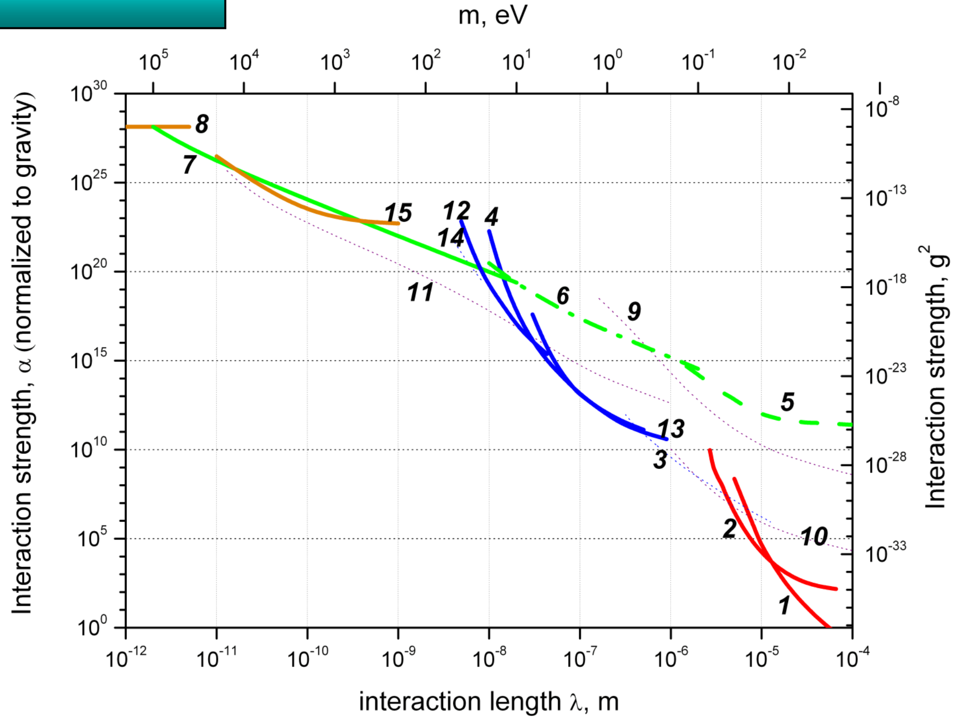
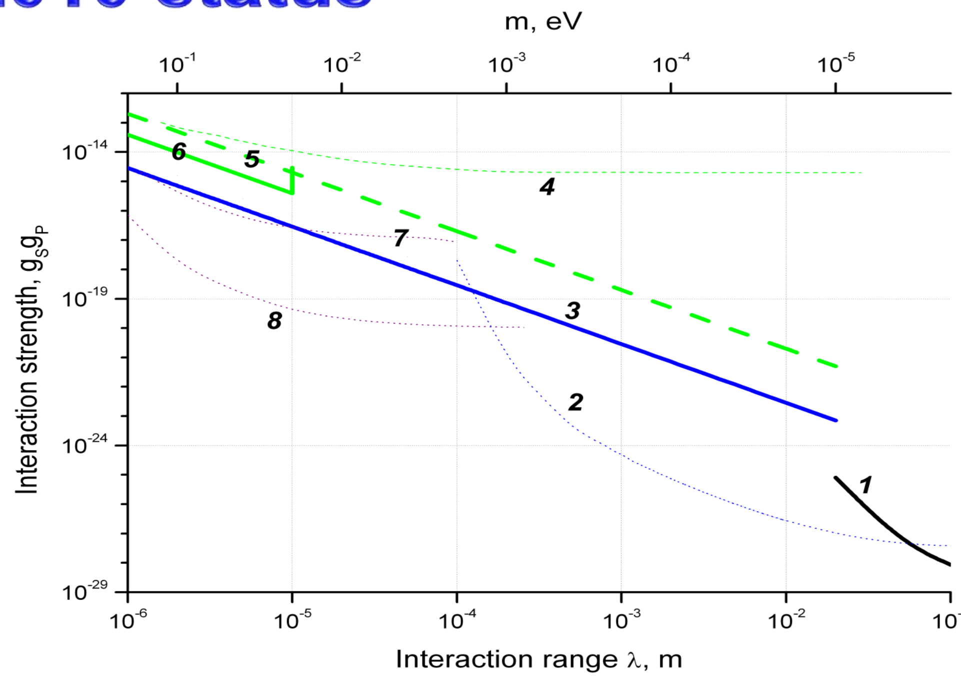
Let's start from the conclusion

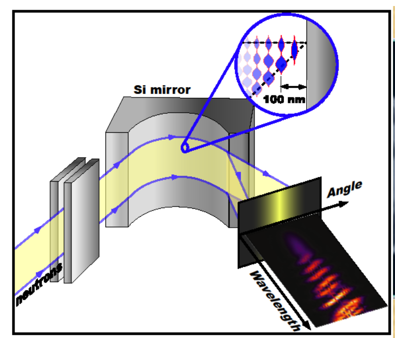
1. Constraints for spin-independent, spin-dependent, chemeleon-like extra short-range forces are being improved over a broad range of distances.
2. The methods used are quantum bouncing and scattering of slow neutrons, atoms and antiatoms.
3. GRANIT is among key facilities in the field, but also many others are being developed over the world.
4. GRANIT is the workshop, which unifies scientific community in the field.
5. You could find more about some presented topics in the new textbook « SURPRISING QUANTUM BOUNCING » to be published soon by Imperial College Press, London (V.V. Nesvizhevsky and A.Yu. Voronin)

