

GRANIT-2010 Workshop

14-19 February 2010, Les Houches, France



*Countries ~12
Europe, Asia, USA, Australia*



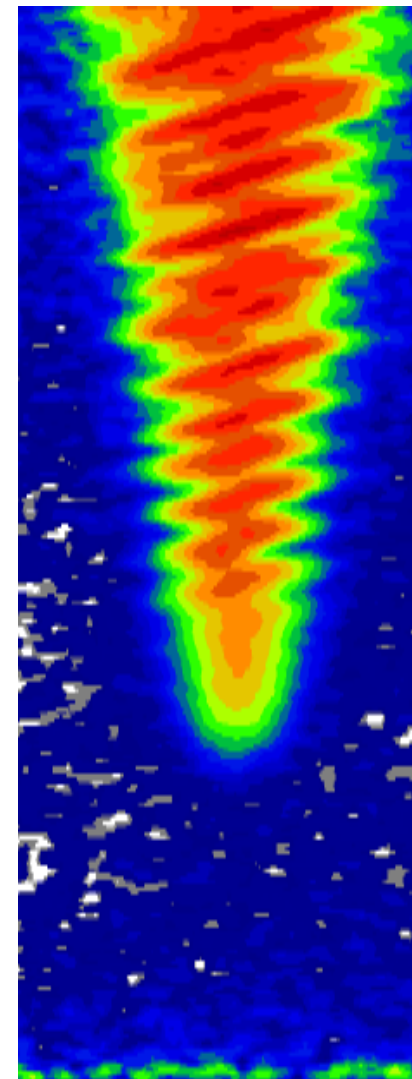
1. Gravitational quantum states of neutrons



2. GRANIT project



3. Centrifugal quantum states of neutrons



Quantum states of neutrons in the Earth's gravitational field

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The discrete quantum properties of matter are manifest in a variety of phenomena. Any particle that is trapped in a sufficiently deep and wide potential well is settled in quantum bound states. For example, the existence of quantum states of electrons in an electromagnetic field is responsible for the structure of atoms¹⁶, and quantum states of nucleons in a strong nuclear field give rise to the structure of atomic nuclei¹⁷. In an analogous way, the gravitational field should lead to the formation of quantum states. But the gravitational force is extremely weak compared to the

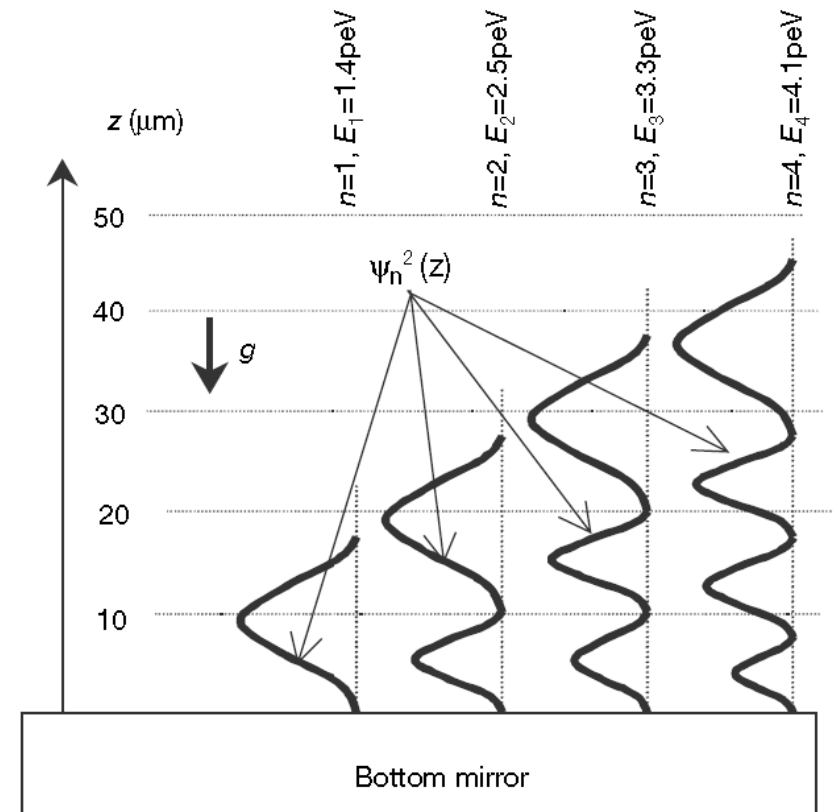
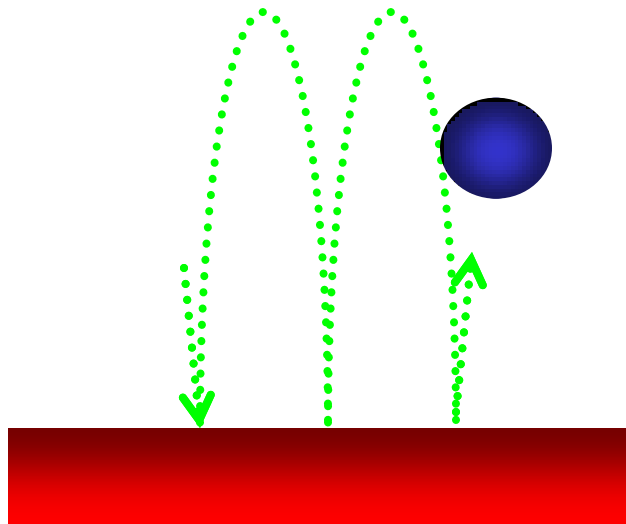


Figure 1 Wavefunctions of the quantum states of neutrons in the potential well formed by the Earth's gravitational field and the horizontal mirror. The probability of finding neutrons at height z , corresponding to the n th quantum state, is proportional to the square of the neutron wavefunction $\psi_n^2(z)$. The vertical axis z provides the length scale for this phenomenon. E_n is the energy of the n th quantum state.

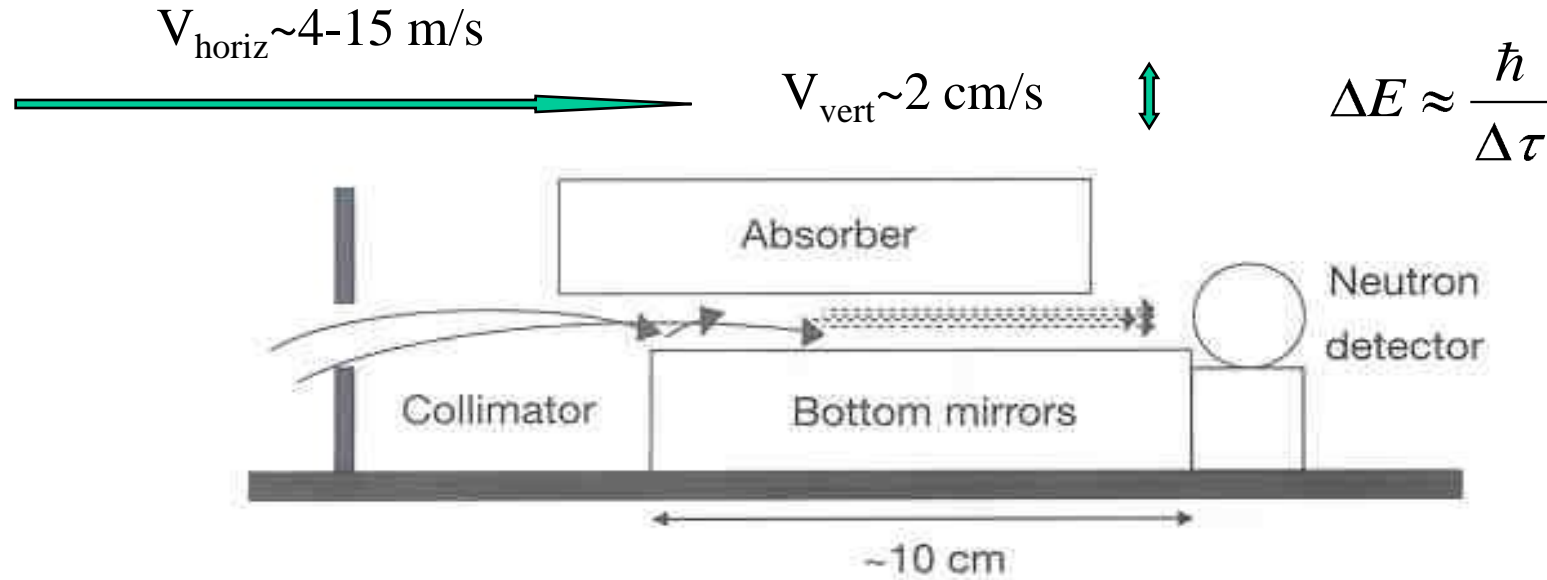


Neutron above mirror in gravity field

- 1) **Electrical neutrality** (usually gravitational interaction of an object with surface is much weaker than other interactions)
- 2) **Long life-time**
- 3) **Small mass** $\left(\Delta v \cdot \Delta x \approx \frac{\hbar}{m} \right) \left(\Delta E \approx \frac{\hbar}{\Delta \tau} \right)$
- 4) **Energy (effective temperature) of UCN is extremely low; it is not equal to the surface temperature (the temperature of neutrons in gravitational quantum states is $\sim 10^{-8} \text{K}$)**

Energy of quantum states, in Bohr-Zommerfeld approximation, equals :

$$E_n \approx \sqrt[3]{\left(\frac{9 \cdot m_n}{8} \right) \cdot \left(\pi \cdot \hbar \cdot g \cdot \left(n - \frac{1}{4} \right) \right)^2}$$



Selection and measurement of vertical and horizontal components of neutron velocity:

Maximum vertical velocity is defined by height of scatterer/absorber above mirror

The range of horizontal neutron velocities is defined by relative position of plates of the entrance collimator and the slit between mirror and scatterer

Experimental installation and method

Model of tunneling through gravitational barrier

$$\xi \gg 1$$

$$\Gamma_n(\xi) = \omega_n \cdot D(\xi)$$

$$\omega_n \approx (E_{n+1} - E_n) / \hbar$$

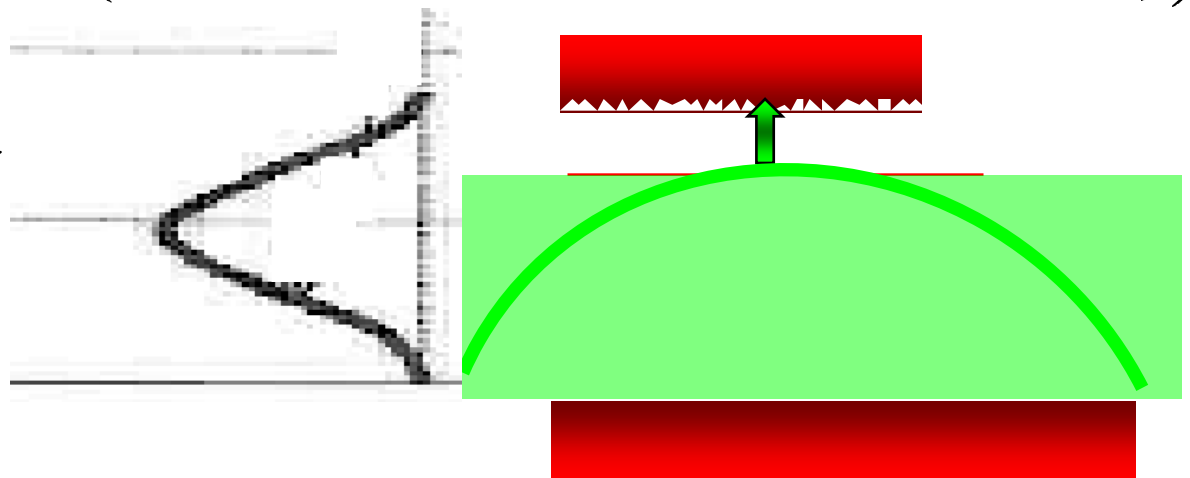
$$D(\xi) \approx \text{Exp}\left[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}\right],$$

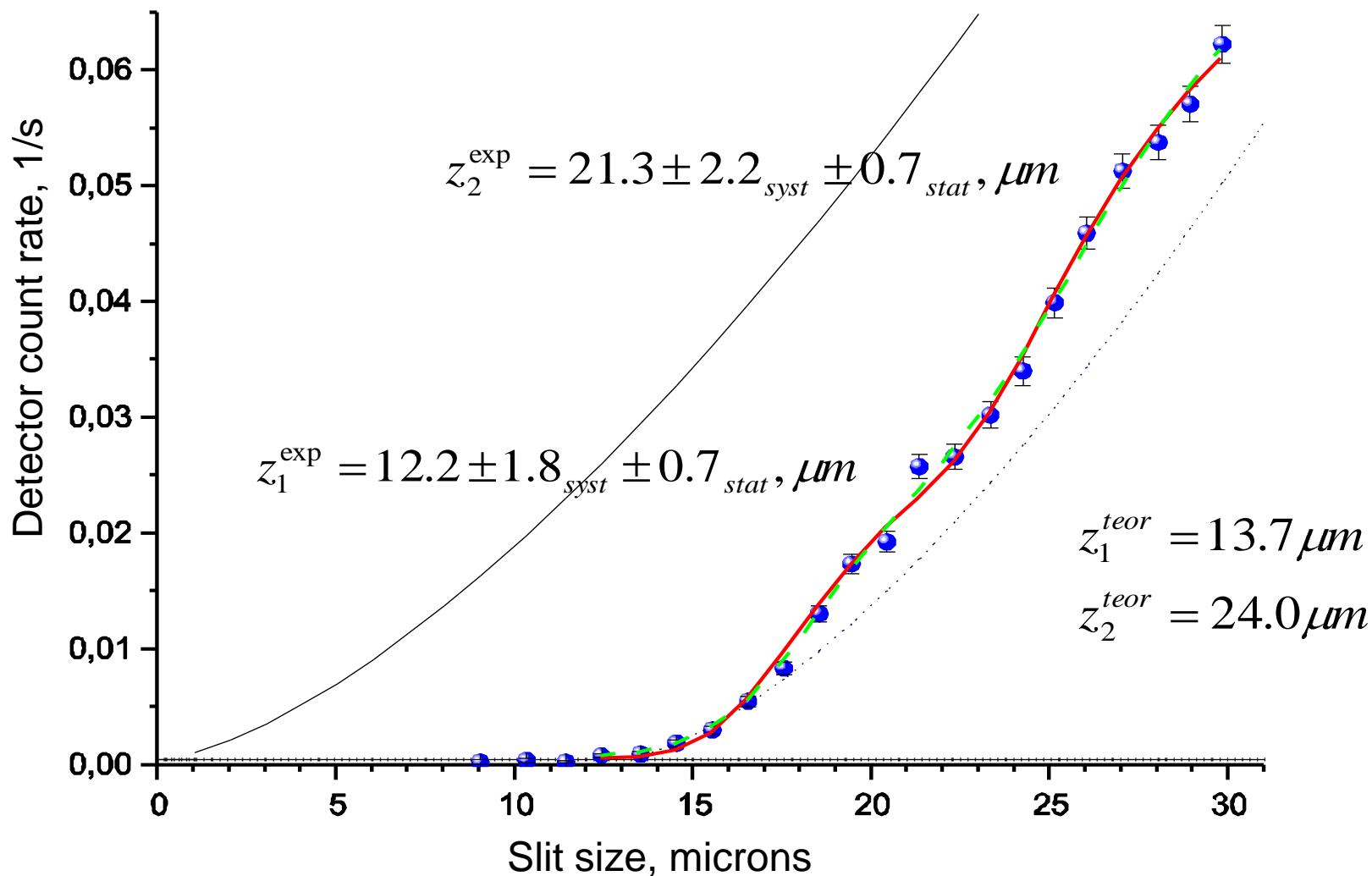
$$P_n(\xi) = \text{Exp}(-\Gamma_n(\xi) \cdot \tau)$$

$$F(\Delta z, V_{hor}) = \sum_n \left(\beta_n \cdot \text{Exp} \left(-\alpha \cdot \frac{L}{V_{hor}} \cdot C_n^2 \cdot \text{Exp} \left(-\frac{4}{3} \cdot \left(\frac{\Delta z - z_n}{z_0} \right)^{\frac{3}{2}} \right) \right) \right)$$

$$D(\xi) = \begin{cases} 1, \xi < 0 \\ A_n \cdot \text{Exp}\left[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}\right], \xi \end{cases}$$

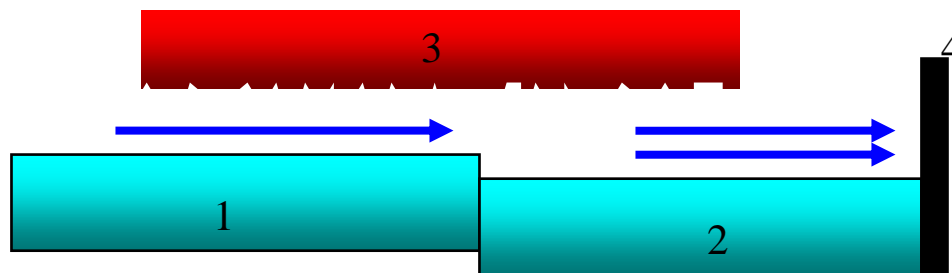
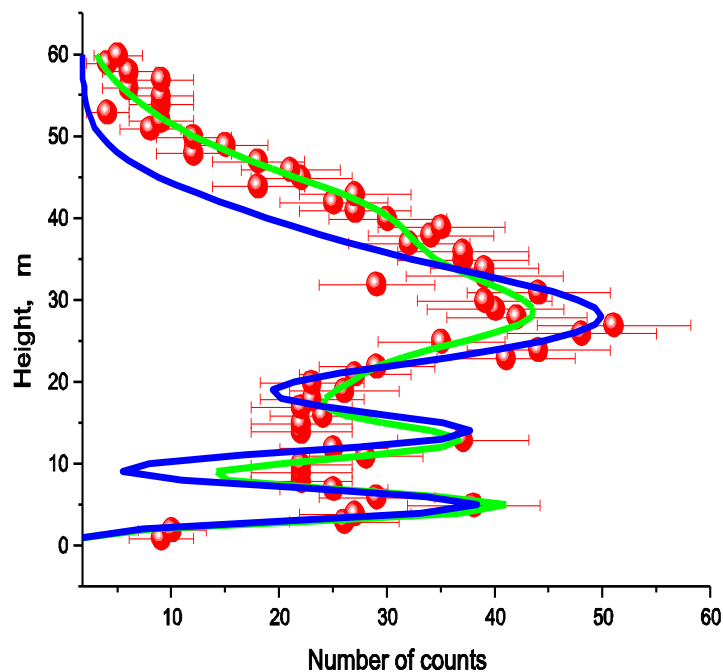
$$P_n(\xi) = \text{Exp}(-\Gamma_n(\xi) \cdot \frac{L}{V_{hor}})$$





