Chameleons in the Laboratory

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“Patras” workshop

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Outline

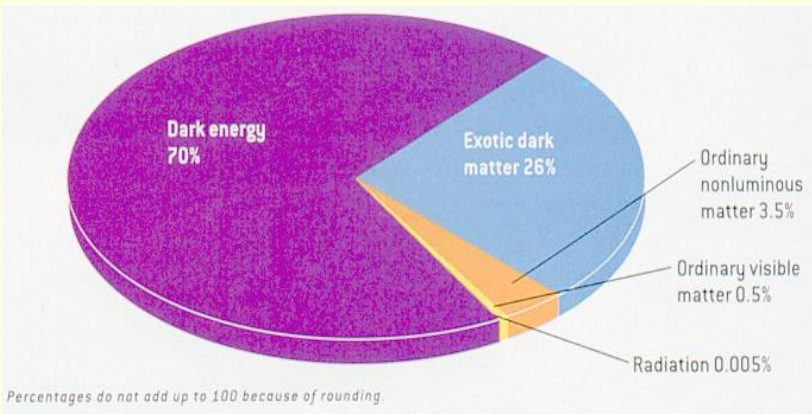
1-Why Chameleons? (Link with Dark Energy)

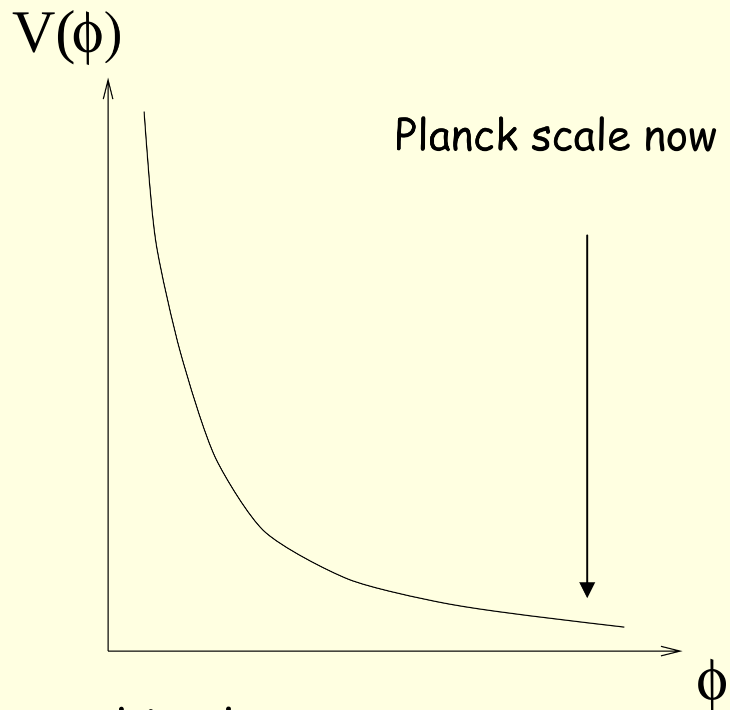
2- Chameleon Optics

3- Chameleonic Casimir Effect

Why Chameleons?

Dark Energy





Field rolling down a runaway potential, reaching large values now (Planck scale)

Extremely flat potential for an almost decoupled field

How Flat?

Energy density and pressure:

$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi), \;\; p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Runaway fields can be classified according to

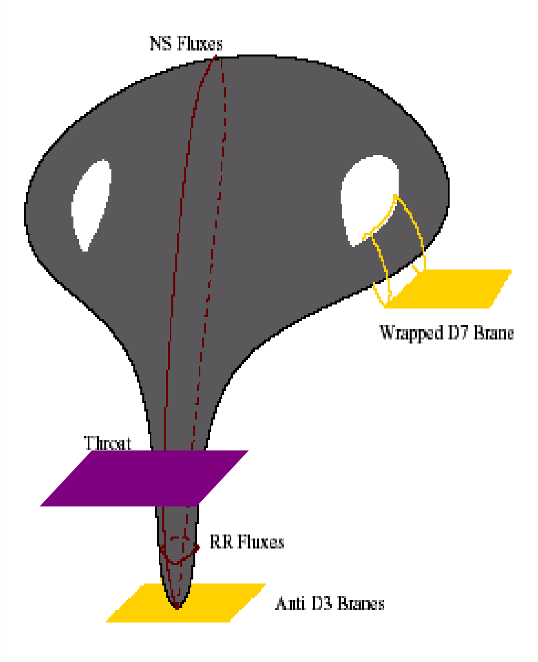
$$w = \frac{p}{\rho}$$

$m \gg H_0$	very fast roll	$w \approx 1$
$m \ll H_0$	slow roll	$w \approx -1$ (inflation)
$m \approx H_0$	gentle roll	$w \neq -1$ (quintessence)

$H_0 \approx 10^{-43}\text{GeV}$ ⟶ strong gravitational constraints

Moduli

KKLT scenario



To all orders of perturbation theory, the moduli have a flat potential. Non-perturbative effects can lead to runaway potentials.

