ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

Towards the first demonstration of gravitational quantum states of atoms with a cryogenic hydrogen beam

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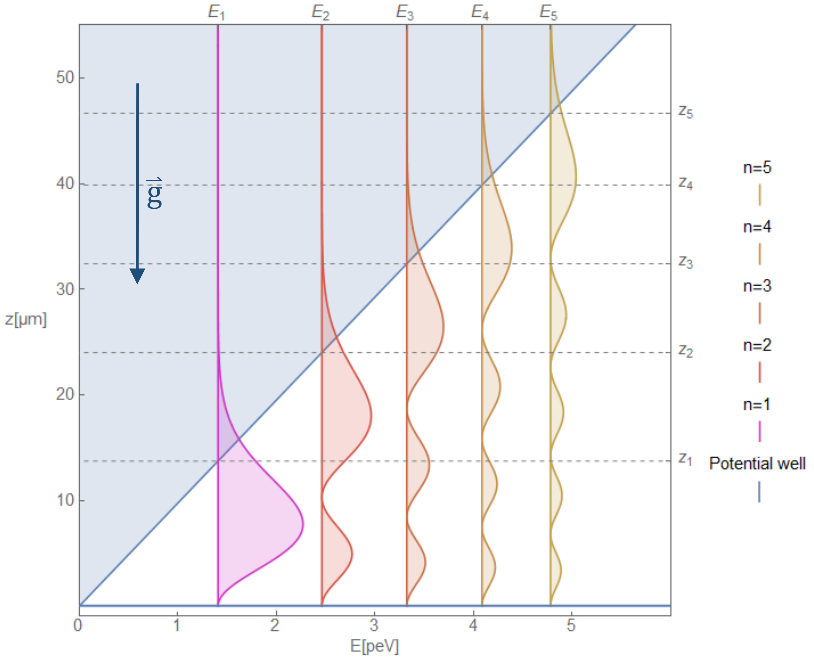
GRASIAN

ETH zürich

Gravitational Quantum States (GQS)

- Particle trapped between Gravity potential ($V_G(z) = mgz$) and horizontal reflecting surface → settles in GQS
- 2002: First demonstration of GQS with ultra cold neutrons [1]
- GQS of atomic hydrogen:
  - Macroscopic spatial heights z_n of the GQS
  - Eigenenergies E_n ~peV ($\approx 10^{-31}$ J)
    - Heisenberg's uncertainty: $\Delta t \Delta E \geq \frac{\hbar}{2} \rightarrow \Delta t \gtrsim 0.5\ \mathrm{ms}$



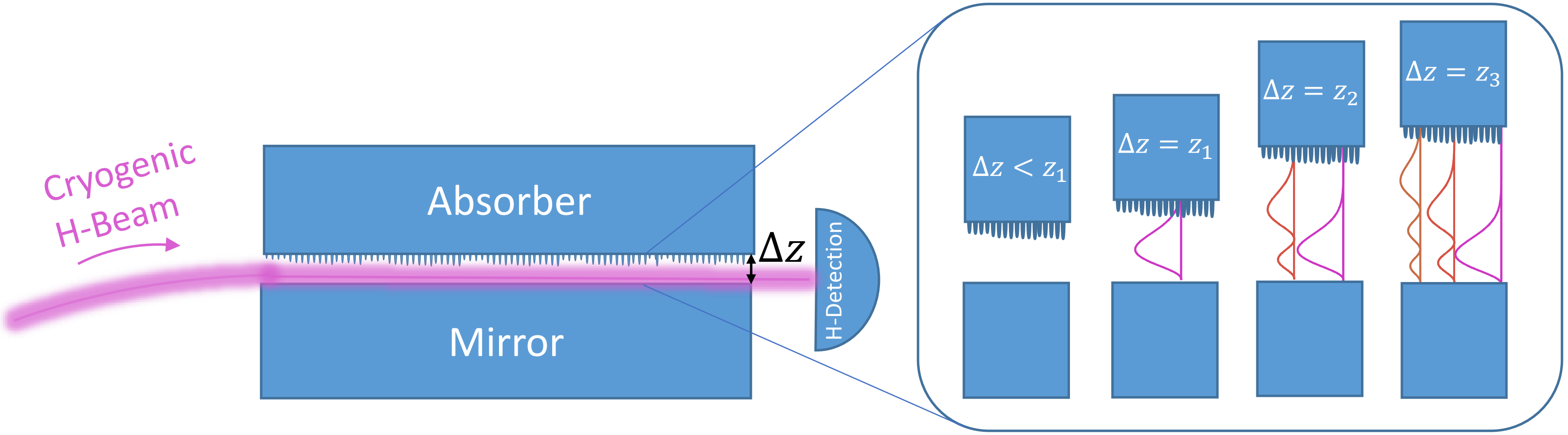
n	E_n [peV]	z_n [μm]
1	1.4	13.8
2	2.5	24.0
3	3.3	32.4
4	4.1	39.9
5	4.8	46.6

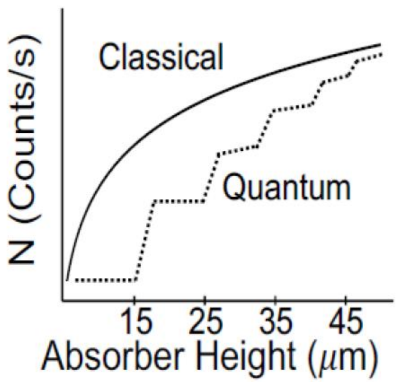
Eigenenergies and spatial heights of the first 5 GQS of hydrogen with
$m_H = 1.6735575 \times 10^{-27}$kg,
$g = 9.81\ \mathrm{m/s}^2$,
$V_{mirr} = \delta(z)$

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

Measurement principle

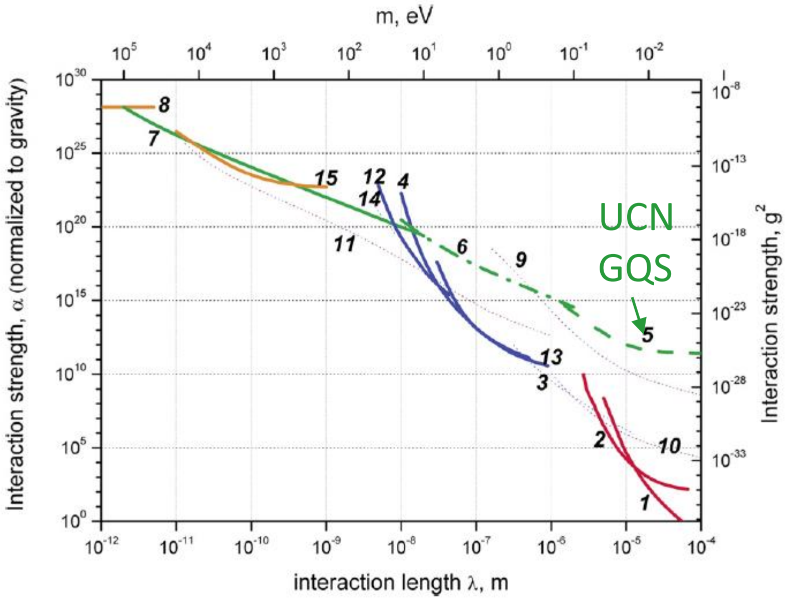
- GQS region: Mirror and absorber separated by a slit (Δz)
- Variation of the slit width Δz
- Measurement of the hydrogen count rate N as a function of Δz
- When stepwise increase of N is measured → **Demonstration of GQS**





