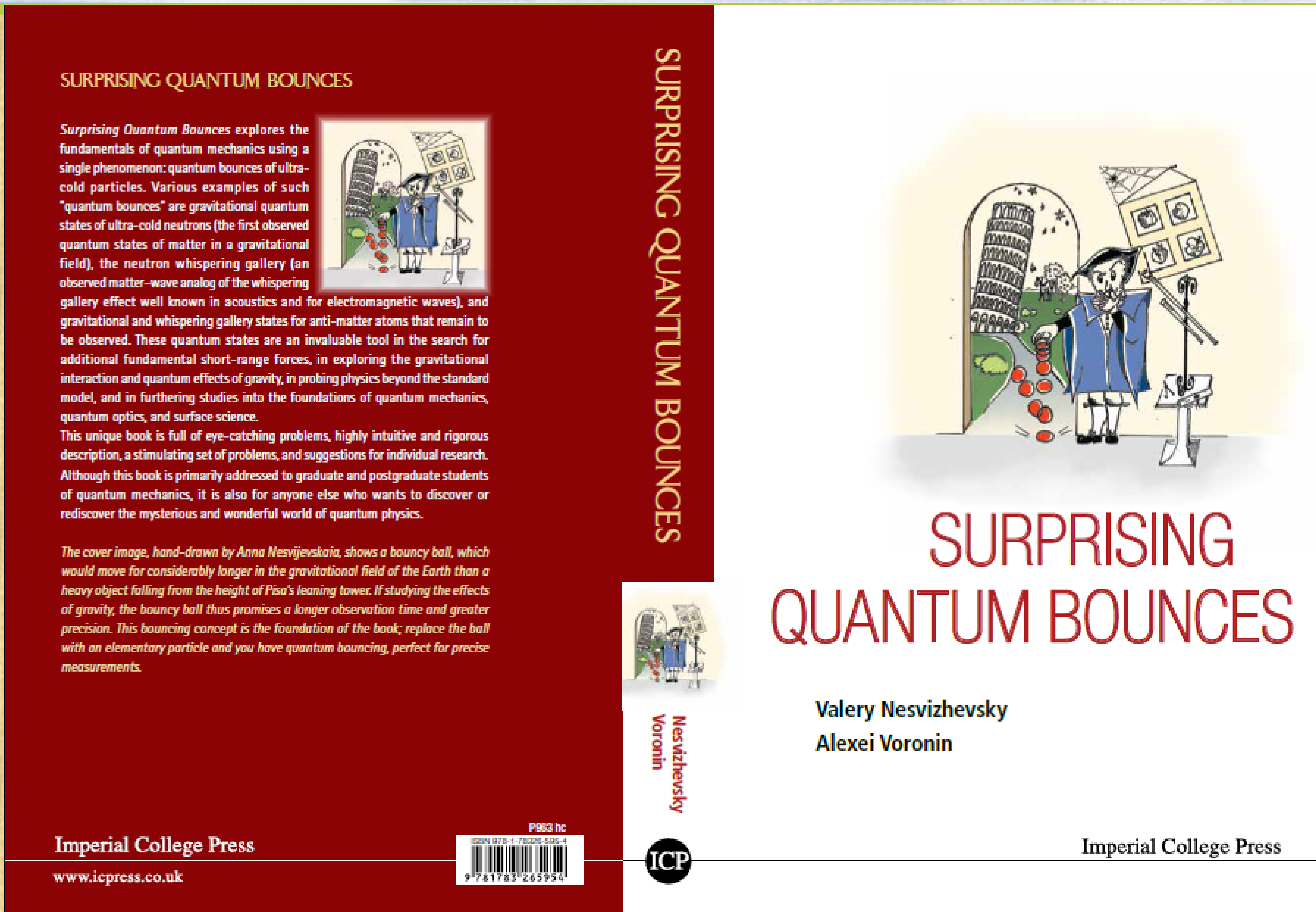
NEUTRONS FOR SCIENCE

Plan of presentation

- Introduction and references
- A broader view: Emerging related topics
- Short-range forces and neutrons
- State of the art
- Recent improvements
- Conclusions and prospects

UCNs, Gravity and Quantum Mechanics



SURPRISING QUANTUM BOUNCES

Surprising Quantum Bounces explores the fundamentals of quantum mechanics using a single phenomenon: quantum bounces of ultra-cold particles. Various examples of such "quantum bounces" are gravitational quantum states of ultra-cold neutrons (the first observed quantum states of matter in a gravitational field), the neutron whispering gallery (an observed matter–wave analog of the whispering gallery effect well known in acoustics and for electromagnetic waves), and gravitational and whispering gallery states for anti-matter atoms that remain to be observed. These quantum states are an invaluable tool in the search for additional fundamental short-range forces, in exploring the gravitational interaction and quantum effects of gravity, in probing physics beyond the standard model, and in furthering studies into the foundations of quantum mechanics, quantum optics, and surface science.

This unique book is full of eye-catching problems, highly intuitive and rigorous description, a stimulating set of problems, and suggestions for individual research. Although this book is primarily addressed to graduate and postgraduate students of quantum mechanics, it is also for anyone else who wants to discover or rediscover the mysterious and wonderful world of quantum physics.

The cover image, hand-drawn by Anna Nesvijevskaia, shows a bouncy ball, which would move for considerably longer in the gravitational field of the Earth than a heavy object falling from the height of Pisa's leaning tower. If studying the effects of gravity, the bouncy ball thus promises a longer observation time and greater precision. This bouncing concept is the foundation of the book; replace the ball with an elementary particle and you have quantum bouncing, perfect for precise measurements.

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SURPRISING QUANTUM BOUNCES

Nesvizhevsky
Voronin

ICP

SURPRISING
QUANTUM BOUNCES

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Alexei Voronin

Imperial College Press

UCNs, Gravity and Quantum Mechanics

NEUTRONS FOR SCIENCE

In this book we aim to discuss fundamental ideas of physics by means of analyzing a single phenomenon of quantum bouncing, which provides numerous physical realizations. We discuss phenomena, which we believe are surprising, and we try to remove some prevailing illusions.

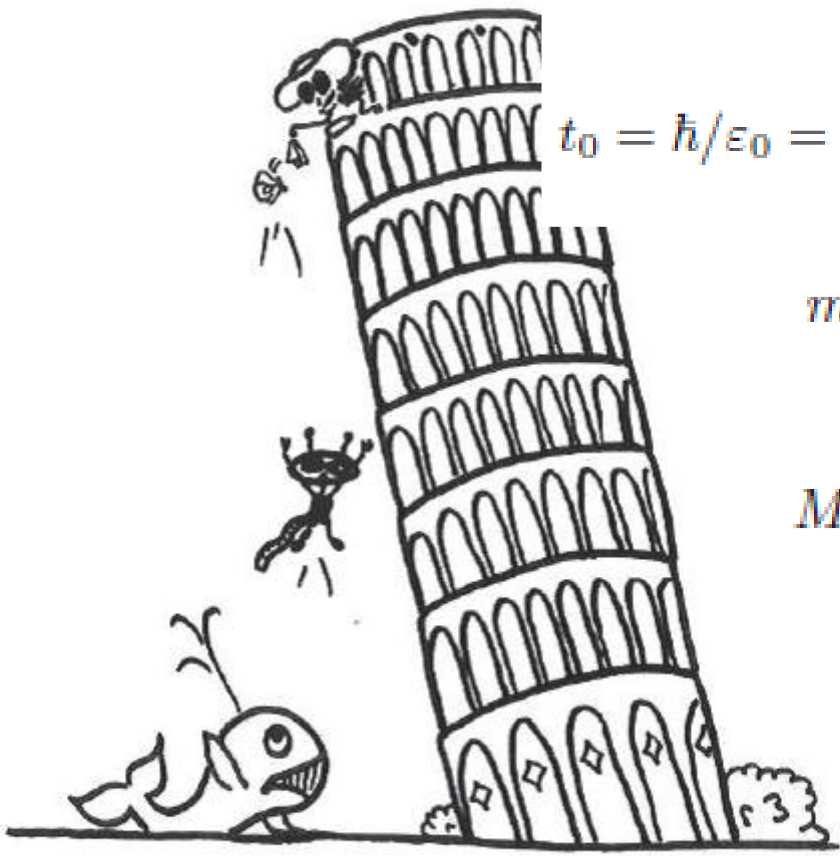
GRANIT workshops, Gravitational Quantum Spectroscopy

GRANIT workshops every 4th (Olympic) year; typically 50 participants from 12 countries on 4 continents; GRANIT-2014, 2-7 March 2014, Les Houches, France

proceedings of GRANIT-2014 are published in a Special Issue "*Gravitational Quantum Spectroscopy*" of *Advances in High Energy Physics (2015).*

Quantum fall and equivalence principle

$$i\hbar\frac{\partial\Psi(z,t)}{\partial t} = \left(-\hbar^2\frac{1}{2m}\frac{d^2}{dz^2} + Mgz\right)\Psi(z,t).$$

