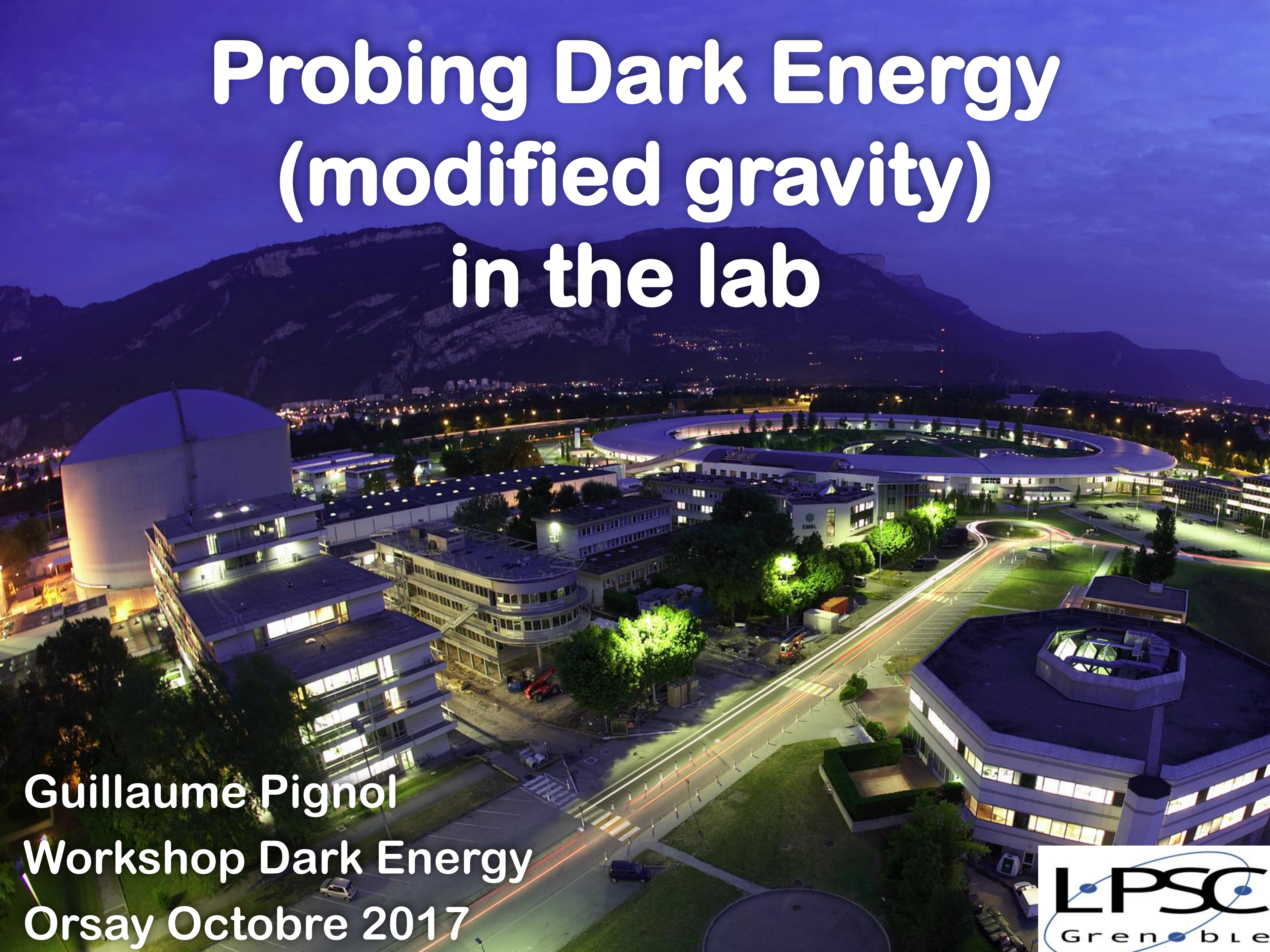


Probing Dark Energy (modified gravity) in the lab

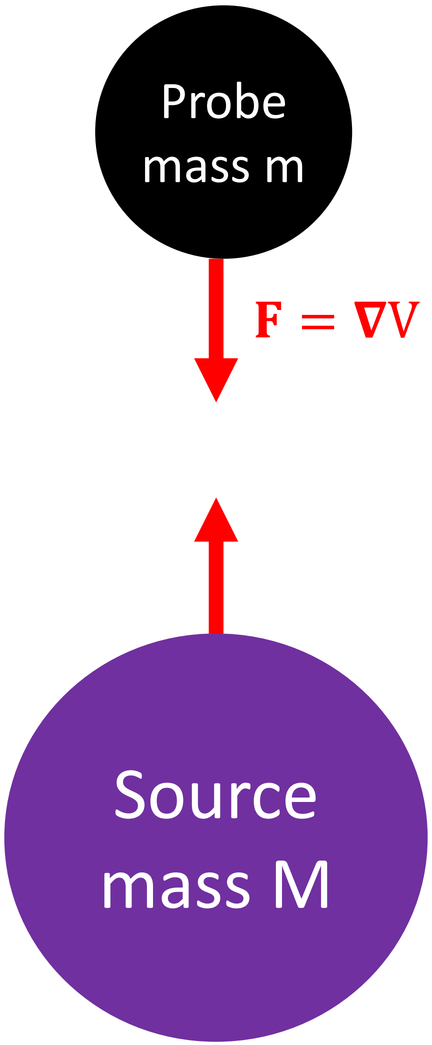
Guillaume Pignol

Workshop Dark Energy

Orsay Octobre 2017

LPSC Grenoble

Testing gravity at short distance



$$\mathrm{V}(r) = \frac{GMm}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

Normal Inverse square law

Hypothetical extra force

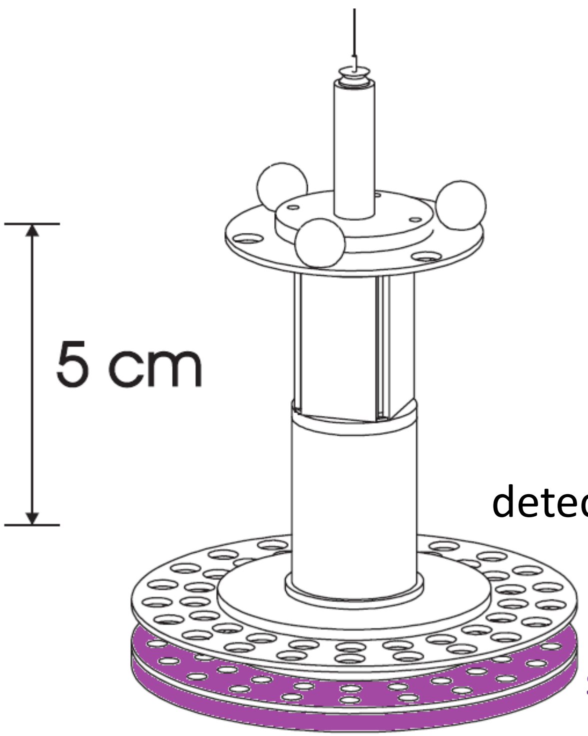
The extra force, of finite range λ, could be mediated by a new scalar particle of mass

