Probing Dark Energy with neutrons

Guillaume Pignol

Rencontres du Vietnam: HiSEBSM

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Outline

1 Dark energy and the chameleon

2 Bouncing neutrons with GRANIT

3 Neutron interferometry

The expansion of the Universe

The Hubble law:
velocity = H_0 x distance

E. Hubble 1929

$$H_0 = 550\,\mathrm{km/s\,/Mpc}$$

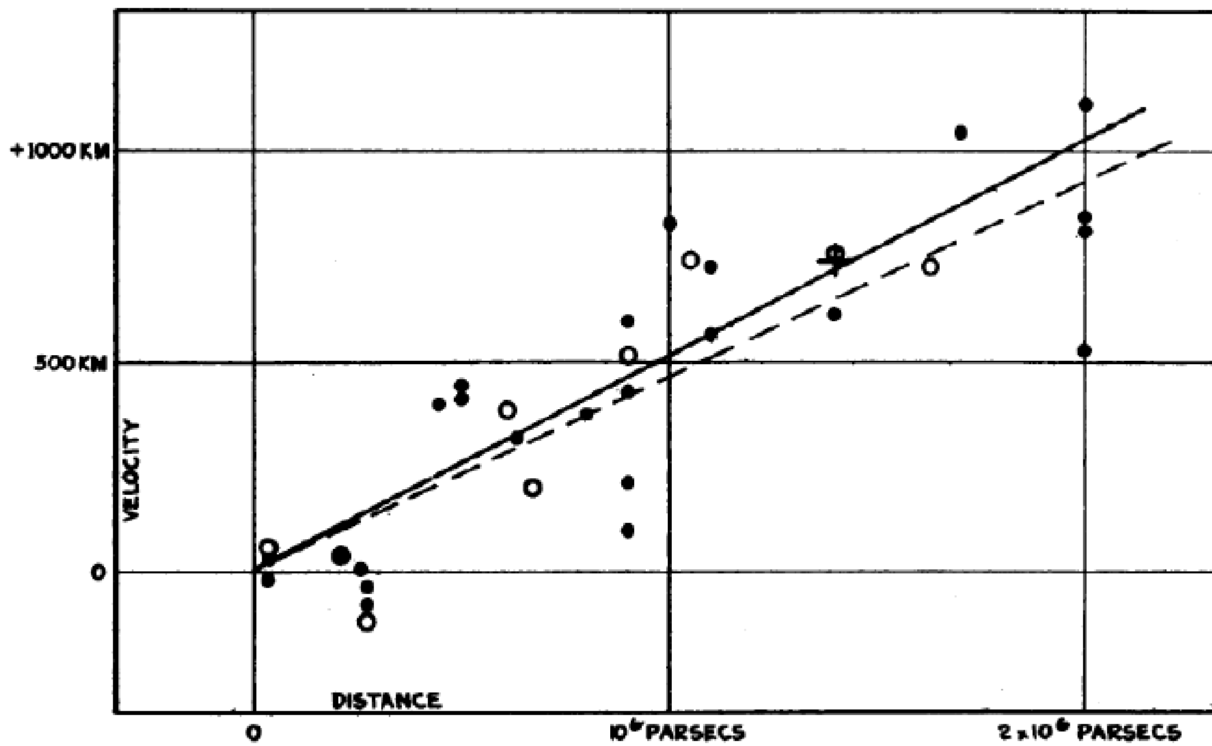
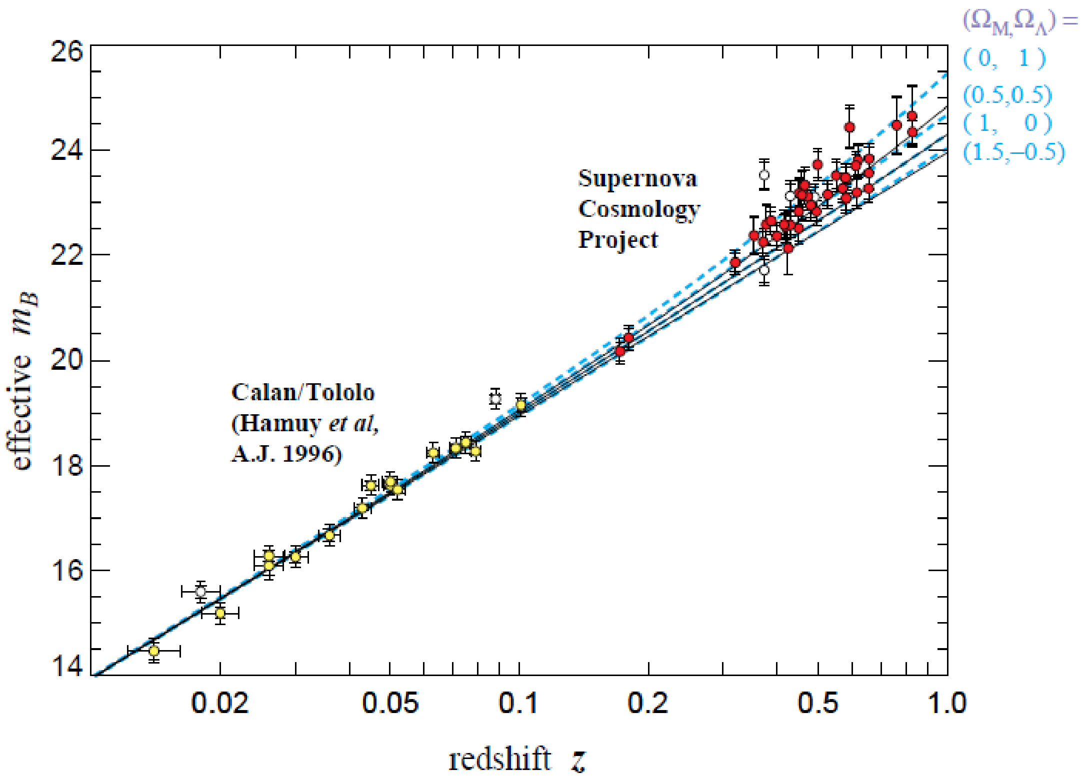


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

The expansion accelerates



S. Perlmuter *et al* (1999)
+ A. Riess *et al* (1998)

Friedmann equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho(1+3w)$$

For a substance with an equation of state

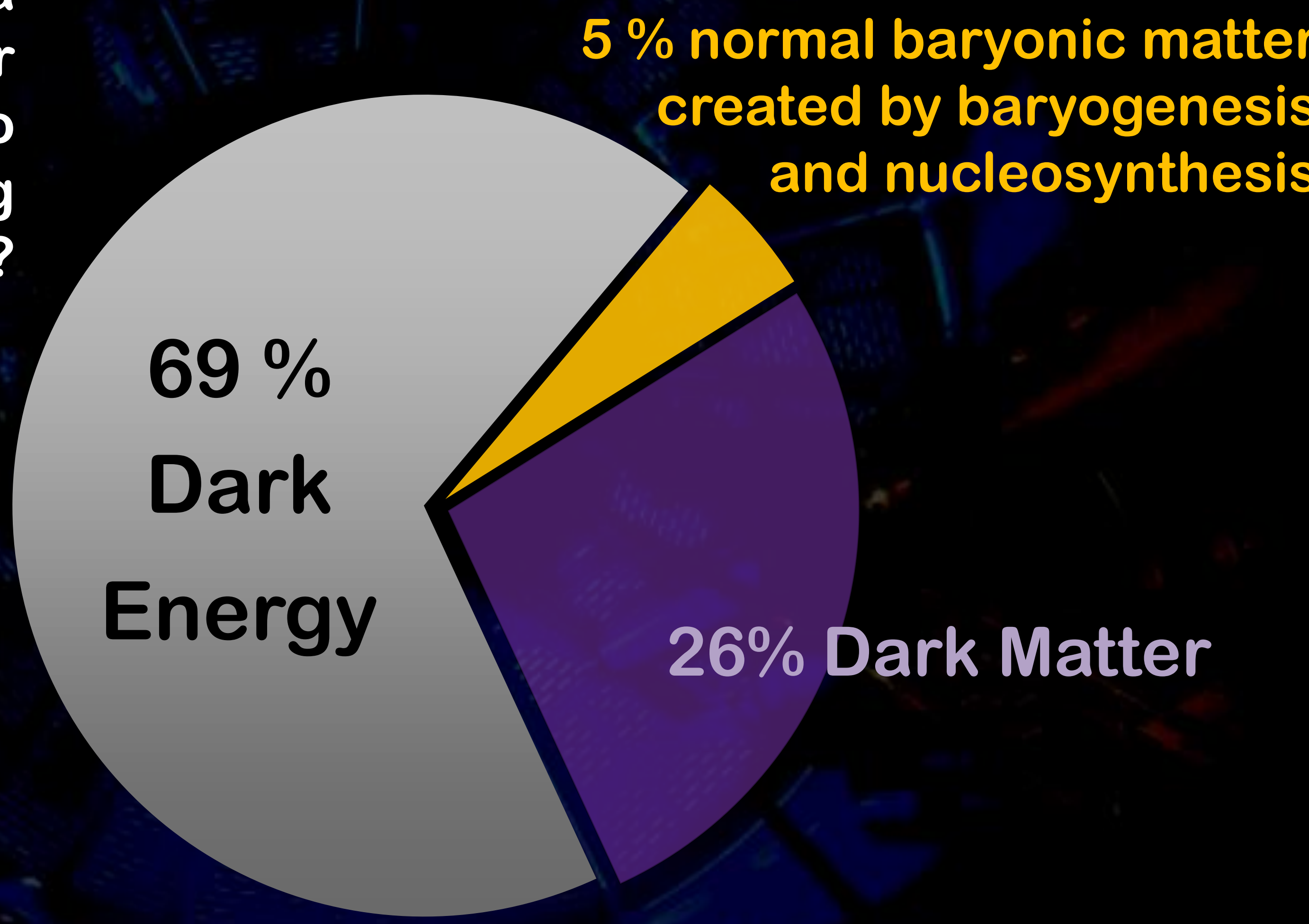
$$p = w\,\rho$$

Acceleration requires

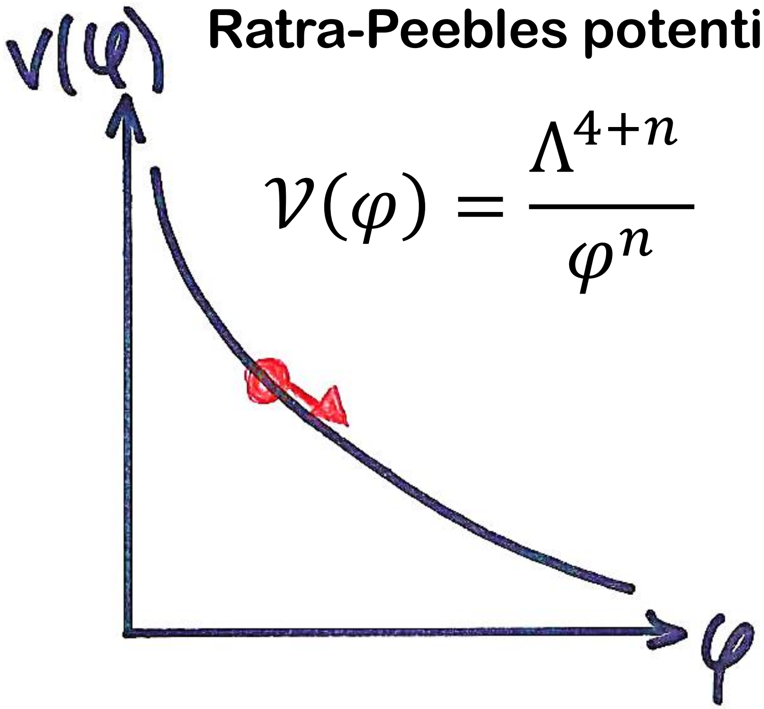
$$w < -1/3$$

Energy budget of the Universe in ΛCDM

Could this be a dynamical scalar field, can we try to probe its coupling to matter?



Quintessence as Dark Energy



Ratra-Peebles potential

$$\mathcal{V}(\varphi) = \frac{\Lambda^{4+n}}{\varphi^n}$$

Dark Energy is (maybe) due to a cosmological scalar field φ

$$\ddot{\varphi} + 3H\dot{\varphi} + \mathcal{V}'(\varphi) = 0$$

$$w = \frac{p}{\rho} = \frac{\dot{\varphi}/2 - \mathcal{V}(\varphi)}{\dot{\varphi}/2 + \mathcal{V}(\varphi)}$$

Very low energy dynamics: $\Lambda \approx \rho_{\mathrm{DE}}^{1/4} = 2.4\ \mathrm{meV}$

Corresponds to a distance scale $\hbar c/\Lambda = 82\ \mu\mathrm{m}$

Should be possible to detect if φ couples to matter!

