Generalizing models with variations of the fine-structure constant driven by scalar fields: extended Bekenstein model coupled to the dark sector

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Motivation

Beyond ΛCDM

Scalar fields

Alternative description of DE

Consistent theories of variable fundamental constants

Original Bekenstein Model

Is the fine-structure constant really a constant?

$$e = e_0 \epsilon(X^\mu)$$

$$\epsilon A_\mu \to \epsilon A_\mu + \partial_\mu \chi$$

$$\mathcal{L}_{EM} \propto \epsilon^{-2} f_{\mu\nu} f^{\mu\nu}$$

→

$$\alpha = \alpha_0 \epsilon^2$$

Jacob D. Bekenstein. "Fine-structure constant: Is it really a constant?" In: Phys. Rev. D 25 (6 Mar. 1982), pp. 1527–1539. DOI: 10.1103/PhysRevD.25.1527.

Original vs Generalized Bekenstein Model

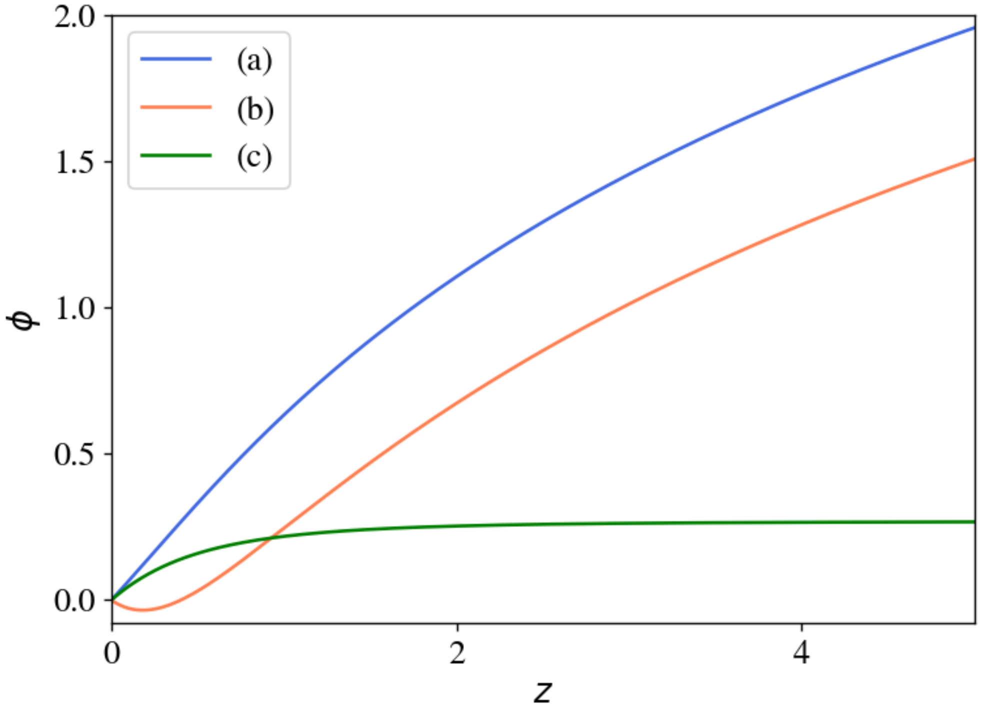
$$\mathcal{L}_{EM} \propto \epsilon^{-2} f_{\mu\nu} f^{\mu\nu}$$

→

$$\mathcal{L}_{EM} \propto B_F(\phi) f_{\mu\nu} f^{\mu\nu}$$

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{2} M_{pl}^2 R + \frac{1}{2} M_*^2 \partial_\mu \phi \partial^\mu \phi - M_{pl}^2 \Lambda_0 B_\Lambda(\phi) - \frac{1}{4} B_F(\phi) F_{\mu\nu} F^{\mu\nu} + \right.$$
$$\left. + \bar{\psi} \left(i\gamma^\mu D_\mu - m_\psi B_\psi(\phi) \right) \psi + \bar{\chi} \left(i\gamma^\mu D_\mu - M_\chi B_\chi(\phi) \right) \chi + V(\phi) \right]$$

