Testing Modified Gravity with Neutrons

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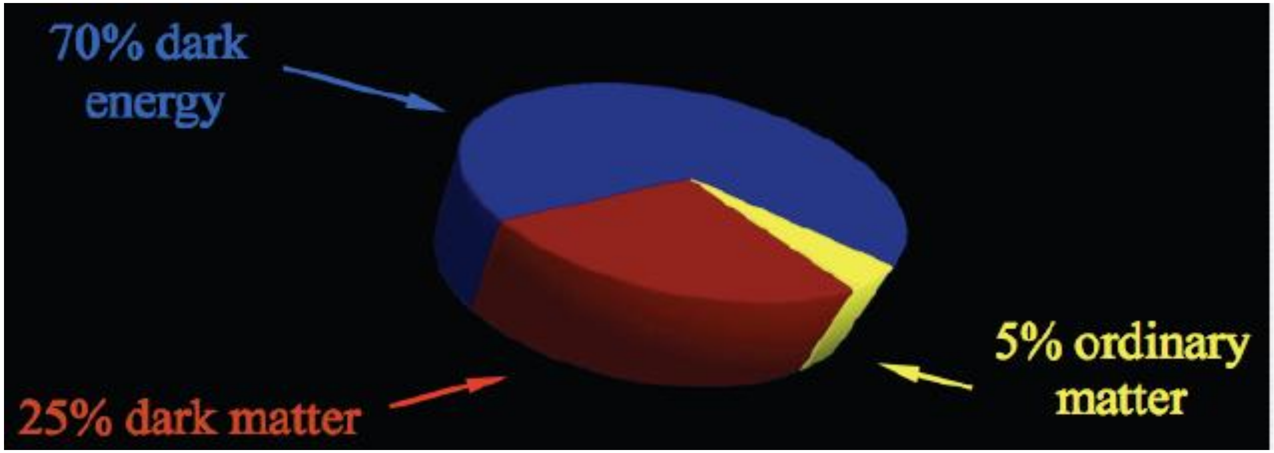
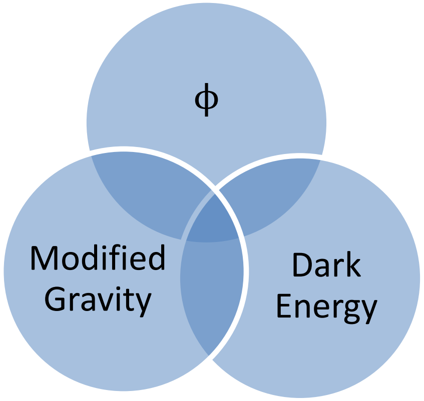
« Microscope» workshop3, November 2014

The Big Puzzle

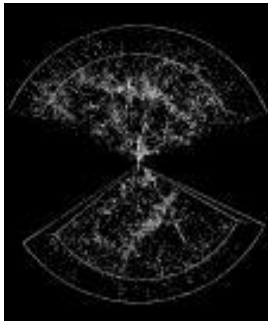


The acceleration of the Universe could be due to either:



In both cases, current models use scalar fields. In modified gravity models, this is due to the scalar polarisation of a massive graviton (5=2+2+1). In dark energy, it is by analogy with inflation.

The fact that the scalar field acts on cosmological scales implies that its mass must be large compared to solar system scales.



Modified Gravity

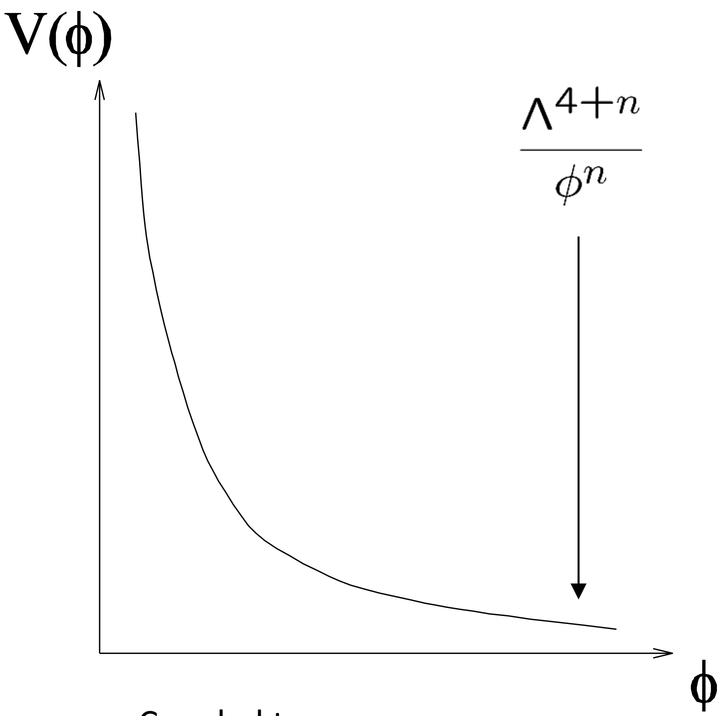
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + V(\phi)$$

