The BOSS-WiggleZ overlap region II: dependence of cosmic growth on galaxy type

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ABSTRACT

The anisotropic galaxy 2-point correlation function (2PCF) allows measurement of the growth of large-scale structures from the effect of peculiar velocities on the clustering pattern. We present new measurements of the auto- and cross-correlation function multipoles of 69,180 WiggleZ and 46,380 BOSS-CMASS galaxies sharing an overlapping volume of \( \sim 0.2 \ (h^{-1}\text{Gpc})^3 \). Analysing the redshift-space distortions (RSD) of galaxy 2-point statistics for these two galaxy tracers, we test for systematic errors in the modelling depending on galaxy type and investigate potential improvements in cosmological constraints. We build a large number of mock galaxy catalogs to examine the limits of different RSD models in terms of fitting scales and galaxy type, and to study the covariance of the measurements when performing joint fits. For the galaxy data, fitting the monopole and quadrupole of the WiggleZ 2PCF on scales \( 24 < s < 80 \ h^{-1}\text{Mpc} \) produces a measurement of the normalised growth rate \( f\sigma_8(z=0.54) = 0.409 \pm 0.059 \), whereas for the CMASS galaxies we found a consistent constraint of \( f\sigma_8(z=0.54) = 0.406 \pm 0.074 \). When combining the measurements, accounting for the correlation between the two surveys, we obtain \( f\sigma_8(z=0.54) = 0.413 \pm 0.054 \), in agreement with the \( \Lambda \)CDM-GR model of structure growth and with other survey measurements.

Key words: cosmology - large scale structure

1 INTRODUCTION

The evolution of the spatial distribution of galaxies on large scales is deeply influenced by the physics of gravitational attraction, cosmic expansion, and the conditions of the early Universe, and constitutes an important probe and discriminator of cosmological models. Spectroscopic galaxy surveys map this distribution using the distance-redshift relation, but due to peculiar velocities induced by the gravitational field, these maps also contain ‘redshift-space distortions’ (RSD) of the spatial positions of the galaxies, which modify the true (i.e., real space) pattern of the spatial clustering of galaxies. Kaiser (1987) showed that on large scales the peculiar velocity field \( \mathbf{v} \) (in dimensionless units of the Hubble velocity) is related to the matter overdensity \( \delta_m \) as \( \nabla \cdot \mathbf{v} = -f\delta_m \), where the proportionality parameter \( f(z) \) is called the linear growth rate of structure. Modelling the redshift-space clustering, in consequence, allows us to constrain cosmological parameters through estimations of \( f(z) \). Using Kaiser’s findings, the pioneering works in the 2dFGRS survey (Peacock et al. 2001; Hawkins et al. 2003) in the local \( z \sim 0.1 \) Universe, measured the redshift-space two-point clustering of galaxies, which resulted in a confirmation of the concordance \( \Lambda \)CDM model at present times. With the advent of galaxy surveys at higher redshifts, we can now trace the history of \( f(z) \) and obtain constraints on cosmological models and the nature of dark energy (Linder & Cahn 2007).

However, important challenges must be addressed before we can use this tool effectively. On the observational side, the most important factors limiting the statistical precision of the clustering measurements obtained from different surveys are the limited volume that the surveys can map, due to the sample variance from fluctuations in the clustering on different regions of the universe, and the discreteness of the galaxy field known as shot noise (e.g. Kaiser 1986; White et al. 2009).

In addition, large-scale structures are subject to a variety of systematic non-linear effects which affect our capacity to model the signal, particularly on small scales. First,
we have non-linear growth of structure, such that even on large scales, the Kaiser relations are insufficient to account for the measured clustering in galaxy data and simulations. Peacock (1992), and more recently Scoccimarro (2004); Taruya et al. (2010); Seljak & McDonald (2011); Wang et al. (2013), among others, have improved the basic ‘Kaiser’ model by including various non-linear effects in the matter clustering. Second, there is scale-dependent complexity in how galaxies trace haloes and cross-correlate to matter, known as galaxy bias. Third, galaxies possess non-linear pairwise velocities on small scales. The latest attempts to use the 2-point clustering pattern to model RSD have taken these and other effects into account (e.g. Reid et al. 2012; Beutler et al. 2012; Sánchez et al. 2013; de la Torre et al. 2013; Contreras et al. 2013; Beutler et al. 2014, as recent examples), allowing us to confront predictions from different cosmological models.

