GRASIAN: Towards the first demonstration of gravitational quantum states of atoms

25.09.2025

Carina Killian on behalf of the GRASIAN collaboration

SSP 2025

Gravitational quantum states (GQS)

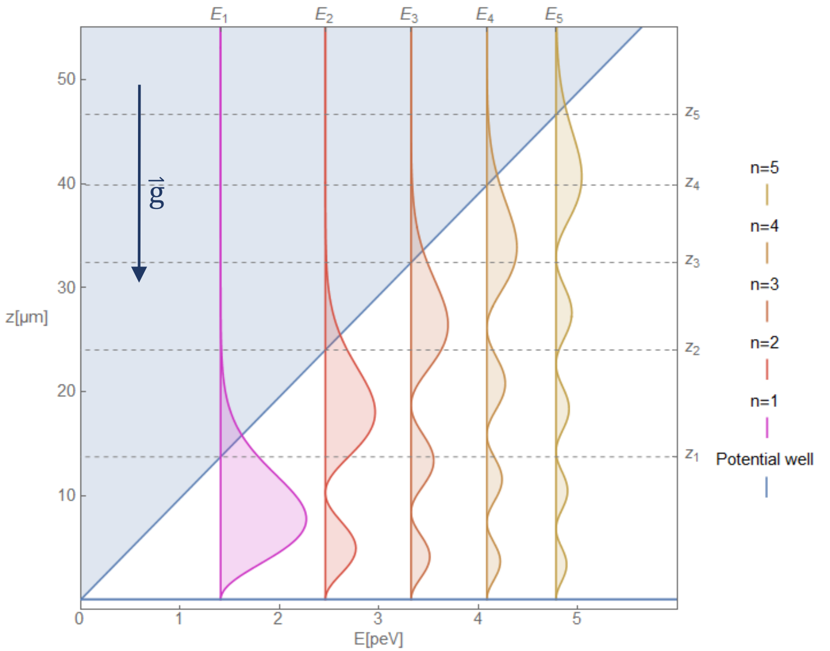
- Gravitational potential well $\leftrightarrow$

  Gravity potential + Perfectly reflecting surface

- 2002: First demonstration of GQS with ultra cold neutrons [1], so far no measurements with neutral atoms.

- GQS of hydrogen
  - Macroscopic spatial heights $z_n \sim$ µm
  - Eigenenergies $E_n \sim$ peV

  → Heisenberg‘s uncertainty: $\Delta t \Delta E \geq \frac{\hbar}{2} \rightarrow \Delta t \gtrsim 0.5 \text{ ms}$



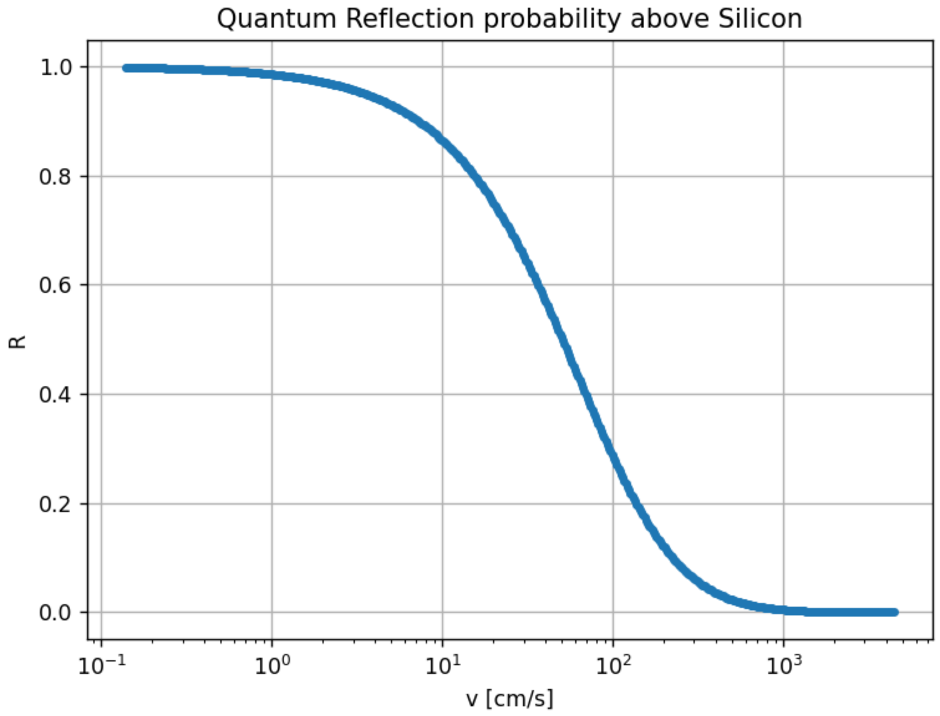
n	E_n [peV]	z_n [µm]
1	1.4	13.8
2	2.5	24.0
3	3.3	32.4
4	4.1	39.9
5	4.8	46.6

Eigenenergies and spatial heights of the first 5 GQS of hydrogen with $m_H = 1.6735575 \times 10^{-27}$kg, $g = 9.81$ m/s², $V_{mirr} = \delta(z)$

[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

Quantum Reflection (QR)

- Purley quantum mechanical phenomenon
- Low energy atoms are reflected from attractive Casimir-Polder potential
- Observed for H atoms over liquid He-surface in 1993 [2]
- H above silicon (Si) surface: QR probability > 90 % for $v_{\perp}$< 7 cm/s above Si surface [3]
  - Never measured before!

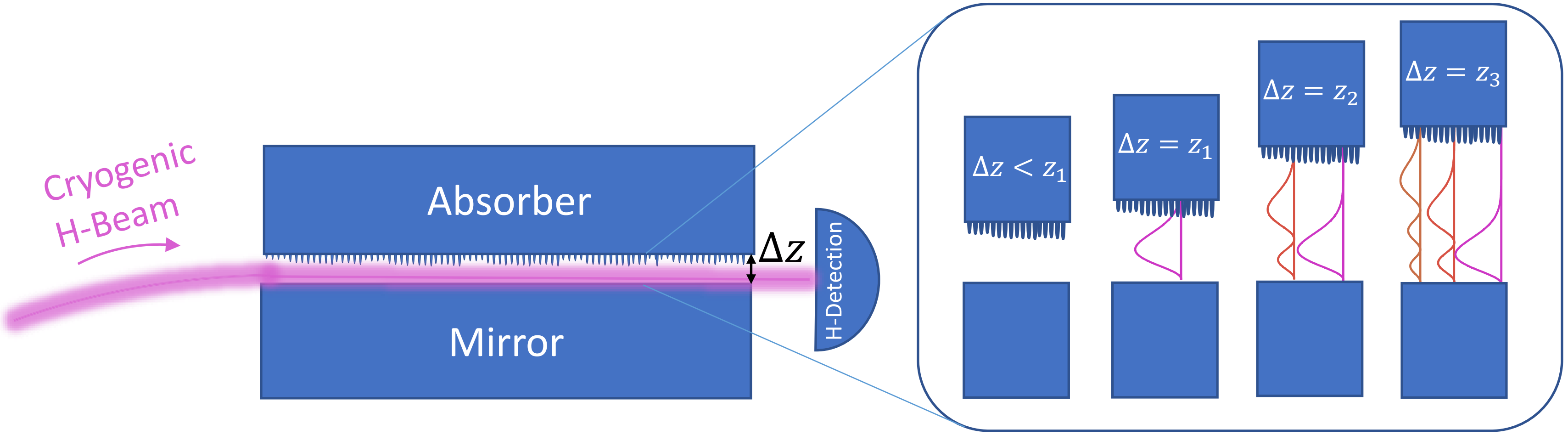


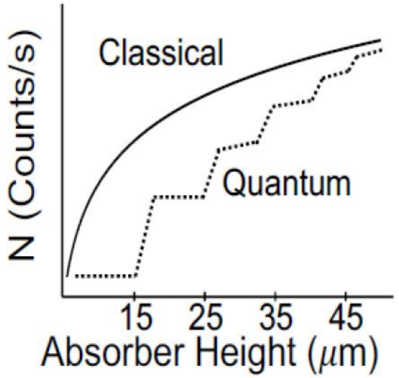
Quantum reflection probability R for antihydrogen as a function of velocity perpendicular to the surface v for silicon. Provided by Serge Reynaud 2025.

[2] 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.
[3] 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

Measurement principle

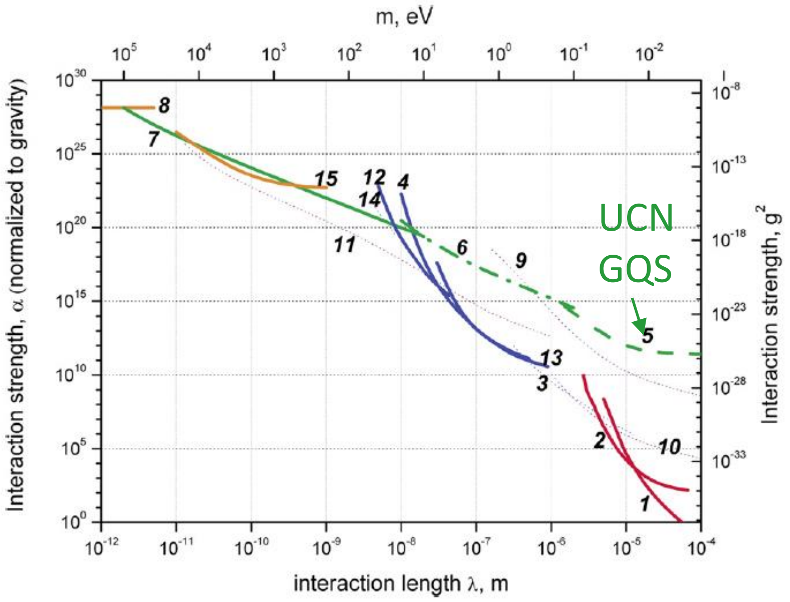
- GQS spectrometer: Si mirror and absorber separated by a slit (Δz)
- Variation of the slit width Δz
- Measurement of the hydrogen count rate N as a function of Δz
- When stepwise increase of N is measured → **Demonstration of GQS**





