

Cosmological Scalars : theory and tests

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Outline

- Introduction to scalar-tensor theories
- Chameleon theories
- Symmetrons and Dilatons
- The axion-dilaton model
- Laboratory Tests of Modified Gravity models
- Constraints
- Discussion; the future

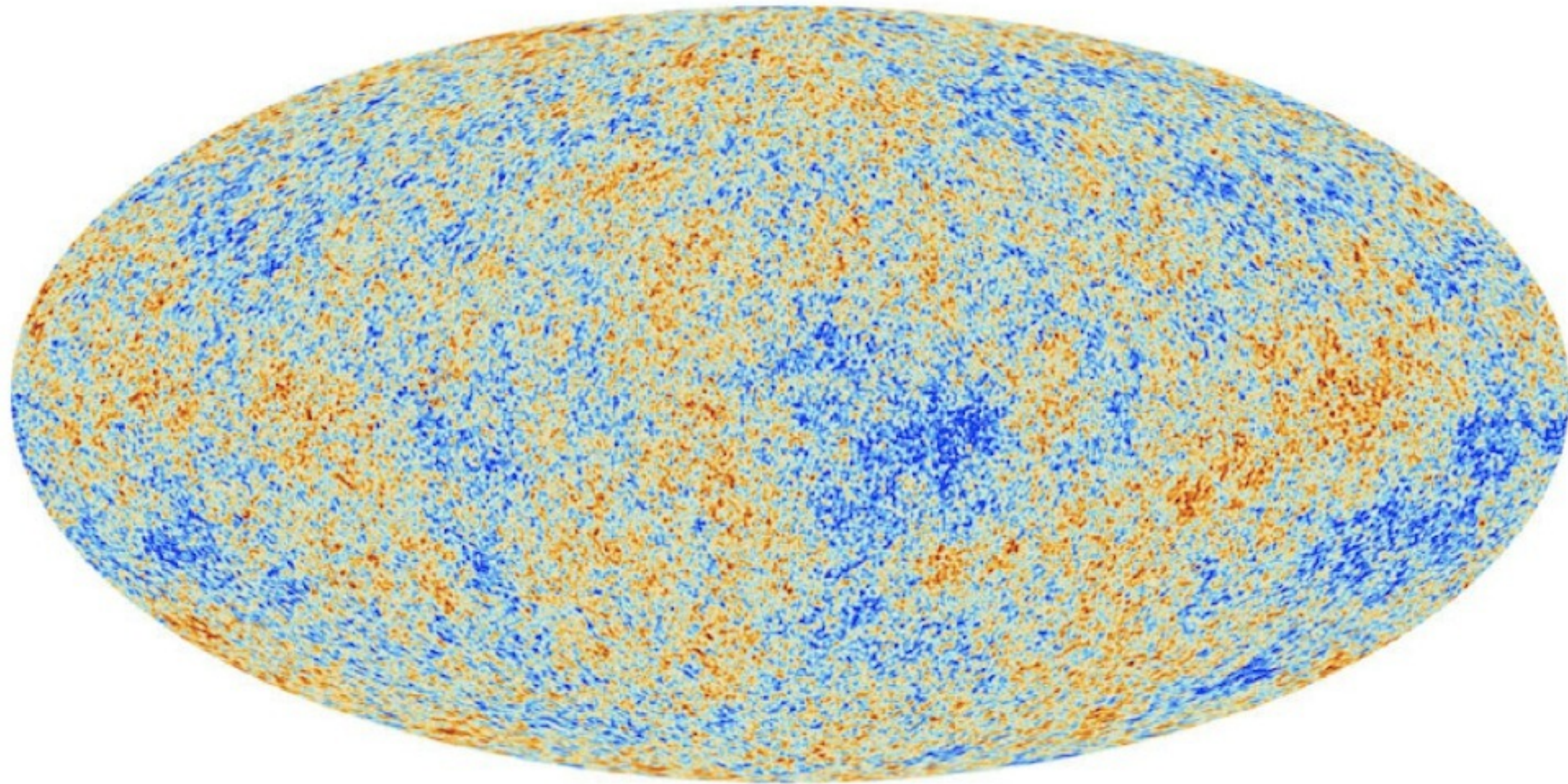
- **Why Modified Gravity?**

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.

Modified Gravity allows one to test General Relativity in new regimes one hadn't originally thought of.

Cosmic Microwave Background



For a scalar field

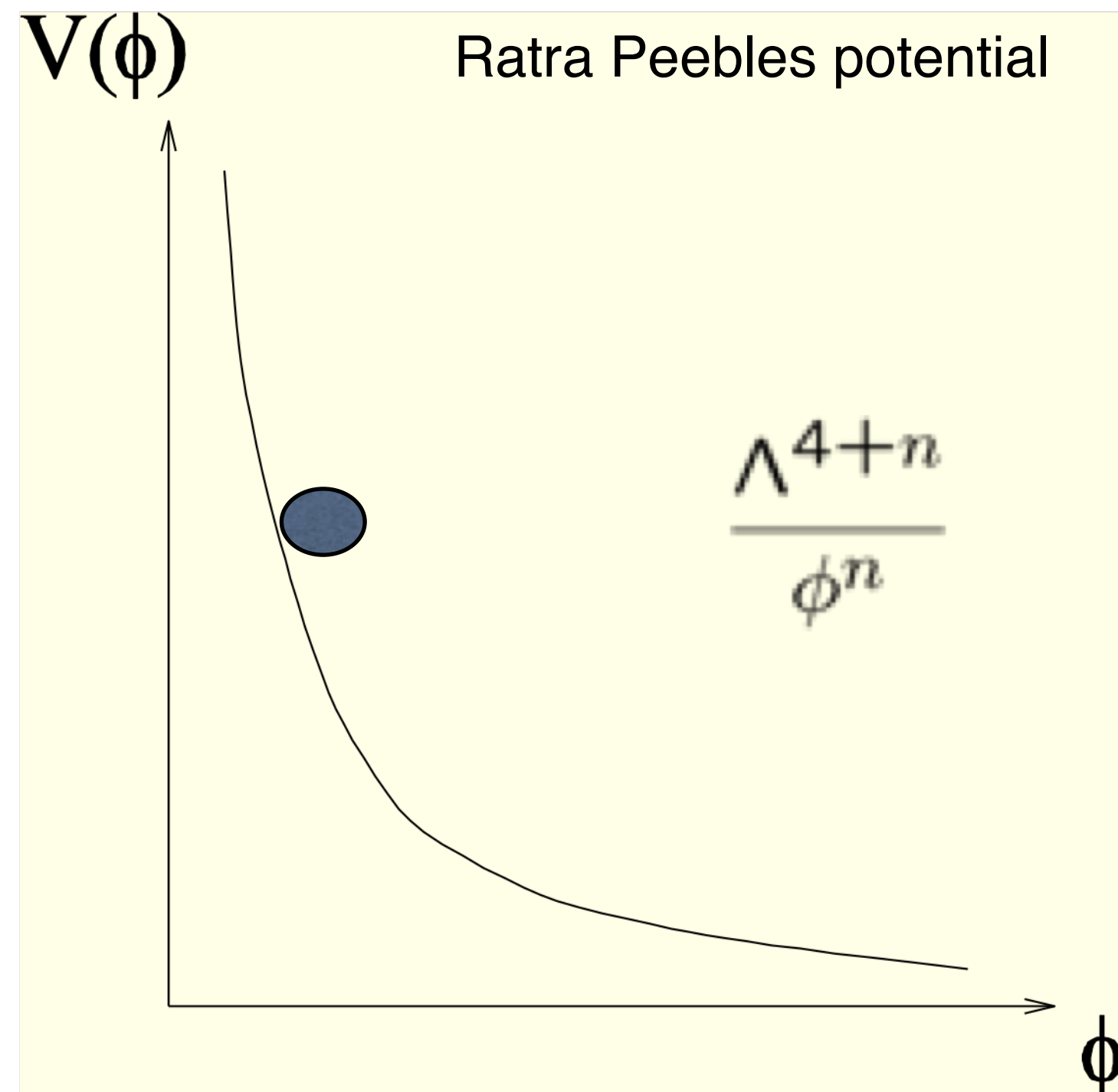
$$\rho_\phi = 1/2\dot{\phi}^2 + V(\phi) \quad \text{kinetic energy} + \text{potential energy}$$

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

If the potential dominates then

$$p_\phi \approx -\rho_\phi$$

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



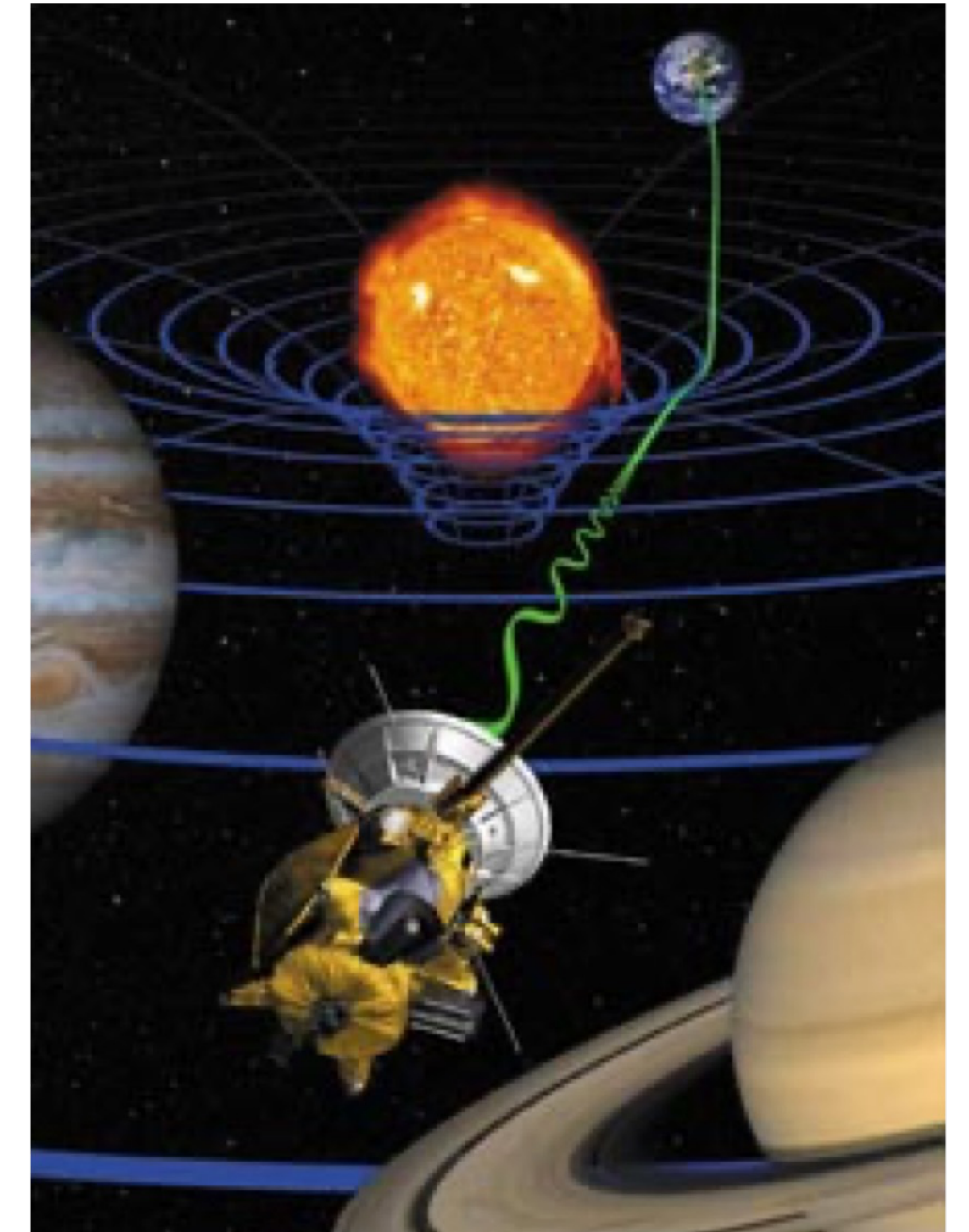
Deviations from Newton's
Laws parametrised by

