Early Dark Energy and Phantom Crossing in axio-dilaton Systems

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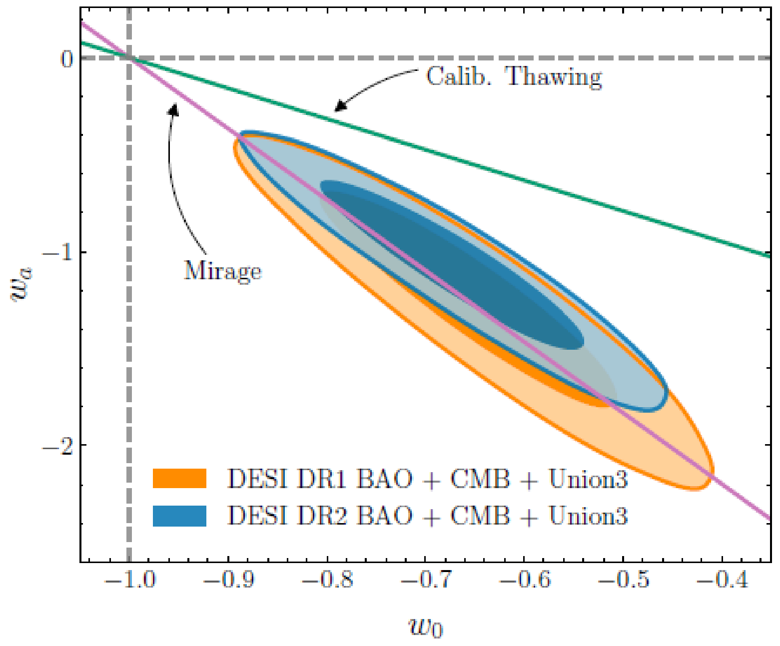
Late Dark Energy

