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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ETH zürich

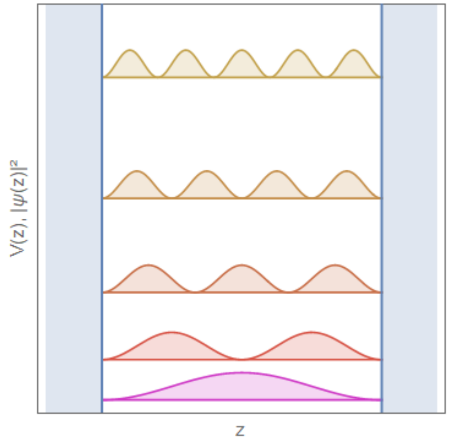
Outline

- Part I – Gravitational Quantum states (GQS)
- Part II – Measurement of GQS with Hydrogen
  - Measurement principle
  - Current experimental status
  - Recent measurements
  - Future measurements

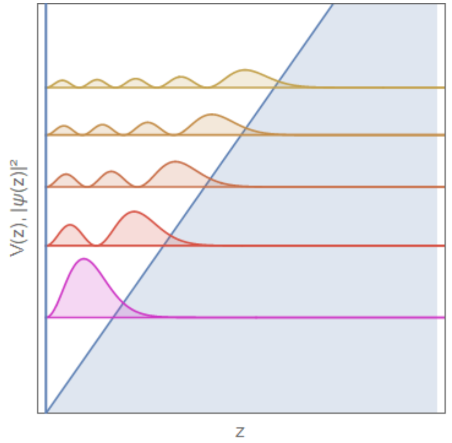
Gravitational Quantum States I

- Gravitational Quantum States (GQS) = Quantum bound states
- Particle trapped in potential well → quantum mechanically bound states
- Examples:
  1. Particle in a box (infinite wall, square well)
  2. Particle in a linear potential (triangular potential well) → Airy functions
- GQS: Potential well ↔

  Gravity Potential ($V_G(z) = mgz$) + reflecting surface (“Mirror”)



1. Square well



2. Triangular well

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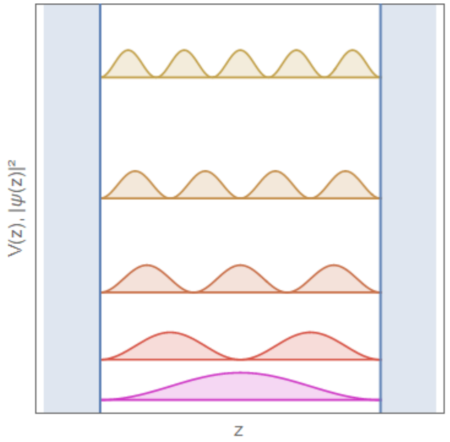
  Linear potential



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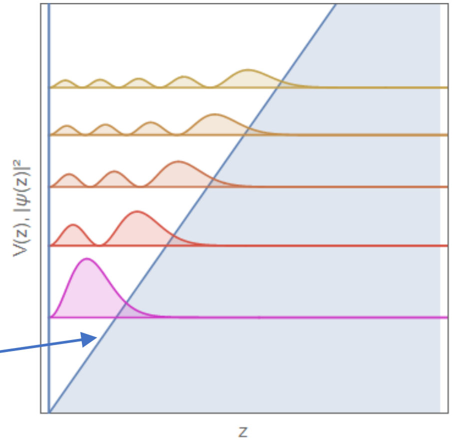

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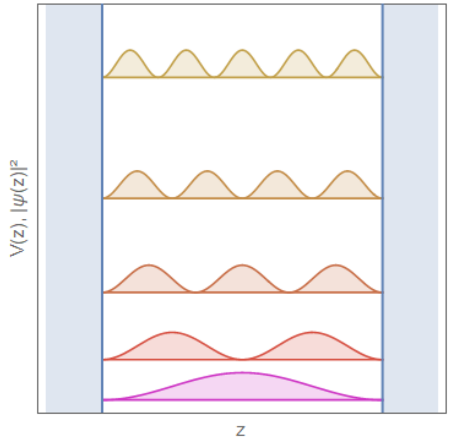
Boundary condition at $z = 0$
↔ infinite potential wall



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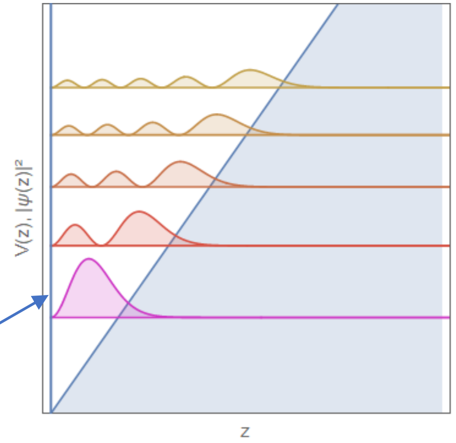


