Clustering of photometric luminous red galaxies – I. Growth of structure and baryon acoustic feature

M. Crocce,¹ E. Gaztañaga,¹ A. Cabré,² A. Carnero³ and E. Sánchez³

¹Instituto de Ciencias del Espacio (IEEC/CSIC), F. de Ciencias, Torre C5-Par-2a, Bellaterra, 08193 Barcelona, Spain
²Department of Physics and Astronomy, University of Pennsylvania, 209 South 33rd Street, Philadelphia, PA 19104-6396, USA
³Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Avenida Complutense 22, E-28040 Madrid, Spain

Accepted 2011 July 11. Received 2011 July 6; in original form 2011 May 2

ABSTRACT
The possibility of measuring redshift-space distortions (RSDs) using photometric data has been recently highlighted. This effect complements and significantly alters the detectability of baryon acoustic oscillations (BAO) in photometric surveys. In this paper we present measurements of the angular correlation function of luminous red galaxies (LRGs) in the photometric catalogue of the final data release [data release 7 (DR7)] of the Sloan Digital Sky Survey II (SDSS-II). The sample compromises ∼1.5 × 10⁶ LRGs distributed in 0.45 < z < 0.65, with a characteristic photometric error of ∼0.05. Our measured correlation centred at z = 0.55 is in very good agreement with predictions from standard ΛCDM in a broad range of angular scales, 0.5 < θ < 6°. We find that the growth of structure can indeed be robustly measured, with errors matching expectations. The velocity growth rate is recovered as fσ⁸ = 0.53 ± 0.42 when no prior is imposed on the growth factor and the background geometry follows a ΛCDM model with 7-year Wilkinson Microwave Anisotropy Probe (WMAP7)+SNIa priors. This is compatible with the corresponding General Relativity (GR) prediction fσ⁸ = 0.45 for our fiducial cosmology. If we adopt a parametrization such that f = Ω_m(z), with γ ≈ 0.55 in GR, and combine our fσ⁸ measurement with the corresponding ones from spectroscopic LRGs at lower redshifts, we obtain γ = 0.54 ± 0.17. In addition we find evidence for the presence of the baryon acoustic feature matching the amplitude, location and shape of ΛCDM predictions. The photometric BAO feature is detected with 98 per cent confidence level at z = 0.55.

Key words: methods: data analysis – cosmological parameters – dark energy – distance scale – large-scale structure of Universe.

1 INTRODUCTION
The discovery of an accelerated cosmic expansion has become one of the biggest puzzles in modern cosmology over the last 10 years. Several scientific probes have been proposed to understand the nature of this acceleration: from ‘geometrical’ tests based on measurements of the distance–redshift relation, such as baryon acoustic oscillations (BAO) or Type Ia supernovae, to ‘growth’ tests sensitive to the growth rate of perturbations such as redshift-space distortions (RSDs), weak lensing or cluster abundance. The success of these probes relies on the implementation of massive observational campaigns that will scan a good fraction of the observable Universe. Some such surveys base their science on galaxy redshifts derived spectroscopically, which provides accurate radial positions. Others will instead measure redshift photometrically. This yields poorer determination of radial positions but allows us to go deeper in redshift and have higher sampling rate. The latter group involves the Dark Energy Survey¹ (DES), the Physics of the Accelerating Universe collaboration² (PAU) and the Panoramic Survey Telescope and Rapid Response System³ (PanStars) as well as proposals such as the Large Synoptic Survey Telescope⁴ (LSST) and the imaging component of ESA/Euclid⁵ survey.

Perhaps the most exciting results related to the large-scale structure of the Universe to date have been obtained using spectroscopic data from surveys such as the two degree field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001), the Sloan Digital Sky Survey

¹ www.darkenergysurvey.org
² www.pausurvey.org
³ pan-stars.ifa.hawaii.edu
⁴ www.lsst.org
⁵ www.euclid-imaging.net
RSDs arise because the receding speed of galaxies with respect to us is due not only to the Hubble expansion but also to their peculiar velocity. Hence, galaxy positions inferred with the Hubble law are modified with respect to their true positions depending on the local velocity field. At large scales, the net effect results from the relative strength of the intrinsic clustering (the bias) and the amplitude of velocity flows set by the conservation of mass through the growth rate of structure parameter \( f = \frac{\partial \ln D}{\partial \ln a} \) (where \( D \) is the linear growth factor and \( a \) is the cosmological scalefactor). Photometric redshift errors are generally assumed to wash out these distortions. As recently discussed by Nock, Percival & Ross (2010) and Crocce, Cabrè & Gaztañaga (2011) this is true to a good extent but does not remove the signal completely if one splits the data in redshift bins. Thus, RSD from photometric data could be a sensitive test for the growth of structure as a function of redshift (Ross et al. 2011). This can then be used to discriminate modifications of Einstein’s gravity from dark energy models.

In turn, BAO originate in the tight coupling between baryons and photons prior to recombination. At the moment of decoupling, their ‘last scattering’ imprints a well-defined comoving scale in the spatial distribution of baryons and matter of \( \sim 100 \text{h}^{-1} \text{Mpc} \), characterized by a slight excess of pairs over random. This scale is today imprinted in the distribution of galaxies. Again, poor distance determination because of photometric redshift estimates washes out this excess, at least in the radial direction. Photometric surveys should still be capable of detecting this signature in the angular distribution of galaxies (e.g. Blake & Bridle 2005).

In this paper we use the angular correlation function of luminous red galaxies (LRGs) in the imaging catalogue of the final data release [data release 7 (DR7)] of SDSS to address whether the growth of structure can be robustly measured with photometric data despite several sources of systematic errors, low-resolution photo-z and other unknowns. In parallel, we investigate whether BAO can be observed in the clustering pattern of LRGs in concordance with model predictions affected by RSDs. In a companion paper, Carrero et al. (2011), we discuss the cosmological implications of the presence of BAO in the clustering signal.

These tests, that extend previous work using angular power spectrum (Blake et al. 2007; Padmanabhan et al. 2007; Thomas, Abdalla & Lahav 2011b), may serve as a proof-of-concept for the potential of future, more accurate, photometric data to place interesting constraints on to the nature of cosmic expansion, and/or provide valuable higher redshift leverage to complement spectroscopic measurements.

This paper is organized as follows. In Section 2.1 we discuss our data, including the selection of the galaxy sample, survey mask and photo-z. In Section 3 we describe our angular correlation measurements including the error estimates and the impact of star contamination. Section 4 refers to our RSD analysis and the implications for the growth rate of structure. Section 5 is dedicated to discuss the evidence for the baryon acoustic feature in the measured correlation. Lastly, Section 6 contains our main conclusions.

