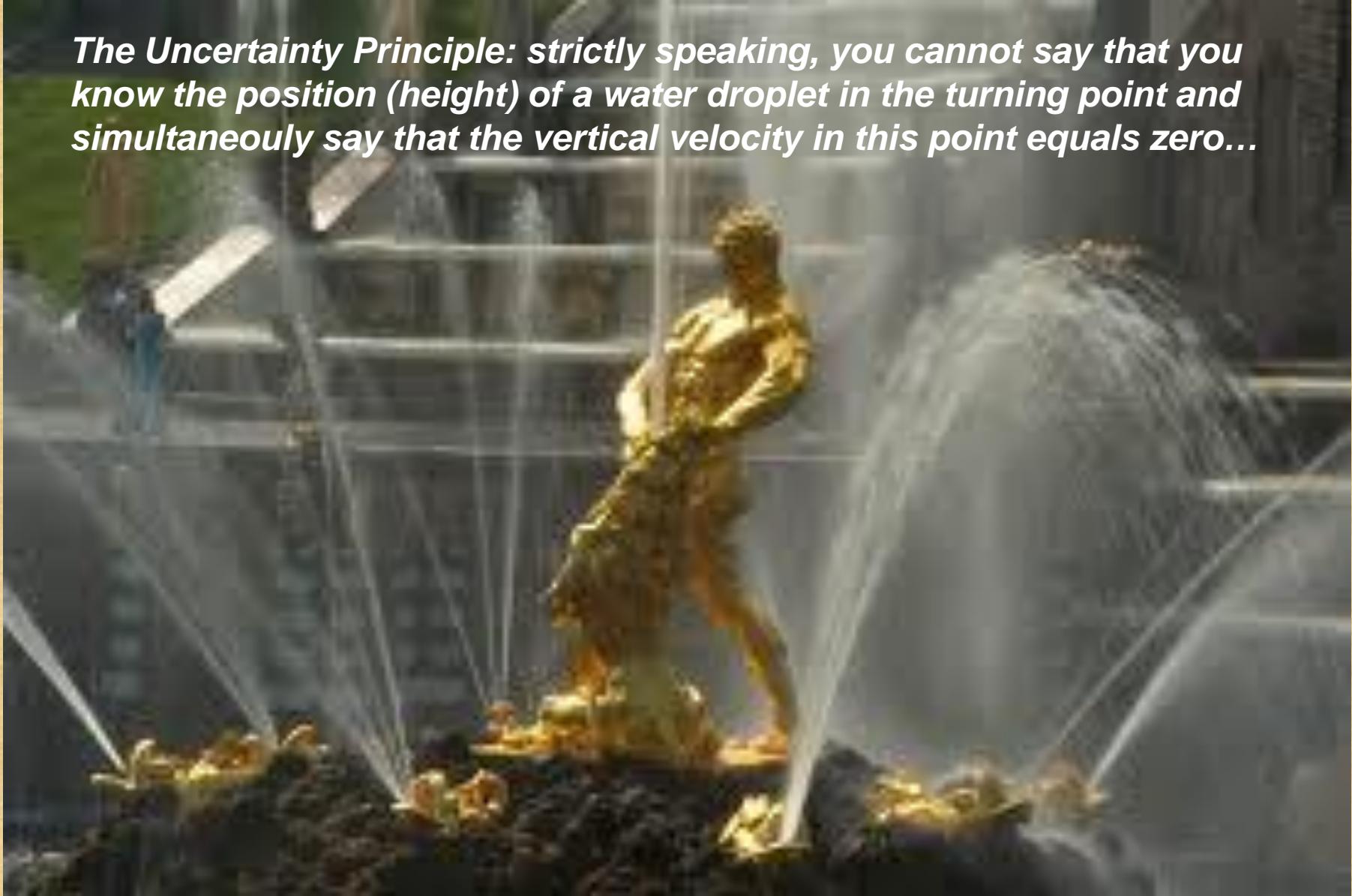


# Gravitational and centrifugal quantum states of matter (neutrons) and anti-matter (anti-hydrogen atoms)

1. **Gravitational and centrifugal quantum states of matter and anti-matter (could be considered as the direct verification of the weak equivalence principle for matter and anti-matter in quantum states. Centrifugal quantum states (the neutron whispering gallery) is the matter-wave analog of the whispering gallery effect known for sound and for electromagnetic waves.**
2. **Comparison of perspective experiments with anti-matter atoms to recent observations of gravitational and centrifugal quantum states of slow neutrons.**
3. **Long lifetimes of neutrons and anti-hydrogen atoms(?) in such quantum states allow one using them for various precision studies**

# Gravitational and centrifugal quantum states of matter (neutrons) and anti-matter (anti-hydrogen atoms)

*The Uncertainty Principle: strictly speaking, you cannot say that you know the position (height) of a water droplet in the turning point and simultaneously say that the vertical velocity in this point equals zero...*



# Gravitational and centrifugal quantum states of matter (neutrons) and anti-matter (anti-hydrogen atoms)

*as well as you cannot say that an apple is fixed at some height and simultaneously say that is not moving...*



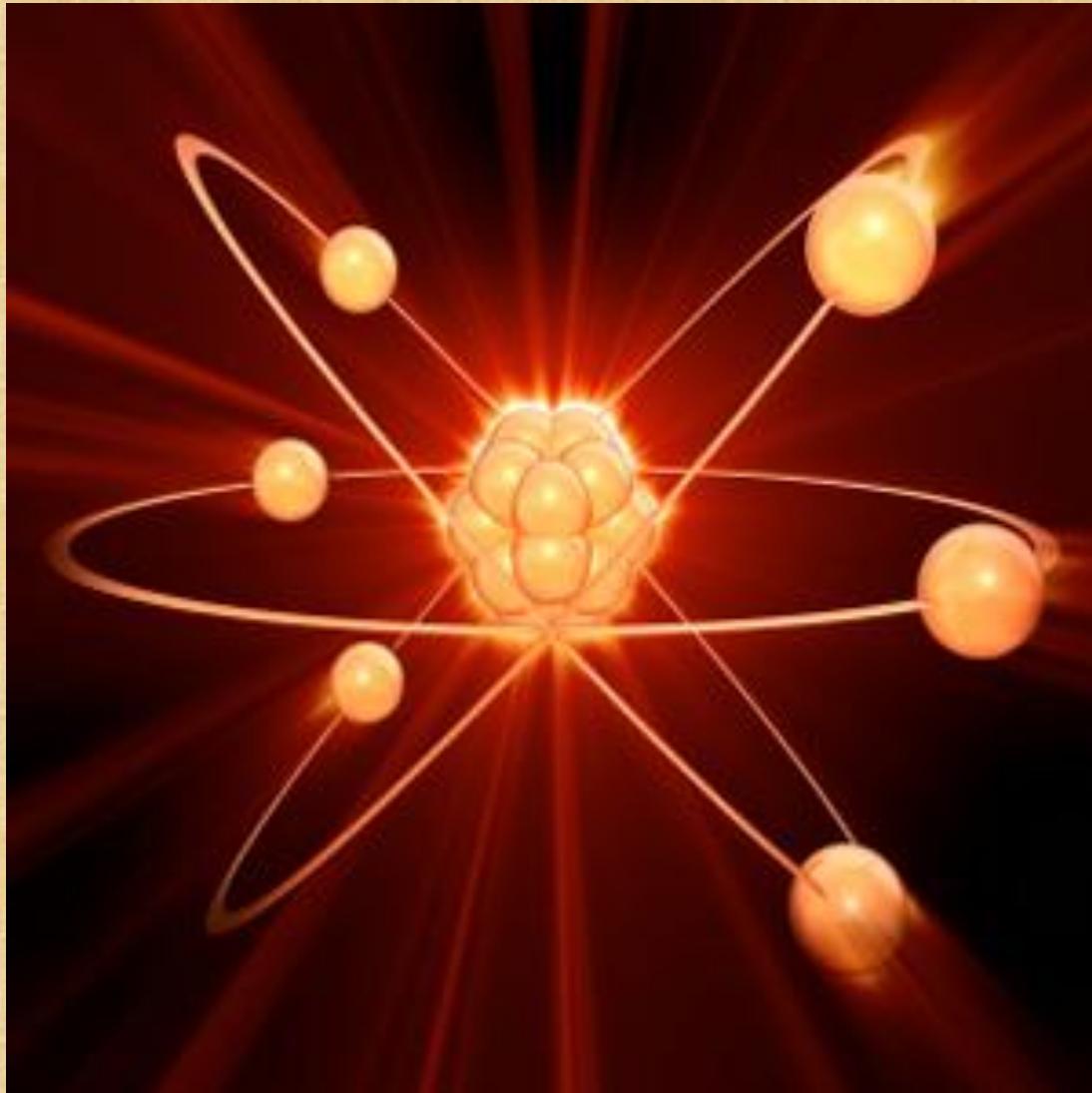
# Gravitational and centrifugal quantum states of matter (neutrons) and anti-matter (anti-hydrogen atoms)

*and when it is moving, this is not a smooth classical motion*



**Quantum bounces** [P.W. Langhoff, Shroedinger particle in a gravitational well, Am. J. Phys. **39** (1971) 954; R.L. Gibbs, The quantum bouncer, Am. J. Phys. **43** (1975) 25; J. Gea-Banacloche, A quantum bouncing ball, Am. J. Phys. **67** (1999) 776]

# Gravitational and centrifugal quantum states of matter (neutrons) and anti-matter (anti-hydrogen atoms)



***There are 4 known fundamental interactions: electromagnetic, strong, weak and gravitational***

***Quantum states of a massive particle should exist independent of the fundamental nature of a bounding potential***

***Preceeding experiment: observation of gravitational phase-shift [R. Collela et al, Observation of gravitationally induced quantum interference, Phys. Rev. Lett. 34 (1975) 1472]***

## Gravity / Acceleration

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

Height above  
mirror

40µm

30µm

20µm

10µm

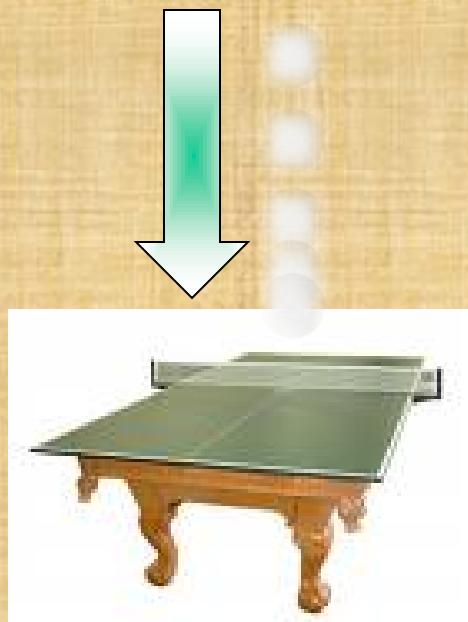


*For more information,  
see V.V.N. Physics-  
Uspekhi 53 (2010) 645*

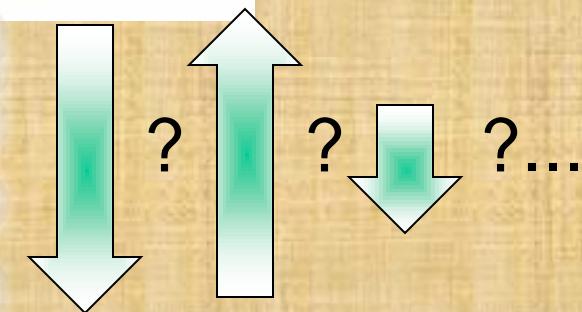
*Illustration for quantum motion of an object above a mirror in the gravitational field and that in the accelerating frame. Positions of the ball correspond to the most probable heights of a neutron in the 5th quantum state.*

*Yesterday's sensation is  
today's calibration and  
tomorrow's background  
[Richard Feynman]*

## Matter / Anti-matter



*Gravitational properties of matter have never been measured directly!  
but aimed at, for instance, in GBAR project at CERN*



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

# GRANIT-2010 Workshop

## 14-19 February 2010, Les Houches, France



Countries ~12

Europe, Asia, USA, Australia

For more information, see Compt. Rend.  
Phys. 12 (2011) 703

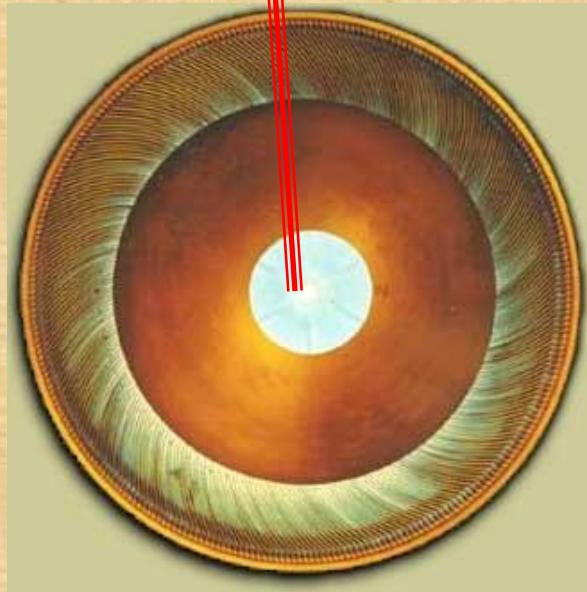
*The next Workshop is planned around  
February 2014, also in Les Houches*



