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Constraints on fundamental constants with galaxy surveys

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Abstract. In this brief work we show how the future Cosmic Microwave Background and galaxy lensing surveys could constrain variation in the fine structure constant in the early universe. We found that lensing data, as those expected from satellite experiments as Euclid could improve the constraint from the Planck Cosmic Microwave Background experiment by a factor ~ 3, leading to a $\Delta\alpha/\alpha \sim 10^{-4}$ accuracy. A variation of the fine structure constant α is strongly degenerate with the Hubble constant H_0 and with inflationary parameters as the scalar spectral index n_s: we investigate how these degeneracies may cause significant biases in the determination of other cosmological parameters.

Key words. Cosmology: observations

1. Introduction

The recent measurements of Cosmic Microwave Background (CMB) anisotropies, galaxy clustering and supernovae type Ia luminosity distances (see e.g. Komatsu, E., et al. 2011; Larson, D. et al. 2011; Reid, B., A. et al. 2011; Amanullah, R. et al. 2010) have confirmed the ΛCDM model, however there are still many problems unresolved in the cosmological "standard" model Planck Collaboration (2013). A variation of fundamental constants in time and in space, for example, represents a radical departure from standard model physics (see Uzan, J. P., 2003, for a review). One of the most investigated constant is the fine structure constant α mainly because of the observational indication of a smaller value in the past, at cosmological redshifts $z = 0.5 - 3.5$, from quasar absorption systems data with $\Delta\alpha/\alpha = (-0.72 \pm 0.18) \times 10^{-5}$ (Webb, J. K,et al. 1999; Webb, J. K., et al. 2001, 2011). In the recent past, the constraints on α have been obtained analyzing CMB data (see e.g. Avelino, P. P. et al., 2001; Martins, C. J. A., et al. 2002, 2004; Ichikawa, K., Kanzaki, T., and Kawasaki, M., 2006; Stefanescu, P., 2007; Menegoni, E., et al. 2009; Scoccola, C. G., Landau, S. .J., Vucetich,H., 2008; Menegoni, E., et al. 2009) with an accuracy at the level of $\sim 10 - 1\%$. In the present

Send offprint requests to: E. Menegoni analysis we parametrize a variation in the fine structure constant as α/α_0, where α_0 is the standard (local) value and α is the value during the recombination, the authors of Menegoni, E., et al. (2012) found the constraint $\alpha/\alpha_0 = 0.984 \pm 0.005$, i.e. hinting also to a more than two standard deviation from the current value. In addition to the CMB data, in the future a new and larger galaxy surveys will provide new galaxy weak lensing measurements that, when combined with Planck, will drastically improve the constraints on cosmological parameters. The Euclid satellite mission Laureijs, R., et al., (2013), selected as part of ESA Cosmic Visions programme and due for launch in 2019, probably represents the most advanced weak lensing survey that could be achieved in the nearly future (e.g. dark energy Kitching , T. D. , et al. 2007; Hannestad , S., Tu, H. and Wong, Y. Y. Y. 2006; Kitching , T. D., et al., 2008; Taylor, A. N.; et al., 2004; Bacon , D.; et al., 2003; Massey R.; et al. 2007). The weak lensing probes are shown to be complementary to CMB measurements and these data lead to significant improvement on the constraints on variation in the fine structure constant.

2. Future data

The fiducial cosmological model assumed in producing the simulated data is the best-fit model from the WMAP-7 year CMB survey (see Ref. Komatsu, E., et al. 2011; Larson, D. et al. 2011). The parameters we sampled are the following: baryon density $\Omega_b h^2 = 0.02258$, cold dark mattter density $\Omega_c h^2 = 0.1109$, spectral index $n_s = 0.963$, optical depth $\tau = 0.088$, scalar amplitude $A_s = 2.43 \times 10^{-9}$ and Hubble constant $H_0 = 71$. For the fine structure constant we assume either the standard value $\alpha/\alpha_0 = 1$, either a small variation $\alpha/\alpha_0 = 0.996$. We consider CMB Planck-like data and galaxy weak lensing measurements from Euclid. For CMB data the main observables are the C_l angular power spectra (temperature, polarization and cross temperature-polarization), while , in the case of the weak lensing data what is important is the convergence power spectra $P(l)$ DeBernardis, F., et al. (2011), Martinelli, M., et al. (2012). All spectra are generated using a modified version of the CAMB code Lewis,A., Challinor A. and Lasenby, A. (2000) for α as discussed in Menegoni, E., et al. (2009). In order to generate a full mock CMB dataset we use the noise properties consistent with those expected for the Planck Planck Collaboration (2006) experiment (see Tab. 1). For each channel we consider a detector noise of $w^{-1} = (\theta\sigma)^2$, with θ the FWHM (Full-Width at Half-Maximum) of the beam assuming a Gaussian profile and σ the temperature sensitivity ΔT (see Tab. 1 for the polarization sensitivity). We add a noise spectrum to each C_l fiducial spectra given by: $N_l = w^{-1}\exp(l(l+1)/l_b^2)$, with l_b given by $l_b \equiv \sqrt{8\ln 2}/\theta$.

