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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COSMO ESPRESSO Cosmology and Fundamental Physics with ESPRESSO

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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

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

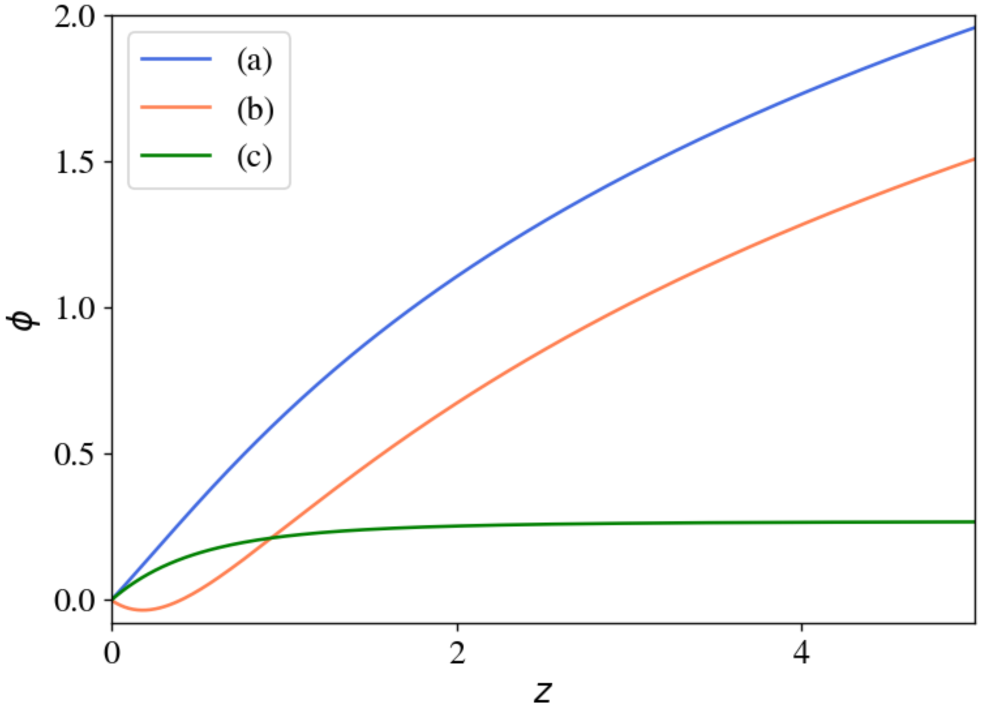
$$\Rightarrow$$

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

$$S = \int d^4x \sqrt{-g} [\mathcal{L}_G + \mathcal{L}_M + \epsilon^{-2} \mathcal{L}_{EM} + \mathcal{L}_\epsilon]$$

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

Generalized Bekenstein Model



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

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

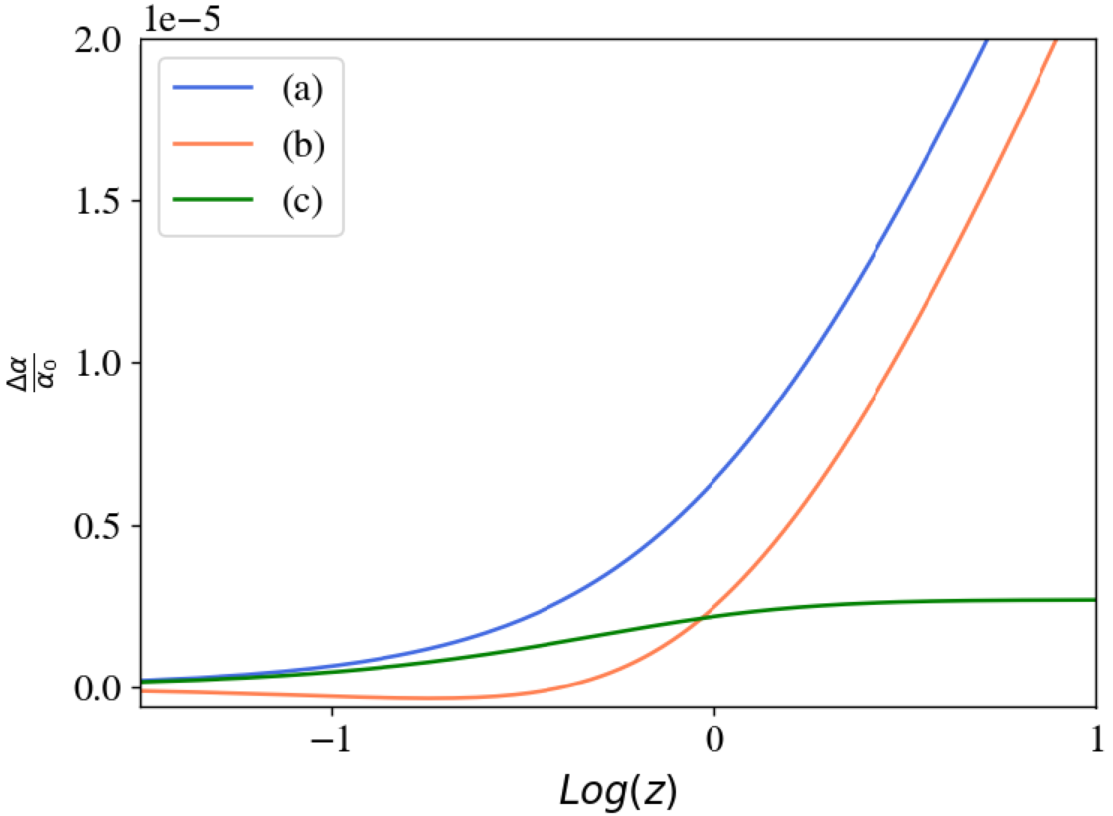
$$\zeta_m\Omega_m = \zeta_b\Omega_b + \zeta_\chi\Omega_\chi$$