## 2 DATA

### 2.1 Selection of the galaxy sample

We perform a colour-based selection of LRGs in the photometric catalogue of the final SDSS-II data release (DR7; Abazajian et al. 2009). We follow two main steps. The first one, based on that published by Cabré et al. (2006), aims at identifying the region in colour–colour space that is populated by high-redshift LRGs (Eisenstein et al. 2001) by selecting all those objects that verify

\[
(r - i) > \frac{(g - r)}{4} + 0.36, \\
(g - r) > -0.72(r - i) + 1.7,
\]

where the variables \( g, r, i \) are model magnitudes corrected by extinction. The second step is a set of cuts that are intended to minimize the star contamination in the sample

\[
7 < \text{petror} < 21, \\
0 < \sigma_{\text{petror}} < 0.5, \\
0 < r - i < 2, \\
0 < g - r < 3, \\
22 < \text{mag}_{50} < 24.5,
\]

where petror is Petrosian magnitude (corrected by extinction), \( \sigma_{\text{petror}} \) is the error on petror and mag\(_{50}\) is the surface brightness in magnitude petror at half-light radius \( r_{50} \) (the radius containing 50 per cent of Petrosian flux), mag\(_{50}\) = petror + 2.5 log(π\(r_{50}^2\)). These cuts yield a total of \( \sim 1.27 \times 10^{5} \) objects with redshifts in the range \( -0.4 \) to \( -0.65 \).

Out of the set of cuts in equation (2), the first ones correspond to our magnitude limits. The next ones ensure that colours correspond to a galaxy and effectively eliminate very few objects. Finally, the cut that is most effective is that in mag\(_{50}\), with an upper bound on 24.5 to ensure well-measured galaxies and a lower bound on 22 to eliminate bright point-like objects (i.e. stars). We have found that eliminating objects with mag\(_{50} > 24.5\) mag arcsec\(^{-2}\) leads to no difference in the clustering signal. However eliminating objects with mag\(_{50} < 22\) mag arcsec\(^{-2}\) reduces the amplitude of clustering at large scales by large factors even though they represent a small percentage of the total sample. Hence, we next discuss the motivation for this cut in more detail (further evidence for this effect is given in Section 3.2).

The distribution of mag\(_{50}\) is given in Fig. 1. It is well concentrated around mag\(_{50} \sim 23\) mag arcsec\(^{-2}\) but shows long tails due to objects contaminating the LRG sample. This contamination is more clearly depicted in the petror versus mag\(_{50}\) diagram in Fig. 2. The top panel corresponds to our photometric sample and shows a different trend for mag\(_{50} < 22\) mag arcsec\(^{-2}\) and mag\(_{50} > 24.5\) mag arcsec\(^{-2}\), with the core of LRGs lying in between. The bottom panel shows the
same diagram but for the SDSS DR7 spectroscopic sample, after imposing the selection in equation (1). This panel nicely shows that all objects with $\text{mag}_{50} < 22$ mag arcsec$^{-2}$ could be contaminated by stars. In addition, Fig. 3 shows a histogram of the number of objects per pixel (here the pixel size is 0.01deg$^2$) as a function of galactic latitude and different redshift bins, including (solid) or excluding (dashed) galaxies with low $\text{mag}_{50}$. Objects with low $\text{mag}_{50}$ clearly concentrate at low galactic latitudes introducing artificial density gradients towards the galactic plane (which then results in large density fluctuations at large scales). There is a slight gradient residual after imposing the cut in $\text{mag}_{50}$, which we avoid but leaving out galactic latitudes (denoted as $b$) lower than 25°. We require

$$b \geq 25^\circ.$$  \hspace{1cm} (3)

This yields a reduction of ~3 per cent of the SDSS area used.

Figure 2. Surface brightness ($\text{mag}_{50}$) versus Petrosian $r$ apparent magnitude. Top panel corresponds to objects in our photometric LRG catalogue and the bottom panel to objects classified as stars in the SDSS DR7 spectroscopic sample that verifies the same selection as the top panel. Top panel shows some distinctive trends for $\text{mag}_{50} < 22$ mag arcsec$^{-2}$ and for $\text{mag}_{50} > 24.5$ mag arcsec$^{-2}$, which contaminate our sample and can modify the clustering signal. Bottom panels make clear that the region of $\text{mag}_{50} < 22$ mag arcsec$^{-2}$ is populated by stars. The region with $\text{mag}_{50} > 24.5$ mag arcsec$^{-2}$ corresponds to badly measured galaxies (not LRGs) and have no impact on our clustering analysis.

Figure 3. Histogram of the number of galaxies per pixel (pixel size of 0.01 deg$^2$) as a function of galactic latitude for different slices in redshift as indicated in the figure. In solid line we plot the histograms when we select galaxies with $18 < \text{mag}_{50} < 24.5$, while in the dash–dotted line we cut $22 < \text{mag}_{50} < 24.5$. Galaxies with low $\text{mag}_{50}$ are contaminating low galactic latitudes ($b \lesssim 25^\circ$).

2.2 Angular mask

We built the angular mask using a HEALPIX pixelization (Górski et al. 2005)\(^6\) over the entire sky with $N_{\text{side}} = 512$ that yields a pixel size of ~0.01 deg$^2$.

We then eliminate from the analysis those pixels where the geometric acceptance of the survey is compatible with bad or no measurement by imposing a minimum number of galaxies per pixel ($N$ pixel$^{-1}$) of 15. We notice that in order to build the mask we use all the objects in the photometric catalogue (i.e. not limiting by petror $< 21$) because the density of LRGs is very low to allow a robust and well-pixelized mask construction. In addition, we look at galactic extinction and magnitude error maps in order to mask badly observed regions. Fig. 4 shows the distribution of errors in $r$-band magnitude averaged in every pixel (i.e. mean error per pixel) in the top panel, and in galactic extinction in the bottom panel. There is a clear correlation between these two quantities in regions of high extinction. Hence, we suppress from our mask pixels with bad mean error rather than applying the cut directly to the LRG selection, as this would imply introducing artificially low density regions and corresponding systematic effects. In summary we discard pixels with extinction higher than 0.2 and mean error higher than 0.3. We have checked that using different pixelization sizes for the mask, as well as different levels of acceptance of a pixel into the mask (varying the threshold in extinction, mean error and $N$ per pixel), does not change the measured angular correlation appreciably.

The resulting angular mask is depicted in the left-hand panel of Fig. 5 in spherical equatorial coordinates, with right ascension (RA) and declination (Dec.) along the $x$ – $y$ axis, respectively. It spans from $\sim 110^\circ$ to $260^\circ$ in RA and $75^\circ$ of Dec. almost fully in the Northern Hemisphere. The vertical band at RA $\sim 172^\circ$ is due to the photo-$z$ used in this analysis (C. Cunha, private communication), which is described in the next section. Notice that we only considered the largest contiguous area of the survey, discarding stripes 76, 82 and 86 that contribute only a small fraction of the total SDSS area.

\(^6\)http://healpix.jpl.nasa.gov
This value-added catalogue was built using and extending the weighting method technique of Lima et al. (2008). As discussed in Lima et al. (2008) and Cunha et al. (2009) the technique aims at estimating the redshift distribution for a photometric galaxy sample (or selected subsamples) rather than estimating individual galaxy redshifts. Hence, as an added value the catalogue provides accurate estimates of the redshift probability distribution, \( p(z) \), of each galaxy.

