

- 1. Gravitational and centrifugal quantum states of matter and anti-matter: verification of the weak equivalence principle for an object in a quantum state**
- 2. Recent first measurement of the centrifugal quantum states of neutrons: the neutron whispering gallery effect**
- 3. Long lifetimes of neutrons in the whispering gallery states allow us to use this phenomenon for precision studies of surface potentials and probably for constraining fundamental short-range potentials**

Co-authors of all results included in this talk are indicated on respective transparencies

## Gravity / Acceleration

V.V. N. « Near-surface quantum states of neutrons in the gravitational and centrifugal potentials », *Phys.-Uspekhi* 53 (2010) 645.

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

Height above  
mirror

40 μm

30 μm

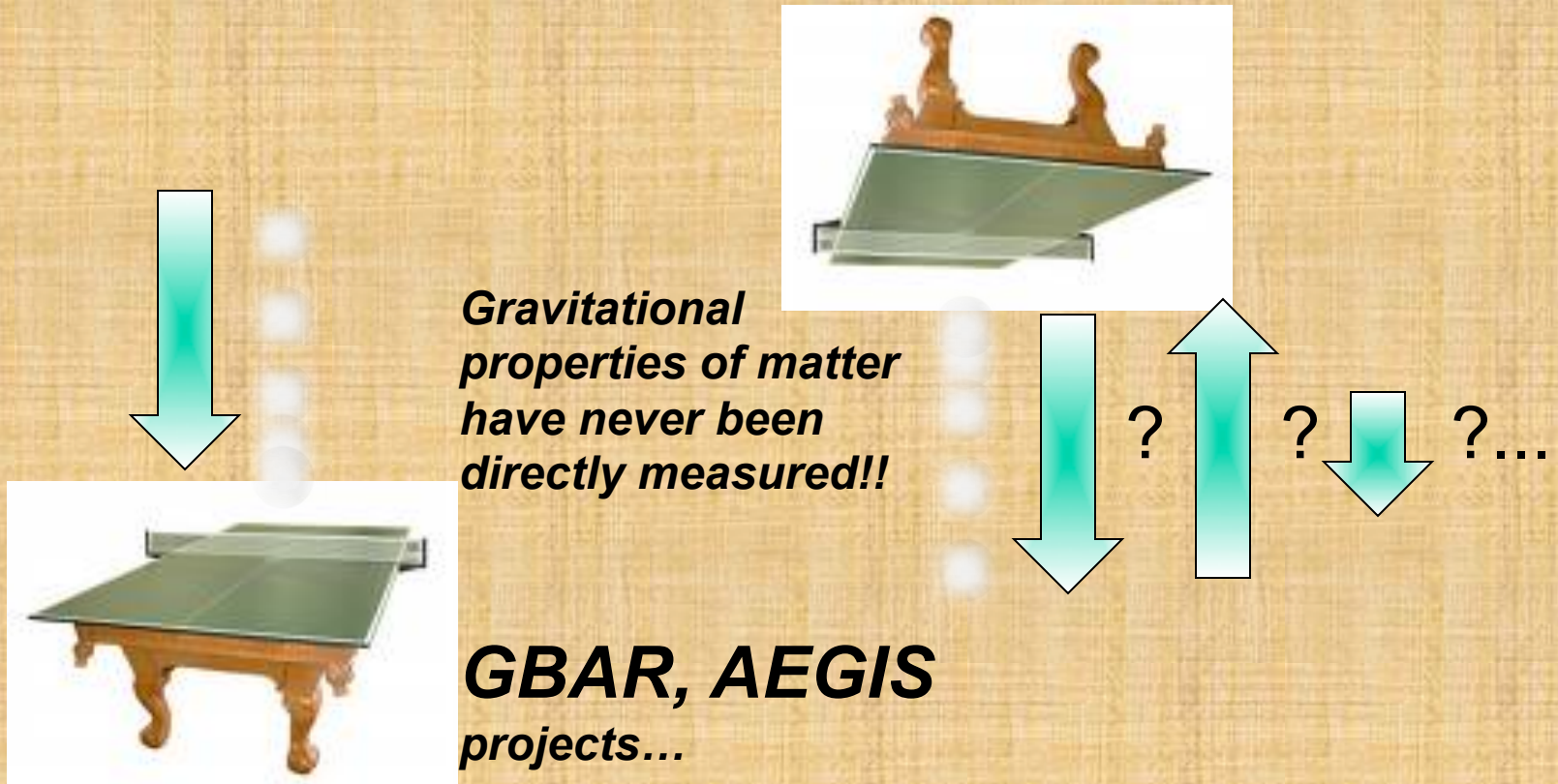
20 μm

10 μm



**Illustration for the quantum motion of an object above a mirror in a gravitational field and that in an accelerating frame. Positions of the ball correspond to the most probable heights of a neutron, or an anti-hydrogen atom, in the 5th quantum state.**

## Matter / Anti-matter



*Illustration for the quantum motion of a matter object and an anti-matter object above a mirror in a gravitational field.*

## Classical / Quantum mechanics

$$\cancel{m\omega = Mg} \Rightarrow \cancel{\omega = g} \quad \left[ -\frac{\hbar^2}{2m} \frac{\partial^2}{\partial z^2} + Mgz - E \right] \varphi(z) = 0$$

$m$  - Inertial mass     $M$  - Gravitational mass

$$\varepsilon_0 = \sqrt[3]{\frac{\hbar^2 M^2 g^2}{2m}} \quad l_0 = \sqrt[3]{\frac{\hbar^2}{2mMg}}$$

$$m = M$$

$$\frac{\varepsilon_0}{\hbar} = \sqrt{\frac{g}{2l_0}}$$

$$\frac{M^2}{m} = \frac{2\hbar\omega_{12}^3}{g^2(\lambda_2^0 - \lambda_1^0)^3}$$

$$CPT : m = m_H$$

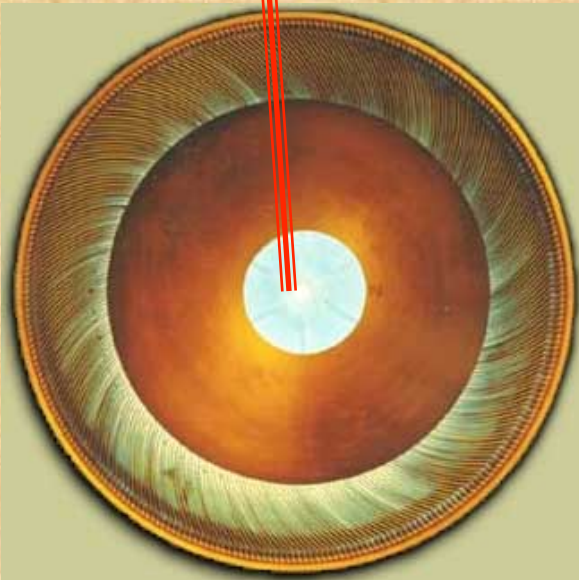
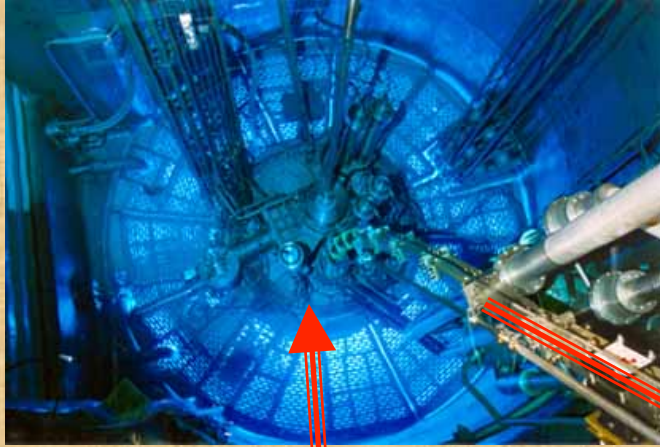
$$M = \sqrt{\frac{2m_H\hbar\omega_{12}^3}{g^2(\lambda_2^0 - \lambda_1^0)^3}}$$



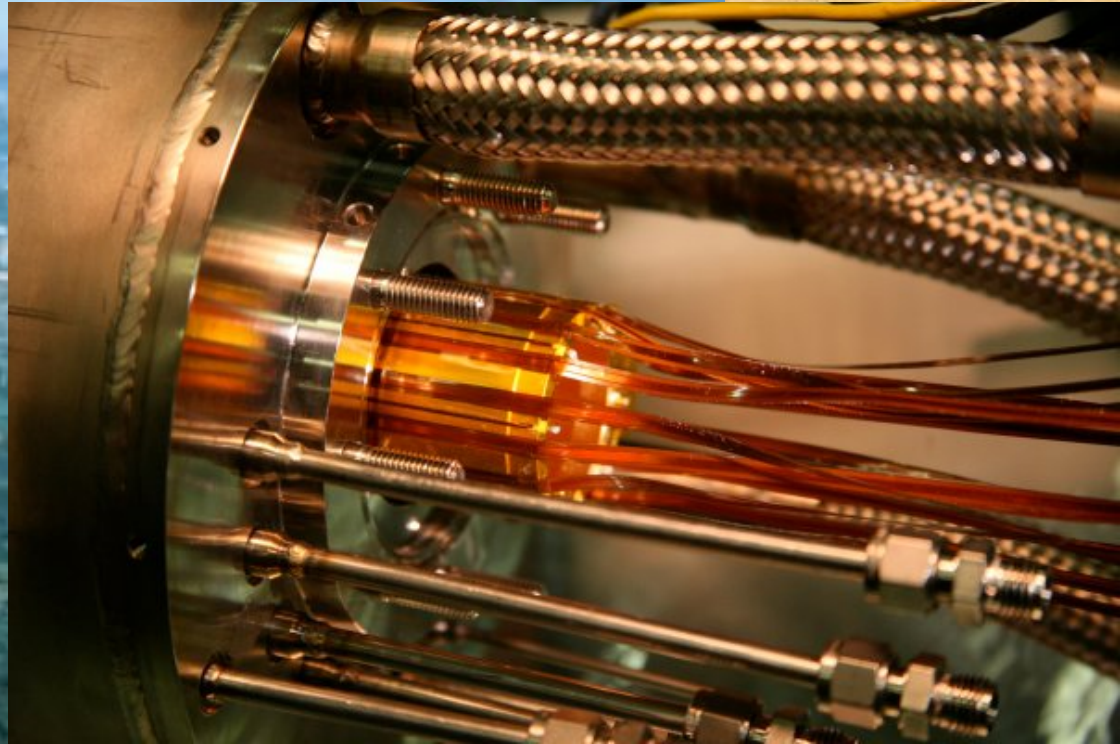
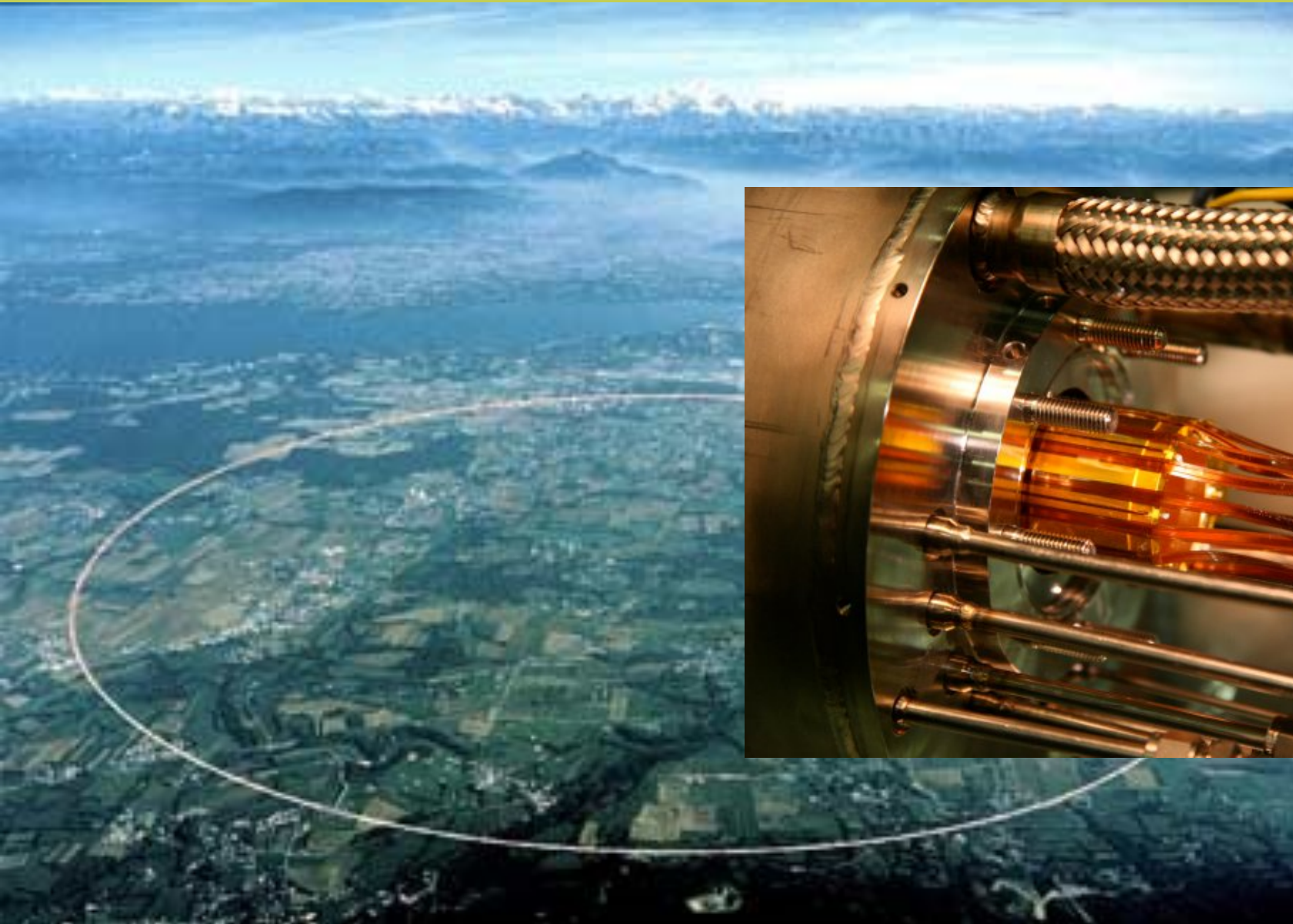
*Countries ~12  
Europe, Asia, USA, Australia  
Proceedings to appear soon in  
Les Comptes Rendus Academie  
des Science*



# Neutron: The European Center for Neutron Research, Grenoble. The largest worldwide research reactor



 **Anti-hydrogen:** The European Organization for Nuclear Research, Geneve. The largest worldwide particle accelerator



## Quantum states of neutrons in the Earth's gravitational field

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Hartmut Abele†, Stefan Baeßler†, Frank J. Rueß†, Thilo Stöferle†,  
Alexander Westphal†, Alexei M. Gagarski‡, Guennady A. Petrov‡  
& Alexander V. Strelkov§

