Varying α through the dynamics of dark energy

CosmoVerse@Lisbon

Vitor da Fonseca in collaboration with Bruno J. Barros

1 June 2023

arXiv: 2209.12189

instituto de astrofísica e ciências do espaço

Ciências ULisboa

Fundação para a Ciência e a Tecnologia

On the variation of the fine-structure constant

$$\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} \approx \frac{1}{137}$$

- Are fundamental couplings spacetime-invariant?
- Running with energy
- Extensions of the standard model of particle physics
- Probed with spectroscopic techniques:
  - atomic clocks experiments
  - quasar absorption spectra
- Test of cosmological models predicting redshift dependence
- Can the variation of α tackle the Hubble tension?

See Martins (2017) arXiv: 1709.02923

The model for varying α

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{1}{2\kappa^2}R + \mathcal{L}_\phi - \frac{1}{4}h(\phi, X)F_{\mu\nu}F^{\mu\nu} - A^\mu j_\nu\right] + \mathcal{S}_m$$

- $\phi(x^\mu)$ coupled to $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$ through $h(\phi, X)$

where

$$X = -\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

- Variability of the fine-structure constant: $\alpha \propto h^{-1}$

- Equations of motion of the electromagnetic fields:

$$\nabla_\mu F^{\mu\nu} = \frac{1}{h}j^\nu + \left(\frac{h_X}{h}\partial_\alpha\phi\nabla_\mu\partial^\alpha\phi - \frac{h_\phi}{h}\nabla_\mu\phi\right)F^{\mu\nu}$$

Disformal transformations and Gordon metric

$$\mathcal{S}_{em} = \int d^4x\sqrt{-\tilde{g}}\Big(\tilde{g}^{\mu\alpha}\tilde{g}^{\nu\beta}F_{\mu\nu}F_{\alpha\beta}\Big)$$

$$\tilde{g}_{\mu\nu} = C(\phi, X)g_{\mu\nu} + D(\phi, X)\partial_\mu\phi\partial_\nu\phi$$

Comparing the two frameworks:

$$\alpha \propto \sqrt{1 - \frac{2DX}{C}} = \frac{1}{h}$$

therefore

$$\tilde{g}_{\mu\nu} = Cg_{\mu\nu} + \frac{C}{2X}\left(1 - \frac{1}{h^2}\right)\partial_\mu\phi\partial_\nu\phi$$

$$\tilde{g}_{\mu\nu} \propto g_{\mu\nu} + \left(1 - \frac{1}{h^2}\right)u_\mu u_\nu$$

$$u_\mu = \frac{\partial_\mu\phi}{\sqrt{2X}}$$

Analogue gravity and susceptibilities

The scalar field can be seen as a linear medium in motion with refractive index h through which light propagates.

$$\nabla_\mu F^{\mu\nu} = \frac{1}{h} j^\nu + \left(\frac{h_X}{h} \partial_\alpha \phi \nabla_\mu \partial^\alpha \phi - \frac{h_\phi}{h} \nabla_\mu \phi \right) F^{\mu\nu}$$

Gauss and Ampère's laws

$$\nabla \cdot \mathsf{E} = \rho - \nabla \cdot \mathsf{P}$$

$$\nabla \times \mathbf{B} - \frac{\partial \mathsf{E}}{\partial t} = \mathbf{J} + \nabla \times \mathbf{M} + \frac{\partial \mathsf{P}}{\partial t}$$

where

$$\mathsf{P} = (h-1)\,\mathsf{E}$$

$$\partial_t \mathbf{P} = (h-1)\,\partial_t \mathsf{E} + \dot{\phi}(h_\phi + \ddot{\phi} h_X)\mathsf{E}$$

$$\mathbf{M} = (1-h)\mathbf{B}$$

in the scalar medium

$$\nabla \cdot \mathbf{D} = \rho$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathsf{D}}{\partial \mathbf{t}}$$

