps, streams and caustics: the structure of ΛCDM halos and its implications for dark matter detection

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The four elements of ΛCDM halos

I Smooth background halo

-- NFW-like cusped density profile

-- near-ellipsoidal equidensity contours

II Bound subhalos

-- most massive typically 1% of main halo mass

-- total mass of all subhalos $\lesssim$ 10%

-- less centrally concentrated than the smooth component

III Tidal streams

-- remnants of tidally disrupted subhalos

IV Fundamental streams

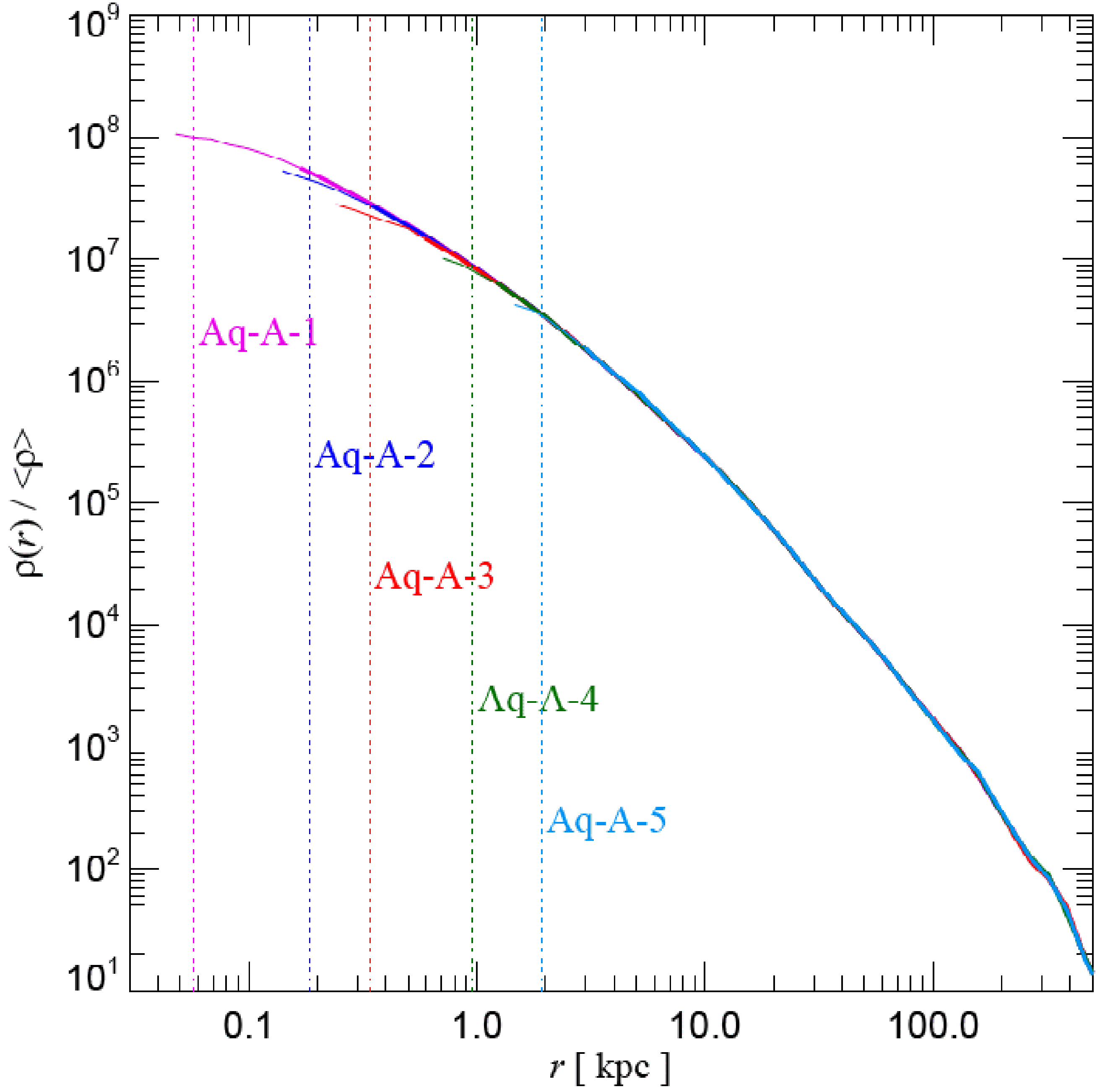
-- consequence of smooth and cold initial conditions

-- very low internal velocity dispersions

-- produce density caustics at projective catastrophes

I Smooth background halo

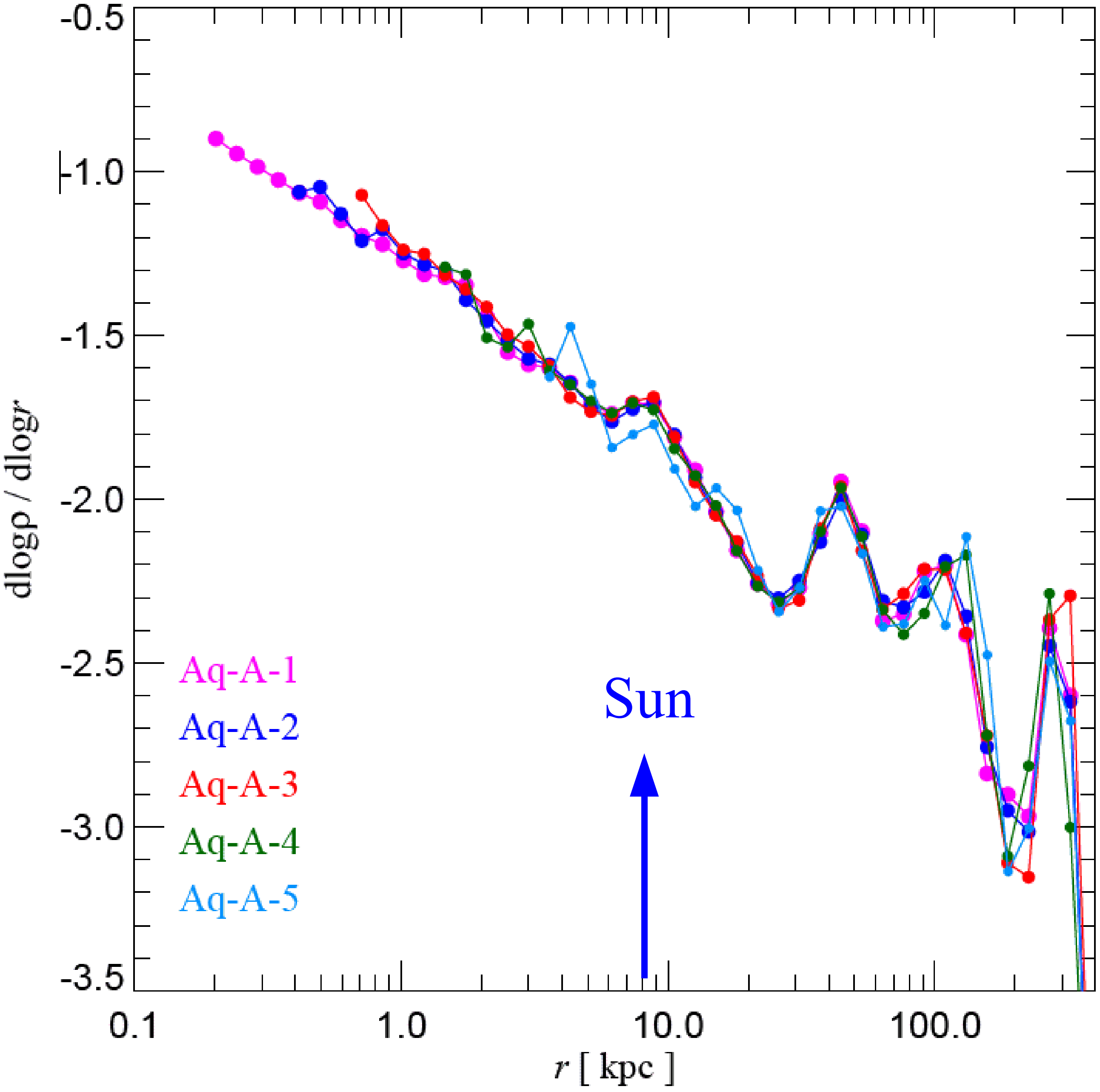
Aquarius Project: Springel et al 2008



- Density profiles of simulated DM-only ΛCDM halos are now very well determined

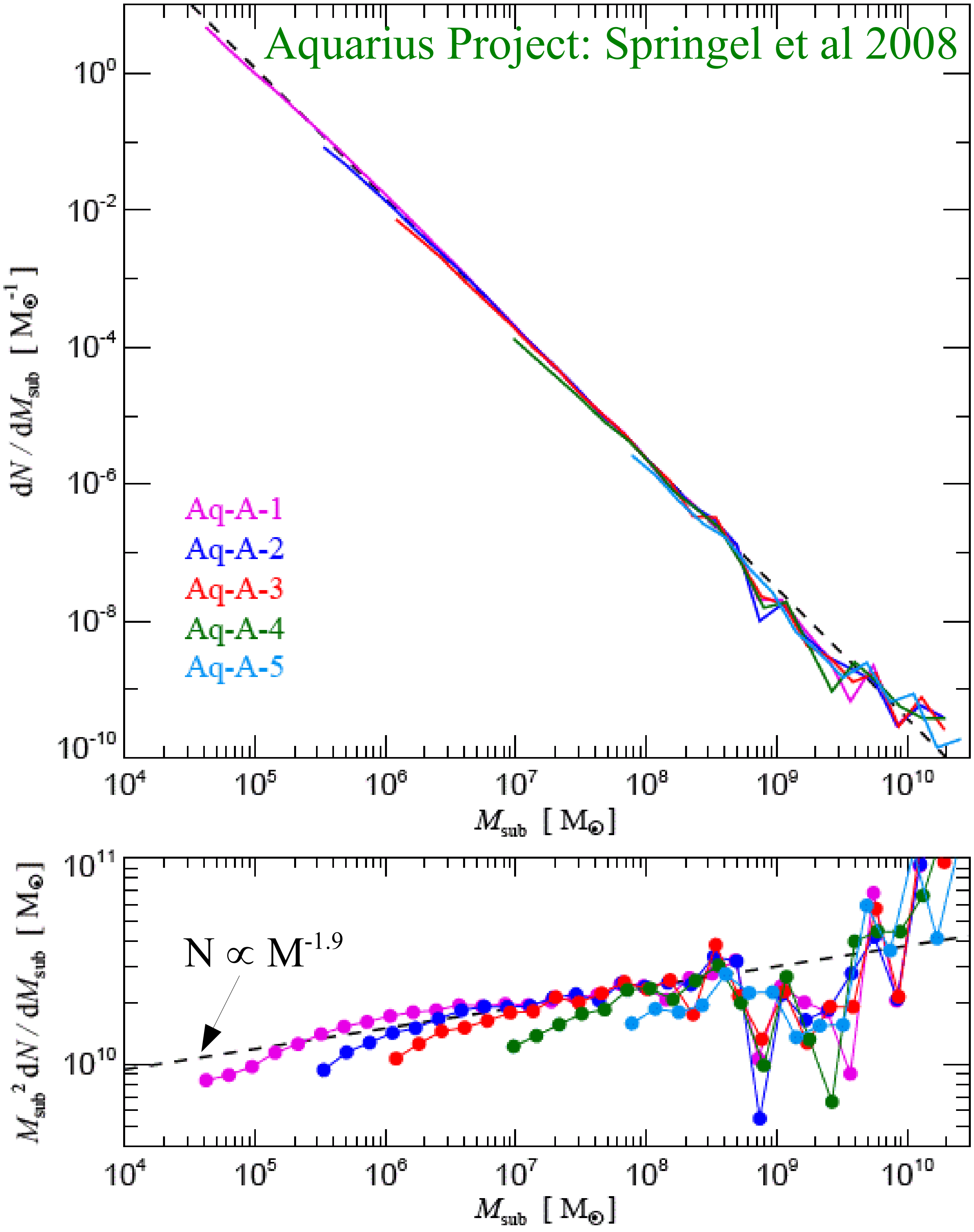
I Smooth background halo

Aquarius Project: Springel et al 2008

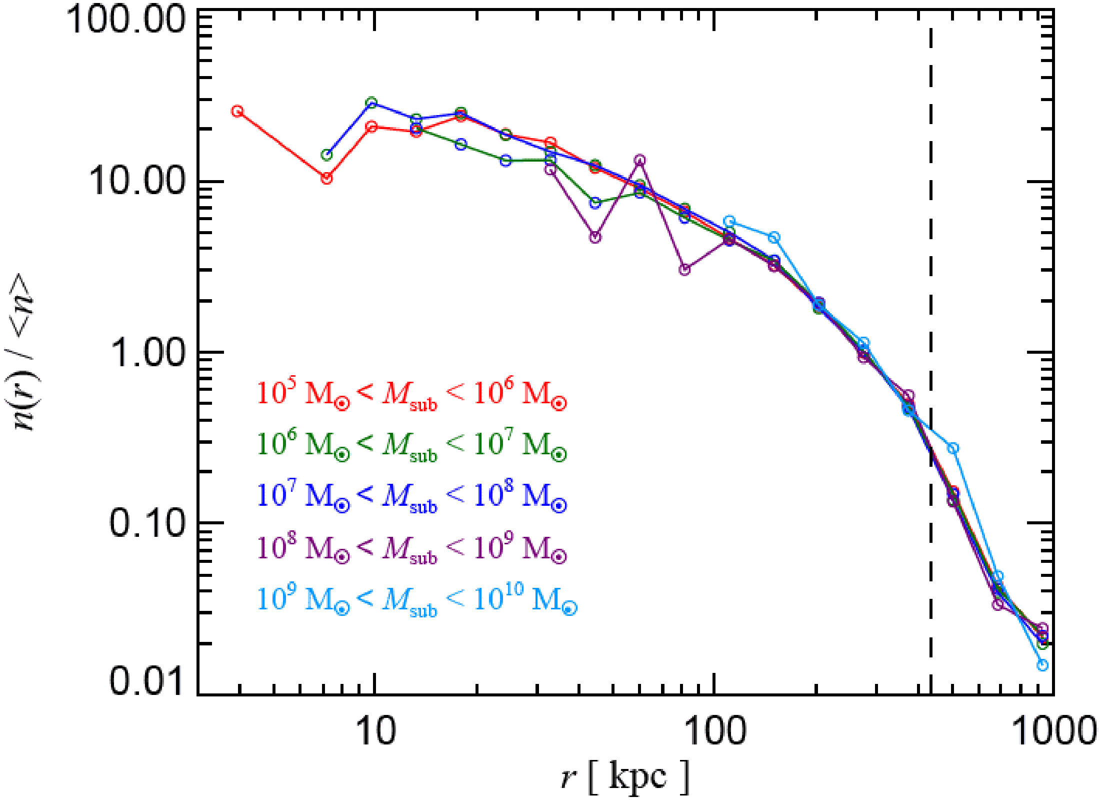


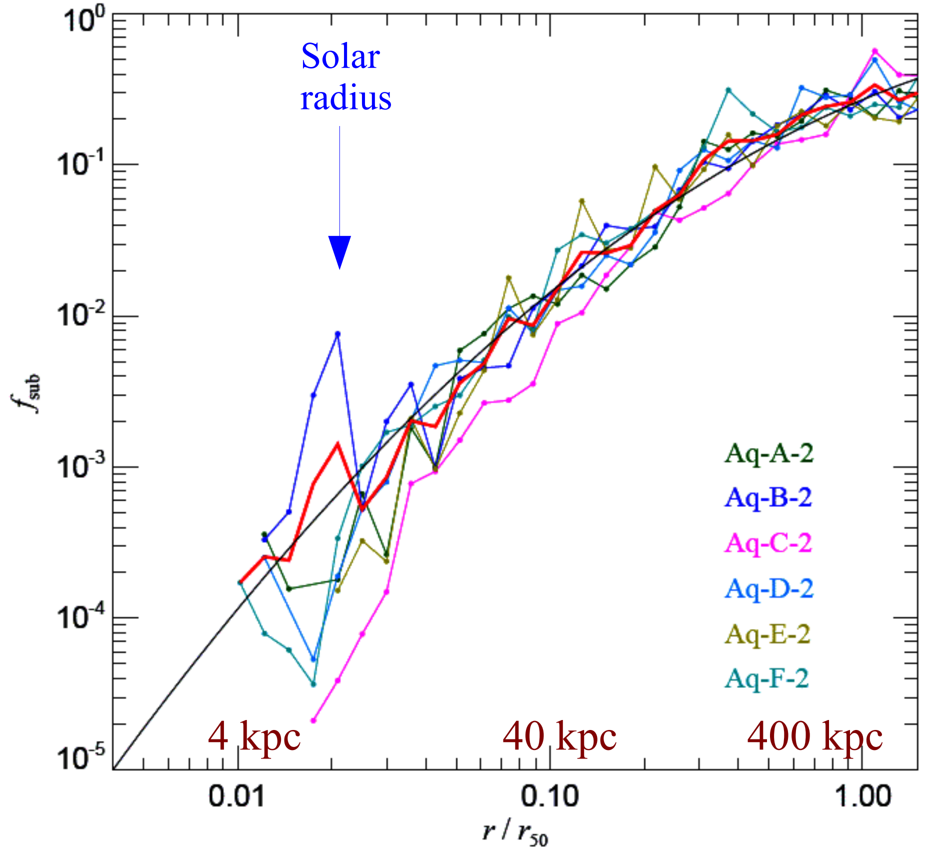
- Density profiles of simulated DM-only ΛCDM halos are now very well determined
- The inner cusp does not appear to have a well-defined power law slope
- Treating baryons more important than better DM simulations