Measurement of GQS with hydrogen

- Motivation:
  - Measurement of GQS sensitive to deviations from Newton’s inverse square law and new short-range forces
  - Better statistics
  - Easy to generate (hydrogen bottle vs. research reactor)
  - GQS never measured for atoms!
  - Developed methods also applicable for antiatoms (→ $\bar{g}$)
- Requirements:
  1. Efficient detection of hydrogen
  2. Low background!
  3. (Very) cold hydrogen beam (50-100 m/s)



Exclusion plot for new spin-independent interactions [2]
1,2: short-range gravity in torsion balance
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5: neutron Gravitational Quantum States (GQS)
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8: precision measurements of exotic atoms
15: low mass bosons from the sun in a high-purity germanium detector

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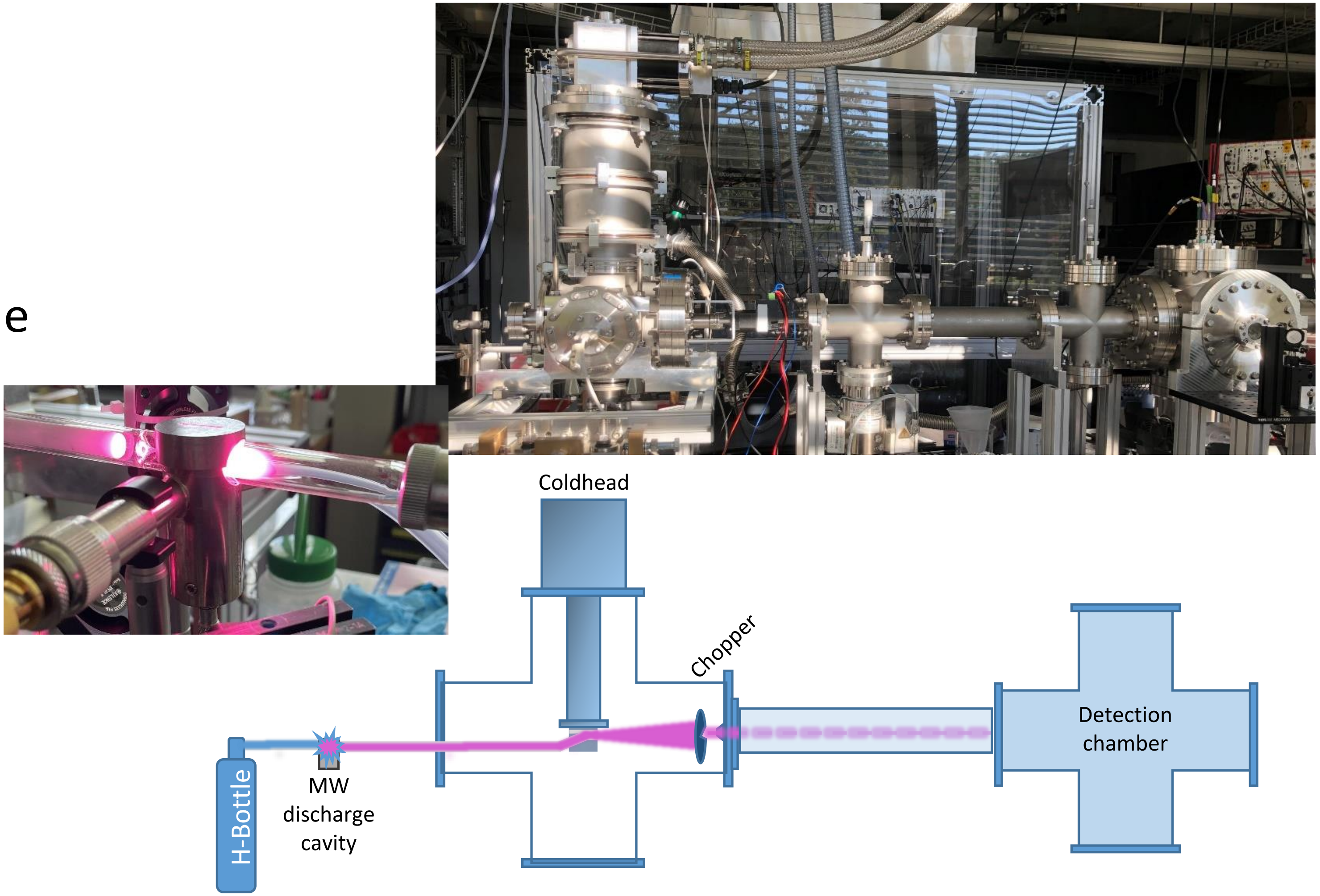
[2] Antoniadis, Ignatios & Baessler, S. & Büchner, M. & Fedorov, Valery & Hoedl, Seth & Lambrecht, Astrid & Nesvizhevsky, V.V. & Pignol, Guillaume & Protasov, K. & Reynaud, Serge & Sobolev, Yu. (2010). Short-range fundamental forces. Forces fondamentales à courte portée.

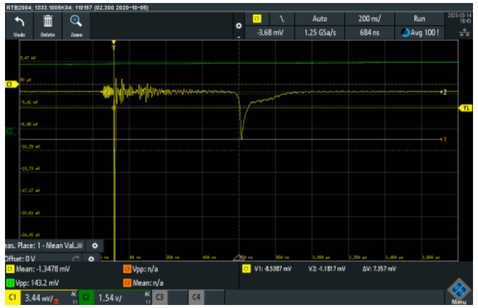
Hydrogen beam – Experimental setup

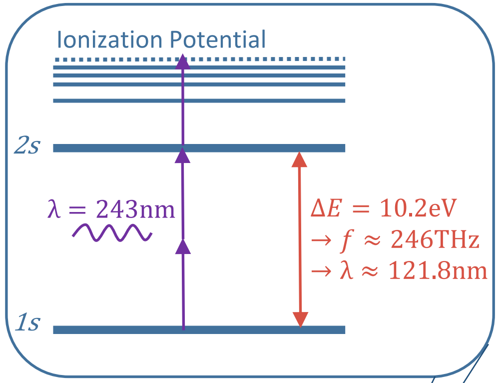
- Hydrogen source: $\mathrm{H_2}$–bottle + Microwave discharge cavity
- Coldhead (6 K) + Cryogenic Nozzle
- Chopper @ 10 Hz
- Beamline
- Hydrogen detection system