Beyond the standard model physics leads to the existence of myriads of scalar fields: the moduli.

Moduli Couple to Matter!

The Standard Model fermion masses become moduli dependent

$$m_{\mathrm{u,d}}(\phi) = \lambda e^{\kappa_4^2 K(\phi)/2} m_{\mathrm{u,d}}$$

Scalar-tensor theory

Yukawa

Kahler $K = -\frac{n}{\kappa_4^2} \ln \kappa_4 (\phi + \bar{\phi})$

n=1 dilaton, n=3 volume modulus

Gravitational Problems

- Deviations from Newton's law are tested on macroscopic objects. The gravitational coupling is:

$$\kappa_4 \alpha = \frac{\mathrm{d} \ln m_{\mathrm{atom}}}{\mathrm{d}\phi_n} \longleftarrow d\phi_n = \sqrt{K_{\phi\phi}} d\phi$$

- The deviation is essentially given by:

$$\alpha \approx [\frac{3}{2}\frac{m_u + m_d}{\Lambda_{QCD}} - \frac{1}{8}\frac{N-Z}{N+Z}\frac{m_u - m_d}{\Lambda_{QCD}}]\kappa_4 \partial_{\phi_n} K$$

- For moduli fields:

$$\kappa_4 \partial_{\phi_n} K = \sqrt{2n}$$

Too Large !

Gravitational Tests

Scalar-tensor theories suffer from the potential presence of a fifth force mediated by the scalar field.

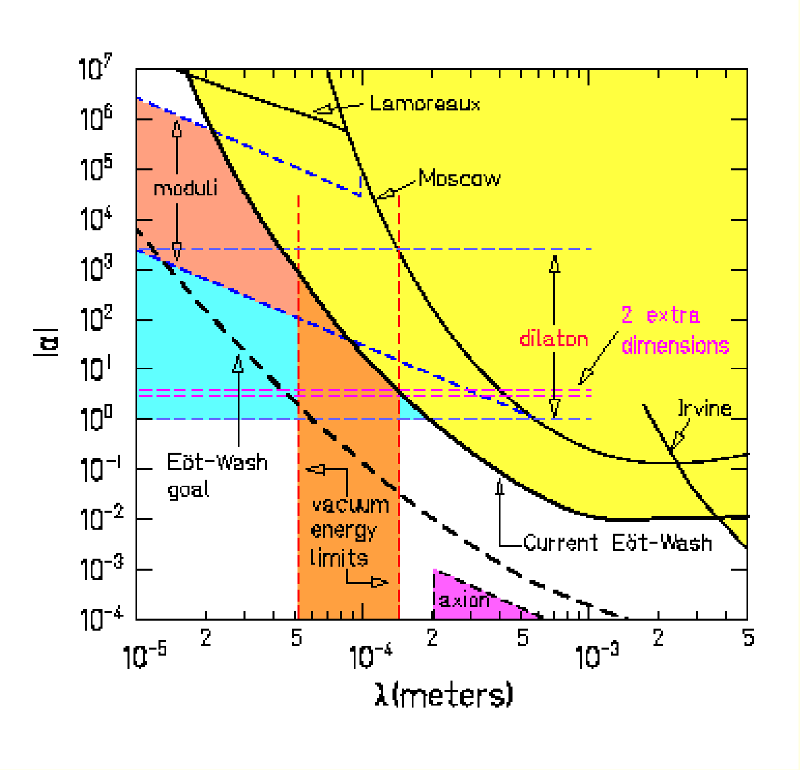
Alternatives:

Non-existent if the scalar field has a mass greater than :

$$m \geq 10^{-3}\ \text{eV}$$

If not, strong bound from Cassini experiments on the gravitational coupling:

$$\alpha^2 \leq 10^{-5}$$



Chameleons!

