Chameleons:

from Cosmology to Laboratory tests

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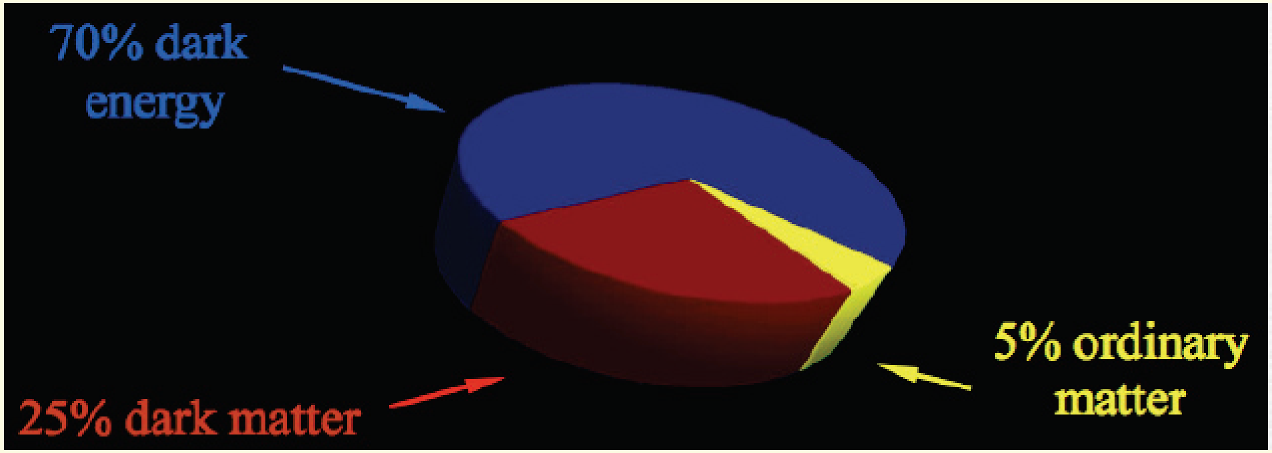
Outline

1-Dark Energy?

2-Modifying gravity locally

3-Laboratory Tests

The Big Puzzle



Dark Energy Really?

In fact we are not absolutely certain that the acceleration of the universe is due to dark energy. On the contrary, the acceleration of the expansion of the universe may be interpreted in four different ways:

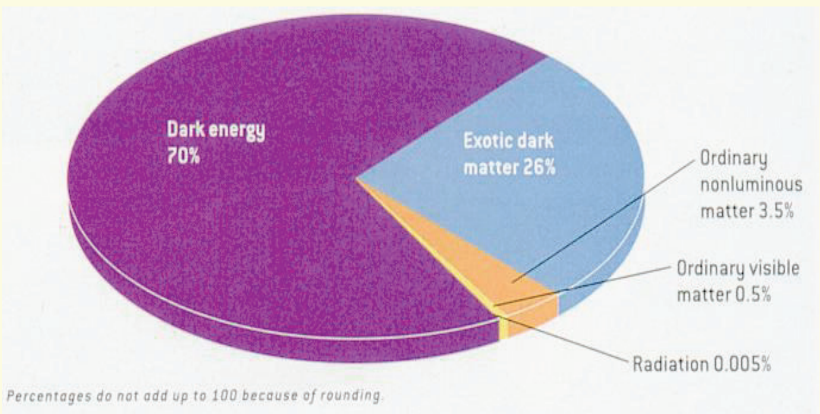
1) The acceleration is entirely due to the presence of a constant vacuum energy (cosmological constant). Anthropic principle and/or string theory?

