Symposium for the 20th birthday of the Stefan Meyer Institute

GRASIAN

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

Pauline Yzombard, laboratoire Kastler Brossel

On behalf of the GRASIAN collaboration

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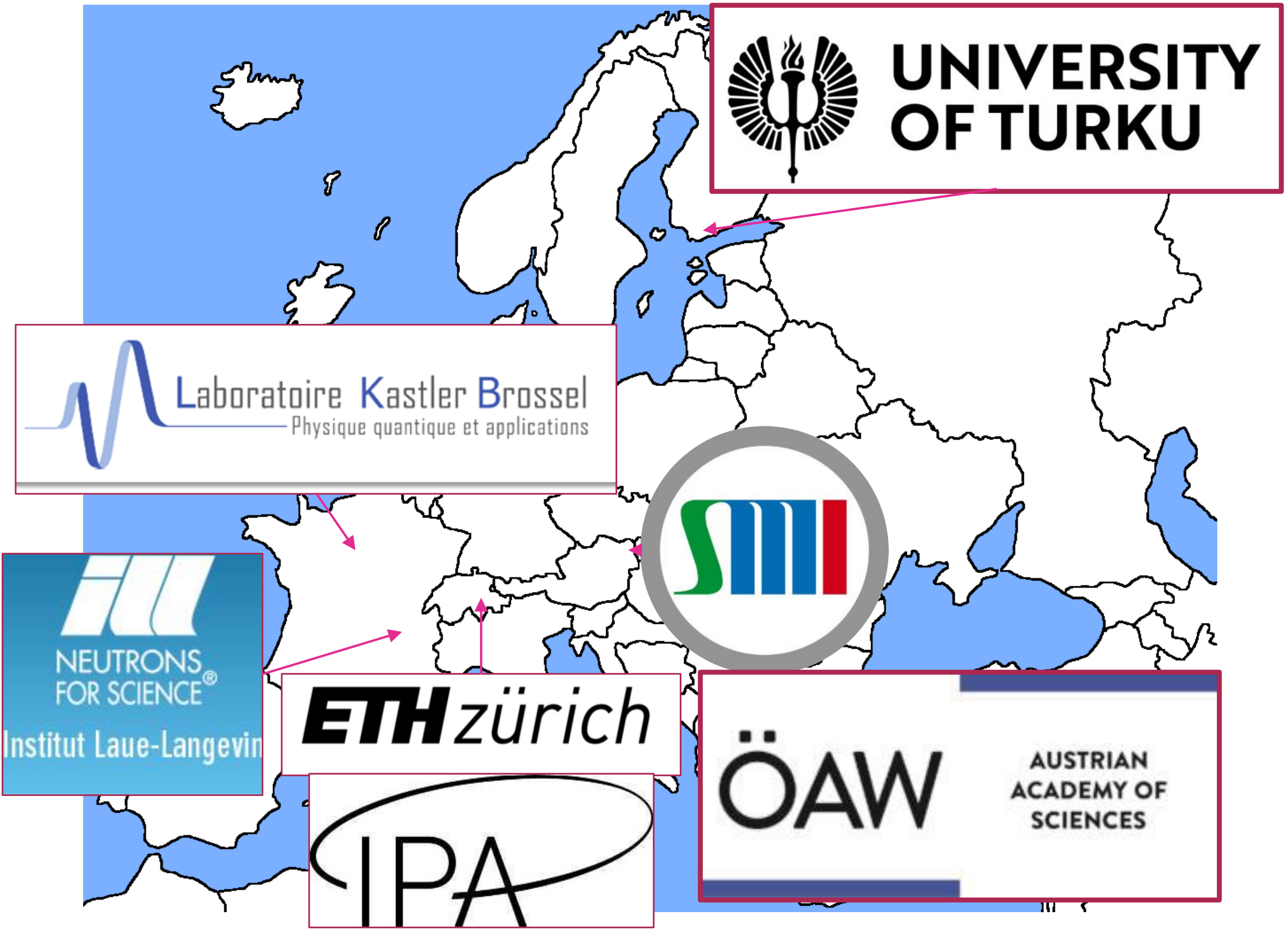
GRASIAN Collaboration



5 institutes accros Europe

- Institut Max von Laue – Paul Langevin,
- Institute of Particle Physics and Astrophysics, ETH Zürich.
- Laboratoire Kastler Brossel,
- Stefan Meyer Institute,
- University of Turku, Wihuri Physical Laboratory

Studying Gravitational Quantum States (GQS) and whispering gallery states of neutrons/hydrogens for:

- Short range fundamental forces caused by dark matter, extra dimension, new light bosons, dark energy
- CPT and Lorentz invariance violation (matter/antimatter tests)
- QED tests (spectroscopy)

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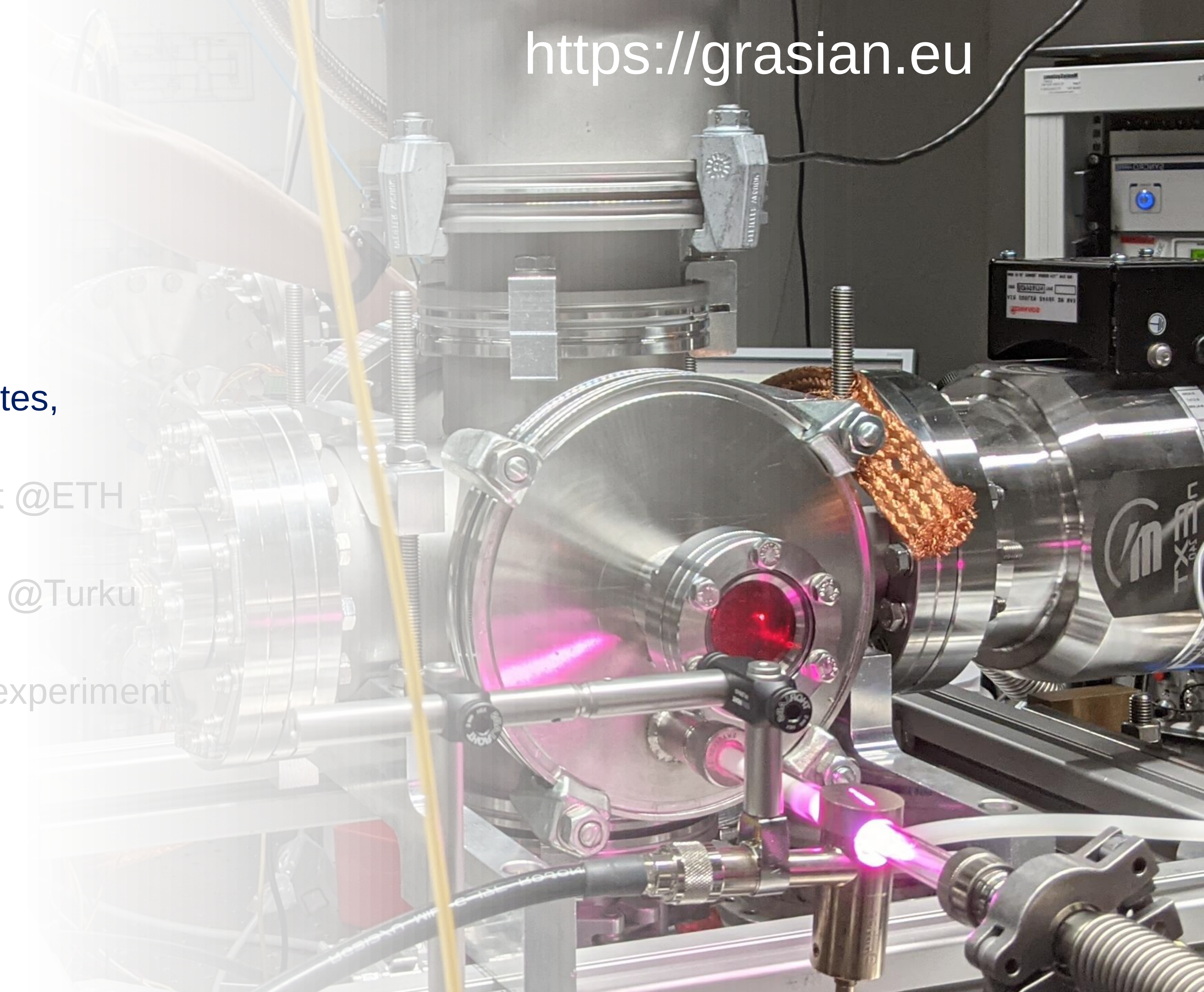
Overview

1. Gravitational quantum states,
   Was ist das ?
2. The “in-beam” experiment @ETH Zürich/ SMI
3. The “trapped” experiment @Turku University (Finland)
4. The whispering galleries experiment @ ILL Grenoble (France)



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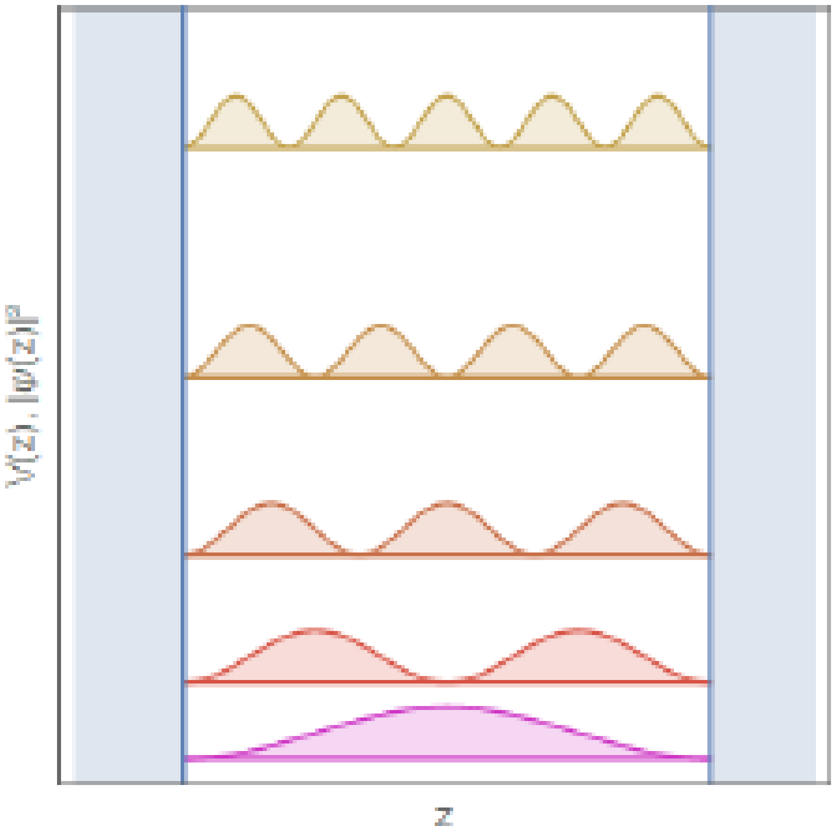
1. Gravitational quantum states (GQS), Was ist das ?

- Any trapped particle in a potential well
  $\Rightarrow$ has its energy quantized E_n
  $\Rightarrow$ has its probability of founding the particle in space $|\varphi_n(z)|^2$ that depends on the quantum state n



Example:
1D infinite squared well

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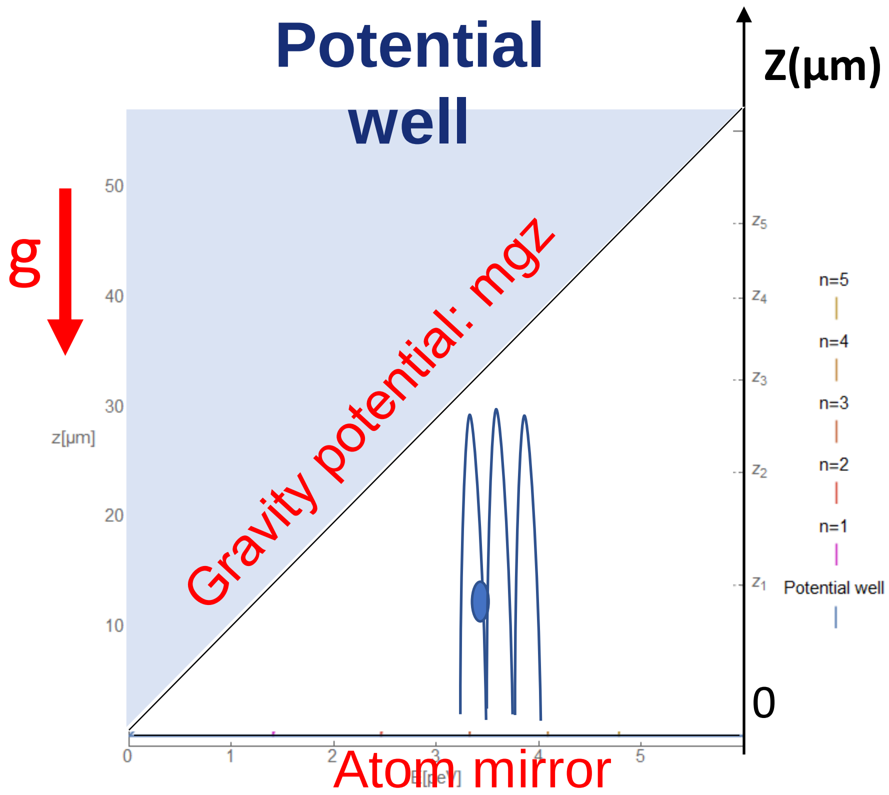


- Particle **confined**: **(1D trap)**
  - In the **top**: by Gravitational potential
  - In the **bottom**: by quantum reflections onto the surface

$\Rightarrow$ behaves like an “atom mirror”.