$$\Phi = \Phi_N + \frac{\beta}{m_{\rm Pl}}\phi$$

Effective gravitational potential

Newtonian potential

Scalar coupled to matter with coupling strength β



Field rolling down a runaway potential, reaching large values now. Coupled to baryons, this modifies gravity due to the existence of a long range fifth force whose range is of the size of the observable Universe.

Deviations from Newton's law are parametrised by:

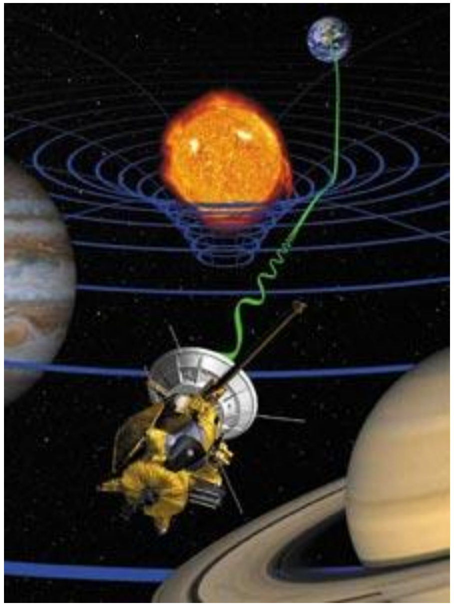
$$\phi_N = -\frac{G_N}{r}(1 + 2\beta^2 e^{-r/\lambda})$$

For fields of zero mass or of the order of the Hubble rate now, the tightest constraint on β comes from the Cassini probe measuring the Shapiro effect (time delay):

$$\beta^2 \leq 1.210^{-5}$$

The effect of a long range scalar field must be screened in the solar system to comply with this bound and preserve effects on cosmological scales.

Despite this screening effects, neutrons can be sensitive to the new scalar interaction.

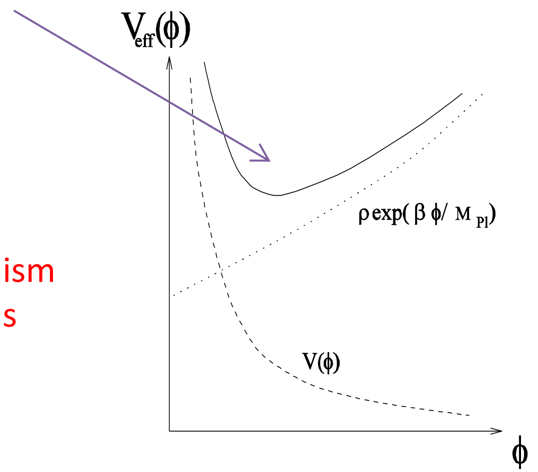


The effect of the environment

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

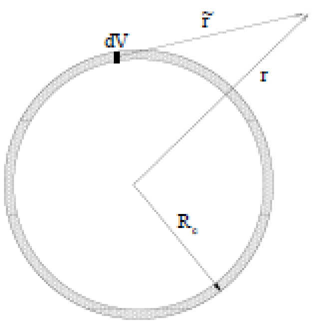
$$V_{eff}(\phi) = V(\phi) + \rho_m (A(\phi) - 1)$$

Environment dependent minimum



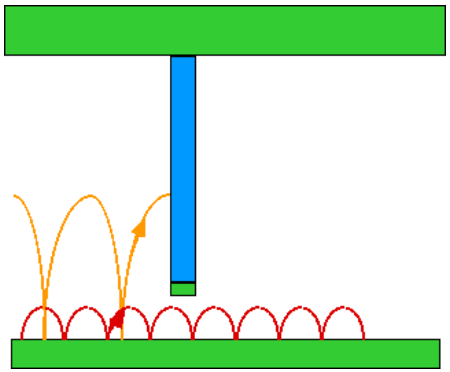
Chameleon mechanism tested with neutrons