$$\mu = \frac{\hbar c}{\lambda}$$

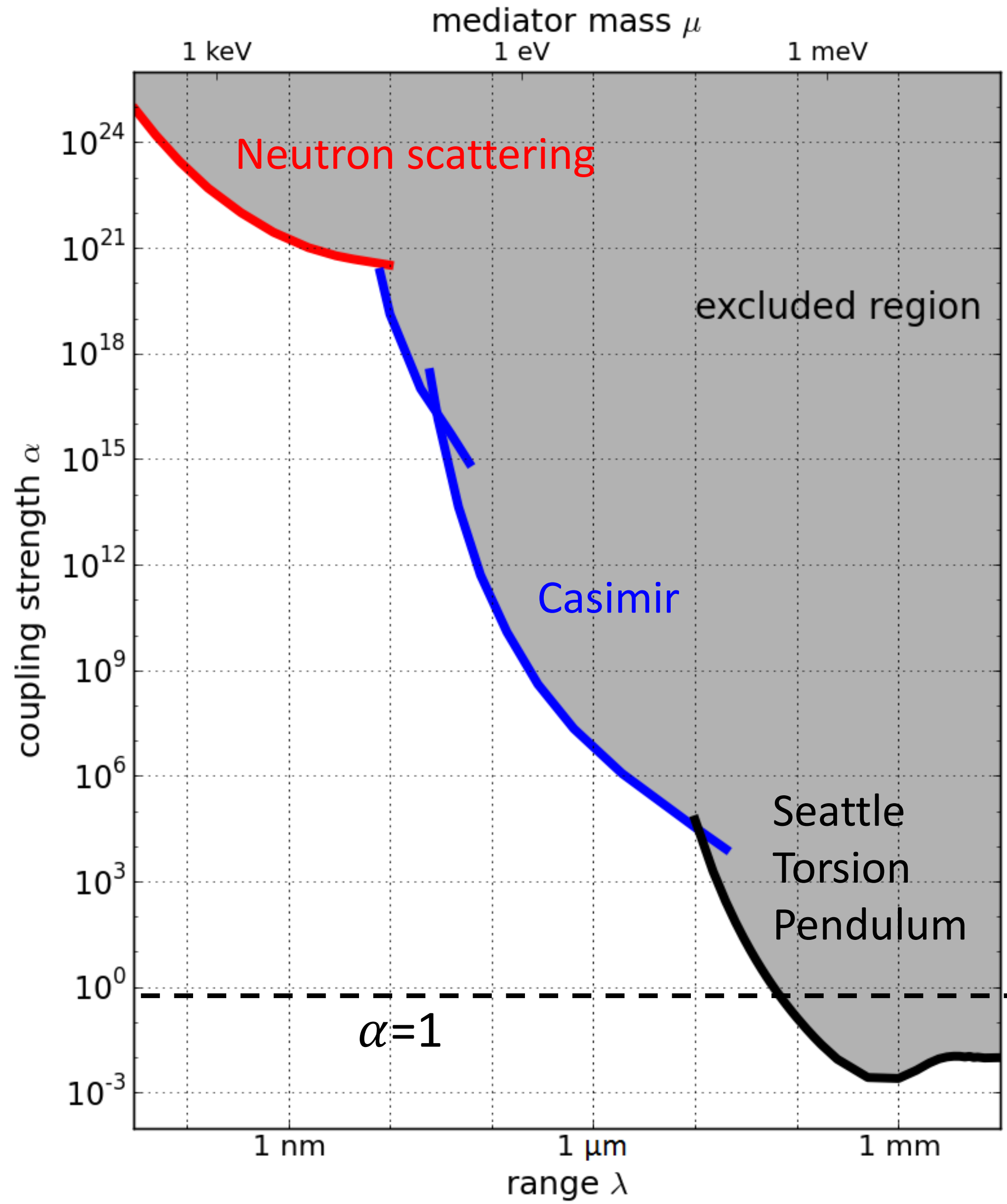
Search for new short range force

$$V_{\mathrm{Yukawa}}(r) = \alpha \frac{GMm}{r} e^{-r/\lambda}$$

Experiments are looking for this force, from subatomic to astrophysical scales



Seattle torsion pendulum experiment



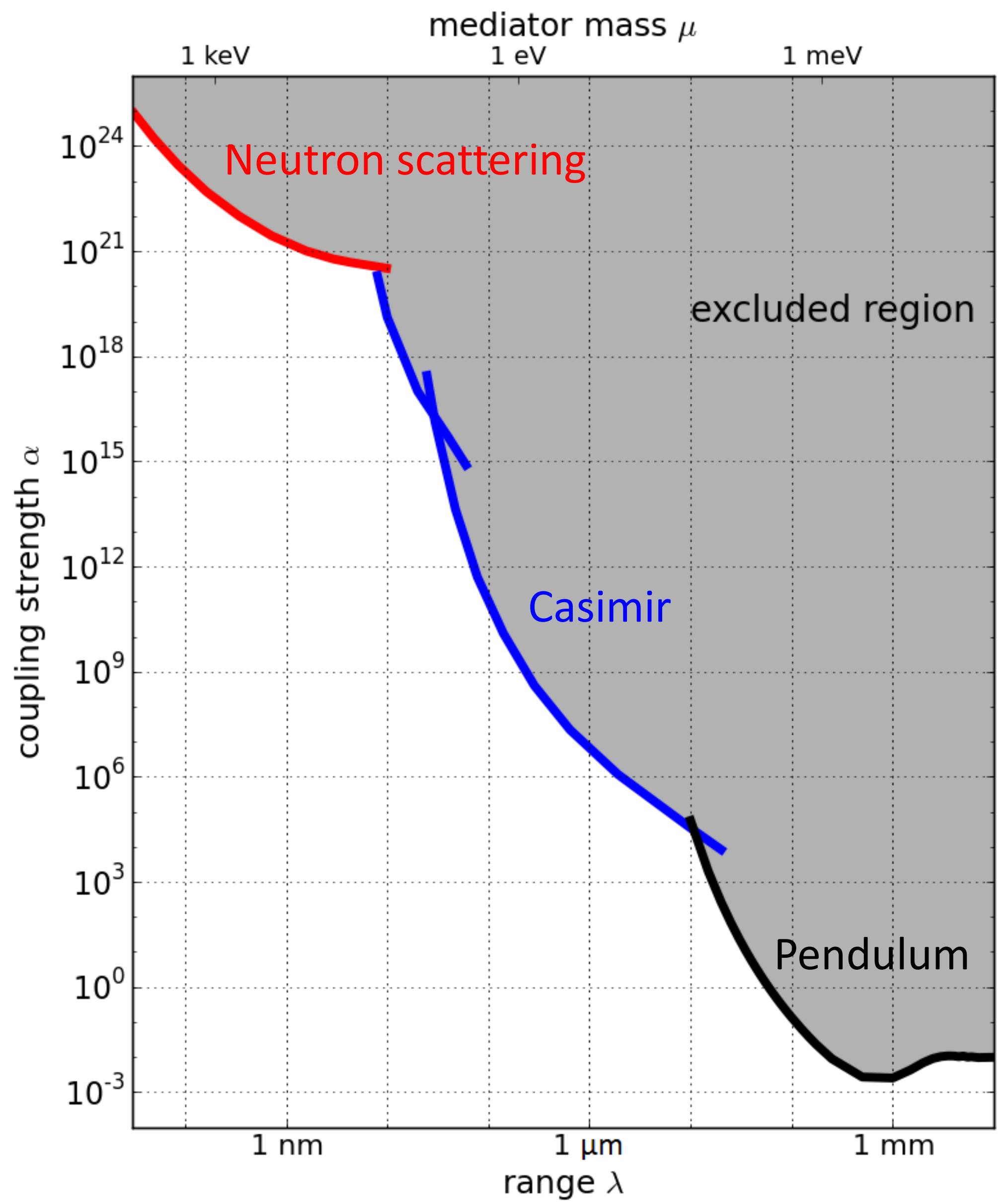
Fifth force searches

Limits valid for
unscreened fifth force
i.e. mediated by a field
governed by a **linear equation**

$$\Delta\varphi - \mu^2\varphi = \frac{\alpha\rho}{M_{\mathrm{Pl}}}$$

Derived from the Klein-Gordon potential:

$$\mathcal{V}(\varphi) = \frac{\mu^2}{2}\varphi^2 + \alpha\frac{\rho}{M_{\mathrm{Pl}}}\varphi$$



The chameleon mechanism

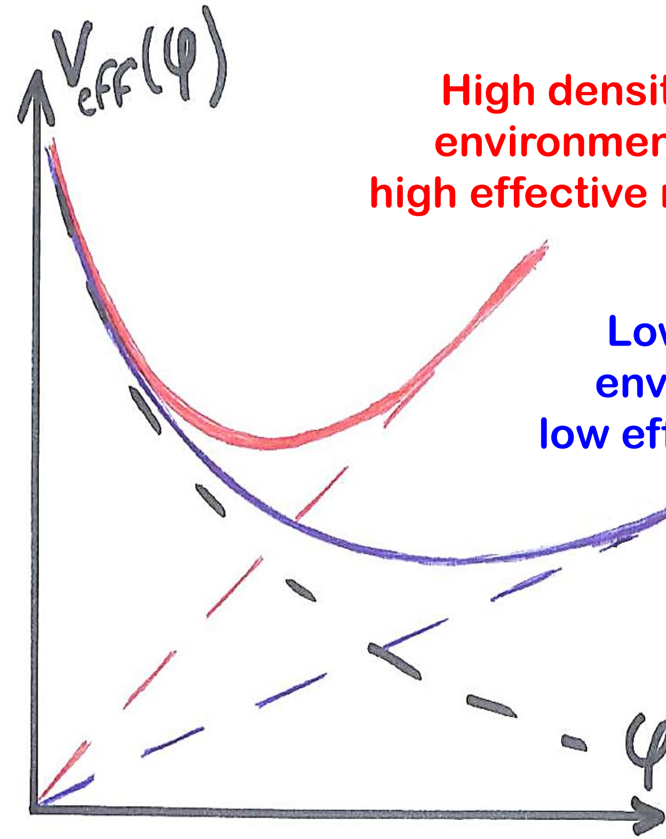
Quintessence field coupled with matter:

Khoury & Weltman PRD 69 (2004)

$$\mathcal{V}(\varphi) = \frac{\Lambda^{4+n}}{\varphi^n} + \beta \frac{\rho}{M_{\mathrm{Pl}}} \varphi$$

Anharmonic self-coupling

Coupling to matter

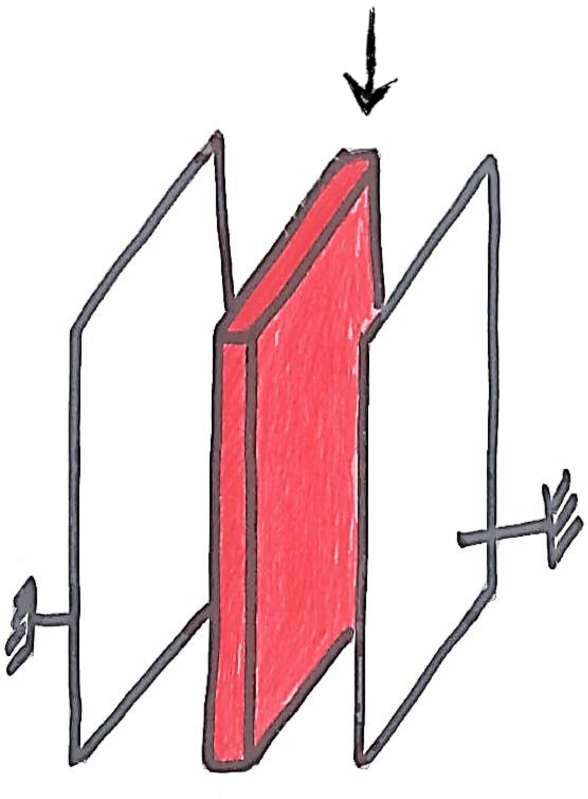


High density environment, high effective mass

Low density environment, low effective mass

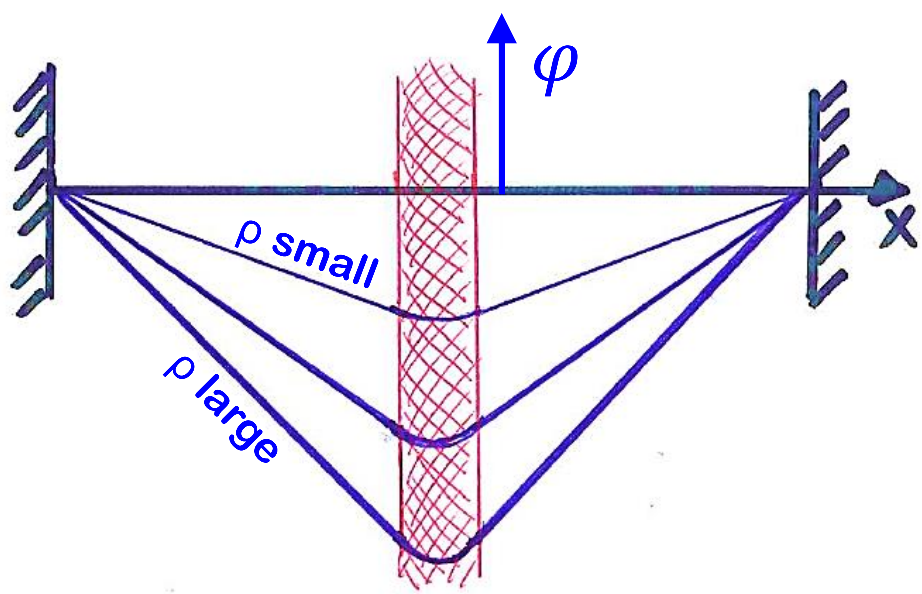
Understanding the chameleon mechanism

Plate with charge density ρ



Poisson equation for the electric potential

$$\Delta\varphi = \rho$$



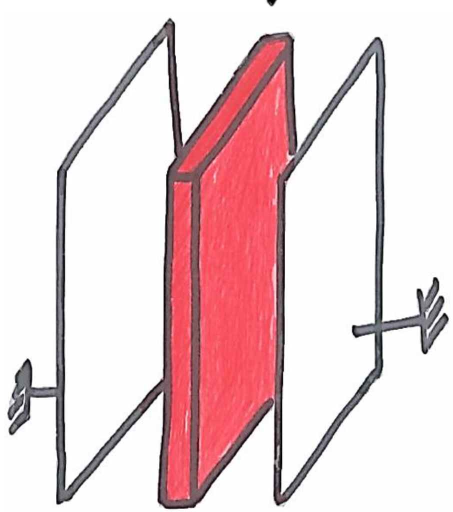
Electric field $\mathrm{d}\varphi/dx$ proportional to ρ

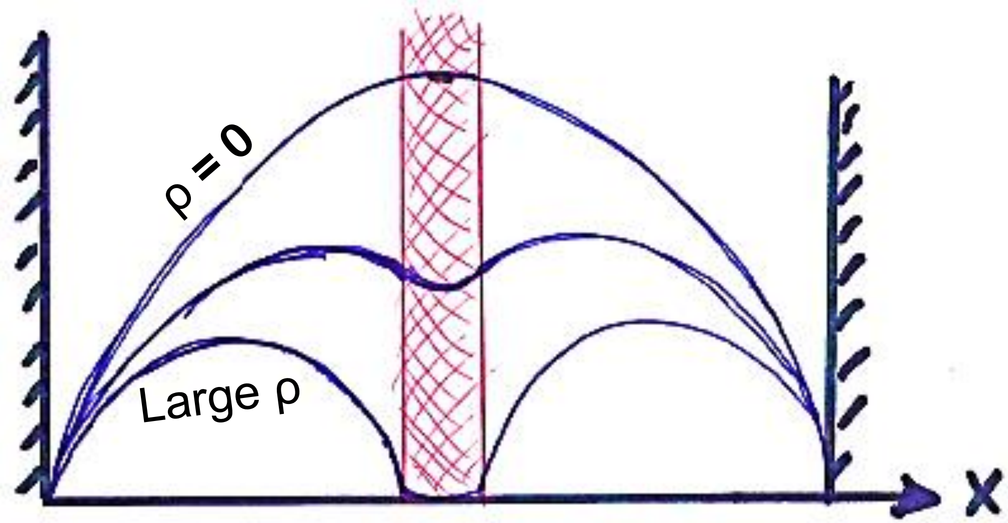
Understanding the chameleon mechanism

Nonlinear equation for the chameleon field

$$\Delta\varphi = -n\frac{\Lambda^{4+n}}{\varphi^{n+1}} + \frac{\beta}{M_{\mathrm{Pl}}}\rho$$

Plate with mass density ρ





Saturation effect and screening mechanism. For large β the force between macroscopic bodies is independent of β

