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Fisher matrix forecasts for astrophysical tests of the stability of the fine-structure constant

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A B S T R A C T

We use Fisher Matrix analysis techniques to forecast the cosmological impact of astrophysical tests of the stability of the fine-structure constant to be carried out by the forthcoming ESPRESSO spectrograph at the VLT (due for commissioning in late 2017), as well by the planned high-resolution spectrograph (currently in Phase A) for the European Extremely Large Telescope. Assuming a fiducial model without α variations, we show that ESPRESSO can improve current bounds on the Eötvös parameter—which quantifies Weak Equivalence Principle violations—by up to two orders of magnitude, leading to stronger bounds than those expected from the ongoing tests with the MICROSCOPE satellite, while constraints from the E-ELT should be competitive with those of the proposed STEP satellite. Should an α variation be detected, these measurements will further constrain cosmological parameters, being particularly sensitive to the dynamics of dark energy.

1. Introduction

Astrophysical tests of the stability of fundamental couplings are an extremely active area of observational research [1,2]. The deep conceptual importance of carrying out these tests has been complemented by recent (even if somewhat controversial [3]) evidence for such a variation [4], coming from high-resolution optical/UV spectroscopic measurements of the fine-structure constant α in absorption systems along the line of sight of bright quasars. The forthcoming ESPRESSO spectrograph [5], due for commissioning at the combined Coudé focus of ESO's VLT in late 2017, should significantly improve the sensitivity of these tests, as well as the degree of control over possible systematics.

Moreover, the results of these tests—whether they are detections of variations or null results—have a range of additional cosmological implications. They provide competitive constraints on Weak Equivalence Principle (WEP) violations [1,6,7] and, in the more natural scenarios where the same dynamical degree of freedom is responsible both for the dark energy and the α variation, can also be used in combination with standard cosmological observables to constrain the dark energy equation of state [8,9] and indeed to reconstruct its redshift dependence [10,11].

While current data already provides useful constraints, the imminent availability of more precise measurements from the ESPRESSO spectrograph will have a significant impact in the field. In this work we apply standard Fisher Matrix analysis techniques to forecast the improvements that may be expected from ESPRESSO, but we also take the opportunity to look further ahead and discuss additional gains in sensitivity from the European Extremely Large Telescope (E-ELT), whose first light will be in 2024.

2. Varying α, dark energy and the weak equivalence principle

Dynamical scalar fields in an effective four-dimensional field theory are naturally expected to couple to the rest of the theory, unless a (still unknown) symmetry is postulated to suppress these couplings [12–14]. We will assume that this coupling does exist for the dynamical degree of freedom responsible for the dark energy, assumed to be a dynamical scalar field denoted ϕ. Specifically the coupling to the electromagnetic sector is due to a gauge kinetic function $B_F(\phi)$

$$\mathcal{L}_{\phi F} = -\frac{1}{4} B_F(\phi) F_{\mu\nu} F^{\mu\nu} . \quad (1)$$

This function can be assumed to be linear,

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$$B_F(\phi) = 1 - \zeta\kappa(\phi - \phi_0)\,, \tag{2}$$

(where $\kappa^2 = 8\pi G$) since, as has been pointed out in [13], the absence of such a term would require the presence of a $\phi \to -\phi$ symmetry, but such a symmetry must be broken throughout most of the cosmological evolution. The dimensionless parameter ζ quantifies the strength of the coupling. With these assumptions one can explicitly relate the evolution of α to that of dark energy [6,15]. The evolution of α can be written

$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha - \alpha_0}{\alpha_0} = B_F^{-1}(\phi) - 1 = \zeta\kappa(\phi - \phi_0)\,, \tag{3}$$

and defining the fraction of the dark energy density (the ratio of the energy density of the scalar field to the total energy density, which also includes a matter component) as a function of redshift z as follows

$$\Omega_\phi(z) \equiv \frac{\rho_\phi(z)}{\rho_{\rm tot}(z)} \simeq \frac{\rho_\phi(z)}{\rho_\phi(z) + \rho_m(z)}\,, \tag{4}$$

where in the last step we have neglected the contribution from the radiation density (we will be interested in low redshifts, $z < 5$, where it is indeed negligible), the evolution of the scalar field can be expressed in terms of Ω_ϕ and of the dark energy equation of state w_ϕ as

$$1 + w_\phi = \frac{(\kappa\phi')^2}{3\Omega_\phi}\,, \tag{5}$$

with the prime denoting the derivative with respect to the logarithm of the scale factor. Putting the two together we finally obtain

$$\frac{\Delta\alpha}{\alpha}(z) = \zeta \int_0^z \sqrt{3\Omega_\phi(z')\left[1 + w_\phi(z')\right]}\,\frac{dz'}{1+z'}\,. \tag{6}$$

