Axion-dilaton interactions in the dark sector

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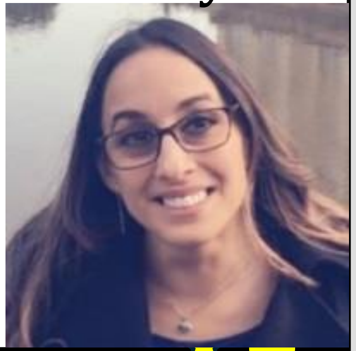
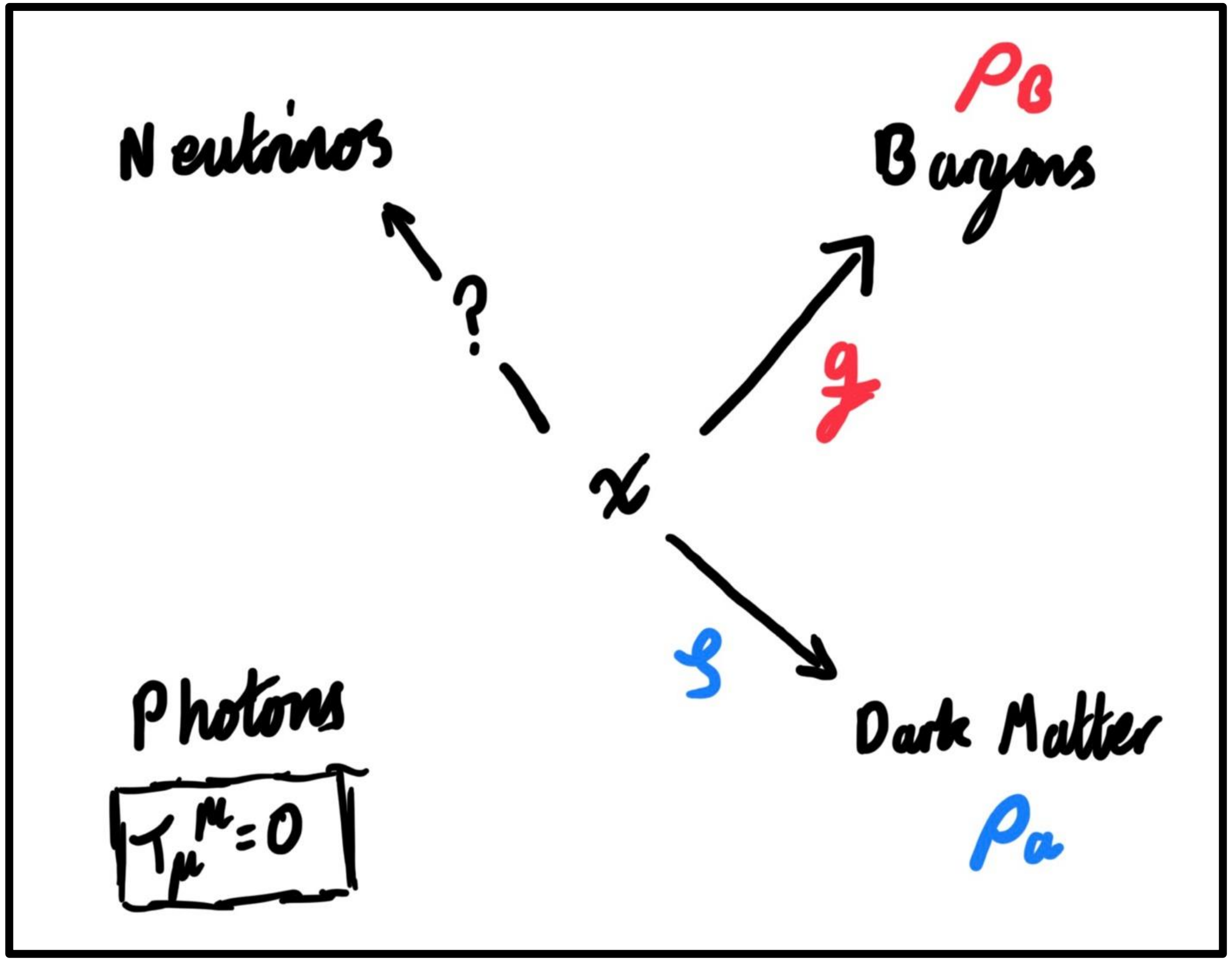


Minimal Axion-Dilaton Models



Axion-Dilaton Class

Consequence of the axion's shift symmetry

$$\mathcal{L}_{axio-dilaton} = -\frac{1}{2}M_p^2\sqrt{-g}\left[(\partial\chi)^2 + W^2(\chi)(\partial\mathfrak{a})^2\right]$$

Axion-Dilaton Class

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Fundamental theory

- Combine into complex fields in extra-dimensional UV completions

$$\Phi = \frac{1}{2}\left(e^{\zeta\chi} + i\mathfrak{a}\right)$$

Dilaton ≪=≫ Volume modulus

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Cosmology

- Dilaton is naturally light, DE scalar candidate

$$V = Ue^{-\lambda\chi}$$

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Cosmology

- Dilaton is naturally light, DE scalar candidate

$$V = Ue^{-\lambda\chi}$$

- Axions have wide range of uses, e.g. CDM

$$V(a) = \frac{m_{\mathfrak{a}}^2}{2}(\mathfrak{a} - \mathfrak{a}_+)^2 + \dots$$

The Late-Time Theory:

$$S = -\int d^4x\sqrt{-g}\left\{\frac{1}{2}M_p^2\left[R + \underbrace{\partial_\mu\chi\,\partial^\mu\chi}_{\text{Dilaton Kinetic Term}} + \underbrace{W^2(\chi)\,\partial_\mu\mathfrak{a}\,\partial^\mu\mathfrak{a}}_{\text{Axion Kinetic Term}}\right] + \underbrace{V(\chi,\mathfrak{a})}_{\text{Axio-dilaton Potential}}\right\} + \mathcal{L}_m(\Psi,\tilde{g})$$

The dilaton couples to matter as a pseudo-Brans-Dicke scalar:

$$\tilde{g}_{\mu\nu} := C^2(\chi)\,g_{\mu\nu}$$

$$C(\chi) = e^{\mathbf{g}\chi}$$

The Late-Time Theory:

$$S = -\int d^4x\sqrt{-g}\left\{\frac{1}{2}M_p^2\Big[R + \underbrace{\partial_\mu\chi\,\partial^\mu\chi}_{\text{Dilaton Kinetic Term}} + \underbrace{W^2(\chi)\,\partial_\mu\mathfrak{a}\,\partial^\mu\mathfrak{a}}_{\text{Axion Kinetic Term}}\Big] + \underbrace{V(\chi,\mathfrak{a})}_{\text{Axio-dilaton Potential}}\right\} + \mathcal{L}_m(\Psi,\tilde{g})$$

The dilaton couples to matter as a pseudo-Brans-Dicke scalar:

$$\tilde{g}_{\mu\nu} := C^2(\chi)\, g_{\mu\nu} \qquad \frac{1}{\sqrt{-g}}\frac{\partial\mathcal{L}_m}{\partial\chi} = \mathbf{g}\rho_m$$

$$C(\chi) = e^{\mathbf{g}\chi}$$

$$\boxed{m_B(\chi) = m e^{\mathbf{g}\chi}}$$

The Late-Time Theory:

$$S = -\int d^4x\sqrt{-g}\left\{\frac{1}{2}M_p^2\left[R + \underbrace{\partial_\mu\chi\,\partial^\mu\chi}_{\text{Dilaton Kinetic Term}} + \underbrace{W^2(\chi)\,\partial_\mu\mathfrak{a}\,\partial^\mu\mathfrak{a}}_{\text{Axion Kinetic Term}}\right] + \underbrace{V(\chi,\mathfrak{a})}_{\text{Axio-dilaton Potential}}\right\} + \mathcal{L}_m(\Psi,\tilde{g})$$

Everything dilaton related is a runaway exponential

$$m_B(\chi) = me^{\mathbf{g}\chi}$$

$$V(a) = \frac{m_{\mathfrak{a}}^2}{2}(\mathfrak{a}-\mathfrak{a}_+)^2 + \dots$$

$$W = W_0e^{-\zeta\chi}$$

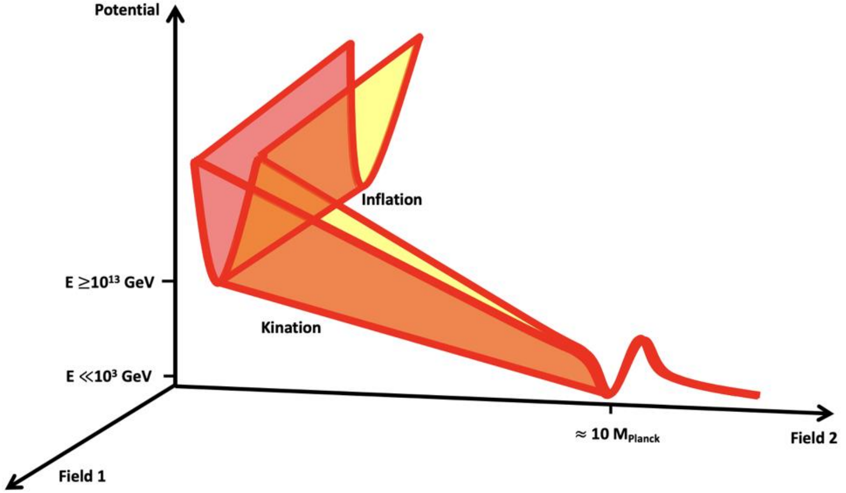
$$V = U(\chi)e^{-\lambda\chi} + V(\mathfrak{a})$$

$$U(\chi) = U_0\left[1 - u_1\chi + \frac{u_2}{2}\chi^2\right]$$

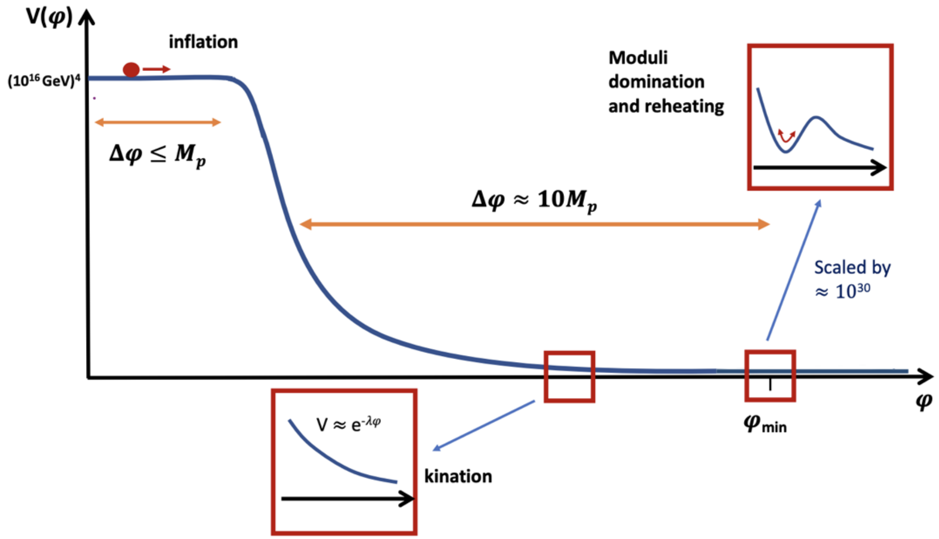
Potential Motivations

Albrecht-Skordis Potential (2001) 0107573

$$V = U(\chi)e^{-\lambda\chi} + V(\mathfrak{a}) \qquad U(\chi) = U_0\left[1 - u_1\chi + \frac{u_2}{2}\chi^2\right]$$