$$w_0 + w_a < -1$$

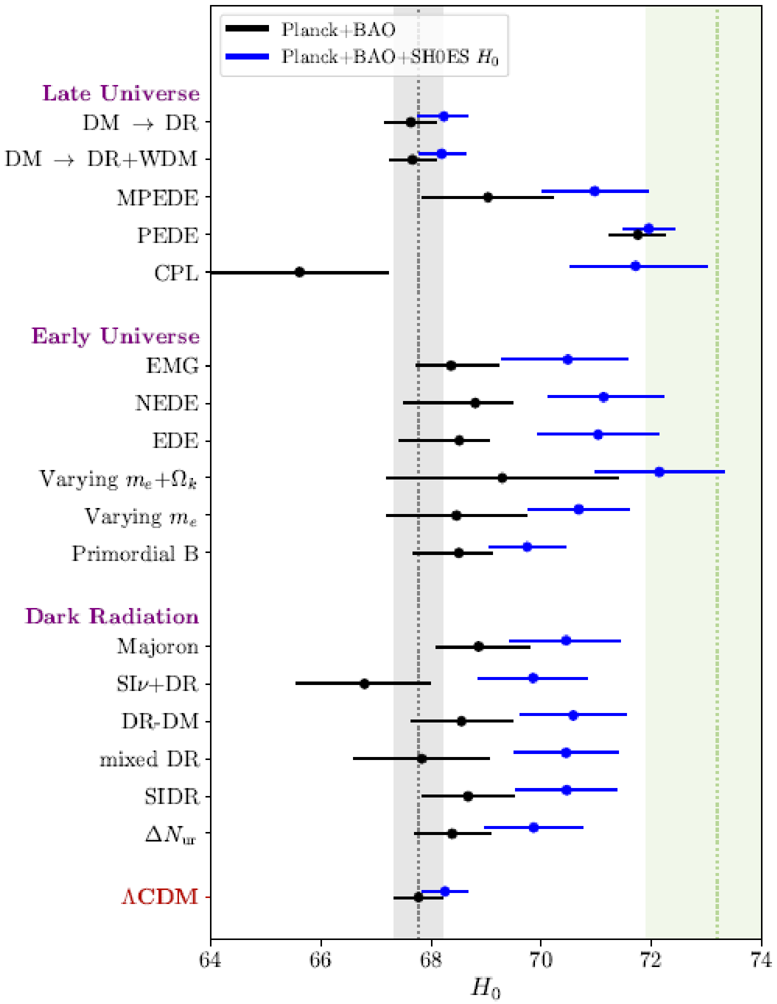
Phantom crossing

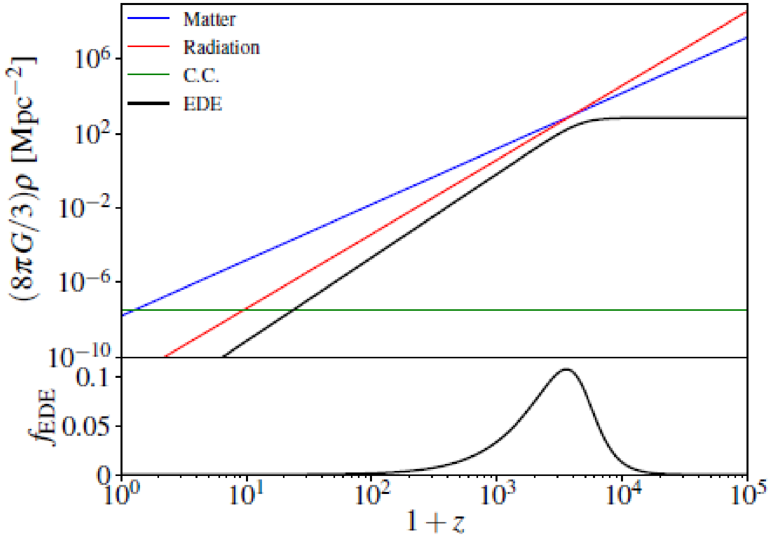


$$\omega = \omega_0 + \omega_a(1-a)$$

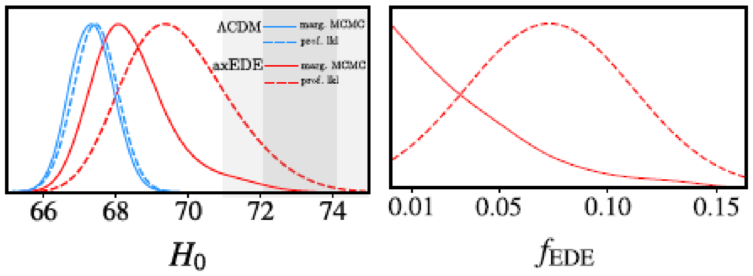
E pur si muove !

Early Dark Energy





Early dark energy fraction



The low energy description

On large scales, GR can be seen as the lowest order effective action involving the metric up to two derivatives:

$$S_{\mathrm{Einstein-Hilbert}} = \frac{m_{\mathrm{Pl}}^2}{2}\int d^4x\sqrt{-g}(R+\dots)$$

Incorporating a single scalar field, the effective action up to second order in derivatives:

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G_N} - \frac{(\partial\phi)^2}{2} - V(\phi) + \mathcal{L}_m(\psi_i, \tilde{g}_{\mu\nu})\right)$$

$$\tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}$$

Higher order terms in derivatives are suppressed unless breaking the expansion scheme by terms of order:

$$\partial/H = \mathcal{O}(1)$$

In these theories the effective potential takes into account the presence of matter

$$V_{\rm eff}(\varphi) = V(\varphi) + (\frac{A(\varphi)}{A(\varphi_c)} - 1)\rho_m$$

The conserved matter density is related to the Einstein frame density by

$$\rho_E = \frac{A(\varphi)}{A(\varphi_c)}\rho_m$$

The dark energy density becomes:

$$\rho_{\rm eff} = \frac{1}{2}\dot\varphi^2 + V_{\rm eff}(\varphi)$$

Calibration with the observed matter density is taken when

$$\varphi = \varphi_c$$

Conservation of dark energy reads:

$$\dot\rho_{\rm eff} + 3H(1+\omega_{\rm eff})\rho_{\rm eff} = 0$$

Calibration is usually taken to be now but in principle this has to be determined by comparison with data.

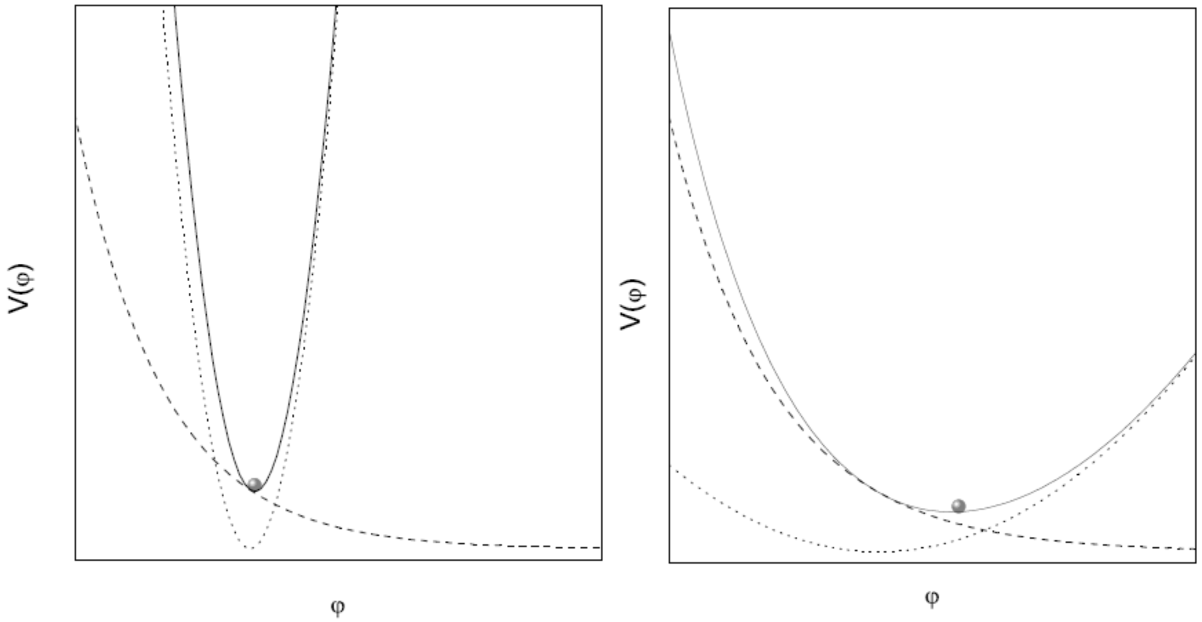
$$\omega_{\rm eff} = \frac{p_\varphi}{\rho_{\rm eff}}$$