Chameleon field: field with a matter dependent mass

A way to reconcile gravity tests and cosmology:

Nearly massless field on cosmological scales

Massive field in the laboratory

Chameleon Effective Theory

Effective field theories with gravity and scalars

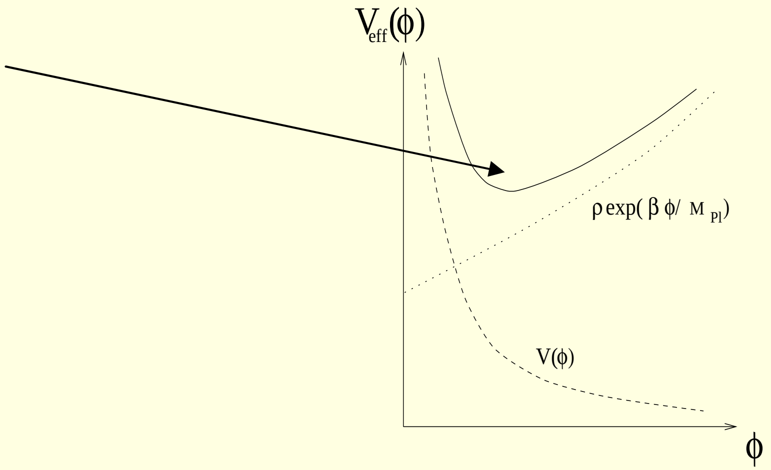
$$S=\int d^4x\sqrt{-g}\left(\frac{1}{16\pi G_N}R-\frac{1}{2}(\partial\phi)^2-V(\phi)+\mathcal{L}_m(\psi_m,A^2(\phi)g_{\mu\nu})\right)$$

