Large Scale Structure and Redshift Surveys

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Galaxies: Units of Large Scale Structures

Galaxies are the basic unit in the discussion on large scale structures.

A typical bright galaxy has around 10^11 stars and a total mass in excess of 10^{12} $\mathrm{M}_\odot$ (One Solar mass $\mathrm{M}_\odot = 2 \times 10^{33}$ g.) and is about 20 kpc across (One kilo-parsec kpc$= 3.08 \ \times \ 10^{21}$ cm.)

One can find galaxies in a range of sizes, from small low mass dwarf galaxies ($M \sim 10^8$ $\mathrm{M}_\odot$) to massive cluster dominant (cD) galaxies ($M \sim 10^{13}$ $\mathrm{M}_\odot$).

Some galaxies are forming stars, while others have been inert for at least 10^9 years. Galaxies with young, massive stars appear blue while galaxies with no recent star formation appear red.

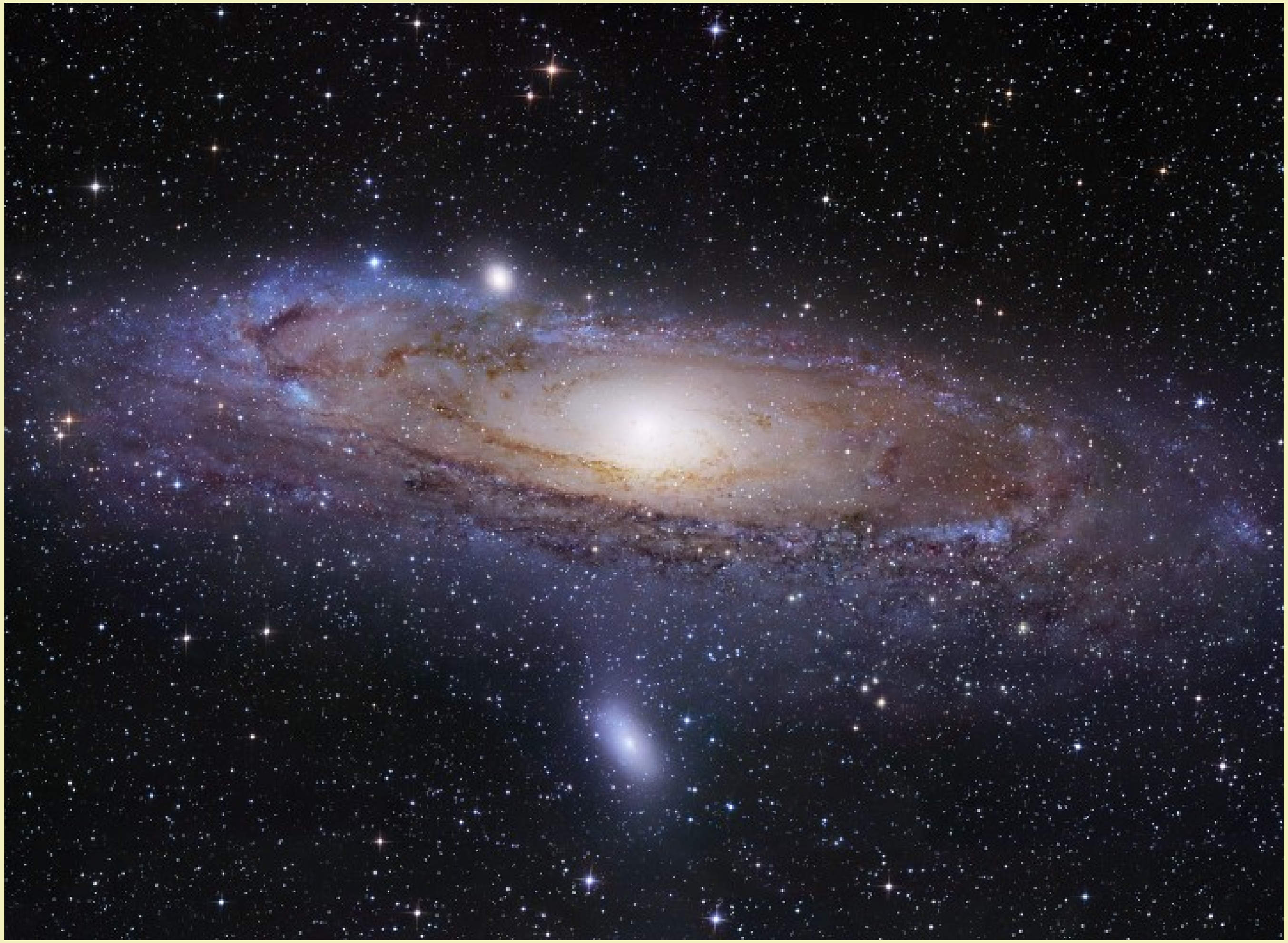

Figure 1: The Andromeda Galaxy. Credit & Copyright: Robert Gendler.

Figure 2: Elliptical Galaxy NGC 4881 in Coma. Credit: W. A. Baum (U. Washington), WFPC2, HST, NASA

