# EuNPC-2018

## 2018 European Nuclear Physics Conference

San Domenico Conference Center in Bologna, Italy, September 02$^{th}$ to 07$^{th}$, 2018

# Constraints for fundamental short-range forces from the neutron whispering gallery, and extension of the method to atoms and antiatoms



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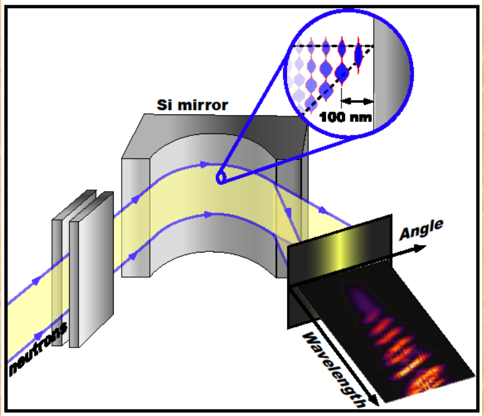
# Neutron whispering gallery




## Neutron whispering gallery could be considered as a particular case of:

## Gravitational Quantum Interferometry/Spectroscopy with Ultracold Particles

Gravitational quantum states of neutrons

Gravitational quantum states of antihydrogen atoms

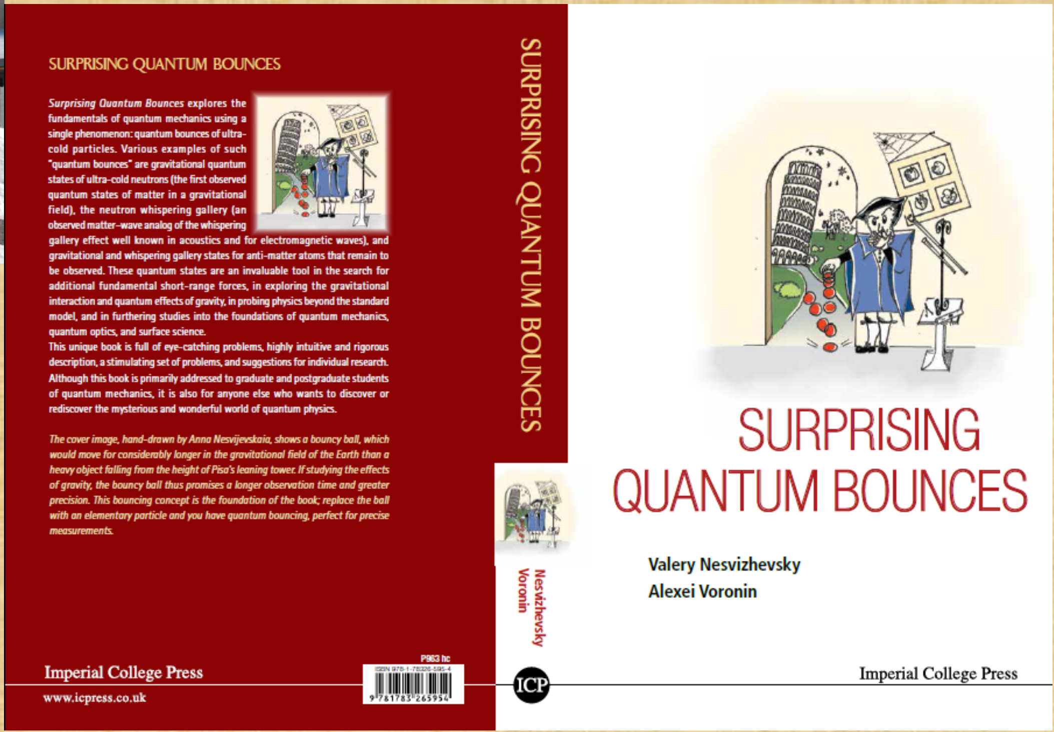
Ultracold: gravitational quantum states: 10 nK, ultracold (anti)hydrogen: 100 µK, ultracold neutrons: 1mK

… Gravitational quantum states of hydrogen atoms

# Gravitational quantum spectroscopy/interferometry

A textbook on quantum mechanics based on one phenomenon: quantum bouncing of ultracold particles

GRANIT workshops
+ proceedings



# Related references

Observation of gravitational states of neutrons: [V.V. N., 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 415:297, 2002];

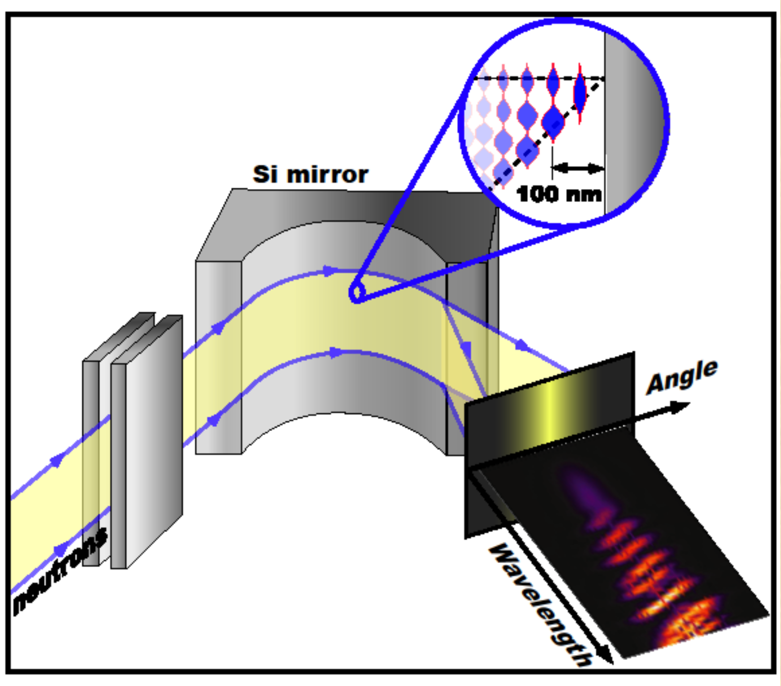
Observation of whispering-gallery states of neutrons: [V.V. N., A.Yu. Voronin, R. Cubitt, and K.V. Protasov, *Neutron whispering gallery*, Nature Physics 6:114, 2010];

Proposal to measure gravitational quantum states of antihydrogen/hydrogen atoms: [A.Yu. Voronin, V.V. N., P. Froelich, *Gravitational quantum states of antihydrogen*, Phys. Rev. A 83:032903, 2011];

Calculations of quantum reflection of (anti)atoms from the surface ([P.-P. Crepin, E.A. Kupriyanova, R. Guerout, A. Lambrecht, V.V. N., S. Reynaud, S. Vasiliev, A.Yu. Voronin, *Quantum reflection of antihydrogen from a liquid helium film*, Europ. Phys. Lett. 119: 33001, 2017];

Also relevant publications of Tokyo, qBounce, GRANIT, GBAR collaborations. Also GRANIT workshop proceedings: [GRANIT-2014, *Gravitational Quantum Spectroscopy*, Adv. High En. Phys. 467409:2, 2014]; [*GRANIT-2010*, Compt. Rend. Phys. 12:703, 2011].

