The Hunt for Dark Matter
- Insights from N-body Simulations -

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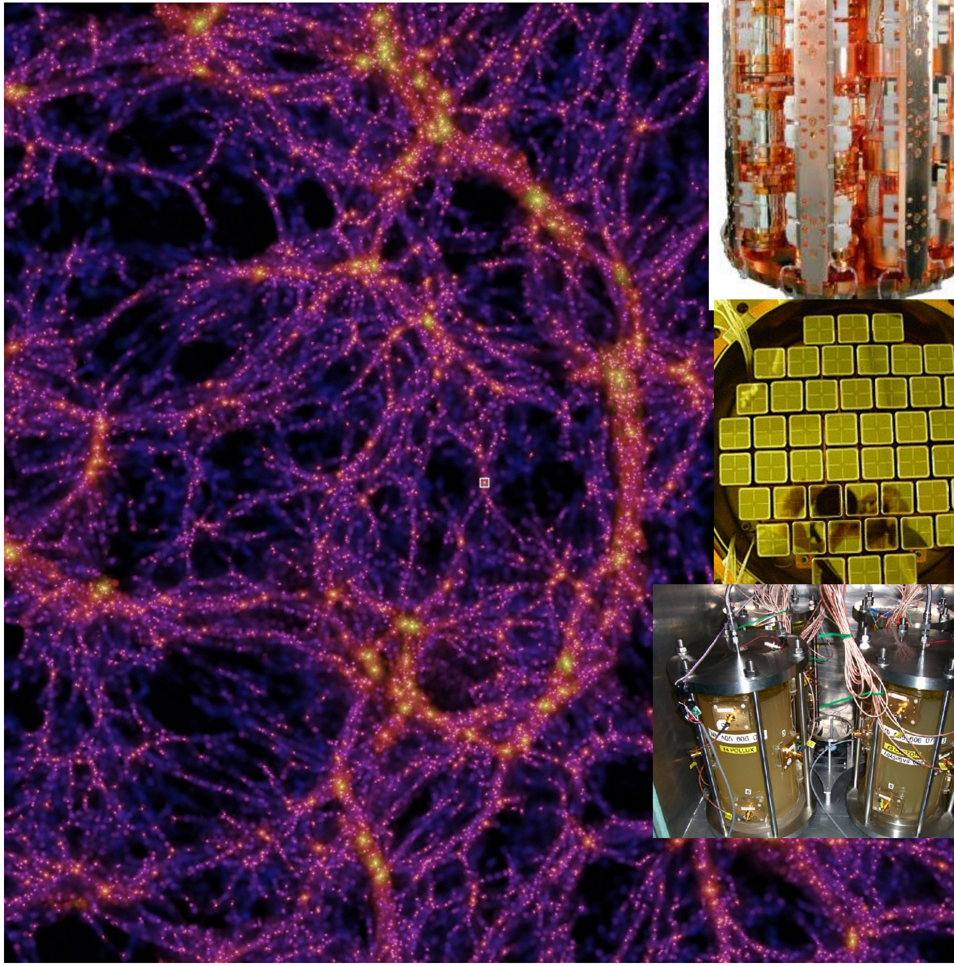
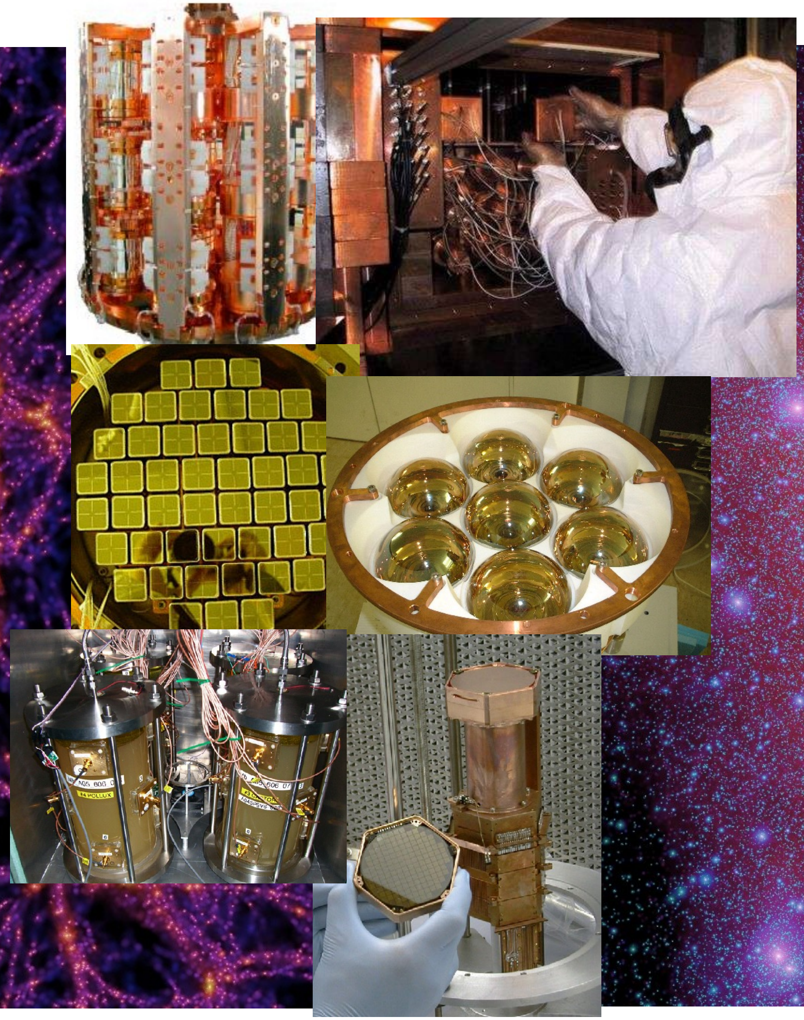




Outline

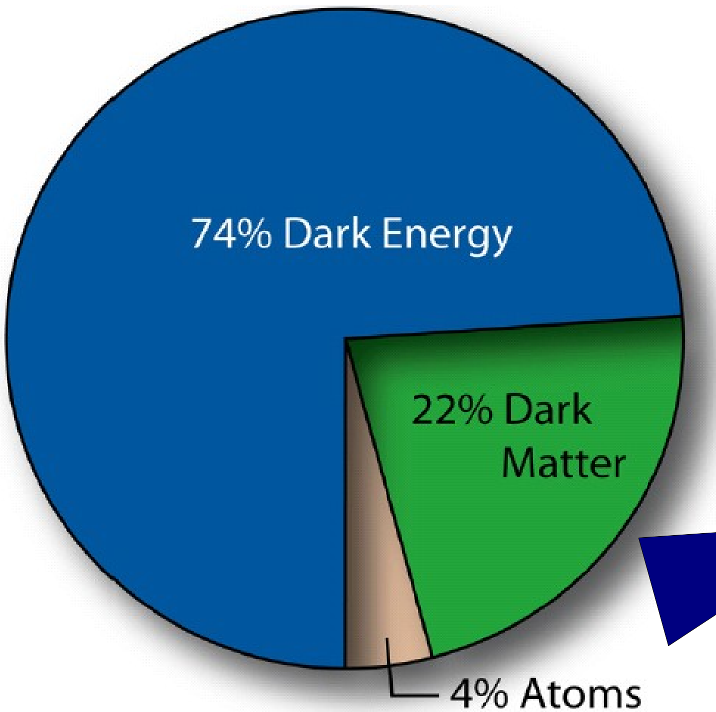
Introduction - Hunting for Dark Matter

High resolution N-body simulations

Local CDM phase-space structure

Very-small-scale CDM phase-space structure

ΛCDM – the current standard



Possible dark matter candidates:

WIMPs, axions.

Searching for dark matter

DIRECT

INDIRECT

Fermi
Gamma-ray Space Telescope

The Hunt for Dark Matter
- Direct Detection -

WIMP searches: nuclear recoil events

Axion searches: axion-photon conversion

***Usually* assumed astrophysical input:**

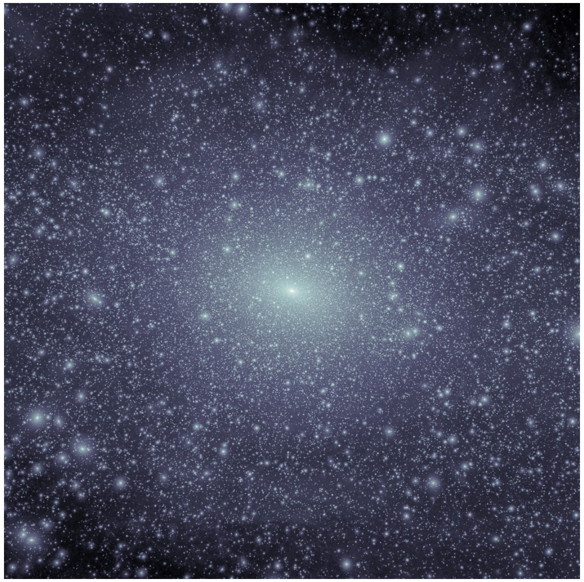
Density: ~0.3 GeV / c^2 / cm^3

Velocity: Maxwellian

Standard Halo Model (SHM):

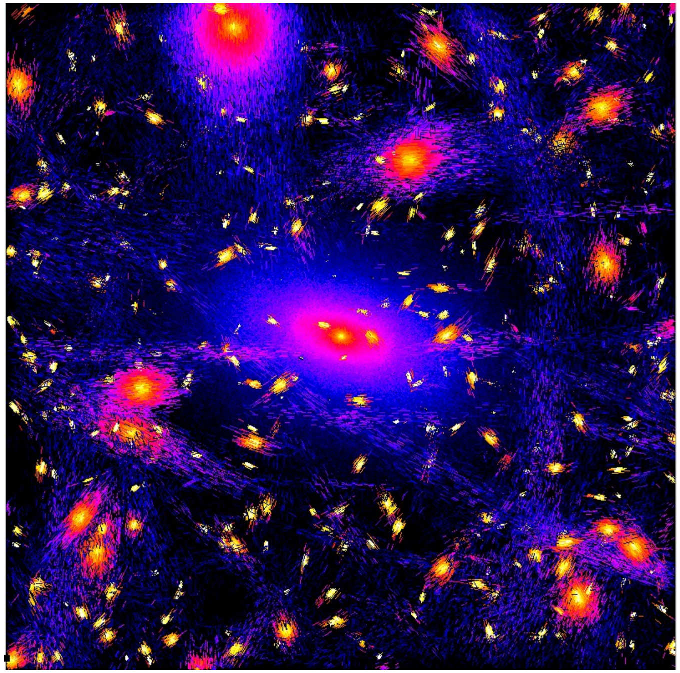
- **Smooth mass distribution**
- **Smooth velocity distribution**
- **“Featureless” phase-space**

"Non-standard" Halo models

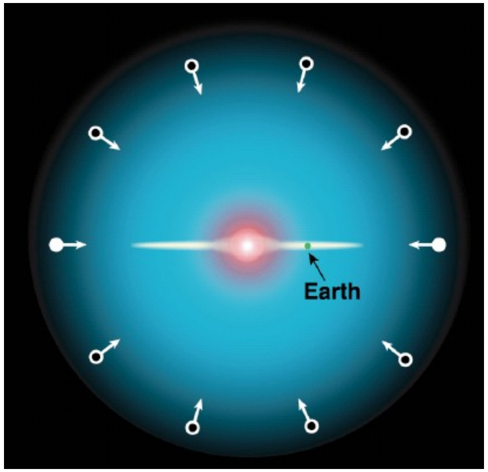


Diemand et al, Nature (2008)

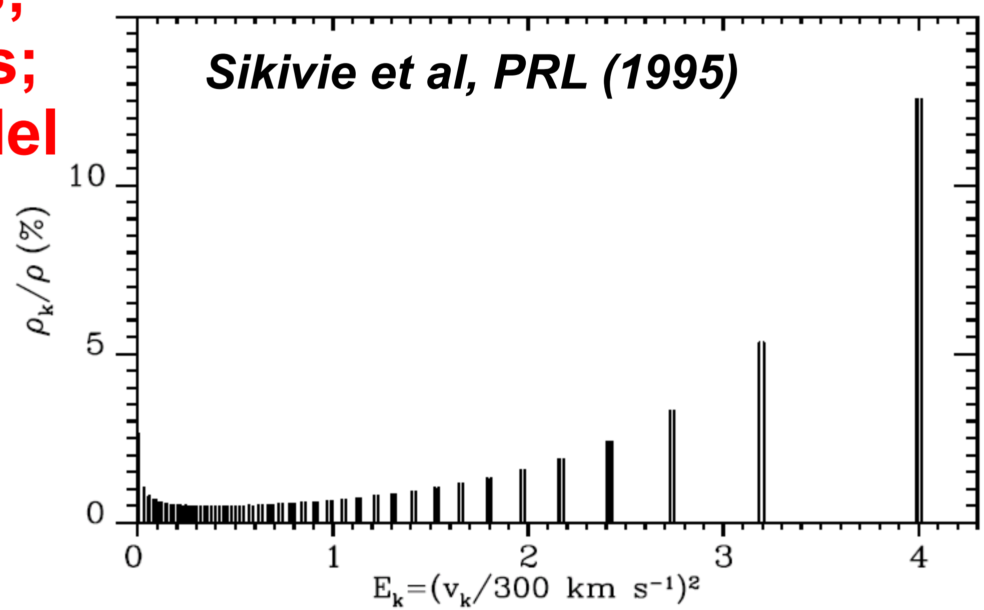
N-body simulations predict lots of phase-space substructure



Analytic models; massive streams; Caustic ring model



Van Bibber, IDM (2008)



Arising questions

Q1: How smooth is the dark matter mass distribution at the solar position?