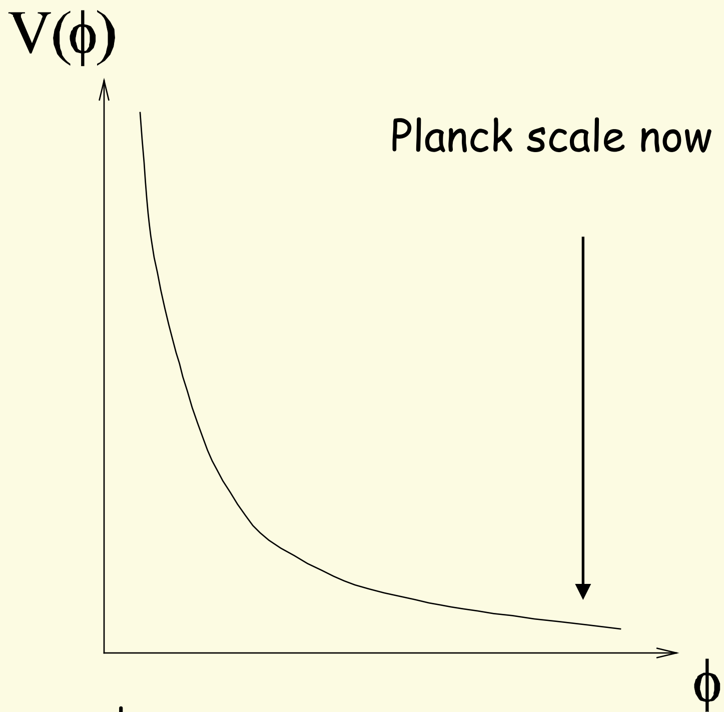
2) The acceleration results from the existence of a new type of matter: dark energy.

3) What is seen as acceleration is in fact a misinterpretation of data and really we must face a modification of gravity at large enough scales.

4) There is no real acceleration. We just live in a void surrounded by more matter. No copernican principle stands.

Dark Energy





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

Extremely flat potential for an almost decoupled field

How Flat?

Equation of state:

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

$m \gg H_0$ very fast roll $w \approx 1$

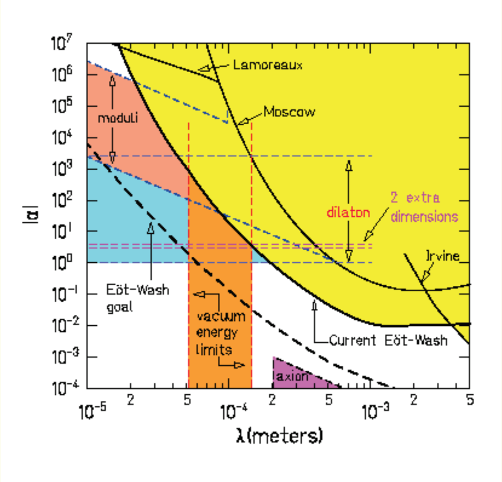
$m \ll H_0$ slow roll $w \approx -1$ (cosmological constant)

$m \approx H_0$ gentle roll $w \neq -1$ (dark energy)

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

- Deviations from Newton's law are parametrised by:

$$\phi_N = -\frac{G_N}{r}(1 + 2\alpha e^{-r/\lambda})$$



The tightest constraint on α comes from the Cassini probe measuring the Shapiro effect (time delay):

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

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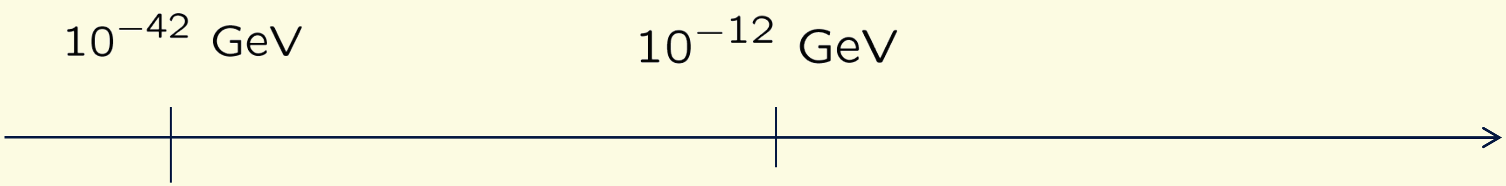
New Scales in Physics



Mass of the scalar field on cosmological scales.

Dark energy scale

The dark energy scale is tantalizingly close to the neutrino mass scale and the scale at which gravity has been tested…

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

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

$$\beta_\phi = m_{\mathrm{Pl}} \frac{d \ln A}{d\phi}$$

An Example: f(R) theories

$$S_{\mathsf{MG}} = \frac{1}{16\pi G_N} \int d^4x \sqrt{-g} f(R)$$

f(R) totally equivalent to an effective field theory with gravity and scalars

$$S = \int d^4x\sqrt{-g}(\frac{1}{16\pi G_N}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) + \mathcal{L}_m(\psi_m, e^{2\phi/\sqrt{6}m_{\rm Pl}}g_{\mu\nu}))$$

The potential V is directly related to f(R).

$$V(\phi) = m_{\rm Pl}^2\frac{Rf' - f}{2f'^2}, \;\; f' = e^{-2\phi/\sqrt{6}m_{\rm Pl}}$$

Same problems as dark energy: coincidence problem, cosmological constant value etc…
and a large coupling!