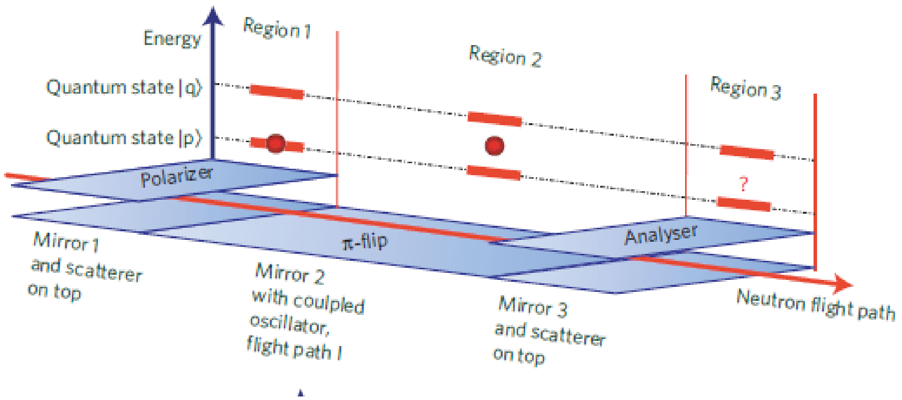
Chameleon=constant coupling



The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.

Bouncing Neutrons

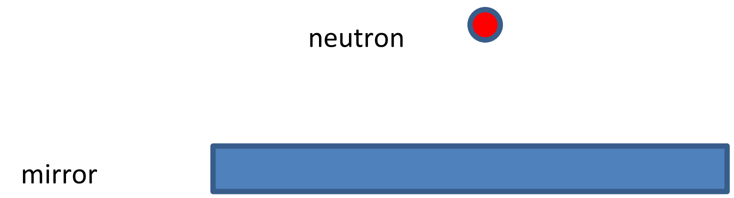




Ultra cold neutrons from a nuclear reactor fly over a mirror in the terrestrial gravitational fields. Their energy levels are quantised with Airy wave functions of extension a few microns (measured at ILL Grenoble (2002)). Perturbations by periodic magnetic fields induce a transition between two level states, hence a measurement of the energy level difference by observations of Rabi oscillations (Granit).

Dark energy scale:

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



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

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

As the extension of the unperturbed wave functions is not dissimilar from the dark energy scale, this sets limits on the coupling of chameleons to matter.

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

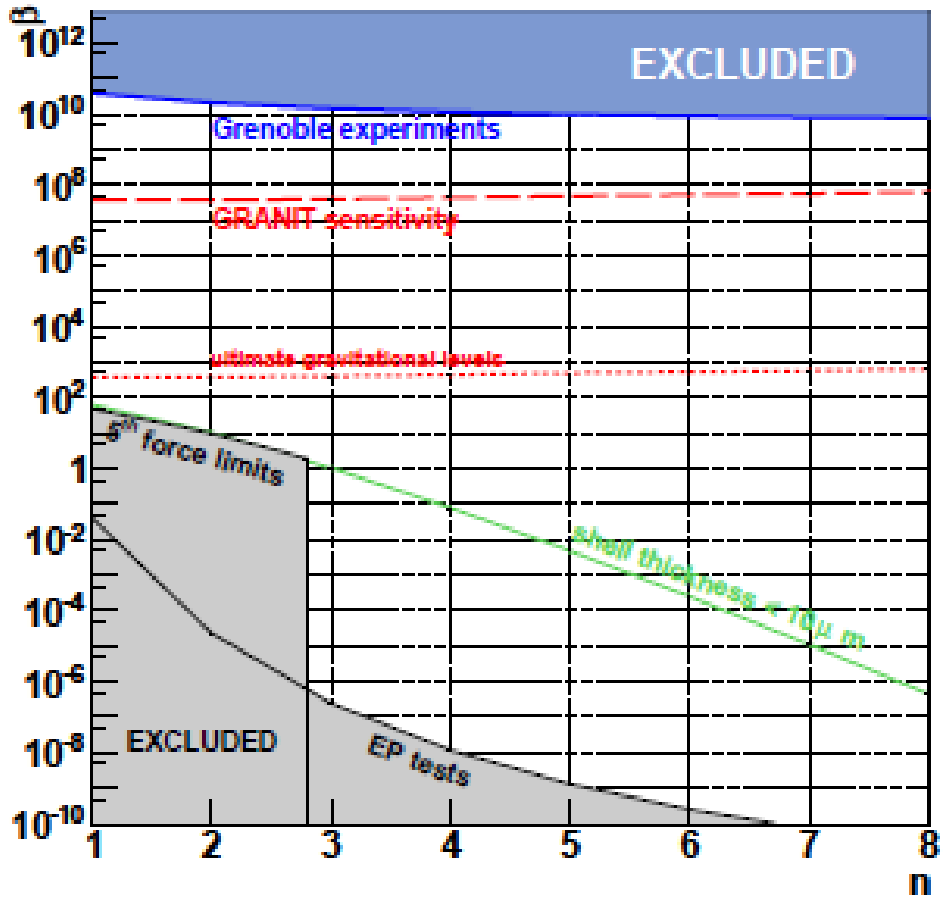
Chameleons shift the energy levels of the neutrons