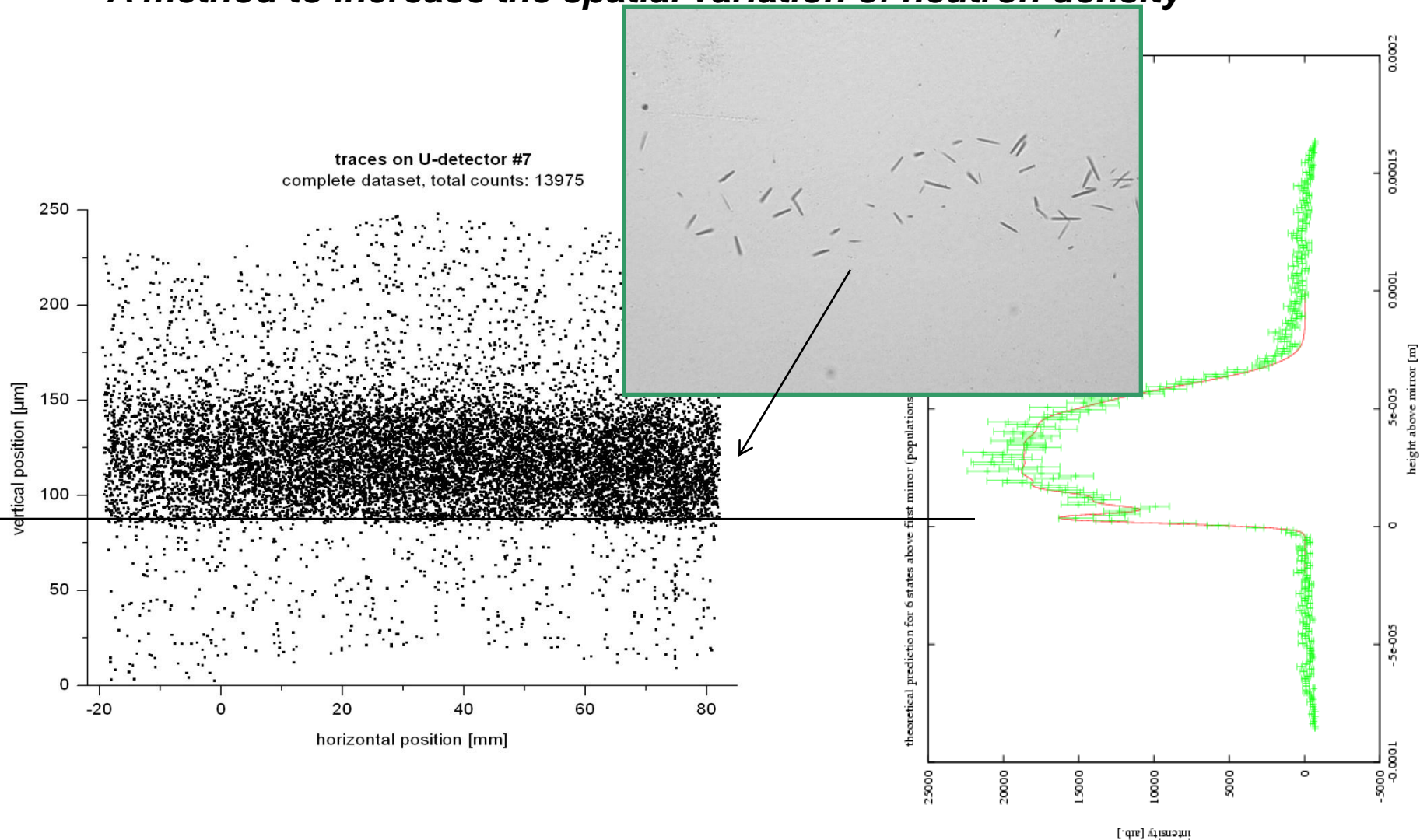
« Differential » method, position-sensitive detectors

A method to increase the spatial variation of neutron density



« Differential » method, position-sensitive detectors

A method to increase the spatial variation of neutron density



Transitions between gravitational quantum states

**Remember: flow-through mode;
modest energy resolution**

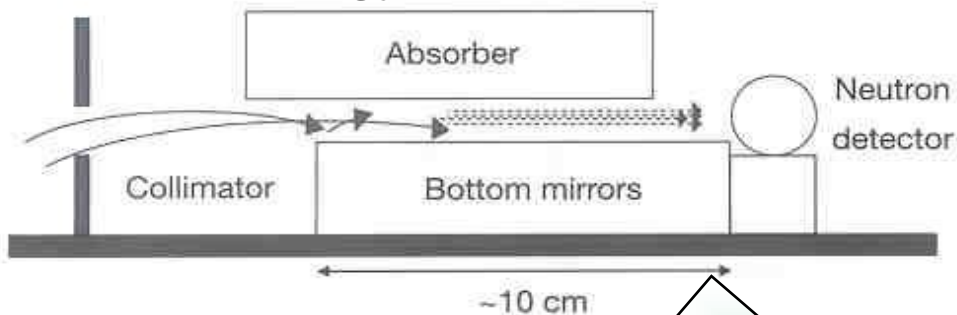
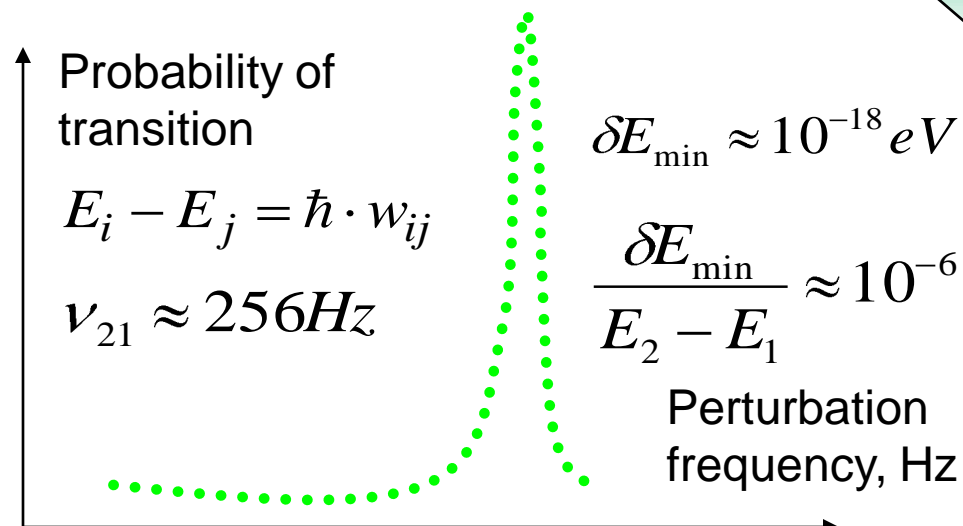


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.



Transitions could be excited, for instance:

- By periodically varying magnetic field gradient;
- By periodically varying local gravitational field;
- By oscillating the mirror (periodic variation of optical nuclear potential)

Now: storage mode, long observation time and high energy resolution

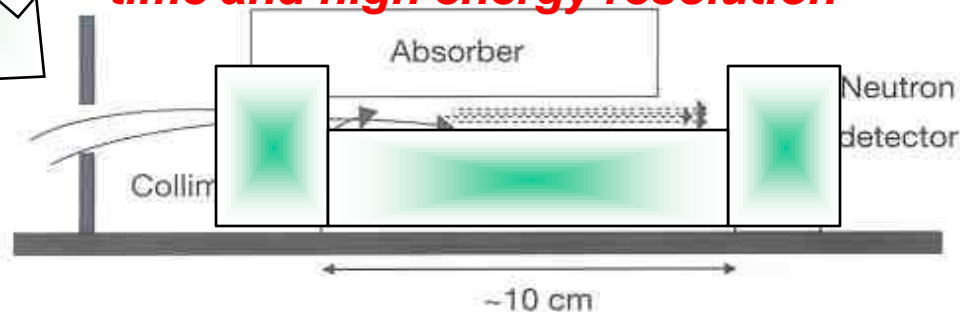
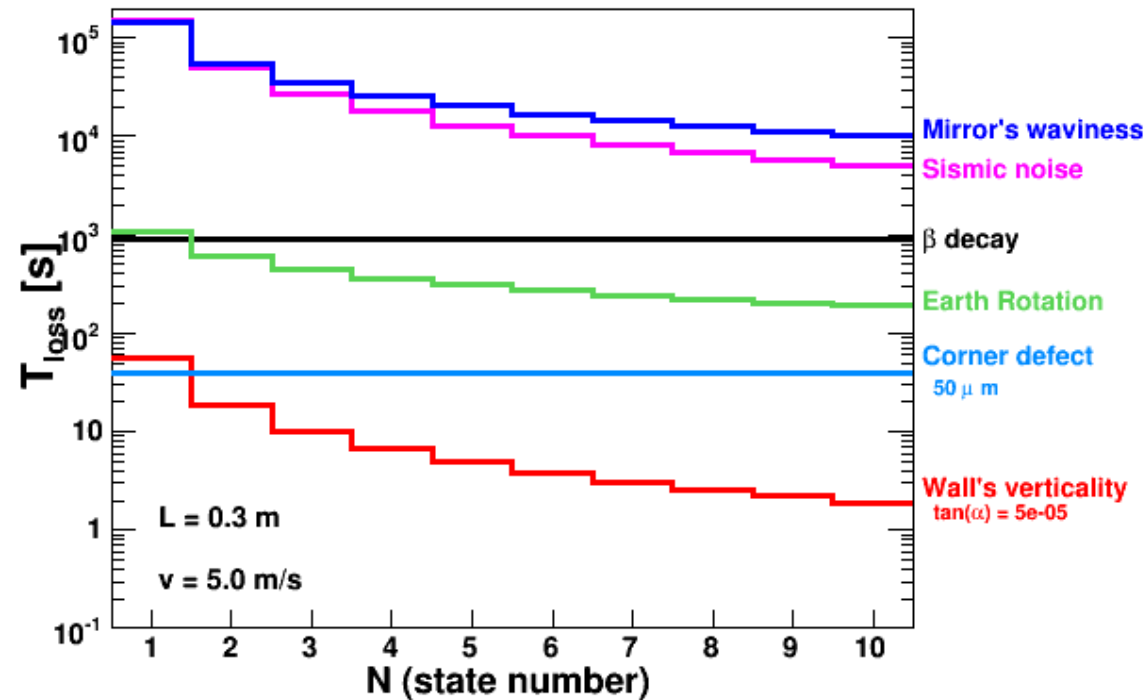


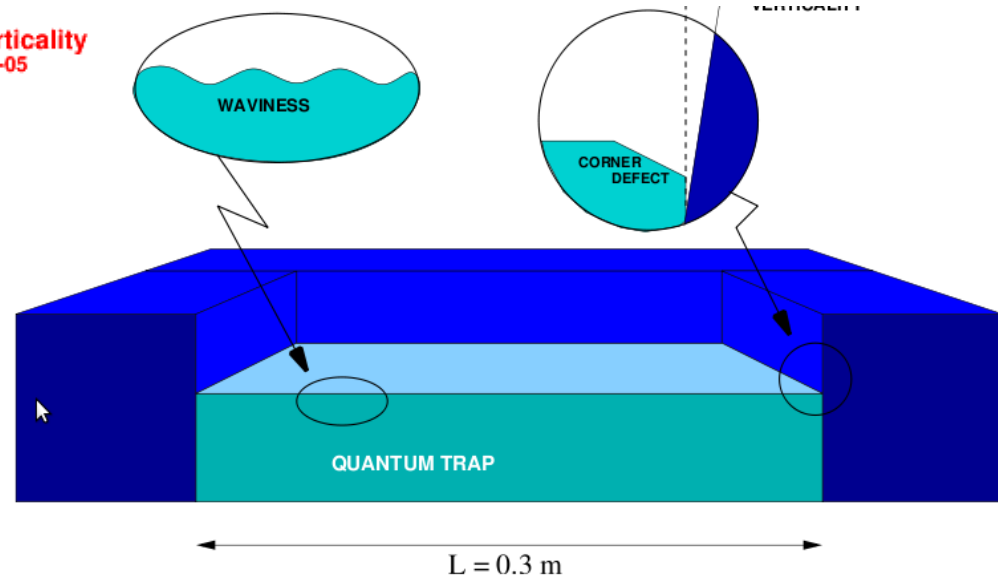
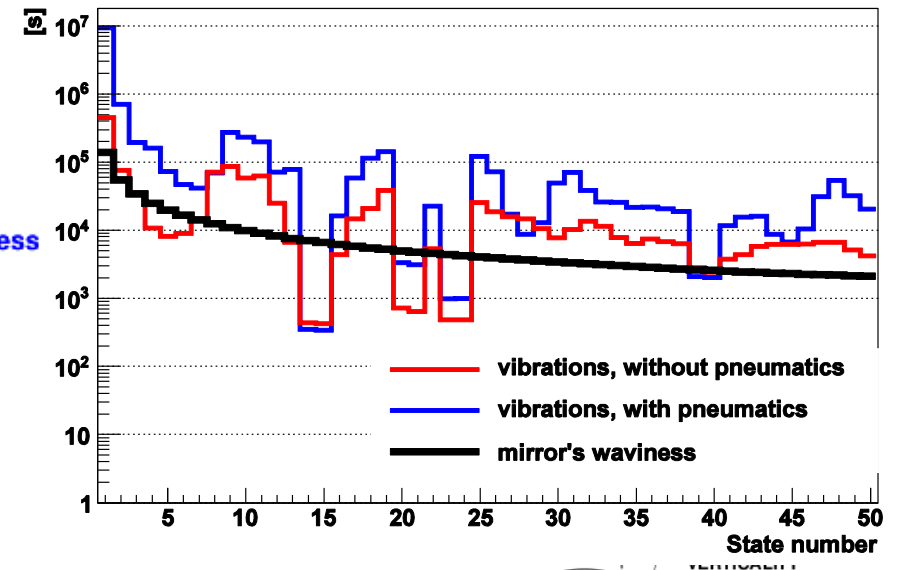
Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

Storage of UCN in gravitational quantum states

QUANTUM LEVELS LIFETIMES

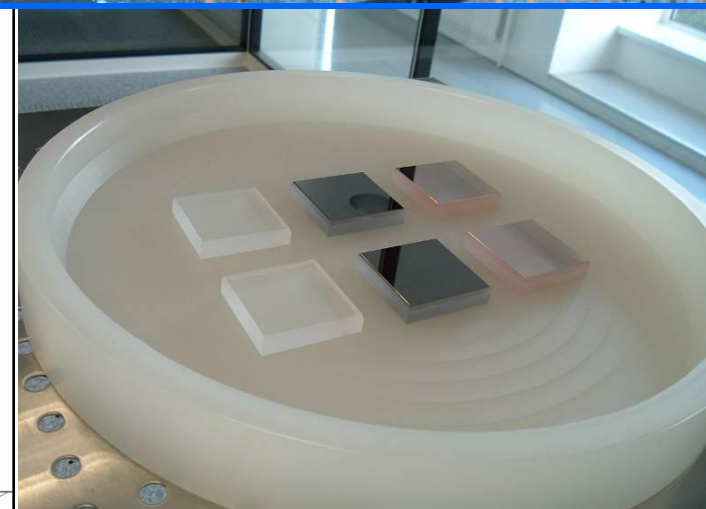
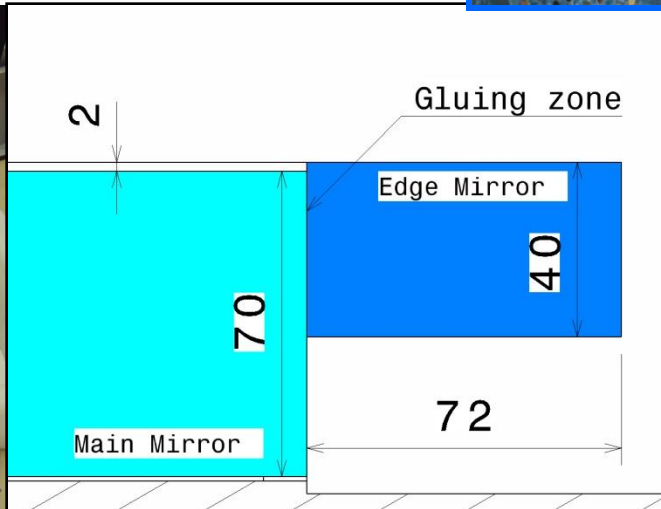
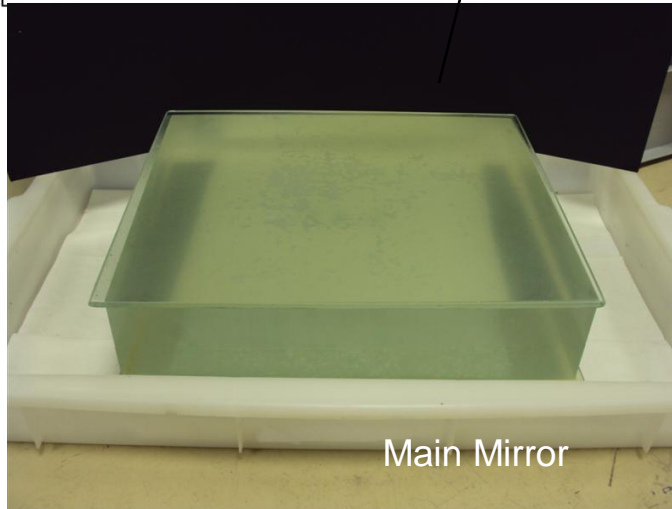
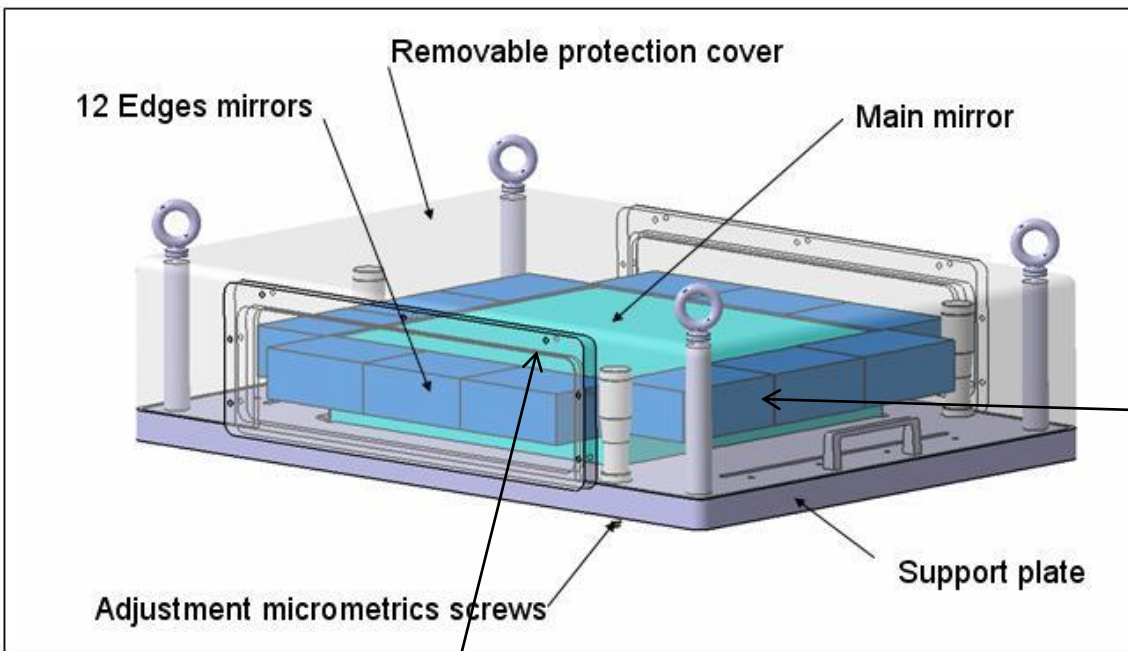