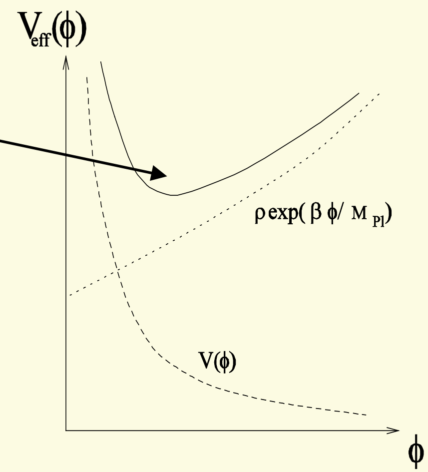
$$\beta_\phi = \frac{1}{\sqrt{6}}$$

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



Chameleons massive enough in dense environment (atmosphere). Not enough in the solar system and cavity experiments, so the thin shell mechanism.

The Thin Shell Effect I

- The force mediated by the chameleon is:

$$F_\phi = -\beta \frac{m}{m_{\text{Pl}}} \nabla \phi,$$

- Outside the field is given by:

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

The Thin Shell Effect II

- The force on a test particle outside a spherical body is shielded:

$$\beta_\phi = 3\beta\frac{\Delta R}{R}$$

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

- The size of the thin-shell is:

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

- Small for large bodies (sun etc..) when Newton's potential at the surface of the body is large enough.

- No thin shell effect for tests of gravity aboard satellites, large deviations from Newton's law.

$$10^{-19} < \frac{\eta}{\beta^2} < 10^{-11}$$

Laboratory Experiments?

- Scalar fields and chameleons could be experimentally detected. Different types of experiments have been proposed and carried out:
- Casimir force experiments could be sensitive to a new scalar field force.
- Helioscopes (CAST(CERN)……) could detect scalars emitted from the inner sun.
- Optical cavity experiments are looking for birefringence and afterglow effects (BMV , ALP (DESY), GammeV (Fermilab), ADMX (Seattle)……)

Matter and Photon Couplings

$$\beta_m = \frac{m_{\mathrm{Pl}}}{M_{\mathrm{matter}}}, \quad \beta_\gamma = \frac{m_{\mathrm{Pl}}}{M_\gamma}$$

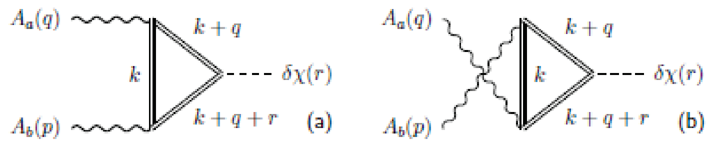


Figure 1. Diagrams contributing to the leading interaction between dark energy and the electroweak gauge bosons, which determine an effective operator acting on $A_a(q)A_b(p)\chi(r)$. Note that the momentum carried by χ is taken to flow into the diagram. Double lines represent a species of heavy fermion charged under $SU(2) \times U(1)$.

When the coupling to matter is universal, and heavy fermions are integrated out, a photon coupling is induced. Other contribution from conformal anomaly too.

$$M_\gamma = \frac{3(4\pi)^2}{N_f e^2} M_{\mathrm{matter}}$$

Atomic Precision Tests

Scalars contribute to a shift in the 1s-2s difference:

$$\delta E_{1s-2s} = \frac{3m_N}{16\pi M_m^2 a_0} m_e + \frac{7\alpha}{32\pi a_o^2 M_m M_\gamma} m_e$$