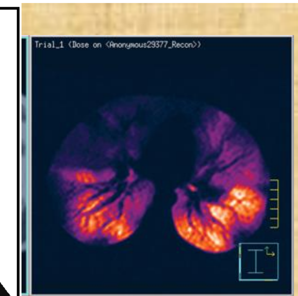
GRANIT: short-range forces with UCNs

Let's start from the conclusion
GRANIT-2010 status



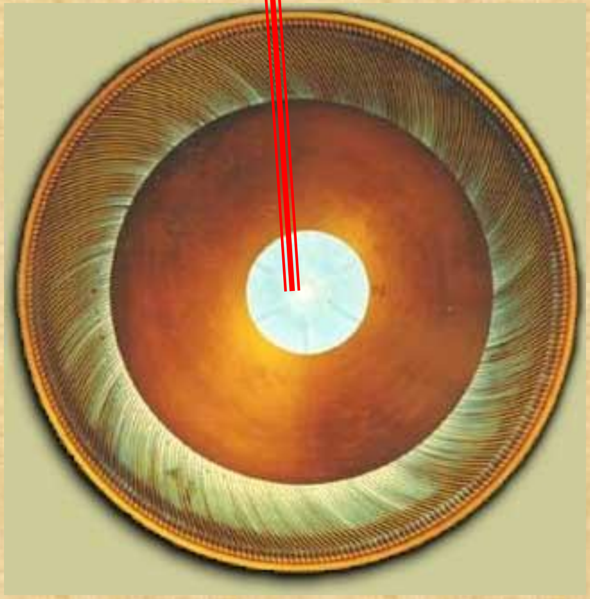




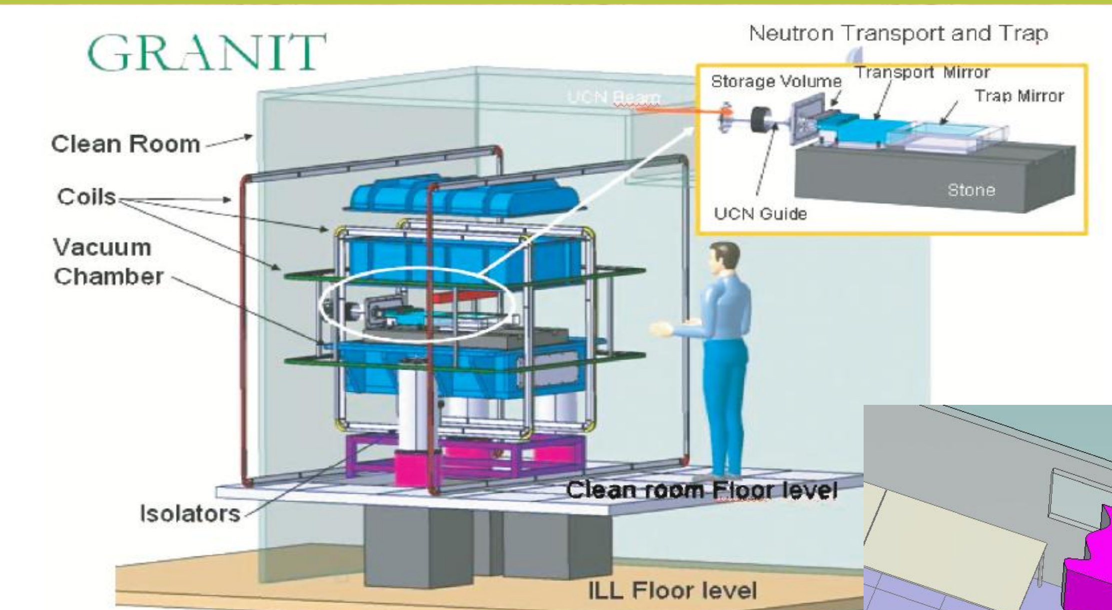


GRANIT facility

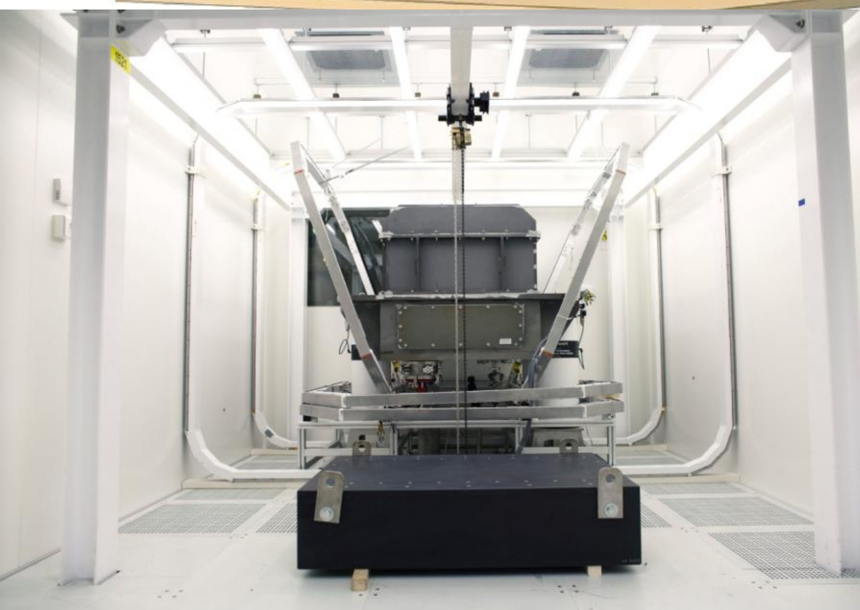
Located at the Institut Laue-Langevin in Grenoble, France (largest nuclear research reactor in the world)

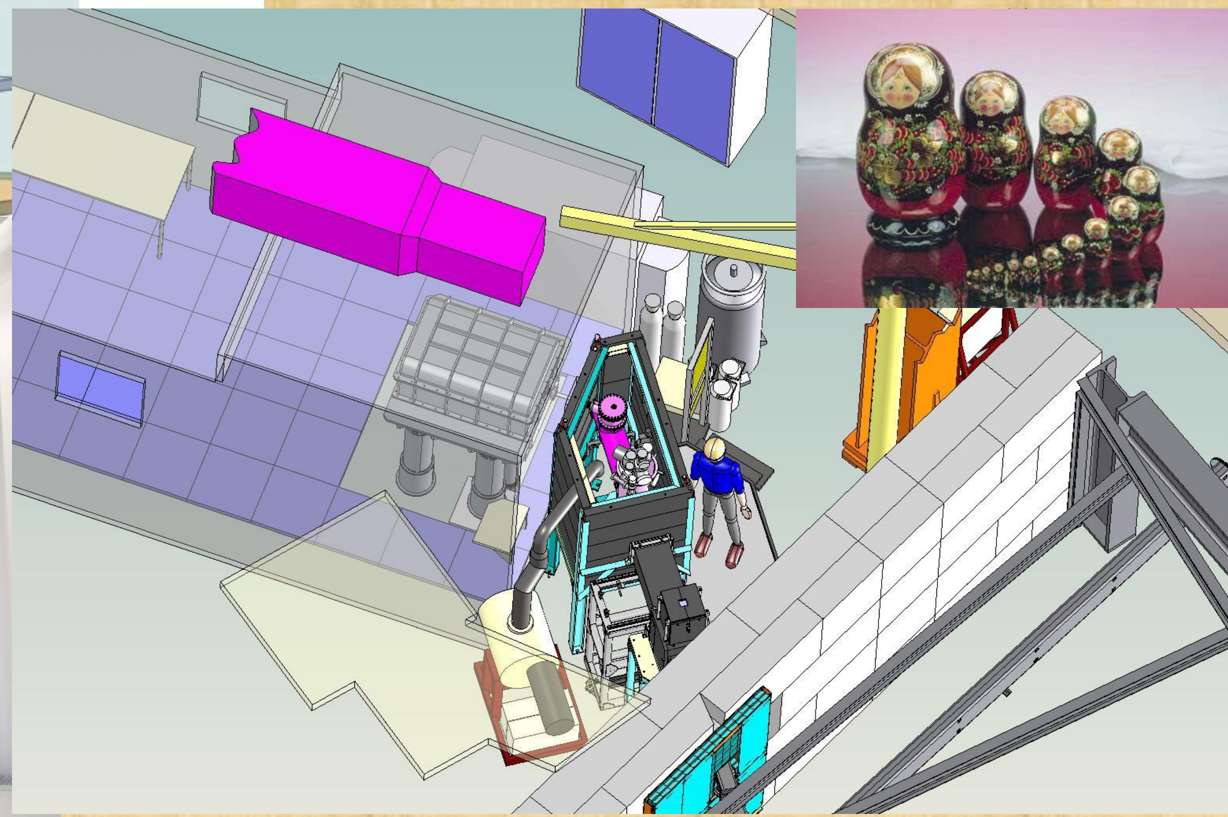


GRANIT facility



ILL reactor; precision optics; dedicated UCN source; clean room; unique detectors