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)

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

$$\eta \sim 1.45 \times 10^{-2}\, \zeta_b\, \zeta_F$$

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

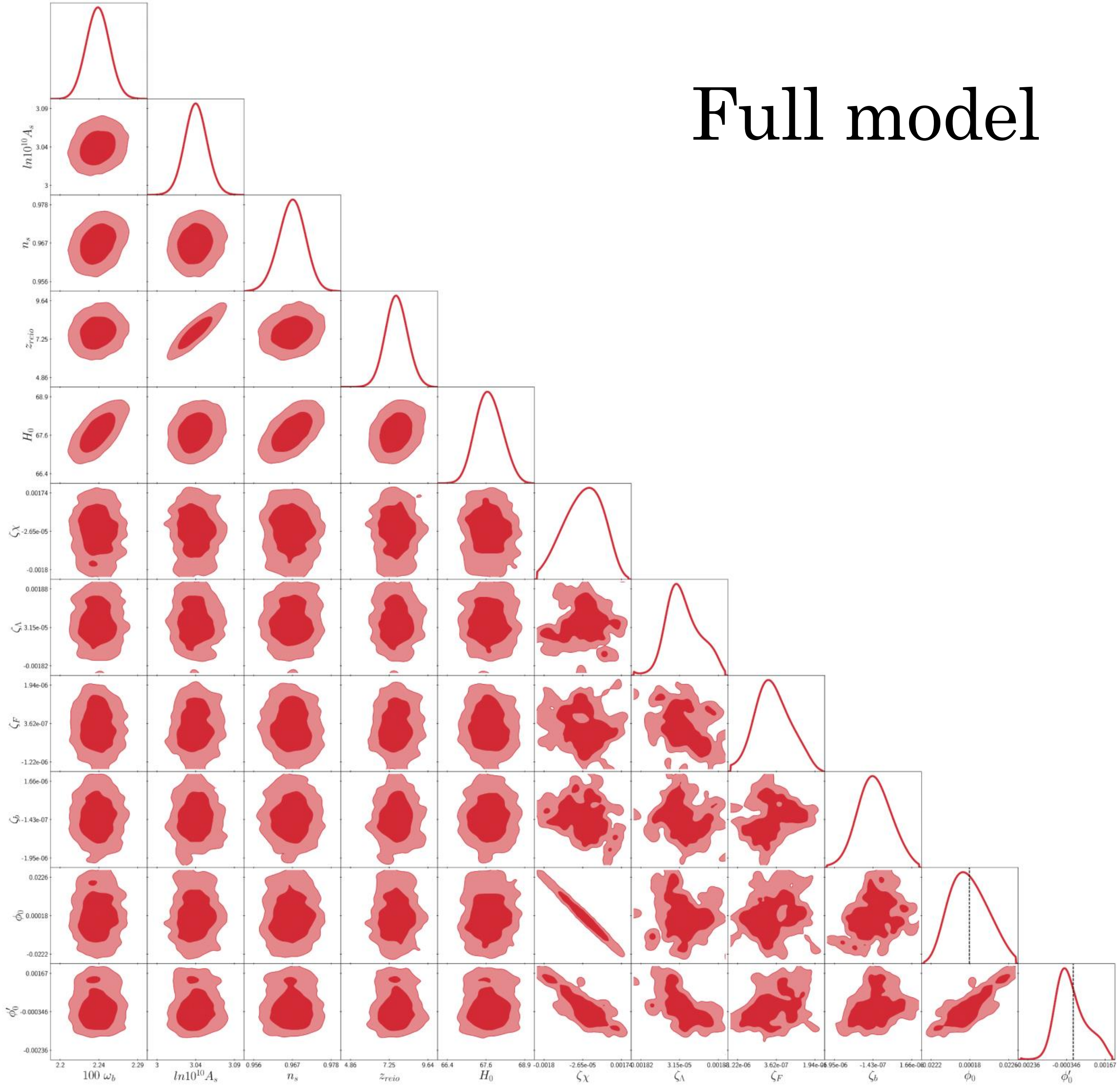
Modified CLASS + MCMC

<u>Other data sets:</u> Planck, BAO, Pantheon.