# Neutron: ILL, Grenoble: The largest research reactor

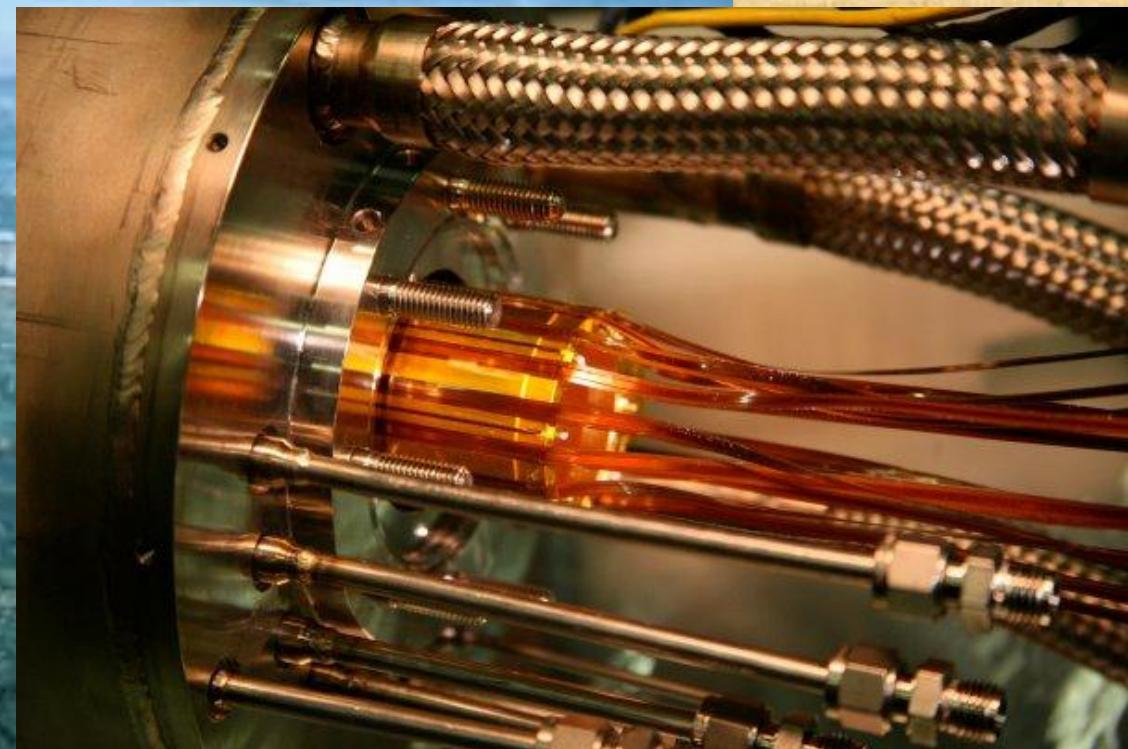


*Experiments are strongly limited by statistics*



# Anti-hydrogen: CERN, Geneve. The largest particle accelerator facility...

*Experiments are strongly limited by statistics*



Recent reviews: S. Baessler, « Gravitationally bound quantum states of ultracold neutrons and their applications », *J. Phys. G* 36 (2009) 104005; V.V.N. « Near-surface quantum states of neutrons in the gravitational and centrifugal potentials. *Phys.-Uspekhi* 53 (2010) 645.

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

**Valery V. Nesvizhevsky\*, Hans G. Börner\*, Alexander K. Petukhov\*, 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

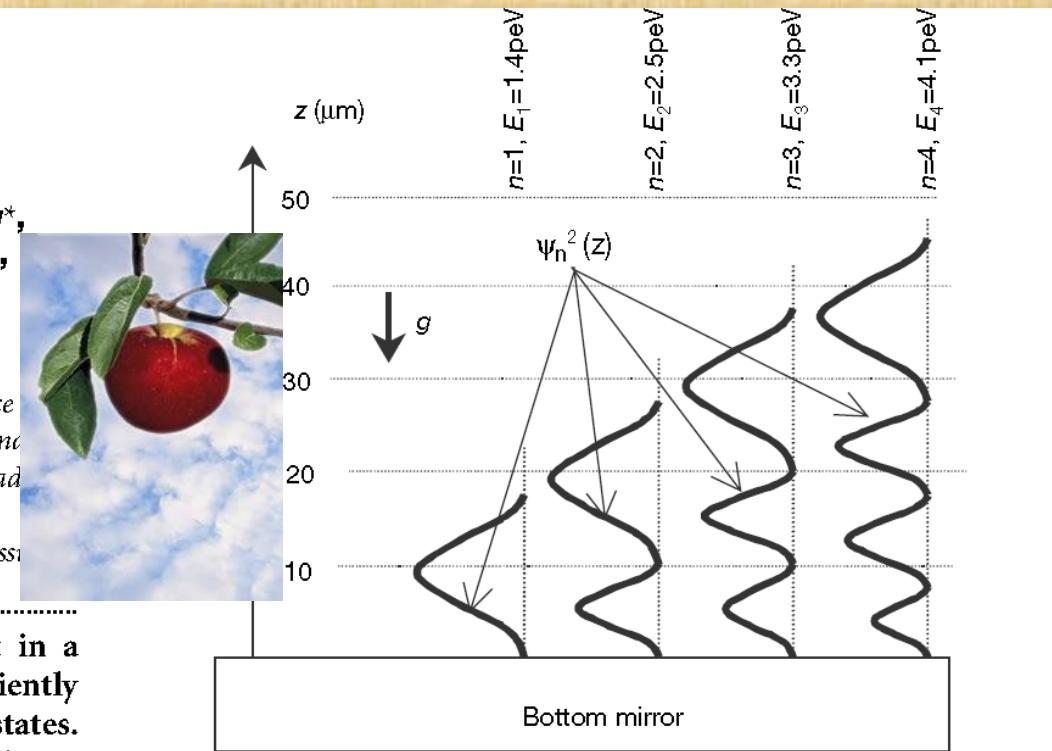
† University of Heidelberg, 12 Philosophenweg, Heidelberg D-69120, Germany

‡ Petersburg Nuclear Physics Institute, Orlova Roscha, Gatchina, Leningrad

R-188350, Russia

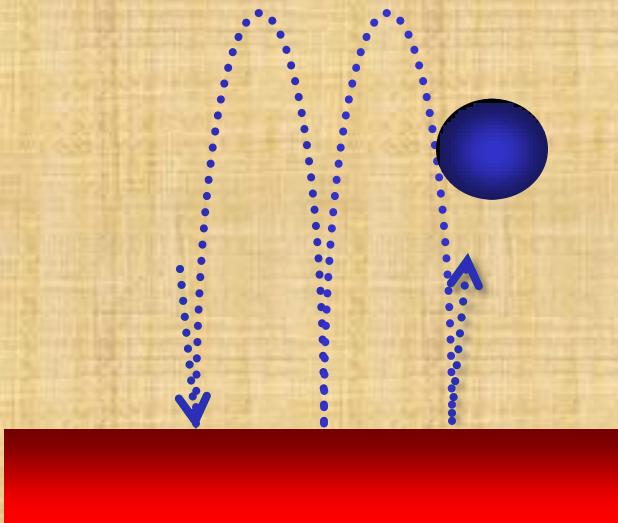
§ Joint Institute for Nuclear Research, Dubna, Moscow reg. R-141980, Russia

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.

# Choosing a quantum system



- 1) **Electrical neutrality** (usually the gravitational interaction for an object above a surface is much weaker than other interactions)
- 2) **Long life-time**
- 3) **Small mass**  $\left( \Delta v \cdot \Delta x \approx \frac{\hbar}{m} \right)$
- 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  $\sim 10$  nK)**

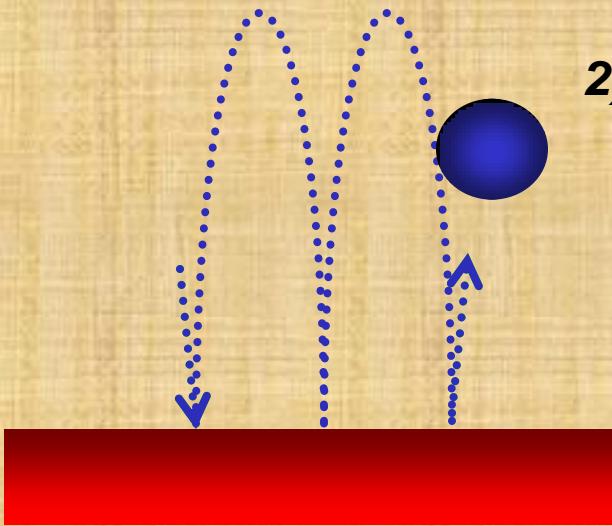
**A particle above a mirror in the gravity field: An ultracold neutron (V.I. Luschkov, A.I. Frank « Quantum effects occurring when ultracold neutrons are stored on a plane », *JETP Lett.* 28 (1978) 759) and ... an anti-hydrogen atom (A.Yu. Voronin, P. Froelich, V.V. N. « Gravitational quantum states 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 :**

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

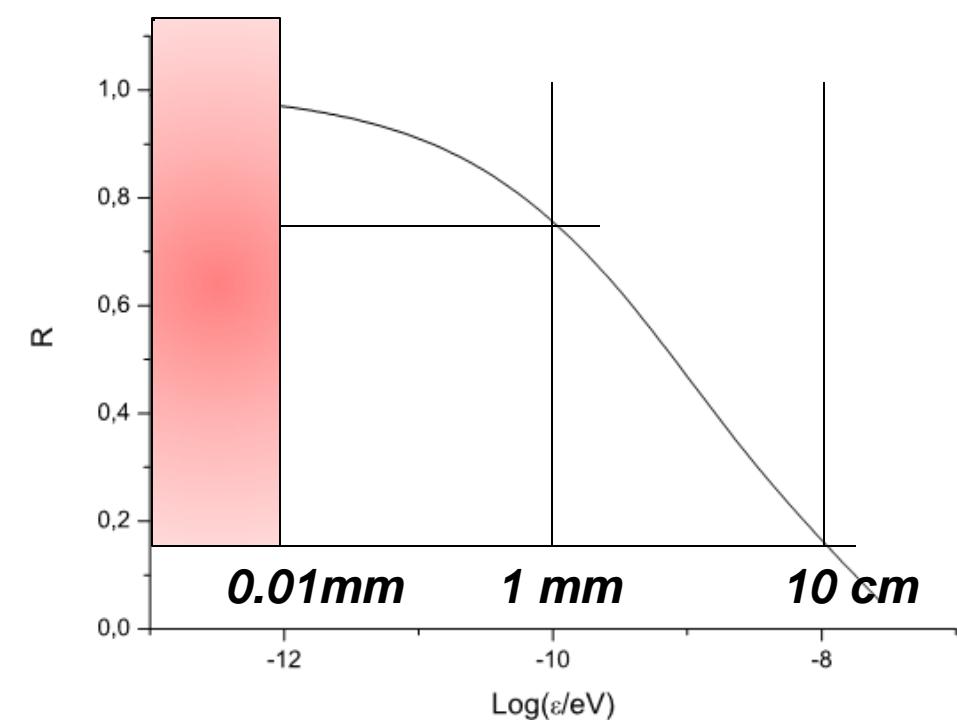
# Choosing a quantum system

- 1) *A neutron is reflected from the nuclear optical potential of a matter due to averaging of the neutron interaction with a huge number of nuclei*
- 2) *An anti-matter (matter) atom is reflected from the sharply-changing (negative) van der Waals/ Casimir-Polder (vdW/CP) potential step (originating from vacuum fluctuations)* A.Yu. Voronin, P. Froelich, B. Zygelman, Phys. Rev. A 72 (2005) 062903



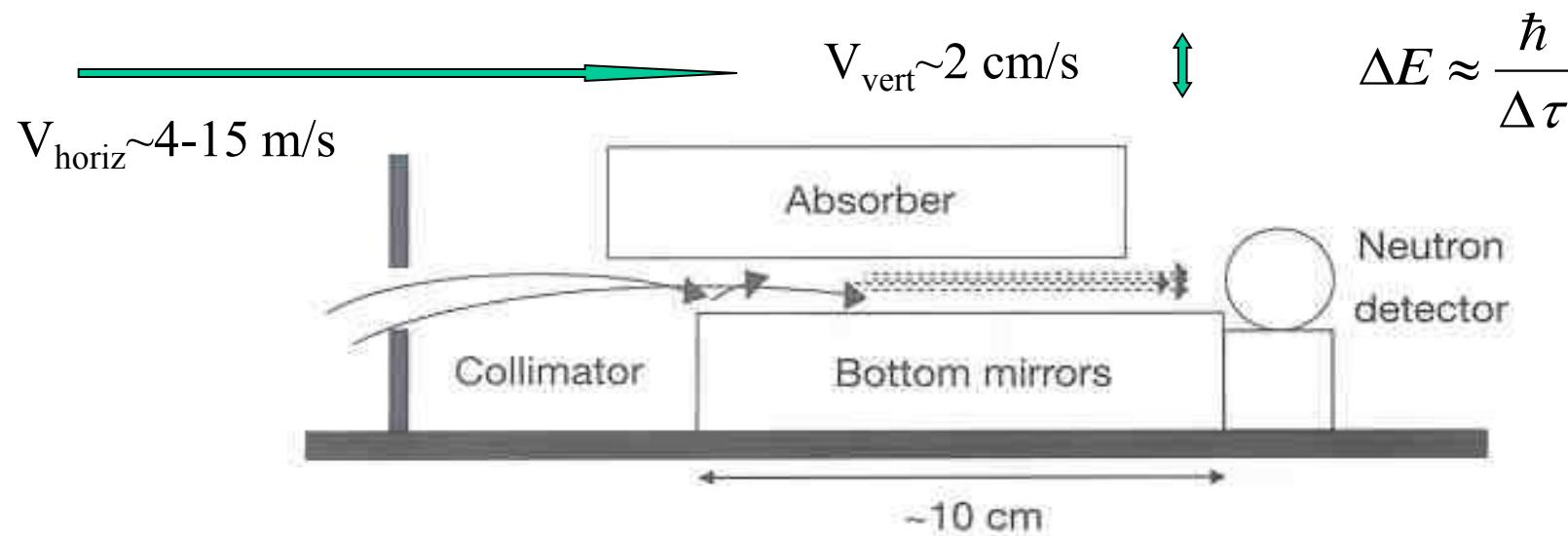
***A(n) (anti)-particle above a mirror in the gravity field***

Dufour, G., Gerardin, A., Guerout, R., Lambrecht, A., Nesvizhevsky, V.V., Reynaud, S., and Voronin, A.Yu. (2013). "Quantum reflection of antihydrogen from the Casimir potential above matter slabs." Phys. Rev. A 87: 012901.