2. Triangular well

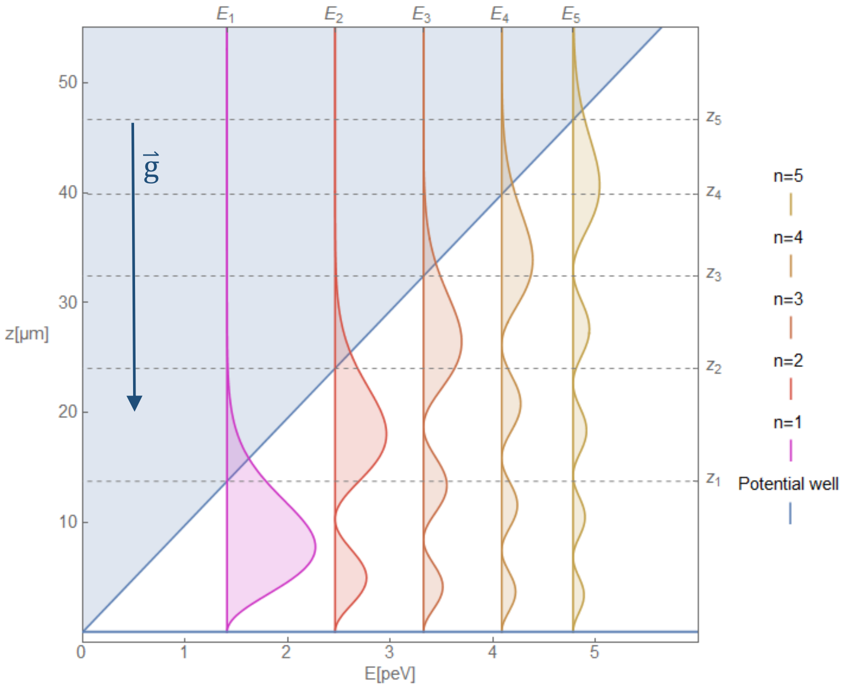
Gravitational Quantum States II

- Test masses: neutral & light particles (Neutrons, Hydrogen …)
- Macroscopic spatial heights z_n of the GQS
- Eigenenergies $E_n \sim \mathrm{peV}$ ($\approx 10^{-31}$J)

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

  → Long observation time needed!

  → Very slow/cold particles or long experimental setup
- 2002: First demonstration of GQS with ultra cold neutrons [1]



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

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

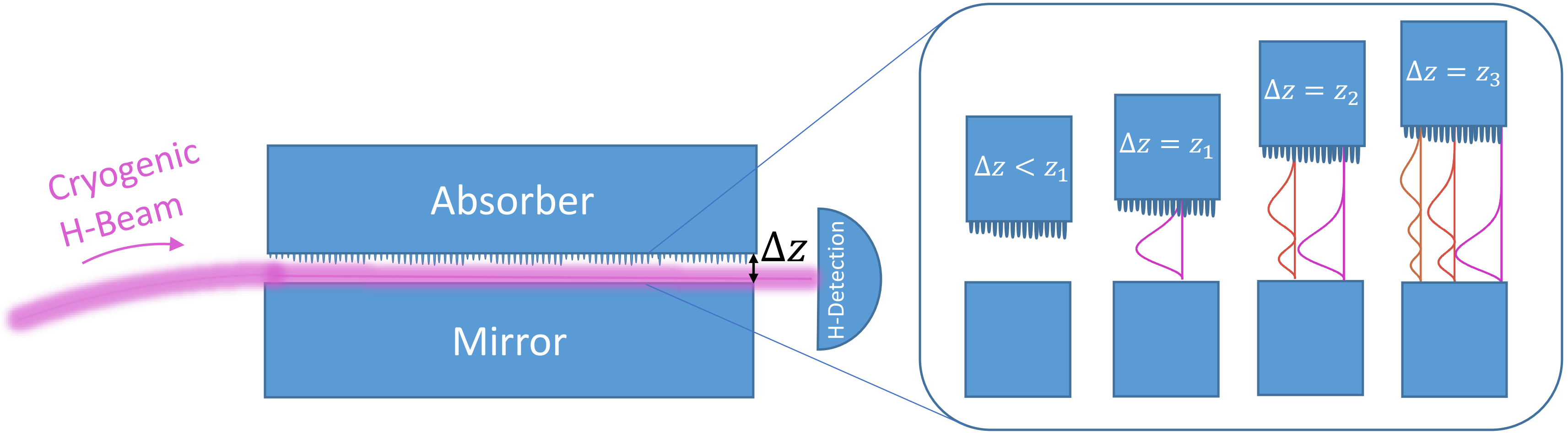
Measurement of GQS with Hydrogen

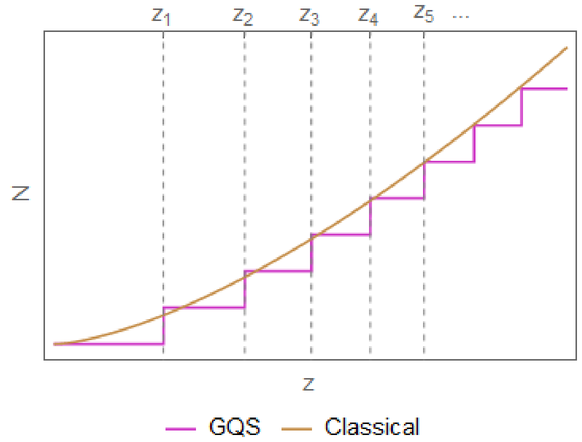
- Our goal: First demonstration of GQS with Hydrogen
- Motivation:
  - GQS never measured for atoms!
  - Sensitive to new physics (short range forces)
  - Easy to generate (Hydrogen bottle vs. research reactor)

    → Much higher fluxes available (vs. neutrons)
- Requirements:
  - Efficient detection of Hydrogen
  - Cold Hydrogen beam