The Khoury-Weltman mechanism

A way to reconcile
gravity tests and cosmology

[Khoury & Weltman PRD 69 (2004)]

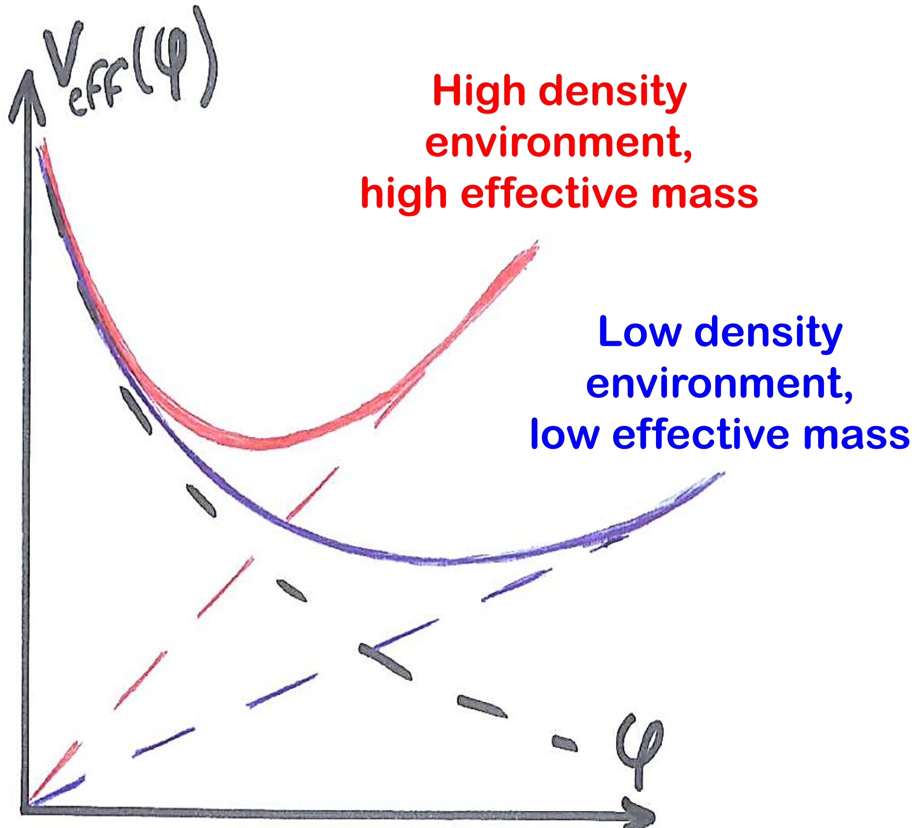
Recall: a massive Klein-Gordon field mediates a force with finite range $\hbar c/M$

$$\mathcal{V}_{\mathrm{KG}}(\varphi) = M^2\,\varphi^2$$

Quintessence field coupled with matter:

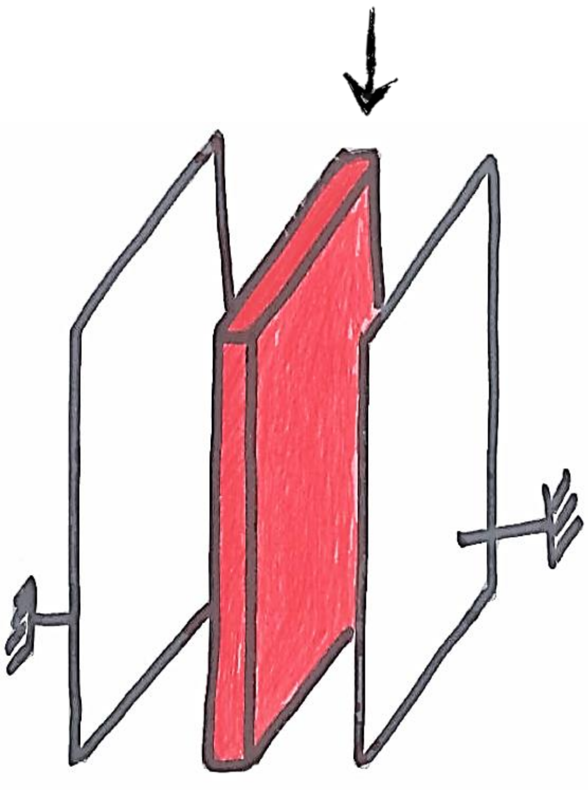
$$\mathcal{V}_{\mathrm{eff}}(\varphi) = \mathcal{V}(\varphi) + \frac{\beta\rho}{M_{\mathrm{Planck}}}\varphi$$

$$\mathcal{V}(\varphi) = \frac{\Lambda^{4+n}}{\varphi^n}$$



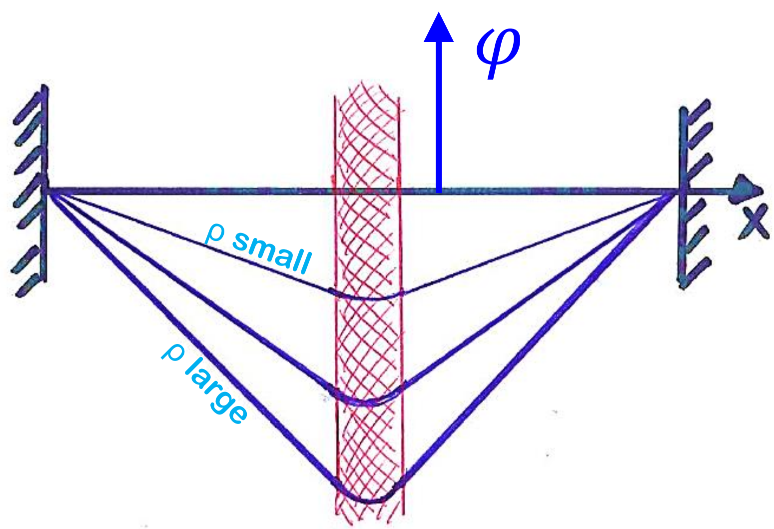
Understanding the chameleon mechanism

Plate with charge density ρ



Poisson equation for the electric potential

$$\Delta\varphi = \rho$$



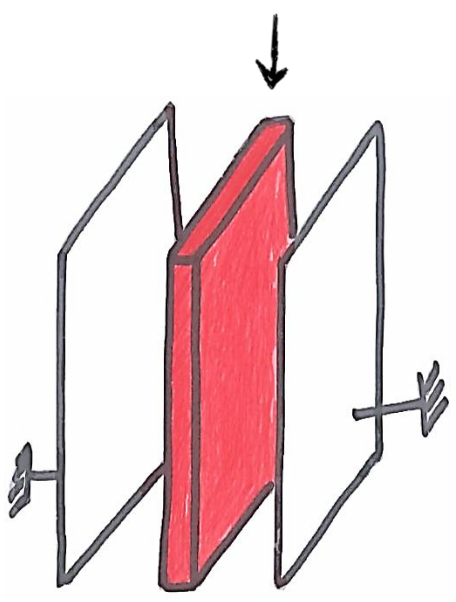
Electric field $\mathrm{d}\varphi/dx$ proportional to ρ

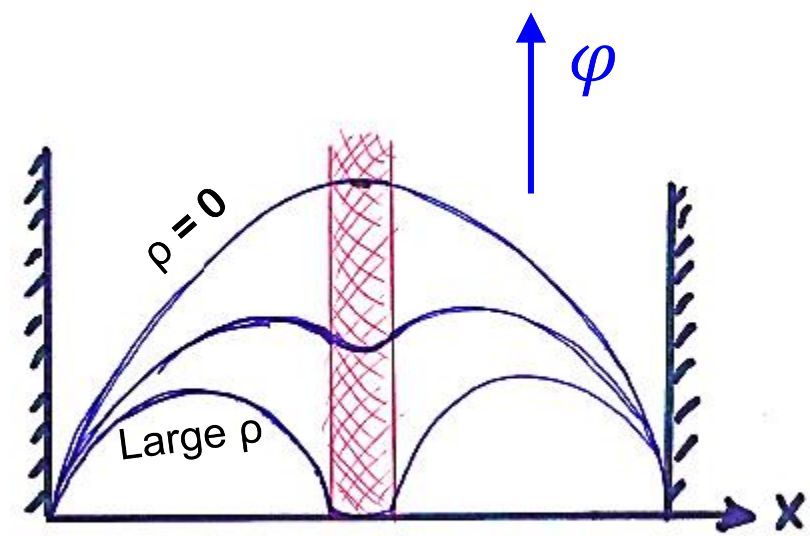
Understanding the chameleon mechanism

Nonlinear equation for the chameleon field

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

Plate with mass density ρ

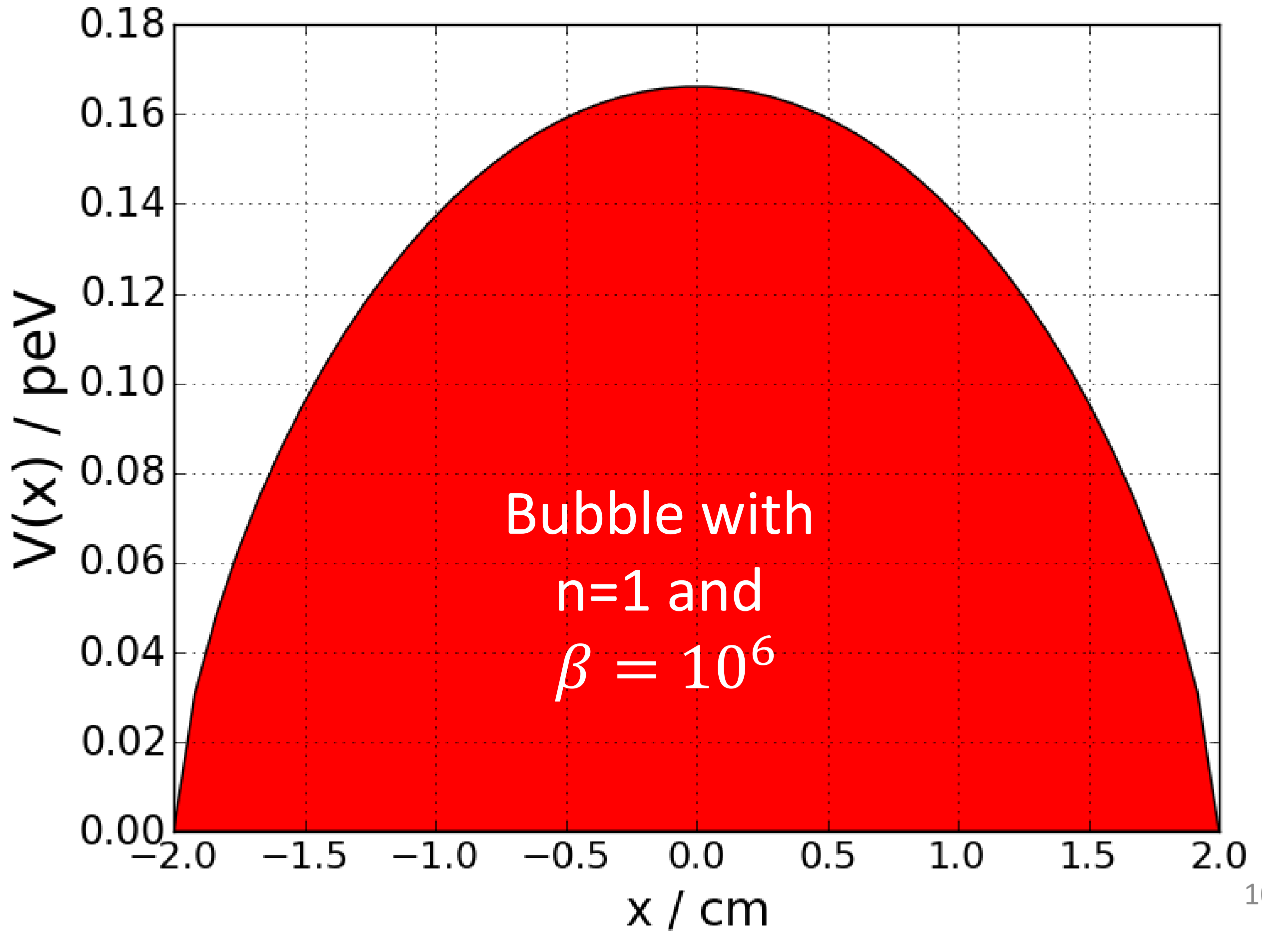




Saturation effect and screening mechanism. For large β the force between macroscopic bodies is independent of β

Detection with neutrons?