$$p_\varphi = \frac{1}{2}\dot\varphi^2 - V(\varphi)$$

Assume that the effective potential has a minimum

$$\frac{dV}{d\phi} = -\frac{\beta(\phi)}{m_{\rm Pl}}\frac{A(\phi)}{A(\phi_c)}\rho_m$$

$$\beta(\phi) = m_{\rm Pl}\frac{d\ln A(\phi)}{d\phi}$$



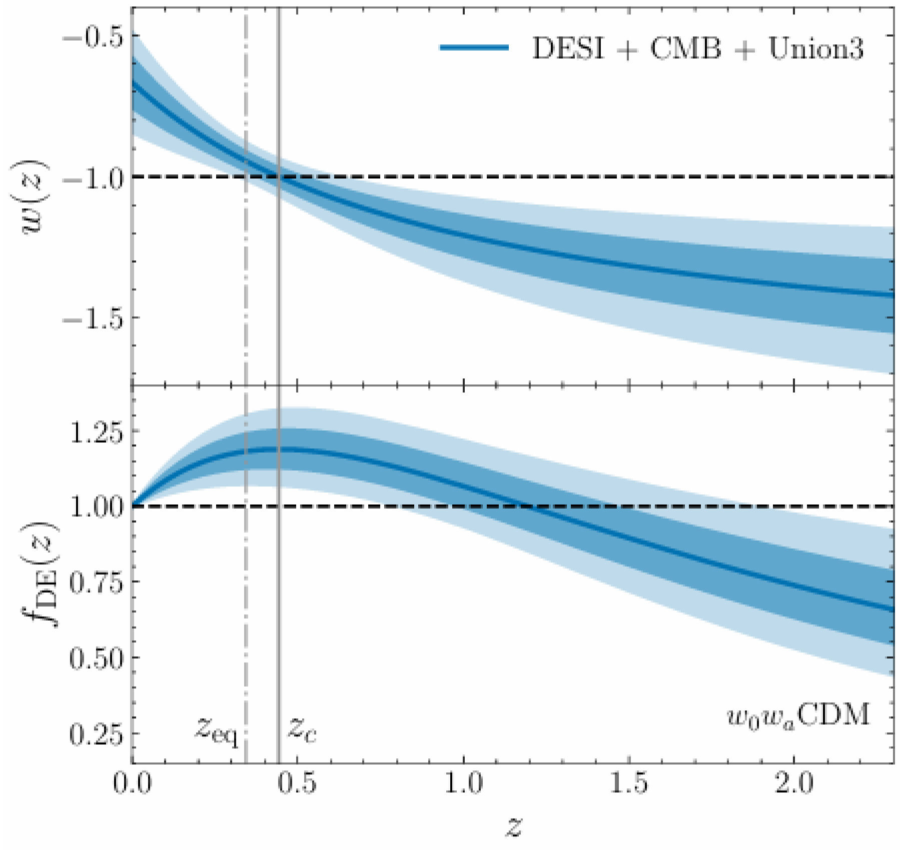
Concentrate on the evolution of the minimum close to calibration taken to be at low redshift:

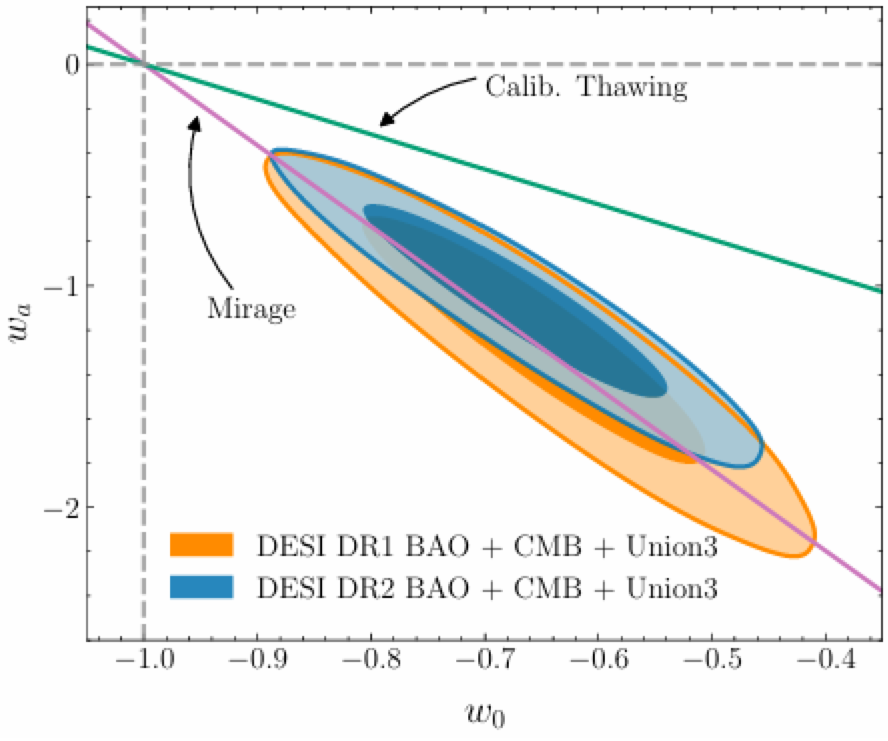
$$\phi - \phi_c = -\frac{\beta(\phi_c)}{m^2_{\rm eff} m_{\rm Pl}}(\rho_m - \rho_c)$$