Perturbed eigenvalues due to the presence of the chameleon

Coupling to matter constrained almost independently of n.

The difference between the 1 and 3 energy levels will be measured at the 0.01 peV level in the future.

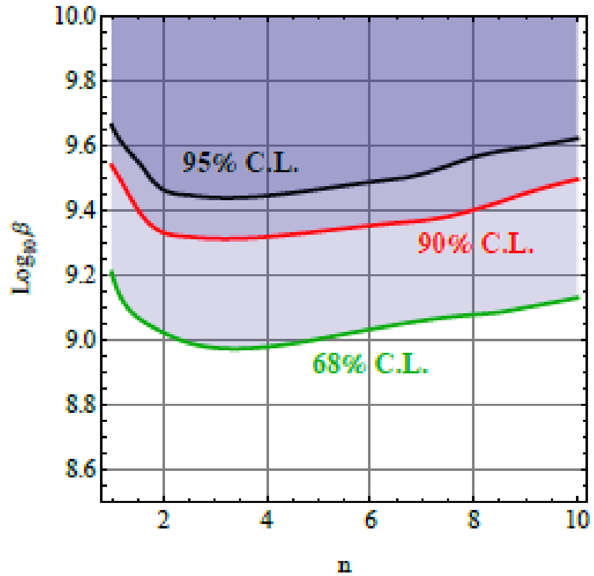
Coupling to matter



Ph.B,G. Pignol (2011)

Inverse power law potential

One order of magnitude lower than
expected GRANIT sensitivity.

