Large Scale Structure of the Universe – current problems

Jaan Einasto
Tartu Observatory
Paris, VIA
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With Maret Einasto, Gert Hütsi, Juhan Liivamägi, Volker Müller, Enn Saar, Ivan Suhhonenko, Erik Tago, Elmo Tempel


Tartu cosmology team in 2005

Summary

- Discovery of the Large Scale Structure (LSS) of the Universe
- Cosmic web consists of filamentary superclusters, joined by weak galaxy filaments, and voids in between
- Does the cosmic web has any regularity?
- Why voids are empty?

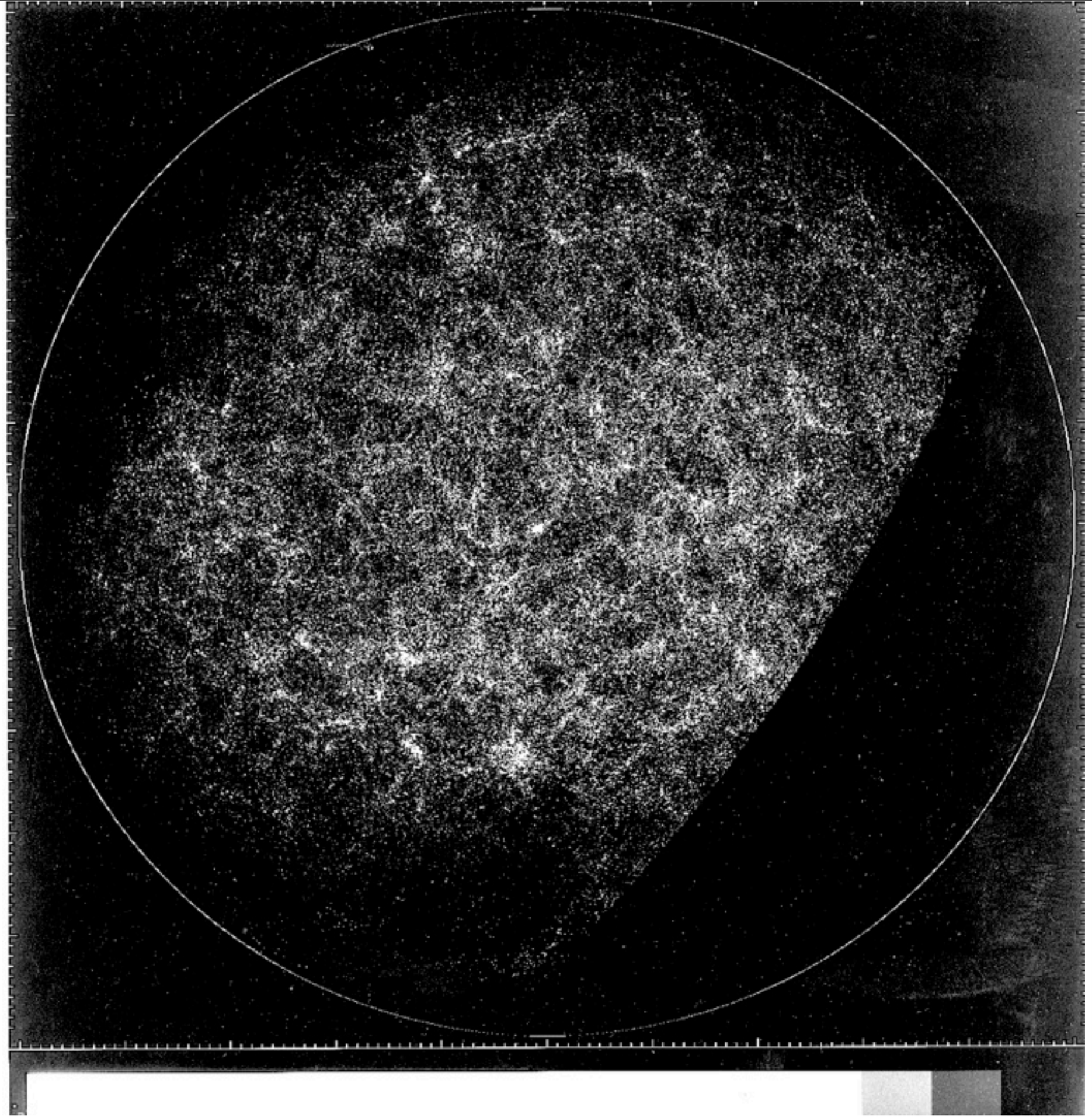
Zeldovich question

- In 1970s two major structure formation theories were discussed: Zeldovich (1970) pancake scenario & Peebles (1971) clustering scenario
- 1974 Zeldovich asked Tartu astronomers to help find observational evidence which could be used to discriminate between various scenarios
- Our main idea: structure evolves slowly; if there exist large-scale structures they must reflect the distribution at the formation epoch
- Search of large-scale structures

2-dimensional data on LSS

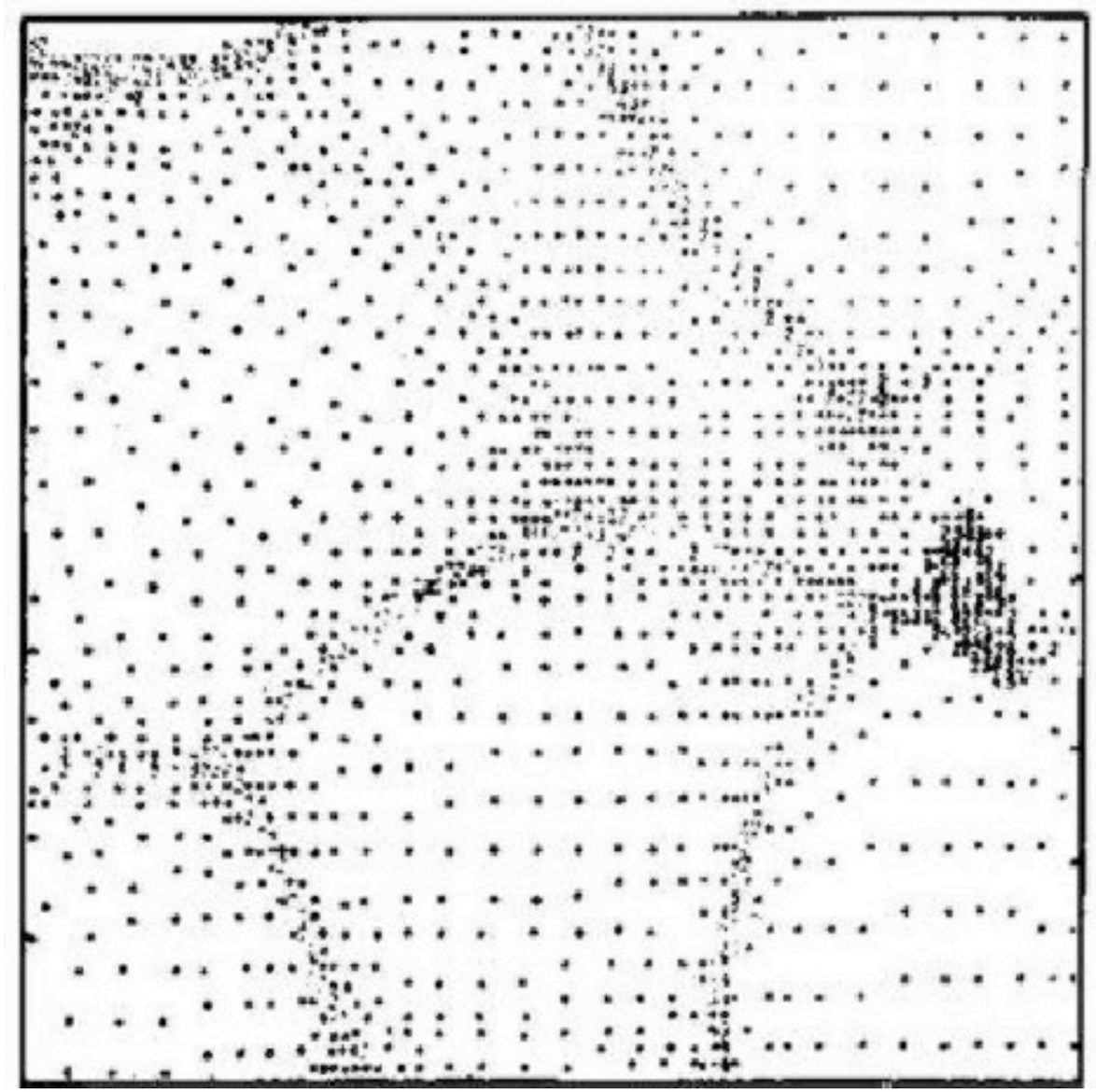
Lick survey of million galaxies. Seldner et al. (1976)
Clusters, superclusters and almost randomly distributed field galaxies are visible.

Peebles random clustering scenario was influenced by his experience in studying 2D distribution of galaxies.



First steps

- Our previous experience from galactic studies shows that galactic populations evolve slowly and the present structure contains info on the formation and evolution
- Numerical simulations by Zeldovich group suggest the formation of a cellular network with high-density knots, chains connecting knots, and low-density regions in between
- During the whole Hubble time a galaxy with peculiar motion ~300 km/s has moved from his place of origin a few Mpc. Thus the present distribution of galaxies is close the the distribution at formation.
- If Zeldovich is right, we should observe high- and low-density regions forming a cellular network



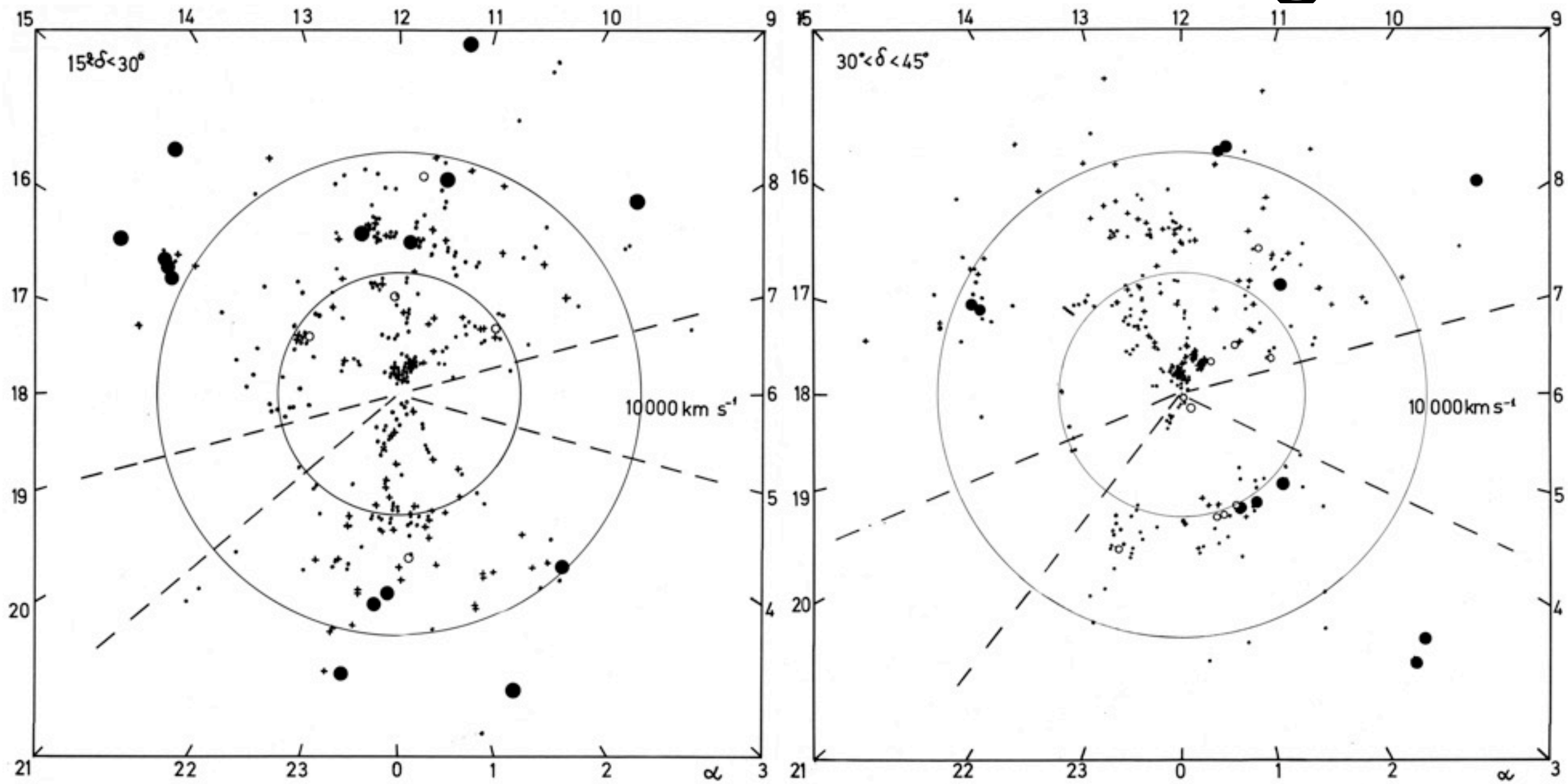
IAU Tallinn Symposium 1977
Large-Scale Structure of the Universe