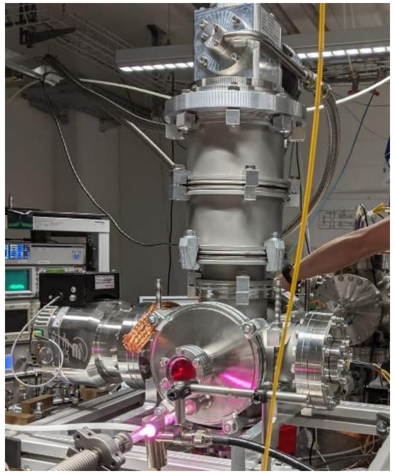
Measurement Principle

- 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 for Hydrogen**

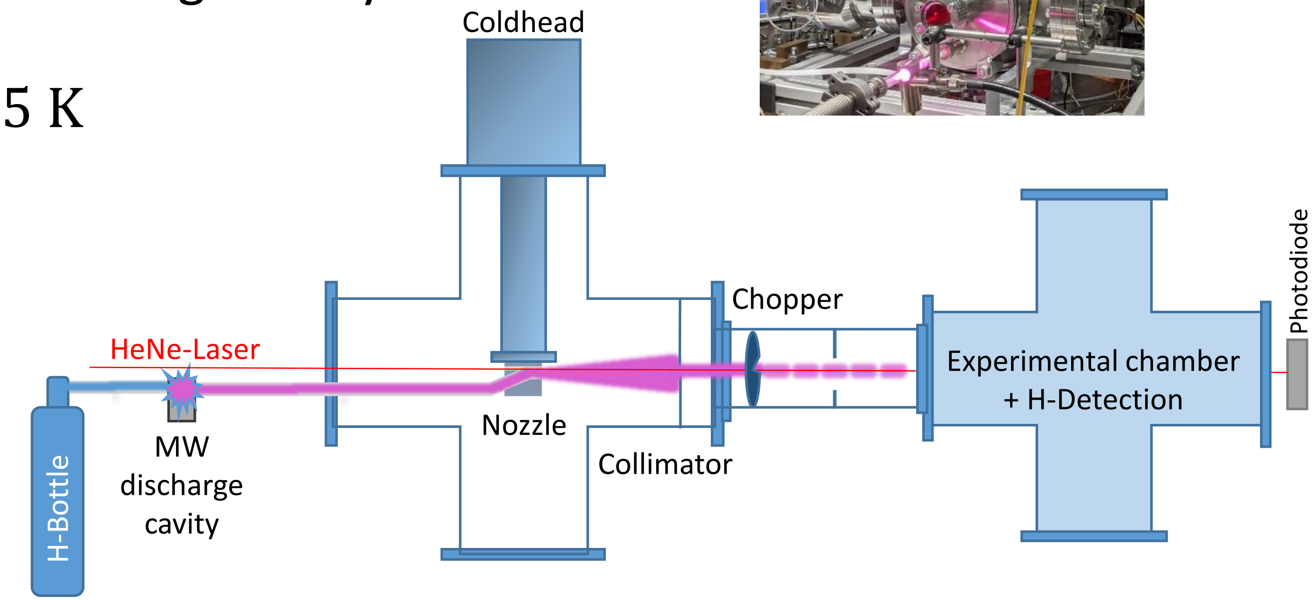




Hydrogen Beam – Experimental Setup

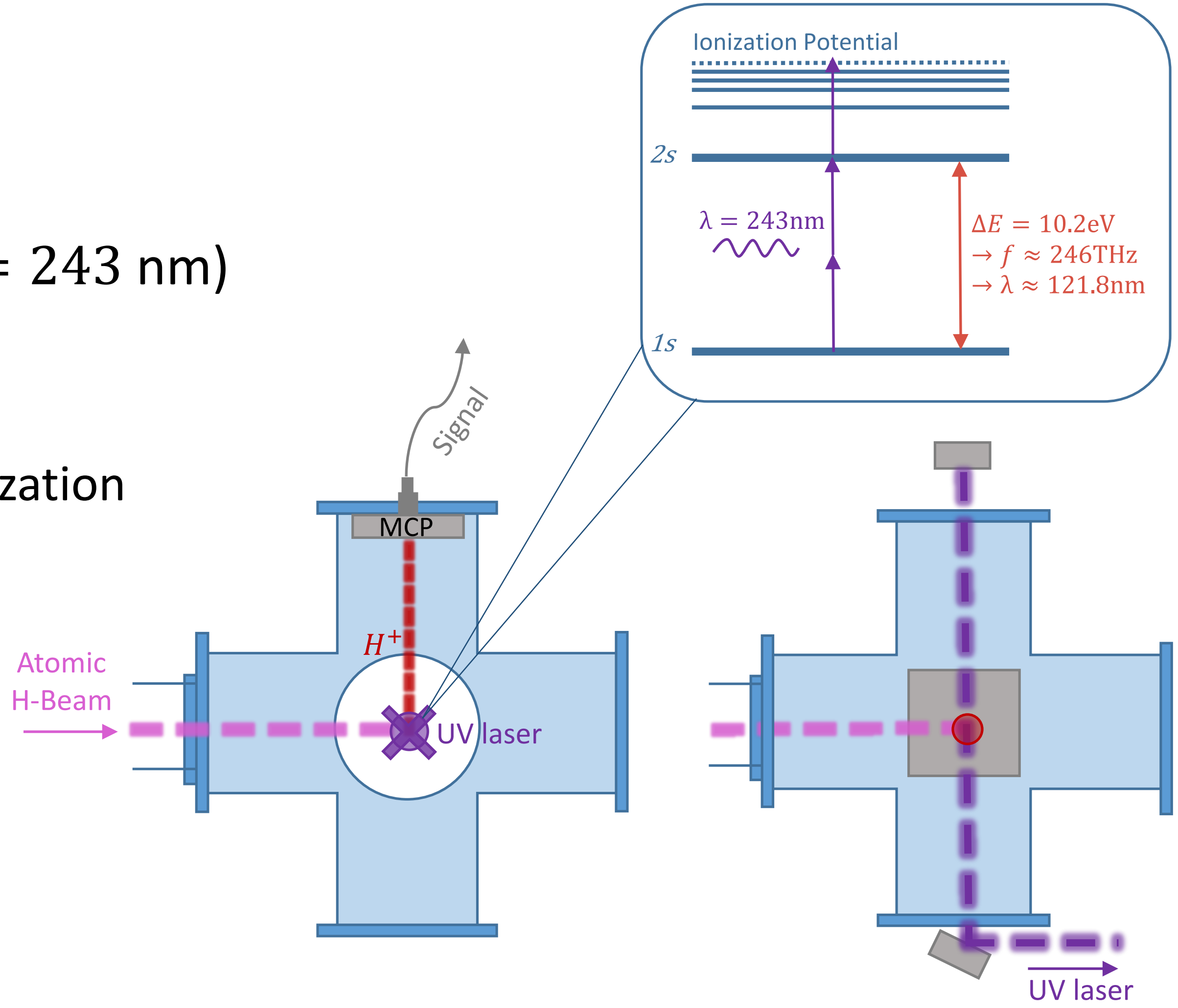


- Developed and situated @ ETH Zurich
- Hydrogen Source: H_2–Bottle + Microwave discharge cavity
- Coldhead + Cryogenic Nozzle: $290\ \mathrm{K} \rightarrow\ 6.5\ \mathrm{K}$
- Chopper to modulate the atomic beam
- Hydrogen detection system



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
  - Ionization efficiency: $\sim 70\%$*
- Detection of H^{+} with an MCP
