Astronomical Data Analysis
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Reliability of the detection of the acoustic peaks in the galaxy distribution

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We study the reliability of the detection of the baryonic acoustic peak in the galaxy two-point correlation function at large scales. We have found additional peaks at very large pair distances (> 200 Mpc/h) in the SDSS LRG data. In order to estimate the statistical confidence of these peaks, we simulate isotropic Gaussian fields with an exactly known oscillating correlation function and test the available estimation methods to see if we can recover the oscillations. We use the turning-band method to generate the realisations, the usual Landy-Szalay estimator for the correlation function, and block jackknife-after-bootstrap to describe its sample distribution. We apply the same methods to the SDSS DR6 LRG data and to the 2dFGRS.

Baryonic Acoustic Oscillations

Prior to the epoch of the recombination, the universe is filled by a plasma where photons and baryons are coupled. Due to the pressure of photons, sound speed is relativistic at this time and the sound horizon has a comoving radius of 150 Mpc. Cosmological fluctuations produce sound waves in this plasma.

At about 380,000 years after the Big Bang, when the temperature has fallen down to 3000 K, and recombination takes place, the universe loses its ionized state and neutral gas dominates. At this state, sound speed drops off abruptly and acoustic oscillations in the fluid become frozen. Their signature can be detected in both the Cosmic Microwave Background (CMB) radiation and the large-scale distribution of galaxies.

D. Eisenstein, http://cmb.as.arizona.edu/~eisenste/acousticpeak/

Baryon-photon fluid:

$$c_s = c / \sqrt{3(1+R)}$$

$$R = 3\rho_b / 4\rho_\gamma = \delta\rho_b / \delta\rho_\gamma$$

- Sound speed:

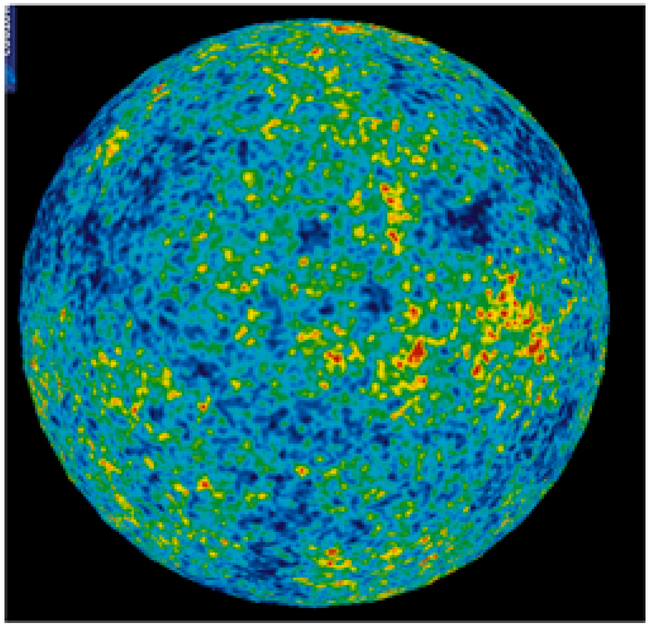
- Before recombination, baryons and radiation form a fluid undergoing acoustic oscillations.
- After decoupling, baryons are free and have nearly no pressure, so they fall to the potential wells of dark matter.

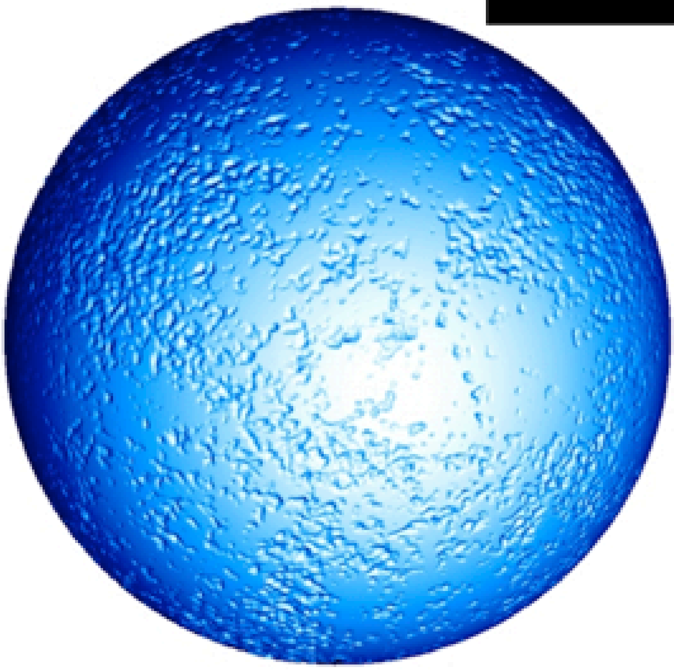
Miralda-Escudé

$$s = \int c_s(t)\, dt / a(t)$$

- At the wavelengths ks=jπ, the baryon density fluctuation is in phase with the dark matter density fluctuation, and that's roughly where we see acoustic peaks in the CMB

