Evading the CAST bound with a chameleon

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Outline

1-Dark Energy and Chameleons

a) Dark Energy

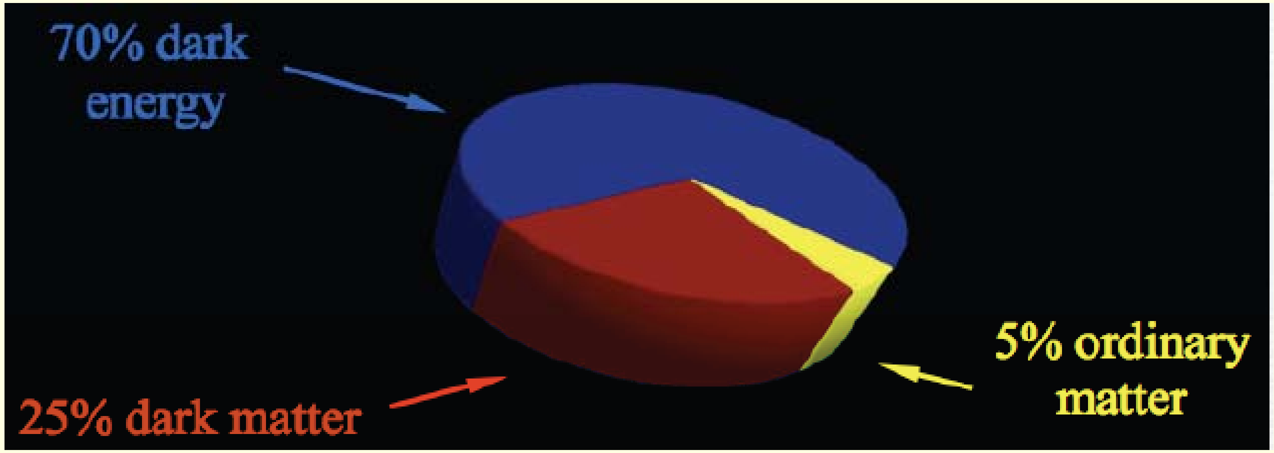
b) Why Chameleons?

2-Chameleons coupled to photons

a) Chameleons and CAST

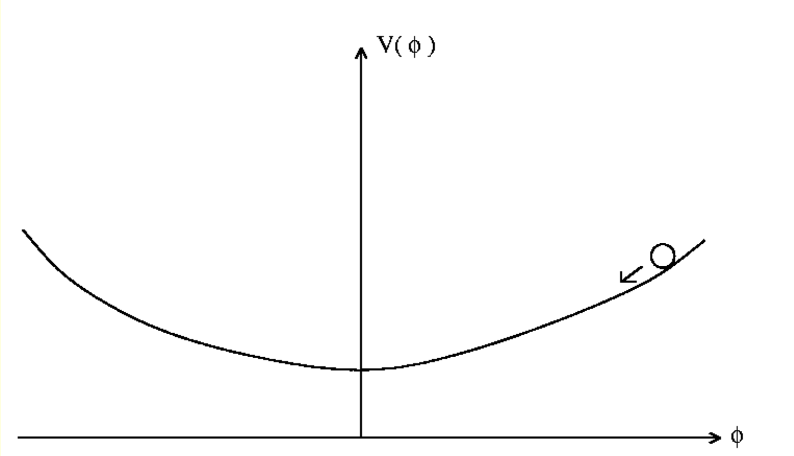
b) Chameleonic optics

The Big Puzzle



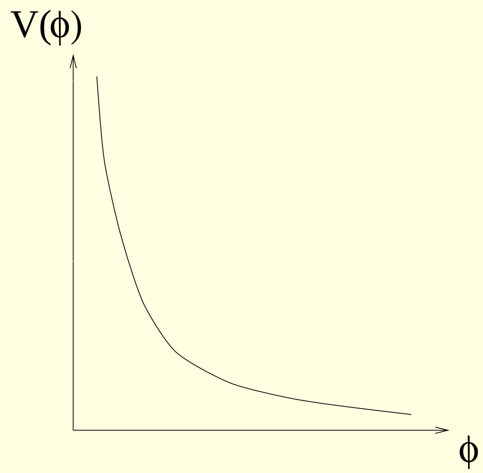
Quintessence?