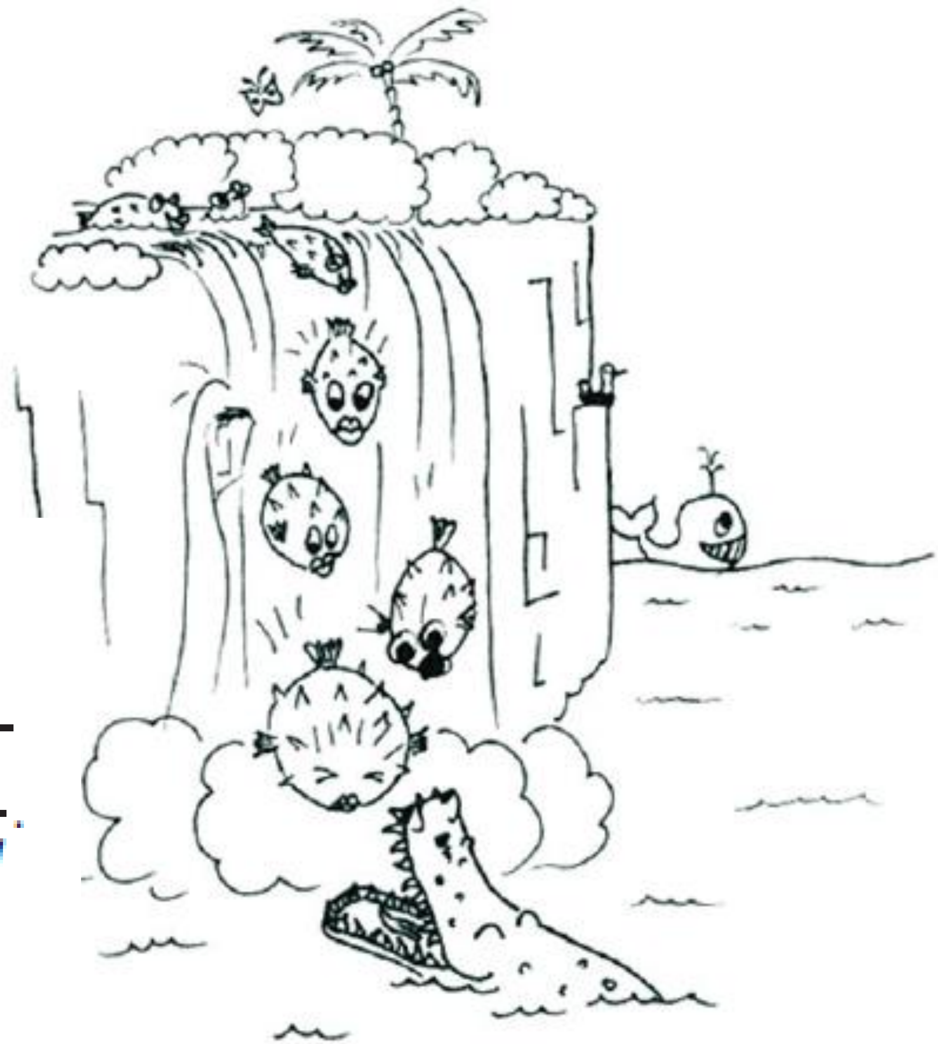


$$l_0 = \sqrt[3]{\frac{\hbar^2}{2mMg}},$$

$$t_0 = \hbar/\varepsilon_0 = \sqrt[3]{\frac{2m\hbar}{M^2g^2}}.$$

$$m = \frac{\hbar t_0}{2l_0^2},$$

$$M = \sqrt{\frac{\hbar}{t_0 l_0 g}}.$$



Quantum bouncing

"Let us consider another possibility, an atom held together by gravity alone. For example, we might have two neutrons in a bound state. When we calculate the Bohr radius of such an atom, we find that it would be 10^8 light years, and that the atomic binding energy would be 10^{-27} Rydberg. There is then little hope of ever observing gravitational effects on systems which are simple enough to be calculated in quantum mechanics." Brian Hatfield in [R.P. Feynman, F.B. Morinigo, and W.G. Wagner (1995) Feynman Lectures on Gravitation (Addison-Wesley, USA), p. 11]

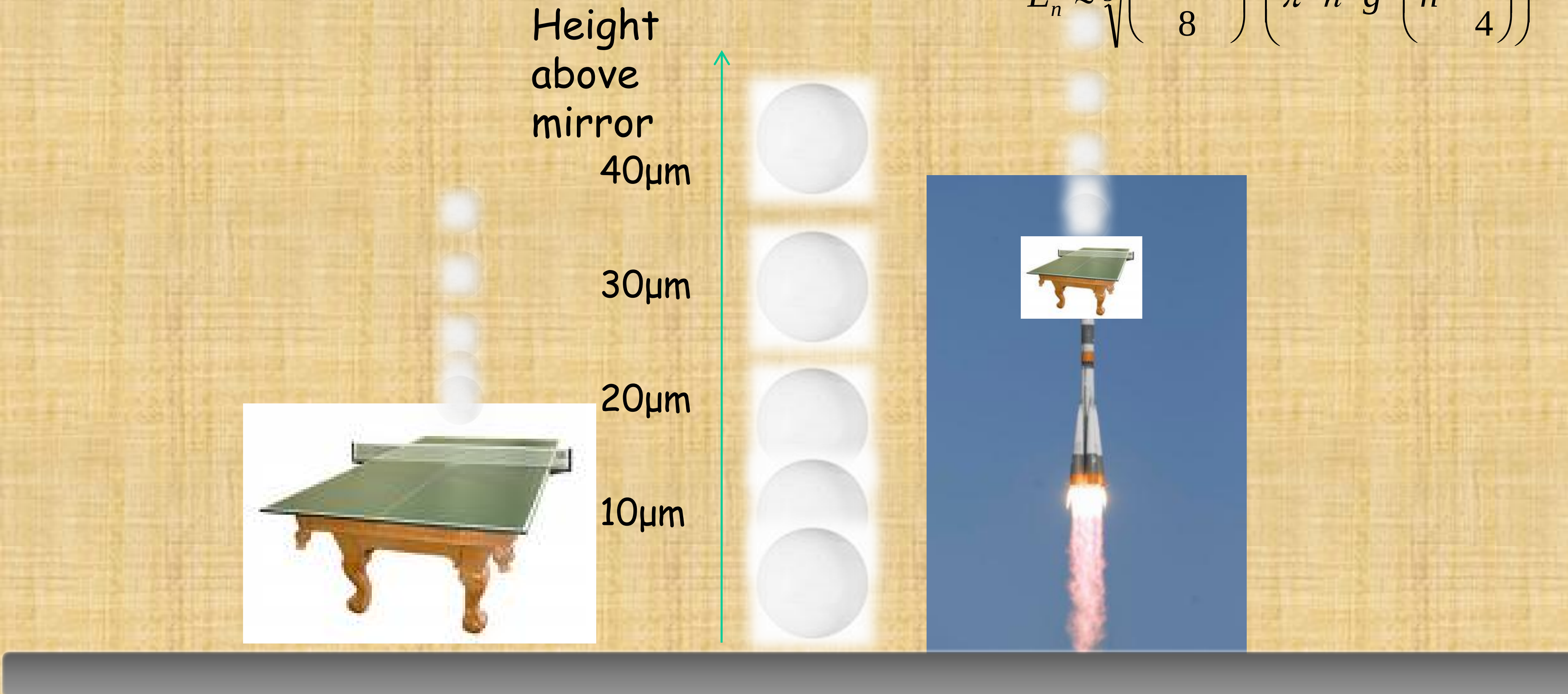
Yesterday's sensation is today's calibration and tomorrow's background" [P.R. Feynman and V.L. Telegdi]

A broader view: Emerging topics

A broader field of research, which is emerging from the first experiments on gravitational and whispering-gallery quantum states of neutrons ([V.V. Nesvizhevsky, H.G. Boerner, A.K. Petukhov, H. Abele, S. Baessler, F.J. Ruess, T. Stoferle, A. Westphal, A.M. Gagarski, G.A. Petrov, and A.V. Strelkov, Quantum states of neutrons in the Earth's gravitational field, Nature 415 (2002) 297], [V.V. Nesvizhevsky, A.Yu. Voronin, R. Cubitt, and K.V. Protasov, Neutron whispering gallery, Nature Physics 6 (2010) 114])

Gravity / Acceleration

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



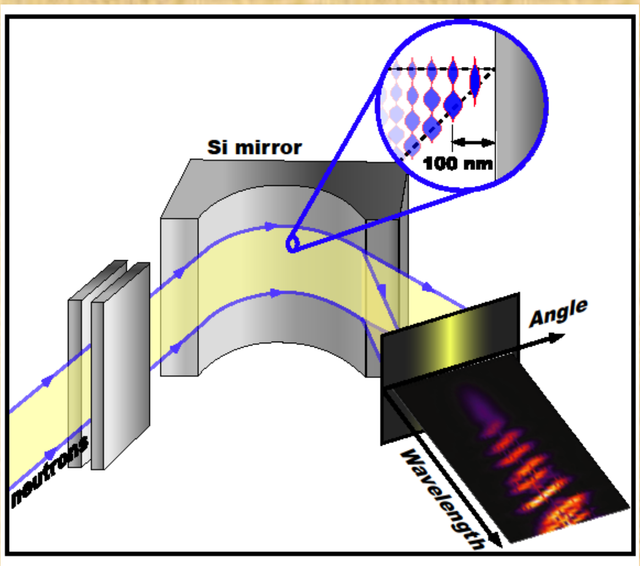
An illustration for quantum motion of a particle above a mirror in a gravitational field and that in an accelerated frame. The heights of the ball correspond to most probable heights of a neutron in 5th quantum state.

Quantum bouncing

Gravitational and whispering-gallery quantum states of neutrons

Essential features:

- The mirror is a uniform potential barrier, with no internal structure.
- The particles are reflected from the mirror elastically.
- Ultracold neutrons (UCNs) are unique particles for measuring such quantum states.



Quantum bouncing

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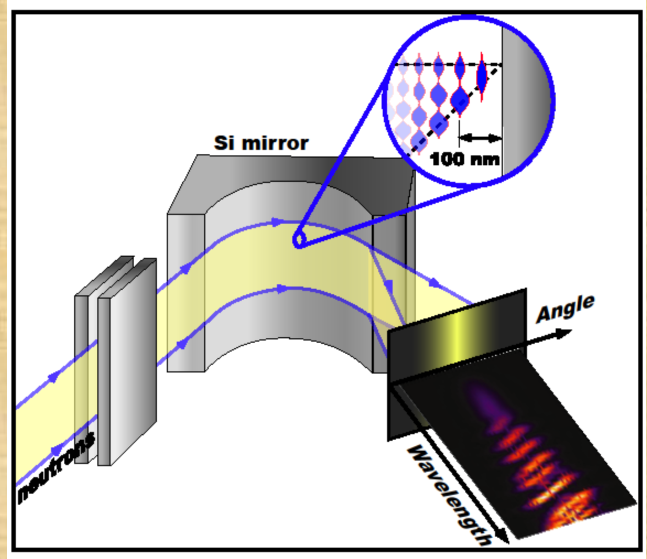
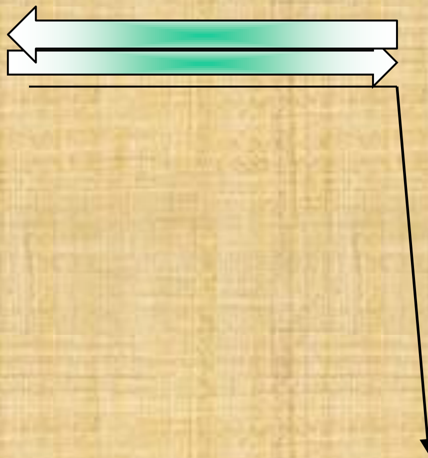


My fault. UCNs are not unique particles in this sense. Nearly ALL particles with sufficiently large wavelength and small energy are reflected elastically from surfaces.

