ÖAW AUSTRIAN ACADEMY OF SCIENCES

SMI – STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS

GRASIAN: Shaping and characterization of the cold hydrogen and deuterium beams for the forthcoming first demonstration of gravitational quantum states of atoms.

10.06.2024

Carina Killian on behalf of the GRASIAN collaboration

PSAS'2024

ETH zürich

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Gravitational quantum states (GQS)

- Gravitational potential well ↔

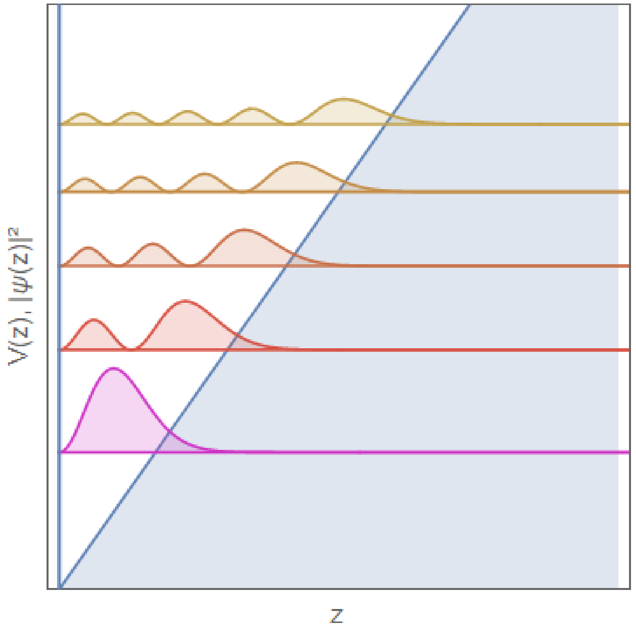
  Gravity potential ($V_G(z) = mgz$) +

  Perfectly reflecting surface (“mirror”)

- Particle trapped in gravitational potential well is settled in gravitationally bound quantum states

- Test masses: neutral & light particles (neutrons, hydrogen …)

- 2002: First demonstration of GQS with ultra cold neutrons [1]



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Gravitational quantum states (GQS)

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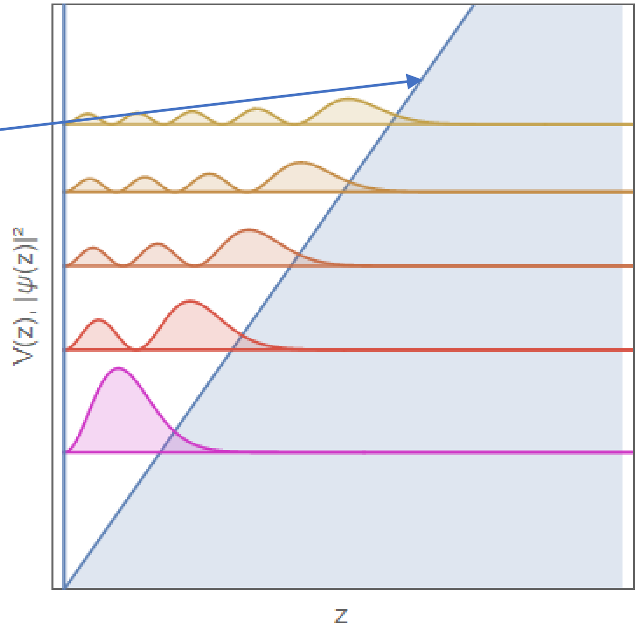
  Gravity potential ($V_G(z) = mgz$) ➡ Linear potential

  Perfectly reflecting surface (“mirror”)



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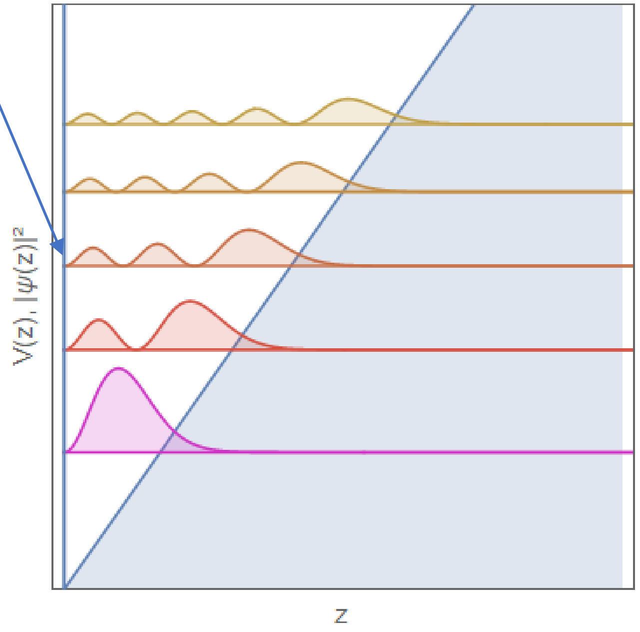
  Gravity potential ($V_G(z) = mgz$)

  Perfectly reflecting surface (“mirror”)

Infinite potential wall ↔
Boundary condition at $z = 0$



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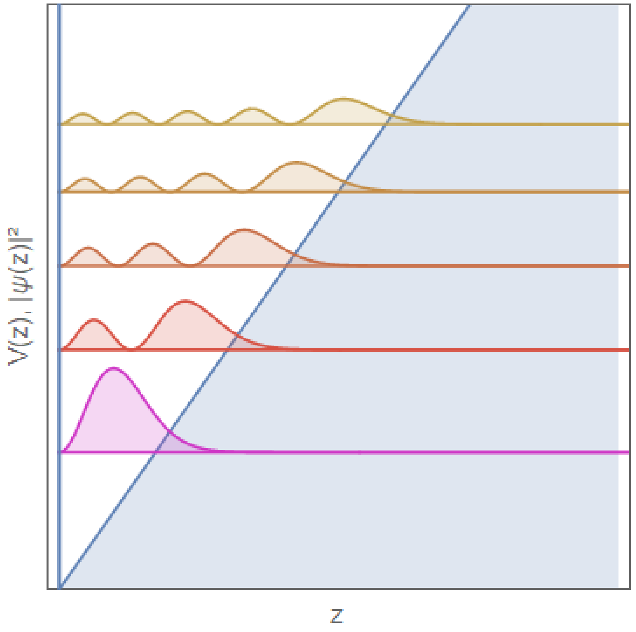

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GQS of atomic hydrogen

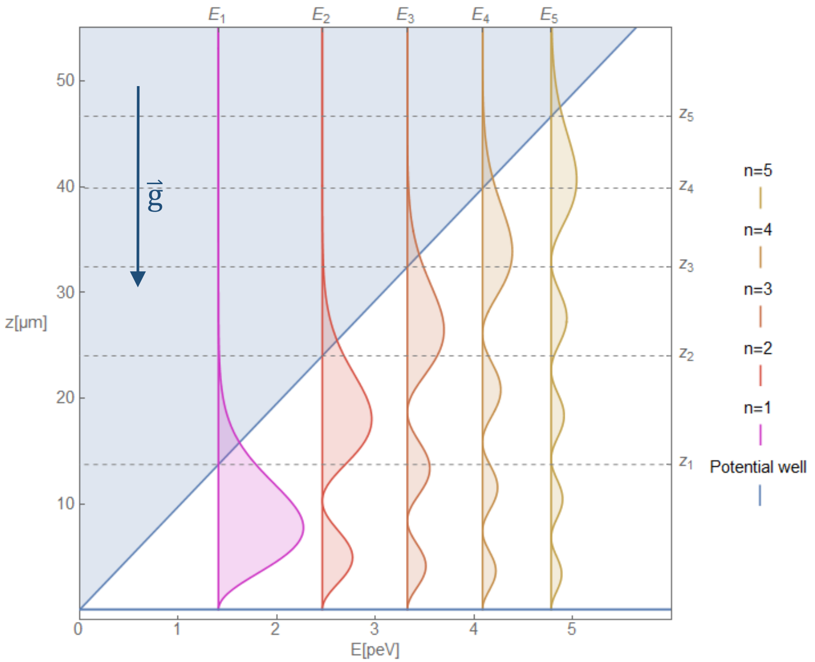
- Macroscopic spatial heights $z_n \sim$ µm of GQS of hydrogen
- Eigenenergies $E_n \sim$ peV

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

  → Long observation time needed!