Although in linear theory all galaxies respond as test particles to the gravitational field, in detail the non-linear systematics depend on tracers themselves. This is because galaxy formation is affected by many non-linear processes such as small-scale dynamics of halo formation, environment, and complex baryonic processes determining the luminosity and colour at a given time, which are the main observables when selecting galaxies for a large-scale survey. Therefore, the analysis and modelling of two overlapping tracers makes it possible to constrain details of the clustering and formation of the galaxy tracers themselves. Previous work has focused on cross-correlating a tracer with well known properties with a section galaxy tracers themselves. This is because galaxy for-

2013; de la Torre et al. 2013; Contreras et al. 2013; Beutler et al. (2010); Seljak & McDonald (2011); Wang et al. (2013), including various non-linear effects in the matter clustering. Sec-

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2 DATA & MOCK CATALOGS

2.1 The WiggleZ survey

The WiggleZ Dark Energy Survey (Drinkwater et al. 2010) is a large-scale galaxy redshift survey performed over 276 nights with the AAOmega spectrograph (Sharp et al. 2006) on the 3.9m Anglo-Australian Telescope. With a area coverage of 816 deg², this survey has mapped 207,000 bright emission-line galaxies over a redshift range 0.1 < z < 1.0. Target galaxies in six different regions were chosen using UV photometric data from the GALEX survey (Martin et al. 2005) matched with optical photometry from the Sloan Digital Sky Survey (SDSS DR4, Adelman-McCarthy et al. 2006) and from the Red-Sequence Cluster Survey 2 (RCS2, Gilbank et al. 2011). The selection criteria consisted of applying magnitude and colour cuts (Drinkwater et al. 2010) in order to select star-forming galaxies with bright emission lines with a redshift distribution centered around z ∼ 0.6. The selected galaxies were observed in 1-hour exposures using the AAOmega spectrograph, and their redshifts were estimated from strong emission lines. The number density of WiggleZ galaxies averages ∼ 3 × 10⁻⁴ (h⁻¹Mpc)⁻³ at z = 0.6.
2.2 The CMASS Sample

The Baryon Oscillation Spectroscopic Survey of the Sloan Digital Sky Survey III (SDSS-III, Eisenstein et al. 2011; Dawson et al. 2013), which is now complete, was designed to obtain spectra and redshifts for 1.35 million bright galaxies over a footprint $\sim 10,000$ deg$^2$. These galaxies are selected from the SDSS-III imaging and have been observed together with 160,000 quasars and 100,000 ancillary targets (Gunn et al. 2006; Bolton et al. 2012; Smee et al. 2013). The CMASS sample is composed of luminous, mostly red galaxies selected to probe large-scale structure at intermediate redshifts, achieving a number density of $\sim 3 \times 10^{-4}$ ($h^{-1}$Mpc)$^{-3}$. The DR11 catalog (Alam et al. 2015) includes 1,100,000 spectra out of which the CMASS sample contains $\approx 550,000$ galaxies in the redshift range $0.43 < z < 0.7$.

2.3 Overlap volumes

We define the overlap regions between CMASS and WiggleZ using the random galaxy catalogs generated for each survey, gridding the sky into 0.1 deg$^2$ regions and selecting cells containing both CMASS and WiggleZ random points. As seen in Figure 1, five of the six WiggleZ regions have considerable overlap with CMASS galaxies, totalling 560 deg$^2$ and a volume of 0.218 ($h^{-1}$Gpc)$^3$ in the $0.43 < z < 0.7$ range. This results in an overlap sample of 69,180 WiggleZ galaxies and 46,380 CMASS galaxies.

Figure 2 shows the redshift distribution of the two samples in the different regions, which is similar in the range $0.5 < z < 0.6$; outside that range the CMASS galaxy counts rapidly decline. To estimate how these differences will affect our results, we calculate the pair-weighted redshift, which consists in taking the average redshift of all pairs at a particular distance range. For the distance range $s = 20 - 35$ $h^{-1}$Mpc, where the signal of the clustering signal is higher, WiggleZ-BW galaxies have a pair weighted redshift of $z_{\text{WiggleZ-BW}} = 0.56$ whereas for CMASS-BW galaxies $z_{\text{CMASS-BW}} = 0.53$. For cross-pairs this redshift is $z_{\text{avg, x}} = 0.54$. These small differences in redshift will not affect our findings given the measurement errors, therefore we generate cosmological models at

$z_{\text{avg, x}} = 0.54$ to compare with our WiggleZ-CMASS clustering data. Table 1 presents details of the samples used.