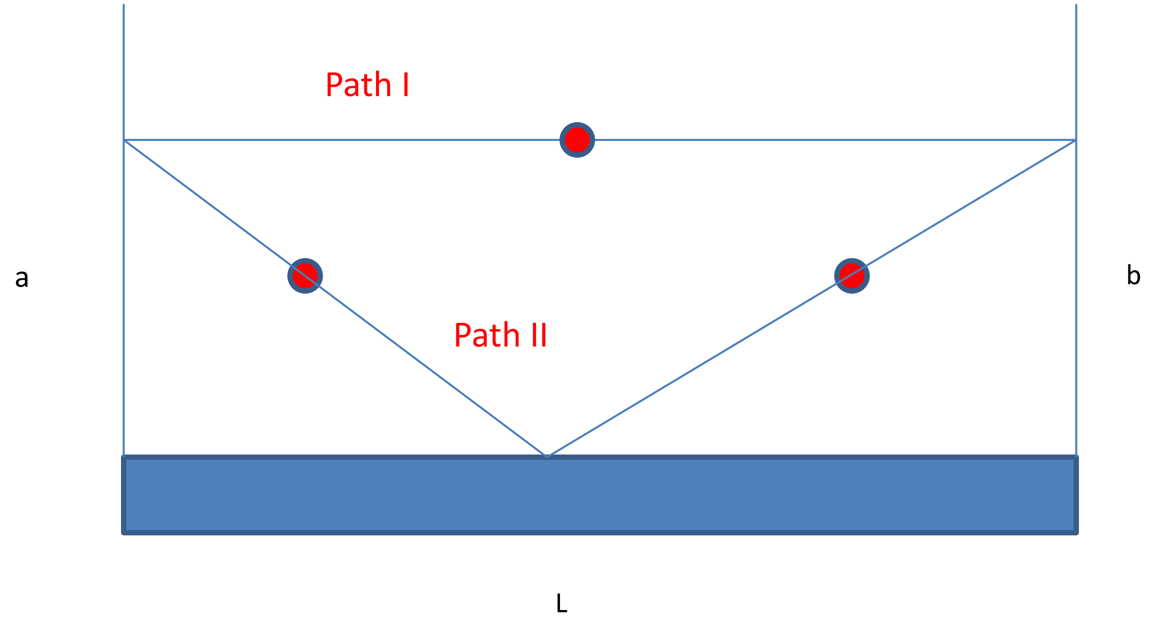


T. Jenke et al. (2012)

Sensitivity: 10^{-14} eV

Transition between levels due to vibration. Levels 1 to 4 excited.

Lloyd's Interferometer



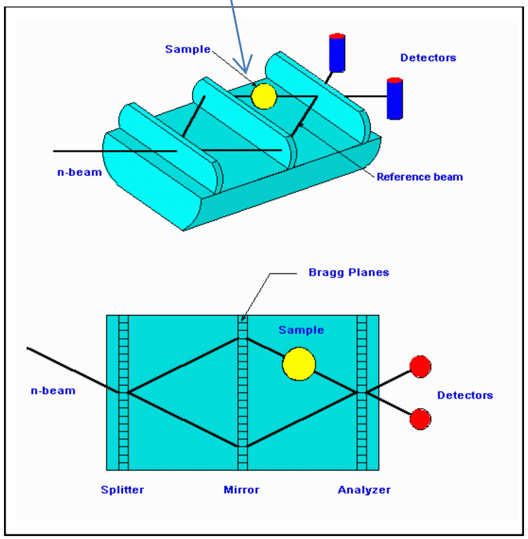
Due to the chameleon potential over the mirror, there is an additional phase shift between the two paths I and II

$$\delta\Phi_{I-II} = \int_{II} dl \frac{\beta}{m_{\rm Pl}} \frac{m^2\phi}{k} - \int_{I} dl \frac{\beta}{m_{\rm Pl}} \frac{m^2\phi}{k}$$

Neutron interferometry

Chameleon bubble

Brax-Pignol (2013).

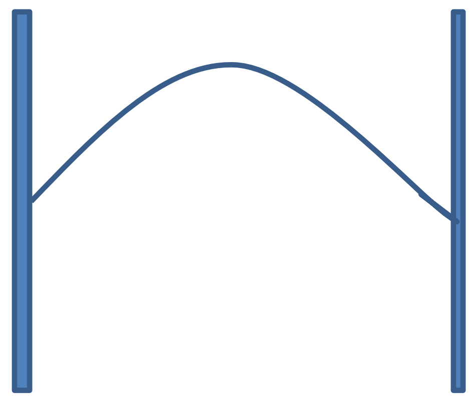


One of the beams traverses a chamber where the chameleon leads to a change of the phase