J. Peebles, S. Tremain, Ya. Zeldovich, M. Longair during the Tallinn Symposium

First use of the term ‘Large-scale Structure of the Universe’

Strong support for Zeldovich pancake scenario

3-D data on the distribution of galaxies



The distribution of clusters (filled circles), groups (open circles), active galaxies (crosses) and galaxies (dots). All objects concentrate to superclusters which are joined by galaxy filaments, the space in between is devoid of galaxies - cosmic voids (Jõeveer, Einasto 1977).

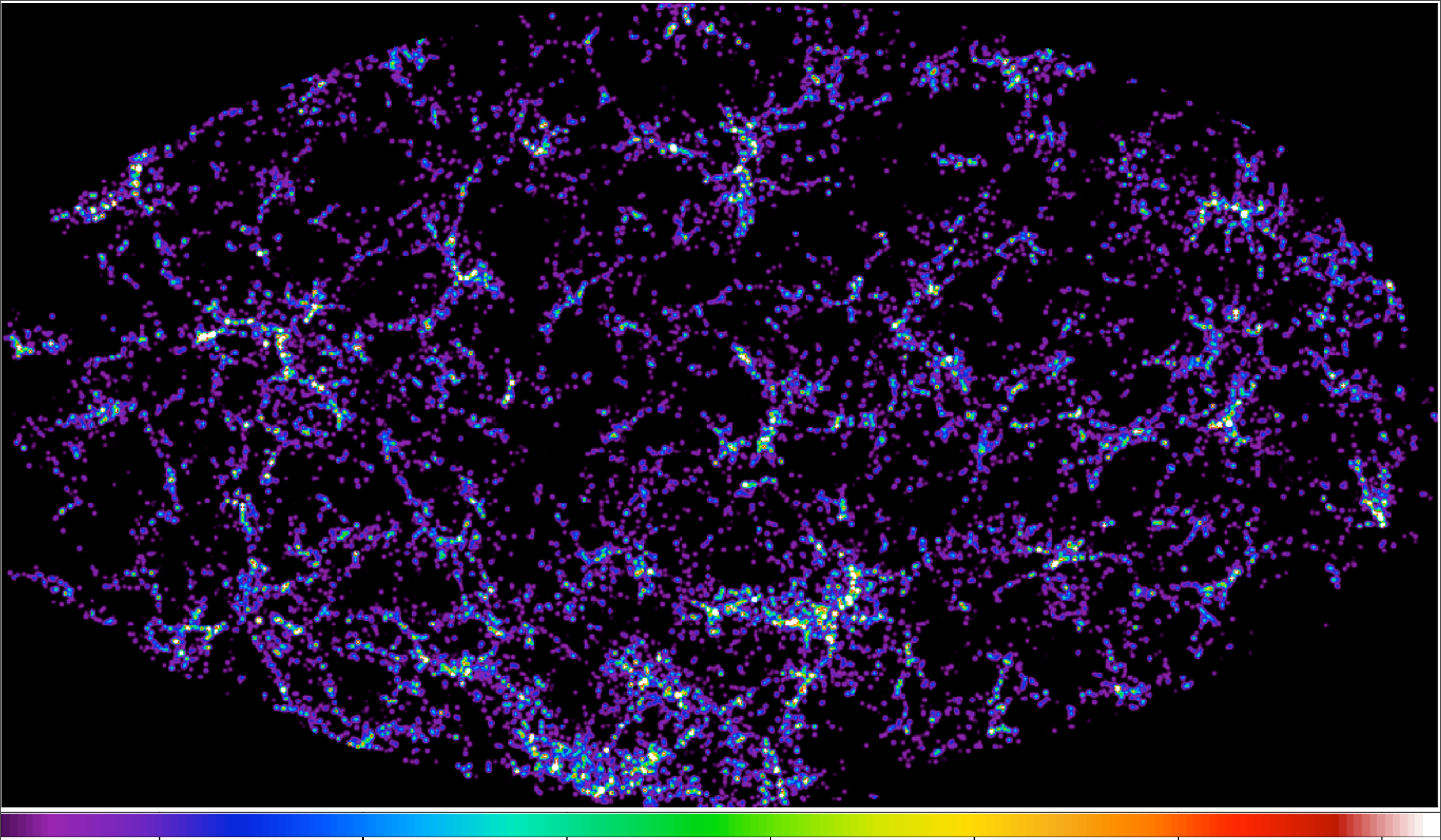
Comparison of observations & models

A direct consequence from this observation is that galaxies and groups/clusters of the chain are already formed within the chain. A later inflow from random locations to the chain is excluded, since in this case it would be impossible to stop galaxies and clusters in the chain after the inflow.

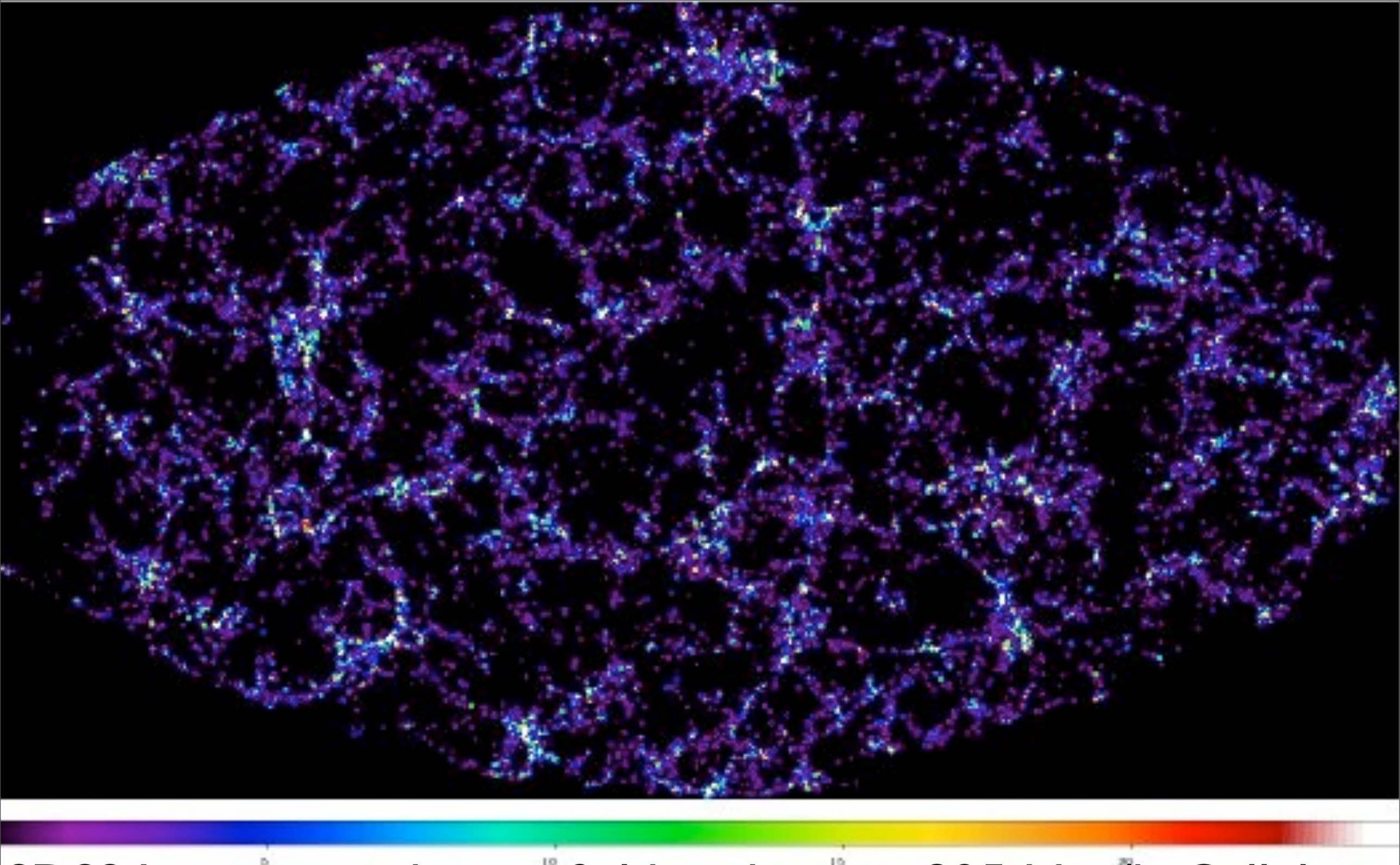
Data support the pancake scenario. However, differences between the model and observations were evident.
1) Simulations showed that there exists a rarefied population of test particles in voids absent in real data. This was the first indication for the presence of physical biasing in galaxy formation -- there is primordial gas and dark matter in voids, but due to low density no galaxy formation takes place here.
2) In the pancake model large-scale structures (superclusters) have rather diffuse forms, real superclusters consist of multiple intertwined filaments.

The LambdaCDM model of structure formation and evolution combines essential aspects of the pancake and the hierarchical clustering scenarios. Structure formation starts in places where the primordial matter has the highest density. This occurs in the central regions of future superclusters. First objects to form are dwarf galaxies, which grow by infall of primordial matter and merging of small galaxies.

The largest project to map the Universe is the Sloan Digital Sky Survey. A dedicated 2.4-m telescope was build for this project by ~10 USA, Japanese & European observatories.



