

Screened Modified Gravity: Theory and Tests

Anne-Christine Davis, Cambridge

Puzzles in Quantum Gravity, Graz 2026

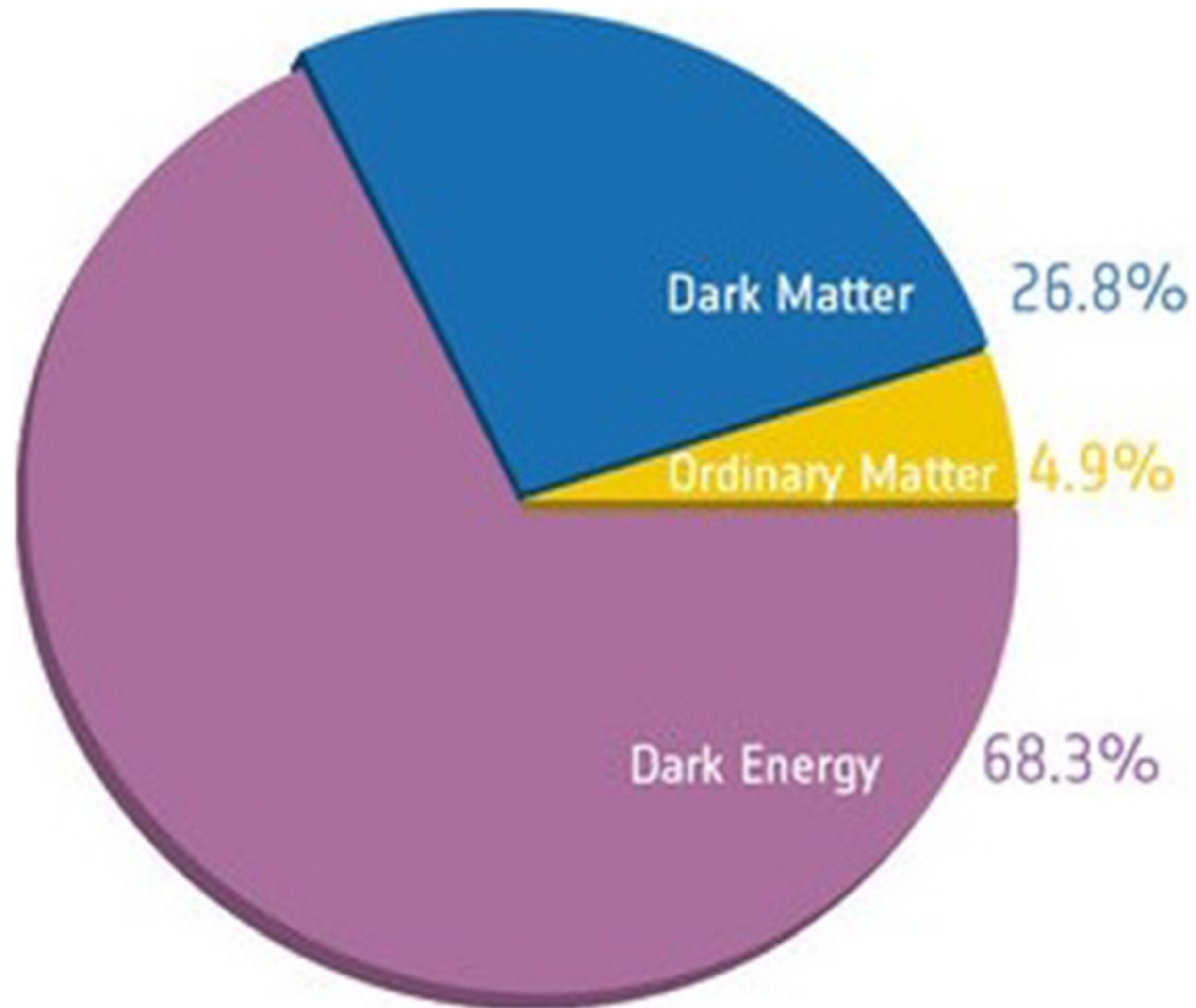
- Why Modified Gravity?

There are several reasons to investigate modified gravity theories. These are theories which modify Einstein theory, but reduce to Einstein relativity in certain limits

Modified Gravity could account for the observed accelerated expansion of the Universe today, eg be the dark energy particle.

Modified Gravity allows one to test General Relativity in new regimes one hadn't originally thought of and look for deviations from General Relativity

Dark Energy



A scalar field could act a dark energy
provided its mass today

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

We only know dark energy dominates today

For a scalar field

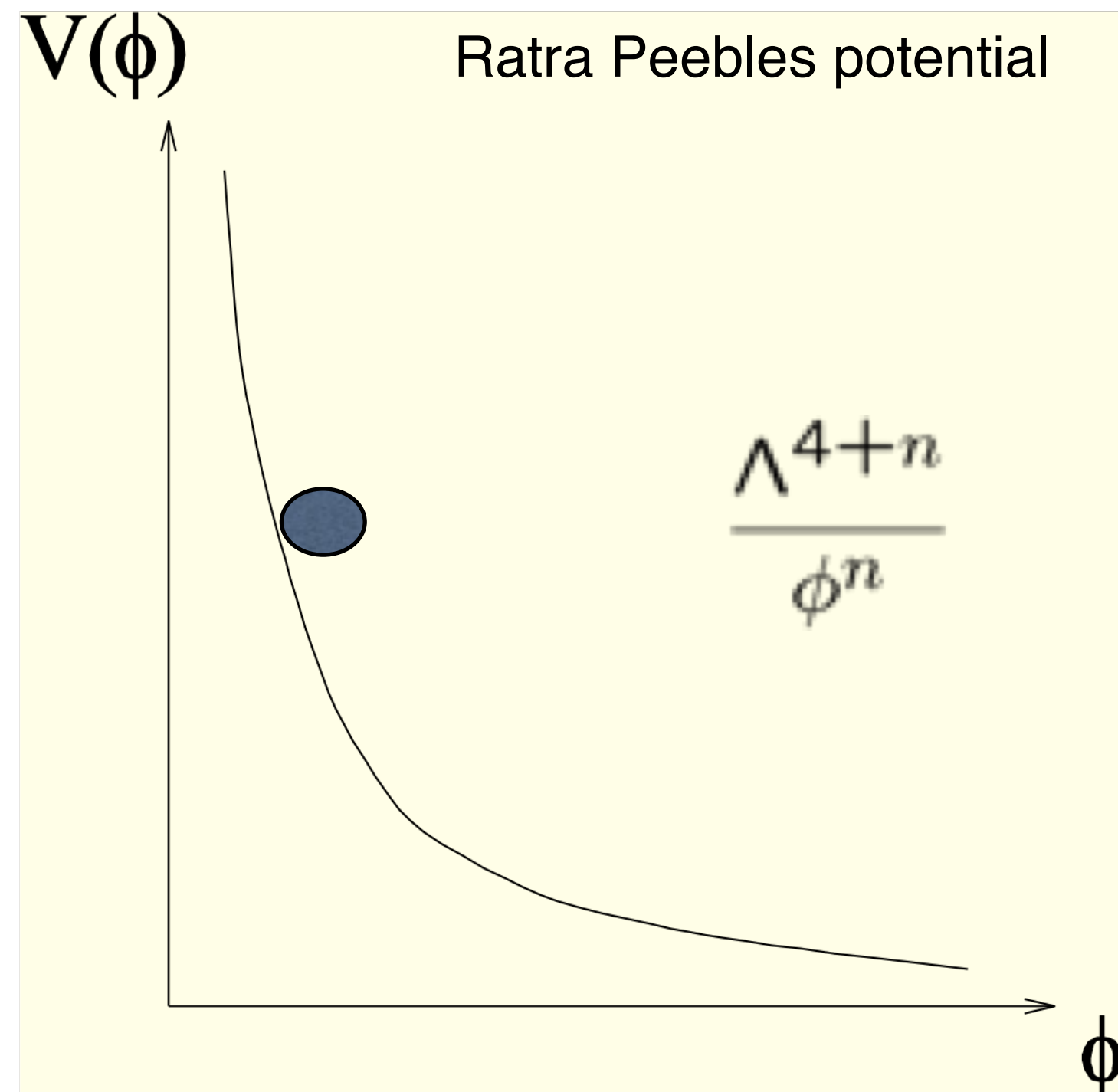
$$\rho_\phi = 1/2\dot{\phi}^2 + V(\phi) \quad \text{kinetic energy} + \text{potential energy}$$

