The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: constraints on the time variation of fundamental constants from the large-scale two-point correlation function

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ABSTRACT

We obtain constraints on the variation of the fundamental constants from the full shape of the redshift-space correlation function of a sample of luminous galaxies drawn from the Data Release 9 of the Baryonic Oscillations Spectroscopic Survey. We combine this information with additional data from recent cosmic microwave background, baryon acoustic oscillations and $H_0$ measurements. We focus on possible variations of the fine structure constant $\alpha$ and the electron mass $m_e$ in the early universe, and study the degeneracies between these constants and other cosmological parameters, such as the dark energy equation of state parameter $w_{DE}$, the massive neutrinos fraction $f_\nu$, the effective number of relativistic species $N_{\text{eff}}$, and the primordial helium abundance $Y_{\text{He}}$. In the case when only one of the fundamental constants is varied, our final bounds are $\alpha/\alpha_0 = 0.9957_{-0.0042}^{+0.0041}$ and $m_e/(m_e)_0 = 1.006_{-0.013}^{+0.014}$. For the joint variation of both fundamental constants, our results are $\alpha/\alpha_0 = 0.9990_{-0.0055}^{+0.0055}$ and $m_e/(m_e)_0 = 1.028_{-0.019}^{+0.019}$. The variations of $\alpha$ and $m_e$ from their present values affects the bounds on other cosmological parameters. Although when $m_e$ is allowed to vary our constraints on $w_{DE}$ are consistent with a cosmological constant, when $\alpha$ is treated as a free parameter we find $w_{DE} = -1.20 \pm 0.13$; more than 1 $\sigma$ away from its standard value. When $f_\nu$ and $\alpha$ are allowed to vary simultaneously, we find $f_\nu < 0.043$ (95% CL), implying a limit of $\sum m_\nu < 0.46$ eV (95% CL), while for $m_e$ variation, we obtain $f_\nu < 0.086$ (95% CL), which implies $\sum m_\nu < 1.1$ eV (95% CL). When $N_{\text{eff}}$ or $Y_{\text{He}}$ are considered as free parameters, their simultaneous variation with $\alpha$ provides constraints close to their standard values (when the $H_0$ prior is not included in the analysis), while when $m_e$ is allowed to vary, their preferred values are significantly higher. In all cases, our results are consistent with no variations of $\alpha$ or $m_e$ at the 1 or 2 $\sigma$ level.

Key words: cosmological parameters, large-scale structure of Universe, early Universe

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1 INTRODUCTION

The overwhelming amount of cosmological observations obtained over the past few years has allowed not only the precise determination of the parameters of the standard cosmological model but also has provided plenty of scope to test non-standard physics and cosmological assumptions such as the constancy of fundamental constants over cosmological timescales.

The variation of fundamental constants is a prediction of theories attempting to unify the four interactions in nature, such as string derived field theories, related brane-world theories and Kaluza-Klein theories (see Uzan 2003 [García-Berro et al. 2007] and references therein). Substantial work has been devoted to constrain such variations using cosmological observations (Rahmani et al. 2012; Coc et al. 2011; Levshakov et al. 2012; Menegoni et al. 2012; Landau & Scóccola 2010). Unifying theories predict the variation of all coupling constants, being all variations related in general to the rolling of a scalar field. In this paper we adopt a phenomenological approach and analyse the possible variation of the fine structure constant $\alpha$ and of the electron mass $m_e$ between the recombination epoch and the present time, without assuming any theoretical model.

The cosmic microwave background (CMB) is a powerful tool to study the early universe. The acoustic oscillations present in the CMB power spectrum are also imprinted through the baryons on the large-scale structure (LSS) power spectrum (Eisenstein & Hu 1998; Meiksin et al. 1999). The correlation function $\xi(s)$ is the Fourier transform of the latter, and the oscillation structure appears there as a single peak whose position is related to the sound horizon at the drag redshift (Matsubara 2004). The ongoing Baryonic Oscillations Spectroscopic Survey (BOSS, Dawson et al. 2012) is a part of Sloan Digital Sky Survey-III (SDSS-III; Eisenstein et al. 2011) and is aimed at obtaining redshifts for $1.5 \times 10^6$ massive galaxies out to $z = 0.7$ over an area of 10,000 deg$^2$. BOSS is designed to measure the baryon acoustic oscillations (BAO) signal to probe the expansion history of the universe. This information places complementary constraints on the variation of fundamental constants. A high redshift galaxy sample from BOSS Data Release 9 (DR9), denoted CMASS, is constructed through a set of colour-magnitude cuts designed to select a roughly volume-limited sample of massive, luminous galaxies (Eisenstein et al. 2011; Padmanabhan et al. in prep.). The clustering properties of the BOSS CMASS sample have been analysed in detail in a recent series of papers (Anderson et al. 2012; Manera et al. 2012; Reid et al. 2012; Ross et al. 2012; Samushia et al. 2012; Sánchez et al. 2012; Tojeiro et al. 2012).

The position of the peak in the correlation function of galaxies can place constraints on the variation of fundamental constants. Moreover, the full shape of the correlation function provides additional information that can break degeneracies, since some parameters vary the full shape, while others affect only the position and height of the BAO peak. We use the full shape of the correlation function of BOSS-CMASS galaxies presented in Sánchez et al. (2012), in combination with CMB observations, to place constraints on the time variation of fundamental constants in the early universe. We focus on possible variations in the fine structure constant, $\alpha$, and the electron mass, $m_e$, at the recombination epoch. Strictly speaking, the acoustic fluctuations in the baryons are frozen in at the drag epoch rather than at last scattering (Hu & Sugiyama 1996). This dynamical decoupling of the baryons from the photons occurs nevertheless near recombination. Therefore, we assume that the values of the fundamental constants are the same throughout this epoch, though they can differ from their current values. We analyze the degeneracies with the basic cosmological parameters, as well as with others, such as the dark energy equation of state, the neutrino mass, the effective number of relativistic species, and the primordial helium abundance.

Limits on the present rate of variation of $\mu = m_e/m_\nu$ (where $m_\nu$ is the proton mass) are provided by atomic clocks (Prestage et al. 1992; Sortais et al. 2001; Bize et al. 2003; Marion et al. 2003; Fischer et al. 2004; Peik et al. 2004). Data from the Oklo natural fission reactor (Damon & Dyer 1992; Fulli et al. 2000) and half-lives of long lived $\beta$ decayers (Olive et al. 2004) allow to constrain the variation of fundamental constants at $z \approx 1$. Absorption systems in the spectra of high-redshift quasars put additional constraints at different redshifts. The method is based on the measurement of the separation between spectral lines in doublets and multiplets, whose dependence on the constants vary among different species (see for example Webb et al. 1999, 2001; Murphy et al. 2003; Agafonova et al. 2011; Kanekar et al. 2012; Wendt & Molaro 2012). Although the limits imposed by CMB and LSS are less stringent than the previous ones, they are important because they refer to earlier times.

The paper is organized as follows. In Section 2 we show how the correlation function depends on the values of $\alpha$ and $m_e$ at the recombination epoch. We describe the datasets used to place constraints on the variation of the fundamental constants and the statistical method performed. The modelling of the correlation function is also summarized. Section 3 presents the results for different parameter spaces. Conclusions are outlined in Section 4.

2 METHODOLOGY

We performed a statistical analysis to constrain the variation of $\alpha$ and $m_e$ at the recombination epoch, together with other cosmological parameters varied. In this Section we describe the datasets used to obtain our results. Then, we summarize the modelling of the correlation function, and present a brief explanation of why the correlation function is an effective observable to constrain the variation of fundamental constants. Finally, we describe the statistical analysis employed.

2.1 Data

In this paper, we use the full shape of the large-scale two-point correlation function $\xi(s)$ of the BOSS-CMASS galaxy sample, computed in Sánchez et al. (2012). This function was computed using the first spectroscopic data release of BOSS (Data Release 9, DR9, SDSS-III Collaboration: Ahn et al. 2012). The galaxy target selection of BOSS is divided in two separate sam-
The aforementioned datasets are used in different combinations to check the consistency of the obtained bounds. Firstly, we use the CMB data alone, and then combine it with the CMASS correlation function. In the end, we combine the four datasets to obtain our final constraints.

We do not consider supernovae (SNe) type Ia data because the light curves of the SNe are obtained assuming that the fundamental constants have their present values at the observing redshift. However, since we are investigating a possible time evolution in the value of $\alpha$ and $m_e$, and the SNe are at considerably high redshift ($0.7 < z < 1.4$ for the high-$z$ sample of Conley et al. 2011), we cannot neglect the possibility that the constants have a different value at those times. In fact, several studies aiming at measuring the value of $\alpha$ at high redshift using quasar absorption systems do not conclusively exclude the variation of fundamental constants at those redshifts (Webb et al. 1999, 2014; Murphy et al. 2003, 2004; King et al. 2012). Therefore, to be conservative, we choose not to consider the supernovae datasets in our analysis.

### 2.2 Model for the correlation function

We follow Sánchez et al. 2012 and model the shape of the large-scale correlation function, $\xi(s)$, by applying the following parametrization:

$$\xi(s) = b^2 \left[ L(s) \otimes e^{-(k_s s)^2} + A_{MC} \xi_s^{(1)}(s) \right],$$  

where the symbol $\otimes$ denotes a convolution, and the bias factor $b$, mode-coupling amplitude $A_{MC}$, and the smoothing length $k_s$ are considered as free parameters and marginalized over. Here $\xi_s^{(1)}(s)$ is the derivative of the linear correlation function $\xi_L$, and $\xi_s^{(1)}(s)$ is defined by

$$\xi_s^{(1)}(s) \equiv \hat{s} \cdot \nabla^{-1} \xi_L(s) = \frac{1}{2\pi^2} \int P_L(k) j_1(k s) k d k,$$

with $j_1(y)$ denoting the spherical Bessel function of order 1.