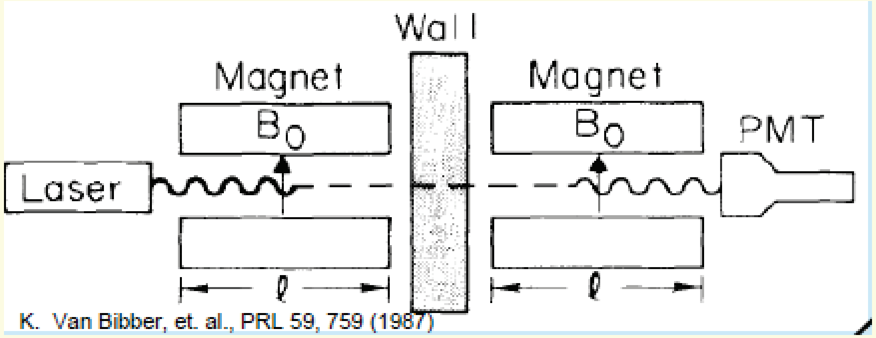
And a contribution to the Lamb shift:

$$\delta E_{2s-2p} = \frac{Z^4\alpha}{48\pi a_0^2 M_m M_\gamma} m_f$$

A stringent bound on the matter coupling can be deduced from the 1s-2s uncertainty:

$$M_m \geq 10\text{TeV}$$

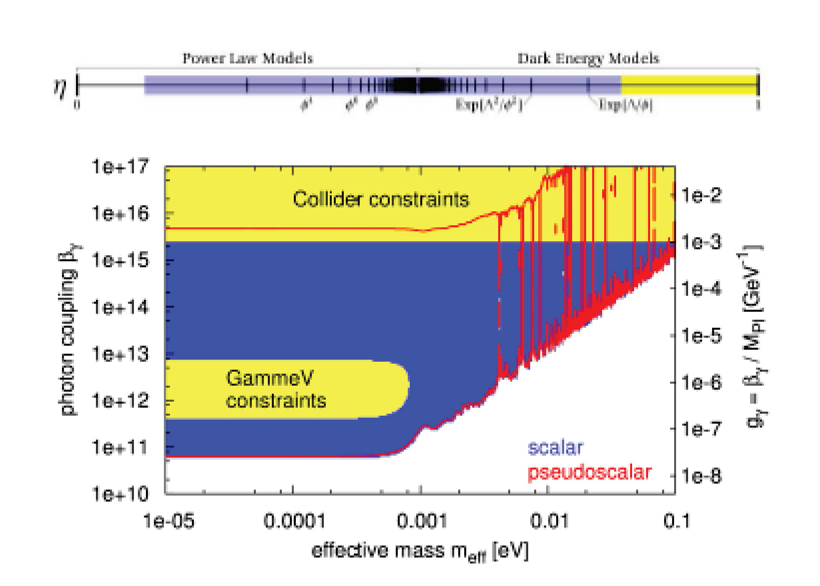
Afterglow

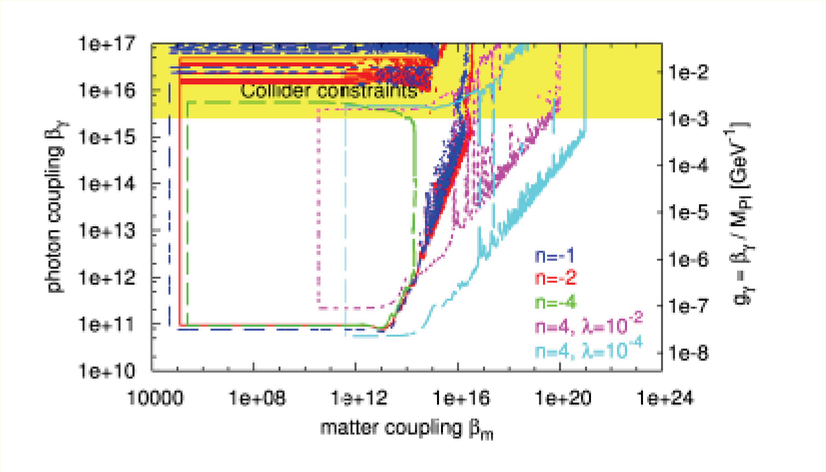


Axion-like particles, once generated can go through the wall and then regenerate photons on the other side.

Chameleons cannot go through but can stay in a jar once the laser has been turned off and then regenerate photons.

Even in the absence of magnetic fields, chameleons can induce atomic transitions and lead to an afterglow phenomenon (to be tested with ALPS (DESY)).

