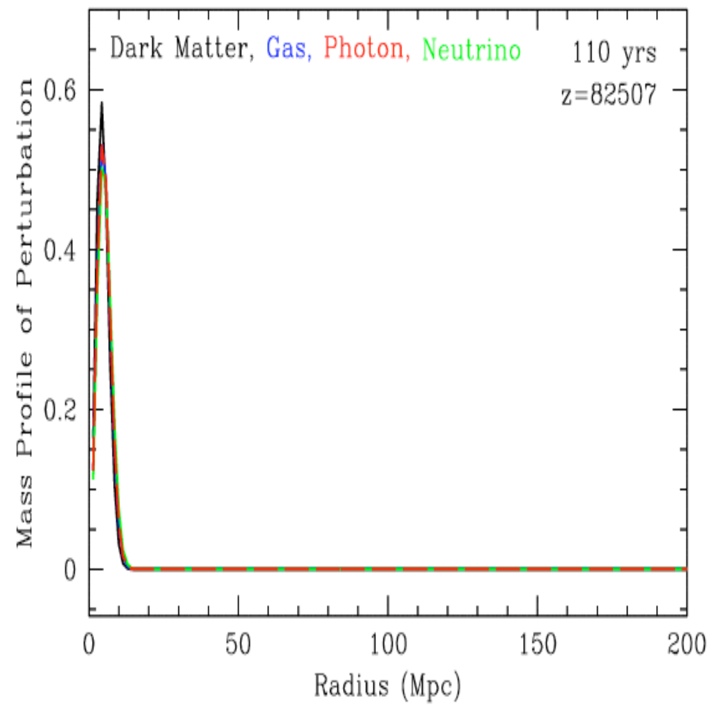
DETECTION OF THE BARYON ACOUSTIC PEAK IN THE LARGE-SCALE CORRELATION FUNCTION OF SDSS LUMINOUS RED GALAXIES

Eisenstein et al., APJ November 10, 2005

WHAT IS THE ACOUSTIC PEAK? – INITIAL DYNAMICS

- Assume Point-like initial perturbation
- The relevant components of the universe are the dark matter, the gas (nuclei and electrons), the cosmic microwave background photons, and the cosmic background neutrinos.
- The dark matter: moves only in response to gravity; no intrinsic motion (CDM). The perturbation (dominated by photons and neutrinos) is overdense - attracts the surroundings, causing more dark matter to fall towards the center.
- Baryons (gas) and photons are locked into a single fluid. The photons are so hot and numerous, that this combined fluid has an enormous pressure relative to its density. The initial overdensity is therefore also an initial overpressure. Result: expanding spherical sound wave.

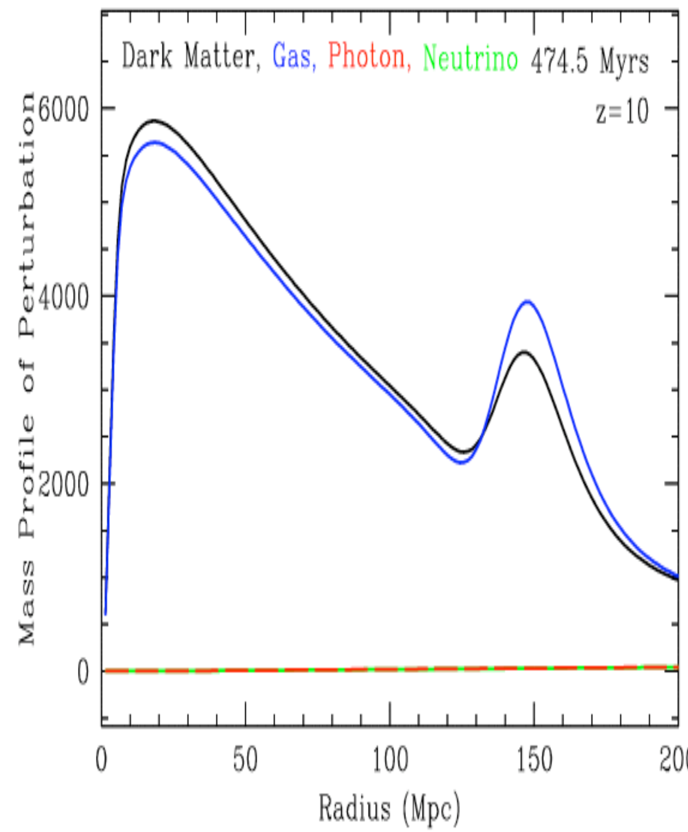


WITH TIME....

- Spherical shell of baryons (gas) and photons continues to expand. The neutrinos spread out. The dark matter collects in the overall density perturbation, which is now considerably bigger because the photons and neutrinos have left the center.
- The expanding universe is cooling. Around 400,000 years, electrons and nuclei begin to combine into neutral atoms. The photons do not scatter efficiently off of neutral atoms, so the photons begin to slip past the gas particles.
- The sound speed begins to drop because of the reduced coupling between the photons and gas and because the cooler photons are no longer very heavy compared to the gas. Hence, the pressure wave slows down.
- This continues until the photons have completely leaked out of the gas perturbation. The photon perturbation begins to smooth itself out at the speed of light (like the neutrinos). The photons travel (mostly) unimpeded until the present-day, where we can record them as the microwave background.