In order to perform a consistent analysis (for details see Martinelli, M., Menegoni, E., Melchiorri, A., 2012). We combine five quadratic estimators into a minimum variance estimator, while, the noise on the deflection field power spectrum C_l^{dd} produced by this estimator can be expressed as in Martinelli, M., Menegoni, E., Melchiorri, A., (2012):

$$N_l^{dd} = \frac{1}{\sum_{aa'bb'} (N_l^{aba'b'})^{-1}}. \quad (1)$$

For the future galaxy weak lensing data we use the specifications of the Euclid weak lensing survey. This survey will observe about 30 galaxies per square arcminute from redshift $z = 0.5$ to $z = 2$ with an uncertainty of about $\sigma_z = 0.05(1+z)$ (see Laureijs, R., et al., 2013). Using these specifications we produce mock datasets of convergence power spectra, again following the procedure of DeBernardis, F., et al. (2011). The 1σ uncertainty on the convergence power spectrum ($P(l)$) can be expressed as in ref. Cooray A. R. (1999). As at high l the non-linear growth of structure is more relevant, the shape of the non-linear matter power spectra is more uncertain Smith R. E. S, et al. (2003); therefore, to exclude these scales, we choose $l_{max} = 1500$. The galaxy distribution of Euclid survey is choosen to be of the form $n(z) \propto z^2 \exp(-(z/z_0)^{1.5})$ (see Laureijs, R., et al., 2013),where z_0 is set by the median redshift of the sources, $z_0 = z_m/1.41$ with $z_m = 0.9$ (Fu, L., et al. 2008).

Table 1. Planck-like experimental specifications. Channel frequency is given in GHz, the temperature sensitivity per pixel in $\mu K/K$, and FWHM (Full-Width at Half-Maximum) in arc-minutes. The polarization sensitivity is assumed as $\Delta E/E = \Delta B/B = \sqrt{2}\Delta T/T$.

Experiment	Channel	FWHM	$\Delta T/T$
Planck	70	14'	4.7
	100	10'	2.5
	143	7.1'	2.2
$f_{sky} = 0.85$			

Table 2. 68% c.l. errors on cosmological parameters from a first analysis made assuming a fiducial model with $\alpha/\alpha_0 = 1$ Martinelli, M., Menegoni, E., Melchiorri, A., (2012).

	Planck		Planck+Euclid	
Model Parameter	Varying α/α_0	$\alpha/\alpha_0 = 1$	Varying α/α_0	$\alpha/\alpha_0 = 1$
$\Delta(\Omega_b h^2)$	0.00013	0.00013	0.00011	0.00010
$\Delta(\Omega_c h^2)$	0.0012	0.0010	0.00076	0.00061
$\Delta(\tau)$	0.0043	0.0042	0.0041	0.0029
$\Delta(n_s)$	0.0062	0.0031	0.0038	0.0027
$\Delta(\log[10^{10}A_s])$	0.019	0.013	0.0095	0.0092
$\Delta(H_0)$	0.76	0.43	0.34	0.31
$\Delta(\Omega_\Lambda)$	0.0063	0.0050	0.0034	0.0033
$\Delta(\alpha/\alpha_0)$	0.0018	–	0.0008	–

Table 3. Best fit values and 68% c.l. errors on cosmological parameters for the case in which a fiducial model with $\alpha/\alpha_0 = 0.996$ is fitted wrongly neglecting a variation in α. The last column shows the absolute value of the difference between the best-fit value estimated fixing $\alpha/\alpha_0 = 1$ and the fiducial value, relative to the 1σ error Martinelli, M., Menegoni, E., Melchiorri, A., (2012).