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

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

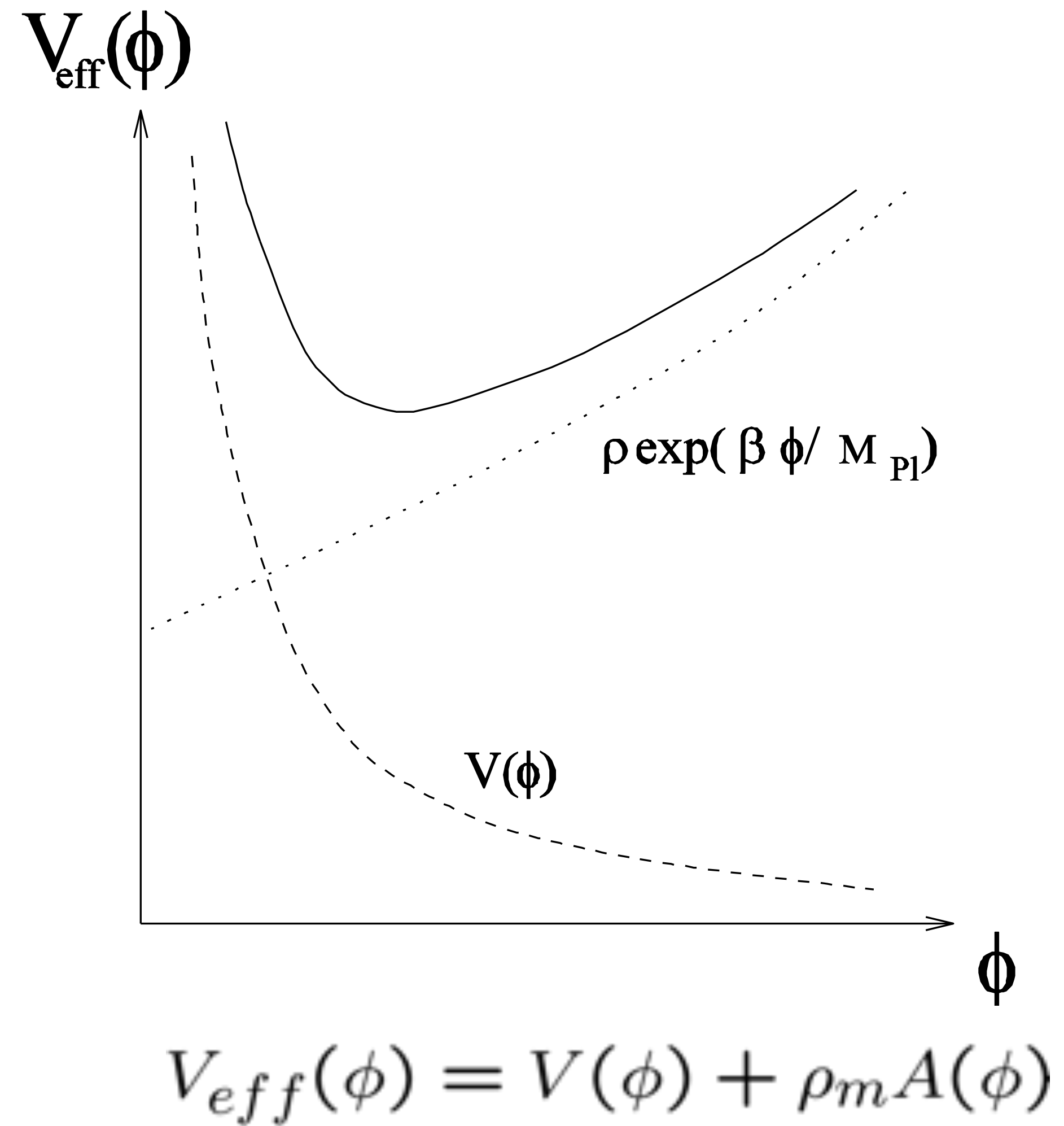
$$S = \int d^4x \sqrt{-g} \left(\frac{R}{16\pi G_N} - \frac{(\partial\phi)^2}{2} - V(\phi) \right) + S_m(\psi_i, A^2(\phi)g_{\mu\nu})$$

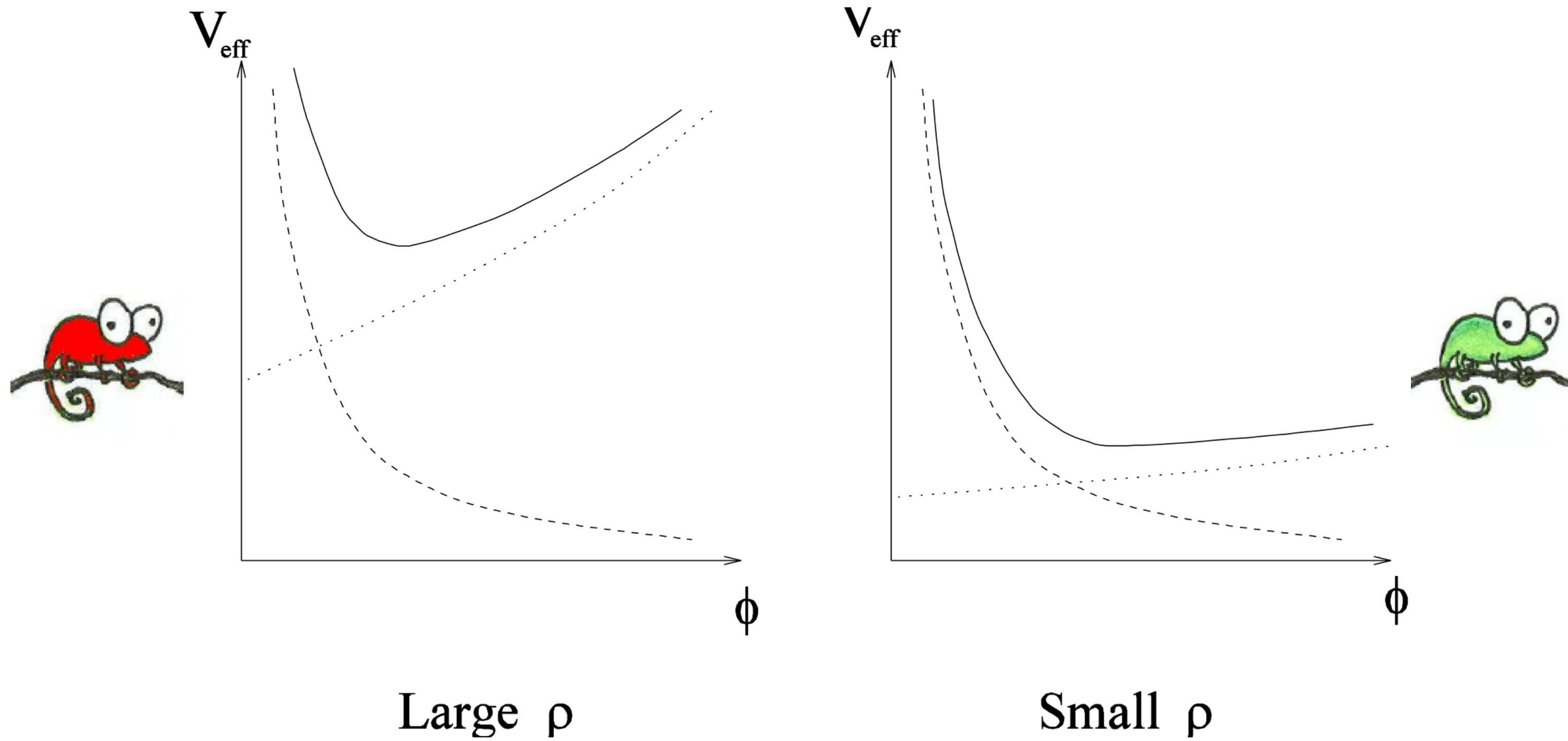
gives the effective potential

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

$$V(\phi) = \frac{\Lambda^{4+n}}{\phi^n}$$

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

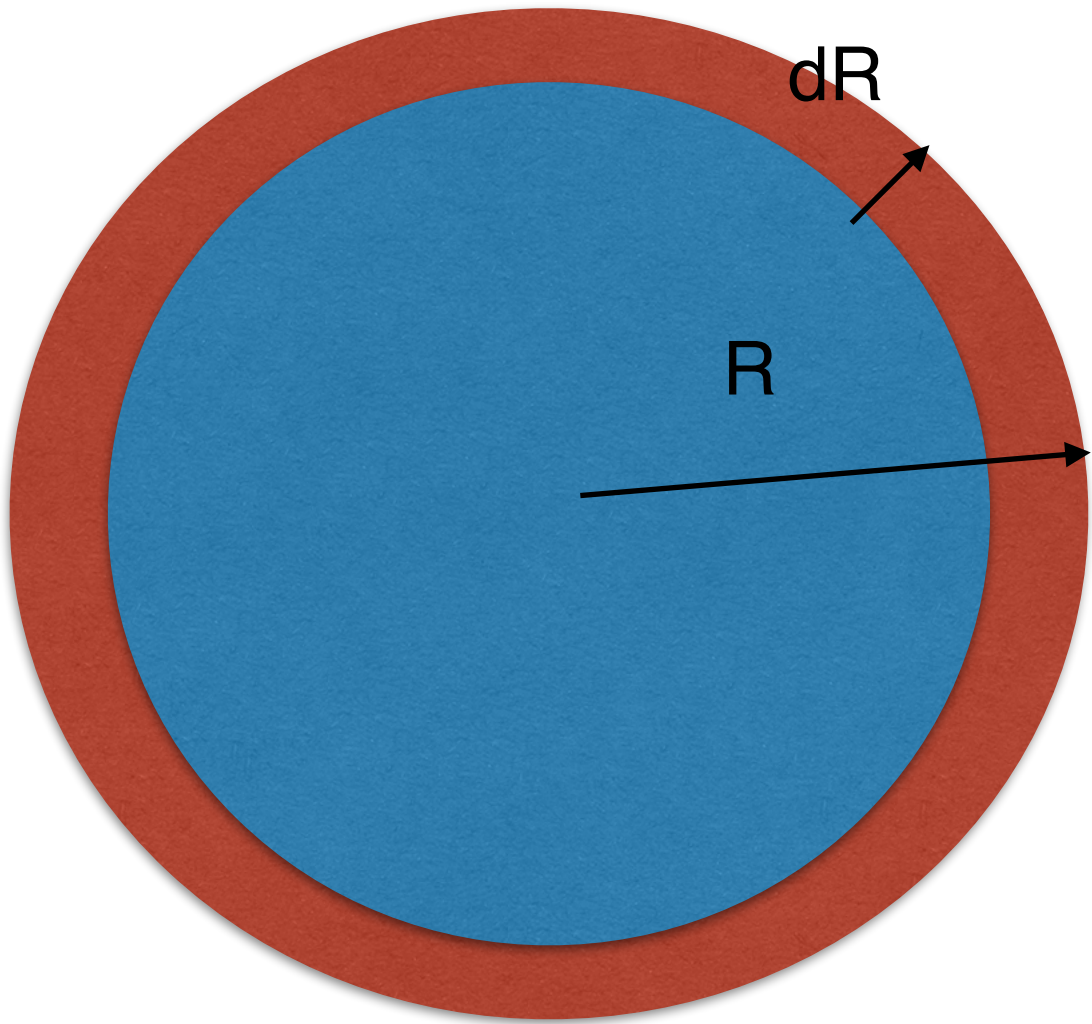




mass is proportional to the second derivative of minimum of the potential
Hence it can be heavy when ρ is large and light when ρ is small

