Zel'dovich's Legacy in Discovery and Understanding the Cosmic Web

Sergei Shandarin
University of Kansas

OUTLINE

* A few words about Ya.B. Zeldovich
* Cosmological background
* Zel'dovich approximation
* Adhesion approximation (Skeleton of the structure)
* Phase space and Lagrangian Submanifold
* Multi-Stream Field
* Flip-Flop Field
* Lagrangian skeleton and flip-flop fiield

Summary

Relativistic Astrophysics and Cosmology

Zeldovich and independently Edwin Salpeter were the first to suggest that accretion disks around massive black holes are responsible for the huge amounts of energy radiated by quasars.

Zel'dovich and Starobinski showed Hawking that, according to the quantum mechanical uncertainty principle, rotating black holes should create and emit particles.

The Sunyaev-Zel'dovich effect (Scatter of CMB photons on hot electrons in clusters of gal.)

The Zeldovich spectrum of primordial fluctuations (scale-free power spectrum)

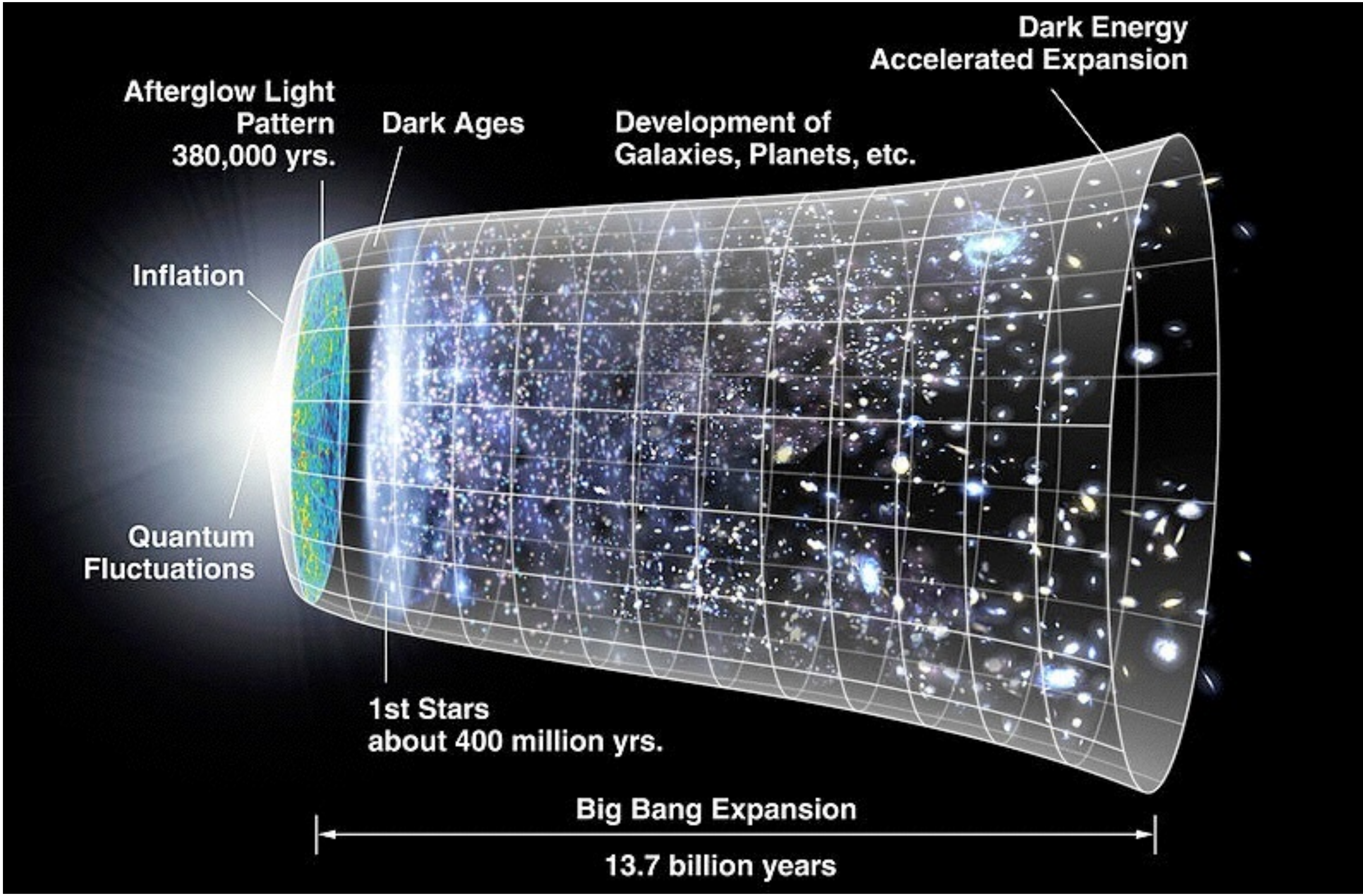
He argued that the relativistically-invariant theory of vacuum would result in non-zero minimum of the vacuum energy with the equation of state $p_{vac} = -\varepsilon_{vac}$. Lambda term in Einstein eq. must be placed on the right hand side.

***** The Zel'dovich approximation in 1970 *****

From recommendation for Zel'dovich to Academy of Sciences of USSR

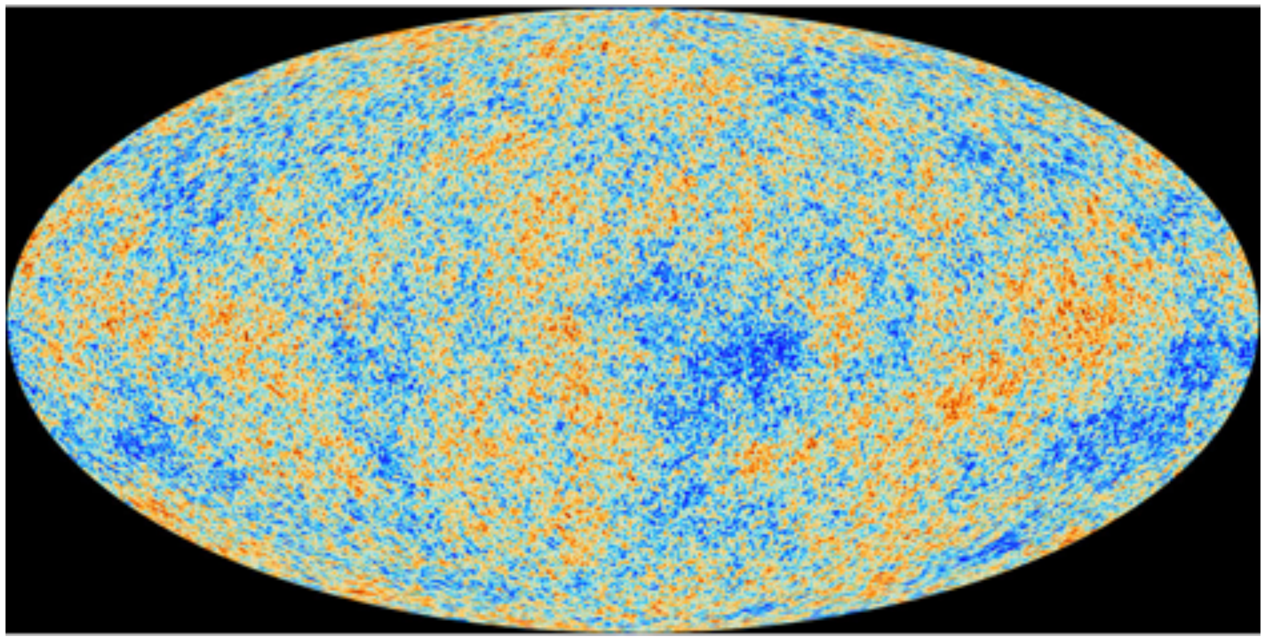
"It is characteristic for Ya.B. Zel'dovich to widely use the methods of hydrodynamics along with "conventional" methods of theoretical physics. This ability to use the both techniques -very rare among theorists - is a very advantageous trait of Zel'dovich, allowing him to solve problems which can be solved by neither pure hydrodynamicists nor "conventional" theorists."

Lev Landau, 1946


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Structure in the Universe

13.7 billion years ago



Plank map

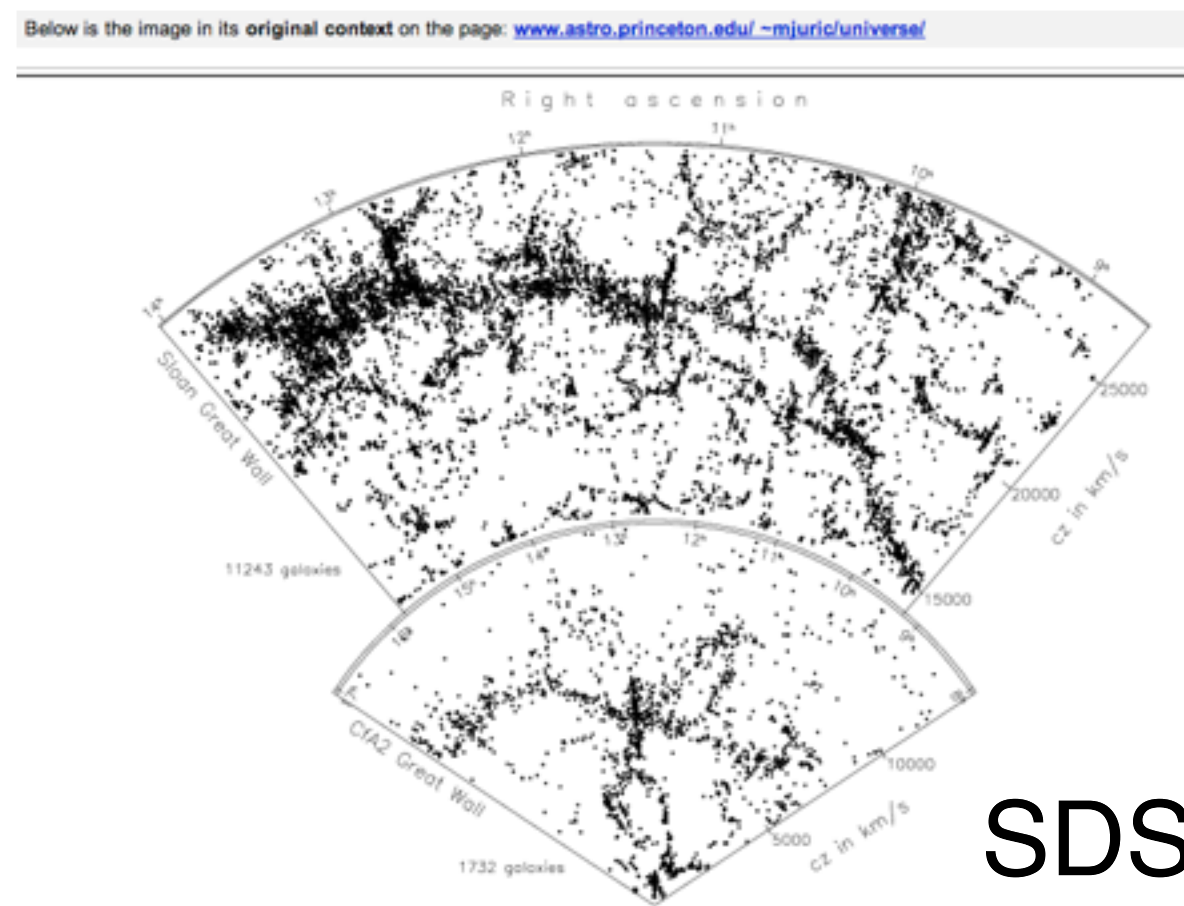
Temperature fluctuations of Cosmic Microwave Background

T=2.73 K

(fluctuations:

of the order of 1/100,000)

NOW



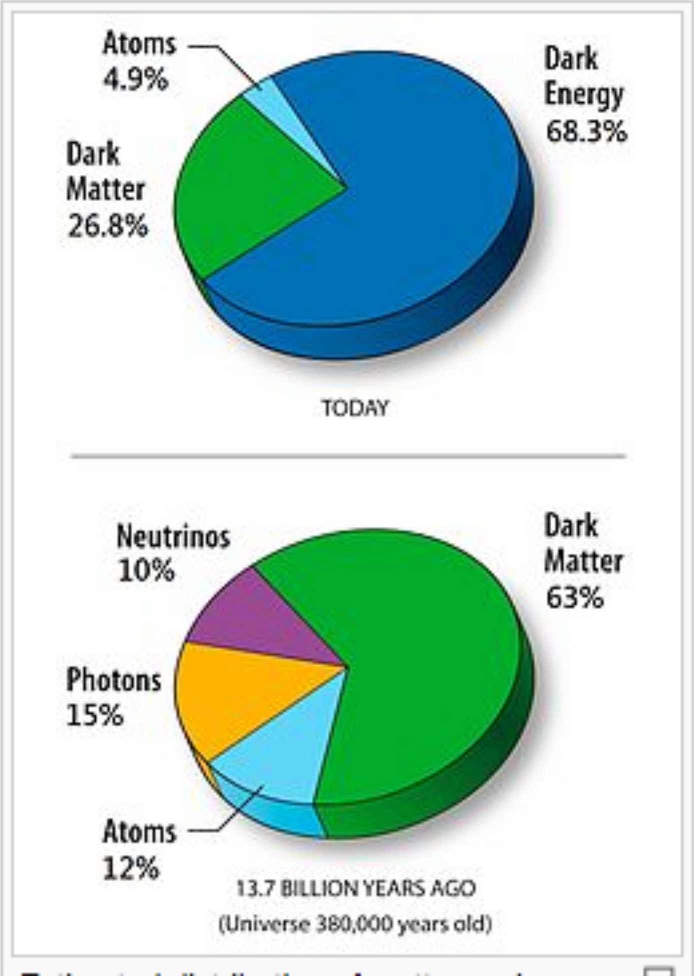
SDSS

Galaxy distribution in a thin slice

Why did complexity begin to grow?

- Thanks to gravitational instability of Dark Matter

Why only Dark matter?
more mass – stronger gravity



NOW

Atoms alone could NOT develop structures because they were unable to overcome the expansion of the universe!

13.7 billion years ago

That's why we focus on the growth of complexity in Dark Matter.

Astron. & Astrophys. 5, 84—89 (1970)

Gravitational Instability: An Approximate Theory for Large Density Perturbations

Ya. B. Zeldovich
Institute of Applied Mathematics, Moscow

Received September 19, 1969

Large-Scale Structure of the universe in 1970
OBSERVATIONS:

de Vaucouleurs (1956), (1960) : The Local Supercluster

The first observational results that claimed the discovery of Superclusters of galaxies

Chincarini & Rood 1976, Gregory & Thompson 1978

de Vaucouleurs 1981

Tully 82

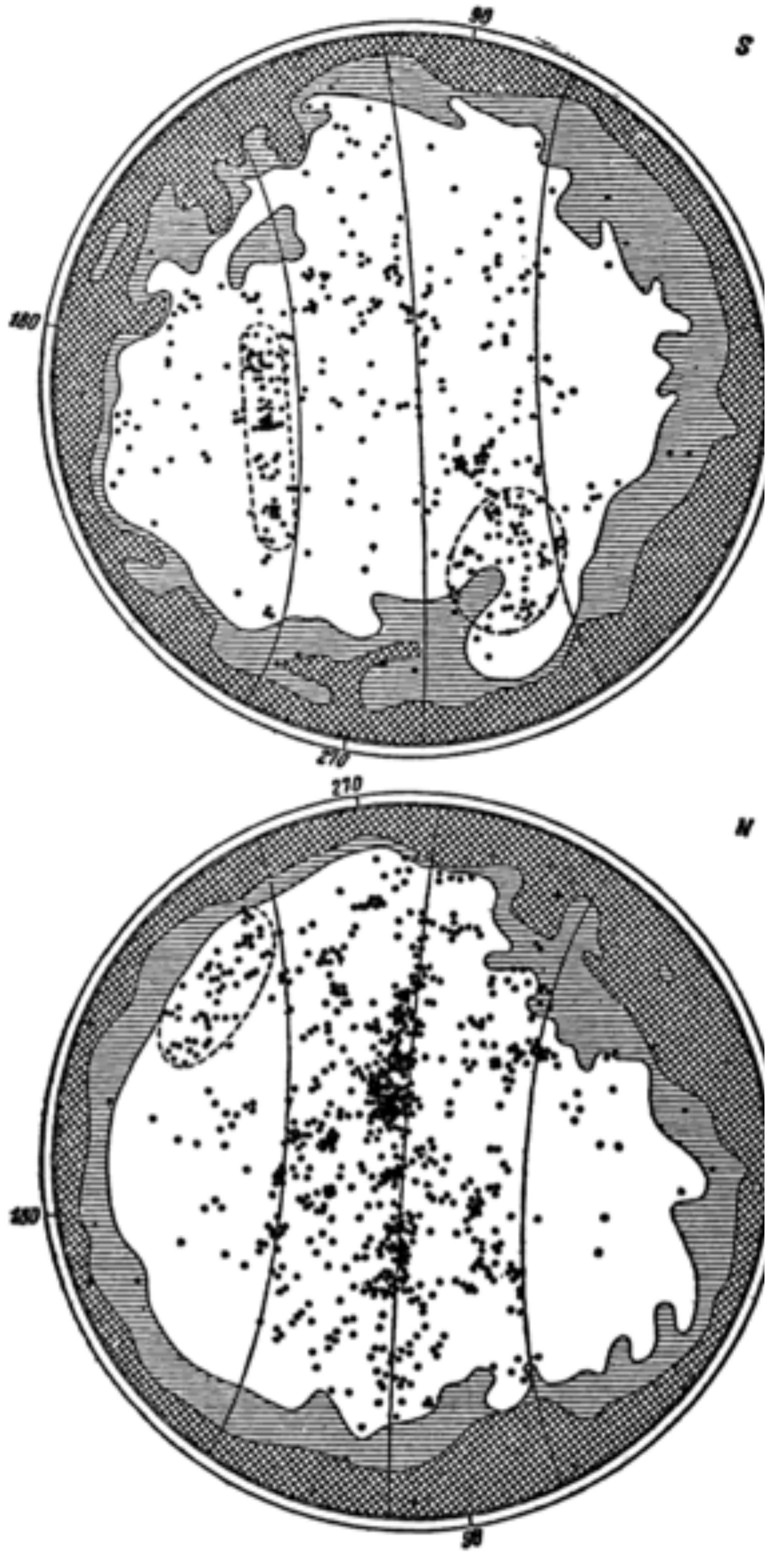


Figure 2. Distribution of the Shapley-Ames galaxies (1932) in (old) galactic coordinates. The zone of avoidance (dark) and of partial obscuration (grey) by the Milky Way is indicated. The super-galactic equator and parallels at ±30° latitude are marked. Two external galaxy clouds in Hydra (l^{I} = 240°) and Pavo-Indus (l^{I} = 310°) and the elongated Dorado-Fornax-Eridanus stream or "southern supergalaxy" are outlined.

