The Cosmic Web

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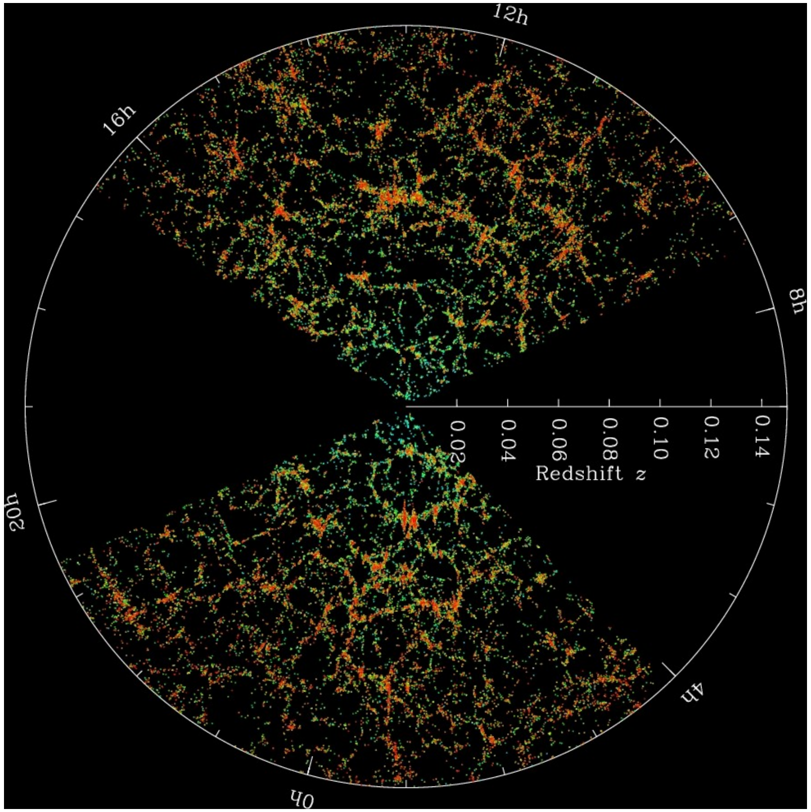
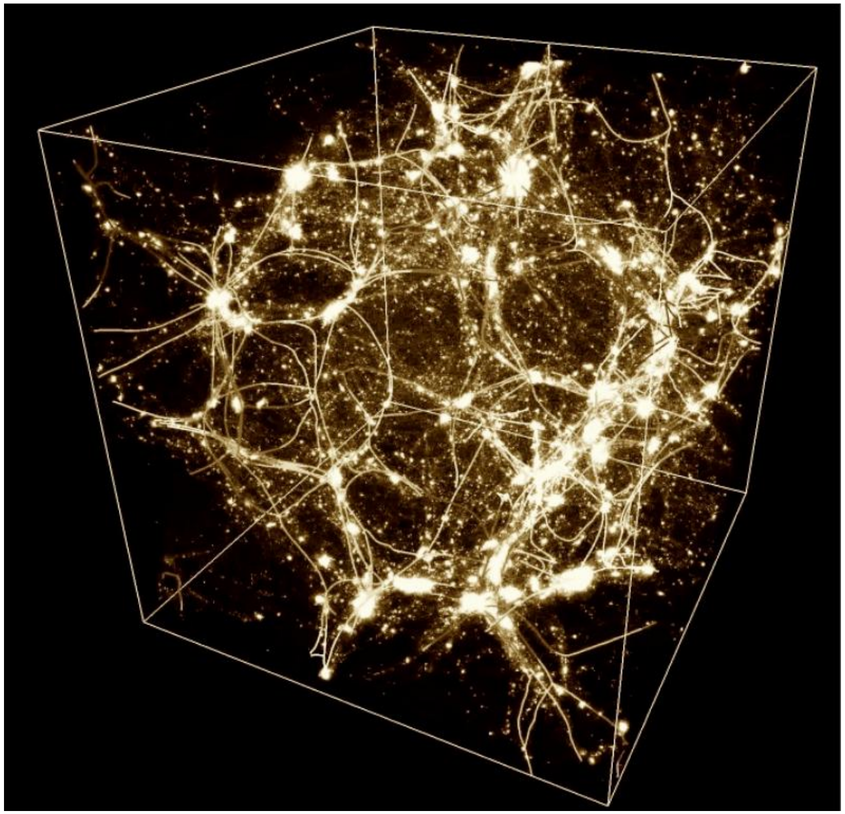
Large scale structure is evident in both observation and simulations



Sloan DS Survey



Horizon project

Cosmological Paradigm for Large Scale Structure (in Dark Matter)