The parametrization of equation (1) was first proposed by Crocce & Scoccimarro (2008) and is based on renormalized perturbation theory (RPT). Crocce & Scoccimarro (2008), Sánchez et al. (2008) compared this model against the results of an ensemble of large volume N-body simulations (L-BASICC-II, Angulo et al. 2008), and showed that it provides an accurate description of the full shape of the correlation function, including also the effects of bias and redshift-space distortions. This parametrization has been applied to obtain constraints on cosmological parameters from clustering measurements from various galaxy samples (Sánchez et al. 2009, Beutler et al. 2011, Blake et al. 2011).

As in Sánchez et al. (2012), we restrict the comparison of the model of equation (1) and the BOSS-CMASS correlation function to $40 < s < 200 h^{-1}$ Mpc, and assume a Gaussian likelihood function.

### 2.3 Effects on the full-shape of $\xi(s)$

During the recombination epoch, the ionization fraction is determined by the balance between photoinization and recombination. The most important effects of changes in $\alpha$ and $m_e$ during this epoch are due to their influence upon Thomson scattering cross section $\sigma_T = 8\pi\alpha^2/(3m_e c^2)$ and
the binding energy of hydrogen $B_1 = \frac{3}{2} \alpha^2 m_e c^2$. The ionization history is more sensitive to $\alpha$ than to $m_e$ because of the $B_1$ dependence on these constants. The main result is the shift of the epoch of recombination to higher $z$ as $\alpha$ or $m_e$ increases, which corresponds to a smaller sound horizon. These effects are imprinted into the matter power spectrum through the transfer function. Hence, they also affect the galaxy correlation function. Consequently, if at recombination $\alpha$ or $m_e$ had a value higher than the present one, the peak in the correlation function would appear at smaller scales, since the position of the peak is related to the size of the sound horizon at the drag epoch.

Fig. 4 shows the effect of a variation in $\alpha$ and in $m_e$, during the recombination epoch, that we should expect in the correlation function of CMASS galaxies, in a flat universe with cosmological parameters $(\omega_\Lambda, \omega_{\text{dm}}, \tau, h, n_s) = (0.0221, 0.1145, 0.696, 0.962)$. We show the prediction for different values of the fundamental constants: their present value, and a variation of $\pm 5\%$ with respect to their values today. Data points are the spherically averaged redshift-space two-point correlation function of the full CMASS sample presented in Sánchez et al. (2012).

The changes in the correlation function due to variations in $\alpha$ are larger than the changes in $m_e$ for a given relative variation of their value. Both constants affect the position and height of the peak, leaving the rest of the curve unchanged. This effect can break degeneracies with other cosmological parameters that affect the full shape of the correlation function, such as the dark energy equation of state. Other parameters also affect the position of the peak. This leads to degeneracies between the fundamental constants and other cosmological parameters, such as $\Omega_m$, as we will see in Sections 5.1 and 5.2. The combination of CMASS data with different datasets helps to break those degeneracies.

2.4 Statistical Analysis

We perform our statistical analysis by exploring the parameter spaces with Monte Carlo Markov chains generated with the CosmoMC code (Lewis & Bridle 2002), which uses the Boltzmann code CAMB (Lewis et al. 2000) and Recfast (Seager et al. 1999) to compute the CMB power spectra. In order to be able to study more general models in which the dark energy component is different from the cosmological constant, we use a generalized version of CAMB which supports values of the dark energy equation of state beyond the phantom divide, $w_{\text{DE}} < -1$ (Fang et al. 2008). We modified these codes to include the variation in $\alpha$ and $m_e$ at recombination as described in Landau et al. (2008). Additional modifications from Keisler et al. (2011) are included to compute the likelihood of the SPT dataset. The dependence on the fundamental constants of the detailed physics relevant in the recombination process is described in Scoccola et al. (2008). Nevertheless, we emphasize that such description is done in terms of a modification to the effective 3-level atom model which is used in Recfast (Wong et al. 2008). Additional physical processes (see e.g., Rubino-Martín et al. 2008, Fendt et al. 2009, for a review) are effectively treated using a correction function inside Recfast v1.5 (Rubino-Martín et al. 2010). This function has, to first order, a negligible dependence on the standard cosmological parameters, but also on non-standard parameters such as $Y_{\text{He}}$ or $N_{\text{eff}}$ (Shaw & Chluba 2011). Although it has not been demonstrated explicitly, this correction function is also expected to have a small dependence on $\alpha$ and $m_e$. Thus, we will use in this paper the correction function as it appears in Recfast v1.5. However, for future CMB experiments with higher sensitivities in the damping tail of the angular power spectrum, a more detailed and complete treatment of the recombination problem might be relevant (Chluba & Thomas 2011).

We consider a spatially-flat cosmological model with adiabatic density fluctuations, described by the following parameters, which define the $\Lambda$CDM model:

$$P = (\omega_\Lambda, \omega_{\text{dm}}, \Theta, \tau, A_s, n_s)$$

(3)

where $\omega_\Lambda = \Omega_\Lambda h^2$ is the baryon density, $\omega_{\text{dm}} = \Omega_{\text{dm}} h^2$ is the
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3 RESULTS

We present the constraints obtained for the fundamental constants and cosmological parameters in each of the cases studied. Errorbars will indicate 68% confidence level (CL) unless otherwise stated. In Section 3.1 we study the variation of the fine structure constant, and do the statistical analysis varying also the cosmological parameters of the $\Lambda$CDM model. In Section 3.2 we study the variation of the electron mass together with the cosmological parameters. Section 3.3 investigates the joint variation of $\alpha$ and $m_e$. In Section 3.4 we analyze the constraints in the case where one of the constants ($\alpha$ or $m_e$) and the dark energy equation of state $w_{DE}$ can take values that differ from the standard ones. In Section 3.5 we study the case where we vary one of the fundamental constants and the massive neutrinos fraction $f_\nu$. Section 3.6 focuses on the constraints obtained when the fundamental constants are varied together with the effective number of relativistic species, $N_{\text{eff}}$, while Section 3.7 presents the constraints when the fundamental constants are varied together with the primordial helium fraction $Y_{\text{He}}$.

In Appendix A, we give the constraints on the $\Lambda$CDM model for our four datasets, to facilitate the comparison to the results presented in this paper.

3.1 Variation of $\alpha$

In this Section, we extend the $\Lambda$CDM model to include possible variations in the fine structure constant during recombination. We present our constraints on $\alpha/\alpha_0$ and the cosmological parameters.

The upper panel of Fig. 2 shows the two-dimensional marginalized constraints in the $\alpha - \Omega_m$ plane obtained from the CMB and CMASS datasets in isolation. As specified in Section 2 when using the information of the CMASS correlation function alone we impose Gaussian priors on $\omega_b$ and $n_s$ consistent with our CMB-only results. The constraints obtained from these datasets exhibit strong degeneracies. As these degeneracies constrain different combinations of $\alpha$ and $\Omega_m$, the combination of the two datasets provides tighter constraints on both parameters simultaneously. As can be seen in the lower panel of Fig. 2 the remaining degeneracy between these parameters is alleviated when more datasets are added to the analysis. The correlation factors are $-0.62$, $-0.38$, and $-0.13$ for CMB, CMB+CMASS, and the full dataset combination (CMB+CMASS+BAO+$H_0$), respectively.

In Fig. 3 we show the constraints in the $\alpha - H_0$ plane. $H_0$ is better constrained when additional datasets are included in the analysis. The value of the HST prior on $H_0$ lies almost 2 $\sigma$ from the value obtained for $H_0$ from the CMB+CMASS dataset, being the latter considerably smaller. Hence, when the HST prior on $H_0$ is taken into account, the obtained value for the Hubble parameter is increased. Due to the degeneracy with $\alpha$, the contours are shifted in the parameter space when the $H_0$ prior is included, and the value of the fine structure constant is increased, being closer to its present value.

In Table 1 we present the constraints on the variation of $\alpha$ and the cosmological parameters. The constraint on $\alpha$ from CMB data alone is $\alpha/\alpha_0 = 0.9914 \pm 0.0055$. The CMB-only constraints on $\Omega_m$ are considerably degraded by the inclusion of $\alpha$ as a free parameter, with $\Omega_m = 0.303^{+0.013}_{-0.016}$ (compare to the $\Lambda$CDM value of $\Omega_m$ in Table A1 of the Appendix). When we add the information encoded in the full shape of the CMASS $\xi(s)$, we find $\alpha/\alpha_0 = 0.9917 \pm 0.0046$ and $\Omega_m = 0.295^{+0.017}_{-0.018}$. In the case that all datasets are used in the analysis, the constraints are $\alpha = 0.9957^{+0.0041}_{-0.0042}$ and $\Omega_m = 0.283 \pm 0.010$, which is the same precision as that obtained in the $\Lambda$CDM model. The inclusion of the additional datasets produces only a mild improvement of the bounds on $\alpha$ with respect to those obtained using CMB information alone. This result arises because our CMB dataset covers the high multipole range, with $\ell \sim 3000$, which imposes strong constraints on this parameter. The bounds obtained for the
cosmological parameters from the full dataset are consistent within 1 \( \sigma \) with their values in the \( \Lambda \)CDM model (see Table [A]).

