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Baryon acoustic oscillations at $z=2.34$ from the correlations of Ly$\alpha$ absorption in eBOSS DR14

Victoria de Sainte Agathe$^1$, Christophe Ballard$^1$, Hélion du Mas des Bourboux$^2$, Nicolás G. Busca$^3$, Michael Blomqvist$^3$, Julien Guy$^4$, James Rich$^5$, Andreu Font-Ribera$^6$, Matthew M. Pieri$^3$, Julian E. Bautista$^7$, Kyle Dawson$^2$, Jean-Marc Le Goff$^5$, Axel de la Macorra$^8$, Nathalie Palanque-Delabrouille$^9$, Will J. Percival$^9$, Ignasi Pérez-Ràfols$^3$, Donald P. Schneider$^{10,11}$, Anže Slosar$^{12}$, and Christophe Yèche$^5$

$^1$ Sorbonne Université, Université Paris Diderot, CNRS/IN2P3, Laboratoire de Physique Nucléaire et de Hautes Energies, LPNHE, 4 Place Jussieu, 75252 Paris, France
e-mail: victoria.de.sainte.agathe@lpnhe.in2p3.fr
$^2$ Department of Physics and Astronomy, University of Utah, 115 S, 1400 E, Salt Lake City, UT 84112, USA
$^3$ Aix Marseille Univ., CNRS, CNES, LAM, Marseille, France
$^4$ Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
$^5$ IRFU, CEA, Université Paris-Saclay, 91191 Gif-sur-Yvette, France
$^6$ University College London, Gower St, Kings Cross, London WC1E 6BT, UK
$^7$ Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth PO1 3FX, UK
$^8$ Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, DF 04510 México, Mexico
$^9$ Department of Physics and Astronomy, University of Waterloo, 200 University Ave. W., Waterloo, ON N2L 3G1, Canada
$^{10}$ Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA, 16802, USA
$^{11}$ Institute for Gravitation and the Cosmos, 2 Center Road, Upton, NY 11973, USA

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ABSTRACT

We measure the imprint of primordial baryon acoustic oscillations (BAOs) in the correlation function of Ly$\alpha$ absorption in quasar spectra from the Baryon Oscillation Spectroscopic Survey (BOSS) and the extended BOSS (eBOSS) in Data Release 14 (DR14) of the Sloan Digital Sky Survey (SDSS)-IV. In addition to 179,965 spectra with absorption in the Lyman-$\alpha$ (Ly$\alpha$) region, we use Ly$\alpha$ absorption in the Lyman-$\beta$ region of 56,154 spectra for the first time. We measure the Hubble distance, $D_M$, and the comoving angular diameter distance, $D_A$, relative to the sound horizon at the drag epoch $r_d$ at an effective redshift $z = 2.34$. Using a physical model of the correlation function outside the BAO peak, we find $D_M(2.34)/r_d = 8.86\pm0.29$ and $D_A(2.34)/r_d = 37.41\pm1.86$, within 1$\sigma$ of the flat-CDM model consistent with CMB anisotropy measurements. With the addition of polynomial “broadband” terms, the results remain within one standard deviation of the CMB-inspired model. Combined with the quasar-Ly$\alpha$ cross-correlation measurement presented in a companion paper, the BAO measurements at $z = 2.35$ are within 1.7$\sigma$ of the predictions of this model.

Key words. cosmology: observations – cosmological parameters – dark energy

1. Introduction

Since the first observations of the imprint of primordial baryonic acoustic oscillations (BAOs) as a peak in the galaxy correlation function (Eisenstein et al. 2005) or as a periodic modulation in the corresponding power spectrum (Cole et al. 2005), the BAO signal has led to significant constraints on cosmological parameters. The BAO peak in the radial direction at a redshift $z$ yields $D_M(z)/r_d = c/(r_d H(z))$, where $H(z)$ is the Hubble parameter and $r_d$ is the sound horizon at the drag epoch (Eisenstein & Hu 1998). The transverse measurement constrains the quantity $D_A(z)/r_d = (1+z)D_M(z)/r_d$, where $D_A(z)$ is the angular diameter distance. Because of its sensitivity to both the distance and the expansion rate, the ensemble of BAO measurements yields tight constraints on a cold dark matter (ΛCDM) parameters (Aubourg et al. 2015) even without the use of cosmic microwave background (CMB) data.

Most BAO measurements have employed discrete objects like galaxies (Percival et al. 2010; Reid et al. 2010; Beutler et al. 2011; Blake et al. 2011; Anderson et al. 2012, 2014a,b; Ross et al. 2015; Alam et al. 2017; Bautista et al. 2018) or quasars (Araujo et al. 2018; Gil-Marín et al. 2018; Hou et al. 2018; Zarrour et al. 2018). An alternative tracer of the density is the intergalactic medium (IGM), itself traced by Ly$\alpha$ absorption in quasar spectra. Such measurements at $z\sim2.4$ were suggested by McDonald (2003) and McDonald & Eisenstein (2007). The first detections of a BAO peak in the Ly$\alpha$ auto-correlation function (Busca et al. 2013; Slosar et al. 2013) used data from the Baryon Oscillation Spectroscopic Survey (BOSS) in the Sloan Digital Sky Survey (SDSS) -DR9, at an effective redshift of $z=2.3$. Delubac et al. (2015), using BOSS in SDSS-DR11, confirmed the detection of a BAO acoustic peak in the Ly$\alpha$ auto-correlation function at the 5$\sigma$ level. Most recently, Bautista et al. (2017; B17 hereafter) used Ly$\alpha$ forests from BOSS DR12 data and provided a measurement of $D_M(r_d)/r_d$ at 3.4% precision level (or of the optimal combination $D_M^2 P_M(r_d)$ at the 2.5% level). The results were within 1$\sigma$ of the prediction of the flat-ΛCDM model favored by CMB anisotropies (Planck Collaboration XIII 2016).
However, when combined with the BAO imprint on the cross-correlation of the Lyα forest with BOSS DR12 quasars (du Mas des Bourboux et al. 2017), the values of $D_{H}/r_{a}$ and $D_{A}/r_{a}$ at $z \sim 2.3$ differ by 2.3σ from this model. This mild tension was already present in the combined constraints of the cross-correlation measurement of Font-Ribera et al. (2014) and the auto-correlation of Delubac et al. (2015).

In the present paper, we use quasar spectra from the BOSS survey and from its extended version eBOSS in the SDSS DR14 to study BAO in the Lyα auto-correlation function. The quasar-Lyα cross-correlation is studied in a companion paper (Blomqvist et al. 2019). As in previous measurements, we use Lyα absorption in the “Lyα region” of quasar spectra, that is, quasar rest-frame wavelengths in the range $104 < \lambda_{RF} < 120$ nm. We refer to the auto-correlation function using only this region as the Lyα(Lyα) × Lyα(Lyα) correlation. To increase the statistical power, we also include Lyα absorption in the Lyβ regions of quasars, $97.4 < \lambda_{RF} < 102$ nm, correlated with the Lyα absorption in Lyγ regions, and refer to this as the Lyα(Lyα) × Lyγ(Lyβ) correlation function. The Lyβ region was previously used by Irfić et al. (2013) to investigate the flux transmission power spectrum within individual spectra.

Besides the use of the Lyβ region, the analysis presented here differs in several ways from that of Bautista et al. (2017) based on DR12 data. For each quasar, we now use all observations instead of just the best one and we analyze ~15% more Lyα regions. We have refined the modeling of the weights (Sect. 3.2), thereby taking into account the effect of unmasked high-column-density (HCD) systems, and the modeling of nonlinearities in the power spectrum (Sect. 4.1). We have not developed new mock spectra beyond those used in the DR12 analysis though this is being done for the final eBOSS analysis.

The layout of the paper is the following. In Sect. 2, we present the Lyα and Lyβ spectral region samples used in the present study. We compute correlation function of Lyα absorption for the DR14 data in Sect. 3 and present our physical model for this function in Sect. 4. The results of fitting the data are presented and discussed in Sect. 5. We draw cosmological conclusions in Sect. 6 and summarize our results in Sect. 7.

The computations of the correlation functions presented in this paper have been performed using a dedicated software package: Package for Igm Cosmological-Correlations Analyses (picca), developed by our team.

## 2. Data sample and reduction

The extended Baryon Oscillation Spectroscopic Survey (eBOSS; Dawson et al. 2016) is the extension of the BOSS experiment (Dawson et al. 2013) which aims to measure cosmology with BAO using optical spectra from quasars, emission line galaxies, and luminous red galaxies. It is one of the four projects of the fourth stage of the Sloan Digital Sky Survey (SDSS-IV; Blanton et al. 2017).

The optical spectra are collected from 1000 fibers, attached to the focal plane of a 2.5 m telescope in Apache Point Observatory (Gunn et al. 2006), by two spectrographs in the wavelength range $[360, 1000]$ nm (Smee et al. 2013). The spectral resolution of the spectrographs is $\sim 2000$.

In this paper, we use the forests of the high-redshift quasar sample from the SDSS Data Release 14 (DR14; Abolfathi et al. 2018). This sample contains the first two years of eBOSS data and the five years of BOSS observations reprocessed using the eBOSS pipeline. It also includes data from the ancillary programs Time-Domain Spectroscopic Survey (TDSS) and SPectroscopic IDeentification of ERosita Sources (SPIEDERS). The quasar target selection is presented in Myers et al. (2015). We note that eBOSS also targets quasars at low redshifts (where the Lyα region is not observable) to be used in other programs (Ata et al. 2018; Wang et al. 2018; Blomqvist et al. 2018; Zhao et al. 2019; du Mas des Bourboux et al. 2019).

