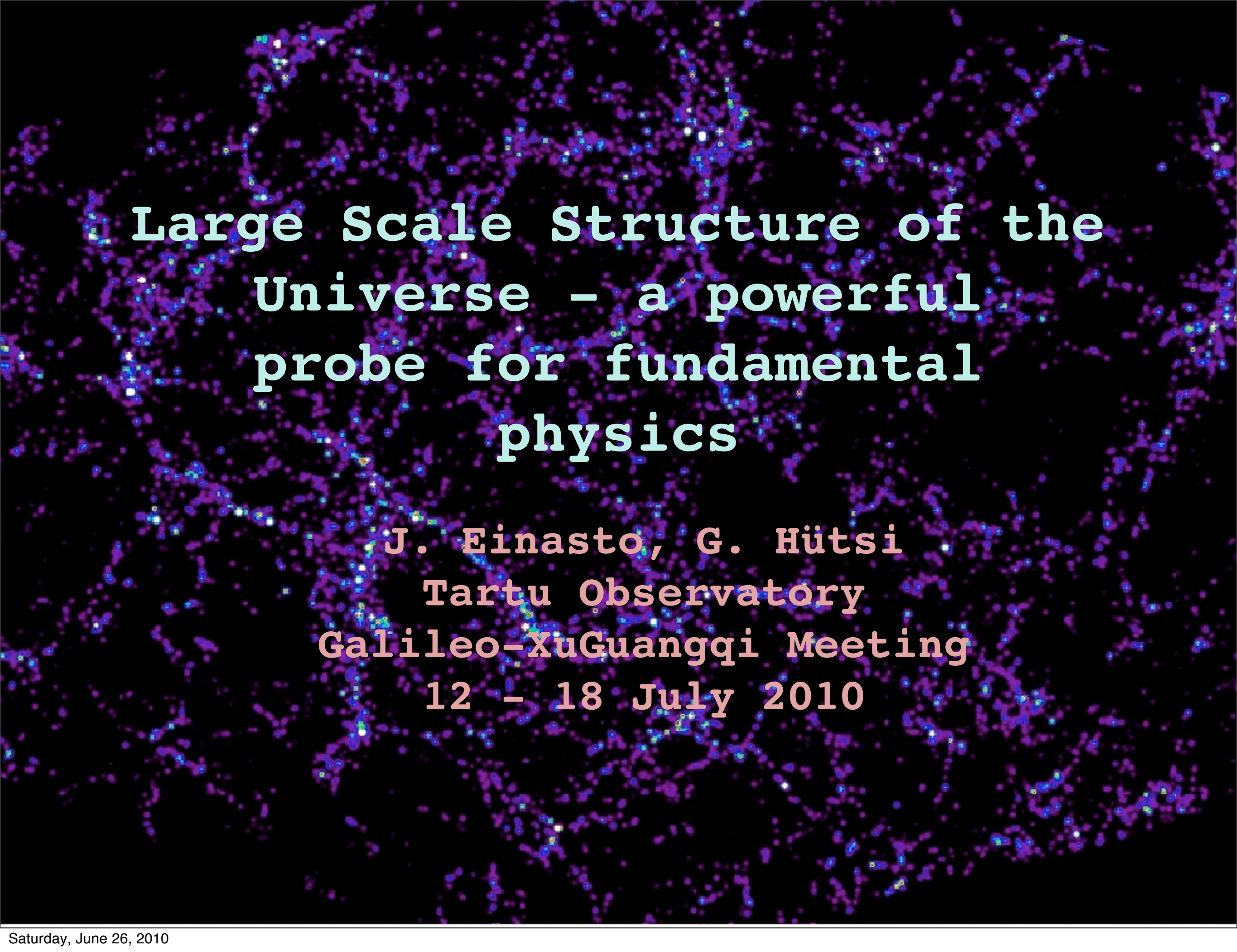


A visualization of the cosmic web, showing a complex network of dark matter filaments and galaxy clusters. The filaments are represented by a dense web of blue and purple dots, while the clusters are represented by denser regions of yellow and white dots. The overall structure is highly interconnected and spans the entire frame.

