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Constraints on varying alpha with future low-medium redshift probes

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Abstract. In several models, alternative to the cosmological constant one, the accelerated expansion of the universe is explained through an additional scalar field. This field could in principle be coupled with other sectors of the underlying theory, such as electromagnetism. This possible coupling drives therefore a time variation of the fine structure constant α. In this work we forecast the constraining power of future low-medium redshifts surveys on this coupling, highlighting the existing degeneracies with the dark energy parameters .

Key words. Cosmology: dark energy Cosmology: observations

1. Introduction

Since the discovery of cosmic acceleration from measurements of luminosity distances of type Ia Supernovae (SNIa) (Perlmutter et al. 1999; Riess et al. 1998), the so-called Dark Energy (DE), has been deeply debated. In the standard cosmological model, the Λ Cold Dark Matter (ΛCDM), the acceleration is produced by the cosmological constant Λ, but even tough this model is favoured by data, its theoretical issues brought to the formulation of alternative explanations for cosmic acceleration.

Several of these alternative models are characterized by the existence of an additional scalar field which drives the accelerated expansion of the universe. If this is the case, it is expected that this additional component is coupled to the rest of the theory's fields.

In this paper we study the coupling of dynamical DE models with the electromagnetic field as the presence of a dynamical DE could, in principle, lead to a space-time variation of

Send offprint requests to: M. Martinelli the fine-structure constant α (Avelino et al. 2006) with respect to the standard local value α_0. This, in turn, would generate distinctive signatures in cosmological data, such as the Cosmic Microwave Background (CMB), see e.g. (Battye et al 2001; Menegoni et al. 2009, 2010; Calabrese et al 2011), but also in low and medium redshift cosmological probes, e. g. in the peak of luminosity in SNIa or in the metal absorption lines of distant quasars (QSO).

The present work is focused on low-medium redshifts observables, forecasting SN and QSO data, Weak Lensing shear power spectrum measurements (WL) and redshift-drift (RD) data, to constrain the coupling between the electromagnetic and DE fields. The peculiarity of the above mentioned combination of probes is the coverage of a wide redshift range ($0 < z \lesssim 5$) and thus it is a very powerful way to discriminate between a Λ and a dynamical DE model. We assume only a time varying fine structure constant α, neglecting spatial variation since there is no evidence from recent CMB data (O'Bryan et al. 2013) and at lower redshifts QSO measurements report very controversial results (Webb et al. 2011).
We consider a class of models where the scalar field causing the α variation is also responsible for the accelerated expansion of the universe. In other classes of models the variation of α is not necessarily given by the same degrees of freedom driving the acceleration; this kind of models are addressed in (Calabrese et al 2013).

2. Theoretical models

In order not to focus on a specific DE model, we choose a phenomenological generic parametrization of the DE equation of state parameter, the Chevallier-Polarski-Linder (Chevallier & Polarski 2001; Linder 2003) parametrization (CPL) where the DE equation of state (EoS) is written as

$$w_{\rm CPL}(z) = w_0 + w_a \frac{z}{1+z}\,, \tag{1}$$

with w_0 and w_a constant parameters. Assuming that this kind of DE is produced by a dynamical scalar field, we expect it to be naturally coupled to the rest of the theory, unless a (still unknown) symmetry suppress this coupling (Carroll 1998).
The coupling between the scalar field, ϕ, and electromagnetism brings to an evolution of α which can be expressed as (Calabrese et al 2011)

$$\frac{\Delta\alpha}{\alpha}(z) = \zeta \int_0^z \sqrt{3\Omega_\phi(z)\,[1+w(z)]}\frac{dz'}{1+z'}\,. \tag{2}$$

In this context, $\Omega_\phi(z)$ is the fraction of energy density given by the scalar field and in the CPL formalism this quantity is given by

$$\Omega_\phi(z) = \frac{\Omega^0_{CPL}}{\Omega^0_{\rm CPL} + \Omega^0_{\rm m}(1+z)^{-3(w_0+w_a)}e^{(3w_a z/1+z)}} \tag{3}$$

where $\Omega^0_{\rm m}$ and $\Omega^0_{\rm CPL}$ are, respectively, the present time energy densities of matter and DE. In Eq.(2) we notice that, as expected, in this class of models the magnitude of the α variation is controlled by the strength of the coupling ζ.