The automated data reduction is organized in two steps (Dawson et al. 2016). The pipeline initially extracts the two-dimensional raw data into a one-dimensional flux-calibrated spectrum. During this procedure, the spectra are wavelength and flux calibrated and the individual exposures of one object are coadded into a rebinned spectrum with $A \log(i) = 10^{-4}$. The spectra are then classified as STAR or GALAXY or QSO, and their redshift is estimated. Objects that cannot be automatically classified are visually inspected (Pâris et al. 2018) and a quasar catalog is produced, which contains 526,356 quasar spectra with redshift $0 < z < 7$. Among these objects, 144,046 were not in DR12. The coverage footprint of DR14 quasars is presented in Fig. 1.

In this study, we examine both Lyα and Lyβ regions (see Fig. 2). The Lyα region in the quasar spectrum lies between the Lyα and the Lyβ emission peaks. We limit its coverage to the rest-frame wavelength range $[104, 120]$ nm in order to exclude the emission peaks, whose shape depends on the environment of the quasar. This approach minimizes the variance of the flux-transmission field defined in Sect. 3.1. Similarly, we define the Lyβ region as the rest-frame wavelength range $[97.4, 102]$ nm (Table 1, Fig. 2).

In the DR14 quasar catalog, selecting quasar redshifts in the range $[2.0, 3.5]$ yields 216,162 spectra containing, at least partially, the Lyα region, and selecting quasar redshifts in the range $2 < z < 3.5$ yields 86,245 spectra containing the Lyβ region. We choose $z_{\min} = 3.5$ as an upper limit, as beyond this redshift the quasar density is insufficient to measure correlations and the rate of redshift misidentification is large (Busca & Ballard 2018). The requirement that the observed wavelength must be greater than 360 nm is due to the low CCD response and atmospheric transmission in the UV region.

In order to mask damped Lyα systems (DLAs), we use the updated DR14 DLA catalog of Noterdaeme et al. (2009, 2012), which contains 34,541 DLAs in 27,212 forests. The absorption of the identified DLAs is modeled with a Voigt profile and the regions with more than 20% of absorbed flux are masked. For the Lyβ regions, we apply this procedure both for Lyα and Lyβ strong absorbers. We also mask the sky emission and absorption lines listed on the SDSS website. The broad absorption line (BAL) quasars are automatically identified (Pâris et al. 2018) and excluded from the data, leaving a sample of 201,286 objects for the Lyα regions and 80,443 for the Lyβ regions.

For the determination of the correlation function, we divide spectra into “analysis pixels” that are the inverse-variance-weighted flux average over three adjacent pipeline pixels. Throughout the rest of this paper, “pixels” refers to analysis pixels unless otherwise stated. Spectral regions with <50 such pixels or regions which have failed the continuum-fitting procedure (Sect. 3.1) are discarded. These selection criteria produce 179,965

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1 We use the notation “absorption(spectral region)” to distinguish the nature of absorption from the wavelength interval where the absorption is observed. Hence, the notation Lyα(Lyα) × Lyα(Lyα) denotes Lyα absorption in Lyα regions correlated with Lyα absorption in Lyα regions.

2 Available at https://github.com/igmhub/picca

3 http://classic.sdss.org/dr6/algorithms/linestable.html
Fig. 1. Sky distribution of the 216 163 quasars with redshift in the [2.0, 3.5] range in the DR14 footprint of the BOSS and eBOSS surveys. The high-density regions are the eBOSS and SEQUELS observations (for the highest declinations in the two Galactic caps) and SDSS-stripe 82 (on the celestial equator in the south Galactic cap).

Fig. 2. Ly\(\alpha\) and Ly\(\beta\) spectral regions defined in Table 1.

Table 1. Definitions of the Ly\(\alpha\) and Ly\(\beta\) regions in terms of restframe wavelength range.

| Regions | \(\lambda_{RF}\) [nm] | \(\lambda_{obs}\) [nm] | \(z_q\) | # forests |
|---------|----------------------|----------------------|------|----------|
| Ly\(\beta\) | [97.4, 102]     | [360, 459]      | [2.53, 3.5] | 56 154 |
| Ly\(\alpha\) | [104, 120]      | [360, 540]      | [2.0, 3.5]  | 179 965 |

Notes. Also listed are the allowed observer frame wavelength ranges, the corresponding quasar redshift ranges and the number of forests available in our sample.

Ly\(\alpha\) regions (compared to 157 783 in B17) and 56 154 Ly\(\beta\) regions (see Table 1).

The analysis procedure described in the following section assigns redshifts to the observed pixel wavelengths by assuming that flux decrements in both the Ly\(\alpha\) and Ly\(\beta\) regions are due to Ly\(\alpha\) absorption. The effect of non-Ly\(\alpha\) absorption is taken into account in the correlation-function model presented in Sect. 4. The weighted distribution of the redshifts

Fig. 3. Weighted distribution of the redshift of pairs used to measure the Ly\(\alpha\)(Ly\(\alpha\)) × Ly\(\alpha\)(Ly\(\alpha\)) and Ly\(\alpha\)(Ly\(\alpha\)) × Ly\(\alpha\)(Ly\(\beta\)) correlation functions. The mean redshift of the combined sample is \(\langle z_{\text{pairs}} \rangle = 2.34\).

3. Computing the Ly\(\alpha\) correlation function from the data

This section describes the measurement of the flux-transmission field and then its correlation function and associated covariance matrix.

3.1. Flux-transmission field \(\delta_q(\lambda)\)

The computation of the correlation function requires an estimation of the transmission field along the line of sight (LOS) towards surveyed quasars. This field arises due to the presence along the LOS of intergalactic gas. More precisely, for the correlation calculation, we only need to know the flux fluctuations
around the average transmitted flux spectrum in the forests of quasars $q$ at wavelength $\lambda$. We thus define the field $\delta_q(\lambda)$, for each quasar $q$ under investigation, as:

$$\delta_q(\lambda) \equiv \frac{f_q(\lambda)}{C_q(\lambda) F(z)} - 1,$$

(1)

where $f_q(\lambda)$ denotes the observed flux of quasar $q$ at observed wavelength $\lambda$, $C_q(\lambda)$ is the continuum flux, and $F(z)$ is the mean transmission at the absorber redshift $z$.

We estimate the quantity $C_q F(z)$ from the average of the transmitted flux of all forest spectra in the sample:

$$C_q F(z) = \frac{\sum_i w_i (\lambda_{RF}) f_i (\lambda_{RF})}{\sum_i w_i (\lambda_{RF})},$$

(2)

where $\lambda_{RF}$ is the rest-frame wavelength and $w_i$ is a weight (see Sect. 3.2). For each quasar, $f(\lambda_{RF})$ is then multiplied by a linear polynomial function of $\Lambda = \log(\lambda)$ to account for the diversity of quasar luminosity and spectral shape:

$$C_q F(z) = \frac{\sum_i w_i (\lambda_{RF}) f_i (\lambda_{RF})}{\sum_i w_i (\lambda_{RF})}.$$

(3)

There are thus two adjustable parameters per quasar, $a_q$ and $b_q$.

Those forests with identified DLAs are given special treatment. All pixels where the absorption due to the DLA is easier to deal with this distortion in the analysis, we follow B17 to following Busca et al. (2013), the weights are corrected to take into account the expected redshift dependence of the correlation function amplitude:

$$w_q(\lambda) = \frac{\gamma_q}{\sigma_{\text{noise}}(\lambda)} \left( \frac{\lambda_{\text{RF}}}{\lambda_{\text{obs}}} \right)^{\gamma_q - 1},$$

(7)

where the Ly$\alpha$ bias redshift-evolution parameter, $\gamma_q$, is the Ly$\alpha$ restframe wavelength.

In practice, one starts with an initial estimate of the weights, allowing a first estimate of the mean spectrum $f(\lambda_{\text{RF}})$ (Eq. (2)) and the quasar parameters $a_q$ and $b_q$ (Eq. (3)). The functions $\eta(\lambda)$, $\epsilon(\lambda)$, and $\sigma_{\text{LSS}}(\lambda)$ are then fit and the mean spectrum is then recalculated with the new weights. This process is repeated until stable values are obtained after about five iterations.

3.3 Correlation function

To compute the correlation function, we correlate absorption at an observed wavelength $\lambda_i$ in the LOS of a given quasar $q$, with absorption at an observed wavelength $\lambda_j$ in the LOS of another quasar $q'$. Assuming the absorption is due to the Ly$\alpha$ transition, one can compute, from the values of $\lambda_i$ and $\lambda_j$, the redshifts $z_i$ and $z_j$ of the matter absorbing these lines. Each pair of absorbers $(z_i, q)$ entering the computation defines a “pixel” in real space and we use $r_{ij}$ to refer to the physical separation between two such pixels $i$ and $j$ (see Fig. 5). This distance is calculated assuming the PI2015 cosmology (Table 2). The distance $r_{ij}$ can be projected on the radial and the transverse directions, leading to two components $r_{r,i,j}$ and $r_{r,t,i,j}$. These components can be expressed in terms of the comoving distances $D(z_i)$ and $D(z_j)$ from us to absorbers $i$ and $j$ and the subtended angle between the two LOSs, $\theta_{i,j}$, as:

$$r_{r,i,j} = \frac{D(z_i) - D(z_j)}{\cos \left( \frac{\theta_{i,j}}{2} \right)},$$

$$r_{r,t,i,j} = \frac{D(z_i) + D(z_j)}{\sin \left( \frac{\theta_{i,j}}{2} \right)}.$$
The covariance between two bins $\xi_{i}$ and $\xi_{j}$ is given by (9). Due to the finite number of sky pixels, the estimate (13) is noisy and must be smoothed before it can be used in fits. We perform the smoothing by approximating the correlation function, $\text{Corr}_{AB} = C_{AB} / \sqrt{C_{AA} C_{BB}}$, as a function of $\Delta r_{i} = |r_{i}^{A} - r_{i}^{B}|$ and $\Delta r_{j} = |r_{j}^{A} - r_{j}^{B}|$, only, ignoring the small dependence on $r_{i}$ and $r_{j}$.