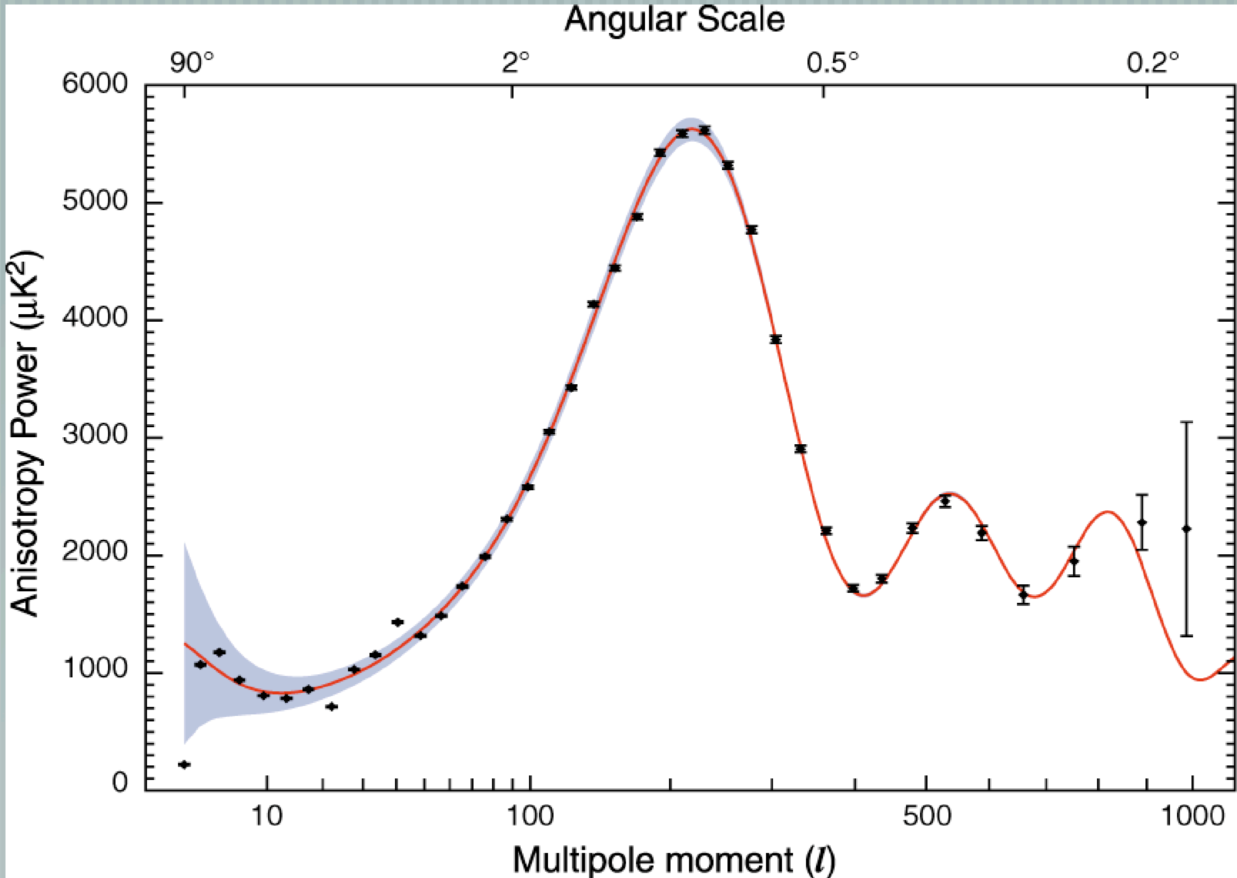
Miralda-Escudé

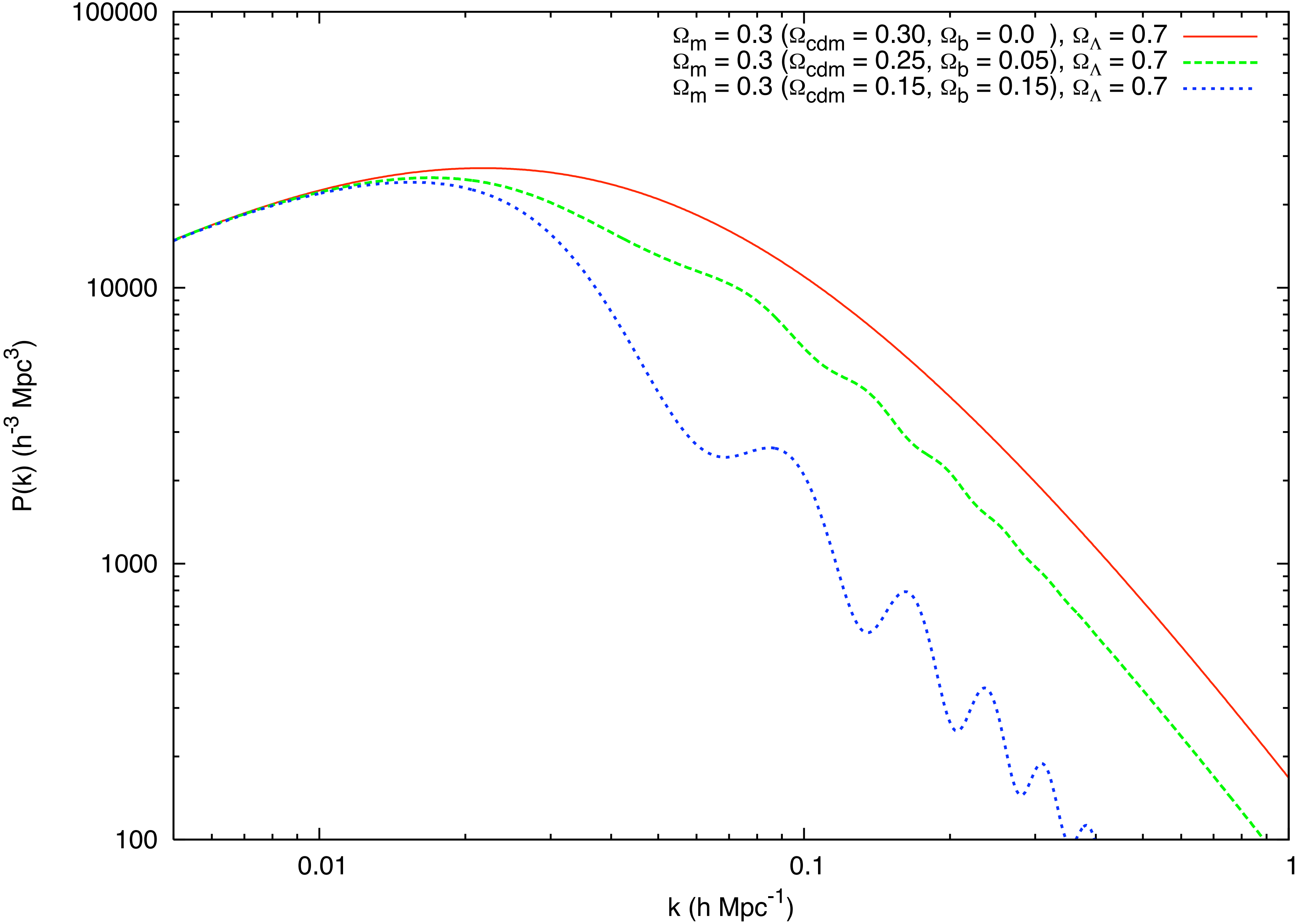




SGP

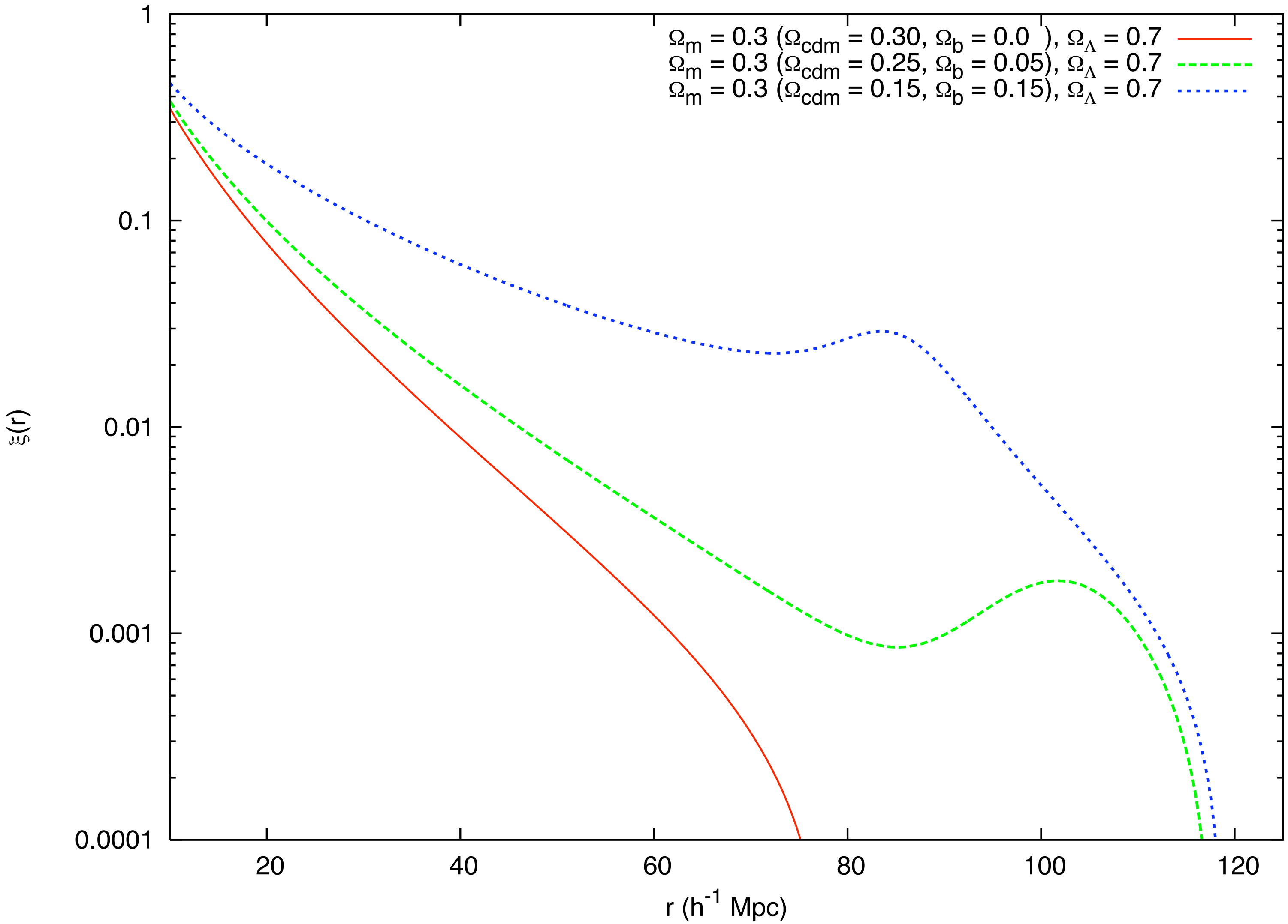
Acoustic peaks in the CMB
WMAP3





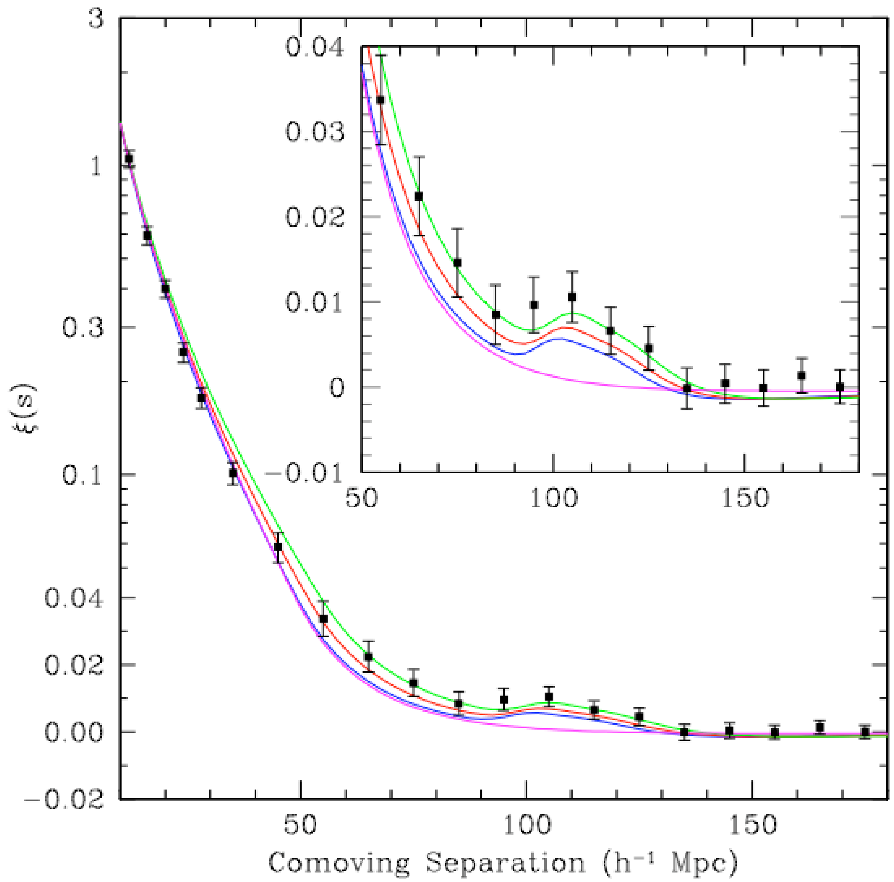
Ω_m = 0.3 (Ω_{cdm} = 0.30, Ω_b = 0.0), Ω_Λ = 0.7
Ω_m = 0.3 (Ω_{cdm} = 0.25, Ω_b = 0.05), Ω_Λ = 0.7
Ω_m = 0.3 (Ω_{cdm} = 0.15, Ω_b = 0.15), Ω_Λ = 0.7
100000
10000
1000
100
0.01
0.1
1
P(k) (h^{-3} Mpc^3)
k (h Mpc^{-1})

Baryonic Acoustic Oscillations



BAO measured in SDSS data (Eisenstein et al. 2005)

Based on 46,748 “luminous red galaxies” from the SDSS spectroscopic galaxy survey



$$\xi(r) = \langle \delta(\vec{r}_1)\delta(\vec{r}_2)\rangle, \delta(\vec{r}) = \frac{\rho(\vec{r}) - \bar{\rho}}{\bar{\rho}}$$

or

$$dP_{12} = \bar{\rho}^2[1 + \xi(r)]dV_1 dV_2, r = |\vec{r}_1 - \vec{r}_2|$$

3.5-σ detection of BAO at <z> = 0.35
(confirmed by 2DF and SDSS photometric surveys at about 2.5 σ)