# 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.

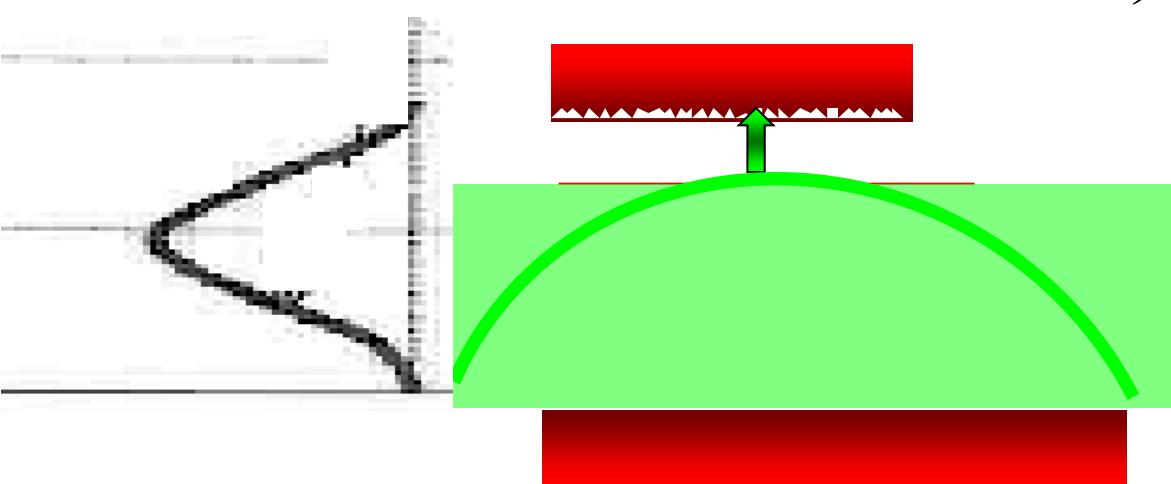
$$\xi \gg 1 \quad \Gamma_n(\xi) = \omega_n \cdot D(\xi) \quad \omega_n \approx (E_{n+1} - E_n)/\hbar$$

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

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

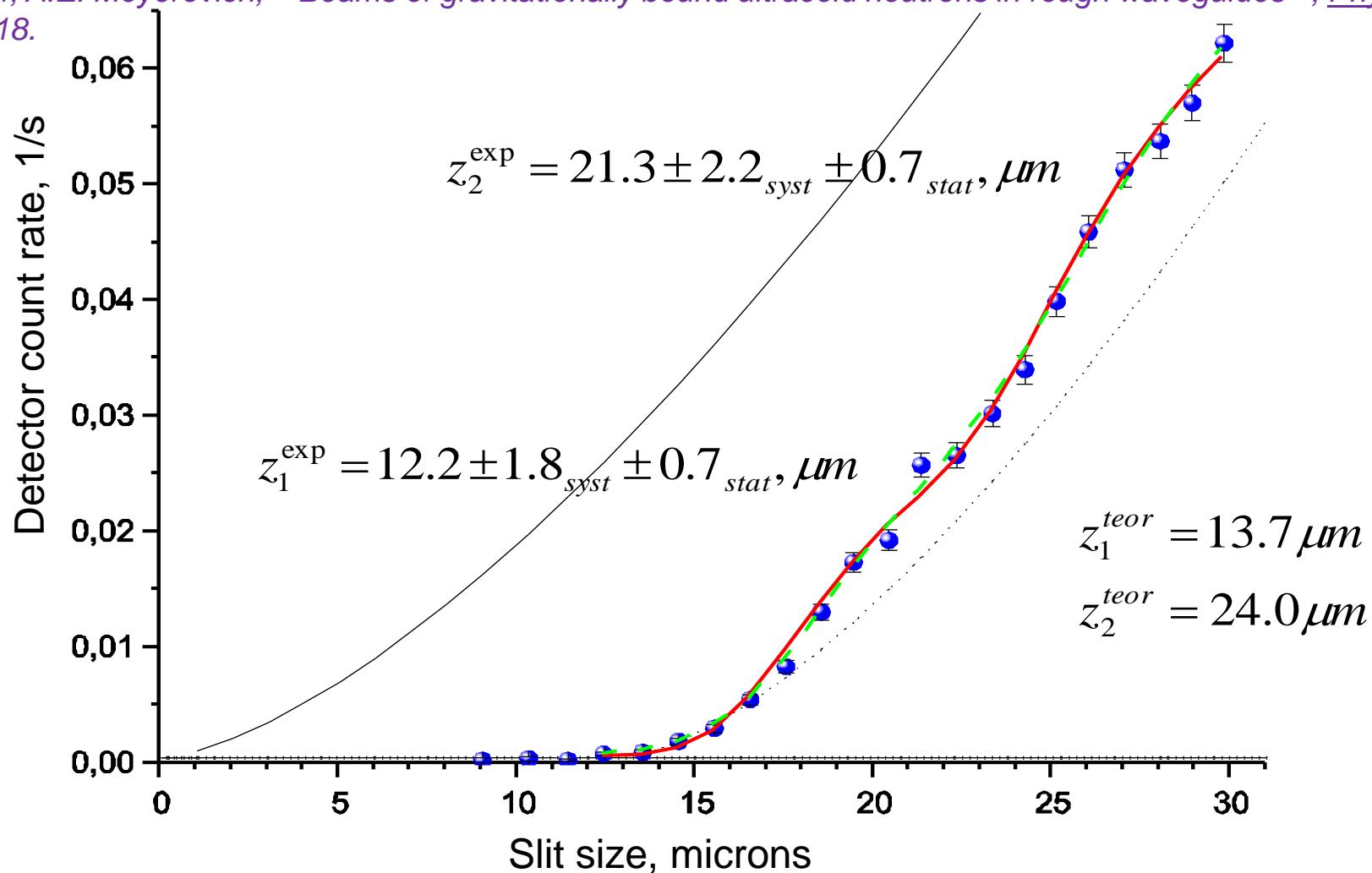
$$D(\xi) = \begin{cases} 1, \xi < 0 \\ A_n \cdot \text{Exp}\left[-\frac{4}{3} \cdot \xi^{\frac{3}{2}}\right], \xi \geq 0 \end{cases}$$

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



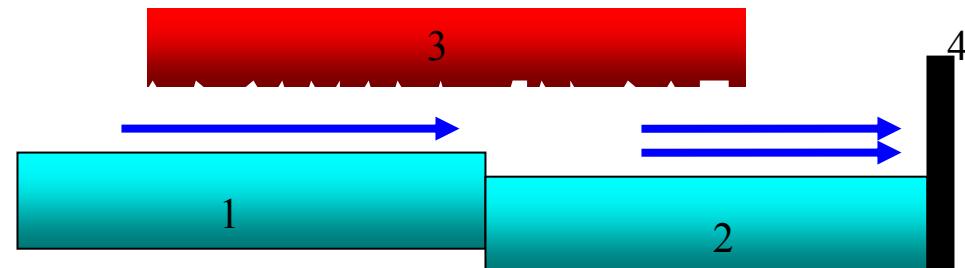
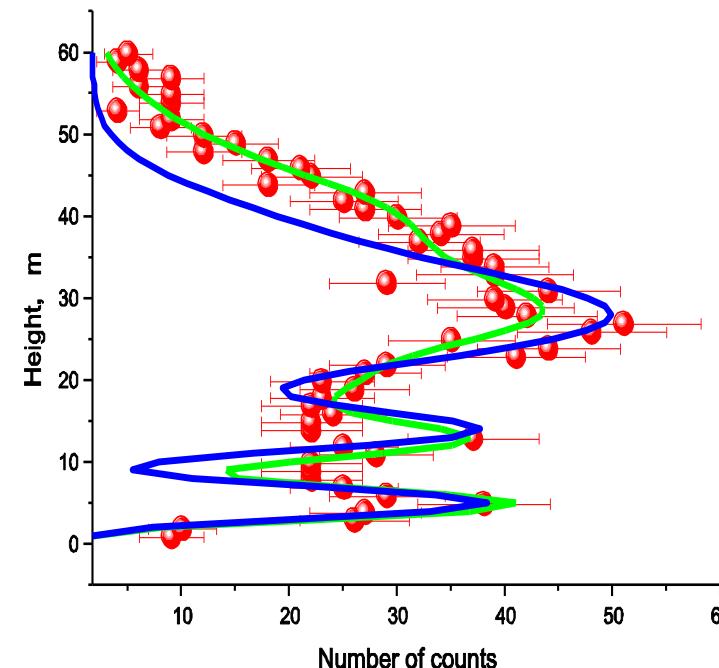
# « Integral » method; soft spectrum

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; M. Escobar, A.E. Meyerovich, « Beams of gravitationally bound ultracold neutrons in rough waveguides », *Phys. Rev. A* 83 (2011) 033618.



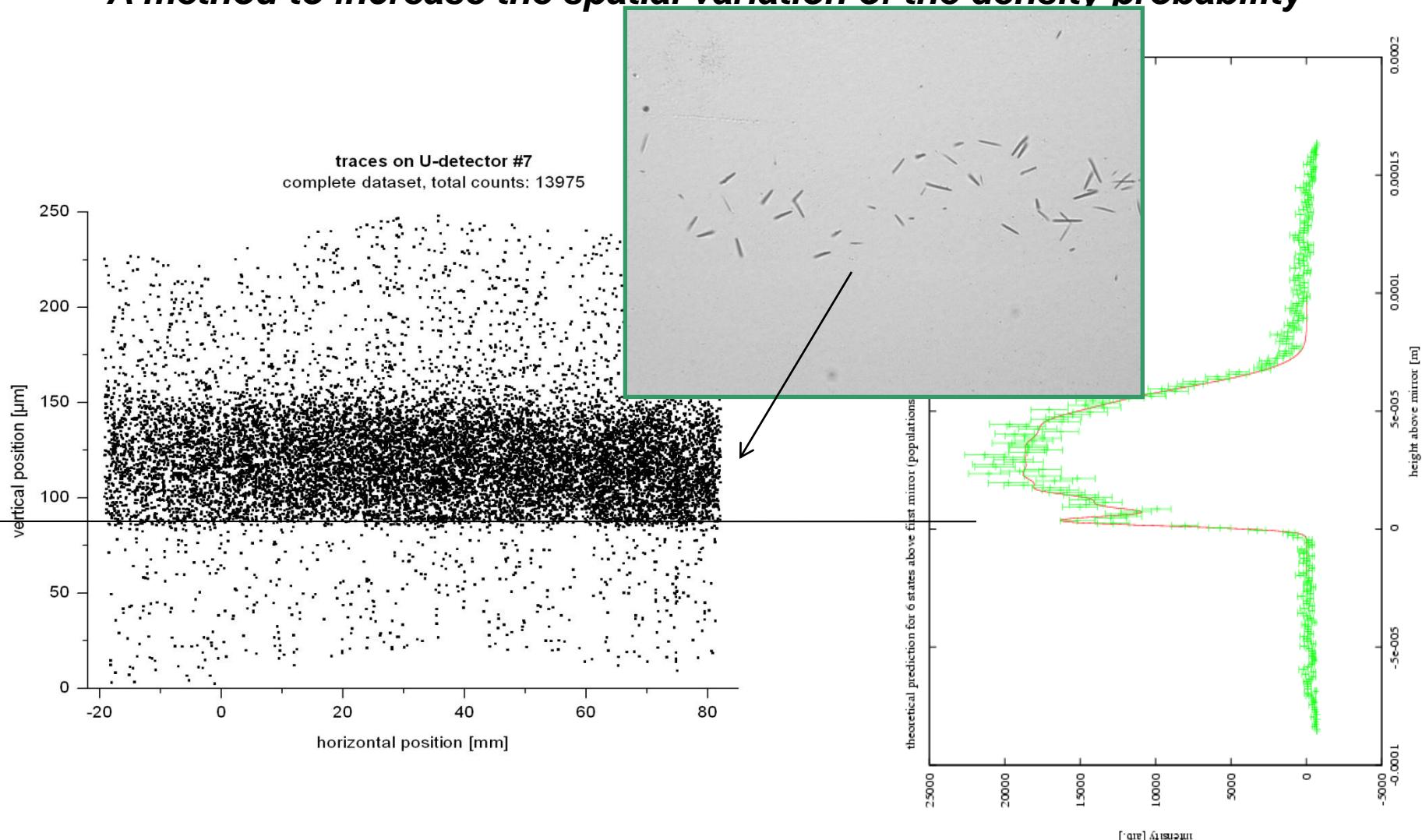
# « Differential » method, position-sensitive detectors

*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**

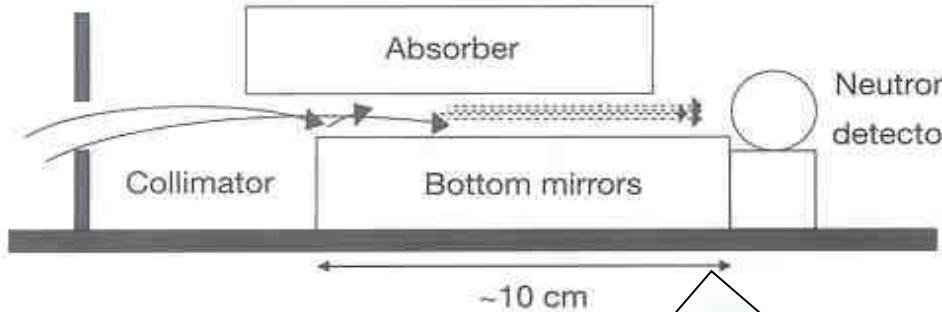
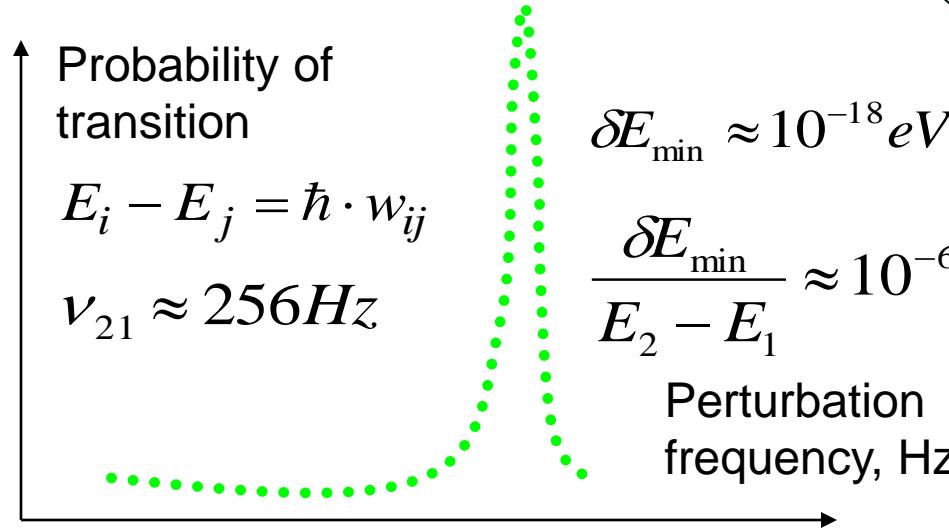


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.