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

If the potential dominates then

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

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



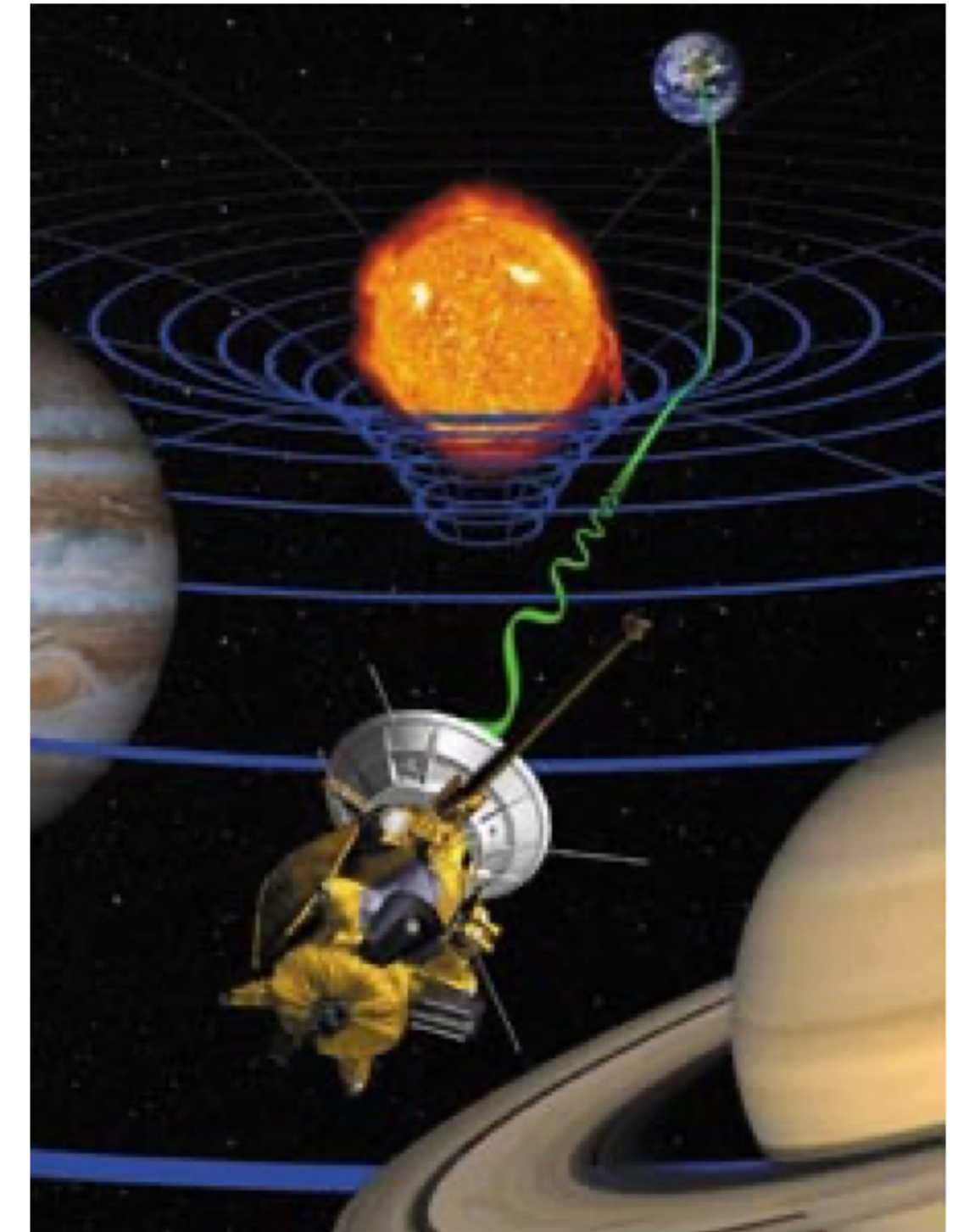
Deviations from Newton's
Laws parametrised by

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

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](#)