$h = H_0$ / (100 km s^{-1} Mpc^{-1}) ~ 0.7

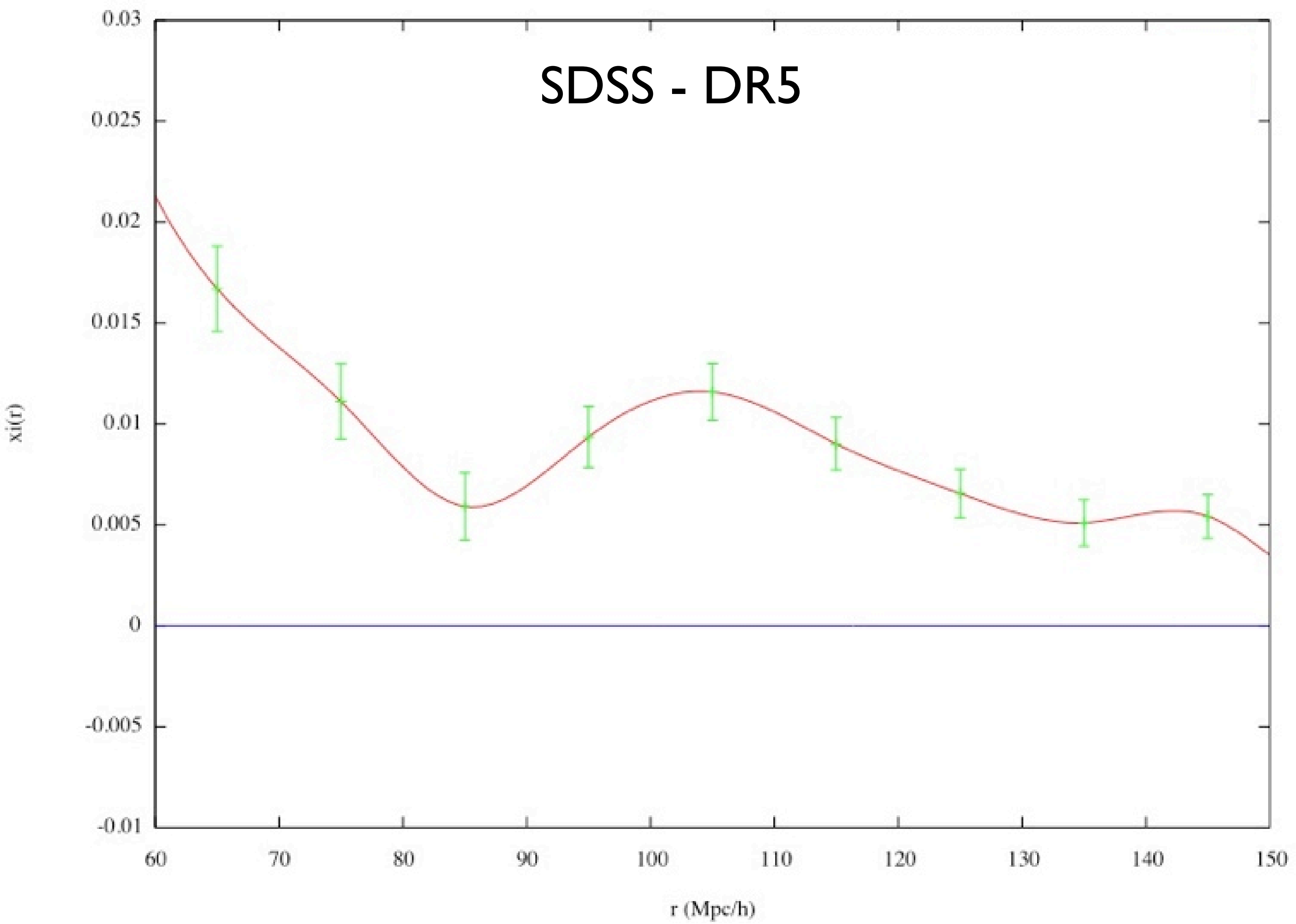
Motivation

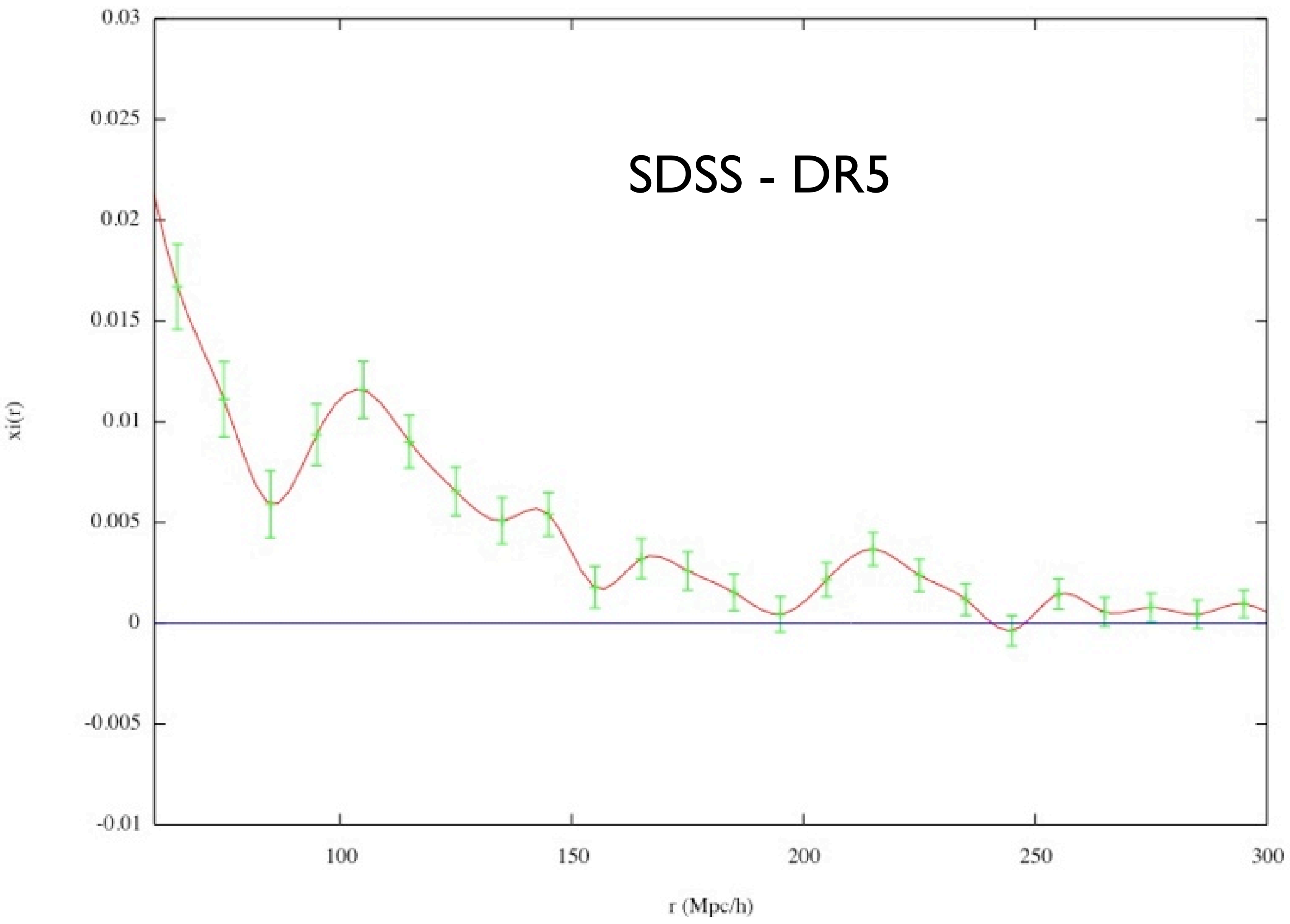
We have known for several years that additional oscillations are seen in the galaxy correlation function, apart from the well-known adiabatic peak at about 100 Mpc/h.

The standard inflation theory with adiabatic perturbations predicts only one peak, so if the other peaks exist, they check directly the physics of the inflation stage. The problem is if these peaks can be considered real.

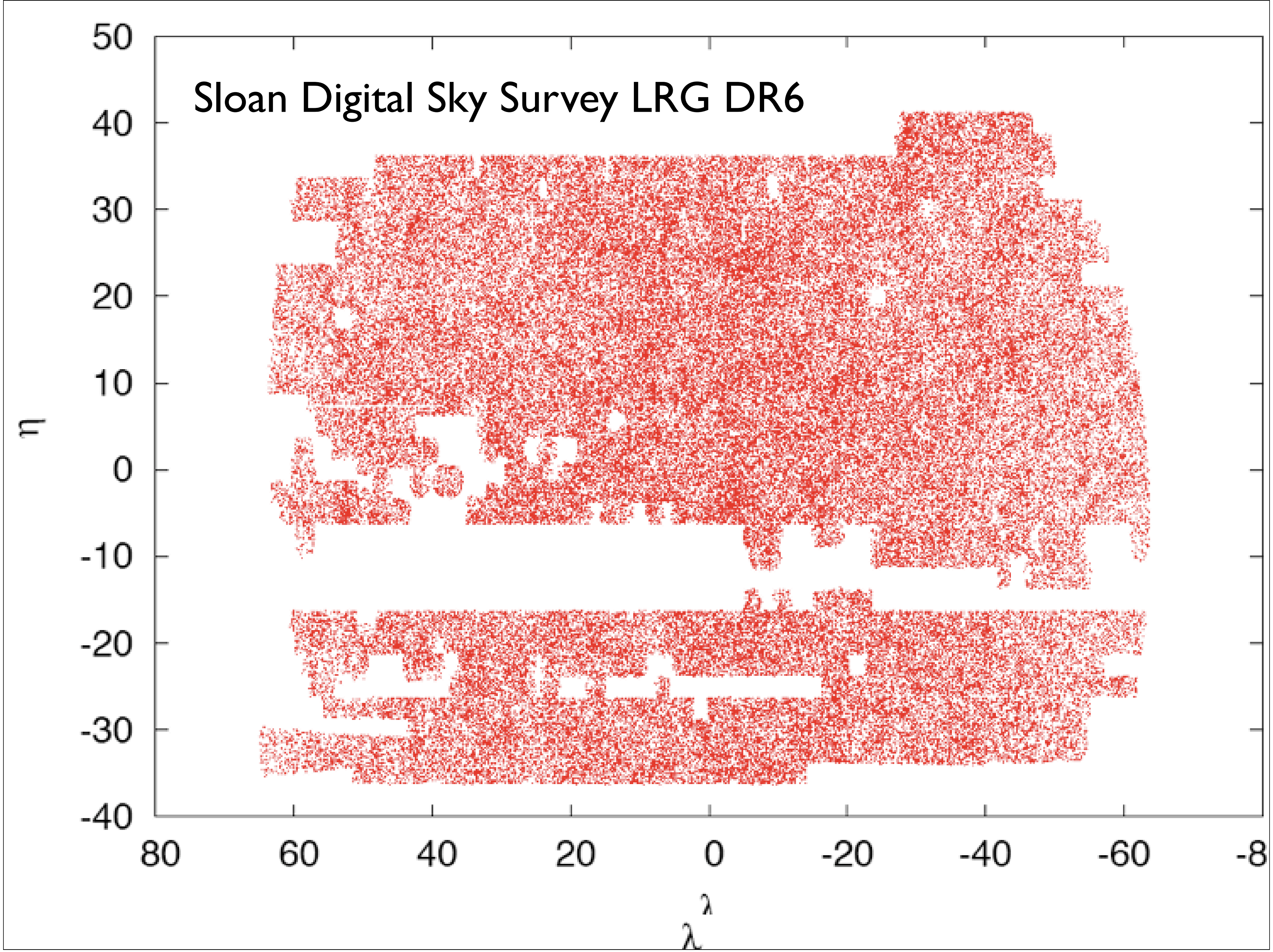
Landy-Szalay estimator for the correlation function

$$\widehat{\xi}_{\mathrm{LS}}(r) = 1 + \left(\frac{N_{\mathrm{rd}}}{N}\right)^2 \frac{DD(r)}{RR(r)} - 2\frac{N_{\mathrm{rd}}}{N}\frac{DR(r)}{RR(r)}.$$

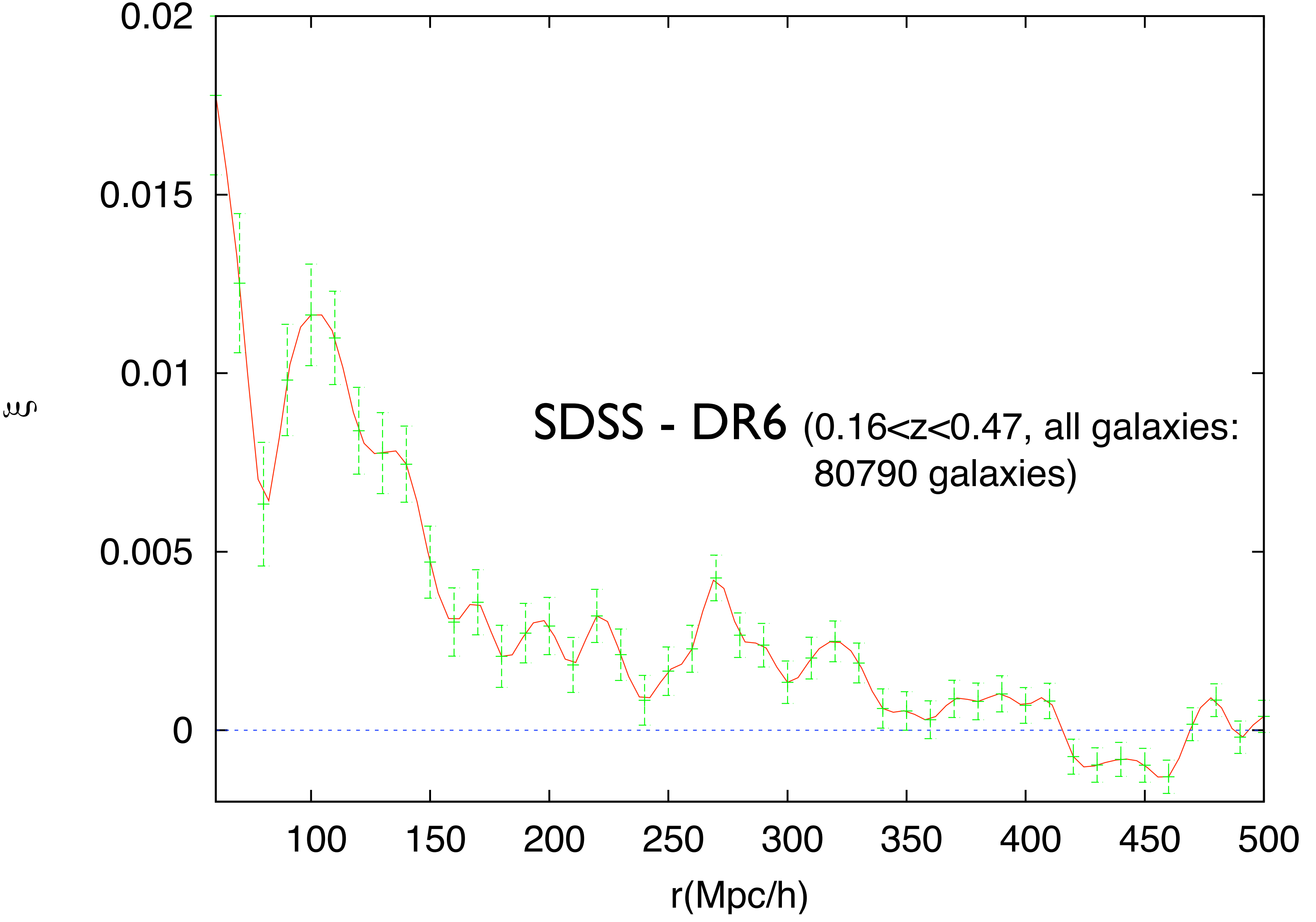

SDSS - DR5
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
xi(r)
60
70
80
90
100
110
120
130
140
150
r (Mpc/h)



