FINE-STRUCTURE CONSTANT CONSTRAINTS ON DARK ENERGY AND THE WEAK EQUIVALENCE PRINCIPLE

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The observational evidence for the recent acceleration of the universe demonstrates that canonical theories of cosmology and particle physics are incomplete (and possibly incorrect) and that new physics is waiting to be discovered. The most fundamental task for the next generation of astrophysical facilities is to search for, identify and ultimately characterise this new physics. Here we provide a brief summary of the CAUP Dark Side team's recent work, consolidating the science case for using astrophysical tests of the stability of fundamental couplings as direct probes of cosmology and fundamental physics. In particular we show that recent measurements already provide competitive constraints on dark energy an on Weak Equivalence Principle violations, and we discuss the road ahead for this field.

1 Introduction

We know (from the LHC) that fundamental scalar fields are among Nature's building blocks, and that fundamental couplings run with energy. These fields will naturally couple to the rest of the model, unless there is a currently unknown principle to suppress them. In a cosmological context, couplings can therefore roll in time and ramble in space.

It follows that such couplings will lead to potentially observable long-range forces and variations of what are usually called fundamental constants [1]. These measurements (whether they are detections or null results) constrain fundamental physics and cosmology, as we will presently show. In particular, this ensures a quantifiable 'minimum guaranteed science' for forthcoming experiments, enabling detailed studies and optimisation of possible observational strategies.

It's worthy of note that we have no 'theory of constants': we don't know what role they play in physical theories, how many are fundamental, and so on (and yet they determine properties of atoms, cells and the universe). Therefore we also have no compelling reason to assume that they are constant—but if they vary, all the physics we know is incomplete.

A detection of varying dimensionless couplings would be revolutionary: *inter alia* it would immediately imply a violation of the Einstein Equivalence Principle (meaning that gravity is not a purely geometric phenomenon) and the existence of a fifth force of nature. On the other hand, improved null results are important and very useful. The simple way to see this is to note that the natural scale for the cosmological evolution of a dynamical scalar field would be the Hubble time, but current bounds are already about six orders of magnitude stronger than this, thereby ruling out many otherwise viable models.

This naturally leads to the question of how low in sensitivity should one go (until either a detection is found or one gives up and stipulates that there is no variation). Dark energy provides an enlightening analogy. If a scalar field is responsible for the dark energy, we would expect its equation of state—more rigorously, the dynamically relevant parameter $(1 + w)$—to be of order unity, but observationally we know it to be less than about 10^{-1}. But if this is not of order unity, there is no known natural scale for the variation: either there is some fine-tuning or a new (currently unknown) symmetry forces it to be zero. Now, the same argument can be made for the relative variation of the fine-structure constant, $\Delta\alpha/\alpha$, the only difference being that this is observationally known to be less than 10^{-5}.

As we will discuss in the following section, the sensitivity of current measurements is typically at the few parts per million (ppm) level. So if no variations are found at this level is it worth pushing on? Certainly yes. The reason is akin to the CP Problem in QCD: a parameter naively of order unity is known to be less than 10^{-10} leading to the postulate of the Peccei-Quinn symmetry[2] and axions. A sufficiently tight bound on α will indicate either that there are no dynamical fields in cosmology or the presence of a new symmetry to suppress the couplings—whose existence would be as significant as that of the original field.

2 Observational status

Astrophysical tests of the stability of fundamental couplings through high-resolution spectroscopy of absorption systems along the line of sight of bright quasars have experienced very significant developments, including gains in sensitivity, over the past five years.

The dataset studied by *Webb et al.*[3] includes 293 archival absorbers, and the nominal weighted mean for the relative variation of α has a systematic uncertainty at the 2 ppm level, but it is known that the systematic uncertainties for each system are typically of order 9 ppm. On the other hand, there are currently 11 dedicated measurements (summarised in Ferreira & Martins[4]), mostly from a UVES Large Program[5,6,7], for which the nominal weighted mean is

$$\frac{\Delta\alpha}{\alpha} = 0.37 \pm 0.94\,ppm\,, \tag{1}$$

with more measurements expected imminently. However, the Large Program collaboration has also identified an irreducible systematics floor of 1ppm, which is intrinsic to all currently available spectrographs and can only be beaten by using more stable ones.

The analysis of *Webb et al.* indicates a statistical evidence at more than four sigma for a spatial dipole in the values of α. It's unclear if this is a pure spatial dipole or has some dependence of lookback time—the data is not good enough to distinguish between the two scenarios. In any case, the recent dataset of dedicated measurements, although small in number, has tight measurements and therefore has some impact in these scenarios[8]: specifically, the allowed dipole amplitude is reduced by 20%, and the direction of the dipole on the sky is also further constrained. It is still not possible to distinguish between a pure spatial dipole and one with a further redshift dependence.