Motivation

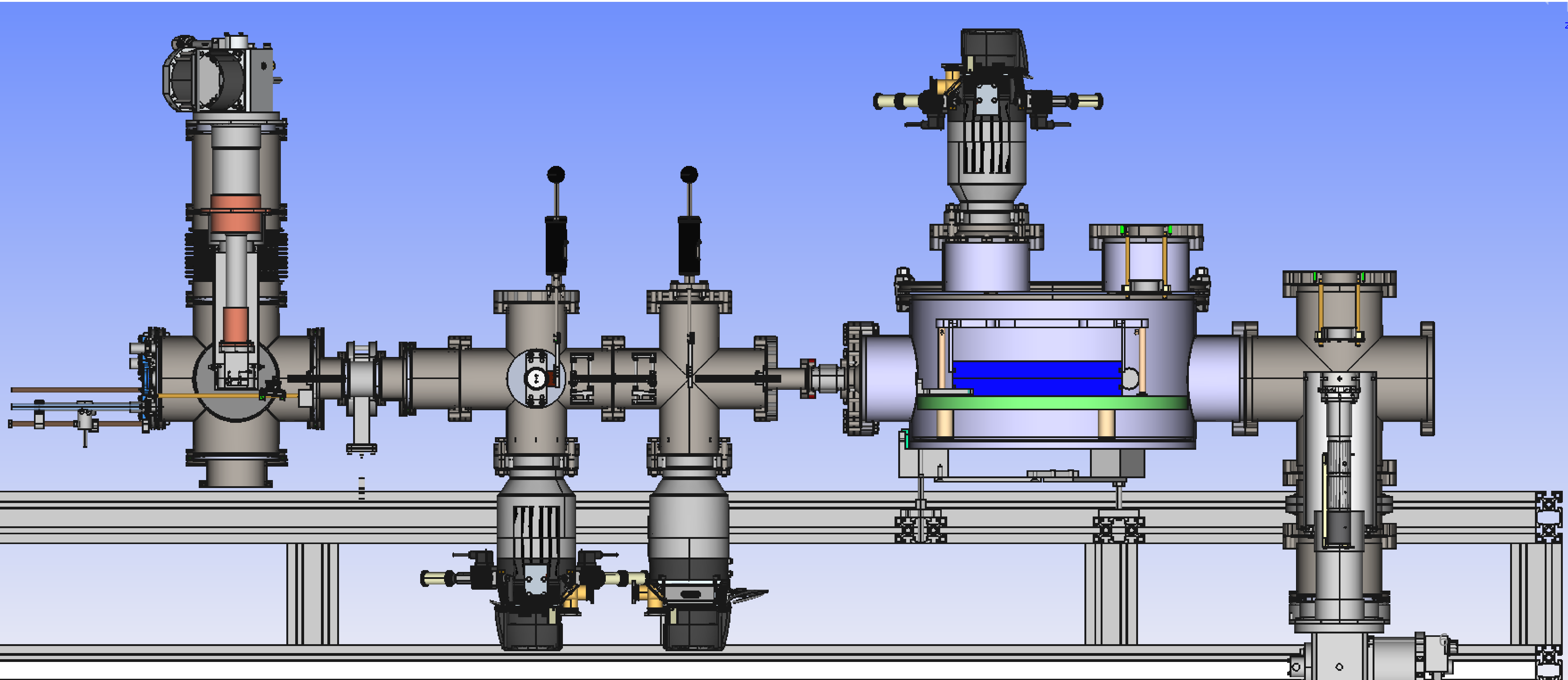
- Measurement of GQS sensitive to hypothetical short-range forces
- Higher densities
- Easy to generate (hydrogen bottle vs. research reactor)
- GQS never measured for atoms!
- Developed methods also applicable for antiatoms ($\rightarrow \bar{g}$)



Exclusion plot for new spin-independent interactions [4]
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

[4] I. Antoniadis et al.(2010). Short-range fundamental forces. Forces fondamentales à courte portée.

Hydrogen beam – experimental setup



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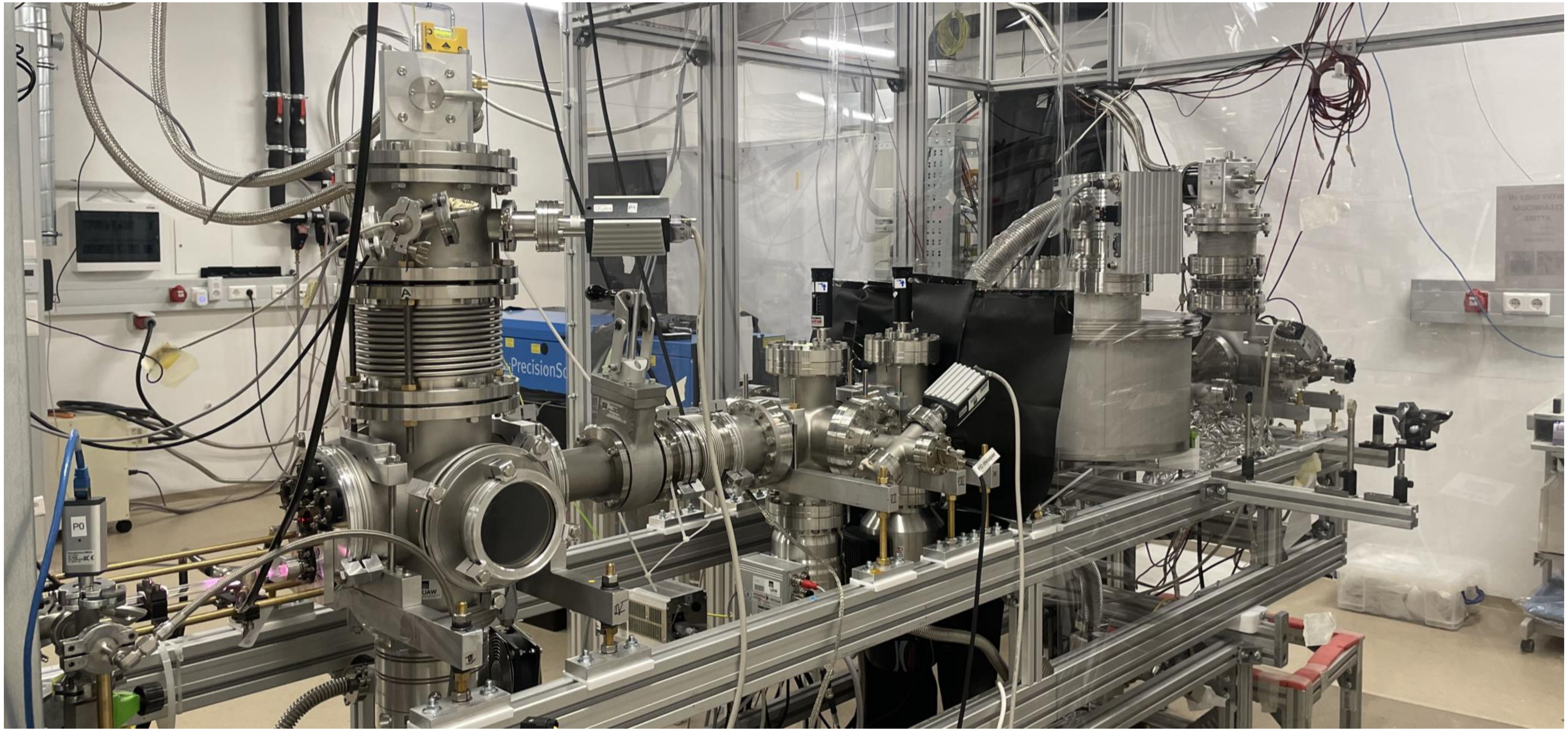


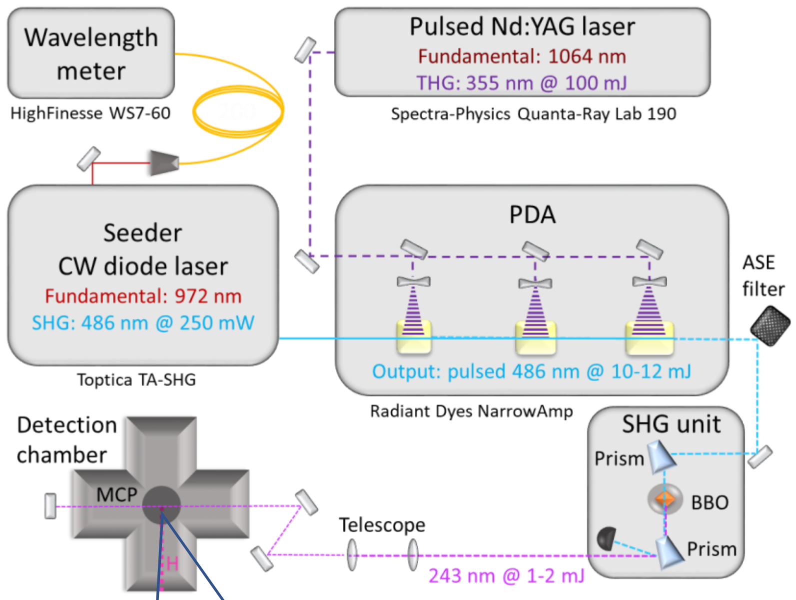
Requirements for a GQS measurement

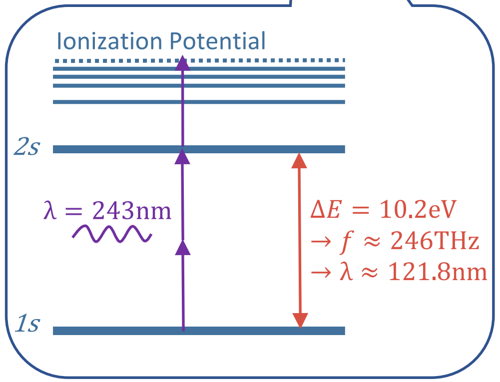
Requirements for a GQS measurement

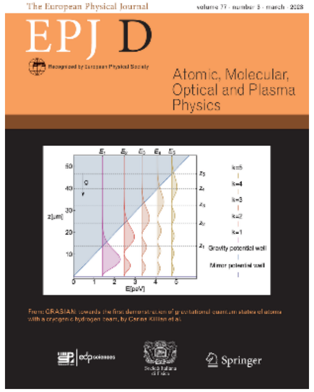
1. Efficient detection of hydrogen

Requirements for a GQS measurement

1. Efficient detection of hydrogen ✔
   - Photoionization of H with a pulsed UV-Laser ($\lambda = 243$ nm)
     - 2 photon excitation (1S-2S) + 1 photon ionization
     - Laser system described in [5]
   - Detection of H^+ with an MCP
   - Integrated MCP-Signal $\propto$ H- count rate
   - Ionization efficiency $\varepsilon \approx 100\%$







[5] 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

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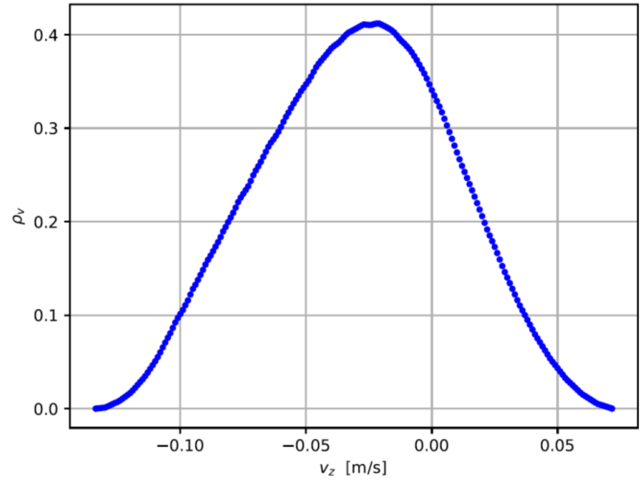
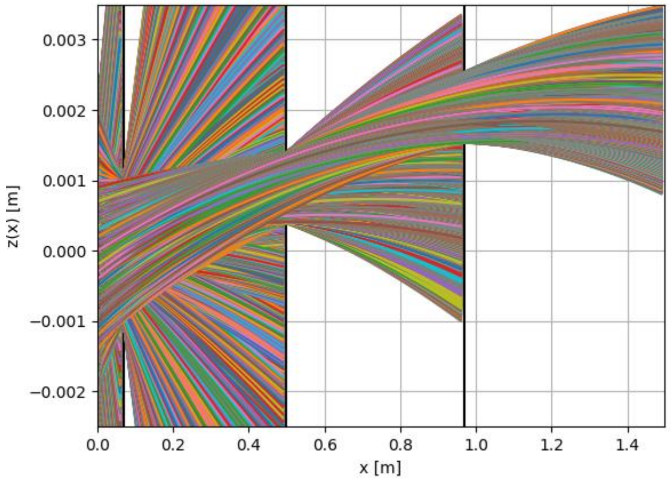
1. Efficient detection of hydrogen ✔
2. Very low vertical velocity components