# Whispering gallery




1. The phenomenon: quantum states of massive particles (neutrons, atoms, antiatoms), which move in the vicinity of a curved mirror. This is an analogue to gravitational quantum states (acceleration replaces gravity, and inertial mass plays the role of gravitational mass).

2. The method of observation: an interference pattern (the intensity) is measured as a function of the particle longitudinal velocity (using the time-of-flight method) and the tangential velocity (the angle of exit measured using a position-sensitive detector).

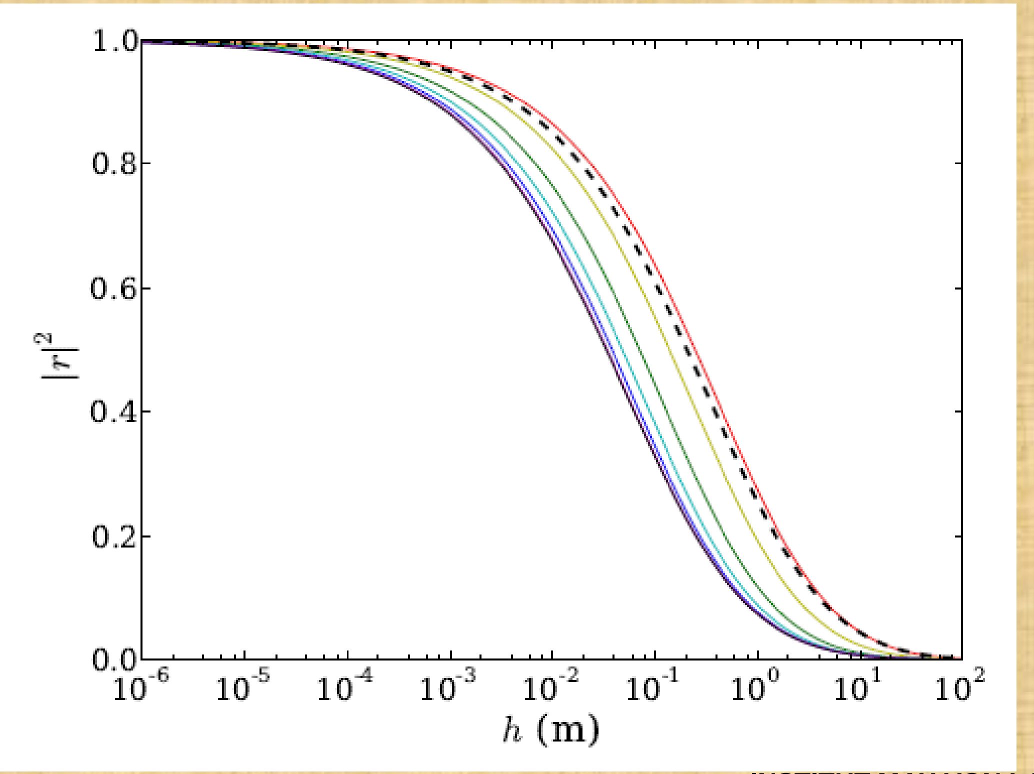
# A mirror for neutrons and (anti)atoms

- Non-local interaction of an ultracold massive particle with matter due to very large wavelength (much larger than a typical interatomic distance in matter);
- A mirror can be described as a uniform (along the surface) potential barrier, with no internal structure, thus specular reflection;
- An ultracold particle (in case of gravity, 10 nK !!!) is reflected from the mirror elastically.

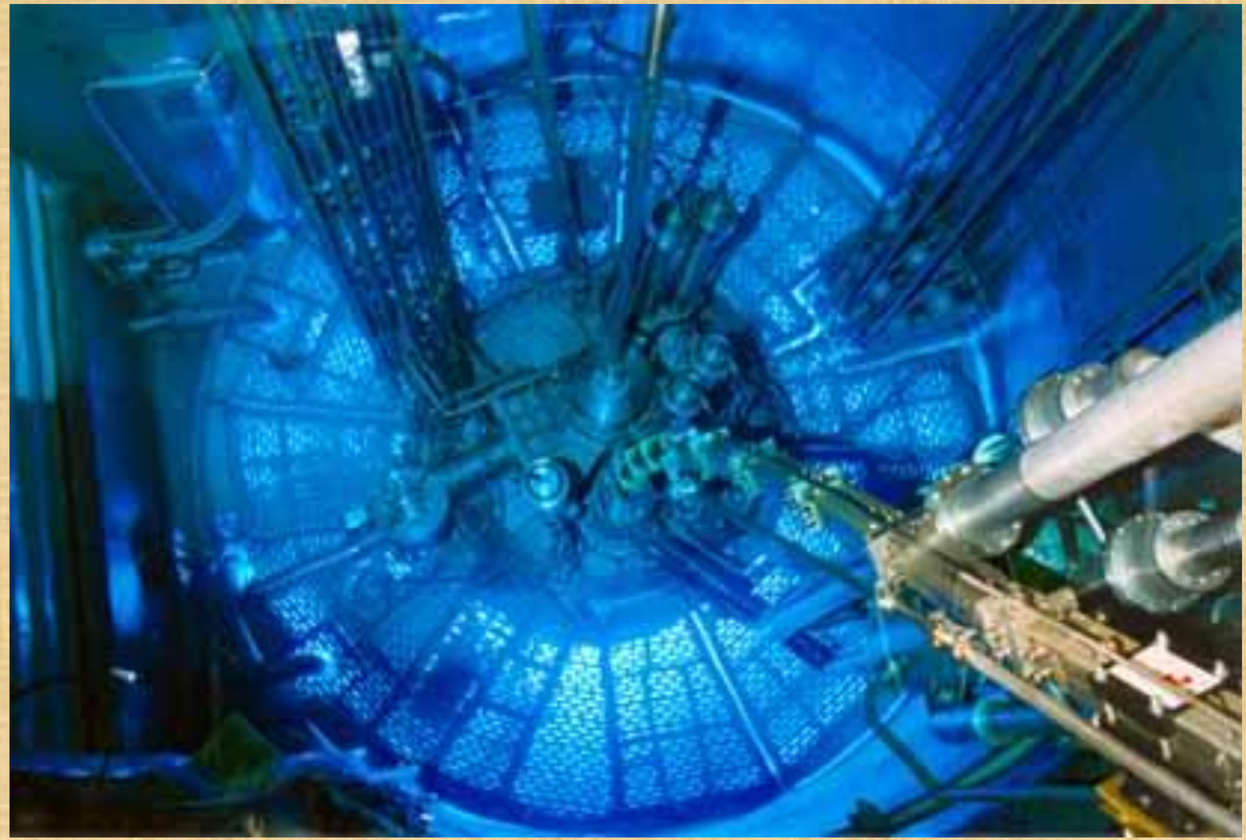
$$\lambda_{n,H,\bar{H}} = \frac{4\text{Å}}{1000 m/s}$$