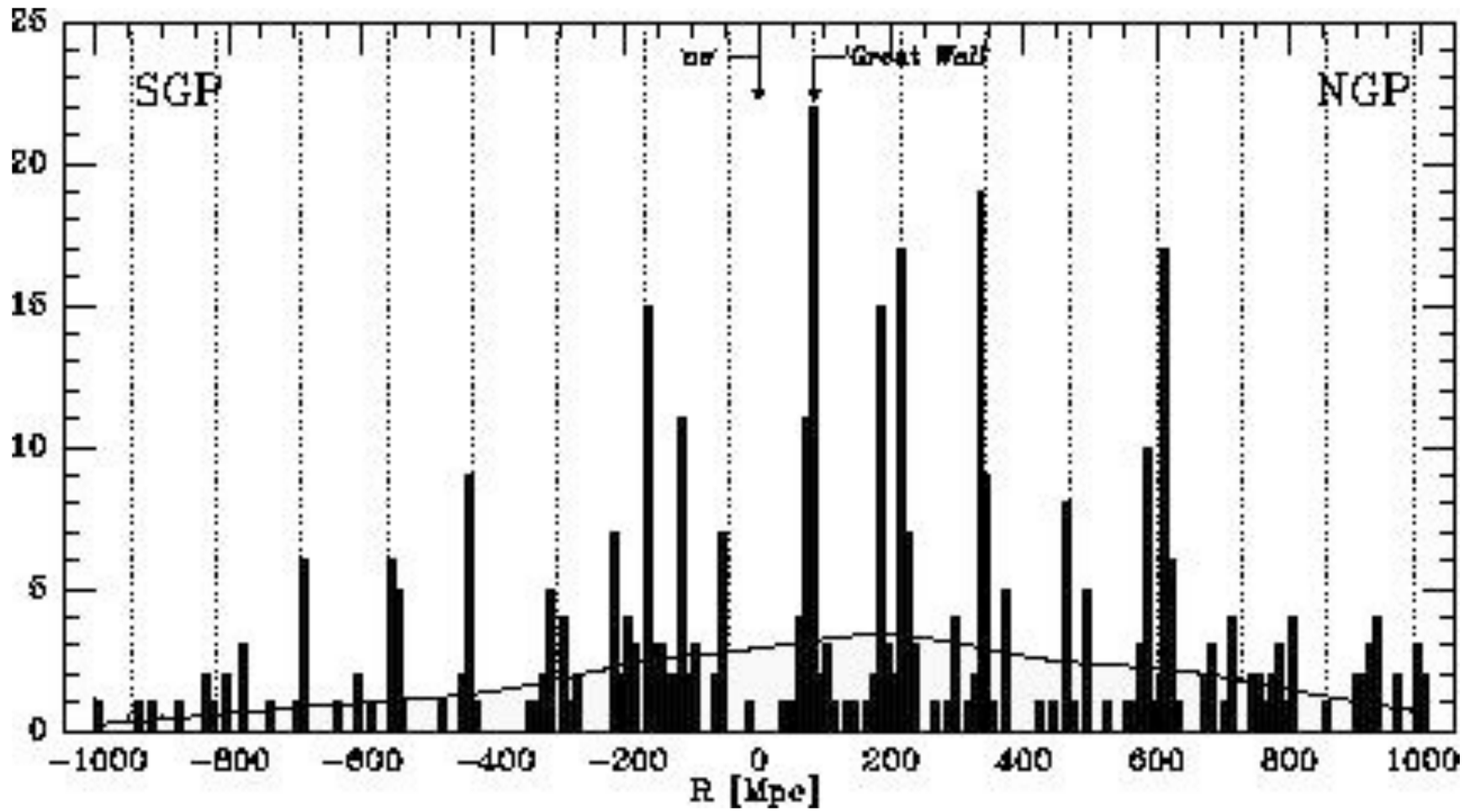
Luminosity density field of SDSS at distance 240 Mpc/h. Rich superclusters in lower part form the Sloan Great Wall. Faint galaxy filaments cross voids.



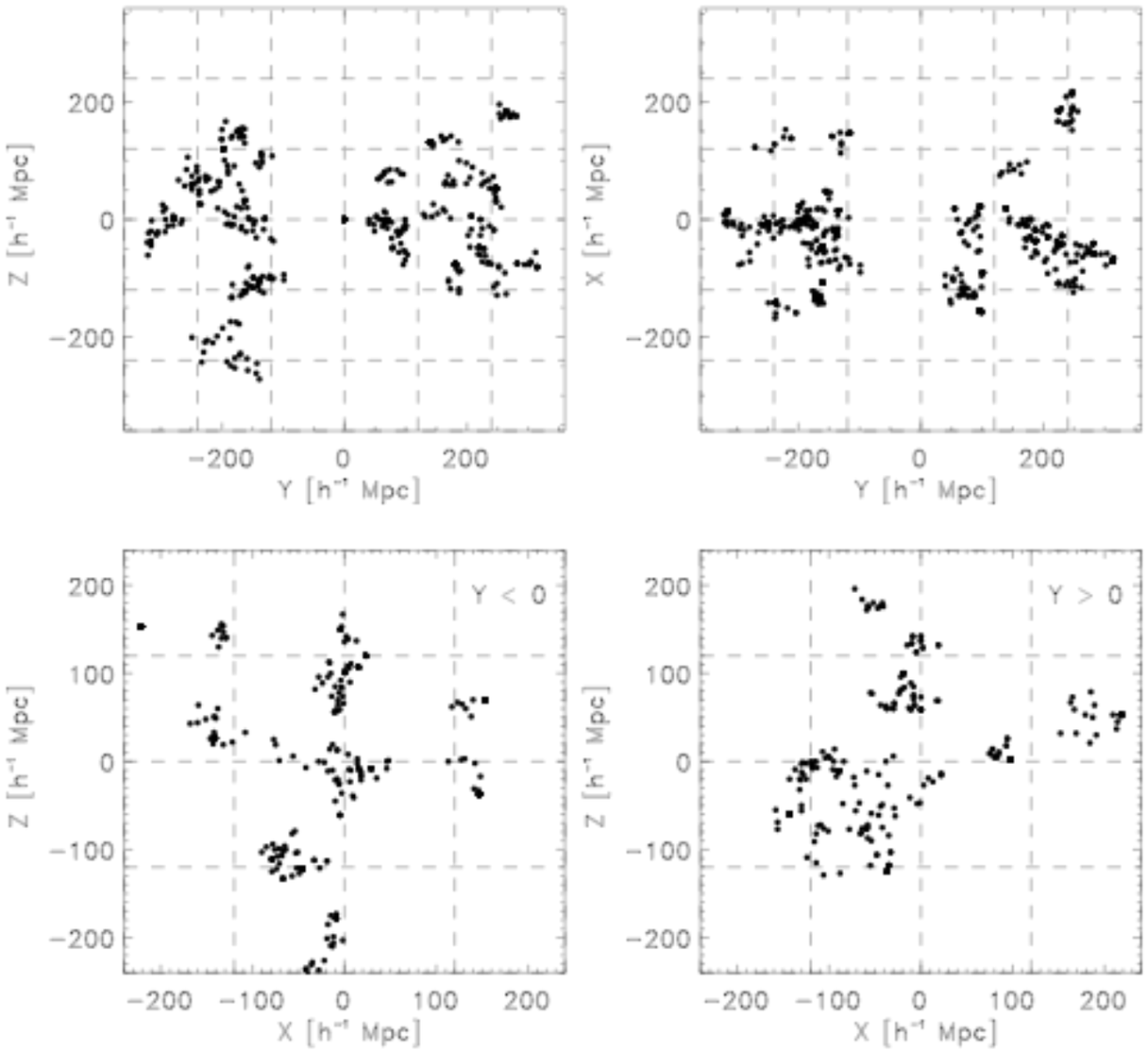
SDSS Luminosity density field at distance 325 Mpc/h. Cellular distribution of rich clusters & superclusters with characteristic scale ~100 Mpc/h.

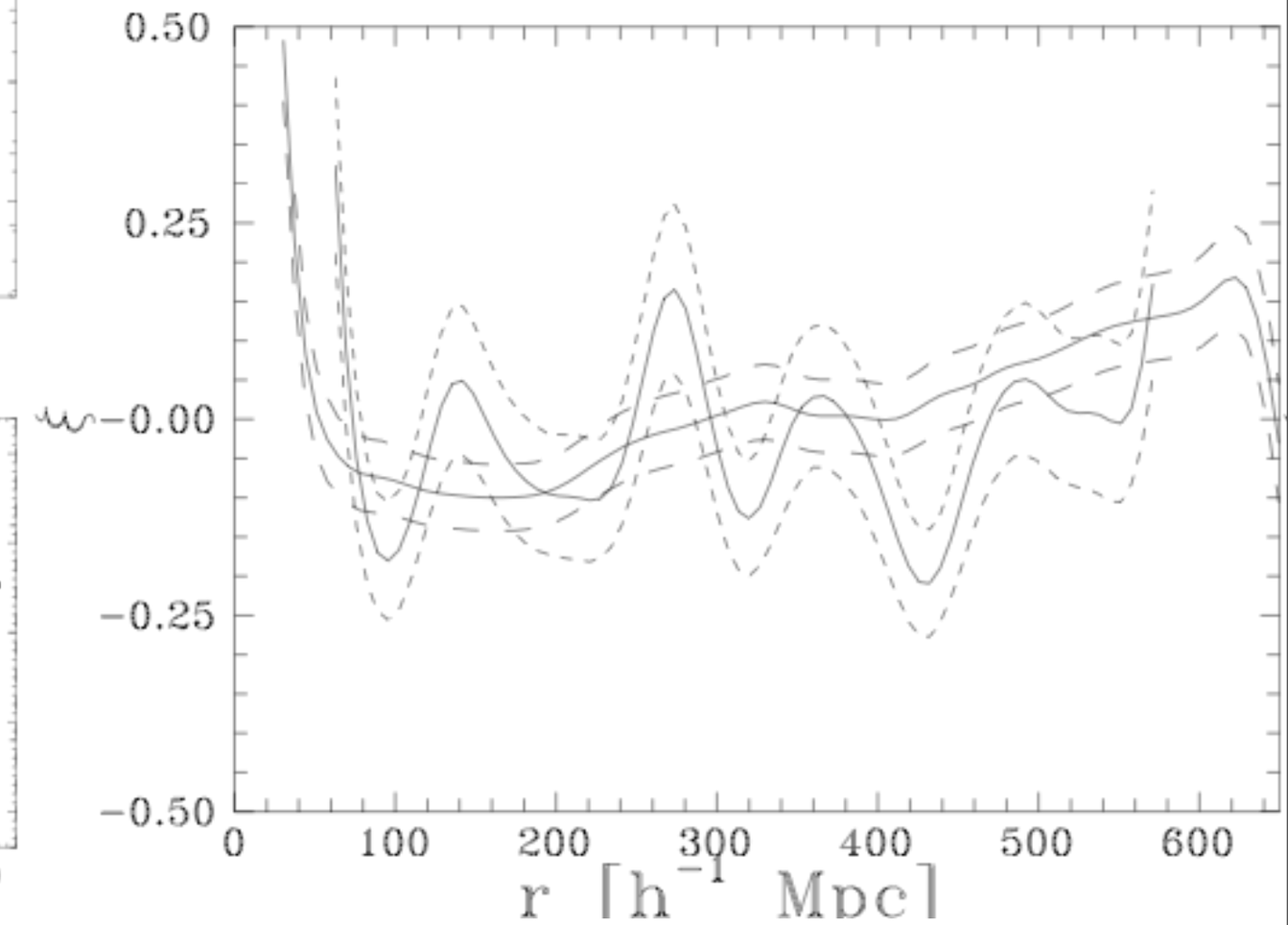
Has the distribution of galaxies, clusters & superclusters some regularity?