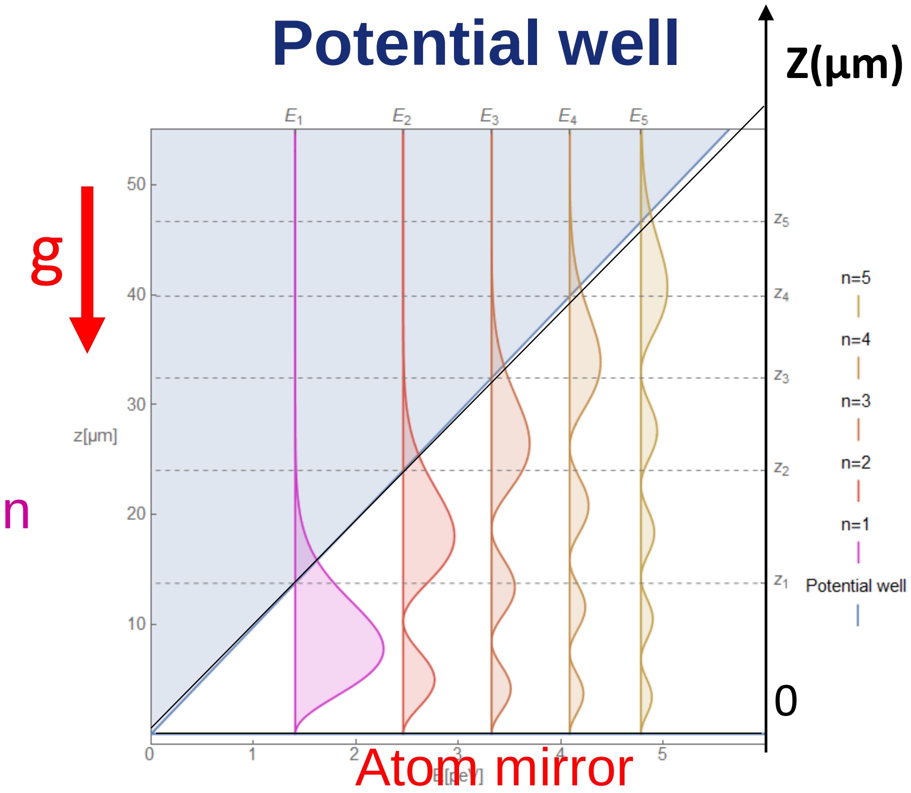
Quantum reflection: specular reflection of the slow particle (wave-packet) which sees a steep potential step when approaching to the surface

1. Gravitational quantum states (GQS), Was ist das ?

- Particle **confined**: **(1D trap)**

$$\frac{\hbar^2}{2m}\frac{d^2\psi(z)}{d^2z}+(E-mgz)\psi(z)=0$$

⇒ Solution Ψ = Airy function
(z_n= zeros of the function)



n	E_n [peV]	z_n [µm]
1	1.4	13.8
2	2.5	24.0
3	3.3	32.4
4	4.1	39.9
5	4.8	46.6

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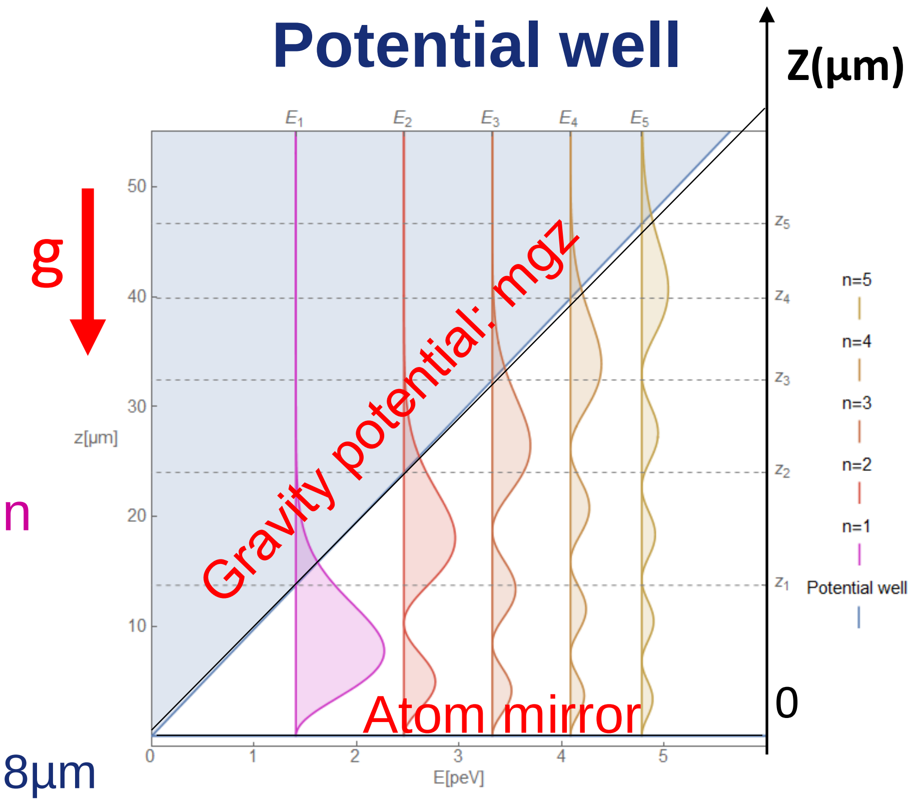

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Eigenenergies E_n ~peV (~100Hz) $E_n = mgz_0\lambda_n$ with $z_0=\sqrt[3]{\frac{\hbar^2}{2m^2g}}$ ~5.8µm

Heisenberg's uncertainty: $\Delta t\Delta E \geq \frac{\hbar}{2} \rightarrow \boldsymbol{\Delta t \gtrsim 0.5\mathrm{ms}}$

⇒ **Needs long interaction** time to "form" the GQS

⇒ **QR coefficient increases** when **m** and $\mathbf{v}_\perp$ decrease

⇒ **Requires "light" + very slow ("ultra-cold") atoms/neutrons**

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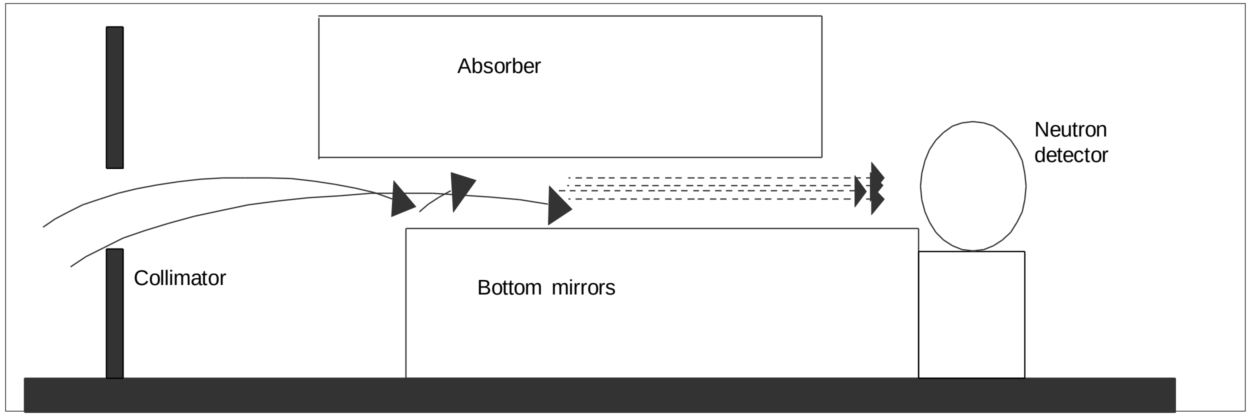
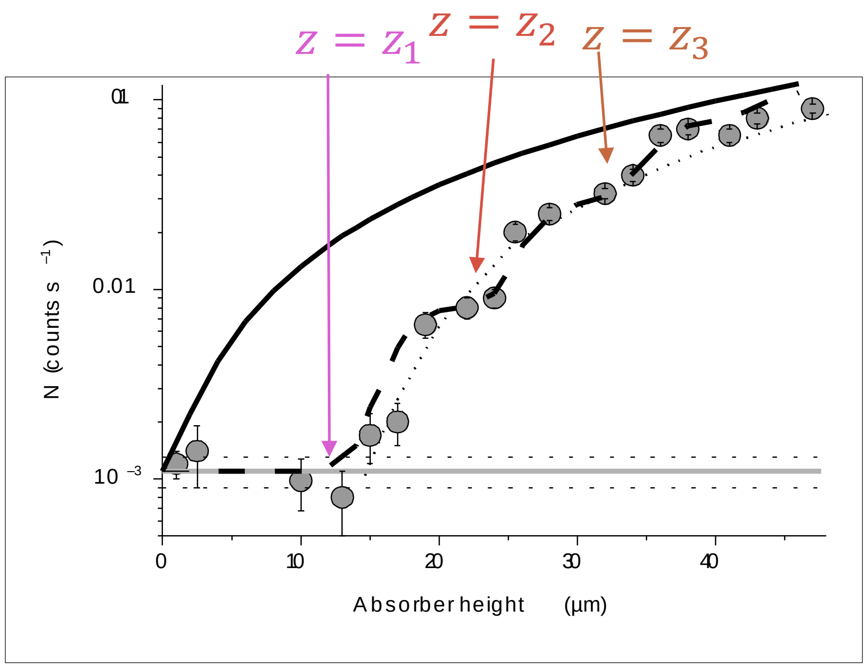
GQS of ultra cold neutrons (UCNs)

2002: First experimental demonstration of GQS with ultra cold neutrons (UCNs) [1]

- UCNs flow between mirror and absorber separated by slit Δz





Figures taken from [1].

- Measurement of neutron transmission N as function of Δz
  - Stepwise increase predicted for GQS (steps at $z = z_n$)
  - Slit only becomes transparent, when $\Delta z \geq z_1$

Realized at ILL (Grenoble)

[1] Nesvizhevsky, V., *et al.* Quantum states of neutrons in the Earth's Gravitational field. *Nature* **415,** 297–299 (2002). https://doi.org/10.1038/415297a

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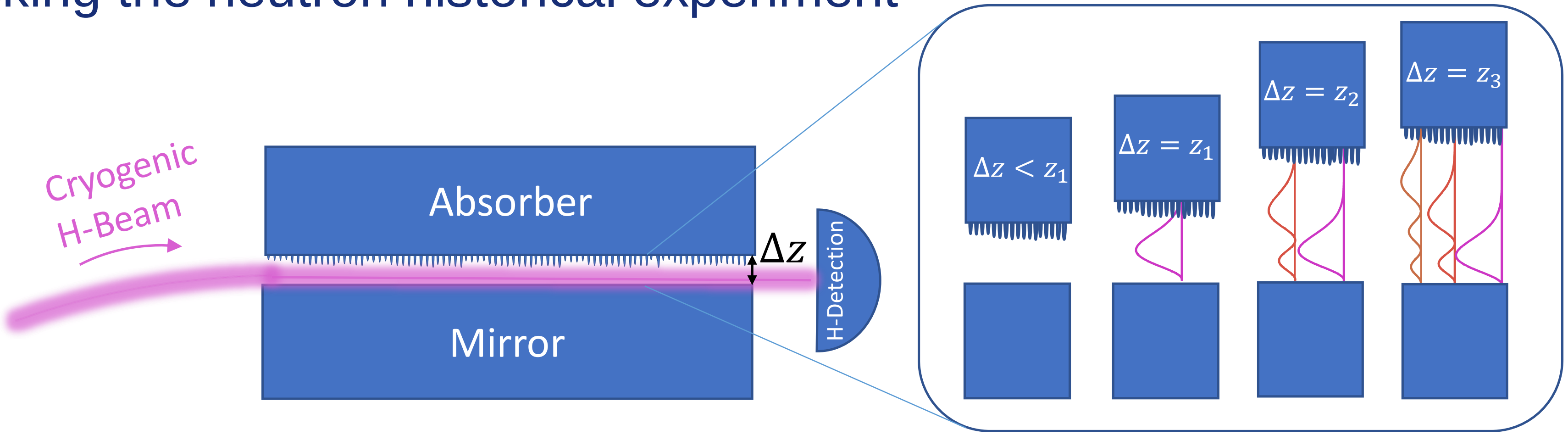
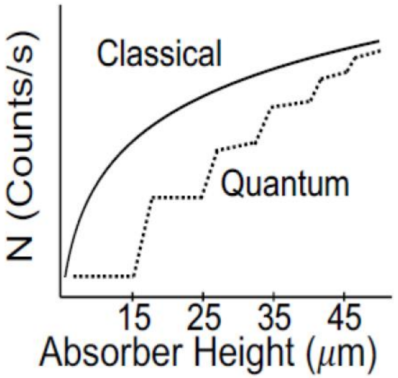
2. The “in-beam” experiment @ETH Z/SMI

towards the 1st demonstration of GQS with H

- Mimicking the neutron historical experiment





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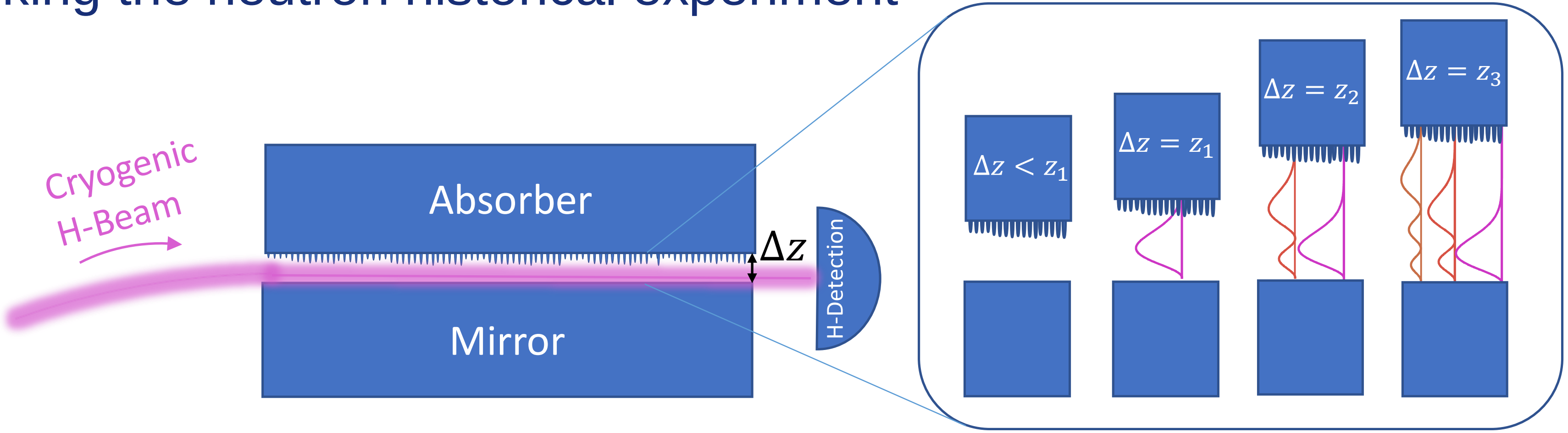

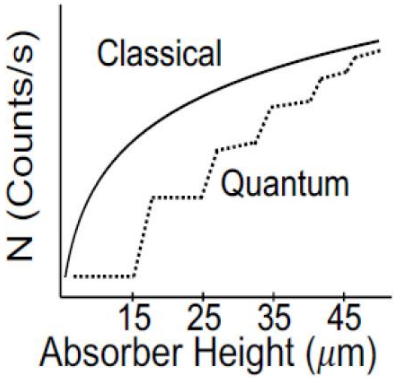

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Motivation (H vs. neutrons):

  - GQS never measured for atoms! Different interaction potential with surface compared to neutron $\Rightarrow$ research of short-range extra forces
  - Easy to generate (hydrogen bottle vs. research reactor) → Much higher fluxes available
  - Developed methods also applicable for antiatoms ($\rightarrow \bar{g}$)

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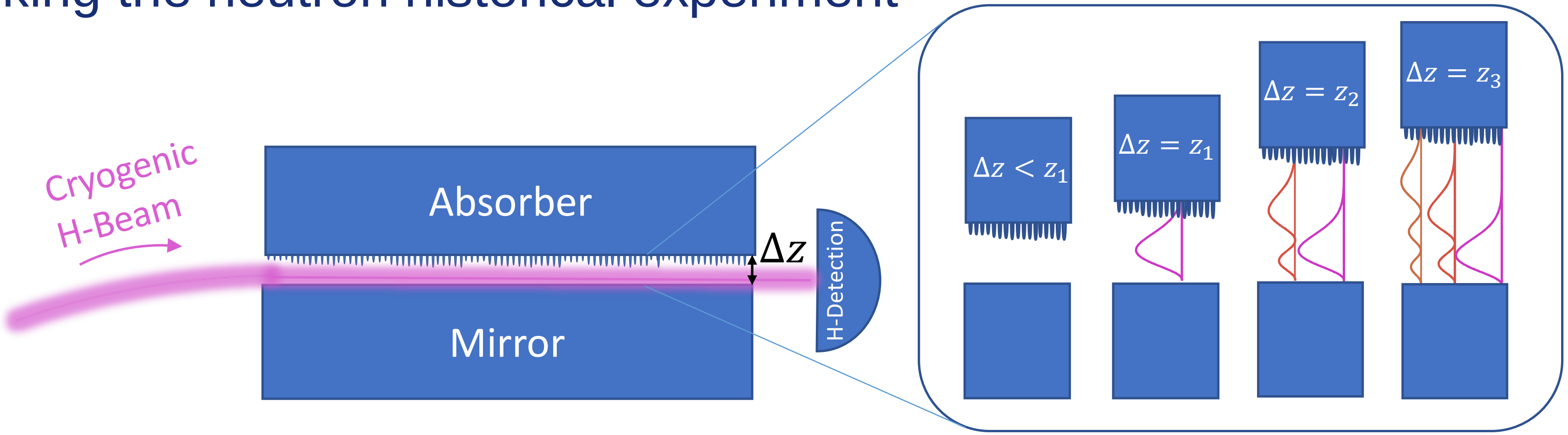