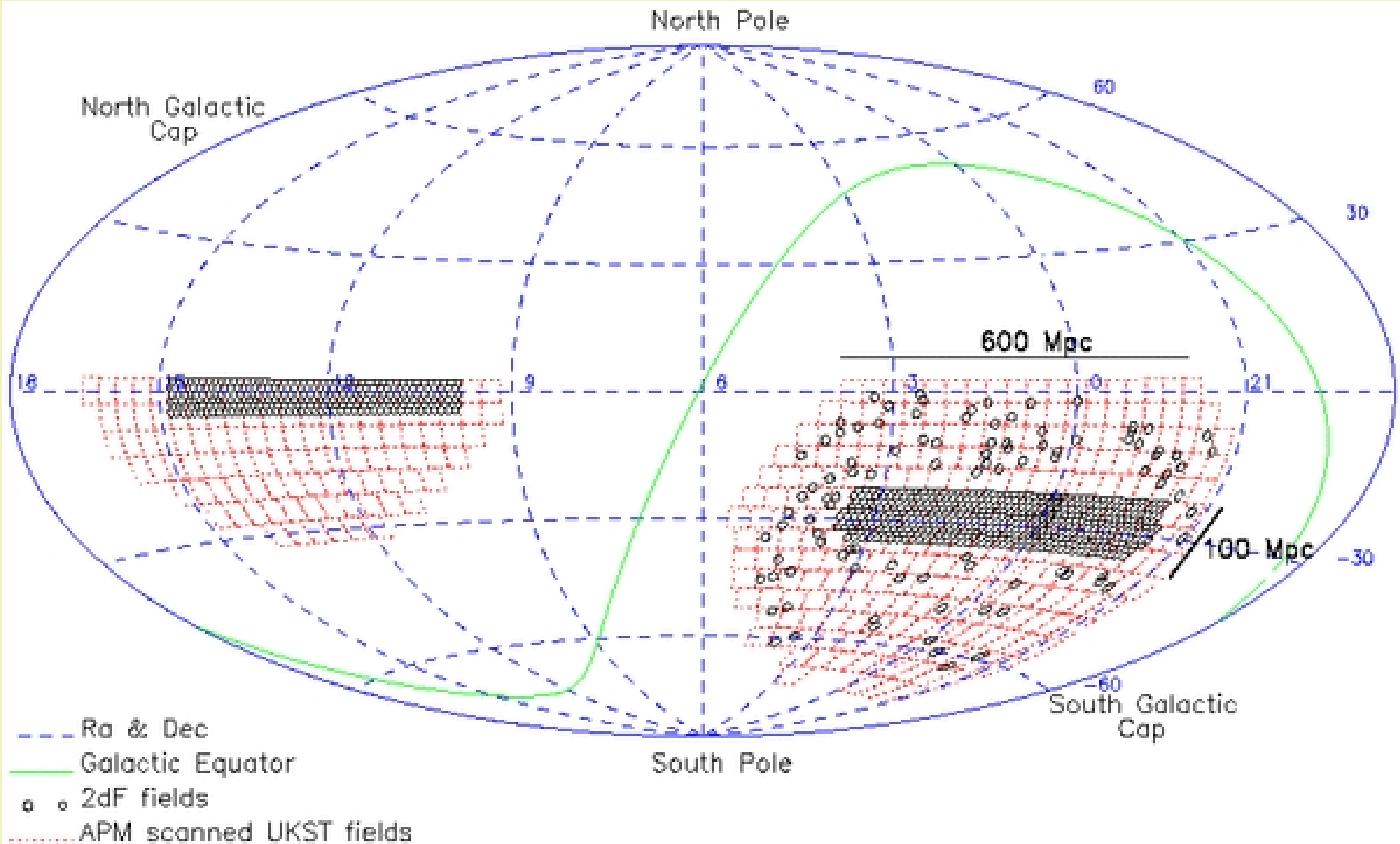

Figure 3: Sky coverage in the 2 degree field galaxy redshift survey. Source: http://www.mso.anu.edu.au/2dFGRS/Public/Survey/description.html.