Menegoni et al. (2012) present constraints on the variation of \( \alpha \) using CMB data including data from SPT and the Atacama Cosmology Telescope (ACT, Dunkley et al. 2011), both probing the damping regime of the CMB fluctuations. By combining this information with the galaxy power spectrum from the SDSS-DR7 luminous red galaxy sample (Reid et al. 2010) and the HST prior on \( H_0 \), they find \( \alpha/\alpha_0 = 0.984 \pm 0.005 \). The precision on this constraint on \( \alpha \) is provided mostly by the CMB data, explaining why our results with CMB data alone have almost the same precision as theirs. Nevertheless, the CMASS \( \xi(s) \) further improves the precision of the bound. It is important to emphasize, however, that our results prefer values for \( \alpha \) that are closer to its present value than theirs. Our results are consistent with no variation of \( \alpha \) at 2 \( \sigma \) (for the full dataset, they are just slightly inconsistent at 1 \( \sigma \)).

### 3.2 Variation of \( m_e \)

Now we turn to the case in which we extend the \( \Lambda \)CDM model to include possible variations in the electron mass during recombination.

The contours in Fig. 4 show the two-dimensional marginalized constraints in the \( m_e - \Omega_m \) plane. The upper panel shows that the constraints obtained from the CMB and CMASS datasets in isolation exhibit strong degeneracies in different directions in the parameter space. The CMB-only constraints exhibit a strong degeneracy between \( m_e \) and \( \Omega_m \), causing \( \Omega_m \) to be poorly constrained by the CMB data alone, with \( \Omega_m = 0.31^{+0.12}_{-0.09} \). The inclusion of the CMB correlation function improves the constraints on \( \Omega_m \) by a factor larger than five to obtain \( \Omega_m = 0.295 \pm 0.021 \). This bound is further reduced by a factor of two when all datasets are included, in which case we find \( \Omega_m = 0.280 \pm 0.010 \), having the same precision than in the \( \Lambda \)CDM model.

In Fig. 5 we show the two-dimensional marginalized constraints in the \( m_e - H_0 \) plane. When \( m_e \) is allowed to vary, CMB information alone is insufficient to place any reliable constraint on \( H_0 \). When the CMASS dataset is added, the constraint improves noticeably. This dataset breaks the degeneracy between \( H_0 \) and \( m_e \). When all the datasets are
considered, the value of $H_0$ is increased due to the HST prior, and the value of $m_e$ is shifted towards its present value.

In Table 1, we present the constraints on the variation of $m_e$ and the cosmological parameters. The constraint on $m_e$ from CMB data alone is $0.987^{+0.067}_{-0.065}$. When we add the information encoded in the full shape of the CMASS $\xi(s)$, the bound is $0.981^{+0.020}_{-0.021}$. In the case that all datasets are used in the analysis, the constraint is $1.006^{+0.014}_{-0.011}$. The precision in the bound is highly improved when we add the information of the CMASS $\xi(s)$ to the analysis. Our final results are completely consistent with no variation of $m_e$ within 1 $\sigma$.

The bounds for the cosmological parameters are consistent within 1 $\sigma$ with those from the ΛCDM model. The mean values of $\sigma_8$ and $h$ for the CMB+CMASS dataset are somewhat smaller than in the ΛCDM model, but still consistent within 1 $\sigma$.

### 3.3 Joint variation of $\alpha$ and $m_e$ 

In this Section, we extend the ΛCDM model to study the joint variation of $\alpha$ and $m_e$. The contours in Fig. 3 show the two-dimensional marginalized constraints in the $m_e - \alpha$ plane. When the $H_0$ prior is used, the mean value of $\alpha$ is marginally decreased, while the mean value of $m_e$ is increased. The inclusion of additional datasets reduces the allowed region in the parameter space, while increasing the correlation between the fundamental constants; the correlation factor is $-0.23$, $-0.55$, and $-0.68$ for CMB, CMB+CMASS, and the full dataset combination (CMB+CMASS+BAO+$H_0$), respectively.

In Table 1, we present the constraints obtained for the fundamental constants and the cosmological parameters. When adding different datasets, the precision in the determination of $\alpha$ remains the same, although the mean value is slightly lower when the full dataset is used. For the CMB

|            | CMB       | CMB + CMASS | CMB + CMASS + BAO + $H_0$ |
|------------|-----------|-------------|-----------------------------|
| $\alpha/\alpha_0$ | $0.9914^{+0.0055}_{-0.0055}$ | $0.9917^{+0.0046}_{-0.0046}$ | $0.9957^{+0.0041}_{-0.0042}$ |
| $100\Omega_m$ | $1.0289^{+0.0078}_{-0.0076}$ | $1.0293^{+0.0064}_{-0.0065}$ | $1.0353^{+0.0057}_{-0.0058}$ |
| $100\omega_b$ | $2.207^{+0.043}_{-0.043}$ | $2.209^{+0.039}_{-0.039}$ | $2.225^{+0.038}_{-0.039}$ |
| $100\omega_c$ | $11.17^{+0.48}_{-0.47}$ | $11.09^{+0.36}_{-0.36}$ | $11.19^{+0.33}_{-0.34}$ |
| $\tau$ | $0.0880^{+0.0064}_{-0.0073}$ | $0.0877^{+0.0064}_{-0.0072}$ | $0.0867^{+0.0061}_{-0.0072}$ |
| $n_s$ | $0.977^{+0.013}_{-0.013}$ | $0.977^{+0.013}_{-0.013}$ | $0.973^{+0.013}_{-0.013}$ |
| $\ln(10^{10} A_s)$ | $3.104^{+0.034}_{-0.034}$ | $3.101^{+0.032}_{-0.031}$ | $3.095^{+0.030}_{-0.030}$ |
| $\Omega_{DE}$ | $0.697^{+0.036}_{-0.037}$ | $0.705^{+0.018}_{-0.017}$ | $0.717^{+0.010}_{-0.010}$ |
| $\Omega_m$ | $0.303^{+0.037}_{-0.036}$ | $0.295^{+0.017}_{-0.018}$ | $0.283^{+0.010}_{-0.010}$ |
| $\sigma_8$ | $0.815^{+0.023}_{-0.023}$ | $0.813^{+0.020}_{-0.020}$ | $0.818^{+0.018}_{-0.018}$ |
| $t_0$/Gyr | $14.12^{+0.26}_{-0.26}$ | $14.10^{+0.20}_{-0.19}$ | $13.90^{+0.17}_{-0.16}$ |
| $\sigma_8 h$ | $10.8^{+0.12}_{-0.12}$ | $10.8^{+0.12}_{-0.12}$ | $10.6^{+0.12}_{-0.12}$ |
| $h$ | $0.668^{+0.033}_{-0.033}$ | $0.672^{+0.018}_{-0.018}$ | $0.689^{+0.012}_{-0.012}$ |

Figure 4. The marginalized posterior distribution in the $m_e$ - $\Omega_m$ plane for the ΛCDM parameter set extended to include the variation of $m_e$. The dot-dashed lines show the 68% and 95% contours obtained using CMB information alone. The dotted contours, in the upper panel, show the results from CMASS correlation function.
Figure 5. The marginalized posterior distribution in the \( m_e - H_0 \) plane for the \( \Lambda \)CDM parameter set extended to include the variation of \( m_e/(m_e)_0 \). The dot-dashed lines show the 68% and 95% contours obtained using CMB information alone. The dashed lines correspond to the results obtained from the combination of CMB data plus the shape of the CMASS \( \xi(s) \). The solid lines indicate the results obtained from the full dataset combination (CMB+CMASS+BAO+\( H_0 \)).

Figure 6. The marginalized posterior distribution in the \( \alpha / \alpha_0 \) plane for the \( \Lambda \)CDM parameter set extended to include the joint variation of \( \alpha \) and \( m_e \). The dot-dashed lines show the 68% and 95% contours obtained using CMB information alone. The dashed lines correspond to the results obtained from the combination of CMB data plus the shape of the CMASS \( \xi(s) \). The solid lines indicate the results obtained from the full dataset combination (CMB+CMASS+BAO+\( H_0 \)).

Figure 7. The marginalized, one-dimensional likelihood distribution for the fine structure constant, when only \( \alpha \) is allowed to vary, and in the case of the joint variation of \( \alpha \) and \( m_e \).

The CMB+CMASS and the full datasets, the increment is more than 1 \( \sigma \) (see Fig. 8 for the full dataset case). For the full dataset combination, the mean value of \( m_e \) takes its largest value. Our final bounds, using the full dataset, are \( \alpha / \alpha_0 = 0.9901^{+0.0054}_{-0.0054} \) and \( m_e/(m_e)_0 = 1.028^{+0.015}_{-0.015} \). Both limits are consistent with no variation of the fundamental constants at the 2 \( \sigma \) level.

Most of the cosmological parameters are consistent within 1 \( \sigma \) with their \( \Lambda \)CDM model values for each of the datasets. The value of \( n_s \) is larger than in the \( \Lambda \)CDM model, for all of the datasets. For the CMB+CMASS and the full datasets, \( n_s \) is larger by slightly more than 1 \( \sigma \). The value of \( \sigma_8 \) is slightly larger than its value in the \( \Lambda \)CDM model, but consistent within 1 \( \sigma \).