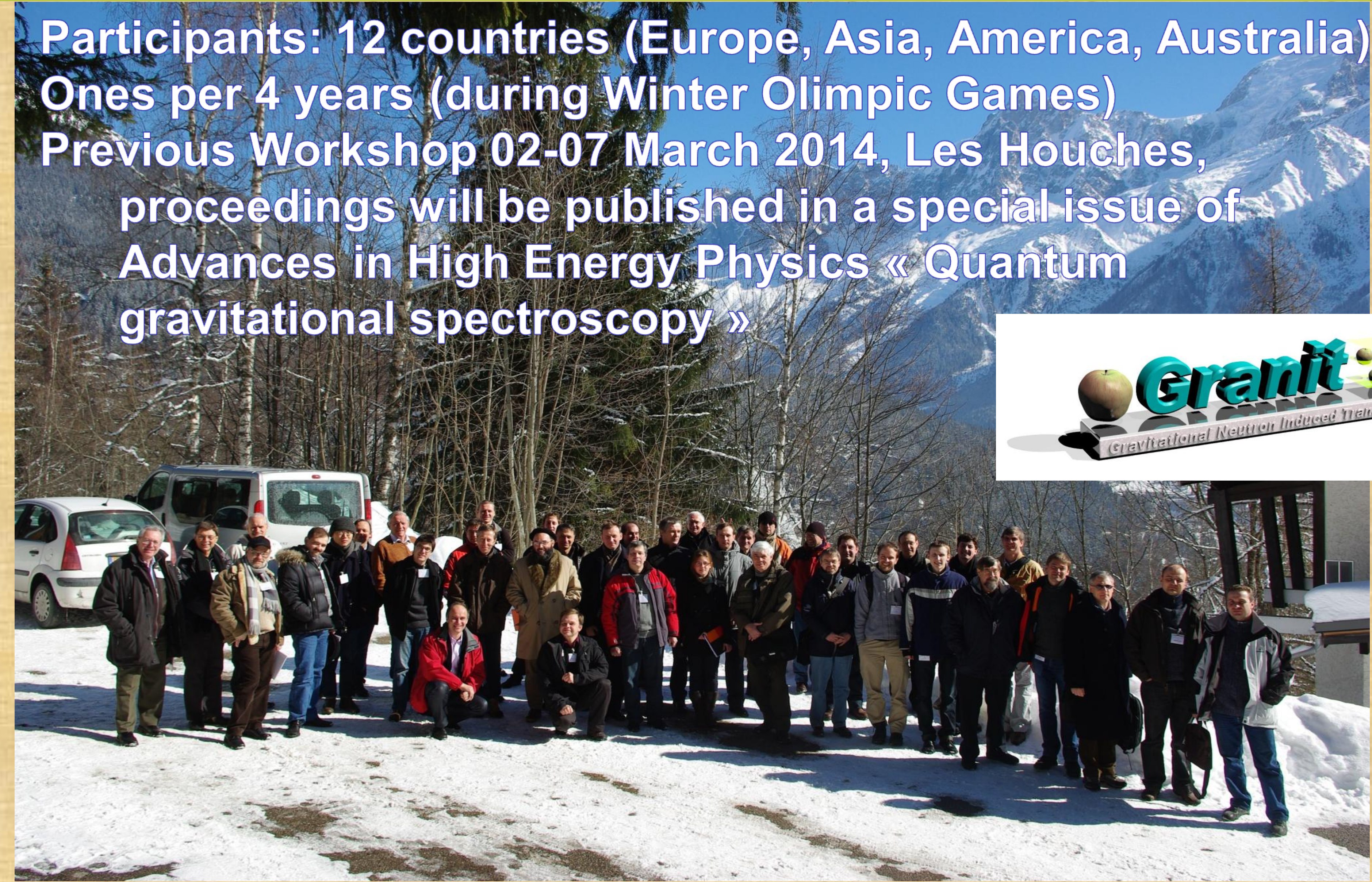


GRANIT-2014 workshop

Participants: 12 countries (Europe, Asia, America, Australia)

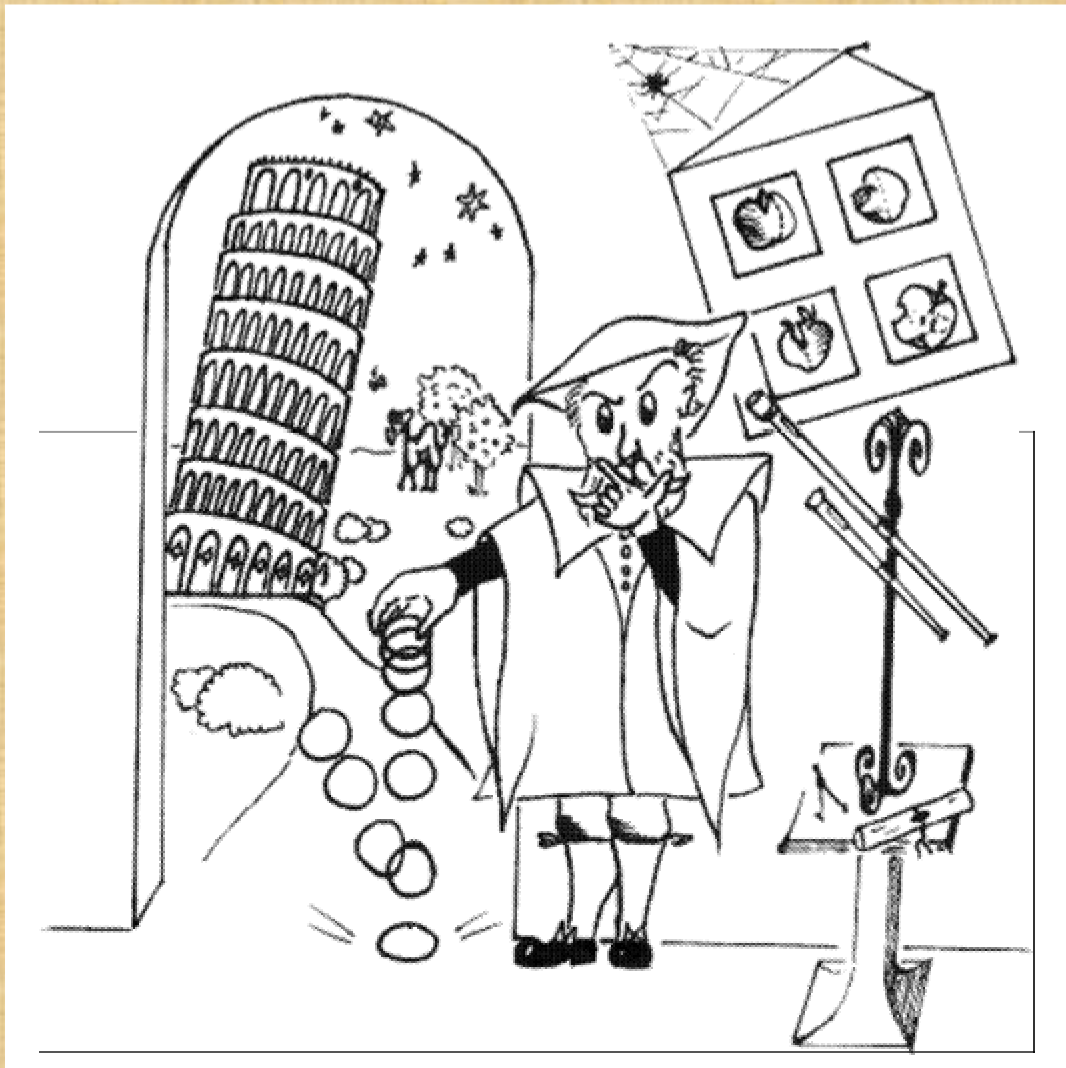
Ones per 4 years (during Winter Olimpic Games)

Previous Workshop 02-07 March 2014, Les Houches, proceedings will be published in a special issue of Advances in High Energy Physics « Quantum gravitational spectroscopy »

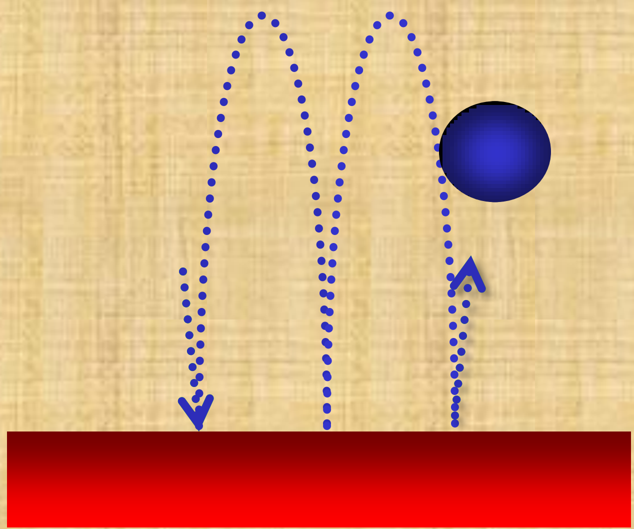


Granit Gravitational Neutron Induced Transitions

Classical and Quantum bouncing



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** $\left(\Delta E \approx \frac{\hbar}{\Delta\tau}\right)$
3) **Small mass** $\left(\Delta \mathrm{v} \cdot \Delta x \approx \frac{\hbar}{m}\right)$
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 ~10 nK)