where

$$\mathsf{D} = \mathsf{E} + \mathsf{P}$$

$$\mathsf{H} = \mathsf{B} - \mathsf{M}$$

$$\mathbf{M} = (-1 + 1/h)\mathbf{H}$$

Interacting scalar field as quintessence

Choice for the scalar field

$$\mathcal{L}_\phi = X - V$$

$$\Box\phi - V_\phi = \frac{1}{4} h_\phi F_{\alpha\beta} F^{\alpha\beta} + \frac{1}{4} \nabla_\mu \left(h_X F_{\alpha\beta} F^{\alpha\beta} \nabla^\mu \phi \right)$$

$$\kappa \left(\phi - \phi_0 \right) = \lambda \ln a$$

arXiv:astro-ph/0310882

Choice for the interaction

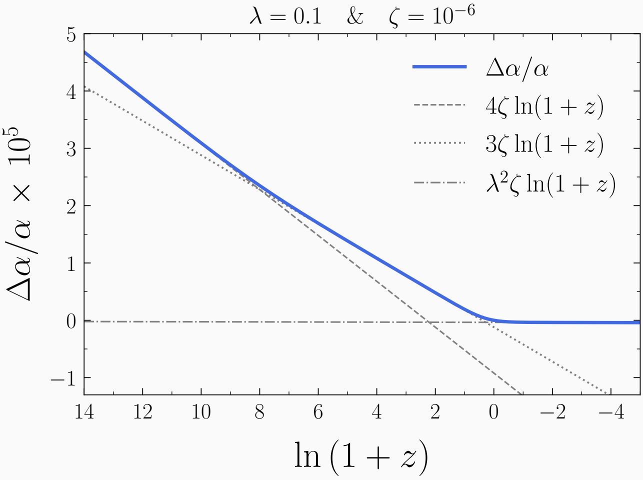
$$h(X) = \left(\frac{X_0}{X} \right)^\zeta$$

arXiv:1901.03972 and arXiv:2207.13682

$$\Rightarrow \frac{\Delta\alpha}{\alpha} = \left(\frac{H^2}{H_0^2} \right)^\zeta - 1$$

$$= \left[\frac{4\Omega_r^0}{4 - \lambda^2} a^{-4} + \frac{3\Omega_m^0}{3 - \lambda^2} a^{-3} + C_\phi a^{-\lambda^2} \right]^\zeta - 1$$

Cosmological variation of α



ζ and λ poorly correlated outside dark energy domination

Observational data

Constraining $\Delta\alpha/\alpha$

- Early universe: CMB 2018 Planck data ($z = 1100$)
- Astrophysical data: QSO absorption spectra 26 $\Delta\alpha/\alpha$ dedicated measurements ($0.5 < z < 2.5$)
- Earth based experiment: Atomic clocks measurements ($z = 0$) *Lange et al. (2021)*

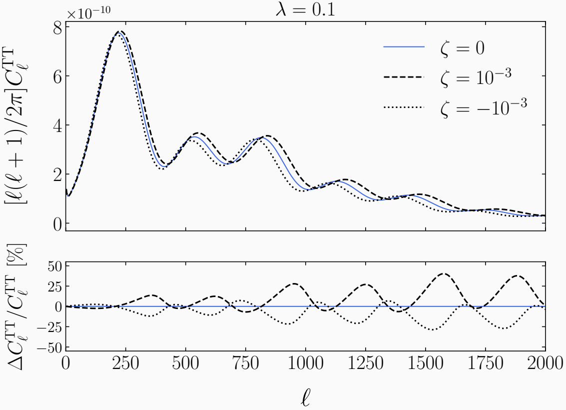
Constraining cosmological parameters ($0.01 < z < 2.3$)