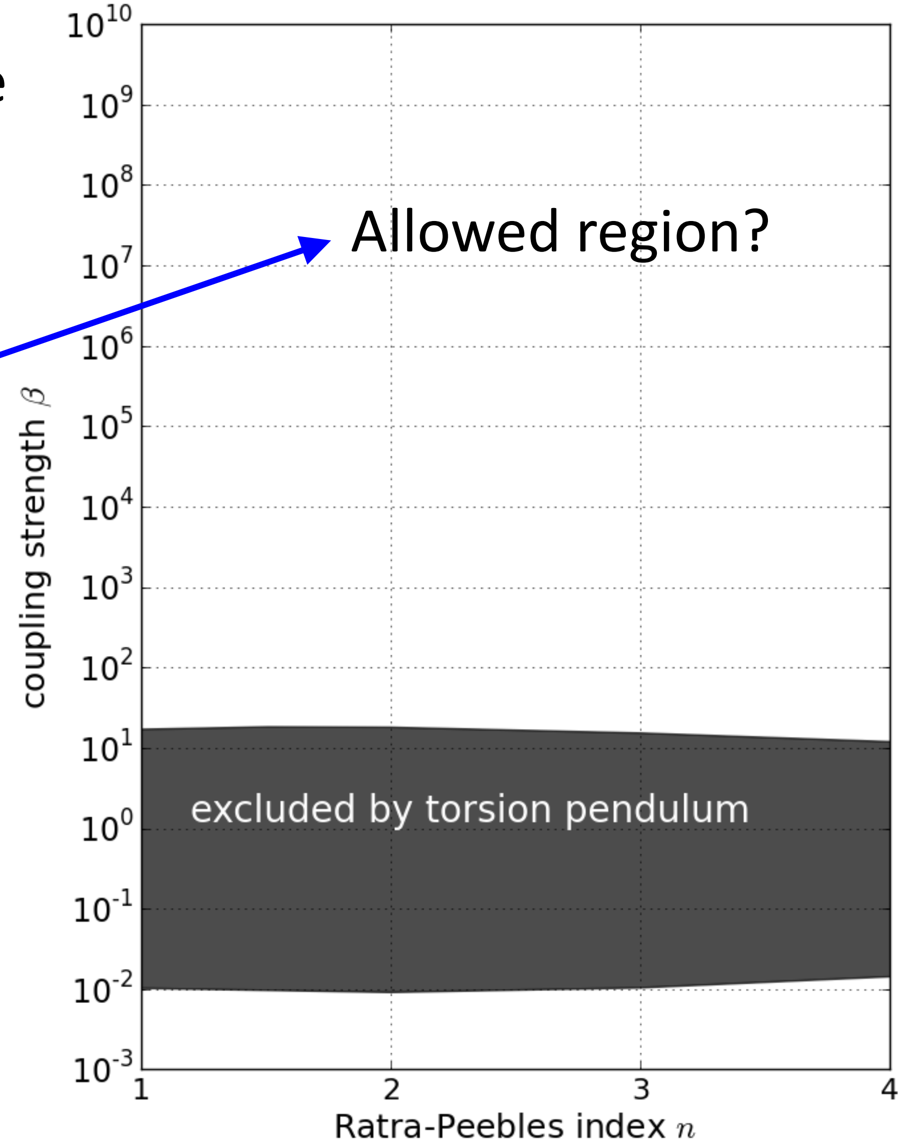
Lab limits on chameleon Dark Energy

Dark Energy scalar field with the scale

$$\Lambda = \rho_{\mathrm{DE}}^{1/4} = 2.4\ \mathrm{meV} = \frac{\hbar c}{82\ \mu m}$$

Due to the screening mechanism, coupling much stronger than gravity is allowed?

Allowed region?

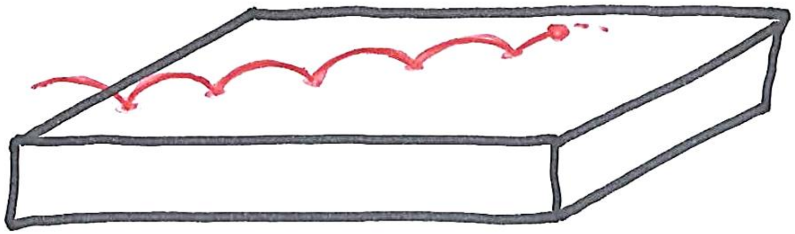


Use experiments with atoms or neutrons to alleviate screening…

Bouncing neutrons: quantum states

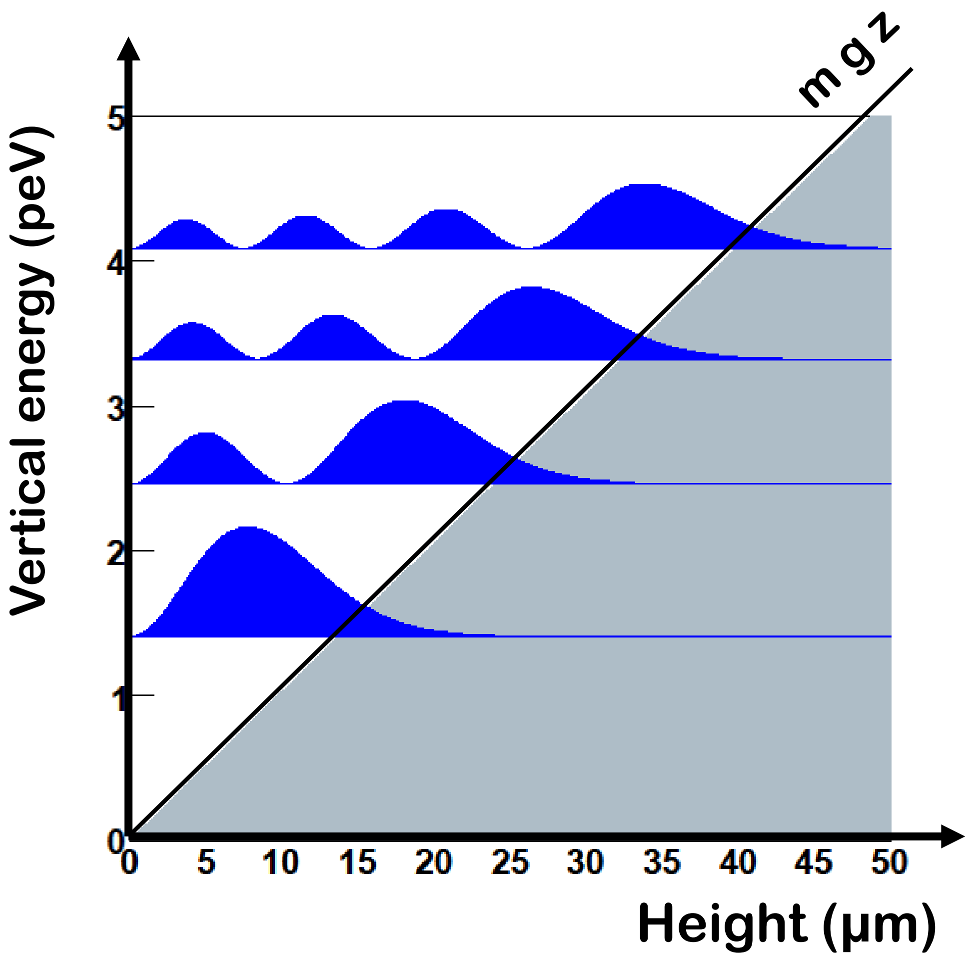
Neutrons with energy < 100 neV

can bounce above a glass mirror.

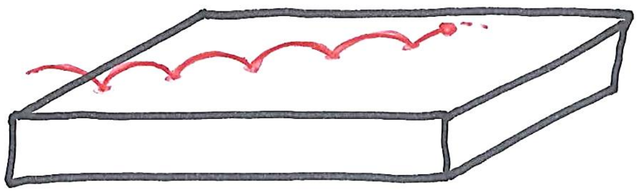


The vertical motion is a
simple quantum well problem

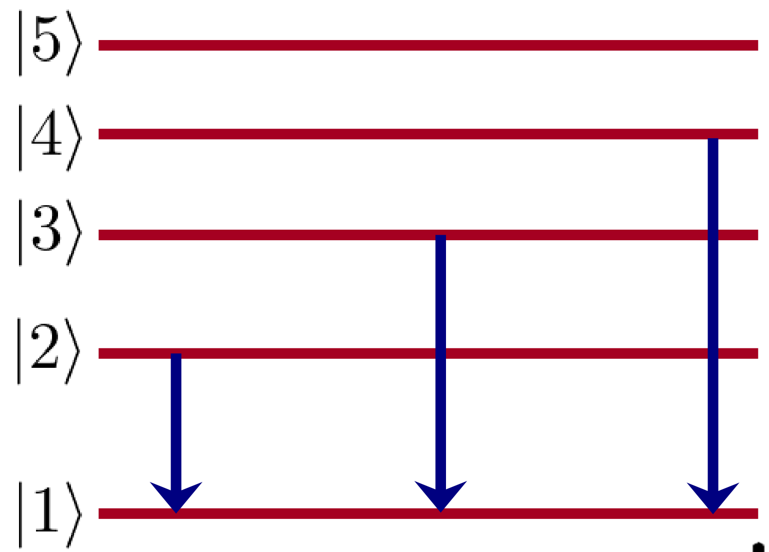
$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2}+mgz\,\psi=E\,\psi$$



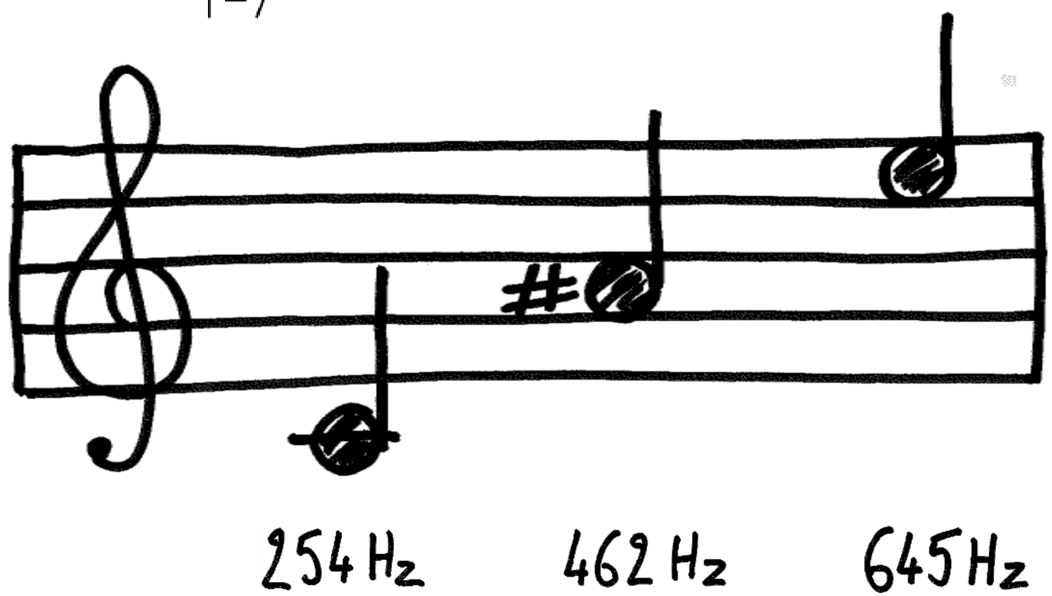
Bouncing neutron: quantum music



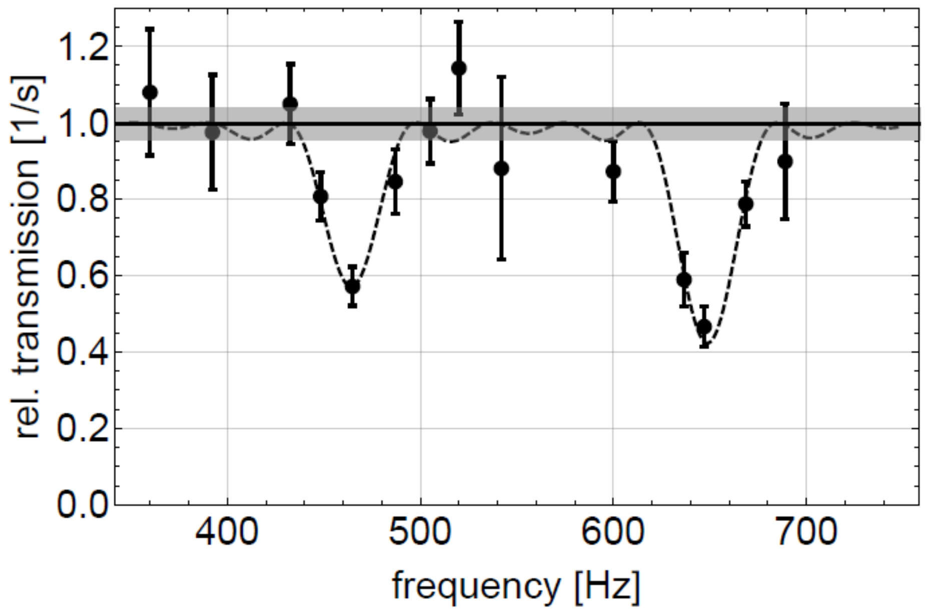
$$\Delta E = h \times f$$



$$\frac{1}{2\pi}\sqrt[3]{\frac{mg^2}{2\hbar}} \times \left| \begin{array}{l} 1{,}75 \\ 3{,}18 \\ 4{,}45 \\ \vdots \end{array} \right.$$