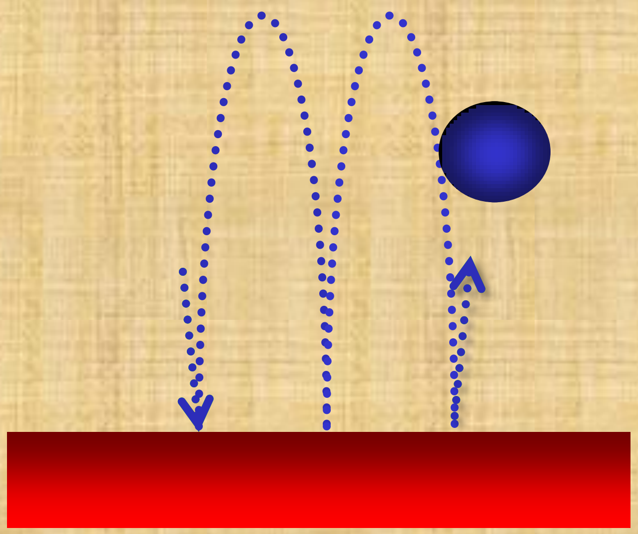
A particle avobe a mirror in the gravity field: An ultracold neutron (V.I. Luschikov, A.I. Frank « Quantum effects occuring when ultracold neutrons are stored on a plane », JETP Lett. 28 (1978) 759**) and … an anti-hydrogen atom (A.Yu. Voronin, P. Froelich, V.V. N.** « Gravitational quantum states of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

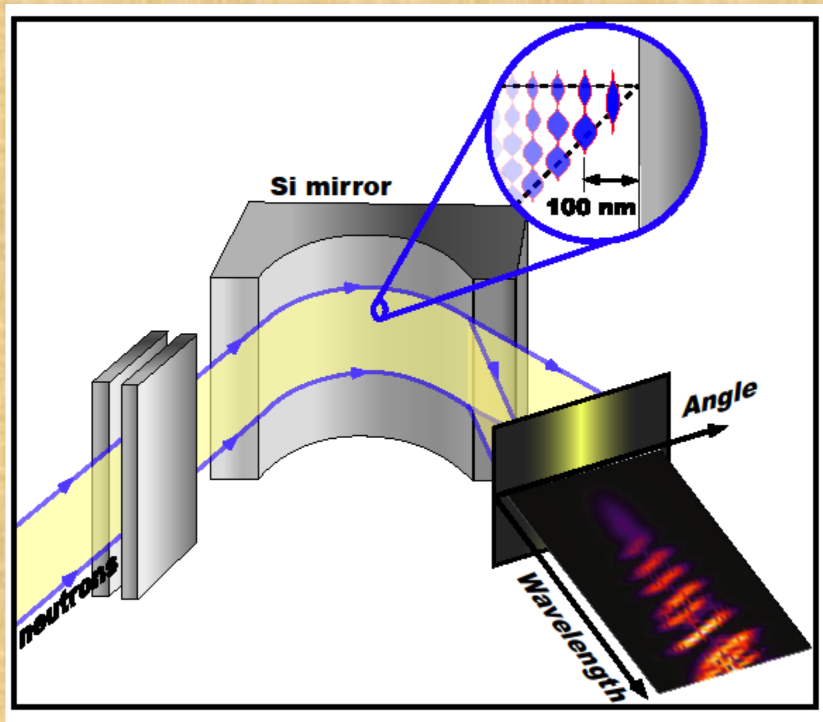
Energy of quantum states, in the Bohr-Zommerfeld approximation, equals :

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

Choosing a quantum system

Observation of gravitational quantum states of neutrons (V.V. N. et al « Quantum states of neutrons in the Earth's gravitational field », Nature 415 (2002) 297





Observation of centrifugal (whispering-gallery) quantum states of neutrons (V.V. N. et al « Neutron whispering gallery », Nature Physics 6 (2010) 114

Gravity / Acceleration

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

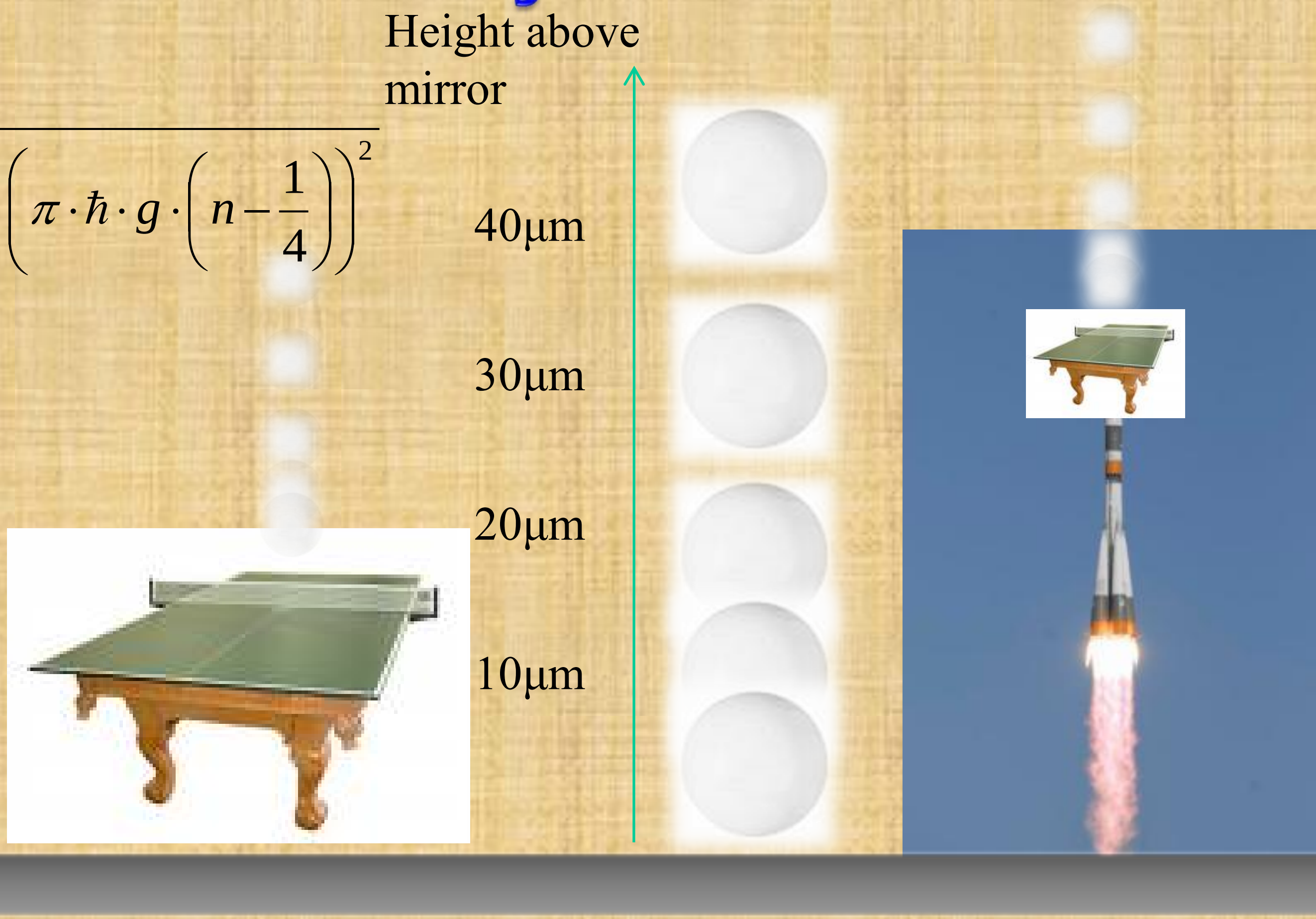
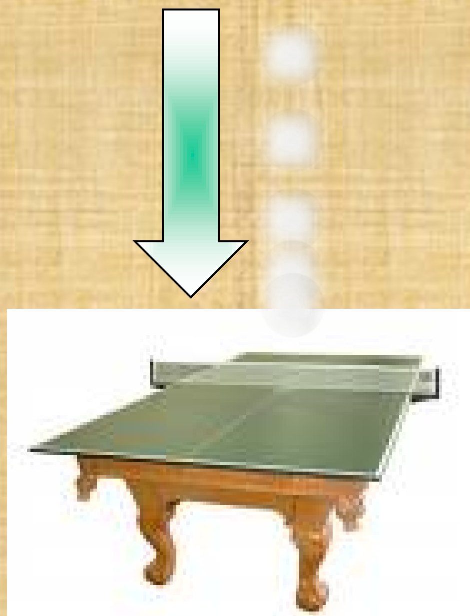


Illustration for quantum motion of an object above a mirror in the gravitational field and that in the accelerating frame. Positions of the ball correspond to the most probable heights of a neutron in the 5th quantum state.

