Austrian Academy of Sciences

MARIETTA BLAU INSTITUTE FOR PARTICLE PHYSICS

GRASIAN: Progress Toward Observing Gravitational Quantum States of Atoms

75th Annual Meeting of the Austrian Physical Society

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on behalf of the GRASIAN collaboration

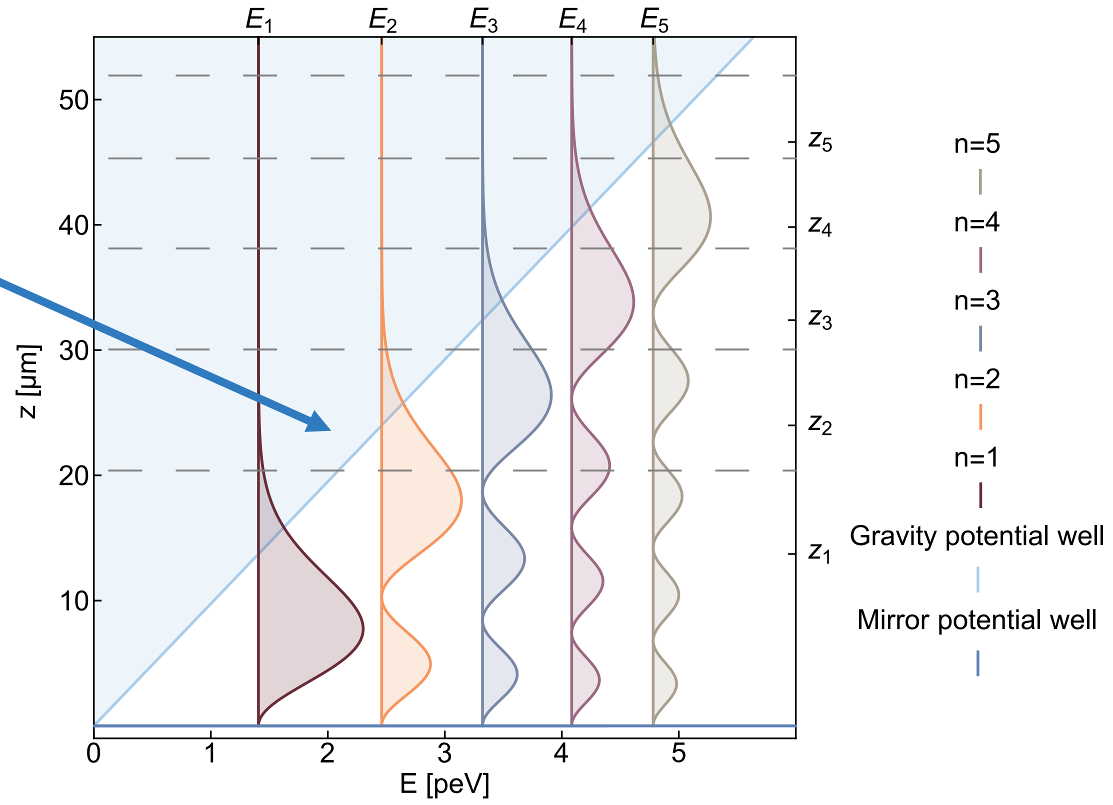
The GRASIAN Collaboration

- Using variety of simple neutral systems
  - (Anti)-Hydrogen
  - Neutrons
  - Positronium
  - Muonium

- To test:
  - new short-range forces
  - violations of the weak equivalence principle
  - Lorentz invariance
  - CPT symmetry
  - gravitational constant G
  - search for the electric charge of the neutron

Gravitational Quantum States

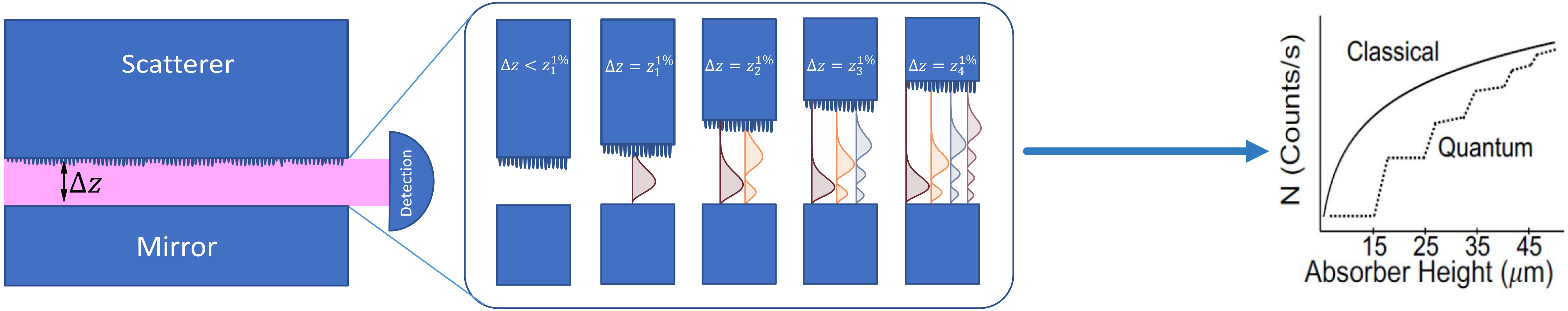
- GQS: Particles are held in potential well:
  - Perfectly reflecting surface ("Mirror")
  - Gravitational Potential: $V(z) = mgz$
- For hydrogen:
  - macroscopic spatial heights $z_n \sim \mu\text{m}$
  - Eigenenergies $E_n \sim \text{peV}$