# A mirror for neutrons and (anti)atoms

- Ultracold neutrons are reflected from average neutron-nuclei optical potential of the surface [E. Fermi, *Sul moto dei neutroni nelle sostanze idrogenate*, Ric. Sci. 7: 13, 1936];
- (Anti)atoms are reflected from van der Waals/Casimir-Polder potential of the surface [J.E. Lennard-Jones, A.F. Devonshire, Proc. R. Soc. 156: 6, 1936].



All measurements with neutrons related to the topic of this talk are performed at the Institut Max von Laue - Paul Langevin (ILL), Grenoble, France, and use various ILL facilities (GRANIT, PF1B, PF2, D17 etc).



# Neutron Whispering Gallery

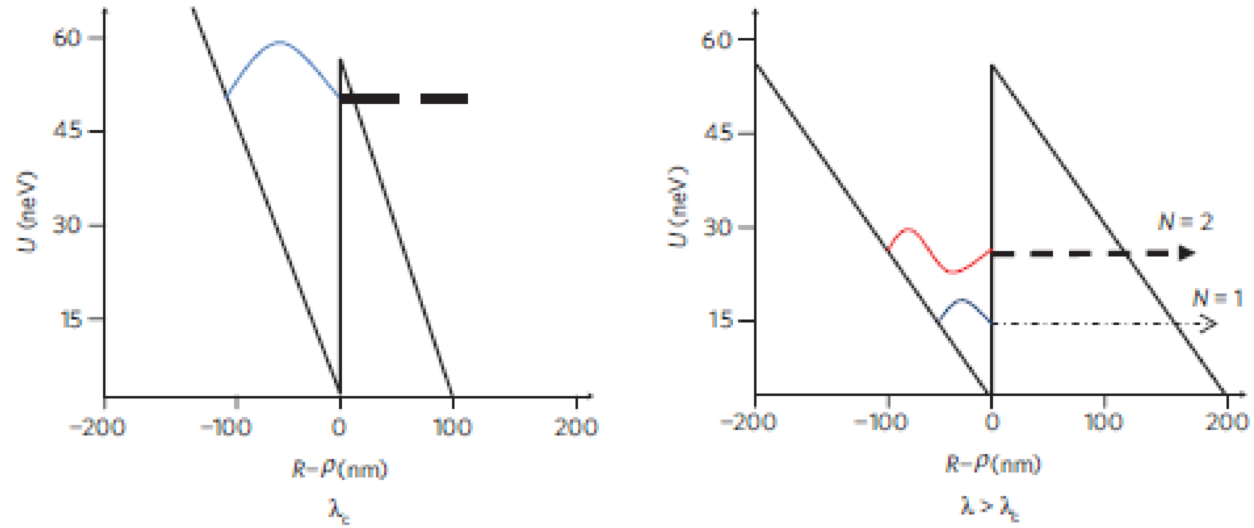
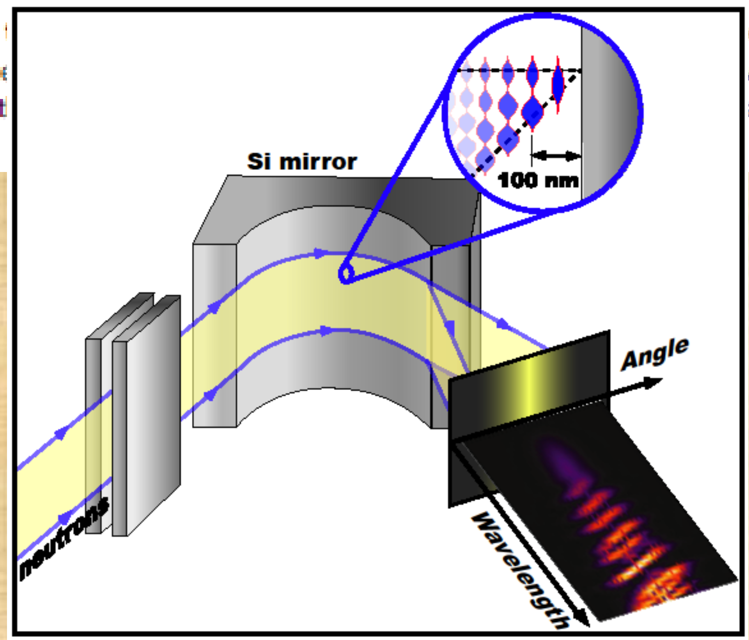