2.4 Simulations and mock catalogs

We estimate the covariance of our measurements and test the regime of validity of our RSD models using mock galaxy catalogs built from N-body simulations. The conventional methods to generate N-body simulations do not allow for the generation of a large number of realisations of cosmological volumes at sufficient mass resolution to encompass the low-mass halos hosting WiggleZ galaxies, which are needed for constructing robust covariance matrices. For this reason we use an approximate, fast method to generate dark matter simulations based on the COmoving Lagrangian Acceleration method (COLA, Tassev, Zaldarriaga, & Eisenstein 2013). We have developed a parallel version of COLA (Koda et al., in preparation, used first in Kazin et al. 2014), where in each simulation contains 1296$^3$ particles in a box of side 600$h^{-1}$Mpc, which gives a particle mass of $7.5\times 10^9 h^{-1}M_\odot$, allowing resolution of low-biased halos with masses $10^{12} h^{-1}M_\odot$, found using friends-of-friends
Table 1. Overlapping samples analysed in this study.

| Region   | WiggleZ-BW | WiggleZ-BW | CMASS-BW | CMASS-BW | Cross-pairs |
|----------|-------------|-------------|-----------|-----------|-------------|
|          | $N_{gal}$   | $z_{avg}$   | $N_{gal}$ | $z_{avg}$ | $z_{avg}$   |
| S01      | 6620        | 0.61        | 5720      | 0.53      | 0.57        |
| N09      | 13940       | 0.56        | 9360      | 0.53      | 0.54        |
| N11      | 15560       | 0.55        | 10580     | 0.53      | 0.54        |
| N15      | 22740       | 0.56        | 14660     | 0.54      | 0.54        |
| S22      | 10320       | 0.55        | 6060      | 0.53      | 0.54        |
| Total    | 69180       | 0.56        | 46380     | 0.53      | 0.54        |

![Figure 3. Projected correlation function $w_p(r_p)$ for WiggleZ and CMASS galaxies in the overlap regions (symbols). Lines are the mean values of $w_p(r_p)$ for the COLA mock catalogs.](image)

3 MEASUREMENTS

3.1 Measuring Correlation Functions

We estimate the redshift-space two-point correlation function $\xi(s, \mu)$ (2PCF) as a function of comoving separation $s$ and the cosine of the angle of the distance vector with respect to the line of sight $\mu = \cos(\theta)$. We use the Landy & Szalay (1993) estimator, counting pairs of objects in data and random catalogs:

$$\xi_{\text{auto}}(s, \mu) = \frac{DD(s, \mu) - 2DR(s, \mu) + RR(s, \mu)}{RR(s, \mu)},$$

(1)

where $DD$, $DR$ and $RR$ are respectively the weight-normalised data-data, data-random and random-random pairs with separation $s$ and $\mu$ (with a given resolution $\Delta s$, $\Delta \mu$). For both the random and data catalogs we use the optimal (inverse-density) FKP weighting (Feldman et al. 1994):

$$w_i(x) = \frac{1}{1 + n(x)P_0}$$

(2)

where $P_0 = 5000$ (h$^{-1}$Mpc)$^3$ for WiggleZ-BW and $P_0 = 20000$ (h$^{-1}$Mpc)$^3$ for CMASS-BW galaxies. For WiggleZ galaxies, angular incompleteness and radial selection are introduced in the random catalogs (Blake et al. 2010). A small fraction of galaxies contain errors in the redshift assignment, but this effect is absorbed into the fitted galaxy bias factor. CMASS galaxies, have additional weights applied to account for the angular incompleteness, fibre collisions, redshift failure and correlation between density of targets and density of stars (Ross et al. 2012).

It is possible to model the 2PCF using the full information from $\xi(s, \mu)$, but that requires a large covariance matrix with the associated problems with its inversion. For this reason it is standard to compress this information in multipoles

$$\xi_l(s) = \frac{2l + 1}{2} \int_{-1}^{1} \xi(s, \mu) L_l(\mu) d\mu,$$

(3)

where $L_l$ is the Legendre polynomial of order $l$. In practice we approximate eq. (3) by a discrete sum over the binned $\xi(s, \mu)$, where we use $\Delta s = 4$ h$^{-1}$Mpc and $\Delta \mu=0.01$ for every WiggleZ-BW and CMASS-BW region. We use the monopole ($l = 0$) and quadrupole ($l = 2$) of the 2-point functions, to analyse the redshift-space distortions, for separations $s < 80$ h$^{-1}$Mpc. Our results are unchanged if large separations are used, whilst the increase in variance due to the finite number of mocks becomes significant.