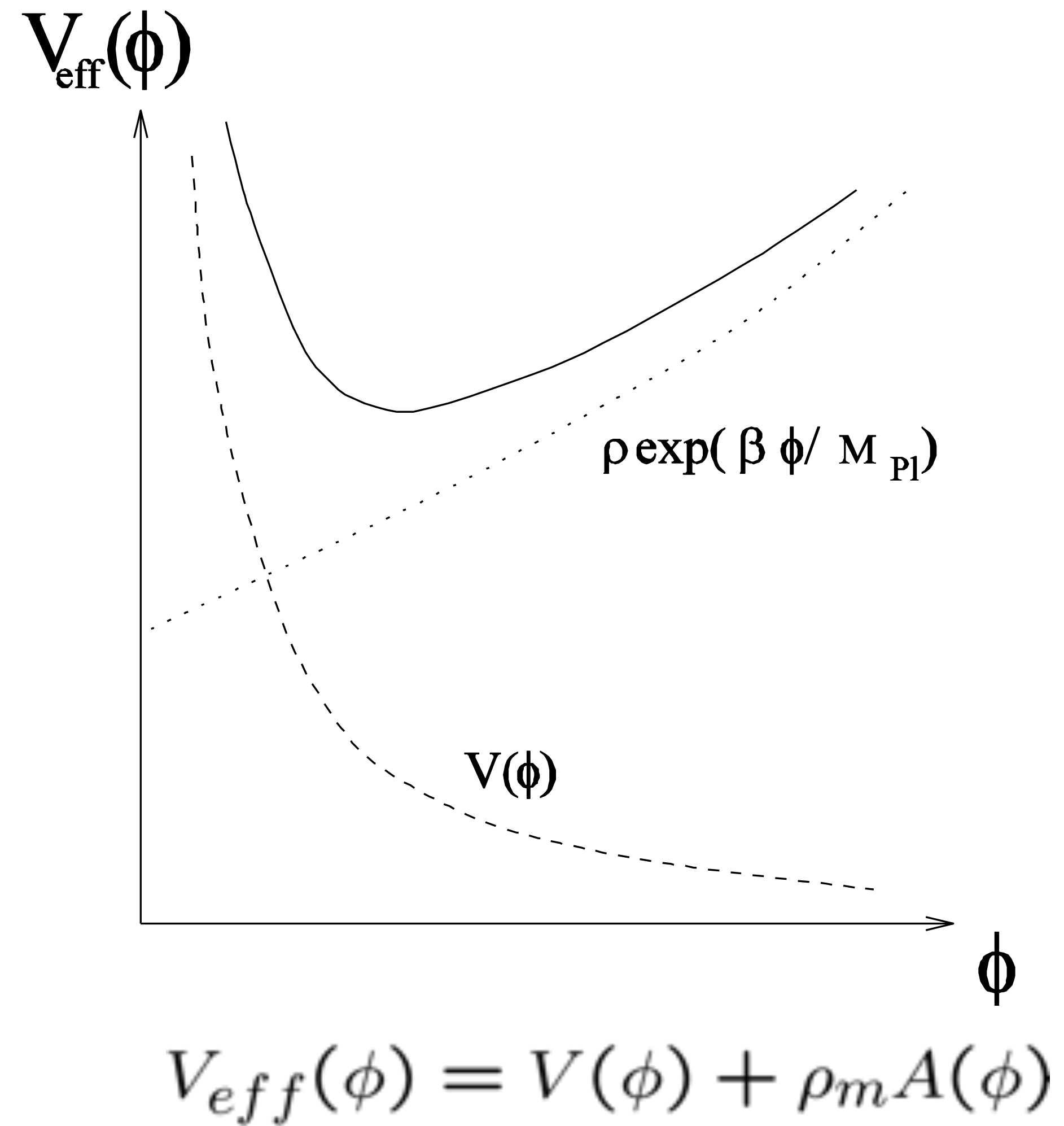
consider the action

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

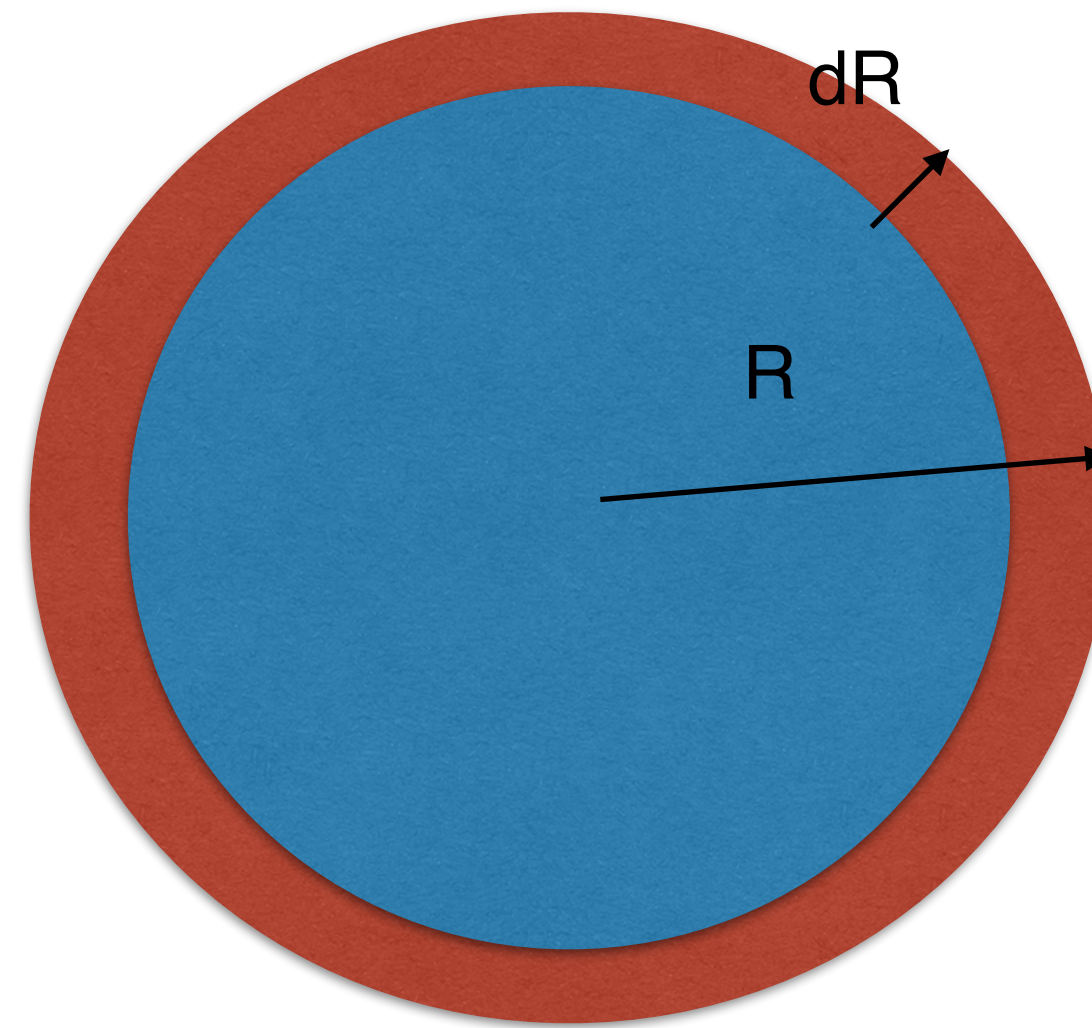
gives the effective potential

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

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



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

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

Symmetrons

Khoury&Hinterbichler, 1001.4525

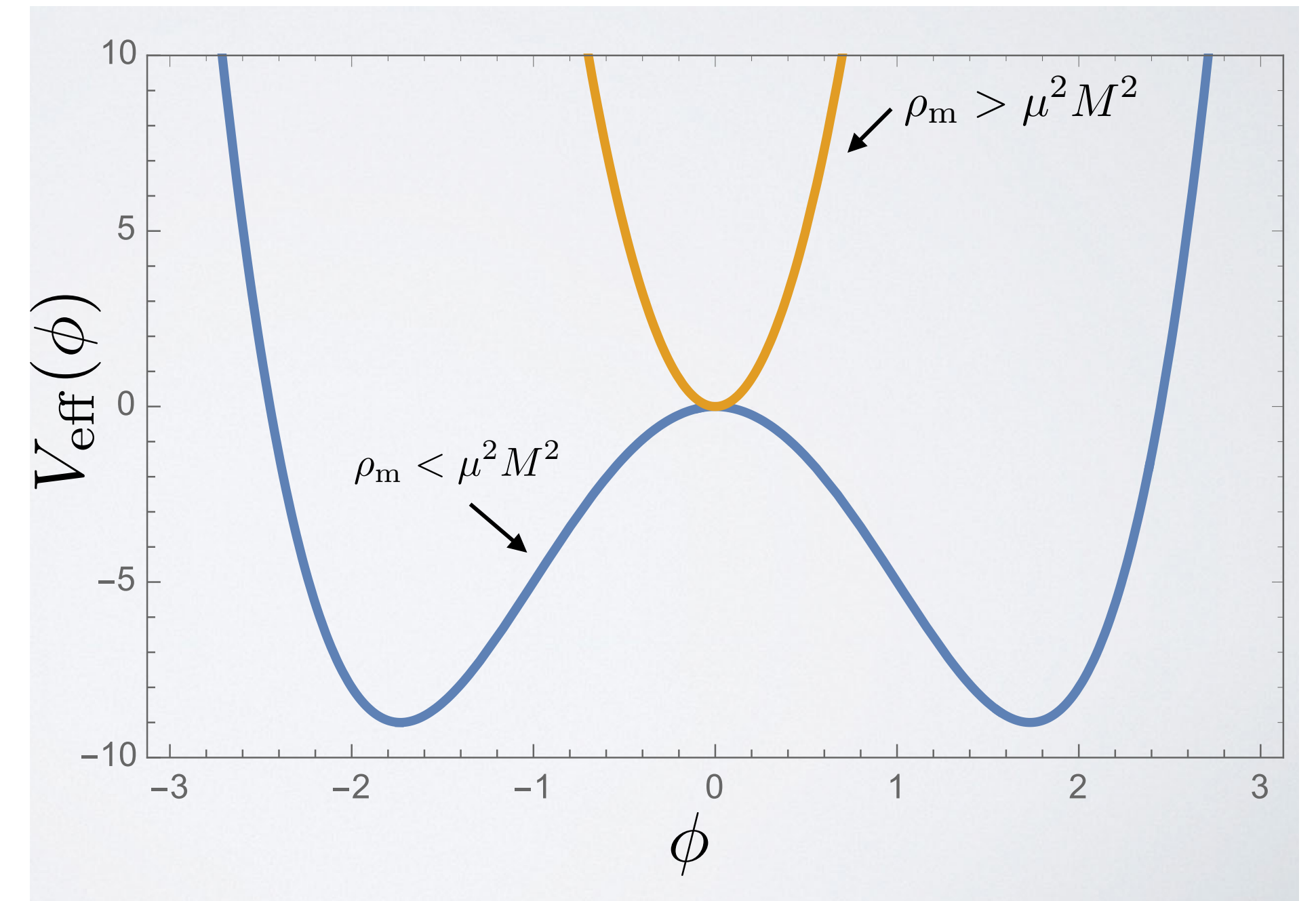
This has potential

$$V(\phi) = V_0 + \frac{\lambda}{4}\phi^4 - \frac{\mu^2}{2}\phi^2$$

and coupling function

$$A(\phi) = 1 + \frac{\beta_\star}{2\phi_\star m_{\text{Pl}}} \phi^2$$

In a dense environment the field is at the origin whilst in a sparser one the field is at the minimum of the potential with the transition happening at density $\rho_\star$