$$m^2_{\rm eff} = \frac{d^2 V_{\rm eff}}{d\phi^2}|_{\phi=\phi_c}$$

$$\omega_{\rm eff} = -\frac{1}{1-\beta^2(\phi_c)\frac{\rho_m}{V_{\rm DE}}\frac{(\rho_m-\rho_c)}{m^2_{\rm Pl} m^2_{\rm eff}}}$$

$$V_{\rm DE} = V(\phi_c)$$





$$-1.6 \leq \omega_a \leq -0.8$$

$$\omega_0 = -1 + \frac{z_c}{z_c+1}\omega_a \Rightarrow z_c \sim 0.37$$

1/3.66

$$\frac{\beta^2(\phi_c)H_0^2}{m_{\text{eff}}^2} = -\frac{\Omega_{\Lambda 0}}{9\Omega_{m0}^2(1+z_c)^5}\omega_a$$

$$0.047 \leq \frac{\beta^2(\phi_c)H_0^2}{m_{\text{eff}}^2} \leq 0.093$$

$$\omega_{\rm eff} = -\frac{1}{1-\beta^2(\phi_c)\frac{\rho_m}{V_{\rm DE}}\frac{(\rho_m-\rho_c)}{m_{\rm Pl}^2 m_{\rm eff}^2}}$$

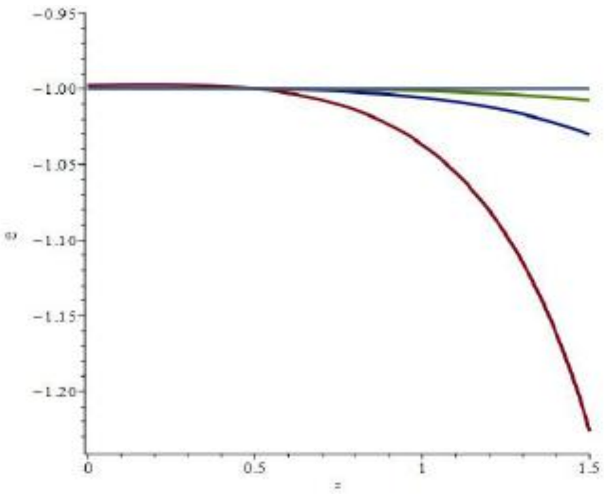
- Crosses the phantom divide when: $\rho_m < \rho_c$

- Negligible variation unless: $m_{\rm eff} \simeq H_0, \quad \beta(\phi_c) \sim 1$

Two major issues!

- ❑ For such a low mass, the minimum is not an attractor so undamped oscillations. Need to make comparison in Jordan frame.
- ❑ Long range forces with gravitational strength!

- Interactions between DE-DM

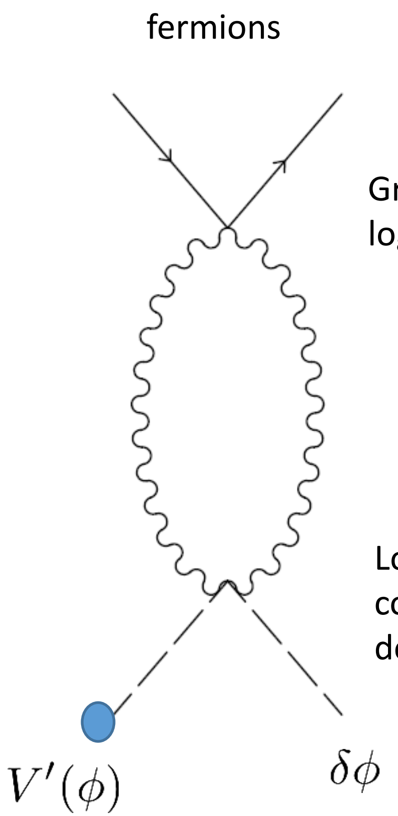


$z_c = 0.5$

$$\beta(\phi_c) = 0.1, \frac{m_{\rm eff}}{H_0} = 2, 5, 10, 10^3$$

- Interaction between DE-baryon

Could be postulated to vanish…

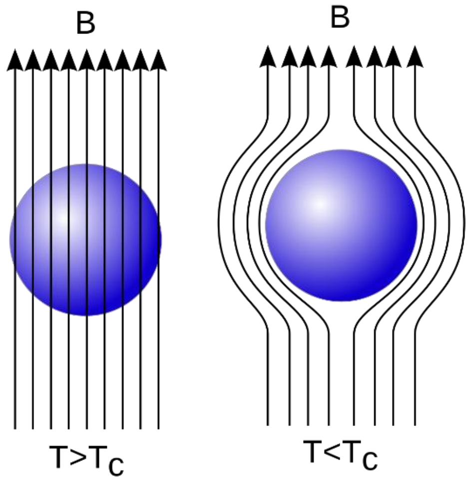


Gravitation induces a logarithmically divergent coupling.