The covariance of each region is estimated from the mock WiZCola and BOSScola catalogs (see section 3.3). After calculating the covariances of the measurements in each overlap region from the COLA mock catalogs, we use inverse-variance weighting to obtain the ‘optimally combined’ measurements. For the statistic $\xi_{l,\text{comb}}(s)$, the optimally combined function is calculated as

$$\xi_{l,\text{comb}}(s) = C_{\text{comb}}^{-1} \sum_{i=1}^{N_{\text{reg}}} C_i^{-1} \xi_i(s)$$

(4)

where $C_{\text{comb}}$ is the overall covariance matrix, calculated from the estimations of the covariance matrices of individual regions $C_i$ (see section 3.3). Results for the auto-2PCF’s are shown in Figure 4, for individual regions (as lines) and for the combined
measurements (as symbols). The different amplitude of clustering of the WiggleZ-BW and CMASS-BW galaxies reflects the difference in the type of halos these galaxies inhabit. Due to the limited volume where the correlations are measured, we correct our correlation function values by the ‘integral constraint’ (Peebles 1980; Beutler et al. 2012). The corrections to the WiggleZ and BOSS correlations differ in each region and have values of the order of 8×10^{-4} and 1×10^{-3} respectively for the smaller regions (where the integral constraint is higher), and do not significantly affect the RSD model constraints.

### 3.2 Cross-correlations between WiggleZ-BW and CMASS-BW clustering

In addition to the auto-correlations, we also measured the cross-correlation between the two sets for tracers using the estimator

\[ \xi_{\text{cross}}(s, \mu) = \frac{D_W D_C - D_W R_C - R_W D_C + R_W R_C}{R_W R_C}, \]

where the W and C subscripts represent the quantities in the WiggleZ and CMASS galaxies, respectively. The cross-correlation function measurement provides an independent validation of the assumption that both galaxy types trace the same large structures on a range of scales, and also serves to test our linear and local galaxy bias model.

To test the strength of the correlation between the tracers is, we also constrain the cross-correlation coefficient, \( r_x \), which is produced from the relation

\[ \xi_{\text{WiggleZ-vmass}}(s) = r_x(s) \xi_{\text{WiggleZ}}(s) \xi_{\text{CMASS}}(s), \]

This corresponds to a correlation coefficient where the WiggleZ and CMASS galaxies, respectively. The cross-correlation between the two sets for tracers using the estimator

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Assuming \( b_W = 1 \) and \( b_C = 2 \) (Reid et al. 2012; Contreras

\[ r_{x,Kaiser} = \frac{1 + \frac{1}{2}(\beta_W + \beta_C) + \frac{1}{2}b_W b_C}{\sqrt{(1 + \frac{1}{2}b_W + \frac{1}{2}b_C) (1 + \frac{1}{2}b_W + \frac{1}{2}b_C)}} \]

assuming \( r_x \) is not too large, and assuming linear, deterministic bias, this quantity should tend to the value (Mountrichas et al. 2009):
et al. 2013), and a growth rate \( f(z = 0.54) = 0.75 \), when estimating \( \beta = f/b \), it is expected that \( r_s,\text{Kaiser} = 0.997 \sim 1 \).

We measure the value of \( r_s \) from our data, assuming it is a constant on all scales (an assumption we do not expect to hold on scales smaller than \( 15 - 20 \, h^{-1}\, \text{Mpc} \)). Using the redshift space distortion model described in section 4.1, and the COLA mocks to build our covariance matrix, we use the correlation monopoles to fit for the bias parameters of the WiggleZ-BW and CMASS-BW galaxies and \( r_s \) for each overlap region and the joint likelihood (see section 4.3 for details of the fitting procedure).

Figure 5 presents the posterior probability distribution of \( r_s \), as a function of the minimum scale of fit \( s_{\text{min}} \). Focusing on the fits to the combined regions, we can see that they are not consistent with \( r_s = 1 \) at the 2\sigma level on scales \( s_{\text{min}} \sim 20 \, h^{-1}\, \text{Mpc} \). This behaviour may be explained by a number of factors such as non-linear pairwise velocities, non-linear bias and stochasticity. CMASS galaxies tend to be hosted in the centres of large halos and in high density regions, precisely the regions that are avoided by WiggleZ galaxies. We expect that on large scales both galaxies trace similar structures, and this is confirmed in the measurements of \( r_s \) being consistent with 1 when fitting on large scales.

Examining individual regions it can be noticed that it is region S22 which reduces the overall fit to \( r_s \). Its lower value of \( r_s \) is driven by a high auto-correlation function in the WiggleZ-BW S22 region, although the scatter is compatible with the variance against mock catalogs. The best fits to the growth rate do not significantly change when the S22 region is excluded, and in the final fits we include all regions.