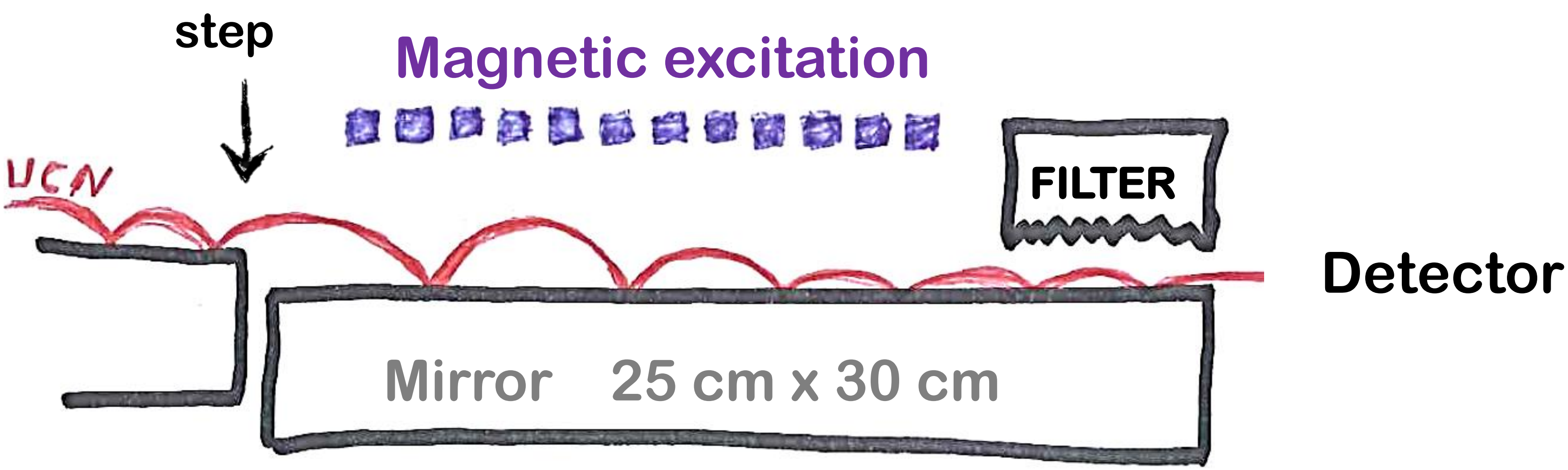


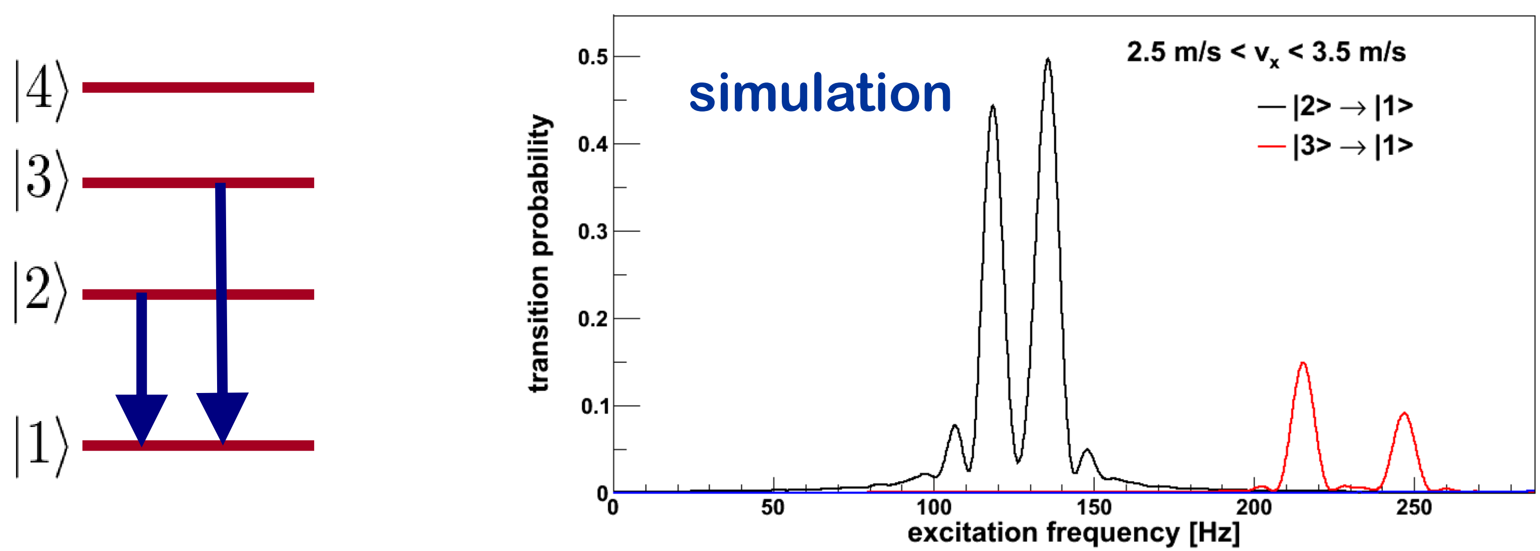
qBounce exp. at Institut Laue Langevin Grenoble



G. Cronenberg, H. Filter, Thalhammer, T. Jenke, H. Abele, P. Geltenbort , arXiv:1512.09134
See also Jenke et al. Nature Phys. 7 (2011) 468

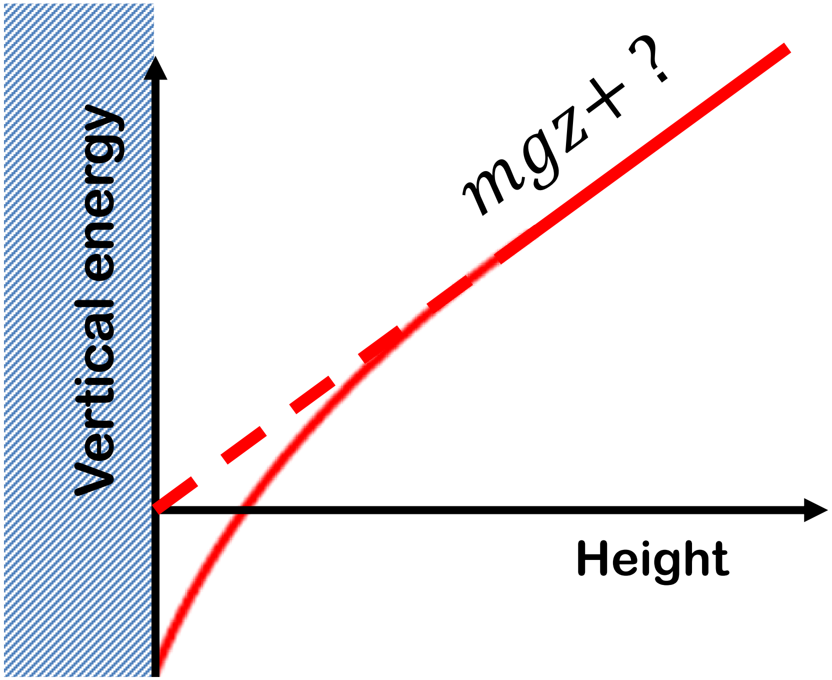
GRANIT exp. at ILL (coming soon)





