Morphological Analysis of the Large-Scale Structure in the Universe

Sergei Shandarin

University of Kansas

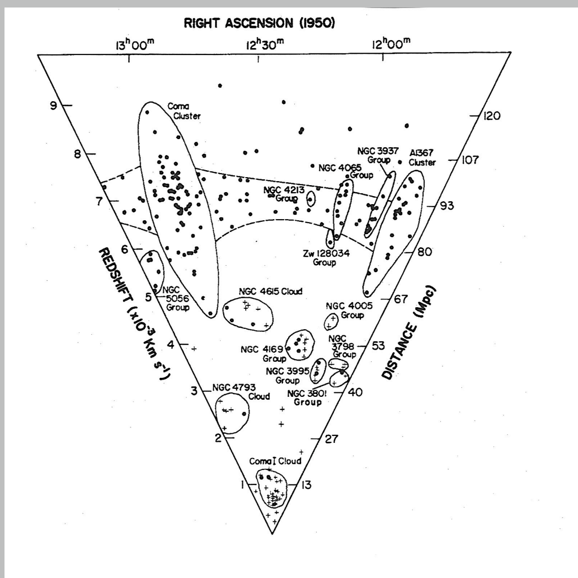
Plan

- Introduction: Cosmic Web
- Non-morphological statistics
  N-point functions.
- Morphology of LSS
  Percolation. Genus. Minkowski Functionals. Shapefinders
- Lambda CDM cosmology
- Supercluster – Void network
- Summary

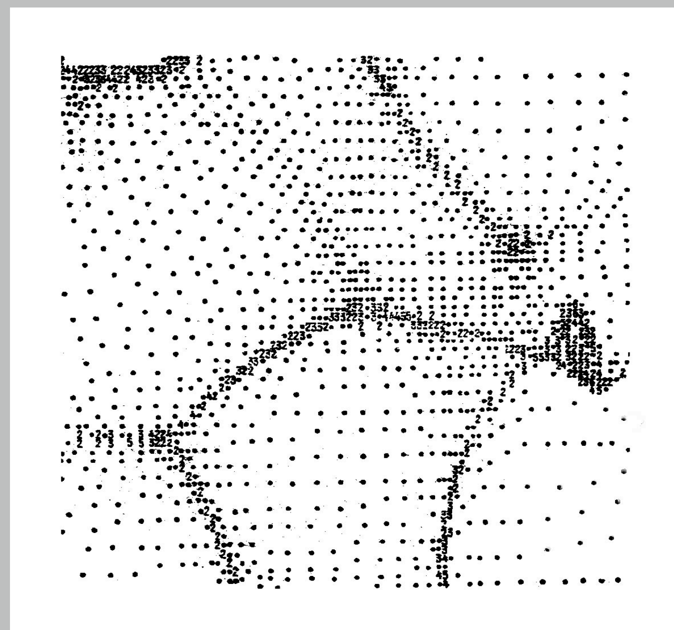
Collaborators: J. Sheth, V. Sahni, Sathyaprakash

Cosmic Web: first hints

Observations **Simulations**

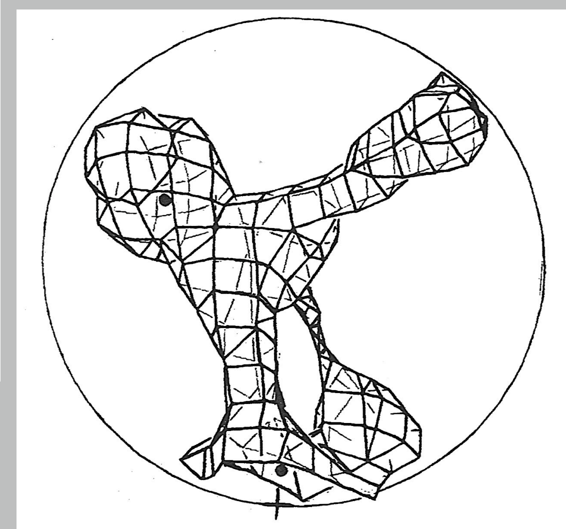


Gregory & Thompson 1978



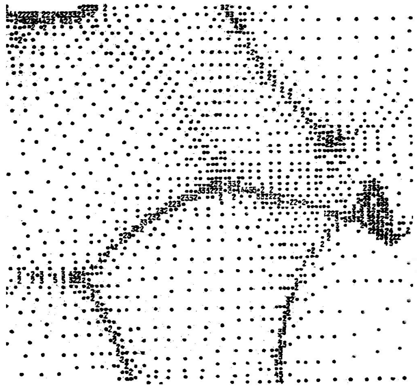
Shandarin 1975

2D
Zel'dovich
Approximation

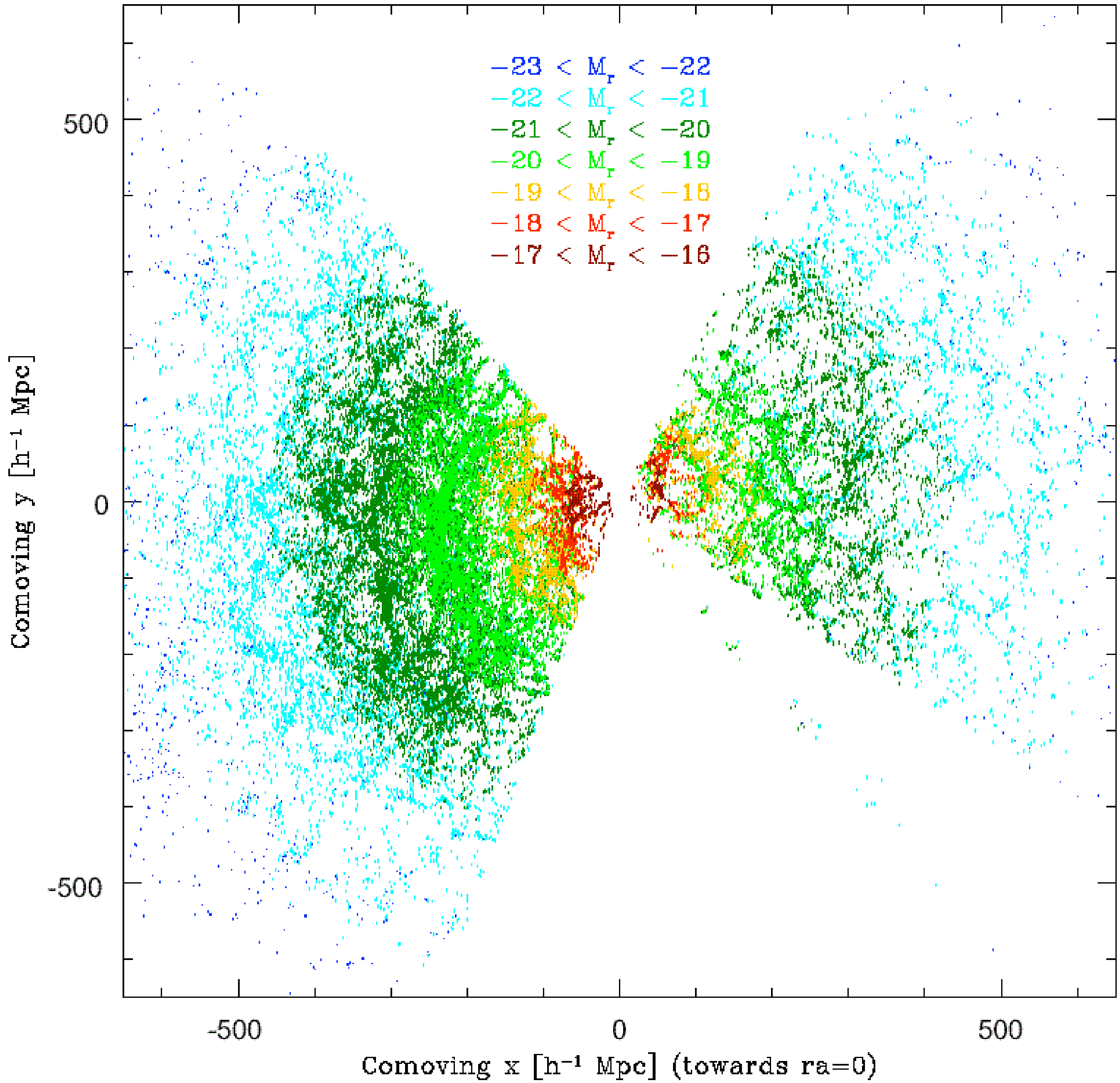


Klypin & Shandarin 1983
3D
N-body Simulation

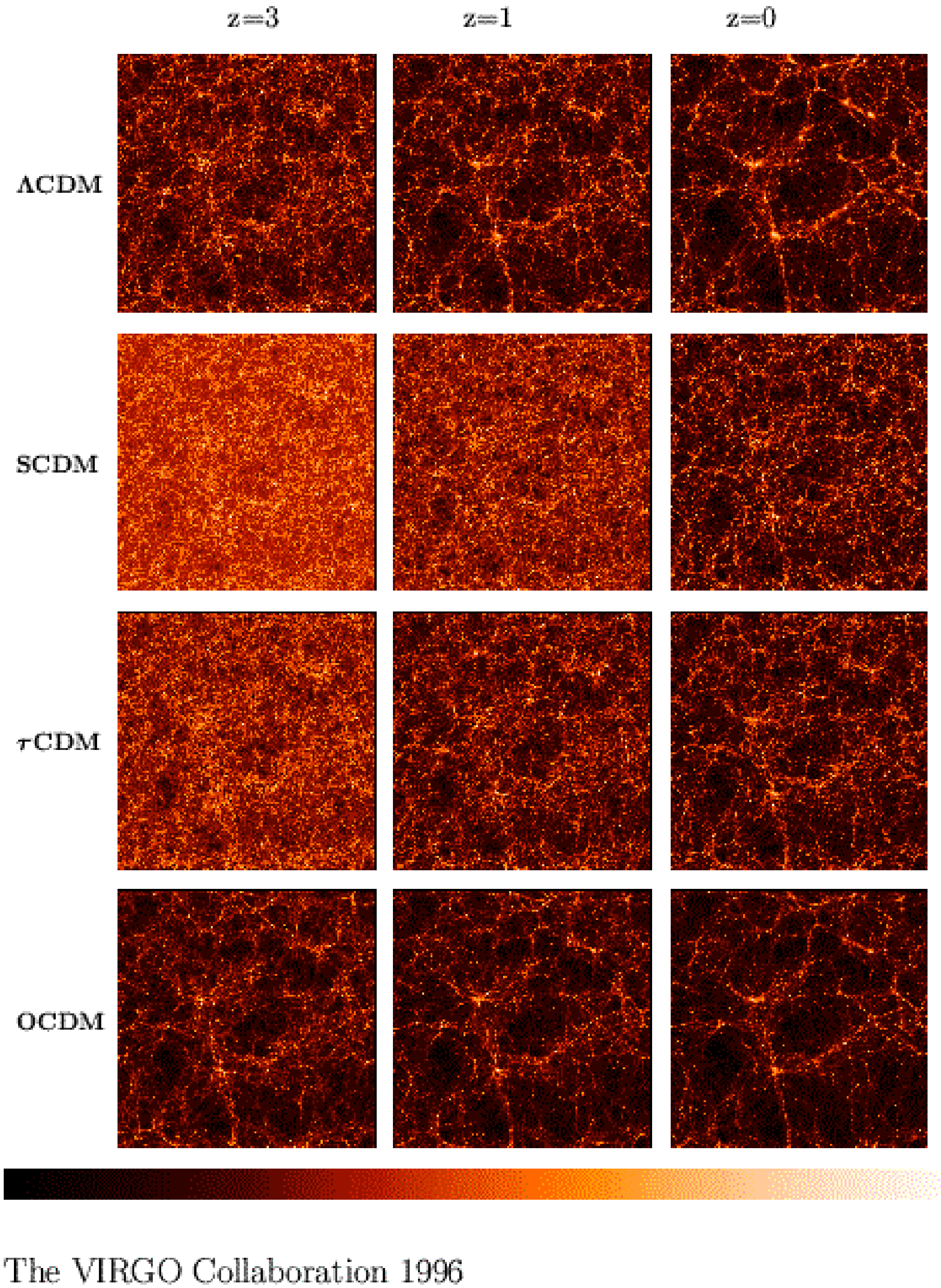
Zel'dovich Approximatin



SDSS



Tegmark et al
astro-ph/0310725


z=3
z=1
z=0
ΛCDM
SCDM
τCDM
OCDM
The VIRGO Collaboration 1996

Soneira & Peebles 1978

Both distributions have similar 1-point, 2-point, 3-point, and 4-point correlation functions

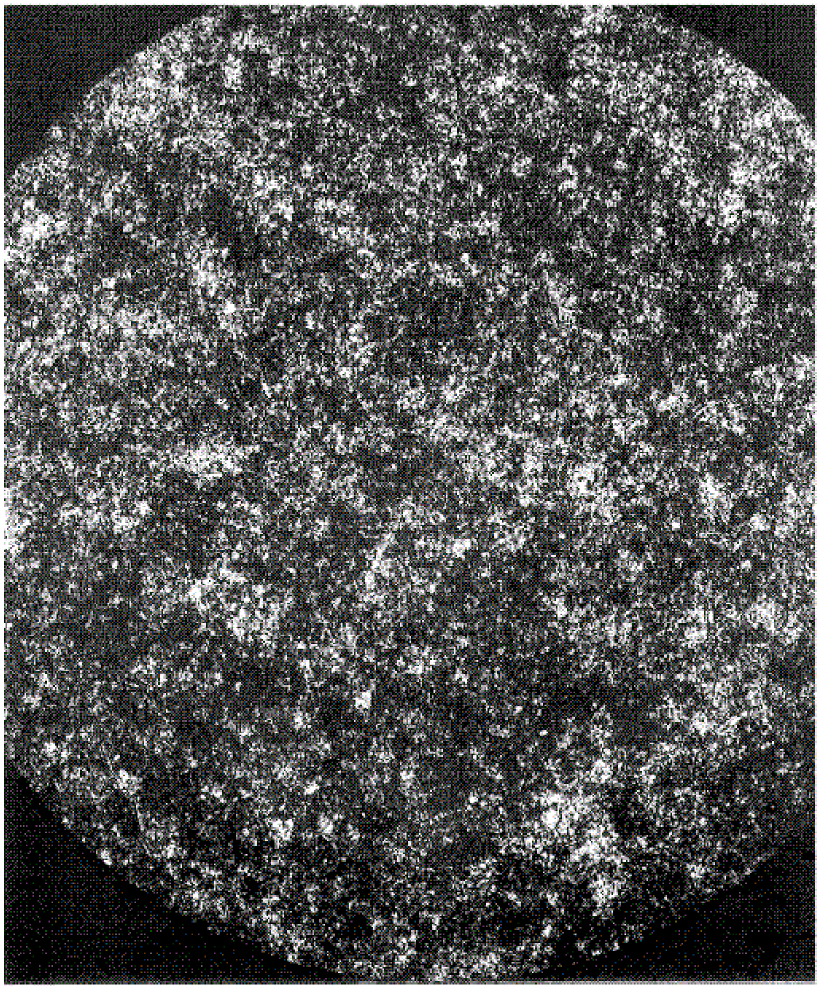


FIG. 2. Galaxy map for the extrapolated $\nu \leq 14$ model as in Fig. 3.