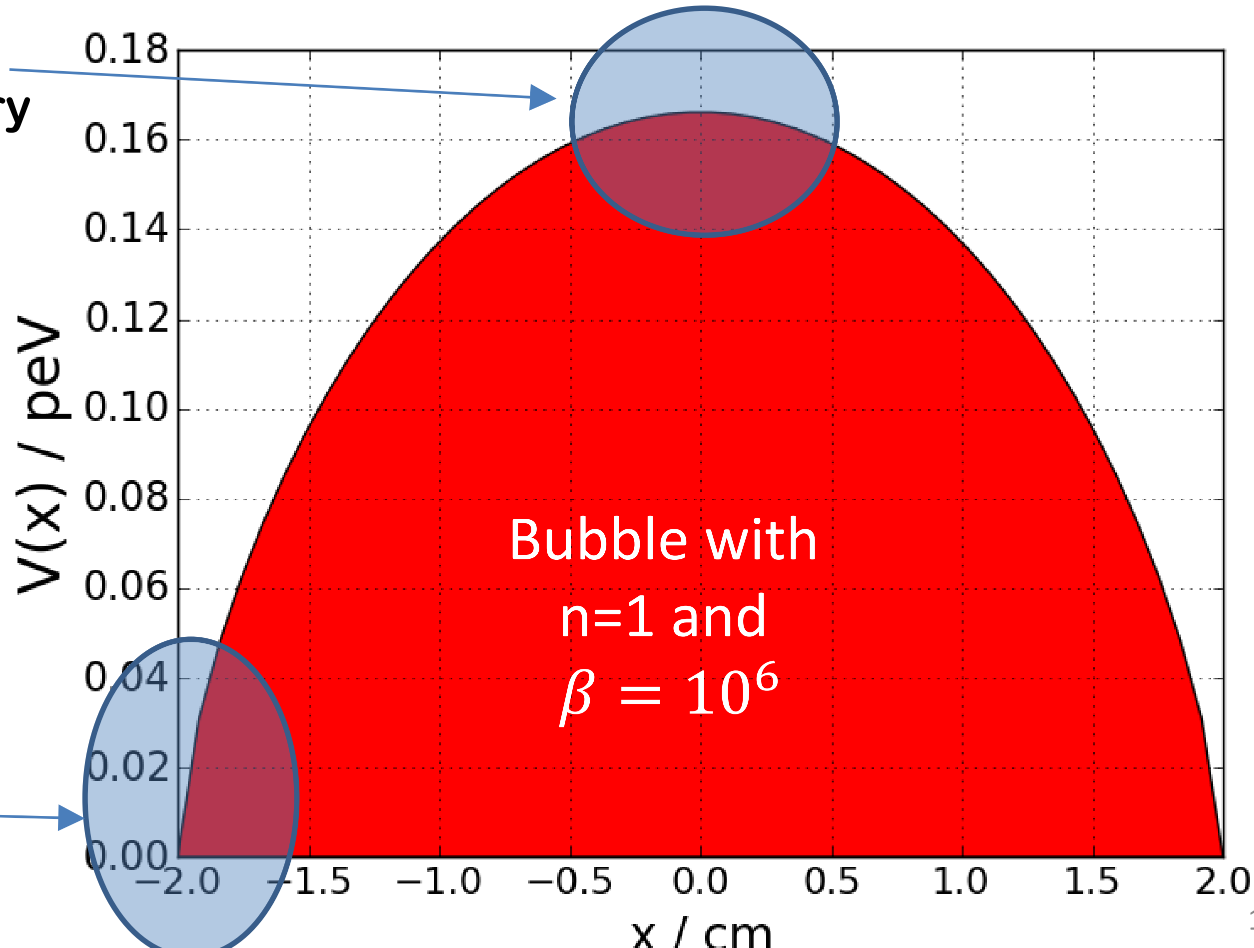
A neutron is affected by the potential energy $$V(r) = \beta \frac{m}{M_{\text{Planck}}} \varphi(r)$$



Detection with neutrons?

A neutron is affected by the potential energy $$V(r) = \beta \frac{m}{M_{\text{Planck}}} \varphi(r)$$

Large potential:
Neutron interferometry
Thermal neutrons



Large force:
Neutron bouncer
Ultracold neutrons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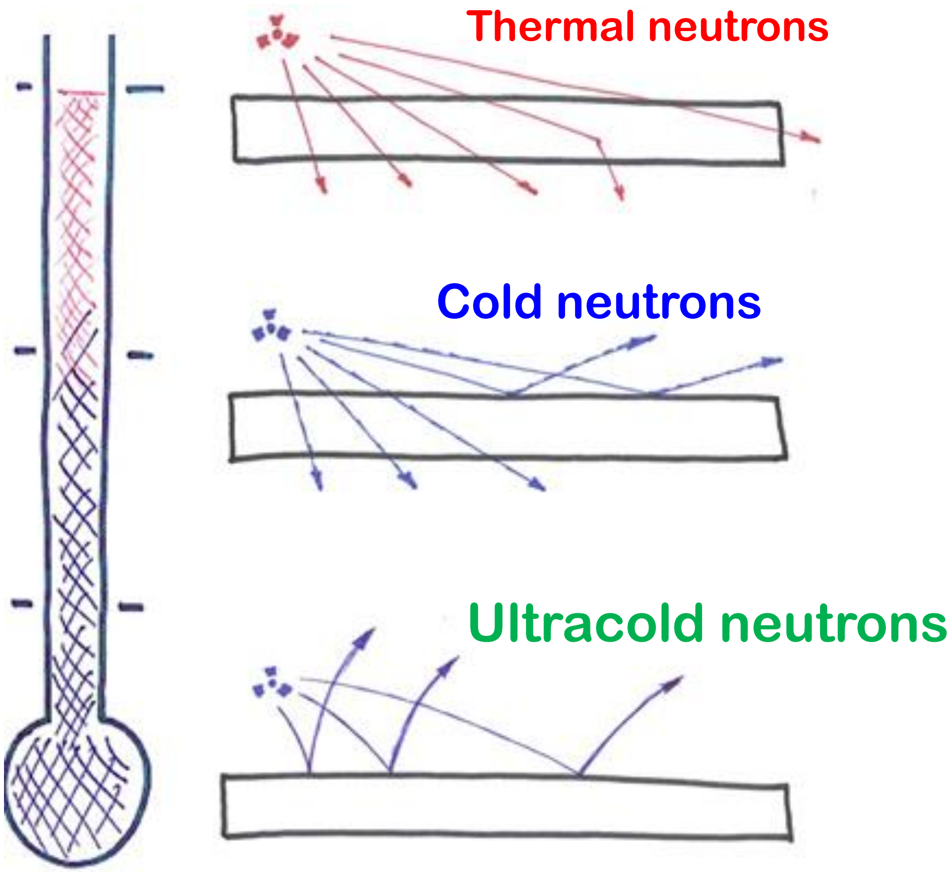
Neutron optics, cold and ultracold neutrons



Cold neutrons

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

have large wavelength

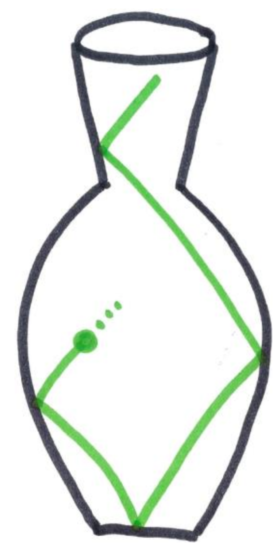
$$\lambda > 0.2 \text{ nm}$$

They behave like waves,

affected by the

Fermi potential of matter

(order of 100 neV)



Neutrons with energy < 100 neV,

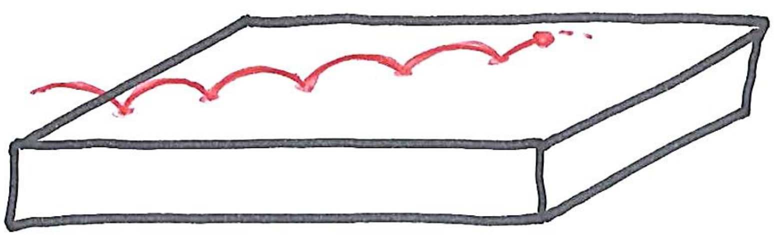
are reflected by material walls

they can be stored in material bottles.

Bouncing neutrons: quantum states

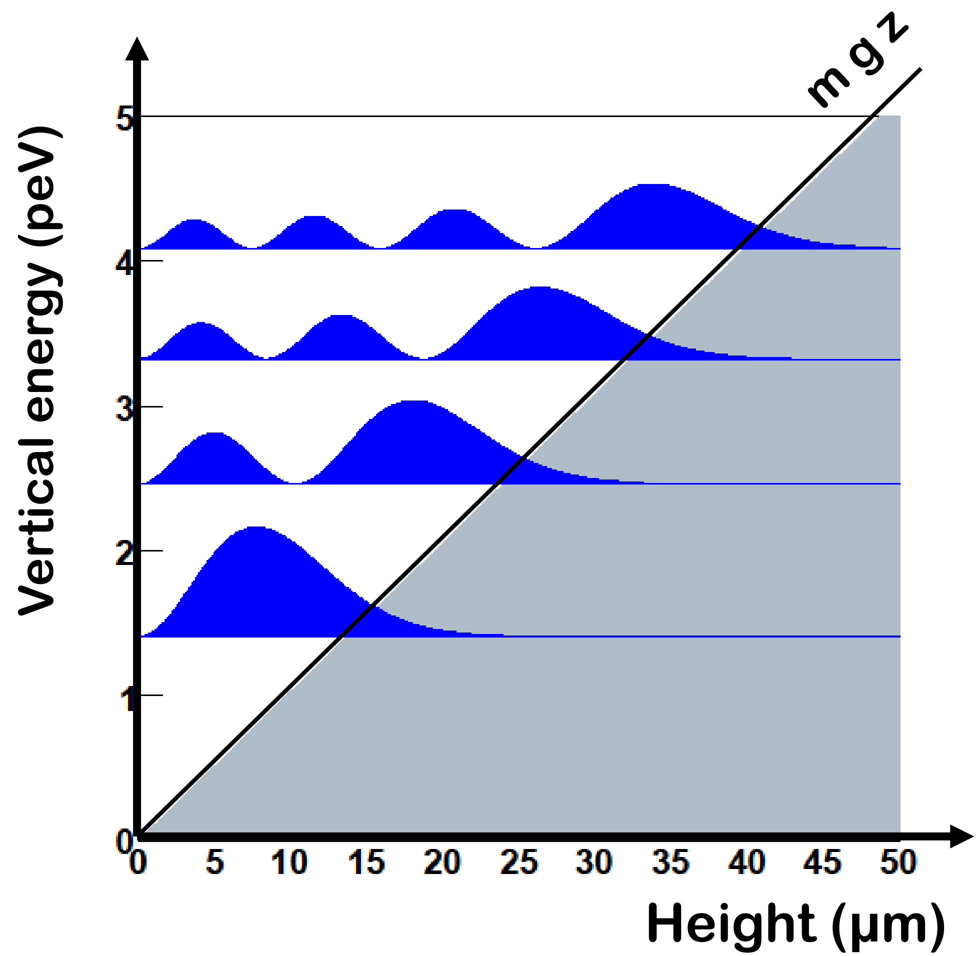
Neutrons with energy < 100 neV

can bounce above a glass mirror.

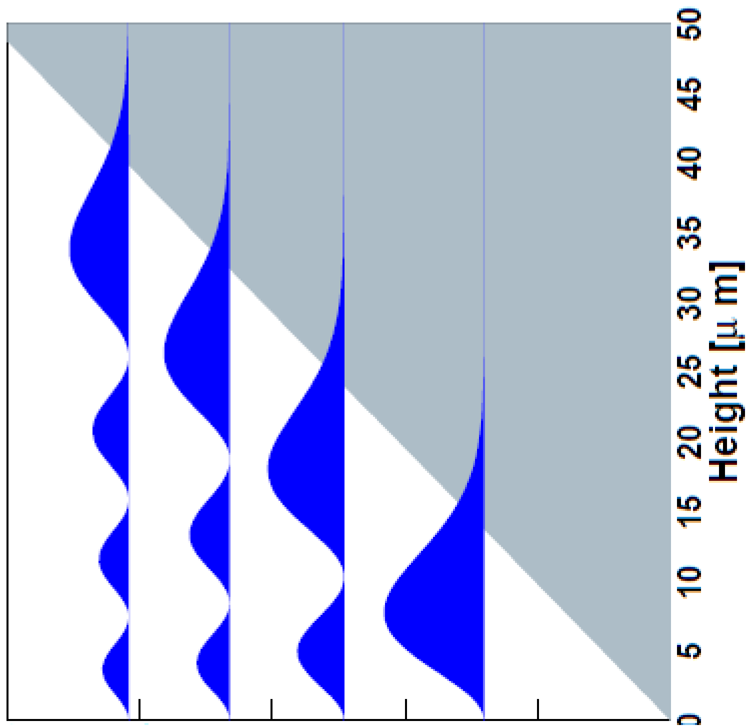


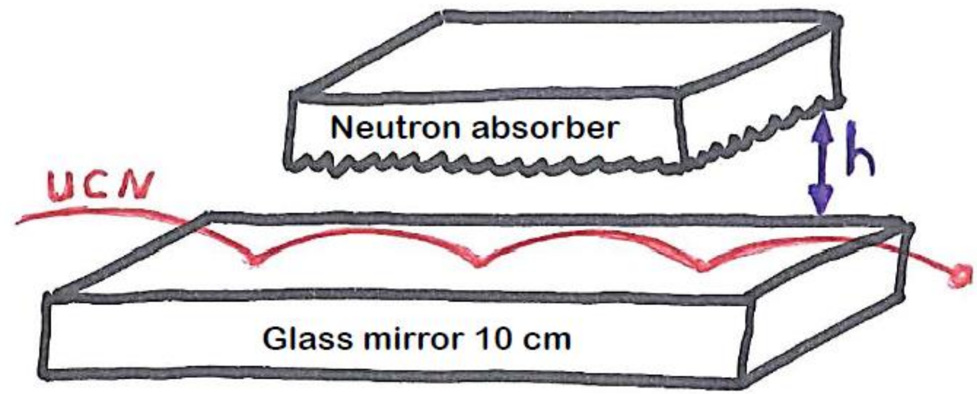
The vertical motion is a simple quantum well problem

