Acceleration of the Universe: Puzzles and Prospects

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The expansion of the Universe: At least ***TWO*** periods of accelerated expansion

Primordial Inflation

- ❖ Described by field theory in a well-defined way
- ❖ At the origin of the growth of structure
- ❖ The first gravitational waves of quantum origin ?

Dark Energy

- ➢ Unknown origin: Field theory? Other?
- ➢ Dynamical or not?
- ➢ Quantum origin of vacuum energy?
- ➢ Coincidence problem?

Single field inflation is a triumph of effective field theory: all the observations can be described by a **few numbers** related to the derivative of the potential during inflation.

$$\epsilon = \frac{m_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2, \quad \eta = m_{\rm Pl}^2 \frac{V''}{V}$$

Quantum fluctuations of the inflaton and of the graviton have a power spectrum:

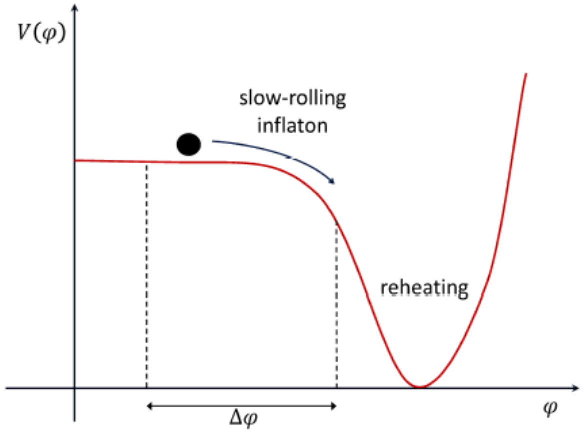
$$\mathcal{P}_\xi = A_s\left(\frac{k}{k_\star}\right)^{n_s-1} \qquad \mathcal{P}_t = A_T\left(\frac{k}{k_\star}\right)^{n_T}$$

The spectral indices are related to the slow roll parameters by:

$$n_s = 1 - 6\epsilon + 2\eta, \quad n_T = -2\epsilon$$

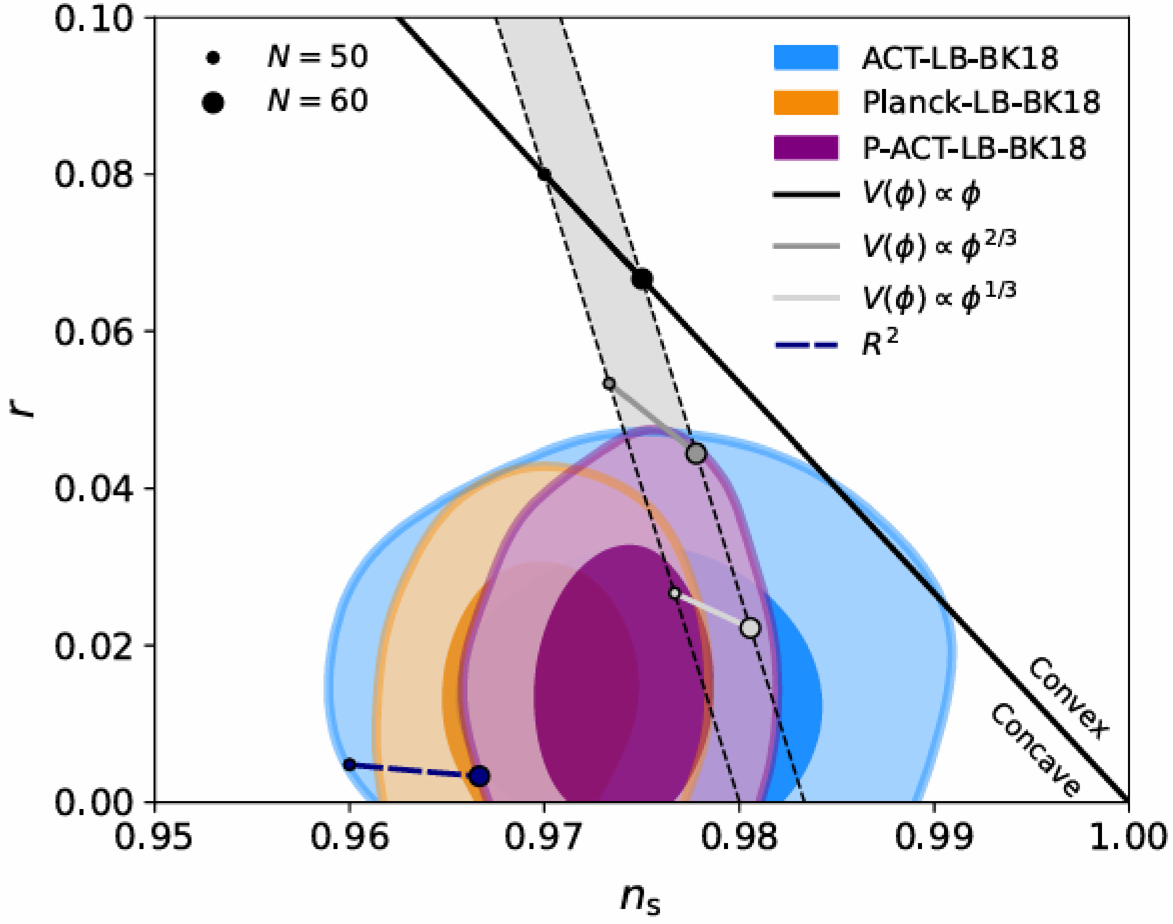
The tensor to scalar ratio is related to the tensor spectral index by the consistency relation:

$$r \equiv \frac{A_T}{A_S} = 16\epsilon = -8n_T$$



Small field inflationary model

Scalar perturbations already constrained by **Planck and ACT**, their tensorial nature is the goal of future experiments such as **Litebird.**