V. Nesvizhevsy, B. Clement, G. Pignol, K. Protasov, D. Rebreyend, F. Vezzu, Y. Xi, S. Baessler, A. Voronin (…)

Limits on chameleon Dark Energy

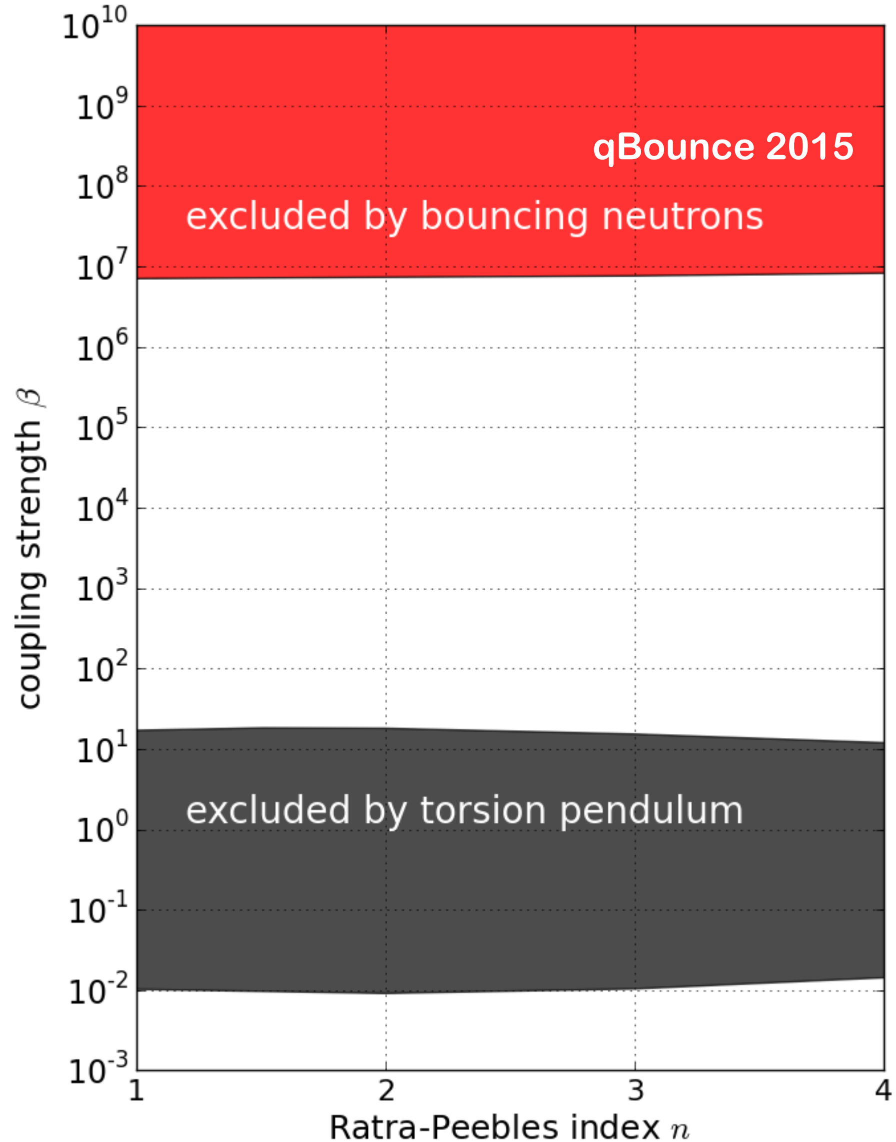


Chameleon case

$$V(z) = mgz + \beta \frac{m}{M_{\mathrm{Pl}}} \varphi(z)$$

Field profile above the mirror

$$\varphi(z) = \Lambda(\Lambda z/\hbar c)^{2/2+n}$$



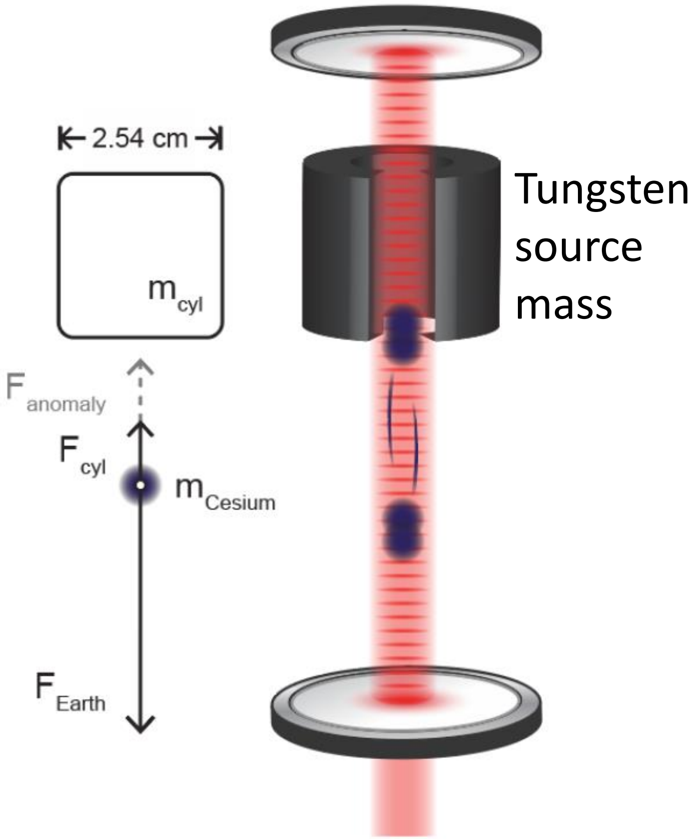
Limits on chameleon Dark Energy

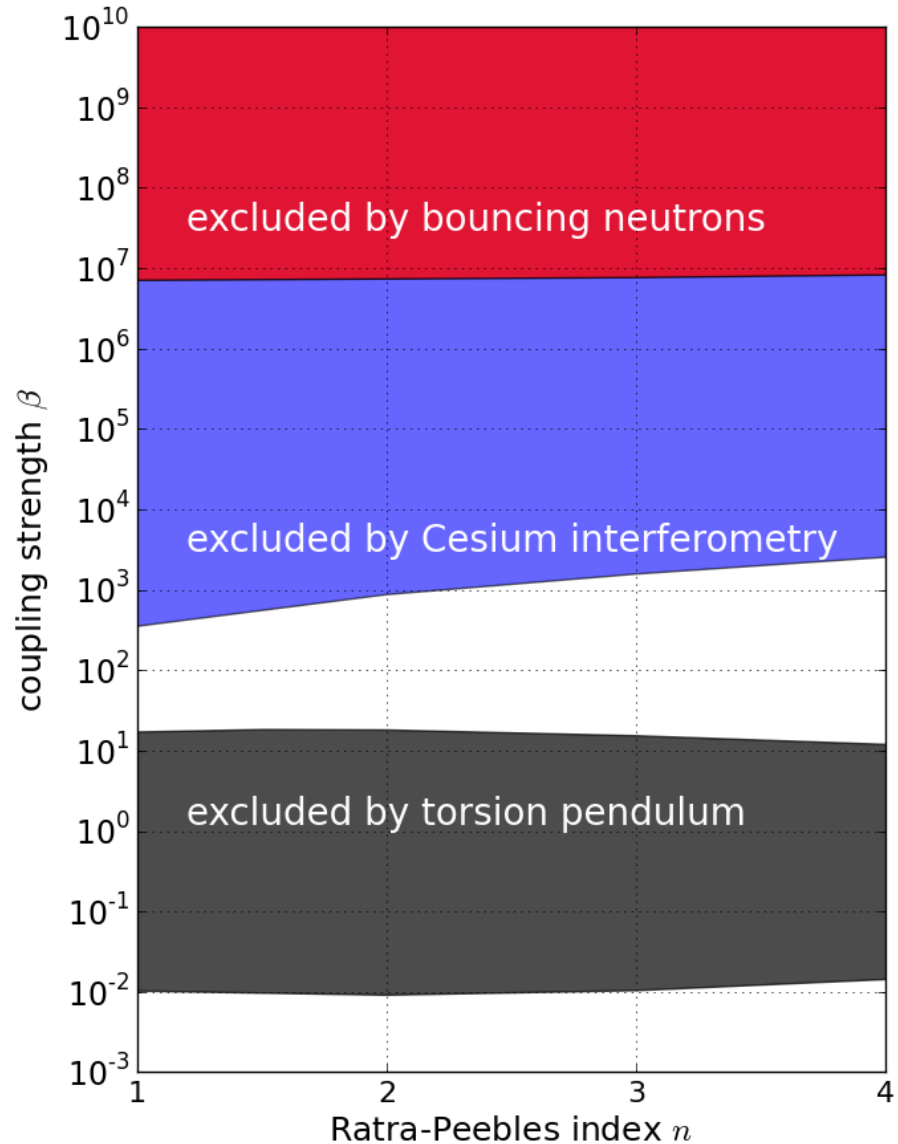
Berkeley Cesium interferometry experiment

M. Jaffe et al. arXiv:1612.05171

P. Hamilton et al. Science 349 (2015) 849

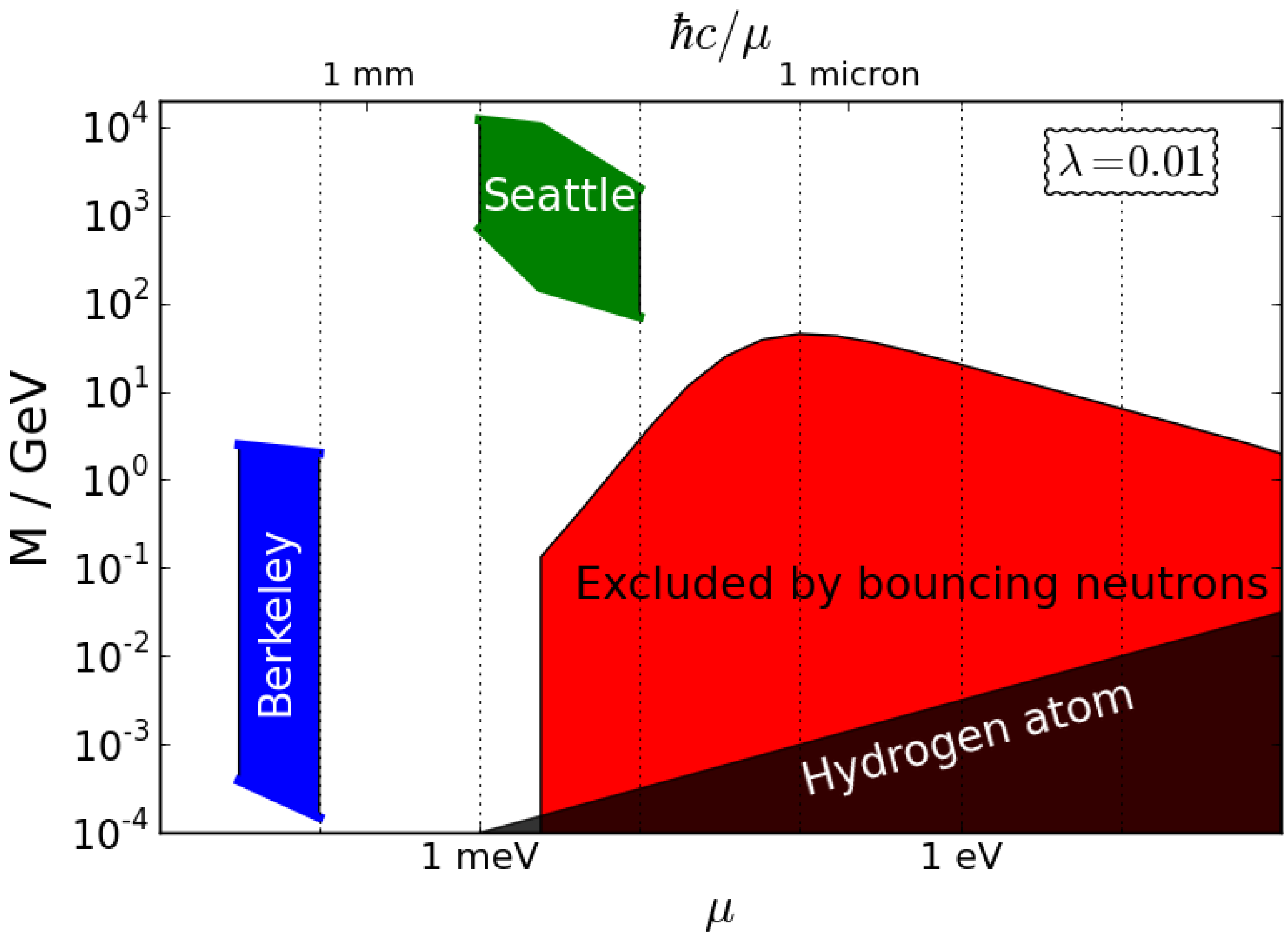
Proposed by C. Burrage et al





Symetron Dark Energy

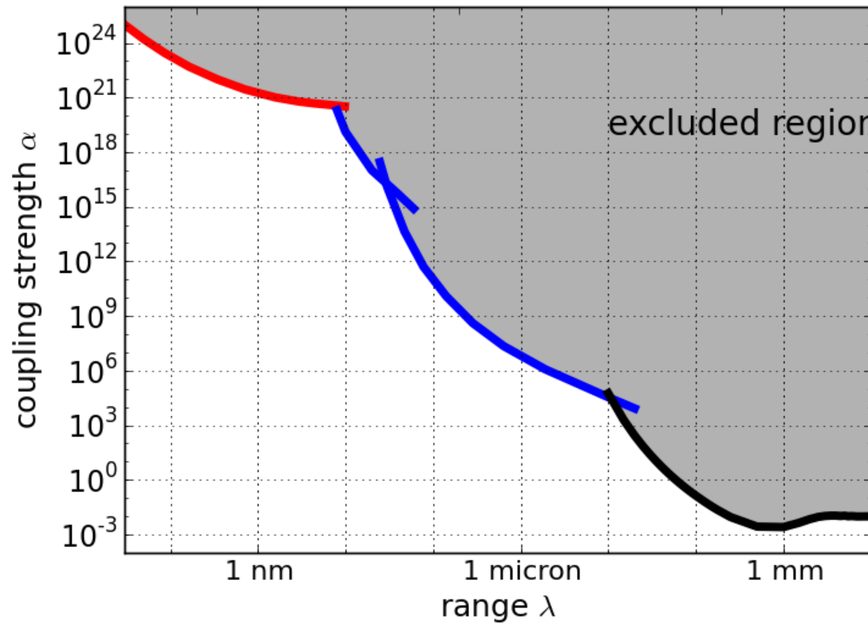
$$\mathcal{V}_{\text{eff}}(\varphi) = \left(\frac{\rho}{M^2} - \mu^2\right)\frac{\varphi^2}{2} + \frac{\lambda}{4}\varphi^4$$



Work in progress…

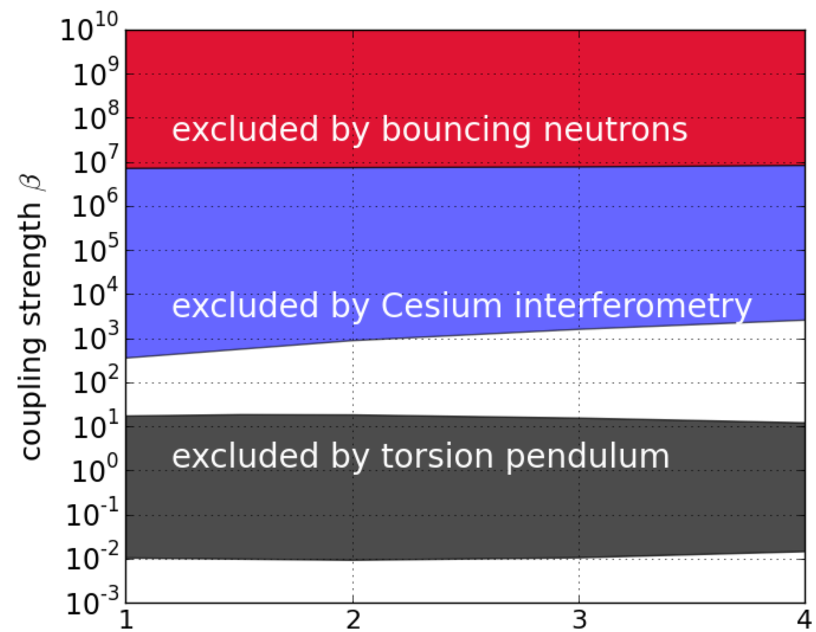
Concluding remarks

- The search for short range modification of gravity is ongoing since decades

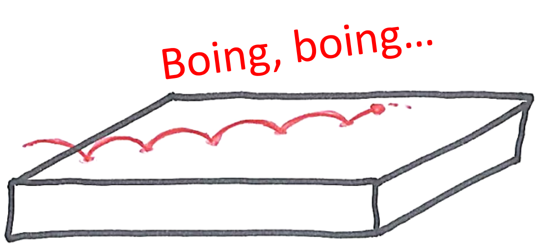


- Dark Energy fields evade constraints due to screening properties
- Recently new lab tests were proposed and performed using different systems

  Bouncing neutrons, atom and neutron interferometry, Casimir-type, microspheres...

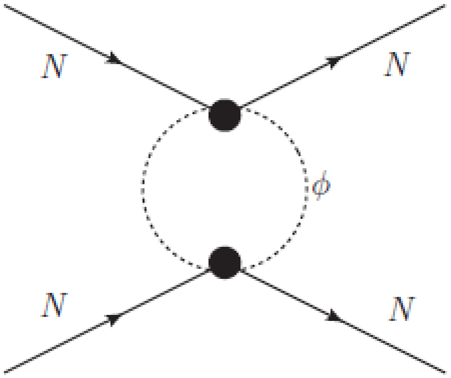


- More to come: extending chameleon searches, exploring symmetron scenario...