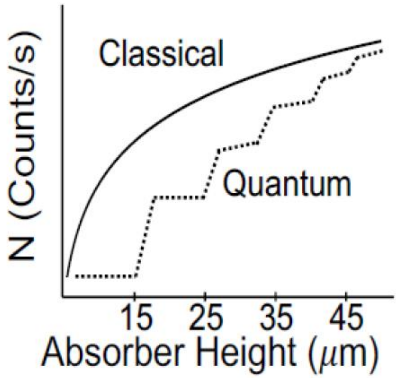

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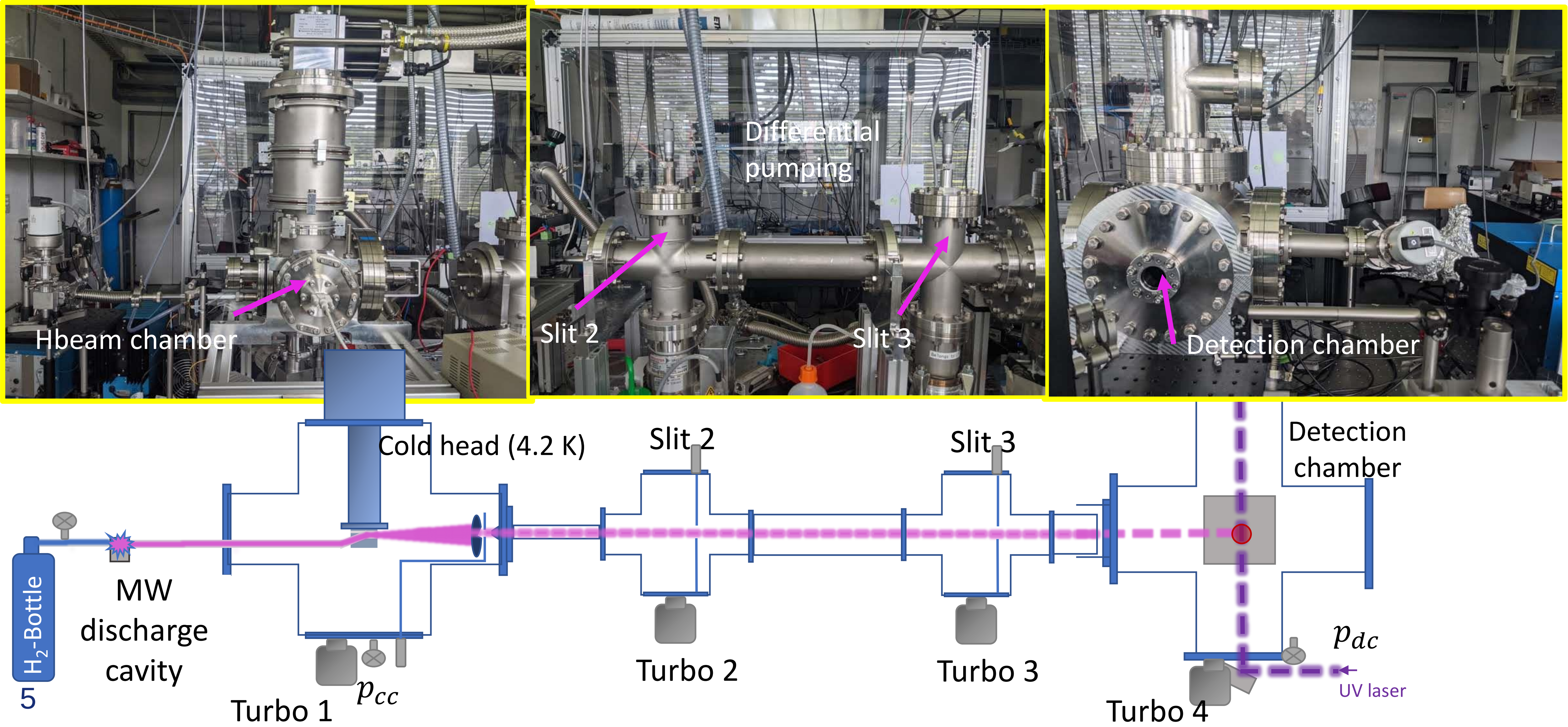
Requirements:

- **Efficient detection of hydrogen**
- **Good signal/background**
- **(Very) Cold hydrogen beam:**
  - **Slow: $v_{\parallel}$ ~ 50 m/s horizontally**
  - **Highly collimated ($v_{\perp}$~3 cm/s)**

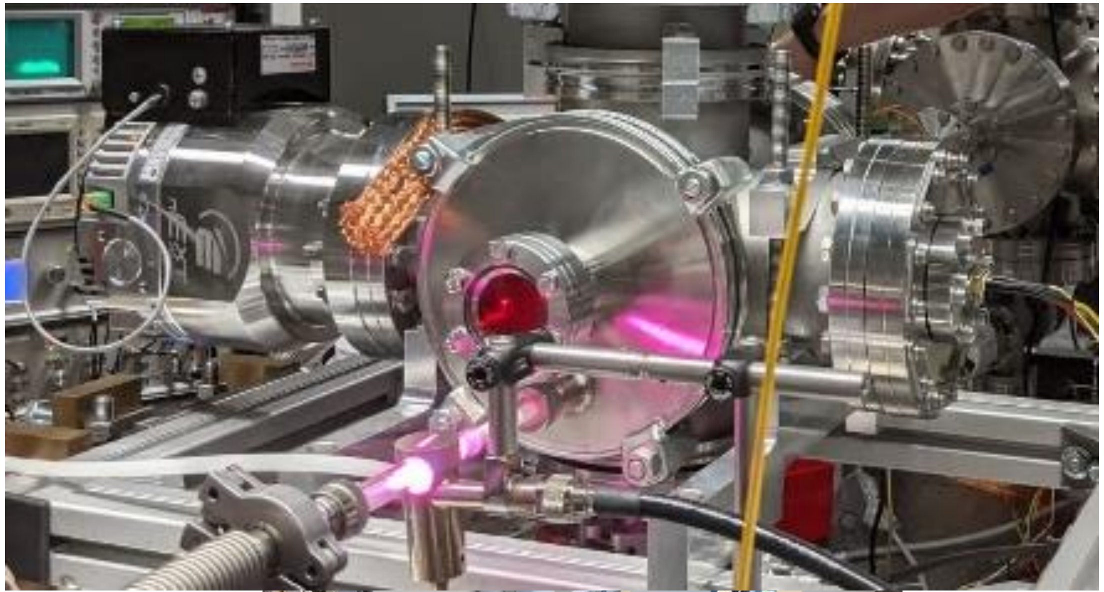
2. **The “in-beam” experiment @ETH Z**

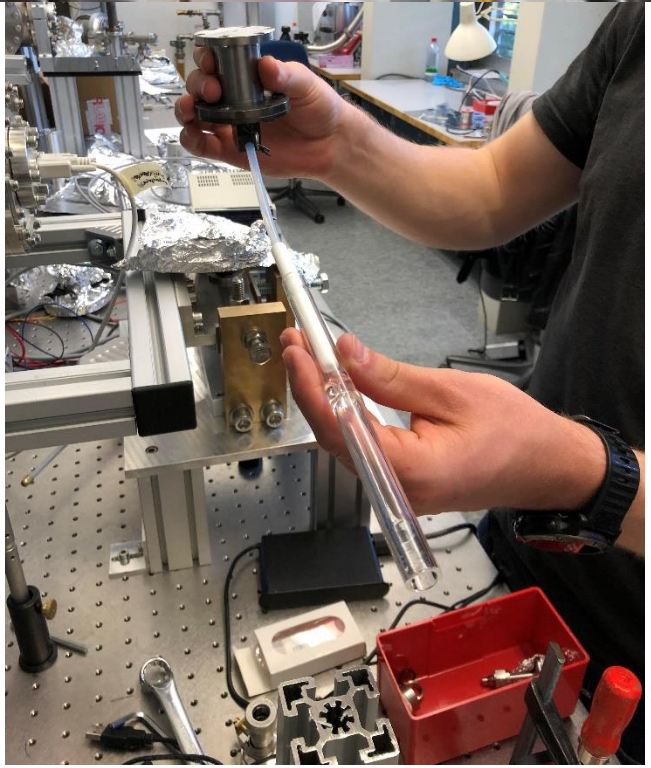
In pictures (ETH Zürich setup – 2020-2023)

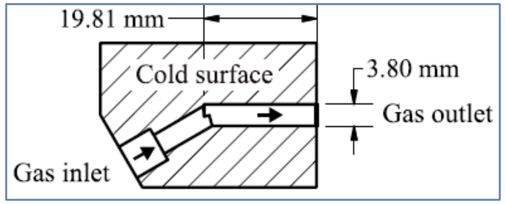


Hydrogen source

- H_2–gas Bottle
- Microwave discharge cavity
  - $\sim 10^{17}$ H/s
- Teflon tube
- Coldhead + Cryogenic nozzle: $290\ \mathrm{K} \rightarrow\ 6.5\ \mathrm{K}$



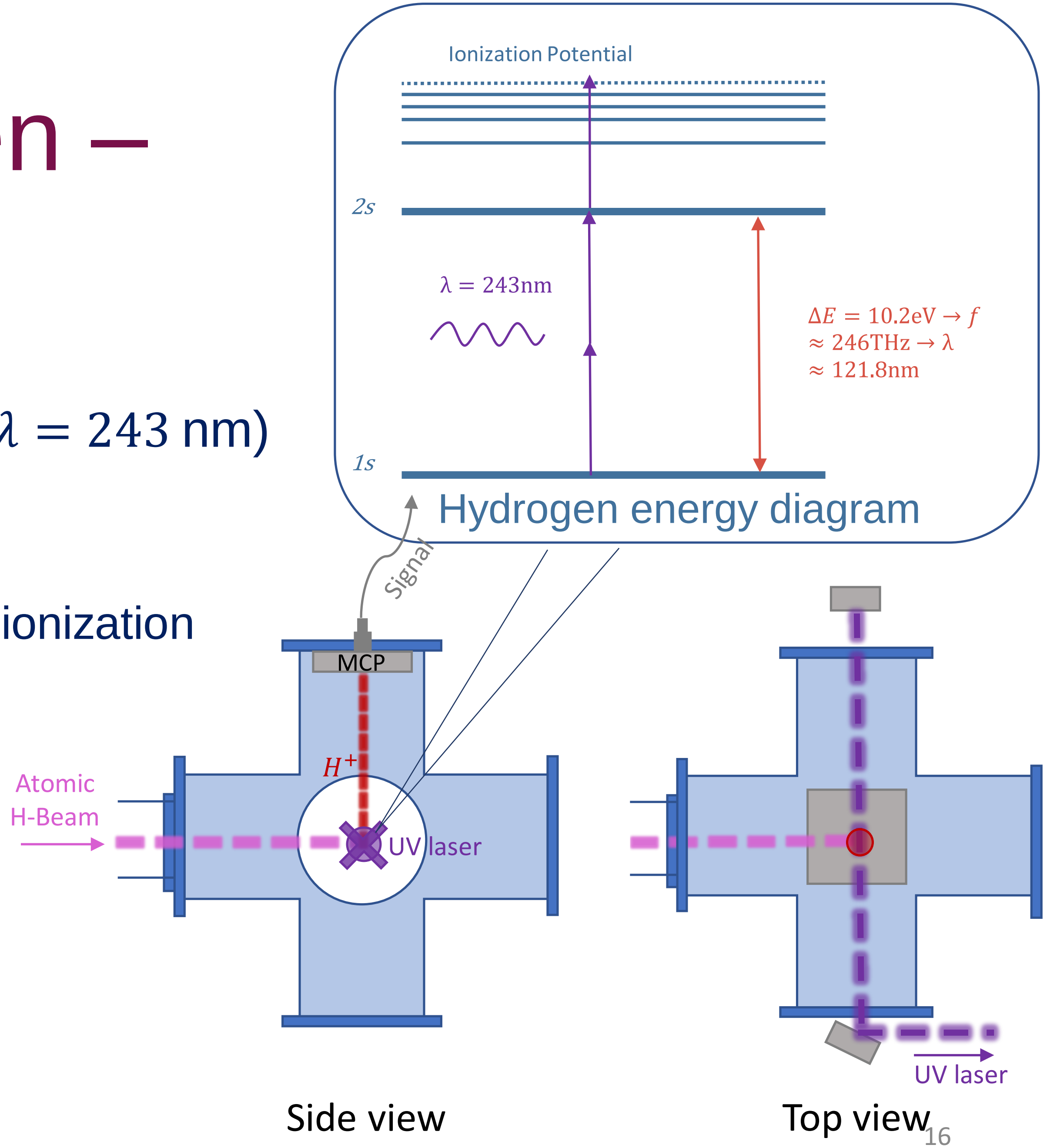




Slide: courtesy of C. Killian

Detection of hydrogen – overview

- Ionization of H with a pulsed UV-laser ($\lambda = 243$ nm)
  - $\mathrm{H} \rightarrow \mathrm{H}^{+} + \mathrm{e}^{-}$
  - 2 photon excitation (1S-2S) + 1 photon ionization
- Detection of H^{+} with an MCP
- Integrated MCP-Signal ∝ H- count rate



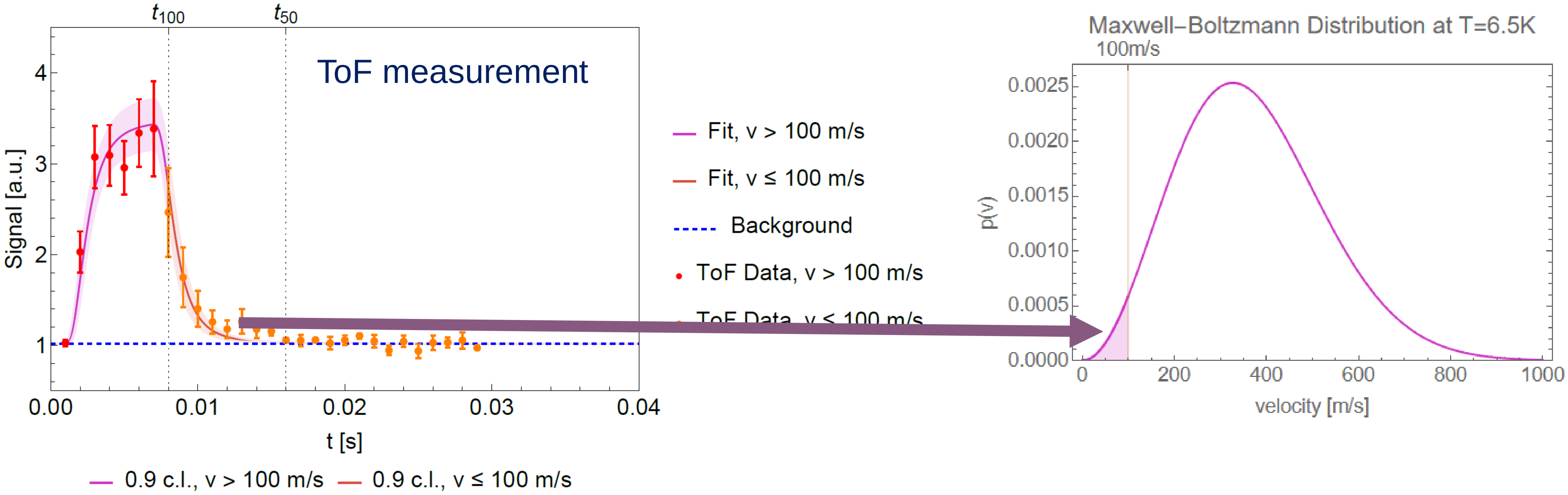
Slide: courtesy of C. Killian

2. Characterization of the H-beam source (ETH Z)

Work performed in 2020- 2022, [2] Killian, Carina, et al.

