FUNDAMENTAL COSMOLOGY WITH ESPRESSO and ELT-HIRES

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The observational evidence for the acceleration of the universe demonstrates that canonical theories of cosmology and particle physics are incomplete, if not incorrect. Forthcoming high-resolution ultra-stable spectrographs will play a crucial role in the quest for new physics by enabling a new generation of precision consistency tests, including tests of the stability of nature's fundamental couplings. We discuss the improvements that can be expected with ESPRESSO and ELT-HIRES and quantify their impact on cosmology.

1 Introduction and Methods

We will drescribe how astrophysical measurements of natures dimensionless fundamental coupling constants can be used to study the properties of Dark Energy. (Nunes & Lidsey 2004 [2]). Our formalism is described in Amendola *et al.*[1], to which we refer the reader for further details. Here we will simply provide a brief summary of the features that will be relevant for our subsequent comparison with data.

One can divide the relevant redshift range into N bins such that in bin i the equation of state parameter takes the value w_i. The precision on the measurement of w_i can be inferred from the Fisher matrix of the parameters w_i. If the Fisher matrix is diagonalized, it defines a new basis in which the new coefficients α_i are uncorrelated. In this processes one also obtains the eigenvalues λ_i (ordered from largest to smallest) and the variance of the new parameters, $\sigma_i^2 = 1/\lambda_i$.

We consider models for which the variation of the fine-structure constant α is linearly proportional to the displacement of a scalar field, and further assume that this field is a quintessence type field, i.e. responsible for the current acceleration of the Universe. We take the coupling between the scalar field and electromagnetism to be

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

where the gauge kinetic function $B_F(\phi)$ is linear, $B_F(\phi) = 1 - \zeta\kappa(\phi - \phi_0)$, $\kappa^2 = 8\pi G$ and ζ is a constant to be marginalized over. 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 α is given by

$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha - \alpha_0}{\alpha_0} = \zeta\kappa(\phi - \phi_0)\,. \tag{2}$$

For a flat Friedmann-Robertson-Walker Universe with a canonical scalar field, $\dot{\phi}^2 = (1+w(z))\rho_\phi$, hence, for a given dependence of the equation of state parameter $w(z)$ with redshift, the scalar field evolves as

$$\phi(z) - \phi_0 = \frac{\sqrt{3}}{\kappa} \int_0^z \sqrt{1+w(z)} \left(1 + \frac{\rho_m}{\rho_\phi}\right)^{-1/2} \frac{dz}{1+z}. \tag{3}$$

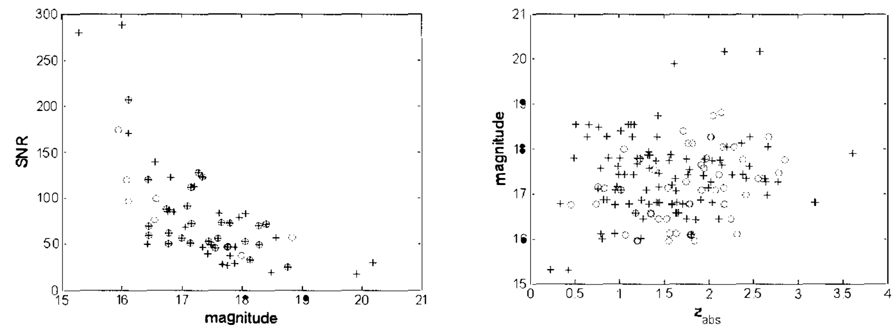

Figure 1 – Left: SNR-Magnitude correlation. Right: Absorption redshift-Magnitude correlation. In both cases the circles represent the best measurements (better then 10ppm accuracy) and crosses the other measurements.

where we have chosen the positive root of the solution.