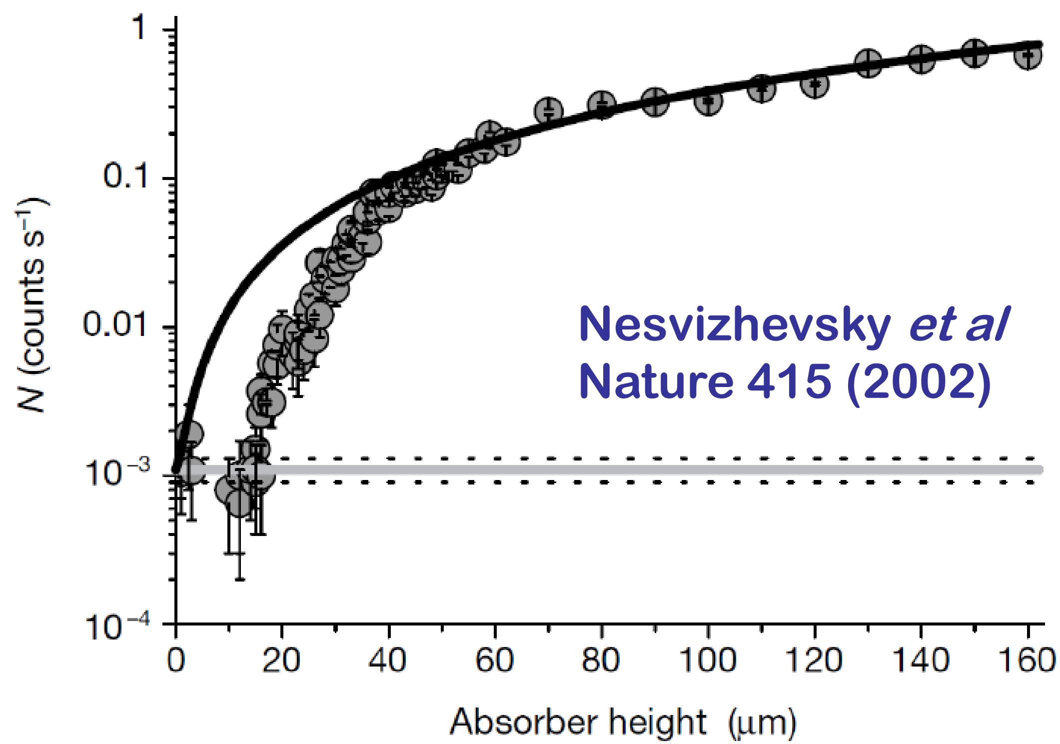
$$-\frac{\hbar^2}{2m}\frac{d^2\psi}{dz^2}+mgz\,\psi=E\,\psi$$



Discovery of the quantum states at ILL Grenoble

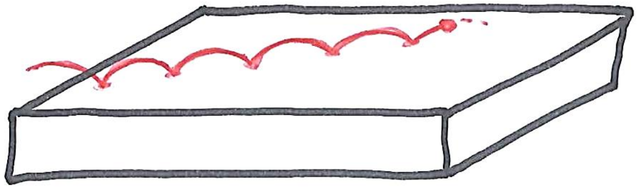






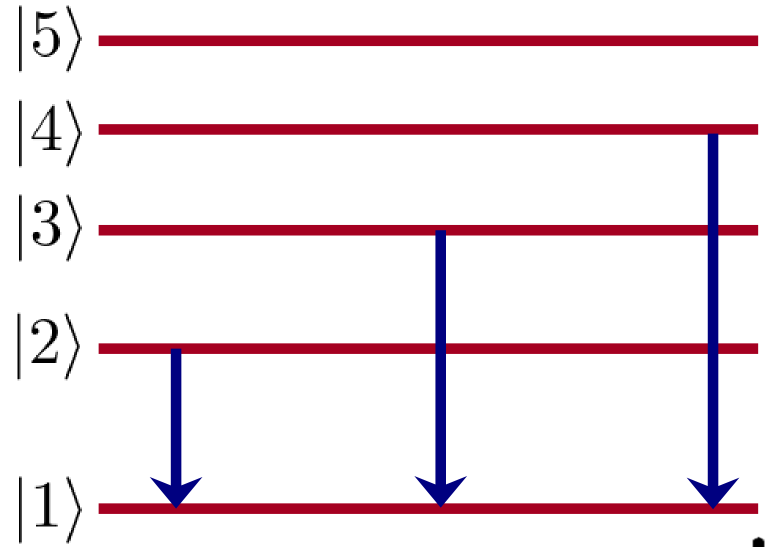
Nesvizhevsky *et al*
Nature 415 (2002)

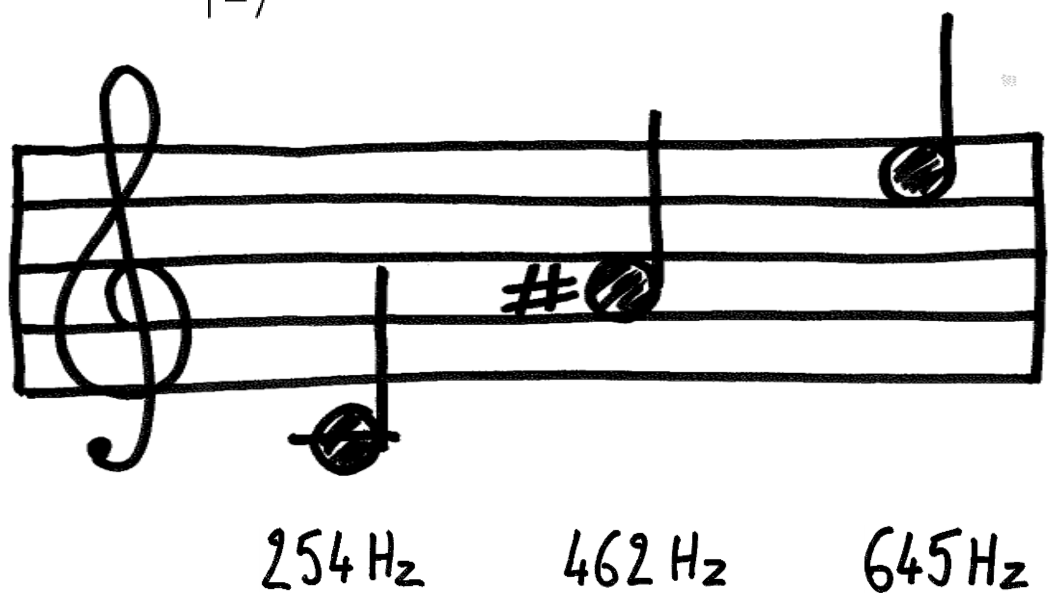
Bouncing neutron: quantum music



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

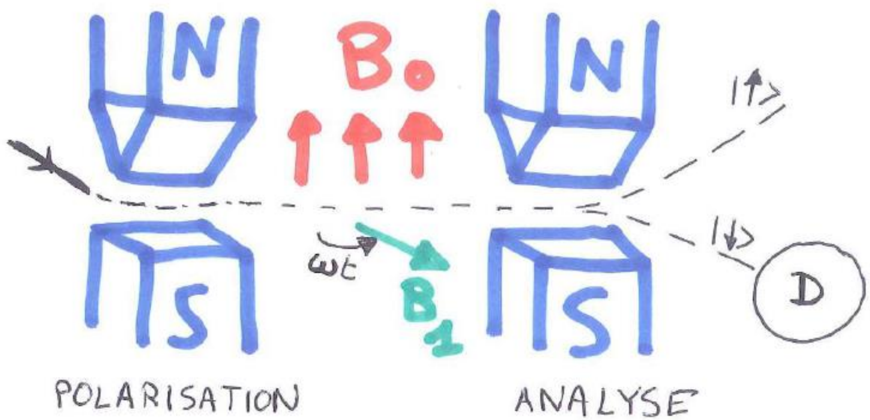
$$\frac{1}{2\pi}\sqrt[3]{\frac{mg^2}{2\hbar}} \times \left| \begin{array}{l} 1{,}75 \\ 3{,}18 \\ 4{,}45 \\ \vdots \end{array} \right.$$

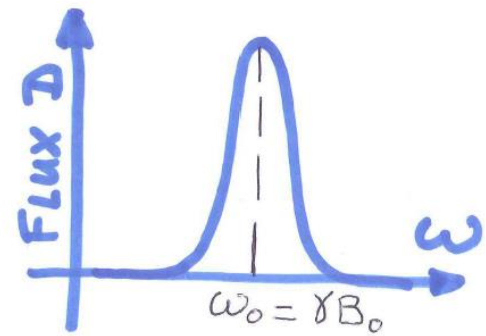




Gravity resonance spectroscopy

Rabi experiment (1939)



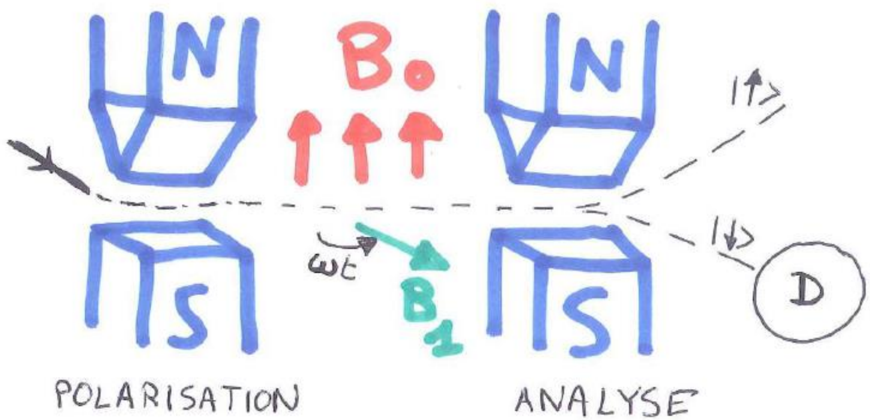


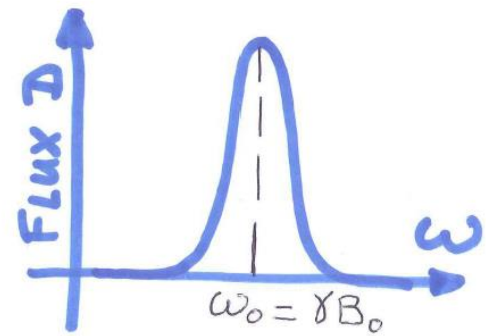
Rabi formula

$$P_{2\to1} = \frac{\sin^2\left(\sqrt{\delta\omega^2 + \Omega^2}\, t/2\right)}{1 + \delta\omega^2/\Omega^2}$$

Gravity resonance spectroscopy

Rabi experiment (1939)





Rabi formula

$$P_{2\to 1} = \frac{\sin^2\left(\sqrt{\delta\omega^2 + \Omega^2}\, t/2\right)}{1 + \delta\omega^2/\Omega^2}$$

$$\Omega = \langle 2|\widehat{V_0}|1\rangle/\hbar$$

State selection

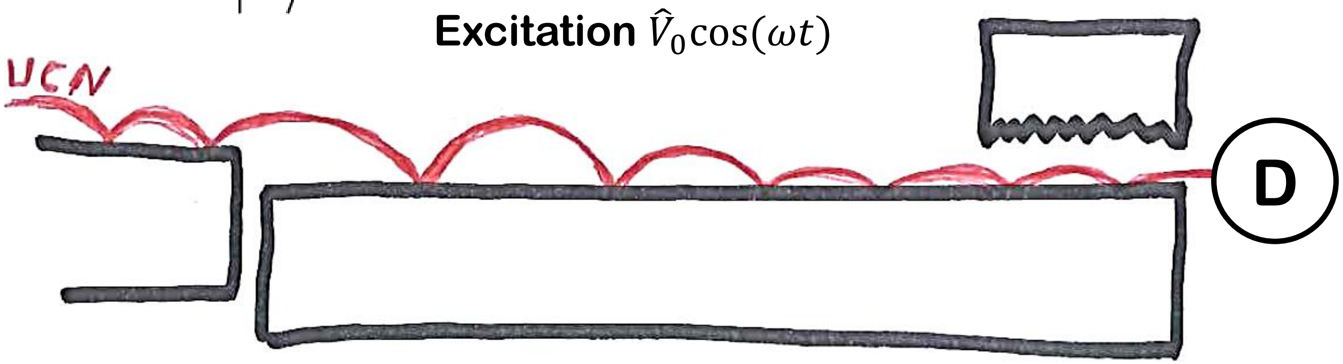
$|2\rangle$

$|2\rangle$

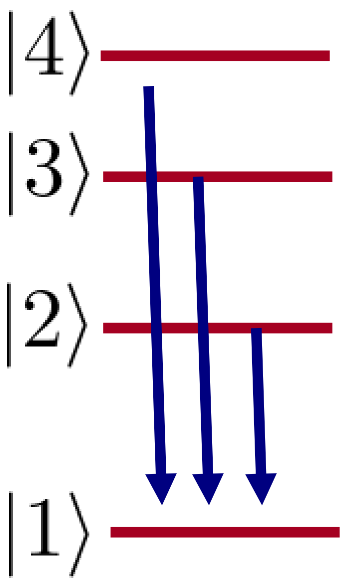
$|1\rangle$

Excitation $\hat{V}_0\cos(\omega t)$

$|1\rangle$ **?**



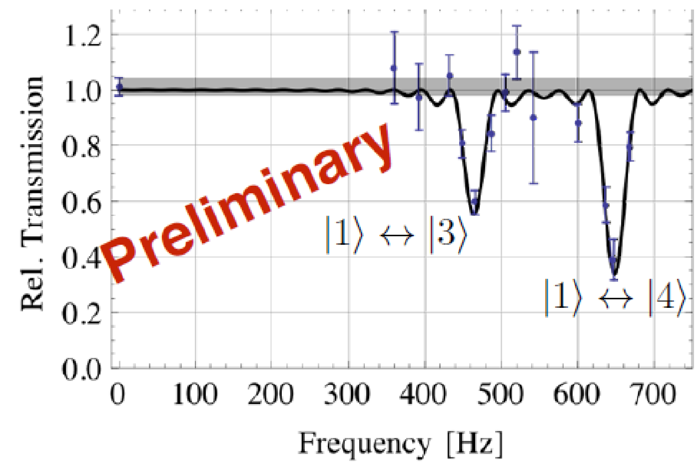
How to excite resonant transitions?