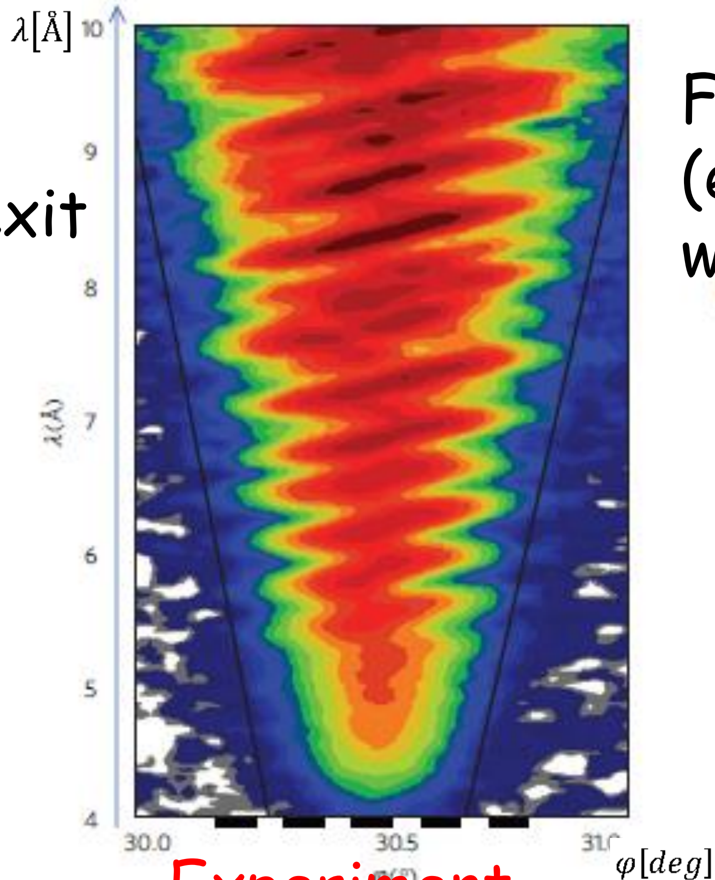

**Figure 2 | A sketch of the effective potential in** … equal to the mirror optical potential $U_0$. The potential slope at $z \neq 0$ is governed by the ce… …wo lowest quantum states ($n = 1,2$) are shown inside the bounding triangle potential at t… …strate tunnelling of neutrons through the bounding triangle potential.