FINALLY…

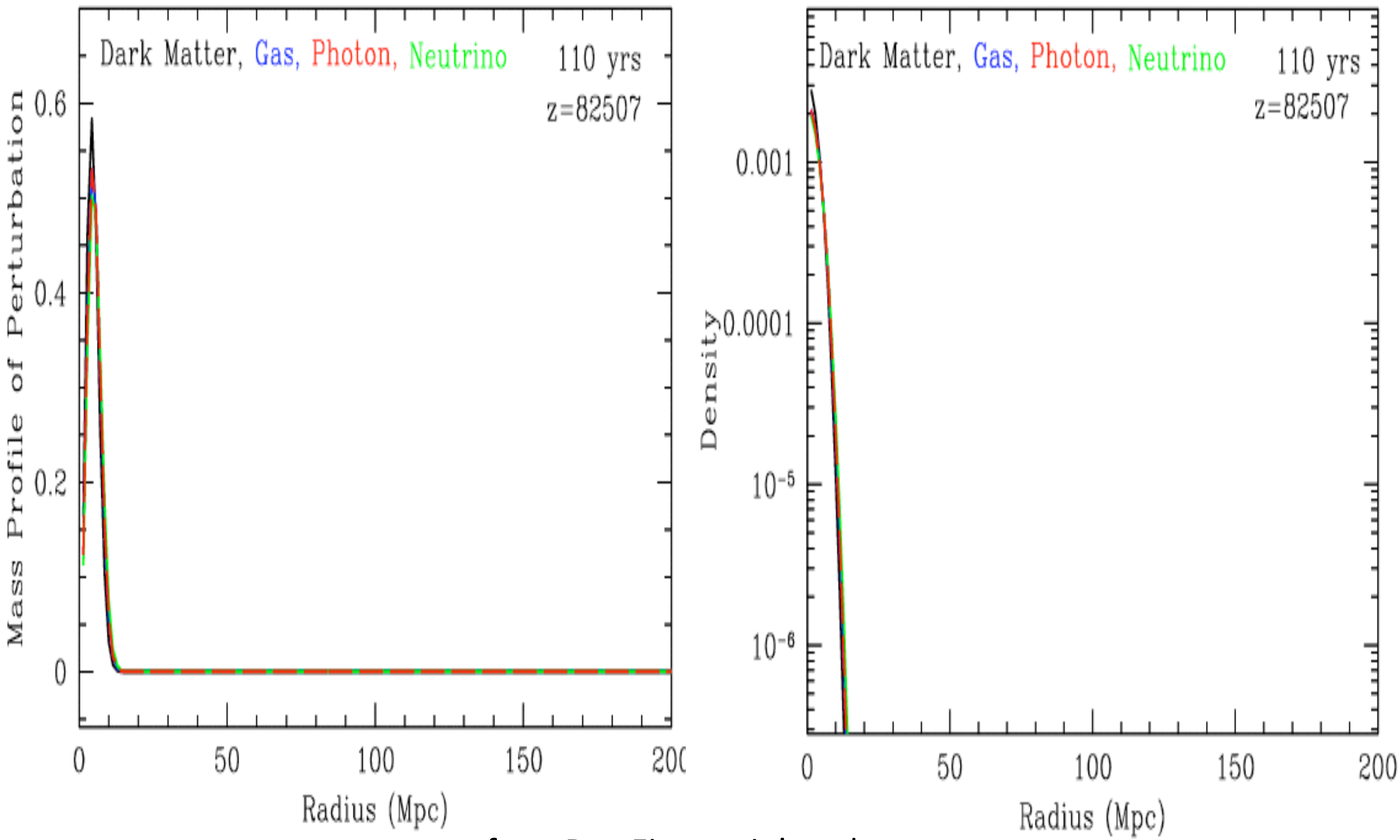
- We are left with a dark matter perturbation around the original center and a gas perturbation in a shell about 150 Mpc (500 million light-years) in radius.
- As time goes on, these two species gravitationally attract each other. The perturbations begin to mix together.
- Eventually, the two look quite similar. The spherical shell of the gas perturbation has imprinted itself in the dark matter. This is known as the acoustic peak.



