Journal of Physics: Conference Series

OPEN ACCESS

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To cite this article: Stefania Pandolfi 2014 *J. Phys.: Conf. Ser.* **566** 012005

Dark Energy coupling with electromagnetism as seen from future low-medium redshift probes

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Abstract. Beyond the standard cosmological model where the late-time accelerated expansion of the universe is driven by a cosmological constant, the observed expansion can be reproduced as well by the introduction of an additional dynamical scalar field. In this case, the field is expected to be naturally coupled to the rest of the theory's fields, unless a (still unknown) symmetry suppresses this coupling. Therefore, this would possibly lead to some observational consequences, such as space-time variations of nature's fundamental constants. In this paper we investigate the coupling between a dynamical Dark Energy model and the electromagnetic field, and the corresponding evolution of the fine structure constant (α) with respect to the standard local value α_0.

1. Introduction

Since the discovery of cosmic acceleration from measurements of luminosity distances of type Ia Supernovae (SN) in 1998 [1, 2] and its confirmation by several other independent cosmological data, the nature of the component driving this acceleration, the so-called Dark Energy (DE hereafter), has been deeply debated. In the standard cosmological model, the Λ Cold Dark Matter (ΛCDM), the acceleration is produced by the cosmological constant Λ. This model is consistent with the majority of the observational data, but the known theoretical problems of the cosmological constant led cosmologists to formulate several other alternative models able, from one side, to relieve the already mentioned theoretical issues and, on the other side, to explain observations.

Alternative models for the DE, such as quintessence, are called dynamical dark energy and, even if not favored, they are currently not excluded by observations [3]. 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 other words, the dynamical scalar fields are expected to be naturally coupled to the rest of the theory, unless a (still unknown) symmetry suppresses this coupling [4].

In this paper we study the coupling of dynamical DE models with the electromagnetic field: the presence of this coupling would lead to a space-time variation of the fine-structure constant α [4]. This, in turn, would generate distinctive signatures in cosmological data, such as the Cosmic Microwave Background (CMB), but also in low and medium redshift cosmological probes, for example in the peak of luminosity in SN or in the metal absorption lines of distant quasars

Journal of Physics: Conference Series **566** (2014) 012005 doi:10.1088/1742-6596/566/1/012005

(QSO). The relevance of this combination of probes is the coverage of a wide redshift range ($0 < z \leq 5$) which is a very powerful way to discriminate between a cosmological constant and a dynamical DE model, as it makes possible to investigate the onset of DE.

2. Theoretical Models

We assume the Dark Energy to be a quintessence component, coupled to the electromagnetic sector, thus leading to the time variation of the fine structure constant α. We consider a phenomenological generic parametrization of the DE equation of state parameter: the Chevallier-Polarski-Linder (CPL) parametrization [5, 6].

In the CPL model the DE equation of state (EoS) is written as $w_{\rm CPL}(z) = w_0 + w_a(z/(1+z))$ where w_0 is the present value of $w_{\rm CPL}$ (i.e. $w_{\rm CPL}(z = 0) = w_0$) and w_a is the coefficient of the time-dependent term of the EoS. In this model the EoS has a trend with redshift that is not intended to reproduce a particular model for dark energy, but rather to allow to probe possible deviations from the ΛCDM standard paradigm without the assumption of any underlying theory. Nevertheless, we can assume that also this kind of DE is produced by a scalar field. Our aim is to study the coupling of the dark energy degree of freedom with the electromagnetic field. It can be shown that the coupling between the scalar field, ϕ, and electromagnetism possibly leads to the evolution of α which is given by :

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

As expected, in this class of models the magnitude of the α variation is controlled by the strength of the coupling ζ. Here $\Omega_\phi(z)$ is the fraction of energy density provided by the scalar field, and $\Omega_{\rm m}^0$ and $\Omega_{\rm CPL}^0$ are, respectively, the present time energy densities of matter and DE.