II Bound subhalos

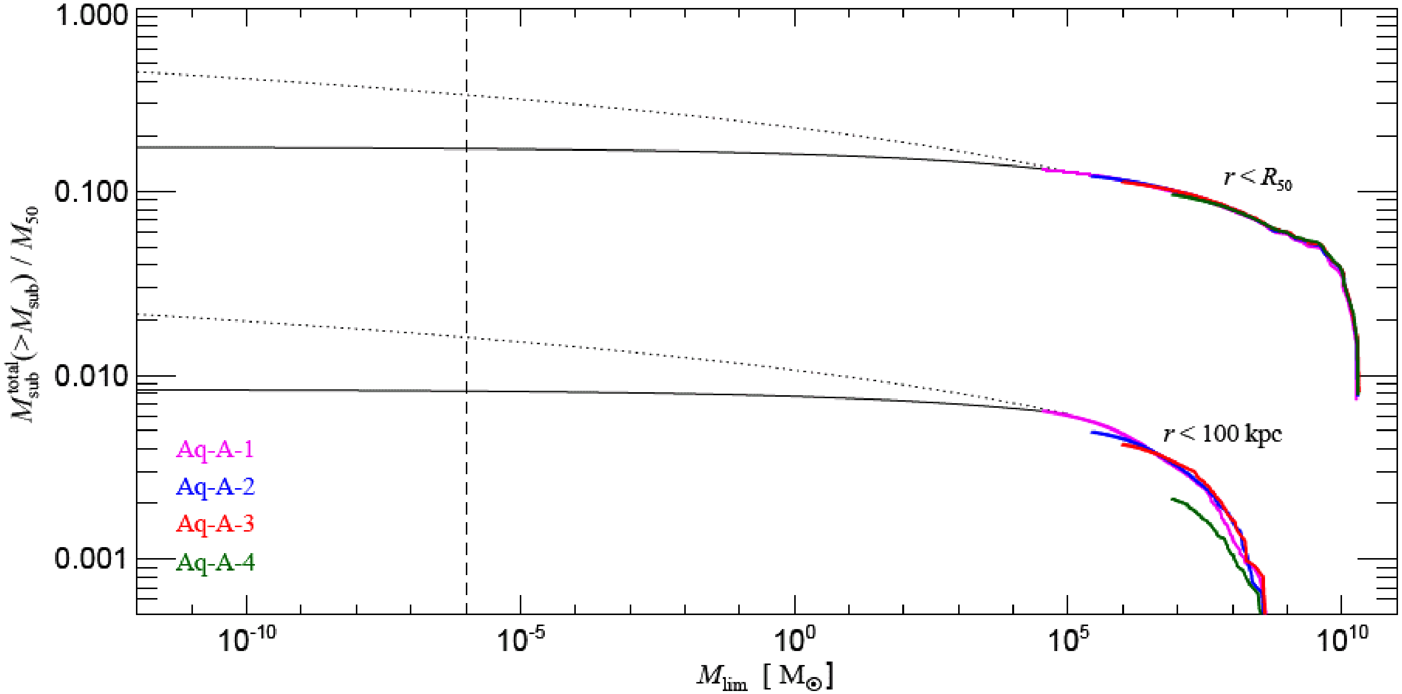


- Abundance of self-bound subhalos is measured to below 10^{-7} M_{halo}
- Most subhalo mass is in the biggest objects (just)





Aquarius Project: Springel et al 2008

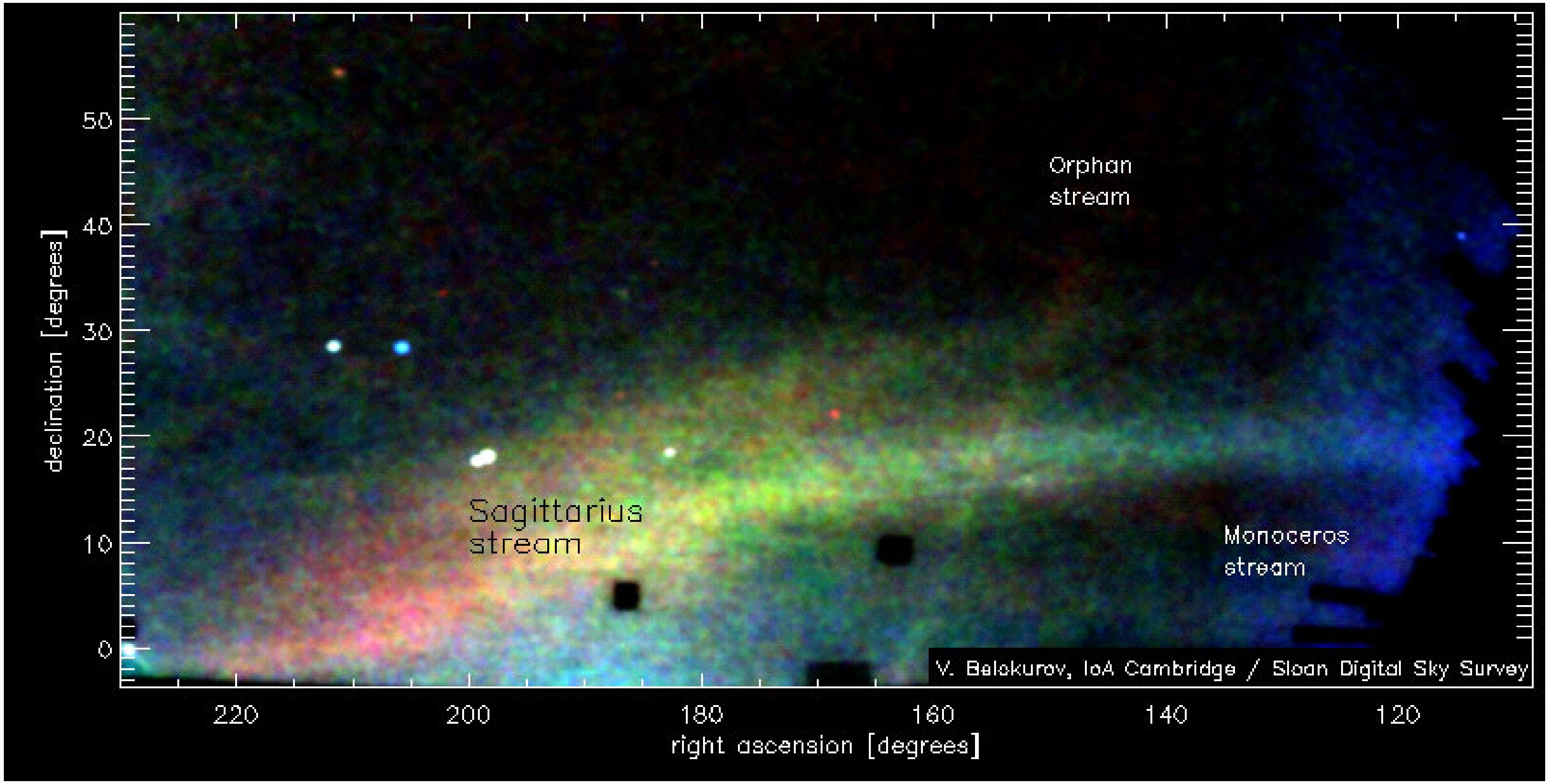


- All mass subhalos are similarly distributed
- A small fraction of the inner mass in subhalos
- <<1% of the mass near the Sun is in subhalos

II Bound subhalos: 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

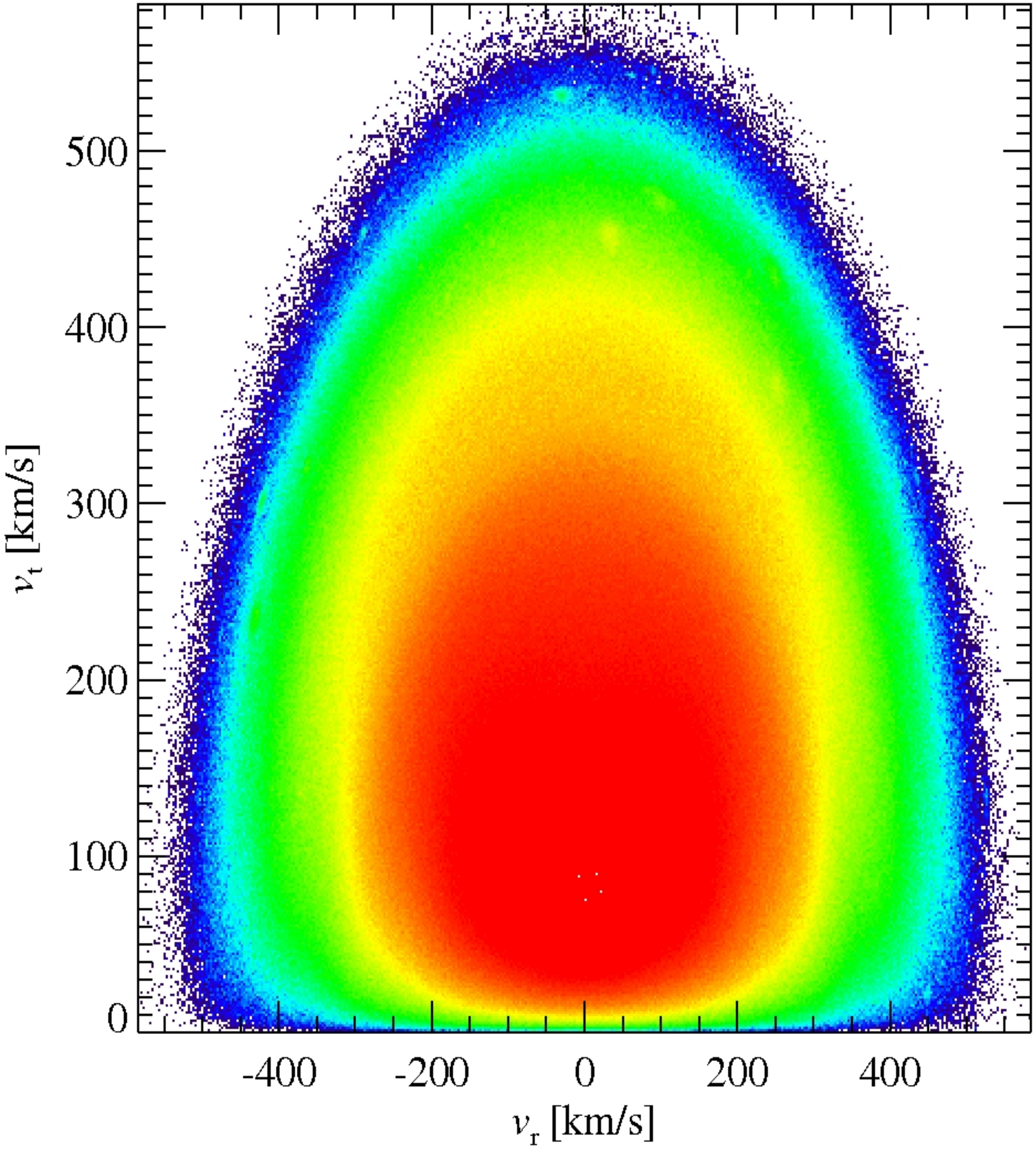
III Tidal Streams



- Produced by partial or total tidal disruption of subhalos
- Analogous to observed stellar streams in the Galactic halo
- Distributed along/around orbit of subhalo (c.f. meteor streams)
- Localised in almost 1-D region of 6-D phase-space ($\underline{\mathbf{x}}$, $\underline{\mathbf{v}}$)