The Chameleon Mechanism

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

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

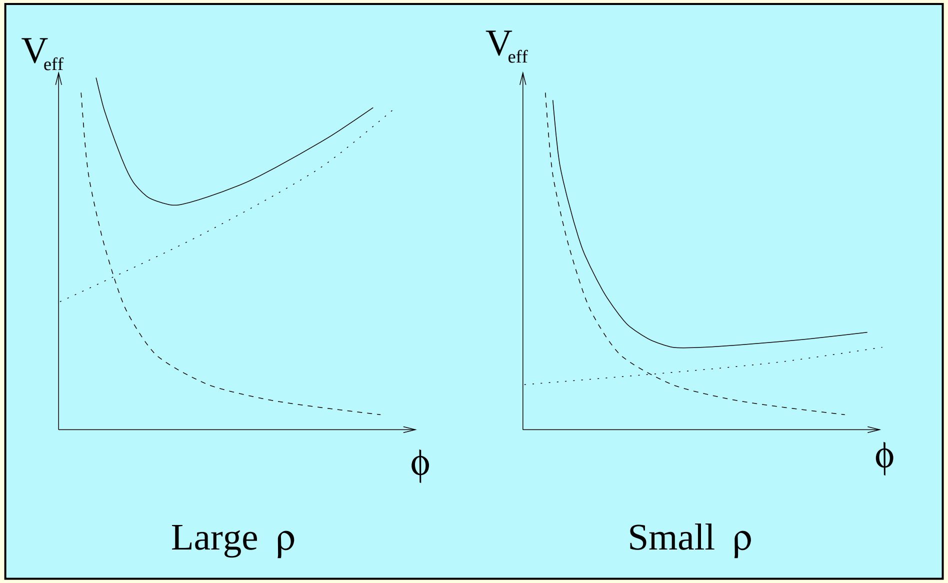
Environment dependent minimum



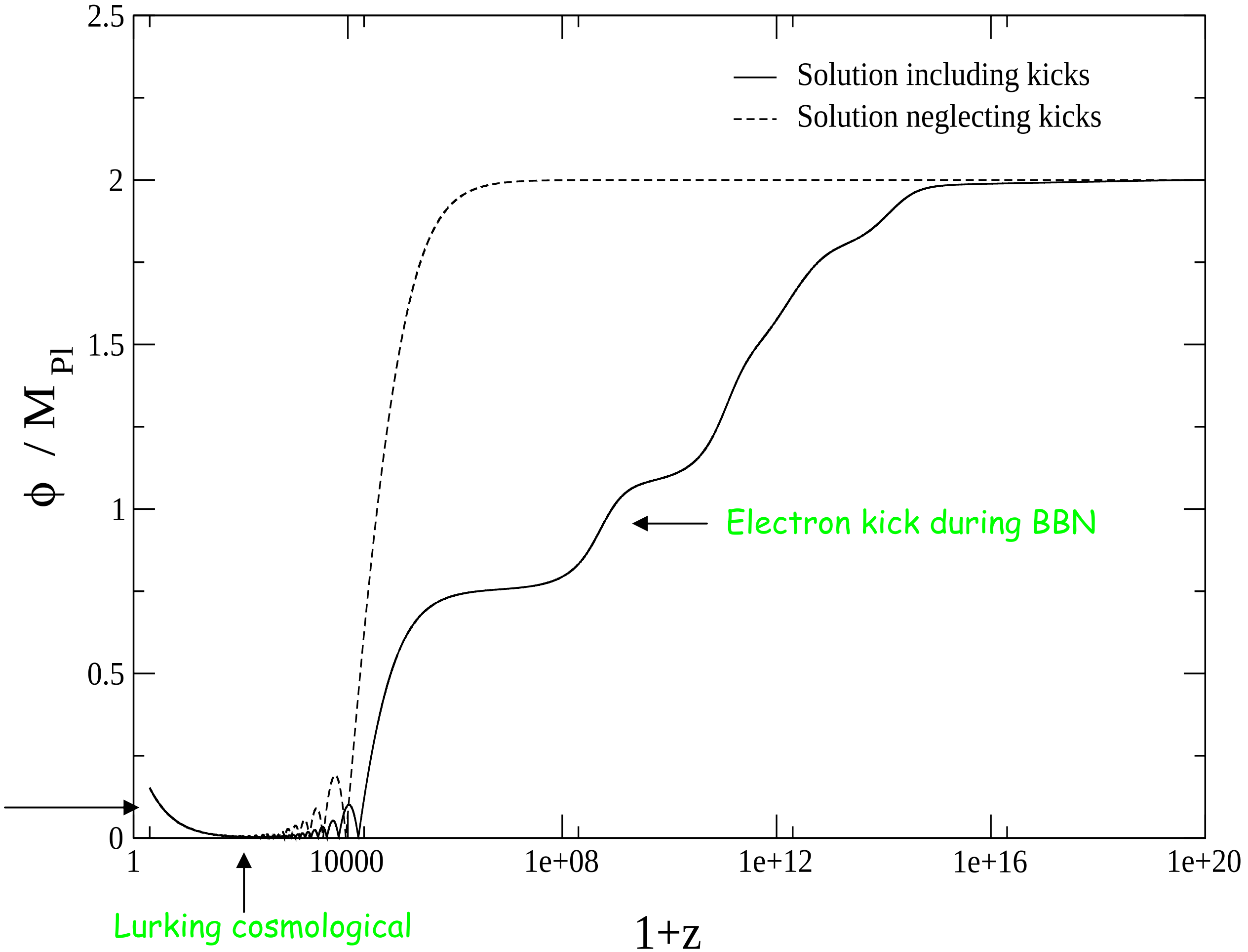
An Example:

Ratra-Peebles potential $V(\phi) \sim \frac{\Lambda^{4+n}}{\phi^n}$

Constant coupling to matter $A(\phi) = \exp \frac{\phi}{M}$



Chameleon Cosmology



Late time acceleration

Possibility of variation of constants

Lurking cosmological constant

Chameleon Optics

Chameleons Coupled to Photons

- Chameleons may couple to electromagnetism:

$$\mathcal{L}_{\rm optics} = \frac{e^{\phi/M}}{g^2} F_{\mu\nu} F^{\mu\nu}$$

- Cavity experiments in the presence of a constant magnetic field may reveal the existence of chameleons. The chameleon mixes with the polarisation orthogonal to the magnetic field and oscillations occur (like neutrino oscillations)

- The coherence length $z_{\rm coh} = \frac{2\omega}{m^2}$

depends on the mass in the optical cavity and therefore becomes pressure and magnetic field dependent:

$$\rho = \rho_m + \frac{B^2}{2}$$

- The mixing angle between chameleons and photons is:

$$\theta = \frac{B\omega}{Mm^2}$$

Ellipticity and Rotation

- Photons remain N passes in the cavity. The perpendicular photon polarisation after N passes and taking into account the chameleon mixing becomes:

$$\psi(z) = N\left(1 - \frac{1}{N}\sum_{n=0}^{N-1} a_n(z)\right)\cos\left(\omega z + \frac{1}{N}\sum_{n=0}^{N-1}\delta_n(z)\right)$$

- The phase shifts and attenuations are given by:

$$a_n(z) = 2\theta^2 \sin^2\frac{m^2(z+nL)}{4\omega}, \quad \delta_n(z) = \frac{m^2\theta^2}{2\omega}(z+nL) - \theta^2\sin\frac{m^2(z+nL)}{2\omega}$$

identified with the phase shift and attenuation after one pass of length nL.

