REGARDING THE LINE-OF-SIGHT BARYONIC ACOUSTIC FEATURE IN THE SLOAN DIGITAL SKY SURVEY AND BARYON OSCILLATION SPECTROSCOPIC SURVEY LUMINOUS RED GALAXY SAMPLES

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ABSTRACT

We analyze the line-of-sight baryonic acoustic feature in the two-point correlation function $\xi$ of the Sloan Digital Sky Survey luminous red galaxy (LRG) sample (0.16 < z < 0.47). By defining a narrow line-of-sight region, $r_p < 5.5 \, h^{-1} $ Mpc, where $r_p$ is the transverse separation component, we measure a strong excess of clustering at $\sim 110 \, h^{-1} $ Mpc, as previously reported in the literature. We also test these results in an alternative coordinate system, by defining the line of sight as $ \theta < 3^\circ$, where $ \theta $ is the opening angle. This clustering excess appears much stronger than the feature in the better-measured monopole. A fiducial Λ CDM nonlinear model in redshift space predicts a much weaker signature. We use realistic mock catalogs to model the expected signal and noise. We find that the line-of-sight measurements can be explained well by our mocks as well as by a featureless $\xi = 0$. We conclude that there is no convincing evidence that the strong clustering measurement is the line-of-sight baryonic acoustic feature. We also evaluate how detectable such a signal would be in the upcoming Baryon Oscillation Spectroscopic Survey (BOSS) LRG volume. Mock LRG catalogs ($z < 0.6$) suggest that (1) the narrow line-of-sight cylinder and cone defined above probably will not reveal a detectable acoustic feature in BOSS; (2) a clustering measurement as high as that in the current sample can be ruled out (or confirmed) at a high confidence level using a BOSS-sized data set; (3) an analysis with wider angular cuts, which provide better signal-to-noise ratios, can nevertheless be used to compare line-of-sight and transverse distances, and thereby constrain the expansion rate $H(z)$ and diameter distance $D_A(z)$.

Key words: cosmology: observations – distance scale – galaxies: elliptical and lenticular, cD – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

The baryonic acoustic feature serves as an important tool for our understanding of the evolution of the universe (Peebles & Yu 1970). Originating from plasma sound-wave residuals that came to a near stop at the end of the baryon drag epoch ($z_d \sim 1010$), it has the potential to serve as a cosmic standard ruler, which, in turn, can help us measure the expansion of the universe (Hubble & Humason 1931, Blake & Glazebrook 2003; Seo & Eisenstein 2003; Hu & Haiman 2003; Linder 2003; Glazebrook & Blake 2005).

In galaxy clustering measurements, this feature is a peak of over-density at separations of $s \sim 100 \, h^{-1} $ Mpc in the two-point correlation function $\xi$, which results in an oscillatory feature in the power spectrum $P(k)$.

Eisenstein et al. (2005) were the first to detect this feature, using the clustering of ~44,000 luminous red galaxies (LRGs) from the Sloan Digital Sky Survey (SDSS; York et al. 2000). (Though see Miller et al. 2001 for “possible” detection using smaller volumes.) Their measurement of the angle-averaged $\xi$, which is commonly referred to as the monopole, has the power to constrain a combination of the Hubble expansion rate $H(z)$ and the angular diameter distance $D_A(z)$.

To measure $H$ and $D_A$ separately, one would like to probe the baryonic acoustic feature independently along the line of sight and transverse directions (Matsumura 2004). Measurements of these potentially promising methods are currently strongly compromised by shot noise and sample variance limitations, due to the large-scale nature of the feature. For this reason, most studies have focused on measuring and analyzing the baryonic acoustic feature in the angle averaged $\xi$ (Martinez et al. 2009; Cabré & Gaztañaga 2009; Labini et al. 2009; Sanchez et al. 2009; Kazin et al. 2010), $P(k)$ (Cole et al. 2005; Tegmark et al. 2006; Hütsi 2006; Percival et al. 2007, 2010; Reid et al. 2010), and the projected two-point function of photo-$z$ samples (Padmanabhan et al. 2007; Blake et al. 2007) in the SDSS and Two Degree Field Galaxy Redshift Survey (Colless et al. 2003) galaxy samples.

Gaztañaga et al. (2009, hereafter referred to as GCH), however, claim to have measured the line-of-sight baryonic acoustic feature. Using ~77,000 LRGs from the SDSS Data Release 6 (DR6; Adelman-McCarthy et al. 2008) and ~100,000 from DR7 (Abazajian et al. 2009) they report a significant detection of a feature at $\pi \sim 110 \, h^{-1} $ Mpc in the line-of-sight direction, within a projected distance of $r_p < 5.5 \, h^{-1} $ Mpc.

The clustering excess they focus on appears much stronger than expected from the baryonic acoustic feature according to the concordance Λ CDM model. The galaxies are observed in redshift space, as opposed to real-comoving space. In redshift space ($z$-space) the line-of-sight peak in the nonlinear correlation function is expected to smear heavily due to velocity dispersion. Furthermore, most of the correlation function should appear negative due to the strong squashing effect (Kaiser 1987) at scales $s > 50 \, h^{-1} $ Mpc in the line-of-sight direction. The peak of the feature might be positive (though very weak) depending on the squashing effect.

These predictions suggest that if the sharp strong positive measurement obtained by GCH is the real feature, it would require a physical explanation.

Magnification bias has been proposed to increase clustering on all scales. This effect results from gravitational lensing modifying the spacial distribution of high redshift objects...
In Table 1, we summarize the different volumes discussed in this study.

### 2. DATA AND METHODS OF ANALYSIS

Here, we briefly present the SDSS LRGs as well as mock realizations used for testing systematics and measurement uncertainties. In-depth descriptions of the data and mock catalogs used here, as well of methods of analysis, are given in our previous study of the monopole (Kazin et al. 2010).

#### 2.1. SDSS-II LRGs

We use the LRG sample from the final release (DR7) of the SDSS.

In what follows, DR7-Full is defined as the full range of the SDSS LRG sample (0.16 < z < 0.47). We also define a subsample DR7-Sub, which focuses on the quasi-volume-limited region (z < 0.36; see Figures 1 and 2 in Kazin et al. 2010, in which the latter is called there DR7-Dim). We calculate ξ by using the Landy & Szalay (1993) estimator, which requires the use of a catalog of random points. For DR7-Full we use 15 random points for each LRG and for DR7-Sub we use 50.

The LRG data set and random points used here are accessible on the World Wide Web.4

#### 2.2. Mock LRGs

To predict ξ and its uncertainties in three different volumes (DR7-Sub, DR7-Full, and BOSS), we make use of mock realizations for each volume. For DR7-Sub we use mocks provided by the LasDamas Collaboration (C. K. McBride et al. 2010, in preparation), and for the other two samples we use mocks generated by the Horizon Run (Kim et al. 2009).

The LasDamas simulations use a cosmology of \([\Omega_0, \Omega_{b0}, n_s, h, \sigma_8] = [0.25, 0.041, 0.7, 0.8] \) and the Horizon Run uses \([0.26, 0.044, 0.96, 0.72, 0.8] \), where \(\Omega_0 \) is the present baryonic density and \(n_s \) is the spectral index. Both these cosmologies are well motivated by constraints obtained by WMAP 5-year measurements of temperature fluctuations in the cosmic microwave background (Komatsu et al. 2009).