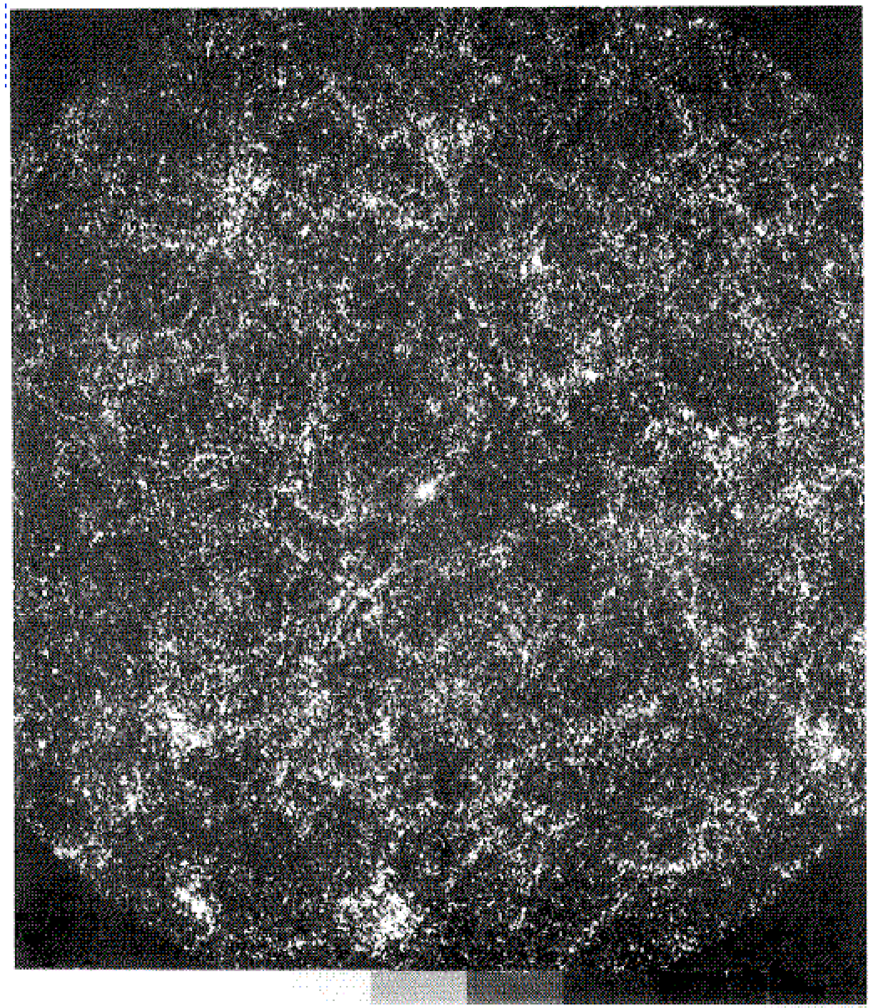


FIG. 3. Galaxy map for the Lick data with $b^{II} \geq 40°$. The map is an array of picture elements, each about the size of one 10′ by 10′ Shane–Wirtanen cell, in which the grey tone represents the galaxy count in the nearest cell. The grey scale shows the steps for successive increases of one galaxy commencing with black for zero.

A COMPUTER MODEL UNIVERSE: SIMULATION OF THE NATURE OF THE GALAXY DISTRIBUTION IN THE LICK CATALOG[a)]

RAYMOND M. SONEIRA and P. J. E. PEEBLES
Joseph Henry Laboratories, Physics Department, Princeton University, Princeton, N. J. 08540
Received 23 February 1978

ABSTRACT

and 386 000 galaxies are visible at $m \leq 18.9$ and $b \geq 40°$. By adjusting parameters in the model within the limits allowed by the correlation functions to fourth order we have arrived at a galaxy map with a visual appearance that seems a reasonable first approximation to that of the Lick data.

Einasto, Klypin, Saar, Shandarin 1984

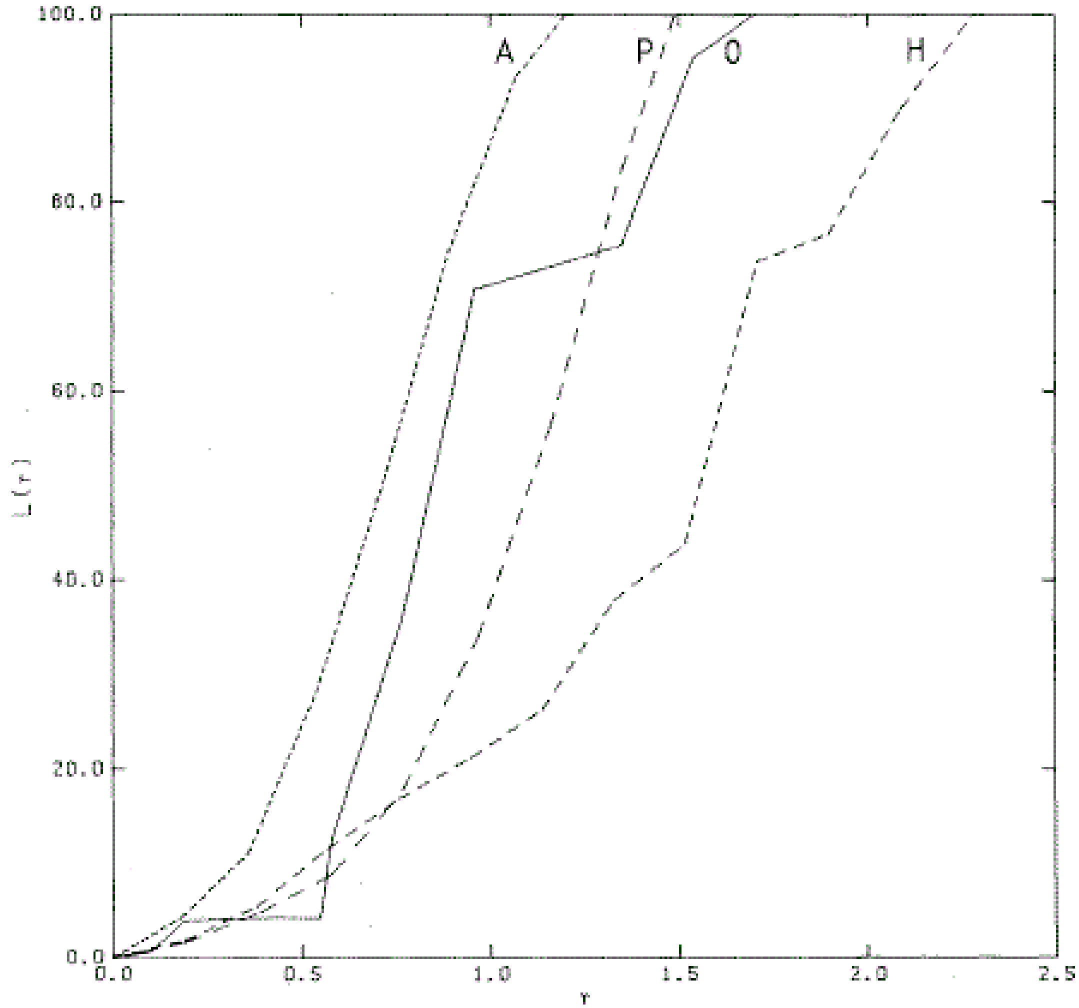


Figure 11. The length, L, of largest clusters in the observed (O), adiabatic (A), hierarchical (H) and Poisson (P) models. The length L is given in Mpc, the neighbourhood radius r is given in dimensionless

Redshift catalog

H.Rood, J.Huchra

Density fields vs. Pointwise distributions

Linear (quasilinear) theory

Real and mock galaxy catalogs

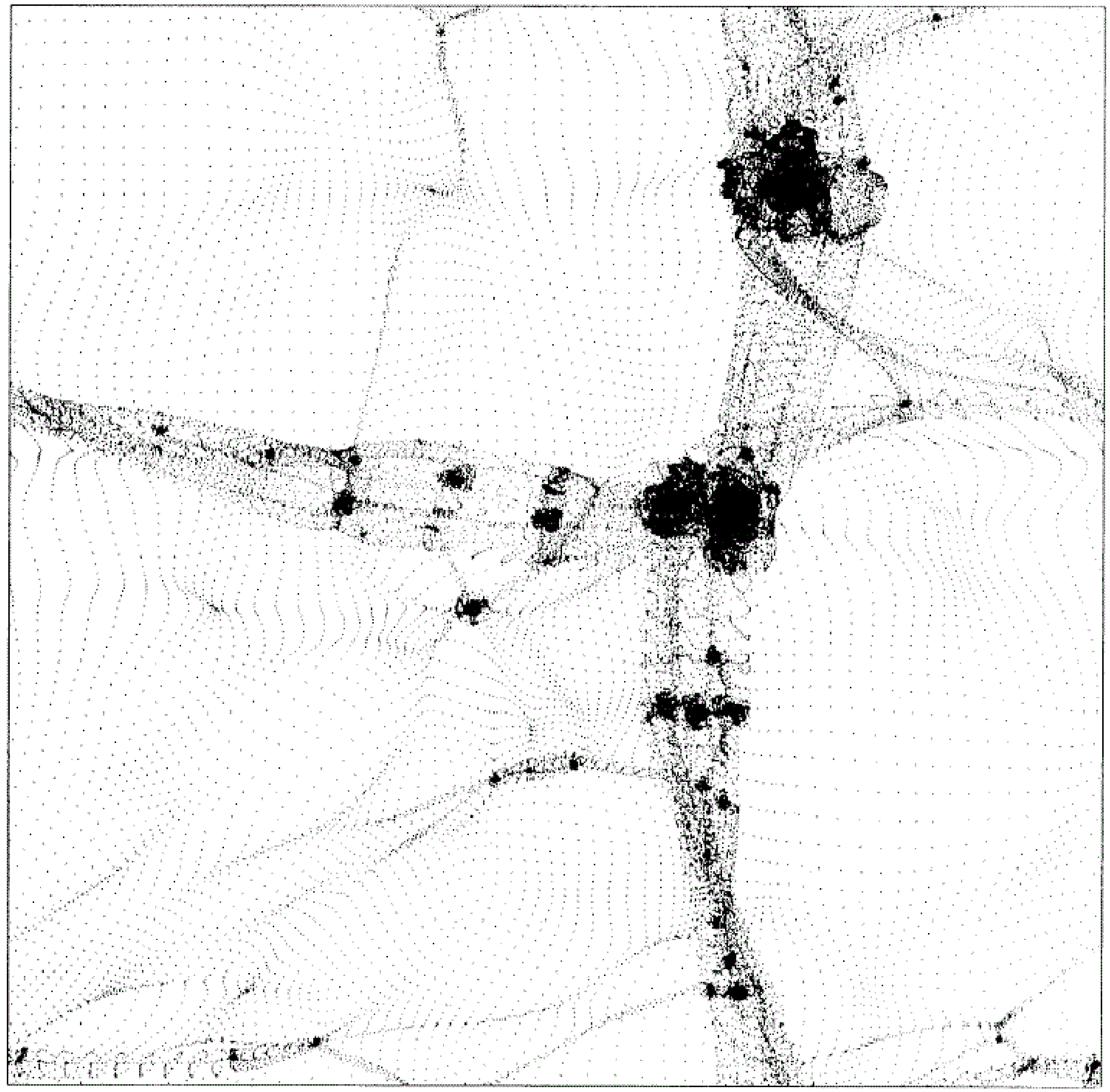
N-body simulations

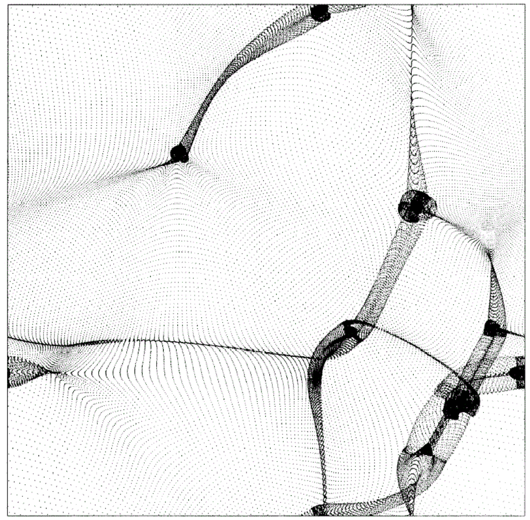
Superclusters vs.. voids

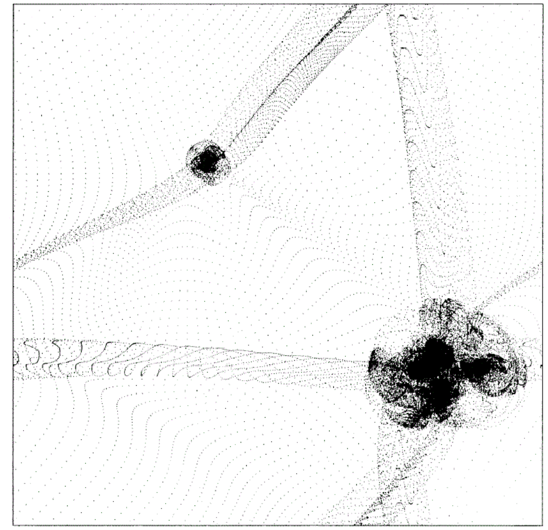
Smoothing with some window (Gaussian, top-hat, CIC), SPH, Wavelets, DTFE)

Quasi Poisson process

Examples of multiscale stuctures in 2D N-body simulations







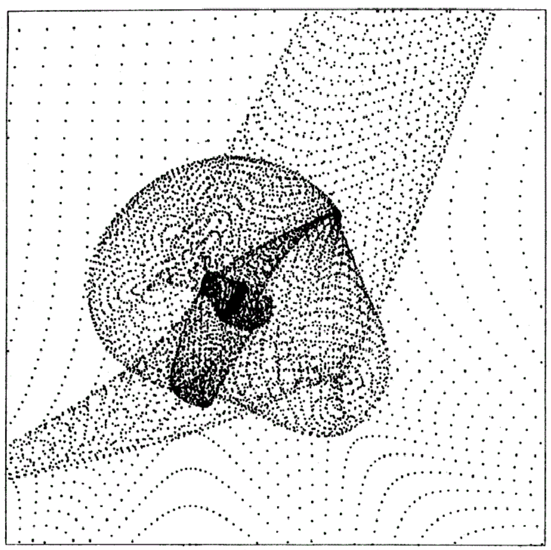


FIG. 3.—J4F4 Center 171, 363. The image is magnified by a factor of 16.