Quantum reflection

Problem: attractive van der Waals/Casimir-Polder potential.

Solution: Quantum reflection is the limit of lowest energies (gravitational quantum states!!!) provides nearly total reflection of a particle from a mirror.

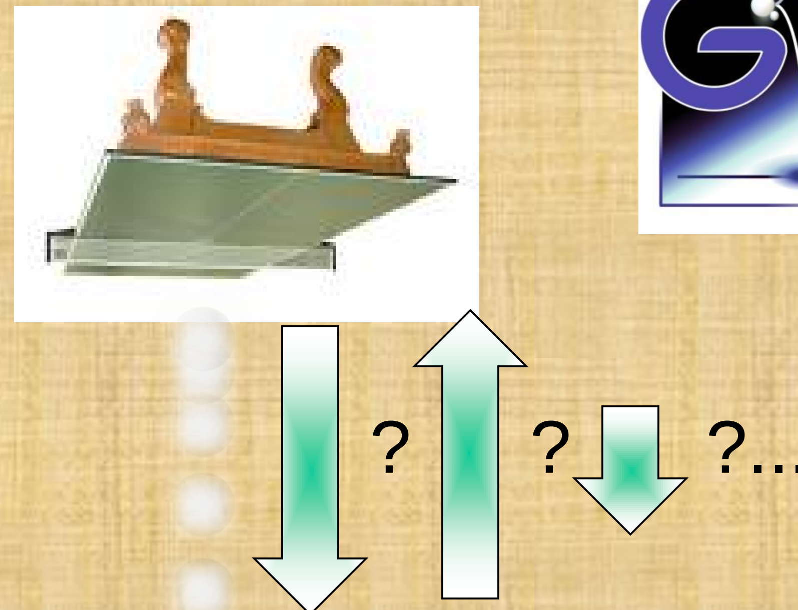


The quantum reflection is demonstrated, for instance, by Maarten de Kieviet.

The importance of the low-energy limit was noticed by Alexei Voronin.

Matter / Antimatter

Granit
Gravitational Neutron Induced Transitions



GBAR

Gravitational properties of antimatter have never been measured directly

An “artistic” illustration for quantum motion of a particle built of normal matter (left) and antimatter (right) in a gravitational field

Various realizations

Gravitational quantum states of anti-hydrogen atoms as a tool for most precision direct measurements of gravitational properties of antimatter (GBAR collaboration). Advantages: precision spectroscopic methods, long observation time, localization in space and in energy -> smaller systematic effects and lower costs

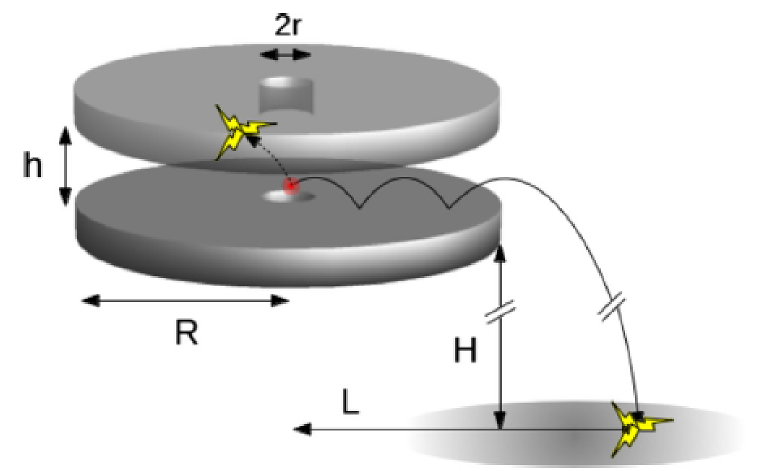
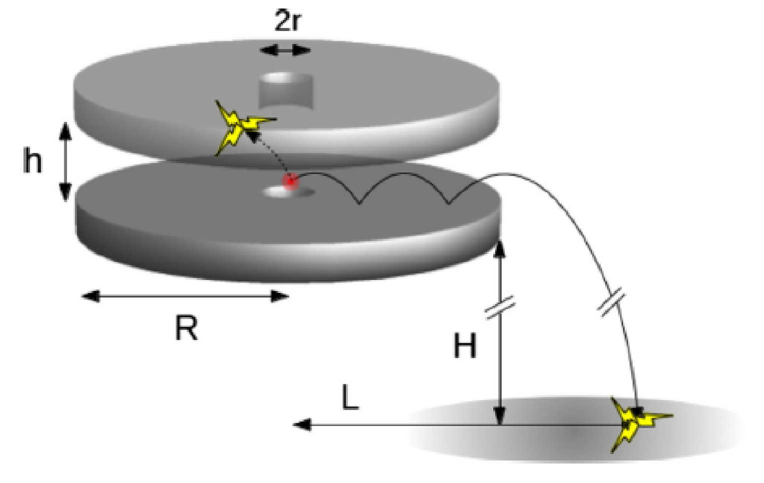


Fig. 1 A scheme of principle of the proposed shaping device: an $\overline{\mathrm{H}}$ atom is released from the Paul trap (*central spot*) and it bounces a few times on the mirror surface of the bottom disk (*arrows*); if it scatters on the rough top surface, it annihilates (*lightnings*); otherwise, it escapes from the aperture between the two disks, and it falls to the detection plate where it annihilates (lightning on the detection plate). R is the radius of the *bottom* and *top disks*, r is the radius of central openings in the disks, h is the distance between the *top surface* of the *bottom disk* and the *bottom surface* of the *top disk*, H is the distance between the top of the detection plate and the *top* of the *bottom disk*, L is the horizontal distance between the initial spot and the detection point

Various realizations

Gravitational quantum states of hydrogen atoms as a tool for prototyping the GBAR experiment with antihydrogen atoms (N. Kolachevsky, A.Yu. Voronin, V.V. N. et al) and also as an independent method for constraining short-range forces. Advantages: huge statistics, existing techniques

The prototyping is based on symmetry of matter and antimatter relative to electromagnetic interactions



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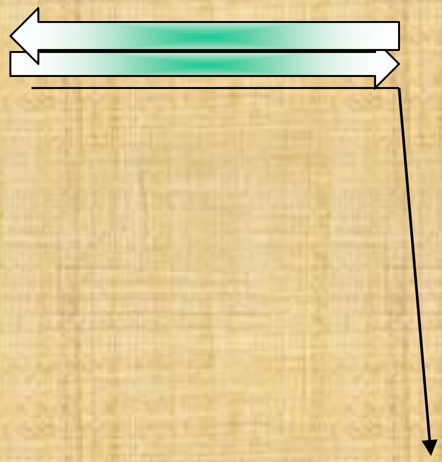
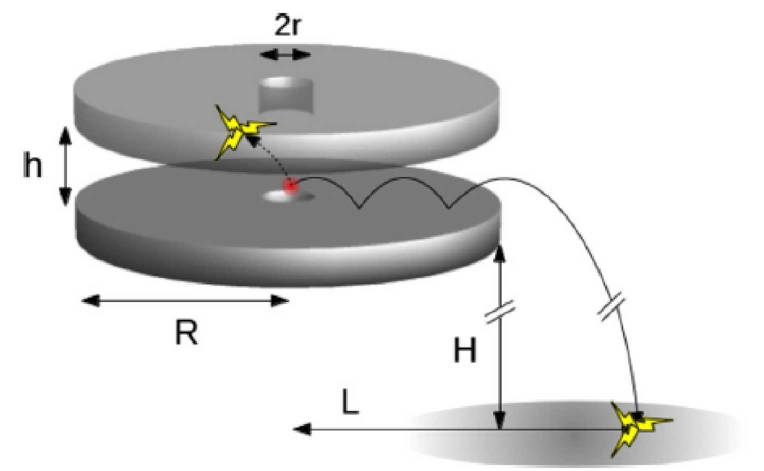
Various realizations

Gravitational quantum states of positronium as a tool to measure gravitational fall of positronium with minimum systematical effects [P. Crivelli et al, Can we observe the gravitational quantum states of positronium? Advances in High Energy Physics (2015) in press]. Advantages: localization in space allows reduction of systematic effects





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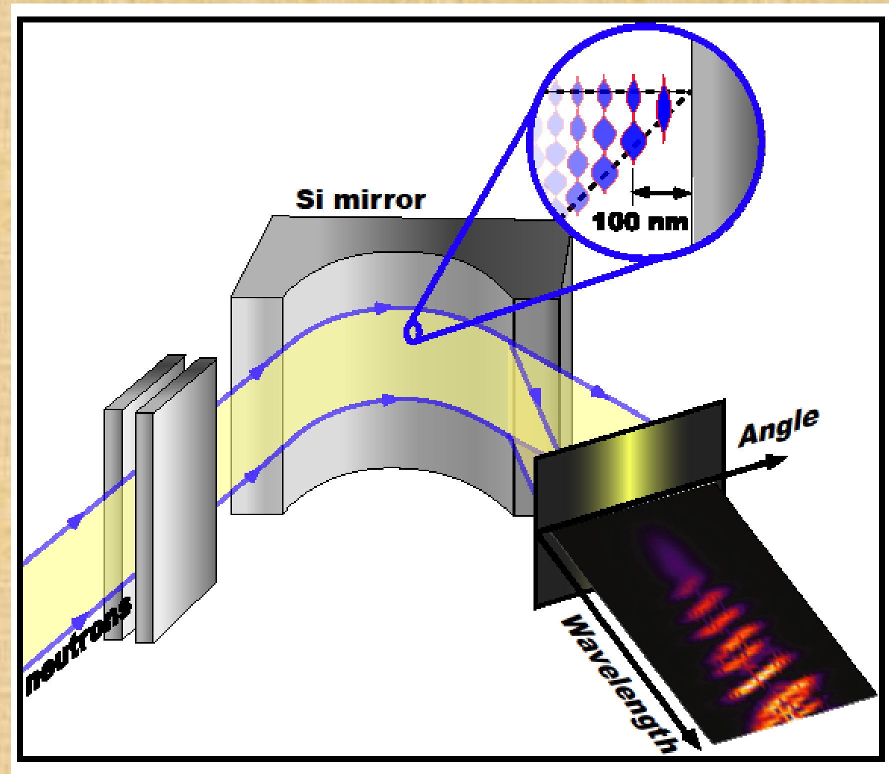
Various realizations

Whispering-gallery quantum states of cold neutrons as a sensitive and universal method to explore surfaces (including the standard surface potentials and fundamental short-range forces). Examples: in-situ monitoring of the growth of thin films, surface diffusion etc.