As a check of the subsampling method, the covariance can also be estimated by neglecting inter-forest correlations, in which case the four-point function vanishes unless the four pixels are drawn from just two spectra:

$$C_{AB} = \frac{1}{W_{A} W_{B} \sum_{k \in C_{BA}} \sum_{l \in C_{AB}} w_{k} w_{l} \hat{\xi}_{id}(\lambda_{k}/\lambda_{i}) \hat{\xi}_{id}(\lambda_{l}/\lambda_{i}),}$$

where $\hat{\xi}_{id}$ is the intra-forest correlation function shown in Fig. 4. The sum can then be estimated from a random sample of forest pairs. Because neighboring forests are nearly parallel, the sum necessarily produces $C_{AB} = 0$ unless $r_{i}^{A} \sim r_{i}^{B}$.

Because the Ly$\alpha$ and Ly$\beta$ forests have different $\hat{\xi}_{id}$, we expect differences between the covariances for Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$) and Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\beta$) correlations. These differences are illustrated in Fig. 6, which shows, for the two lowest values of $\Delta r_{i}$, the correlation $\text{Corr}_{AB}$. For $\Delta r_{i} = 0$, there is good agreement between the subsampling (13) and independent-forest (14) calculations.

Figure 7 displays the $\text{Corr}_{AB}$ between the Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$ (Ly$\alpha$) and Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\beta$) correlation functions. The $\text{Corr}_{AB}$ are $<1\%$, and will be ignored in the fits of the correlation functions.

4. Modeling the correlation function

This section details the model of the Ly$\alpha$ auto-correlation function that is fitted against the estimator $\hat{\xi}_{A}$ of Eq. (9). Table 4 lists
We start from the CAMB linear power spectrum (Lewis et al. 2000) which is decomposed into a smooth component and a peak component, following the side-band technique described by Kirkby et al. (2013). This allows one to constrain the position of the BAO peak independently of the correlation function at scales much smaller or much larger than the BAO distance scale. We thus model the matter power spectrum as the sum of two terms corresponding to the smooth and the peak terms in the correlation function. Moreover, in order to incorporate the effects of the nonlinear growth of matter that lead to broadening of the BAO peak, the peak term is corrected by a Gaussian factor (Eisenstein et al. 2007). The “quasi-linear” power spectrum hence reads

\[ P_{QL}(k, z) = P_{\text{smooth}}(k, z) + \exp \left( -\frac{k^2 \Sigma^2_{\parallel}}{2} - \frac{k^2 \Sigma^2_{\perp}}{2} \right) P_{\text{peak}}(k, z), \tag{16} \]

where \( P_{\text{smooth}}(k, z) \) and \( P_{\text{peak}}(k, z) \) are the power spectra of the smooth and peak components, and \( \Sigma_{\parallel} \) and \( \Sigma_{\perp} \) represent the rms displacements in the parallel and transverse directions, respectively. We adopt the values of Kirkby et al. (2013) for these parameters: \( \Sigma_{\parallel} = 6.41 \, h^{-1} \, \text{Mpc} \) and \( \Sigma_{\perp} = 3.26 \, h^{-1} \, \text{Mpc} \).

The power spectrum is obtained from \( P_{QL} \) as

\[ P_{\text{Ly} \alpha-\text{Ly} \beta}(k, z) = P_{QL}(k, z) d_{\text{Ly} \alpha}(k, z) D_{\text{NL}}(k) G(k), \tag{17} \]

where \( d_{\text{Ly} \alpha} \) is the Kaiser factor (Kaiser 1987) for the Ly\( \alpha \) absorption and \( D_{\text{NL}}(k) \) takes into account nonlinear effects. The function \( G(k) \) models the effect of binning of the correlation function on the separation grid.

The Kaiser factor can be written as

\[ d_{\text{Ly} \alpha} = b'_{\text{Ly} \alpha}(z)(1 + \beta'_{\text{Ly} \alpha} \mu^2), \tag{18} \]

where \( b'_{\text{Ly} \alpha} \) is the effective bias of Ly\( \alpha \) absorbers with respect to the underlying matter density field, \( b'_{\text{Ly} \alpha} \) is the effective redshift space distortion (RSD) parameter, and \( \mu = k_0/k \). The two effective parameters \( (b'_{\text{Ly} \alpha} \text{ and } b'_{\text{Ly} \beta}) \) combine Ly\( \alpha \) absorption in the IGM and in unmasked HCD systems, i.e., HI absorbers with column densities \( N_{\text{HI}} > 10^{17.2} \, \text{cm}^{-2} \):

\[
\begin{align*}
& b'_{\text{Ly} \alpha} = b_{\text{Ly} \alpha} + h_{\text{HCD}} F_{\text{HCD}}(k_0), \\
& b'_{\text{Ly} \beta} = b_{\text{Ly} \beta} + h_{\text{HCD}} b_{\text{Ly} \beta} F_{\text{HCD}}(k_0),
\end{align*}
\tag{19}
\]
Following McDonald et al. (2006), we assume that the product of $b_{\text{Ly}$ and the growth factor of structures varies with redshift as $(1+z)^{-2}$, with $\chi_\alpha = 2.9$, while we make use of the approximation that $b_{\text{Ly}}$ does not depend on redshift.

HCD absorbers are expected to trace the underlying density field and their effect on the flux-transmission field depends on whether or not they are identified and given the special treatment described in Sect. 2. If they are correctly identified with the total absorption region masked and the wings correctly modeled, they can be expected to have no significant effect on the field. Conversely, if they are not identified, the measured correlation function will be modified because their absorption is spread along the radial direction. This broadening effect introduces a $k_\parallel$ dependence of the effective bias (Font-Ribera & Miralda-Escudé 2012). Following the study of Rogers et al. (2018), we adopt a simple exponential form, $F_{\text{HCD}} = \exp(-L_{\text{HCD}}k_\parallel)$, where $L_{\text{HCD}}$ is a typical length scale for these systems. DLA identification is possible if the width (wavelength interval for absorption greater than 20%) of the system(s) is above $\sim 0.2$ nm, corresponding to $\sim 14 h^{-1}$ Mpc in our sample. Based on results from Rogers et al. (2018), we impose $L_{\text{HCD}} \sim 10 h^{-1}$ Mpc while fitting for the bias parameters $b_{\text{HCD}}$ and $b_{\text{Ly}}$. Fixing $L_{\text{HCD}}$ is necessary because otherwise the model becomes too unconstrained. We have verified that setting $L_{\text{HCD}}$ in the range $7 < L_{\text{HCD}} < 13 h^{-1}$ Mpc does not significantly change the inferred BAO peak position.

We focus on the minimal model able to reproduce the data, designated the “baseline model”. This baseline model does not include the correction of the UV background fluctuations (Pontzen et al. 2014; Gontcho A Gontcho et al. 2014) used in B17. In Sect. 5 we discuss the improvement of the fit when this UV correction is added.

The function $D_{\text{NL}}(k)$ accounts for nonlinear effects such as thermal broadening, peculiar velocities, and nonlinear structure growth. A fitting formula for $D_{\text{NL}}$ is given by Eq. (21) of McDonald (2003) and has been extensively used in previous studies. More recently, Arinyo-i-Prats et al. (2015) proposed a new fitting formula involving six free parameters given by their Eq. (3.6). Besides reducing the number of free parameters with respect to McDonald (2003), it has the correct behavior at small wavenumber $k$ and an explicit dependence on $P_{\alpha}(k)$, whereas this dependence is only implicit in the McDonald (2003) formula. In practice, the two approaches yield similar results but for the above reasons we adopt the formula of Arinyo-i-Prats et al. (2015) in the present work and linearly interpolate the parameter values from their Table 7 at the effective redshift $z = 2.34$.

To account for the effect of the binning of the correlation function on the separation grid, we assume the distribution to be homogeneous on each bin and compute the function $G(k)$ as the product of the Fourier transforms of the rectangle functions that model a uniform square bin:

$$G(k) = \sin\left(\frac{k_\parallel R_\parallel}{2}\right) \sin\left(\frac{k_\perp R_\perp}{2}\right),$$

where $R_\parallel$ and $R_\perp$ are the radial and transverse widths of the bins, respectively.