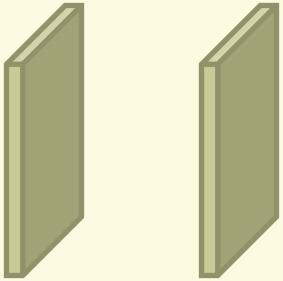




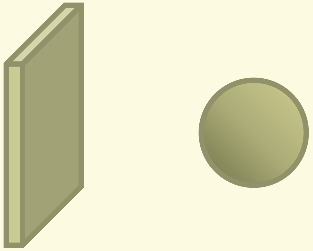
GammeV (Fermilab) and ADMX (Seattle) cover a large part of the parameter space. Constraints from BMV (Toulouse) too. Best constraints from Chase (Fermilab).

Casimir Force Experiments

- Measure force between
  - Two parallel plates



  - A plate and a sphere



The Casimir Force

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

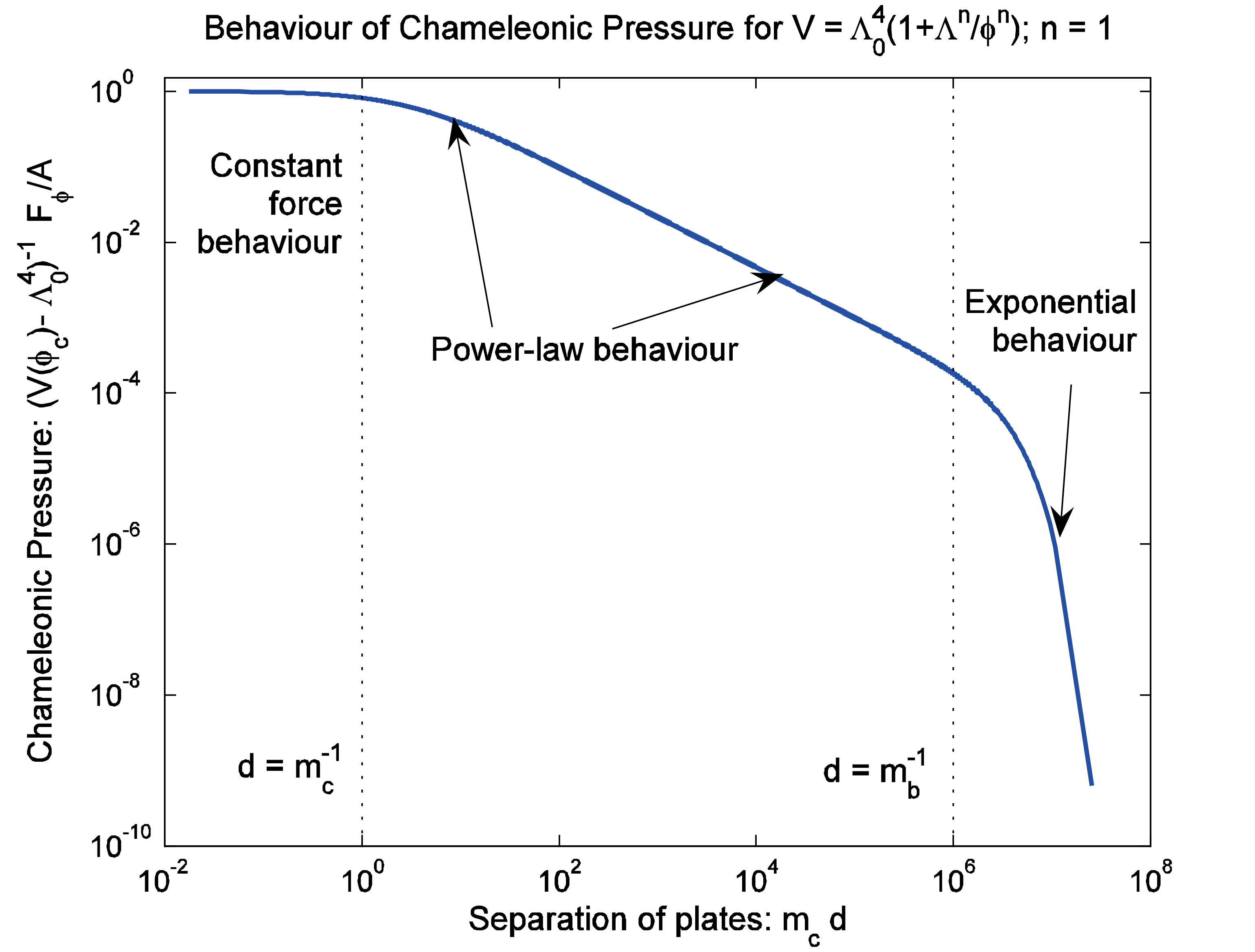
Mass in the plates → $$m_c^{-1} \leq d \leq m_b^{-1}$$ ← Mass in the cavity