$$m_{\phi}^2(\rho) = \partial^2 V(\rho) / \partial \phi^2$$

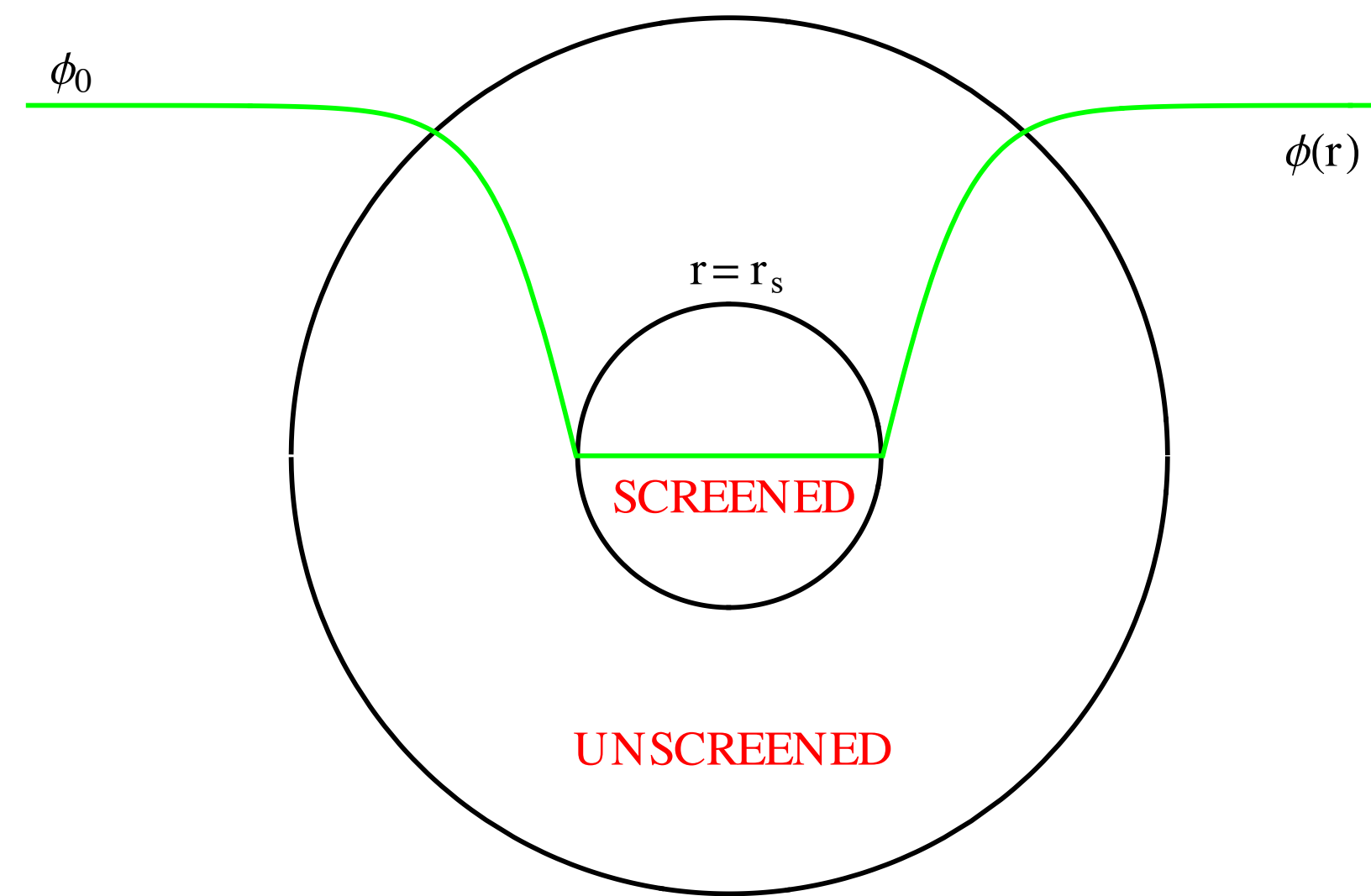
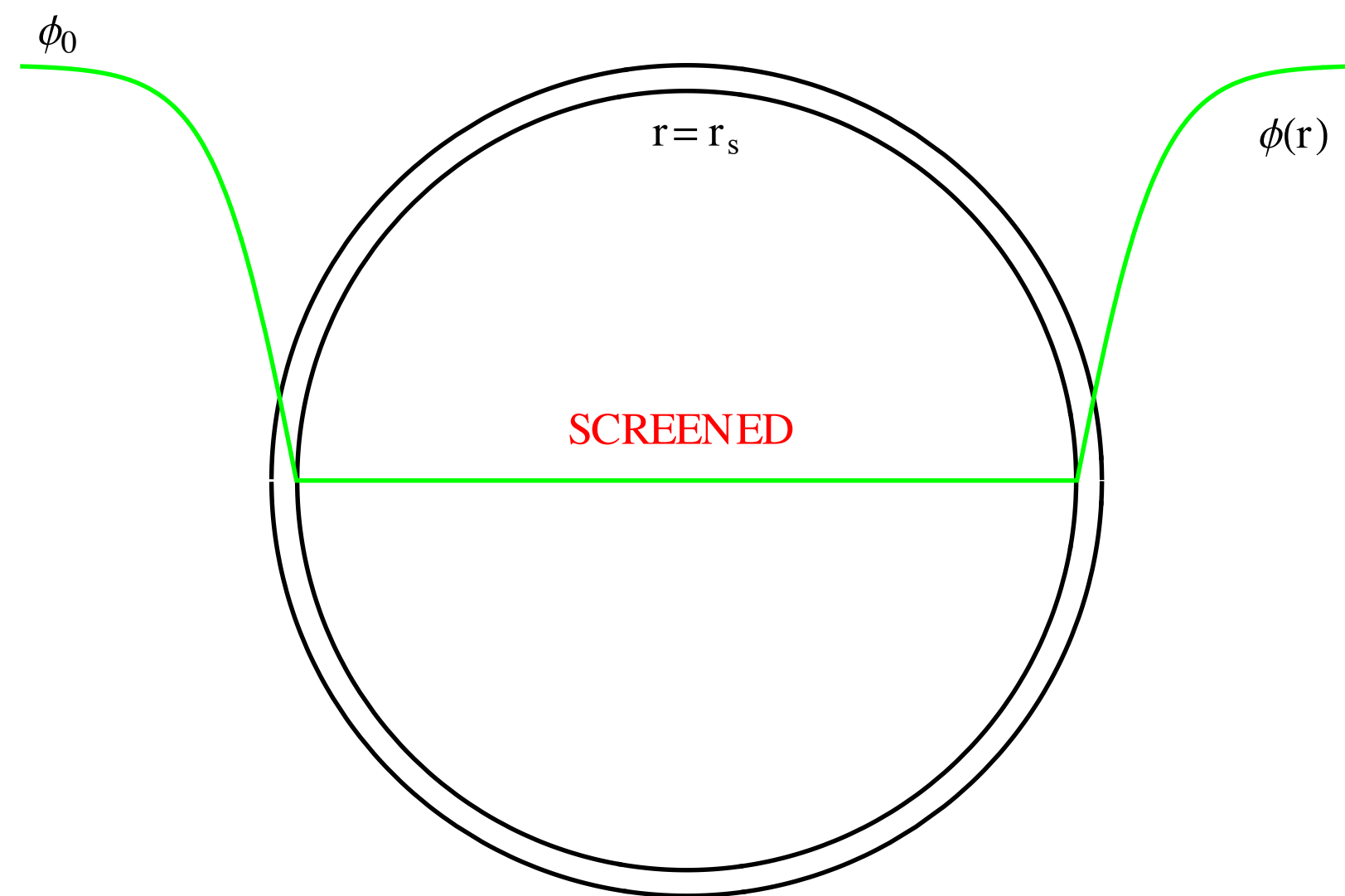
To screen fifth forces in the solar system one needs the thin shell effect.



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

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

Object	Φ_N
Main-sequence star	10^{-6}
Post-main-sequence star ($1-10M_{\odot}$)	$10^{-7}-10^{-8}$
Spiral Galaxy	10^{-6}
Dwarf Galaxy	10^{-8}





