Probing dark energy with varying fundamental couplings

C.J.A.P. Martins (CAUP, Porto) Carlos.Martins@astro.up.pt

N.J. Nunes (ITP, Heidelberg) N.Nunes@thphys.uni-heidelberg.de

G. Robbers (MPA, Garching) robbers@MPA-Garching.MPG.DE

1 Introduction

Assuming that the variations of parameters of nature and the current acceleration of the universe are related and governed by the evolution of a single scalar field, we show how information can be obtained on the nature of dark energy from observational detection of (or constraints on) cosmological variations of the fine structure constant and the proton-to-electron mass ratio. We comment on the current observational status, and on the prospects for future spectrographs such as ESPRESSO and CODEX.

2 Assumptions

Our method requires a number of assumptions: first, that there is dark energy due to a rolling scalar field; second, that there is a cosmological variation of the fine structure constant, as recently suggested ([1, 2]); and thirdly, that any variation of α arises from the evolution of the quintessence field. We note that if dark energy results from an evolving scalar field, it naturally couples to other forms of matter and leads to variations of masses and couplings unless some unknown symmetry principle explicitly forbids these couplings.

We take the coupling between the scalar field and electromagnetism to be $\mathcal{L}_{\phi F} = -\frac{1}{4}B_F(\phi)F_{\mu\nu}F^{\mu\nu}$ where the gauge kinetic function $B_F(\phi)$ is linear, $B_F(\phi) = 1 - \zeta\kappa(\phi - \phi_0)$ (and $\kappa^2 = 8\pi G$). This can be seen as the first term of a Taylor expansion, and should be a good approximation if the field is slowly varying at low redshift. Then, the evolution of alpha is given by

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

We can also consider the variation of $\mu \equiv m_p/m_e$. In GUTs we expect a correlation between the variation of α and μ [3] given by $\Delta\mu/\mu = R\,\Delta\alpha/\alpha$. Under simple theoretical assumptions we obtain $R \sim -20$, in severe tension with observations [4, 5] with equal or better precision. This simple exercise illustrates the potential of cosmological observations of fundamental parameters in discriminating particle physics models.

3 Reconstruction procedure

Our approach [6, 7] is to parametrize $B_F(\phi)$ with a linear function and the evolution of α and/or μ with a polynomial. All we need is a functional form of $\phi'(N)$, then we integrate $\sigma' = -(\kappa\phi')^2(\sigma + a^{-3})$, where $\sigma = \rho_\phi/\rho_0\Omega_{M0}$. The solution provides the evolution of the equation of state parameter through

$$w = -1 + \frac{(\kappa\phi')^2}{3}\left(1 + \frac{1}{\sigma a^3}\right)\,, \tag{2}$$

One starts by obtaining data on the evolution of α and/or μ. We have studied simulated data from the forthcoming `ESPRESSO` spectrograph for VLT and the planned `CODEX` for the E-ELT. The only missing ingredient is the value of ζ. We must estimate its value from independent observations such as SnIa or weak lensing. For typical values we obtain $\zeta \sim 10^{-7} - 10^{-4}$ which is comparable to bounds resulting from tests of the weak equivalence principle. Below we illustrate a reconstruction example using α and μ data in combination.

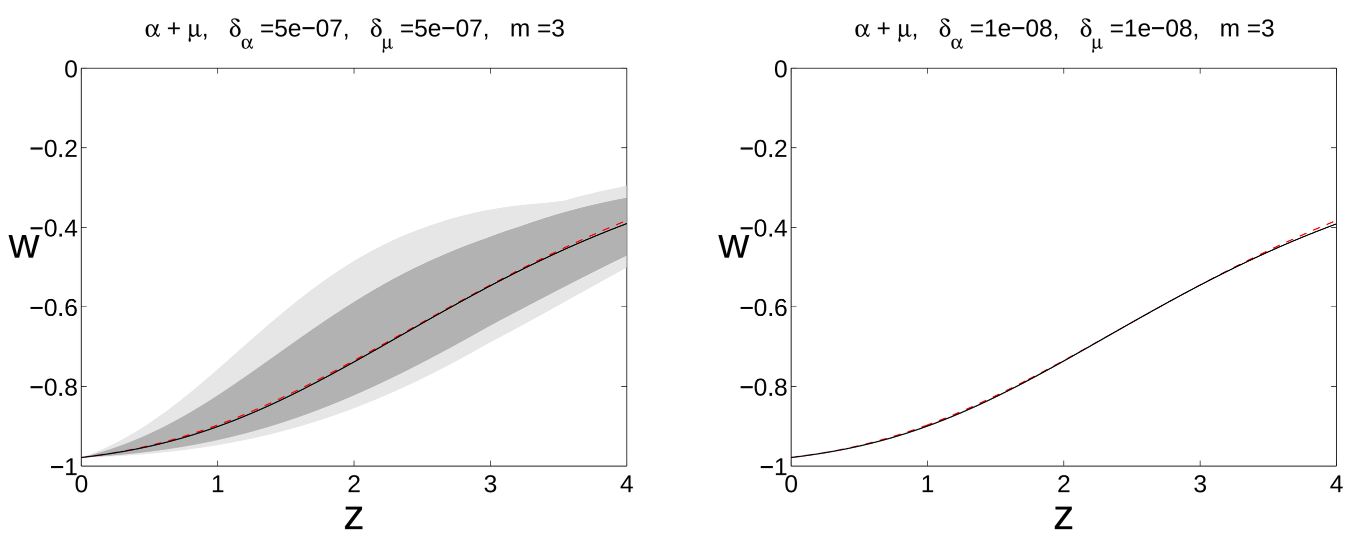

Figure 1: Simulated ESPRESSO and CODEX reconstructions for the potential $V(\phi) = V_0(e^{10\kappa\phi} + e^{0.1\kappa\phi})$. (Dashed line: fiducial model; solid line: best fit reconstruction; grey bands: 1σ and 2σ errors.)

