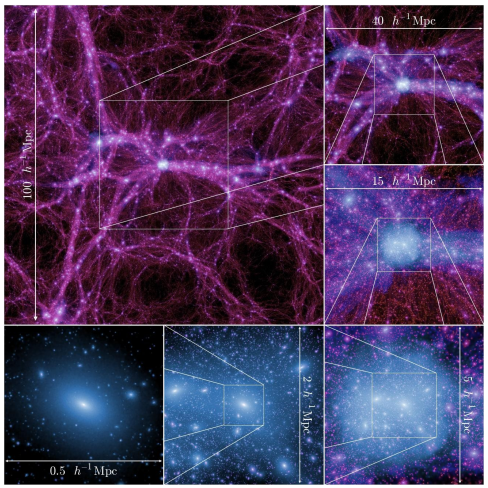
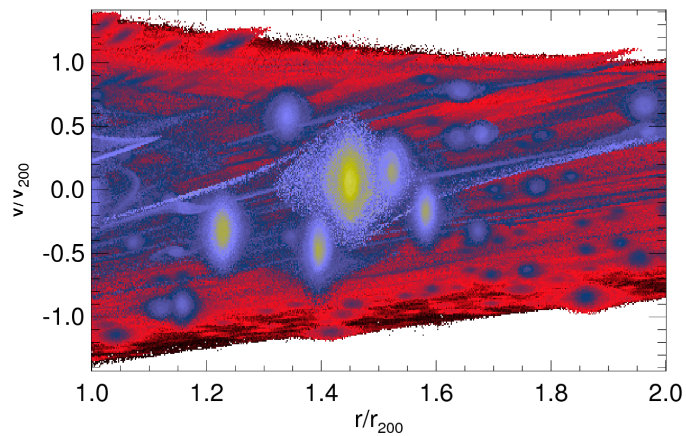
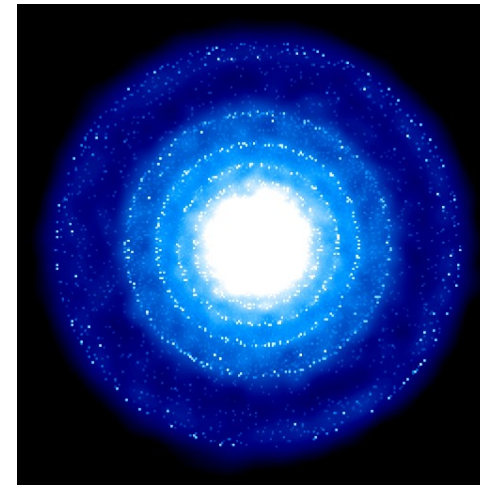
The (fine-grained) phase-space structure of Cold Dark Matter Halos

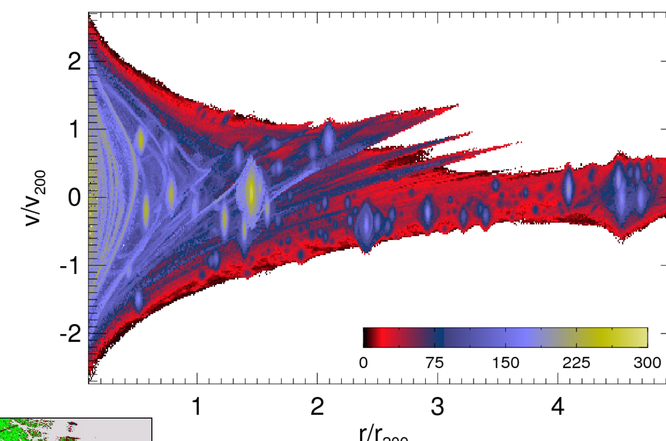
- and its influence on dark matter searches -

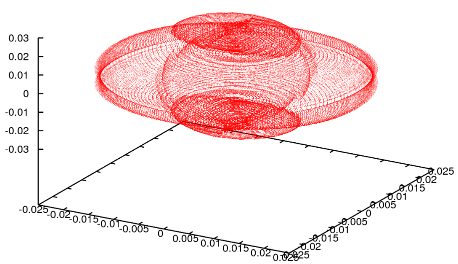
Mak Vogelsberger, Harvard/CfA

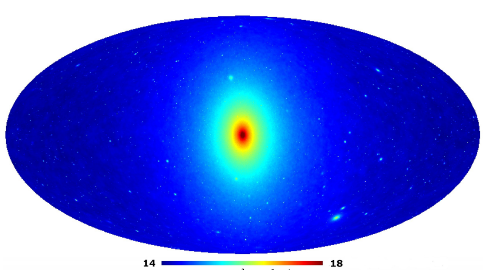


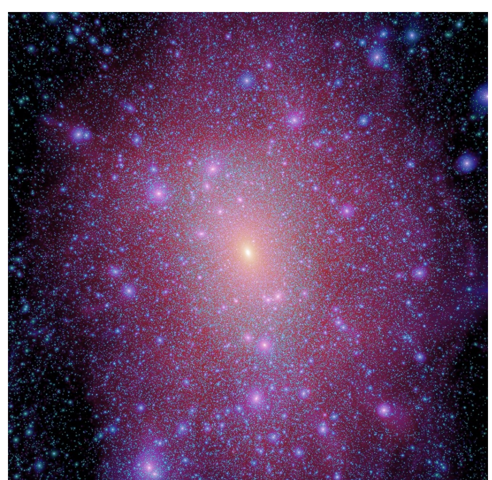


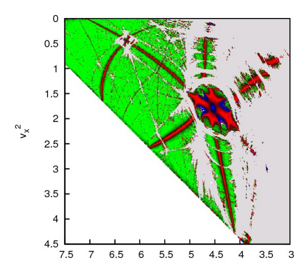


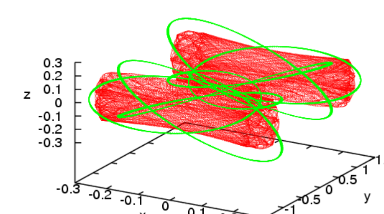




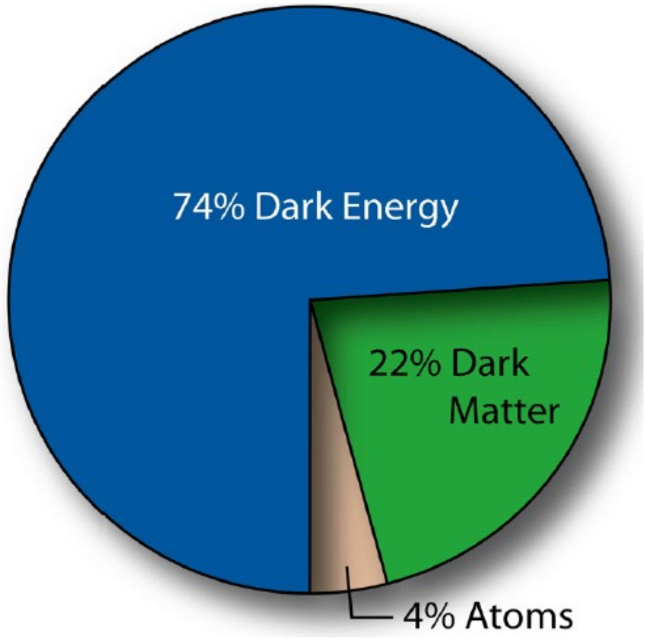


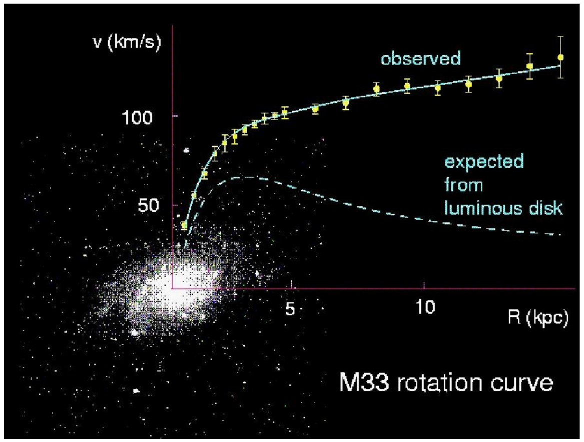




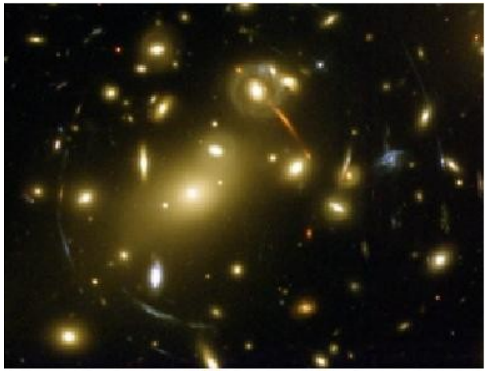


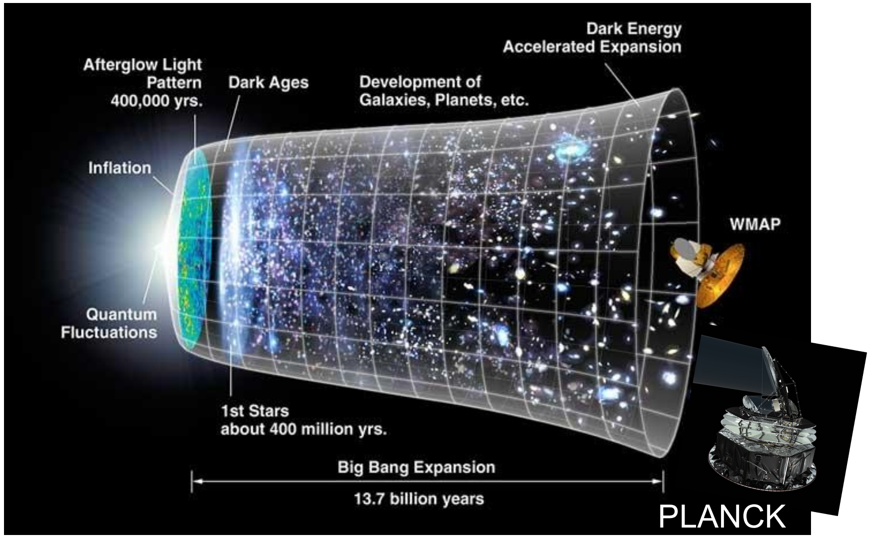
The content of the Universe





Evidence ↔ Existence: WIMP, Axion, … ?



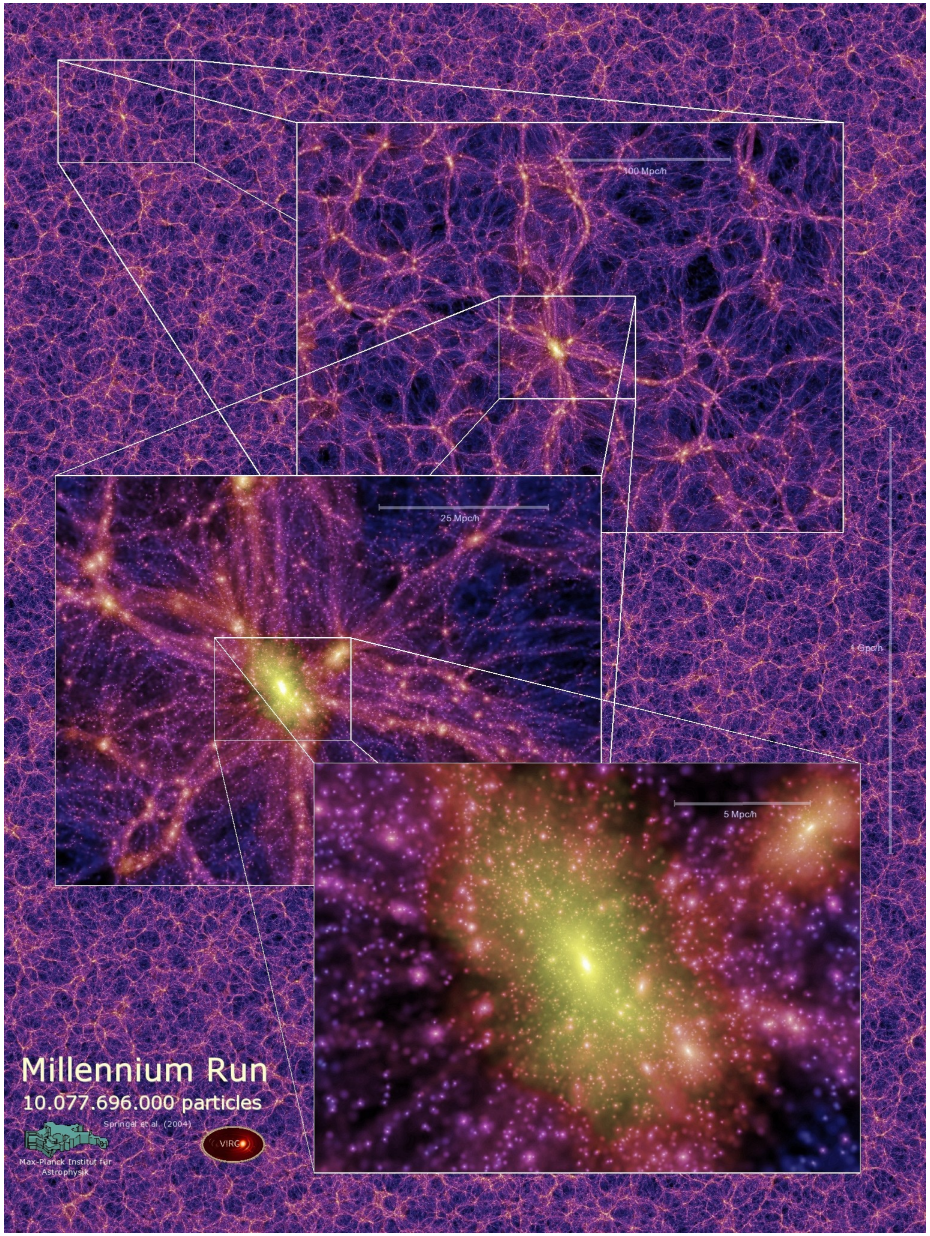


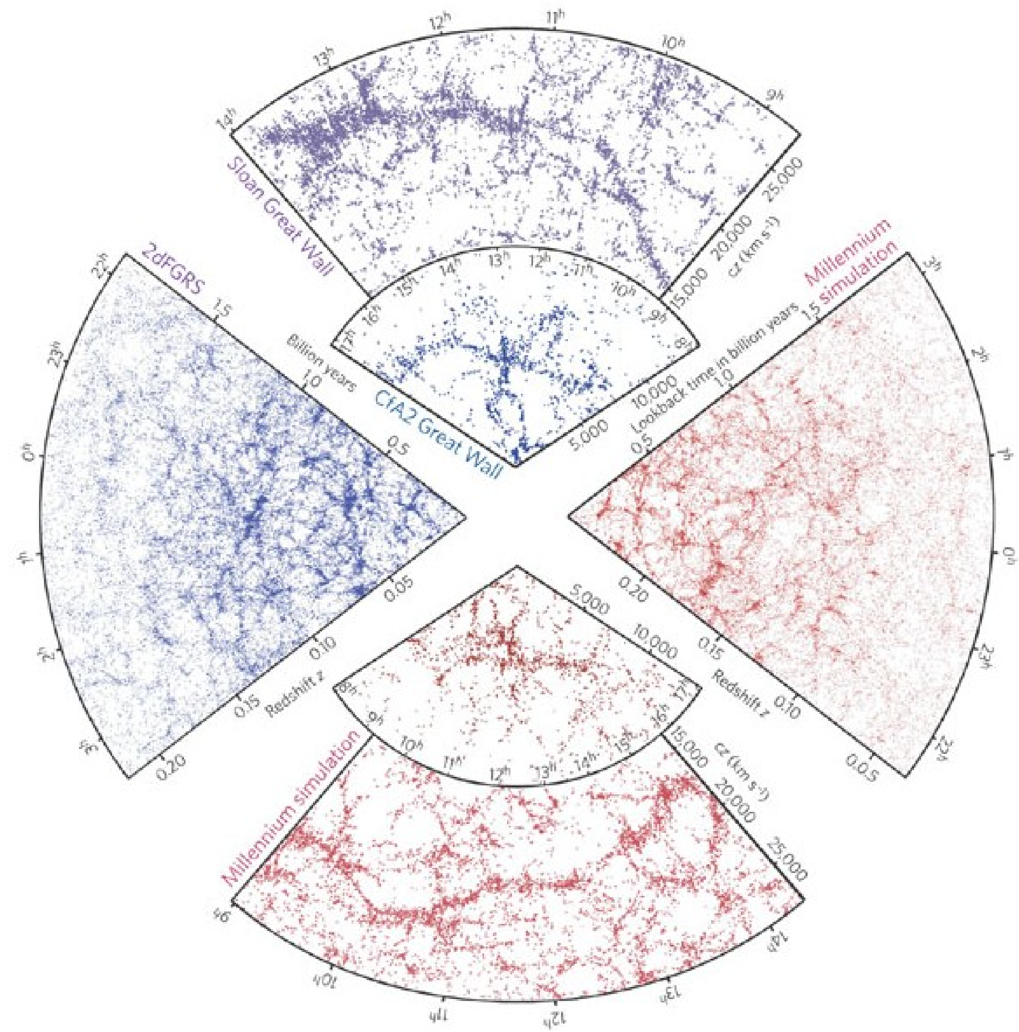
N-body simulations:

→ calculate DM gravitational interaction

→ structure formation

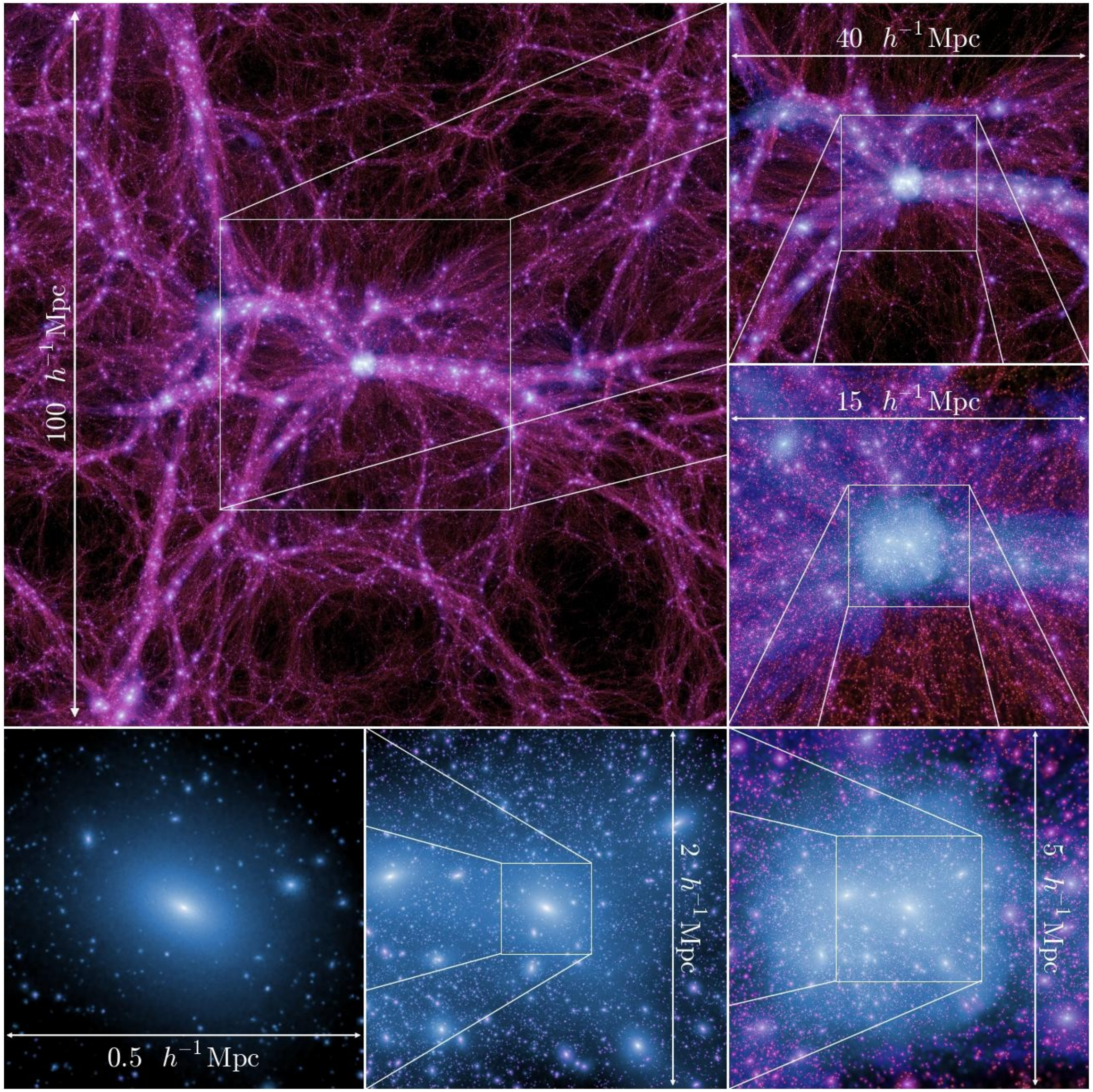
Large-scale structure





Springel et al (2005)

Large-scale structure



a playground for
galaxy formation
(semi-analytic modeling)

~6.000 Milky Way-mass halos with ~100.000 particles

use a large calculator

Boylan-Kolchin et al (2009)

Millennium II

Do we need more?!

Do we simulate reality?

Is there really dark matter?

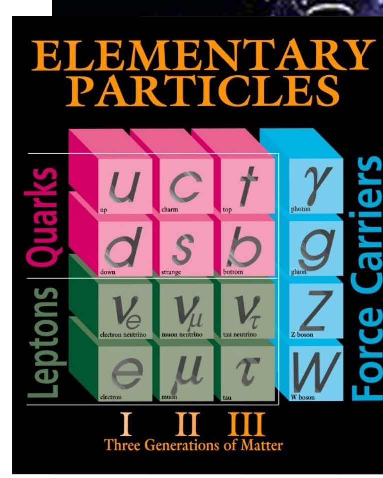
How to be sure?

Detect it!

- <u>indirectly</u> via annihilation products
- <u>directly</u> via scattering in underground detectors

And ideally:

- <u>produce</u> a suitable particle at LHC

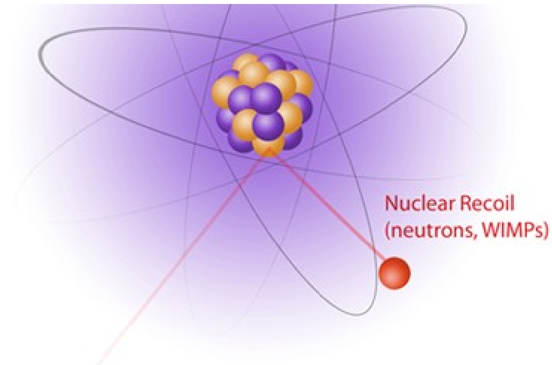


Complete the puzzle

The Hunt for Dark Matter

Direct searches:
nuclear recoil events

CRESST, XENON, ZEPLIN,
EDELWEISS, CDMS, DAMA, ...

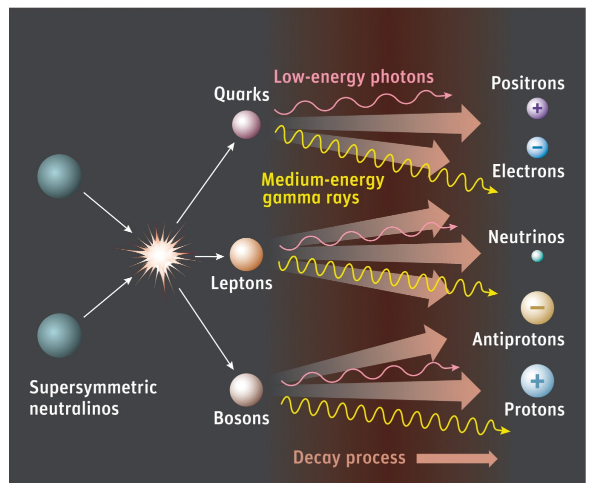


Accelerator searches:
producing DM

LHC

Indirect searches:
annihilation products

FERMI, PAMELA, ...



***Usually* assumed astrophysical input:**

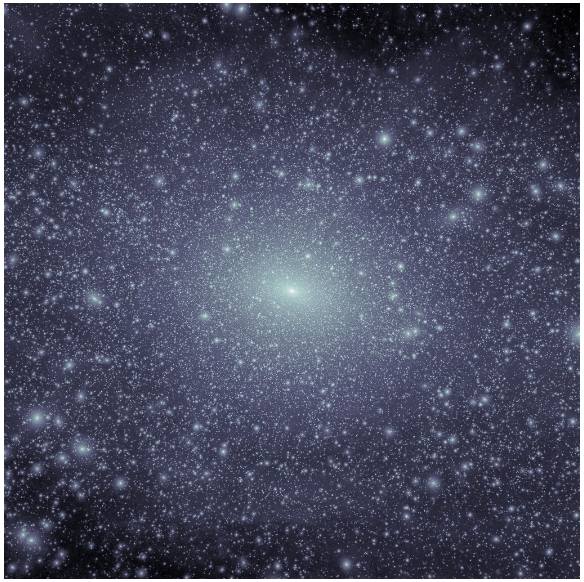
Density: ~0.3 GeV / c^2 / cm^3

Velocity: Maxwellian

Standard Halo Model (SHM):

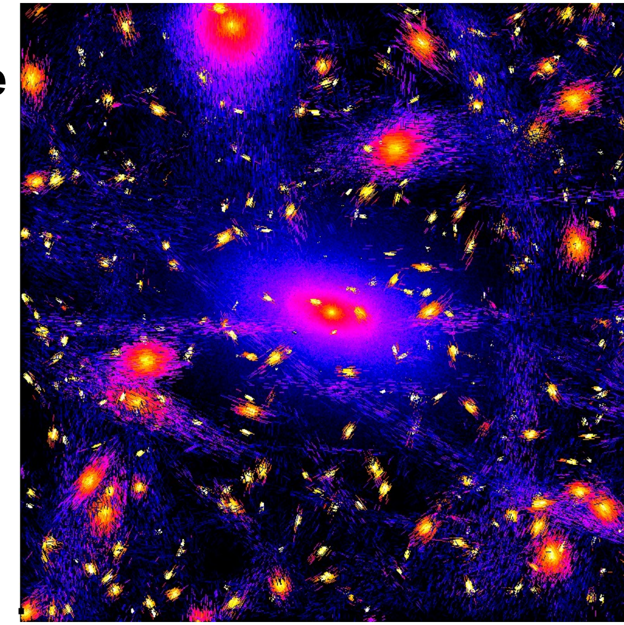
- **Smooth mass distribution**
- **Smooth velocity distribution**
- **'Featureless' phase-space**

'Non-standard' Halo models



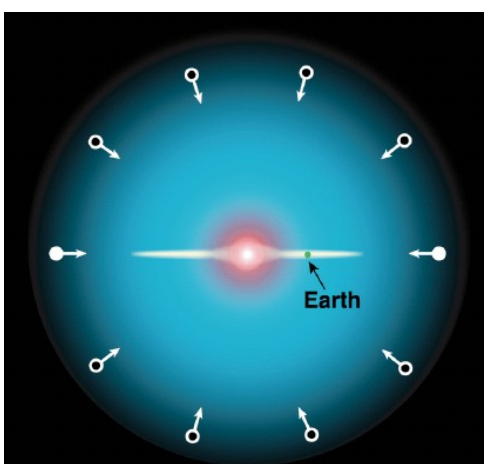
Diemand et al (2008)

N-body simulations:
lots of phase-space substructure



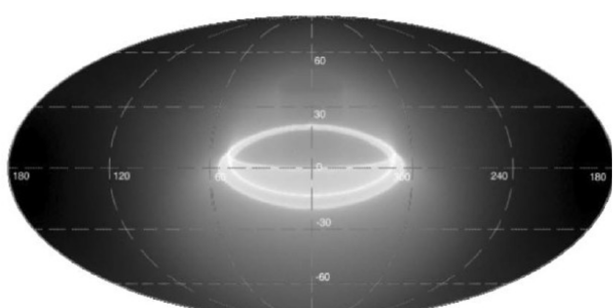
Standard halo model assumption wrong?!

Dark matter parameter-space limits wrong?!

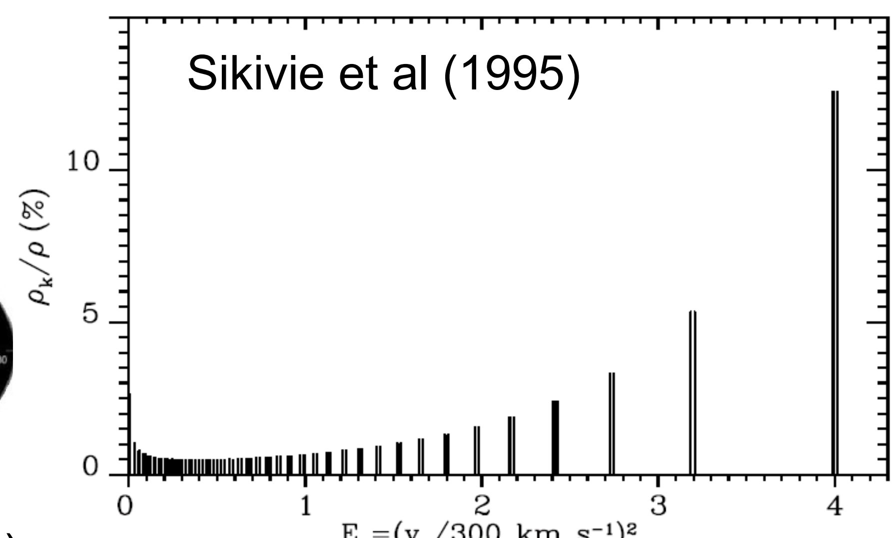


Van Bibber (2008)

Analytic models:
→ massive streams
→ caustic ring model



Natarajan & Sikivie (2008)