- The structure in matter distribution originates in random, Gaussian, initial density perturbations $\rho - \bar{\rho}$
- Initial velocities of matter particles are potential and are not independent on density contrast

$$\nabla \cdot v \propto \rho - \bar{\rho}$$

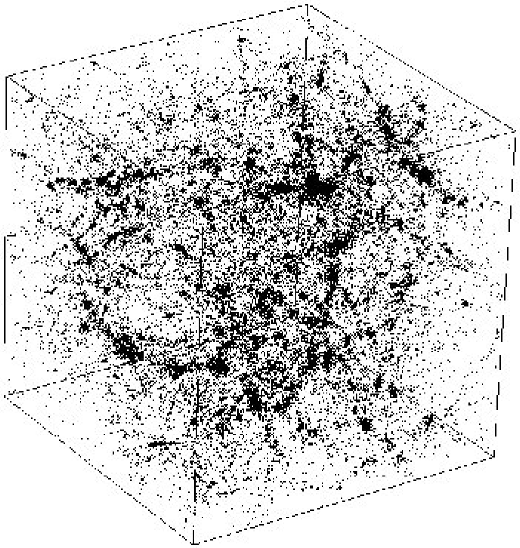
- Initial conditions are set by only one scalar degree of freedom. This leads to very non-generic relations. E.g., *non-local* tide on a Lagrangian patch is proportional to *local* velocity shear *within* the patch
- Growth of inhomogeneities is governed by gravity
- Structure assembles from small scales (that become nonlinear earlier) to large ones

The Cosmic Web (Bond, Kofman, Pogosyan 1996)

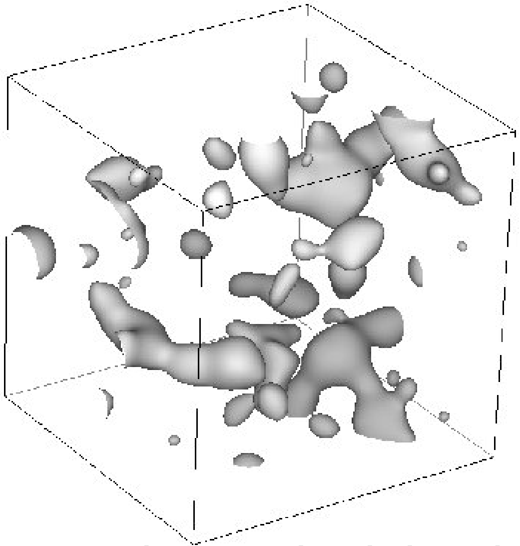
Part I – what mechanism is responsible for LSS and its morphology ?

- The observed LSS on mildly non-linear scales has originated in the geometrical features of the random field of initial inhomogeneities, amplified by the gravitational instability.
- The most prominent features of the Cosmic Web at z=0 are clusters of galaxies that form from rare density peaks, and filamentary bridges between them that are generic for Gaussian initial conditions.

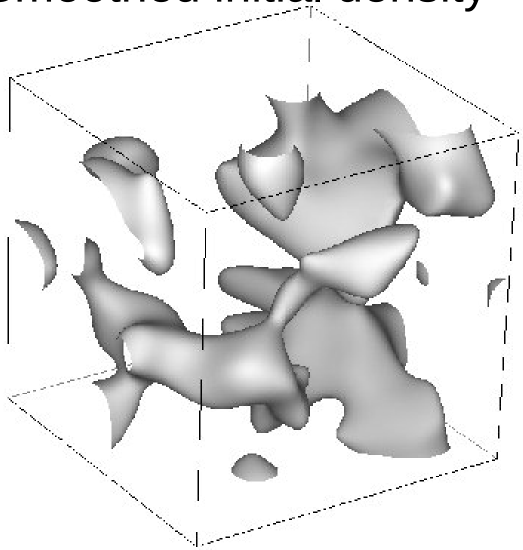
N-body



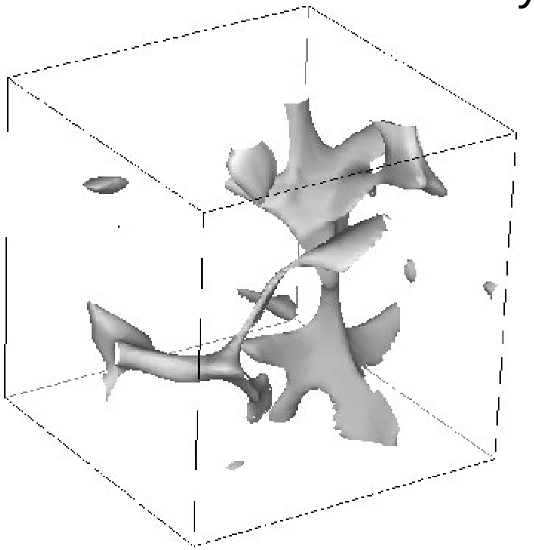
Smoothed end density



Smoothed initial density



Evolved smoothed density



V. Springel movie

Theoretical issues back in mid 90-s:

Two prevalent approaches:

- Zeldovich caustics (Shandarin, Arnold, Zeldovich) – structure formation is caustics (multistream region) formation, proceeds starting from planar pancakes, then matter moves to intersection of pancakes – filaments (as next order caustics) and then to knots. Originally came from HDM models.