3. Observational probes

In order to investigate the coupling between DE and α variations, we need observables able to probe both the variation of α and the DE parameters.

3.1. Supernovae type Ia data

Type Ia Supernovae are, at present, the most effective and mature probe of DE.
Moreover, as the SN peak luminosity (L_{peak}) depends on photon diffusion time, which in turn depends on α through the opacity, the α variation affects L_{peak} (Chiba & Kohri 2003), thus leading to a variation of the absolute magnitude at peak (M)

$$\frac{\Delta\alpha}{\alpha} \sim 0.98\,\Delta M \tag{4}$$

where $\Delta M = M - M_0$ and the subscript 0 indicates quantities where the variation of α is not accounted for. Therefore varying α modifies the distance modulus $\mu = m - M$, with m the apparent magnitude, which depends on cosmological parameters through the luminosity distance

$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz}{E(z)} \ . \tag{5}$$

The $E(z) = H(z)/H_0$ expression encodes the chosen DE model

$$E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_\phi(z)\frac{H^2}{H_0^2}} \ . \tag{6}$$

We build the SN datasets following the procedure presented in (Cardone et al. 2012). We use Euclid expected observations of 1700 SN in a redshift range $0.75 < z < 1.5$ (Laureijs et al. 2011; Hook 2012) to forecast our SN survey at low-intermediate z.

3.2. Quasar absorption systems data

The frequencies of narrow metal absorption lines in quasar absorption systems are sensitive to α (Bahcall et al. 1967), and the different transitions have different sensitivities. The comparison of the relative shifts between different transition can be used to obtain measurements of α in these absorption systems.

For representative future datasets we use the baseline (conservative) case discussed in (Amendola et al. 2012). We consider the ELT-HIRES spectrograph, currently under study for the E-ELT telescope, for which the CODEX Phase A study (CODEX 2010) provides a baseline reference. We assume uniformly distributed measurements in the redshift range $0.5 < z < 4.0$, with an error $\sigma_\alpha = 10^{-7}$.

3.3. Redshift-drift data

QSOs observations can be also used to constrain DE models through the so called redshift-drift of these sources (Sandage 1962; Loeb 1998). The redshift-drift is the change of the redshift due to the expansion of the universe for two different observations of the same source, repeated after a given amount of (terrestrial) years.

This kind of observations allows to probe the expansion of the universe in a model independent way (Pasquini et al. 2005; Corasaniti et al. 2007; Quercellini et al. 2012).
As pointed out in Vielzeuf & Martins (2012) snd Martinelli et al. (2012) QSOs are the ideal astrophysical objects to observe the redshift variation Δz between two observations. This Δz can be expressed as a spectroscopic velocity $\Delta v = c\Delta z/(1+z)$ and connected to cosmological quantities through the relation

$$\frac{\Delta v}{c} = H_0 \Delta t \left[1 - \frac{E(z)}{1+z}\right], \tag{7}$$

where c is the speed of light and Δt is the time interval between two observations of the same astrophysical source.

The European Extremely Large Telescope (E-ELT) equipped with a high-resolution, ultra-stable spectrograph (ELT-HIRES) such as the COsmic Dynamics Experiment (CODEX 2010) will have the ability to detect the cosmological redshift drift in the Lyman α absorption lines of distant ($2 < z < 5$) QSOs, even though this is a very small signal. The E-ELT can decisively detect the redshift variation with a 4000 hours of integration in a period of $\Delta t = 20$ years (Liske et al. 2008). According to Monte Carlo simulations of the CODEX Phase A study (CODEX 2010), the error on the measured spectroscopic velocity shift Δv can be computed using experimental specifications for E-ELT, i.e. a signal to noise ratio $S/N = 3000$ and a number of QSO $N_{\rm QSO} = 30$ assumed to be uniformly distributed among the following redshift bins $z_{\rm QSO} = [2.0, 2.8, 3.5, 4.2, 5.0]$.

