Title: The Small-Scale Structure of Galactic Dark Matter

Date: Sep 23, 2011 02:40 PM

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Abstract: In my talk I will discuss the relevant astrophysical input for dark matter detection experiments, i.e. the expected distribution of dark matter at the solar position. Based on high resolution N-body simulations I will then show that the formation history of the galactic dark matter halo leaves imprints in the velocity and energy distribution. In the second part of my talk I will focus on the fine-grained dark matter structure and discuss the importance of caustics and streams for detection experiments.

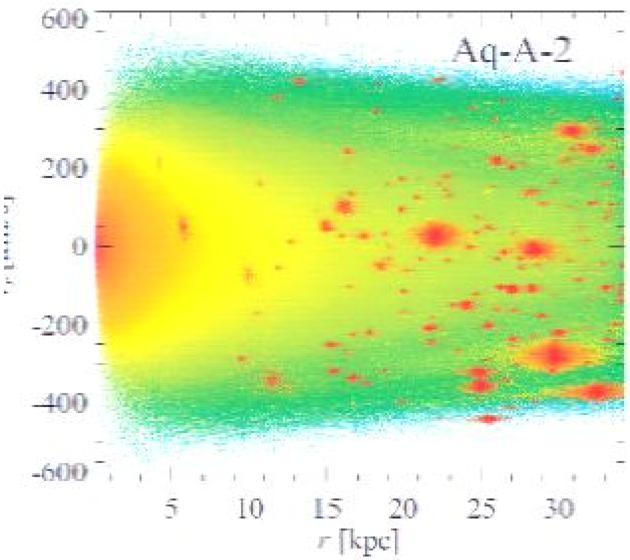
The Small-Scale Structure of Galactic Dark Matter

Mark Vogelsberger, Harvard/CfA

Simon White, Volker Springel, Jesus Zavala,
Michal Maciejewski, Amina Helmi, Roya Mohayee

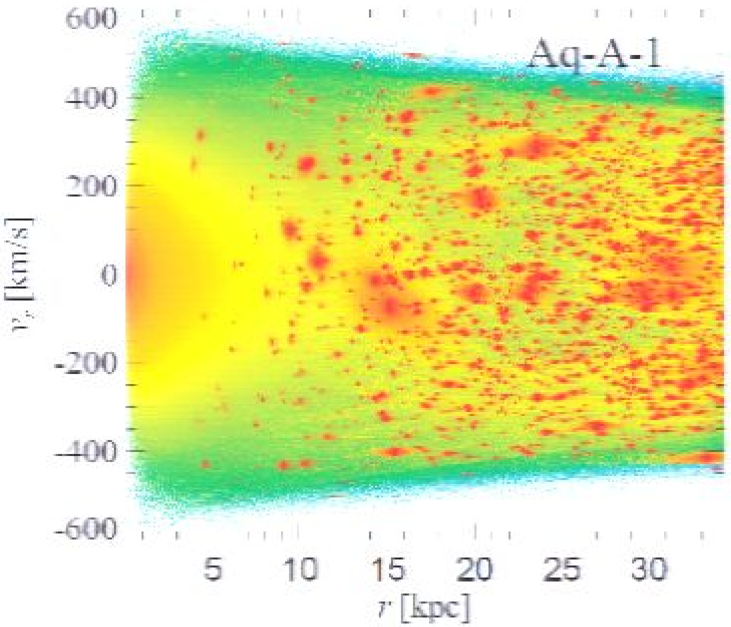
Coarse-Grained Structure of LCDM Halos

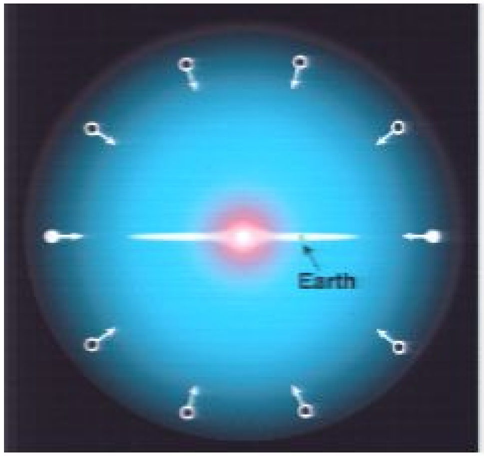
Halo Phase-Space Structure



Maciejewski et al. (2011)

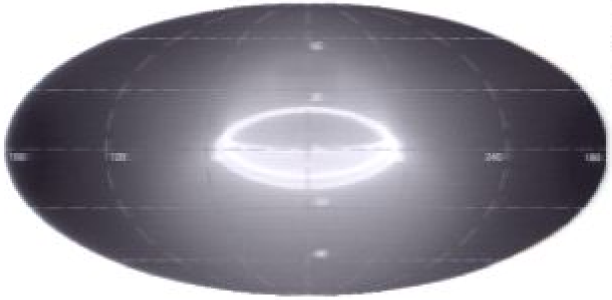
dark matter phase-space space structure (beyond SHM)



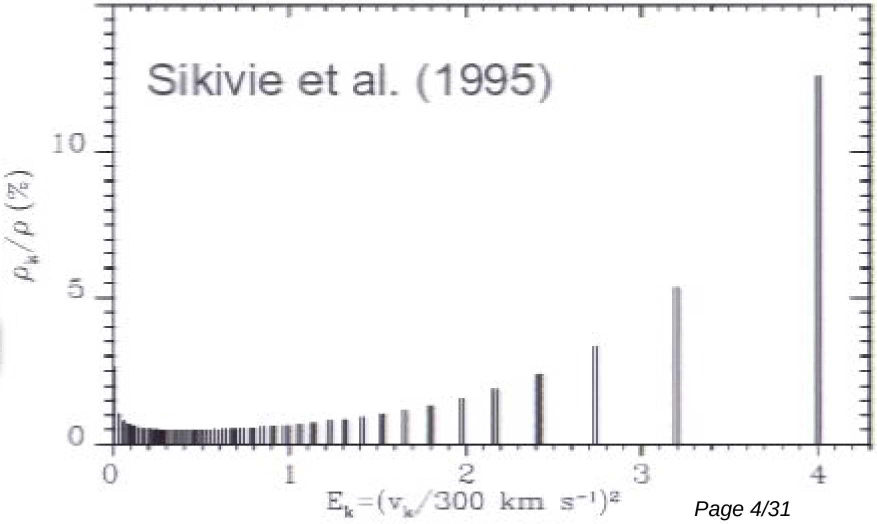


Van Bibber (2008)

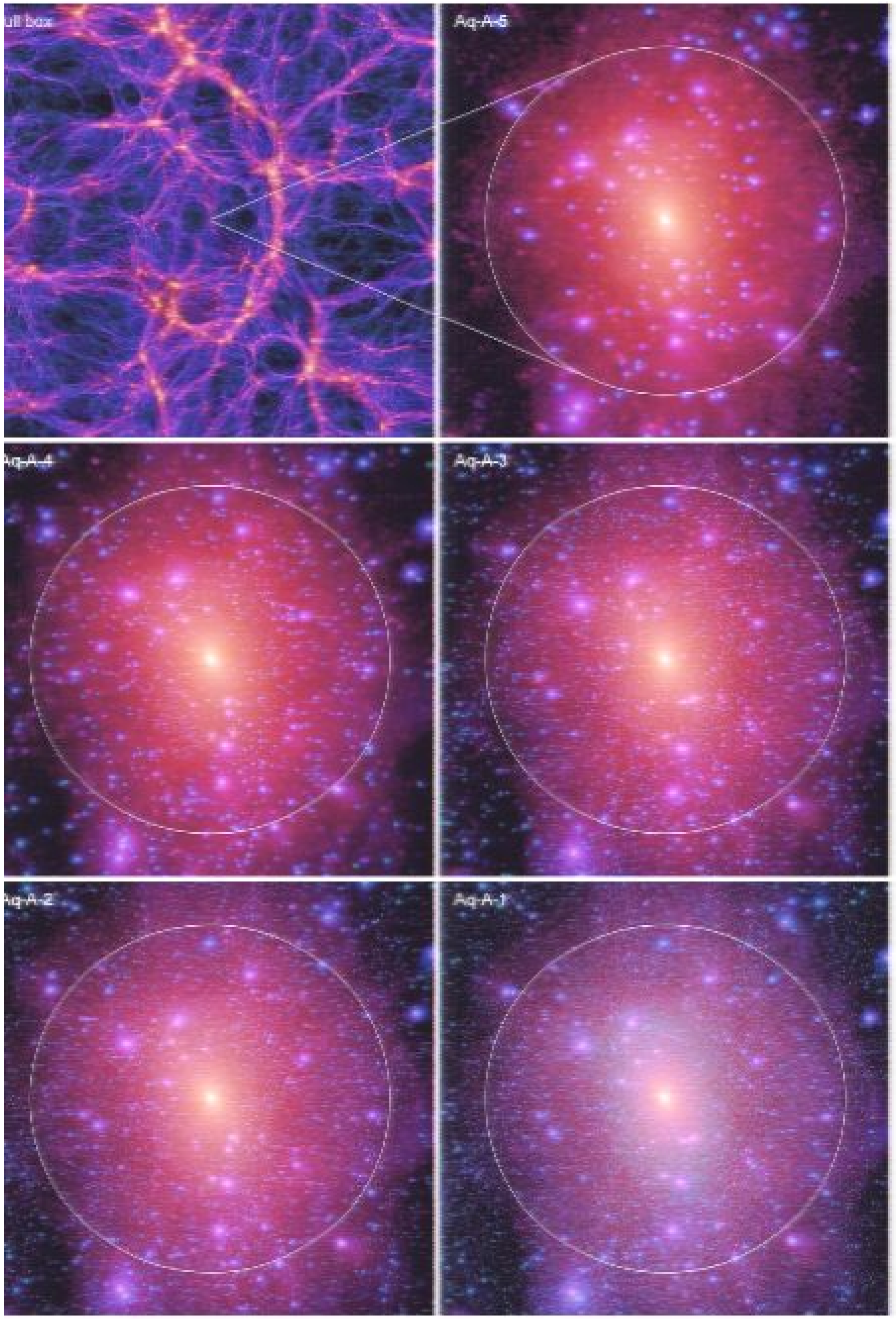
Analytic models:
→ massive streams
→ caustic ring model



Natarajan & Sikivie (2008)



Sikivie et al. (1995)

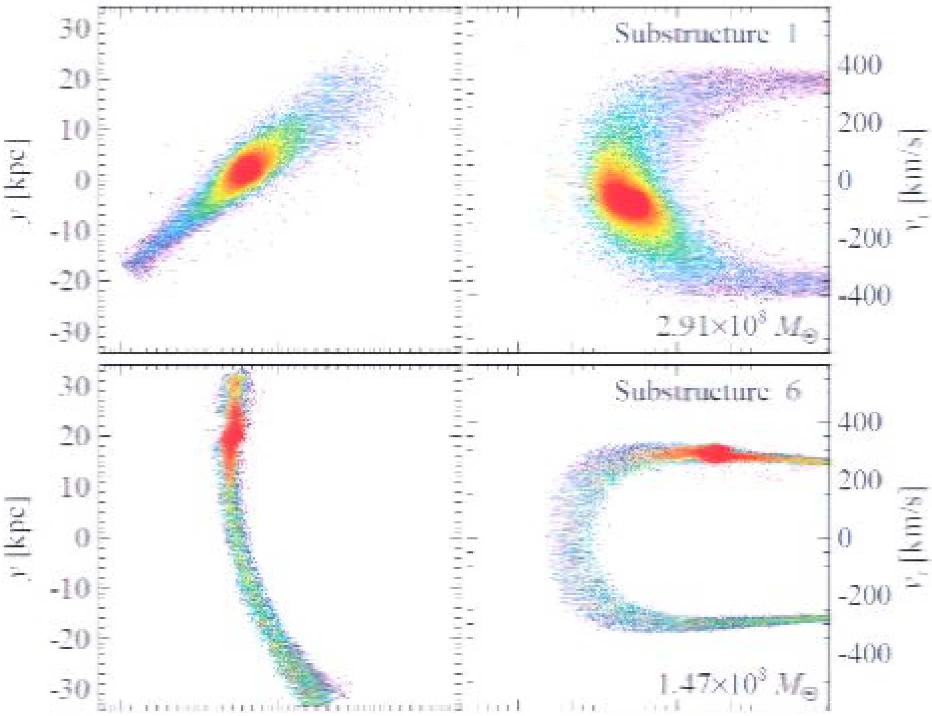


Aquarius

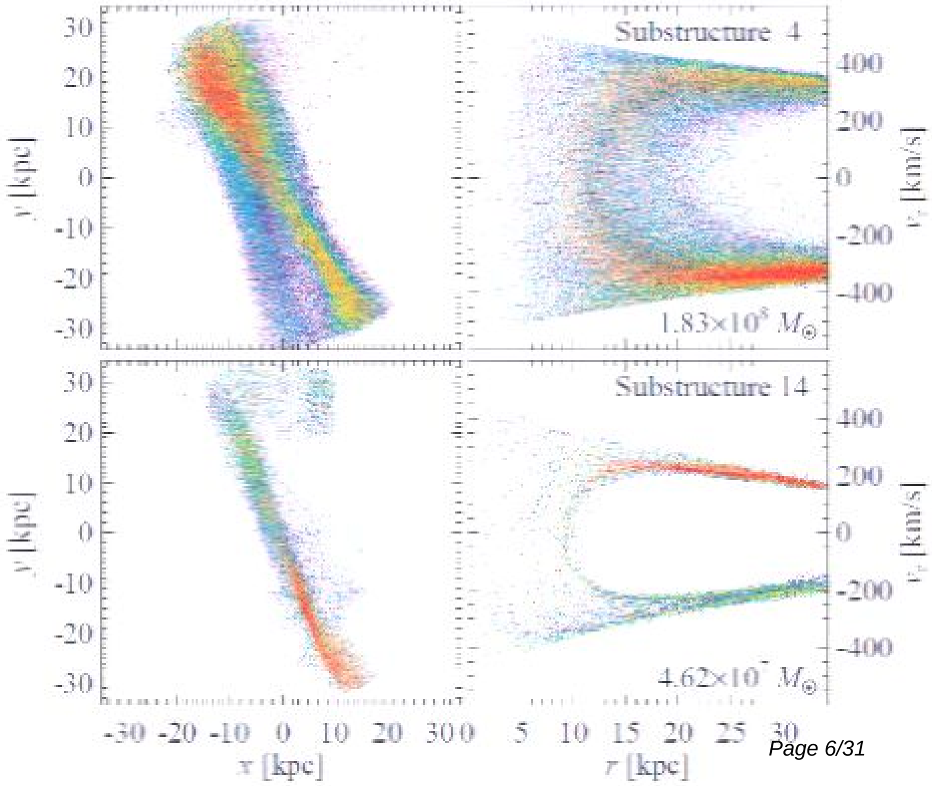
Springel et al. (2008)

[see also **Via Lactea** by Diemand & Kuhlen]

Phase-Space Structure near the Sun



Maciejewski et al. (2011)

