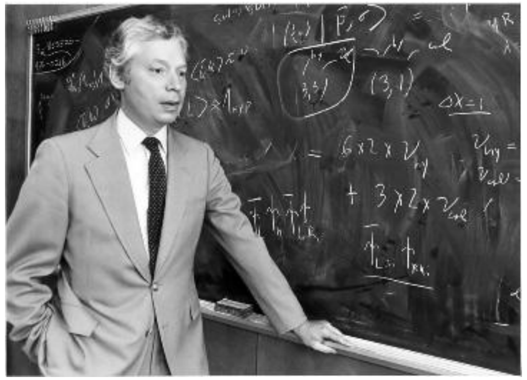
Dark Energy and Screening

Philippe Brax
Institut de Physique Théorique
Université Paris-Saclay

The dark energy scale is in the ***meV range***: apparent fine-tuning compared to standard model scales.

$$\delta\rho_\Lambda = M^4, \quad M \sim 100\text{GeV}$$

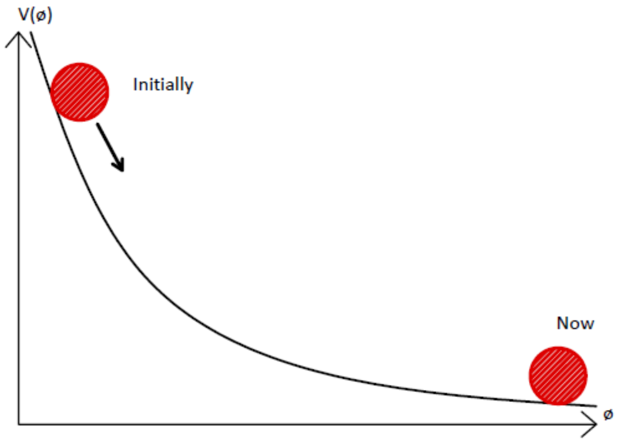
Weinberg's theorem states that there is no non fine-tuned nearly vanishing vacuum energy in a 4d quantum field theory respecting **Poincare invariance**.



Dynamical configurations

↓

Dark energy



Scalar field rolling down its potential

A good example: the ***dilaton*** *of broken scale invariance can be such a candidate.*

Some expected features of dark energy:

- Dark energy is determined by the position of the field now:

$$3\Omega_\Lambda H_0^2 m_{\rm Pl}^2 = V(\phi_{\rm now})$$

- The field is ***extremely light***:

$$m_\phi^2 = \frac{d^2V}{d\phi^2}|_{\rm now} \sim \frac{V_{\rm now}}{m_{\rm Pl}^2} = 3\Omega_\Lambda H_0^2$$