**Transitions could be excited, for instance:**

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

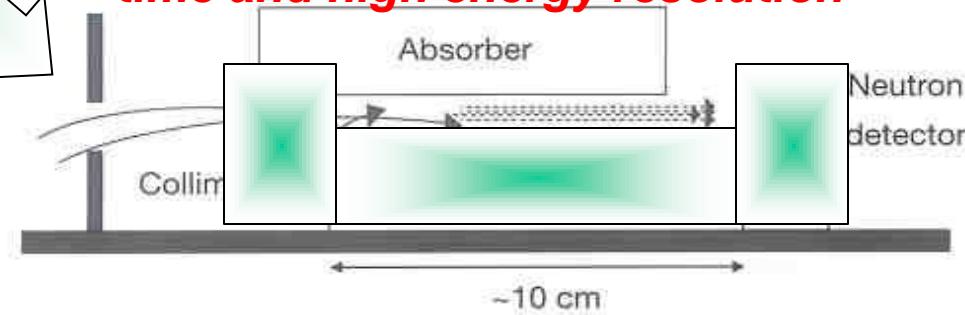
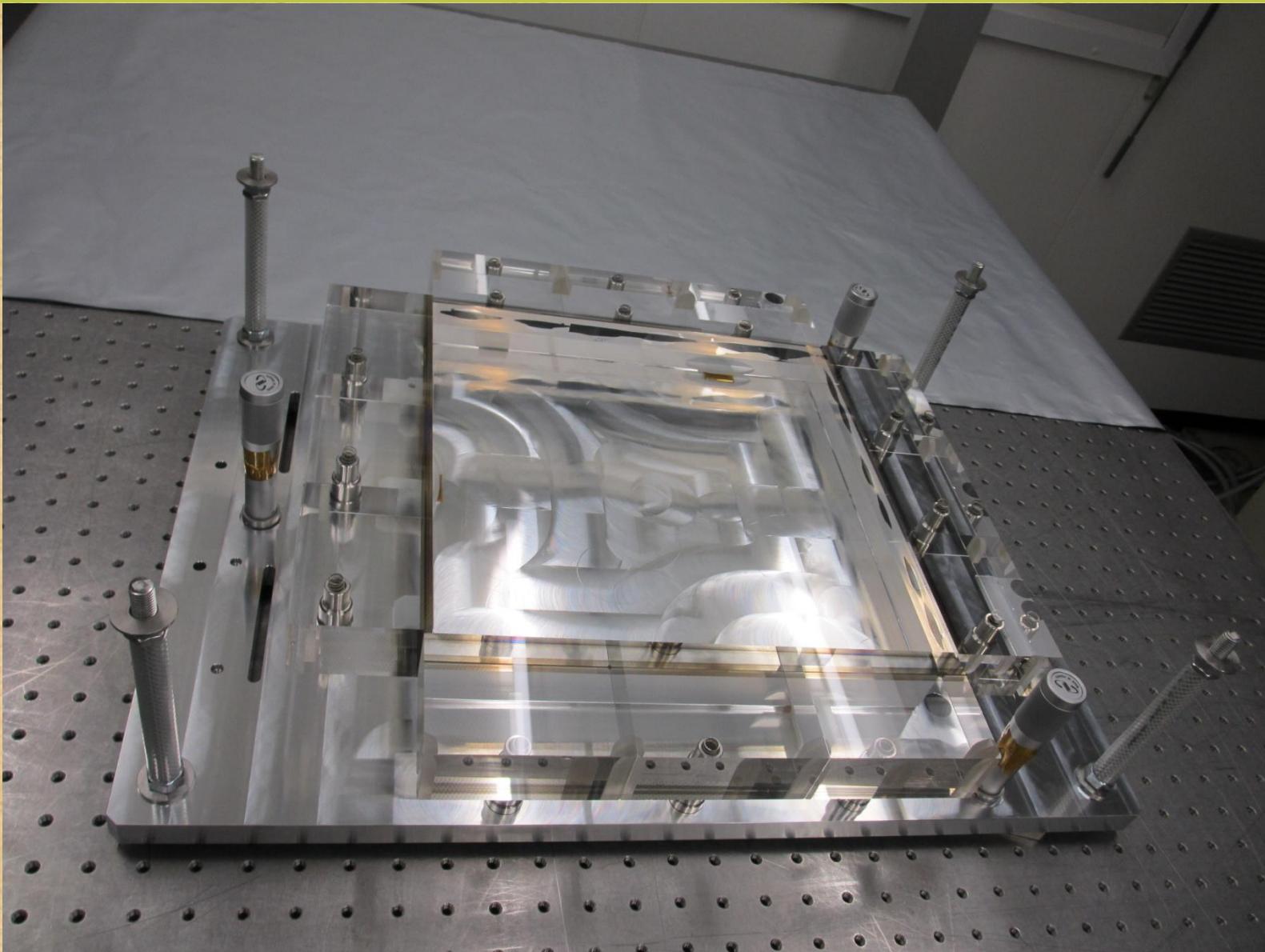


Figure 2 Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

# Transitions between gravitational quantum states

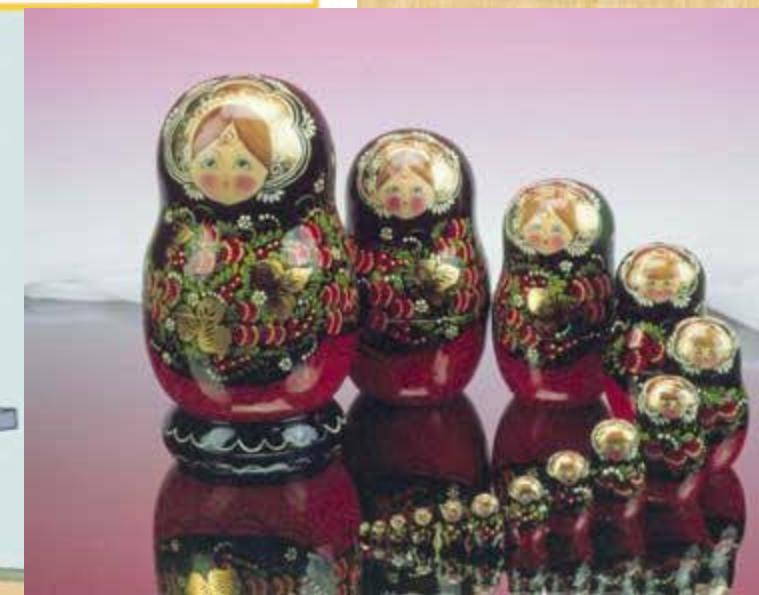
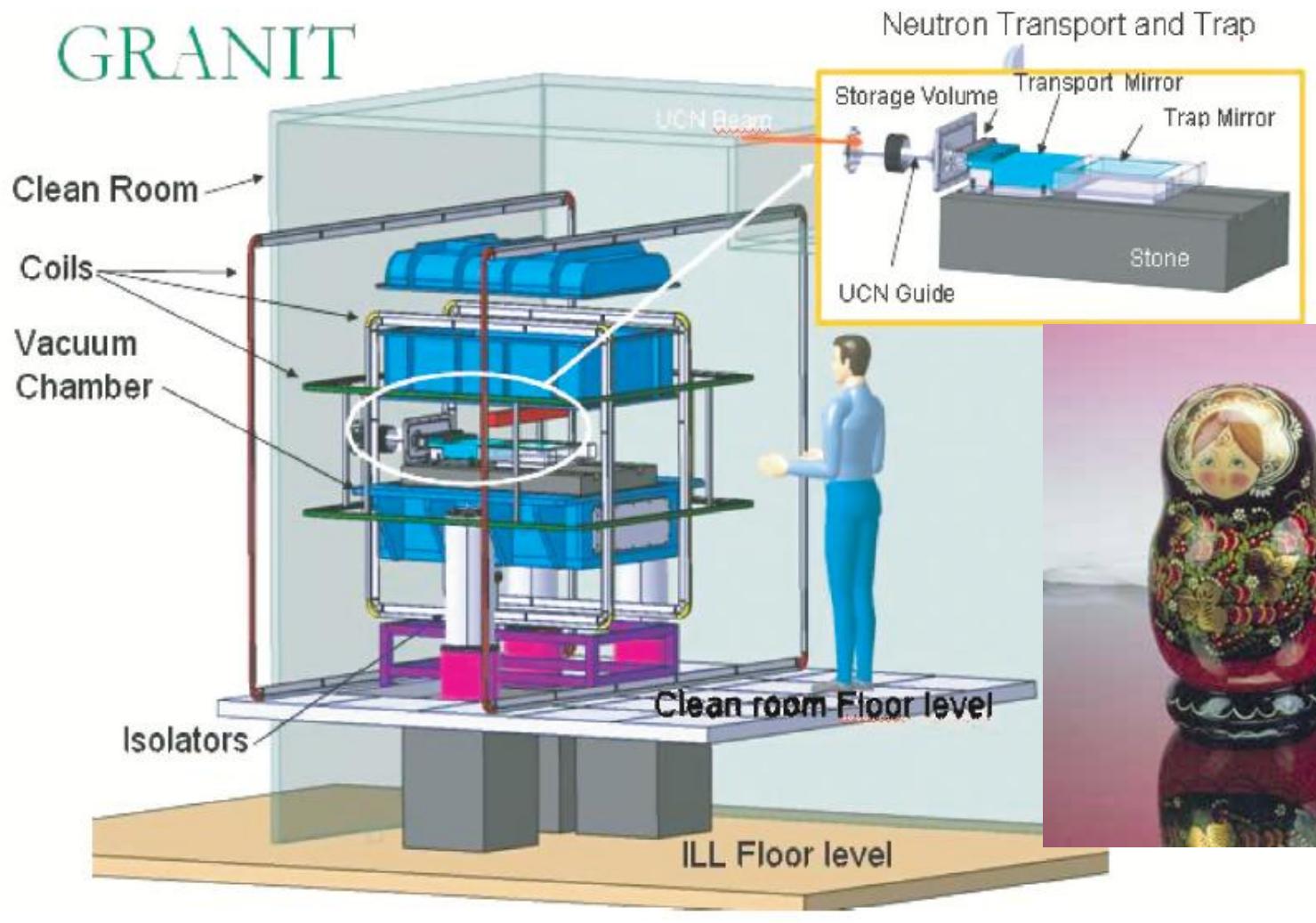
## Quantum trap 30cm by 30cm; Height of edges 1 mm