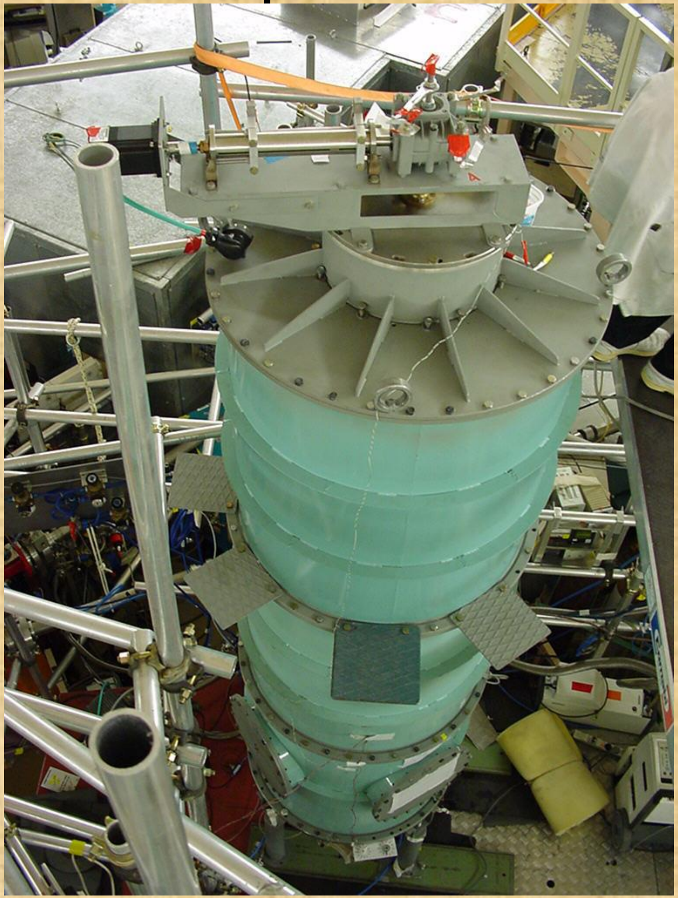
Advantages: long observation time thus huge increase in sensitivity; a possibility to use standard reflectometers for cold neutrons available in all neutron centers in the world.

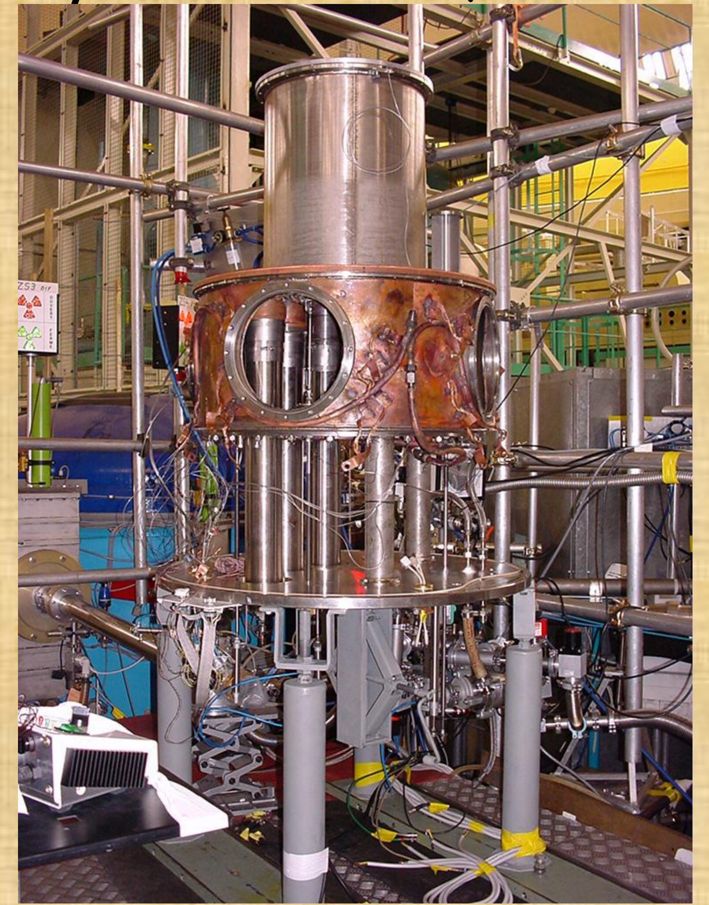


Various realizations

Other options being discussed but not yet developed and formalized:

- Astrophysical realizations of quantum bouncing,
- Nanoparticles and nanodroplets in the vicinity of surfaces,
- Polarized He^3.





Fundamental short-range forces and neutrons

Short-range forces

Phenomenologically:

- Spin-independent,
- Spin-dependent.

Origin:

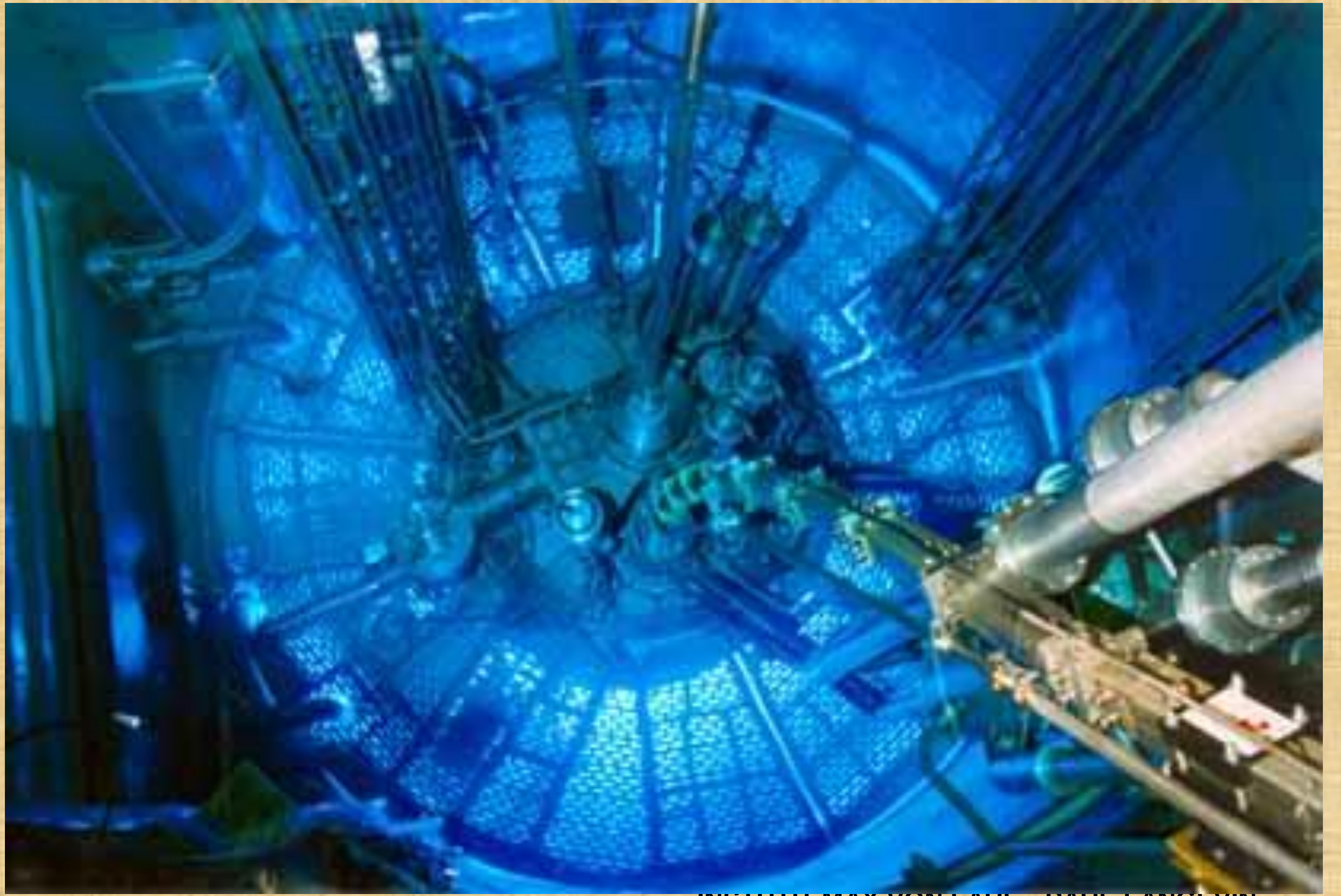
- Extra light bosons,
- Extra spatial dimensions,
- Dark matter (chameleons),
- Axion-like particles etc

Neutrons

- Electric neutrality,
- Availability of high fluxes of neutrons with wavelengths comparable to the spatial scale of extra interactions to probe,
- High probability of elastic interaction with matter.