1) Mirror vibrations $h(t)$

$$\hat{V}(t) = -\frac{dh}{dt}\,\widehat{p_z}$$

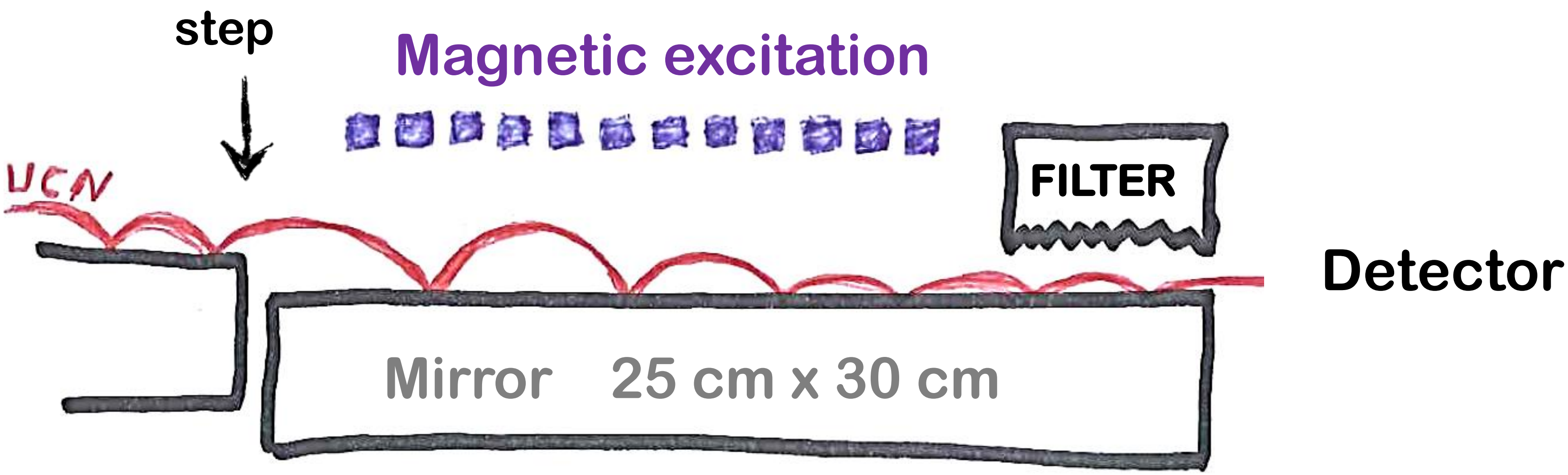
qBounce

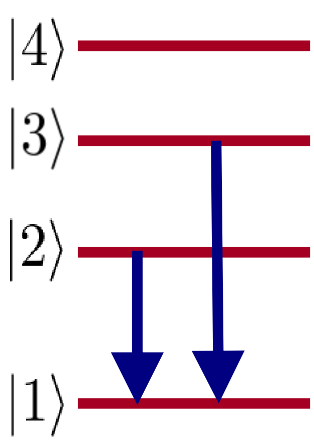


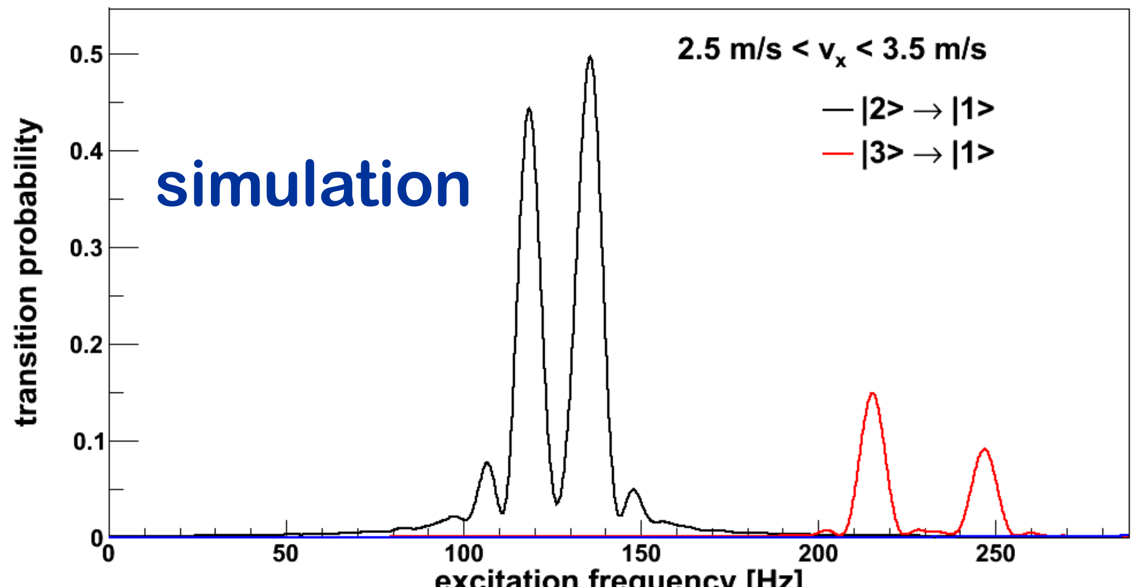
2) Magnetic excitation

$$\hat{V}(t) = \pm\mu\,|B|(t) \approx \pm\mu\frac{d|B|}{dz}(t)\,\hat{z}$$

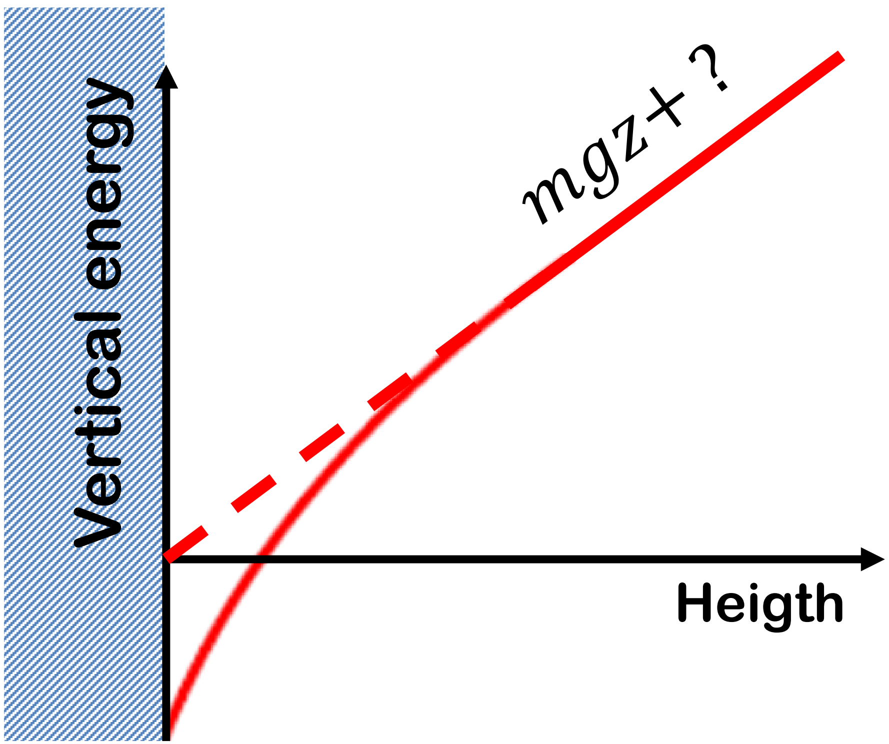
Resonant transitions in GRANIT (coming soon)







Searching for a fifth force



Consequences for the quantum states

1. **Squeezing of the wave functions**
2. **Dilatation of the energy spectrum**

Chameleon case:

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

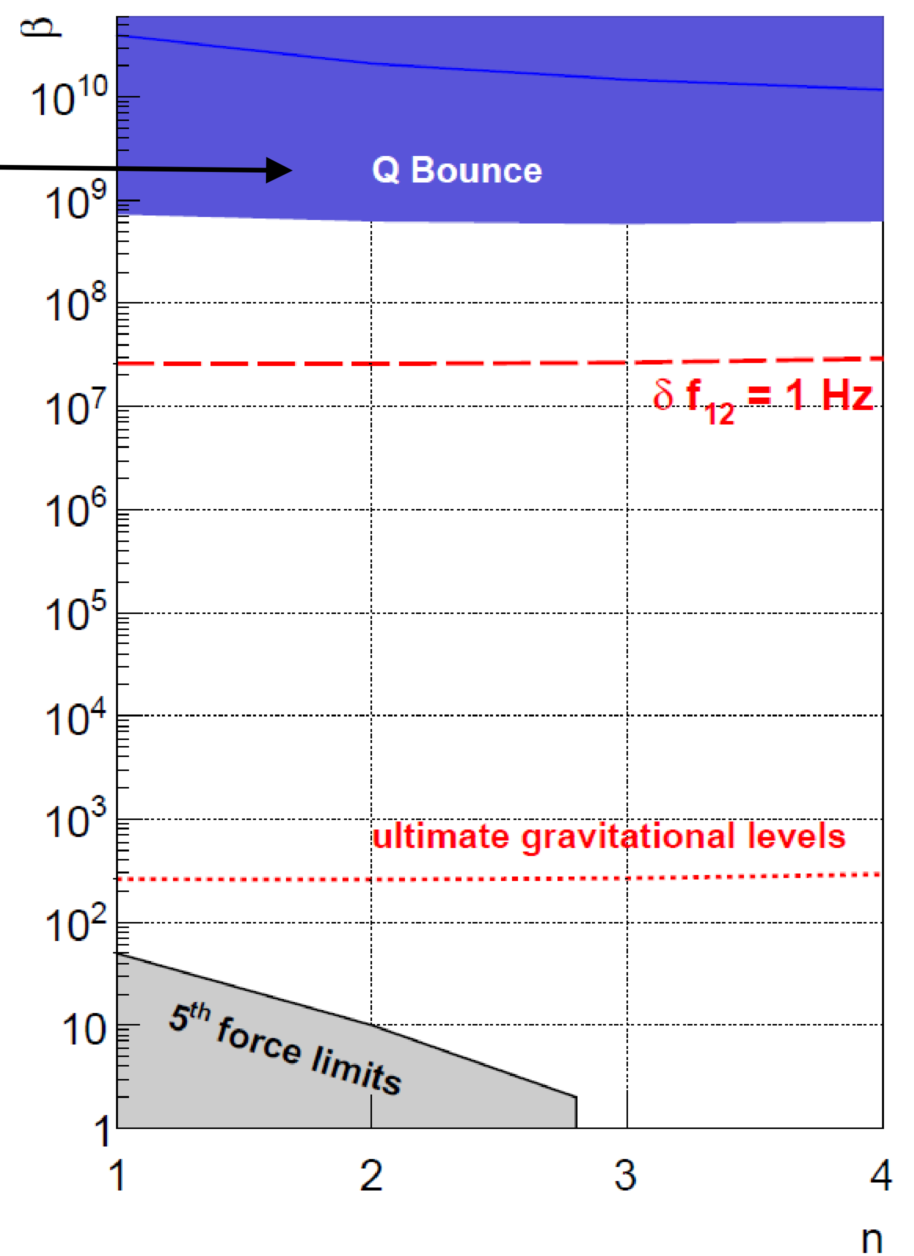
Field profile above the mirror

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

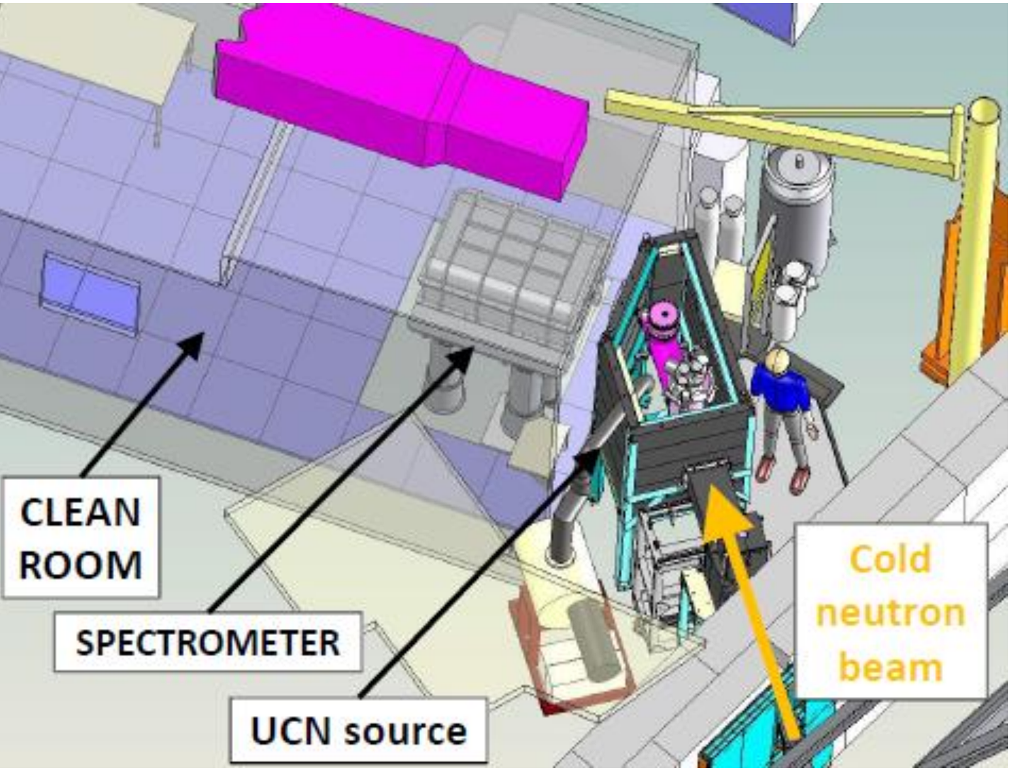
Bouncing neutron sensitivity to the chameleon