Requirements for a GQS measurement

1. Efficient detection of hydrogen ✔
2. Very low vertical velocity components ✔
   - Quantum reflection probability $> 90\%$ for $|v_z| < 7\ \mathrm{cm/s}$ [3]
   - Trajectory selection with vertical adjustable slits (0.5 mm)





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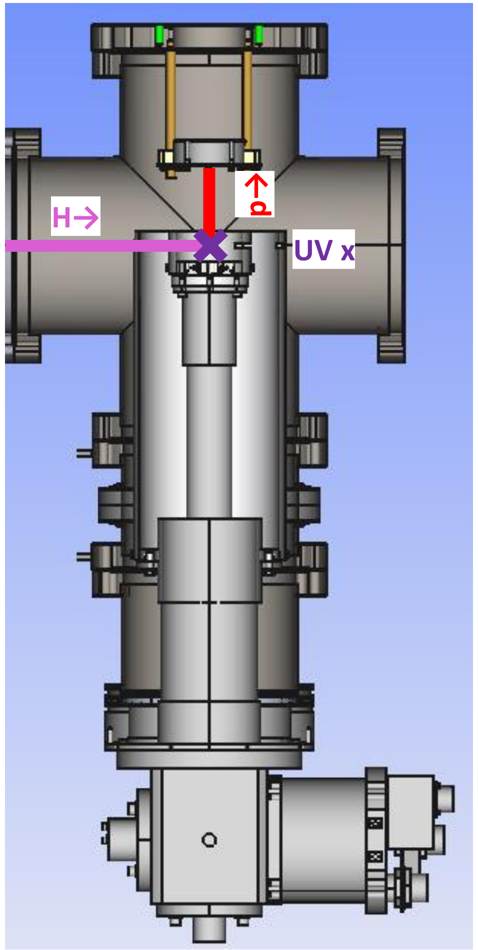
2. Very low vertical velocity components ✔
3. Low background

Requirements for a GQS measurement

1. Efficient detection of hydrogen ✔
2. Very low vertical velocity components ✔
3. Low background ✔
    - Cryopumped detection chamber
        - 9K Heatshield around ionization area
    - BG reduced by > 1 order of magnitude



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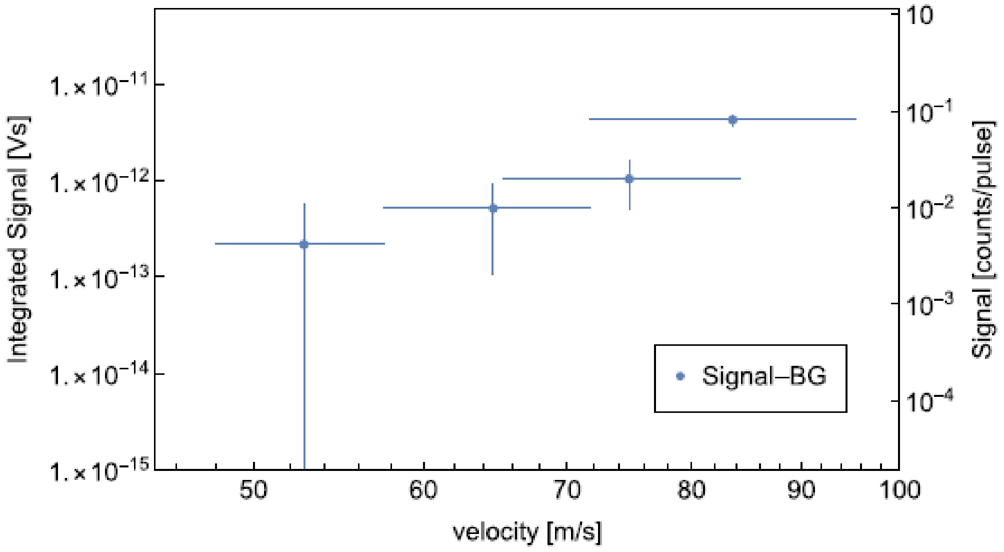
Requirements for a GQS measurement

1. Efficient detection of hydrogen ✔
2. Very low vertical velocity components ✔
3. Low background ✔
4. Low horizontal velocities ✔
   - Time of flight measurements
   - Slowest resolvable velocity $v \in [58, 72]$ m/s



[6] Killian, C et al. 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). https://doi.org/10.1140/epjd/s10053-024-00916-5

Requirements for GQS measurement

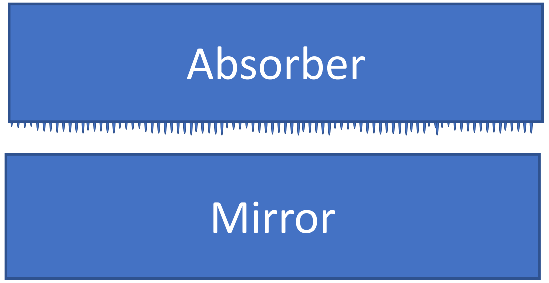
1. Efficient detection of hydrogen ✔
2. Very low vertical velocity components ✔
3. Low background ✔
4. Low horizontal velocities ✔

→ Requirements fulfilled

→ Next step: insert GQS spectrometer

Installation of GQS spectrometer

- Silicon Mirror + Absorber separated by 200 µm spacers were inserted
- Horizontal alignment of the experimental chamber 0.10 ± 0.16 mrad



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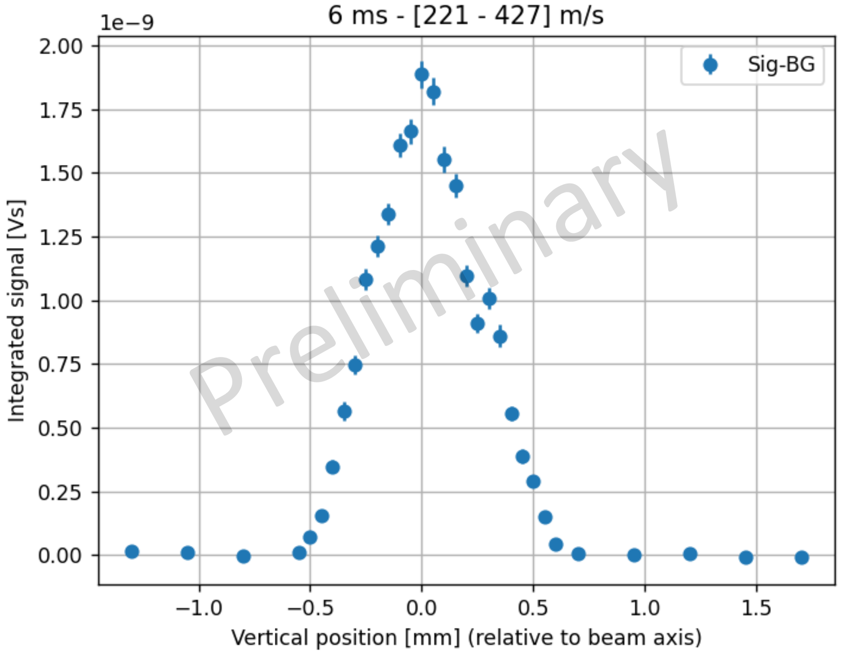
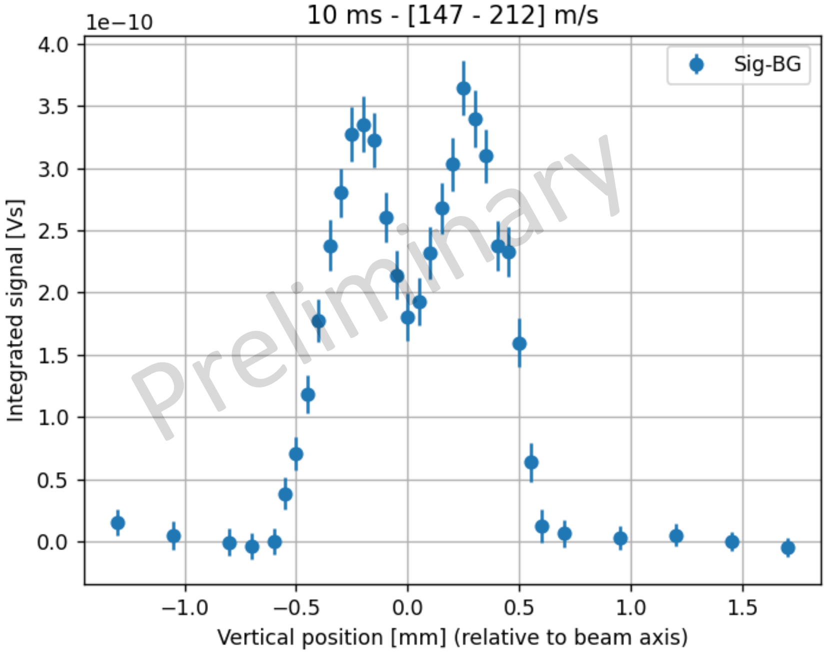
First measurements with 200 µm mirror-absorber separation

- Recorded vertical profiles for different velocity intervals
- A second peak appears above the beam axis for lower velocities





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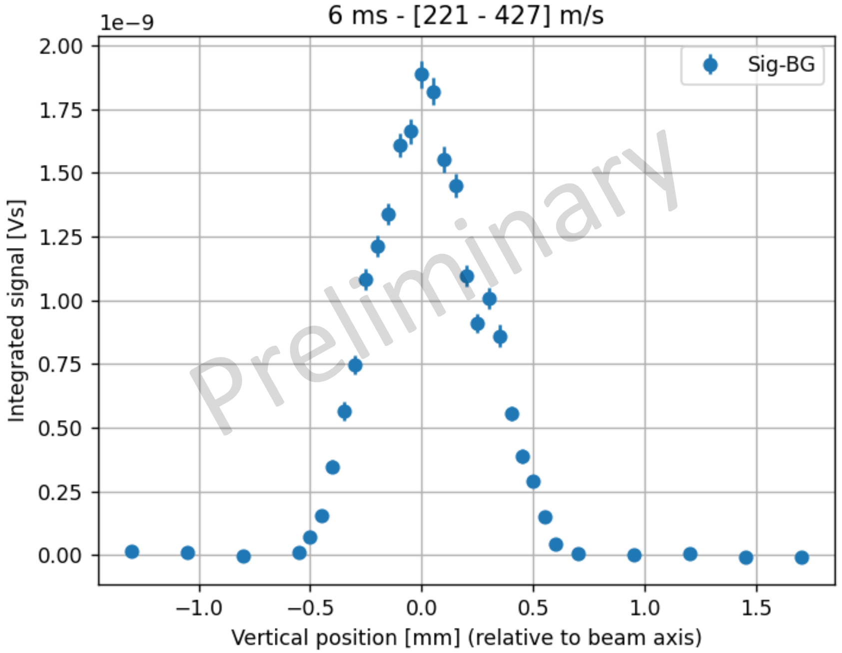