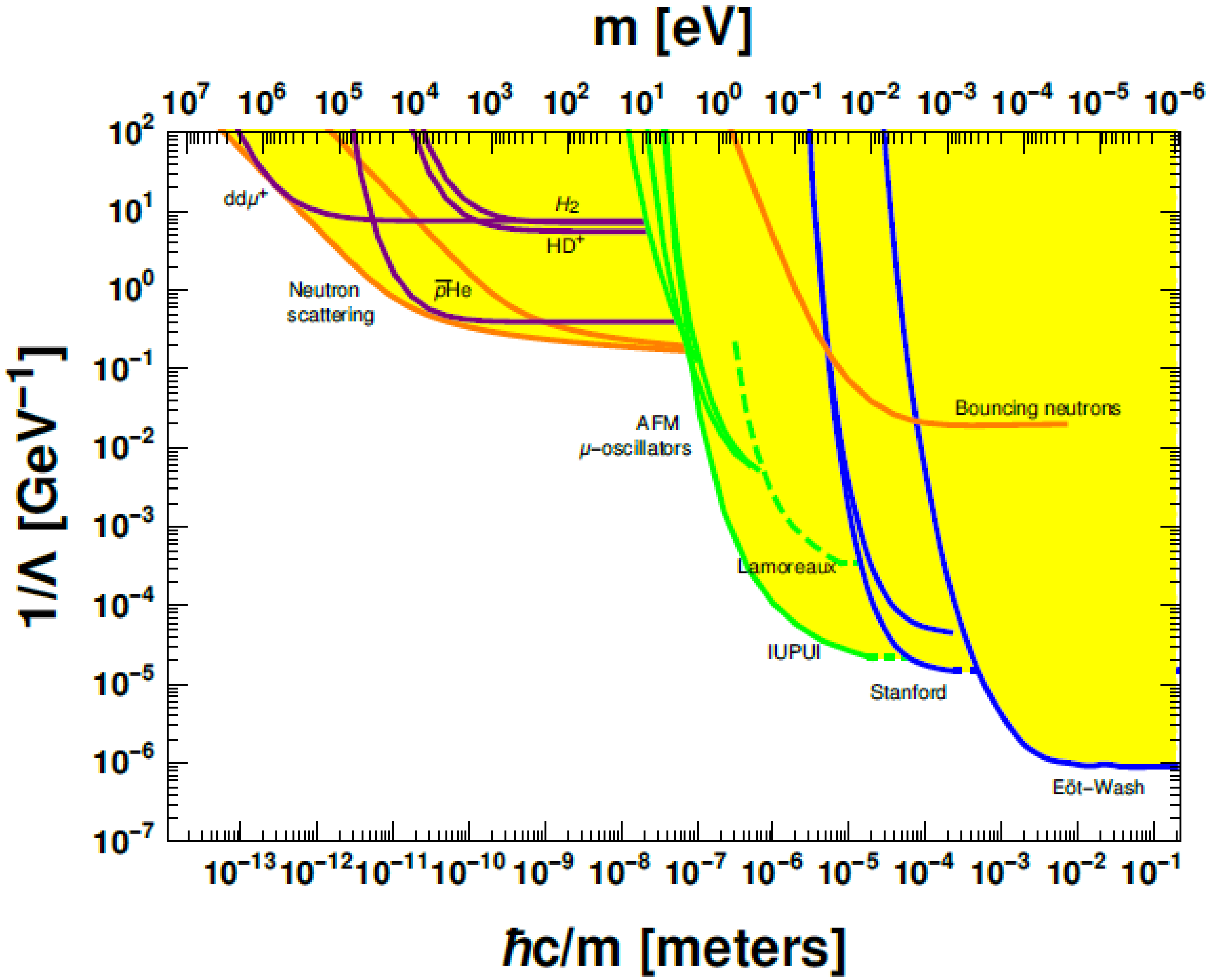
Thank you

Other possibilities

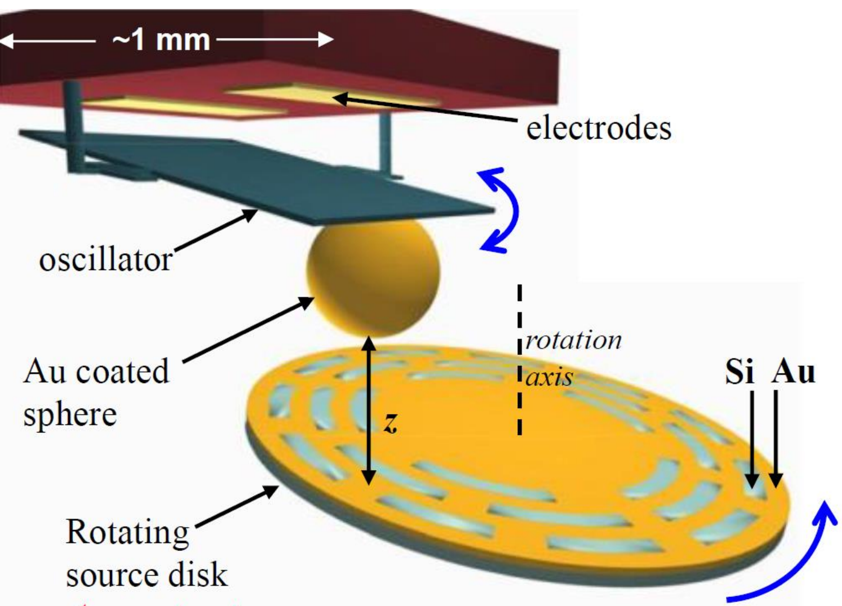


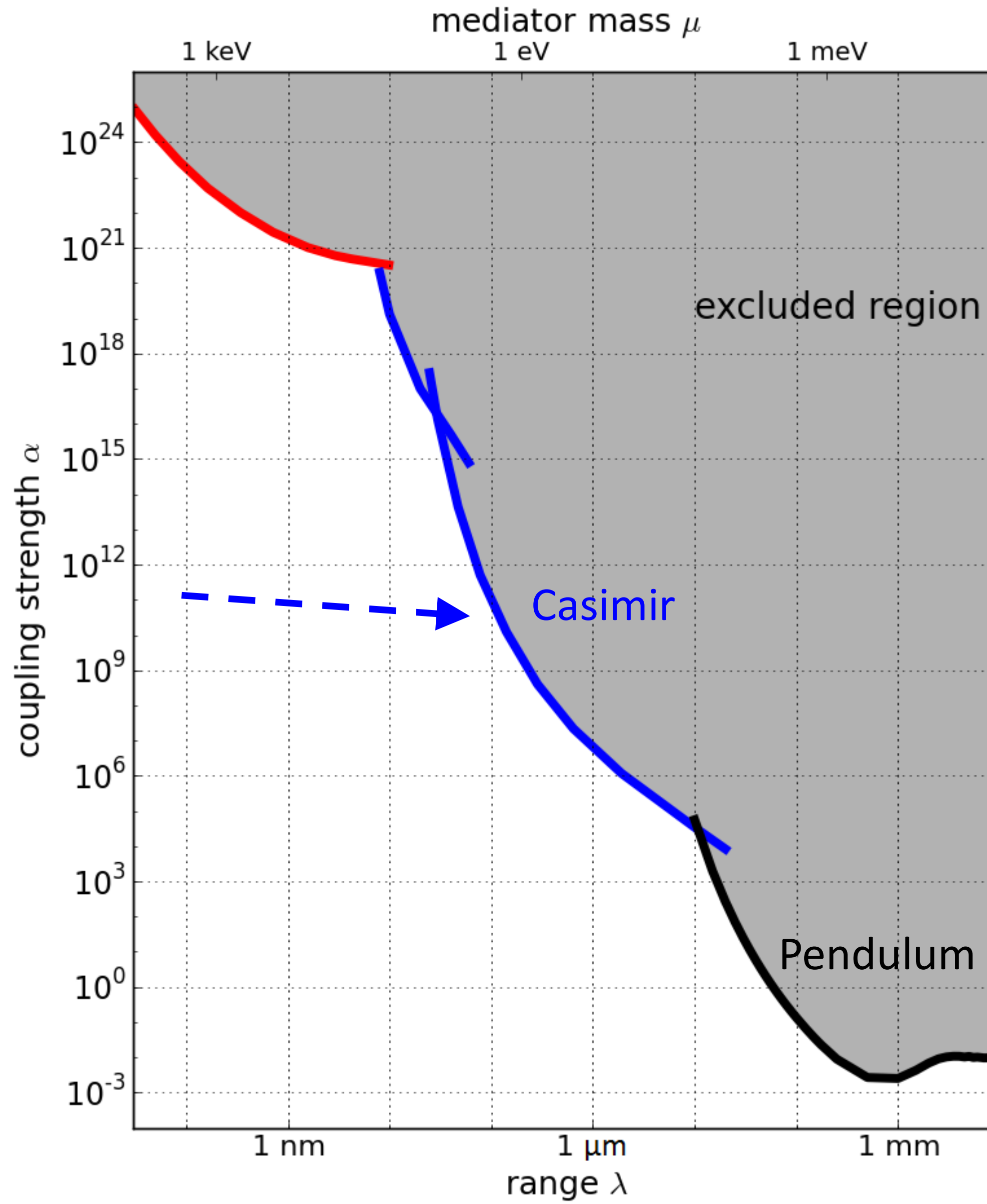
$$\mathcal{O}_a^0 = \frac{1}{\Lambda}\bar{N}N\frac{\phi^2}{2}$$

[arXiv:1710.00850](https://arxiv.org/abs/1710.00850)



Fifth force search at the (sub)micrometer scale



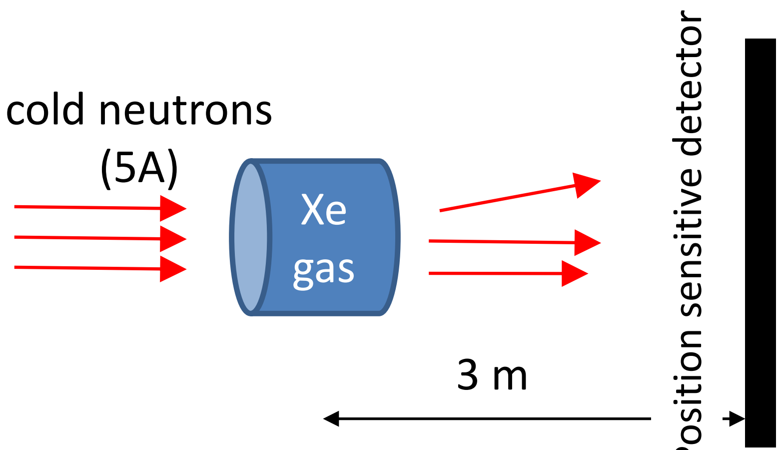


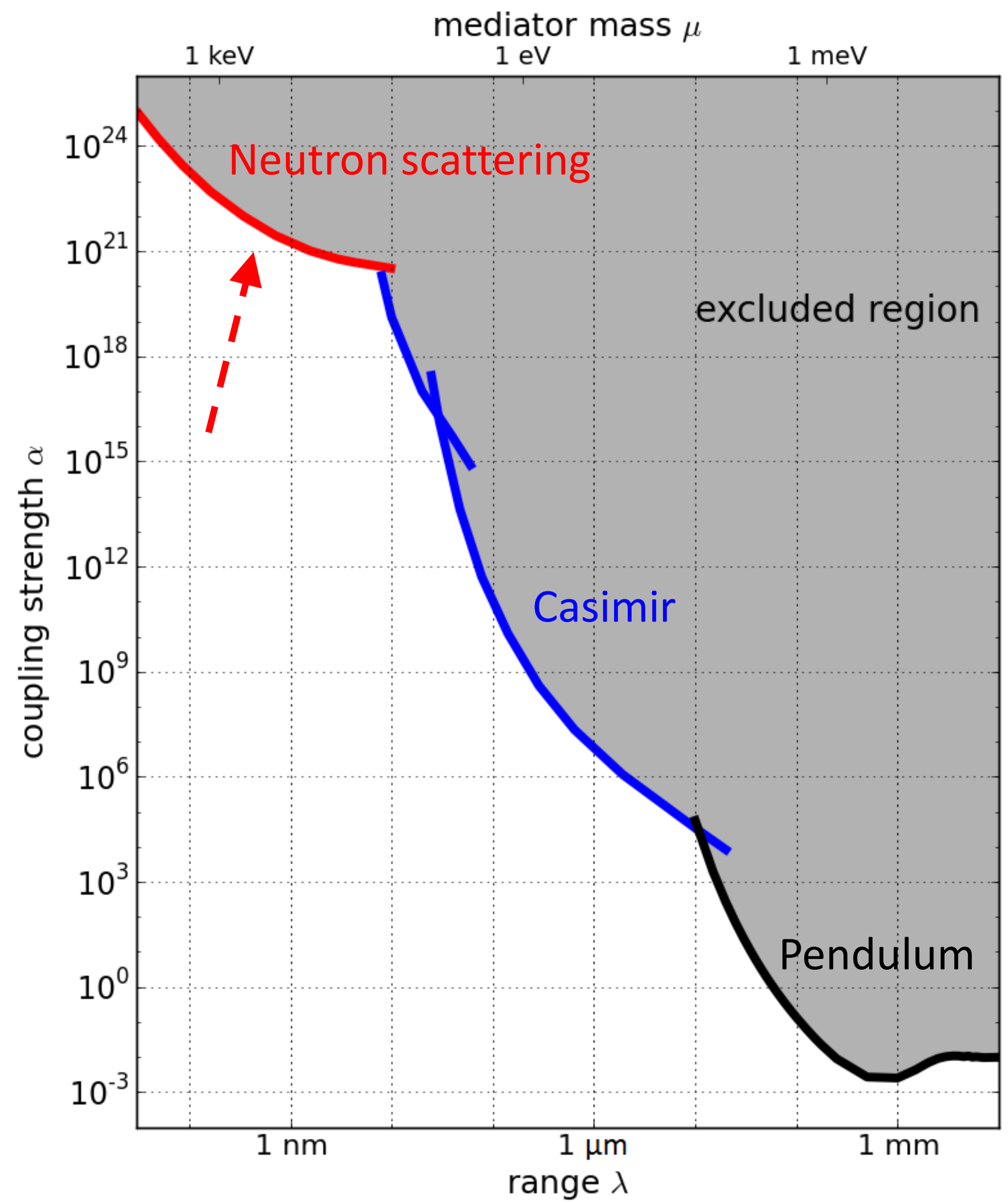
Probe mass = Sphere Ø 300 µm
Minimum z distance = 200 nm