Outline

1) The coarse-grained structure of LCDM halos

2) Towards the fine-grained structure of LCDM halos

3) The fine-grained structure of LCDM halos

4) A note: Dynamics with the Geodesic Deviation Equation

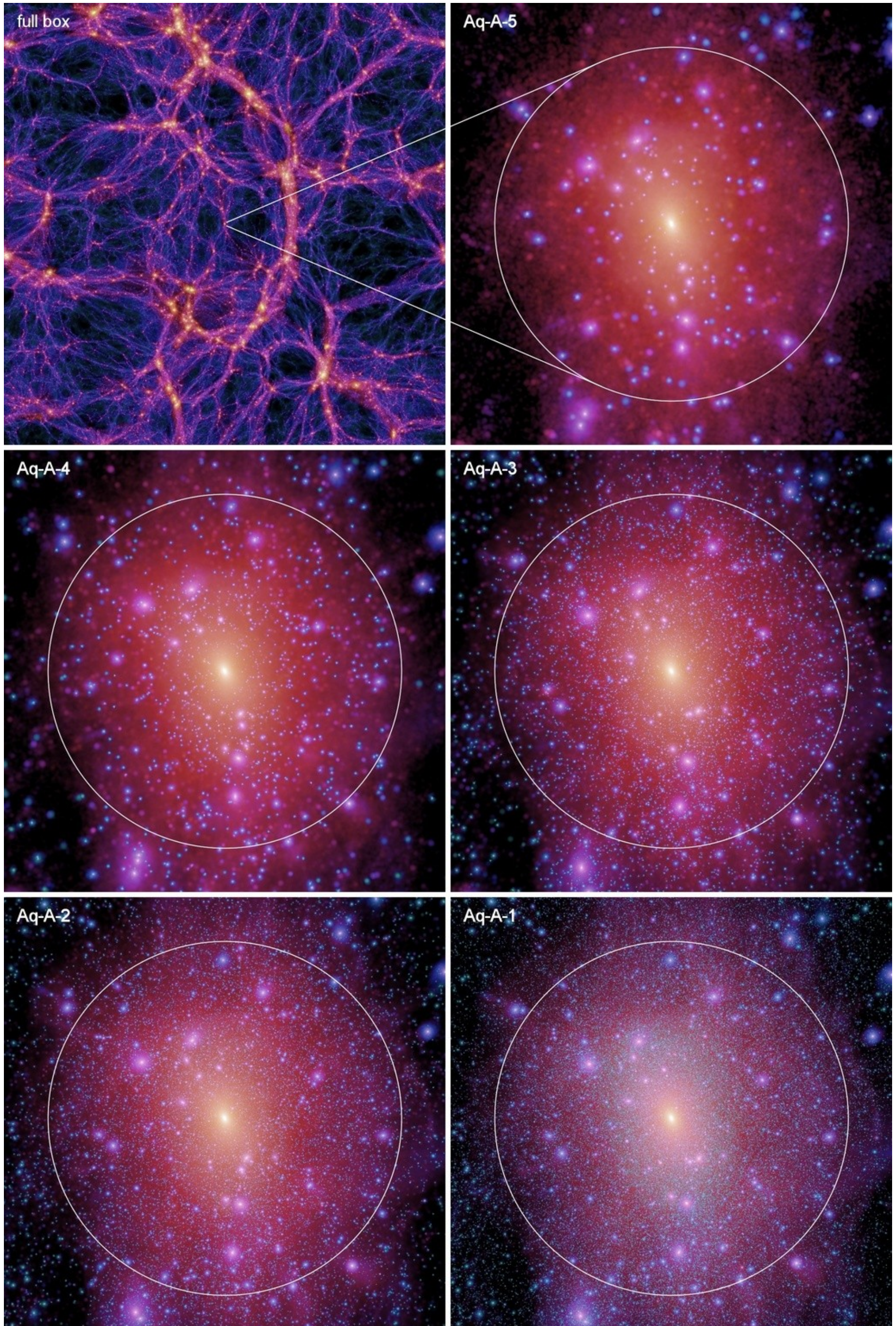
5) Conclusions

1) The coarse-grained structure of LCDM halos

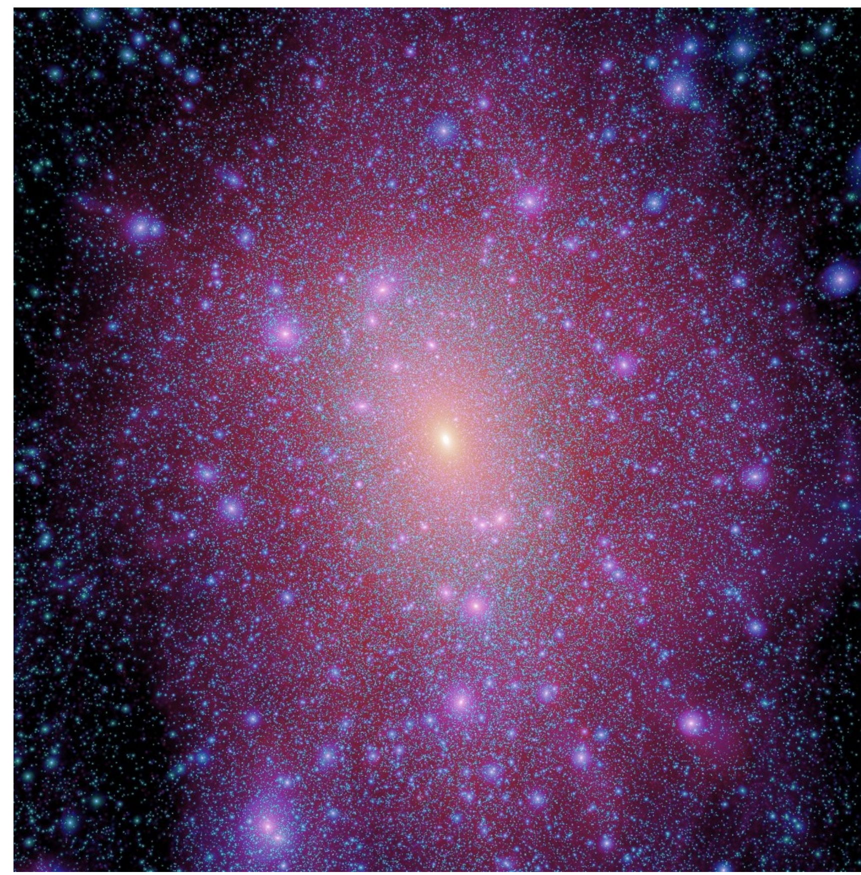
Aquarius Project

-six Milky Way-like Halos-

$m_{\rm p}$ [$M_\odot$]	ϵ [pc]	$N_{\rm hr}$
1.712×10^3	20.5	4,252,607,000



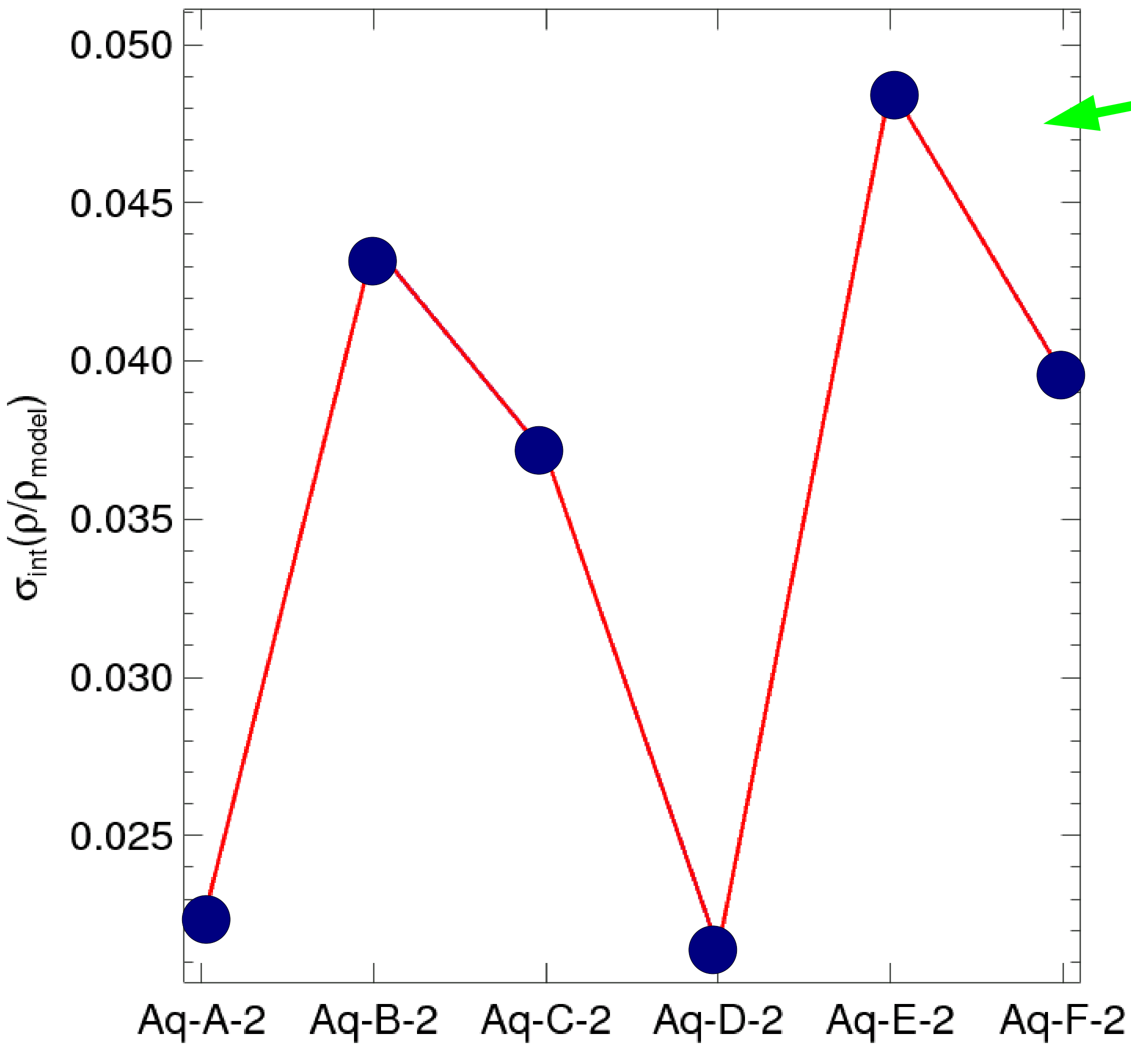
Springel et al (2008)

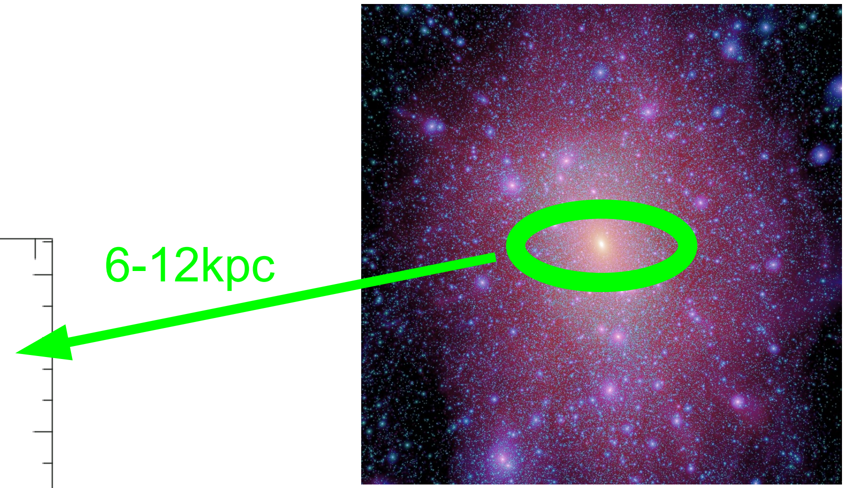


Probing DM near the Sun!

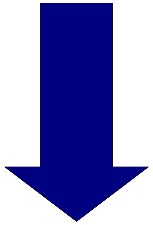
DM smoothness near the Sun

Scatter standard deviation < 5%
(variation due to halo shape taken out)





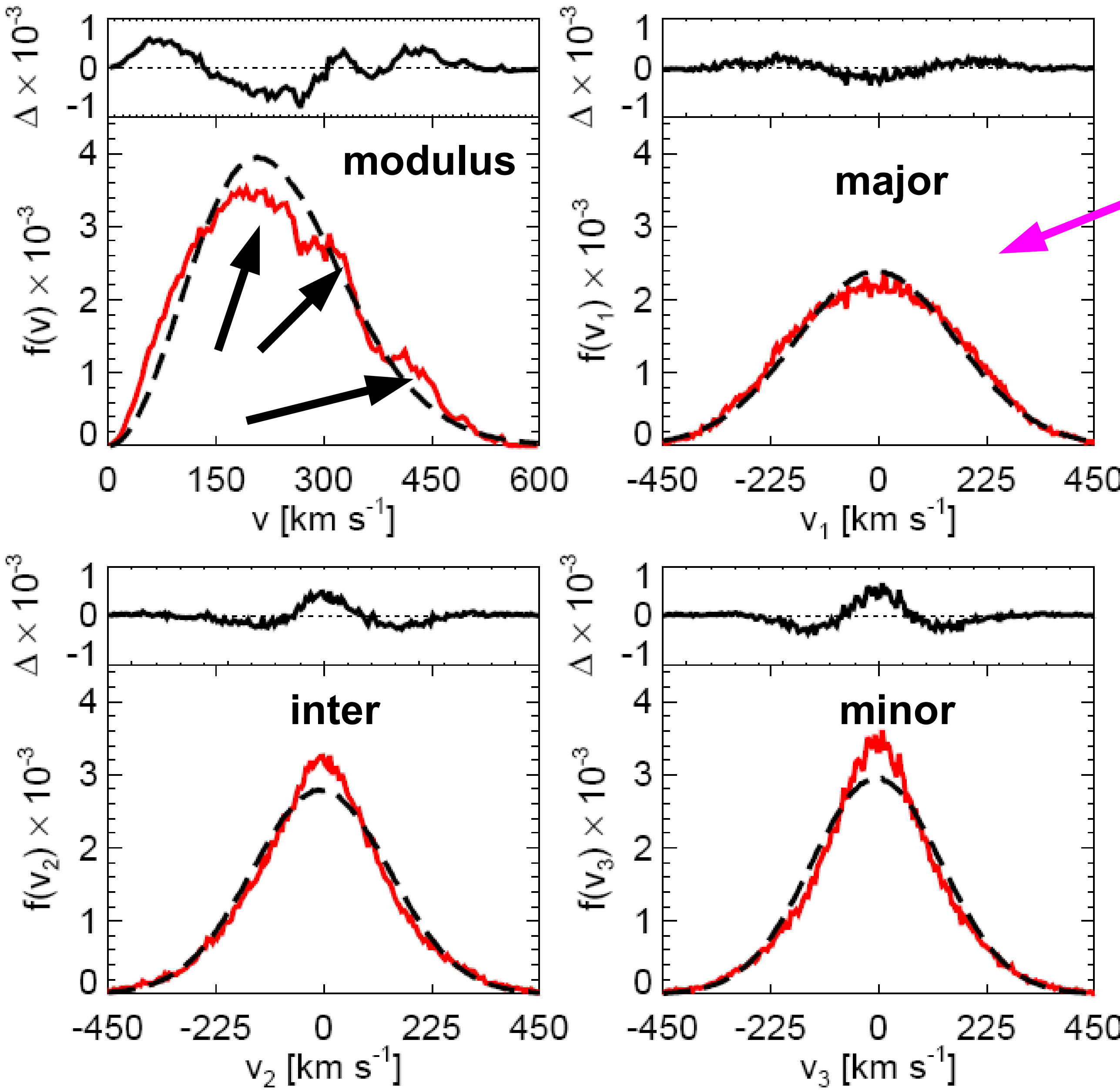
Chance of 'hitting' a subhalo is very small: $\sim 10^{-4}$

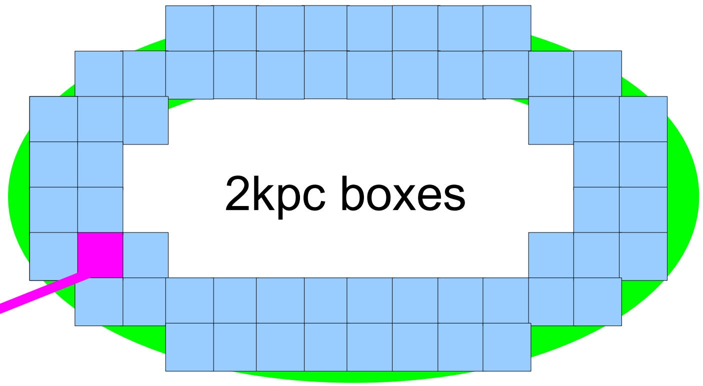


Experimentalists can use <u>smooth models</u>

MV et al (2009)