# GRANIT

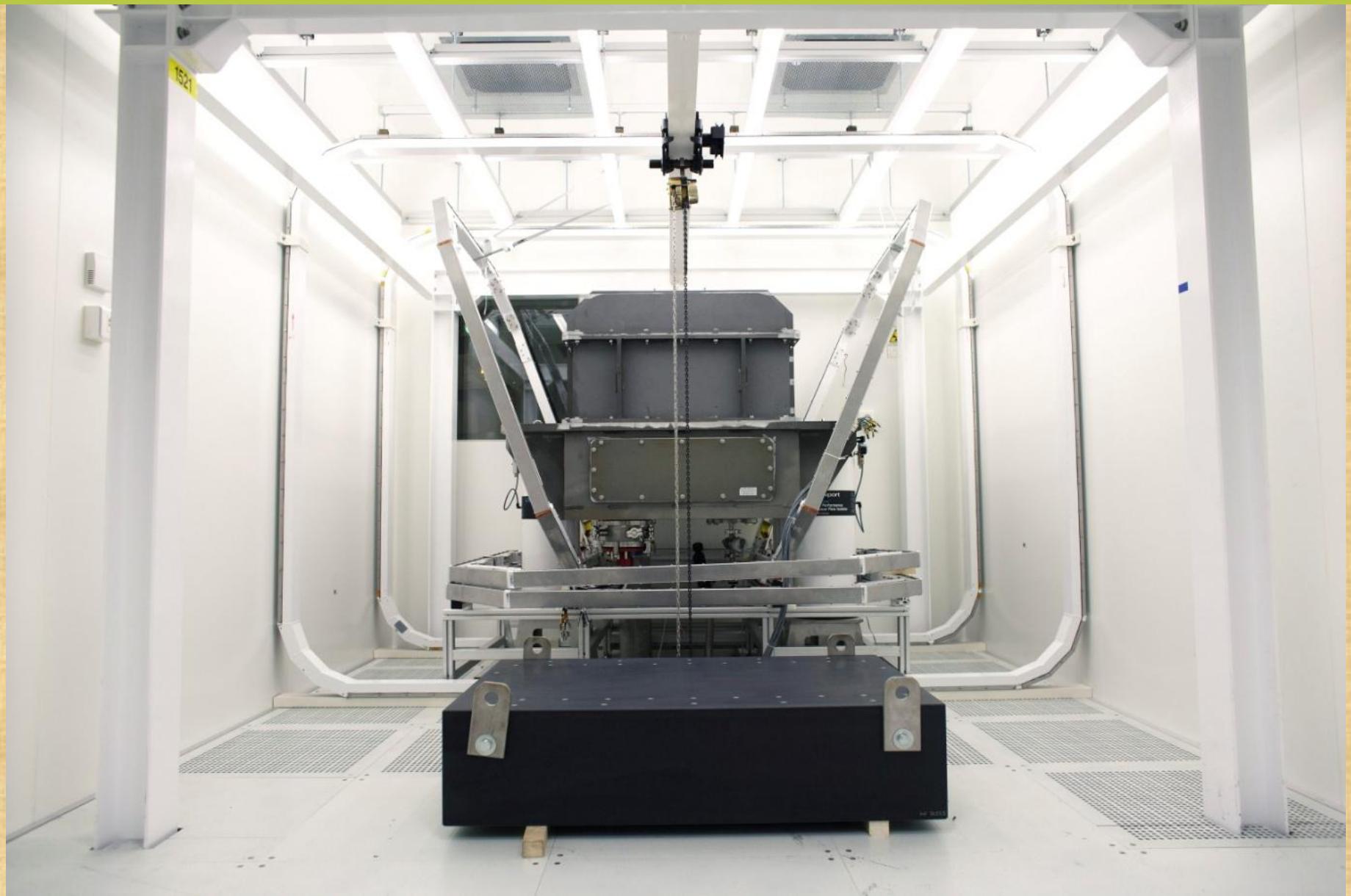
## Assembling the spectrometer

# GRANIT

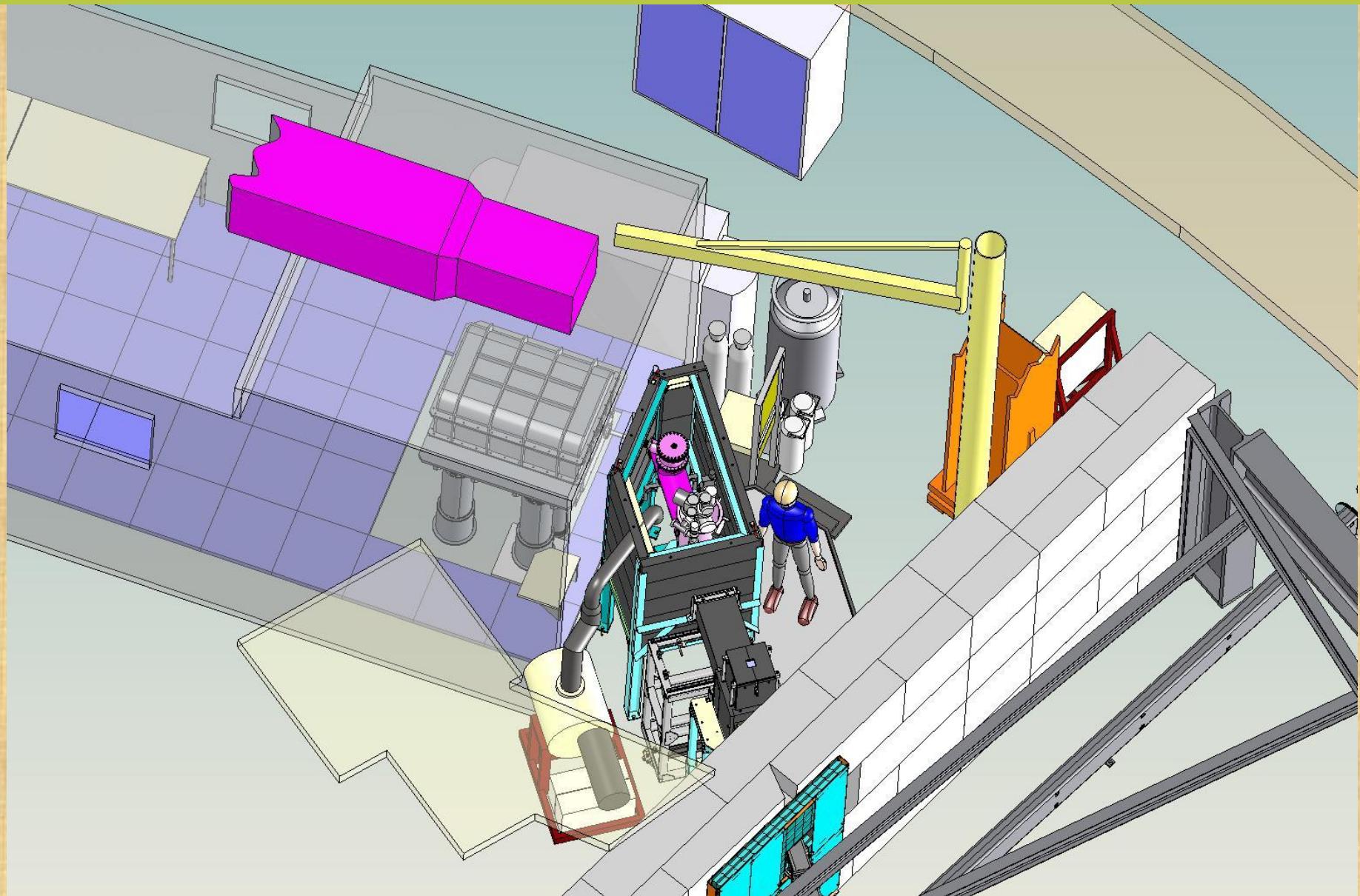


# GRANIT

## Assembling the spectrometer

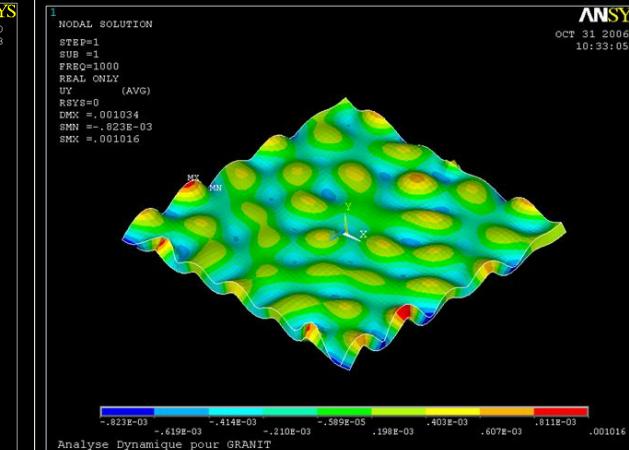
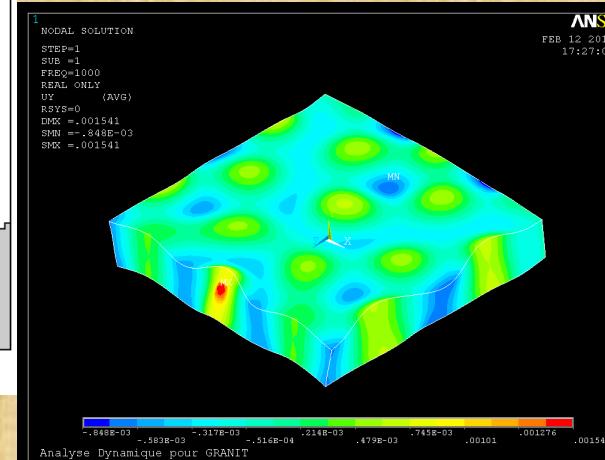
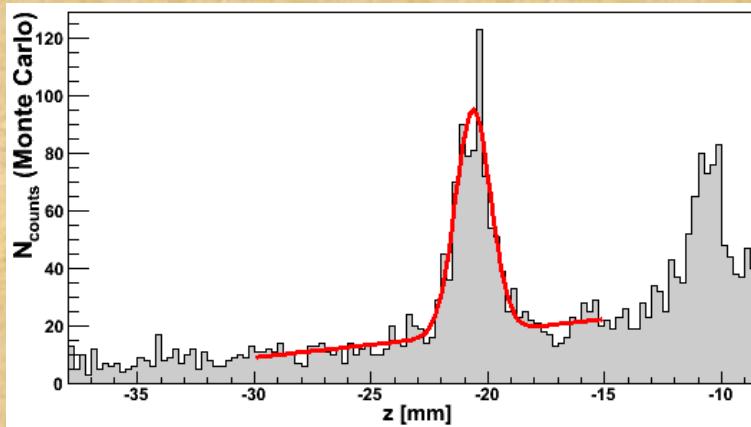
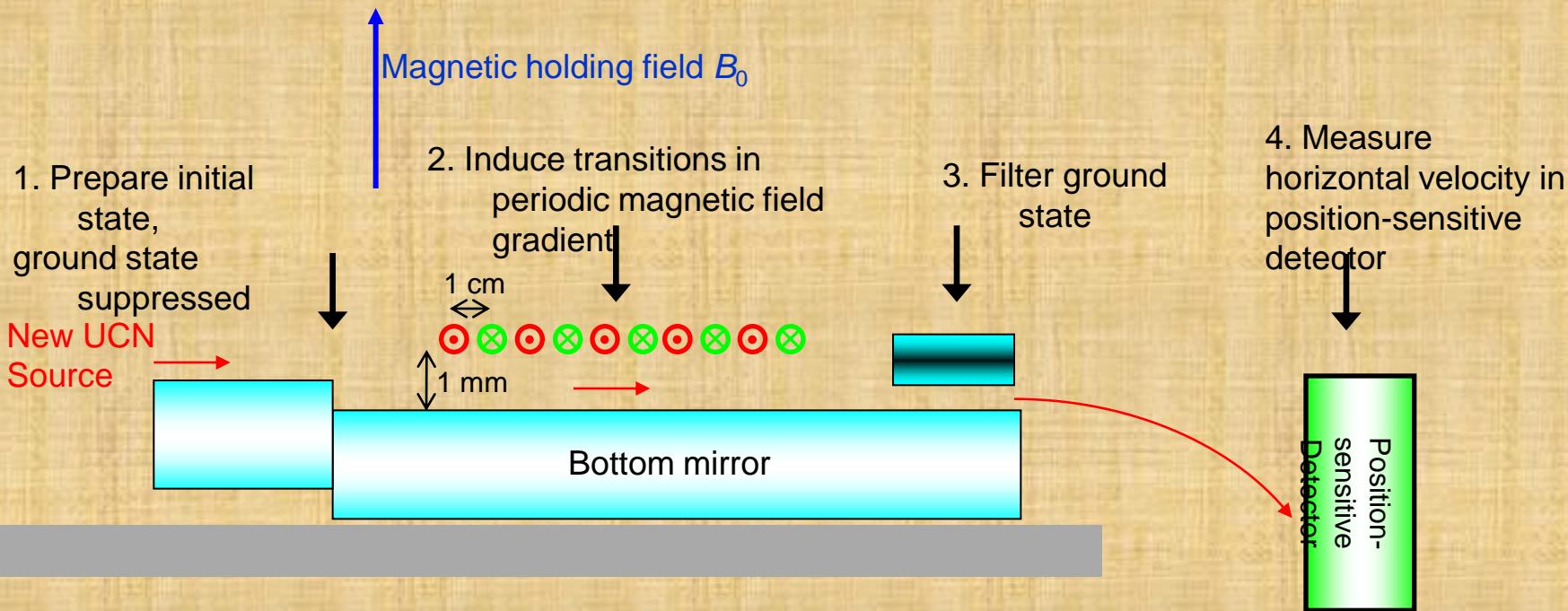


# Installation of GRANIT spectrometer at the level C at ILL



# GRANIT

## on methods of excitation the transitions



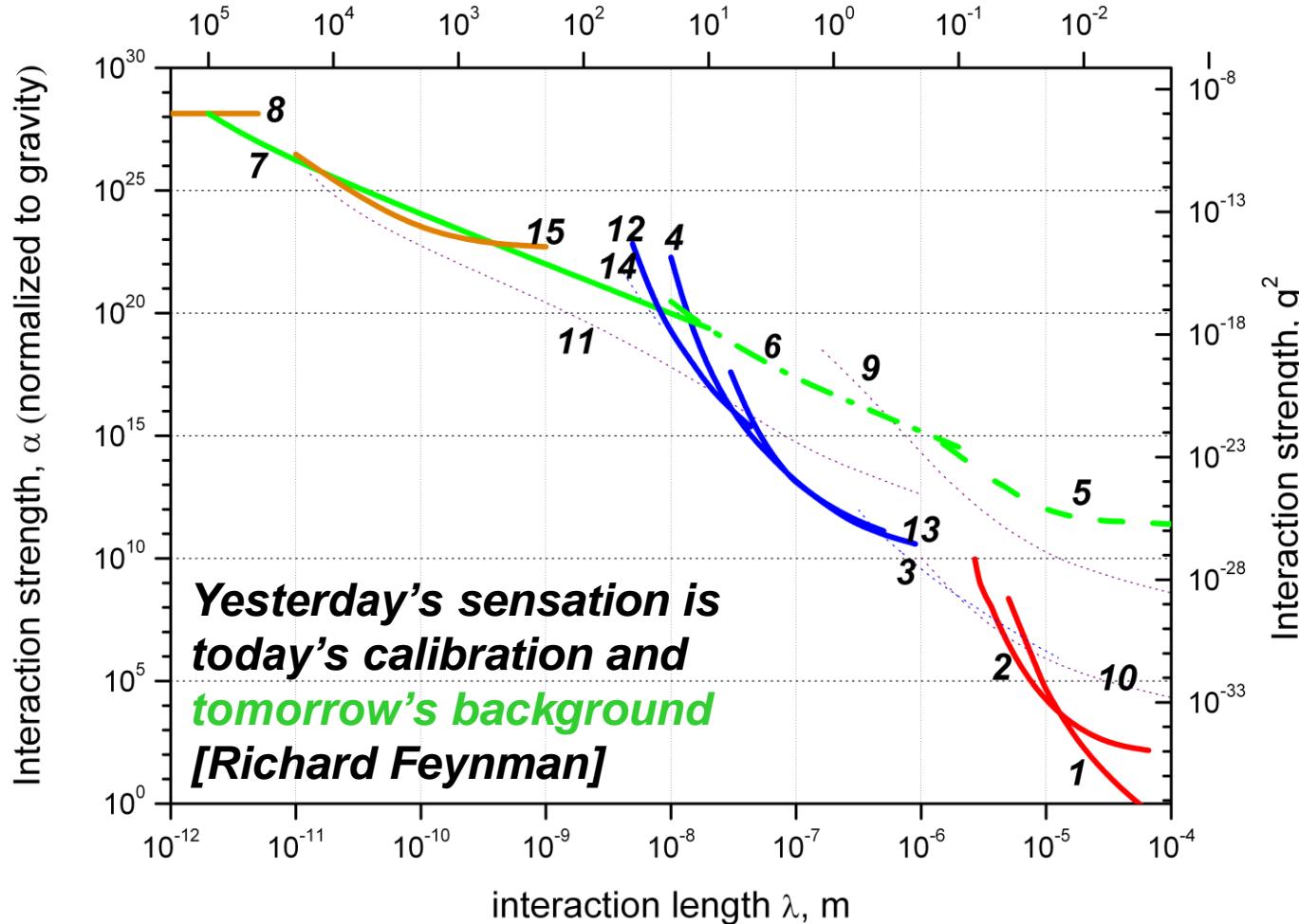
*The phenomenon of gravitational quantum states of neutrons could be used in various applications, as apriory it provides a very « clean » system with well-defined quantum states.*

- Constraints for short-range forces;** 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 12 (2011) 775.
- Constraints for axion-like forces;**
- Constraints for neutron electric charge;**
- Non-commutative quantum mechanics;** O. Bertolami et al « Noncommutative gravitational quantum well », Phys. Rev. D 72 (2005) 025010.
- Neutron quantum optics effects; UCN reflectometry;**
- Quantum revivals;** R.W. Robinett « Quantum wave packet revivals », Phys. Rep. 392 (2004) 1.
- Constraints for a logarithmic term in the Schrödinger equation;**
- Loss of quantum coherence; UCN extraction, transport, tight valves;**
- Study of thin surface layers;**
- Nature of gravity;** A. Kobakhidze, « Gravity is not an entropic force », Phys. Rev. D 83 (2011) 021502; M. Chaichian, M. Oksanen, A. Tureanu « On gravity as an entropic force », Phys. Lett. B 702 (2011) 419.
- Physics beyond the Standard model** P. Pedram, K. Nozari, S.H. Taheri « The effects of minimal length and maximum momentum on the transition rate of ultra cold neutrons in gravitational field », J. High En. Phys. 3 (2011) 093.