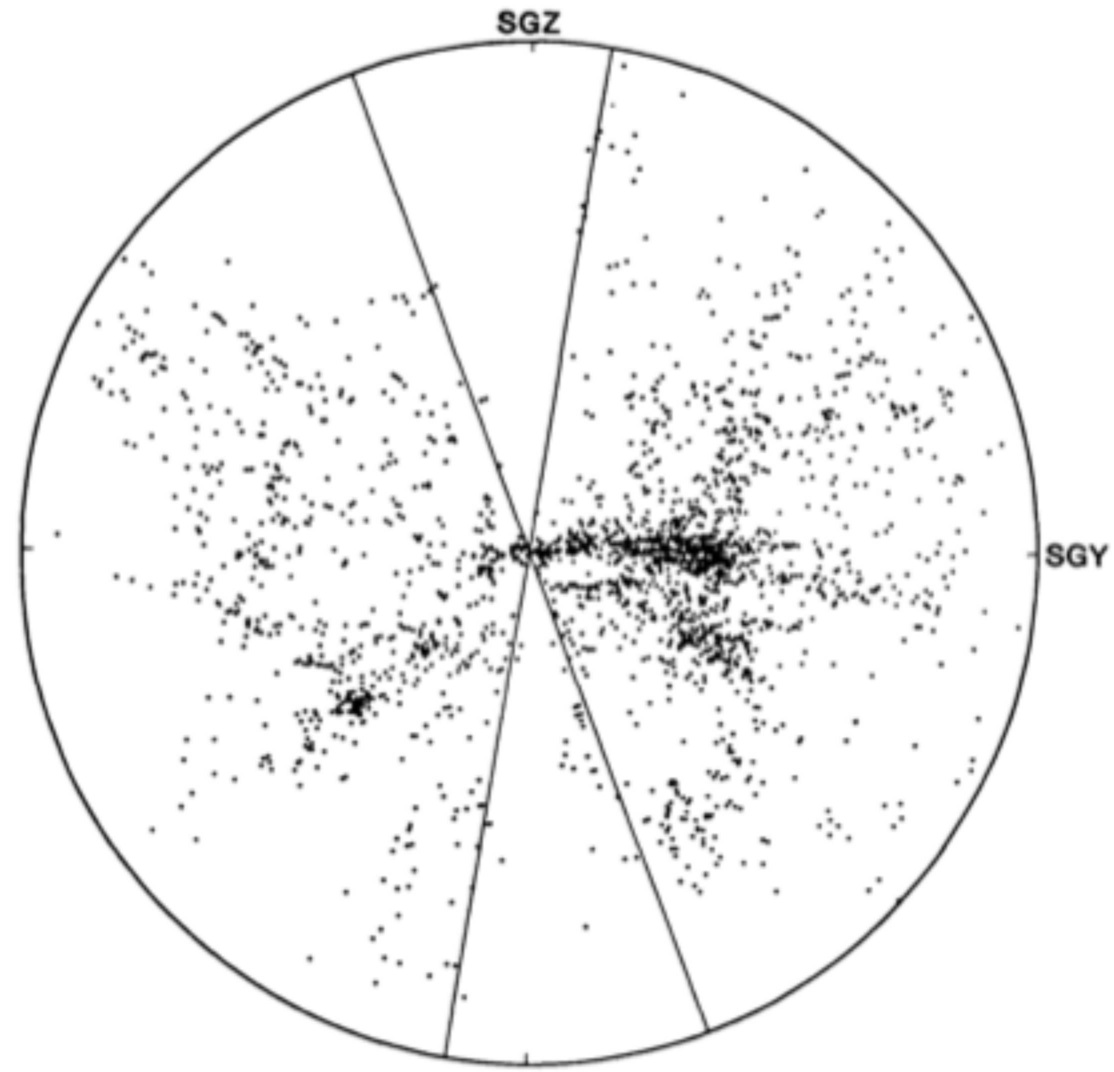


Figure 3 All 2175 galaxies in the Nearby Galaxy Catalog (NBG) projected onto the *SGY*-*SGZ* plane. The *SGY*-axis is directed toward supergalactic longitude 90°, supergalactic latitude 0° ($\ell^{\mathrm{II}} = 227°$, $b^{\mathrm{II}} = +83\overset{\circ}{.}7$), the *SGZ*-axis toward supergalactic latitude 90° ($\ell^{\mathrm{II}} = 47\overset{\circ}{.}4$, $b^{\mathrm{II}} = +6\overset{\circ}{.}3$). The radius of the outer boundary is 60 Mpc. The galactic zone of avoidance ($b < 15°$) is contained within the opposed wedges tilted by 6° with respect to the *SGZ*-axis. There is a zone of incompletion ($\delta < -45°$), which is projected across most of the southern supergalactic hemisphere. Figures 3–6 are reproduced by courtesy of R. B. Tully (92).

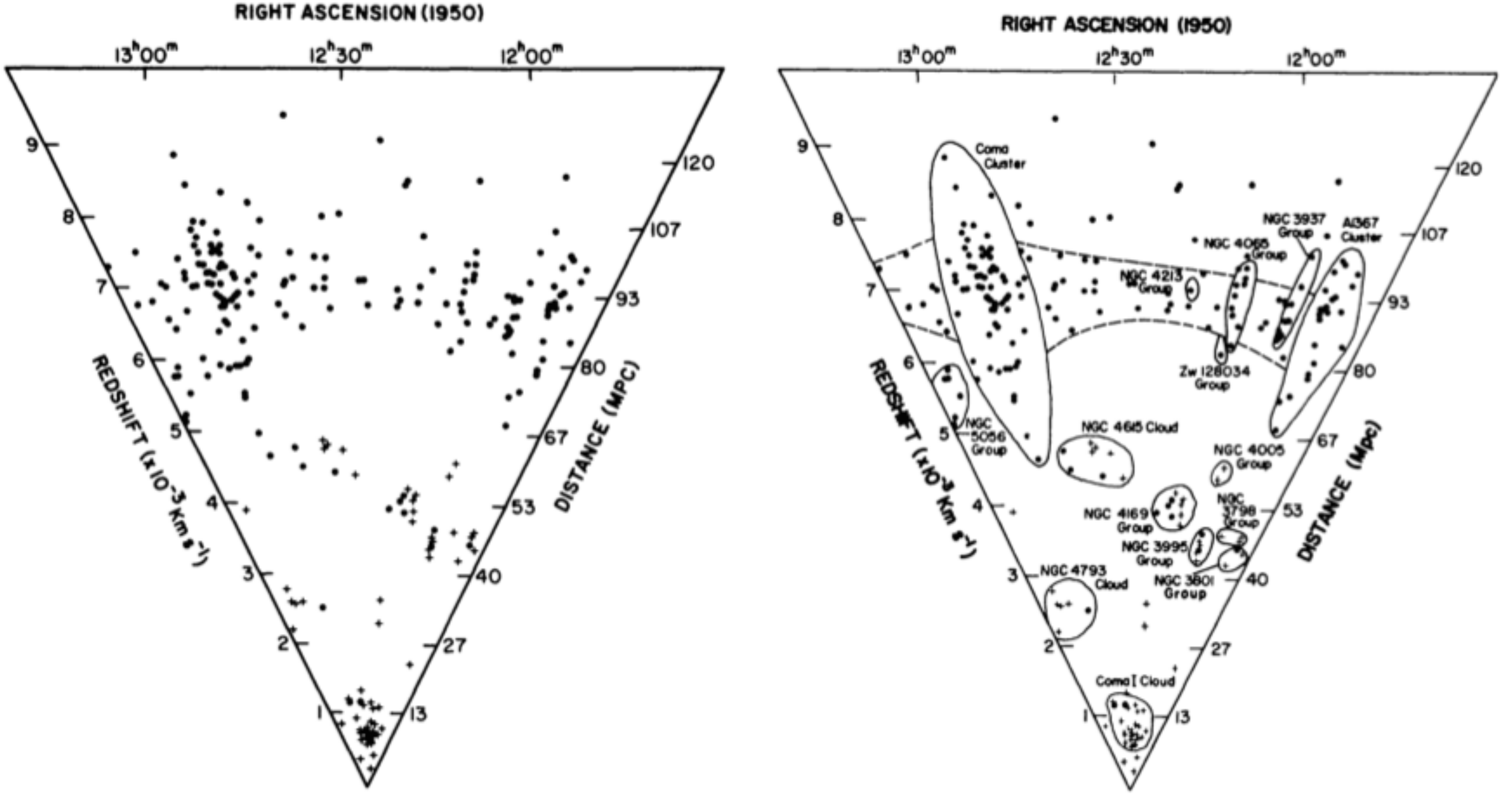


Figure 12 "Wedge diagram" of the Coma supercluster [Gregory & Thompson (40)]. As the supercluster is elongated in the east-west direction, right ascensions have been chosen as position coordinates; the galaxies lie between +19° and +32° declination. The angular size has been magnified about two times compared with the indicated distance scale.

Gregory & Thompson 1978
see also Chincarini & Rood 1976

Large-Scale Structure of the universe in 1970

THEORY:

"Gravitational Instability is similar to capitalism:

in the course of time
rich become richer
while
poor become poorer

and the gap between the rich and poor is widening
and becomes catastrophic."

Zel′dovich

1979 Aarseth, Gott III, Ed Turner
ApJ, 228, 664

Z=14.2

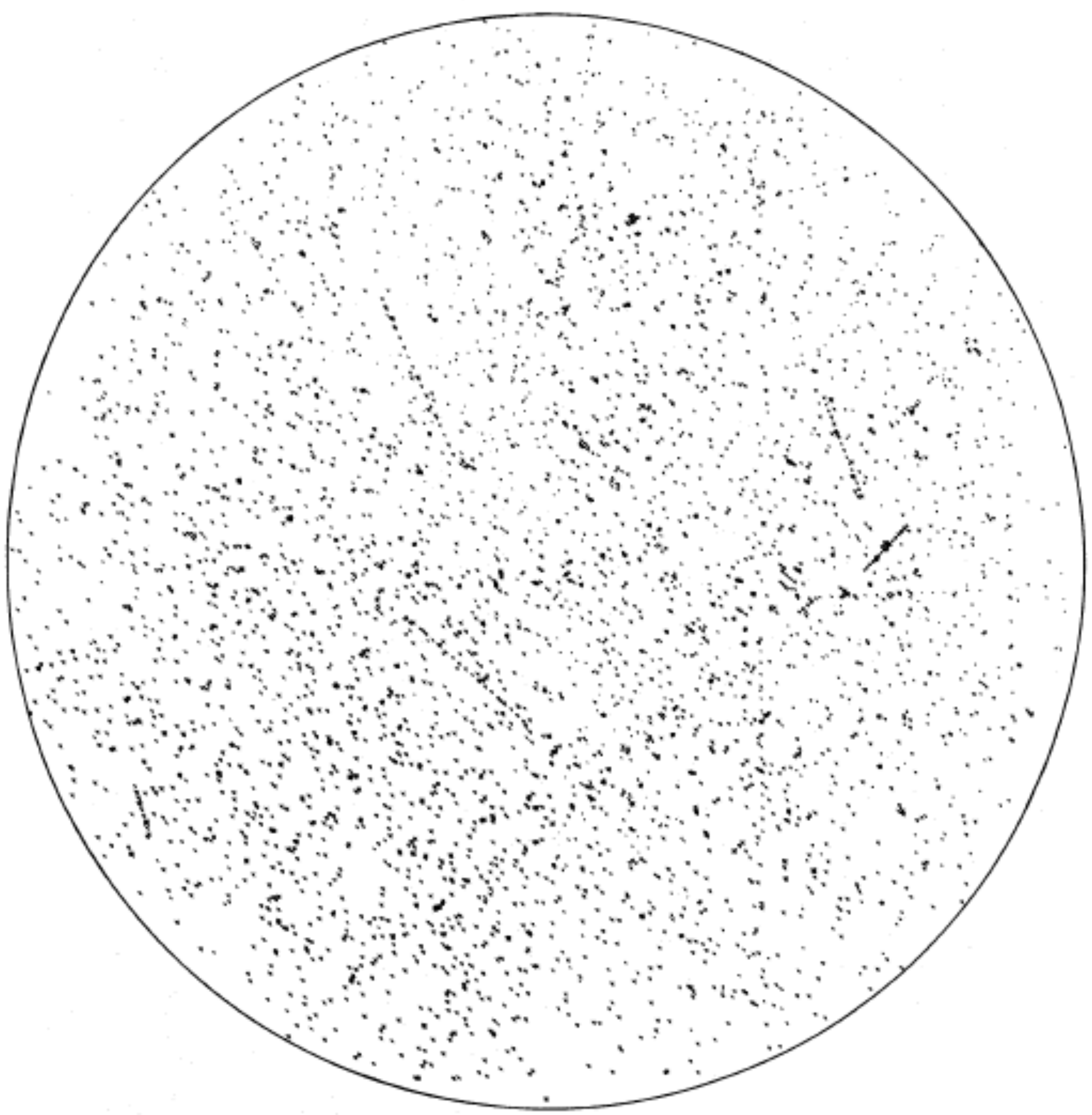


Fig. 1a

Z=0

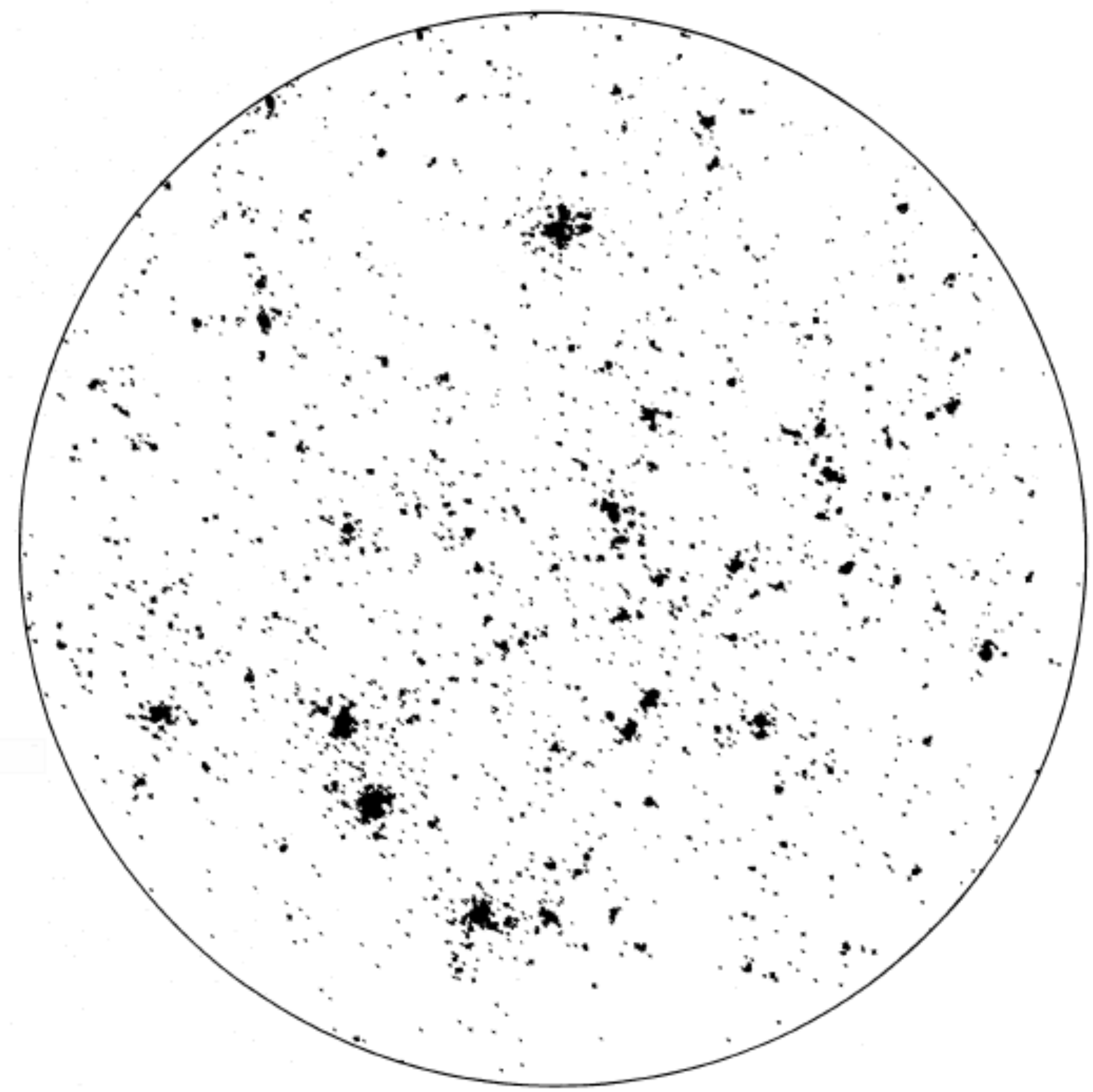


Fig. 1f

State of art N-body simulations

1981 Efstathiou, Eastwood, MNRAS, 194, 503

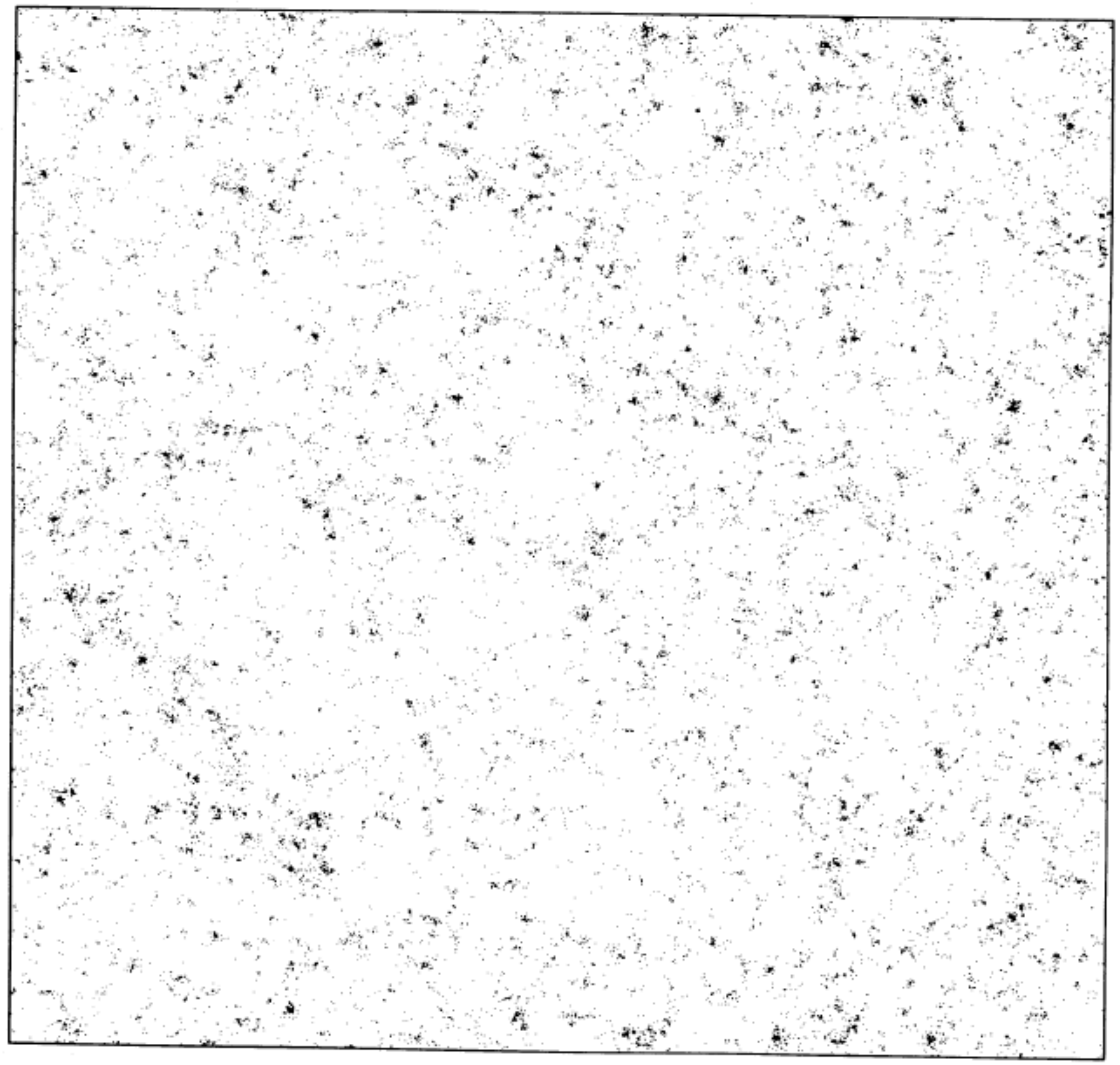


Figure 1. $X-Y$ projection of the particle positions for a 20 000-body numerical experiment after the system has expanded by a factor of 9.9. In this case the expansion follows that of an Einstein–de Sitter model, $\Omega_0 = 1.0$.