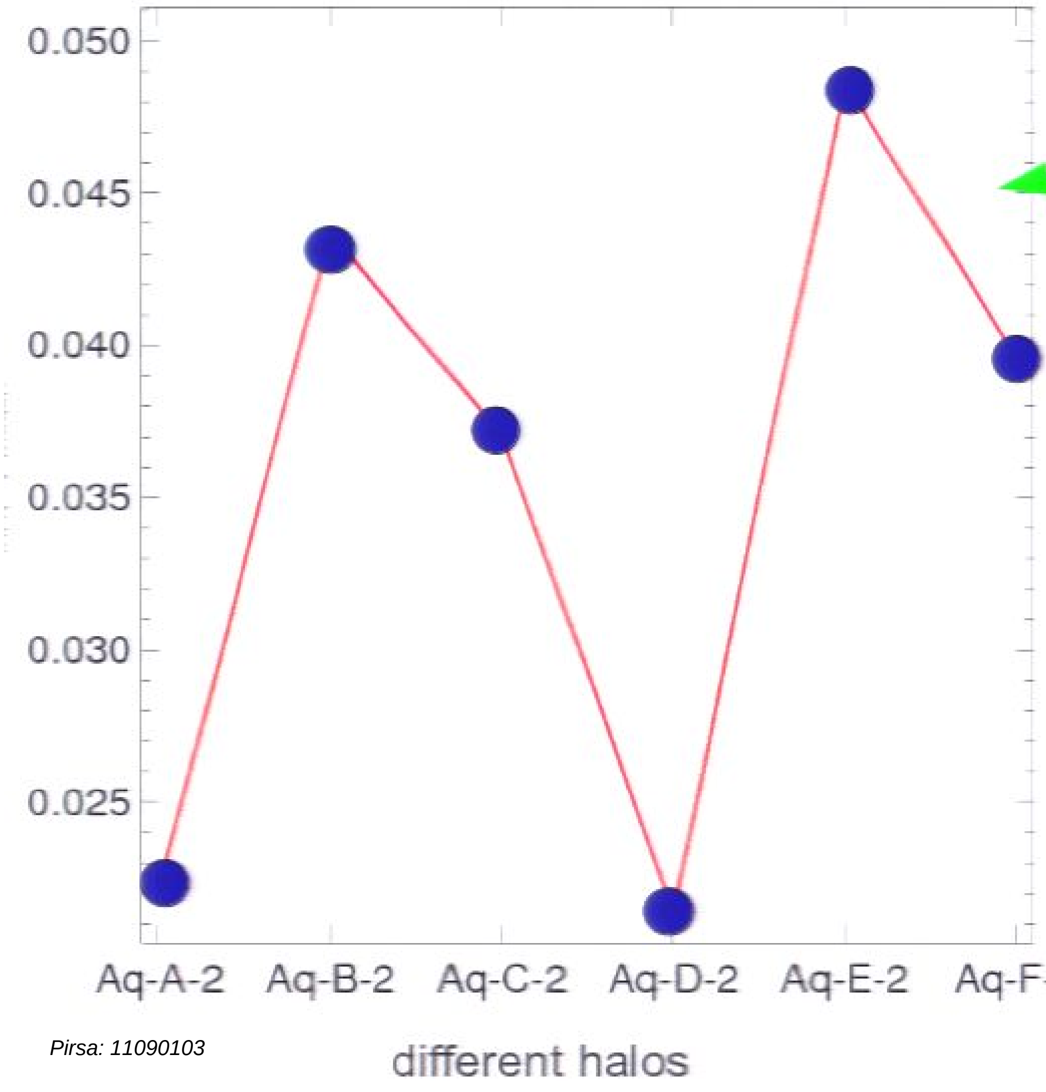


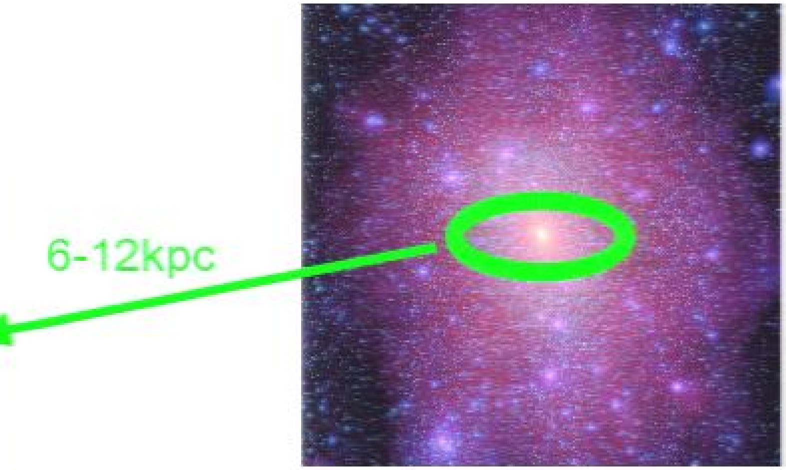
subhalos and **tidal** streams

6D structure finding

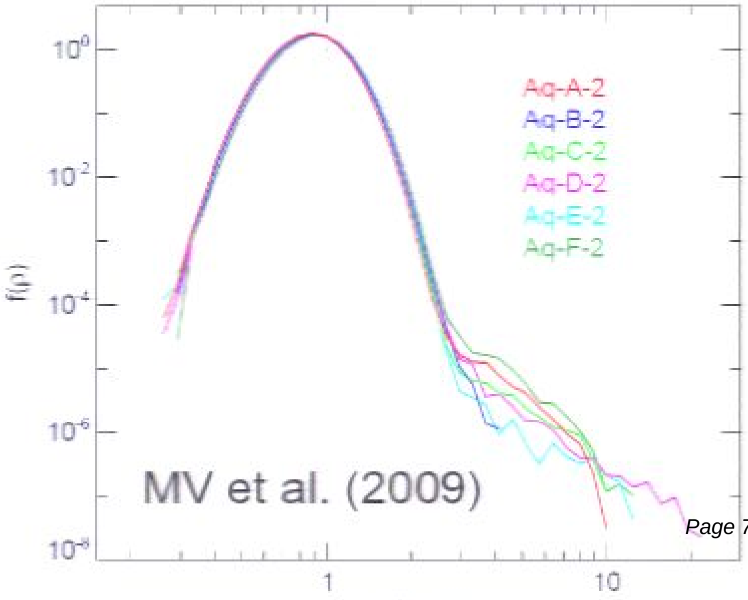
DM Smoothness near the Sun

scatter standard deviation < 5%



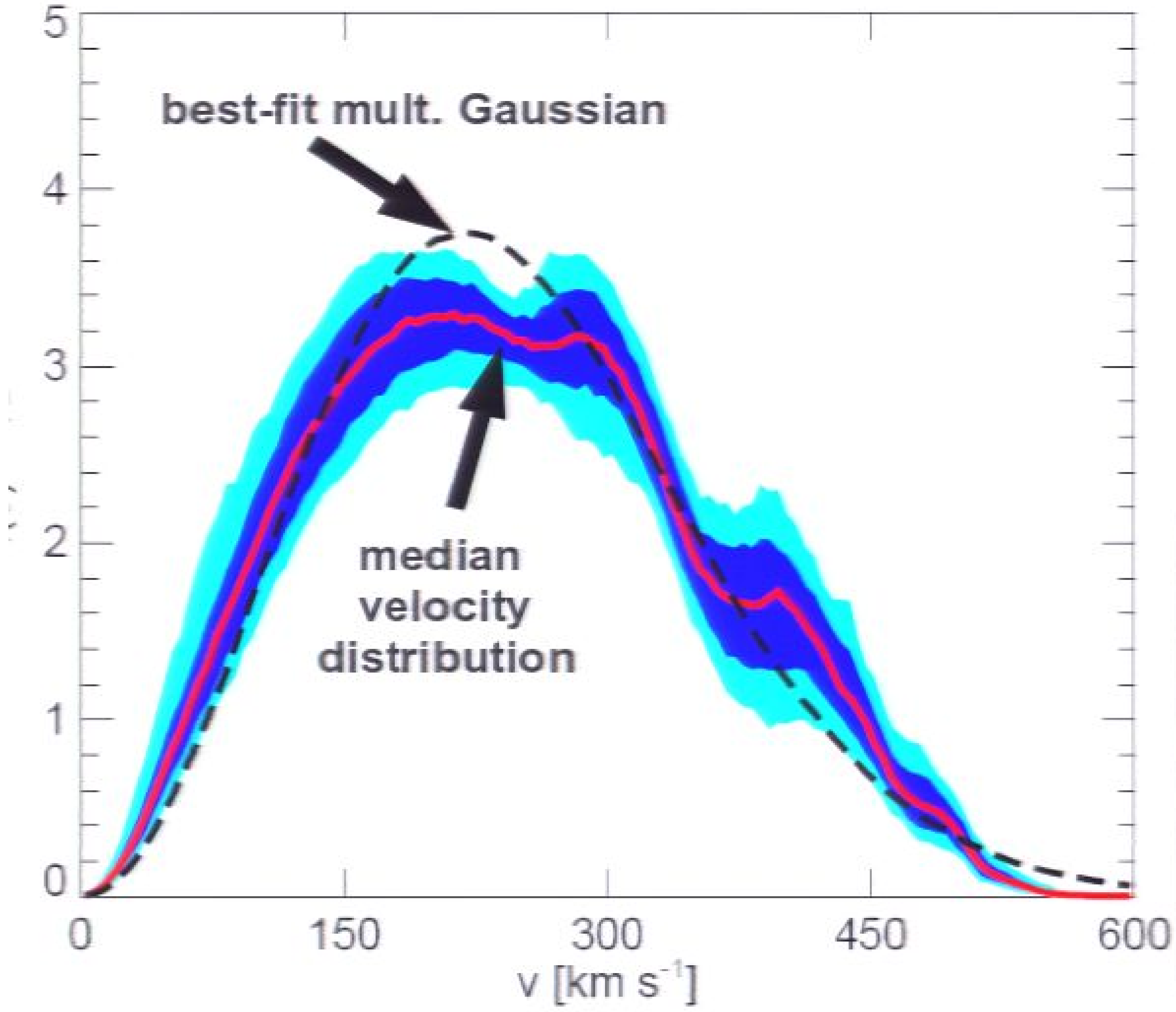


Chance of hitting a subhalo small: ~10^{-4}



MV et al. (2009)

Local Velocity Structure



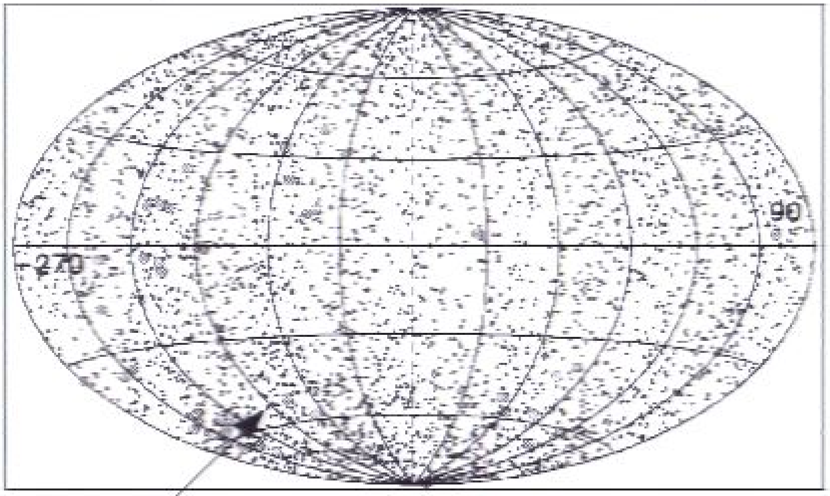
best-fit mult. Gaussian

median velocity distribution

velocity space structures at same velocity for given halo

not Maxwellian

directions of motions

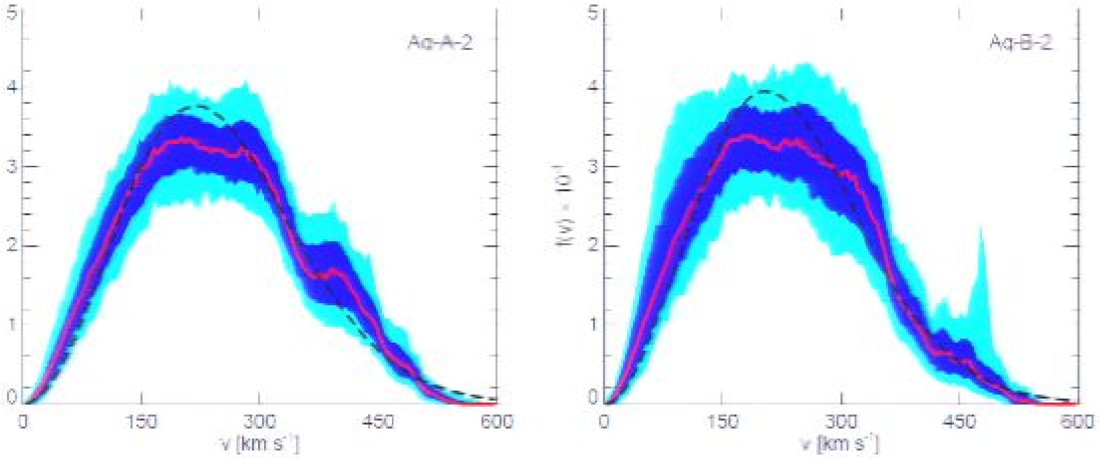


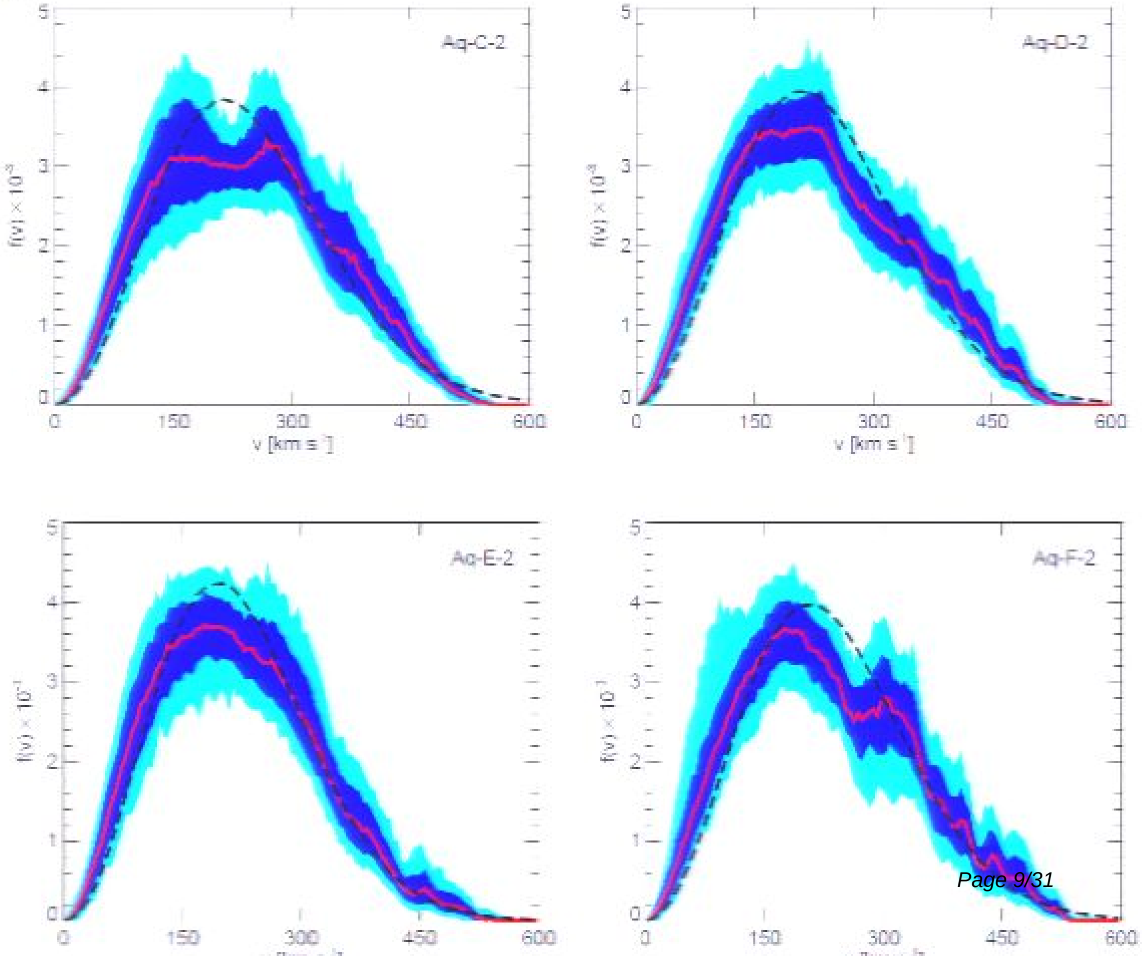
Helmi et al. (2002)

high velocity particles:
anisotropic distribution
(→ directional detection)