# Constrains 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. 12 (2011) 775.

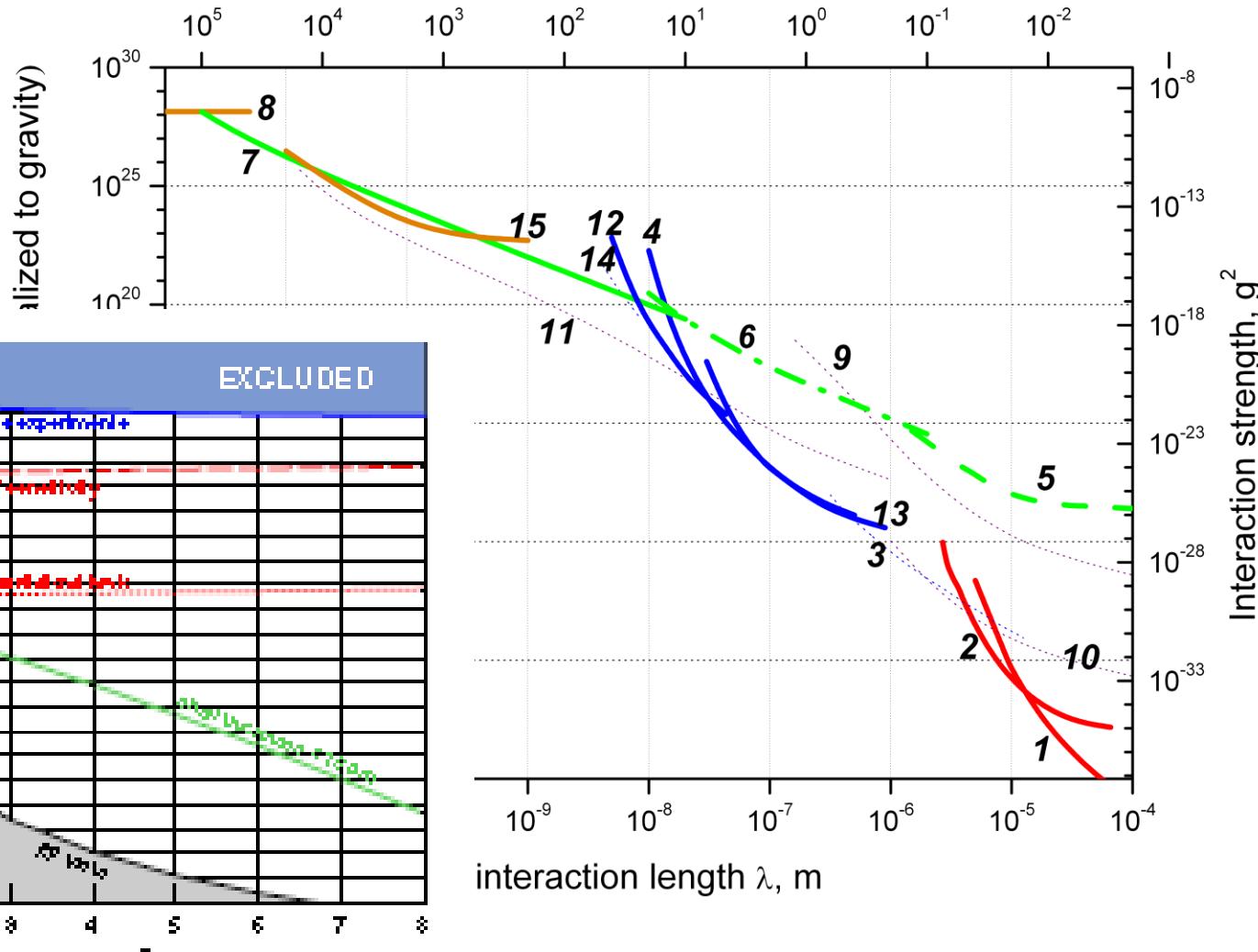
m, eV



# Constraints for short-range forces

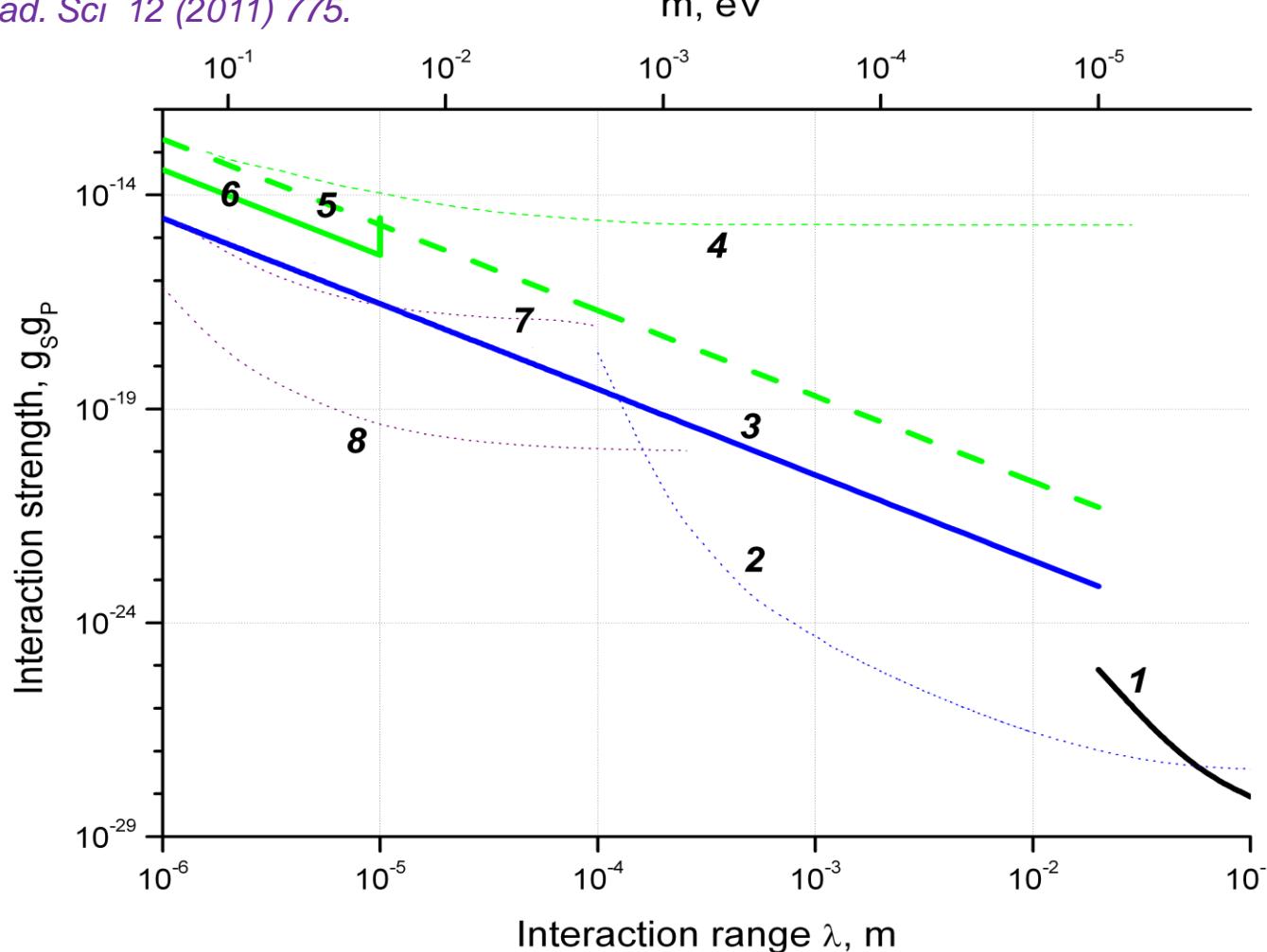
Ph. Brax, G. Pignol, « Strongly coupled chameleons and the neutronic quantum bouncer », Phys. Rev. Lett. 107 (2011) 111301.

$m$ , eV



# Constrains 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. 12 (2011) 775.



# Numerous follow-up projects and technical developments to study and use 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.*

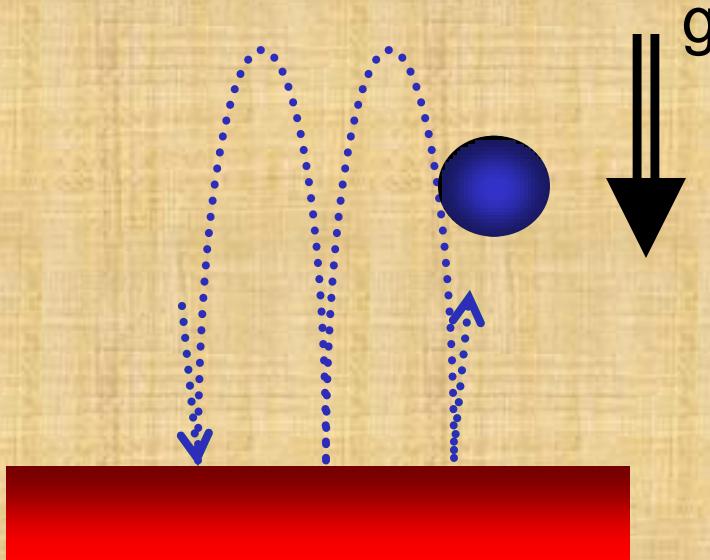
***T. Jenke, P. Geltenbort, H. Lemmel, H. Abele, « Realization of a gravity-resonance-spectroscopy technique », Nature Phys. 7 (2011) 468.***

## Similarities:

- A.Yu. Voronin, P. Froelich, V.V. N. « Gravitational quantum states of antihydrogen », Phys. Rev. A 83 (2011) 032903
1. *The anti-hydrogen mass is about equal to the neutron mass*
  2. *Modifications, due to the vdW/CP potential, of the anti-hydrogen quantum states energies and wave-functions are negligible*
  3. *Lifetimes of anti-hydrogen in quantum states are at least ~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 promissing.***

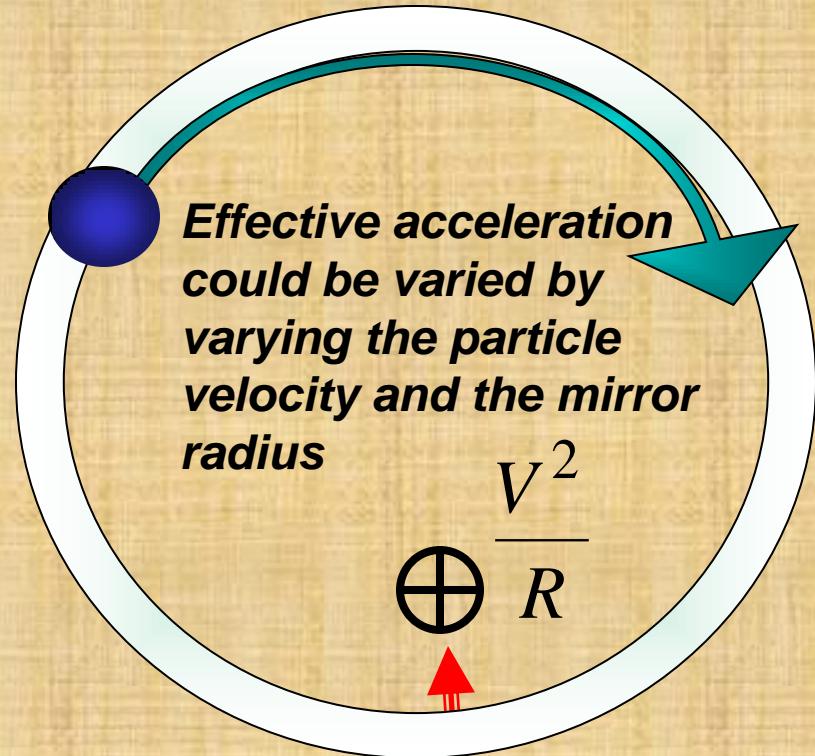
1. 2002, First observation of quantum states of UCN in the gravitational field above a mirror; first demonstration (and still the only one!) of quantum states of matter in a gravitational field
2. Applications in fundamental and surface physics
3. New gravitational spectrometer GRANIT, with all parameters largely improved compared to the first setup, is becoming operational
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 :*