Astron. & Astrophys. 5, 84—89 (1970)

Gravitational Instability: An Approximate Theory for Large Density Perturbations

Ya. B. Zeldovich
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Zel'dovich approximation (1970)

Comoving coordinates: r_i,

Zel'dovich approximation is a map: $r_i(\mathbf{q},t) = q_i + D(t)s_i(\mathbf{q})$

If $\Phi(\mathbf{q})$ is the linear perturbation of grav. potential then $s_i(\mathbf{q}) = -\partial\Phi/\partial q_i$

Density can be found from the conservation of mass

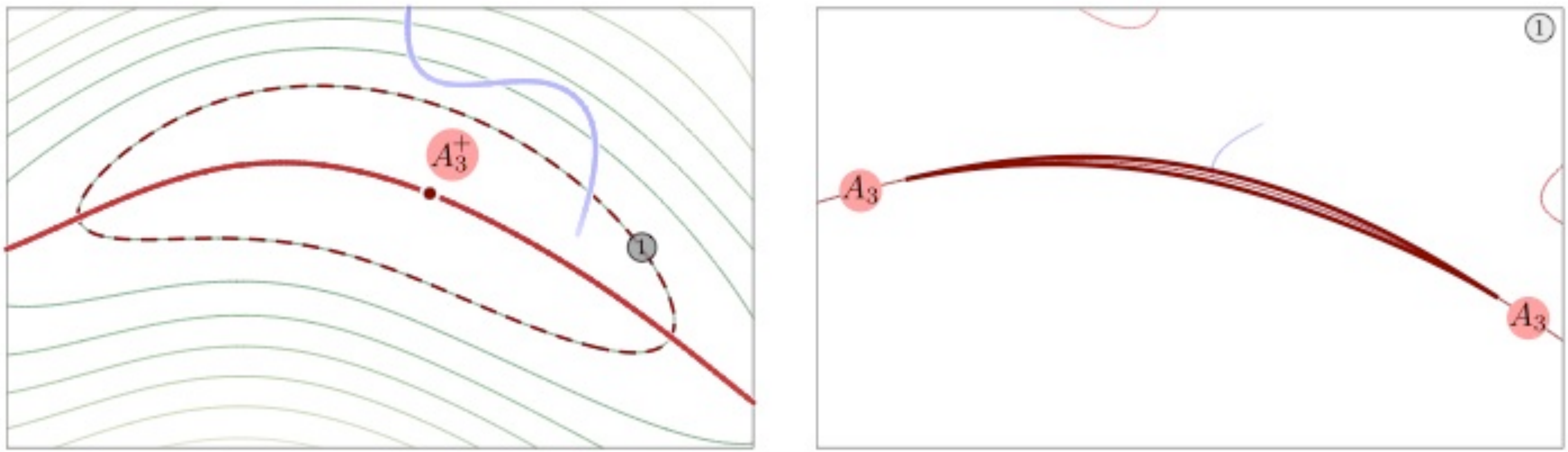
$$\rho(\mathbf{q},t) = \bar{\rho}(t)\left|\frac{\partial r_i}{\partial q_k}\right|^{-1} = \bar{\rho}\left|[(1 - D(t)\alpha(\mathbf{q})]^{-1}[(1 - D(t)\beta(\mathbf{q})]^{-1}[(1 - D(t)\gamma(\mathbf{q})]^{-1}\right.$$

$\alpha(\mathbf{q}) \geq \beta(\mathbf{q})$ and $\beta(\mathbf{q}) \geq \gamma(\mathbf{q})$ are the eigen values of the deformation tensor

$$d_{ik}(\mathbf{q}) = \frac{\partial s_i}{\partial q_k} = -\frac{\partial^2\Phi}{\partial q_i \partial q_k}$$

Linear density fluctuations: $\delta\rho/\rho = D(t)(\alpha+\beta+\gamma).$

The Zel'dovich approximation describes anisotropic collapse and motion.

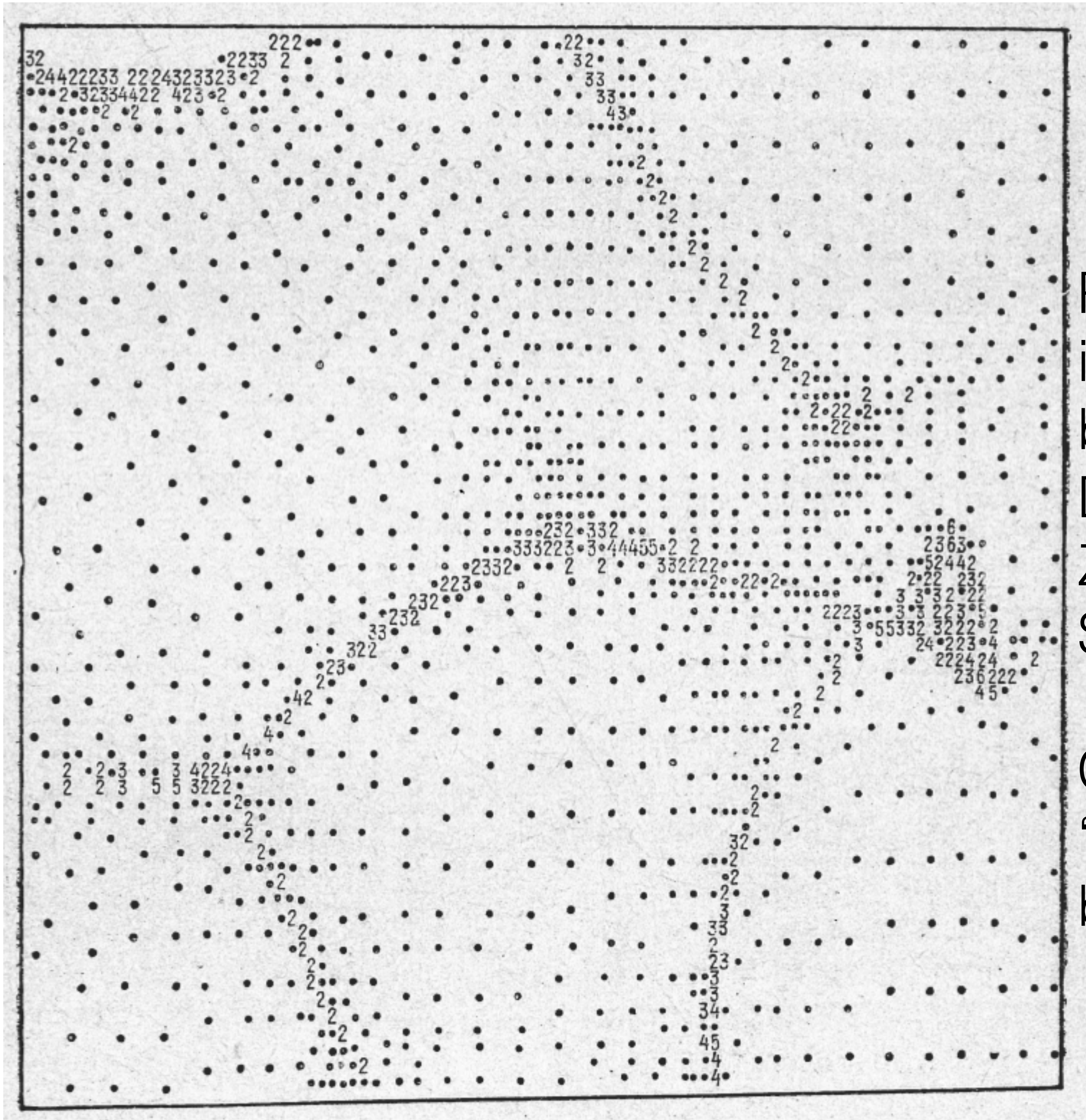


Hidding, Shandarin, van de Weygaert 2014

P.J.E.Peebles 1980 The Large-Scale Structure of the Universe

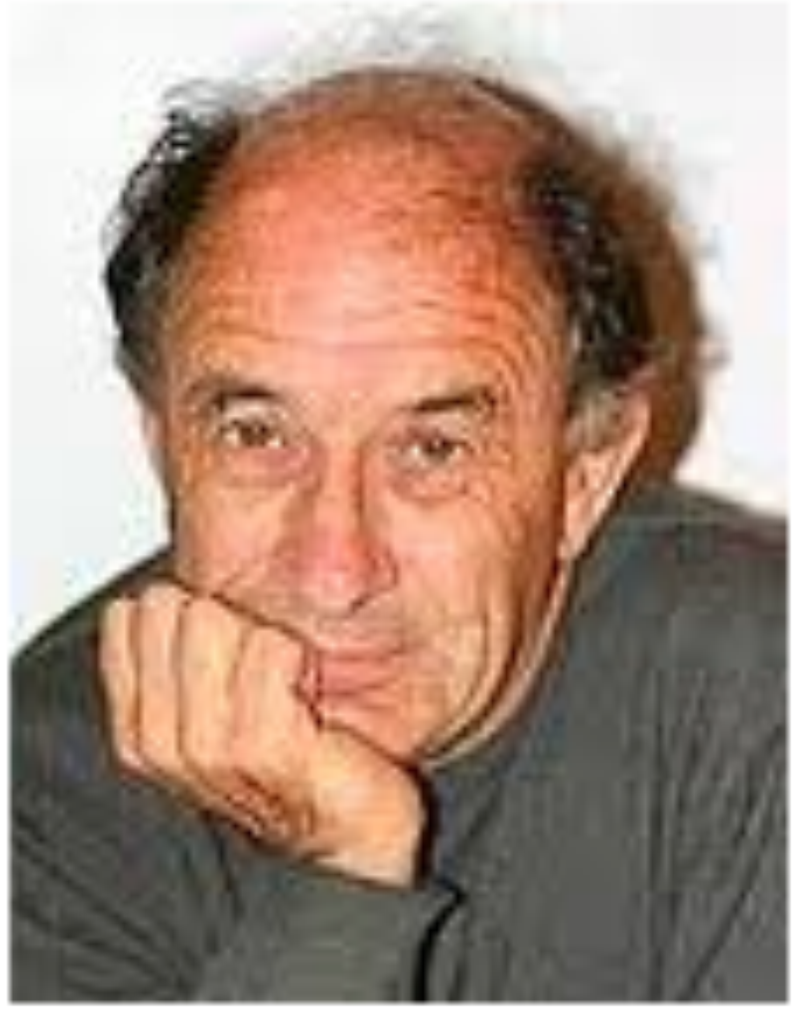
8 pages on Caustics and Pancakes with the verdict: death

Assumptions are not realistic, approximation is kinematic, pancakes are unstable therefore no observational traces remain



Published
in a review paper
by
Doroshkevich,
Zeldovich,
Sunyaev 1976.

Caption says:
“the figure is made
by S. Shandarin”



Vladimir Igorevich
Arnold
1937 - 2010

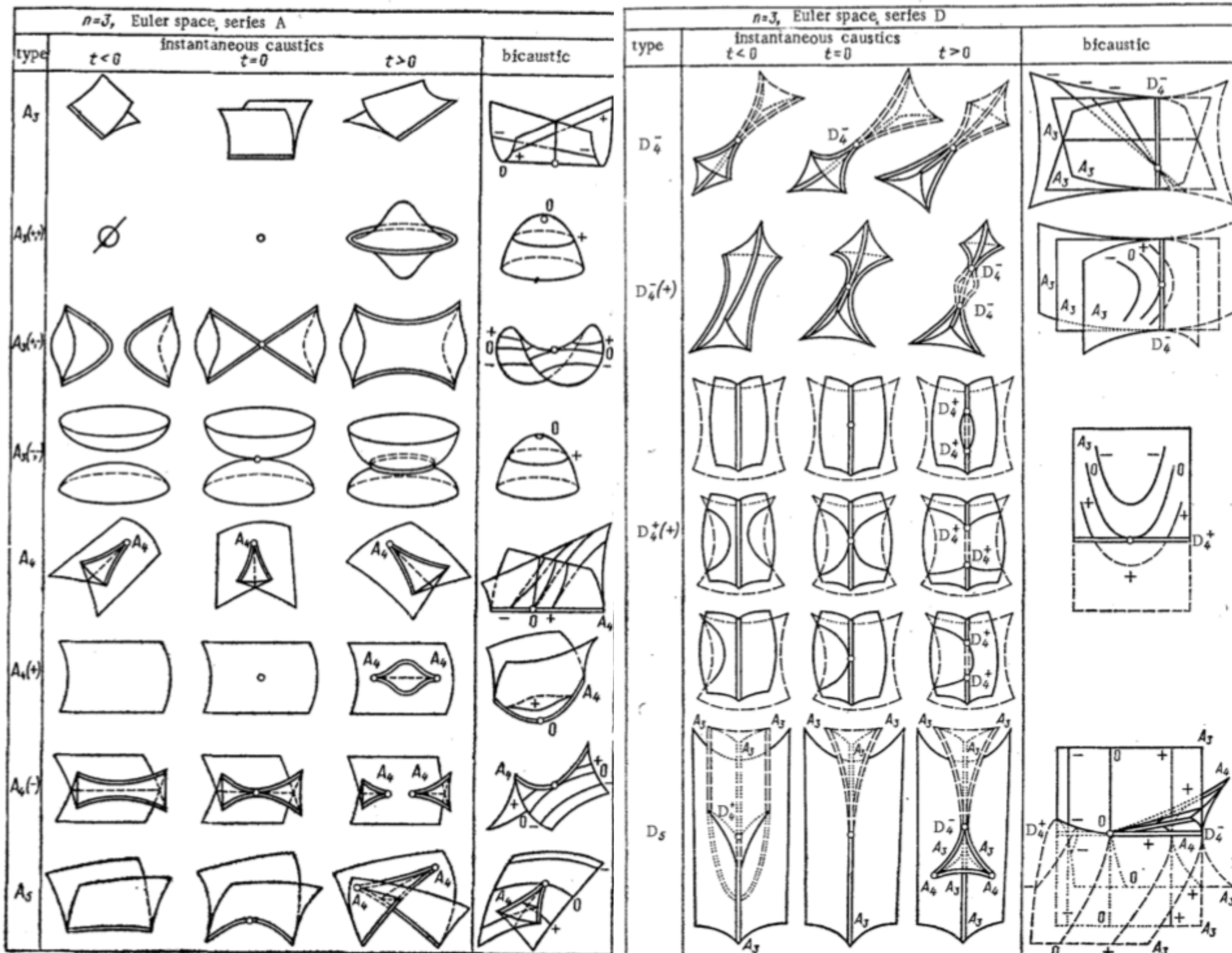
“Mathematics is a part of physics.

Physics is an experimental science, a part of natural science.

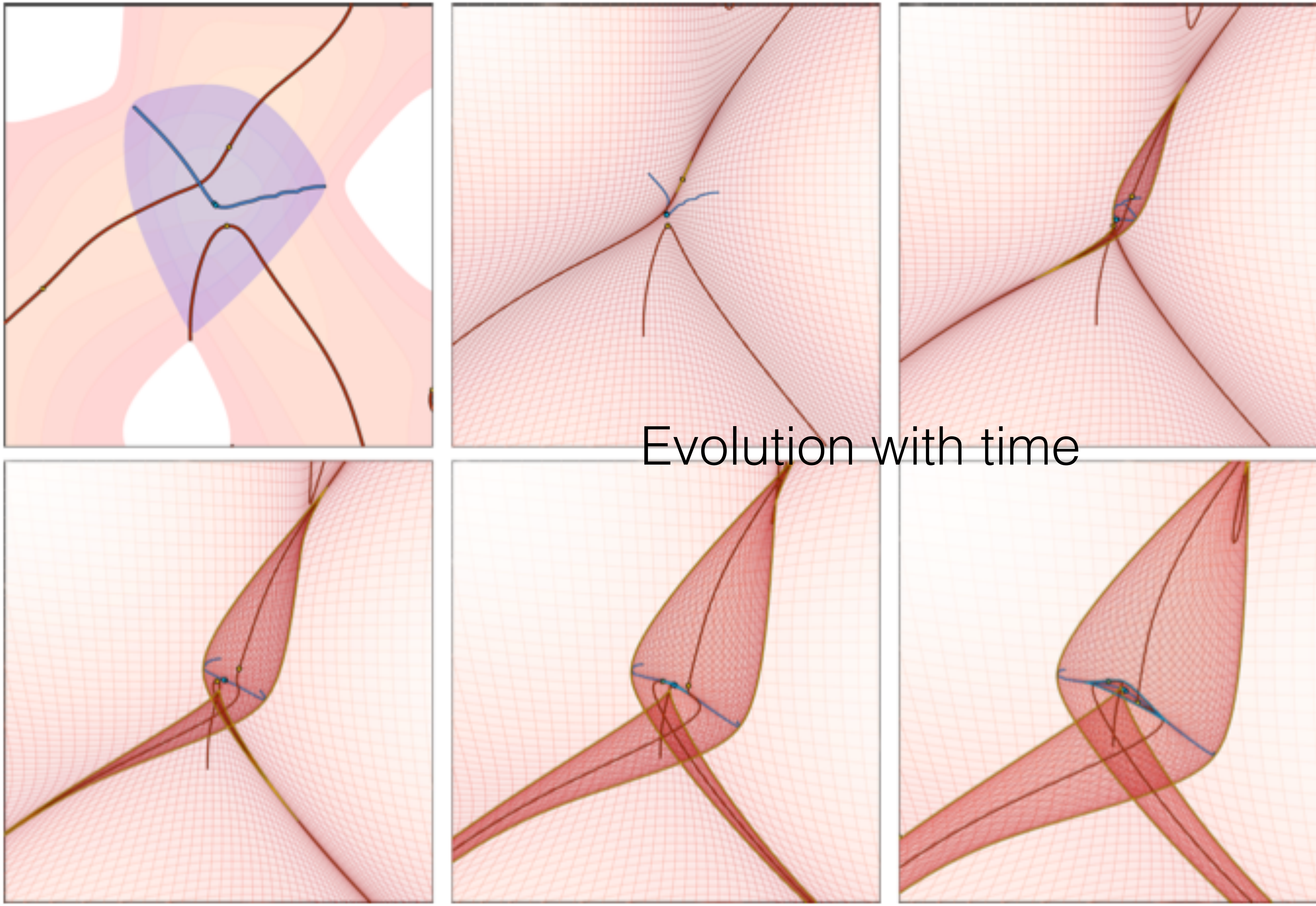
Mathematics is the part of physics where experiments are cheap.”