- **Goal**: generating H atoms @ **$v_{\parallel}$ ~ 50-100 m/s horizontally**

⇒Selection of the atoms in the tails of the Maxwellien distribution



[2] Killian, Carina, et all (Grasian Collaboration) *Grasian: towards the first demonstration of Gravitational quantum states of atoms with a cryogenic hydrogen beam*. Eur. Phys. J. D, 77(3):50, 2023.

2. Optimization of the background (ETH Z)

Work performed in 2023, [3] Killian Carina, et al.

Goal: reducing as much as possible the background H signal (“H rest gas in the chamber” not coming from the H beam directly)

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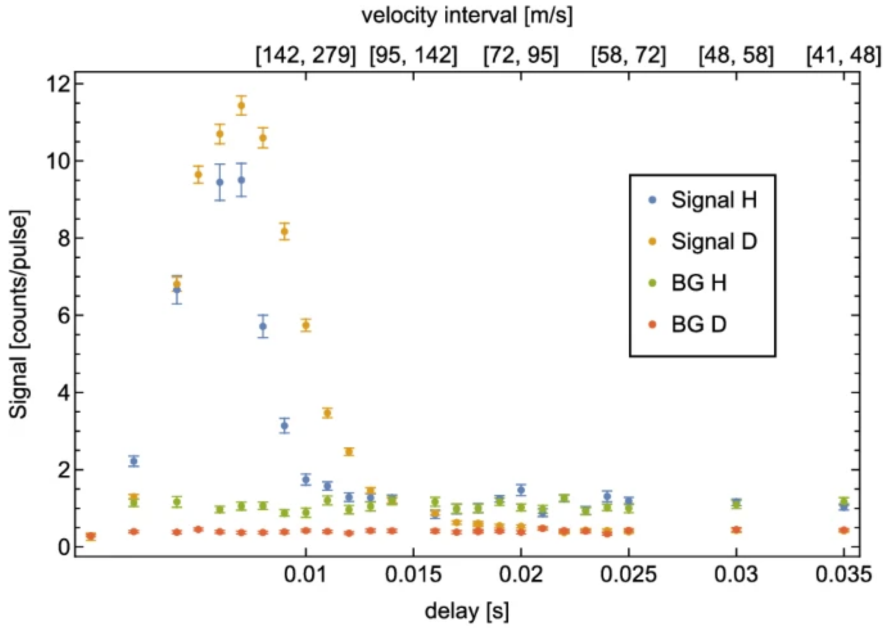
⇒Switching to Deuterium atoms

Fig. 13



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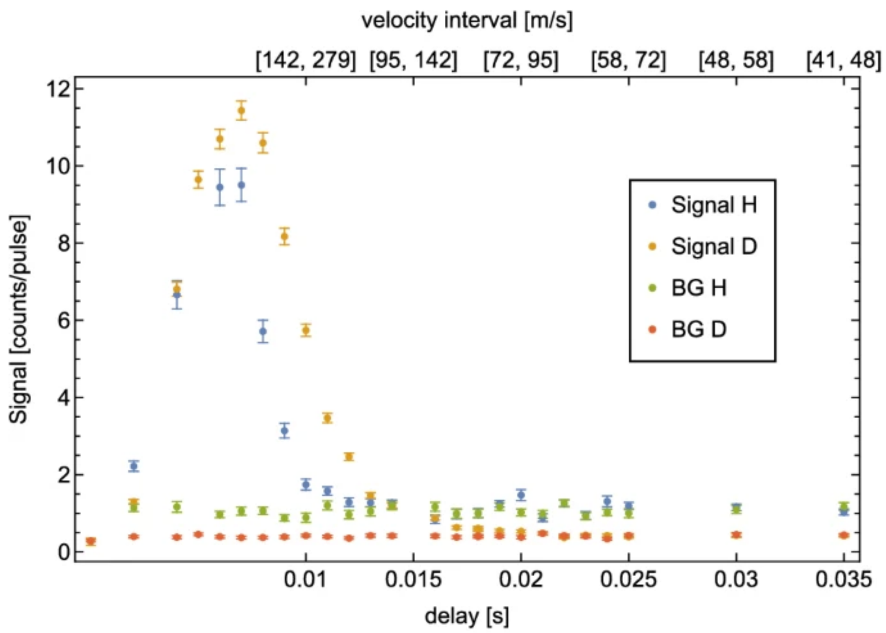
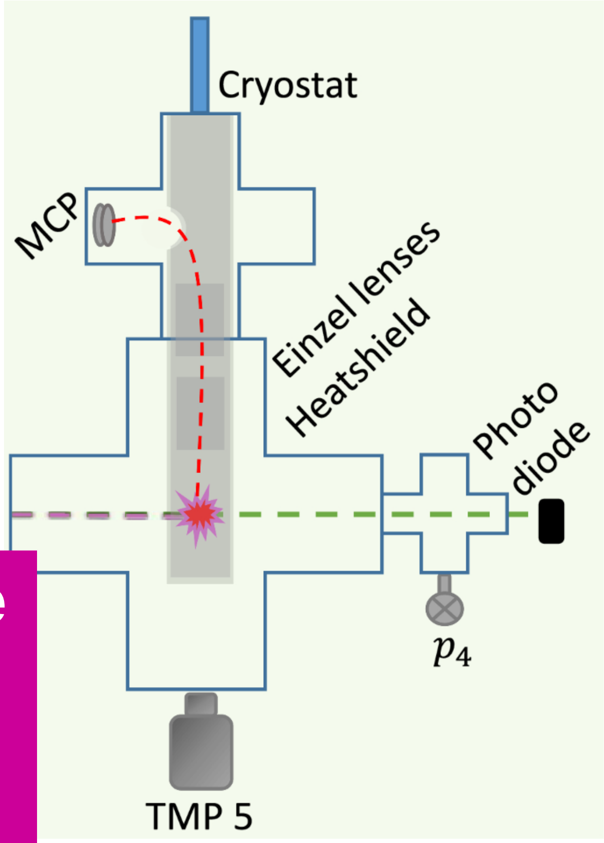


⇒Test of cryogenic shield in the detection Chamber

(Turku design -S. Vasiliev- Wet cryostat)

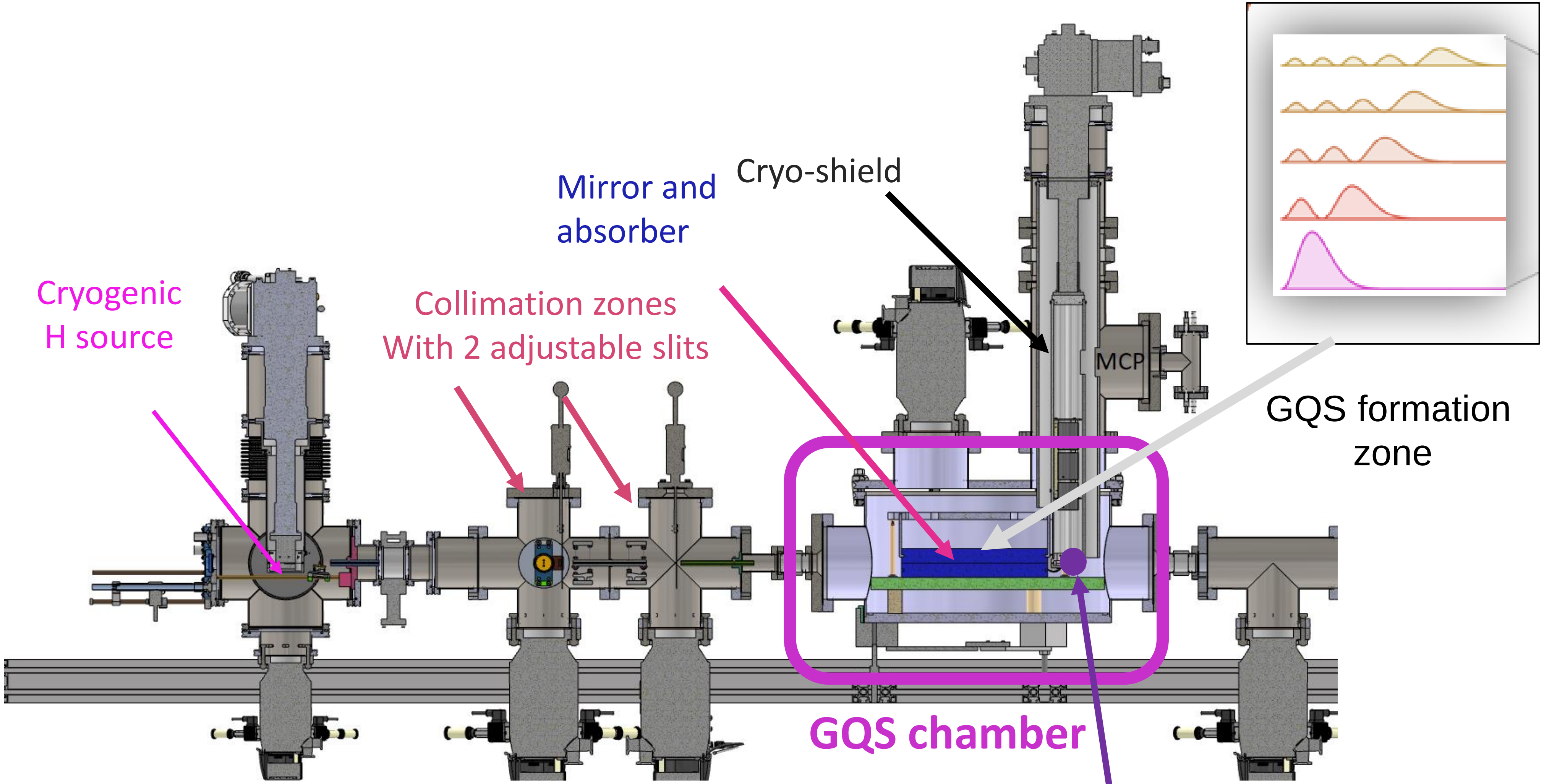


Total reduction of the background signals by 2 orders of magnitude

[3] Killian, Carina, et al. (Grasian Collaboration) *GRASIAN: shaping and characterization of the cold hydrogen and deuterium beams for the forthcoming first demonstration of gravitational quantum states of atoms*. Eur. Phys. J. D, 78 132 2024.

2. The “in-beam” experiment @SMI

Experimental status – new design (2024)



Mirror and
absorber

Cryo-shield

Cryogenic
H source

Collimation zones
With 2 adjustable slits

GQS formation
zone

GQS chamber

Photodetachment laser (detection zone)

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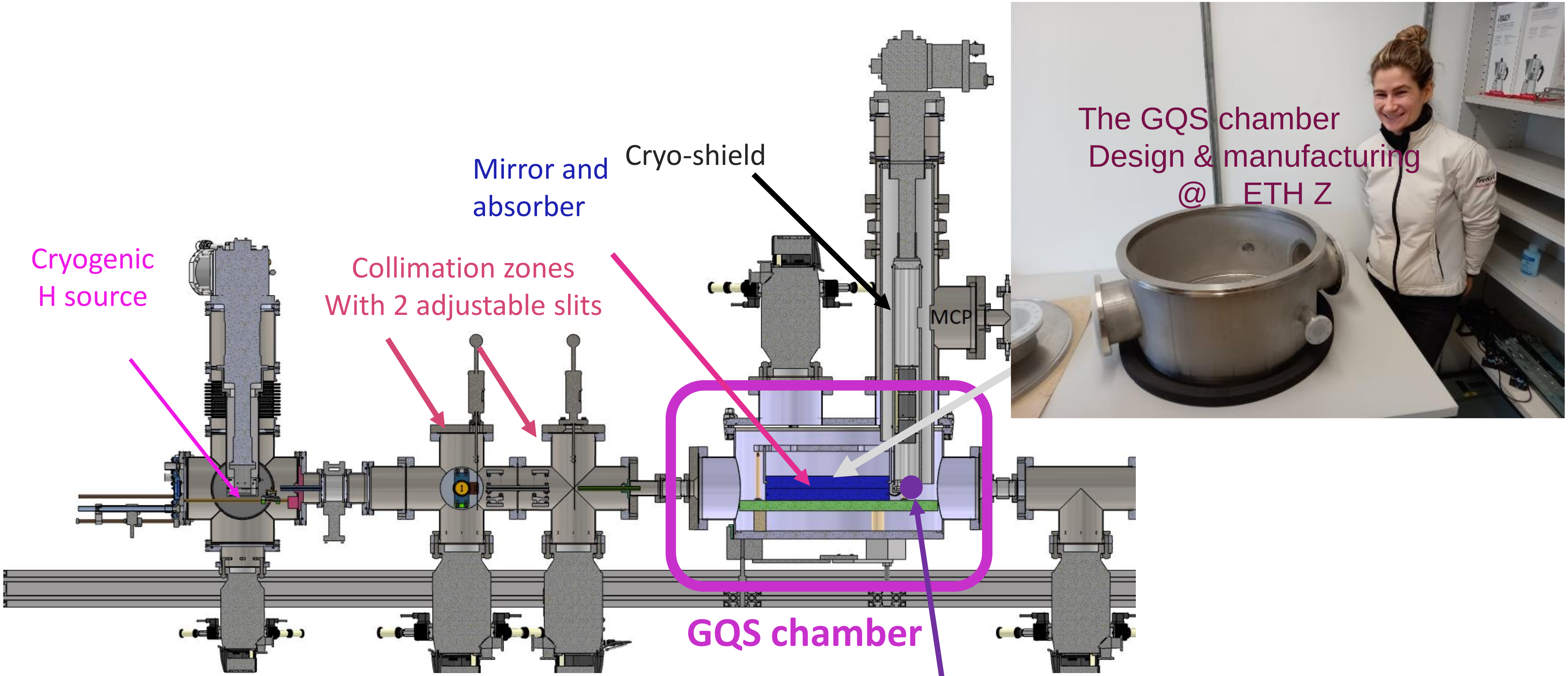