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

Matter / Anti-matter



Gravitational properties of antimatter have never been measured directly!

but aimed at, for instance, in GBAR project at CERN

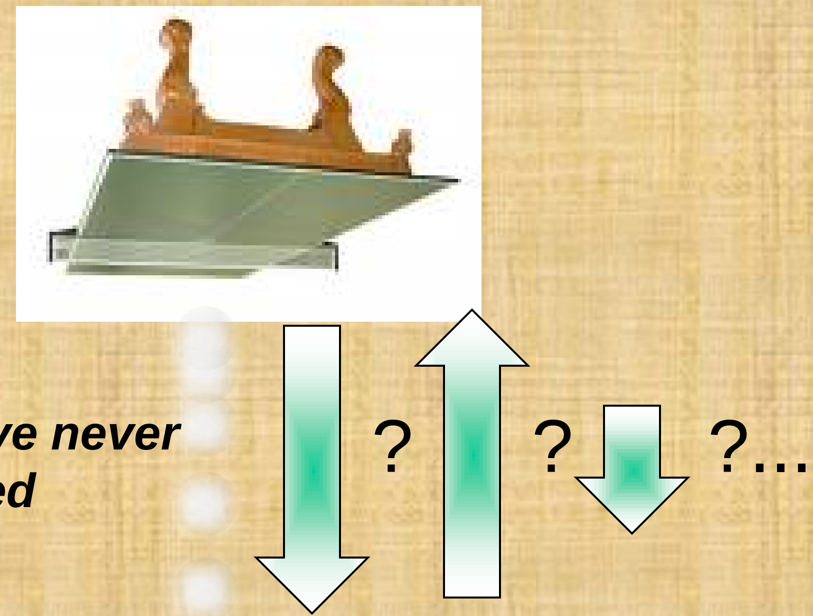


Illustration for quantum motion of a matter object and an anti-matter object above a mirror in a gravitational field.

Long storage of UCNs in gravitational quantum states

Remember: flow-through mode; modest energy resolution

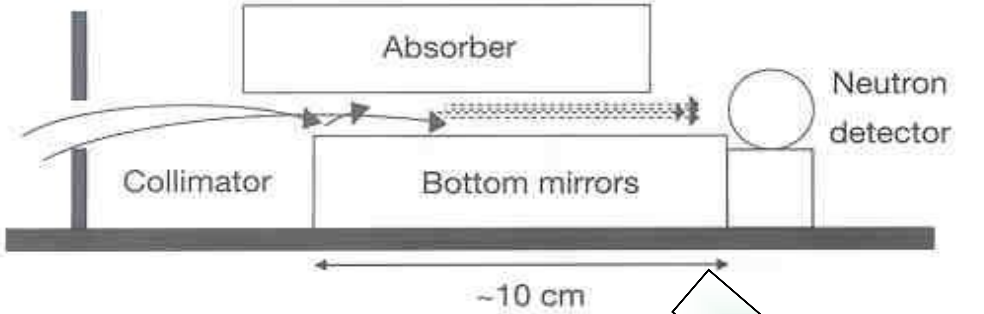


Figure 2 Layout of the experiment. The limitation of the vertica... component depends on the relative position of the absorber and mirror. To limit th... ntal velocity component we use an additional entry collimator. The relative height and ... the entry collimator can be adjusted.

Transitions could be excited, for instance:

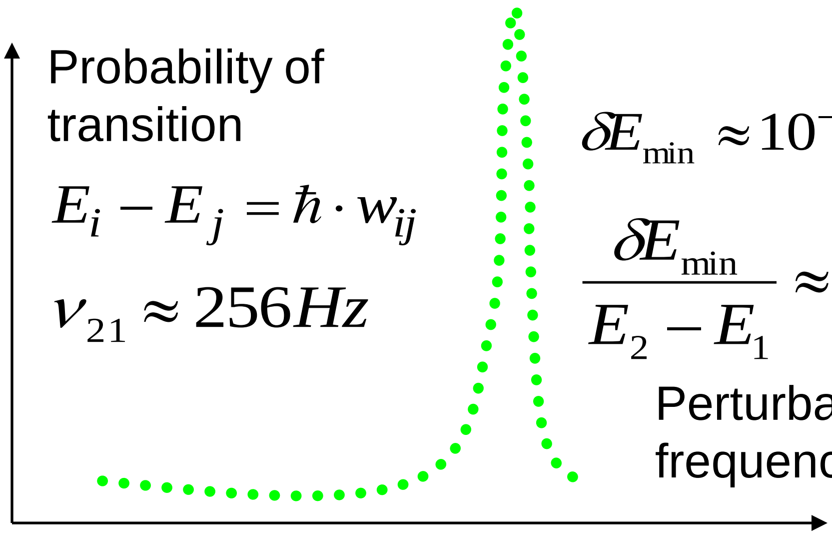
- By periodically varying magnetic field gradient;

-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



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

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

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

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

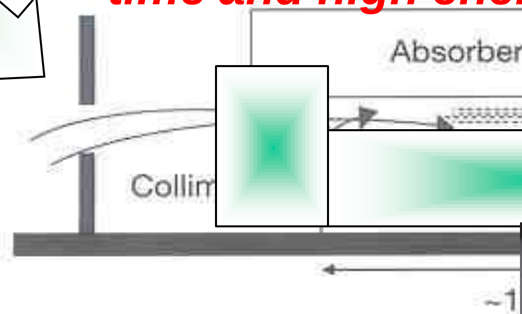
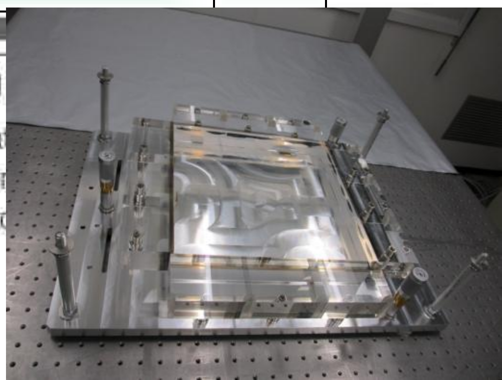


Figure 2 Layout of the experiment. The limita... depends on the relative position of the absorber... component we use an additional entry collimat... collimator can be adjusted.