We applied photo-z quality cuts to the catalogue in order to remove badly defined \( p(z) \) (e.g. double or multiple peaked distributions that can represent outliers) as well as very broad ones (that can be interpreted as galaxies with bad photo-z). To this end we impose two cuts, \(|z_{\text{peak}} - z_{\text{mean}}| < 0.05\) and \(\sigma_z < 0.1\), where \(z_{\text{peak}}\) is the peak of the distribution, \(z_{\text{mean}}\) is computed as \(\int z p(z) \, dz\) and \(\sigma_z = \int (z - z_{\text{mean}})^2 p(z) \, dz\).\(^8\) The first cut eliminates roughly \(\sim 11\) per cent of objects and the second \(\sim 9\) per cent. Imposed together these cuts reduce the sample by \(\sim 16\) per cent. These threshold values in \(\sigma_z\) and \(|z_{\text{peak}} - z_{\text{mean}}|\) were obtained by identifying the tails in the distribution of values for these quantities in the full catalogue. One can of course be more conservative and impose more stringent cuts but at the expense of biasing the population towards brighter objects (that typically have better photo-z) or introduce shot-noise error due to large decrements in the number of galaxies per bin. Our results, in terms of the \(\chi^2\) of the best-fitting models that we obtain, are robust and stable in front of the photo-z quality cut.

In this paper, we split the galaxy sample into redshift bins according to whether the maximum of \(p(z)\) lies in the bin or not. That is, we identify the maximum of \(p(z)\) as the photometric estimate of the true redshift (\(z_{\text{phot}}\)) and do top-hat bins in photometric redshift. In turn, one of the most important ingredients in order to interpret the galaxy clustering signal is a robust estimate of the distribution in true (spectroscopic) redshift, \(N(z)\), of all the galaxies in each bin. Cunha et al. (2009) discuss several methods to obtain \(N(z)\) and shows, using both mock SDSS catalogues and training spectroscopic subsamples, that their best and almost unbiased estimate is provided by the weighted sum of the training distribution (see also Lima et al. 2008), which is equivalent to sum of the \(p(z)\) distributions of all the galaxies in the photometric bin,

\[
N(z) = \sum_{i=1}^{N_{\text{gal,bin}}} p_i(z).
\]

To test the accuracy in this determination of \(N(z)\) we have selected all those galaxies in our sample that are also included in the 2SLAQ spectroscopic catalogue\(^9\) (\(\sim 6000\) objects) and computed their distribution of true redshifts as well as \(N(z)\) according to equation (4). These two distributions are remarkably similar as shown in Fig. 6. A Gaussian fit to each of them shows that their peak differs by less than 1 per cent and their width by less than 9 per cent.\(^{10}\) This difference is in perfect agreement with the intrinsic scatter in true redshift distributions obtained from different photo-z codes (e.g. see table A1 in Thomas et al. 2011b). Notice that we cannot use 2SLAQ to estimate \(N(z)\) for our complete catalogue since our LRG selection is different from that in 2SLAQ (in particular the magnitude cuts). None the less, the previous study shows the degree of unknown in

---

\(^{7}\) Available at http://www.sdss.org/dr7/products/value_added

\(^{8}\) The catalogue provides \(p(z)\) in 100 bins between \(z = 0.03\) and 1.47, hence these integrals are sums over these 100 bins.

\(^{9}\) 2df-SDSS LRG and Quasar (2SLAQ) survey, a stripe close to 0° declination within the imaging area of DR7 (Cannon et al. 2006).

\(^{10}\) Peak and width are defined as the mean and standard deviation of the best-fitting Gaussian distribution.
Figure 5. Left-hand panel: the mask used in this analysis depicted with the HEALPix mollview projection routine. The white regions are excluded from the analysis. Different grey levels display the 81 JK zones used as one of two methods to estimate the errors. The vertical band is due to the photo-z used in this analysis. Right-hand panel: angular density map of the galaxy distribution in the photometric bin [0.5–0.6].

Figure 6. Direct reconstruction of the true redshift distribution for the spectroscopic subsample of our photometric catalogue against the estimate for the same distribution using individual galaxy redshift probability distribution functions (PDF). The spectroscopic subsample was constructed from the 2SLAQ catalogue (Cannon et al. 2006), while PDFs are provided as a part of the DR7 SDSS value-added catalogue of Cunha et al. (2009).

Figure 7. True (spectroscopic) redshift distribution for the bin 0.5–0.6 resulting from the sum of the individual redshift probability distributions. A fit to a Gaussian function (shown in solid black) yields a median of $\mu = 0.549$ and standard deviation $\sigma = 0.062$.

We also consider three narrower redshift bins, with photo-z ranges [0.45–0.5], [0.5–0.55] and [0.55–0.6]. The redshift distribution for these cases is shown in Fig. 8. They are clearly highly correlated and not narrower than the wider top-hat bin discussed above. The number of LRGs in these three bins is 451 753, 317 882 and 346 988, respectively. In addition to an increase of shot-noise and overlap, one expects the estimation of $N(z)$ to be not so robust for a bin narrower than the intrinsic photo-z (possible evidence for this is discussed in Section 4.3). These are the reasons why we decided to concentrate on a single-redshift bin, and repeat our analysis in these three bins as consistency checks.

Redshifts bins lower than $z = 0.45$ and higher than $z = 0.6$ do not have enough number of LRGs to obtain precise measurements of the angular correlation (we find 52845 LRGs in the photometric range [0.4–0.45] and 30412 in [0.6–0.65]). At those extreme bins our measurements also become too sensitive to our cuts (e.g. in galactic latitude and/or photo-z quality). This might be due to various reasons, for example, large magnitude errors that correlate with galactic latitude and lead to large photo-z errors.
The angular correlation function measurements were performed starting from HEALPIX angular maps as described in Section 2.2 ($N_{\text{side}} = 512$, pixel size of $\sim 0.01 \, \text{deg}^2$) and using a standard pixel estimator (Barriga & Gaztañaga 2002; Eriksen et al. 2004)

$$\hat{\omega}(\theta) = \frac{1}{N_{\text{pairs}}(\theta)} \sum_i \sum_j \delta_i \delta_j$$

where $\delta_i = N_{\text{gal}}^i - \bar{N}_{\text{gal}} = 1$ is the fluctuation in number of galaxies in the $i$th pixel with respect to the mean in the angular map, pixels $i$ and $j$ are separated by an angle $\theta$ and $N_{\text{pairs}}(\theta)$ is the corresponding number of pixel pairs. Pixels were weighted by 0 or 1 according to the angular mask discussed in Section 2.2. We have also implemented a standard Landy & Szalay (Landy & Szalay 1993) estimator, and the resulting measured correlations were within 1 per cent of that from equation (5).

The measured correlations in the three bins of width 0.05 as well as in the bin 0.1 are shown in Fig. 9. Error bars displayed in this figure were obtained using jackknife (JK) resampling. In what follows we discuss our different error estimates.

### 3.1 Error estimates

We estimate the error and covariance between angular bins in the measured correlation function using two independent methods.

The exact meaning of excess is only loosely defined in the literature, in general taken to be a roughly more than two sigma difference between model and measurements.
that the distribution of best-fitting values for the bias and growth rate of structure recovered in survey mocks agreed very well with the errors obtained when using equation (7). Furthermore, these studies used an angular mask comparable to the simple geometry treated in this paper.

To compute the angular spectra in equation (7) we assume a cold dark matter ($\Lambda$CDM) cosmology with 7-year Wilkinson Microwave Anisotropy Probe (WMAP) parameters (Komatsu et al. 2011) and use the redshift distributions in Figs 7 and 8. In turn, initial values for large-scale bias $b$ and growth rate $f$ are obtained from a $\chi^2$ minimization using JK errors (see Section 4). Provided with the full $C_\ell$ spectra we then compute the covariance matrix in equation (7) with $f_{\Delta \sigma} = 0.1682$.