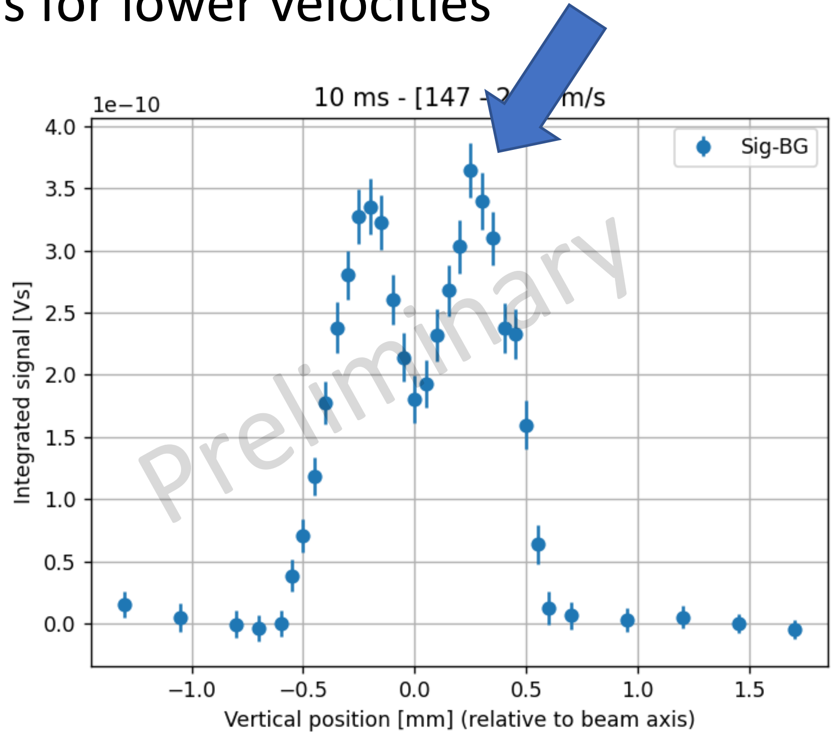

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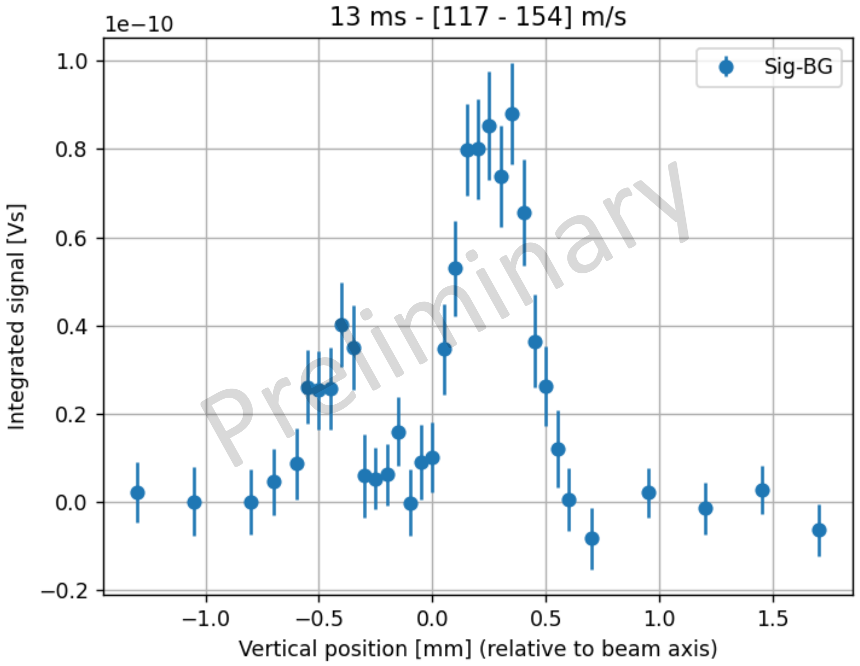
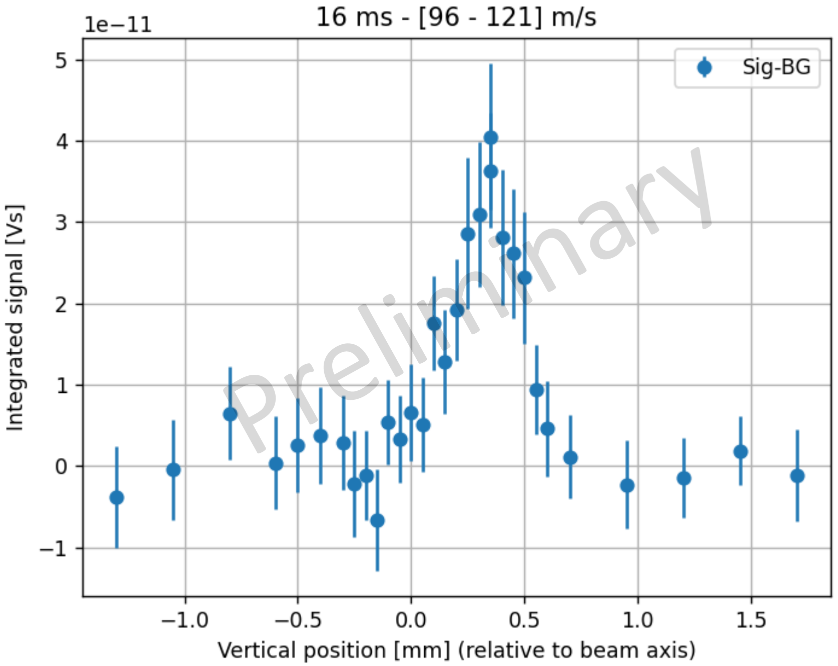
- For even lower velocities “main” peak disappears





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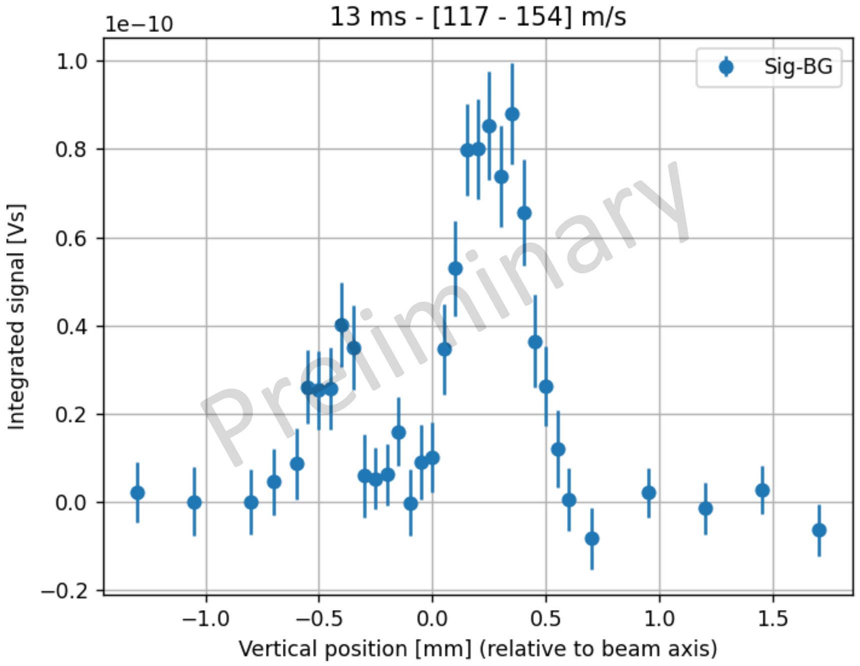
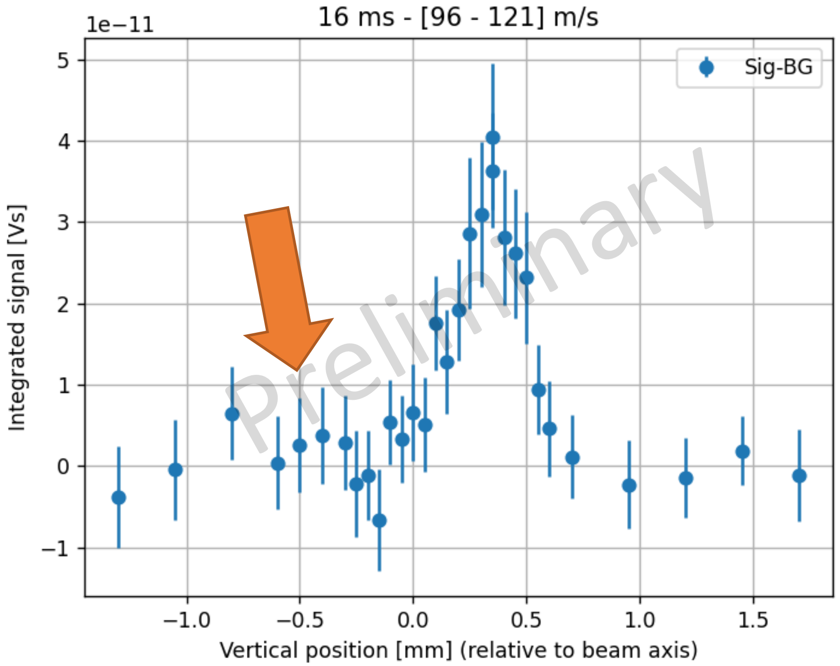
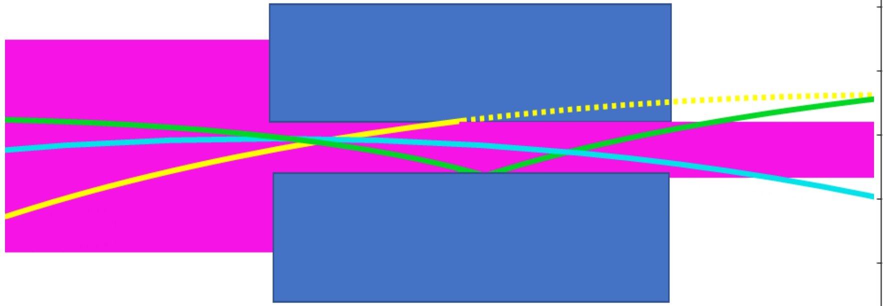
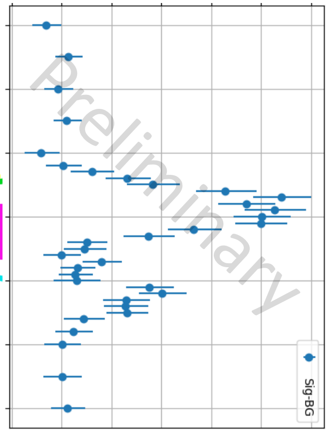
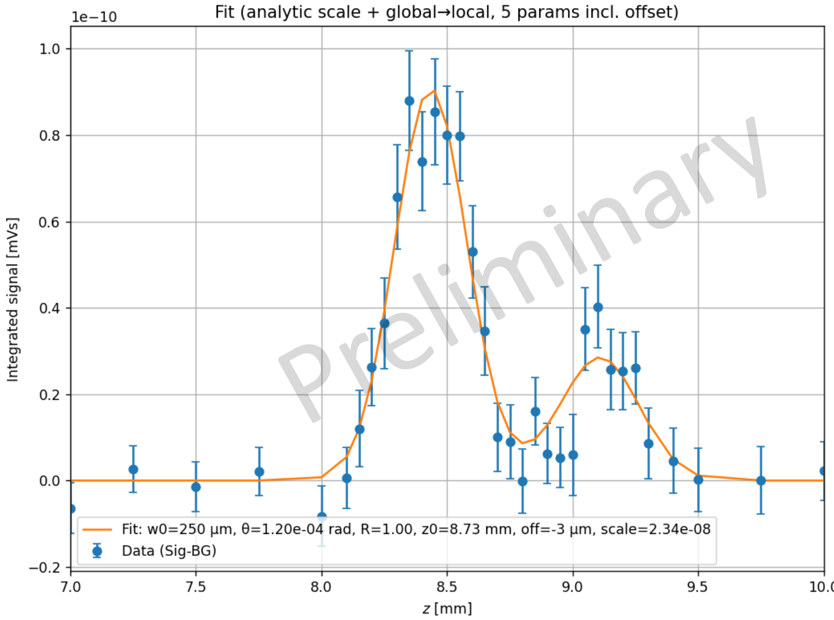