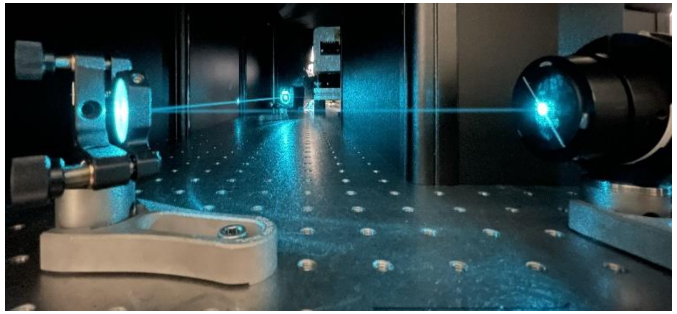


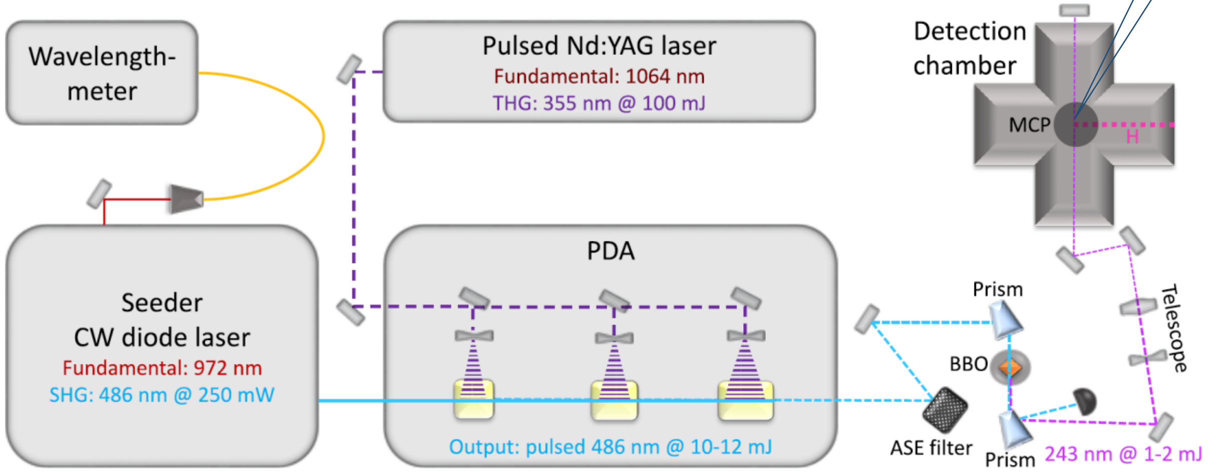
Requirement #1:
Efficient detection of hydrogen

- 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









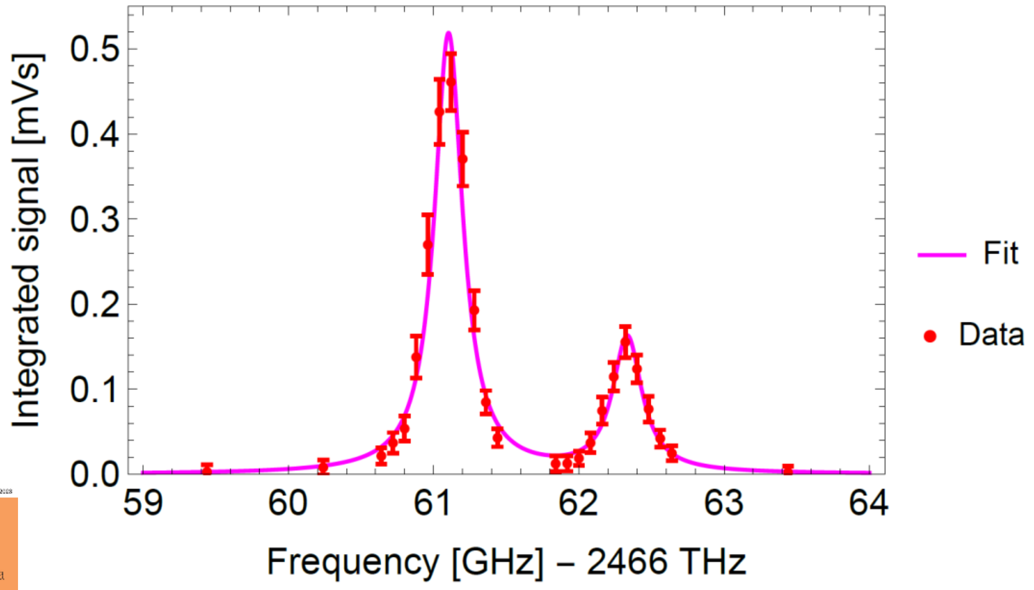
Test of hydrogen detection

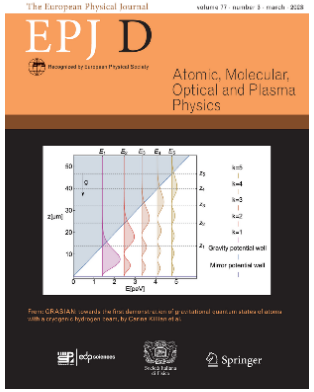
- Variation of laser frequency
- Measurement of signal strength

→ Observation of hyperfine splitting (HFS)

- $(f2 - f1) = 1.23 \pm 0.02\ \mathrm{GHz}$ corresponds to $\left(f_{1s}^{HFS} - f_{2s}^{HFS}\right) = 1.24\ \mathrm{GHz}$

→ We detect hydrogen! ✓





The frequency values on the abscissa correspond to the measured frequency of the seeder laser fundamental, shifted by 230MHz (outdated wavelength meter calibration) and multiplied by a factor of 8 (two SHG processes, two photon excitation). This was done to to match the absolute literature values [3]. Figure taken from [4].

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[3] C.G. Parthey, et al., Improved Measurement of the Hydrogen 1S - 2S Transition Frequency. Phys. Rev. Lett. **107**, 203-001 (2011). https://doi.org/10.1103/PhysRevLett.107.203001. arXiv:1107.3101 [physics.atom-ph]

[4] Killian, C. et al. GRASIAN: towards the first demonstration of gravitational quantum states of atoms with a cryogenic hydrogen beam. Eur. Phys. J. D 77, 50 (2023). https://doi.org/10.1140/epjd/s10053-023-00634-4

Intensity dependency

- Laser energy sweep
  - $I = P/(\omega_0^2 \pi)$, ω_0 … laser beam waist
  - I^3 dependency until $\sim 5 \times 10^6$W/cm² (sat. of 2S ion.)
  - I^2 dependency until $\sim 3 \times 10^7$W/cm² (sat. of 1S-2S excitation) [5]
- Goal: run laser at point of saturation
  - Compress beam size

  → focusing lenses around detection chamber installed
  - Run at higher UV energies

  → new laser system installed in ‘02 2023
- Now:
  - Saturation reached
  - Positive slope (0.47) after saturation point due to nonuniform intensity profile [5]

