NEUTRONS FOR SCIENCE

Gravitational quantum states of neutral particles

This area of research is rapidly developing and expanding (ultracold neutrons -> atoms, heavier atoms?, antiatoms?, molecules? nanoparticles and nano-droplets? muonium? positronium? ; interferometry, spectroscopy, whispering galleries, induced transitions, gravitationally induced transitions etc). To avoid telling "nothing about everything", I will follow the organizers advice and present "the most essential about the most interesting" (of course, this choice is subjective).

1. Recent measurements of the gravitational shift of neutron whispering gallery.
2. Future measurements of gravitational quantum states of hydrogen and deuterium atoms

1. Recent measurements of the gravitational shift of neutron whispering gallery.

2. Future measurements of gravitational quantum states of hydrogen and deuterium atoms

GRASIAN

+ S. Baessler, J. Pioquinto, M. Shi

https://grasian.eu/

GRAvity, Spectroscopy and Interferometry with ultra-cold Atoms and Neutrons

In the GRASIAN collaboration we pursue research with the lightest neutral particles/atoms at lowest kinetic energies, nearly at rest. Subject of our work are hydrogen and antihydrogen, neutrons, muonium and positronium. Their quantum properties in the field of gravity, Casimir-Polder and Van-der-Waals potentials, precise optical and microwave spectroscopy are in the focus of our collaboration. GRASIAN combines experimental and theoretical activities of several groups and institutions:

Institut Laue Langevin (ILL Grenoble): V. Nesvizhevsky; ***Laboratoire Kastler Brossel*** (LKB Paris): F. Nez, S. Reynaud, P. Yzombard; ***Stefan Meyer Institute*** (SMI Vienna): E. Widmann; ***University of Turku*** (UTU Turku): *S. Vasiliev*; Eidgenössische Technische Hochschule (***ETH Zürich***): P. Crivelli

Plan of presentation

- Introduction about gravitational/whispering-gallery quantum states.

- Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

- Prospects for measuring gravitational quantum states of hydrogen and deuterium atoms.

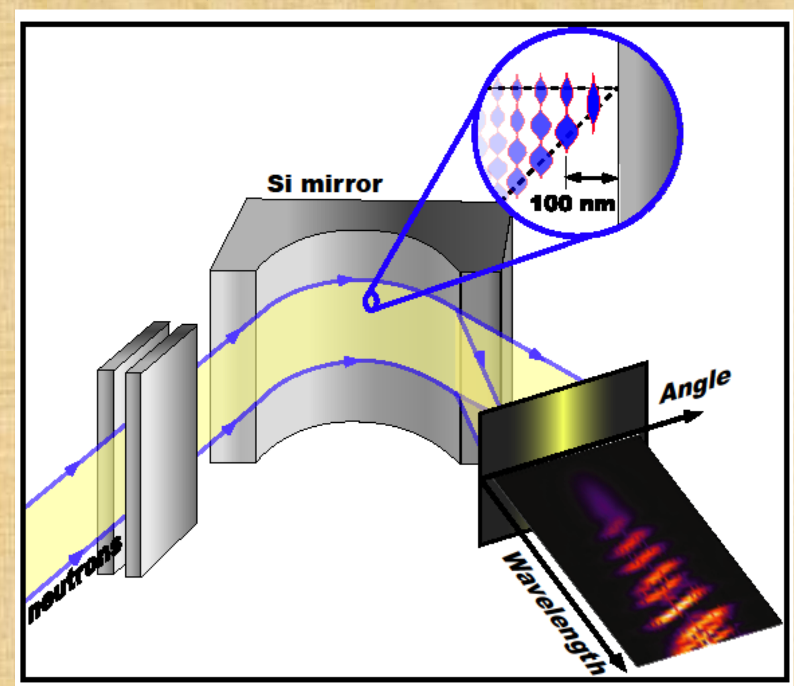
- Ultimate accuracy in measuring the gravitational quantum states of hydrogen atoms. A source of ultracold hydrogen atoms and a magneto-gravitational hydrogen trap.

Introduction about gravitational/whispering-gallery quantum states (GQS/WGS)

1. What is this?

GQS (gravitational quantum states)

WGS (whispering gallery quantum states)



Introduction about gravitational/whispering-gallery quantum states (GQS/WGS)

1. What is this?

GQS/WGS for nearly **whatever their realization** are shown in the figure + rainbow + how the whales speak to each other + Wi-Fi signal in a cylindrical building + many-many other cases