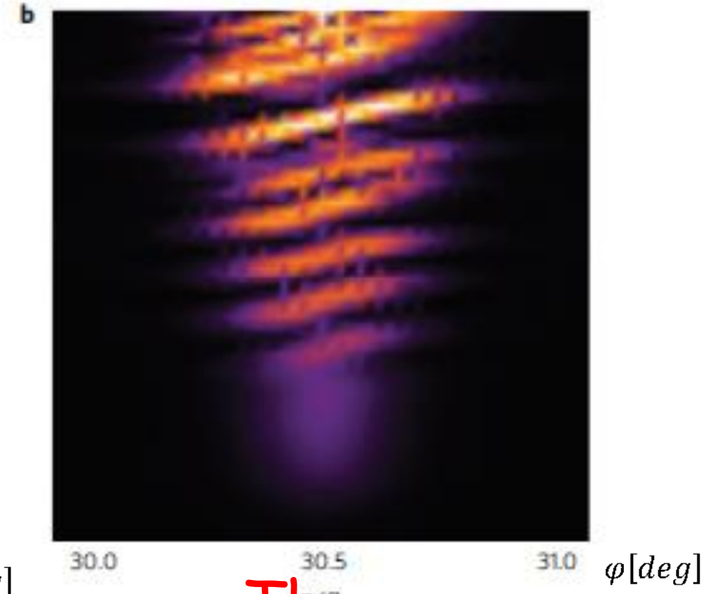
# Neutron Whispering Gallery

Neutrons downstream the mirror exit

First observation in 2010 (experiment versus theory) with a Si concave mirror



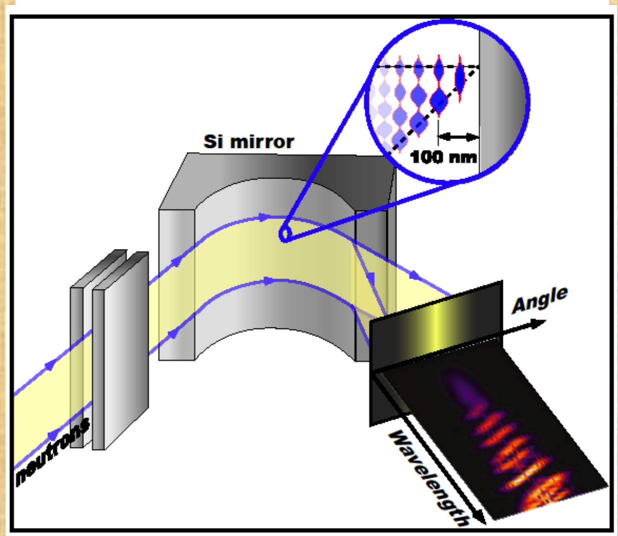

Experiment



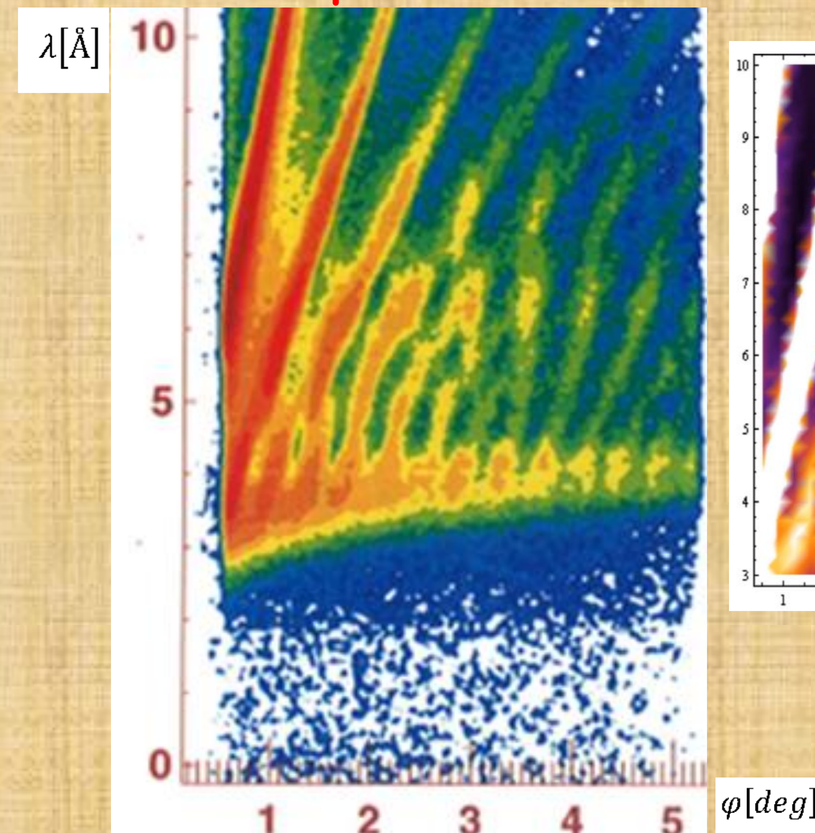

Theory

**Figure 4 | Long-living centrifugal quantum states. a**, The scattering probability as a function of neutron wavelength λ (Å; vertical axis) and deviation angle φ (°; horizontal axis). Neutrons enter through the entrance edge of the mirror. The geometrical angular size of the mirror is 30.5°. The inclined solid lines show the signal shape for the classical Garland trajectories. The dashed horizontal line illustrates a characteristic wavelength cutoff $\lambda_c$. **b**, Theoretical simulation of the data in accordance with refs 9–11. Some of the difference between these two pictures is probably due to the thin oxide layer on the mirror surface.

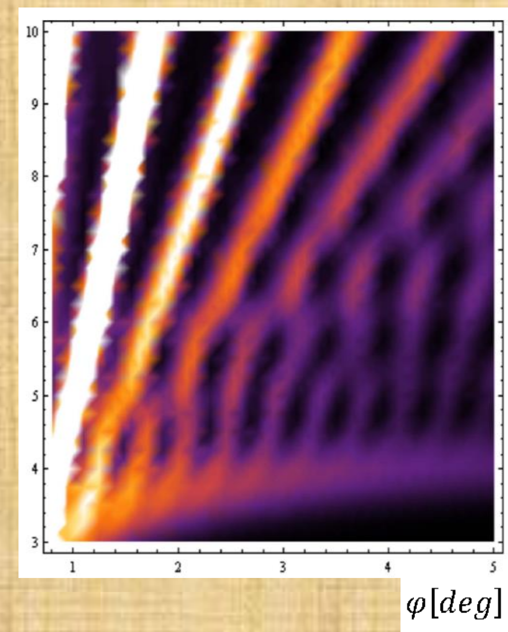
# Neutron Whispering Gallery


Experiment




Theory




Neutrons tunneling through the mirror

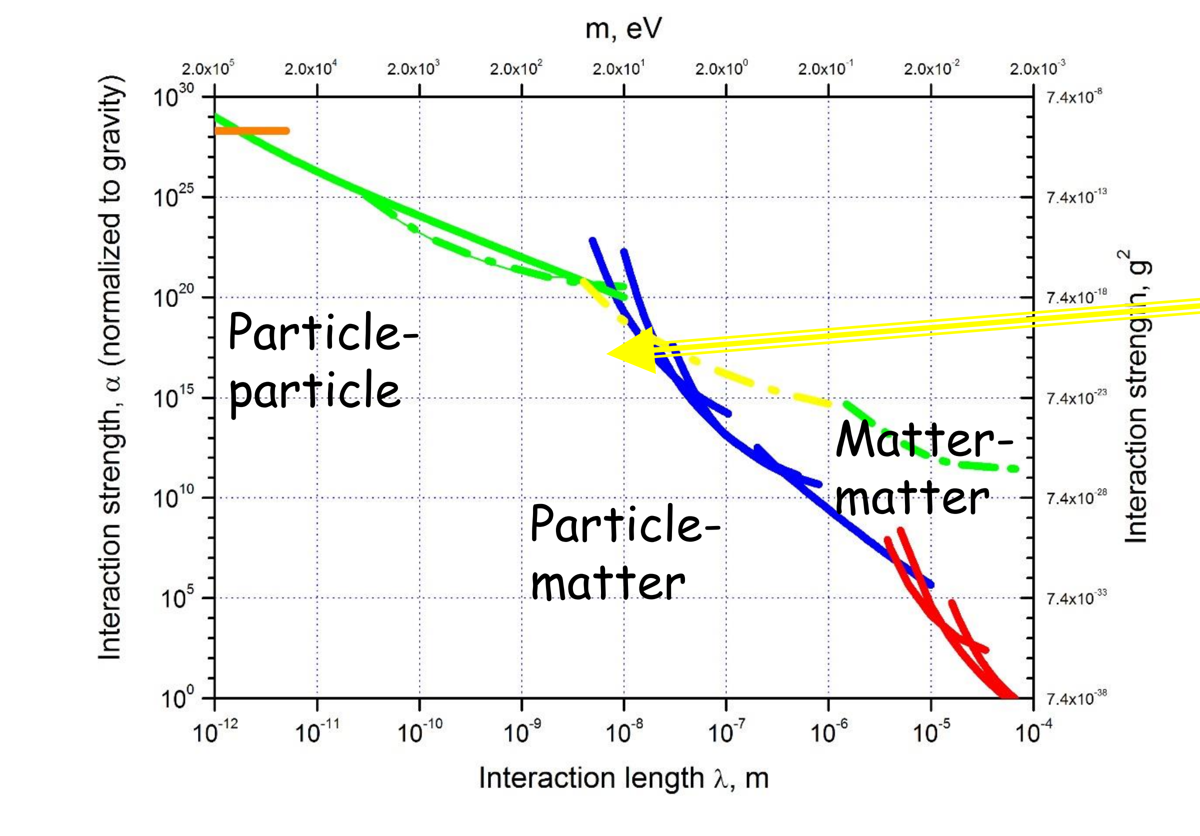
# Neutron Whispering Gallery with a $MgF_2$ mirror

