



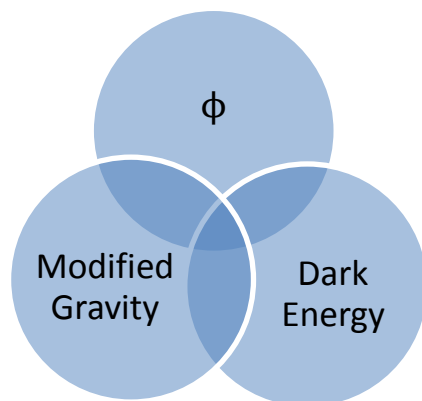
*IPhT
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Dark Energy and Experimental Tests

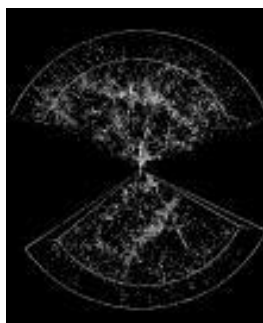
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The acceleration of the Universe could be due to the presence of a new type of matter, whose presence would manifest itself as **both dark energy** and **a modification of gravity**:



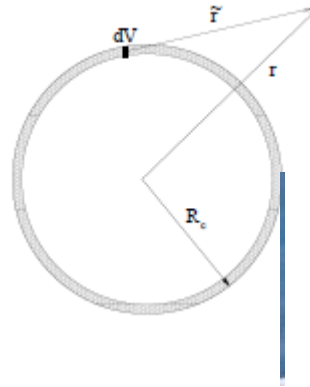
Its impact on cosmological scales implies the existence of a new long range force modifying the dynamics of gravity.



SCREENING

Mechanisms whereby nearly massless scalars evade local gravitational tests

Three mechanisms of screening have been uncovered. The simplest one: the chameleon effect.




Inside a dense body, the range of the new force is so small that no force emanates from the body: the new force is screened.



The range of the new force is extremely small in matter and very large in vacuum. This is the environment dependence of chameleons.

This mechanism is present for certain scalar-tensor theories:

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



Interaction potential

Coupling between
scalar and matter

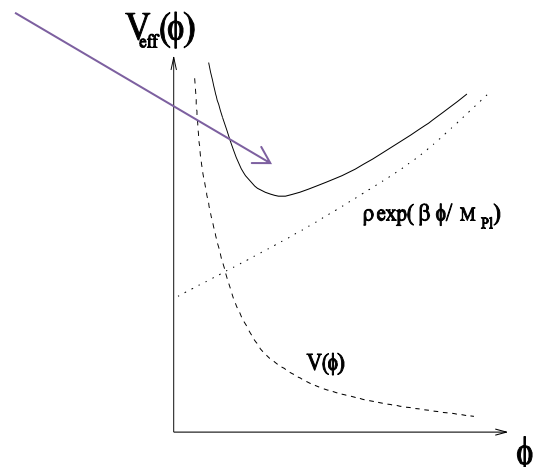
The effect of the environment

Due the coupling to matter, normalised scalar fields have a **matter dependent effective potential**