From this one can calculate the Fisher matrix using standard techniques, as discussed in Amendola *et al.*[1]. As in that work, we will consider three fiducial forms for the equation of state parameter: $w_c(z) = -0.9$, $w_s(z) = -0.5 + 0.5\tanh(z - 1.5)$, and $w_b(z) = -0.9 + 1.3\exp\left(-(z-1.5)^2/0.1\right)$. At a phenomenological level, these describe the three qualitatively different scenarios. In what follows we will refer to these three cases as the *constant*, *step* and *bump* fiducial models.

In order to systematically study possible observational strategies, it's of interest to find an analytic expression for the behaviour of the uncertainties of the best determined PCA modes. We explore the range of parameters such as the number of α measurements (N_α) and the uncertainty in each measurement (σ_α). For simplicity we will assume that this uncertainty is the same for each of the measurements in a given sample. We take N_α between 20 and 200, uniformly distributed in redshift up to $z = 4$, and individual measurement uncertainties between 10^{-5} and 10^{-8}, and we find that the following fitting formula for the uncertainty σ_n for the n-th best determined PCA mode

$$\sigma_n = A\frac{\sigma_\alpha}{N_\alpha^{0.5}}\left[1 + B(n-1)\right]. \tag{4}$$

The present expression is accurate for all values up to and including $n = 6$, while for a smaller number of measurements the number of accurately determined modes is less than 6. The coefficients A and B will depend on the choice of fiducial model, and also on the number of PCA bins assumed for the redshift range under consideration. Assuming the constant fiducial model and 20 bins,the coefficients will be: $A = 1.14$ and $B = 0.52$, further results will be presented elsewhere[3].

2 Current VLT Data

The next step is to connect these theoretical tools to observational specifications. We can assume a simple (idealised) observational formula, $\sigma^2_{sample} = C/T$, where C is a constant, T is the time of observation necessary to acquire a sample of N measurements and σ_{sample} is the uncertainty in $\Delta\alpha/\alpha$ for the whole sample. This is expected to hold for a uniform sample (ie, one in which one has N_α identical objects, each of which produces a measurement with the same uncertainty σ_α in a given observation time). Clearly any real-data sample will not be uniform, so there will be corrections to this behaviour.

The uncertainty of the sample will be given by $\sigma^2_{sample} = 1/\sum_{i=1}^{N}\sigma_i^{-2}$, and for the above simulated case with N measurements all with the same α uncertainty we simply have $\sigma^2_{sample} =$

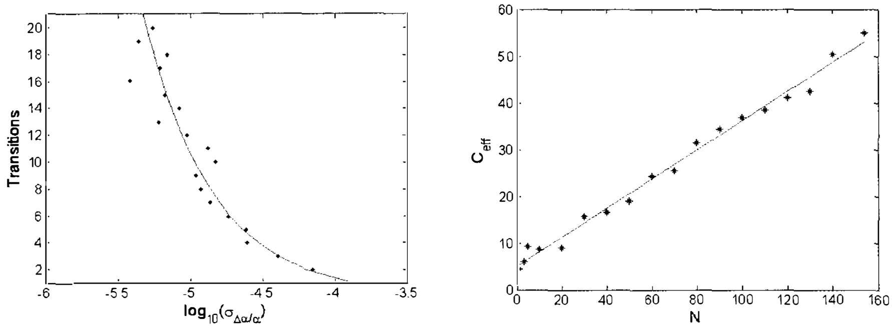

Figure 2 – Left: Correlation between the number of transitions used for a measurement and its uncertainty. Right: Values of the effective parameter C as a function of the number of systems considered. In both cases the red line is the best fit discussed in the text.

σ_α^2/N. Clearly there are also other relevant observational factors that a simple formula like this does not take into account, anyway this formula is adequate for our present purposes, as will be further discussed below.

We have used the UVES data from Julian King's PhD thesis[4], complemented by observation time data kindly provided by Michael Murphy, to build a sample to calibrate the observational formula. As can be seen in Figs. 1 , this sample is far form ideal, as it does not display the types of correlations that one would expect from such a sample.