A classical problem: Quasi-regularity of the distribution of galaxies & clusters



Broadhurst et al (1990) - regular distribution of galaxies towards SGP & NGP





Distribution of rich Abell clusters (left) and their correlation function (right). A quasi-regularity of scale ~120 Mpc/h is evident (JE et al 1997)

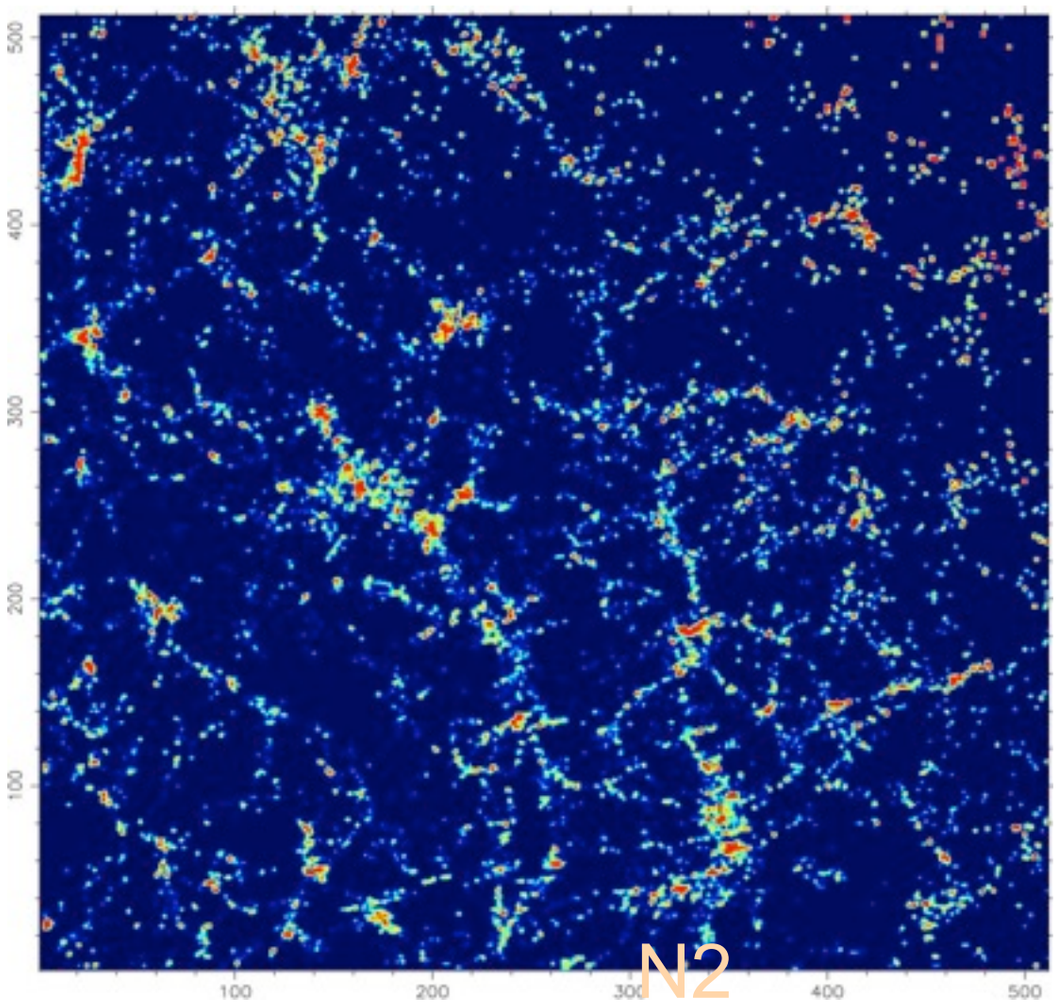
To understand properties of the distribution of systems of galaxies we use wavelet and Fourier analyses of the density field

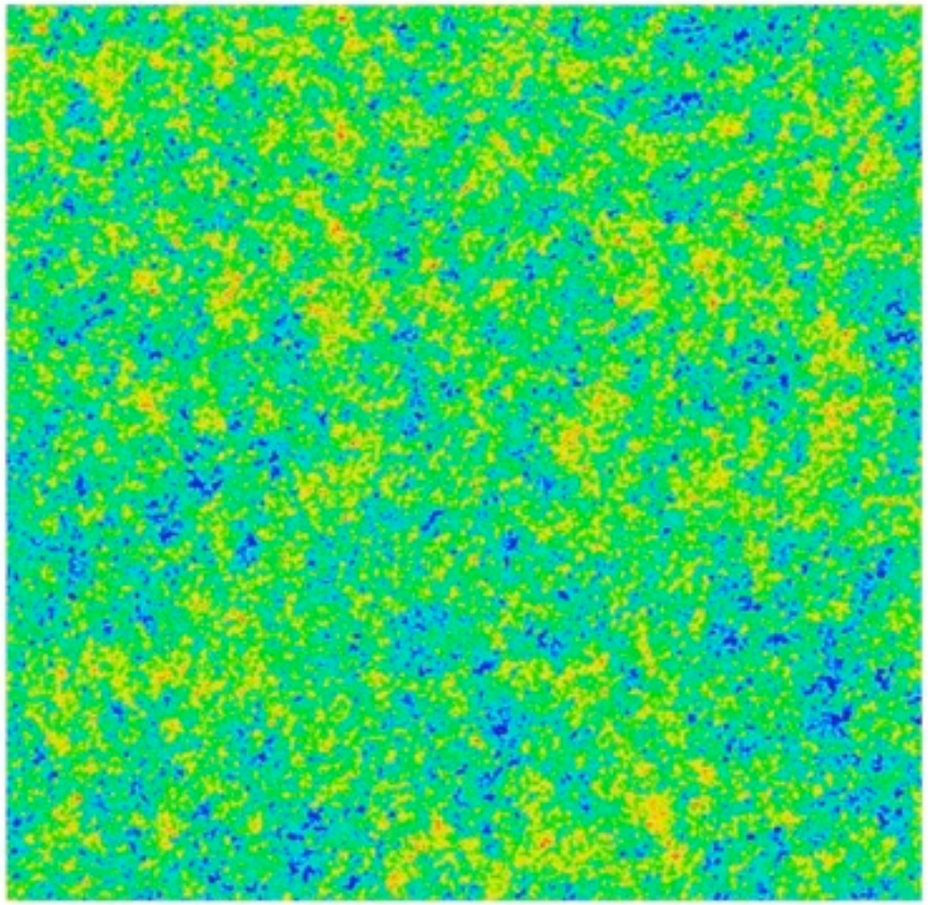
We use the Fourier analysis and the wavelet decomposition of the density field (DF) of SDSS.

In the wavelet analysis the field is decomposed into several frequency bands, each band contains frequencies twice the previous band, in the range $\pm\sqrt{2}$ x main frequency. Wavelets of the order 1, 2, 3, 4, 5, 6 characterise waves of scale 2, 4, 8, 16, 32, 64 times the size of the cell of DF.

To follow the evolution of the LSS we analyse simulations in cubes of sizes 100, 256, 768 Mpc/h

