Evolution of the fine-structure constant in runaway dilaton models

Matteo Martinelli*

Institut für Theoretische Physik, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 16, 69120, Heidelberg, Germany
**E-mail: m.martinelli@thphys.uni-heidelberg.de*

Erminia Calabrese

Sub-department of Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH, UK

Carlos J.A.P. Martins

Centro de Astrofìsica, Universidade do Porto, Rua das Estrelas, 4150-762 Porto, Portugal
Instituto de Astrofìsica e Ciencias do Espaco, CAUP, Rua das Estrelas, 4150-762 Porto, Portugal

We use a combination of simulated cosmological probes as expected from the forthcoming European Extremely Large Telescope (E-ELT), to constrain the class of string-inspired runaway dilaton models of Damour, Piazza and Veneziano. We improve previously existing analyses investigating in detail the degeneracies between the parameters ruling the coupling of the dilaton field to the other components of the universe, and we consider three different scenarios for the dark sector couplings. We show the constraining power of the E-ELT and highlight how degeneracies will affect this in different fiducial cosmologies.

Keywords: Fine-structure constant; future experiments; cosmology; dilaton.

1. The Runaway Dilaton Model

In the quest for an alternative to the standard cosmological constant - cold dark matter model (ΛCDM) a class of viable theories relies on a dynamical "dark energy" to take the role of Λ to explain the late time cosmic acceleration; the most natural way tintroduce a new dynamical degree of freedom is through a scalar field, a possibility not excluded by modern particle physics.

In particular, string theory predicts the presence of a scalar partner of the spin-2 graviton, the dilaton, hereafter denoted ϕ. Here, we will study the cosmological consequences of a particular class of string-inspired models, the runaway dilaton scenario of Damour, Piazza and Veneziano.[1,2] This particular scenario allows to avoid the tension a massless dilaton has with local measurments of gravity producing, through supersymmetry breaking, a mass for the dilaton, large enough to supress detectable deviations from GR. A dilaton coupled with the gravitational and matter sectors is described by the Lagrangian

$$\mathcal{L} = \frac{R}{16\pi G} - \frac{(\nabla\phi)^2}{8\pi G} - \frac{1}{4}B_F(\phi)F^2 ... \tag{1}$$

where R is the Ricci scalar, F is the electromagnetic tensor and B_F is the gauge kinetic function (which will determine the evolution of α). Varying the action one can obtain the field equation for ϕ

$$\frac{2}{3-\phi'^2}\phi'' + \left(1-\frac{p}{\rho}\right)\phi' = -\sum_i \alpha_i(\phi)\frac{\rho_i - 3p_i}{\rho} \quad (2)$$

where the i index runs on the components of the Universe, neglecting relativistic matter, i.e. barions (b), cold dark matter (m) and effective dark energy (V). This last component encodes the contribution to the ϕ equation of motion brought by the potential of the dilaton itself. In the following we assume

$$\frac{\alpha_b(\phi)}{\alpha_{b,0}} = e^{-(\phi(z)-\phi_0)}, \quad \alpha_V(\phi) = const, \quad (3)$$

where the 0 subscript indicates a quantity evaluated at present time, while we use 3 different choices for α_m (see Ref. 3 for a discussion of these choices):

- Dark Coupling $\alpha_m = \alpha_V$
- Matter Coupling $\alpha_m(\phi) = \alpha_b(\phi)$
- Field Coupling $\alpha_m(\phi) = -\phi'$

Solving Eq.(3), through the redefinition $\phi(z) \to \phi(z) - \phi_0$ and using as initial conditions

$$\phi_0 = 0, \quad \phi'_0 = -\frac{\alpha_b\Omega_b + \alpha_m\Omega_m + 4\alpha_V\Omega_V}{\Omega_b + \Omega_m + 2\Omega_V}, \quad (4)$$

where Ω_i is the adimensional density of the i-th species, one obtains the evolution shown in Fig.1, which highlights the different redshift behaviour of the field and its derivative depending on the choice of the α_m coupling.

