Probing dark energy beyond z=2 with CODEX

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Based on:

- P.E. Vielzeuf and C. J. A. P. Martins , Phys. Rev. D85, 087301 (2012)
- Rodger. I. Thompson, C.J.A.P. Martins and P. E. Vielzeuf, Mon. Not. R. Astron. Soc. 000, 19(2011) A
- Matteo Martinelli, Stefania Pandol, C. J. A. P. Martins, P. E. Vielzeuf, arXiv:1210.7166

Table of contents

- Ultrastable optical high-resolution spectrograph for the E-ELT (phase A).
- Abilities of interest :
  - Perform a direct measurement of the accelerating expansion of the universe.
  - Test the stability of fundamental constants.
  - Measurement of the CMB temperature

Accuracy expected (from DRM):

$$\sigma_{\Delta v} = 1.35 \times \left(\frac{S/N}{2370}\right)^{-1} \left(\frac{N_{QSO}}{30}\right)^{-1/2} \left(\frac{1+z_{QSO}}{5}\right)^{-1.7}$$

$$\sigma_{\Delta\alpha} \sim \mathrm{few} \times 10^{-8}$$

$$\sigma_{\Delta T} \sim 0.07K$$

From the redshift to the velocity drift

- The evolution of the Hubble expansion causes the redshifts of distant objects to change slowly with time:

$$\Delta z = \Delta t_0 \times H_0 \times \left[1 + z_s - \frac{H(z)}{H_0}\right]$$

- Relation with the spectropic velocity

$$\Delta v = c \times \frac{\Delta z_s}{(1 + z_s)}$$

Complementary with Planck

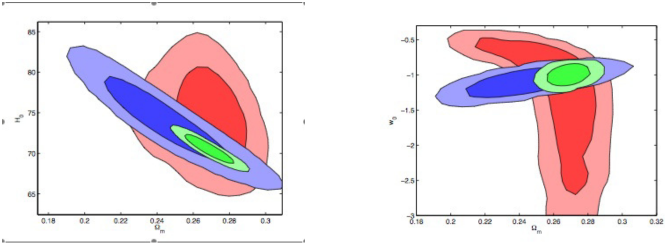


Figure: 2-D constraints on H_0 and Ω_m (left) and on w_0 and Ω_m(right) using CMB (blue), SL (red) and combining the two probes (green).

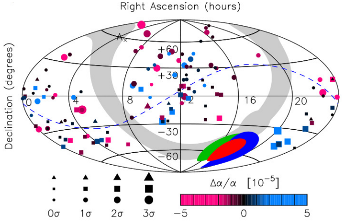
- Using SL together with CMB will break the degeneracies between cosmological parameters and will improve the constraints.(Martinelli et al 2012)

Fine structure constant & Proton-to-electron mass ratio

- Fine-structure constante:

$$\alpha = \frac{e^2}{\hbar c}$$

- Webb et al (2011) :



- Proton-to-electron mass ratio:

$$\mu = \frac{m_p}{m_e}$$

- Previous measurements: So far, there are no evidence of variation of μ

Object	Redshift	$\Delta\mu/\mu$	Error	$(w+1)\zeta_\mu^2$	Accuracy	Reference
Q0347−383	3.0249	2.1×10^{-6}	$\pm 6.0 \times 10^{-6}$	$\leq 3.8 \times 10^{-11}$	1σ	Wendt & Reimers (2008)
Q0405−443	2.5974	10.1×10^{-6}	$\pm 6.2 \times 10^{-6}$	$\leq 4.0 \times 10^{-11}$	1σ	King et al. (2009)
Q0528−250	2.811	3.0×10^{-7}	$\pm 3.7 \times 10^{-6}$	$\leq 1.4 \times 10^{-11}$	1σ	King et al. (2011)
J2123−005	2.059	5.6×10^{-6}	$\pm 6.2 \times 10^{-6}$	$\leq 4.0 \times 10^{-11}$	1σ	Malec et al. (2010)
PKS 1830−211	0.89	0.0	$\pm 6.3 \times 10^{-7}$	$\leq 6.5 \times 10^{-13}$	3σ	Ellingsen et al. (2012)
B0218+357	0.6847	0.0	$\pm 3.6 \times 10^{-7}$	$\leq 2.8 \times 10^{-13}$	3σ	Kanekar (2011)