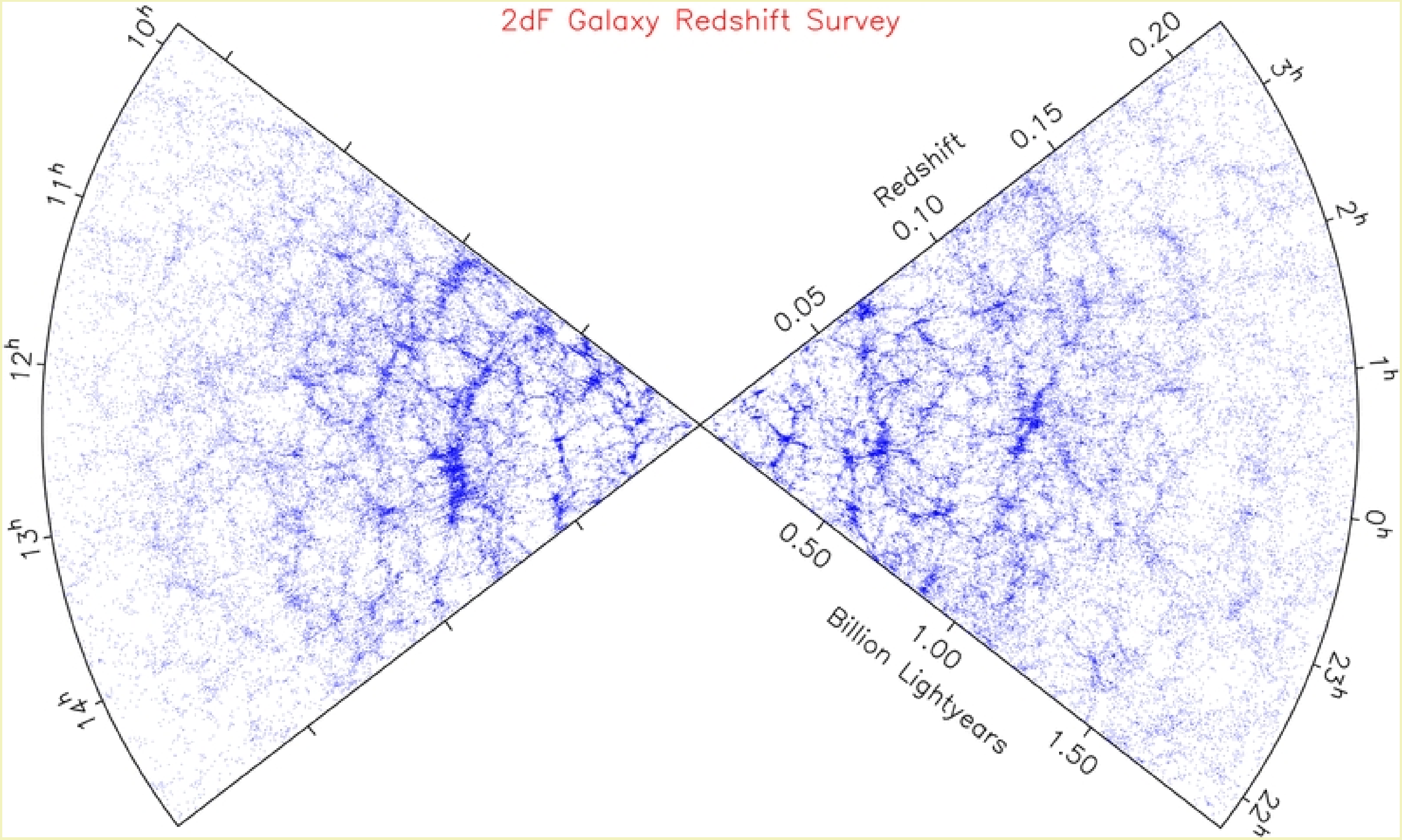

Figure 4: Distribution of galaxies in the 2 degree field galaxy redshift survey. Source: http://www.mso.anu.edu.au/2dFGRS/Public/Survey/description.html.

Large Scale Structures

Observations show that the distribution of galaxies is extremely inhomogeneous at small scales ($l \leq 10$ Mpc).

There are large (almost) empty regions in the distribution of galaxies, these are called voids. The largest of these are almost 100 Mpc across.

At scales larger than 100 Mpc, the distribution of galaxies appears to be smooth.

Characterizing Large Scale Structures

Redshift surveys give us information about the position of each galaxy on the sky, its redshift and its brightness in a few wavebands. We have to use these inputs to characterize the large scale structures in the universe.

Galaxies, in general, are not located at fixed comoving locations. These move about in gravitational field of large scale perturbations and sometimes even have close encounters with other galaxies. Thus the relation between red-shift and distance is:

$$z = \frac{\dot{r}}{c} = \frac{r}{cH_0^{-1}} + \frac{v}{c}$$

where v is the component of velocity of the galaxy being observed along the line of sight.

Characterizing Large Scale Structures

Given a distribution of galaxies within the survey, we can find out the number density of galaxies as a function of position: $n(\theta, \phi, z)$. From here we can derive the average number density of galaxies $\bar{n}$.

Using these, we can define the contrast in number density of galaxies:

$$n(\theta, \phi, z) = \bar{n}\,(1 + \delta_g(\theta, \phi, z))$$

δ_g is similar in spirit to the density contrast δ that is defined for matter in theoretical models. The two are proportional to each other at sufficiently large scales. At small scales it is essential to introduce a stochastic element as clustering of galaxies can depend on a number of evolutionary and environmental factors (Dekel & Lahav, 1999).

Characterizing Large Scale Structures

By definition, it is clear that the volume average $\langle \delta_g \rangle = 0$. Hence to obtain non-trivial information we need to measure at least the second moment.

The joint probability of finding one galaxy in two cells located at $\mathbf{r}_1$ and $\mathbf{r}_2$ is:

$$P = \bar{n}^2\, \delta V_1\, \delta V_2 \ \ (1 + \xi(\mathbf{r}_{12})) = \bar{n}^2\, \delta V_1\, \delta V_2 \ \ (1 + \xi(r_{12}))$$

where ξ is the two point correlation function. In absence of a special direction or location, we expect statistical isotropy and homogeneity. Therefore the two point correlation function should not depend on the direction of $\mathbf{r}_{12}$.

Characterizing Large Scale Structures

Rephrasing the above definitions, we have:

$$\langle n_i n_j \rangle = \bar{n}^2 \, \delta V_i \, \delta V_j \; (1 + \xi(r_{ij}))$$

And the correlation function is essentially the second moment of δ_g:

$$\langle \delta_g(\mathbf{r}_i) \delta_g(\mathbf{r}_j) \rangle = \xi(r_{ij})$$

The correlation function is often used to characterize the distribution of galaxies in redshift surveys.

Characterizing Large Scale Structures

An equivalent function is the power spectrum of galaxy distribution.

$$P(k) = \langle |\delta_{g\mathbf{k}}|^2 \rangle \qquad .$$

The power spectrum is essentially the Fourier transform of the correlation function, but it is much easier to measure in real surveys.

In galaxy redshift surveys, the probability that a galaxy would or would not be observed is a function of position. Thus strictly speaking $\bar{n}$ is not a constant. This variation is quantified with the help of the selection function W.

The observed δ_g^{obs} is a result of the convolution between δ_g and W. If we can model W, we can recover the power spectrum from $\delta_{g\mathbf{k}}^{obs}$.