ADE classification of caustics in 3D (Arnold 1981)

Arnold
Shandarin
Zeldovich
1981

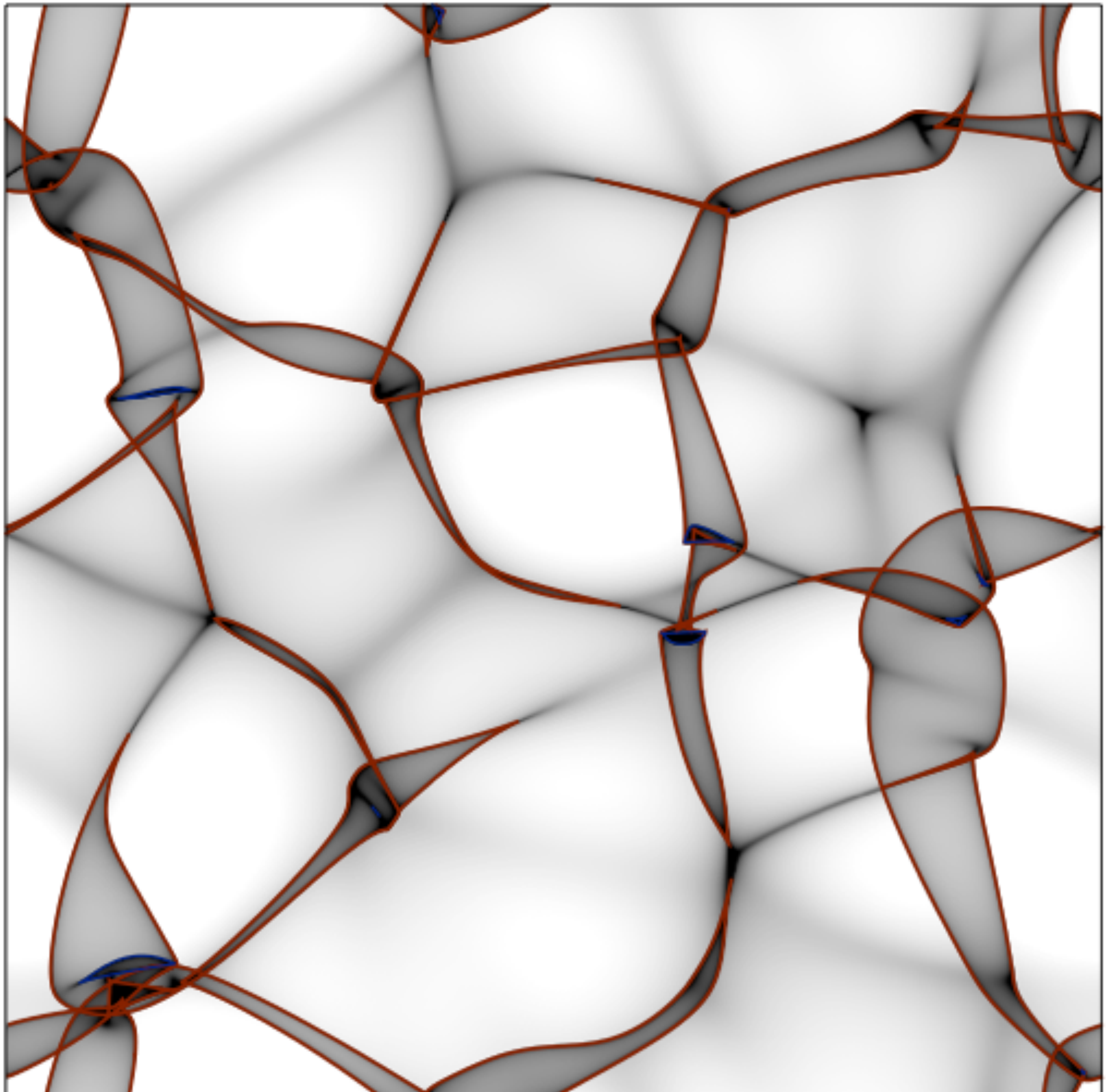


Pancake connectivity in 2D

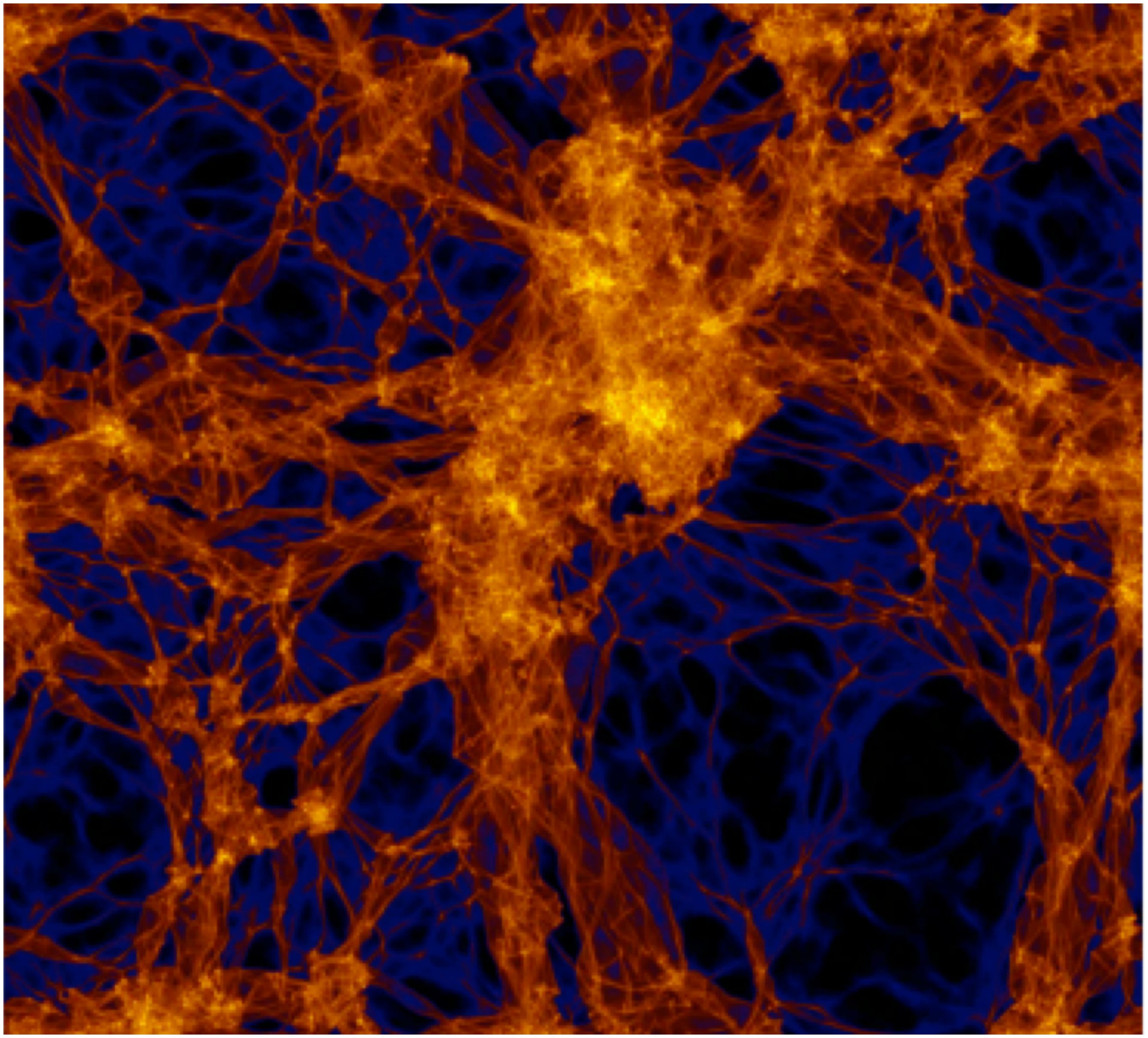


Evolution with time

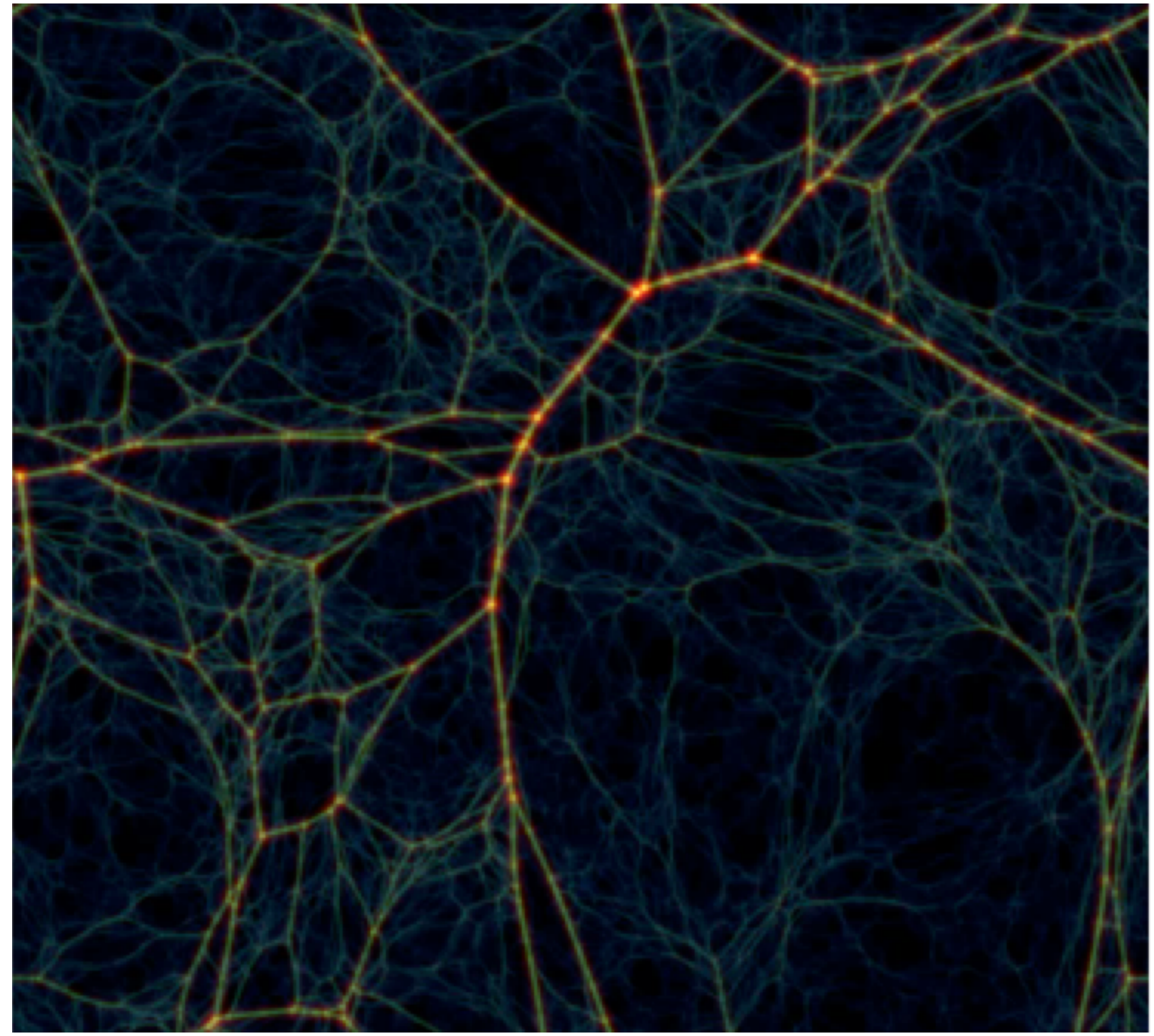
Hidding, Shandarin,
van de Weygaert 2014



Hidding,
Shandarin,
van de Weygaert
2014



Zel'dovich Approximation



Adhesion Approximation
Skeleton of structure

Hidding 2010

W E B

or

IRREGULAR HONEYCOMB

Klypin & Shandarin 1983; Shandarin & Klypin 1984

First demonstration of filaments in 3D N-body by plotting density contours

3D numerical model of the Universe 903

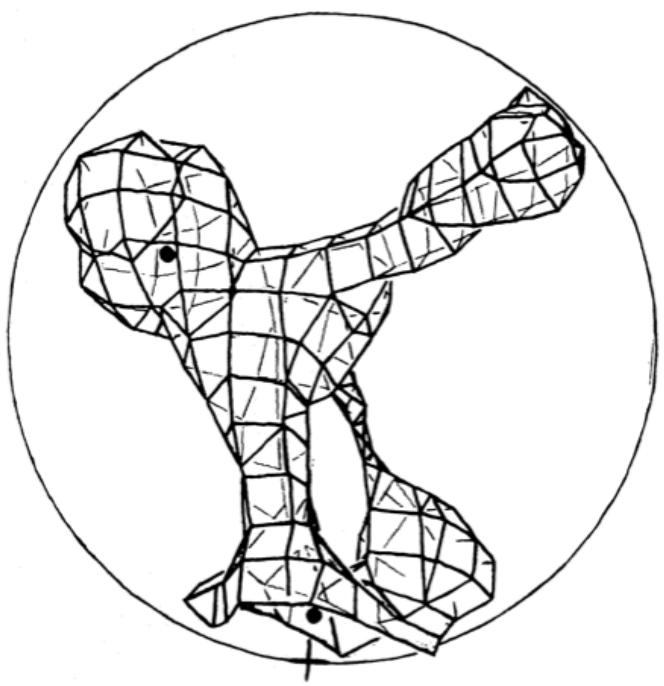


Figure 4. A surface of constant density level is plotted for the same region as that in Fig. 3.

'Cosmic chicken'
C. Frenk

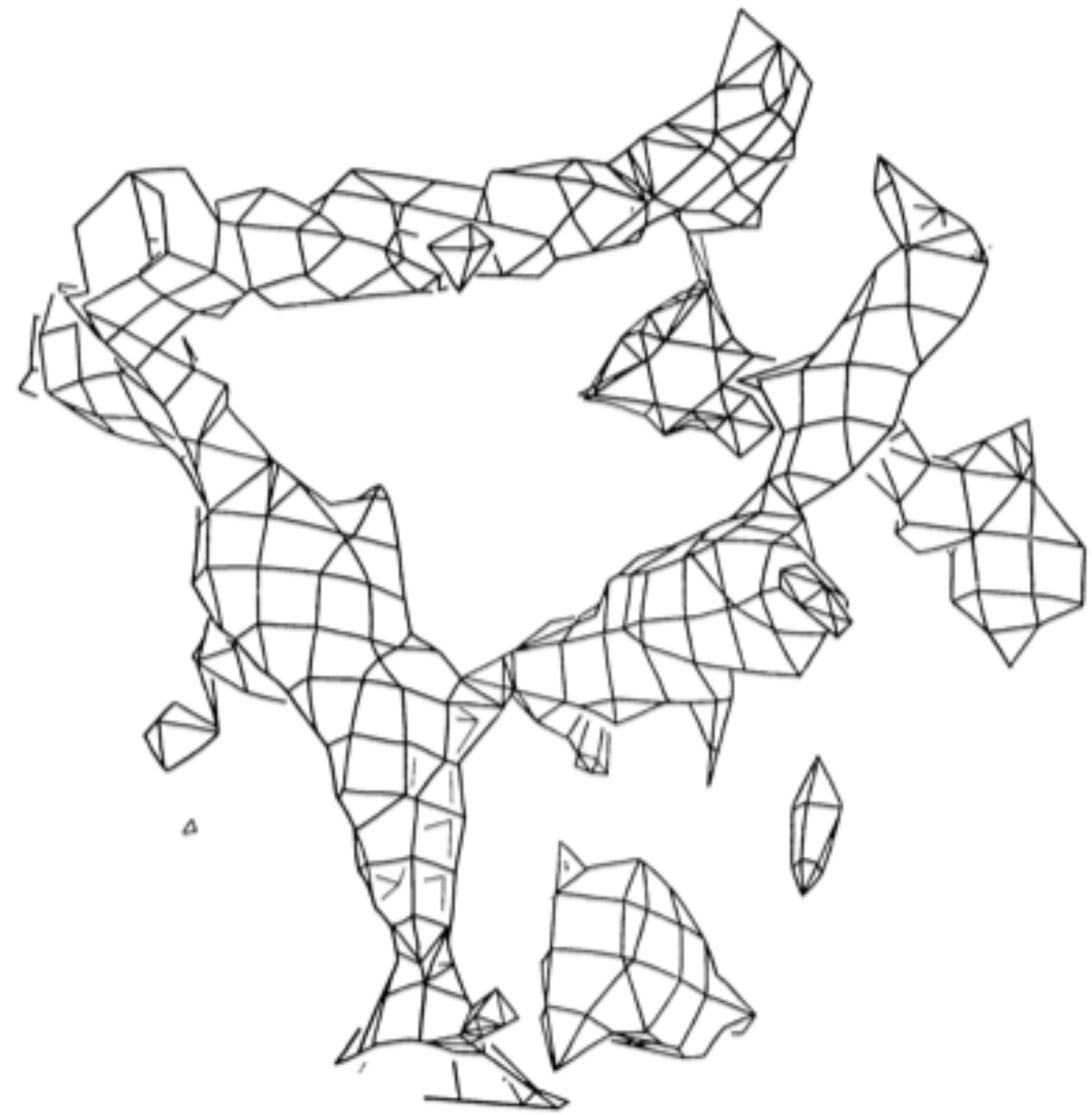


FIG. 1. A typical model isodensity surface, $\rho = 2.5\ \bar{\rho}$, within a randomly selected sphere of radius 45 h^{-1} MPc.

"… one may conventionally divide the cluster formation process into three steps. In the first stage, contraction along the axis with the maximum deformation rate would rise to a pancake, but its development would not halt any contraction that may take place along the other two directions.

In the second step some of the pancake material would contract along a second direction, forming curvilinear (not straight, in general) structures or "filaments", having a finite thickness substantially smaller than their length, as depicted in Fig. 1.

Finally, in the third stage flows along the filaments would produce compact clumps. Thus clusters would be born at points where even during the filament stage contraction had been occurring along all three directions."