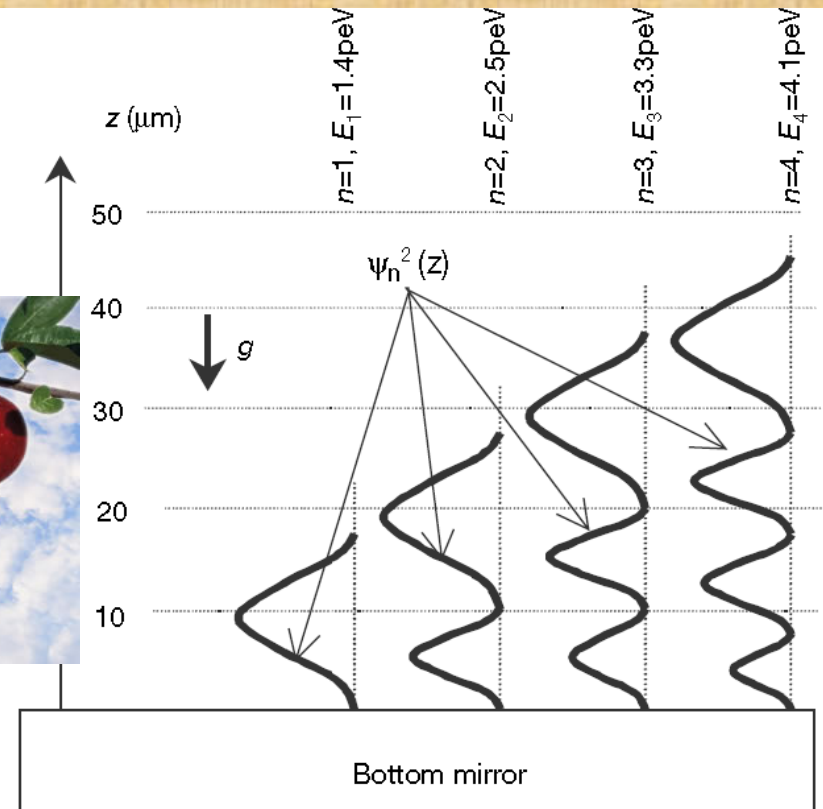
\* Institute Laue-Langevin, 6 rue Jules Horowitz, Grenoble F-38042, France

† University of Heidelberg, 12 Philosophenweg, Heidelberg D-69120, Germany

‡ Petersburg Nuclear Physics Institute, Orlova Roscha, Gatchina, Leningrad  
R-188350, Russia

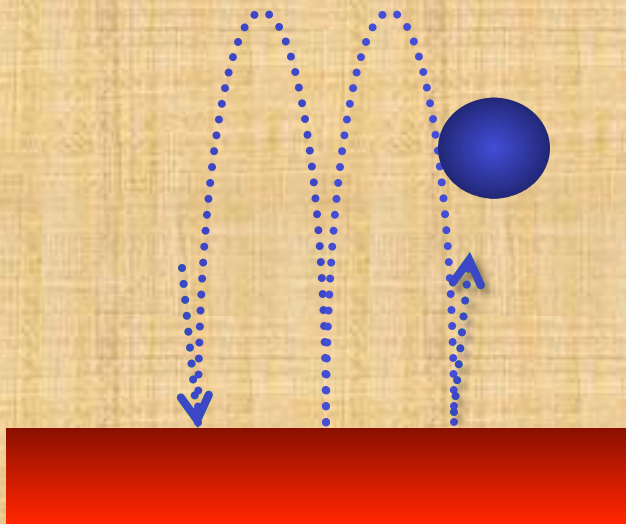
§ Joint Institute for Nuclear Research, Dubna, Moscow reg. R-141980, Russia

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 atoms<sup>16</sup>, and quantum states of nucleons in a strong nuclear field give rise to the structure of atomic nuclei<sup>17</sup>. 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.





1) **Electrical neutrality** (usually gravitational interaction of an object with a surface is much weaker than other interactions)

2) **Long life-time**

3) **Small mass**

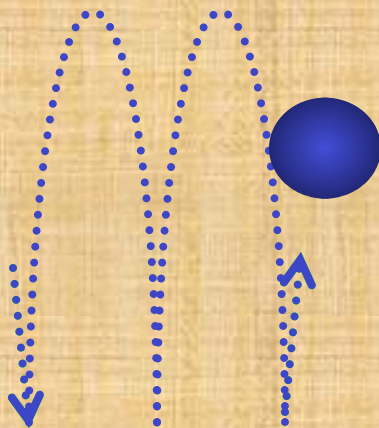
$$\left( \Delta v \cdot \Delta x \approx \frac{\hbar}{m} \right) \left( \Delta E \approx \frac{\hbar}{\Delta \tau} \right)$$

4) **Energy (effective temperature) of UCN, or an atom, is extremely low; it is not equal to the surface temperature (the effective temperature of a particle in gravitational quantum states is  $\sim 10^{-8}\text{K}$ )**

**A particle above a mirror in the gravity field: *An ultracold neutron* (V.I. Luschnikov, A.I. Frank « Quantum effects occurring when ultracold neutrons are stored on a plane », *JETP Lett.* 28 (1978) 759) and ... *an anti-hydrogen atom* (A.Yu. Voronin, P. Froelich, V.V. N. « Gravitational quantum states of antihydrogen », *Phys. Rev. A* 83 (2011) 032903) (a mirror represents a nearly infinitely-high and sharp potential step)**

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

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

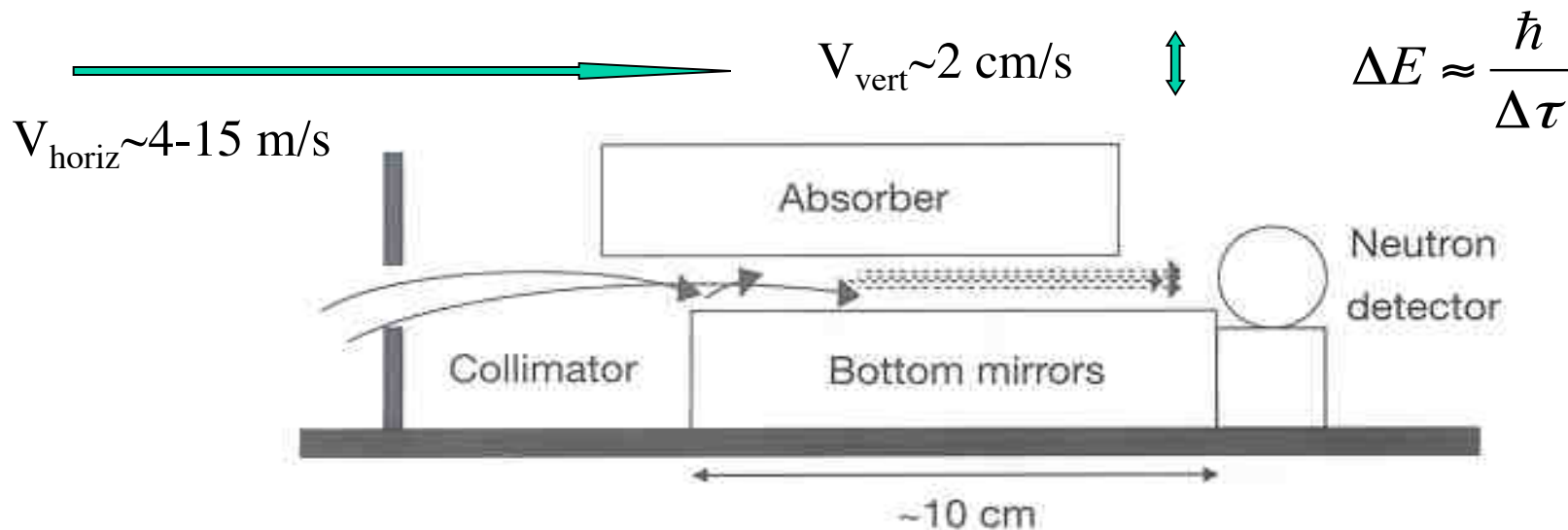


*A(n) (anti)-particle above a mirror in the gravity field*

- 1) A neutron is reflected from the effective nuclear-optical potential of matter due to averaging of its interaction with a huge number of nuclei in matter*
- 2) An anti-matter (matter) atom is reflected from the van der Waals/ Casimir-Polder (vdW/CP) potential appearing due to polarization of the anti-hydrogen atom and the surface atoms*

# The experimental installation and the method used in the first neutron experiment

V.V. N., H.G. Borner, A.K. Petukhov, H. Abele, S. Baessler, F.J. Ruess, Th. Stoferle, A. Westphal, A.M. Gagarski, G.A. Petrov, A.V. Strelkov « Quantum states of neutrons in the Earth's gravitational field », *Nature* 415 (2002) 297; V.V. N., H.G. Boerner, A.M. Gagarski, A.K. Petukhov, G.A. Petrov, H. Abele, S. Baessler, G. Divcovic, F.J. Ruess, Th. Stoferle, A. Westphal, A.V. Strelkov, K.V. Protasov, A.Yu. Voronin, « Measurement of quantum states of neutrons in the Earth's gravitational field », *Phys. Rev. D* 67 (2003) 102002.



## **Selection and measurement of the vertical and horizontal velocity components:**

**The maximum vertical velocity is defined by the scatterer/absorber height above the mirror**

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

# The experimental installation and the method

## Model of tunneling through a gravitational barrier

V.V. N., A.K. Petukhov, H.G. Boerner, T.A. Baranova, A.M. Gagarski, G.A. Petrov, K.V. Protasov, A.Yu. Voronin, S. Baessler, H. Abele, A. Westphal, L. Lucovac, « Study of the neutron quantum states in the gravity field », *Europ. Phys. J. C* 40 (2005) 479; A. Yu. Voronin, H. Abele, S. Baessler, V.V. Nesvizhevsky, A.K. Petukhov, K.V. Protasov, A. Westphal, « Quantum motion of a neutron in a waveguide in the gravitational field », *Phys. Rev. D* 73 (2006) 044029.

$$\xi \gg 1 \quad \Gamma_n(\xi) = \omega_n \cdot D(\xi) \quad \omega_n \approx (E_{n+1} - E_n) / \hbar$$

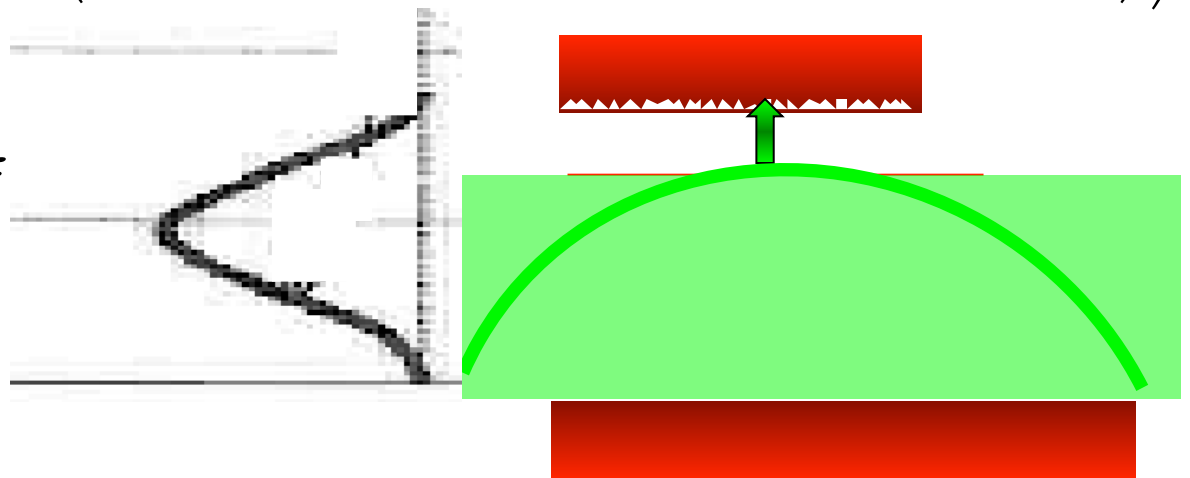
$$D(\xi) \approx \text{Exp}\left[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}\right],$$

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

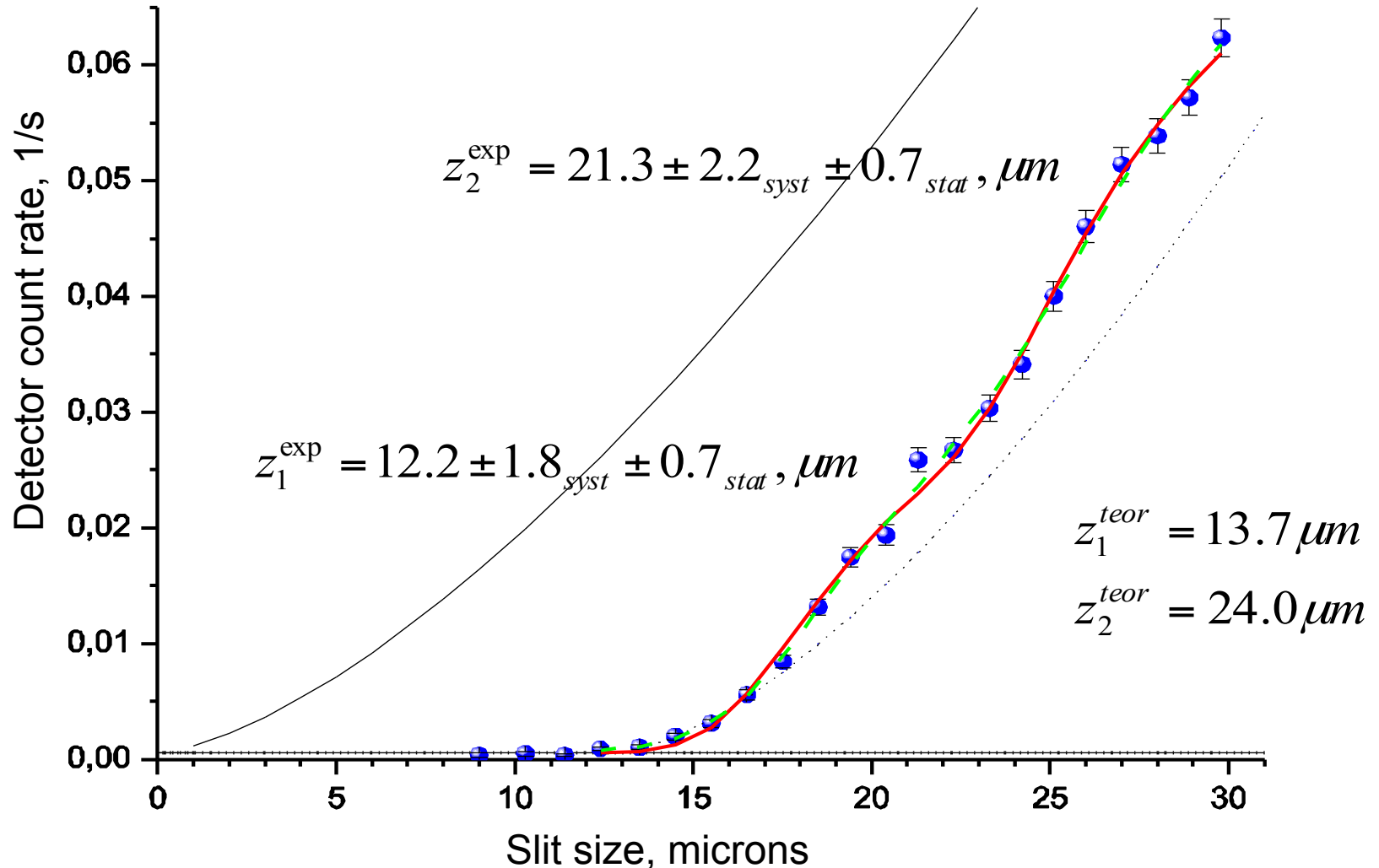
$$F(\Delta z, V_{hor}) = \sum_n \left( \beta_n \cdot \text{Exp} \left( -\alpha \cdot \frac{L}{V_{hor}} \cdot C_n^2 \cdot \text{Exp} \left( -\frac{4}{3} \cdot \left( \frac{\Delta z - z_n}{z_0} \right)^{\frac{3}{2}} \right) \right) \right)$$