  → Very slow/cold particles or long experimental setup

- (Quantum-) Reflection from mirror surface governed by Casimir-Polder potential

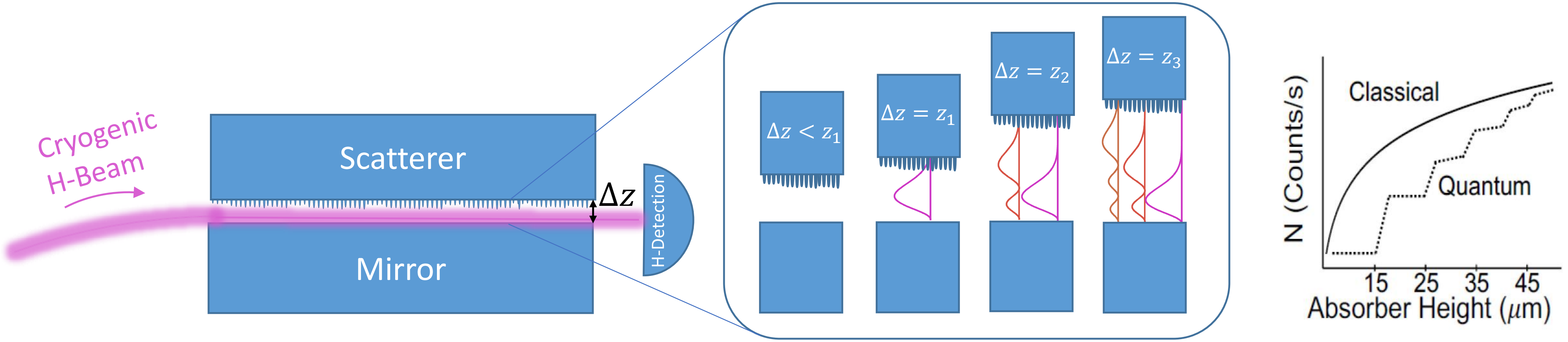


n	E_n [peV]	z_n [µm]
1	1.4	13.8
2	2.5	24.0
3	3.3	32.4
4	4.1	39.9
5	4.8	46.6

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, $V_{mirr} = \delta(z)$

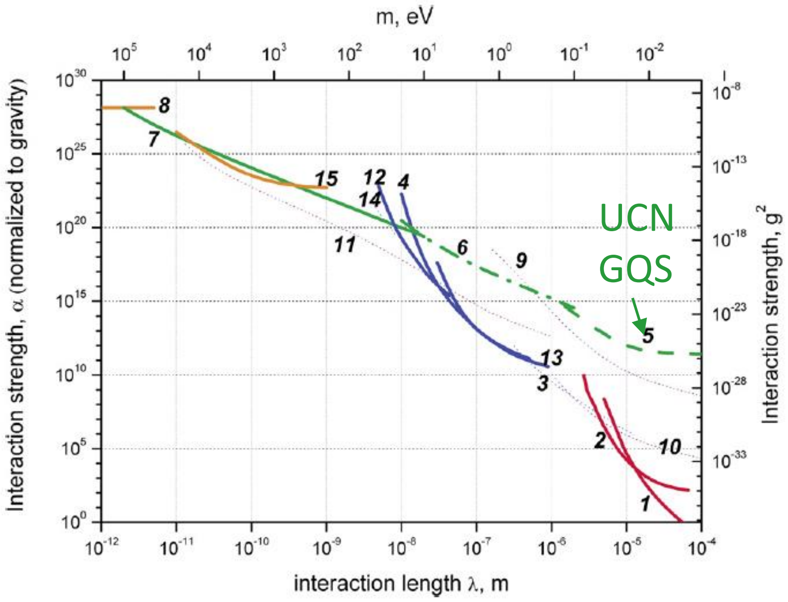
Measurement principle

- GQS Region: mirror and scatterer 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 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 ($\rightarrow \bar{g}$)
- Requirements:
  1. Efficient detection of hydrogen
  2. Collimated beam
  3. Very low vertical velocity components
  4. Low horizontal velocity components
  5. Low background



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

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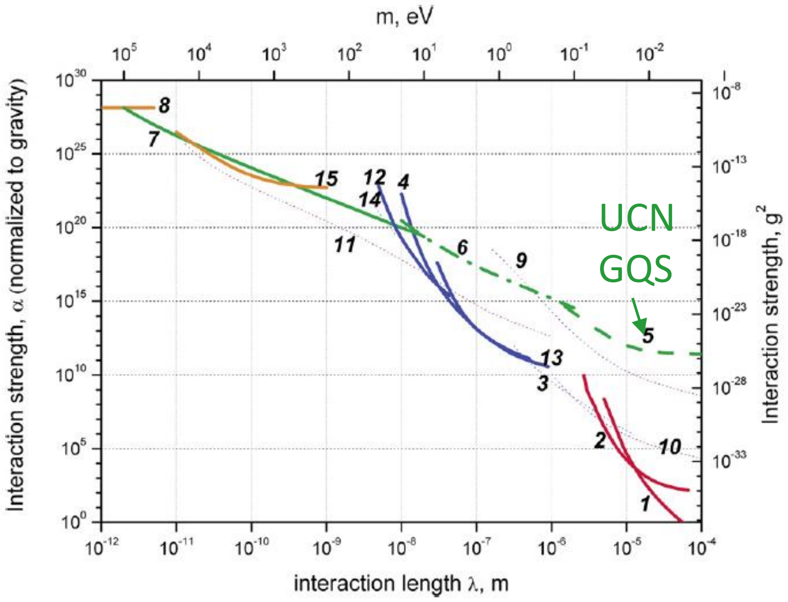

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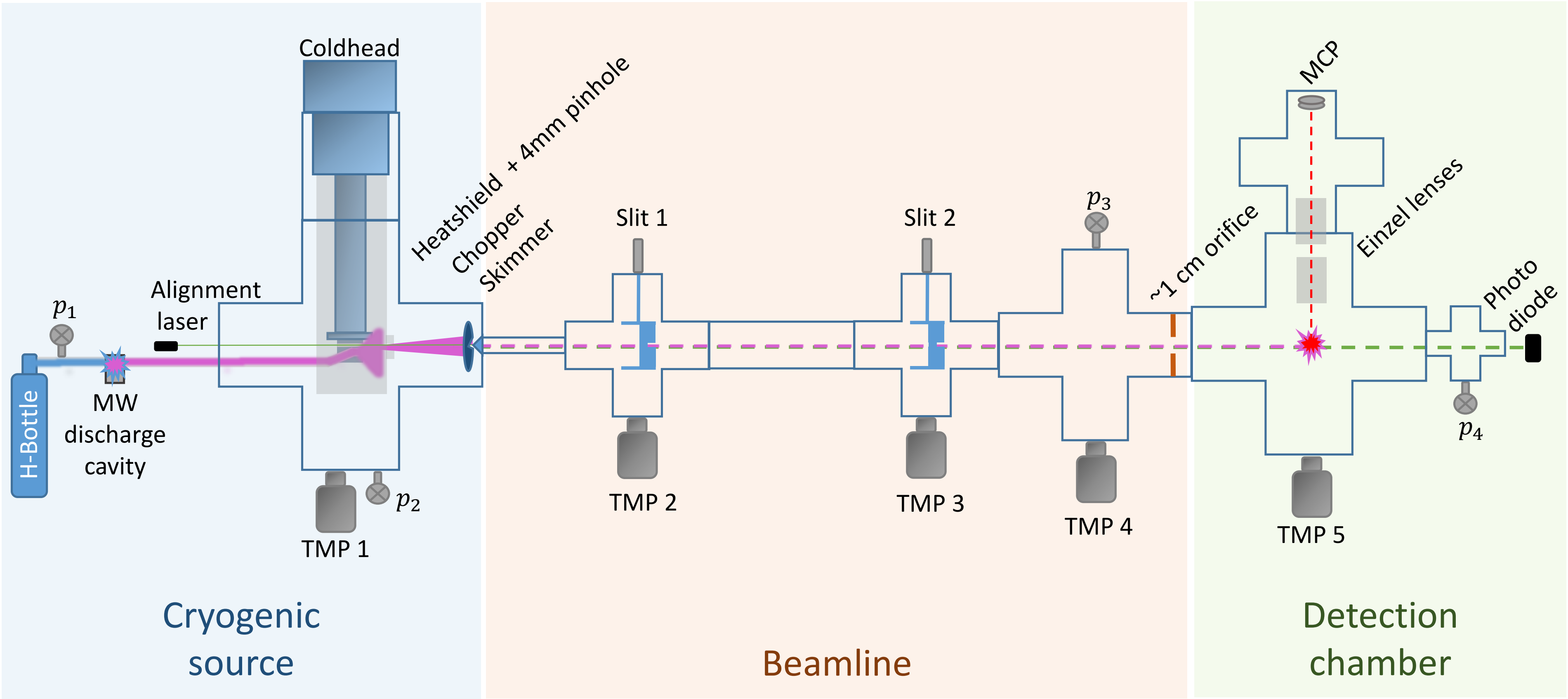
Hydrogen beam – experimental setup