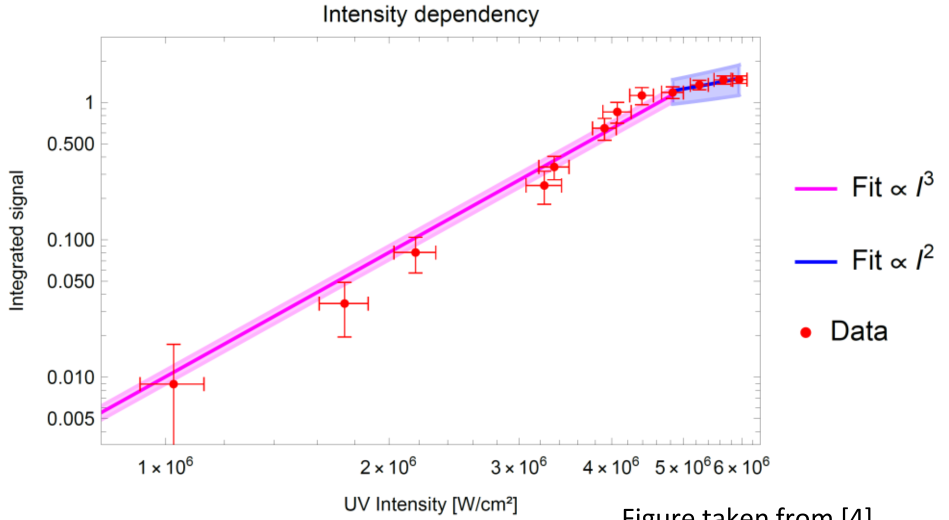
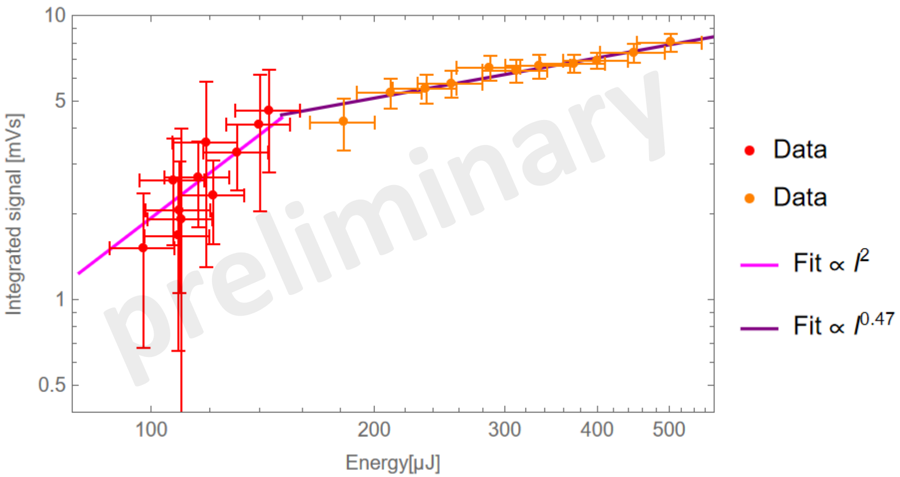


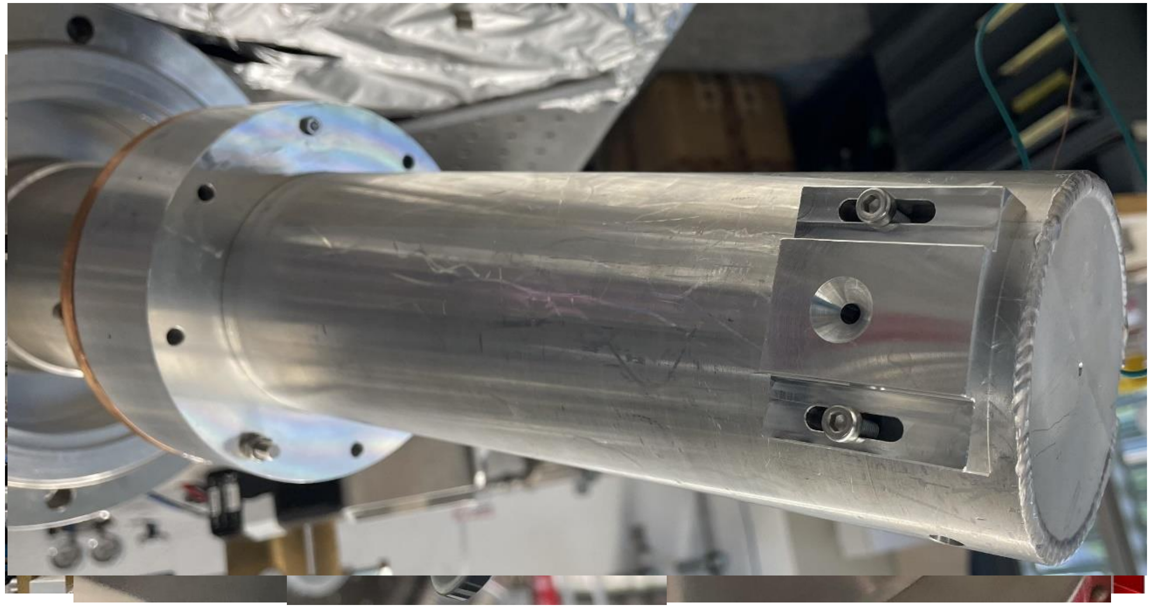
Figure taken from [4].

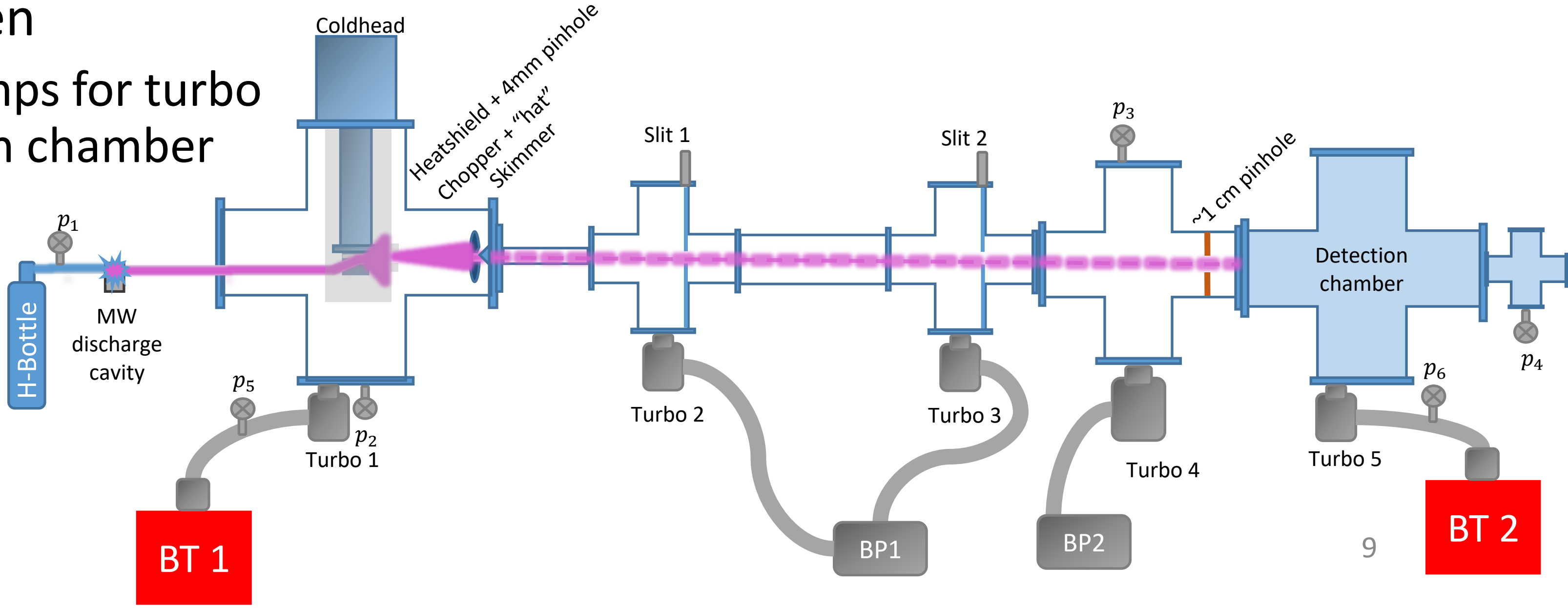


[5] S.W. Downey, R.S. Hozack, Saturation of three-photon ionization of atomic hydrogen and deuterium at 243 nm. Opt. Lett. 14(1), 15–17 (1989). https://doi.org/10.1364/OL.