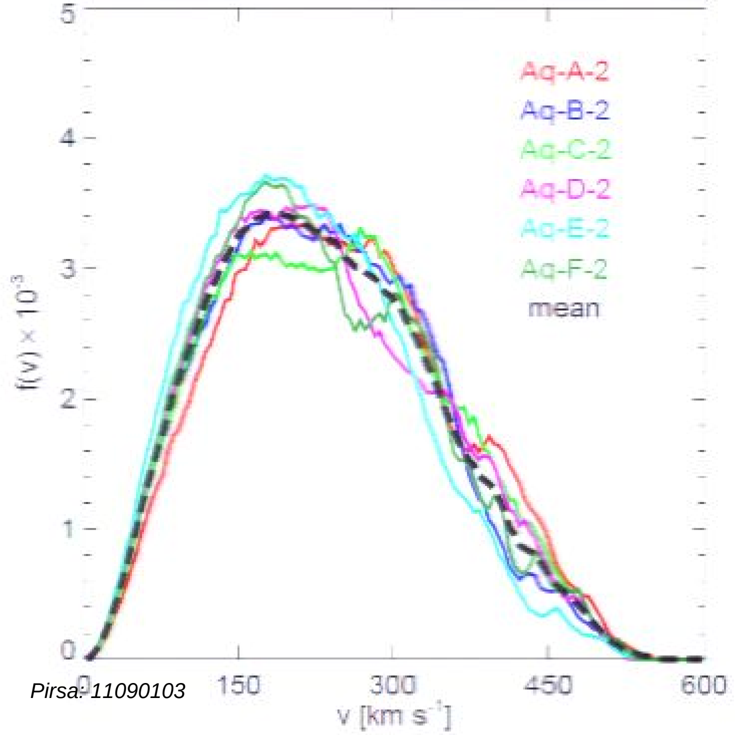
Different Halos

features are present in all halos
but at different velocities





mean velocity distribution

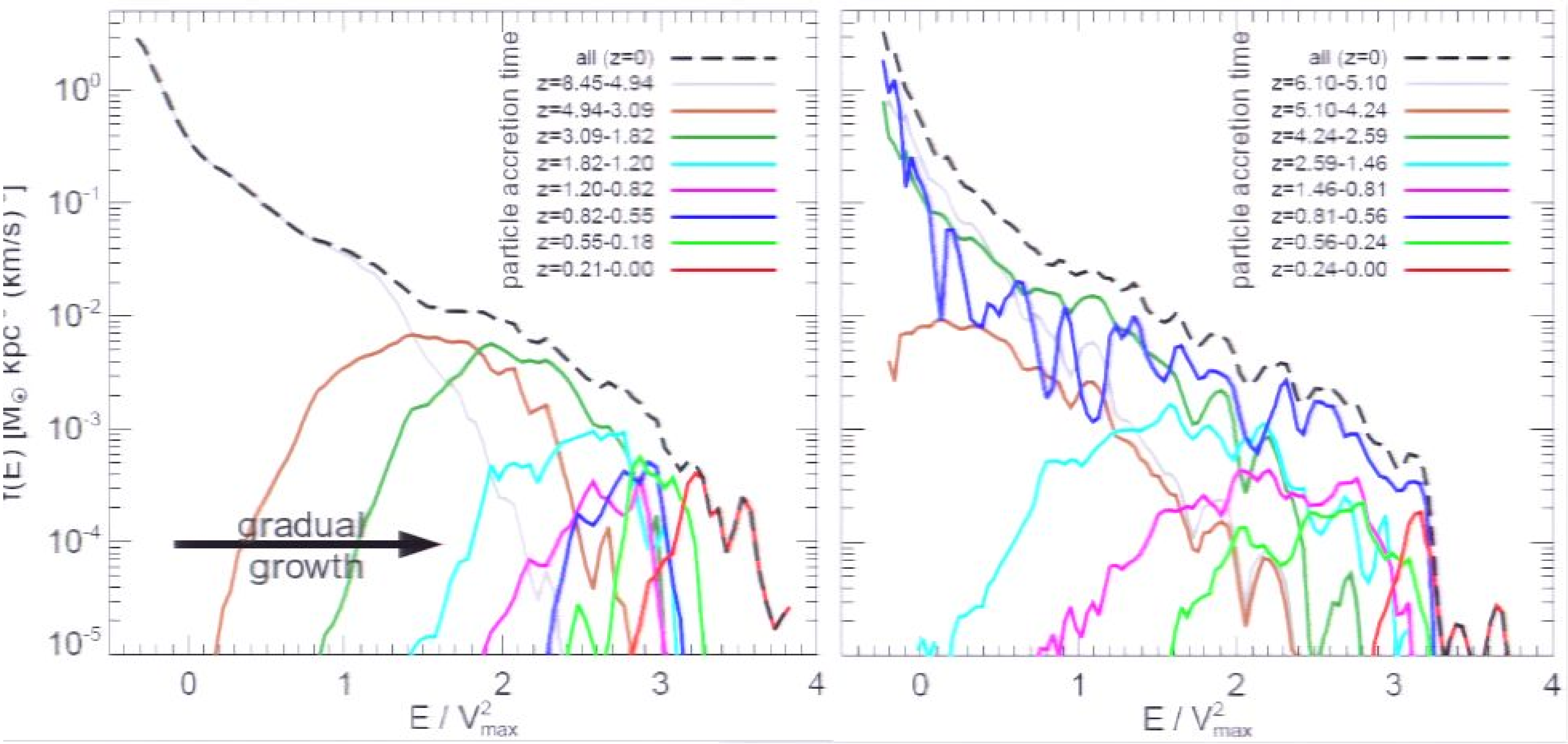


Phase-Space Density

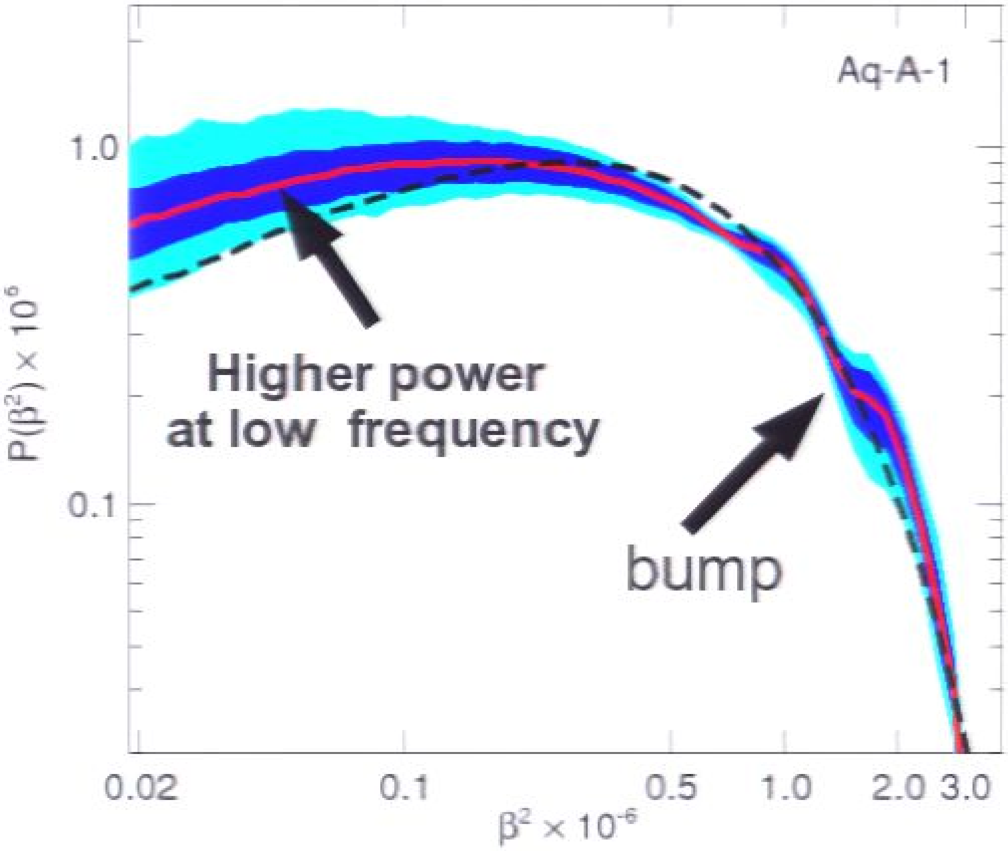
structure related to formation history

Halo A: quiet formation history

Halo B: active formation history



Signature in Detector Signal



Axion microwave spectrum

$$\nu_a = 241.8\left(\frac{m_a}{1\mu\mathrm{eV}/c^2}\right)\left(1+\frac{1}{2}\beta^2\right)\mathrm{MHz}$$

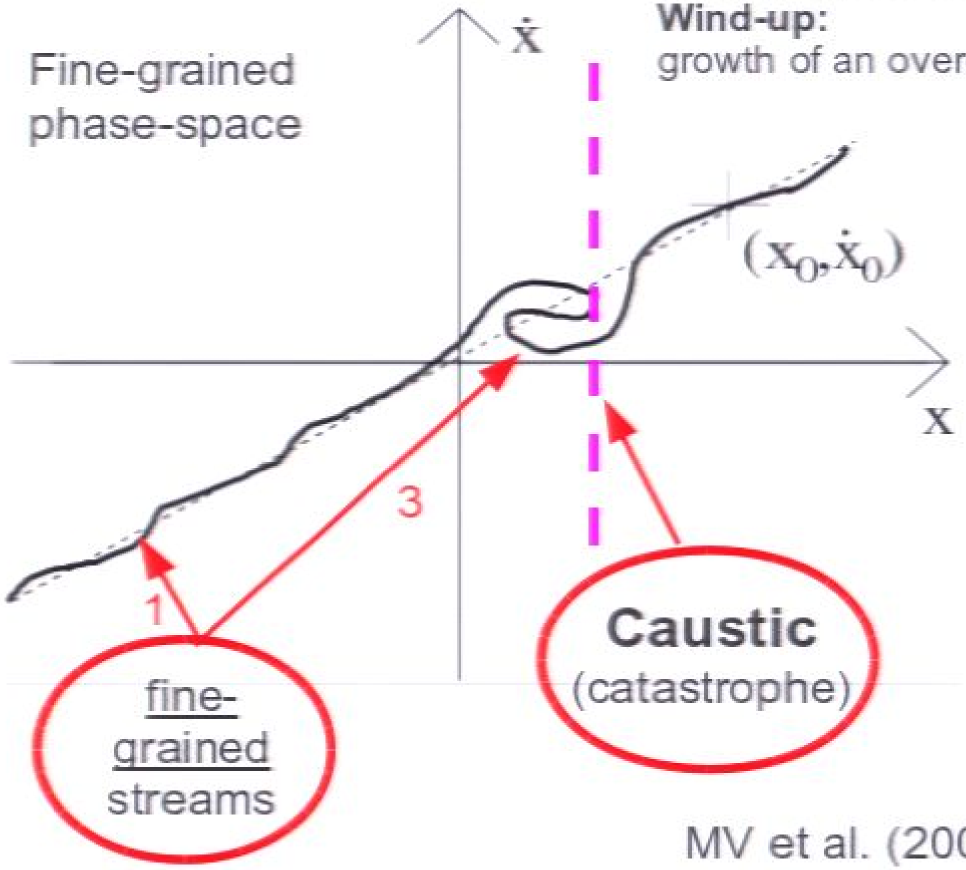
Fine-Grained Structure of LCDM Halos

CDM – Small Scales

CDM is **cold** and **collisionless** → **CDM restricted to 3D hypersurface in 6D phase-space**

Thickness of line:
primordial velocity dispersion
Amplitude of wiggles:
velocity due to density perturbations
Wind-up:
growth of an overdensity

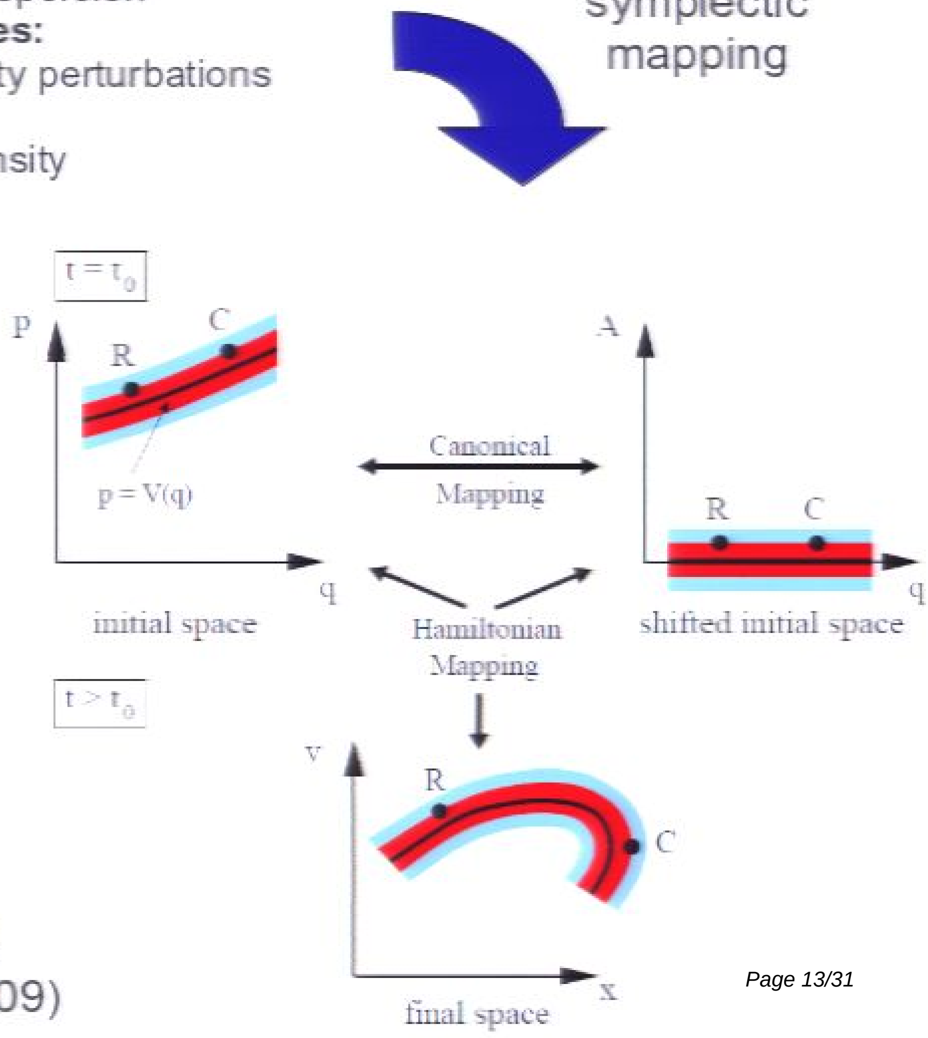
Fine-grained phase-space



fine-grained streams

Caustic
(catastrophe)

symplectic mapping



MV et al. (2008)
White & MV (2009)

Analytic Estimates

Self-similar halo formation:

Fillmore & Goldreich (1984), Bertschinger (1985),
Mohayaee & Salati (2008);
Mohayaee et al (2006); ...