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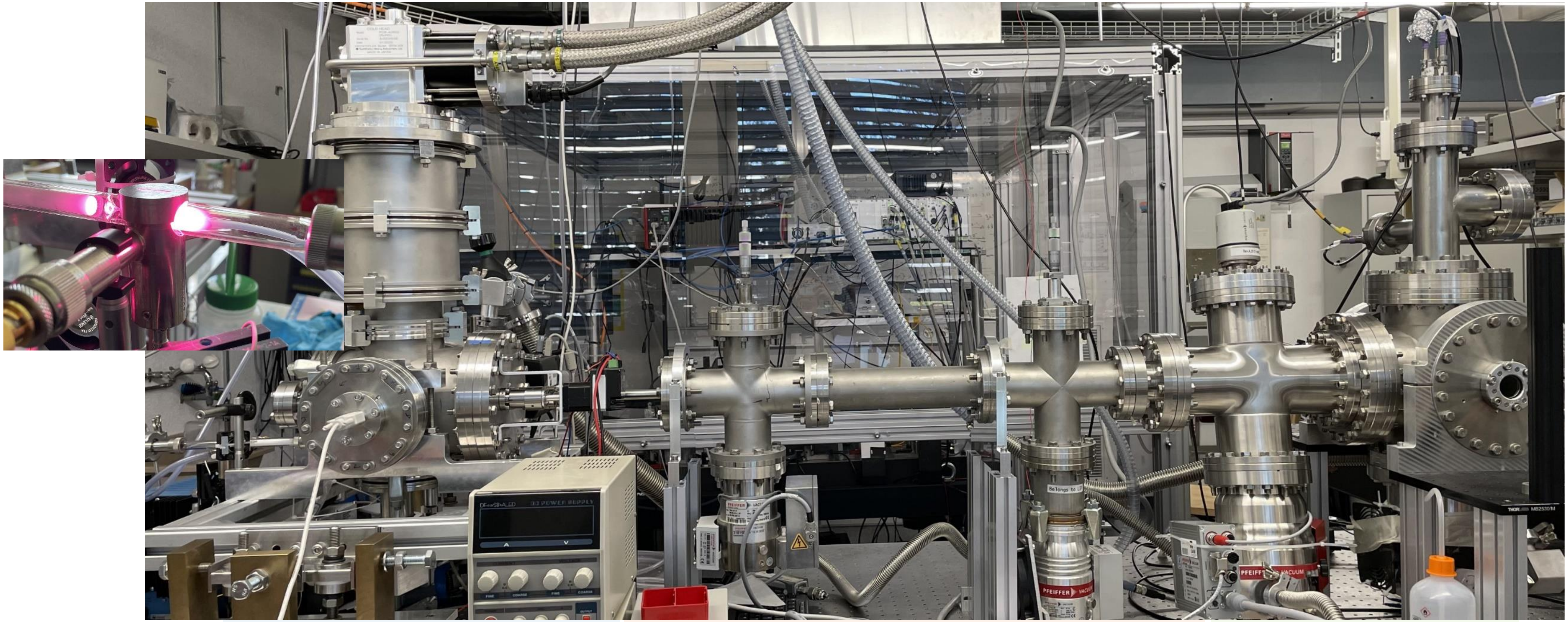
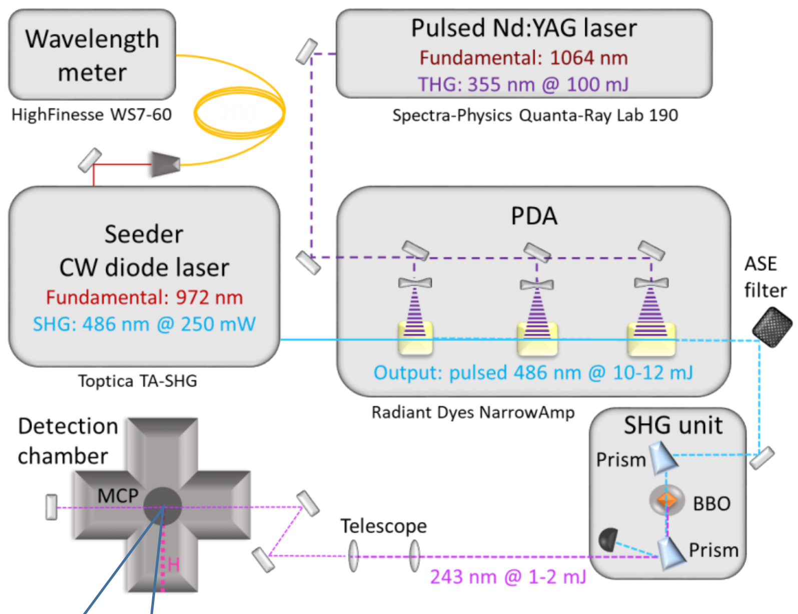
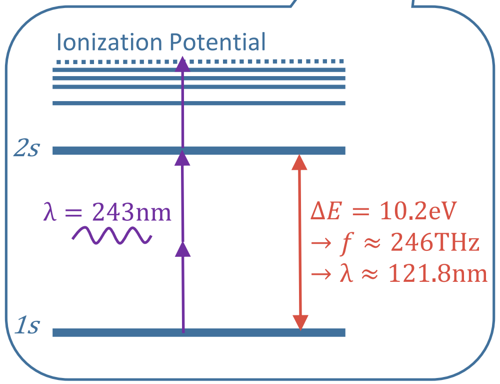


Cryogenic source | Beamline | Detection chamber

Requirement #1: Efficient detection of hydrogen

- Ionization of H with a pulsed UV-Laser ($\lambda = 243\ \mathrm{nm}$)
    - $\mathrm{H} \rightarrow \mathrm{H}^+ + \mathrm{e}^-$
    - 2 photon excitation (1S-2S) + 1 photon ionization
    - Laser system described in [3]
- Detection of H^+ with an MCP
- Integrated MCP-Signal $\propto$ H- count rate
- Ionization efficiency $\varepsilon \approx 99.36\%$





[3] 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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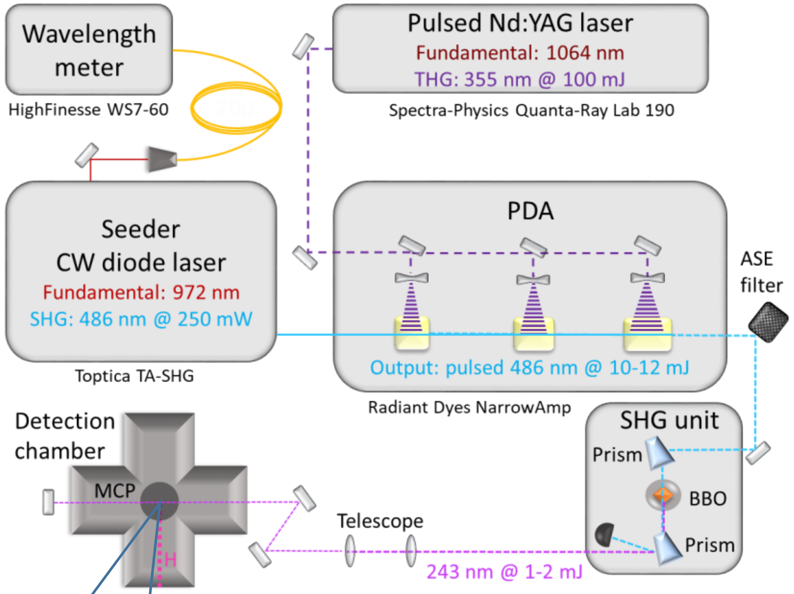

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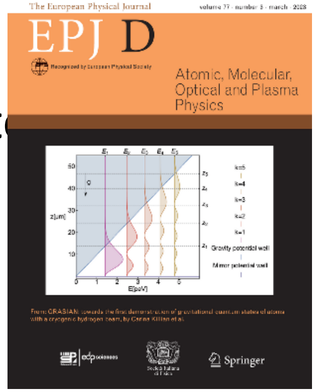