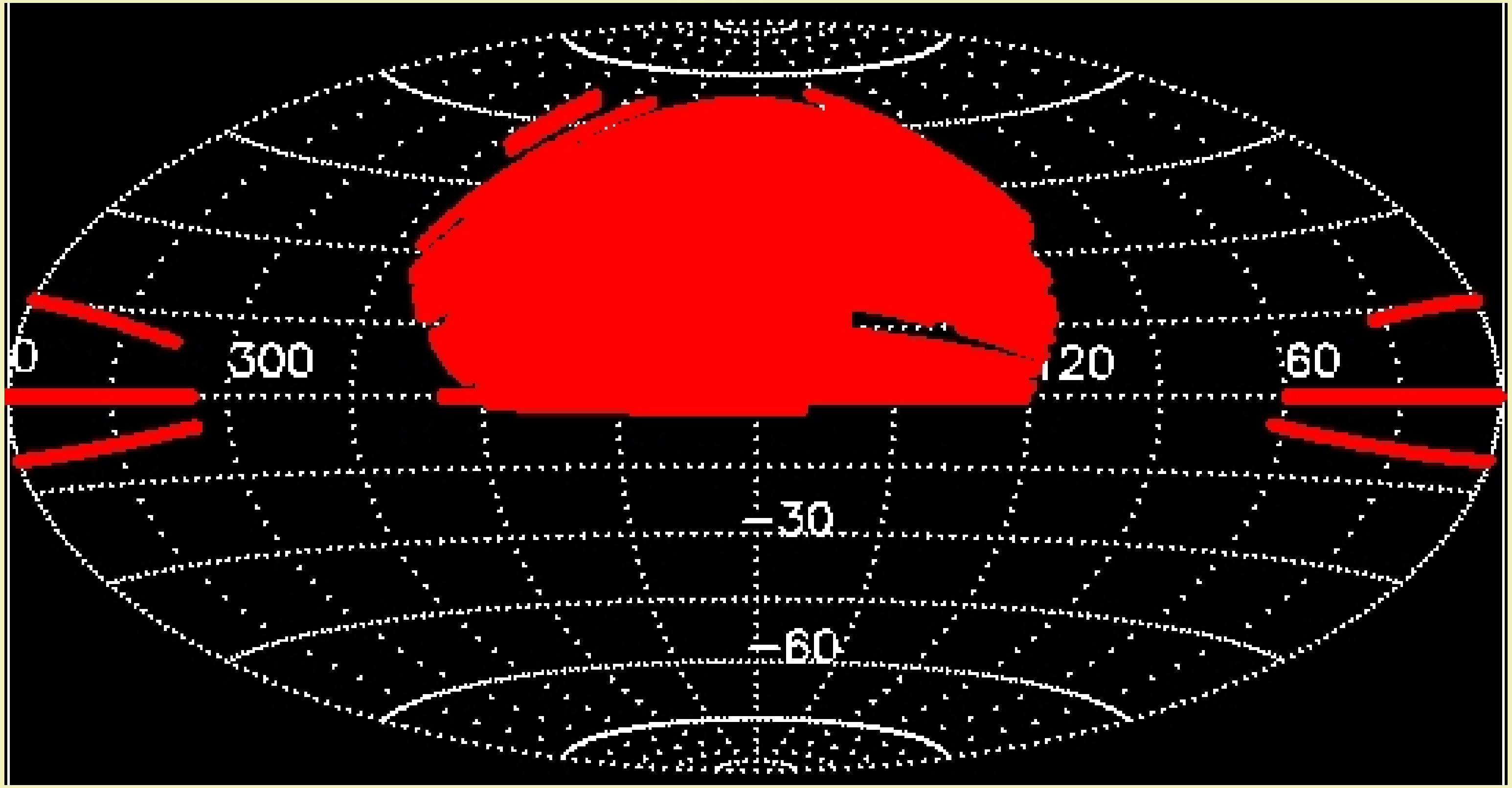

Figure 5: Sky coverage for photometry in the SDSS survey (data release 5). Source: http://www.sdss.org/

