The Dark Universe

The Axio-Dilaton Dark Sector

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Axions in Stockholm 2025

Outline

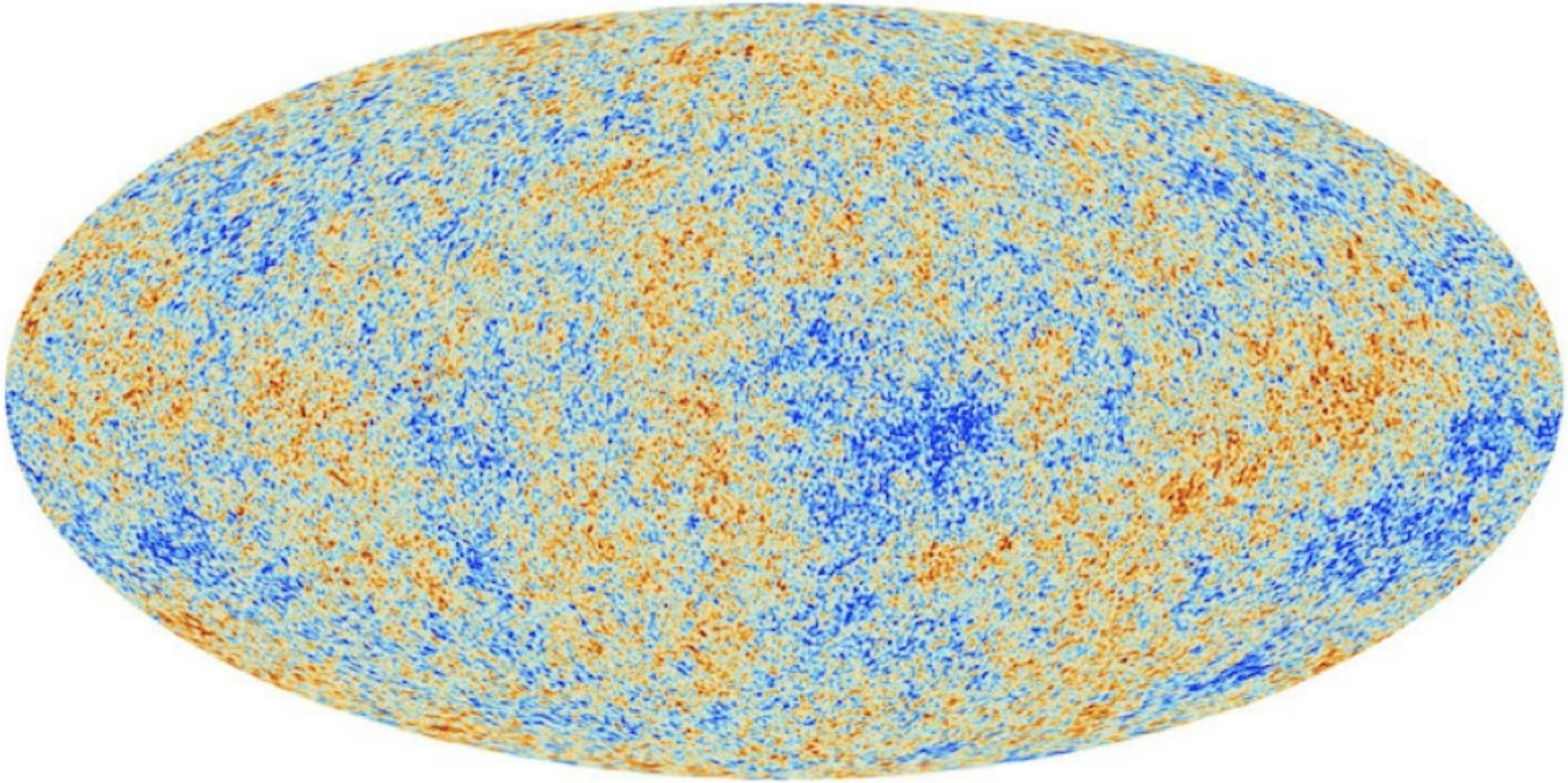
General Introduction

Screened Scalar tensor models —- Chameleon and Dilaton models

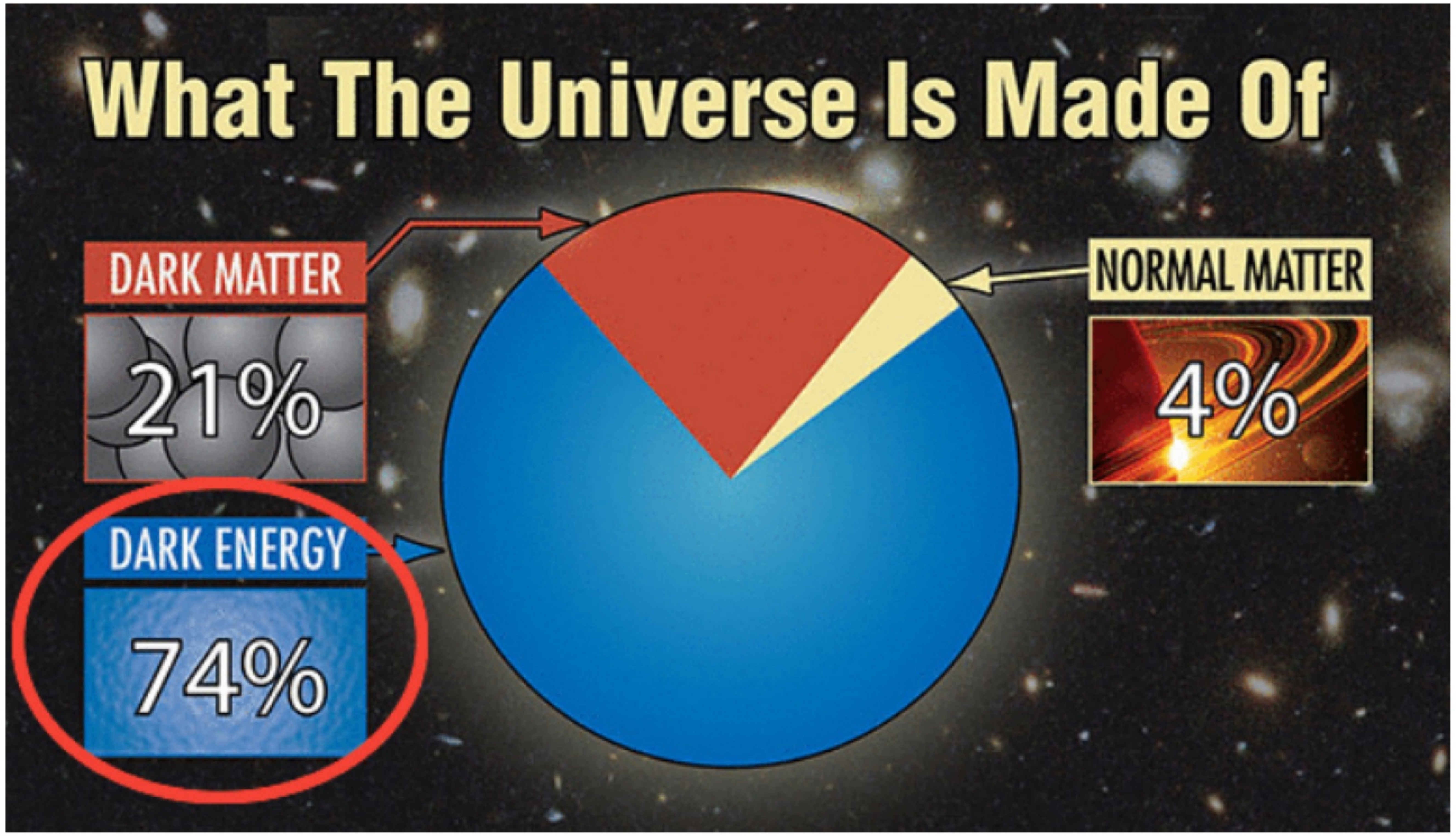
The Axio-Dilaton Dark Sector 2410.11099

Coupling the Axion to matter — The screened model 2505.05450

Cosmic Microwave Background



Dark Energy



The Universe is undergoing accelerated expansion today.