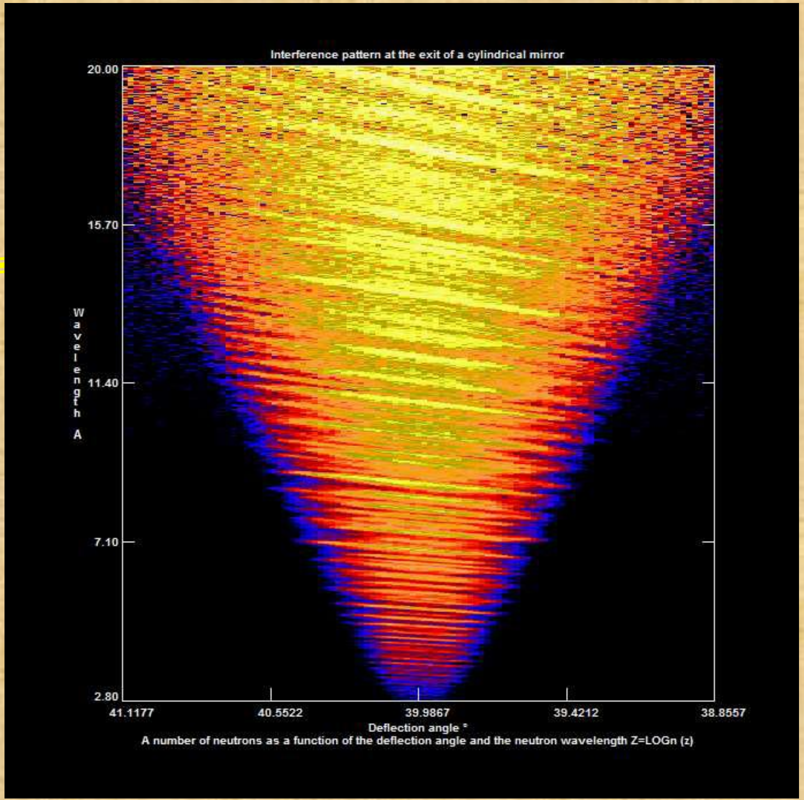
**Methodical improvements**:

- No Si-oxide layer on the surface (as in the experiment with Si mirror), thus better defined surface potential and smaller systematics;
- Lower impurities on the surface, thus smaller systematics;
- Suppression of parasitic transitions between whispering-gallery states;
- Optimization of the neutron beam shaping and resolutions, thus higher statistics and smaller systematics;
- Better control of false effects;
- Higher critical velocity of the mirror material, thus the access to shorter distances also higher statistics.

To be continued with a closed trap…

# Neutron Whispering Gallery with a $MgF_2$ mirror

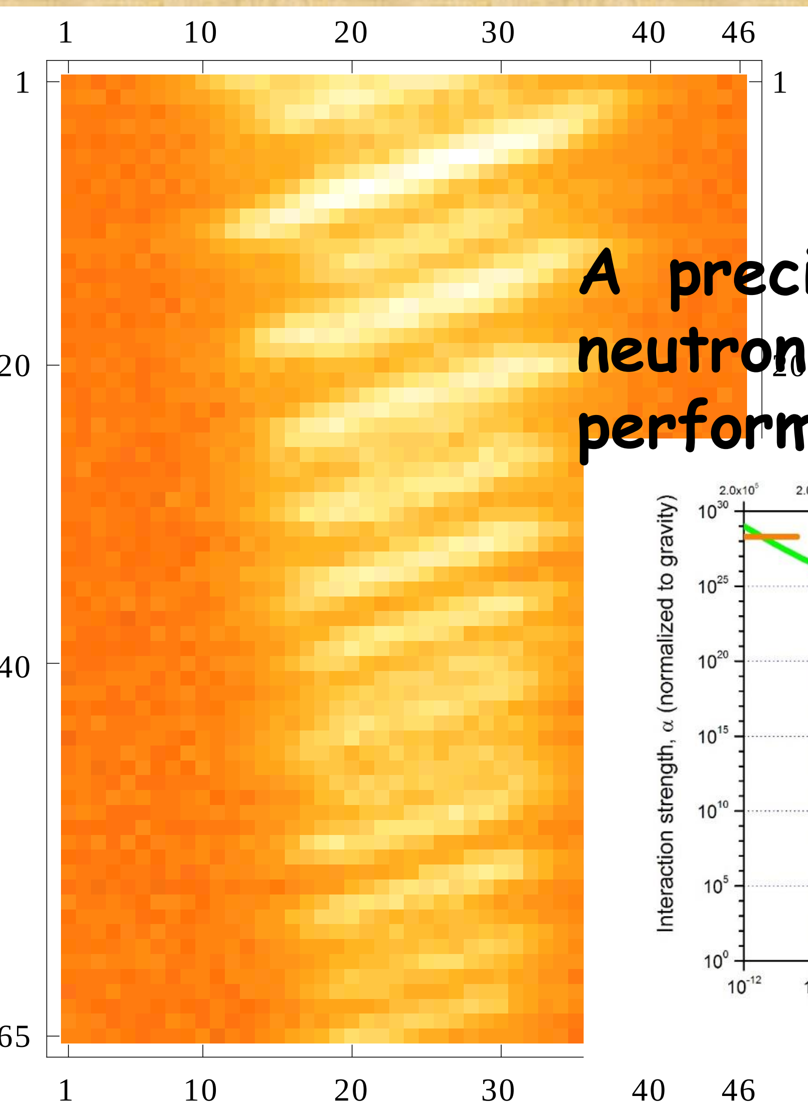



[I. Antoniadis, S. Baessler, M. Buchner, V.V. Fedorov, S. Hoedl, V.V. N., G. Pignol, K.V. Protasov, S. Reynaud, Yu. Sobolev, *Short-range fundamental forces*, Compt. Rend. Phys. 12: 775, 2011], updated by [C.C. Haddock, N. Oi, K. Hirota, T. Ino, M. Kitaguchi, S. Matsumoro, K. Mishima, T. Shima, H.M. Shimizu, W.M. Snow, T. Yoshioko, *A search for deviations from the inverse square law of gravity at nm range using a pulsed neutron beam*, ArXiv:nucl-ex/1712.02984], [Y. Kamiya, K. Itagaki, M. Tani, G.N. Kim, and S. Komamiya, *Constraints on new gravitylike forces in the nanometer range*, ArXiv:hep-ex/1504.02181]