- At the end of the cavity z=L, this can be easily identified for commensurate cavities whose lengths corresponds to P coherence lengths

Rotation → $$a_T = \theta^2, \quad \delta_T = \pi\frac{N}{P}\theta^2$$ ← ellipticity

Ellipticity vs Rotation

- For a large number of passes, the ellipticity is always larger than the rotation

$$\frac{\text{ellipticity}}{\text{rotation}} = \pi \frac{N}{P}$$

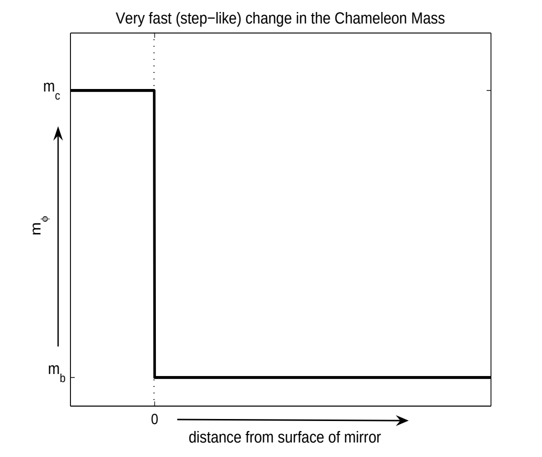
Realistic Chameleon Optics

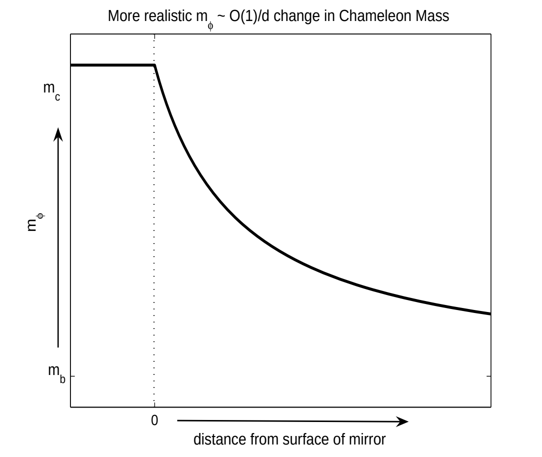
- Must take other effects into account.
- Chameleons never leave the cavity (outside mass too large, no tunnelling)
- Chameleons do not reflect simultaneously with photons.

