Cume: #400

Passing grade for the cume is 70 points

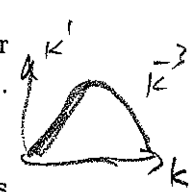
1. **20pt** Two flat cosmological models at redshift $z = 0$ have the same Hubble constant and the same spectrum and amplitude of perturbations. One model has a cosmological constant $\Omega_\Lambda = 0.7$, another does not have the cosmological constant ($\Omega_\Lambda = 0$). Which model predicts more clusters of galaxies at redshift 1?

   Answer: The number-density of clusters of galaxies depends on the amplitude of perturbations on cluster scales: the larger the amplitude, the larger is the number of clusters to form. Thus, the model, which predicts the largest amplitude of perturbations, is the model with more clusters. In turn, the growth-rate of perturbations $\delta(a)$ depends on the density of matter $\Omega_{\rm matter}(a)$, where $a = 1/(1+z)$ is the expansion parameter. For the plain-vanilla cosmological model (a) $\delta(a) \propto a$. This is the fastest growth possible. In the LCDM the fraction of mass in matter was declining with time resulting in slowing down the growth of perturbations. Once models are normalized to the same amplitude of perturbations at $z = 0$, the model with the cosmological constant will have the largest $\Omega_{\rm matter}$ at $z = 1$, the largest amplitude of perturbations, and, thus, the largest abundance of clusters of galaxies.

2. **20pt** The plot on the first page (#1) shows the power spectrum of density fluctuations in the Universe $P(k)$. The full curve is the LCDM theory and symbols are observations. Note that the axes have funny units. The comoving wave number k is in units of h/Mpc and the power spectrum is in units of $(h^{-1}Mpc)^{-3}$. Masses are typically presented in units of mass $h^{-1}M_\odot$. Here h is the Hubble constant in units of 100 km/s/Mpc. Explain why each of the measured quantities of $P(k)$, mass, and wavenumbers scale with the Hubble constant in this way.

   Answer: This is all about measuring distances using the Hubble flow: $V = Hr$. The recession velocity is measured observationally, and it does depend on H. We then get the distance $R = V/H \propto h^{-1}$. If mass of an astronomical object is measured dynamically, it scales as $M \propto v^2R/G$, where v is a measure of random velocities in the object and R is its radius. Then v is measured observationally (e.g., los velocities in groups of galaxies, or temperature of gas in clusters of galaxies).Then, $M \propto R \propto h^{-1}$. Wavenumber is $k = 2\pi/\lambda \propto h$. The power spectrum $P(k)$ is defined in units of inverse volume. Thus, the scaling is $P \propto h^3$

3. **10pt** Plot #1 shows only a fraction of all wavenumbers. Draw a diagram of the power spectrum from very low wavenumbers (very long wavelengths) to very large wavenumbers. Indicate slopes $d\log P/d\log k$ of the power spectrum on long and short waves.



4. **20pt** Figure #2 on the second page shows the correlation function of galaxies $\xi(r)$ for galaxies similar to our Milky Way. As you can see, it is reasonably well approximated by a power low on scales from 100 kpc to 20 Mpc. Using these results and assuming that the number-density of galaxies is $n = 10^{-2}h^3Mpc^{-3}$, estimate the average number of galaxies inside a sphere of radius $R = 10h^{-1}Mpc$ for (a) randomly selected point in space and (b) randomly

selected galaxy. To make calculations easier, assume that the correlation function is equal to $\xi(r) = (r/5h^{-1}Mpc)^{-1.8}$.

Answer: For randomly selected point in space the number expected galaxies is simply $N = nV \approx 40$. By definition, the correlation function ξ is the number of galaxies in excess of random at distance r: $dN = n(1 + \xi(r))dV$. The total number of galaxies inside radius R is just an integral: $N = 4\pi n \int_0^{10}(1+\xi)r^2dr$. We already found the first contribution to this integral. The contribution due to ξ is $4\pi n5^3(10/5)^{1.2} \approx 30$. So the total number of galaxies is 70.

5. **20pt** Correlation functions are measured in redshift space with the coordinate along the line of sight being $r = V_{\rm los}/H$, where $V_{\rm los}$ is the line-of-sight velocity. This leads to distortions in the correlation function and power spectrum. You can see manifestations of these redshift distortions in Fig #3 and #4, which show two-dimensional correlation function $\xi(\sigma, \pi)$, where σ is the distance between a pair of galaxies in the plane of the sky and π is the distance along the line of sight. Without distortions contours of constant ξ should be circles, and they are clearly not circles in the plots. (a) What is the nature of these distortions? (b) There are two physical processes that produce those distortions. Name and explain those.