Dark matter phase-space structure in the inner MW

M. Maciejewski



6 kpc < r < 12 kpc

All particles

$N = 3.8 \times 10^7$

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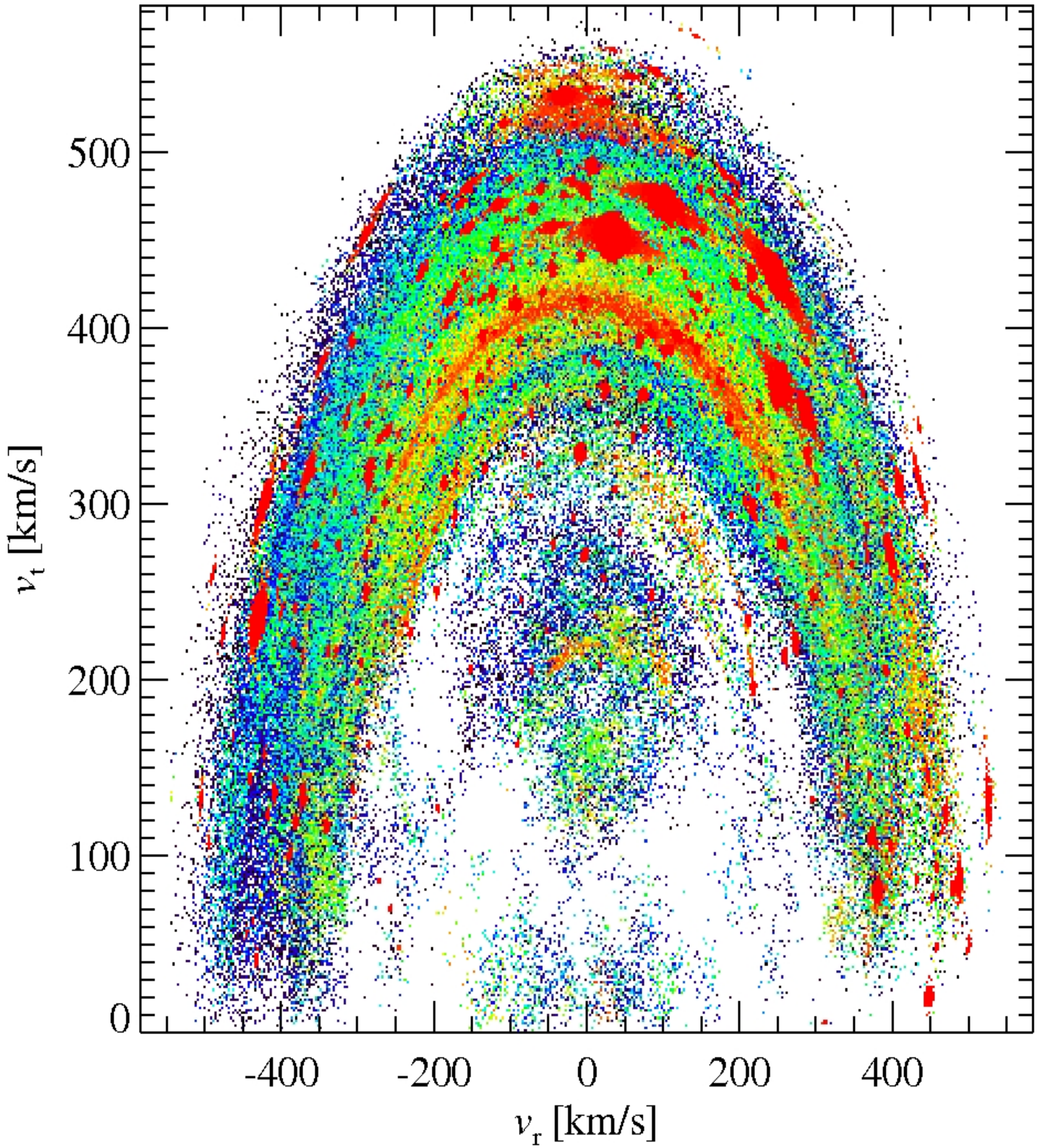


6 kpc < r < 12 kpc

Particles in detected phase-space structure

$N = 3.0 \times 10^5$

$N_{subhalo} = 3.9 \times 10^4$

IV Fundamental streams

After CDM particles become nonrelativistic, but *before* they dominate the density (e.g. $z \sim 10^5$) their distribution function is

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

where $\rho(t)$ is the mean mass density of CDM,

$\delta(\boldsymbol{x},t)$ is a Gaussian random field with finite variance $\ll 1$,

$\boldsymbol{V}(\boldsymbol{x},t) = \nabla\psi(\boldsymbol{x},t)$ where $\nabla^2\psi \propto \delta$,

and N is normal with $\sigma^2 << \langle|\mathbf{V}|^2\rangle$ (today $\sigma \sim 0.1$ cm/s)

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 *all* times.
Nonlinear evolution leads to <u>multi-stream</u> structure and <u>caustics</u>

IV Fundamental streams

Consequences of Df / Dt = 0

- The 3-D phase sheet can be stretched and folded but not torn
- At least one 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. $\longrightarrow \sigma \sim \rho^{-1/3}$
- 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: $\delta\dot{X} = \begin{bmatrix}\delta\mathbf{v} \\ T\cdot\delta\mathbf{x}\end{bmatrix} = \begin{bmatrix}0 & I \\ T & 0\end{bmatrix}\cdot\delta X\,;\ \ T = -\nabla(\nabla\phi)$

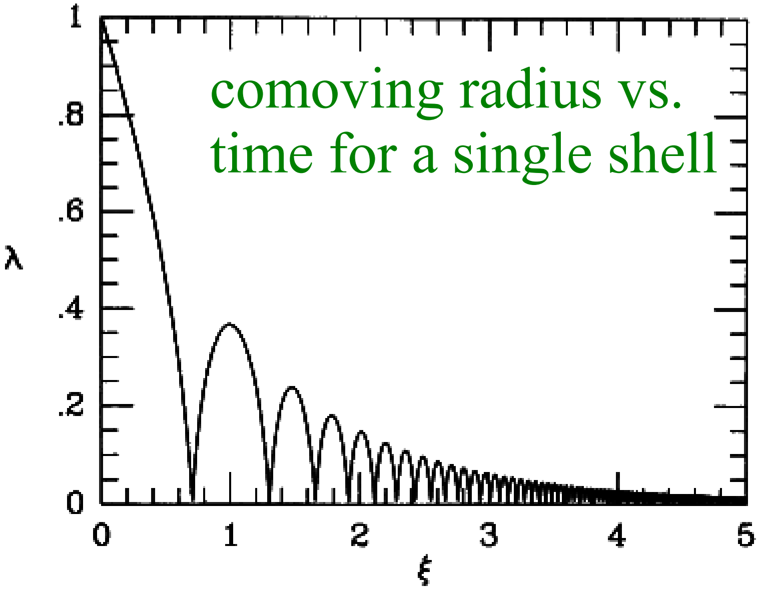
Write $\delta X(t) = D(X_0, t)\cdot\delta X_0$, then differentiating w.r.t. time gives,

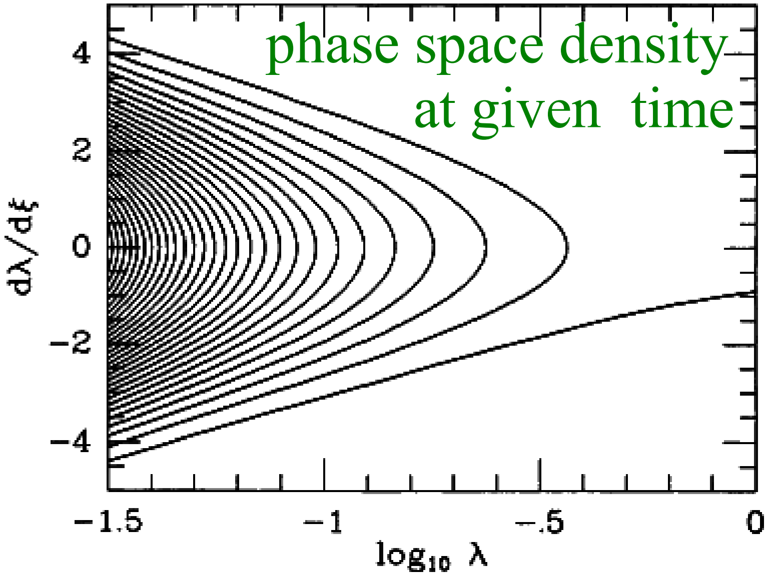
$$\boxed{\dot{D} = \begin{bmatrix}0 & I \\ T & 0\end{bmatrix}\cdot D \quad \text{with } D_0 = I}$$

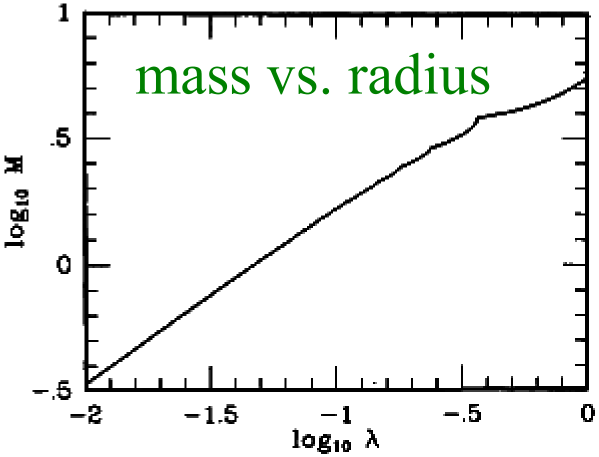
- Integrating this equation together with each particle's trajectory gives the evolution of its local phase-space distribution
- No symmetry or stationarity assumptions are required
- $\det(D) = 1$ at all times by Liouville's theorem
- For CDM, $1/|\det(D_{xx})|$ gives the decrease in local 3D space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

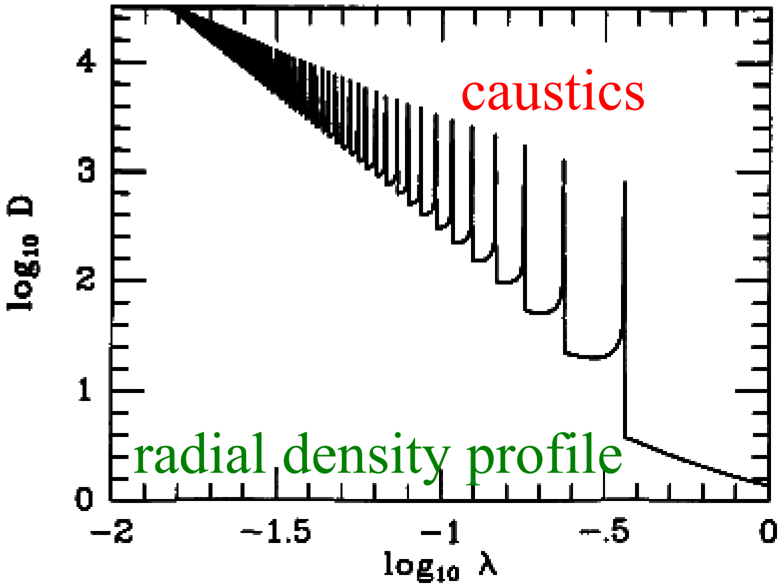
Similarity solution for spherical collapse in CDM