$$V_{eff}(\phi) = V(\phi) + \rho_m(A(\phi) - 1)$$

Environment dependent
minimum

$$\beta(\phi) = m_{Pl} \frac{d \ln A(\phi)}{d\phi}$$

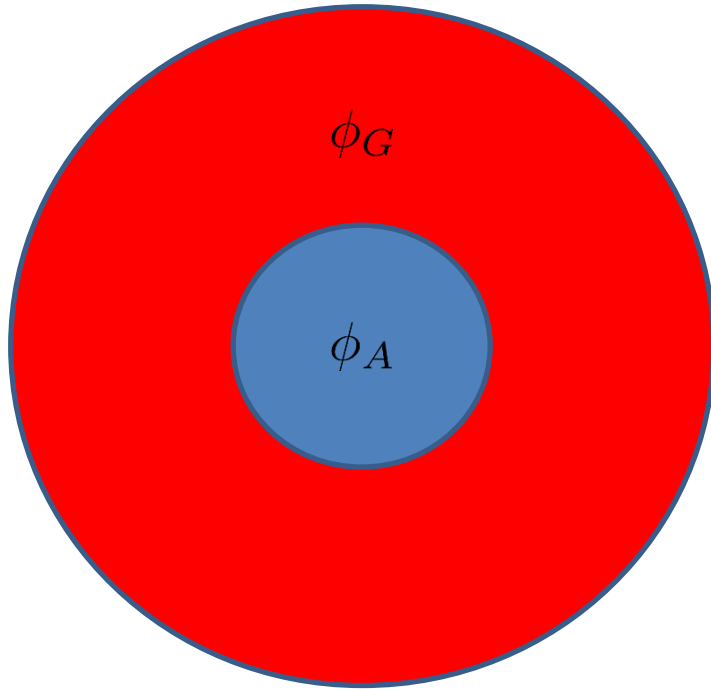


$$V(\phi) \sim \frac{\Lambda^{4+n}}{\phi^n}$$

Chameleon

Chameleons:

The screening criterion for an object **BLUE** embedded in a larger region **RED** expresses the fact that the Newtonian potential of an object must be larger than the variation of the field:



Scalar charge: $Q_A = \frac{|\phi_G - \phi_A|}{2m_{\text{Pl}}\Phi_A}$

$$Q_A \leq \beta_G$$

Self screening: large Newton potential

Blanket screening: due to the environment G

Φ_A Newton's potential at the surface

Other mechanisms involve non-linear properties of the kinetic terms in the scalar field Lagrangian:

Effective Newtonian potential:

$$\Psi = \left(1 + \frac{2\beta^2(\phi)}{Z(\phi)}\right)\Phi_N$$

For theories with second order eom:

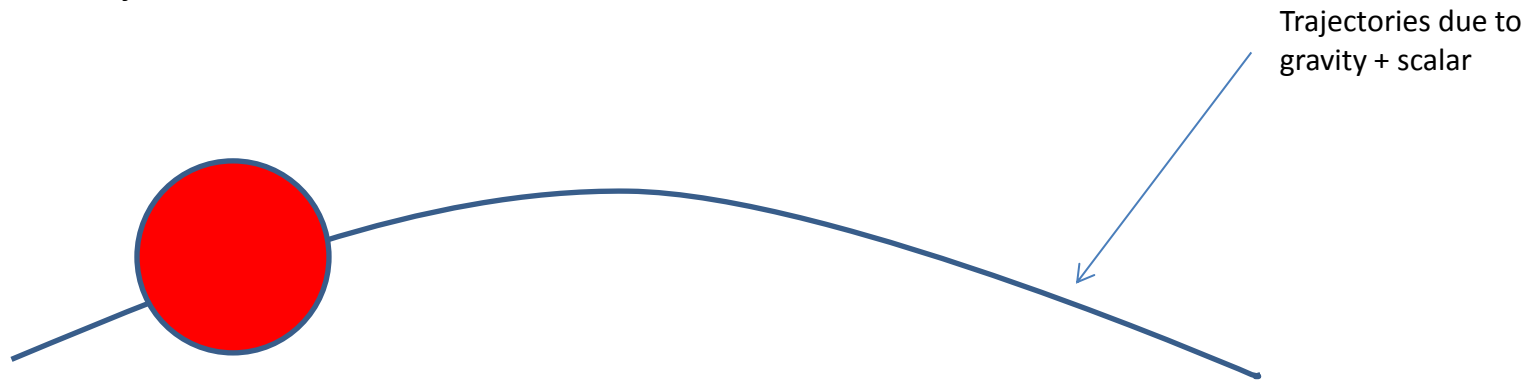
$$Z(\phi) = 1 + a(\phi)L^2 \frac{D^\mu D_\mu \phi}{m_{\text{Pl}}^2} + b(\phi) \frac{(\partial\phi)^2}{M^4} + \dots$$

Vainshtein

K-mouflage

$$M^4 \sim 3H_0^2 m_{\text{Pl}}^2, \quad L \sim H_0^{-1}$$

The motion of objects in all such theories:



$$\ddot{\mathbf{X}} = -\nabla\Phi_N - Q\nabla\phi_{\text{ext}}$$

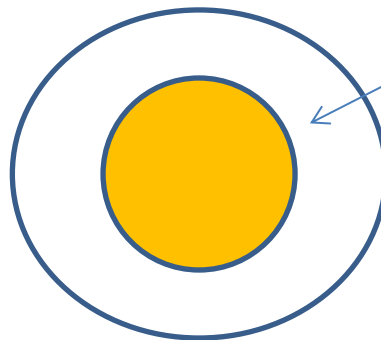
Chameleons: $Q \ll \beta$

Unlike chameleons, K-mouflage and Vainshtein do not affect the charge Q :

$$Q = \beta$$



Outside the screening radius, the object feels the scalar force



$$\nabla\phi_{\text{ext}} \ll 2\beta\nabla\Phi_N$$

$$\nabla\phi_{\text{ext}} = 2\beta\nabla\Phi_N \text{ outside the screening radius}$$

Laboratory Tests ??