We do find a strong correlation between the number of transitions used to make one measurement (N_λ) and the uncertainty corresponding to it, as can be observed in Fig. 2 where, for each N_λ, we plot the average uncertainty in the α measurements achieved with that number of transitions. We find the following approximate relation

$$\sigma_{\Delta\alpha/\alpha} = 1,39 \times 10^{-4} N_\lambda^{-1,11} \,. \tag{5}$$

One consequence of these properties of the sample is that the simple observational relation assumed will not strictly hold. Nevertheless, there is a simple way to correct it, which consists of allowing the former constant C to itself depend on the number of sources. This is easy to understand: in a small sample one typically will have the best available sources; by increasing our sample we'll be adding sources which are not as good as the previous ones, and therefore the overall uncertainty in the α measurement will improve more slowly than in the ideal case. Using standard Monte Carlo techniques we have generated several tens of thousands of sub-samples of the VLT sample, from which we infer the behaviour for the empirical function $C(N)$. The results of this analysis are shown in Fig. 2. We find that a good fit is provided by the linear relation

$$C(N) = 0.31\,N + 5.02 \,. \tag{6}$$

here the constant has been normalised such that σ_{sample} is given in parts per million and T is in nights.

3 Future observational strategies

Putting together the observational studies from the previous sections we can combine Eq.4, the simple observational hypothesis and Eq.6, and get a general expression

$$\sigma_n = A[1 + B(n-1)] \left[\frac{aN_\alpha + b}{T}\right]^{0.5} \,. \tag{7}$$

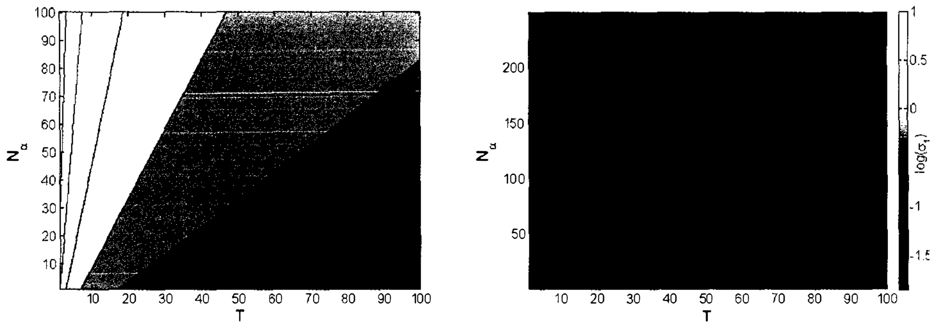

Figure 3 – Uncertainty of first mode in fuction of the observational time and the number of measurements. Left: A baseline scenario for ESPRESSO; Right: For ELT-HIRES.

The way we can extrapolate this formula to ESPRESSO and ELT-HIRES will be explored in detail in future work [3]. In Fig. 3 we show the behaviour of the uncertainty of the first mode with the time of observation and the number of measurements, assuming the constant fiducial model. It can be seen that indeed there is expected a big improvement using HIRES-ELT. Future improvements will come from a better sample selection, optimised acquisition/calibration methods and (in the case of the ELT-HIRES) from collecting power.

Further improvements will come from adding additional datasets. For example, the impact of adding supernova surveys such those of Euclid and ELTs to the PCA analysis can be quantified. The E-ELT case is particularly interesting due to the potentially higher redshift coverage (up to $z = 5$). A detailed study will be reported elsewhere [3].

Acknowledgments

We are grateful to Luca Amendola, Paolo Molaro, Michael Murphy, Nelson Nunes and John Webb for many interesting discussions and suggestions. Special thanks to Michael Murphy for providing us with the observation times for the VLT sources. We acknowledge the financial support of grant PTDC/FIS/111725/2009 from FCT (Portugal). CJM is also supported by an FCT Research Professorship, contract reference IF/00064/2012.

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