The LasDamas Collaboration provides very realistic LRG mock catalogs by placing galaxies inside dark matter halos using a Halo Occupation Distribution (HOD; Berlind 

#### Table 1

| Sample   | No. of LRGs | \(z_{\text{min}}\) | \(z_{\text{max}}\) | \(\langle z \rangle\) | \(M_{g,\text{min}}\) | \(M_{g,\text{max}}\) | \(\langle M_g \rangle\) | Area (deg\(^2\)) | Volume (h\(^{-3}\) Gpc\(^3\)) | Density (10\(^{-5}\) h\(^3\) Mpc\(^{-3}\)) |
|----------|-------------|---------------------|---------------------|-----------------------|----------------------|----------------------|-----------------------|------------------|-------------------|---------------------|
| DR7-Sub  | 61899       | 0.16                | 0.36                | 0.278                 | -23.2                | -21.2                | -21.65                | 7189             | 0.66              | 9.4                 |
| DR7-Full | 105831      | 0.16                | 0.47                | 0.324                 | -23.2                | -21.2                | -21.72                | 7908             | 1.58              | 6.7                 |
| BOSS\(^a\) | 12000000    | 0.16                | 0.60                | 0.444                 | ···                  | ···                  | ···                   | 10000            | 3.89              | 30.8                |

Note. \(^a\) For BOSS we present estimates for 0.16 < z < 0.6. The survey intends to observe z < 0.8 (8.1 h\(^{-3}\) Gpc\(^3\)) but the comoving number density is expected to fall sharply at z > 0.6.

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3 DR7-Sub (DR7-Dim) is not a dimmer sample of galaxies than DR7-Full, but a subsample limited by \(z < 0.36\). The term “dim” was used in our previous study to distinguish from a brighter overlapping subsample of DR7-Full.

4 http://cosmo.nyu.edu/~eak306/SDSS-LRG.html

5 http://lss.phy.vanderbilt.edu/lasdamas/
space catalog is similar to the redshift-space catalog in all aspects, except the shift in $z$ due to peculiar velocities. Another small difference is that we do not mock the observed comoving density $n(z)$ by diluting the original mock sample, but use the whole real-space catalog. In Appendix A.2 and Figure 13 of Kazin et al. (2010), we discuss the negligible differences between a sample with the observed $n(z)$ to that originally provided by LasDamas. For both redshift and real space, we use a ratio of $\sim 50$ random points for each mock data.

The Horizon Run\(^6\) provides a catalog of 32 BOSS volume realizations of mock LRGs with a higher number density than DR7, as expected in BOSS ($n \sim 3 \times 10^{-4} h^3$ Mpc$^{-3}$ in BOSS, which drops quickly after $z \sim 0.6$, versus $\sim 0.9 \times 10^{-4} h^3$ Mpc$^{-3}$ in DR7-Sub). LRG positions are determined by identifying physically self-bound dark matter sub-halos that are not tidally disrupted by larger structures. Our only manipulations of the real-space catalogs are to divide each of their eight full sky realizations into four quadrants each to map real space into redshift space, and to limit the samples to the expected volume-limited region of the BOSS LRGs ($0.16 < z < 0.6$). This results in 8 $\times$ 4 = 32 BOSS mock realizations. For the BOSS volume analysis we use $\sim 2$ random points per mock data in $z$-space and real space.

For our DR7-Full volume analysis we limit each realization to the range $0.16 < z < 0.47$. DR7-Full has a flux-limited region ($0.36 < z < 0.47$; see Figure 2 in Kazin et al. 2010), meaning that as $z$ increases the sample is more biased toward the more luminous LRGs. This also affects the number counts of galaxies, meaning an increase in shot noise.

We attempt to take these two effects into account by subsampling the original Horizon Run catalog to fit the observed selection function. The Horizon Run team provides halo masses, which we use in Equation (3) from Park & Kim (2007) to sub-sample. In each realization, we limit ourselves to 7908 deg$^2$ to match the SDSS volume of DR7-Full. The number count of the mock halos is similar to that of the LRGs. For the DR7-Full volume analysis we use $\sim 10$ random points per mock data.

3. RESULTS: ANISOTROPIC CLUSTERING $\xi(z)$

In Figure 1, we show the anisotropic $\xi$ of DR7-Full. Redshift distortions due to peculiar velocities are apparent. On small scales the velocity-dispersion effect dominates the line-of-sight clustering (Jackson 1972), and on large scales gravitational infall causes a squashing effect (Kaiser 1987) that distorts the contours toward smaller scales along the line of sight.

The top panel shows $\xi(r_p, \pi)$ in the standard coordinates: $\pi$ is the line-of-sight component of pair separation and $r_p$ is the transverse component. Redshift distortions in this logarithmic contour plot appear as deviations from circles. The effect of velocity dispersion is clearly seen as the feature at small $r_p$. On larger $\pi$ scales the squashing effect is evident. Two notable features are the “negative sea” on the line of sight (also shown by Cabré & Gáztañaga 2009) and the baryonic acoustic ridge (Okumura et al. 2008; GCH).

The bottom panel shows the same information in a different coordinate system. We define $s$ as the separation length in redshift space:

$$s = \sqrt{\pi^2 + r_p^2}$$  \hspace{1cm} (1)

and $\theta$ is the polar angle from the line-of-sight direction, i.e., $\cos(\theta) = \pi/s$. In these coordinates, redshift distortions appear as deviations from horizontal lines. In E. A. Kazin et al. (2010, in preparation) we give a full description of our angular analysis methods when examining the distortions on scales $s < 80 h^{-1}$ Mpc. Briefly, when counting pairs, we define the line-of-sight direction ($\theta = 0^\circ$) as the vector that bisects the pair separation vector and all four quadrants are binned into one. We mirror this quadrant symmetrically for presentation purposes. For clarity, these plots have been smoothed using a Gaussian filter with $\sigma = 5 h^{-1}$ Mpc in distance and with $\sigma = 3^\circ$ in angle.

(A color version of this figure is available in the online journal.)

\footnotetext[6]{http://astro.kias.re.kr/Horizon-Run/}

![Figure 1. DR7-Full anisotropic $\xi(\pi)$. The top panel shows the $\pi$-$r_p$ plane; in these coordinates, redshift distortions are deviations from circles; the bottom panel shows the $s$-$\theta$ plane; redshift distortions are deviations from horizontal lines. $\theta = 0^\circ$ is the line-of-sight direction. The color coding is the same for both, where the strongest signal is red and the purple is a negative region. Contour lines indicate values of 10, 5, 1 (thick), 0.5, 0.1, 0.05, 0.03, 0.01, 0 (thick), and $-0.01$. For the purposes of these plots, we have smoothed the correlation function using a Gaussian filter with $\sigma = 5 h^{-1}$ Mpc in distance and with $\sigma = 3^\circ$ in angle. (A color version of this figure is available in the online journal.)}
These plots can be misleading, due to the smoothing, so we now focus on one-dimensional angular cuts.

Before performing a direct comparison with results obtained by GCH on the full sample (0.16 < z < 0.47; Section 5), which is flux limited, in the next section we focus on a quasi-volume limited sample (0.16 < z < 0.36).