Indiana Casimir(less) experiment
Y. Chen et al., PRL 116 221102 (2016)

Fifth force search at the (sub)nanometer scale

Small angle neutron scattering
Source = Xe atom
Probe = neutron

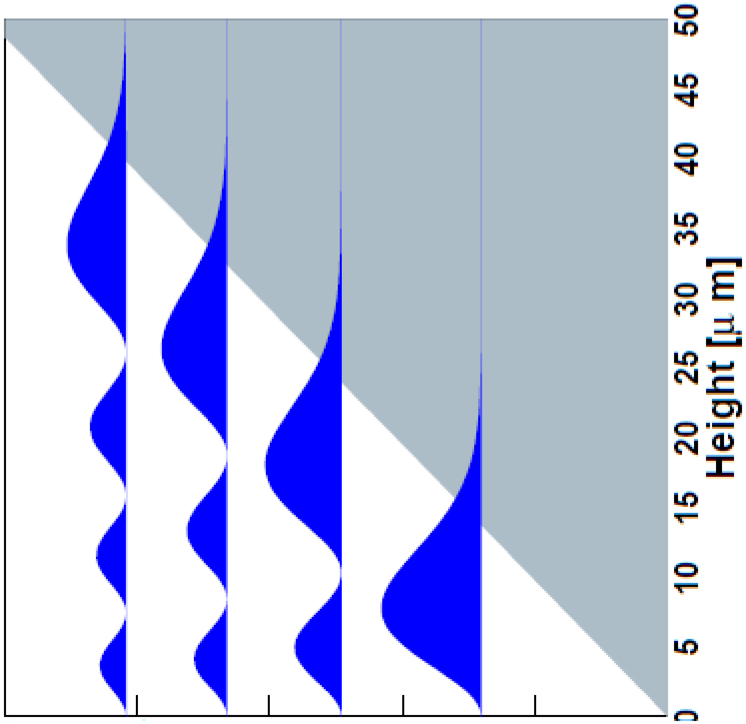


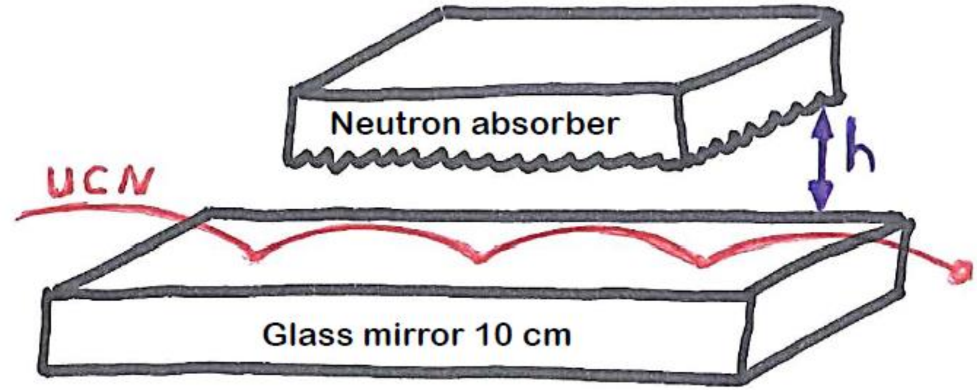


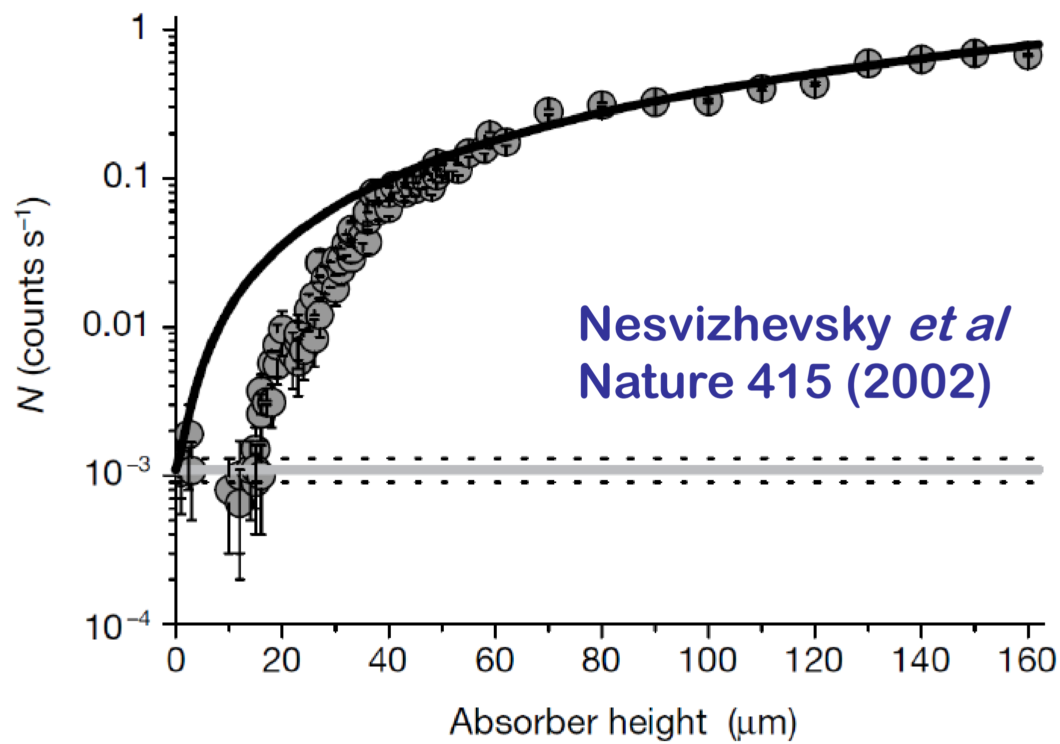
Y. Kamiya et al., PRL 114 161101 (2015)

See also
Nesvizhevsky, Pignol, Protasov., PRD 77 034020 (2008)

Discovery of the quantum states at ILL Grenoble







Nesvizhevsky *et al*
Nature 415 (2002)

Quantum test of the equivalence principle

$$-\frac{\hbar^2}{2m_i}\frac{d^2\psi}{dz^2}+m_g g\,z\,\psi=E\,\psi$$

Inertial
Mass

Gravitational
Mass

Measuring the wavefunctions one access

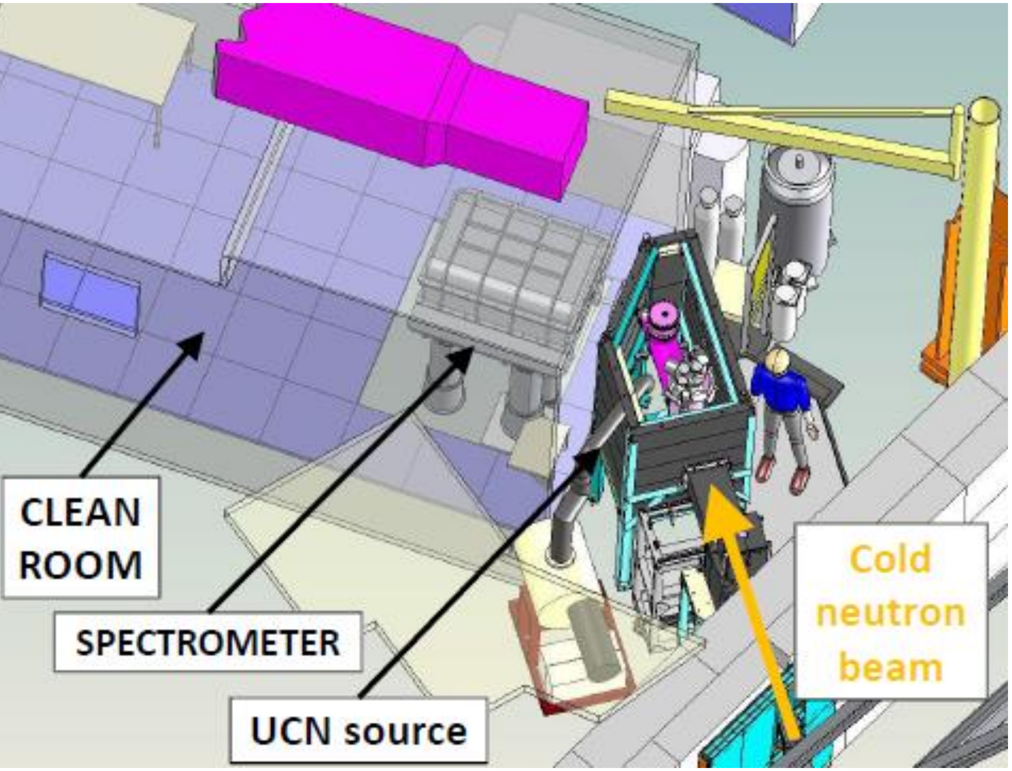
$$z_0=\left(\frac{\hbar^2}{2m_i m_g g}\right)^{1/3}$$

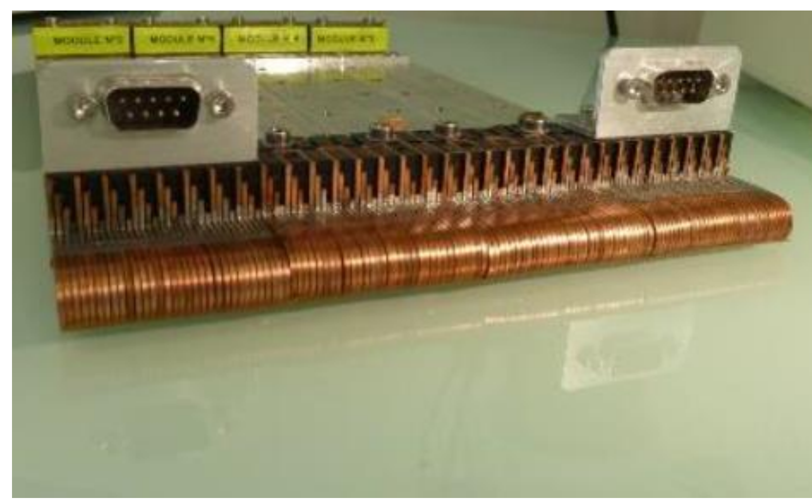
Measuring transition frequencies one access

$$E_0=m_g g z_0=\left(\frac{m_g^2}{m_i}\frac{g^2\hbar^2}{2}\right)^{1/3}$$

One can tell separately the
inertial and gravitational mass !