Logarithmic running of the coupling from a value determined in the UV.

Generically non-vanishing coupling becomes unobservable thanks to:

Screening



In single field case, screening implies:

$$m_{\rm eff}/H_0 \gtrsim 10^3 \Rightarrow \omega_{\rm eff} \simeq -1$$

Multi-field dark energy sector

$$\mathcal{L} = -\frac{1}{2} g_{ij}(\phi^k)\partial_\mu \phi^i \partial^\mu \phi^j - V(\phi^i)$$

For light dark energy fields, such a screening can only happen with more than one field and a **non-trivial σ-model metric**.

Screening even if dark energy field **light** and with non-negligible **coupling to matter**

$$\mathcal{L} \supset -\frac{1}{2}((\partial\phi)^2 + W^2(\phi)(\partial a)^2)$$

Dilaton **Axion**

The axio-dilaton case corresponding to the volume modulus of compactifications from 10d to 4d:

$$K = -3m_{\rm Pl}^2 \ln(T + \bar{T}) \longrightarrow \beta = \frac{1}{\sqrt{6}}$$

The volume modulus can be decomposed in:

$$T = e^{\phi} + ia \longrightarrow e^{K/6m_{\rm Pl}^2} = e^{-\phi/2}$$

dilaton

axion

Dilaton coupling to matter of order one!

$$W(\phi) = e^{-\phi}$$

Screening depends on the profile of the dilaton in compact objects

$$\Box\phi = WW'(\partial a)^2 + \frac{\beta}{m_{\rm Pl}^2}\rho$$

The screening criterion depends on the large mass of the axion inside the object

$$m_{\rm in}R \gg 1$$

It also requires a sharp jump of the axion between vacuum and matter:

$$V(a) = \frac{1}{2}m_a^2(a-a_+)^2 + \rho_m\frac{(a-a_-)^2}{2\Lambda_a^2}$$

Exponential Screening:

Screening takes place when:

$$W^2(\phi) = e^{-\xi\phi/m_{\rm Pl}}$$

The coupling to matter becomes:

$$\beta_{\rm eff} = \beta \frac{R}{2\xi G_N M}$$

Screening in solar system:

$$\xi = \sqrt{\frac{2}{3}}$$

$$\xi \gtrsim 10^9 \Rightarrow \frac{m_{\rm Pl}}{\xi} \lesssim 10^9 \mathrm{GeV}$$

$$\Lambda_\phi = \frac{m_{\rm Pl}}{\xi}$$

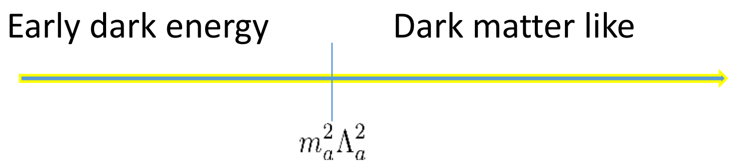
Early dark energy for free!

$$V(a) = \frac{1}{2} m_a^2 (a - a_+)^2 + \rho_m \frac{(a - a_-)^2}{2\Lambda_a^2}$$

$$V(a_-) = \frac{1}{2} m_a^2 (a_+ - a_-)^2$$

Early dark energy

A fraction of added matter



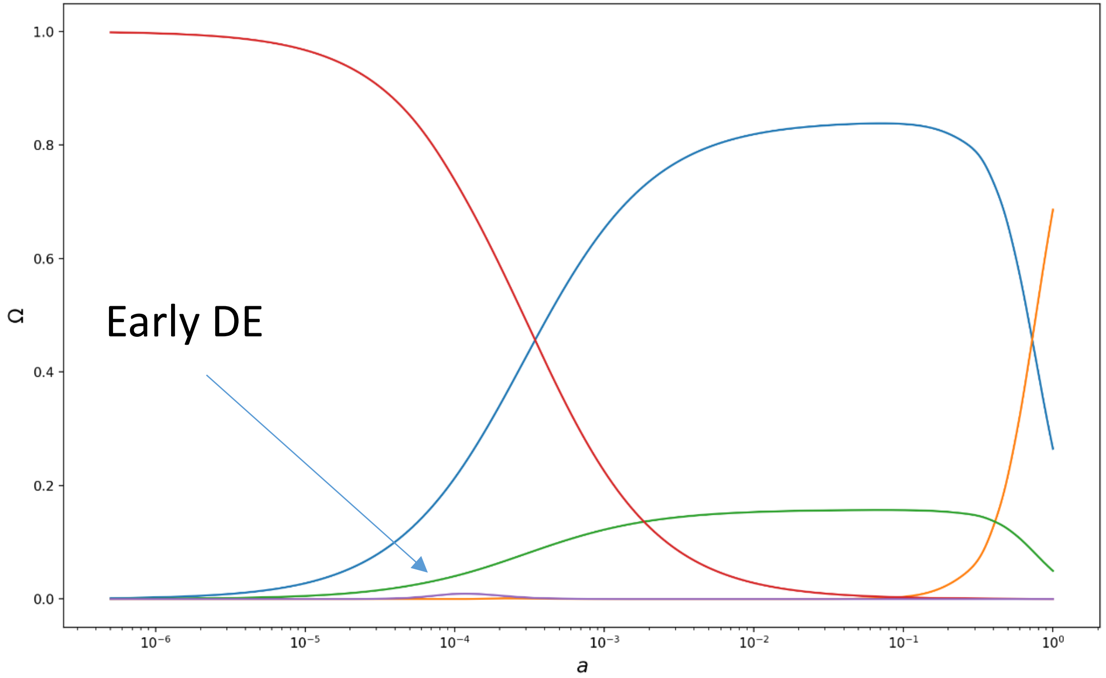
$$V(a_+) = \rho_m \frac{(a_+^2 - a_-)^2}{2\Lambda_a^2}$$