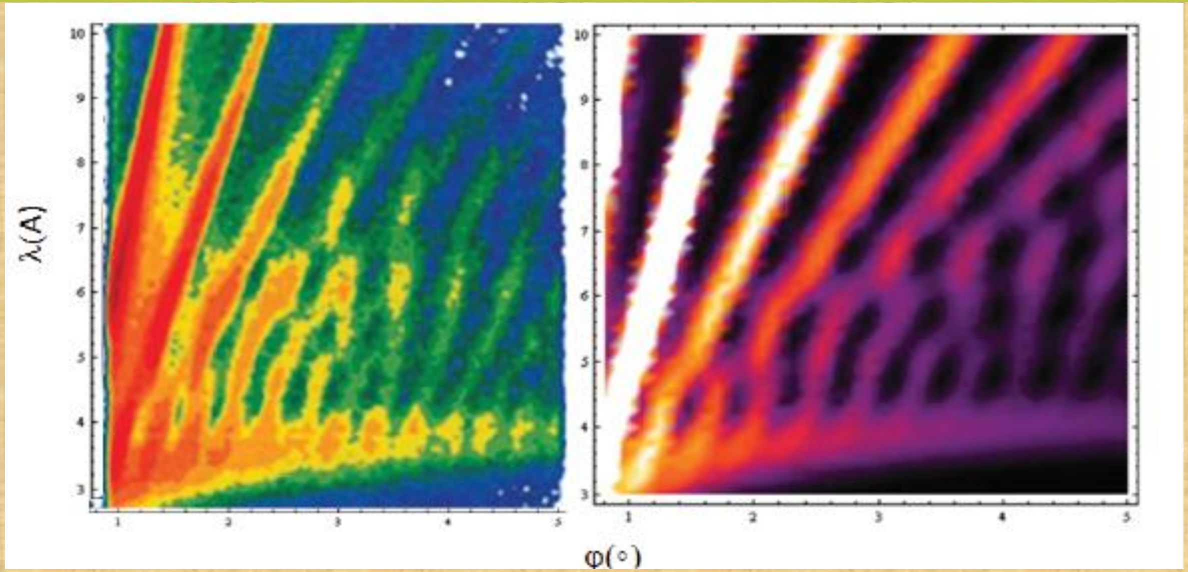


Long storage of UCNs in gravitational quantum states

NEUTRONS FOR SCIENCE

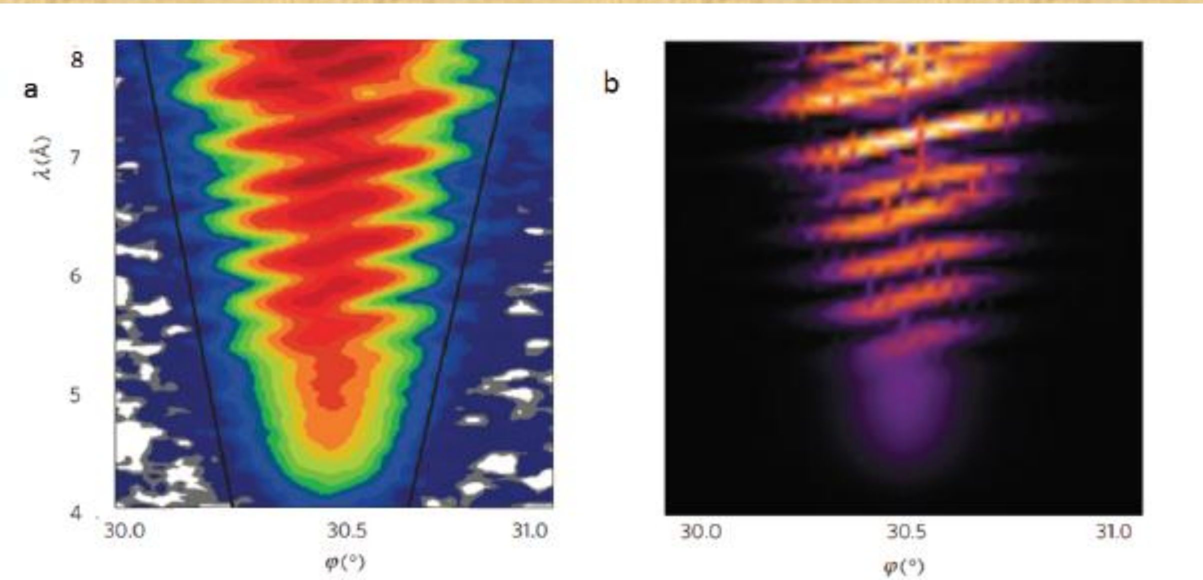
- The GRANIT facility has been constructed and is in its comissioning stage;
- First UCNs were delivered to the GRANIT detector during previous reactor cycle in 2013;
- Restart of the ILL reactor and continuation of measurement in July 2014;
- First measurements (a couple of years) in the « flow-through » mode;
- Meantime « flow-through » measurements are in progress by qBounce and Tokyo collaborations;
- Then precision measurements with GRANIT in the accumulation mode with long storage of UCNs in gravitational and whispering-gallery quantum states.

Neutron rainbow (whispering gallery states)



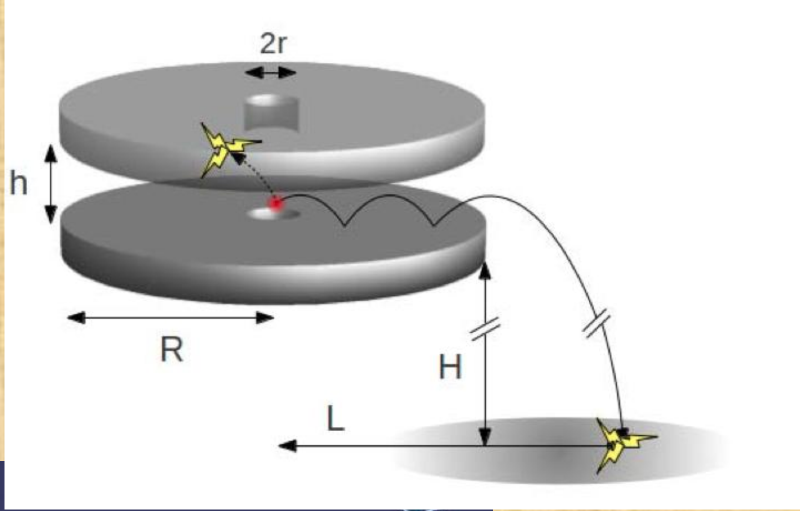
Neutrons tunneling IN and then OUT of quantum states

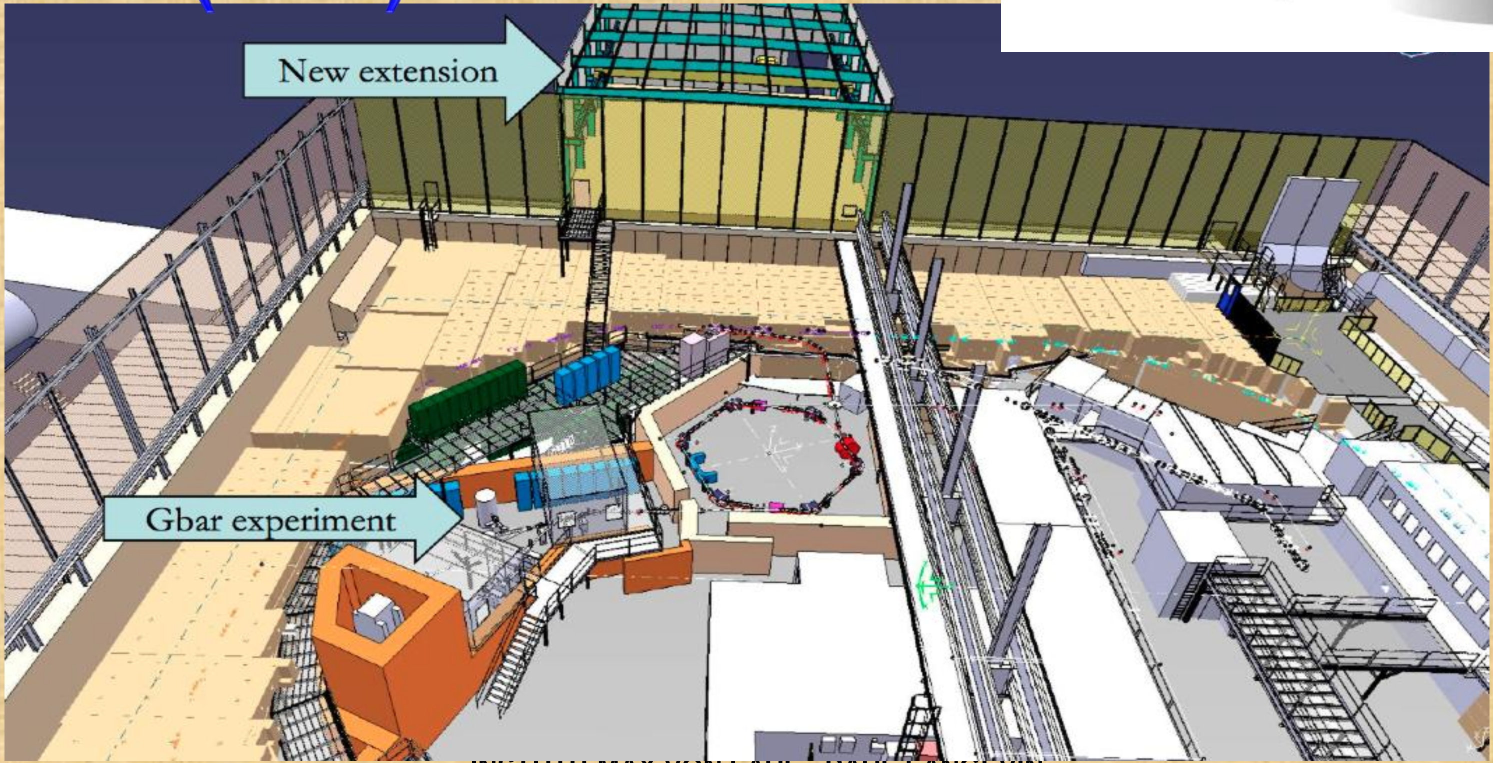
Neutrons entering from the edge of a truncated mirror and then exiting from the opposite edge