Cicoli et al (2023) 2303.04819

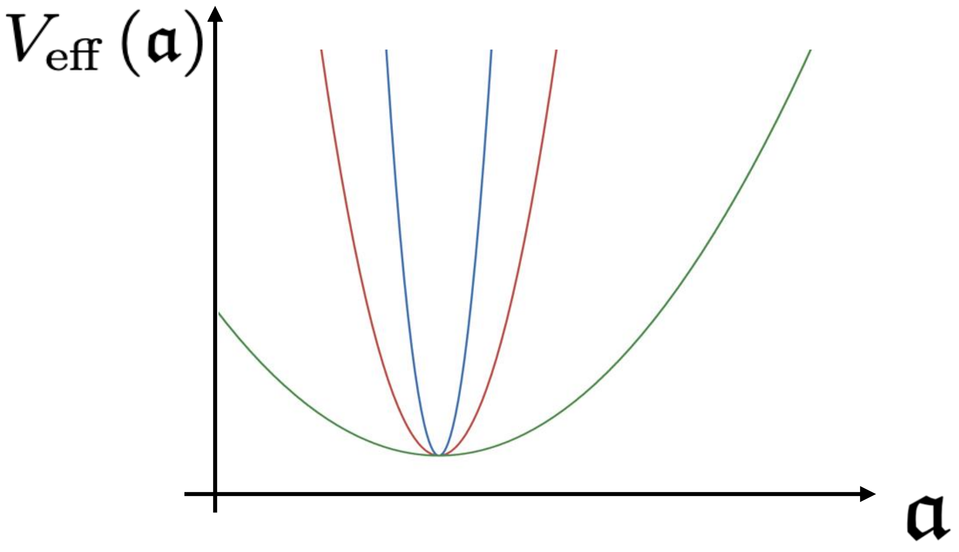


Apers et al (2024) 2401.04064

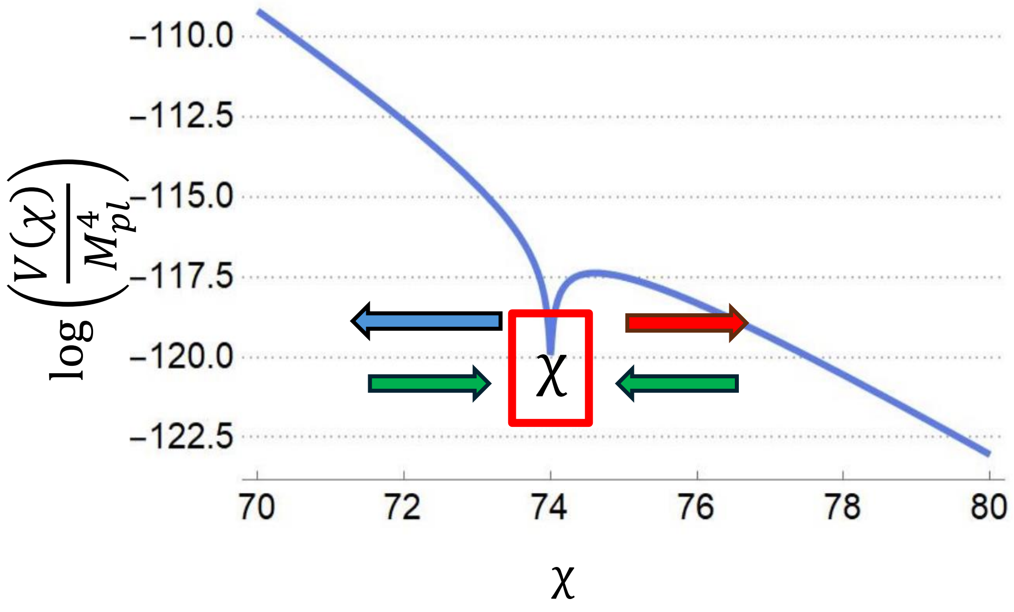
Axion

$$W = W_0 e^{-\zeta\chi}$$

Dilaton



$$\bar{\chi}'' + 2\mathcal{H}\bar{\chi}' + \frac{a^2}{M_p^2}V_{,\chi} = \frac{a^2}{M_p^2}\left(\mathbf{g}\bar{\rho}_B - \zeta\bar{\rho}_{\mathrm{ax}}\right)$$



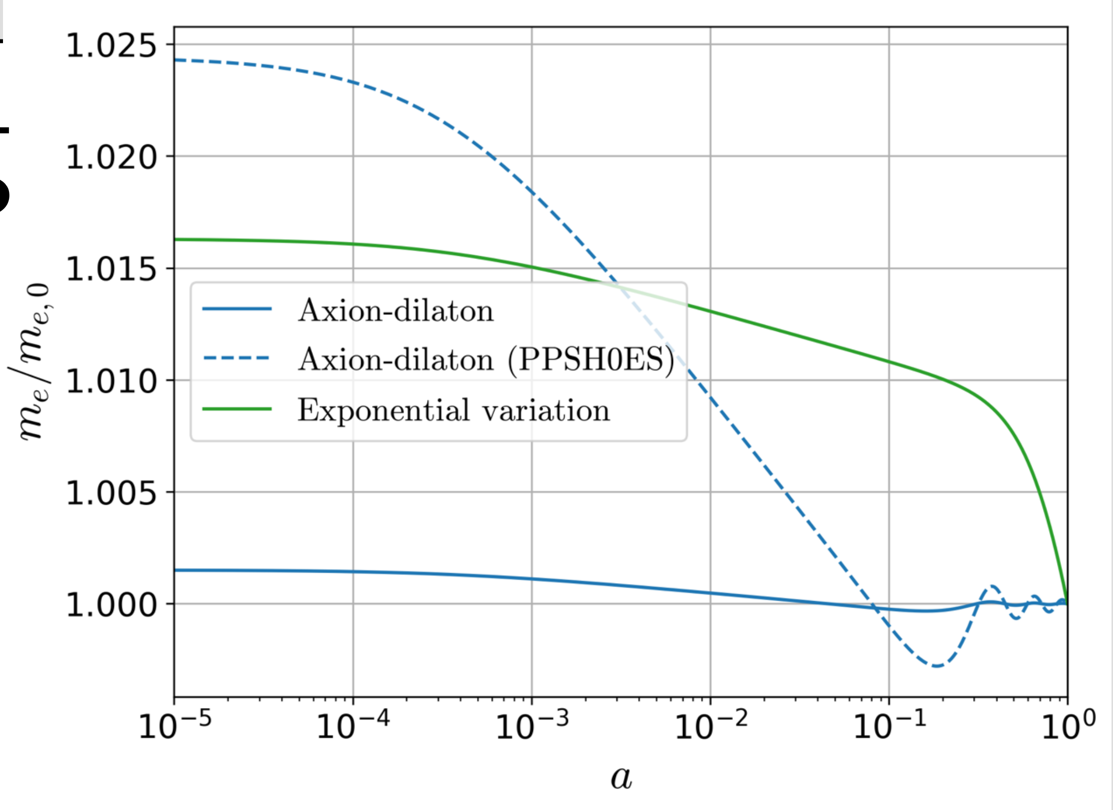
$$\bar{\rho}_{\mathrm{ax}} = \frac{C\mathfrak{m}(t)}{a^3}$$

$$\mathfrak{m}^2(t) = \frac{m_{\mathfrak{a}}^2}{W^2(\bar{\chi})}$$

Observable implications and MCMC constraints

1. Dilaton-SM coupling
2. Dilaton-Axion coupling

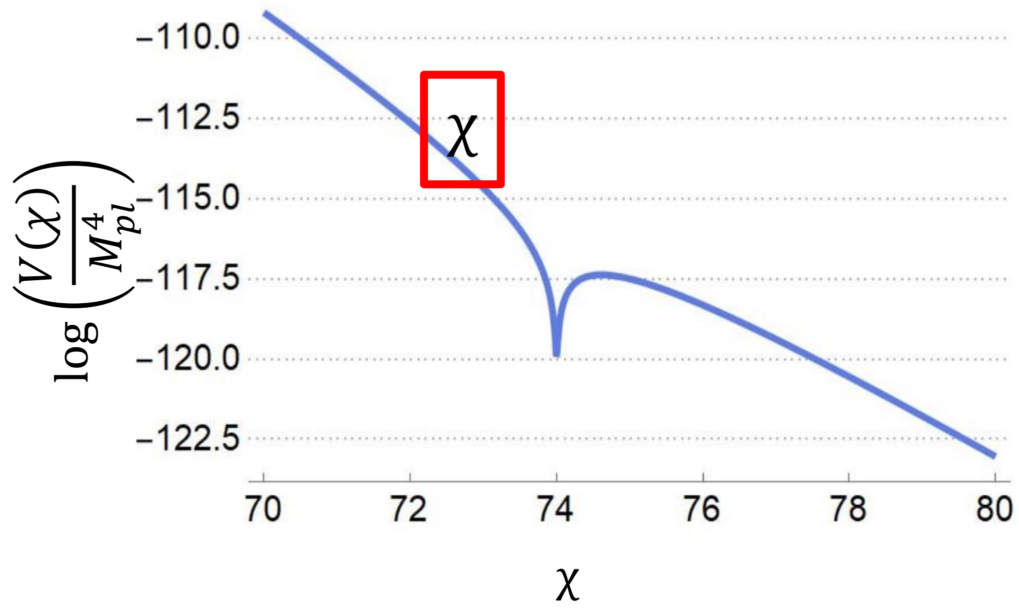
1. Dilaton-SM Coupling



Best-fitting cosmology

MCMC results using:

- Planck 2018 + ACT Dr6 lensing
- Desi Dr2 BAO
- Pantheon +



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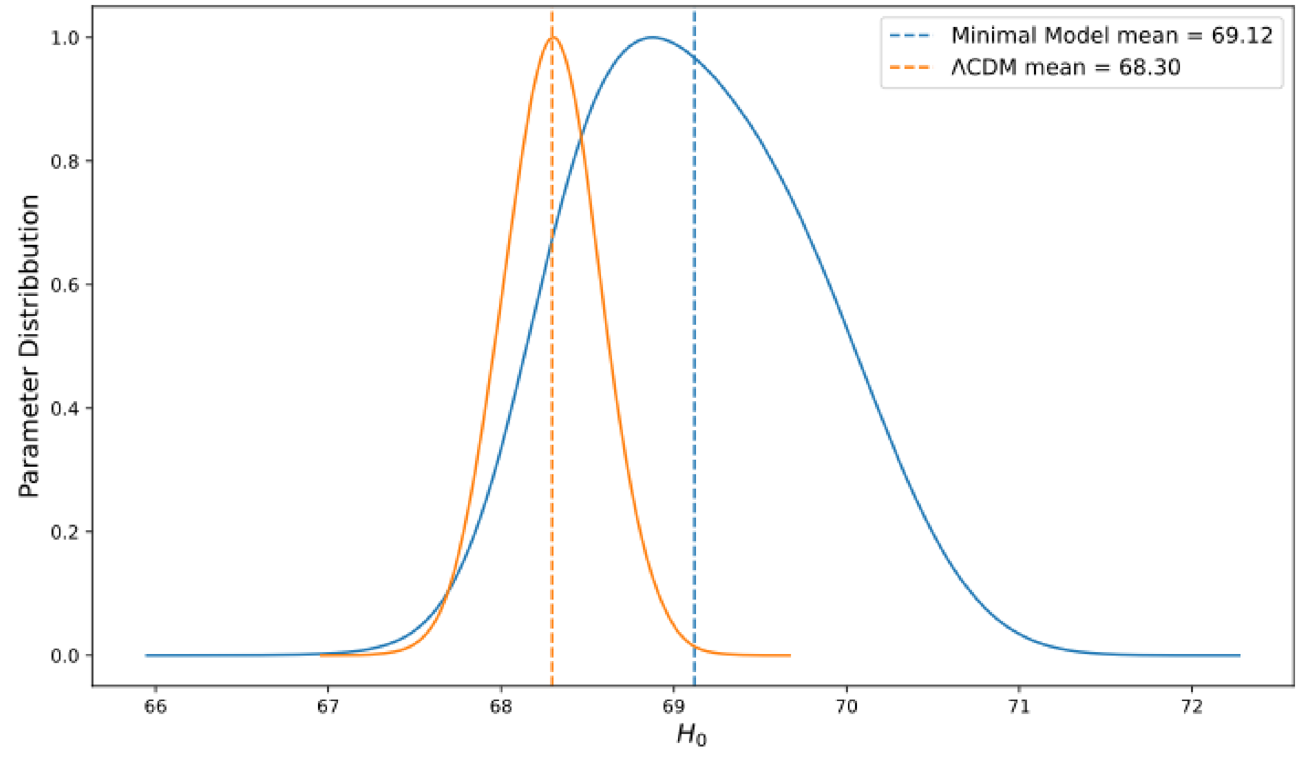
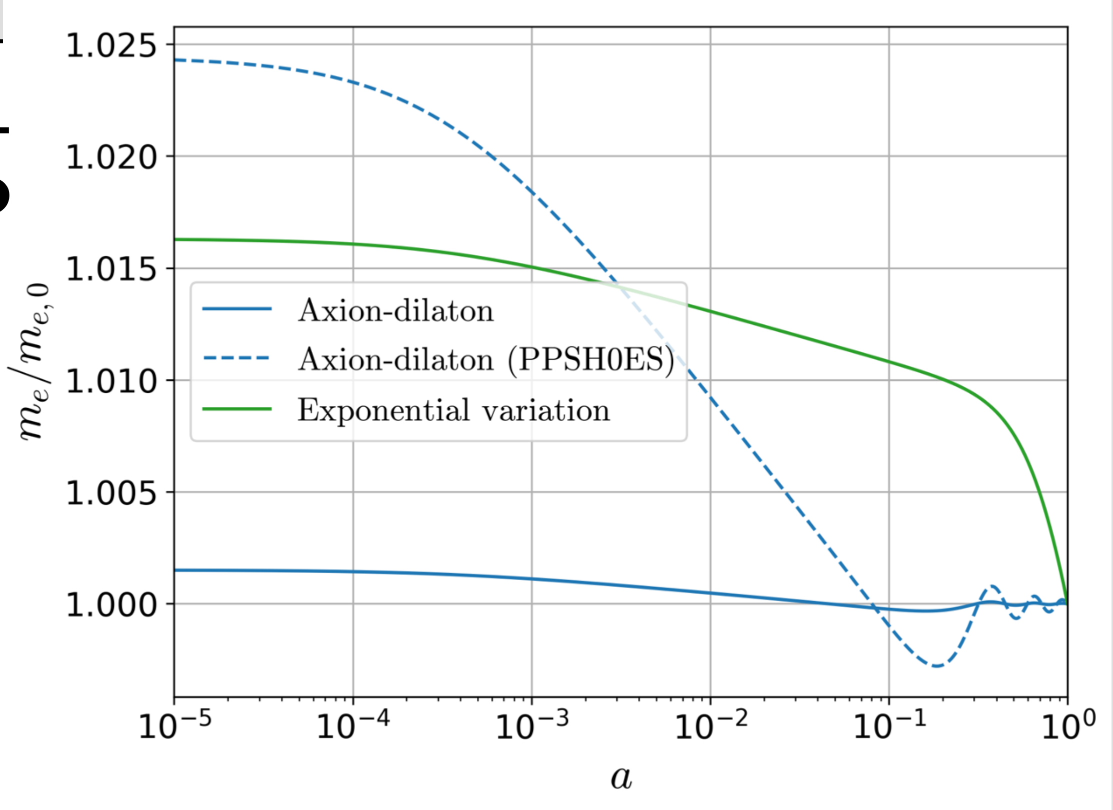