Large Scale Structure of the Universe – a powerful probe for fundamental physics

J. Einasto, G. Hütsi
Tartu Observatory
Galileo–XuGuangqi Meeting
12 – 18 July 2010

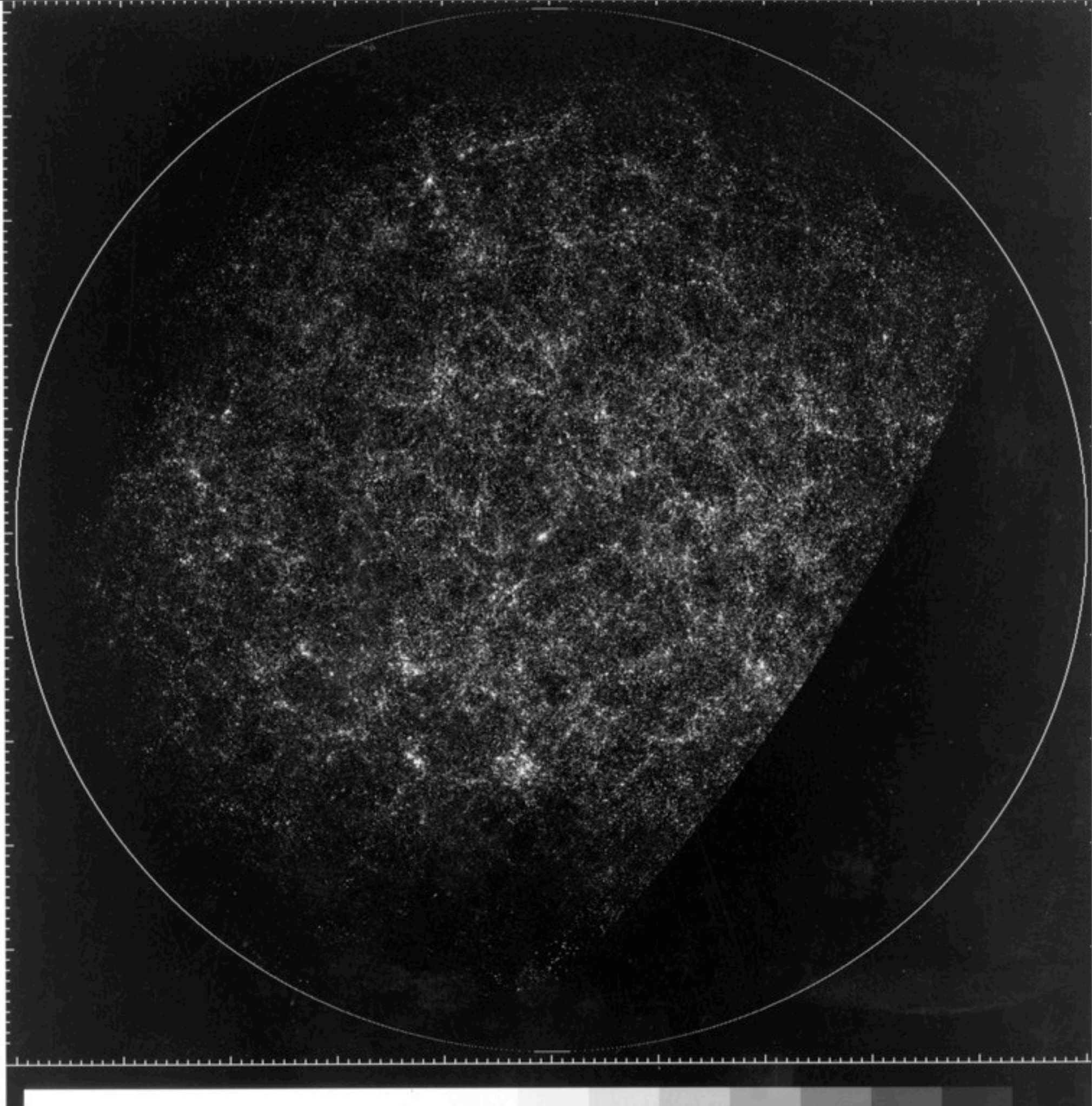
Summary

An overview is given on properties of the LSS using recent sky surveys (SDSS Main and LRG samples). LSS evolves very slowly, thus it contains imprints of physical conditions in the early Universe, as well as processes during its evolution. Present physical experiments are still unable to reproduce conditions in the very early Universe, thus the study of the properties of the LSS yields valuable information for fundamental physics.

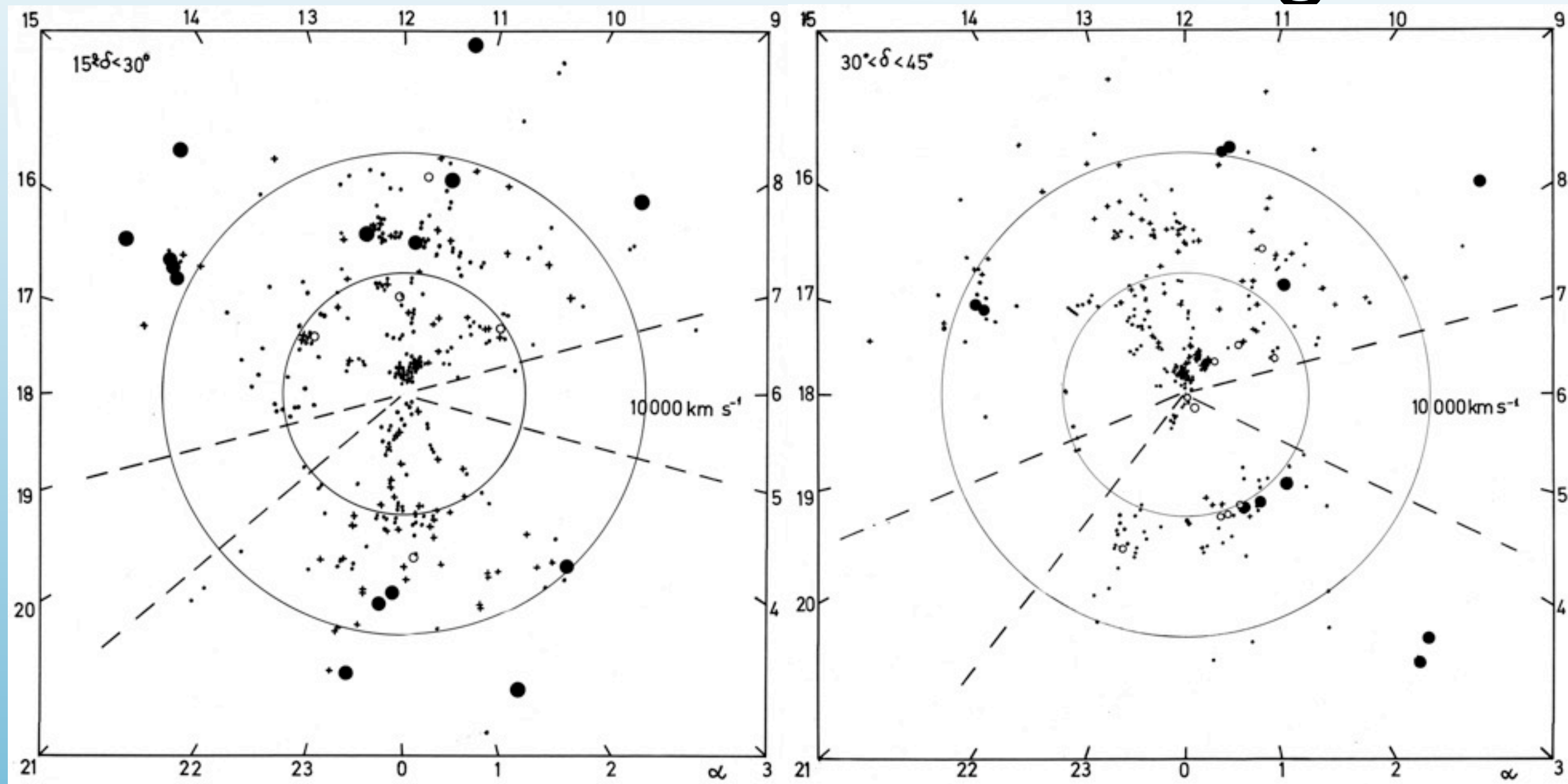
Two dimensional data

Lick survey of million
galaxies. Seldner et al.
(1976)

Clusters, superclusters
and almost randomly
distributed field
galaxies are visible