Caustic ring model:

Duffy & Sikivie (2008);
Natarajan & Sikivie (2008);
Onemli & Sikivie (2007);
Natarajan & Sikivie (2007);
Sikivie et al (1997); ...

General arguments:

Hogan (2001)

Predictions

- ~100 streams at solar position
- significant annihilation boost (5-100)
- strong caustic rings
- discrete velocity distribution
- distinct caustic structures

How realistic are these models?

SELF-SIMILAR GRAVITATIONAL COLLAPSE IN AN EXPANDING UNIVERSE[1]

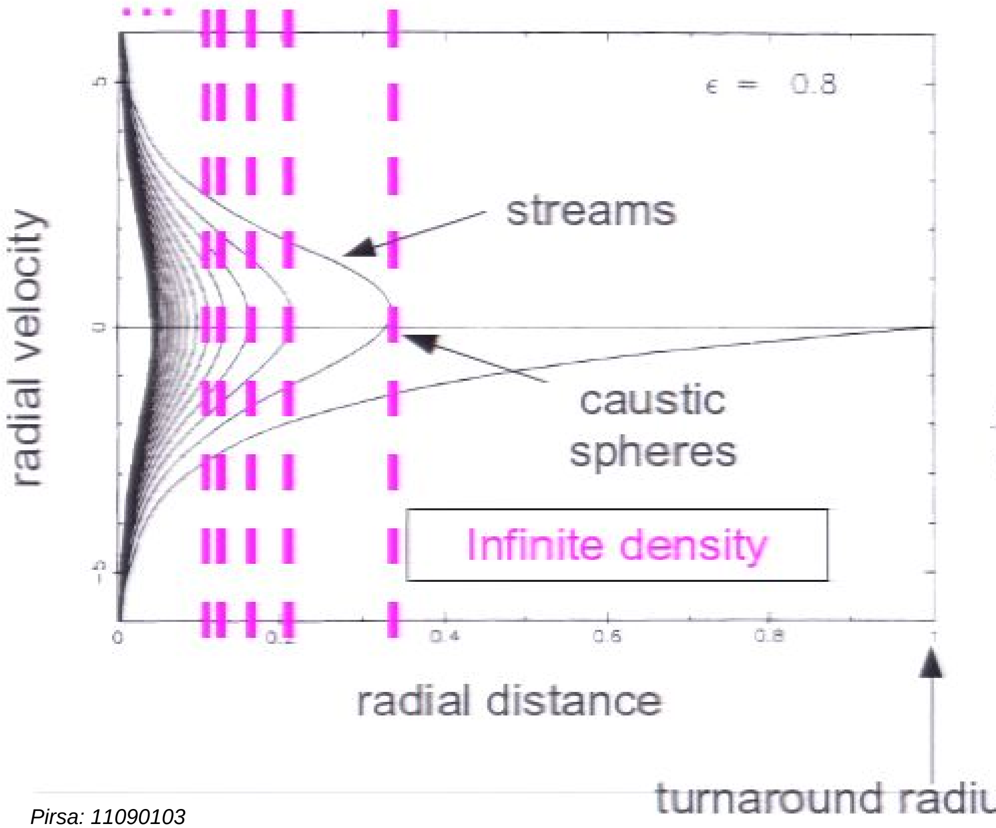
JAMES A. FILLMORE AND PETER GOLDREICH
California Institute of Technology

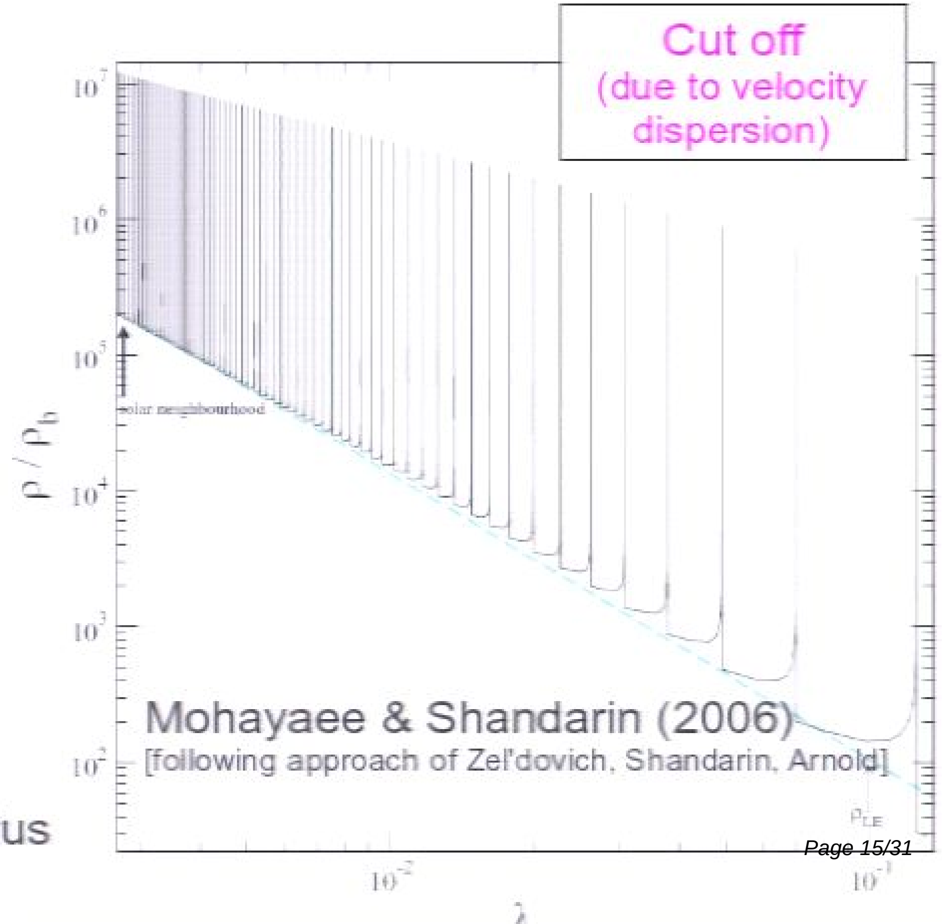
Received 1983 October 10; accepted 1983 December 5

ABSTRACT

We derive similarity solutions which describe the collapse of cold, collisionless matter in a perturbed Einstein–de Sitter universe. We obtain three classes of solutions, one each with planar, cylindrical, and spherical symmetry. Our solutions can be computed to arbitrary accuracy, and they follow the development of structure in both the linear and nonlinear regimes.

Subject headings: cosmology — relativity





Mohayaee & Shandarin (2006)
[following approach of Zel'dovich, Shandarin, Arnold]

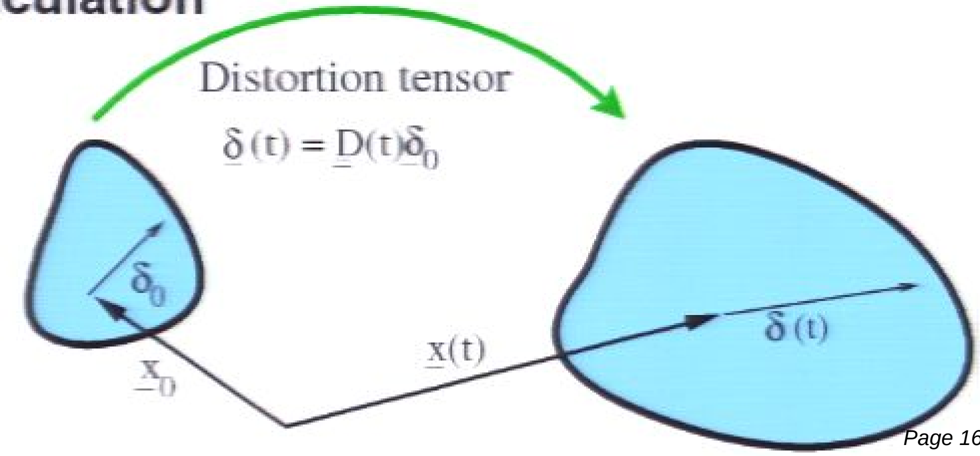
Resolving Fine-Grained Structures

Problem: simulations have too coarse phase-space sampling
(→ missing many orders of magnitude in mass resolution/particle number)

Solution: follow the local phase-space evolution
(→ with a phase-space geodesic deviation equation)

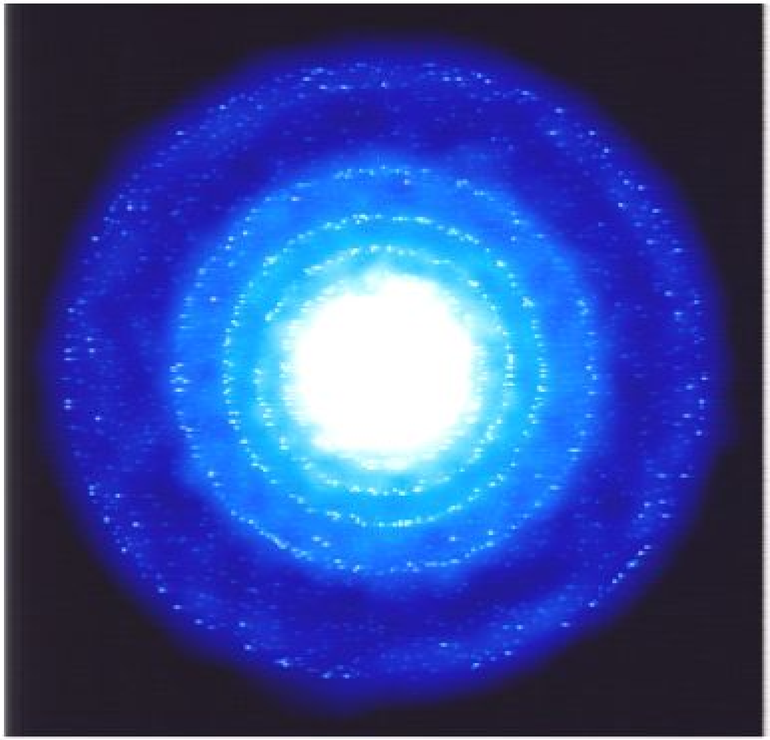
- **calculation of stream density**
- **identification of caustics**
- **Monte-Carlo estimate of intra-stream annihilation**

→ allows caustic annihilation calculation

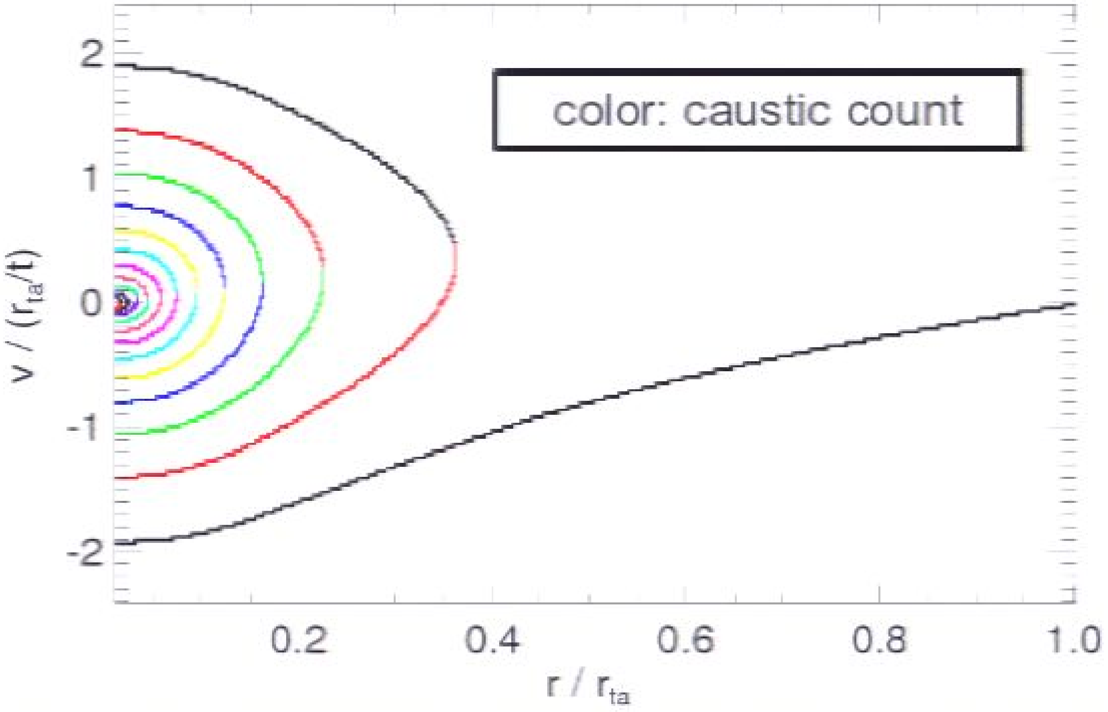


Caustic Annihilation Radiation: 1D Gravity

annihilation signal

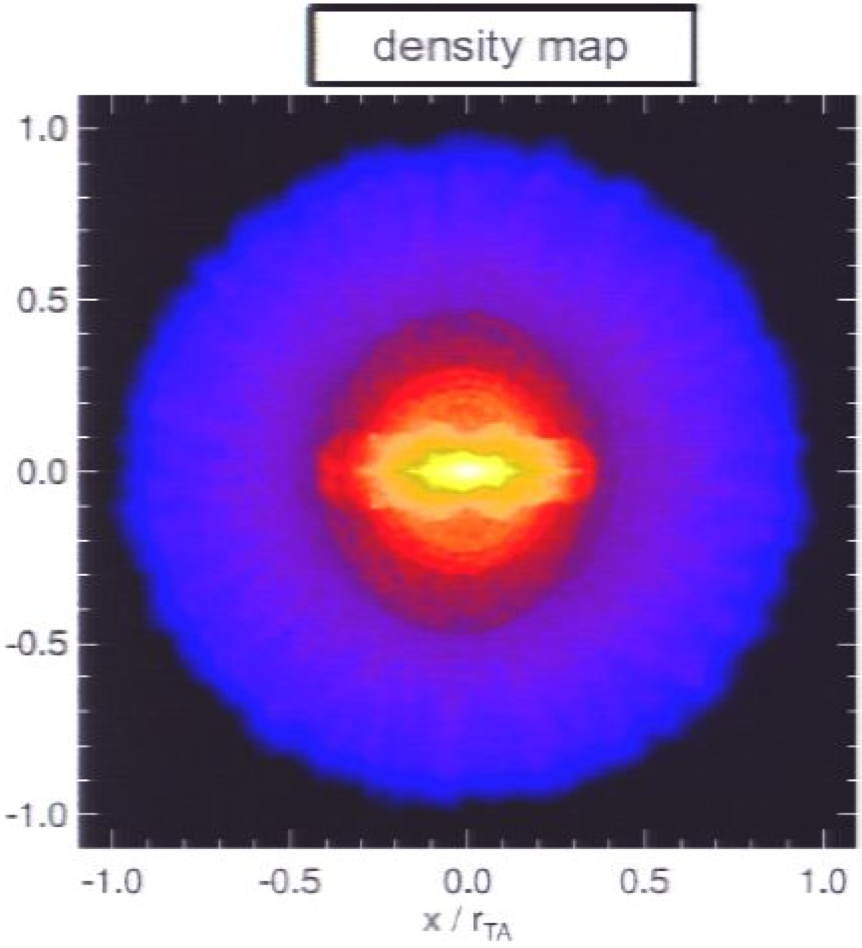


caustic spheres on top of smooth annihilation signal



initial conditions:
single density perturbation in an otherwise unperturbed EdS universe