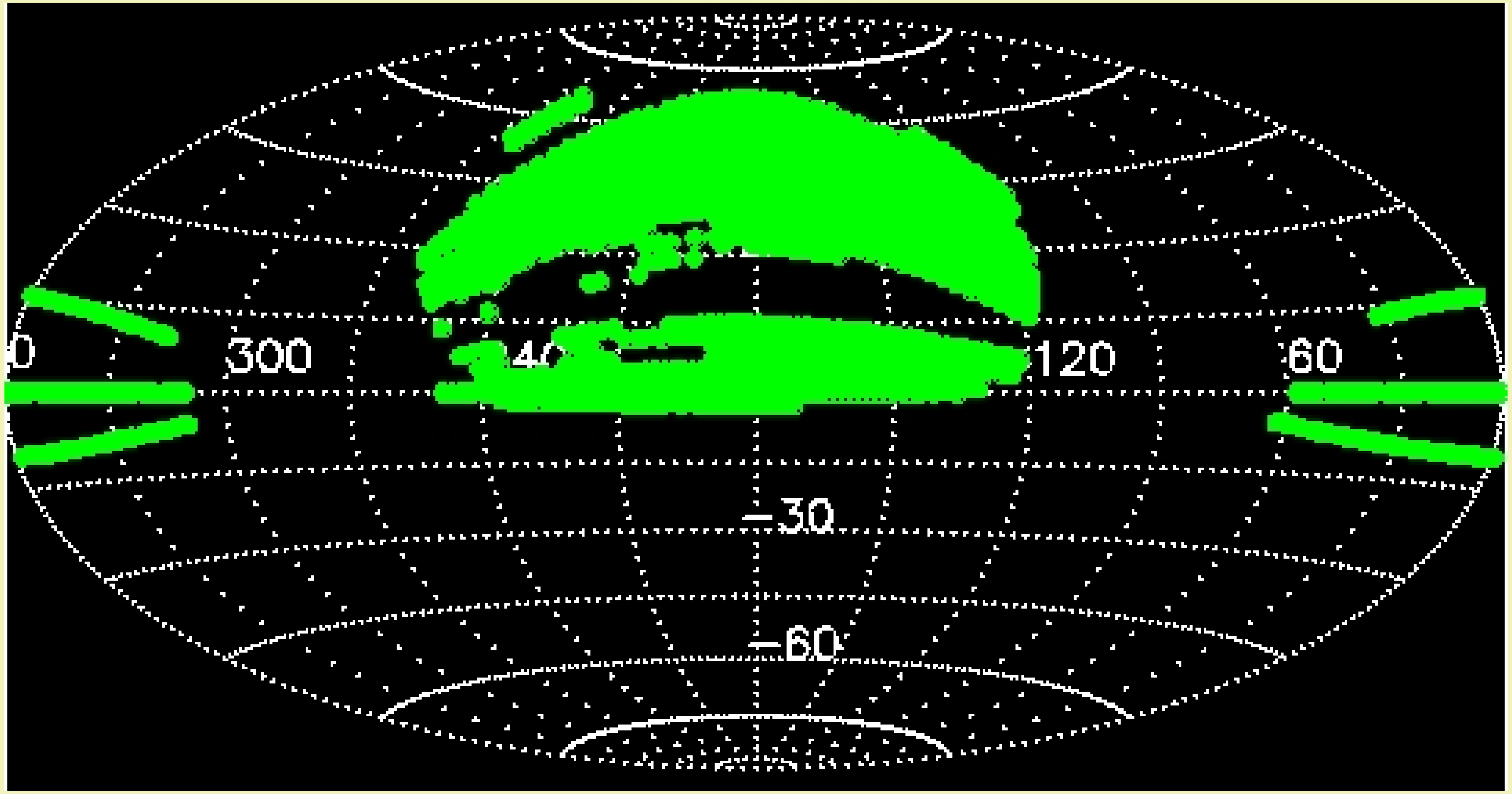

Figure 6: Sky coverage for spectroscopic followup in the SDSS survey (data release 5). Source: http://www.sdss.org/

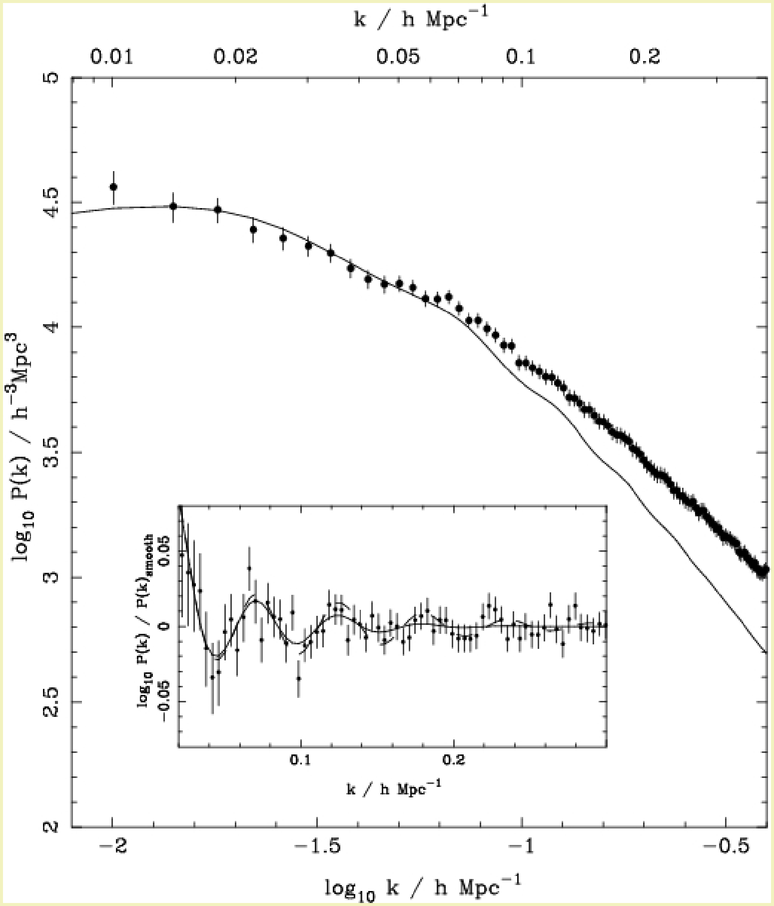

Figure 7: Power spectrum of SDSS galaxies + Luminous Red Galaxies. Percival et al. (astro-ph/0608636).

Power Spectrum: SDSS DR5

The power spectrum of galaxies in the SDSS survey and the LRG sample has been measured over a large range of scales.

Features introduced by baryon acoustic oscillations (BAO) in the matter+radiation fluid prior to decoupling of the two are also detected.

The detection of BAO features and the shape of the power spectrum can be used to constrain $\Omega_m h$ and Ω_b.

Along with WMAP observations, these put strong constraints on cosmological parameters.

Beyond the second moment

With an observed distribution of such a large number of galaxies, we can easily measure higher moments of the galaxy distribution.

The higher moments in real space are very sensitive functions of the shape of the power spectrum.

Such measurements have been carried out in detail for the 2dFGRS (Croton et al. 2004).

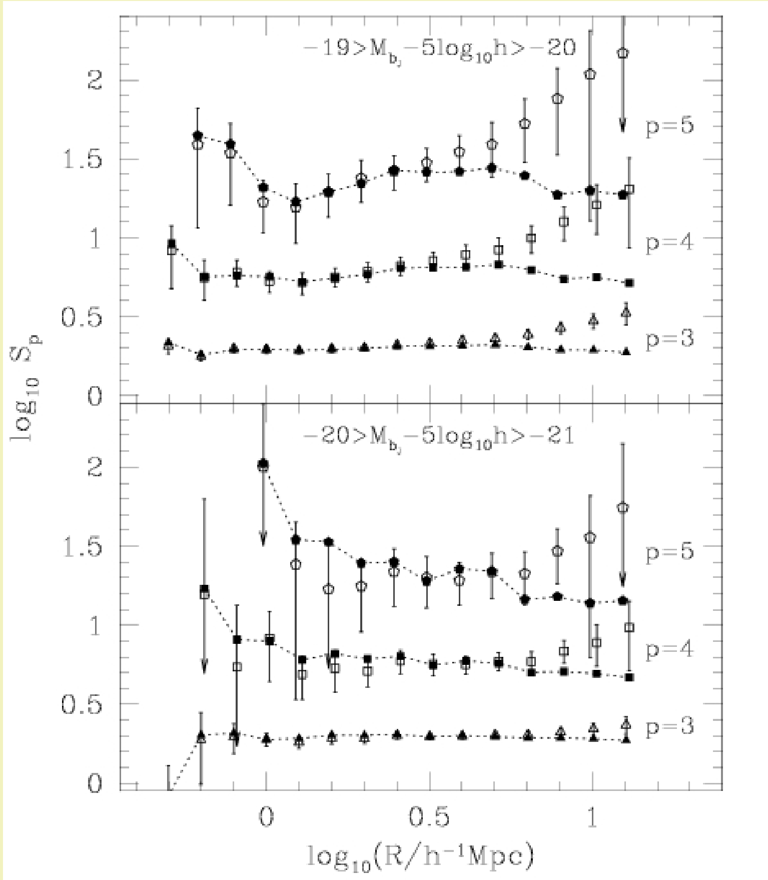

Figure 8: S_n for the 2dFGRS data. (Croton et al, 2004)

Beyond the second moment

The almost scale independent value of S_n is puzzling as these are expected to be strongly scale dependent.