  Was not directly supported by simulations, even early HDM ones (Klypin 1983) showed flattened filaments rather than pancakes (but were inconclusive). J.Peebles argued that caustic picture is inapplicable for CDM where velocity coherence is not present – we had to talk about ‘second generation pancakes’ of LSS 10+Mpc scales, that would be if you smooth initial conditions (good idea). Peebles then argued, correctly, that anyway matter does not have enough velocity to migrate over distances of such large structures, so LSS has to form where kind of where it is already is.

- On the other hand there was Halo collapse and clustering models (from spherical collapse to Bond/Myers peak patches) – local definition of halos, successful in explaining cluster halo bias. But did not go down to study other morphological configurations

- Besides, there was a puzzle that the length of filaments exceeds isotropic density correlation length by few factors – why would we have such extended objects ?

So in Cosmic Web picture we mostly tried to reconcile/resolve this different views

Starting point was to split displacement of particles in large-scale (background) and small-scale parts

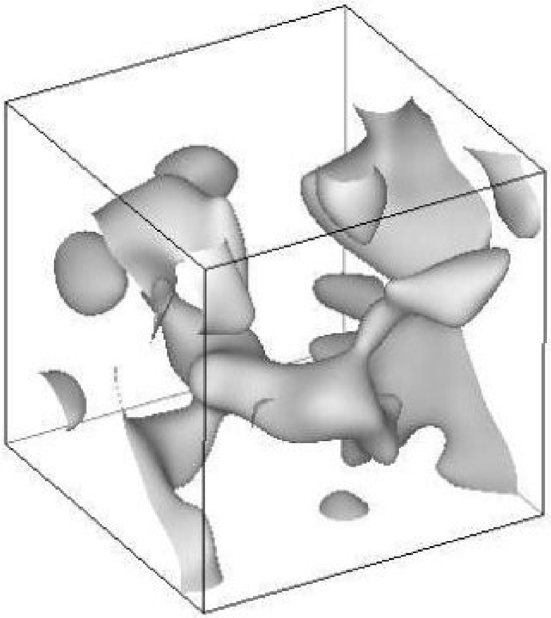
$$\mathbf{s} = \mathbf{s}_b + \mathbf{s}_s$$

where background was defined to produce map that is in a single stream almost everywhere (besides perhaps in very dense objects), and focus on the structures created by such truncated background maps where we no there is no shell-crossing. We found that we should smooth initial field to z=0 linear σ=0.65 (which basically means – to R=8 h^{-1} Mpc tophat)

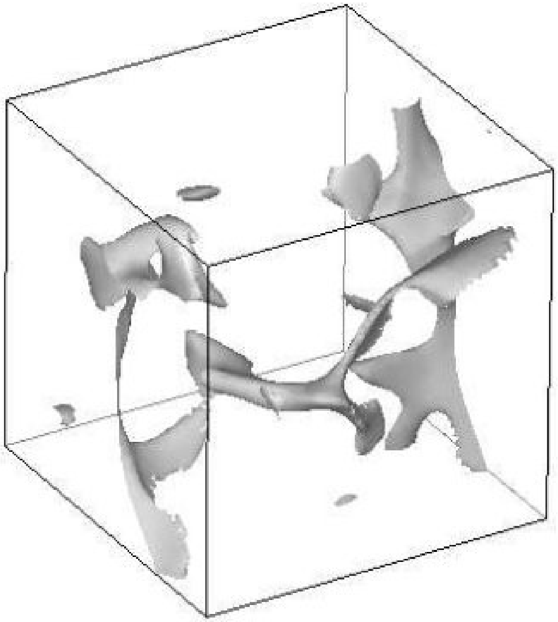
The question was – what structures one actually should expect to arise from truncated map ?