AND FURTHER WITH TIME…

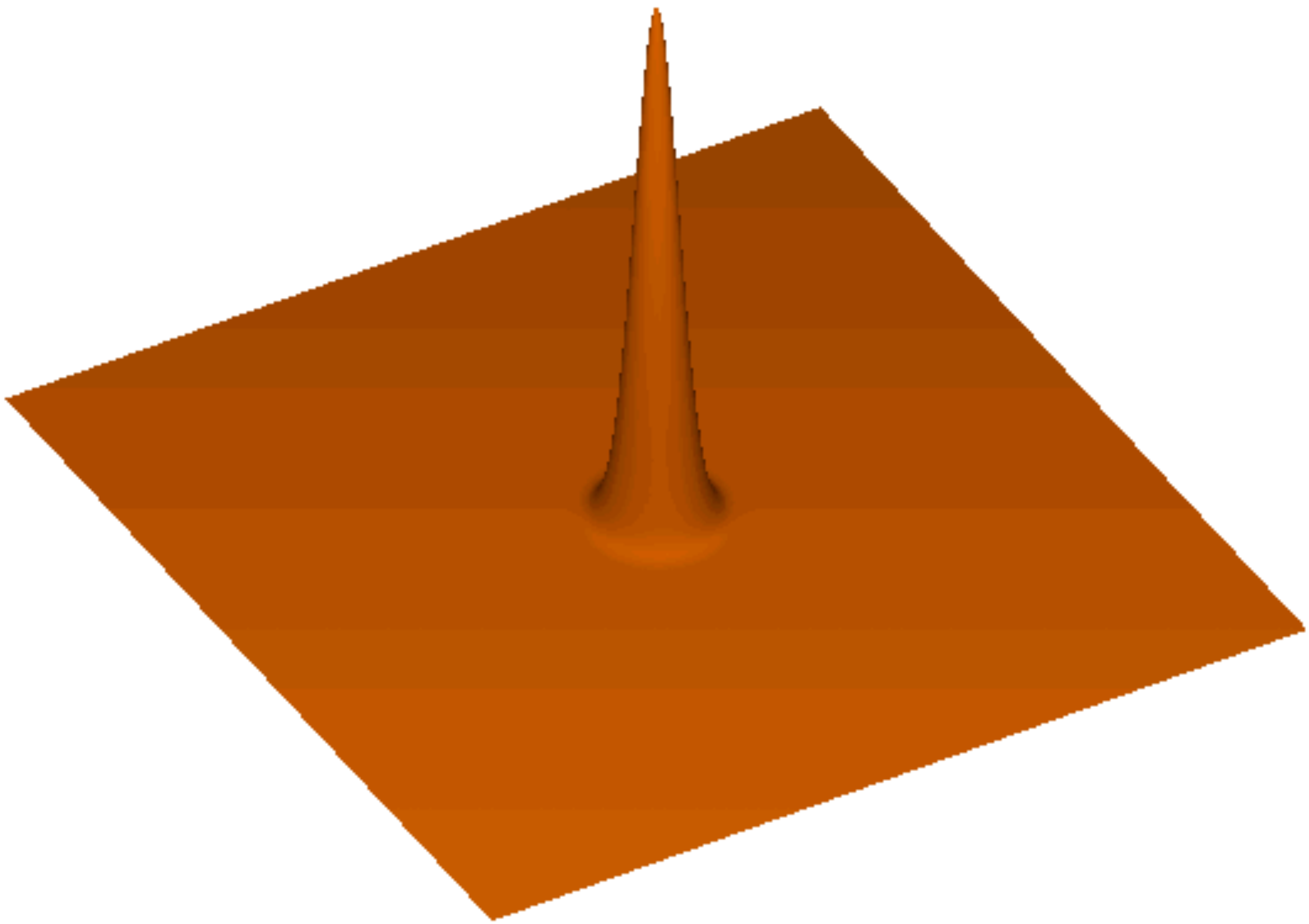
- At late times, galaxies form in the regions that are overdense in gas and dark matter. For the most part, this is driven by where the initial overdensities were, since we see that the dark matter has clustered heavily around these initial locations.
- However, there is a 1% enhancement in the regions 150 Mpc away from these initial overdensities. Hence, there should be an small excess of galaxies 150 Mpc away from other galaxies, as opposed to 120 or 180 Mpc. We can see this as a single *acoustic peak* in the correlation function of galaxies.
- Alternatively, if one is working with the power spectrum statistic, then one sees the effect as a series of *acoustic oscillations*.
- Acoustic features in matter correlations are weak in large scales – this paper presents large-scale correlation function from SDSS of 46,748 luminous red galaxies (LRGs) covering 3816 deg^2 out to a redshift of z=0.47.
- The first clear detection of acoustic peak at late times is presented.