Q2: How smooth is the dark matter velocity distribution at the solar position?

Q3: Does the halo formation process leave “observable” imprints?

How to answer these questions?

- DM phase-space on smallest scales
- in highest non-linear regime

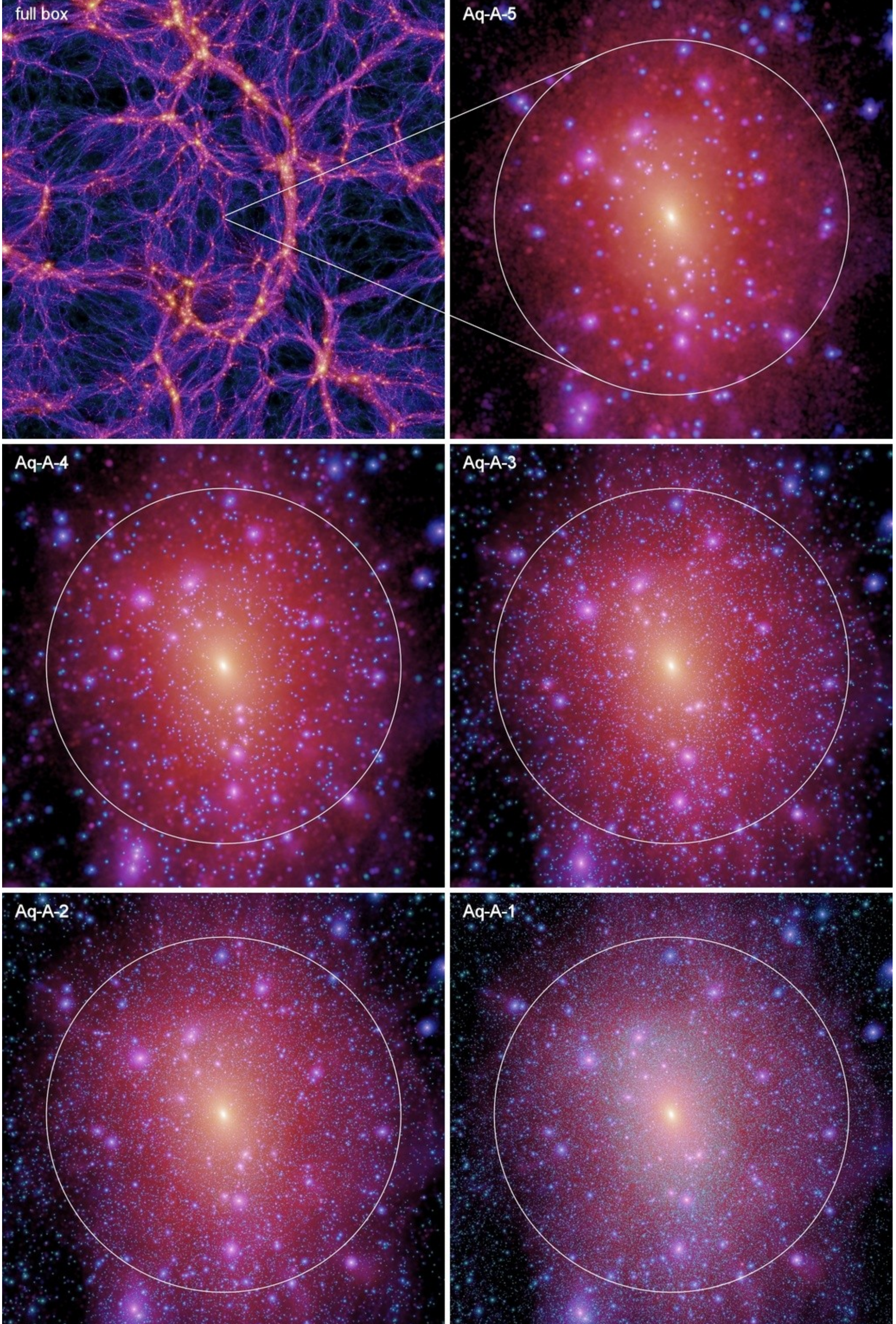
The Aquarius Project

- a large-scale collaborative program of the Virgo Consortium -

Springel et al, Nature (2008)

Springel et al, MNRAS (in press)

Navarro et al, MNRAS (submitted)



High resolution simulations of Milky Way-like Dark Matter haloes

a one billion particle halo with two goals in mind:

quantity

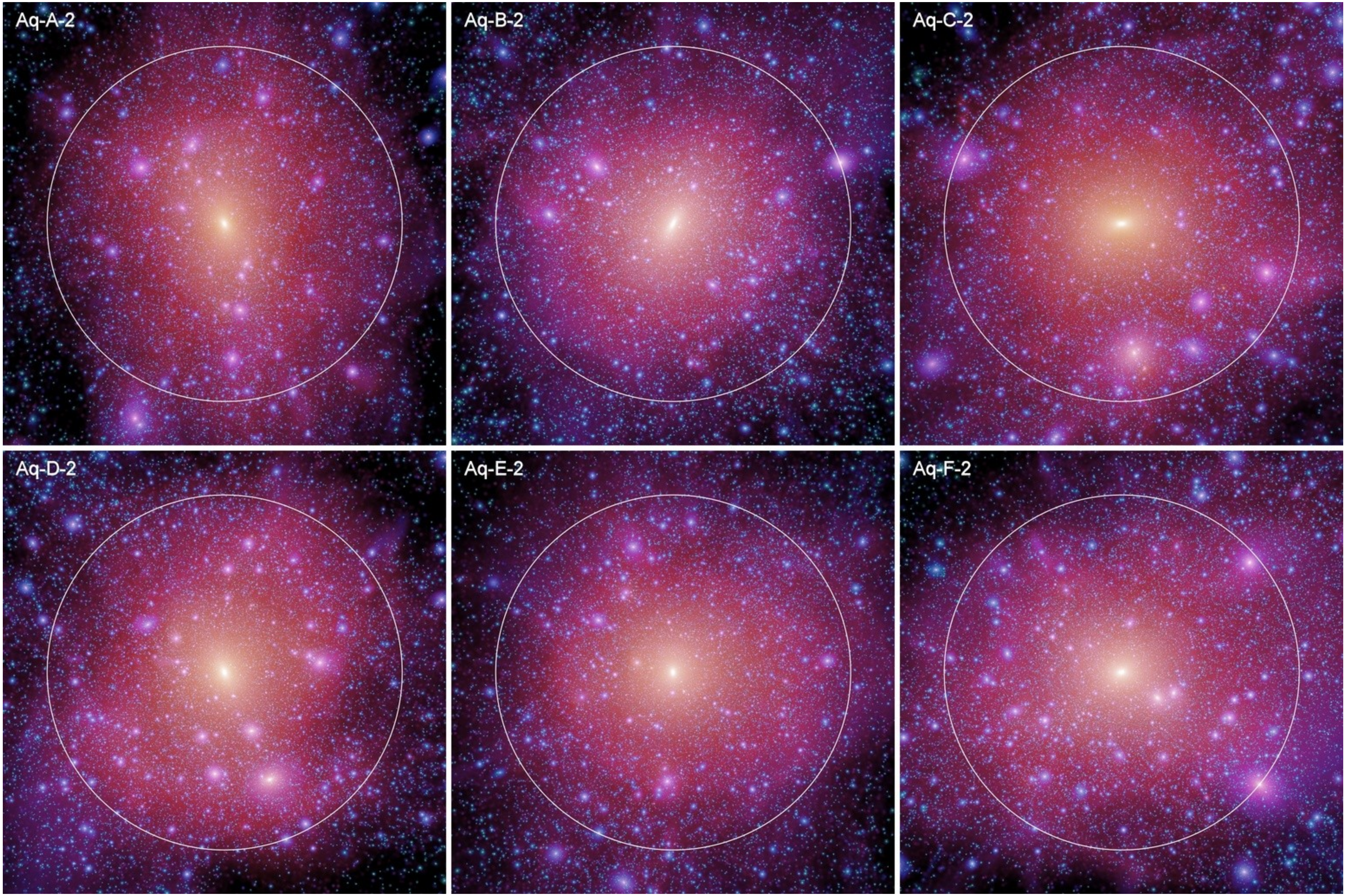
AND

quality

m_p $[M_\odot]$	ϵ [pc]
1.712×10^3	20.5
1.370×10^4	65.8
4.911×10^4	120.5
3.929×10^5	342.5
3.143×10^6	684.9

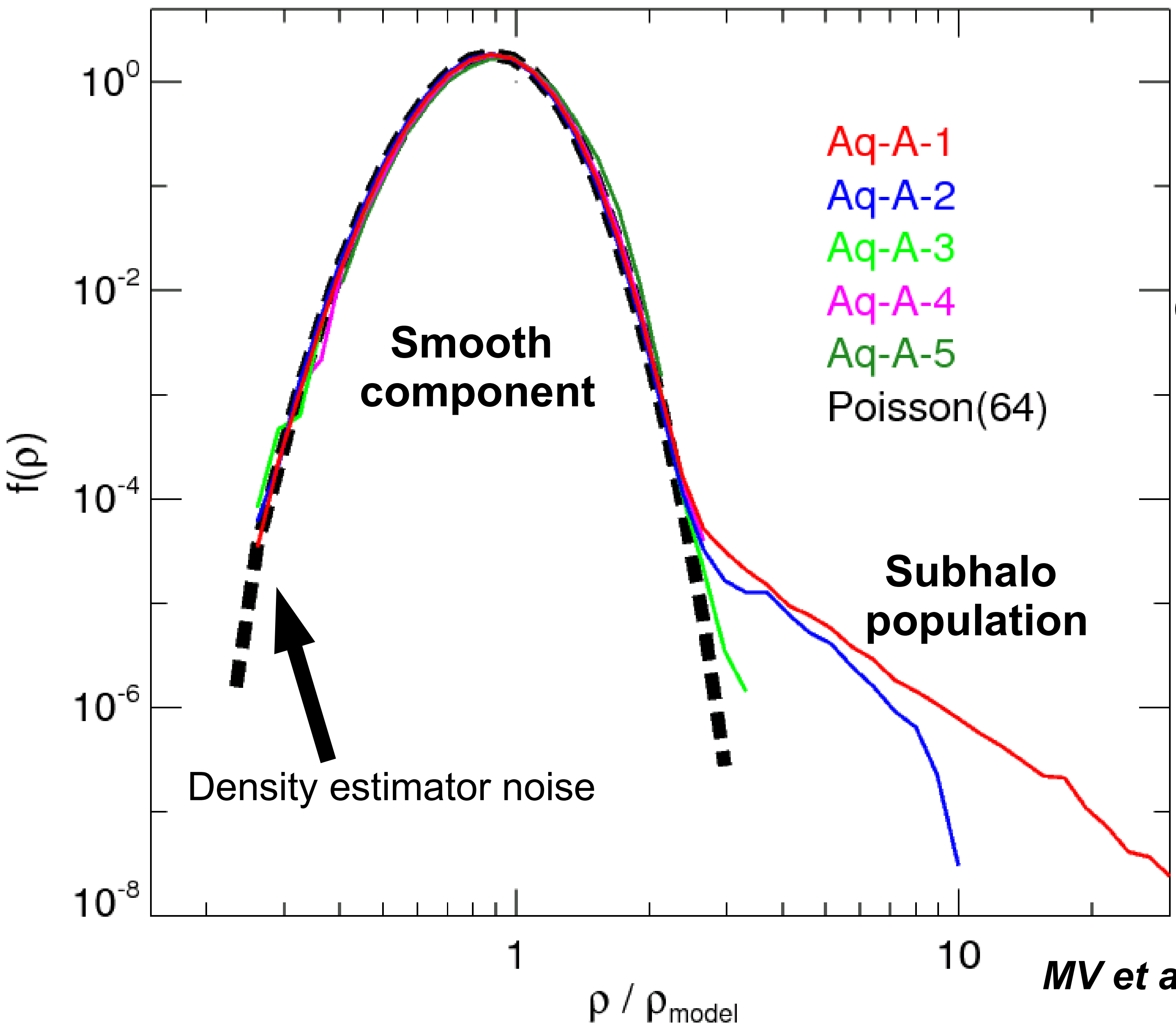
http://www.mpa-garching.mpg.de/aquarius

[further information, pictures, movies]



Object-to-Object scatter ?!