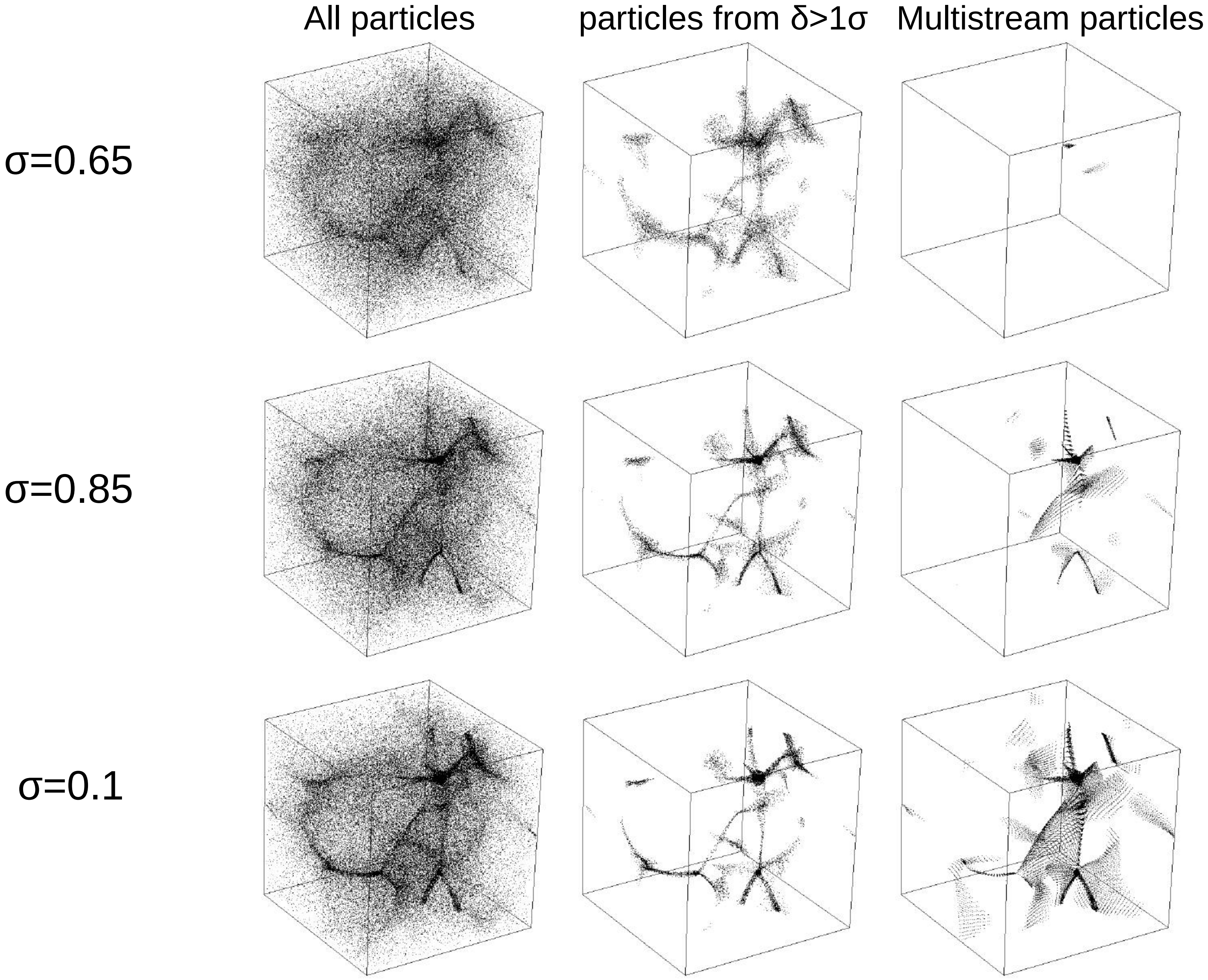
In the truncated map we see highly complex, predominantly filamentary Cosmic Web, that preserves morphology from initial conditions. Non-linear dynamics sharpen the structures up, and flatten some of then, such us making ribbons from filaments