4. RESULTS: DR7-SUB (0.16 < z < 0.36) LINE-OF-SIGHT CLUSTERING

In their Figure 15, GCH show strong line-of-sight clustering measurements where we expect to detect the baryonic acoustic feature. Here we perform a similar procedure to reproduce their results. Two main differences are (1) they examine 0.15 < z < 0.30, while we probe 0.16 < z < 0.36 and (2) we analyze here both the s-θ plane and the π-rp plane.

In this section, when analyzing the s-θ plane, we define line-of-sight clustering as: \( \langle \xi(s, \theta) \rangle = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} \xi(s, \theta) \sin(\theta) d\theta. \) (2)

In practice, we calculate \( \langle \xi(s, \theta_{\text{range}}) \rangle \) by counting all pairs within the bin of dimensions Δθ and Δs.

When analyzing the π-rp plane we define line-of-sight clustering, as in GCH, as \( \langle \xi(\pi, r_p^{\text{min}} < r_p < r_p^{\text{max}}) \rangle \). In practice, this means that we count all pairs within these bins and apply our \( \xi \) estimator. In order to avoid fiber collision effects, GCH limit themselves to the \( r_p \) region [0.5, 5.5] \( h^{-1} \) Mpc. We test effects of fiber collisions by comparing data results with and without fiber collision corrections in weighting when counting galaxy pairs, as well as with and without region \( r_p < 0.5 h^{-1} \) Mpc and find no significant difference in the results. (See Kazin et al. 2010 for details on fiber collision effects on the correlation function monopole.)

Here we use \( \theta_{\text{max}} = 3^\circ \) corresponding to 0.5 \( h^{-1} \) Mpc < \( r_p < 5.5 h^{-1} \) Mpc at \( s \sim 100 h^{-1} \) Mpc. This choice means that one expects similar line-of-sight clustering measurements and uncertainties at scales of the baryonic acoustic feature. In Section 7, we discuss similarities and differences between these coordinate systems.

Figure 2 displays our line-of-sight results in both coordinate systems. In the top panels of both plots, DR7-Sub line-of-sight clustering results are shown by the black diamonds. As in Figure 1, the region between 50 and 100 \( h^{-1} \) Mpc is mostly negative.

At scales of \( \sim 110 h^{-1} \) Mpc (adjacent to the red upward arrow, which indicates the line-of-sight peak position according to GCH) we see a strong line-of-sight clustering excess in DR7-Sub, which is much stronger than the baryonic acoustic feature in the monopole (crosses; Kazin et al. 2010). Note the agreement, as expected, between the high excess at scale 108.9 \( h^{-1} \) Mpc in both choices of coordinate systems.

In the top panels of Figure 2, we show the expected redshift line-of-sight result (solid red line with uncertainty bars) on the mean of 160 realizations, as well as the 1σ (68% CL; bright gray band) and 2σ (95% CL; dark gray) regions for a single DR7-Sub sample. The blue dotted lines are not one realization in particular, but the outermost values of all mocks. The gray bands show the large scatter around the expected mean.

The expected (mock mean) line-of-sight baryonic acoustic feature is not obvious, but appears suppressed and smeared.

To test if the mock radial acoustic peak is consistent with theory, we use linear radial \( \Lambda \)CDM predictions according to

\( (\text{Hamilton} 1992, \text{meaning applying the Kaiser effect}). Using variance from LasDamas mock DR7-Sub we generate 160 linear-theory noisy \( \xi_{\text{LOS}} \). Below we show weak off-diagonal covariance elements, indicating that limiting ourselves to variance is a good approximation. We find that the linear mean yields noisy results with a trough–peak–trough similar to that in the LasDamas mock mean. Increasing to 300 linear \( \xi_{\text{LOS}} \) yields a clearer mean signal. This indicates that the trend in the

![Figure 2](link-to-figure)
LasDamas mock mean corresponds to that expected from linear theory, only smeared in the peak.

Redshift distortions weaken the signal. To evaluate their importance, we examine the line-of-sight $\xi$ obtained from the real-space LasDamas mocks, which are not affected by the peculiar velocities.

In the bottom panels of Figure 2, we compare the expected line-of-sight signal in the LasDamas real space (thin green solid line) and redshift space (thick red solid line; same as top panel) to the monopoles to which they each contribute (thin green dashed and thick red dotted, respectively). The data monopole is the same as in the top panel.

The real-space line-of-sight mock mean traces the monopole very well until $\sim 30 \, h^{-1} \text{Mpc}$ (not shown here) and continues with a similar trend, though with considerable noise. Note that at $\sim 110 \, h^{-1} \text{Mpc}$ the $\pi - r_p$ system (top panel) and $s - \theta$ (bottom) both show signals that appear similar to the monopole, but with more noise. There is an indication of a peak, but it is not obvious.

We remind the reader that the uncertainty bars on the line-of-sight mock signals (solid green and red) are for the mock mean (of 160), not one for one DR7-Sub volume. Along with the linear $\Lambda$CDM test mentioned above, these indicate that even with a volume much larger than that of DR7-Sub a line-of-sight peak (as defined here) would not be obvious in real space, and in redshift space it would be heavily smeared and weak.

In Section 8, we show that by using wider line-of-sight wedges the S/N increases, yielding an apparent feature.

As another consistency check, we perform the same line-of-sight test on a mock catalog with larger volume and higher density (Horizon Run, $z < 0.6$; see Section 2.2). Using 32 realizations of real-space catalogs, we obtain a mock mean of $\langle \xi(s, 0^\circ < \theta < 3^\circ) \rangle$ that mimics the monopole with baryonic acoustic feature peak positions in fair agreement.

We also estimate uncertainties with jackknife subsampling of the data, using 24 equal area subsamples (as used in Kazin et al. 2010). The jackknife uncertainties are similar to those determined from the mock catalogs (Figure 6).

To test the consistency of the DR7-Sub measurement with the mock-mean value we perform a $\chi^2$-fit, where the (noisy but invertible) covariance matrix is constructed from all 160 mock realizations (data point uncertainties are correlated).

In Figure 3, we present the normalized covariance matrix (relative to the variance) of $\xi(r_p < 5.5 \, h^{-1} \text{Mpc}, \pi)$ around the radial baryonic acoustic feature for DR7-Sub. The bin widths are $\Delta \pi = 4.4 \, h^{-1} \text{Mpc}$. The largest off-diagonal value is 0.365 and quickly diminishes to zero and anti-covariances. Comparing with that of the monopole presented in Figure 9 in Kazin et al. (2010), we see that the radial clustering is weakly correlated and as expected much more noisier. Similar results are shown in Figure 6 of GCH. We test for $\xi(\theta < 3^\circ, s)$ and obtain consistent results.

Examining the range 40–140 $h^{-1} \text{Mpc}$ we obtain $\chi^2 = 30.6$ (23.2) for 23 (20) degrees of freedom (dof) when defining line of sight as $r_p < 5.5 \, h^{-1} \text{Mpc}$, and similar results when using $\theta < 3^\circ$. A $\xi = 0$ model yields $\chi^2 = 26.5$ (23.2). For these measurements we use binning $\Delta \pi = 4.4$ (5.0) $h^{-1} \text{Mpc}$ and $\Delta s = 4.4$ (5.0) $h^{-1} \text{Mpc}$, respectively. These results show that all these tests indicate a $\sim 1\sigma$–$1.5\sigma$ agreement between the data and the expected result, as well as with a null hypothesis.