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

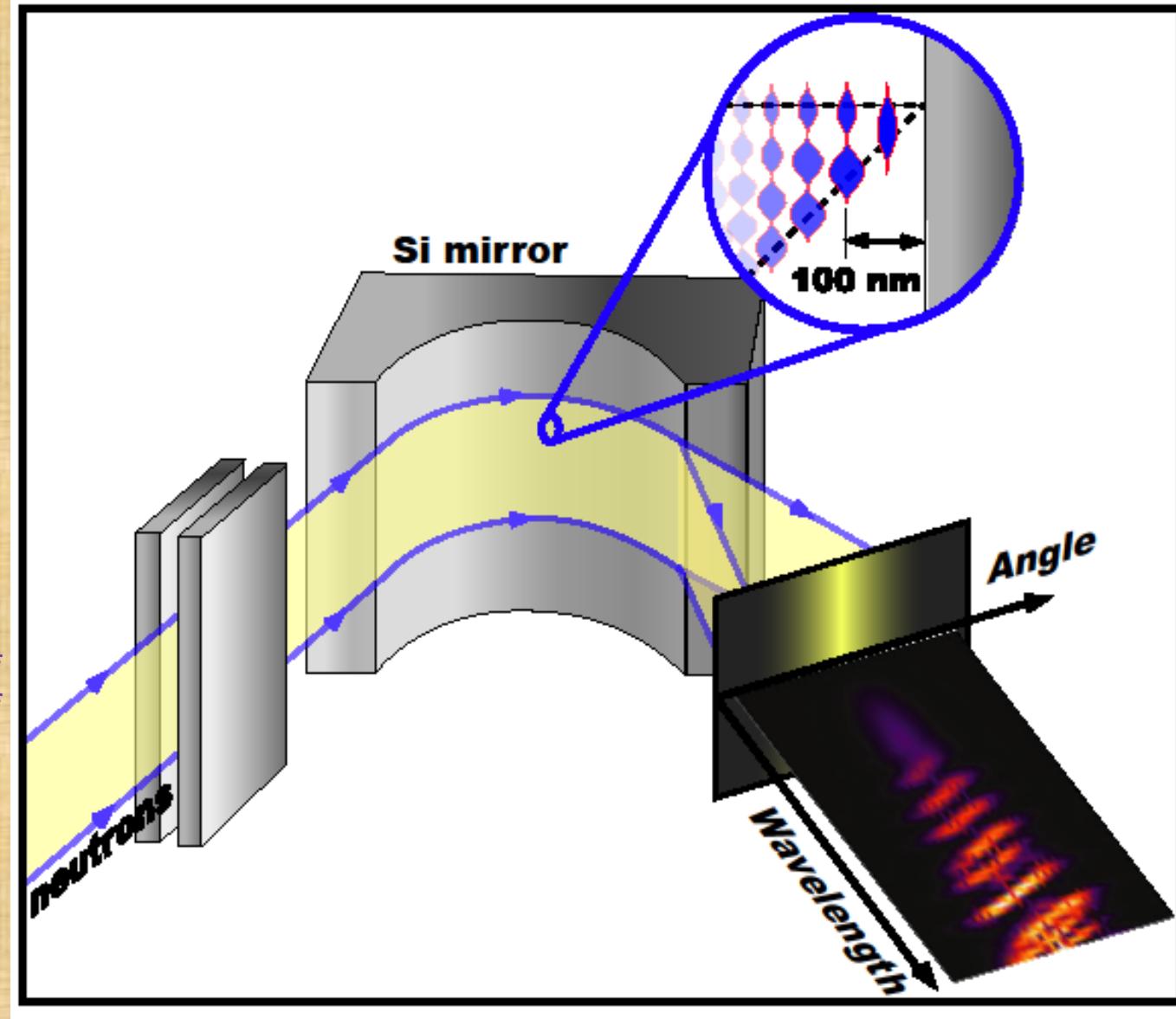
# Neutron whispering gallery

## Analogies:

**sound** [J.W. Strutt, *The theory of sound*. Macmillan, 1878]

**e.m. waves** [G. Mie, *Beitrage zur Optik truber medien, Speziell kolloidaler metallosungen*, Ann. Phys. 25 (1908) 377; K.J. Vahala, *Optical microcavities*, Nature 424 (2003) 839]

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.



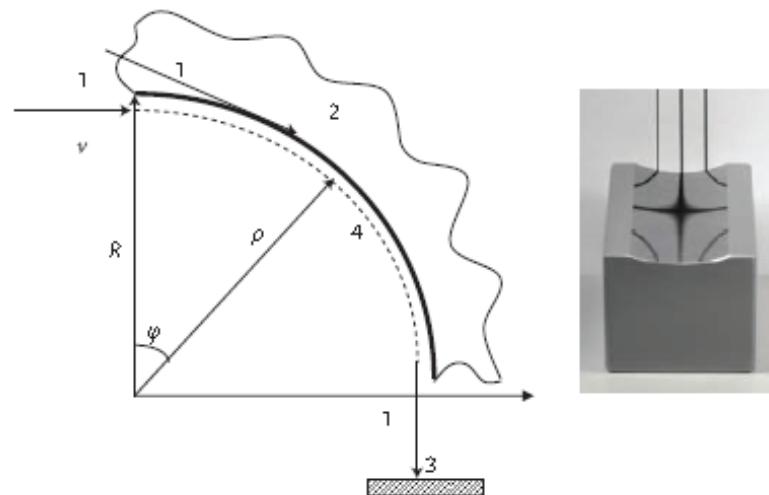
*Nature Physics*, 6, 114-117 (2010)

## 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.

# Neutron whispering gallery

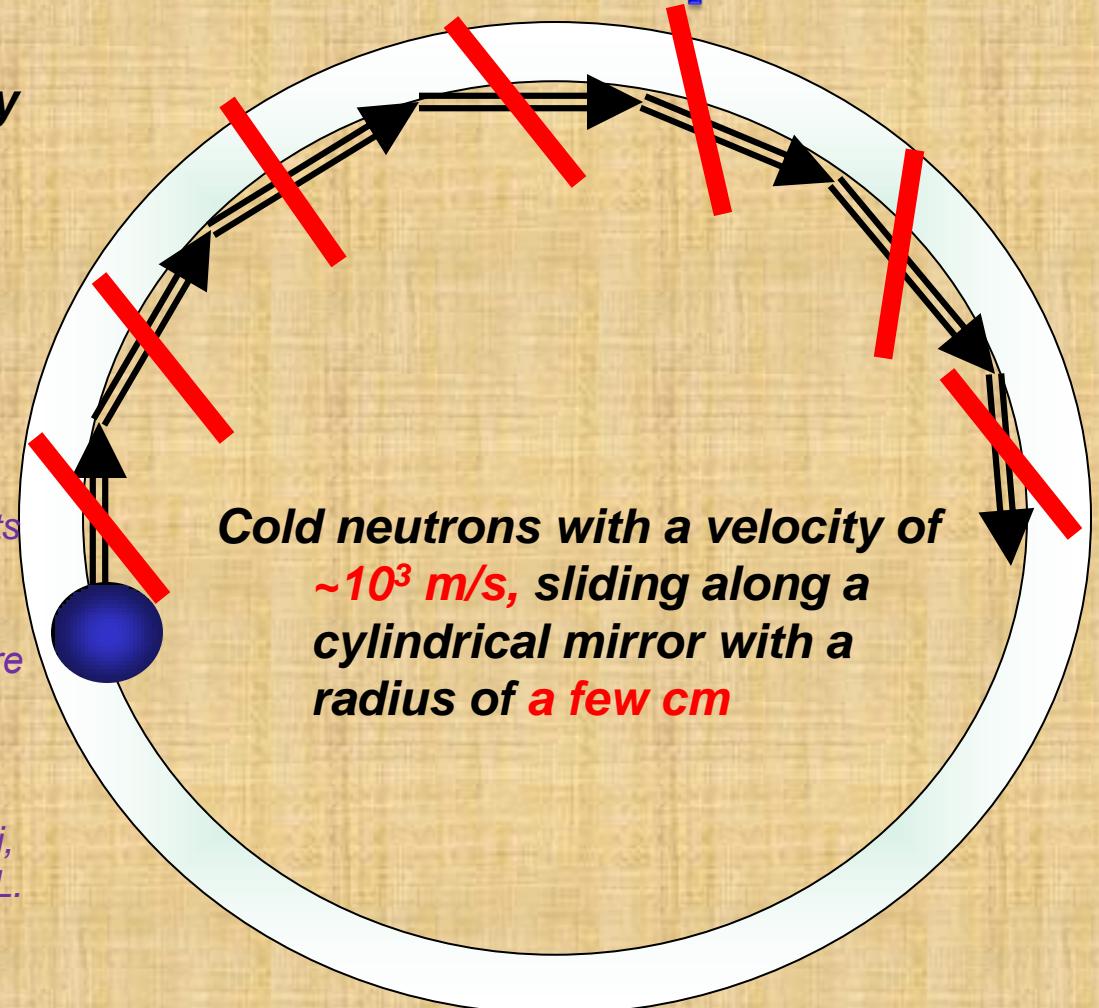
**Massive particle, sliding along a curved mirror surface is settled, under certain conditions, in quasi-stationary quantum states**

**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).
- Vernooy D. M. & Kimble H.J. "Quantum structure and dynamics for atom galleries." Phys. Rev. A 55, 1239-1261 (1997).

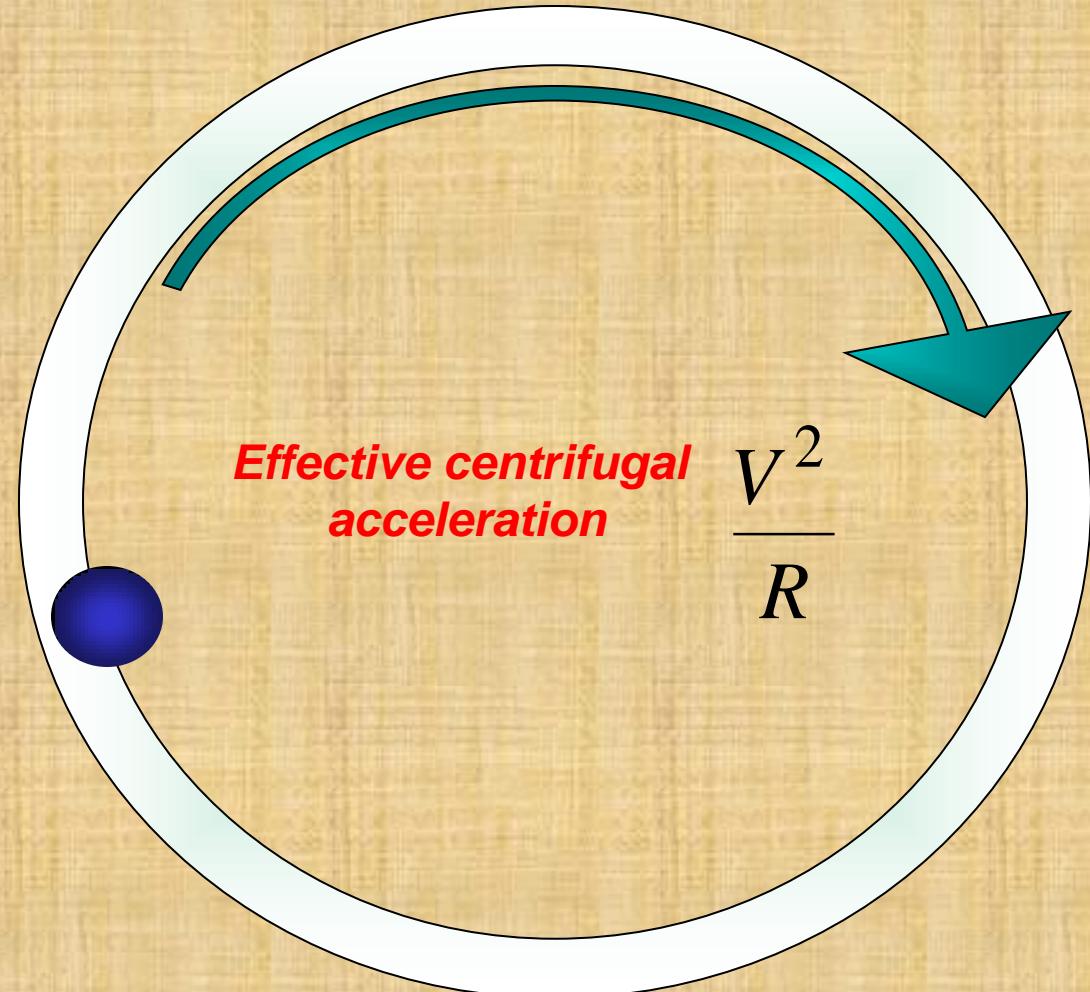
Close optical analogy: G. Della Valle, M. Savoini, M. Ornigotti, P. Laporta, V. Foglietti, M. Finazzi, L. Duo, S. Longhi, "Experimental observation of a photon bouncing ball", Phys. Rev. Lett. 102 (2009) 180402.