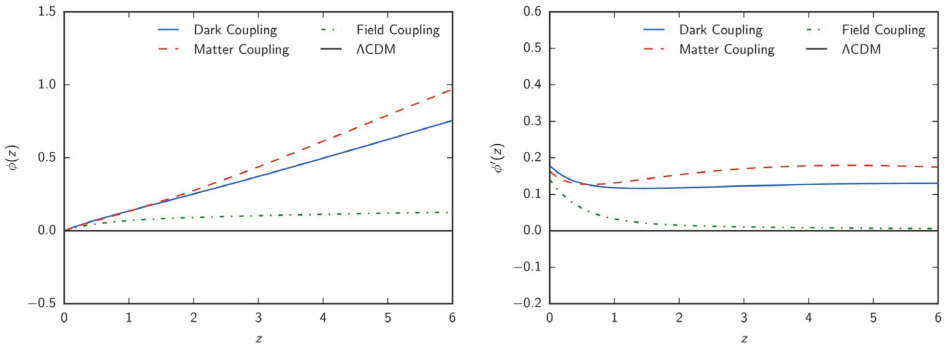

Fig. 1. Redshift evolution of the dilaton scalar field ϕ (left panel) and of its derivative ϕ' (right panel) in the Dark (blue solid line), Matter (red dashed line) and Field (green dot-dashed line) Coupling cases, assuming $\alpha_{b,0} = 10^{-4}$ and $\alpha_V = 0.1$. These quantities vanish in the standard ΛCDM scenario, as shown with the black solid line for reference.

1.1. *Observational Signatures*

Current solar system tests of the equivalence principle (see Refs 4, 5, 6) and recent measurements by Planck (Refs. 7, 8) constrain the dilaton parameters as

$$|\alpha_{b,0}| \lesssim 10^{-4} \qquad |\alpha_V| \lesssim 0.4. \tag{5}$$

These constraints on the parameter space still allow the model to account for the late time accelerated expansion of the Universe, therefore it is interesting to investigate the cosmological consequences of a dilaton driven cosmology.

For this purpose it is needed to identify its distinctive signatures and in particular departures from the standard ΛCDM model. As discussed in Ref. 3, the background expansion of the Universe, produced by a dilaton driven dark energy is extremely close to the one predicted by ΛCDM; although this feature makes the dilaton a viable alternative to the cosmological constant, it also means that background observables cannot be used to distinguish the two models.

However, the coupling of the scalar field to other sectors of the underlying theory produces distinctive effects of this theory; here, we will focus on the redshift variation of the fine structure constant α, produced by the coupling B_F of the scalar field with the electromagnetic tensor $F^{\mu\nu}$

$$\frac{\Delta\alpha}{\alpha} = \frac{\alpha_{b,0}}{40}\left[1 - e^{-(\phi(z)-\phi_0)}\right]. \tag{6}$$

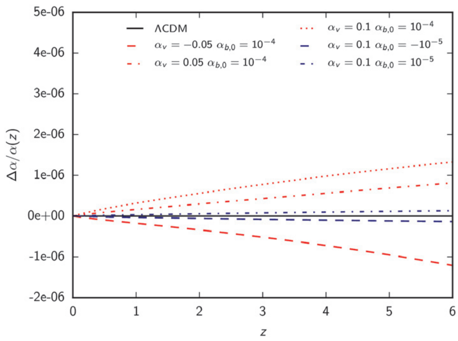

Fig. 2. Redshift dependence of the relative variation of α in the Dark Coupling case for several values of the coupling parameters.

This feature is of particular interest, given the recent hints, from archival Keck and VLT data, of space-time variations of the fine-structure constant discussed in Ref. 9. These data are used to test the dilaton model in Ref. 10 with no significative conclusion, but it is to be expected that further measurements improvement will allow to better constrain this model.