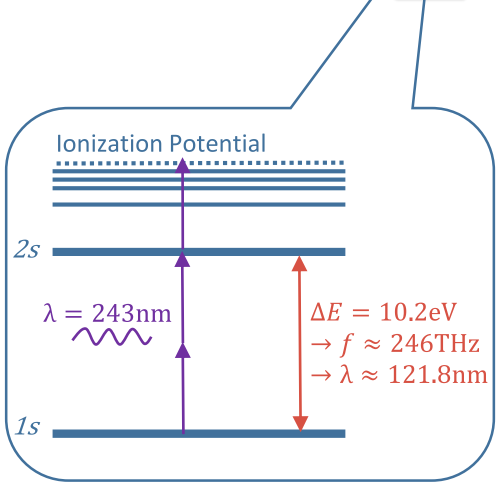

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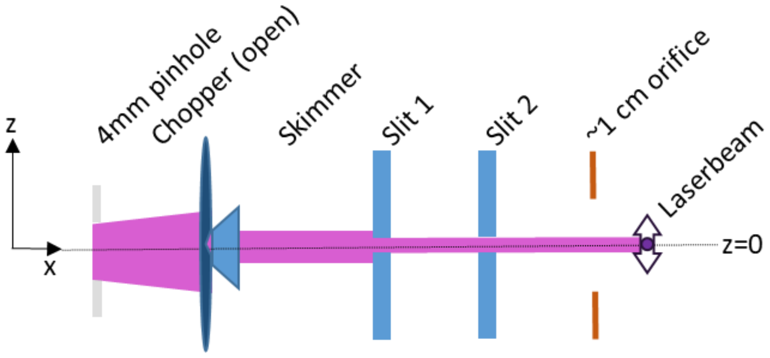
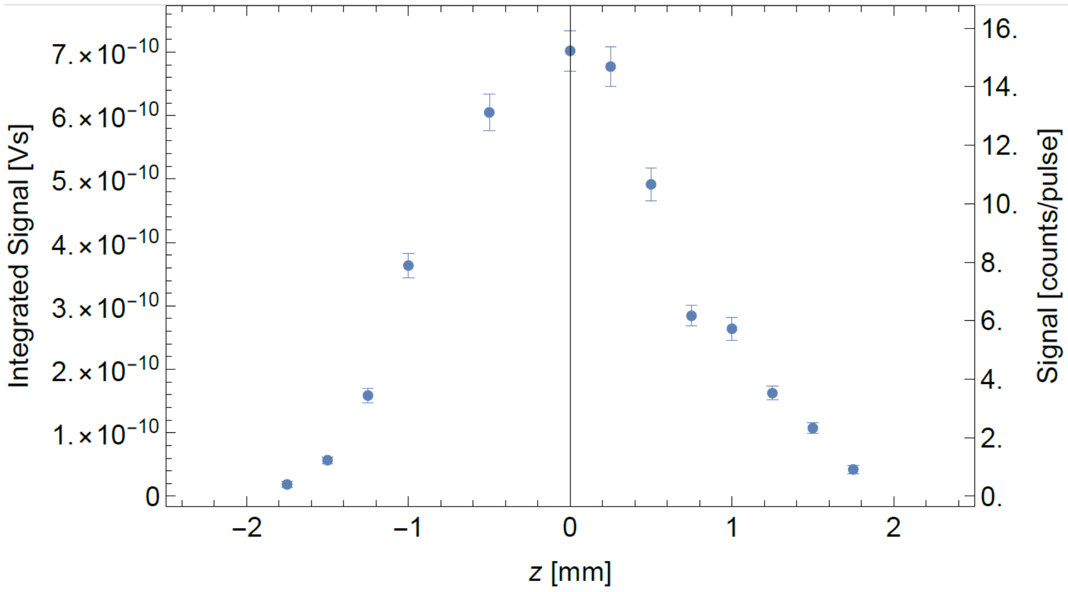
Requirement #2: Collimated beam

- Beam shaping components
  - 4 mm pinhole
  - 2 mm skimmer
  - Two 1 × 30 mm slits → adjustable vertical position
  - 1 cm orifice
- ~2 mm H beam

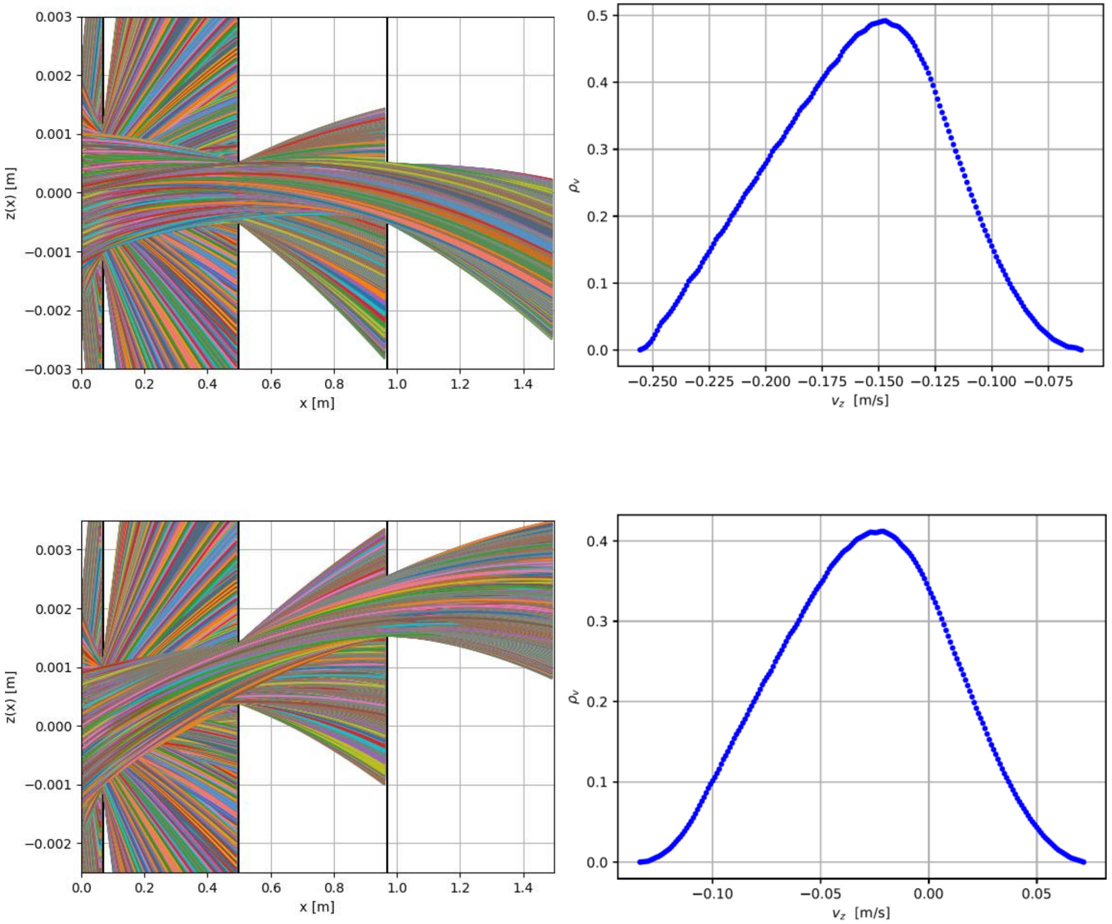
→ our beam shaping components work





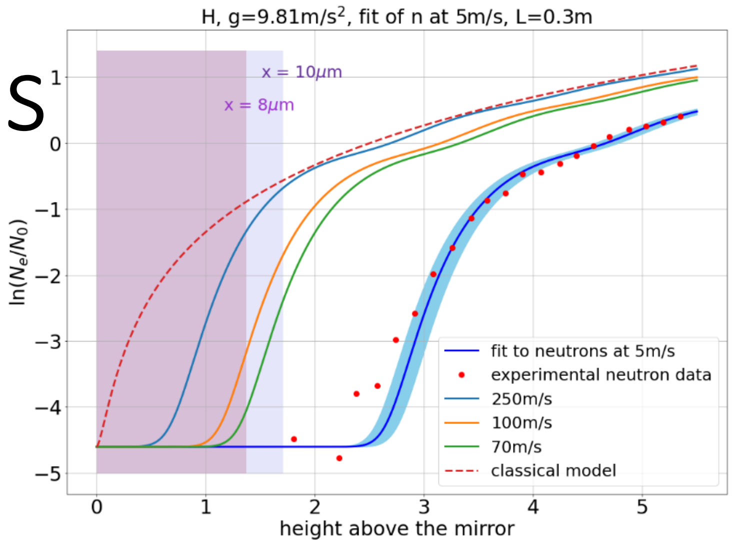
Requirement #3: Very low vertical velocity components

- Quantum reflection probability $> 90\%$ for $|v_z| < 10\ \mathrm{cm/s}$
- Trajectory selection with vertical adjustable slits
  - All slits on axis: $v_z \sim -15\ \mathrm{cm/s}$
  - Optimization of vertical slit position $v_z \sim\ -2\ \mathrm{cm/s}$



Requirement #4: Low horizontal velocity components

- 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 ($\emptyset \lesssim 8 - 10\ \mu\mathrm{m}$, steril environment planned around experimental chamber to avoid dust particles)
- Resolution of first step could be possible for $70\ \mathrm{m/s}$ atoms



*calculations & simulations done by K. Schreiner

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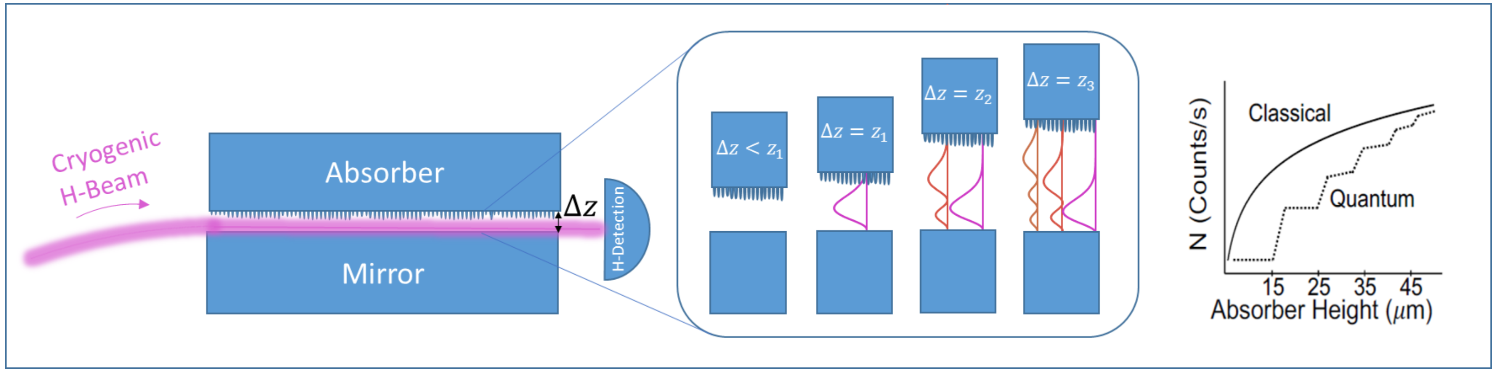