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

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

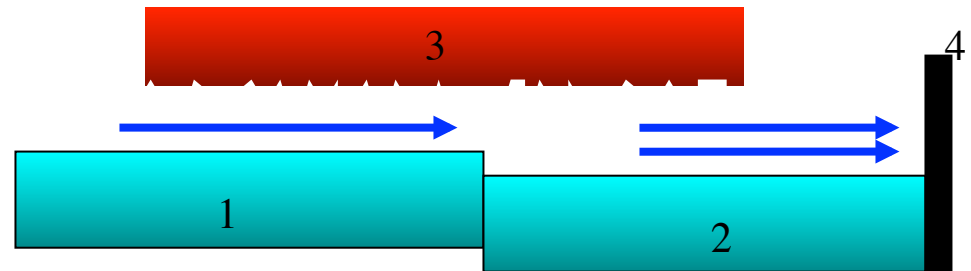
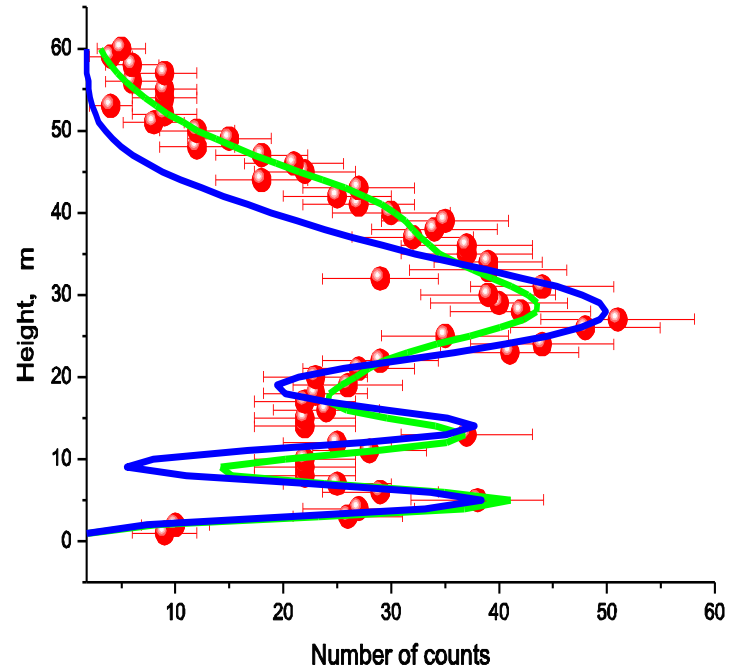


V.V. N., A.K. Petukhov, H.G. Boerner, T.A. Baranova, A.M. Gagarski, G.A. Petrov, K.V. Protasov, A.Yu. Voronin, S. Baessler, H. Abele, A. Westphal, L. Lucovac, « Study of the neutron quantum states in the gravity field », *Europ. Phys. J. C* 40 (2005) 479.



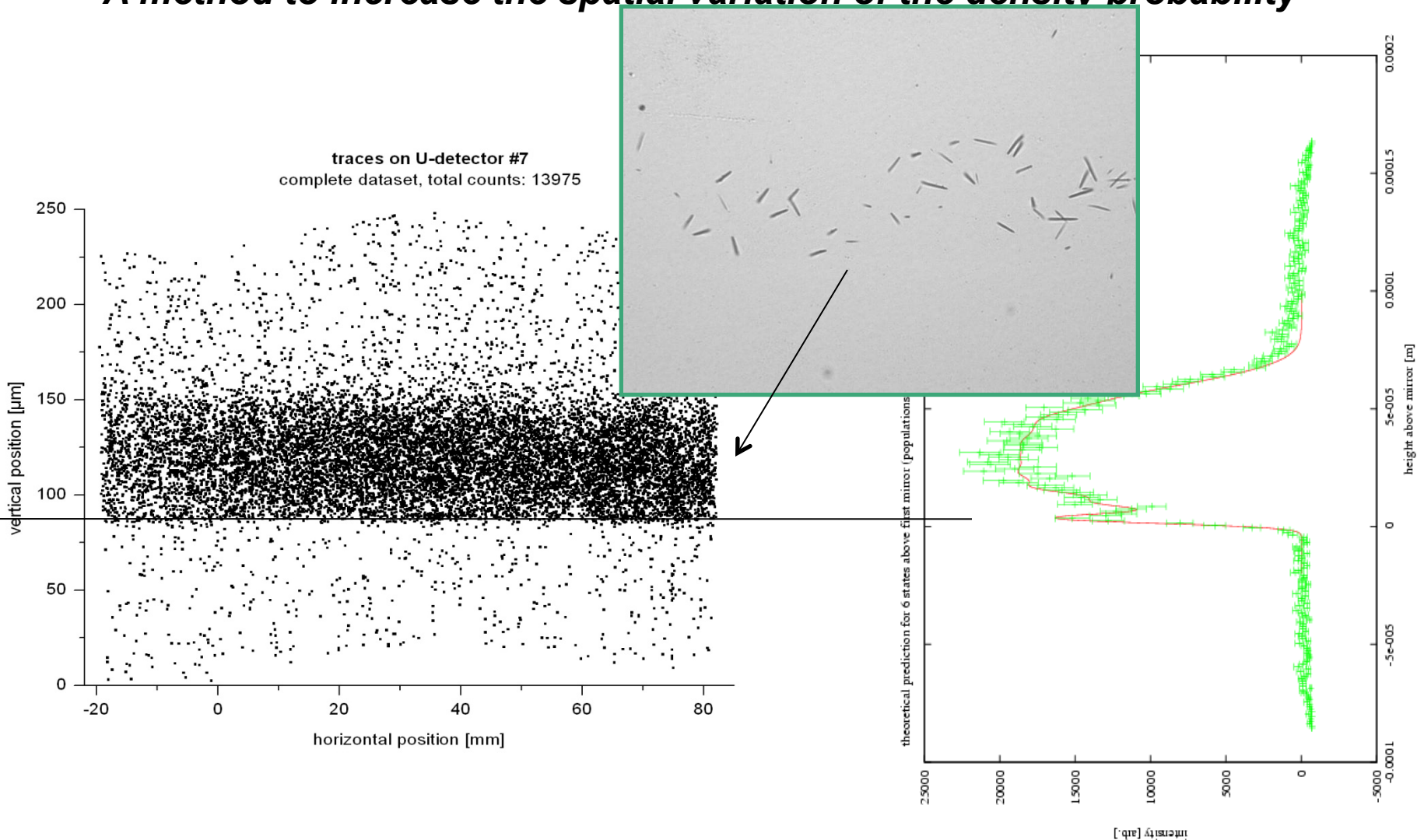
# « Differential » method, position-sensitive detectors

*A method to increase the spatial variation of the density probability*



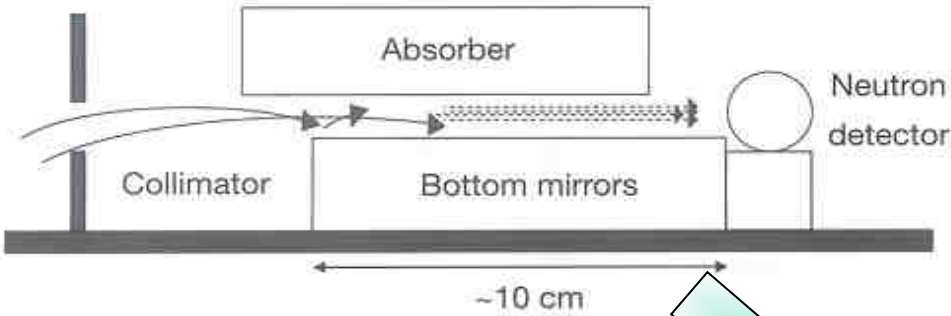
# « Differential » method, position-sensitive detectors

*A method to increase the spatial variation of the density probability*



# Transitions between gravitational quantum states

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

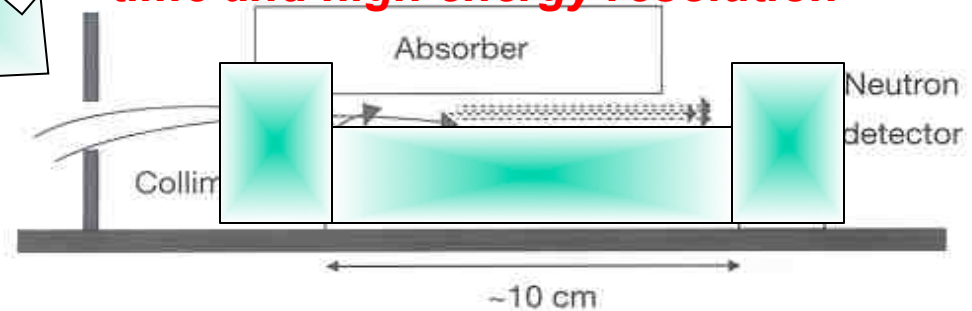


*Transitions could be excited, for instance:*

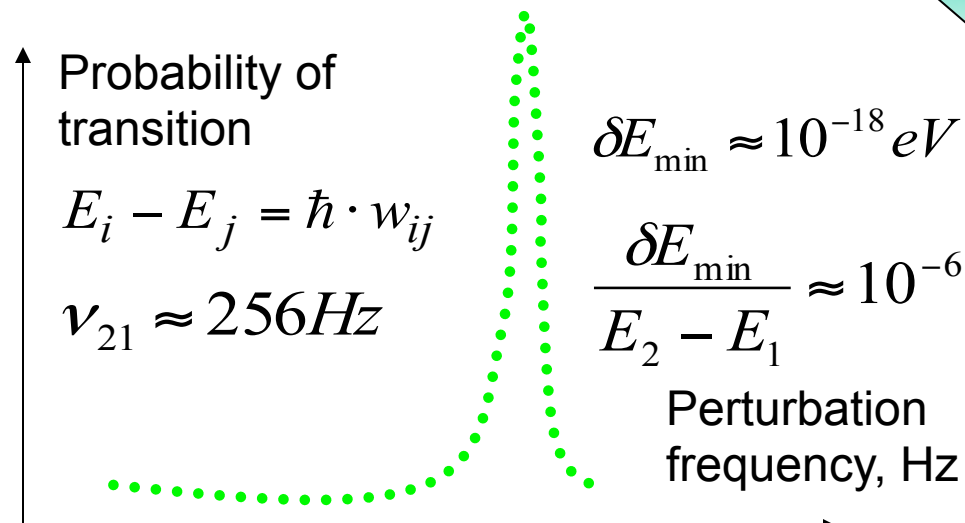
- *By periodically varying magnetic field gradient;*
- *By periodically varying local gravitational field;*
- *By oscillating mechanically the mirror*

*V.V. N., K.V. Protasov, « Quantum states of neutrons in the Earth's gravitational field: state of the art, applications, perspectives », Ed. Book on Trends in Quantum Gravity Research (NOVA science publishers, New York, 2006).*

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



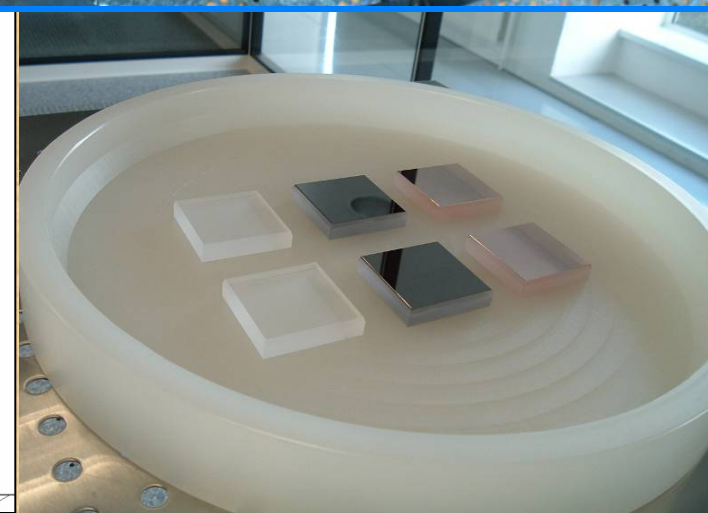
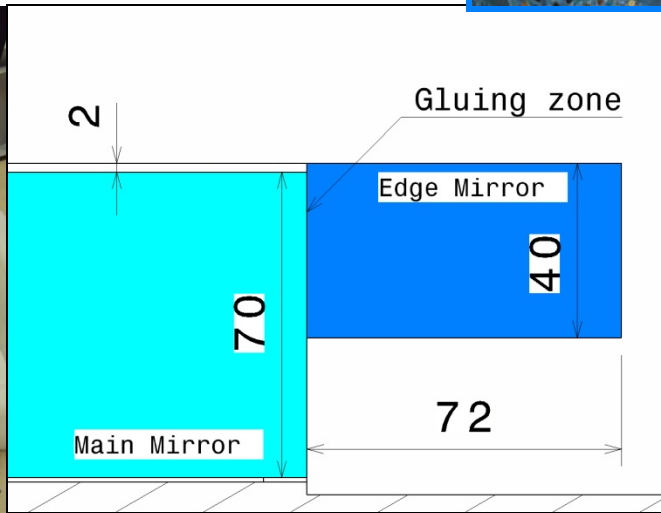
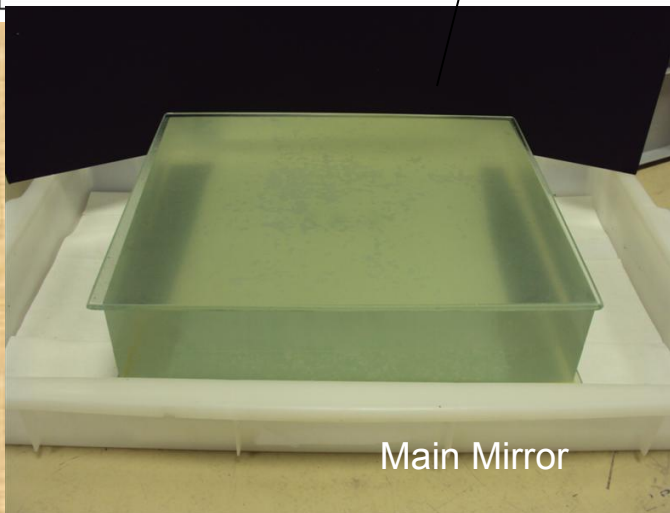
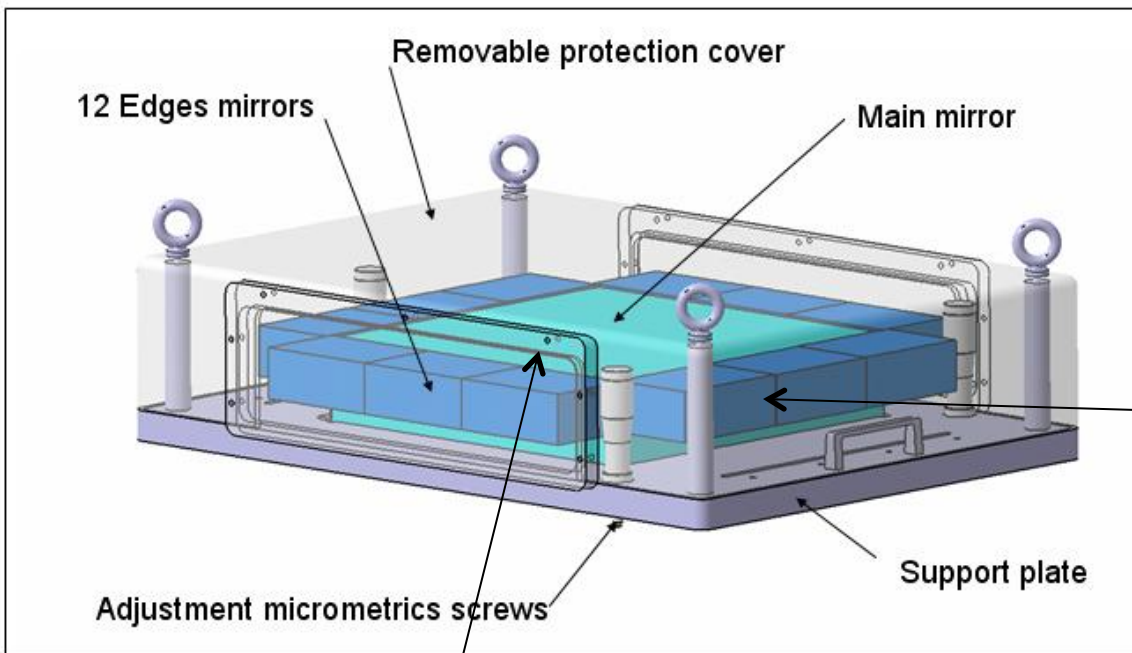
**Figure 2** Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