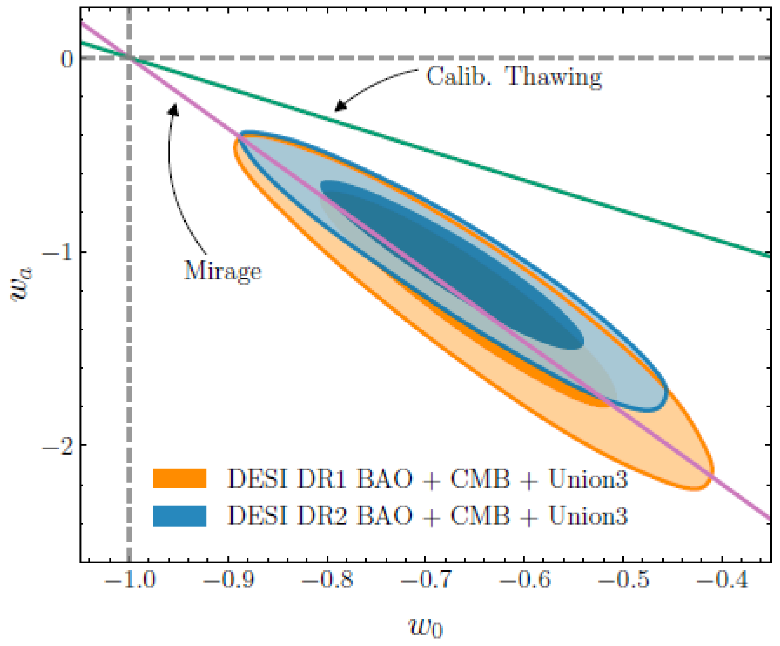


Current status

Late Dark Energy

$$w_0 + w_a < -1$$

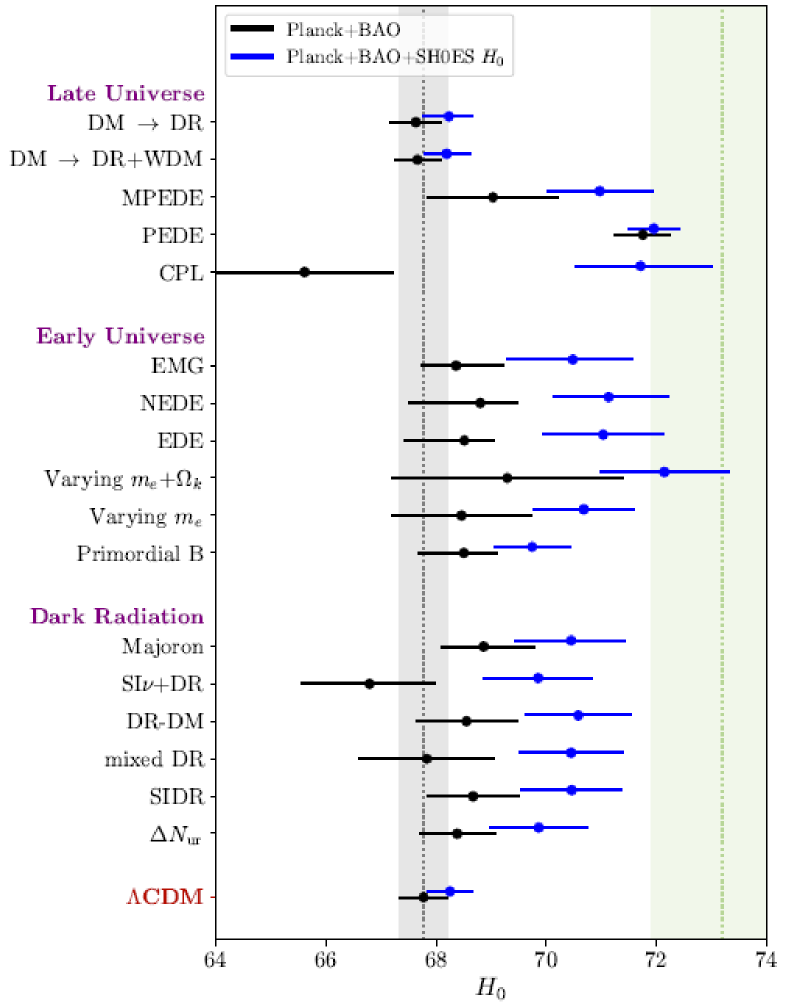
Phantom crossing

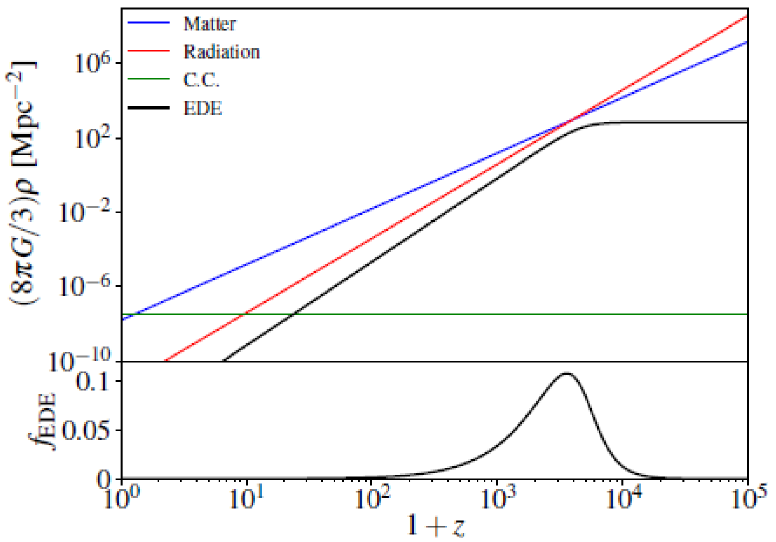


$$\omega = \omega_0 + \omega_a(1-a)$$

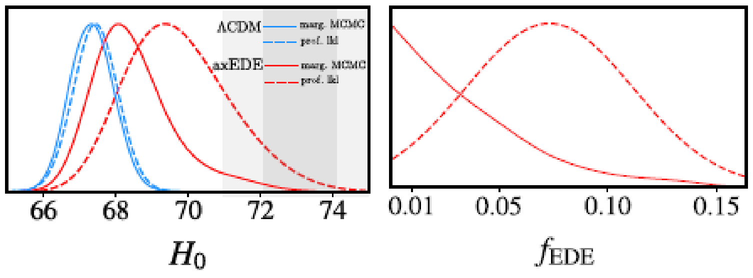
E pur si muove !