QUANTUM LEVELS LIFETIMES DUE TO NOISE-LIKE PERTURBATIONS



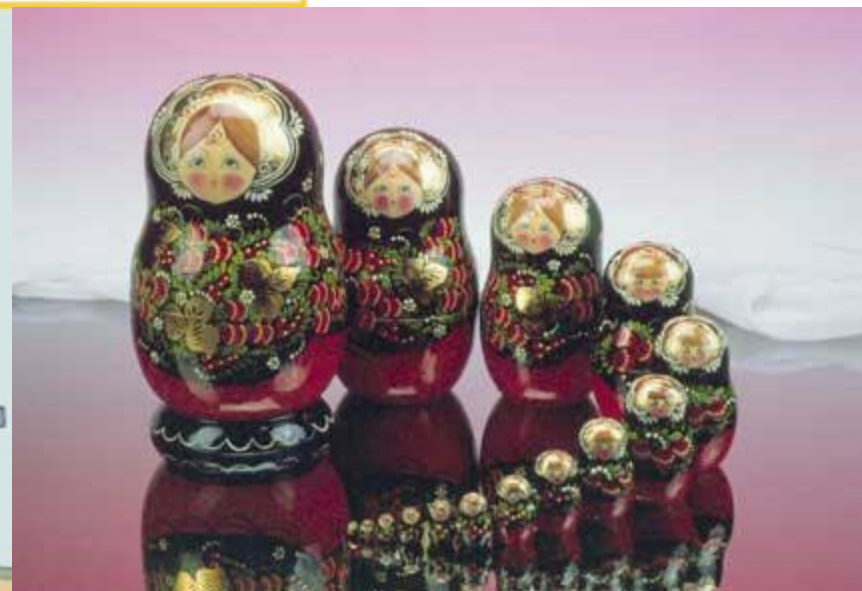
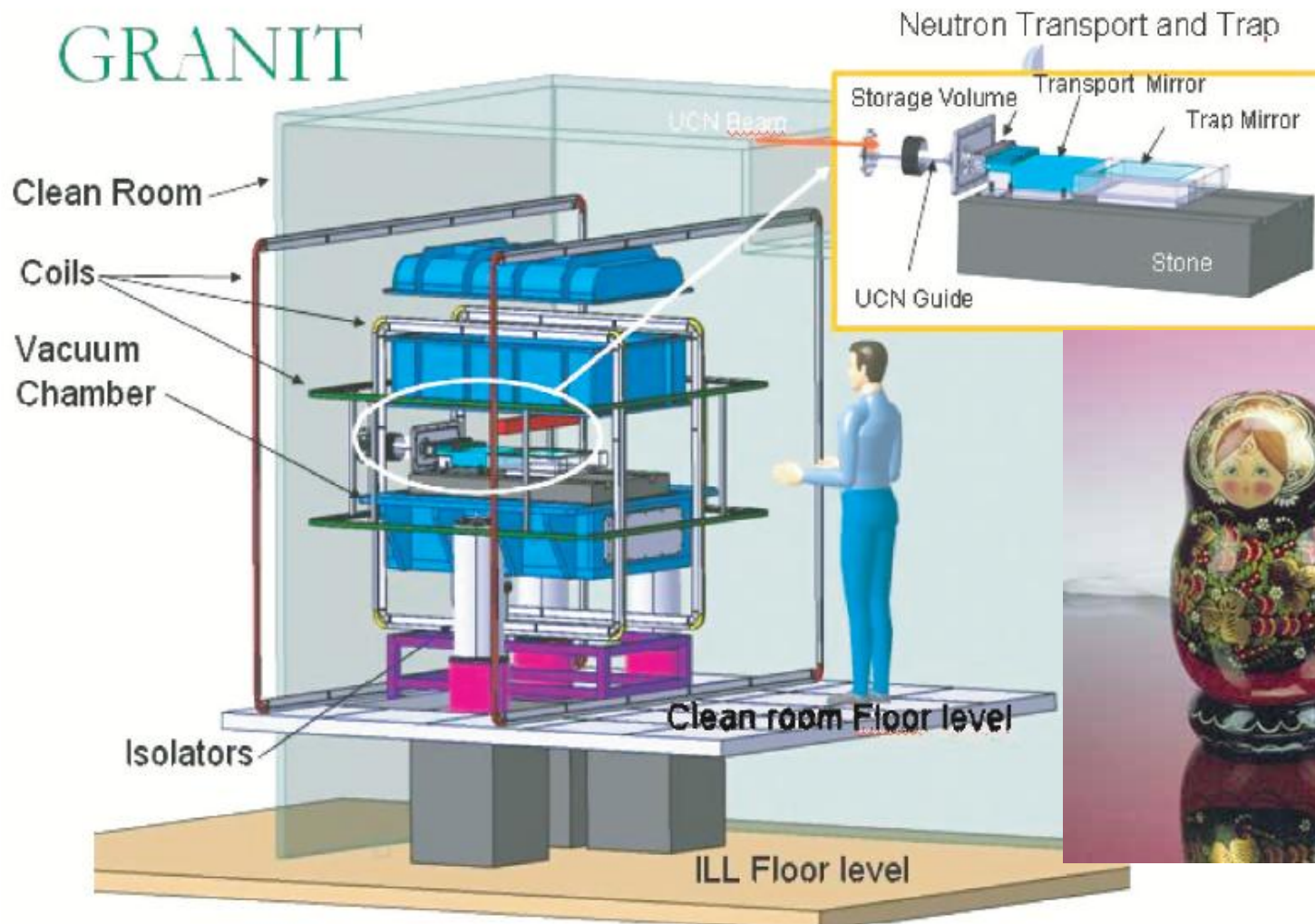
Transitions between gravitational quantum states

Quantum trap 30cm by 30cm; Height of edges 0.5mm

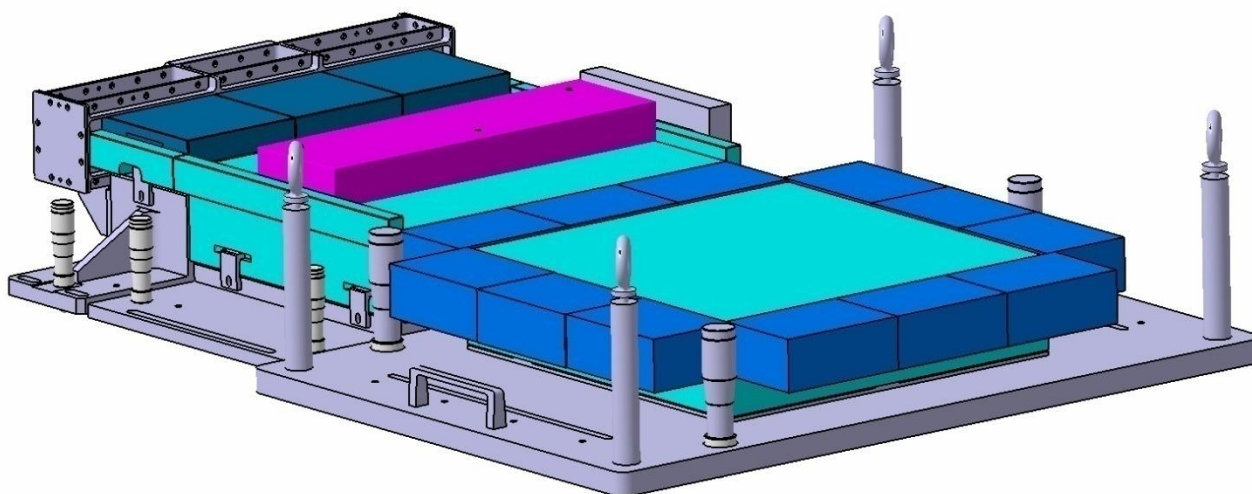
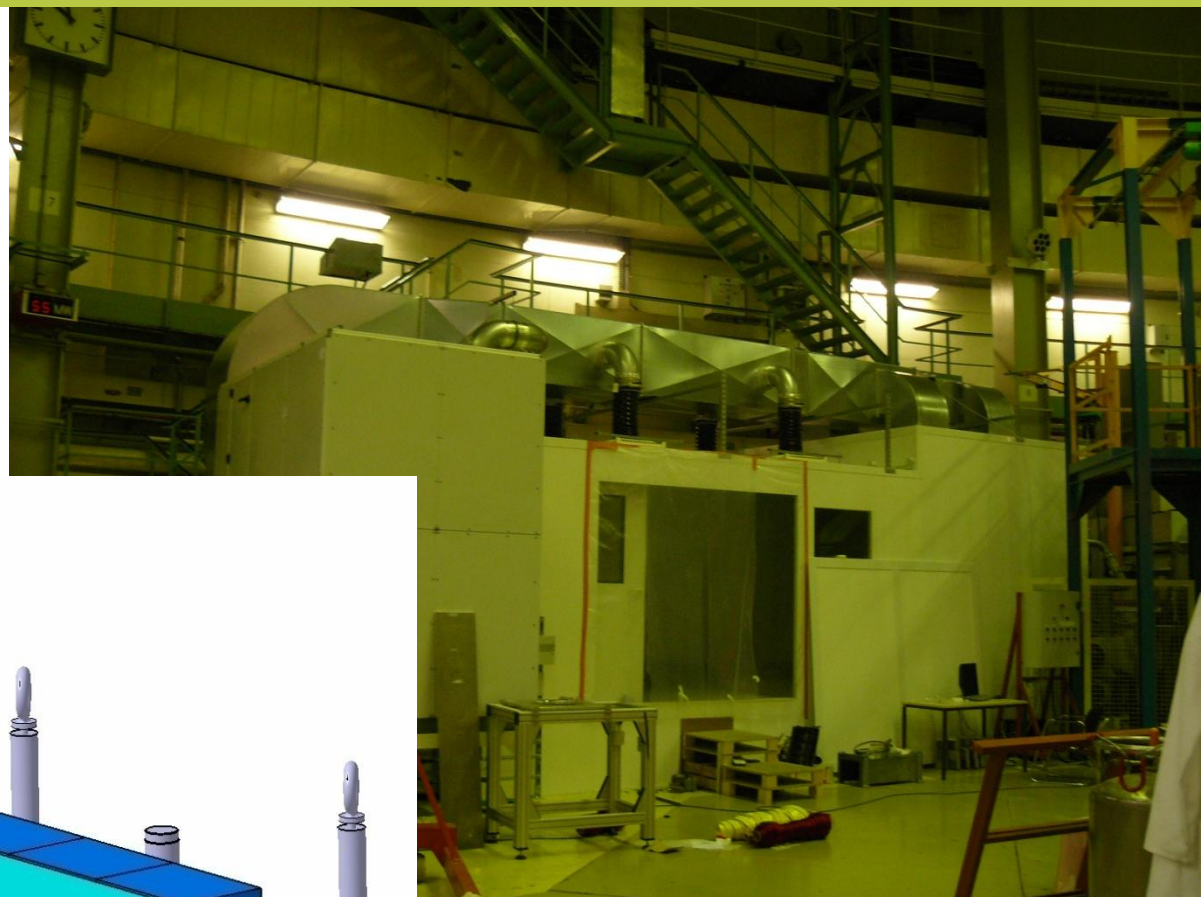


GRANIT

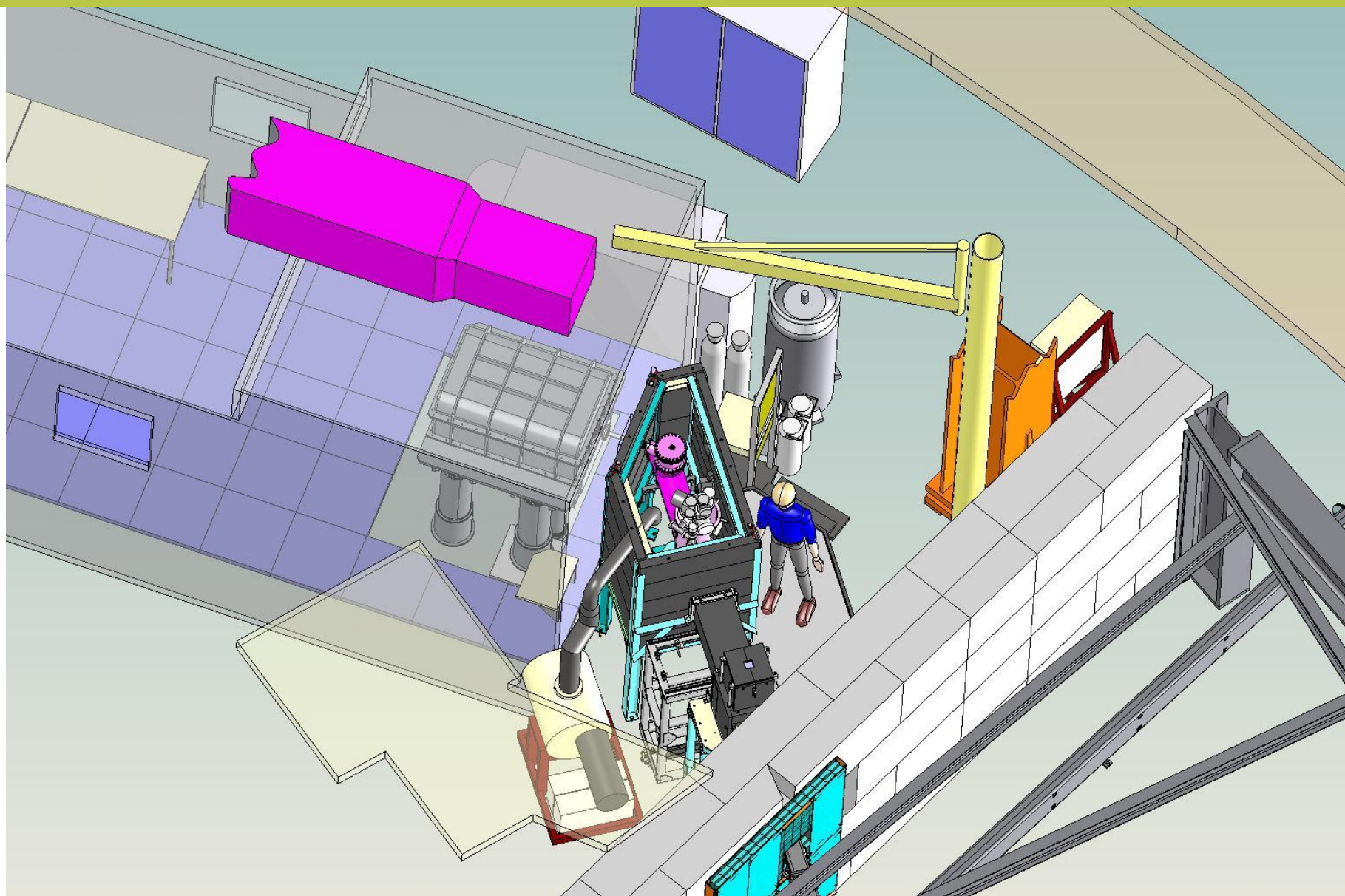
Assembling the spectrometer



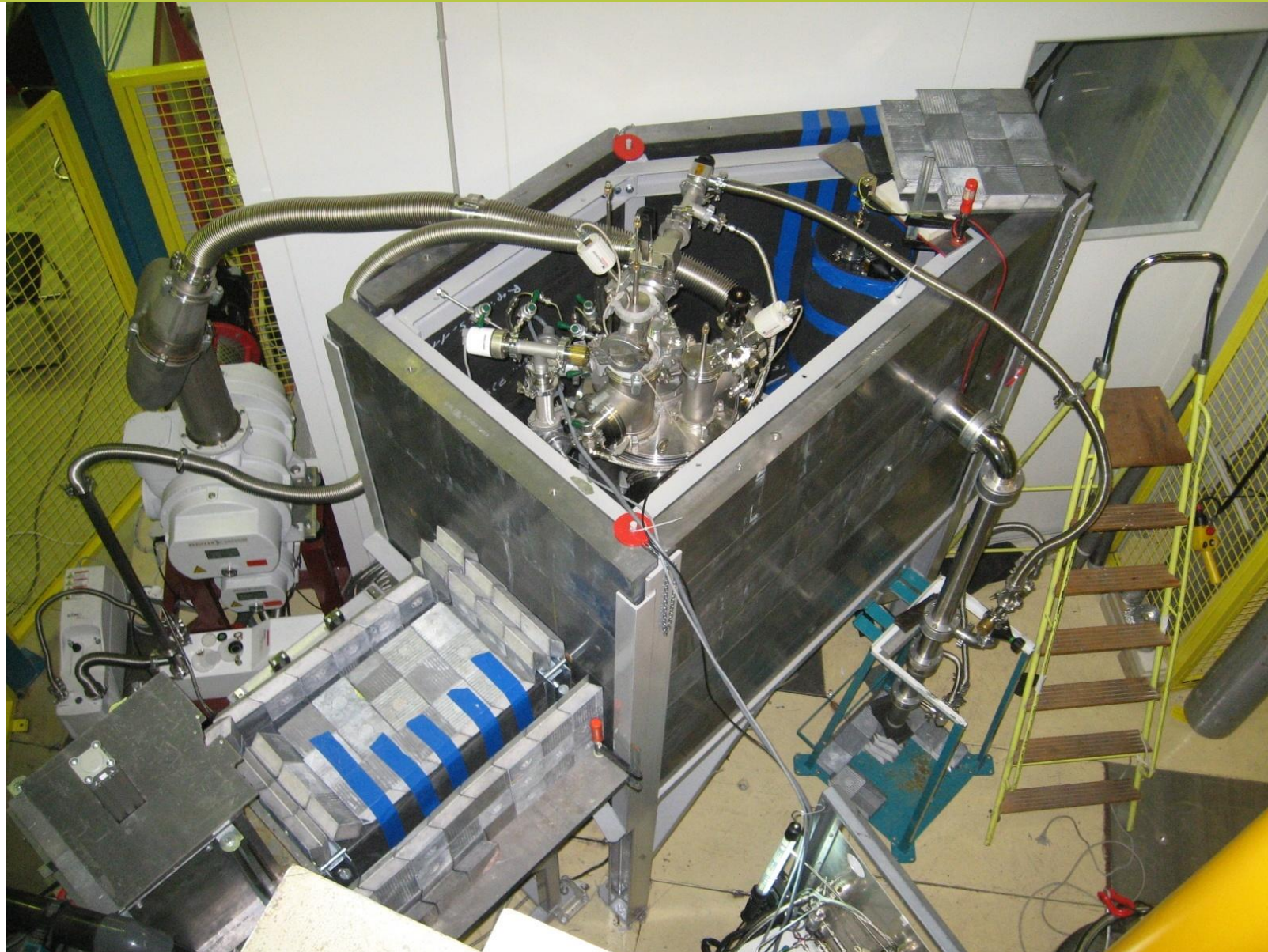
Extraction, transport, and storage mirrors; Clean room