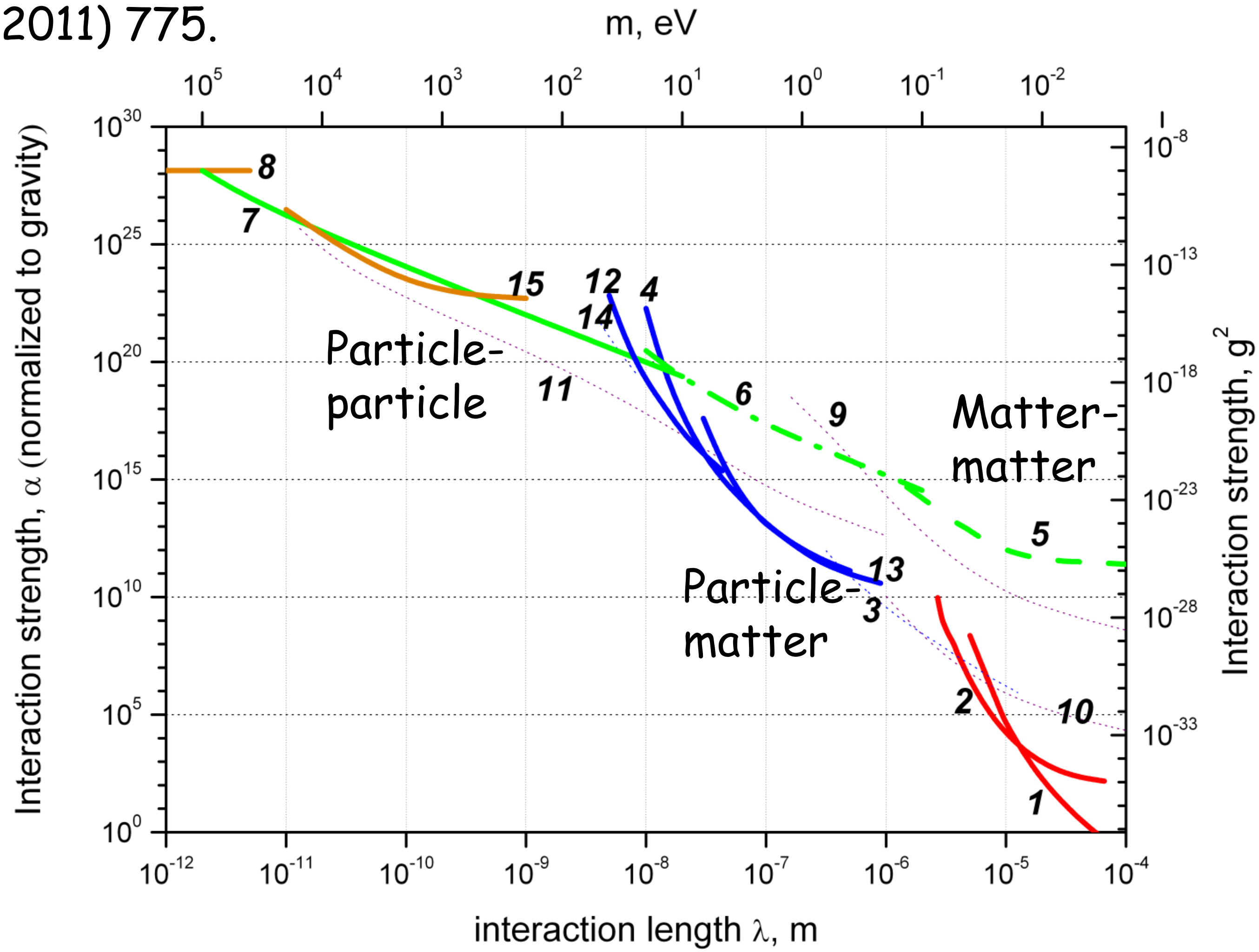
Fundamental short-range forces and neutrons

All measurements with neutrons related to the topic of my talk are performed at the Institut Max von Laue – Paul Langevin (ILL), Grenoble, France. All measurements involve ILL scientists and also all measurements use ILL facilities.



Short-range forces. State of the art

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.



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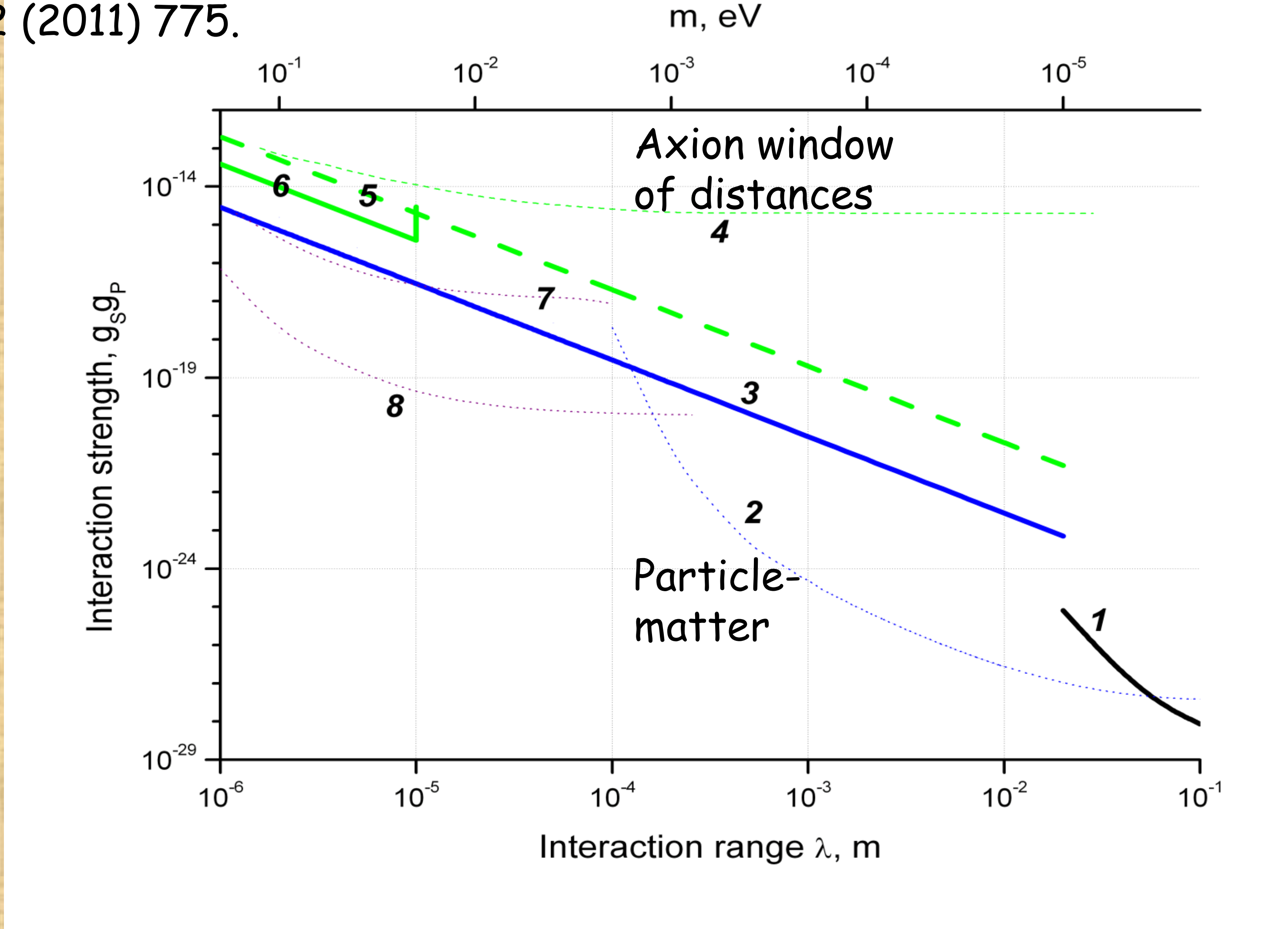

Short-range forces. Recent improvements

Measurements using UCNs in the EDM apparatus at PSI (Villigen, Switzerland) [S. Afach et al, Phys. Let. B (2015) in press].

Red line (H) shows the new constrain derived from this experiment.

Solid line (I) indicates an achievable constraint that could be obtained with a modified installation.

Slightly better (then H) constraint was recently measured with polarized He^3 (A.K. Petukhov, G. Pignol et al)

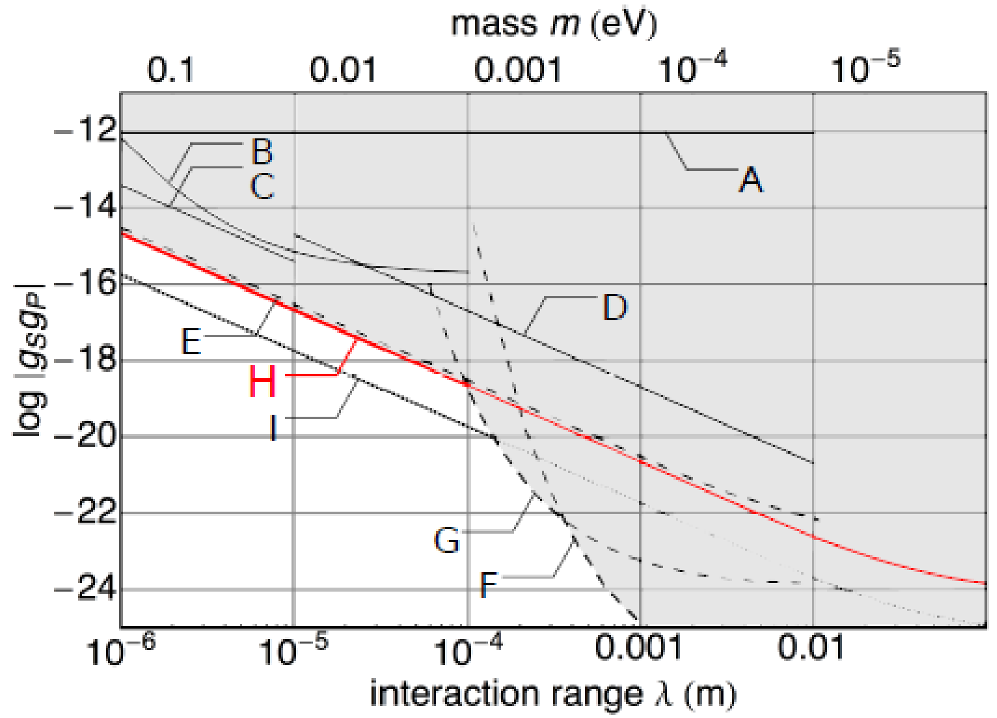

Figure 2: Overview of current limits on the product of scalar and pseudoscalar coupling constants $g_S g_P$ as function of the interaction range λ of a short range spin-dependent force at 95 % confidence level. On the top, the corresponding mass range of the mediating particle, i.e. axion or axion-like particle, is shown. The shaded region is excluded by different experiments. Solid line limits were obtained using cold or ultracold neutrons. Dashed line limits were obtained using ^{3}He, ^{129}Xe, or ^{131}Xe precession experiments. A [24]; B [25], assuming an attractive interaction; C [26]; D [6]; E [23]; F [20]; G [21]; and H (red) this work. The line I (dotted) depicts the achievable limit by a simple modification of our apparatus (see text).