$$\delta\Phi = \int dx \frac{\beta}{m_{\rm Pl}} \frac{m^2\phi(x)}{k}$$

$$\delta\Phi \sim \beta \frac{m^2}{m_{\rm Pl} k} (d\Lambda)^{(4+n)/(2+n)}$$

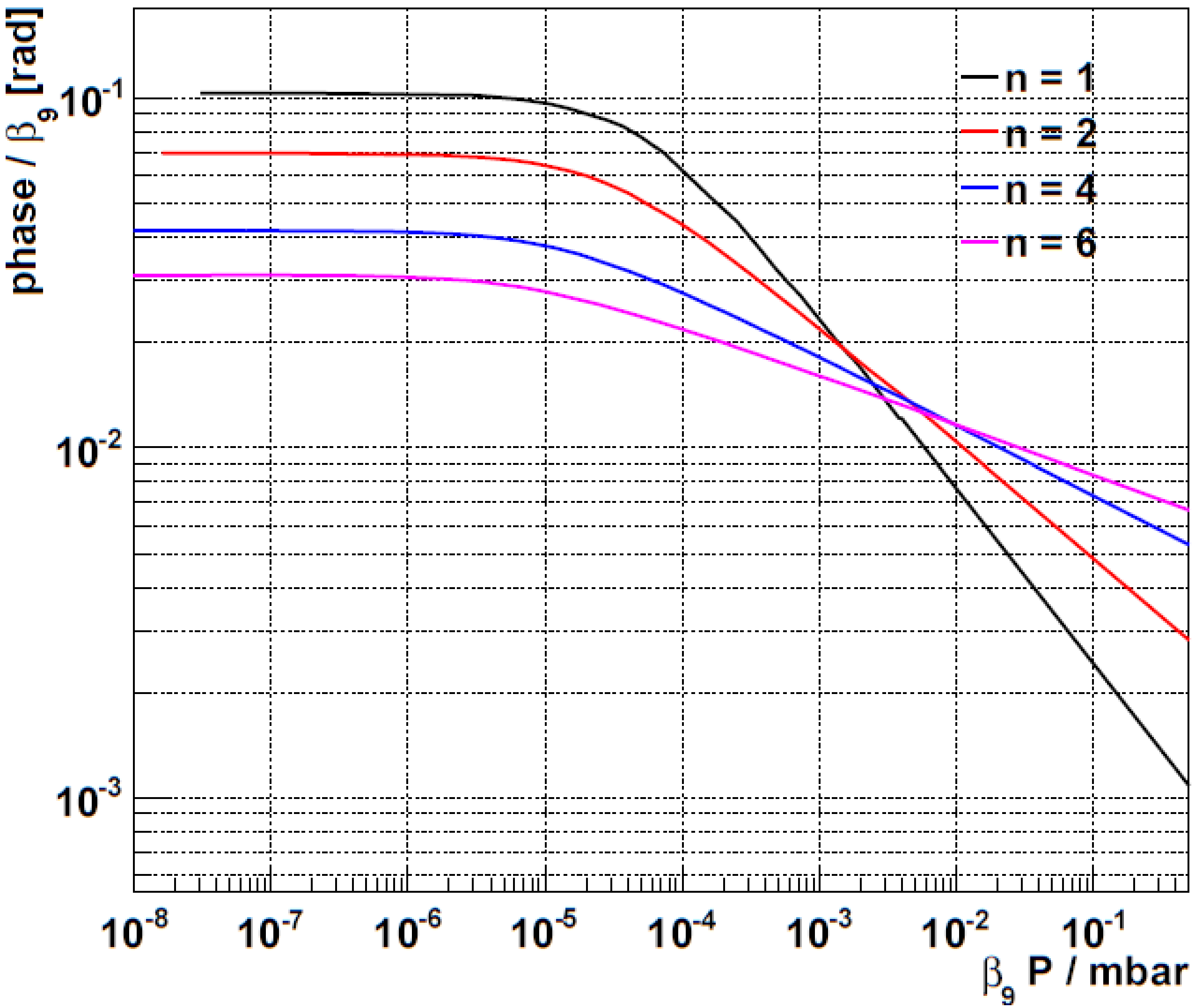
vacuum



Chameleon bubble

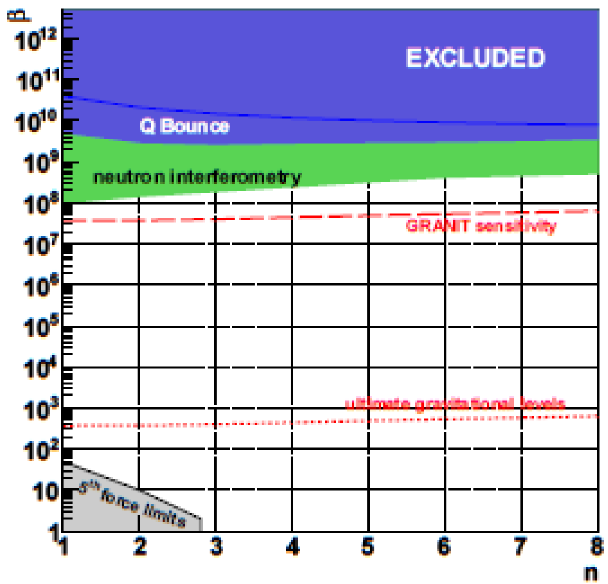
D=1 cm

λ=0.27 nm



$\beta = \beta_9 10^9$

Interferometry is competitive with current bouncing neutron experiments.



Interferometry vs GRANIT

Summary

Ultra cold neutrons test the existence of screened modified gravity: CHAMELEON MECHANISM

New tests (interferometry) have been proposed and tested.