Table 2. The marginalized 68% allowed regions on the cosmological parameters of the \( \Lambda \)CDM model, adding the variation of the electron mass, \( m_e \), obtained using different combinations of the datasets.

| Parameter          | CMB                  | CMB + CMASS               | CMB + CMASS + BAO + \( H_0 \) |
|--------------------|----------------------|---------------------------|-------------------------------|
| \( m_e/(m_e)_0 \)  | 0.989^{+0.067}_{-0.069} | 0.981^{+0.020}_{-0.021}  | 1.006^{+0.014}_{-0.013}       |
| \( 100\Theta_0 \)  | 1.033^{+0.049}_{-0.051} | 1.027^{+0.015}_{-0.015}  | 1.044^{+0.0097}_{-0.0094}     |
| \( 100\omega_b \)  | 2.20^{+0.17}_{-0.17}  | 2.177^{+0.054}_{-0.054}  | 2.228^{+0.042}_{-0.042}       |
| \( 100\omega_c \)  | 11.06^{+0.87}_{-0.88} | 10.95^{+0.63}_{-0.64}    | 11.67^{+0.55}_{-0.54}         |
| \( \sigma \)       | 0.0850^{+0.0063}_{-0.0071} | 0.0850^{+0.0061}_{-0.0069} | 0.0813^{+0.0059}_{-0.0066}    |
| \( n_s \)          | 0.965^{+0.012}_{-0.012} | 0.9646^{+0.0010}_{-0.0009} | 0.9620^{+0.0008}_{-0.0008}    |
| \( \ln(10^{10}A_s) \) | 3.080^{+0.031}_{-0.031} | 3.078^{+0.031}_{-0.030}  | 3.089^{+0.029}_{-0.029}       |
| \( \Omega_{DE} \)  | 0.691^{+0.12}_{-0.12} | 0.705^{+0.021}_{-0.021}  | 0.720^{+0.010}_{-0.010}       |
| \( \Omega_m \)     | 0.31^{+0.12}_{-0.11}  | 0.295^{+0.021}_{-0.021}  | 0.280^{+0.010}_{-0.010}       |
| \( \sigma_8 \)     | 0.799^{+0.074}_{-0.072} | 0.794^{+0.039}_{-0.039}  | 0.839^{+0.031}_{-0.031}       |
| \( t_0/\text{Gyr} \) | 14.1^{+1.7}_{-1.6}   | 14.26^{+0.47}_{-0.47}   | 13.64^{+0.28}_{-0.28}         |
| \( \tau_{re} \)    | 10.3^{+1.4}_{-1.4}   | 10.2^{+1.1}_{-1.1}       | 10.3^{+1.2}_{-1.2}            |
| \( h \)            | 0.69^{+0.15}_{-0.15}  | 0.668^{+0.032}_{-0.032}  | 0.704^{+0.017}_{-0.017}       |
Table 3. The marginalized 68% allowed regions on the cosmological parameters of the ΛCDM model, adding the variation of the fine structure constant α and of the electron mass $m_e$, obtained using different combinations of the datasets.

|                | CMB         | CMB + CMASS | CMB + CMASS + BAO + $H_0$ |
|----------------|-------------|-------------|---------------------------|
| $\alpha/\alpha_0$ | $0.990^{+0.005}_{-0.005}$ | $0.991^{+0.005}_{-0.005}$ | $0.990^{+0.005}_{-0.005}$ |
| $m_e/(m_{e0})$  | $1.012^{+0.073}_{-0.073}$ | $1.004^{+0.025}_{-0.025}$ | $1.028^{+0.019}_{-0.019}$ |
| $100\Theta$    | $1.036^{+0.051}_{-0.052}$ | $1.031^{+0.015}_{-0.015}$ | $1.046^{+0.0095}_{-0.0094}$ |
| $100c_{bh}$    | $2.24^{+0.18}_{-0.18}$ | $2.216^{+0.059}_{-0.059}$ | $2.265^{+0.046}_{-0.046}$ |
| $100\omega_{dm}$ | $11.29^{+0.92}_{-0.92}$ | $11.20^{+0.65}_{-0.66}$ | $11.83^{+0.56}_{-0.55}$ |
| $\tau$         | $0.0879^{+0.0066}_{-0.0074}$ | $0.0877^{+0.0071}_{-0.0071}$ | $0.0848^{+0.0063}_{-0.0063}$ |
| $n_s$          | $0.978^{+0.014}_{-0.014}$ | $0.978^{+0.013}_{-0.013}$ | $0.977^{+0.012}_{-0.012}$ |
| $\ln(10^{10}A_s)$ | $3.105^{+0.035}_{-0.035}$ | $3.104^{+0.035}_{-0.035}$ | $3.114^{+0.033}_{-0.033}$ |
| $\Omega_{DE}$  | $0.69^{+0.11}_{-0.12}$ | $0.706^{+0.020}_{-0.020}$ | $0.719^{+0.019}_{-0.010}$ |
| $\Omega_m$     | $0.31^{+0.11}_{-0.11}$ | $0.294^{+0.020}_{-0.020}$ | $0.281^{+0.010}_{-0.010}$ |
| $\sigma_8$     | $0.824^{+0.078}_{-0.081}$ | $0.820^{+0.042}_{-0.043}$ | $0.860^{+0.036}_{-0.035}$ |
| $t_0$/Gyr      | $14.0^{+1.7}_{-1.7}$ | $14.0^{+0.47}_{-0.47}$ | $13.5^{+0.27}_{-0.28}$ |
| $z_{re}$       | $10.9^{+1.5}_{-1.5}$ | $10.8^{+1.3}_{-1.3}$ | $11.0^{+1.3}_{-1.3}$ |
| $h$            | $0.70^{+0.16}_{-0.16}$ | $0.677^{+0.033}_{-0.033}$ | $0.708^{+0.017}_{-0.017}$ |

3.4 Variation of fundamental constants and $w_{DE}$

Until now, we have assumed that the dark energy component corresponds to a cosmological constant, with a fixed equation of state specified by $w_{DE} = -1$. In this Section we explore the constraints on the value of $w_{DE}$, assumed to be redshift-independent, in the context of the variation of fundamental constants.

In this study, the dynamical dark energy models are allowed to cross the so-called phantom divide, $w_{DE} = -1$, to explore models with $w_{DE} < -1$. In the framework of general relativity, a single scalar field cannot cross this threshold, since it becomes gravitationally unstable (Feng et al. 2005; Vikman 2005, Hu 2005, Xia et al. 2008). Thus, more degrees of freedom are required, which are difficult to implement in general dark energy studies. We follow the parametrized post-Friedmann (PPF) approach of Fang et al. (2008), as implemented in CAMB, which provides a simple solution to these problems for models in which the dark energy component is smooth compared to the dark matter.

First, we perform a statistical analysis varying $\alpha$ and $w_{DE}$, together with the rest of the cosmological parameters. Fig. 8 presents the constraints on the $\alpha - w_{DE}$ plane. Again, the inclusion of additional datasets reduces the allowed region in the parameter space, while increasing the anti-correlation between the fundamental constants. The correlation factor is $-0.16, 0.37$, and $0.54$ for CMB, CMB+CMASS, and the full dataset combination (CMB+CMASS+BAO+$H_0$), respectively. For the full dataset, the value $w_{DE} \geq -1$ is excluded at more than $1 \sigma$.

Table 4 shows the constraints obtained for $\alpha$, $w_{DE}$, and the cosmological parameters. The inclusion of more datasets slightly improves the constraint on $\alpha$ and does not appreciably affect the mean value. In the case of $w_{DE}$, a large improvement is observed, and the mean value of $w_{DE}$ shifts towards lower values. Our final bounds, using the complete dataset, are $\alpha/\alpha_0 = 0.9915^{+0.0048}_{-0.0048}$ and $w_{DE} = -1.20^{+0.13}_{-0.13}$. Our results are consistent with no variation of $\alpha$ at the $2 \sigma$ level, while $w_{DE}$ is compatible with a cosmological constant.
also within 2 $\sigma$, although at 1 $\sigma$, both quantities differ from their standard values.

There is a slight tension at the 1 $\sigma$ level in the values of some of the cosmological parameters with respect to their values in the ACMD model. At 2 $\sigma$, however, the results are consistent. Indeed, when compared to the ACMD model, we find that the value of $\Omega$ is lower and the age of the universe is higher for all of the datasets. The value of $n_s$ is higher for the CMB and the CMB+CMASS datasets, and $\sigma_8$ is higher for the full dataset.

We then perform a statistical analysis varying $m_\nu$ and $w_{DE}$. Fig. 10 presents the resulting constraints on the $m_\nu$ - $w_{DE}$ plane. CMB data alone cannot place strong constraints on the value of $w_{DE}$ and $m_\nu$. The inclusion of the CMASS correlation function restricts the allowed region in the parameter space, reducing the allowed range of values of $m_\nu$ by a factor of two. Using the full dataset, our bounds are $m_\nu/(m_\nu)_{0} = 0.969 \pm 0.029$ and $w_{DE} = -1.12 \pm 0.23$. In Table 4 we also present the constraints on the other cosmological parameters. The standard case of $m_\nu = (m_\nu)_{0}$ and $w_{DE} = -1$ is completely consistent with all of the datasets. The values of the cosmological parameters are consistent within 1 $\sigma$ with their values in the ACMD model.

### 3.5 Variation of fundamental constants and $f_\nu$

In the standard ACMD scenario, the dark matter component is given entirely by cold dark matter. However, neutrino oscillations found in recent experiments imply that they have a non-zero mass that contributes to the total energy budget of the universe. A variation in the neutrino mass can alter the redshift of matter-radiation equality, thus modifying the CMB power spectrum. Furthermore, until they.