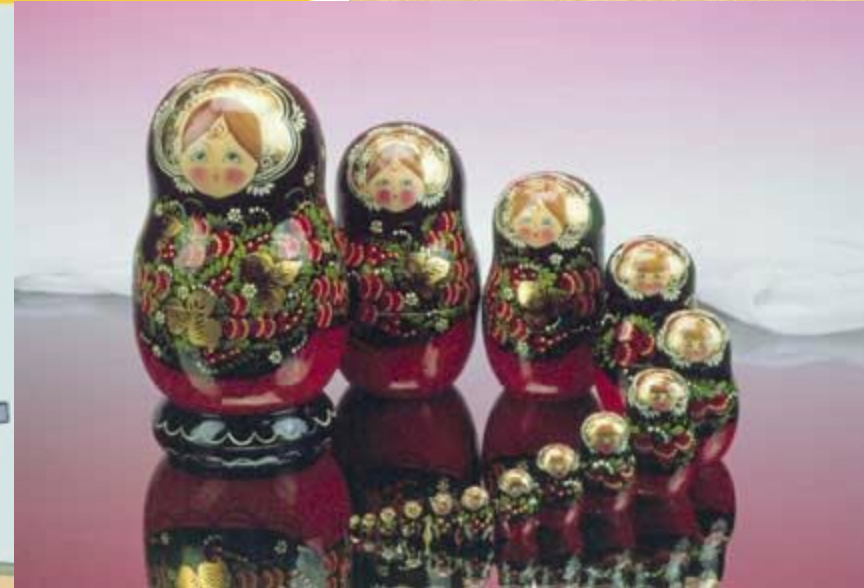
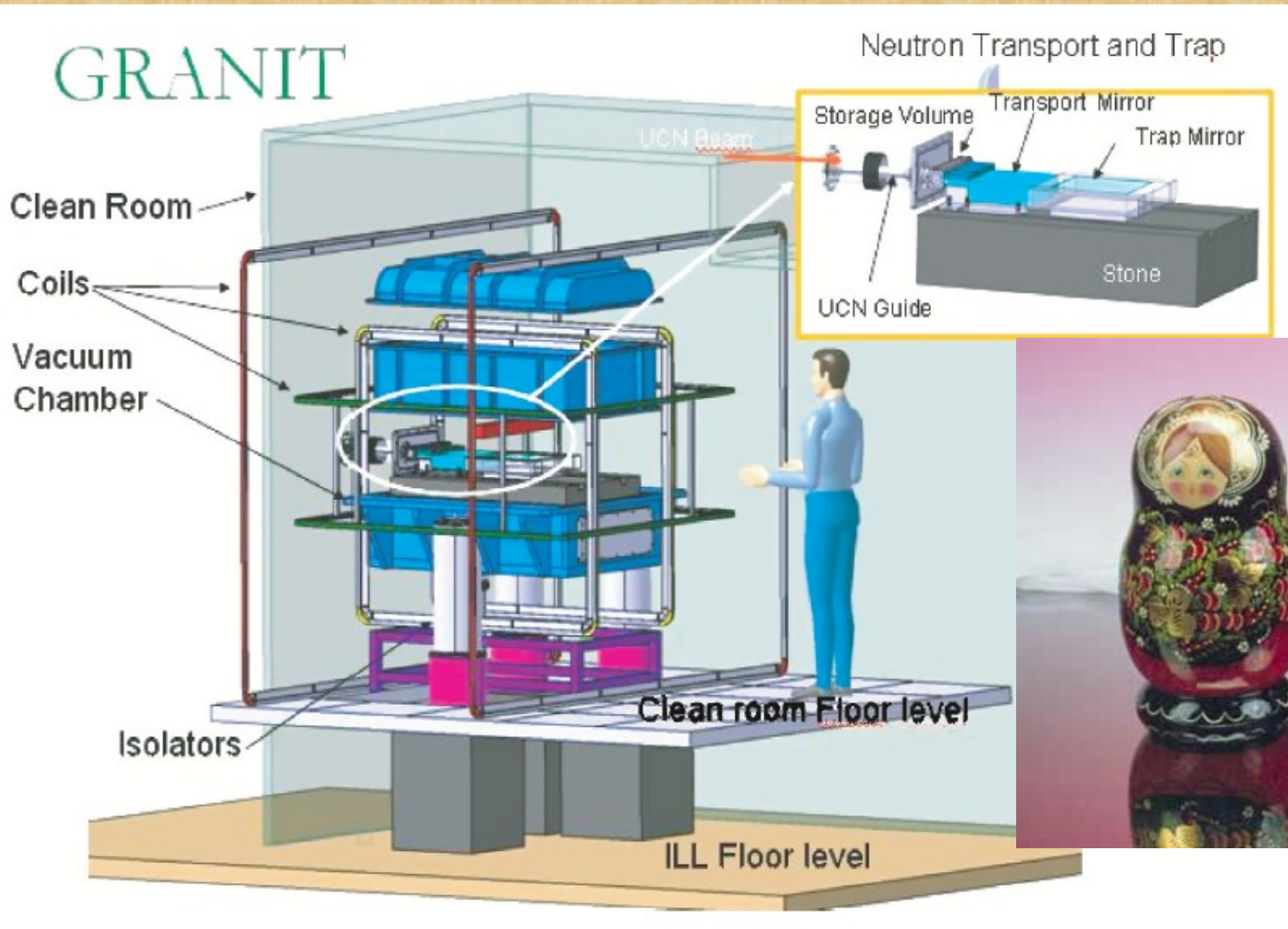




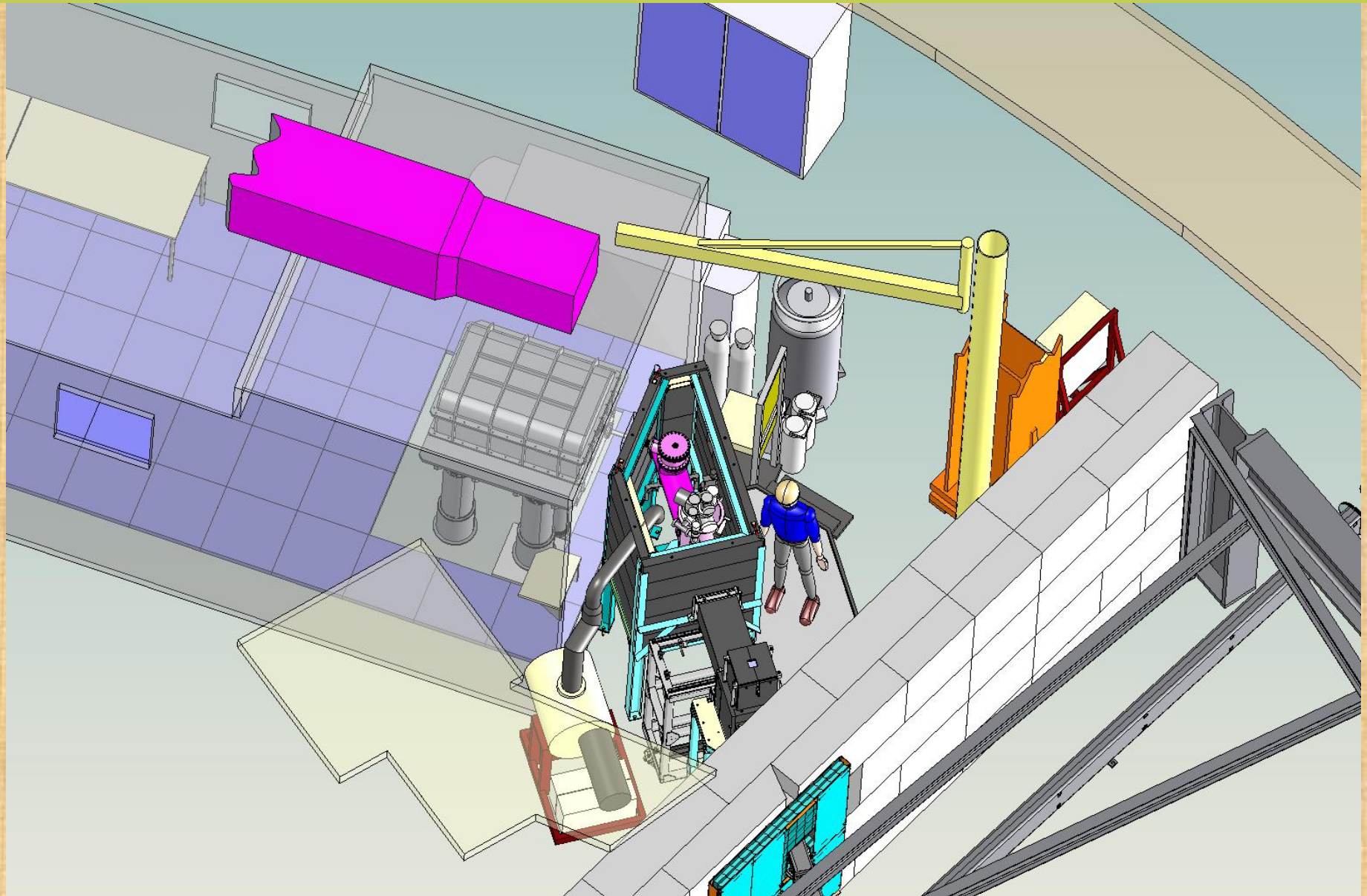
# Transitions between gravitational quantum states

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

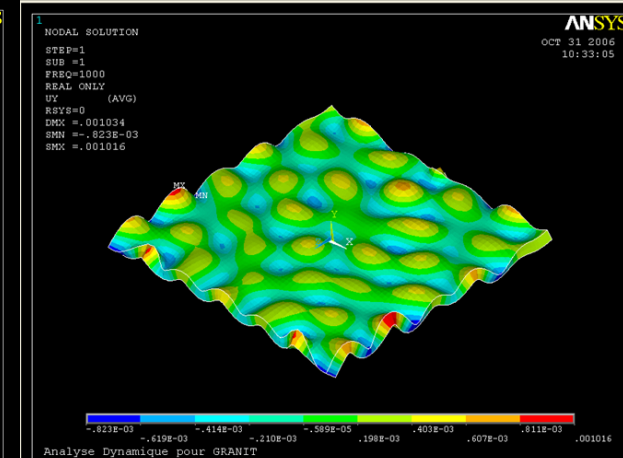
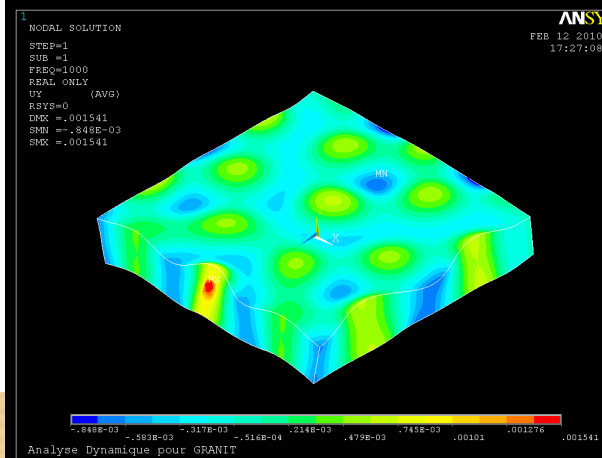
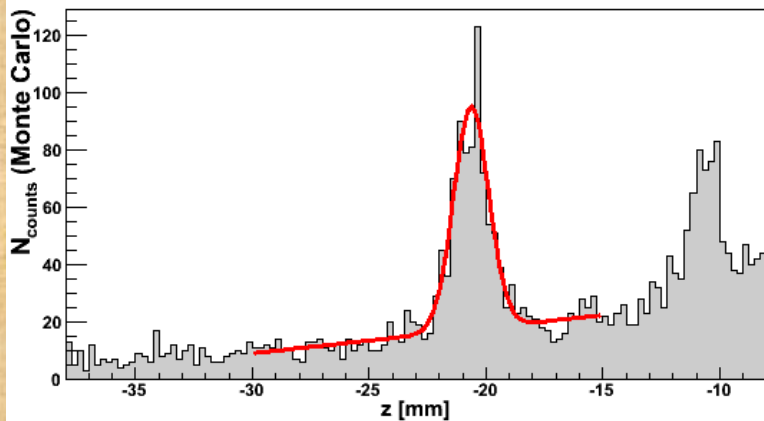
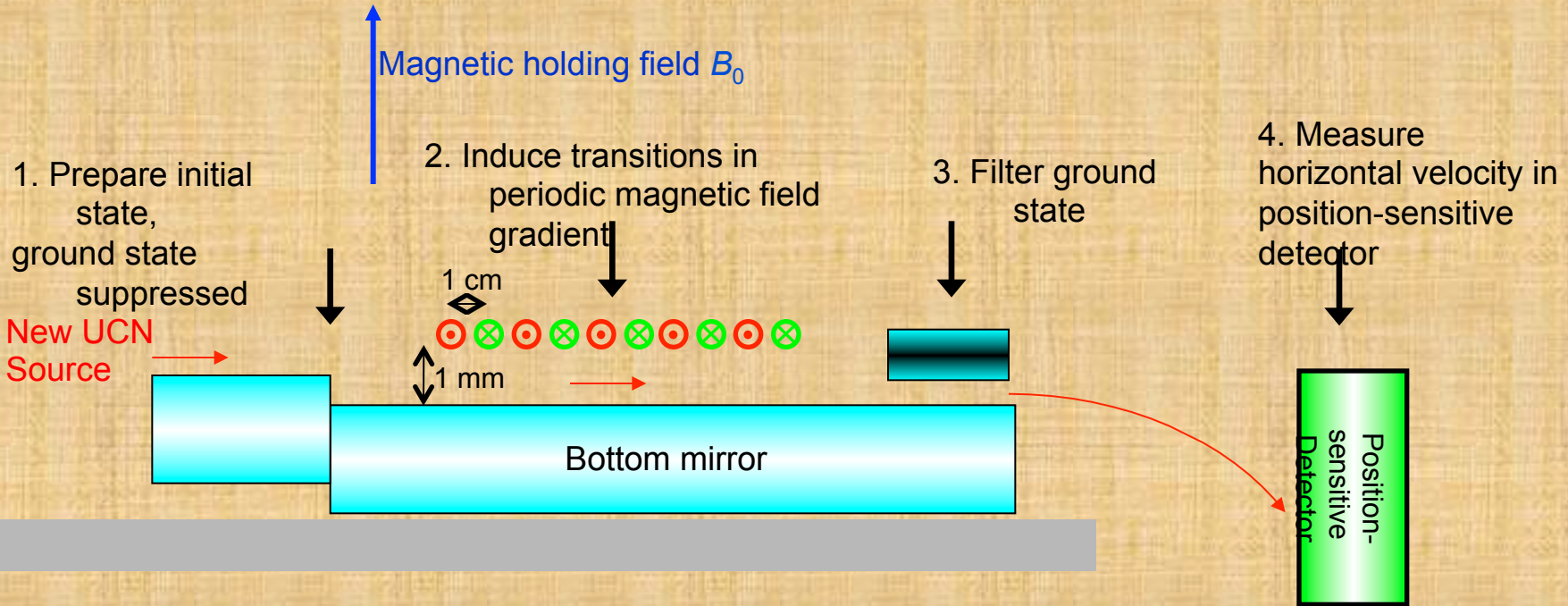