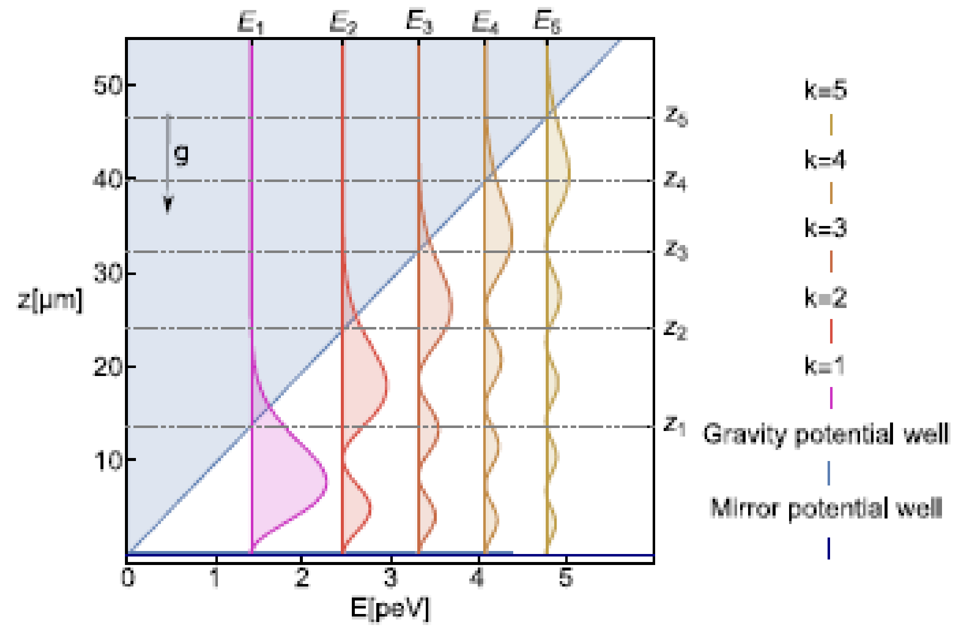


Fig. 1 Squared modules of the neutron wavefunctions $|\psi_k(z)|^2$ as a function of the height z for the five lowest quantum states; they correspond to the probabilities of observing neutrons at a height z.

There will be a question to the conference about **GQS in the gravitational field of a galaxy and dark matter**

Introduction about gravitational/whispering-gallery quantum states (GQS/WGS)

2. Typical parameters:

GQS: mass 1 at.un.; energy ~0.6 peV, height ~5.9 μm, effective temperature ~10 nK, formation time ~1.1 ms

WGS: $g \rightarrow a = \frac{v^2}{R}$ (v - velocity, R - mirror radius), thus, a possibility to "tune" parameters

[V.V. N. et al, *Quantum states of neutrons in the Earth's gravitational field*, Nature 415 (2002) 297; *Neutron whispering gallery*, Nature Physics 6:114, 2010]

NEUTRONS FOR SCIENCE

Introduction about gravitational/whispering-gallery quantum states (GQS/WGS)

3. Why are such states interesting?

- In addition to the evident pleasure of discovering and exploring a unique system whose existence is determined by quantum states in a gravitational field…

- It's a very "clean" systems with parameters which can be precisely predicted and controlled:

One wall of the potential well is the Earth's gravitational field. The other wall of the potential well is quantum reflection from the surface of the mirror. Since the mirror potential is "infinitely sharp" compared to the characteristic size of the quantum state, its parameters are not included in the problem. Typical corrections to this "ideal" picture are 10^{-5} (and they can be taken into account with a certain accuracy).

Introduction about gravitational/whispering-gallery quantum states (GQS/WGS)

4. Scientific motivations.

- New physics beyond the Standard Model, which can be generalized as a search for extra fundamental short-range interactions (depending on spin (axion-type) and not depending on spin) between the particle and the mirror.

- Many modern physics problems could be probed: dark matter, dark energy, the origin of gravity, matter-antimatter asymmetry, theories with extra light bosons, extra dimensions of space, etc,

- Also various applications in quantum mechanics studies, surface studies, precision spectroscopy, etc

Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

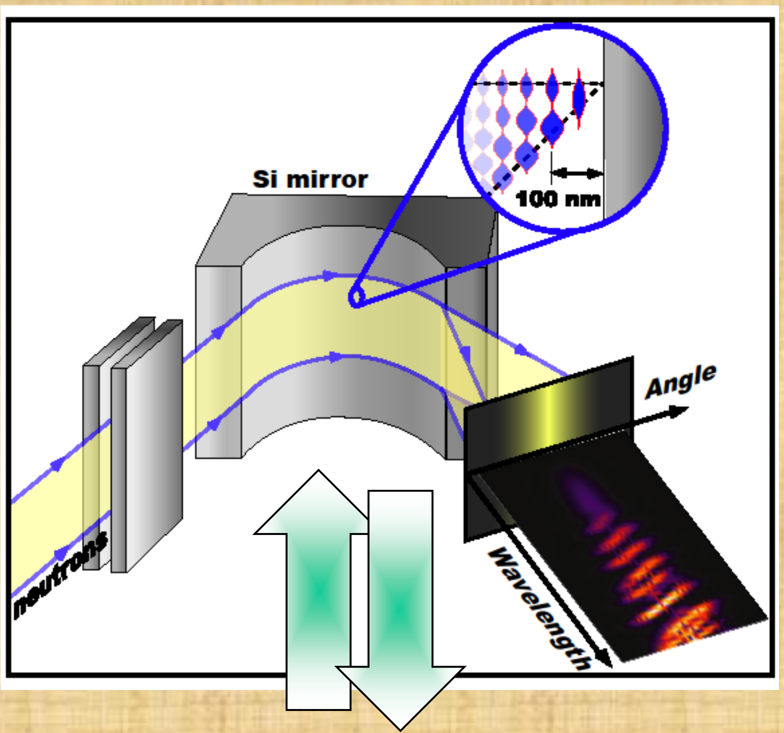
The photo was taken at "Searching for New Physics at the Quantum Technology Frontier" workshop, 02-07.07.2023, Ascona, Switzerland,

where we first promised to measure this phenomenon with neutrons.

You will see that the interference pattern on the bottle (which also inspired this study…) is very characteristic for the WGS

This idea was considered in connection with the possibility of directly measuring the gravitational interaction of antimatter (muonium, antiatoms, positronium), but has wider application.

Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.