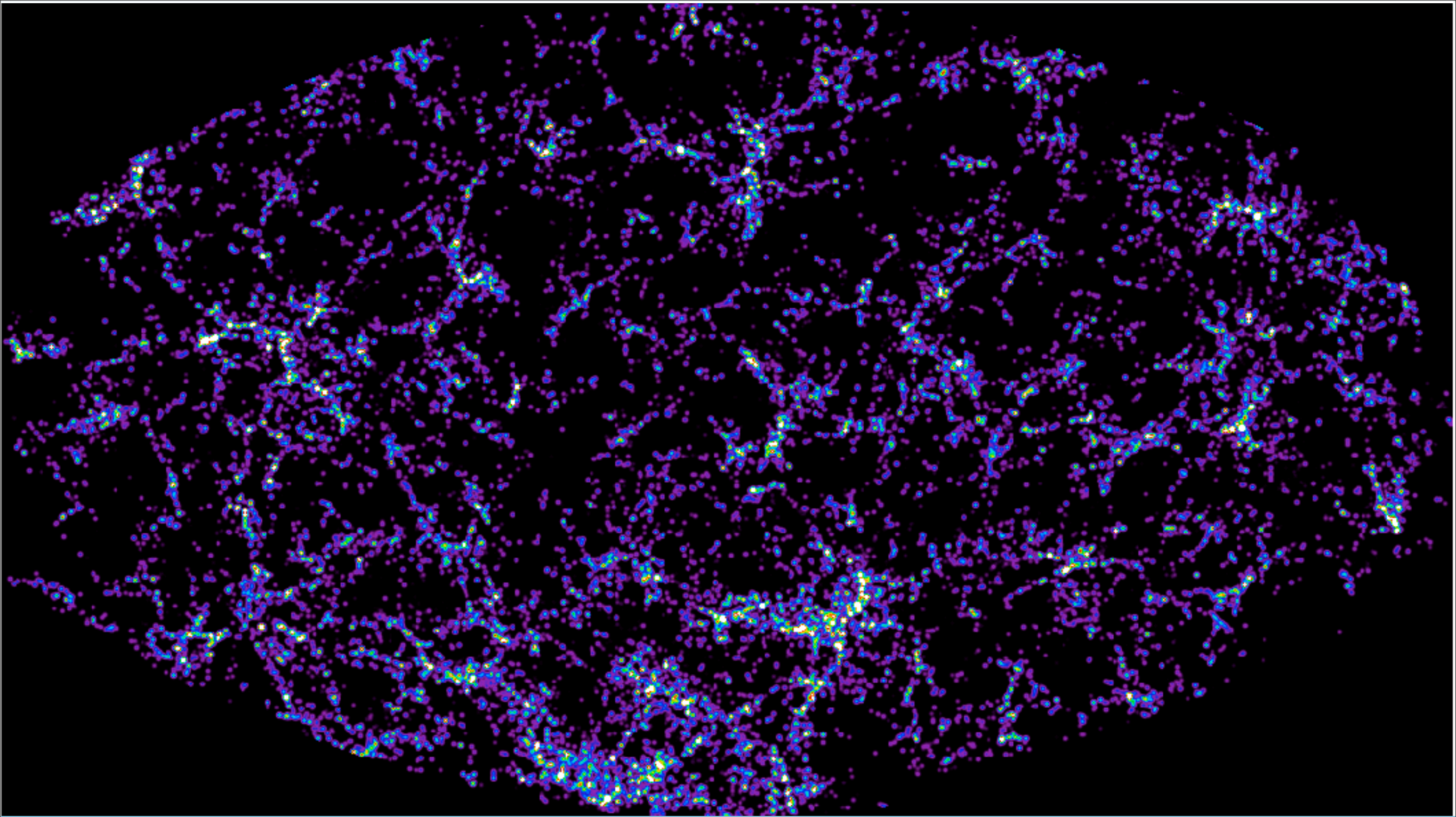
3-D data on the distribution of galaxies



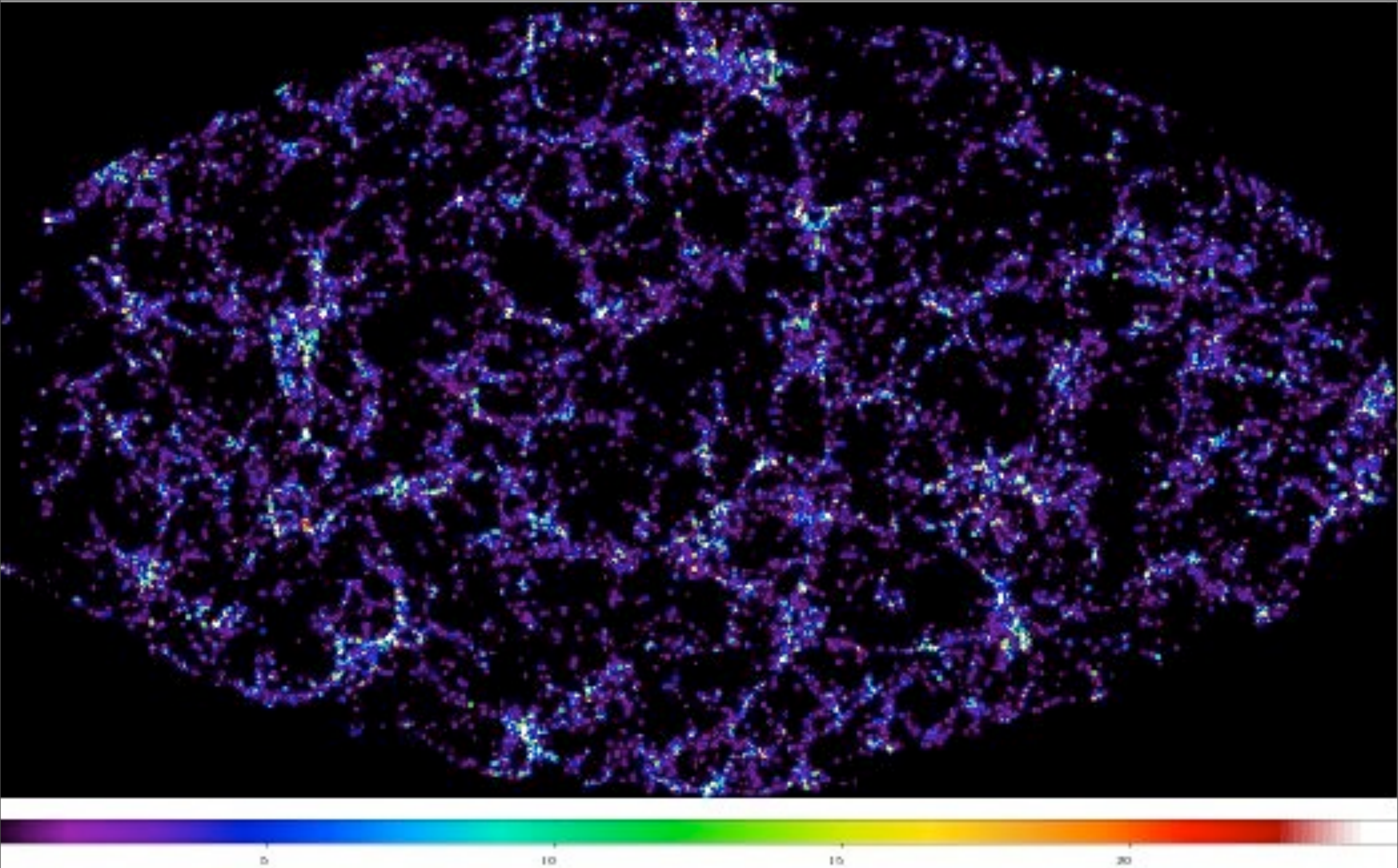
The distribution of clusters (filled circles), groups (open circles), active galaxies (crosses) and galaxies (dots). All objects concentrate to superclusters which are joined by galaxy filaments, the space in between is devoid of galaxies - cosmic voids (Jõeveer, Einasto 1977).