The two terms in $P_{\alpha}(k, z)$ (Eq. (16)) are Fourier transformed to the smooth and peak components of the correlation function:

$$\xi_{\alpha\text{mod}}(r_\parallel, r_\perp, \alpha_\parallel, \alpha_\perp) = \xi_{\alpha}\text{smooth}(r_\parallel, r_\perp) + A_{\text{peak}} \xi_{\text{peak}}(\alpha_\parallel r_\parallel, \alpha_\perp r_\perp).$$

The amplitude of the peak, $A_{\text{peak}}$, is fixed to unity in the standard fit. In the peak component we have introduced the parameters $(\alpha_\parallel, \alpha_\perp)$ which allow us to fit for the peak position independently of the smooth component:

$$\alpha_\parallel = \frac{D_{\text{H}}(\bar{z})/r_{\text{fid}}}{D_{\alpha}(\bar{z})/r_{\text{fid}}}, \quad \alpha_\perp = \frac{D_{\alpha M}(\bar{z})/r_{\text{fid}}}{D_{\text{H}}(\bar{z})/r_{\text{fid}}},$$

where $\bar{z}$ is the effective redshift of the measurement and the suffix “fid” denotes the Pi2015 cosmology from Table 2.

### 4.2. Contamination by metals

The second term in the model correlation function (Eq. (15)) accounts for absorption by metals along the quasar LOS. Such absorption is correlated with Ly$\alpha$ absorption (Pieri et al. 2014) and can be used as a tracer of the density field (Blomqvist et al. 2018; du Mas des Bourboux et al. 2019). Here, it is a complicating factor in the analysis because the redshifts of pixels are calculated assuming Ly$\alpha$ absorption.

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**Table 3.** Ly$\alpha$/metal and metal/metal pairs contributing to the flux correlation function.

| Transitions               | $\lambda_1/\lambda_2$ | $r_{\parallel}^{30}$ [h$^{-1}$ Mpc] |
|---------------------------|------------------------|--------------------------------------|
| Si III(1193)/Si III(1190)| 1.002                  | 7                                    |
| Ly$\alpha$(1216)/Si III(1207)| 1.008                  | 21                                   |
| Si III(1207)/Si III(1190)| 1.011                  | 31                                   |
| Si III(1207)/Si III(1190)| 1.014                  | 38                                   |
| Ly$\alpha$(1216)/Si III(1207)| 1.019                  | 52                                   |
| Ly$\alpha$(1216)/Si III(1190)| 1.021                  | 59                                   |
| Si III(1207)/Ly$\alpha$(1216)| 1.037                  | 105                                  |
| Si III(1207)/Si III(1190)| 1.045                  | 126                                  |
| Si III(1207)/Si III(1193)| 1.056                  | 157                                  |
| Si III(1207)/Si III(1193)| 1.059                  | 164                                  |

**Notes.** The table shows the ratio of transition wavelengths and the corresponding apparent separation, $r_{\parallel}^{30}$, for pairs at vanishing physical separation, computed at an average redshift of 2.34 using Eq. (23).

**Table 4.** Parameters of the model of the correlation function.

| Parameter | Description |
|-----------|-------------|
| $\alpha_\parallel, \alpha_\perp$ | BAO peak-position parameters |
| $b_{\text{Ly}}$, $b_{\text{Ly}}$ | Bias parameters for Ly$\alpha$ absorption |
| $b_{\text{HCD}}$, $b_{\text{HCD}}$ | Bias parameters of HCD systems |
| $b_{\text{metal}}$ | Bias of metal species |

**Notes.** The standard-fit parameters are given in the first section of the table. The second section lists parameters that are fixed in the standard fit, together with their values.

---

The table shows the ratio of transition wavelengths and the corresponding apparent separation, $r_{\parallel}^{30}$, for pairs at vanishing physical separation, computed at an average redshift of 2.34 using Eq. (23).
The important metals can be seen in the 1D correlation function, \( \xi_{\text{DFL}}(l_1/l_2) \), shown in Fig. 4. Column 2 of Table 3 lists the wavelength ratios for the main metal/metal and metal/Ly\(\alpha\) absorption correlations, relevant for the Ly\(\alpha\) auto-correlation function computation. The corresponding apparent radial separation at vanishing physical separation is

\[
r^\text{ap}_{\parallel} \approx (1 + \bar{z})D_H(z)\frac{J_1 - A_2}{\lambda_\alpha},
\]

where \( \bar{z} \) is the mean redshift of the pair. Values are given in Table 3 for \( \bar{z} = 2.34 \).

We model the power spectrum of each pair of absorbers, \((m, n)\), with the same form as that for Ly\(\alpha\)–Ly\(\alpha\) absorption (17) except that HCD effects are neglected:

\[
P_{\text{mod}}(k, z) = b_mb_n(1 + \beta_m\mu^2_l)(1 + \beta_n\mu^2_l)G(k)P_L(k, z).
\]

Since the \( b_m \) and \( b_n \) are mostly determined near \((r_3, r_1) \sim (0, r^p)\), they cannot be determined separately. We therefore fix \( \beta_{\text{DFL}}(\mu) = 0.27 \) (Blomqvist et al. 2018). For the other metal species we keep the value \( \beta = 0.50 \) used in Bautista et al. (2017) which comes from DLA measurements (Font-Ribera & Miralda-Escudé 2012).

The Fourier transform of \( P_{\text{mod}}(k, z) \) is then the model correlation function of the pair \((m, n)\): \( \xi^{\text{mod}}_{\alpha}(\hat{r}_i, \hat{r}_j) \), where \((\hat{r}_i, \hat{r}_j)\) are the separations calculated using the correct restframe wavelengths, \((\lambda_m, \lambda_i)\).

Since we assign a redshift, \( z_\alpha \), assuming Ly\(\alpha\) absorption, the rest-frame wavelength we ascribe to a metal transition \( m \) observed at wavelength \( \lambda_i \) is not equal to the true rest-frame wavelength \( \lambda_i/(1 + z_m) \), where \( z_m \) is the true redshift of the metal absorber. This misidentification results in a shift of the model contaminant correlation function. For each pair \((m, n)\) of contaminants, we compute the shifted model correlation function with respect to the unshifted model metal correlation function \( \xi^{\text{mod}}_{\text{metals}} \) by introducing a metal matrix \( M_{AB} \) (Blomqvist et al. 2018), such that:

\[
\xi^{\text{mod}}(A) = \sum_{B} M_{AB}\xi^{\text{mod}}_{\text{metals}}(\hat{r}_i(B), \hat{r}_j(B)),
\]

where

\[
M_{AB} = \frac{1}{W_A} \sum_{(m,n)\in A} \sum_{l,m} w_m w_n
\]

and \((m, n) \in A\) refers to pixel separation computed assuming \( z_m \) and \((m, n) \in B\) to pixel separation computed using the redshifts of the \( m \) and \( n \) absorbers, \( z_m \) and \( z_n \). We take into account the redshift dependence of the weights (Eq. (7)) in the computation of \( w_m \) and \( w_n \).

The total metal contaminant correlation function, \( \xi^{\text{metals}}_{\text{mod}} \), is the sum of all the \( \xi^{\text{mod}}_{\text{metals}} \) contributions, where \((m, n)\) runs over all the involved transition pairs for the Ly\(\alpha\) auto-correlation function; see Table 3:

\[
\xi^{\text{mod}}(A) = \sum_{m,n} \xi^{\text{mod}}_{\text{metals}}(A).
\]

### 4.3. Distorted model

The model correlation function, \( \xi_{\text{mod}} \) of Eq. (15) cannot be fit directly to the estimated correlation function (9) because the measured \( \delta_i(\lambda) \) are only related to the true \( \delta_i(\lambda) \) through the transformation (4). Following B17, we can account for this effect in the fit by using a distorted model:

\[
\xi_{\text{mod}}(A) = \sum_{B} D_{AB}\xi_{\text{mod}}(B),
\]

where \( D_{AB} \) is the distortion matrix which, following Eq. (5), is given by

\[
D_{AB} = W_A^{-1} \sum_{i \in A} w_i \sum_{j \in B} \eta_i \eta_j f.
\]

The accuracy of this method of accounting for the distortion of the correlation function was tested with mock data sets by Bautista et al. (2017).

In practice, to avoid prohibitive computational time, the distortion matrix is computed using only a random 5% portion of the total number of pairs.

### 5. Fitting the BAO peak position

Table 5 presents the best-fit parameters for the Ly\(\alpha\)–Ly\(\alpha\) correlation function alone and those including the Ly\(\beta\) region, that is, the Ly\(\alpha\)–Ly\(\alpha\) correlation function. Figure 8 displays data for the latter in four ranges of \( \mu \) along with the best fits. The BAO peak is apparent for \( \mu > 0.8 \) and is suggested for \( 0.5 < \mu < 0.8 \).

The BAO parameters for the fit using both Ly\(\alpha\) and Ly\(\beta\) regions are

\[
\begin{align*}
\alpha_0 &= 1.033^{+0.034+0.071} _{-0.034-0.068} \\
\alpha_\perp &= 0.953^{+0.050+0.108} _{-0.045-0.091}
\end{align*}
\]

Using the \( D/r_d \) values for the Pl2015 cosmology in Table 2, these values yield

\[
\begin{align*}
D_{\text{H}}(2.34)/r_d &= 8.86^{+0.29+0.61} _{-0.29-0.58} \\
D_{\text{M}}(2.34)/r_d &= 37.41^{+9.64+4.24} _{-1.77-3.57}
\end{align*}
\]

These results can be compared with those of B17, who found \( \alpha_0 = 1.053 \pm 0.036 \) and \( \alpha_\perp = 0.965 \pm 0.055 \) at \( z = 2.33 \) using only the Ly\(\alpha\) region. These values are very near the present results using only the Ly\(\alpha\) region: \( \alpha_0 = 1.047 \pm 0.035 \) and \( \alpha_\perp = 0.960 \pm 0.041 \). Our use of the Ly\(\beta\) region produces consistent results, given the increase in the data set; the main improvement is that on the precision on \( D_{\text{M}}/r_d \) by \( \sim 25\% \).