It could be a cosmological constant

$$\Lambda \approx (H_0 M_{pl})^2 \approx (meV)^4$$

or the dynamics of a light scalar field

$$m_\phi < H_0 \approx 10^{-33} eV$$

If coupled to gravity this will give rise to a fifth force, unless screened

For a scalar field

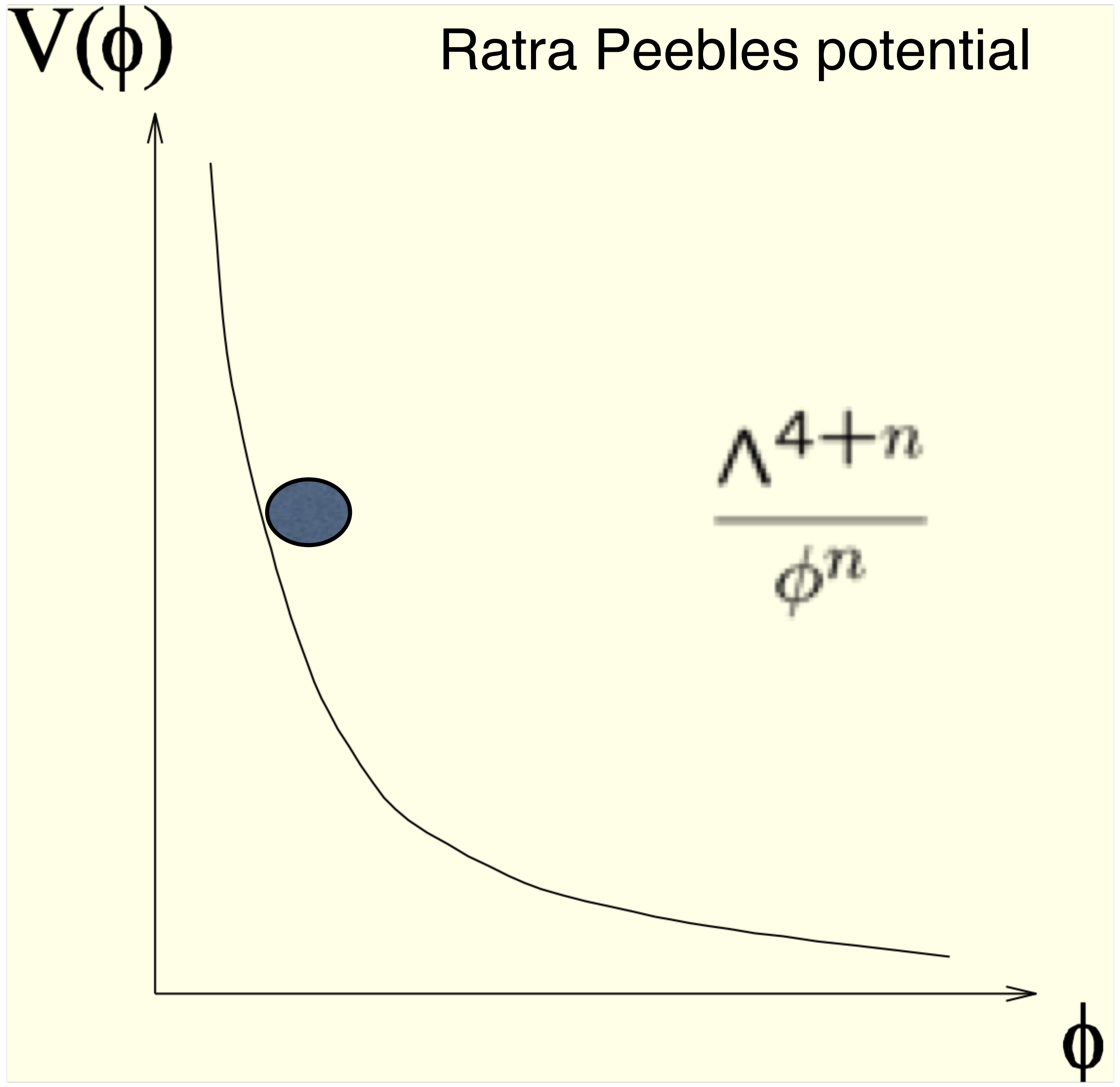
$$\rho_\phi = 1/2\dot{\phi}^2 + V(\phi)$$ kinetic energy + potential energy

$$p_\phi = 1/2\dot{\phi}^2 - V(\phi)$$ kinetic energy - potential energy

If the potential dominates then

$$p_\phi \approx -\rho_\phi \qquad \omega_\phi \approx -1$$

so the scalar field plays the role of an effective cosmological constant. Since it's dynamical, this wouldn't have been the case for all times in the universe. We only need the scalar field to dominate the energy density of the universe today



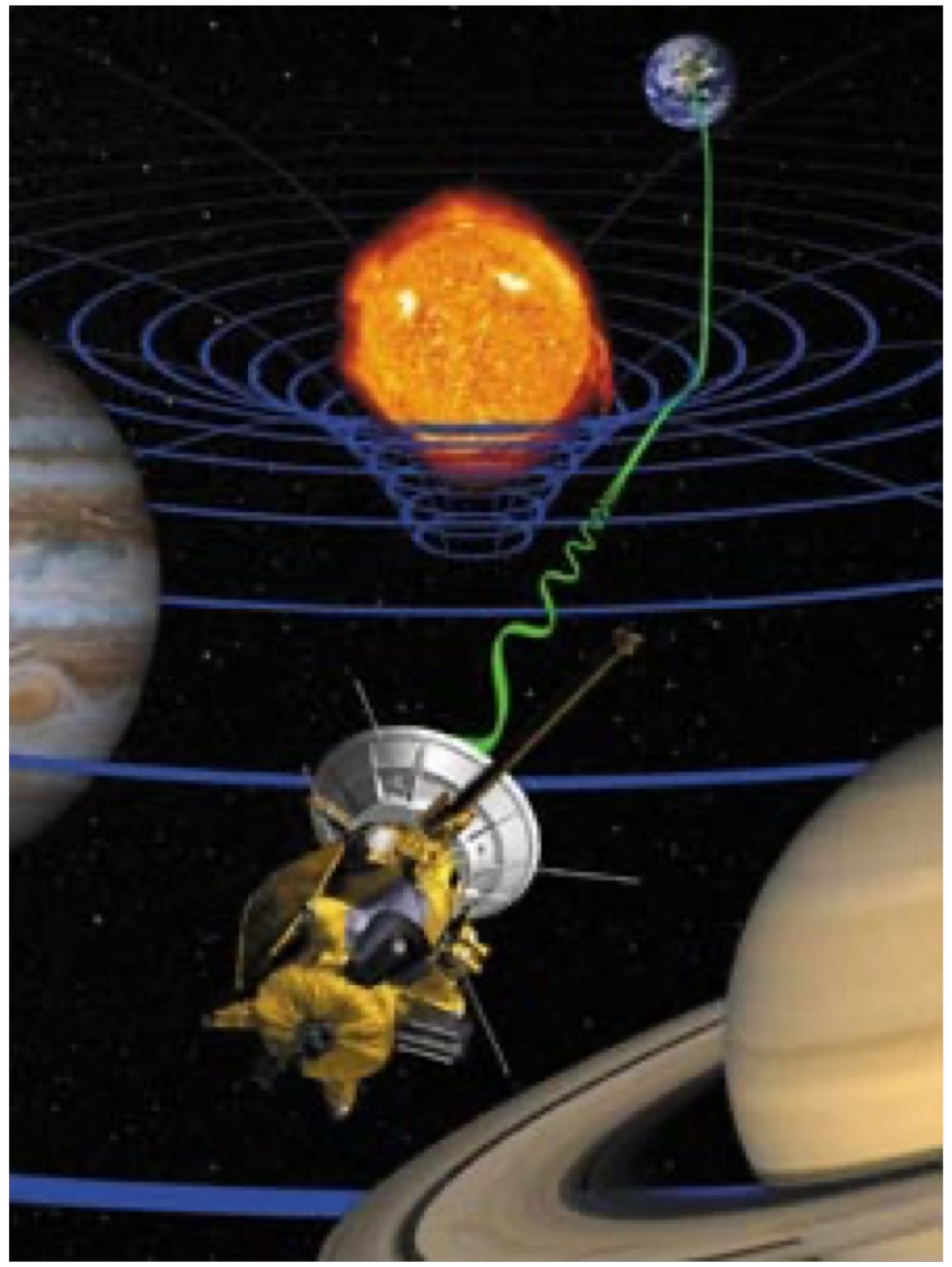
Deviations from Newton's Laws parametrised by