Bertschinger 1985


comoving radius vs. time for a single shell


phase space density at given time

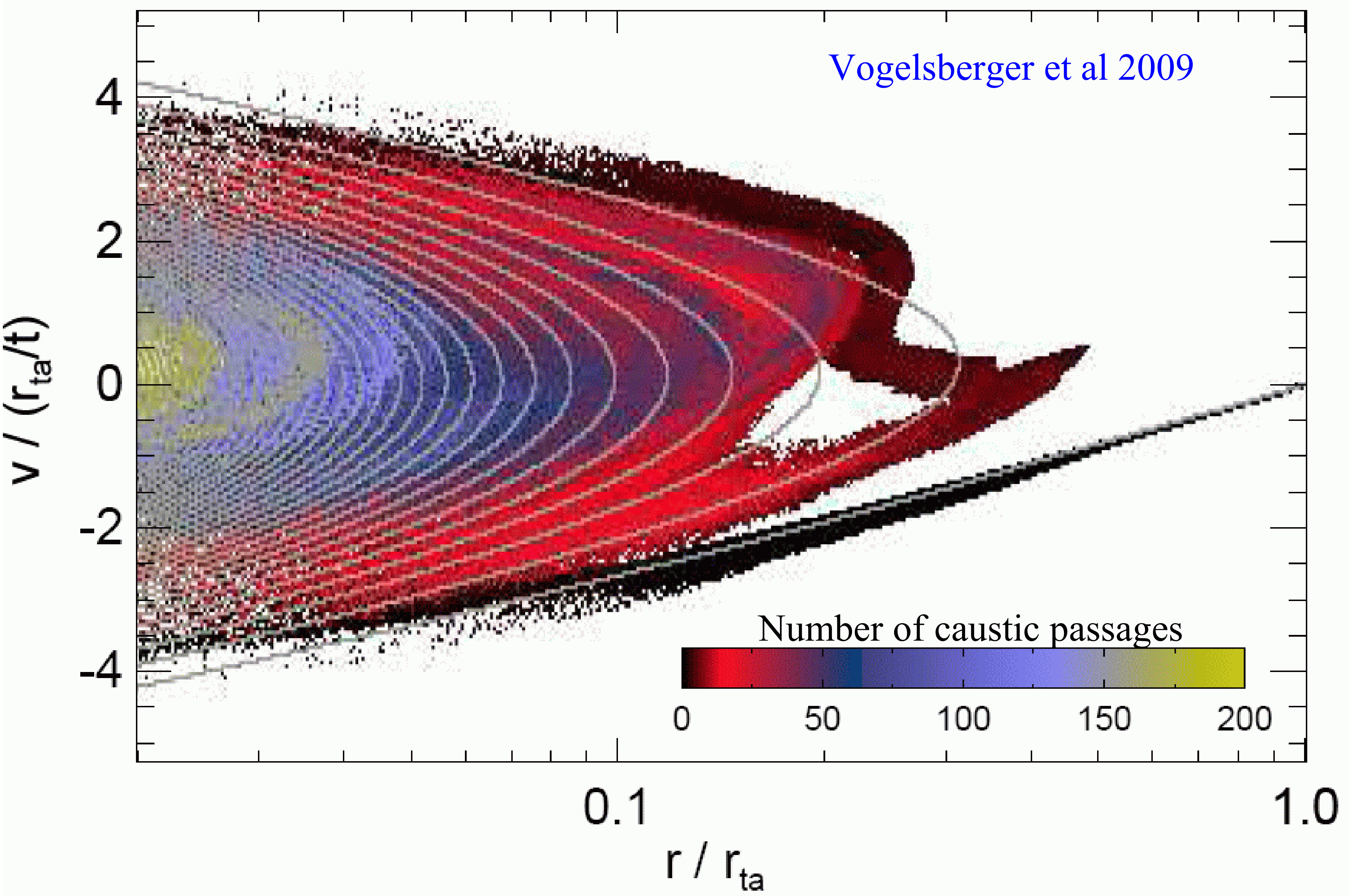

mass vs. radius


caustics

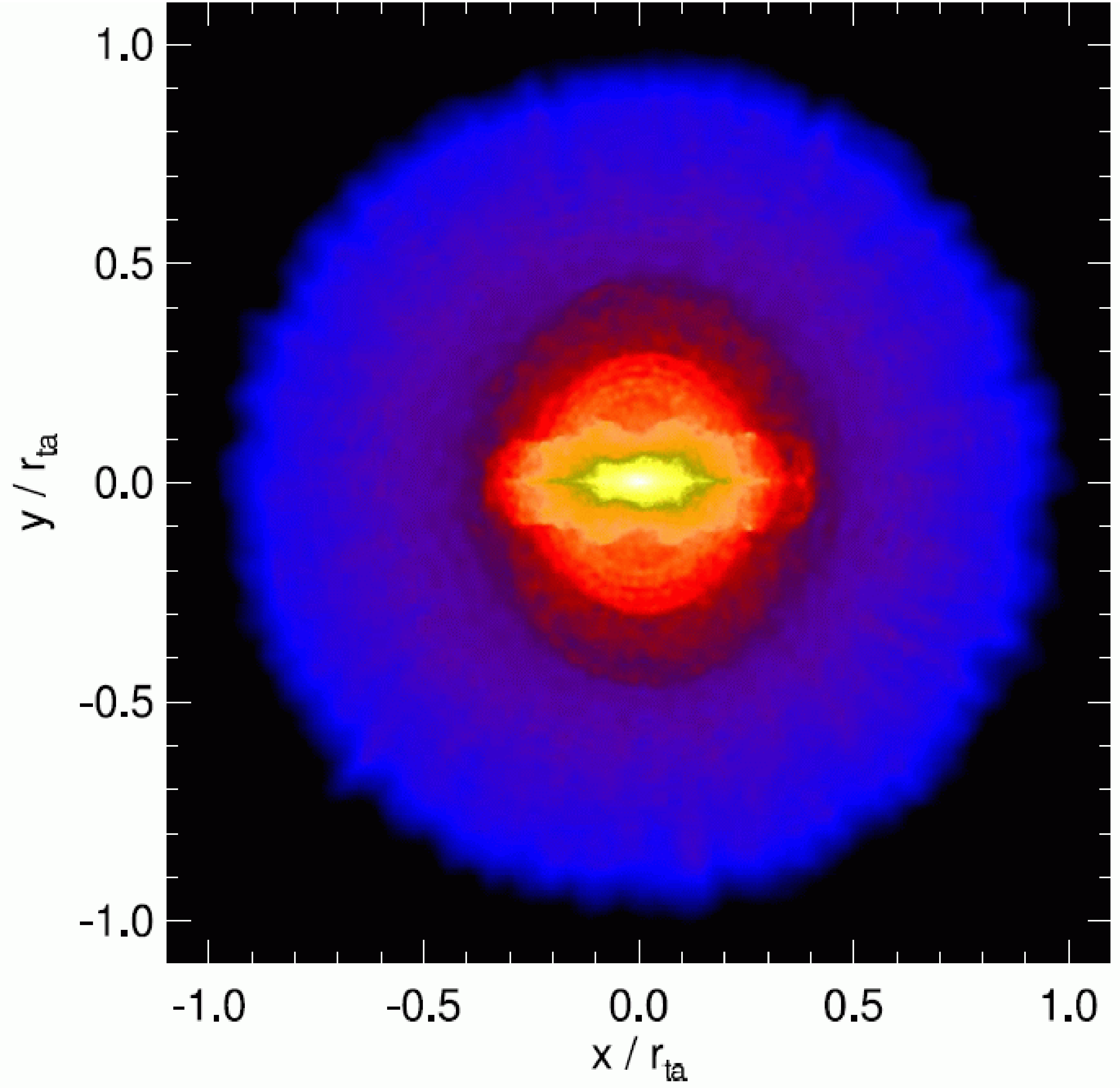
radial density profile

Simulation from self-similar spherical initial conditions

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



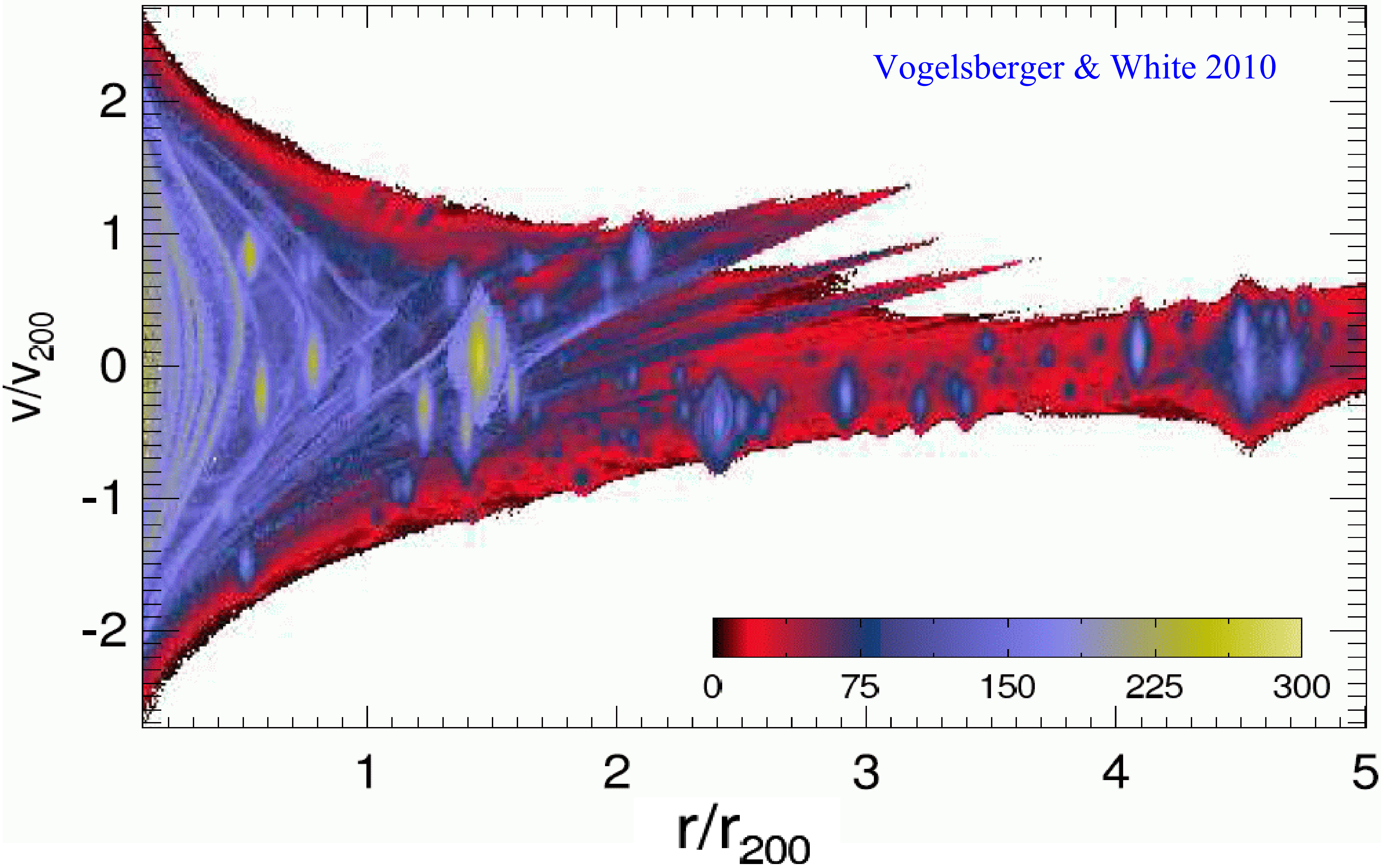
Simulation from self-similar spherical initial conditions



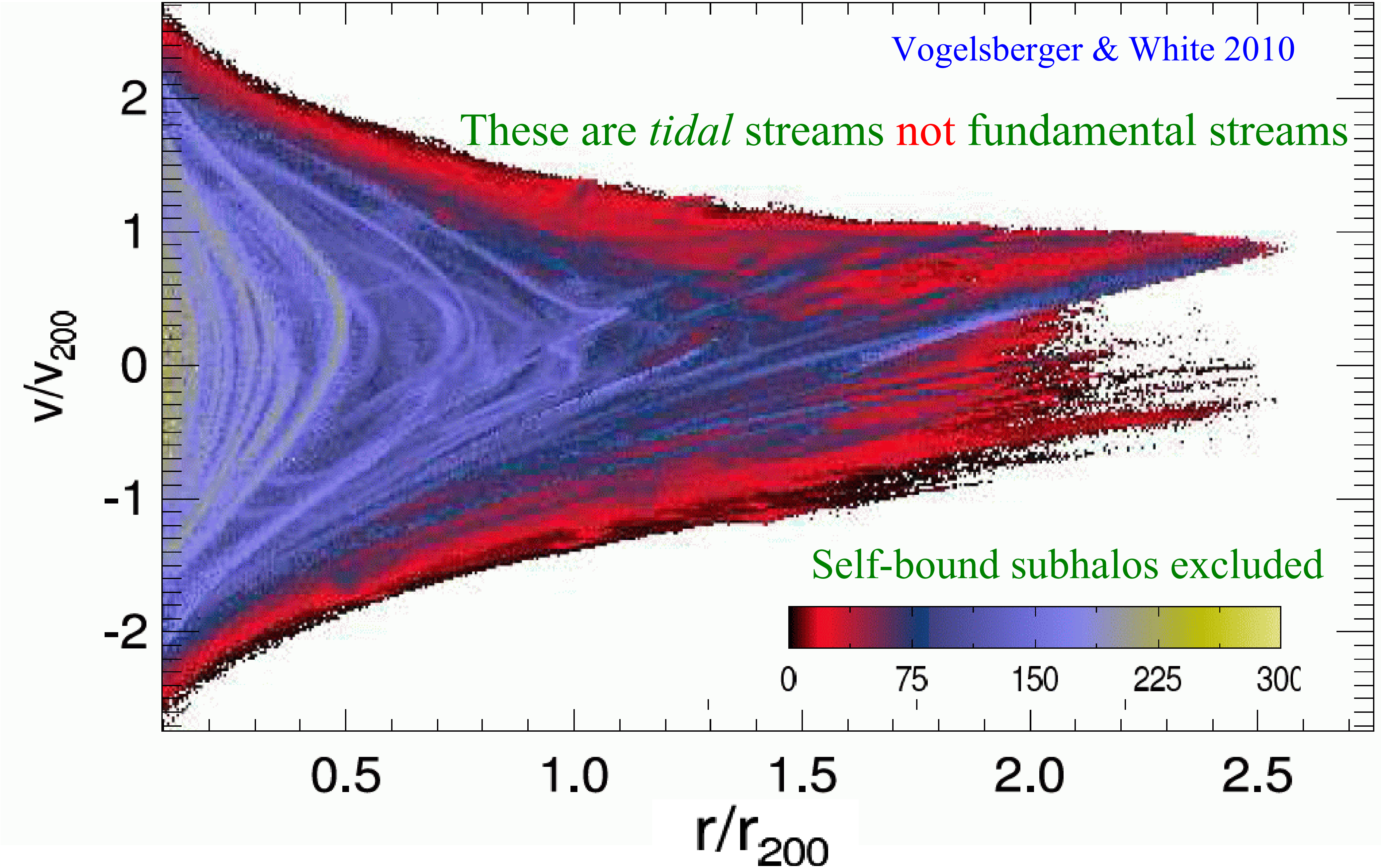
Vogelsberger et al 2009

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

Caustic crossing counts in a ΛCDM Milky Way halo



Caustic crossing counts in a ΛCDM Milky Way halo

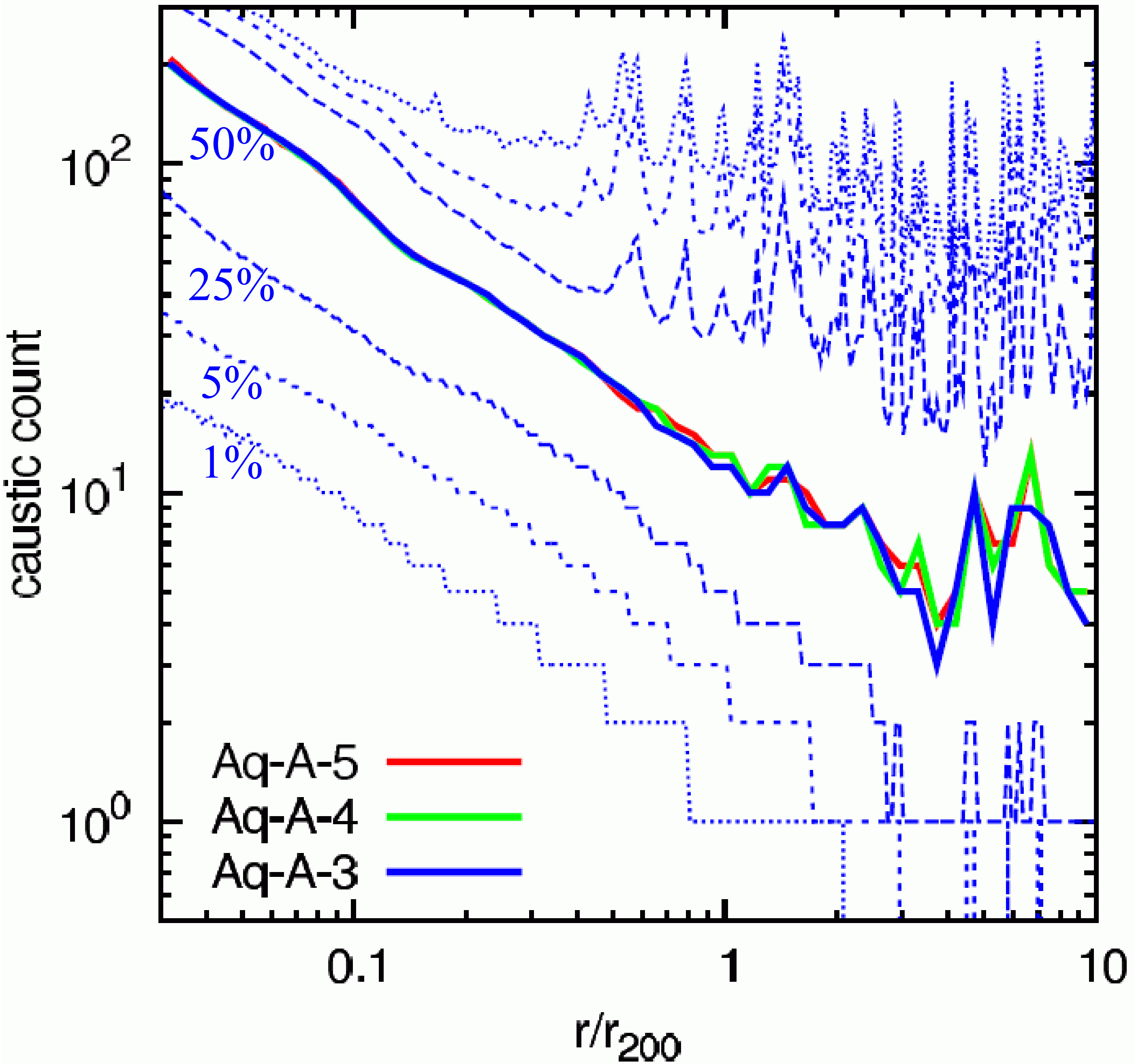


These are *tidal* streams not fundamental streams

Self-bound subhalos excluded

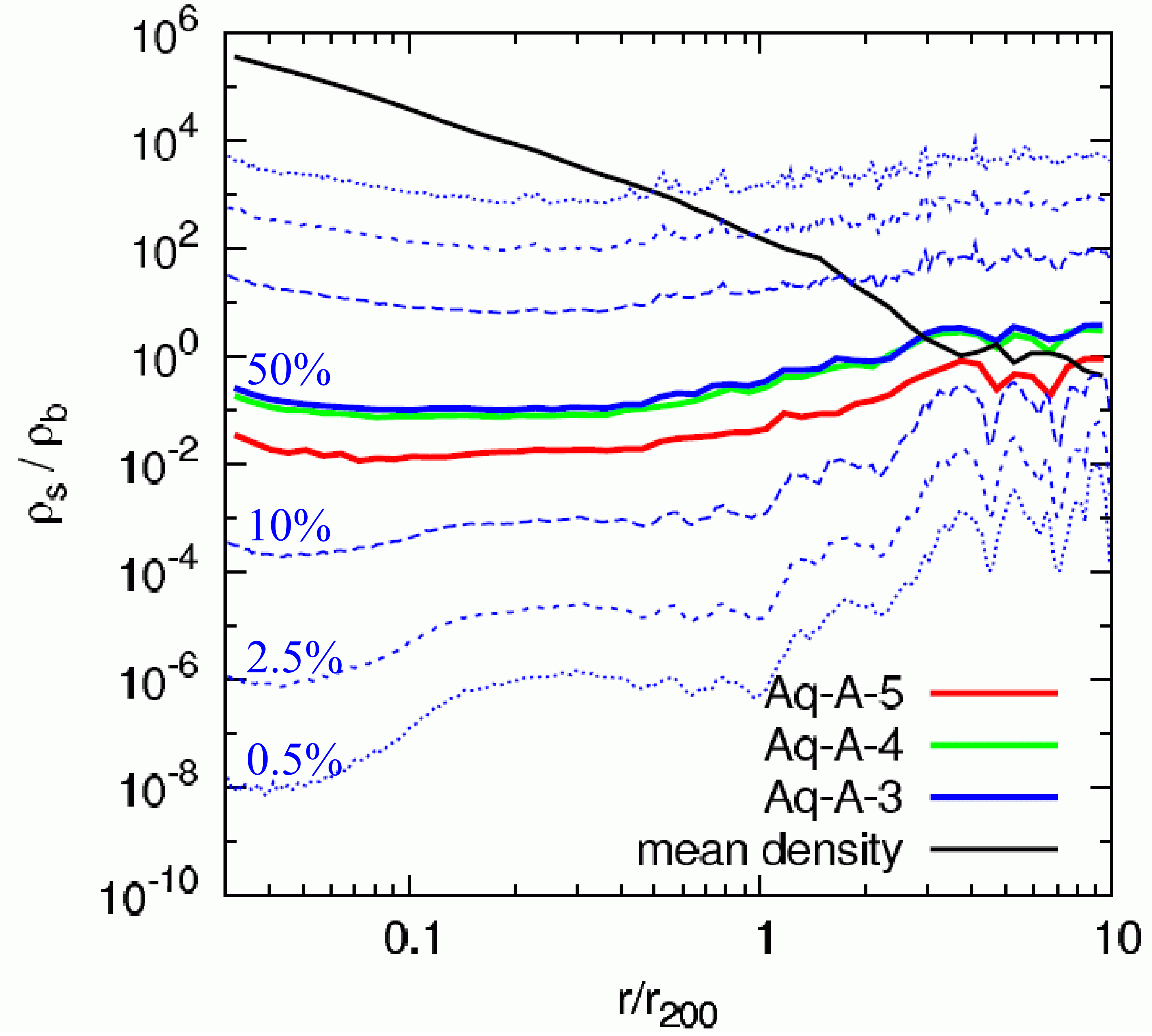
Caustic count profiles for Aquarius halos