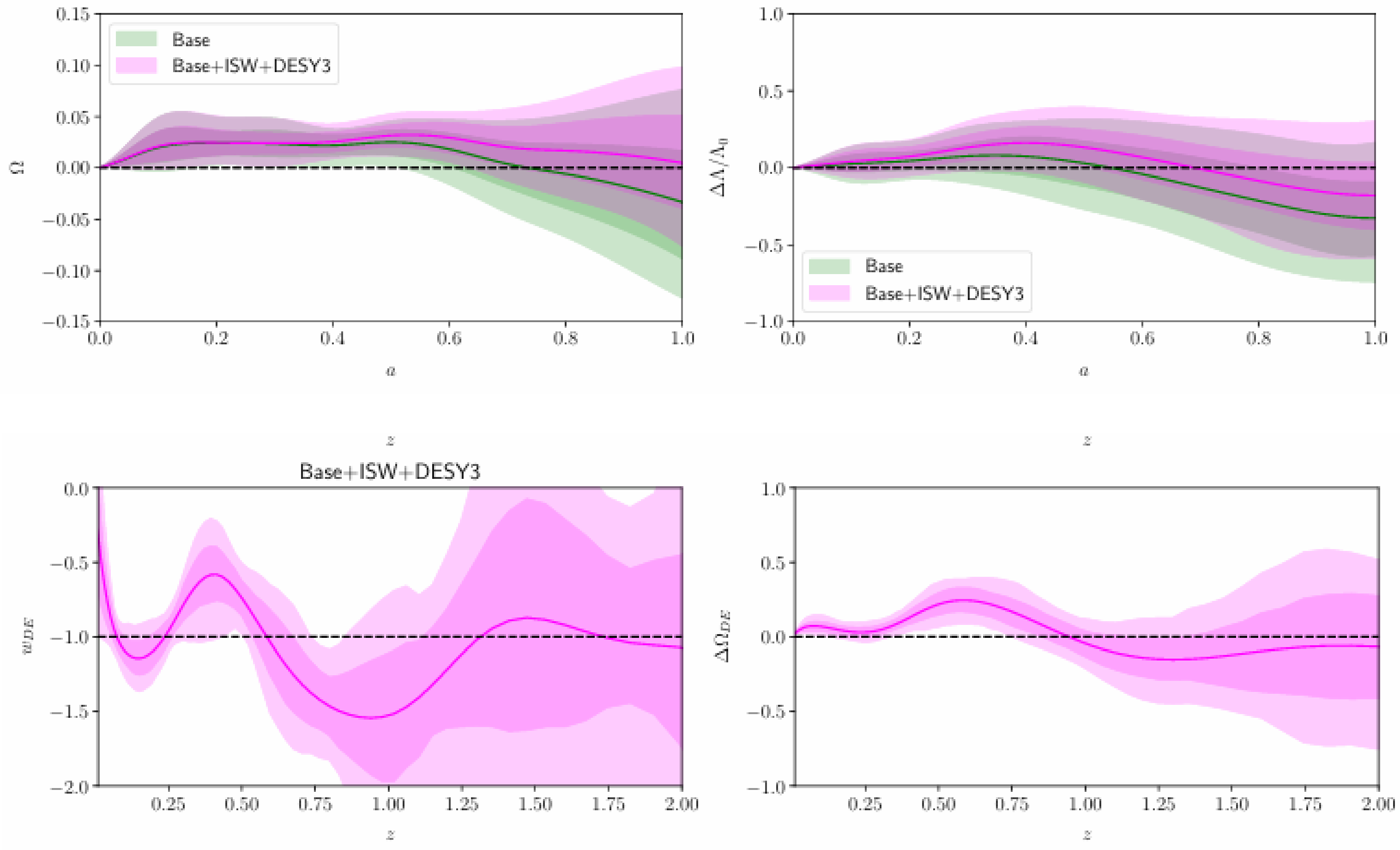
Early Dark Energy?





Early dark energy fraction





Parameterisation-independent reconstruction of the cosmological background in the effective dark energy action.

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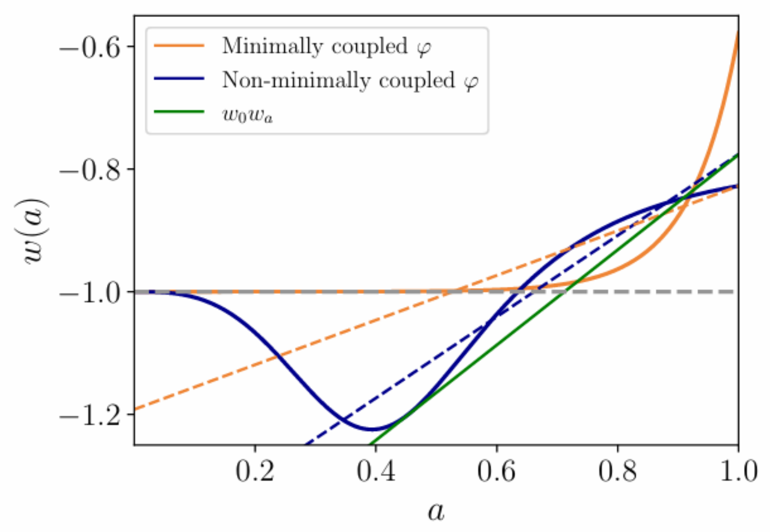
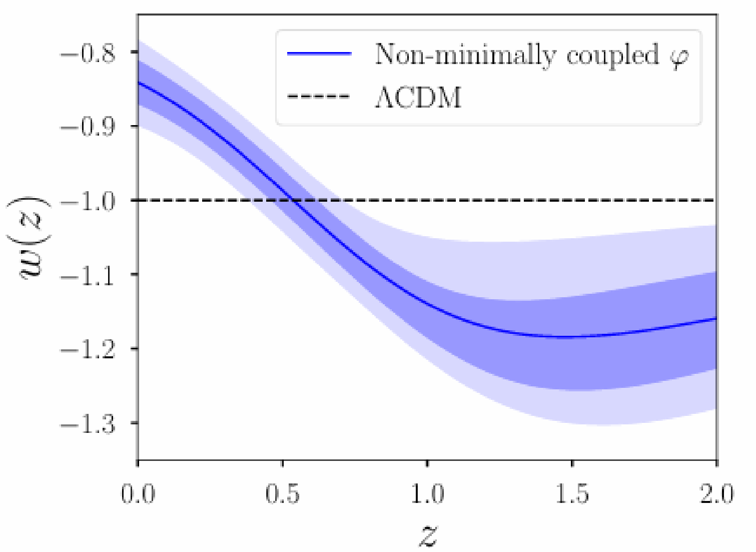
$$S = \int d^4x\sqrt{-g}\left(\frac{m_{\rm Pl}^2}{2}(1+\Omega(t))R + \Lambda(t) + \dots\right)$$