- Integrated MCP-Signal ∝ H- count rate



Side view

Top view

*Laser energy $E_{laser} \approx 1.5\mathrm{mJ}$,
Laser beam waist $w_0 \approx 0.5\mathrm{mm}$

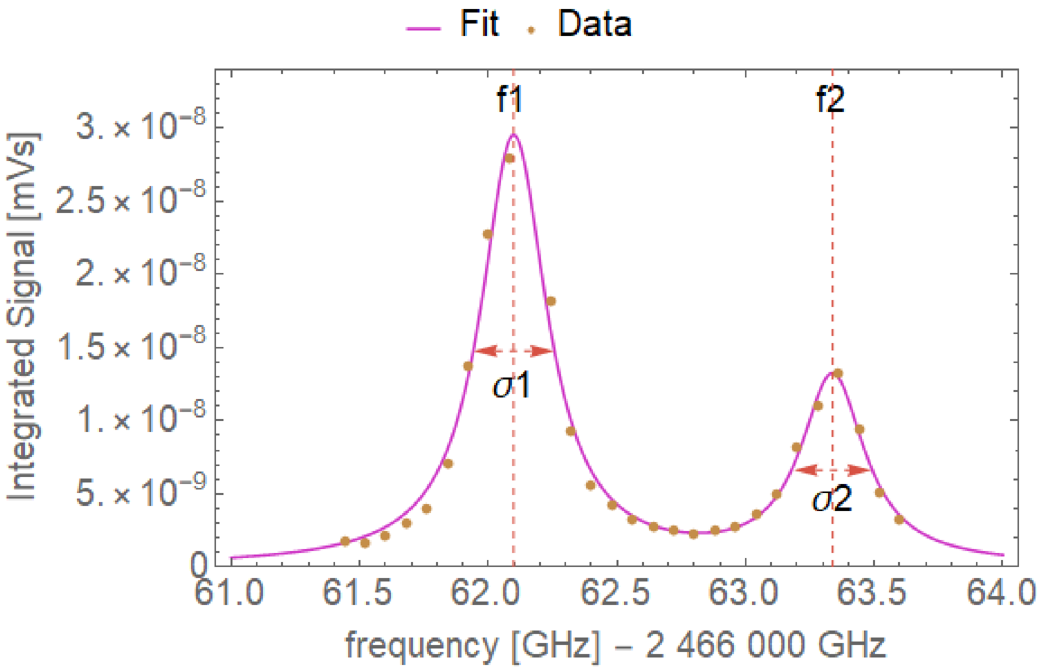
Test of Hydrogen Detection

- Variation of Laser frequency
- Measurement of signal strength

→ Observation of Hyperfine Splitting (HFS)

- $(f2 - f1) = 1.240 \pm 0.013\ \mathrm{GHz}$ corresponds to $\left(f_{1s}^{HFS} - f_{2s}^{HFS}\right) = 1.243\ \mathrm{GHz}$

→ We detect Hydrogen! ✓



Fit to sum of two Lorentzians:

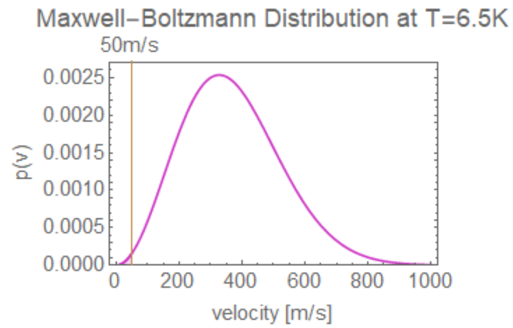
$f1 = 2466062.098 \pm 0.004$ GHz $\sigma 1 = 0.314 \pm 0.011$ GHz