The Runaway Dilaton

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

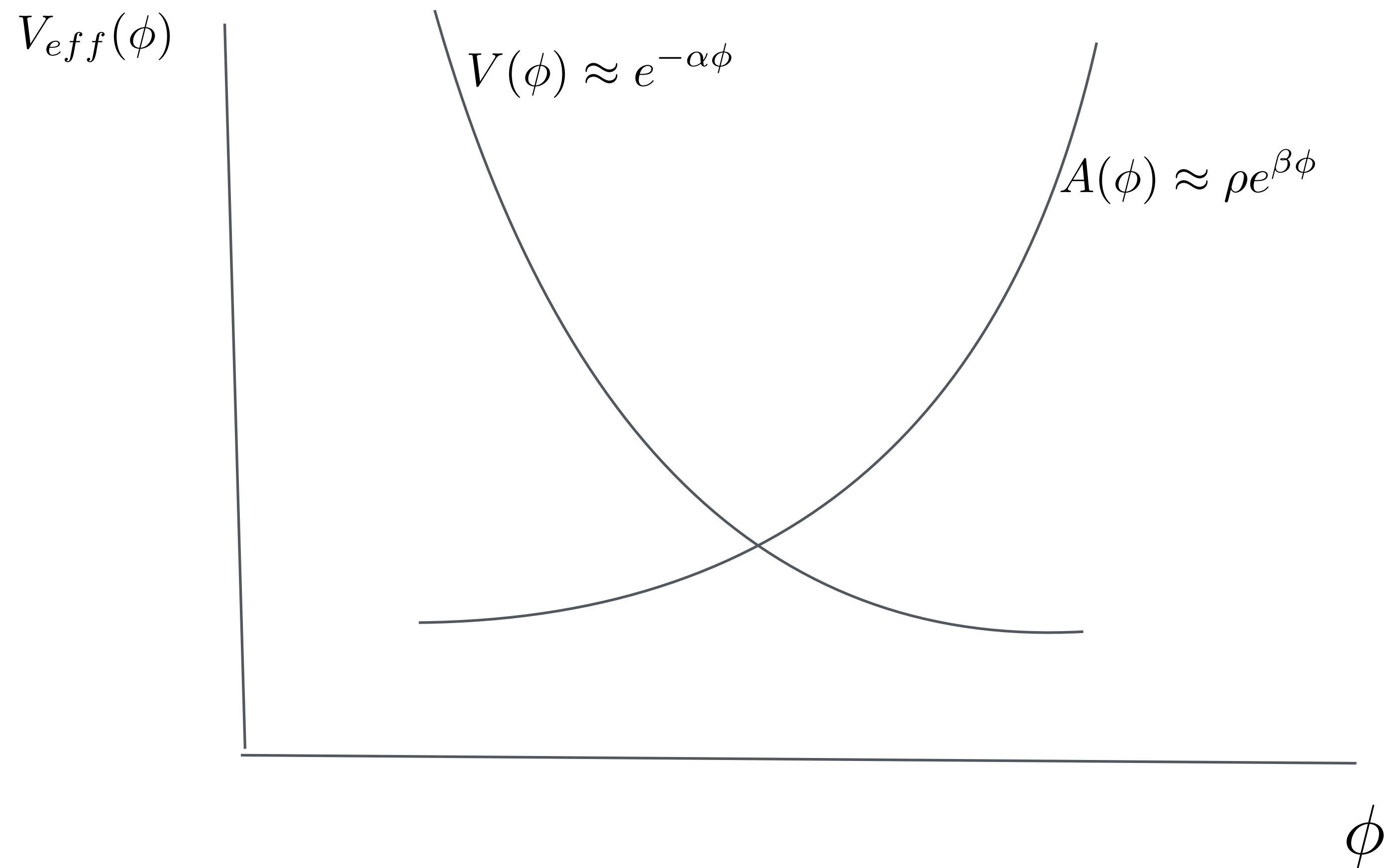
$$V(\phi) = V_0 e^{-\alpha\phi}$$

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

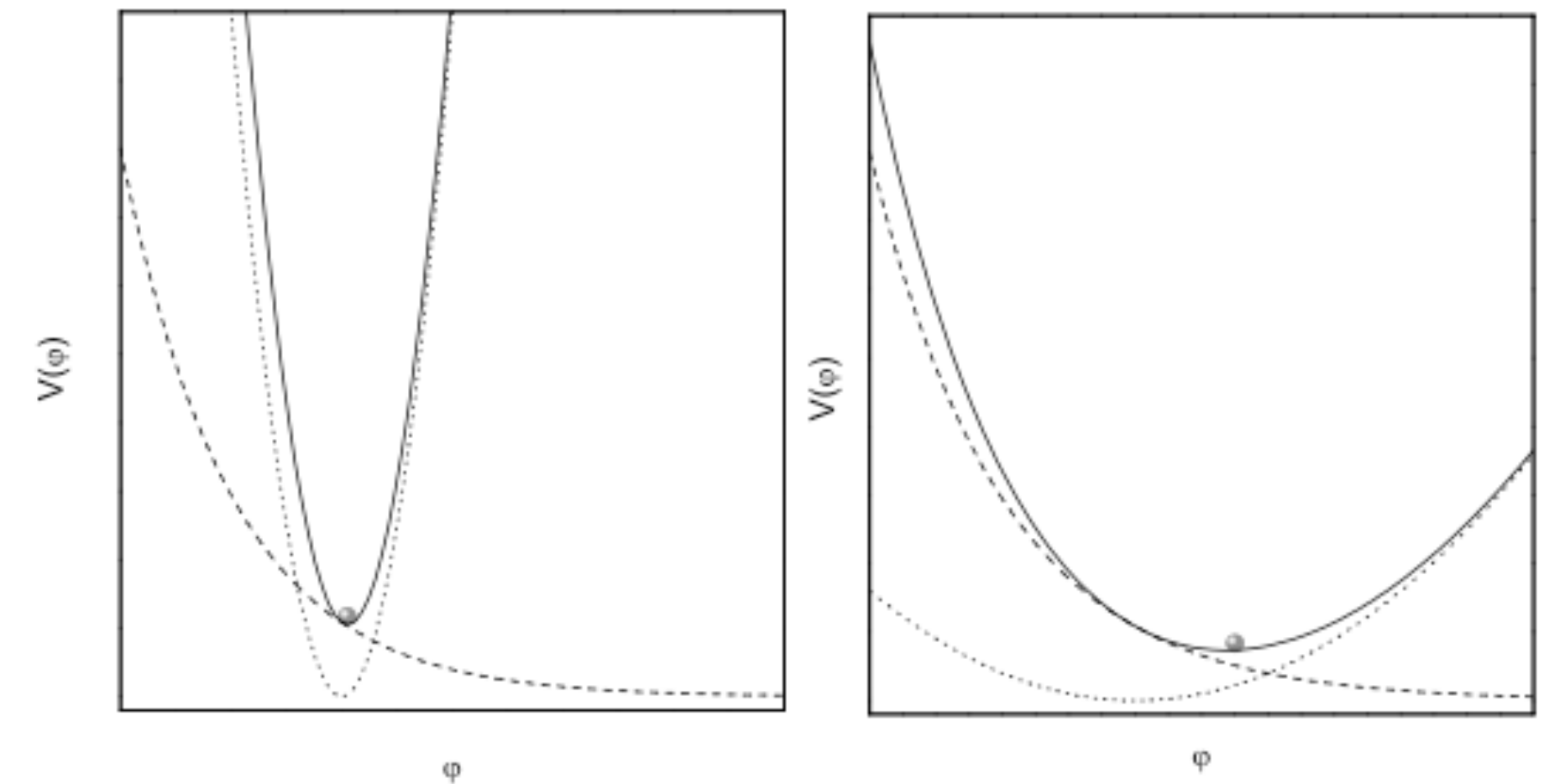
Brax, van de Bruck, ACD& Shaw 1005.3735

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

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



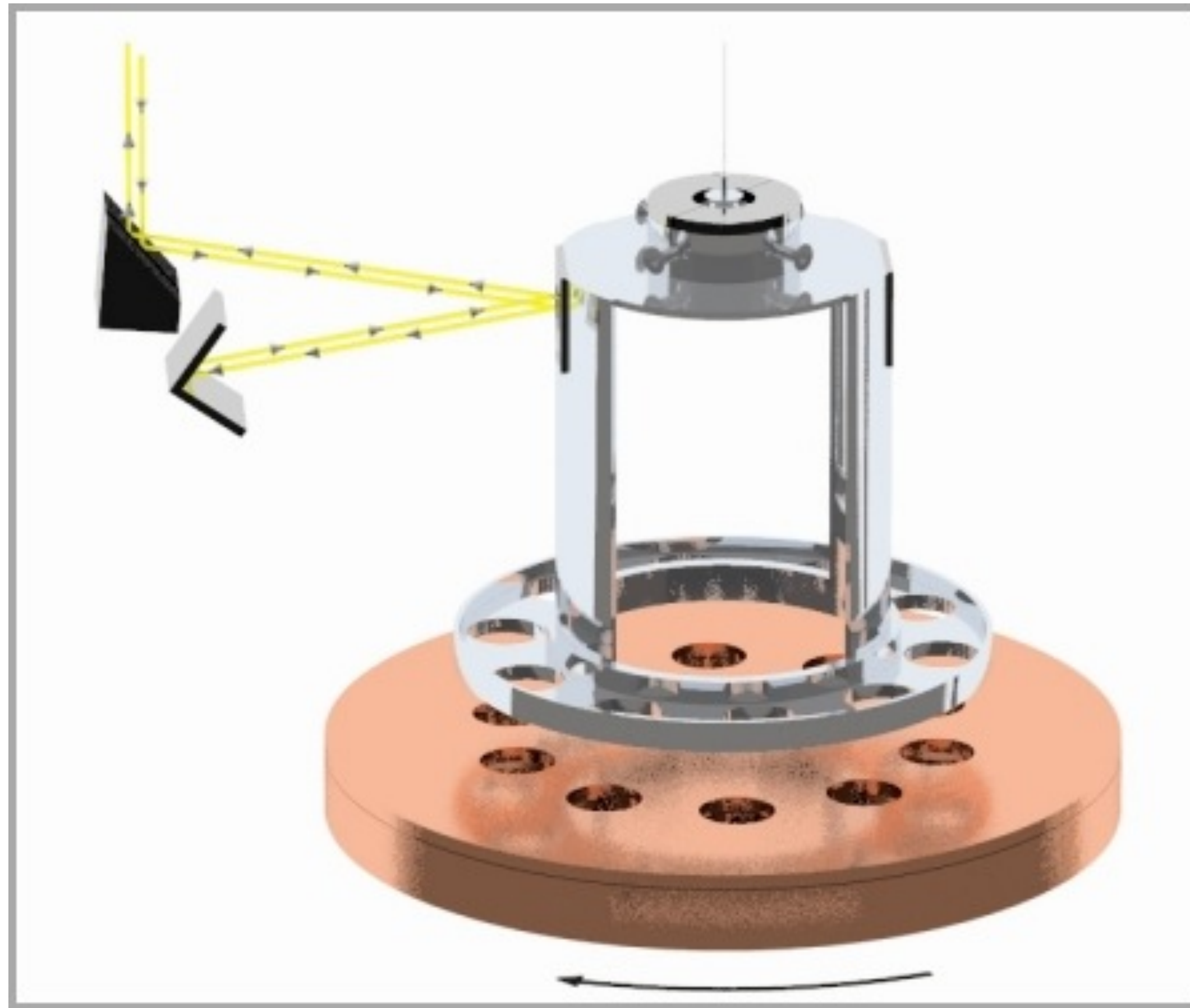
But the dilaton arises as part of a multiplet; in particular with the axion! Can the axio-dilaton model account for the dark sector?