$$\chi_i$$

$$W = W_0 e^{-\zeta\chi}$$

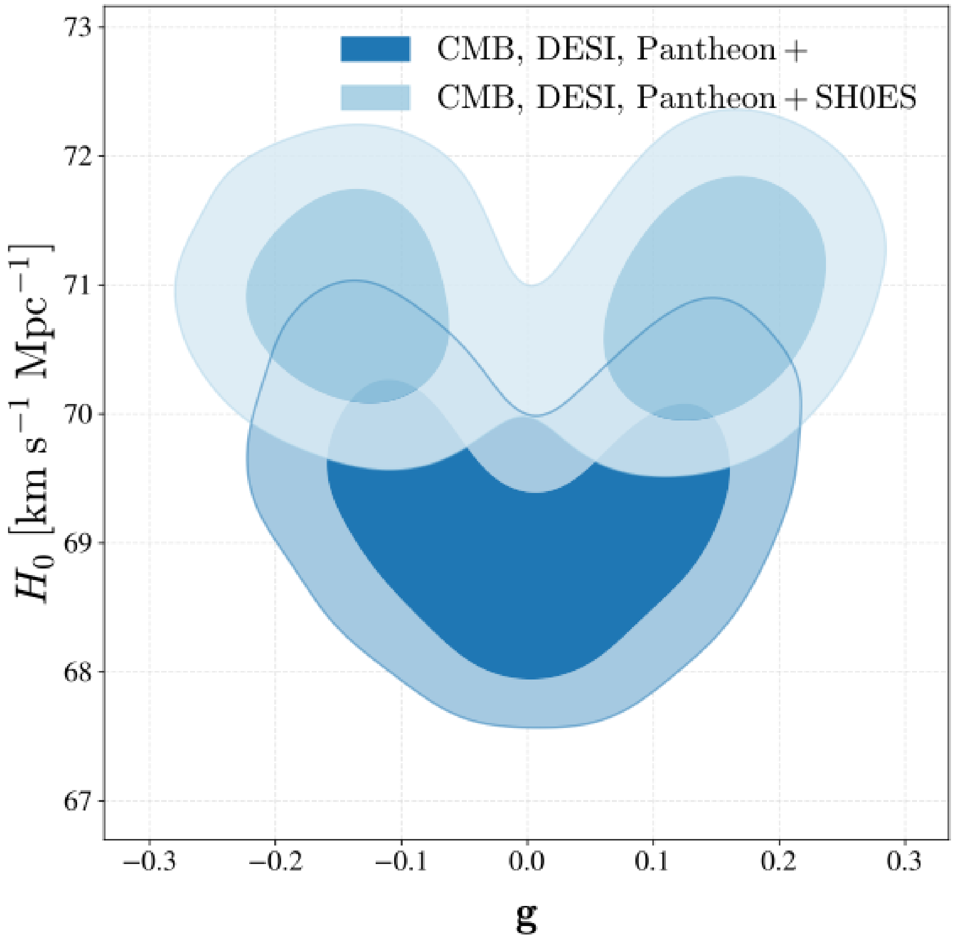
$$m_B(\chi) = m e^{\mathbf{g}\chi}$$

Hubble Tension

$$m_B(\chi) = m e^{\mathbf{g}\chi}$$

- Alleviating the Hubble tension requires couplings preferred non-zero

- Grossly violates local physics constraints (unless screened)