Constraints on the BAO parameters (\( \alpha_0, \alpha_\perp \)) are presented in Fig. 9. Following the method introduced and described in detail in du Mas des Bourboux et al. (2017), we estimate the relation between \( \Delta \chi^2 = \chi^2 - \chi^2_{\text{min}} \) and confidence levels (CLs) for the BAO parameters using a large number of simulated correlation functions generated from the best-fit model and the covariance matrix measured with the data. The results of the study, summarized in Table D.1, indicate that the 68.27, 95.45\% confidence levels for \( (\alpha_0, \alpha_\perp) \) correspond to \( \Delta \chi^2 = (2.74, 7.41) \); instead of the nominal values \( \Delta \chi^2 = (2.3, 6.18) \). These levels are shown as the red contours in Fig. 9 for the Ly\(\alpha\)–Ly\(\alpha\) correlation function. The best fit is within one standard deviation of the Pl2015 model.

In addition to the baseline fits, we performed a variety of nonstandard fits to verify that our BAO results are robust and independent of the model. The results of this exercise are given
Table 5. Parameters of the model of the correlation function and the best-fit values of the Lyα(Lyα) × Lyα(Lyα) data (third column) and those of the Lyα(Lyα) × Lyα(Lyα) and Lyα(Lyα) × Lyα(Lyβ) data (fourth column).

| Parameter description | Lyα(Lyα) × Lyα(Lyα) | Lyα(Lyα) × Lyα(Lyα) + Lyα(Lyα) × Lyα(Lyβ) |
|-----------------------|-----------------------|--------------------------------------------|
|                       | η_{pairs}             | 5.44 × 10^{11}                             | 6.94 × 10^{11}                       |
|                       | Σ w_{pairs}           | 3.56 × 10^{13}                             | 4.20 × 10^{13}                       |
| Radial BAO peak-position | α_∥                   | 1.047 ± 0.035                               | 1.033 ± 0.031                        |
|                       | α_⊥                   | 0.969 ± 0.041                               | 0.953 ± 0.042                        |
| Transverse BAO peak-position | β_{Lyα}              | 1.773 ± 0.066                               | 1.933 ± 0.100                        |
|                       | β_{Lyβ}               | −0.208 ± 0.004                              | −0.211 ± 0.004                       |
| Lyα redshift-space distortion | h_{β_{Lyα}}           | 0.845 ± 0.157                               | 1.031 ± 0.153                        |
| HCD redshift-space distortion | β_{HCD}              | −0.047 ± 0.003                              | −0.051 ± 0.004                       |
| HCD bias Lyα(Lyα) × Lyα(Lyα) | h_{Lyα(Lyα)×Lyα(Lyα)} | −0.072 ± 0.005                              |                                      |
| Metal absorption bias | h_{SiII(1190)}         | −0.0051 ± 0.0010                            | −0.0050 ± 0.0010                     |
|                       | h_{SiII(1193)}         | −0.0046 ± 0.0010                            | −0.0046 ± 0.0010                     |
|                       | h_{SiIII(1207)}        | −0.0082 ± 0.0010                            | −0.0080 ± 0.0010                     |
|                       | h_{SiIII(1260)}        | −0.0025 ± 0.0013                            | −0.0022 ± 0.0013                     |
|                       | h_{CIV(1457)}          | −0.0185 ± 0.0078                            | −0.0163 ± 0.0089                     |
| χ^2_{min}             |                        | 1619.77                                     | 3258.92                              |
| d.o.f.                |                        | 1590−11                                     | 3180−12                              |
| Probability           |                        | 0.232                                       | 0.127                                |
| χ^2(α_∥ = α_⊥ = 1)   |                        | 1621.55                                     | 3260.54                              |

Notes. Errors on parameters correspond to Δχ^2 = 1.
in Table 6. The first group of fits starts with the simple Kaiser redshift-space model and then includes progressively metals, HCD absorption, and UV background fluctuations. Including HCD absorption is necessary to obtain a good $\chi^2$ but adding UV fluctuations such as those characterized in Gontcho A Gontcho et al. (2014) does not improve the fit, justifying our choice of ignoring the UV issue in the baseline fit. In the standard fit, the physical parameters ($L_{\text{HCD}}, \Sigma_{\perp}, \Sigma_{\parallel}, \beta_{\text{HCD}}$) are fixed (see Table 4) in order to avoid degeneracies with other parameters and non-physical values. We verified that letting them free has no impact on the $\alpha_\parallel$ and $\alpha_\perp$ parameters.

An important test of systematic effects in the position of the BAO peak is performed by adding polynomial “broadband” terms to the correlation function (before distortion). We follow the procedure and choice of broadband forms used by B17 and adopt the form

$$B(r, \mu) = \sum_{j=0}^{m_{\text{max}}} \sum_{r_{\text{min}}}^{r_{\text{max}}} \frac{L_j(\mu)}{r^j} \quad (j \text{ even}),$$

(32)

where the $L_j$ are Legendre polynomials.

We want to ensure that the power-law terms model variations of the slowly varying part of the correlation function under the BAO peak. We therefore perform these fits only over the restricted range $40 < r < 180 \, h^{-1} \, \text{Mpc}$, avoiding the introduction of undue influence of the $10 < r < 40 \, h^{-1} \, \text{Mpc}$ range on the amplitudes of the power laws. Following B17, we fit with $(l_{\text{min}}, l_{\text{max}}) = (0, 2)$ corresponding to a parabola in $r^2 \xi_{\text{smooth}}$ underneath the BAO peak. We set $j_{\text{max}} = 6$, giving four values of $j$ corresponding to approximately independent broadbands in each of the four angular ranges in Fig. 8.

We performed the broadband fits in two ways. The first placed “physical priors” on ($b_{\text{LyA}}, \beta_{\text{LyA}}, b_{\text{HCD}}$) in the form of a Gaussian with the same mean and width as those of the fit without broadband terms. Such priors ensured that the broadband terms were relatively small perturbations to the physical model. The second type of fit placed no priors on ($b_{\text{LyA}}, \beta_{\text{LyA}}, b_{\text{HCD}}$).

The results of these fits are given in Table 6 and Fig. 9. We see that the addition of such terms does not change $\alpha_\parallel$ significantly but does shift $\alpha_\perp$ by 0.5$\sigma$ or 0.7$\sigma$ for fits with and without physical priors, respectively. This effect was already seen in B17 but with less significance. Figure 9 shows that in all cases the BAO peak position is within one standard deviation of the prediction of the Planck 2015 model.

Table 6: Best-fit values of ($\alpha_\parallel, \alpha_\perp$) for the Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) correlation function fit with various models.

| Models                      | $\alpha_\parallel$ | $\alpha_\perp$ | $\chi^2$/d.o.f. | Probability |
|-----------------------------|--------------------|----------------|-----------------|-------------|
| Kaiser                      | 1.021 ± 0.028      | 0.977 ± 0.040  | 3624.74(3180–4) | 3.46 × 10^{-8} |
| +Metals                     | 1.025 ± 0.032      | 0.979 ± 0.044  | 3607.96(3180–9) | 7.14 × 10^{-8} |
| +HCD (baseline)            | 1.033 ± 0.031      | 0.953 ± 0.042  | 3258.92(3180–12)| 0.127       |
| +UV                         | 1.033 ± 0.031      | 0.953 ± 0.042  | 3258.84(3180–13)| 0.125       |
| Broadband                   |                    |                |                 |             |
| Physical priors on ($b_{\text{LyA}}, \beta_{\text{LyA}}, b_{\text{HCD}}$) | 1.037 ± 0.028      | 0.972 ± 0.040  | 3006.25(3030–36) | 0.434       |
| No additional priors       | 1.032 ± 0.027      | 0.980 ± 0.032  | 3001.00(3030–36) | 0.460       |

Notes. The first group includes physical models starting with the basic Kaiser redshift-space model and then including, progressively, metals, HCD, and UV corrections. Fits in the second group include polynomial broadband terms, as described in the text.
yielded values of ($\alpha_0, \alpha_1$) that are within 1.2$\sigma$ of the PI2015 model (Fig. B.2). We also fit the Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) correlation as described in Appendix C. Adding the Ly$\beta$ absorption data does not add a significant signal to the BAO peak, but it does allow us to measure the Ly$\beta$ bias parameters.

Finally, we combine the measurement of Ly$\alpha$ auto-correlation function of the present analysis with the Ly$\alpha$–quasar cross-correlation measurement of Blomqvist et al. (2019) by performing a joint fit of the two correlation functions. We use the baseline models of the two analyses and consider the errors to be independent. The joint fit has 18 free parameters and the effective redshift is $z = 2.34$. The results are given in the column four of Table 7 and the constraints on ($\alpha_\perp, \alpha_\parallel$) in the right panel of Fig. 9. From this combined fit, we obtain:

$$
\begin{align*}
\alpha_\parallel & = 1.049^{+0.026}_{-0.025}^{+0.052}_{-0.051} \\
\alpha_\perp & = 0.942^{+0.032}_{-0.030}^{+0.067}_{-0.059}
\end{align*}
$$

(33)

corresponding to

$$
\begin{align*}
D_H(2.34)/r_d & = 9.00^{+0.22}_{-0.20}^{+0.45}_{-0.43} \\
D_M(2.34)/r_d & = 36.98^{+3.26}_{-1.18}^{+2.63}_{-2.32}
\end{align*}
$$

(34)

The value of $\chi^2$ for ($\alpha_\parallel = 1, \alpha_\perp = 1$) is 4.99 greater than the best fit. Using the confidence levels of Table D.1, we conclude that the results of the combined fit are 1.7$\sigma$ from the predictions of the PI2015 model (Planck Collaboration XIII 2016).