First indication of quantum reflection of H above a Silicon surface

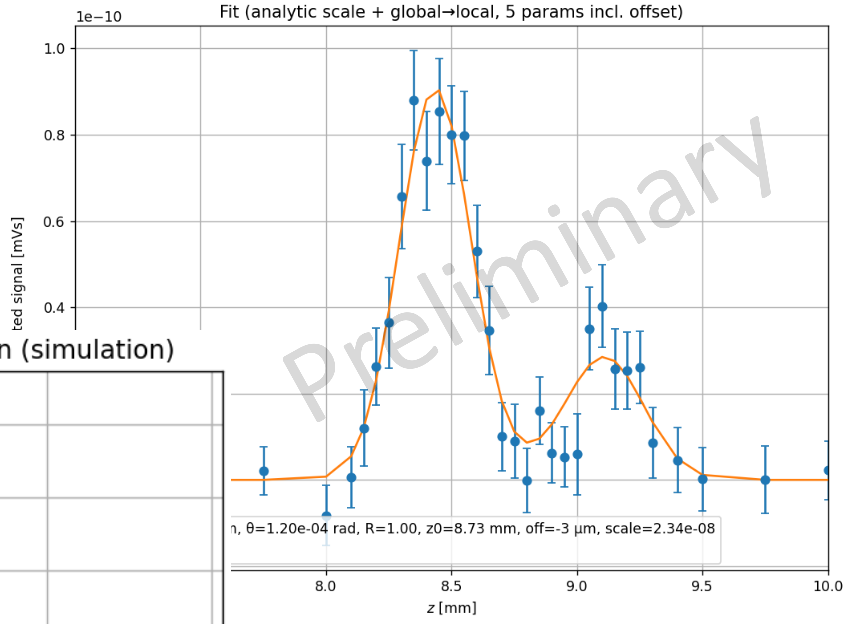


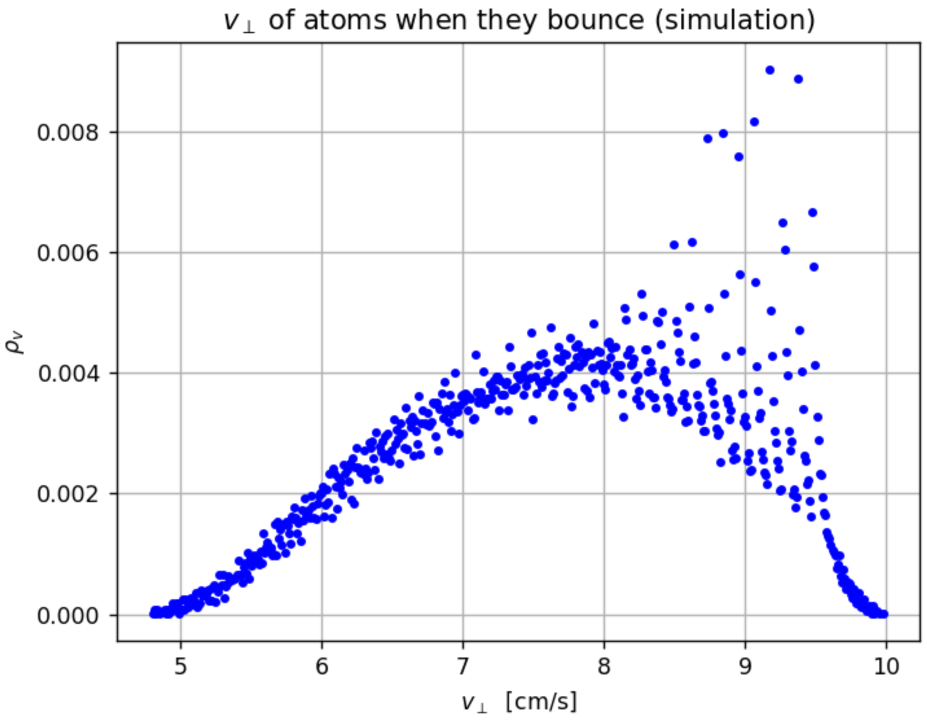


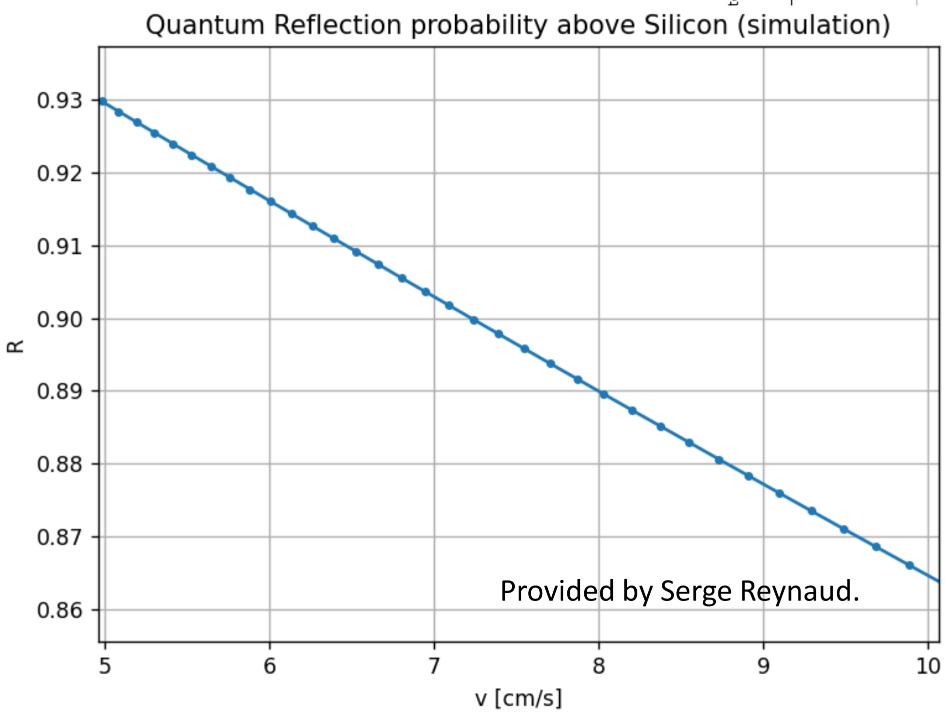


- Trajectories leading to 2nd peak only possible if bounce (reflection) occurs
- Trajectory simulations confirm / predict the shapes of the vertical profiles
- Fitting procedure and extensive analysis in progress

First indication of quantum reflection of H above a Silicon surface

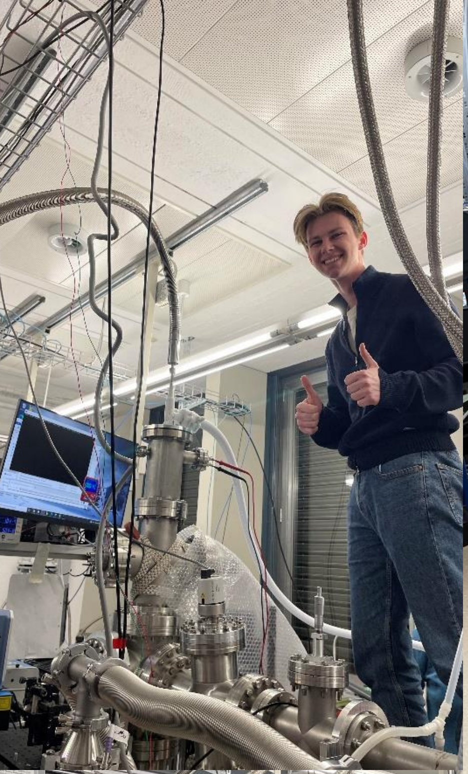


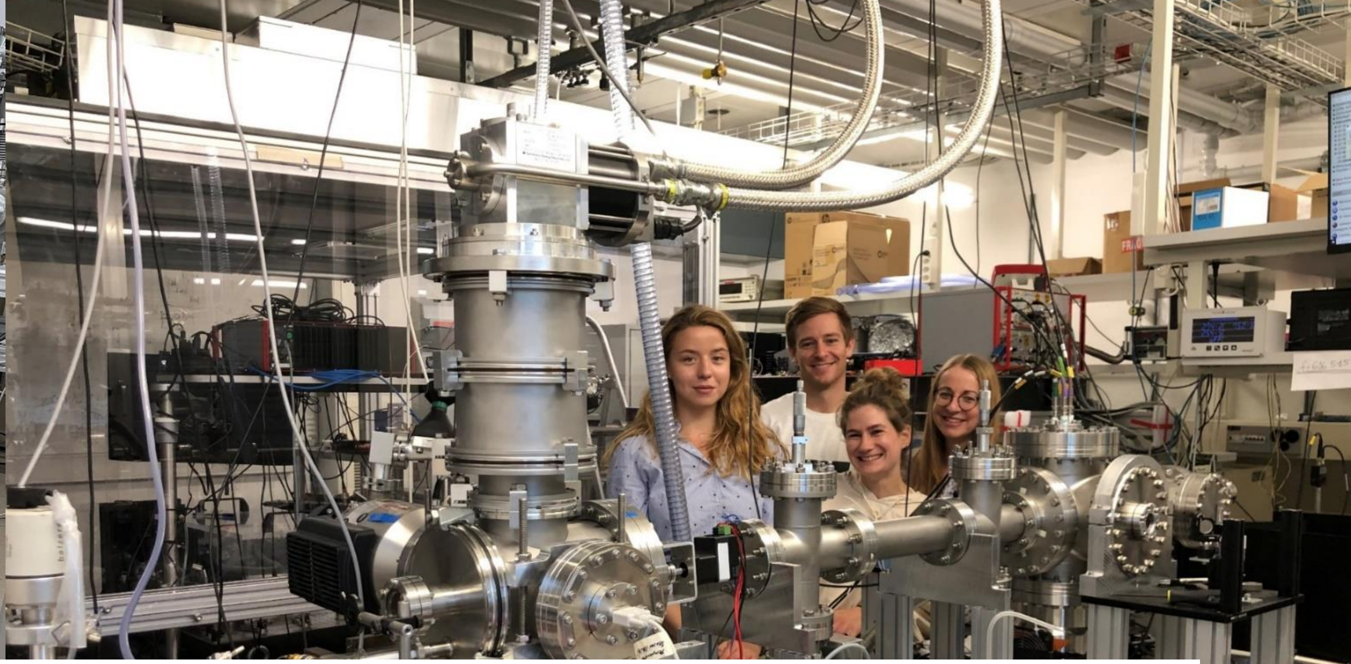




Summary and Outlook

- Requirements for GQS measurement fulfilled
- GQS spectrometer installed
- First measurements with 200 µm separation
- Indication of quantum reflection of H above Si surface
- Outlook:
  - Analysis in progress → extraction of QR coefficient
  - Piezo actuators to dynamically change mirror-absorber-separation will be inserted next week
  - Stay tuned 😉