Requirement #2: Low background (BG)

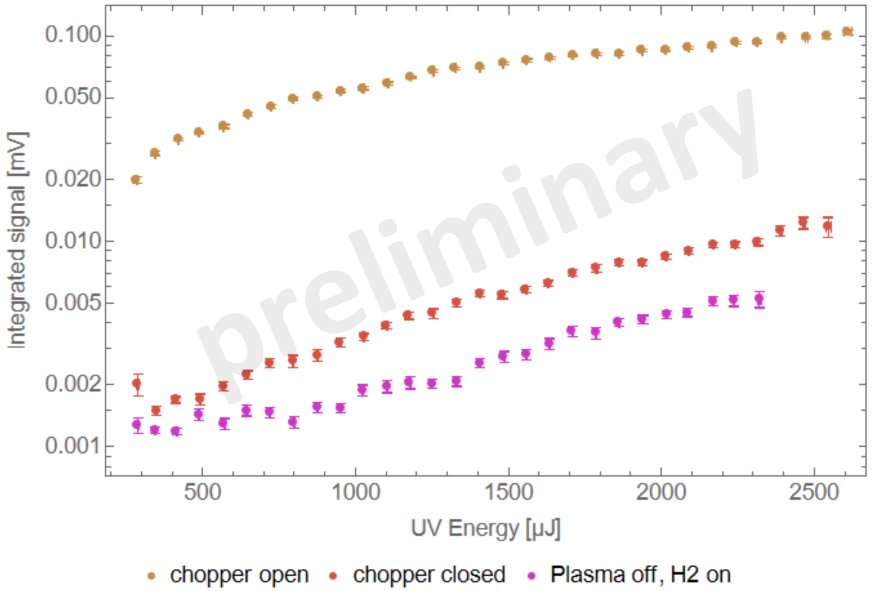
- Added 4 differential pumping stages
  - 3 new turbo pumps
  - Skimmer in cryo chamber
  - 2 height adjustable apertures
  - 1 pinhole
- Improved pumping of hydrogen
  - Turbo pumps as backing pumps for turbo pumps in cryo- and detection chamber
- Brought chopper wheel ~1mm close to skimmer
- Pinhole on heatshield

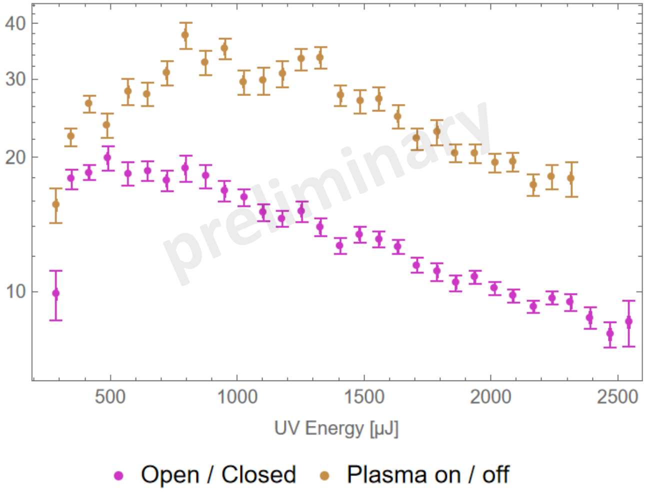


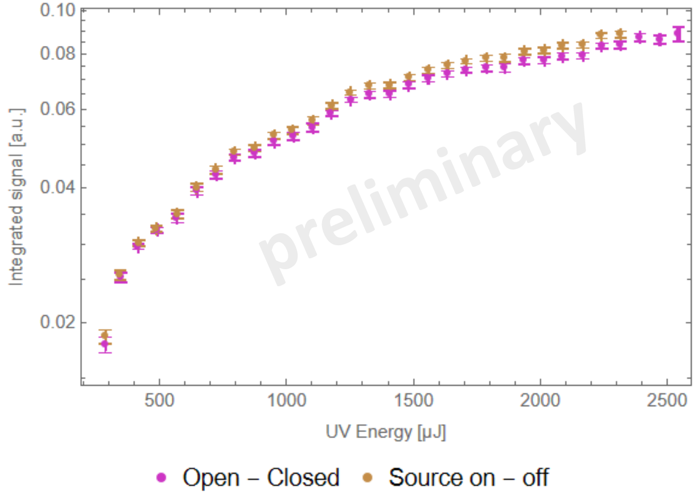


BG measurements

- Variation of laser energy
- Measurement of signal with different settings
  - Chopper open = signal
  - Chopper closed = beam related BG
  - Plasma off, H2 flow on = chamber related BG
- Signal / BG optimum at ~ 800 μJ
  - Signal / BG (beam) $\cong 19$
  - Signal / BG (chamber) $\cong 38$
- Signal – BG optimum at $\gtrsim 2.2$ mJ
  - Chose this optimum for delay measurement





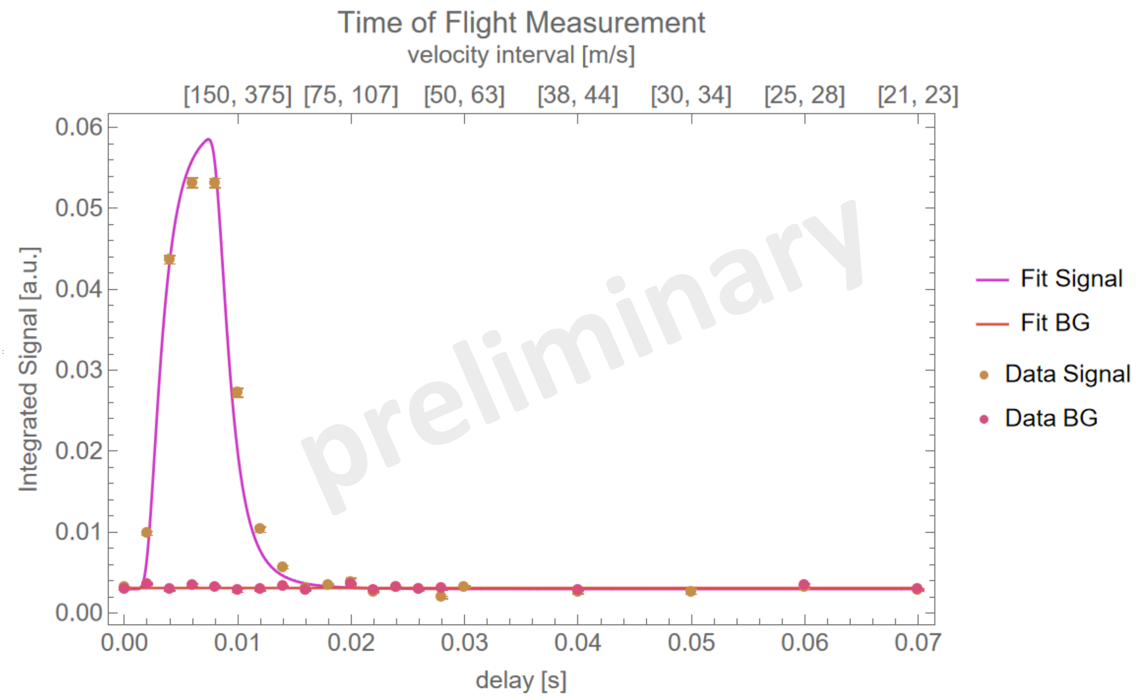


Requirement #3:
(Very) cold hydrogen beam (50-100 m/s)