When restricting the test around the expected baryonic acoustic feature at 100–125 $h^{-1} \text{Mpc}$ we obtain $\chi^2 = 11.2$ (13.6) for 6 (5) dof, and line-of-sight definition, respectively. A $\xi = 0$ model yields $\chi^2 = 9.9$ (12.1).

These tests show that the line-of-sight observation is in good agreement with a fiducial $\Lambda$CDM model, as well as a nonphysical model $\xi = 0$.

In the next section, we perform a similar analysis on DR7-Full, which has a much larger volume. We also compare results directly with GCH.

5. RESULTS: DR7-FULL (0.16 < $z$ < 0.47)

LINE-OF-SIGHT CLUSTERING

In the top panel of Figure 4, we show a direct comparison between our DR7-Full line-of-sight clustering $\xi_{\text{LOS}}$ results (black diamonds) to those in Table 1 of GCH and their Figure 13 (purple triangles; DR6). The $1\sigma$ uncertainties on our data are explained below. We omit uncertainties of GCH to avoid cluttering, but show in Figure 6 that our uncertainties are similar to theirs on these scales.

As expected, the measurement is very noisy. Our results are similar to those obtained by GCH in two ways. First, we both measure the negative region between 50 and 95 $h^{-1} \text{Mpc}$, and second, we each measure a very high value that happens to be where one expects the acoustic feature to be. This strong excess at $\pi \sim 110 \, h^{-1} \text{Mpc}$ appears five times stronger than that obtained in the much higher S/N monopole (crosses; Kazin et al. 2010).

In Section 2.2, we explain the technical details of diluting the original Horizon Run mocks (which were originally designed for BOSS volume and density), to the properties of DR7-Full. The resulting expected $z$-space monopole is shown as the red dotted line in the bottom panel of Figure 4. The agreement with the data around the baryonic acoustic feature seems good. However, we do note a $\sim 10\%$ bias difference ($\sqrt{\sum_{\text{mocks}} / \sum_{\text{SDSS}}}$) at smaller scales. This might indicate that we have excluded a few more low mass halos than we should have, since clustering...
is known to correlate with mass (Zehavi et al. 2005). We doubt that this mismatch will affect our line-of-sight analysis around the baryonic acoustic feature. In the previous section, we obtained similar conclusions to those presented here when using very realistic mocks provided by LasDamas, that are fit to data on low scales. In the bottom panel of Figure 6, we also show excellent agreement between our uncertainty measurements and those obtained by GCH.

The predicted line-of-sight correlation function in redshift space is shown in both panels of Figure 4 as the solid thick red lines. The bottom panel is a zoomed-in version of the top. The uncertainty bars indicate the uncertainty in the mock mean given 32 realizations. In the top panel of Figure 4, the gray band indicates the 68.2% CL region for a single volume, and the blue dotted lines are the outermost values of all mocks (not one in particular).

We see that the expected line-of-sight correlation function has a negative valley around 55–100 h$^{-1}$ Mpc. The signal increases toward the baryonic acoustic feature area and decreases on larger scales.

Comparing these predictions to observations, we see that the very strong measurement at $\pi \sim 100 h^{-1}$ Mpc, although unlikely, is still acceptable according to the mock realizations.

We note that, although our measurements are very similar, we do not obtain the exact same results as GCH. Differences might result from any combination of systematics in analysis. For example, our methods of weighting galaxies may slightly differ when counting pairs, or perhaps it may be due to the differences in the samples (we use $\sim 105,000$ LRGs while they use $\sim 77,000$). We note that these differences are less than the systematic uncertainties. Also, when comparing the much more stable monopole we obtain similar results to theirs. As for the anisotropic $\xi$, from A. Cabré (2010, private communication), we find that we obtain a normalized quadrupole $Q(s)$ similar to that published in Cabré & Gaztañaga (2009).

Our line-of-sight $\xi$ results, as well as covariance matrices, may be obtained on the World Wide Web.$^7$

6. INTERPRETATION OF DATA RESULTS

In the previous section, we show that our measurements are very similar to those previously obtained by GCH and in Figure 6 we show agreement in uncertainty estimates. These agreements show that the results are not sensitive to minor systematic differences (selection of LRGs, weighting algorithms, etc.). We do, however, disagree on the interpretation of the results, as we now clarify. The main distinction between the two interpretations is that we do not agree on the importance of a null $\xi = 0$ test. They claim that it is “only slightly disfavored compared to the best-fit model”. Here we compare the null test to physical models and conclude that the $\xi = 0$ is a good fit to the data, and physical models do not perform significantly better. This means that the line-of-sight data alone is too noisy to infer the presence of a peak.

GCH argue for a significant detection of the line-of-sight baryonic acoustic feature based on $\chi^2$ fits to the data (see their Figures 13 and 15). Here we investigate the significance of their results compared to ours.

In Table 2, we summarize the $\chi^2$ results that they and we obtain with various models on similar data sets. We analyze DR7-Sub and DR7-Full, while GCH investigate the full DR6 as well as a smaller volume ($0.15 < z < 0.30$). In all cases, the line-of-sight $\xi(\pi, r_p < 5.5 h^{-1}$ Mpc) is investigated at scales of $40 h^{-1}$ Mpc $< \pi < 140 h^{-1}$ Mpc with bin widths of $\Delta \pi = 5 h^{-1}$ Mpc ($N = 20$ bins).

The models that GCH investigate are

1. BAO: best-fit $\Lambda$CDM based line-of-sight model based on $k = 5$ parameters;
2. BAO+mag: the same as BAO including lensing magnification effect ($k = 6$);
3. No BAO: a $\Lambda$CDM model based on a featureless $P(k = 5)$; and
4. $\xi = 0$: null test ($k = 0$).

We investigate two fiducial flat $\Lambda$CDM models based on our mocks (LasDamas, Horizon Run). These models are very similar ($\Omega_m = 0.25, 0.26$, respectively). As we do not vary the cosmology in our estimates, here we use $k = 0$. Both use $N$-body simulations that produce very realistic mock LRG catalogs. As described in Section 2.2, the mocks take many observational effects into account. Assuming the correctness of $\Lambda$CDM, this procedure yields very reliable uncertainties ($C_{ij}$), as well as nonlinear fiducial models. The models used by GCH are analytical (giving them the advantage of probing many cosmological models), but they do not account for effects of the survey mask in their modeling or in their $C_{ij}$.

We also investigate the $\xi = 0$ model, which is, of course, not a physical one. It is, however, an interesting straw-man model in the context of claiming a detection.

We test our models on both our data and those in Table 1 of GCH (with our own covariance matrices).