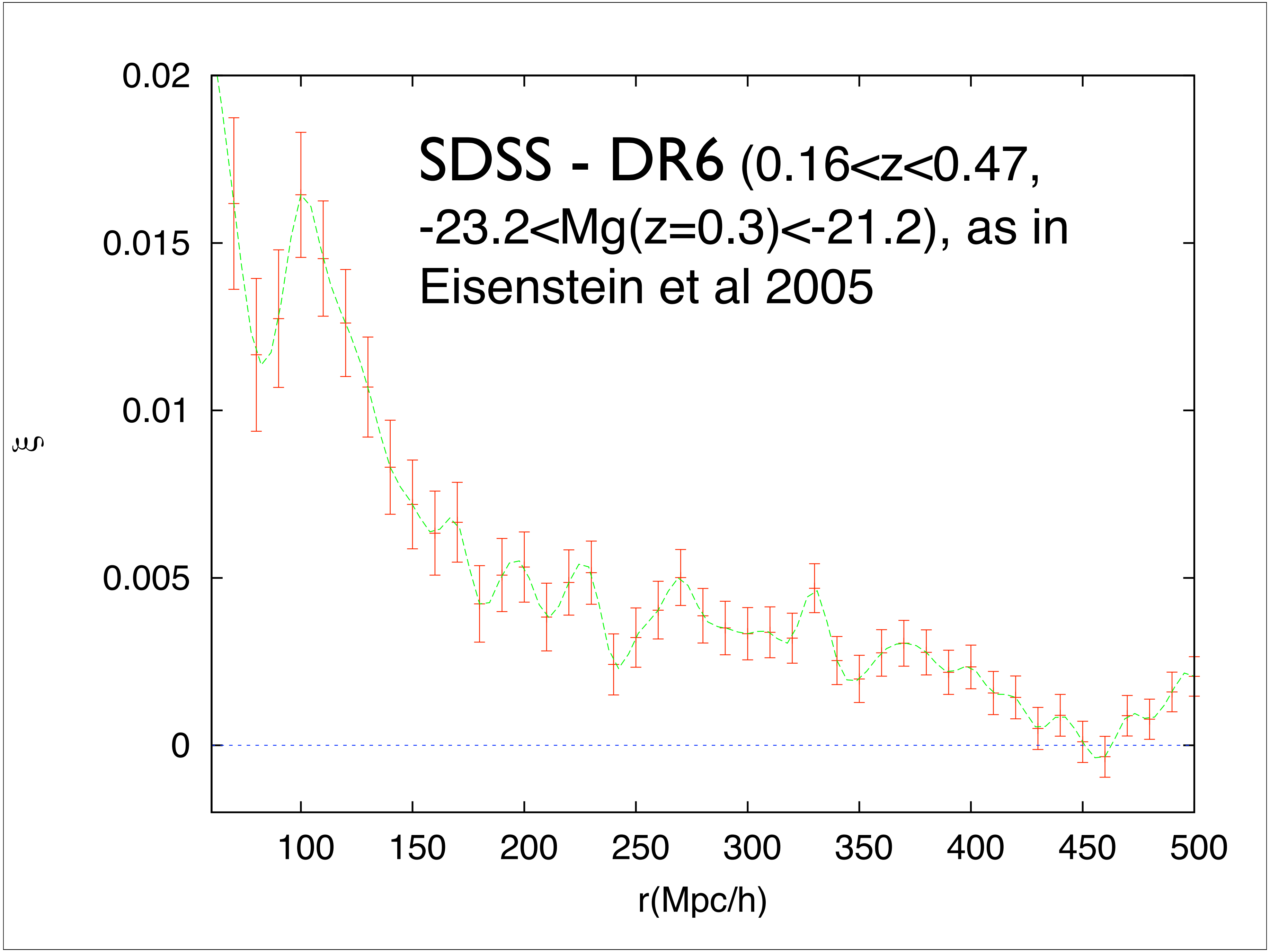
SDSS - DR5
xi(r)
r (Mpc/h)
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
100
150
200
250
300



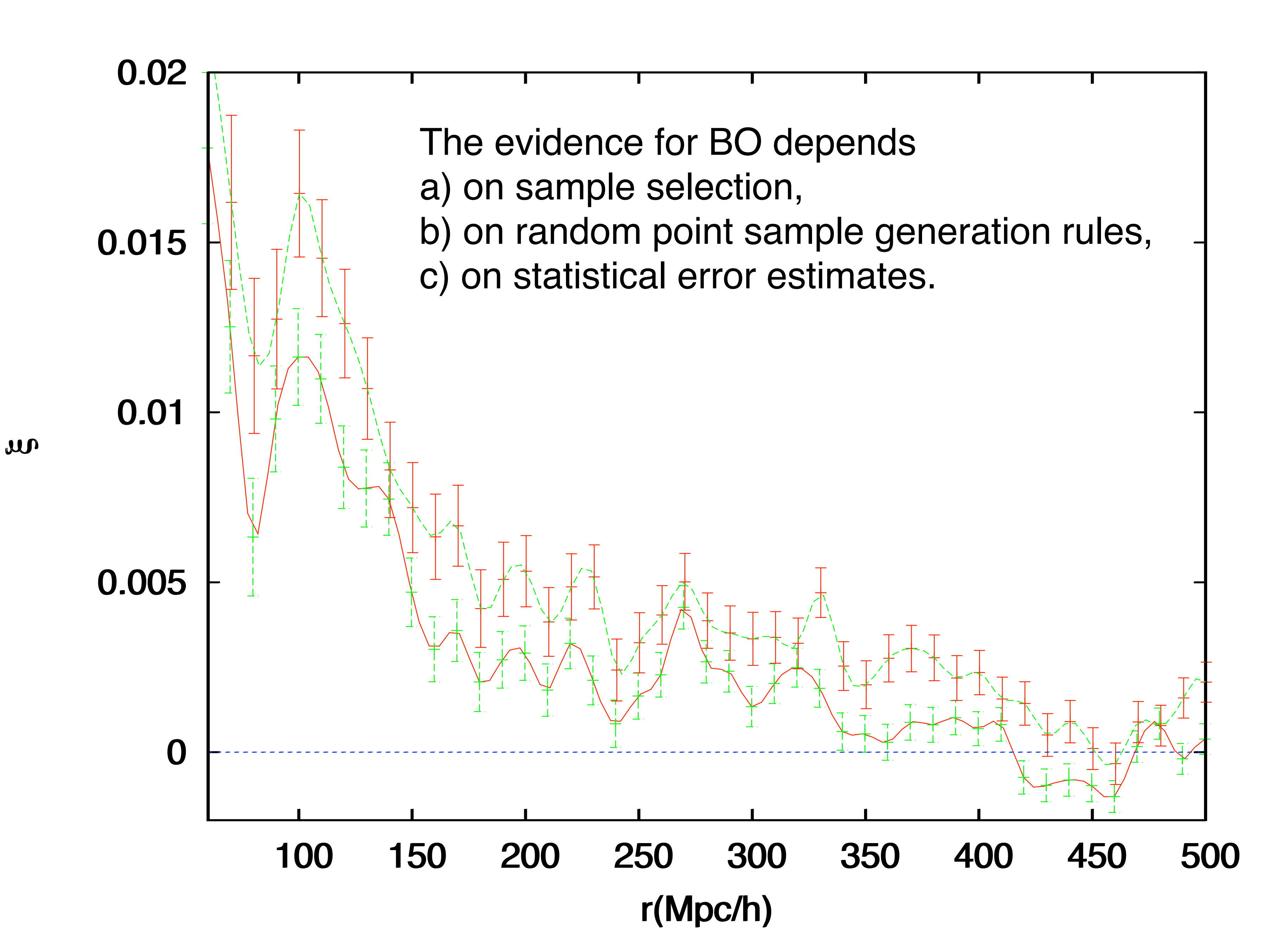
Sloan Digital Sky Survey LRG DR6
50
40
30
20
10
0
-10
-20
-30
-40
η
80
60
40
20
0
-20
-40
-60
-8
λ
λ



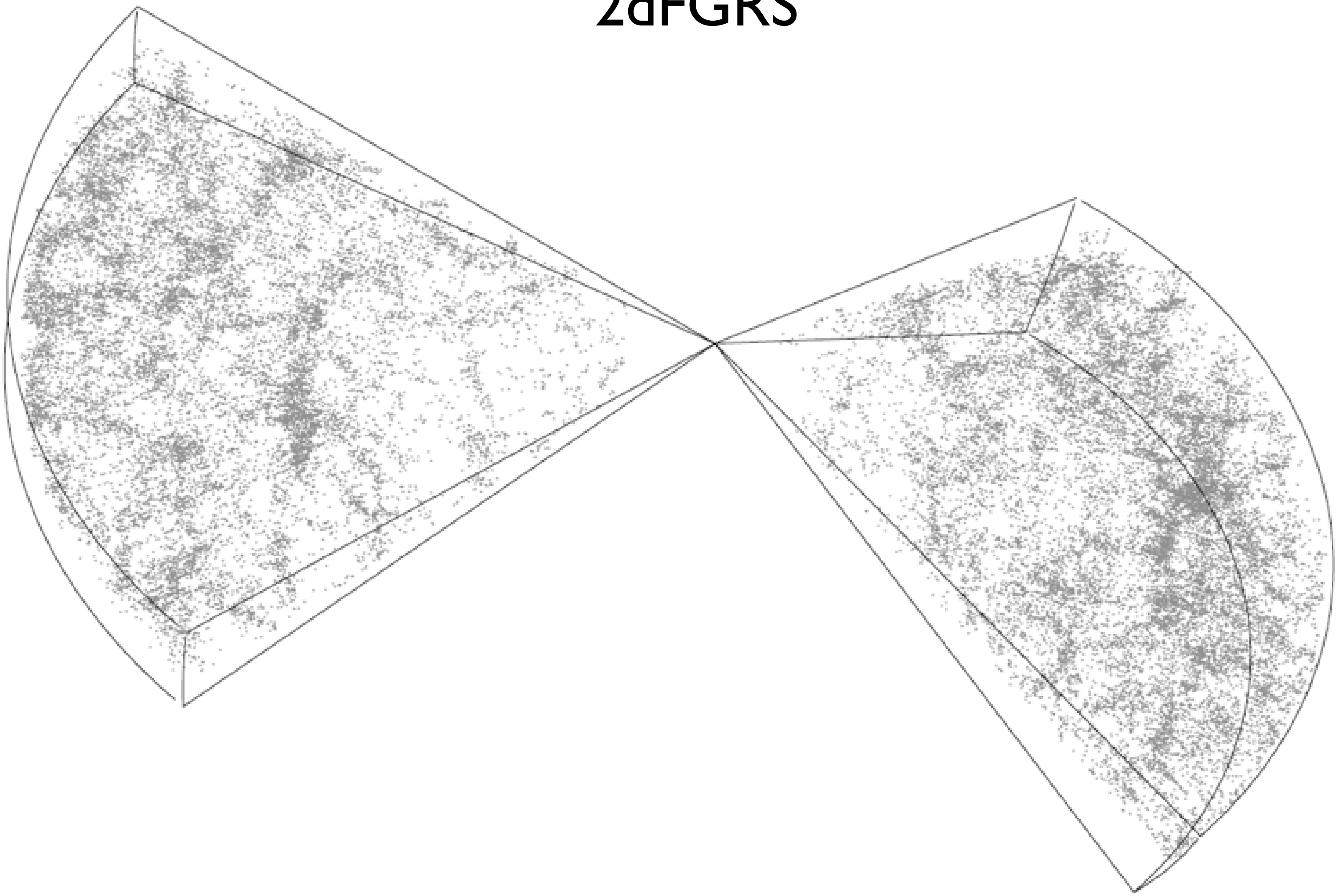
0.02
0.015
0.01
0.005
0
ξ
100
150
200
250
300
350
400
450
500
r(Mpc/h)
SDSS - DR6 (0.16<z<0.47, all galaxies:
80790 galaxies)

