Probing Fundamental Physics with Varying Couplings


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1 Scalar Fields

The deepest question of modern physics is whether or not there are fundamental scalar fields in nature. The early universe is an ideal place to search for them. Observations suggest that the recent universe is dominated by an energy component whose gravitational behaviour is akin to that of a cosmological constant. This could be the right answer, but the observationally required value is so much smaller than expected from particle physics that a dynamical scalar field is arguably a more likely explanation. The slow-roll of this field (mandatory so as to yield negative pressure) and the fact that it is presently dominating the universe are sufficient to ensure that couplings of this field lead to observable long-range forces.

2 Varying Couplings

A dynamical scalar field coupling to matter mediates a new interaction. Joint analyses of varying coupling and Equivalence Principle measurements will soon provide key tests of a number of fundamental paradigms such as string theory, and may be our only opportunity to find evidence for it. The expected spacetime variations of dimensionless quantities like the fine-structure constant $\alpha$ and the electron-to-proton mass ratio $\mu$, will also be related to each other (in a model-dependent way), and simultaneous measurements of both are a powerful discriminating tool between competing models: we can test GUT models without ever needing to detect any GUT model particles, say at accelerators.

![Fig. 1: Forecasts of joint confidence in the $\alpha$ vs. optical depth ($z$) plane, with all other parameters marginalized, for ESA’s Planck Surveyor and an ideal cosmic variance limited (CVL) experiment, from temperature data alone (red), E-mode polarization alone (yellow), and both jointly (white). The dashed contour is the WMAP measurement. Current constraints are at the few percent level, while an ideal CMB experiment can measure $\alpha$ at redshift $z \sim 10^8$ to about $10^{-6}$ accuracy.](image1)

![Fig. 2: Evolution of $\alpha$ induced by non-linear density perturbations in the simplest quintessence models. Previous results from a spherical infall model are inconsistent with a more realistic local linearized gravity study. The time evolution of $\alpha$ (including spatial variations) in the vicinity of a spherical mass distribution with $r_0 = 2H_0^{-1}$ is shown for the local (solid) and infinite wavelength (dashed) approximations. With the realistic value $r_0 \sim 10^{-3} Mpc$ (for a typical galaxy cluster), spatial variations of $\alpha$ in the local approximation should be scaled down by about 6 orders of magnitude. The dotted line is the background evolution of $\alpha$. We therefore predict that in this class of models the spatial variations of $\alpha$ are too small to be of cosmological interest.](image2)

![Fig. 3: Dark energy equation of state reconstruction precision for a particular quintessence model. The dashed line is the true equation of state and the solid line is the reconstruction’s best fit (the dark and light regions are the 1 and 2 $\sigma$ confidence levels). Left panels use only $\alpha$ data, while those on the right use only $\mu$ data (a joint analysis will lead to smaller errors). The dataset used for the top panels should be available within 2-3 years (from currently existing facilities), while the bottom panels show what can be obtained with the proposed CODEX spectrograph on the E-ELT. This analysis highlights the benefits of $\mu$ measurements. Note that standard reconstruction methods are inaccurate beyond $z \sim 1$.](image3)

![Fig. 4: Existing $\mu$ measurements come from UVES spectra on VLT, at a resolution $R \sim 30000$. The spectra were analyzed with the standard UVES pipeline. We are developing new optimized techniques optimized, which we’ll use to re-reduce all existing UVES $H_e$ observations to more accurately measure $\mu$. A second step is using the PEPSI spectrograph on LBT (above) to obtain better spectra ($R \sim 300000$) of northern hemisphere systems. An additional goal is to design a dedicated facility for ultra-high resolution ($R \sim 10^5$) and signal to noise spectra of point objects for measuring both $\alpha$ and $\mu$. We’ll measure $\mu$ to ten times higher accuracy than any other astronomical measurement at several lookback times ranging from a few to 12 billion years.](image4)

3 Probing Dark Energy

A key goal of cosmology is characterizing the properties of dark energy, notably by looking for dynamical behaviour. A first step is measuring its equation of state, $w = p/\rho$. Probes include type Ia supernovae and weak lensing, but it’s known that these are of limited efficacy: detailed analysis shows that a convincing detection of a dynamical $w$ is unlikely even with planned satellite experiments (say DUNE or JDEM). Better alternatives exist: varying couplings can be used to infer the scalar field dynamics, thus mapping $w$. This is analogous to reconstructing the 1D potential for the classical motion of a particle given its trajectory, and involves only first derivatives of the data (standard methods require second derivatives). The key advantage is a much larger lever arm: such measurements can be made up to $z \sim 4$, so we can probe the otherwise inaccessible redshift range where scalar field dynamics is expected to be fastest.

4 Observational Program

Most efforts focus on $\alpha$, but $\mu$ variations may be easier to detect, and provide tighter constraints. Such measurements are rarer than $\alpha$’s (finding $H_0$ clouds is hard) but significant efforts are in progress. Assuming that the current observational evidence for varying couplings is correct, a several-sigma detection of dynamical dark energy could be obtained with only a few hundred hours of observation on a VLT-class telescope.