Initial



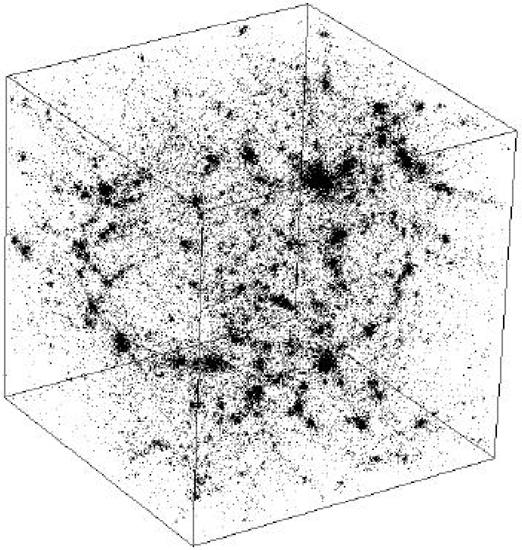
Final



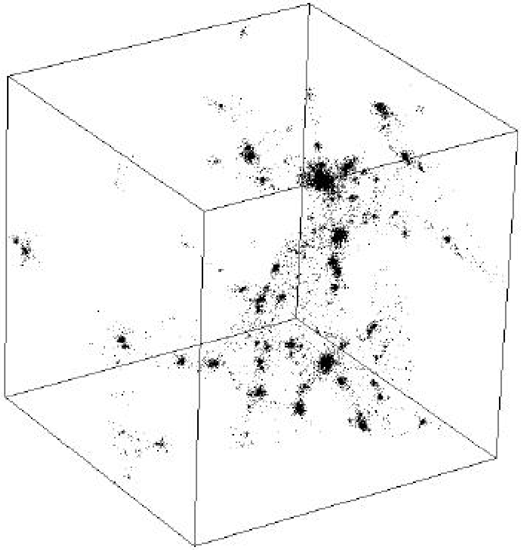

All particles
particles from δ>1σ
Multistream particles
σ=0.65
σ=0.85
σ=0.1

Matter distribution in (truncated) multistream region

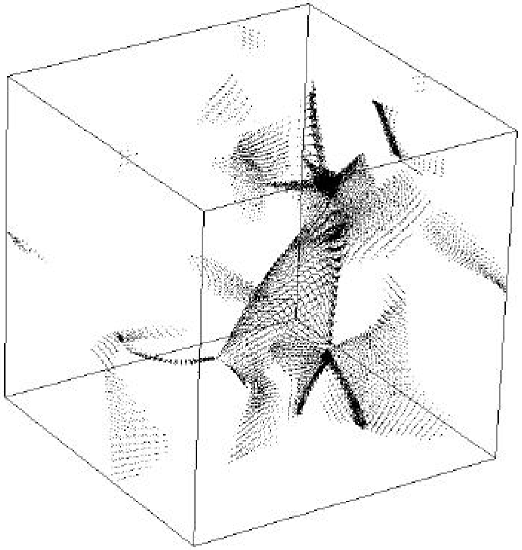
Full N-body map



Full N-body map of
multistream particles



truncated map of
multistream particles



“Multisteam” is defined on truncated map. By the time caustics become prominent in truncated map, they are fragmented

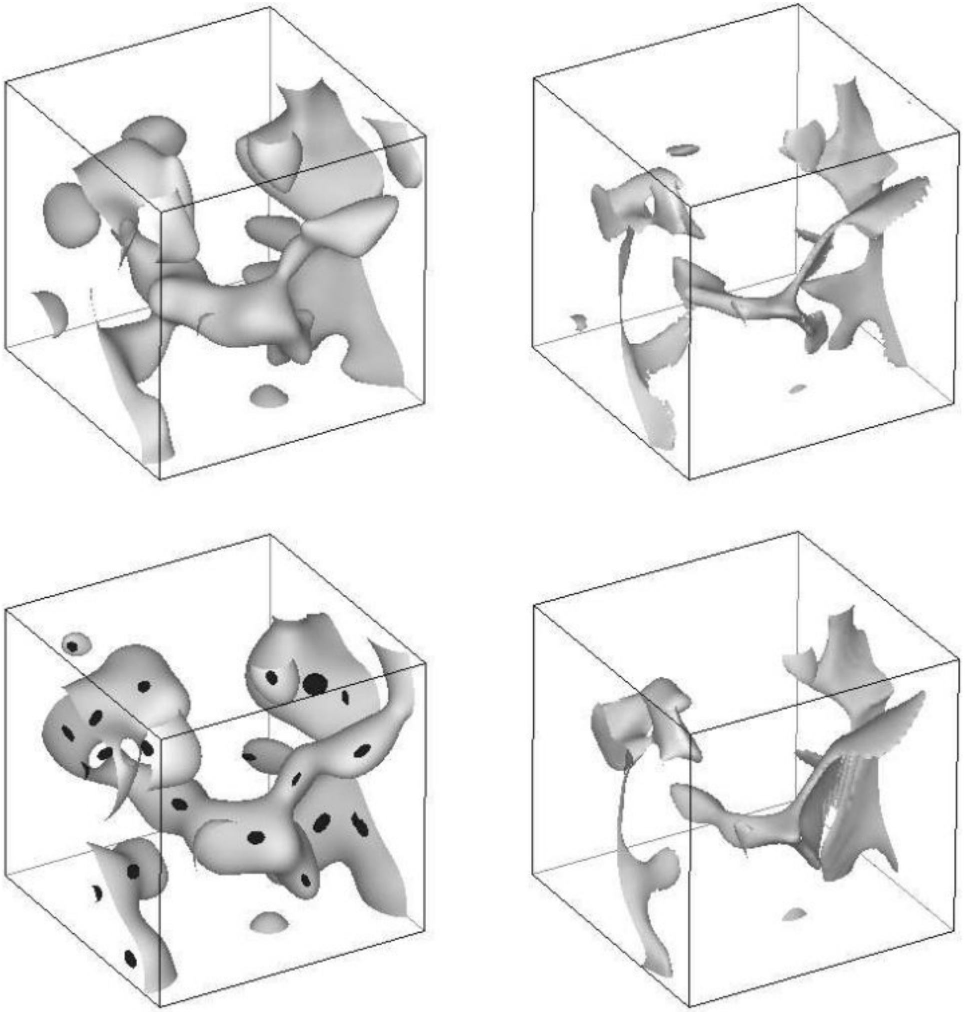
Part II: how the LSS morphology is built into Gaussian initial field ?

This leads to study of geometry of random fields, all subsequent work on skeleton, critical points, etc, but first task was to explain the length

- The high rare peaks of the density field largely define how large scale structure looks like. Filaments are dense bridges between the peaks