Fig. 10 shows the relative error $\Delta w/w$ in the measurement of the angular correlation for our main case bin in photo-z range $[0.5–0.6]$ [where $\Delta w = \text{Cov}(\theta, \theta)^{1/2}$]. The agreement with the relative error recovered from the JK technique is remarkable. Fig. 11 shows instead the reduced covariance matrix, $\text{Cov}_{\text{red}}(\theta, \theta') \equiv \text{Cov}(\Delta w(\theta)\Delta w(\theta'))$, obtained from the data with JK (top panel) and analytically (bottom panel). They show a similar structure, with the JK estimate being more noisy as expected. In addition at large angles ($\theta \gtrsim 3^\circ$) there is a stronger covariance between separated angular bins in the JK estimate probably due to systematics in the data. None the less, as discussed in Section 4, this has no major impact in our study since the recovered best-fitting models (and errors) derived using either JK or analytical estimates for the covariance are in broad agreement. Overall, the underlying reason why the JK and analytical error estimates coincide is due to the fact that the model correlation functions are in good agreement with those measured in the data. This is the subject of the following sections.

### 3.2 Star Contamination

Lastly, we study the star contamination of the sample as a function of the redshift. The quality of the star–galaxy separation is a major concern in photometric catalogues since the broad-band colours of stars can mimic those of galaxies and yield similar photometric redshift estimates and important distortions in the clustering signal. We investigate the degree of contamination in our selected photometric sample performing the same selection (equations 1–3) in the SDSS spectroscopic sample. In addition, we only take the spectroscopic objects that overlap with our angular mask. For the bins where our analysis is performed we find $f_{\Delta \sigma} = 4 \pm 1$ per cent. That is, a negligible dependence with redshift and a broad agreement with the residual contamination found in comparable clustering studies at these redshifts (Sawangwit et al. 2011; Thomas et al. 2011b).

The next step is to estimate the impact of these contaminants on the large-scale angular clustering signal since they introduce a density gradient through the galactic plane. Hence, we measure the correlation function of stars from the SDSS spectroscopic sample, relaxing the cut in $\text{mag}50$ to have enough statistics. We also use the publicly available Tycho-2 star catalogue (Høg et al. 2000a, b) cut to the same selection and mask as our LRG sample to obtain a second estimate of the correlation of stars. Both determinations are in perfect agreement, as presented in Fig. 12, where the lines represent the correlation function for the SDSS sample, and the circles correspond to the Tycho-2 catalogue. This correlation is then included in the theoretical model for $w(\theta)$ taking into account that LRGs and stars are uncorrelated populations, as (see also Myers et al. 2006, 2007):

$$w_{\text{obsamodel}}(\theta, z) = (1 - f_{\Delta \sigma}^2)w_{\text{galmodel}}(\theta, z) + f_{\Delta \sigma}^2w_{\text{starsfit}}(\theta) \quad (8)$$
where $w_{\text{obs,mod}}$ is the model for the ‘observed’ correlation function, $w_{\text{gal,mode}}$ is the model for the true correlation function of galaxies and $w_{\text{obs,fit}}$ is a simple fit to the measured correlation function for stars (see Fig. 12). Notice that in (equation 8) we have removed the explicit dependence of the star fraction and correlation with redshift for simplicity.

4 BIAS AND GROWTH OF STRUCTURE

In this section, we will employ the measured angular correlation function to place joint constraints in the growth rate of structure and bias of the LRG sample.

4.1 Theoretical model

We will use the theoretical model for the angular correlation function presented in Crocce et al. (2011). It was extensively tested against mock catalogues of photometric surveys with specifications similar to our present case. It was shown that the inclusion of RSDs and bias to linear order together with a model for non-linear matter clustering accurately reproduced the measured angular correlation in scales $\theta \gtrsim 0.5$ for redshift bins centred at $z \sim 0.5$. We now recall some basic expressions of the model and refer the reader to Crocce et al. (2011) for further details.

The model angular correlation function is given by

$$w_{\text{gal,mode}}(\theta) = \int dz_1 n(z_1) \int dz_2 n(z_2) \xi^\prime(r_{12})$$

where $r_{12} = r_{12}(z_1, z_2, \theta)$ is the separation of a pair of galaxies at redshift $z_1$ and $z_2$ subtending an angle $\theta$ with the observer. In turn, $n(z)$ is the spectroscopic redshift distribution of the photometric sample under study. Notice that the inclusion of photo-z errors in the theory is solely through $n(z)$ (e.g. Budavári et al. 2003).

Given the area and mean redshift of our sample we are allowed to make the plane-parallel approximation (see Raccanelli, Samushia & Percival 2010 and references therein for discussions of its validity).

In this limit, the redshift-space correlation is given by (Hamilton 1992)

$$\xi^\prime(s, \mu) = \xi_0(s) P_0(\mu) + \xi_2(s) P_2(\mu) + \xi_4(s) P_4(\mu).$$

where $P_n(\mu)$ denote the standard Legendre polynomials, $w(\theta)$ is the model for the ‘observed’ correlation function, $w_{\text{gal,mode}}$ is the model for the true correlation function of galaxies and $w_{\text{obs,fit}}$ is a simple fit to the measured correlation function for stars (see Fig. 12). Notice that in (equation 8) we have removed the explicit dependence of the star fraction and correlation with redshift for simplicity.

Figure 12. Angular correlation function of stars from the SDSS spectroscopic sample (error bars) and the Tychos-2 catalogue (circles) verifying our sample selection and mask. The correlation is well fit by $w_{\text{obs,fit}}(\theta) = 0.0904 - 0.00313\theta$. Displayed error bars correspond to Poisson estimates, $\Delta w = (1 + w)/\sqrt{N_{\text{pupil}}}$ (negligible for Tychos-2).

Figure 13. Angular dependence of the three additive terms making up the model angular correlation. They are proportional to $b^2(z)$, $b(z)f(z)$ and $f^2(z)$ [in units of $\sigma(z)$] and are shown in solid red, dashed blue and dot-dashed black, respectively. Their different shapes make it possible to constrain simultaneously $b(z)$ and $f(z)$. This figure corresponds to our photo-z bin [0.5–0.6].

where $P_r$ denote the standard Legendre polynomials, $s^2 = r^2(z_1) + r^2(z_2) - 2r(z_1)r(z_2) \cos \theta$ and $\mu = (r(z_2) - r(z_1))/s$, with $r(z)$ being the comoving distance to redshift $z$. The $\xi_i$ are the multi-poles of the spatial correlation

$$\xi_0(r) = (b^2 + 2bf/3 + f^2/5)[\xi(r)]$$

$$\xi_2(r) = (4bf/3 + 4f^2/7)[\xi(r) - \xi'(r)]$$

$$\xi_4(r) = (8f^2/35)[\xi(r) + 5/2 \xi'(r) - 72 \xi''(r)]$$

with $\xi' = 3r^{-3}\int_0^r \xi(x)x^2 \, dx$ and $\xi'' = 5r^{-5}\int_0^r \xi(x)x^4 \, dx$. Hence the angular correlation in equation (9) can be written as

$$w(\theta) = (b^2 + 2bf/3 + f^2/5) w_0(\theta)$$

$$+ (4bf/3 + 4f^2/7) w_2(\theta) + (8f^2/35) w_4(\theta),$$

where $w_i(\theta)$ are the bin projection of the functions in square brackets in equation (11). Equation (12) can of course be re-arranged into three terms scaling as $b^2$, $bf$ and $f^2$.