Q1: Density PDF convergence

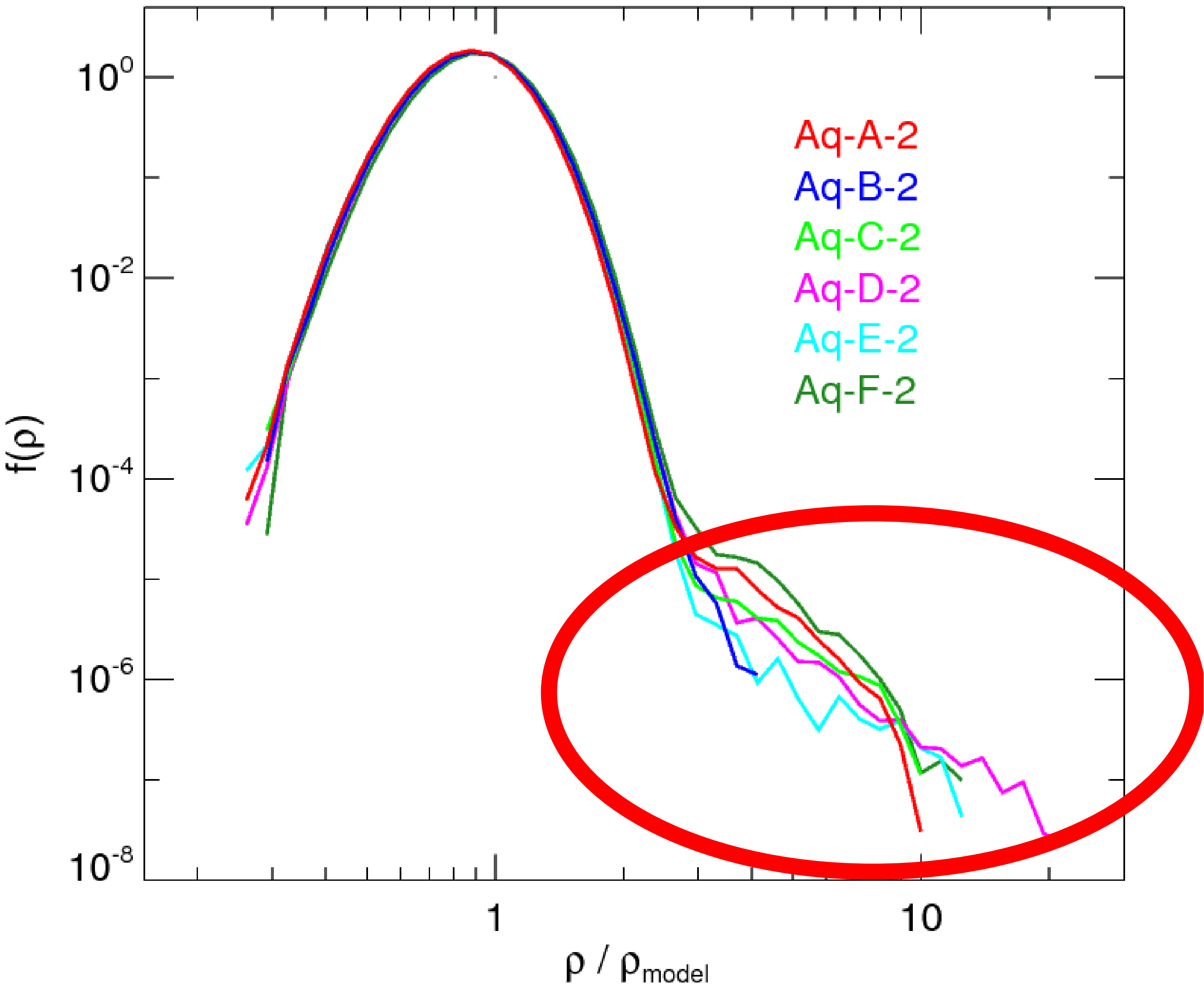


Density probability distribution function around solar circle

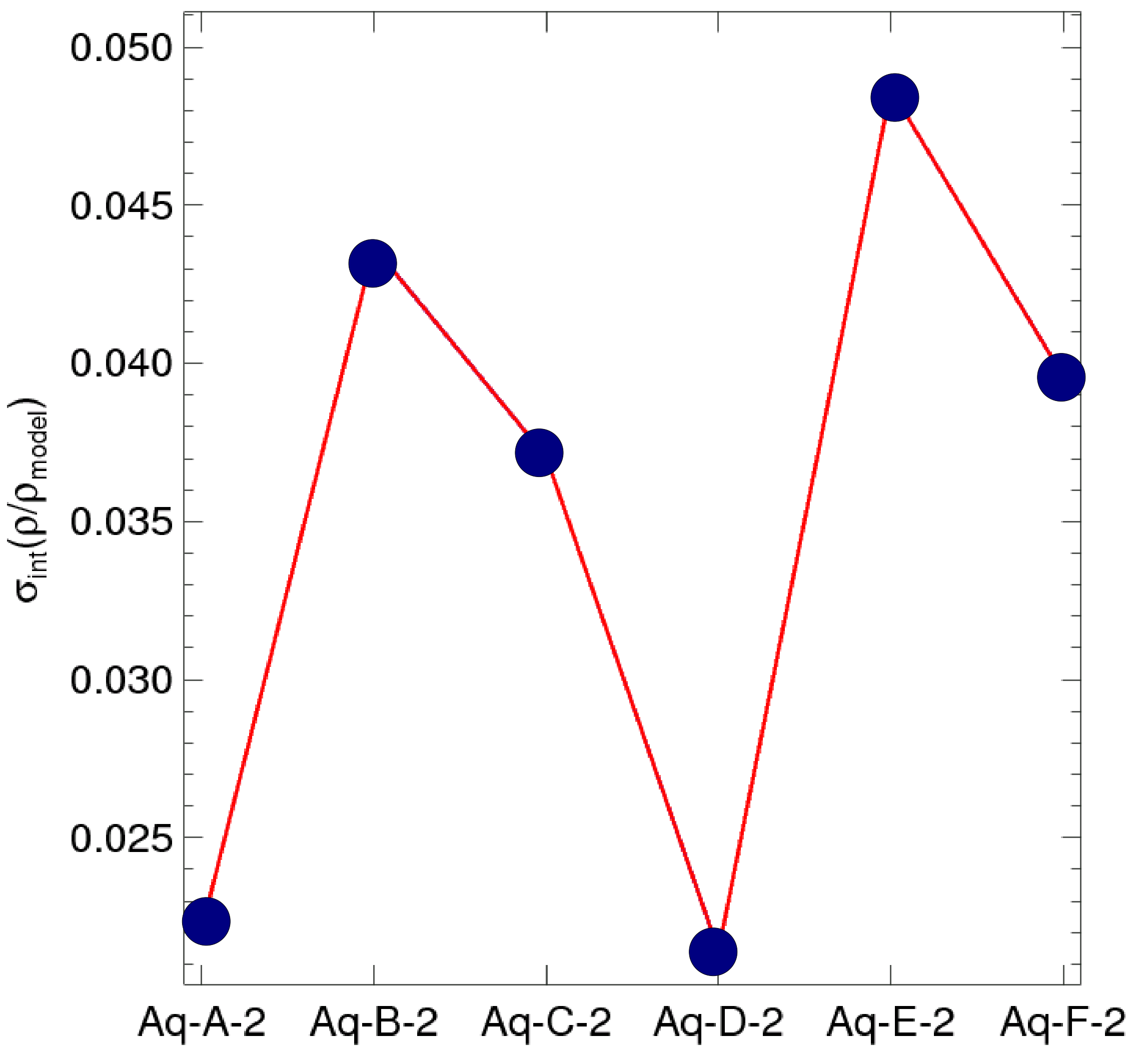
MV et al, MNRAS (submitted)

Q1: Density PDF: object-to-object scatter

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



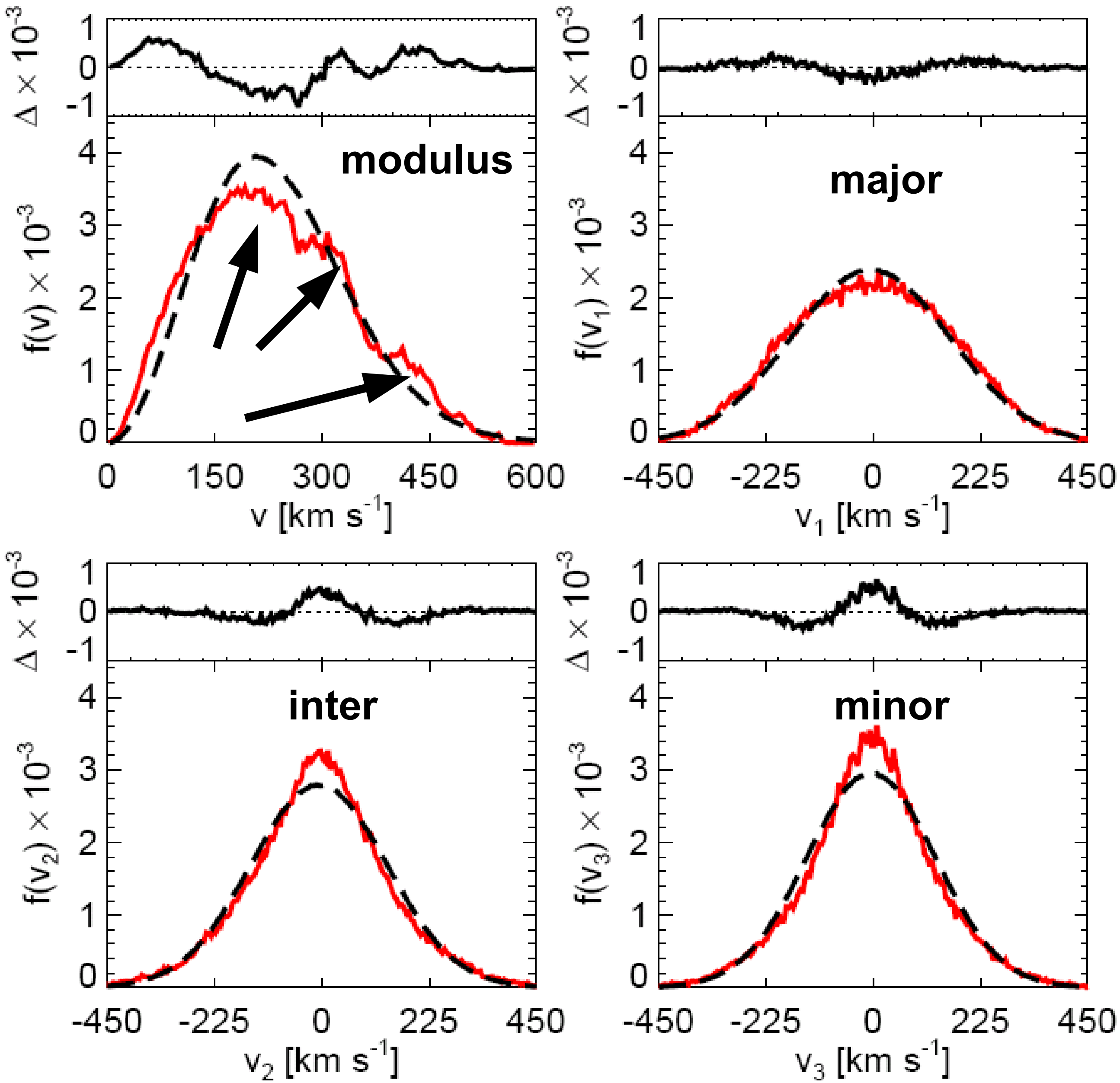
Q1: Intrinsic density fluctuations



Scatter standard deviation < 5%

Experimentalists can use smooth models

Q2: Velocity vector components



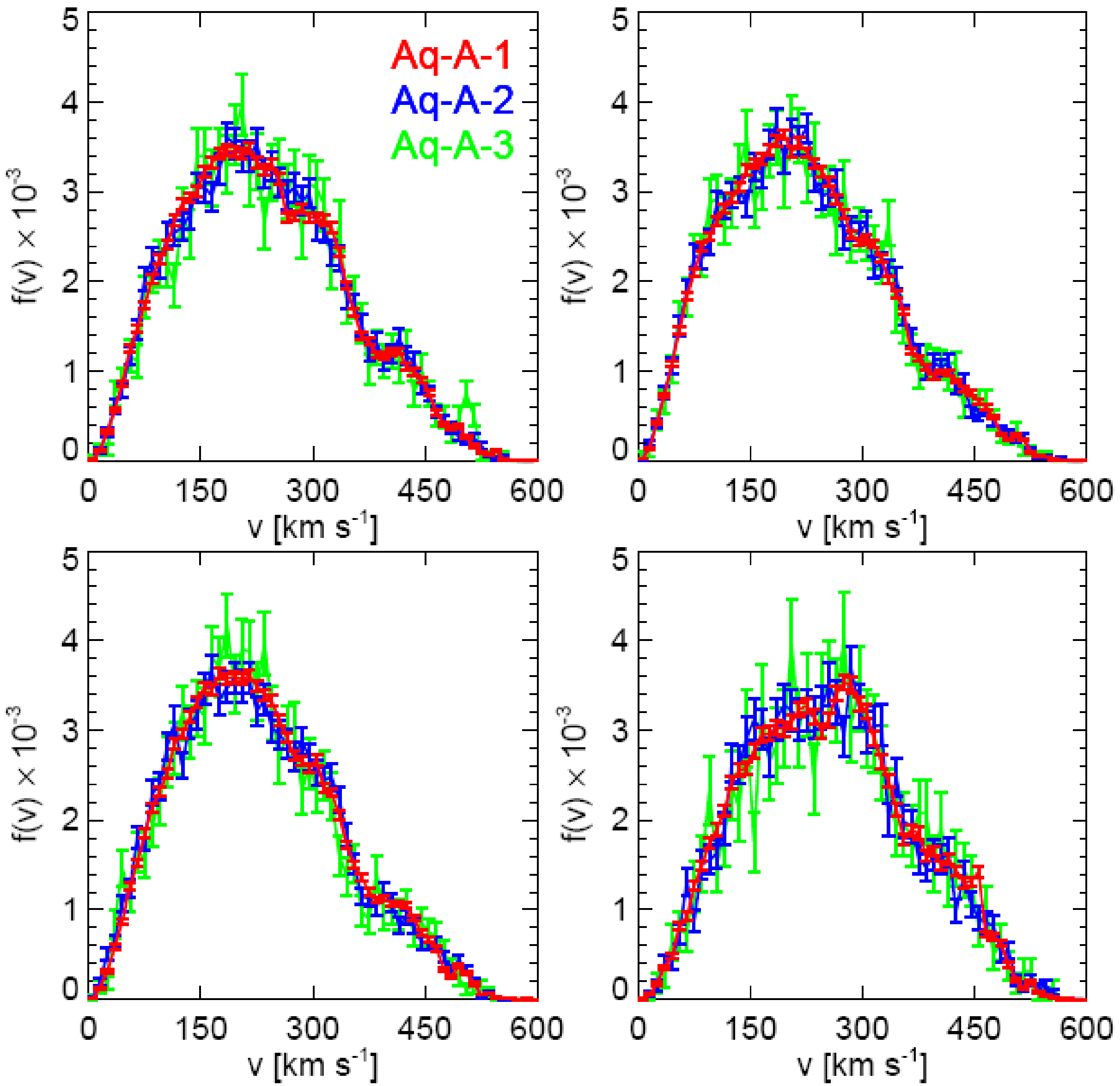
Velocity distribution in a 2kpc box at solar circle