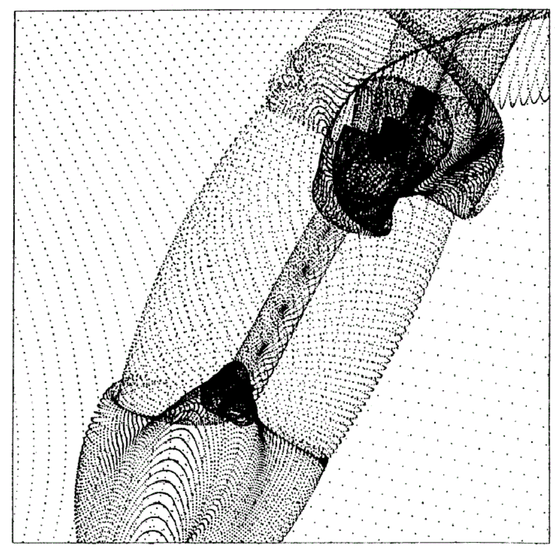
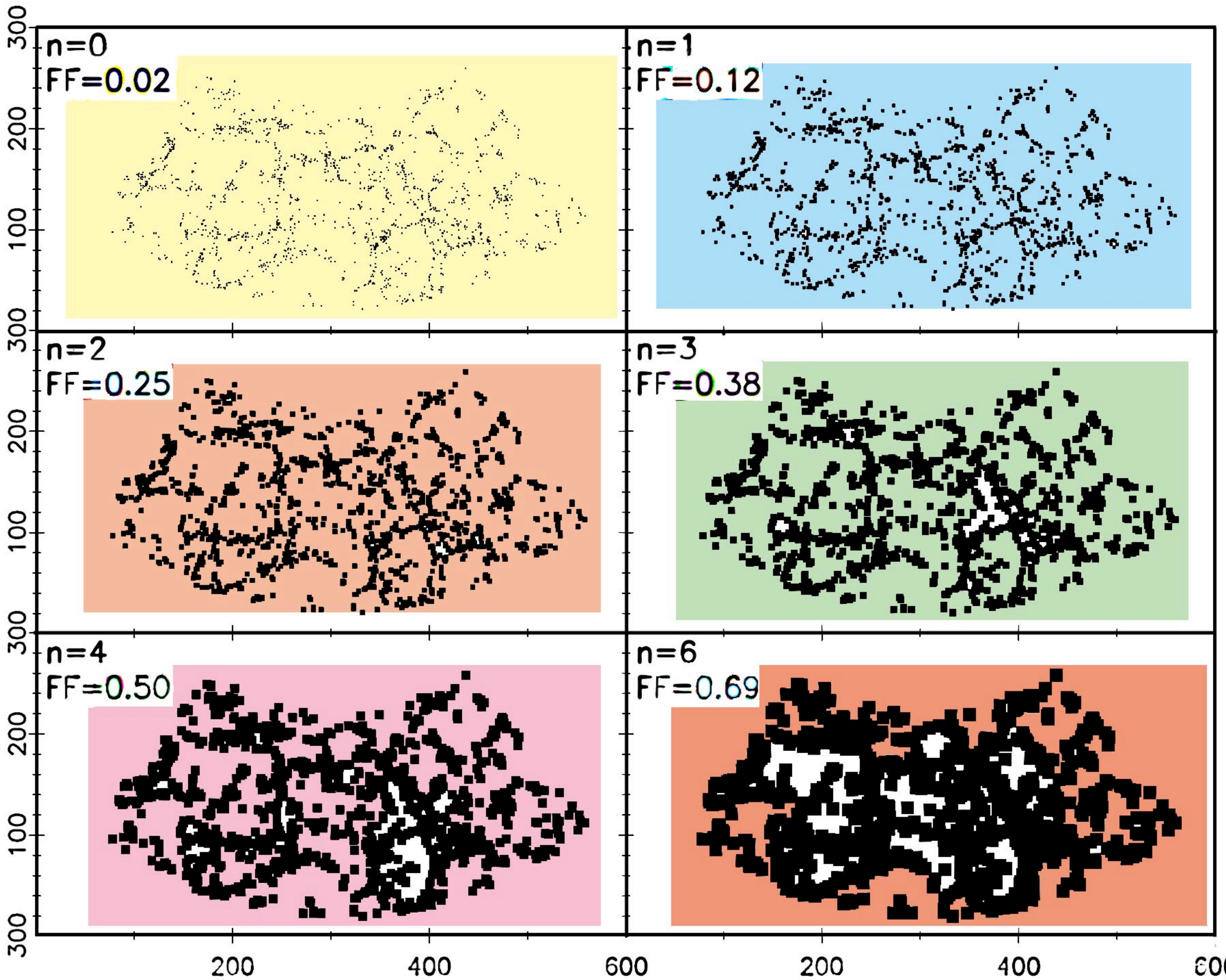


FIG. 4.—(*a*) J4F4 Center 424, 88. The image is magnified by a

Bharadwaj, Sahni, Sathyaprakash, & Shandarin 2000, ApJ, 528, 21

LCRS

central part of the slice



n specifies the level of coarse graining

FF = Filling Factor =Fraction of Area in Black

SUPERCLUSTERS and VOIDS are defined as the regions enclosed by isodensity surface.

Interface surface is build by SURFGEN algorithm, using linear interpolation

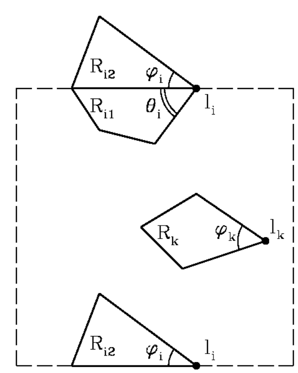
The density of a supercluster is higher than the density of the boundary surface.

The density of a void is lower than the density of the boundary surface.

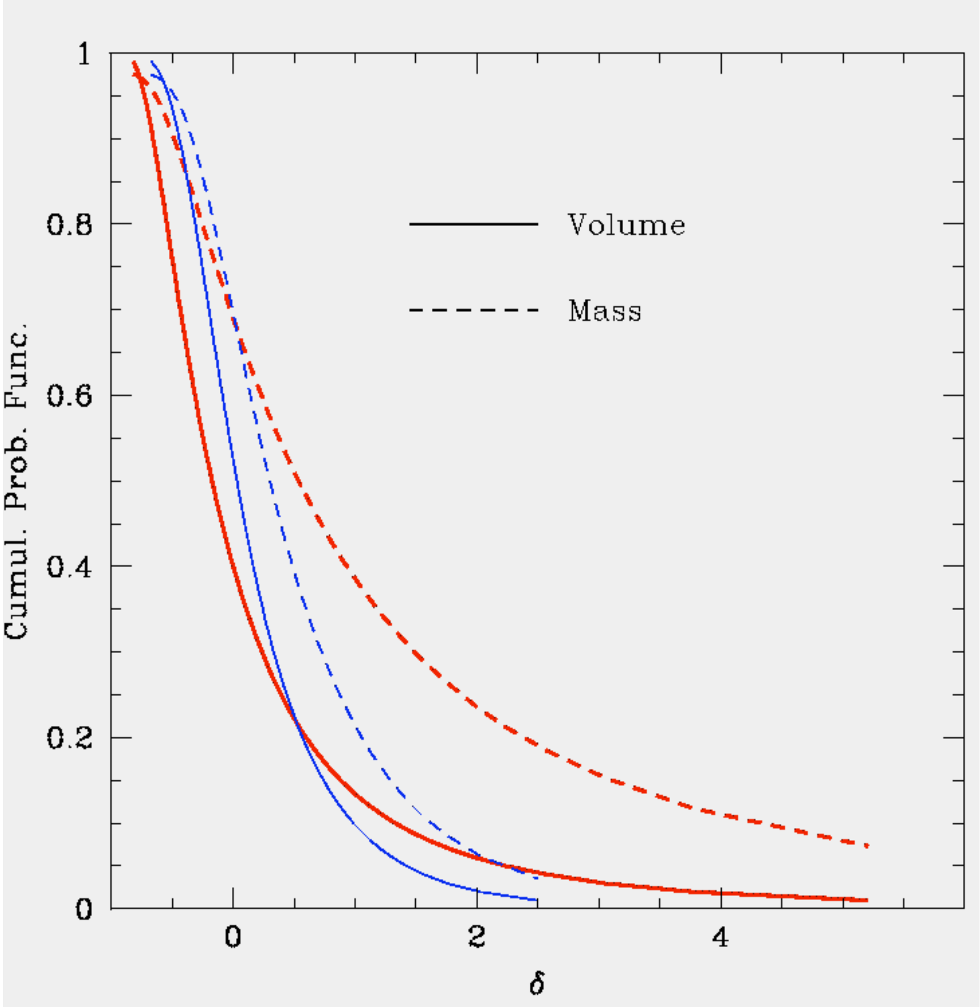
The boundary surface may consist of any number of disjointed pieces.

Each piece of the boundary surface must be closed.

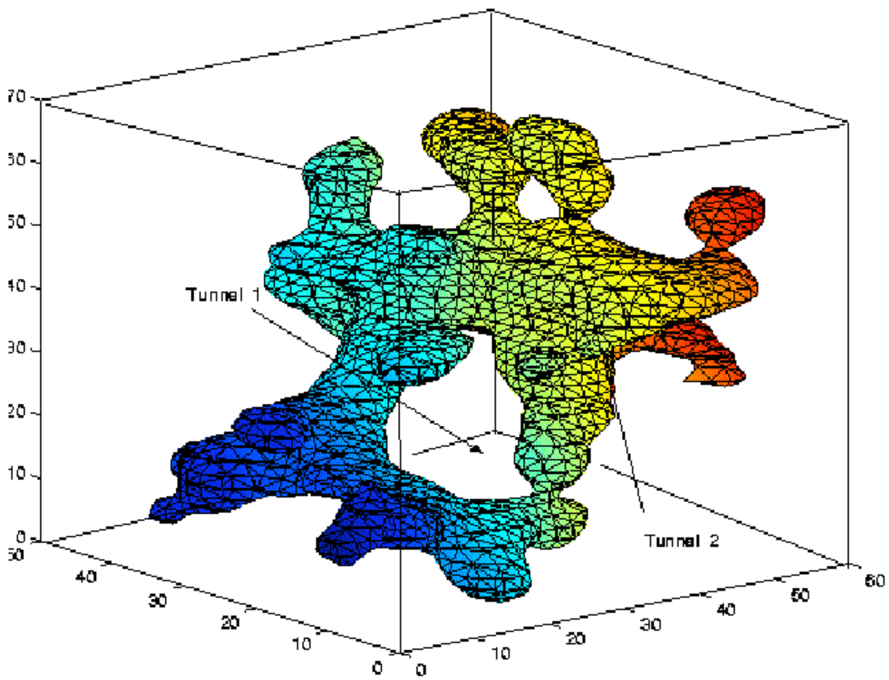
Boundary surface of SUPERCLUSTERS and VOIDS cut by volume boundary are closed by parts of the volume boundary

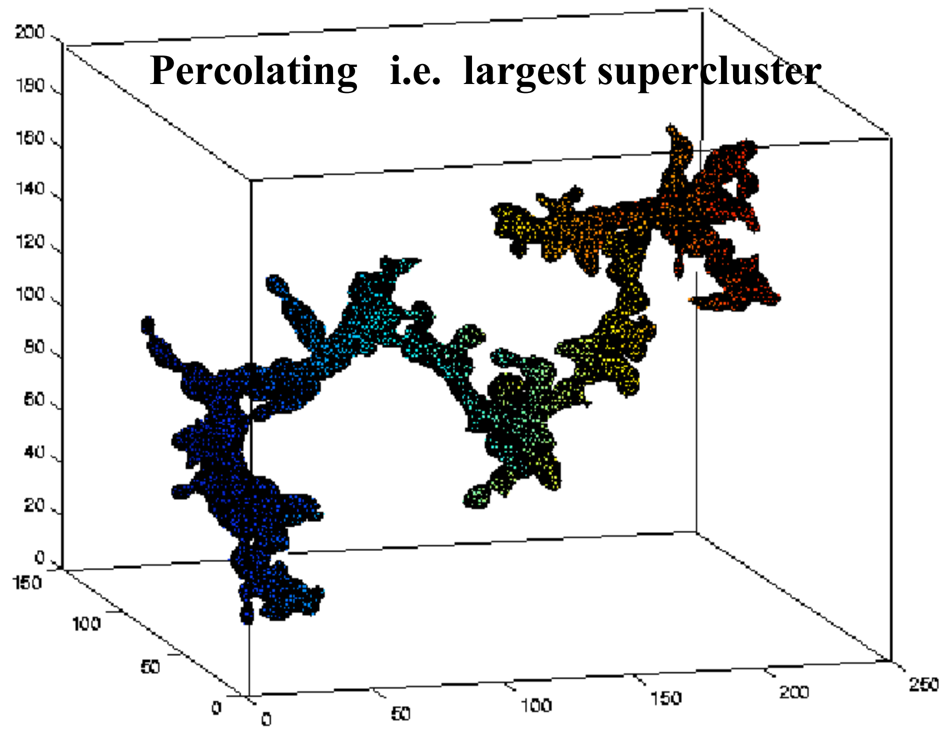


Filling Factor of overdense regions



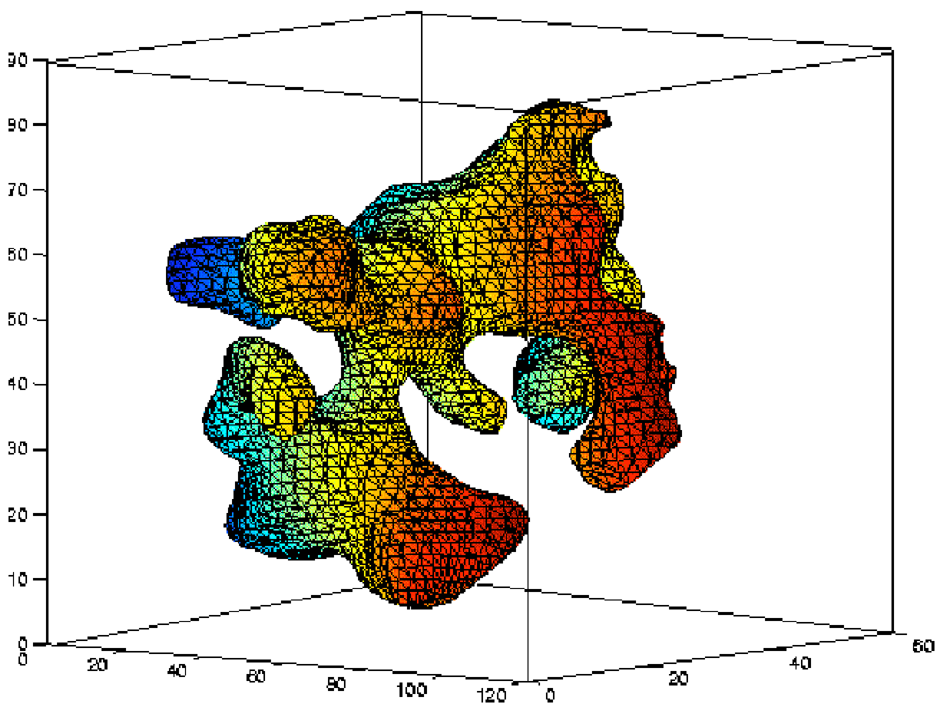
Superclusters in LCDM simulation (VIRGO consortium) by SURFGEN