### 3.3 Covariance estimation

We estimate the correlations between the multipoles of the auto- and cross-2PCF by calculating the covariance matrix in each region \( n \) from COLA mocks. A deviation from the mean of a quantity \( X \), in separation bin \( i \), for the mock \( k \) can be written as

\[
\Delta_i^k = X_i^k - \langle X_i \rangle
\]

where, in our case, \( X \) corresponds to the monopole or quadrupole of the auto- or cross-2PCF in each bin. The covariance matrix of each region \( n \) is determined as

\[
C_{n,ij} = \frac{1}{N_{\text{mocks}}} \sum_{k=1}^{N_{\text{mocks}}} \Delta_i^k \Delta_j^k
\]

After calculating \( C_n \) for all regions, we can determine the combined covariance matrix (Blake et al. 2011a)

\[
C^{-1}_{\text{comb}} = \sum_{n=1}^{N_{\text{reg}}} C_n^{-1}
\]

Figure 6 shows the correlation matrix (normalised covariance matrix) for all our measurements, showing the strong correlation between the measurements of the two tracers.

Since we used a large, but finite number of mock catalogs for the covariance estimation, there is an underestimation of the uncertainties. Following the work of Hartlap et al. (2007); Percival et al. (2014), we correct for the finite number of mocks by multiplying the variance estimated from the likelihood distribution by

\[
m_a = \frac{1 + B(N_{\text{bins}} - N_p)}{1 + 2A + N(N_p + 1)}
\]

where \( N_{\text{bins}} \) is the number of bins entering the fits, \( N_p \) is the number of free parameters, and

\[
A^{-1} = (N_{\text{mocks}} - N_{\text{bins}} - 1)(N_{\text{mocks}} - N_{\text{bins}} - 4),
\]

\[
B = A(N_{\text{mocks}} - N_{\text{bins}} - 2),
\]

where \( N_{\text{mocks}} \) is the number of mock realisations. Also, the sample variance should be multiplied by

\[
m_v = m_a \frac{N_{\text{mocks}} - 1}{N_{\text{mocks}} - N_{\text{bins}} - 2}
\]

We use \( N_{\text{mocks}} = 480 \) and perform measurements in separation bins up to \( s = 80 \, h^{-1}\, \text{Mpc} \). From constraining models using one-tracer auto-correlation function multipoles to simultaneous fits using both auto and cross correlations, the \( m_a \) factor lies in the range \( m_v = 1.1 - 1.45 \).

### 4 CONSTRAINTS ON COSMIC GROWTH

#### 4.1 Modelling the RSD

Redshift-space distortions modify the 2-point clustering of galaxies on both large and small scales, which we will summarise here. Due to its peculiar velocity \( v \), a galaxy at a position in real space \( r \) gets mapped to \( s \) in redshift space:

\[
s = r + \frac{(1 + z)v \cdot \hat{r}}{H(z)} \hat{r}
\]

where \( \hat{r} \) is the galaxy unit vector along the line of sight (LOS) direction, \( v \) is the line-of-sight component of its velocity, and \( H(z) \) is the Hubble parameter at a redshift \( z \).

On large scales, as described by Kaiser (1987), hereafter KS7 (also see Hamilton 1998 for derivations in configuration space), matter overdensities \( \delta_m \) grow coherently as \( \nabla \cdot \mathbf{v} = -f \delta_m \) where \( f \equiv d\ln G(a)/d\ln a \) is the linear growth rate of fluctuations. The evolution of the growth rate in certain models can be approximated by the evolution of the matter
density in the universe $f(z) = \Omega_m(z)^{\gamma}$, where $\gamma = 0.55$ in the case that the large-scale gravity obeys General Relativity; for alternative theories of gravity, $\gamma$ can take on different values (Linder & Cahn 2007). If we assume that the difference in clustering between dark matter and galaxies can be described by a linear bias model where $\delta_g = b_s \delta_m$ then in Fourier space the redshift space galaxy overdensity takes the form

$$\delta_g(k) = (b + f_\sigma^2)\delta_m(k),$$

(16)

creating in configuration space the so-called ‘squashing’ effect on large scales.