Velocity Distribution near the Sun



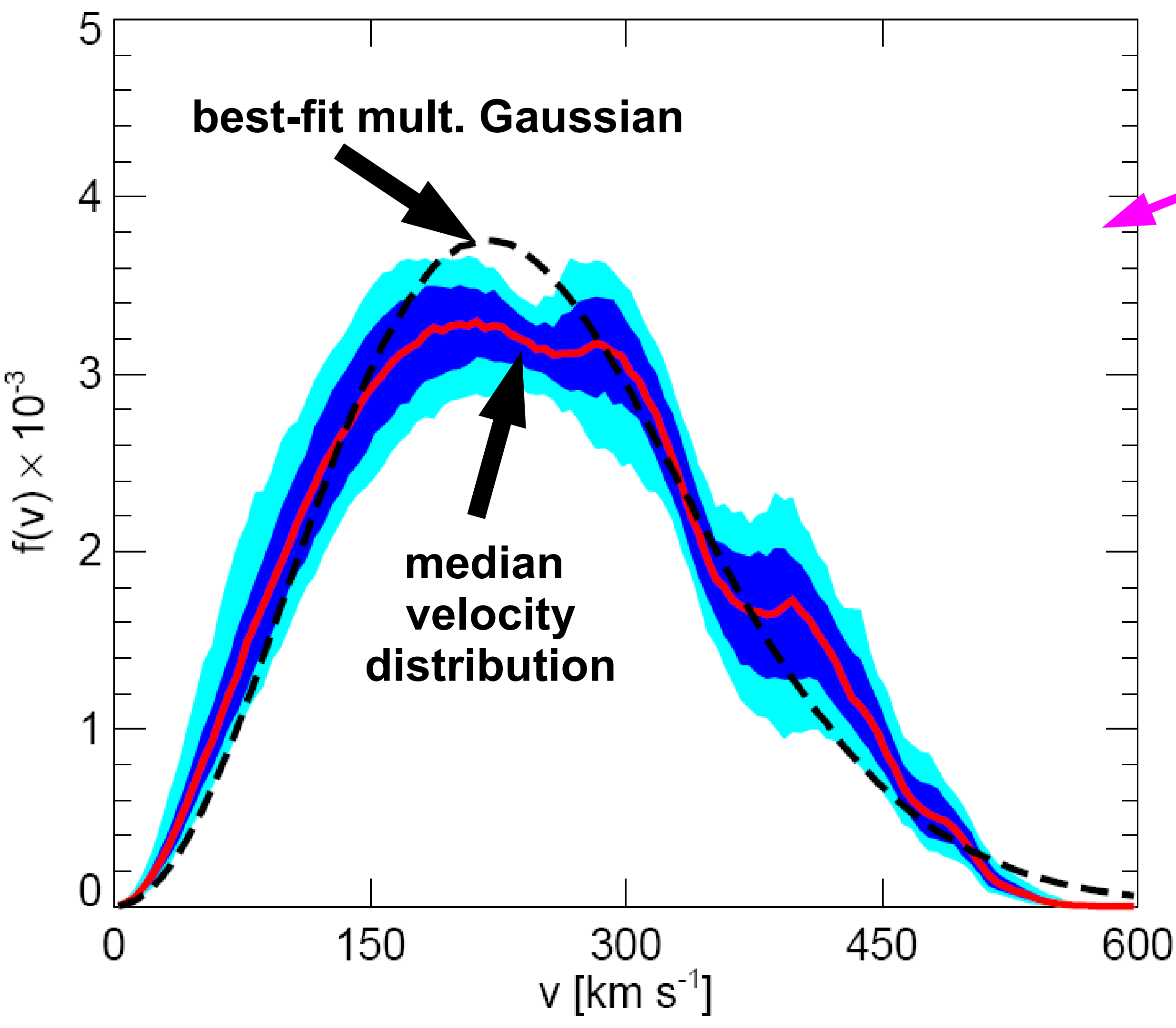


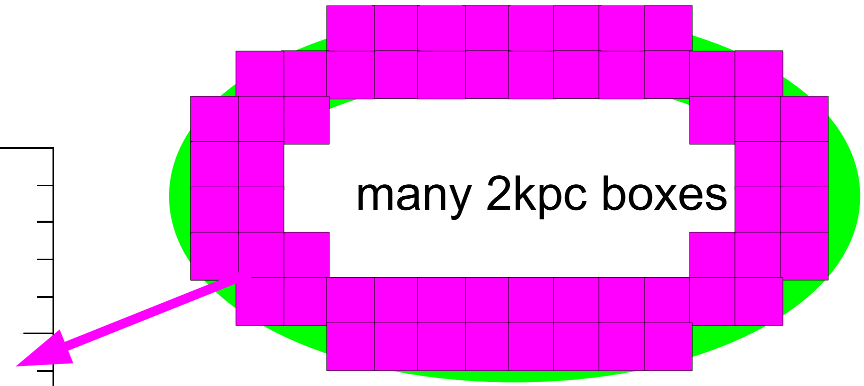
No signs for distinct/massive streams

Bumps/dips in velocity vector modulus

Not Maxwellian

… at Solar Circle



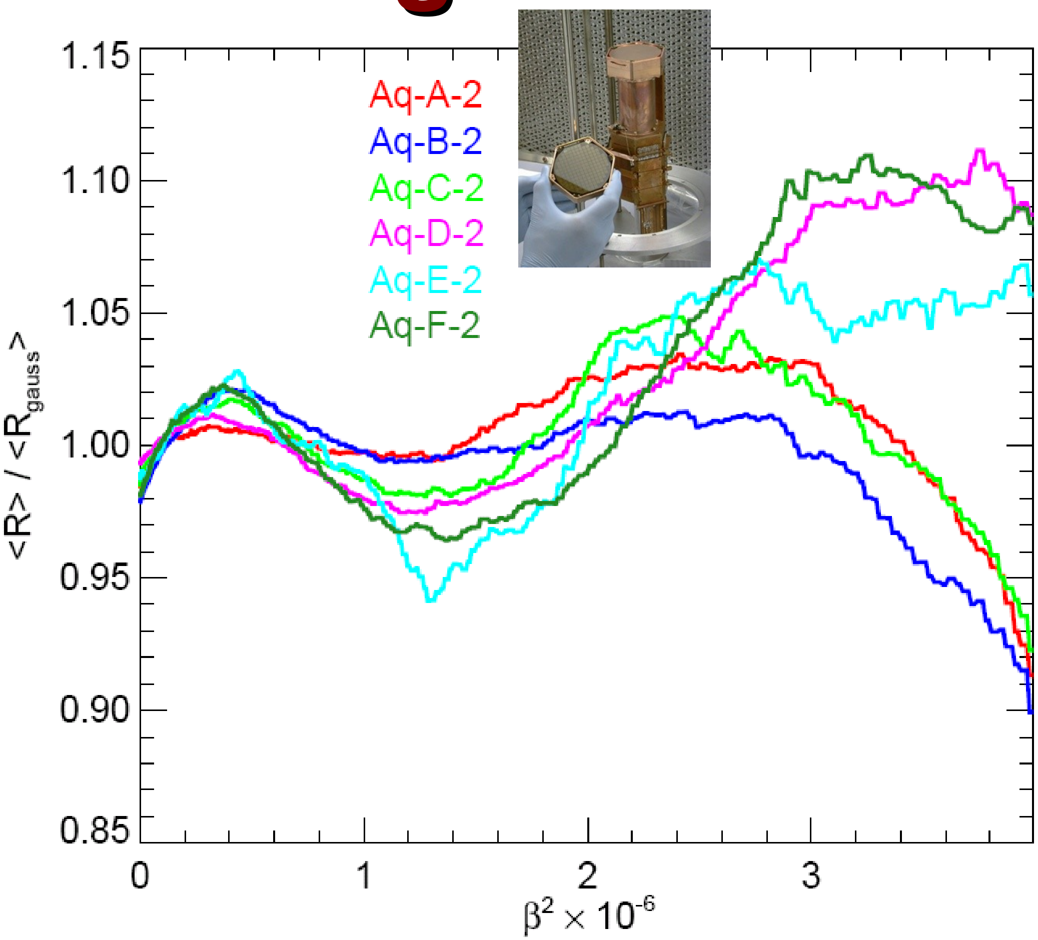


Bumps in velocity modulus at the same velocity

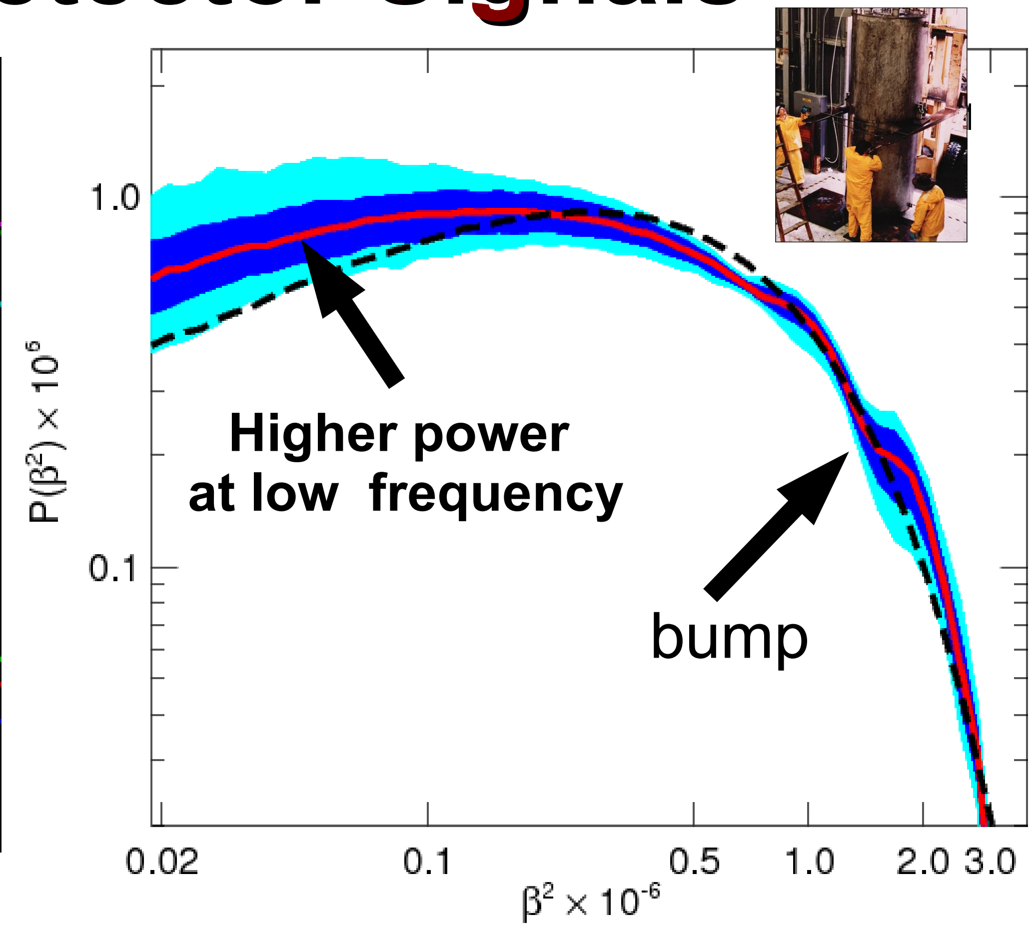
Not Maxwellian

Not Gaussian

Signature in Detector Signals



WIMP recoil spectrum



Axion microwave spectrum

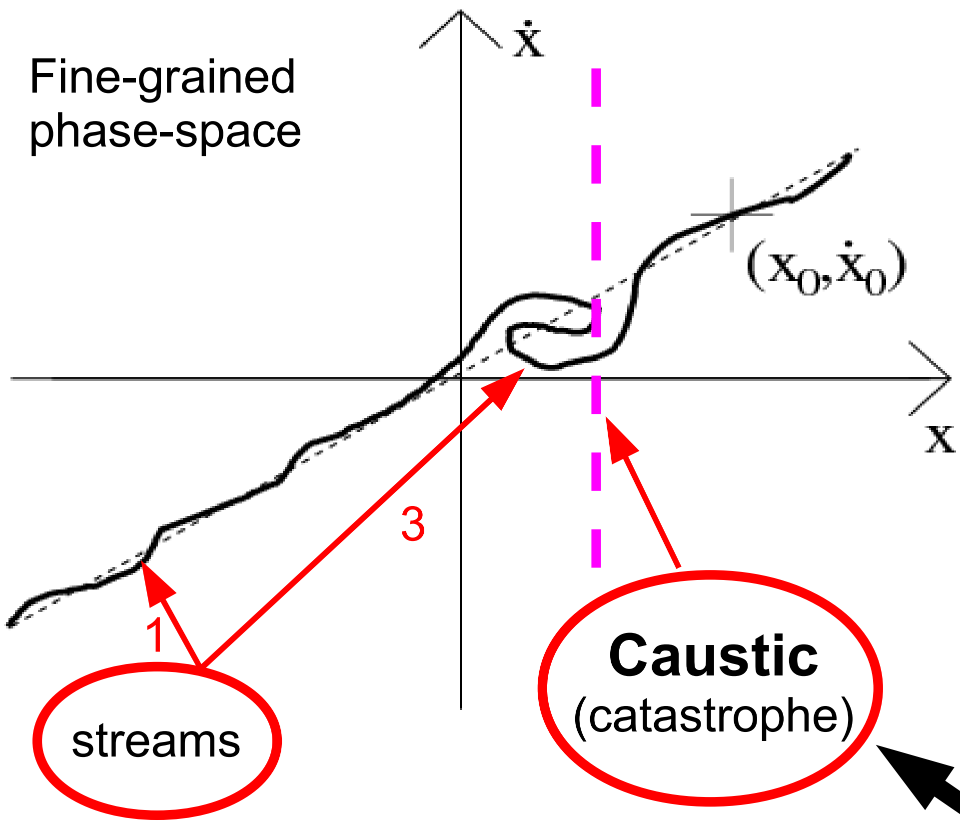
$$E = \frac{2\, m_\chi^2\, m_A}{(m_\chi + m_A)^2}\, c^2\ \ \beta^2\ \ \times\ \ 10^6\ \ \mathrm{keV}$$

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

2) Towards the fine-grained structure of LCDM halos

CDM – very small scales

CDM is **cold** and **collisionless** → **CDM lies on 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

Phase space sheet:

$$(\vec{r}, \vec{v}) : H(t)\vec{r} + \Delta\vec{v}(\vec{r}, t)$$

regions of **very high CDM** density

Estimates/Calculations so far

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),
Afshordi et al (2009), ...

Predictions

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

→ Significant effects on search experiments

How realistic are these models?

Correct caustic structure?

Correct caustic densities?

Correct number of streams?

Correct boost?

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

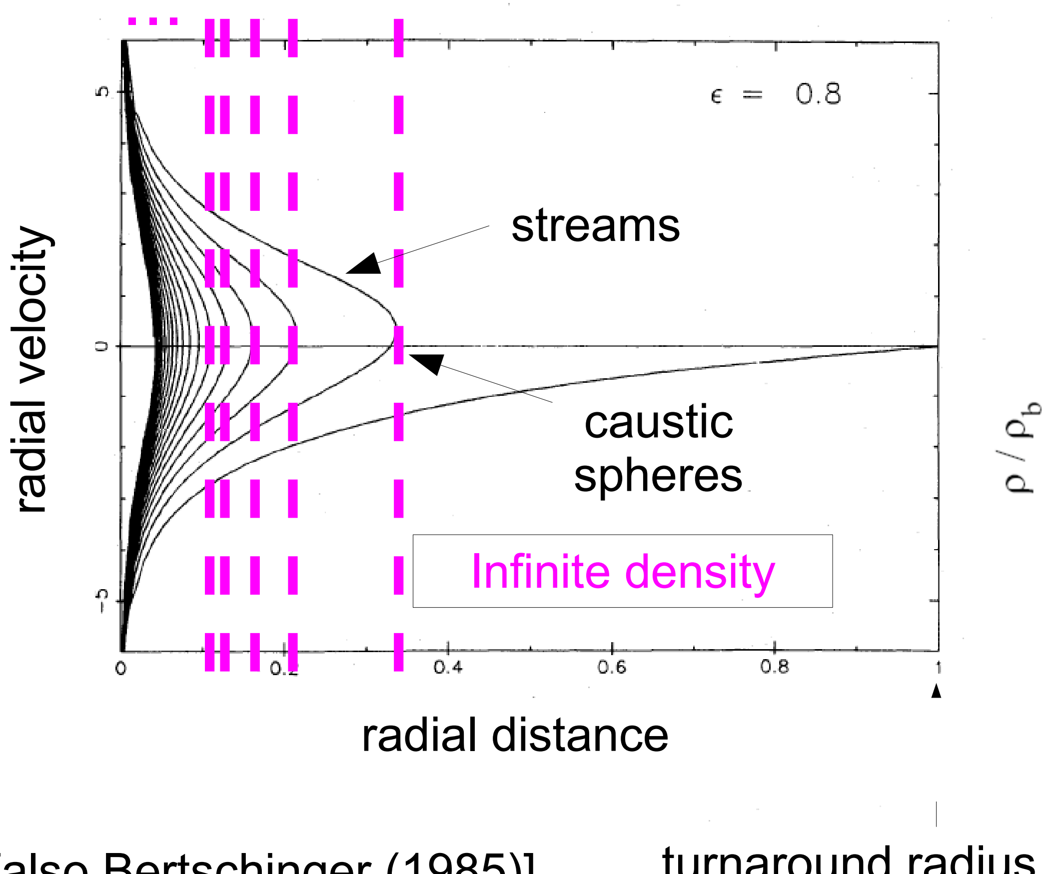
James A. Fillmore and Peter Goldreich
California Institute of Technology
Received 1983 October 10; accepted 1983 December 5

Starting point
Analytic 1D model

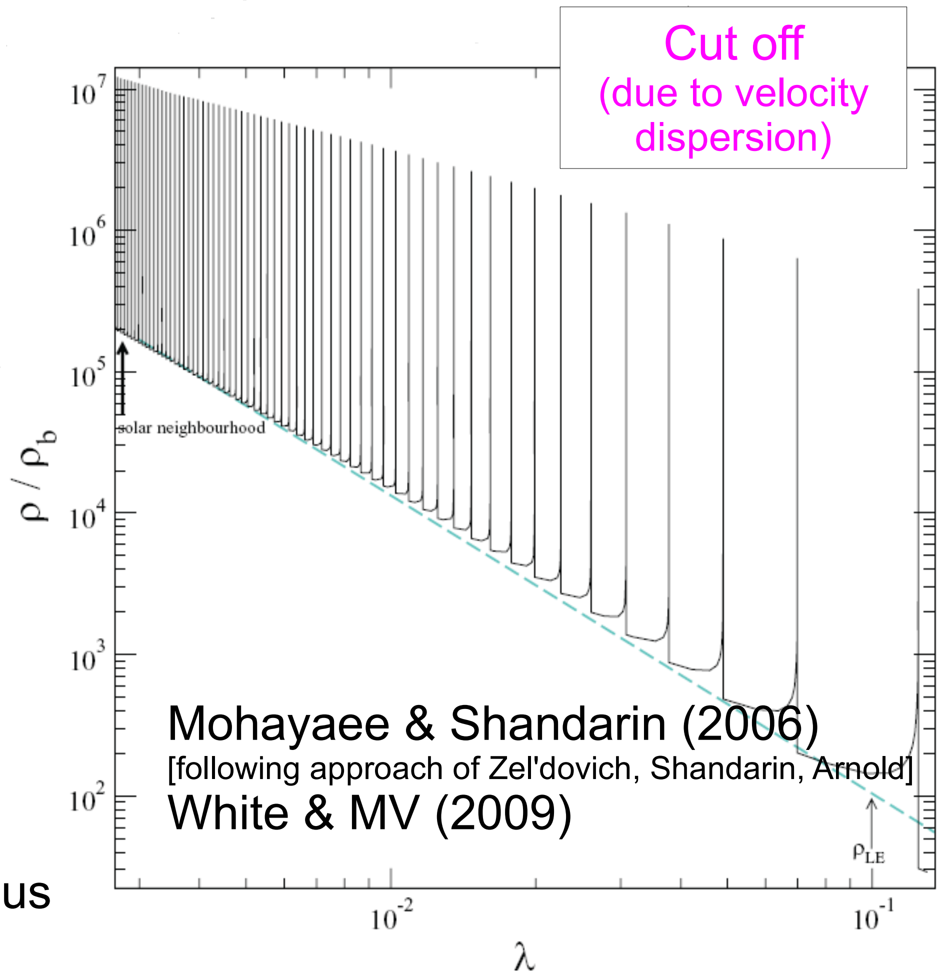
ABSTRACT

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



[also Bertschinger (1985)]



Resolving fine-grained caustics with N-body simulations

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

Solution: Follow the local phase-space evolution for each particle
(→ with a phase-space geodesic deviation equation)

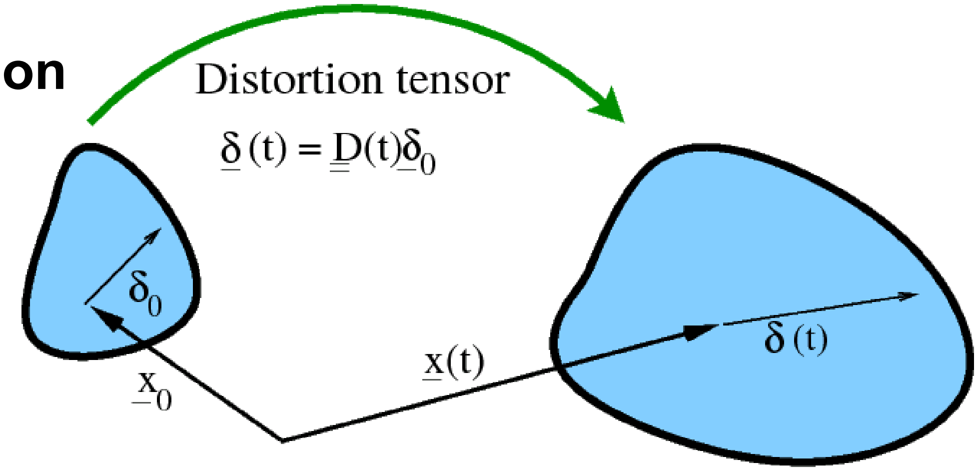
- **calculation of stream density**
- **identification of caustics**
- **Monte-Carlo estimate for intra-stream annihilation**

gaining resolution *without* using larger computers

→ **allows caustic annihilation calculation**

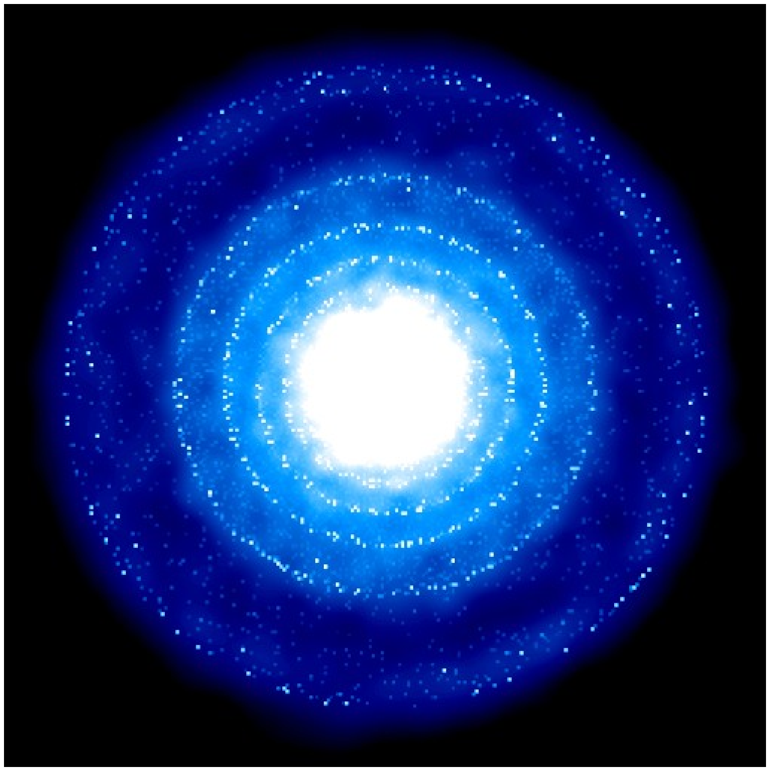
$$\frac{\mathrm{d}\mathcal{A}_{s,i}}{\mathrm{d}t} = \frac{<\sigma v>_\chi}{m_\chi^2} m_i \rho_{s,i}$$

[Implementation in GADGET-3]

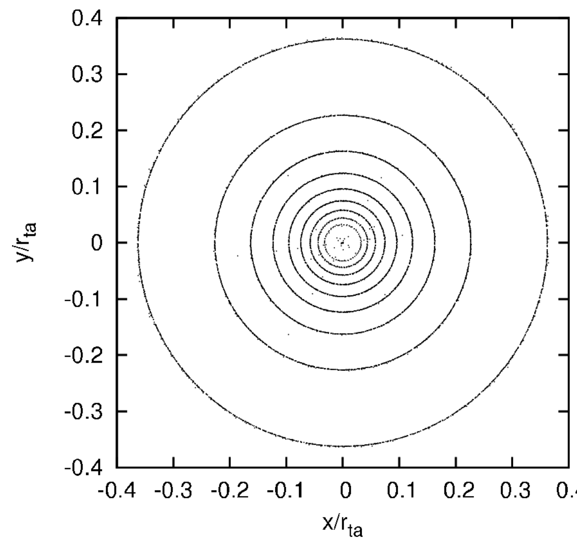


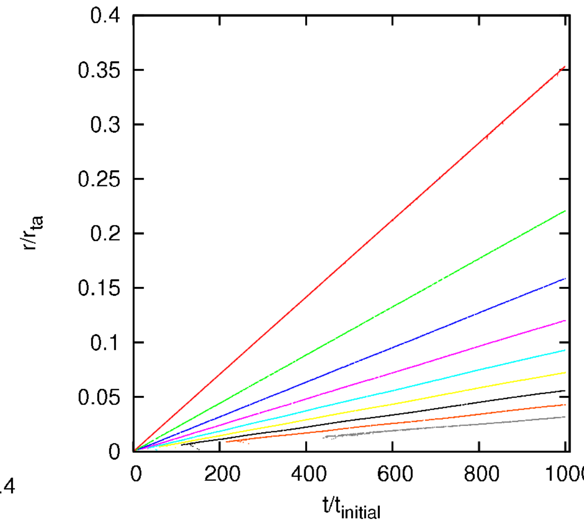
MV et al (2008)