Symmetrons

Khoury&Hinterbichler, 1001.4525

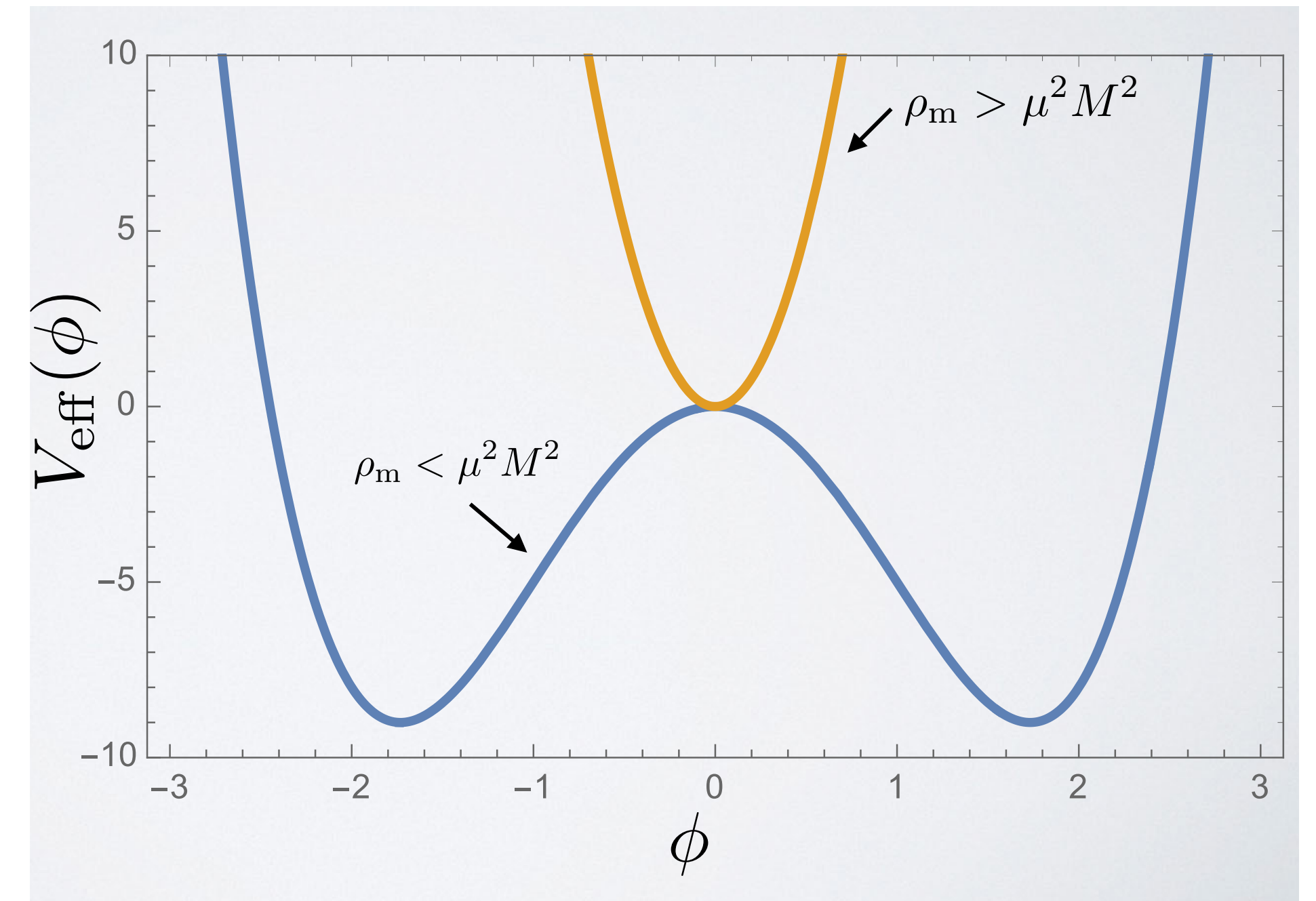
This has potential

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

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

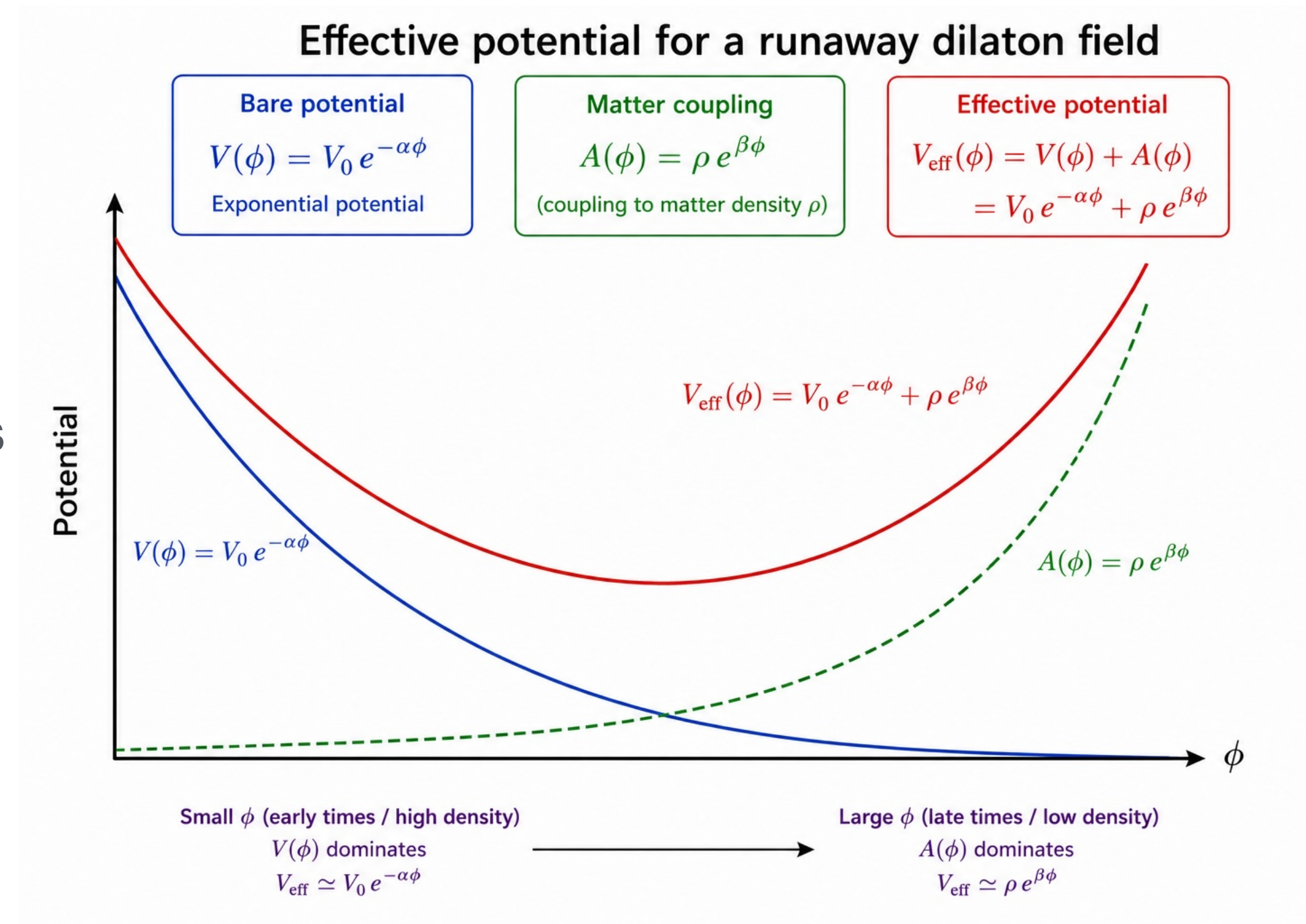
$$V(\phi) = V_0 e^{-\alpha\phi}$$

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



Environmentally Dependent Dilaton

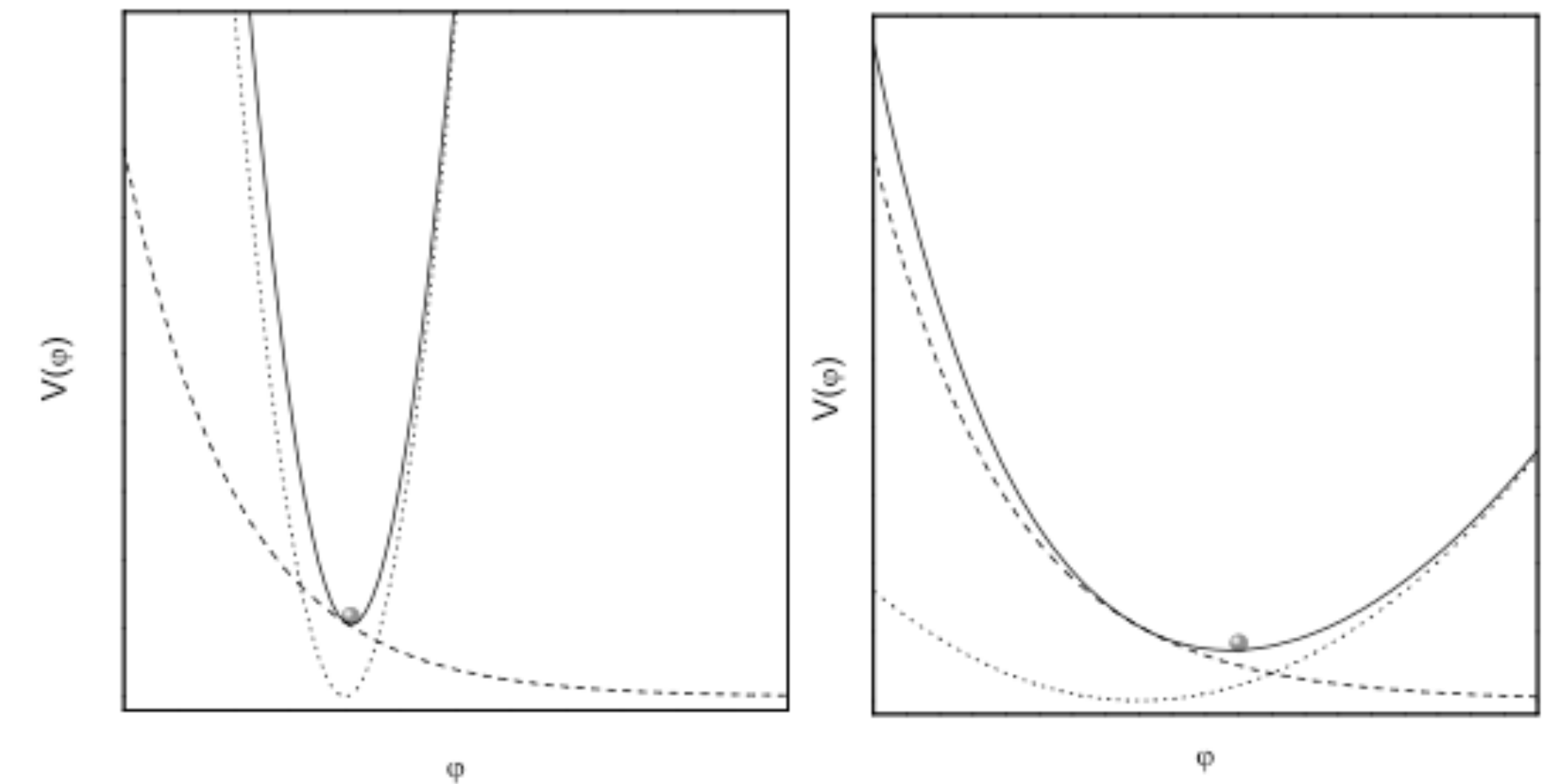
Brax, van de Bruck, ACD& Shaw 1005.3735

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

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 comes as part of the scalar multiplet with the axion. Need to consider an axion-dilation model. This results in an interacting theory.

The Axio-Dilaton Model

A.Smith, P.Brax, C.vdBruck, C.Burgess, ACD —2505.05450, see Carsten talk tomorrow

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 — see BBQ 2310.02092, 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

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

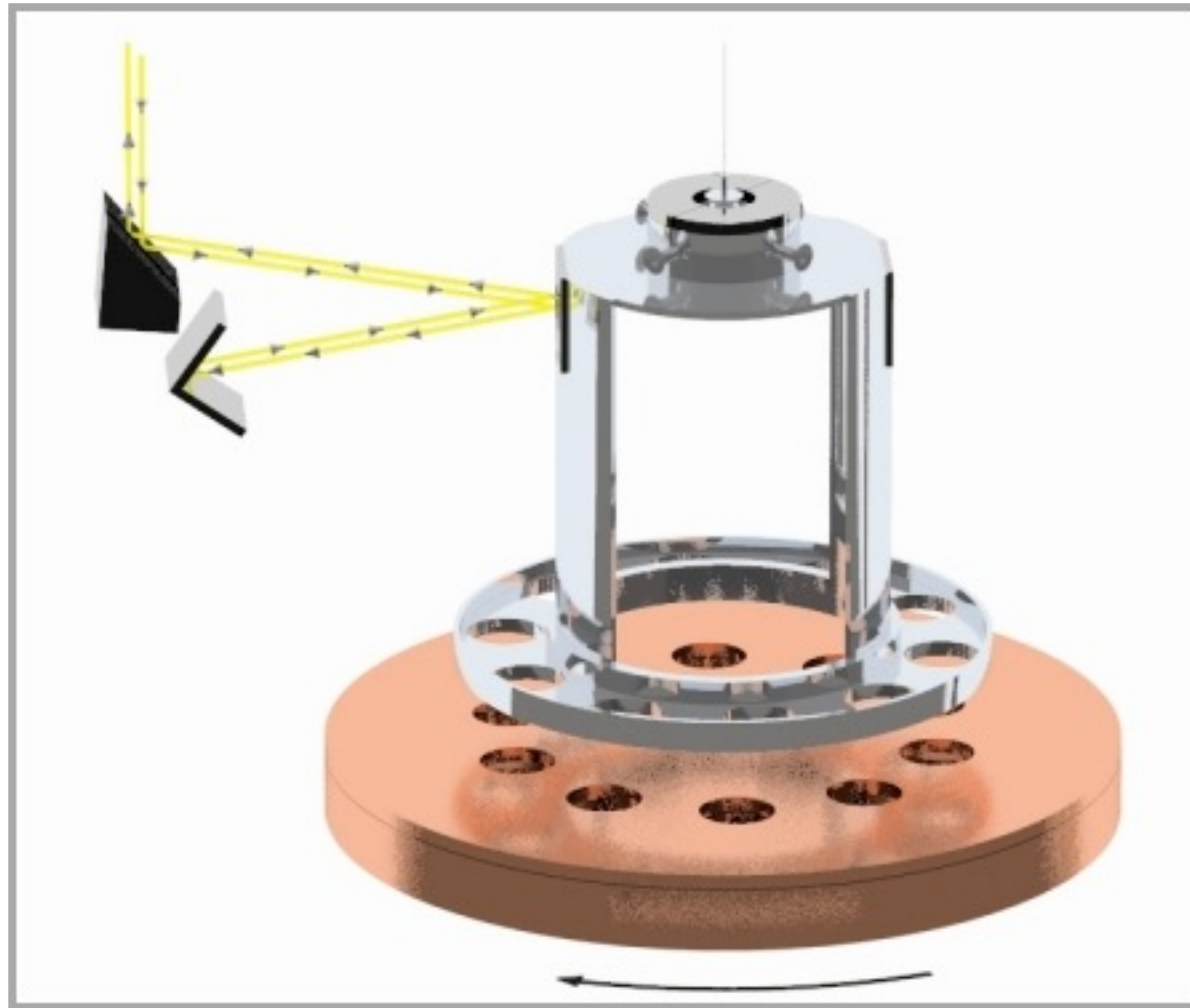
This is then checked against solar system constraints, full details in 2505.05450 and 2603.13986