- Delay Measurement:
  - Distance (chopper – detection): $\Delta x = 1.1\ \mathrm{m}$
- Evidence of atoms with velocities < 100 m/s
- Measurement at 2.2 mJ UV energy
- Signal / BG ≈ 11.6

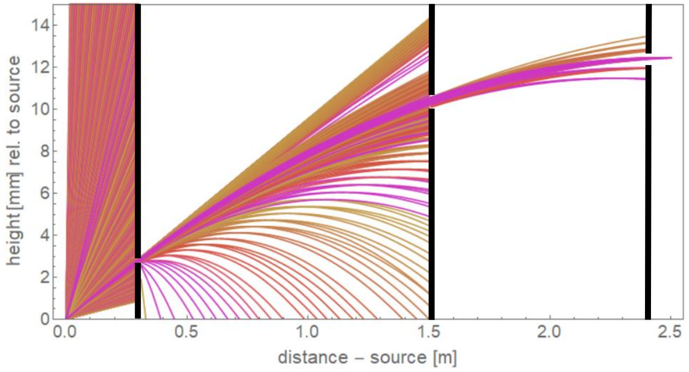
→ Improvement by factor $\gtrsim 3$ compared to old setup

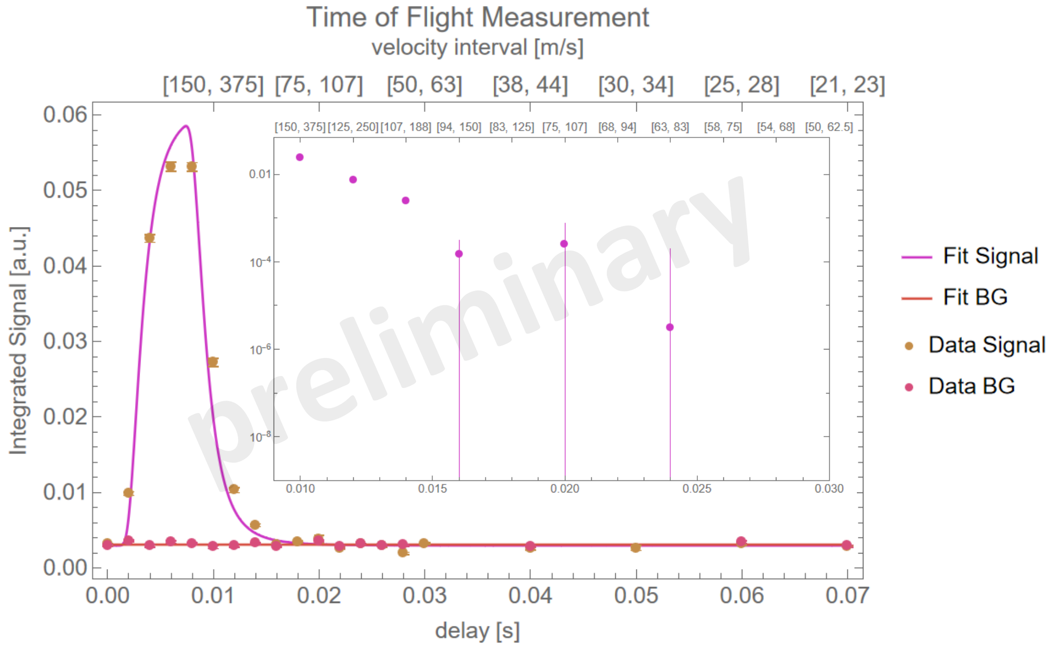
→ Still needs to be further improved!

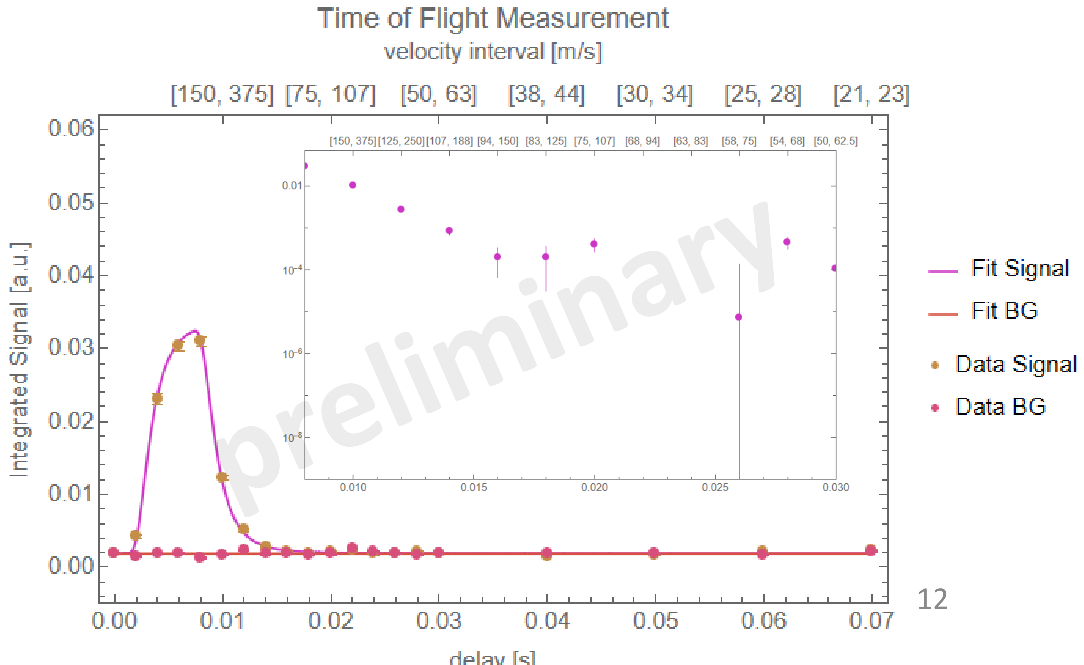


Velocity selection aperture

- Two height adjustable slits (1 mm)
- Selection of specific velocity with adjustment of slit-heights
- Selection of velocity components: $v_z(\mathrm{GQS} - \mathrm{Region}) = 0$
- First test: all slits on axis (left) vs. slit 2: +1 mm (right)







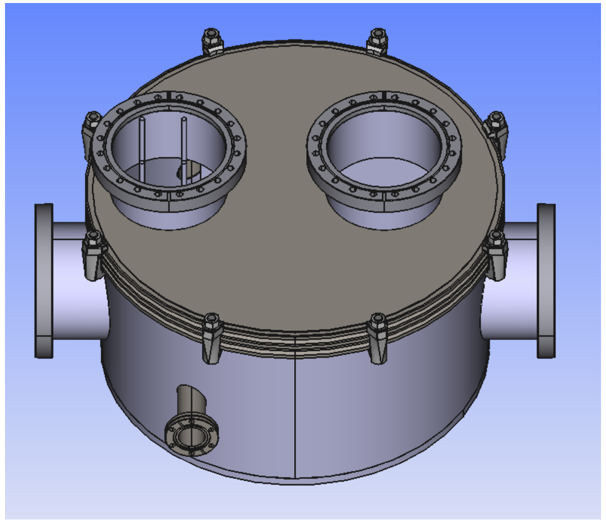
Summary and outlook

- Efficient detection of the H atoms ✓
- Atomic hydrogen beam with velocities $v < 100\ \mathrm{m/s}$ ✓
- Signal / Background still needs to be improved

  → Sig/BG already improved by a factor 3

  → Next steps:

    - Installation of 3rd slit in CF100 cross
    - Baking of detection chamber
    - Installation of cryo-pumping stage in detection chamber
- Outlook:
  - GQS chamber ready to be installed, as soon as BG is reduced



Thank you for your attention!