Link to Dark Energy

- Asumption: Dark energy and varying constants are due to the same dynamical field:

$$\frac{\Delta\alpha}{\alpha} = \frac{\alpha - \alpha_0}{\alpha_0} = \xi\kappa(\Phi - \Phi_0)$$

- If the variation of the couplings is driven by a dilaton-type scalar field and that unification occurs at some unspecified high energy scale (Nunes and Lidsey 2004) :

$$\frac{\dot{\mu}}{\mu} \approx \frac{\dot{\Lambda}_{QCD}}{\Lambda_{QCD}} - \frac{\dot{\nu}}{\nu} \approx \chi\frac{\dot{\alpha}}{\alpha}$$

- The evolution of the scalar field can be expressed as:

$$w + 1 = \frac{(\kappa\Phi')^2}{3\Omega_\Phi}$$

- Hence the evolution of α can be written as:

$$\frac{\Delta\alpha}{\alpha} = -\xi \int \sqrt{3\Omega(a)(1 + w(a))}\mathrm{dln}a$$

CMB temperature

- Adiabatic expansion:

$$T = T_0(1+z)$$

  - This relation is violated if photons couple to scalar or pseudo-scalar degrees of freedom; a simple parametrization is:

$$T(z) = T_0(1+z)^{1-\beta}$$

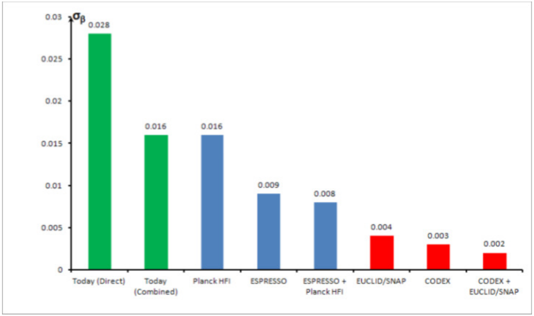


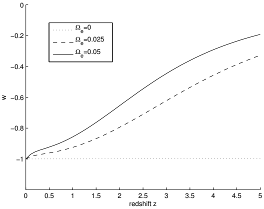
Figure: Current constraints on β (Avgoustidis et al 2012)

Early Dark Energy: Sandage-Loeb

- Model assumption: Dark energy remains a significant fraction of the universes energy density .(Doran and Robbers 2006)

$$\Omega_{de}(a) = \frac{\Omega^0_{de} - \Omega_e(1 - a^{-3w_0})}{\Omega^0_{de} + \Omega^0_m a^{3w_0}} + \Omega_e(1 - a^{-3w_0})$$

$$w(a) = -\frac{1}{3(1 - \Omega_{de}(a))} \frac{d\ln\Omega_{de}(a)}{d\ln(a)} + \frac{a_{eq}}{3(a + a_{eq})}$$



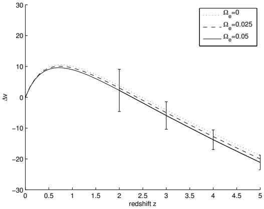


Figure: Equation of state (left) and SL signal (right) for different values of the parameter Ω_e , and for an observation time of $\Delta t = 20$ years, with the vertical bars being the CODEX measurement accuracy expected

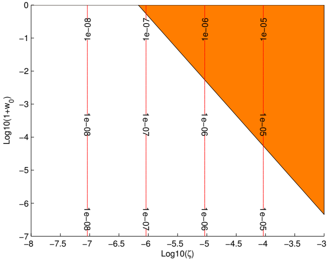


Figure: The relative variation of the fine-structure constant, $\frac{\Delta\alpha}{\alpha}$, at redshift z $= 4$, as a function of ξ and w_0 , with $\Omega_e = 0.05$. The shaded region is the local atomic bound of equation : $\xi\sqrt{3\Omega_{\Phi,0}(1+w_0)} < 10^{-6}$

- Joining S-L and α measurements can constrain this class of model.