3. Observational Probes

3.1. Supernovae Type Ia data

Type Ia Supernovae are bright, standardizable candles, and can be used to constrain cosmic acceleration through the Hubble diagram. At present, they are the most effective and mature probe of dark energy. 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 could affect L_{peak} [8]. Decreasing alpha decreases the opacity, allowing photons to escape faster, thus increasing L_{peak}. This can be translated (see[8]) to a change in the distance modulus $\mu = m - M$, with m the apparent magnitude, as

$$\mu(z) = m - M = m - (M_0 + \Delta M) = \mu_0(z) - \frac{1}{0.98}\frac{\Delta\alpha}{\alpha}(z) \tag{2}$$

where $\mu_0(z) = 5\log_{10}(d_L(z)) + 25$ is function of the luminosity distance, whose expression encodes the chosen dark energy model. We build the SN datasets following the procedure presented in [9], using Euclid specifications [10, 11] to forecast a SN survey at low-intermediate z, containing 1700 supernovae uniformly distributed in the redshift range $0.75 < z < 1.5$.

3.2. Quasar absorption systems data

The frequencies of narrow metal absorption lines in quasar absorption systems are sensitive to α [12], and the different transitions have different sensitivities. Observationally, one expects relative velocity shifts between transitions in a given absorber, in a single spectrum, if α does vary; this comparison can therefore be used to obtain measurements of α in these absorption systems. Indeed a survey able to observe quasar absorption lines at different redshifts is able to reconstruct the variation of α with respect to the present value and to provide a dataset corresponding to the left-hand side of Eq. (1). For representative future datasets we use the baseline (conservative) case discussed in [13]. We consider the European Extremely Large Telescope (E-ELT) equipped with a high-resolution, ultra-stable spectrograph (ELT-HIRES), for which the COsmic Dynamics Experiment (CODEX) Phase A study [14] 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

QSO observations can be also used to constrain DE models through the so called redshift-drift of these sources [15, 16]. The redshift-drift is the change of the redshift due to the expansion of the universe between two observations of the same distant source spectrum, repeated after a given amount of (terrestrial) years. The required time lapse depends on the instrument used (and specifically on its calibration stability) but is typically of the order of a decade with next-generation facilities.

With this kind of observations one can exploit distant astrophysical sources as a probe of the expansion of the universe in a model independent way [17, 18, 19]. As pointed out in [20, 7] QSO are the ideal astrophysical objects to observe the redshift variation Δz between two observations. This Δz can be translated to a spectroscopic velocity $\Delta v = c\Delta z/(1+z)$ and connected to cosmological quantities through the relation

$$\frac{\Delta v}{c} = H_0 \Delta t \left[1 - \frac{E(z)}{1+z}\right], \tag{3}$$

where c is the speed of light, Δt is the time interval between two observations of the same astrophysical source, and $E(z) = H(z)/H_0$ where $H(z)$ is the Hubble parameter and H_0 is it's value today, is expression encodes the chosen dark energy model.

A CODEX-like spectrograph on the E-ELT will have the ability to detect the cosmological redshift-drift in the Lyman α absorption lines of distant $(2 < z < 5)$ QSOs, in a period of $\Delta t = 20$. According to [14], the error on the measured spectroscopic velocity shift Δv that can be expressed as:

$$\sigma_{\Delta v} = 1.35 \, \frac{2370}{S/N} \sqrt{\frac{30}{N_{\rm QSO}}} \left(\frac{5}{1+z_{\rm QSO}}\right)^x \; cm \; s^{-1}, \tag{4}$$

where S/N is the signal to noise ratio, $N_{\rm QSO}$ the number of observed quasars, $z_{\rm QSO}$ their redshift and the exponent x is equal to 1.7 when $z \leq 4$, while it becomes 0.9 beyond that redshift.

Therefore, we can forecast a redshift-drift dataset where the error bars are computed using Eq.(4), with $S/N = 3000$ and a number of QSO $N_{\rm QSO} = 30$ is 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 dark matter distribution. We simulate a weak lensing dataset according to the specifications expected for the Euclid survey [10]: the mission will observe $n_g \simeq 30$ gal/arcmin^2 over an area $\Omega = 15000$ deg^2, corresponding to a sky fraction $f_{sky} \sim 33\%$. The large galaxy number density and the wide area observed will allow Euclid to provide us with a tomographic reconstruction of the weak lensing signal. We therefore divide the redshift space in 10 bins, chosen in such a way to have the same fraction of the total observed galaxies in each one. Using these specifications we build the ℓ-by-ℓ convergence power spectrum and the 1σ uncertainties, computed as in [21, 22].