Motivation for Gravity tests on small scales

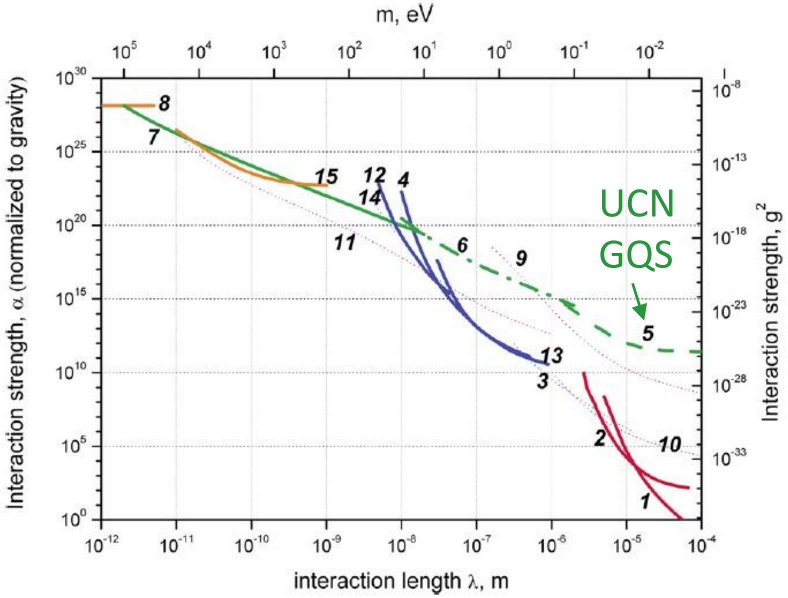
Deviations from Newton's inverse square could be governed by

- ➢ Spin-dependent short range forces
  - New light pseuda-scalar bosons (Axion)
- ➢ 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
  - New light bosons (Dark Matter)
  - …



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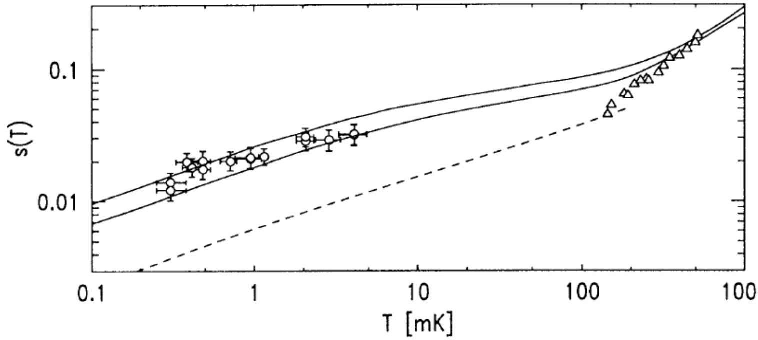
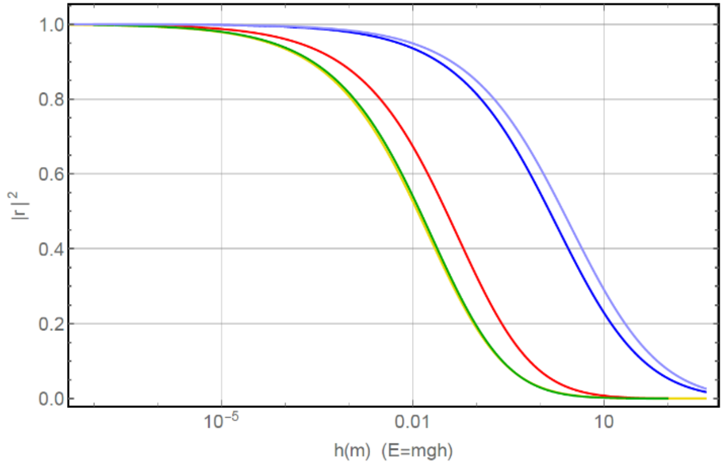
Quantum Reflection (QR)

- Attractive Casimir-Polder (CP) Potential
- Counter intuitive:
  - QR occurs with same probability for a particle approaching an attractive valley as a repulsive step
  - QR becomes more efficient for weaker CP potentials
- Observed for H atoms over liquid He-surface in 1993 [3]
- Suitable materials: helium (^{3}He, ^{4}He), silica, silicon, gold



Sticking probability of H on thick He film. Taken from [3].

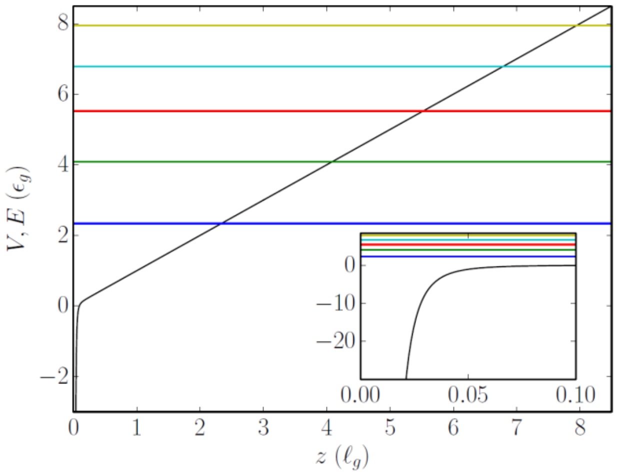


Quantum reflection probability for antihydrogen as a function of the free fall height of the atom h (∝ energy E = mgh) for different materials: 3He (light blue), 4He (dark blue), silica (red), silicon(green) and gold (yellow). Taken from [4].

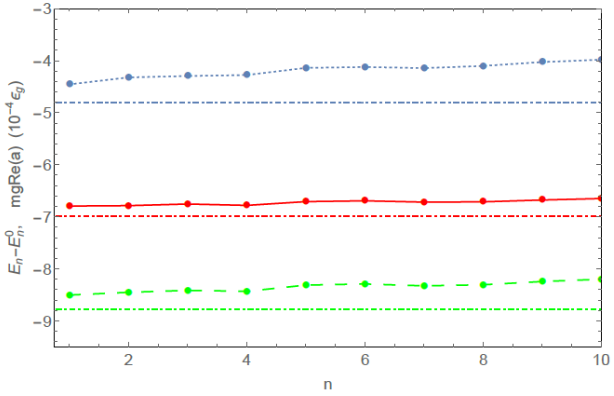
[3] Ite A. Yu, John M. Doyle, Jon C. Sandberg, Claudio L. Cesar, Daniel Kleppner, and Thomas J. Greytak. Evidence for universal quantum reflection of hydrogen from liquid 4He. Phys. Rev. Lett., 71:1589–1592, Sep 1993.
[4] Crépin, P.-P. and Kupriyanova *et al.* Quantum reflection of antihydrogen from a liquid helium film. *EPL* **119,** 1286-4854 (2017). http://dx.doi.org/10.1209/0295-5075/119/33001

CP – shifts

- CP potential ≠ infinitely steep wall
  - $V(z) = mgz + V_{CP}(z)$
  - V_{CP} has a range of $l_{CP} \approx$ 27.5nm ($\ll l_g \approx$ 6 µm)
- Calculations for $\overline{\mathrm{H}}$ [5]
- Scattering length approximation
  - Decoupling the effects of Gravity and the CP-interactions
  - $E_n = E_n^0 + mga$ … Energies are shifted by mga, resulting from the complex phase shift experienced by the atom upon reflection on the CP tail
  - Shifts $\sim 10^{-4}\epsilon_g$ ($\epsilon_g \approx 0.602$ peV)
  - Max. relative error of approximation $\sim 10^{-5}$



$V(z) = mgz + V_{CP}(z)$ (black curve) above a silica bulk. Horizontal lines correspond to energies of an ideal quantum bouncer. Taken from [5].