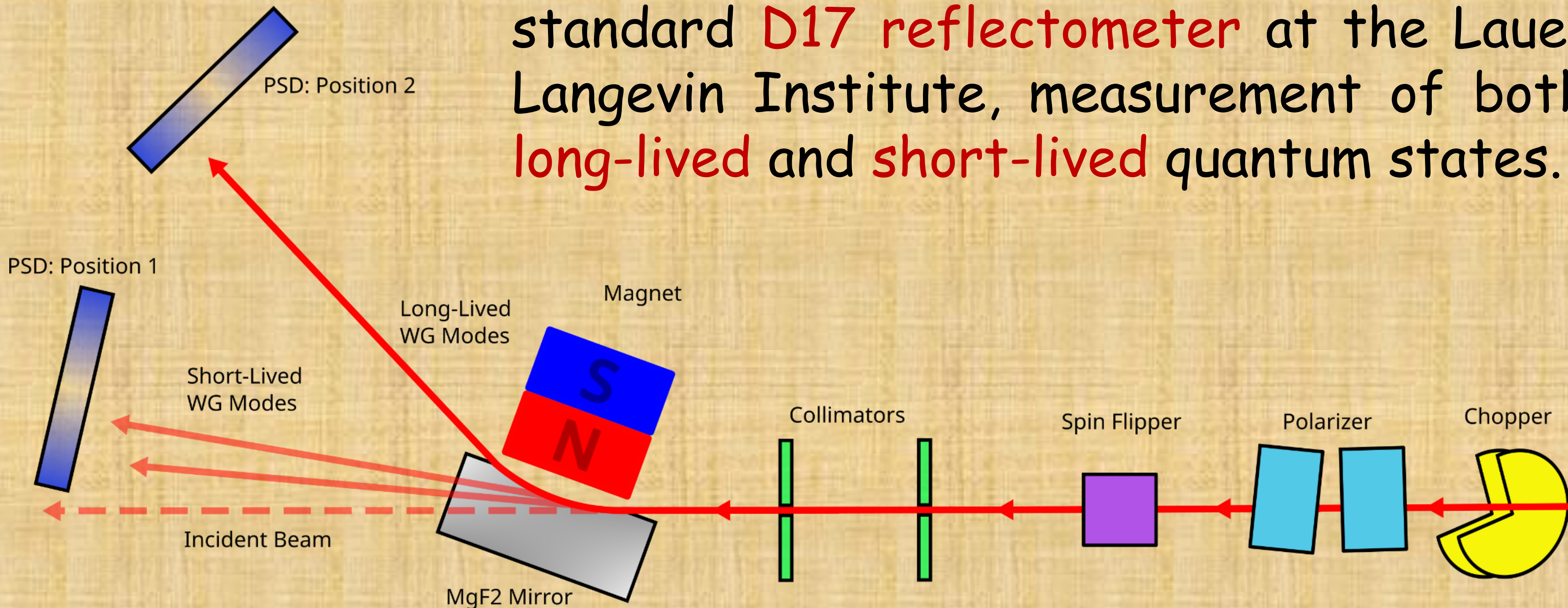
Measurement method: add additional force first in the direction of the mirror surface, then in the direction away from the mirror surface; measure the interference pattern in both cases and compare the results.

High sensitivity of the complex interference pattern.

Gravitational force if you rotate the mirror by 90 degrees (surface up and down).
Or simply apply a magnetic field gradient (turn the particle's spin toward or away from the surface).

Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

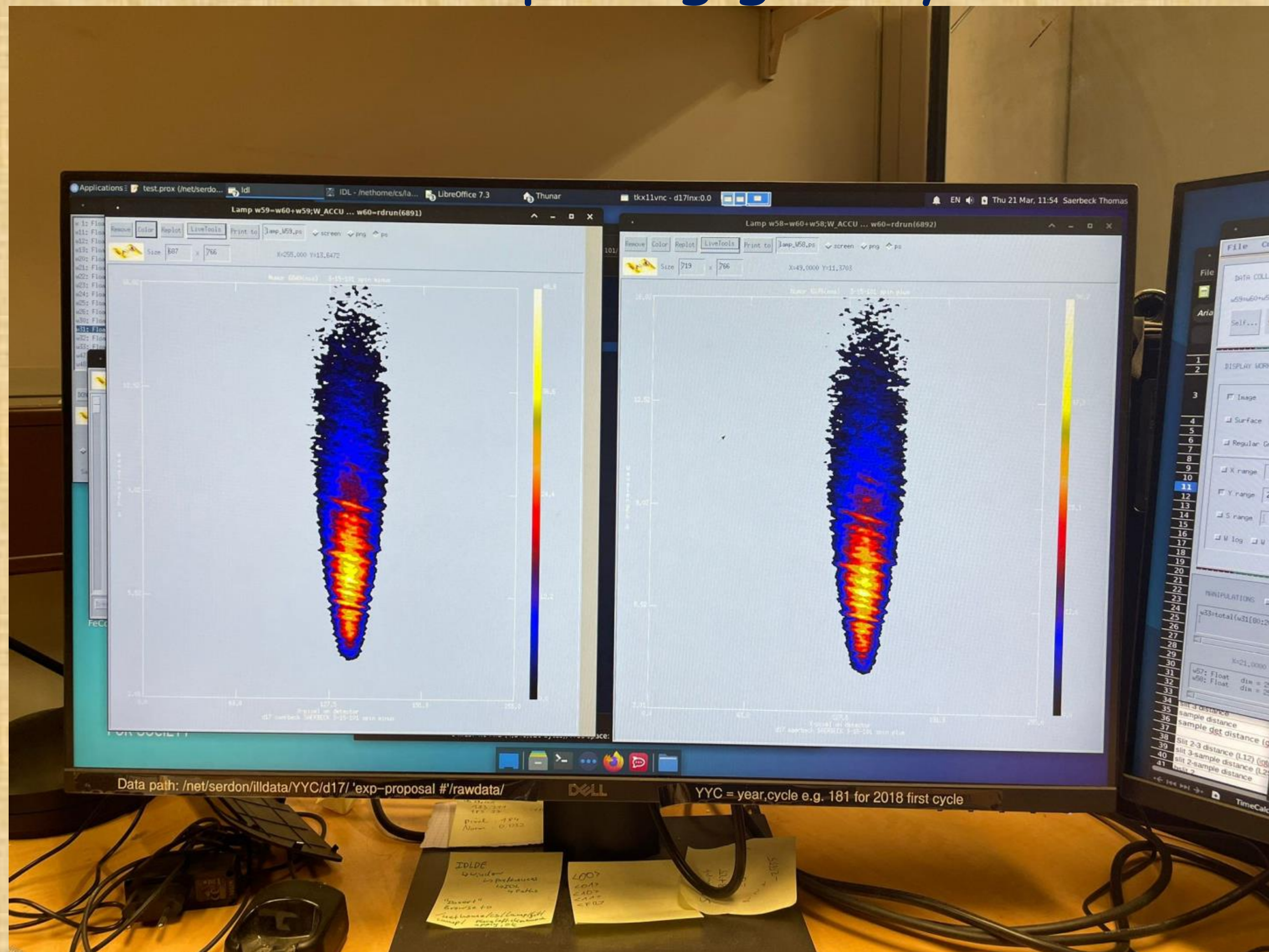
Specific implementation: an existing MgF_2 mirror, strong permanent magnets, standard D17 reflectometer at the Laue-Langevin Institute, measurement of both long-lived and short-lived quantum states.



Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

Spins **"in"** and **"out"**

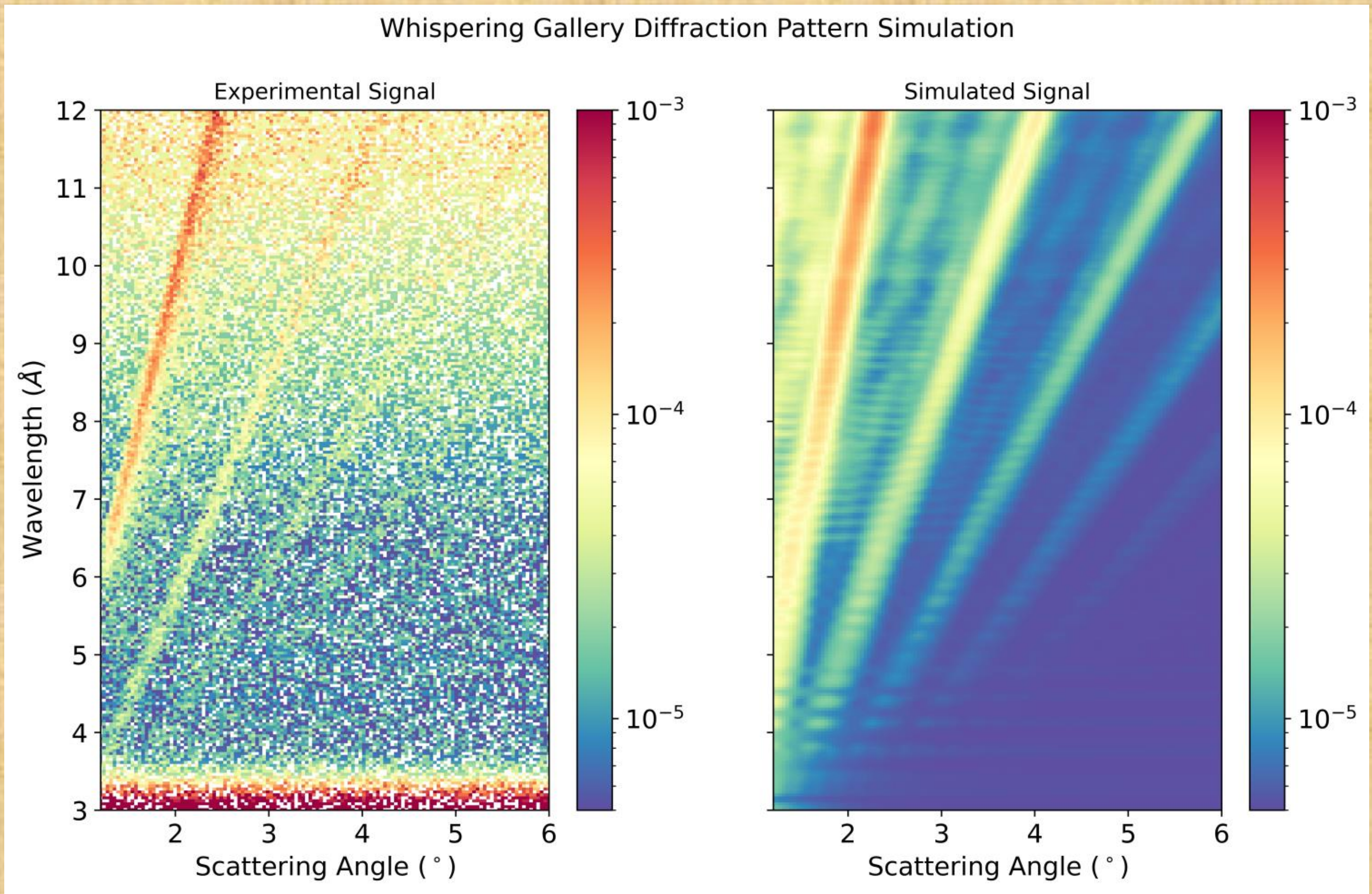
The interference patterns look identical, but they are not; there is a **~10^{-5}** difference in the attracting force which can lead to **measurable** effects.



Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

Short-lived WGS are very sensitive to the potential diffuseness,

thus they could be used to control false effects.