The GQS chamber
Design & manufacturing
@ ETH Z

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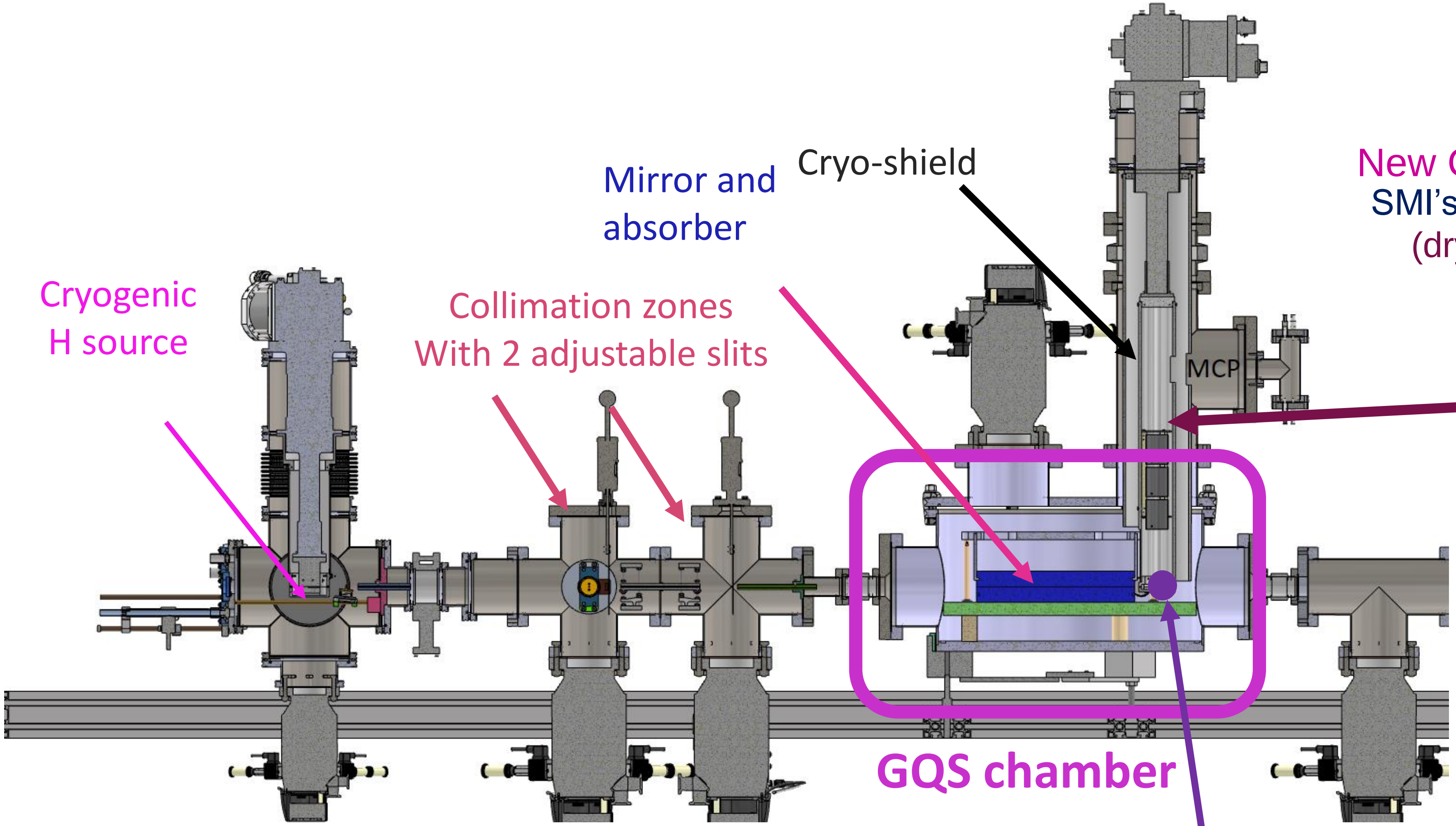

Cryogenic H source

Collimation zones With 2 adjustable slits

Mirror and absorber

Cryo-shield

GQS chamber

Photodetachment laser (detection zone)

New Cryo-shield

SMI’s new design (dry system)

2. The “in-beam” experiment @SMI
Experimental status – new design (2024)

30th of July 2024 !

A fully refurbished lab !

2. The "in-beam" experiment @SMI
Experimental status – new design (2024)

September 2024 !

A fully refurbished lab !

Improved results

- **Requirements:**
  - **Efficient detection of hydrogen** ✓
  - **Good signal/background** ✓ *(to be confirmed soon)*
  - **(Very) Cold hydrogen beam:**
    - **Slow: $v_{\parallel}$ ~ 50 m/s horizontally** ✓
    - **Highly collimated ($v_{\perp}$~3 cm/s)** *In progress*

Ready for first trials of GQS observations on H beam soon !

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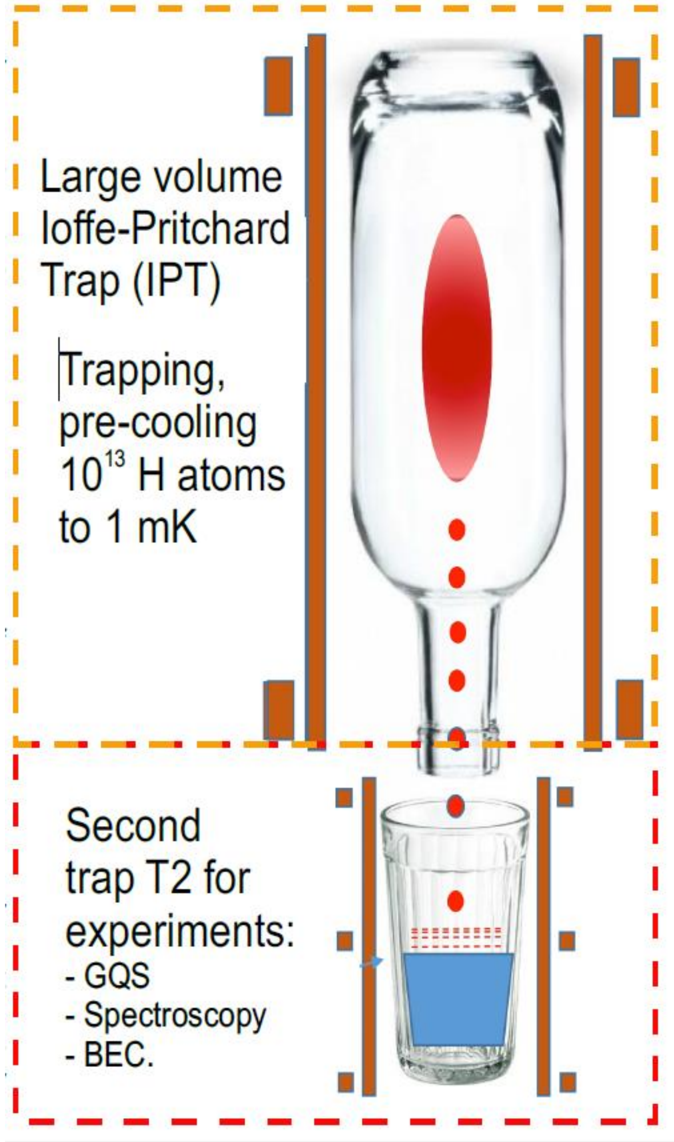
3.The “trapped” experiment @Turku University,Finland

Goal: trapping ultra-cold H for long-living GQS

Idea:
Magnetic bottle (IPT) and magneto gravity (T2) traps in cryogenic environment
(<100 mK)

V. V. Nesvizhevsky, et al. A magneto-Gravitational trap for precision studies of Gravitational quantum states. Eur. Phys. J. C 123, 1–10 (2020)



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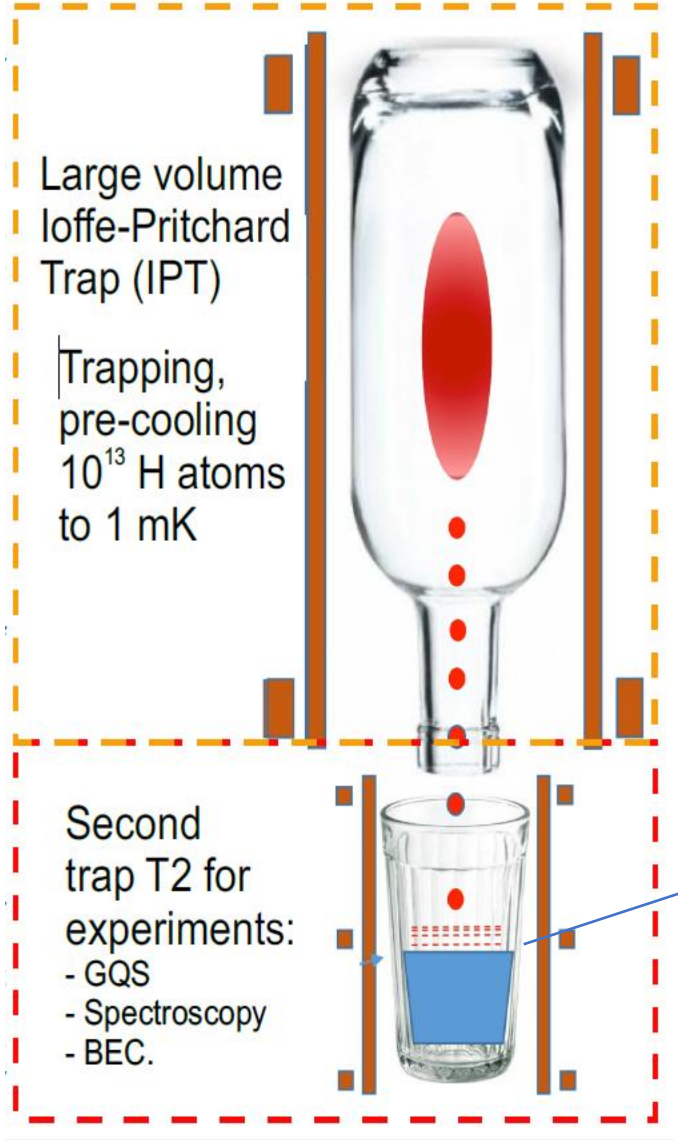
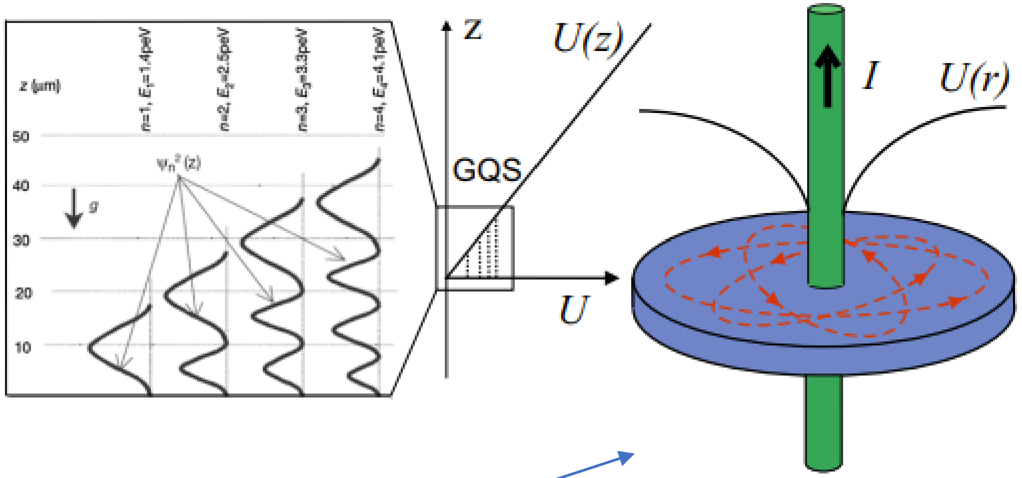


Large volume Ioffe-Pritchard Trap (IPT)

Trapping, pre-cooling 10^{13} H atoms to 1 mK

Second trap T2 for experiments:
- GQS
- Spectroscopy
- BEC.



Magneto-Gravitational trap:
Z-axis trapped by gravity and QR
Radial trapping: magnetic confinement

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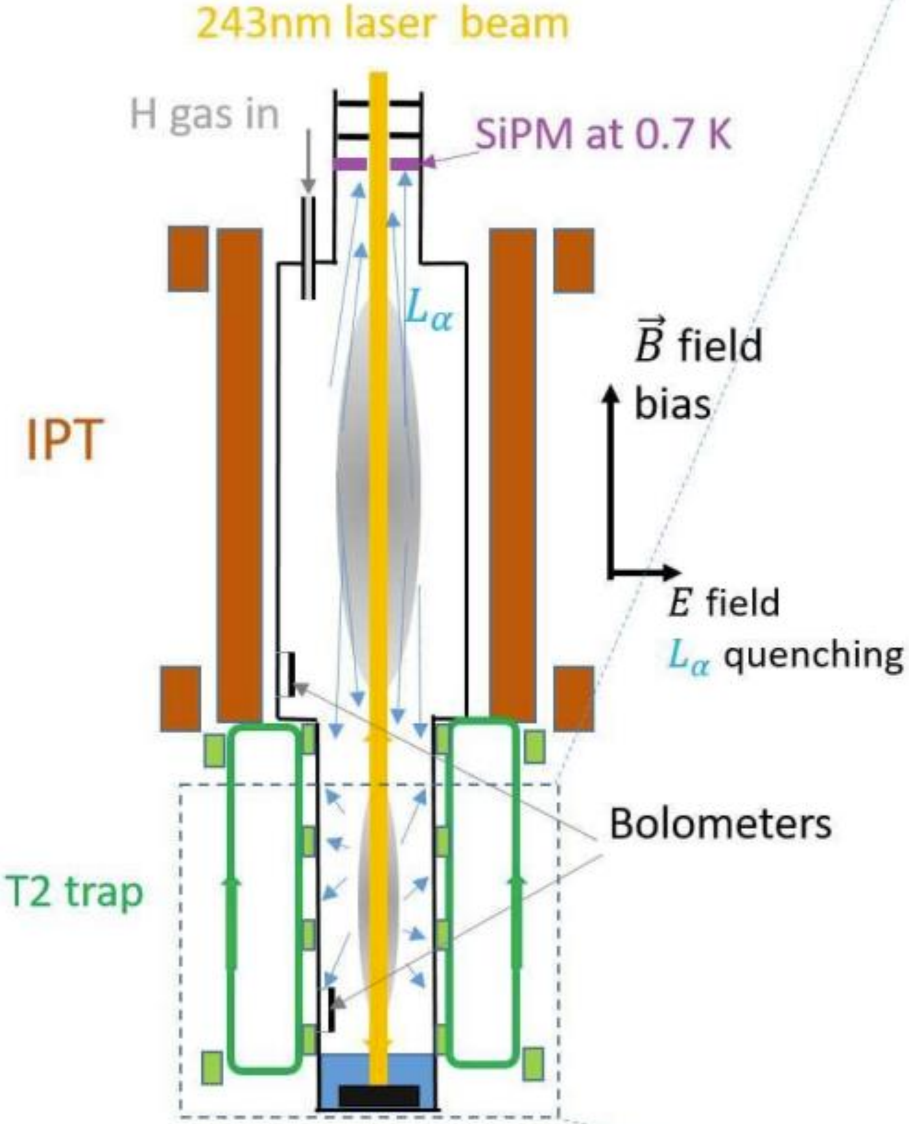
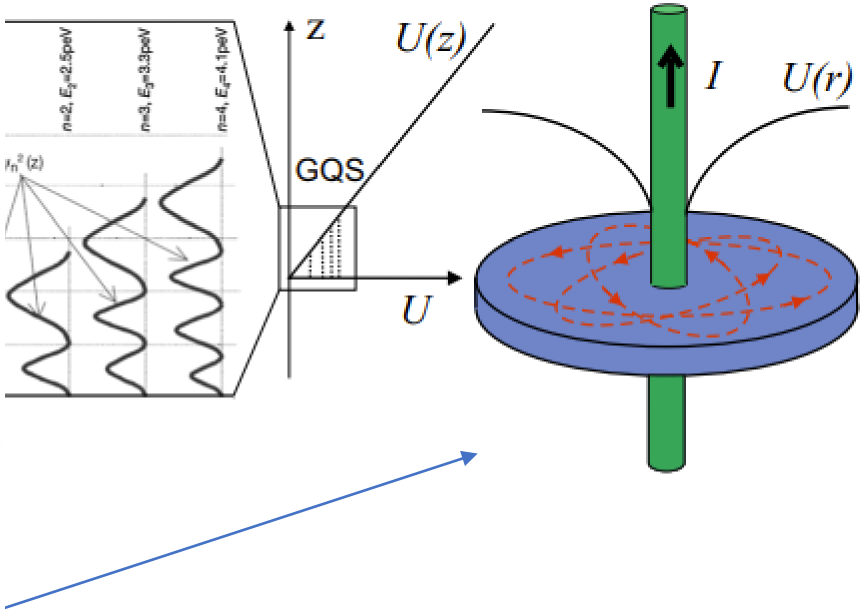
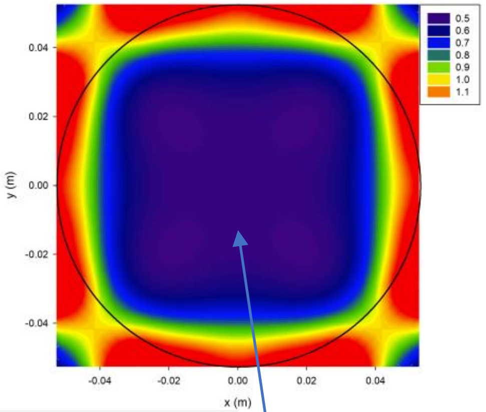