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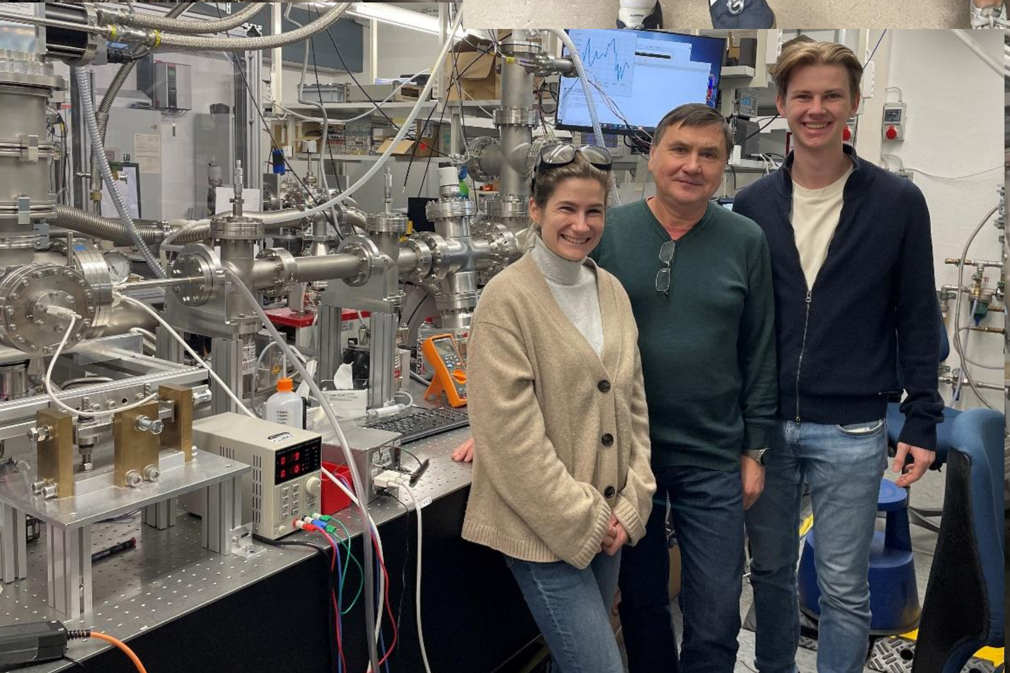
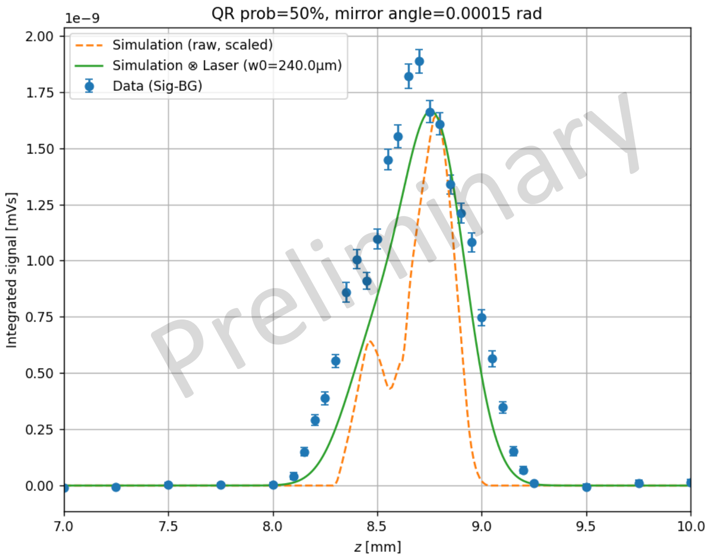
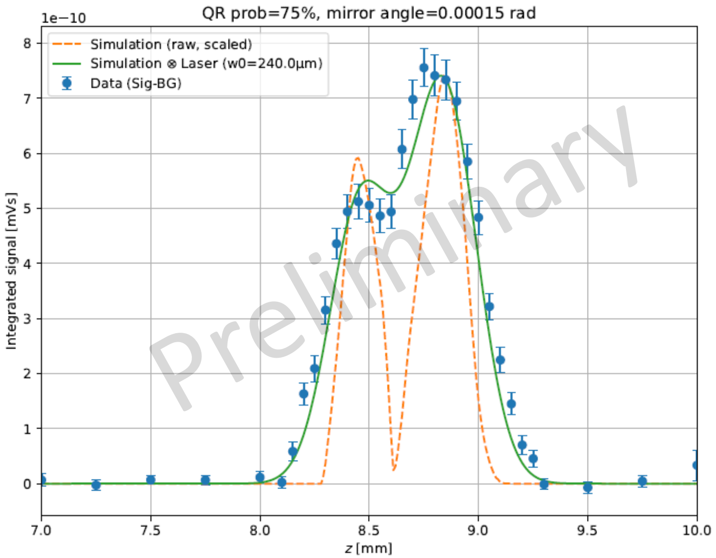
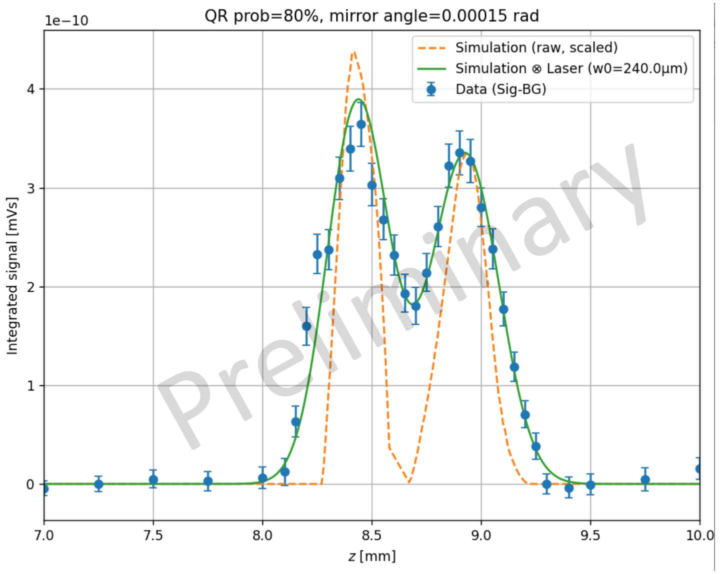
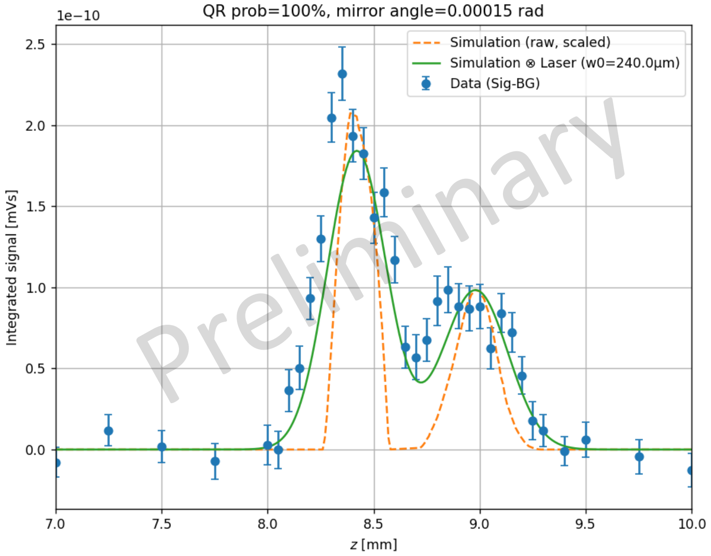