MASS AND DENSITY PROFILES OF PERTURBATION

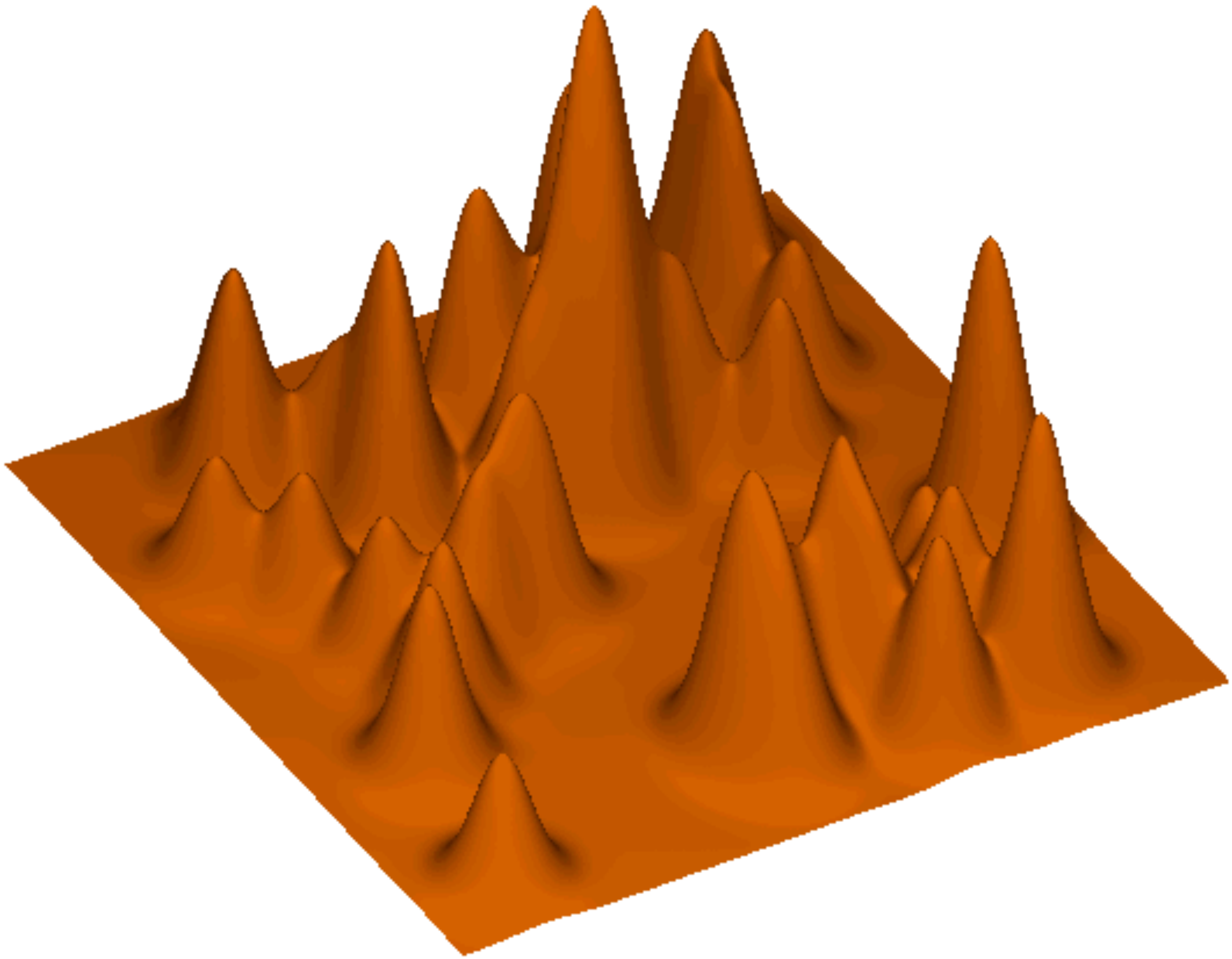


from Dan Eisenstein's web pages:
http://cmb.as.arizona.edu/~eisenste/acousticpeak/index.html

EXPANDING WAVES



EXPANDING WAVES



SDSS LRG SAMPLE

- Imaging in five passbands – u, g, r, i, z
- Primary sample – SDSS main sample – targets galaxies brighter than r=17.77, surface density of galaxies = 90 per sq. degree
- SDSS LRG selects ~ 12 additional galaxies per square degree, using color magnitude cuts in g, r , i to select galaxies to a magnitude r < 19.5 in z range 0.16-0.47.
- Performance of a survey is given by effective volume:

$$V_{\rm eff}(k) = \int d^3r \left[\frac{n(\boldsymbol{r})P(k)}{1+n(\boldsymbol{r})P(k)}\right]^2,$$

- n(r) is the comoving number density of the sample at every location r ; the effective volume is a function of the wavenumber k via the power amplitude P.