Journal of Physics: Conference Series **566** (2014) 012005 doi:10.1088/1742-6596/566/1/012005

4. Analysis

We build simulated datasets assuming a fiducial cosmology given by the observations of the WMAP satellite after 9 years of data [23] for the standard parameters. We fix the DE parameters in such a way to mimic the ΛCDM expansion (i.e. $w_0 = -1$, $w_a = 0$) and a vanishing coupling $\zeta = 0$.

In a second case, we also build simulated datasets with a non vanishing variation of α assuming the same value of the previous case for the standard parameters, but different values for the ones involved in the α variation.

We rely on a MCMC analysis to sample the parameter space and we use a modified version of the publicly available MCMC package `cosmomc` [24] with a convergence diagnostic using the Gelman and Rubin statistics. We assume flat priors on the sampled parameters.

5. Results

As stated in the previous section, the first investigation we carry out deals with vanishing $\Delta\alpha/\alpha$ mock datasets. 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) affect constraints on DE parameters and on the coupling ζ.

In Fig. 1 we can notice how the Euclid survey will greatly narrow the allowed parameter space for the EoS parameters w_0 and w_a, mainly thanks to the combination of the SN and WL measurements. When we consider all datasets we get $\sigma(w_0) = 0.007$ and $\sigma(w_a) = 0.03$.

The constraints on the coupling parameter are instead puzzling at a first look (see last panel in Fig. 1), as the use of the Euclid observations loosens the bounds on ζ. This result is however

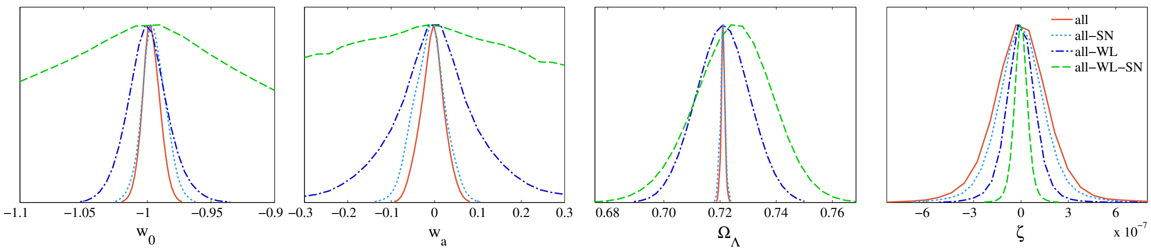

Figure 1. Marginalized 1-dimensional posterior distributions for the DE parameters w_0, w_a, Ω_Λ and the coupling ζ, for different combinations of probes.

easily explained considering the chosen fiducial cosmological model. Eq.(1) in fact implies 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 zero. 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.

In a second step of our analysis we select a fiducial model where $\Delta\alpha/\alpha$ is not vanishing and the DE parameters move from the standard ΛCDM scenario. In this case, the peculiar $w - \zeta$ behavior mentioned above, due to the $\zeta = 0$ fiducial value, is not present and the degeneracies between these parameters show up clearly, as we report in Fig. 2.

We also notice that probing a different fiducial cosmology will give different constraints on the parameters. The constraint on w_0 improves by a factor of about two and the measurement of w_a becomes about one order of magnitude better: moving the fiducial region away from the special point ($\zeta = 0$, $w_0 = -1$) prevents the loss of constraining power because of the