   Answer: The origin of the redshift distortions is in the fact that galaxies do not move in perfect Hubble flow but have some deviations called peculiar velocities $V_{\rm peculiar}$. The true velocity along line-of-sight is $V = Hr + V_{\rm peculiar}$. In observations we do not know how large is the peculiar velocity. This gives an error in the distance: $s = r + V_{\rm peculiar/H}$, where s is the redshift space distance. There are two sources of the peculiar velocities. On large scales (> 2Mpc) galaxies experience infall on large forming clusters and superclusters. This results in negative relative peculiar velocities, which, in turn, makes s smaller than r. In figure #3 this is observed as flattening of contours of $\xi(\sigma, \pi)$ at 10-20Mpc distances. At small distances the dominant process is called the "finger-of-god" effect. It is related with large random peculiar velocities of galaxies in virialized objects such as clusters and groups of galaxies. These large random velocities produce large deviations along the line-of-sight at distances < 2Mpc.

6. **10pt** Figure #4 on the 4-th page shows the 2-dimensional correlation function $\xi(\sigma, \pi)$ for blue and for red galaxies. There is a striking difference between those at small distances $\sigma < 2h^{-1}Mpc$. Please, explain these differences.

   Answer: In dense virialized object galaxies tend to be early-type ellipticals or S0's. Thus, when we select red galaxies, we preferentially select galaxies inside dense environments where peculiar velocities are larger. This produces significantly stronger elongation of $\xi(\sigma, \pi)$ along the line-of-sight.

1

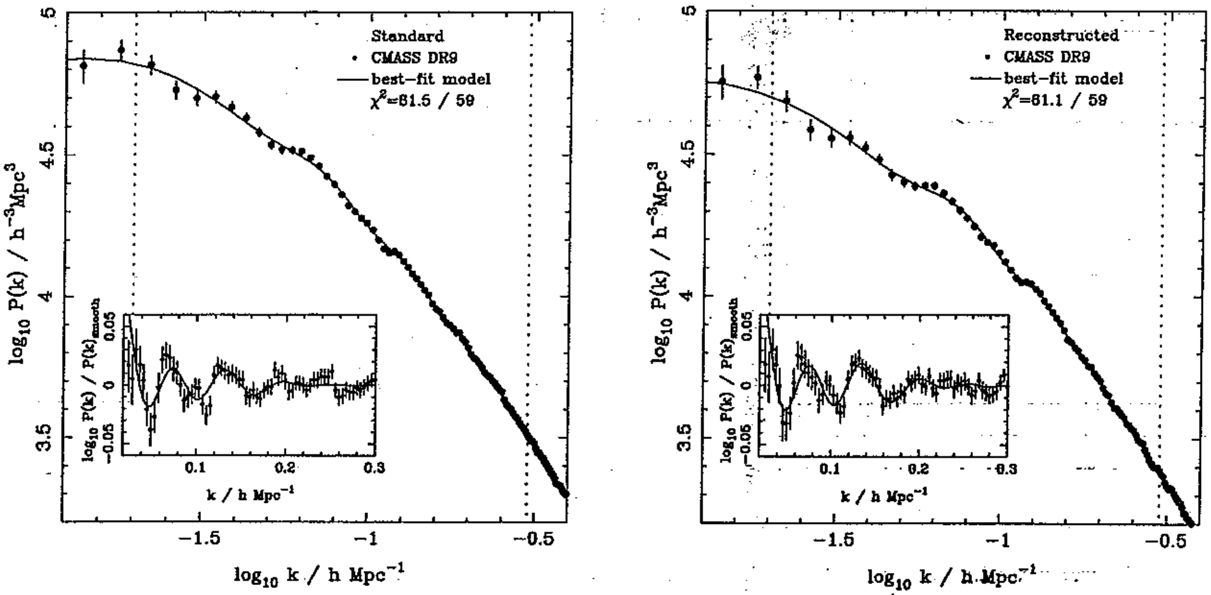


Figure 8. The CMASS DR9 power spectra before (left) and after (right) reconstruction with the best-fit models overplotted. The vertical dotted lines show the range of scales fitted ($0.02 < k < 0.3\,h\,\mathrm{Mpc}^{-1}$), and the inset shows the BAO within this k-range, determined by dividing both model and data by the best-fit model calculated (including window function convolution) with no BAO. Error bars indicate $\sqrt{C_{ii}}$ for the power spectrum and the rms error calculated from fitting BAO to the 600 mocks in the inset (see Section 4.2 for details).