Short-range forces. Recent improvements

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Neutron gravitational states.

- Several independent groups (Tokyo, QBounce, GRANIT);
- Many new good results in the flow-through mode !! (Qbounce, Tokyo);
- Building a dedicated facility at ILL for experiments with gravitational quantum states of neutrons in the long-storage mode (GRANIT);
- Neutron results for short-range forces are not yet competitive to results of short-range gravity and Casimir experiments but they are rapidly improving (remember that one should improve by 5-6 orders of magnitude; however, no major systematic effects associated with neutrons have been identifies);
- Significant worldwide effort to increase available densities of UCNs.

Transitions between gravitational quantum states

Flow-through mode; limited observation time

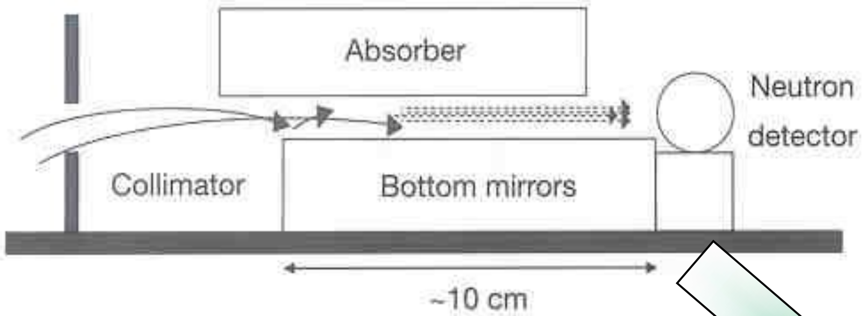


Figure 2 Layout of the experiment. The limitation of the vertical velocity co… depends on the relative position of the absorber and mirror. To limit the horizonta… component we use an additional entry collimator. The relative height and size of the e… collimator can be adjusted.

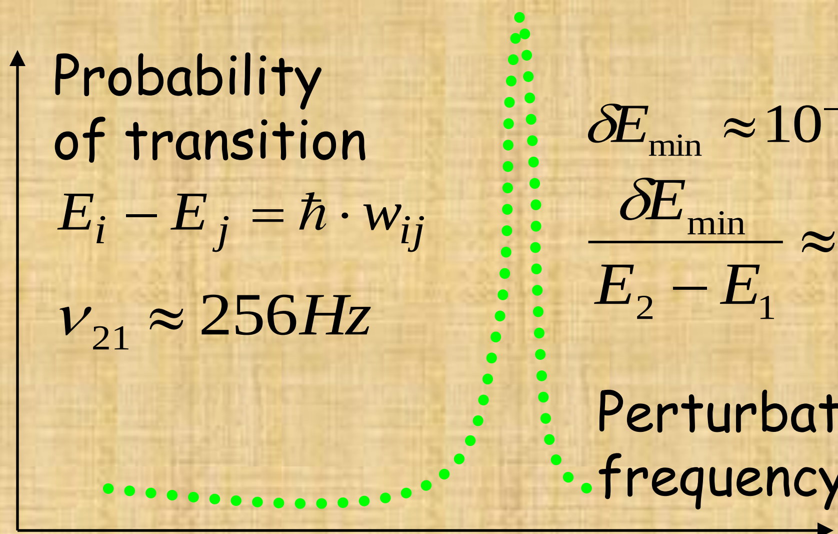
Transitions could be excited, for instance:

- By periodically varying magnetic field gradient;

-By periodically varying local gravitational field;

-By oscillating mechanically the mirror.

V.V. Nesvizhevsky, and K.V Protasov, "Quantum states of neutrons in the Earth's gravitational field: state of the art, applications, perspectives" in Edited book on Trends in Quantum Gravity Research (D.C. Moore, New York, USA, NOVA; pp. 65-107) Ξ "irresistible wish…"

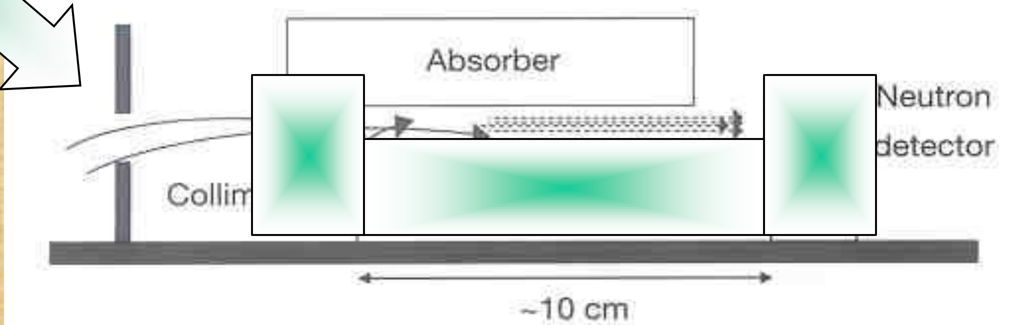


$$E_i - E_j = \hbar \cdot w_{ij}$$

$$\nu_{21} \approx 256 Hz$$

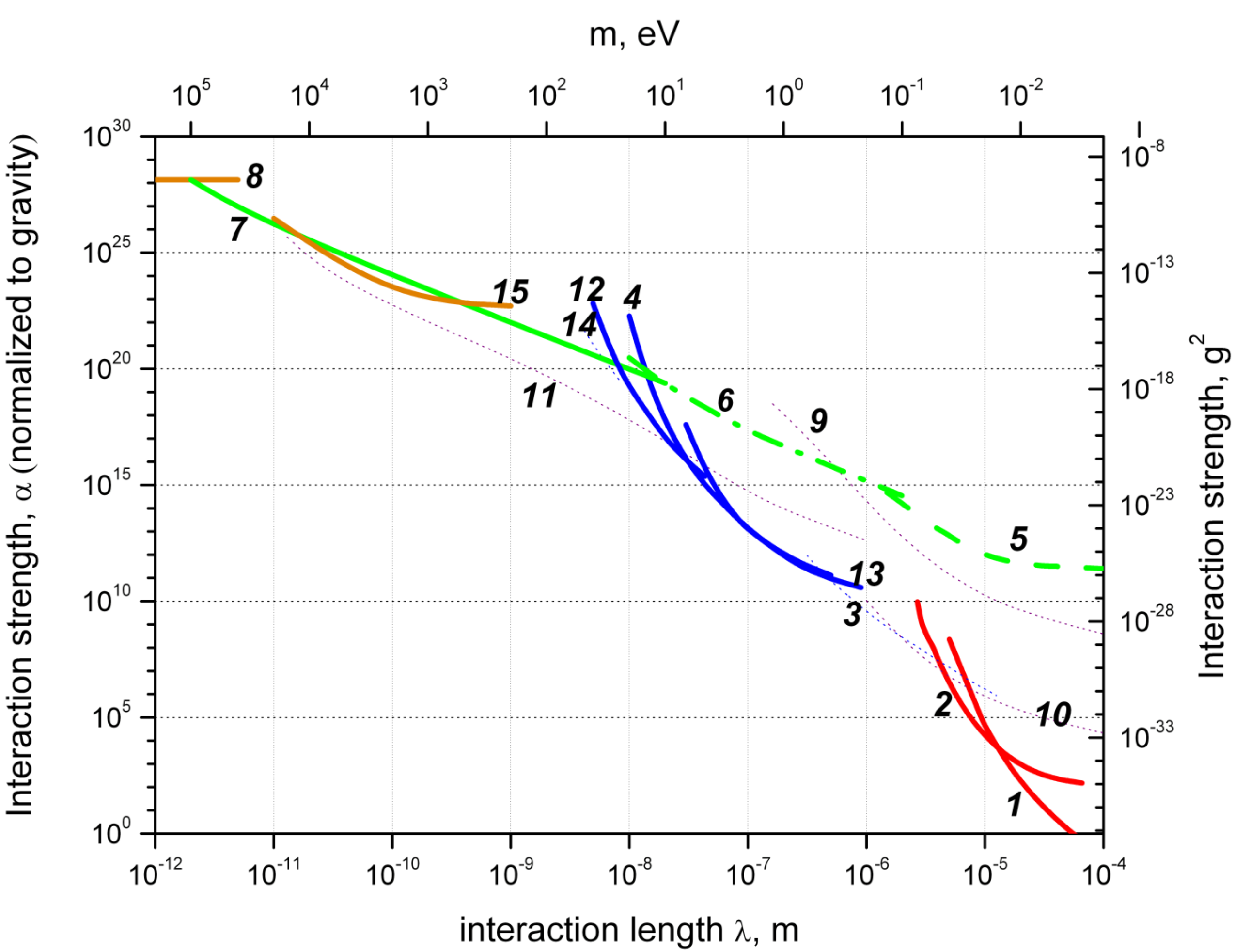
$$\delta E_{\min} \approx 10^{-18} eV$$

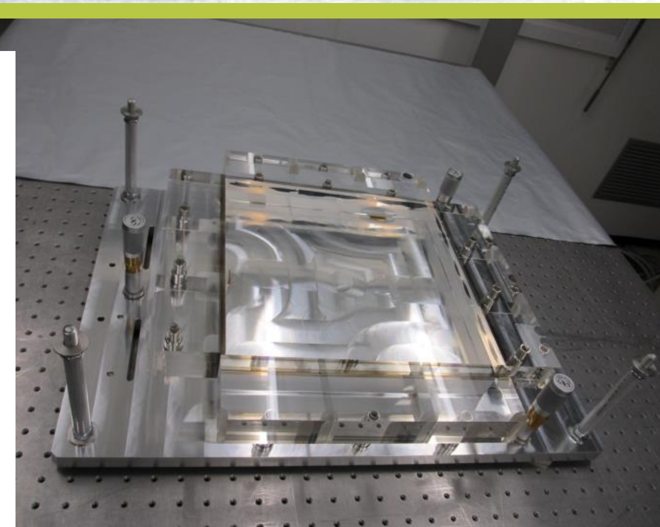
$$\frac{\delta E_{\min}}{E_2 - E_1} \approx 10^{-6}$$