Shandarin and Klypin 1984, Sov. Astron. 28, 491

This describes the evolution of structure with time.

« The order in which the physically significant structures arise
is basically the inverse of that in the classical pancake picture:

first, high-density peaks,

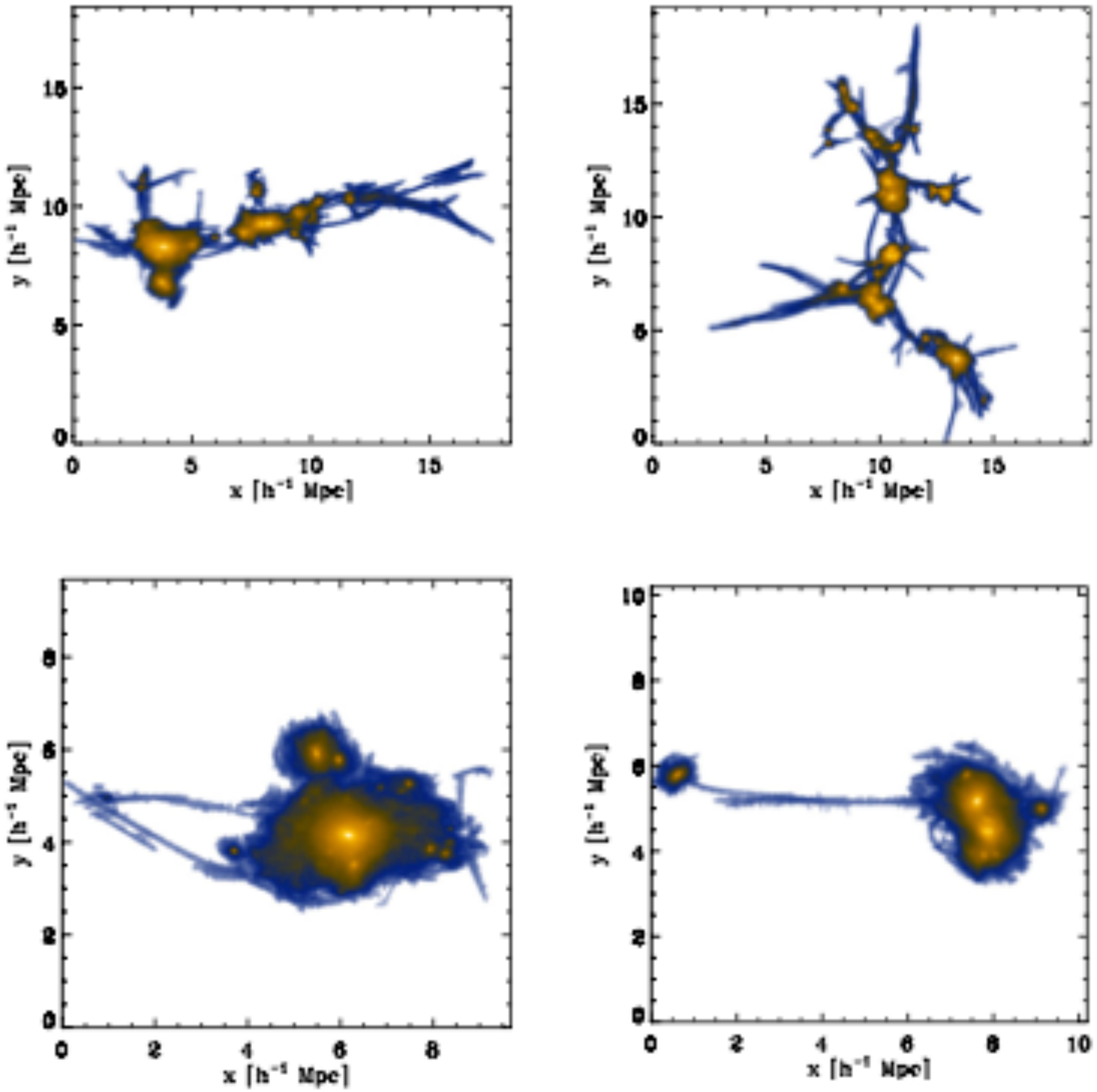
then filaments between them,

and possibly afterwards the walls,
defined as the rest of the mass between voids.”

Bond, Kofman, Pogosyan 1996, Nature, 380, 603
(top of page 605)

This is not a description of the evolution in time, instead this describes unfolding of four generic structures in the excursion set with decreasing threshold.

It is universal for all generic fields, no exceptions!



z= 1

z=0

Figure 2. The 'standard' linking length $b = 0.2$ selects large parts of a WDM simulation once the forces are captured accurately enough that filaments do not artificially fragment. Density projections of the particles belonging to the two most massive FoF 'haloes' in our WDM T4PM simulation of a 250 eV DM model are shown. Objects at $z = 1$ (top row) and $z = 0$ (bottom row) are shown. These haloes have a mass of 2.7×10^{14} and $1.6 \times 10^{14}\ h^{-1}\ M_\odot$ ($z = 1$), and of 6.4×10^{14} and $2.8 \times 10^{14}\ h^{-1}\ M_\odot$ ($z = 0$).

Angulo et al 2013

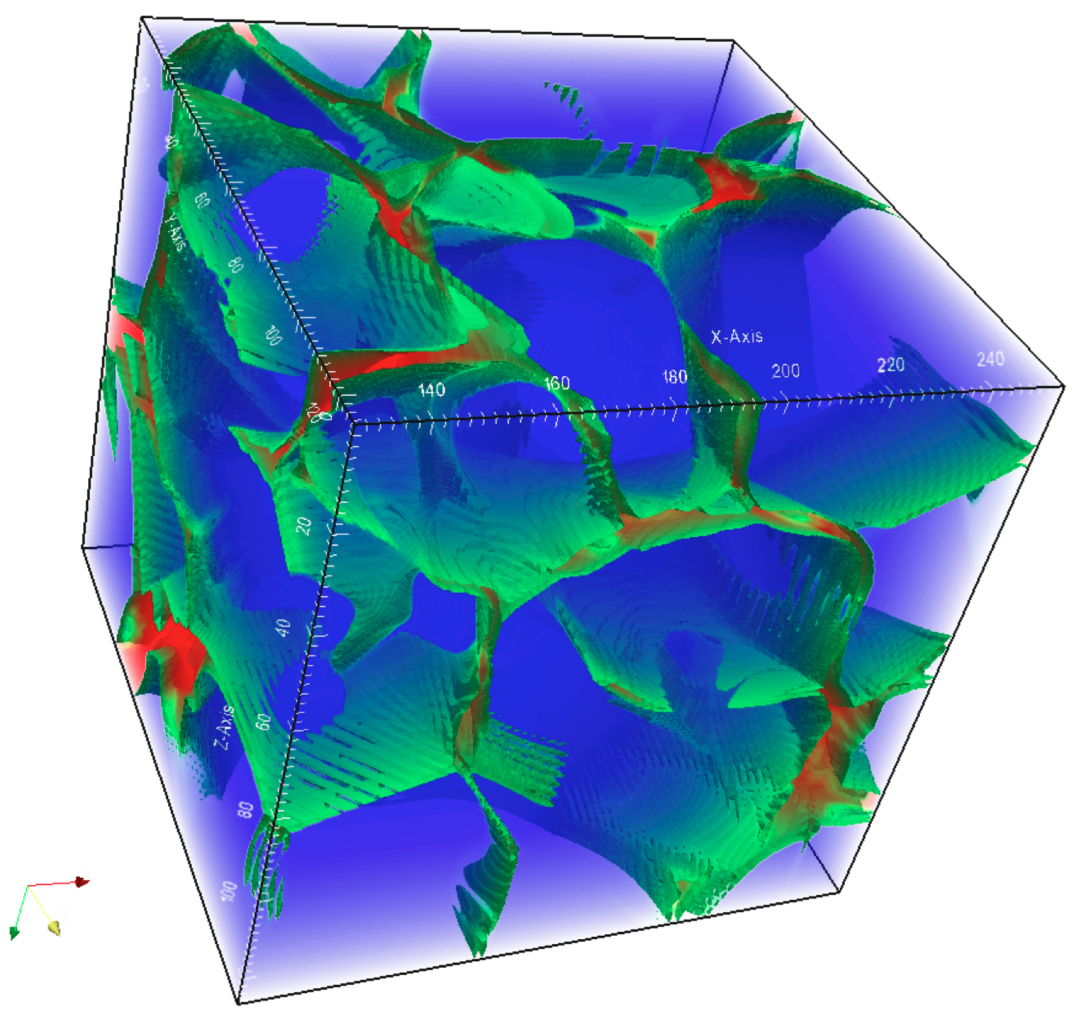
Three-dimensional numerical model of the formation of large-scale structure in the Universe

A. A. Klypin and S. F. Shandarin *The Keldysh Institute of Applied Mathematics, Academy of Sciences of USSR, Miusskaja Sq. 4, Moscow 125047, USSR*

Received 1982 November 15; in original form 1982 April 28

Summary:

(5) The regions of high density seem to form a single three-dimensional web structure. However, it is not clear from our simulations whether honeycomb structure arises or not.

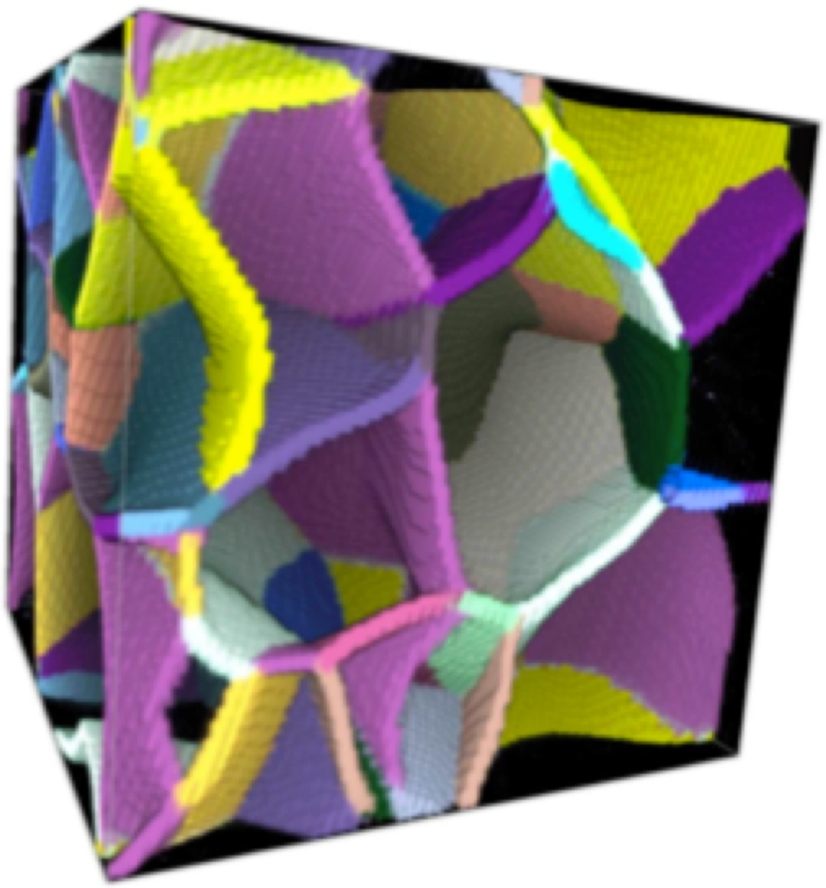


A new method of the analysis of cosmological N-body simulations based on computing the Lagrangian submanifold suggested by Shandarin, et al (2012) Abel et al (2012)
allowed to demonstrate that
the irregular honeycomb structure
is formed in Dark Matter distribution.

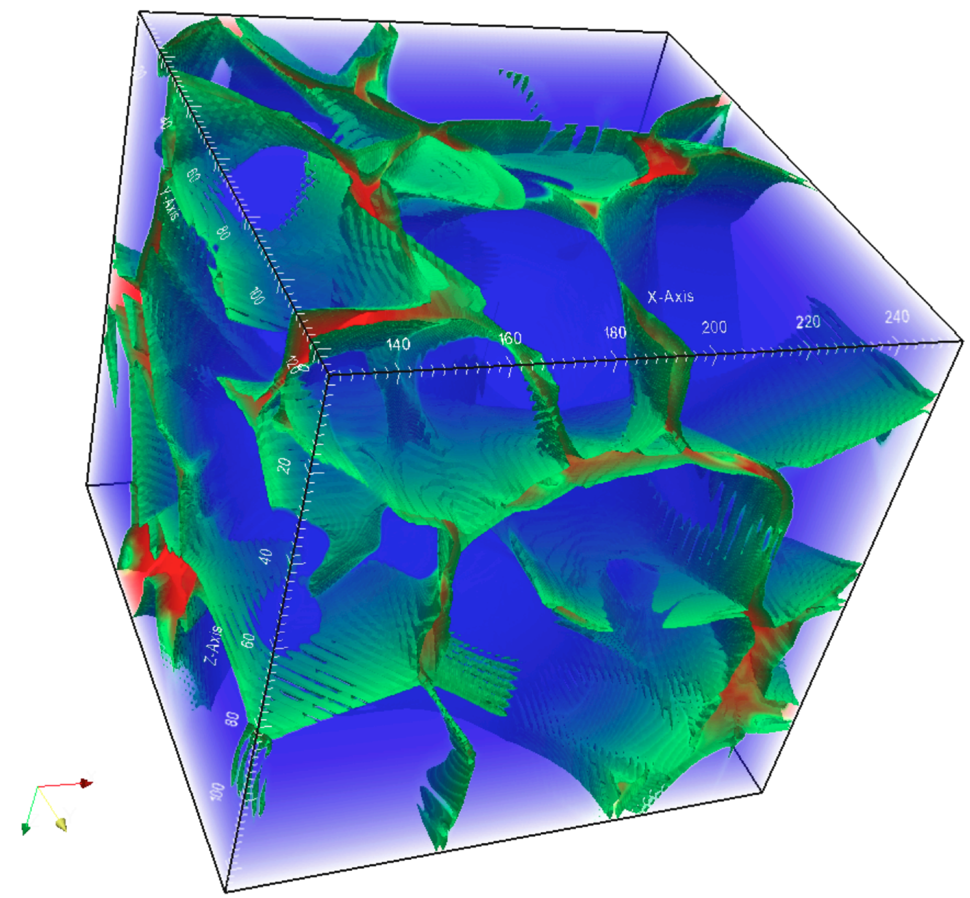
Zeldovich's pancakes in 3D

N-body Simulations Zeldovich Approximation

(note: initial random number are different)



Sausbie 2010
based on computing
Morse-Smale
complex

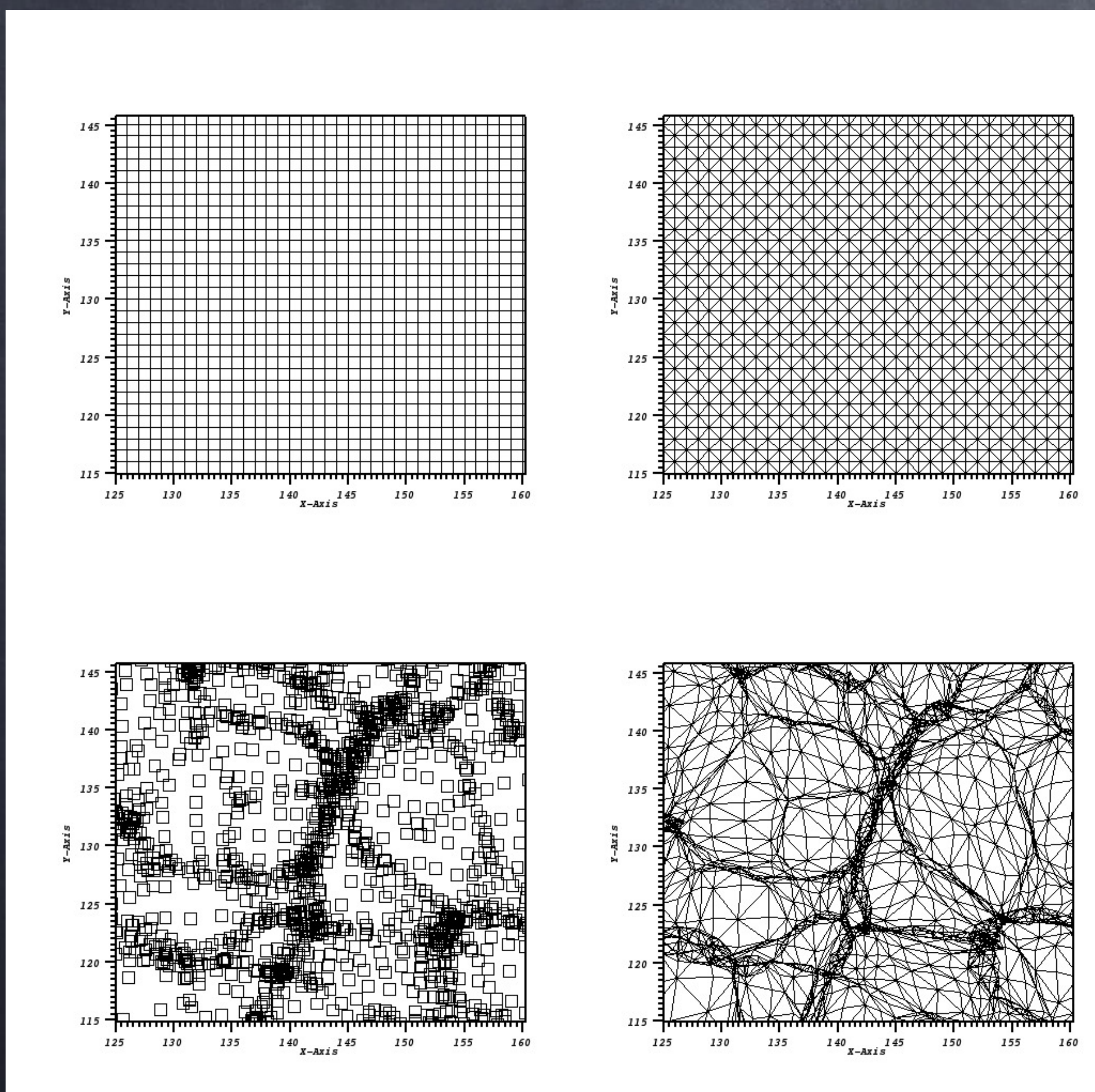


Hidding, Shandarin, van de Weygaert 2014

Multistream flows

2D example of triangulation of Lagrangian submanifold

triangulation of initial (Lagrangian) plane



projection of Lagrangian submanifold on Eulerian space

Decomposition of a cube in tetrahedra in 3D

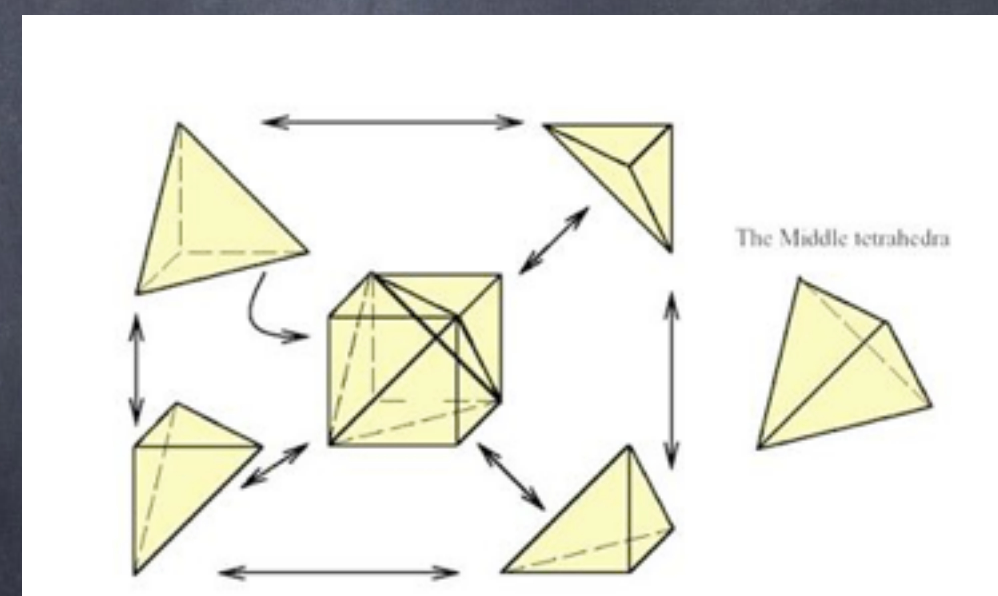


Figure 1.9: The Tetrahedra orientation within a cube

Why detecting Zeldovich's pancake in 3D simulations took so long?