We have shown recently that this scale independence is caused by redshift space distortions in the largest haloes. (JSB and S. Ray, 2006)

We demonstrate this effect in simulations and also explain it with the halo model.

We have shown that the differences between δ_g and δ also suppress S_n.

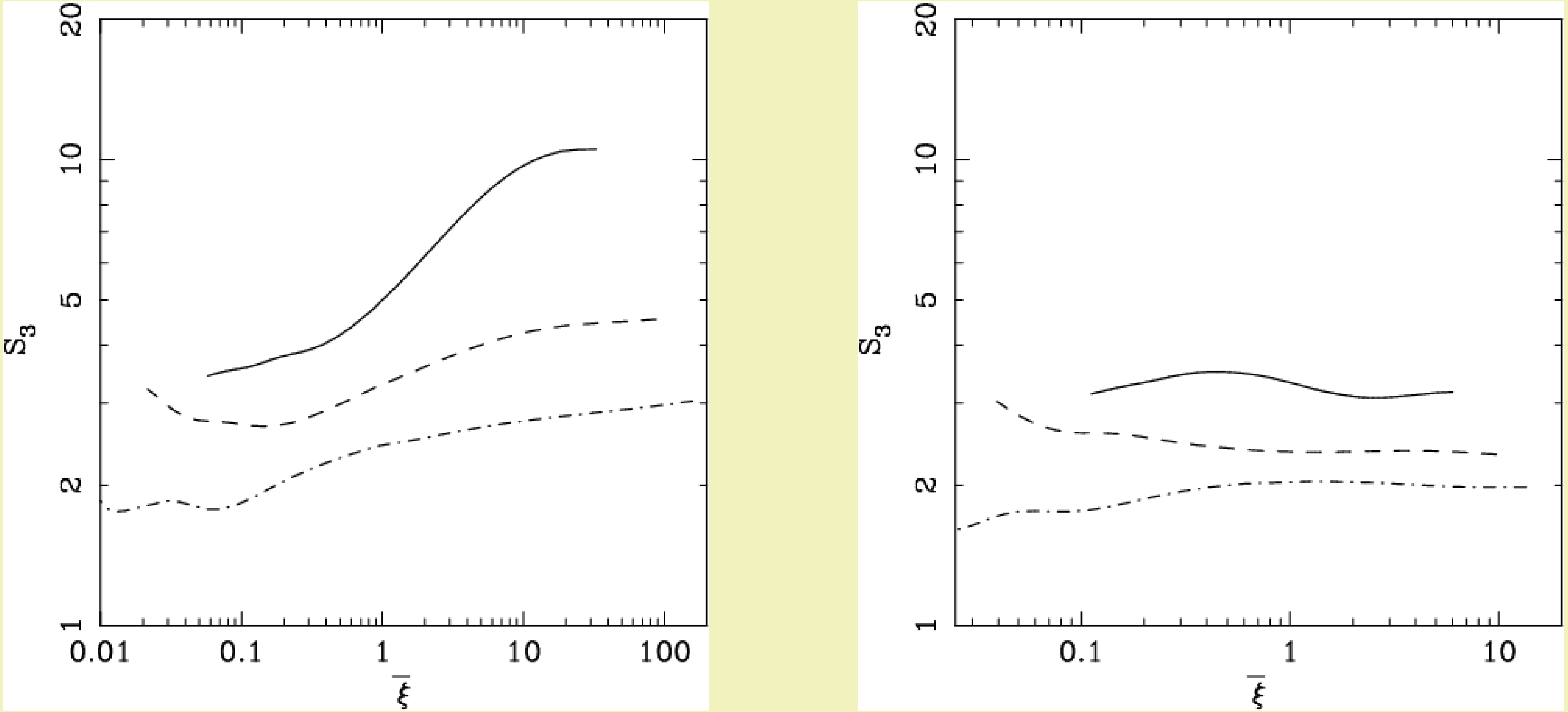

Figure 9: S_n in real and redshift space. (JSB and S. Ray, 2006)

Redshift space distortions

Redshift space distortions make the distribution of galaxies anisotropic for any observer.

These anisotropies can be observed in the two point correlation function.

A measure of the anisotropies at large scales allows us to estimate cosmological parameters.