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

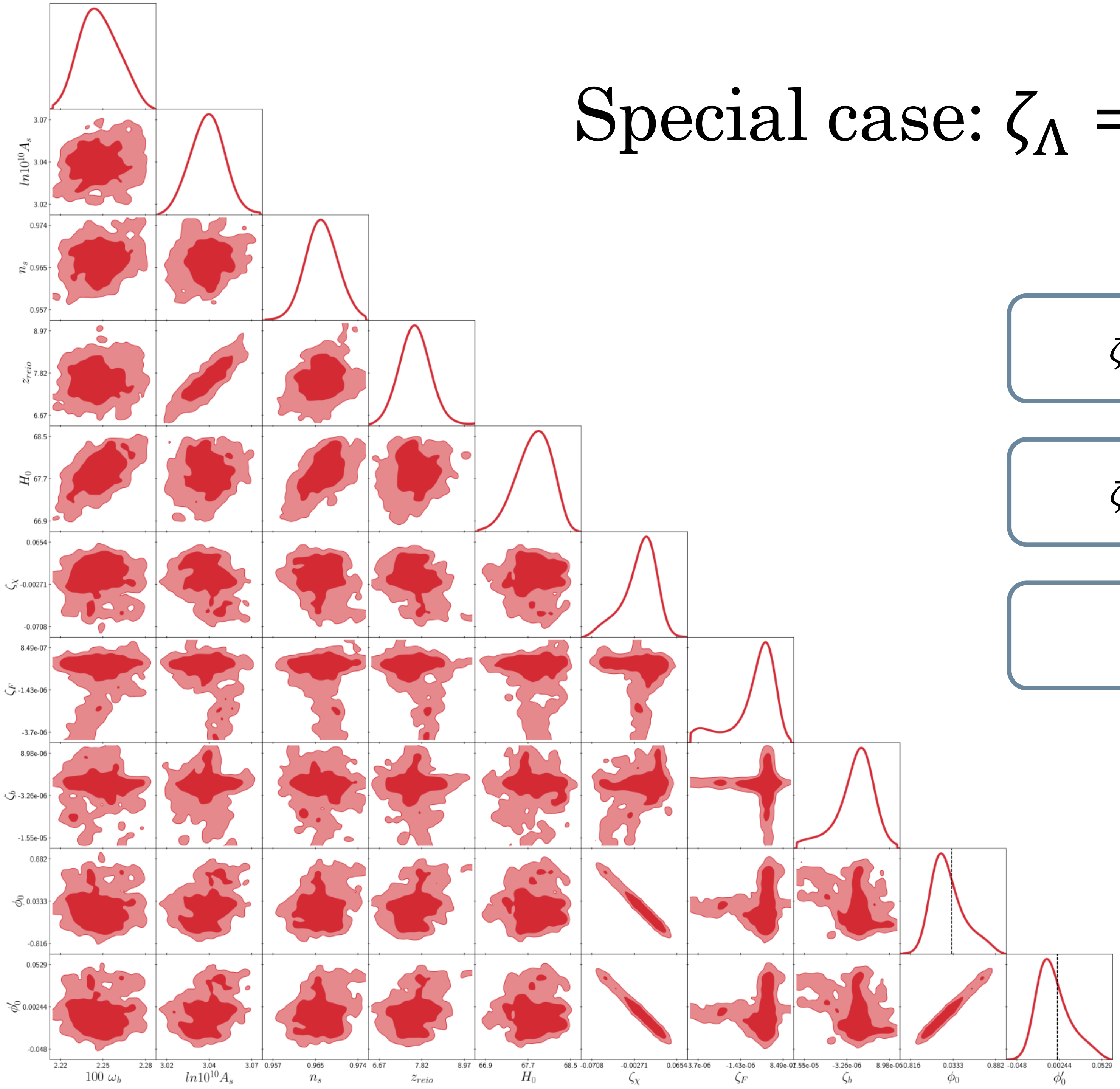
Diego Blas, Julien Lesgourgues, and Thomas Tram. “The Cosmic Linear Anisotropy Solving System (CLASS). Part II: Approximation schemes”. In: Journal of Cosmology and Astroparticle Physics 2011.07 (July 2011), pp. 034–034. DOI: 10.1088/1475- 7516/2011/07/034.

Full model



$ln10^{10}A_s$
n_s
z_{reio}
H_0
ζ_χ
ζ_Λ
ζ_F
ζ_b
ϕ_0
ϕ'_0
$100\ \omega_b$

Special case: $\zeta_\Lambda = 0$



$\zeta_F = -0.51^{+0.92}_{-0.12}$ ppm

$\zeta_b = -0.78^{+3.99}_{-2.84}$ ppm

$\zeta_\chi = -0.0059^{+0.036}_{-0.014}$

Conclusion and Outlook

- Couplings of order one are excluded
- Look at other special cases: $\zeta_m = 0,\ \zeta_\Lambda = \zeta_\chi$
- Explore other models (e.g. rolling tachyon)