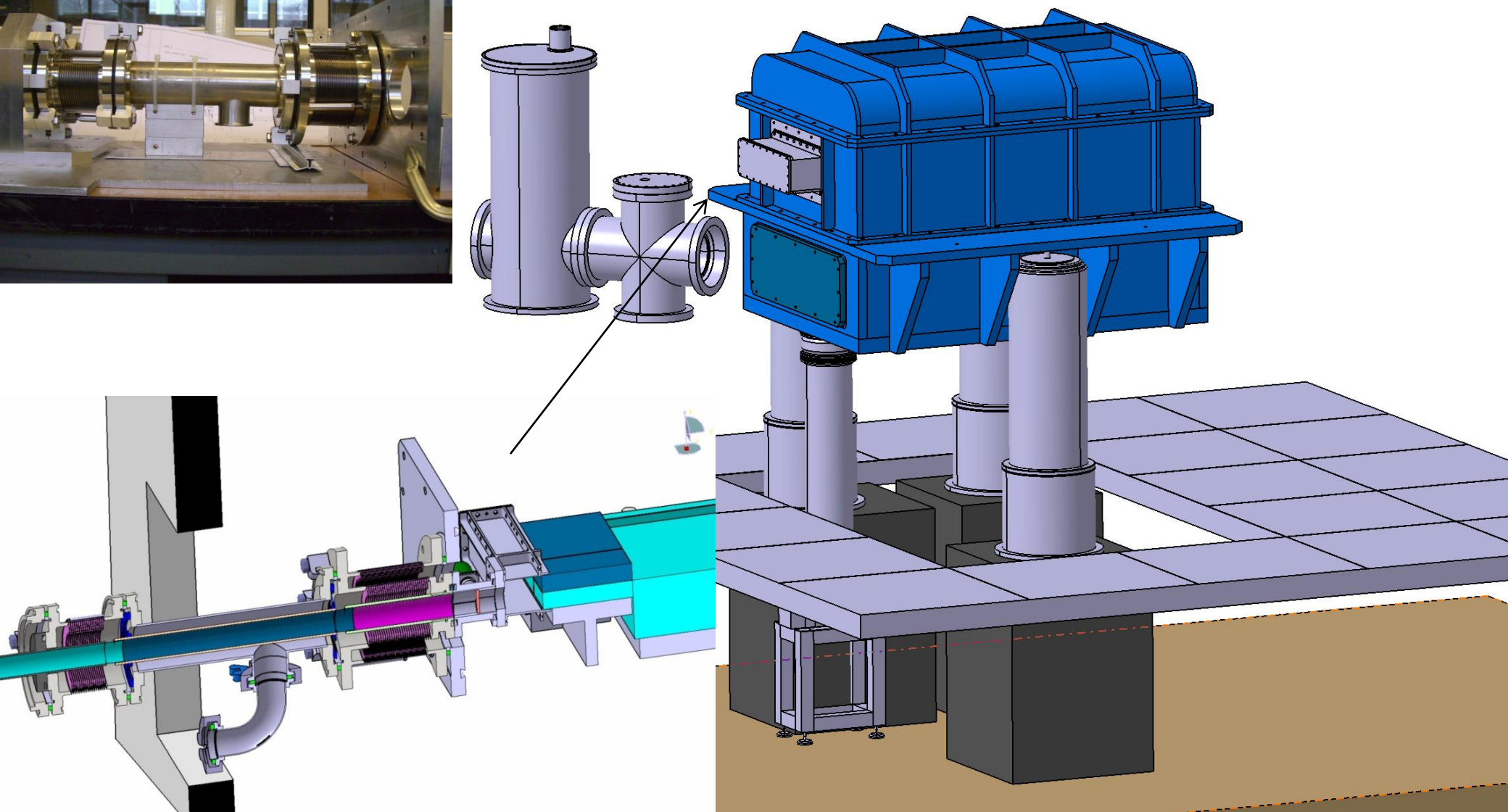
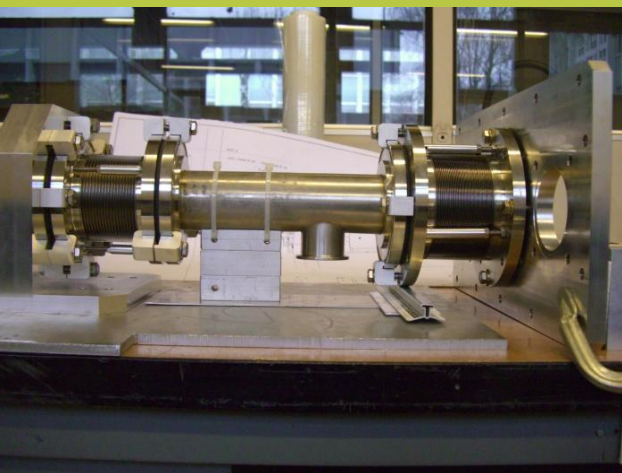
Installation of GRANIT spectrometer at the level C at the ILL



Installation of GRANIT spectrometer at the level C at the ILL

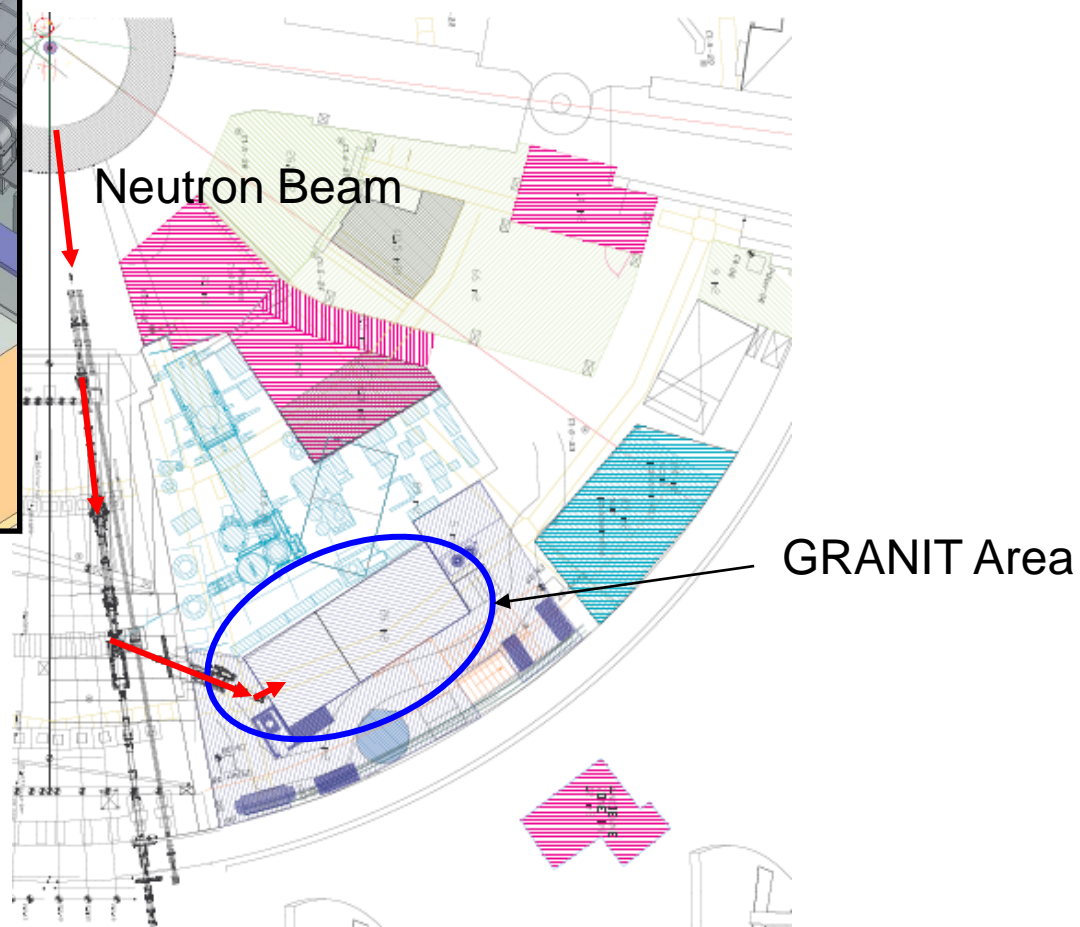
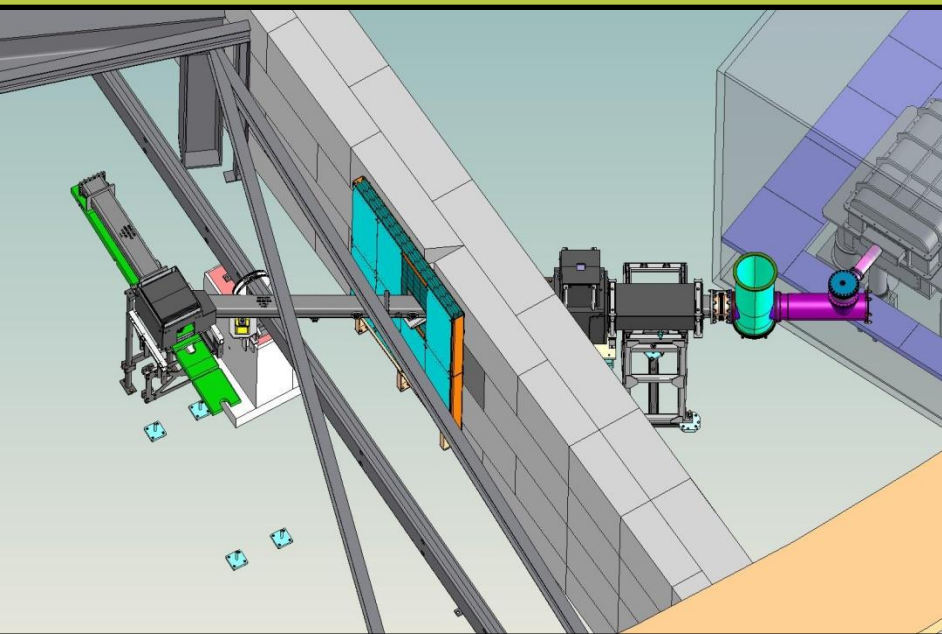


GRANIT and UCN source



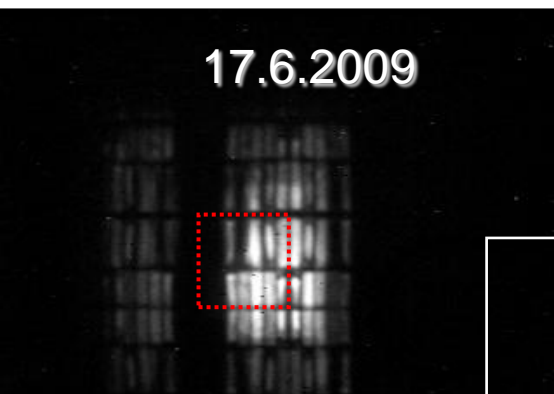


Installation of GRANIT spectrometer at the level C at the ILL



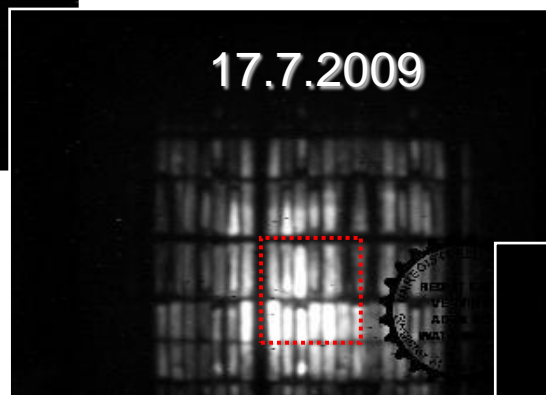
Located in the ILL reactor at level C

Installation of GRANIT spectrometer at the level C at the ILL



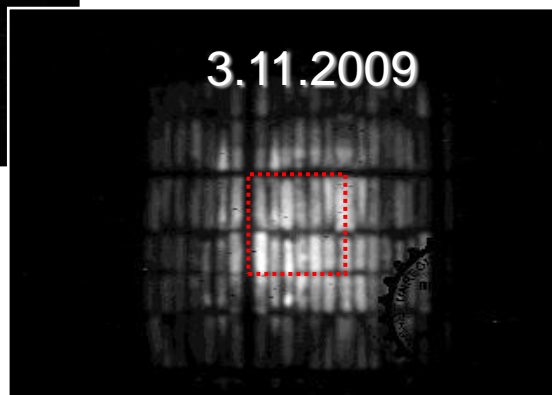
$3.1 \times 10^8 \text{ n cm}^{-2}\text{s}^{-1}$

Monochromator
turned

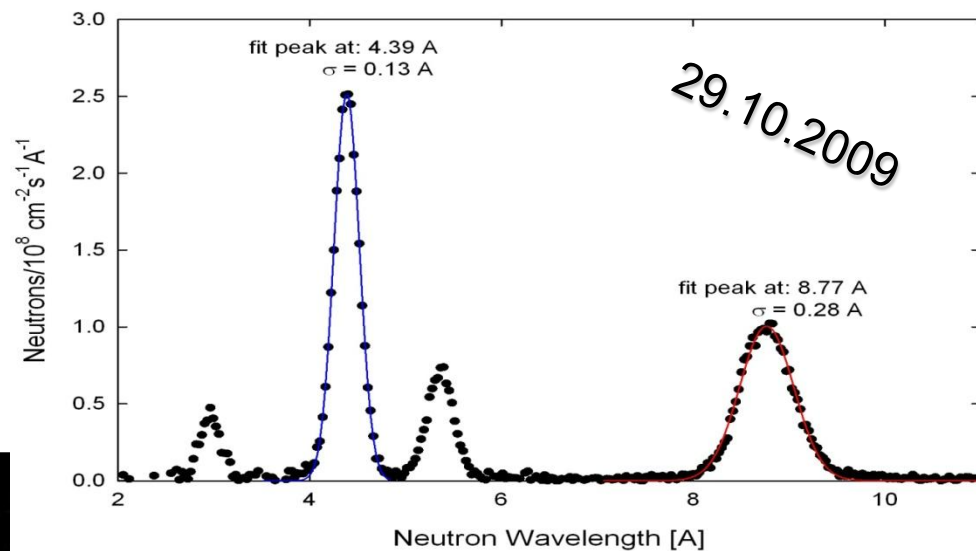



$5.9 \times 10^8 \text{ n cm}^{-2}\text{s}^{-1}$

Crystals readjusted

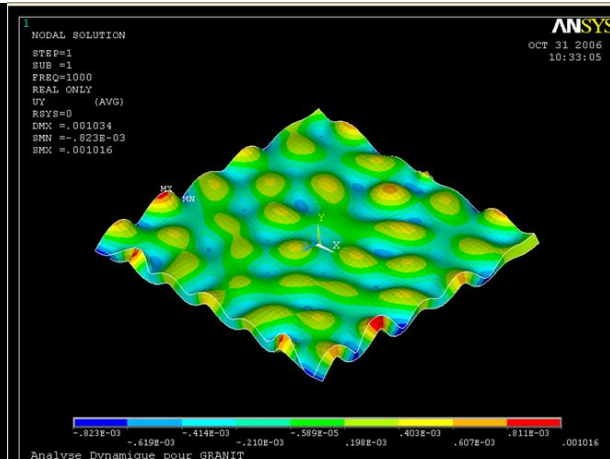
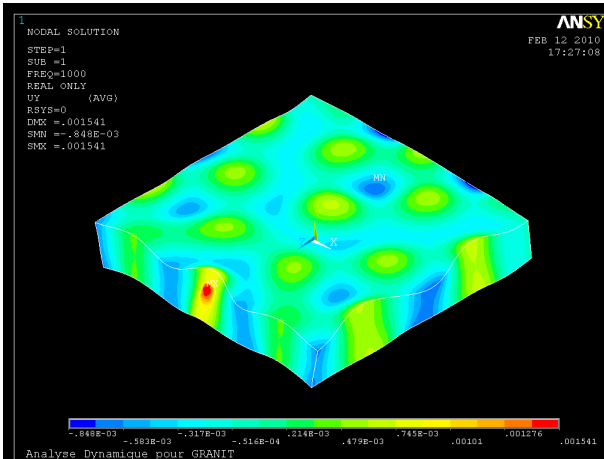
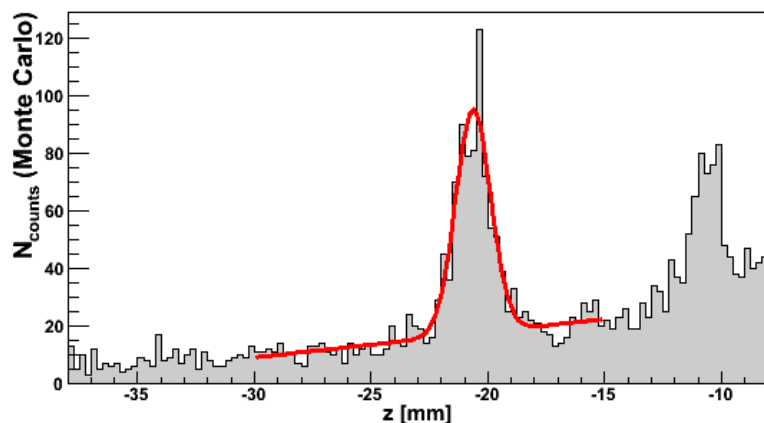
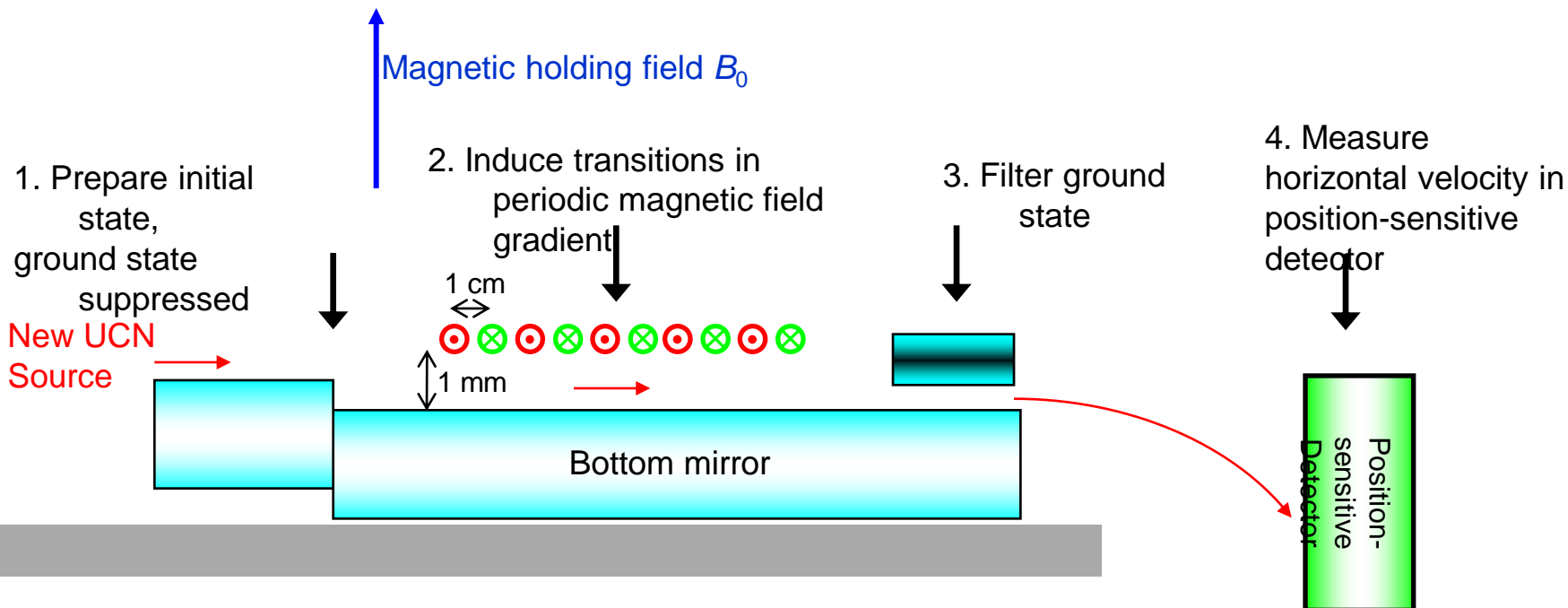