The fact that each of these three terms have a different angular dependence (through the different linear combinations of $w_i$) makes it possible to constrain both $b$ and $f$ at the same time. These terms are displayed in Fig. 13 (without the multiplicative factors involving $b$ and $f$). The BAO is only present in the $\ell = 4$ or ‘real-space’ term determined by the bias. In real space, the correlation becomes negative for scales larger than $\sim 5$. The effect of RSD, in particular of the cross term $bf$, is to make the correlation positive until larger scales, broadening the BAO feature (see also fig. 5 in Crocce et al. 2011). Hence, at these scales the value of $f$ can be degenerate with ‘excess-power’ caused by systematic effects that also make the correlation positive (e.g. extinction, star–galaxy separation or magnitude errors).

4.2 Fits to growth and bias

We will now use the measurements of the angular correlation function and the model described above to investigate the constraining
power of the SDSS LRG photometric catalogue on to the two-parameter space given by the velocity growth factor $f$ and large-scale galaxy bias $b$. Recall, however, that the multipoles $\xi_i$ are arbitrarily normalized to, say, the amplitude of fluctuations $\sigma_8(z=0)$ in spheres of $8 \, h^{-1} \, \text{Mpc}$ (e.g. Song & Percival 2009). Thus, $f$ and $b$ are perfectly degenerate with this normalization and our two parameter space is in fact given by $b(z)\sigma_s(z)$ and $f(z)\sigma_s(z)$, where $\sigma_s(z) = D(z)\sigma_s(z=0)$ and $D(z)$ is the linear growth factor.

Notice that we will not make any assumption for the relationship between the velocity growth factor $f$ and cosmological parameters, but rather take $f$ as a free-parameter. In particular, we will not assume that the underlying theory of gravity is General Relativity (GR; where to a good approximation $f = \Omega_m^0(z)$ and $\gamma = 0.55$) because our ultimate goal is in fact understanding to what extent photometric data can help to constrain GR.

This is different from other works in the literature where constraints from RSDs for $f$ (or $\beta = f/b$) are recast or combined with the ones for $\Omega_m$ assuming GR (e.g. Blake et al. 2007; Padmanabhan et al. 2007; Thomas et al. 2011b; see also Section 4.4). Our approach corresponds to the "free growth" model of Samushia, Percival & Raccanelli (2011).

For the cosmological model we will assume a $\Lambda$CDM universe compatible with WMAP7 (Komatsu et al. 2011) with $\Omega_m = 0.272$, $\Omega_{DE} = 0.728$, $\Omega_b = 0.0456$, $n_s = 0.963$, $h = 0.704$. In our approach, these parameters determine the shape of the real-space matter correlation function and the distance-redshift relation.

As shown in Section 2.3 splitting the data in multiple bins results in samples that are highly correlated. Thus, we decided to focus on a single-redshift bin to present our main results and defer the study of narrow bins to Section 4.3, in the context of robustness and consistency studies.

Hence we concentrate on the bin [0.5–0.6]. This width is about twice the typical photometric error while the centre of the bin makes these data uncorrelated with the SDSS LRG spectroscopic sample (that we refer to later on). The estimate for the true redshift distribution of galaxies in this bin is shown in Fig. 7. Using a spline-fit to it we computed the observed model correlation following (equations 8, 9–12) sampling the two-parameter space given by $f\sigma_s - b\sigma_8$. We then perform a standard $\chi^2$ minimization, where

$$\chi^2(f\sigma_s, b\sigma_8) = \sum_{i,j=1}^{N_m} \Delta w(\theta_i) \text{Cov}_{ij}^{-1} \Delta w(\theta_j) \quad (14)$$

and $\Delta w = w_{\text{obs,model}}(f\sigma_s, b\sigma_8) - w_{\text{measured}}$. To begin with we use the JK covariance. The resulting best-fitting values and $1\sigma$ errors are listed in Table 1 [to convert to $f$ and $b$ one can use that $\sigma_8(0.55) = 0.611$ for our fiducial cosmology if $\sigma_8(z=0) = 0.8$]. The fit yields $\chi^2_{\text{min}} = 26.67$ for 28 bins in $\theta$ in the range [0.6°–6°] and two fitting parameters. Hence the quality of the fit is very good. The joint error distribution is displayed in Fig. 14 and shows that these two parameters are not degenerate. The significance of RSD in our data is $\sim 1.26 \, \sigma$ (i.e. the degree by which the recovered value for $f$ is away from zero).

Alternatively one can assume that the velocity growth rate is given by GR, i.e. $f(z)\sigma_s(z) = \sigma_s(z) \ln D(z)/\ln a = 0.45$ for our fiducial cosmology and $\sigma_s(z=0) = 0.8$, and fit only for the overall amplitude of clustering. In this case we recover a similar $\chi^2_{\text{min}} = 26.7$ and $b\sigma_8 = 1.125 \pm 0.017$. Hence, the fit does not vary appreciably, showing that agreement with standard $\Lambda$CDM is also very good and that the sensitivity of our data to redshift distortions is weak, as expected.

The results so far were obtained assuming 4 per cent star contamination (as discussed in Section 3.2 and equation 8). If we now assume that our sample is perfectly clean of stars ($f_{\text{stars}} = 0$) we get $b\sigma_8 = 1.08 \pm 0.02$ and $f\sigma_s = 0.66 \pm 0.39$ and a $\chi^2_{\text{min}} = 26.87$. This model is hardly differentiable from the case with $f_{\text{stars}} = 4$ per cent (the $\chi^2$ becomes only negligible worse; see Fig. 15). Hence stellar contamination can mimic the effect of RSD and become a worrisome source of systematic effect in future and better data.

In the present case the agreement between the best-fitting value of $f$ and the ‘GR’ value degrades only slightly when $f_{\text{stars}} = 0$, with differences well within the errors. We conclude that the star contamination in our sample is sufficiently under control and does not drive our results.

Fig. 15 shows the resulting best-fitting models discussed above against the measured angular correlation function. In all cases the model matches the data quite well in all the angular range, with no signal of excess clustering on large scales. This is to some extent at variance with the recent study by Thomas et al. (2011b) (see also the follow up Thomas et al. 2011a) who find the amplitude of the angular power spectra of photometric LRGs to have a $2\sigma$ excess clustering away from the $\Lambda$CDM prediction at the lowest multipoles. This result was obtained using the MegaZ catalogue over three redshift bins in the range [0.4–0.65]. The MegaZ catalogue is also build upon the DR7 SDSS photometric catalogue. However, the LRG selection criteria in MegaZ are different from the one in this paper, most notably by the magnitude cuts ($i_{\text{AB}} < 19.8$ in MegaZ compared

### Table 1. Best-fitting values for bias, velocity growth factor and growth rate. Top three rows correspond to the analysis of spectroscopic SDSS LRG data as presented in Cabré & Gaztañaga (2009) and the bottom row to our single-redshift bin using the photometric LRG catalogue.

| Redshift bin | $b(z)\sigma_s(z)$ | $f(z)\sigma_s(z)$ | $dD/da$ |
|-------------|--------------------|--------------------|----------|
| 0.15–0.30   | 1.46 ± 0.16        | 0.49 ± 0.10        | 0.76 ± 0.15 |
| 0.30–0.40   | 1.28 ± 0.08        | 0.42 ± 0.06        | 0.70 ± 0.10 |
| 0.40–0.67   | 1.46 ± 0.16        | 0.50 ± 0.12        | 0.90 ± 0.21 |
| 0.50–0.60   | 1.12 ± 0.02        | 0.53 ± 0.42        | 1.04 ± 0.81 |

© 2011 The Authors, MNRAS 417, 2577–2591. Monthly Notices of the Royal Astronomical Society. © 2011 RAS.