Tests of Screened Scalars

Eot-Wash Experiment

For a review see Wagner et al 1207.2442

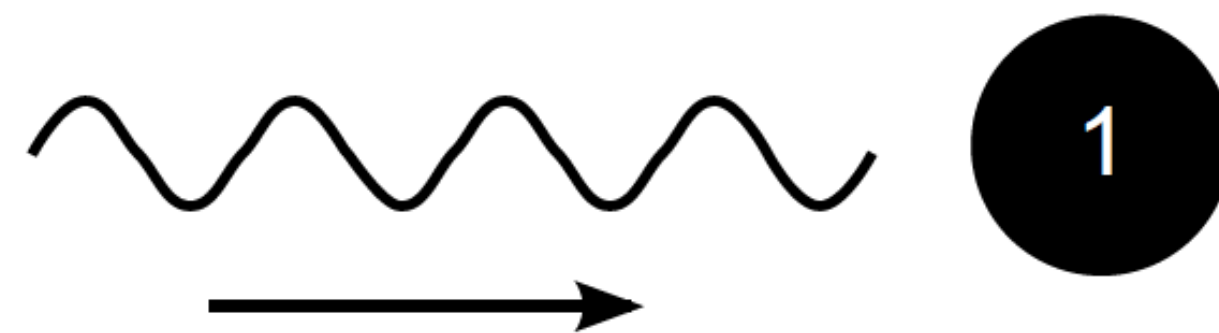
Be-Ti and
Be-Al test
masses



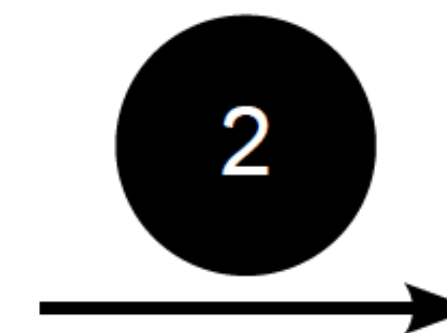
Atom Interferometry

An interferometer where the wave is made of atoms

Atoms can be moved around by absorption of laser photons



Photon Momentum = k
Atom in ground state

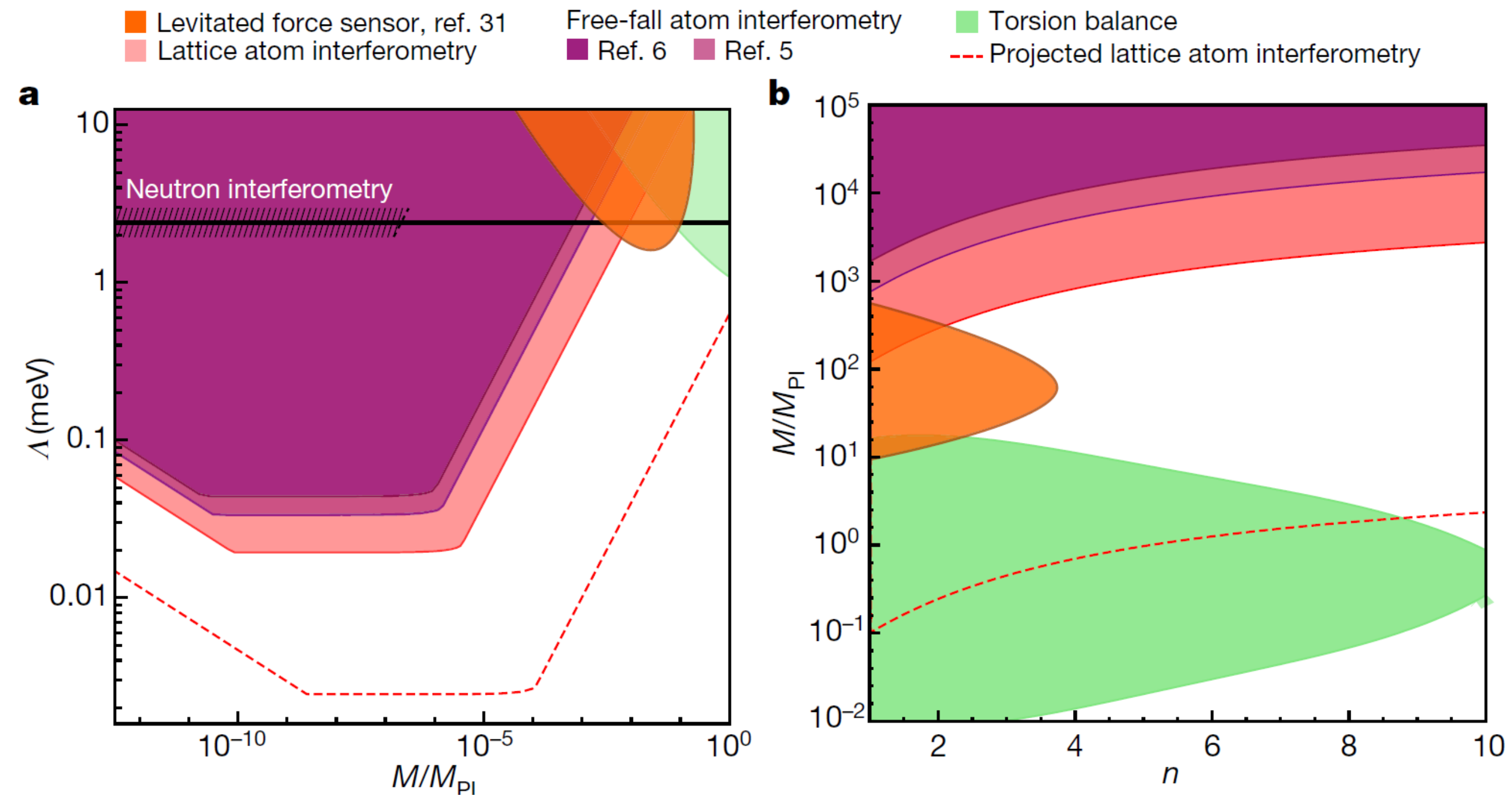


Atom in excited state
with velocity = V

Chameleon: Combined Constraints

Bare potential: $V(\phi) = \Lambda^{n+4}/\phi^n$

Bare matter coupling: M



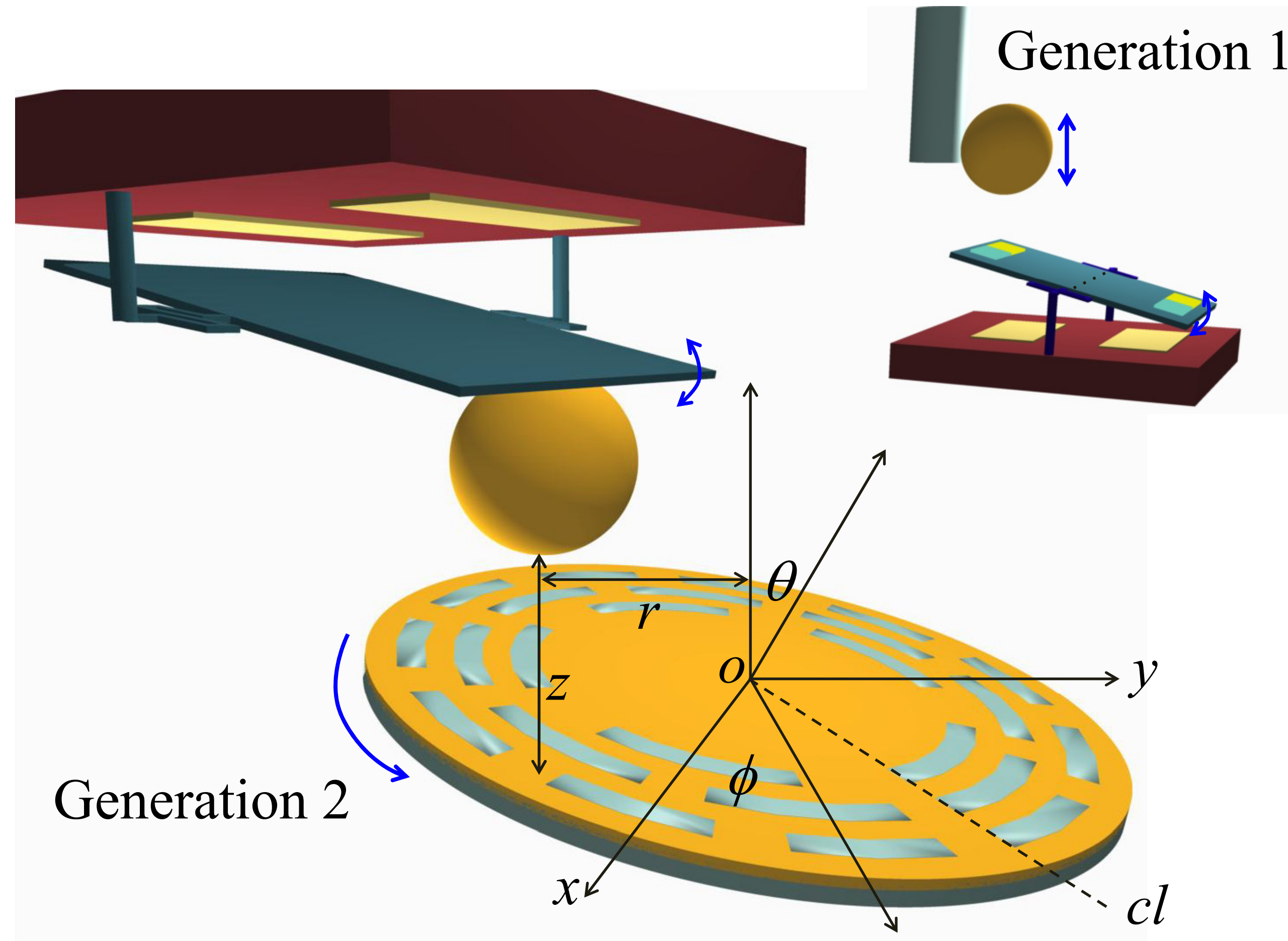
Panda, Tao, Ceja, Khoury, Tino, Muller. Nature 631, 515–520 (2024)

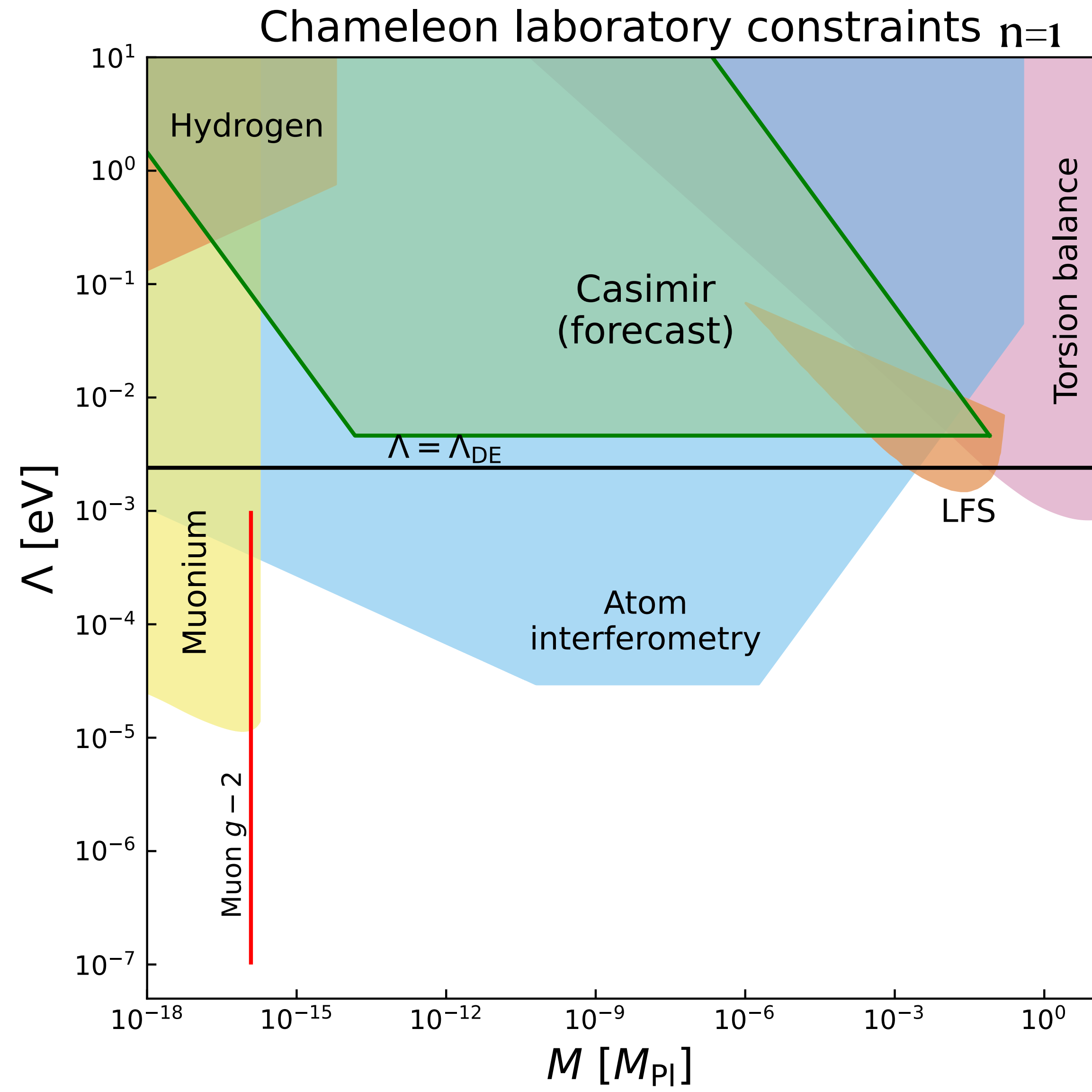
See also: Sabulsky, Dutta, Hinds, Elder, CB, Copeland. Phys.Rev.Lett. 123 (2019) 6, 061102

Brax, Davis, Elder. Phys. Rev. D 107 (2023) 084025

Casimir Force Experiments

Decca Experiment —
1410.7267; 1509.05349





The Axio-Dilaton Model

A.Smith, P.Brax, C.vdBruck, C.Burgess, ACD —2505.05450

A new screening mechanism for two-field model

The axio-dilaton model has a non-trivial kinetic coupling, motivated by SUSY and string theory with Lagrangian

$$S = \int d^4x \sqrt{-g} \left\{ \frac{M_p^2}{2} R - \frac{1}{2} \left[(\partial\phi)^2 + W^2(\phi) (\partial\mathfrak{a})^2 \right] - V(\phi, \mathfrak{a}) \right\} + S_m[A^2(\phi) g_{\mu\nu}, \mathfrak{a}, \psi]$$