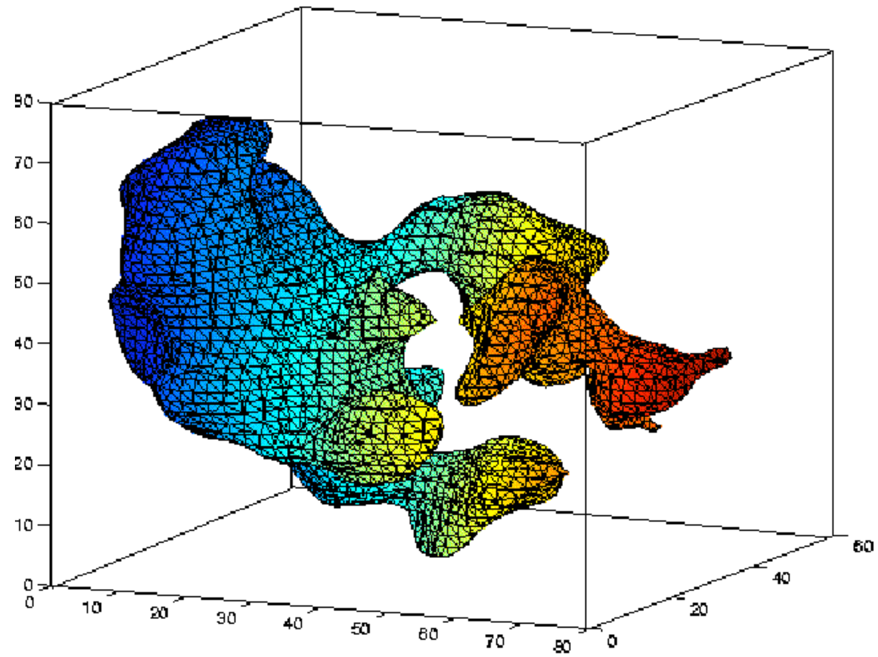




Sheth, Sahni, Shandarin, Sathyaprakash 2003, MNRAS, 343, 22

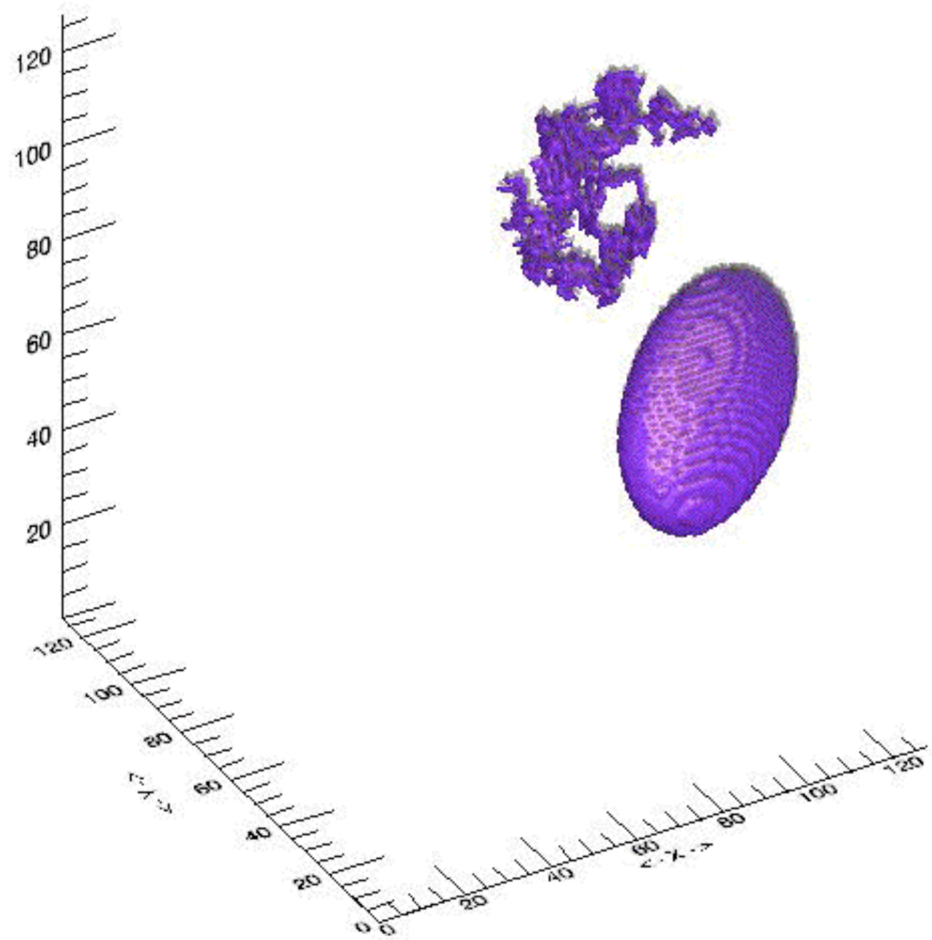
VOIDS

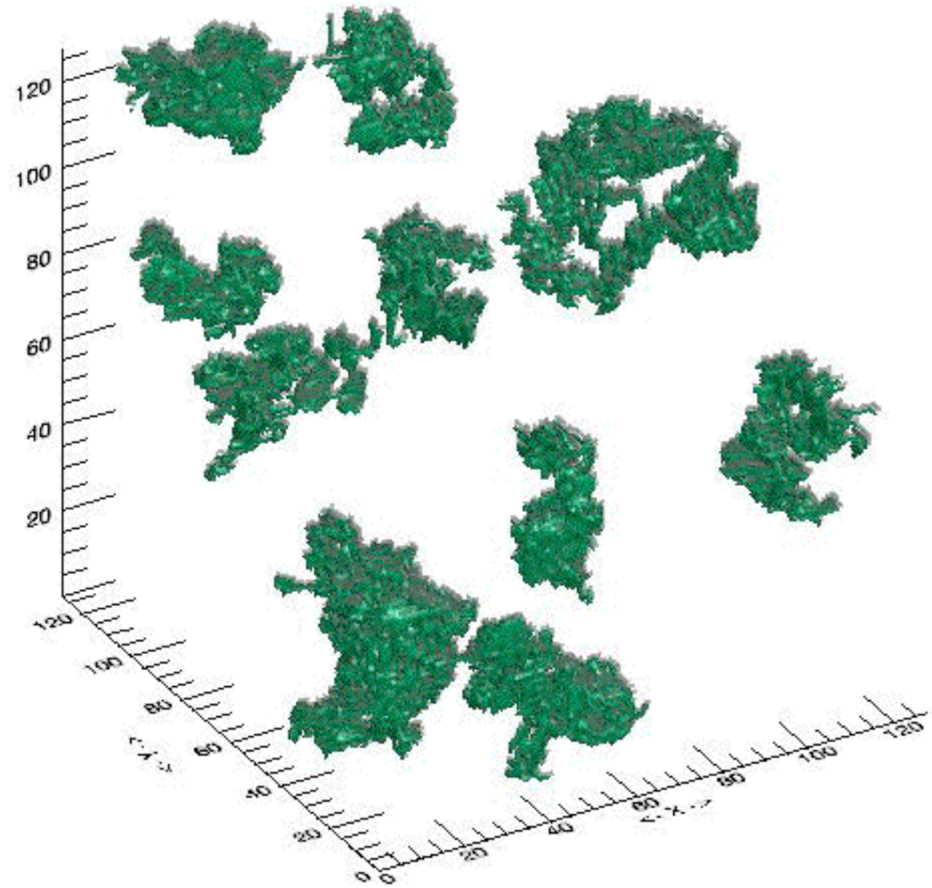




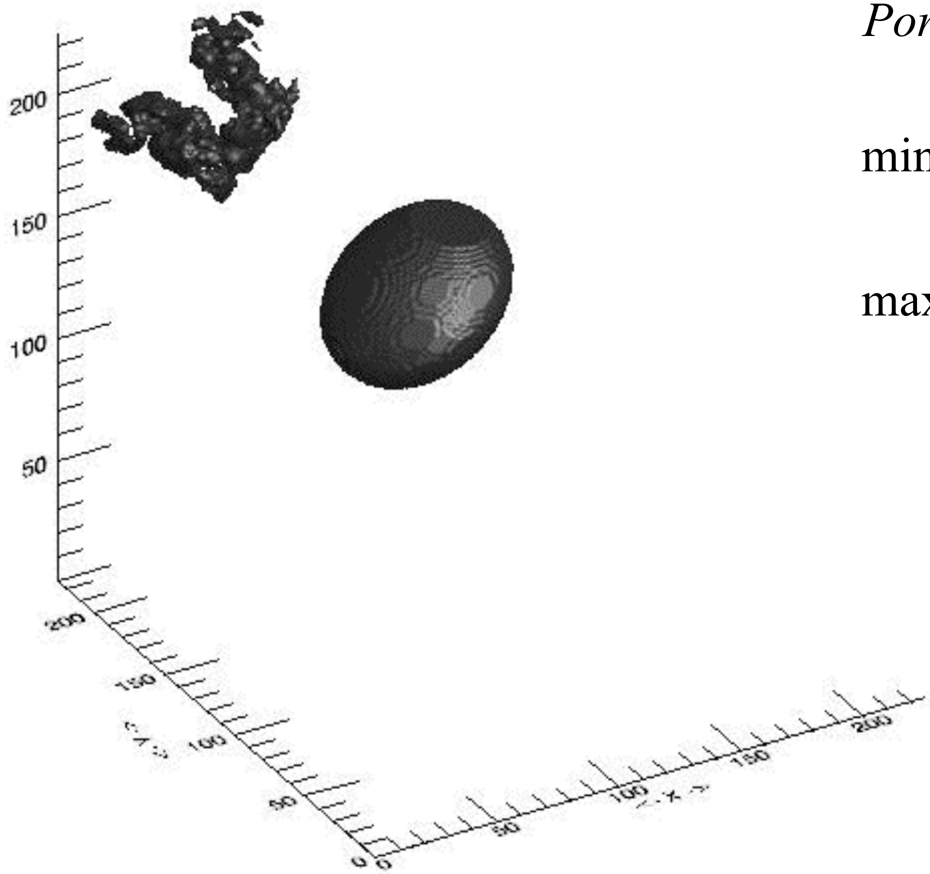
Shandarin et al. 2004, MNRAS,

Approximation of a void by the inertia tensor ellipsoid




120
100
80
60
40
20
120
100
80
60
40
20
0
0
20
40
60
80
100
120

$V = 2.4 \cdot 10^4 \text{cells} \quad Por = 4.78 \quad \frac{b}{a} + \frac{c}{b} = 1.47$



$$Por = \frac{V_E}{V}$$

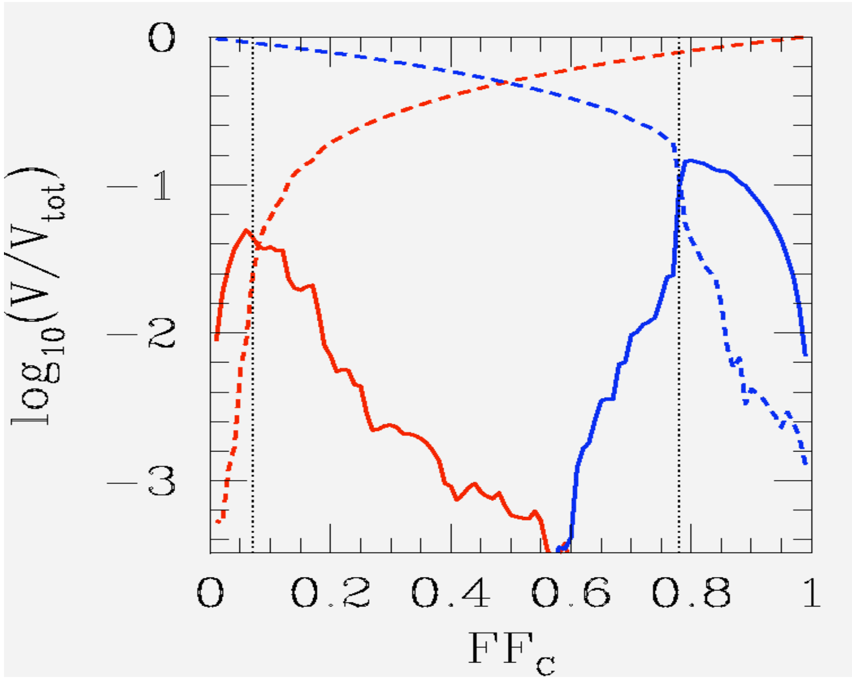
$$\min\left(\frac{V_E}{V}\right) = 1 \qquad \text{for perfect fit by ellipsoid}$$

$$\max\left(\frac{b}{a} + \frac{c}{b}\right) = 2 \qquad \text{for a sphere}$$

Superclusters vs.. Voids

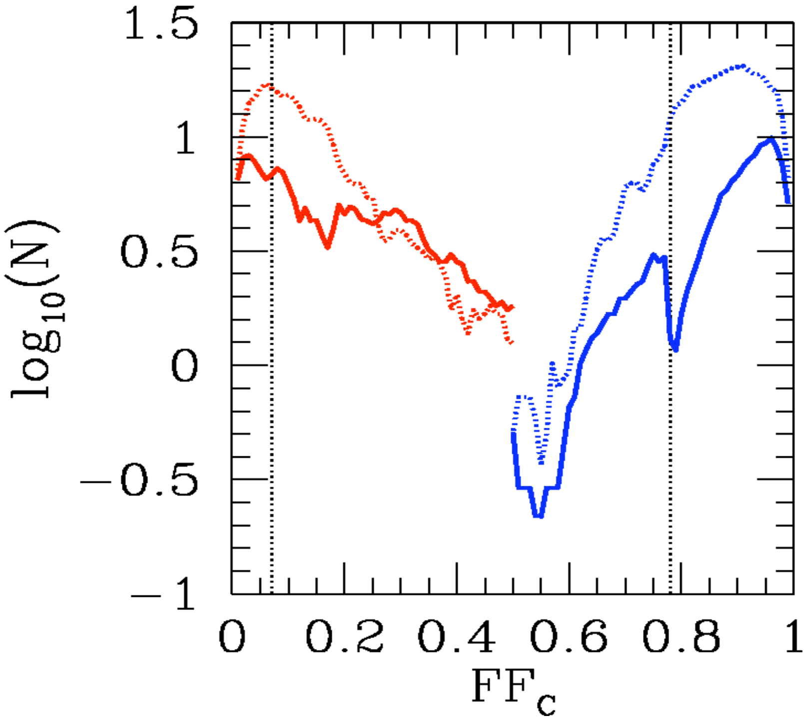
Red: super clusters = *overdense* Blue: voids = *underdense*

dashed: the largest object
solid: all but the largest



Solid: 90%
Dashed: 10%

Superclusters by mass
Voids by volume



SUPERCLUSTERS and VOIDS should be studied before percolation in the corresponding phase occurs.