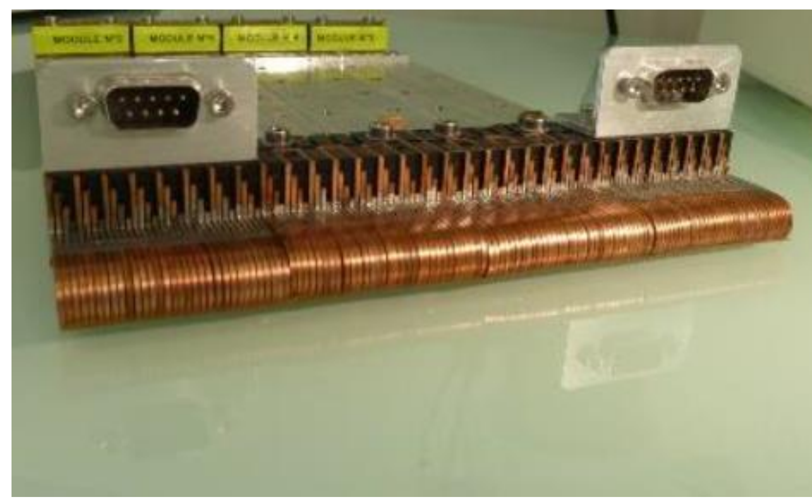
PRL **112** 151105 (2014)

Based on the first (2011) Qbounce experiment.



The GRANIT instrument
at ILL level C

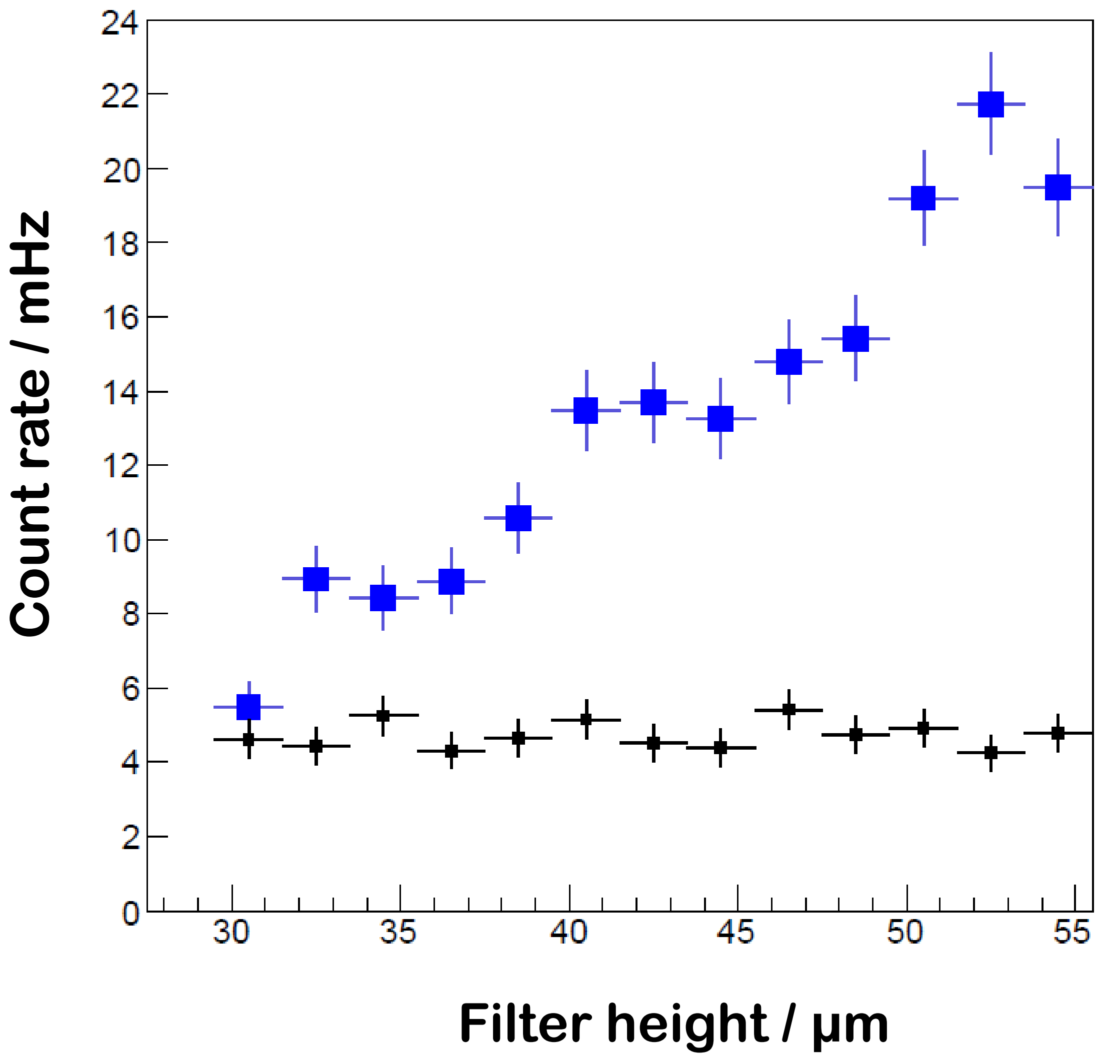




First UCNs in GRANIT in 2013.

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

First result (July 2016): testing the filter



UCN valve open

UCN valve closed
(Background)

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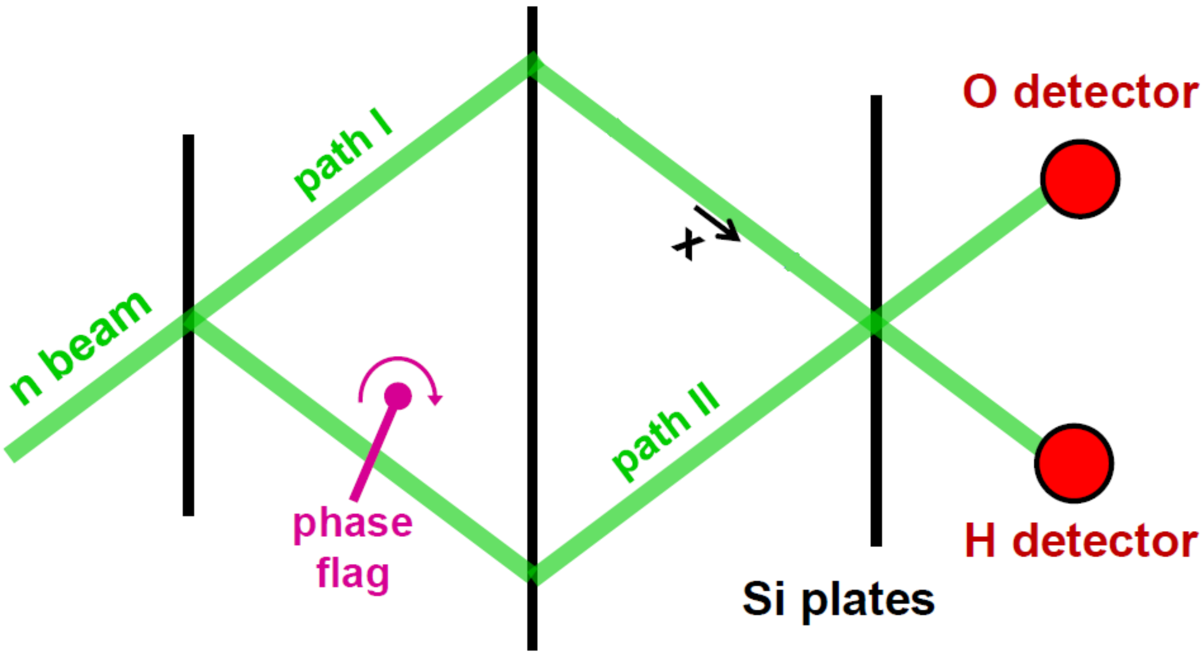
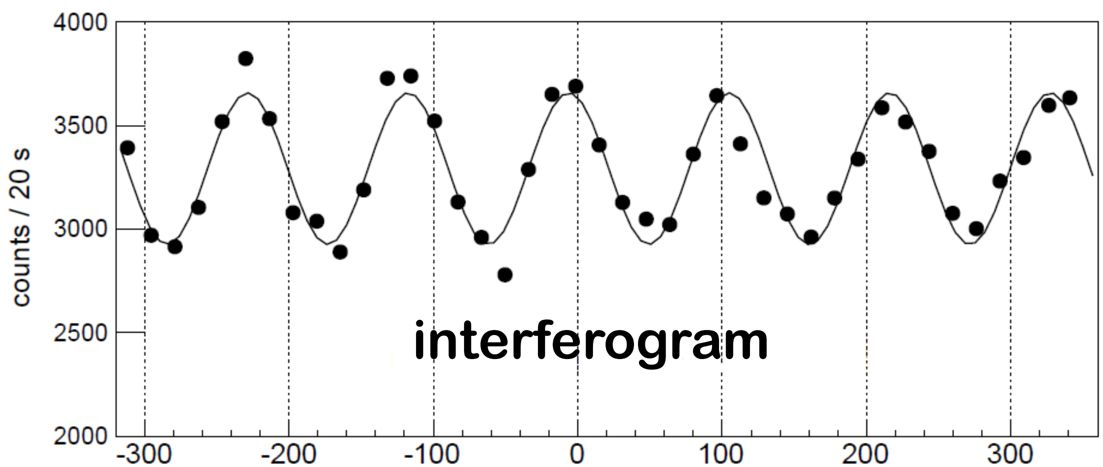
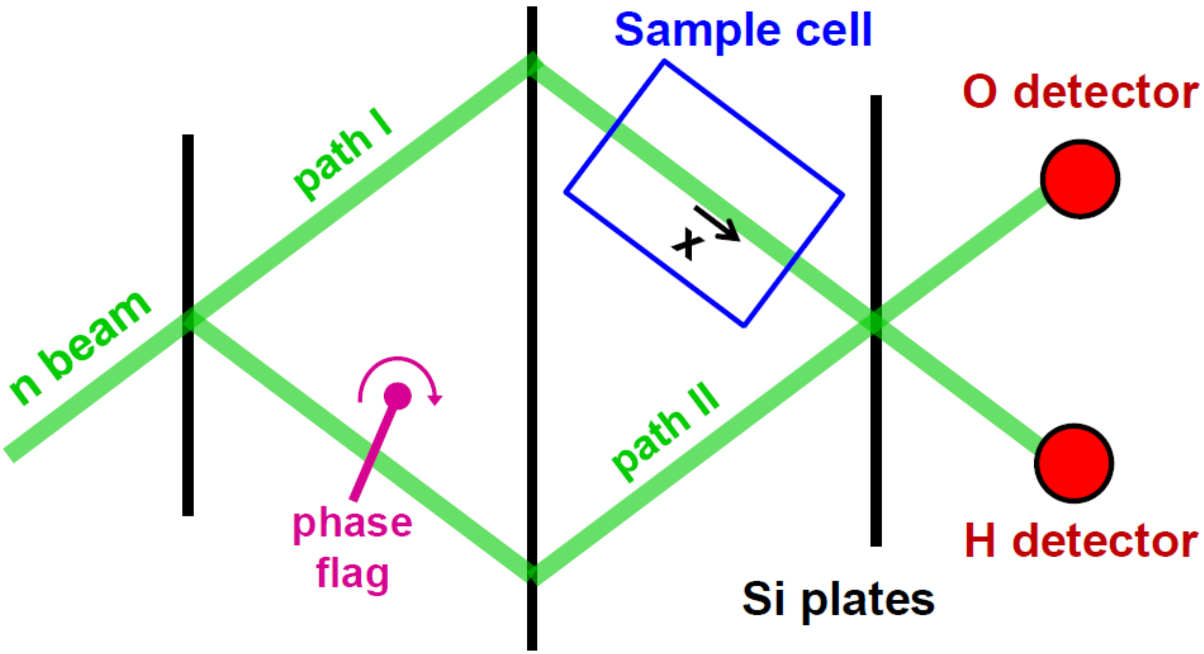
Principle of neutron interferometry 1