$7.2 \times 10^8 \text{ n cm}^{-2}\text{s}^{-1}$



GRANIT

on methods of excitation the transitions

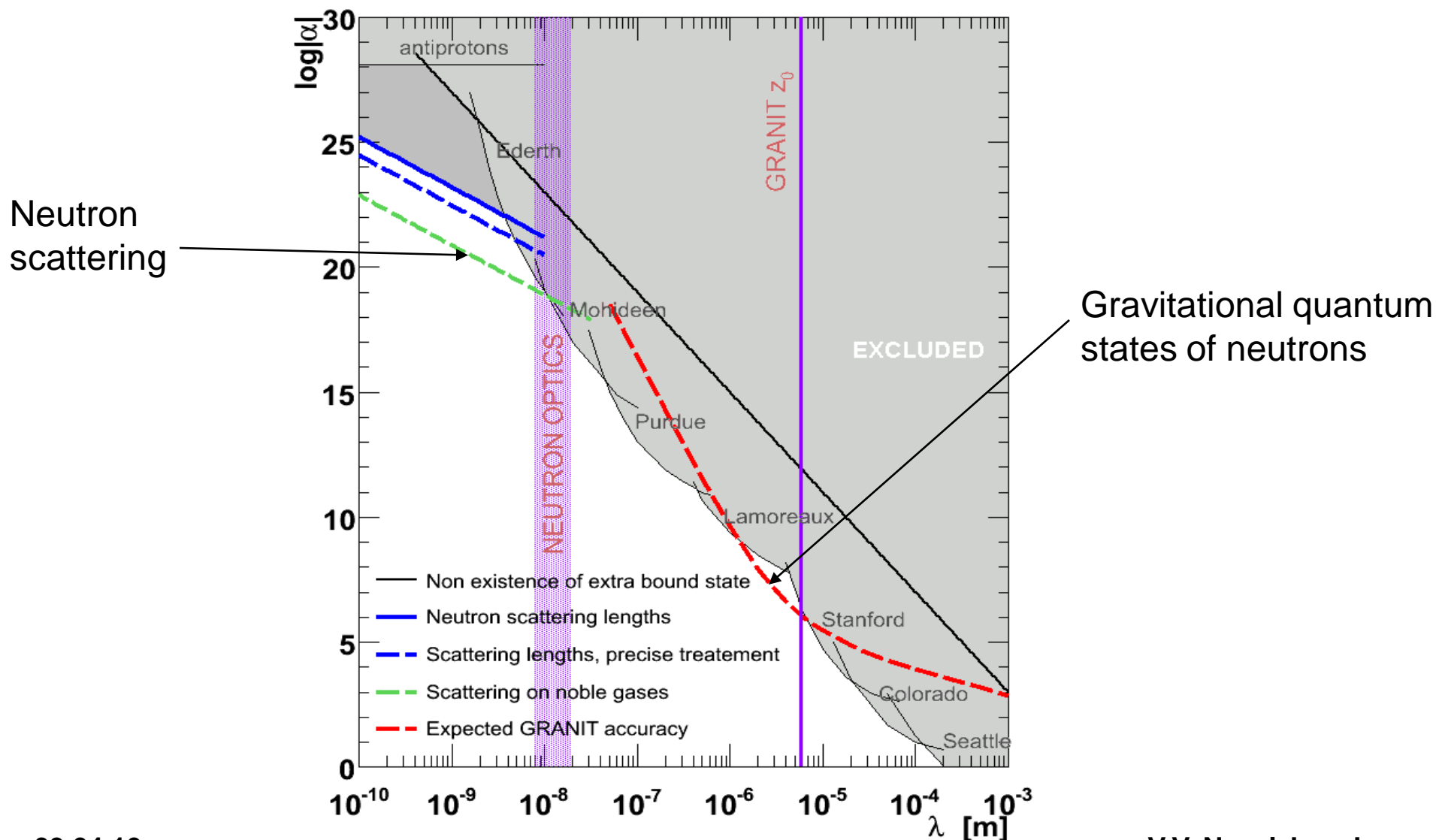


The phenomenon of gravitational quantum states of neutrons could be used in various applications, as apriory this is a very « clean » system with well-defined quantum states.

- Constraints for short-range forces;***
- Constrains for axion-like forces;***
- Constrains for neutron electric charge;***
- Neutron quantum optics;***
- UCN reflectometry;***
- Quantum revivals;***
- Constrains for logarithmic term in Schrödinger equation;***
- Loss of quantum coherence;***
- UCN extraction, transport, tight valves;***
- Study of thin surface layers;***
- etc....***

Constrains for short-range forces

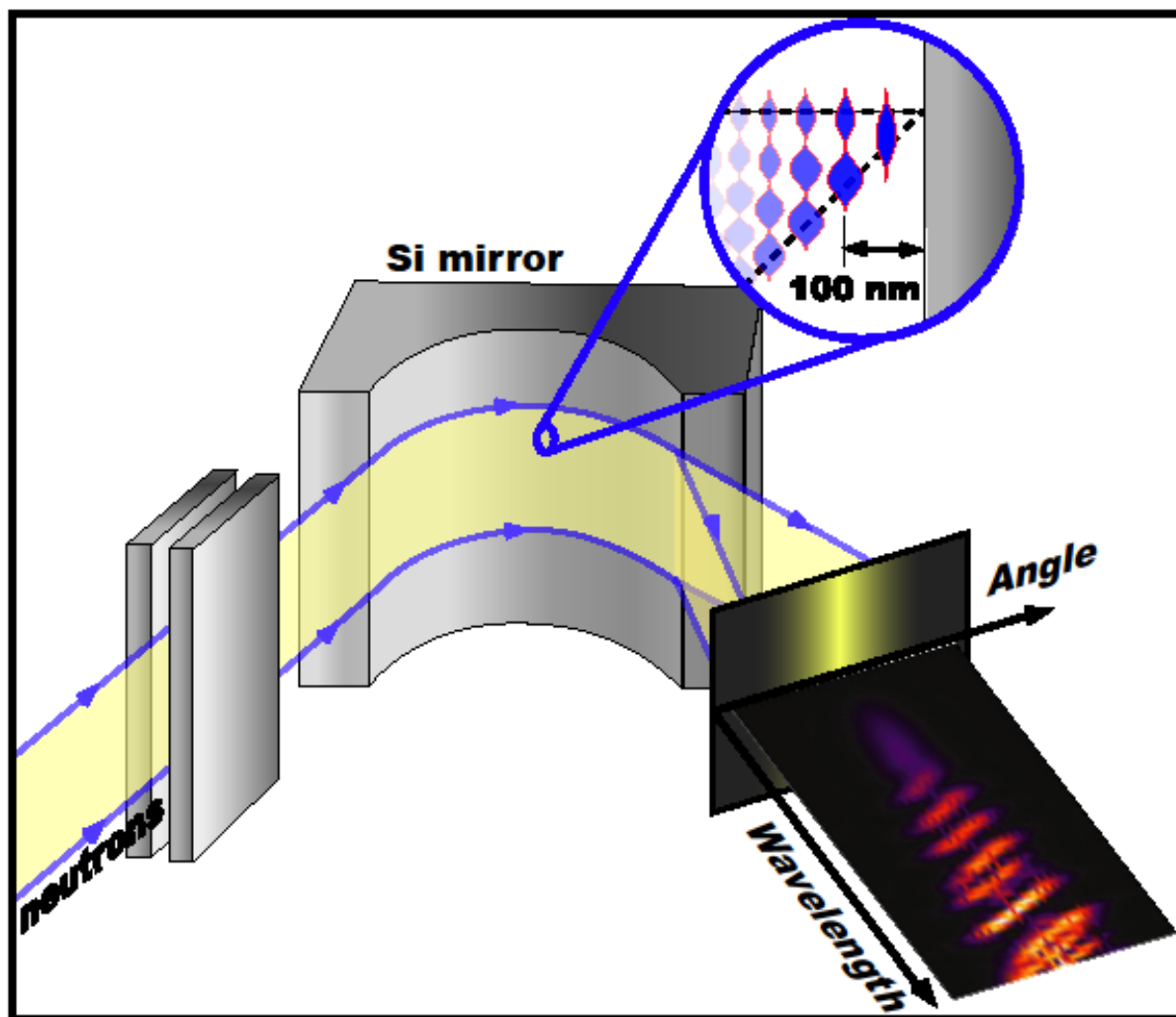
Limits on extra Yukawa force



1. First observation of quantum states of ultracold neutrons in gravitational field above mirror
2. First direct demonstration (and still the only one!) of quantum states of matter in gravitational field
3. Applications of this phenomenon in fundamental and applied physics
4. New gravitational spectrometer GRANIT, with all parameters improved by many orders of magnitude compared to the first setup, is going to become operational this year



R. Cubitt, Ch. Dornes, P.A. Gurzhiyants, V.V. Nesvizhevsky, A.K. Petukhov, G. Pignol, K.V. Protasov, T. Soldner, A.Yu. Voronin



Nature Physics, 6, 114–117 (2010)

Neutron whispering gallery

Valery V. Nesvizhevsky^{1*}, Alexei Yu. Voronin², Robert Cubitt¹ and Konstantin V. Protasov³

The ‘whispering gallery’ effect has been known since ancient times for sound waves in air^{1,2}, later in water and more recently for a broad range of electromagnetic waves: radio, optics, Roentgen and so on^{3–6}. It consists of wave localization near a curved reflecting surface and is expected for waves of various natures, for instance, for atoms^{7,8} and neutrons⁹. For matter waves, it would include a new feature: a massive particle would be settled in quantum states, with parameters depending on its mass. Here, we present for the first time the quantum whispering-gallery effect for cold neutrons. This phenomenon provides an example of an exactly solvable problem analogous to the ‘quantum bouncer’¹⁰; it is complementary to the recently discovered gravitationally bound quantum states of neutrons¹¹. These two phenomena provide a direct demonstration of the weak equivalence principle for a massive particle in a pure quantum state¹². Deeply bound whispering-gallery states are long-living and weakly sensitive to surface potential; highly excited states are short-living and very sensitive to the wall potential shape. Therefore, they are a promising tool for studying fundamental neutron-matter interactions^{13–15}, quantum neutron optics and surface physics effects^{16–18}.

The classical whispering-gallery phenomenon can be understood

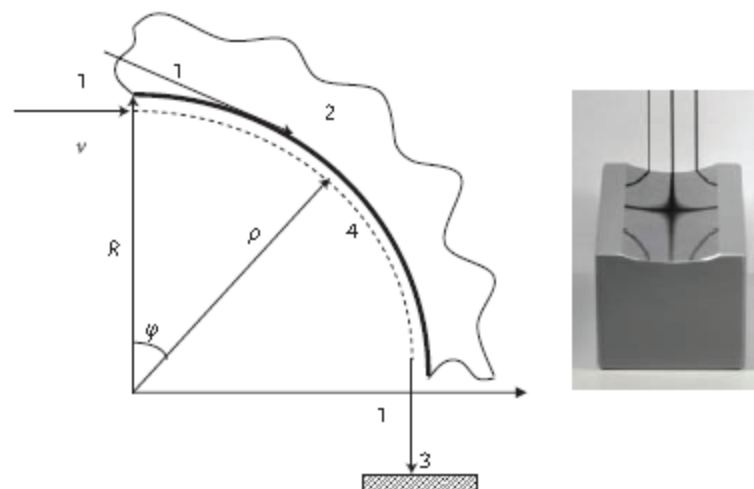
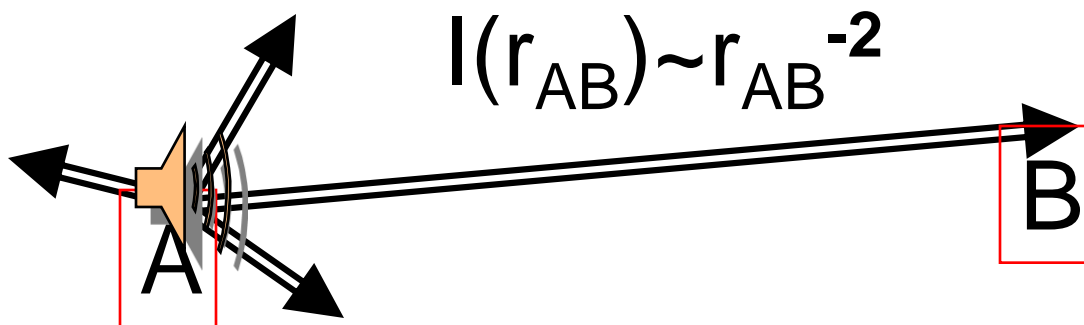


Figure 1 | A scheme of the neutron centrifugal experiment. 1: Classical trajectories of incoming and outgoing neutrons, 2: cylindrical mirror, 3: neutron detector, 4: quantum motion along the mirror surface. Inset: A photo of the single-crystal cylindrical silicon mirror used for the presented experiments, with an optical reflection of black stripes for illustrative purposes.

*Propagation of sound (or other) wave in loss-free medium in 3-D space **without boundaries***

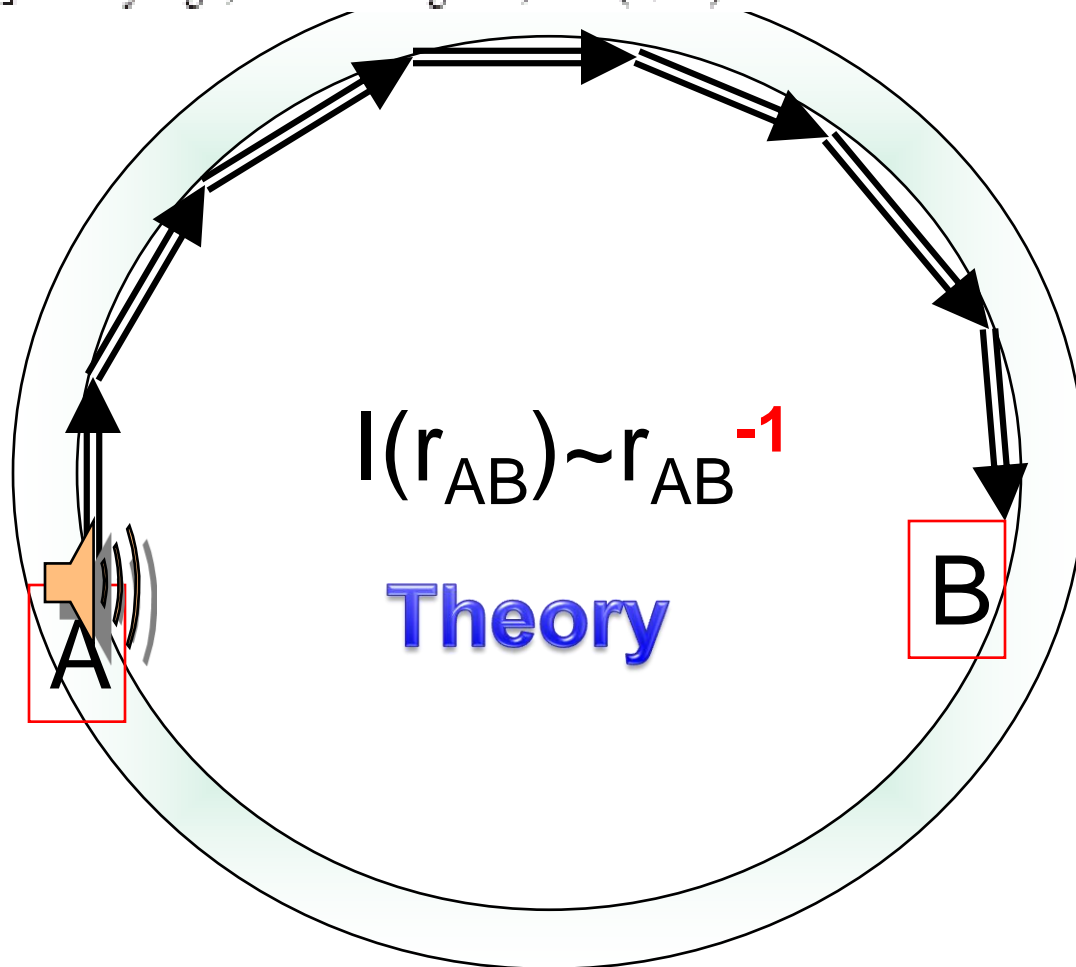
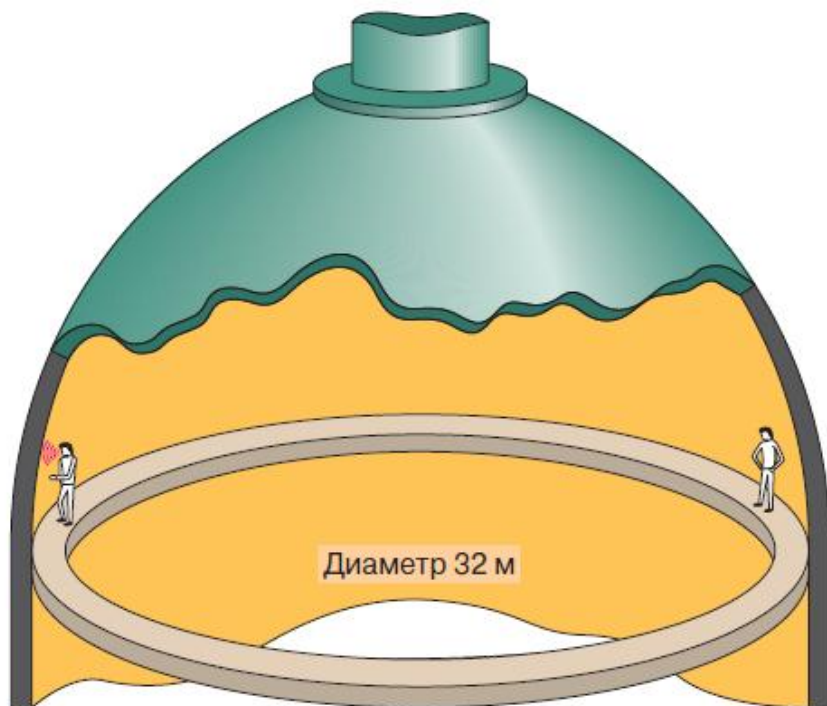


Any wave

**Known phenomenon of
“*Whispering Gallery*”:**

- [1] J. W. Strutt Baron Rayleigh, *The Theory of Sound* (Macmillan, London 1878), Vol. 2.
[2] L. Rayleigh, *Philos. Mag.* 27, 100 (1914).