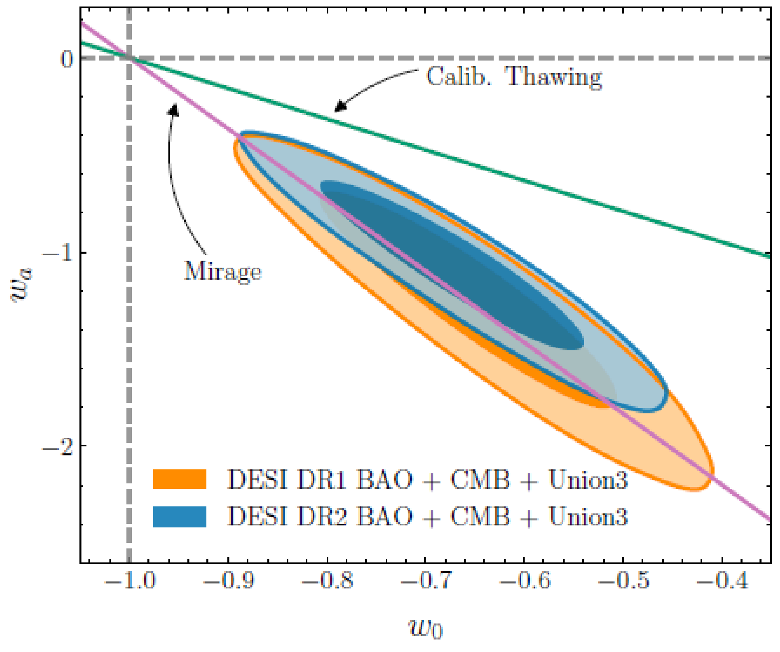
Mass of the order of the Hubble rate

$H_0 \sim 10^{-42}$ GeV

Late Dark Energy

$$w_0 + w_a < -1$$

Phantom crossing

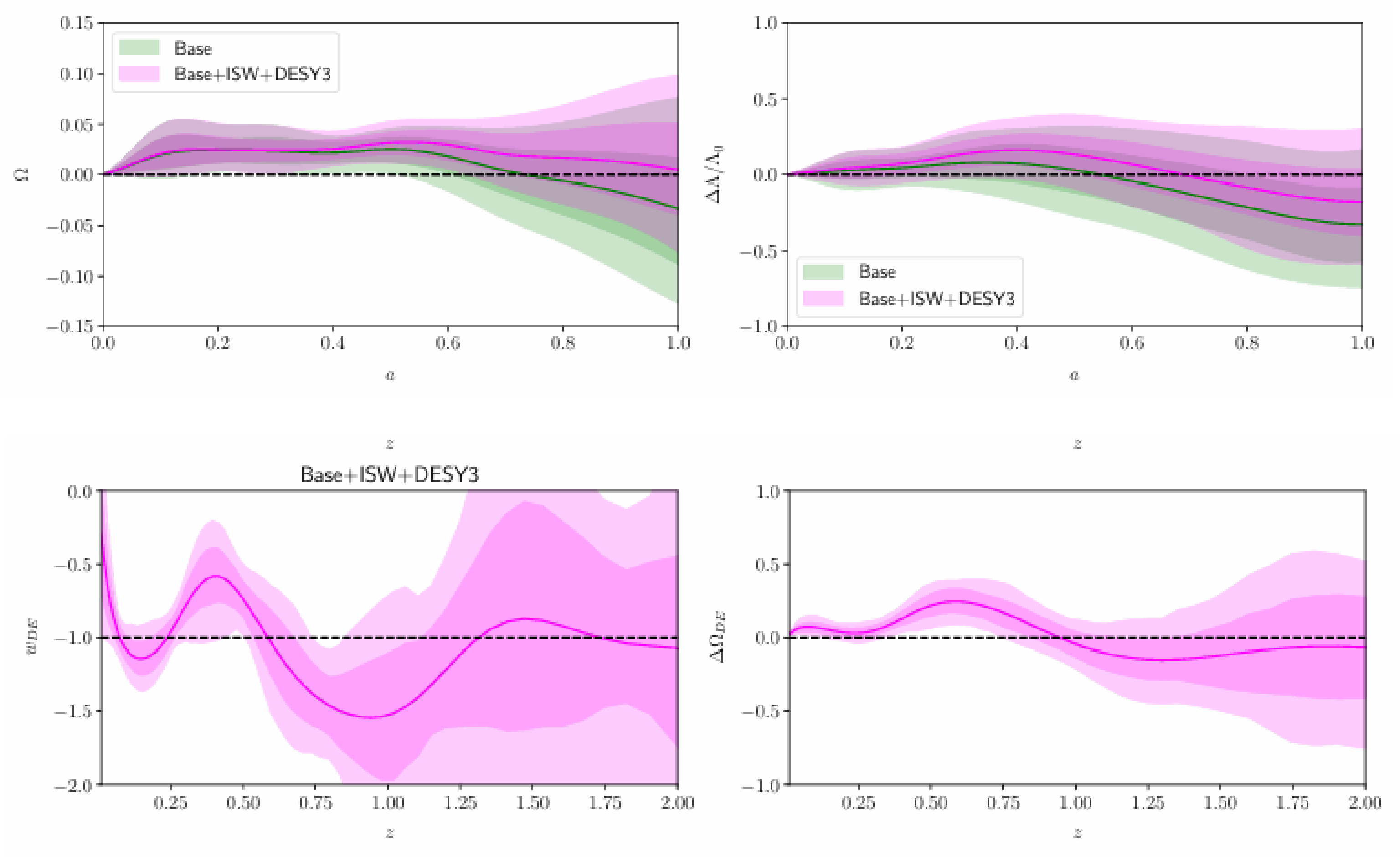


$$\omega = \frac{p}{\rho}$$

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

$$\omega(z) < -1, \quad z \geq 0.5$$

E pur si muove !   G.G.(1633)



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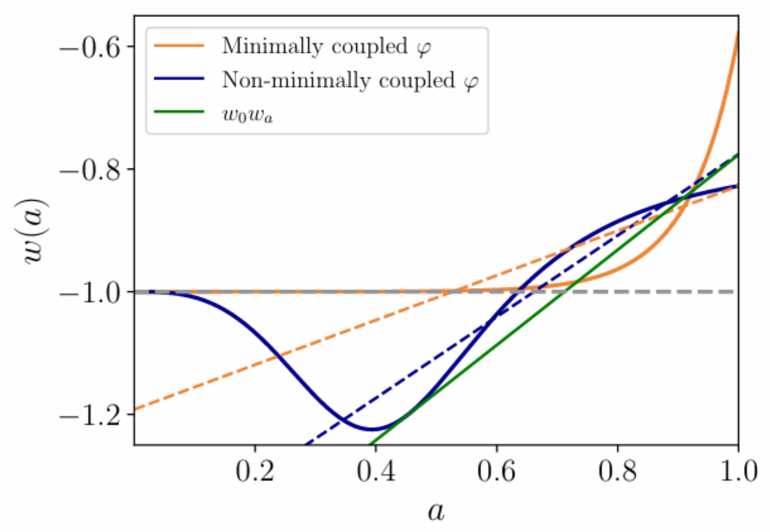
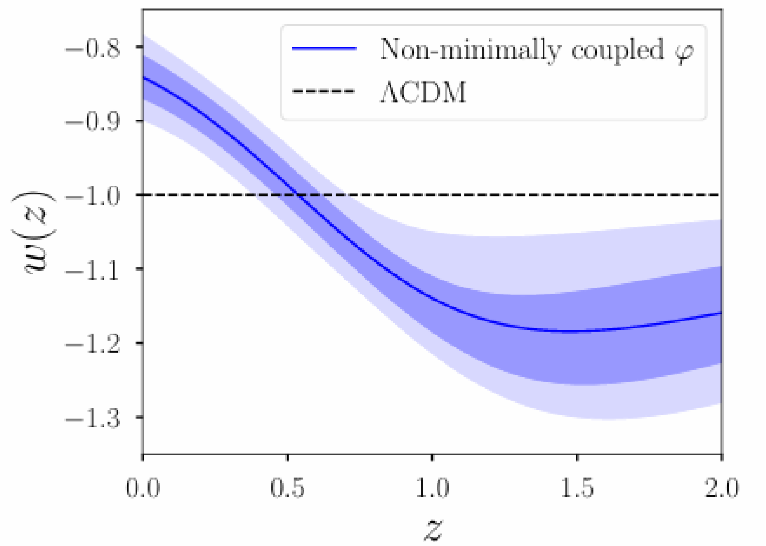
Parameterisation-independent reconstruction of the cosmological background in the effective dark energy action.

Simplest extension:

Effective dark energy action

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





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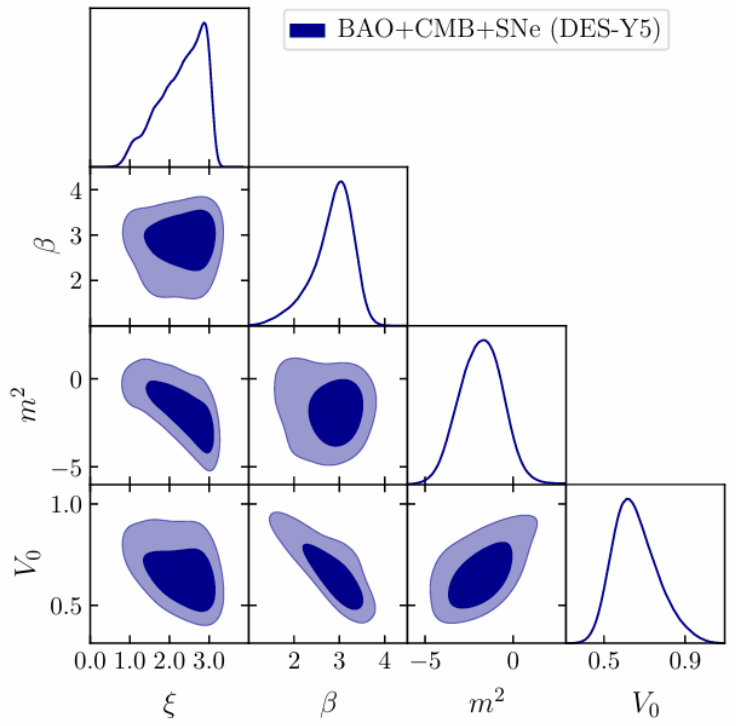


$$S = \int d^4x\sqrt{-g}(\frac{m_{\rm Pl}^2}{2}F(\phi)R - V(\phi))$$

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

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

Evidence for scalar-tensor models

The models here are in the Jordan frame

The low energy description

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

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

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

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

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

Higher order terms in derivatives are suppressed unless breaking the expansion scheme by terms of order (see Tessa Baker):

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

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

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

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:

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

Calibration with the observed matter density is taken when

$$\varphi = \varphi_c$$

Conservation of dark energy reads:

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

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

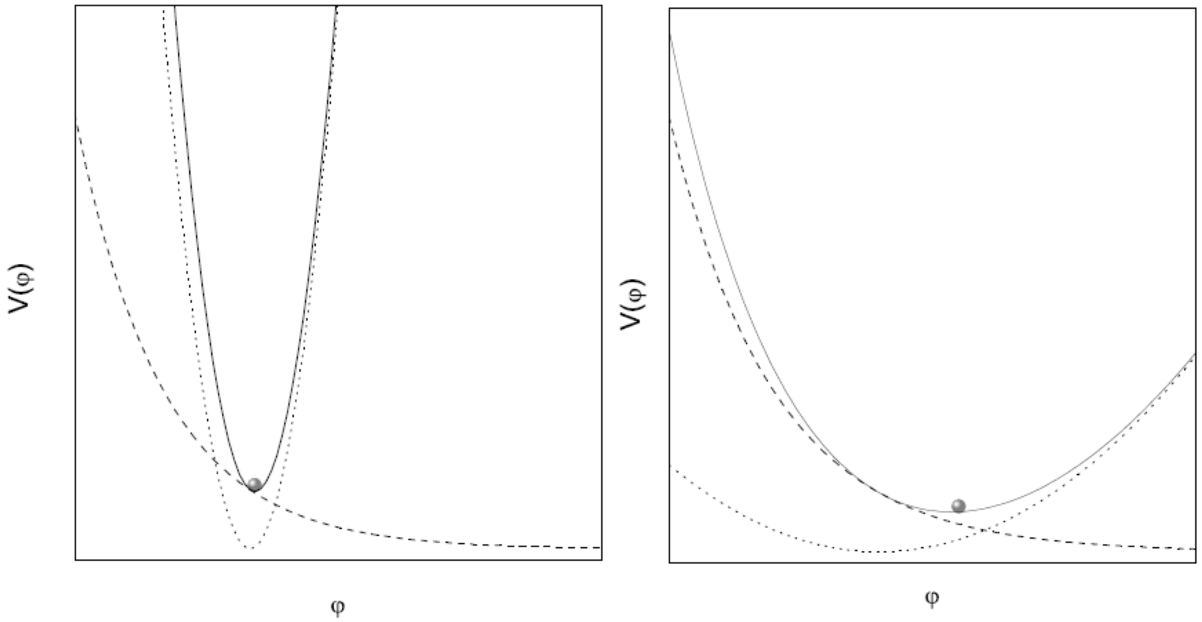
$$\omega_{\text{eff}} = \frac{p_\varphi}{\rho_{\text{eff}}}$$

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

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:

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

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

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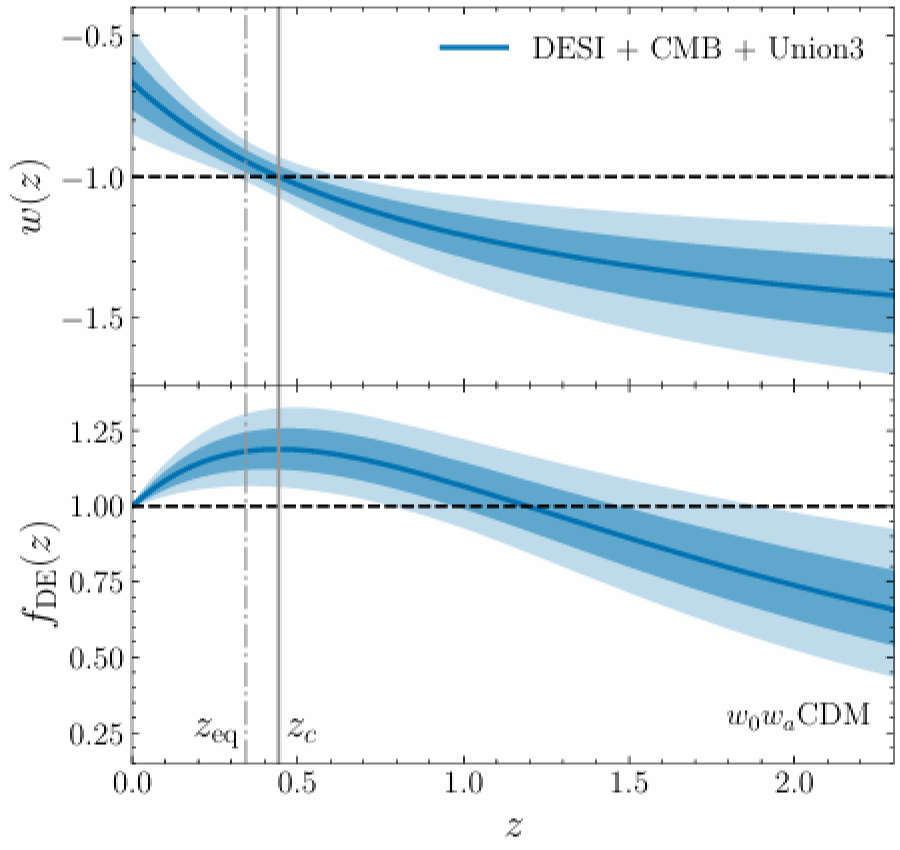
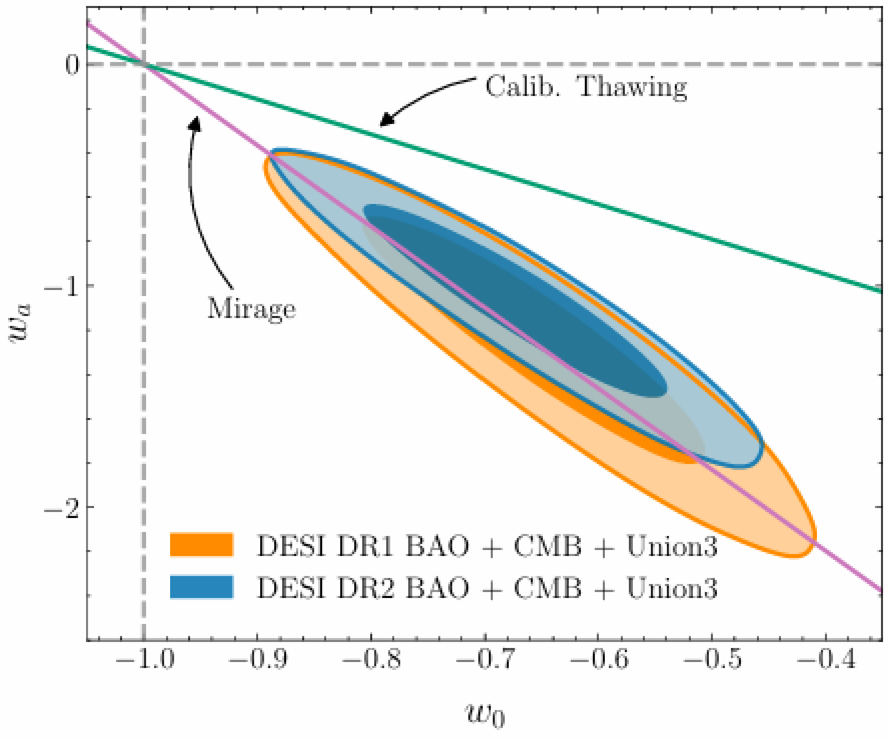
$$\omega_{\rm eff} = -\frac{1}{1-\beta^2(\phi_c)\frac{\rho_m}{V_{\rm DE}}\frac{(\rho_m-\rho_c)}{m_{\rm Pl}^2 m_{\rm eff}^2}}$$

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





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

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

$$-1.6 \le \omega_a \le -0.8$$

1/3.66

corresponding to “mirage” fits.