Like during primordial inflation, scalar fields can trigger the late acceleration of the universe.



An attractive possibility: runaway behaviour.

The mass of the field now is of order of the Hubble rate. Almost massless.



Experimental consequences?

Long lived scalar fields which couple with ordinary matter lead to the presence of a new Yukawa interaction:

$$F_{12} = \frac{G_N m_1 m_2}{r^2}(1 + \alpha_1 \alpha_2 e^{-mr})$$

This new force would have gravitational effects on the motion of planets, the laboratory tests of gravity etc.. Stringent bounds on fifth forces exist.

Gravitational Tests

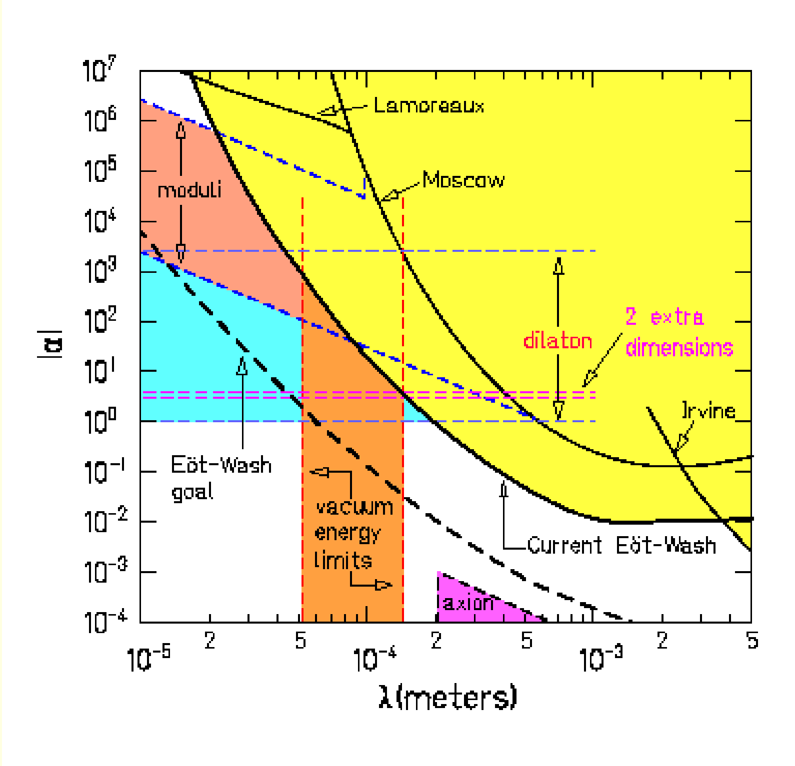
Non-existent fifth force if the scalar field has a mass greater than

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

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

$$\alpha \lesssim 10^{-2}$$

If coupling O(1), then need a new mechanism: chameleons! They are hidden in a dense environment



Chameleon field: field with a matter dependent mass

$$m_Q^2 \approx 8\pi G_N \rho_{\mathrm{matter}}$$

A way to reconcile gravity tests and cosmology:

Nearly massless field on cosmological scales

Massive field in the laboratory

Where do Chameleons Come from?

Effective field theories with gravity and scalars

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

deviation from Newton's law

$$\alpha=\frac{\partial \ln A}{\partial\phi}$$

The Ratra- Peebles Example

Potential of the form:

$$V = \Lambda_0^4 + \frac{\Lambda^{4+\alpha}}{\phi^\alpha} + \ldots$$

Cosmology implies that:

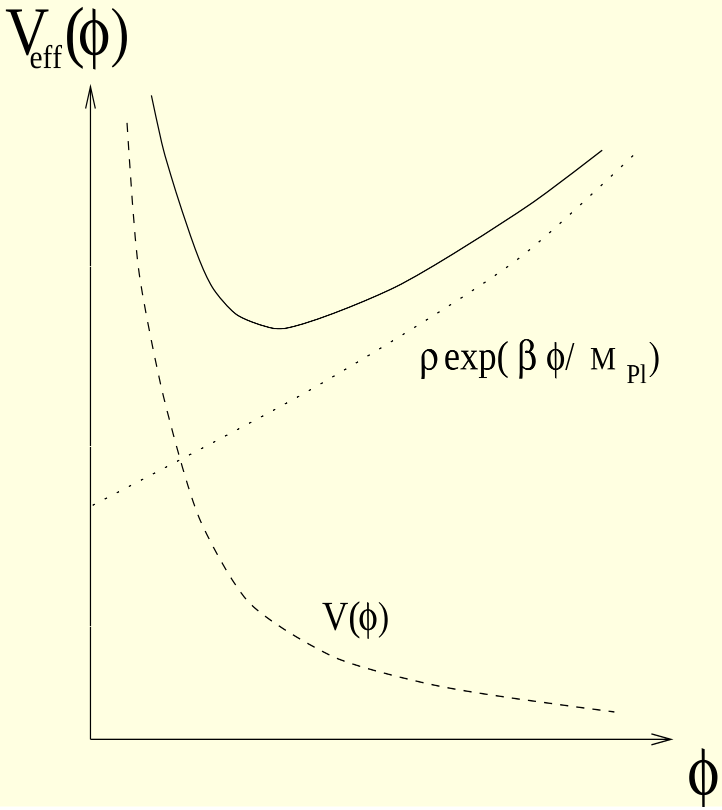
$$\Lambda_0 \sim 10^{-3}\ \text{eV}$$

Gravitational tests lead to a similar constraint on Λ

The Chameleon Mechanism

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

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



Chameleons and Gravity

- The mass of the scalar field becomes environment dependent. When the density of matter gets larger, the mass gets larger too hence the range of the fifth force becomes smaller

$$d \geq m(\rho)^{-1}, \text{usual gravity}$$

$$d \leq m(\rho)^{-1}, \text{modified gravity}$$

$$F = -(1+\theta)\frac{G_N m_a m_b}{r_{ab}^2}$$

$$\theta = 0, \; d \geq m(\rho)^{-1}$$
$$\theta = 2\alpha^2, \; d \leq m(\rho)^{-1}$$

What is dense enough?

- The environment dependent mass is enough to hide the fifth force in dense media such as the atmosphere, hence no effect on Galileo's Pisa tower experiment!

$$\rho \approx 10^{-4} \mathrm{g/cm^3}$$

- It is not enough to explain why we see no deviations from Newtonian gravity in the lunar ranging experiment

$$\rho \approx 10^{-22} \mathrm{g/cm^3}$$

- It is not enough to explain no deviation in laboratory tests of gravity carried in "vacuum"

$$\rho \approx 10^{-14} \mathrm{g/cm^3}$$

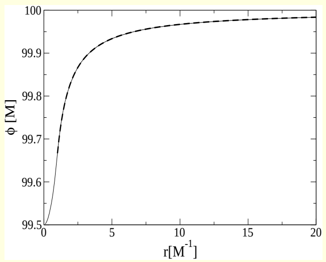
The Thin Shell Effect

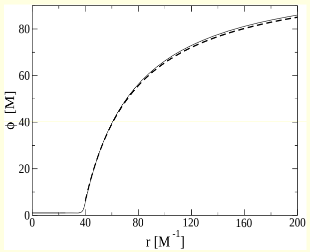
For compact bodies, gravity is screened off by the thin shell effect. The field outside a compact body of radius R interpolates between the minimum inside and outside the body

Inside the solution is nearly constant up to the boundary of the object and jumps over a thin shell

$$\theta = \alpha \frac{\phi_\infty - \phi_c}{m_{\mathrm{Pl}} \Phi_N}$$

bodies with large Newtonian potential on their surface interact very weakly!