### Table 5. The marginalized 68% allowed regions on the cosmological parameters of the ACMD model, adding the variation of the electron mass $m_\nu$, and the dark energy equation of state $w_{DE}$, obtained using different combinations of the datasets.

|                | CMB          | CMB + CMASS  | CMB + CMASS + BAO + $H_0$ |
|----------------|--------------|--------------|---------------------------|
| $w_{DE}$       | $-1.30^{+0.59}_{-0.64}$ | $-1.30^{+0.48}_{-0.56}$ | $-1.12^{+0.11}_{-0.23}$ |
| $m_\nu/(m_\nu)_{0}$ | $0.969^{+0.006}_{-0.007}$ | $0.974^{+0.029}_{-0.029}$ | $0.996^{+0.029}_{-0.029}$ |
| $100\Theta$    | $1.022^{+0.045}_{-0.045}$ | $1.022^{+0.022}_{-0.021}$ | $1.037^{+0.021}_{-0.021}$ |
| $100\omega_{b}$| $2.156^{+0.078}_{-0.076}$ | $2.156^{+0.078}_{-0.076}$ | $2.204^{+0.076}_{-0.075}$ |
| $100\omega_{dm}$| $10.7^{+0.6}_{-0.8}$ | $10.9^{+0.6}_{-0.6}$ | $11.5^{+0.6}_{-0.6}$ |
| $\tau$         | $0.084^{+0.006}_{-0.007}$ | $0.084^{+0.006}_{-0.007}$ | $0.081^{+0.006}_{-0.007}$ |
| $n_s$          | $0.963^{+0.012}_{-0.012}$ | $0.963^{+0.011}_{-0.010}$ | $0.963^{+0.009}_{-0.010}$ |
| $\ln(10^{10}A_s)$ | $3.078^{+0.031}_{-0.031}$ | $3.078^{+0.030}_{-0.031}$ | $3.087^{+0.029}_{-0.029}$ |
| $\Omega_{DE}$  | $0.69^{+0.17}_{-0.15}$ | $0.743^{+0.063}_{-0.073}$ | $0.729^{+0.019}_{-0.019}$ |
| $\Omega_{m}$   | $0.31^{+0.17}_{-0.15}$ | $0.257^{+0.063}_{-0.073}$ | $0.271^{+0.019}_{-0.019}$ |
| $\sigma_8$     | $0.83^{+0.15}_{-0.15}$ | $0.85^{+0.12}_{-0.11}$ | $0.852^{+0.049}_{-0.048}$ |
| $100\omega_{b}$| $14.8^{+1.6}_{-1.6}$ | $14.30^{+0.56}_{-0.56}$ | $13.86^{+0.55}_{-0.56}$ |
| $100\omega_{dm}$| $9.9^{+1.3}_{-1.3}$ | $10.1^{+1.2}_{-1.2}$ | $10.2^{+1.2}_{-1.2}$ |
| $h$            | $0.70^{+0.20}_{-0.19}$ | $0.730^{+0.11}_{-0.091}$ | $0.712^{+0.021}_{-0.020}$ |
Variation of fundamental constants: constraints from BOSS-CMASS $\xi(s)$

In Table 6 we present the constraints obtained for $\alpha$, $f_\nu$, and the remaining cosmological parameters. In the case of only CMB data, we find $f_\nu < 0.098$ at 95% CL, and $\alpha/\alpha_0 = 0.9932^{+0.0054}_{-0.0033}$. When we also include the information from the CMASS correlation function, this limit is reduced to $f_\nu < 0.049$ at 95% CL, and the constraint on $\alpha$ is $\alpha/\alpha_0 = 0.9946^{+0.0049}_{-0.0050}$. The constraints for the full data set are $f_\nu < 0.043$ at 95% CL and $\alpha/\alpha_0 = 0.9978^{+0.0044}_{-0.0045}$. We find no degeneracy between $\alpha$ and $f_\nu$. When all datasets are included in the analysis, the value of $\alpha$ is increased (due to the larger value of $h$), our results being consistent with no variation of $\alpha$ within 1 $\sigma$.

Regarding the constraints on the primary cosmological parameters, we find that they are consistent with the LCDM values at 1 $\sigma$ in most of the cases. For the CMB and CMB+CMASS datasets, some of the derived parameters differ by more than 1 $\sigma$ from their values in the LCDM model, but they are consistent within 1 $\sigma$ when we consider the full dataset, with exception of $\sigma_8$, which is lower by more than 1 $\sigma$ also for the full dataset. For the CMB dataset, $h$ differs by more than 2 $\sigma$ from the LCDM value, by 1 $\sigma$ for the CMB+CMASS dataset, and is fully consistent for the full dataset.

Figure 11. The marginalized posterior distribution in the $\alpha - f_\nu$ plane for the LCDM parameter set extended to include the variation of $\alpha$ and a non-negligible fraction of massive neutrinos. The dot-dashed lines show the 68% and 95% contours obtained using CMB information alone. The dashed lines correspond to the results obtained from the combination of CMB data plus the shape of the CMASS $\xi(s)$. The solid lines indicate the results obtained from the full dataset combination (CMB+CMASS+BAO+$H_0$).

Figure 12. The marginalized posterior distribution in the $m_\nu - f_\nu$ plane for the LCDM parameter set extended to include the variation of $m_\nu$ and a non-negligible fraction of massive neutrinos. The dot-dashed lines show the 68% and 95% contours obtained using CMB information alone. The dashed lines correspond to the results obtained from the combination of CMB data plus the shape of the CMASS $\xi(s)$. The solid lines indicate the results obtained from the full dataset combination (CMB+CMASS+BAO+$H_0$).

In Table 7 we present the constraints obtained for $m_\nu$, $f_\nu$, and the cosmological parameters. In the case of only CMB data, we find $f_\nu < 0.11$ at 95% CL, and $m_\nu/(m_\nu)_{0} = 1.011^{+0.067}_{-0.066}$. When we also include the information from the CMASS correlation function, this limit is reduced to $f_\nu < 0.074$ at 95% CL, and the constraint on $m_\nu$ is $m_\nu/(m_\nu)_{0} = 1.099^{+0.029}_{-0.028}$. The constraints for the full data set are $f_\nu < 0.086$ at 95% CL and $m_\nu/(m_\nu)_{0} = 1.035 \pm 0.021$. When all datasets are included in the analysis, the value of $m_\nu$ is increased (due to the larger value of $h$), and our results are consistent with no variation of $m_\nu$ at 2 $\sigma$.

With regards to the constraints on the cosmological parameters, we find that they are consistent with the LCDM values at 1 $\sigma$ in most of the cases, although $\omega_{de0}$ differs from the LCDM value by 1 $\sigma$ for the full dataset. There is also tension for $\sigma_8$ at the 1 $\sigma$ level for all of the datasets, in the sense that our constraints are lower than the LCDM values. For the full dataset, the age of the universe is lower and $h$ is higher by more than 1 $\sigma$ than their corresponding...
Table 6. The marginalized 68% allowed regions on the cosmological parameters of the ΛCDM model, adding the variation of the fine structure constant α and f_e as a free parameter, obtained using different combinations of the datasets.

| Parameter            | CMB       | CMB + CMASS | CMB + CMASS + BAO + H_0 |
|----------------------|-----------|-------------|-------------------------|
| f_e                  | < 0.098 (95% CL) | < 0.049 (95% CL) | < 0.043 (95% CL) |
| α/α₀                 | 0.9933±0.0057 | 0.9940±0.0059 | 0.9978±0.0044 |
| 100Ω                 | 1.0312±0.0081 | 1.0326±0.0069 | 1.0382±0.0062 |
| 100ω_{cd}            | 2.187±0.044  | 2.209±0.039  | 2.228±0.038  |
| 100ω_{dim}           | 11.86±0.71   | 11.25±0.39   | 11.27±0.34   |
| τ                    | 0.0857±0.0061| 0.0889±0.0065| 0.0869±0.0070|
| ηₙ                  | 0.968±0.016  | 0.974±0.013  | 0.972±0.013  |
| ln(10^{10}A_s)      | 3.097±0.034  | 3.094±0.033  | 3.086±0.031  |
| Σmν                  | < 1.2 eV (95% CL) | < 0.53 eV (95% CL) | < 0.46 eV (95% CL) |
| Ω_{DE}               | 0.636±0.062  | 0.696±0.020  | 0.714±0.011  |
| Ω_{m}                | 0.364±0.062  | 0.304±0.020  | 0.286±0.011  |
| ηₙ                  | 0.715±0.073  | 0.761±0.043  | 0.772±0.039  |
| t₀/Gyr               | 14.32±0.28   | 14.11±0.20   | 13.90±0.16   |
| z_{re}               | 10.8±1.3     | 10.9±1.3     | 10.6±1.2     |
| h                    | 0.626±0.041  | 0.666±0.039  | 0.688±0.012  |

Table 7. The marginalized 68% allowed regions on the cosmological parameters of the ΛCDM model, adding the variation of the electron mass mₑ and f_e as a free parameter, obtained using different combinations of the datasets.

| Parameter            | CMB       | CMB + CMASS | CMB + CMASS + BAO + H_0 |
|----------------------|-----------|-------------|-------------------------|
| f_e                  | < 0.11(95%CL) | < 0.074(95%CL) | < 0.086(95%CL) |
| mₑ/(mₑ)₀            | 1.011±0.067 | 1.009±0.029 | 1.035±0.021 |
| 100Ω                 | 1.048±0.048 | 1.047±0.021 | 1.065±0.014 |
| 100ω_{cd}            | 2.225±0.16  | 2.225±0.065 | 2.276±0.047 |
| 100ω_{dim}           | 12.9±1.1    | 11.81±0.92  | 12.60±0.77  |
| τ                    | 0.0840±0.0063| 0.0839±0.0061 | 0.0818±0.0061 |
| ηₙ                  | 0.957±0.013  | 0.962±0.010  | 0.9593±0.0098 |
| ln(10^{10}A_s)      | 3.081±0.030  | 3.081±0.031  | 3.089±0.029  |
| Σmν                  | < 1.4 eV (95% CL) | < 0.91 eV (95% CL) | < 1.1 eV (95% CL) |
| Ω_{DE}               | 0.64±0.13   | 0.702±0.021  | 0.711±0.012  |
| Ω_{m}                | 0.36±0.13   | 0.297±0.021  | 0.289±0.011  |
| ηₙ                  | 0.694±0.090  | 0.745±0.048  | 0.748±0.054  |
| t₀/Gyr               | 14.6±1.6    | 13.76±0.52   | 13.28±0.33   |
| z_{re}               | 10.7±1.4    | 10.6±1.3     | 10.8±1.3     |
| h                    | 0.67±0.15   | 0.689±0.037  | 0.718±0.019  |

values in the ΛCDM model. The constraints at 95% CL on the sum of the neutrinos masses are \( \sum m_ν < 1.4 \) eV (CMB), \( \sum m_ν < 0.91 \) eV (CMB+CMASS), and \( \sum m_ν < 1.1 \) eV (full dataset).