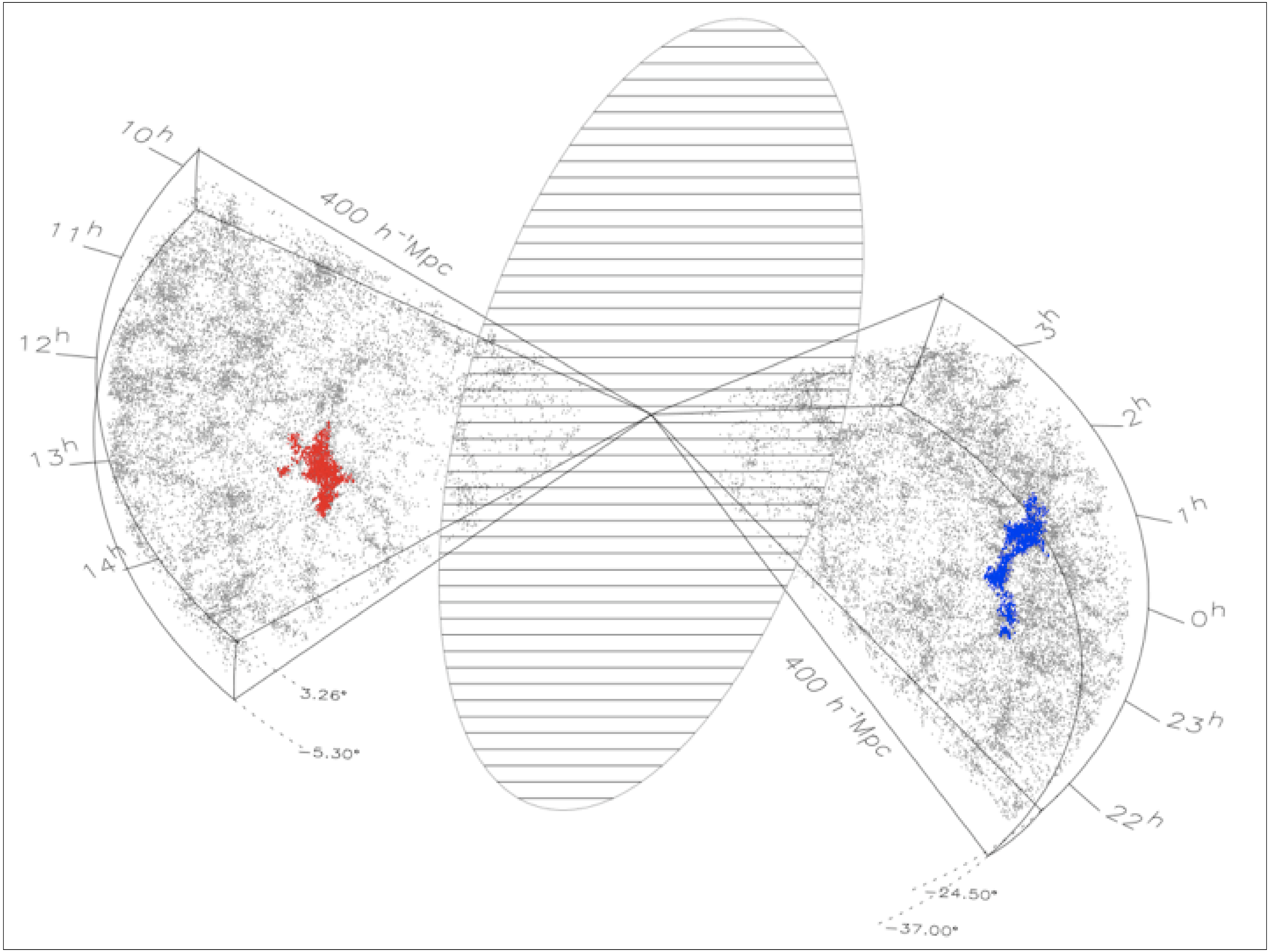


SDSS - DR6 (0.16<z<0.47,
-23.2<Mg(z=0.3)<-21.2), as in
Eisenstein et al 2005
0.02
0.015
0.01
0.005
0
ξ
100
150
200
250
300
350
400
450
500
r(Mpc/h)

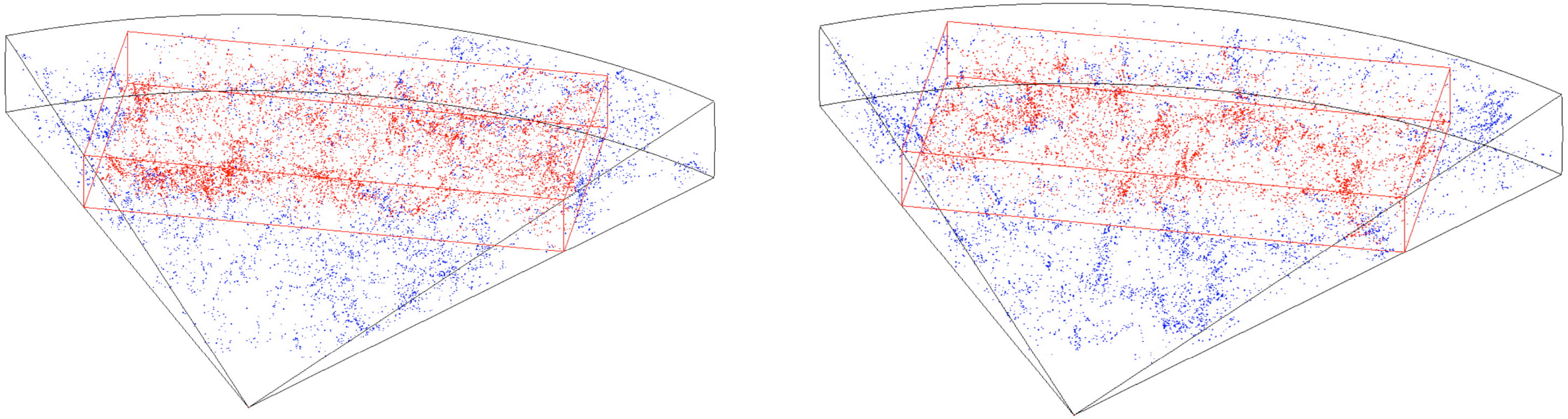

The evidence for BO depends
a) on sample selection,
b) on random point sample generation rules,
c) on statistical error estimates.
0.02
0.015
0.01
0.005
0
ξ
100
150
200
250
300
350
400
450
500
r(Mpc/h)

2dFGRS




10h
11h
12h
13h
14h
400 h⁻¹Mpc
3.26°
−5.30°
3h
2h
1h
0h
23h
22h
400 h⁻¹Mpc
−24.50°
−37.00°

2dF Mock

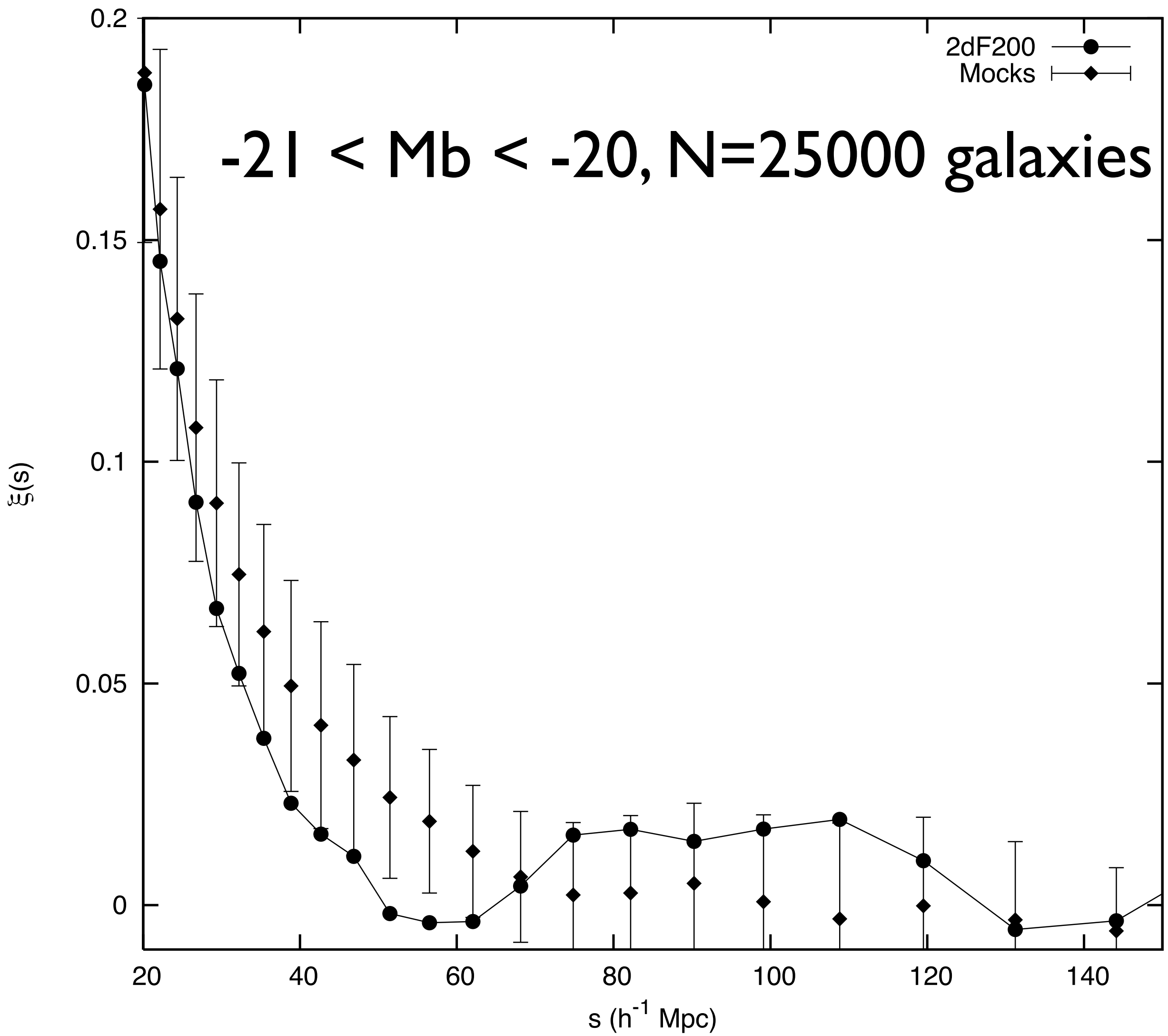


We might get the impression that N-Body simulations are better than the real thing.

In the early 1970's people were enthusiastic about a mere 1000 particles (which reproduced the correct two-point correlation function so ``it had to be right").

They got even more enthusiastic with a million particles in the 1990's and now it is indeed better than life, especially with reality enhancing graphics, and ready-to-play in your PowerPoint presentation movies.

Is this enthusiasm justified? N-Body simulations are certainly a success story, and they certainly make a huge contribution to our understanding of cosmology. The models are nevertheless extremely limited simply because they lack any real gasdynamics

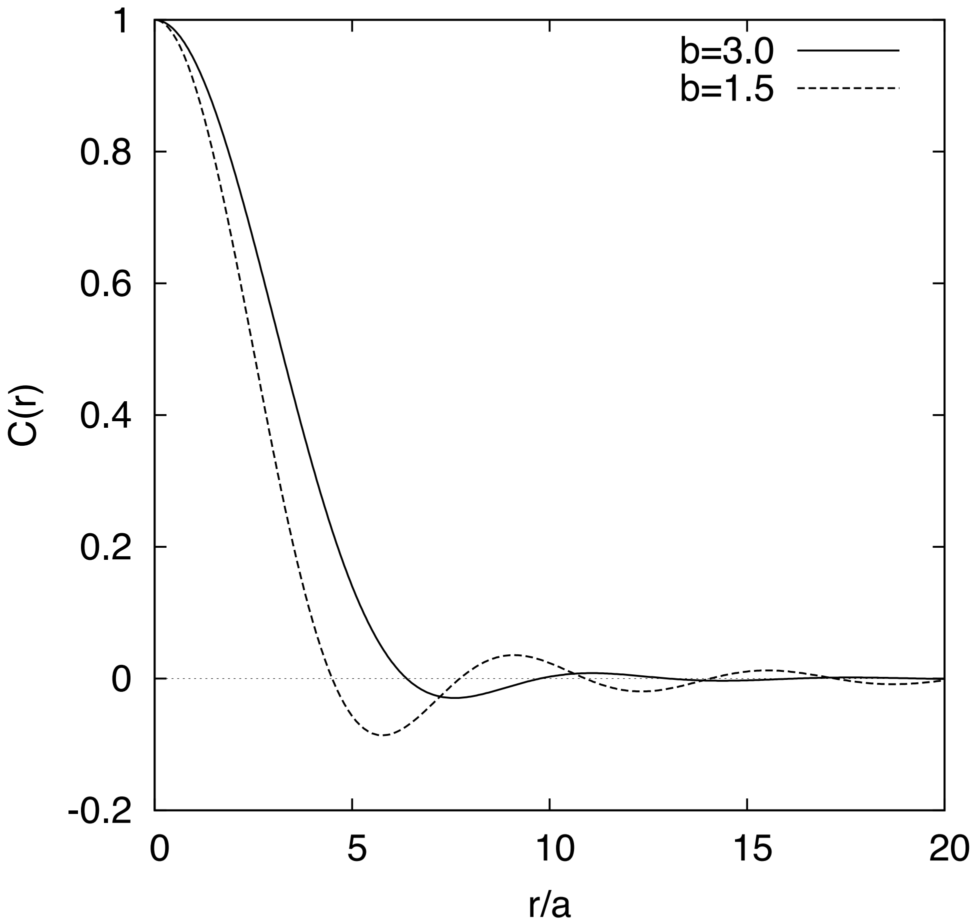


2dF200
Mocks
-21 < Mb < -20, N=25000 galaxies
ξ(s)
s (h^-1 Mpc)
0.2
0.15
0.1
0.05
0
20
40
60
80
100
120
140