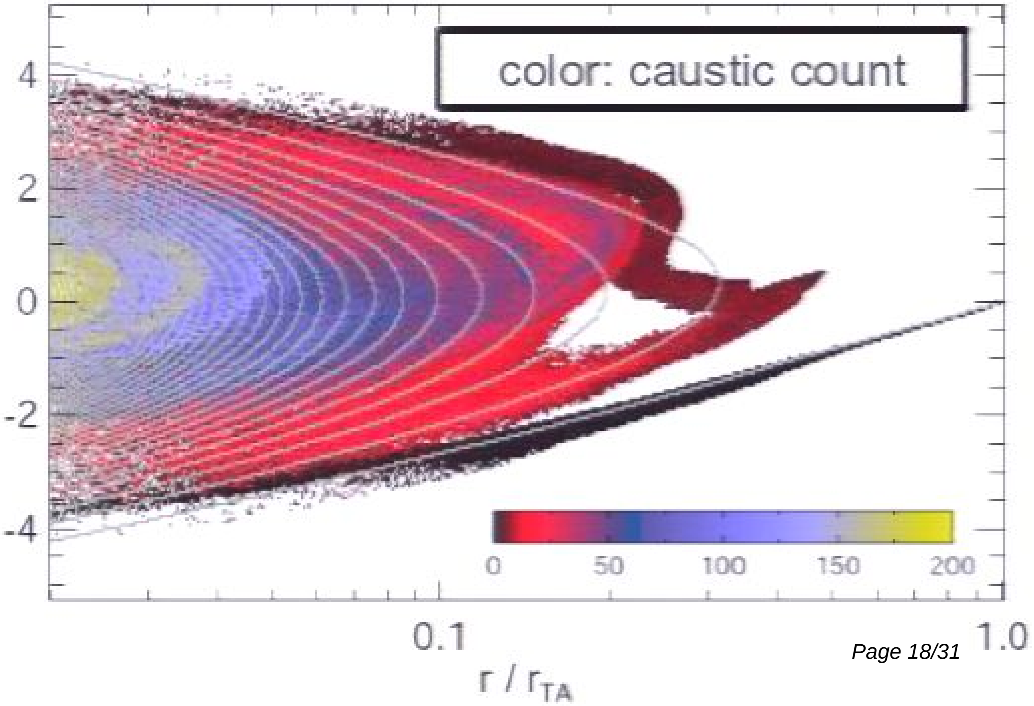
Collapse of an Isolated Halo in 3D Gravity



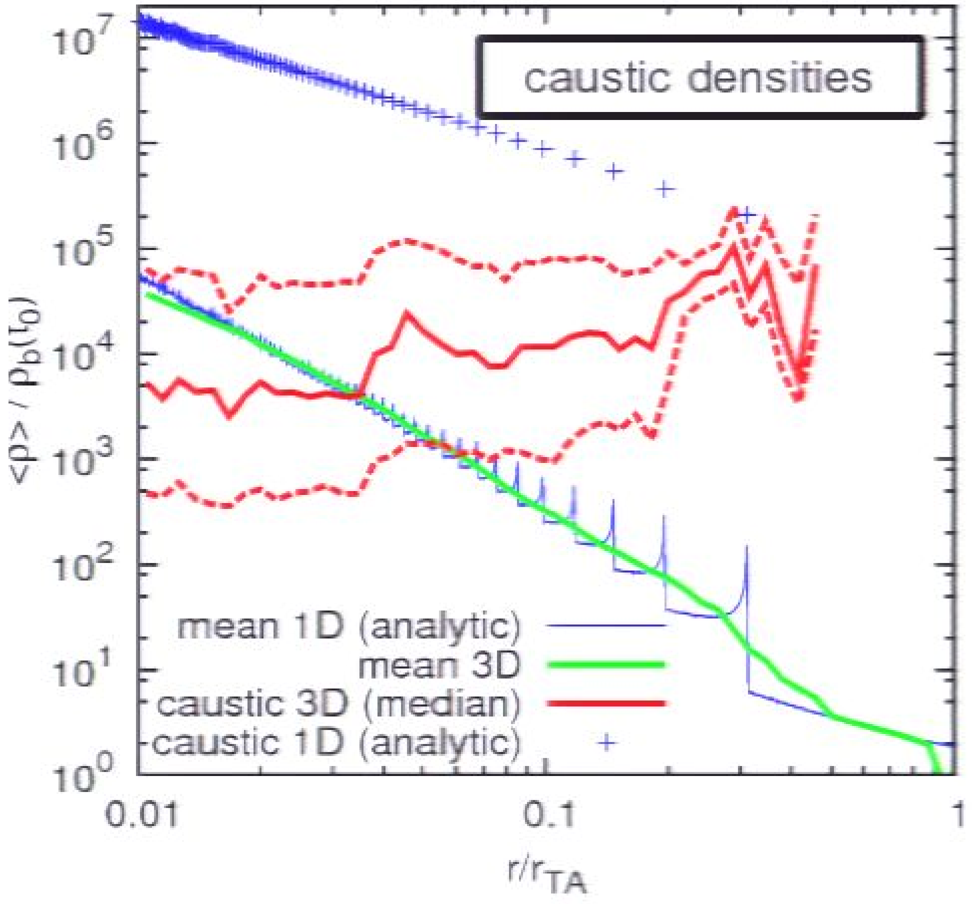
Instabilities

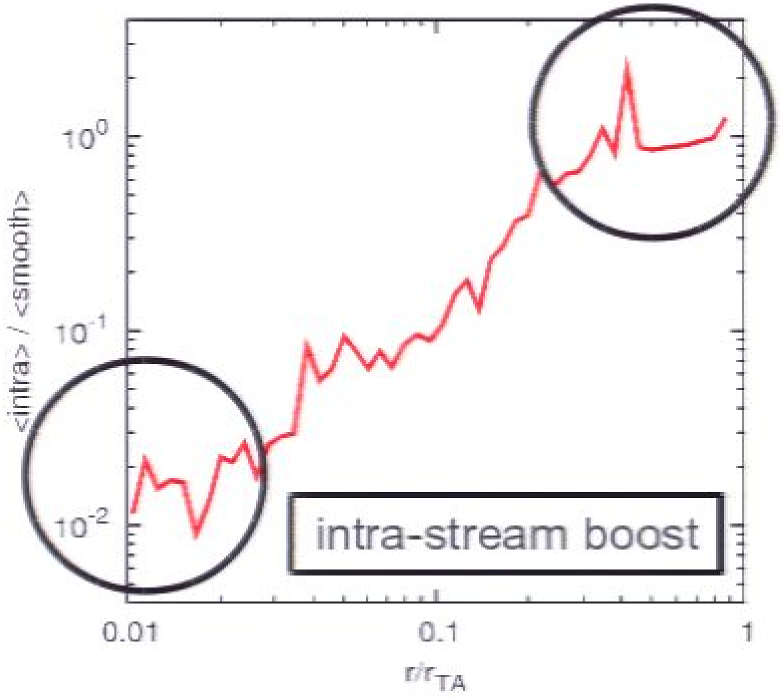
MV et al. (2009)

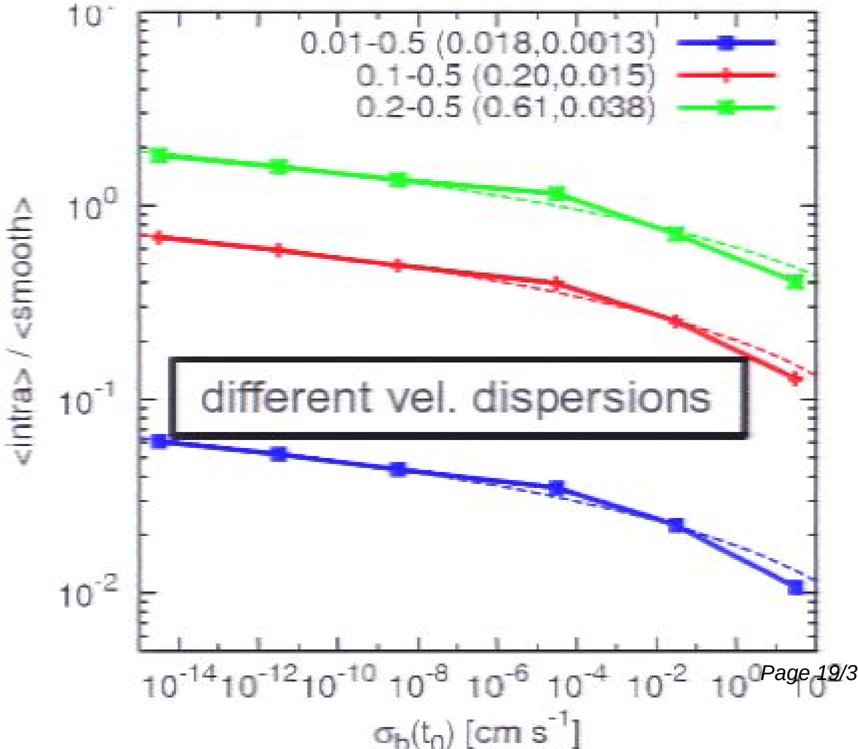
1D to 3D → higher dimensional hypersurface



Caustics in 3D



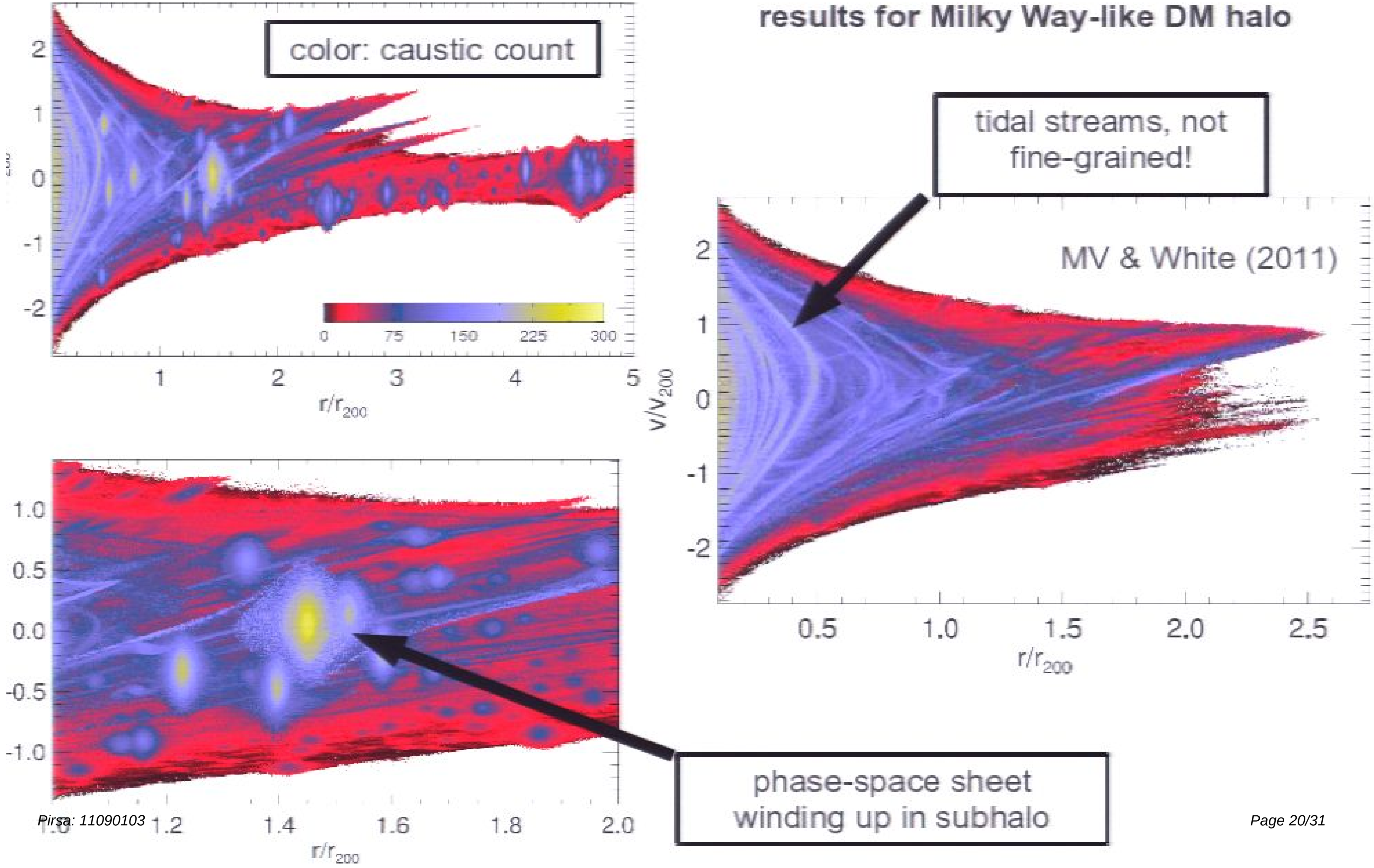




caustic annihilation negligible in inner halo, but can boost signal in the outer part

Fine-Grained Structure of LCDM Halos

results for Milky Way-like DM halo

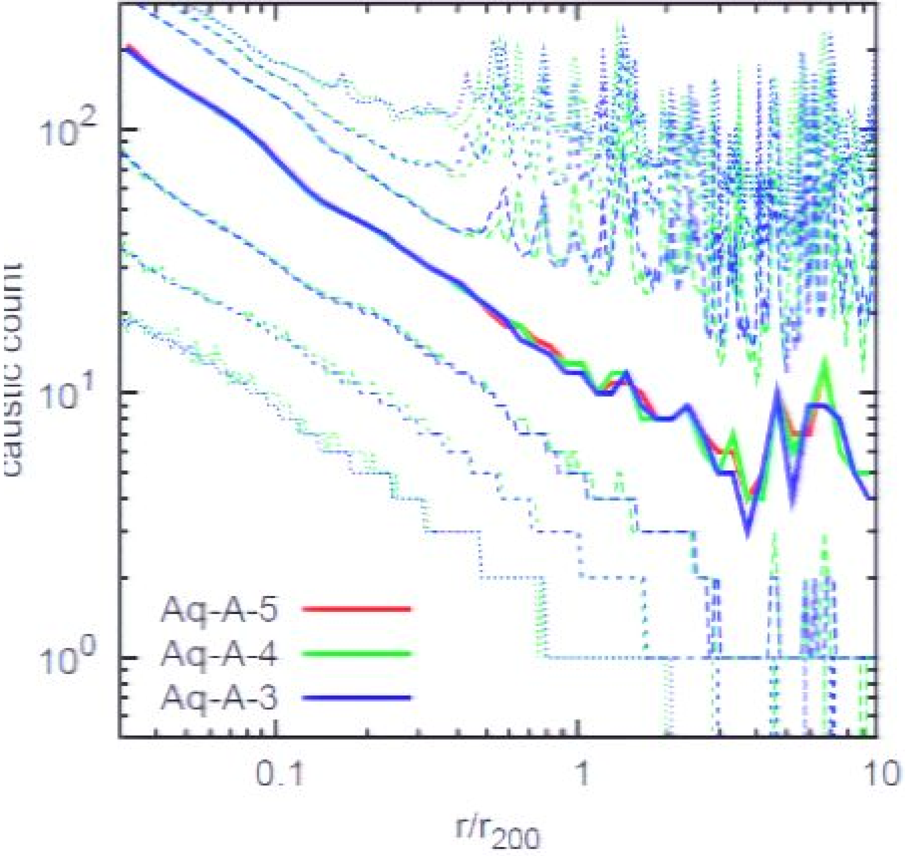


tidal streams, not fine-grained!