	Planck+Euclid		Fiducial values	$\Delta/\sigma\vert$
Model: Parameter	$\alpha/\alpha_0 = 1$	varying ξ		
$\Omega_b h^2$	0.02232 ± 0.00010	0.02259 ± 0.00011	0.02258	2.7
$\Omega_c h^2$	0.1129 ± 0.00059	0.1106 ± 0.00078	0.1109	3.4
τ	0.075 ± 0.0025	0.088 ± 0.0041	0.088	5.3
n_s	0.950 ± 0.0028	0.964 ± 0.0039	0.963	4.6
H_0	71.8 ± 0.30	71.0 ± 0.33	71.0	2.7
Ω_Λ	0.737 ± 0.0032	0.736 ± 0.0034	0.735	0.6
σ_8	0.801 ± 0.0009	0.803 ± 0.0010	0.804	3.3

2.1. Analysis method

In order to constrain the cosmological parameters we perform a MCMC analysis based on the publicly available package `cosmomc` Lewis, A. and Bridle, S. (2002) with a convergence diagnostic using the Gelman and Rubin statistics. The set of cosmological parameters sampled are the standard cosmological parameter, plus

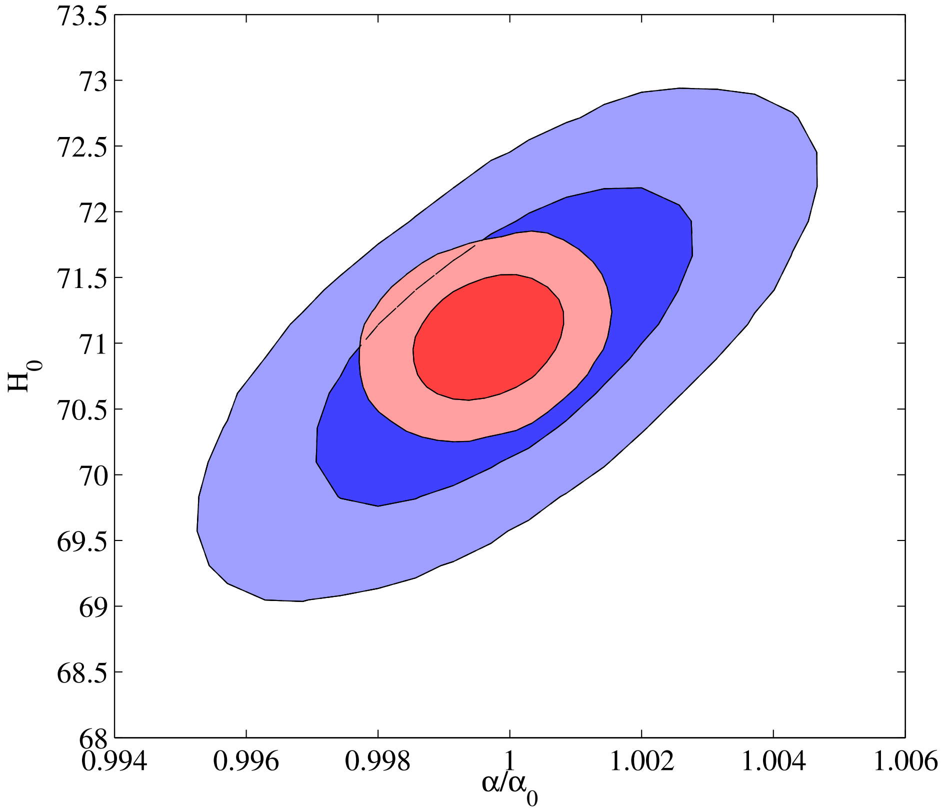

Fig. 1. 2-D constraints on α and H_0 using Planck data (blue contours) and Planck+Euclid data (red contours)Martinelli, M., Menegoni, E., Melchiorri, A., (2012).

the variation of the fine structure constant parameter α/α_0. We perform two different analysis: in a first run we assume $\alpha/\alpha_0 = 1$ in the fiducial model and we investigate the constraints achievable on α and on the remaining parameters using the future simulated datasets; in the second run we take a fiducial model with a variation in α such that $\alpha/\alpha_0 = 0.996$, and analyse the new dataset wrongly assuming a standard ΛCDM scenario with $\alpha/\alpha_0 = 1$ Martinelli, M., Menegoni, E., Melchiorri, A., (2012). This analysis allow us to investigate how wrongly neglecting a possible variation in α could shift the best cosmological parameters.