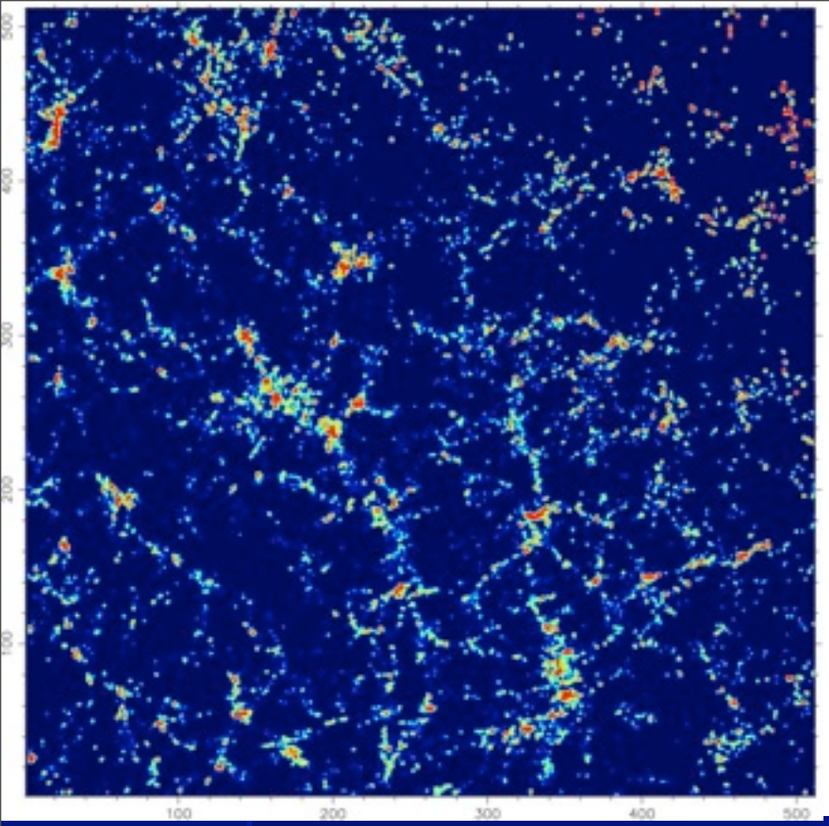
Cosmic web: the role of phases

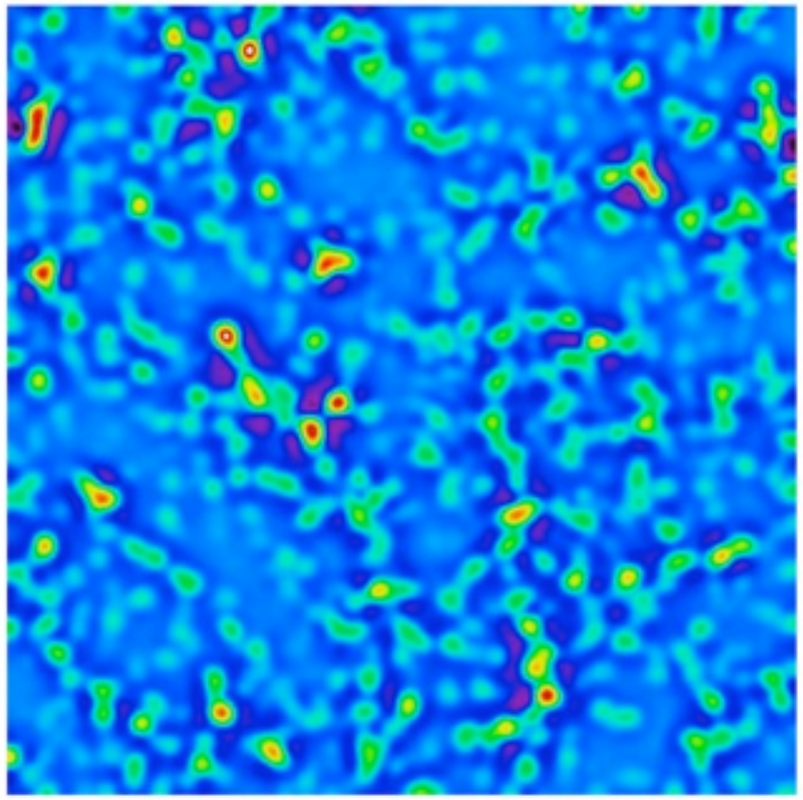


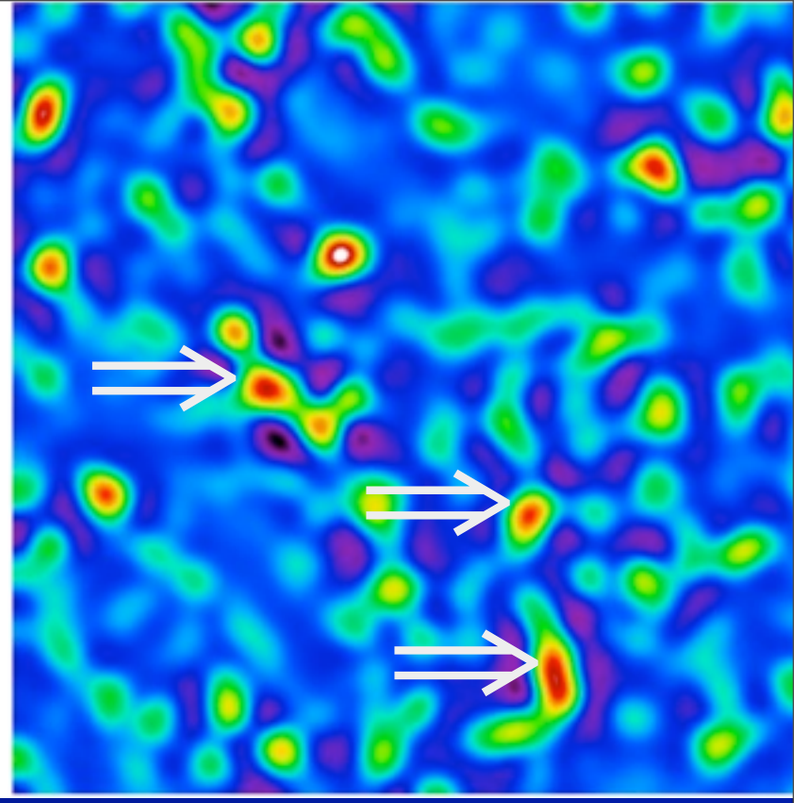


Left: Northern SDSS slice
Right: The same field but phases of density waves randomised by Fourier transform.
There are no filaments, superclusters & voids.

Phases are important in the formation of the cosmic web. Similar results by Szalay, Coles & Chiang (2000) and others.

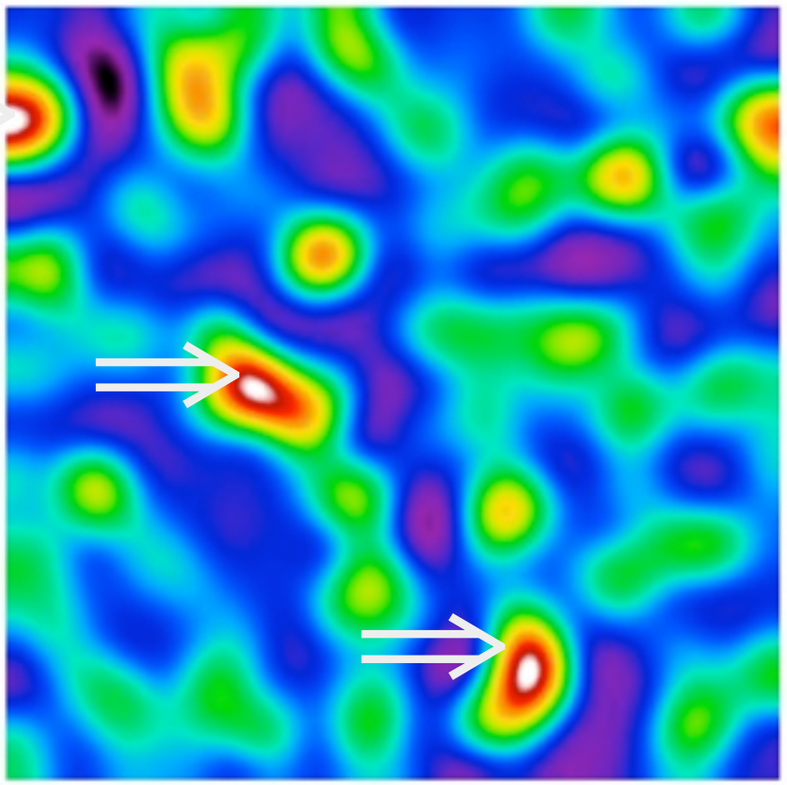


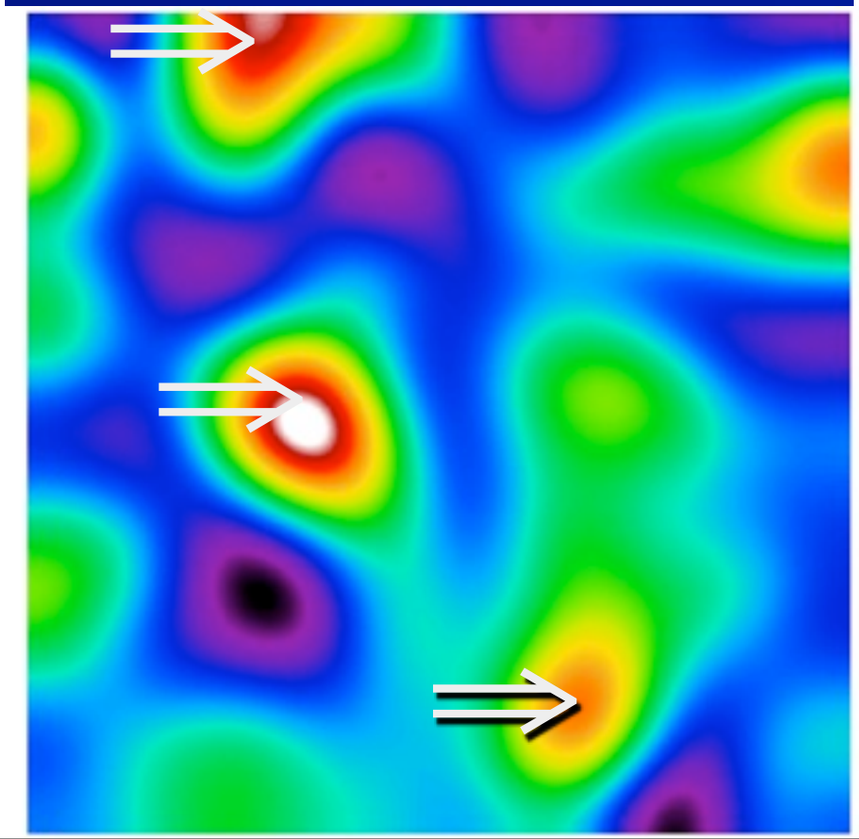


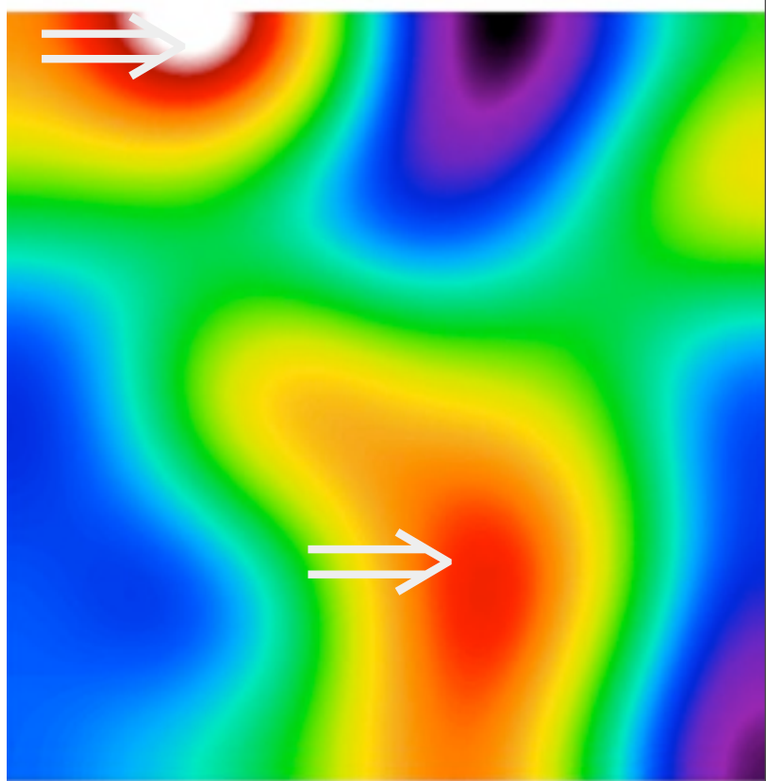


SDSS Original L=500 Mpc wavelet w2 w3

w4 w5 w6







Results of the SDSS wavelet analysis

Very rich superclusters are objects where density waves of **all** large scales > 32 Mpc combine in similar phases to generate high density peaks.

Rich superclusters are objects where density waves of scales 32 - 128 Mpc combine in similar phases.

Poor superclusters are objects where only medium scale density waves (32 - 64 Mpc) combine in similar phases.

Voids are regions in space where negative sections of large-scale density waves combine in similar phases to generate low-density regions.

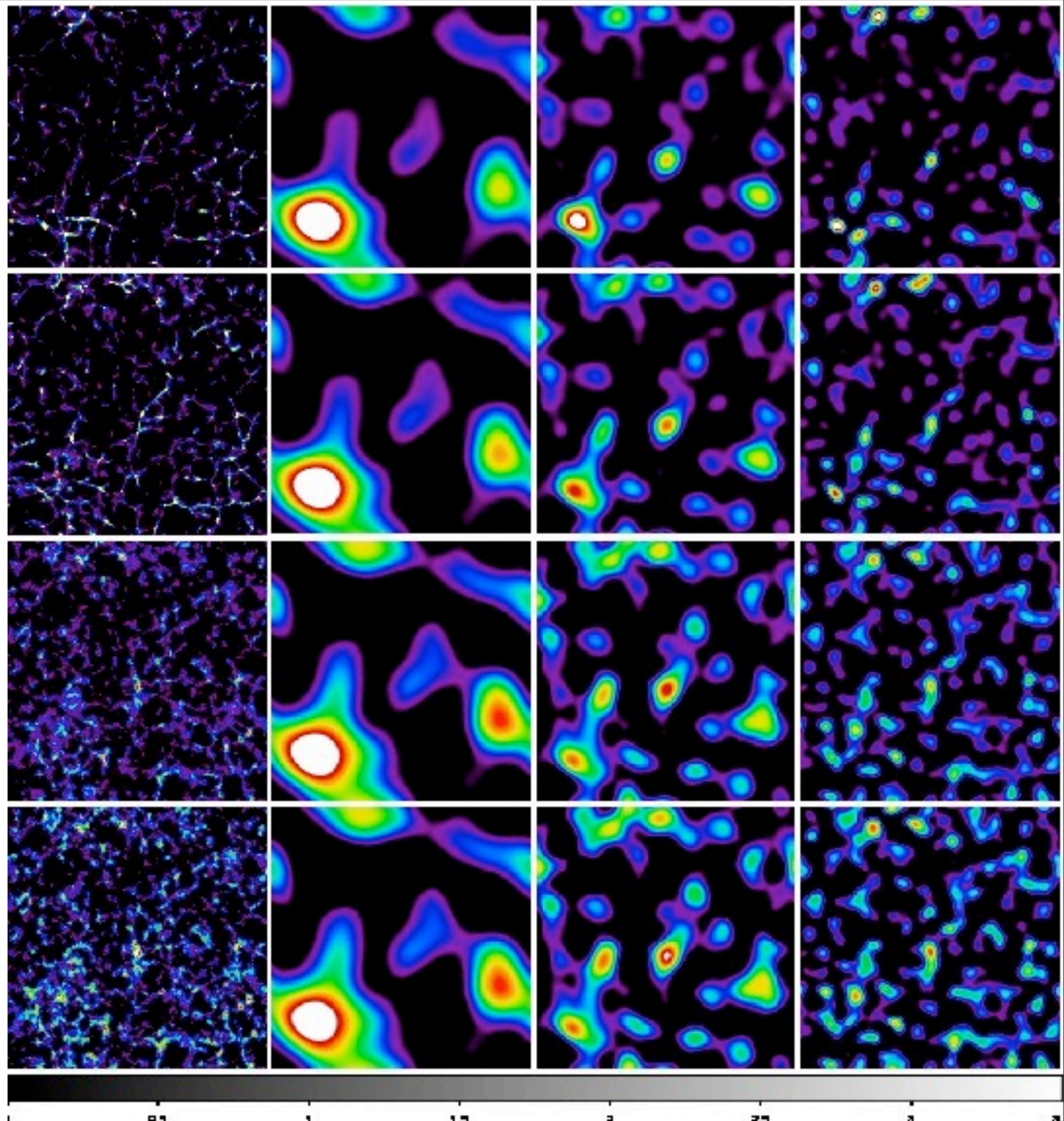
Wavelet analysis of the evolution of the density field

To answer this question we performed numerical simulations of models with cube size 256 & 768 Mpc and resolution 256^3 & 512^3. We calculated series of models with identical initial conditions, but in power spectra large-scale waves were cutoff at scales 8, 16, 32, 64, 128 Mpc to see the influence of waves of various scale.