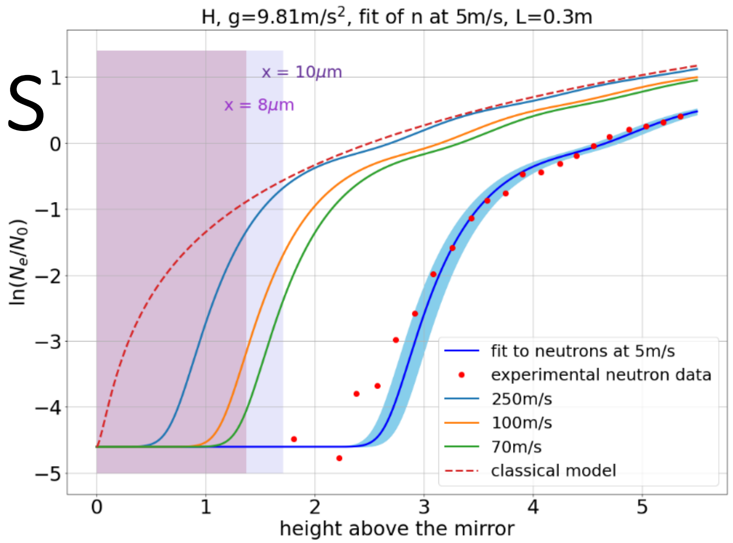

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- Resolution of first step could be possible for 70 m/s atoms

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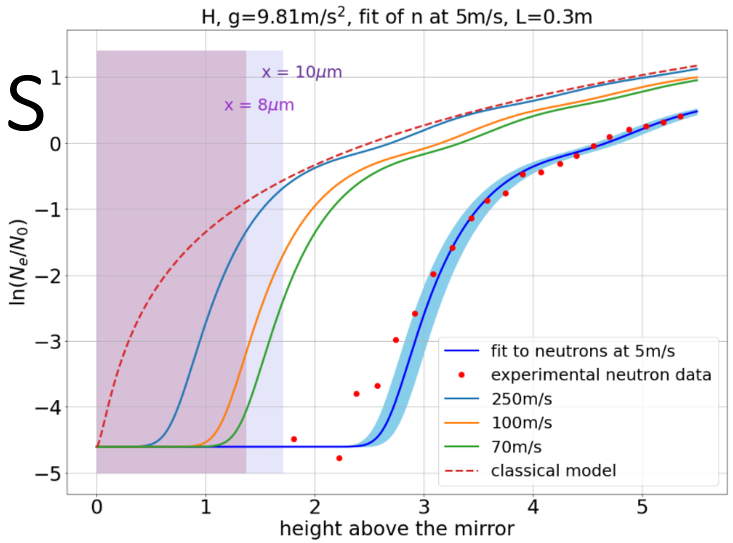

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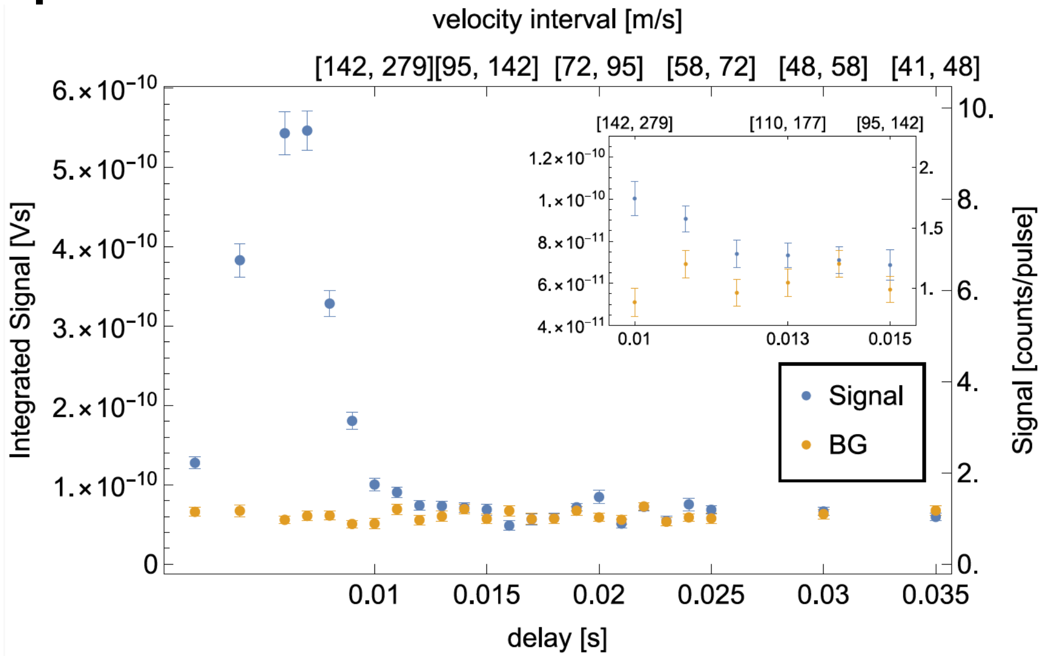
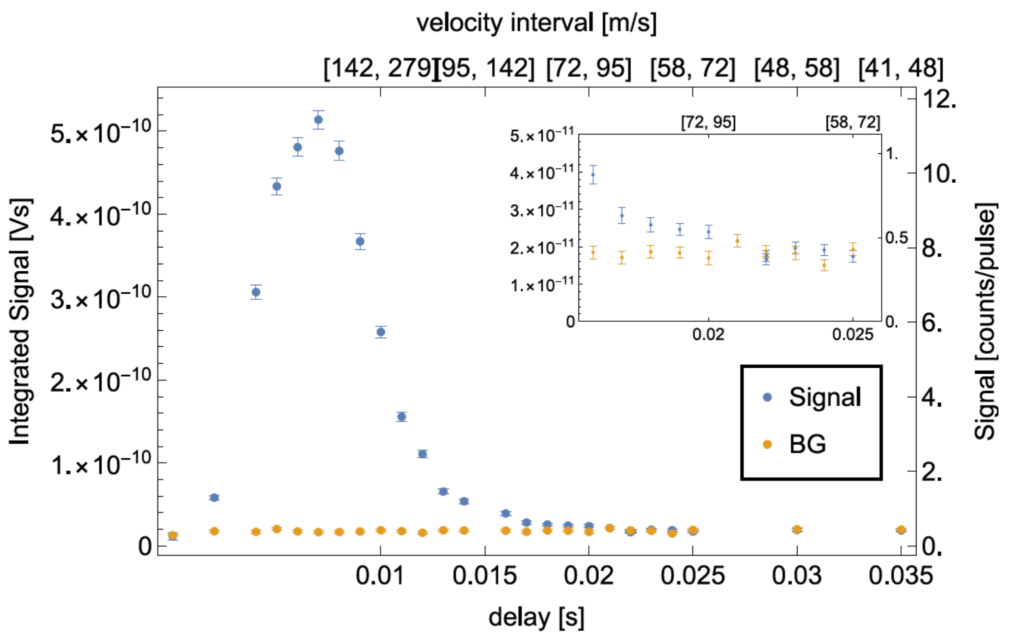
Requirement #4:
Low horizontal velocity components

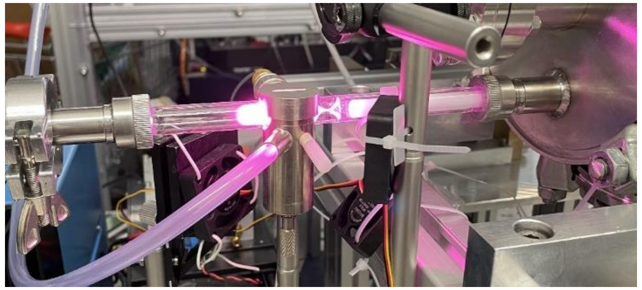
- H beam cooled down to 6K
- Delay Measurement:
  - Variation of the delay τ between chopper opening and firing of the Laser
  - Distance (chopper – detection): $\Delta x = 1.45\ \mathrm{m}$
  - Chopper is open for 5 ms
- Slowest resolvable velocity interval at t $= 13\ \mathrm{ms}$: $v \in [110, 177]\ \mathrm{m/s}$
- BG needs to be reduced!

