

# Varying $\alpha$ through the dynamics of dark energy

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[arXiv: 2209.12189](https://arxiv.org/abs/2209.12189)



# 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  $\alpha$  tackle the Hubble tension?

See Martins (2017) [arXiv: 1709.02923](https://arxiv.org/abs/1709.02923)

## The model for varying $\alpha$

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

- $\phi(x^\mu)$  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

$$\mathcal{S}_{em} = \int d^4x \sqrt{-\tilde{g}} \left( \tilde{g}^{\mu\alpha} \tilde{g}^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} \right)$$
$$\tilde{g}_{\mu\nu} = C(\phi, X) g_{\mu\nu} + D(\phi, X) \partial_\mu \phi \partial_\nu \phi$$

Comparing the two frameworks:

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

therefore

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

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

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

# 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

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

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

where

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

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

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

in the scalar medium

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

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

where

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

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

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

# Interacting scalar field as quintessence

## Choice for the scalar field

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

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

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

[arXiv:astro-ph/0310882](https://arxiv.org/abs/astro-ph/0310882)

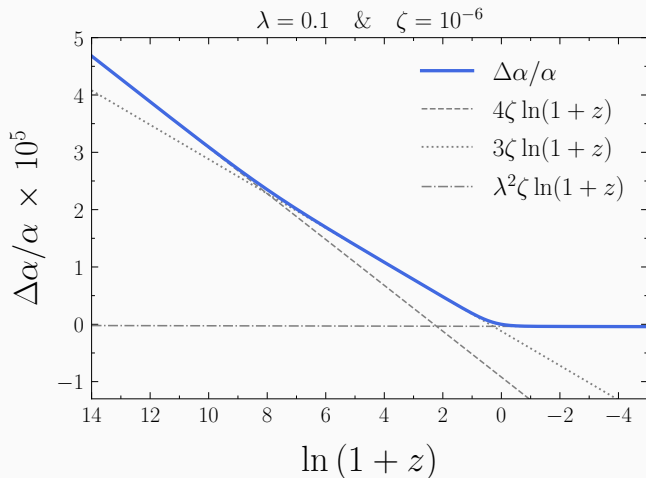
## Choice for the interaction

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

[arXiv:1901.03972](https://arxiv.org/abs/1901.03972) and [arXiv:2207.13682](https://arxiv.org/abs/2207.13682)

$$\begin{aligned}\Rightarrow \frac{\Delta\alpha}{\alpha} &= \left(\frac{H^2}{H_0^2}\right)^\zeta - 1 \\ &= \left[\frac{4\Omega_r^0}{4-\lambda^2} a^{-4} + \frac{3\Omega_m^0}{3-\lambda^2} a^{-3} + C_\phi a^{-\lambda^2}\right]^\zeta - 1\end{aligned}$$

# Cosmological variation of $\alpha$



$\zeta$  and  $\lambda$  poorly correlated outside dark energy domination

## 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 ( $0.01 < z < 2.3$ )

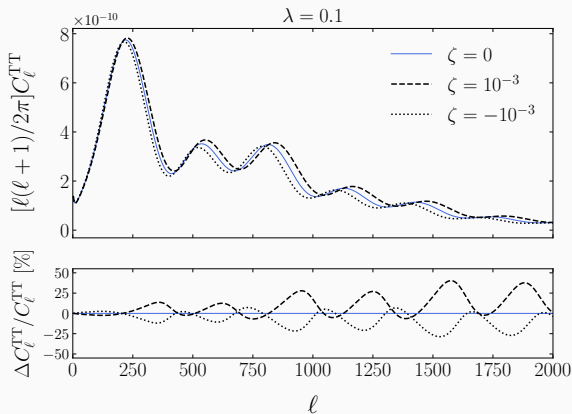
- Supernovae Type Ia: **Pantheon** sample
- Prior on  $H_0$ : **SH0ES** collaboration



# Angular power spectrum observable

Modification of the ionization history

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



# CMB constraints

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

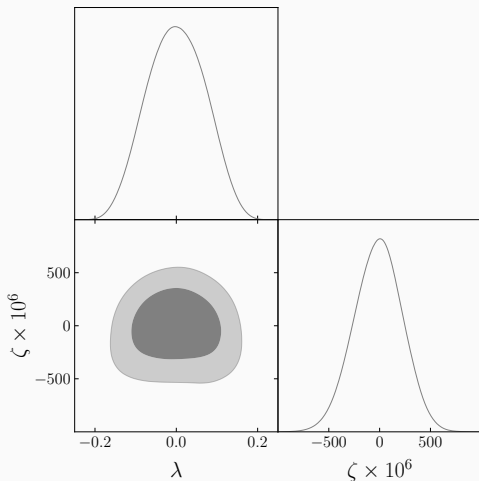
$$\lambda = 0.000 \pm 0.071$$

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

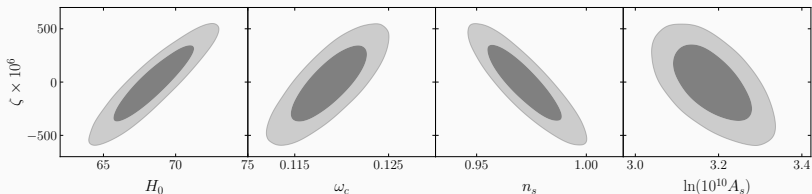
Existing constraints

[arXiv:1705.03925](https://arxiv.org/abs/1705.03925)