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

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

- Crosses the phantom divide when: $\rho_m < \rho_c$
- Negligible variation unless: $m_{\rm eff} \simeq H_0, \quad \beta(\phi_c) \sim 0.1$

Major issues!

- ❑ Long range forces with gravitational strength!

- *Interactions between DE-DM*

$$\beta \leq 10^{-2}$$

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

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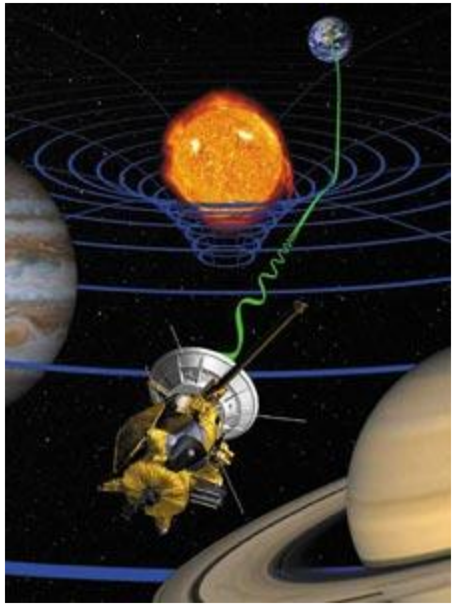
Major issues!

- ❑ Long range forces with gravitational strength!

- *Interaction between DE-baryons*

Interactions with baryons induce a change in Newton's law:

$$\Phi = -\frac{G_N M}{r}(1 + 2\beta^2 e^{-r/\lambda})$$



Bertotti et al. (2004)

For long range forces with large λ, the tightest constraint on the coupling β comes from the Cassini probe measuring the Shapiro effect (time delay around a big object: the Sun):

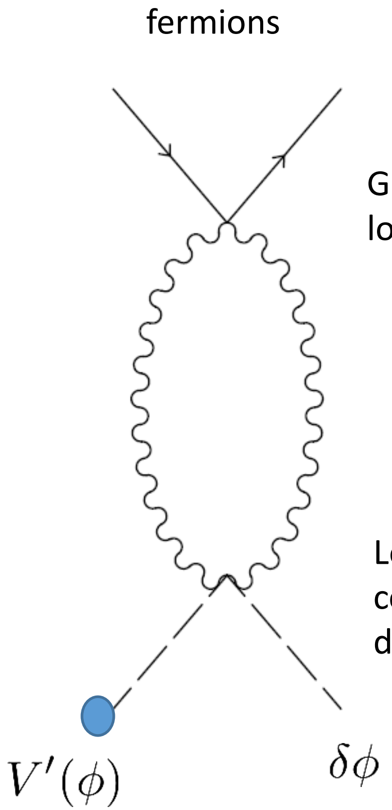
$$\beta^2 \leq 2 \cdot 10^{-5}$$

Fifth force:

$$\vec{a}_\phi = -\frac{\beta}{m_{\rm Pl}}\vec{\nabla}\phi$$

- Interaction between DE-baryon

Could be postulated to vanish…

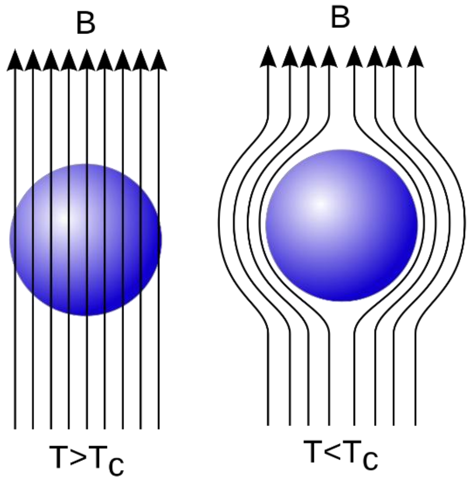


Gravitation induces a logarithmically divergent coupling.

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

But generically non-vanishing coupling becomes unobservable thanks to:

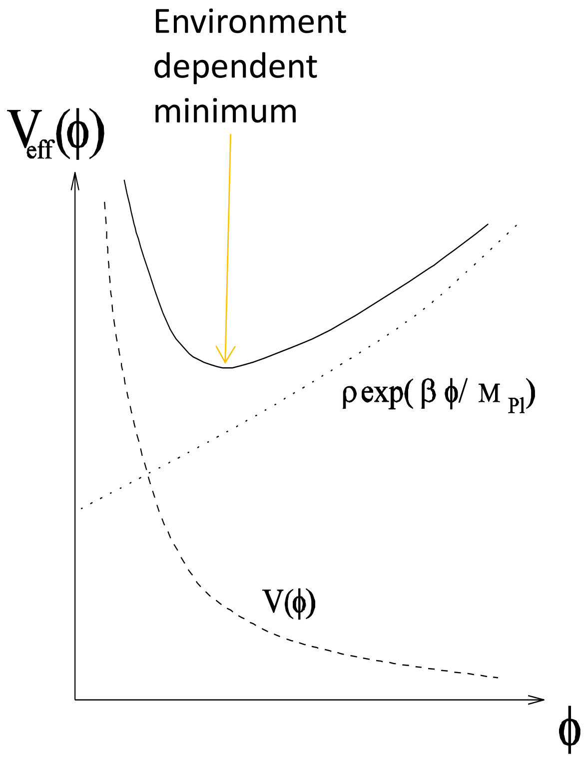
Screening

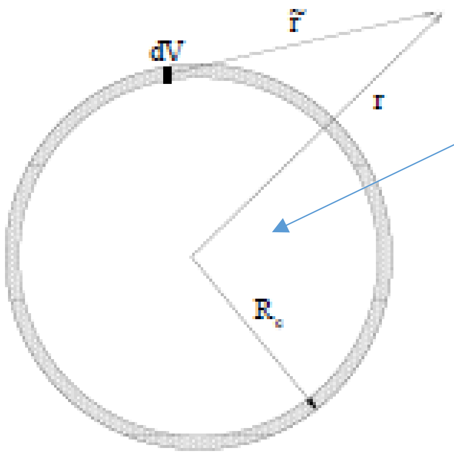


Chameleon Screening

When coupled to matter, scalar fields have a ***matter dependent effective potential***

$$V_{eff}(\phi) = V(\phi) + \rho_m(\frac{A(\phi)}{A(\phi_c)} - 1)$$





Large mass inside object

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

The field generated from deep inside is Yukawa suppressed. Only a *thin shell* radiates outside the body. Hence suppressed scalar contribution to the fifth force.

In single field case, screening implies:

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

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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, screening and phantom crossing can happen with more than one field and a **non-trivial σ-model metric**.