6. Cosmological constraints

Baryon acoustic oscillation data over the redshift range 0.1 < z < 2.4 is in overall good agreement with the predictions of the flat LCDM models consistent with CMB anisotropies, as illustrated in Fig. 10. A striking illustration of the expansion history can be made by transforming $D_H(z)/r_d$ to $H(z)r_d$. The measurement presented here gives

$$
H(2.34)/r_d(P\!\!\!\! \Lambda \!\!\!\! C) = (227 \pm 7)\, \text{km s}^{-1}\, \text{Mpc}^{-1}.
$$

(35)

Figure 11 plots this value along with other measurements. The data are consistent with the expected behavior of deceleration at high redshift followed by acceleration at low redshift.

Independent of CMB data and without assuming flatness, the BAO data by themselves constrain the parameters ($\Omega_m, \Omega_k, H(r_d)$) of the (a)LCDM model. Using the combined fit (Eq. (34)), the galaxy data of Beutler et al. (2011), Ross et al. (2015), Alam et al. (2017), and Bautista et al. (2018) and the quasar data of Ata et al. (2018) yield

$$
\Omega_m = 0.293 \pm 0.027, \quad \Omega_k = 0.675 \pm 0.099,
$$

(36)

corresponding to $\Omega_m = 0.032 \pm 0.117$. The best fit gives ($c/H_0)/r_d = 29.78 \pm 0.55$, corresponding to $H(r_d) = (0.683 \pm 0.013) \times 147.33$ Mpc. The PI2015 model has $\chi^2 = 13.76$ for 12$\nu$ of freedom and is within one standard deviation of the best fit, as illustrated in Fig. 12.

7. Conclusions

We used Ly$\alpha$ and Ly$\beta$ spectral regions from the BOSS and eBOSS DR14 data sample to study BAO. Following B17, we

Table 7. Best-fit results of the Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) correlation function (second column), of the QSO × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) correlation function given by Blomqvist et al. (2019) (third column), and of the two correlation functions (fourth column).

| Parameters | Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) | QSO × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) | Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) + QSO × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) |
|-----------|---------------------------------|---------------------------------|---------------------------------|
| $\alpha_\parallel$ | 1.033 ± 0.034 | 1.076 ± 0.042 | 1.049 ± 0.026 |
| $\alpha_\perp$ | 0.953 ± 0.048 | 0.923 ± 0.046 | 0.942 ± 0.031 |
| $\beta_{\parallel}$ | 1.933 ± 0.101 | 2.28 ± 0.31 | 1.994 ± 0.099 |
| $b_{\parallel,\perp;\alpha}$ | −0.211 ± 0.004 | −0.267 ± 0.014 | −0.214 ± 0.004 |
| $\beta_{\parallel,\perp;\beta}$ | 0.257 | 0.209 ± 0.006 |
| $b_{\parallel,\perp;\beta}$ | 1.031 ± 0.153 | 0.500 ± 0.200 | 0.972 ± 0.150 |
| $b_{\parallel,\perp;\alpha}$ | −0.051 ± 0.004 | −0.052 ± 0.004 |
| $b_{\parallel,\perp;\beta}$ | −0.072 ± 0.005 | −0.073 ± 0.005 |
| $b_{\parallel,\perp;\alpha}$ | −0.000 ± 0.004 | −0.000 ± 0.004 |
| $\sigma_\nu [h^{-1}\text{Mpc}]$ | 7.60 ± 0.61 | 7.053 ± 0.357 |
| $\Delta r_H [h^{-1}\text{Mpc}]$ | −0.22 ± 0.32 | −0.169 ± 0.284 |
| $\xi_0$ | 0.276 ± 0.158 | 0.478 ± 0.112 |
| $A_{\text{ell}}$ | −13.5 ± 5.8 | −13.573 ± 4.721 |

Notes. Errors on BAO parameters correspond to CL = 68.27%, while the other parameters have errors corresponding to $\Delta \chi^2 = 1$. The $\sigma_\nu$, $\Delta r_H$, $\xi_0$, TP and $A_{\text{ell}}$ parameters are fit on the QSO × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) correlation function and fully described in Blomqvist et al. (2019).

The statement 'yielded values of ($\alpha_0, \alpha_1$) that are within 1.2$\sigma$ of the PI2015 model (Fig. B.2). We also fit the Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) correlation as described in Appendix C. Adding the Ly$\beta$ absorption data does not add a significant signal to the BAO peak, but it does allow us to measure the Ly$\beta$ bias parameters.' suggests that the Ly$\beta$ absorption data, while not providing a significant signal to the BAO peak, is useful for measuring the Ly$\beta$ bias parameters.
Collaboration XIII (2016). Solid lines show the Pl2015 values (Planck et al. 2011; Ross et al. 2015; Bautista et al. 2018) and BOSS-eBOSS quasars (Ata et al. 2018). The red square is the present measurement at \(z = 0.106\) (Beutler et al. 2011) and \(z = 0.15\) (Ross et al. 2015) are converted from \(D_V\) to \(H(z)\) using the SNIa measurement of \(q_0\) given by Betoule et al. (2014). Solid black line shows the PI2015 values (Planck Collaboration XIII 2016).

![Fig. 10. Baryon acoustic oscillation measurement of \(D_H/r_d\) and \(D_M/r_d\) using BOSS galaxies (Alam et al. 2017). Ly\(\alpha\) absorption in BOSS-eBOSS quasars and Ly\(\alpha\) absorption (Blomqvist et al. 2019). Other measurements give \(D_V/r_d\) with \(D_V = D_M^{1/3} (zD_H)^{1/3}\), using galaxies (Beutler et al. 2011; Ross et al. 2015; Bautista et al. 2018) and BOSS-eBOSS quasars (Ata et al. 2018). Solid lines show the PI2015 values (Planck Collaboration XIII 2016).](image1)

The \(D_H/r_d\) ratio is measured with a precision of \(\sim 3.3\%\), a slight improvement over the precision obtained by B17 for this ratio. The \(D_M/r_d\) ratio is measured with a precision of \(\sim 4.4\%\), which represents an improvement of about 25\% with respect to B17. The cosmological measurements obtained in this analysis are in agreement with the predictions of the flat \(\Lambda\)CDM model (PI2015) favored by the measurement of CMB anisotropies by Planck.

We also combined the measurements of the present analysis with those obtained from the cross-correlation of Ly\(\alpha\) absorption and quasars by Blomqvist et al. (2019). The latter alone favor a value of the \(D_H/r_d\) ratio \(\sim 3\%\) higher than the one favored by the Ly\(\alpha\) auto-correlation. As a result, the best-fit value of \(D_H/r_d\) for the combined fit is shifted towards a higher value than the best-fit from the Ly\(\alpha\) auto-correlation alone. Combining the measurement of Ly\(\alpha\) auto-correlation (this paper) with the quasar-Ly\(\alpha\) cross-correlation of Blomqvist et al. (2019), the BAO measurements at \(z = 2.34\) are within 1.7\(\sigma\) of the predictions of the PI2015 model.

The ensemble of BAO measurements is in good agreement with the PI2015 model (Planck Collaboration XIII 2016). They provide an independent way of determining cosmological parameters that is based only on low-redshift measurements. As illustrated in Fig. 12, the BAO results are also consistent with the recent Pantheon SNIa results (Scolnic et al. 2018).

The present measurements will be much improved by the greater statistical power of the upcoming DESI (DESI Collaboration 2016) and WEAVE-QSO (Pieri et al. 2016) projects. The challenge will be to improve the physical modeling of the correlation function in order to fully profit from the improved data.

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Appendix A: Effective redshift of the fitted parameters

In this section we present a method to determine the region in \((r_1, \eta_i, z)\) space that is most constraining for the various parameters in the fits of the correlation function. We can expect that the parameters \((\alpha_1, \alpha_2)\) are mostly determined by \((r_1, \eta_i)\) bins near the BAO peak and at a redshift near the mean redshift of the pixel pairs used in the BAO region. Previous studies (B17, Busca et al. 2013; Delubac et al. 2015) defined the effective redshift of the BAO measurement in this way. Here, we make this intuitive conclusion more precise by using a Fisher matrix analysis.