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

tightest constraint from Cassini

$$\beta^2 \leq 4 \cdot 10^{-5}$$

Fifth Force must be screened



Two general classes of theories

1) Chameleon type screening. Can be tested in the lab, in the solar system, astrophysics and cosmology. Does not affect speed of gravitational waves, so no test from LIGO/VIRGO or eLISA

2) Vainshtein screening. For example Galileons, Horndeski, massive gravity, k-mouflage. Vainshtein radius is very large, so no laboratory tests, but astrophysical and cosmological tests. Some models give speed of gravitational waves to be different from that of photons, so severely constrained by pulsar constraints and by LIGO/VIRGO and will be even more constrained by eLISA

The Chameleon Mechanism

Khoury&Weltman astro-ph/0309411; Brax et al astro-ph/0408415

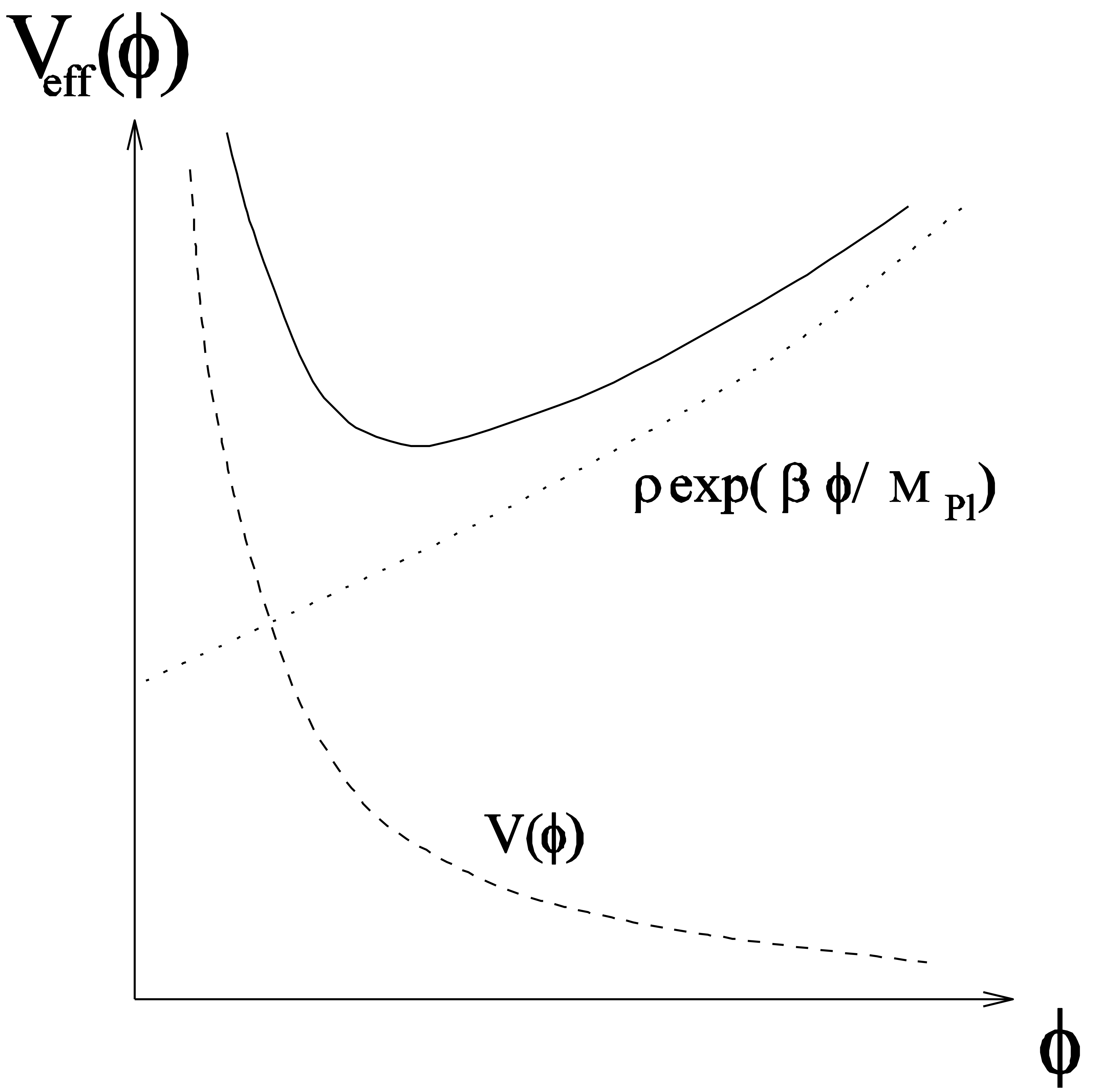
consider the action

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

gives the effective potential

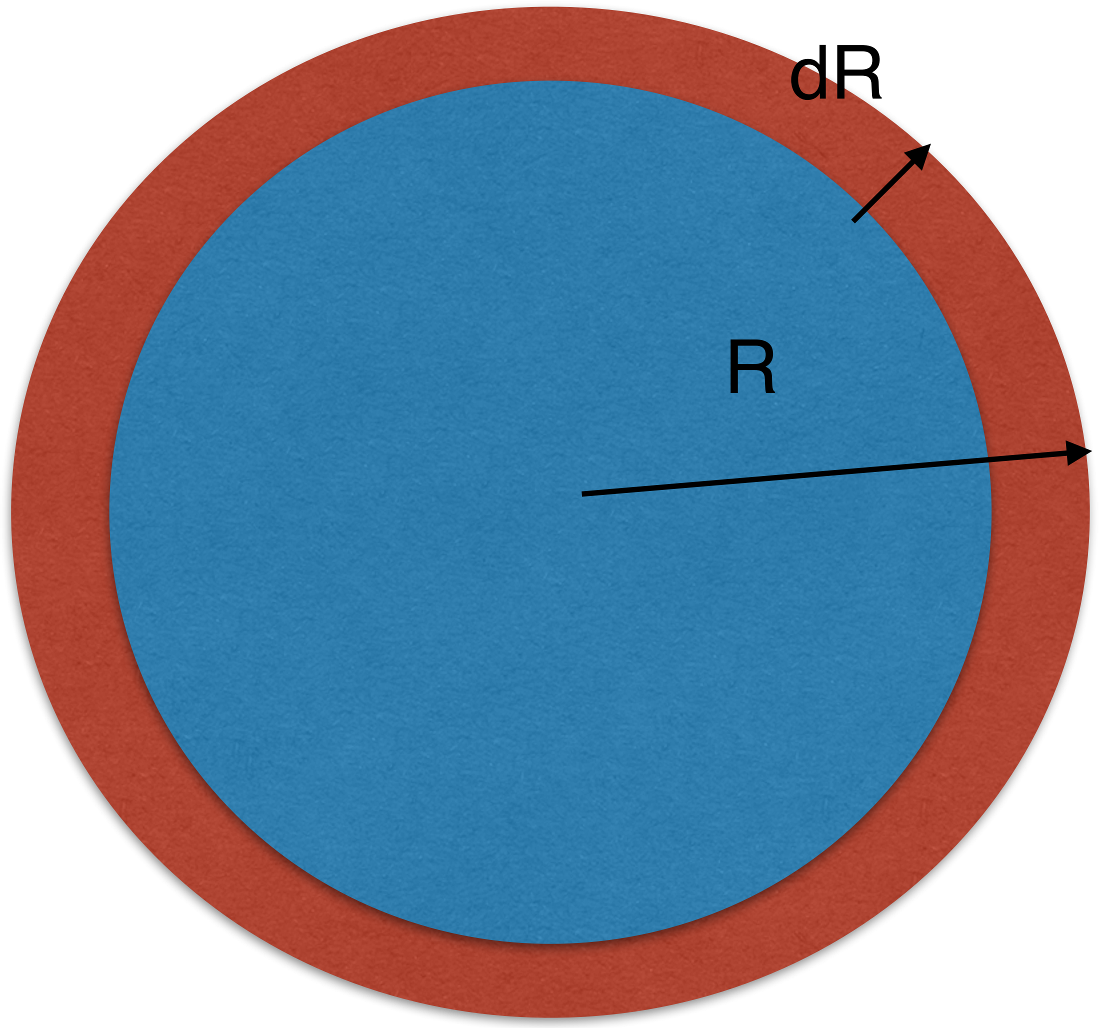
$$V_{\rm eff}(\phi) = V(\phi) - (A(\phi) - 1)T$$

There is an environmental effect: when coupled to matter the potential depends on the ambient matter density as well



$$V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)$$

To screen fifth forces in the solar system one needs the thin shell effect.