2310.02092

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

Dilaton

Axion

Multi-field dark energy sector

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

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

Dark energy **Screening**

Screening 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:

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

Can lead to dark matter, see
Adam Smith's talk on Thursday.

The Klein-Gordon for the dilaton is:

Coupling constant to matter.

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

Axion driven "potential"

Far away from the body we expect:

$$\phi = \phi_\infty - \frac{L m_{\rm Pl}}{r}$$

$$L = 2\beta G_N M$$

In the absence of screening.

Local value of the field in the environment

The scalar charge L is determined by the competition between the different energy sources for the scalar field profile. This competition will select the **local value of the field** and determine the scalar charge.

In the **axio-dilaton** case, the "solar" system is small enough that the local energy is dominated by the local dynamics which differ from the cosmological one.

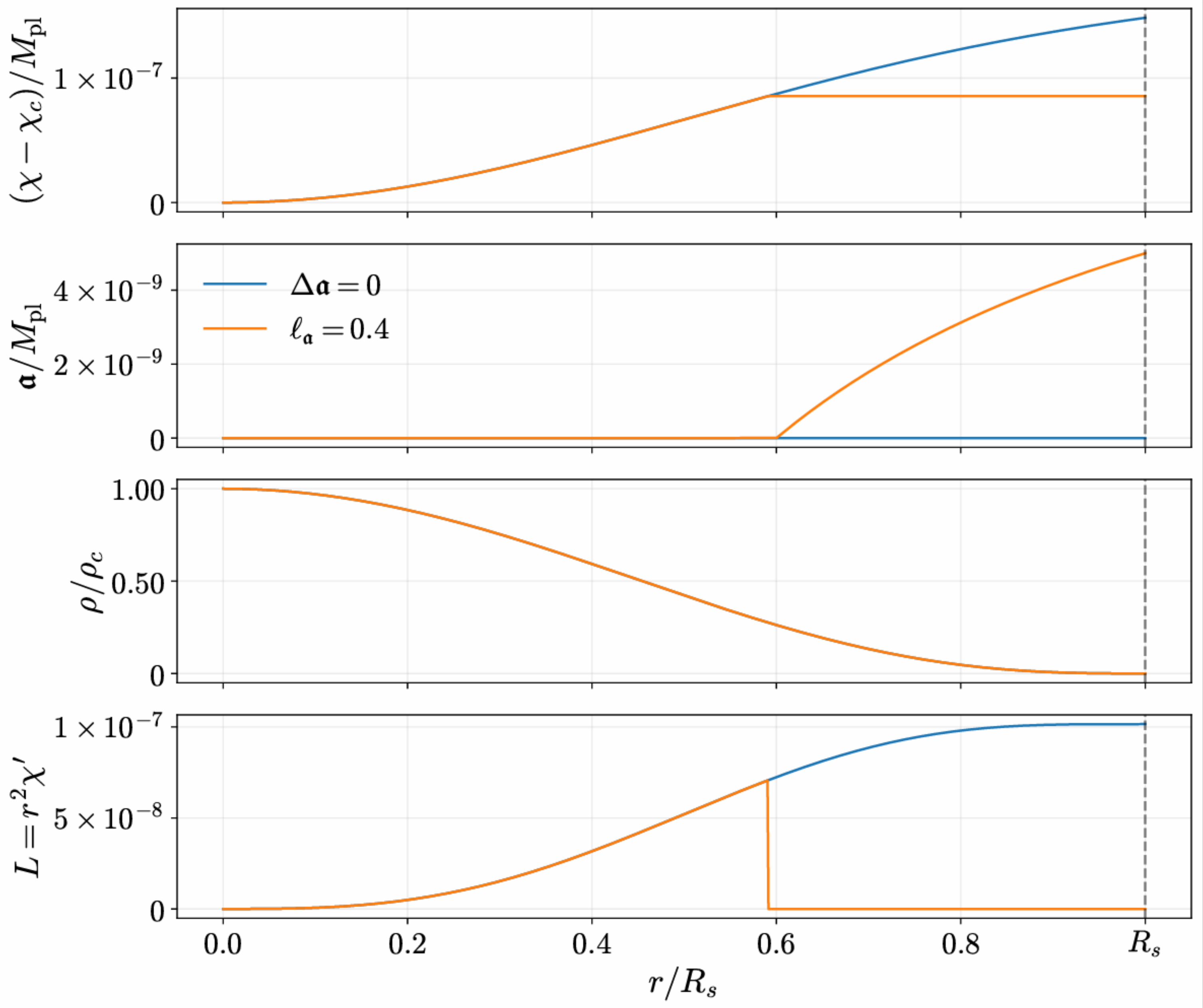
$$E_{\rm kin} = 2\pi \int_0^\infty dr\; r^2 (W^2 (a')^2 + (\phi')^2)$$

Wants to be minimised to zero

$$E_{\rm kin,a} = \frac{\pi}{\ell} R^2 W^2 (r=R)(a_+^2 - a_-^2)$$

$$E_{\rm kin} = E_0 + \frac{L^2}{4 G_N R}$$

$$L = 2\beta G_N M + R^2 \left(\frac{WW'}{2\ell}\right)_{r=R} \frac{(a_+ - a_-)^2}{m_{\rm Pl}}$$



$(\chi-\chi_c)/M_{\rm pl}$
1×10^{-7}
0
$\mathfrak{a}/M_{\rm pl}$
4×10^{-9}
2×10^{-9}
0
$\Delta\mathfrak{a}=0$
$\ell_{\mathfrak{a}}=0.4$
ρ/ρ_c
1.00
0.50
0
$L=r^2\chi'$
1×10^{-7}
5×10^{-8}
0
0.0
0.2
0.4
0.6
0.8
R_s
r/R_s