We use the Fisher matrix formalism as follows: given a parameter \(p\) varying linearly with redshift, we define the effective redshift \(z_0\) at which it is measured by

\[
p(z) = p_0 + p_1(z - z_0),
\]

where \(p_0\) is the value given by the fit at \(z = z_0\). The covariance matrix \(C_p\) between two parameters \(p_0\) and \(p_1\) is given by

\[
C_p \equiv \begin{pmatrix} \sigma^2_{p_0} & \rho \sigma_{p_0} \sigma_{p_1} \\ \rho \sigma_{p_0} \sigma_{p_1} & \sigma^2_{p_1} \end{pmatrix},
\]

where \(\sigma^2_p\) is the variance of the parameter \(p_i\), and \(\rho\) is the correlation coefficient between \(p_0\) and \(p_1\). By definition, \(C_p\) is the inverse of the Fisher matrix \(F_p\):

\[
C^{-1}_p \equiv F_p \equiv \begin{pmatrix} \sum_i \frac{\partial M_i}{\partial p} C^{-1}_{ij} \frac{\partial M_j}{\partial p} \sum_j \frac{\partial M_i}{\partial p} C^{-1}_{ij} \frac{\partial M_j}{\partial p} \end{pmatrix},
\]

with \(M_i\) the model at bin \(i\). In the case of the linear redshift dependency (A.1), the Fisher matrix \(F_p\) at redshift \(z\), computed using the set of all the fitted parameter values, \(\{\alpha_i\}\), is given by

\[
F_p(z) = \sum_{i,j} \frac{\partial M_i}{\partial p} \bigg|_{\{\alpha_i\}} C^{-1}_{ij} \frac{\partial M_j}{\partial p} \bigg|_{\{\alpha_i\}} \begin{pmatrix} 1 & (z_i - z)(z_j - z) \\ (z_i - z)(z_j - z) & (z_i - z)(z_j - z) \end{pmatrix},
\]

with \(z_i\) the mean redshift of the pairs in bin \(i\).

We represent the quantities \(\frac{\partial m}{\partial p}\) for 4 of the 12 fitted parameters of the Lyα auto-correlation function in Fig. A.1. The covariance matrix \(C_p(z)\) then reads

\[
C_p(z) = \frac{1}{|F_p|} \sum_{i,j} M_{ij} \begin{pmatrix} (z_i - z)(z_j - z) & - (z_i - z) \\ - (z_i - z) & 1 \end{pmatrix},
\]

with

\[
M_{ij} = \frac{\partial M_i}{\partial p} \bigg|_{\{\alpha_i\}} C^{-1}_{ij} \frac{\partial M_j}{\partial p} \bigg|_{\{\alpha_i\}}.
\]

Since \(M_{ij}\) is symmetric, the determinant of the Fisher matrix, \(|F_p|\), does not depend on redshift and is given by

\[
|F_p| = \sum_{i,j} M_{ij} M_{ji}.
\]

Table A.1. Effective redshifts at which the \(\alpha_0\) and \(\alpha_z\) parameters are measured.

| Correlation functions       | \(\tilde{z}\) | \(z_{0}\) | \(z_{\alpha}\) |
|----------------------------|--------------|----------|-------------|
| Ly\(\alpha\)(Ly\(\alpha\)) | 2.35         | 2.34     | 2.34        |
| Ly\(\alpha\)(Ly\(\alpha\)) × Ly\(\alpha\)(Ly\(\alpha\)) | 2.29         | 2.29     | 2.28        |
| Ly\(\alpha\)(Ly\(\alpha\)) × Ly\(\alpha\)(Ly\(\alpha\)) + Ly\(\beta\) | 2.34         | 2.33     | 2.33        |
| Ly\(\alpha\)(Ly\(\alpha\)) × Ly\(\alpha\)(Ly\(\alpha\)) (low \(z\)) | 2.19         | 2.19     | 2.18        |
| Ly\(\alpha\)(Ly\(\alpha\)) × Ly\(\alpha\)(Ly\(\alpha\)) (high \(z\)) | 2.49         | 2.49     | 2.49        |
| Ly\(\alpha\)(Ly\(\alpha\)) × Ly\(\alpha\)(Ly\(\alpha\)) (Ly\(\beta\))(Ly\(\beta\)) | 2.76         | 2.77     | 2.78        |

Notes. The average redshift of pairs is also given. Ly\(\alpha\)(Ly\(\alpha\)) × Ly\(\alpha\)(Ly\(\alpha\)) (low \(z\)) and (high \(z\)) are introduced in Appendix B.

The variance of \(p_0\) at redshift \(z\) becomes:

\[
\sigma^2_{p_0}(z) = \frac{1}{|F_p|} \sum_{i,j} M_{ij}(z_i - z)(z_j - z).
\]

The effective redshift \(z_0\) is the value which minimizes the error on \(p_0\):

\[
\frac{d\sigma^2_{p_0}}{dz} \bigg|_{z_0} = - \frac{2}{|F_p|} \sum_{i,j} M_{ij}(z_i - z_0) = 0,
\]

that is,

\[
z_0 = \frac{\sum_{i,j} M_{ij} z_i}{\sum_{i,j} M_{ij}}.
\]

In the case of a combined fit, we compute one matrix \(M^d\) for each correlation function entering the fit:

\[
M^d_{ij} = \frac{\partial m^d}{\partial p} \bigg|_{\{\alpha_i\}} (C^{d}_{ij})^{-1} \frac{\partial m^d}{\partial p} \bigg|_{\{\alpha_i\}},
\]

where \(m^d\) is the model for the correlation function \(d\) at bin \(i\). In this case, \(z_0\) reads

\[
z_0 = \frac{\sum_{i} \sum_{j} M^d_{ij} z_i}{\sum_{i} \sum_{j} M^d_{ij}}.
\]
Fig. A.1. Quantity $\partial m / \partial p$ in the $(r_\perp, r_\parallel)$ plane for the fitted parameters $p \in \{\alpha_\parallel, \alpha_\perp, b_{\text{Ly}\alpha}, b_{\text{Si}\text{III}(1207)}\}$, where $m$ is the baseline model of the Ly$\alpha$ auto-correlation function. The graphs show which pixels contribute the most to the constraints on the considered parameter. BAO parameters $\alpha_\parallel$ and $\alpha_\perp$ are constrained by the bins around the location of the BAO peak, while the Ly$\alpha$ bias is mostly constrained by the bins at approximately zero separation. We also note that the Si$\text{III}(1207)$ bias is mostly constrained by the bins $r_\perp \sim 0$, $r_\parallel \sim 21 \, h^{-1}$ Mpc, in agreement with the $r_\parallel^\text{apparent}$ separation given in Table 3.
Appendix B: Fits in two redshift bins

The present data set is large enough to constrain the BAO parameters in two independent redshift bins, in a way similar to what will be done in forthcoming cosmological surveys, such as the DESI project (DESI Collaboration 2016). To simplify the analysis, we consider only the Lyα(Lyα) × Lyα(Lyα) correlation function. A straightforward way of defining a high- and low-redshift sample of pixel pairs would be to simply use pixel pairs of mean redshift less than or greater than an appropriately chosen value, z_{cut}. The drawback of such an approach is that a given pair of forests could belong to both bins, as some pixels in a given forest would be associated with some pixels in the other forest, either in pixel pairs with mean redshift less than z_{cut}, or in pixel pairs with mean redshift greater than z_{cut}. The fact that some pairs of forests belong to both redshift bins introduces unwanted correlations when correcting for the distortions introduced by our continuum fitting procedure. To circumvent this problem, we choose to assign forest pairs to the high- or low-redshift sample by cutting on the mean of the maximum of the two forests.

We thus evaluate, for all pairs of forests (i, j), the following quantity:

\[ z_{ij} = \frac{z_{\text{max,abs}}^i + z_{\text{max,abs}}^j}{2}, \]  

(\ref{eq:zij})

where \( 1 + z_{\text{max,abs}}^k \) and \( \lambda_{\text{obs}} \) are the last pixel of forest k and the rest-frame wavelength of the considered transition. The condition \( z_{ij} < z_{\text{cut}} \) defines the low-redshift bin, while the opposite condition defines the high-redshift one.

The value of \( z_{\text{cut}} \) is tuned so that the sum of the weights of all absorber pairs in the high-redshift correlation function equals the one of all pairs in the low-redshift correlation function. This ensures the two bins have a comparable statistical power. This process leads us to select \( z_{\text{cut}} = 2.5 \). The redshift distribution of absorber pairs obtained in this way is shown on Fig. \ref{fig:B1}. The average pair redshift is \( \bar{z} = 2.19 \) and \( z = 2.49 \) for the low- and high-redshift bin, respectively.

Figure \ref{fig:B3} presents the result of fitting the Lyα(Lyα) × Lyα(Lyα) correlation baseline model to the data in the low- (blue points) and high-redshift (red points) bins in the usual four \( \mu \) wedges.

Table \ref{table:B1} shows the associated best-fit parameters. From the table, we note that \( \beta_{\text{Lyα}} \) is notably different at low and high redshift. When fitting the full sample, we assumed \( \beta_{\text{Lyα}} \) to be constant, following Kirkby et al. (2013). A redshift-dependent \( \beta_{\text{Lyα}} \) could therefore be an improvement in future analyses.

From the lower right panel of Fig. \ref{fig:S1}, we see that the amplitude of the high-redshift correlation function is higher than the amplitude of the low-redshift one. This is expected, as \( b_{\text{Lyα}} \) increases with redshift (Kirkby et al. 2013).

Figure \ref{fig:B2} presents the constraints obtained, in the \( (\alpha_\perp, \alpha_\parallel) \) parameter space, from fitting the Lyα auto-correlation Lyα(Lyα) × Lyα(Lyα) in the low- (blue contours) and high-redshift (red contours) bins. The values of \( \Delta \chi^2 \) corresponding to a given confidence level were taken from Table \ref{table:B1}. The black dot corresponds to the P1015 model.