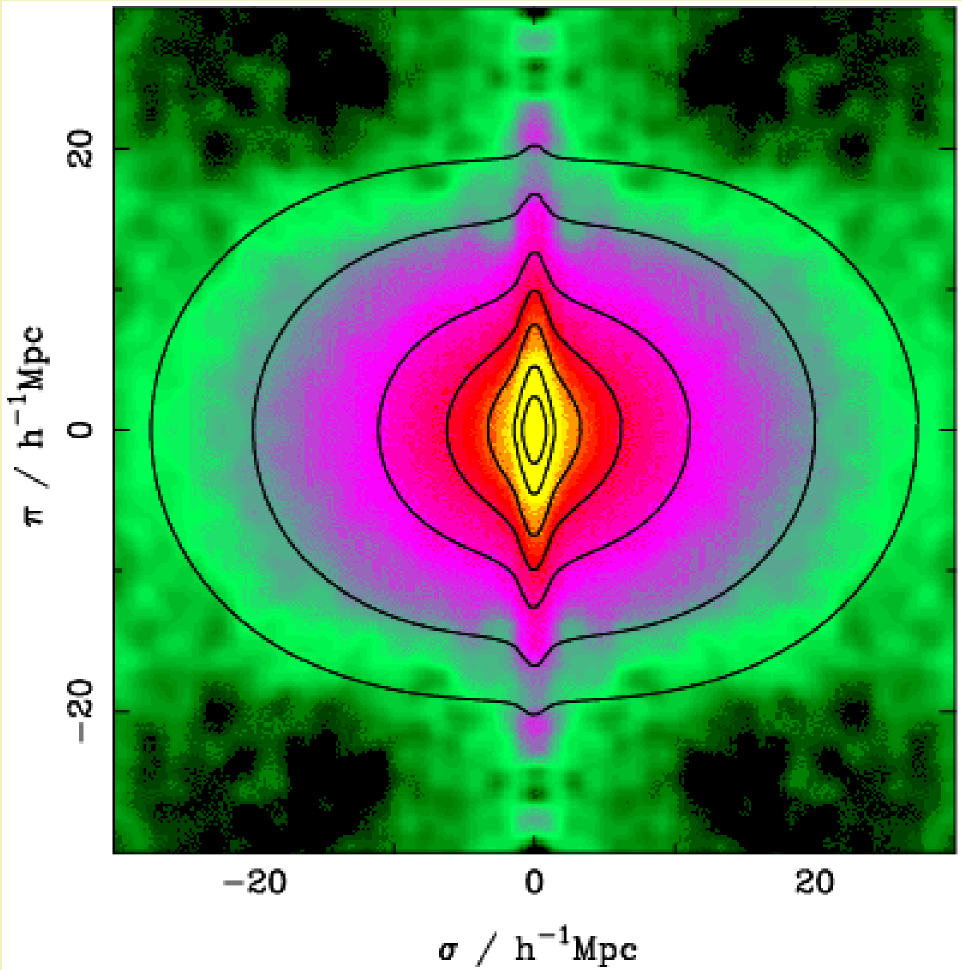

Figure 10: Redshift space distortions for the 2dFGRS data. (Peacock et al, 2002)

Topology of the galaxy distribution

Topological analysis of the distribution of galaxies offers a completely independent method for analyzing the data.

While it is difficult to relate the results of the analysis to the initial power spectrum of the model in a direct manner, one can look for patterns using N-Body simulations.

Such analysis has been done for the SDSS survey (e.g. see Park et al., 2005).

Recently it has been suggested that filamentarity of the galaxy distribution is a sensitive function of the "bias" between the galaxy and matter distributions (Pandey & Bharadwaj, 2007).

Bias

Clustering properties of galaxies vary somewhat with galaxy properties like absolute luminosity, star formation rate, etc.

While this had been known for several decades, large data sets like 2dFGRS and SDSS allow us to a fairly detailed analysis.

It has been found that brighter galaxies cluster more strongly.

Galaxies that are forming stars often cluster less strongly.

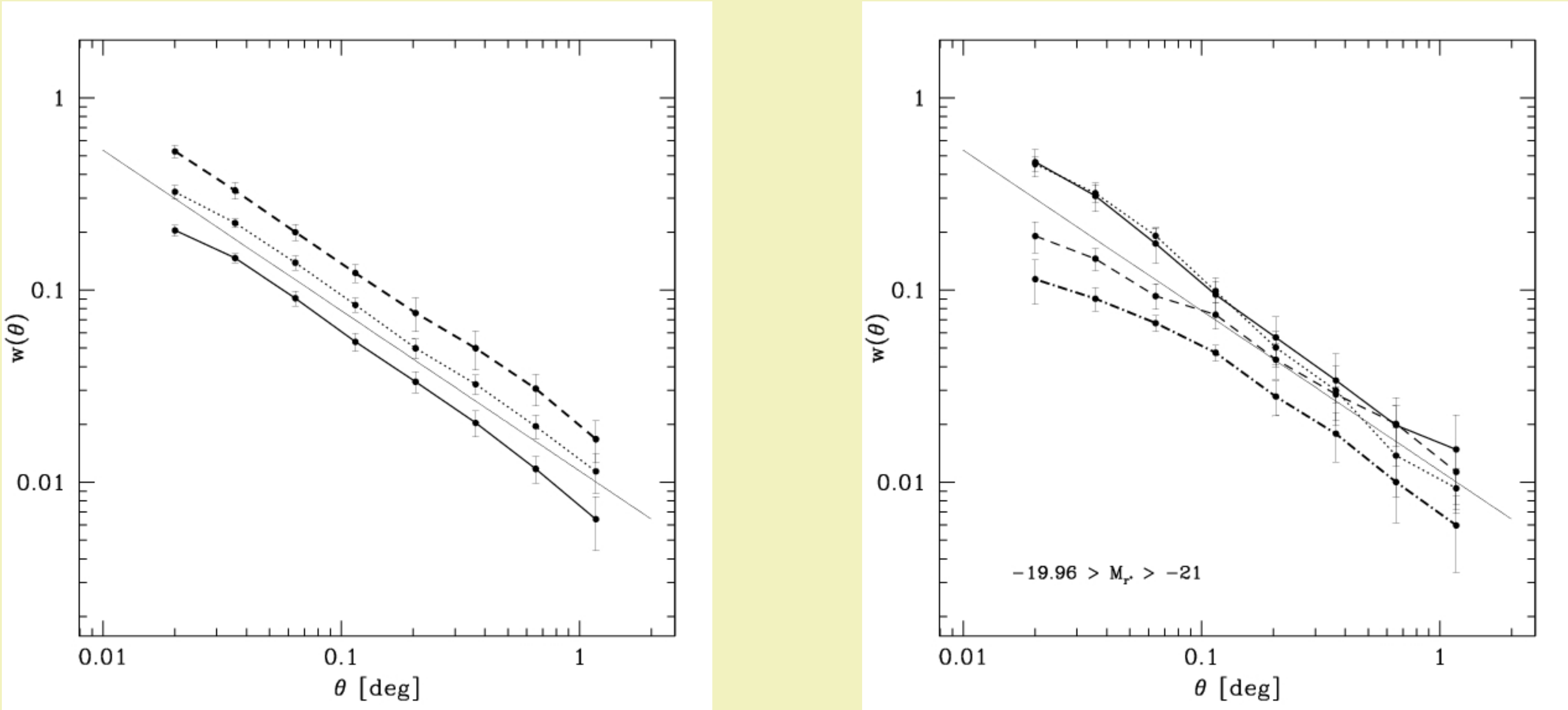

Figure 11: Angular clustering for different subsets of galaxies. (Budavari et al. 2003)

