# STABILITY OF FUNDAMENTAL COUPLINGS AND DARK ENERGY: A PRE-ESPRESSO ANALYSIS AND FORECAST

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We highlight some recent developments in tests of the stability of nature's fundamental couplings, which provide a direct handle on new physics: a detection of variations will be revolutionary, but even improved null results provide competitive constraints on a range of cosmological and particle physics paradigms. A joint analysis of all currently available data shows a preference for variations of $\alpha$ and $\mu$ at about the two-sigma level, but inconsistencies between different sub-sets (likely due to hidden systematics) suggest that these statistical preferences need to be taken with caution. On the other hand, these measurements strongly constrain Weak Equivalence Principle violations. Plans and forecasts for forthcoming studies with facilities such as ALMA, ESPRESSO and the E-ELT, which should clarify these issues, are also briefly discussed, showing how a new generation of precision consistency tests of the standard paradigm will soon become possible.

## 1 Scalars, because they are there

We now know, from experiments at the LHC, that fundamental scalar fields are among Nature's building blocks and that Nature's fundamental dimensionless couplings run with energy. Whenever one such field is included in the Lagrangian, it will naturally couple to the rest of the model's degrees of freedom, unless a new (unknown) principle is postulated to suppress them. This leads to potentially observable long-range forces and spacetime varying couplings [1,2,3], which can therefore roll in time (or equivalently redshift) and ramble in space (in practice, depending on the local environment).

Tests of the stability of nature's fundamental couplings, whether they reveal detections of variations or simply null results, constrain fundamental physics and cosmology. Varying dimensionless physical constants imply a violation of the Einstein Equivalence Principle (demonstrating that gravity is not a purely geometric phenomenon) as well as the presence of a fifth force of nature. There will also be violations of the temperature-redshift relation and the distance duality relation, which provide key consistency tests [4,5]. Conversely, null results provide upper bounds on Equivalence Principle violations as well as on dynamical dark energy and several particle physics paradigms. These constraints ensure a 'minimum guaranteed science', which is relevant when developing the science cases and technical designs of future facilities.

The importance of improved bounds can be ascertained by comparison to constraining the dark energy equation of state or, to be more specific, its present-day value $w_0$. The dynamically relevant parameter $(1 + w_0)$ (the ratio of the square of the field speed to its total density, in the simple case of a canonical scalar field) is naively or order unity, but observationally known to be less than 0.1. But if this is not of order unity, there is no known natural physical scale to set its value: either there is fine-tuning, or a new (currently unknown) symmetry forces it to be zero. The same argument can be made for the relative variation of say the fine-structure constant $\alpha$, henceforth defined as $\Delta\alpha/\alpha(z) = (\alpha(z) - \alpha_0)/\alpha_0$, with $\alpha_0$ being its present-day laboratory value, the difference being that this parameter is observationally constrained to be (conservatively) less that $10^{-5}$, as we will discuss in the rest of this article. Stringent as this bound is, it is important to go further, as illustrated by the strong CP Problem in QCD: a parameter naively expected to be of order unity is known to be smaller than $10^{-10}$, leading to the postulate of Peccei-Quinn symmetry and the axion (an interesting dark matter candidate)[6]. A sufficiently tight bound would either indicate that there are no dynamical fields in cosmology or that a new symmetry suppresses the couplings—whose existence would be as significant as that of the original field.

## 2 Current measurements

A compilation of the current astrophysical tests of the stability of fundamental couplings has recently been published in[7]. They comprise 293 archival measurements of the fine-structure constant $\alpha$ of Webb *et al.*[8], 21 more recent dedicated measurements of $\alpha$, 16 measurements of the proton-to-electron mass ratio $\mu$, and 29 measurements of various combinations of $\alpha$, $\mu$ and the proton gyromagnetic ratio $g_p$.

A global likelihood analysis of all this data, assuming a single redshift-independent astrophysical value for each of the dimensionless couplings, yields

$$\frac{\Delta\alpha}{\alpha} = -1.6 \pm 0.5\,ppm\,, \quad \frac{\Delta\mu}{\mu} = -0.2 \pm 0.1\,ppm\,, \quad \frac{\Delta g_p}{g_p} = 1.7 \pm 1.3\,ppm\,, \tag{1}$$

where the values are given in units of parts per million ($10^{-6}$), and unless otherwise stated all values are quoted with one-sigma (68.3%) confidence level. A more detailed tomographic analyis, dividing the data into several redshift bins has also been done[7]. This reveals inconsistencies at the one to two sigma level beween radio/mm and optical/UV measurements. Since the former and the latter typically yield measurements at redshifts $z < 1$ and $z > 1$ respectively, naive theorists may interpret this as differences between acceleration and matter era values (which are indeed expected in realistic models for varying couplings) while skeptical observers will suspect hidden systematics in one or both types of measurements. Efforts are ongoing to clarify these issues through obervations with APEX and ALMA, while the forthcomng ESPRESSO spetrograph will play a key role in this endeavour.

The archival data of Webb *et al.*[8] provides a $4.2\sigma$ statistical evidence for a dipole in the values of $\alpha$. An updated analysis including all currently available data[7] lowers this statistical evidence to only $2.3\sigma$, with the posterior likelihood for the amplitude of the dipole (marginalized over sky direction) being $A_\alpha = 5.6 \pm 1.8\,ppm$. A similar analysis can be done for the $\mu$ measurements. In this case the statistical preference for a dipole is less than $2\sigma$, and the two sigma (95.4% confidence) upper bound on its amplitude is $A_\mu < 1.9\,ppm$; furthermore the preferred directions of both putative dipoles differ by about $3\sigma$. A defintive test of a parts per million level dipole will be carried out by ESPRESSO. Meanwhile, a more robust method to constrain spatial variation will be discussed below.