- Supernovae Type Ia: Pantheon sample
- Prior on H_0: SH0ES collaboration

Angular power spectrum observable

Modification of the ionization history

$$\theta_s = \frac{r_s(z_*)}{d_A(z_*)}$$

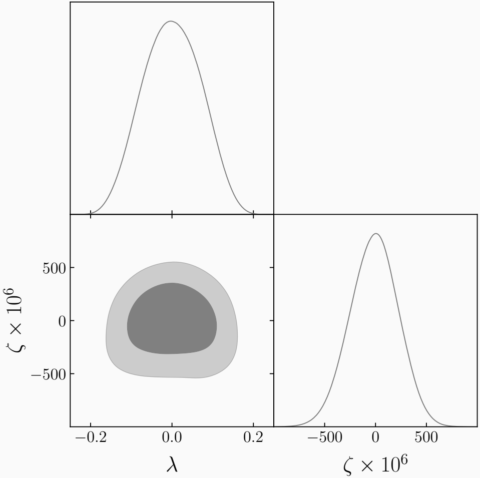


CMB constraints

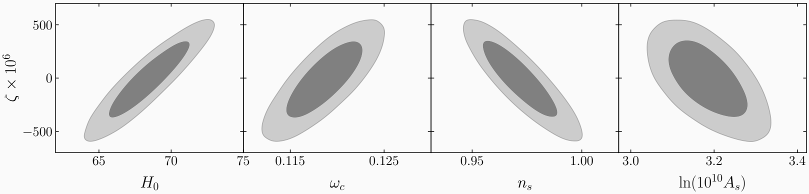
$$\zeta = -15 \pm 240 \text{ ppm}$$
$$\lambda = 0.000 \pm 0.071$$

$\Delta\alpha/\alpha \approx 20\zeta$ at $z = 1100$

Existing constraints
arXiv:1705.03925
$\Delta\alpha/\alpha = (-0.7 \pm 2.5) \times 10^{-3}$

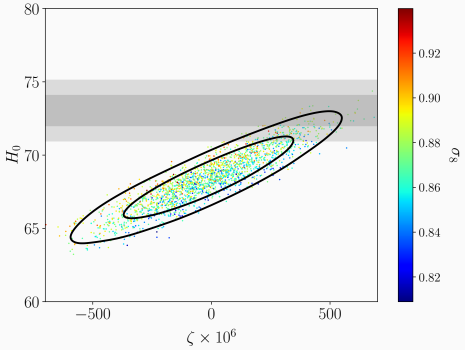


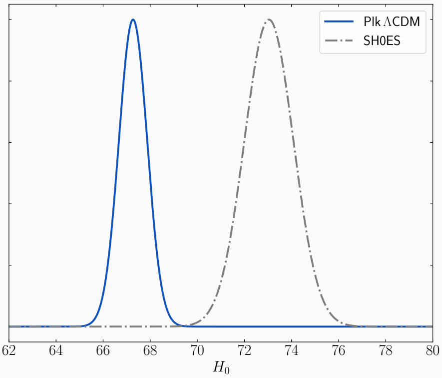
Examples of degeneracies with cosmological parameters



Interplay between ζ and other cosmological parameters influencing the amplitude or the position of the CMB acoustic peaks

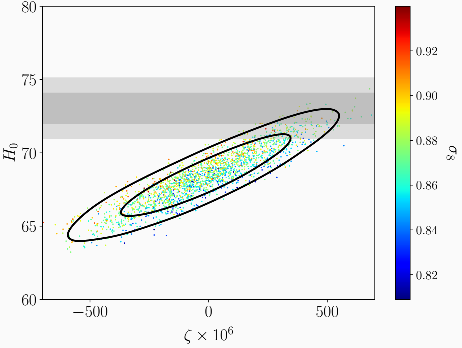
What about the Hubble tension?