Shandarin, Habib, Heitman 2012
see also
Abel, Hahn, Keuhler 2012

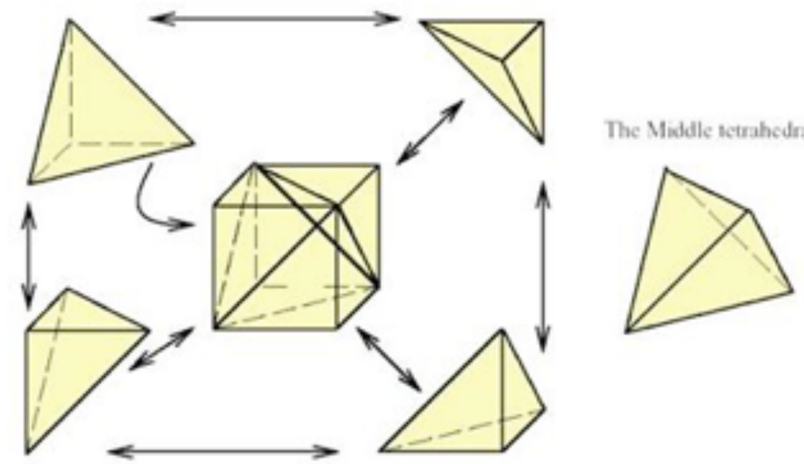
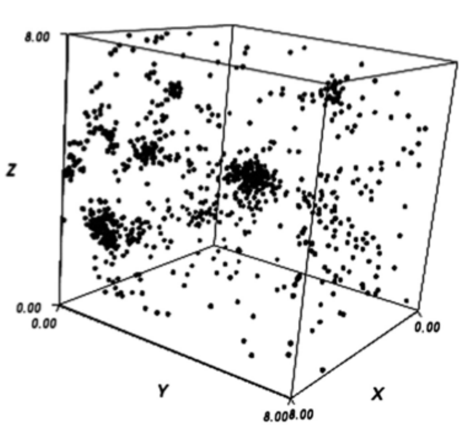
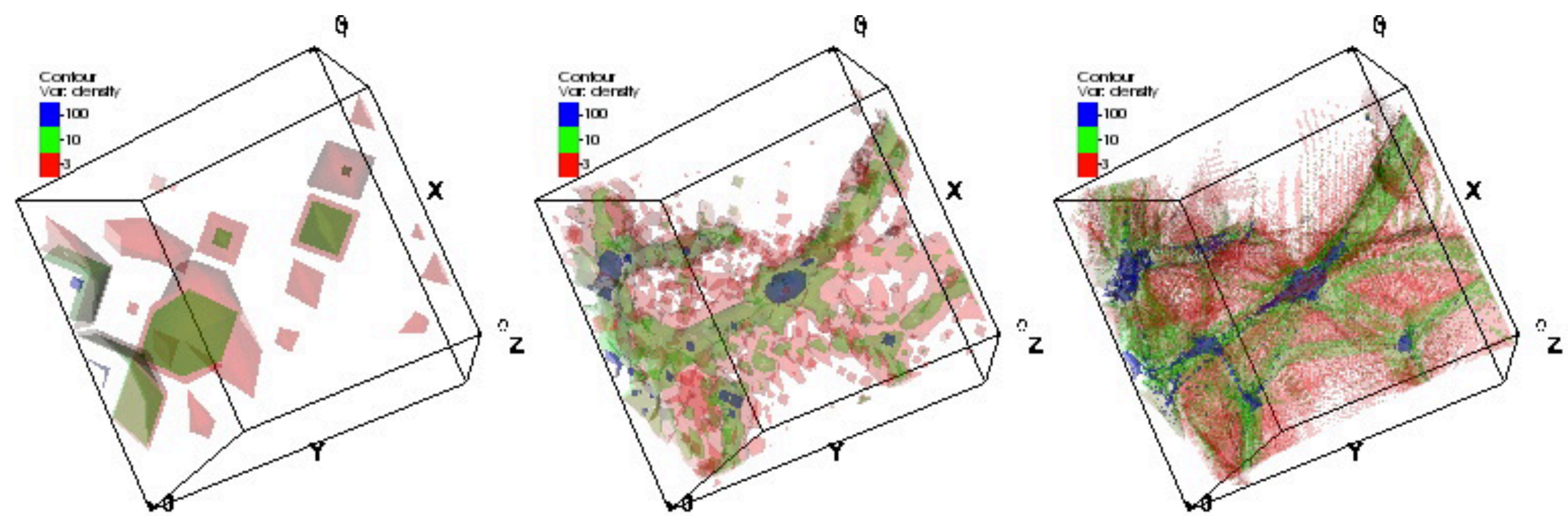


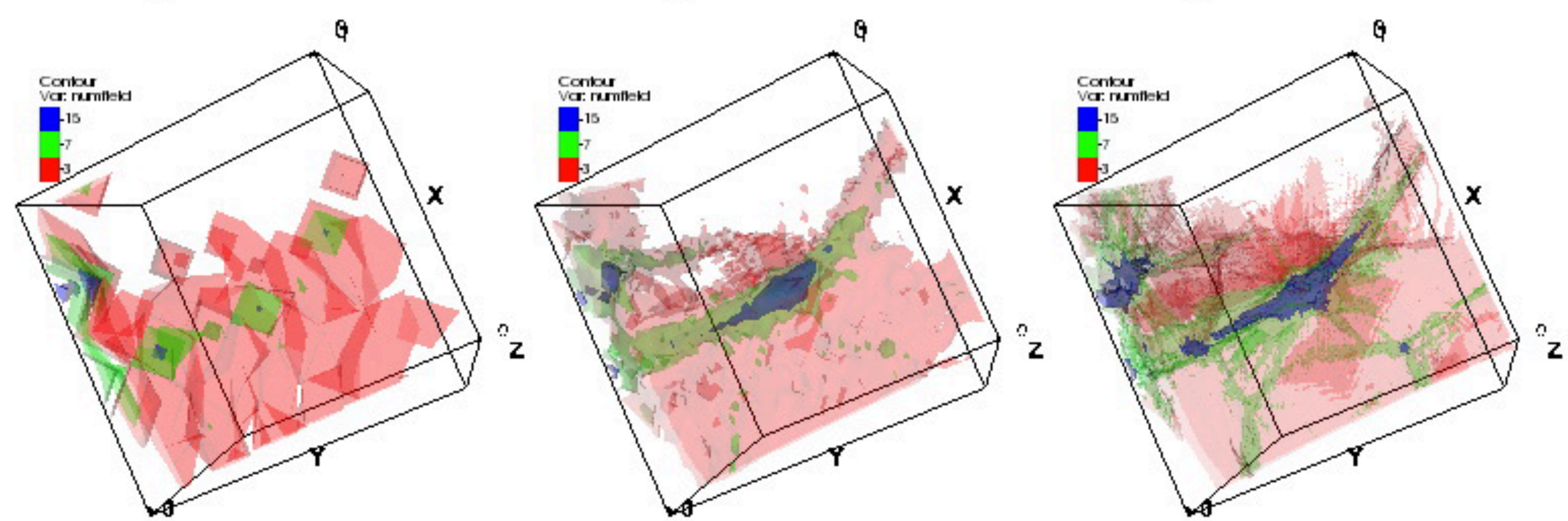
Figure 1.9: The Tetrahedra orientation within a cube



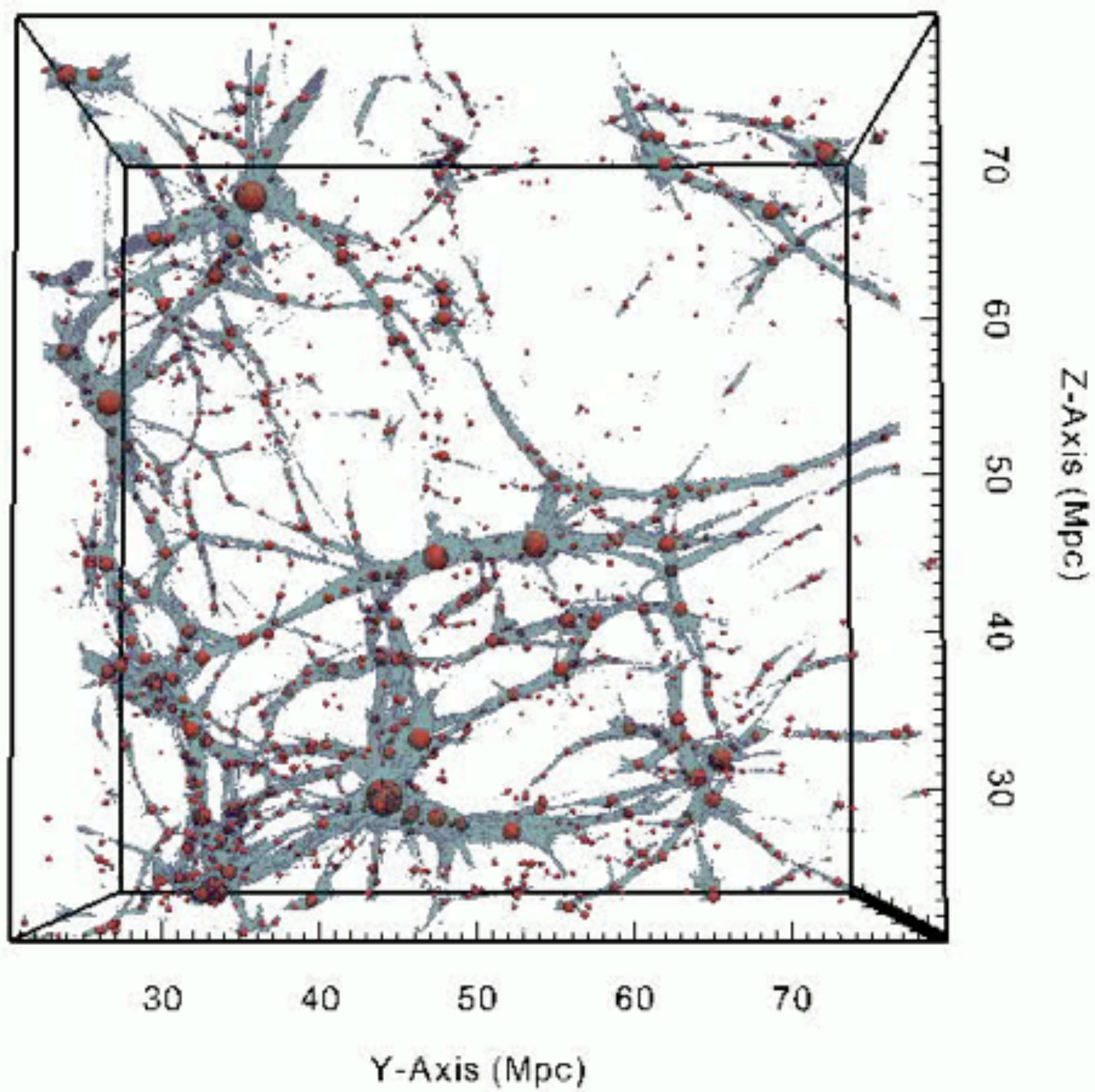
DENSITY FIELD



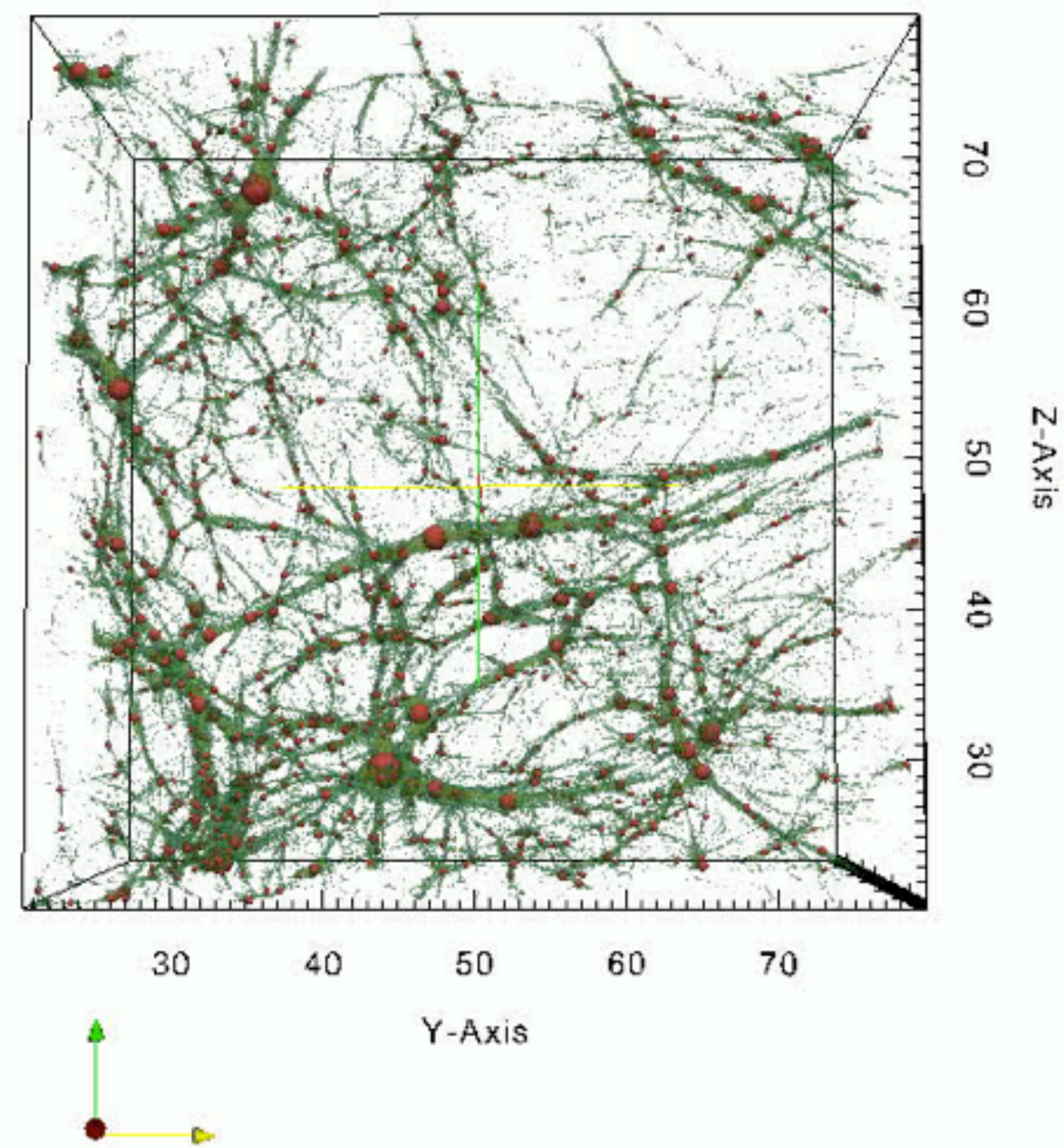
MULTI-STREAM FIELD



All halos are embedded in filaments



streams

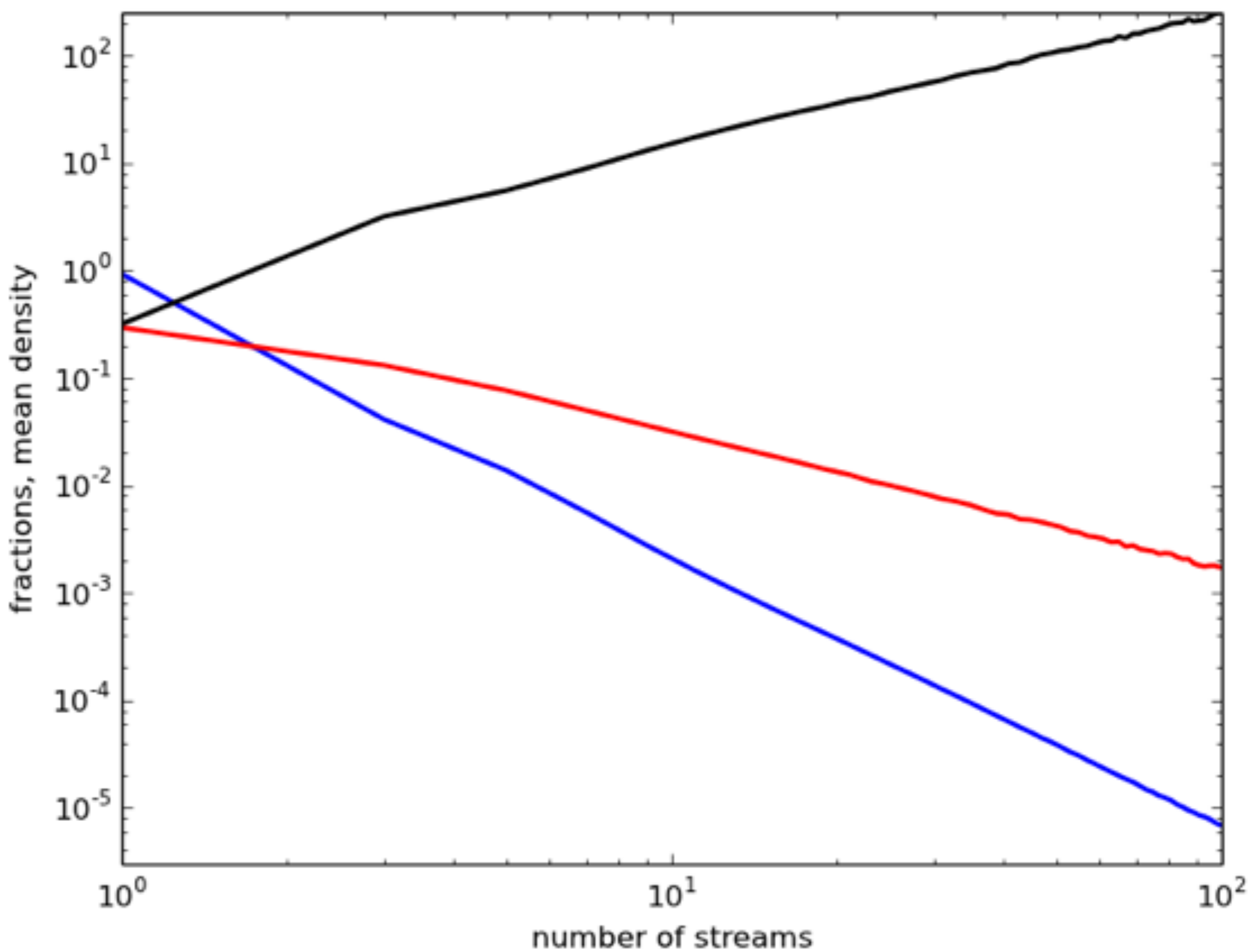


density

Fraction of volume with given number of streams - blue

Fraction of mass with given number of streams - red

Mean density in cells with given number of streams - black



den >= 200*(mean den)