# Installation of GRANIT spectrometer at the level C at ILL



# on methods of excitation the transitions

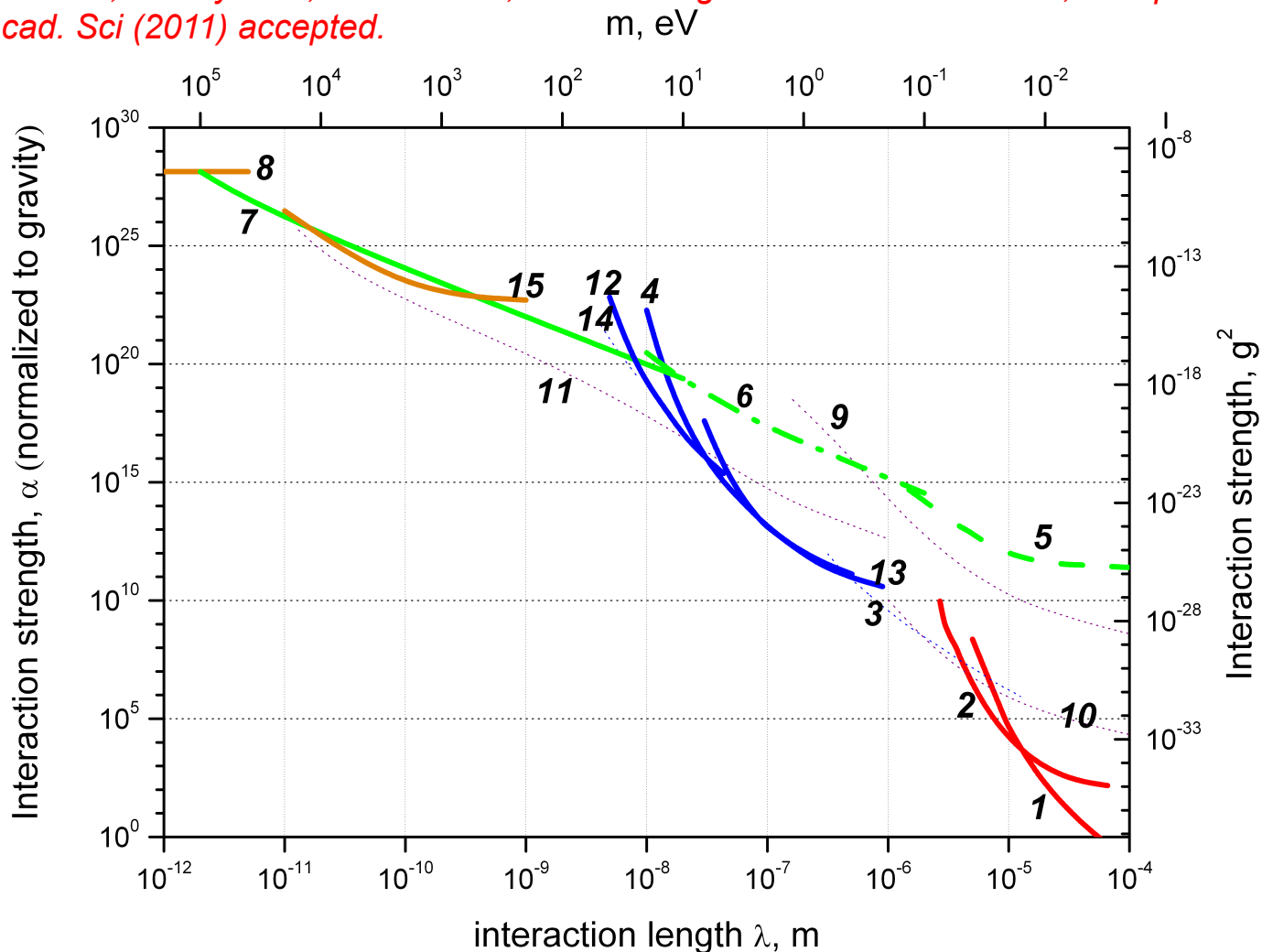


***The phenomenon of gravitational quantum states of neutrons could be used in various applications, as apriory it provides a very « clean » system with well-defined quantum states.***

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

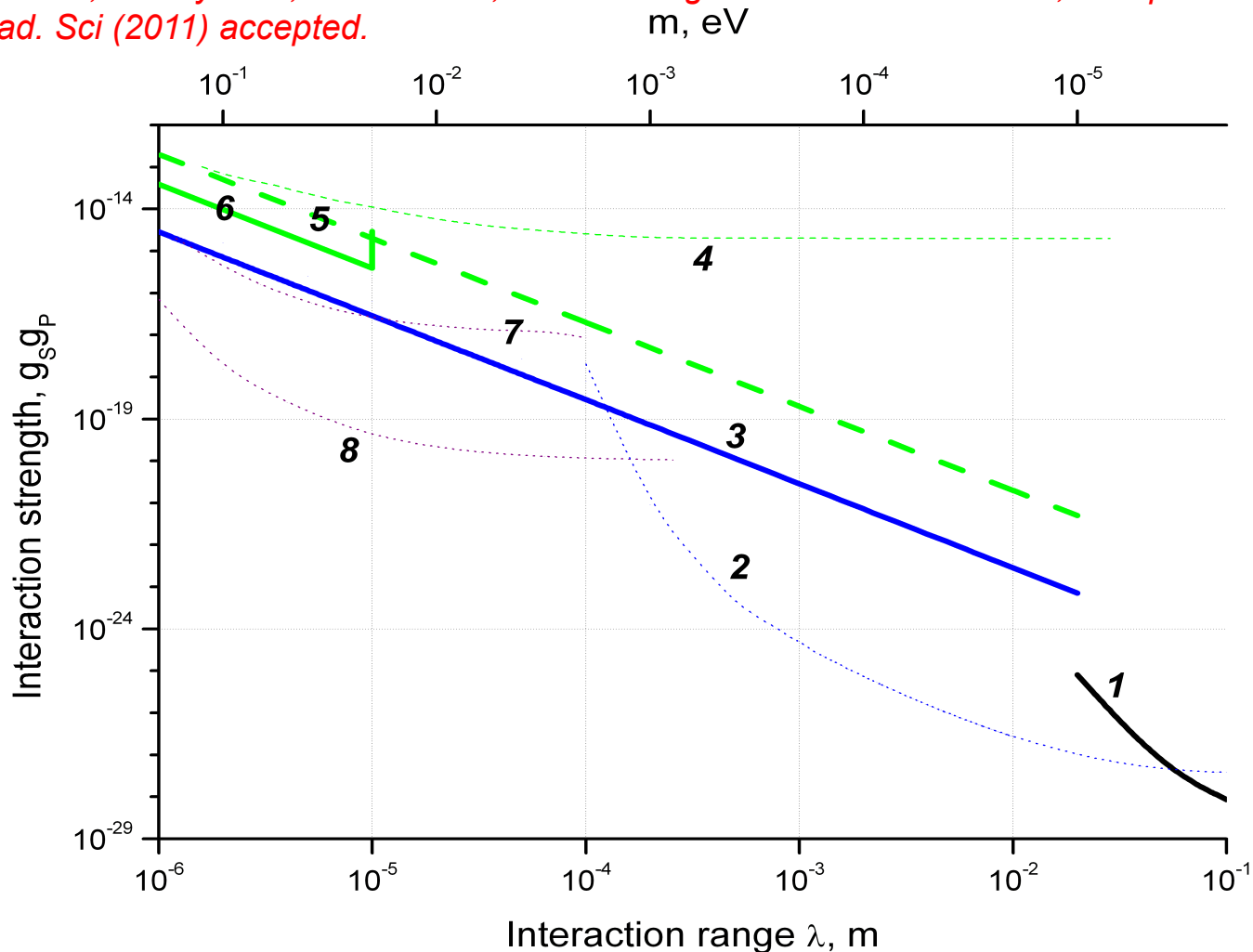
# Constraints for short-range forces

*I. Antoniadis, S. Baessler, M. Buchner, V.V. Fedorov, S. Hoedl, V.V. N., G. Pignol, K.V. Protasov, S. Reynaud, Yu. Sobolev, « Short-range fundamental forces », Compt. Rendu Acad. Sci (2011) accepted.*



# Constraints for short-range forces

*I. Antoniadis, S. Baessler, M. Buchner, V.V. Fedorov, S. Hoedl, V.V. N., G. Pignol, K.V. Protasov, S. Reynaud, Yu. Sobolev, « Short-range fundamental forces », Compt. Rendu Acad. Sci (2011) accepted.*



# Numerous follow-up projects and technical developments to study gravitational quantum states of neutrons

*T. Sanuki, S. Komamiya, S. Kawasaki, S. Sonoda, « Proposal for measuring the quantum states of neutrons in the gravitational field with a CCD-based pixel sensor », NIM A 600 (2009) 657.*

*J. Jakubek, Ph. Schmidt-Wellenburg, P. Geltenbort, M. Platkevic, Ch. Plonka-Spehr, J. Solc, T. Soldner, « A coated pixel device TimPix with micron spatial resolution for UCN detection », NIM A 600 (2009) 651.*

*J. Jakubek, M. Platkevic, Ph. Schmidt-Wellenburg, P. Geltenbort, Ch. Plonka-Spehr, M. Daum, « Position-sensitive spectroscopy of ultra-cold neutrons with Timepix pixel detector », NIM A 607 (2009) 45.*

*H. Abele, T. Jenke, D. Stadler, P. Geltenbort, « QuBounce: the dynamics of ultracold neutrons falling in the gravity potential of the Earth », Nucl. Phys. A 827 (2009) 593.*

*T. Jenke, T. Stadler, H. Abele, P. Geltenbort, « Q-Bounce-experiments with quantum bouncing ultracold neutrons », NIM A 611 (2009) 318.*

*S. Kawasaki, G. Ichikawa, M. Hino, Y. Kamiya, M. Kitaguchi, S. Komamiya, T. Sanuki, S. Sonoda, « Development of a pixel detector for ultracold neutrons », NIM A 615 (2010) 42.*

*T. Jenke, P. Geltenbort, H. Lemmel, H. Abele, « Realization of a gravity-resonance-spectroscopy technique », Nature Phys. 7 (2011) 468.*



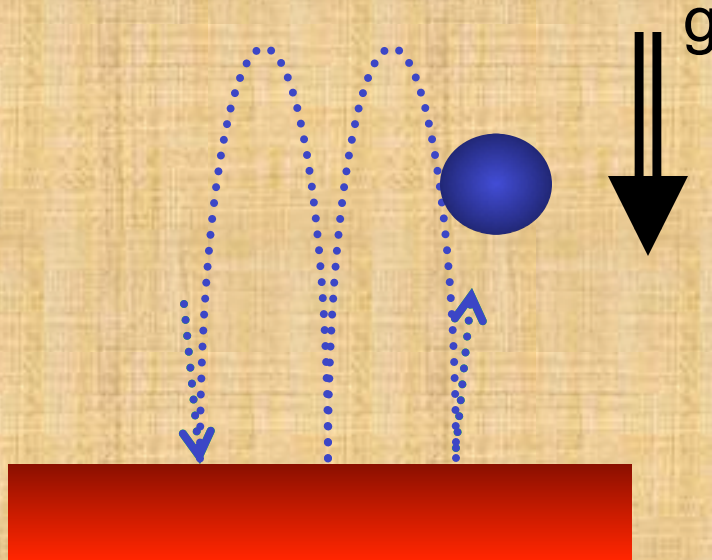
*A.Yu. Voronin, P. Froelich, V.V. N. « Gravitational quantum states of antihydrogen », Phys. Rev. A 83 (2011) 032903*