Bessel universes

Schlather, M., "*Introduction to positive definite functions and to unconditional simulation of random fields*" Technical Report ST-99-10,Lancaster University, UK, 1999

$$C_J(r) = 2^b\Gamma(1+b)\left(\frac{r}{a}\right)^{-b} J_b\left(\frac{r}{a}\right).$$



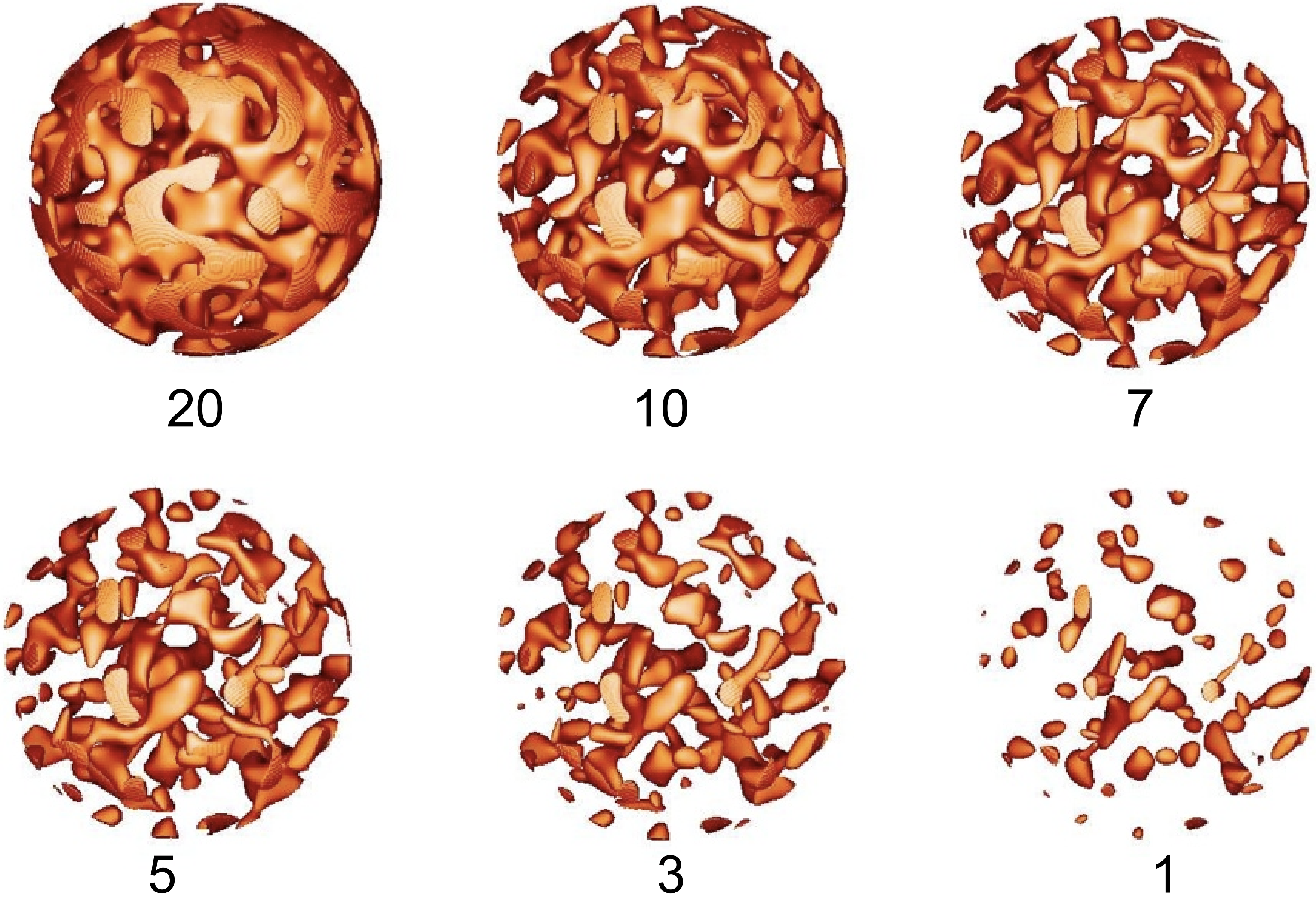
Emery, X., Lantuéjoul, C., "*TBSIM: A computer program for conditional simulation of three-dimensional Gaussian random fields via the turning bands method*"
Computers & Geosciences 32, 1615-1628, 2006.

Our Bessel universe is based on a realization of a (Gaussian) field $G(x)$ with a covariance C_J. As we want to faithfully represent the large-scale structure of the field, we use the turning bands method for that; the FFT method usually used in astronomy has a bad resolution at large scales and does not generate isotropic fields. We turn this Gaussian field into density by the exponential transform:

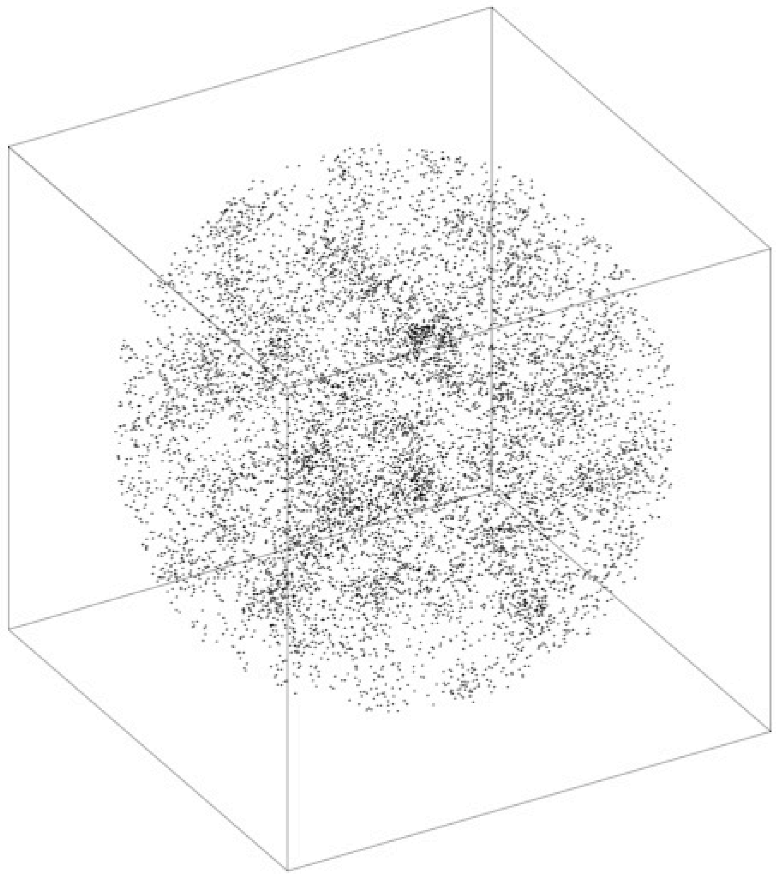
$$\rho(x) = \exp(G(x)).$$

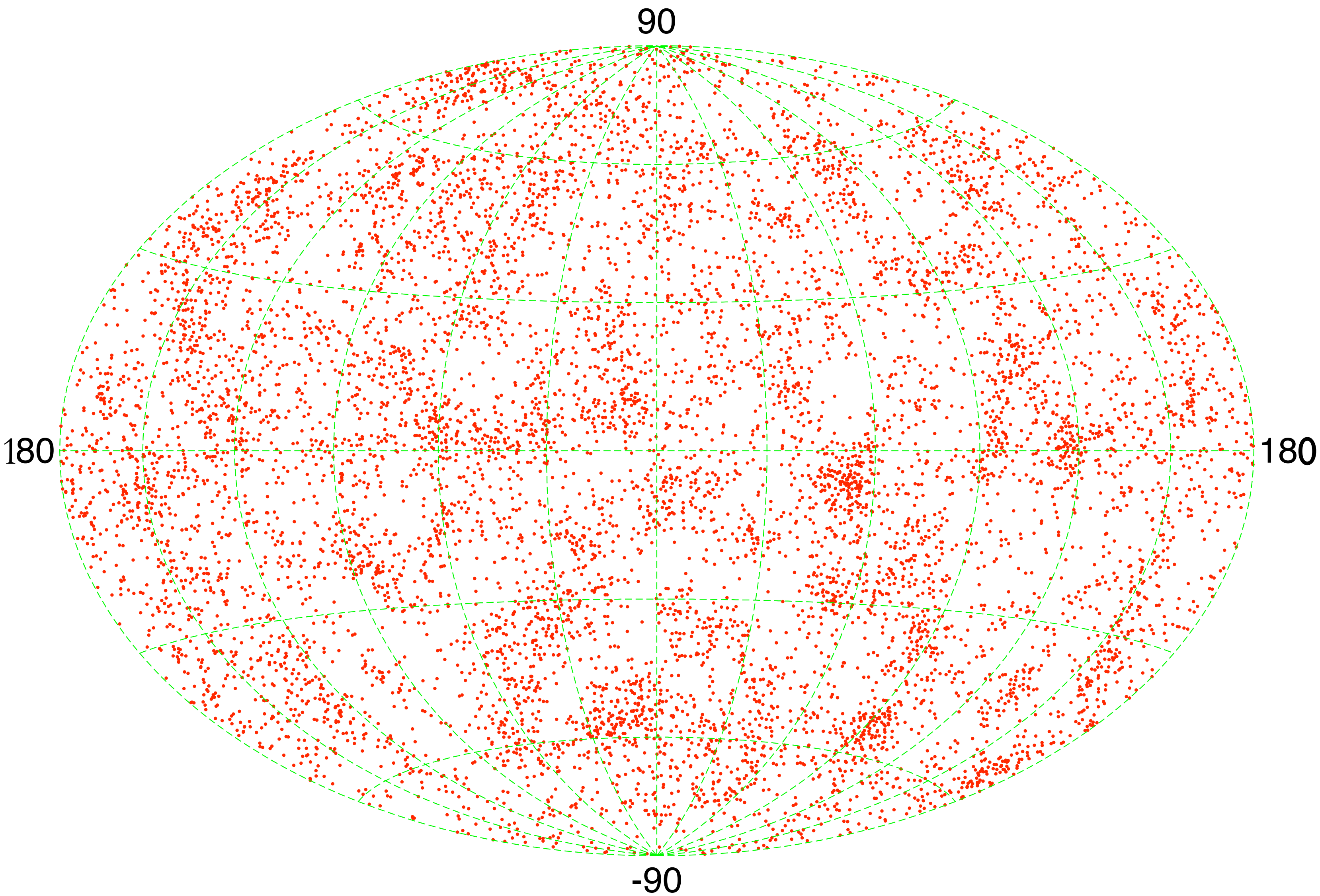
This gives us a density field that is everywhere positive and has the correlation function