Individual SUPERCLUSTERS should be studied at the density contrasts corresponding to filling factors

Individual VOIDS should be studied at density contrasts corresponding to filling factors

There are practically only two very complex structures in between: infinite supercluster and void.

CAUTION:

The above parameters depend on smoothing:

with decreasing smoothing scale i.e. better resolution

critical density contrast for SUPERCLUSTERS will increase while critical Filling Factor will decrease

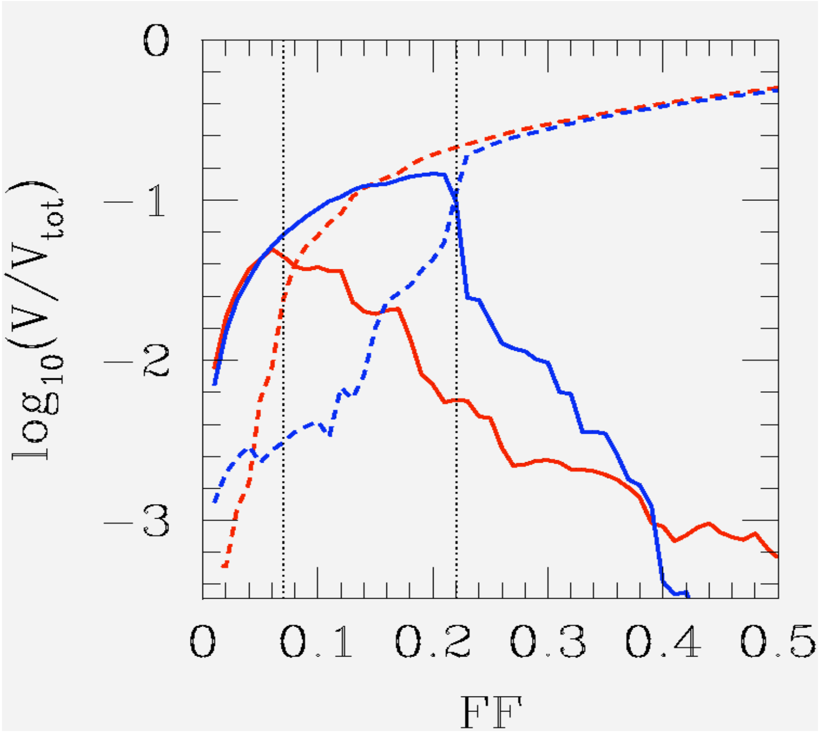
the critical density contrast for VOIDS will decrease while the critical Filling Factor will increase

Superclusters vs. Voids

Red: super clusters = *overdense*

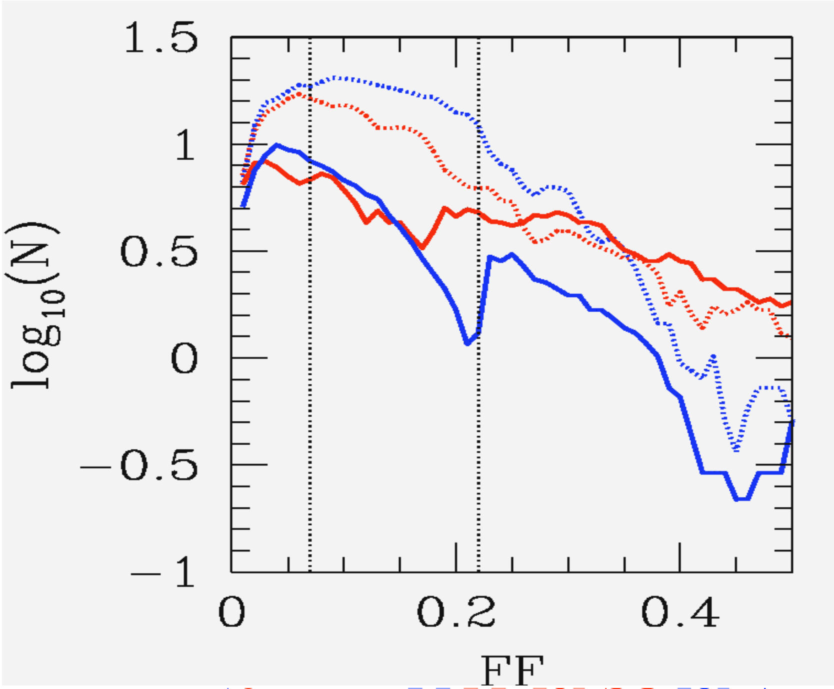
Blue: voids = *underdense*

dashed: the largest object
solid: all but the largest



Solid: 90%
Dashed: 10%

Superclusters by mass
Voids by volume



Plotting morphological characteristics of SUPERCLUSTERS
as a function of

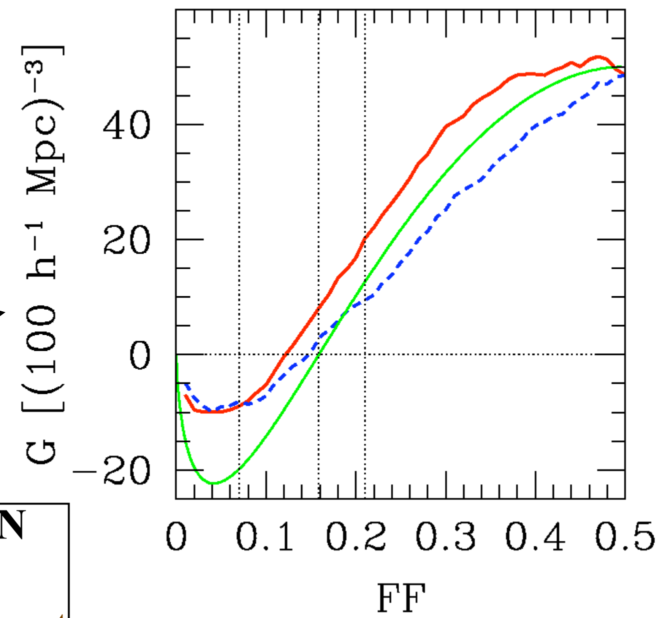
while morphological characteristics of VOIDS
as a function of

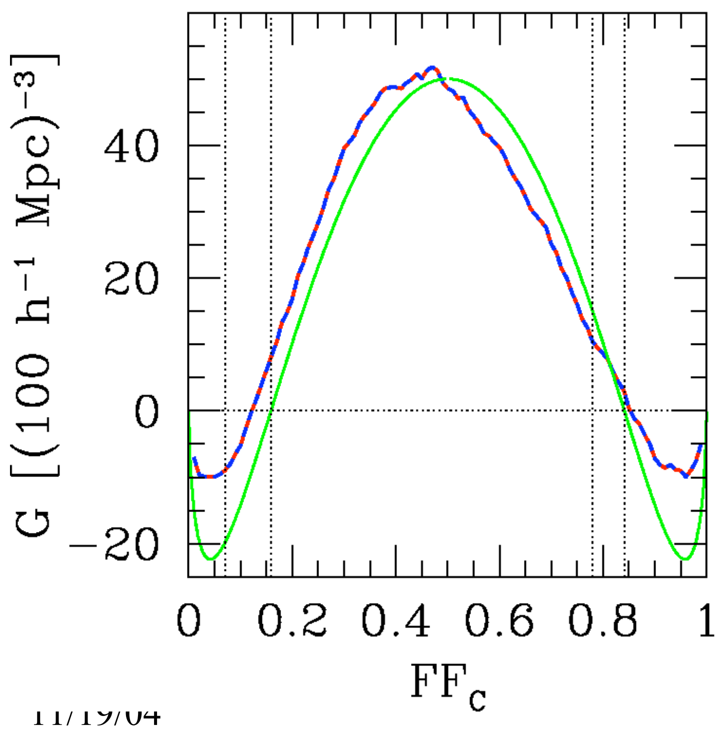
allows direct comparison of SUPERCLUSTERS and VOIDS

Genus vs. Percolation

Red: Superclusters
Blue: Voids
Green: Gaussian

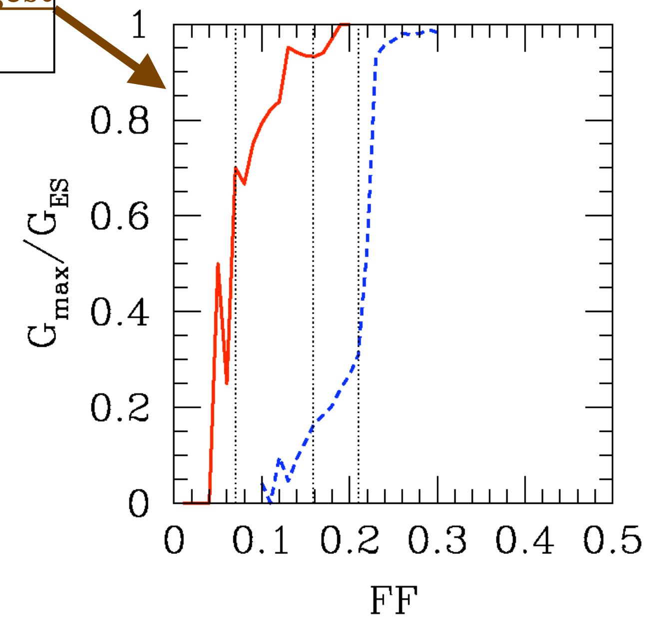
Genus as a function of Filling Factor





PERCOLATION
Ratio

$$\frac{\text{Genus of the Largest}}{\text{Genus of Exc. Set}}$$



At percolation

number of superclusters/voids
and
volume, mass and other parameters of the largest supercluster/void
rapidly change

but

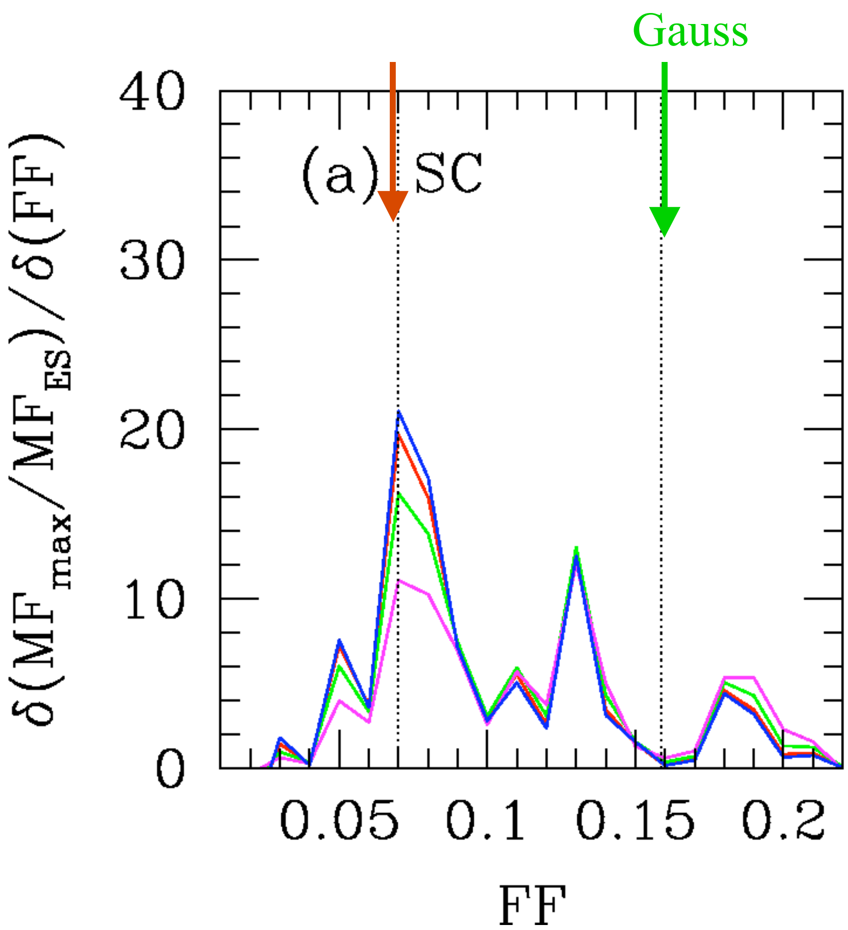
genus curve shows no peculiarity

Minkowski Functionals

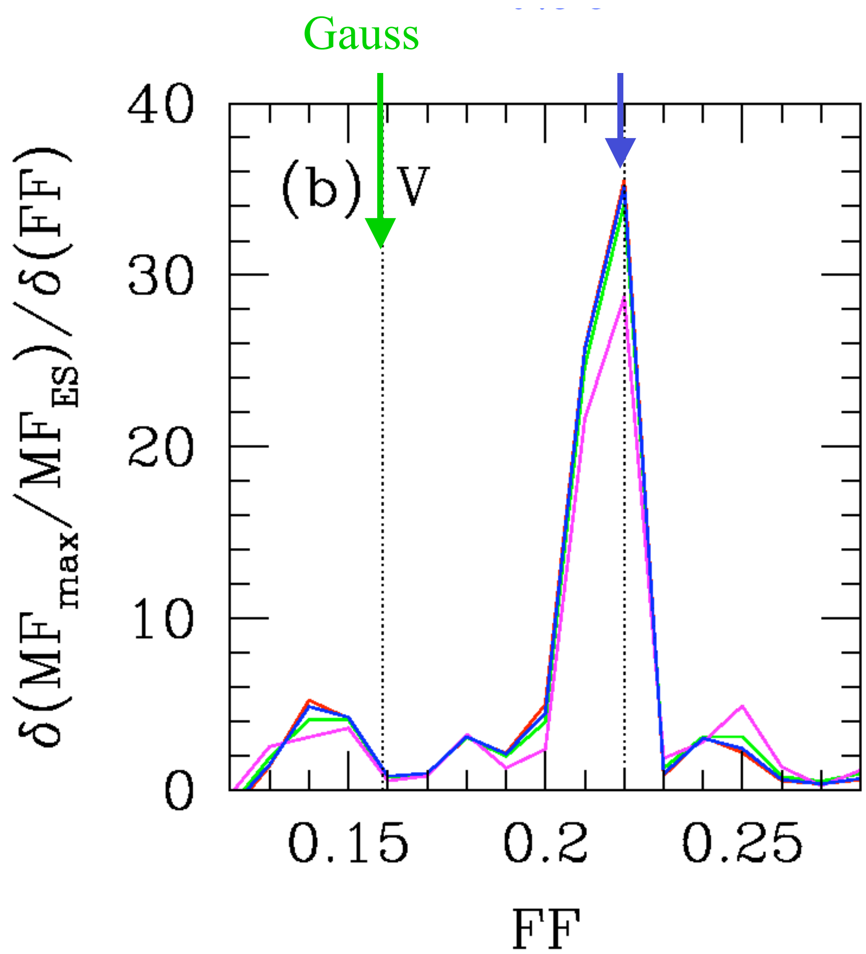
Mecke, Buchert & Wagner 1994

Percolation thresholds

Blue: mass estimator
Red: volume estimator
Green: area estimator
Magenta: curvature estimator