Vogelsberger & White 2010



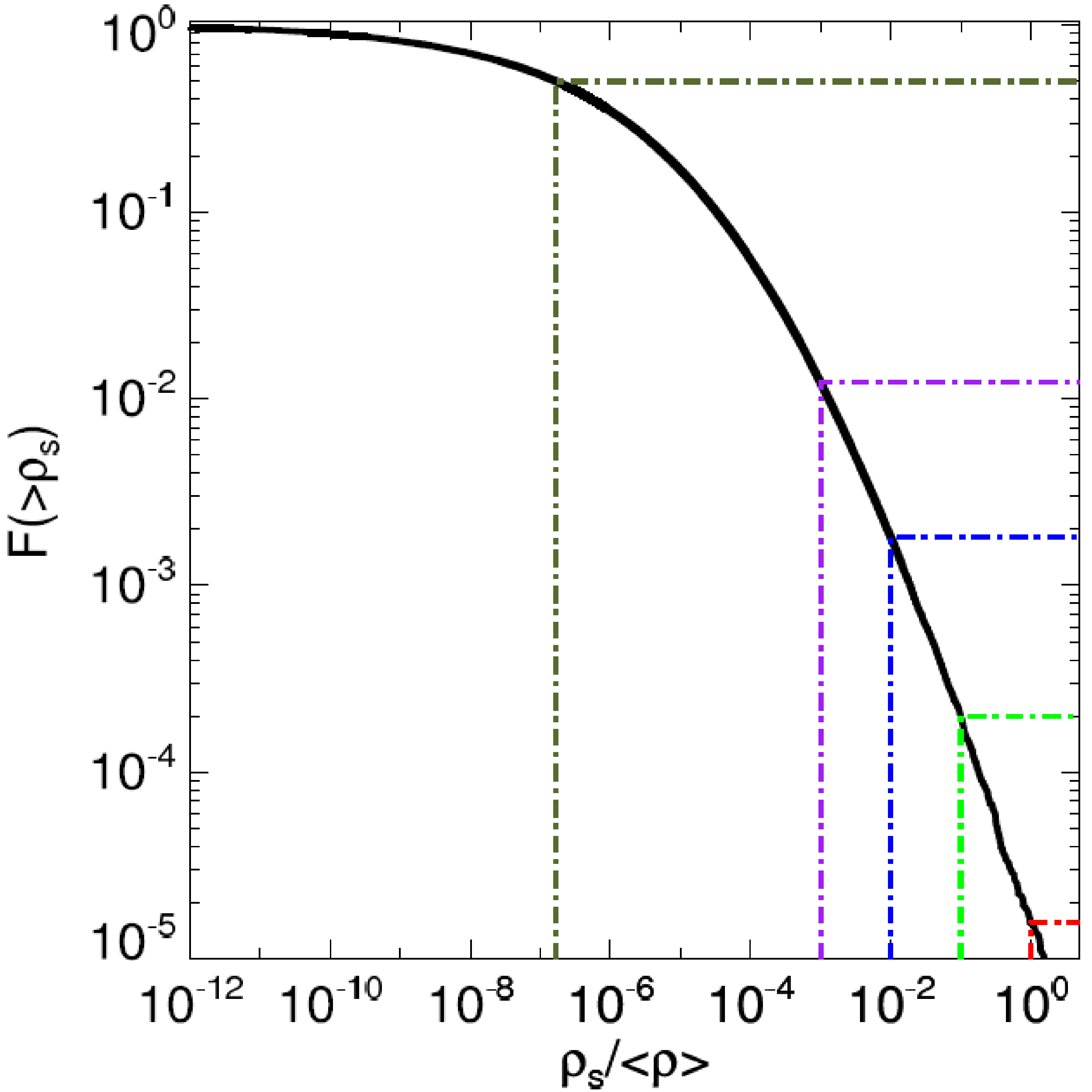
Stream density distribution in Aquarius halos

Vogelsberger & White 2010



Stream density distribution at the Sun

Vogelsberger & White 2010



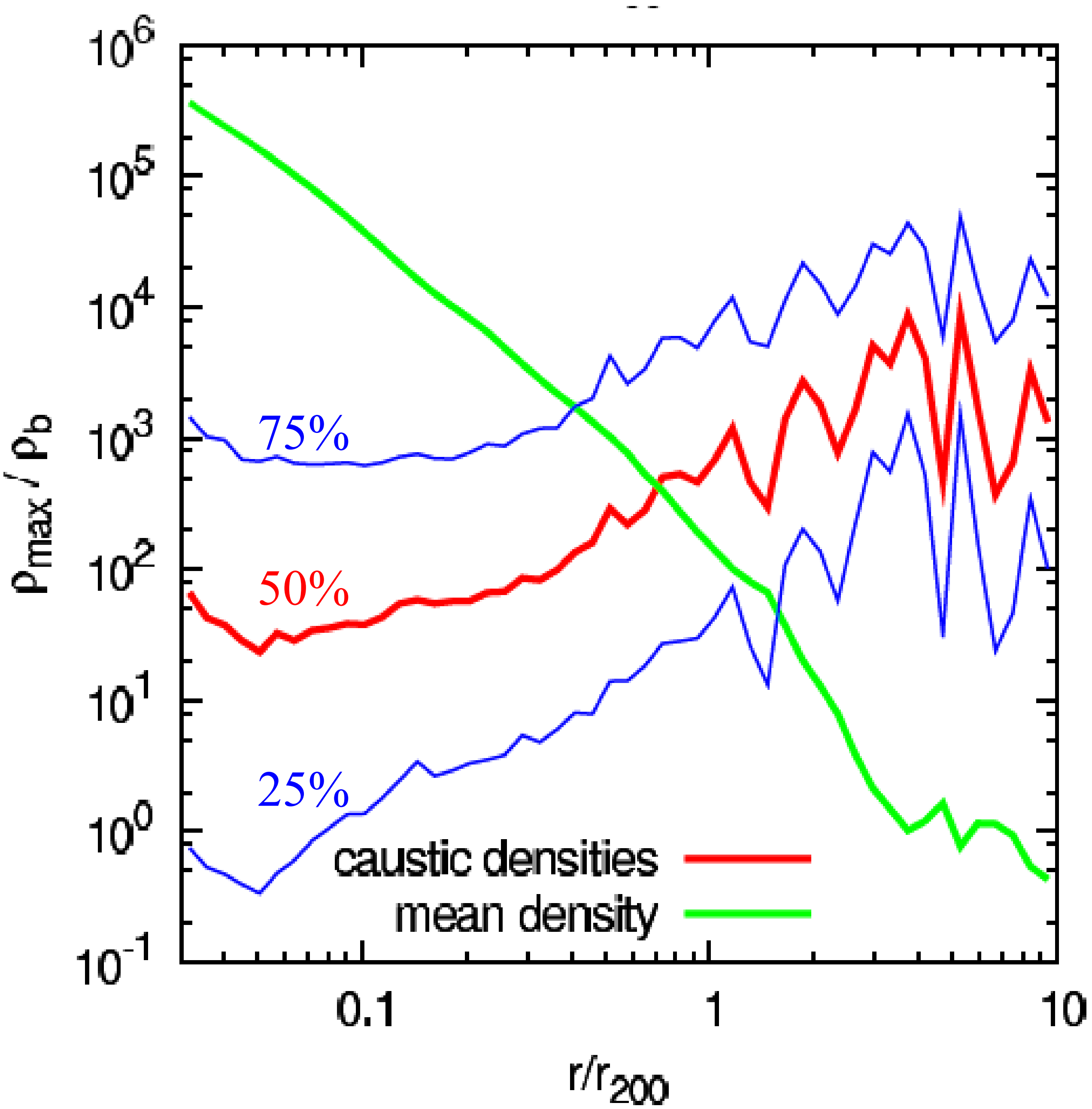
Cumulative stream density distribution for particles with $7\text{ kpc} < r < 13\text{ kpc}$

Probability that the Sun is in a stream with density $> X \langle\rho\rangle$ is P

X	P
1.0	0.00001
0.1	0.002
0.01	0.2
0.001	~1

Radial distribution of peak density at caustics

Vogelsberger & White 2010

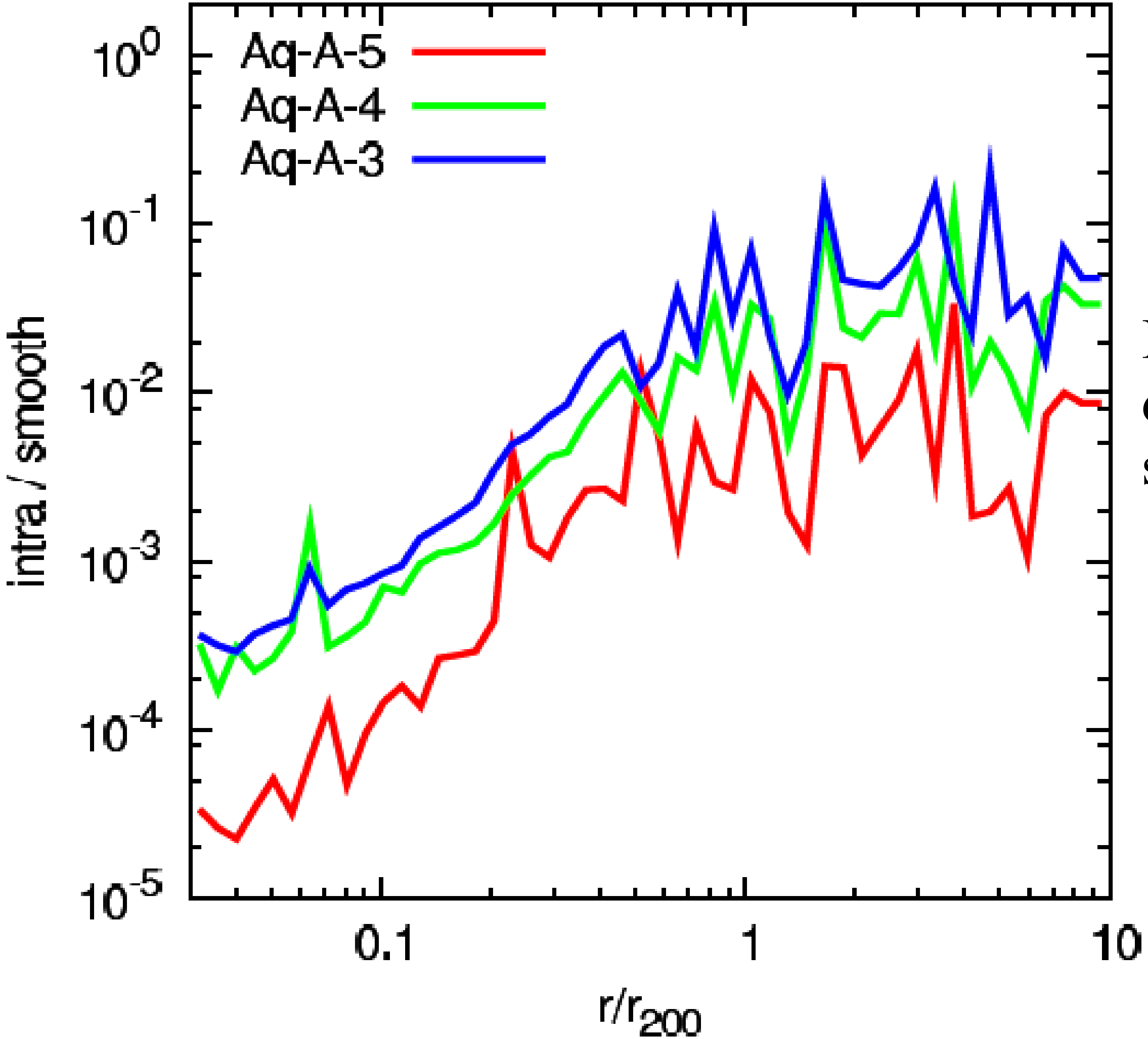


Initial velocity dispersion assumes a standard WIMP with

$m = 100$ GeV/c^2

Fraction of annihilation luminosity from caustics

Vogelsberger & White 2010



Initial velocity dispersion assumes a standard WIMP with $m = 100\ \mathrm{GeV}/c^2$