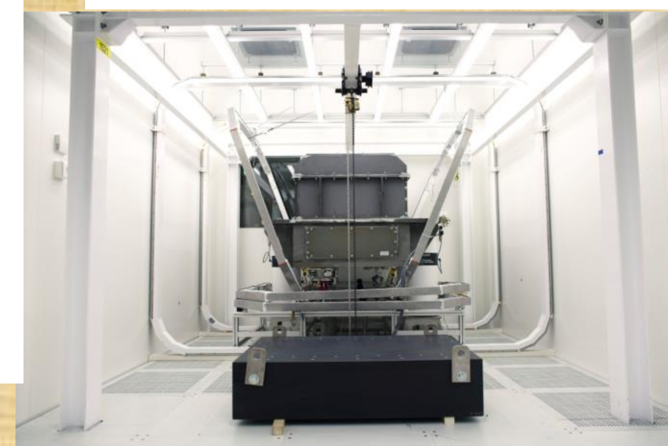


Storage mode: ultimate observation time and energy resolution

Gravitational quantum states in a storage mode

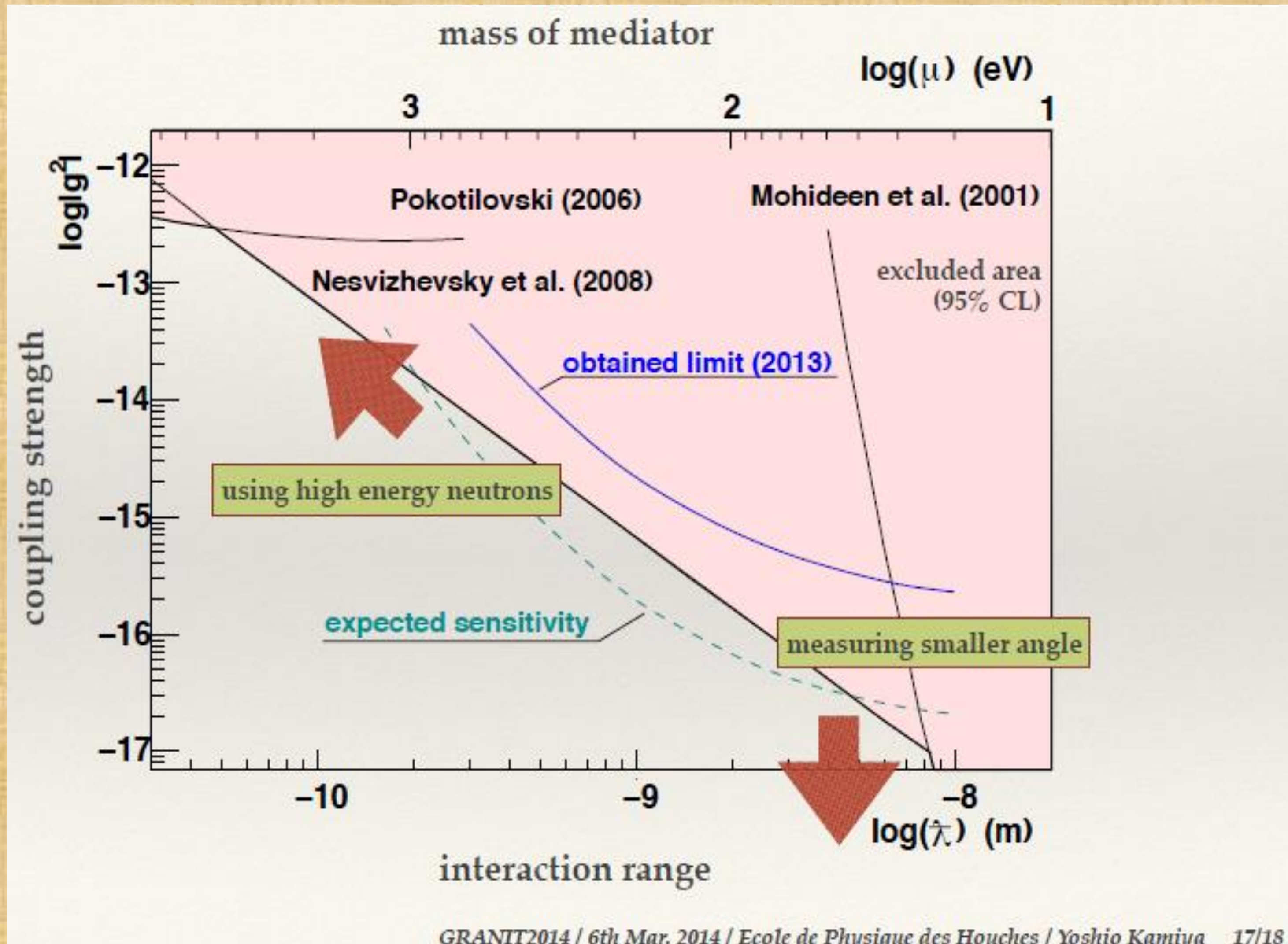






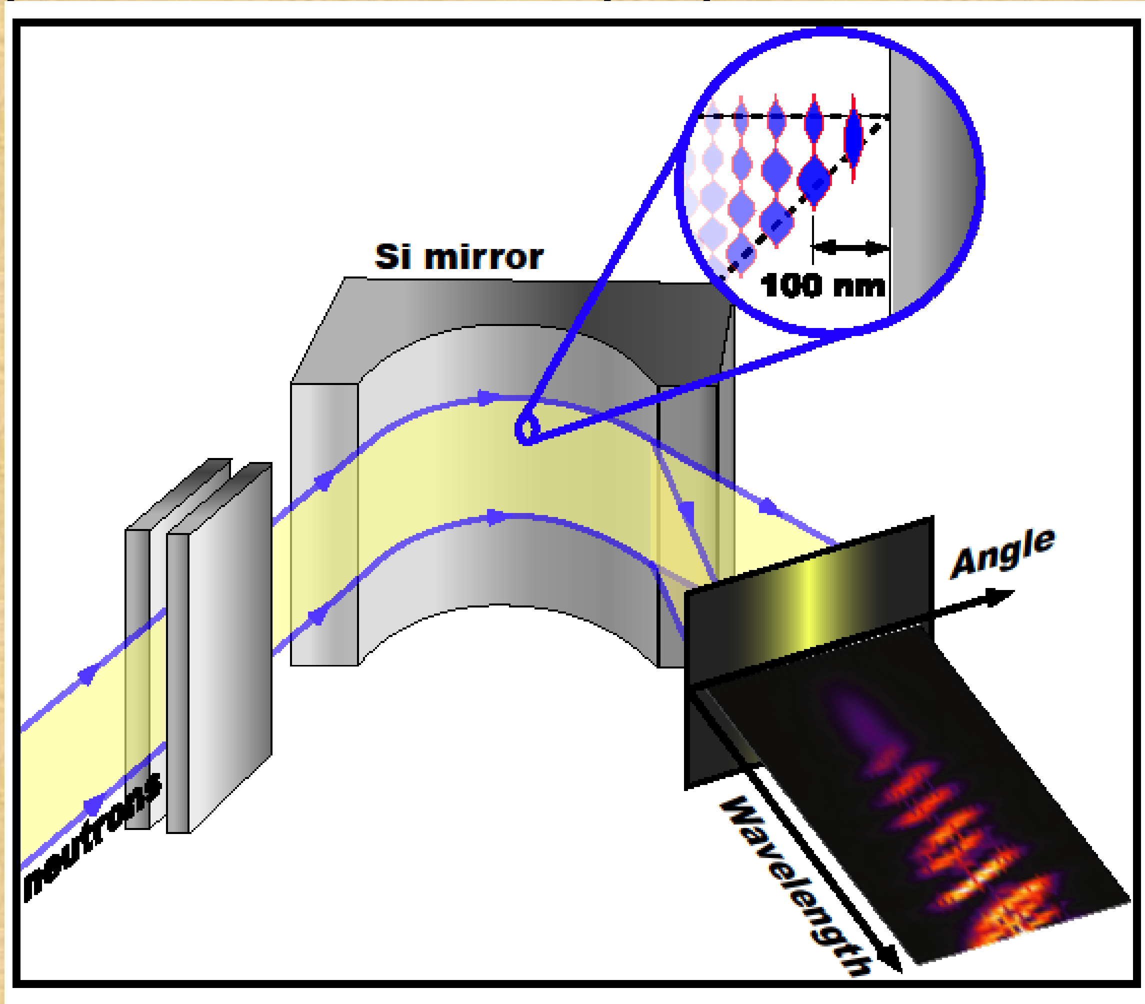
Short-range forces. Recent improvements

Neutron scattering on noble gases (Xe); the method approaching record sensitivity and having good chances of further success (the talk of Yoshio Kamiya at GRANIT-2014 Workshop).



Short-range forces. Recent improvements

Better precision and reliability for experiments with neutron whispering gallery; record sensitivity; good chances for major improvements