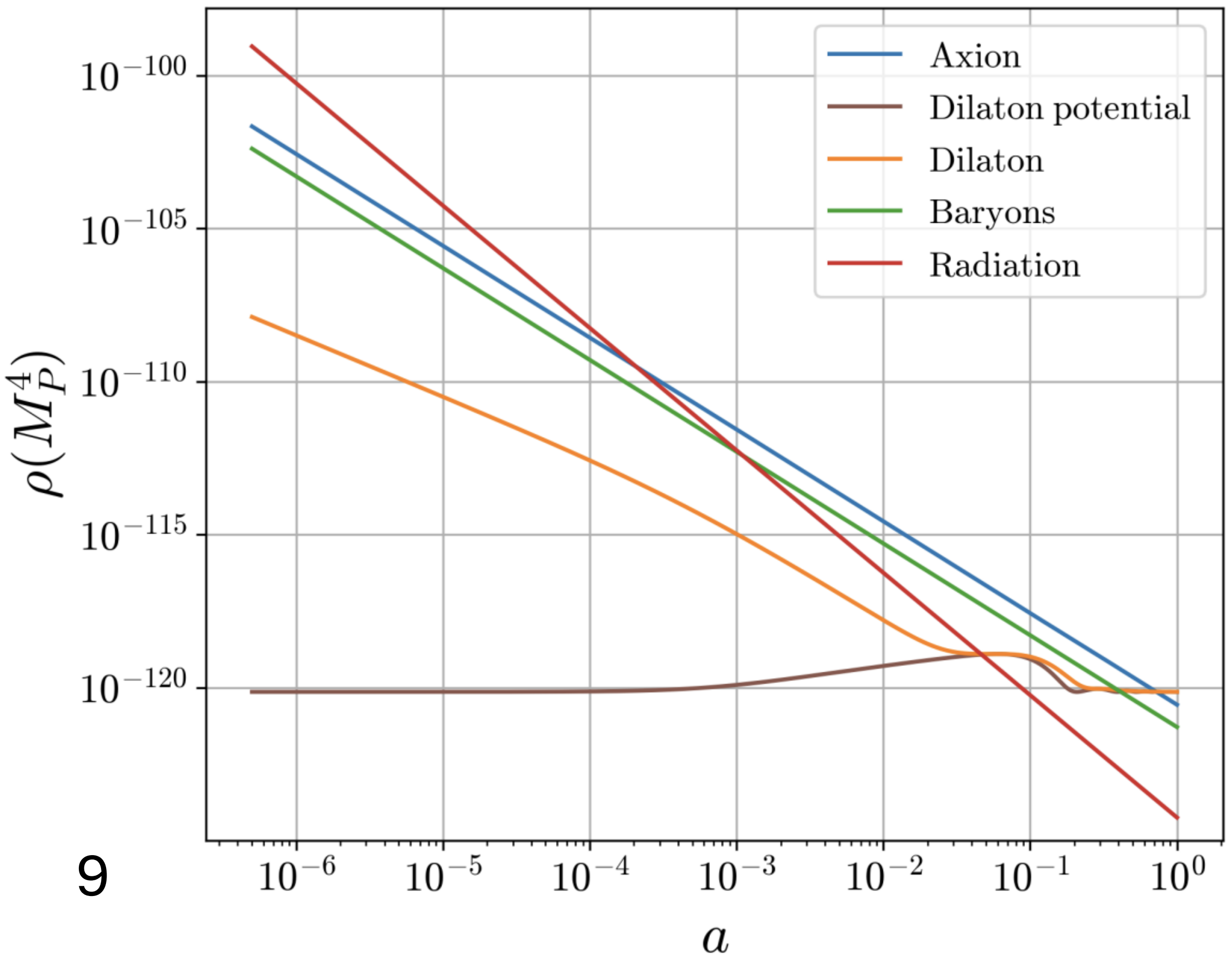


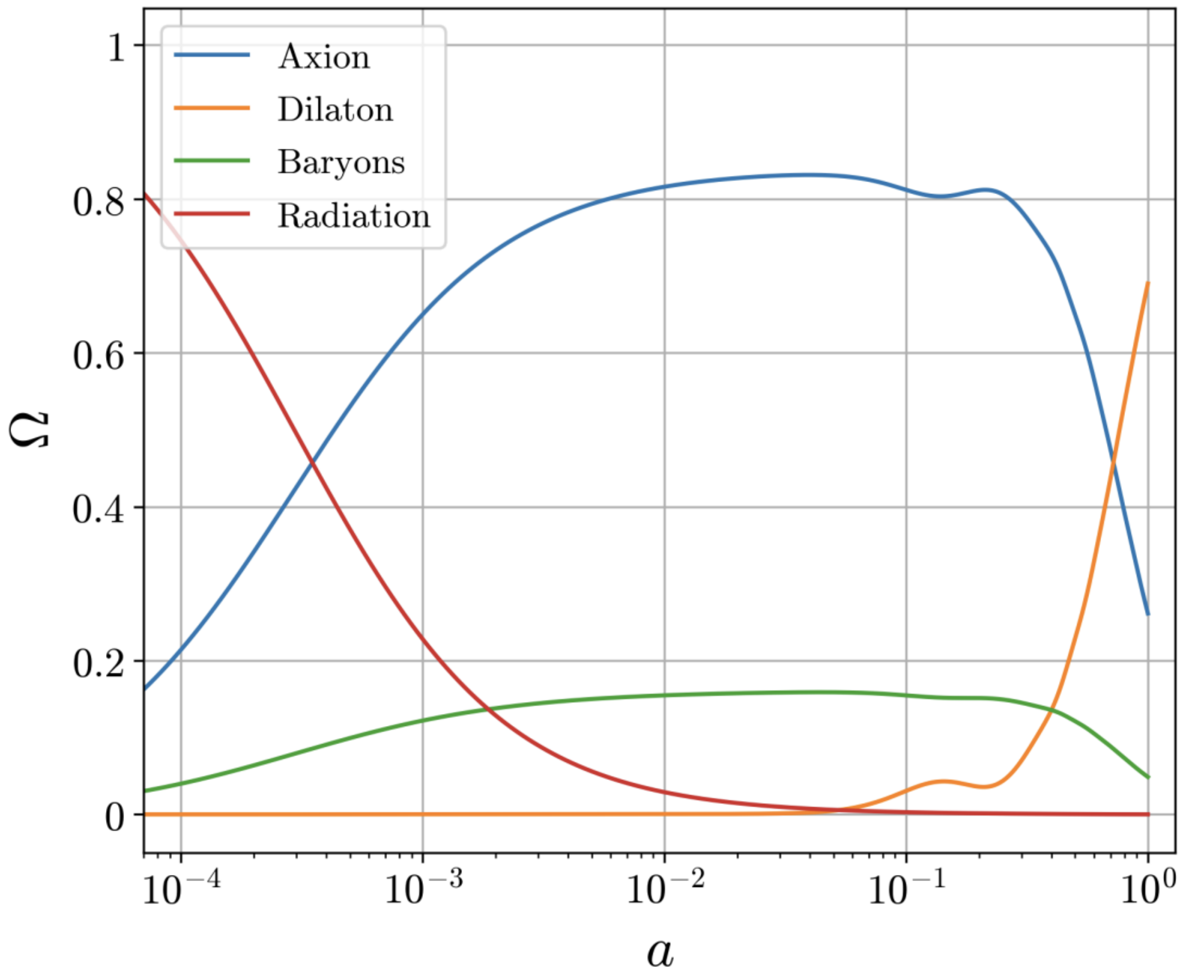
Observable implications and constraints

1. Dilaton-SM coupling
2. Dilaton-Axion coupling

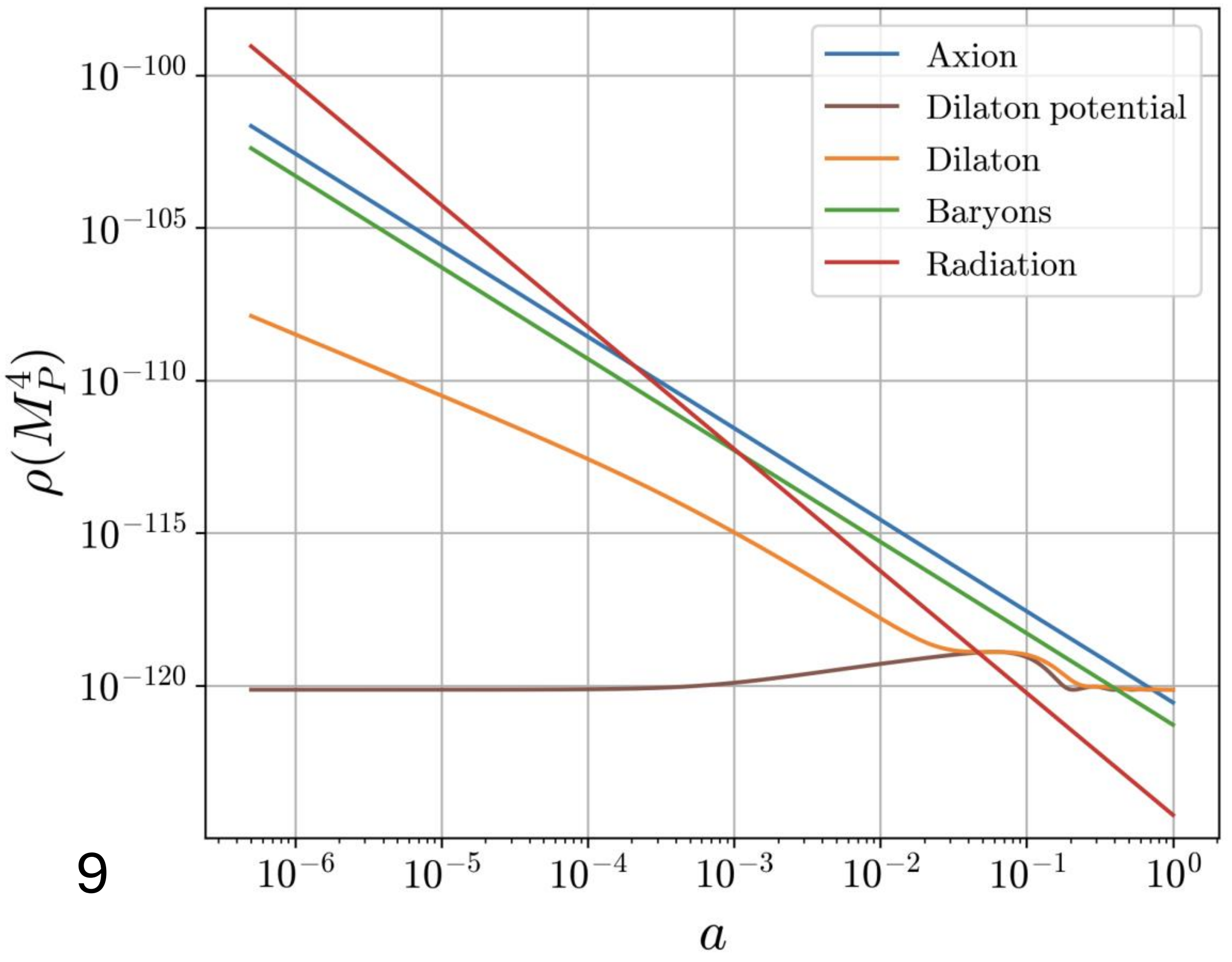
2. Dilaton-Axion Coupling

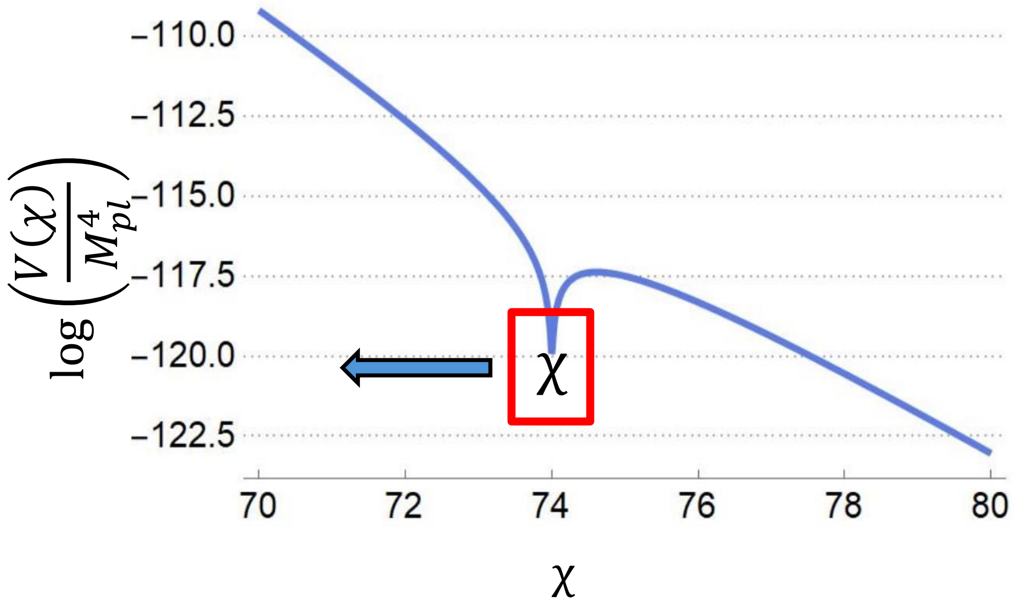
$\zeta = 0.1 \quad \text{and} \quad \mathbf{g} = -10^{-3}$





2. Dilaton-Axion Coupling





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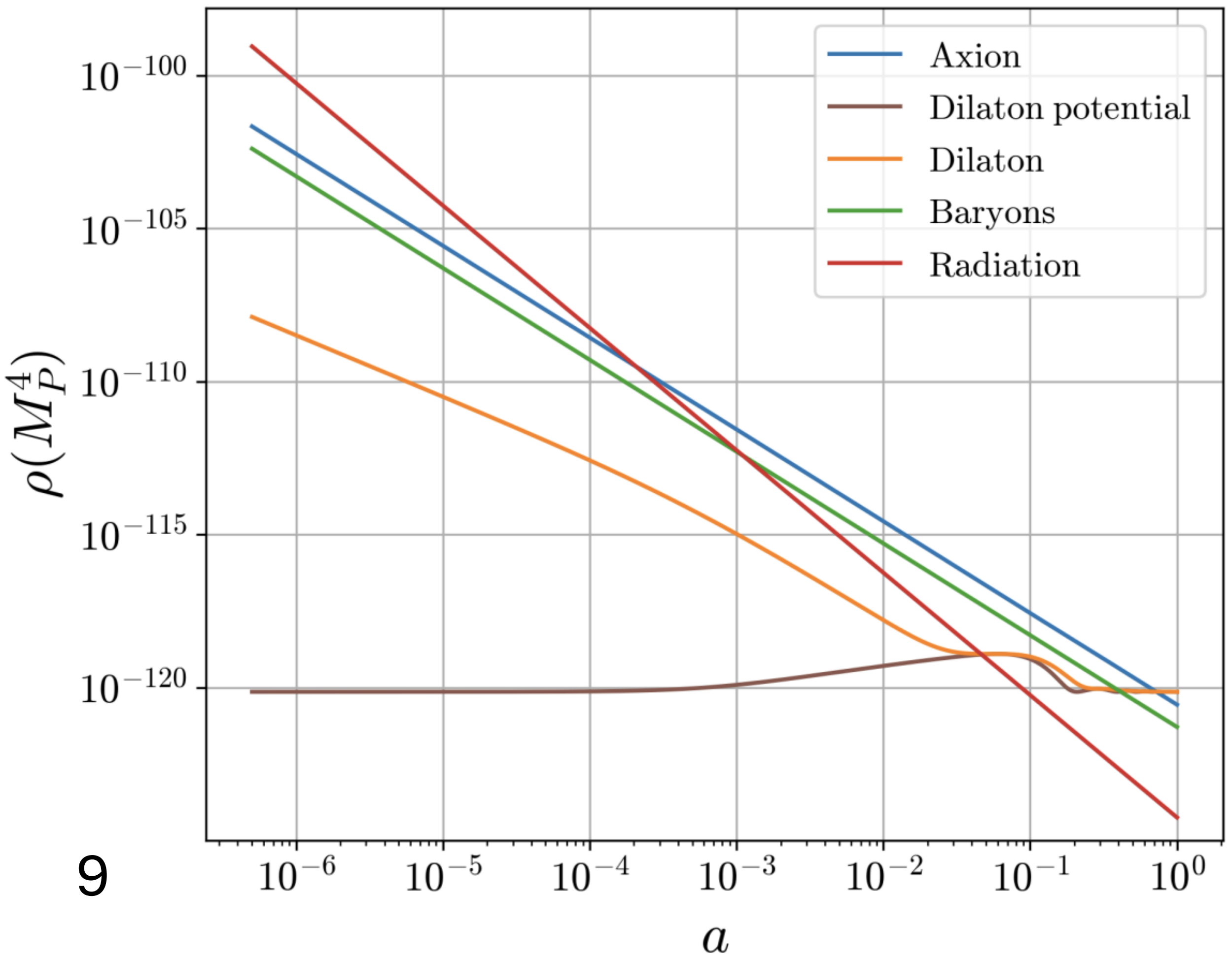
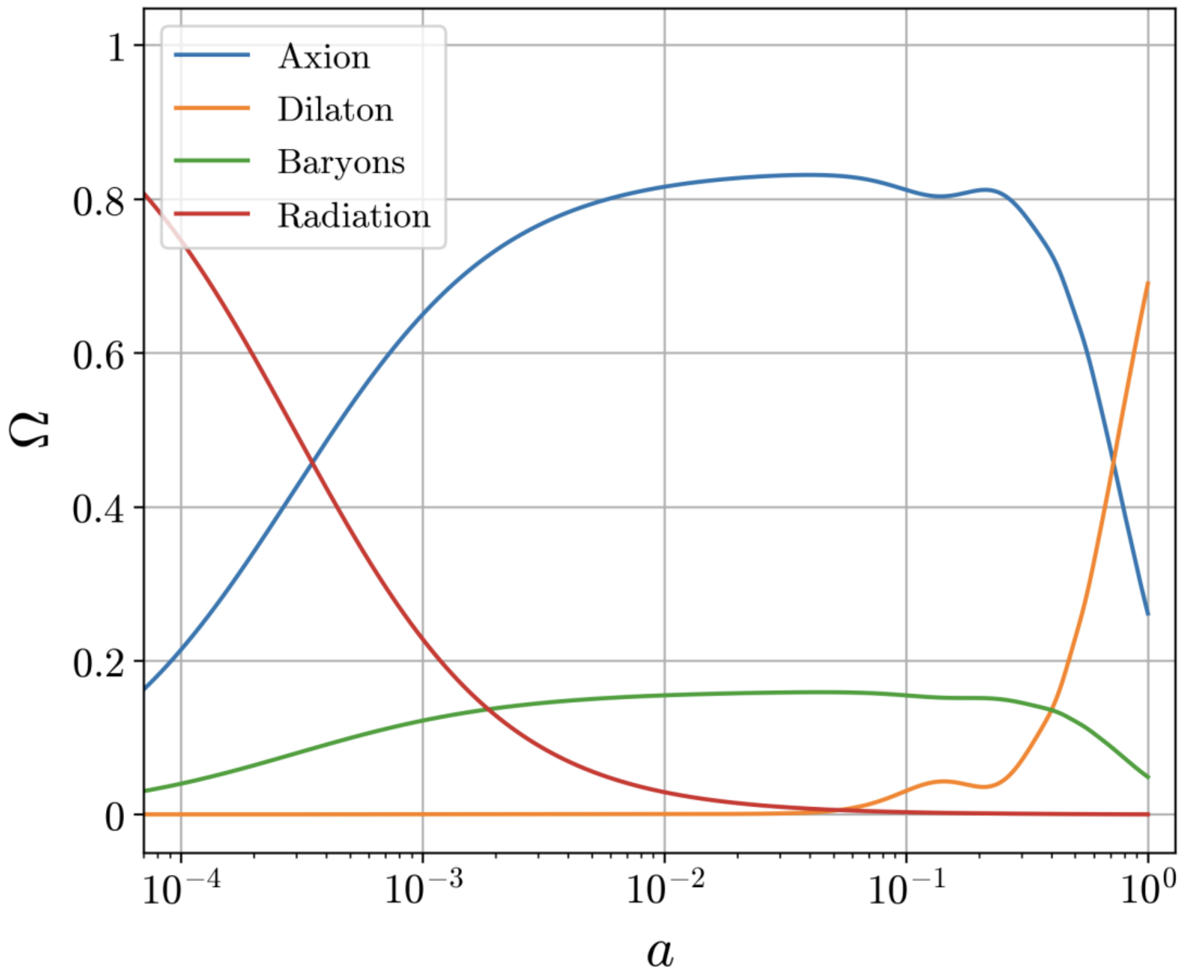
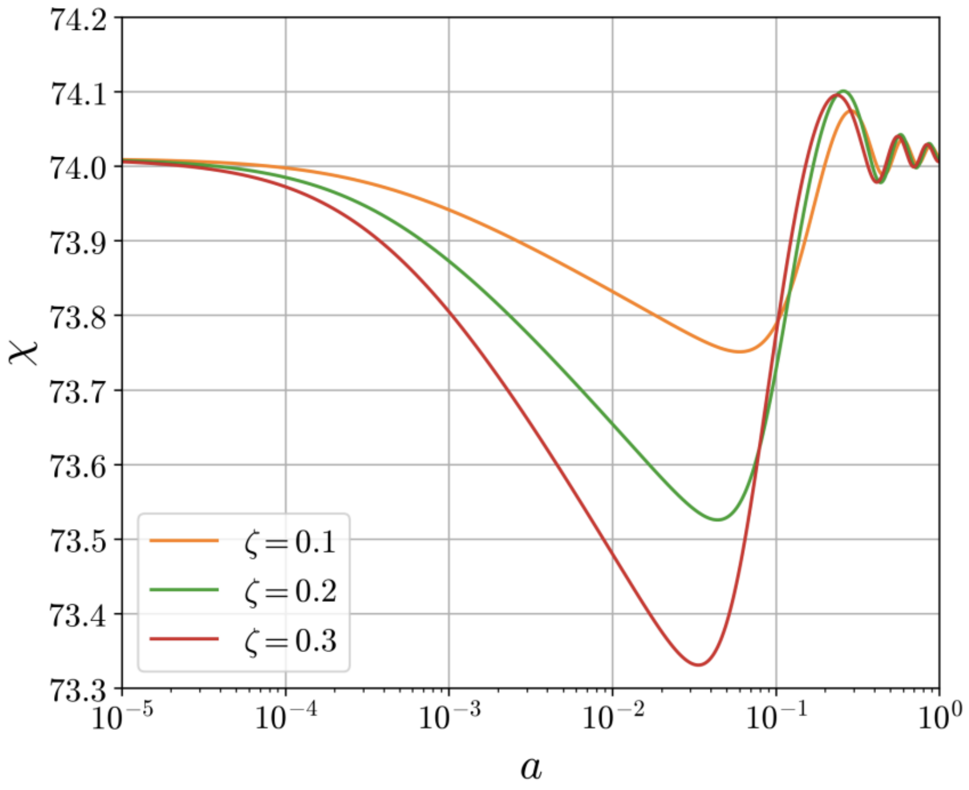
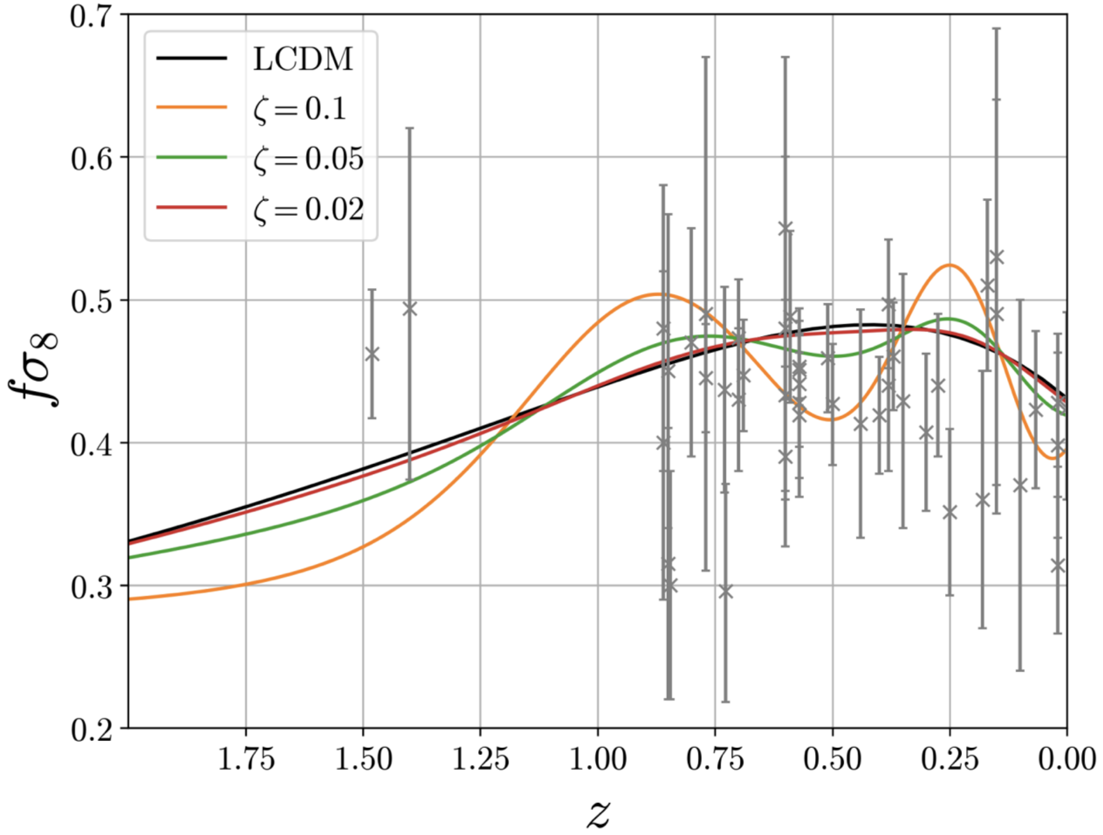