3.4. Weak lensing data

Weak gravitational lensing of distant galaxies is a powerful observable to probe the geometry of the universe and to map the matter distribution.
Future surveys will observe billions of galaxies, thus allowing the possibility of a tomographic reconstruction of the matter distribution. We can define the convergence

power spectra in each redshift bin following Martinelli et al. (2011)

$$P_{jk}(\ell) = H_0^3 \int_0^\infty \frac{dz}{E(z)} W_i(z) W_j(z) P_{\rm NL}(\ell, z) \quad (8)$$

where $P_{\rm NL}$ is the non-linear matter power spectrum at redshift z, obtained correcting the linear one $P_{\rm L}$, and $W(z)$ is a weighting function. The observed power spectra are affected mainly by systematic uncertainties arising from the intrinsic ellipticity of galaxies $\gamma^2_{\rm rms}$. These uncertainties can be reduced averaging over a large number of sources. The observed convergence power spectra will hence be:

$$C_{jk} = P_{jk} + \delta_{jk}\gamma^2_{\rm rms}\tilde{n}_j^{-1} \quad (9)$$

where $\tilde{n}_j$ is the number of sources per steradian in the $j-th$ bin.

In this paper we forecast a weak lensing dataset, computing the errors on the convergence spectrum following De Bernardis et al. (2011) and Cooray (1999) and using specifications in agreement with what is expected for the Euclid survey (Laureijs et al. 2011): the mission will observe $n_g \simeq 30$ gal/arcmin^2 over an area $\Omega = 15000$ deg^2. We divide the redshift space in 10 bins, chosen in such away to have the same fraction of the total observed galaxies in each one.

3.5. Atomic clocks bounds

In models where the same dynamical degree of freedom is responsible for the DE and the variation of α at redshift 0, the atomic clock bounds (Rosenband et al. 2008) will always give a constraint on the combination of a fundamental physics parameter (e.g. the coupling of the field, which is obtained by the Equivalence Principle violation) and a cosmological parameter (usually the DE equation of state w_0, although depending on the model other parameters may be involved too). For the models considered, we have

$$\sqrt{3\Omega_{\phi 0}(1+w_0)}H_0\zeta = (-1.6 \pm 2.3)\times 10^{-17} yr^{-1} \quad (10)$$

and there will be analogous relations for the other models.

4. Analysis & results

The cosmological parameters that we sample can be divided in "standard parameters", $\{\Omega_b h^2, \Omega_c h^2, \Omega_\Lambda, n_s, A_s\}$, DE parameters, $\{w_0, w_a\}$, and the coupling ζ.

We build simulated datasets assuming a fiducial cosmology given by the WMAP9 results (Hinshaw et al. 2012) on the standard parameters: the baryon and cold dark matter densities, $\Omega_b h^2 = 0.02264$ and $\Omega_c h^2 = 0.1138$, the amount of energy density given by DE at the present time $\Omega_\Lambda = 0.722$, the optical depth to reionization $\tau = 0.089$, the scalar spectral index $n_s = 0.972$ and the overall normalization of the spectrum $A_s = 2.4\times 10^{-9}$. We fix the DE parameters reproducing the ΛCDM expansion (i.e. $w_0 = -1$, $w_a = 0$) and a vanishing coupling $\zeta = 0$; basically, this fiducial set of parameters represents the standard ΛCDM cosmology. We also assume a flat Universe.

We analyze the produced mock datasets, sampling the aforementioned parameters with MCMC technique, using a modified version of the publicly available package `cosmomc` (Lewis & Bridle 2002) with a convergence diagnostic given by the Gelman and Rubin criteria. We assume flat priors on the sampled parameters. We consider different combinations of the probes introduced in Section 3 and discuss the main features obtained by this analysis, exploring how the main geometrical probes (WL and SN) affects constraints on DE parameters and on the coupling ζ.

As expected, we obtain that the Euclid survey strongly constrains the EoS parameters w_0 and w_a, mainly thanks to the combination of the SN and WL measurements. When all the datasets are considered, we get an estimate for errors on DE parameters $\Delta(w_0) = 0.007$ and $\Delta(w_a) = 0.03$.