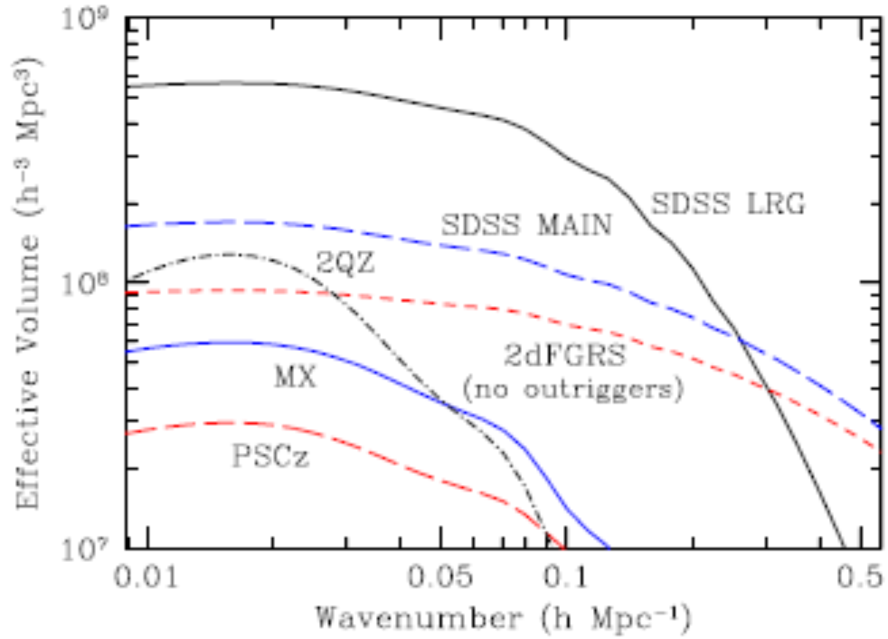


FIG. 1.— The effective volume (eq. [1]) as a function of wavenumber for various large redshift surveys. The effective volume is a rough guide to the performance of a survey (errors scaling as $V_{\rm eff}^{-1/2}$) but should not be trusted to better than 30%. To facilitate comparison, we have assumed 3816 square degrees for the SDSS Main sample, the same area as the SDSS LRG sample presented in this paper and similar to the area in Data Release 3. This is about 50% larger than the sample analyzed in Tegmark et al. (2004a), which would be similar to the curve for the full 2dF Galaxy Redshift Survey (Colless et al. 2003). We have neglected the potential gains on very large scales from the 99 outrigger fields of the 2dFGRS. The other surveys are the MX survey of clusters (Miller & Batuski 2001), the PSCz survey of galaxies (Sutherland et al. 1999), and the 2QZ survey of quasars (Croom et al. 2004a). The SDSS DR3 quasar survey (Schneider et al. 2005) is similar in effective volume to the 2QZ. For the amplitude of $P(k)$, we have used $\sigma_8 = 1$ for 2QZ and PSCz and 3.6 for the MX survey. We used $\sigma_8 = 1.8$ for SDSS LRG, SDSS Main, and the 2dFGRS; For the latter two, this value represents the amplitude of clustering of the luminous galaxies at the surveys' edge; at lower redshift, the number density is so high that the choice of σ_8 is irrelevant. Reducing SDSS Main or 2dFGRS to $\sigma_8 = 1$, the value typical of normal galaxies, decreases their $V_{\rm eff}$ by 30%.

REDSHIFT-SPACE CORRELATION FUNCTION

- Correlation function is computed using Landay-Szalay estimator: random catalogs w/ 16 times more galaxies than LRG sample
- Flat cosmology with $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$
- Each data point is placed in its comoving coordinate location based on its redshift and comoving separation between two points is measured using vector difference. Bins are used in separation of 4 h^{-1} Mpc from 10 to 30 h^{-1} Mpc and bins of 10 h^{-1} Mpc thereafter to 180 h^{-1} Mpc, for a total of 20 bins.
- Each galaxy and random point is weighted by $1/[1+n(z)P_w]$, where $n(z)$ is the comoving number density and $P_w = 40{,}000\ h^{-3}\ \mathrm{Mpc}^3$
- Spherically averaged correlation function is used to even out redshift distortions – four angular bins are used for this averaging.

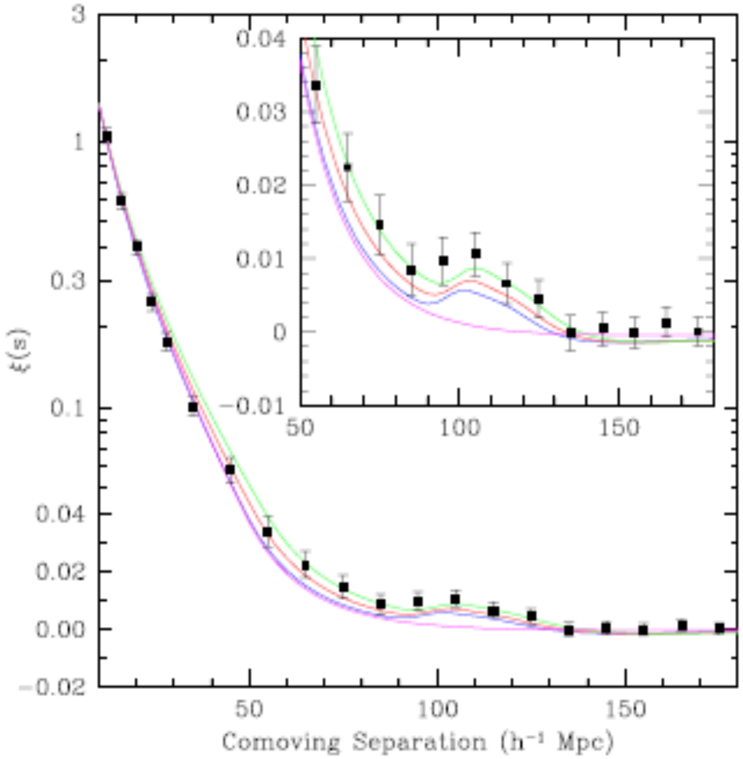


FIG. 2.— The large-scale redshift-space correlation function of the SDSS LRG sample. The error bars are from the diagonal elements of the mock-catalog covariance matrix; however, the points are correlated. Note that the vertical axis mixes logarithmic and linear scalings. The inset shows an expanded view with a linear vertical axis. The models are $\Omega_m h^2 = 0.12$ (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2 = 0.024$ and $n = 0.98$ and with a mild non-linear prescription folded in. The magenta line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak. It is interesting to note that although the data appears higher than the models, the covariance between the points is soft as regards overall shifts in $\xi(s)$. Subtracting 0.002 from $\xi(s)$ at all scales makes the plot look cosmetically perfect, but changes the best-fit χ^2 by only 1.3. The bump at $100h^{-1}$ Mpc scale, on the other hand, is statistically significant.