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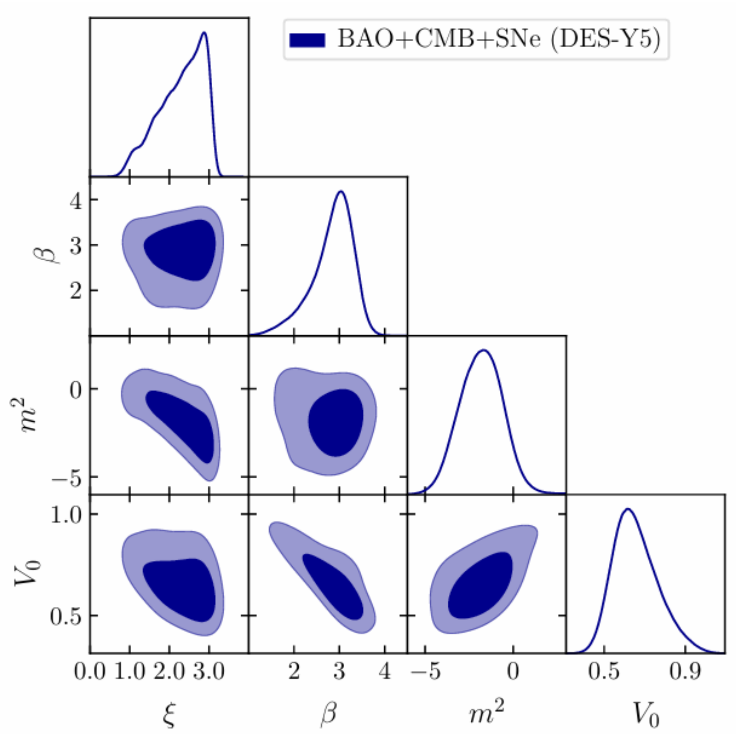
$$S = \int d^4x\sqrt{-g}(\frac{m_{\rm Pl}^2}{2}F(\phi)R - V(\phi))$$



$$F(\phi) = 1 - \xi\frac{\phi^2}{m_{\rm Pl}^2}$$

$$V(\Phi) = V_0 + \beta\phi + \frac{1}{2}m^2\phi^2$$

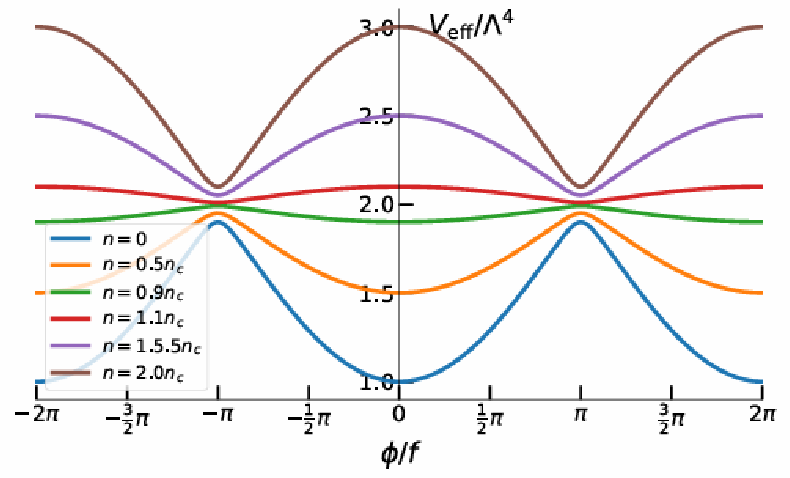
Evidence for scalar-tensor models

The models here are in the Jordan frame

QCD inspired model:

$$V(\phi) = \Lambda^4 (1 + v - \sqrt{1 - \xi \sin^2(\frac{\phi}{2f})})$$

$$A(\phi) = 1 + \frac{\sigma_N}{m_0} \sqrt{1 - \xi \sin^2(\frac{\phi}{2f})}$$



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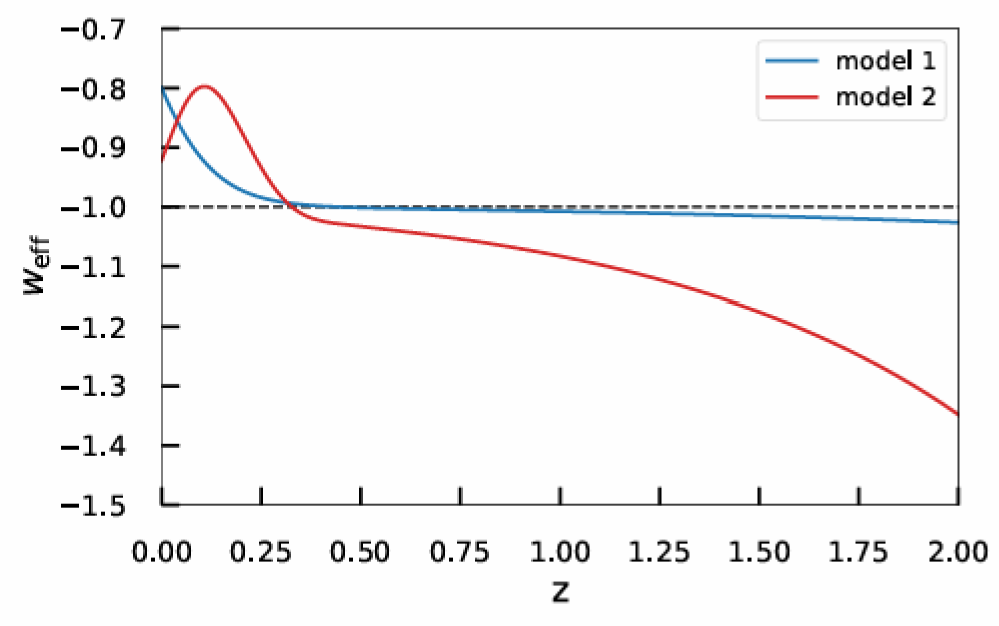


- **Model 1** has $\frac{\sigma_N}{m_0} = 0.01$, $f = 0.25\, M_{\rm Pl}$, and $v = 0$.
- **Model 2** has $\frac{\sigma_N}{m_0} = 0.02$, $f = 0.035\, M_{\rm Pl}$, and $v = 4$.