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

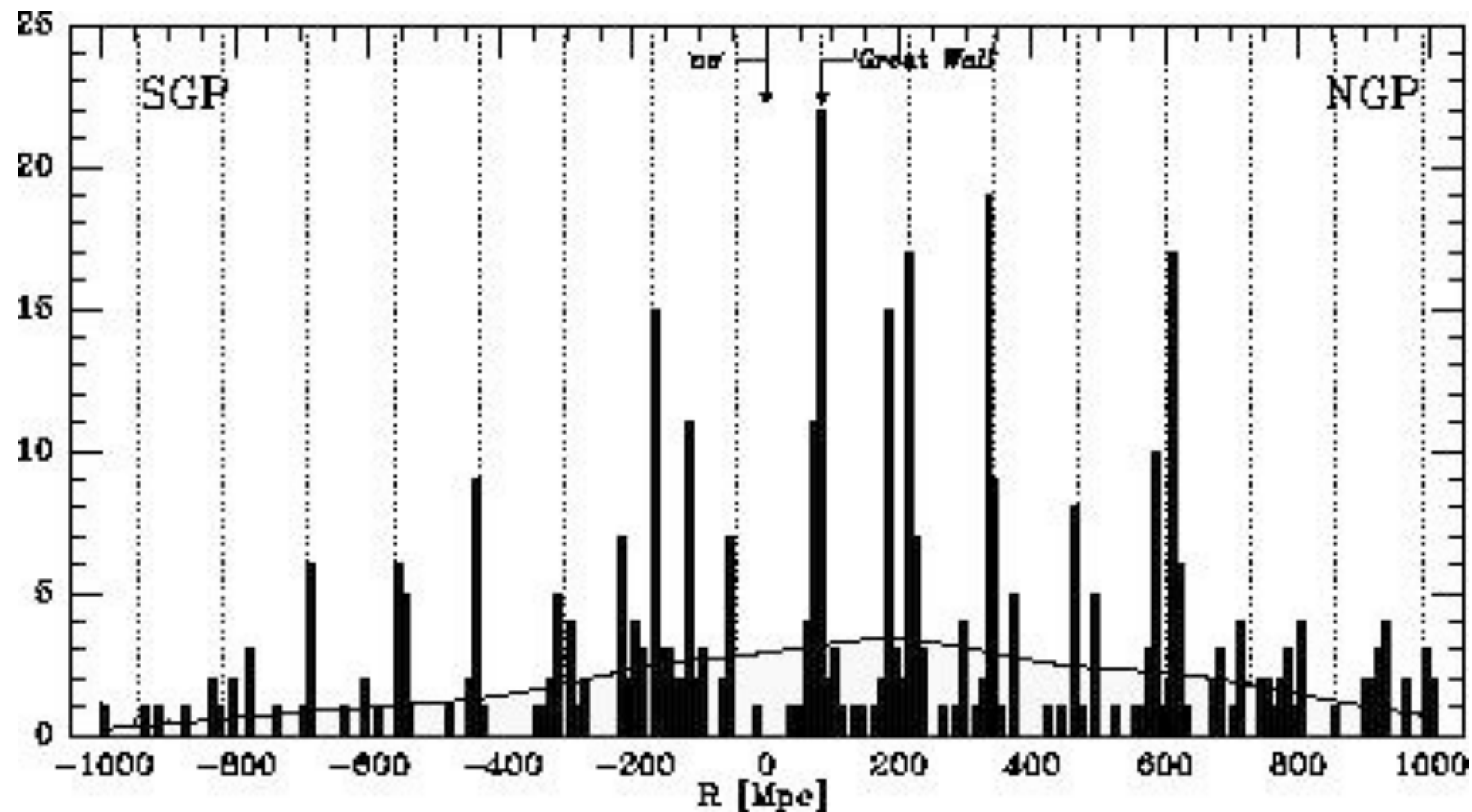


Luminosity density field of SDSS at distance 240 Mpc/h.
Rich superclusters in lower part form the Sloan Great Wall

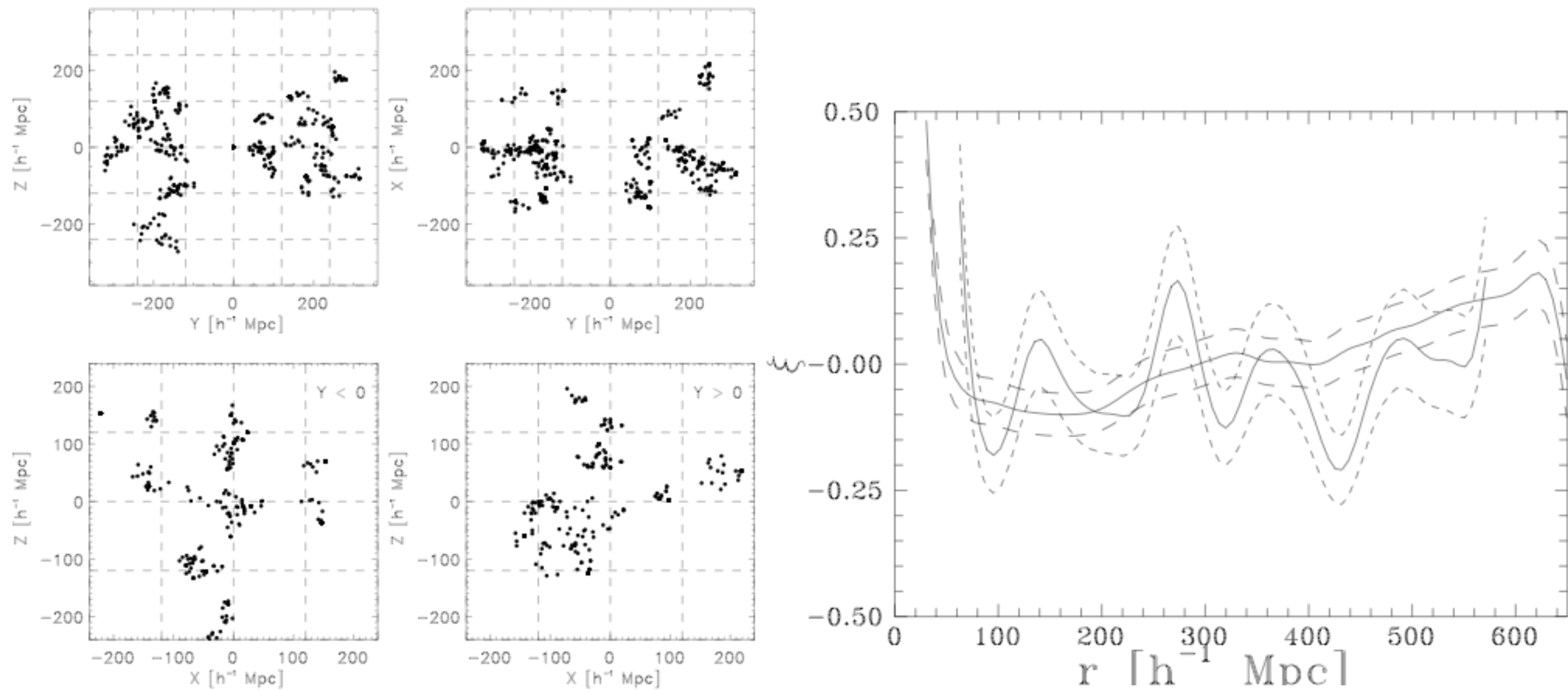


SDSS Luminosity density field at distance 325 Mpc/h

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 $\sim 120 \text{ Mpc}/h$ is evident (JE et al 1997)