For specific application, we take an Albrecht-Skordis potential:

$$V(\phi) = U(\phi)e^{-\lambda\phi/m_{\rm Pl}}$$

Quadratic with non-trivial minimum

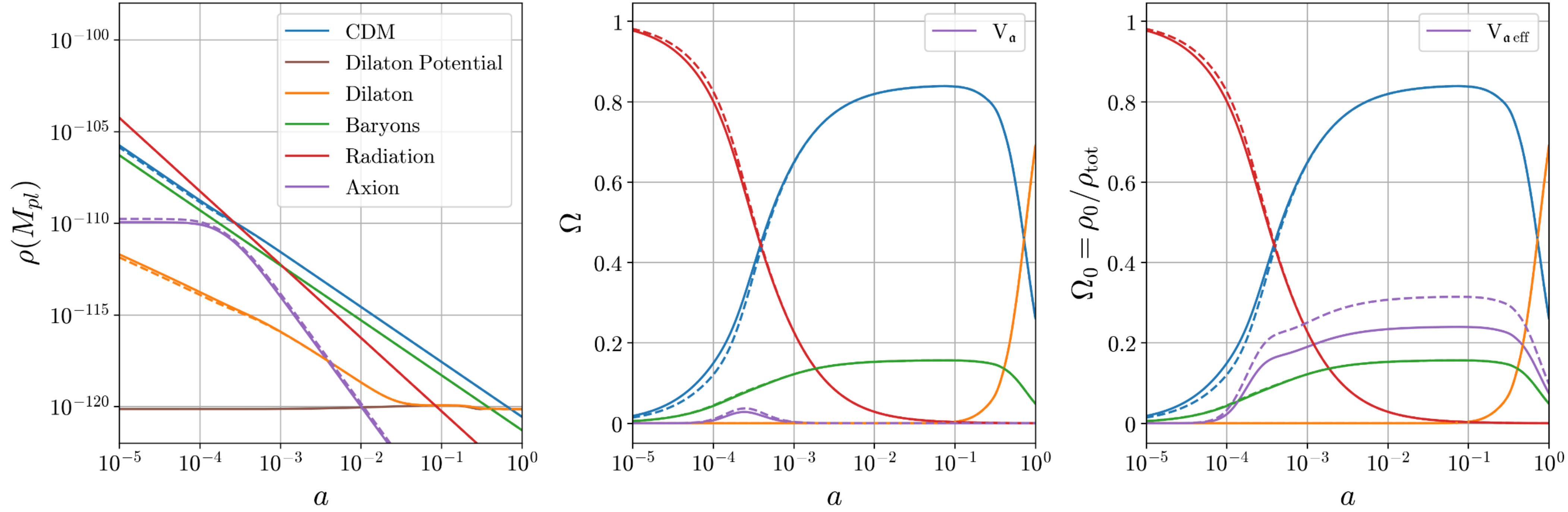
$$A(\phi) = e^{-\beta\frac{\phi}{m_{\rm Pl}}}$$