The low energy description

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

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

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

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

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

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

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

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:

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

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

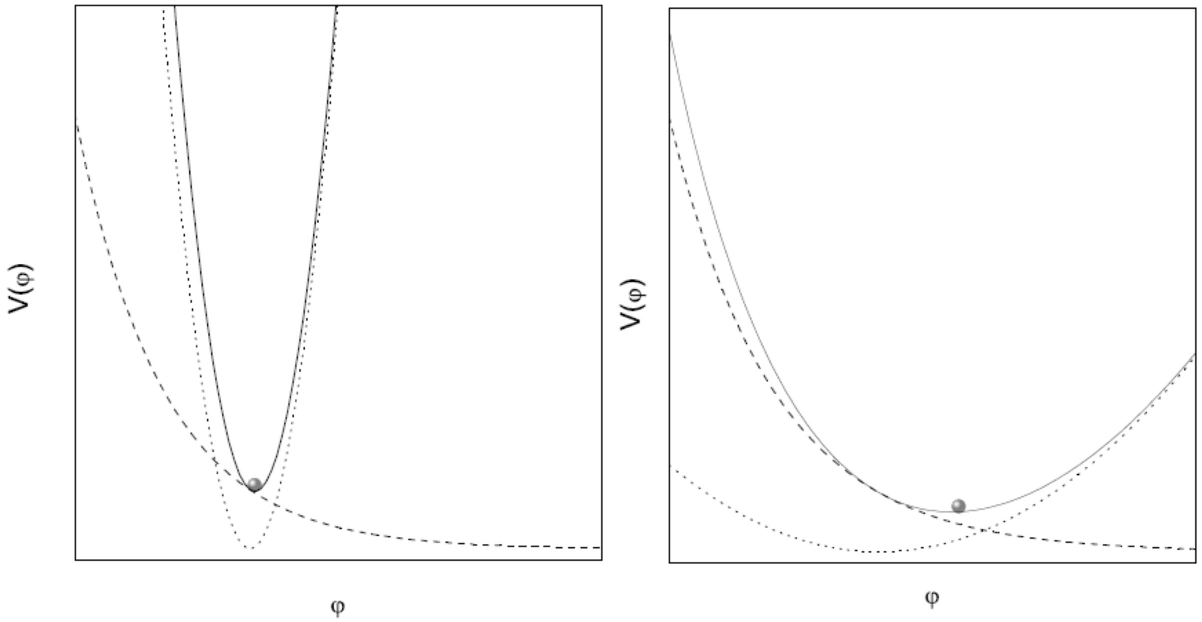
$$p_\varphi = \frac{1}{2}\dot{\varphi}^2 - V(\varphi)$$

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

Assume that the effective potential has a minimum

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

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



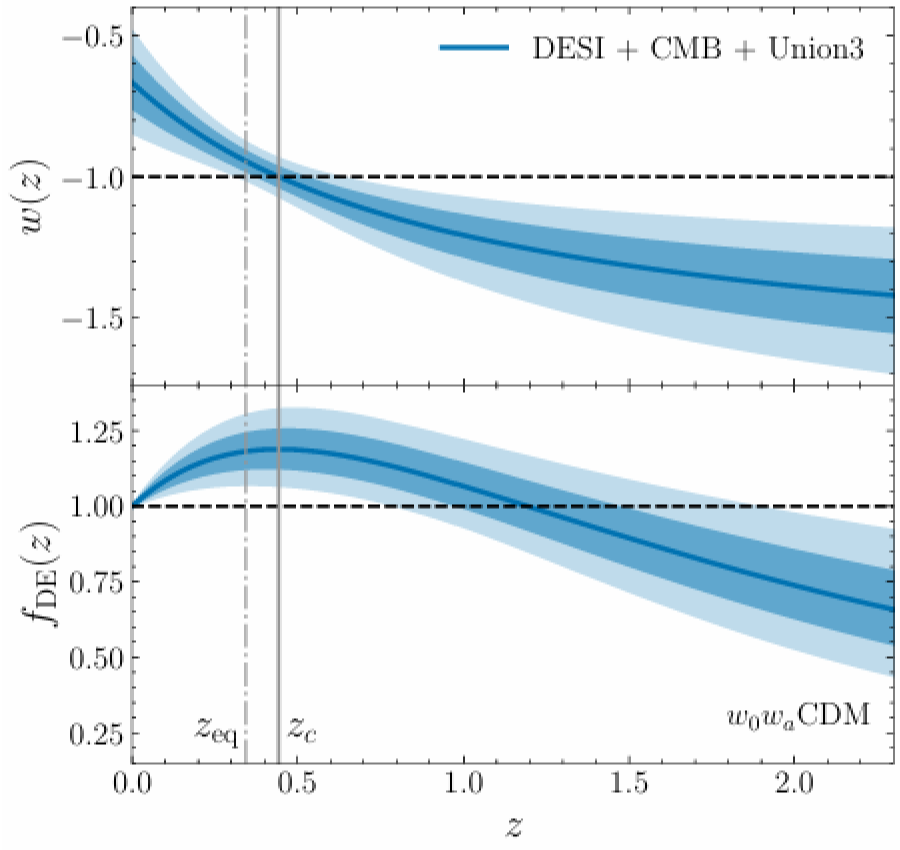
Concentrate on the evolution of the minimum close to calibration taken to be at low redshift:

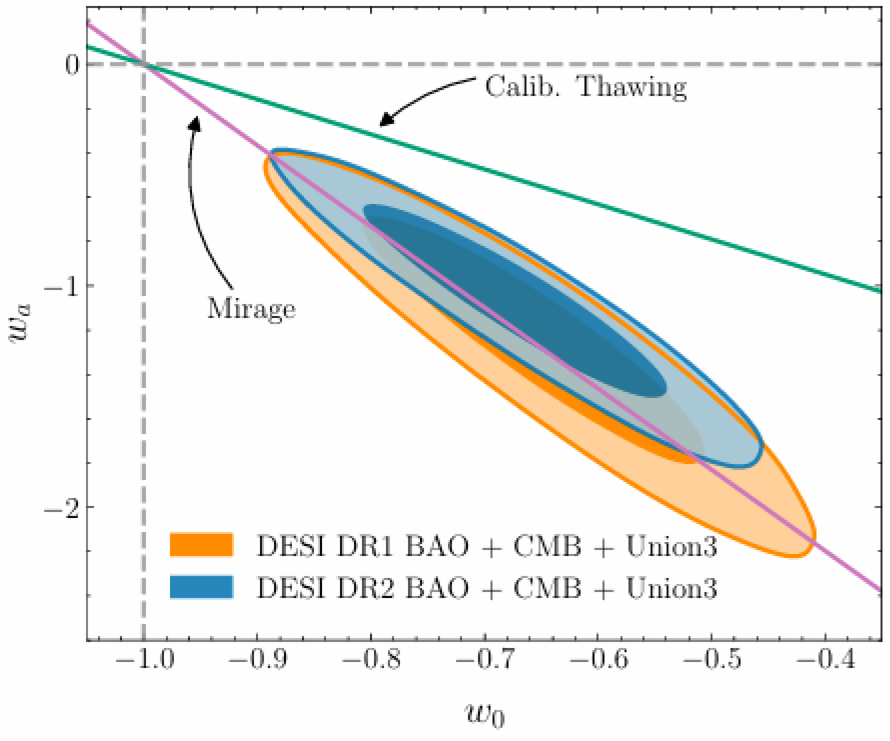
$$\phi - \phi_c = -\frac{\beta(\phi_c)}{m^2_{\rm eff} m_{\rm Pl}}(\rho_m - \rho_c)$$