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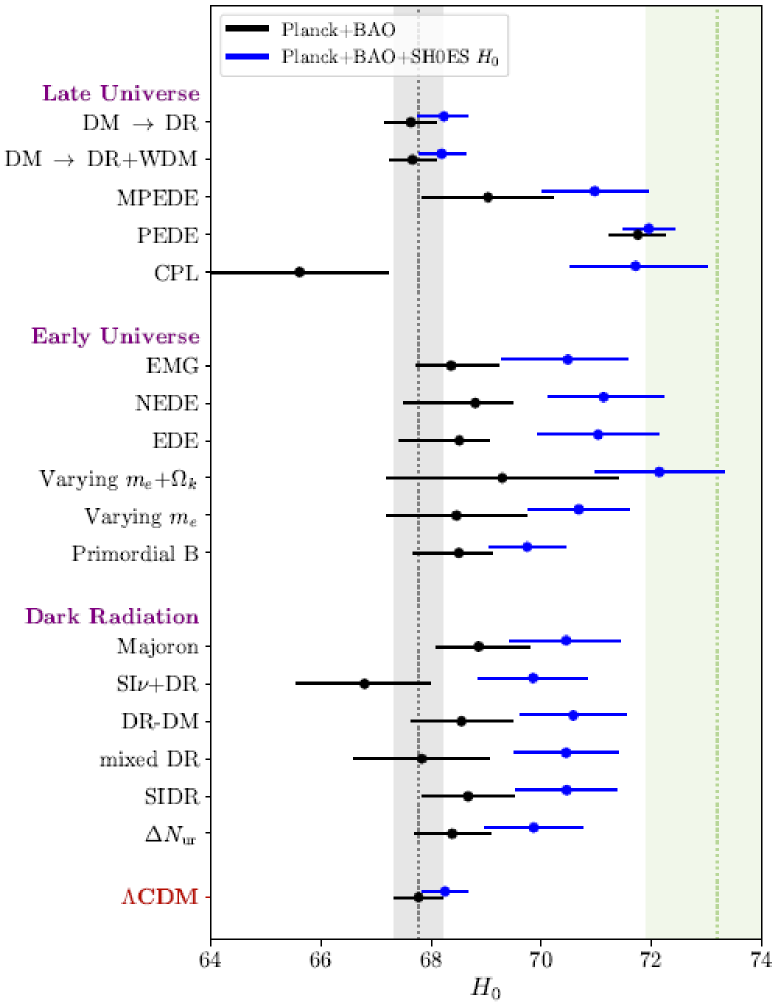
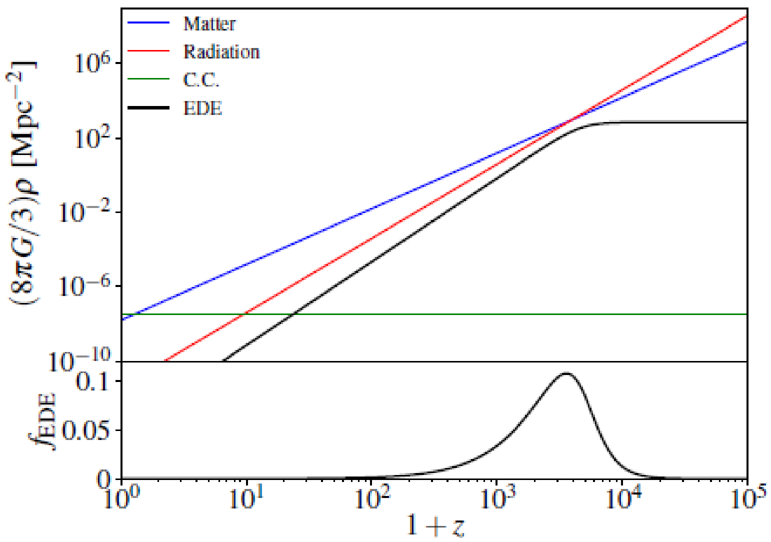
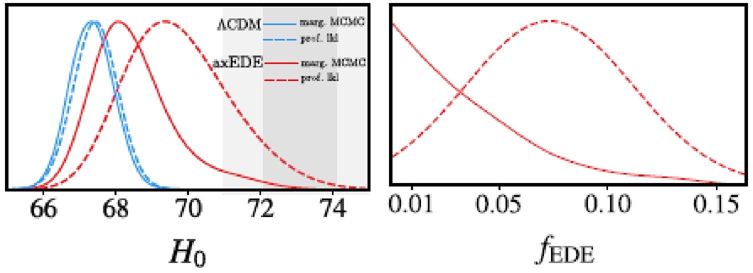
The cosmological dynamics

Early Dark Energy





Early dark energy fraction



Early dark energy for free!