Laboratory tests

- In a typical experiment, one measures the force between two test objects and compare to Newton's law.

- In a vacuum chamber, the chameleon "resonates" and the field value adjusts itself according to:

$$m_{\text{vac}} L \sim 1$$

- The vacuum is not dense enough to lead to a large chameleon mass, hence the need for a thin shell.

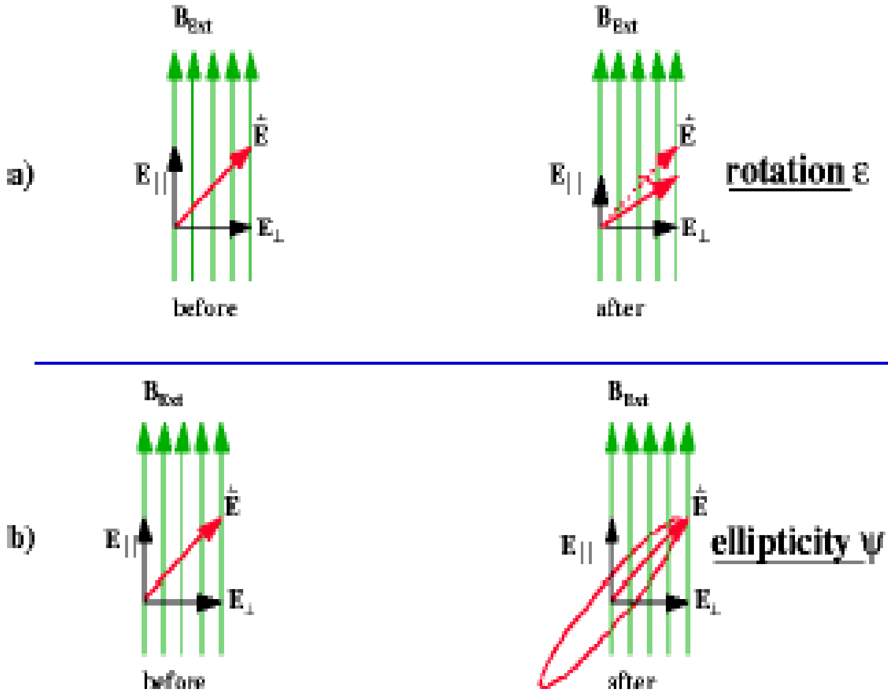
$$\phi_{\text{vac}} \leq 10^{-28} m_{\text{Pl}}$$

- Typically for masses of order 40 g and radius 1 cm, the thin shell requires for the Ratra-Peebles case:

$$\Lambda \leq 10^{3n/(n+4)} 10^{-3} \text{ eV}$$

1. Vacuum Magnetic Dichroism and Birefringence

- Send linearly polarized laser beam through transverse magnetic field ⇒ measure changes in polarization state:
  - rotation (dichroism)
  - ellipticity (birefringence)



[Brandi *et al.* '01]

PVLAS and CAST Bounds

PVLAS experimental results could be seen as a constraint on the coupling:

$$\frac{e^{\phi/M}}{g^2} F_{\mu\nu} F^{\mu\nu}$$

Limits on mass of scalar quite stringent:

$$m \leq 10^{-3}\text{eV}, \quad M \geq 10^{6}\text{GeV}$$

No contradiction with CAST experiments on scalar emitted from the sun!

$$M \geq 10^{10}\text{GeV}$$

What if $10^6 \leq M \leq 10^{10}$?

CHAMELEON ?