Examining the reduced $\chi^2$ column ($\chi^2/(N - k)$) in Table 2, we conclude that the data agree fairly well with all the models tested. We see this in the Prob column, which indicates the probability of a random variable from a $\chi^2$ distribution with $N - k$ dof to have a value larger than that in the $\chi^2$ column. Note that all models range between 4.5% and 96%. In other words,

http://cosmo.nyu.edu/~eak306/BAF.html
Table 2
Jeffreys Scale Test for Line-of-sight Models

| Data                  | Model   | $\chi^2$ | $k$ | $N$ | $\chi^2/(N-k)$ | Prob (%) | $-\ln E \sim \chi^2 + k \ln(N)$ | $-\ln E \sim \chi^2 + 2k$ |
|-----------------------|---------|---------|-----|-----|----------------|----------|-----------------------------------|---------------------|
| GCH DR6 (0.15 < $z$ < 0.30) | No BAO  | 25      | 5   | 20  | 1.7            | 5        | 40.0                             | 35.0                |
| GCH DR6 (0.15 < $z$ < 0.30) | BAO     | 21      | 5   | 20  | 1.4            | 13       | 36.0                             | 31.0                |
| GCH DR6 (0.15 < $z$ < 0.47) | BAO+mag | 15      | 6   | 20  | 1.1            | 38       | 33.0                             | 27.0                |
| GCH DR6 (0.15 < $z$ < 0.47) | No BAO  | 18      | 5   | 20  | 1.2            | 26       | 33.0                             | 28.0                |
| GCH DR6 (0.15 < $z$ < 0.47) | BAO     | 12      | 5   | 20  | 0.8            | 68       | 27.0                             | 22.0                |
| GCH DR6 (0.15 < $z$ < 0.47) | BAO+mag | 8       | 6   | 20  | 0.6            | 89       | 26.0                             | 20.0                |
| GCH DR6 (0.15 < $z$ < 0.47) | $\xi = 0$ | 14      | 0   | 20  | 0.7            | 83       | 14.0                             | 14.0                |
| GCH DR6 (0.15 < $z$ < 0.47) | BAO     | 12      | 0   | 20  | 0.6            | 89       | 12.6                             | 12.6                |
| GCH DR6 (0.15 < $z$ < 0.47) | BAO+mag | 9.7     | 1   | 20  | 0.5            | 96       | 12.7                             | 11.7                |
| GCH DR6 (0.15 < $z$ < 0.47) | $\xi = 0$ | 15.8    | 0   | 20  | 0.8            | 73       | 15.8                             | 15.8                |
| GCH DR6 (0.15 < $z$ < 0.47) | Horizon Run | 17.2   | 0   | 20  | 0.9            | 64       | 17.2                             | 17.2                |
| DR7-Sub (0.16 < $z$ < 0.36) | $\xi = 0$ | 23.2    | 0   | 20  | 1.2            | 28       | 23.2                             | 23.2                |
| DR7-Sub (0.16 < $z$ < 0.36) | LasDamas | 24.8    | 0   | 20  | 1.2            | 21       | 24.8                             | 24.8                |
| DR7-Full (0.16 < $z$ < 0.47) | $\xi = 0$ | 31.8    | 0   | 20  | 1.6            | 4.5      | 31.8                             | 31.8                |
| DR7-Full (0.16 < $z$ < 0.47) | Horizon Run | 28.7   | 0   | 20  | 1.4            | 9.4      | 28.7                             | 28.7                |
| DR7-Full (0.16 < $z$ < 0.47) | $\xi = 0$ | 13.7    | 0   | 10  | 1.4            | 19       | 13.7                             | 13.7                |
| DR7-Full (0.16 < $z$ < 0.47) | Horizon Run | 12.6   | 0   | 10  | 1.3            | 25       | 12.6                             | 12.6                |

Notes. $I_{\text{line-of-sight}}$ model statistics: models are the same as mentioned in the text. $\xi = 0$, although not physical, gives indication of how noisy the data are. The $\chi^2$ is a statistic that tells us how well each model fits the data. To compare goodness of two models calculate $\Delta \ln E$ (we present both BIC and AIC values). Following Table 1 from Liddle (2009): $\Delta \ln E < 1$—“Not worth more than a bare mention,” $1 < \Delta \ln E < 2.5$—“Significant,” $2.5 < \Delta \ln E < 5$—“Strong to very strong,” $5 < \Delta \ln E$—“Decisive.” For descriptions of LasDamas and Horizon Run mocks, please refer to Section 2.2. All tests are conducted on bins in the range $\pi = [40, 140] \ h^{-1} \text{Mpc}$. 

a Assuming a $\chi^2$ distribution this answers: what is the probability to obtain a random variable from a $\chi^2$ distribution larger than in the $\chi^2$ column? 

b Here we apply our own DR7-Full $C_0$ to the DR6 data in Table 1 of GCH. To the $C_0$ we also apply a normalization of the ratio of volumes of DR7 and DR6, 1.58/1.35, which takes into account different sky coverage as well as the fact that GCH use LRGs at $z > 0.15$. 

c For DR7-Full, we use the $C_0$ based on 160 DR7-Sub mocks normalized by the $C_0$ of 32 DR7-Full mocks

For completeness we mention that the $\chi^2$ for the physical models posted in GCH might be misestimated for the purpose of comparing them to each other. When fitting models to data they use a Gaussian prior likelihood indicated in their Section 3.8.2. This prior should be taken into account when calculating the full $\chi^2$. This means that an additional term $\chi^2_\text{prior} = \sum_{i=r}^{N_{\text{prior}}} \gamma_i / \sigma_i^2$, where $\gamma_i$ is the $i$th parameter, should be added. They use $N_{\text{prior}} = 4$ parameters as priors: $[\Omega_m, \Omega_{\text{tot}}, b_0, b_8]$, where $b_8$ is the Kaiser squashing parameter and $b_8$ is the linear bias factor relating matter and LRG over-densities. Through E. Gaztaña-ga et al. (2010, private communication) we learn that their best-fit values for the BAO+mag model are [0.049, 0.240, 1.73, 0.39]. This yields $\chi^2_\text{prior} = 9.4$ which should be added to their stated $\chi^2 = 8$ and correcting the number of data points from $N = 20$ to 24 (one additional “data point” for each prior). They claim that they obtain similar parameter values ($\gamma_i$) for the other physical models, so when comparing between them this term should approximately cancel out. However, the correct manner to incorporate this correction utilizing BIC and AIC when comparing with $\xi = 0$ and our mock models, which do not use prior likelihoods, is not clear. For simplicity we quote values published by GCH in Table 2.

So far we have used a rigid definition of number of parameters $k$. A thorough analysis would investigate the relative influence of each parameter on the model. This could be done by investigating the full parameter space, which is out of the scope of this study. To attempt to minimize the effect of free parameters, we asked the authors of GCH (E. Gaztaña-ga et al. 2010, private communication), for results using the minimum number of free parameters. Setting all parameters to the prior means and the shift in the radial scale $D_L$ to their fiducial model they obtain for the BAO model $\chi^2 = 12.6 (k = 0)$ as listed in Table 2, and all models fit the data at $2\sigma$ or better. This procedure tests each model independently, but to compare between them is more complicated.

There are various ways to compare models and determine significance of difference. Here we present a few common tests used in the literature (Liddle 2009 and references within).

The Jeffreys scale uses a value called the “Evidence” $E$, which is the average likelihood of the parameters averaged over the parameter prior. The difference of $\ln E$ may be used to describe how much better one model agrees with data from another. For example, in order for one model to perform significantly better than another, $\Delta \ln E$ should be larger than unity. Other useful divisions in significance are for values 2.5 (posterior odds of 12:1) and 5 (148:1; see the caption of Table 2).