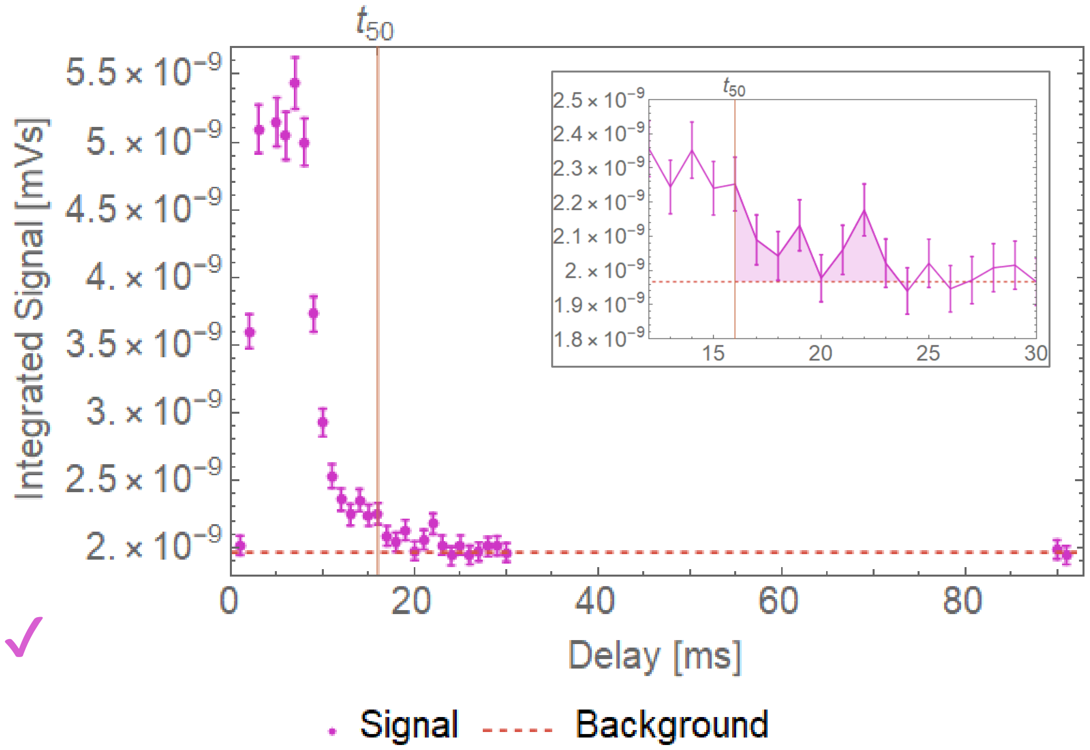
$f2 = 2466063.338 \pm 0.008$ GHz $\sigma 2 = 0.302 \pm 0.025$ GHz

Velocities of the Hydrogen Beam

- Coldhead → $6.5\ \mathrm{K}$
- Delay Measurement:
  - Variation of the delay τ between chopper opening and firing of the Laser
  - Distance (chopper – detection)

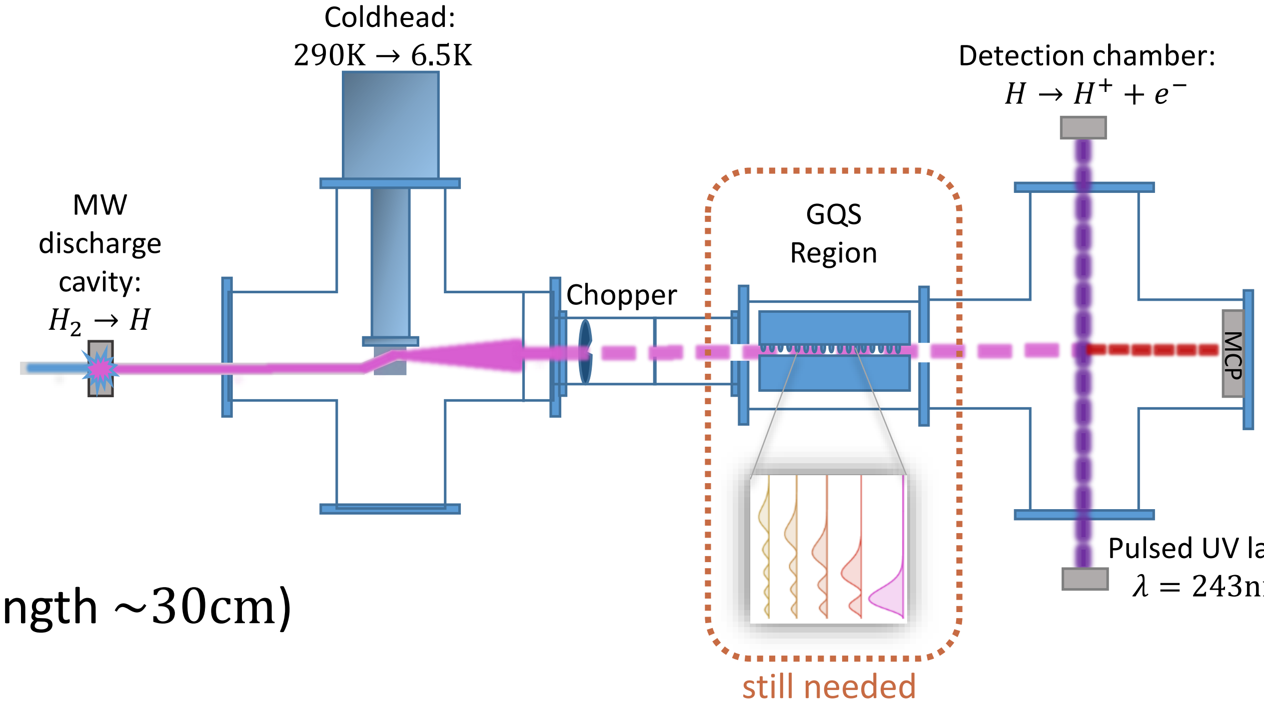
    $\mathrm{D} = 0.8\mathrm{m} \rightarrow v = \frac{D}{\tau}$
- A $50\mathrm{m/s}$ atom would take $t_{50} = 16\mathrm{ms}$
- Clear evidence of atoms with velocities $< 50\ \mathrm{m/s}$ ✓