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

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

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





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

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

1/3.66

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

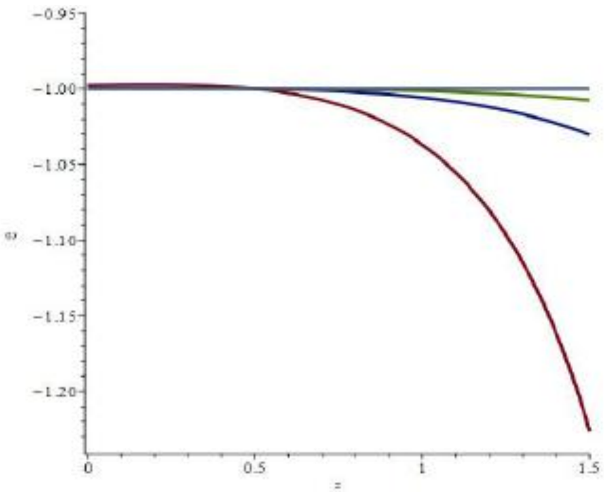
$$\boxed{0.047 \leq \frac{\beta^2(\phi_c)H_0^2}{m_{\rm eff}^2} \leq 0.093}$$

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

- 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!



$z_c = 0.5$

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

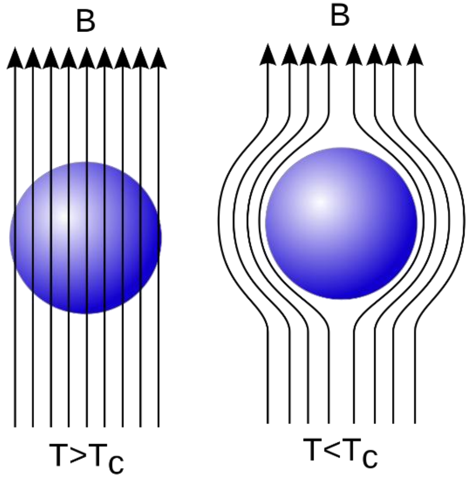
- Interactions between DE-DM $\beta(\phi_c) \leq 10^{-2}$

- Interaction between DE-baryon

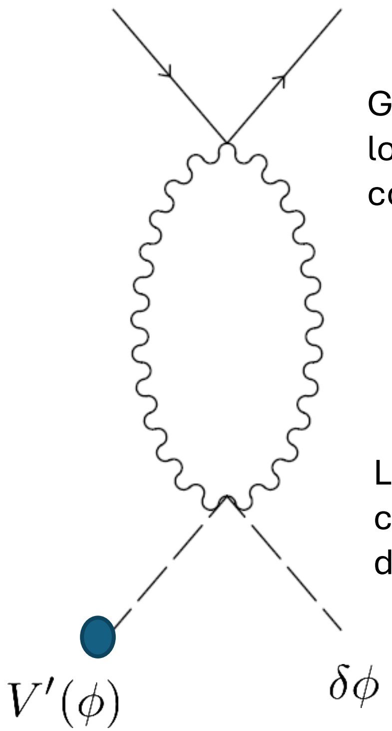
Could be postulated to vanish…

Generically non-vanishing coupling becomes unobservable thanks to:

Screening



fermions



Gravitation induces a logarithmically divergent coupling.

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

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**

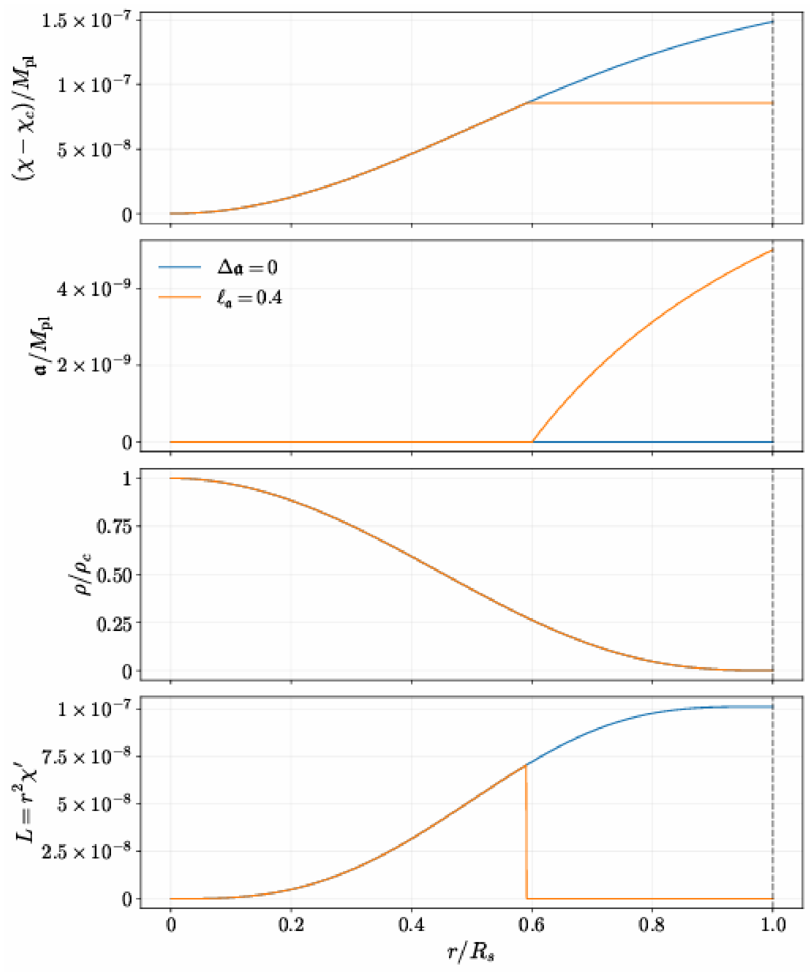
$$\mathcal{L} \supset -\frac{1}{2}((\partial\phi)^2 + W^2(\phi)(\partial a)^2)$$

Dilaton

Axion

Screening is induced by the kinetic coupling between the fields

$$\chi = \chi_\infty - \frac{L}{r}$$



The scalar charge essentially vanishes outside the compact object

Early dark energy for free!