The fifth force is proportional to the size of the thin shell where the field varies

$$F_\phi \approx \frac{\Delta R}{R\Phi_N}$$

The Runaway DIlaton

In the strong coupling limit of string theory the dilaton has a runaway potential

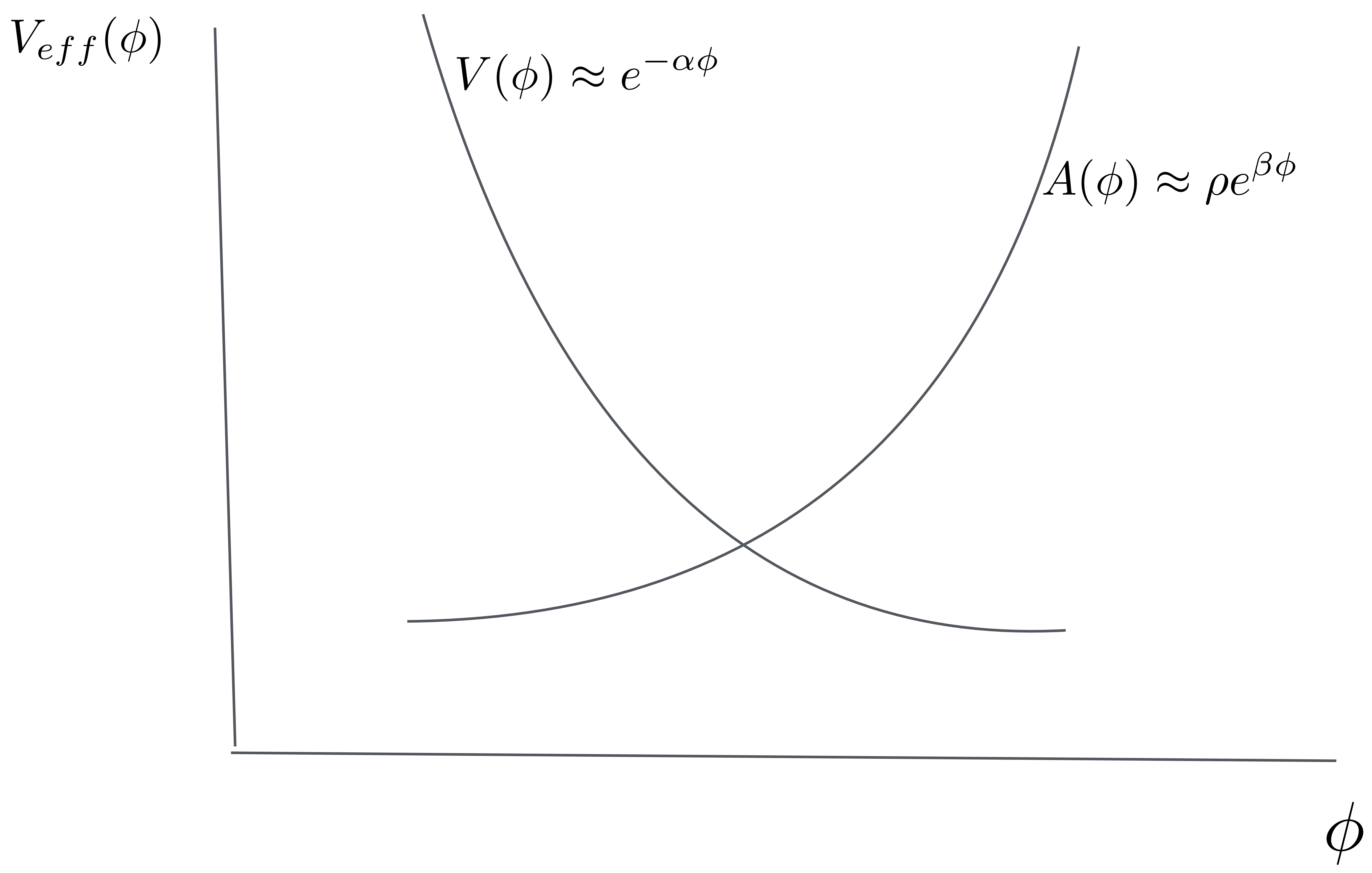
$$V(\phi) = V_0 e^{-\alpha\phi}$$

Gasperini et al, gr-qc/0108016, investigated the runaway dilaton as a quintessence field. With Damour, gr-qc/0204094, they realised there were equivalence violations when the dilaton coupled to matter

In the weak coupling limit the dilaton coupling to matter is

$$A(\phi) = e^{\beta\phi}$$

Does this have a screening mechanism? Actually NO. You might think it is viable until computing the thin shell condition — such a model doesn’t have a thin shell so will not pass all solar system tests



What's wrong with this?
There's no thin shell! Fifth forces won't be screened

Environmentally Dependent Dilaton

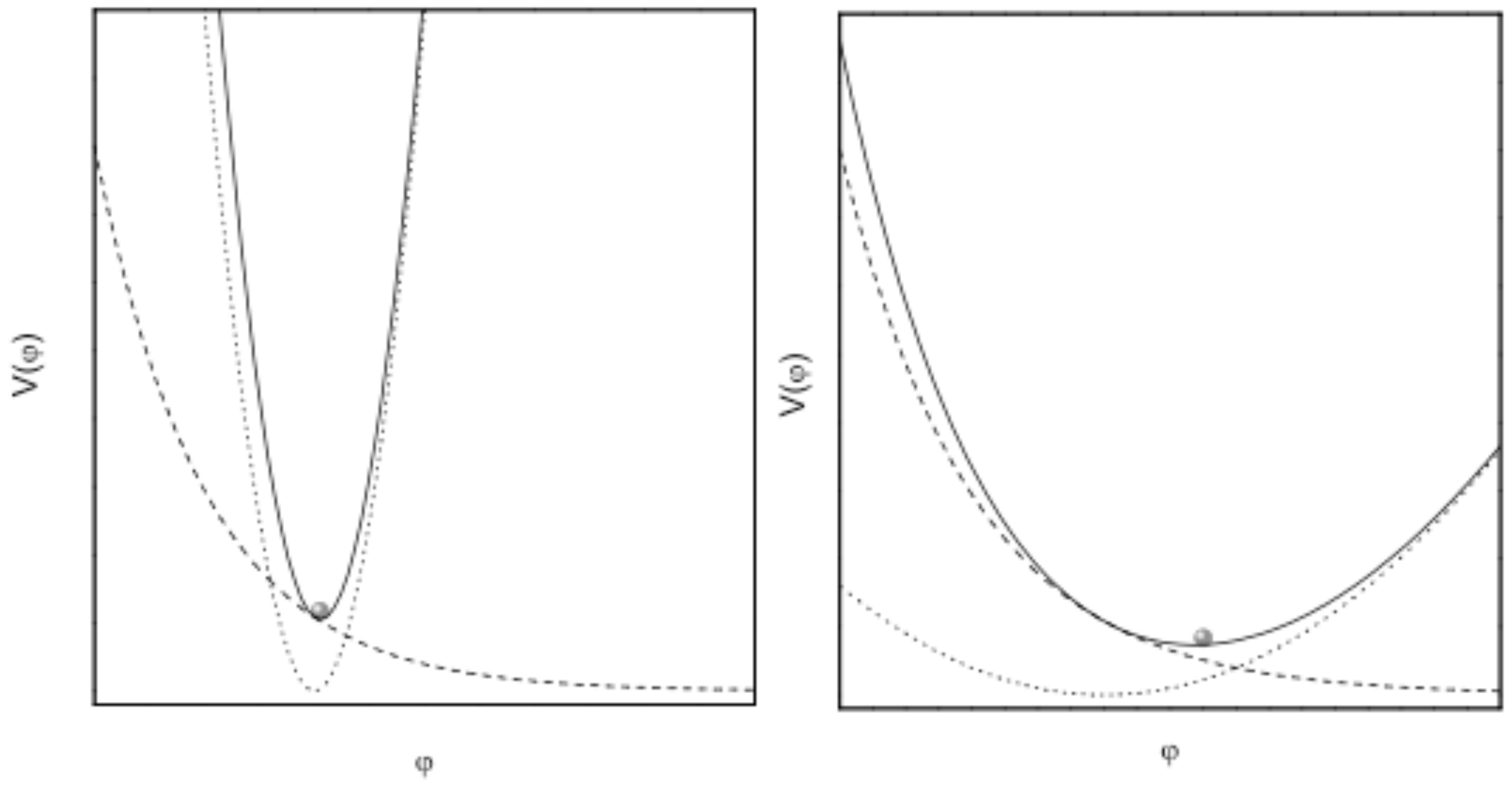
Brax, van de Bruck, ACD& Shaw 1005.3735

$$V(\phi) = V_0 e^{-\alpha\phi}$$

Where the potential is derived from string theory in the strong coupling limit. We chose the coupling to matter to be