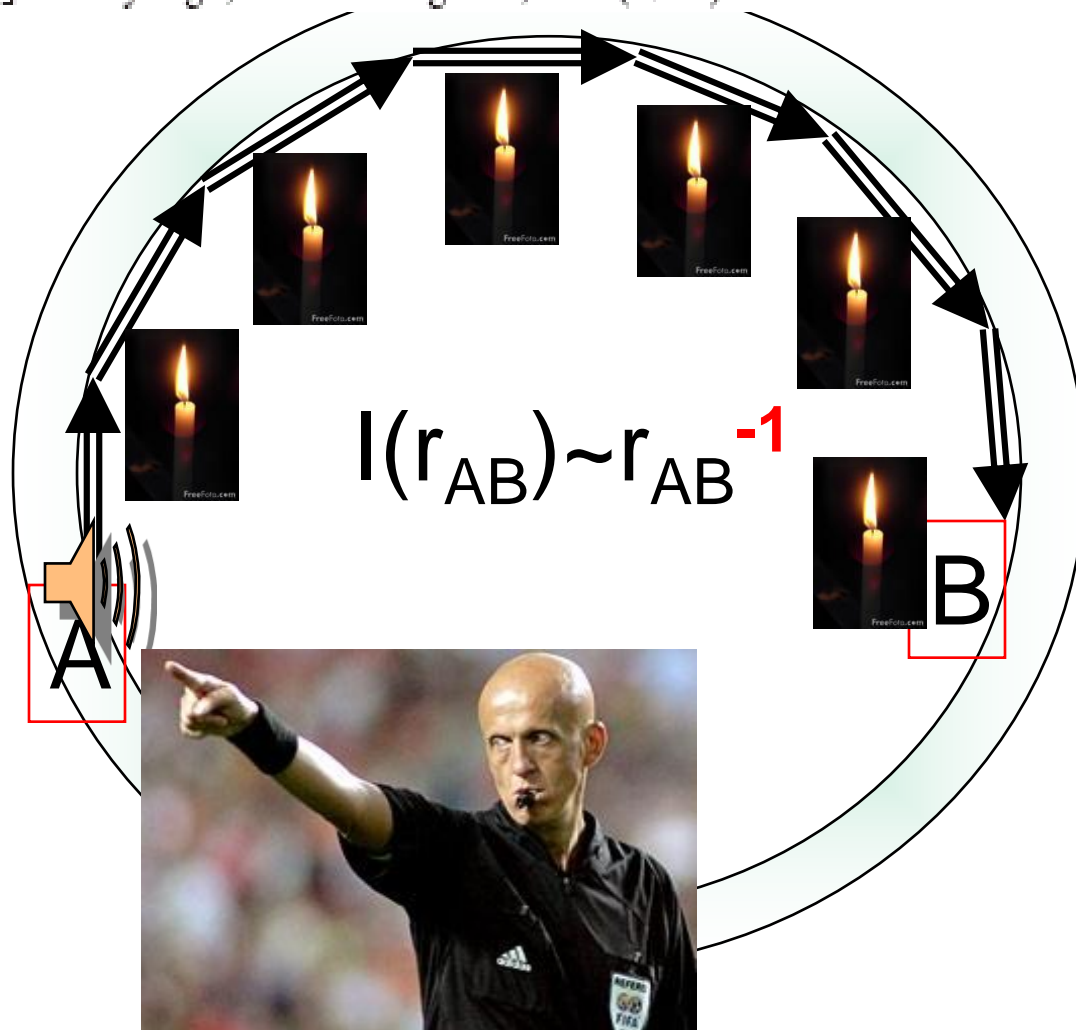
**Proragation of sound in closed
building (distance r_{AB} is
measured along surface)**



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[2] L. Rayleigh, *Philos. Mag.* 27, 100 (1914).

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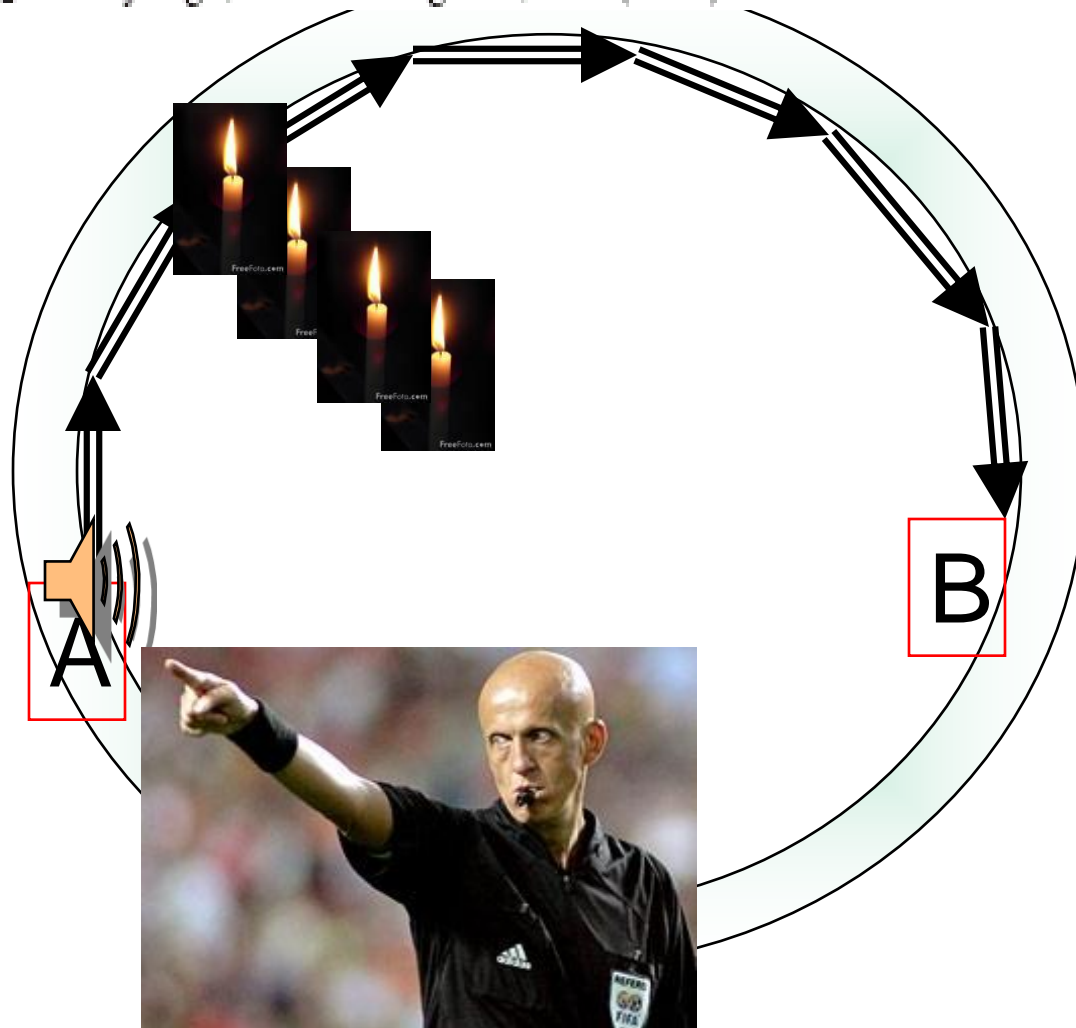


Experiment

- [1] J. W. Strutt Baron Rayleigh, *The Theory of Sound* (Macmillan, London 1878), Vol. 2.
[2] L. Rayleigh, *Philos. Mag.* 27, 100 (1914).

**Known phenomenon of
“Whispering Gallery”:**

**Proragation of sound in closed
building (distance r_{AB} is
measured along surface)**



Experiment



Whales are supposed to communicate at huge distances using analogous effect in surface ocean water layers (due to gradient of salt concentration, thus due to gradient of refractive index).

Other examples

Analogous phenomena are observed and used in optics, for radio-, Roentgen waves ...

Radio: Debye, P. Der lichtdruck auf kugeln von beliebigem material. *Ann. Physik* **30**, 57-136 (1909).

In optics, for example: to stabilize laser frequency, for non-linear signal transformation

[3] A. N. Oraevsky, *Quantum Electron.* **32**, 377 (2002).

[4] K. J. Vahala, *Nature (London)* **424**, 839 (2003).

Neutron whispering gallery / proposal

PHYSICAL REVIEW A 78, 1 (2008)

Centrifugal quantum states of neutrons

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K. V. Protasov

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A. Yu. Voronin

P.N. Lebedev Physical Institute, 53 Leninsky prospekt, 119991, Moscow, Russia

(Received 24 June 2008)

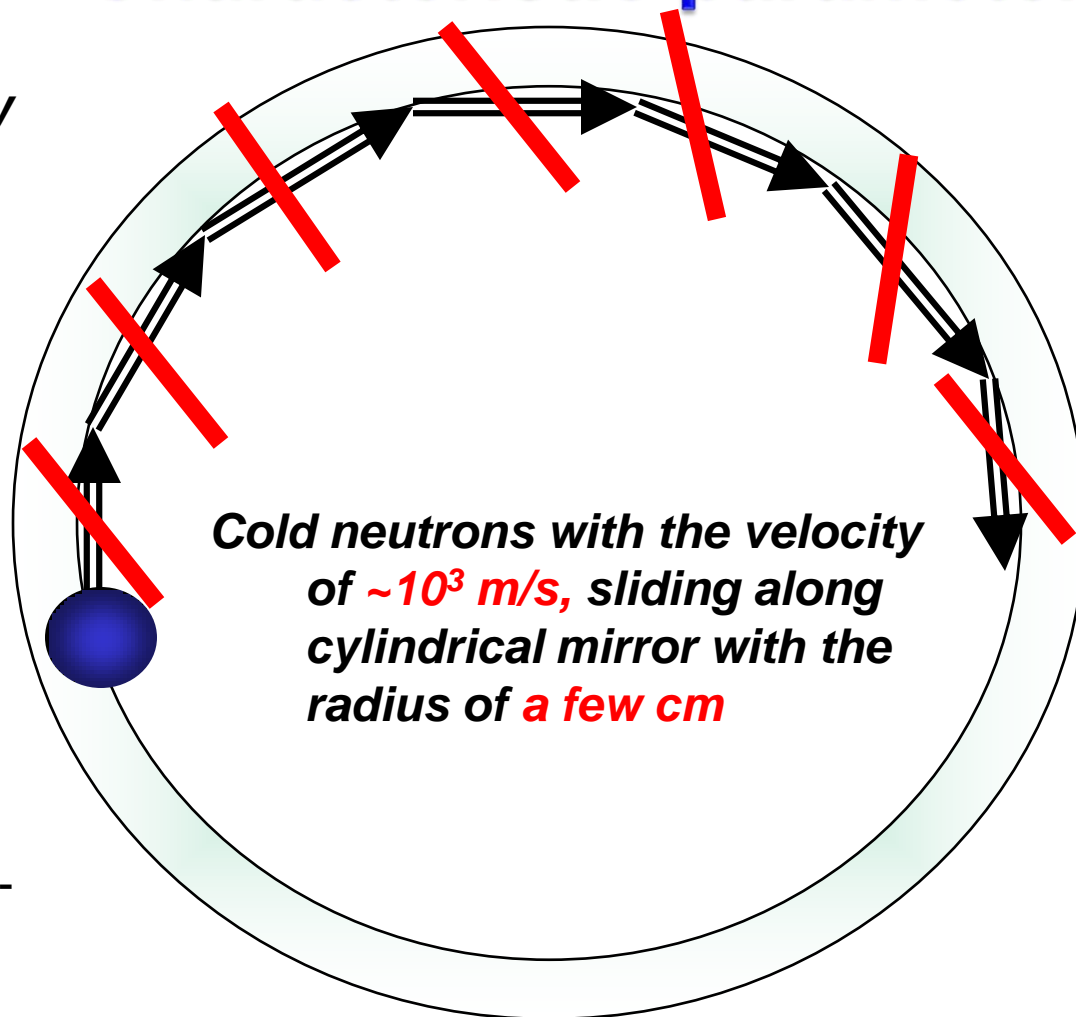
We propose a method for observation of the quasistationary states of neutrons localized near a curved mirror surface. The bounding effective well is formed by the centrifugal potential and the mirror Fermi potential. This phenomenon is an example of an exactly solvable “quantum bouncer” problem that can be studied experimentally. It could provide a promising tool for studying fundamental neutron-matter interactions, as well as quantum neutron optics and surface physics effects. We develop a formalism that describes quantitatively the neutron motion near the mirror surface. The effects of mirror roughness are taken into account.

Massive particle, sliding along curved mirror surface is settled, under certain conditions, in quasi-stationary quantum states

Such a phenomenon has been considered (but not yet observed) for ultracold atoms:

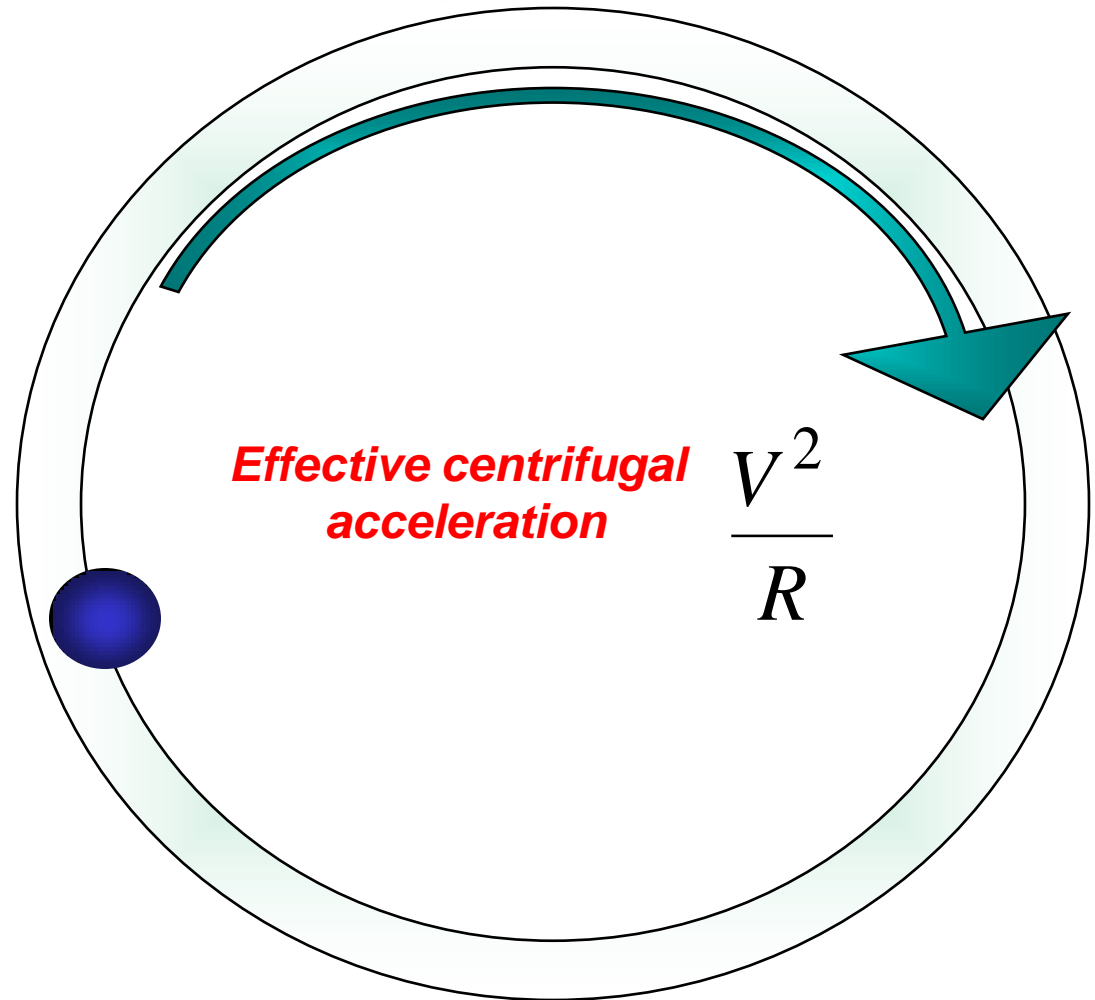
- Mabuchi H. & Kimble H.J. Atom galleries for whispering atoms – binding atoms in stable orbits around an optical resonator. *Opt. Lett.* **19**, 749-751 (1994).
- Vernooy D. M. & Kimble H.J. Quantum structure and dynamics for atom galleries. *Phys. Rev. A* **55**, 1239-1261 (1997).