GBAR experiment with ultracold antihydrogen

G. Dufour et al, *Shaping the distribution of vertical velocities of antihydrogen in GBAR*, Europ. Phys. J. C 74 (2014) 2731

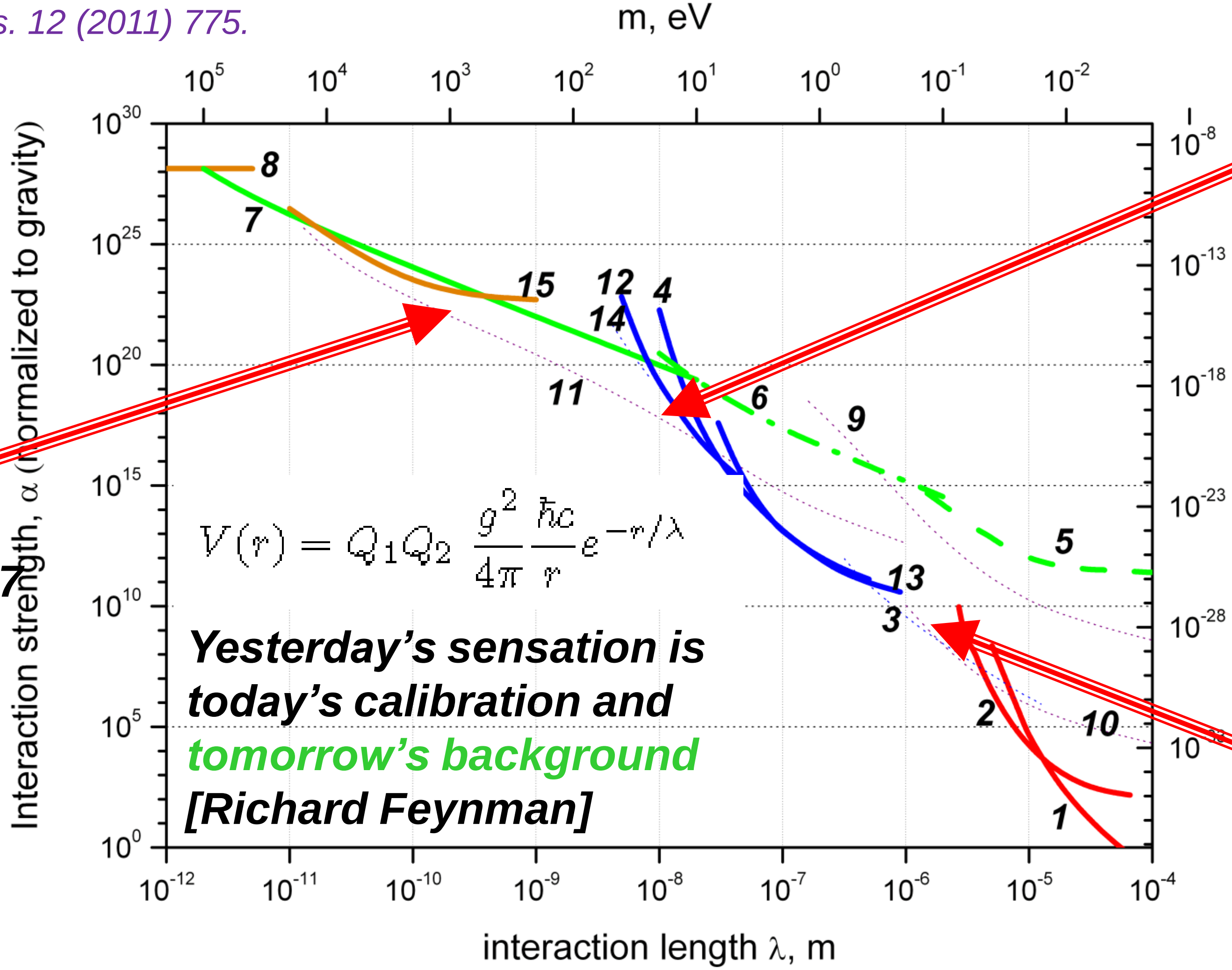




Constrains for short-range forces

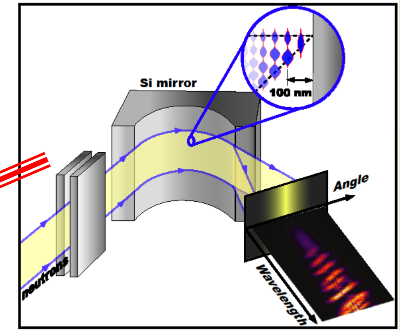
I. Antoniadis, S. Baessler, M. Buchner, V.V. Fedorov, S. Hoedl, V.V. N., G. Pignol, K.V. Protasov, S. Reynaud, Yu. Sobolev, « Short-range fundamental forces », Compt. Rendu Phys. 12 (2011) 775.

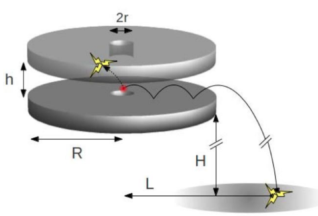
[V.V. N. et al, Neutron scattering and extra short range interactions, Phys. Rev. D 77 (2008) 034020]

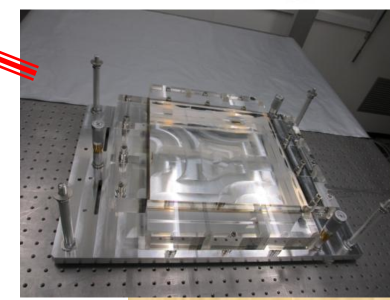


$$V(r) = Q_1 Q_2 \frac{g^2}{4\pi} \frac{\hbar c}{r} e^{-r/\lambda}$$

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







Constrains for chameleon-like short-range forces

[Ph. Brax et al, Probing strongly coupled chameleons with slow neutrons, Phys. Rev. D 88 (2013) 083004]

instance a Ratra-Peebles model [6]

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

where $n > 0$ is the Ratra-Peebles index.

$$V_{\rm eff}(\varphi) = V(\varphi) + \frac{\beta}{M_{\rm Pl}}\varphi\rho, \qquad (3)$$

where ρ is the mass density of matter and β is the dimensionless coupling constant of chameleons with matter. This effective potential is drastically different from

$$\varphi(\rho) = \Lambda \left(\frac{n\Lambda^3 M_{\rm Pl}}{\beta\rho}\right)^{1/(n+1)}$$