On small scales, in the non-linear regime for overdensities and velocities, large structures appear elongated along the line of sight, creating the observed ‘Fingers of God’. In Fourier space this effect can be modelled by multiplying a Gaussian or a Lorentzian pairwise velocity distribution (i.e. a convolution of a Gaussian or an exponential profile in configuration space) into the large-scale redshift-space distortion of the power spectrum. The simplest model, using Gaussian damping for the galaxy power spectrum in redshift space, is

$$P^*(k, \mu) = (b + f_\sigma^2)P_m(k)e^{-(k\mu v/H)^2},$$

(17)

where, in the K87 formalism, $P_m = \delta_m$. However, this simple model has been shown in simulations to be insufficiently accurate even on large scales, because there is not a perfect correlation between density and the velocity (divergence) field (e.g. Okumura & Jing 2011; Kwan et al. 2012; de la Torre & Guzzo 2012; White et al. 2014). Scoccimarro (2004), hereafter S04, suggested a modification of the simple Kaiser formalism by including the velocity field terms. In the case of one tracer, the RSD in the galaxy auto-power spectrum reads:

$$P^*(k, \mu) = (b + f_\sigma^2)P_m(k) + \mu^2 f^2P_\delta(k) + \mu^2 f^2P_\sigma(k)e^{-(k\mu v/H)^2},$$

(19)

where $P_\delta$, $P_\sigma$ and $P_\theta$ are the non-linear matter-density, density-velocity and velocity-velocity power spectra, respectively. In our analysis, these terms are obtained from fitting formulae derived by Jennings (2012), from a suite of N-body simulations. In this case our fiducial model (based on WMAP5 results, see §1) predicts (via Eq.18) the large-scale velocity dispersion $\sigma_v$ to be $\sigma_v(z = 0.6) \sim 220$ km/s. However, we choose to leave $\sigma_v$ as a free parameter to account for any additional non-linearities on smaller scales. Whilst there are additional improvements and implementations of RSD models (e.g. Taruya et al. 2010; Seljak & McDonald 2011; Reid & White 2011; Wang et al. 2013), this particular formalism has been successfully used in a number of studies (e.g. Blake et al. 2011b; de la Torre et al. 2013; Blake et al. 2013), and, as we will see below, reproduces the expected constraints on the growth rate from the COLA mock catalogs and provides a good description of the galaxy anisotropic clustering at the current statistical level.

In the case of the redshift-space cross-power spectrum, assuming that both tracers are described by the same dispersion parameter $\sigma_v$, we can write the large-scale terms as

$$P^*(k, \mu) = \left[ b_1b_2P_\delta(k) + \mu^2 f(b_1 + b_2)P_\sigma(k) + \mu^2 f^2P_\theta(k) \right] \times e^{-(k\mu v/H(z))^2},$$

(20)

where $b_1$ and $b_2$ are the biases of the different tracers. Since we are measuring the multipoles of the 2PCF, we calculate first the power spectrum multipoles as

$$P^*_l(k) = \frac{2\ell + 1}{2\pi} \int_{-1}^{1} P^*(k, \mu)L_l(\mu)d\mu,$$

(21)

where $l$ is the multipole order and $L_l$ is the Legendre polynomial of order $l$. Then for the two-point correlation function in configuration space we have

$$\xi^*_l(s) = \frac{1}{2\pi^2} \int P^*_l(k)j_l(ks)k^2dk,$$

(22)

where $j_l$ is the spherical Bessel function of order $l$.

### 4.2 Tests using COLA mocks

We tested the validity of these models using our COLA mock catalogs. In summary, we compared the K87 and S04 models for the large-scale distortions to $P(k)$ (calculated using our fiducial cosmological parameters), using a Gaussian function for the small-scale damping (we also tried fits using the Lorentzian profile without significant differences), constraining the growth rate $f$ at the simulation output redshift $z = 0.6$, marginalising over the bias of each tracer and the common velocity dispersion $\sigma_v$. We performed these fits for every COLA mock on scales $s < 80$ h$^{-1}$Mpc, although changes when using larger scales were not significant.

Figure 7 shows the mean and standard deviation of the best-fitting values of $f(z = 0.6)$ across the mocks. For the WIZCola mocks the K87-Gaussian model tends to underpredict the value of the growth rate whereas the S04-Gaussian model agrees well for scales $s_{\text{min}} > 20$ h$^{-1}$Mpc. For the BOSS-cola mocks the differences are less pronounced, but the input growth rate is recovered with a systematic error less than the statistical error. In both cases the goodness of fit is similar with $\chi^2/d.o.f.$ $\sim 1$ for both WizCola and BOSS COLA mocks on larger scales $s_{\text{min}} > 20$ h$^{-1}$Mpc, worsening considerably on scales $s_{\text{min}} < 10$ h$^{-1}$Mpc. In what follows we will use the S04-Gaussian model for our parameter fits.