## **Similarities:**

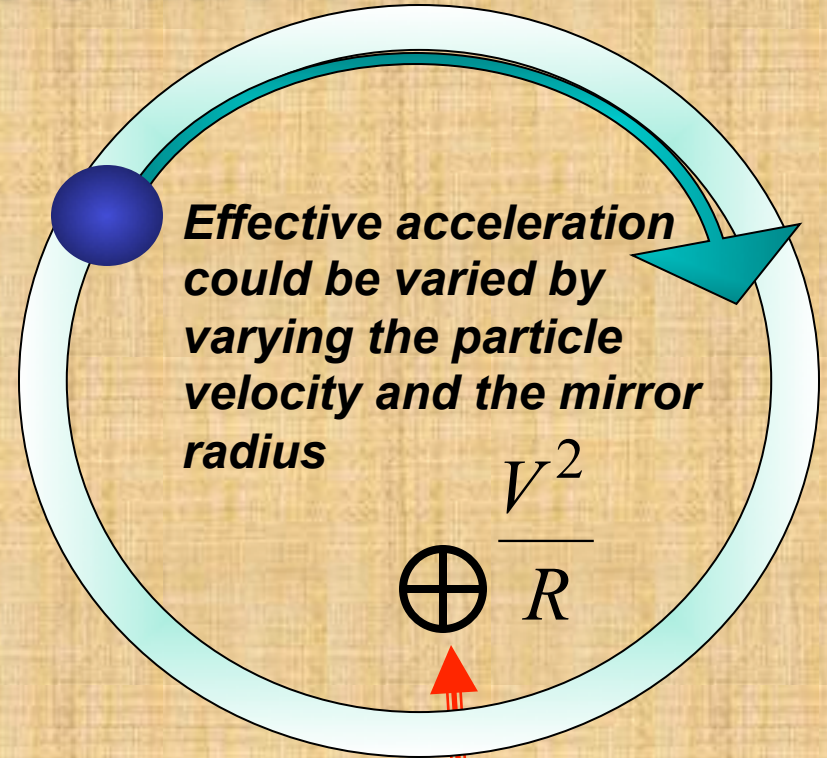
- 1. The anti-hydrogen mass is about equal to the neutron mass***
- 2. Modifications, due to vdW/CP potential, of the anti-hydrogen quantum states energies and wave-functions are negligible***
- 3. Lifetimes of anti-hydrogen in quantum states are of the order of 0.1 s that is even longer than the time of UCN passage through the setup used for the first neutron experiment***
- 4. Projected anti-hydrogen velocities are even smaller than typical UCN velocities.***
- 5. Projected anti-hydrogen phase-space densities are even larger than the highest UCN densities available.***
- 6. But: effects of parasitic electromagnetic fields to anti-hydrogen atoms are much larger than those to neutrons!  
Should not be overlooked, but looks very promising.***

- 1. First observation of quantum states of UCN in the gravitational field above a mirror; first demonstration (and still the only one!) of quantum states of matter in a gravitational field**
- 2. Applications in fundamental and surface physics**
- 3. 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**
- 4. Such an experiment is feasible with anti-hydrogen**
- 5. The GRANIT spectrometer could be used for one-to-one prototyping of an experiment measuring quantum states of anti-hydrogen atoms**

## Gravity / Acceleration



*A particle above a mirror in the gravity field*



*The energy of quantum states in the Bohr-Zommerfeld approximation :*

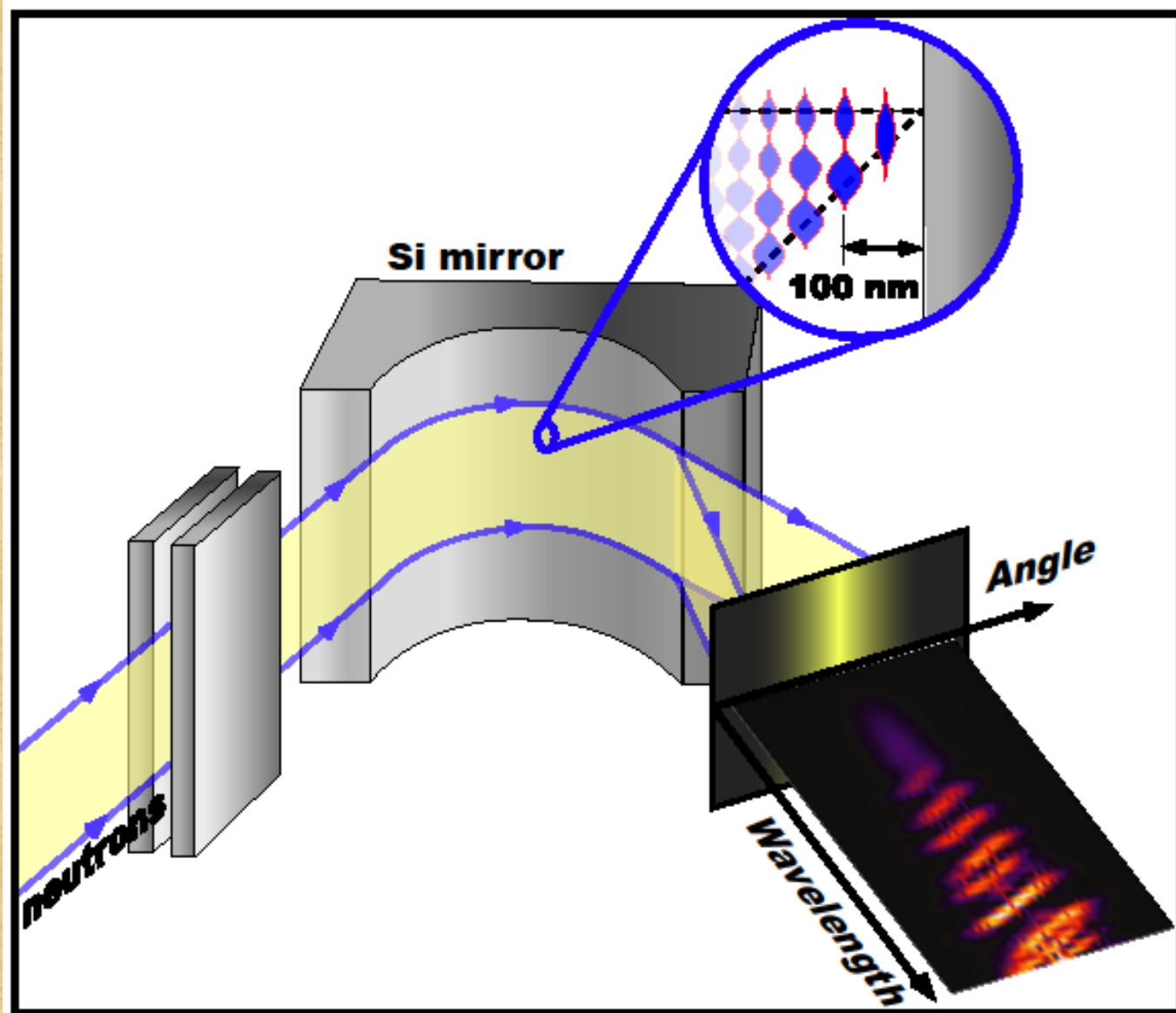
$$E_n \approx \sqrt[3]{\left(\frac{9 \cdot m}{8}\right) \cdot \left(\pi \cdot \hbar \cdot g \cdot \left(n - \frac{1}{4}\right)\right)^2}$$

V.V. N., A.K. Petukhov, K.V. Protasov, A.Yu. Voronin, «Centrifugal quantum states of neutrons », *Phys. Rev. A* 78 (2008) 033616;

R. Cubitt, V.V. N., A.K. Petukhov, A.Yu. Voronin, G. Pignol, K.V. Protasov, « Methods of observation of the centrifugal quantum states of neutrons », *NIM A* 611 (2009) 322;

V.V. N., A.Yu. Voronin, R. Cubitt, K.V. Protasov, « Neutron whispering gallery », *Nature Phys.* 6 (2010) 114;

V.V. N., R. Cubitt, K.V. Protasov, A.Yu. Voronin, « The whispering gallery effect in neutron scattering », *New J. Phys.* 6 (2010) 113050.



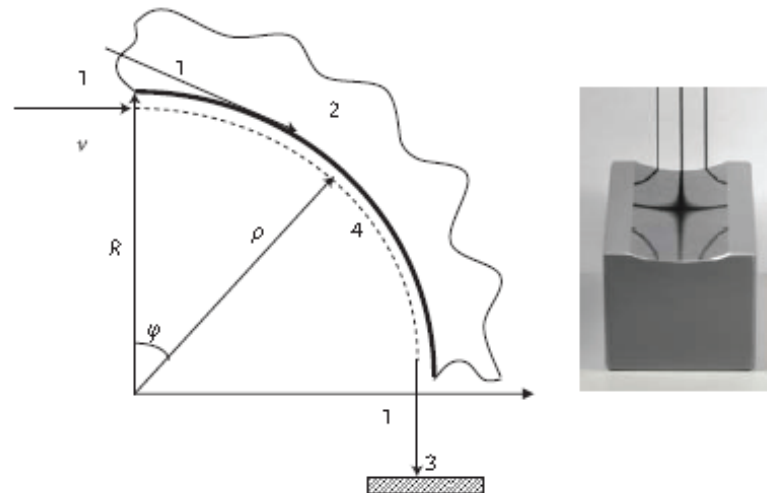
*Nature Physics*, 6, 114-117 (2010)

## Neutron whispering gallery

Valery V. Nesvizhevsky<sup>1\*</sup>, Alexei Yu. Voronin<sup>2</sup>, Robert Cubitt<sup>1</sup> and Konstantin V. Protasov<sup>3</sup>

The ‘whispering gallery’ effect has been known since ancient times for sound waves in air<sup>1,2</sup>, later in water and more recently for a broad range of electromagnetic waves: radio, optics, Roentgen and so on<sup>3-6</sup>. It consists of wave localization near a curved reflecting surface and is expected for waves of various natures, for instance, for atoms<sup>7,8</sup> and neutrons<sup>9</sup>. 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’<sup>10</sup>; it is complementary to the recently discovered gravitationally bound quantum states of neutrons<sup>11</sup>. These two phenomena provide a direct demonstration of the weak equivalence principle for a massive particle in a pure quantum state<sup>12</sup>. 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<sup>13-15</sup>, quantum neutron optics and surface physics effects<sup>16-18</sup>.

The classical whispering-gallery phenomenon can be understood



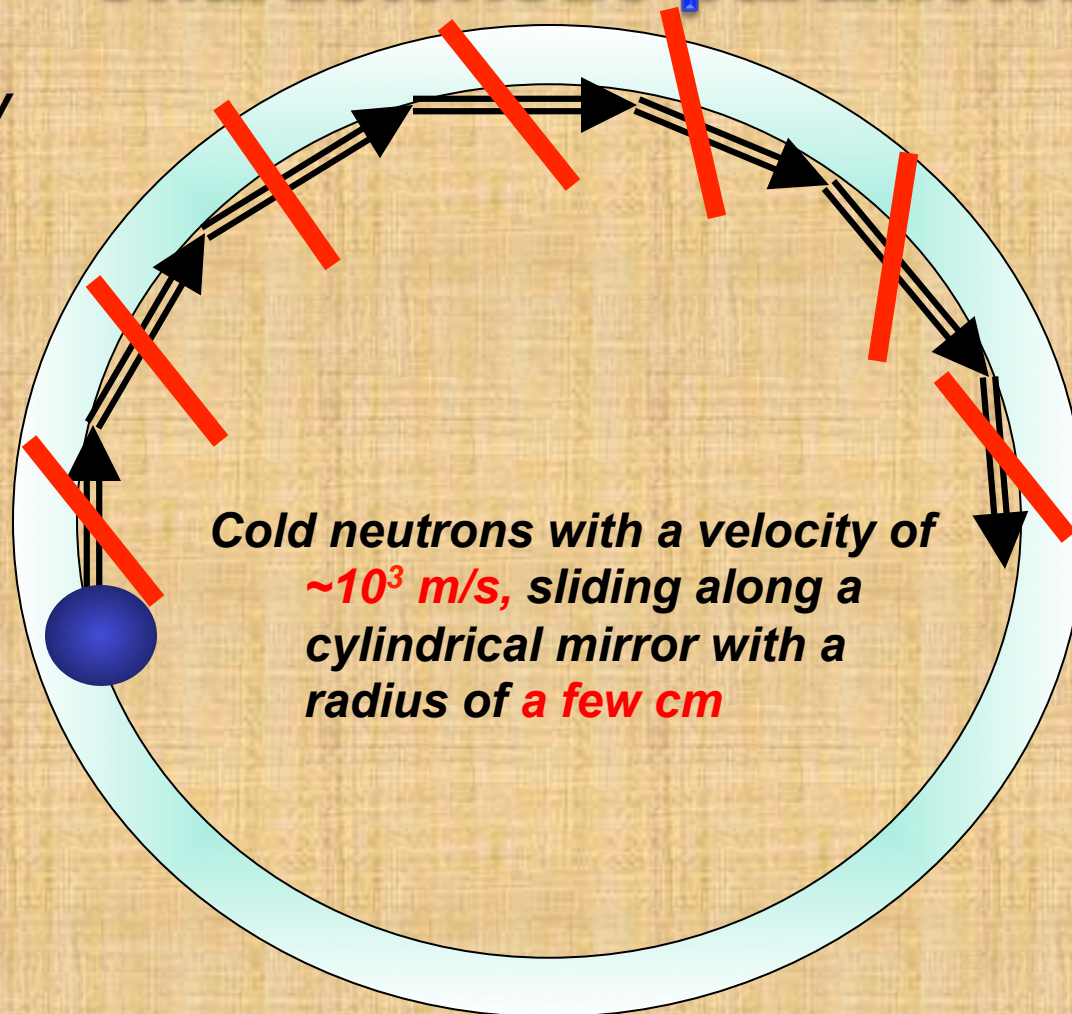
**Figure 1 | A scheme of the neutron centrifugal experiment.** 1: Classical trajectories of incoming and outgoing neutrons, 2: cylindrical mirror, 3: neutron detector, 4: quantum motion along the mirror surface. Inset: A photo of the single-crystal cylindrical silicon mirror used for the presented experiments,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

**Massive particle, sliding along a 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:**

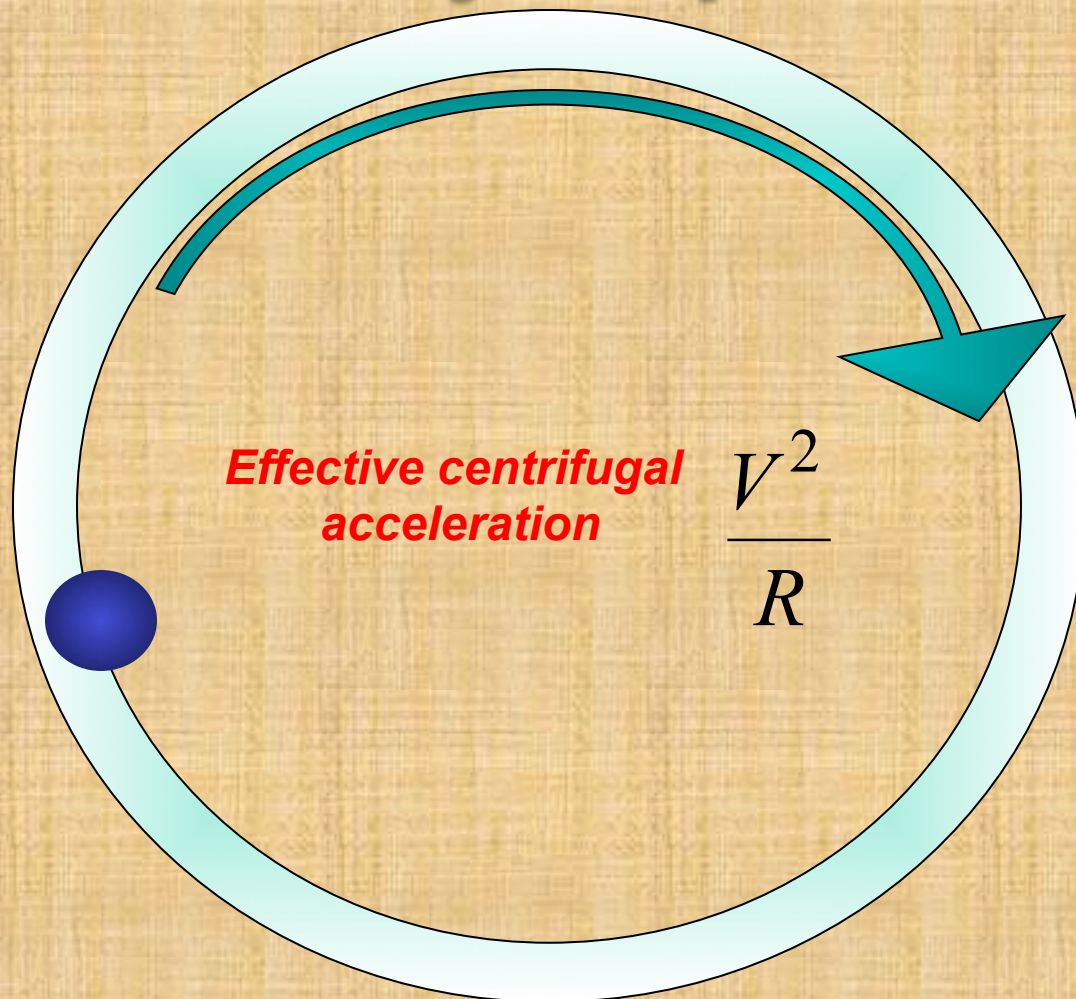
- Mabuchi H. & Kimble H.J. Atom galleries for whispering atoms – binding atoms in stable orbits around an optical resonator. *Opt. Lett.* **19**, 749-751 (1994).
- Vernooij D. M. & Kimble H.J. Quantum structure and dynamics for atom galleries. *Phys. Rev. A* **55**, 1239-1261 (1997).