We approximate $E$ by using the Bayesian information criterion (BIC; Schwarz 1978) defined as

$$-\ln(E) \sim \text{BIC} = -2 \ln(L_{\text{max}}) + k \ln(N),$$

where $k$ is the number of parameters and $N$ is the number of data points. Assuming the likelihood $L$ is Gaussian $-2\ln(L_{\text{max}}) = \chi^2_{\text{min}}$. Using this criterion, we prefer models that yield a lower BIC result. A similar technique is the Akaike Information Criterion (AIC; Akaike 1974) defined by replacing $k \ln(N)$ with $2k$. Both these criteria are summarized in Table 2 in separate columns.

Applying BIC and AIC to the GCH results, the “No BAO” model is clearly disfavored in respect of the other models. This result does not mean, however, that the data reveal a significant line-of-sight baryonic acoustic feature. One way to look at this is to realize that $\xi = 0$ is a good fit. Below we elaborate on this point.
for BAO+mag they obtain $\chi^2 = 9.7 (k = 1)$. Comparing BAO to their $\xi = 0$ ($\chi^2 = 14; k = 0$) we obtain $\Delta \chi^2 = 1.4$, showing no significant improvement (slightly above 1$\sigma$). Comparing BAO+mag to $\xi = 0$ we obtain BIC = 1.4 and AIC = 2.4. We also examine our Horizon Run model and $\xi = 0$ to their data. We use our DR7-Full covariance matrix, though normalize it by using the ratio of volumes of DR7 and DR6 (see caption in Table 2), and obtain $\Delta \chi^2 = 1.4$. We conclude that using the DR6 data the physical models do not out-perform $\xi = 0$ in a significant manner.

In the case of DR7-Full data, we see that the fiducial Horizon Run model performs better than $\xi = 0$ ($\Delta \chi^2 = 3.1$). This does not yield much confidence that we have detected a line-of-sight peak for a few reasons. First, the model baryonic acoustic feature is much weaker than the strong clustering in the data (Figure 4). Second, the physical model is preferred by less than 2$\sigma$. Third, the number of bins might be of concern. We conduct tests with wider bins ($\Delta \pi \sim 10 \ h^{-1} \ Mpc$) and obtain a better agreement between the models $\Delta \chi^2 = 1.1$. This shows that the criterion is sensitive to the width of the binning when $k = 0$.

We note that the $\xi = 0$ fit to DR7-Full is much worse than that to DR6 (GCH data). We mentioned the normalization of the $C_{ij}$; without this normalization we obtain only slightly better fits. Another notable difference that might contribute to this discrepancy is that the GCH data are much smoother than ours. They explain binning techniques applied on the data, though normalize it by using the ratio of volumes of DR7 and DR6 (see caption in Table 2), and obtain $\Delta \chi^2 = 1.4$. We conclude that using the DR6 data the physical models do not out-perform $\xi = 0$ in a significant manner.

We emphasize here that many assumptions are made when performing this comparison. We assume $C_{ij}$ is model independent, but do not expect it to change significantly within parameter space. In addition, we assume the likelihood to be Gaussian and the correctness of the BIC and AIC. As noted above, we find sensitivity in $\Delta \chi^2$ model comparisons when varying size of $\pi$ bins.

To summarize, both studies demonstrate that the line-of-sight measurement is very noisy (in a $\chi^2$ sense). It is our opinion that these correlation functions do not convincingly show a line-of-sight feature.

The main distinctions between our conclusions and those of GCH are that when investigating significance we take into account the addition of free parameters $k$, as well as the importance of the $\xi = 0$ test. Here, $k$ serves in both BIC and AIC as a “penalty” for adding parameters. Ignoring $k$ (which is the wrong thing to do) would cause this test to favor a BAO model with magnification, whereas including it, this comparison shows that the current data cannot distinguish between physical models in a convincing manner. The physical models do perform better than a No BAO model. This last point, however, is not a proof for the detection of a peak in the line-of-sight clustering. No BAO is not physically motivated and there is no physical reason to prefer this model over other featureless models. We show here that the physical models do not perform better significantly than a null $\xi = 0$, which yields a good fit to the data.

The reader should keep in mind that there is no apparent reason to prefer this model over other featureless models. We show here that the physical models do not perform better significantly than a null $\xi = 0$, which yields a good fit to the data.

Figure 5 displays the predictions for the line-of-sight signal. In this case, we work in $\pi - r_p$ space and define the line of sight using a cut at $r_p = 5.5 \ h^{-1} \ Mpc$ (using $\Delta \pi = 5 \ h^{-1} \ Mpc$ bins). The solid red line is the line-of-sight prediction for the mean BOSS signal and the gray band is the $1\sigma$ sample variance. The thick black diamonds are the observed results from DR7-Full using the same line-of-sight definition (same values as in Figure 4). The dashed line shows the expected monopole (with $1\sigma$ uncertainties for a given BOSS volume).

(A color version of this figure is available in the online journal.)

expansion rate of the nearby universe, noise must be reduced by probing larger volumes.

In the following section, we examine the line-of-sight signal expected in a much larger volume survey.

### 7. PREDICTION: BOSS LINE-OF-SIGHT CLUSTERING

The Baryonic Oscillation Spectroscopic Survey (BOSS; Schlegel et al. 2009) plans to map 1.5 million LRGs in a much larger volume than DR7, up to $z \sim 0.7$. We examine here what can be expected from the line-of-sight correlation function in the BOSS volume.

Figure 5 displays the predictions for the line-of-sight signal. In this case, we work in $\pi - r_f$ space and define the line of sight using a cut at $r_f = 5.5 \ h^{-1} \ Mpc$ (using $\Delta \pi = 5 \ h^{-1} \ Mpc$ bins). The solid red line is the line-of-sight prediction for the mean BOSS signal and the gray band is the $1\sigma$ sample variance. The black thick diamonds are the observed results from DR7-Full using the same line-of-sight definition (same values as in Figure 4). The dashed line shows the expected monopole prediction for comparison.

Although the line-of-sight mock signal is negative at these scales due to the linear redshift-space distortions (the squashing effect), there is a signature of a peak with a position in fair agreement with the monopole. The $1\sigma$ uncertainties suggest, however, that even in BOSS we do not expect a significant line-of-sight detection of the baryonic acoustic feature, if we define the line-of-sight as narrowly as GCH do (that is, within $\theta < 3^\circ$ or $r_p < 5.5 \ h^{-1} \ Mpc$).

The estimated uncertainties do indicate that BOSS will have the statistical power to rule out (or confirm) at high confidence a clustering excess at the level claimed by GCH at $\pi \sim 100 \ h^{-1} \ Mpc$. To test this proposition quantitatively, we
evaluate χ² of the DR7-Full result versus the model constructed from the Horizon Run mock mean, using all 32 realizations to determine the covariance matrix. We obtain χ² = 151 for 4 dof (the bins between 100 h⁻¹ Mpc < s < 120 h⁻¹ Mpc). Our mocks thus predict that a measurement as strong as that seen in DR7-Full is extremely unlikely in BOSS.

In Figure 6, we examine the uncertainties of the line-of-sight (left panels) and monopole (top right panels) measurements of the correlation function. We examine differences between the two line-of-sight definitions: the top left panel shows for θ < 3° and the bottom r_p < 5.5 h⁻¹ Mpc. Included in this figure are the estimates of the DR7-Sub sample (both using LasDamas and data jackknife subsamples), DR6 (as estimated by GCH), DR7-Full (Horizon Run), and for BOSS (Horizon Run). Finally, we also compare our monopole predictions to those found using the linear theory estimate of Cohn (2006). For descriptions of the mocks realizations used please refer to Section 2.2.