$$\Delta\alpha/\alpha = (-0.7 \pm 2.5) \times 10^{-3}$$

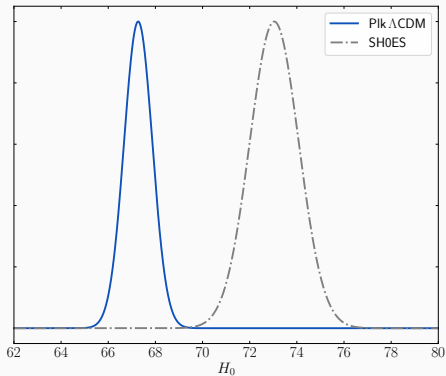
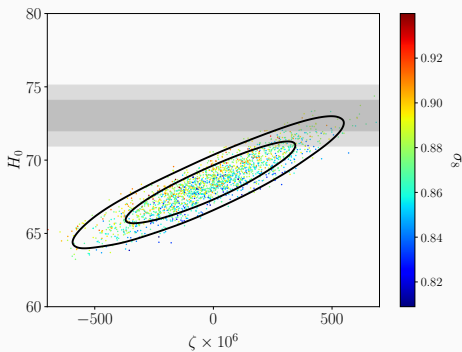


# Examples of degeneracies with cosmological parameters



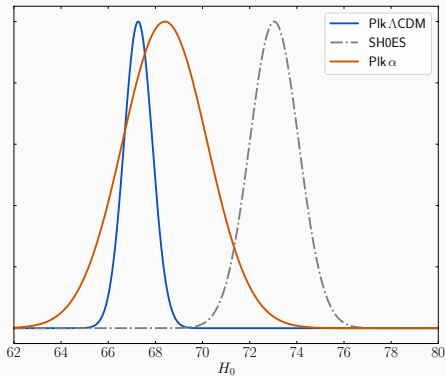
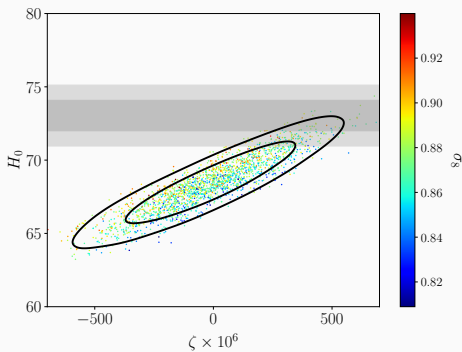
Interplay between  $\zeta$  and other cosmological parameters influencing the amplitude or the position of the CMB acoustic peaks

# What about the Hubble tension?



Tension  $\sim 4.8\sigma$

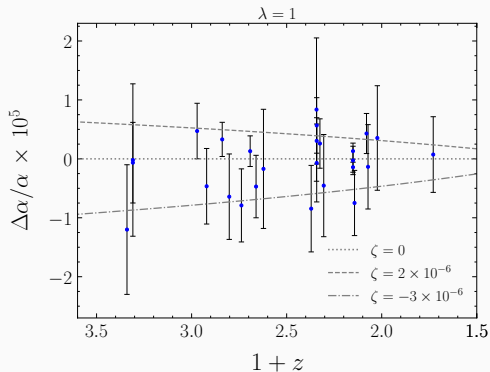
# What about the Hubble tension?



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

Homogeneous sample of measurements

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



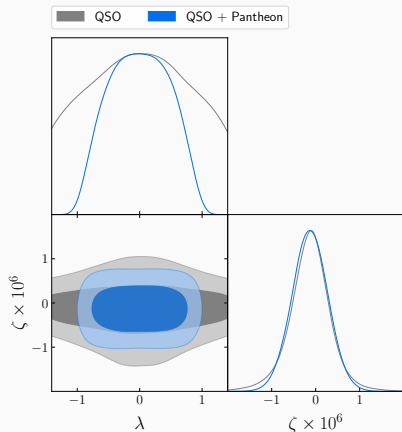
# QSO constraints

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

$$\lambda = 0.00 \pm 0.47$$

$$\Delta\alpha/\alpha \approx 3\zeta \ln(1+z)$$

at  $0.5 < z < 2.5$



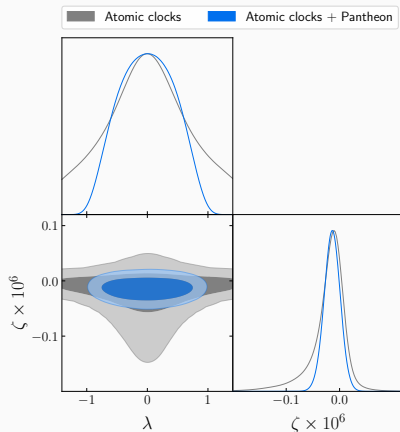
# Atomic clocks constraints

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

$$\lambda = 0.00 \pm 0.44$$

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

arXiv:2010.06620





## Concluding remarks

Data	$\zeta$ (ppm)	$\lambda$
Planck	$-15 \pm 240$	$0.000 \pm 0.071$
QSO + Pantheon	$-0.13 \pm 0.41$	$0.00 \pm 0.47$
Atomic clocks + Pantheon	$-0.014 \pm 0.015$	$0.00 \pm 0.44$

- 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
- $\alpha$  only plays a marginal role for solving the Hubble tension
- $m_e$  as a more promising avenue?