Tests of Screened Scalars

Eot-Wash Experiment

For a review see Wagner et al 1207.2442

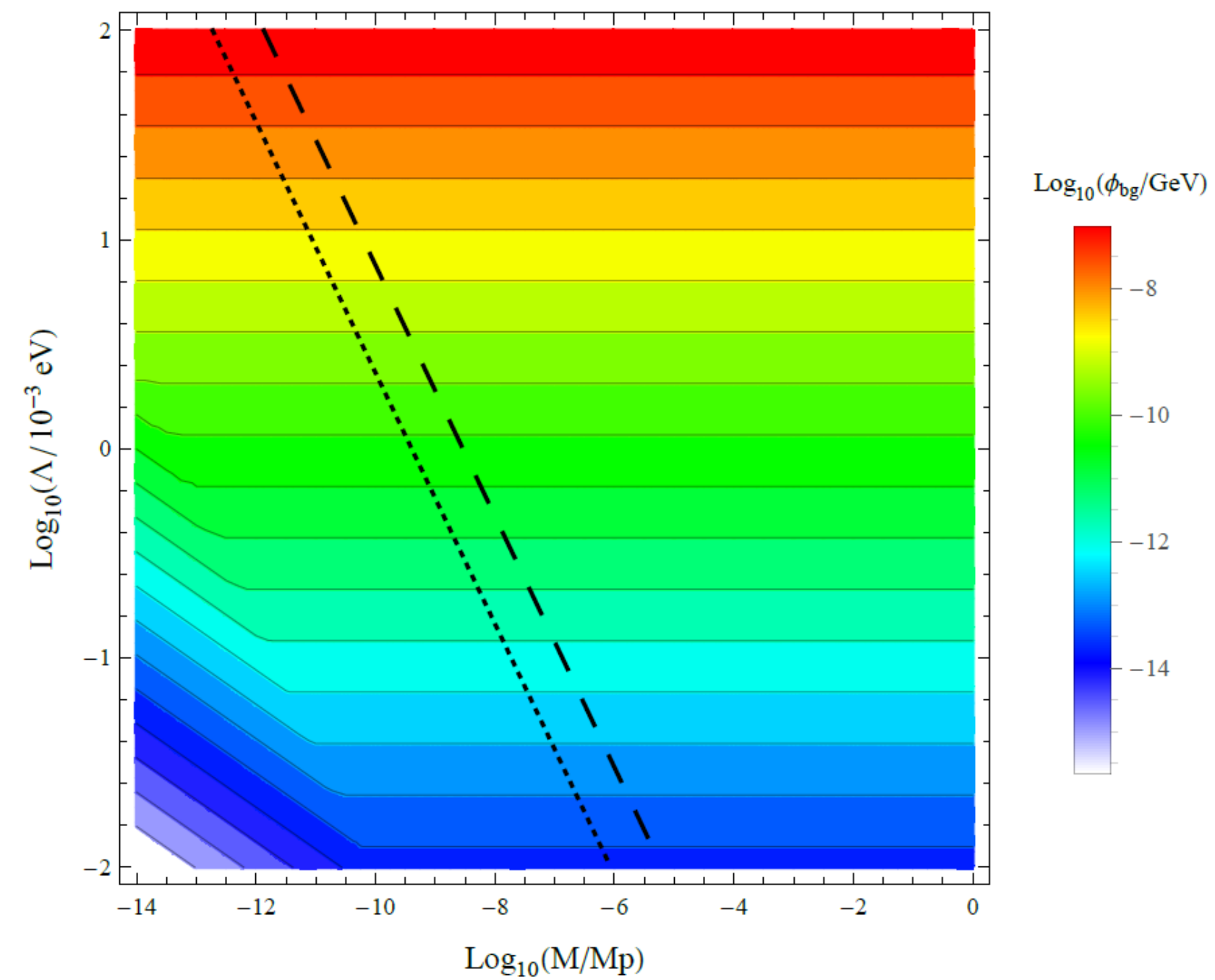
Be-Ti and
Be-Al test
masses



Why Atom Interferometry?

In a spherical vacuum chamber, radius 10 cm, pressure 10^{-10} Torr

Atoms are unscreened above black lines
(dashed = caesium, dotted = lithium)

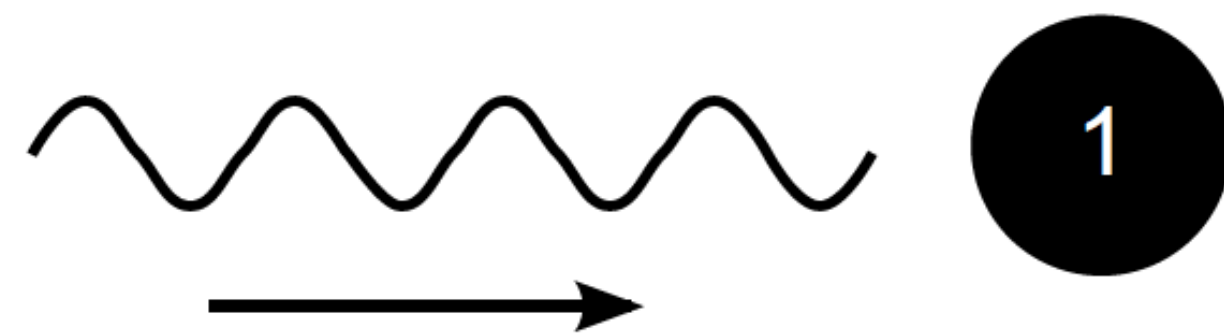


CB, Copeland, Hinds. (2015)

Atom Interferometry

An interferometer where the wave is made of atoms

Atoms can be moved around by absorption of laser photons

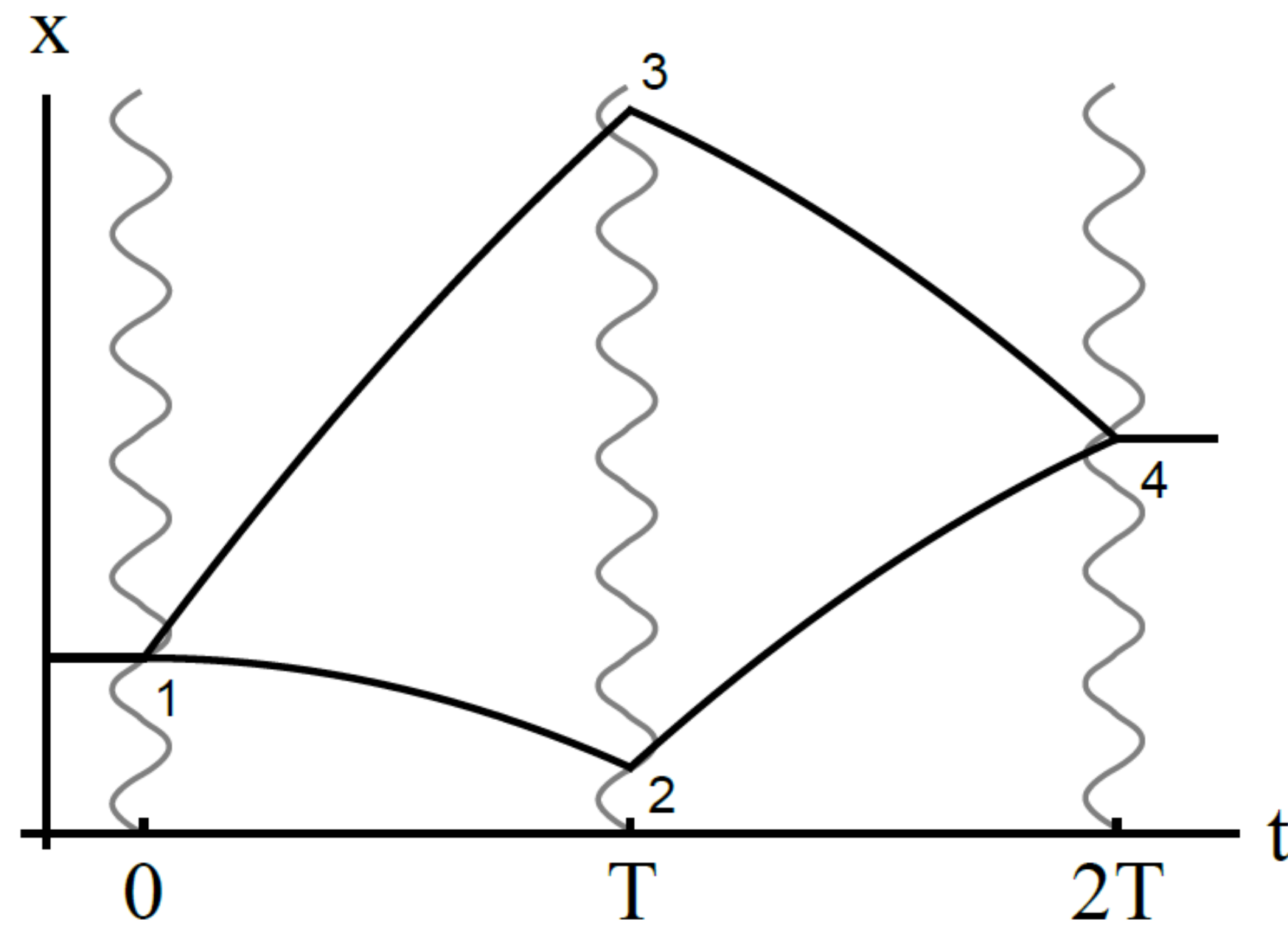


Photon Momentum = k
Atom in ground state



Atom in excited state
with velocity = V

Atom Interferometry



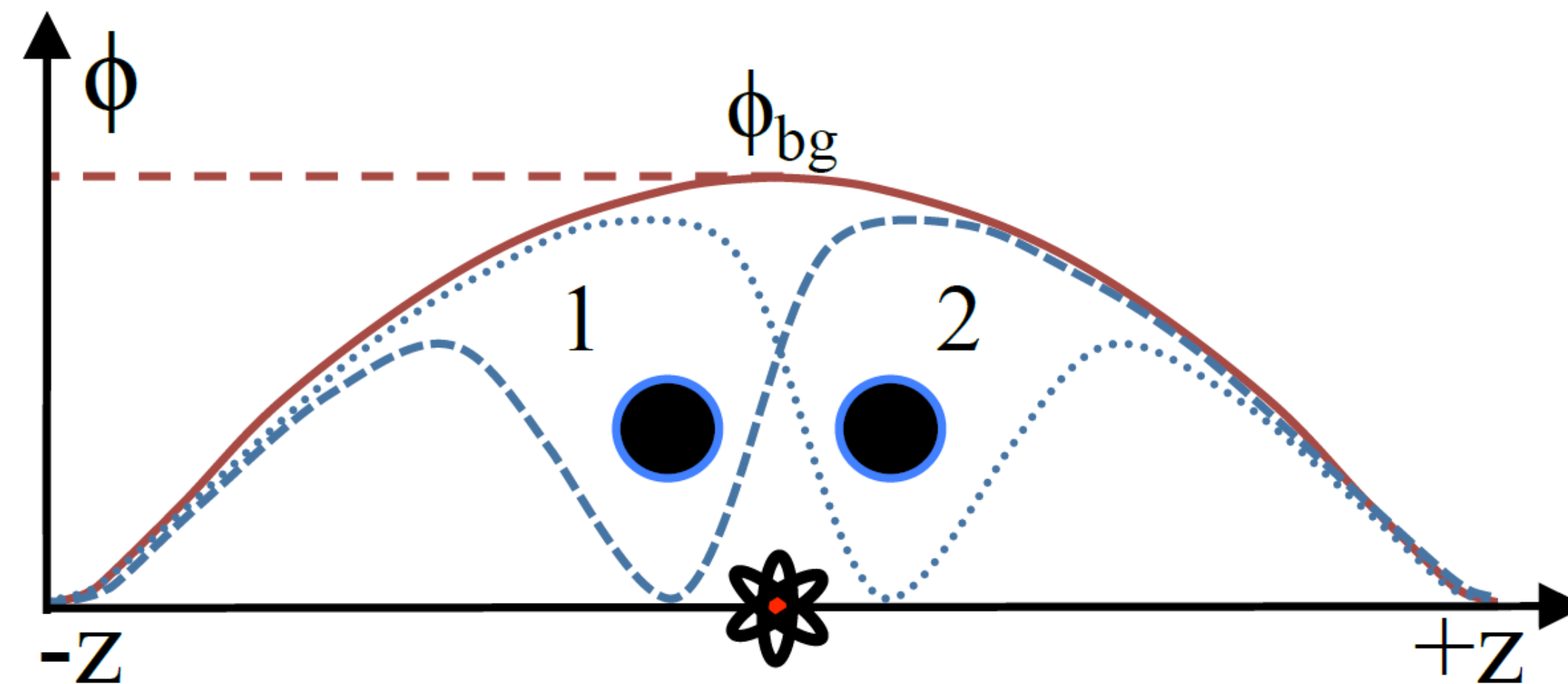
Probability measured in excited state at output