The MCMC constraints on cosmological parameters at 68% c.l. are shown in Table 2 from our simulated dataset. We consider two cases: a standard analysis where $\alpha/\alpha_0 = 1$ and an analysis where also α/α_0 is varied. The Euclid data improves the Planck constraint on α/α_0 by a factor ~ 2.6. There is a high level of correlation among α/α_0 and the cosmological parameters H_0 and n_s when only the Planck data is considered. This is also clearly shown in Figs. 1 and 2 where we plot the 2-D likelihood contours at 68% and 95% c.l. between α/α_0, n_s and H_0. Namely, a larger/lower value for α is more consistent with observations with a larger/lower

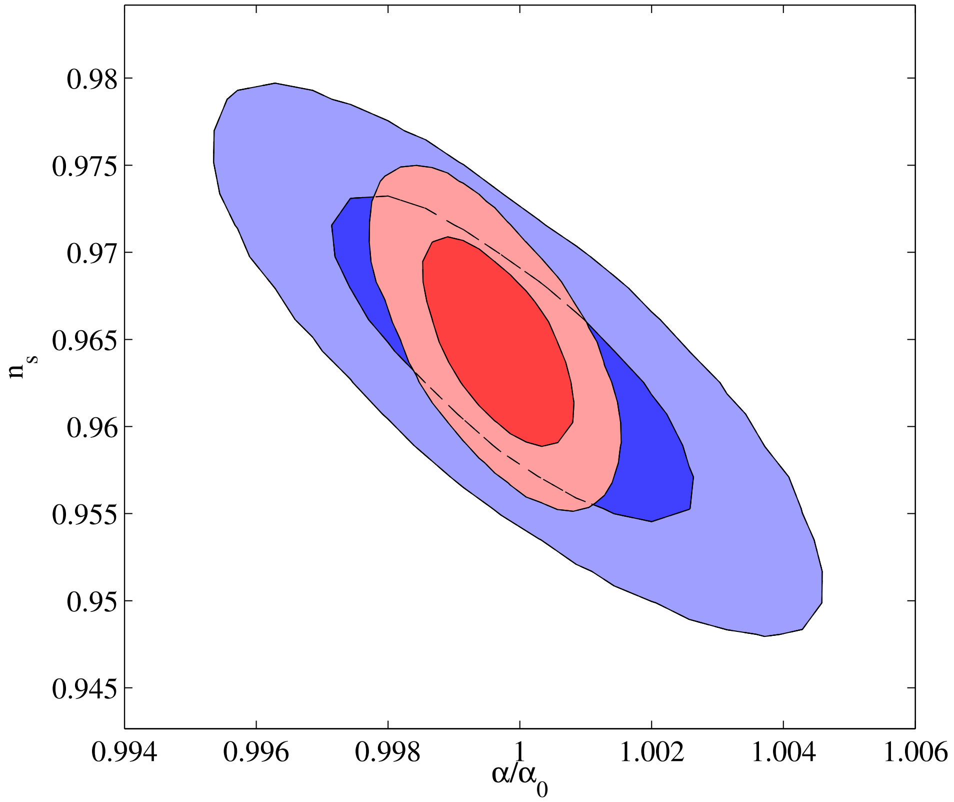

Fig. 2. 2-D constraints on α and n_s using Planck data (blue contours) and Planck+Euclid data (red contours)Martinelli, M., Menegoni, E., Melchiorri, A., (2012).

value for H_0 and a lower/larger value for n_s. When Planck and Euclid data are combined, the degeneracy with H_0 is removed, yielding a better determination of α. However the degeneracy with n_s (see Fig.2) is only partially removed. This is mainly due to the fact that the n_s parameter is degenerate with the reionization optical depth τ, to which Euclid is insensitive.