Generalized Bekenstein Model



$$\left(\frac{H}{H_0}\right)^2 = (\zeta_b\Omega_b + \zeta_\chi\Omega_\chi)\left(\frac{a_0}{a}\right)^3 + \zeta_\Lambda\Omega_\Lambda$$

$$\ddot{\phi} + 3H\dot{\phi} = -3H_0\omega\left[\zeta_m\Omega_m\left(\frac{a_0}{a}\right)^3 + \zeta_\Lambda\Omega_\Lambda\right]$$

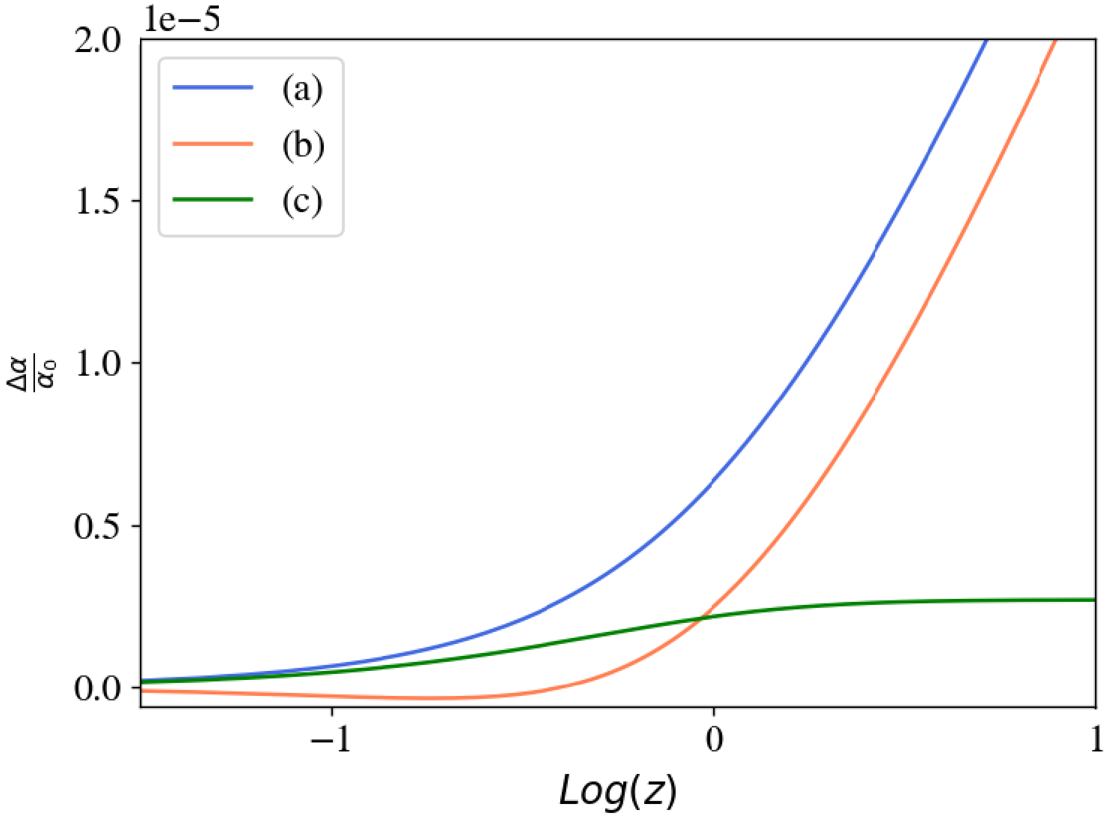
$$\zeta_m\Omega_m = \zeta_b\Omega_b + \zeta_\chi\Omega_\chi$$