$$P = \cos^2 \left(\frac{kaT^2}{2} \right)$$

Atom Interferometry for Chameleons

The walls of the vacuum chamber screen out any external chameleon forces

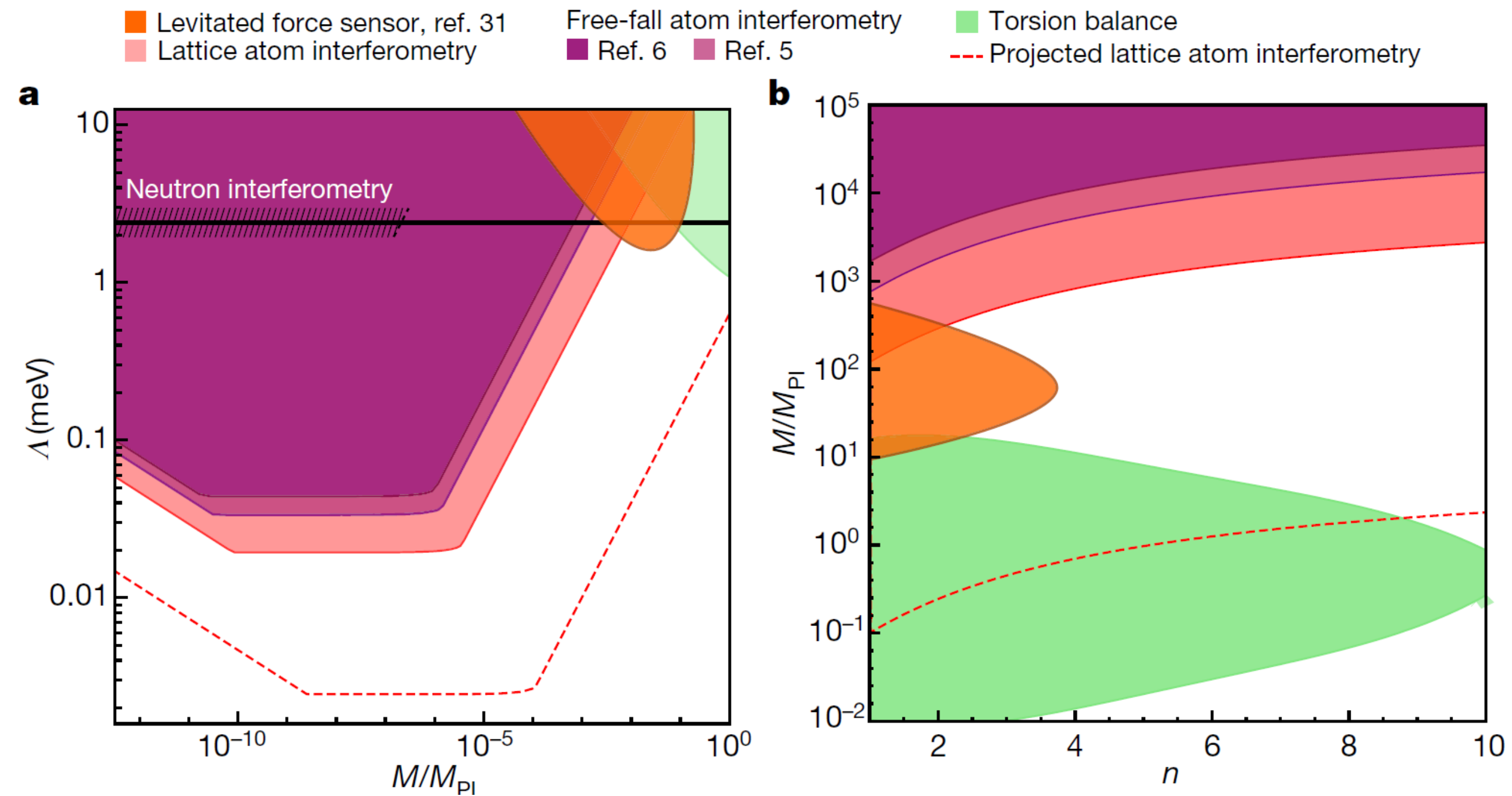
Macroscopic spherical mass, produces chameleon potential felt by cloud of atoms



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

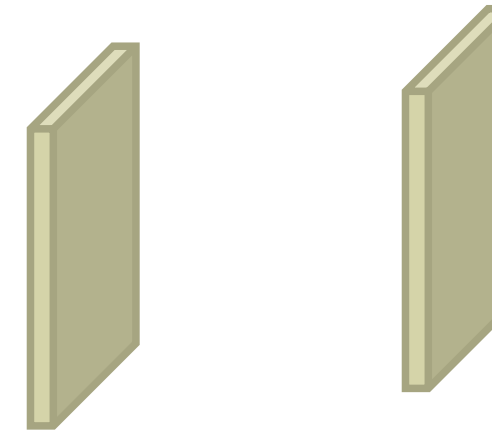
Brax, Davis, Elder. Phys. Rev. D 107 (2023) 084025

Casimir Force Experiments

Brax et al PRD76(07)124034

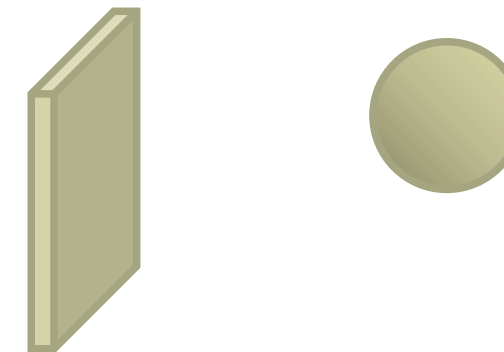
The scalar force could be detected in Casimir type experiments

force between parallel plates



$$F_{cas} \approx d^{-4}$$

force between a plate and a sphere



chameleonic force

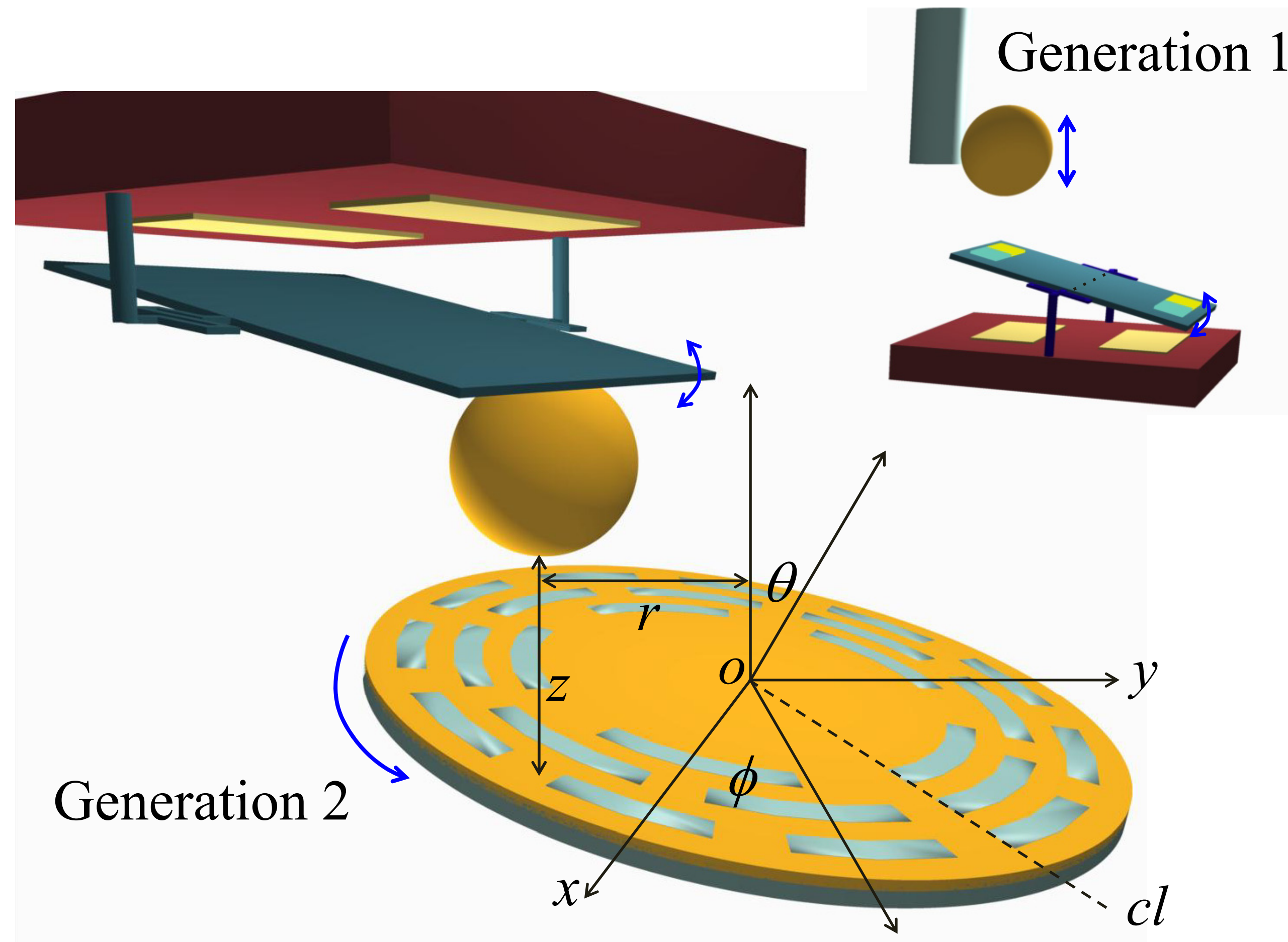
$$\frac{F_\phi}{A} \sim \Lambda^4 (\Lambda d)^{-\frac{2n}{n+2}}$$

$$\frac{F_\phi}{F_{cas}} \sim \frac{240}{\pi^2} (\Lambda d)^{\frac{2(n+4)}{n+2}}$$

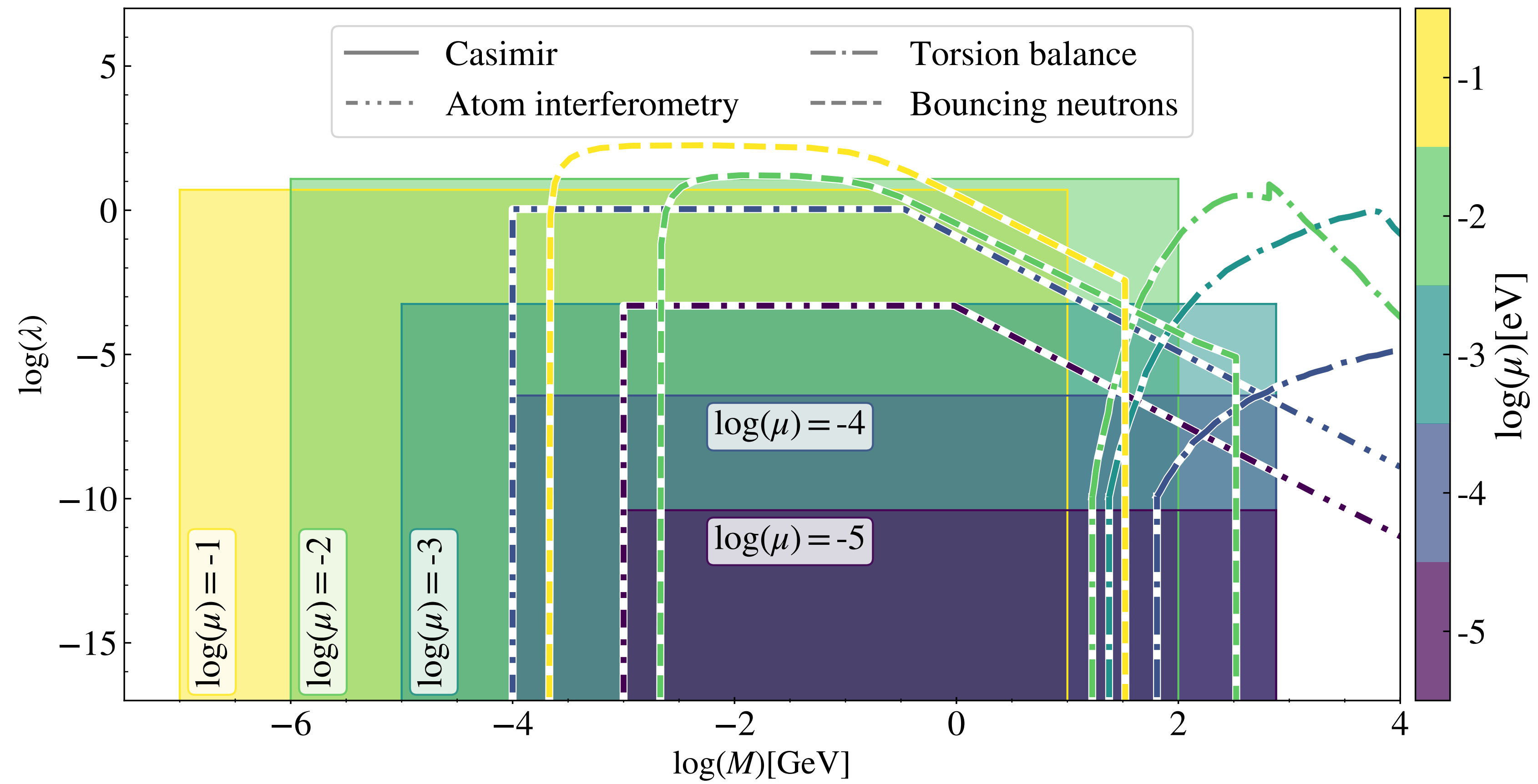
dark energy scale is

$$\Lambda^{-1} \sim 82 \mu m$$

Decca Experiment — 1410.7267; 1509.05349



$$R = 150 \text{ } \mu\text{m} \quad D_{\text{near}} = 15 \text{ } \mu\text{m} \quad D_{\text{far}} = 65 \text{ } \mu\text{m} \quad \delta\text{Force} \lesssim 0.1 \text{ fN}$$