$$A(\phi) = 1 + \frac{A_2}{2}(\phi - \phi_\star)^2$$

This keeps the scalar in the strong coupling regime as the Universe evolves. See Brax et al 1005.3735 for full details of the cosmological behaviour, local constraints and linear perturbation theory



But the dilaton arises as part of a multiplet; in particular with the axion! Can the axio-dilaton model account for the dark sector?

Axio-Dilaton Model

With Adam Smith, Maria Myklova, Philippe Brax, Carsten van de Bruck, Cliff Burgess

In this class of models, motivated by SUSY and string theory there is a two derivative interaction with lagrangian given by.

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

$\mathcal{G}_{ab}(\phi)\,\partial_\mu\phi^a\,\partial^\mu\phi^b = \partial_\mu\chi\,\partial^\mu\chi + W^2(\chi)\,\partial_\mu\mathfrak{a}\,\partial^\mu\mathfrak{a}$

Thus the Lagrangian is

$$\mathcal{L} = -\sqrt{-g}\Big[V(\phi) + \tfrac{1}{2}\,M_p^2 R + \tfrac{1}{2}\,M_p^2\,\mathcal{G}_{ab}(\phi)\,\partial_\mu\phi^a\,\partial^\mu\phi^b + \cdots\Big] + \mathcal{L}_m(\psi, \phi, g_{\mu\nu})$$

and for the axio-dilaton model

$$\mathcal{G}_{ab}(\phi)\,\partial_\mu\phi^a\,\partial^\mu\phi^b = \partial_\mu \underset{\substack{\uparrow \\ \text{dilaton}}}{\chi}\,\partial^\mu\chi + W^2(\chi)\,\partial_\mu \underset{\substack{\uparrow \\ \text{axion}}}{\mathfrak{a}}\,\partial^\mu\mathfrak{a}$$

The dilaton is a pseudo Goldstone boson for an approximate space-time symmetry. it is typically very light and the scaling conditions lead to exponential potentials, so we take the coupling function and dilaton potential to be

$$W(\chi) = W_0\, e^{-\zeta\chi} \quad \text{and} \quad V_{\rm dil}(\chi) = U\, e^{-\lambda\chi}$$

The axion potential can be taken as

$$V_{\rm ax}(\mathfrak{a}) \simeq \tfrac{1}{2} m_{\mathfrak{a}}^2 M_p^2 \left(\mathfrak{a} - \mathfrak{a}_0\right)^2$$

The axion moves near the minimum of the potential. It is the oscillations about the minimum that lead to the axion being dark matter, where the oscillations are faster than lthe Hubble time

The final point to note is that the dilaton couples to matter with a coupling function

$$\tilde{g}_{\mu\nu} := e^{2\mathbf{g}\chi}\, g_{\mu\nu}$$

It behaves as a Brans-Dicke scalar with matter moving in the Jordan frame

The standard model particles thus couple to the dilaton with runaway coupling function, so the particle masses vary as

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

The coupling, g, must be small to satisfy solar system tests and ensure the variation in particle masses is not too large; we take

$$g \leq 10^{-3}$$

This also ensures mass variations on earth are sufficiently small to not have been detected yet

$$\frac{\Delta m}{m} \sim \frac{\mathbf{g}^2 G M_{\oplus} h}{R_{\oplus}^2} \sim 10^{-19} \left(\frac{\mathbf{g}^2}{10^{-6}}\right)\left(\frac{h}{1\,\mathrm{km}}\right)$$

We can now compute the perturbations and input into CLASS to make predictions for the spectrum. Before we can do this we need to consider the axion field; It undergoes fast oscillations about its VEV. Thus we use the Mandelung formalism whereby the oscillating axion is considered as a fluid description centred about the VEV so we average over oscillations

Note that the axion only couples to the dilaton, and thus can behave as a component of dark matter, whilst the dilaton couples to ordinary matter. To analyse the model we used two different potentials for the dilaton.

The simple case $$V_{\rm dil}(\chi) = V_0\, e^{-\lambda\chi}$$

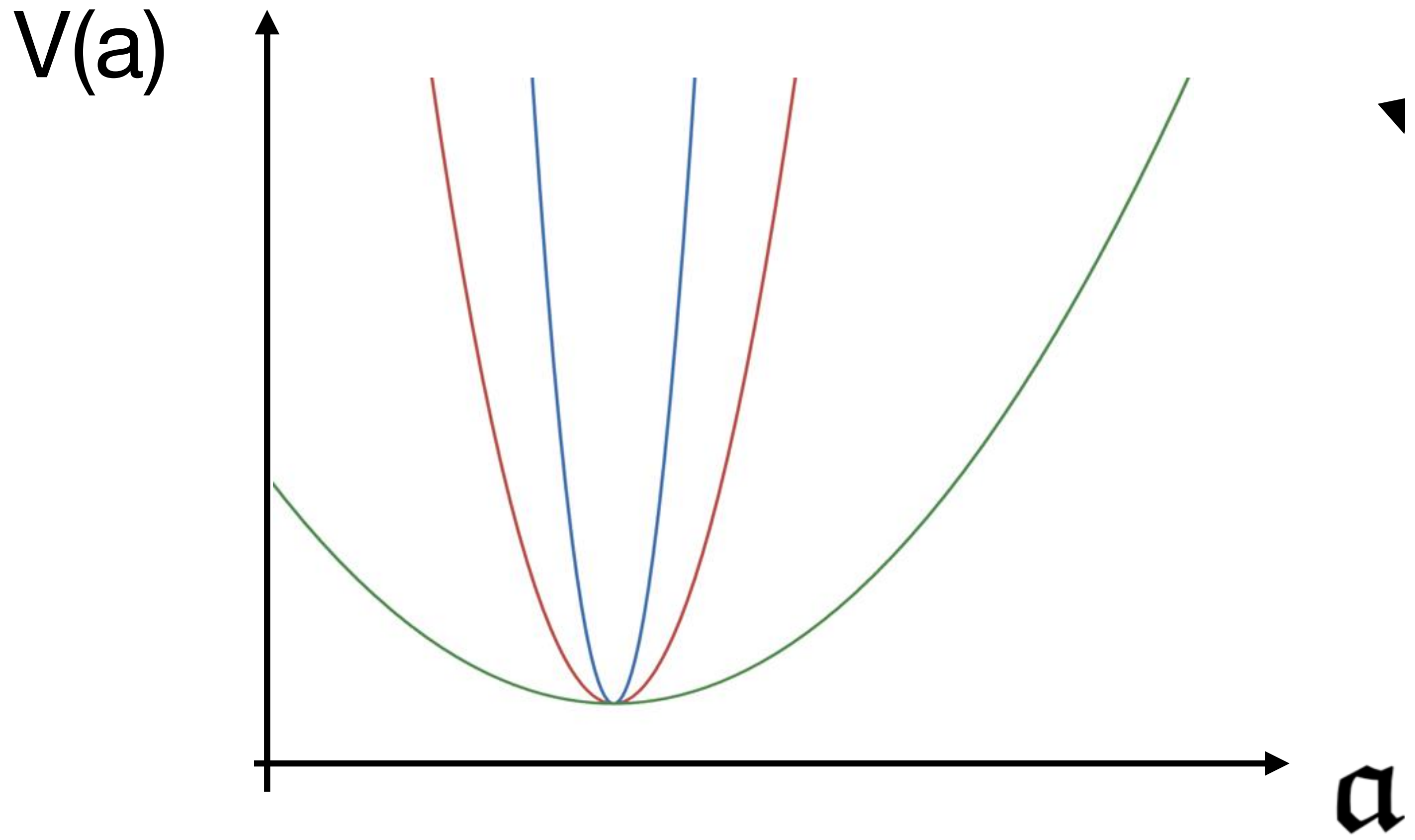
The yoga case $$V_{\rm dil}(\chi) = U(\chi)\, e^{-4\zeta\chi} \qquad U(\chi) = V_0\left[1 - u_1\,\chi + \frac{u_2}{2}\,\chi^2\right]$$