Hydrogen Beam – Current Status and Future Plans

- Efficient detection of the H atoms ✓
- Atomic Hydrogen beam with velocities $v < 50\ \mathrm{m/s}$ ✓
- Next step: Installation of GQS Region
  - Mirror + Absorber (flatness $\sim 0.5\mu\mathrm{m}$, length $\sim 30\mathrm{cm}$)



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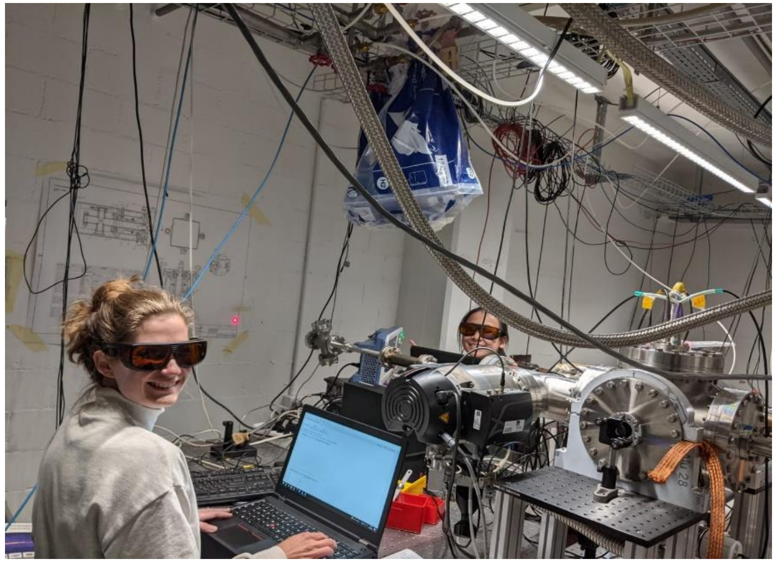
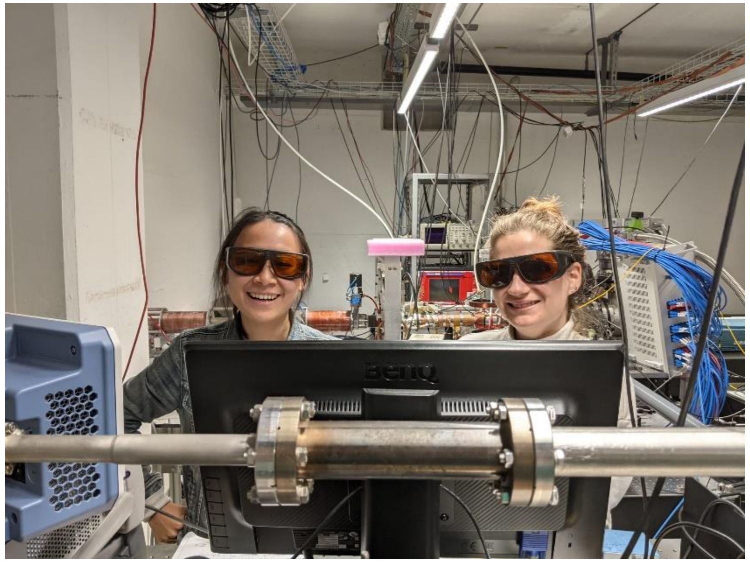