SCL luminosity and multiplicity functions

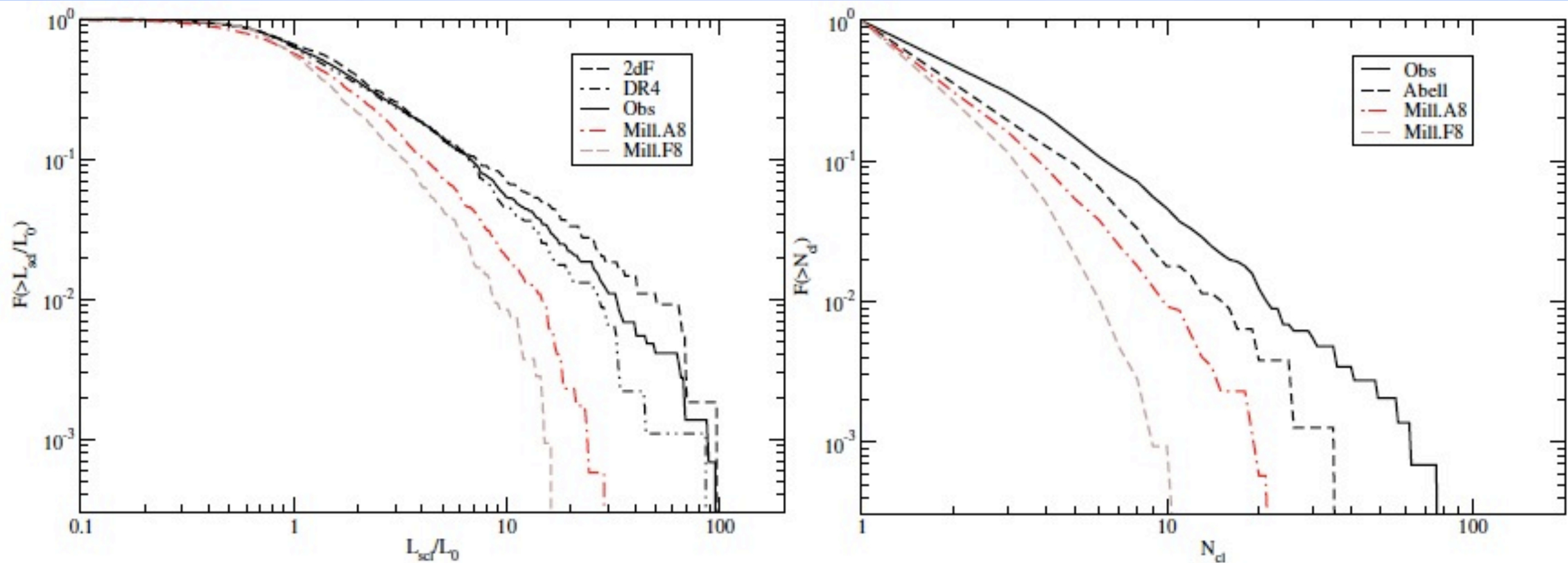
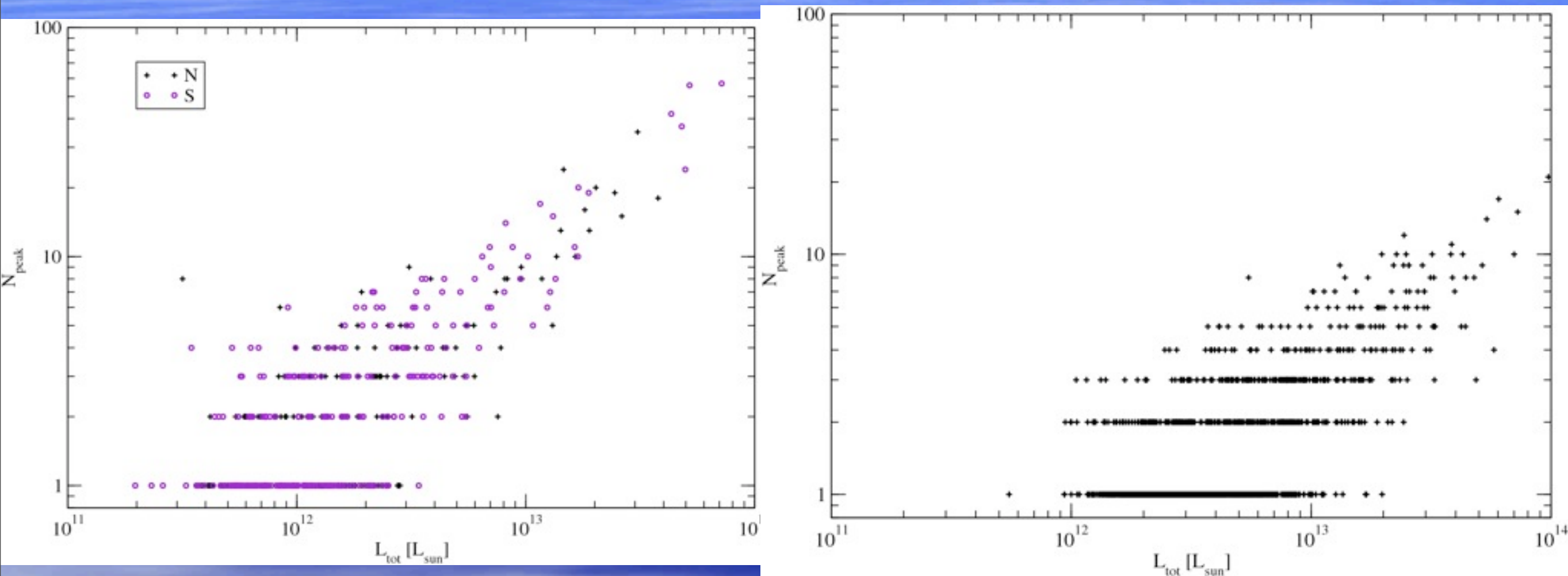


Fig. 1. The comparison of relative luminosity functions and multiplicity functions of observational and model supercluster samples. The spatial density of superclusters is expressed in terms of the total number of superclusters in the respective sample to avoid small differences due to the mean number 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.