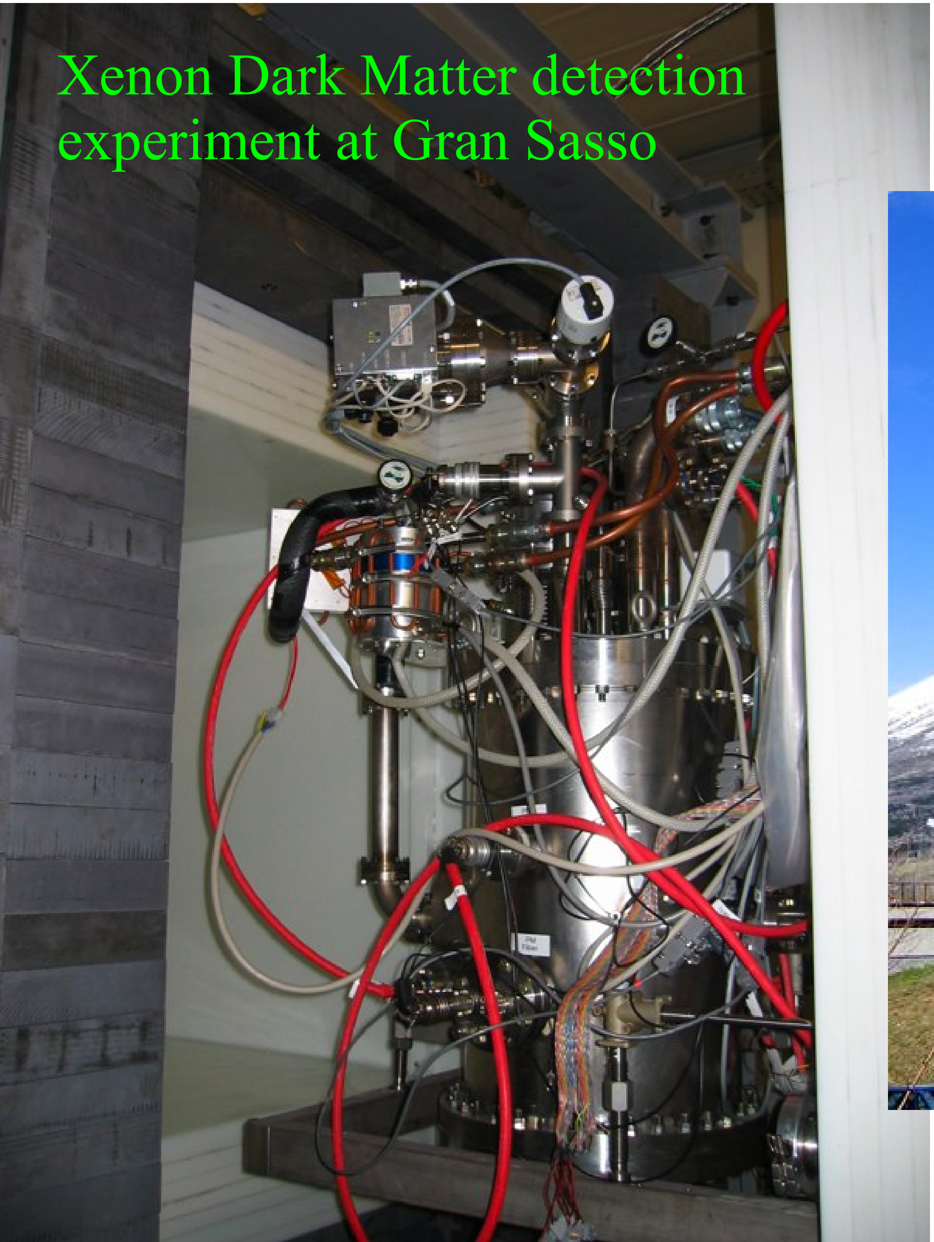
Conclusions: fundamental streams and caustics

- Integration of the GDE can augment the ability of ΛCDM simulations to resolve fine-grained structure by 15 to 20 orders of magnitude

- Fundamental streams and their associated caustics will have no significant effect on direct and indirect Dark Matter detection experiments

- The most massive stream at the Sun should contain roughly 0.001 of the local DM density and would have an energy spread $\Delta E/E < 10^{-10}$. It might be detectable in an axion experiment

Maybe Dark Matter can be detected in a laboratory

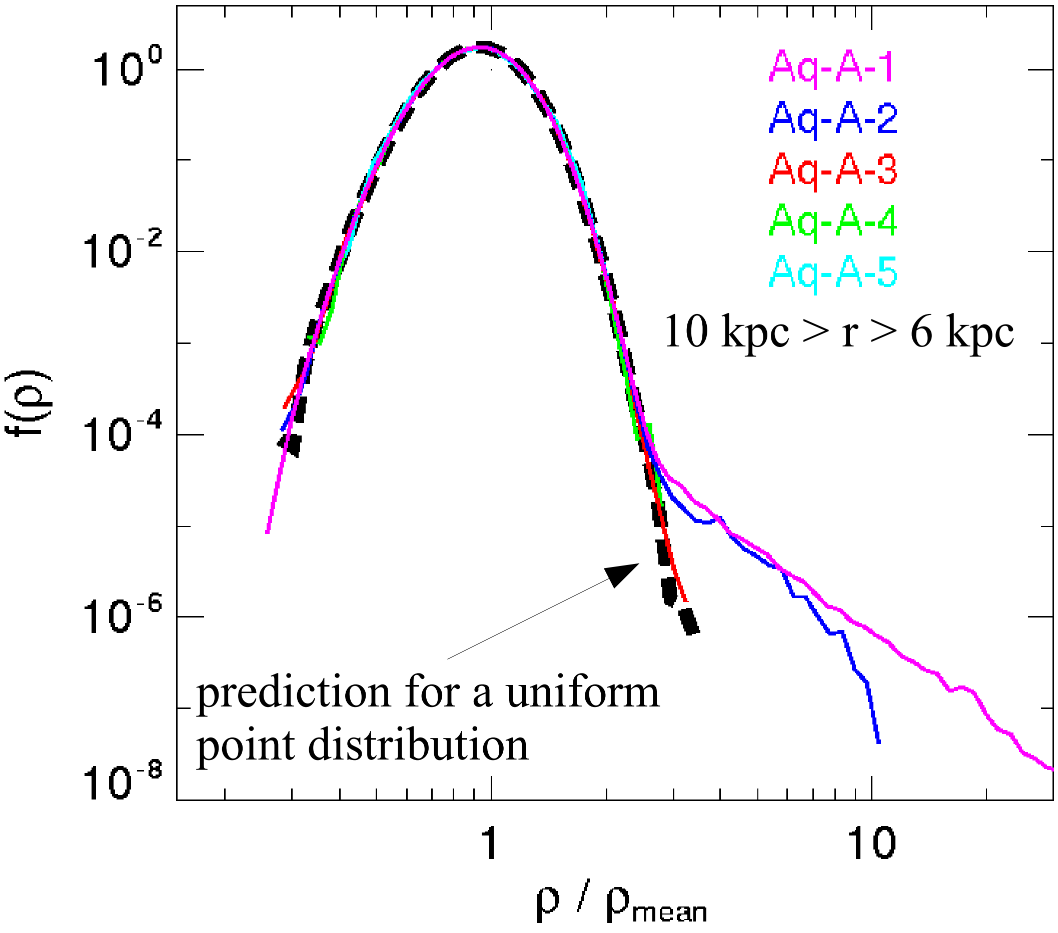


Xenon Dark Matter detection experiment at Gran Sasso

External view of Gran Sasso Laboratory

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

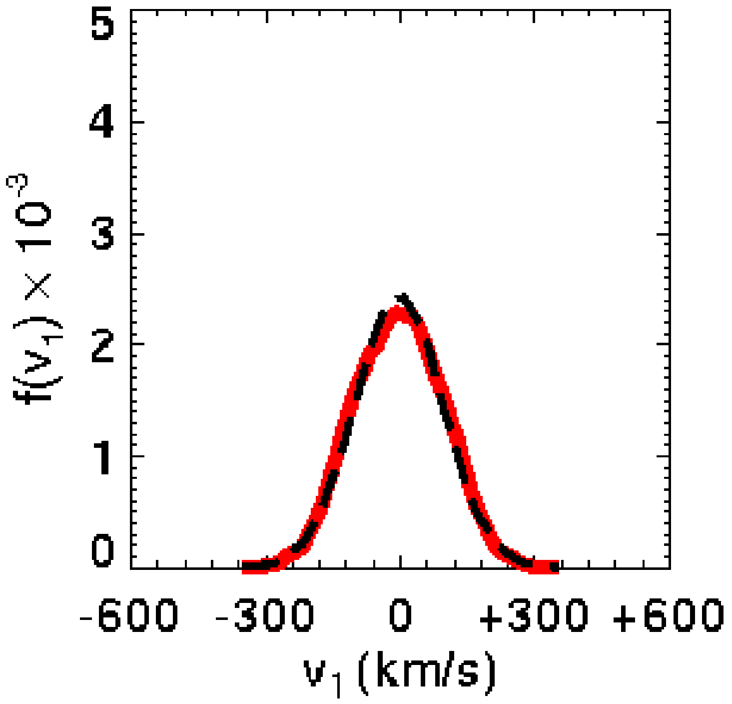
Vogelsberger et al 2008

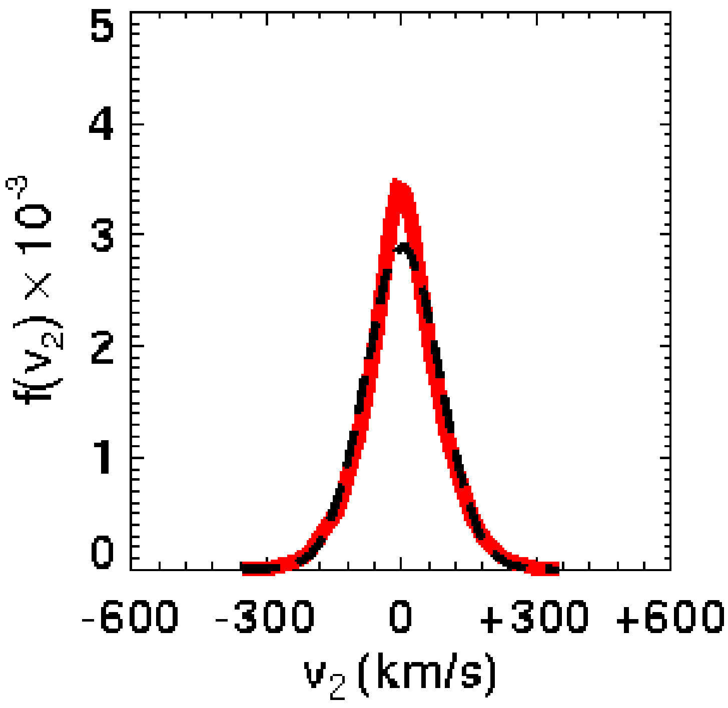


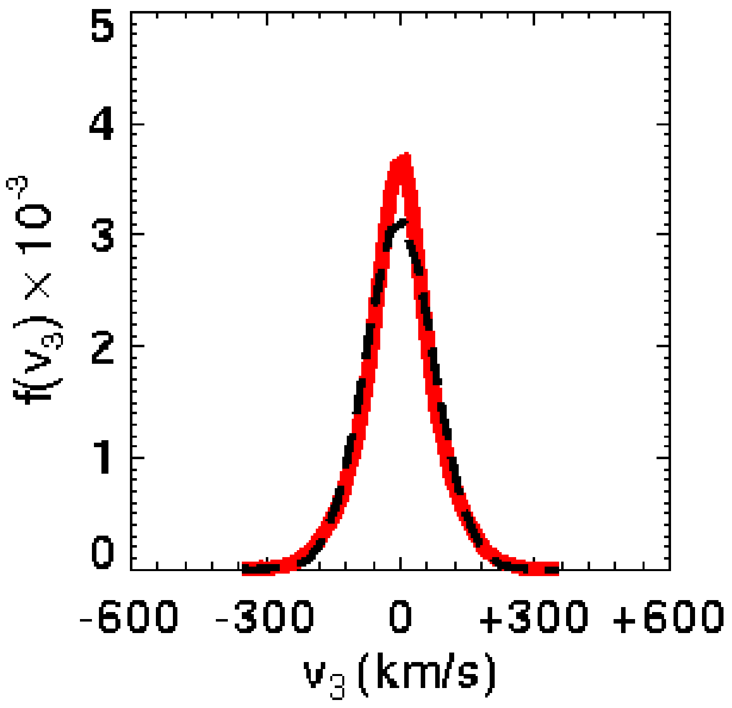
- Estimate a density ρ at each point by adaptively smoothing using the 64 nearest particles
- Fit to a smooth density profile stratified on similar ellipsoids
- The chance of a random point lying in a substructure is $< 10^{-4}$
- The *rms* scatter about the smooth model for the remaining points is only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

Local velocity distribution

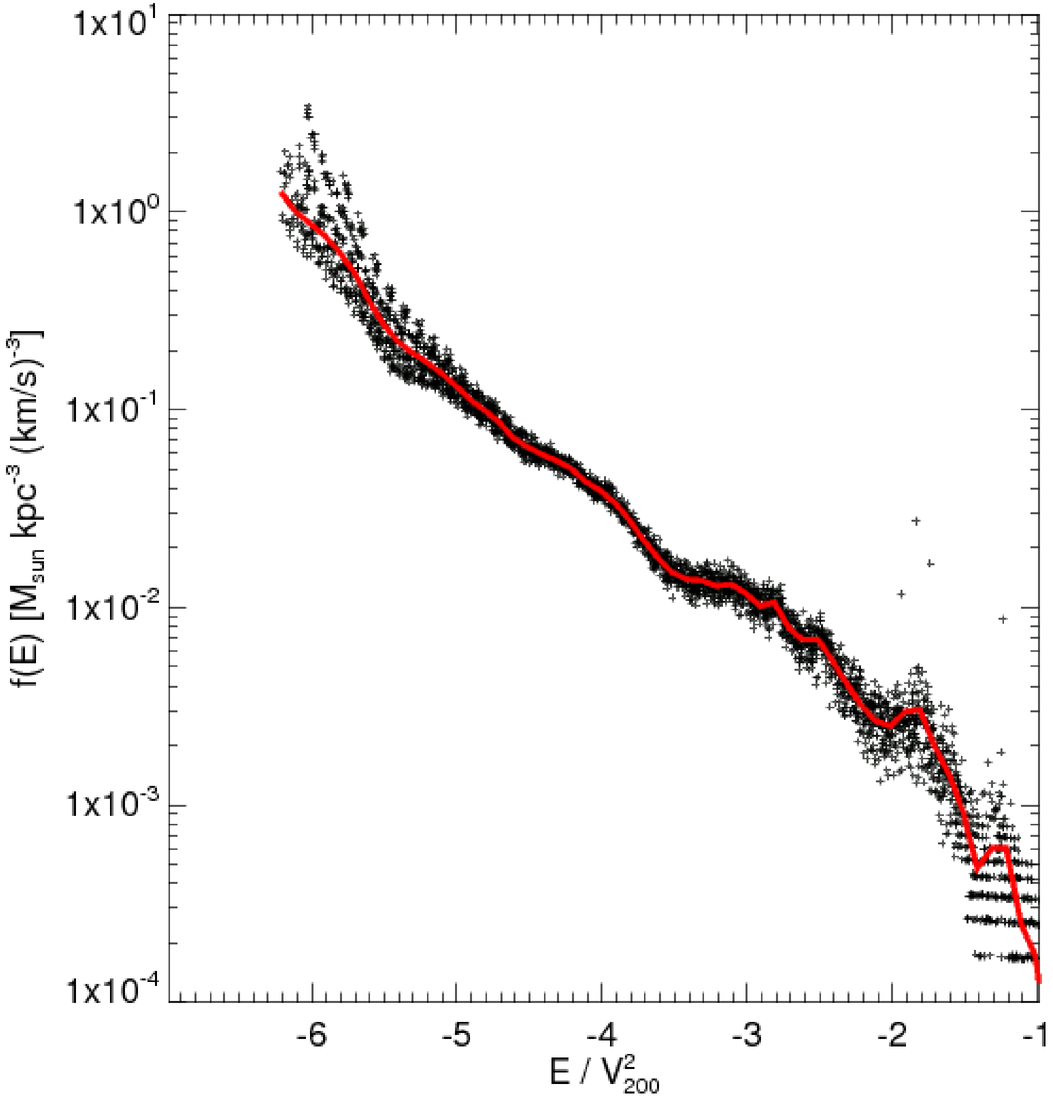
- Velocity histograms for particles in a typical $(2\text{kpc})^3$ box at R = 8 kpc
- Distributions are smooth, near-Gaussian and different in different directions
- No individual streams are visible







Energy space features – fossils of formation



The energy distribution within (2 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