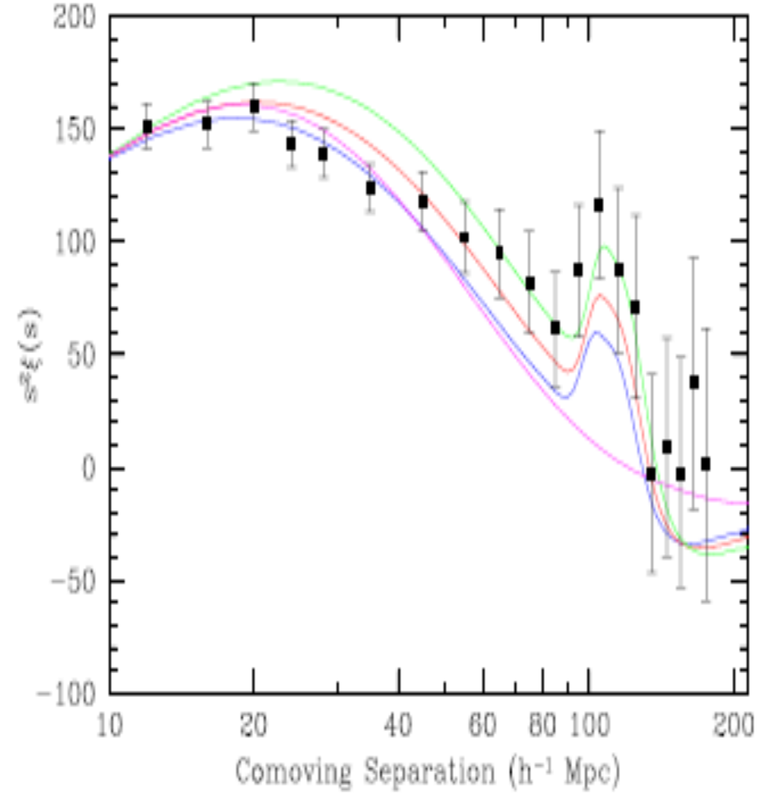


FIG. 3.— As Figure 2, but plotting the correlation function times s^2. This shows the variation of the peak at $20h^{-1}$ Mpc scales that is controlled by the redshift of equality (and hence by $\Omega_m h^2$). Varying $\Omega_m h^2$ alters the amount of large-to-small scale correlation, but boosting the large-scale correlations too much causes an inconsistency at $30h^{-1}$ Mpc. The pure CDM model (magenta) is actually close to the best-fit due to the data points on intermediate scales.

Measurements of Acoustic and Equality Scales

- Dilation scale $$D_V(z) = \left[D_M(z)^2 \frac{cz}{H(z)} \right]^{1/3}$$
- $H(z)$=Hubble parameter; $D_M(z)$=co-moving angular diameter distance
- Typical z of sample = 0.35
- For $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$, $D_V(0.35) = 1334$ Mpc
- WMAP data constrain $\Omega_b h^2 = 0.024$ and $n = 0.98$ well. Consider variations only in $\Omega_m h^2$

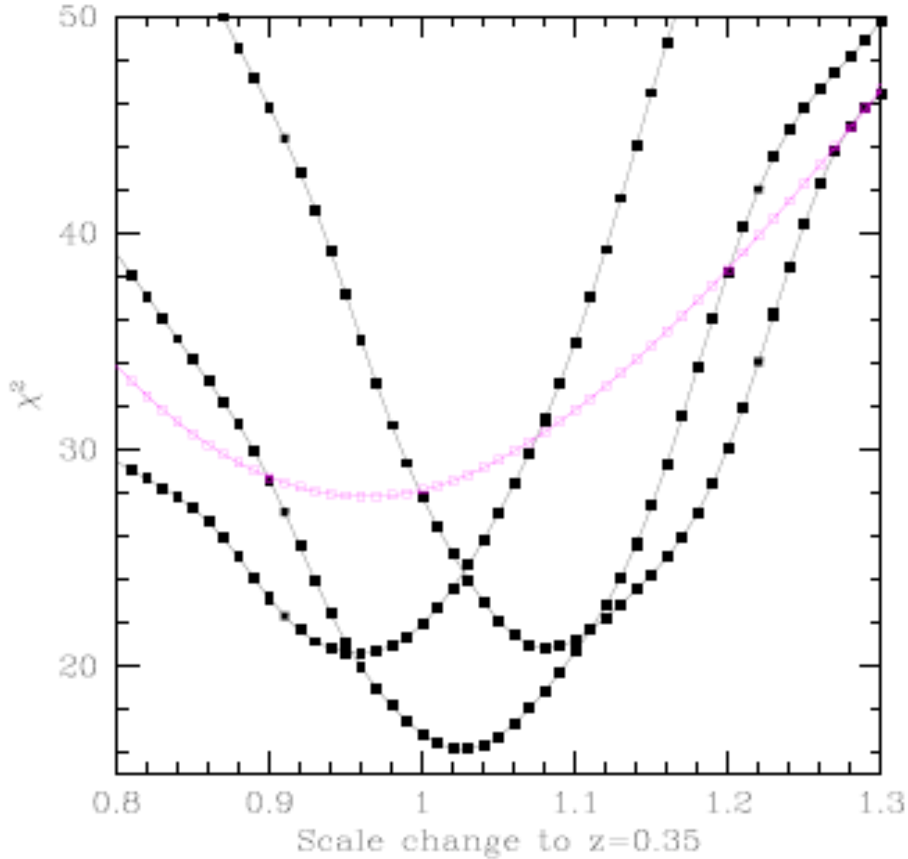


FIG. 6.— The χ^2 values of the models as a function of the dilation of the scale of the correlation function. This corresponds to altering $D_V(0.35)$ relative to the baseline cosmology of $\Omega = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.7$. Each line (save the magenta line) in the plot is a different value of $\Omega_m h^2$, 0.11, 0.13, and 0.15 from left to right. $\Omega_b h^2 = 0.024$ and $n = 0.98$ are used in all cases. The amplitude of the model has been marginalized over. The best-fit χ^2 is 16.1 on 17 degrees of freedom, consistent with expectations. The magenta line (open symbols) shows the pure CDM model with $\Omega_m h^2 = 0.10$; it has a best χ^2 of 27.8, which is rejected at 3.4 σ. Note that this curve is also much broader, indicating that the lack of an acoustic peak makes the scale less constrainable.