Legend: $\zeta_F = 10^{-5}$ and (a) $\zeta_m = 1$, $\zeta_\Lambda = 0$. (b) $\zeta_m = 1$, $\zeta_\Lambda = -2$, (c) $\zeta_m = 0$, $\zeta_\Lambda = 1$.

$$B_i(\Delta\phi) = 1 + \zeta_i\,\Delta\phi$$

Bekenstein Model

Variation of the fine-structure constant



$$\alpha = \frac{\alpha_0}{B_F(\phi)}$$

$$\frac{\Delta\alpha}{\alpha}(z) = \frac{\alpha - \alpha_0}{\alpha_0} \sim -\zeta_F\, \Delta\phi$$

$$\frac{1}{H_0}\left(\frac{\dot{\alpha}}{\alpha}\right)_0 \sim -\zeta_F\, \phi_0'$$

Legend: $\zeta_F = 10^{-5}$ and (a) $\zeta_m = 1$, $\zeta_\Lambda = 0$. (b) $\zeta_m = 1$, $\zeta_\Lambda = -2$, (c) $\zeta_m = 0$, $\zeta_\Lambda = 1$.

Local Constraints

Atomic clocks: $\frac{1}{H_0}\left(\frac{\dot{\alpha}}{\alpha}\right)_0 = (1.4 \pm 1.5) \times 10^{-8}$

Lange *et al.* (2021)

Oklo: $\frac{\Delta\alpha}{\alpha}(z = 0.14) = (0.5 \pm 6.1) \times 10^{-8}$

Petrov *et al.* (2006)

$$\eta = 2\frac{a_1 - a_2}{a_1 + a_2}$$

$$\eta \sim 2.9 \times 10^{-2}\, \zeta_b\, \zeta_F$$

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

Touboul *et al.* (2019)

Cosmological Constraints

Quasar spectra: $\frac{\Delta\alpha}{\alpha} = -0.64 \pm 0.65$ ppm [1]

Set of 21 different measurements $(1.02 < z < 2.31)$

Agafonova *et al.* (2011), Molaro *et al.* (2013), Evans *et al.* (2014), Songaila and Cowie (2014), Murphy *et al.* (2016), Bainbridge and Webb *et al.* (2016), Kotus *et al.* (2017)

Webb: $\frac{\Delta\alpha}{\alpha}(0.2 < z < 4.2) = -2.16 \pm 0.86$ ppm

Webb *et al.* (2011)

ESPRESSO: $\frac{\Delta\alpha}{\alpha} = 1.3 \pm 1.3_{stat} \pm 0.4_{sys}$ ppm

Murphy *et al.* (2021)

[1] C J A P Martins. "The status of varying constants: a review of the physics, searches and implications". In: Reports on Progress in Physics 80.12 (Nov. 2017), p. 126902. DOI: 10.1088/1361-6633/aa860e.

Simulation

Modified CLASS

+

MCMC

Other data sets: Planck, BAO, Pantheon.