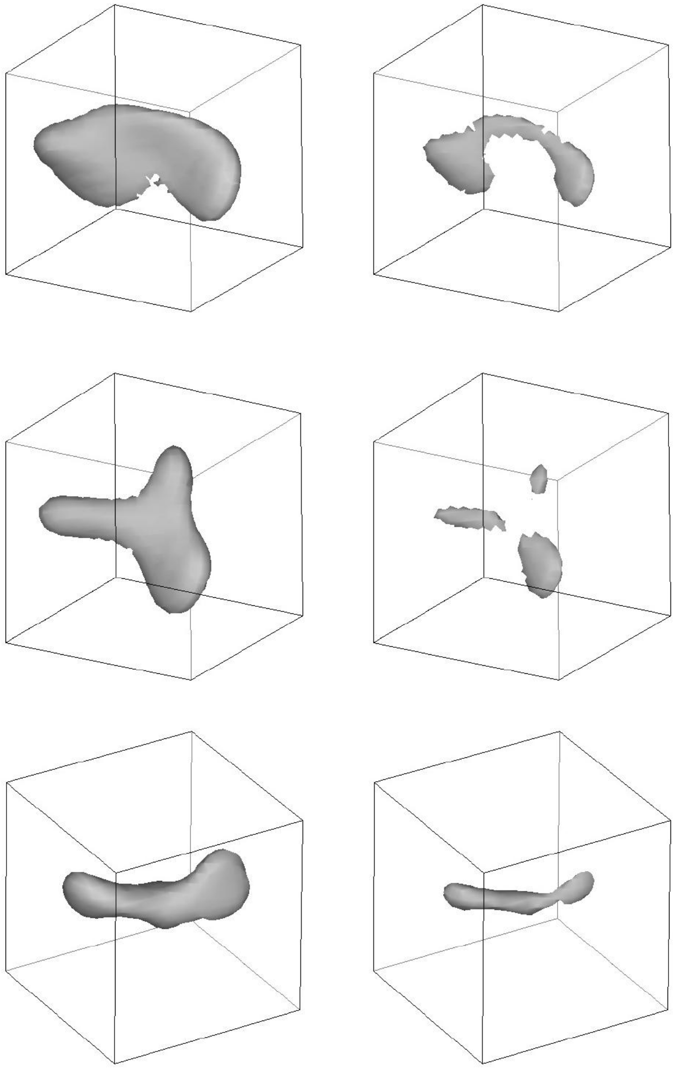
- Prominent filaments appear between peaks with aligned tidal (or shear) fields around

- Density correlation length in the direction of aligned shear is enhanced by several factors, which reflects the length of a bridge.



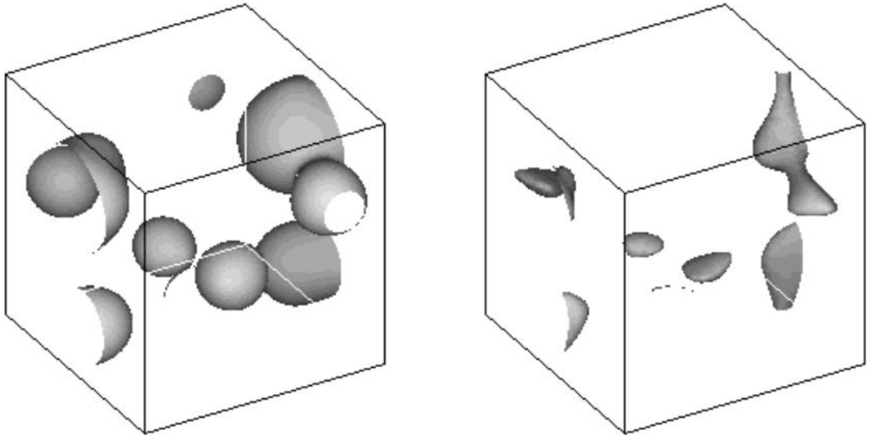
“Molecular” elements of the Web

(three clusters and the web between, In initial conditions (left) and mapped to the final state (right)