Principle of neutron interferometry 2



Phase shift due to the sample:

$$\xi = -\frac{1}{v\,\hbar}\int V(x)\,dx$$

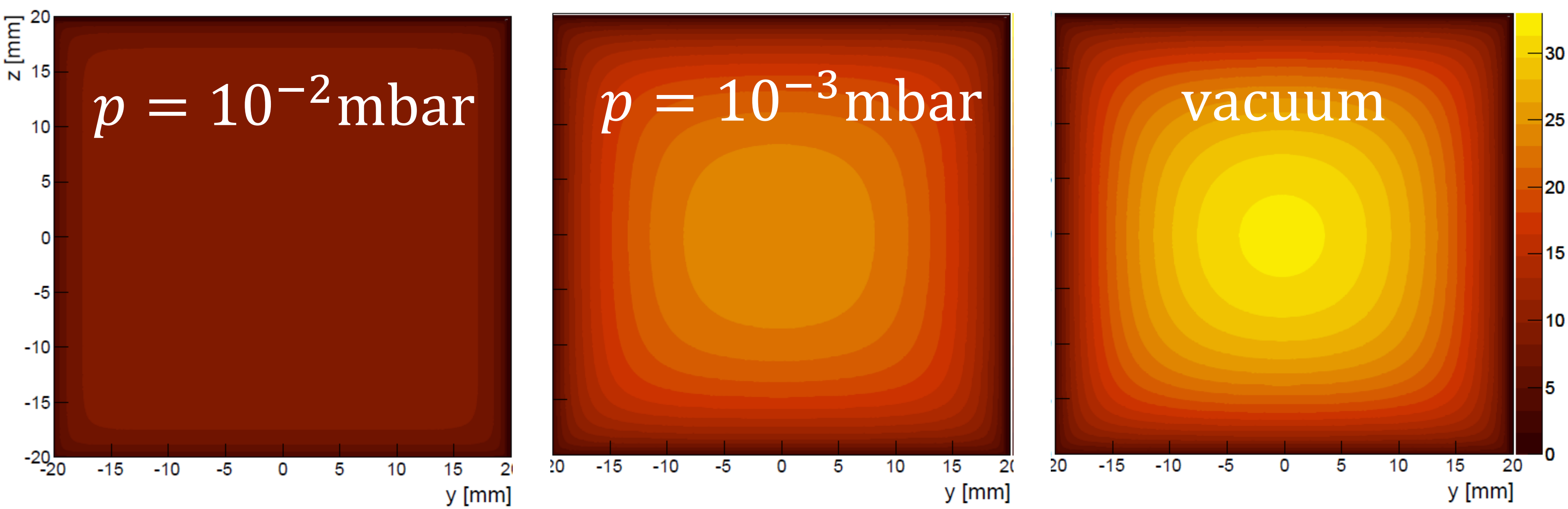
neutron potential in a chameleon field:

$$V(x) = \beta\,\frac{m}{M_{\mathrm{Planck}}}\,\varphi(x)$$

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)

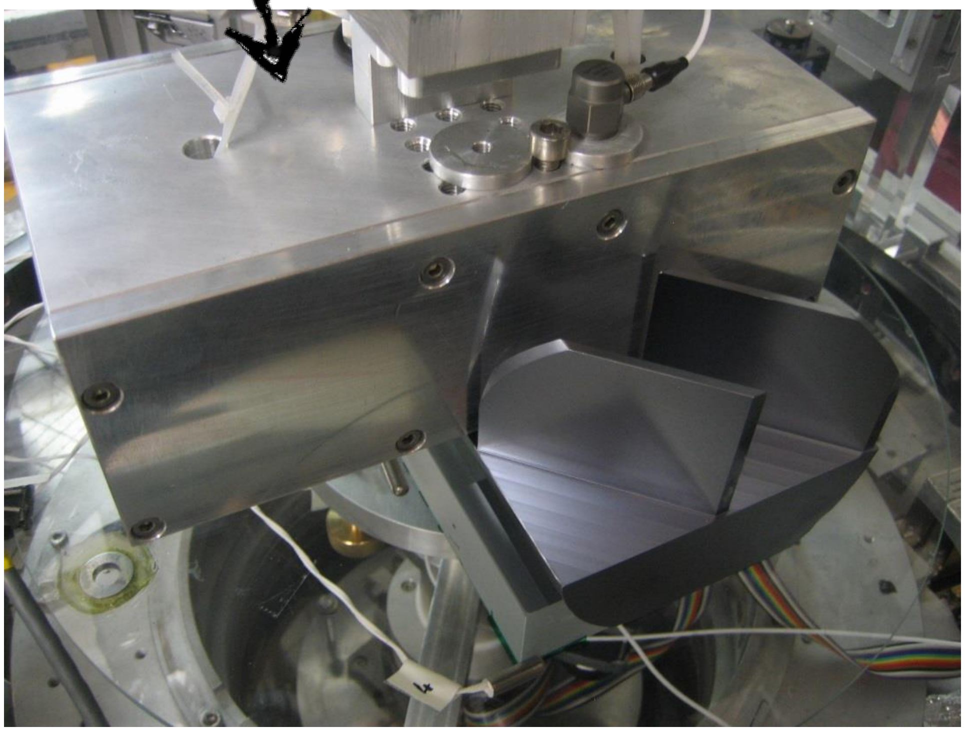
We plot the transverse field profile $\varphi(y,z)/\Lambda$



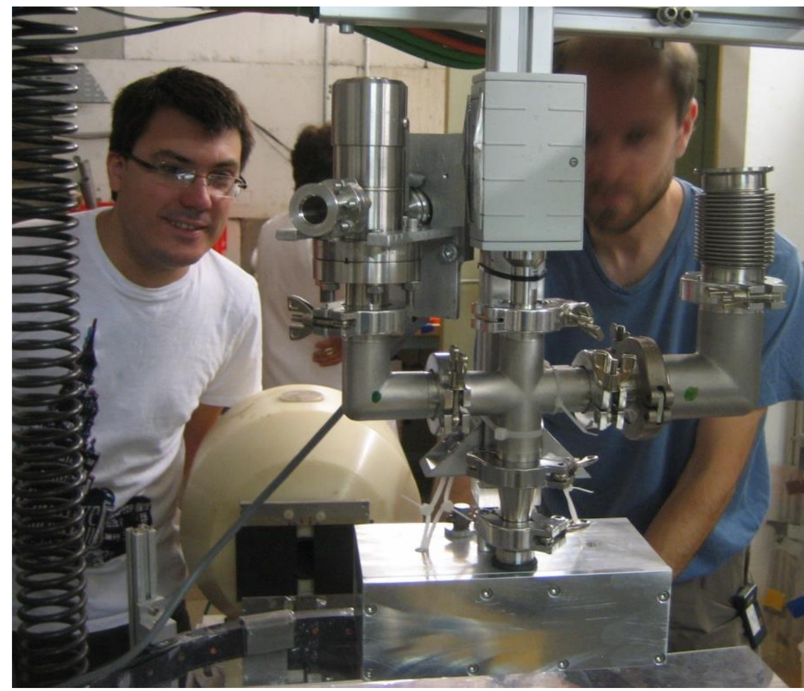
Numerical solution of the chameleon equation for $n = 1$ and $\beta = 5 \times 10^7$

The first experiment at the S18 instrument (ILL)

Dedicated vacuum chamber built by the Atominstitut in Vienna

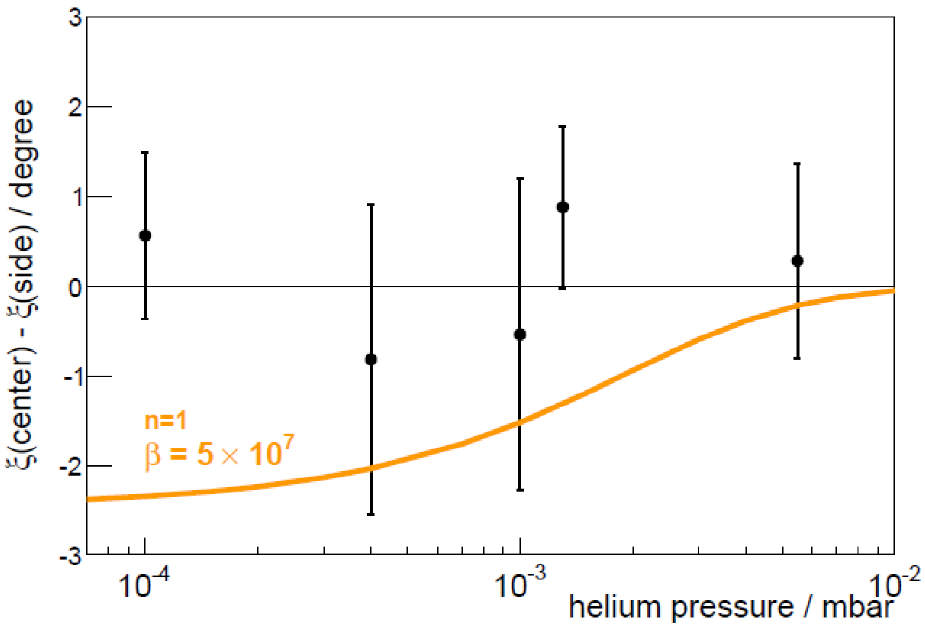


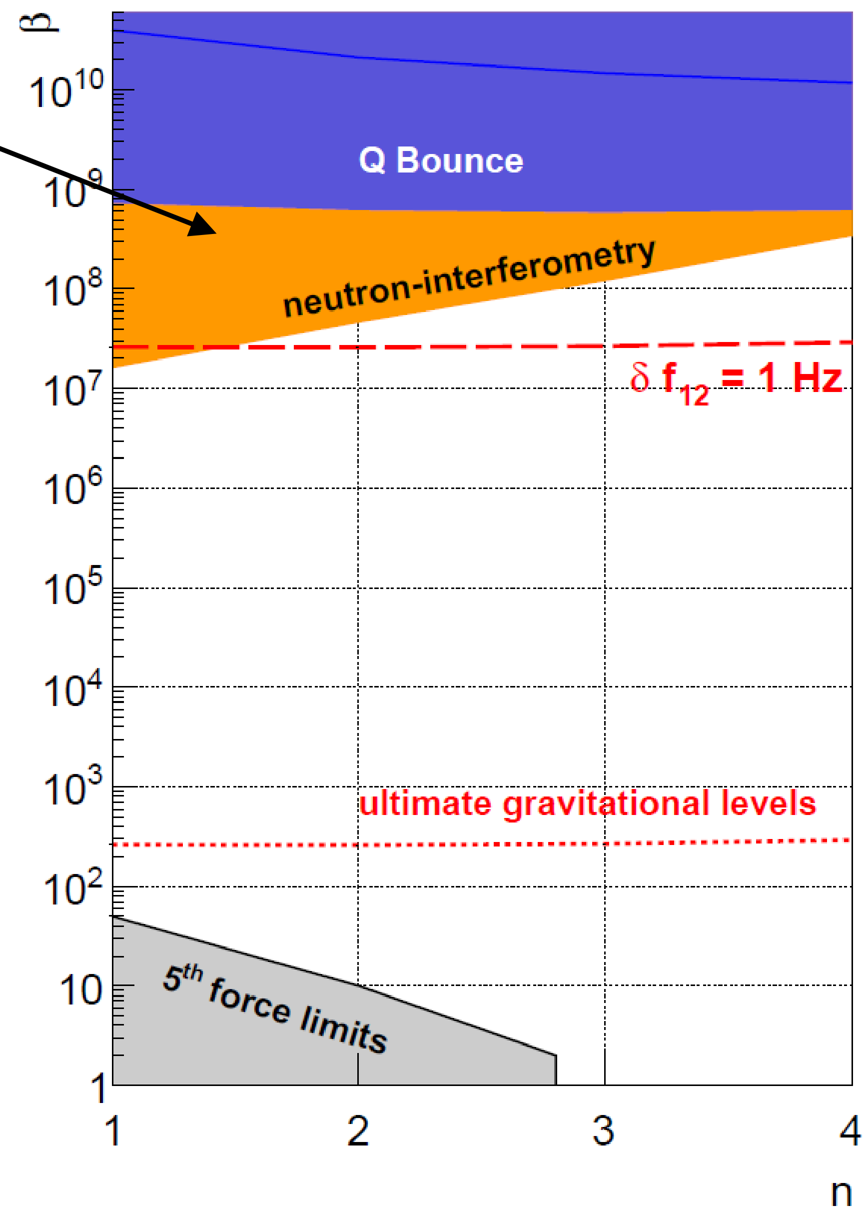
Hartmut Lemmel



Results of the summer 2013 experiment

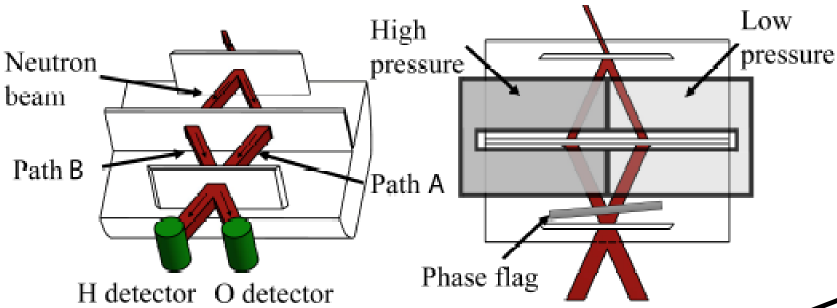
Phys. Lett. B **743**, 310 (2015)