Structure Growth



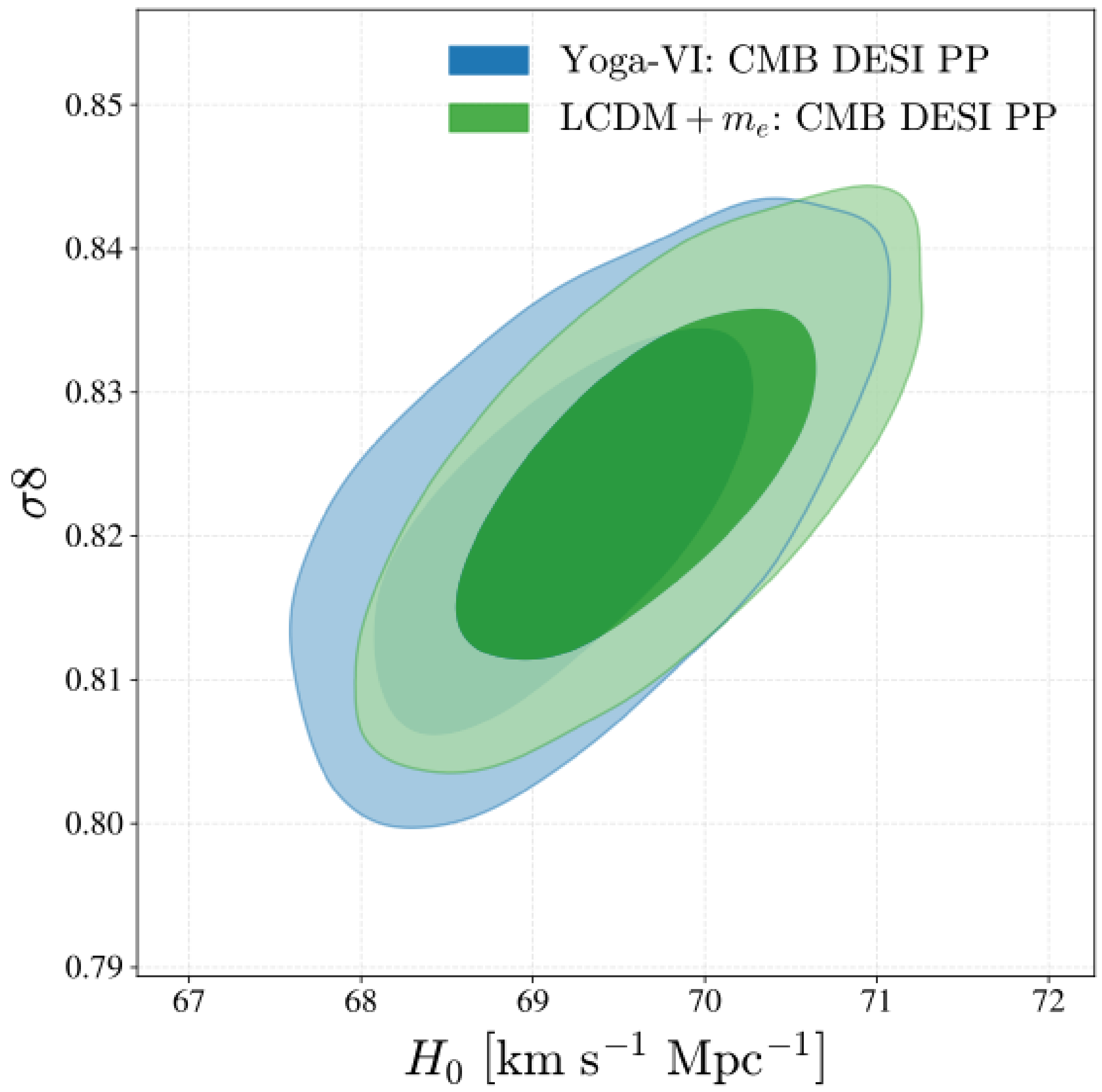


$$f\sigma_8 = \frac{\sigma_8(z, k_{\sigma 8})}{\mathcal{H}} \frac{\delta'_m(z, k_{\sigma 8})}{\delta_m(z, k_{\sigma 8})}$$

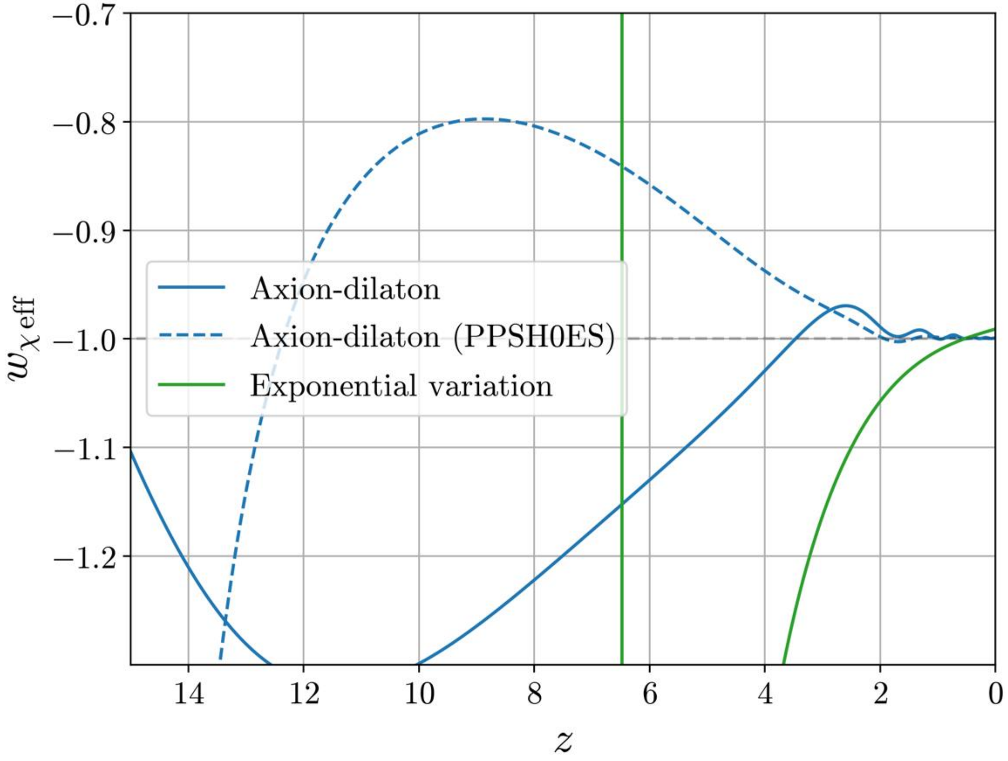
Data points catalogued from SDSS redshift space distortions

Structure Growth

- Models trace the same degeneracy line with H_0 as standard varying electron mass extensions.
- Don't expect these models to alleviate problems with σ_8