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

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

Early dark energy

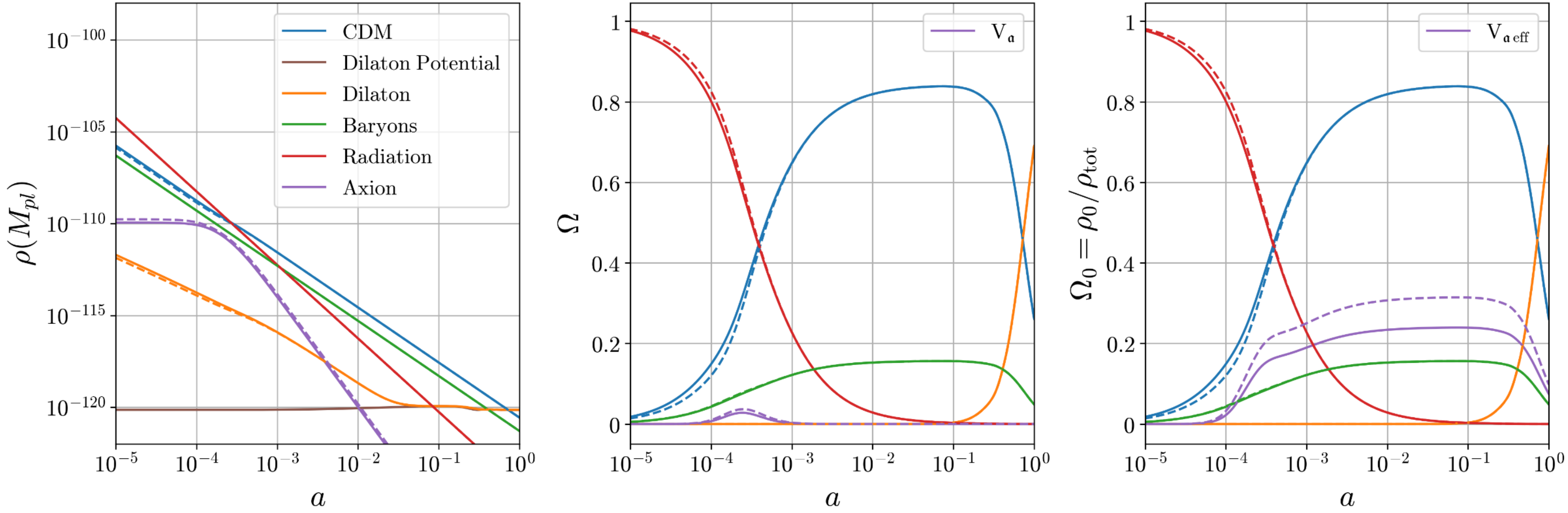
A fraction of added matter

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

Early dark energy | Dark matter like

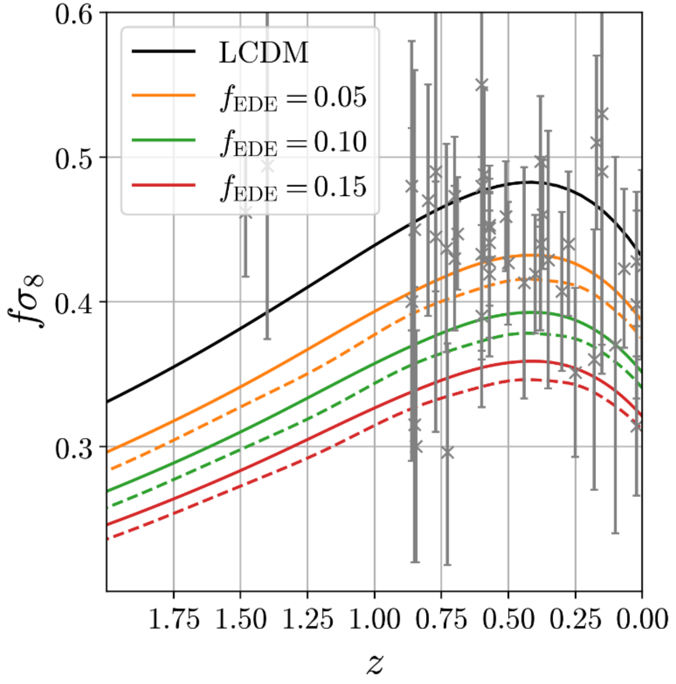
$m_a^2 \Lambda_a^2$

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

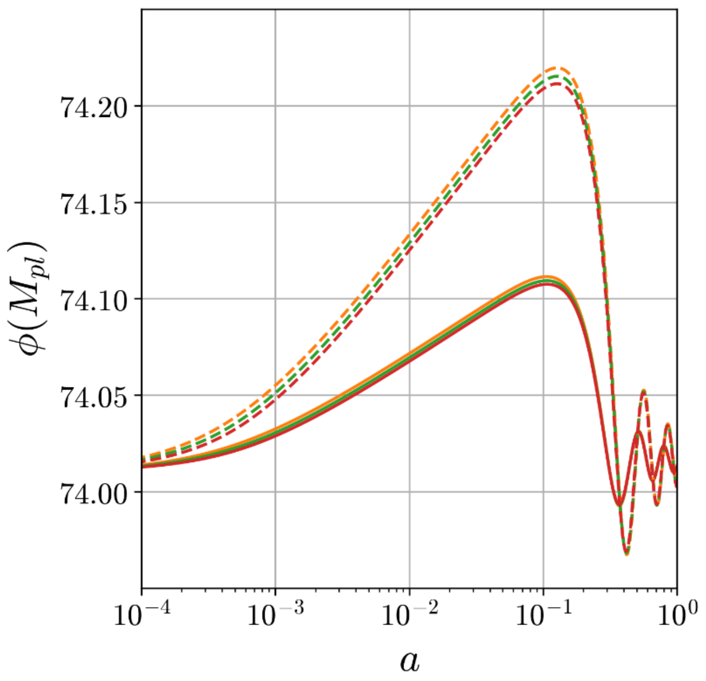


Early dark energy shows its face in the form of the axion potential.

Less growth!

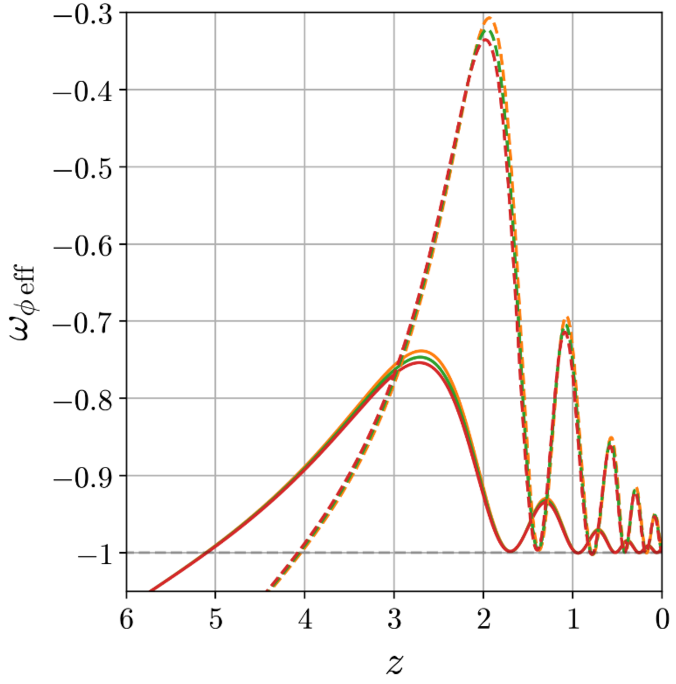


Dotted lines: the coupling to matter increases and growth reduces.



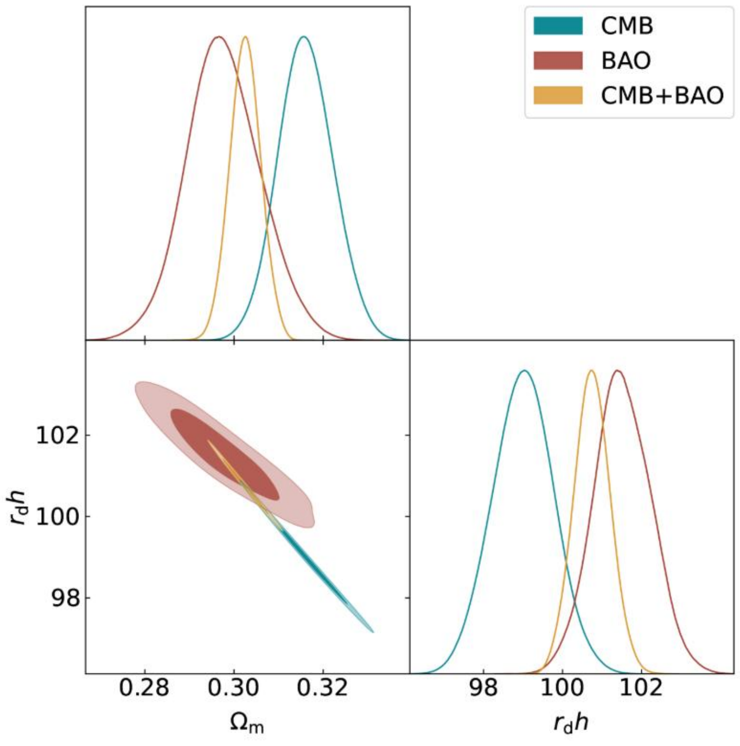
The dilaton is light and oscillates as de rigueur for dark energy.

Compatible with Desi ?



The effective equation states oscillates and crosses the phantom divide.