2. E-ELT and Forecasted Data

Following the discussion of the previous section, our interest is focused on the improvement that future measurements of the redshift evolution of α will bring on constraints of the dilaton model. To this purpose we consider an upcoming facility, the European Extremely Large Telescope (E-ELT), equipped with an high-resolution ultra-stable spectrograph currently dubbed ELT-HIRES. This will allow to measure α in approximately 100 QSO systems in the range $0.5 < z < 4$, with a sensitivity $\sigma_\alpha \approx 10^{-7}$;[11] these measurements will naturally complement future local constraints, allowing to reconstruct $\alpha(z)$ with great accuracy and over an extended range of redshifts. In order to understand the impact of these future cosmological observations, we analyze mock E-ELT observations of $\alpha(z)$ as produced in Ref. 3, using 3 different fiducial cosmologies, based on the Planck best fit for the standard cosmological parameters and distinguished by different fiducial values of the dilaton couplings $\alpha_{b,0}$ and α_m:

- $\alpha_{b,0} = 0\,, \alpha_V = 0$ (null case)
- $\alpha_{b,0} = 1 \times 10^{-5}\,, \alpha_V = 0.05$ (weak coupling case)
- $\alpha_{b,0} = 5 \times 10^{-5}\,, \alpha_V = 0.1$ (strong coupling case).

In order to break possible degeneracies between standard parameters and dilaton couplings, we also analyze mock Redshift Drift datasets, see Refs 12-15, as achievable by the E-ELT itself (see e.g. Ref. 16 for related forecasts) and a forecasted SNIa catalogue, which can be obtained by the James Webb Space Telescope in synergy with the HARMONI spectrograph of the E-ELT.[17,18]

3. Results and Conclusions

We fit the theoretical predictions of the dilaton model to the forecasted datasets described in the previous section, We sample five parameters: the baryon and cold dark matter densities $\Omega_b h^2$ and $\Omega_c h^2$, the ratio between the sound horizon and the angular diameter distance at decoupling θ_s, and the runaway dilaton free parameters $\alpha_{b,0}$ and α_V. We adopt flat prior distributions and we reconstruct the posterior distribution of these parameters with an MCMC sampling of the parameter space using the publickly available package `cosmomc`.[19] Our analysis shows that, depending on the values of the dilaton couplings, there are three different regimes for which the E-ELT data will have different impacts; we refer to these as the null case, the weak coupling case and strong coupling case.

In the null case we notice that, in spite of the high sensitivity of the E-ELT on α variations, the constraints provided by this experiment on the coupling parameters only improve upon the prior range we assumed by a factor of a few (see Figure 3). Figure 3 also highlights how a strong degeneracy arises when a ΛCDM fiducial cosmology is used. This behaviour is connected to the dependence of the variation of the fine structure constant on the coupling parameters, indeed setting one of the couplings to zero will reproduce exactly the standard non varying fine structure constant. Moreover, Figure 3 shows that the 3 coupling cases are undistinguishable as they all reduce to the ΛCDM scenario in the same way.

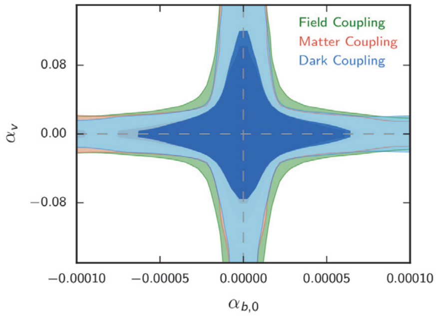

Fig. 3. 68% and 95% c.l. contours in the $\alpha_{b,0}$-α_V plane for null case analyses in the 3 coupling assumptions. The grey dashed lines identify the fiducial values.

Moving to the weak coupling case, the obtained results begin to show a more interesting behaviour; the left panel of Figure 3 shows how a strong degeneracy between the coupling parameters is still present which prevents the improvement on constraints expected by E-ELT. Moreover, as stated in Ref. 3, although the fiducial cosmology assumes positive couplings, negative values of $\alpha_{b,0}$ and α_V are still able to fit the forecasted datasets as, when $\phi(z) << 1$, the variation of α is symmetric for a change of the couplings' sign.[3]