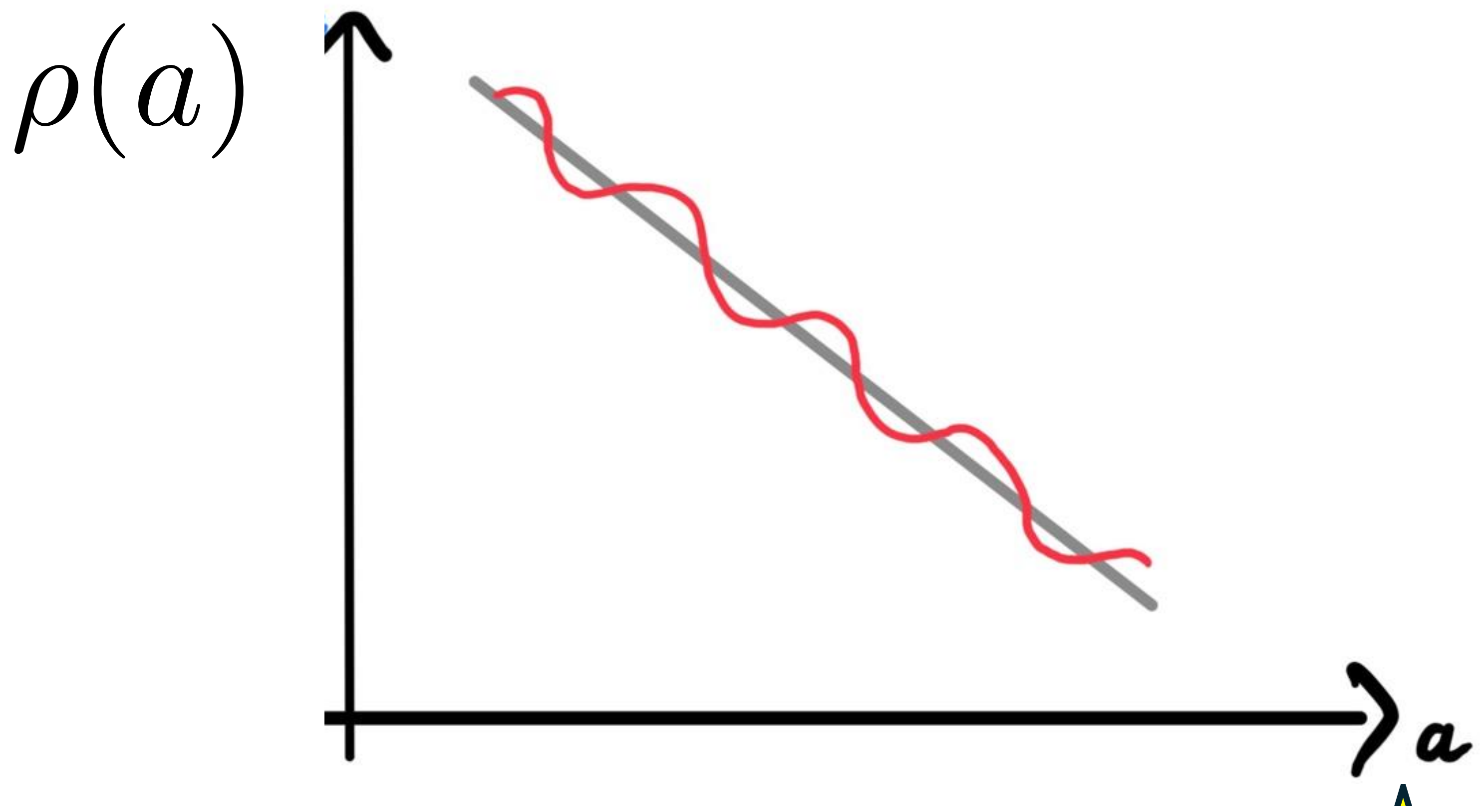
We can compute the perturbation theory and insert both the simple, runaway and the yoga case into CLASS to extract the spectrum. In both cases the axion only couples to the dilaton field whilst the dilaton couples to matter. Thus the axion could be a component of dark matter and the dilaton could behave as dark energy.

The axion energy density is

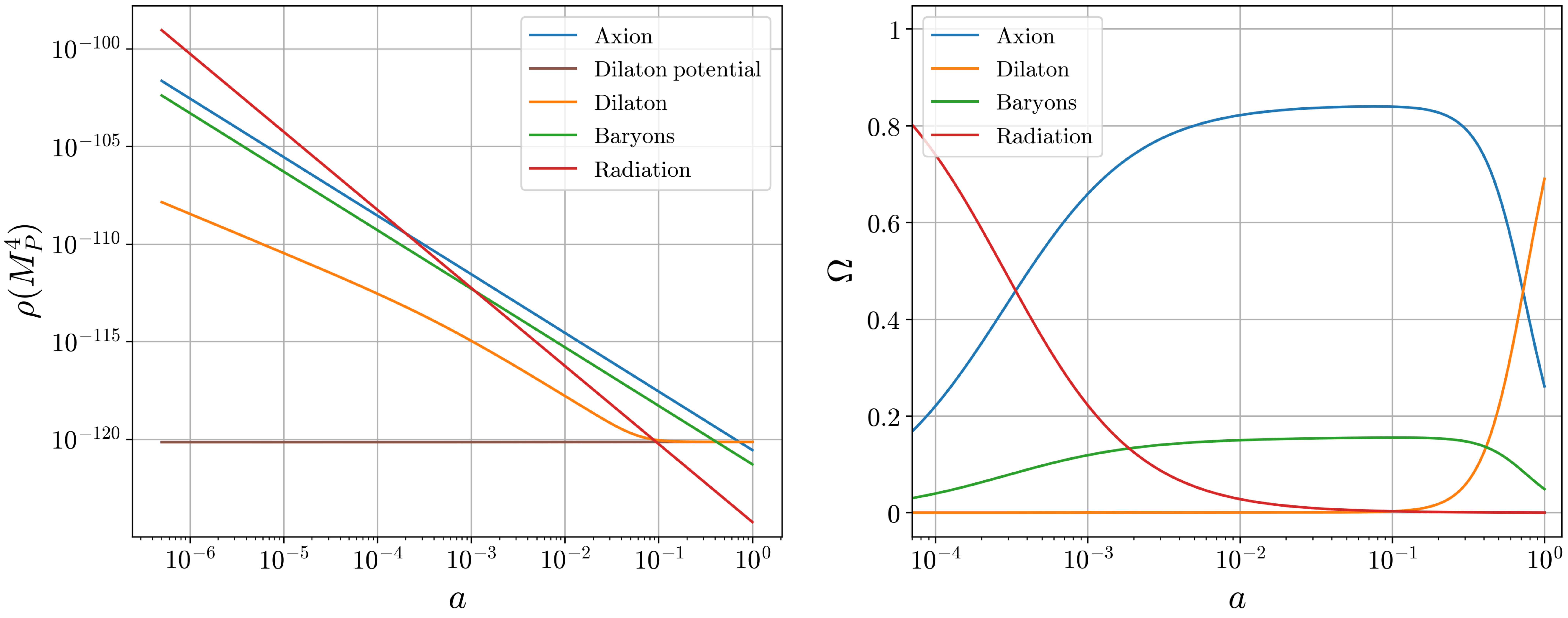
$$\bar{\rho}_{\rm ax} = W^2(\bar{\chi})\bar{\rho}_{\mathfrak{a}} = \frac{C\mathfrak{m}(t)}{a^3} \qquad \mathfrak{m}^2(t) = \frac{m_{\mathfrak{a}}^2}{W^2(\bar{\chi})}$$