There are, however, specific differences in the scale of validity of the models depending on which tracer is used. It can be seen that for low-bias galaxies represented by the WizCola mocks, the agreement between the model fits and the input value of $f(z = 0.6)$ extends to lower scales than in the case of galaxies residing in more massive halos. Although the Kaiser effect is stronger for lower bias galaxies, the higher non-linearities arising from the formation and high-clustering of high-mass halos lead to a model break-down on larger scales. For the particular case of the WiggleZ-BOSS overlap, $s_{\text{min}} = 24$ h$^{-1}$Mpc is the minimum scale where both models recover adequately the fiducial growth rate with negligible systematic error.

### Multitracer approach

Having chosen the model to analyse redshift-space clustering, we examined the consequences of using multiple tracers when recovering model parameters. For each realisation of the COLA mocks we fit the S04-Gaussian RSD model first using the autocorrelations independently, then analysing both autocorrelations but considering the common covariance matrix, and lastly adding the cross-correlations using the monopole...
and quadrupole of $\xi(s,\mu)$ in the range $24 < s < 80 \, h^{-1}\text{Mpc}$. Results are shown in Figure 8, which displays the 1σ contours enclosing the best-fitting values of $f(z = 0.6)$ and $\sigma_v$. The expected values for these parameters are consistent with our COLA constraints, and the approximation that $\sigma_v$ is the same for both tracers is valid for this range of scales. The constraints for the parameters are correlated between the two surveys, with a cross-correlation coefficient $\rho^f_{\text{WC}} = \sigma^f_W / \sigma^f_C = 0.4$ for the growth rate between both surveys.

When analysing the 2PCFs of the two tracers simultaneously, taking into account the common covariance, an improvement in the measurement of $f$ is obtained, of the order 30% compared to using the BOSScola mocks alone (which because of a higher bias, have a lower value of $\beta$ and hence a lower signal) but only 5% compared to using WiZcola mocks alone. Adding the cross-2PCF produces an improvement of 20% compared to the WiZcola-only constraints, mostly due to an increased signal in the shot-noise-dominated regime. Analysing individual mocks shows that the improvement also varies in each realisation. As predicted by McDonald & Seljak (2009), Gil-Marín et al. (2010) and Blake et al. (2013), although our tracers have big differences in their biasing, due to the sparsity of our sampling we are in the regime where shot noise dominates and improvement via the cancellation of cosmic variance is small.

### 4.3 Data Fitting procedure

In our analysis we fixed the cosmological parameters of the matter power spectra to the best-fit WMAP5 model (Komatsu et al. 2009), the fiducial cosmology of our COLA mocks, and constrain the parameters $(b_W, b_C, f(z = 0.54), \sigma_v)$. Due to the degeneracy of the first three parameters with $\sigma_8(z)$, the r.m.s. of the matter density field in $8 \, h^{-1}\text{Mpc}$ spheres, we are effectively constraining $(b_W \sigma_8, b_C \sigma_8, f \sigma_8, \sigma_v)$. We also include the WiggleZ-CMASS cross-correlation in the analysis, additionally fit for the parameter $\tau_X$. We compare the constraints from the single-tracer model for each galaxy type to each other, and then include the common covariance and the cross-correlations in the cosmological fits.

We use the monopole and quadrupole of the tracers, and present results as a function of the minimum-scale fitted $s_{\text{min}}$, with $s_{\text{max}} = 80 \, h^{-1}\text{Mpc}$. We execute a Maximum Likelihood parameter estimation test, where we minimise the quantity

$$
\chi^2 = \sum \frac{1}{2}(X_{i,\text{model}} - X_{i,\text{data}})C^{-1}\text{comb}(X_{i,\text{model}} - X_{i,\text{data}}),
$$

(23)

where $X$ is one of the elements of the vector formed by the multipoles of $\xi(s,\mu)$ of WiggleZ-BW, CMASS-BW and/or WiggleZ-CMASS-BW correlations. We explore the parameter space using a Monte Carlo Markov Chain method (MCMC) imposing the prior that all parameter values must be bigger than zero.

### 4.4 Fits for the growth rate

Figure 9 presents the parameter fits of $f \sigma_8(z = 0.54)$ fitting the monopole and quadrupole of the WiggleZ and CMASS auto- and cross-correlation on scales between $s_{\text{min}} = 24 \, h^{-1}\text{Mpc}$, and $s_{\text{max}} = 80 \, h^{-1}\text{Mpc}$. As shown in the previous section, $s_{\text{min}} = 24 \, h^{-1}\text{Mpc}$ is the minimum scale where there are not important systematic deviations in the parameters from the study with the COLA mocks, and our fits to the observed data follow this trend. Table 2 lists the results for the parameter fits.