![Figure 14. Two-dimensional constraints in $f \times \sigma_s(z)$ and $b(z) \times \sigma_s(z)$. Dashed line corresponds to the $1\sigma$ marginalized contour ($\Delta \chi^2 = 1$) and solid line to the un marginalized case ($\Delta \chi^2 = 2.3$). In our fiducial cosmology $\sigma_s(z = 0.5) = 0.61$, leading to best-fitting values $f(z = 0.5) = 0.87$ and $b(z = 0.5) = 1.84.$]
to $petror < 21$ in our case), $^{12}$ but also in the colour and $mag_{50}$
cuts intended to isolate stars from galaxies. The photo-$z$ code used
for MegaZ is also different from ours, although both are based on
the artificial neural networks photometric redshifts (ANNz) code
of Collister & Lahav (2004). Sawangwit et al. (2011) also find
an excess clustering when searching for the baryon acoustic scale,
but this result is difficult to compare with ours as they use an
oversimplified method to stack the signal from wider redshift bins
calibrated with different spectroscopic samples.

The constraints recovered so far, albeit large, match the study of
Ross et al. (2011) that forecast how well-redshift distortions
potentially be measured with galaxies selected from a photometric
survey. This match can be clearly seen from their fig. 8 after scaling
the results for a sample of unbiased galaxies binned around $z = 0.5$
by our bias factor $b \sim 2$ [since $\Delta(f\sigma_8) \propto b$]. For our redshift bin
width the forecast yields $\Delta(f\sigma_8) \sim 0.4$–$0.5$, in very good agreement
with the results we obtain with the actual data (e.g. see Table 1). This
implies that systematics, photo-$z$ errors, selection and modelling
can be controlled sufficiently well in present photometric data to
yield expected constraints of redshift distortions. Near future data,
provided with a better handle on systematics due to stars and photo-

$^{12}$ The MegaZ selection is done to match the magnitude cut in 2SLAQ from
where the photo-$z$ calibration is obtained. We find that the angular correlation
of galaxies in MegaZ matches the clustering amplitude in our sample if we
cut in $petror < 20.7$. Hence MegaZ is slightly brighter than our sample.

$z$ should be able to complement shallower spectroscopic surveys in
placing bounds to the growth of structure in the universe.

4.3 Robustness and impact of systematics effects

In this section we investigate different components of our analysis
that could potentially change our results.

Analytical covariance matrix. We now investigate how our re-
sults change when we use the analytical error estimate discussed
in Section 3.1. This estimate accounts for statistical and shot-noise
errors but does not account for systematic errors introduced by, say,
stars (at least in the way presented in Crocce et al. 2011). Hence, we
compute the $C_\ell$ spectra, and $\text{Cov}_{\text{Th}}$, in equation (7) using the best-
fitting values for $f$ and $b$ corresponding to the model with $f_{\text{stars}} = 0$
discussed above. Using this covariance, the best-fitting values
for the angular correlation in the bin [0.5–0.6] change to $h\sigma_8 = 1.13$ $\pm$ $0.02$ and $f\sigma_8 = 0.35$ $\pm$ $0.54$ while the $\chi^2_{\text{min}}$
degrades to 32 (for a model with $f_{\text{stars}} = 4$ per cent). Hence, the change in
the recovered best-fitting values is within half $\sigma$ compared to the results
shown in Table 1. In turn, the error in $h\sigma_8$ is unchanged while that
in $f\sigma_8$ increases by about 25 per cent.

The resulting model matches the data as well as the one derived
using JK errors and the goodness of the fit are comparable. The
only difference is in the resulting error on the velocity growth fac-
tor. This may be due to the structure of the covariance on large

![Figure 15. Angular correlation function in our central bin of width 0.1 centred at $z = 0.55$. Solid red line is our best-fitting model including the effect of star contamination ($f_{\text{stars}} = 4$ per cent). Solid blue line is the corresponding best-fitting model if $f_{\text{stars}} = 0$. The values for $f$ and $b$ are given in Table 1. For reference we include with a dashed black line a WMAP7 ΛCDM model assuming GR, that is with $f$ set to $\Omega_{m,0}^{0.55}$ ($f_{\text{stars}} = 0$ in this case). The inset panel zooms in the region where the baryon acoustic peak is located (see Fig. 18 for the BAO significance). Notably the different models match the data very well in all the range of scales.](https://academic.oup.com/mnras/article-abstract/417/4/2577/1093359)
separations that may be affected by some systematics not captured by the theoretical estimate.

Redshift distribution. One important but difficult to estimate component in clustering analysis of photometric data is the distribution of galaxies in true redshift. In Section 2.3, we studied the degree of uncertainty left in the estimate of $N(z)$, about 1 per cent in the peak position and 9 per cent in the width. To investigate the impact of this systematic in our analysis we computed the model correlation and found best-fitting parameters assuming $N(z)$ is a Gaussian distribution with $\mu = 0.549$ and $\sigma_z = 0.062$ (model 1), that are the best-fitting values to $N(z)$ in Fig. 7. We then recomputed the model by increasing $\mu$ by 1 per cent and decreasing $\sigma_z$ by 9 per cent (model 2), and subsequently did the best-fitting analysis. The $\chi^2$ of these two models is almost equal, changing by $\sim 1$ per cent. The resulting best-fitting values for $b\sigma_8$ decrease from 1.12 $\pm$ 0.02 (for model-1) to 1.08 $\pm$ 0.02 (for model-2), while from 0.76 $\pm$ 0.57 to 0.7 $\pm$ 0.5 for $f\sigma_8$. This is because a narrower $N(z)$ implies less bin projection which leads to a higher amplitude angular correlation and slightly more sensitivity to redshift distortions (Nock et al. 2010; Crocce et al. 2011). These differences are only marginal given the overall large errors provided by present photometric data. However, future surveys will probably need more accurate estimates of $N(z)$.

Narrower redshift bins. As mentioned earlier we have also considered splitting the data into three narrower bins of width similar to the typical photo-z error : [0.45–0.5], [0.50–0.55] and [0.55–0.60]. The galaxy redshift distributions for these bins are shown in Fig. 8 while the measured correlations and best-fitting models are displayed in Fig. 16.

The best-fitting values for the bias in each bin decrease slightly with increasing redshift: $b\sigma_8$ = 1.26, 1.21 and 1.1, respectively (with 2 per cent error).

In turn, the best-fitting values for $f\sigma_8$ are 1.14 $\pm$ 0.57, 0.024 $\pm$ 0.53 and 1.39 $\pm$ 0.46, respectively (assuming $f_{\text{stat}} = 4$ per cent). Hence we see some spread in the recovered values for the velocity growth rate. Compared to the corresponding values in GR they still agree at $\sim 1 - 2\sigma$.