- The force is algebraic:

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

- Dark energy sets a typical scale:

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



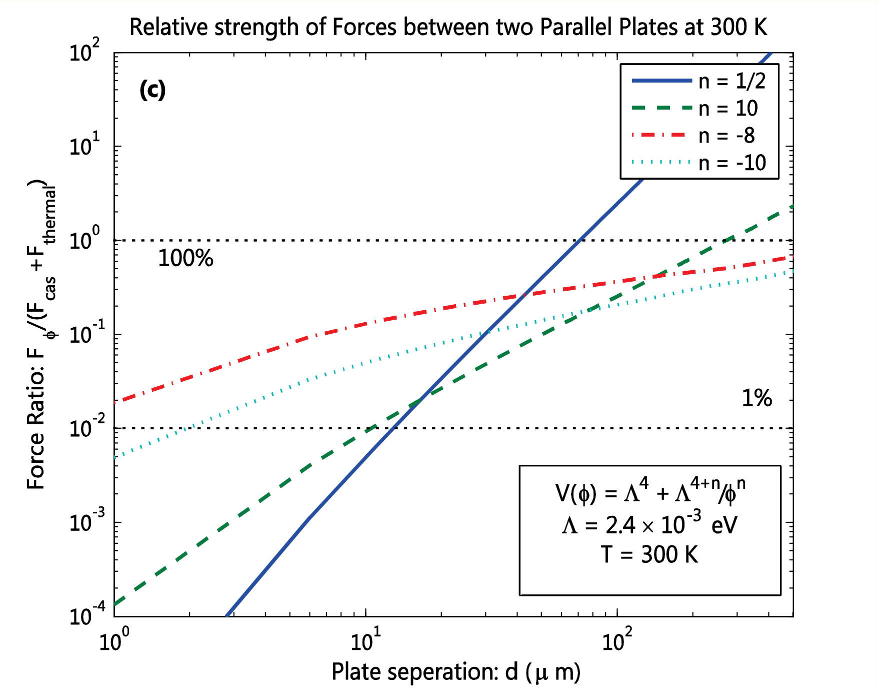
Ph. Brax , C. van de Bruck, A. C. Davis , D. Mota and D. Shaw, Phys.Rev.D76:124034,2007

Detectability

- The Casimir forces is also an algebraic law implying:

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

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



From 100 nm to the edge of the Universe with Casimir force experiments

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(Dated: September 28, 2010)

The first part of the talk will be focused on the description of the Amsterdam Casimir force setup. After an in depth introduction on the measurement method, I will use a few examples extracted from our most recent works to illustrate the possibility offered by our setup as well as its limitations.

In the second part of the talk I will present a new approach to explore the existence of chameleon fields in table-top Casimir-like experiments. The idea is to bring two metallic plates at a separation of a few tens of microns and then measure the force between them as a function of the density of a gas allowed in the gap. At low densities, chameleons are nearly massless, giving rise to an attractive force. This force, however, can not be detected via direct measurements, as it is largely dominated by other interaction mechanisms. At higher gas densities, however, chameleons become heavier and the force that they generate becomes much weaker. One can show that the change of the chameleon force is then larger than the change of any other force. A precise comparison of the experimental results at low and high gas densities should thus allow one to claim whether the chameleon force has decreased with the increase of the gas density, and, therefore, whether chameleons exist or not.

500 kE granted to carry out experiments in Amsterdam over the next 4 years.

Conclusions

- Dark energy?

- Locally, Newtonian gravity must be restored: chameleon effects. Possible violation of the equivalence principle seen by satellite experiments.

- Like dark matter, dark energy should be tested in laboratory experiments through the coupling to photons and matter.