Comparing the single-tracer fits for WiggleZ-BW and CMASS-BW galaxies, there is agreement at the 1σ level for the values of $f \sigma_8(z = 0.54)$, meaning that when fitting to...
these scales there is evidence of no systematics depending on the type of galaxy used. Our constraints on the growth rate are consistent with our fiducial cosmology \( f_8(z = 0.54) = 0.46 \).

Consistent with previous work, we recover that the bias of the WiggleZ-BW galaxies, \( b_W \sim 1 \), is smaller than that of the CMASS-BW galaxies, \( b_C \sim 2 \). The value of the best-fitting chi-squared statistic indicates that the model provides a reasonable fit to the data in all cases. For the pairwise dispersion, values for the different tracers are consistent with the predicted value from theory (section 4.1).

Combining the two tracers including their cross-covariance yields slightly better constraints for \( f_8(z = 0.54) \) at the level of 10% (compared to WiggleZ constraints alone). This result indicates that for these tracers, in a low density regime (where the common cosmic variance cancellation does not improve the constraints, see Blake et al. 2013), even in the presence of a slightly larger Hartlap-Percival correction, the improvement is due to reduced shot noise. When including the cross-correlations the improvement is of the order of 20% (again, compared with WiggleZ constraints alone). In the case when we include the cross-correlations, we obtain our poorest value for \( \chi^2 / \text{d.o.f.} \), implying that our simple constant \( r_s \) model may not describe all of the complexities of the cross-correlation. Given this result, we quote as result of our paper for the growth rate constraint the one obtained when we combine only the auto-correlations, yielding \( f_8(z = 0.54) = 0.413 \pm 0.054 \).

5 SUMMARY & CONCLUSIONS

In this work we have presented the first cosmological RSD analysis using data from two overlapping surveys, WiggleZ and CMASS. After defining the overlap volumes, we measured 2-point auto- and cross-correlations functions of these tracers; after obtaining their multipoles and calculating their cross-covariance using N-body mock catalogs, we compared them with RSD models in order to measure the growth rate of structure \( f_8 \) at an effective redshift \( z = 0.54 \). Our main findings are:

- The cross-correlation coefficient \( r_s \) between the WiggleZ-BW and CMASS-BW galaxies agrees with the expectation that on large scales, the two classes trace similarly the large scale structure with \( r_s \sim 1 \). On smaller scales \( s > 24 \ h^{-1} \text{Mpc} \) we recover our fiducial cosmological parameters using different tracers, and that a single velocity dispersion provides an adequate description for the distortions in our range of scales. We confirmed a lack of a significant improvement when using the multitracer technique, given the sparsity of the sampling for these tracers.
- The fits to \( f_8(z) \) from all tracers are consistent with each other and with the predictions of a \( \Lambda \)CDM universe, showing no evidence for strong modelling systematic errors as a function of galaxy type.

As shown in Figure 10, our combined fit for the growth rate \( f_8(z = 0.54) = 0.413 \pm 0.054 \) is in excellent agreement with estimates from different surveys. Although more sophisticated models for the RSD can be employed, the motivation for our work was to show consistency in the cosmological fits when using different tracers. This agreement provides further strong evidence for the robustness in the growth rate measurements which are important for answering the outstanding questions on the nature of dark energy and large-scale gravity.
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Table 2. Fits to the RSD model parameters when using multipoles with 24 < s < 80 h⁻¹Mpc assuming WMAP5 σ₈(z = 0) = 0.812

| Tracers             | bn·σ₈(z = 0.54) | bc·σ₈(z = 0.54) | fs·σ₈(z = 0.54) | σᵥ(kms⁻¹) | rₛ | χ²/d.o.f. | d.o.f. |
|---------------------|-----------------|-----------------|-----------------|-----------|---|----------|-------|
| WiggleZ only        | 0.051±0.004     | -               | 0.409±0.059     | 205±144   | 4 | 1.11     | 28 - 4 |
| CMASS only          | -               | 1.204±0.062     | 0.466±0.074     | 130±116   | 4 | 1.43     | 28 - 4 |
| WiggleZ+CMASS       | 0.646±0.043     | 1.233±0.054     | 0.413±0.054     | 117±113   | 4 | 1.28     | 56 - 5 |
| WiggleZ+CMASS+x2PCF | 0.648±0.038     | 1.242±0.043     | 0.403±0.048     | 88±104    | 4 | 0.93 ± 03| 1.57  | 84 - 6 |
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