Only the chameleon mechanism can be tested in the laboratory. For K-mouflage and Vainshtein, too much suppression deep inside the screening radius.

What can be tested is the scalar interaction between macroscopic bodies or between one macroscopic body and a particle.

Casimir Effect

Eotwash experiment



Bouncing Neutrons

Neutron Interferometry



All these tests are insensitive to a cosmological constant. In fact they only probe the screening mechanisms.

Two typical classes of models:

$3/2 < r < 3$ inverse power law chameleons.

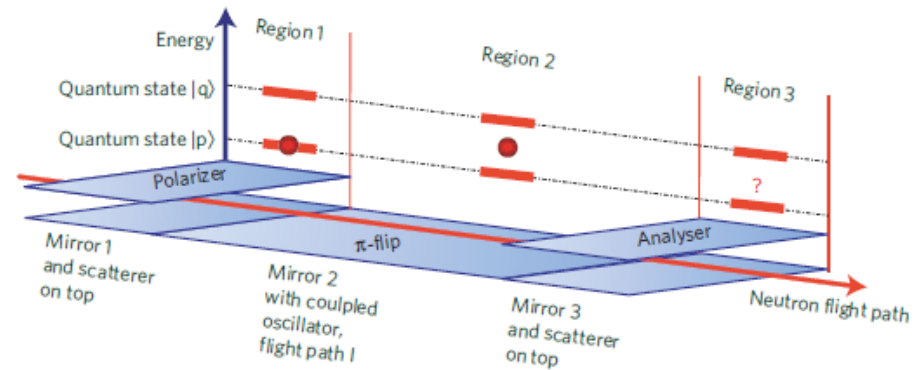
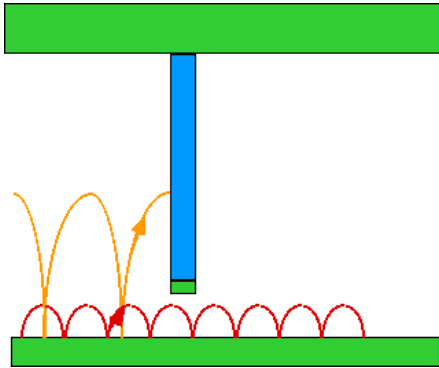
$$m(\rho) \sim \rho^{r/3}$$

$r > 3$ large curvature $f(R)$ models.

Only inverse power law chameleons can be efficiently tested in the laboratory.

$$n = \frac{6 - 2r}{2r - 3}$$

Bouncing Neutrons



Ultra cold neutrons from a nuclear reactor fly over a mirror in the terrestrial gravitational fields. Their energy levels are quantised with wave functions of extension a few microns (measured at ILL Grenoble (2002)). Sensitive to new interactions.

Dark energy scale:

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

neutron



mirror



$$\Phi = mgz + \beta \frac{m}{m_{\text{Pl}}} \Lambda \left(\frac{2+n}{\sqrt{2}} \Lambda z \right)^{2/(n+2)}$$

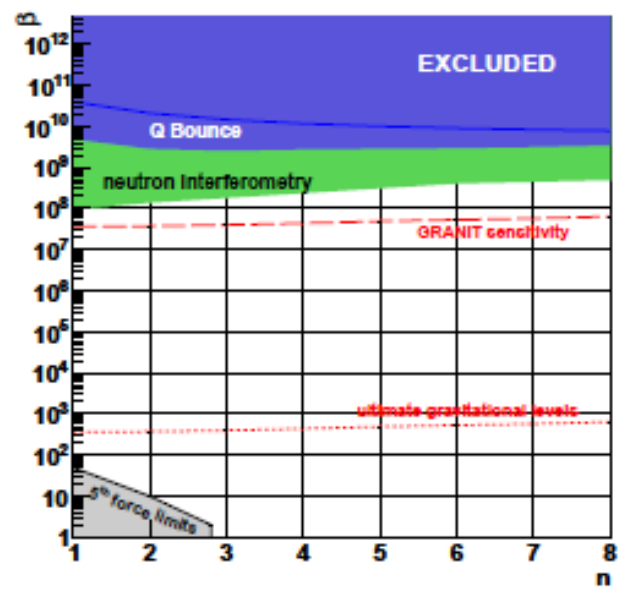
The chameleonic potential above the mirror perturbs the neutron energy levels:

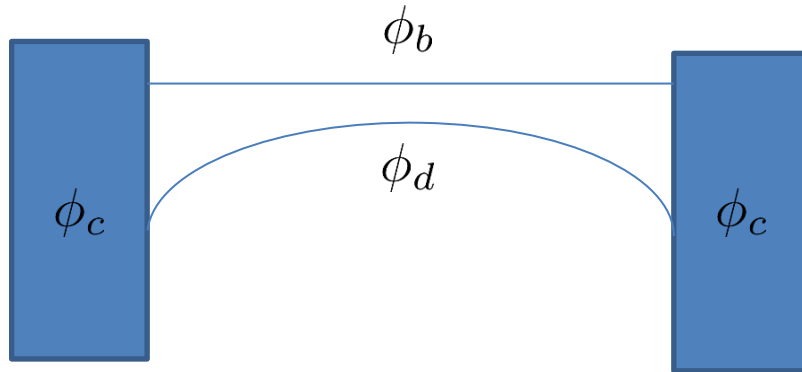
.

$$\left(-\frac{\nabla^2}{2m} + \Phi \right) \psi = E\psi$$

Perturbed eigenvalues due to the presence of the chameleon

Chameleons shift the energy levels of the neutrons (see T. Jenke's talk).
Strong dependence on the coupling constant β .





As long as the two boundary plates are screened, the scalar interaction between the plates is essentially independent of β .

$$\frac{\Delta F_\phi}{A} = V_{\text{eff}}(\phi_b) - V_{\text{eff}}(\phi_d)$$

The scalar pressure is dependent on the density between the plates. When the density increases, the scalar pressure decreases giving an experimental way of testing the chameleon mechanism.

Eotwash experiment

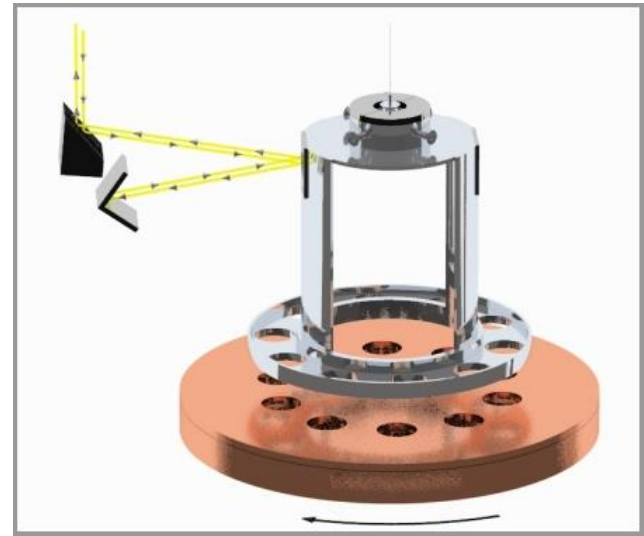
Measurement of the torque between two plaques with holes. The potential energy of the system due to a chameleon force between the plates is simply the work