Superclusters



Voids

Set of Morphological Parameters

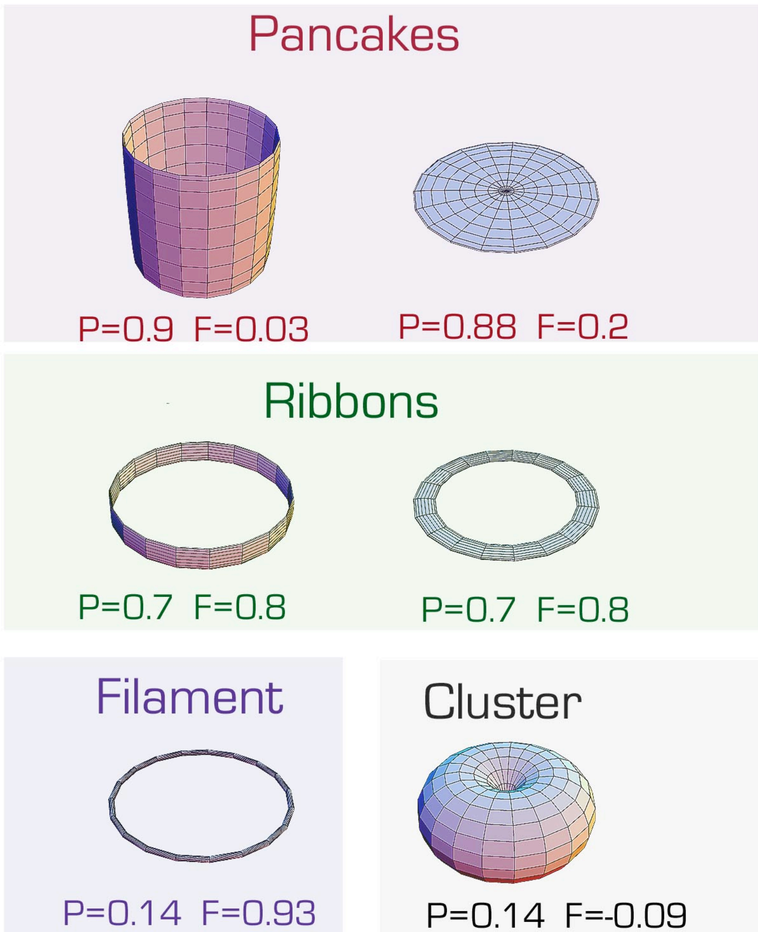
Sizes and Shapes

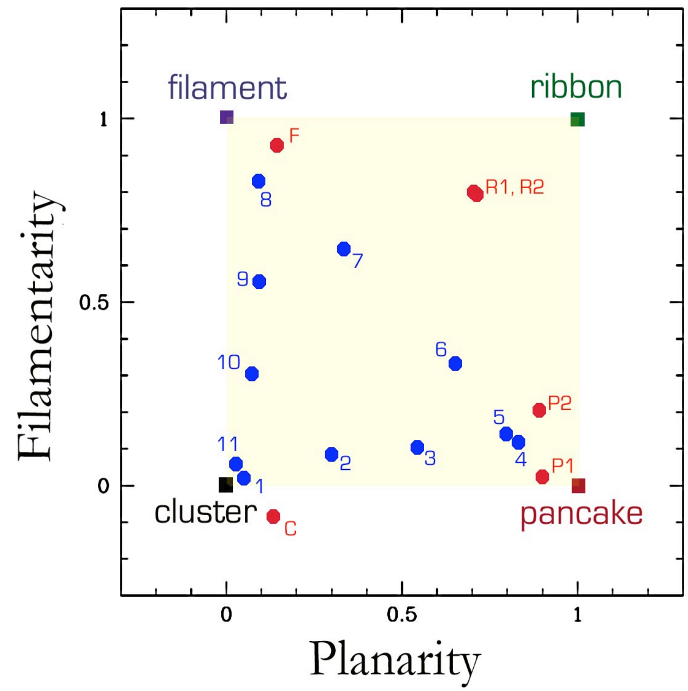
For each supercluster or void

Sahni, Sathyaprakash & Shandarin 1998

Convex boundaries !

Toy Example: Triaxial Torus



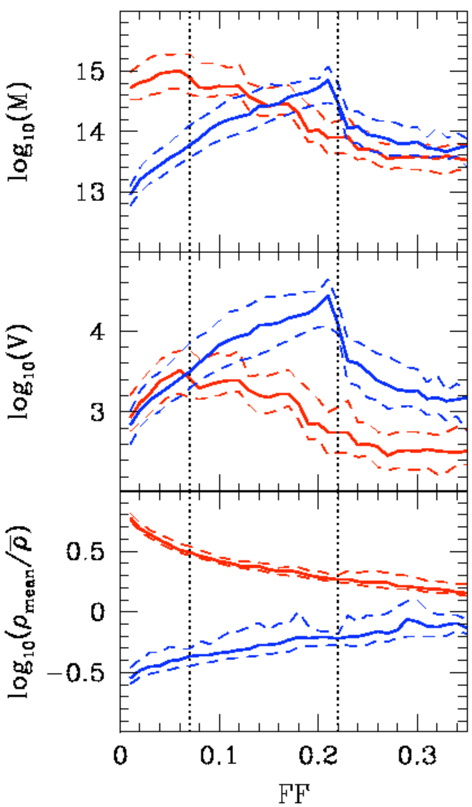


Sahni, Sathyaprakash & Shandarin 1998

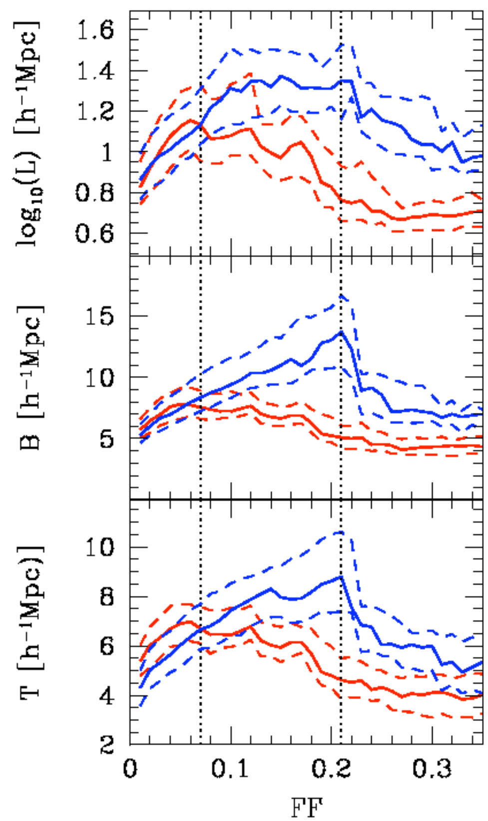
LCDM

Superclusters vs.. Voids

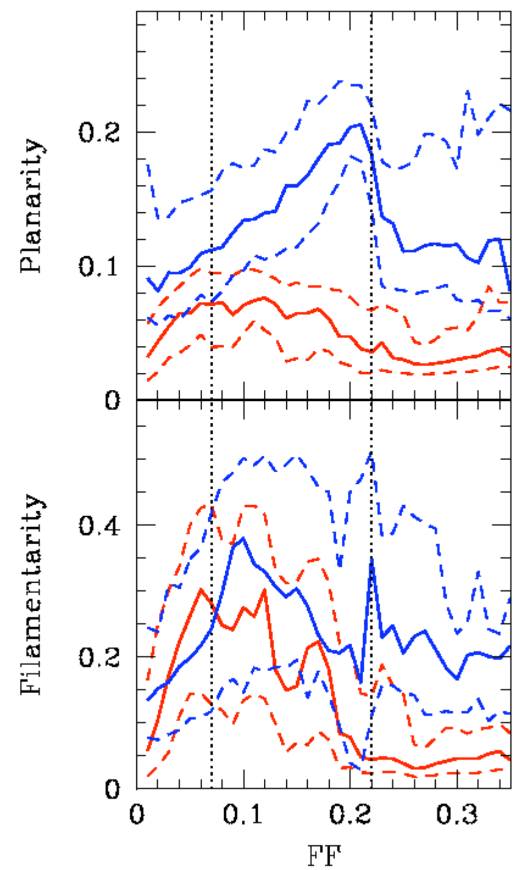
Mass
Volume
Density



log(Length)
Breadth
Thickness

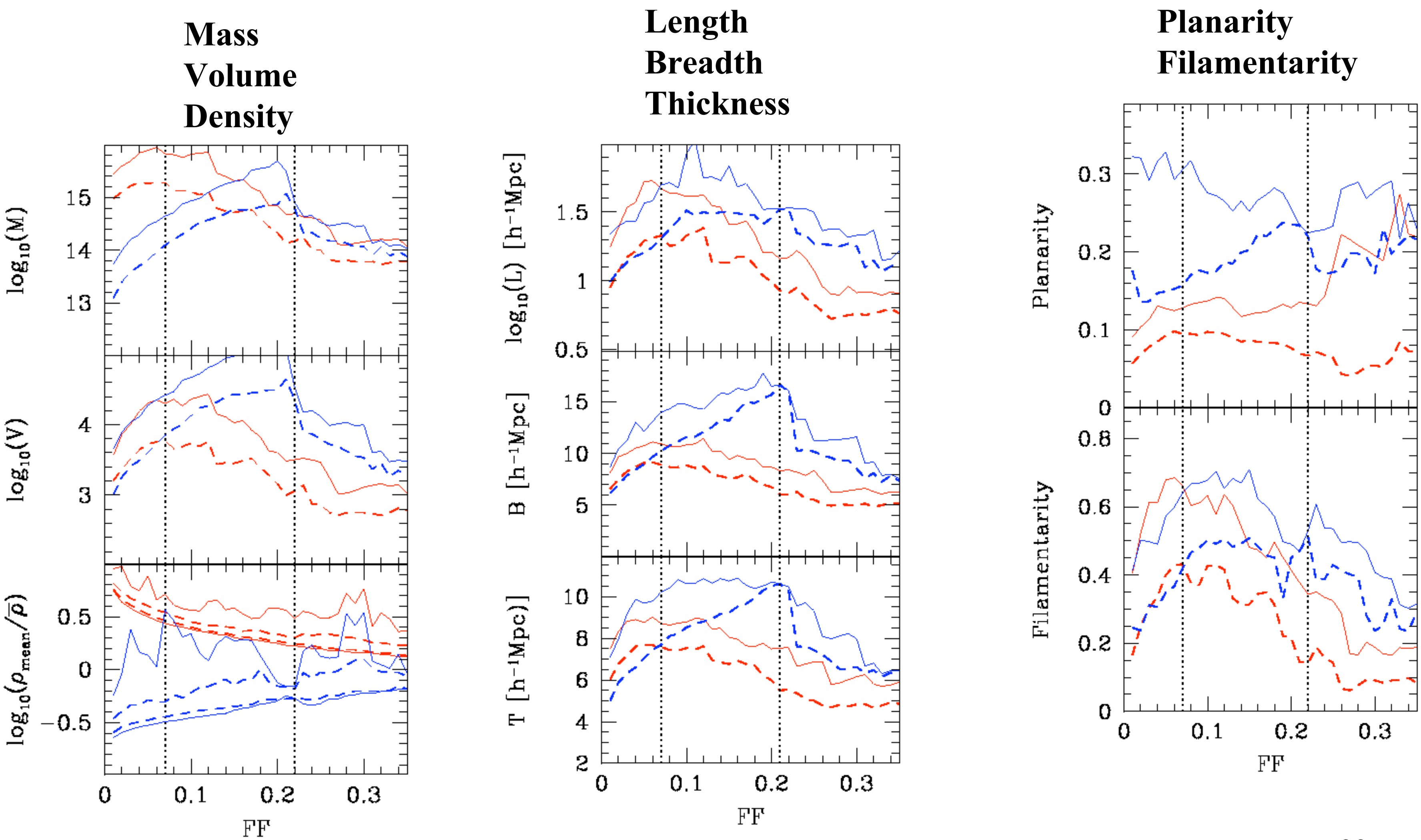


Planarity
Filamentarity



LCDM

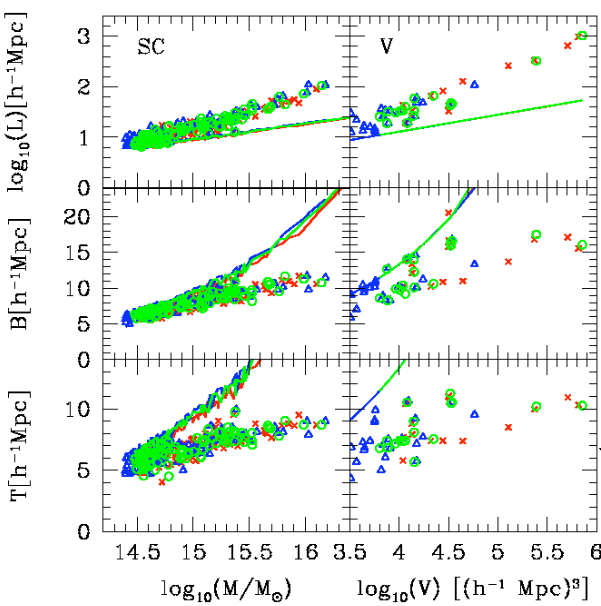
Superclusters vs. Voids



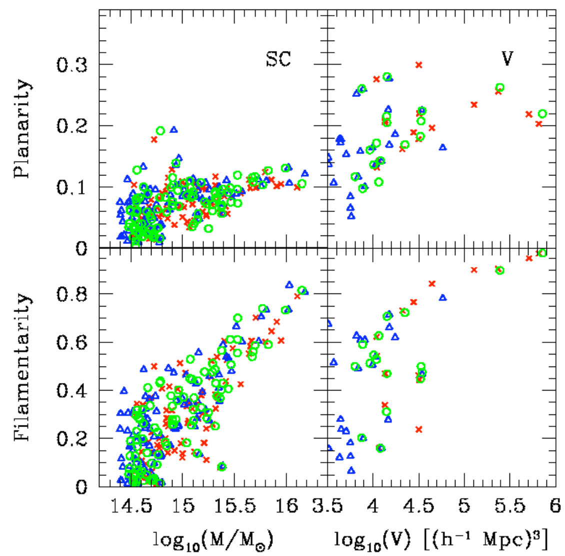
Correlation with mass (SC) or volume (V)