We have measured the field profile,
by moving the vacuum cell,
as a function of the helium pressure

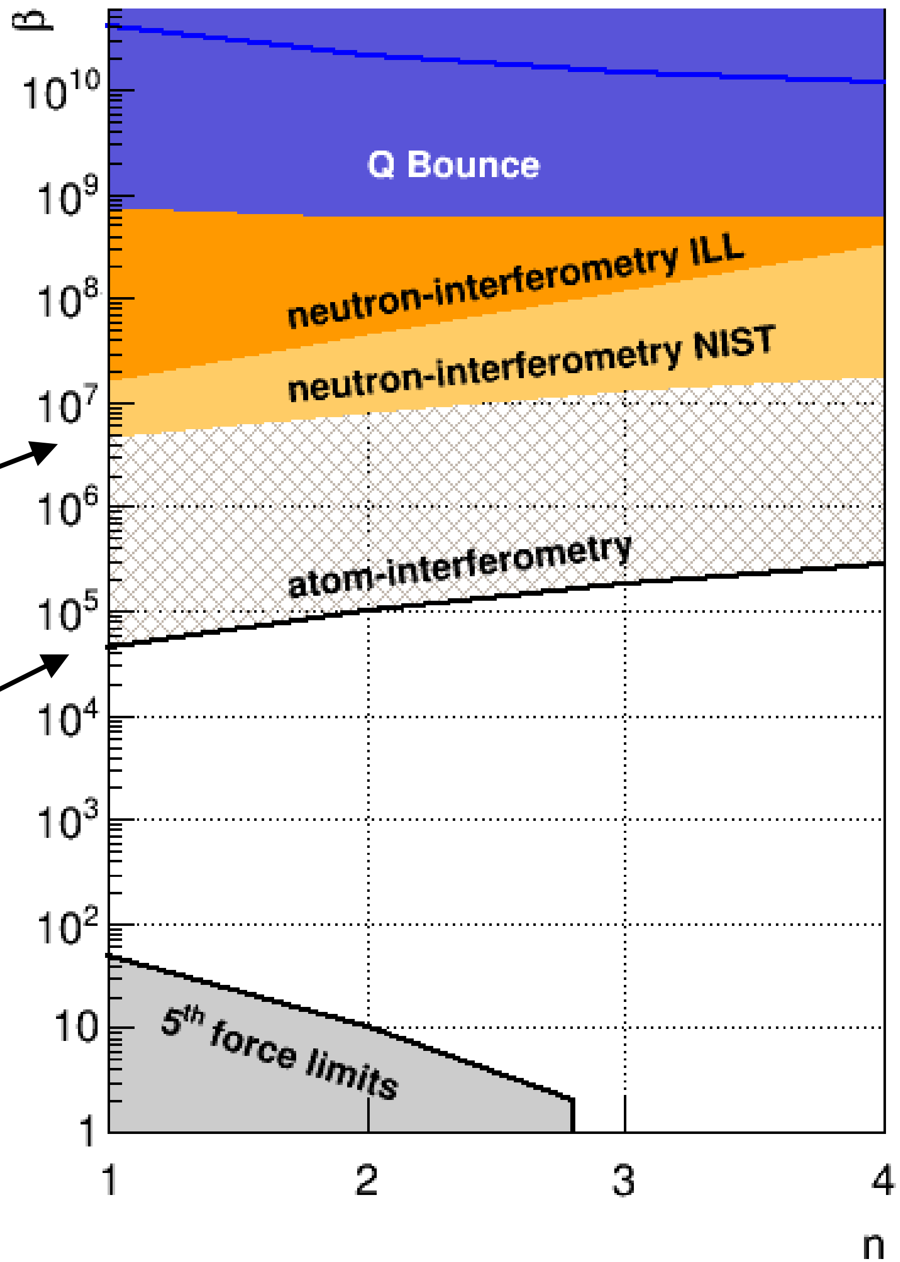
Status in 2016



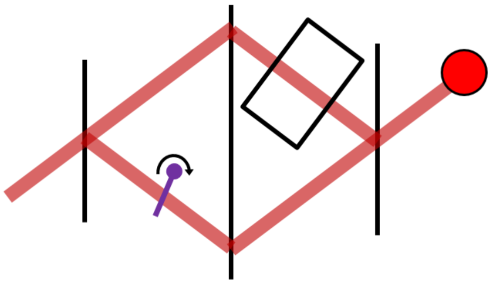
PRD **93**, 062001 (2016)

Science **349** 849 (2015)

Interferometry with Cs atoms

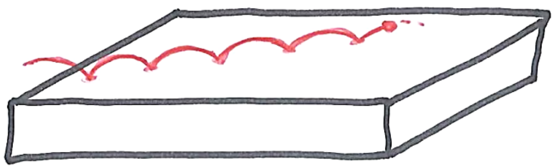


Concluding remarks



Two n.interf experiments: ILL and NIST

Ultimate sensitivity not reached yet.
Maybe do interferometry with colder neutrons?



Two n.bouncing experiments:
QBounce@ILL and GRANIT@ILL

Neutron bouncer: exciting prospects to test the equivalence principle and to search for exotic forces.

Thank you

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

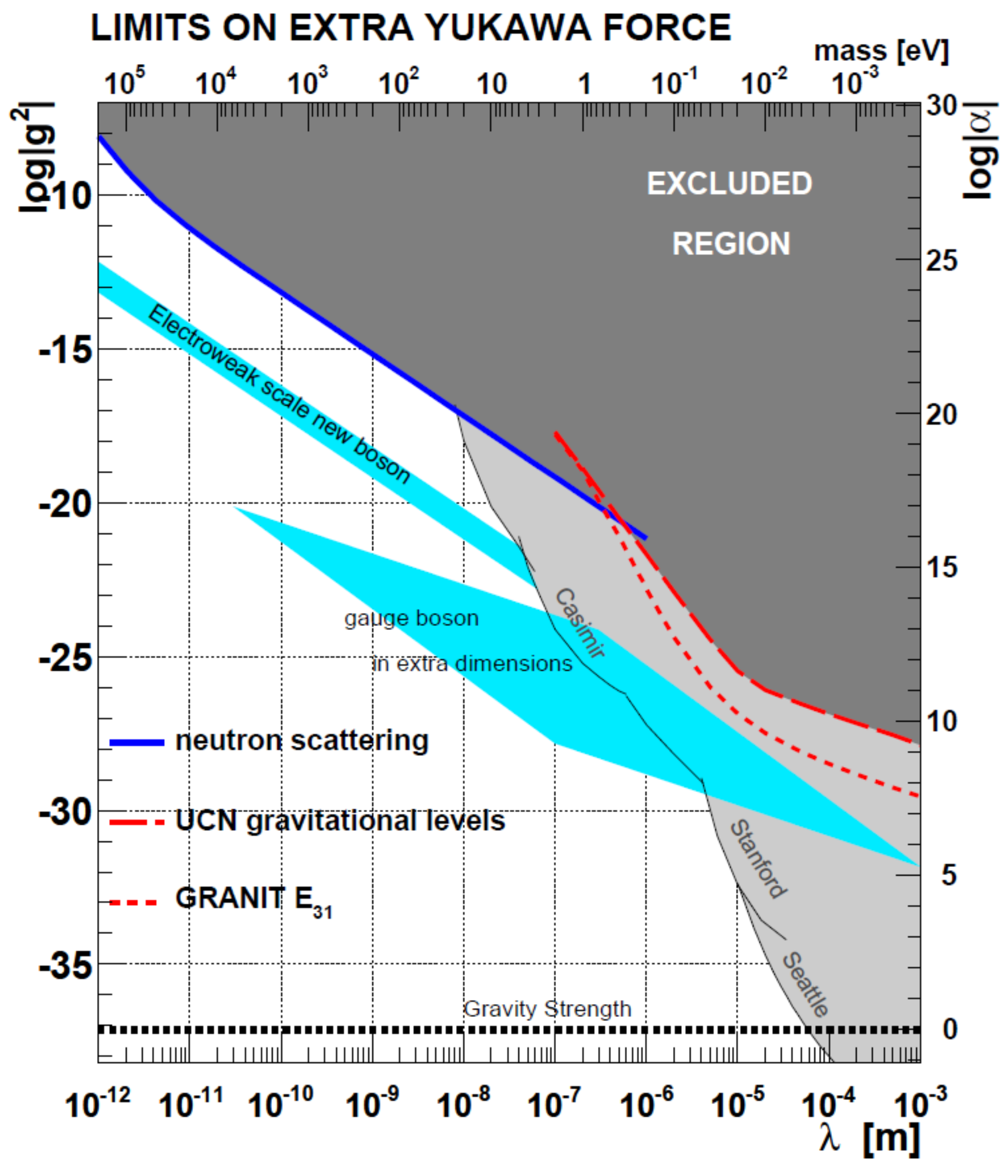
$$E_0 = m_g g z_0 = \left(\frac{m_g^2}{m_i}\frac{g^2\hbar^2}{2}\right)^{1/3}$$

One can tell separately the inertial and gravitational mass !

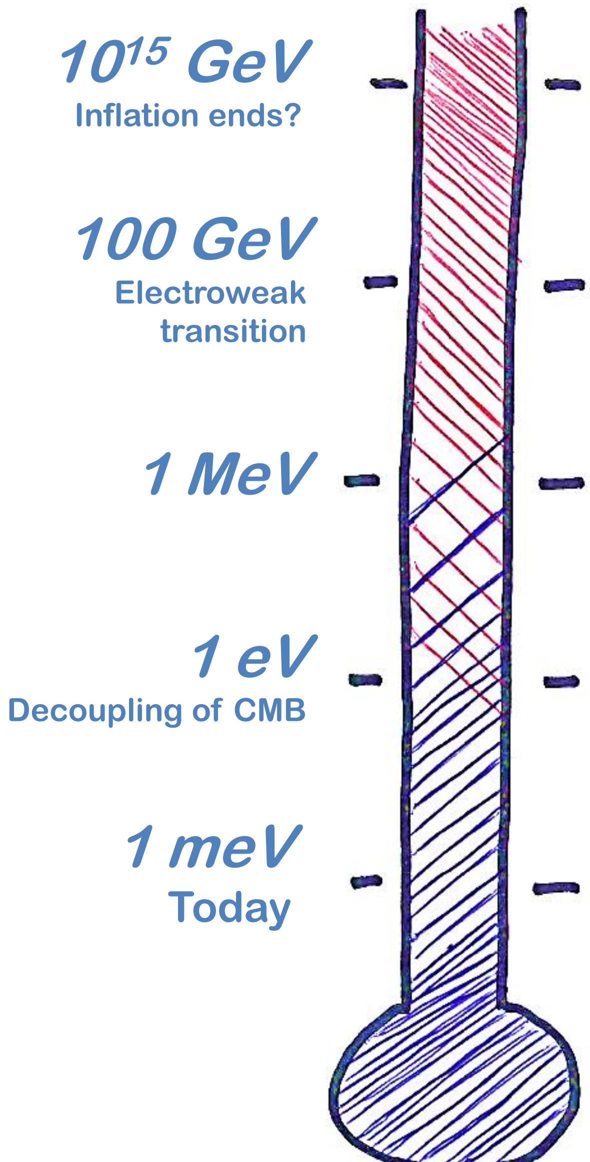
Searching for a fifth force

Modification of the Newton's law?

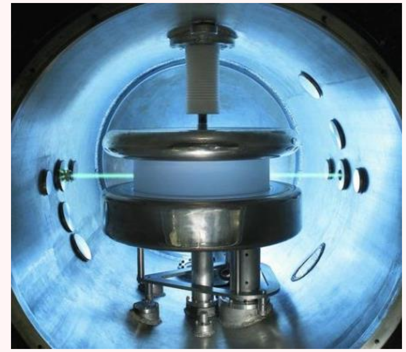
$$V(r) = -\frac{GMm}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right)$$



neutrons and the Universe



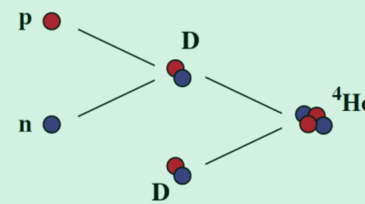
Baryogenesis



CP violation:
Search for the neutron electric dipole moment to explain the matter-antimatter asymmetry

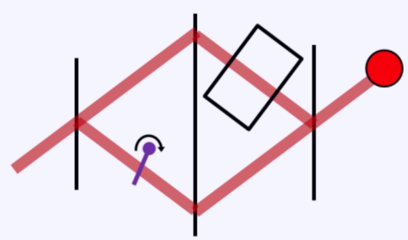
Nucleosynthesis

Measuring the neutron lifetime to predict the primordial production of light elements



Dark energy

neutron interferometry



bouncing neutrons