No evolution of VEV,



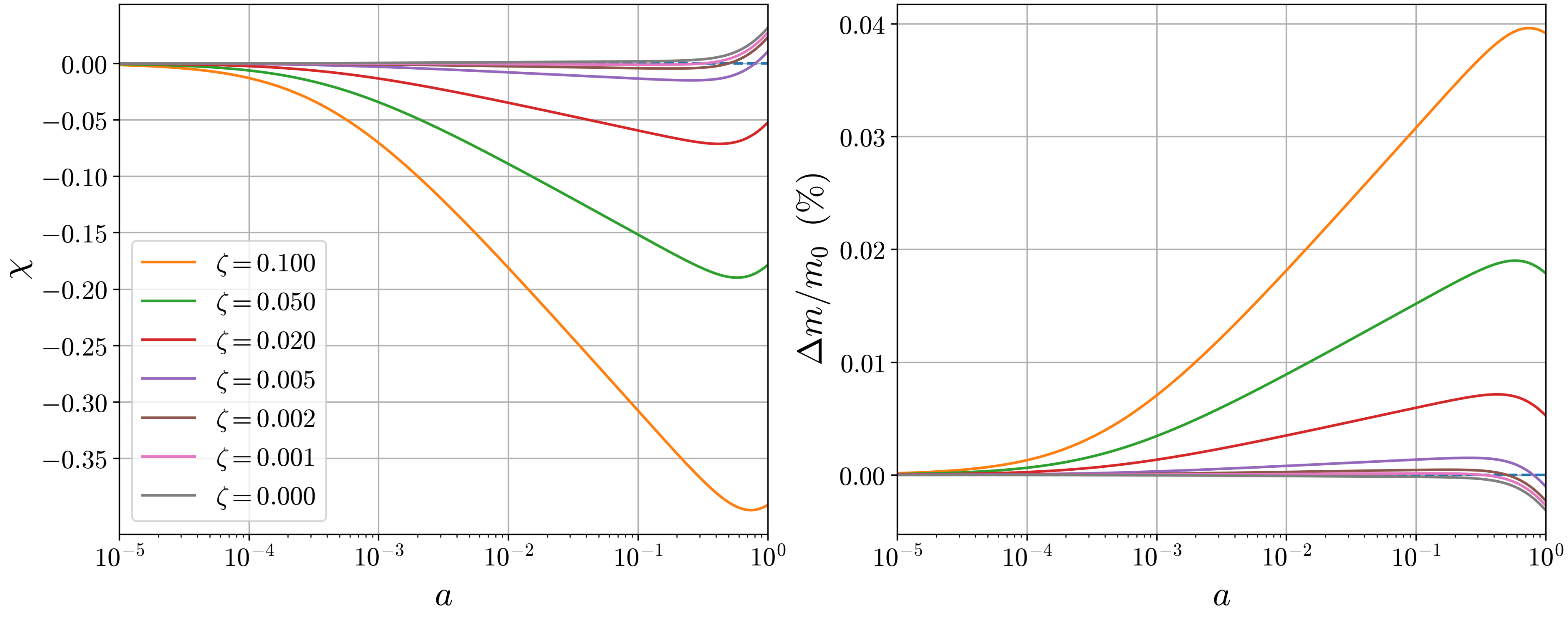


Minimal Dark Sector

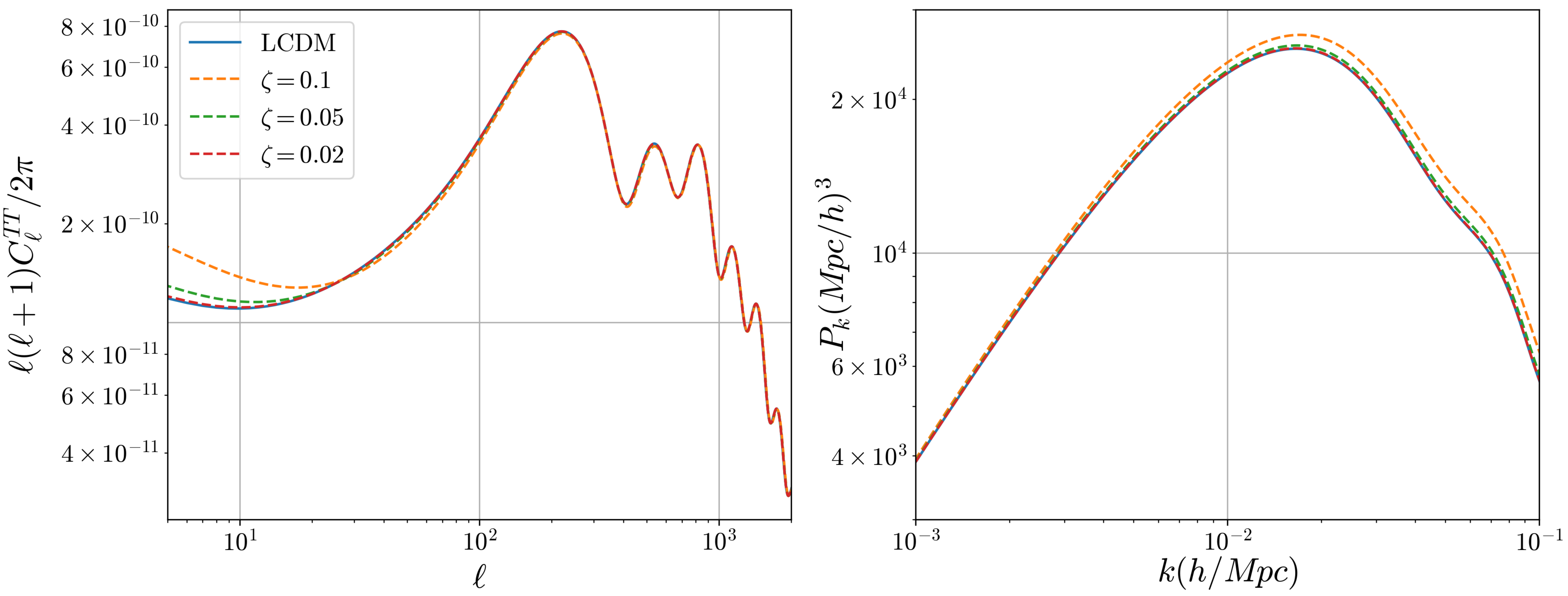


$$\zeta = 0.1 \quad \text{and} \quad \mathbf{g} = -10^{-3}$$

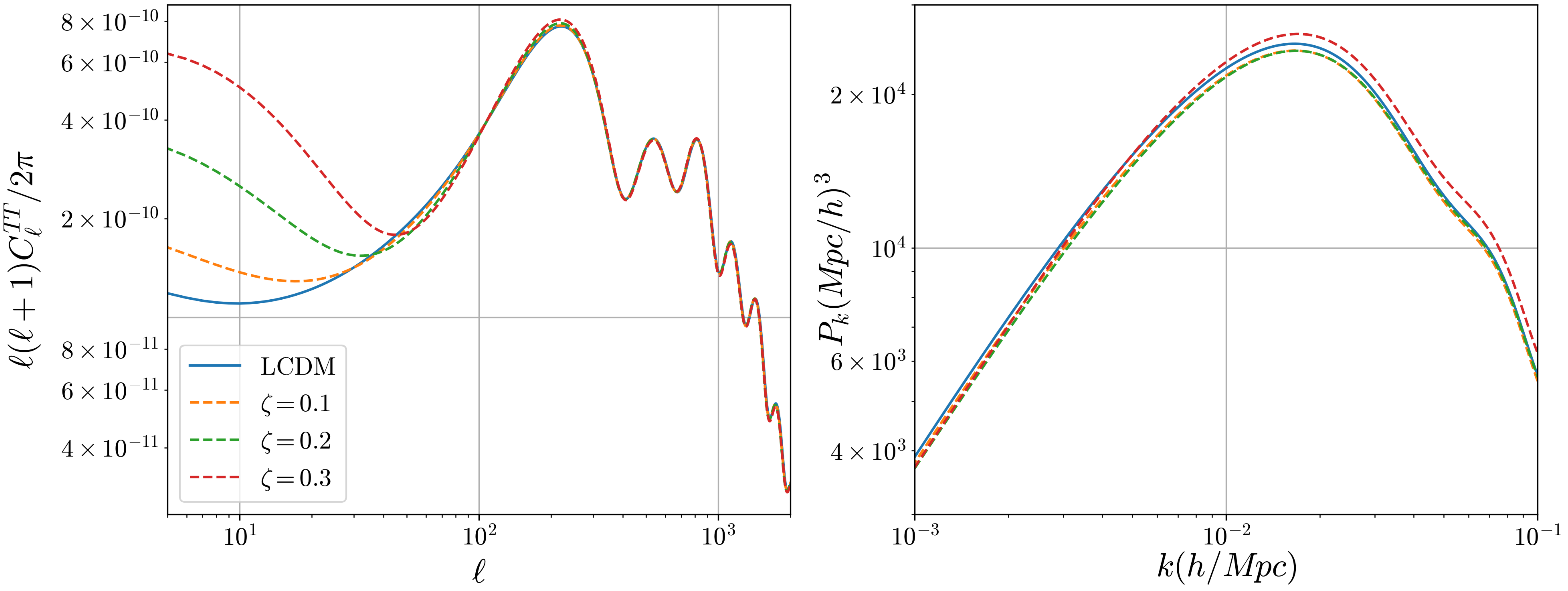
A couple of things to note are that the dilaton evolution affects matter clustering with deviations from LCDM arising due to the axion, which couples to the dilaton. This makes the axion mass more sensitive to dilaton field excursions. The variation in the axion mass causes the axion density to deviate from a^{-3} this induces large integrated Sachs-Wolfe effect. At present the effect is not detachable but is a prediction of this class of models and could be detectable in future surveys.