20 data points,
3 parameters - $\Omega_m h^2$, $D_V(0.35)$, amplitude => 17 degrees of freedom

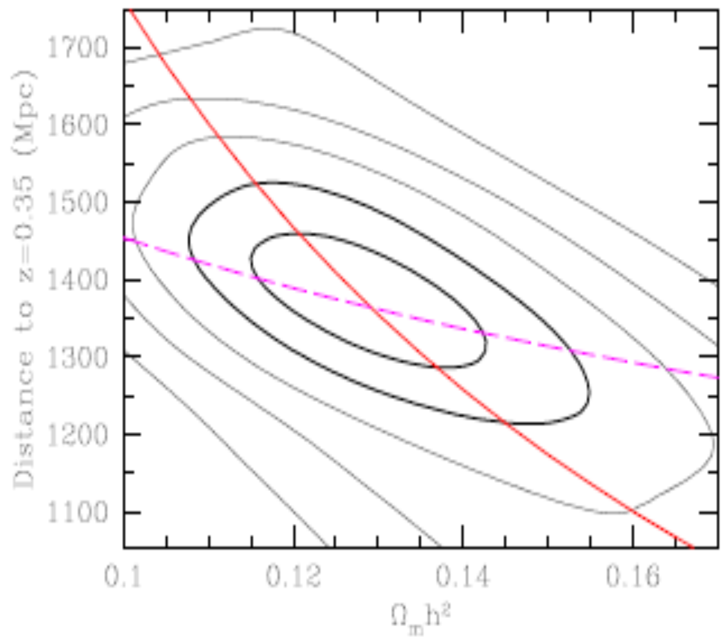


FIG. 7.— The likelihood contours of CDM models as a function of $\Omega_m h^2$ and $D_V(0.35)$. The likelihood has been taken to be proportional to $\exp(-\chi^2/2)$, and contours corresponding to 1 σ through 5 σ for a 2-d Gaussian have been plotted. The one-dimensional marginalized values are $\Omega_m h^2 = 0.130 \pm 0.010$ and $D_V(0.35) = 1370 \pm 64$ Mpc. We overplot lines depicting the two major degeneracy directions. The solid (red) line is a line of constant $\Omega_m h^2 D_V(0.35)$, which would be the degeneracy direction for a pure CDM model. The dashed (magenta) line is a line of constant sound horizon, holding $\Omega_b h^2 = 0.024$. The contours clearly deviate from the pure CDM degeneracy, implying that the peak at $100h^{-1}$ Mpc is constraining the fits.

- Solid line denotes the matter-radiation equality scale at a constant apparent location

- Dashed line holds constant sound horizon divided by distance.
This is the apparent location of acoustic scale

- The long axis of the contours falls between these two scales; since neither direction is degenerate, both equality and acoustic scales have been detected.

PARAMETER CONSTRAINTS FROM LRGs

- Most of distance leverage comes from acoustic scale – most robust distance measurement is ratio of distance to z=0.35 to distance to z=1089
- For $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, h = 0.7;

$$R_{0.35} \equiv \frac{D_V(0.35)}{D_M(1089)}.$$

TABLE 1

SUMMARY OF PARAMETER CONSTRAINTS FROM LRGs

Parameter	Constraint
$\Omega_m h^2$	$0.130(n/0.98)^{1.2} \pm 0.011$
$D_V(0.35)$	1370 ± 64 Mpc (4.7%)
$R_{0.35} \equiv D_V(0.35)/D_M(1089)$	0.0979 ± 0.0036 (3.7%)
$A \equiv D_V(0.35)(\Omega_m H_0^2)^{1/2}/0.35c$	$0.469(n/0.98)^{-0.35} \pm 0.017$ (3.6%)

NOTES.—We assume $\Omega_b h^2 = 0.024$ throughout, but variations permitted by *WMAP* create negligible changes here. We use $n = 0.98$, but where variations by 0.1 would create 1 σ changes, we include an approximate dependence. The quantity A is discussed in § 4.5. All constraints are 1 σ.