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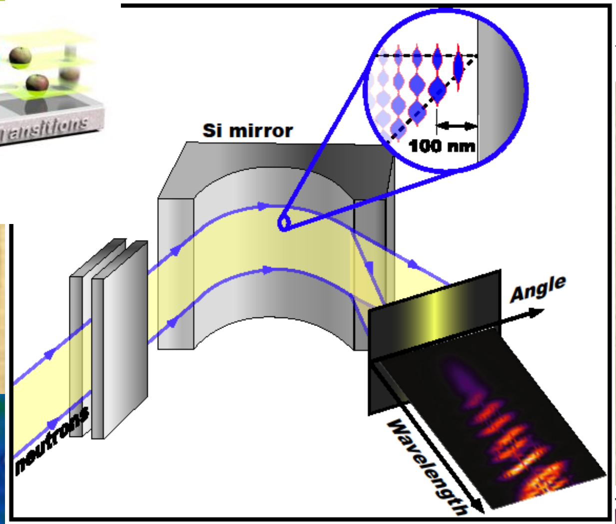
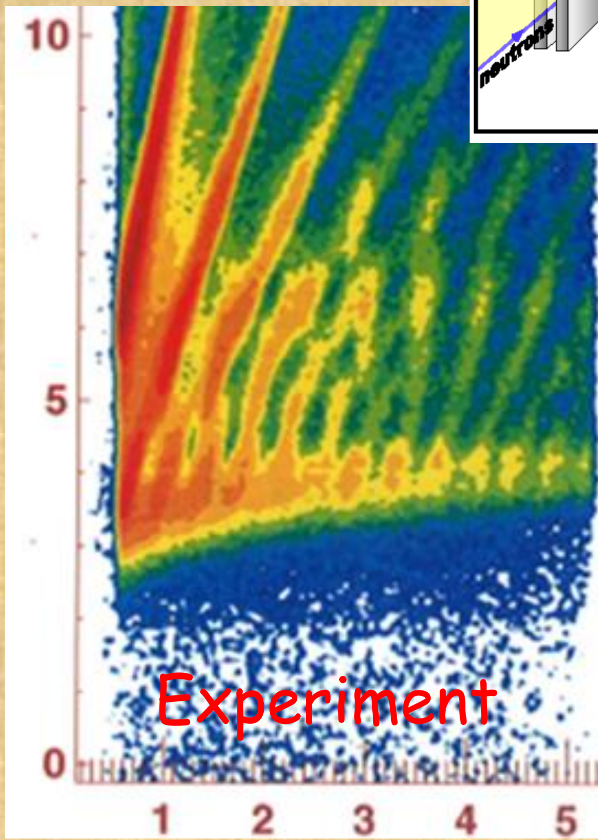
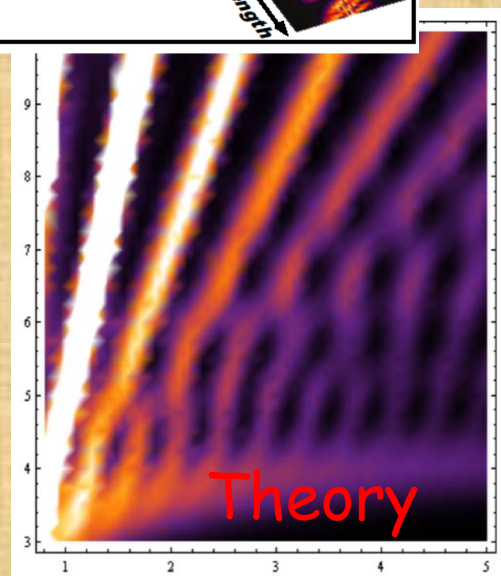
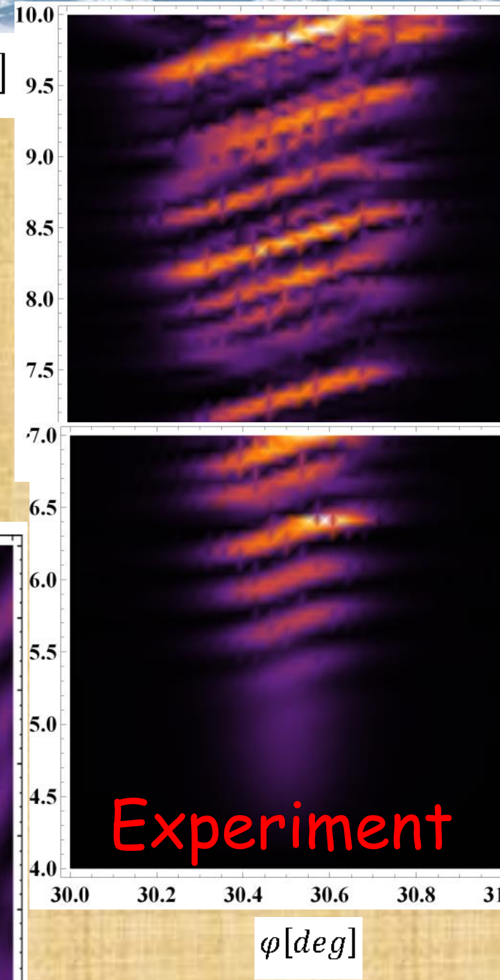
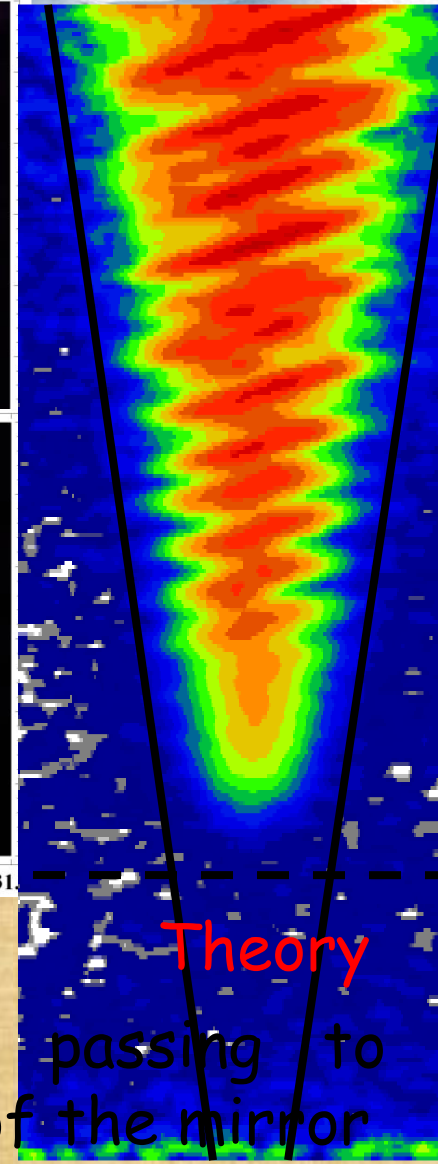






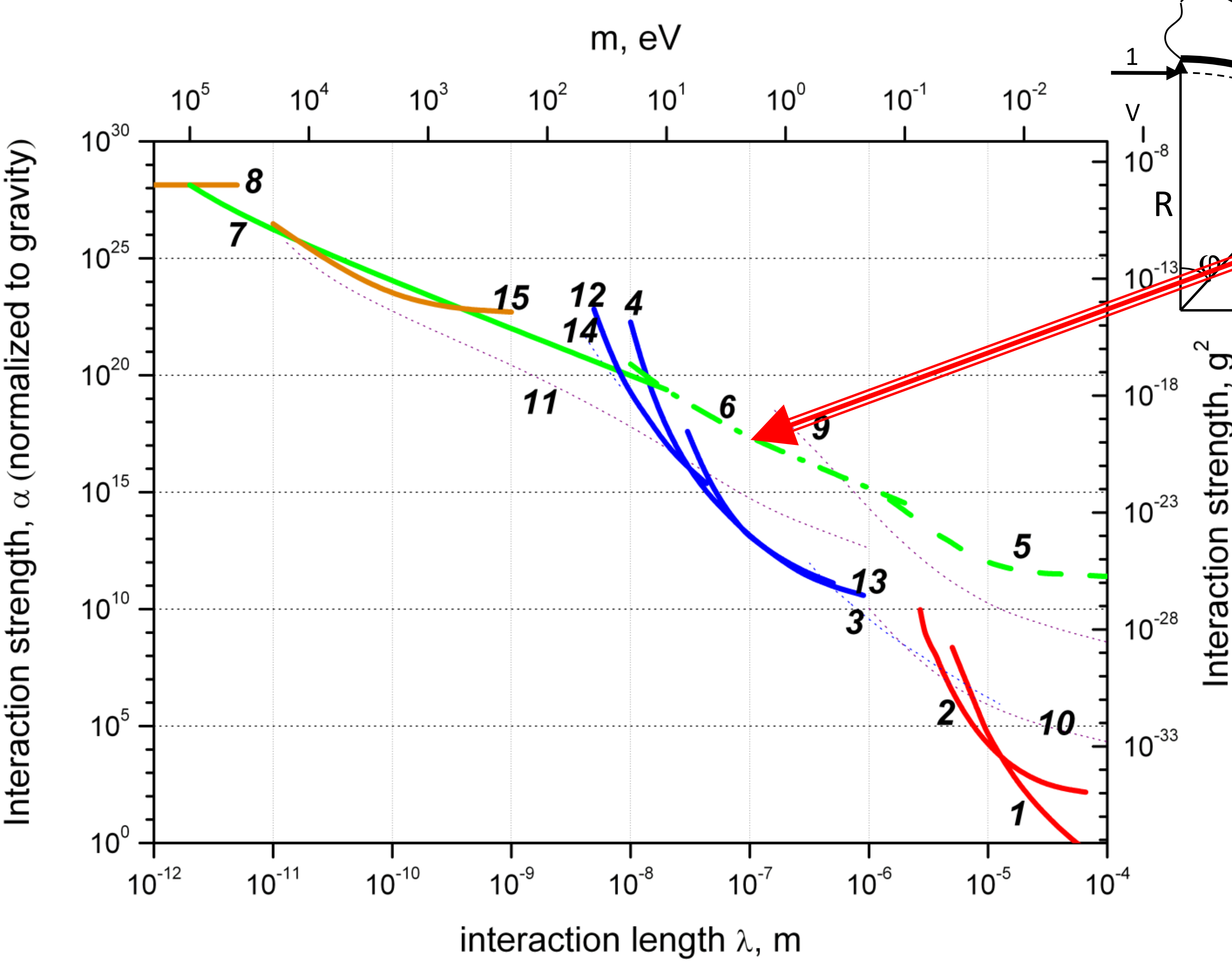
Neutrons tunneling through the mirror

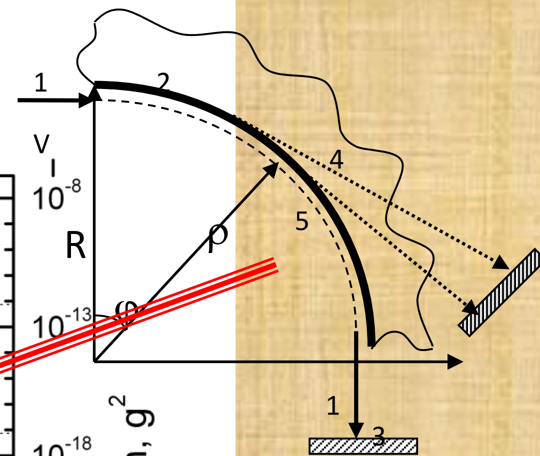




Neutrons passing to the exit of the mirror

Short-range forces. Recent improvements





Better precision and reliability for experiments with neutron whispering gallery; record sensitivity; good chances for major improvements

Conclusions

- The method of gravitational quantum states is rapidly gaining attention and support – good sign! It means that the method is powerful, and "easy" for implementation.

- Neutron, and neutron-related, constraints for fundamental short-range forces are steadily improving due to the efforts of different groups using different methods.

- All these activities are efficient in terms of results/resources.

- These tendencies will stay for the observable future.