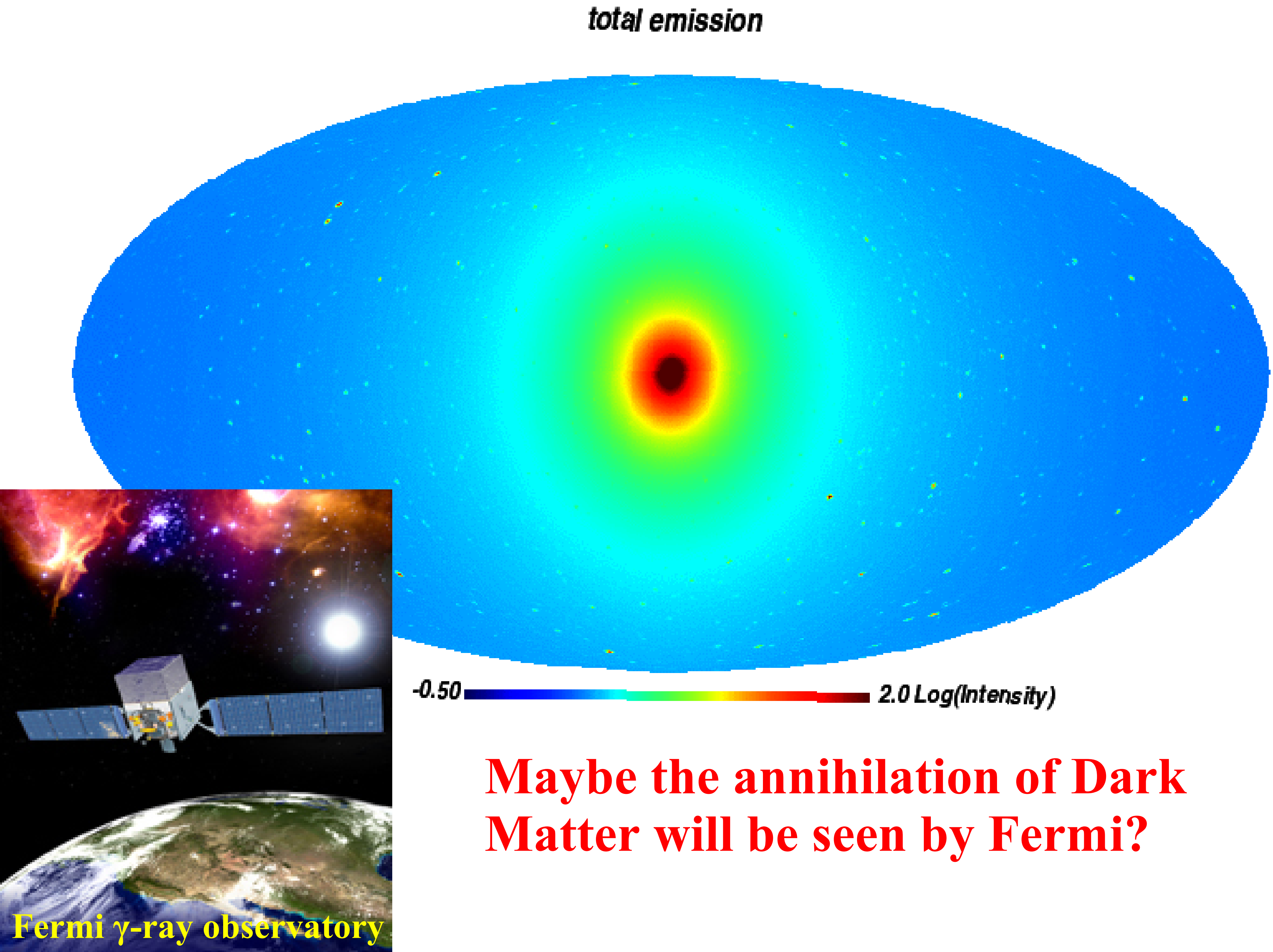
Conclusions for direct detection experiments

- 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

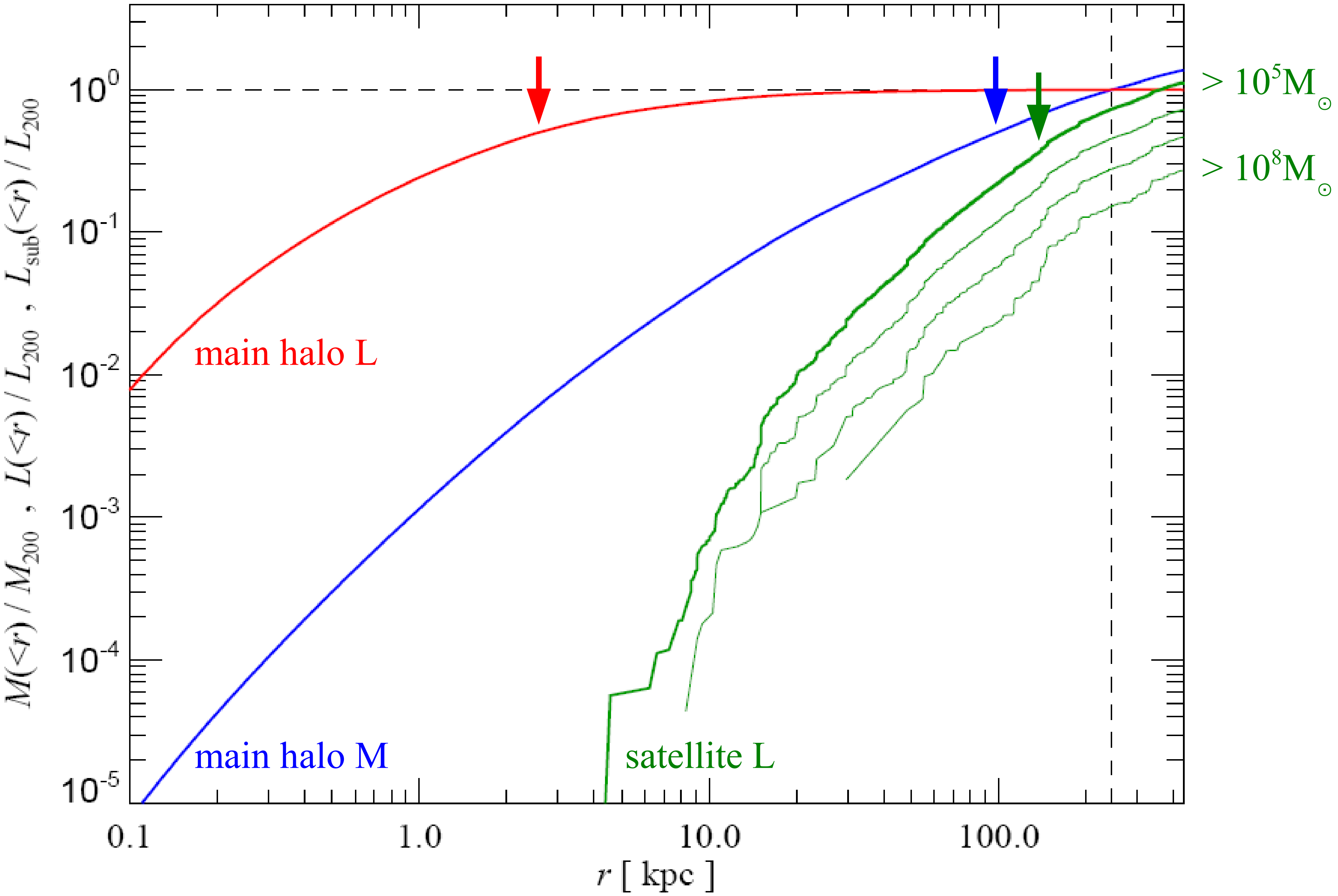
- The energy distribution of DM particles should contain broad features with ~20% amplitude which are the fossils of the detailed assembly history of the Milky Way's dark halo

→ Dark matter astronomy



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

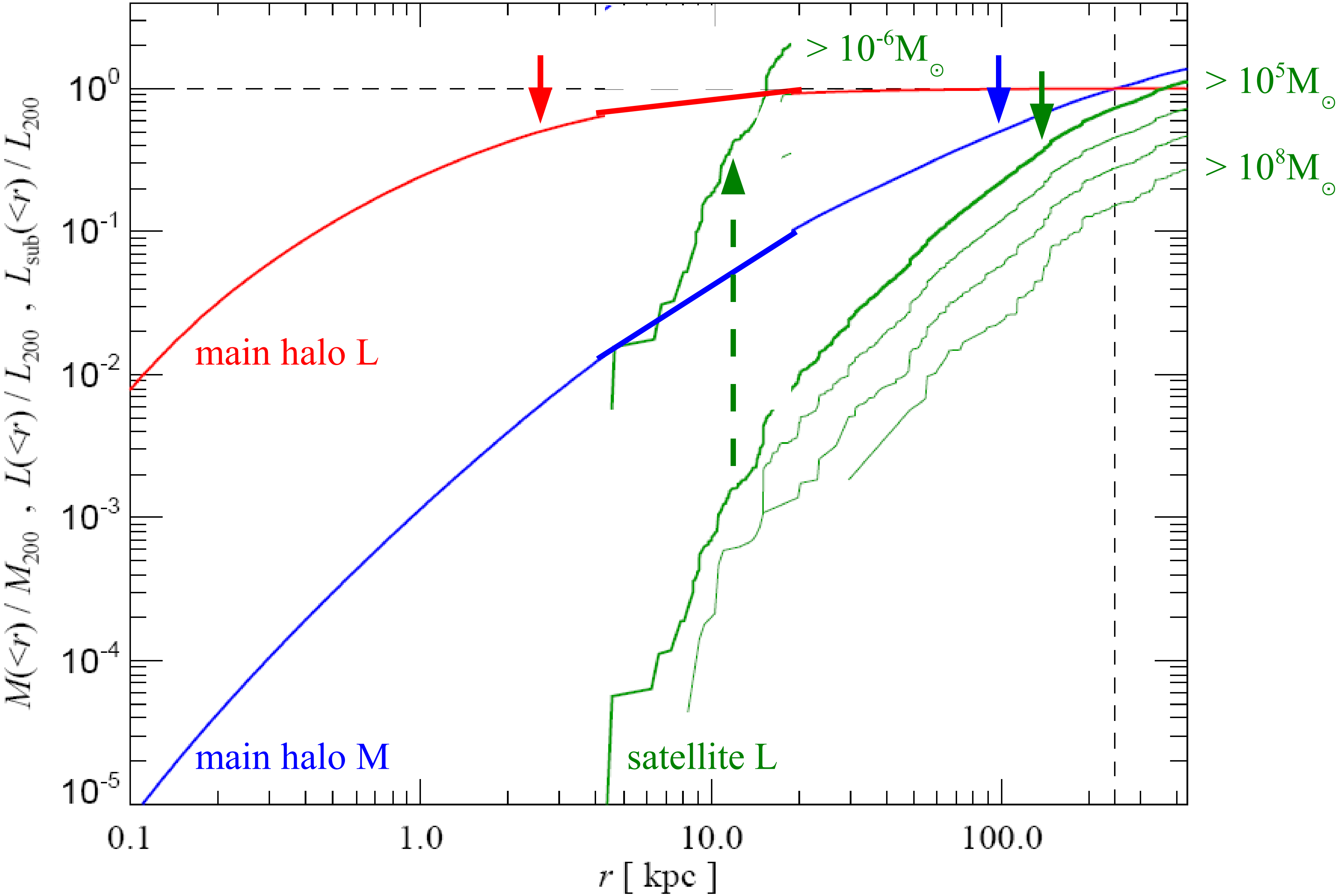
Mass and annihilation radiation profiles of a MW halo