Characteristic parameters



Two velocity components

*If the characteristic size of quantum states and quasi-classical distance between two collisions are much smaller than the mirror radius then **tangential and longitudinal motions could be separated***



$$-\frac{\hbar^2}{2m} \frac{d^2}{dz^2} \psi + m \frac{v^2}{R} z \psi = E \psi \quad \text{outside the mirror}$$

$$-\frac{\hbar^2}{2m} \frac{d^2}{dz^2} \psi + \left(m \frac{v^2}{R} z + V_F \right) \psi = E \psi \quad \text{inside the mirror}$$

$$V_F \sim 10^{-7} \text{ eV}$$

Radial motion of neutrons (axis z) close to mirror surface is described using this Schrödinger equation

Precise solution

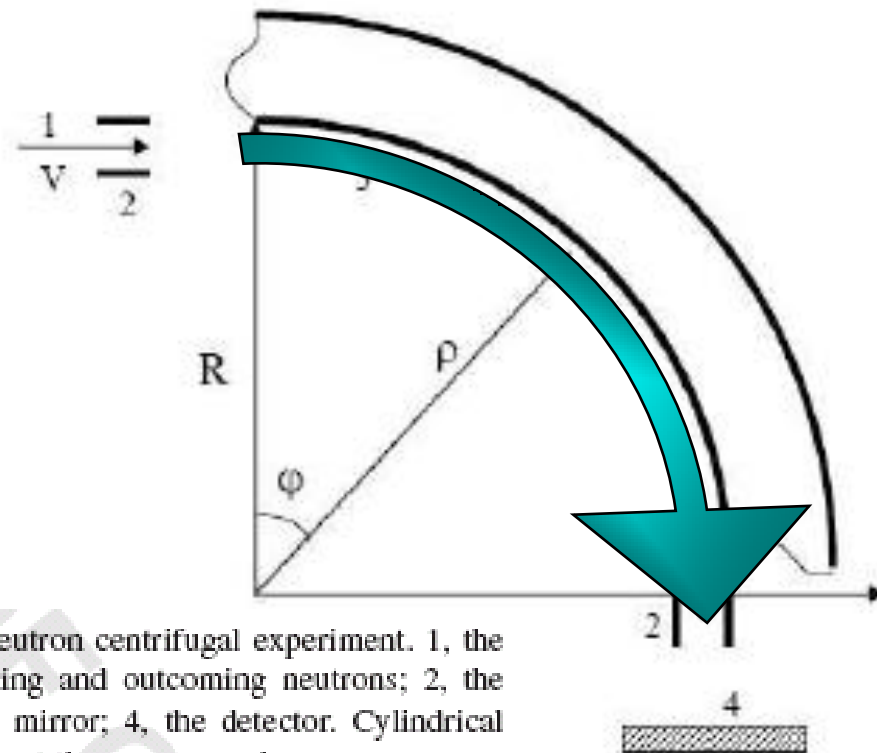
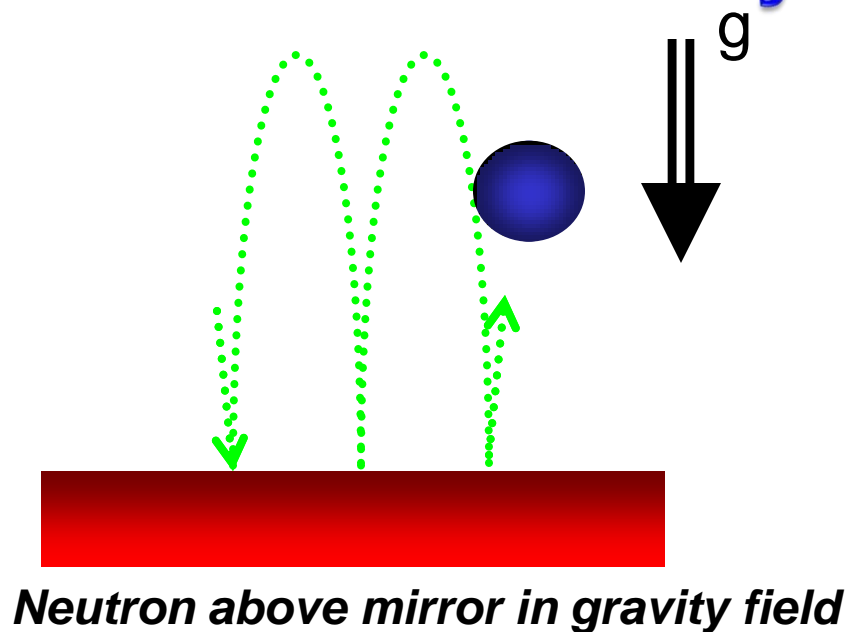


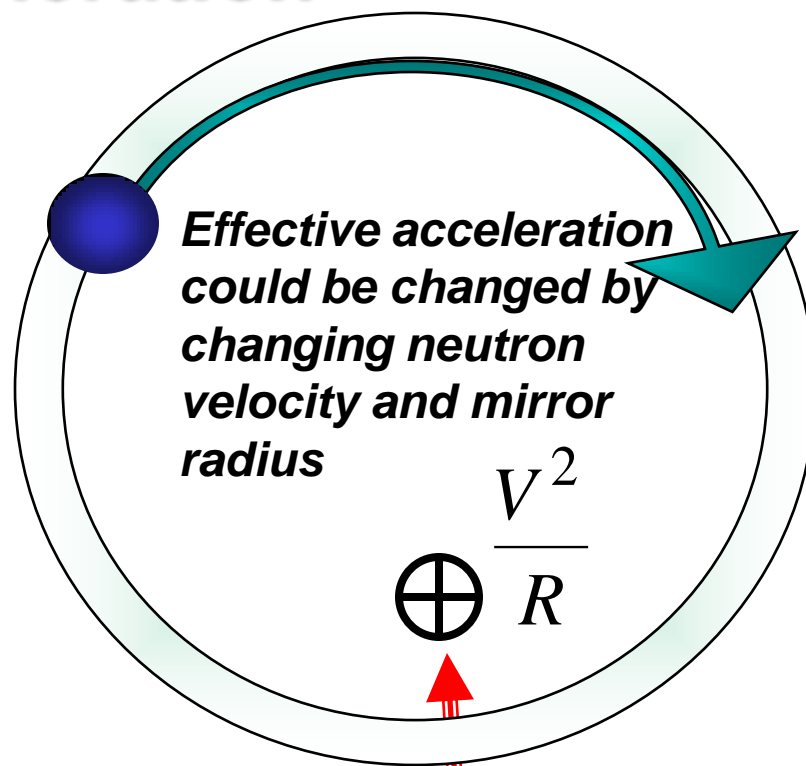
FIG. 1. A scheme of the neutron centrifugal experiment. 1, the classical trajectories of incoming and outgoing neutrons; 2, the collimators; 3, the cylindrical mirror; 4, the detector. Cylindrical coordinates ρ - φ used throughout the paper are shown.

Gravity / Acceleration



Energy of quantum states in Bohr-Zommerfeld approximation :

$$E_n \approx \sqrt[3]{\left(\frac{9 \cdot m_n}{8}\right) \cdot \left(\pi \cdot \hbar \cdot g \cdot \left(n - \frac{1}{4}\right)\right)^2}$$



Gravity / Acceleration

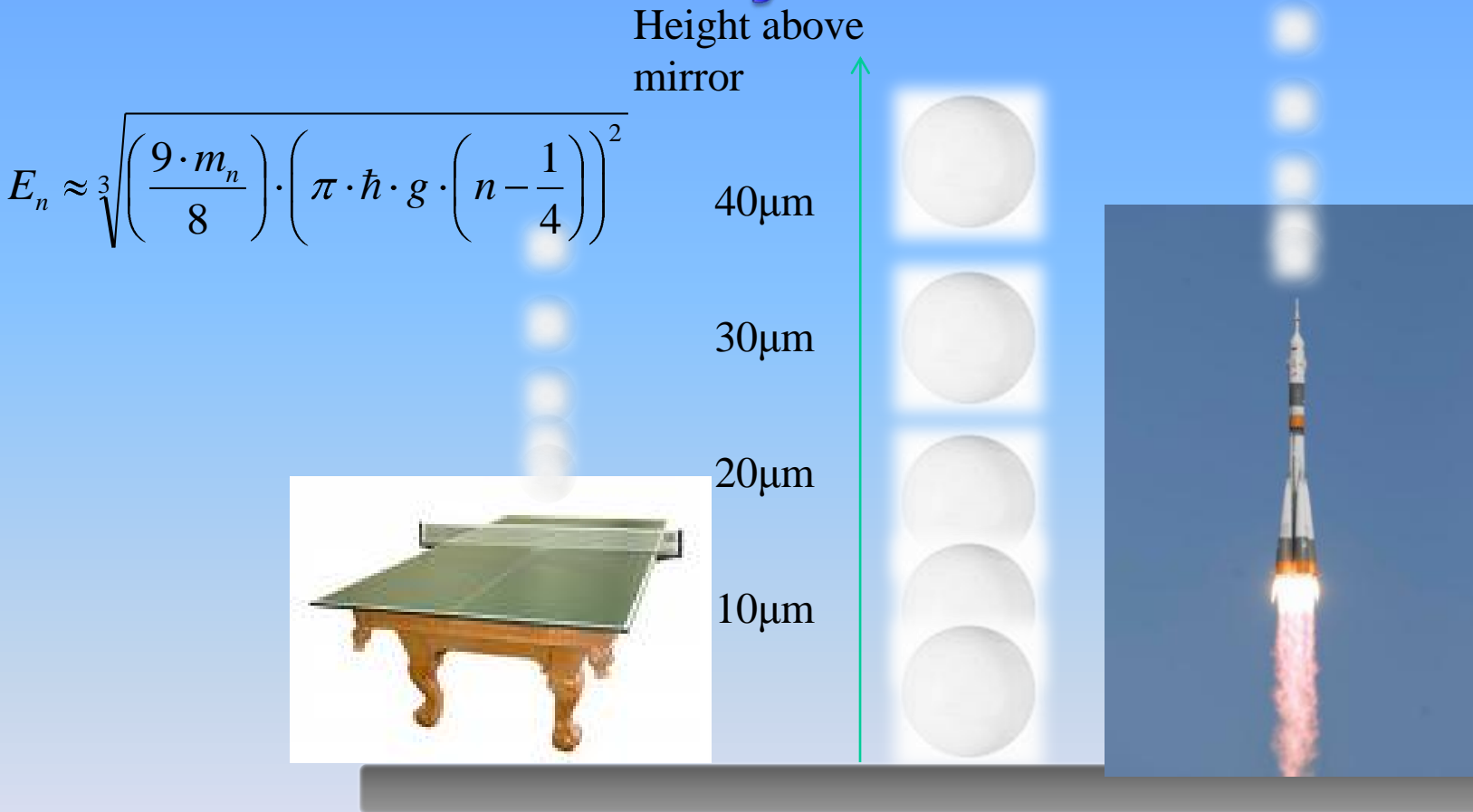
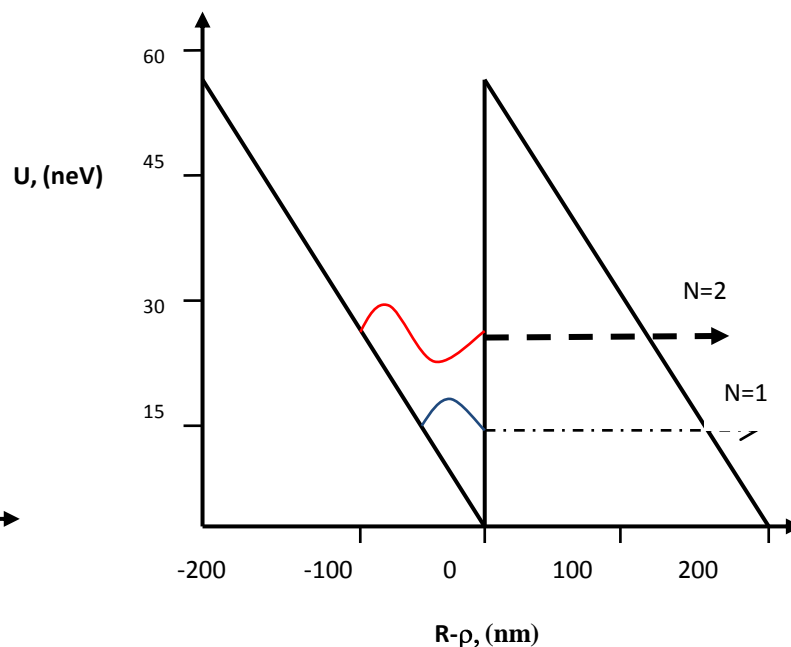
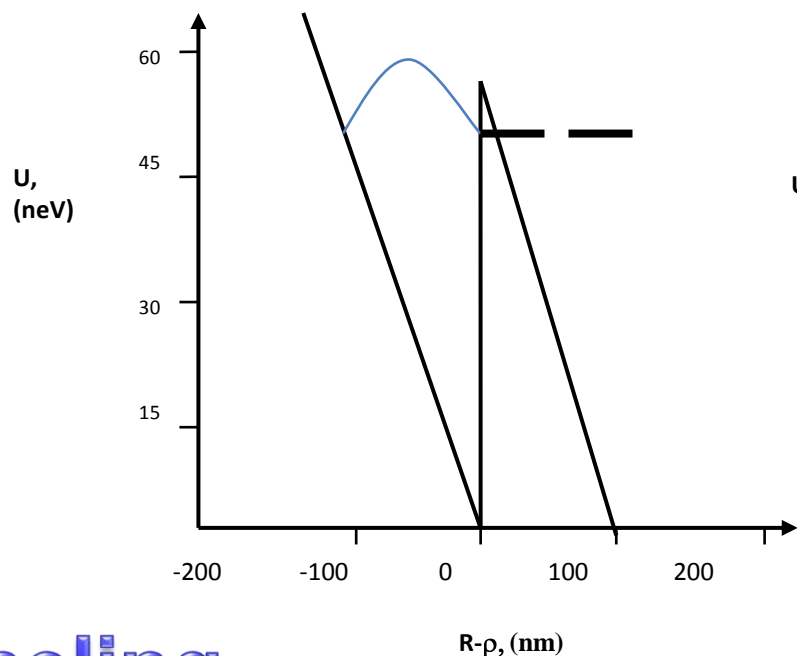


Illustration for quantum motion of an object above mirror in gravitational field and that in accelerating frame. Positions of the ball correspond to its most probable heights in 5th quantum state. The vertical scale corresponds to the neutron mass.

$$\Gamma_n = \left(\frac{\hbar^2 M v^4}{2R^2} \right)^{1/3} \frac{\sqrt{z_0 - \lambda_n}}{z_0} \exp \left[-\frac{4}{3} (z_0 - \lambda_n)^{3/2} \right]$$

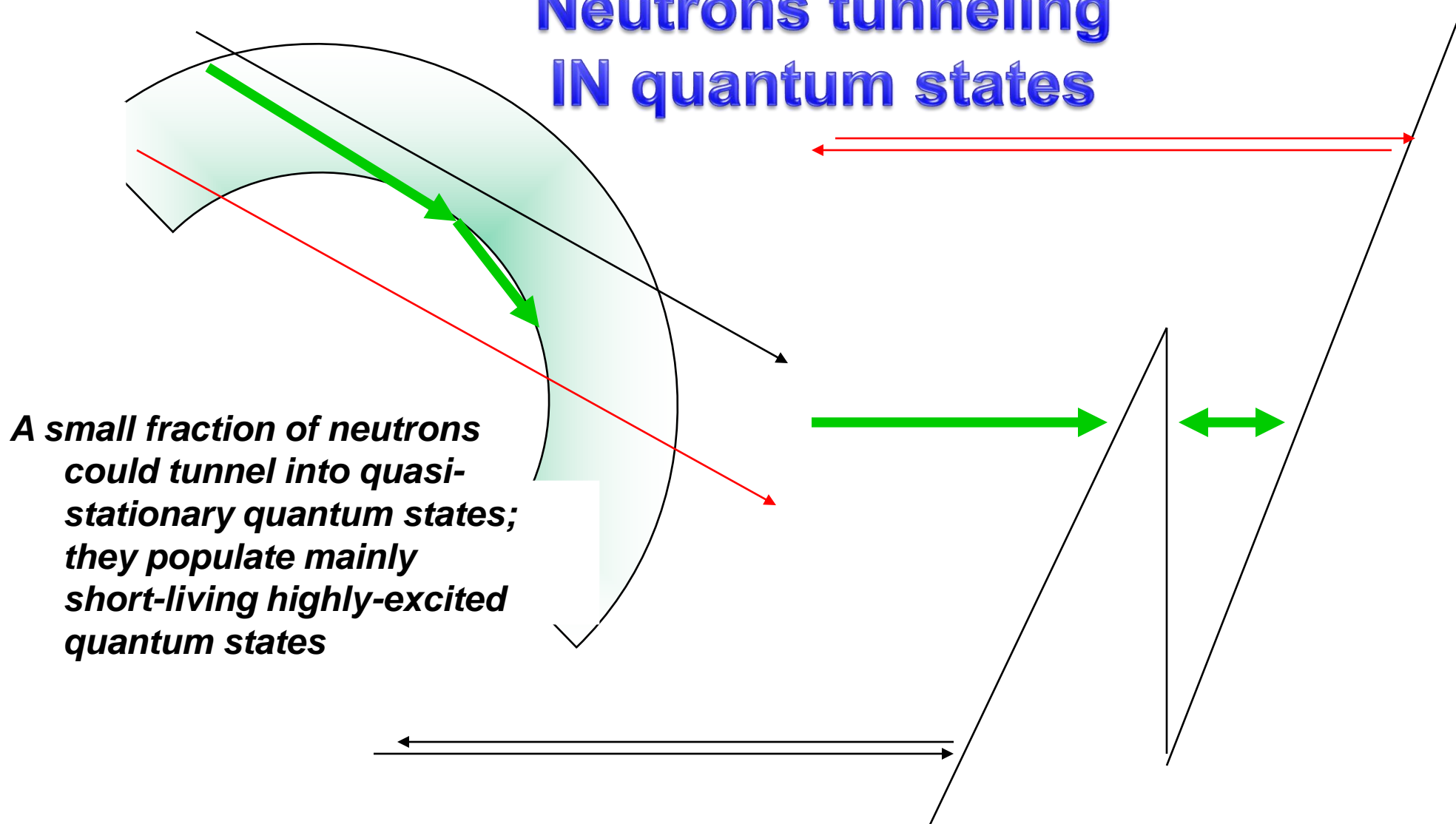
$$\lambda_n = E_n / \left(\frac{\hbar^2 M v^4}{2R^2} \right)^{1/3} \quad z_0 = V_F / \left(\frac{\hbar^2 M v^4}{2R^2} \right)^{1/3}$$

Life-times of quasi-stationary states due to tunneling as a function of energy



Tunneling

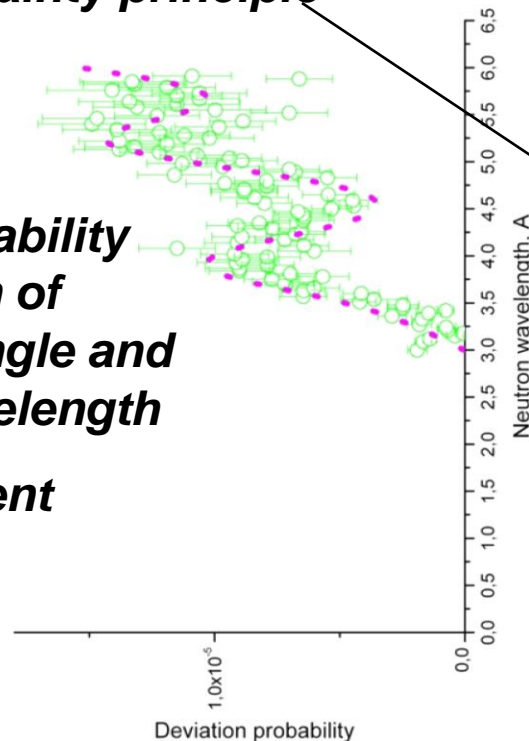
Neutrons tunneling IN quantum states



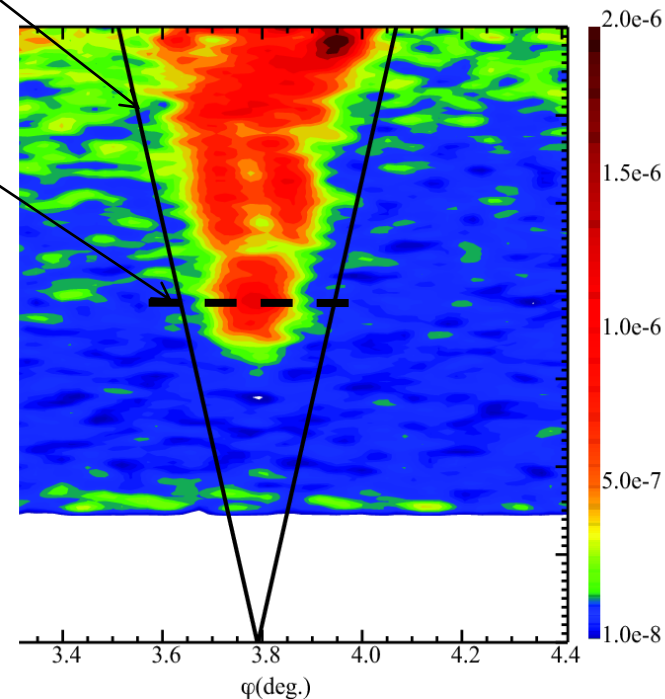
Neutrons tunneling IN quantum states

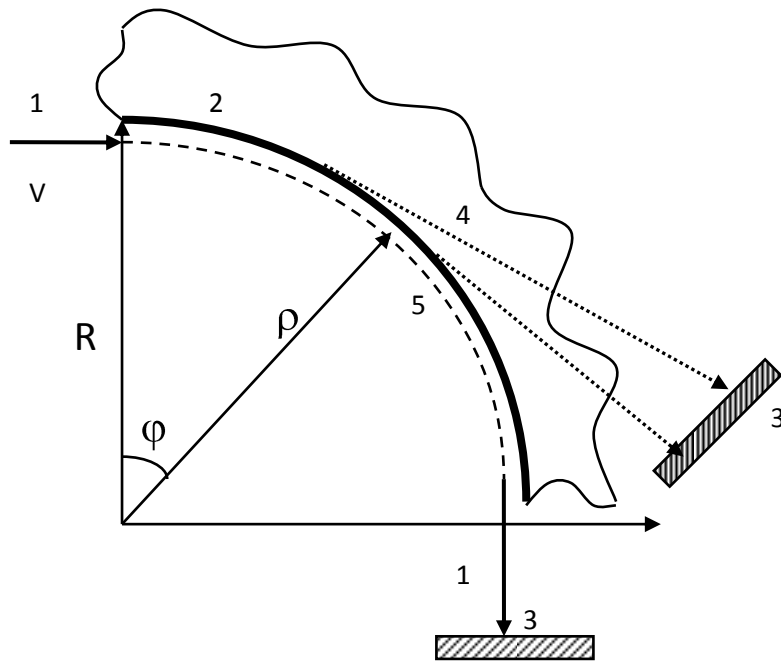
**Solid lines define « classical »
shape of the signal; horizontal
line indicates estimation of the
neutron wavelength resulting
from the uncertainty principle**