2

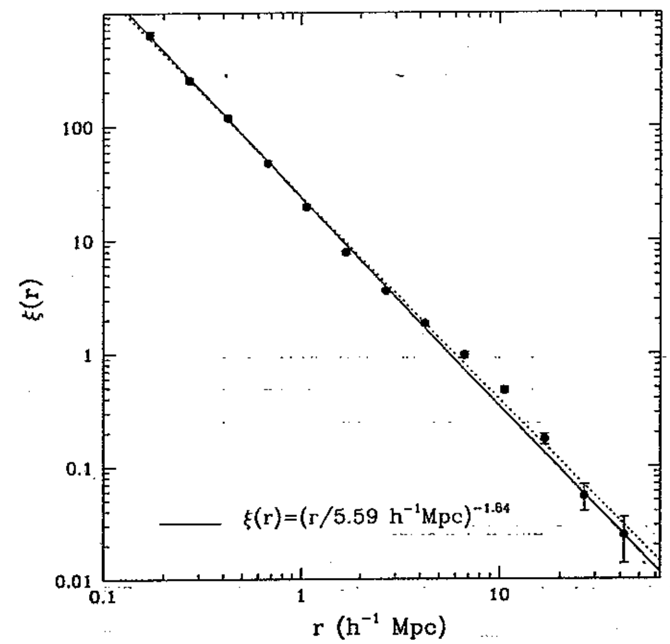


FIG. 7.—Real-space correlation function $\xi(r)$ for the flux-limited galaxy sample, obtained from $w_p(r_p)$ as discussed in the text. The solid and dotted lines show the corresponding power-law fits obtained by fitting $w_p(r_p)$ using the full covariance matrix or just the diagonal elements, respectively.

3

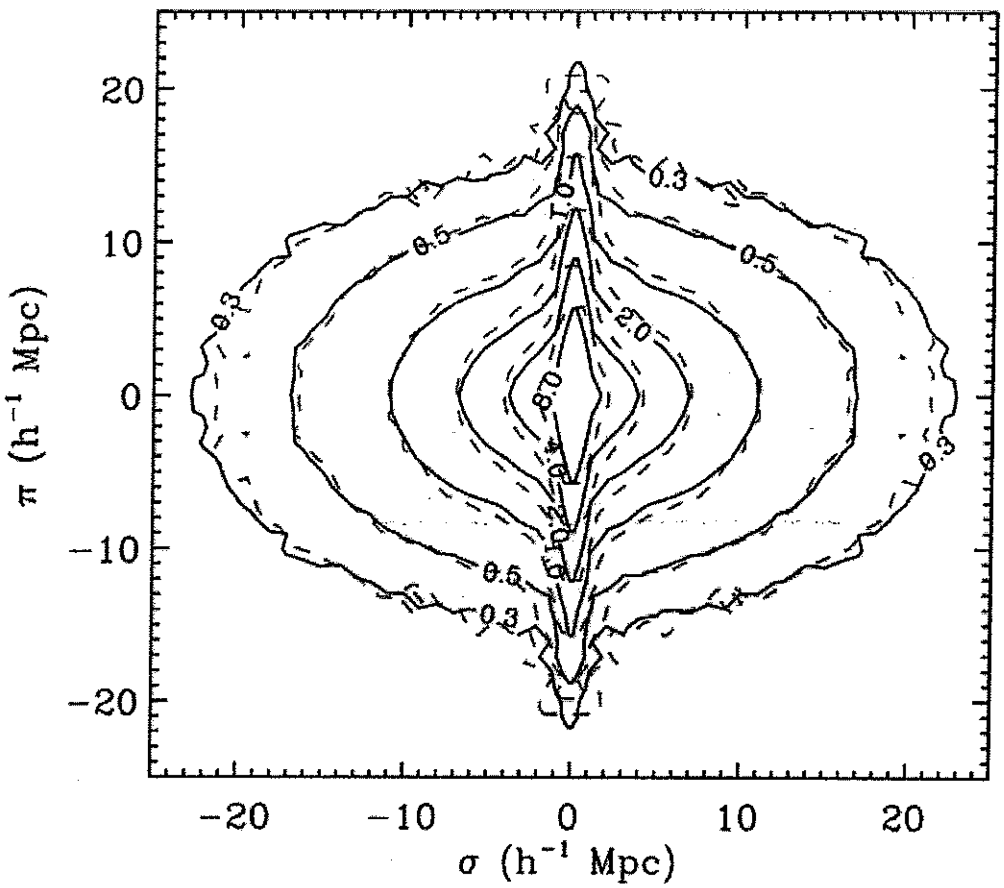


Figure 5. Contours of the two-dimensional correlation function $\xi(\sigma, \pi)$ estimated from the DR9 BOSS-CMASS north galaxy sample (dashed contours) at $0.4 < z < 0.7$ and for our MultiDark halo catalogue constructed using the HAM technique at $z = 0.53$ (solid contours).

Redshift distortions: 'finger-of-god' effect on small scales

4