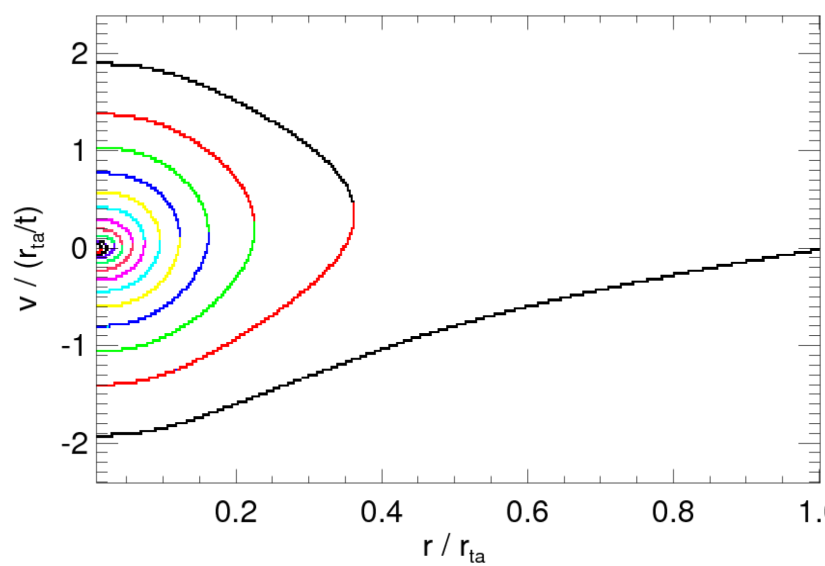
Caustic Annihilation radiation
- 1D gravity -



caustic spheres
on top of smooth
annihilation signal

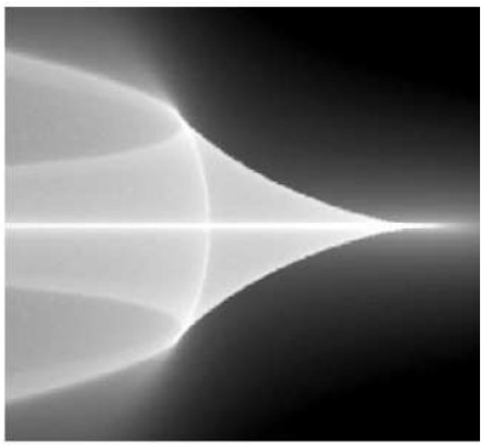






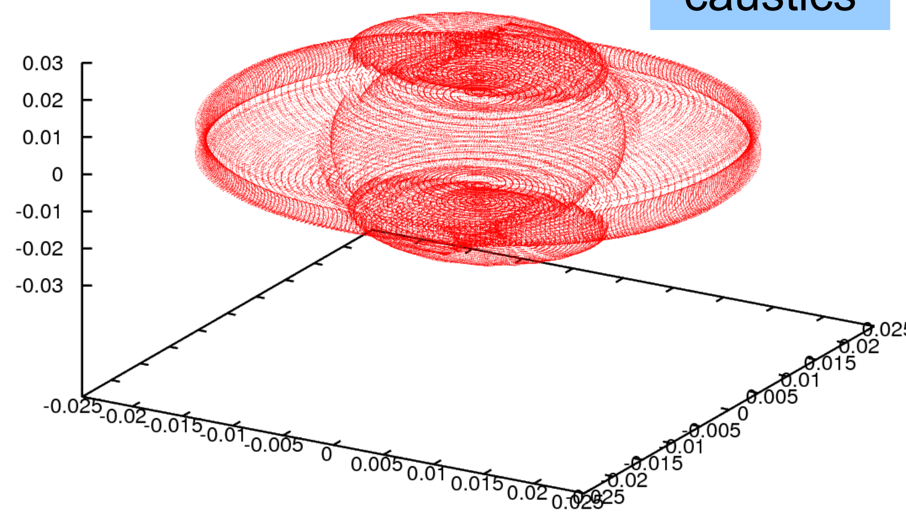
Caustic structures - non-radial halo model -

lead to interest in impact on annihilation radiation

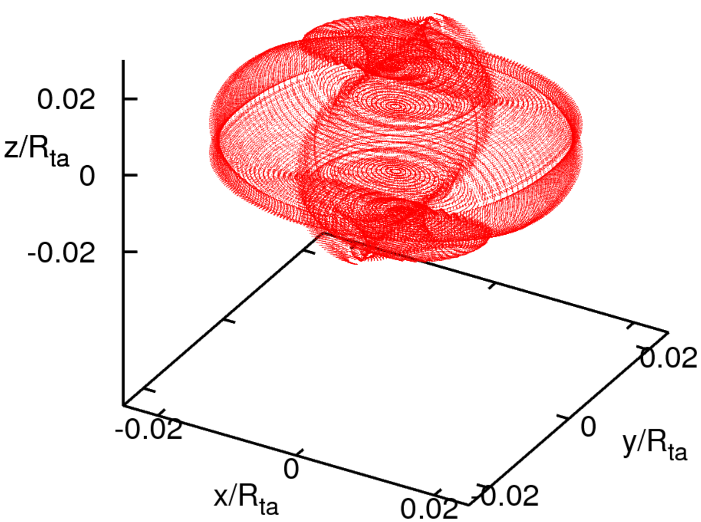


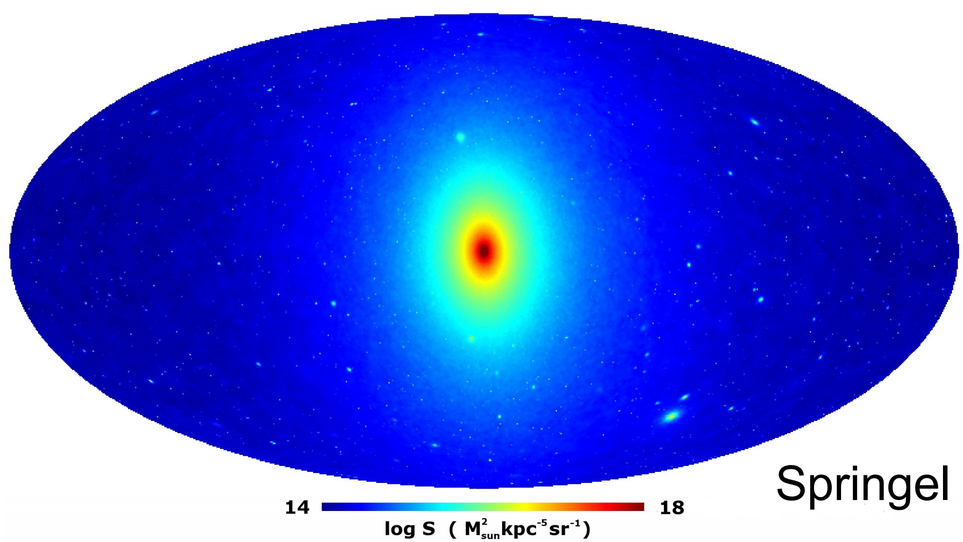
Natarajan & Sikivie (2008)

Inner caustics



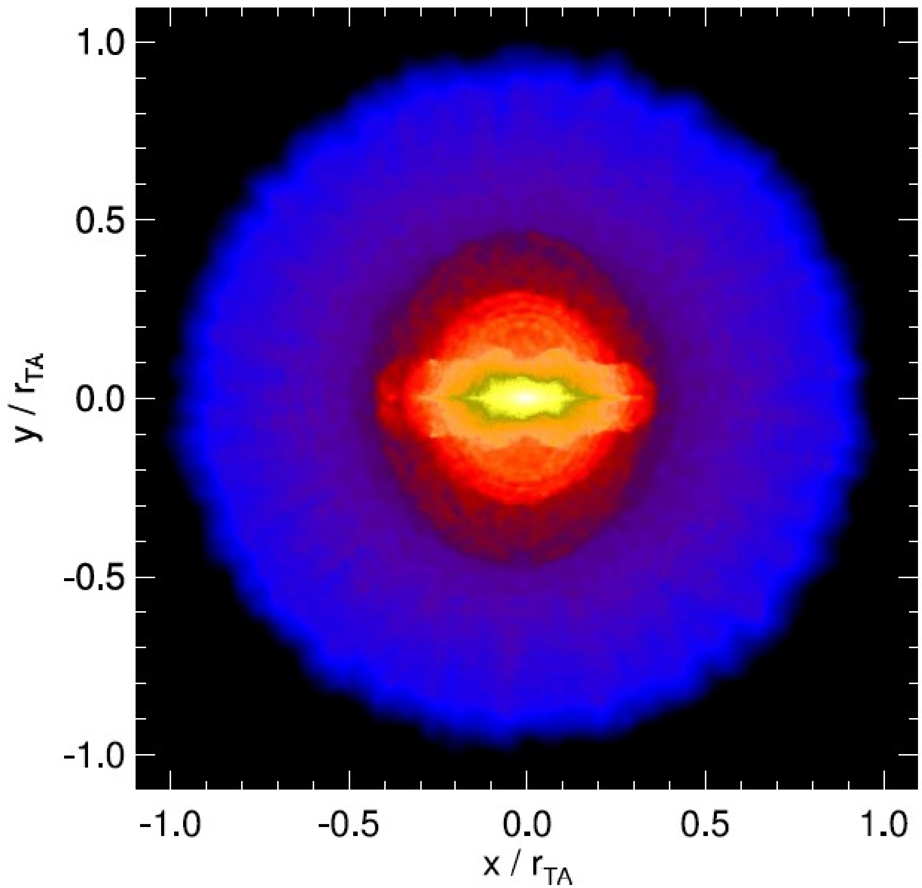
But N-body simulations predict:





Springel et al (2008)

Collapse of an isolated halo in 3D gravity

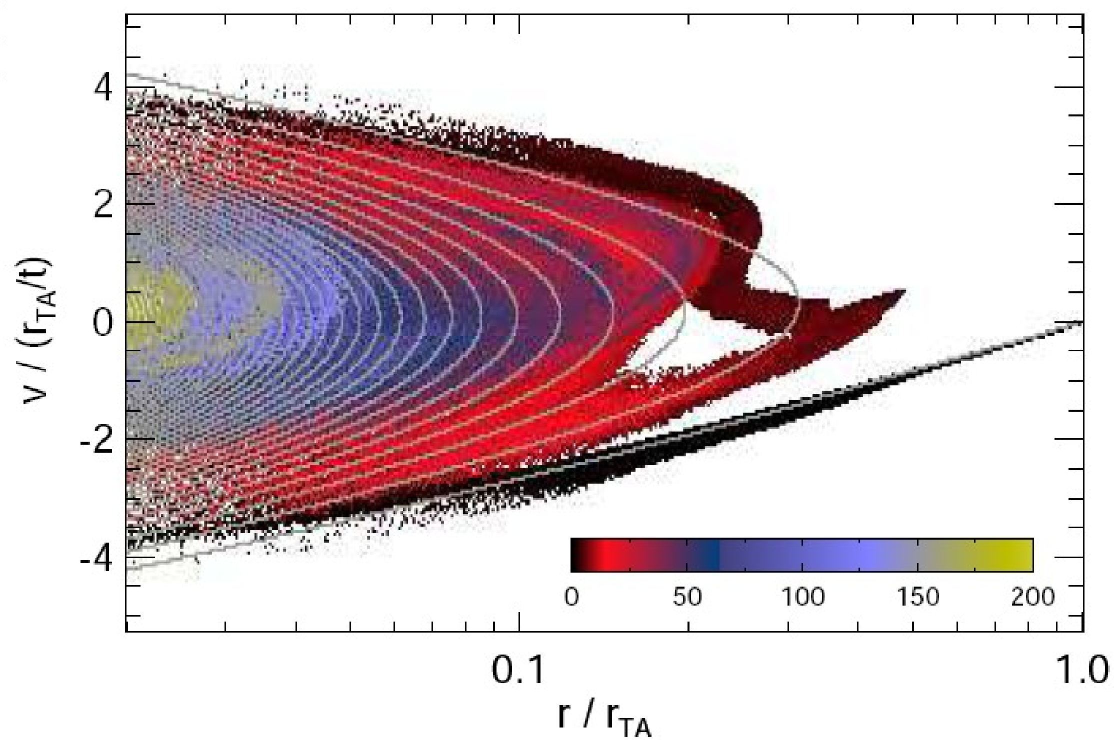


Density slice → **bar formation**

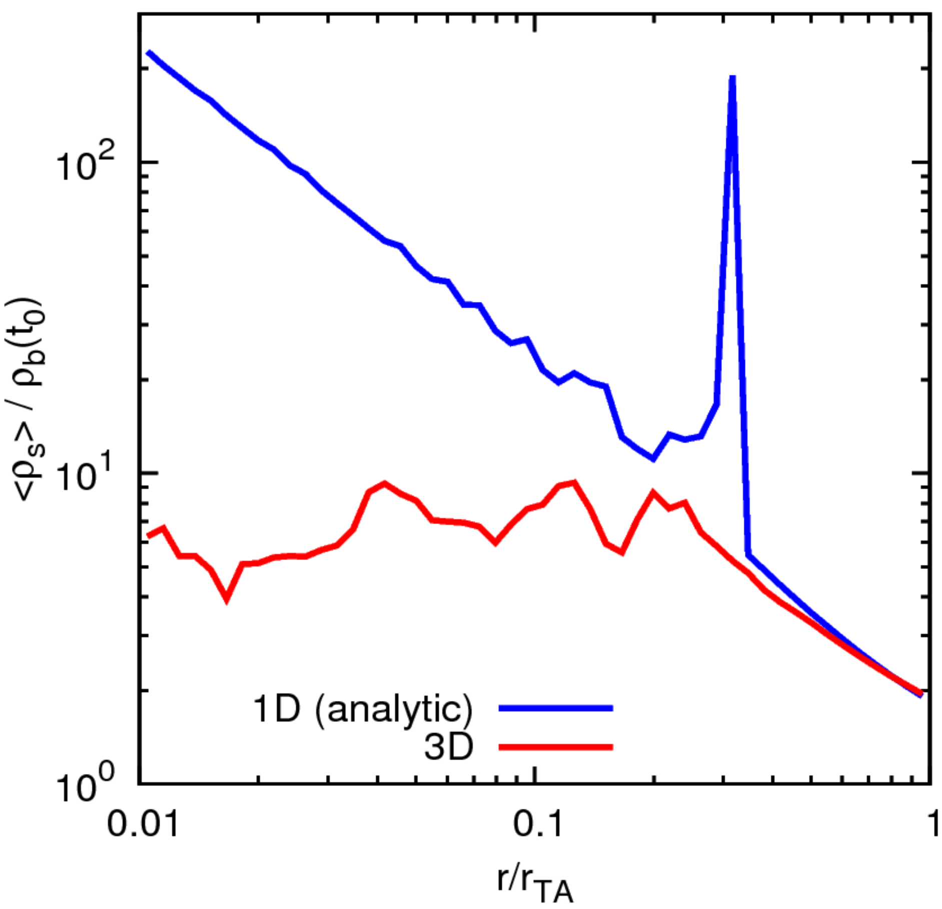
Instabilities lead to different phase-space evolution!

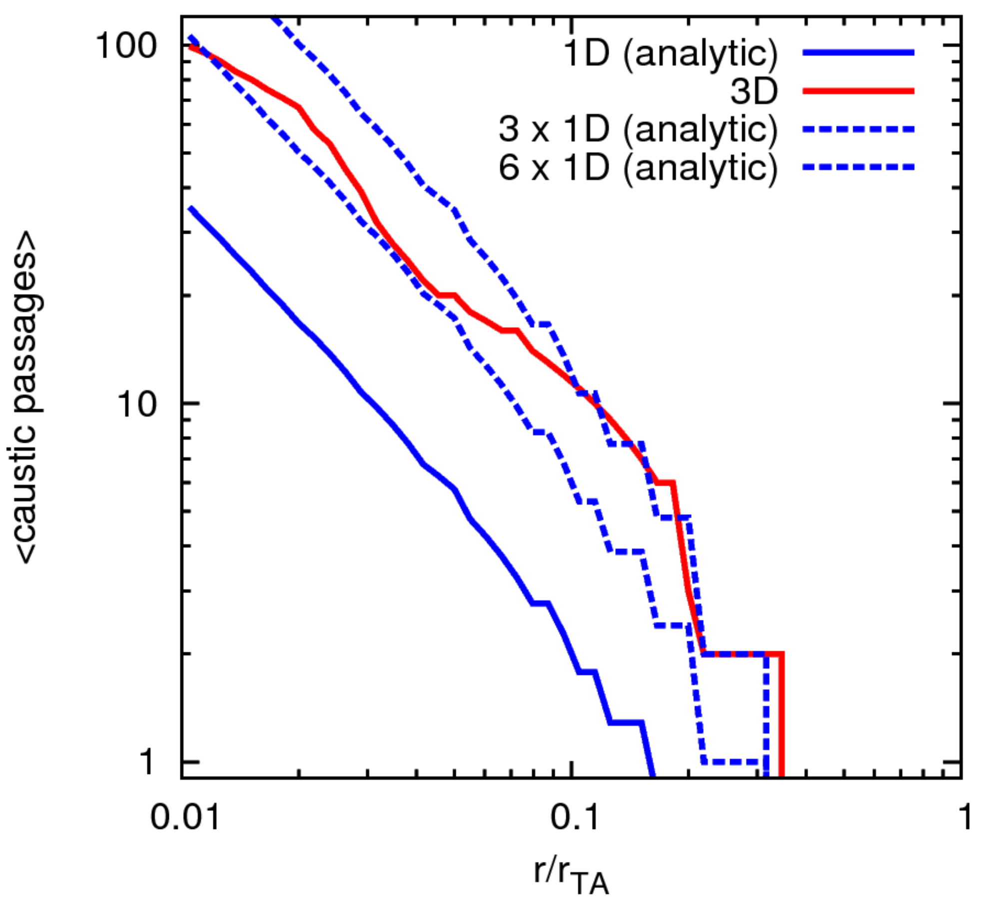
MV et al (2009)