CMB Power Spectrum



We can compute the CMB for the yoga potential as well. In this case the u's are non-zero and the dilaton field has a local minimum.



The recent data release by DESI suggest that the ‘dark energy’ equation of state is evolving and could be < -1.0. how could this come about? Phantom dark energy? No. it can come about by an interacting dark sector.

The dilaton equation of state is

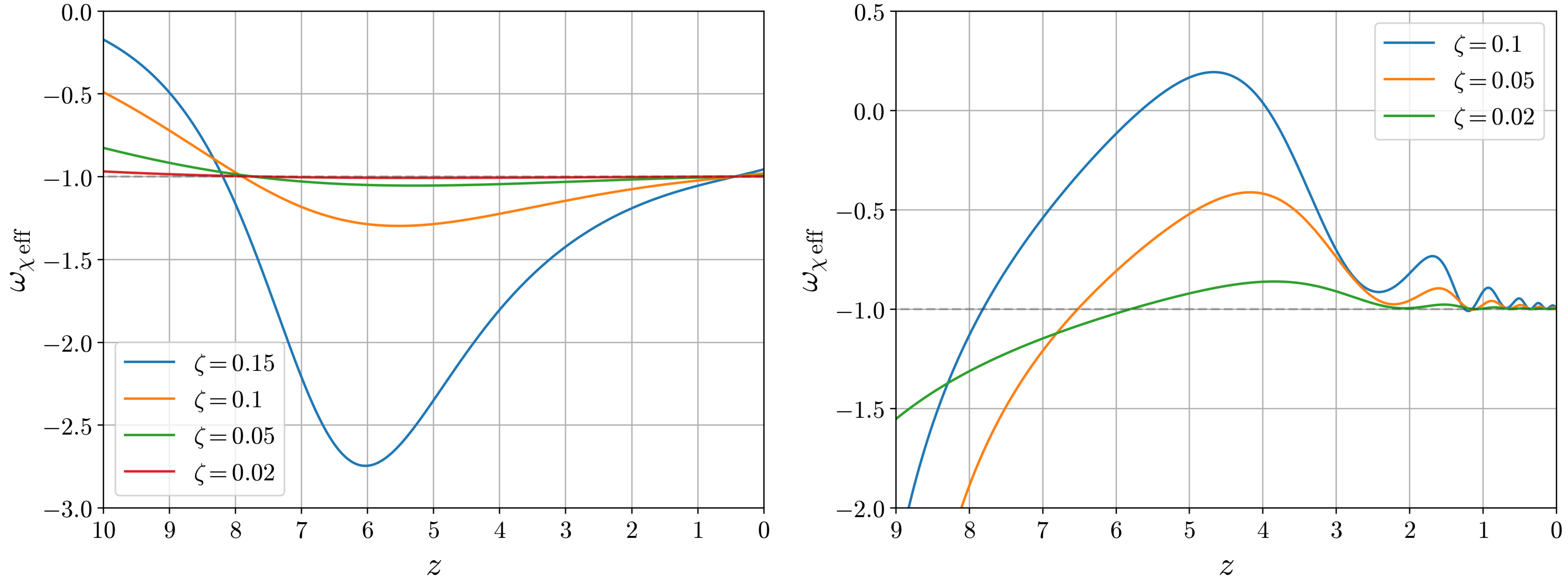
$$\omega_\chi(\chi) = \frac{\chi'^2 - 2a^2V(\chi)}{\chi'^2 + 2a^2V(\chi)} \geq -1$$

It is not a phantom. However, it does interact with the axion particle. Once this interaction is taken into account we obtain an effective equation of state for dark energy

$$\omega_{\chi\,\mathrm{eff}} = \frac{\omega_\chi(\chi)}{1 + \left[e^{\zeta(\chi-\chi_0)} - 1\right] \frac{\rho_{\mathrm{ax0}}}{a^3\rho_\chi}}$$

This is not bounded by > -1.0. DESI could be observing the interactions between the dark sectors

Dilaton Effective Equation of State



Minimal, exponential potential

Non-minimal Yoga potential

Axion Matter Coupling

With Adam Smith, Philippe Brax, Carsten van de Bruck, Cliff Burgess

What happens when the axion couples to matter? We chose an example where the axion couples to electrons and other dark matter species

$$V_{eff}(a) = V(a) + U_e(a)\rho_e + U(a)\rho$$

taking

$$U(a) = 1 + \frac{(a - a_-)^2}{2\Lambda_a^2} \qquad U_e(a) = 1 + \frac{(a - a_{-e})^2}{2\Lambda_e^2}$$

Dynamically the axion mass becomes density dependent

$$m_a^2(\rho_e) = m_a^2 + \frac{\rho_e}{\Lambda_e^2}$$

In a heavy body the axion is massive. The axion field interpolates between the value inside the body and the one in the solar system, with the jump taking place over a narrow region. We take

$$a(r) \simeq a_- \theta(R-r) + a_+ \theta(r-R)$$

This results in the dilaton having an effective coupling

$$\beta(\phi_{\rm loc}) = \frac{\beta}{1+(R/\ell)\frac{(a_+ - a_{-e})^2}{4\Lambda_\phi^2}}$$

which is suppressed compared to the bare coupling, resulting in the fifth force being screened

Analysing as before we find an early period of dark energy at high redshift

8×10^{-10}
6×10^{-10}
4×10^{-10}
2×10^{-10}
8×10^{-11}
6×10^{-11}
4×10^{-11}
$\ell(\ell+1)C_\ell^{TT}/2\pi$
10^1
10^2
10^3
ℓ
LCDM
$f_{\rm EDE} = 0.05$
$f_{\rm EDE} = 0.10$
$f_{\rm EDE} = 0.15$
2×10^4
10^4
6×10^3
4×10^3
$P_k(Mpc/h)^3$
10^{-2}
10^{-1}
$k(h/Mpc)$

What next? Well can we test the model in more detail? For example could we detect the production of axio-dilaton from the sun? Extra species can't account for more than 3% of the solar luminosity. Could this be a way to test our models. We've bounded chameleon models in this way and are working to bound symmetron models. Could we bound the axio-dilaton model?

Summary

We introduced scalar models of dark energy and how fifth forces in these models are screened

We discussed an axio-dilaton model of the dark sector whereby the axion field plays the role of dark matter and the dilaton as dark energy. This is a minimal model with the axion coupled only to the dilaton, but the dilaton coupled to matter. In this model fifth forces are screened by taking the dilaton coupling to be small enough to evade solar system constraints

Coupling the axion to electrons gives rise to an early period of dark energy. The kinetic coupling between the axion and dilaton results in the dilaton fifth force being screened.

Can we detect these models? Can we constrain them?