INTRODUCING DARK ENERGY COMPONENT

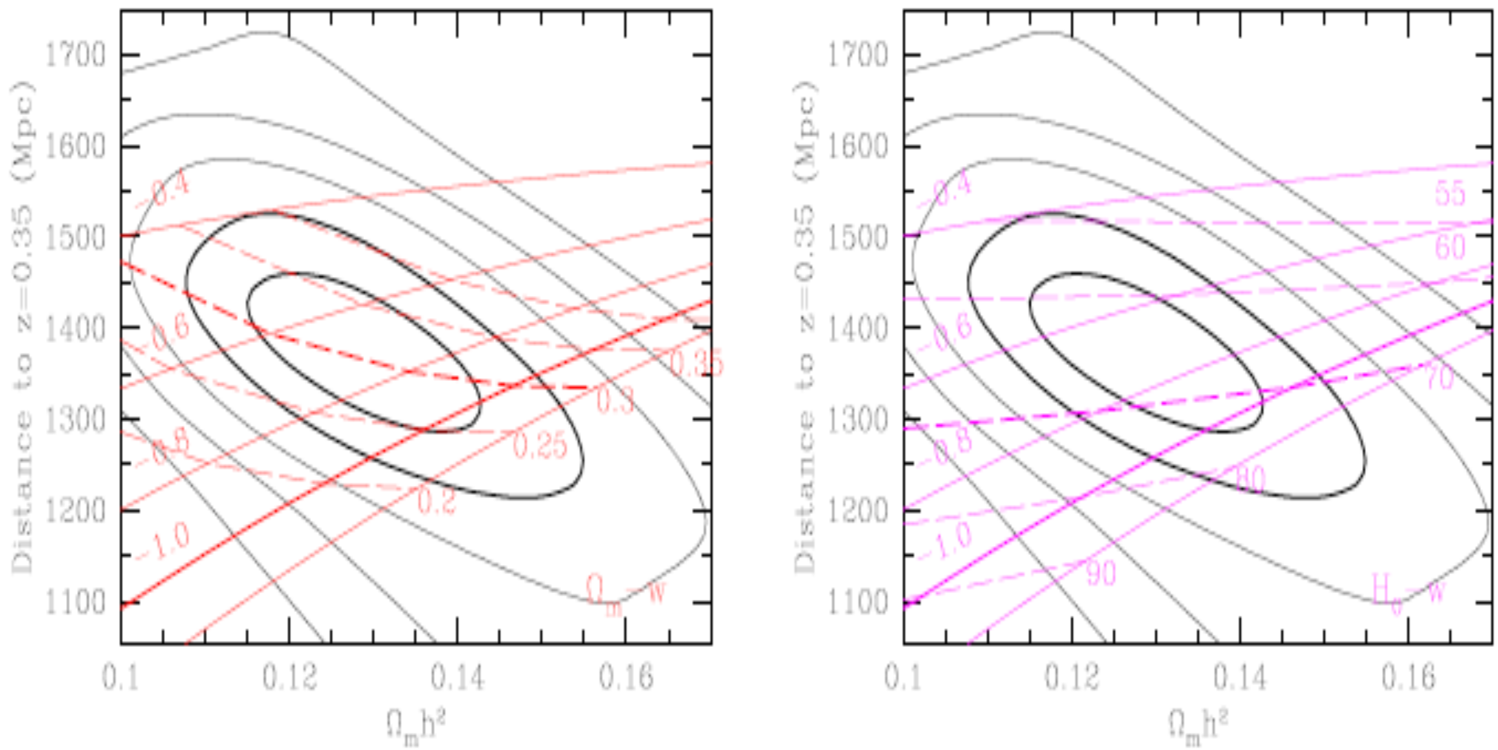


FIG. 10.— a) As Figure 7, but overplotted with model predictions from constant w flat models. For a given value of $\Omega_m h^2$ and w, the angular scale of the CMB acoustic peaks (known to 1%) determines Ω_m and H_0. Of course, the required Ω_m is a function of w and $\Omega_m h^2$. The solid red lines show lines of constant w; the dashed lines show lines of constant Ω_m. Our knowledge of $\Omega_m h^2$ still limits our inference of w. b) As (a), but the dashed lines are now lines of constant H_0.

TABLE 2

JOINT CONSTRAINTS ON COSMOLOGICAL PARAMETERS INCLUDING CMB DATA

PARAMETER	CONSTANT w, FLAT		$w = -1$, CURVED		$w = -1$, FLAT	
	WMAP+Main	+LRG	*WMAP*+Main	+LRG	*WMAP*+Main	+LRG
w	-0.92 ± 0.30	-0.80 ± 0.18	...	...	...	...
Ω_K	...	...	-0.045 ± 0.032	-0.010 ± 0.009	...	...
$\Omega_m h^2$	0.145 ± 0.014	0.135 ± 0.008	0.134 ± 0.012	0.136 ± 0.008	0.146 ± 0.009	0.142 ± 0.005
Ω_m	0.329 ± 0.074	0.326 ± 0.037	0.431 ± 0.096	0.306 ± 0.027	0.305 ± 0.042	0.298 ± 0.025
h	0.679 ± 0.100	0.648 ± 0.045	0.569 ± 0.082	0.669 ± 0.028	0.696 ± 0.033	0.692 ± 0.021
n	0.984 ± 0.033	0.983 ± 0.035	0.964 ± 0.032	0.973 ± 0.030	0.980 ± 0.031	0.963 ± 0.022

NOTES.—Constraints on cosmological parameters from the Markov chain analysis. The first two data columns are for spatially flat models with constant w, while the next two are for $w = -1$ models with spatial curvature. In each case, the other parameters are $\Omega_m h^2$, $\Omega_b h^2$, n_s, h, and the optical depth τ (which we have required to be less than 0.3). A negative Ω_K means a spherical geometry. The mean values are listed with the 1 σ errors. The first column in each set gives the constraints from Tegmark et al. (2004b) from combining *WMAP* and the SDSS main sample. The second column adds our LRG constraints: $R_{0.35} = 0.0979 \pm 0.036$ and $\Omega_m h^2 = 0.130(n/0.98)^{-1.2} \pm 0.011$. In all cases, $\Omega_b h^2$ is constrained by the CMB to an accuracy well below where we would need to include variations in the LRG analysis.

$$\Omega_m = 0.273 + 0.123(1 + w_0) + 0.137\Omega_K \pm 0.025.$$