No clear phase-space pattern



Fine-grained phase-space in 3D





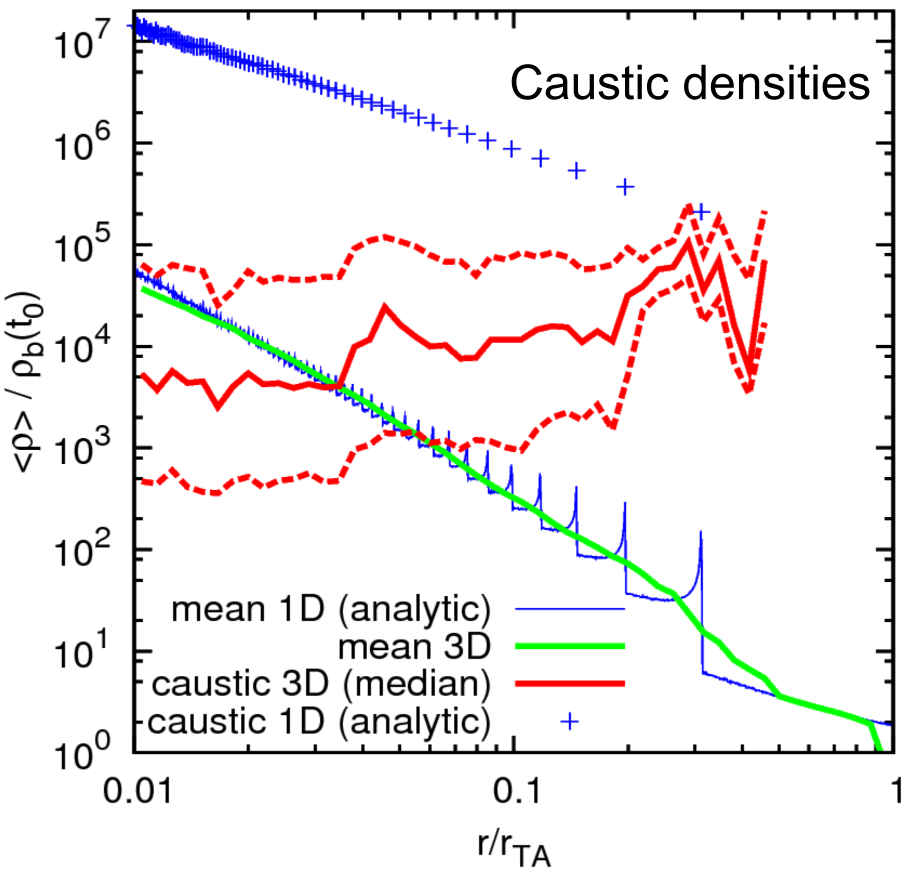
Stream density: **lower in 3D**

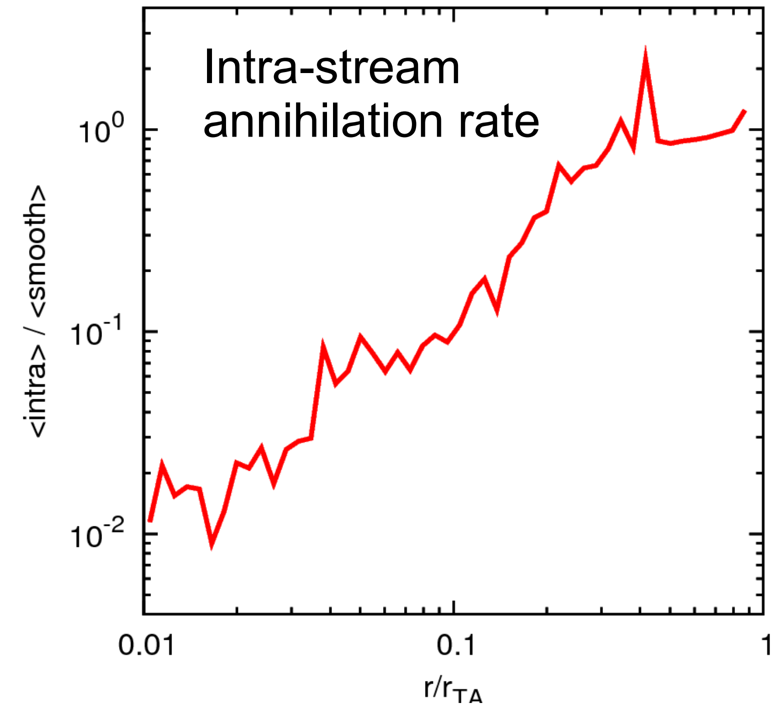
Caustic passages:
Increases in 3D
→ **more turning points**

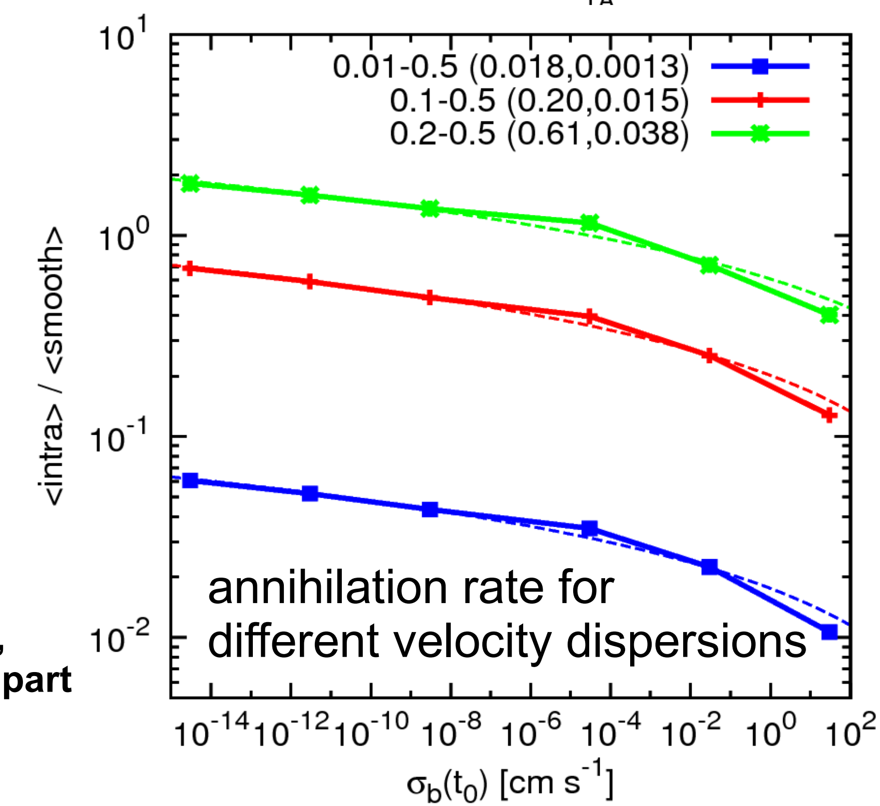
More efficient mixing in higher dimensions

Caustics in 3D

100 GeV/c^2 Neutralino







boost factor due to caustics:

→ 4% in range 0.01 to 0.5 x turnaround radius

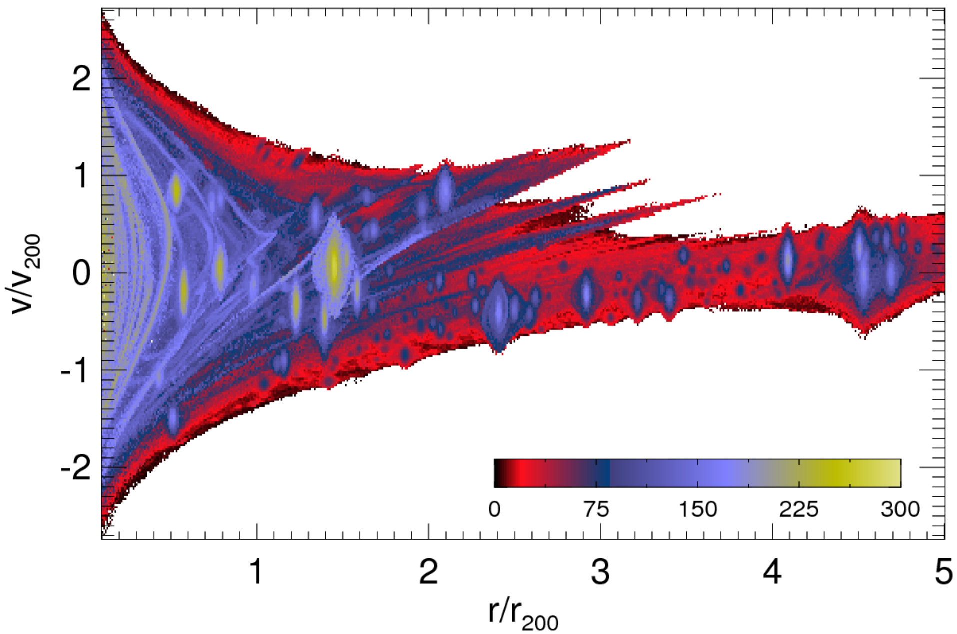
→ 24% ... 0.1 to 0.5 x ...

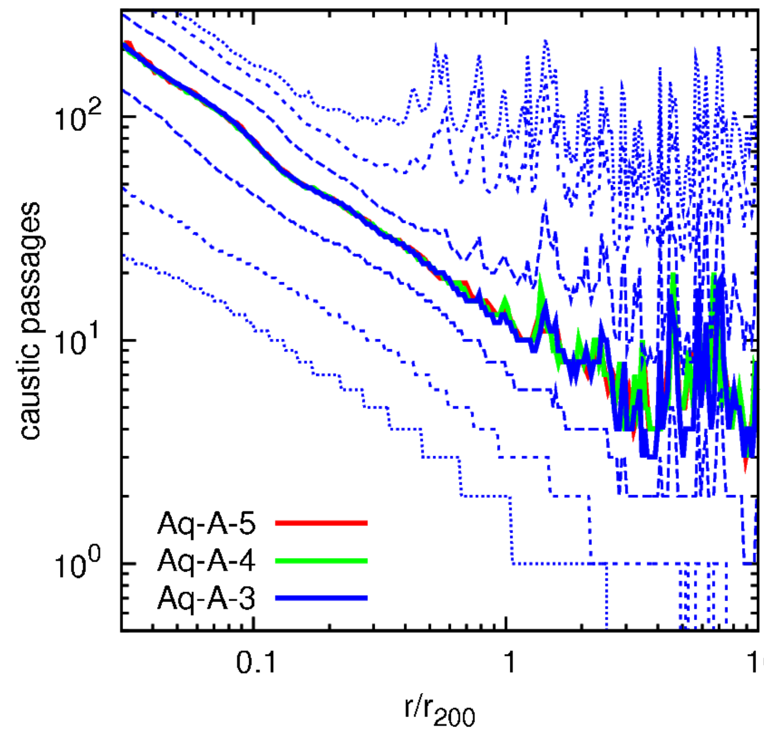
→ 64% … 0.2 to 0.5 x ...

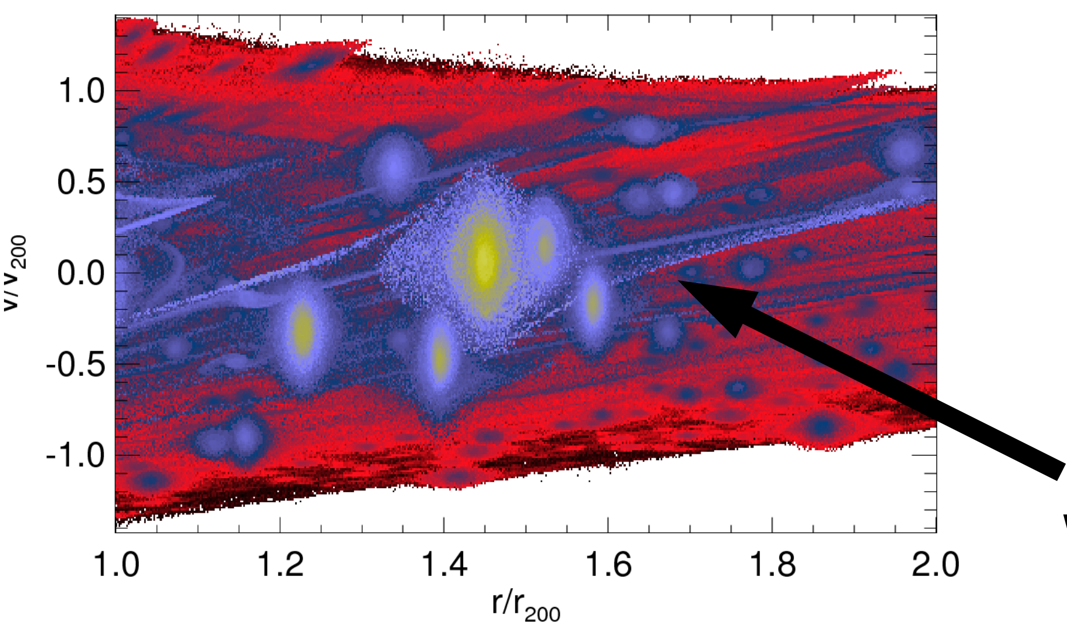
→ **caustic annihilation is negligible in the inner halo, but can boost the signal by more than 50% in the outer part**

3) The fine-grained structure of LCDM halos

Caustics in LCDM Haloes



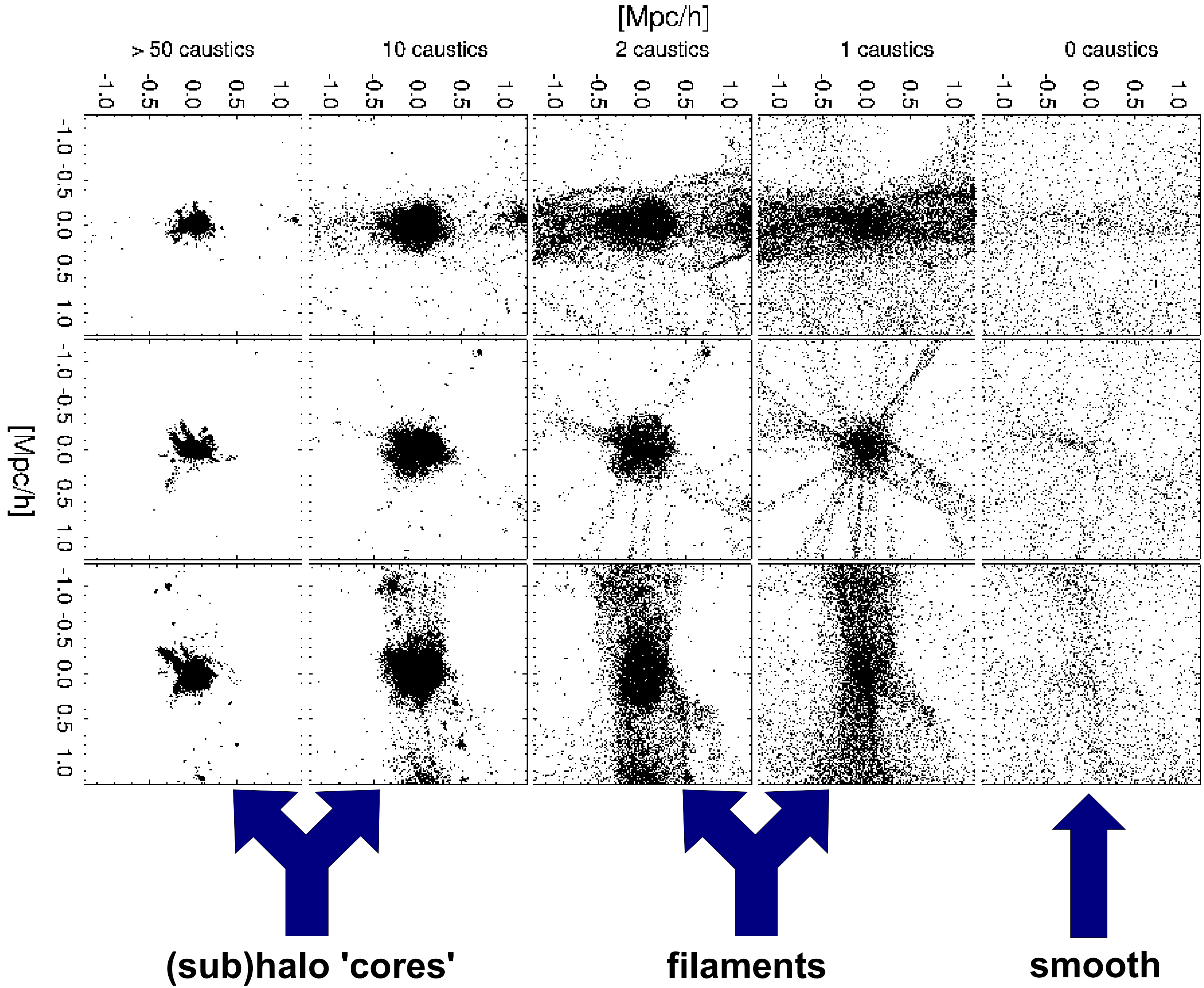




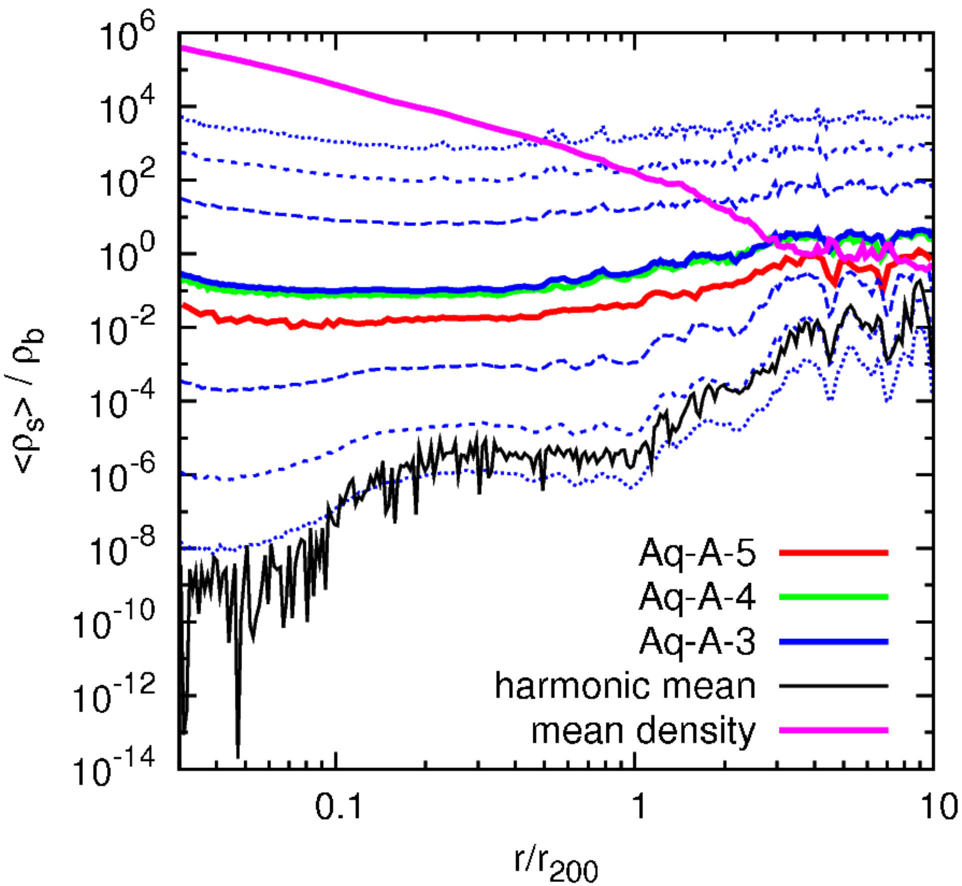
MV & White (in prep)