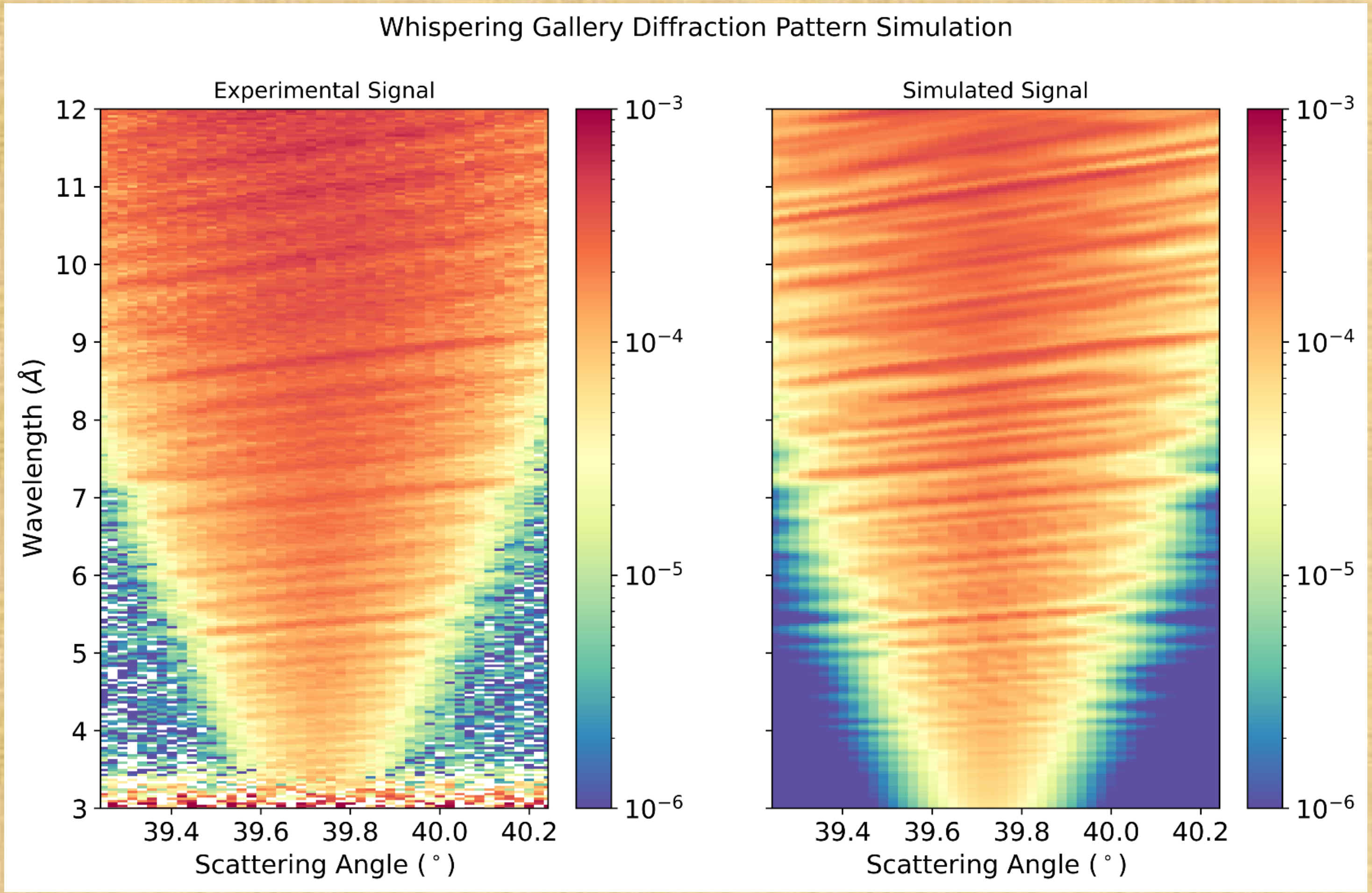


Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

Long-lived WGS states are very sensitive to the extra forces.

Quite precise theoretical description.

Relative measurements are reliable.



Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

Measurements were carried out in **March 2024**; analysis of the experimental data will be completed in the coming months:

- Sensitivity to long-range forces (gravitational, magnetic, etc.) is no worse than 10^{-5} and can be optimized;
- There are elements of interference patterns that are much more sensitive to additional long-range forces (due to the non-equidistance of quantum states);
- The method can easily be extended to other neutral particles that is of special interest for measurements with antimatter particles.

NEUTRONS FOR SCIENCE

Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

A bonus of this experiment is the improved constraint on **extra short-range fundamental interactions** (**spin-dependent** and **spin-independent**).