No signs for distinct/massive streams

Bumps/dips in velocity vector modulus

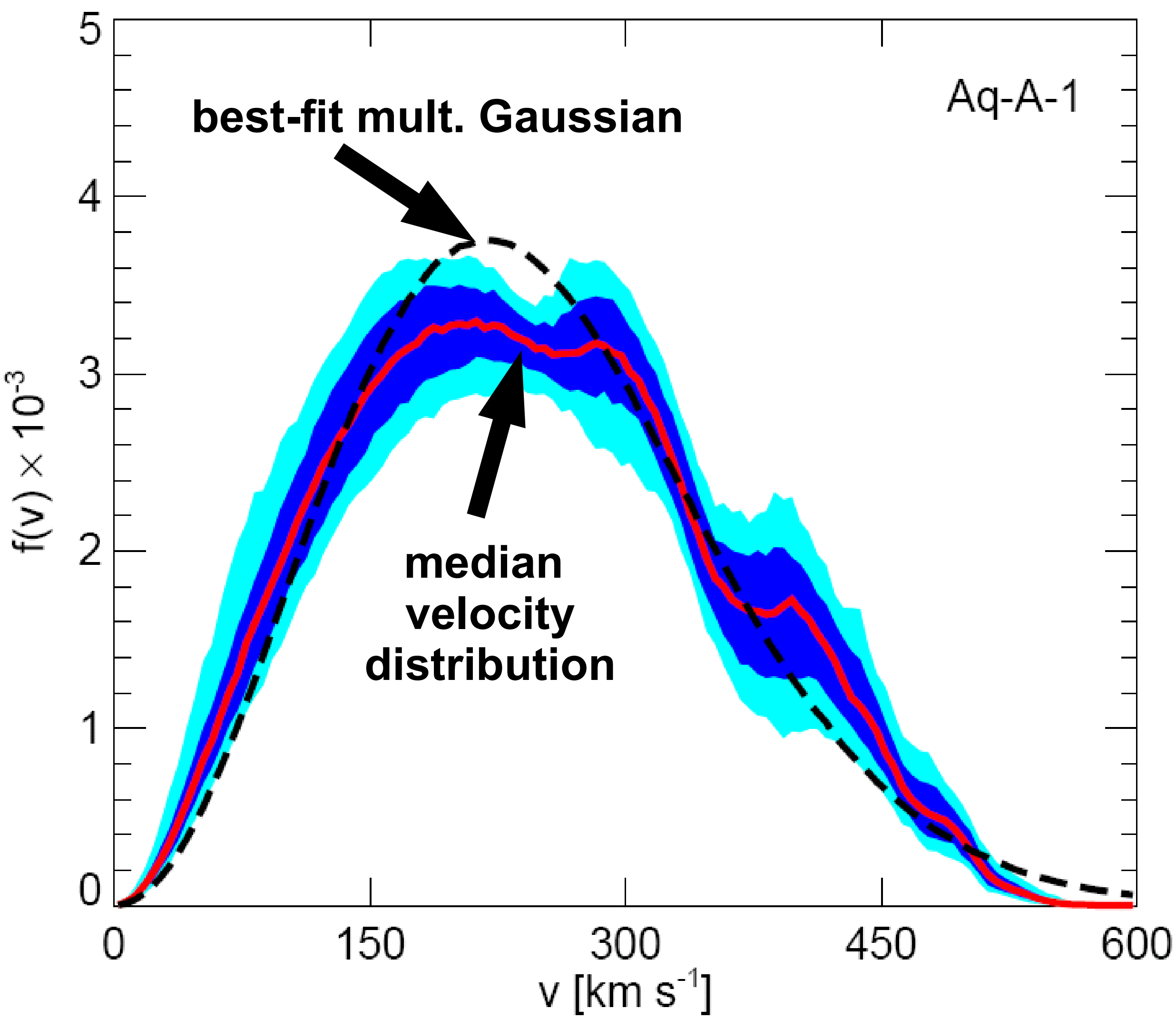
Q2: Convergence of the modulus

Velocity distribution at
<u>different positions</u>
and
<u>different resolutions</u>



Features in velocity distribution converge

Q2: Modulus at different locations



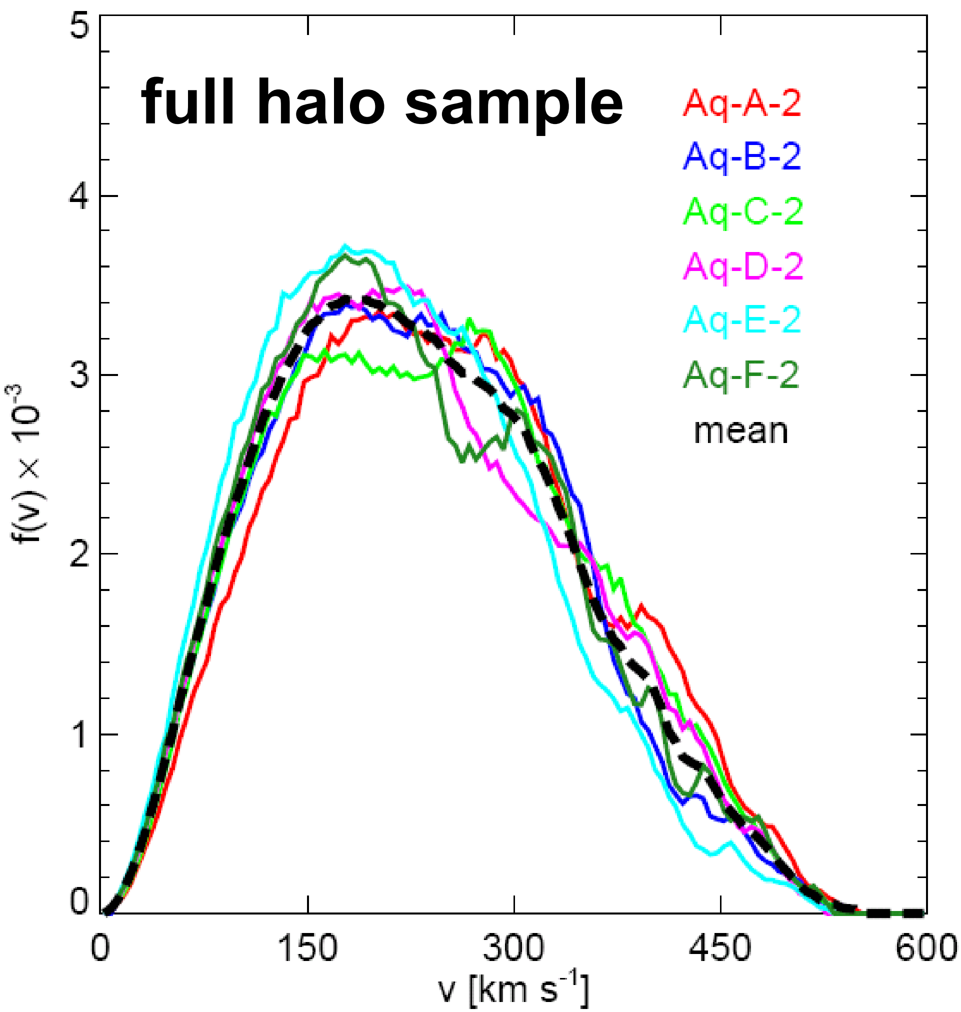
Velocity distribution:
<u>many</u> 2kpc boxes