The constraints on the coupling parameter are instead puzzling at a first look (see panel 4 in Fig. 1), as the use of the Euclid observations loosens the bounds on ζ. This result is however easily explained considering the chosen fiducial cosmological model. Eq. (2) implies, in fact, that a vanishing $\Delta\alpha/\alpha$ can be obtained in two ways: either $\zeta = 0$ and/or $w(z) = -1$. This leads to the fact that when w_0 and w_a are poorly constrained (i.e. when WL and SN are removed from the analysis) the QSO forecasted measurements require a coupling ζ close to 0. On the contrary, when WL and SN impose tight independent constraints on DE parameters and the recovered $w(z)$ is close to -1, a larger range of ζ values is in agreement with the QSO measurements.

This effect is displayed in Fig. 1 where we re-

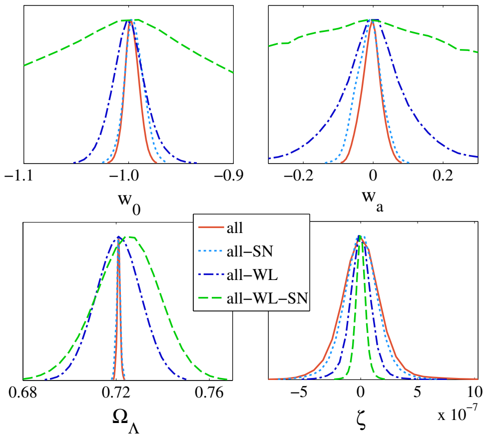

Fig. 1. Marginalized 1-dimensional posterior distributions for the DE parameters w_0, w_a, Ω_Λ and the coupling ζ, for different combinations of probes. Solid red curves show the combination of all observables; dotted cyan curves are obtained removing SN; blue dot-dashed lines exclude WL; the green dashed distributions show parameters when removing both WL and SN.

port the recoved 1-dimensional posteriors for the coupling and the DE parameters, showing how the most stringent constraints on ζ are achieved when limits on w_0 and w_a are loose. In Fig. 2 we show the 2-dimensional contours at 68% and 95% confidence levels in the ζ-w_0 and ζ-w_a planes only for the two extreme cases: the combination of all probes and the analysis excluding WL and SN. Again we can see that when DE parameters are constrained thanks to WL and SN the coupling can lie in a large region, it is instead tightly constrained when no bounds on w_0-w_a are obtained.

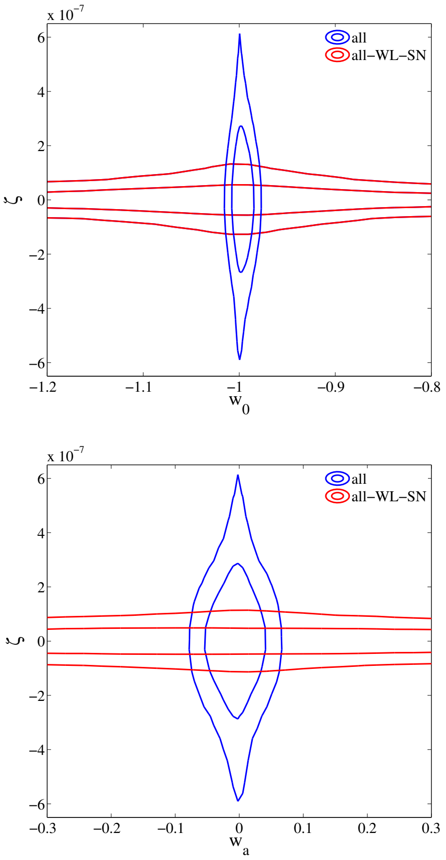

Fig. 2. Contour plots showing ζ and w_0, w_a confidence levels with and without the effect of Weak Lensing and Supernovae observations.

5. Conclusions

Here we investigated how upcoming surveys probing the low-medium redshift range will constrain the possible coupling between a scalar field driving the accelerated expansion of the Universe and electromagnetism. We showed how the combination of weak lensing, supernovae, redshift-drift and QSO observations highly enhance the constraining power on DE parameters with respect to present-day constraints. We also showed the degeneracy between these parameters and the coupling between DE and electromagnetism ζ: forecasting results with a fiducial ΛCDM universe model,

a shrinkage of the allowed parameter space for DE leads to a broadening of ζ constraints and vice versa.
A more detailed analysis, including also different DE models and fiducial cosmologies departing ΛCDM paradigm, can be found in (Calabrese et al 2013).

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