Cosmological constraints on a simple model for varying alpha

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Introduction

On the variation of fundamental parameters

- Dirac (Large Number hypothesis), Jordan (Lagrangian formulation), Dicke (violation of UFF)
- In the standard model of particle physics, interactions are associated with fundamental couplings: α, α_w, α_s, α_G
- Variation with the energy scale and spacetime variation motivated in a number of theories
- The fine-structure constant defines the strength of the electromagnetic interaction: $\alpha = \frac{1}{4\pi\epsilon_0} \frac{e^2}{\hbar c} \approx \frac{1}{137}$
- Variation of α constrained by many physical systems, directly with spectroscopic methods

(Uzan 2011)

Constraints on the variation of α

- Sharp constraints obtained on α current drift rate by comparing atomic clocks: $(\dot{\alpha}/\alpha)_0 = (1.0 \pm 1.1) \times 10^{-18}/\text{yr}$ *Lange et al. (2021)*

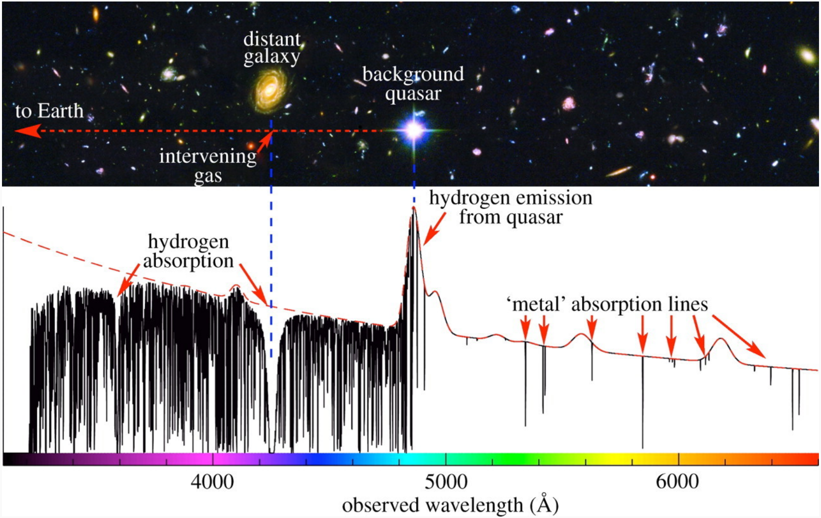
- QSO as main tool to constrain the variation of α at large redshifts (look-back-time)

- Measure of the relative shifts between metal transitions in intervening absorption systems

- Many-Multiplet method *(Dzuba et al. 1999a,b and Webb et al. 1999)*

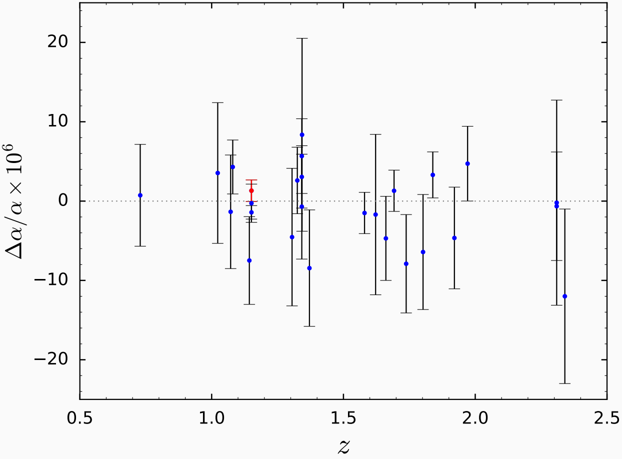
- Even null results are useful to test cosmological models with varying α *(see Martins 2017)*

Quasar absorption line spectroscopy



Webb & Murphy

Astrophysical results on the stability of α



First precise ESPRESSO measurement *(Murphy et al. 2022)*:
$\Delta\alpha/\alpha = 1.31 \pm 1.36$ ppm at redshift $z = 1.15$