3.6 Variation of fundamental constants and \( N_{eff} \)

The effective number of relativistic species, \( N_{eff} \), has been reported as higher than the expected standard value of \( N_{eff} = 3.046 \) (Dunkley et al. 2011; Keisler et al. 2011). This may indicate either additional relativistic species, or evidence for non-standard decoupling. Here we study the con-
constraints from the CMASS correlation function on the variation of $\alpha$ and $m_e$ when $N_{\text{eff}}$ can differ from its standard value, providing details on the constraints set by the different datasets considered in this paper.

In the case of no variation of the fundamental constants, Keisler et al. (2011) present a bound of $N_{\text{eff}} = 3.85 \pm 0.62$ for the CMB dataset (WMAP+SPT). We consider the LCDM+$N_{\text{eff}}$ model and obtain the constraints $N_{\text{eff}} = 3.75 \pm 0.58$ for CMB+CMASS and $N_{\text{eff}} = 3.86^{+0.39}_{-0.40}$ for the full dataset.

The contours in Fig. 13 show the two-dimensional marginalized constraints in the $N_{\text{eff}} - \alpha$ plane. There is a strong degeneracy between $\alpha$ and $N_{\text{eff}}$ in the CMB dataset. When we add the CMASS dataset, this degeneracy is partially alleviated, and it disappears for the full dataset. The inclusion of the HST $H_0$ prior shifts the contours towards higher values of $N_{\text{eff}}$ and $\alpha$, making the latter consistent with its present value at 1 $\sigma$.

In Table 8 we present the constraints on $N_{\text{eff}}$, $\alpha$, and the rest of the cosmological parameters for all of our datasets. When $\alpha$ is allowed to vary, $N_{\text{eff}} = 3.37^{+0.95}_{-0.97}$ for the CMB dataset, which is a value more consistent with the standard one than when $\alpha$ is fixed to its present value (as said before, for WMAP+SPT data, the value presented by Keisler et al. 2011, is $N_{\text{eff}} = 3.85 \pm 0.62$). The constraint on $\alpha$ is $\alpha/\alpha_0 = 0.9935 \pm 0.0093$. By adding the CMASS correlation function, we tighten the bounds on $N_{\text{eff}}$ and $\alpha$, which become $N_{\text{eff}} = 3.21^{+0.66}_{-0.67}$ and $\alpha/\alpha_0 = 0.9926 \pm 0.0058$. For CMB+CMASS+BAO, $N_{\text{eff}} = 3.19 \pm 0.64$ and $\alpha/\alpha_0 = 0.9926^{+0.0054}_{-0.0055}$. When all datasets are considered in the analysis, the constraints are $N_{\text{eff}} = 3.83 \pm 0.40$ and $\alpha/\alpha_0 = 0.9967 \pm 0.0042$. The $H_0$ prior shifts $N_{\text{eff}}$ towards higher values, which lie almost 2 $\sigma$ from the standard value of 3.046. On the other hand, $\alpha$ is consistent with no variation at 1 $\sigma$. Menegoni et al. (2012) studied the variation of $\alpha$ when $N_{\text{eff}}$ can have values different from the standard one, allowing also for variations in the primordial helium abundance, $Y_{\text{He}}$. Their constraints are $\alpha/\alpha_0 = 0.990 \pm 0.006$ and $N_{\text{eff}} = 4.10^{+0.24}_{-0.28}$. The difference in the datasets is that they use the DR7 LRG power spectrum and add the ACT data to their analysis, presenting their results only for the full dataset.

There is tension at the 1 $\sigma$ level in some of the cosmological parameters with respect to their LCDM model values. For the full dataset, $\Theta$ and $t_0$ are more than 1 $\sigma$ lower, and $n_s$, $\sigma_8$, $h$ and $\omega_{\text{de}}$ are larger by more than 1 $\sigma$. $\Theta$ is also more than 1 $\sigma$ lower than its concordance value for the CMB+CMASS dataset. In the rest of the cases, the parameters are all consistent within 1 $\sigma$ with their LCDM values.

We now analyze the results for the case in which $m_e$ and $N_{\text{eff}}$ are allowed to vary. In Fig. 14 we show the two-dimensional marginalized constraints in the $N_{\text{eff}} - m_e$ plane. There is no degeneracy between $m_e$ and $N_{\text{eff}}$ for the CMB and CMB+CMASS datasets. When the full dataset is considered, a mild correlation between both quantities appears.

In Table 9 we present the constraints on $N_{\text{eff}}$, $m_e$, and the rest of the cosmological parameters for all of our datasets. For the CMB dataset, $N_{\text{eff}} = 3.86 \pm 0.60$, which is more than 1 $\sigma$ higher than the standard value. The constraint on $m_e$ is $m_e/(m_e)_0 = 0.988 \pm 0.065$. By adding the CMASS correlation function, we significantly tighten the bounds on $m_e$ but only slightly improve the limits on $N_{\text{eff}}$, which become $N_{\text{eff}} = 3.80 \pm 0.57$ and $m_e/(m_e)_0 = 0.981 \pm 0.020$. For CMB+CMASS+BAO, $N_{\text{eff}} = 3.78 \pm 0.58$ and $m_e/(m_e)_0 = 0.981 \pm 0.018$. When all datasets are considered.

| Parameter          | CMB     | CMB + CMASS | CMB + CMASS + BAO + H_0 |
|--------------------|---------|-------------|--------------------------|
| $N_{\text{eff}}$   | 3.37^{+0.95}_{-0.97} | 3.21^{+0.66}_{-0.67} | 3.83^{+0.40}_{-0.40} |
| $\alpha/\alpha_0$ | 0.9935^{+0.0093}_{-0.0093} | 0.9926^{+0.0058}_{-0.0058} | 0.9967^{+0.0042}_{-0.0042} |
| $100\Theta$       | 1.032^{+0.012}_{-0.012} | 1.0304^{+0.0075}_{-0.0074} | 1.0349^{+0.0057}_{-0.0058} |
| $100\omega_b$     | 2.228^{+0.079}_{-0.079} | 2.218^{+0.055}_{-0.055} | 2.254^{+0.041}_{-0.041} |
| $100\omega_{\text{dm}}$ | 11.7^{+1.1}_{-1.8} | 11.4^{+1.3}_{-1.4} | 12.7^{+0.88}_{-0.87} |
| $\gamma$          | 0.0886^{+0.0063}_{-0.0074} | 0.0882^{+0.0064}_{-0.0073} | 0.0878^{+0.0062}_{-0.0072} |
| $n_s$              | 0.981^{+0.021}_{-0.029} | 0.979^{+0.017}_{-0.017} | 0.988^{+0.015}_{-0.015} |
| $\ln(10^{10}A_s)$ | 3.112^{+0.049}_{-0.049} | 3.106^{+0.044}_{-0.045} | 3.134^{+0.036}_{-0.036} |
| $\Omega_{\text{DE}}$ | 0.705^{+0.050}_{-0.049} | 0.707^{+0.019}_{-0.019} | 0.715^{+0.010}_{-0.010} |
| $\Omega_{\text{m}}$ | 0.295^{+0.049}_{-0.050} | 0.293^{+0.019}_{-0.019} | 0.285^{+0.010}_{-0.010} |
| $\sigma_8$        | 0.832^{+0.060}_{-0.061} | 0.822^{+0.048}_{-0.049} | 0.867^{+0.032}_{-0.032} |
| $h$               | 13.8^{+1.3}_{-1.3} | 13.95^{+0.81}_{-0.79} | 13.20^{+0.38}_{-0.38} |
| $\omega_{\text{de}}$ | 10.9^{+1.3}_{-1.3} | 10.9^{+1.3}_{-1.3} | 11.1^{+1.3}_{-1.3} |
| $m_e$             | 0.696^{+0.092}_{-0.092} | 0.683^{+0.047}_{-0.048} | 0.725^{+0.022}_{-0.022} |
Figure 14. The marginalized posterior distribution in the $m_e$ - $N_{\text{eff}}$ plane for the LCDM parameter set extended to include the variation of $m_e$ and a variable effective number of relativistic degrees of freedom $N_{\text{eff}}$. The dot-dashed lines show the 68% and 95% contours obtained using CMB information alone. The dashed lines correspond to the results obtained from the combination of CMB data plus the shape of the CMASS $\xi(s)$. The solid lines indicate the results obtained from the full dataset combination (CMB+CMASS+BAO+$H_0$).