Green: at percolation
Red: just before percolation
Blue: just after percolation

log(Length)
Breadth
Thickness

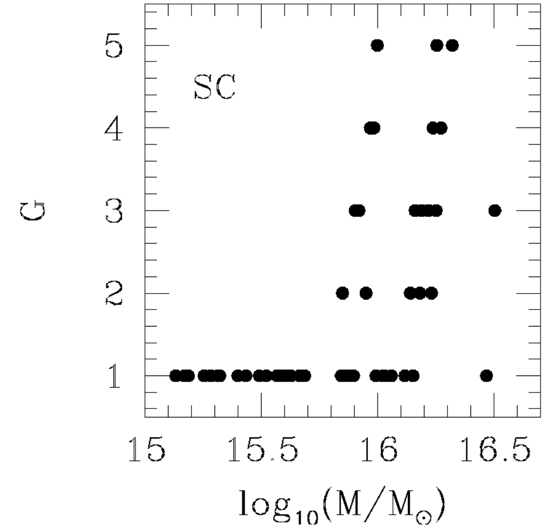


Planarity
Filamentarity

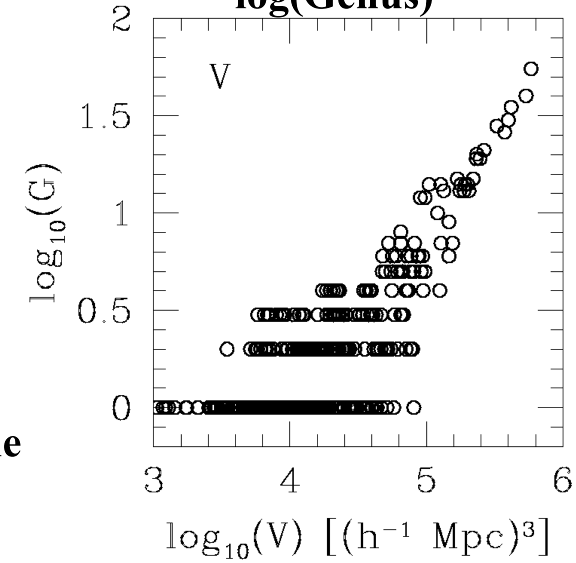


Solid lines mark the radius of sphere having same volume as the object.

Genus



log(Genus)



For both SUPERCLUSTERS and VOIDS

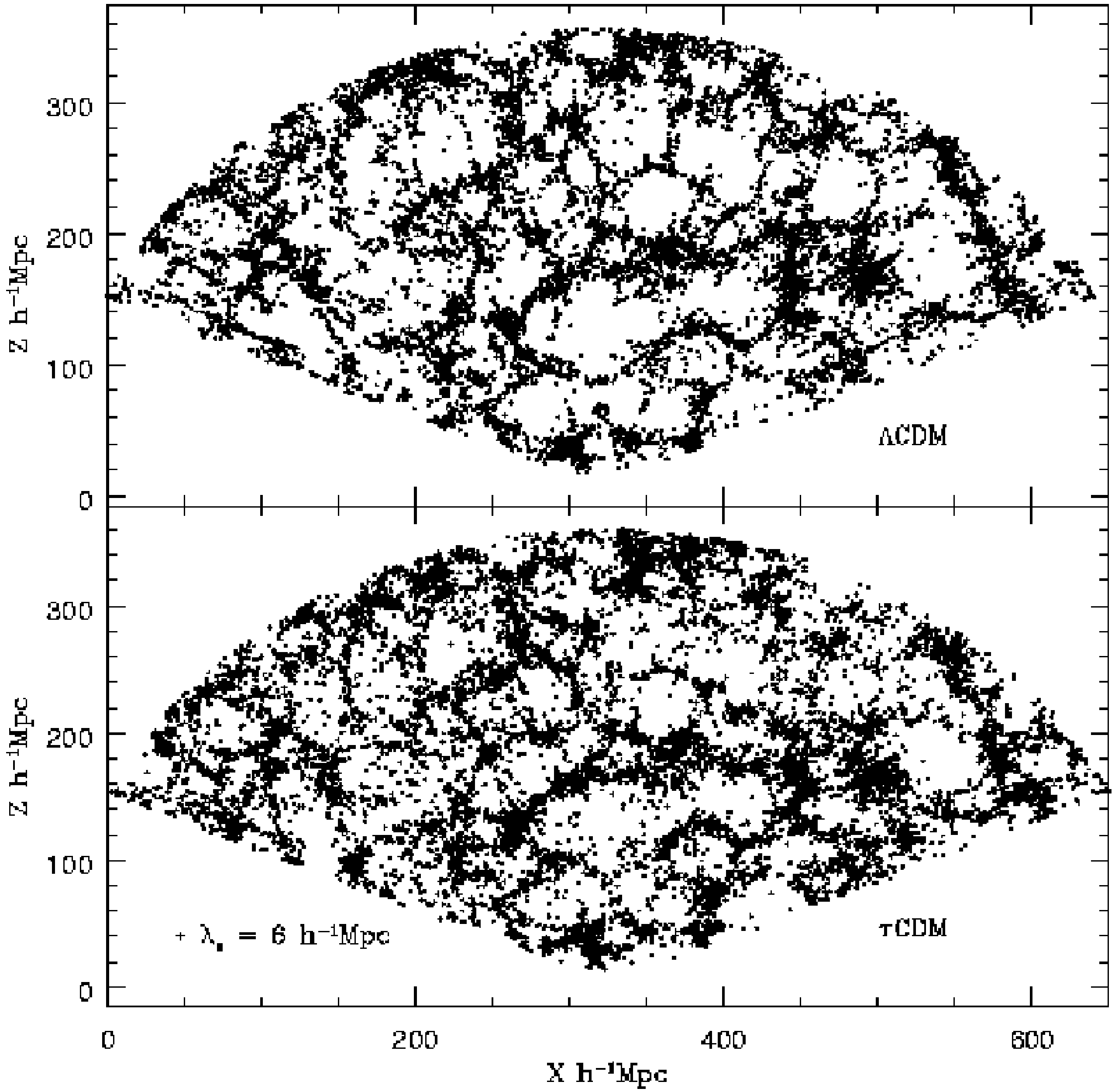
Length > R, while Breadth < R and Thickness < R.

Where R is radius of sphere
having same volume as SUPERCLUSTER or VOID

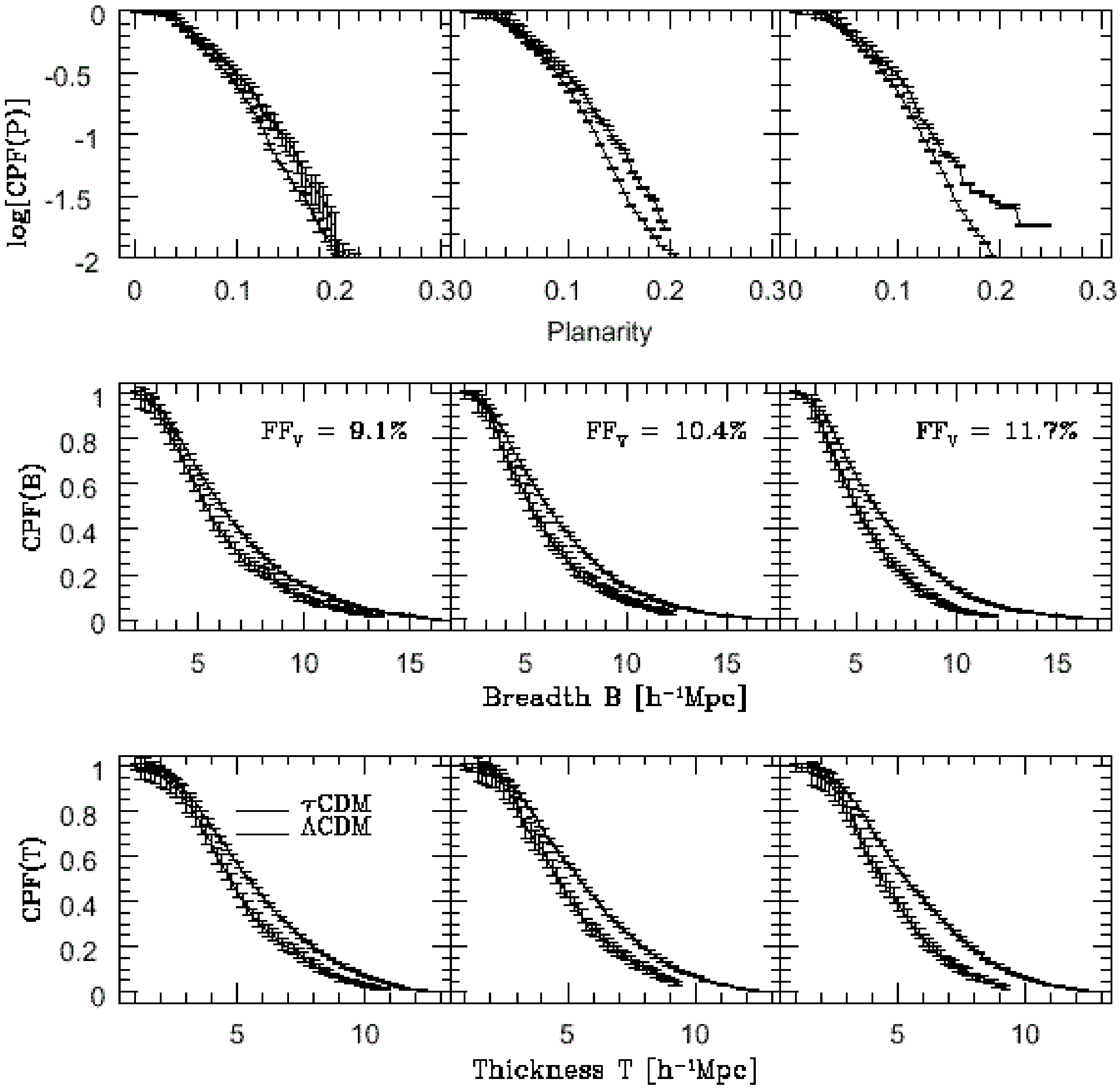
Difference increases with growth of mass of SUPERCLUSTERS
and
volume of VOIDS