Slow-rolling Quintessence

- Class of a slow rolling freezing or thawing quintessence fields.

$$1 + w = \frac{1}{3}\lambda_0^2 \left[\frac{1}{\sqrt{\Omega_\Phi}} - \left(\frac{1}{\Omega_\Phi} - 1 \right) \left(\tanh^{-1} \left(\sqrt{\Omega_\phi} \right) + C \right) \right]^2$$

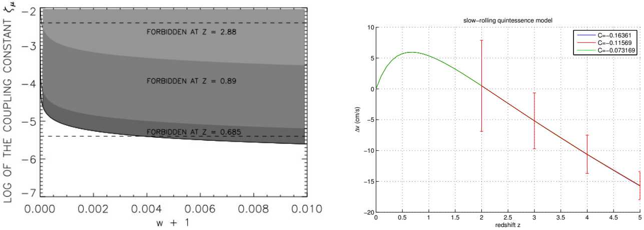


Figure: Upper limit on μ variations (left) and Sandage-Loeb test (right) for different values of the parameter C, with λ_0 fixed at 0.08, for an observational time interval $\Delta t = 30$ years.

- Assuming slow-roll extends in the matter era, SL test can't distinguish these models from ΛCDM(but more precise α or μ measurements might)

- Model assumptions:
    - The Dark energy is due to a cosmological constant.
    - Variation of α is due to some other field with negligible contribution to the universe energy density:

$$\frac{\Delta\alpha}{\alpha} = -4\epsilon \ln(1+z)$$

- If one wrongly assumes that the dark energy is due to the α-field and reconstruct the equation of state (Nunes and Lidsey 2004):

$$w(N) = (\lambda^2 - 3)\left[3 - \frac{\lambda^2}{w_0}\frac{\Omega_{m,0}}{\Omega_{\Phi,0}} exp^{(\lambda^2-3)N}\right]^{-1}$$

with (N=ln(1+z)) and $\lambda = \sqrt{3\Omega_{\Phi,0}(1+w_0)} = 4\frac{\epsilon}{\xi}$

BSBM results: Sandage-Loeb signal

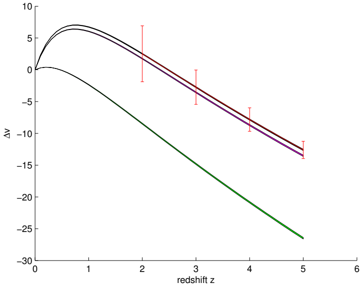


Figure: The SL test for reconstructed BSBM models with $\lambda = 1$ (bottom band) and $\lambda = 0.3$, compared to the standard ΛCDM case (top band). The bands correspond to the range of $\Omega_{\Phi,0} = 0.73 \pm 0.01$.

- Small λ correspond to large couplings this will be detectable by Equivalence Pripnle tests.
- Large λ produce a SL signal that CODEX can easily distinguish from $\Lambda\mathrm{CDM}$.
- In both cases, inconsistent assumptions would be detected.

BSBM results: CMB temperature correction

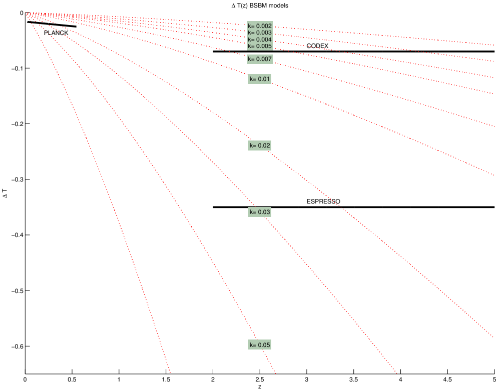


Figure: Variation of the temperature (relative to the standard model) as function of redshift in a BSBM-like class of models, for different values of k and using $T_0 = 2.725 \pm 0.002$. Also depicted are the limits of detection of this difference with CODEX, ESPRESSO and Planck clusters. The span of each bar is meant to represent the redshift range of each set of measurements.

Conclusion

- We illustrated with examples the abilities of CODEX to probe the nature of Dark Energy in the otherwise unexplored redshift range $2 < z < 5$.
- Being able to simultaneously carry out the SL test and precision tests of the standard model (measurements of fundamental constants and CMB temperature) gives CODEX an unique advantage.
- We also highlighted how Sandage-Loeb observations alongside CMB data can break degeneracies between different parameters.
- Synergies with EUCLID and ALMA are currently being explored.

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