More than meets the eye



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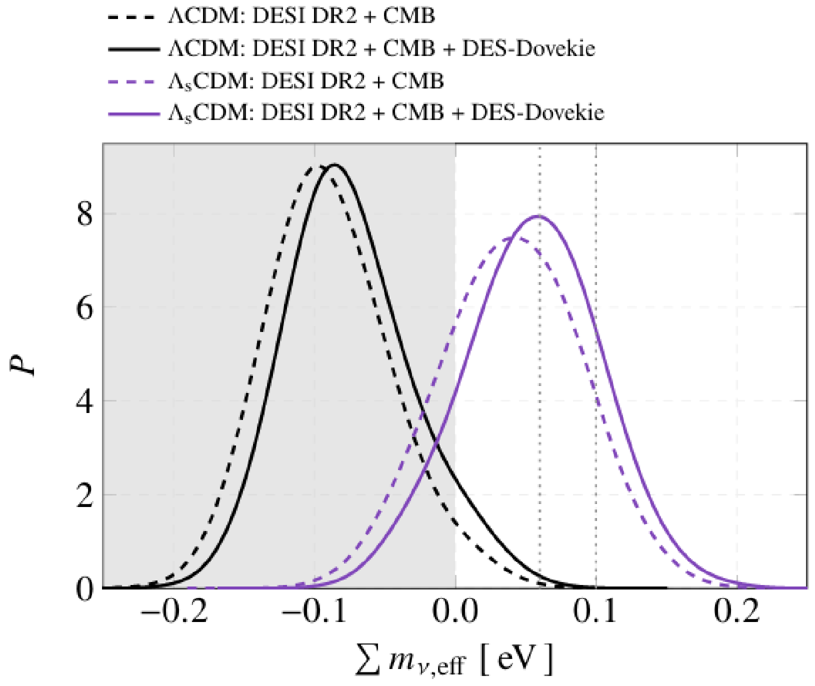

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Summary

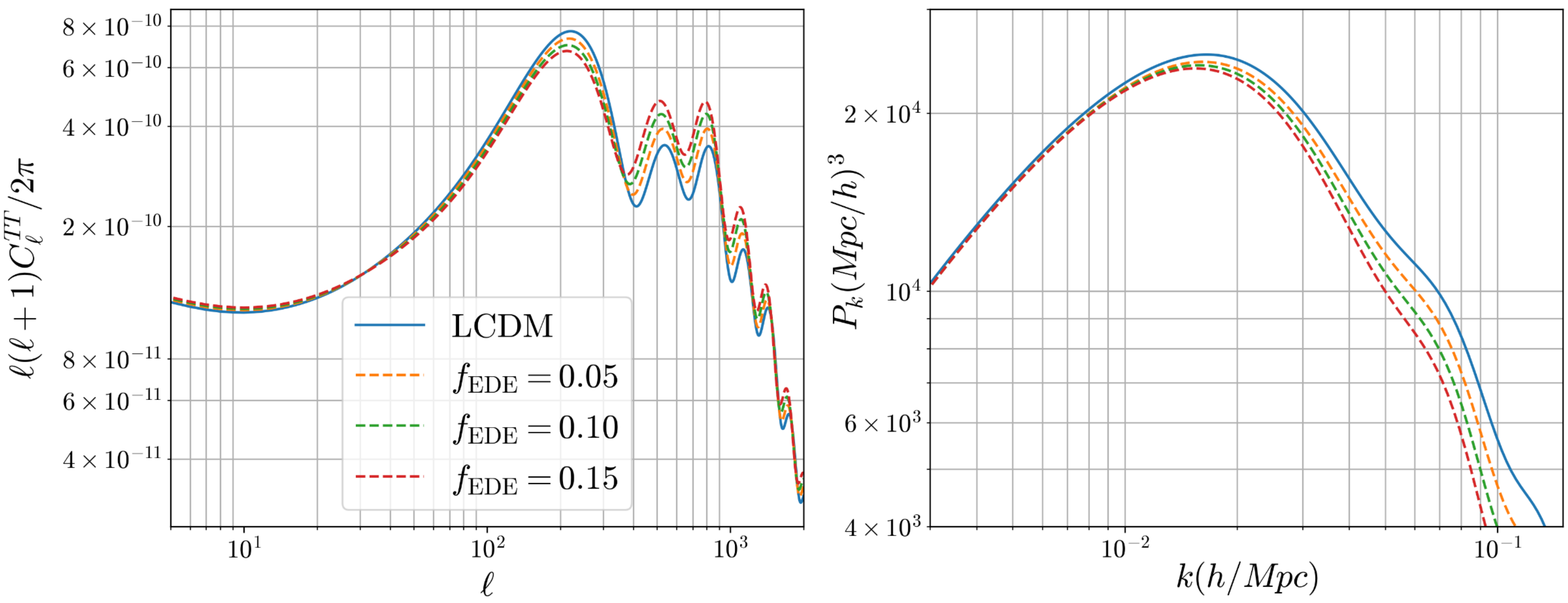
Multi-field dark energy models coupled to matter can have a number of interesting features:

- ✓ 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.

Open questions

- Is there an issue with the matter fraction and can coupled model address it?
- Do we need a period of negative dark energy? How to generate it?

More



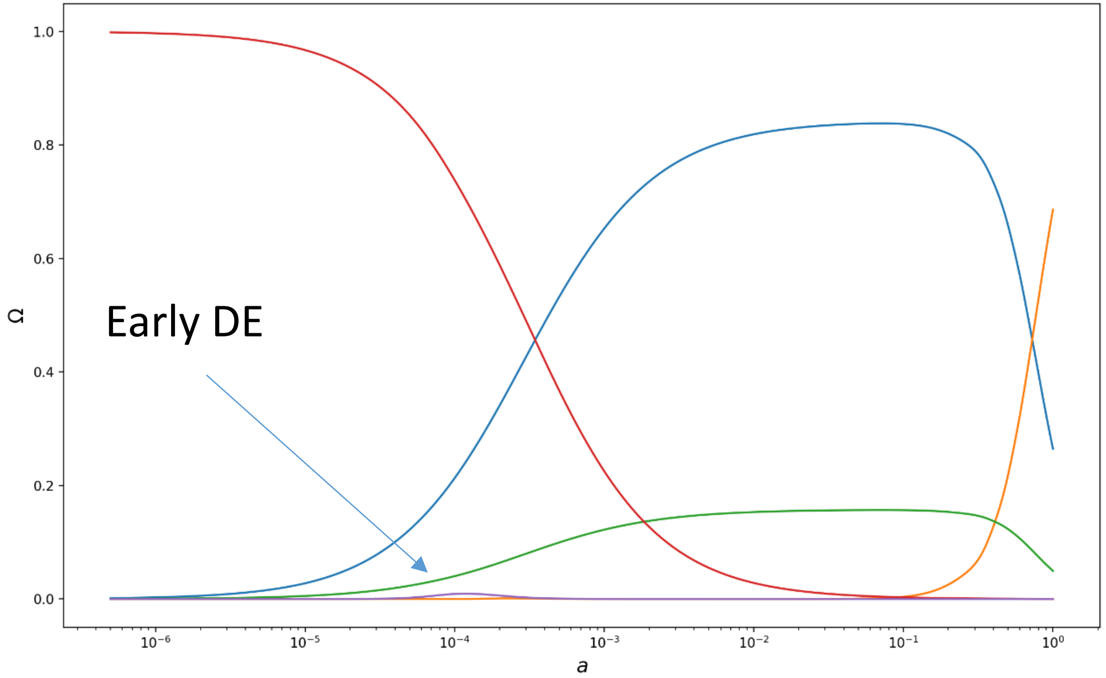
Increasing the early dark energy fraction increases the deviation from LCDM.

For specific applications, we take an Albrecht-Skordis potential (also called Yoga for idiosyncratic reason) :

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

Quadratic with non-trivial minimum. Only purpose is to reproduce the amount of dark energy.

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



$$\lambda = 4\beta$$

Conformal rescaling can violate the swampland bound.