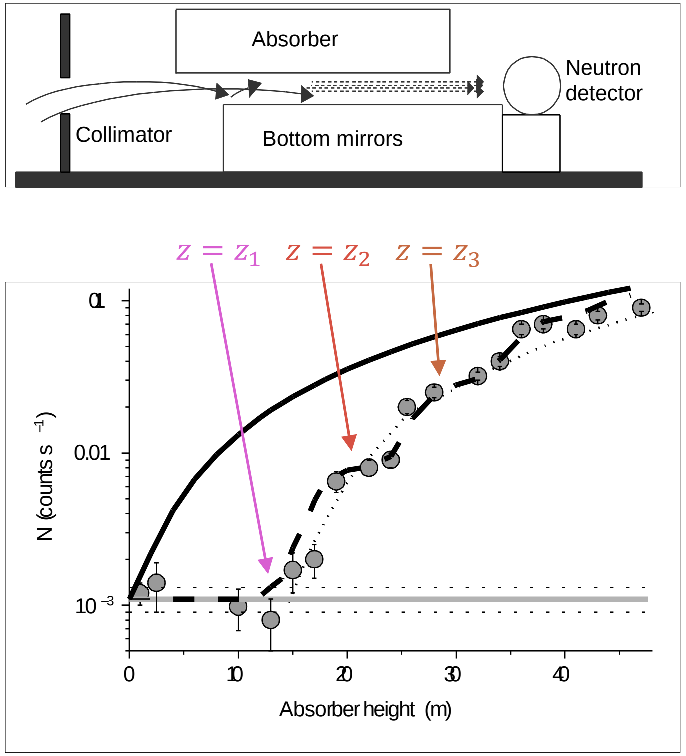
Energy shifts for antihydrogen interacting with a perfect mirror (blue), a silicon bulk (green) or a silica bulk (red), in units of $10^{-4}\epsilon_g$. The shift corresponding to the real part of mga is represented by the horizontal lines. Taken from [5].

[5] P.-P. Crépin, G. Dufour, R. Guérout, A. Lambrecht, and S. Reynaud. Casimir-polder shifts on quantum levitation states. Physical Review A, 95(3), mar 2017.

Measurement of GQS with ultra cold neutrons

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

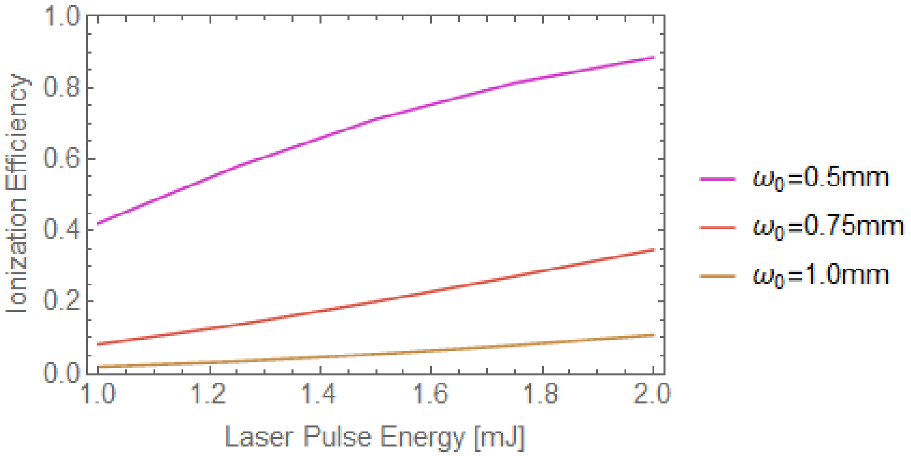
- UCNs pass through slit Δz between mirror and absorber
- Measurement of neutron transmission N as function of Δz
  - Stepwise increase predicted for GQS (steps at $z = z_n$)
  - Slit only becomes transparent, when $\Delta z \geq z_1$



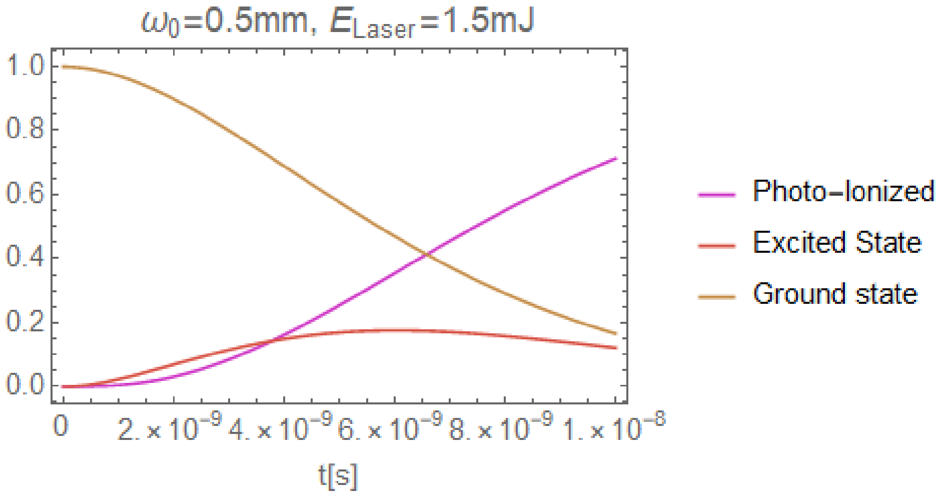
First demonstration of GQS ith UCNs: The neutron throughput vs. the absorber height Δz and experimental setup. Figures taken from [2].

Ionization Efficiency

- Simulation of ionization efficiency by solving optical Bloch equations
- Transition matrix element for 2 photon transition $\beta = 3.68111 \times 10^{-5} \frac{\mathrm{Hz\,m^2}}{\mathrm{W}}$
- Beam waist $\approx 0.5\ \mathrm{mm}$, Pulse Energy $\approx 1.5\ \mathrm{mJ}$, Pulse duration $\approx 10\ \mathrm{ns} \rightarrow \varepsilon_{ion} \approx 71\%$



Simulated ionization efficiencies for different Laser pulse energies and beam waists.



Evolution of states during a 10 ns pulse of 1.5mJ with a beam waist of 0.5 mm.

Detection of Hydrogen - MCP

- Microchannel plate (MCP)
  - (Single) particle detection
    - Single Ion: ~5.5 mV signal height
  - Amplification via secondary emission
  - Grid -50-300 V
  - Front/Back/Anode -2200/-244/GND
- Read out of signal: Oscilloscope