The Effective Equation of State



Best-fitting cosmology when combining CMB DESI Pantheon +

- The preference for a phantom equation of state from DESI results assumes matter species evolve $\propto 1/a^3$
- This preference remains in the coupled quintessence cases studied here.

$$\rho_\chi^{\mathrm{eff}} = \rho_\chi + \left[\frac{W(\chi_0)}{W(\chi)} - 1\right]\frac{\rho_{\mathrm{ax}0}}{a^3}$$

$$\omega_{\chi\,\mathrm{eff}} = \frac{\omega_\chi(\chi)}{1 + \left[e^{\zeta(\chi-\chi_0)} - 1\right]\frac{\rho_{\mathrm{ax}0}}{a^3\rho_\chi}}$$

Fitness Tests (With SHoES calibration)

Model	H_0	g	ζ	$\Delta\chi^2$
Yoga VI	70.85 ± 0.58 (71.11)	$0.03^{+0.17}_{-0.20}$ (-0.214)	-0.012 ± 0.060 (0.082)	-19.7
EXP	70.79 ± 0.59 (71.03)	0.000 ± 0.160 (0.161)	-0.003 ± 0.062 (-0.058)	-18.9
Λ CDM+m_e	70.97 ± 0.57 (71.34)	–	–	-19.2
$w_0 w_a$+m_e	70.51 ± 0.73 (70.37)	–	–	-19.4

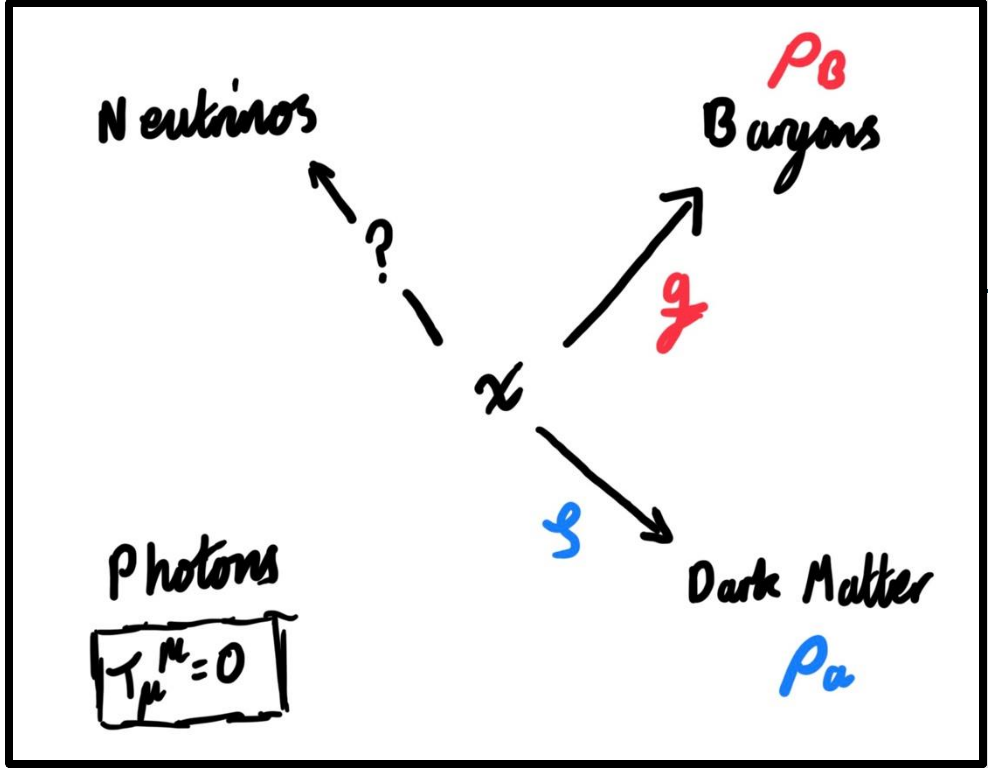
- Any model with varying electron mass gets massively preferred
- Not possible to distinguish between them with current data

Conclusion

- Axion can play the role of dark matter
- Dilaton can play the role of dark energy

Interactions between them can give:

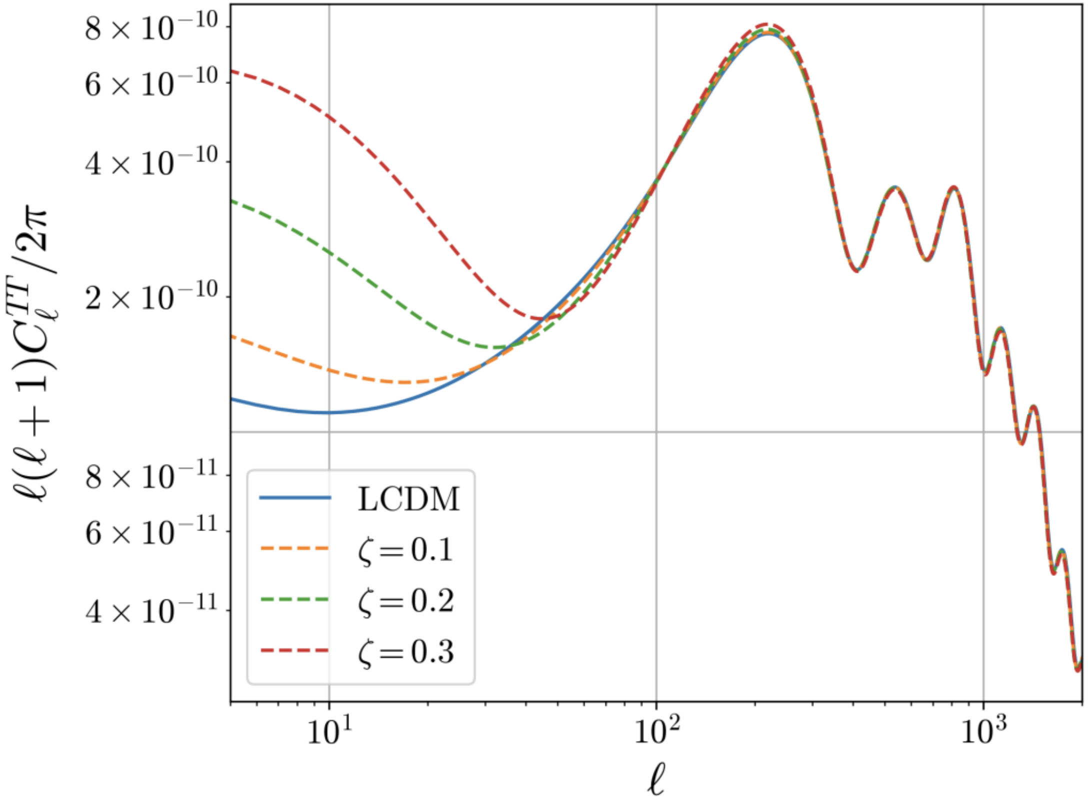
i. Oscillations in structure growth
ii. Deviations in the CMB
iii. Particle masses to oscillate at late times

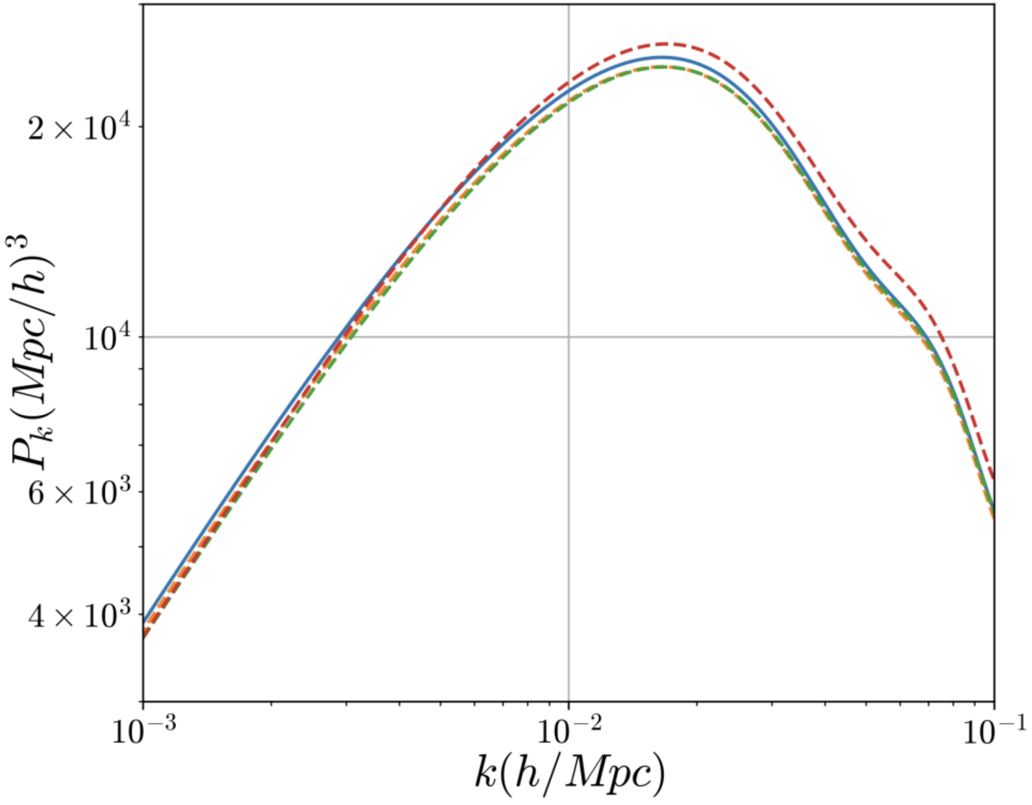


Models like this can reproduce the results from phenomenological parametrizations very well, but are un-screened and violate solar system gravity tests

Backup Slides

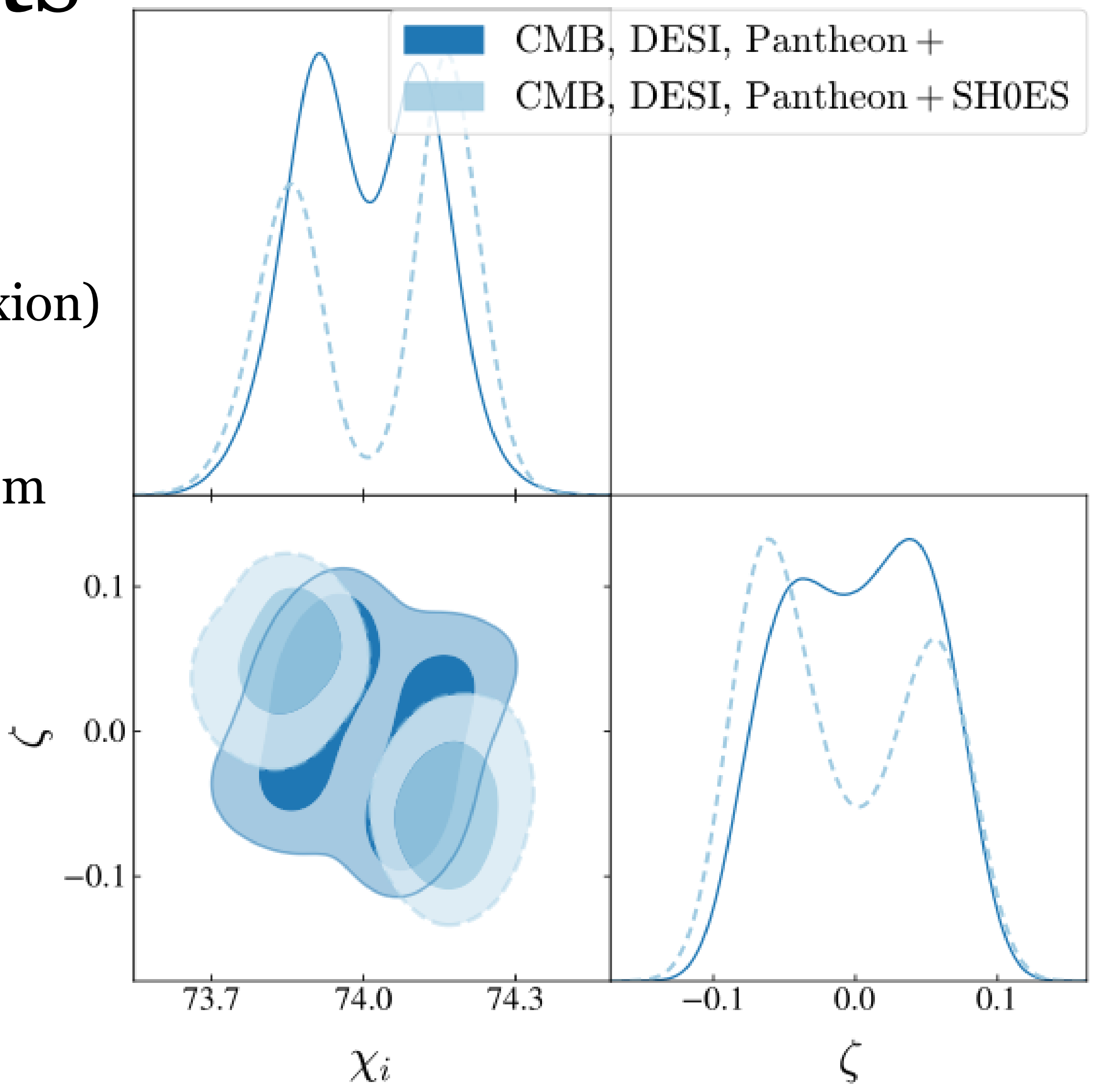
Power Spectra of the CMB





Coupling Constraints

- Late time ISW effect is constraining:
  - Dark energy (dilaton) – Dark matter (axion) coupling to $\zeta < 0.1$
  - Initial condition of dilaton $< 0.2\ M_{pl}$ from local minimum