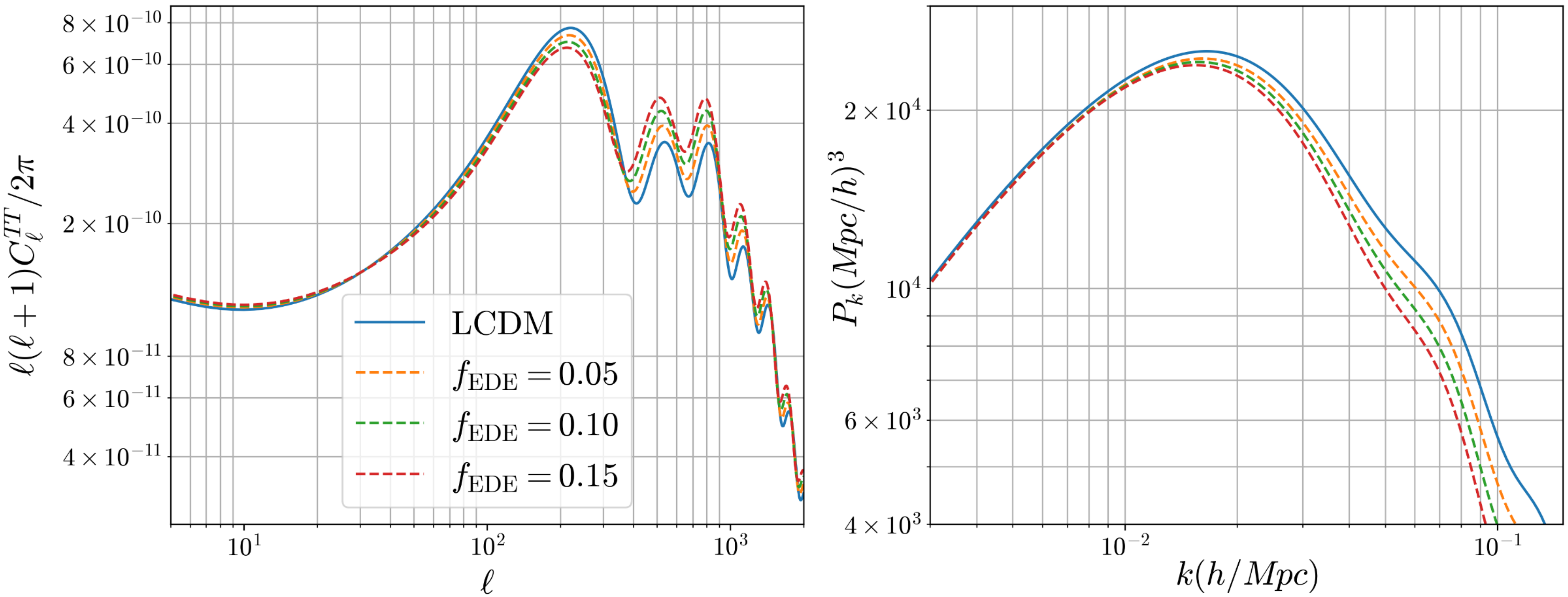
$$\lambda = 4\beta$$

Conformal rescaling

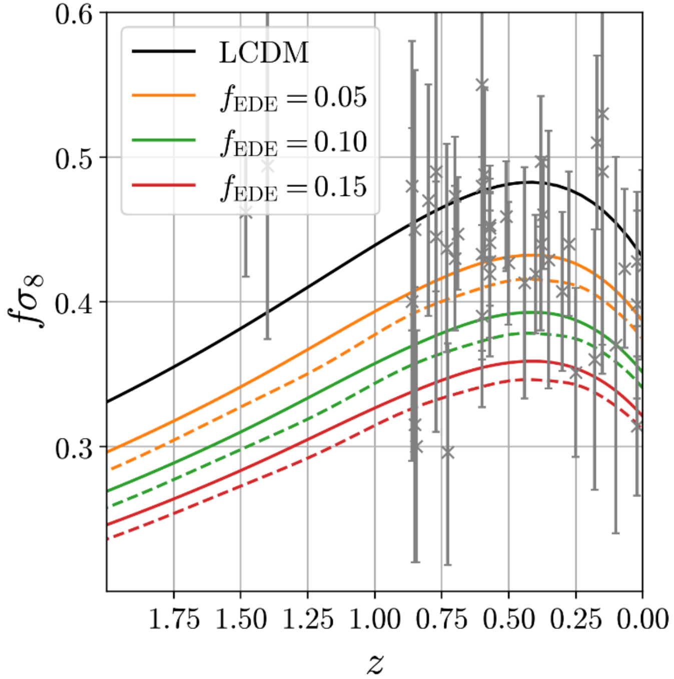
$$m_a = 2.10^{-15}\text{eV},\ \Lambda_\phi = 2.10^8\text{GeV}, \Lambda_a = 5.10^5\text{GeV}$$



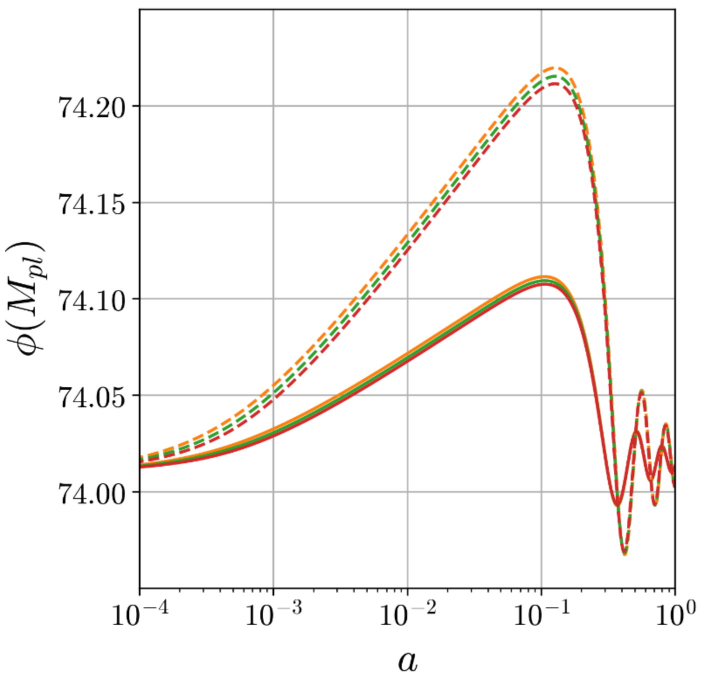
Early dark energy shows its face in the form of the axion potential.