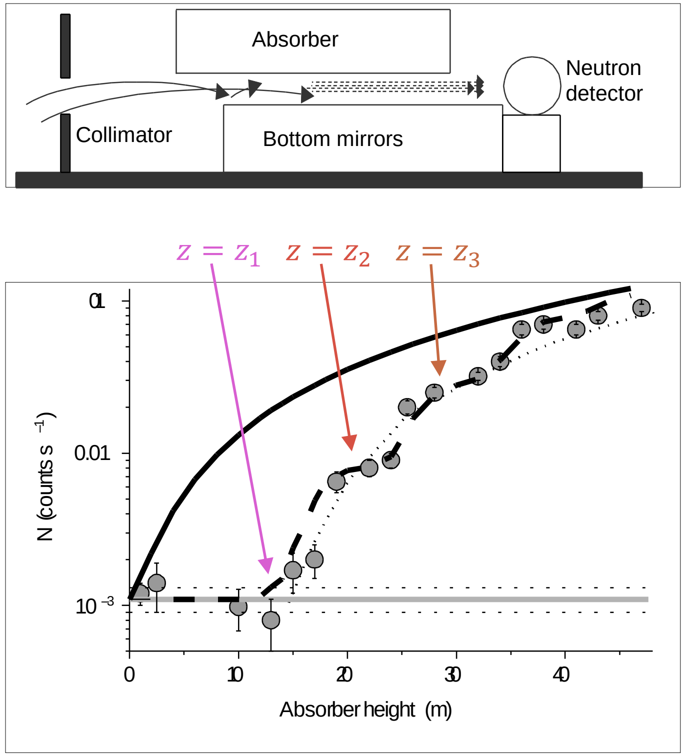
Thank you for your attention! ☺

Backup

GQS of ultra cold neutrons

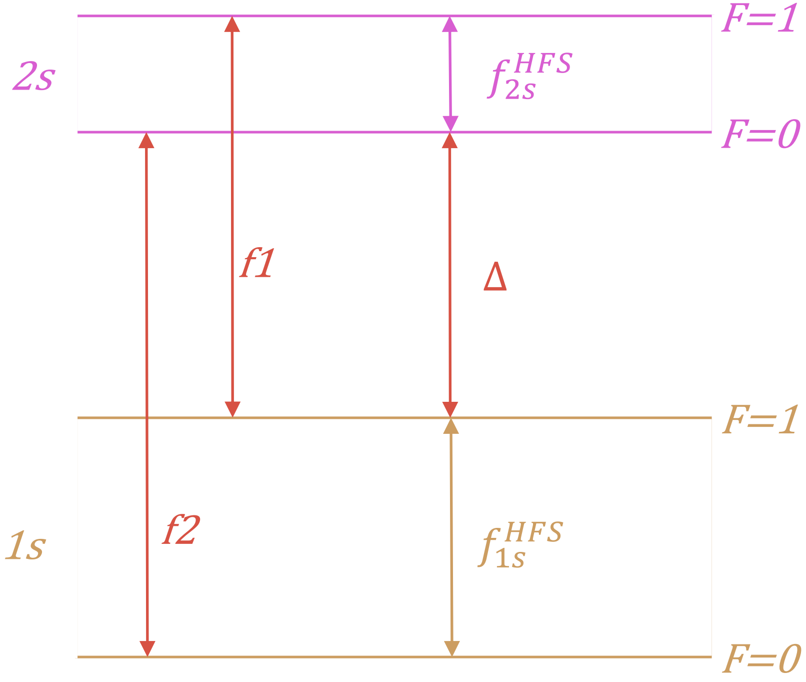
2002: First demonstration of GQS with ultra cold neutrons (UCNs) [1]

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

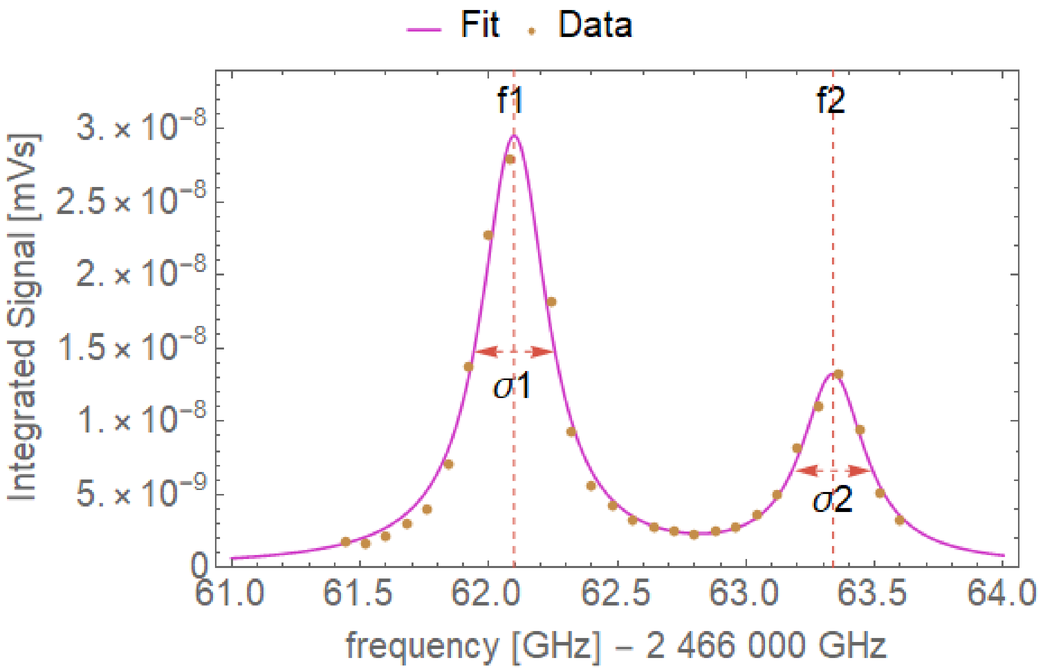


First demonstration of GQS ith UCNs: The neutron throughput vs. the absorber height Δz and experimental setup. Figures taken from [1].

Hyperfinesplitting & Selection Rule



Selection rule: in the *1s-2s*-transition, the total anguar momentum F has to be conserved