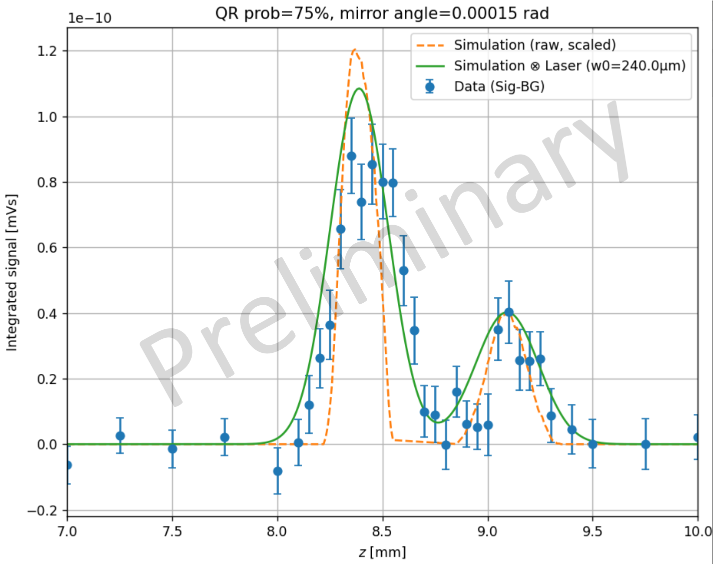
Simulations

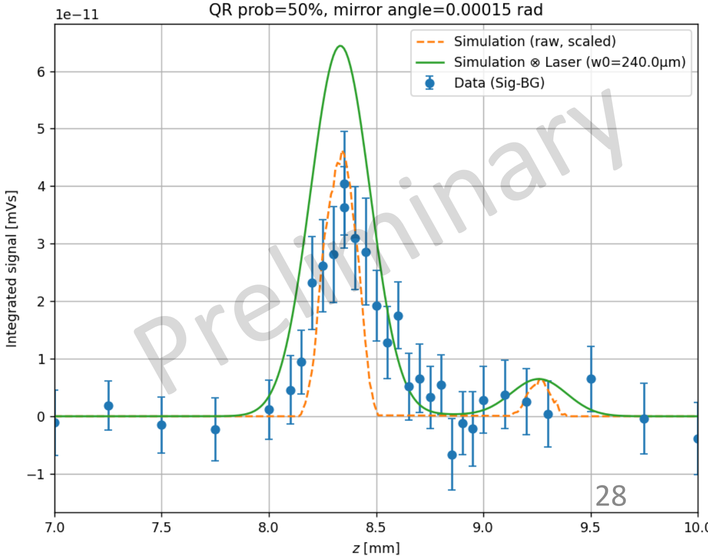




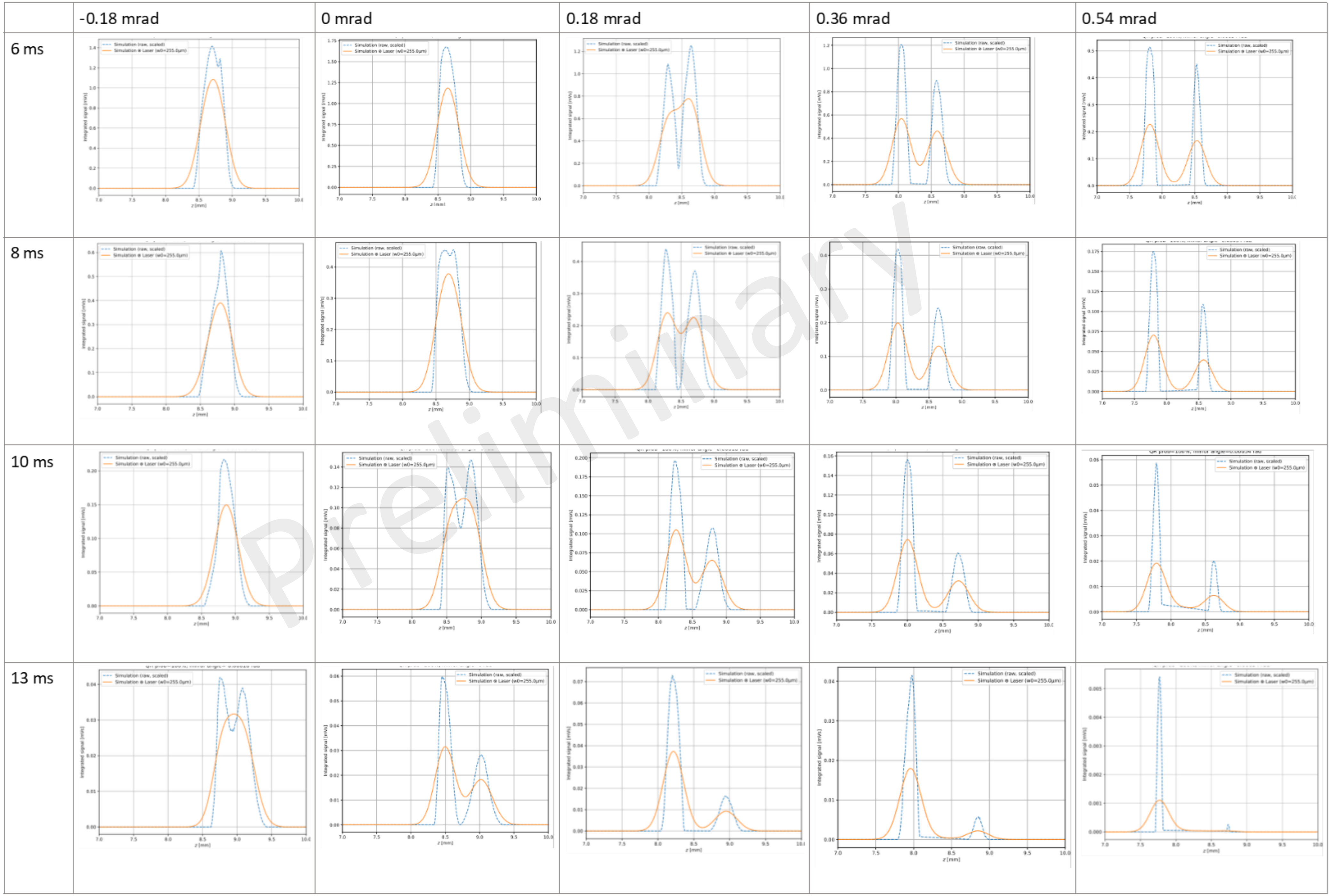






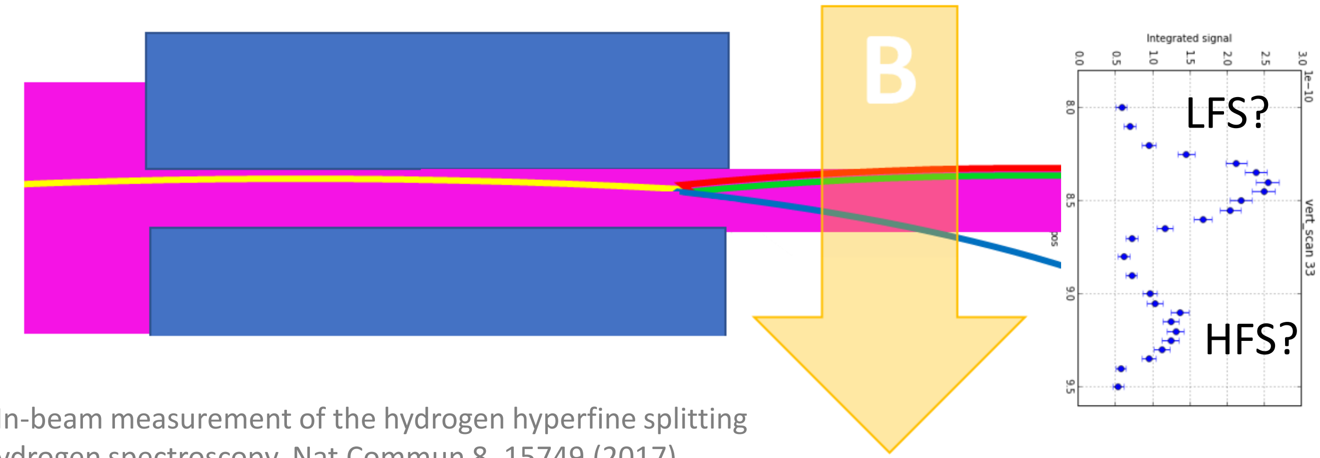


Simulations – velocity x angle



Alternative explanation – magnetic field ?

- UV freq. set to F=1 resonance
  - Triplett – 2x LFS, 1x HFS
  - Magnetic field gradient could generate separated trajectories for different spin states
- UV freq. set to F=0 resonance
  - Singlett – 1x HFS
  - Only HFS trajectory should be detectable



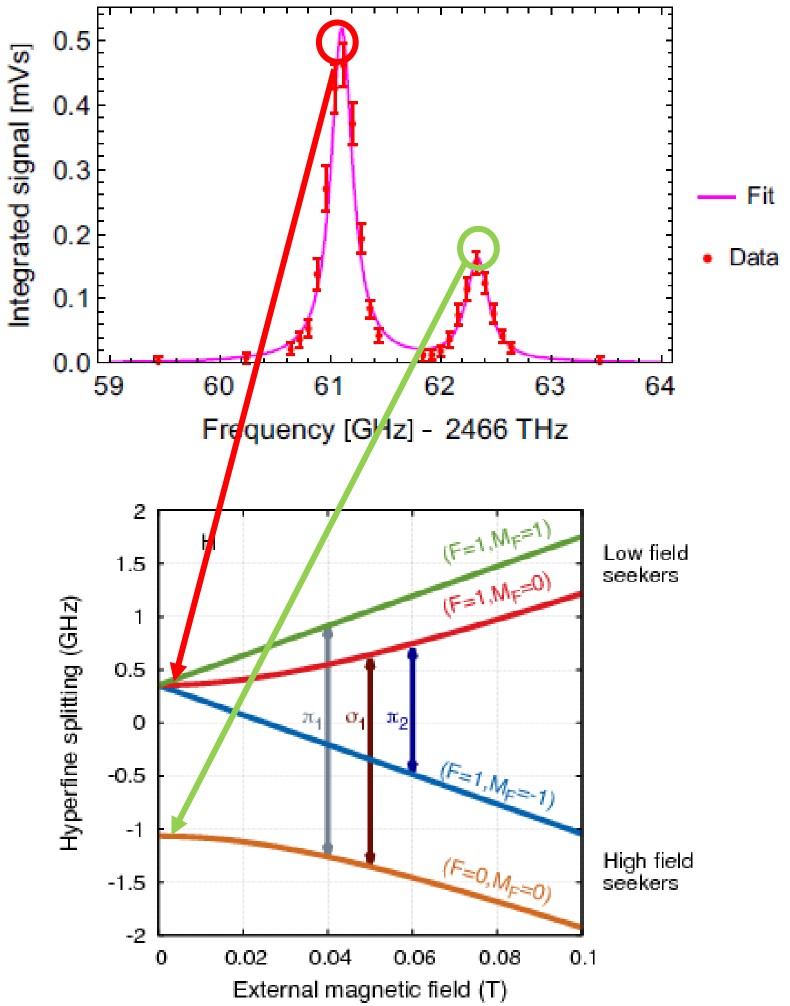
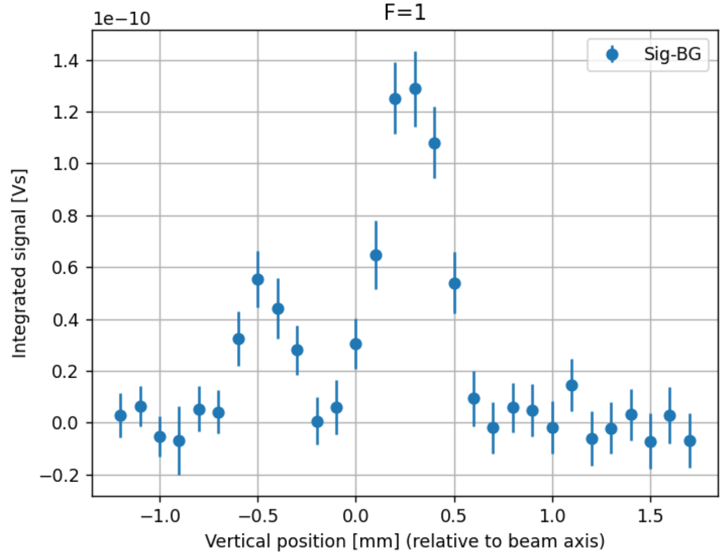


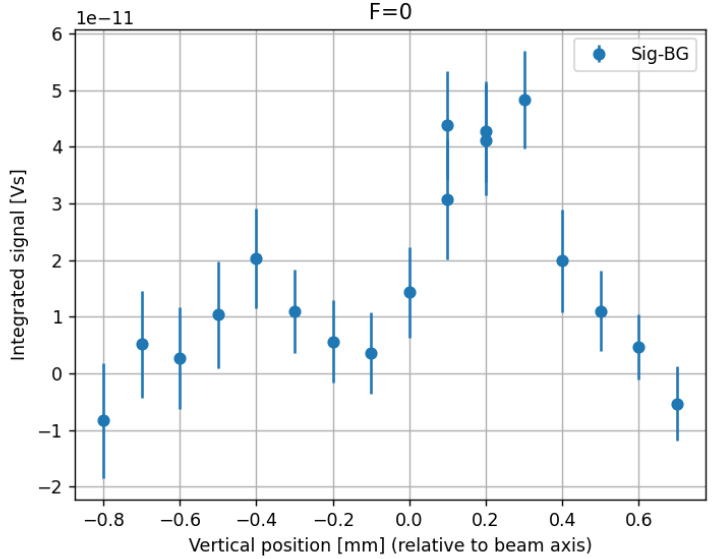
Figure taken from [7].