Theoretical model for varying α

Description of the cosmological model

- Scalar field ϕ accounting for dark energy

- coupled to the electromagnetic field

$$S = -\frac{1}{2\kappa^2}\int R\sqrt{-g}\,d^4x + \int\left(\mathcal{L}_M + \mathcal{L}_\phi + \mathcal{L}_{\phi F}\right)\sqrt{-g}\,d^4x\,,$$

$$\mathcal{L}_\phi = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V\left(\phi\right)\,,$$

$$\mathcal{L}_{\phi F} = -\frac{1}{4}B_F\left(\phi\right)F_{\mu\nu}F^{\mu\nu}\,,$$

$$\alpha\left(\phi\right) \propto B_F^{-1}\left(\phi\right)\,.$$

Choice of the parametrisation

Taylor expansion at first order

$$B_F(\phi) = 1 - \zeta\kappa(\phi - \phi_0)$$

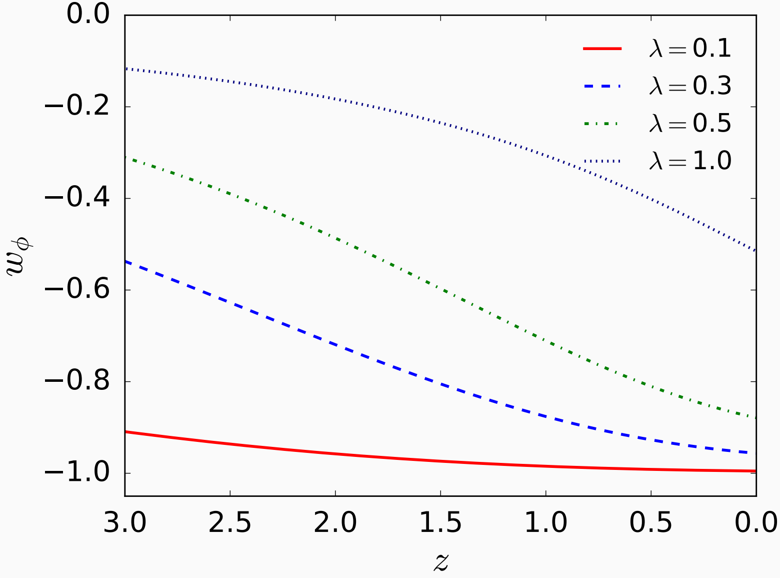
Nunes&Lidsey (2004)

$$\begin{aligned} \kappa\phi' = \lambda \qquad & \Rightarrow \\ \kappa(\phi - \phi_0) &= -\lambda\ln(1+z) \\ V(\phi) &= A\,e^{-\frac{3}{\lambda}\kappa\phi} + B\,e^{-\lambda\kappa\phi} \end{aligned}$$

Theoretical variation of α

$$\frac{\Delta\alpha}{\alpha} = -\zeta\lambda\ln(1+z)$$

Diversity of possible dark energy evolution



Observational constraints

Observational data

- QSO dataset $\Delta\alpha/\alpha = -\zeta\lambda\ln(1+z)$
- Atomic clocks $(\dot{\alpha}/\alpha)_0 = \zeta\lambda H_0$
- MICROSCOPE $\eta \approx 10^{-3}\zeta^2$

  $\eta = (-0.1 \pm 1.3) \times 10^{-14}$

  Touboul et al. (2019)
- Planck prior CMB distance prior on λ

Likelihood analysis

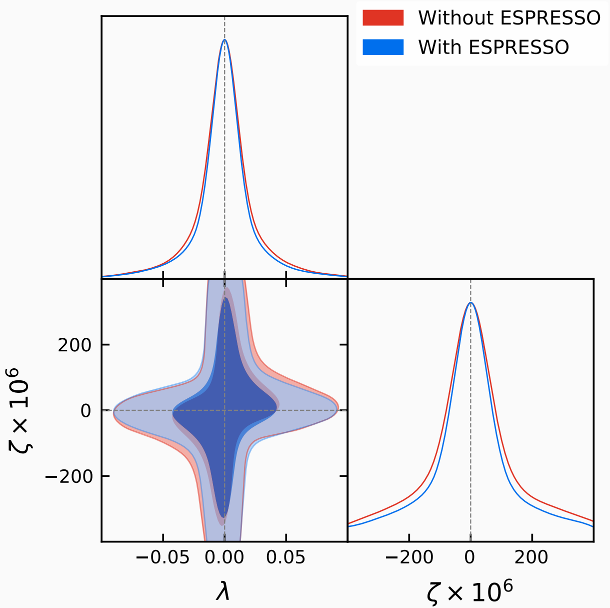
$$\ln \mathcal{L}_{\mathrm{QSO}} = -\frac{1}{2} \sum_i \frac{1}{\sigma_i^2} \left[\left.\frac{\Delta\alpha}{\alpha}\right|_{\mathrm{th}} (z_i) - \left.\frac{\Delta\alpha}{\alpha}\right|_{\mathrm{obs}} (z_i) \right]^2 ,$$

$$\ln \mathcal{L}_{\mathrm{clocks}} = -\frac{1}{2} \frac{\left[\left(\frac{\dot\alpha}{\alpha}\right)_0 \Big|_{\mathrm{th}} - \left(\frac{\dot\alpha}{\alpha}\right)_0 \Big|_{\mathrm{obs}} \right]^2}{\sigma^2} ,$$