Luminosity and multiplicity of superclusters



The multiplicity of superclusters of various luminosity

Left: 2dF superclusters

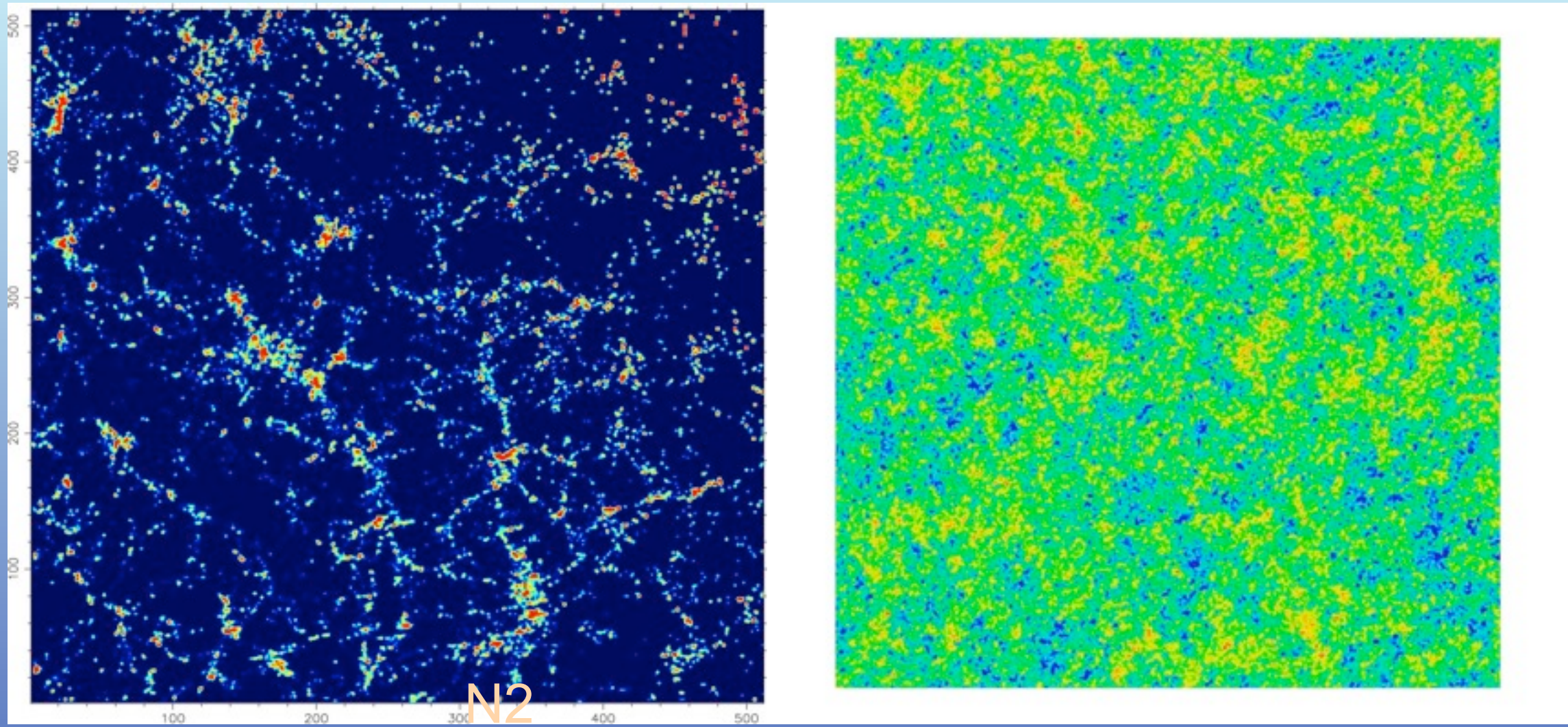
Right: Millennium superclusters

To understand deviations of the model from real Universe we use wavelet and Fourier analyses of the density field

We use the 'a trous wavelet transform. 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. The sum of these bands restores the original field.

We show the Fourier analysis and the decomposition of the density field of SDSS around SCL126

Cosmic web: the role of phases

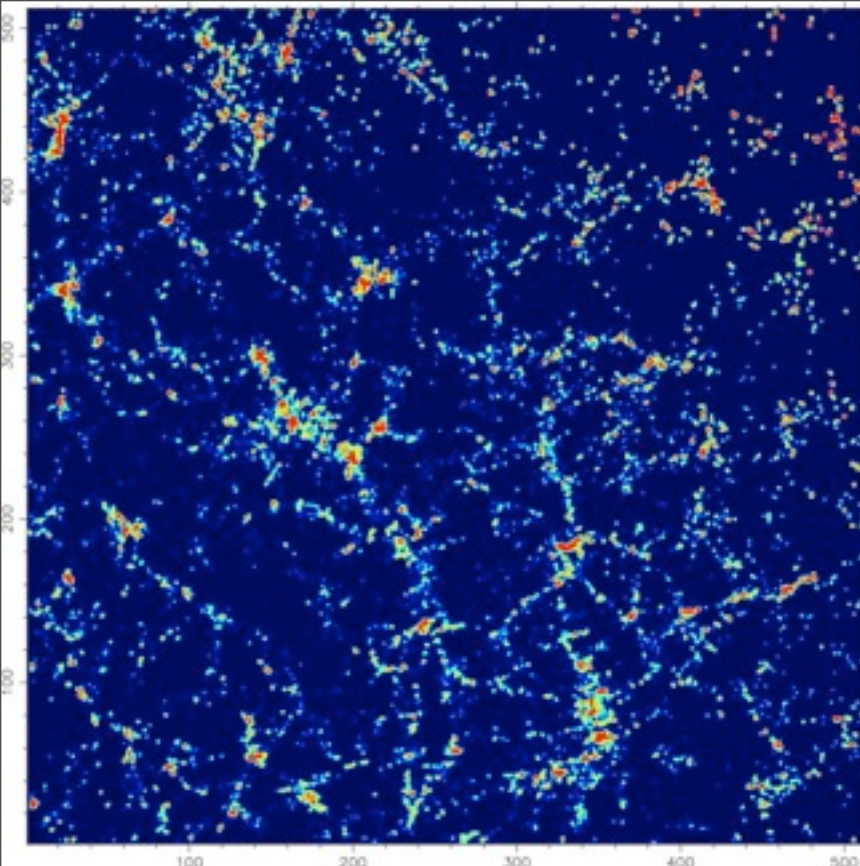


Left: Northern SDSS slice

Right: The same field but phases of density waves randomised by Fourier transform.

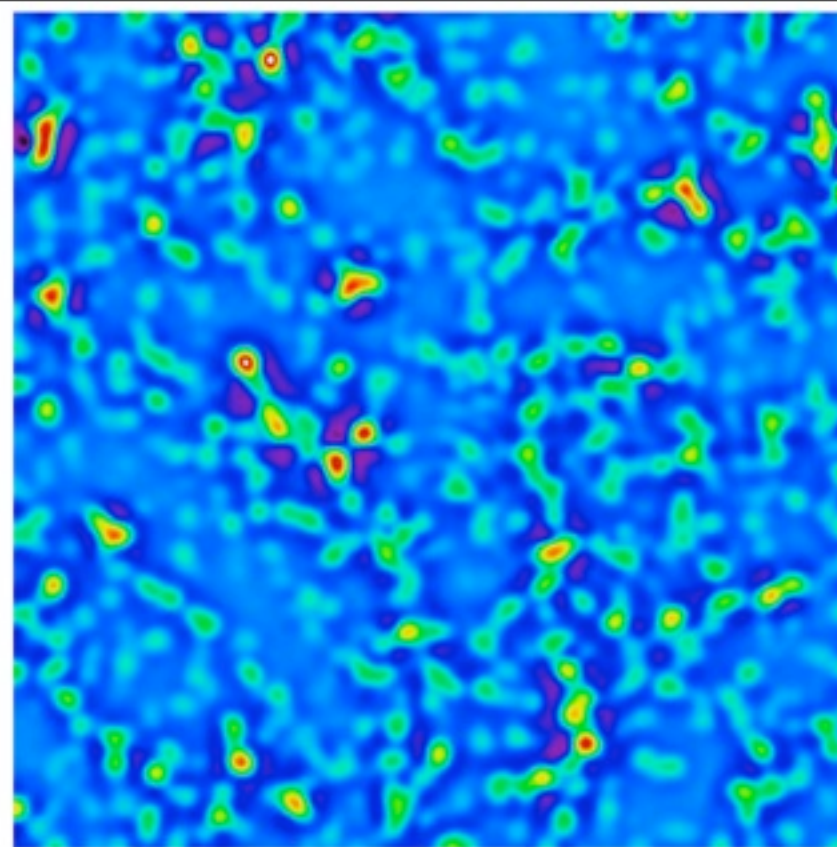
There are no filaments, superclusters & voids.