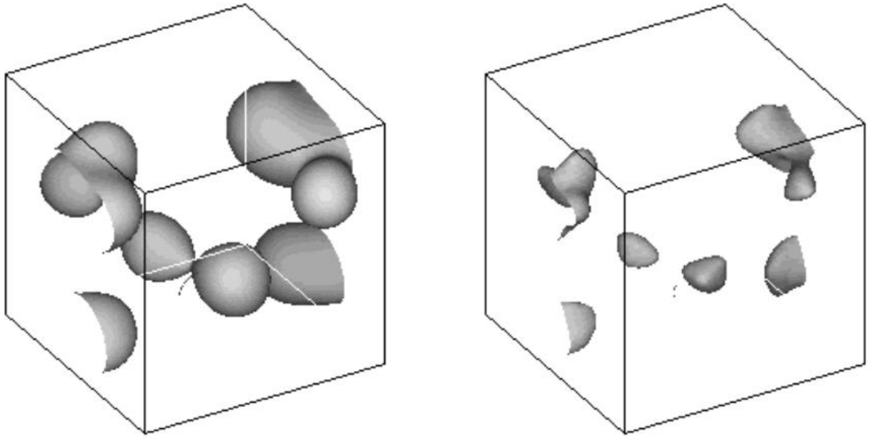


Role of shear/tide

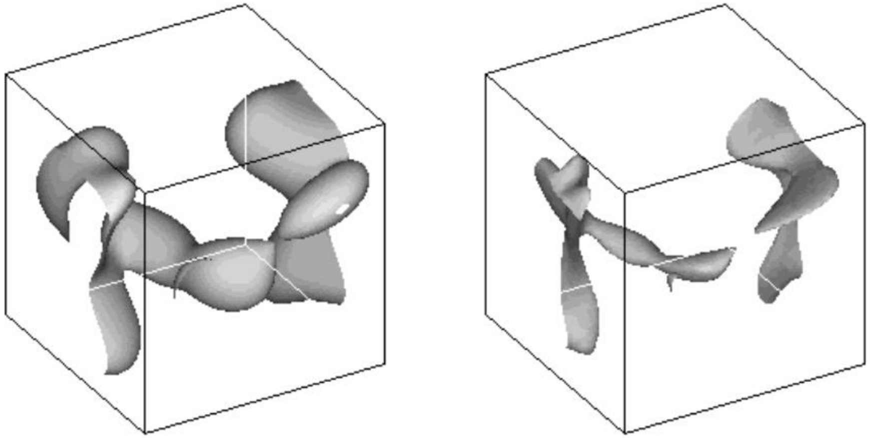
Only density constraints at peaks.
No filamentary bridges are predicted.



density and velocity of peaks are constrained



density and velocity shear (or tides) reveal the filamentary bridges.

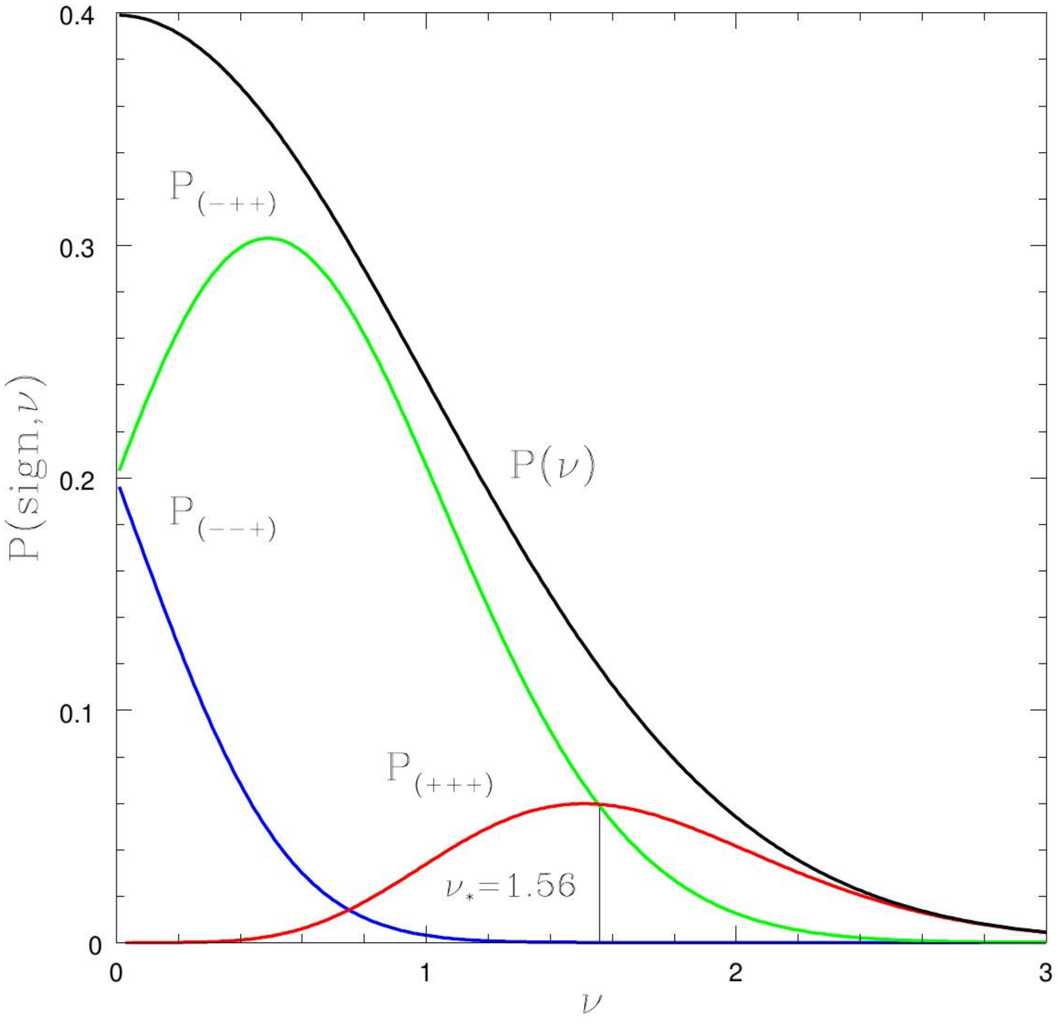


Typical overdensitities of different morphological regions in Gaussian field by the type of shear field