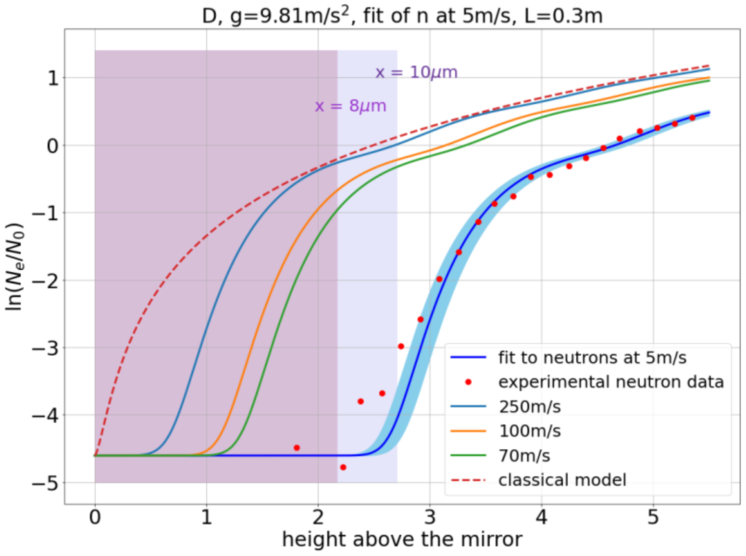


Requirement #5: Low background – measurements with D

- 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

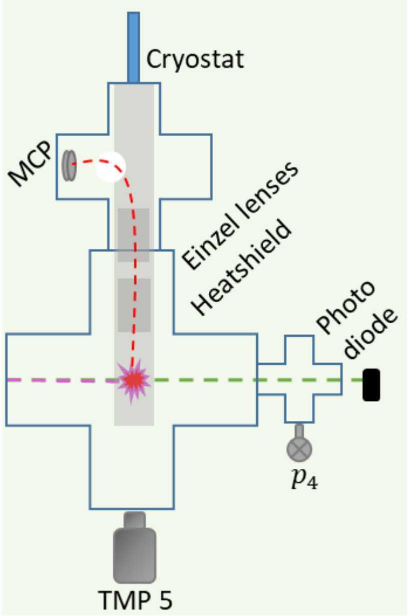






Requirement #5:
Low background –
cryopumped detection chamber

- Cryopumped detection chamber
  - 4K Heatshield around ionization area and proton path to MCP
  - BG reduced by a factor of ~ 10
- Delay measurement :
  - Slowest resolvable velocity interval at $\mathrm{t} = 19\ \mathrm{ms}$: $v \in [76, 102]\ \mathrm{m/s}$
  - High statistics measurement (10000 waveforms per delay): slowest resolvable velocity interval at $\mathrm{t} = 25\ \mathrm{ms}$ $v \in [58, 72]\ \mathrm{m/s}$



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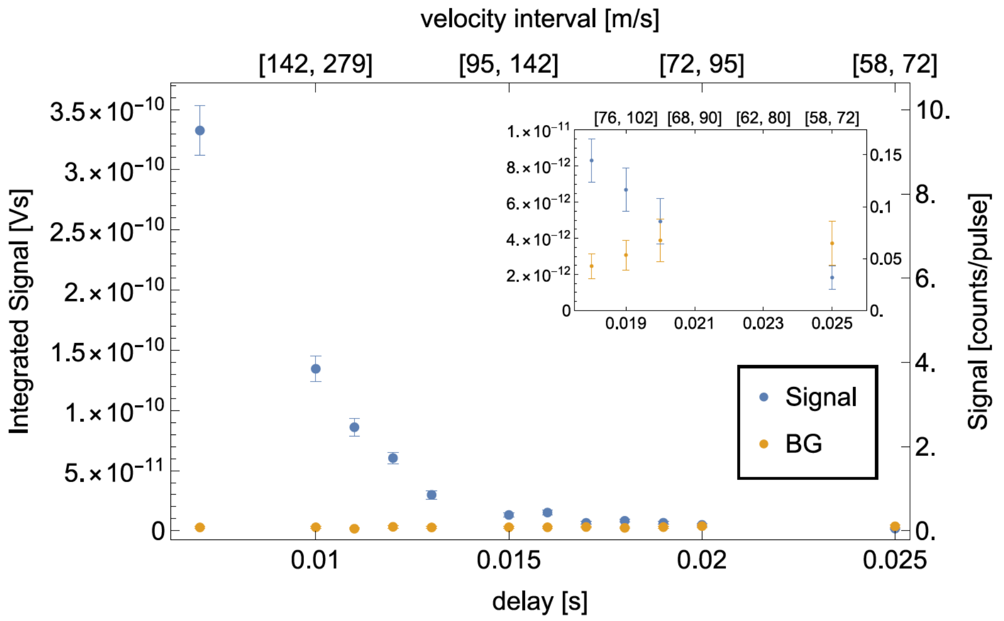

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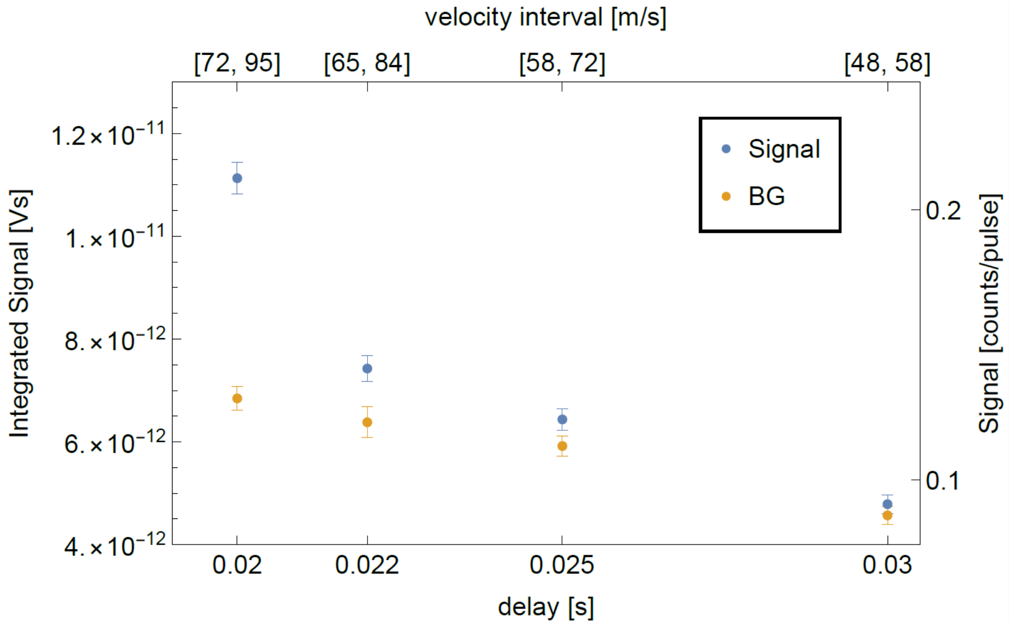
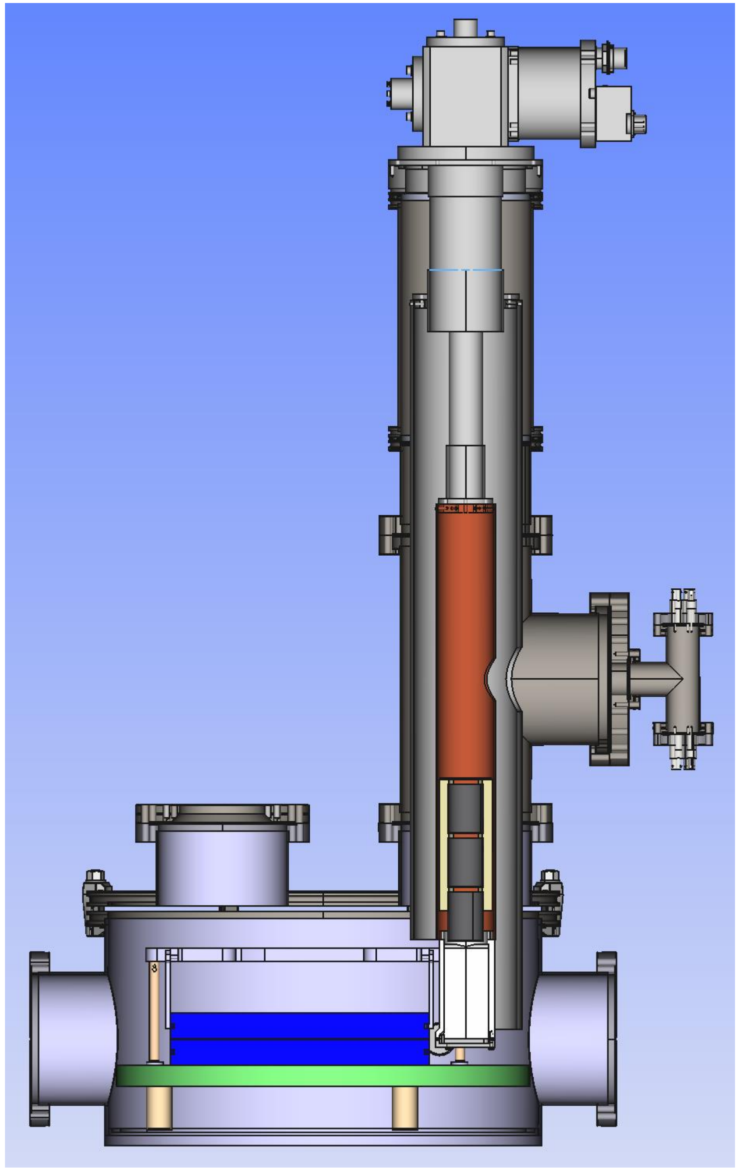


Summary and Outlook

- Efficient detection of the H atoms ✓
- Well collimated H beam ✓
- Simulations confirm the selectability of vertical velocity components ~ cm/s ✓
- Detection of horizontal velocities $v < 72\ \mathrm{m/s}$ ✓
- Outlook:
  - Deuterium measurements with cryopumped detection chamber planned
  - Experimental chamber will replace detection chamber
  - GQS measurement planned for Q3 2024
- Presented data will be published in PSAS conference proceedings *"GRASIAN: Shaping and characterization of the cold hydrogen and deuterium beams for the forthcoming first demonstration of gravitational quantum states of atoms."*