v_frac = 0.03%

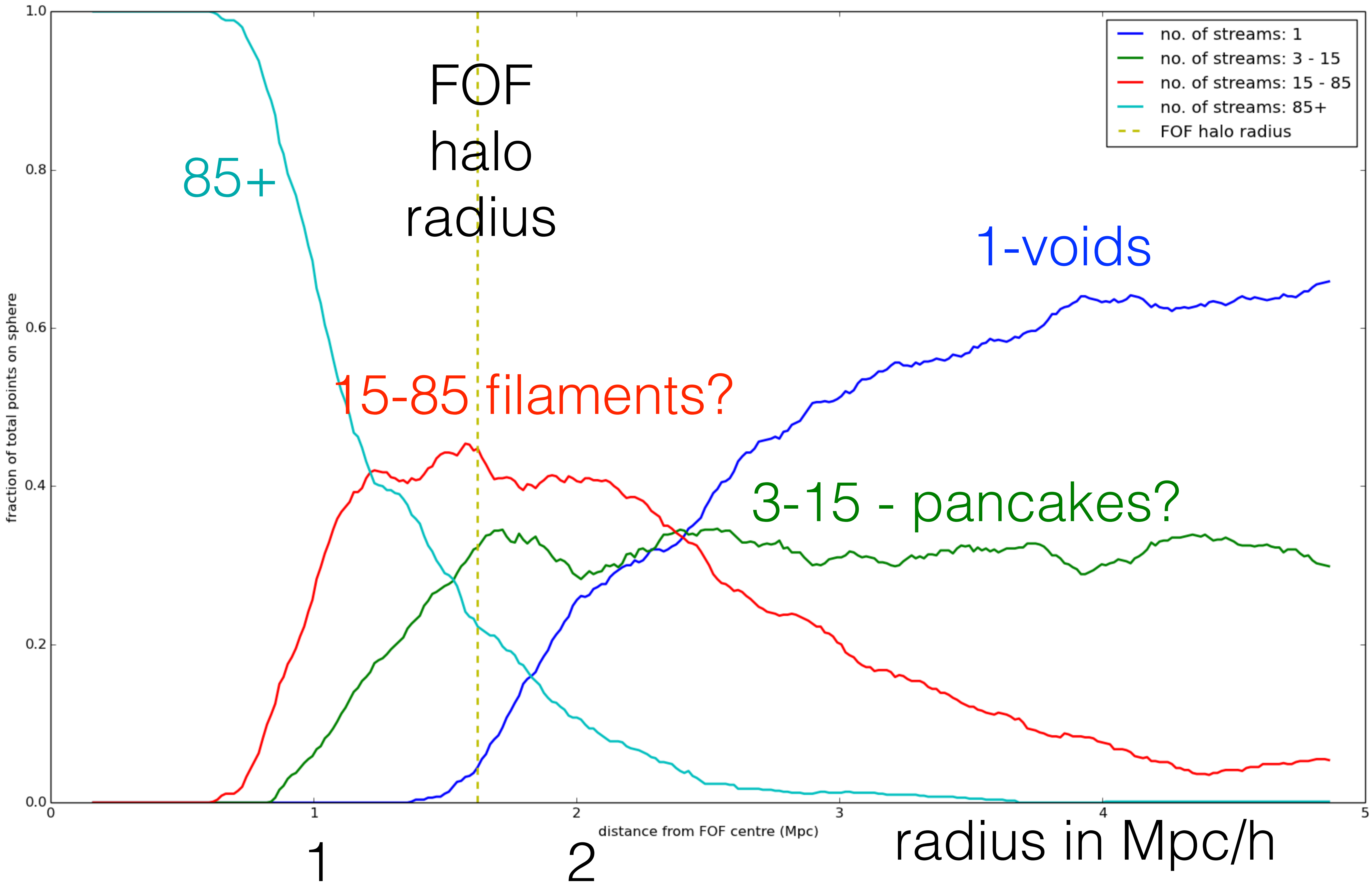
m_frac = 16%

<den> = m_frac/v_frac

= 492

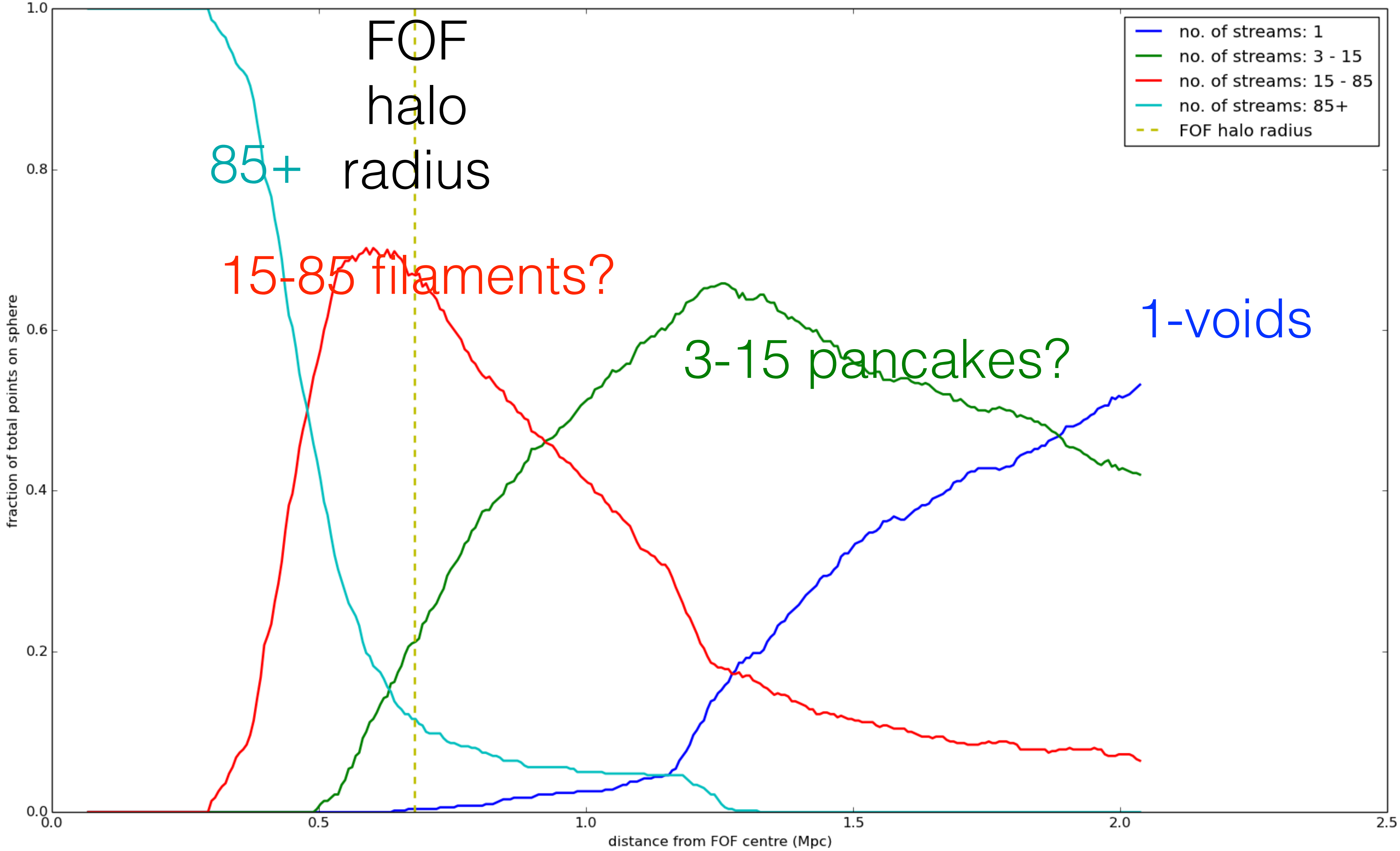
Fraction of points with a given number of streams as a function of radius

M=6e14 M_sun



Fraction of points with a given number of streams as a function of radius

M=4e13 M_sun



Lagrangian submanifold

Number of streams field

Flip-Flop field

Lagrangian Submanifold (LS) is N-dim surface in 2N-dim space

Zel'dovich 1970

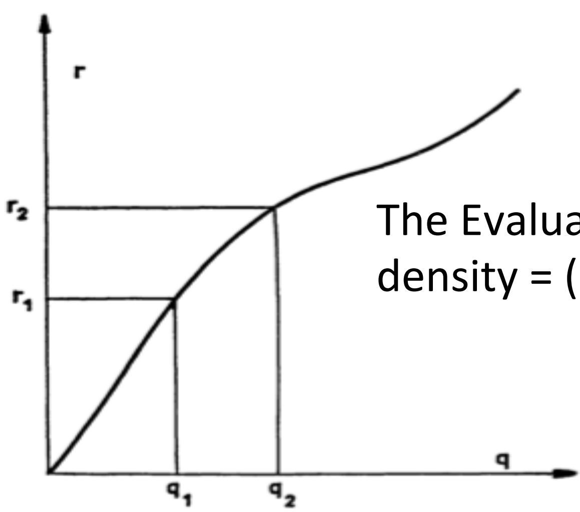
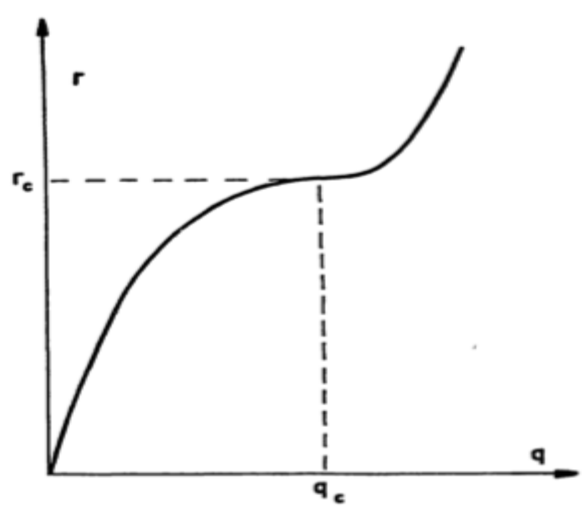
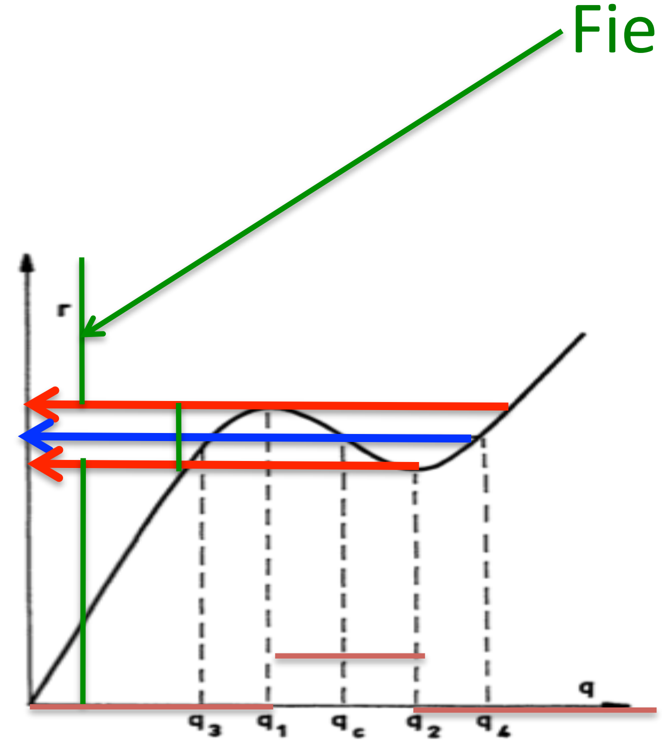


Fig. 1

The Evaluation of Density:
density = (q[i+1]-q[i]) / (r[i+1] - r[i])