As discussed before a bin width smaller or comparable to the photo-z is subject to large bin to bin migration [in other words, the estimate of $N(z)$ itself is more sensitive to photo-z unknowns]. Therefore, we expect to recover more robust results in bins larger than the underlying photo-z.

4.4 Implications for the growth rate and comparison with spectroscopic studies

We now put our results in context of similar ones derived using spectroscopic data. In Table 1 we show constraints in $b(z)\sigma_s(z)$ and $f(z)D(z)$ as obtained by Cabré & Gaztañaga (2009) using spectroscopic LRGs from SDSS. Table 2 in Cabré & Gaztañaga (2009) lists the best-fitting values of the clustering amplitude $Amp = b(z)\sigma_s$ and $\Omega_m$. This table refers to $\sigma_z$ at $z = 0$ because the best-fitting value of $\Omega_m$ was used to estimate the linear growth $D(z)$ at the corresponding redshift according to standard cosmological equations in GR. Here, we do not want to assume GR or any other relation between $\Omega_m$ and $D(z)$ and we therefore scale these amplitudes back to the original data amplitudes, i.e. $\sigma_s(z)$, by multiplying $Amp$ by the best-fitting value of $D(z)$ in GR. The resulting amplitudes are listed here as $b(z)\sigma_z(z)$ in Table 1. We can then find an estimate of $f(z)\sigma_s(z)$ by just multiplying these $b(z)\sigma_z(z)$ estimates with the values of $\beta$ listed in Table 1 of Cabré & Gaztañaga (2009) for the corresponding samples.

One can turn these values, and those at $z = 0.55$ from the photometric data, into estimates for the linear growth rate of structure as follows:

$$\frac{\partial D}{\partial a} = \frac{D(z)}{a} f(z) = \frac{1 + z}{\sigma_8(0)} f(z)\sigma(z),$$

(15)

where we assume our fiducial value $\sigma_8(0) = 0.8$ (consistent with, e.g., Tinker et al. 2011). Results are listed in Table 1 and displayed altogether in Fig. 17.

These estimates can be used to put constraints in the growth index assuming the $\gamma$-parametrization of the growth, for which $f = \Omega_m(z)^\gamma$ and $\gamma$ is a scale- and redshift-independent constant (Linder 2005). In this case,

$$\frac{\partial D}{\partial a} = (1 + z)D(z)\Omega_m(z)^\gamma$$

(16)
and $D(z) = \exp\left(-\int_0^z \Omega_m(x)'/(1 + x) \, dx\right)$. This yields

$$\gamma = 0.54 \pm 0.17$$

for the combination of spectroscopic and photometric data given in the fourth column of Table 1.

Before moving on we note that novel constraints on the growth rate up to $z = 0.9$ were very recently reported by the WiggleZ survey using blue galaxies instead of LRGs (Blake et al. 2011). At $z < 0.5$ they improve to some extent over the ones we used, e.g. $\Delta(f \sigma_8) = 0.07$ at $z = 0.2$ and $\Delta(f \sigma_8) = 0.04$ at $z = 0.4$ (see Table 1). At $z > 0.5$ they are considerably tighter than those we derive with imaging data, as expected. Yet, for concreteness we have decided to present our results in terms of SDSS LRG clustering (either spectroscopic or photometric) as the focus of the paper is to demonstrate that imaging data are able to yield constraints in RSD.

5 BARYON ACOUSTIC OSCILLATIONS

One of the most important probes of the accelerated cosmic expansion is the existence of an excess clustering imprinted at a well-defined comoving length-scale of about $\sim 100 \, h^{-1}\text{Mpc}$ in the correlation of galaxies and $\sim 1^\circ$ in the one of CMB photons. It originates in the coupling of the baryon–photon plasma prior to recombination and hence can be very well determined with CMB data. This distance scale can also be measured with galaxy data and used to constrain the distance–redshift relation in the local universe, that in turn is sensitive to the nature of dark energy (and/or the appropriate law of gravity). The main obstacle of this pathway is that the excess clustering signal in galaxies represents only $\sim 1$ per cent over that of a random distribution. None the less several surveys are dedicated or include BAO in their scientific plans.

The BAO signature has been extensively studied in the clustering of spectroscopic data, in particular using LRGs since they span the largest volume possible compared to other galaxy types (e.g. Eisenstein et al. 2005; Hütsi 2006; Percival et al. 2007; Cabré & Gaztañaga 2009; Gaztañaga et al. 2009a; Gaztañaga, Cabré & Hui 2009b; Kazin et al. 2010; Percival et al. 2010). The advantage in this case is that one has three-dimensional information to sample this 1 per cent excess of pairs. The disadvantage is that the sampling of the overdensity field is much more poorer with spectra and is eventually limited to lower redshifts when compared to photometric catalogues (which on the converse only yield projected quantities with lower significance). Hence it is very important to investigate what evidence for this signature is already present in our data given the number of such photometric surveys already undergoing or planned for the near-future.

The use of photometric data to investigate BAO has been relegated to some extent, probably due to the lower signal-to-noise ratio, the impact of systematics and the quality of the photo-z. In Blake et al. (2007) and Padmanabhan et al. (2007), this signature was studied stacking photometric redshift bins in order to reconstruct the 3D spectrum. Both studies find evidence for BAO at $\approx 3\sigma$. In turn, only Sawangwit et al. (2011) (to our knowledge) have explored the possibility of locating the signature in configuration space, with ambiguous results (e.g. too high in amplitude compared to $\Lambda$CDM expectations).

We will now investigate how well our measurements agree with the shape of the model correlation including or excluding the effect of baryons. In a separate paper we present a detailed analysis of the significance and implication of the baryon acoustic peak imprinted in the angular clustering of our sample (see Carnero et al. 2011).

Fig. 18 shows the measured angular correlation in the photo-z bin $[0.5–0.6]$ in a way that highlights the shape of $w(\theta)$ at large angular scales. We also display the standard Eisenstein & Hu (1998) model prediction including the baryons effect (solid blue) and excluding it, i.e. with the wiggles smoothed out (solid red). Fig. 18 shows a quite clear bump in the correlation function at $\theta \sim 4^\circ$, in very good agreement with the model in both shape and location. For this figure we have not attempted to fit for redshift distortion parameter.
f(z) as in Section 4.2 but rather have assumed GR [f(z = 0.55) = 0.74] and fit for the overall bias only (with fixed cosmological parameters as given in Section 4.2). We note that the ‘BAO’ model correlation obtained with the approximation of Eisenstein & Hu (1998) is very similar to the one derived with Code for Anisotropies in the Microwave Background (CAMB) in Section 4.2.

To estimate the statistical significance of this feature we compare the two best-fitting models, with and without BAO. The difference in their χ² yields 5.4 suggesting that the BAO model is preferred with a significance ~2.3σ (~98 per cent confidence). Notice that both models have the same number of degrees of freedom since only the bias is fit. This result is unchanged if we allow for 4 per cent star contamination in both models and is in perfect agreement with the finding of Carnero et al. (2011) using a completely independent analysis method.

Although the significance is low the good agreement with ΛCDM expectations is very encouraging for future photometric campaigns that will achieve better error bars thanks to improved photo-z survey depth. In addition, this is, to our knowledge, the first time the BAO bump is clearly depicted in agreement with ΛCDM predictions in the angular correlation of photometric LRG data at this high redshift.