Phases are important in the formation of the cosmic web. Similar results by Szalay (private communication)



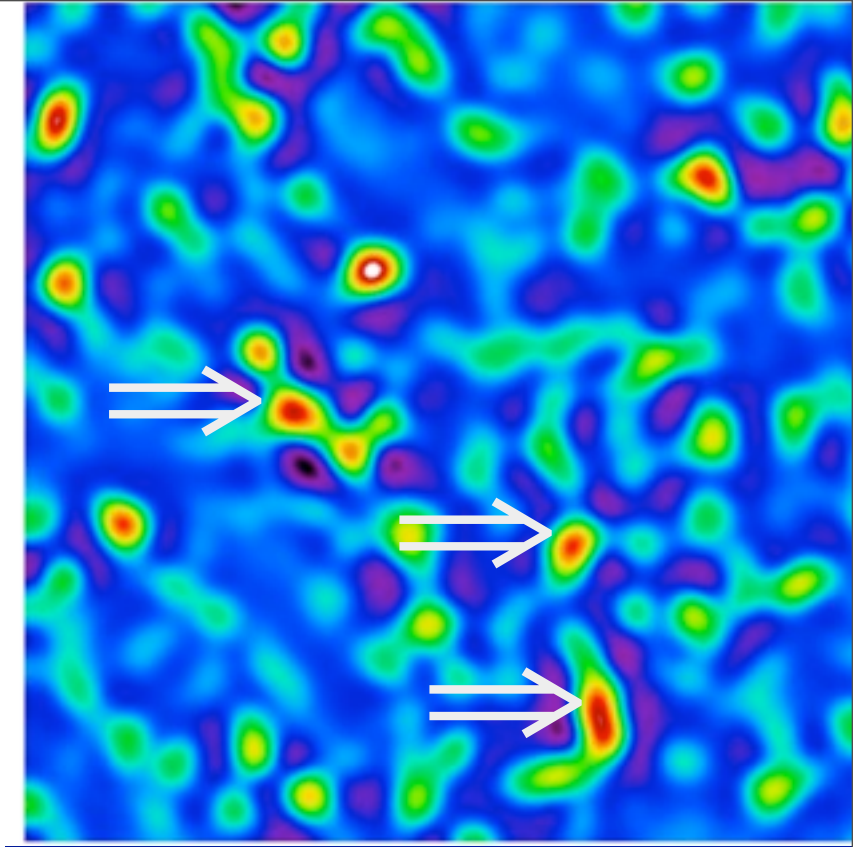
SDSS
w4

Original L=500 Mpc



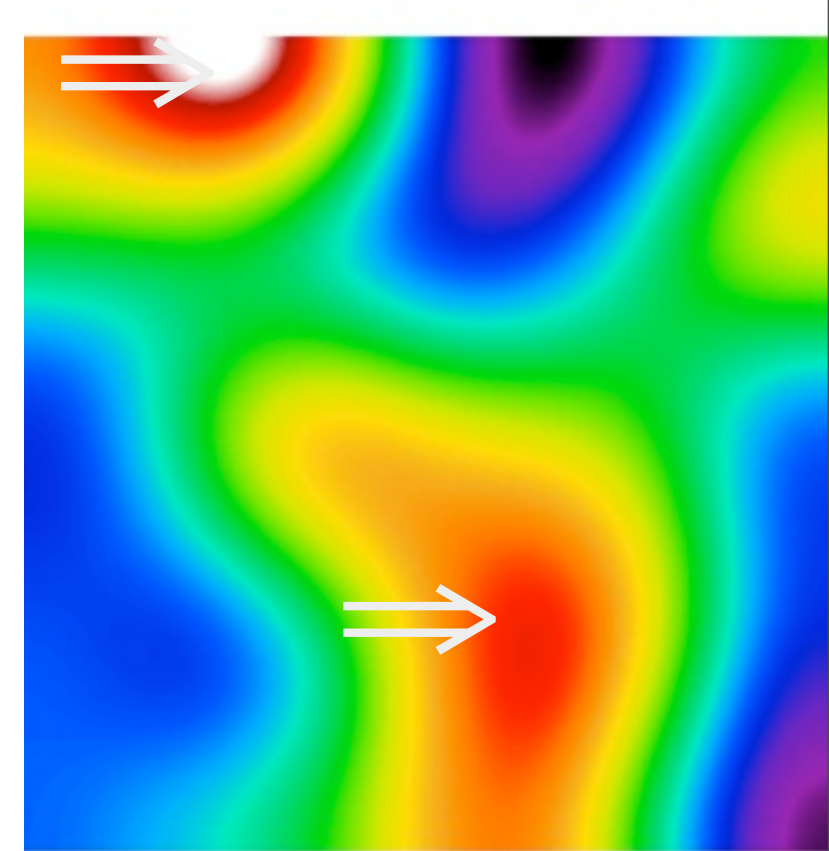
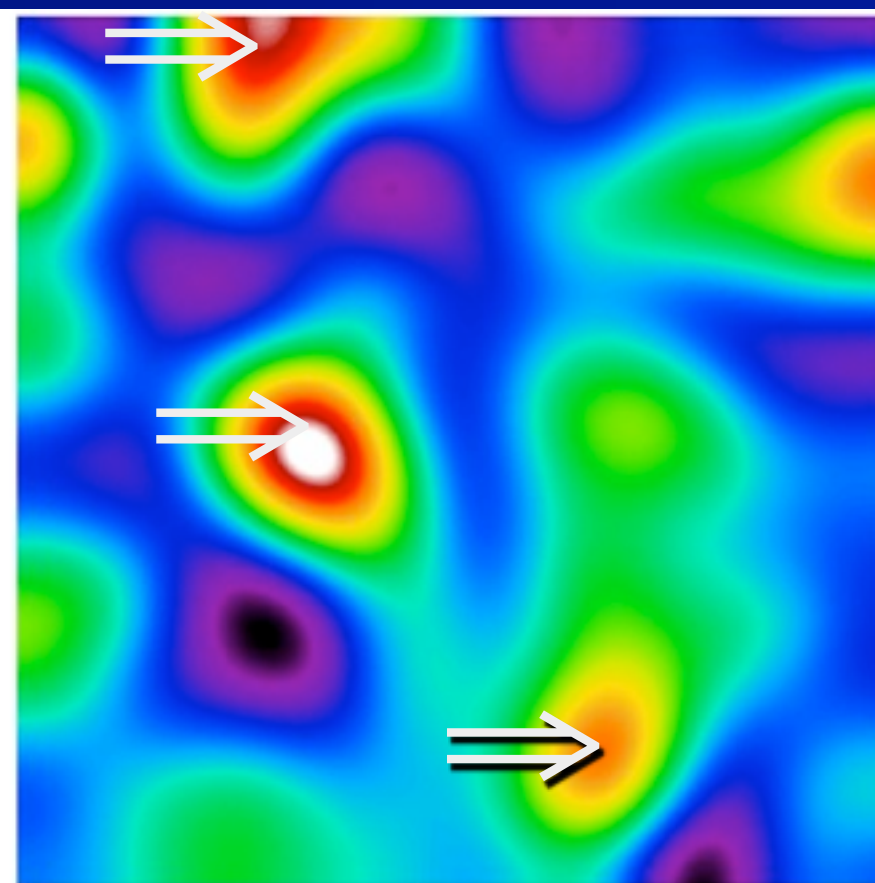
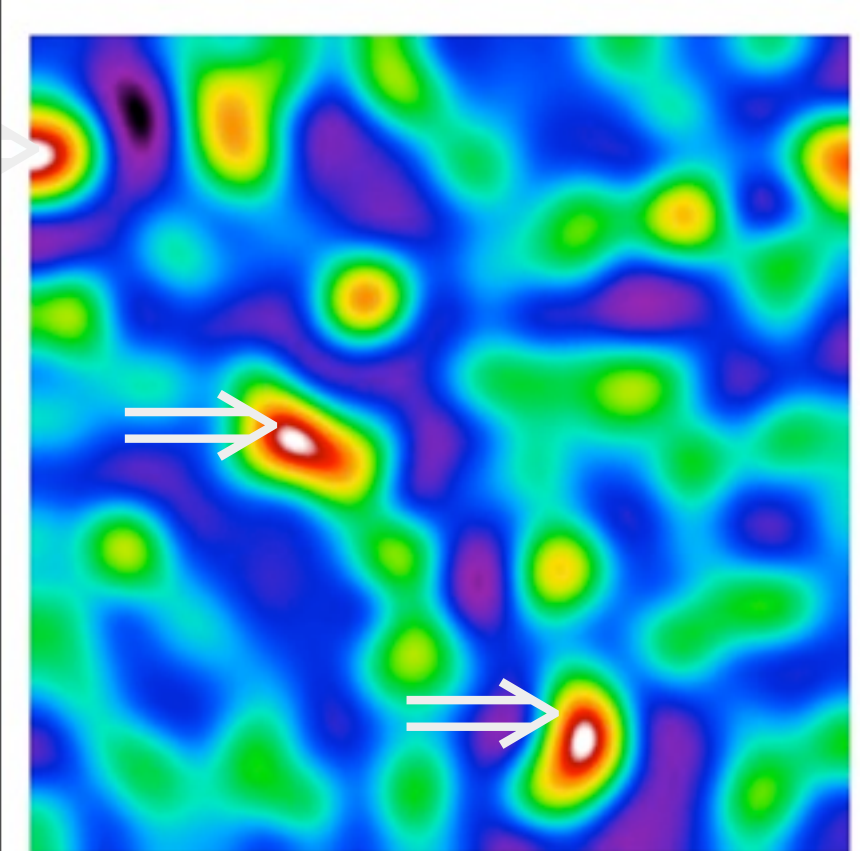
wavelet w2