phase-space sheet
Wind-up around subhalo

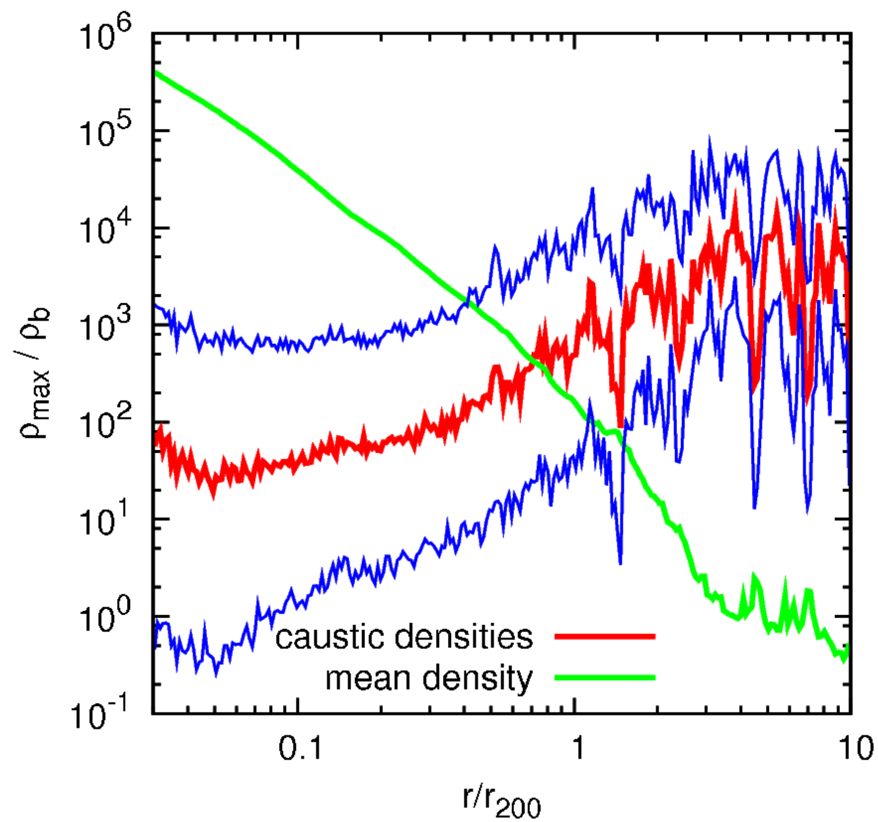
'Filtering' the cosmic web



Stream and caustic densities



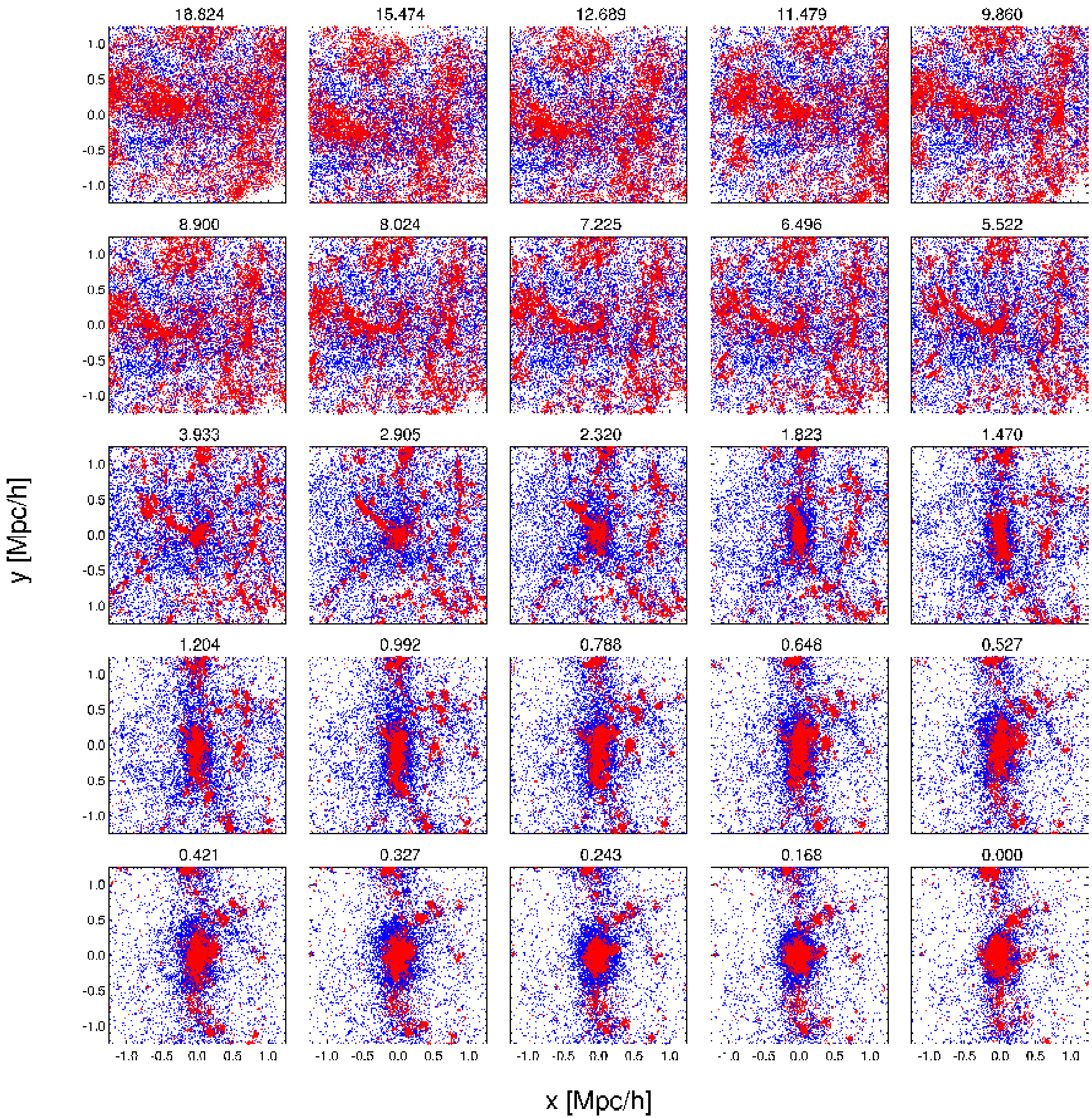
caustics subdominant
within virial radius



directly influences
annihilation radiation
due to caustics

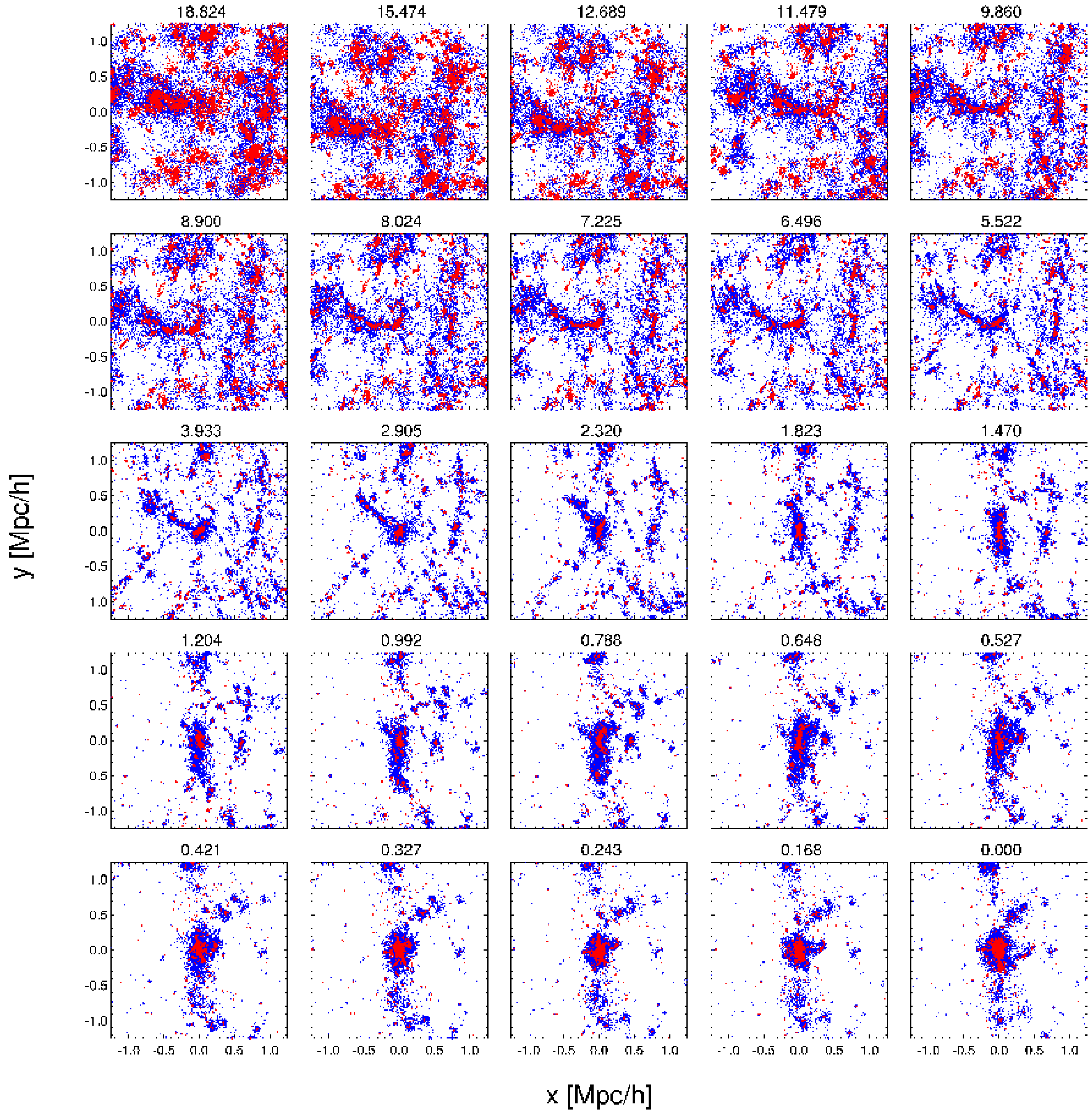
High/Low stream density particles

Where do they come from?

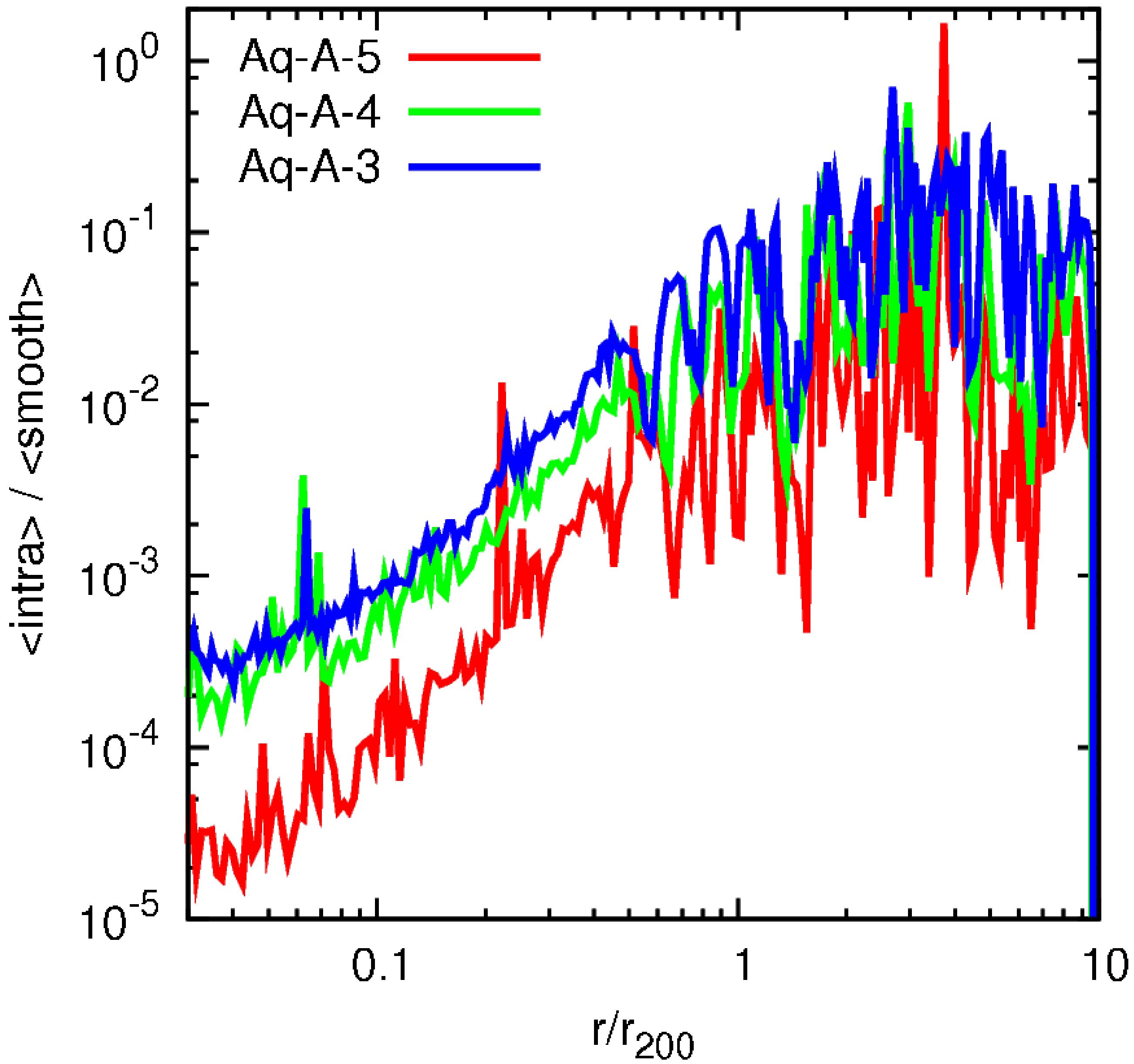


High/Low caustic counter particles

Where do they come from?



Local annihilation boost factor

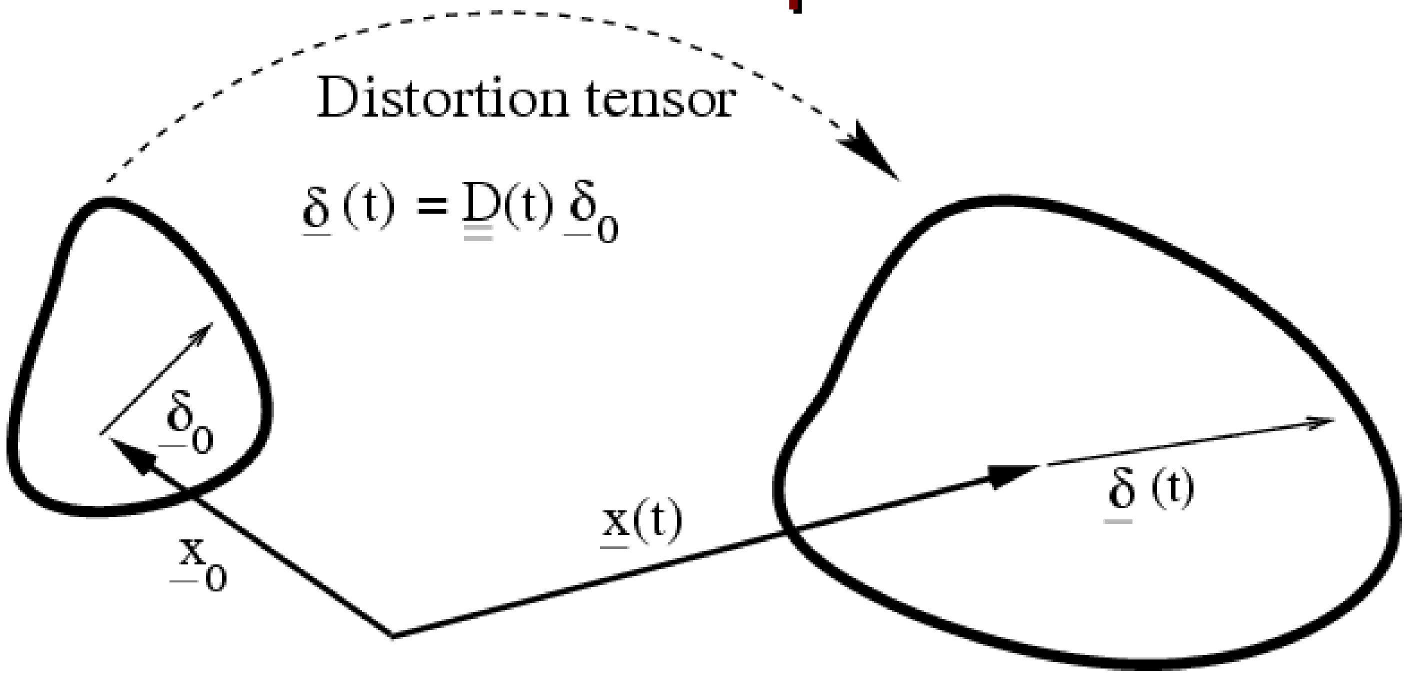


4) A note:Dynamics with the Geodesic Deviation Equation

The Geodesic Deviation Equation

$$\overline{\overline{D}}(t;\overline{x}_0) = \frac{\partial \overline{x}}{\partial \overline{x}_0}(t;\overline{x}_0)$$

$$\dot{\overline{\overline{D}}}(t;\overline{x}_0) = \overline{\overline{T}}(t;\overline{x}_0)\,\overline{\overline{D}}(t;\overline{x}_0)$$



phase-space tidal tensor

$$\overline{\overline{T}}(t;\overline{x}_0) = \begin{pmatrix} \underline{\underline{0}} & \underline{\underline{1}} \\ \underline{\underline{T}}(t;\underline{x}_0) & \underline{\underline{0}} \end{pmatrix}$$

projection to configuration space

projection operators:
phase-space to
configuration-space

$$\underline{\underline{D}}(t;\overline{x}_0) = \begin{pmatrix} \underline{\underline{1}} & \underline{\underline{0}} \end{pmatrix} \overline{\overline{D}}(t;\overline{x}_0) \begin{pmatrix} \underline{\underline{1}} \\ \underline{\underline{V}}_x(\overline{x}_0) \end{pmatrix}$$

initial CDM

sheet orientation

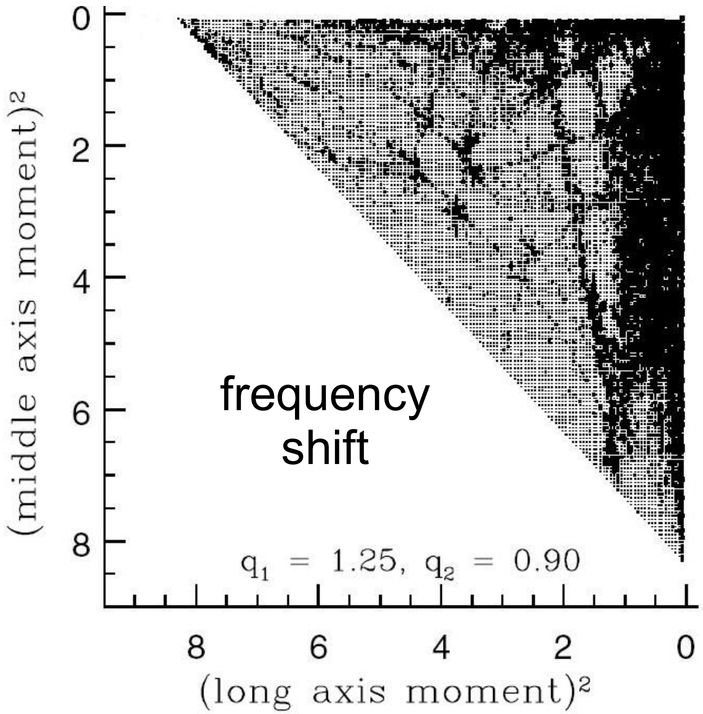
zeroth order perturbation theory
=> Hubble flow