Model M256 (full)

Colums 1, 2, 3, 4:
DF, w6,w5,w4

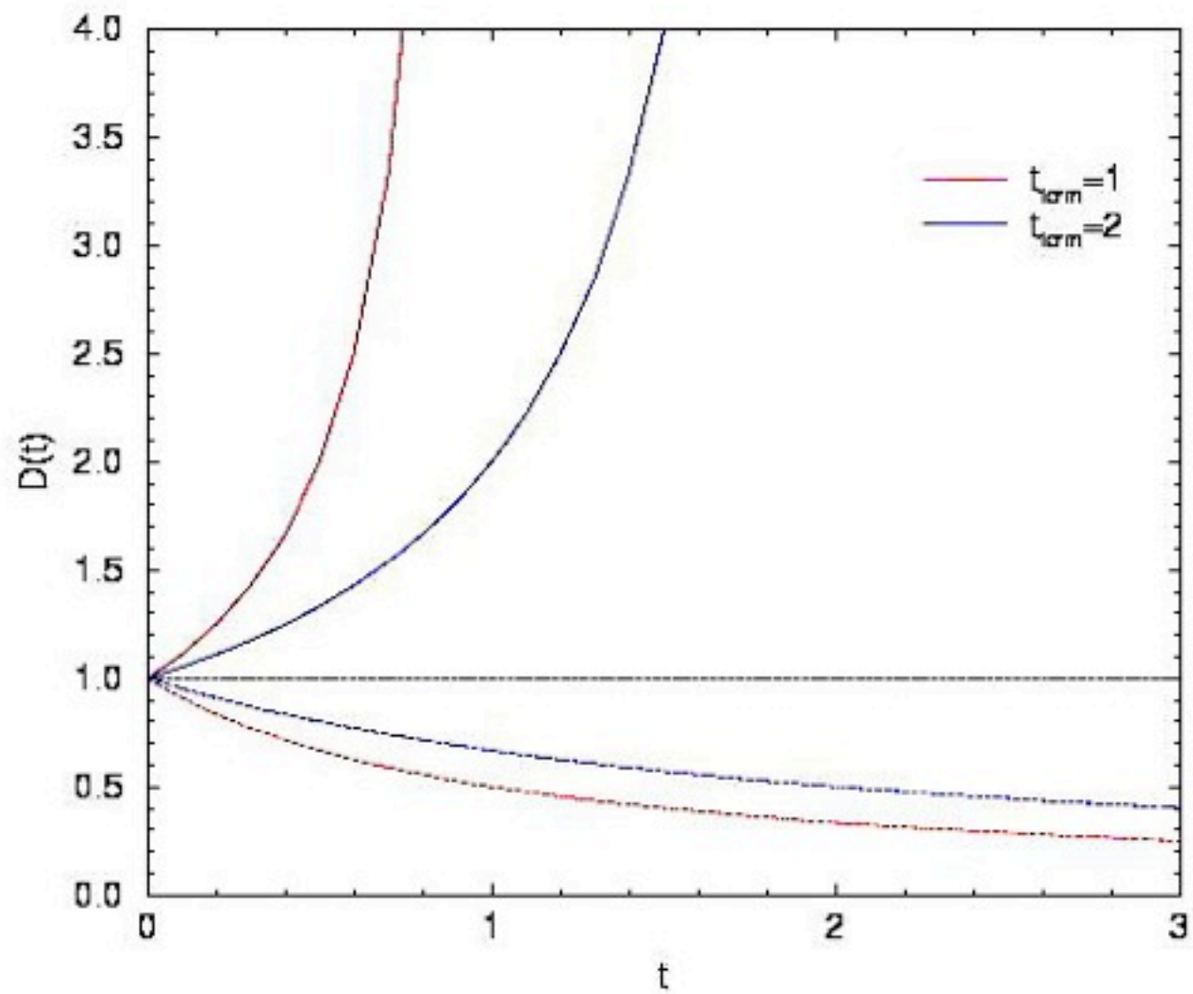
Rows: 1, 2, 3, 4
z=0
z=1
z=5
z=10
Colours correspond to linear growth factor



Results of the wavelet analysis

- The shape of density waves & the positions of density maxims of waves of large and medium scales practically do not change during the evolution.
- Positions of density maxims of waves of large & medium scale coincide - phase synchronisation.
- On small scales (of scale < 25 Mpc) changes of the wavelet pattern are the larger the smaller the scale of waves

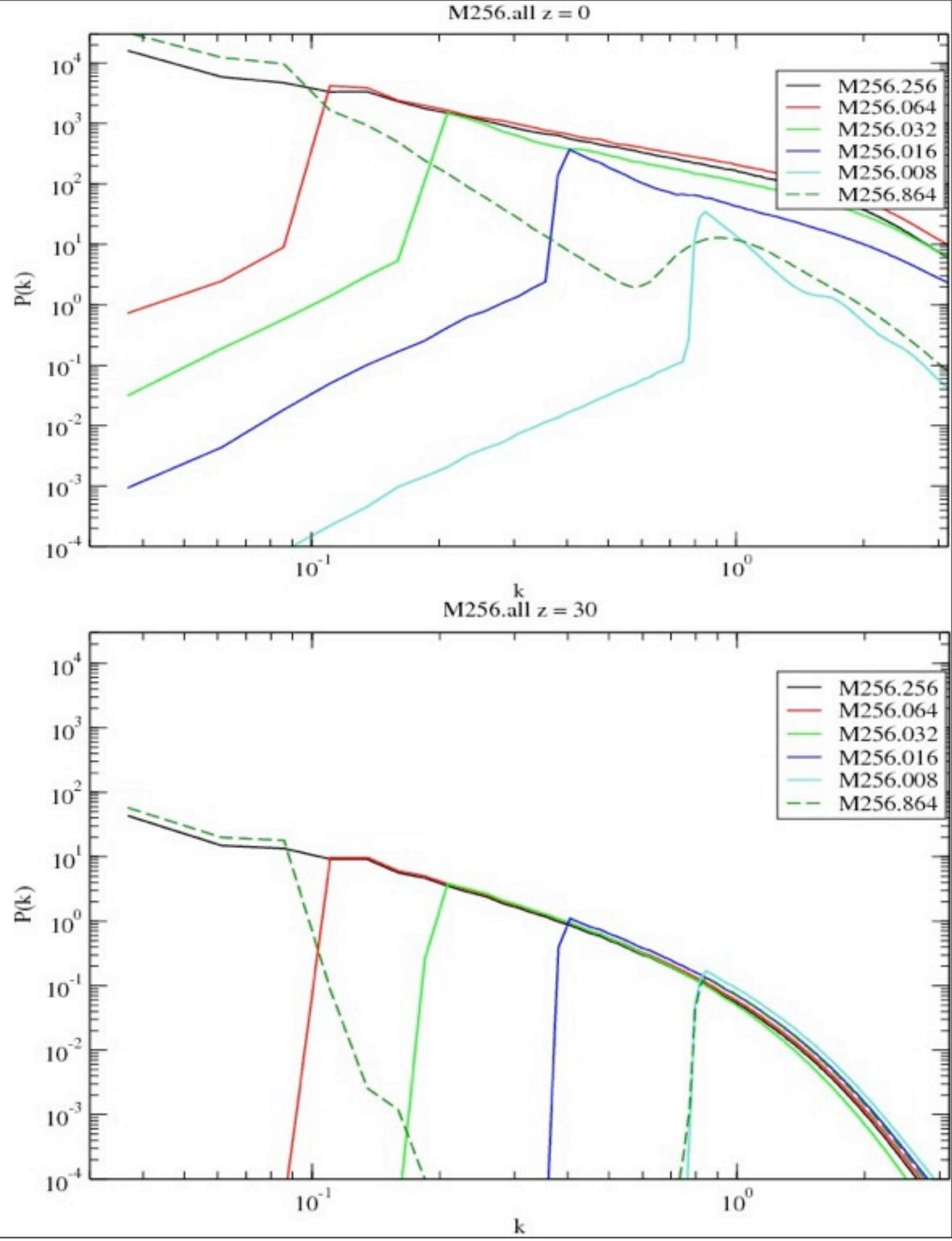
Why voids are empty?



In under-density regions the density continuously decreases, in over-density regions in increases until collapses; this is formation of galaxies, sheets and chains. The collapse (and void emptifying) is the more rapid the higher is the over(under)-density.