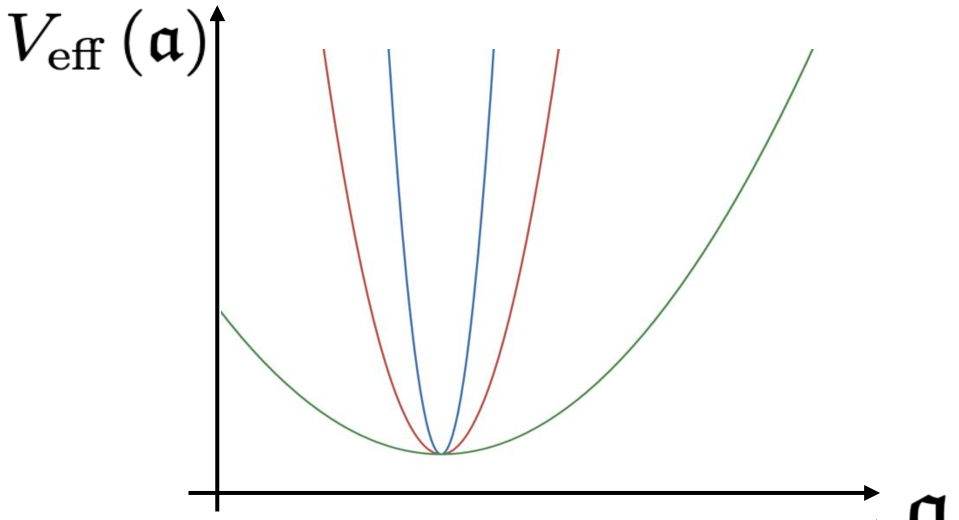
$$W = W_0 e^{-\zeta \chi}$$

Axion Phenomenology

$$\mathfrak{a} = \bar{\mathfrak{a}}(\bar{\rho}) + \frac{1}{\sqrt{2}}\left(e^{-i\int_0^t dt\,\mathfrak{m}(t)}\psi + e^{i\int_0^t dt\,\mathfrak{m}(t)}\psi^\star\right), \quad \text{where} \quad \mathfrak{m}^2(t) = \frac{m_\mathfrak{a}^2}{W^2(\bar{\chi})}$$

$$V(a) = \frac{m_\mathfrak{a}^2}{2}(\mathfrak{a} - \mathfrak{a}_+)^2 + \dots$$

$$\bar{\rho}_\mathfrak{a} = \frac{C\mathfrak{m}(t)}{a^3}$$



Yoga Dilatons

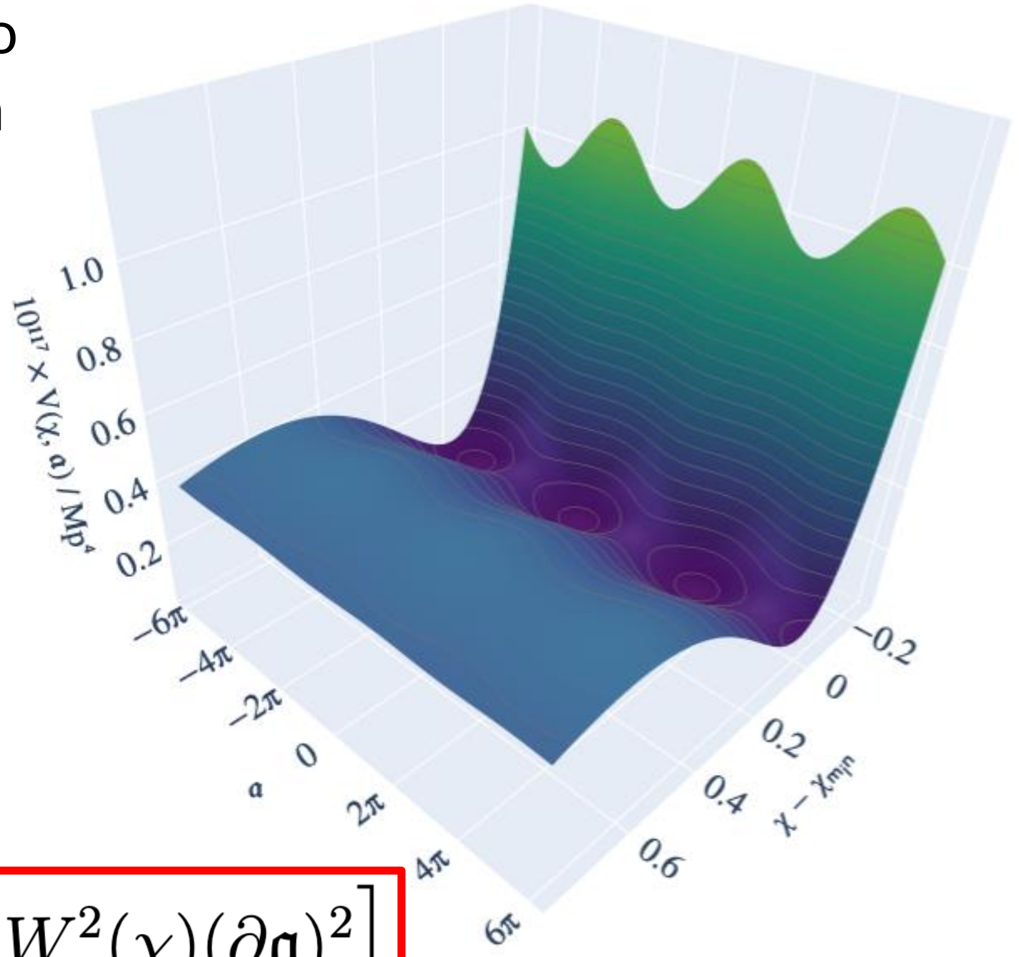
arXiv:2111.07286: **Yoga Dark Energy** C.P. Burgess, Danielle Dineen, F. Quevedo

- Special class of dilatons that are designed to address the cosmological constant problem

- Approximate scale invariance supplied by the dilaton

- Supersymmetric gravity sector
  (No Standard Model SUSY)

- Relaxation framework



$$\mathcal{L}_{axio-dilaton} = -\frac{1}{2} M_p^2 \sqrt{-g} \left[(\partial\chi)^2 + W^2(\chi)(\partial \mathfrak{a})^2 \right]$$

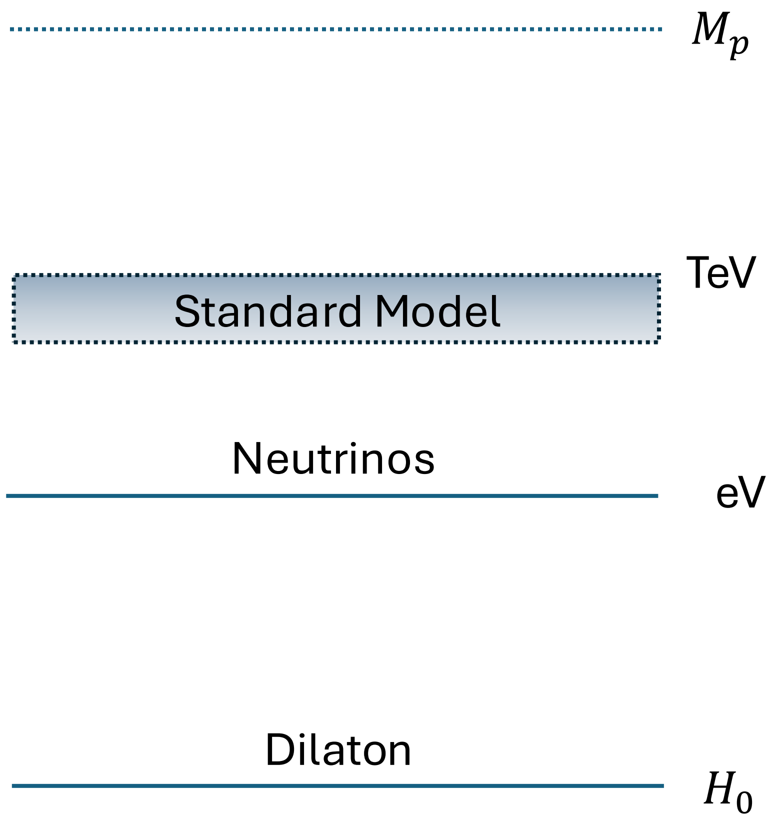
Yoga Dilatons

arXiv:2111.07286: **Yoga Dark Energy** C.P. Burgess, Danielle Dineen, F. Quevedo

- In these models, **all** scales track the dilaton

$$m_{\rm ew} \propto \sqrt{e^{-\zeta\chi}}$$
$$m_\nu \propto e^{-\zeta\chi}$$
$$m_\chi \propto e^{-2\zeta\chi}$$

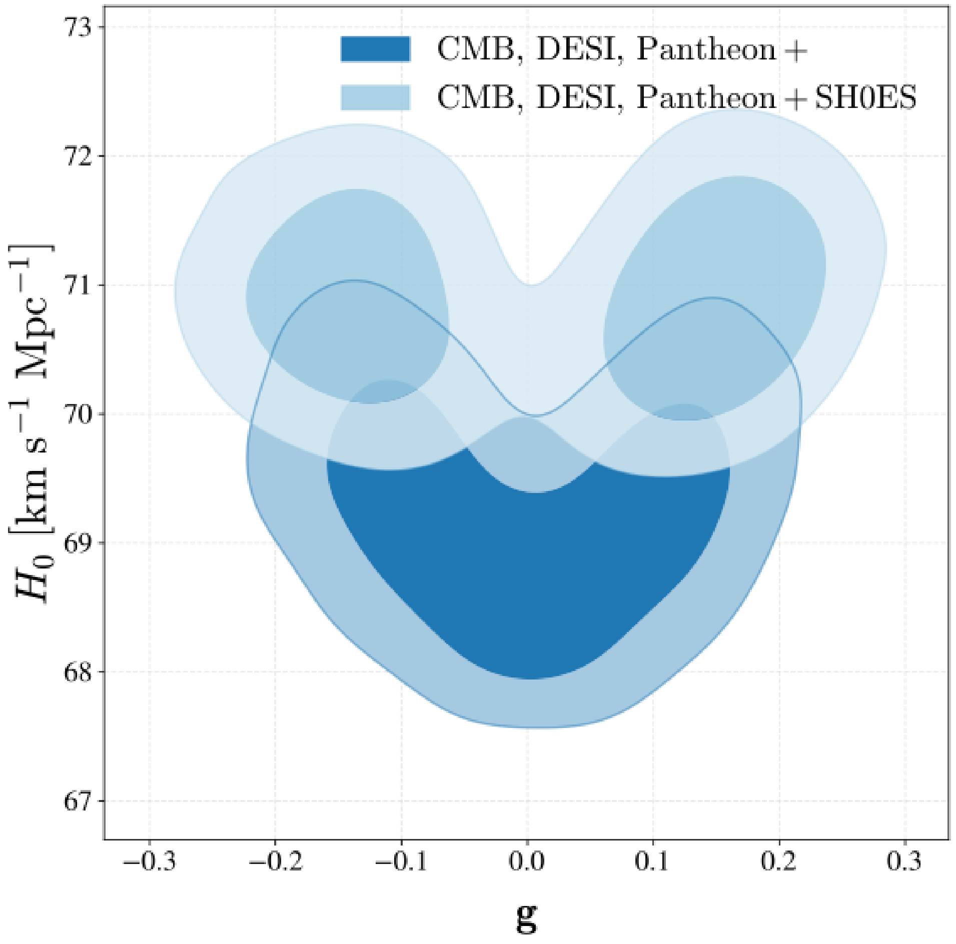
- **Every** field's vacuum potential gets supressed as dilaton rolls down to the dark energy scale