Hydrogen and Muonium Spectroscopy

Brax, ACD, Elder 2207.11633

Modified gravity models change the Hamiltonian for Hydrogen and hence the energy levels. One can compute constraints from the energy gap, taking into account whether or not the nucleus is screened

$$\delta E_2 - \delta E_1$$

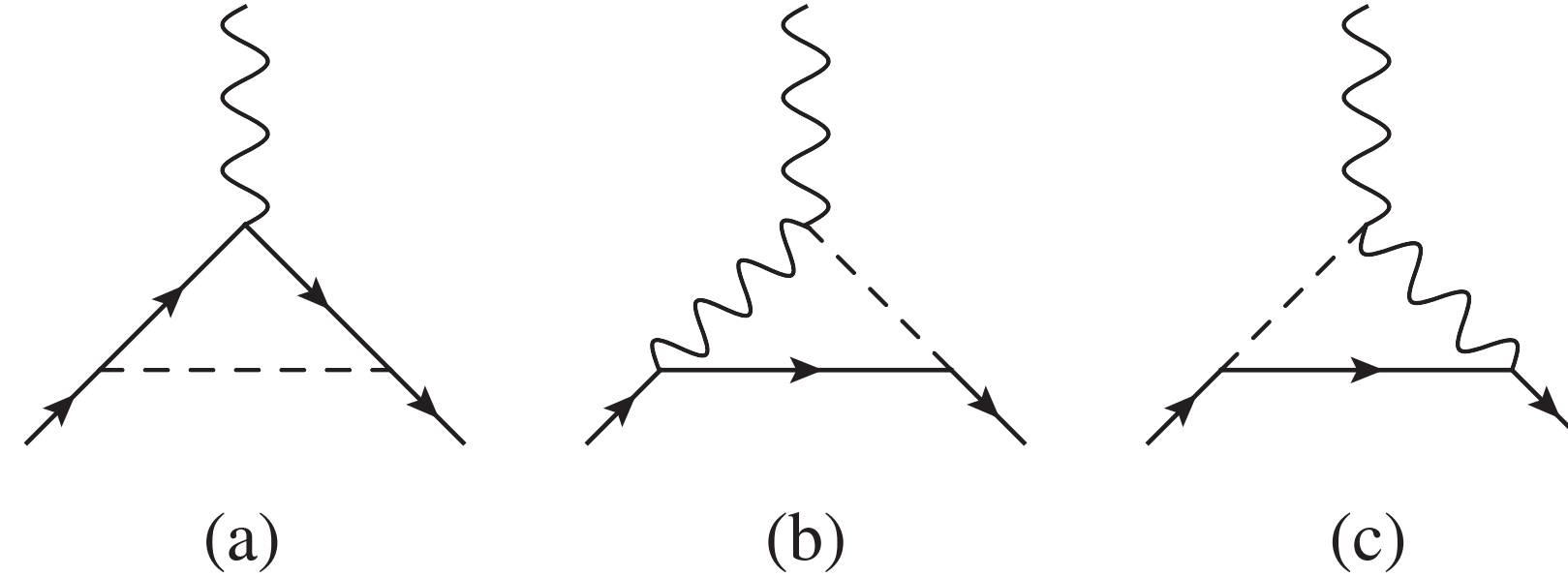
Muonium, an electron orbiting an anti-muon, has a similar feature but has the advantage that, since the muon is an elementary particle it is always unscreened potentially giving stronger constraints

Anomalous Magnetic Moment of the Muon

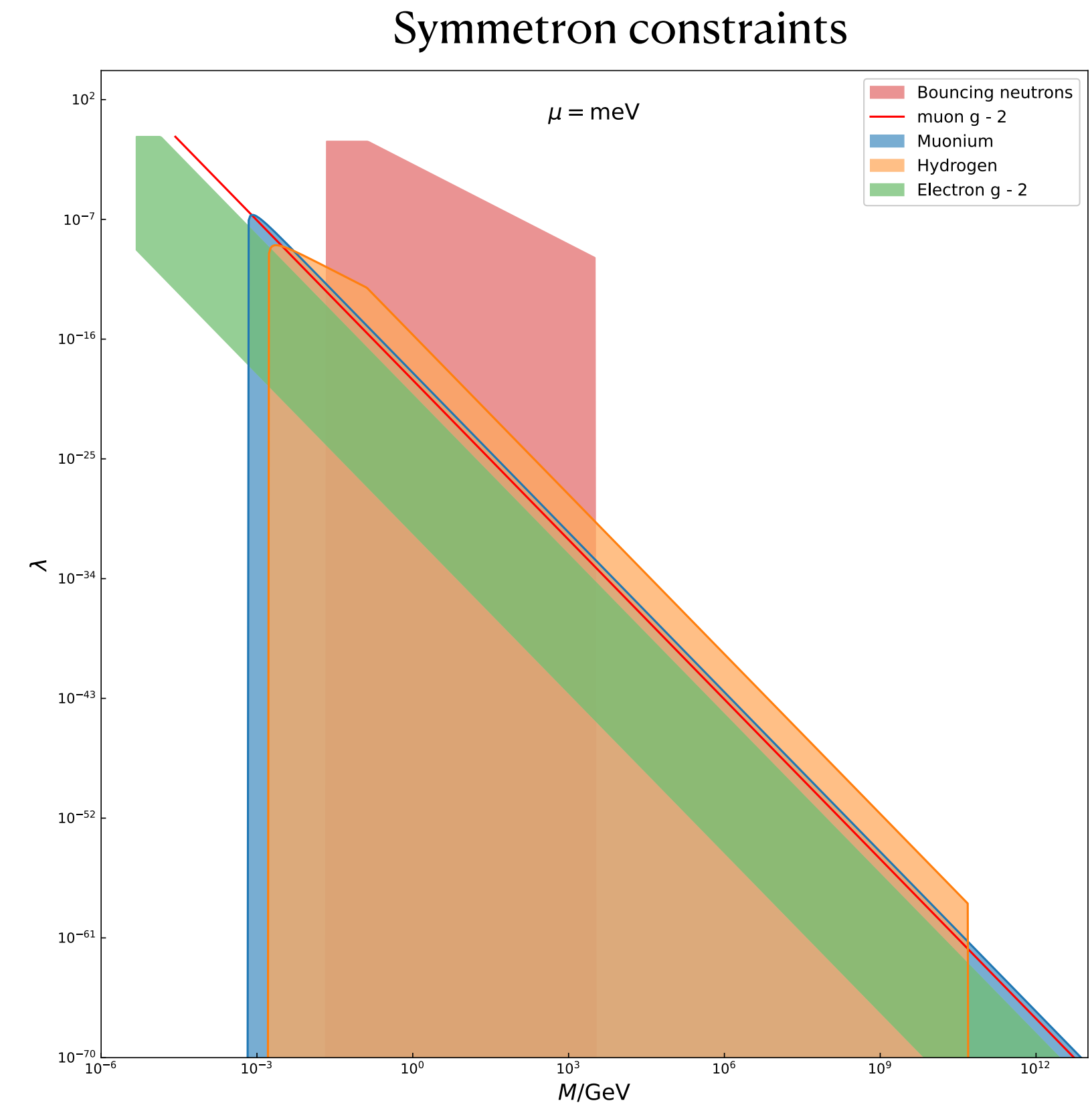
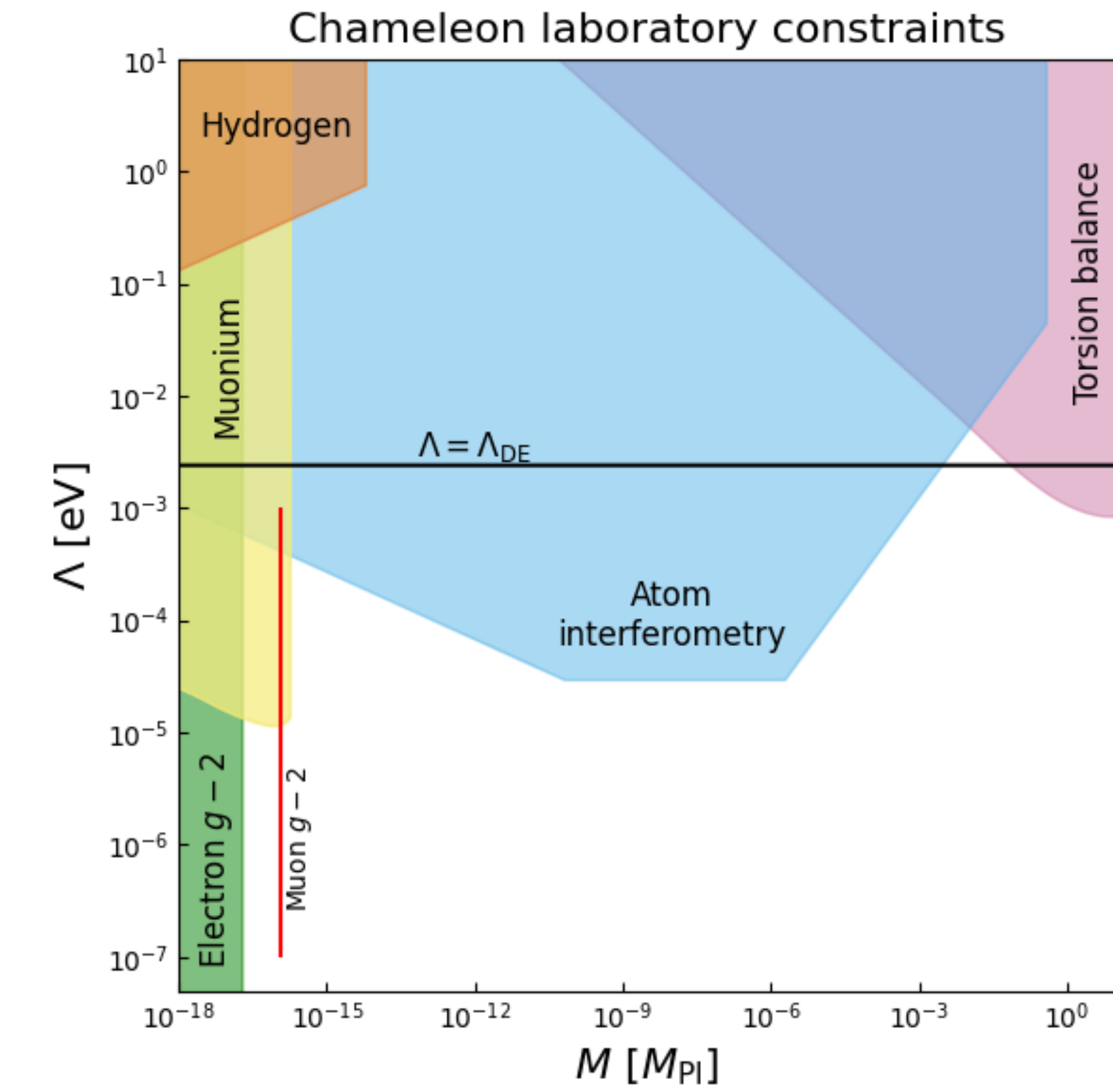
Brax, ACD and Elder 2111.01188

A dark energy scalar can contribute to the anomalous magnetic moment of the muon. There are two contributions; classical and quantum. Classically the extra scalar gives an extra contribution to the BMT equation, used to compute the spin precession vector. In practice the classical contribution is considerably smaller than the quantum one.