**Scattering probability
as a function of
scattering angle and
neutron wavelength
theory/experiment**



**Scattering probability as a function
of neutron wavelength (axis y)
and scattering angle (axis x)**





D17 instrument at the ILL

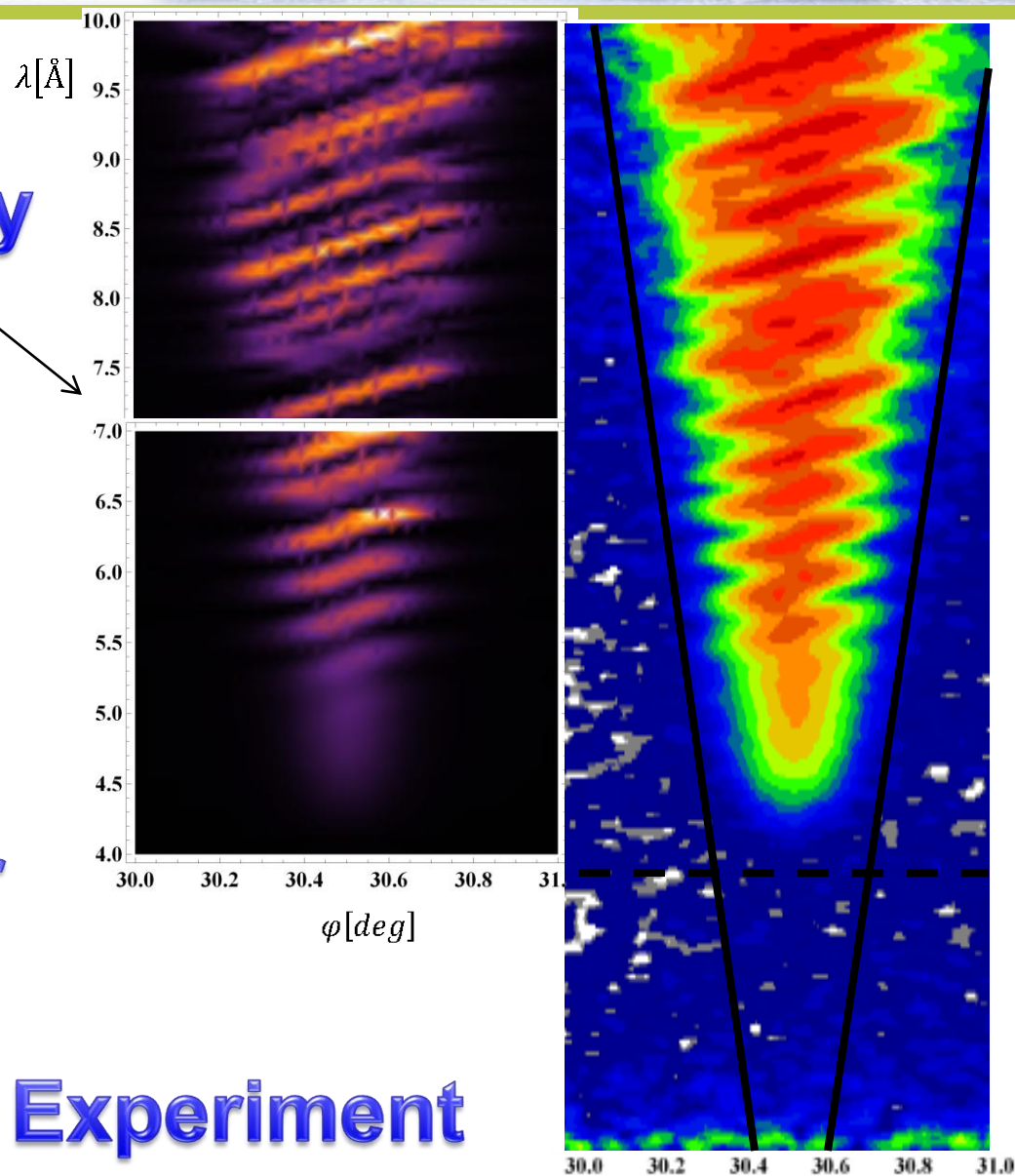
**Neutrons entering
from edge of
truncated cylindrical
mirror**

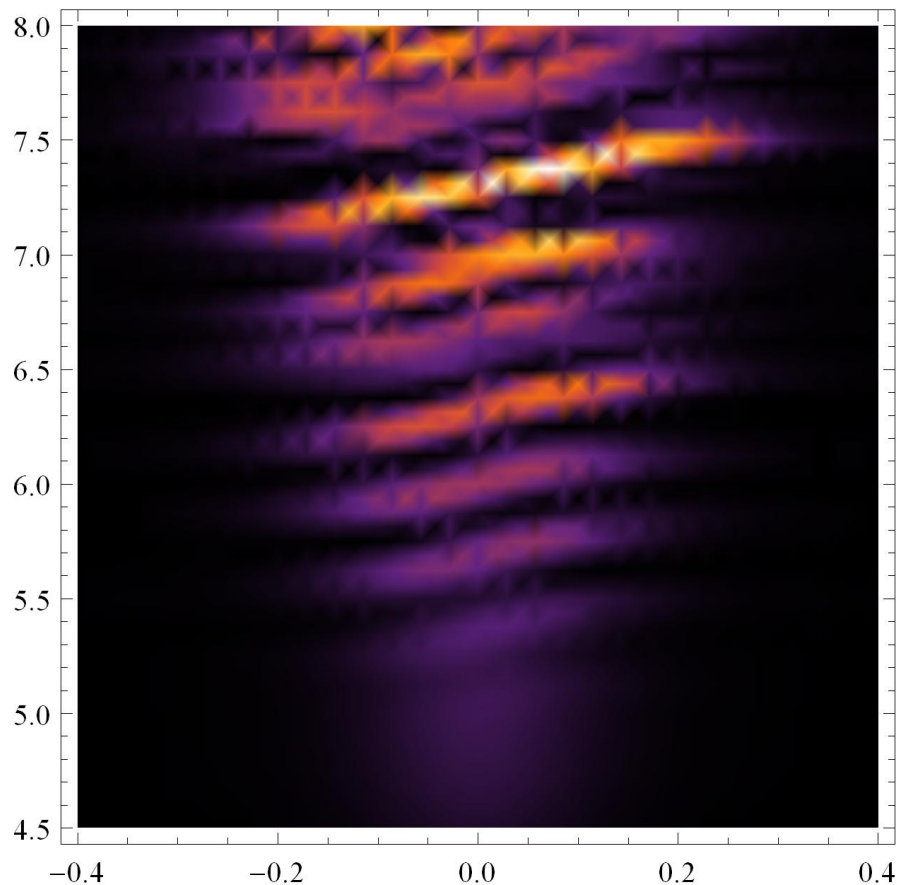
- 1) *Tangential neutron velocity is defined by time-of-flight method;*
- 2) *Scattering angle (radial velocity) is measured in a position-sensitive neutron detector.*

Theory

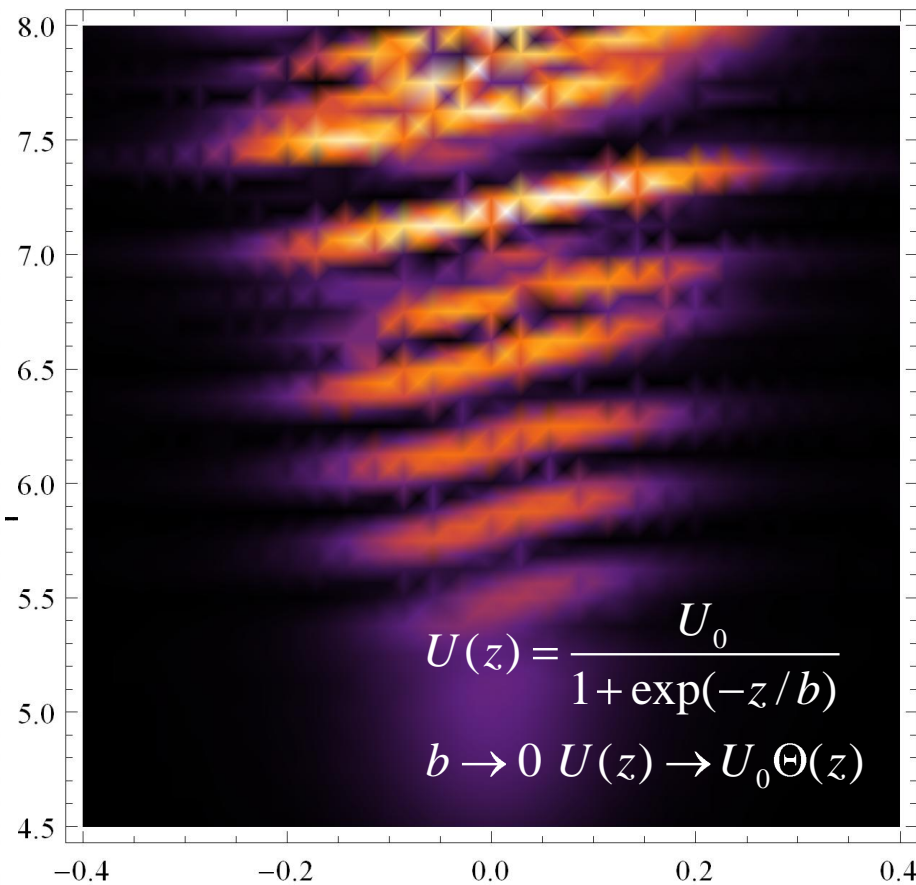
Neutrons
entering
from mirror
edge

Experiment



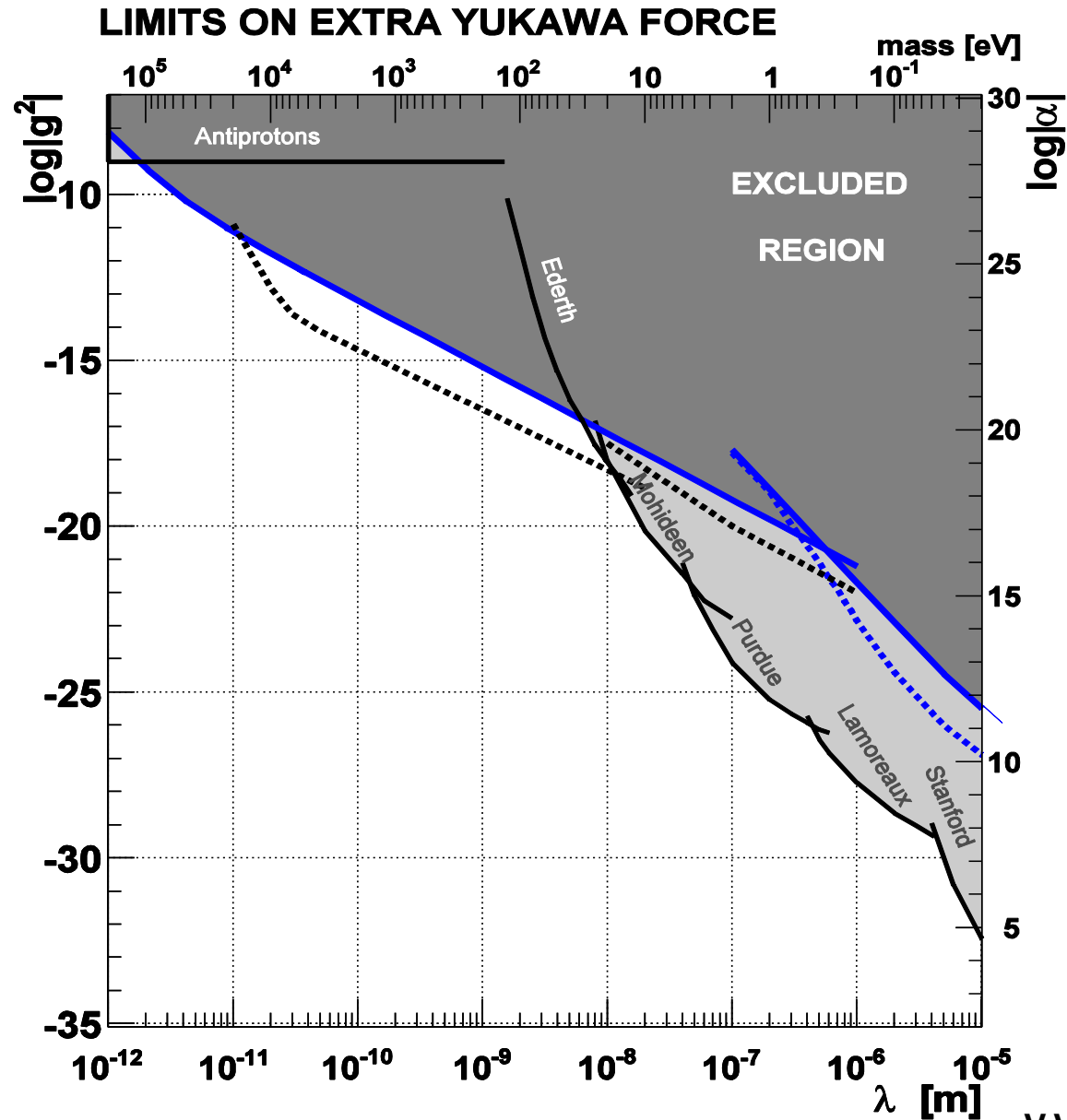


$b=0$



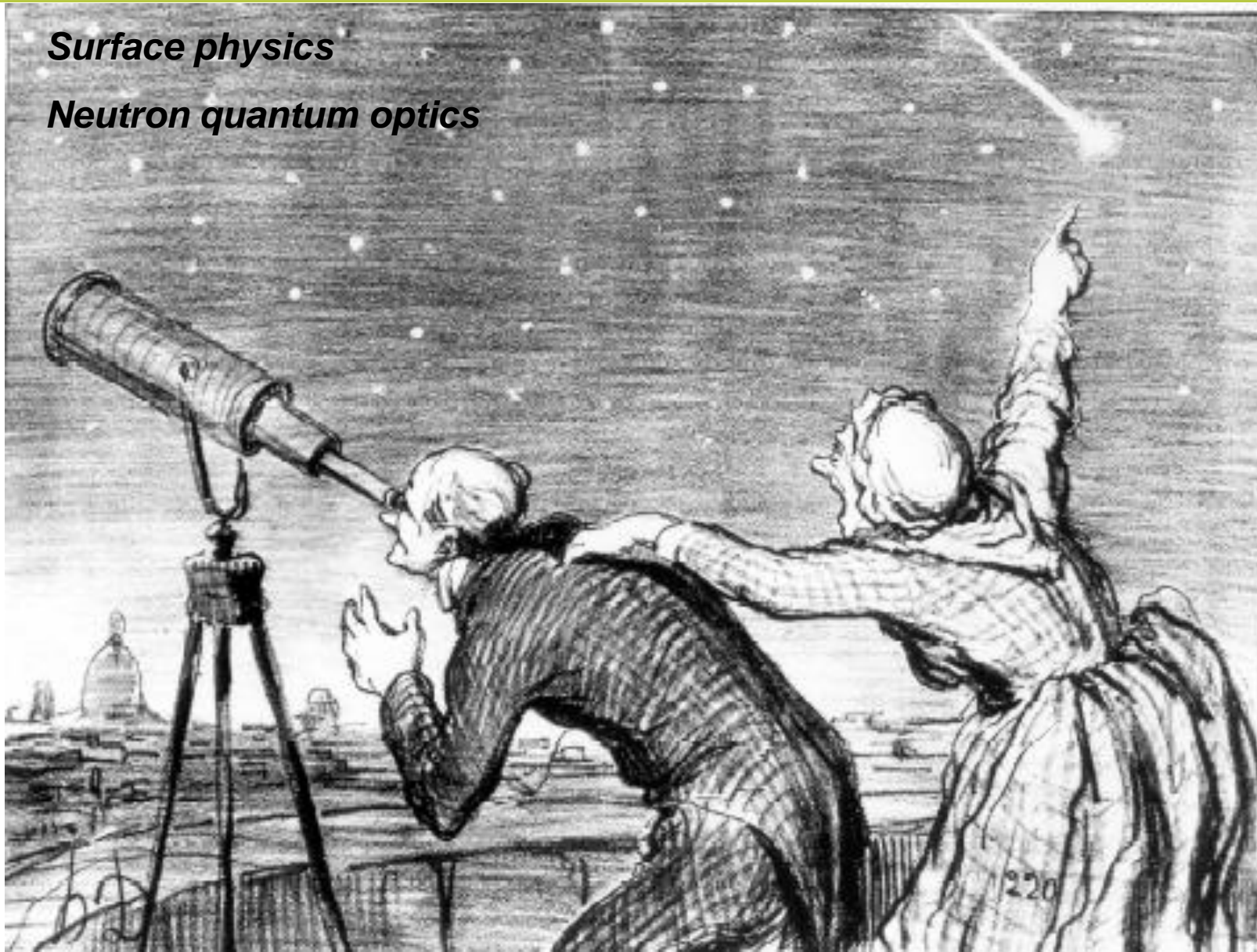
$b=4\text{nm}$

Sensitivity to additional forces



Surface physics

Neutron quantum optics



- 1. First observation of quasi-stationary quantum states of cold neutrons in vicinity of curved mirror surface: neutron whispering gallery**
- 2. First direct demonstration of the weak equivalence for an object in quantum state.**
- 3. Long lifetimes of neutrons in the quantum states allow us to use this phenomenon for precision studies of surface potentials and probably for constraining fundamental short-range potentials**