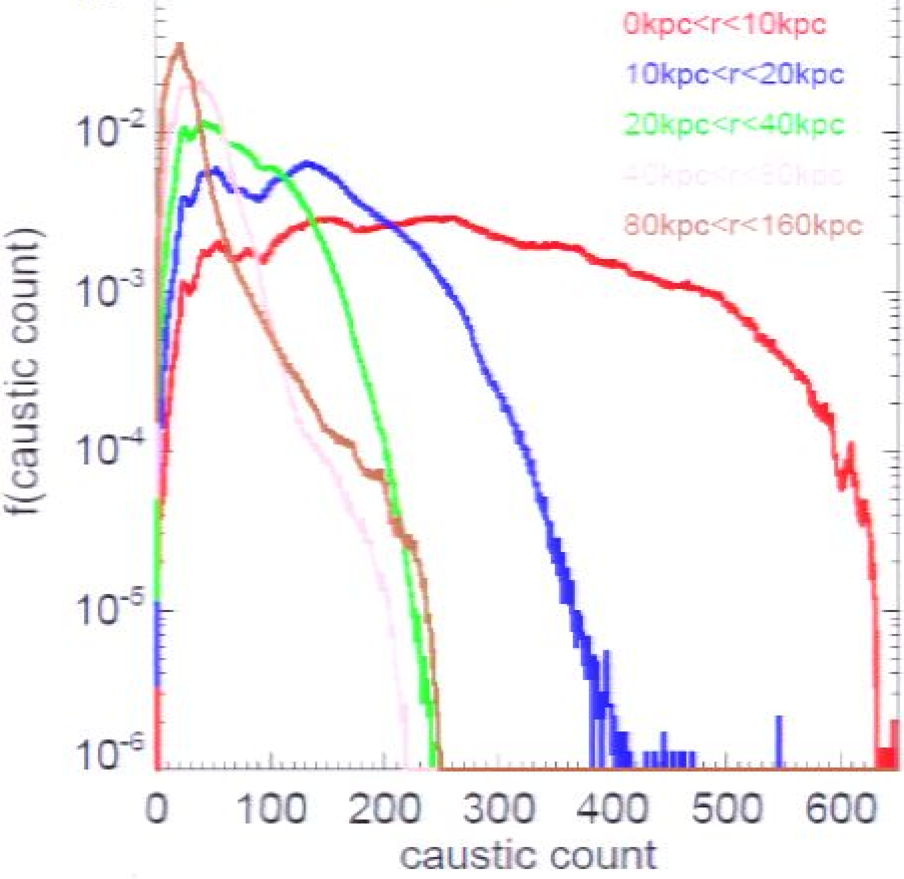
phase-space sheet winding up in subhalo

Caustic Count Distribution

caustic count profile

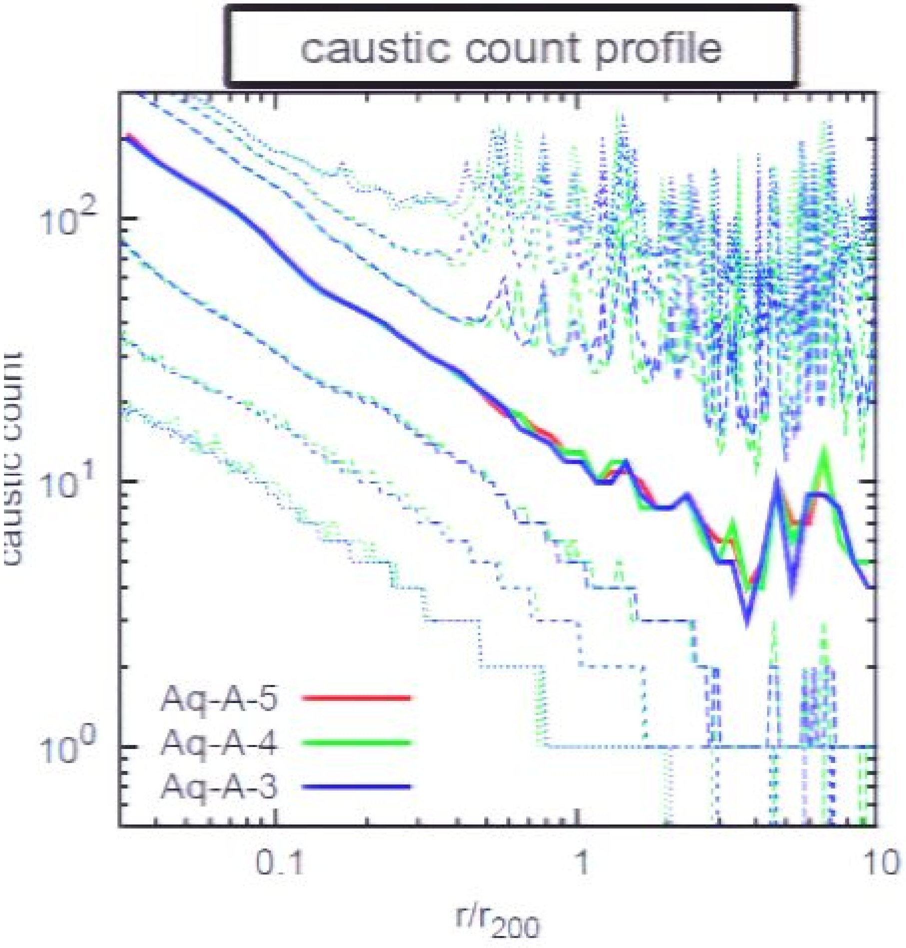


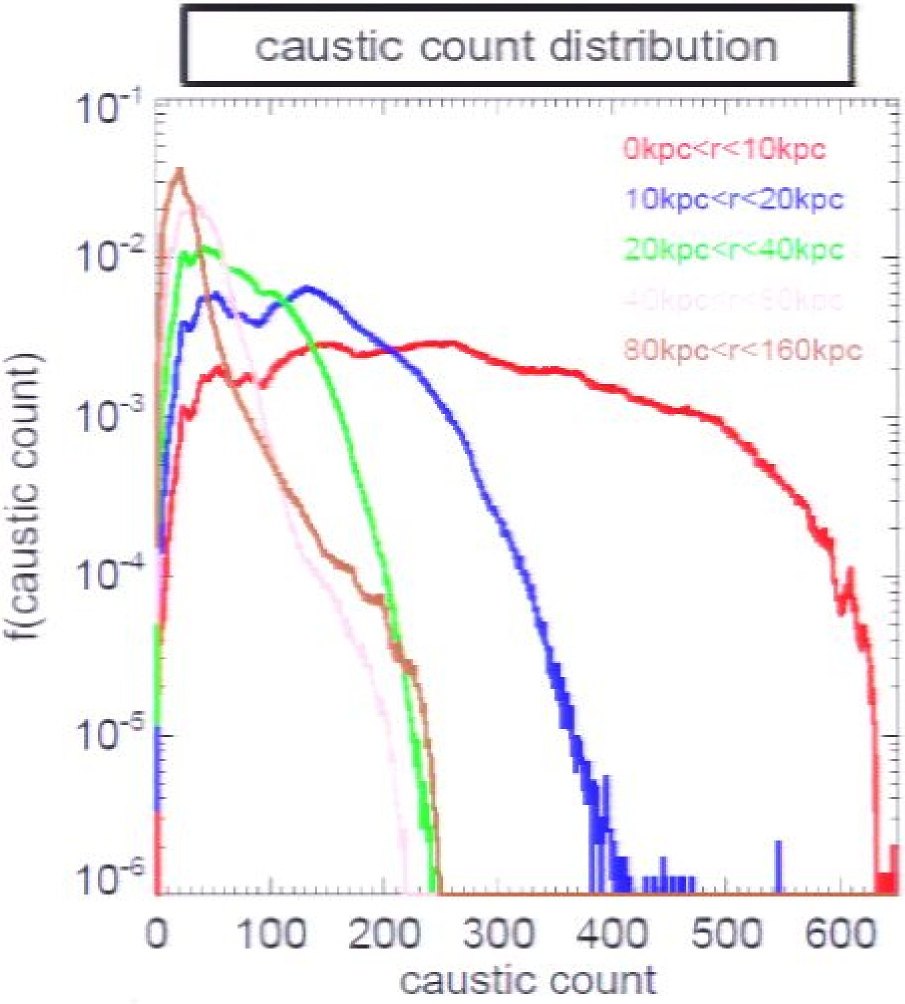
caustic count distribution



- broad distribution at all radii
- outer part broader due to subhalos
- tracks dynamical age (largest in center)

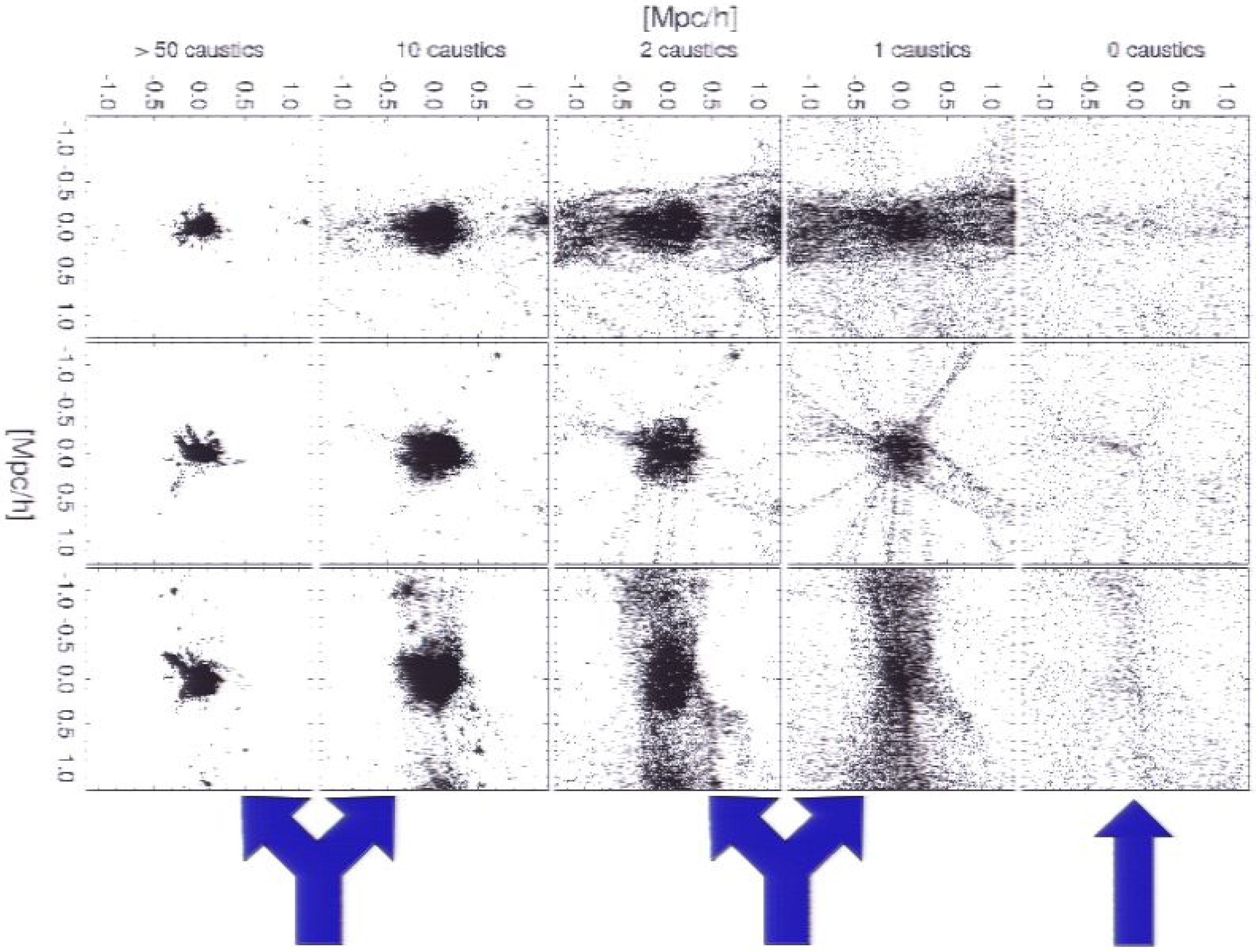
Caustic Count Distribution





- broad distribution at all radii
- outer part broader due to subhalos
- tracks dynamical age (largest in center)