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

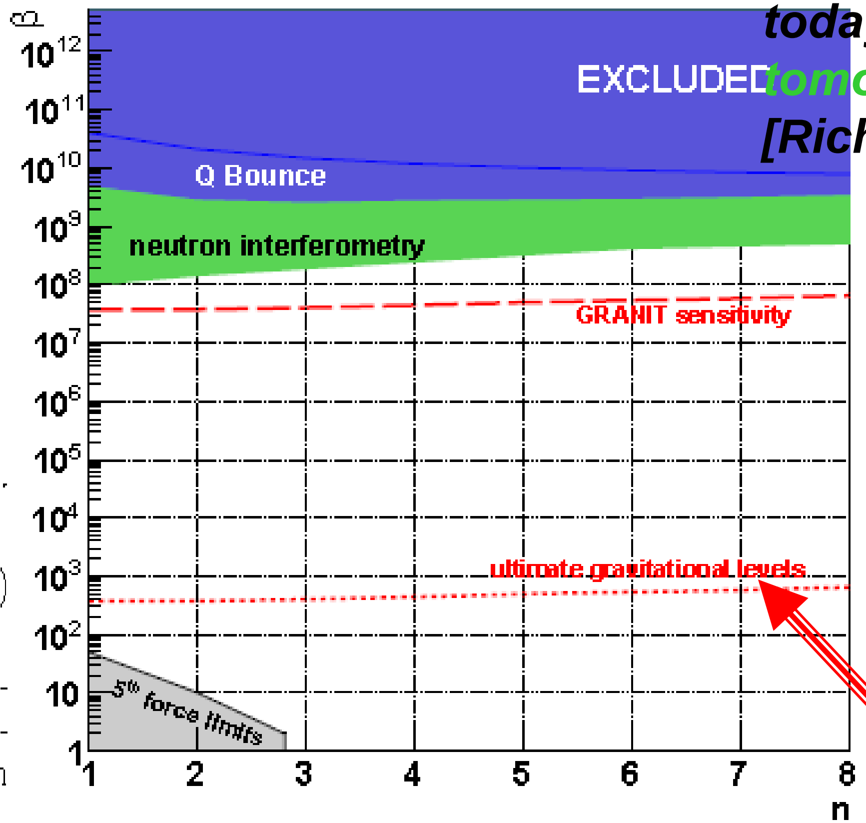
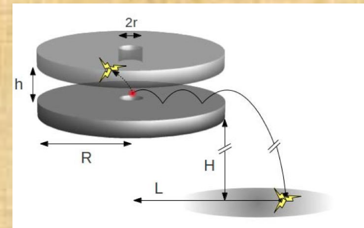
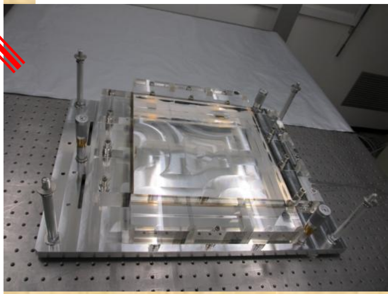


FIG. 8: The chameleon exclusion plot. The blue zone is excluded from [8]. The red lines are sensitivities calculated in [7] and confirmed in this work. The green zone is the potential reach of the neutron interferometry experiment proposed in this work.





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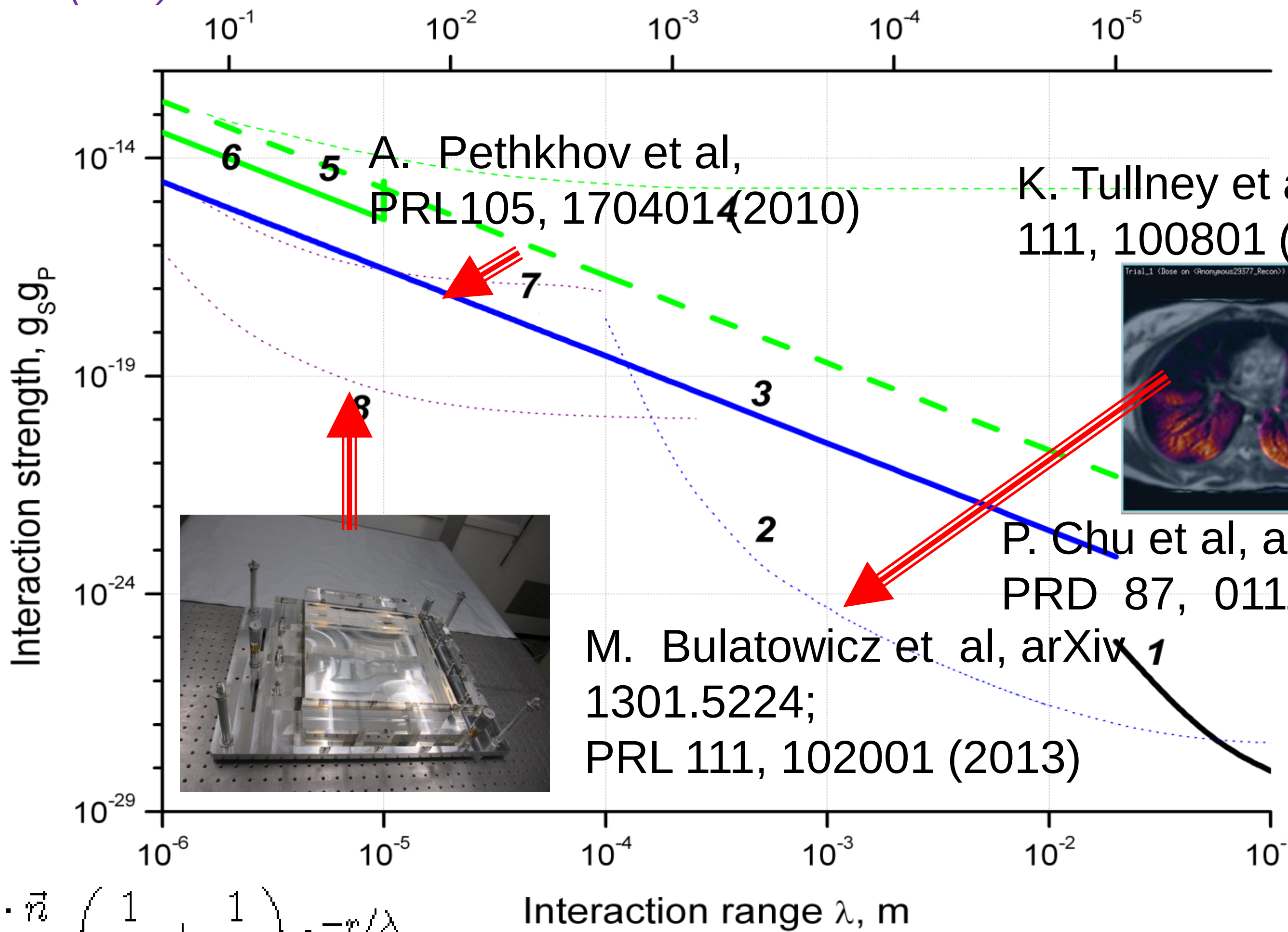

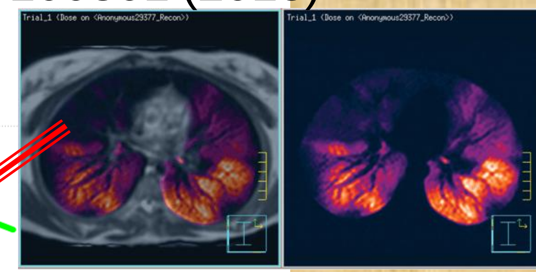

A. Pethkhov et al, PRL105, 170401 (2010)

K. Tullney et al Phys.Rev.Let. 111, 100801 (2013)

P. Chu et al, arXiv 1211.2644 PRD 87, 011105 (2013)

M. Bulatowicz et al, arXiv 1301.5224; PRL 111, 102001 (2013)

$$V(\vec{r}) = \hbar g_p g_s \frac{\vec{\sigma}\cdot\vec{n}}{8\pi mc}\left(\frac{1}{\lambda r}+\frac{1}{r^2}\right)e^{-r/\lambda}$$

Conclusion

I do not show new solid constraints, because we are analyzing new data of other and our groups at the moment;

For more results on spin-dependent forces at larger (than GRANIT) distances, see for instance talks at the GRANIT-2014 workshop by Mike Snow or Philipp Shmidt-Wellenburg;

Some of new results are expected to be summarized soon in S. Baessler et al (Advances in High Energy Physics, special issue « Quantum gravitational spectroscopy », 2014)

Conclusion

1. Constraints for spin-independent, spin-dependent, chemeleon-like extra short-range forces are being improved over a broad range of distances.
2. The methods used are quantum bouncing and scattering of slow neutrons, atoms and antiatoms.
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