The dilaton coupling to matter and kinetic coupling are taken to be

$$A = e^{-\beta\phi/M_p} \qquad W^2(\phi) = e^{-\xi\phi/M_p} = e^{-\phi/\Lambda_\phi}$$

The potential is given by

$$V(\phi, \tilde{\mathfrak{a}}) = V_{\text{dil}}(\phi) + V_{\text{ax}}(\mathfrak{a})$$

$$\text{With } V_{\text{dil}} = U(\phi) e^{-\lambda\phi/M_p} \quad V_{\text{ax}} \simeq \frac{1}{2} m_{\mathfrak{a}}^2 \mathfrak{a}^2$$

$$\text{The axion couplings to matter are taken to be } \mathcal{U}_i(\mathfrak{a}) \simeq \frac{(\mathfrak{a} - \mathfrak{a}_i)^2}{2\Lambda_i^2}$$

$$\text{Note that this gives the matter field an axion dependent mass } m_i = m_{i0} \left[1 + \mathcal{U}_i(\mathfrak{a}) \right]$$

Screening

The screening in the two field models is more complicated —
Smith et al 2505.05450; Brax, CvdBruck, ACD, Smith 2603.13986

In a compact object the axion acquires a density dependent mass with the mass in vacuum being much smaller than the mass inside the compact object, so there is a ‘jump’ at the surface, which generates an axion gradient. Given the coupling between the axion and dilaton this gives a ‘jump’ in the dilaton effective charge, L . Typically in the absence of screening

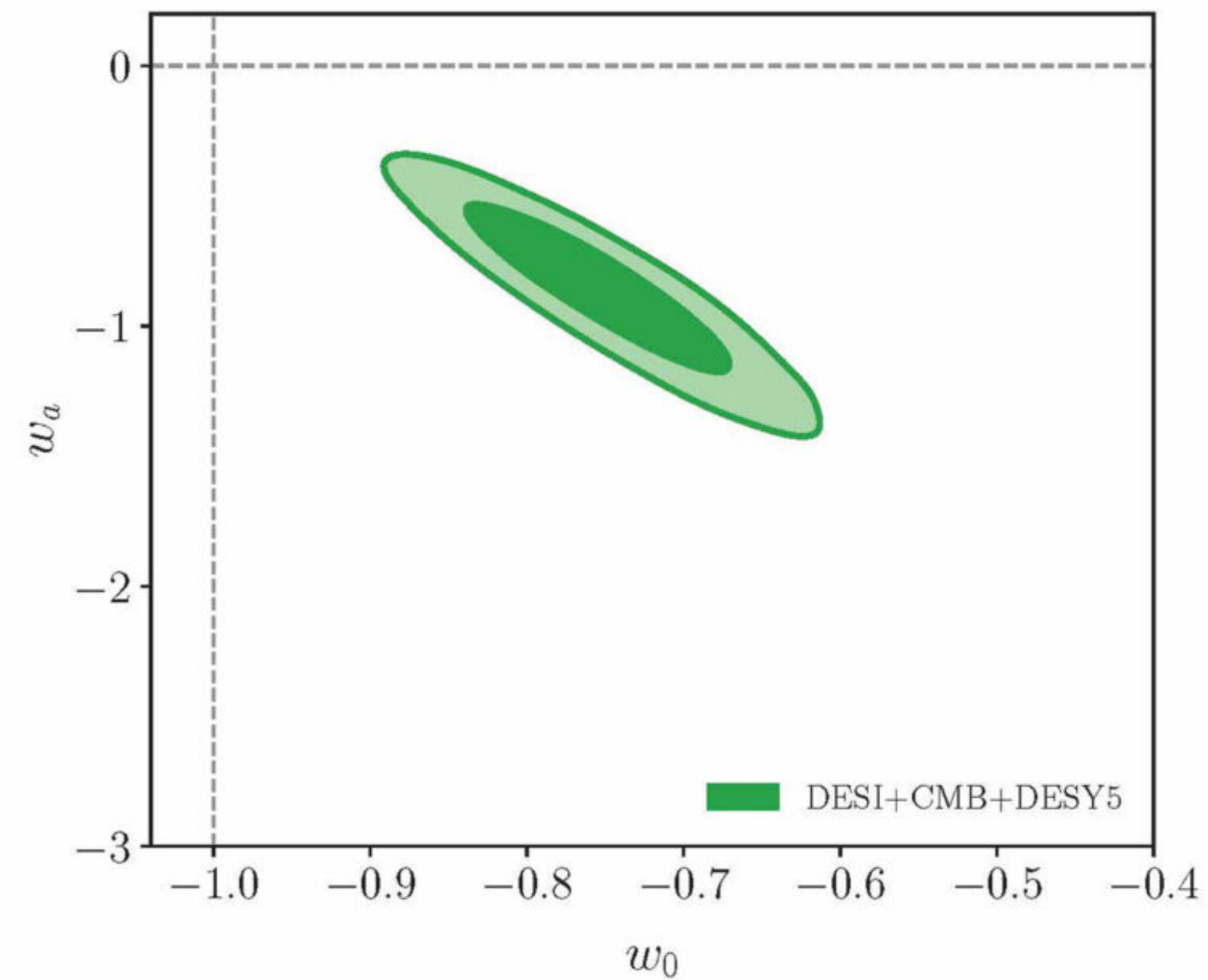
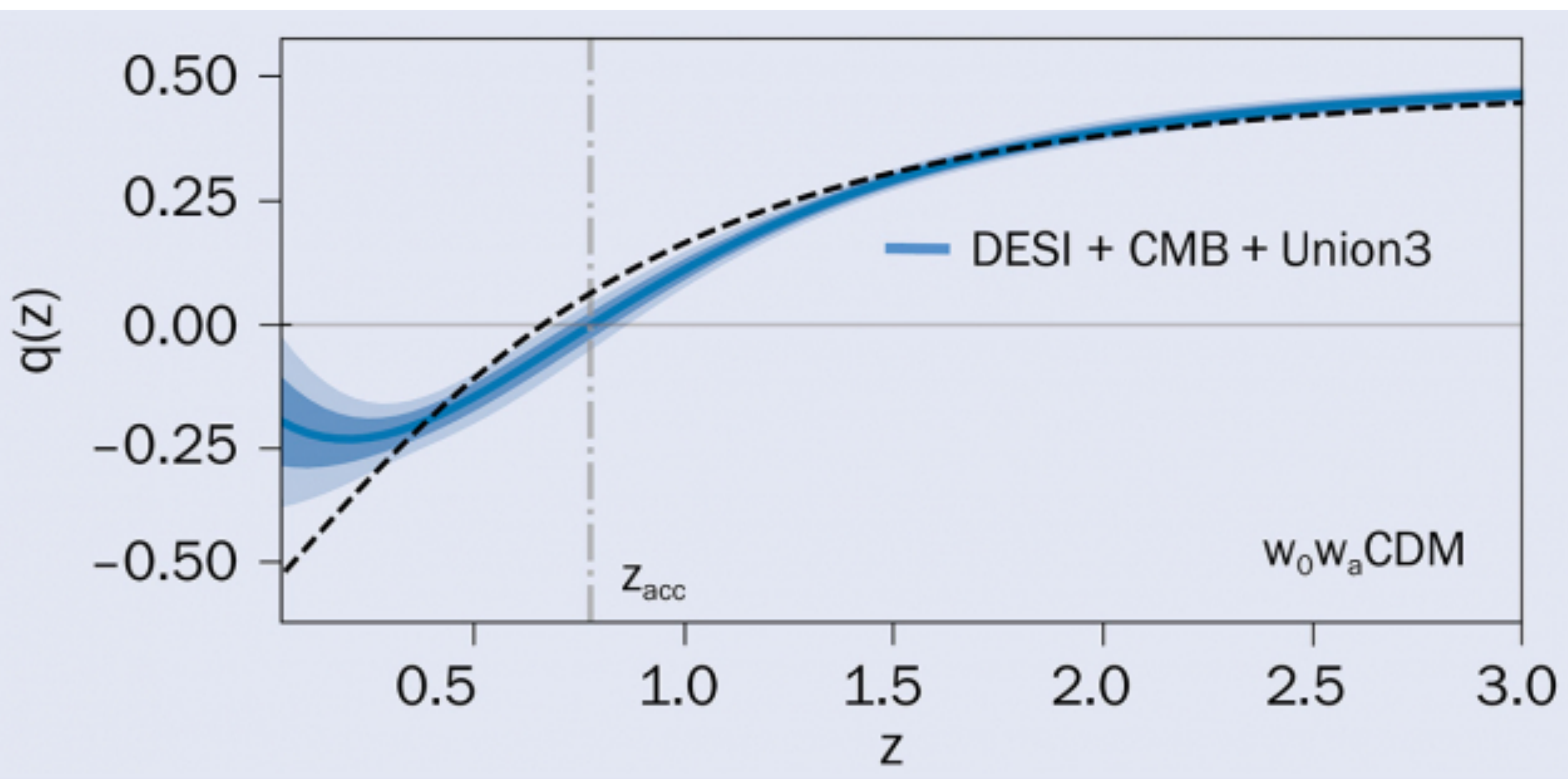
$$L = L_0 := 2\beta G_N M \quad \text{and with screening} \quad L = 2\beta_{\text{eff}} G_N M$$

Since the effective coupling depending on the dilaton field value at the surface we need to check the energetics due to the discontinuity at the surface of the object. Minimising the dilaton energy gives

$$\beta_{\text{eff}} \simeq \frac{\beta}{1 + (R/\ell) \frac{a_e^2}{4\Lambda_\phi^2}}$$