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

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

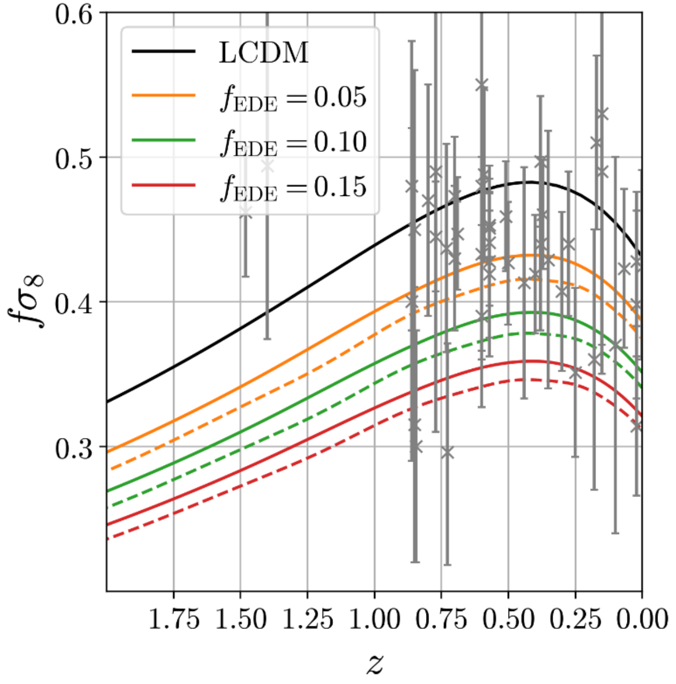
Early dark energy

A fraction of added matter

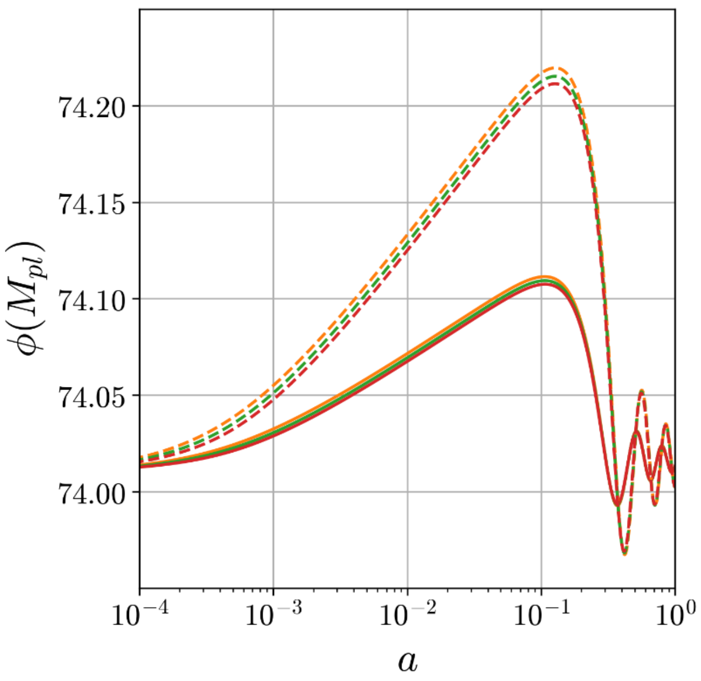
$$V(a_+) = \rho_m \frac{(a_+^2 - a_-)^2}{2\Lambda_a^2}$$