Bumps in velocity modulus at ~the same velocity

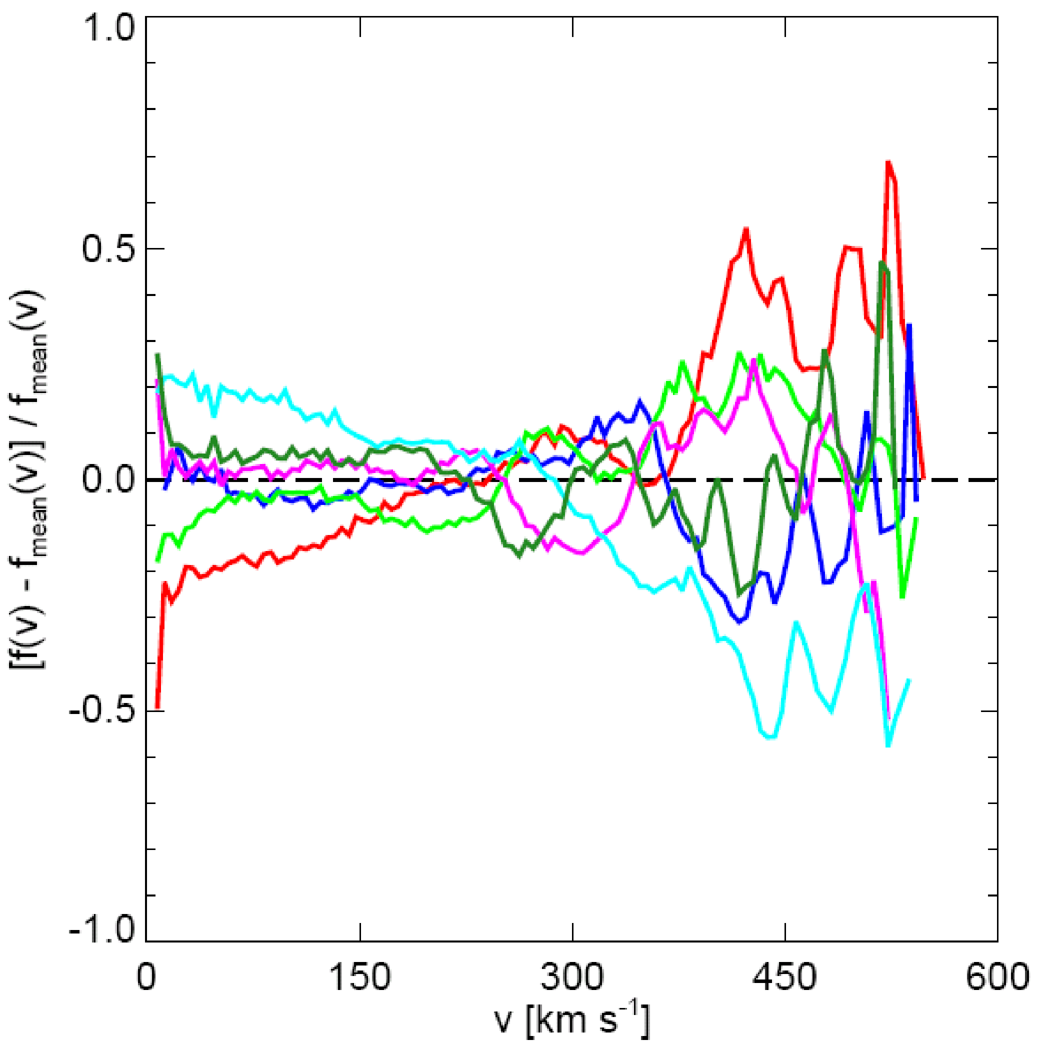
Not Maxwellian

Not exactly multivariate Gaussian

Q2: Mean velocity distribution

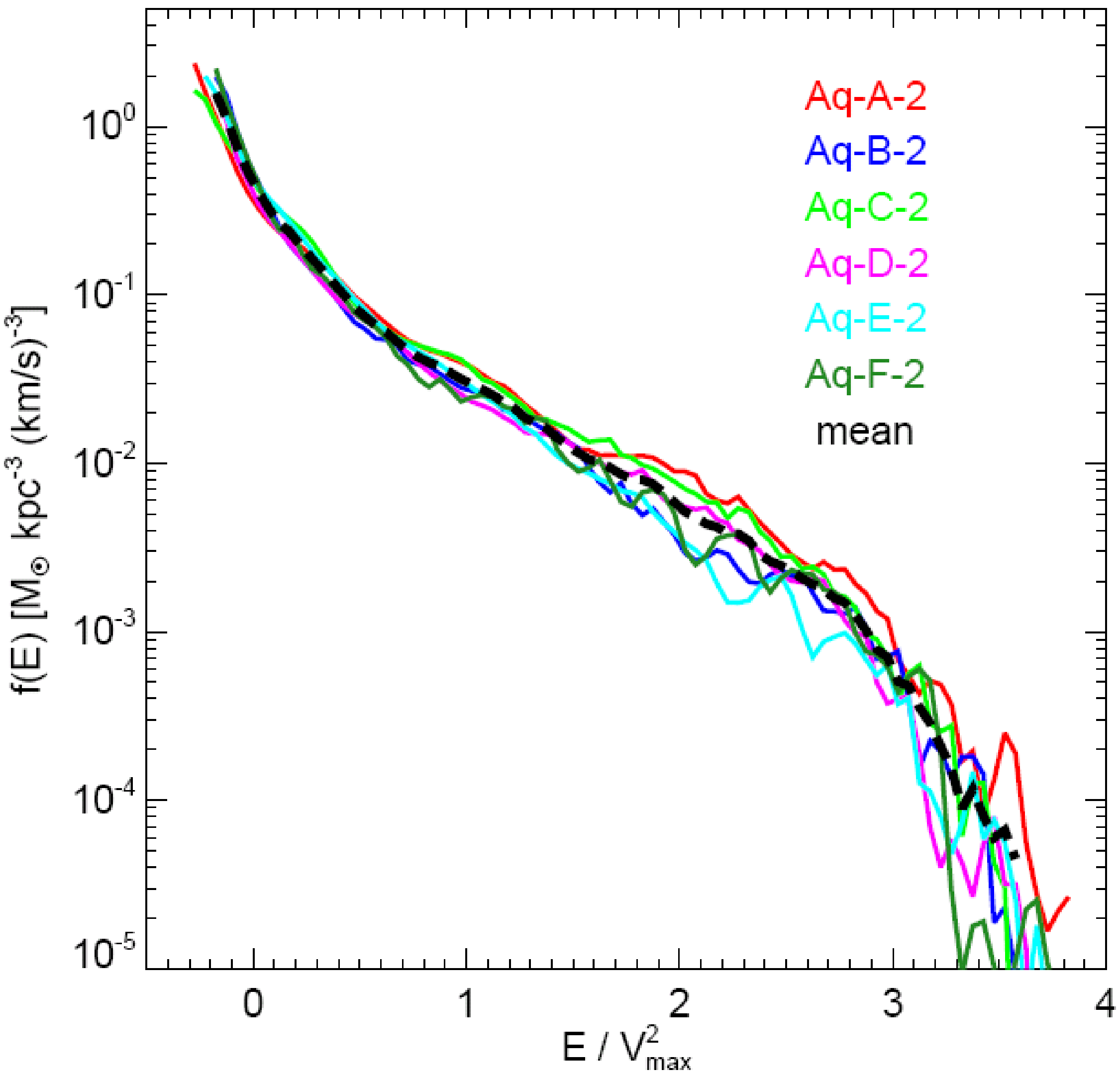


mean velocity distribution



relative deviations:
larger at high velocities

Q3: Local Phase-space density



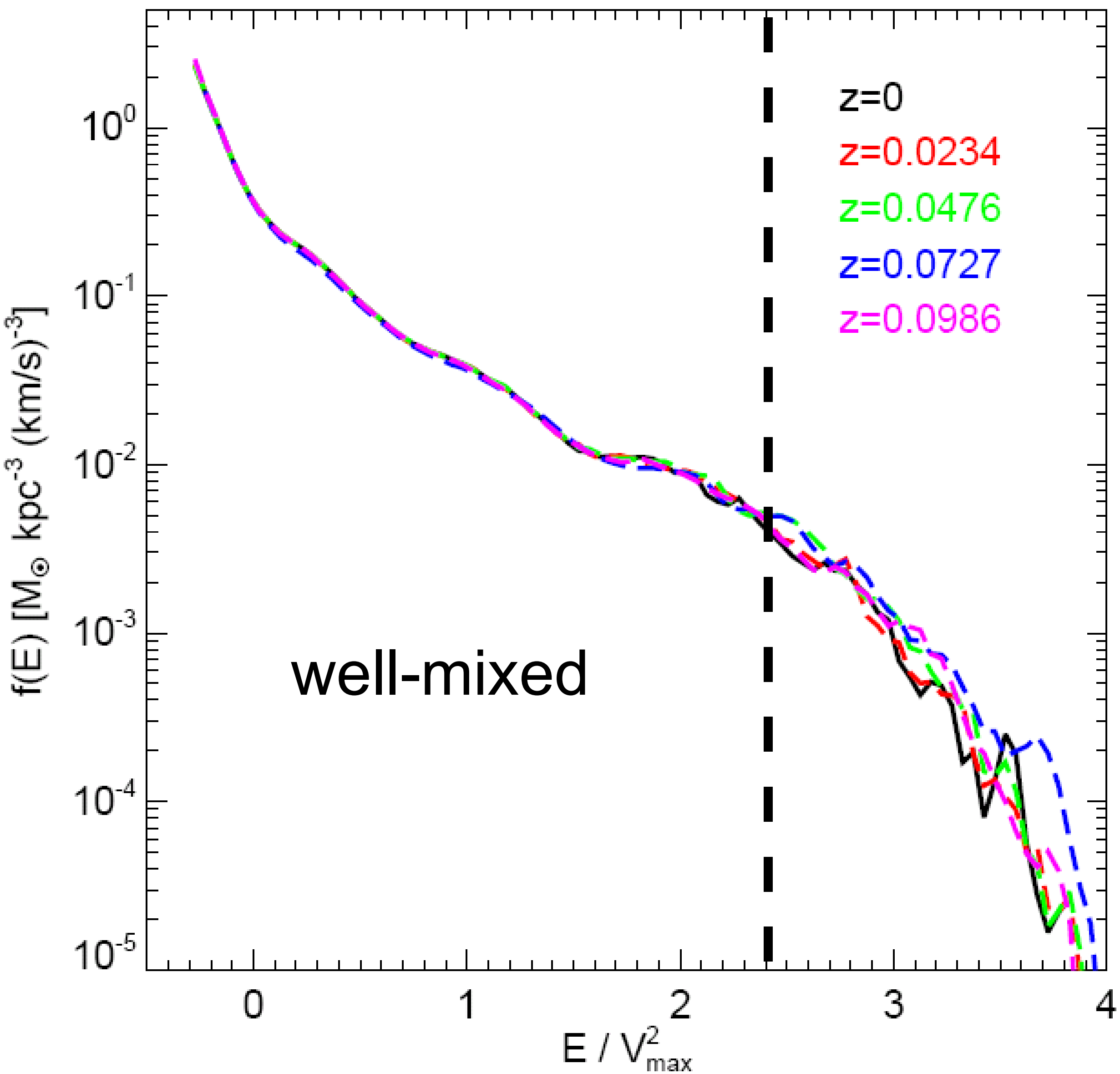
$$f(E) = \frac{\mathrm{d}M}{\mathrm{d}E} \frac{1}{g(E)}$$