The top left panel of Figure 6 shows results for the line of sight (θ < 3°). For comparison, the solid line is the expected signal (in absolute value) using the BOSS mocks from the Horizon Run. The thick dashed line shows the uncertainty estimates for this case, demonstrating again that even in BOSS the line-of-sight signal, as defined here, will be very difficult to measure. The thin dashed line shows our uncertainty estimates using the LasDamas DR7-Sub mocks. For comparison the diamonds show jackknife estimates of the uncertainties from the data itself, which are in excellent agreement with the mocks. Obviously, the SDSS-II results are much noisier than the BOSS results will be.

The bottom panel shows similar predictions when defining the line-of-sight region as r_p < 5.5 h⁻¹ Mpc. The medium width dashed red line corresponds to our DR7-Full uncertainties, the purple triangles are uncertainties according to GCH (see their Table 1). The DR7-Sub uncertainty (thin blue dashed line), the predicted BOSS signal (thick solid black line), and uncertainty (thick dashed black line) have the same notation as before. Cabrè & Gaztañaga (2009) argue that at r > 20 h⁻¹ Mpc shot noise dominates the noise.

Comparing the BOSS results, we see clear differences between the uncertainties in the two coordinate systems. The s−θ has a negative slope with respect to scale where the θ−rp has a very slight positive slope (also noticeable in Figure 4). The reason for this is simple: θ < 3° corresponds to a cone, whereas r_p < 5.5 h⁻¹ Mpc corresponds to a cylinder. The uncertainties in the former decrease with s because more data are included, reducing the noise. The latter is very flat because all scales each bin contains roughly the same number of pairs. The slight positive slope indicates minor effects of boundary conditions at these scales. We thank E. Gaztañaga (2010, private communication) for pointing this difference out.

As a consistency check, we verified that, although the scale dependence differs, the uncertainty for BOSS at ~100 h⁻¹ Mpc is similar in the two coordinate systems, as expected.

Our DR7-Full uncertainties are in excellent agreement with those of GCH. This result is slightly surprising because we expect our DR7-Full uncertainties to be slightly smaller than those obtained by GCH, who investigate the slightly smaller DR6 volume. This might be an artifact of the way we subsampled the Horizon Run mocks, as explained in Section 2.2. Overall, however, we consider our result to be in general agreement with those of GCH.

The right panel shows results for the monopole. For comparison, the solid line is the absolute value of the expected signal from the BOSS mocks. The thin dashed line shows the uncertainty estimates from LasDamas for SDSS-II (DR7-Sub). The thick dashed line shows the uncertainty estimates from Horizon Run for BOSS, which are obviously much smaller. The thin and thick dotted lines show the estimates for each survey from linear theory (Cohn 2006), which are in remarkable agreement with the mock catalog results. This comparison demonstrates that our estimates from the mock catalogs are reasonable and strengthens our confidence in our estimates for the radial uncertainty estimates.

BOSS will have a larger volume than DR7-Sub, and hence yields much smaller uncertainties in σ_{ξ-LOS} (line-of-sight) and σ_{ξ-monopole} (monopole). We estimate that the monopole uncertainty at the baryonic acoustic feature will be reduced by a factor of 4 and the line-of-sight signal by approximately the same amount. We predict the S/N for BOSS at the baryonic acoustic feature scale at S/N ≈ |ξ_{monopole}|/σ ~ 6. These calculations are based on a single bin, so should be considered a lower limit of the true statistical power of the survey.

Note that the BOSS σ_{ξ-LOS} (left panel of Figure 6) is expected to be slightly larger than that of the SDSS-II σ_{ξ-monopole} (right panel of Figure 6). Moreover, the BOSS ξ_{LOS} appears negative at scales larger than s > 50 h⁻¹ Mpc resulting in a baryonic acoustic dip in the left panel, which is significantly smaller in absolute magnitude than σ_{ξ-LOS}, making a detection of the feature unlikely.
Figure 7. BOSS expected line-of-sight and transverse angular slices of $\xi$. Each panel shows two angular wedges of the redshift-space correlation function $\xi(s)$ as predicted for BOSS from the Horizon Run simulations. The size of the wedges is indicated in each panel (starting at 45° at the top and decreasing toward the bottom). The solid red lines show the wedges closest to the line-of-sight direction and the dotted blue lines show the wedges closest to the transverse direction. In each case, we give the 1σ uncertainty in the mock mean as the errorbars and the uncertainty for a single BOSS volume as the gray band. The angular slices are $\Delta\theta = 45°, 22.5°, 11.2°, 5.6°,$ and $3°$. The dashed line is the monopole prediction and is the same in all panels, with uncertainties given for one BOSS volume (i.e., not the mock mean). The symbols in the top right panel are the result for DR7-Full in the $\Delta\theta = 45°$ slices, where red diamonds are for the line-of-sight direction and the blue squares are for the transverse direction.

(A color version of this figure is available in the online journal.)
In the subsequent panels, we slice the anisotropic $\xi$ into finer angular divisions (each $\Delta \theta$ is indicated in the legend and the caption). Again, for each wedge size, we display the wedges closest to the line-of-sight direction (solid red line) and closest to the transverse direction (dotted blue line). We plot the monopole result in each panel for comparison (black dashed line). Although the signal is noisier for smaller wedges, a clear detection of the relative peak position in each direction appears obtainable by BOSS.

We refer to the future a thorough analysis of the precision with which BOSS will measure $H(z)$ and $D_A$ by measuring the baryonic acoustic feature as a function of angle $\theta$. Here we simply note that the low S/N expected for the very narrow line-of-sight cone studied by GCH should not discourage us from this measurement.

This independent measure of the line-of-sight and transverse features in clustering can be interpreted as a test of the Alcock & Paczynski (1979) effect. When counting pairs we have assumed a fiducial cosmology for the purpose of converting the observed redshifts to comoving distances. Although this cosmology is well motivated by WMAP 5-year results (Komatsu et al. 2009), small deviations from the true underlying cosmology will result in distortions in $\xi$, and of most concern, the position of the baryonic acoustic feature.

Alcock & Paczynski (1979) describe how an intrinsically spherical body in real space appears distorted to an observer who measures the object in redshift space and uses an incorrect cosmology to convert to comoving space. In real space, the baryonic acoustic feature appears as such a spherical body (in the statistical sense) and the line of sight baryonic acoustic feature should yield the same result as the transverse direction.

The spherical nature of the baryonic acoustic feature is only approximate in redshift space because it is somewhat distorted due to gravitational dynamics. However, the effect of these dynamic distortions on the position of the feature is understood. Thus, by comparing the line-of-sight feature to the transverse feature, we can learn about the true underlying cosmology.

We emphasize that in Figure 7 we merely show disentanglement of line-of-sight and transverse clustering signals. We do not perform the Alcock & Paczynski (1979) test as the fiducial cosmology used to calculate mock $\xi$ is the same as the simulations.