The above relation assumes a canonical scalar field, but the argument can be repeated for phantom fields, leading to

$$\frac{\Delta\alpha}{\alpha}(z) = -\zeta \int_0^z \sqrt{3\Omega_\phi(z')\left|1 + w_\phi(z')\right|}\,\frac{dz'}{1+z'}\,; \tag{7}$$

the change of sign stems from the fact that one expects phantom fields to roll up the potential rather than down. Note that in these models the evolution of α can be expressed as a function of cosmological parameters plus the coupling ζ, without explicit reference to the putative underlying scalar field. In these models the proton and neutron masses are also expected to vary—by different amounts—due to the electromagnetic corrections of their masses. Therefore, local tests of the Equivalence Principle also constrain the dimensionless coupling parameter ζ [1], and (more to the point for our present purposes) they provide us with a prior on it.

We note that there is in principle an additional source term driving the evolution of the scalar field, due to the derivative of the gauge kinetic function, i.e. a term proportional to $F^2 B_F'$. By comparison to the standard (kinetic and potential energy) terms, the contribution of this term is expected to be subdominant, both because its average is zero for a radiation fluid and because the corresponding term for the baryonic density is constrained by the aforementioned Equivalence Principle tests. For these reasons, in what follows we neglect this term (which would lead to environmental dependencies). We nevertheless note that this term can play a role in scenarios where the dominant standard term is suppressed.

A light scalar field such as we are considering inevitably couples to nucleons due to the α dependence of their masses, and therefore it mediates an isotope-dependent long-range force. This can be quantified through the dimensionless Eötvös parameter η, which describes the level of violation of the WEP [1]. One can show that for the class of models we are considering the Eötvös parameter and the dimensionless coupling ζ are simply related by [1,13,14]

$$\eta \approx 10^{-3}\zeta^2\,; \tag{8}$$

we note that while this relation is correct for the simplest canonical scalar field models we will consider in what follows, it is somewhat model-dependent (for example, it is linear rather than quadratic in ζ for Bekenstein-type models [7]).

3. Forecasting tools and fiducial models

We will be considering three fiducial dynamical dark energy models where the scalar field also leads to α variations according to Eq. (6), as follows

- A constant dark energy equation of state, $w_0 = const$.
- A dilaton-type model where the scalar field ϕ behaves as $\phi(z) \propto (1+z)$; this is well motivated in string theory inspired models [16], but for our purposes it also has the advantage that despite the fact that it leads to a relatively complicated dark energy equation of state

  $$w(z) = \frac{[1 - \Omega_\phi(1+w_0)]w_0}{\Omega_m(1+w_0)(1+z)^{3[1-\Omega_\phi(1+w_0)]} - w_0}\,, \tag{9}$$

  (where we are assuming flat universes, so the present-day values of the matter and dark energy fractions satisfy $\Omega_m + \Omega_\phi = 1$); in this case Eq. (6) simplifies to [6]

  $$\frac{\Delta\alpha}{\alpha}(z) = \zeta\sqrt{3\Omega_\phi(1+w_0)}\,\ln(1+z)\,. \tag{10}$$

  Thus this case allows us to carry out analytic calculations, which we have used to validate our numerical pipeline.
- The well-known Chevallier–Polarski–Linder (CPL) parametrization [17,18], where the redshift dependence of the dark energy equation of state is described by two separate parameters, w_0 (which is still its present-day value) and w_a describing its evolution, as follows

  $$w(z) = w_0 + w_a\frac{z}{1+z}\,. \tag{11}$$

All of these have been used in previous works to obtain constraints from current data [6,8,9] or to forecast dark energy equation of state reconstructions [10,11], and therefore these previous works can easily be compared with ours.

Our forecasts were done with a Fisher Matrix analysis [19,20]. If we have a set of M model parameters $(p_1, p_2, ..., p_M)$ and N observables—that is, measured quantities—$(f_1, f_2, ..., f_N)$ with uncertainties $(\sigma_1, \sigma_2, ..., \sigma_N)$, then the Fisher matrix is

$$F_{ij} = \sum_{a=1}^{N} \frac{\partial f_a}{\partial p_i}\frac{1}{\sigma_a^2}\frac{\partial f_a}{\partial p_j}\,. \tag{12}$$

For an unbiased estimator, if we don't marginalize over any other parameters (in other words, if all are assumed to be known) then the minimal expected error is $\theta = 1/\sqrt{F_{ii}}$. The inverse of the Fisher matrix provides an estimate of the parameter covariance matrix. Its diagonal elements are the squares of the uncertainties in each parameter marginalizing over the others, while the off-diagonal terms yield the correlation coefficients between parameters. Note that the marginalized uncertainty is always greater than (or at