A joint analysis of all existing optical/UV and radio/mm data is also interesting[4]: in particular, it reveals inconsistencies at the one to two sigma level between the optical and the radio measurements. This is especially true for data deep in the matter era. This should be clarified with APEX and ALMA, which have the capability of carrying out, in the radio/mm, measurements at the same high redshifts that are currently probed by optical/UV spectrographs such as UVES (and will soon be probed by ESPRESSO[9]). We note that considering all currently available data the best-fit for $\Delta\alpha/\alpha$ is -2ppm (at the two sigma level), though this is not statistically significant given the aforementioned systematics floor. Nevertheless, the possibility of a different behaviour in the matter and acceleration epochs is something that deserves additional observational exploration.

3 Fundamental cosmology

Recent cosmological observations suggest that the universe is dominated by an energy component whose gravitational behaviour is similar to that of a cosmological constant. A dynamical scalar field is (arguably) a more natural explanation. Such a field must be slow-rolling (which is mandatory for $p < 0$) and dominate at low z. Standard methods (type Ia supernovas, etc) are known to be of limited use as dark energy probes[10,11], since the relevant cosmological parameters are hidden behind two integrals. Moreover, since the field is slow-rolling when dynamically important, a convincing detection of $w(z)$ will be tough at low z. Instead we must probe the deep matter era, where the scalar field dynamics is presumably fastest.

Fundamental couplings ideally probe the field dynamics beyond the domination regime, with the advantage that for the simplest models the relevant cosmological parameters are hidden behind only one integral—and in some specific classes of models the relation is even more direct. Thus astrophysical facilities such as ALMA, ESPRESSO and ELT-HIRES will map dark energy well into the matter era[9,12]—out to $z \sim 4$ and possibly beyond.

In the simplest class of models where the same scalar degree of freedom is responsible for the dark energy and (through a coupling to the electromagnetic sector) the varying α, the latter's evolution is parametrically determined. Specifically, for a quintessence-type field we have

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

where $w_\phi(z)$ is the dark energy equation of state, $\Omega_\phi(z)$ the fraction of the universe's energy density in this component, and ζ is the field coupling.

Current QSO, atomic clock[13] and background cosmology[14,15] data strongly constrains these models[16,17,18]. For example, taking the simple assumption of a constant equation of state[16] the 1D marginalised constraints are

$$|\zeta| < 5 \times 10^{-6}\,, \quad (95.4\% CL) \tag{3}$$

$$|1 + w_0| < 0.06\,, \quad (99.7\% CL)\,. \tag{4}$$

For comparison, with 12 ESPRESSO GTO measurements (see Ana Catarina Leite's contribution) one expects improvements by a factor 1.5 (assuming that there are no variations) or a detection of a non-zero coupling ζ assuming a variation that saturates current bounds.

Given the aforementioned parametric relation, these results are mildly dependent on the underlying fiducial model[17,18]. For example if we assume the CPL parameterisation we obtain weaker 1D marginalised constraints on the present-day dark energy equation of state

$$1 + w_0 = 0.00^{+0.15}_{-0.05}\,, \quad (99.7\% CL) \tag{5}$$

(and no significant constraint on the equation of state slope w_a), but correspondingly stronger constraints on the coupling

$$\zeta = (1 \pm 3) \times 10^{-6}\,, \quad (95.4\% CL)\,. \tag{6}$$

In these models the scalar field will inevitably couple to nucleons (through the a dependence of their masses) and therefore will also lead to violations of the Weak Equivalence Principle[19,20,21]. Depending on the dark energy model considered, this leads to a bound on the Eotvos parameter[17,18].

$$\eta < (2 - 4) \times 10^{-14}\,, \quad (95.4\% CL)\,. \tag{7}$$

These are one order of magnitude stronger than the current direct bounds, coming from torsion balance and lunar laser ranging experiments, but testable by the MICROSCOPE satellite). On the other hand, in models where dark energy and the α variation are due to different physical processes, the WEP bound is somewhat weaker, typically $\eta < (5-10)\times10^{-14}$. Forthcoming high-resolution ultra-stable spectrographs will keep providing competitive constraints: ESPRESSO can reach a sensitivity on η of few x 10^{-16} (that is, better than MICROSCOPE) while ELT-HIRES can reach 10^{-18} similar to that of the proposed STEP.

4 Outlook

The observational evidence for the acceleration of the universe demonstrates that canonical theories of cosmology and particle physics are incomplete, if not incorrect. Precision astrophysical spectroscopy provides an optimal probe of the (still unknown) new physics. Currently it is clear that dimensionless fundamental couplings are stable at the 10^{-5} level. This is already a tight constraint: it is stronger than the Cassini bound, and it leads to the best available constraints on Weak Equivalence Principle violations.

Things are currently unclear at the ppm level, but significant improvements are coming. New dedicated instruments (ESPRESSO imminently, and ELT-HIRES in the next decade) will lead to a new generation of precision consistency tests of the standard model and enable a characterisation of new physics. Our work demonstrates their competitive 'guaranteed science' implications for dark energy and fundamental physics. They will also deliver a unique value of complementarity, redundancy, and synergies with other facilities (including ALMA, Euclid and SKA), that are currently being explored in more detail.

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