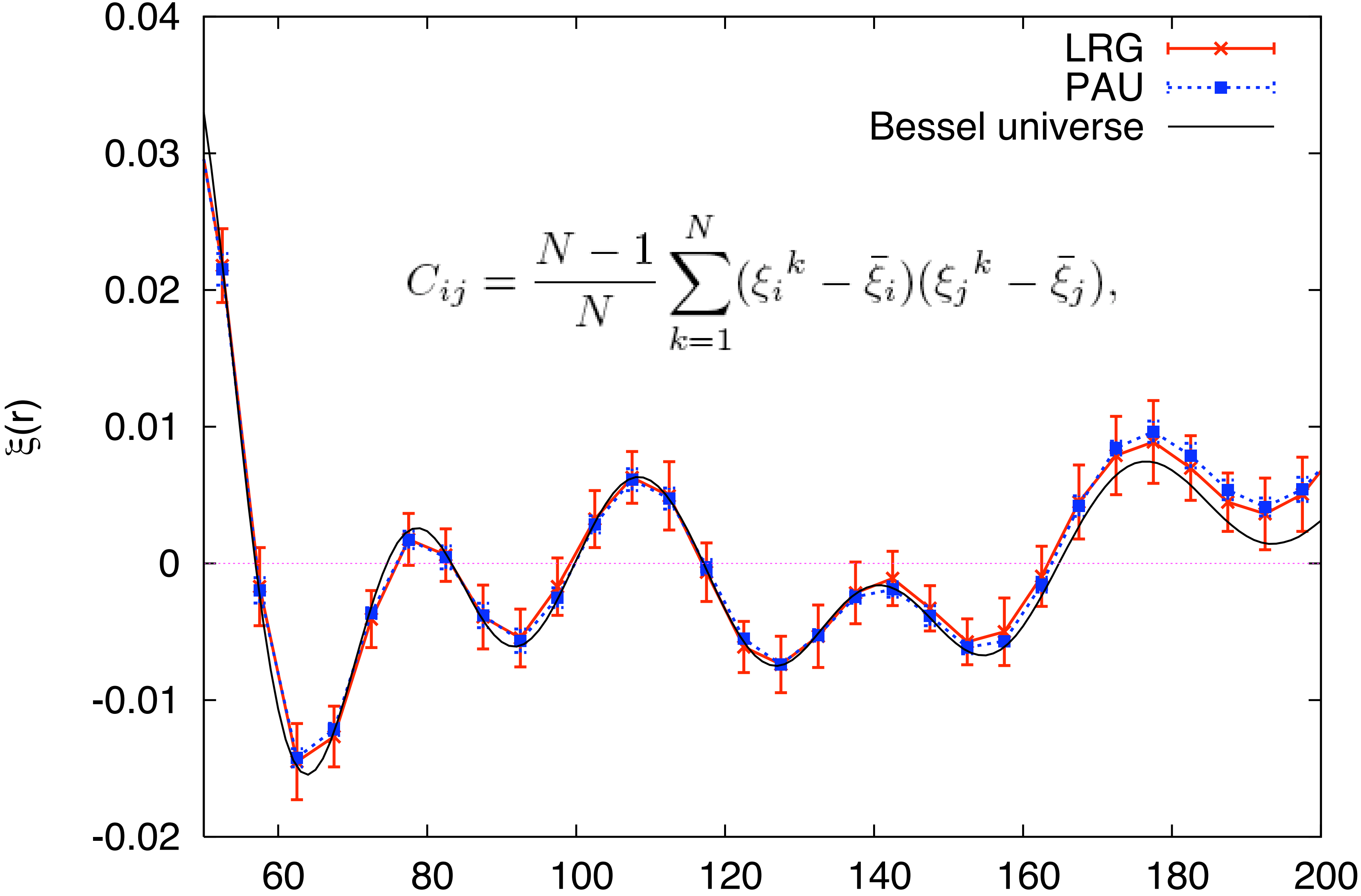
$$\xi_\rho(r) = \exp(C_j(r)).$$


20
10
7
5
3
1

Populating the density field with a Cox process

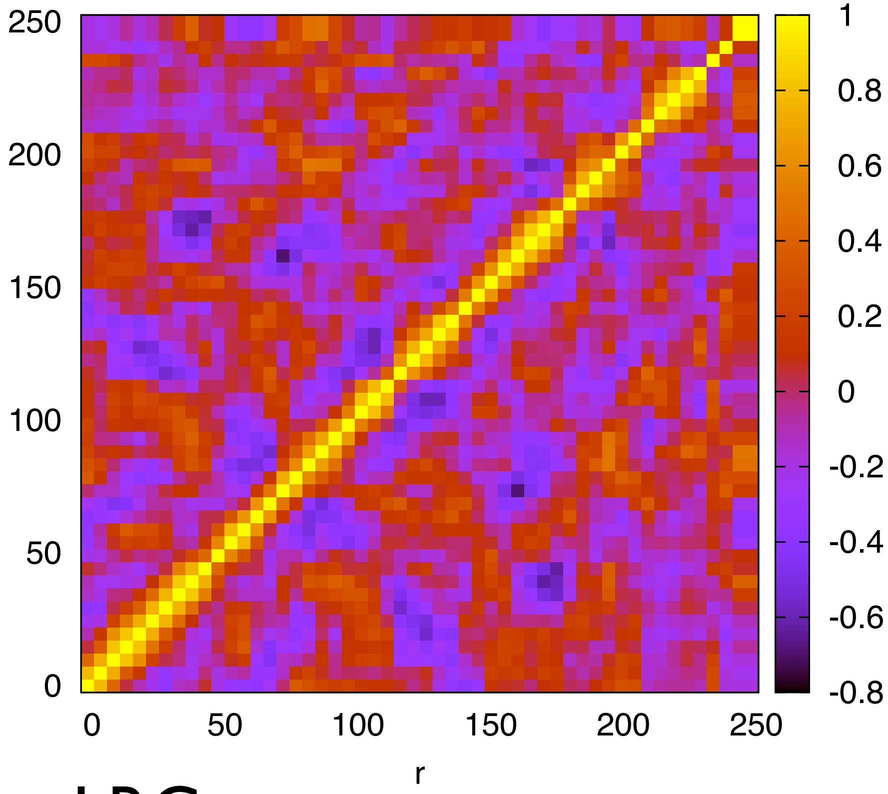



90
180
180
-90

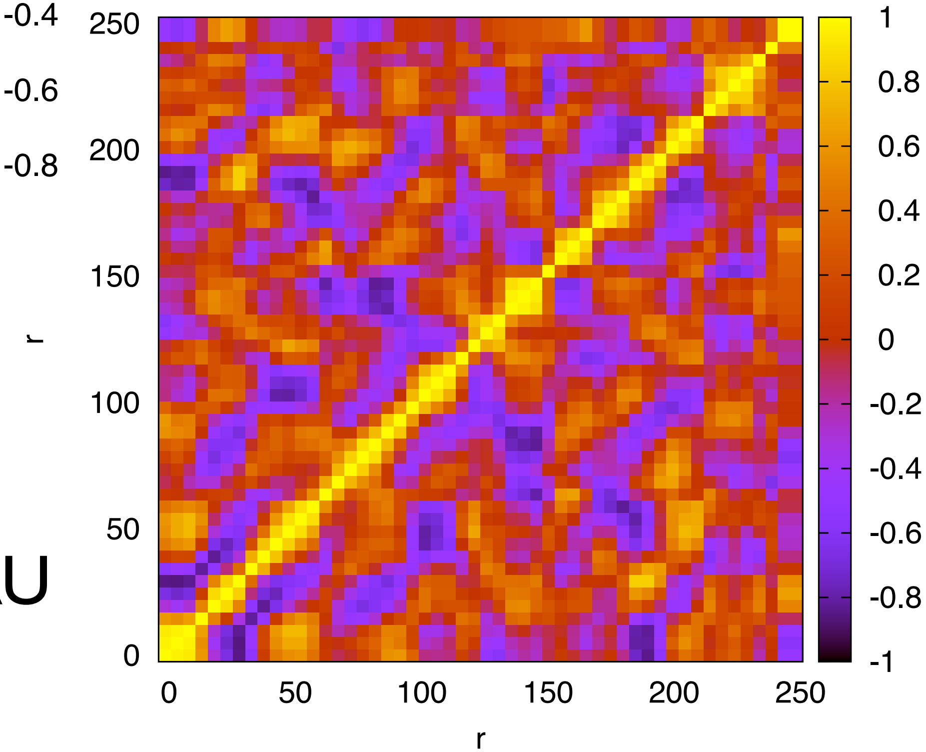


LRG
PAU
Bessel universe
$$C_{ij} = \frac{N-1}{N}\sum_{k=1}^{N}(\xi_i{}^k - \bar{\xi_i})(\xi_j{}^k - \bar{\xi_j}),$$
ξ(r)
0.04
0.03
0.02
0.01
0
-0.01
-0.02
60
80
100
120
140
160
180
200

Covariance matrices



LRG

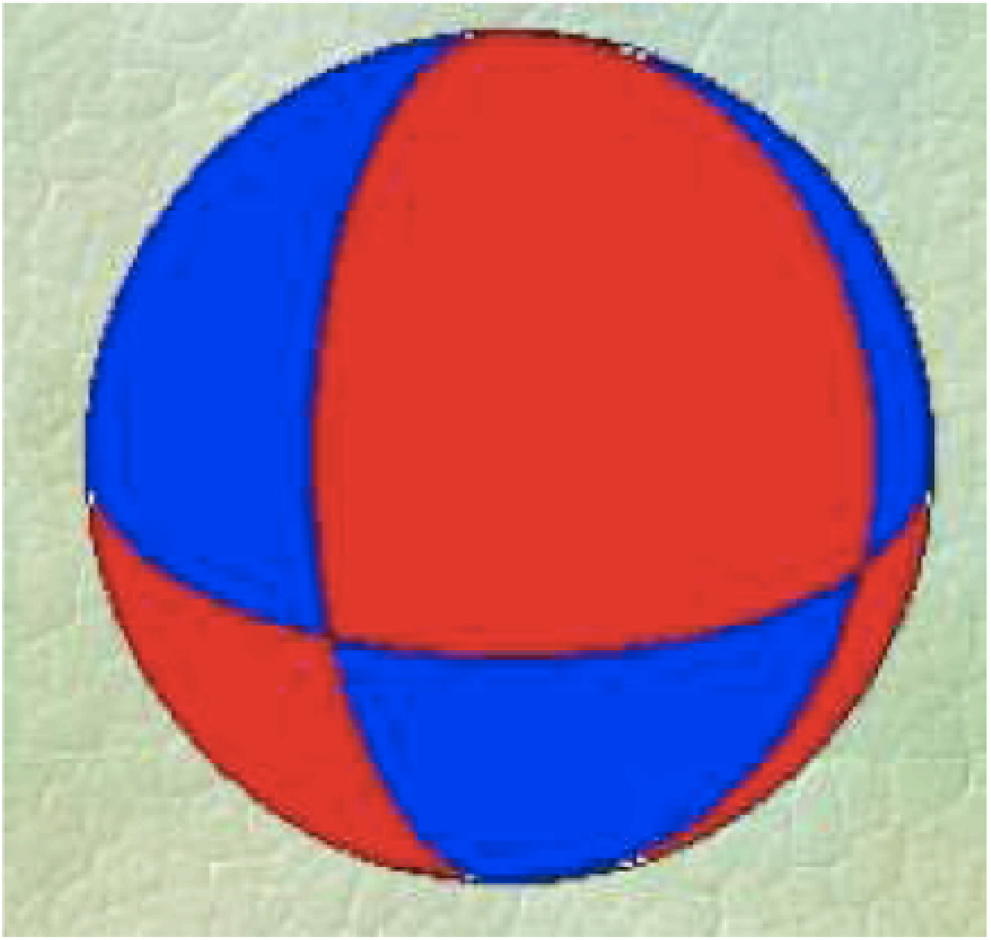


PAU

Block Jackknife covariances

We test this block jackknife approach in our Bessel Universes – we can calculate the block jackknife C_{ij} and compare it with the C_{ij} obtained using different realizations of the point process.