Chameleons in the sun

The energy density depends on the magnetic field:

$$\rho = \rho_{\rm gas} + \frac{B^2}{2}$$

The mass of the chameleon is given by:

$$\phi = \left(\frac{n\Lambda^{4+n}M}{\rho}\right)^{1/(n+1)} \quad m^2 = n(n+1)\frac{\Lambda^{n+4}}{\phi^n}$$

No chameleon production in the sun if massive enough:

$$m_{\rm sun} = m_{\rm lab}\left(\frac{\rho_{\rm sun}}{\rho_{\rm lab}}\right)^{(n+2)/2(n+1)}$$

For a density $\rho_{\rm sun}/\rho_{\rm lab} \approx 10^{14}$ the mass in the sun is:

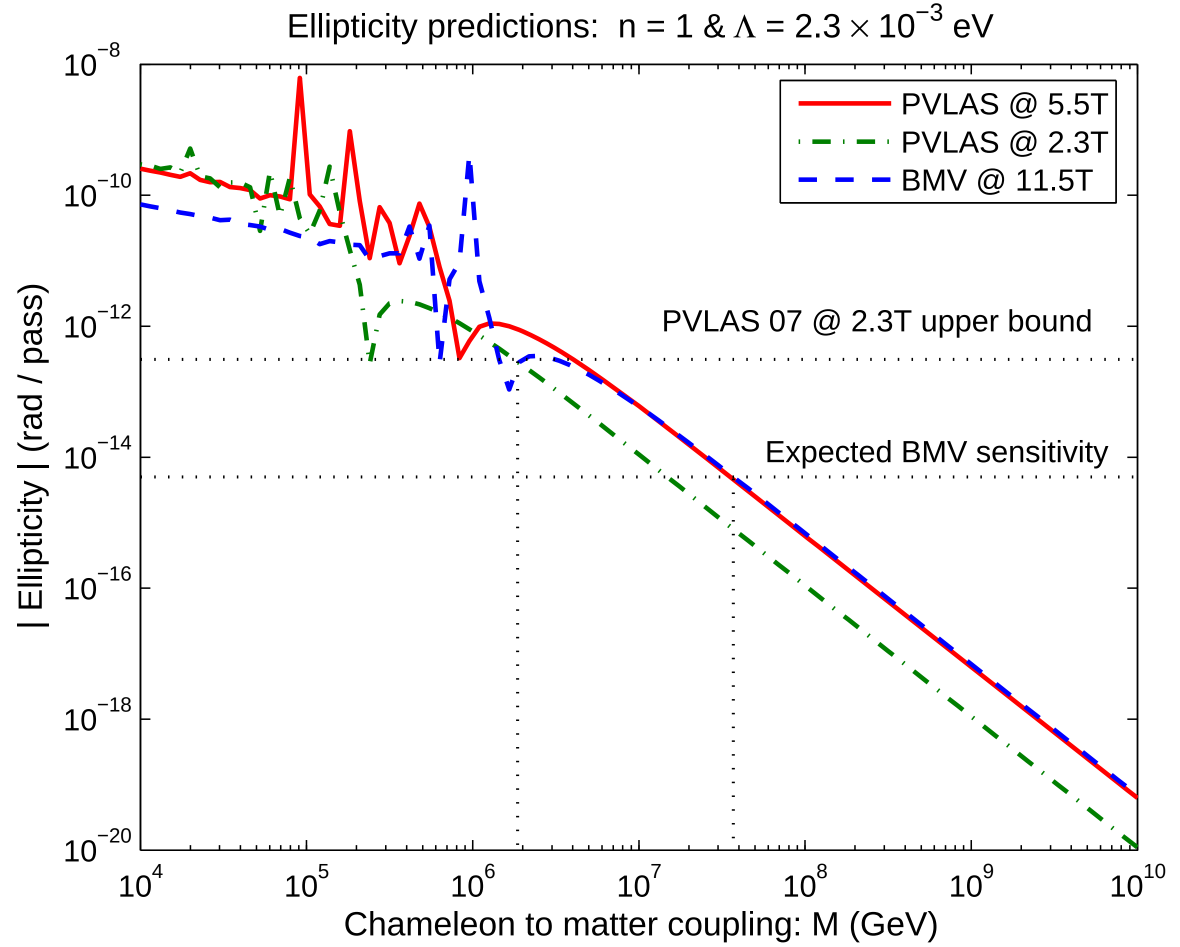
$$m_{\rm sun} \sim 10^{-2}\,{\rm GeV} \gg 10^{-5}\,{\rm GeV} \quad {\rm n} = {\rm O}(1)$$

Hence chameleons evade the CAST bound. Similar result for chameleons produce at the surface of the sun where the density is smaller.