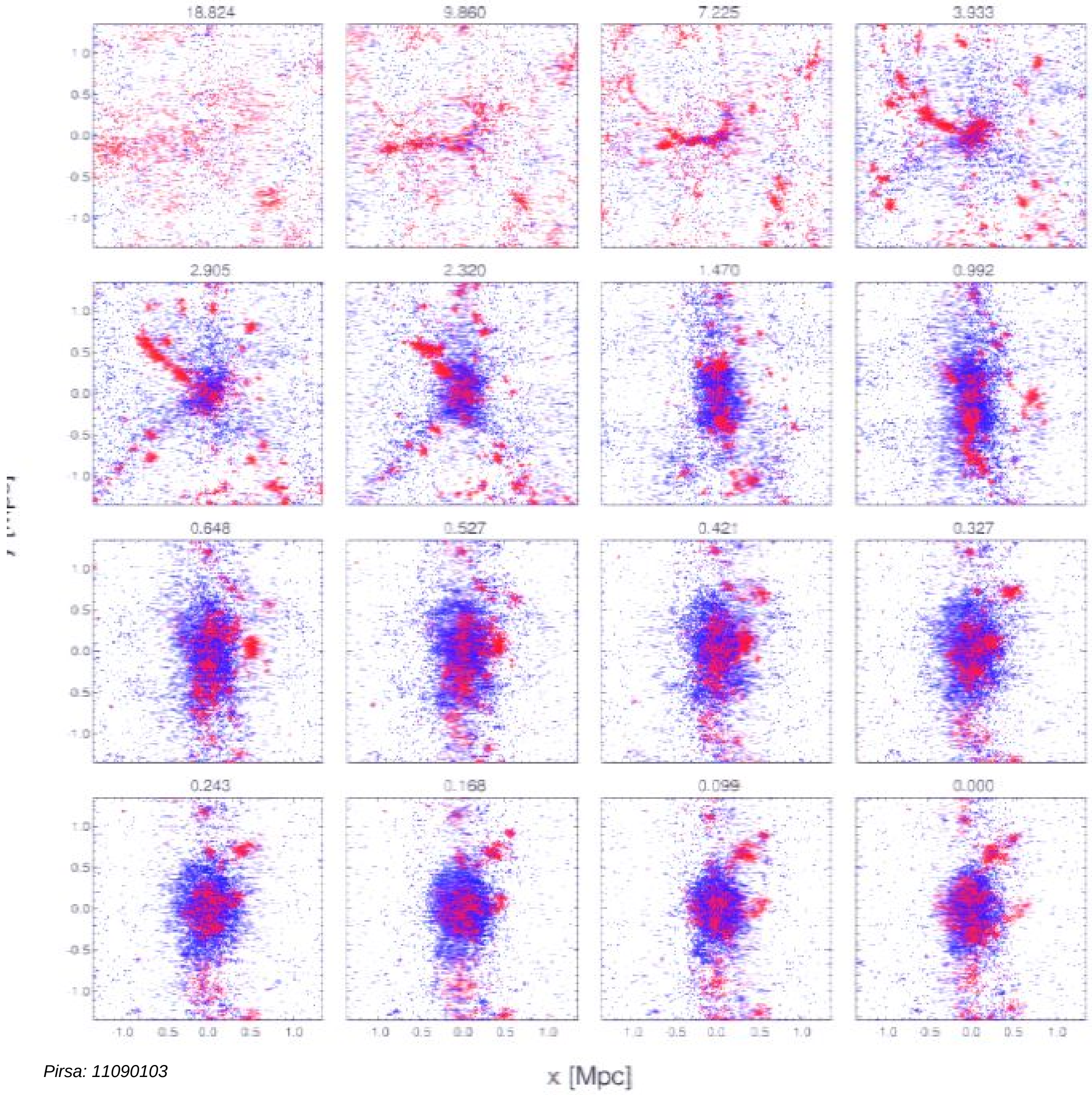
Filtering the Cosmic Web



(sub)halo cores

filaments

smooth

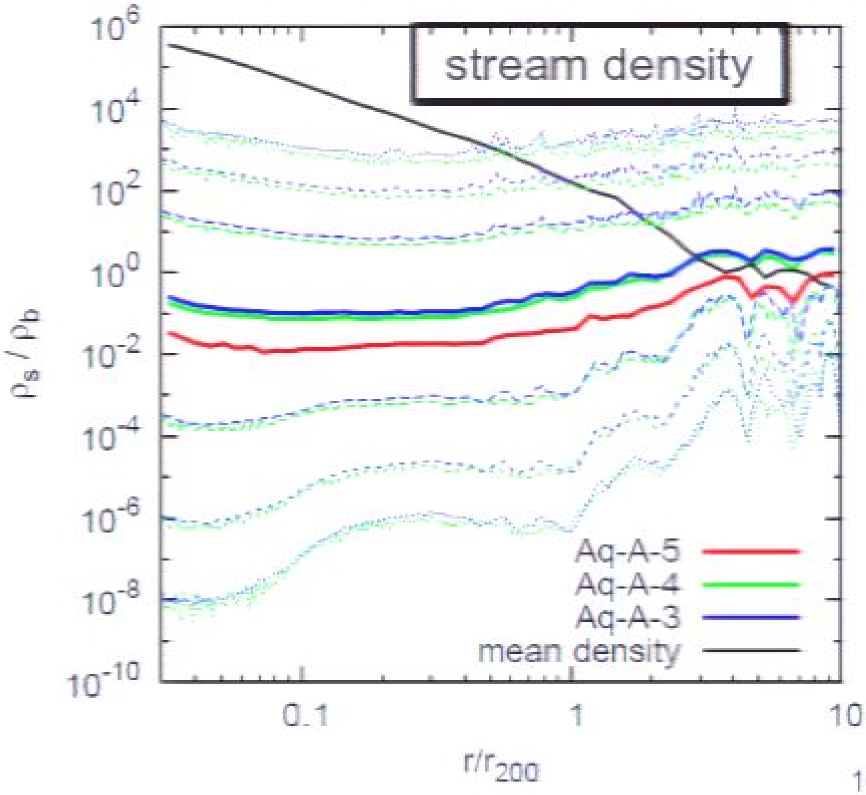


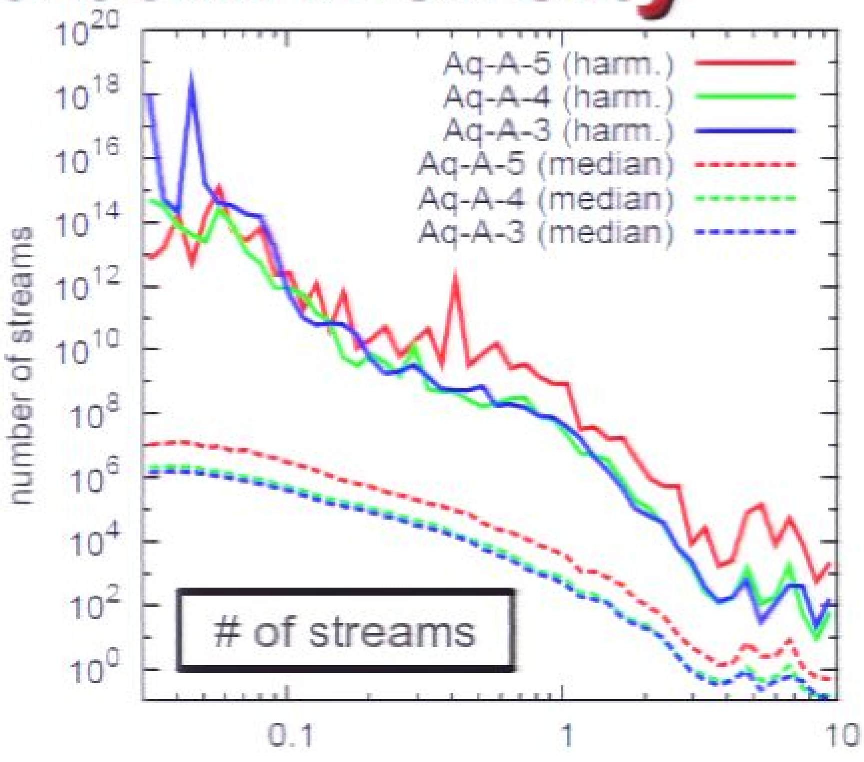
Origin of high / low Stream Density Regions

low stream density regions:
stronger mixing in early forming objects at high z
→ strong mixing

high stream density regions:
more diffuse, smoothly accreted at low z
→ less mixing

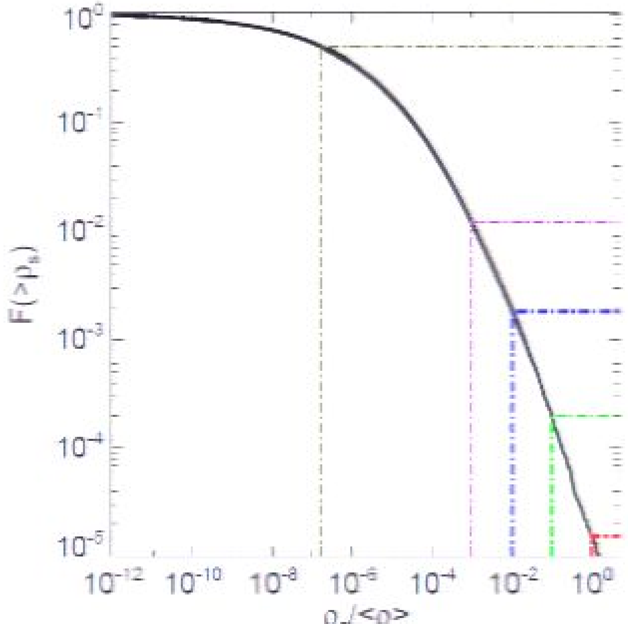
Fine-Grained Stream Density





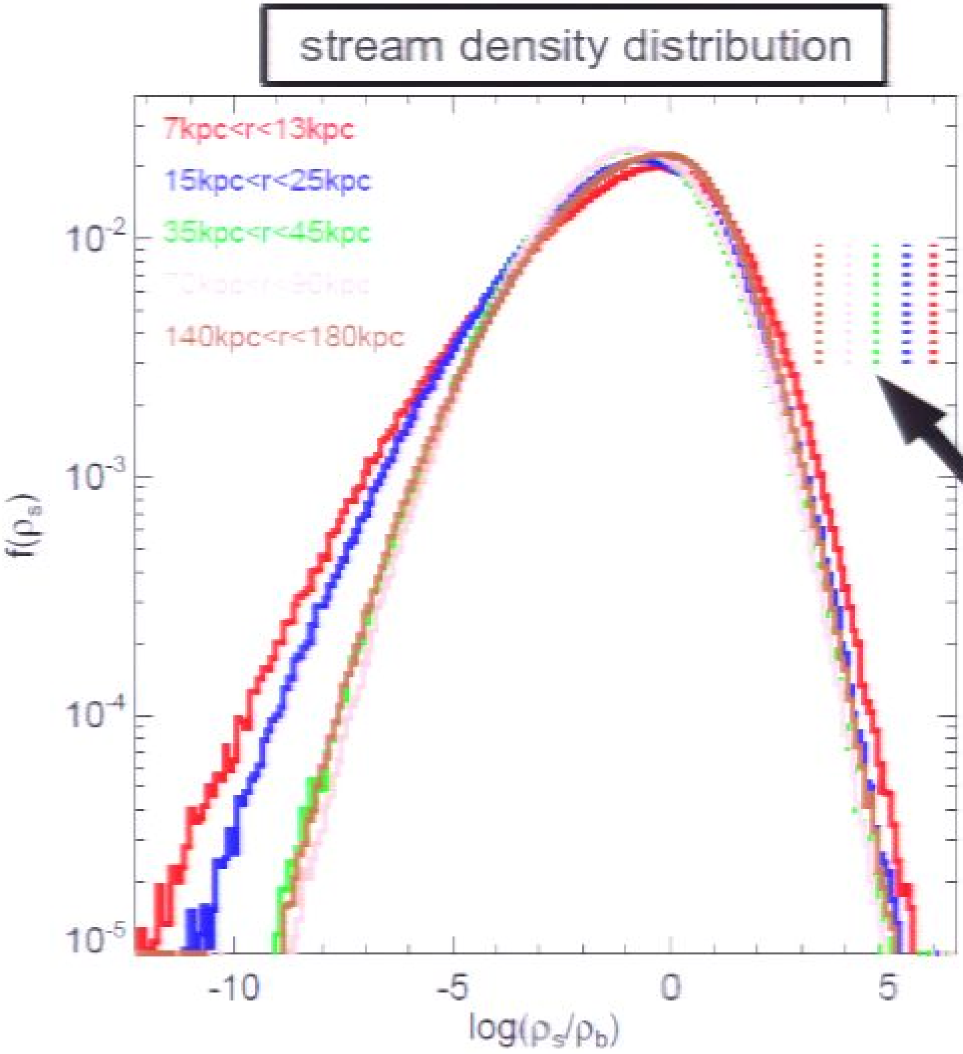
- stream density low
- locally large number of streams

If the dark matter is made of **axions** then a resonant detector should find an energy spectrum where a few tenths of a percent of the total energy density is concentrated in a few very narrow spectral lines.



small amount of high stream density mass

Fine-Grained Stream Density

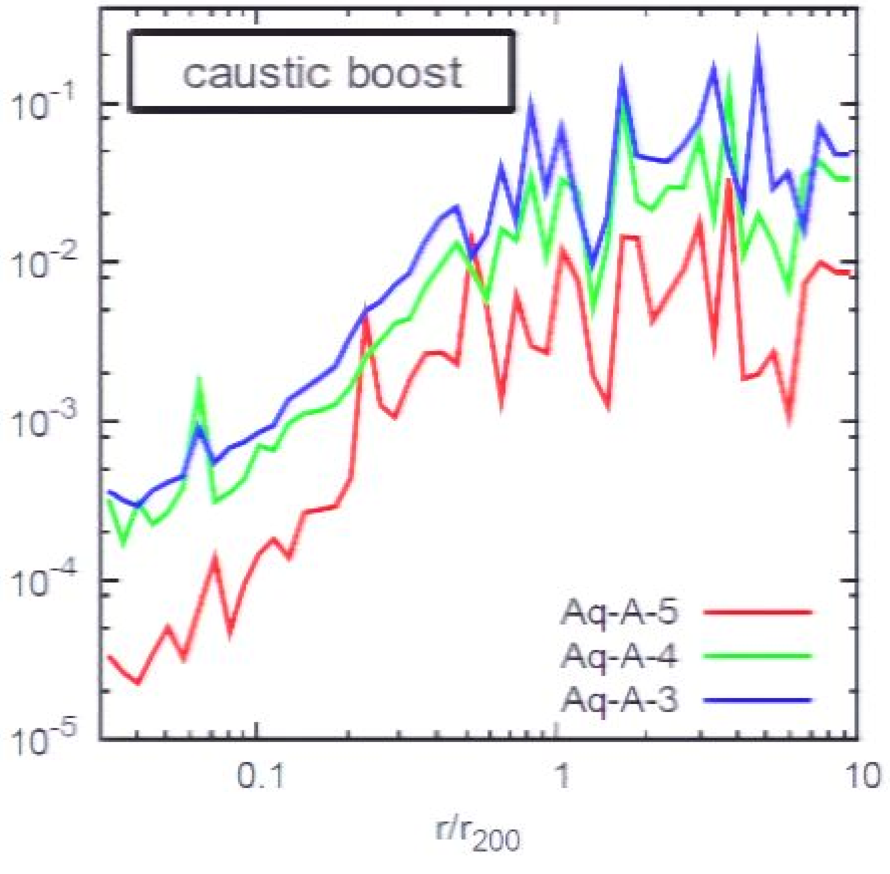


stream density distribution in different radial shells:

- very broad distribution
- smaller than local density

mean density in shell

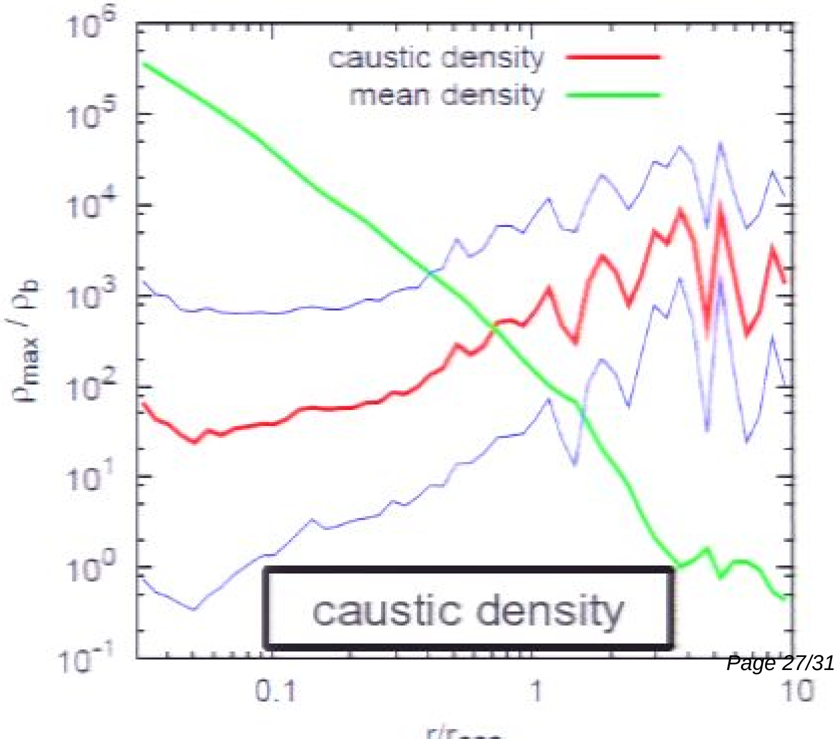
Local Annihilation Boost Factor



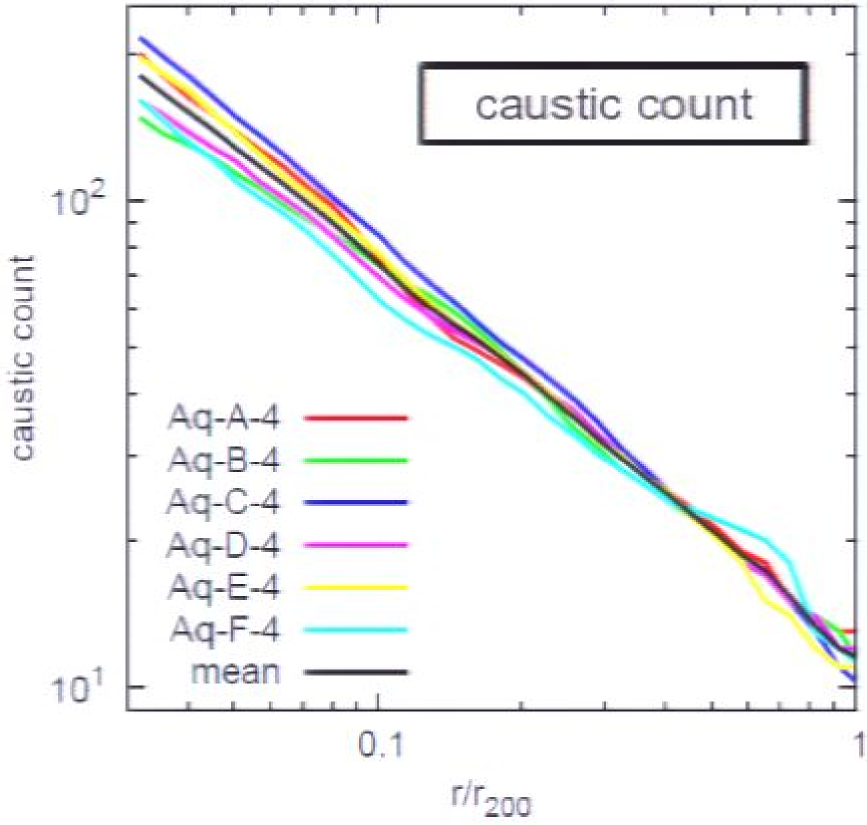
- essentially no boost at solar circle
- no distinct/dense caustic structures

'standard' annihilation rate calculations do not miss a large fine-grained contribution

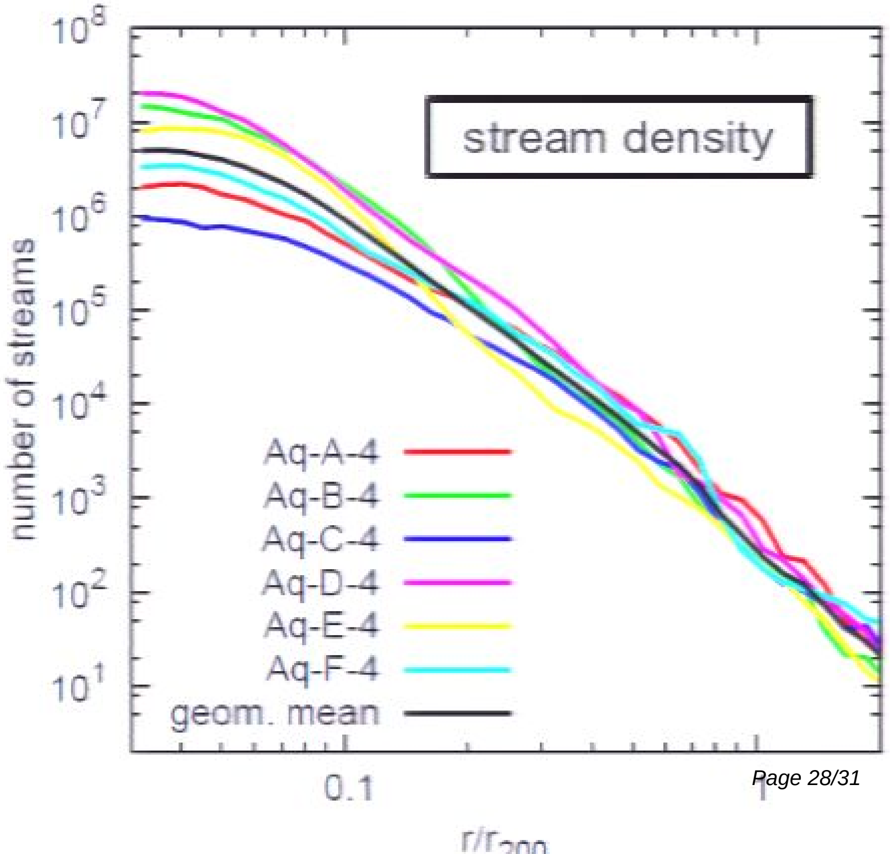
reason:
caustic density small compared to mean density



Halo-to-Halo Scatter



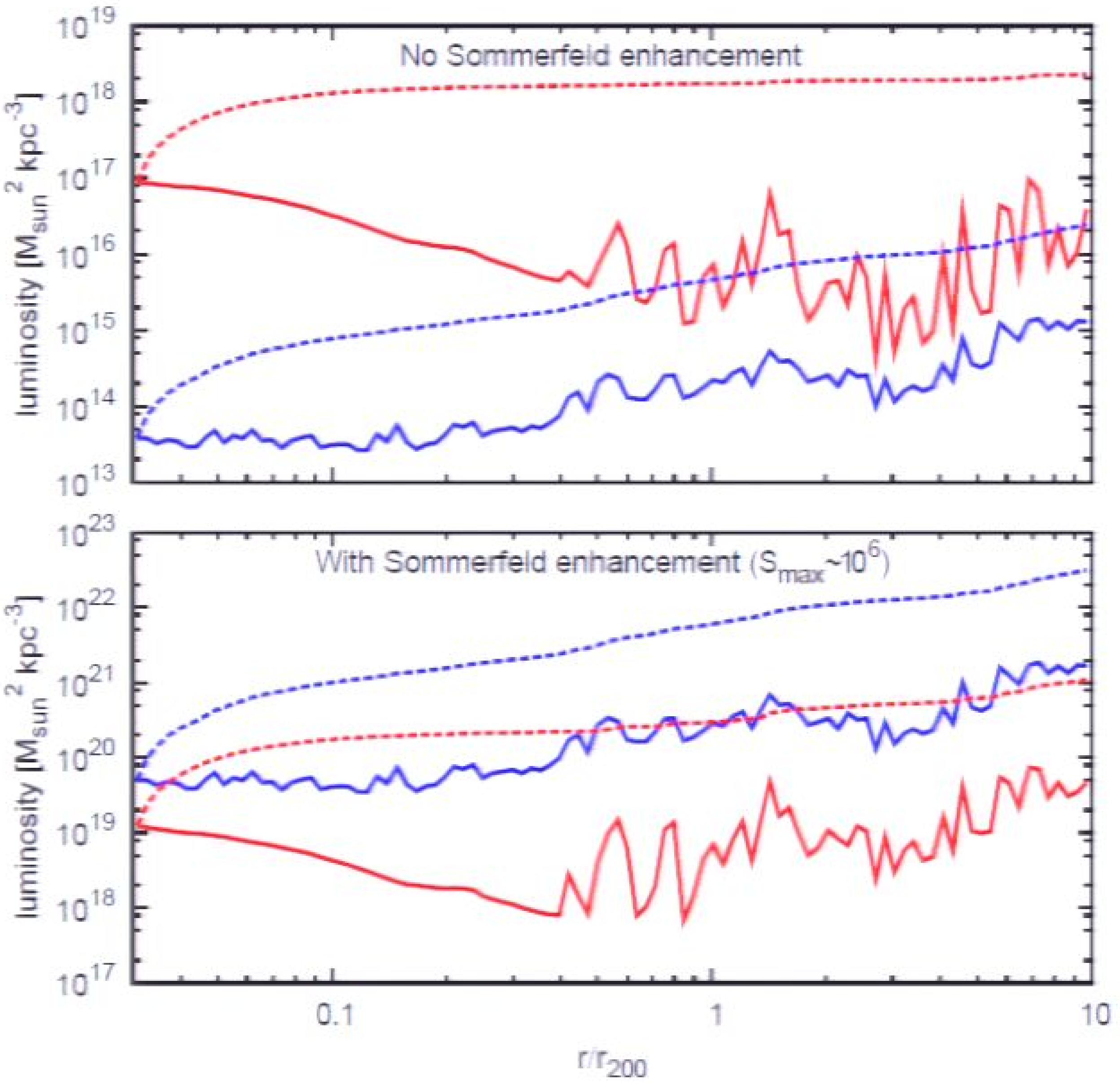
check different halos in same mass range



- there is not much variation
- results pretty universal for that halo mass

→ Galactic halo should look similar

Sommerfeld Enhancement



Zavala et al. (2011)

regions of low velocity dispersion dominate annihilation signal:

Liouville Theorem:
→ streams contribute a lot

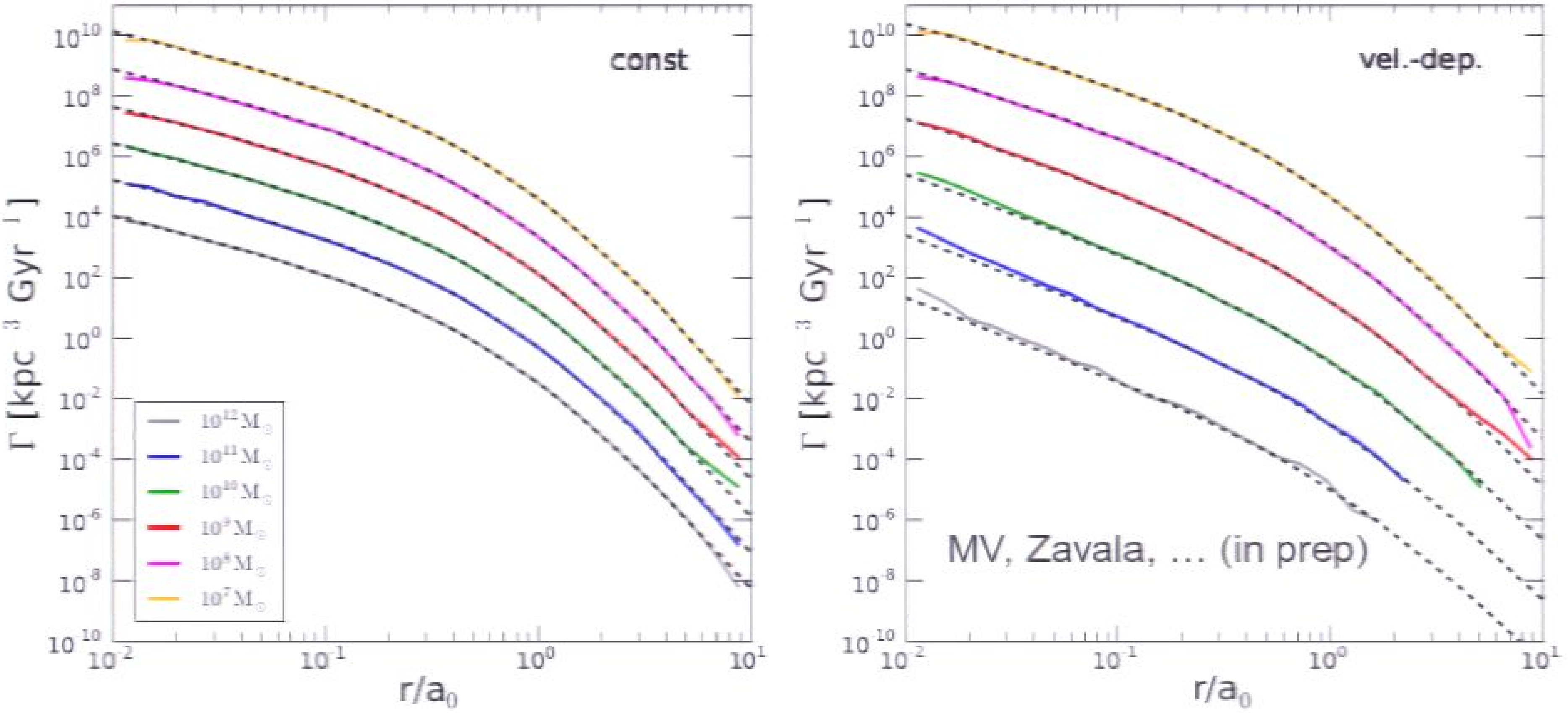
→ caustics negligible

↓

in a Sommerfeld-enhanced scenario the fine-grained structure dominates the smooth annihilation signal

red: smooth halo
blue: streams

Outlook: Non-Standard N-body



N-body simulations of SIDM, e.g. $$\frac{\sigma_T}{\sigma_{\max}} \approx \begin{cases} \frac{4\pi}{22.7}\,\beta^2 \ln\left(1+\beta^{-1}\right) & ,\ \beta < 0.2 \\ \frac{8\pi}{22.7}\,\beta^2\left(1+1.5\beta^{1.65}\right)^{-1} & ,\ 0.2 < \beta < 10^3 \\ \frac{\pi}{22.7}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & ,\ \beta > 10^3 \end{cases}$$

Loeb & Weiner (2011)

Implications

- local DM distribution very grainy [wrong] [<5% deviation from smooth]
- massive streams near the Sun [wrong] [at most 1%]
- discrete velocity distribution [wrong] [smooth distribution]
- Maxwellian/Gaussian velocity distribution [wrong] [~10% deviations]
- Sun might be close to a subhalo [wrong] [chances below ~0.01%]
- ~100 streams near the Sun [wrong] [a lot more due to faster mixing]
- dense caustic structures [wrong] [caustics subdominant in inner halo]
- simulations miss much caustic annihilation [wrong] [<10% even in outskirts]