Halo-like patches +++
Filamentary regions -++
Wall-like regions --+

$$\langle \nu | +++ \rangle = 1.66$$
$$\langle \nu | -++ \rangle = 0.61$$
$$\langle \nu | --+ \rangle = -0.61$$

$$\langle (\nu - \bar{\nu})^2 | +++ \rangle^{\frac{1}{2}} = 0.54$$
$$\langle (\nu - \bar{\nu})^2 | -++ \rangle^{\frac{1}{2}} = 0.55$$
$$\langle (\nu - \bar{\nu})^2 | --+ \rangle^{\frac{1}{2}} = 0.55$$



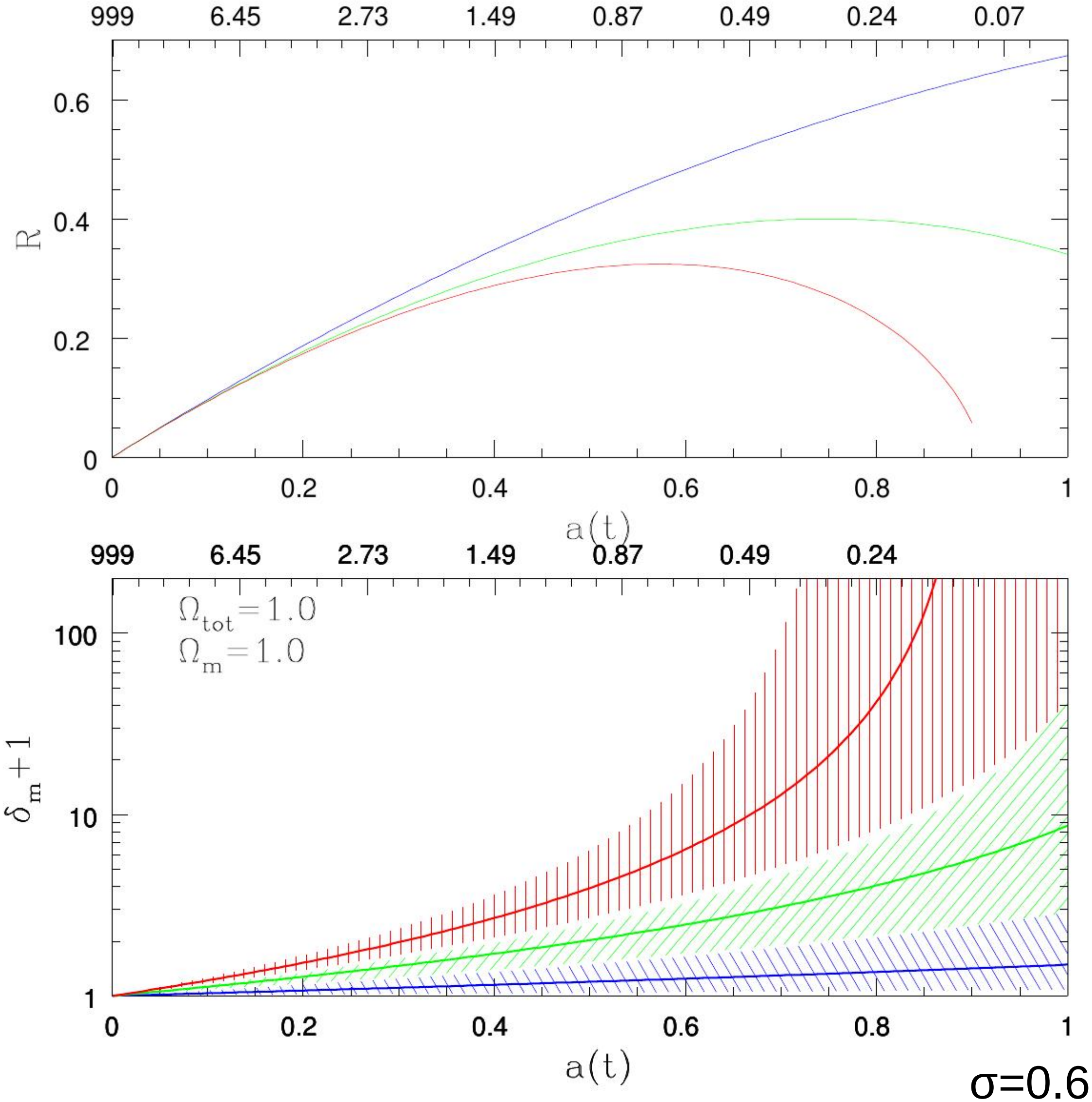
Collapse of 2σ objects of different types

2 σ halo
ν=2.8

2 σ filament
ν=1.7

2 σ wall
ν=0.5

Halos, filaments, walls remain distinct in density during mildly non-linear evolution.



σ=0.65

So what to be concerned with in Cosmic Web

- Overdensities of filaments and walls are not very high – maybe 10. Do they matter ?
- Cosmic Web leave little signature in isotropized 2-point correlation function – can you derive all cosmological parameters from that without studying Cosmic Web ?
- At smaller, rather nonlinear, scales, the Web in dark matter is transient – does it affect small non-linear objects (like galaxies) ?
- Can halo history be understood locally, studying development of isolated halo proto-patch, without reference to their connectivity into the Web ?