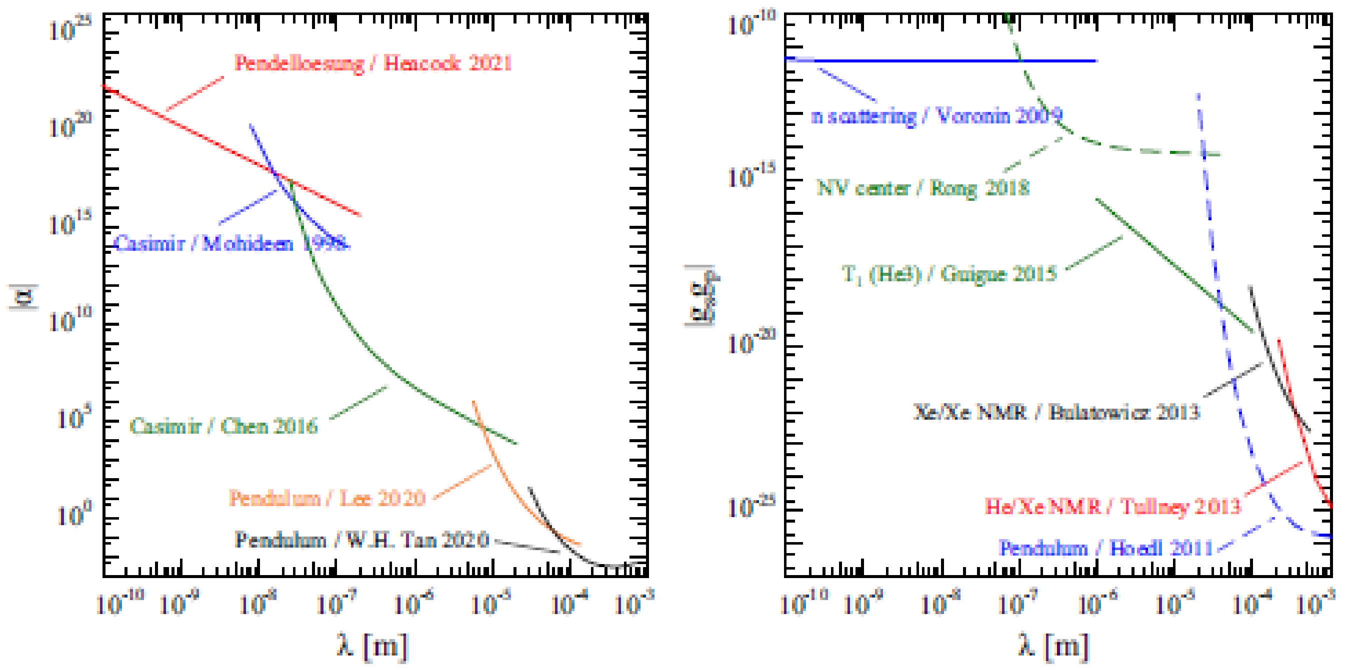


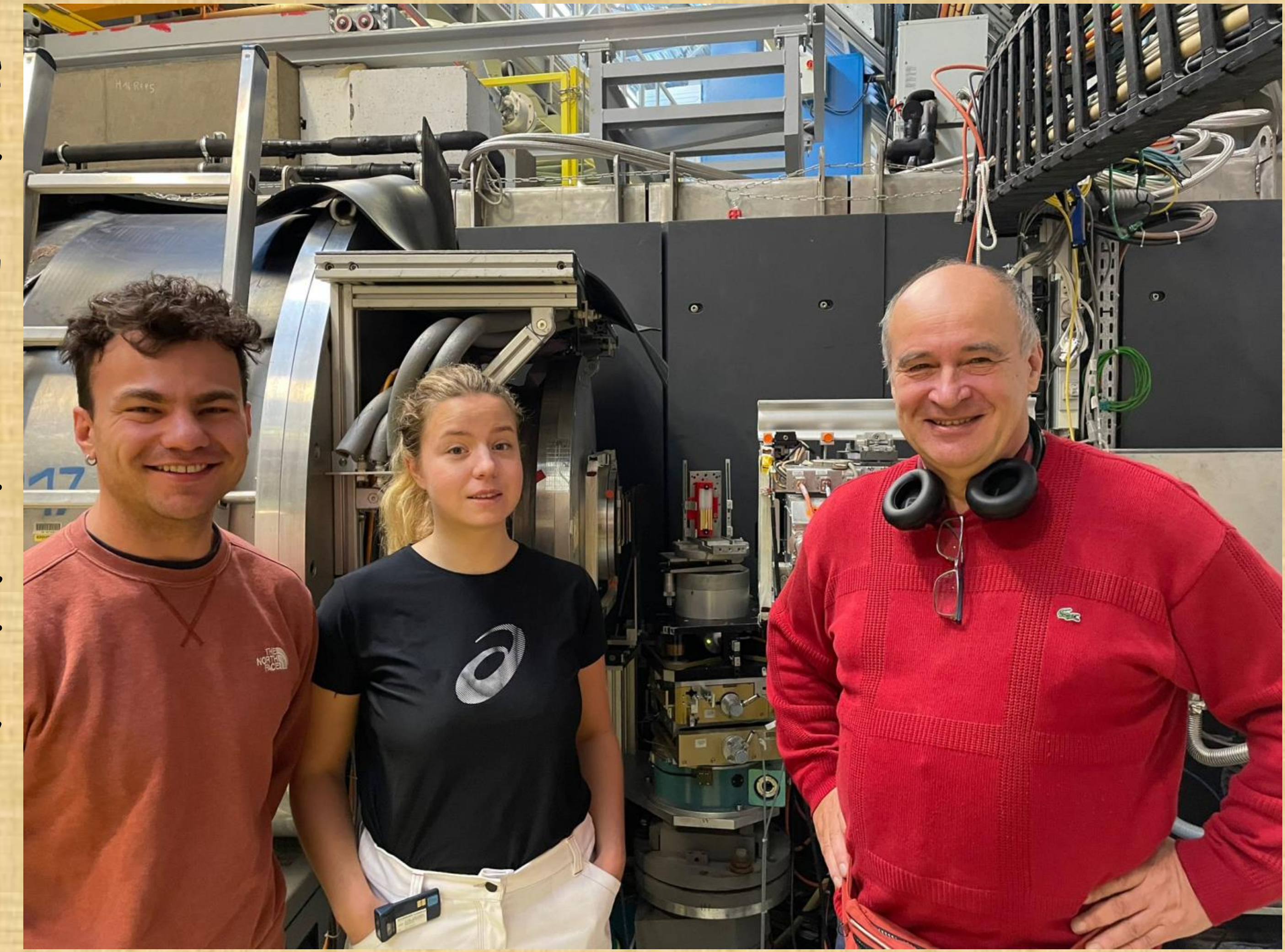
Figure 8: Left: Current most constraining limits for new spin-independent short-range forces. The first experiment (red line, [179]) uses free neutrons. At higher λ ranges, other techniques and probes are more sensitive [180, 181, 182, 183]. Right: Current most constraining limits for new spin-dependent interactions. Experiments [184, 185, 186, 187] use the neutron as the polarized particle, for the first of those it is a free neutron. In [188, 189], the polarized particle is an electron.