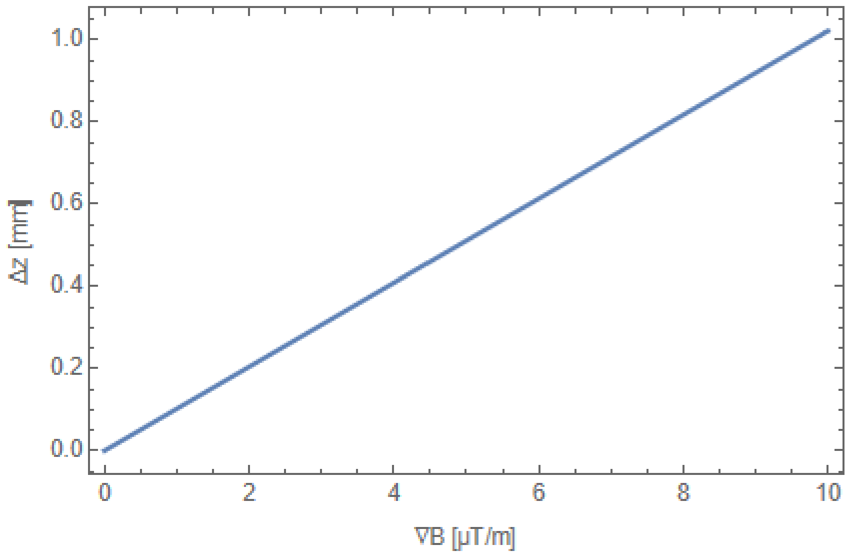
[7] Diermaier, M. et al. In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy. Nat Commun 8, 15749 (2017). https://doi.org/10.1038/ncomms15749

Alternative explanation – magnetic field ?

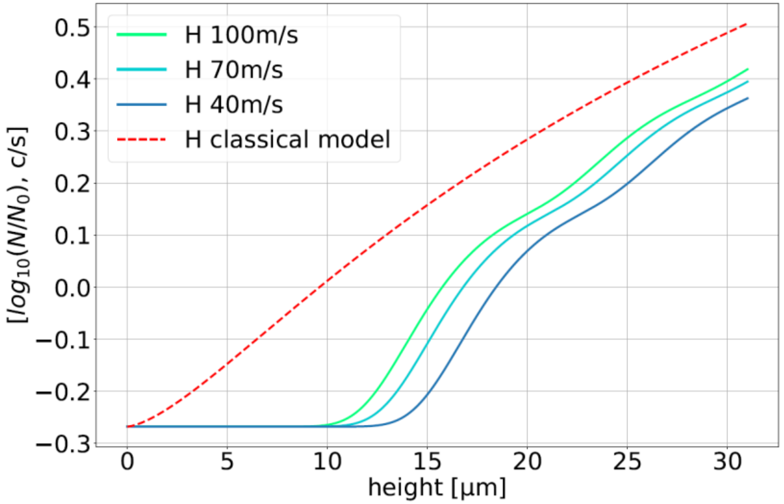
- Recorded vertical profiles with laser frequency set to F=1 and F=0 resonance
- Both peaks visible for both frequencies
- Magnetic field gradient needed for a 0.6 mm separation of HFS and LFS ~ 5.88 mT/m (for 140 m/s atoms)







Measurement principle

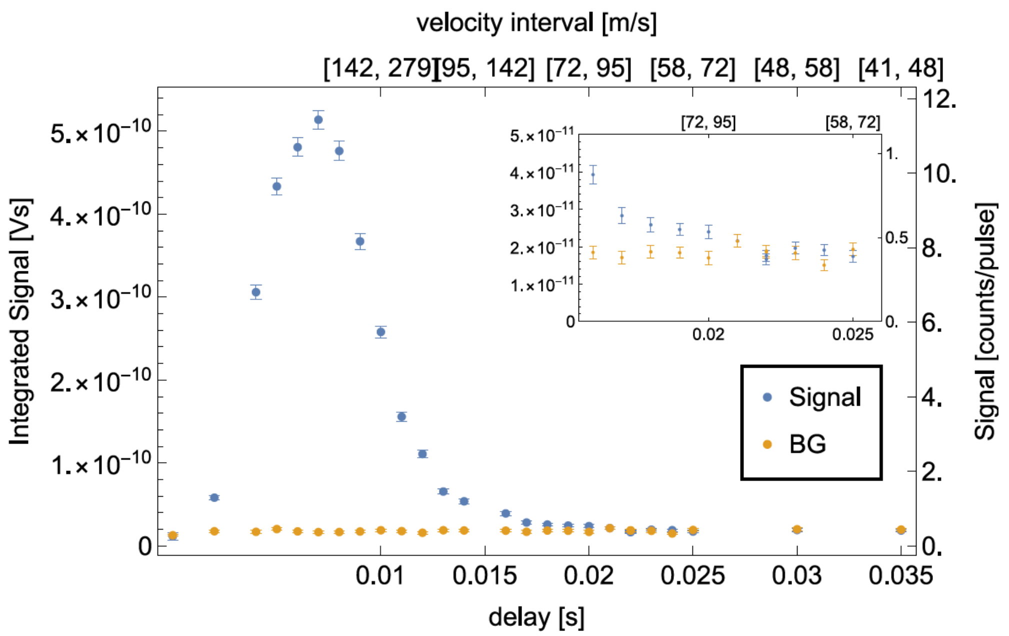


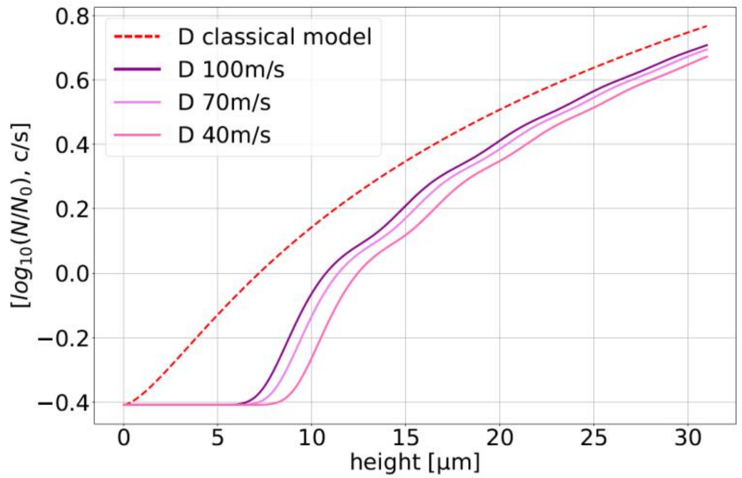
- Heisenberg‘s uncertainty: $\Delta t \Delta E \geq \frac{\hbar}{2} \rightarrow \Delta t \gtrsim 0.5\ \mathrm{ms}$
  - $l(mirror) = 0.3\ \mathrm{m} \rightarrow v \ll 600\ \mathrm{m/s}$
- Simulations of H passing through scatterer* → curves depend on:
  - Scatterer „efficiency“ (estimated from neutron data, but higher efficiency expected with new scatterer)
  - Size of the GQS (← particle mass, acceleration toward mirror)
  - Interaction time (← particle velocity)
- Small slit widths Δz are difficult to reach due to dust particles ($\varnothing \lesssim 8 - 10\ \mu\mathrm{m}$, steril environment („cleanroom“) around experimental chamber to avoid dust particles)
- Resolution of first step could be possible for $100\ \mathrm{m/s}$ atoms

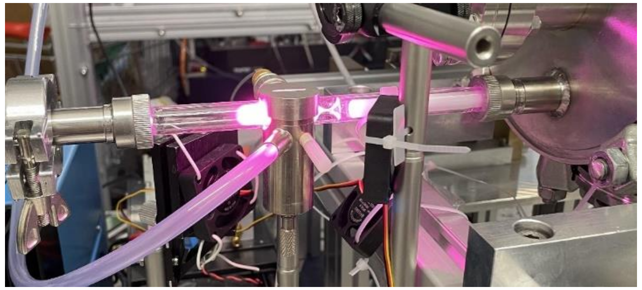
*calculations & simulations done by K. Schreiner

Deuterium measurements

- Delay Measurement with deuterium (D)
  - Slowest resolvable velocity interval at $t = 20$ ms: $v \in [72, 95]$ m/s
  - BG reduced by factor ~ 2.65
- But: higher mass → smaller GQS → need even lower velocities to resolve 1st step

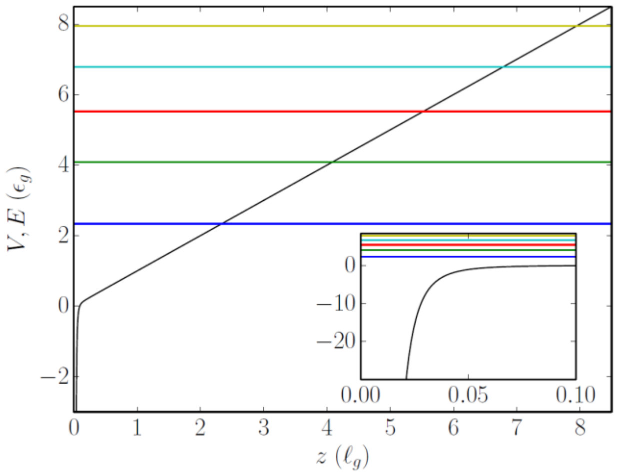




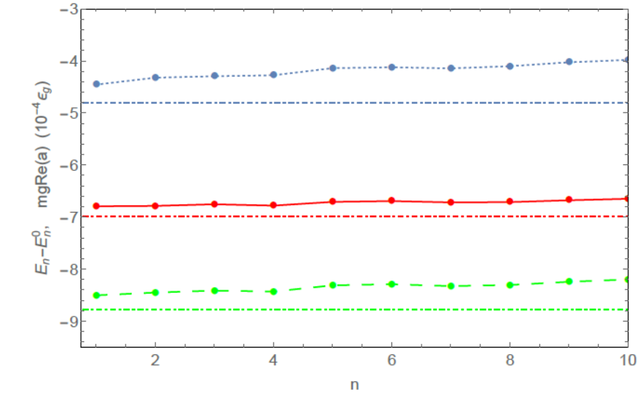


CP – shifts

- 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 $\overline{\mathrm{H}}$ [3]
- 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 [6].



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 [6].

[3] 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.

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 ≈ 0.13 mm, Pulse Energy ≈ 500 μJ, Pulse duration ≈ 10 ns $\rightarrow$ $\varepsilon_{ion} \approx 99.36\%$