## Characteristic parameters



## Two « independent » velocity components

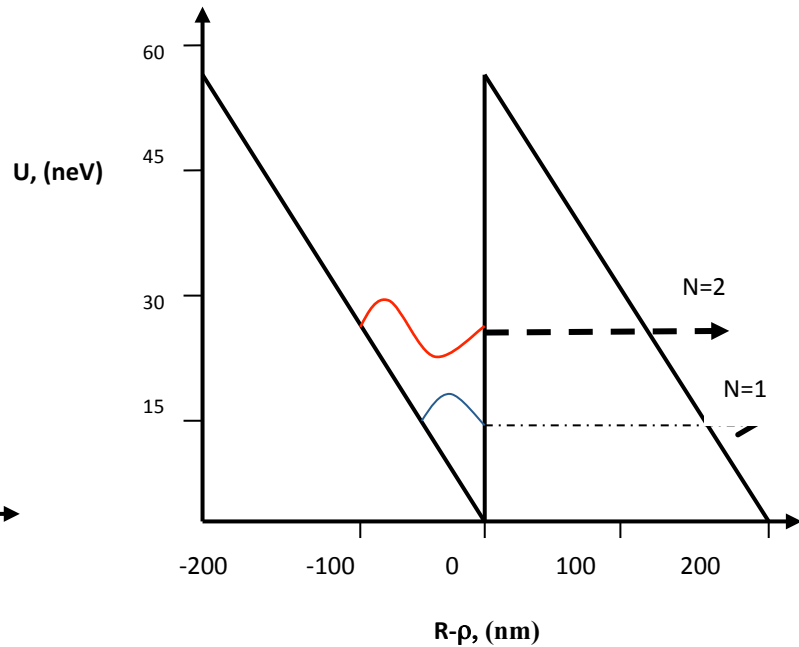
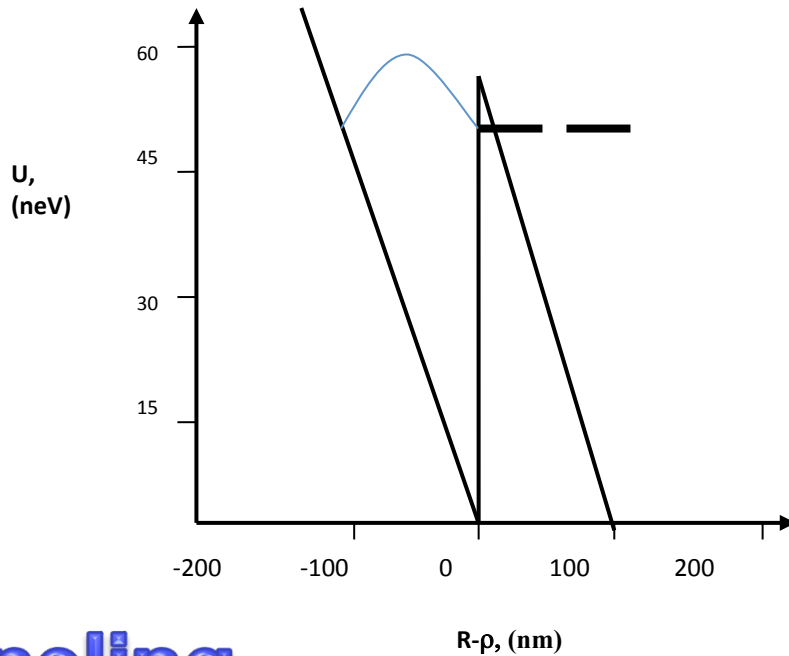
If the characteristic size of quantum states and the quasi-classical distance between two collisions are much smaller than the mirror radius then **tangential and longitudinal motions could be separated**



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

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

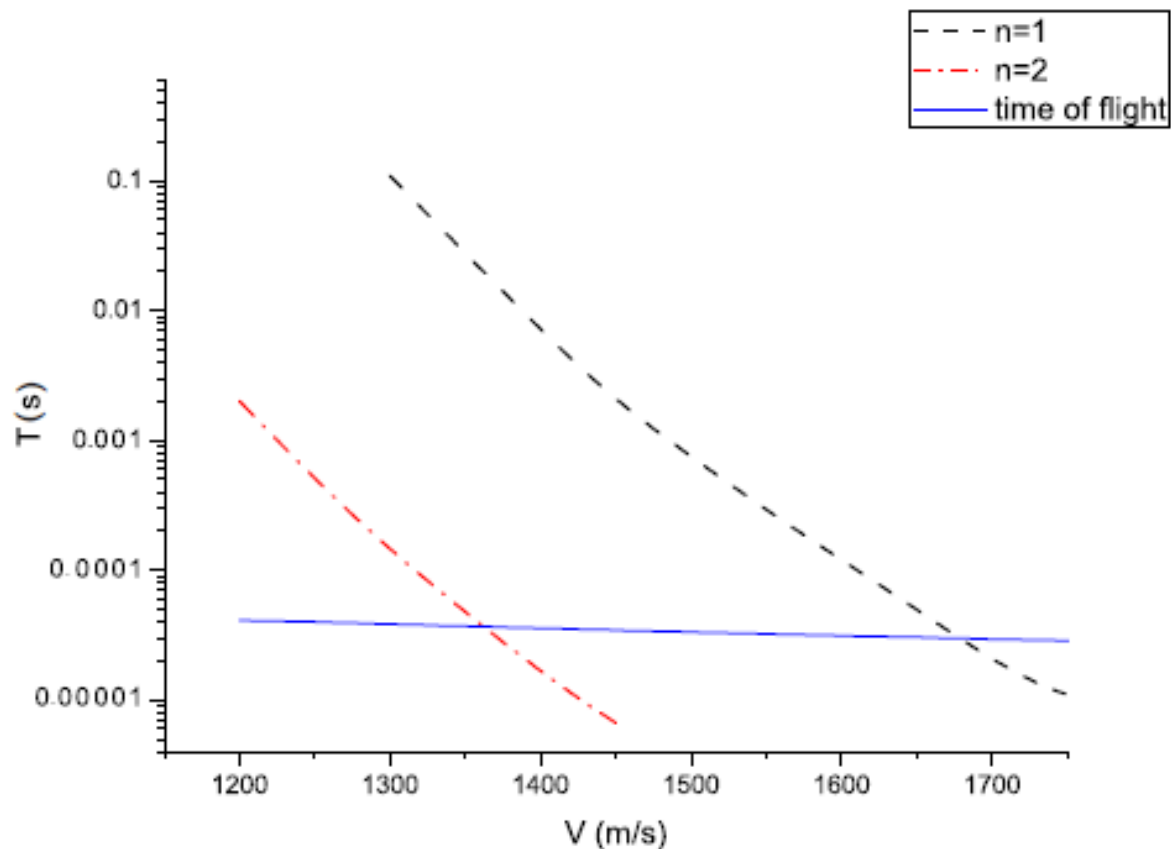
***Life-times of quasi-stationary states due to tunneling change rapidly as a function of the neutron energy***