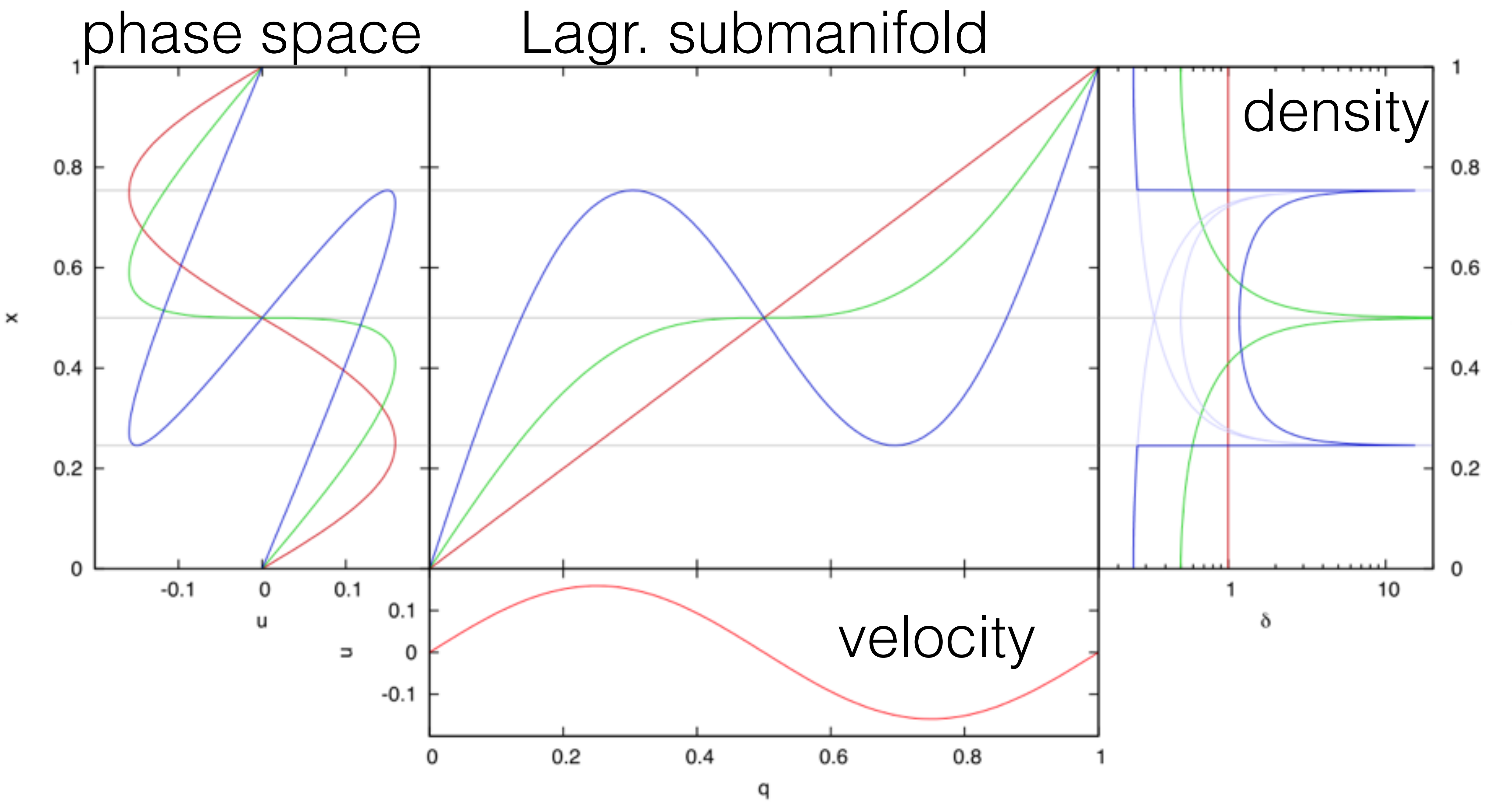


Multi-Stream Field



Flip-Flop Field

Phase space and Lagrangian submanifold in 1D

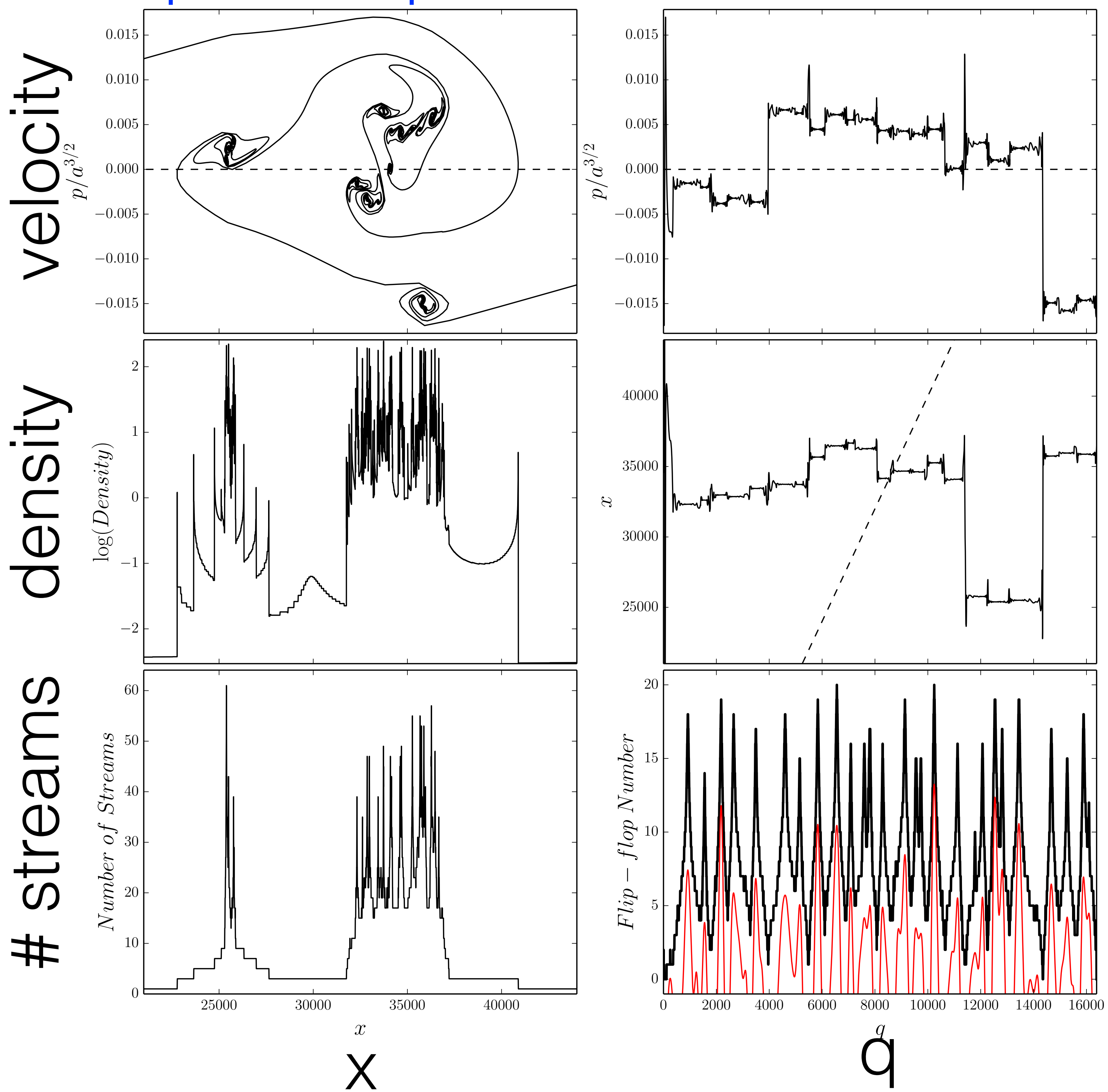


Three stages are shown: initial - red
critical - green
final - blue

Halo in 1D N-body simulation

Shandarin,
Medvedev,
Hidding 2014
in preparation

phase space



Phase space sheet : multivalued, non metric

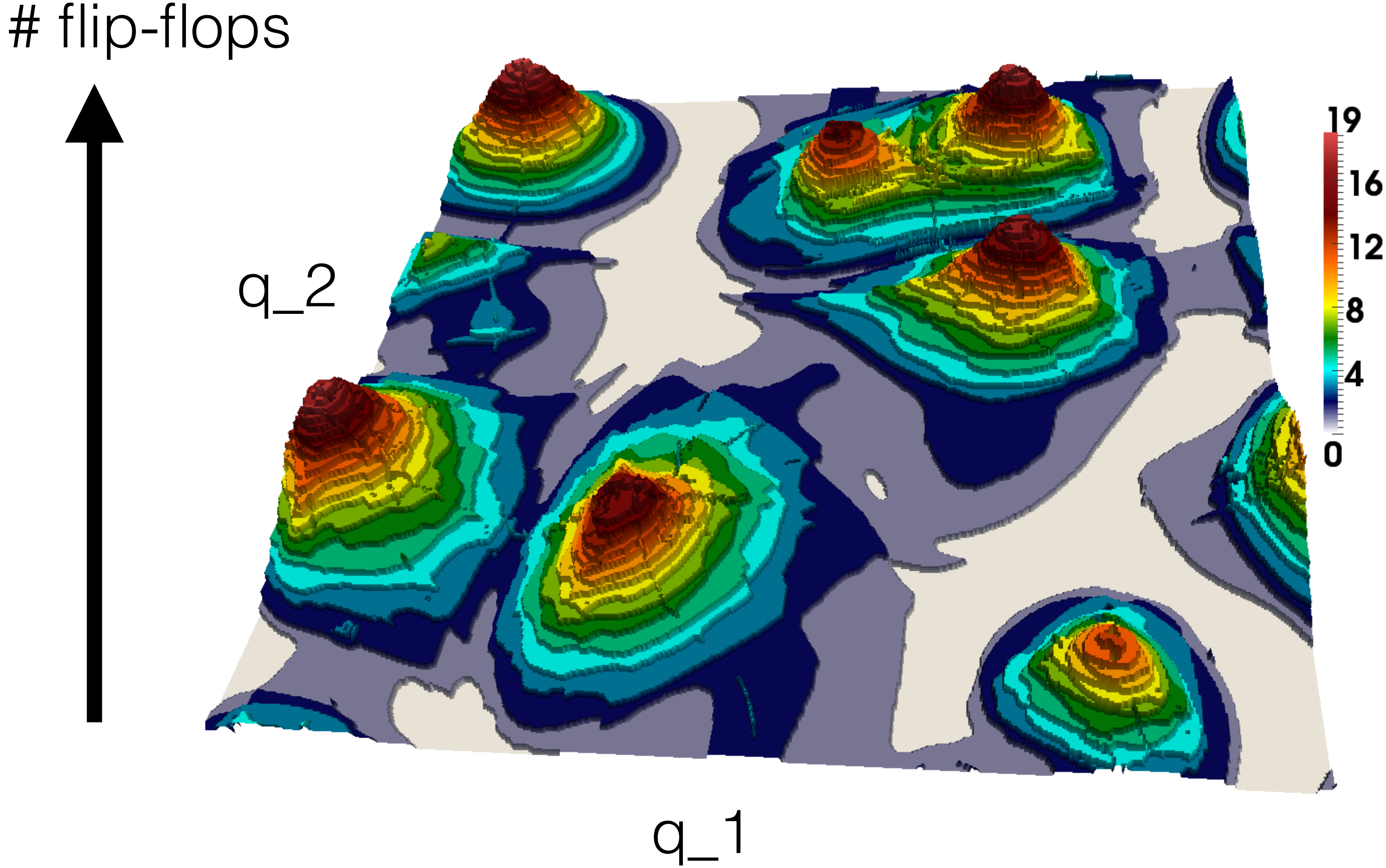
Lagr. submanifold: single valued, metric

Lagrangian submanifold: x = x(q)

Flip-flop number

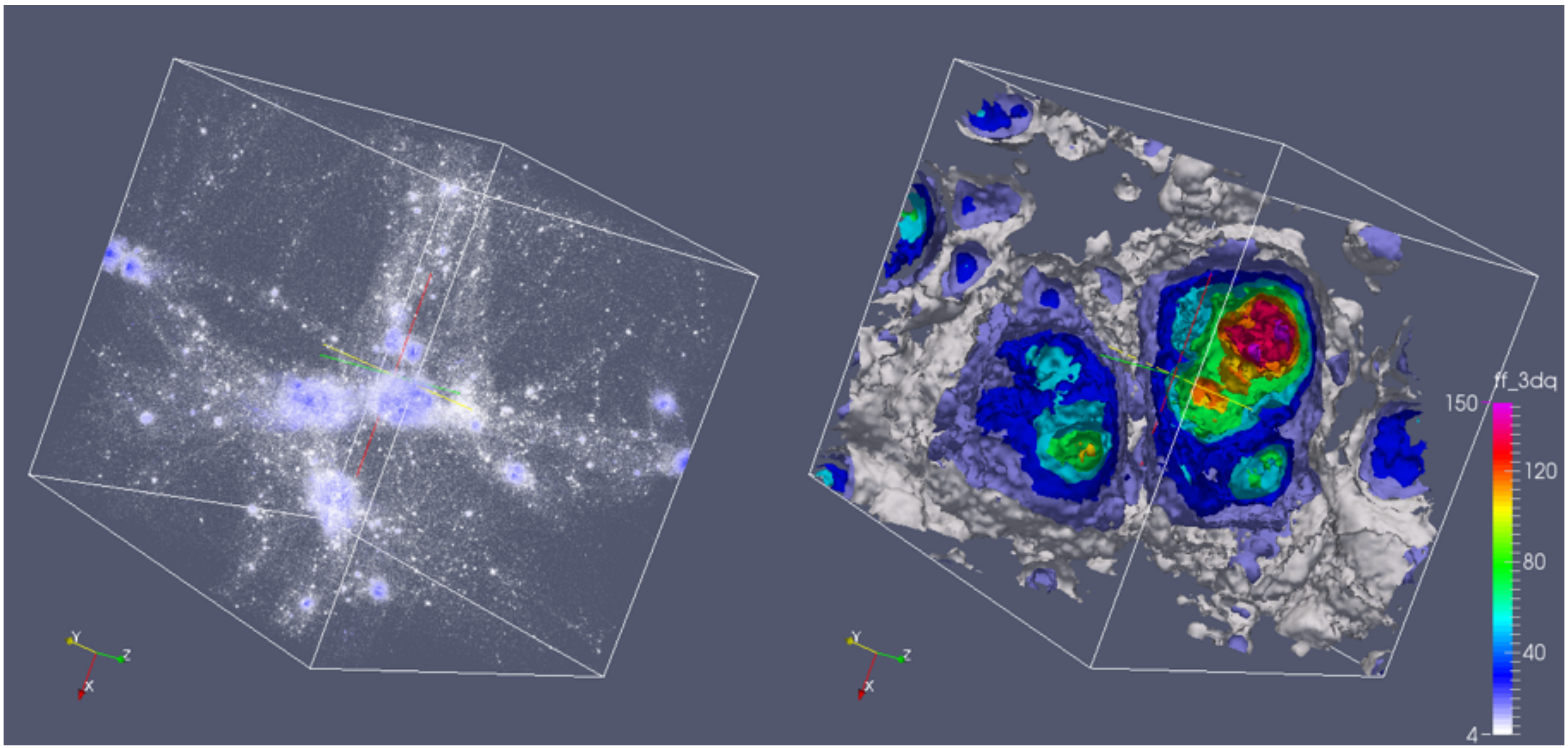
2D

Flip-Flop Field in Lagrangian space in 512^2 simulation
(smooth initial conditions)



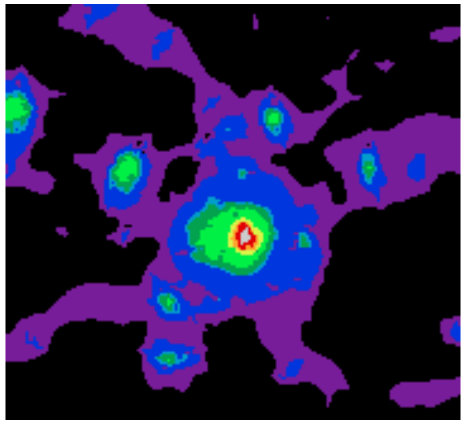
Shandarin, Medvedev, Hidding 2014, in preparation

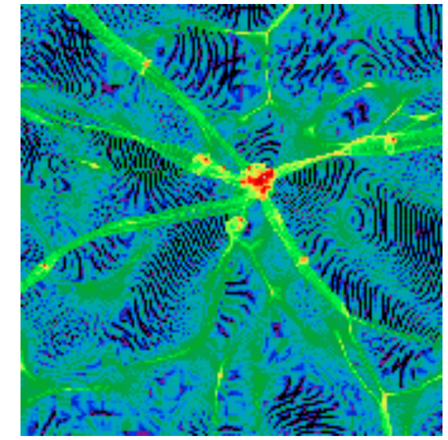
3D simulation in LCDM model: box size 1 Mpc/h, Np= 256^3



Lagrangian Skeleton

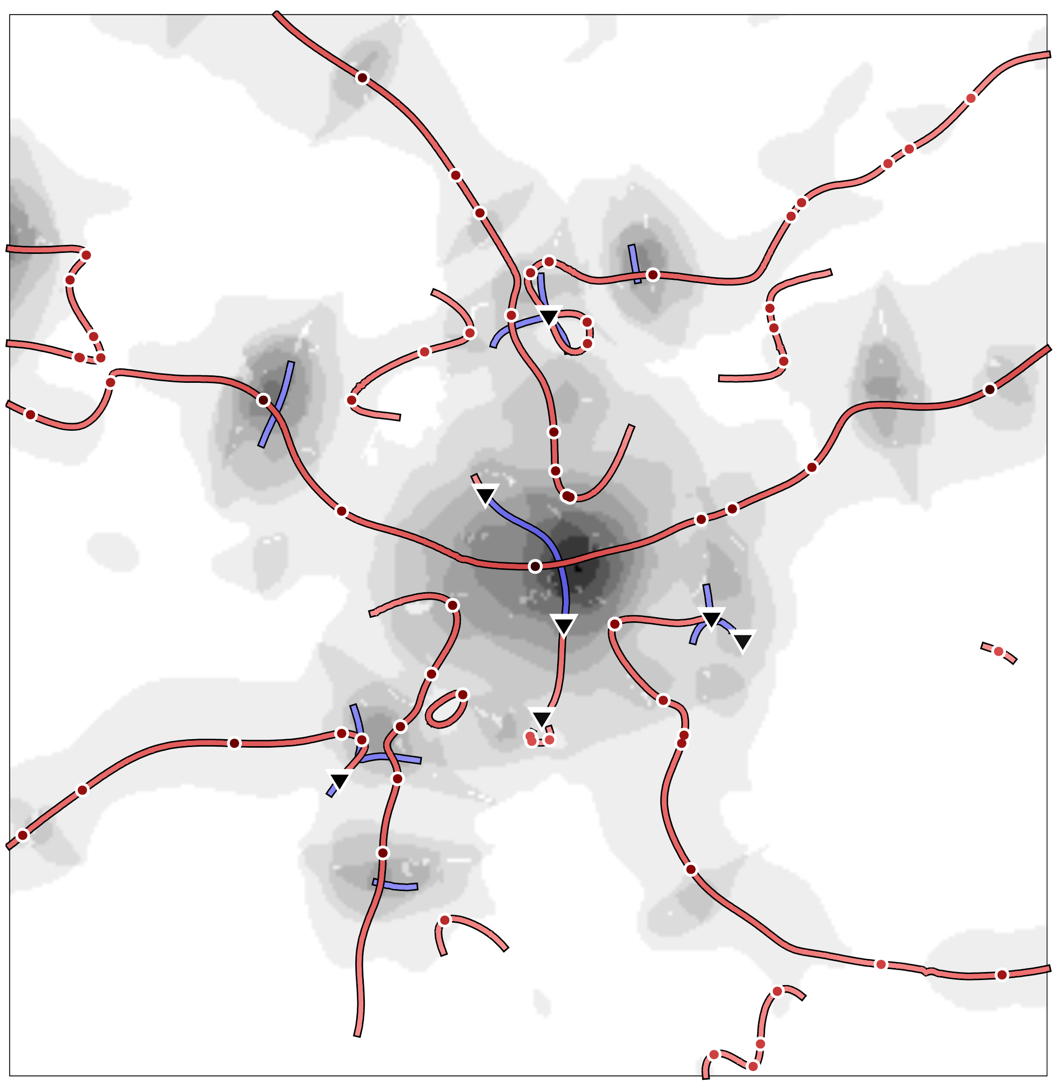
and Flip-Flop Field

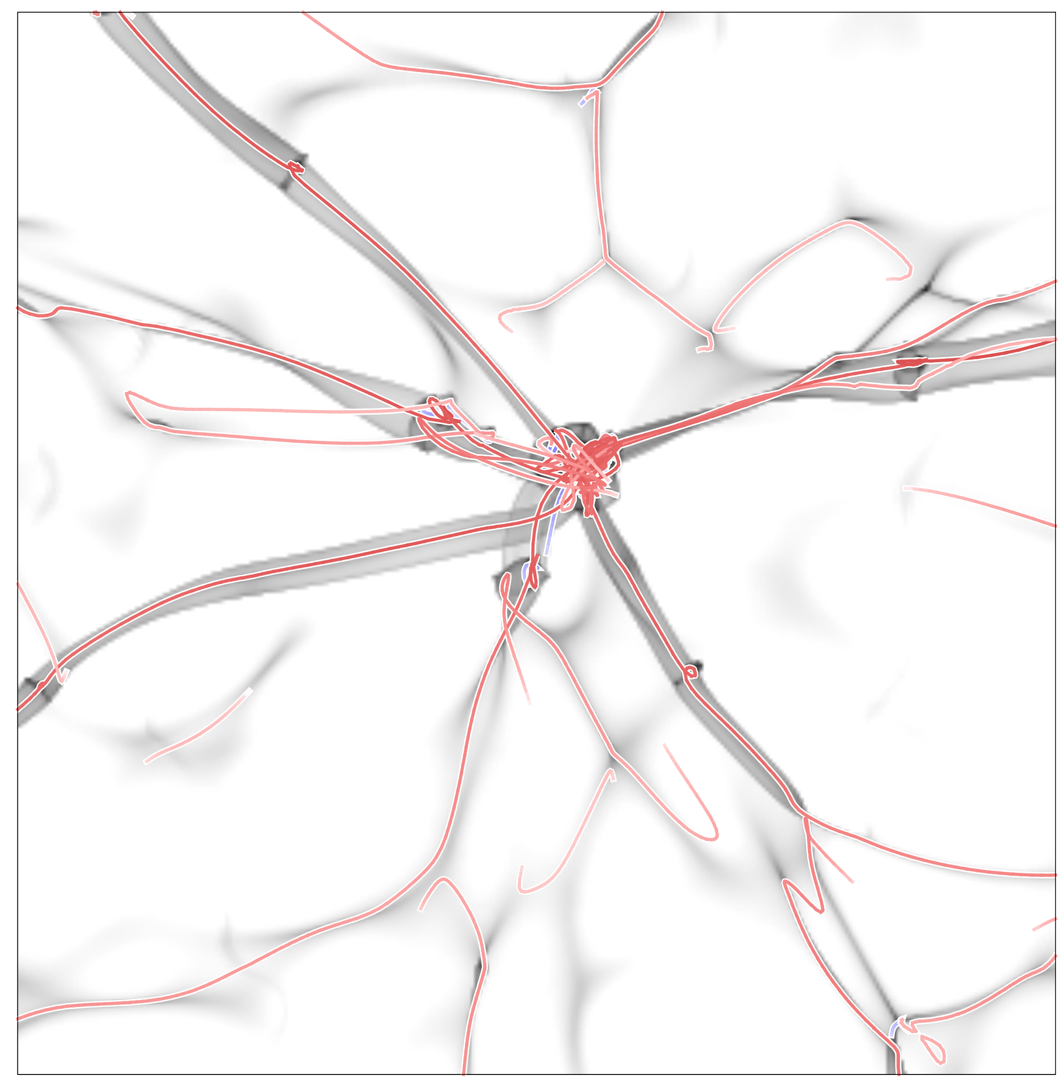




Lagrangian

Eulerian





Summary

The Zel'dovich approximation provides the necessary concepts and language for describing complex geometry and dynamics of DM structures.

The sequence of formation of generic elements in DM structure is
1) pancakes,
2) filaments on the crossings of pancakes,
3) halos on the crossing of filaments

Halos are embedded in filaments and filaments are embedded in pancakes.

The skeleton of the Cosmic Web derived from Zel'dovich approximation allows to trace the dynamical evolution of the Cosmic Web and provides quantitative characteristics of the web.

Summary

New fields: number of streams and flip-flop fields reveal new properties of the cosmic web. They are easy to compute from standard cosmological simulations.

Number of streams field as a function of Eulerian coordinates allows to set physical limit on the total volume and mass of the voids:

for LCDM volume fraction is ~93% and mass fraction 24%

The number of flip-flops as a function of Lagrangian coordinate stores the information about the substructure of DM halos.