We have also analysed a mock dataset generated with $\alpha/\alpha_0 = 0.996$ but (wrongly) assuming a standard value ($\alpha/\alpha_0 = 1$). The results, reported in Tab.3, show a consistent and significant bias in the recovered best fit value of the cosmological parameters due to the strong degeneracies among α/α_0 and the Hubble constant H_0, the spectral index n_s and the matter energy density Ω_m parameters Martinelli, M., Menegoni, E., Melchiorri, A., (2012). In Figures 1, 2 and Figures 3 and also in the results in Tab. 3 we shown that the shift in the best fit values is, as expected, orthogonal to the direction of the degeneracy of α/α_0 with these parameters. For example, lowering α damps the CMB small scale anisotropies and this effect can be compensated by increasing n_s (see 1). In the last column of Tab. 3 we show the difference between the *wrong* value estimated

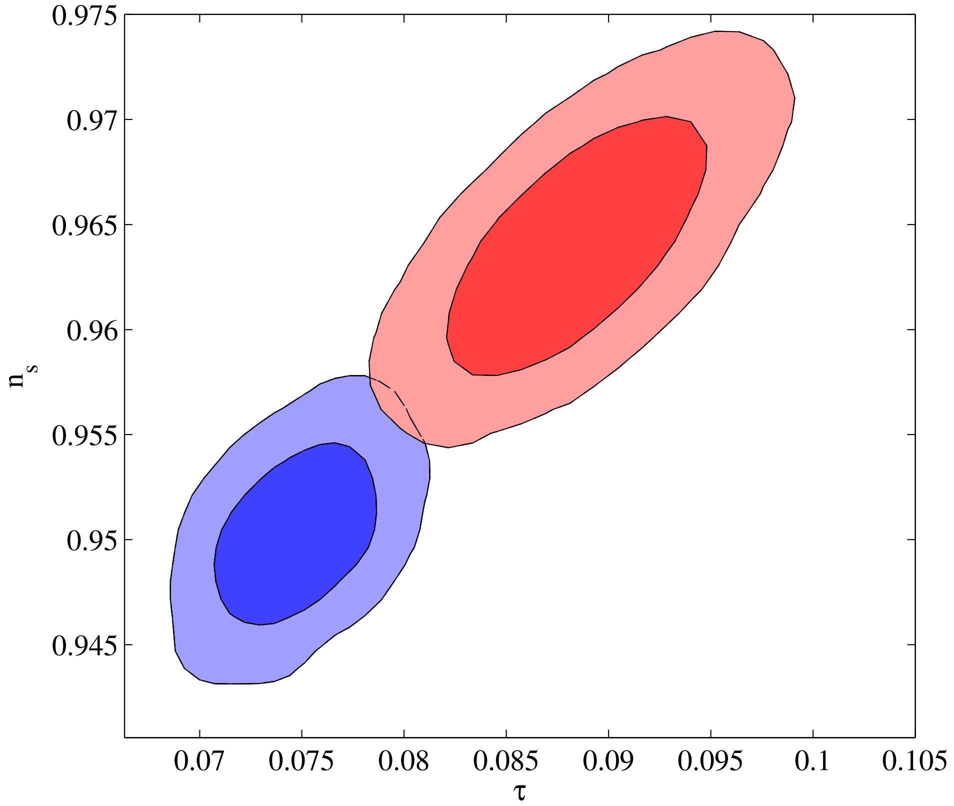

Fig. 3. 2-D constraints on n_s and τ using a fiducial model with $\alpha/\alpha_0 = 0.996$, fitting it with a fixed $\alpha/\alpha_0 = 1$ (blue contours) and with α/α_0 aloowed to vary (red contours).

fixing $\alpha/\alpha_0 = 1$ and the fiducial value, relative to the 1σ error. We note that also other parameters, as $\Omega_c h^2$ and $\Omega_b h^2$, have significant shifts. When a variation of α is considered, the correct fiducial values are recovered, however at the expenses of less tight constraints Martinelli, M., Menegoni, E., Melchiorri, A., (2012).

3. Conclusions

By combining CMB and weak lensing measurements as those expected from the Planck and Euclid satellite experiments we have found that the two experiments provide a constraint on α of the order of $\Delta\alpha/\alpha = 8 \times 10^{-4}$. These constraints can be reasonably futher improved by considering additional datasets. In particular, accurate measurements of large angle CMB polarization that could provide a better determination of the reionization optical depth will certainly make the constraints on α more stringent. We have shown that a variation of α of about 0.4% can significantly alter the conclusions on n_s, H_0 and τ parameters. Moreover changes on the value of the fine structure constant by 0.4% shifts the redshift at which the free electron fraction falls to $x_e = 0.5$ by about $\sim 1\%$ from $z_* = 1275$ to $z_* = 1262$. An unknown physical process that delays recombination as, for example, dark matter annihilation (see e.g. Galli, S., Iocco, F., Bertone, G. and Melchiorri, A. 2009), may have a similar impact in cosmological parameter estimation.

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