9. DISCUSSION AND CONCLUSIONS

In this paper, we demonstrate that the claim of a significant detection in the line-of-sight baryonic acoustic feature in the SDSS LRG sample by GCH is unjustified. We perform a similar analysis to theirs and obtain similar results. The main difference in our interpretation, as we elaborate in Section 6, is that we use a more conservative criterion regarding whether we detect a feature. We find that the data agree very well with a $\Lambda$CDM redshift space nonlinear model tested here, which does not contain a clear line-of-sight feature due to its low S/N. We also find that physical line-of-sight models tested by us and GCH do not out-perform a null $\xi = 0$ model, indicating no clear evidence of a line-of-sight baryonic acoustic feature. The BOSS survey, which has just begun, will have the statistical power to rule out (or confirm) this strong clustering excess at high significance (Figure 5), though not to usefully detect the baryonic acoustic feature in such a narrowly defined line-of-sight measurement. By using broader angular bins, BOSS will be able to independently measure baryonic acoustic feature along the line-of-sight and transverse directions.

We examine two different volumes in the SDSS LRG sample (SDSS-II). In the smaller one (0.16 < $z$ < 0.36, DR7-Sub; Section 4), for which we use very realistic mock catalogs, we find a good agreement (1$\sigma$–1.5$\sigma$) between the line-of-sight observation and a $\Lambda$CDM model, which does not have an apparent feature even in $\sim$160 DR7-Sub volumes. For our full sample (0.16 < $z$ < 0.47, DR7-Full) we find that a fiducial model agrees within 1.5$\sigma$–2$\sigma$.

Figures 2, 4, and 6 clearly show that the line-of-sight clustering excess at $s \sim 110$ $h^{-1}$ Mpc in both volumes is dominated by noise.

We confirm the number of pairs estimate of Miralda-Escude (2009) which they used on GCH results. The bin of interest is 106.7 $h^{-1}$ Mpc < $s$ < 111.1 $h^{-1}$ Mpc and $0^\circ < \theta < 3^\circ$, corresponding to the choice in GCH of $\Delta \pi$ and $r_p < 5.5$ $h^{-1}$ Mpc. In our case, we count the number of effective pairs, including the effects of weighting (see Kazin et al. 2010 for details). DR7-Sub yields 2259 pairs and DR7-Full yields 3104. Examining 160 very realistic mock catalogs, we find that the high DR7-Sub value of $\xi = 0.085$ in this bin, although unlikely, is consistent with $\Lambda$CDM (one mock of 160 has a higher value).

We point out that the strong clustering excess that happens to be at the correct scale is probably noise, that will be reduced with increase of volume. We see a hint of this effect when the volume increases from DR7-Sub (0.66 $h^{-1}$ Gpc$^3$) to DR7-Full (1.6 $h^{-1}$ Gpc$^3$) the line-of-sight clustering excess ($\theta < 3^\circ$) at $s \sim 108.9$ $h^{-1}$ Mpc is decreased from $\xi \sim 0.085$ to $\xi \sim 0.045$. This is shown also in GCH in their Figures 13 and 15. We interpret the difference between both measurements and the expected value from $\Lambda$CDM as noise.

Assuming correctness of our fiducial cosmology, the predicted BOSS results, presented in Figure 5, show that the strong line-of-sight clustering excess seen in DR7 should be ruled out at a very high CL when measuring $\xi$ in the BOSS LRG sample.

In the left panels of Figure 6, we show the low S/N expected from the line-of-sight measurement in BOSS. We also examine by eye all 32 line-of-sight results (defined as $r_p < 5.5$ $h^{-1}$ Mpc) and find that 7 of 32 (~22%) mocks do not show a clear line-of-sight baryonic acoustic feature, where 12 do show a clear signal (~38%). This analysis is, of course, subjective, but suggests that the LRGs alone might not detect the line-of-sight baryonic acoustic feature in the BOSS volume, if the line-of-sight definition is limited to $0^\circ < \theta < 3^\circ$ or $r_p < 5.5$ $h^{-1}$ Mpc.

In Figure 7, we show, however, reason for optimism in disentangling $H(z)$ and $D_A(z)$ in the future BOSS LRG data. Unsurprisingly, using wider angular cuts yields better S/N results. The various $\Delta \theta$ slices contain line of sight and transverse information that may be used to probe $H(z)$ and $D_A(z)$.

Throughout this study, we have ignored the effects of any potential reconstruction techniques that might be employed on the BOSS data (Eisenstein et al. 2007; Huff et al. 2007; Padmanabhan et al. 2009; Noh et al. 2009). Reconstruction may allow better precision in measuring the peak position than indicated here.

We emphasize that our measurements and uncertainty estimates are similar to those carried out previously by GCH (see Figure 6 for direct comparison). We also confirm that the strong clustering signal at the line of sight cannot be explained by systematics. We check various binning widths in both $\pi$ and $r_p$ as well as fiber-collision weightings and do not find
significant changes. We do, however, disagree on the interpretation of the results.

The main dispute is regarding the use of the strong line-of-sight clustering in the data as the baryonic acoustic feature to determine \( H(z) \) directly. In their Table 3, GCH show results for \( H(z) \) obtained by two different methods.

1. “Shape Method”: Using the full shape of the line-of-sight clustering with priors from monopole, quadrupole clustering as well as CMB temperature fluctuations to determine \( H(z)/H_0 \).
2. “Peak Method”: Using the line-of-sight baryonic acoustic feature peak position to determine \( H(z) \) directly.

While both methods are correct procedures to perform, the second should be considered valid only if the line-of-sight baryonic acoustic feature is convincingly detected.

To explain the insignificance of a detection, we consider the null \( \xi = 0 \). Using a Jeffreys scale, in Section 6 we show that the physical models do not out-perform \( \xi = 0 \). This does not mean, of course, that \( \xi = 0 \) is the line-of-sight clustering at these scales, but rather indicates that models cannot be distinguished significantly and a clear line-of-sight baryonic acoustic feature cannot be declared detected using this data set.

Only future surveys can show definitively what the line-of-sight correlation function is in these bins. In particular, BOSS will be able to do so. In Figure 5, we show that BOSS, which is underway, will be able to rule out this detection or verify it. BOSS is due to cover a comoving volume of \( \sim 8.1 \, h^{-3} \, \text{Gpc}^3 \) (0.16 < \( z < 0.80 \)) by 2014. For a comoving volume of \( \sim 3.9 \, h^{-3} \, \text{Gpc}^3 \) (0.16 < \( z < 0.60 \)) and density expected in BOSS, we find that all our 32 mock realizations have an apparent monopole feature (as opposed to SDSS-II volumes; Kazin et al. 2010).

Another survey that is on its way to refine baryonic acoustic feature measurements is the WiggleZ. The WiggleZ Dark Energy Survey (Drinkwater et al. 2010) is expected to complete very soon a narrower redshift survey (area \( \sim 1000 \, \text{deg}^2 \)), using Blue Emission Line Galaxies, in a comoving volume of \( \sim 1 \, \text{Gpc}^3 \) between 0.2 < \( z < 1 \). When analyzing a quarter of the predicted final sample, Blake et al. (2010) show in Figure 20 a hint of a baryonic acoustic wiggle in the \( P(k) \) monopole. Although it is not clear whether this survey will detect a significant peak in the line-of-sight \( \xi \) (assuming \( \theta < 3^\circ \)), we are hopeful that it will give us indication of the true signal.

If the claim for detection by GCH is correct, the unexpected strong line-of-sight signal would require an explanation.

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