## 3 Dark energy and Equivalence Principle constraints

The energy content of the Universe is dominated by a component whose gravitational behavior is known to be quite similar to that of a cosmological constant. This may well turn out to be the case, but given the well known theoretical problems associated with this explanation a dynamical scalar field is (arguably) more likely. Such a field must be slow-rolling (which is mandatory for a negative pressure) and be dominating the cosmological dynamics around the present day. These are enough to ensure that couplings of this field will lead to potentially observable long-range forces and varying 'constants'[1,2,3]. As we presently show, current measurements already provide competitive constraints on fundamental physics and cosmology, and the improvement of these constraints is among the flagship science cases (and design drivers) for forthcoming ESO facilities, including ESPRESSO and the E-ELT.

If the same degree of freedom is responsible for dark energy and varying $\alpha$, the latter's evolution is parametrically determined. In the simplest case of a canonical quintessence-type scalar field, one has

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

where $\zeta$ is the dimensionless coupling between the scalar field and the electromagentic part of the Lagrangian and $\Omega_\phi(z) = \rho_\phi(z)/(\rho_\phi(z) + \rho_m(z))$ is the fraction of the universe's energy in the dark energy component, where for simplicity we have neglected the contribution form the radiation density since the astrophysical measurements under consideration are all at low redshifts. Current constraints, combining the aforementioned astrophysical measurements of $\alpha$ with atomic clock constraints on its present-day drift rate [9] and background cosmology measurements of Type Ia supernova and Hubble parameter measurements [10,11] lead to the following $2\sigma$ upper bound [12,13,14] $|\zeta| < 4 \times 10^{-6}$. The ESPRESSO GTO measurements, discussed in Ana Catarina Leite's contribution to these proceedings, should improve this bound by a factor of 10, assuming null results [15].

In these models the scalar field will inevitably couple to nucleons (through the $\alpha$ dependence of their masses) and lead to violations of the Weak Equivalence Principle [2,3,16]. Thus measurements of $\alpha$ constrain the Eotvos parameter $\eta$: the current $2\sigma$ bound for these models is [13,14]

$$\eta < 1.6 \times 10^{-14}\,. \tag{3}$$

This is an order of magnitude stronger than the current best direct bounds from torsion balance and lunar laser ranging experiments [17,18]. We therefore predict that the MICROSCOPE satellite, whose foreseen sensitivity on $\eta$ should be around $10^{-15}$ (cf. the contributions by M. Rodrigues and G. Métris in these proceedings) will not find violations at least up to the above level. On the other hand, with the ESPRESSO GTO measurements we expect to reach a sensitivity on $\eta$ of $2 \times 10^{-16}$ (about 5 times better than MICROSCOPE). In the longer term, the ELT-HIRES sensitivity is expected to be at the level of a few times $10^{-18}$, similar to that of proposed STEP satellite.

## 4 Other models: rollng tachyons and symmetrons

Astrophysical measurements of $\alpha$ constrain other classes of models. A rolling tachyon is a Born-Infeld scalar motivated in string theory which naturally yields coupling to gauge fields. The tachyon Lagrangian generalizes the one for a relativistic particle, like quintessence one generalizes that of a non-relativistic one. In these models the potential slope determines both $w(z)$ and $\alpha(z)$, unavoidably leading to thawing models with $\Delta\alpha/\alpha < 0$. Nhe current $\alpha$ measurements lead to the extremely tight constraint on the present-day dark energy equation of state, at the $3\sigma$ (99.7%) confidence level $(1 + w_0) < 2.4 \times 10^{-7}$. Therefore background cosmology probes can not distinguish these models from standard $\Lambda$CDM, while $\alpha$ data can.

Above we discussed constraints on pure spatial $\alpha$ dipoles. While one can also fit a dipole to any such dataset, physically such a behavior is not expected to ensue from any realistic model (except perhaps at the cost of significant fine-tuning). In these cases one rather expects that $\alpha$ will have environmental variations (e.g., it can depend on the local density). In [20] we have introduced a methodology to test models with spatial variations of $\alpha$, based on the calculation of the angular power spectrum of these measurements. This enables comparisons of observations and theoretical models through their predictions on the statistics of the $\alpha$ variation. Applying it to the case of symmetron models we find no deviations from the standard behavior, with current data providing an upper limit to the strength of the symmetron coupling to gravity

$\log\beta^2 < -0.9$ when this is the only free parameter, and not able to constrain the model when also the symmetry breaking scale factor is also free to vary. The forthcoming ESPRESSO data will enable more stringent constraints on this and other models with spatial variations.

## 5 Conclusions

Precision spectroscopy is a direct and competitive probe of the (unknown) new physics behind the universe's acceleration. It provides the best current constraints on Weak Equivalence Principle violations, and it offers unique opportunities to map the behavior of the dark energy equation of state deep into the matter era[21].

The ESPRESSO spectrograph is coming soon, and will be a game changer. It will provide a consistency test of the MICROSCOPE results (and enable interesting joint analyses) as well as a range of competitive 'guaranteed science' implications for dark energy and fundamental physics. In the 2020's the E-ELT will be the flagship tool in a new generation of precision consistency tests, which together have a unique value of complementarity, redundancy, and synergies with other facilities, including ALMA, Euclid and the SKA.

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