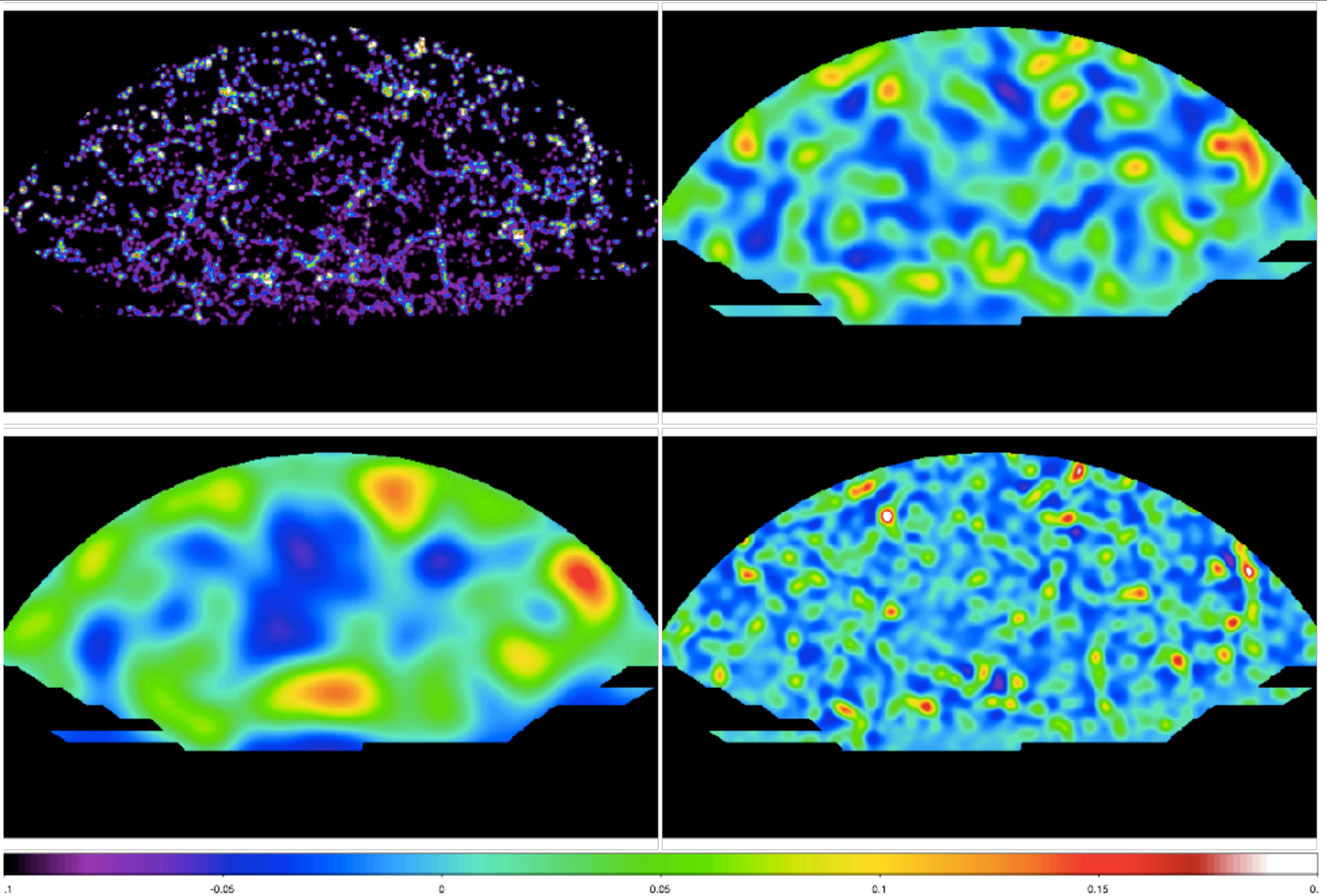
w5



w3

w6





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

Results of the wavelet 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