Density of states

Nearly universal shape at high binding energy

Large fluctuations at lower binding energies

Q3: Phase-space density time evolution



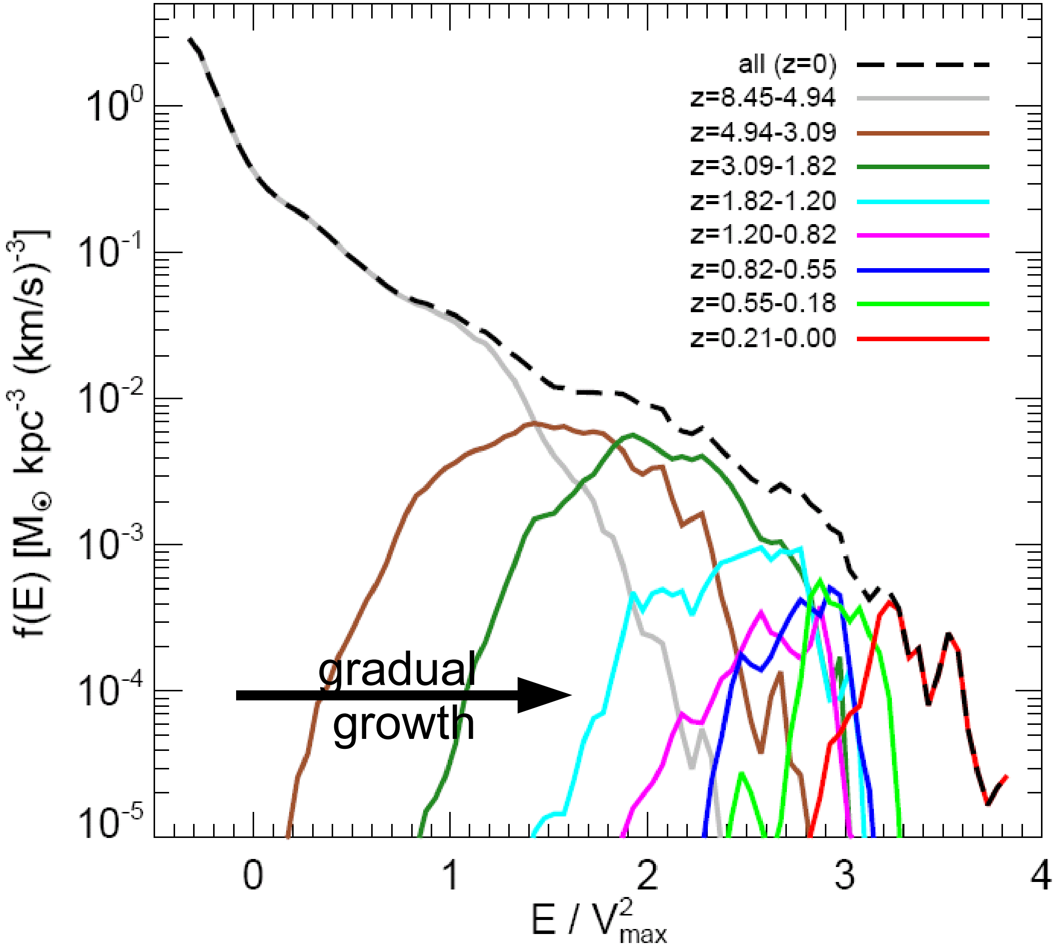
z=0.1 → z=0

Fluctuations in less bound part

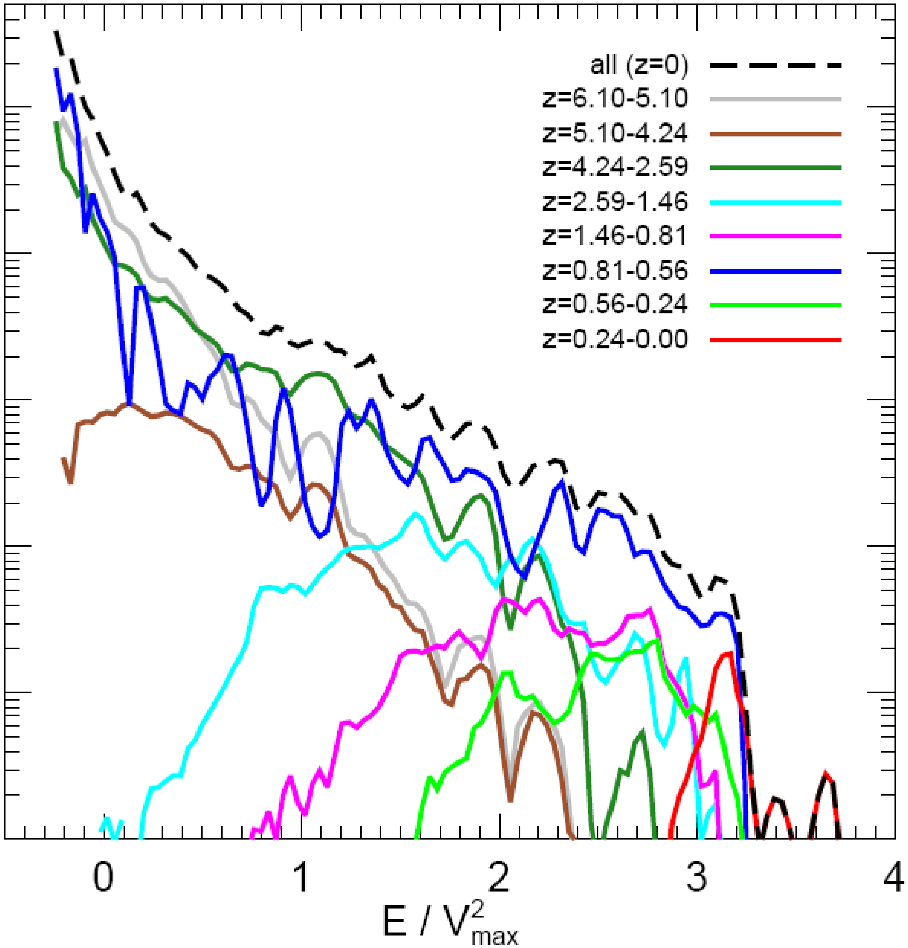
Features in most bound part are stable

Q3: Phase-space density accretion history

“quiet” formation history



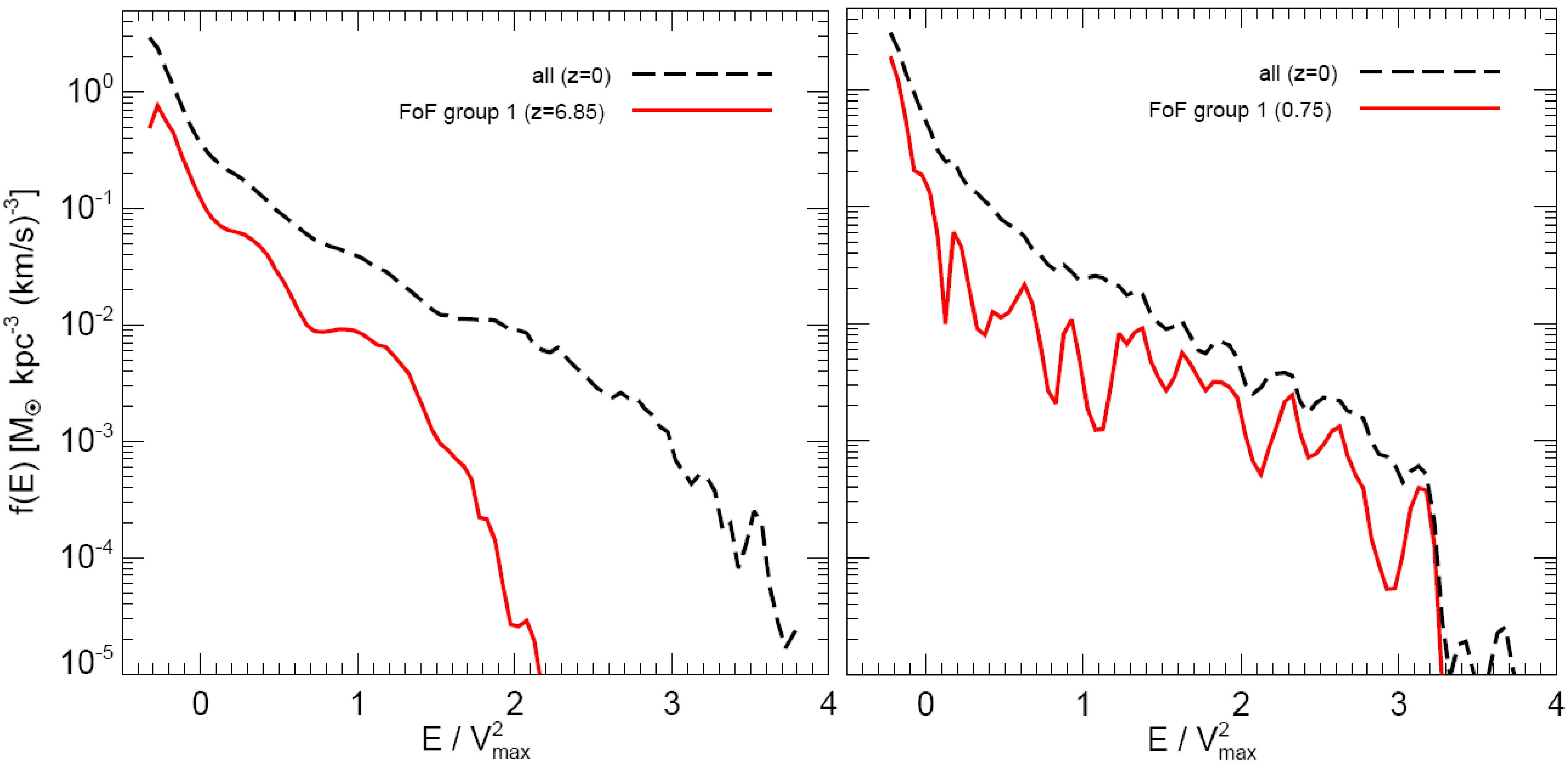
“active” formation history



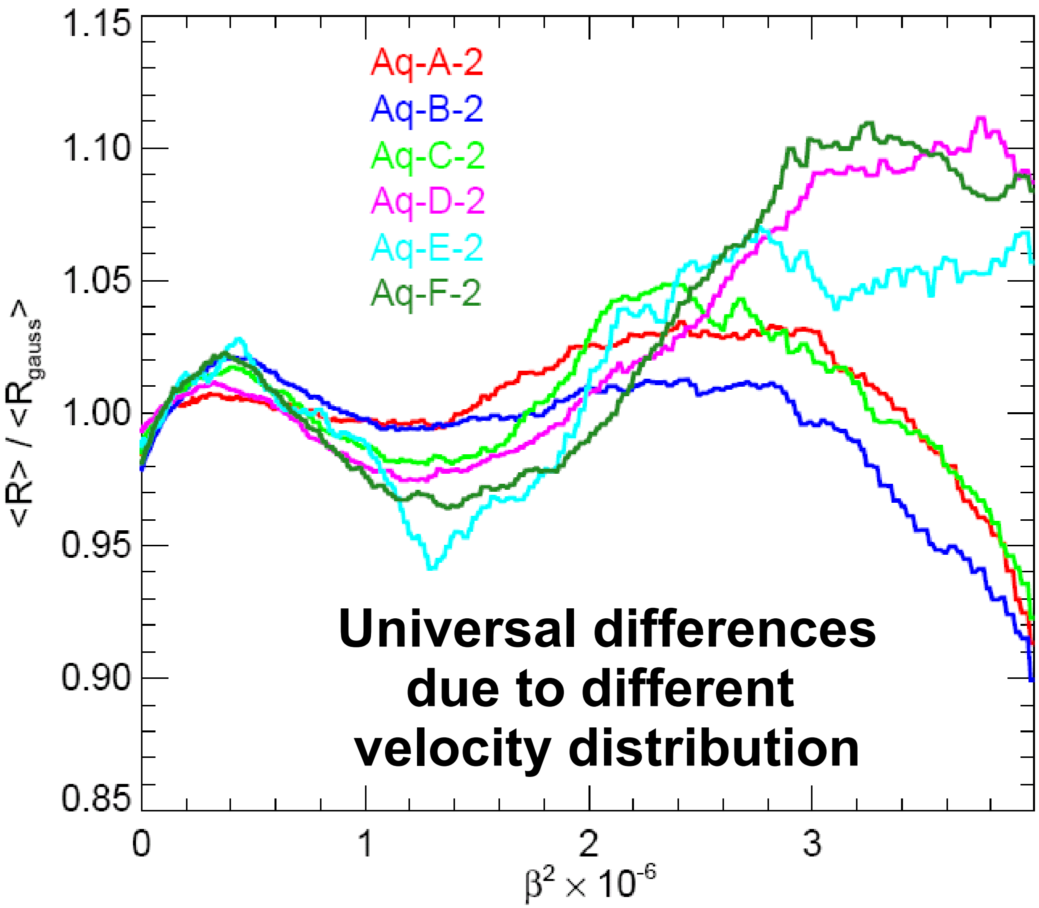
Q3: Influence of single merger events

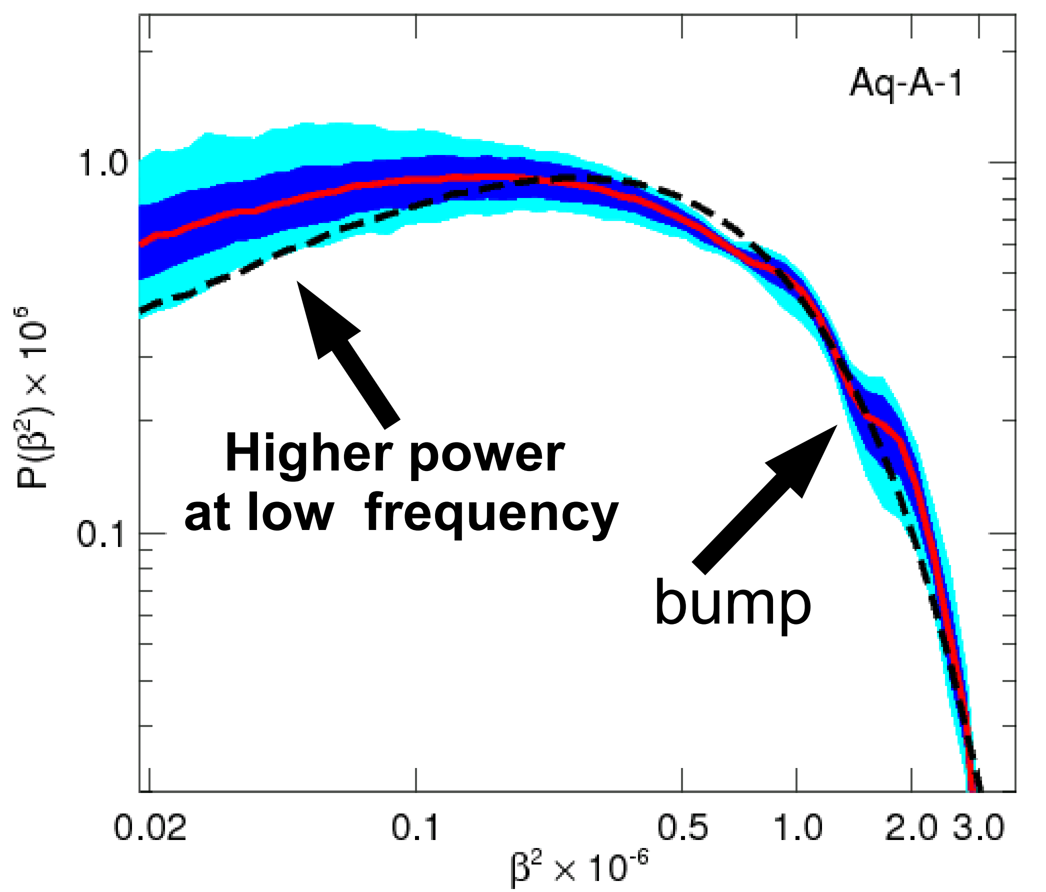
“quiet” formation history

“active” formation history



Q3: Signatures in detector signals





WIMP recoil spectrum

Axion microwave spectrum

Conclusions: local phase-space

- **dark matter mass distribution is very smooth**

- **dark matter velocity distribution smooth;**
  no sign for massive streams;
  significant deviations from multivariate Gaussian

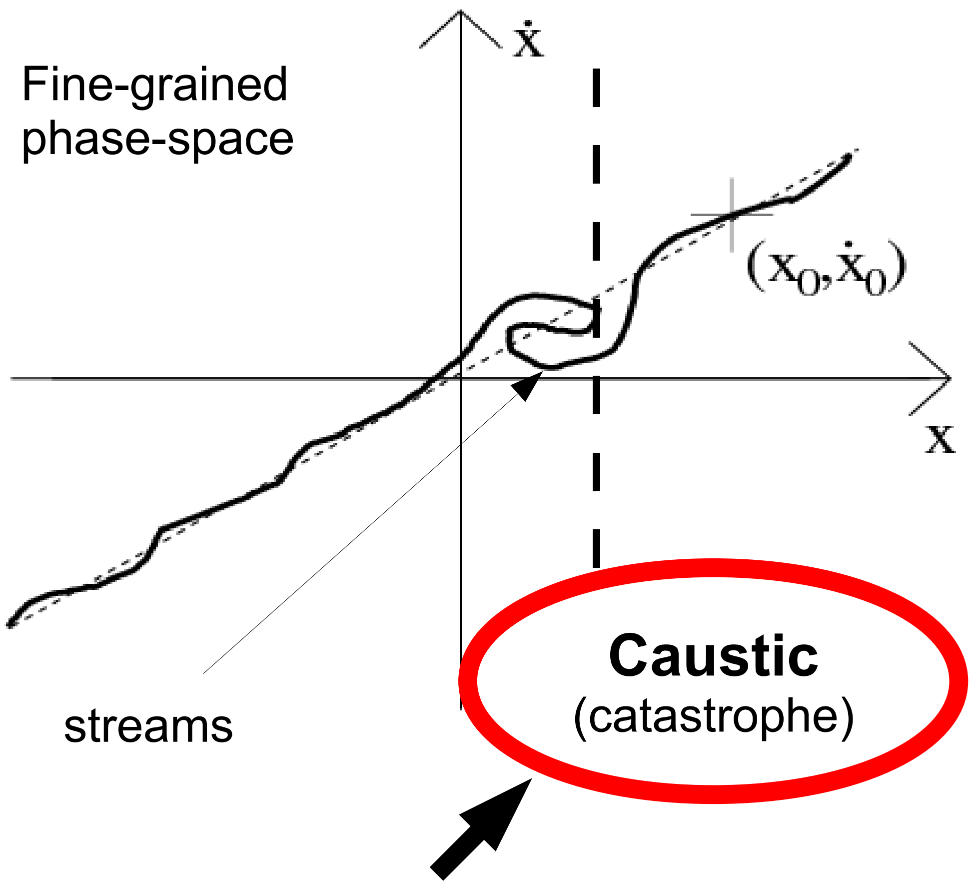
- **velocity modulus shows features in form of bumps/dips**