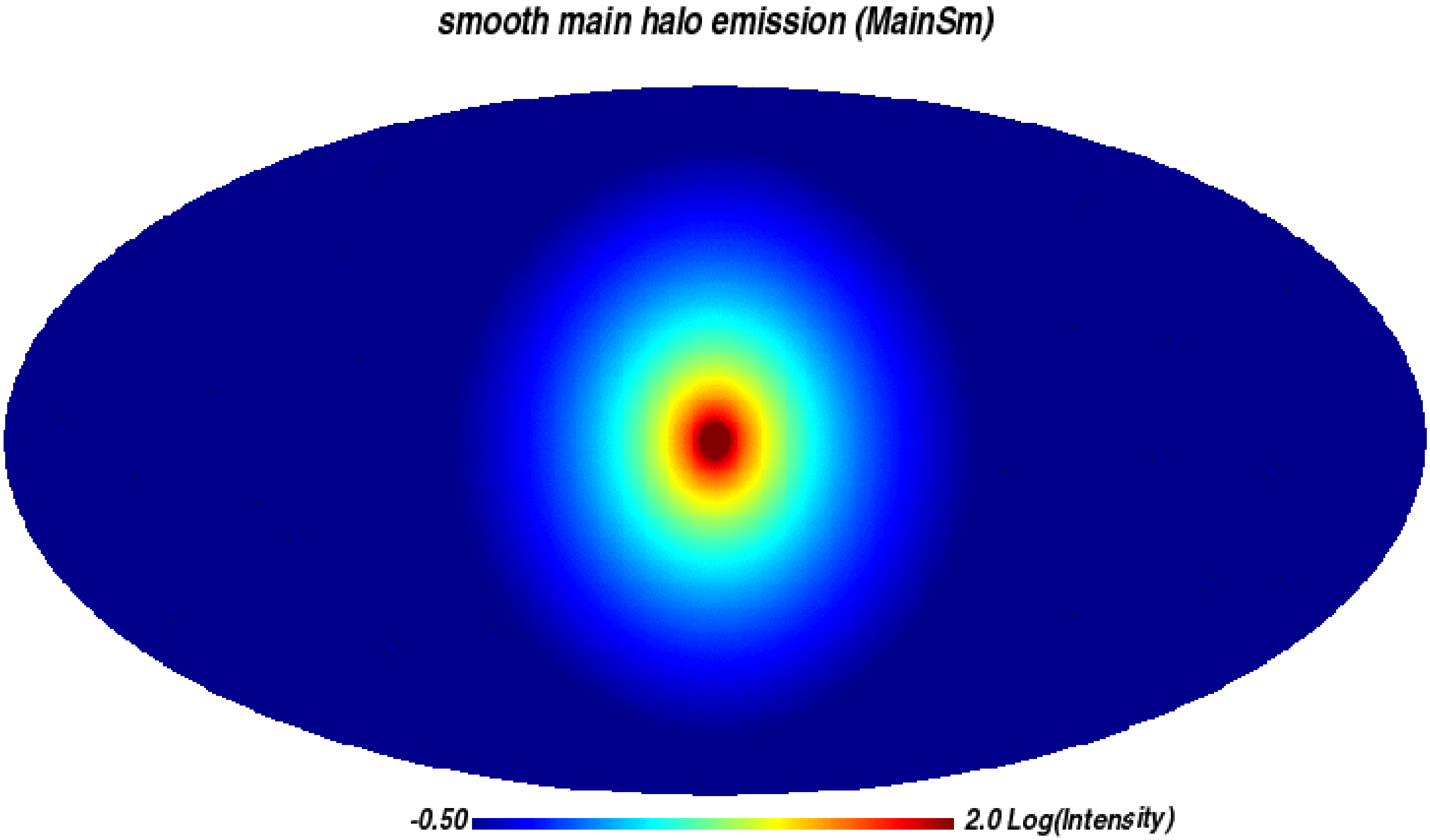
Springel et al 2008

Mass and annihilation radiation profiles of a MW halo

Springel et al 2008

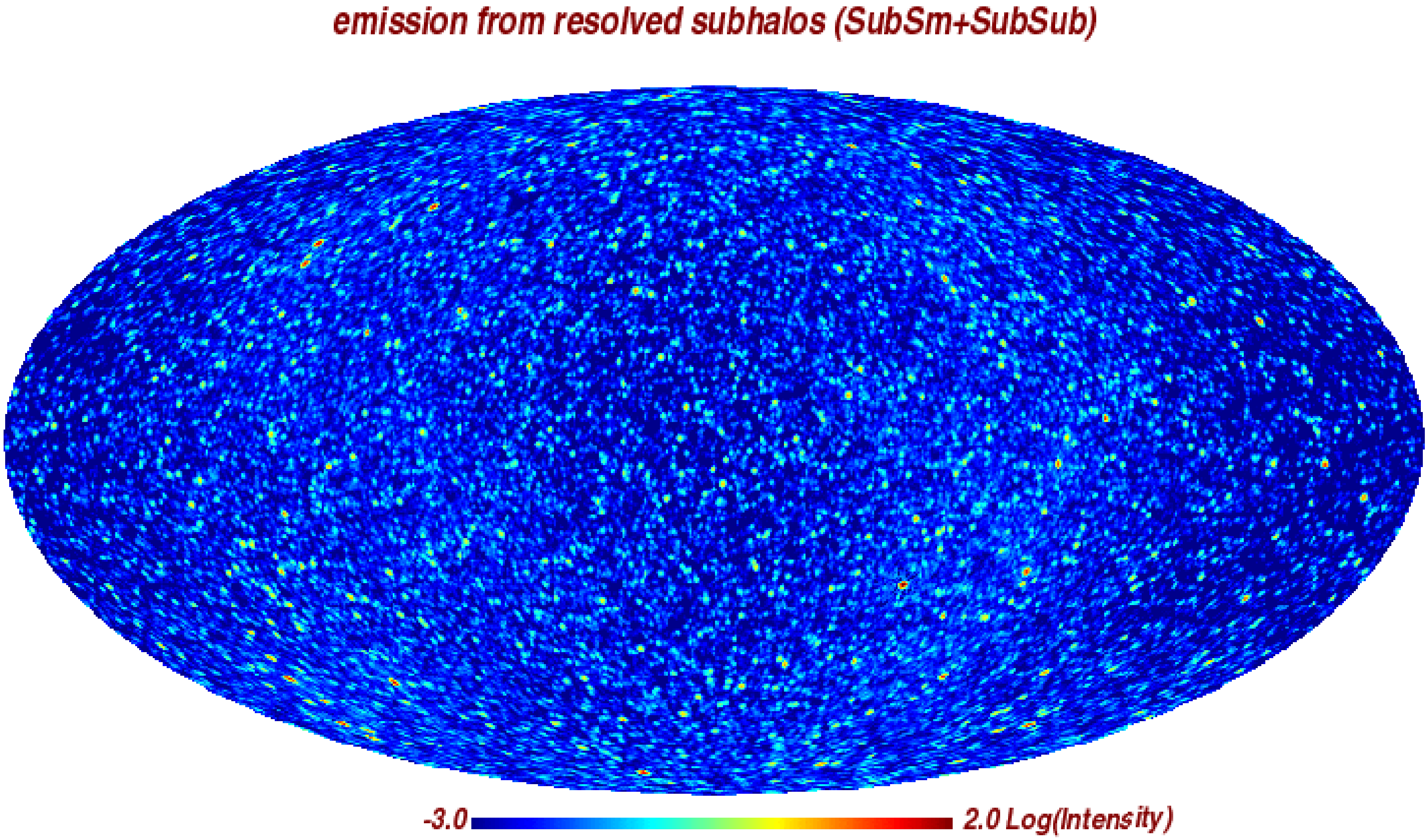


Milky Way halo seen in DM annihilation radiation



smooth main halo emission (MainSm)

Milky Way halo seen in DM annihilation radiation



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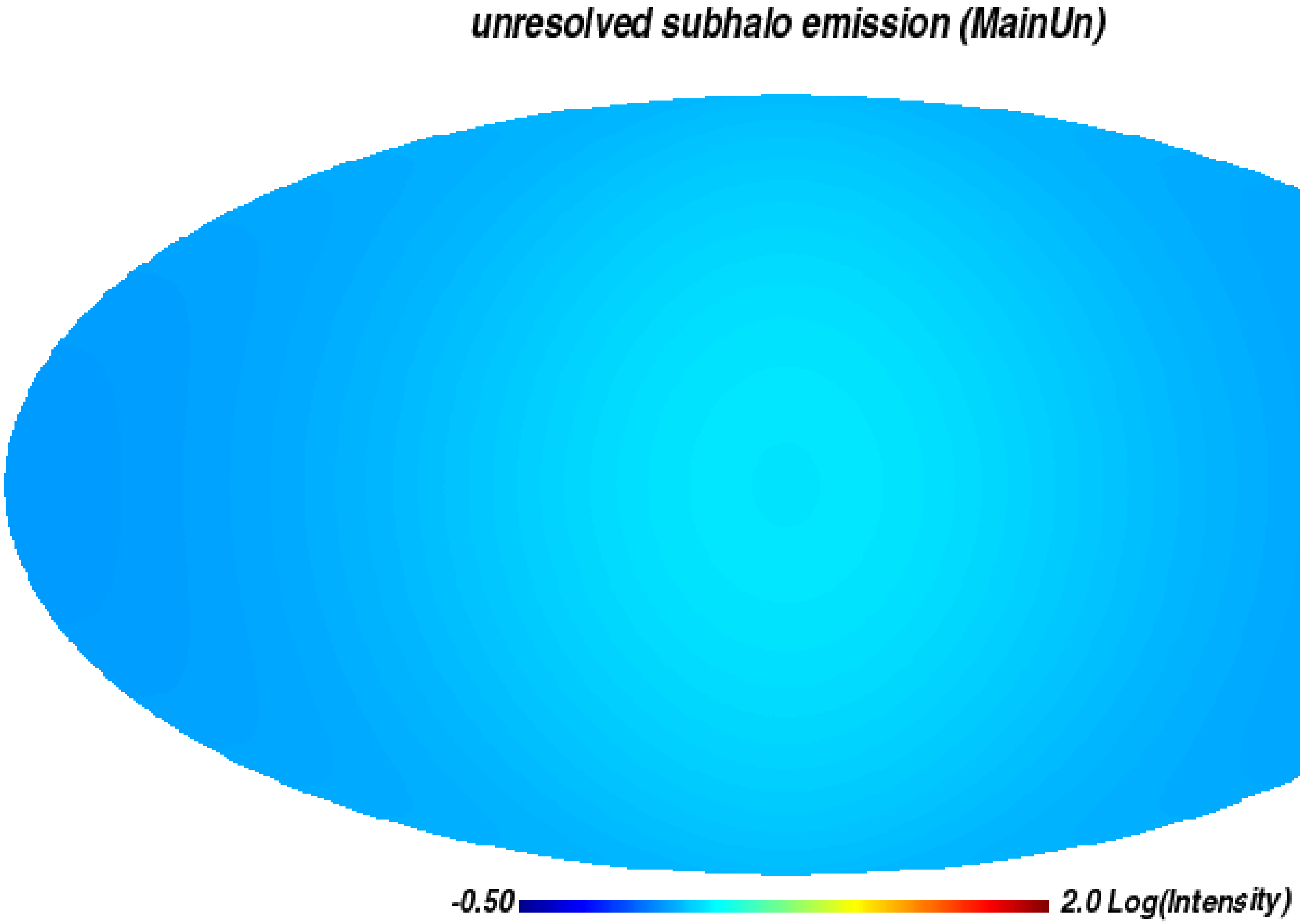

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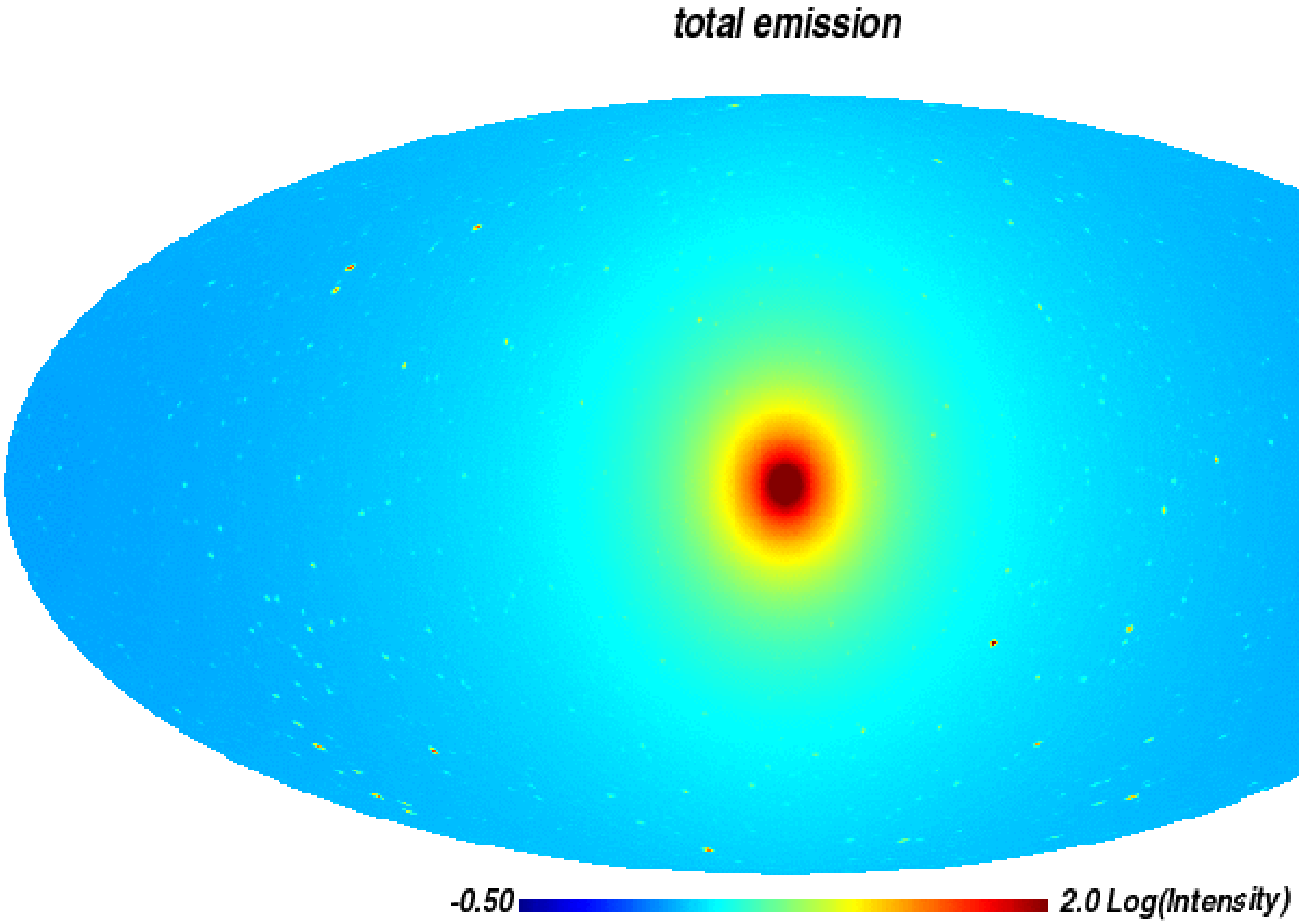
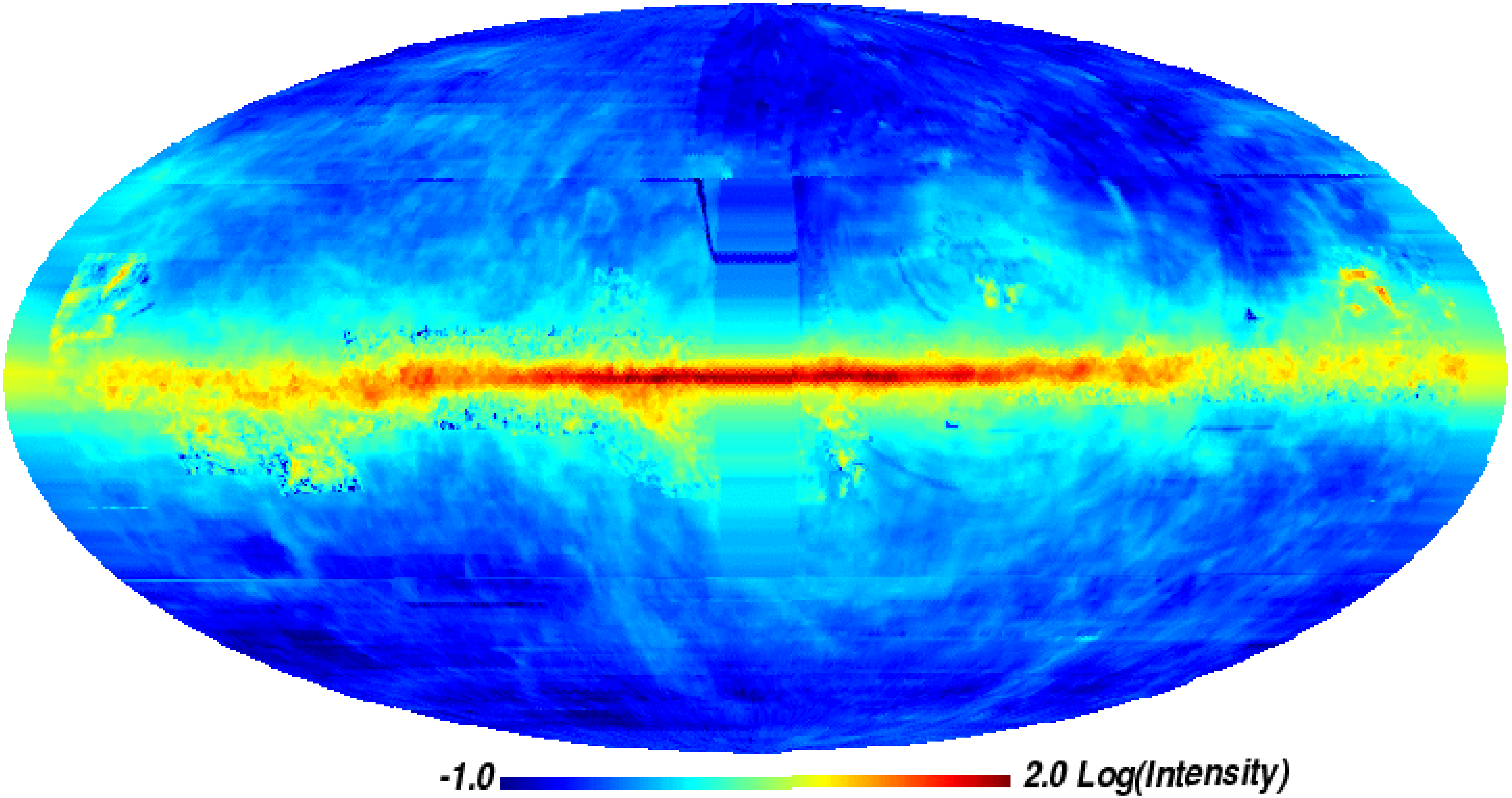


GALPROP, optimized



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

"Milky Way" halo

$z = 1.5$

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

Aquarius-A-1

Springel et al 2008