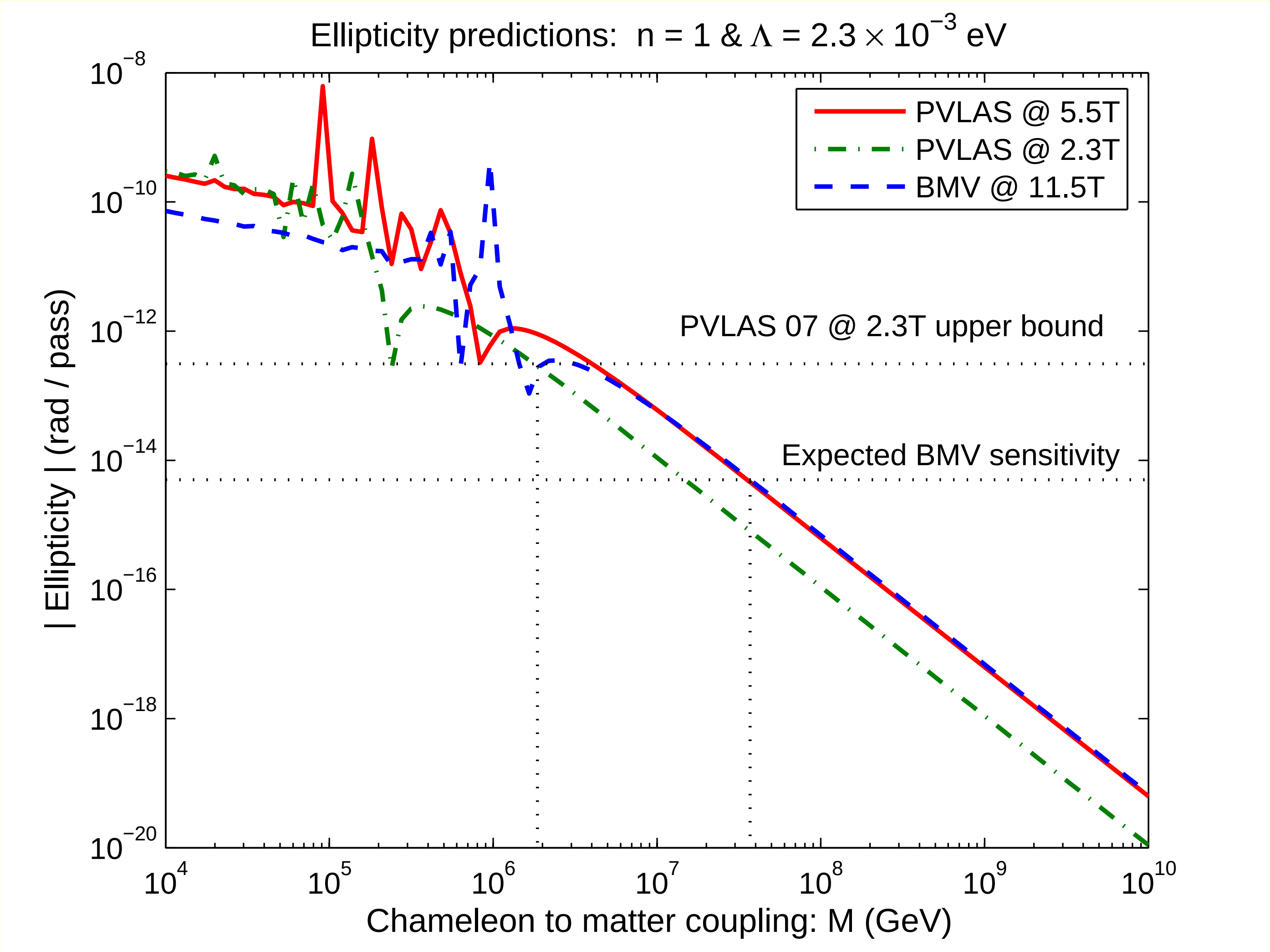
$$\Delta_r = \frac{\pi n}{n+2}$$

- Chameleons propagate slower in the no-field zone within the cavity

$$\Delta_d = \frac{m_\phi^2 d}{\omega}$$






Ellipticity predictions: n = 1 & Λ = 2.3 × 10^−3 eV
PVLAS @ 5.5T
PVLAS @ 2.3T
BMV @ 11.5T
PVLAS 07 @ 2.3T upper bound
Expected BMV sensitivity
| Ellipticity | (rad / pass)
Chameleon to matter coupling: M (GeV)
10^−8
10^−10
10^−12
10^−14
10^−16
10^−18
10^−20
10^4
10^5
10^6
10^7
10^8
10^9
10^10

Chameleonic Casimir Force

The Thin Shell Effect I

- The force mediated by the chameleon is:

$$F_\phi = -\beta \frac{m}{m_{\mathrm{Pl}}} \nabla \phi, \quad \beta = \frac{m_{\mathrm{Pl}}}{M}$$

- The force due to a compact body of radius R is generated by the gradient of the chameleon field outside the body.
- The field outside a compact body of radius R interpolates between the minimum inside and outside the body
- Inside the solution is nearly constant up to the boundary of the object and jumps over a thin shell ΔR
- Outside the field is given by:

$$\phi \approx \phi_\infty - \frac{\beta}{m_p} \frac{3\Delta R}{R} \frac{M_c}{r}$$

The Thin Shell Effect II

- The force on a test particle outside the body is proportional to Newton's attraction

$$F_\phi = 6\beta^2 \frac{\Delta R}{R} F_N$$

- When the shell is thin, the deviation from Newtonian gravity is small.

- The size of the thin-shell is:

$$\frac{\Delta R}{R} = \frac{\phi_\infty - \phi_c}{6\beta m_p \Phi_N}$$

- For bodies used in the Casimir experiments, this is always the case when β is greater than 1000.

The Casimir Force

- We focus on the plate-plate interaction in the range:

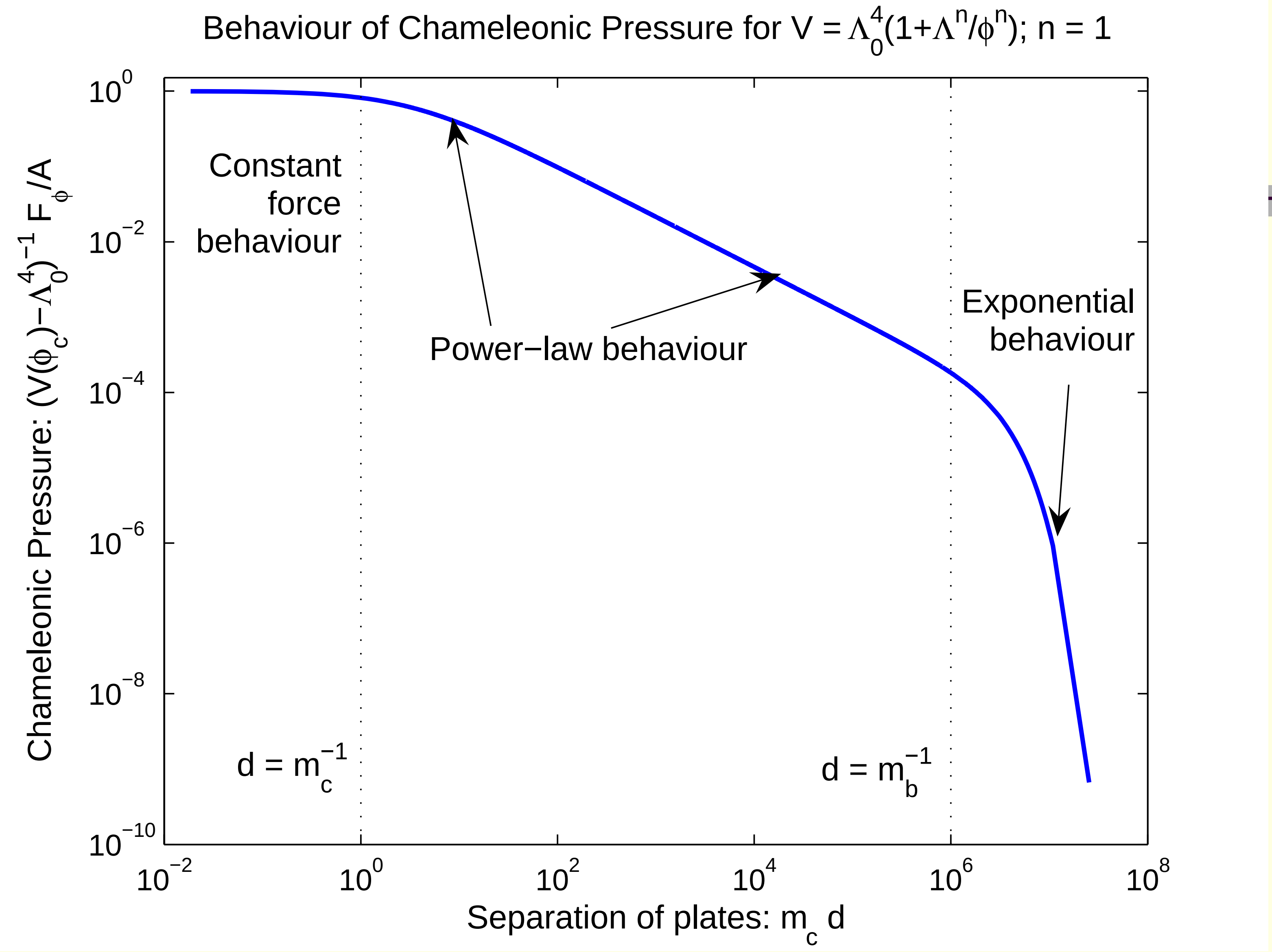
Mass in the plates → $$m_c^{-1} \leq d \leq m_b^{-1}$$ ← Mass in the cavity

- The force is algebraic:

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

- The dark energy scale sets a typical scale:

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



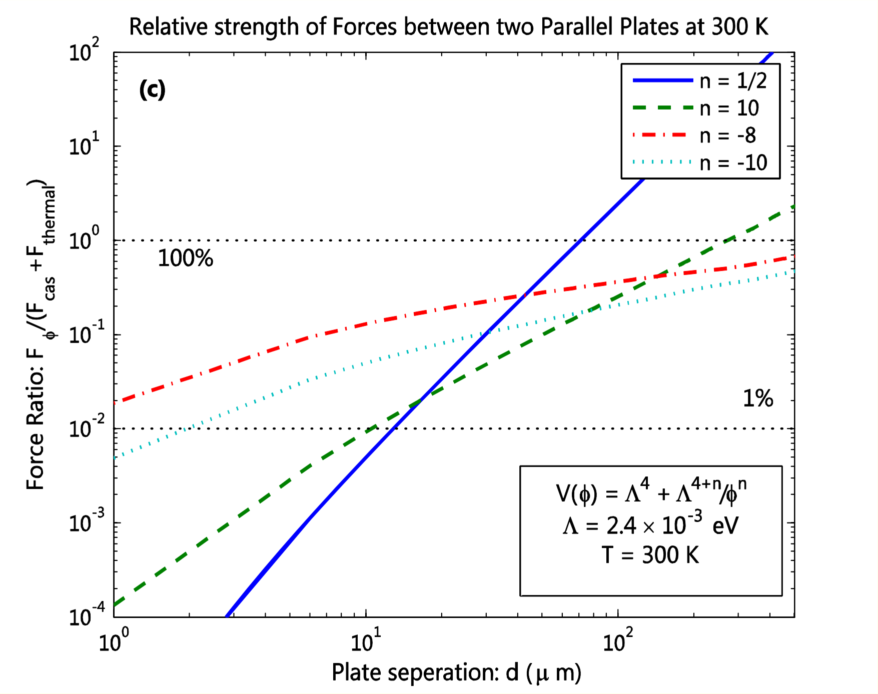
Behaviour of Chameleonic Pressure for V = $\Lambda_0^4(1+\Lambda^n/\phi^n)$; n = 1
Constant force behaviour
Power−law behaviour
Exponential behaviour
$d = m_c^{-1}$
$d = m_b^{-1}$
Chameleonic Pressure: $(V(\phi_c)-\Lambda_0^4)^{-1} F_\phi/A$
Separation of plates: $m_c d$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-2}
10^0
10^2
10^4
10^6
10^8

Detectability

- The Casimir forces is also an algebraic law implying:

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

- This can be a few percent when d=10μm and would be 100% for d=30 μm



Conclusions

- Chameleons offer the only known way of reconciling gravity tests with the existence of a dark energy particle.
- If strongly coupled to photons, they would show up in cavity experiments.
- Casimir experiments would also see a clear signal provided probed distances are large enough.