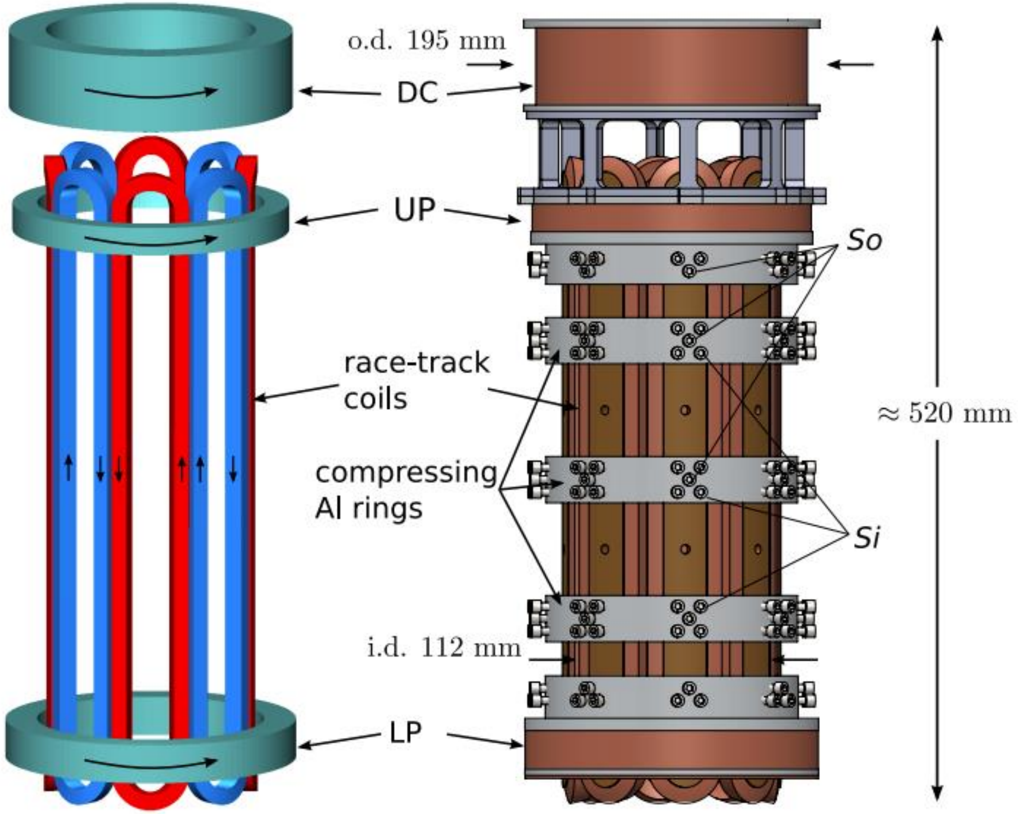


Magneto-Gravitational trap:
Z-axis trapped by gravity and QR
Radial trapping: magnetic confinement

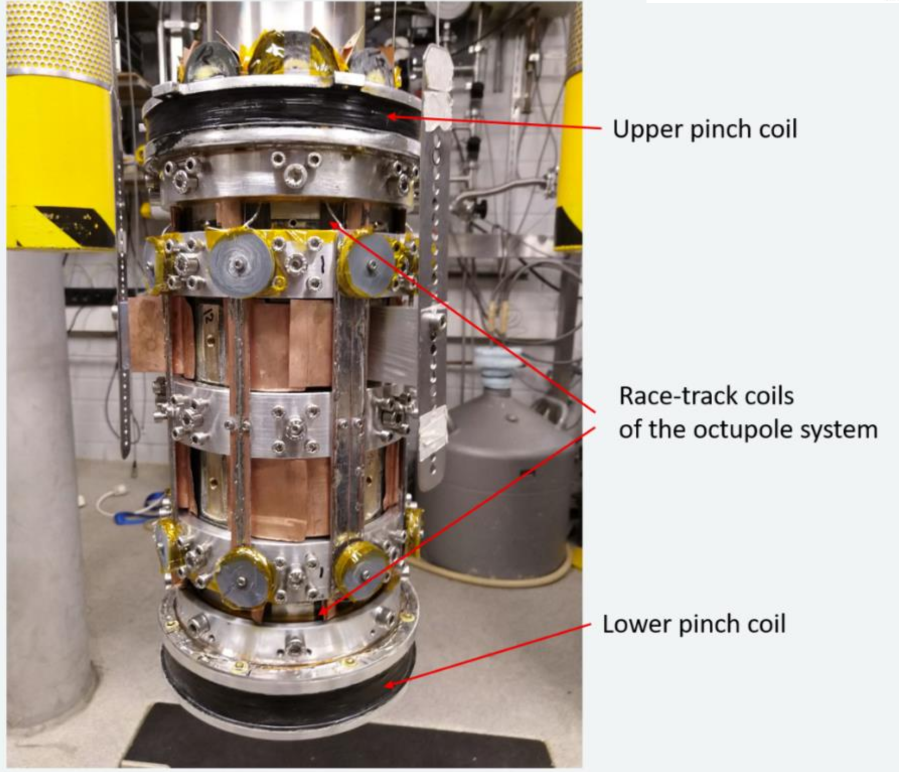
The IPT trap: a large octupole magnetic trap [5]



Trapping
region
of low-field
H seekers



IPT prototype in Turku



[5] J. Ahokas, et al., *A large octupole magnetic trap for research with atomic hydrogen*, RSI **93** (2022) ARTN 023201

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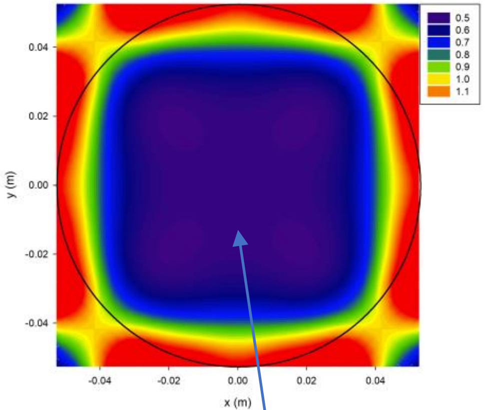

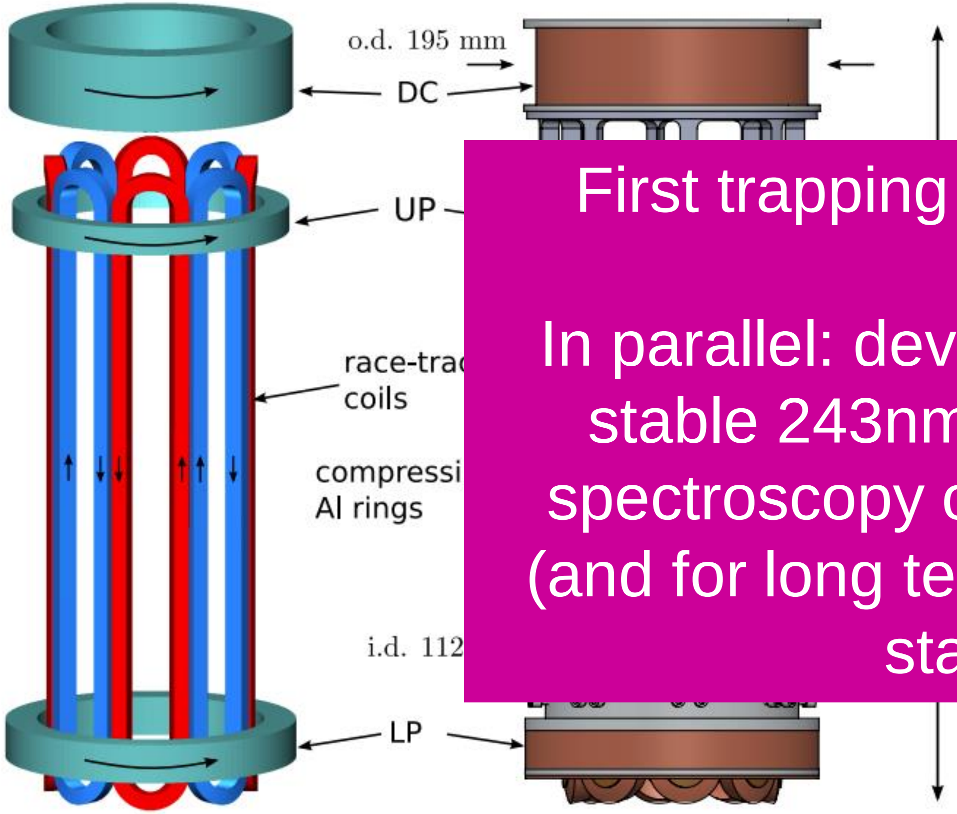

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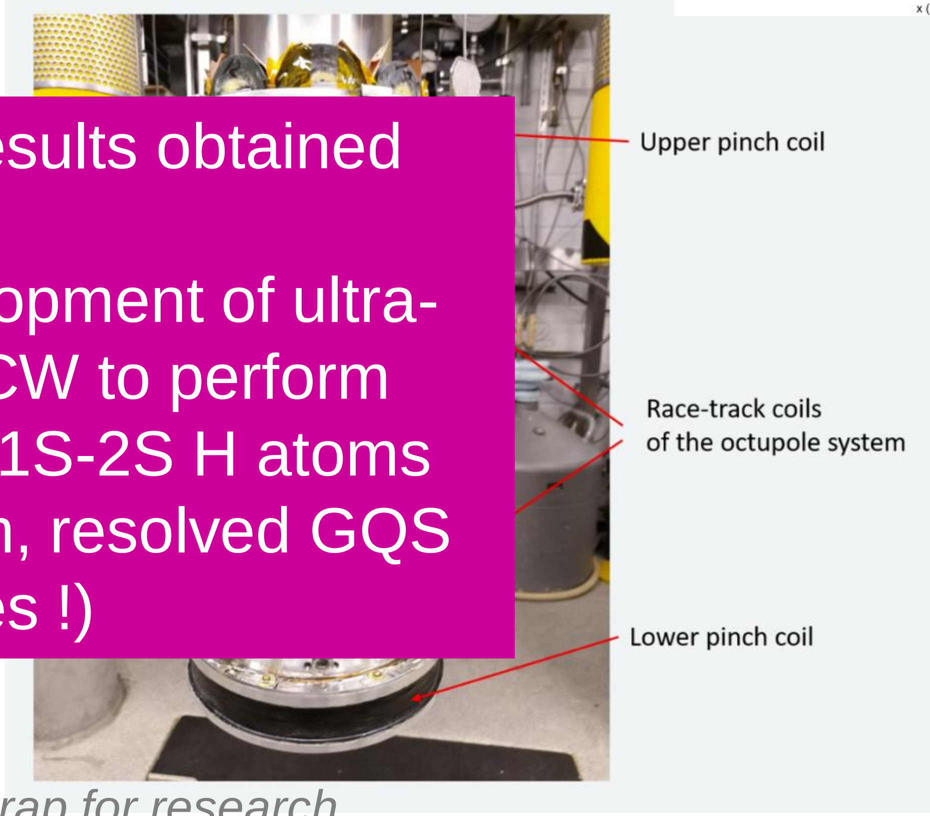

First trapping results obtained

In parallel: development of ultra-stable 243nm CW to perform spectroscopy of 1S-2S H atoms (and for long term, resolved GQS states !)

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region
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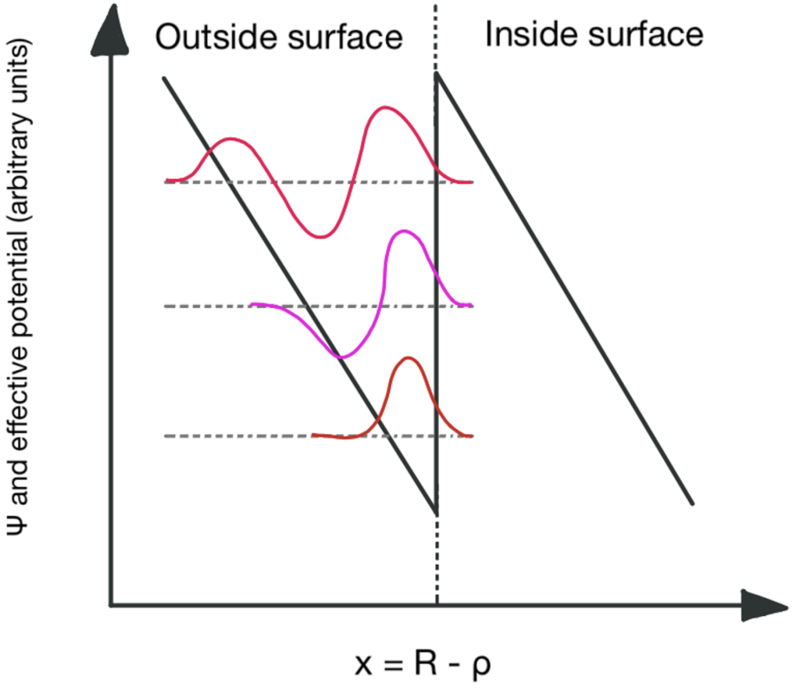
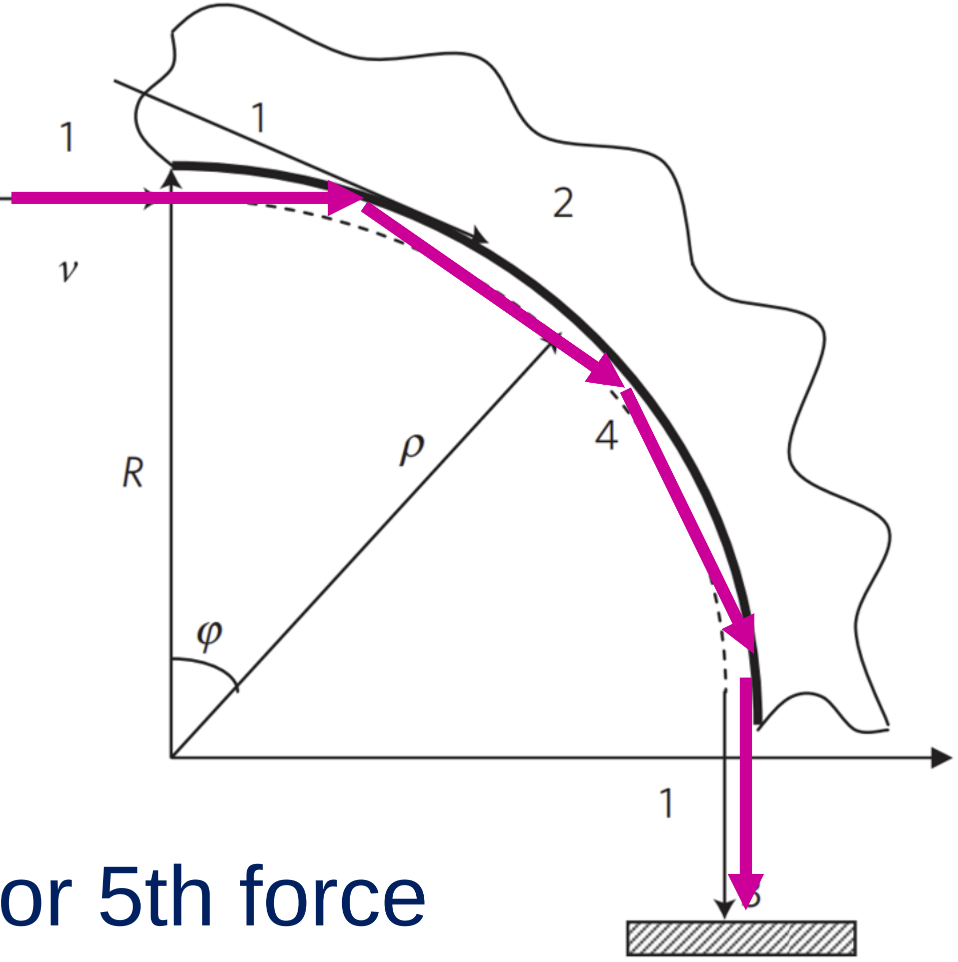
With Ultra-cold NEUTRONS