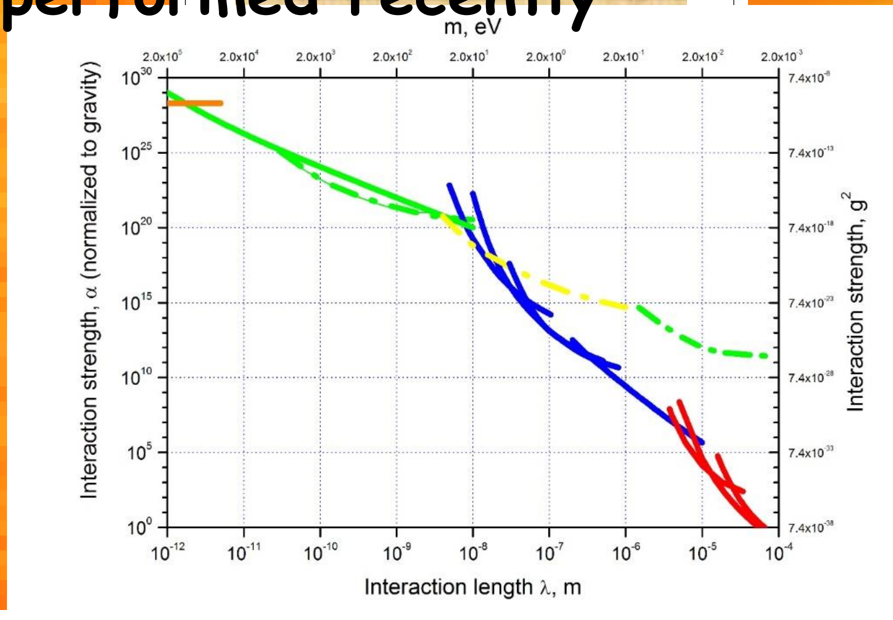
# New experiment with MgF2 concave mirror (unpublished)

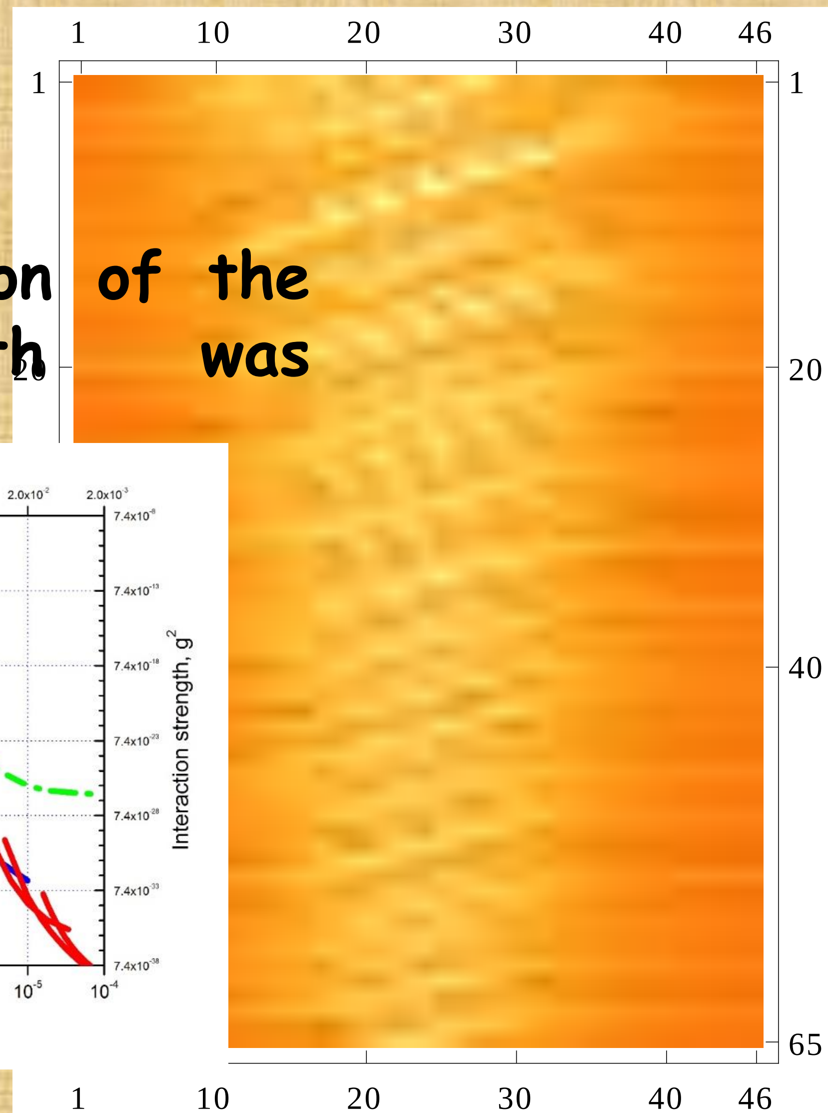
- Examples of data/theory calculations




**Analysis of the data is in progress**

**A precision calibration of the neutron wavelength was performed recently**



# ...and extension of the method to (anti)atoms

- Time-of-flight spectroscopy of antihydrogen longitudinal velocities is provided by precise timing of antihydrogen release from the GBAR precision trap and detection;
- Tangential velocities are measured using GBAR position-sensitive annihilation detector;
- The whispering-gallery method does not require a sharp shaping of the initial vertical spectrum and extreme energy resolution corresponding to a single quantum state;
- Thus, easy to realize;
- Thus, higher statistics (due to measurements of several gravitational quantum states simultaneously) and lower systematics simultaneously.

# GBAR

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

Characteristic quantum time equals $\Delta\tau \sim \hbar/\Delta E \sim 0.5$ms

Characteristic precision equals $\Delta g/g \sim \Delta\tau/T/10 \sim 10^{-4}$, where **T** is the time of storage of antiatoms in gravitational states

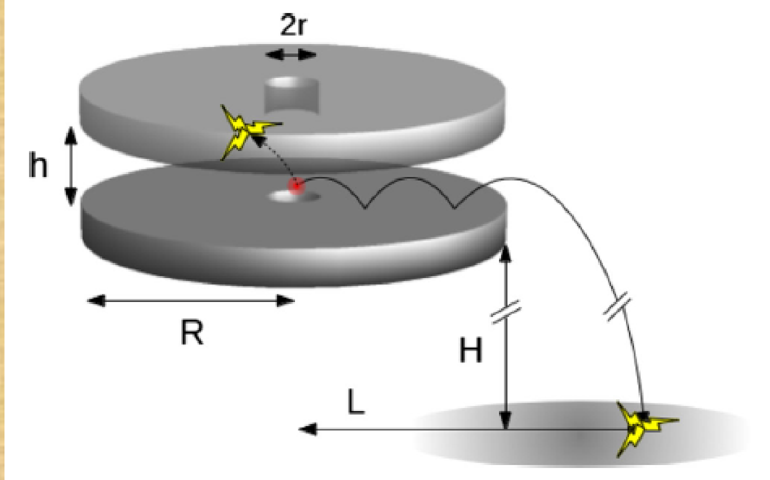



**Fig. 1** A scheme of principle of the proposed shaping device: an $\overline{H}$ atom is released from the Paul trap (*central spot*) and it bounces a few times on the mirror surface of the bottom disk (*arrows*); if it scatters on the rough top surface, it annihilates (*lightnings*); otherwise, it 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