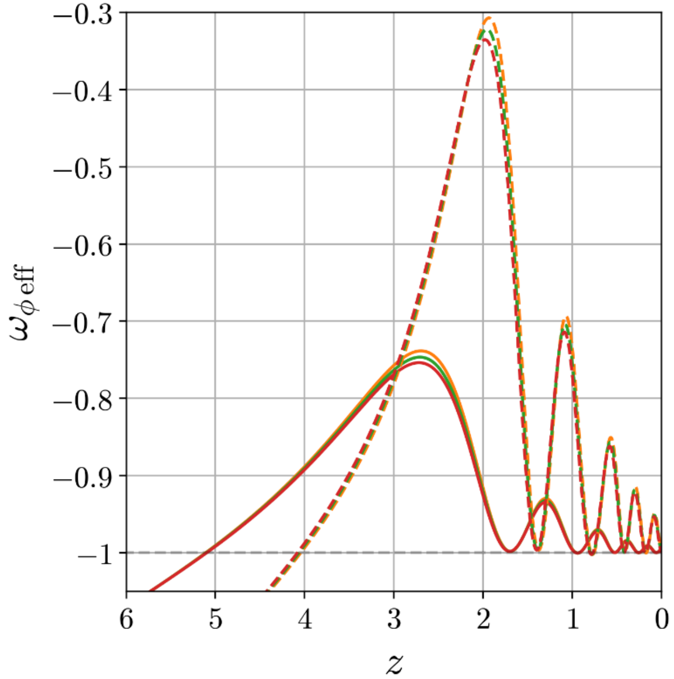
Increasing the early dark energy fraction increases the deviation from LCDM.



Dotted lines: the coupling to matter increases and growth reduces



The dilaton is light and oscillates



The effective equation states oscillates and crosses the phantom divide.

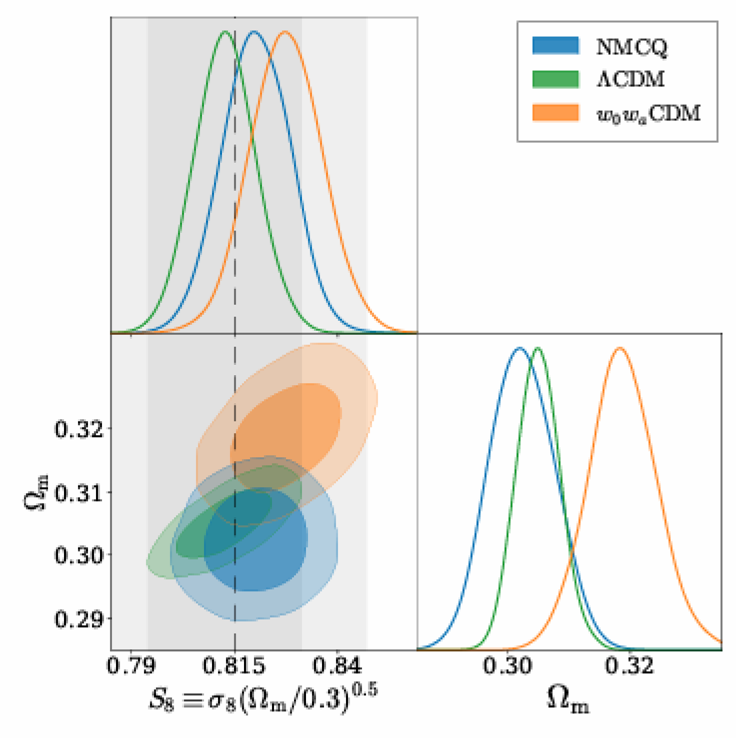
Summary

Multi-field dark energy models coupled to matter can have a number of interesting features:

- ✓ Can accommodate a fraction of early dark energy whilst screening.
- ✓ Varying equation of state crossing phantom divide and oscillations.
- ✓ Have less growth than LCDM despite long range fifth forces.

Model Building?

Prospects



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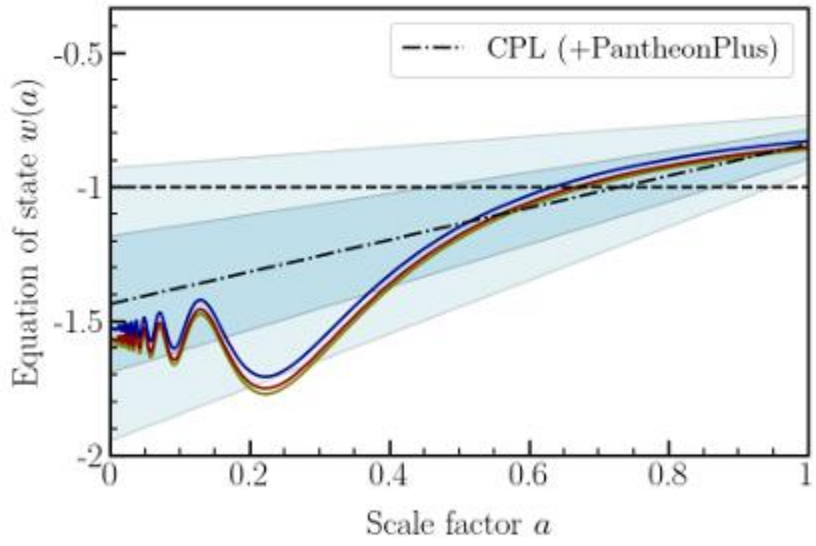

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Multi-field screening is a **natural** solution to:

an evolving equation of state crossing the **phantom** divide

A bit more