Table 9. The marginalized 68% allowed regions on the cosmological parameters of the LCDM model, adding the variation of the electron mass $m_e$ and $N_{\text{eff}}$ as a free parameter, obtained using different combinations of the datasets.

| Parameter                  | CMB                  | CMB + CMASS          | CMB + CMASS + BAO + $H_0$ |
|----------------------------|----------------------|----------------------|---------------------------|
| $N_{\text{eff}}$           | $3.86^{+0.60}_{-0.60}$ | $3.80^{+0.57}_{-0.57}$ | $4.04^{+0.47}_{-0.46}$   |
| $m_e/(m_e)_0$              | $0.988^{+0.005}_{-0.005}$ | $0.981^{+0.020}_{-0.020}$ | $0.988^{+0.015}_{-0.016}$ |
| $100\theta$               | $1.030^{+0.048}_{-0.048}$ | $1.026^{+0.015}_{-0.015}$ | $1.031^{+0.011}_{-0.011}$ |
| $100\omega_b$             | $2.24^{+0.17}_{-0.17}$   | $2.216^{+0.062}_{-0.062}$  | $2.245^{+0.042}_{-0.042}$  |
| $100\omega_{\text{dm}}$   | $12.4^{+1.5}_{-1.4}$    | $12.2^{+1.2}_{-1.2}$     | $12.85^{+0.82}_{-0.80}$   |
| $\tau$                    | $0.0891^{+0.0067}_{-0.0075}$ | $0.0884^{+0.0075}_{-0.0075}$ | $0.0882^{+0.0066}_{-0.0075}$ |
| $n_s$                      | $0.986^{+0.019}_{-0.020}$ | $0.985^{+0.017}_{-0.017}$   | $0.990^{+0.016}_{-0.016}$   |
| $\ln(10^{10}A_s)$         | $3.124^{+0.044}_{-0.045}$ | $3.119^{+0.042}_{-0.042}$   | $3.134^{+0.036}_{-0.036}$   |
| $\Omega_{\text{DE}}$      | $0.69^{+0.11}_{-0.11}$   | $0.709^{+0.020}_{-0.020}$   | $0.715^{+0.011}_{-0.011}$   |
| $\Omega_m$                | $0.31^{+0.011}_{-0.011}$  | $0.291^{+0.020}_{-0.020}$   | $0.285^{+0.011}_{-0.011}$   |
| $\sigma_8$                | $0.844^{+0.086}_{-0.086}$ | $0.835^{+0.049}_{-0.049}$   | $0.862^{+0.033}_{-0.033}$   |
| $\theta_0$/Gyr            | $13.4^{+1.6}_{-1.6}$     | $13.53^{+0.65}_{-0.65}$    | $13.14^{+0.34}_{-0.34}$    |
| $z_{\text{re}}$            | $10.9^{+1.5}_{-1.5}$     | $10.7^{+1.3}_{-1.3}$       | $10.9^{+1.3}_{-1.3}$       |
| $h$                       | $0.73^{+0.16}_{-0.16}$   | $0.705^{+0.043}_{-0.043}$  | $0.728^{+0.020}_{-0.020}$  |

3.7 Variation of fundamental constants and $Y_{\text{He}}$

Light nuclei begin to form in a process known as big bang nucleosynthesis (BBN, Alpher et al. 1948; Schramm & Turner 1995; Steigman 2007), when the universe cools to $T \sim 0.1$ MeV. We denote the primordial abundance (mass fraction) of $^4\text{He}$ as $Y_{\text{He}}$, which is a function of the baryon density and the expansion rate during BBN. The value of $Y_{\text{He}}$ can be estimated by the effect of helium on the CMB damping tail. Helium combines earlier than hydrogen, and thus more helium (at fixed baryon density) leads to fewer free electrons during hydrogen recombination. This, in turn, leads to larger diffusion lengths for photons and less power in the CMB damping tail. We study the constraints from the CMASS correlation function on the variation of $\alpha$ and $m_e$ when $Y_{\text{He}}$ can differ from its standard value of $Y_{\text{He}} = 0.24$.

In the case of no variation of the fundamental constants, Keisler et al. (2011) present a bound of $Y_{\text{He}} = 0.296 \pm 0.030$ for the CMB dataset (WMAP+SPT). We consider the LCDM+$Y_{\text{He}}$ model and obtain the constraints $Y_{\text{He}} = 0.297 \pm 0.030$ for CMB+CMASS and $Y_{\text{He}} = 0.301^{+0.028}_{-0.029}$ for the full dataset.

The contours in Fig. 15 show the two-dimensional marginalized constraints in the $Y_{\text{He}}$ - $\alpha$ plane. There is a strong degeneracy between $\alpha$ and $Y_{\text{He}}$ in all of the datasets. When $\alpha$ is allowed to vary, CMB information alone is insufficient to place any reliable constraint on $Y_{\text{He}}$. When the CMASS dataset is added, the constraint improves noticeably. The inclusion of the HST $H_0$ prior improves further the constraints, and shifts the contours towards higher values of $Y_{\text{He}}$ and $\alpha$, making the former measurement inconsistent with its standard value at $1\sigma$.

In Table 10 we present the constraints on $Y_{\text{He}}$, $\alpha$, and the rest of the cosmological parameters for all of our datasets. When $\alpha$ is allowed to vary, $Y_{\text{He}} = 0.26 \pm 0.15$ for the CMB dataset, which is a value consistent with the standard one, contrary to the case when $\alpha$ is fixed to its present value (for WMAP+SPT data, the value presented by Keisler et al. 2011, is $Y_{\text{He}} = 0.296 \pm 0.030$). The constraint on $\alpha$ is $\alpha/\alpha_0 = 0.994^{+0.026}_{-0.025}$. By adding the CMASS correlation function, we tighten the bounds on $Y_{\text{He}}$ and $\alpha$ to $Y_{\text{He}} = 0.249 \pm 0.064$ and $\alpha/\alpha_0 = 0.9920^{+0.0092}_{-0.0093}$. When all datasets are considered in the analysis, the constraints are $Y_{\text{He}} = 0.314 \pm 0.043$ and $\alpha/\alpha_0 = 1.0023^{+0.0062}_{-0.0061}$. The $H_0$ prior shifts $Y_{\text{He}}$ towards higher values, which are almost $2\sigma$ above the standard value of 0.24. On the other hand, $\alpha$ is consistent with no variation at $1\sigma$. Menegoni et al. (2012) studied the joint variation of $\alpha$, $N_{\text{eff}}$ and $Y_{\text{He}}$; their con-
Figure 15. The marginalized posterior distribution in the $\alpha - Y_{\text{He}}$ plane for the $\Lambda$CDM parameter set extended to include the variation of $\alpha$ and a variable primordial helium abundance $Y_{\text{He}}$. The dot-dashed lines show the 68% and 95% contours obtained using CMB information alone. The dashed lines correspond to the results obtained from the combination of CMB data plus the shape of the CMASS $\xi(s)$. The solid lines indicate the results obtained from the full dataset combination (CMB+CMASS+BAO+$H_0$).

Constraint is $Y_{\text{He}} = 0.215 \pm 0.096$ but with $N_{\text{eff}}$ higher by more than 3 $\sigma$ than its standard value.

There is a slight tension at the 1 $\sigma$ level for the parameter $n_s$, which is higher than its $\Lambda$CDM value for the CMB+CMASS and the full datasets. In the rest of the cases, the parameters are all consistent within 1 $\sigma$ with their $\Lambda$CDM values.

We now analyze the results for the case in which $m_e$ and $Y_{\text{He}}$ are allowed to vary. Fig. 16 shows the two-dimensional marginalized constraints in the $Y_{\text{He}} - m_e$ plane. There is no degeneracy between $m_e$ and $Y_{\text{He}}$ for any of the datasets.

In Table 11 we present the constraints on $Y_{\text{He}}$, $m_e$, and the rest of the cosmological parameters for all of our datasets. For the CMB dataset, $Y_{\text{He}} = 0.296 \pm 0.029$, which is almost 2 $\sigma$ higher than the standard value. The constraint on $m_e$ is $m_e/(m_e)_0 = 0.994^{+0.020}_{-0.022}$. By adding the CMASS correlation function, we tighten the bounds on $m_e$ by a factor of three $(m_e/(m_e)_0 = 0.985^{+0.020}_{-0.022})$ but the bound on $Y_{\text{He}}$ is unchanged. When all datasets are considered in the analysis, the constraints are $Y_{\text{He}} = 0.302 \pm 0.029$ and $m_e/(m_e)_0 = 1.006^{+0.013}_{-0.014}$. The $H_0$ prior shifts $Y_{\text{He}}$ towards slightly higher values, which are more than 2 $\sigma$ above the standard value of 0.24. On the other hand, $m_e$ is consistent with no variation at 1 $\sigma$, for all of the datasets.

Regarding the values of the remaining cosmological parameters, we find that there is a slight tension at the 1 $\sigma$ level for the parameter $n_s$, which is higher than its $\Lambda$CDM value for the CMB+CMASS dataset, and for the parameter $\sigma_8$, which is higher than its $\Lambda$CDM value for the full dataset. In the rest of the cases, the parameters are all consistent within 1 $\sigma$ with their $\Lambda$CDM values.