# GBAR

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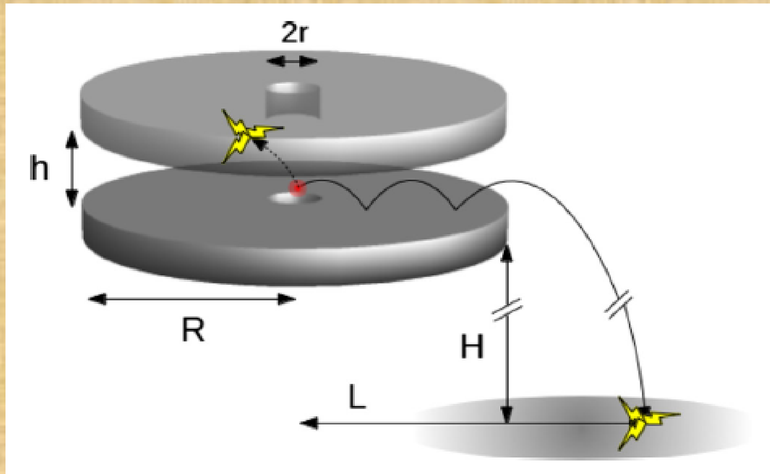
- For specially "adjusted" van der Waals/Casimir potentials (liquid $^4$He, $^3$He, as extreme cases), storage times of gravitational quantum states can be significantly increased (seconds);
- Careful analysis of systematic effects and better statistics can allow further significant improvements of accuracy

Characteristic quantum time equals $\Delta\tau \sim \hbar/\Delta E \sim 0.5$ms

Precision can probably approach (?) $\Delta g/g \sim \Delta\tau/T/10^3 \sim 10^{-6}$, where T is the time of storage of antiatoms in gravitational states

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# Gravitational and whispering states of hydrogen

Gravitational quantum states of hydrogen atoms as

- a tool for prototyping the GBAR experiment with antihydrogen atoms (the prototyping is based on symmetry of matter and antimatter relative to electromagnetic interactions);
- as an independent method for constraining short-range fundamental forces even better than with neutrons (due to higher statistical accuracy);
- for more precise spectroscopy of hydrogen atoms by cooling them to the extreme temperature of ~10 nK (quantum gravitational states) simultaneously keeping statistics quite high (larger velocities are allowed in other-than-gravity directions).

(An) experimental configuration(s) as well as the collaboration are going to be set up

# For completeness: various other realizations

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Gravitational quantum states of **positronium** as a tool to measure gravitational fall of positronium [P. Crivelli et al, *Can we observe the gravitational quantum states of positronium?* Advances in High Energy Physics (2015)].

Advantages: (compared to free fall) localization in space allows reduction of systematic effects, reasonable statistics can be easily achieved

Difficulties: positronium has to be exited to a high quantum state, short observation times caused by high positronium velocities

No particular project, simply general feasibility has been established

# For completeness: various other realizations

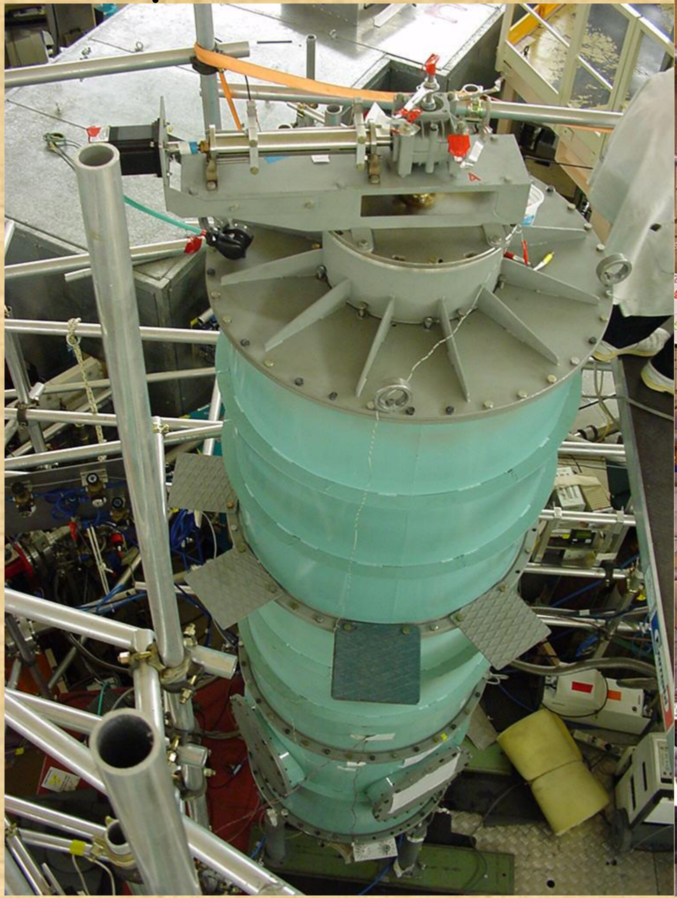
Other options being discussed but not yet developed and formalized:

- Astrophysical realizations of quantum bouncing,
- Nanoparticles and nanodroplets in the vicinity of surfaces.

Not yet any particular project on precision measurements:

Advantages: existing method and setup.

Difficulties: a “dirty” system with poorly resolved quantum states



# Conclusion

- The method of neutron whispering gallery with a curved mirror allows competitive constraints for fundamental short-range forces;

- The method of neutron whispering gallery with a curved mirror can be extended to atoms and antiatoms, thus providing probably even better constraints for fundamental short-range forces;

- A method analogous to neutron whispering gallery with a flat mirror can be applied to antihydrogen atoms, thus providing simultaneously easy implementation, higher statistics and smaller systematics in measurement of a gravitational acceleration of antimatter ($10^{-4}$-$10^{-6}$);

- Exiting perspectives for analogous experiments with hydrogen.