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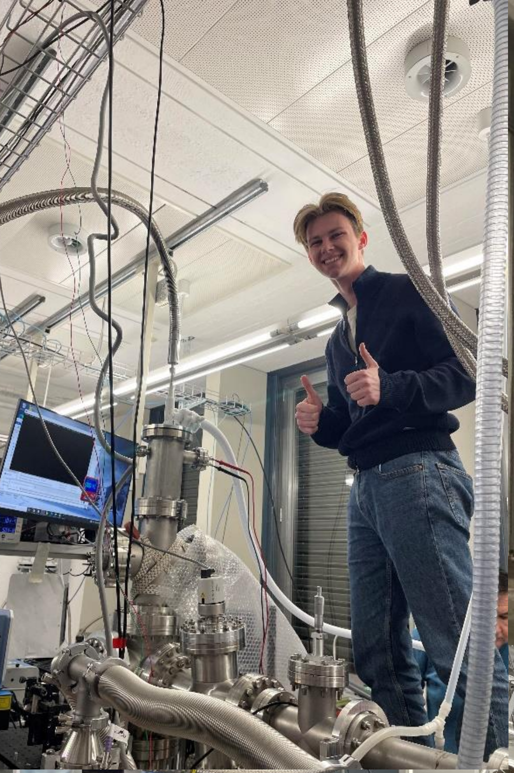
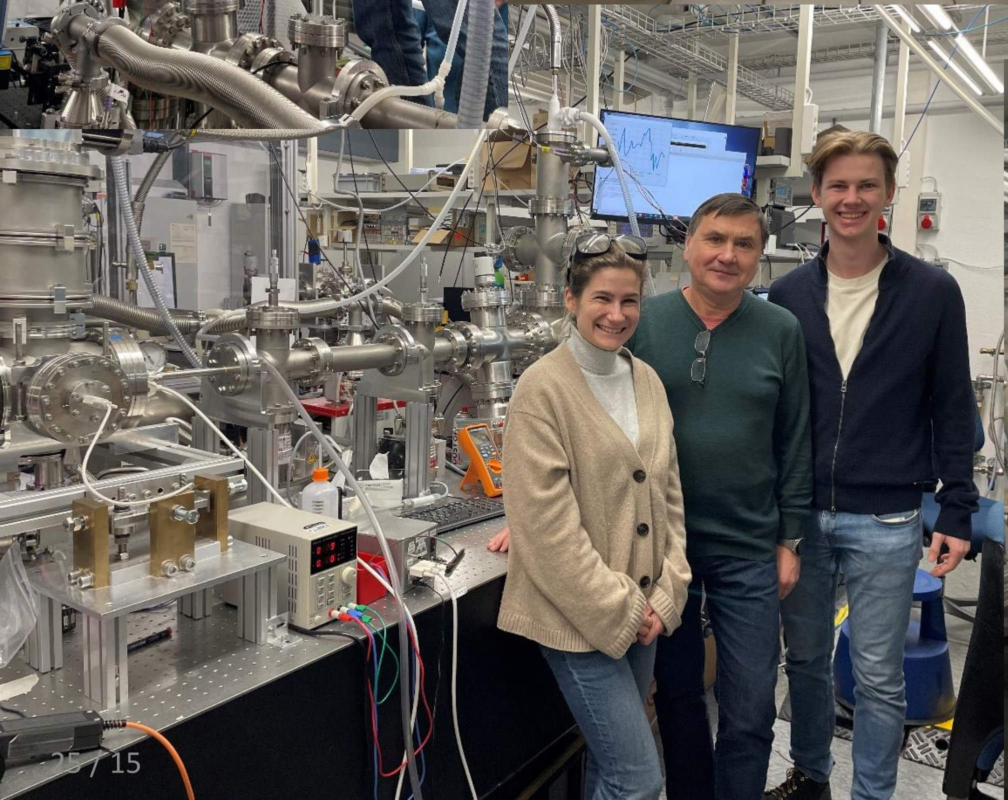
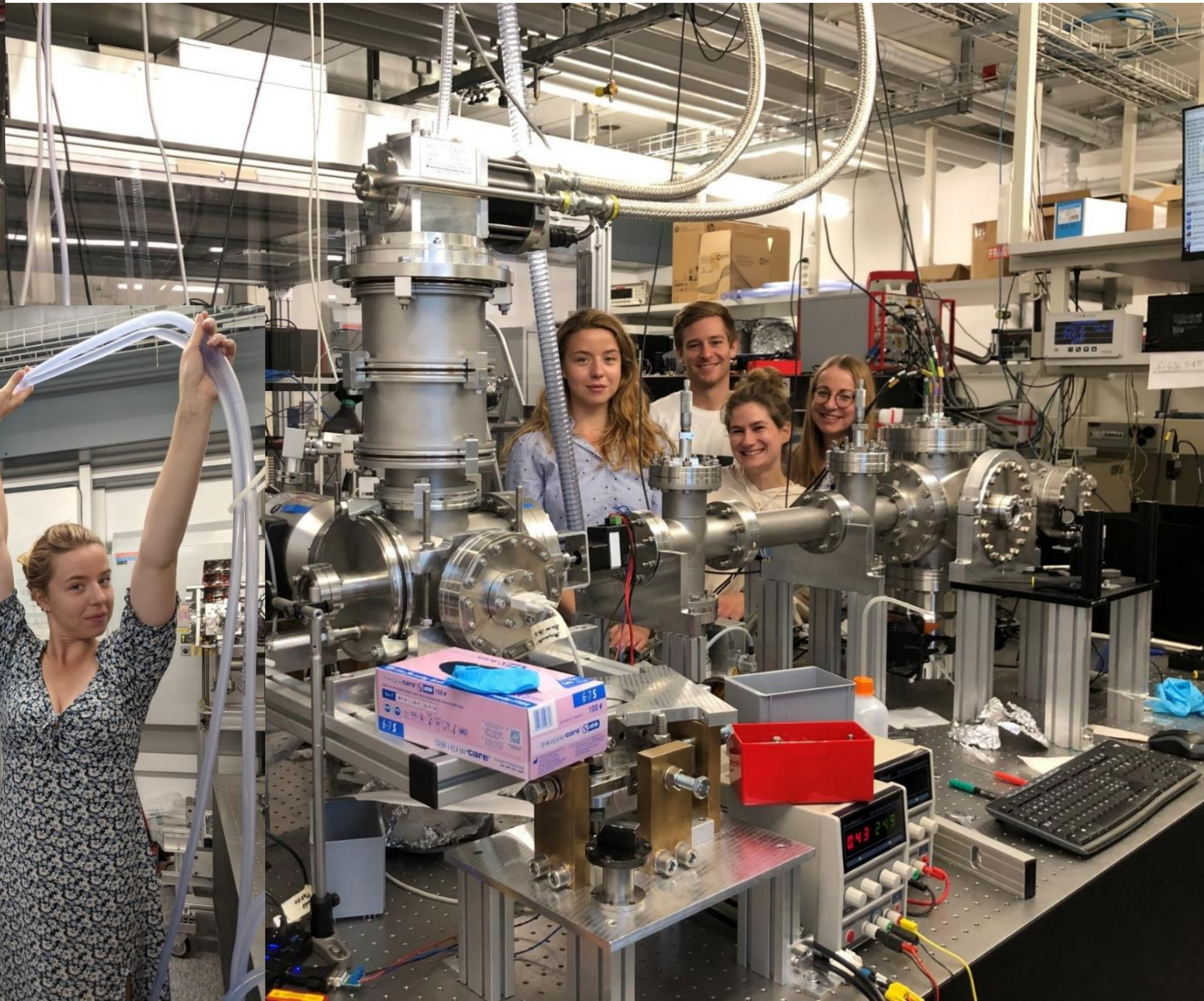
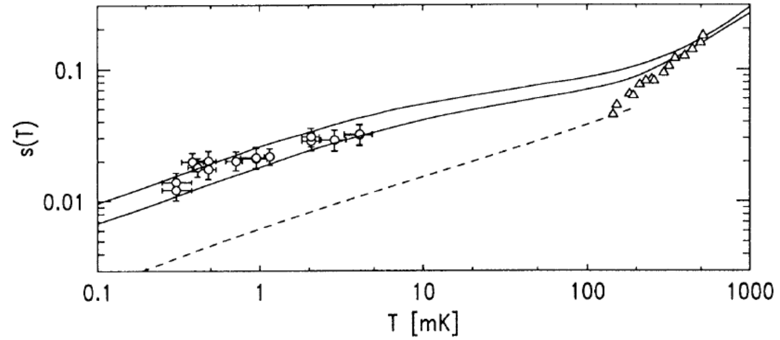