- Whispering modes



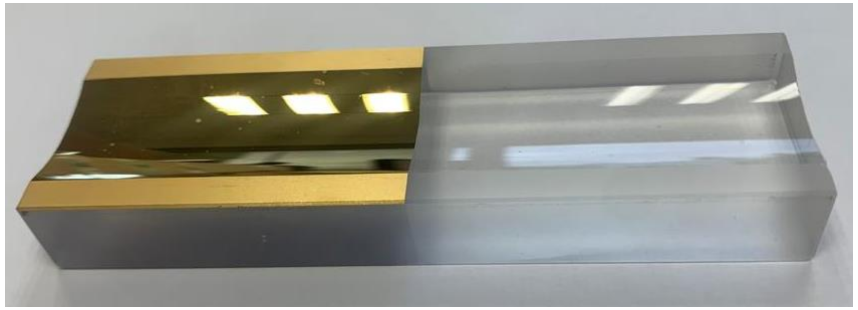


Research for 5th force

$$V_{total}(x) = U_0 \Theta(-x) + \frac{m {v_\parallel}^2}{R} x + \frac{\alpha e^{-x/\lambda}}{x}$$

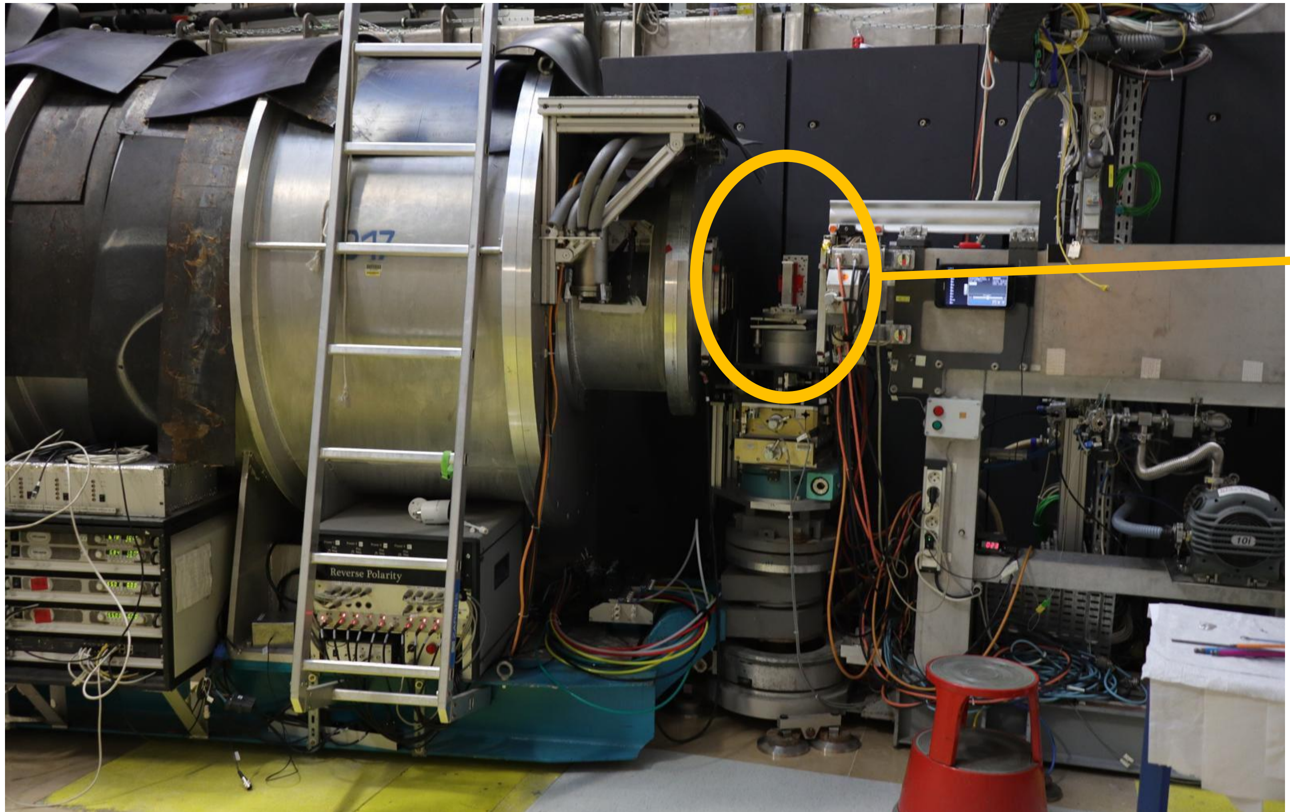
Hypothetical Yukawa-type force

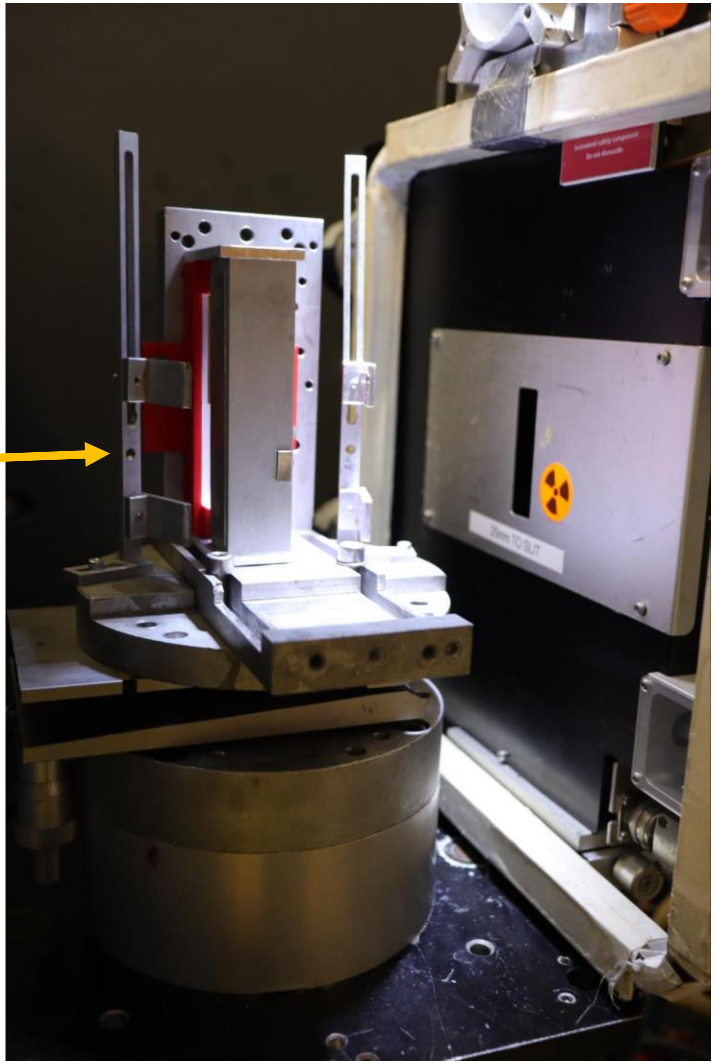
4. The whispering galleries experiment @ ILL Grenoble (France)



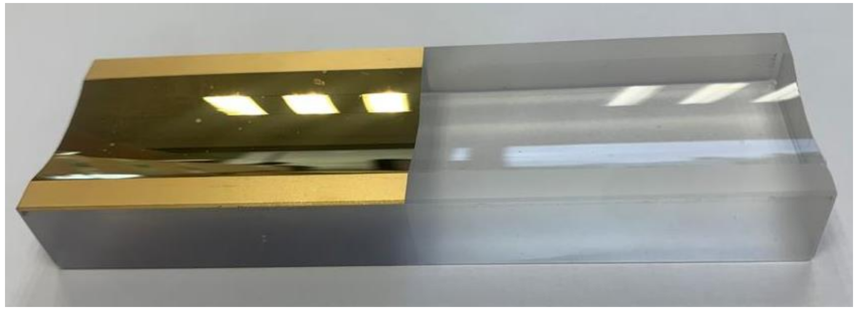
With Ultra-cold NEUTRONS

- Whispering modes





4. The whispering galleries experiment @ ILL Grenoble (France)



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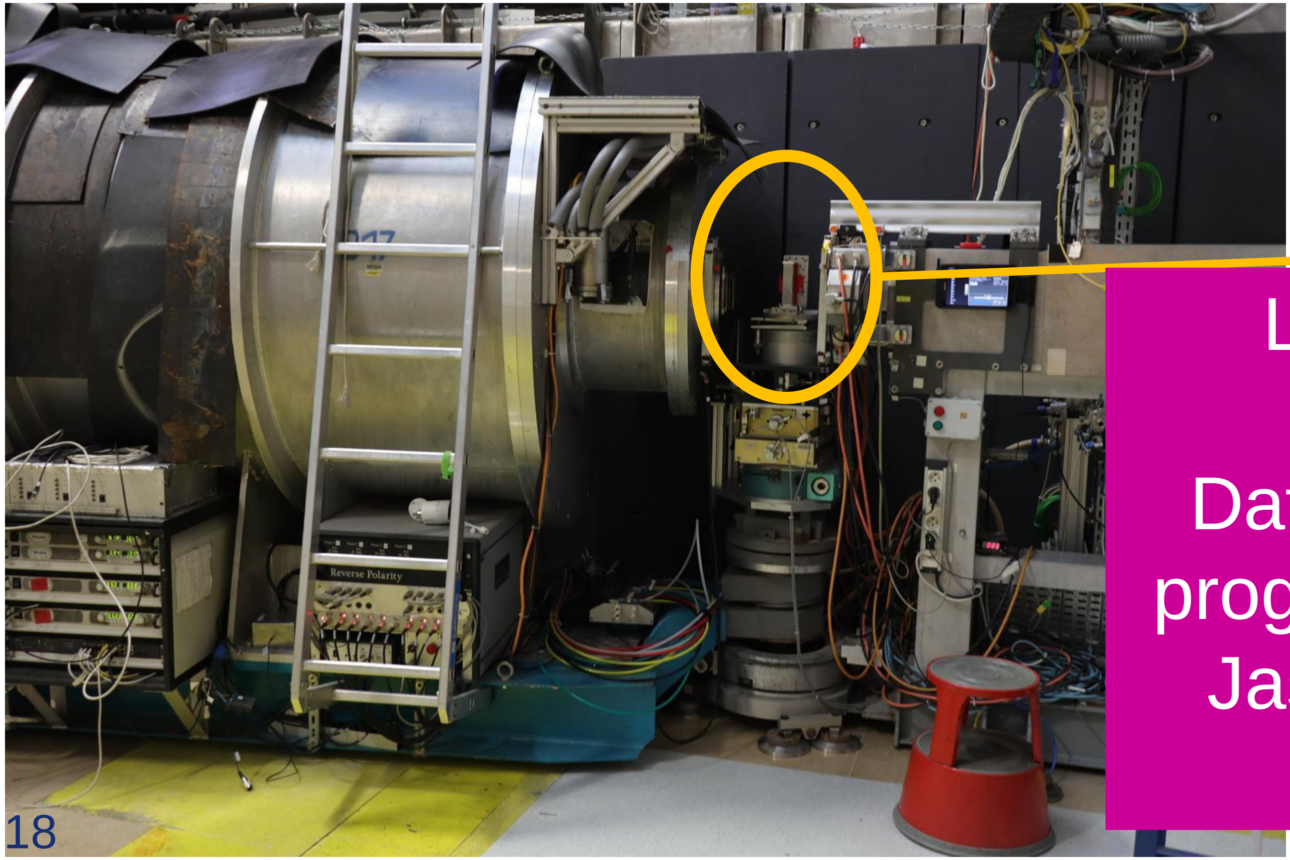


Last beam time in spring 2023

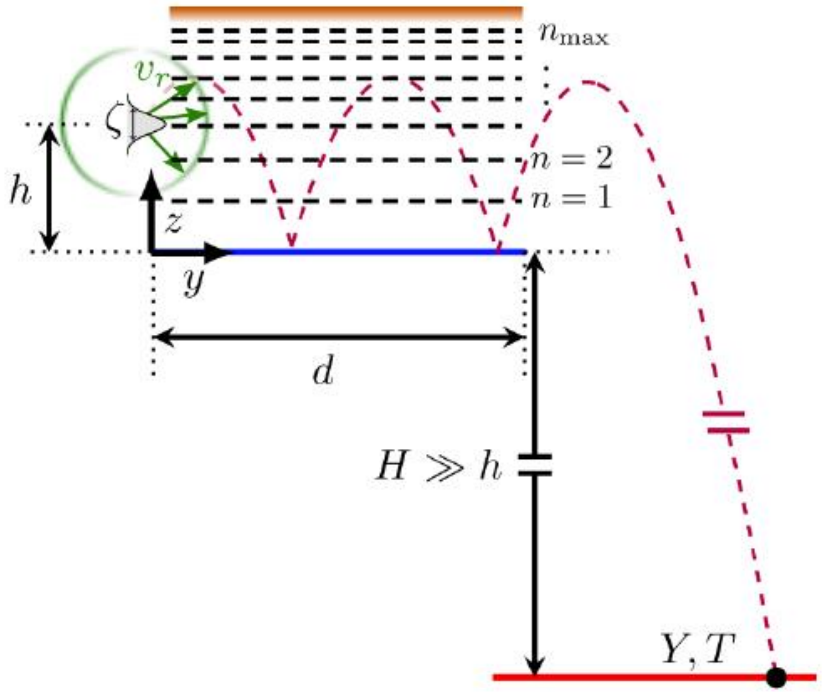
Data analysis and modelling under progresses (Katharina Schreiner and Jason Pioquinto, Serge Reynaud, Valery Nesvizhevsky

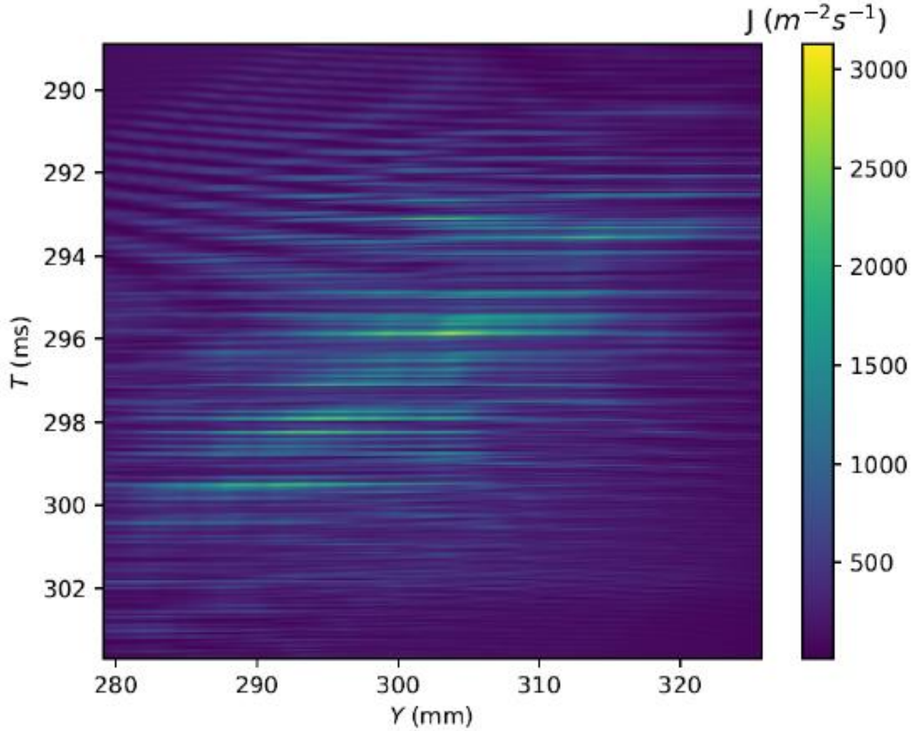
Thanks for your attention

Bonus project ?