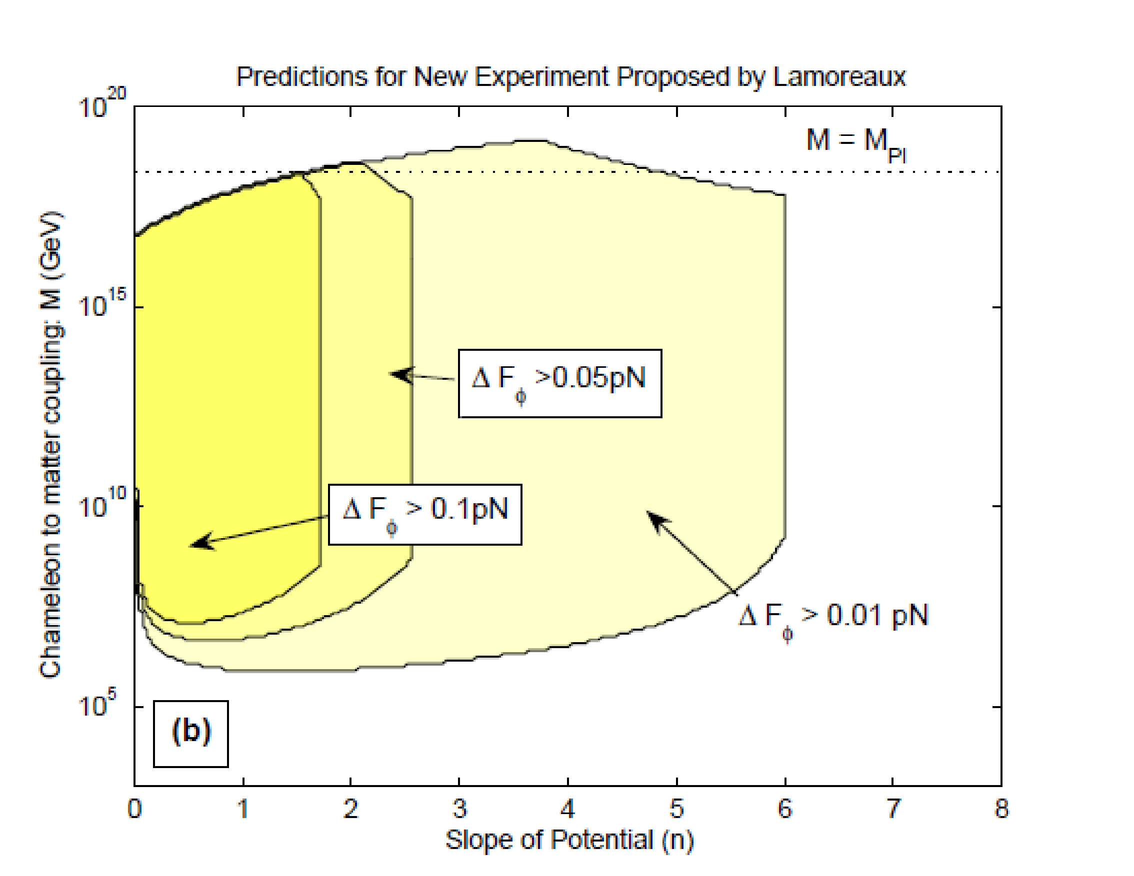
Variations of Constants

- Scalar tensor theories predict a variation of the fundamental particle masses:

$$m_\psi = A(\phi) m_\psi^0$$

- The gauge coupling constants are field-independent.
- The mass of the proton is essentially a pure gluon condensation effect in Quantum ChromoDynamics, hence constant too.
- The electron to proton ratio is field dependent:

$$\frac{m_e}{m_p} \approx A(\phi) \frac{m_e}{m_p}|_0$$



Predictions for New Experiment Proposed by Lamoreaux
M = M_Pl
Δ F_ϕ >0.05pN
Δ F_ϕ > 0.1pN
Δ F_ϕ > 0.01 pN
(b)
Chameleon to matter coupling: M (GeV)
10^20
10^15
10^10
10^5
0
1
2
3
4
5
6
7
8
Slope of Potential (n)