A strong constraint on the current variation of α was obtained from atomic clocks [8], $\dot\alpha/\alpha = (-1.6 \pm 2.3) \times 10^{-17}\mathrm{yr}^{-1}$. This rules out most models of quintessence with a monotonic evolution of the field and a linear coupling if $\Delta\alpha/\alpha(z=3) \sim 10^{-5}$, but there are some ways of evading these bounds.

4 Thoughts on current data

We'll dismiss theoretical prejudices and seek to take the currently available data at face value and understand what it might be telling us. The Rosenband bound may compell us to consider a sharp transition in the value of $\Delta\alpha/\alpha$ at about redshift $z = 1$ [9]. With this in mind we may keep the linear dependence of the gauge kinetic function but set

$$\phi - \phi_0 = c\left[\tanh\left(\frac{N - N_t}{\Delta}\right) - \tanh\left(-\frac{N_t}{\Delta}\right)\right]\,, \tag{3}$$

a field evolving from a local maximum of the potential, falling in a steep well and riseing again approaching another local maximum. The velocity of the field is decreasing today and a large vacuum energy is attained. The alternative

$$\phi - \phi_0 = c\frac{N}{N_t}\left[\tanh\left(\frac{N - N_t}{\Delta}\right) - \tanh\left(-\frac{N_t}{\Delta}\right)\right]\,. \tag{4}$$

does not require that the field is initially at a local maximum, but instead allows an equation of state parameter that approaches $w(z) \approx 0$ at large redshifts. These potentials look distinctly unnatural, however we emphasise that our objective here is to disregard theoretical prejudices and to use the data to uncover viable forms of the scalar potential. This simple exercise highlights the importance of an independent observational confirmation of these variations.

A likelihood analysis will yield the observationally preferred values for the amplitude of the transition, $A = c\zeta$, and the width of the transition, Δ. Combining the data and constraints on the variation of α with SnIa data we are then able to constrain c and therefore ζ. The only upper limit on ζ comes from tests of the equivalence principle. Small values of ζ, however, given an evolution deviating substantially from ΛCDM and one should be able to put lower bounds on this quantity with cosmological data at redshift $z > 1$, as illustrated below.

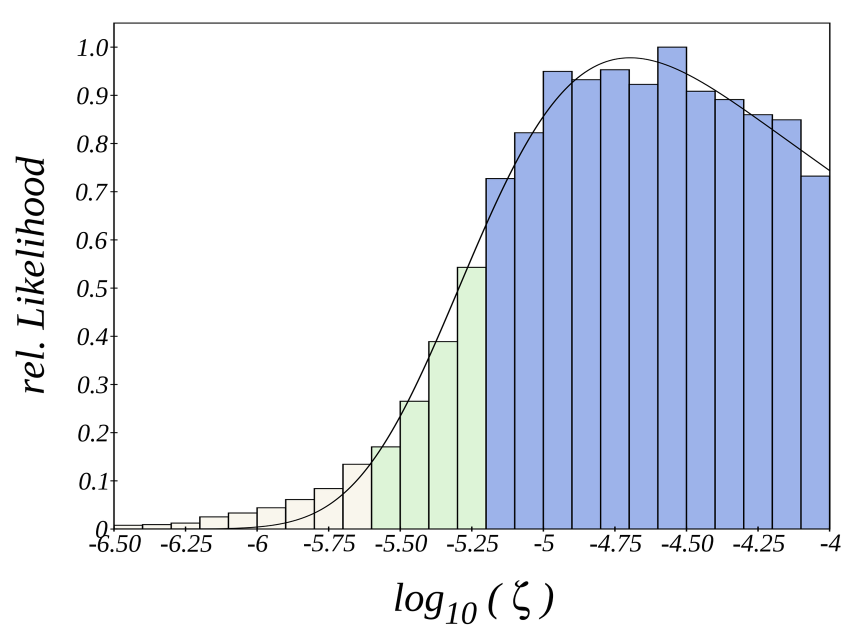

Figure 2: Marginalized 1-d probability distribution for $log_{10}(\zeta)$, using quasar data together with the Rosenband bound, Oklo and meteorite data as well as the Union supernovae sample. The shaded regions represent the 1σ and 2σ confidence limits.

5 Conclusions

We have shown that under simple assumptions we can determine the nature of dark energy, not by *fitting* the parameters of a scalar potential to cosmological data, but by performing the inverse procedure, that consists in using quasar data to *reconstruct* the potential. This type of reconstruction directly probes the scalar field dynamics and may be carried out, with current data, to redshifts beyond $z = 4$, far higher than the limiting value $z = 1.7$ of SnIa searches. Future astrophysical techniques may extend this to even higher redshifts. Moreover, the observations can be done from the ground and are consequently cheaper than satellite-based observations.

6 Acknowledgements

CM is funded by a Ciência2007 Research Contract, supported by FSE and POPH-QREN funds. NJN is supported by DFG project TRR33. This work was done in the context of the CAUP-ITP project *The dark side of the universe*, funded under the FCT-DAAD cooperation agreement.

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