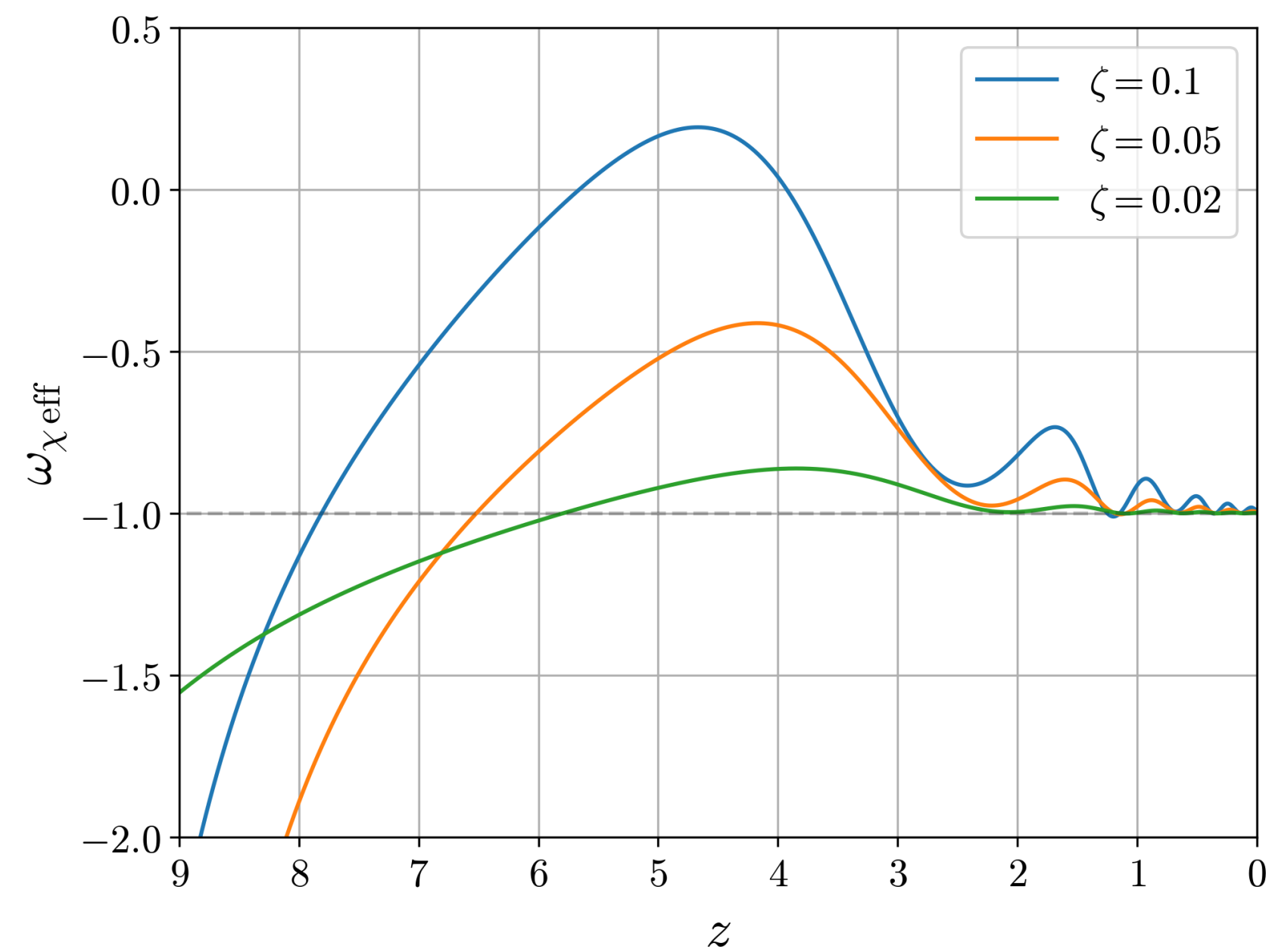
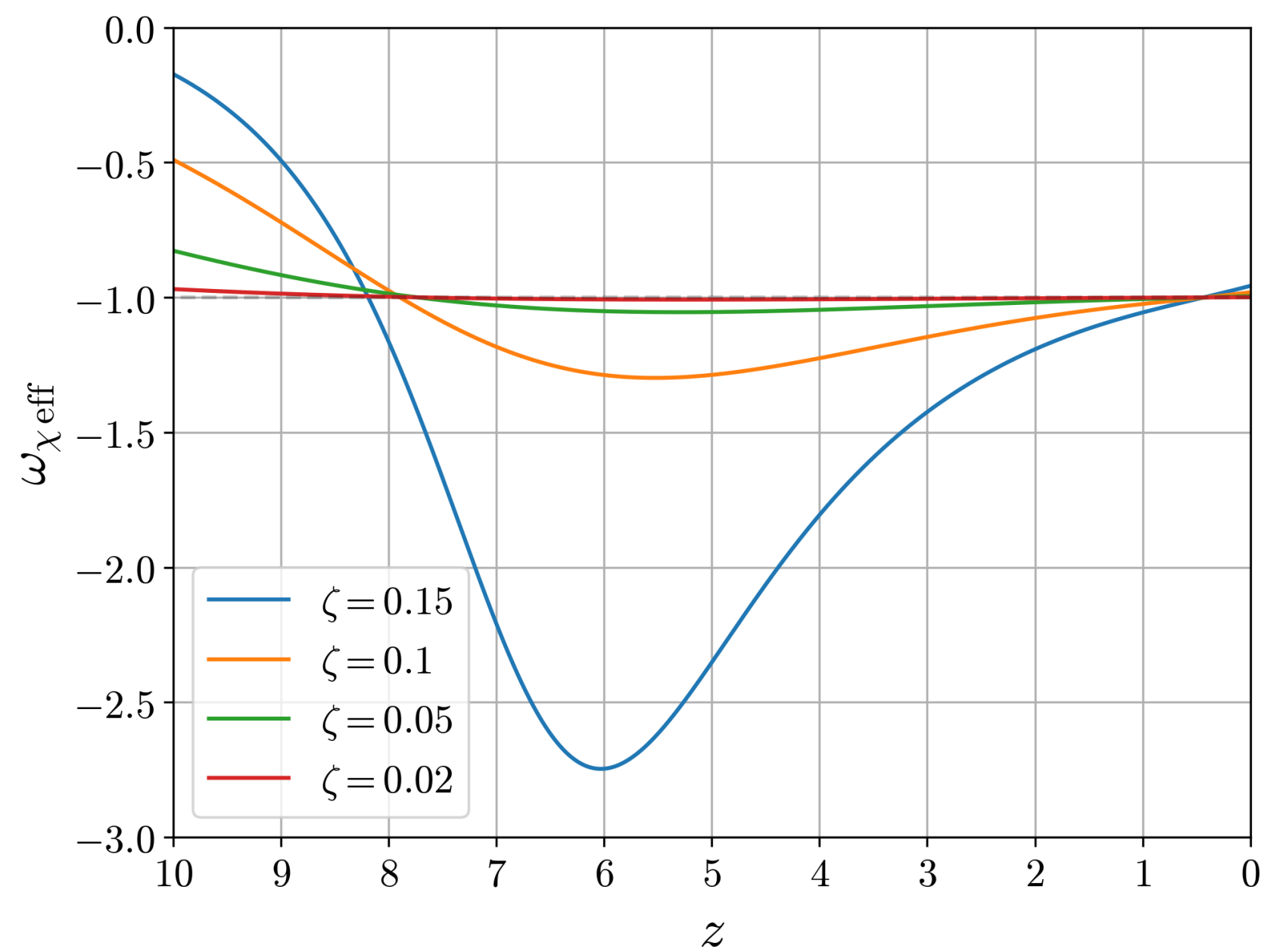
This is then checked against solar system constraints, full details in 2505.05450 and 2603.13986. In the axio-dilaton model the axion can be dark matter and the dilaton dark energy. Um, more work needed

Evolving Dark Energy?



Does it cross the phantom divide?

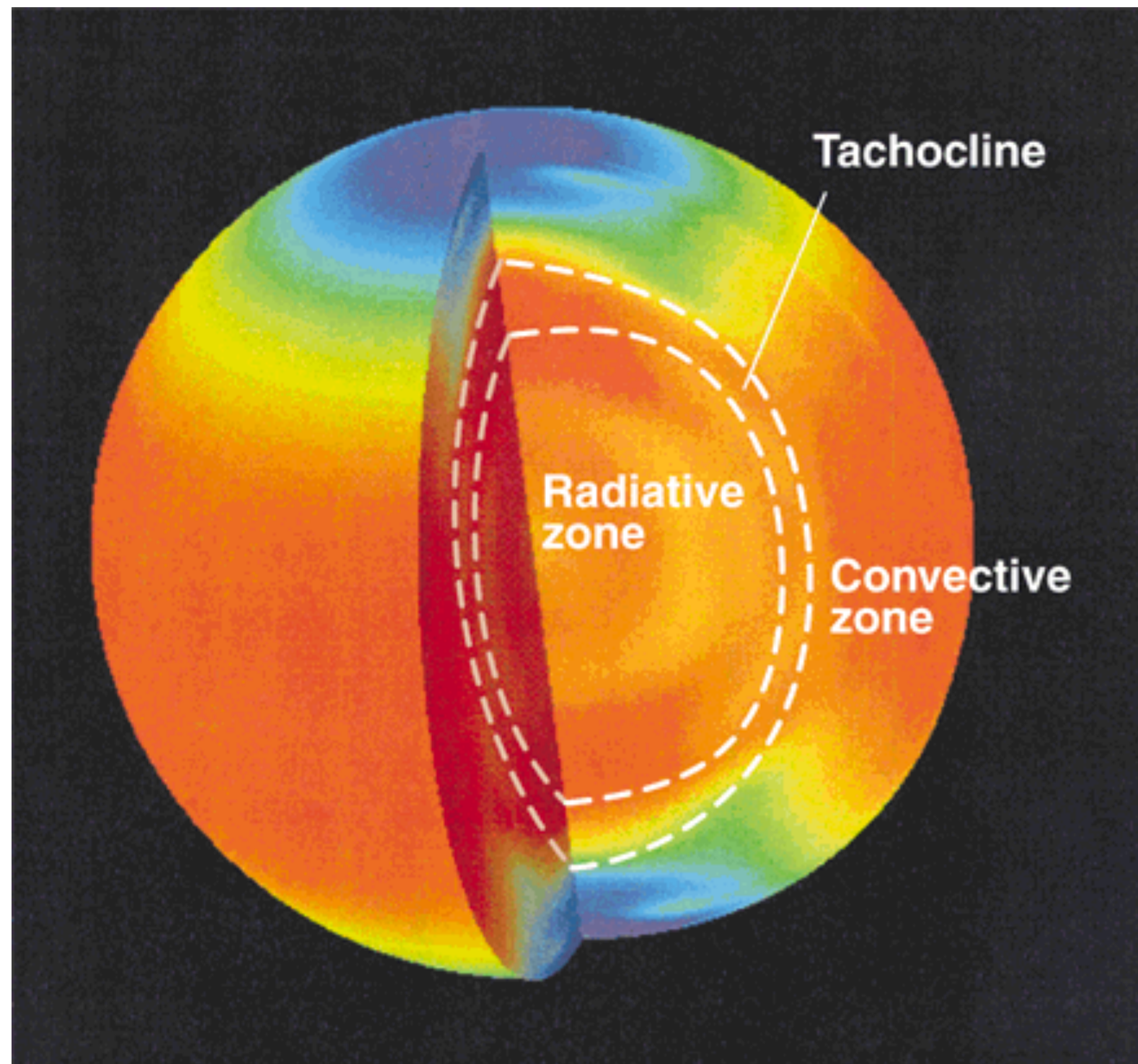
$$\omega_{\chi \text{ eff}} = \frac{\omega_{\chi}(\chi)}{1 + \left[e^{\zeta(\chi - \chi_0)} - 1 \right] \frac{\rho_{\text{ax}0}}{a^3 \rho_{\chi}}}$$