Is the universe homogeneous at large scales?

Early work on this question using fractal dimensions (Bharadwaj, Gupta and Seshadri 1999) indicated that the universe is smooth at scales beyond 120 Mpc.

Recent work using the SDSS data indicated that the scale of homogeneity was perhaps smaller, as small as 60 Mpc. (Yadav et al. 2005)

Using theoretical modeling, we find that departures from can be seen more easily by using the generalized dimension D_q for a large q as D_q/q is a constant (JSB, Yadav and Seshadri, in Preparation).

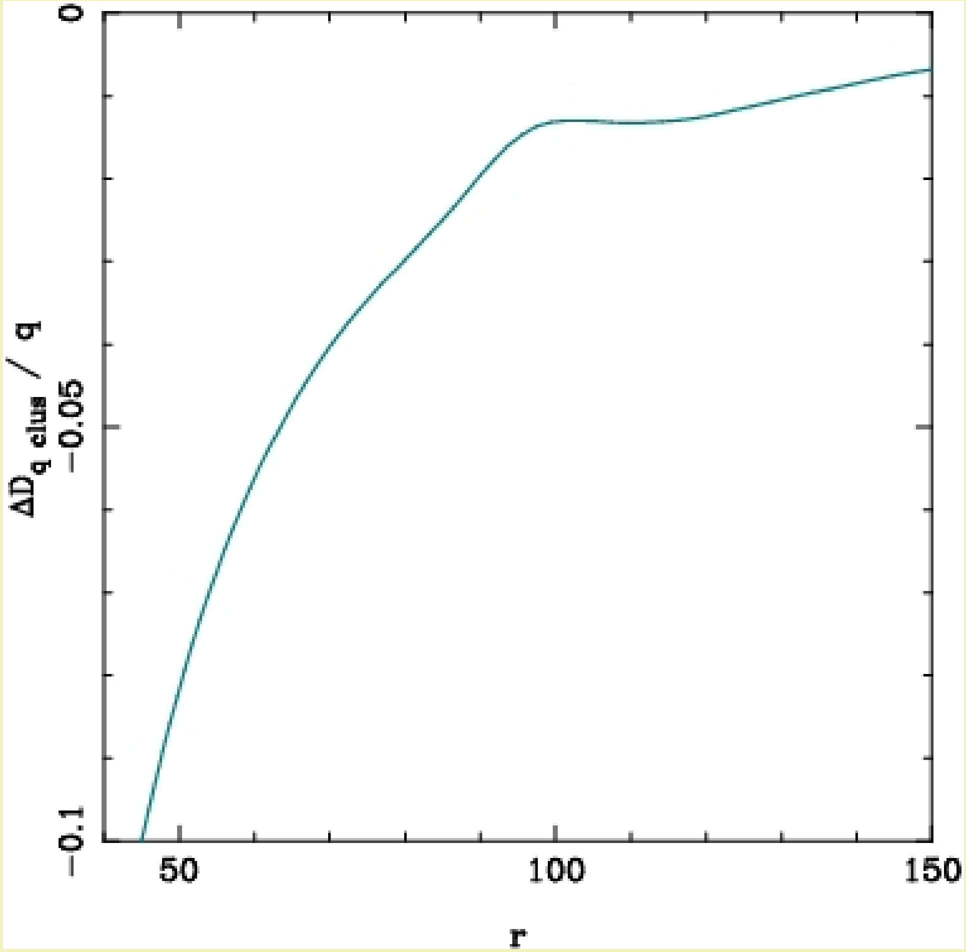

Figure 12: D_q for the best fit ΛCDM model. (JSB, Yadav and Seshadri, in Preparation)

Are different surveys consistent?

Given the wealth of data, we should also be able to check whether different surveys give consistent results. This is a good way to search for systematic effects OR for signatures of clustering at very large scales.

The clustering properties of galaxies in the 2dFGRS and SDSS differ by a small amount. The difference can be explained using variation of clustering with galaxy properties, and the different method of selecting galaxies for spectroscopy in the two surveys. (Cole et al, 2007)

Evolution of Large Scale Structures

The SDSS and the 2dFGRS probe clustering of galaxies at low redshifts ($z \leq 0.3$).

Several redshift surveys are going on to probe the evolution of large scale structures with redshift. These include:

The GOODS survey ($2 \leq z \leq 5$).

The VLT Virmos Deep Survey ($0.5 \leq z \leq 5$).

The COSMOS Survey.

The DEEP survey ($z/geq0.7$).

Evolution of Large Scale Structures

Many of these surveys will deliver multi-wavelength data for a large fraction of the objects, making it possible to model galaxy evolution as well as evolution of clustering.

Data from almost all the surveys will be available in the public domain within a few years of it being collected. This offers us an exciting possibility of working with good quality data.

Summary

Completed and ongoing redshift surveys of galaxies have given us considerable information about large scale structures.

For the first time, it is becoming possible to measure the power spectrum from galaxy surveys and CMB observations at the same scales.

With public availability of data, and no dearth of issues to explore, this is an exciting area to work in.