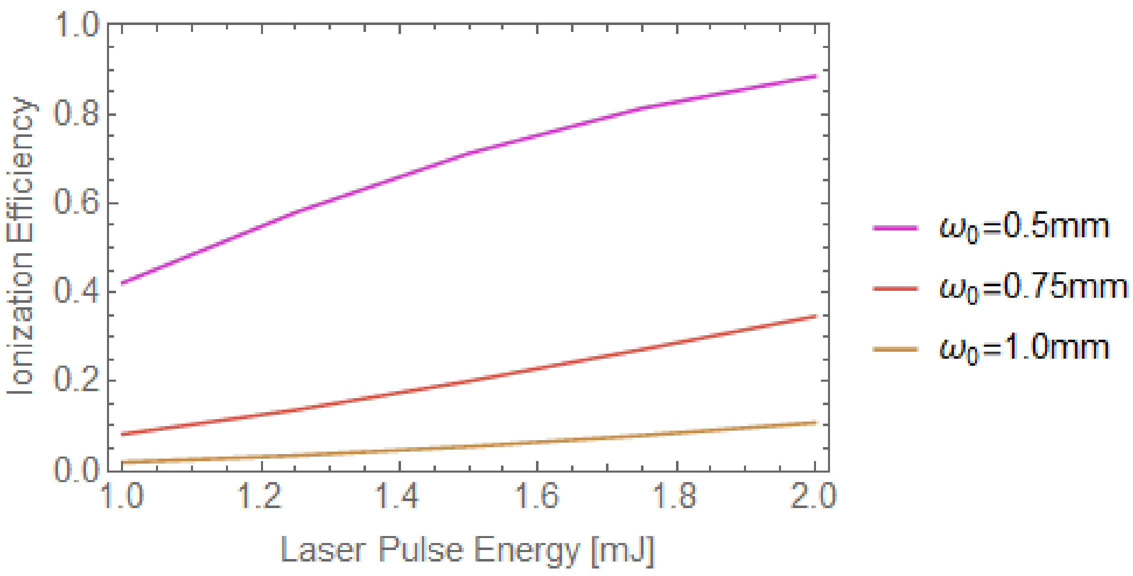


$(f2 - f1) = 1.240 \pm 0.013$ GHz corresponds to

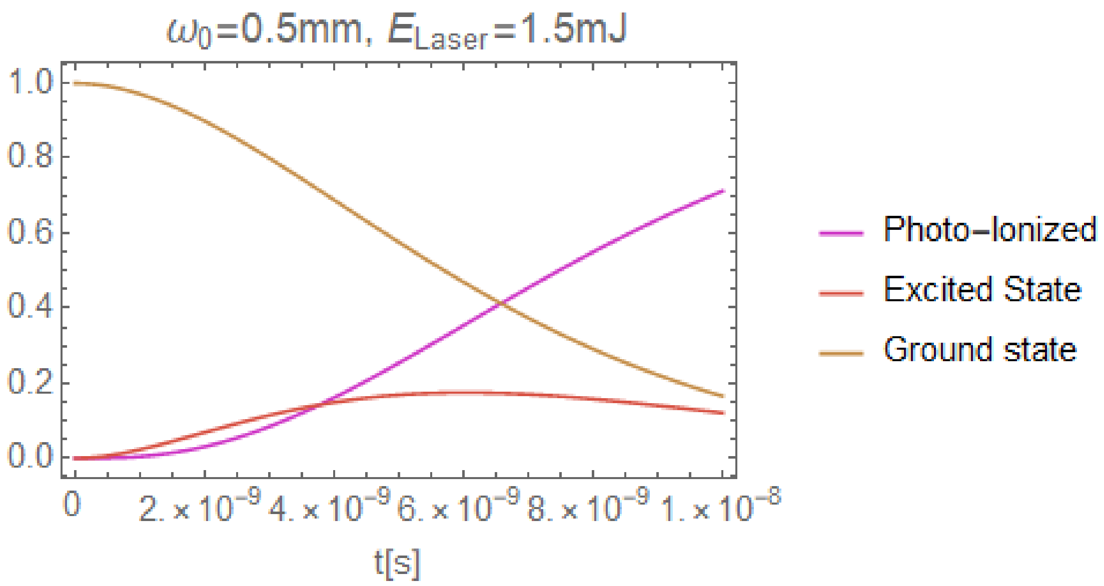
$(f_{1s}^{HFS} - f_{2s}^{HFS}) = 1.243$ GHz

Ionization Efficiency

- Simulation of ionization efficiency by solving optical Bloch equations
- Beam waist ≈ 0.5 mm, Pulse Energy ≈ 1.5 mJ, Pulse duration ≈ 10 ns



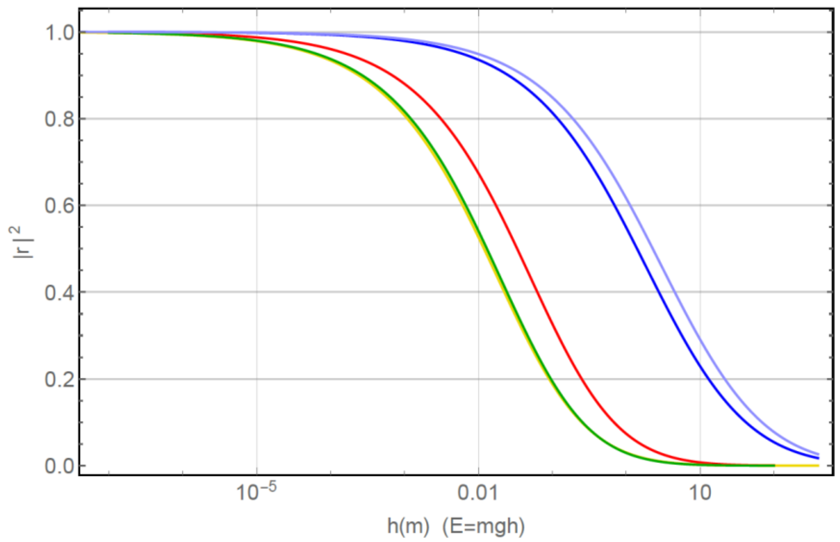
Simulated ionization efficiencies for different Laser pulse energies and beam waists.



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

Quantum Reflection (QR)

- Reflection from mirror surface governed by Casimir-Polder Potential (vs. Fermi-Pseudo-Potential for neutrons)
- QR = non classical phenomenon
- A low-energy quantum particle has a significant probability to be reflected by a rapidly varying attractive potential
- Suitable materials: helium (^{3}He, ^{4}He), silica, silicon, gold



Quantum reflection probability 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 [2].