Yoga Dilatons

$$m_B(\chi) = m e^{\mathbf{g}\chi}$$

$$\mathbf{g} = -1/\sqrt{6} \approx -0.4$$



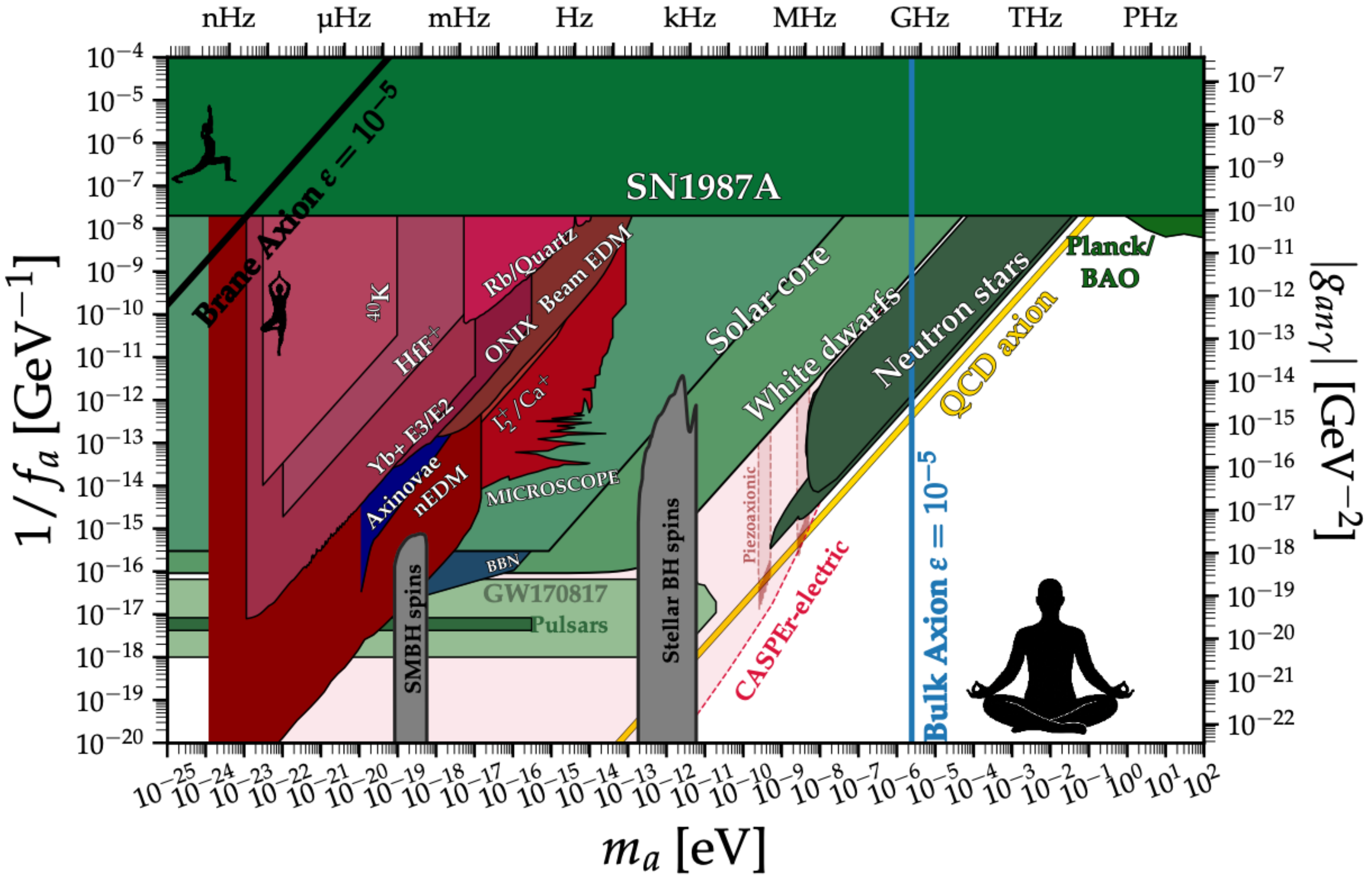
Off by a factor of 2!

QCD Axions in Yoga Models

- QCD Axions don’t work in this setup.
- Scalar potential of axions gets supressed by the dilaton.

$$V_{\rm vac}(\mathfrak{a}, \tau) \;=\; -\,\varepsilon^2\, V_0\,\left[1 - \cos(\mathfrak{a})\right] e^{-\lambda\chi}$$

- Matter coupling dominates.
- Higgs & collider physics work in these models!



Particle Mass Variation

$$m_i(z) = A(\chi)\, m_i^{(0)} \qquad \Lambda_{\rm QCD}(z) = A(\chi)\, \Lambda_{\rm QCD}^{(0)}$$

- Cosmology accommodates up to 10% shifts
- Astrophysics has no constraint

Epoch / probe	z range	Observable	Mass dependence	Constraint
BBN	$z \sim 10^9$–10^7	Y_p, D/H, ^{3}He, ^{7}Li	Δm_{np}, $Q_{n\beta}$, B_D	$\lvert\Delta \ln A\rvert_{\rm BBN} \lesssim 10^{-2}$
CMB (recombination)	$z \simeq 1100$	Peaks, damping tail	m_e via E_H, σ_T	$\lvert\Delta \ln A\rvert_{z\simeq 1100} \lesssim 2\times 10^{-2}$
CMB (drag)	$z \simeq z_d \sim 10^3$	Sound horizon $r_s(z_d)$	m_B, m_e via $R = 3\rho_B/4\rho_\gamma$	$\lvert\Delta \ln A\rvert_{\rm drag} \lesssim (6$–$14)\times 10^{-3}$
CMB (post-rec.)	$10^4 \gtrsim z \gtrsim 10^2$	τ, kSZ, μ/y distortions	m_e through σ_T, ionisation	$\lvert\Delta \ln A\rvert_{\rm post} \lesssim \mathcal{O}(10^{-1})$
BAO / LSS	$z \lesssim 3$	D_H/r_s, D_M/r_s, $f\sigma_8$	Ω_B, Ω_m via $A(\chi)$	$\lvert\Delta \ln A\rvert_{z<3} \lesssim \text{few}\times 10^{-2}$
21 cm	$z \sim 10$–200	Global signal, $P_{21}(k)$	μ, residual $x_e(m_e)$	$\lvert\Delta\mu/\mu\rvert \sim 10^{-3}$ (forecast, non-univ.)
Astrophysics	$z \lesssim 1$	Stellar tracks, SNe Ia	Environment-dependent $A(\chi)$ (screened)	None if universal; strong if broken
Spectroscopy	$0 \lesssim z \lesssim 4.5$	Atomic / molecular lines	μ (inversion, vib/rot)	$\lvert\Delta\mu/\mu\rvert \lesssim 3\times 10^{-8}$ (non-univ.)
Geochemical	$z \simeq 0$	Resonances, decay Q	$m_q/\Lambda_{\rm QCD}$ vs. m_e	10^{-7}–10^{-6} (non-univ.)
Laboratory	$z \simeq 0$	Clocks, EP tests	$\dot\mu/\mu$, $\dot\alpha/\alpha$	$<10^{-17}\,{\rm yr}^{-1}$; $\eta \lesssim 10^{-13}$

- Only thing that can constrain these models are gravity tests

SPT data Included

Model	Dataset	H_0	$\mathbf{g}$	ζ	χ_i	$R-1$	$\Delta\chi^2$
Yoga-VI	CMB-B DESI PP	69.19 ± 0.70 (69.13)	0.003 ± 0.095 (-0.052)	0.002 ± 0.050 (-0.003)	74.020 ± 0.150 (73.844)	0.075	-7.2
	CMB-B DESI	69.42 ± 0.71 (69.50)	-0.012 ± 0.098 (-0.037)	-0.001 ± 0.048 (-0.032)	$73.98^{+0.21}_{-0.18}$ (73.814)	0.228	-6.8
EXP	CMB-B DESI PP	69.16 ± 0.68 (69.99)	0.002 ± 0.093 (0.104)	-0.001 ± 0.044 (-0.022)	–	0.165	-7.3
	CMB-B DESI	69.38 ± 0.71 (70.16)	$-0.013^{+0.090}_{-0.10}$ (-0.164)	0.001 ± 0.045 (0.071)	–	0.596	-6.2
	CMB-B	$67.47^{+0.68}_{-1.2}$ (67.78)	-0.004 ± 0.074 (0.041)	0.001 ± 0.048 (-0.002)	–	0.039	–
w0-wa + me	CMB-B DESI PP	68.40 ± 0.84 (68.51)	–	–	–	0.007	-12.3
	CMB-B DESI	$64.2^{+1.9}_{-2.6}$ (63.78)	–	–	–	0.041	-10.5
w0-wa	CMB-B DESI PP	67.65 ± 0.59 (67.52)	–	–	–	0.010	-9.6
Λ CDM	CMB-B DESI PP	68.04 ± 0.26 (68.25)	–	–	–	0.007	0.0
	CMB-B DESI	68.13 ± 0.26 (68.23)	–	–	–	0.006	0.0

TABLE IV: Posterior means with quoted 1σ marginal uncertainties and best-fit values in parentheses for all models fit to the CMB-B dataset combinations including SPT-3G. Columns list the inferred Hubble constant, the dilaton coupling $\mathbf{g}$, the axion CDM kinetic coupling ζ, the initial dilaton value χ_i when present, and the change in best-fit $\Delta\chi^2$ relative to the corresponding ΛCDM run.

Coupling just base datasets

Model	Dataset	H_0 [km s^{-1} Mpc^{-1}]	g	ζ	χ_i	$R-1$	$\Delta\chi^2$
Yoga-VI	CMB-A DESI PP	$69.18^{+0.63}_{-0.81}$ (69.71)	0.00 ± 0.10 (0.14)	0.002 ± 0.052 (-0.061)	74.00 ± 0.13 (74.10)	0.071	-2.1
	CMB-A DESI	$69.38^{+0.68}_{-0.83}$ (69.61)	0.00 ± 0.10 (0.15)	0.000 ± 0.052 (-0.060)	74.00 ± 0.14 (74.09)	0.034	-3.5
(no-m_e)	CMB-A DESI PP	68.50 ± 0.35 (68.51)	0.006 ± 0.083 (-0.009)	-0.001 ± 0.054 (-0.050)	$74.01^{+0.18}_{-0.16}$ (73.88)	0.016	-2.1
Yoga	CMB-A DESI PP	68.42 ± 0.35 (68.33)	-0.038 ± 0.086 (-0.055)	$0.020^{+0.077}_{-0.094}$ (0.032)	–	0.010	-0.7
	CMB-A DESI	68.53 ± 0.36 (68.54)	-0.041 ± 0.088 (-0.078)	$0.023^{+0.076}_{-0.097}$ (0.050)	–	0.025	-1.8
EXP	CMB-A DESI PP	$69.10^{+0.64}_{-0.76}$ (68.81)	-0.003 ± 0.099 (0.127)	0.005 ± 0.049 (-0.058)	–	0.082	-2.7
	CMB-A DESI	$69.35^{+0.69}_{-0.78}$ (69.96)	$0.004^{+0.12}_{-0.098}$ (-0.167)	-0.001 ± 0.049 (0.077)	–	0.057	-3.8
	CMB-A	$68.03^{+0.78}_{-1.6}$ (67.43)	0.000 ± 0.089 (-0.013)	0.001 ± 0.051 (0.036)	–	0.051	-1.1
w0-wa + me	CMB-A DESI PP	68.26 ± 0.87 (68.29)	–	–	–	0.008	-8.2
	CMB-A DESI	$63.9^{+1.9}_{-2.7}$ (64.78)	–	–	–	0.006	-8.6
w0-wa	CMB-A DESI PP	67.64 ± 0.60 (67.71)	–	–	–	0.012	-6.9
Λ CDM+me	CMB-A DESI PP	69.62 ± 0.69 (69.91)	–	–	–	0.007	-2.6
	CMB-A DESI	69.85 ± 0.69 (70.12)	–	–	–	0.006	-4.2
Λ CDM	CMB-A DESI PP	68.30 ± 0.28 (68.03)	–	–	–	0.021	0.0
	CMB-A DESI	68.39 ± 0.29 (68.53)	–	–	–	0.009	0.0
	CMB-A	67.30 ± 0.54 (67.27)	–	–	–	0.007	0.0

TABLE III: Posterior means with 1σ confidence intervals, best-fit values in parentheses, and $\Delta\chi^2$ relative to the corresponding ΛCDM run for each dataset combination. The table summarises how the different axio–dilaton (Yoga and EXP), w_0–w_a, and varying-m_e models shift H_0, the scalar couplings ($\mathbf{g}, \zeta$), and the overall goodness of fit relative to ΛCDM across the CMB-A, CMB-A DESI, and CMB-A DESI PP datasets.