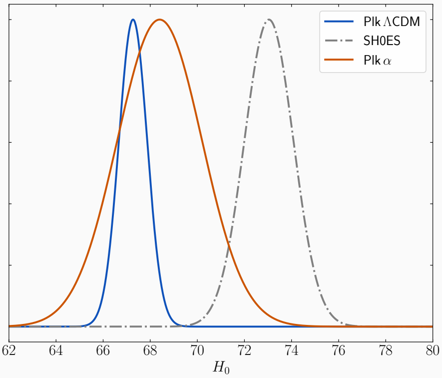




Tension $\sim 4.8\sigma$

What about the Hubble tension?



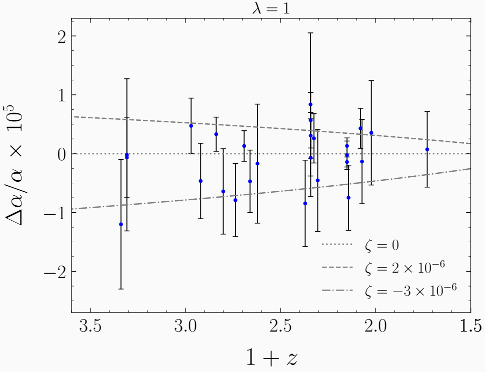


Tension $\sim 4.8\sigma$ vs. $\sim 2.2\sigma$

QSO observable

Homogeneous sample of measurements

- VLT/UVES
- Keck/HIRES
- Subaru/HDS
- VLT/ESPRESSO

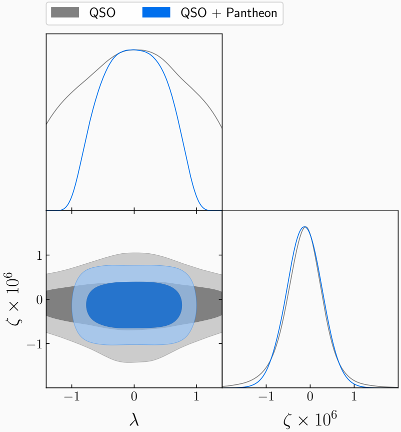


QSO constraints

$$\zeta = -0.13 \pm 0.41 \text{ ppm}$$

$$\lambda = 0.00 \pm 0.47$$

$\Delta\alpha/\alpha \approx 3\zeta \ln(1+z)$
at $0.5 < z < 2.5$

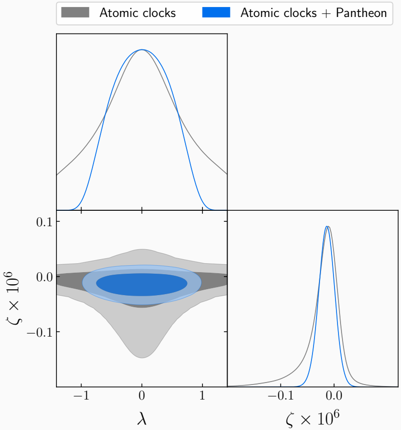


Atomic clocks constraints

$$\zeta = -0.014 \pm 0.015 \text{ ppm}$$
$$\lambda = 0.00 \pm 0.44$$

$$\left.\frac{\dot{\alpha}}{\alpha}\right|_0 = -\zeta H_0 \left(\lambda^2 + 3\Omega_m^0 + 4\Omega_r^0\right)$$
$$= (1.0 \pm 1.1) \times 10^{-18} \text{ yr}^{-1}$$

arXiv:2010.06620



Concluding remarks

Data	ζ (ppm)	λ
Planck	-15 ± 240	0.000 ± 0.071
QSO + Pantheon	-0.13 ± 0.41	0.00 ± 0.47
Atomic clocks + Pantheon	-0.014 ± 0.015	0.00 ± 0.44

- Quasar constraint consistent with WEP tests ($z = 0$)
- Same order as strongest BBN bound ($z \sim 4 \times 10^8$)
- Espresso and Andes to improve the constraints at large redshifts
- α only plays a marginal role for solving the Hubble tension
- m_e as a more promising avenue?