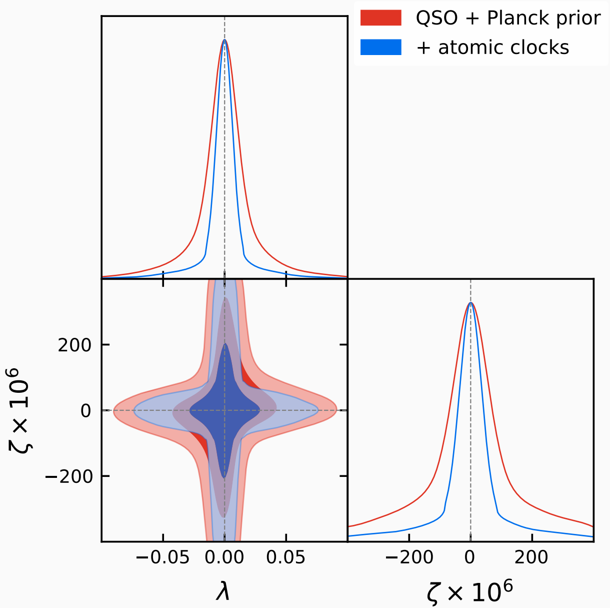
$$\ln \mathcal{L}_{\mathrm{MICROSCOPE}} = -\frac{1}{2} \frac{\left(\eta_{\mathrm{micro}} - \eta\right)^2}{\sigma^2} ,$$

$$\ln \mathcal{L}_{\mathrm{cmb}} = -\frac{1}{2} \left(\nu - \nu_{\mathrm{cmb}}\right)^\top C_{\mathrm{cmb}}^{-1} \left(\nu - \nu_{\mathrm{cmb}}\right) ,$$

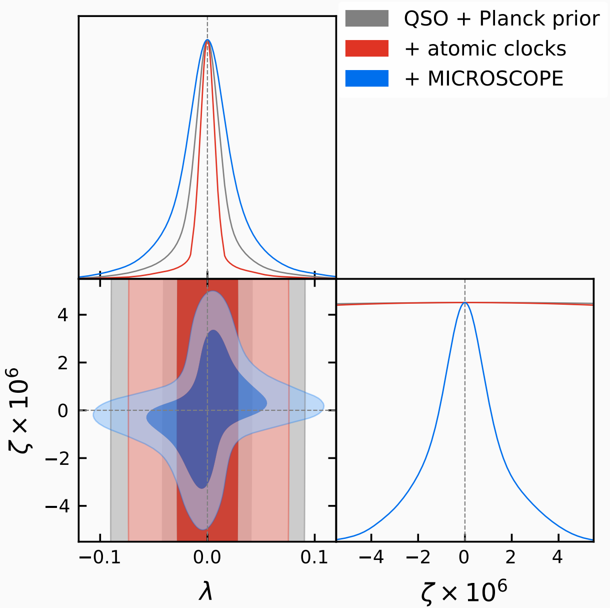
ESPRESSO constraining power



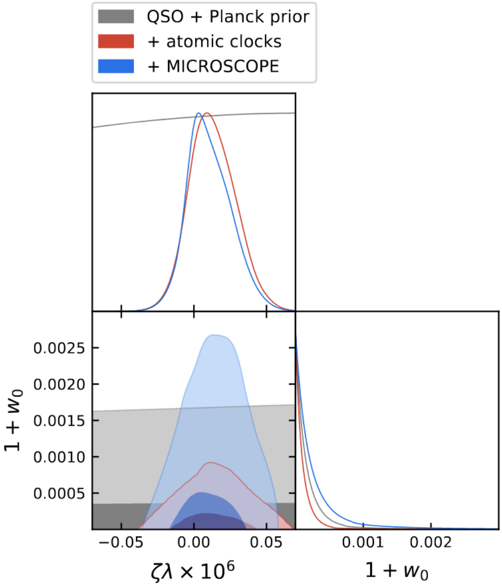
QSO vs Atomic clocks



Domination of the MICROSCOPE bound



Constraints on the equation of state



Conclusions

Main results

- Astrophysical probes and local tests to constrain dark energy models with varying α
- Simple parametrisation with two additional free parameters
- λ constraints compatible with Λ, loosening the constraints on ζ
- ESPRESSO improves the astrophysical limits on ζ but local constraints largely dominate
- $\zeta = 0.0 \pm 1.6$ ppm
- ESPRESSO essential to probe the large redshift regime not accessible otherwise
- Models departing from this simple parametrisation to be considered