CDM stream densitv:

$$\rho_{\mathrm{stream}}(t) \propto \frac{1}{\left|\det\left(\underline{\underline{D}}(t;\overline{x}_0)\right)\right|}$$

Properties:
- phase-space distortion tensor volume conserved
- configuration-space distortion tensor changes sign when passing through caustic

Chaos maps

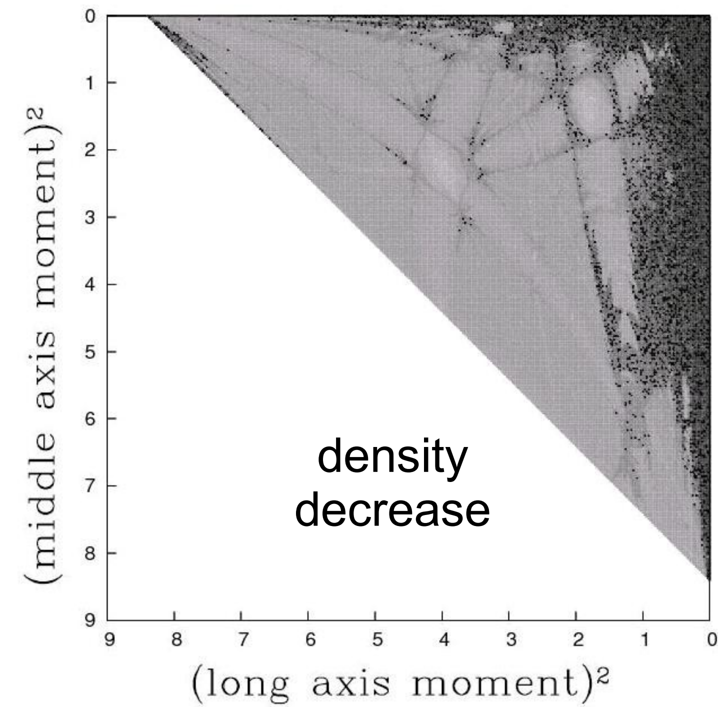


Papaphilippou & Laskar (1998)

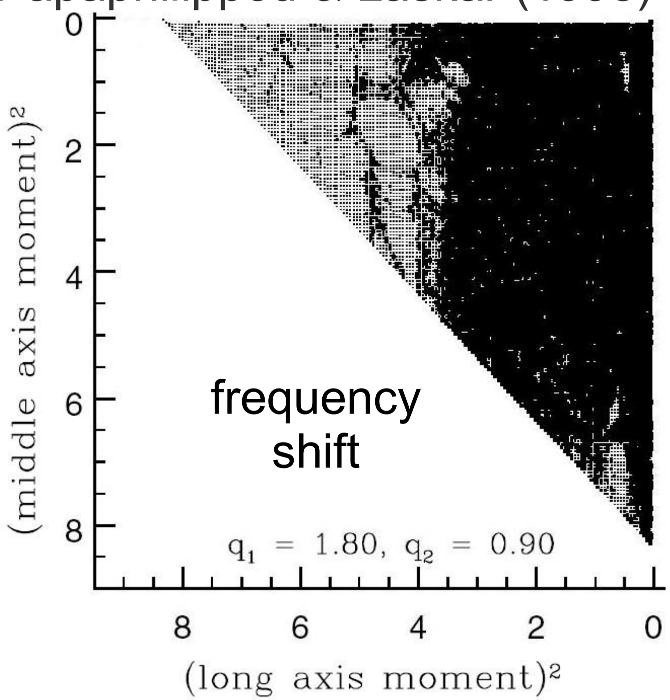
moderate triaxiality

↓

density mostly decaying like power law



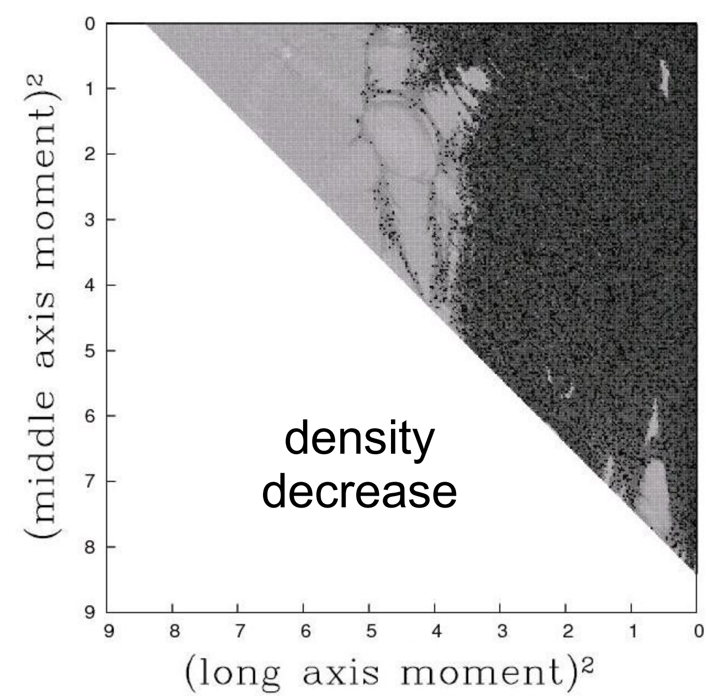
MV et al (2008)



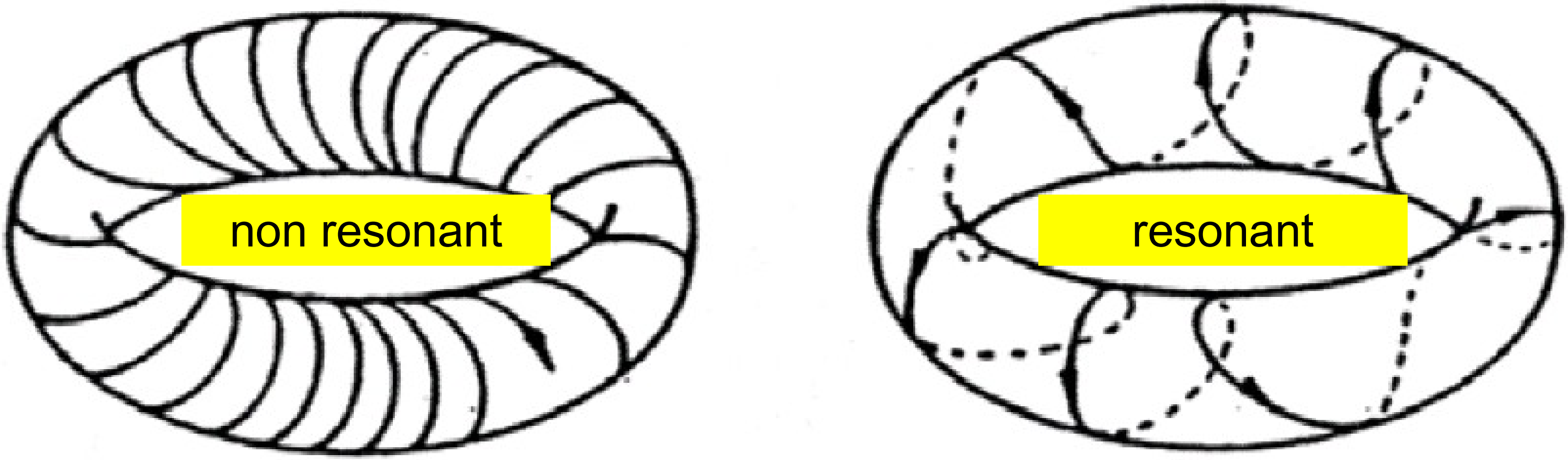
↓

large fraction of chaotic orbits

density mostly decaying
lots of faster than power law

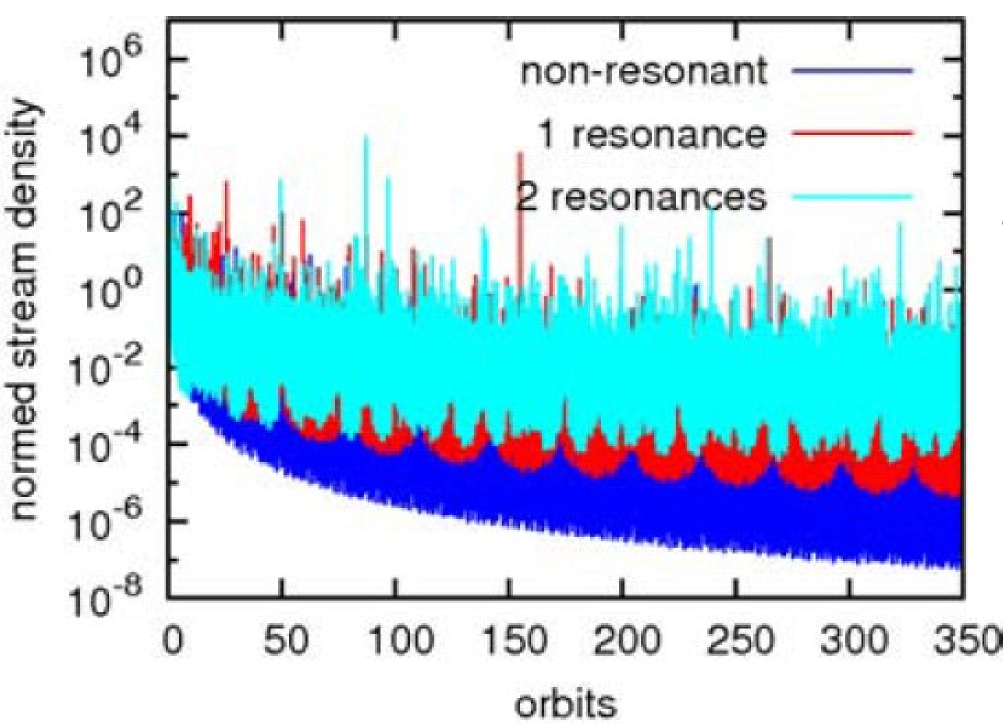


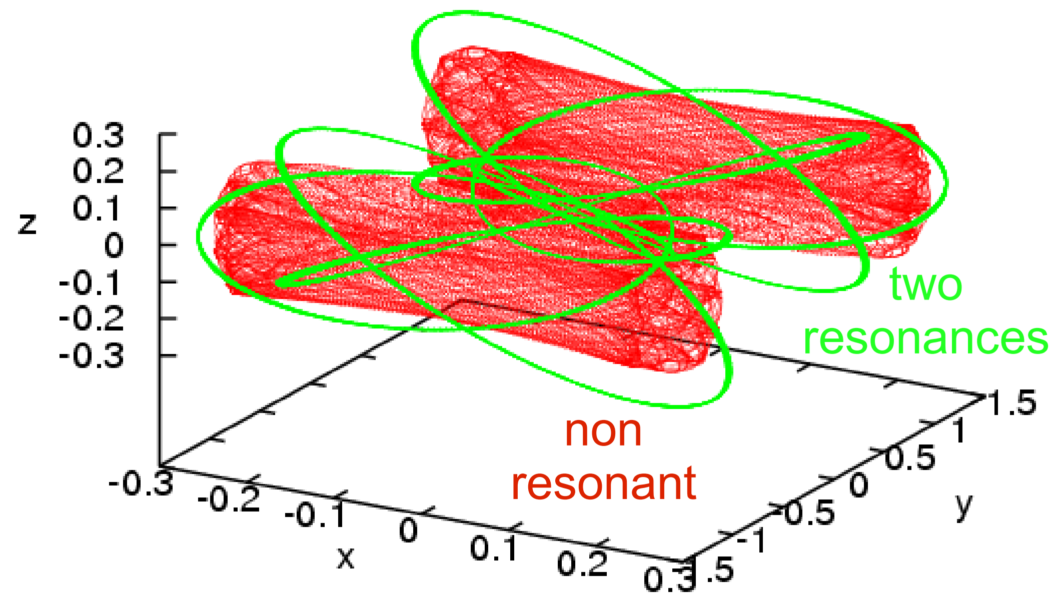
Resonances in phase-space



$$m_1 \omega_1 + m_2 \omega_2 + m_3 \omega_3 = 0$$

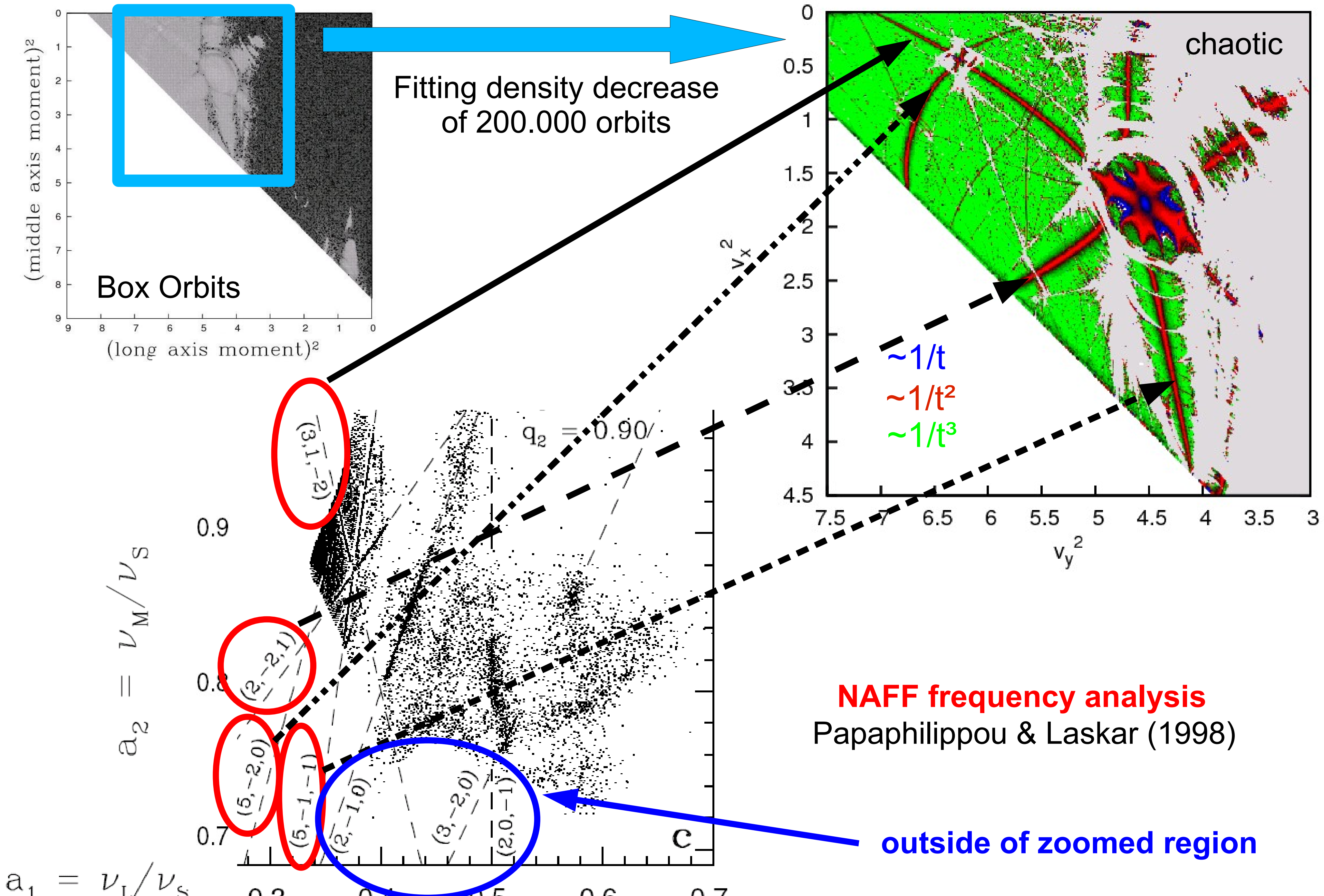
→ **KAM torus** not densely covered





configuration-space

Resonances: scanning phase-space



NAFF frequency analysis

Papaphilippou & Laskar (1998)

Conclusions

- ~100 streams near the Sun [wrong] [~millions due to faster mixing]
- massive caustic structures [wrong] [non-regular fine-grained phase-space]
- 1D models predict fine-grained phase-space [wrong] [missing instabilities]
- simulations miss much caustic annihilation [wrong] [~10% in outskirts]

The smooth halo model is not too bad!