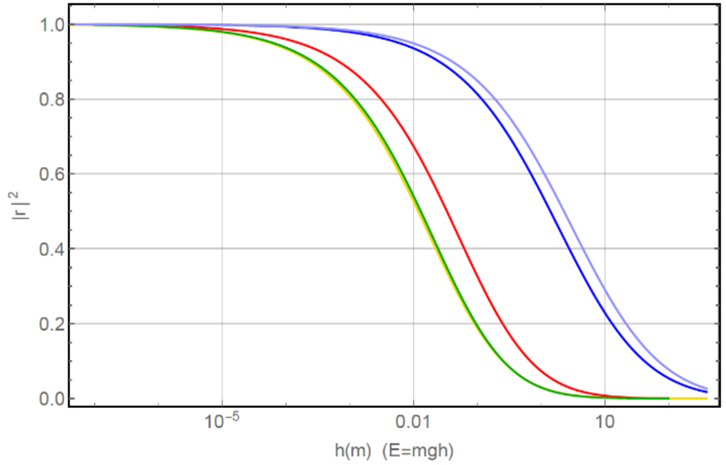


Quantum Reflection (QR)

- 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 [4]
- Suitable materials: helium (^{3}He, ^{4}He), silica, silicon, gold



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

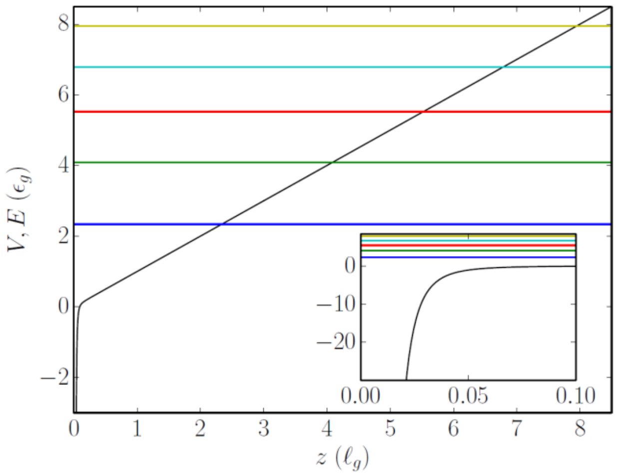


Quantum reflection probability for antihydrogen as a function of the free fall height of the atom h (∝ energy E = mgh) for different materials: 3He (light blue), 4He (dark blue), silica (red), silicon(green) and gold (yellow). Taken from [5].

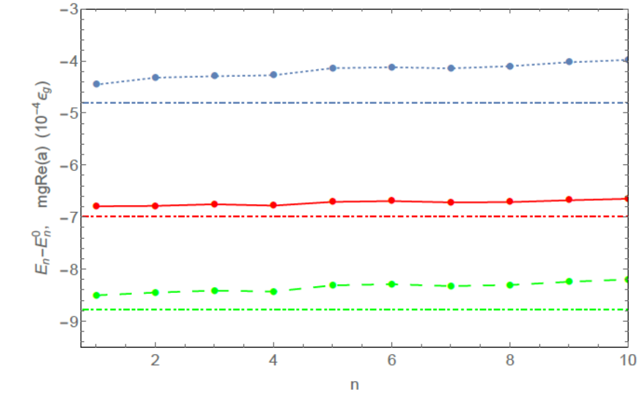
[4] Ite A. Yu, John M. Doyle, Jon C. Sandberg, Claudio L. Cesar, Daniel Kleppner, and Thomas J. Greytak. Evidence for universal quantum reflection of hydrogen from liquid 4He. Phys. Rev. Lett., 71:1589–1592, Sep 1993.
[5] Crépin, P.-P. and Kupriyanova *et al.* Quantum reflection of antihydrogen from 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.

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 ($\omega_0 \ \approx 130$ μm)
  - Positive slope (0.47) after saturation point due to nonuniform intensity profile [5]

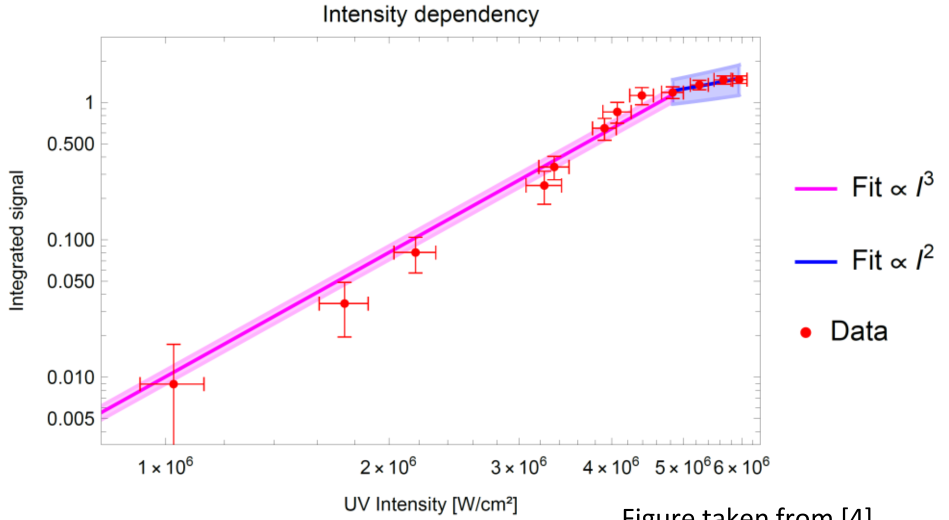
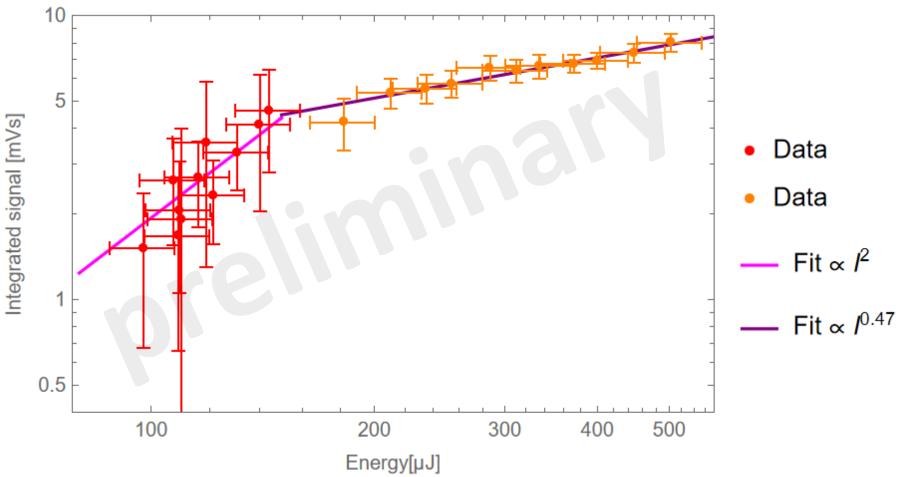


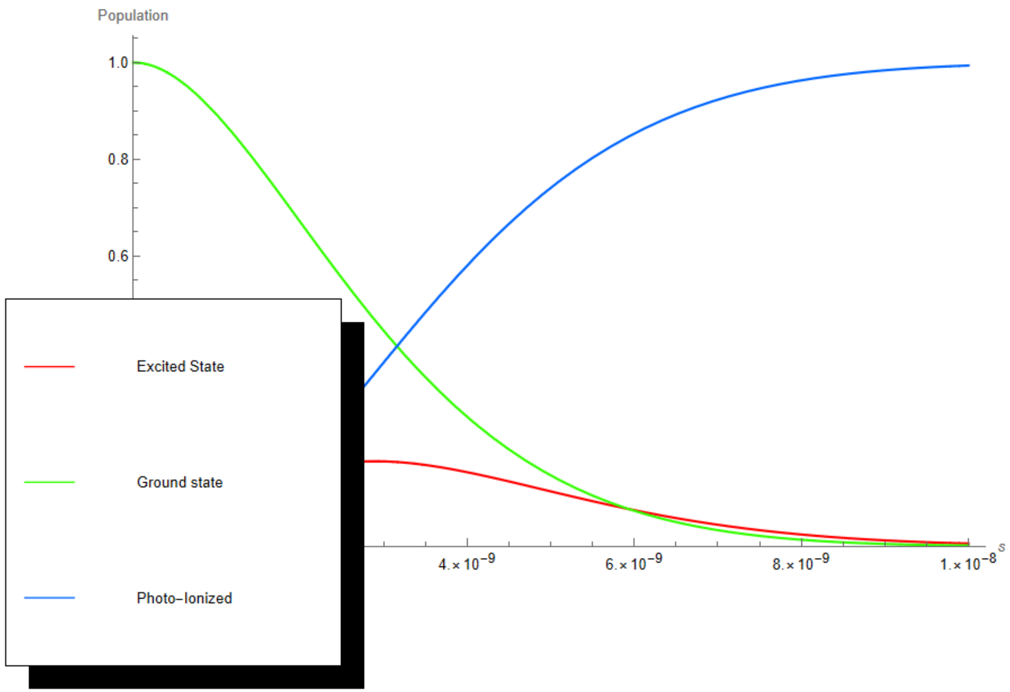
Figure taken from [4].



[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.

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 $\approx 500\ \mu\mathrm{J}$, Pulse duration ≈ 10 ns $\rightarrow \varepsilon_{ion} \approx 99.36\%$



MCP signal calibration

- Single ion MCP signal $\sim 4.5 \times 10^{-11}$ Vs
  - BG measurement
  - Dark counts