Power spectra of model L = 256 Mpc/h, z = 30, z = 0

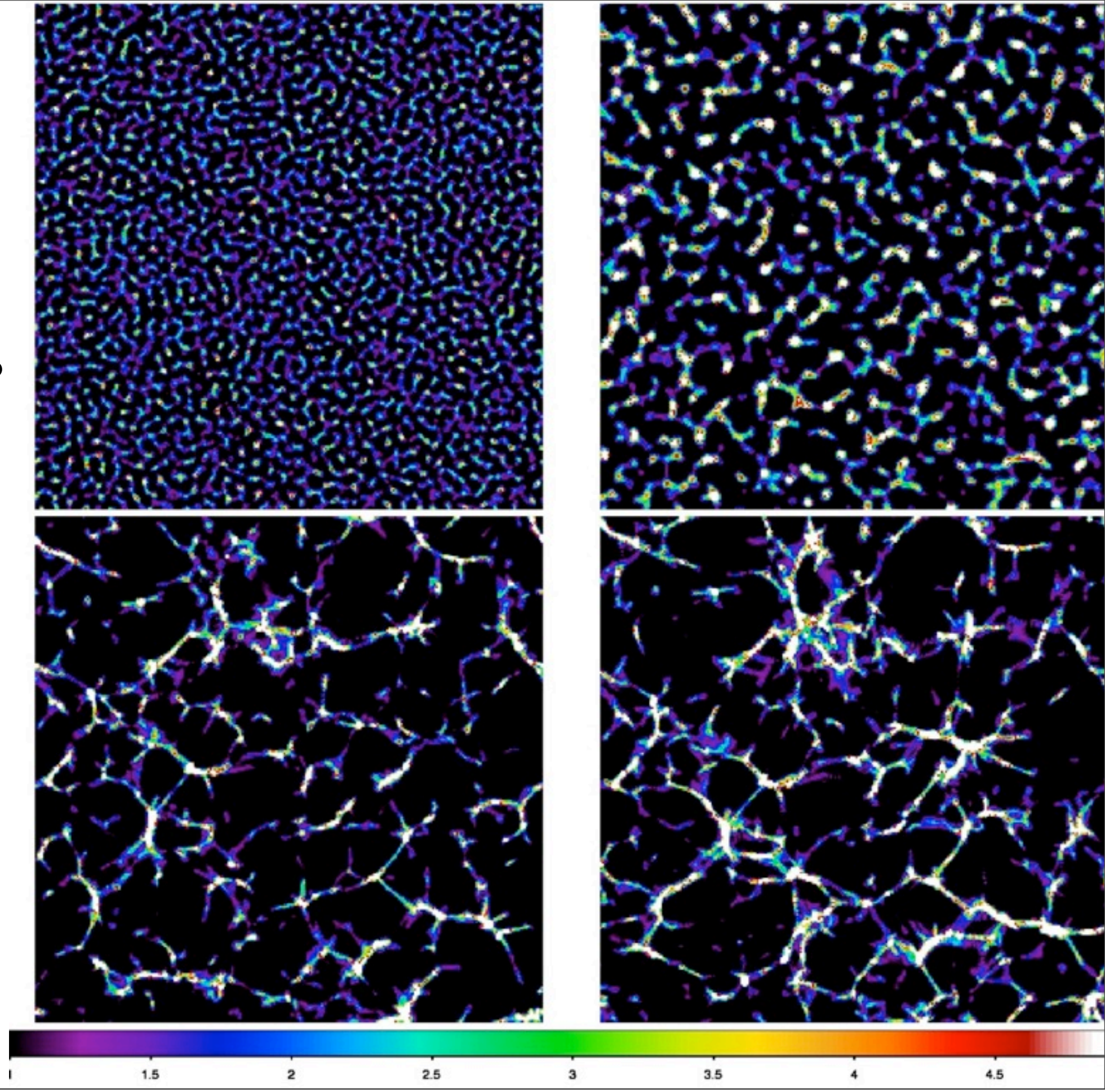
Initial spectra are cut sharply, during the evolution some power is transferred to larger scales.
For all particles *local & global densities* were calculated.
Local density is responsible for galaxy/cluster formation, *global density* is needed to divide the simulation volume into void, filament & supercluster regions.

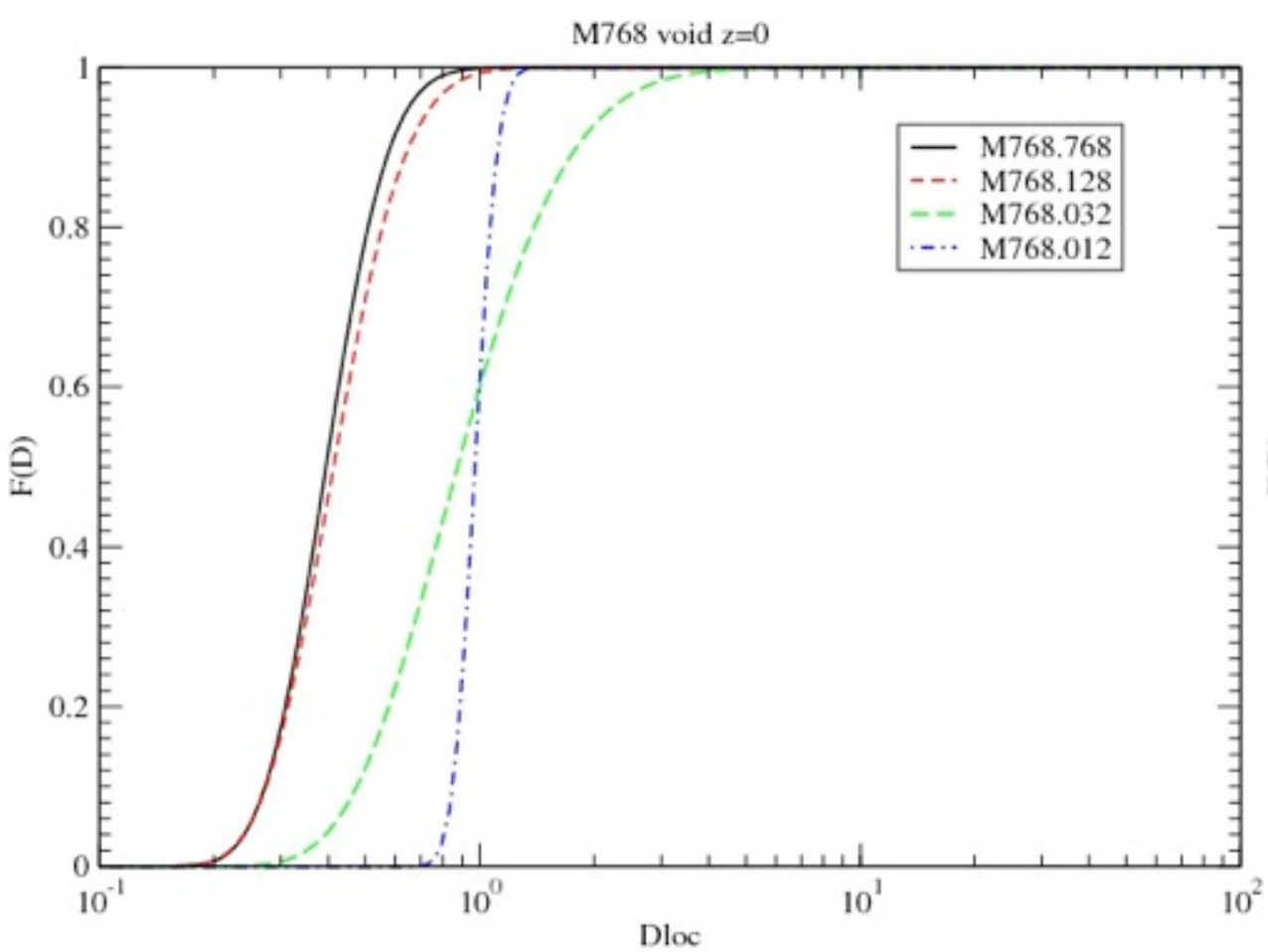


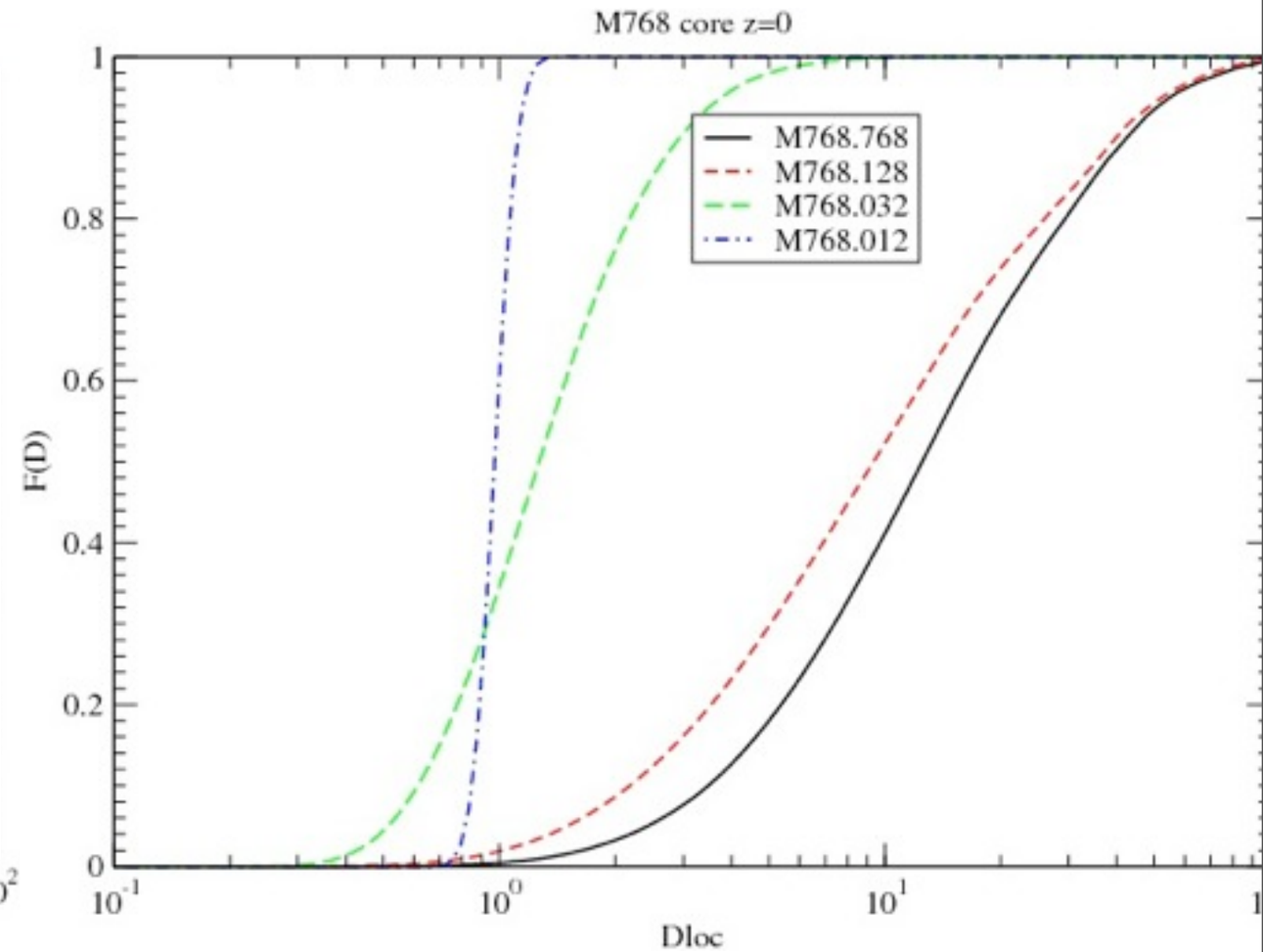
Model M256

High-resolution density fields of models with spectra cut at 8, 32, 64 & 256 (full spectrum) Mpc.

The scale of cosmic web depends on the presence of large waves up to ~100 Mpc, larger waves to not alter the web pattern, but amplify structures: voids become emptier and clusters - superclusters richer.