6 CONCLUSIONS

In this paper we used the angular correlation function of the imaging sample of LRGs in the DR7 of the SDSS as a testing ground for measuring the growth rate of expansion through RSDs using photometric data. In addition, we investigated the evidence for the baryon acoustic feature in the angular correlation.

We put a strong emphasis in the selection of the galaxy sample and overall robustness against several systematic effects, such as magnitude errors, bad extinction zones, photo-z outliers and more. We paid particular attention to the impact of stellar contamination in the angular clustering measurements. On the one hand, we minimized such contamination introducing a cut in surface brightness, maggo. On the other hand, we estimated the distortion that the residual contamination introduces in the correlation measurements.

Our measured correlation, in the range [0.50–0.60], is in good agreement with expectations from standard ΛCDM. In particular, it shows no excess clustering on the largest scales, contrary to other works in the literature. This is an encouraging proof that systematic effects in photometric data can be controlled sufficiently well to use them as a cosmological tool (Blake et al. 2007; Padmanabhan et al. 2007; Thomas et al. 2011b). The distortions introduced by the intrinsic clustering of contaminating stars does not change our results but might become a worrisome source of systematic biases in future surveys with smaller error bars. A similar conclusion was reached with regard to the estimation of the true redshift distribution of the sample.

Indeed, we found that RSDs can be measured using photometric data, albeit with large error bars due to the high bias of the sample and the poor photo-z error. Our results are in very good agreement with the recent forecast by Ross et al. (2011). Hence, this paper can be taken as a validation of the forecast for an SDSS like case as presented in Ross et al. (2011) and a proof-of-concept of the promising expectations for upcoming photo-z surveys such as DES, Euclid and PanStarrs.

In addition, we found quite strong evidence for the baryon acoustic peak in the measured angular correlation, something not observed before. The shape, amplitude and location of the BAO feature are in very good agreement with ΛCDM expectations yielding a ~2.3σ significance over a model without BAO. In a separate work (Carnero et al. 2011), we discuss this detection of BAO and its cosmological implication using an independent analysis from the one presented here.

Overall, our results strengthen the expectations on the ability of future photometric surveys to compete and/or complement spectroscopic data, as well as to serve to other approaches such as weak lensing or supernovae, in the quest to understand the nature of cosmic acceleration.

ACKNOWLEDGMENTS

We are thankful to Carlos Cunha for his help with photo-z. Funding for the SDSS and SDSS-II was provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory and the University of Washington.

We thank the Spanish Ministry of Science and Innovation (MICINN) for funding support through grants AYA2009-13936-C06-01, AYA2009-13936-C06-03, AYA2009-13936-C06-04 and through the Consolider Ingenio-2010 program, under project CSD2007-00060.

REFERENCES

Abazajian K. N. et al., 2009, ApJS, 182, 543
Bariggs J., Gaztañaga E., 2002, MNRAS, 333, 443
Blake C., Bridle S., 2005, MNRAS, 363, 1329
Blake C., Collister A., Bridle S., Lahav O., 2007, MNRAS, 374, 1527
Blake C. et al., 2011, MNRAS, 415, 2876
Budavári T. et al., 2003, ApJ, 595, 59
Cabré A., Gaztañaga E., 2009, MNRAS, 393, 1183
Cabré A., Gaztañaga E., Manera M., Fosalba P., Castander F., 2006, MNRAS, 372, L23
Cabré A., Fosalba P., Gaztañaga E., Manera M., 2007, MNRAS, 381, 1347
Cannon R. et al., 2006, MNRAS, 372, 425
Carnero A., Sánchez E., Crocce M., Cabré A., Gaztañaga E., 2011, MNRAS, in press (arXiv:1104.5426)
Colless M. et al., 2001, MNRAS, 328, 1039
Collister A. A., Lahav O., 2004, PASP, 116, 345
Crocce M., Cabré A., Gaztañaga E., 2011, MNRAS, 414, 329
Cunha C. E., Lima M., Oyaizu H., Frieman J., Lin H., 2009, MNRAS, 396, 2379
Drinkwater M. J. et al., 2010, MNRAS, 401, 1429
Eisenstein D. J., Hu W., 1998, ApJ, 496, 605
Eisenstein D. J. et al., 2001, AJ, 122, 2267
APPENDIX A: EXCESS POWER FOR $z > 0.6$

One frequent issue when analysing the clustering of LRGs is the fact that at the largest scales (e.g. BAO) the amplitude of clustering appears generally high when compared to standard $\Lambda$CDM models (Eisenstein et al. 2005; Blake et al. 2007; Padmanabhan et al. 2007; Okumura et al. 2008; Cabré et al. 2009; Sánchez et al. 2009; Kazin et al. 2010; Samushia et al. 2011; Sawangwit et al. 2011). The significance of this mismatch is, however, uncertain since these scales are expected to be the most sensitive to different systematic uncertainties as well as the ones with largest statistical variance.

Within the context of photometric data as in our work, Thomas et al. (2011a,b) recently found $\sim 2\sigma$ excess in the lowest multipoles of the angular power spectrum of LRGs in the MegaZ catalogue of DR7 SDSS. As discussed in Section 4, we do not find such a discrepancy in our catalogue. More so if one recalls that in configuration space data points are expected to co-variate to some level. Potentially much more worrisome is their finding of $\sim 4\sigma$ excess for the bin $[0.6-0.65]$ (see also Blake et al. 2007). Thomas et al. (2011a) performed a series of checks for systematic errors but none was conclusively the source of such an effect that led them to speculate with the possibility that this could be due to the imprint of ‘new physics’, such as primordial non-Gaussianities, modifications of gravity or clustering dark energy.

In Fourier space, this excess may not be prejudicial because it only affects few low-$\ell$ multipoles that can be cut-out of the analysis (they have the lowest signal-to-noise ratio anyway). When translated to configuration space this impacts a broad range of scales. Hence, it is interesting to see how does the clustering in configuration space looks like at $z \geq 0.6$ to complement the study of Thomas et al. (2011a,b).

In Fig. A1 we show the measured angular correlation function for our photometric bin $[0.6-0.65]$. Evidently, the clustering signal does not only show an excess power at BAO scales but is in fact also anomalous at all scales (except perhaps $\theta < 0.5$). On the one hand, the number of objects in this bin is small ($\sim 30\,000$) and dominates the error budget (shot-noise). On the other hand, the correlation is very sensitive to various systematic uncertainties. This is reflected in Fig. A1: the solid magenta line corresponds to the measured correlation when no cut in galactic latitude is imposed. Blue solid line is the result when objects with ‘bad’ photo-$z$ are discarded from the sample (as discussed in Section 2.3). Lastly, solid red line is the result when the mask is reduced by leaving out low galactic latitudes $b < 25^\circ$ (to avoid star contamination; see Section 2.1). One could continue with more stringent constrains but the signal does not approach the one at lowest bins (shown with black symbols). Displayed error bars in this figure were obtained with the JK estimate.
This result signals to unknown systematic uncertainties as the most probable cause for the anomalous shape. One possibility could be an incomplete treatment of the distortions introduced by star contamination. The contamination by stars results in a change of the mean density across the survey area (and towards the galactic plane). This would impact only the low-\ell spectra that encodes the mean density information but a broad range of scales in the angular correlation (as shown in Fig. 12). However, testing this in Fourier space is beyond the scope of this paper and will be discussed elsewhere.