[H. Abele et al, *Particle physics at the European spallation source*, Phys. Rep. 1023 (2023) 1 – the latest review

Results of measurements of the gravitational/magnetic shift of the neutron whispering gallery.

A major part of this work has been done by two PhD students: **Jason Pioquinto** and **Katharina Schreiner**

During the recent experiment at the D17 instrument, at the PF1B, Grenoble, France

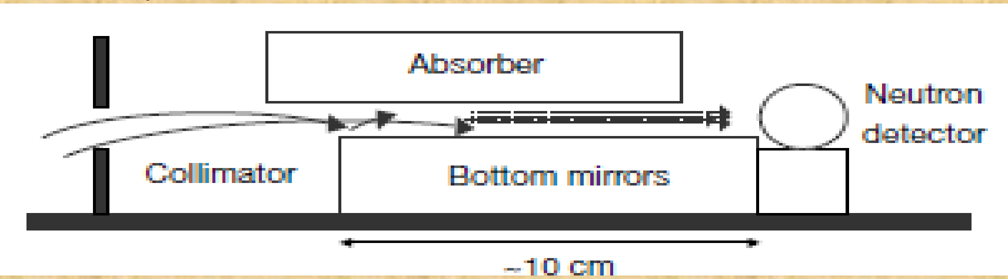


Prospects for measuring gravitational quantum states of hydrogen and deuterium atoms.

Are neutrons unique? Are they the best?

[C. Killian, Z. Burkley, P. Blumer, P. Crivelli, F.P. Gustafsson, O. Hanski, A. Nanda, F. Nez, V. Nesvizhevsky, S. Reynaud, K. Schreiner, M. Simon, S. Vasiliev, E. Widmann, P. Yzombard, *GRASIAN: towards the first demonstration of gravitational quantum states of atoms with a cryogenic hydrogen beam*, EPJD 77 (2023) 50]

The first step would be to repeat the experiment with neutrons, demonstrating the existence of the phenomenon itself for atoms.



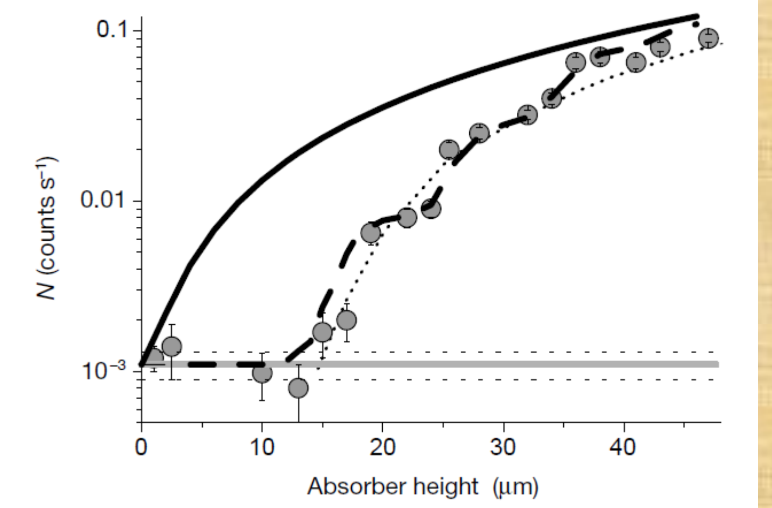


Figure 4 The neutron throughput versus the absorber height at low height values. The data points are summed up in intervals of 2 µm. The dashed curve corresponds to a fit using the quantum-mechanical calculation, in which all level populations and the height resolution are fitted from the experimental data. The solid curve is again the full classical treatment. The dotted line is a truncated fit in which it is assumed that only the lowest quantum state—which leads to the first step—exists.

Prospects for measuring gravitational quantum states of hydrogen and deuterium atoms.

Ultracold neutrons are replaced in this experiment by a beam of cold hydrogen/deuterium atoms.

The advantages include, in particular,
- much larger expected statistics,
- independence from reactors (spallation neutron sources),
- prototyping future experiments with anti-atoms,
- as we will see later, the possibility of long storage of atoms in GQS, thus, their precision gravitational spectroscopy.

If neutrons are reflected from the optical (Fermi) potential of the surface, then atoms are reflected from the (too sharp) van der Waals and Casimir-Polder potentials.

Prospects for measuring gravitational quantum states of hydrogen and deuterium atoms.

Status of this experiment (at ETH, Zurich, then at Stefan Meyer Institute, Vienna):

- We have done significant work to obtain an intense beam of hydrogen/deuterium atoms with minimal velocities and minimal backgrounds,
- Another article with the results of this work will be sent to the journal (EPJD) in the coming weeks,
- The system is ready to begin experiments to observe GQS of hydrogen/deuterium atoms in the coming months,
- The expected accuracy (in the flow-through method), as in the case of experiments with neutrons, is a few percent.

Ultimate accuracy in measuring the gravitational quantum states of hydrogen atoms. A source of ultracold hydrogen atoms and a magneto-gravitational hydrogen trap.

Obviously, to increase the accuracy of such experiments it is required (simply from the uncertainty principle):

- increasing the density of atoms in phase space,
- decreasing their velocity,
- increasing the time of observation of atoms in GQS.