We divided our universe into eight octants:

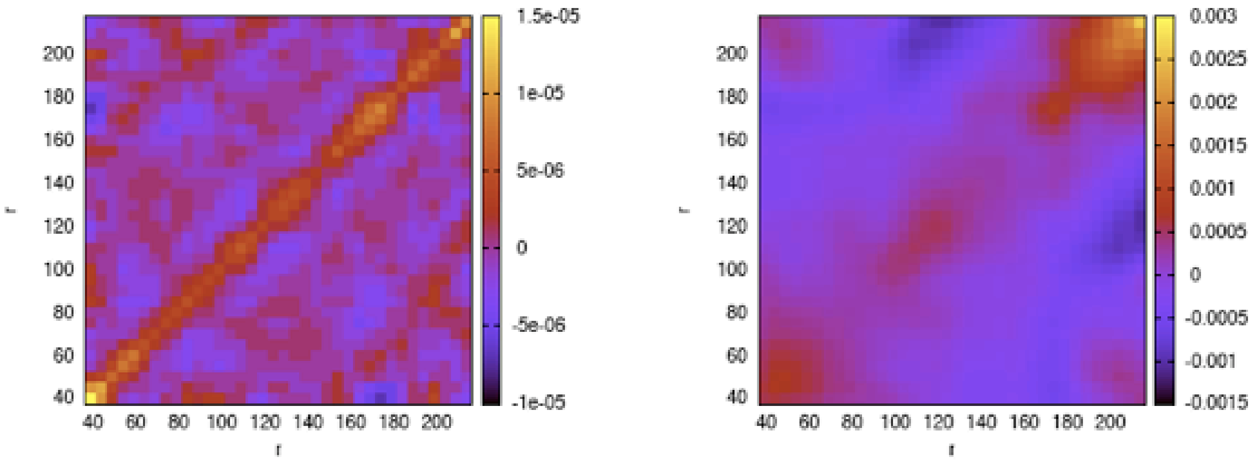


The covariance matrix of the correlation function is estimated as

$$\mathrm{C_{ij}}\xi(r_k) = \frac{N-1}{N}\sum_{i=1}^{i=N}\left(\xi_i(r_k) - \bar{\xi}(r_k)\right)\left(\xi_j(r_k) - \bar{\xi}(r_k)\right)$$

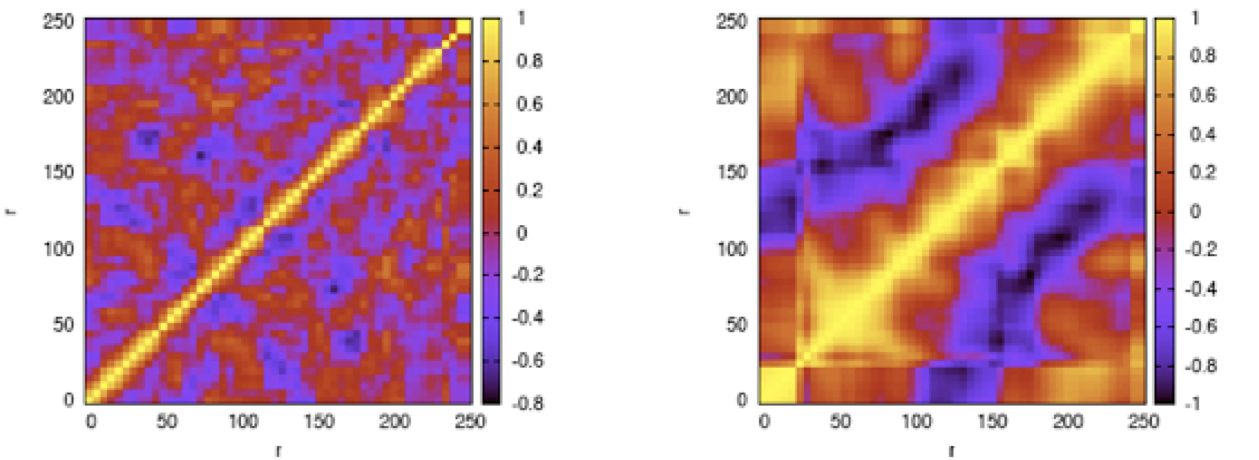
where $\bar{\xi}(r_k)$ is the mean of the N correlation functions for the bin r_k.

There is no proof that this estimate should mean anything; its only virtue is that it can be calculated. The covariance matrix is important, for example, if we want to fit correlation function with a theoretical one, to estimate parameters of theory, etc. If it is wrong, the fit will be wrong.

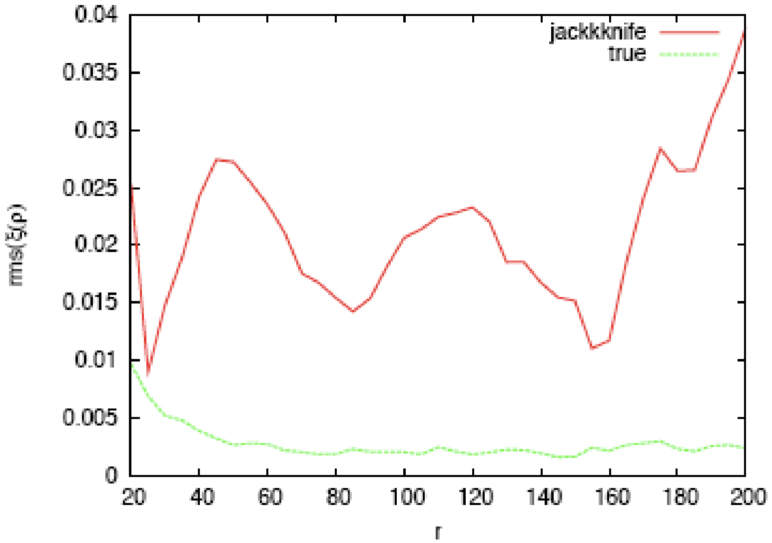


Covariances for the LRG case: left panel – different realizations, right panel – single realization, block jackknife.

Let us compare now the normalized covariance matrices; this trick shows better the structure of the matrix:

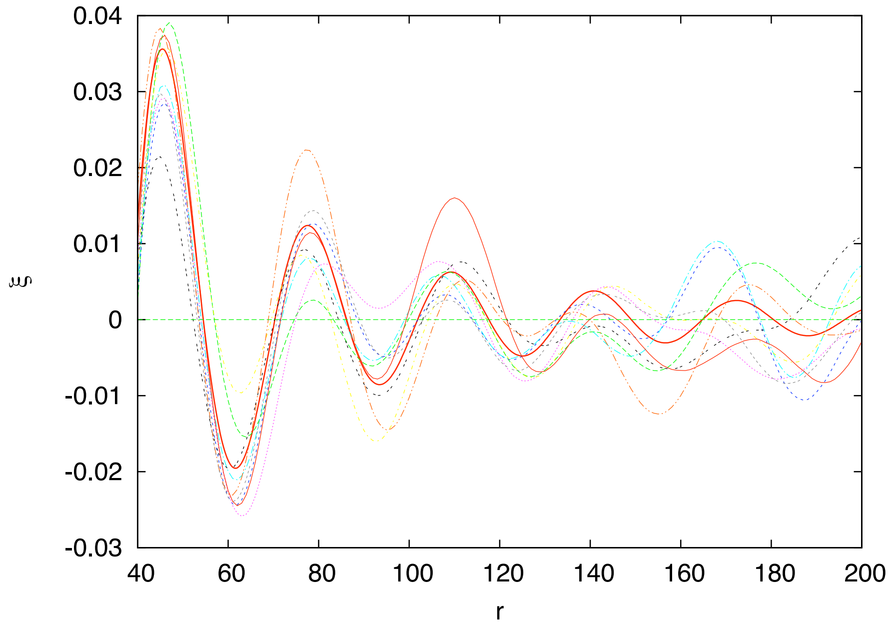


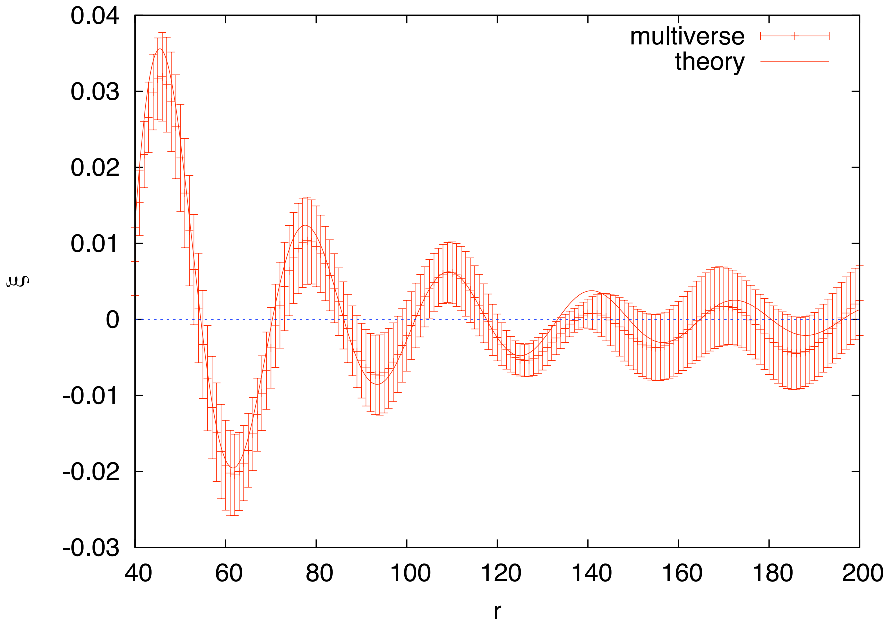
Normalized covariances for the LRG case: left panel – different realizations, right panel – single realization, block jackknife.

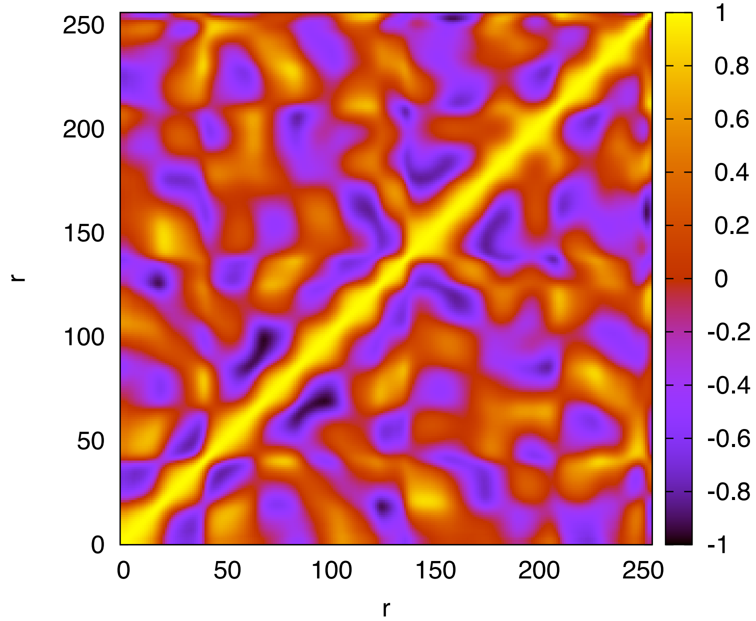


Correlation function rms error estimates for the LRG case: lower curve – different realizations, upper curve – single realization, block jackknife.

Smooth density field







Some conclusions...

C1 . The clear conclusion is that block jackknife is a bad method for correlation function covariances. The covariances found this way are too large, and the covariance matrix has large off-diagonal values.
Better methods should be found; maybe we shall have them by ADA6; tests are in progress!

C2. We have seen that the point samples reproduce the smooth density (at least its corrs. fun.) very well.

C3. The last slide shows that corr. fun. variations between realizations (density fields) are much larger -- the real structure of a universe (realization) depends on the algorithm (physical process) that generates the realization.

Some thoughts...

T1. Maybe we have got a bad realization -- an example is the low quadrupole amplitude of the CMB spectrum or the cold spot.

T2. So far we assume that the realization (universe) is ideal, but it assumes some unknown algorithm that generates the realization.

T3. Information about early physics can be obtained by comparing the realization with the ideal physical process by means of corrs. funcs, etc.). Of course, if our present picture of the initial Gaussian field is true...