Testing Chameleons in the Laboratory I

Optical Experiments:

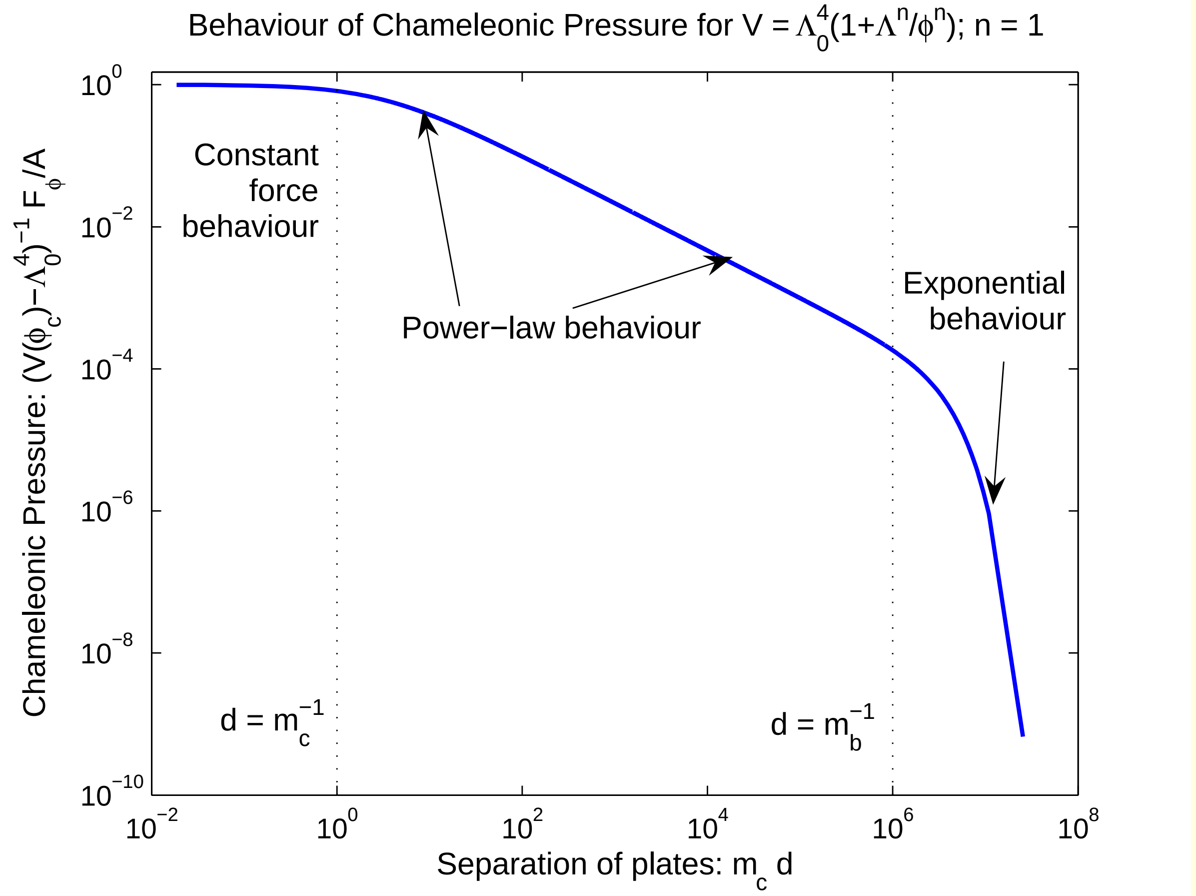
Measuring the induced ellipticity of polarised laser beam through a magnetic field



Testing Chameleons in the Laboratory II

Casimir Force:

Necessitates to see deviations from the Casimir force of order 1% at 10 microns.



Conclusions

- The chameleon mechanism is a powerful effect allowing to hide scalar fields in dense media
- Still these fields are detectable in laboratory experiments