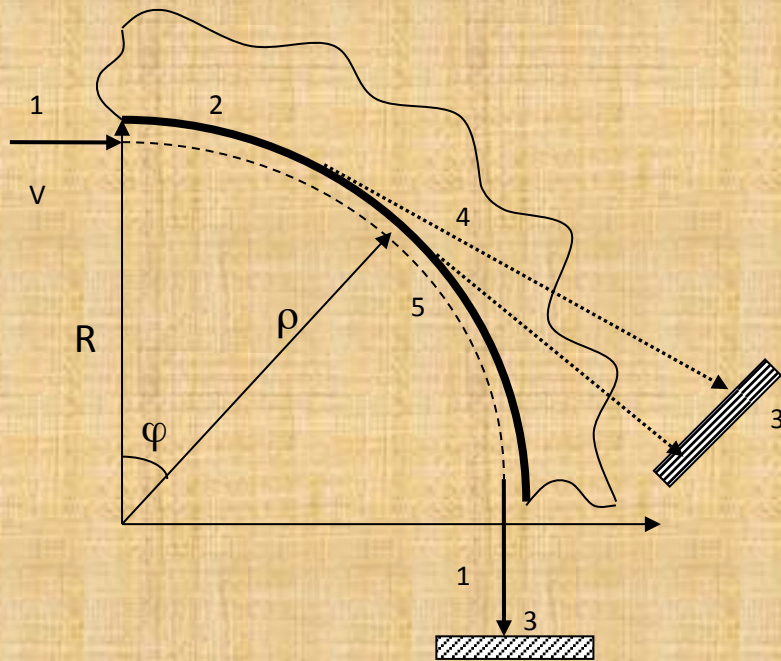


## Tunneling



***Life-times of quasi-stationary states due to tunneling change rapidly as a function of the neutron energy***

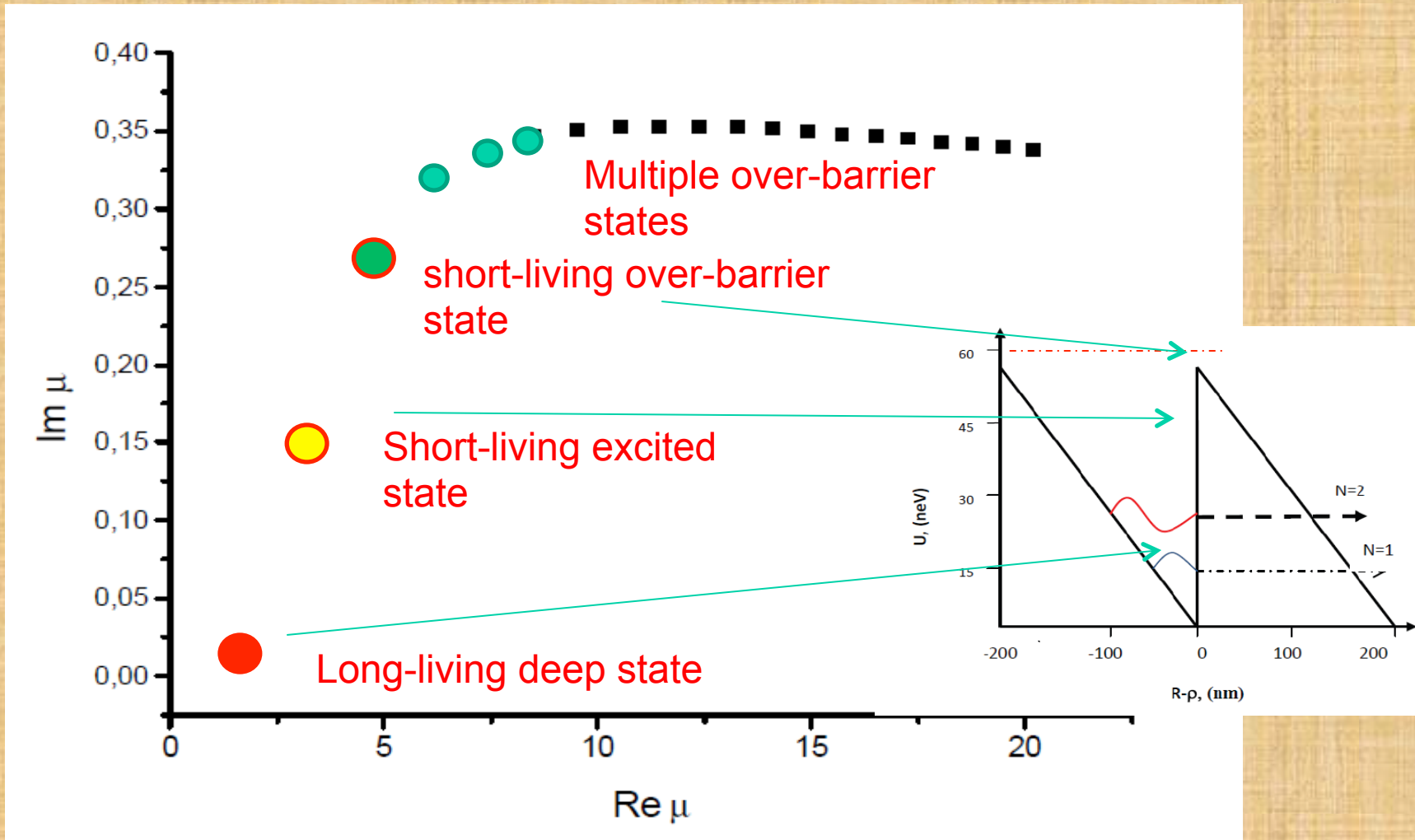


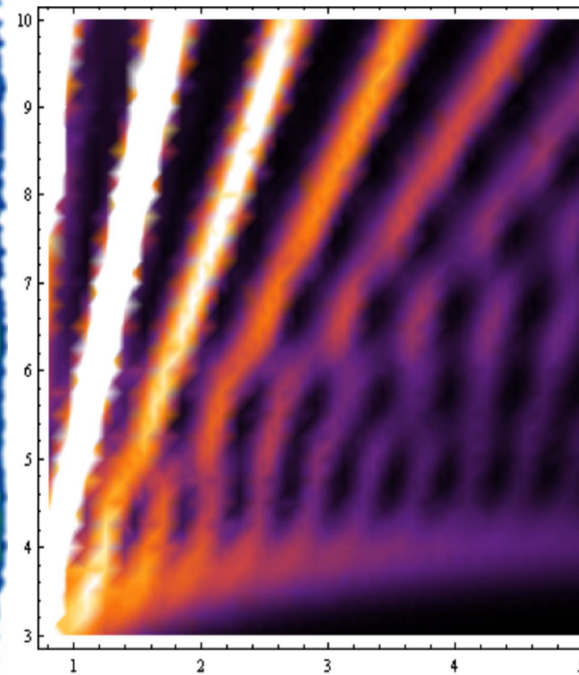
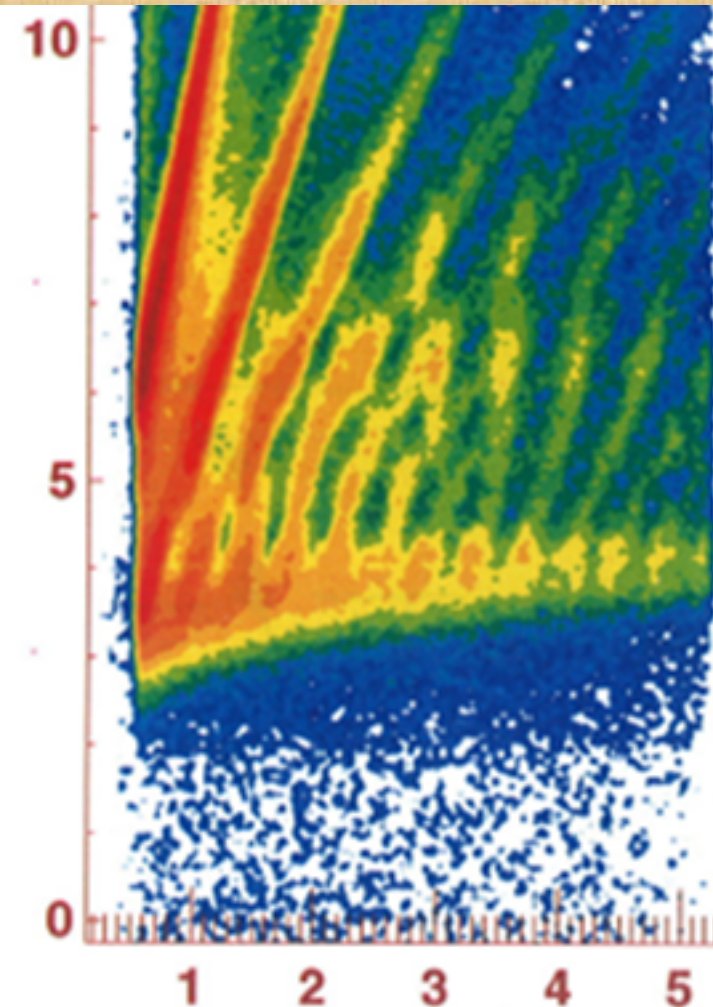


*D17 instrument at the ILL*

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

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

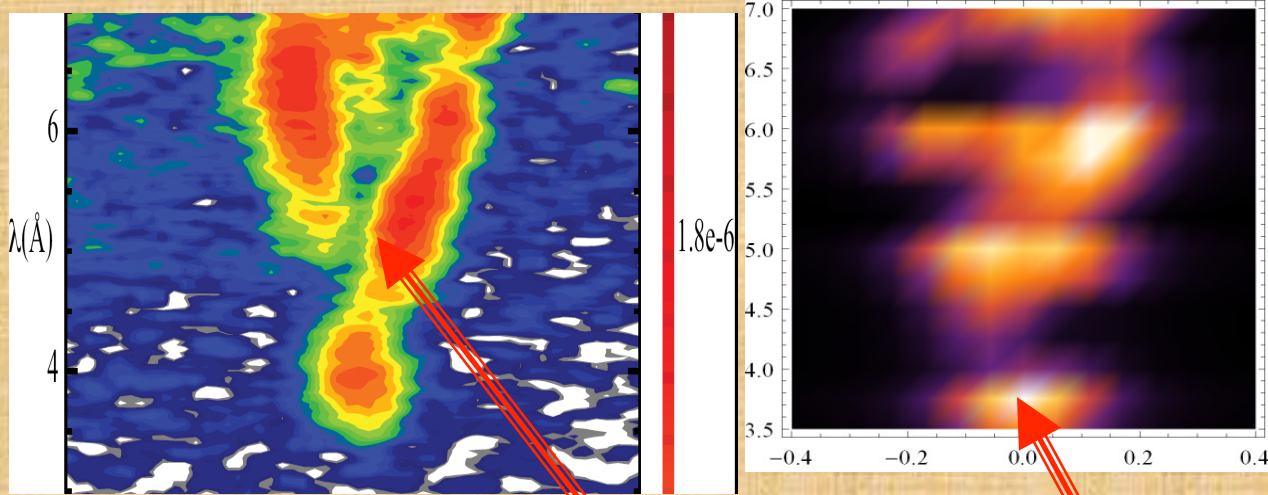




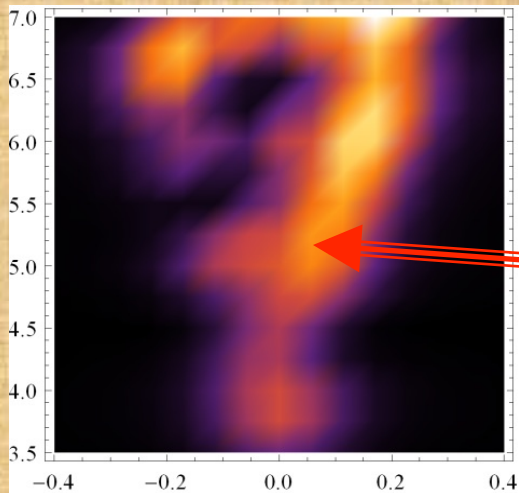
**Neutrons  
tunneling OUT of  
quantum states**

*Neutrons populate quantum states states through the entrance edge of a truncated cylinder and tunnel out through the triangular potential barrier*

# Results: NEUTRON RAINBOW



Neutrons  
entering from  
the mirror edge



$b=0$

Experiment

Theory

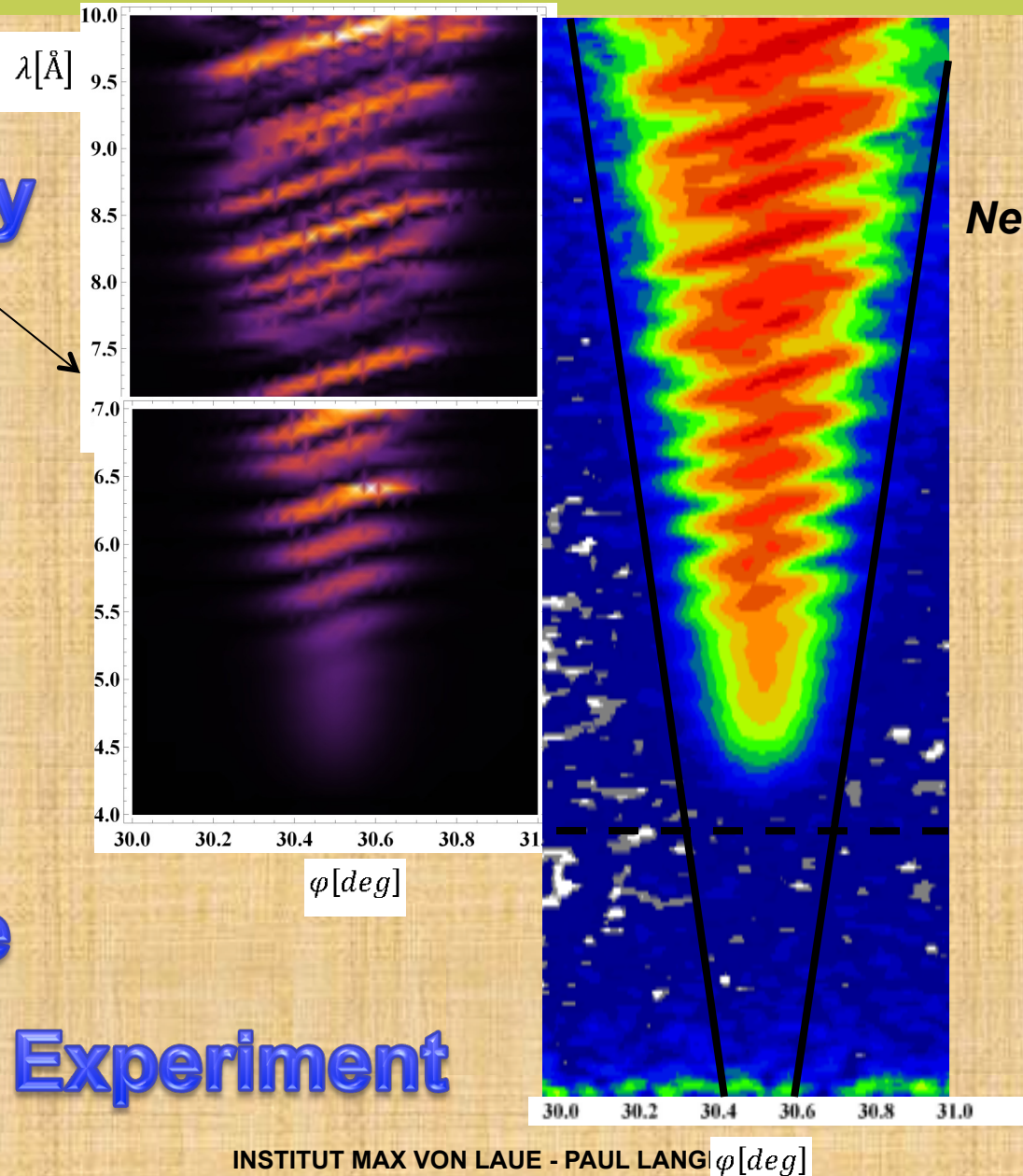
*The interference pattern is very sensitive to surface potential shapes even for small angular size of the mirrors; 3.95 degrees in this case*

$b=4\text{nm}$

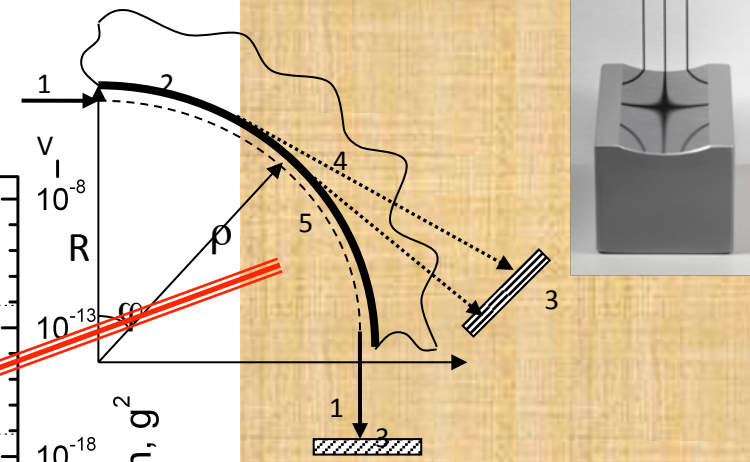
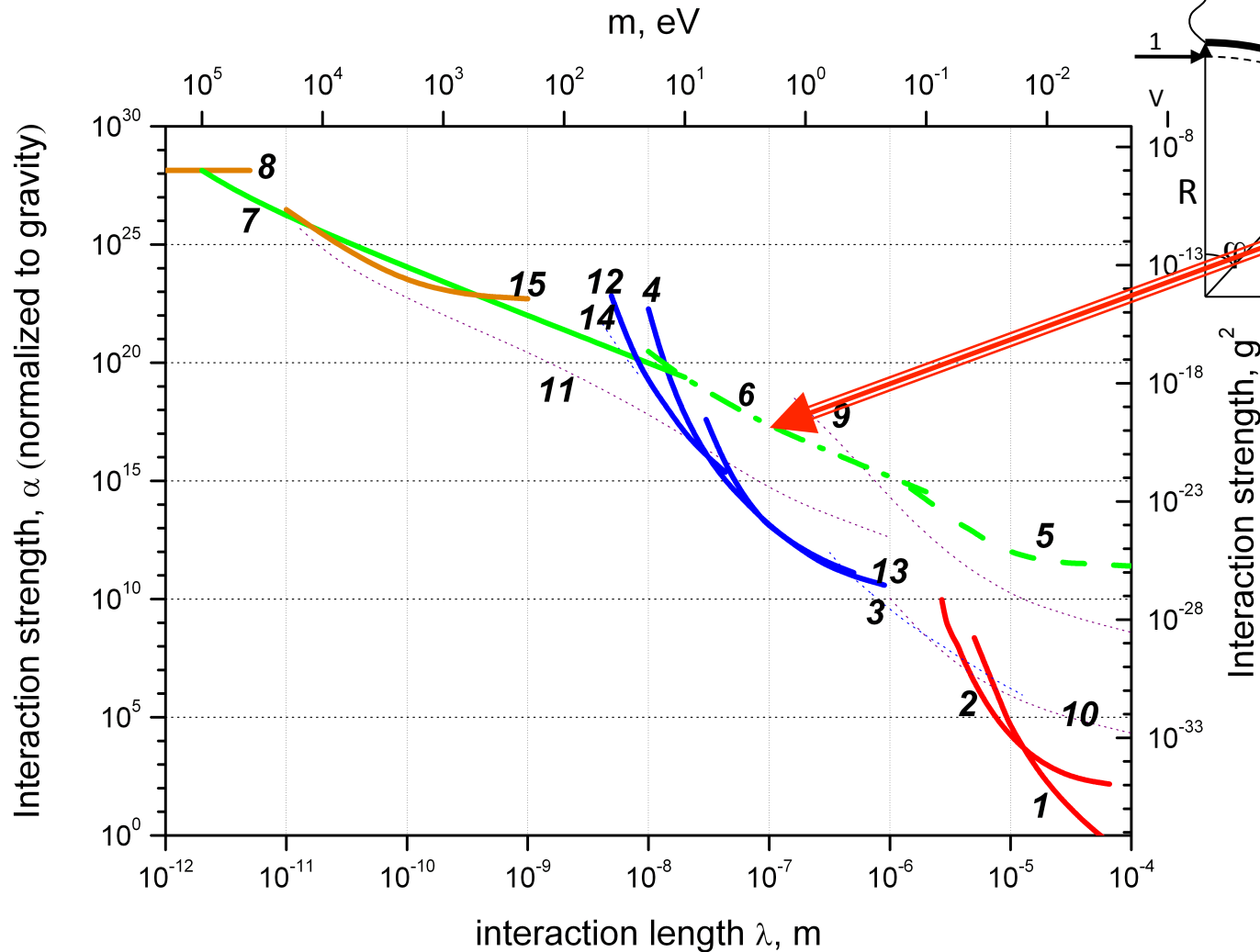
Theory

Neutrons  
entering  
from the  
mirror edge

Experiment



*Neutrons populate  
quantum states  
states through the  
entrance edge of a  
truncated cylinder  
and are counted  
behind the exit  
edge*



**Constrain for  
fundamental short-  
range forces from  
the neutron  
whispering gallery  
experiment**

- 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 a 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**
- 4. Such an experiment is feasible with anti-hydrogen**
- 5. The GRANIT spectrometer could be used for one-to-one prototyping of an experiment measuring quantum states of anti-hydrogen atoms**



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