Early dark energy | Dark matter like

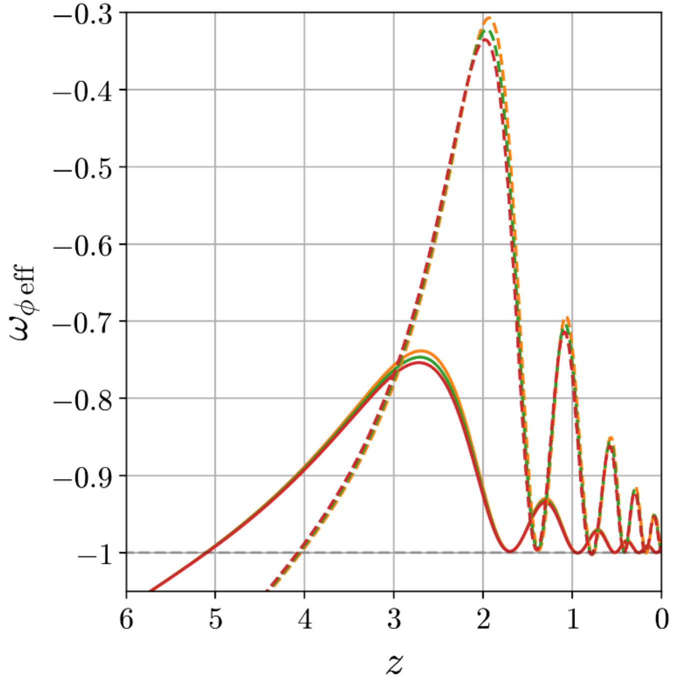
$m_a^2 \Lambda_a^2$



Dotted lines: the coupling to matter increases and growth reduces

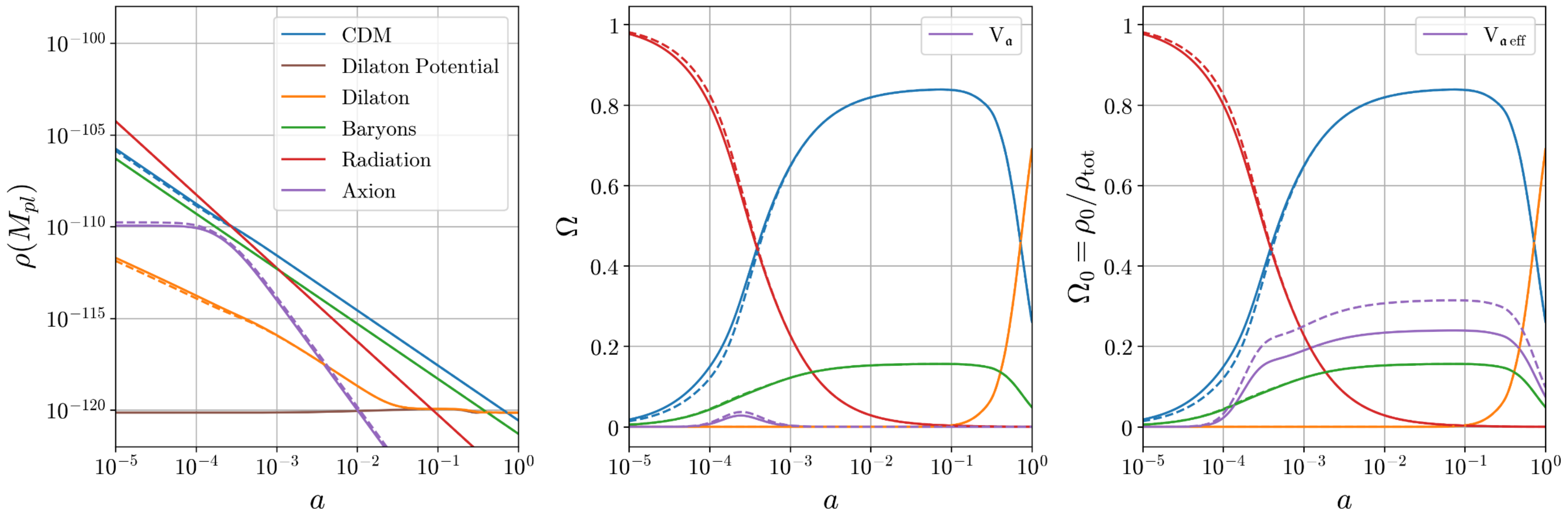


The dilaton is light and oscillates



The effective equation states oscillates and crosses the phantom divide.

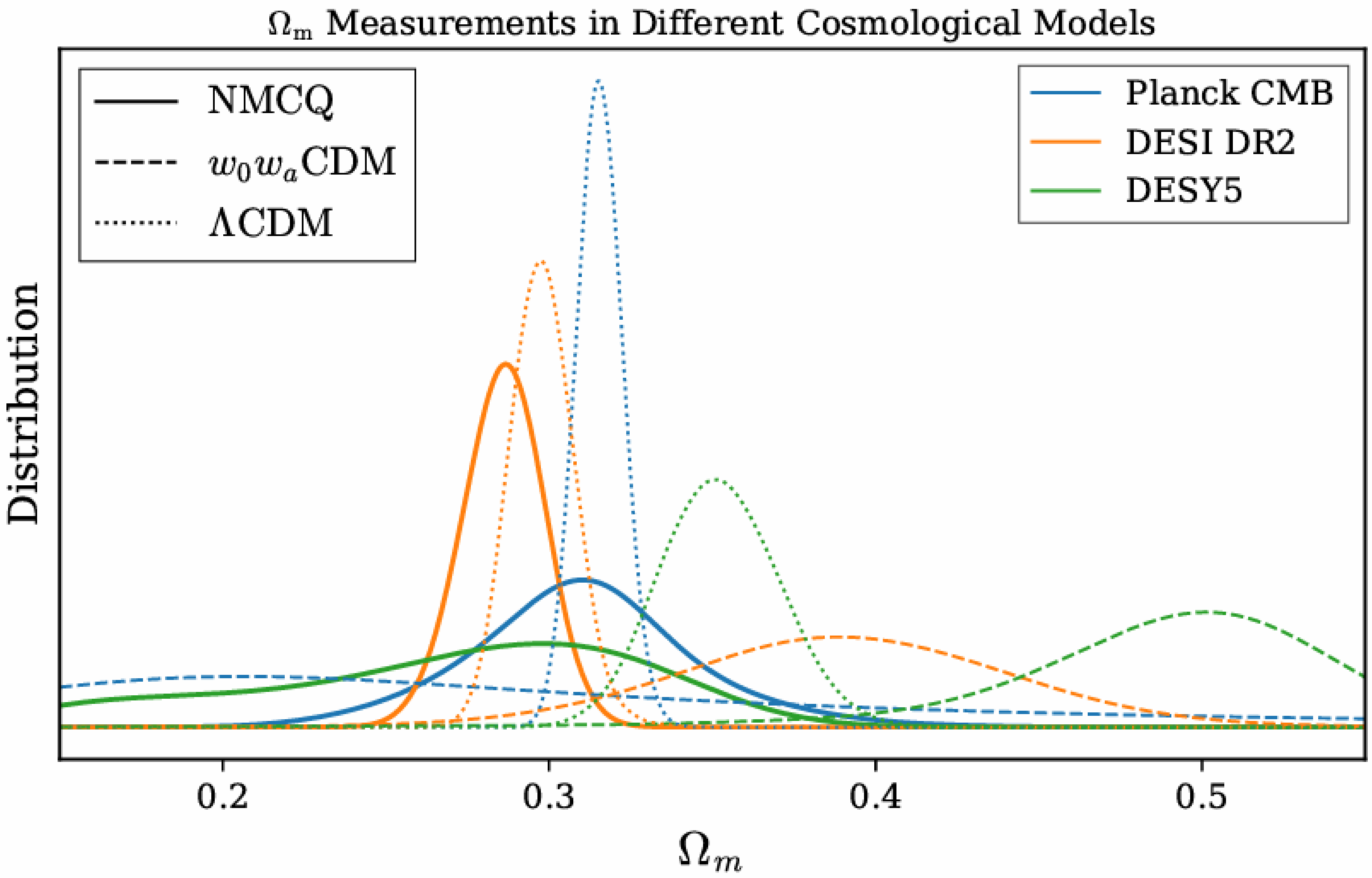
$$m_a = 2.10^{-15}\mathrm{eV},\ \Lambda_\phi = 2.10^{8}\mathrm{GeV}, \Lambda_a = 5.10^{5}\mathrm{GeV}$$



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

Conclusions

- ❑ Phantom crossing would be a change of paradigm for dark energy
- ❑ Multi-field models would reconcile phantom crossing and screening of long-range forces
- ❑ Two elephants in the room:
  - ✓ Scalar field model with no tuning of the vacuum energy?
  - ✓ Coincidence with the matter density?


Ω_m Measurements in Different Cosmological Models
NMCQ
w_0w_aCDM
ΛCDM
Planck CMB
DESI DR2
DESY5
Distribution
0.2
0.3
0.4
0.5
Ω_m

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