What else can we do with GQS of H/anti-H ?

Measuring the interferences of several GQS on (anti-)hydrogen atoms and extracting “g” value with 1e-4 uncertainty (application for GBAR)





Clade P. et al. Quantum interference measurement of the free fall of anti-hydrogen, Eur. Phys. J. D, 76:209, 2022.

Appendix

Gravity on different scales

Macroscopic scales

- Gravitational interaction accurately described by Newton's Law in most cases.
- In the limit of high mass densities / high velocities → General relativity

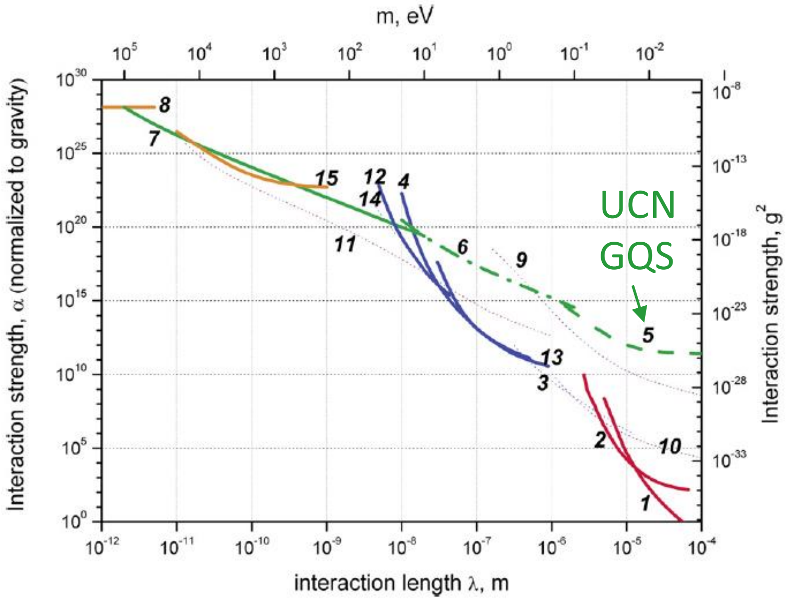
Microscopic (≤ µm) scales

- Gravity escapes perception
- How can the gravitational interaction be described at "quantum mechanical" scales?
- Are there any deviations from Newton's Law?

Motivation for Gravity tests on small scales

- Deviations from Newton’s inverse square law
- New short range forces
  - Motivated by theories with large extra dimensions
  - New light bosons (Dark Matter)
  - ➢ Spin-dependent short range forces
  - ➢ Spin-independent short range forces
    - Yukawa-type forces with range λ and strength α: $V_G = G\frac{m_1 m_2}{r}\boldsymbol{\alpha e}^{-\frac{r}{\lambda}}$
    - Extra dimensions

      → 2 large extra spatial dimensions: $\lambda \approx 10^{-5}$m
    - …



Exclusion plot for new spin-independent interactions [2]

1,2: short-range gravity in torsion balance

4,12,13: Extra forces on top of Casimir and v.d.W interactions

5: neutron Gravitational Quantum States (GQS)

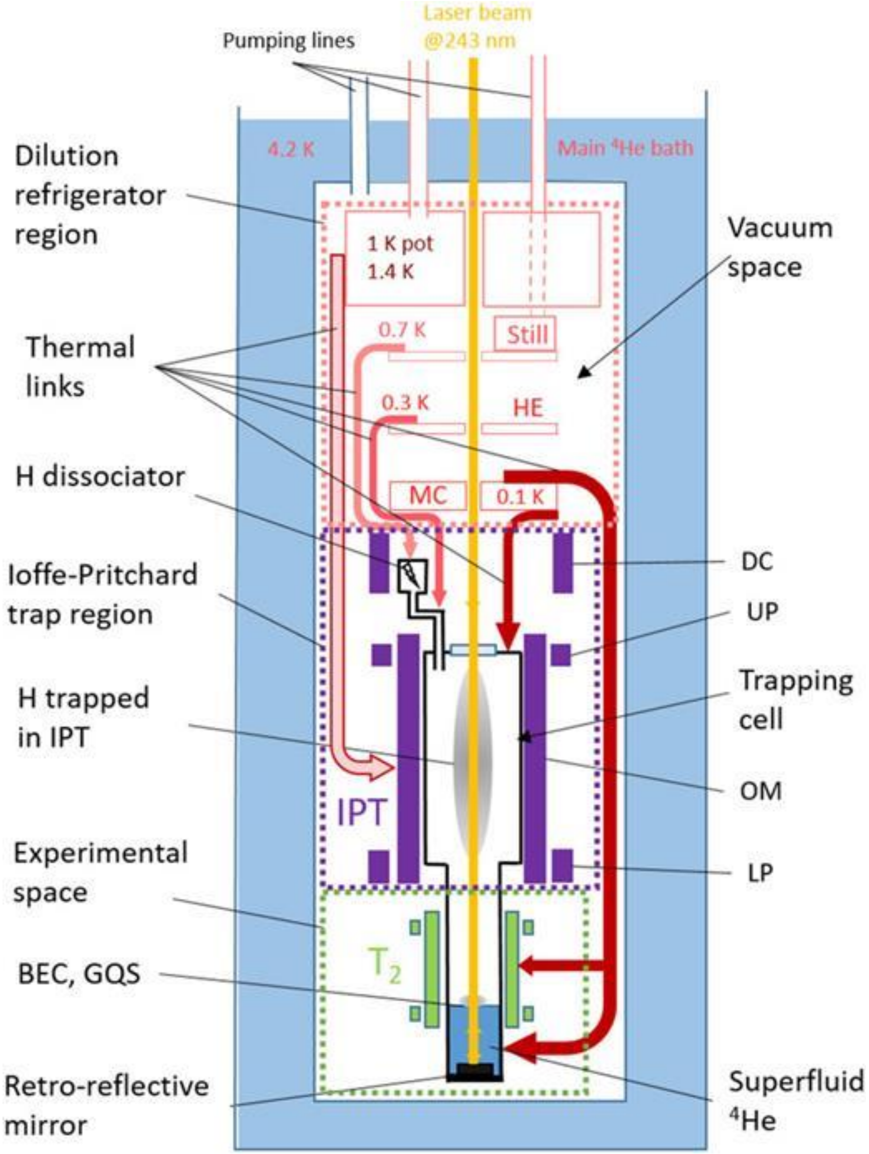
6: neutron whispering gallery effects

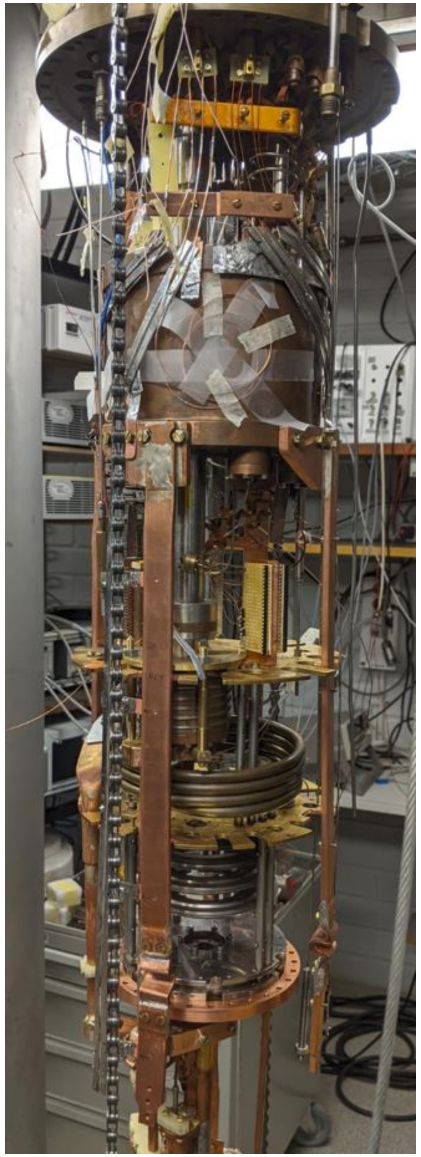
7: neutron scattering on nuclei

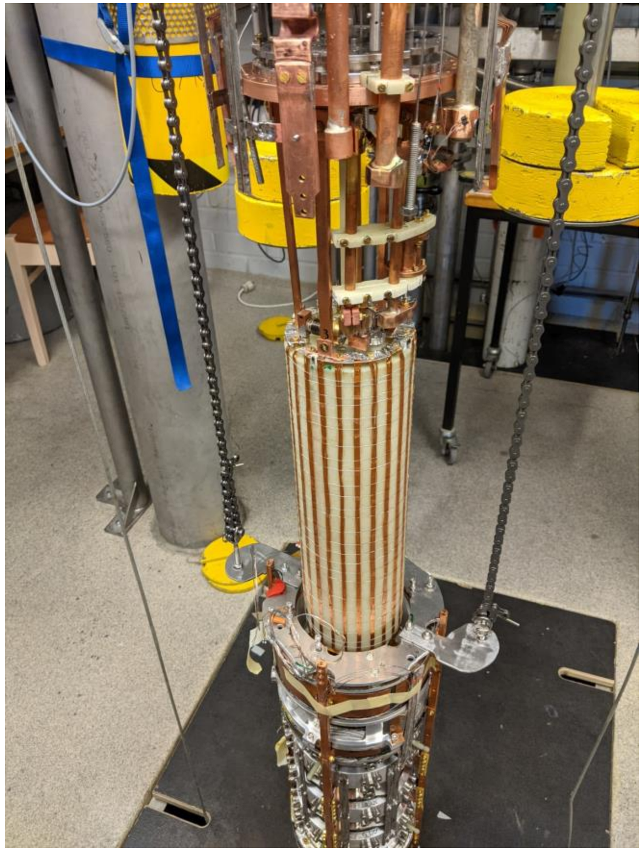
8: precision measurements of exotic atoms

15: low mass bosons from the sun in a high-purity germanium detector

[2] Antoniadis, Ignatios & Baessler, S. & Büchner, M. & Fedorov, Valery & Hoedl, Seth & Lambrecht, Astrid & Nesvizhevsky, V.V. & Pignol, Guillaume & Protasov, K. & Reynaud, Serge & Sobolev, Yu. (2010). Short-range fundamental forces. Forces fondamentales à courte portée.


Laser beam
@243 nm
Pumping lines
4.2 K
Main ^{4}He bath
Dilution
refrigerator
region
1 K pot
1.4 K
Vacuum
space
Thermal
links
0.7 K
Still
0.3 K
HE
H dissociator
MC
0.1 K
Ioffe-Pritchard
trap region
DC
UP
H trapped
in IPT
Trapping
cell
IPT
OM
Experimental
space
LP
T_2
BEC, GQS
Retro-reflective
mirror
Superfluid
^{4}He

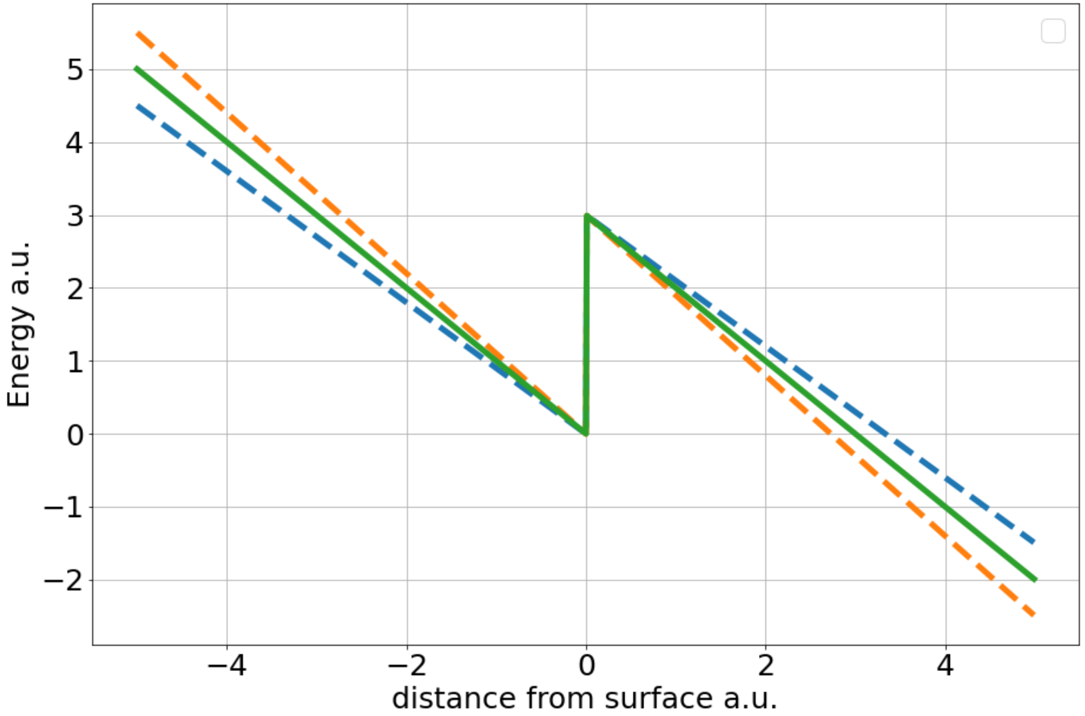




Gravitational/magnetic shift of the whispering gallery

- WG Measurements in other particles:
  - Possible to measure in Mu, Ps (**gravitational shift**)
  - With smaller velocities measurement of **gravitational shift possible with antihydrogen** (Gbar)
- **Test measurement:** In future measurements we want to measure gravitational shift, this experiment is to test the measurement and analysis procedure
- We add a magnetic field with a strong gradient (20T/m)
- By controlling the polarization we should be able to observe a **shift in the lines depending on the gradient orientation w.r.t. the neutron polarization**
- The potential barrier will be broader/smaller, changing the tunneling probability and lifetime
- We can observe this effect if we see statistical significance in (more specifically a **vertical shift** (see next slide))

$$\mathrm{f} = \frac{N_{UP} - N_{DOWN}}{\sqrt{\sigma_{UP}^2 + \sigma_{DOWN}^2}}$$



Hydrogen GQS

- Length scale depends on gravity and mass of particle
- **High background with hydrogen**, Deuterium measurement has less background but states closer to mirror surface
- **Experimental limit:** Minimally measured distance between mirror and scatterer (distinction between classical and quantum model must be feasible at this length scale)
- Maximal observation time:
  - Better resolution
  - Higher scattering probability of particles passing below scatterer
- Velocities of <100ms^{-1} needed (cryogenic beam at ~6K)
- Goal is **proof existence of GQS** (resolution of first step) rather than resolution of multiple excited states (more challenging due to significant increase in necessary observation time)