Table B.1. Results in two redshift bins from fitting the baseline model to the Lyα(Lyα) × Lyα(Lyα) correlation function.

| Parameters | low z | high z |
|------------|-------|--------|
| \( \alpha_\parallel \) | \( 1.008 \pm 0.043 \) | \( 1.088 \pm 0.046 \) |
| \( \alpha_\perp \) | \( 0.861 \pm 0.062 \) | \( 0.977 \pm 0.044 \) |
| \( \beta_{\text{Lyα}} \) | \( 2.083 \pm 0.160 \) | \( 1.585 \pm 0.113 \) |
| \( b_{\text{Lyα}} \) | \(-0.218 \pm 0.006 \) | \(-0.201 \pm 0.005 \) |
| \( \beta_{\text{HCD}} \) | \( 0.745 \pm 0.174 \) | \( 0.678 \pm 0.179 \) |
| \( b_{\text{HCD}} \) | \(-0.058 \pm 0.007 \) | \(-0.040 \pm 0.006 \) |

| \( \chi^2_{\min} \) | \( 1580.95 \) | \( 1737.15 \) |
| d.o.f. | \( 1590–11 \) | \( 1590–11 \) |
| Probability | \( 0.481 \) | \( 0.003 \) |
| \( \chi^2(\alpha_\parallel = \alpha_\perp = 1) \) | \( 1584.30 \) | \( 1740.89 \) |
Fig. B.3. Lyα(Lyα) × Lyα(Lyα) function in four ranges of µ = r∥/r values, computed in a low-redshift (blue dots) and in a high-redshift (red dots) bin obtained by splitting our sample so that the two bins have equivalent statistical power. The dashed lines correspond to the simple fits to the data of the Lyα(Lyα) × Lyα(Lyα) correlation function, the solid line to the combining fits to the data of the Lyα(Lyα) × Lyα(Lyα) and Lyα(Lyα) × Lyα(Lyβ) correlation functions.
Appendix C: The Lyα(Lyα) × Lyβ(Lyβ) cross correlation

Table C.1. Same as Table 3 for the main metal/metal, metal/Lyβ, and Lyα/metal correlations relevant to the computation of the Lyα(Lyα) × Lyβ(Lyβ) correlation function.

| Transitions | $A_1/A_2$ | $r_\|/h^{-1}\text{Mpc}$ |
|-------------|-----------|-----------------|
| Si II(1190)/O VI(1038) | 1.147 | −88 |
| Si II(1193)/O VI(1038) | 1.150 | −81 |
| Si II(1190)/O VI(1032) | 1.154 | −73 |
| Si II(1193)/O VI(1032) | 1.156 | −66 |
| Si II(1190)/Lyβ(1026) | 1.161 | −56 |
| Si II(1207)/O VI(1038) | 1.163 | −52 |
| Si II(1193)/Lyβ(1026) | 1.163 | −50 |
| Si II(1207)/O VI(1032) | 1.169 | −37 |
| Lyα(1216)/O VI(1038) | 1.172 | −31 |
| Si II(1207)/Lyβ(1026) | 1.176 | −20 |
| Lyα(1216)/O VI(1032) | 1.178 | −16 |
| Si II(1260)/O VI(1038) | 1.215 | 68 |
| Si II(1260)/O VI(1032) | 1.221 | 83 |
| Si II(1260)/Lyβ(1026) | 1.229 | 100 |

Notes. The apparent separation $r_\|= (1 + z) H(z) \left( \frac{A_1}{A_2} - \frac{A_2}{A_1} \right)$ is computed at the average redshift of 2.76.

As an extension of our main analysis, we compute the Lyα(Lyα) × Lyβ(Lyβ) correlation function, following the procedure previously described. We computed the 1D correlation function in the Lyβ region (Fig. C.1) to identify the contaminating metals (see Table C.1).

The results of this analysis are presented in Table C.2. The Lyβ absorption signal is clearly detected as $b_{\text{Lyβ}}$ is nonzero at the 2.9σ level. We also see the signal due to O VI(1032) and O VI(1036). We note that the correlation between Lyβ and Si II(1260) occurs near the BAO peak (last line of Table C.1). Due to the small Lyβ absorption cross-section and to the small wavelength extent of the Lyβ region, it is harder to detect the BAO peak than for the Lyα auto-correlation function. Moreover, the Lyβ-Si II correlation further overlaps the BAO signal at small $r_\|$, hampering its detection in our data.

Figure C.2 presents for the first time the 2D Lyα(Lyα) × Lyβ(Lyβ) correlation function. It is shown in the usual four wedges of $\mu$ values, as a function of $r = \sqrt{r_\|^2 + r_\perp^2}$ multiplied by the sign of $r_\|$. We note that the model is not symmetric around zero separation.

The oscillator strength of Lyβ absorption is a fifth of that of Lyα, and consequently there are far fewer Lyβ HCD systems than Lyα HCD systems. On the other hand Lyβ absorption in our analysis occurs at a systematically higher redshift. Overall we find that $b_{\text{Lyβ}(Lyα) × Lyβ(Lyβ)}^\text{HCD}$ is consistent with zero.

In summary, there are not enough data at present to constrain the BAO peak position with Lyβ absorption only. However, Lyβ absorption could be used to access to physical IGM parameters at redshifts for which the Lyα absorption is saturated (Dijkstra et al. 2004; Iršič & Viel 2014).
Fig. C.2. Measured Lyα(Lyα)×Lyβ(Lyβ) correlation function in four ranges of $\mu$. In order to see the asymmetry of this correlation function, 
$r = (r^2_\parallel + r^2_\perp)^{1/2}$ is multiplied by the sign of $r_\parallel$ which is positive if the Lyα absorber is farther than the Lyβ absorber, and negative in the opposite configuration. The model for this correlation function (red solid line) is fitted on Lyα(Lyα)×Lyα(Lyα), Lyα(Lyα)×Lyα(Lyβ) and Lyα(Lyα)×Lyβ(Lyβ).
Appendix D: Confidence levels

To make a precise estimate of the relation between $\Delta \chi^2$ and confidence level, we closely followed the procedure of du Mas des Bourboux et al. (2017). We generated a large number of simulated correlation functions using the fiducial cosmological model and the best-fit values of nonBAO parameters, randomized using the covariance matrix measured with the data. Each simulated correlation function was then fit for the model parameters and the $\chi^2$ for the best-fit parameters compared with the best $\chi^2$ with one or more parameters set to the known input values. Confidence levels are the fractions of the generated data sets that have best fits below the $\Delta \chi^2$ limit. The uncertainties are estimated using a bootstrap technique.

The analysis of du Mas des Bourboux et al. (2017) followed this procedure using models that incorporated only Ly$\alpha$ absorption and models that incorporated also HCDs and metals. Since no significant differences were seen in the two methods, we use here only Ly$\alpha$ absorption, simplifying the analysis considerably.

The results are summarized in Table D.1 for various correlation functions. In all cases the $\Delta \chi^2$ values corresponding to a given confidence level are increased above the standard values. For example, for the Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) correlation, the one- and two-standard deviation contours for $(\alpha_{\|}, \alpha_{\perp})$ correspond to $\Delta \chi^2 = 2.77$ and $\Delta \chi^2 = 7.33$, to be compared with the standard values of 2.29 and 6.18.

### Table D.1. Values of $\Delta \chi^2$ corresponding to confidence levels (CLs) (68.27, 95.45%).

| Parameter | $\Delta \chi^2$ (68.27%) | $\Delta \chi^2$ (95.45%) |
|-----------|---------------------------|---------------------------|
| Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) | | |
| $\alpha_{\|}$ | 1.19 ± 0.03 | 4.74 ± 0.09 |
| $\alpha_{\perp}$ | 1.23 ± 0.03 | 4.83 ± 0.08 |
| $(\alpha_{\|}, \alpha_{\perp})$ | 2.77 ± 0.04 | 7.33 ± 0.10 |
| Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) + QSO × Ly$\alpha$(Ly$\alpha$ + Ly$\beta$) | | |
| $\alpha_{\|}$ | 1.08 ± 0.02 | 4.29 ± 0.10 |
| $\alpha_{\perp}$ | 1.08 ± 0.02 | 4.28 ± 0.10 |
| $(\alpha_{\|}, \alpha_{\perp})$ | 2.47 ± 0.03 | 6.71 ± 0.13 |
| Ly$\alpha$(Ly$\alpha$) × Ly$\alpha$(Ly$\beta$) | | |
| $\alpha_{\|}$ | 1.19 ± 0.02 | 4.65 ± 0.09 |
| $\alpha_{\perp}$ | 1.17 ± 0.02 | 4.32 ± 0.07 |
| $(\alpha_{\|}, \alpha_{\perp})$ | 2.65 ± 0.04 | 6.99 ± 0.10 |
| low $z$ | | |
| $\alpha_{\|}$ | 1.28 ± 0.02 | 5.09 ± 0.08 |
| $\alpha_{\perp}$ | 1.35 ± 0.02 | 5.09 ± 0.10 |
| $(\alpha_{\|}, \alpha_{\perp})$ | 2.89 ± 0.04 | 7.55 ± 0.12 |
| high $z$ | | |
| $\alpha_{\|}$ | 1.28 ± 0.03 | 4.92 ± 0.09 |
| $\alpha_{\perp}$ | 1.23 ± 0.03 | 4.74 ± 0.08 |
| $(\alpha_{\|}, \alpha_{\perp})$ | 2.83 ± 0.04 | 7.44 ± 0.11 |

**Notes.** Values are derived from 10 000 Monte Carlo simulations of the correlation function that are fit using the model containing only Ly$\alpha$ absorption.