The GRANIT instrument
at ILL level C

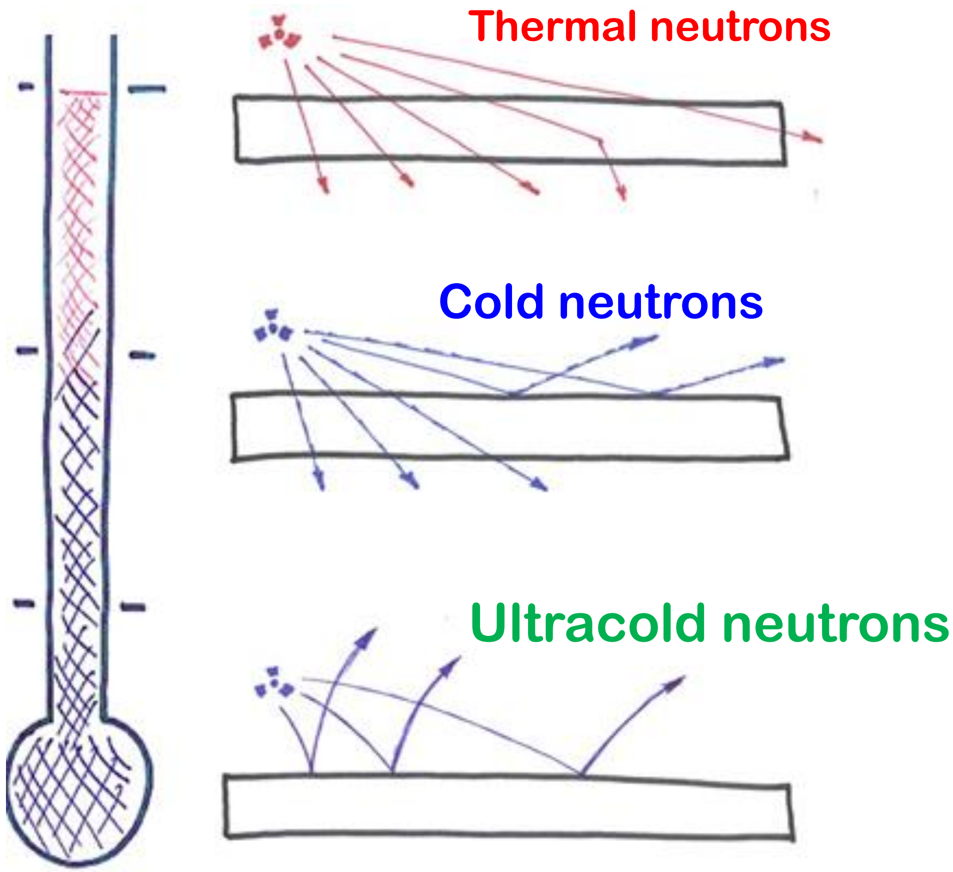




First UCNs in GRANIT in 2013.

Full potential of the source not reached yet, it is hard.

Neutron optics, cold and ultracold neutrons



Cold neutrons

$$E < kT = 25 \text{ meV}$$

have large wavelength

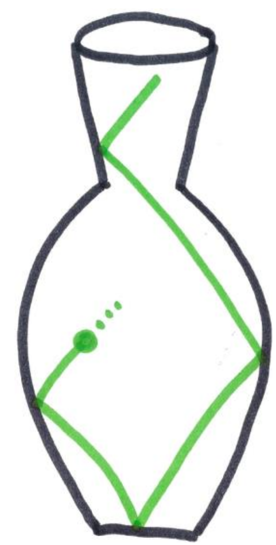
$$\lambda > 0.2 \text{ nm}$$

They behave like waves,

affected by the

Fermi potential of matter

(order of 100 neV)

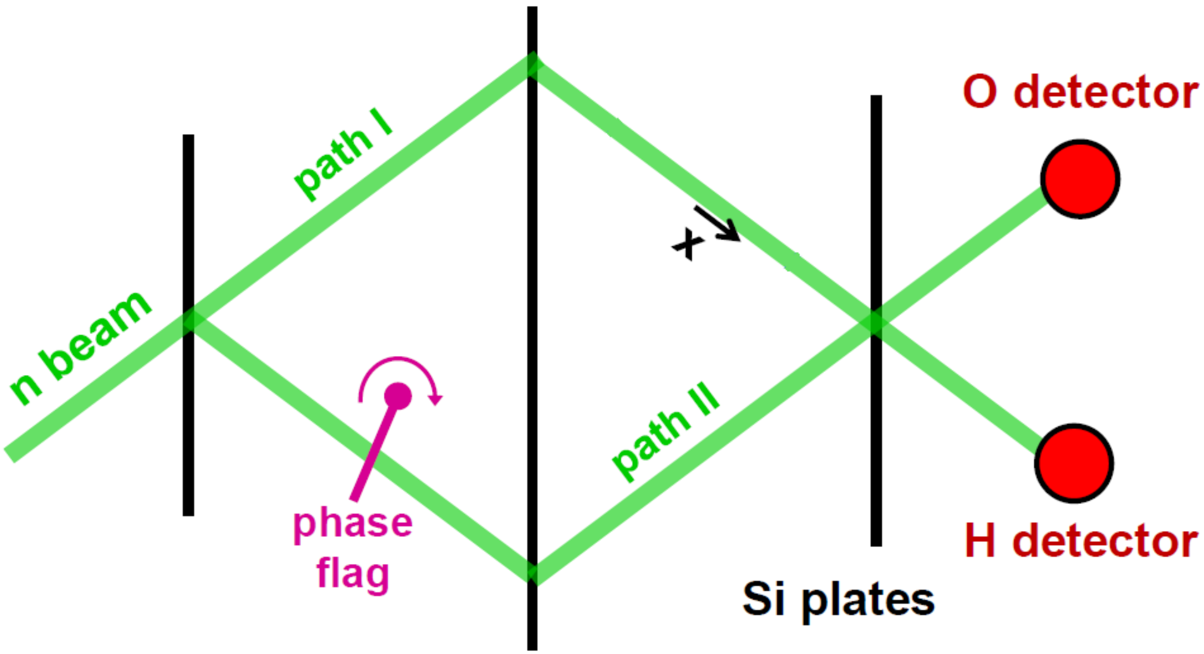


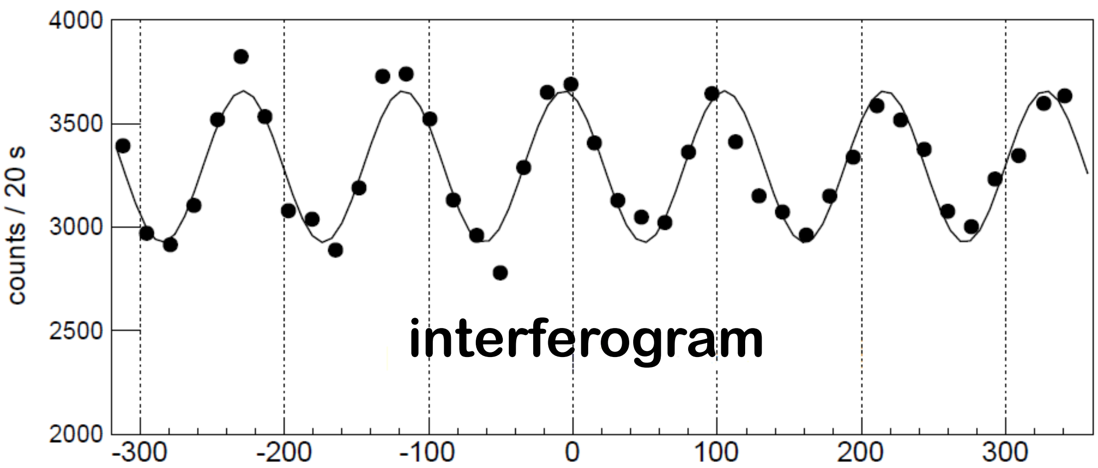
Neutrons with energy < 100 neV,

are reflected by material walls

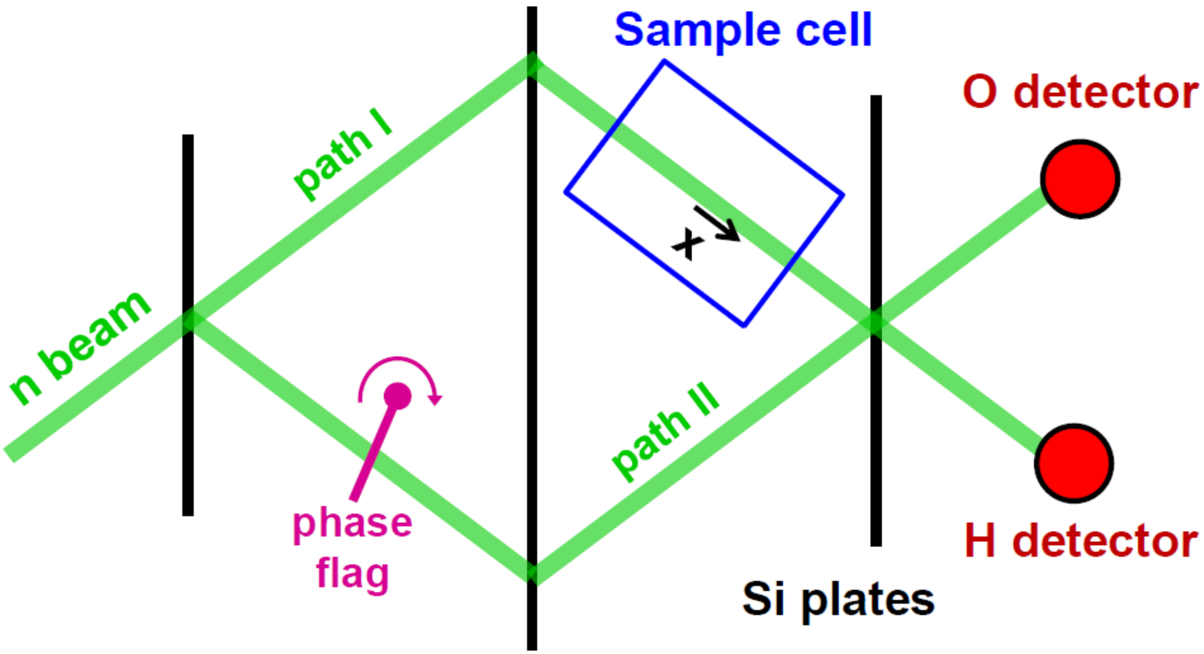
they can be stored in material bottles.

Principle of neutron interferometry 1





Principle of neutron interferometry 2



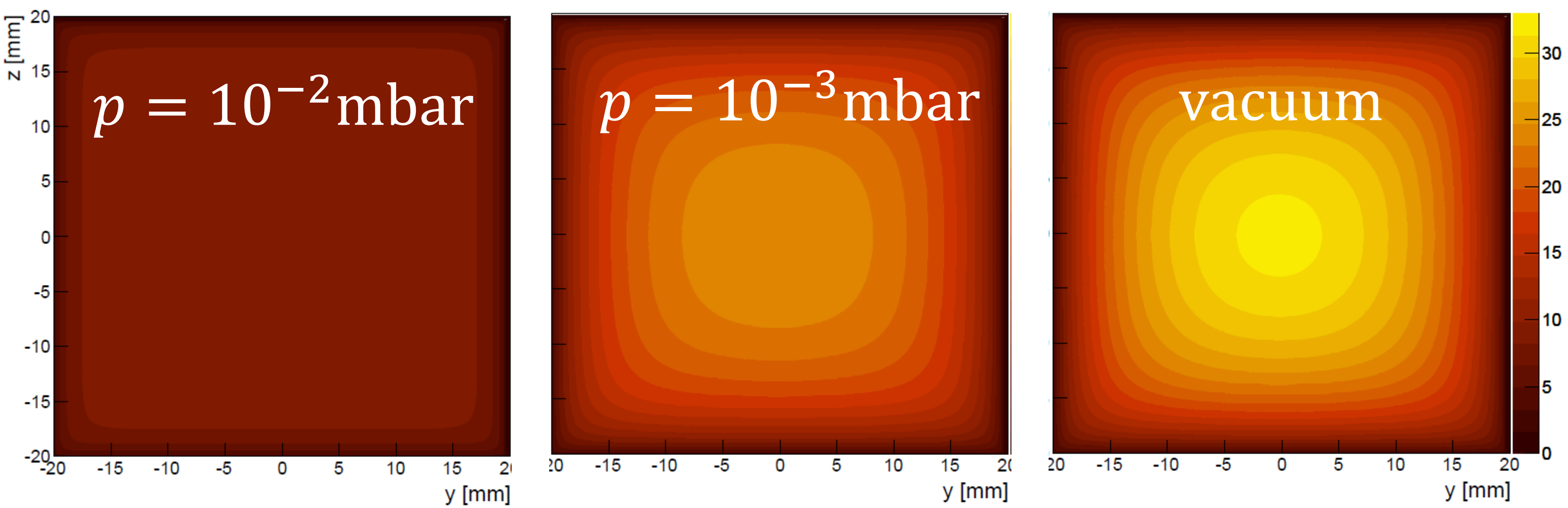
Phase shift due to the sample: $$\xi = -\frac{1}{v\,\hbar}\int V(x)\,dx$$

neutron potential in a chameleon field: $$V(x) = \beta\,\frac{m}{M_{\mathrm{Planck}}}\,\varphi(x)$$

The chameleon cell

Idea:
the chameleon field in a cell exists only in vacuum,
it is suppressed
by a small amount of gas
(here helium)

We plot the transverse field profile $\varphi(y,z)/\Lambda$



Numerical solution of the chameleon equation
for $n = 1$ and $\beta = 5 \times 10^7$