SDSS mock catalog
Cole et al. 1998

Volume limited catalog
J. Sheth 2003



Cumulative probability functions



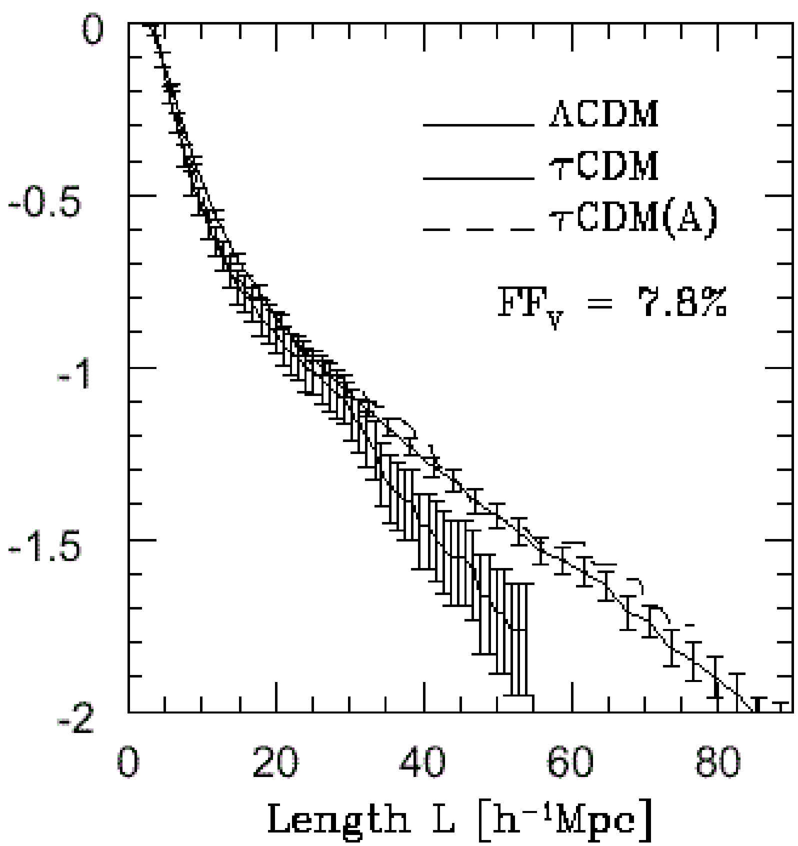
Top curves
TCDM

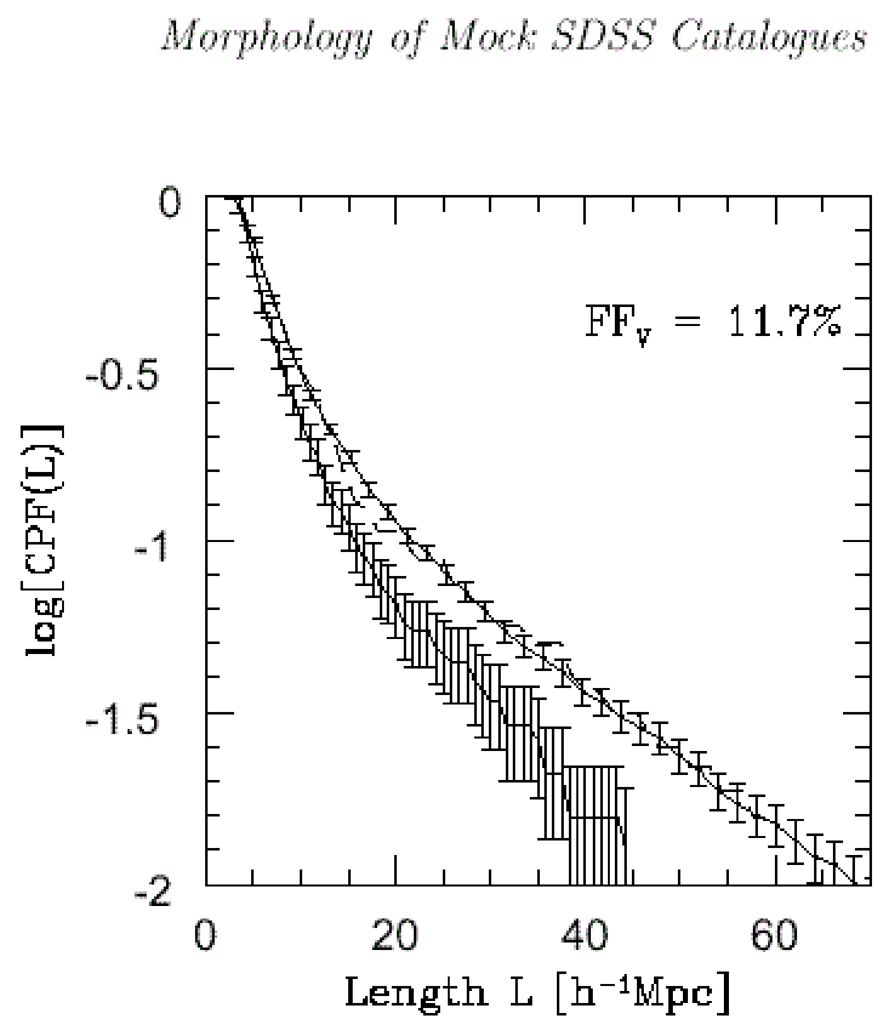
Bottom curves
LCDM

Top curves
TCDM

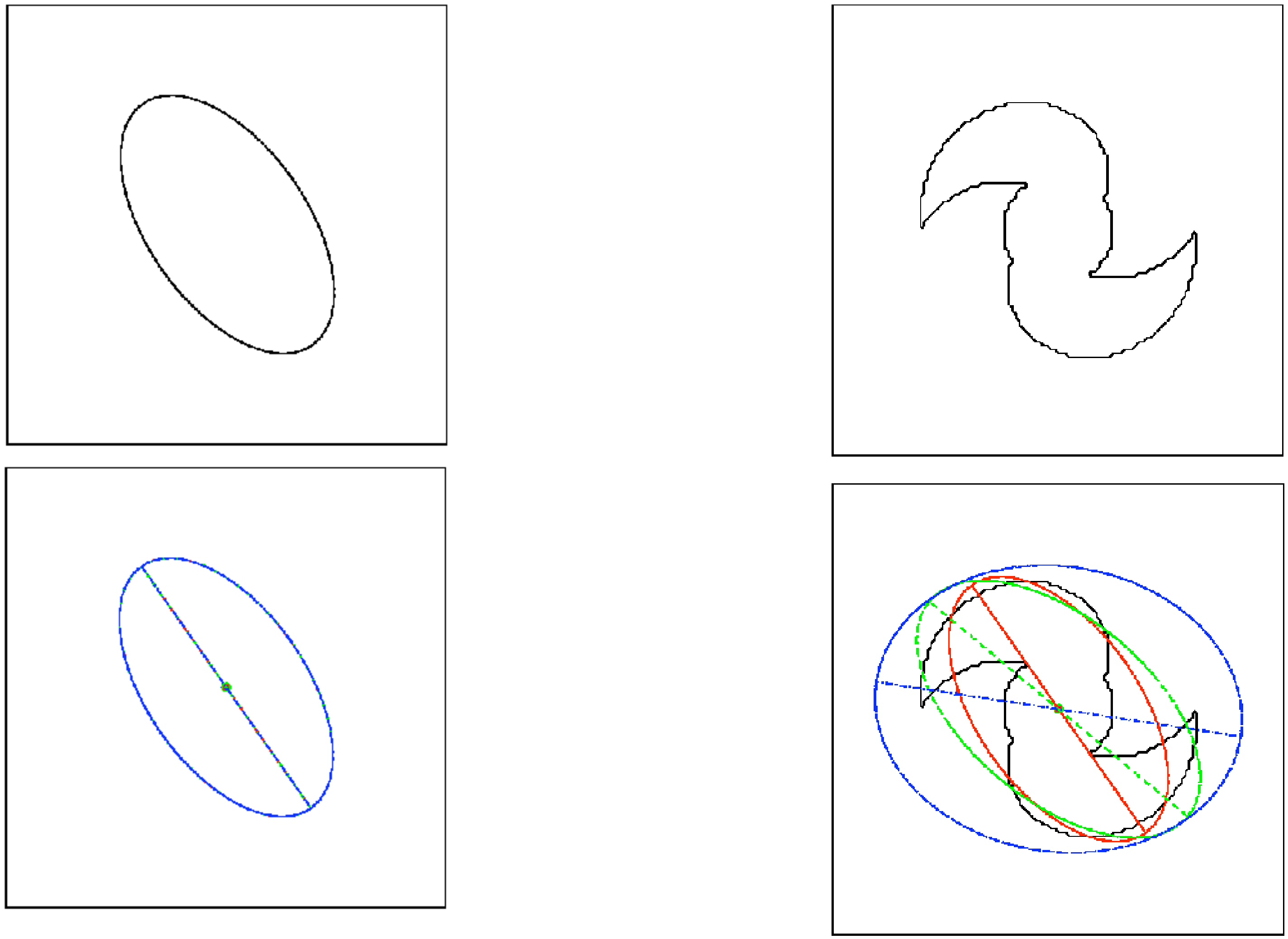
Bottom curves
LCDM

Cumulative probability functions





Galaxy Morphology



Ellipticity

Rahman & Shandarin 2004

Ellipticals (e>0.2)

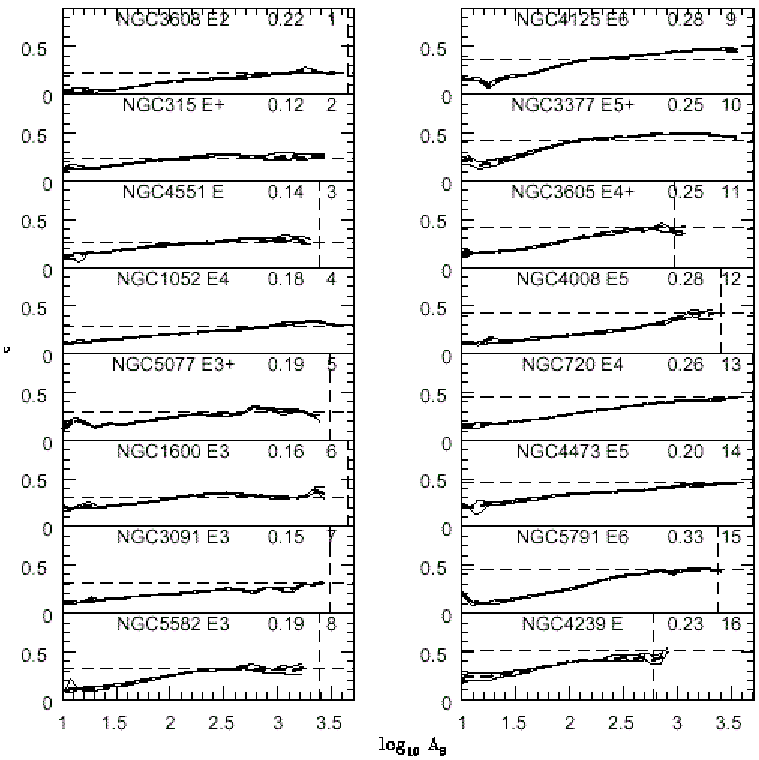


Figure 6. Ellipticity as a function of contour area (A_S) for elliptical galaxies in group 2 (2MASS $\epsilon > 0.2$).

Spirals (in optics)

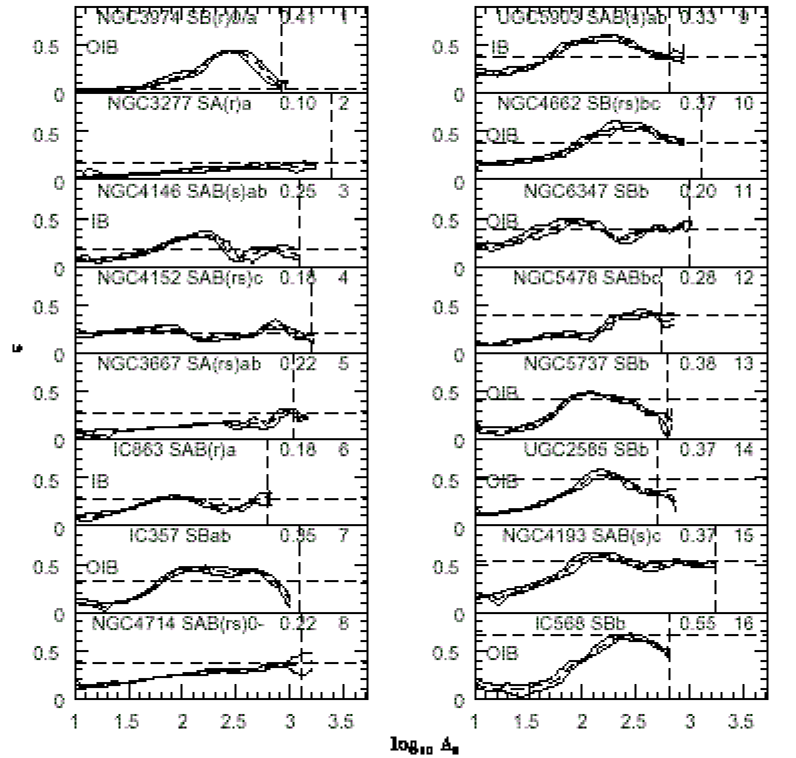


Figure 12. Ellipticity as a function of contour area (A_S) for spiral galaxies in group 2. The galaxies have scatter in ellipticity in the range $0.05 < \delta\epsilon \leq 0.1$ when J, H, and K_s band measurements are compared.

Orientation

Ellipticals (e>0.2)

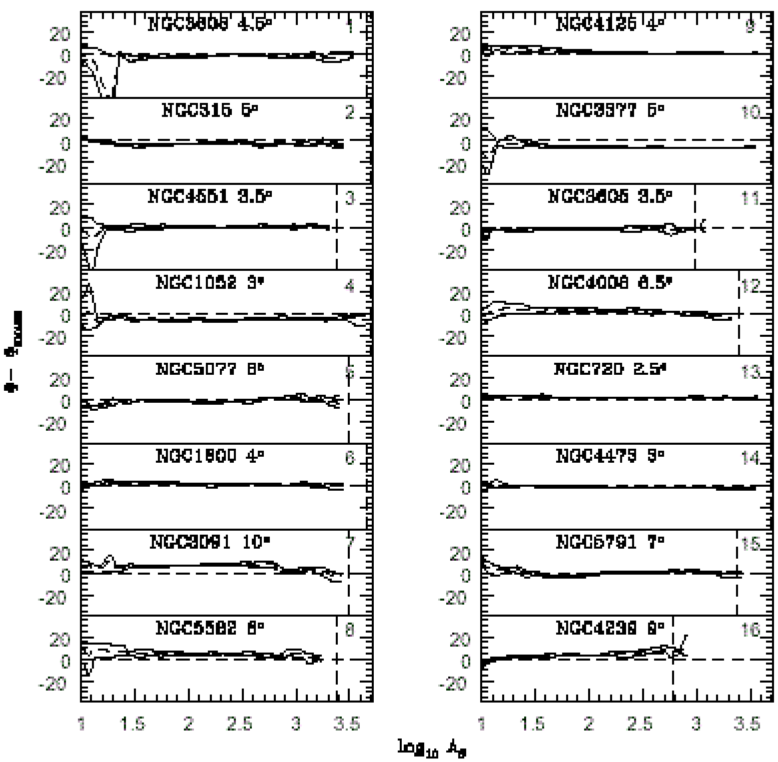


Figure 7. The orientations of elliptical galaxies in group 2 (2MASS $\epsilon > 0.2$).

Spirals (in optics)

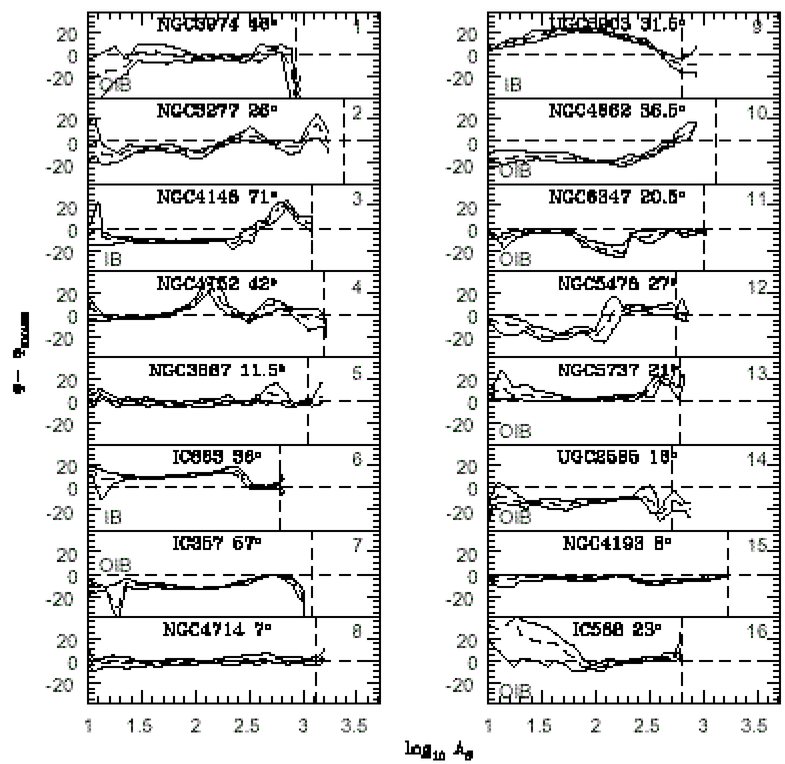


Figure 13. Orientations of galaxies in spiral group 2. Galaxies numbered as 3, 6, and 7, are scaled by a factor 2 to fit the range along the vertical axis. No scaling is applied to other galaxies.

Summary

Real space studies are interesting especially if we know cosmological model (parameters, initial spectrum…)

LCDM: density field in real space seen with resolution 5/h Mpc displays filaments but no isolated pancakes have been detected.

Web has both characteristics: filamentary network and bubble structure (at different density thresholds !)

At percolation: number of superclusters/voids, volume, mass and other parameters of the largest supercluster/void rapidly change (phase transition) but genus curve shows no features/ peculiarites.

Percolation and genus are different (independent?) characteristics of the web.

Morphological parameters (L,B,T, P,F) can discriminate models.

Voids defined as closed regions in underdense excurtion set are different from common-view voids. Why? 1) different definition, 2) uniform 5 Mpc smoothing, 3) DM distribution 4) real space

Voids have complex substructure. Isolated structures are possible along with tunnels.

Voids have more complex topology than superclusters. Voids: G~50; superclusters: G~a few