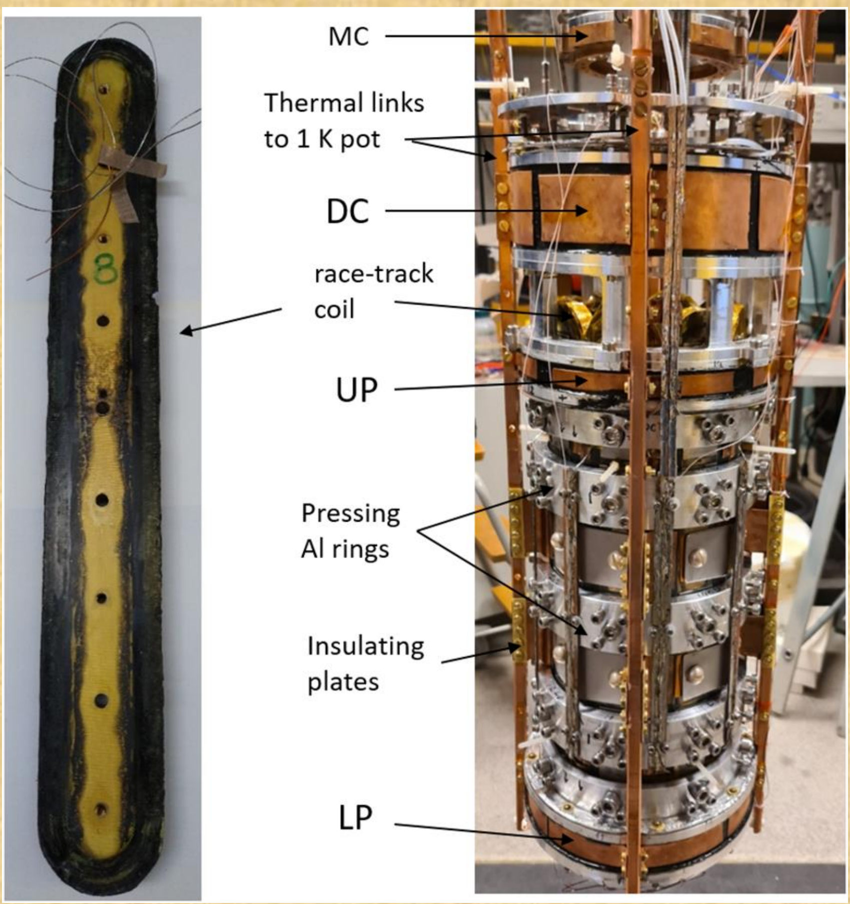
Ultimate accuracy in measuring the gravitational quantum states of hydrogen atoms. A source of ultracold hydrogen atoms and a magneto-gravitational hydrogen trap.

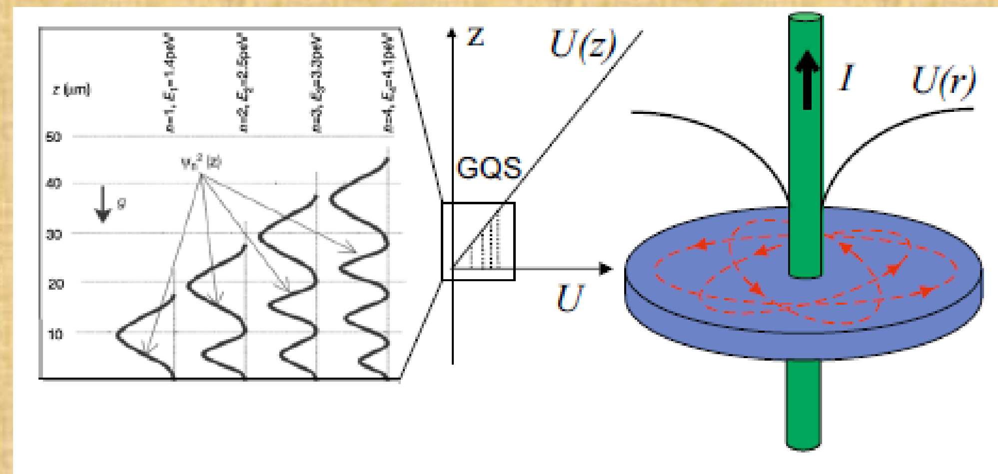
We plan to achieve this (at the University of Turku) as follows:

- Development of a source of ultra-cold atomic hydrogen/deuterium with record volume and density ([J. Ahokas, et al, *A large octupole magnetic trap for research with atomic hydrogen*, Rev. Sci. Instr. 93 (2022) 023201] and subsequent publications),
- Development of a magneto-gravitational trap [V.V. N. et al, *A magneto-gravitational trap for studies of gravitational quantum states*, Europ. Phys. J. C 80 (2020) 520] for long storage of atoms in GQS.

The expected accuracy of experiments can reach 10^{-6} or better, however, it is better to wait for real results and not predict them in detail in advance.

Ultimate accuracy in measuring the gravitational quantum states of hydrogen atoms. A source of ultracold hydrogen atoms and a magneto-gravitational hydrogen trap.





(Anti)atoms versus neutrons:

- Much larger phase-space density, compact, smaller systematics, smaller magnetic fields

Ultimate accuracy in measuring the gravitational quantum states of hydrogen atoms. A source of ultracold hydrogen atoms and a magneto-gravitational hydrogen trap.

Not only ultimate precision **gravitational spectroscopy** and search for **extra fundamental interactions**;

Also ultimate **Doppler-free** conditions for the improvement of **optical and hyperfine spectroscopy**

Conclusion

The methods of GQS and WGS have passed a long way: from an issue of **textbooks** to the **observation** with UCNs and possible **extension** to **other particles** (**atoms**, **antiatoms**, etc), also to the **applications** (including **search for fundamental short-range interactions**, physics **beyond Standard Model**, **surface studies**, **spectrometry**, etc).

- A **gravitational shift** of WGS of neutrons **has been measured** (the data analysis is in progress). The method **can and should be extended** to other neutral particles.
- Observation of **GQS of ultracold hydrogen/deuterium** atoms is a near-term prospect.
- **Precision** experiments with GQS and WGS of atoms offer exciting prospects, but require more effort.