![Figure 16](image_url)
Table 11. The marginalized 68% allowed regions on the cosmological parameters of the ΛCDM model, adding the variation of the electron mass \(m_e\) and \(Y_{\text{He}}\) as a free parameter, obtained using different combinations of the datasets.

| \(Y_{\text{He}}\) | CMB | CMB + CMASS | CMB + CMASS + BAO + \(H_0\) |
|----------------|-----|-------------|-----------------------------|
| 0.296_{-0.029}^{+0.029} | 0.295_{-0.030}^{+0.029} | 0.302_{-0.029}^{+0.029} |
| 0.994_{-0.007}^{+0.008} | 0.985_{-0.021}^{+0.020} | 1.006_{-0.014}^{+0.013} |
| 1.007_{-0.050}^{+0.051} | 1.031_{-0.015}^{+0.015} | 1.047_{-0.095}^{+0.099} |
| 2.24_{-0.17}^{+0.17} | 2.216_{-0.058}^{+0.058} | 2.267_{-0.046}^{+0.046} |
| 11.3_{-0.92}^{+0.91} | 11.20_{-0.66}^{+0.65} | 11.87_{-0.56}^{+0.55} |
| 0.0881_{-0.0064}^{+0.0064} | 0.0882_{-0.0075}^{+0.0075} | 0.0849_{-0.0060}^{+0.0063} |
| 0.978_{-0.014}^{+0.014} | 0.978_{-0.013}^{+0.013} | 0.977_{-0.013}^{+0.013} |
| \ln(10^{10} A_s) | 3.106_{-0.035}^{+0.035} | 3.105_{-0.034}^{+0.034} | 3.116_{-0.033}^{+0.033} |
| 0.69_{-0.11}^{+0.11} | 0.706_{-0.020}^{+0.020} | 0.718_{-0.010}^{+0.010} |
| \Omega_m | 0.31_{-0.11}^{+0.11} | 0.294_{-0.020}^{+0.020} | 0.282_{-0.010}^{+0.010} |
| \sigma_8 | 0.827_{-0.079}^{+0.077} | 0.821_{-0.042}^{+0.041} | 0.863_{-0.035}^{+0.035} |
| t_0/Gyr | 13.9_{-1.6}^{+1.6} | 14.0_{-0.47}^{+0.47} | 13.54_{-0.28}^{+0.28} |
| \tau_{\text{ee}} | 10.9_{-1.3}^{+1.5} | 10.8_{-1.2}^{+1.3} | 11.9_{-1.3}^{+1.3} |
| h | 0.70_{-0.15}^{+0.16} | 0.677_{-0.033}^{+0.031} | 0.709_{-0.017}^{+0.017} |

4 CONCLUSIONS

In this paper we have presented new constraints on the variation of the fine structure constant and on the electron mass using the latest CMB observations, and the full shape of the (spherically averaged) redshift-space correlation function of the CMASS sample of galaxies, drawn from the Data Release 9 (DR9) of the Baryonic Oscillations Spectroscopic Survey (BOSS). Recent BAO and \(H_0\) measurements were also considered. We have studied the degeneracies between these constants and other cosmological parameters, such as the dark energy equation of state, the neutrino mass, the effective number of relativistic species, and the primordial helium abundance. The main results can be summarized as follows:

(i) In the case of variation of only \(\alpha\), our bound is \(\alpha/\alpha_0 = 0.9957_{-0.0042}^{+0.0041}\), consistent with no variation at the 2 \(\sigma\) level (almost at 1 \(\sigma\)). The constraints from CMB data alone are slightly improved when CMASS and other cosmological datasets are included.

(ii) When only \(m_e\) is allowed to vary, the bounds are highly improved when additional datasets are considered in the analysis. Our best estimate including all datasets is \(m_e/(m_e)_0 = 1.06_{-0.013}^{+0.014}\), consistent with no variation of \(m_e\) within 1 \(\sigma\). The CMASS dataset improves largely the CMB-only constraints.

(iii) When both \(\alpha\) and \(m_e\) are allowed to vary, the constraints on \(\alpha\) do not improve with the addition of new datasets, while they do for \(m_e\). With each dataset addition, the variation of the constants becomes more correlated. Our final bounds, using the complete dataset, are \(\alpha/\alpha_0 = 0.9901_{-0.0054}^{+0.0054}\) and \(m_e/(m_e)_0 = 1.028 \pm 0.019\). Both limits are consistent with no variation of the fundamental constants within 2 \(\sigma\).

(iv) When we study the variation of \(\alpha\) taking the value of \(w_{DE}\) as a free parameter, the allowed region for \(\alpha\) hardly depends on the addition of further datasets. The constraints on \(w_{DE}\), however, are noticeably improved. The bounds for the complete datasets are \(\alpha/\alpha_0 = 0.9915 \pm 0.0048\) and \(w_{DE} = -1.20 \pm 0.13\), which deviates from the standard value \(w_{DE} = -1\) at 1 \(\sigma\).

(v) When both \(m_e\) and \(w_{DE}\) are allowed to vary, the CMB dataset cannot place tight constraints on both quantities. The inclusion of CMASS correlation function helps to improve the bounds. Our results for the full dataset are \(m_e/(m_e)_0 = 0.996 \pm 0.029\) and \(w_{DE} = -1.12 \pm 0.23\).

(vi) When we allow for a non-negligible contribution of massive neutrinos to the dark matter component, our result is \(\alpha/\alpha_0 = 0.9978_{-0.0045}^{+0.0044}\), and \(f_\nu < 0.043\) at 95\% CL for the full dataset. The constraint on the sum of the neutrino masses is \(\sum m_\nu < 0.46\) eV at 95\% CL.

(vii) In the case of joint variation of \(m_e\) and \(f_\nu\), the bounds for the full dataset are \(m_e/(m_e)_0 = 1.035 \pm 0.021\), and \(f_\nu < 0.086\) at 95\% CL. The degeneracies between these quantities and \(H_0\) shift the constraints to higher values when the HST \(H_0\) prior is included.

(viii) When \(N_{\text{eff}}\) and \(\alpha\) are allowed to vary, the values of \(N_{\text{eff}}\) are consistent within 1 \(\sigma\) with its standard value for the CMB and CMB+CMASS datasets. When the HST \(H_0\) prior is added, the value of \(N_{\text{eff}}\) is much higher, being slightly consistent at 2 \(\sigma\) with its standard value. The constraint on \(\alpha\) is \(\alpha/\alpha_0 = 0.9967 \pm 0.0042\), fully consistent with no variation at 1 \(\sigma\).

(ix) When \(N_{\text{eff}}\) and \(m_e\) are allowed to vary, the value of \(N_{\text{eff}}\) is more than 1 \(\sigma\) higher than its standard value, and the value of \(m_e\) is consistent with no variation at 1 \(\sigma\), for all of the datasets.

(x) In the case of joint variation of \(Y_{\text{He}}\) and \(\alpha\), there is a strong degeneracy between these quantities, for all of the datasets. For the CMB and CMB+CMASS datasets, \(Y_{\text{He}}\) is consistent with the standard value of 0.24. When the HST prior is added, \(Y_{\text{He}}\) is almost 2 \(\sigma\) higher than the standard value. For all of the datasets, there is no variation of \(\alpha\) at the 1 \(\sigma\) level.

(xi) In the case of joint variation of \(Y_{\text{He}}\) and \(m_e\), there is no correlation between these quantities for any dataset. The bounds on \(Y_{\text{He}}\) are similar for all of the datasets, a value around 2 \(\sigma\) higher than the standard one. For all of the datasets, \(m_e\) is consistent with no variation at 1 \(\sigma\).

(xii) We present new bounds on \(N_{\text{eff}}\) and \(Y_{\text{He}}\) in the case of no variation of fundamental constants. For the full dataset, in the \(\Lambda\)CDM+\(N_{\text{eff}}\) model, the constraint is \(N_{\text{eff}} = 3.86_{-0.40}^{+0.39}\). In the \(\Lambda\)CDM+\(Y_{\text{He}}\) model, the constraint is \(Y_{\text{He}} = 0.301_{-0.029}^{+0.014}\).

The analysis carried out in this paper is based on the first spectroscopic data release of BOSS. Future data releases will provide even more accurate views on the LSS clustering pattern by probing a larger volume of the universe. Together with Planck satellite data to be released in early 2013, this will enable to put more stringent constraints on the variation of fundamental constants.


Table A1. The marginalized 68% allowed regions on the cosmological parameters of the ΛCDM model, obtained using different combinations of the datasets.

| Parameter | CMB | CMB + CMASS | CMB + CMASS + BAO + H₀ |
|-----------|-----|-------------|------------------------|
| H₀        | 1.0411^{+0.0016}_{-0.0016} | 1.0407^{+0.0015}_{-0.0015} | 1.0410^{+0.0015}_{-0.0015} |
| w₀b       | 2.223^{+0.042}_{-0.042} | 2.212^{+0.037}_{-0.038} | 2.223^{+0.038}_{-0.038} |
| Ω_m       | 11.18^{+0.48}_{-0.48} | 11.45^{+0.29}_{-0.29} | 11.45^{+0.21}_{-0.21} |
| r         | 0.0850^{+0.0063}_{-0.0066} | 0.0820^{+0.0057}_{-0.0066} | 0.0826^{+0.0059}_{-0.0064} |
| n_s       | 0.966^{+0.011}_{-0.011} | 0.9620^{+0.0091}_{-0.0091} | 0.9641^{+0.0088}_{-0.0087} |
| ln(10¹⁰A_s) | 3.081^{+0.030}_{-0.030} | 3.084^{+0.028}_{-0.028} | 3.086^{+0.028}_{-0.028} |
| Ω DE      | 0.73^{+0.025}_{-0.025} | 0.718^{+0.015}_{-0.015} | 0.7193^{+0.0099}_{-0.0099} |
| Ω_m       | 0.267^{+0.025}_{-0.025} | 0.282^{+0.015}_{-0.015} | 0.2807^{+0.0099}_{-0.0099} |
| σ₈        | 0.81^{+0.02}_{-0.02} | 0.825^{+0.018}_{-0.018} | 0.82^{+0.016}_{-0.016} |
| ξ_v       | 13.729^{+0.089}_{-0.090} | 13.769^{+0.071}_{-0.071} | 13.750^{+0.065}_{-0.064} |
| z_v       | 10.4^{+1.2}_{-1.2} | 10.2^{+1}_{-1} | 10^{+1.1}_{-1.1} |
| h         | 0.710^{+0.021}_{-0.021} | 0.697^{+0.012}_{-0.012} | 0.698^{+0.0083}_{-0.0083} |

APPENDIX A: CONSTRAINTS ON THE ΛCDM MODEL

In Table A1, we present our constraints on the cosmological parameters of the ΛCDM model, for better comparison with the results obtained in this paper. These are consistent with the constraints given in Sánchez et al. [2012].

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