## 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**

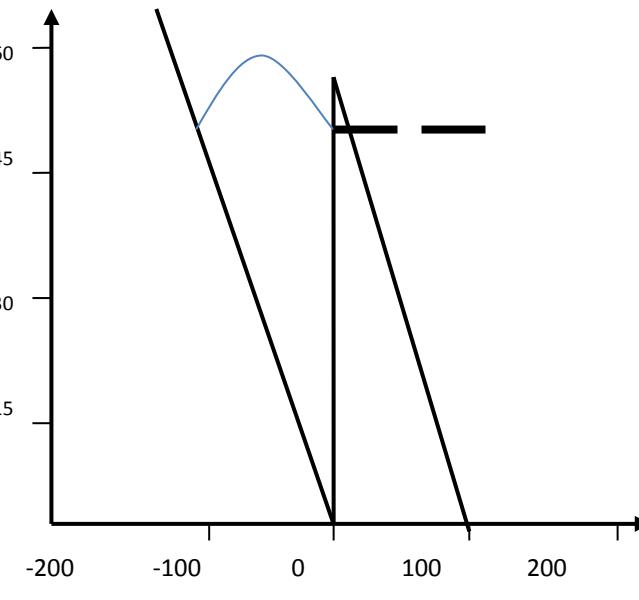


# Methods of observation

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

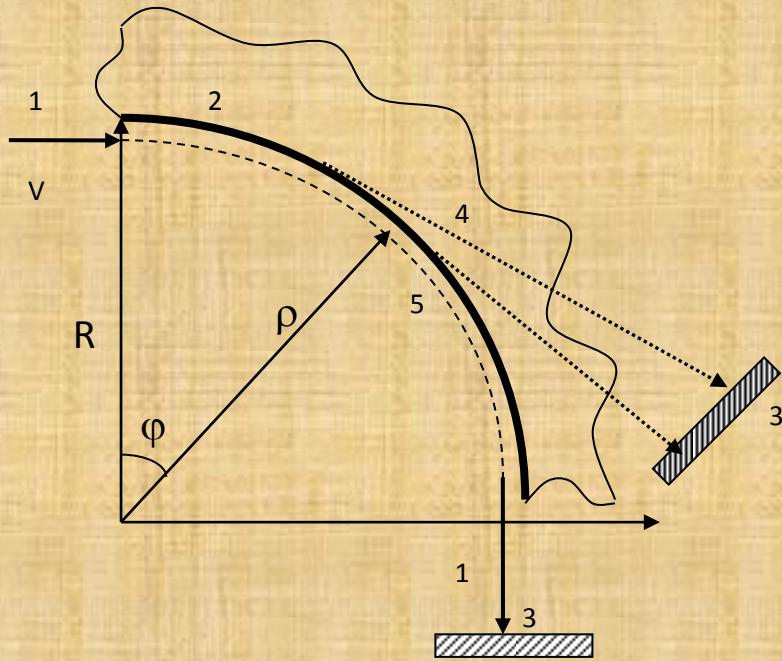
$$\lambda_n = E_n / \left( \frac{\hbar^2 M v^4}{2 R^2} \right)^{1/3} \quad z_0 = V_F / \left( \frac{\hbar^2 M v^4}{2 R^2} \right)^{1/3}$$

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



## Tunneling

# Methods of observation

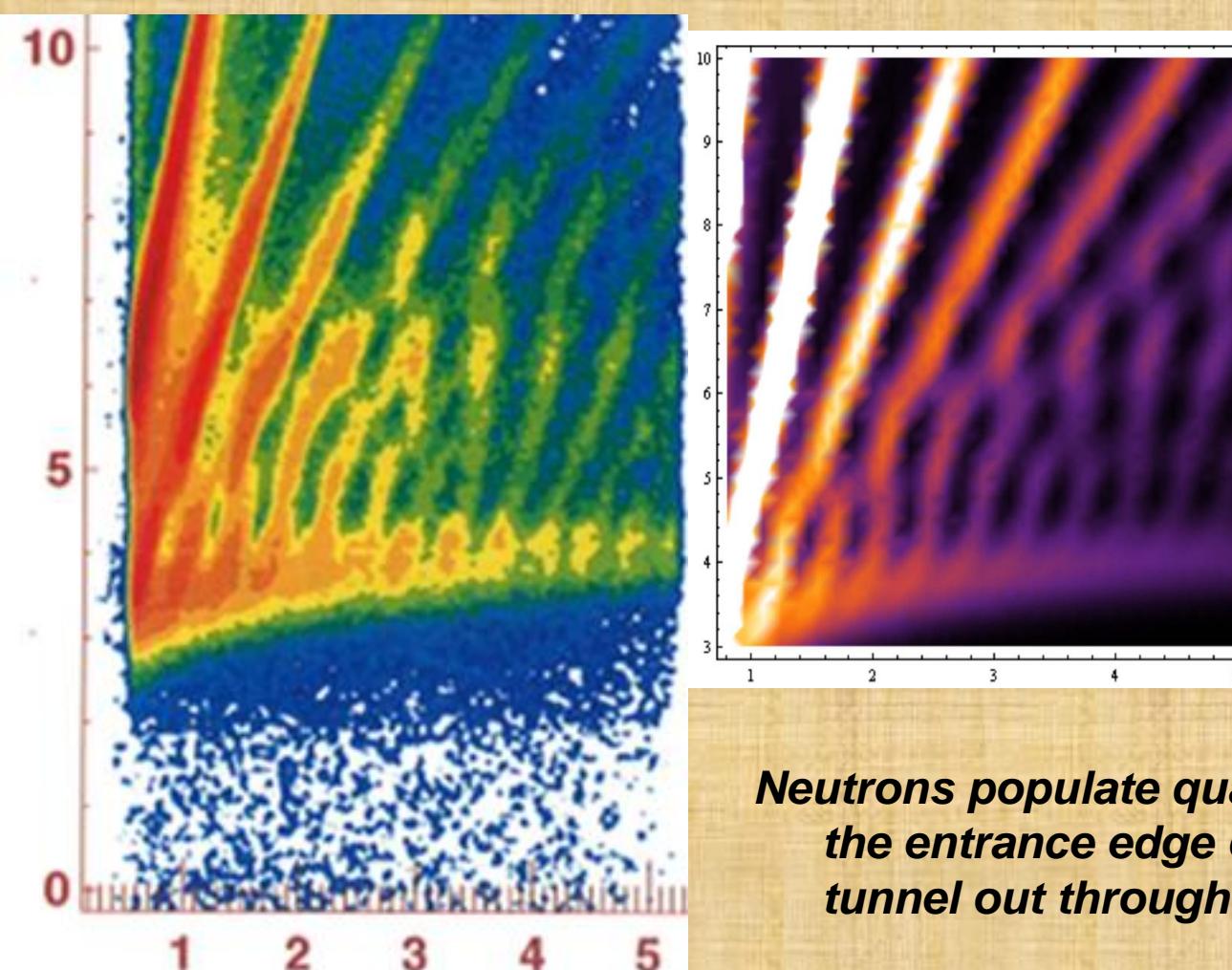


*D17 instrument at the ILL*

**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.*

# Results: NEUTRON RAINBOW



Neutrons  
tunneling OUT of  
quantum states

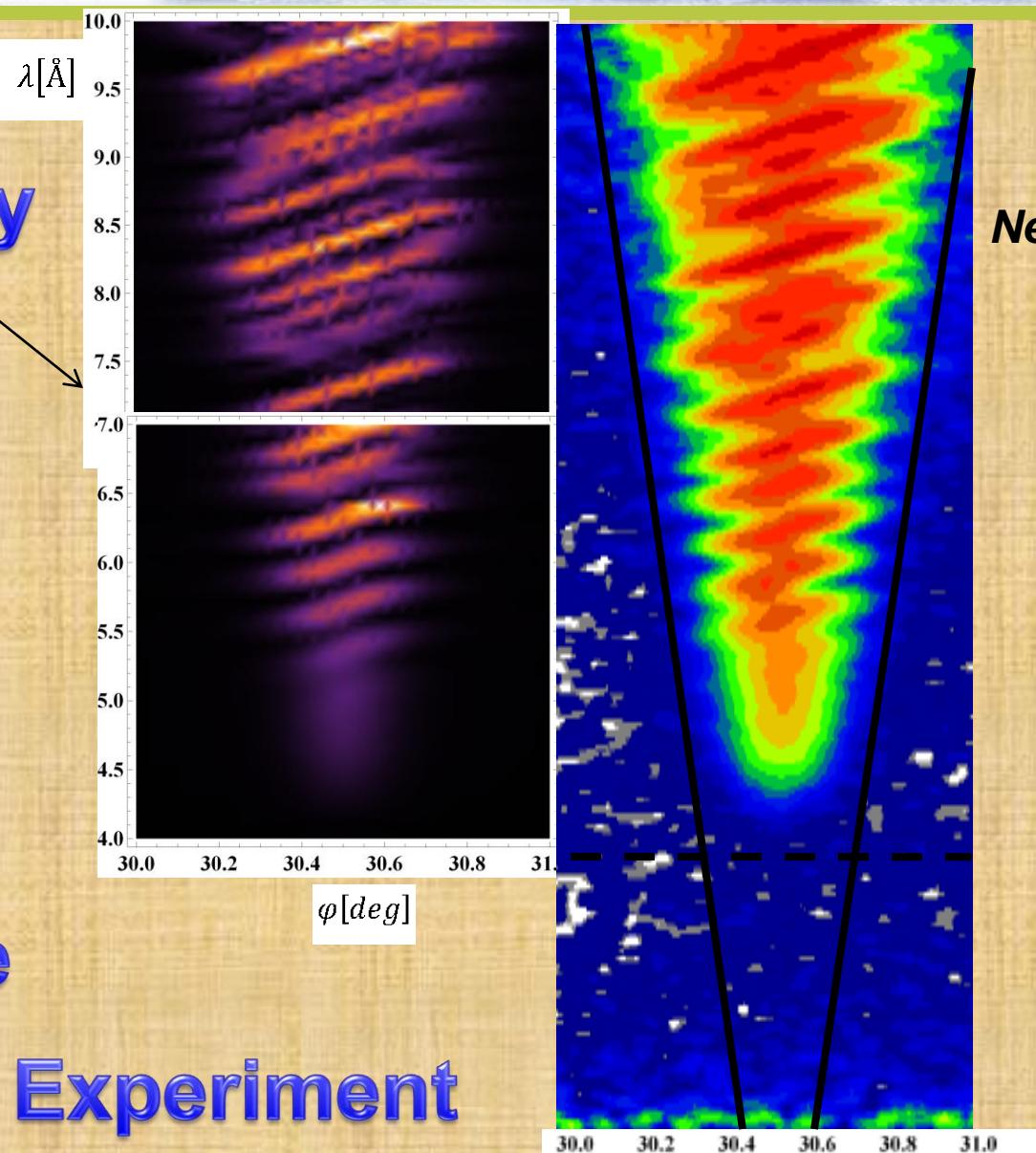
*Neutrons populate quantum states states through  
the entrance edge of a truncated cylinder and  
tunnel out through the triangular potential barrier*

# Results: NEUTRON RAINBOW

## Theory

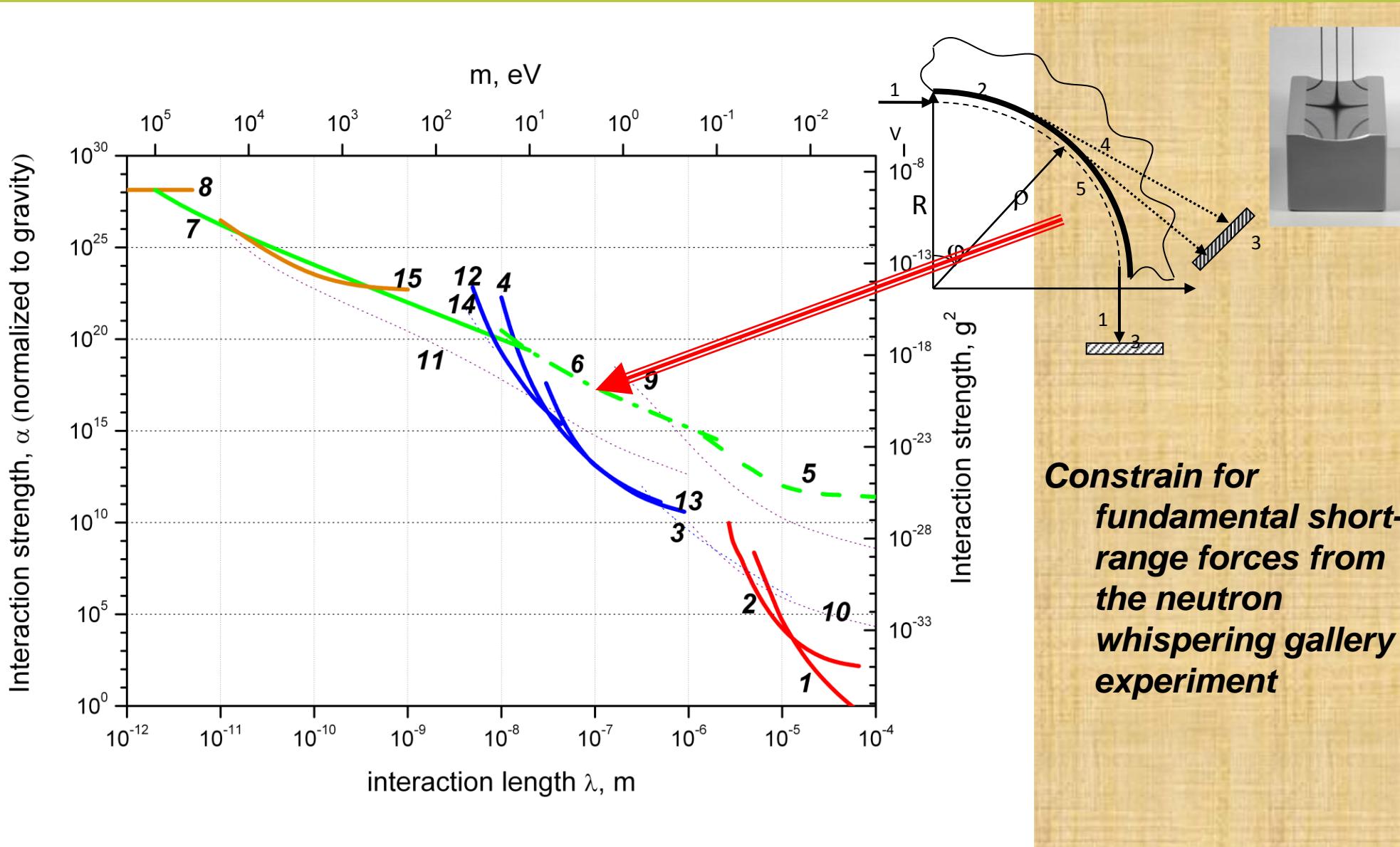
Neutrons  
entering  
from the  
mirror edge

## Experiment



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

# Results: NEUTRON RAINBOW



1. **2010, First observation of quasi-stationary quantum states of cold neutrons in vicinity of a 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 for constraining fundamental short-range forces**
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. Observation of gravitational and centrifugal quantum states of slow neutrons**
- 2. The first direct demonstration of the Weak equivalence principle for an object in a quantum state.**
- 3. Long lifetimes of neutrons in these quantum states allow one using them for precision studies**
- 4. Very similar precision experiments could be performed with anti-matter atoms. GBAR project.**