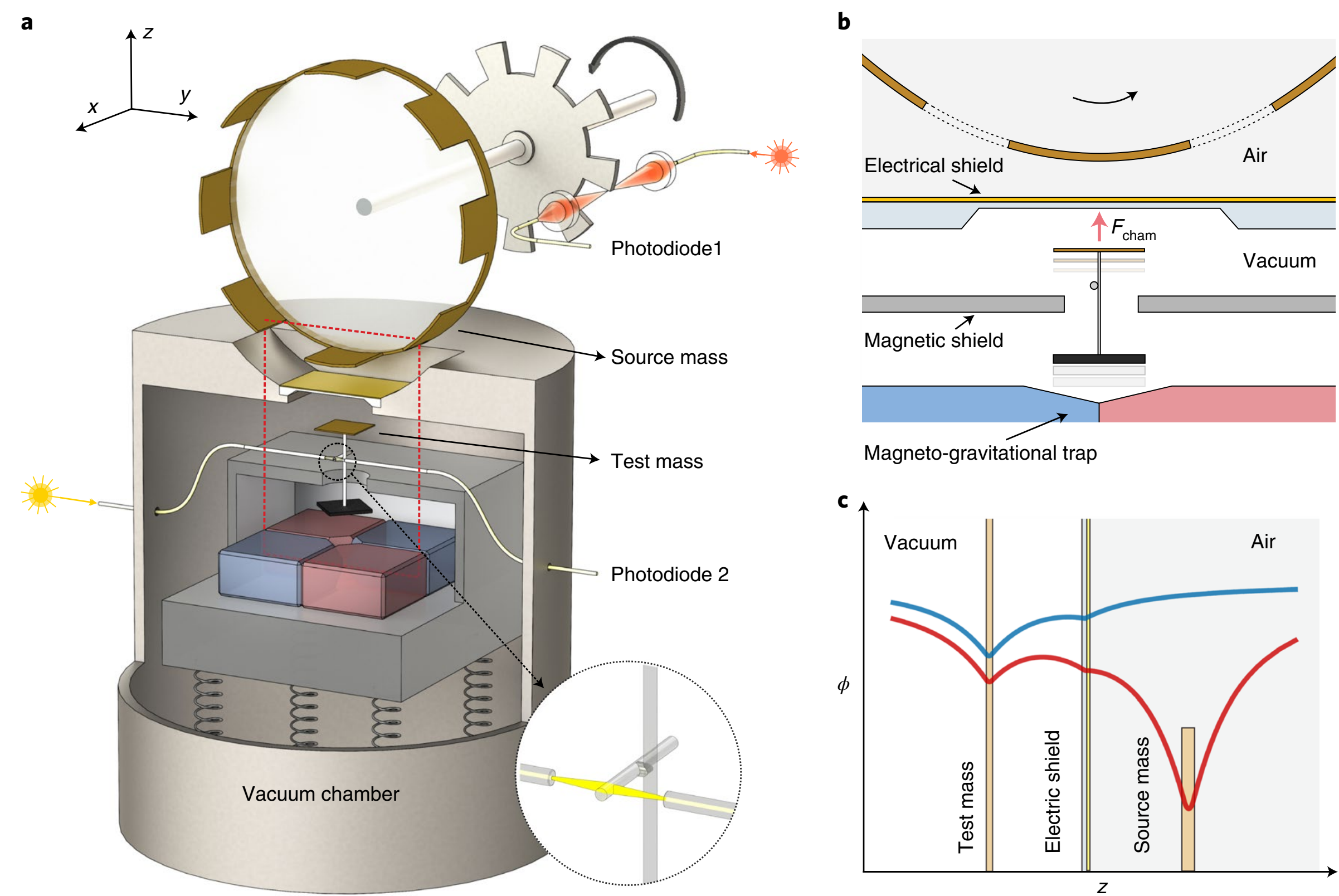
There are two sources of quantum corrections from

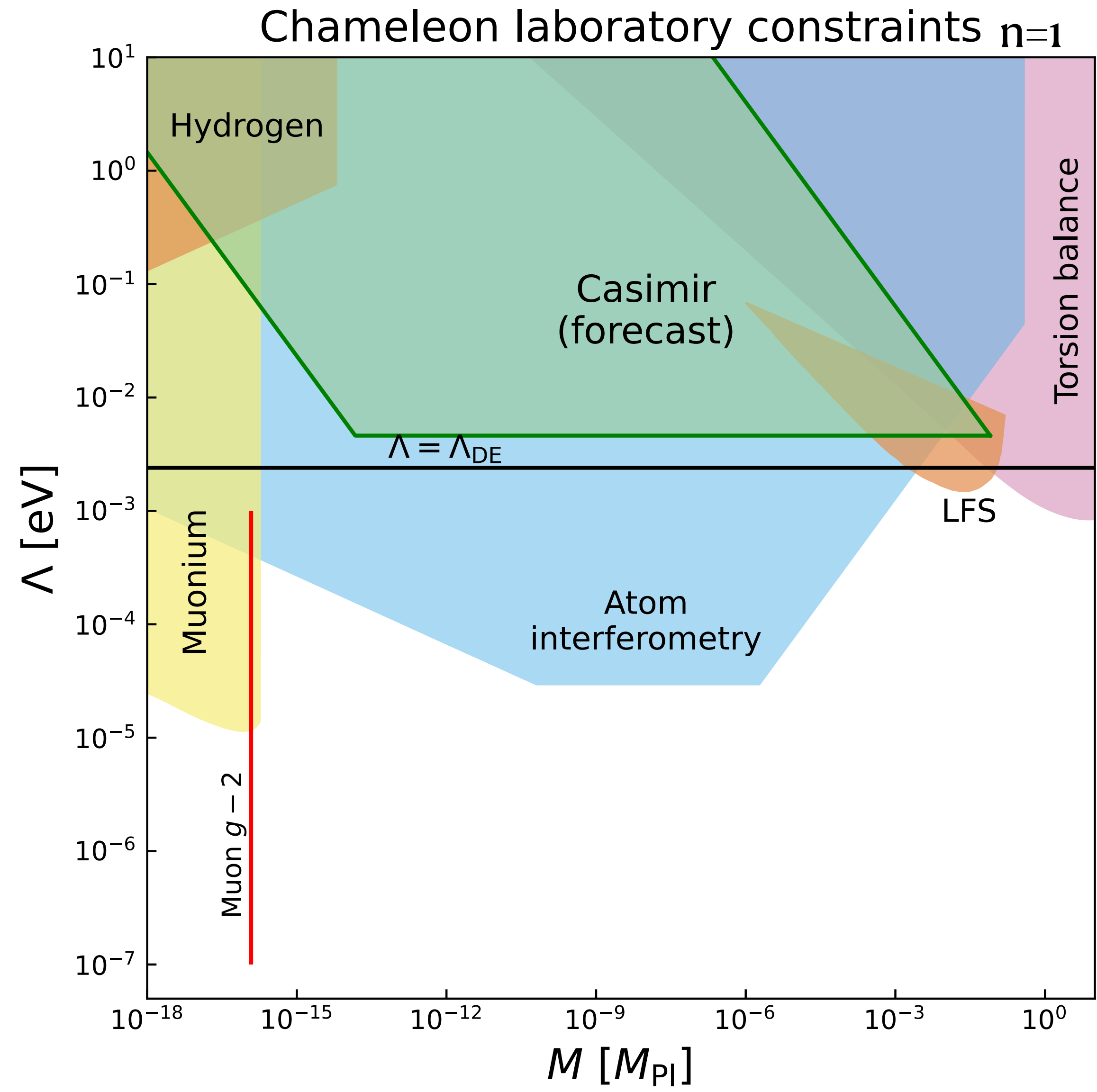


$$\mathcal{L}_m \supset - \left(\frac{\beta_m m_\mu}{m_{\text{Pl}}} \right) \bar{\psi} \psi \chi - \frac{1}{4} \left(\frac{\beta_\gamma}{m_{\text{Pl}}} \right) \chi F_{\mu\nu} F^{\mu\nu}$$



Levitating spheres Yin et al Nature Physics Vol 18 (2022) 1181



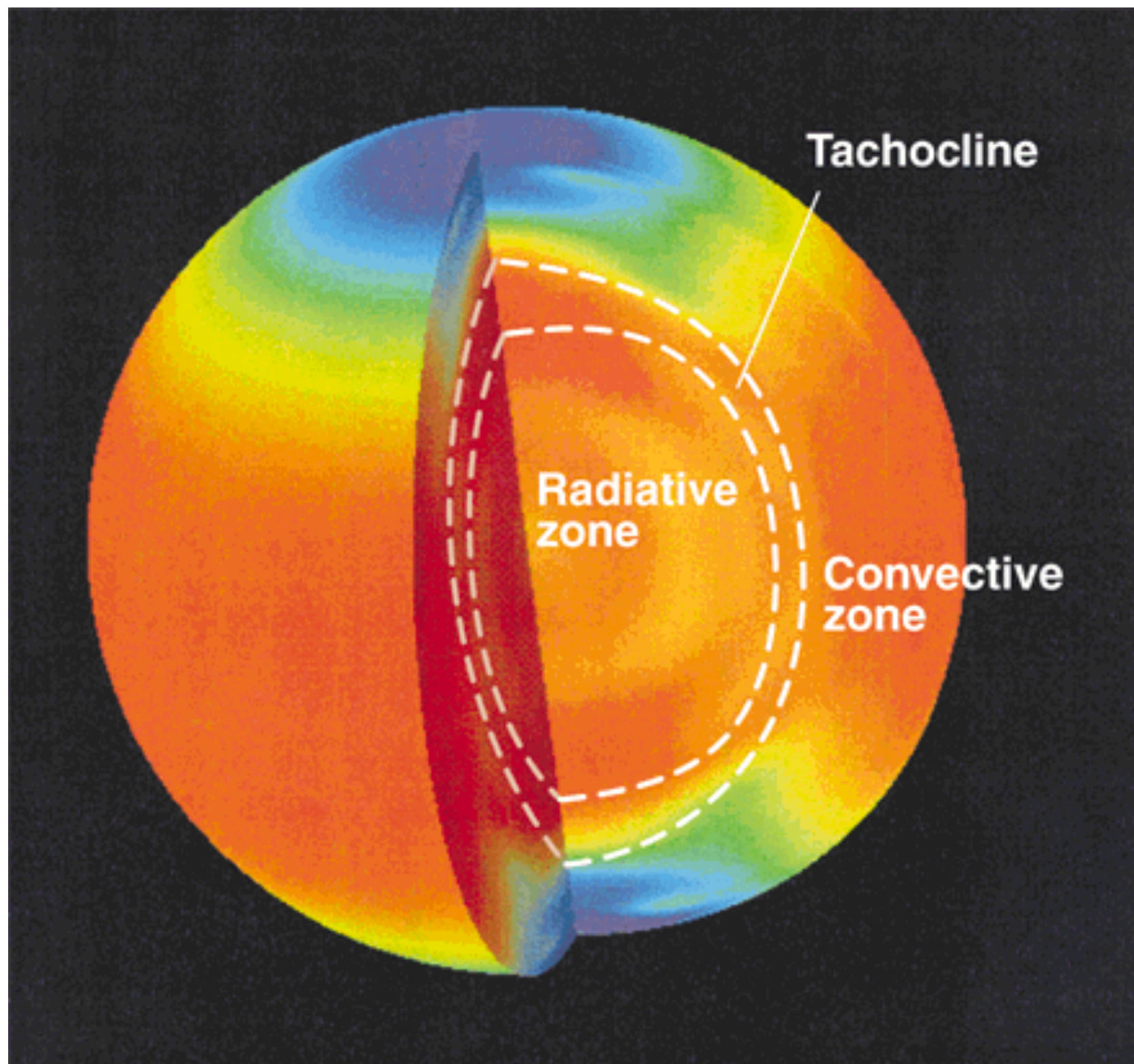


Can we test the axion-dilation model?
Require detailed solar system constraints

Both axions and dilatons couple to photons

$$aF_{\mu\nu}\tilde{F}^{\mu\nu} \quad \phi F_{\mu\nu}F^{\mu\nu}$$

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