Open Problems in Axio-Dilaton Model

We showed that the axion can behave as dark matter and the dilaton as dark energy, but in a model without screening. Can we keep this property and screen the fifth force?

How do we test the model? We can test some bits but can we test the complete model, eg solar constraints



Both axions and dilatons couple to photons

$$aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

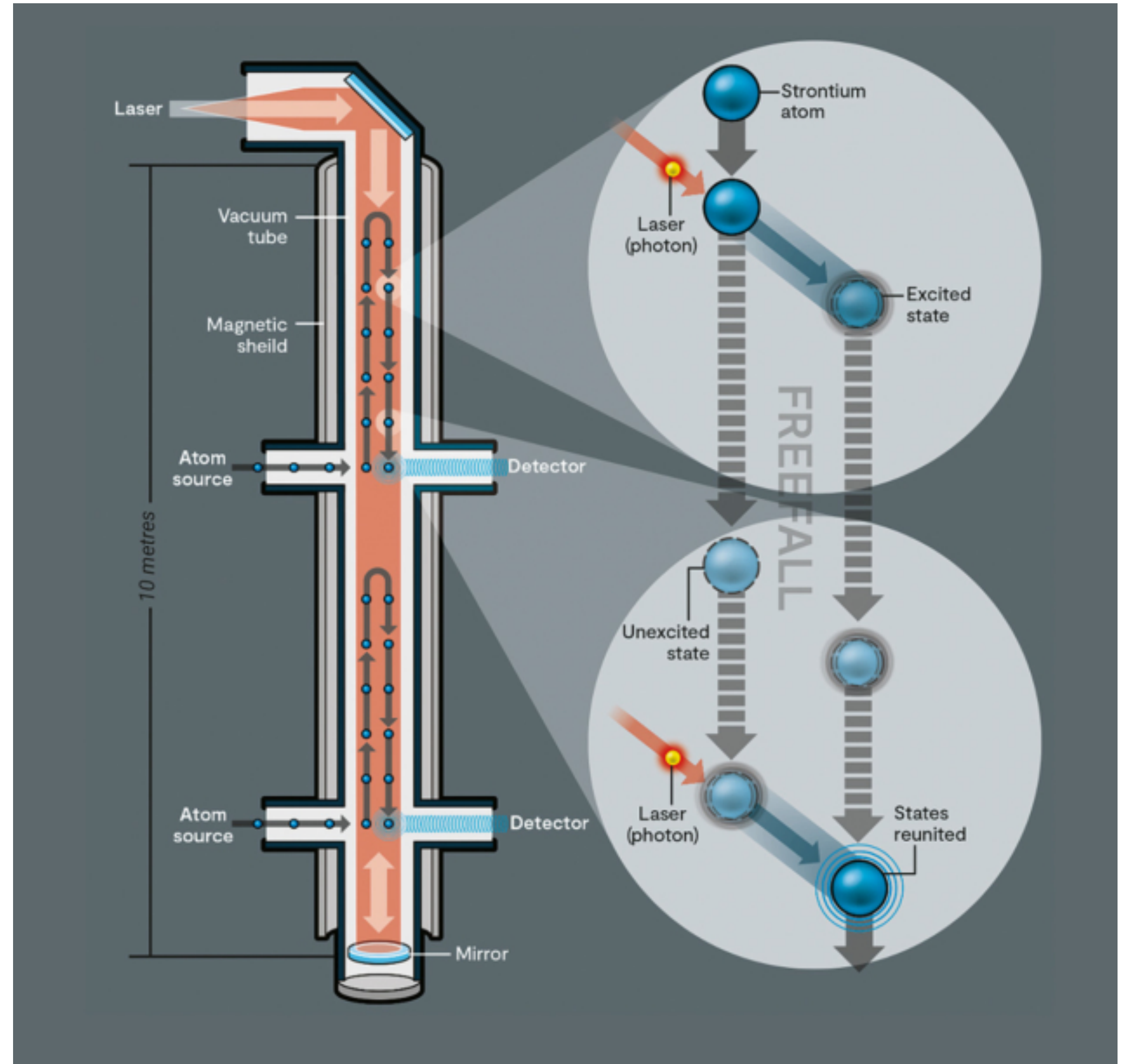
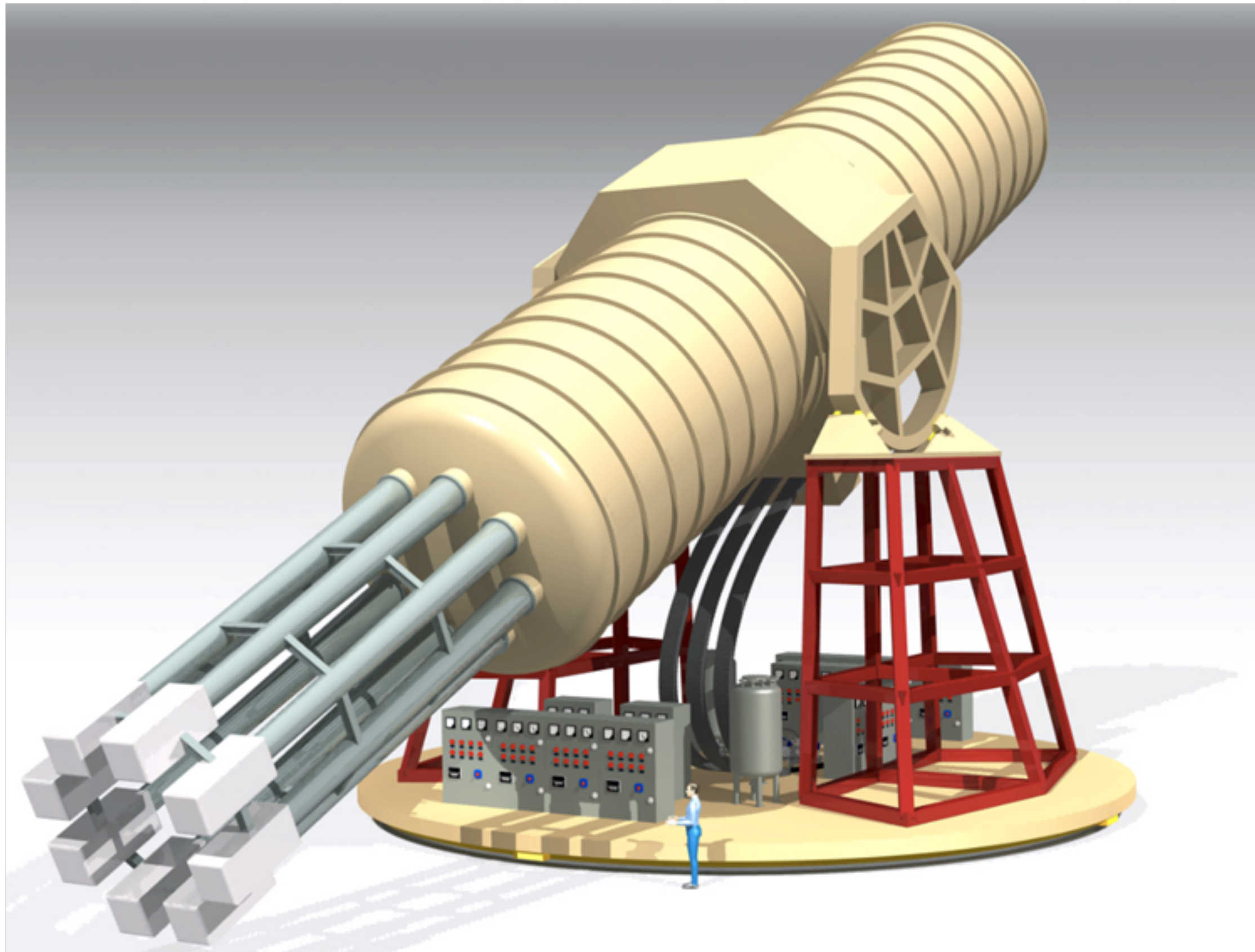
$$\phi F_{\mu\nu}F^{\mu\nu}$$

Can they be produced in the sun and constrained with solar constraints? The axion field would switch off the dilaton in the core, but depending on parameters (to be checked) both axions and dilatons could be produced in the tachocline.

New Experiments

AION

IAXO



Open Questions and Puzzles

What is dark energy? Is it a scalar field?

Could dark energy be a modification of General Relativity, a more radical modification than scalar-tensor gravity?

Could 'dark energy' be related to quantum gravity?