- **formation history leaves imprints in the energy distribution**

"Dark Matter Astronomy"

CDM – the very-small-scale structure

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

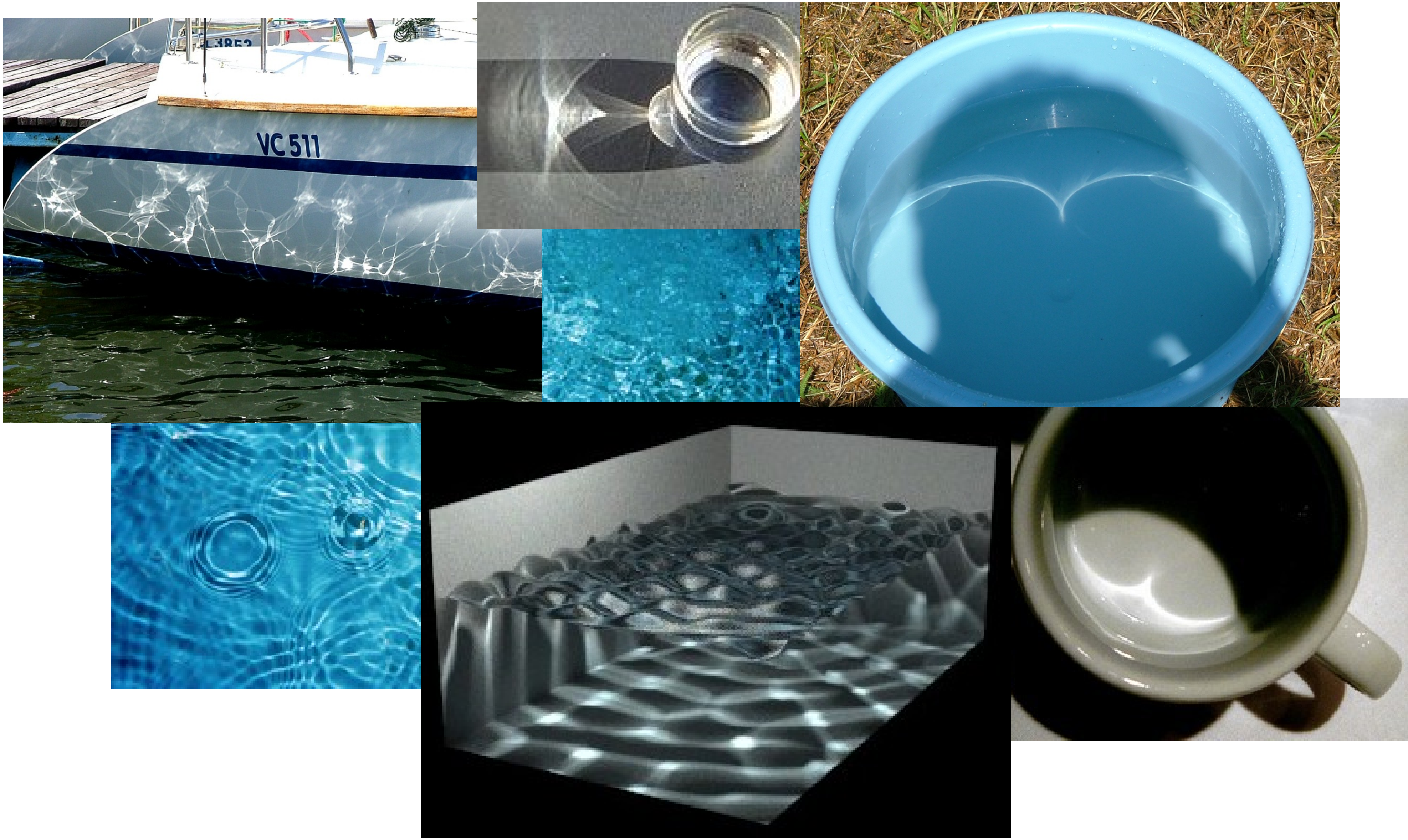
Wind-up:
growth of an overdensity

Phase space sheet:

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

Caustics are regions of **very high CDM** density

Caustics

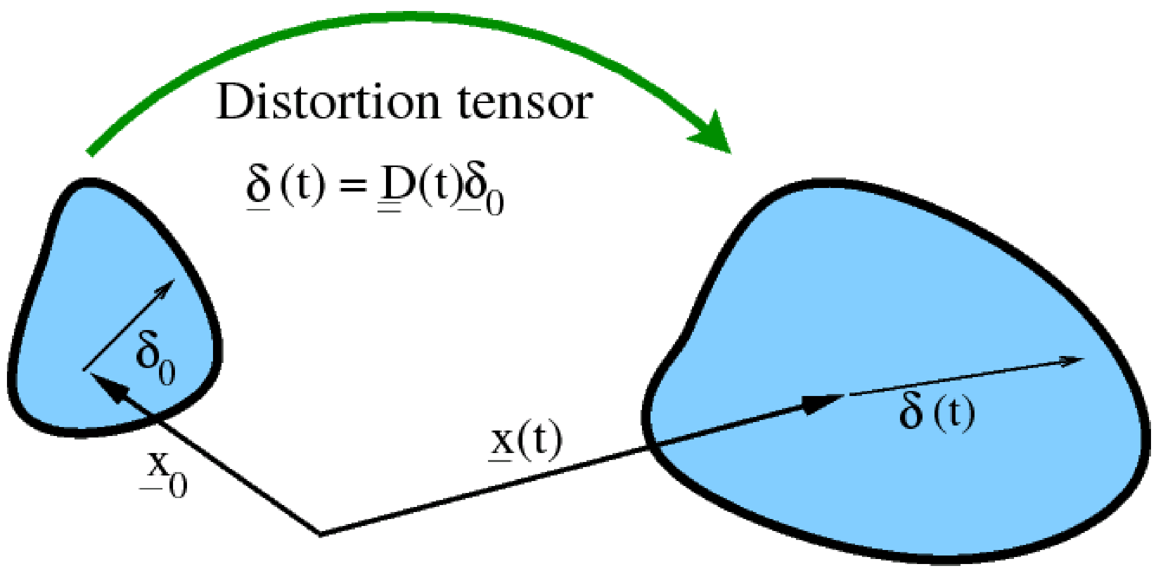


Caustic impact on: annihilation, ...?

Resolving caustics in N-body simulations

Problem: **Standard N-body simulations cannot resolve caustics (in the sense of fine-grained caustics)**

Solution: Follow the local phase-space evolution for each particle



- **calculation of stream density**
- **identification of caustics**
- **Monte-Carlo estimate for intra-stream annihilation**
  - **-missing in standard N-body annihilation calculations**
  - **-allows caustic annihilation calculation in N-body simulations**

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

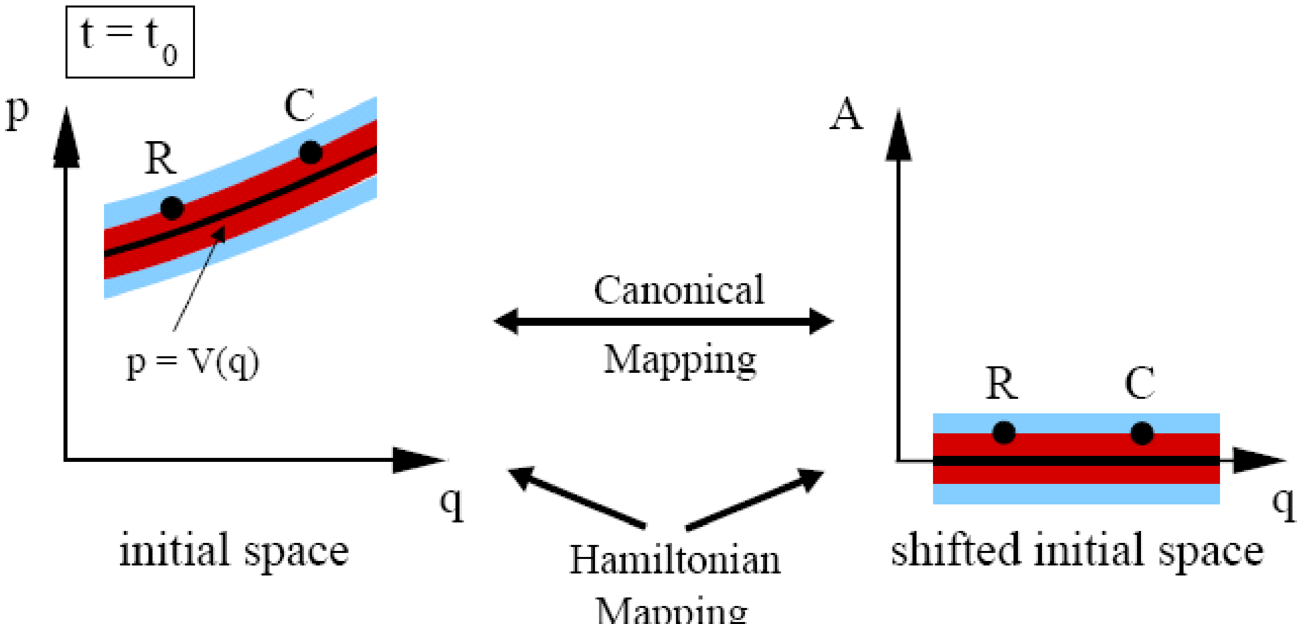
local stream density

MV et al, MNRAS (2008)

Regularization of caustics

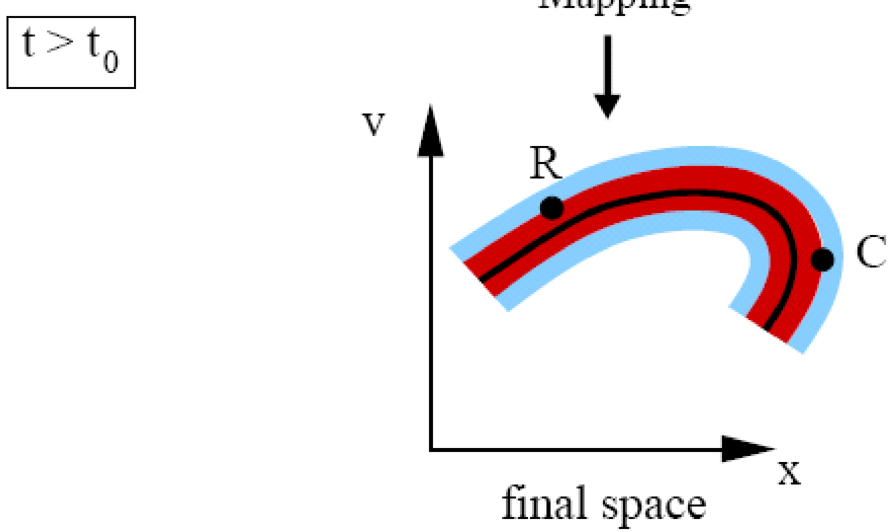
<u>Mathematically</u>: caustics have an infinite real-space density

<u>Physically</u>: regularization by finite velocity dispersion



Density at regular point R:

$$f_0 m_p \left| \det\left(\frac{\partial \underline{x}}{\partial \underline{q}}\right)\right|^{-1}$$

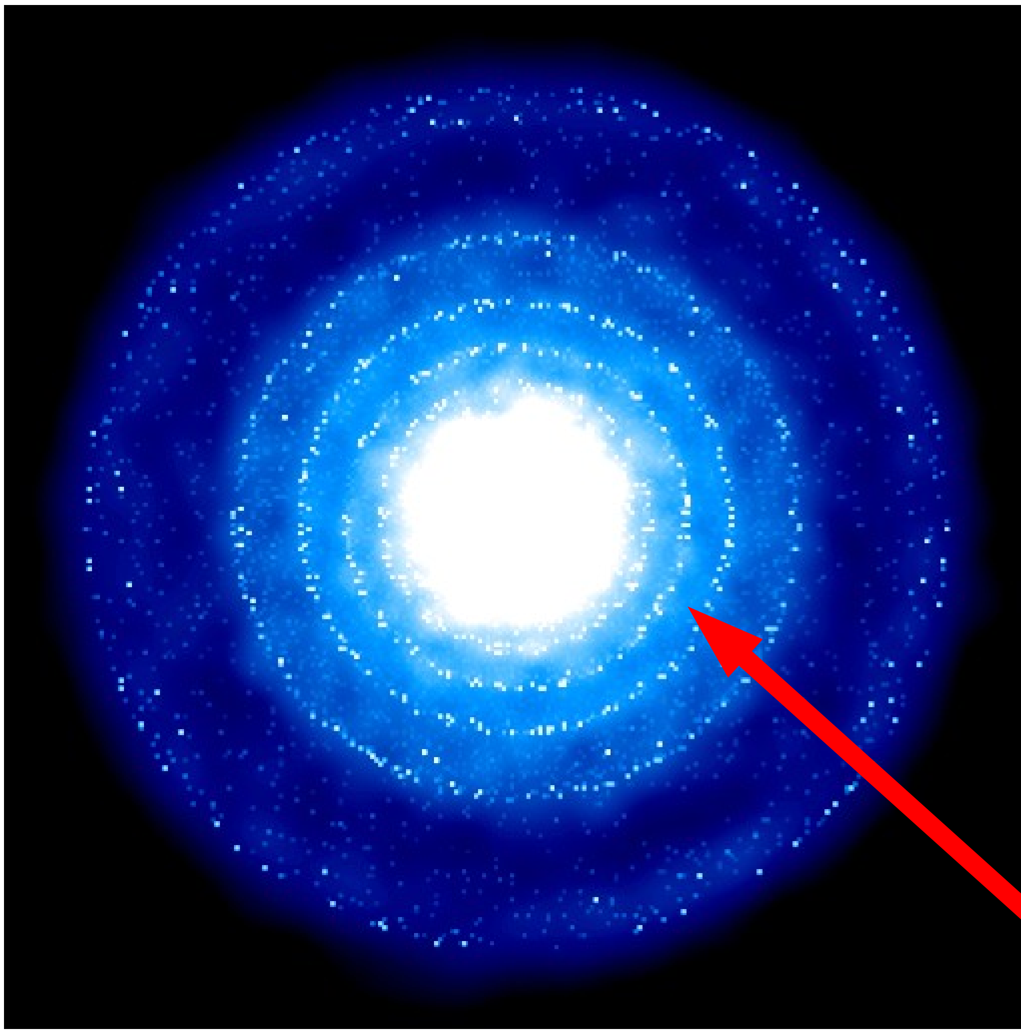


Density at caustic point C:

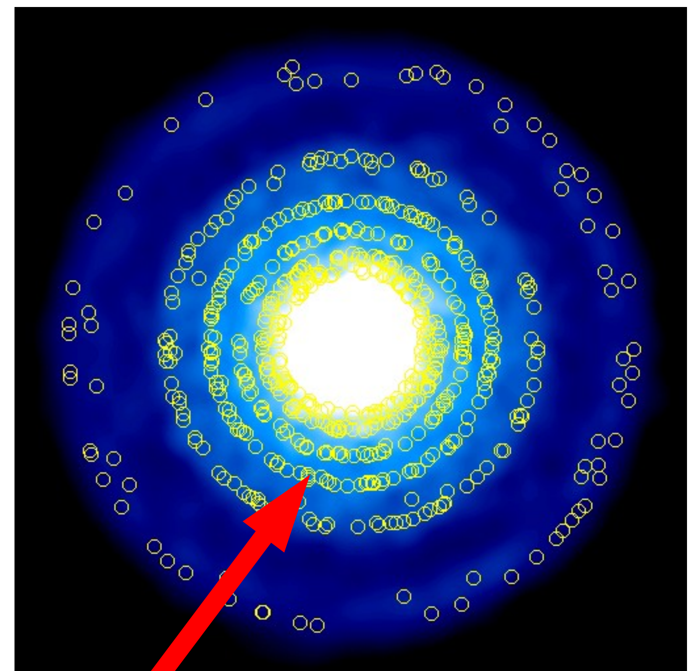
$$\frac{f_0 m_p}{|s_1 s_2|} \quad \frac{\Gamma'\left(\pm|A_{p,3}|/\sigma\right)}{|\sigma \partial^2 A_3/\partial v_3^2|^{1/2}} \quad \exp(-A_{p,3}^2/2\sigma^2)$$

White & MV, MNRAS (in press)

Application: Annihilation radiation



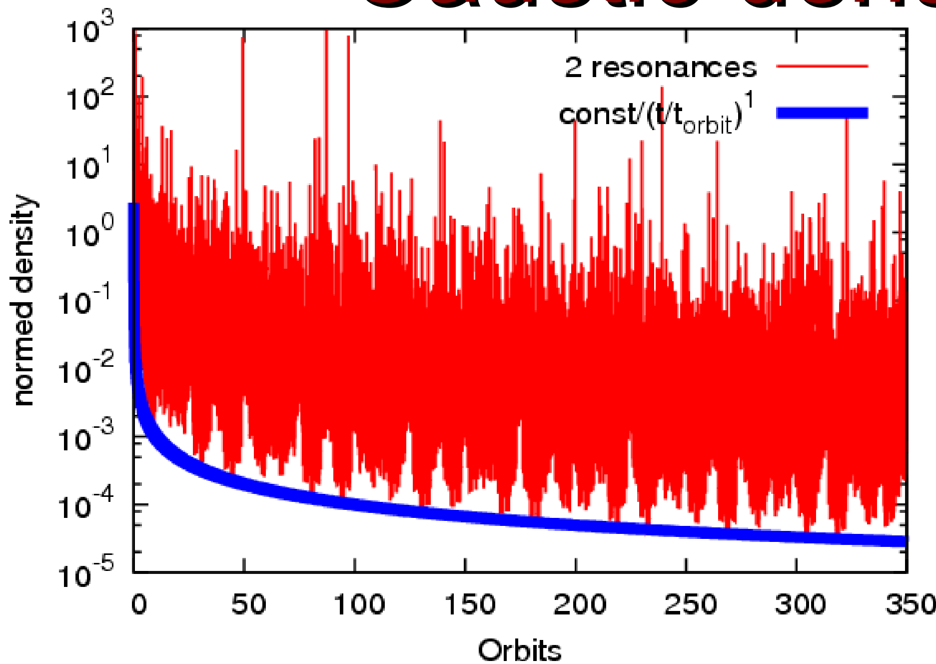
Self-similar infall in N-body code (1D gravity)



(outer) caustic spheres

MV et al, (in prep)

Caustic density – 1D vs. 3D



1/t stream density decrease

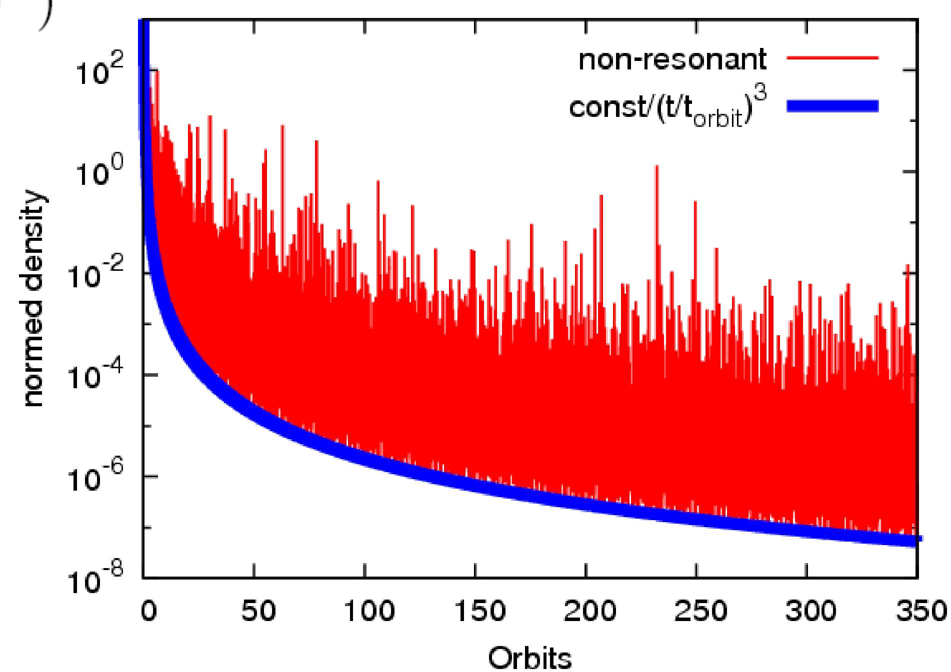
1D

$$\frac{f_0 m_p}{|s_1 s_2|} \frac{\Gamma'\left(\pm|A_{p,3}|/\sigma\right)}{|\sigma \partial^2 A_3/\partial v_3^2|^{1/2}} \exp(-A_{p,3}^2/2\sigma^2)$$

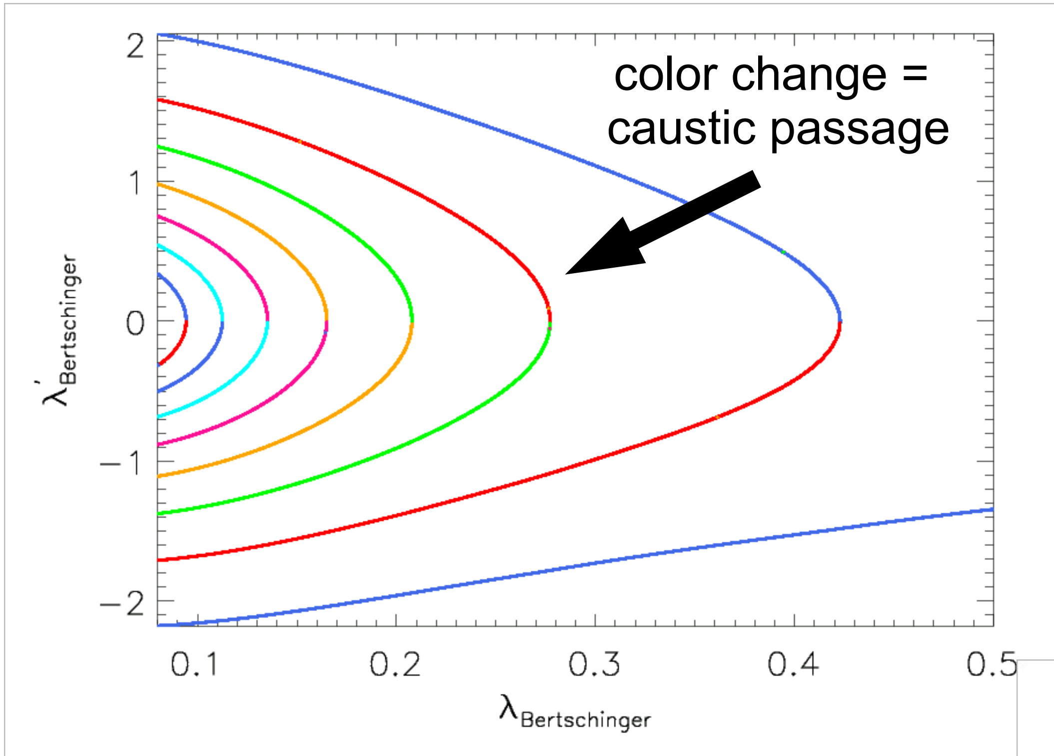
dilution factor

3D

$1/t^3$ stream density decrease



Caustic structure – 1D vs. 3D

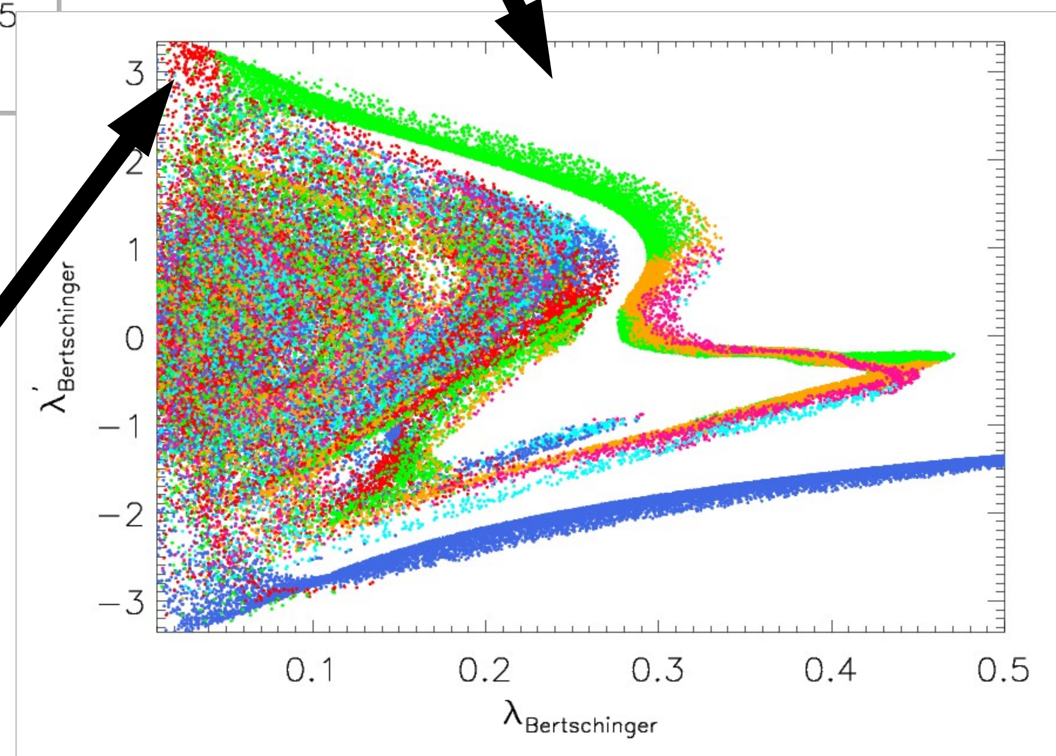


1D

- **Instability**
- **non-radial orbits**

Destruction of **phase-space pattern** in a full 3D collapse

inner caustics



3D

Conclusions: very-small-scale structure

- **caustics can now be resolved in N-body simulations**
- **caustics do not form simple, dense geometrical structures**
- **1D models overestimate the maximum density of caustics**
- **it seems that caustics do not provide a strong boost of the diffuse emission in the inner halo regions, no massive rings**