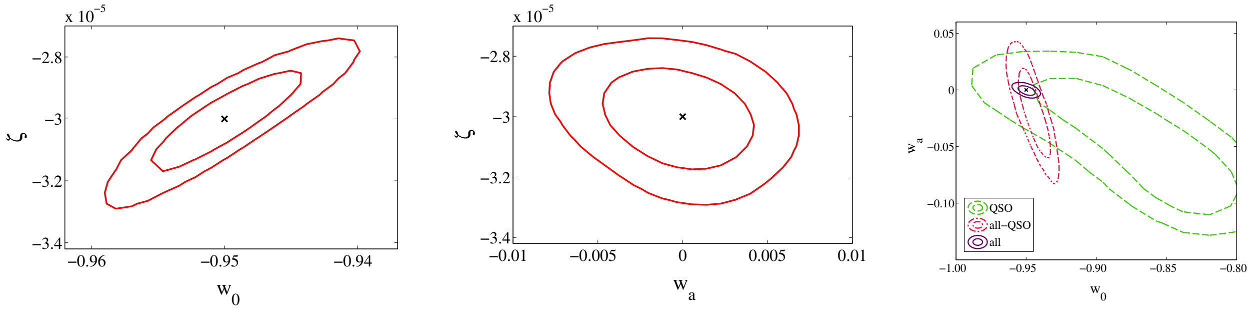

Figure 2. *Left and middle panel* : 2-dimensional contours at 68% and 95% confidence levels showing ζ versus w_0/w_a for the CPL model. *Right panel* QSO contribution to the w_0-w_a constraints. We report contour plots at 68% and 95 % confidence levels as obtained from QSO data only (dashed green line), all probes except QSO (dash-dotted red line) and all probes (solid purple line). The black cross shows the fiducial input values.

pathological degeneracies described in Fig. 1 and therefore all the observables can fully contribute in constraining the cosmological parameters. In particular, in these non standard scenarios, the QSO contribution will be non vanishing. Even though QSO data have a much lower constraining power than other dark energy observables, in the rightmost panel of Fig. 2, it is possible to notice how this dataset can provide independent (and almost orthogonal) limits on dark energy parameters and can be used to break degeneracies between w_0 and w_a.

References

[1] Perlmutter S *et al.* [Supernova Cosmology Project Collaboration] 1999 *Astrophys. J.* **517** 565.
[2] Riess A G *et al.* [Supernova Search Team Collaboration] 1998, *Astron. J.* **116** 1009.
[3] Ade P A R *et al.* [Planck Collaboration] 2013, arXiv:1303.5076 [astro-ph.CO].
[4] Carroll S M 1998 *Phys. Rev. Lett.* **81** 3067.
[5] Chevallier M, Polarski D, 2001 *Int. J. Mod. Phys.* D **10** 213 [gr-qc/0009008].
[6] E. V. Linder 2003 *Phys. Rev. Lett.* **90** 091301
[7] Martinelli M, Pandolfi S, Martins C J A P and Vielzeuf P E 2012, *Phys. Rev.* D **86** 123001
[8] Chiba T and Kohri K 2003 *Prog. Theor. Phys.* **110** 195
[9] Cardone V F , Spiro S, Hook I and Scaramella R 2012, *Phys. Rev.* D **85** 123510
[10] Laureijs R, Amiaux J, Arduini S, Augueres J L, Brinchmann J, Cole R, Cropper M and Dabin C *et al.*, arXiv:1110.3193 [astro-ph.CO].
[11] Hook I M, 2012 arXiv:1211.6586 [astro-ph.CO].
[12] Bahcall J N, Sargent W L and Schmidt M, 1967 *Astrophys. J.* **149** L11
[13] Amendola L, et al. , 2012 *Phys. Rev.* D **86** 063515
[14] CODEX Phase A Science Case, 2010 document E-TRE-IOA-573-0001 Issue 1
[15] Sandage A, 1962 *Ap.J.* **136**, 319-33
[16] Loeb A, 1998 *Astrophys. J.* **499** L111
[17] Pasquini L , et al., 2005, *The Messenger*, 122, 10
[18] Corasaniti P S, Huterer D and Melchiorri A, 2007 *Phys. Rev.* D **75** 062001
[19] Quercellini C, Amendola L, Balbi A, Cabella P and Quartin M, 2012 *Phys. Rept.* **521** 95
[20] Vielzeuf P E and Martins C J A P, 2012 *Phys. Rev.* D **85** 087301
[21] De Bernardis F, Martinelli M, Melchiorri A, Mena O and Cooray A, 2011 *Phys. Rev.* D **84**, 023504
[22] Cooray A R, 1999 *A&A* , **348**, 31 (1999)
[23] Hinshaw G *et al.* [WMAP Collaboration], 2012
[24] Lewis A and Bridle S, 2002 *Phys. Rev.* D **66** 103511
[25] Liske J, Grazian A, Vanzella E, Dessauges M, Viel M, Pasquini L, Haehnelt M and Cristiani S *et al.*, 2008 *Mon. Not. Roy. Astron. Soc.* **386**, 1192