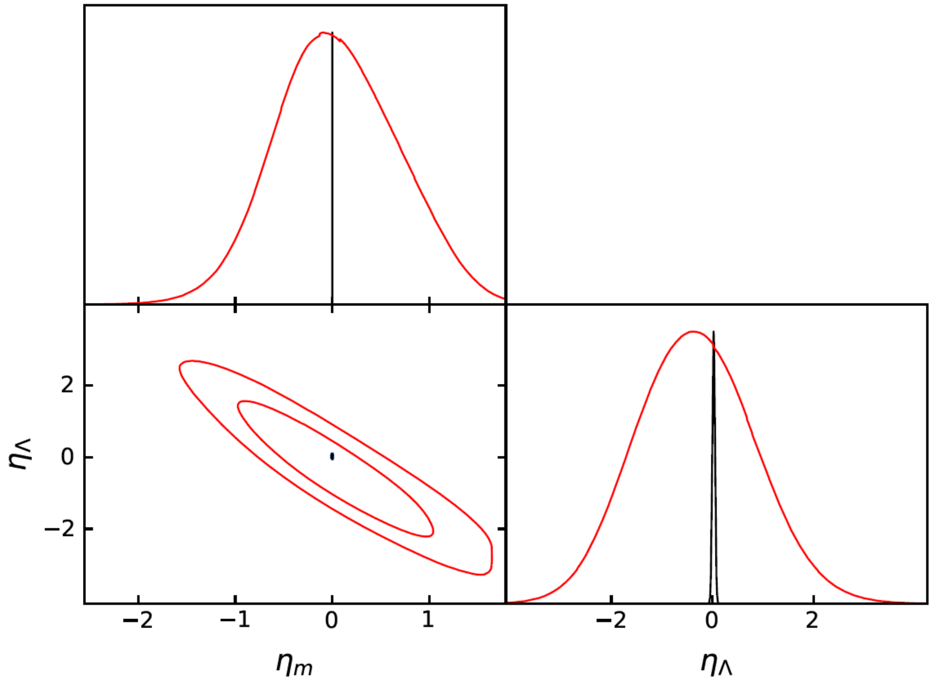
Planck VI (2018), Alam *et al.* (2016). Riess *et al.* (2017)

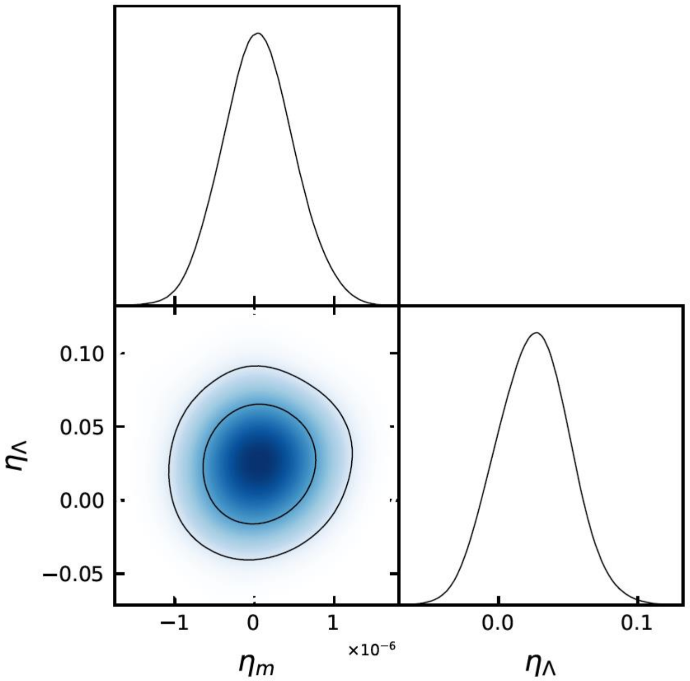
Diego Blas, Julien Lesgourgues, and Thomas Tram. "The Cosmic Linear Anisotropy Solving System (CLASS). Part II: Approximation schemes". In: Journal of Cosmology and Astroparticle Physics 2011.07 (July 2011), pp. 034–034. DOI: 10.1088/1475- 7516/2011/07/034.

Results

$\eta_m = (0.5 \pm 4.5) \times 10^{-7}$ ppm

$\eta_\Lambda = 0.025 \pm 0.026$ ppm





C. S. Alves, A. C. O. Leite, C. J. A. P. Martins, T. A. Silva, S. A. Berge, and B. S. A. Silva, Current and future constraints on extended Bekenstein-type models for a varying fine-structure constant, Phys. Rev. D 97, 023522 (2018).

Conclusion and Outlook

- Couplings of order of ppm are excluded (also for the full model)

- Improve constraints by $\sim 10^7$ for η_m and ~ 100 for η_Λ

- Explore other models (e.g. rolling tachyon)