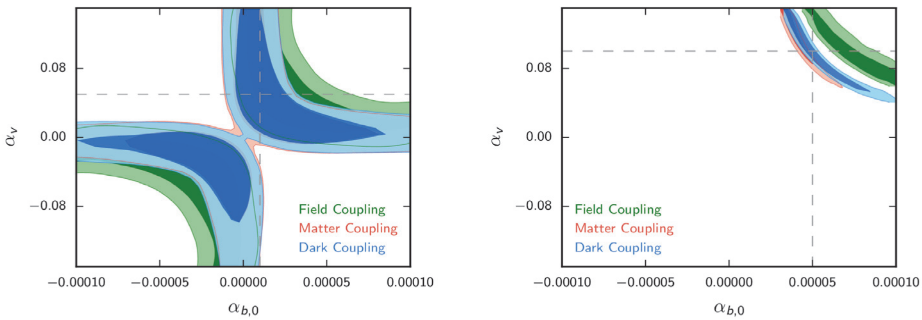

Fig. 4. 68% and 95% contours in the $\alpha_{b,0}$-α_V plane for weak (left panel) and strong (right panel) coupling analyses in the 3 coupling assumptions. The grey dashed lines identify the fiducial values.

This symmetry breaks down in the strong coupling case (see Ref. 3 for more details); this leads to the behaviour observed in the right panel of Figure 3, where the fiducial model can be recovered only with the right sign of the couplings. This result shows how moving away from the ΛCDM fiducial model allows to obtain stronger constraints on the parameters. Moreover, in this extreme fiducial cosmology, the physical difference between the 3 choices for α_m starts to emerge. This effect arises from the fact that while the 3 models produce similar behaviours of the fine structure constant for values of the parameters close to the ΛCDM limit, the differences between them become observable in the strong coupling case.

Given the results presented here, we conclude that E-ELT will be a crucial facility to investigate the runaway dilaton model, but strong constraints can be obtained only when the cosmological model departs significantly from the standard ΛCDM. Should this not be the case, it would be necessary to rely on other observable effects of the dilaton to break the physical degeneracy between the parameters.

In any case, astrophysical tests carried out by the E-ELT will provide an important complement to local equivalence principle tests on a wide range of redshifts.

Acknowledgments

MM acknowledges the DFG TransRegio TRR33 grant on The Dark Universe.

References

1. T. Damour, F. Piazza and G. Veneziano, Phys. Rev. Lett. **89** (2002) 081601
2. T. Damour, F. Piazza and G. Veneziano, Phys. Rev. D **66** (2002) 046007
3. M. Martinelli, E. Calabrese and C. J. A. P. Martins, JCAP **1511** (2015) 11, 030 doi:10.1088/1475-7516/2015/11/030
4. T. A. Wagner *et al.*, Class. Quant. Grav. **29** (2012) 184002
5. B. Bertotti, L. Iess and P. Tortora, Nature **425** (2003) 374
6. J. Müller, F. Hofmann and L. Biskupek, Class. Quant. Grav. **29** (2012) 184006
7. P. A. R. Ade *et al.* [Planck Collaboration], arXiv:1502.01589 [astro-ph.CO]
8. A. R. Neben and M. S. Turner, Astrophys. J. **769** (2013) 133
9. J. Webb et al., Phys.Rev.Lett. **107** (2011) 1911901
10. C. J. A. P. Martins *et al.*, Phys. Lett. B **743** (2015) 377
11. J. Liske *et al.*, Document ESO 204697 Version 1 (2014)
12. A. Sandage, Ap.J. 136, 319-33 (1962)
13. A. Loeb, Astrophys. J. **499** (1998) L111
14. P. S. Corasaniti, D. Huterer and A. Melchiorri, Phys. Rev. D **75** (2007) 062001
15. C. Quercellini *et al.*, Phys. Rept. **521** (2012) 95
16. M. Martinelli *et al.*, Phys. Rev. D **86** (2012) 123001
17. A. G. Riess and M. Livio, Astrophys. J. **648** (2006) 884
18. N. A. Thatte *et at.*, SPIE 9147 (2014) 914725.
19. A. Lewis and S. Bridle, Phys. Rev. D **66** (2002) 103511