$$W = A_\theta \int_d^\infty dx \frac{\Delta F_\phi}{A}(x)$$

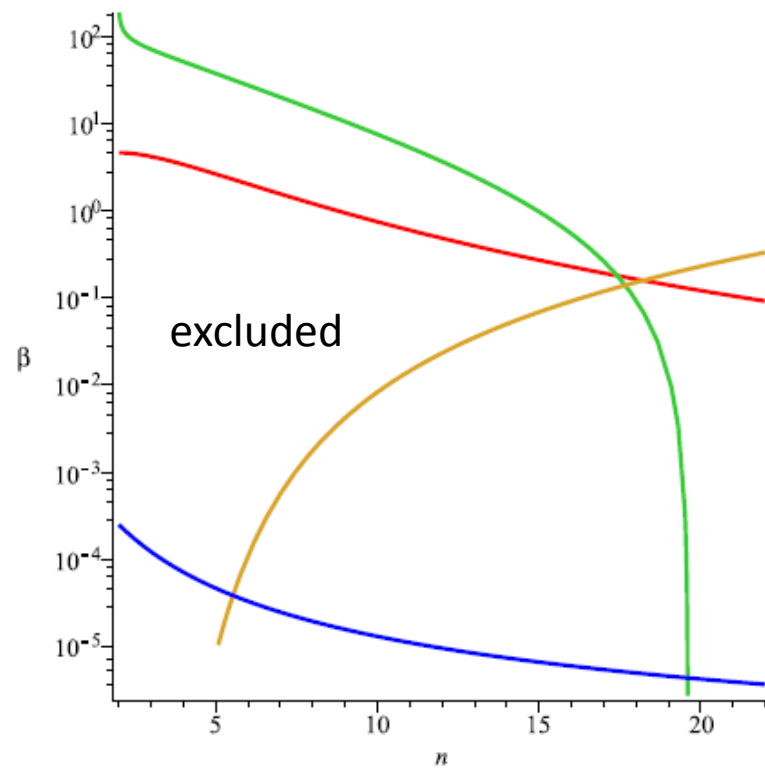
The torque between the plates can be approximated:

$$T = a_T e^{-m_c d_s} \int_d^\infty dx \frac{\Delta F_\phi}{A}(x)$$

Electrostatic shielding

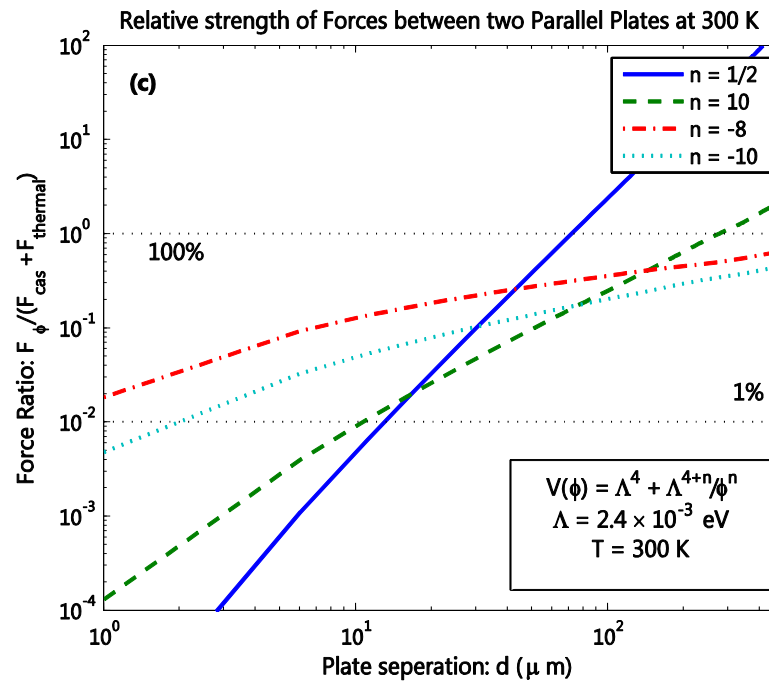


$$a_T = \frac{dA}{d\theta}$$



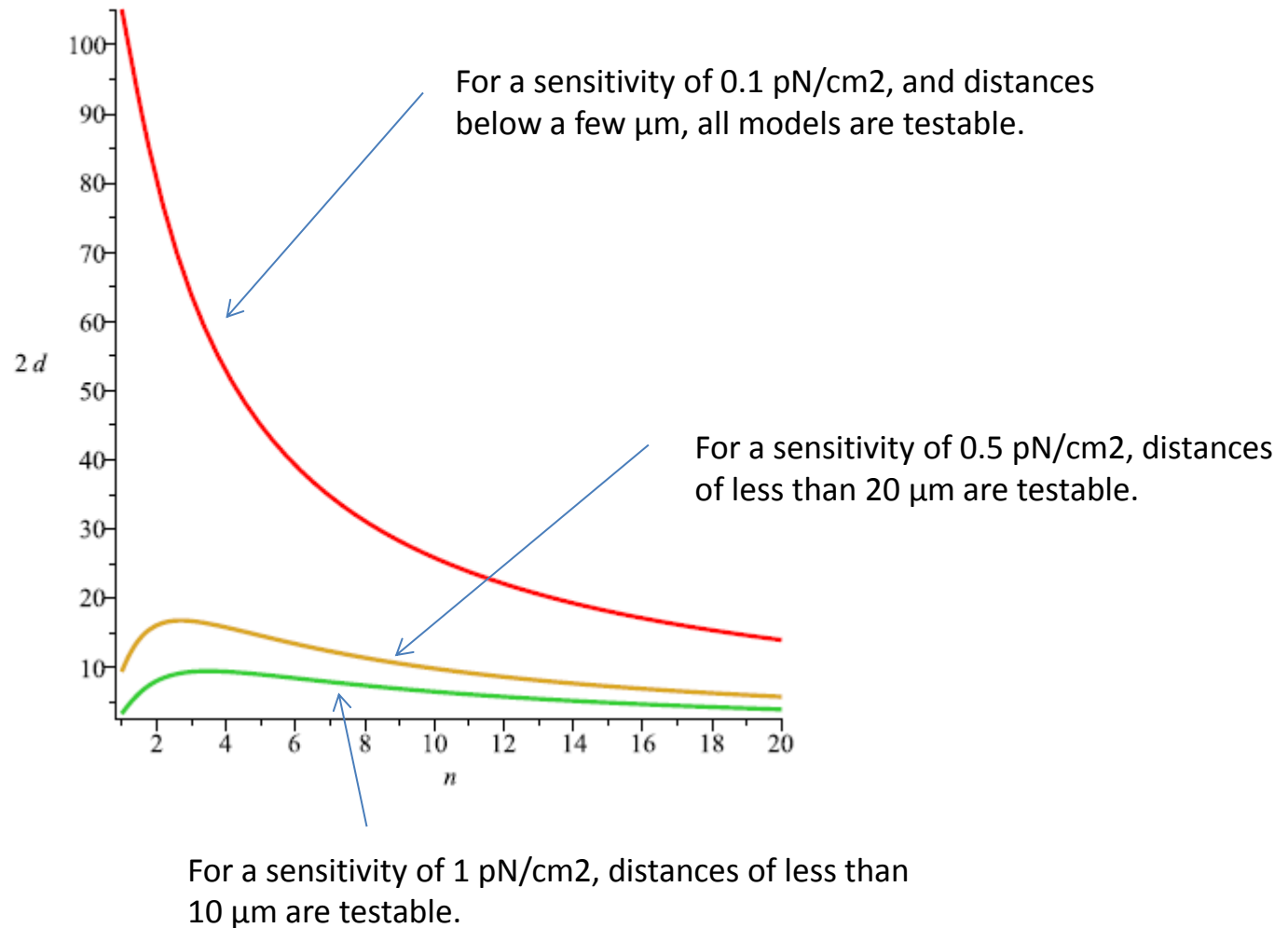
Casimir experiments

The force is algebraic and becomes of the order of electromagnetic Casimir force for large enough separations:

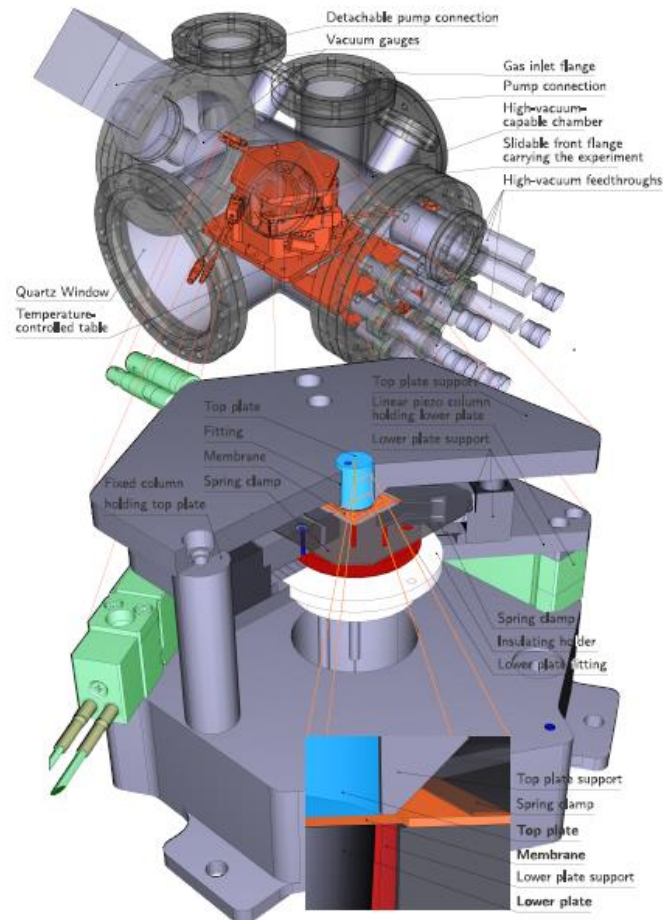


$$\frac{F_\phi}{A} \sim \Lambda^4 (\Lambda d)^{-\frac{2n}{n+2}}$$

In particular, one may ask oneself what would be the smallest distance from which one could detect the scalar interaction for a given experimental sensitivity.



CANNEX experiment in Amsterdam is currently testing Casimir at distances around $10\mu\text{m}$ with a sensitivity of 1 pN/cm^2 The chameleon pressure and the chameleon mechanism are on the verge of being tested.



<http://cannex.vu.nl>

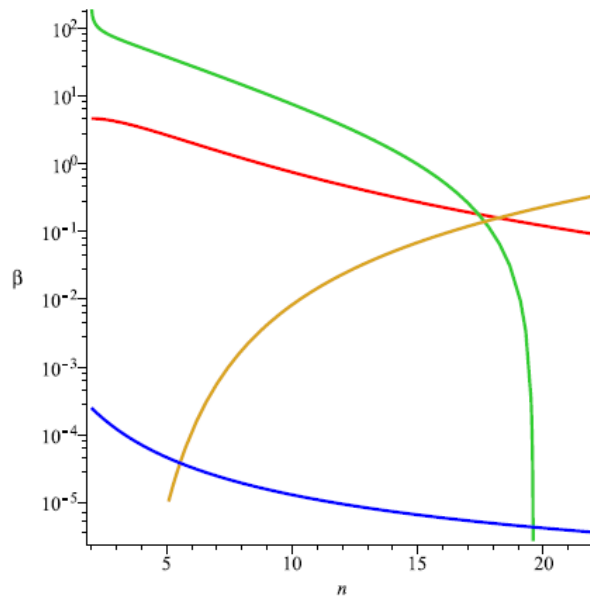
Conclusions

Modified gravity is intimately linked to dark energy: nearly massless degree of freedom. These scalar fields must be screened. Many interesting cosmological consequences (see K. Koyama's talk).

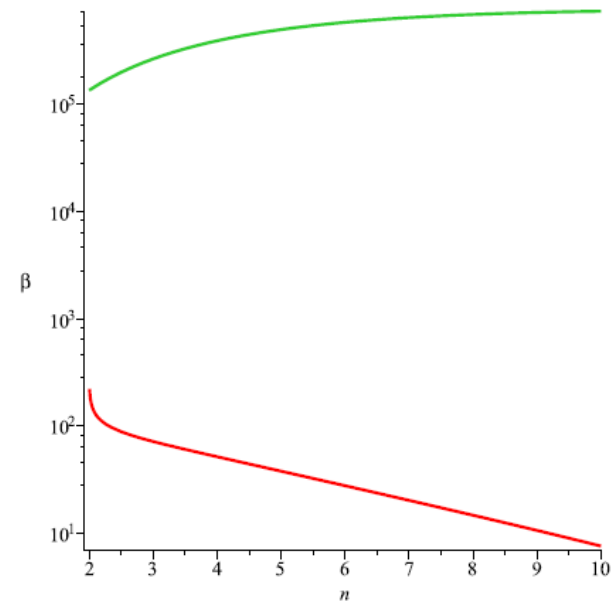
Only one of the three screening mechanisms, chameleons, is testable in the laboratory.

Eotwash (low β) and Neutron levels (high β) have bounded the parameter space of chameleons. Casimir experiments have the potential to close down the parameter space of chameleons altogether (or discover them...) in the near future.

When the coupling is too large (above the red curve), the theory is not calculable anymore as it becomes strongly coupled in the boundary plates.



In fact, for even larger values of the coupling (above the green curve), the background scalar field is not homogeneous anymore and in this strong coupling phase, quantum corrections are small.



The new field configuration around each atom of the boundary plates. On average away from the atoms, the field becomes very different from its homogeneous value (in fact between the atoms the field forms a bubble similar to the one between two plates but on much smaller scales). In this configuration, quantum corrections are negligible.