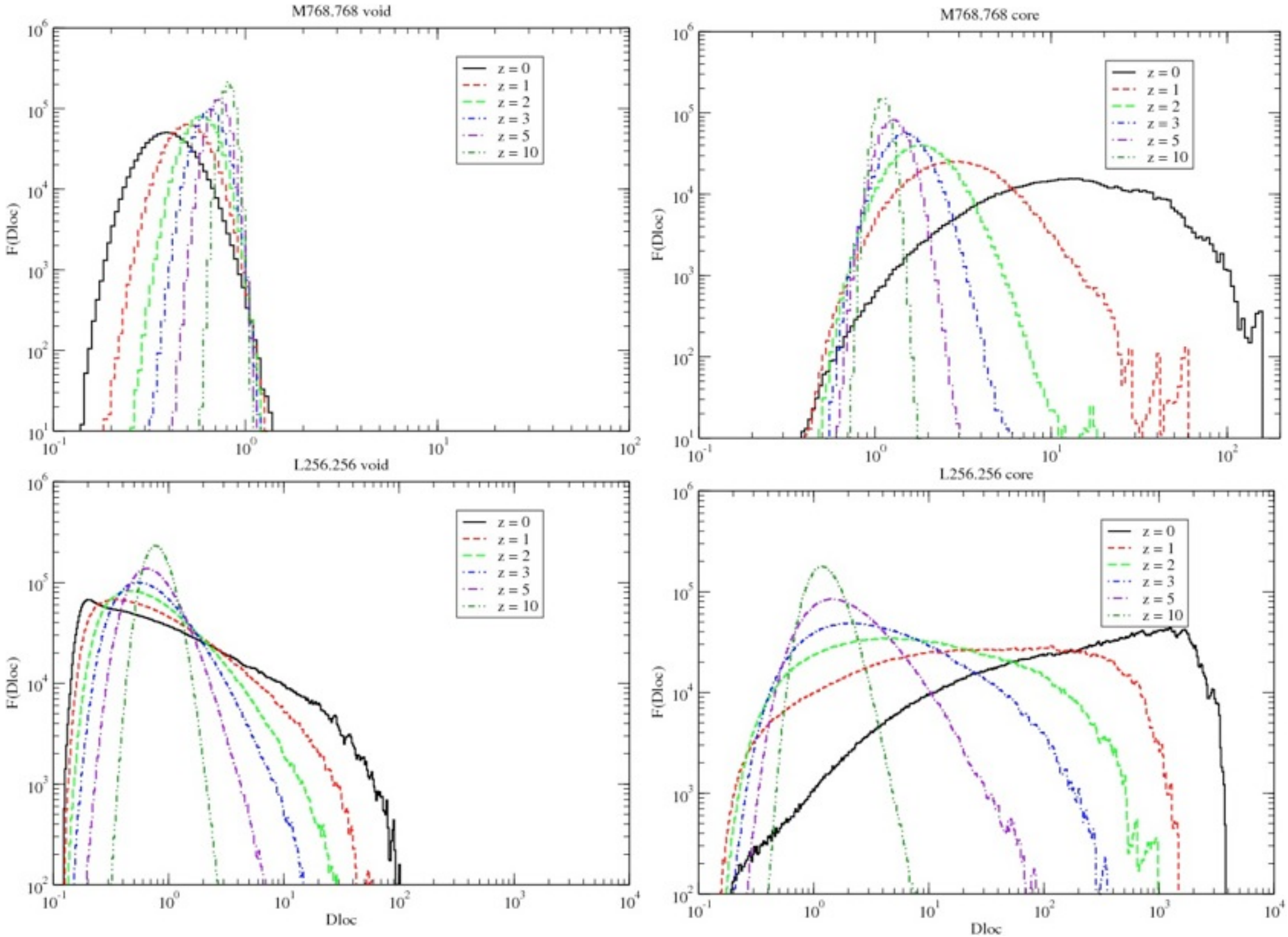




The integrated distribution of particle *local density distribution* at present epoch z = 0 in extreme void & supercluster core regions for models of the M768 series, cut at 12, 32, 128 Mpc, & full model.

Void particle sample is chosen as 5% of all particles located in full model in less global density regions, core particle sample are 5% of all particles in highest global density regions.

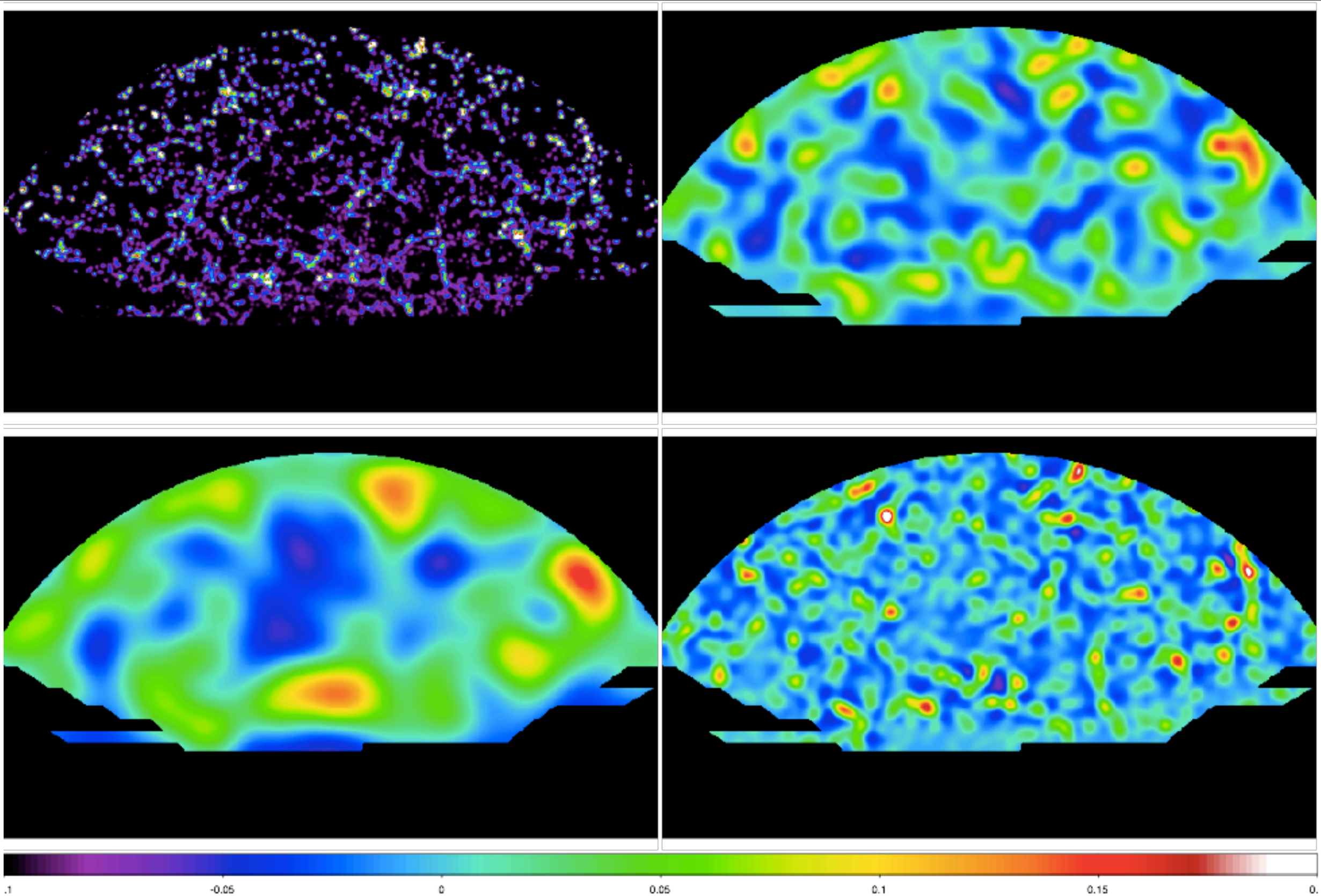
Local density distribution characterises particles located in various systems: void particles have Dloc < 1, the higher Dloc, the richer are systems they belong. Medium scale waves form galaxy systems of medium richness; large waves form superclusters & voids, very large waves amplify existing systems.



Evolution of void and core particle local densities in models M768 and M256. Model M256 has higher mass resolution, thus in voids we see formation of weak filaments. Over most of the void region particle local densities decrease with time, preventing galaxy formation.

Questions

- Is the phase synchronisation a natural process for initial gaussian density field or there are some deviations from gaussian field?
- If there are deviations, what they tell us from the inflation epoch?



SDSS MGS: DF, w5, w6, w4 (at k=160). The separation of extremely rich superclusters and their complexes is ~500 Mpc/h.

SCL luminosity and multiplicity functions

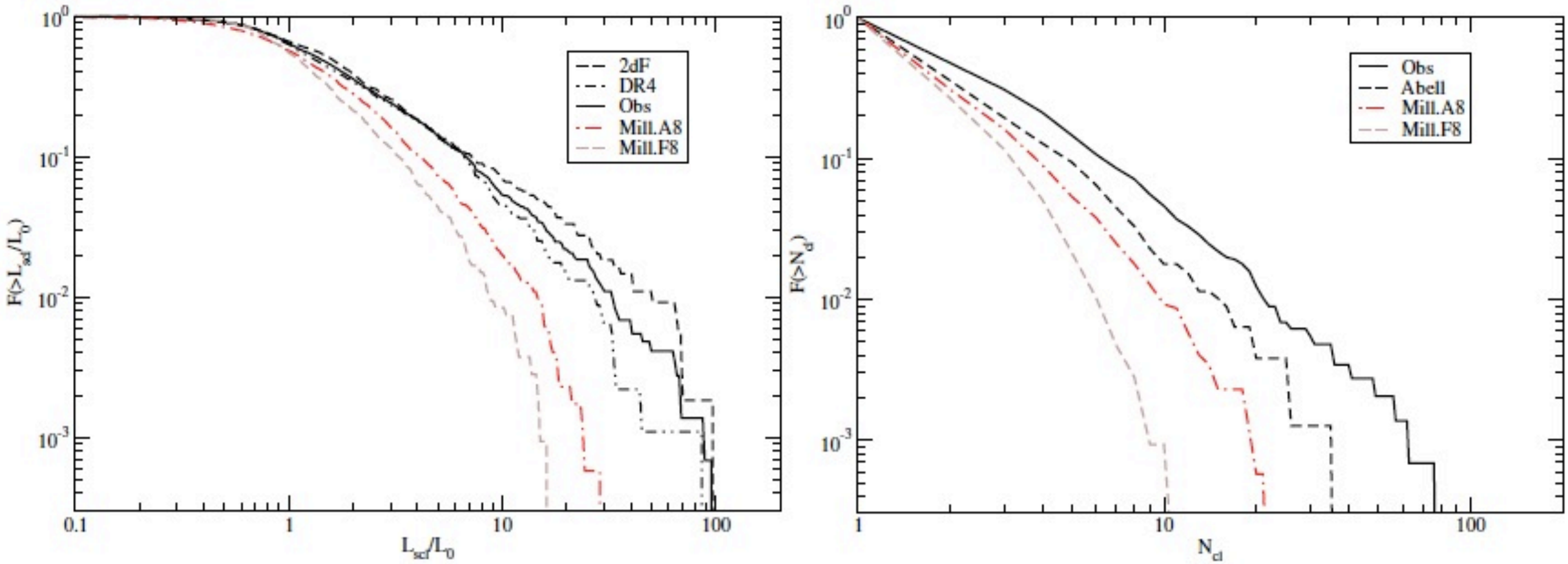


Fig. 1. The comparison of relative luminosity functions and multiplicity functions of observational and model supercluster samples. The spatial density of superclusters is expressed in terms of the total number of superclusters in the respective sample to avoid small differences due to the mean number density of superclusters in different samples. In the left panel we show relative luminosity functions separately for observational samples SDSS DR4, 2dF and the combined sample Obs, in the right panel we plot the multiplicity function of the combined observational sample Obs, and the Abell supercluster sample (here multiplicity is defined by the number of Abell clusters, isolated Abell clusters are considered as richness class 1 superclusters).

Note the difference between real and simulated superclusters. The fraction of real very rich superclusters is higher.

Results of the analysis

- Large-scale waves evolve almost linearly - amplitudes grow proportional to linear growth factor, positions of density maxima do not change
- Distribution of extrema of waves of different scale are correlated: near maxima of large waves there are maxima of shorter waves (phase synchronisation)
- Rich clusters form in places where density maxima of medium scale waves coincide
- Superclusters form in places where density maxima of large scale waves coincide
- Superclusters & clusters are the richer the larger is the wavelength of phase synchronisation
- Voids form in regions where large scale density perturbations combine near minima of waves
- The skeleton of the cosmic web was formed in a very early stage of evolution
- **Why real richest superclusters are richer than models predict? Is there evidence for the presence of some characteristic scale in the Universe? What this means?**