Killian, C. *et al.* 2023.

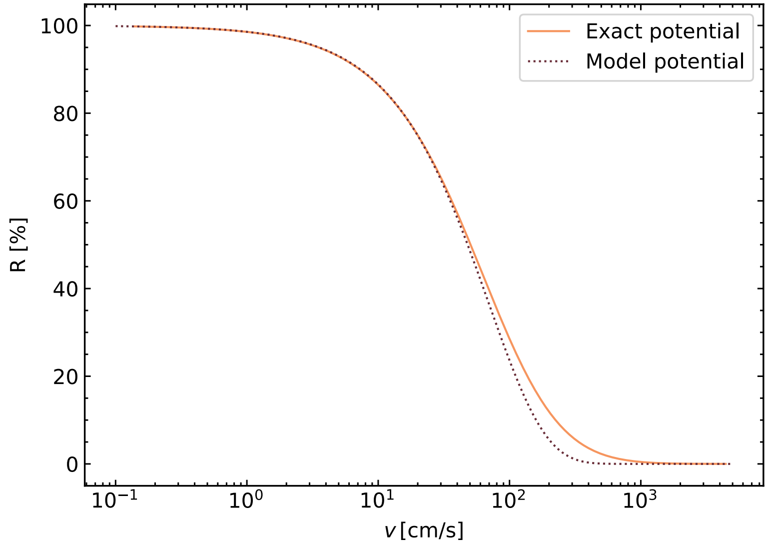
GQS Measurement principle

- Add Scatter above the mirror $\rightarrow$ state selection depending on distance Δz
- Variation of slit width Δz for state selection
- Measure the number of atoms N as a function of Δz $\rightarrow$ stepwise increase



Quantum Reflections

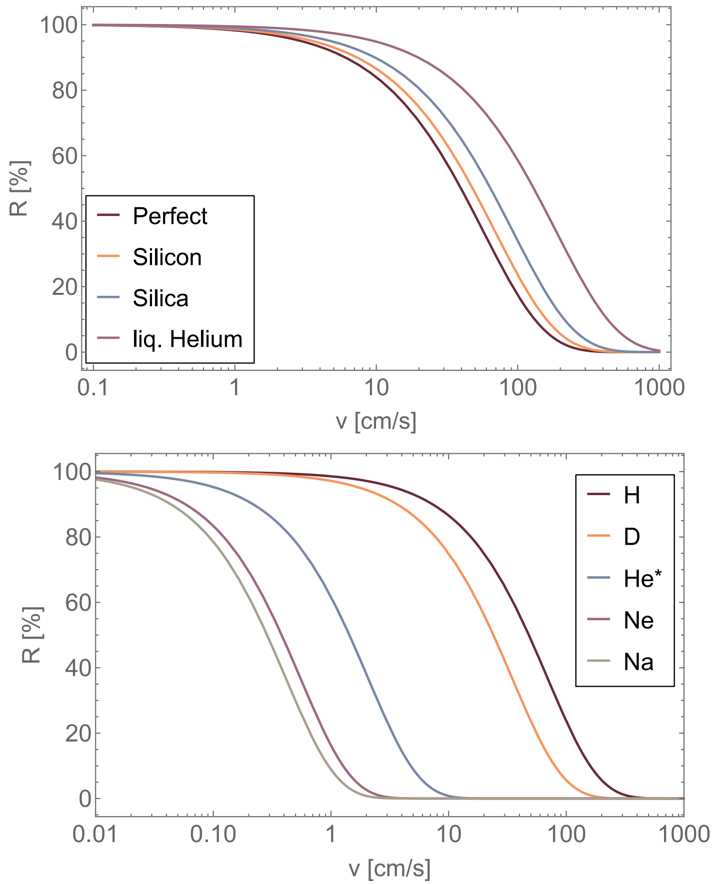
- Purely quantum mechanical phenomenon
- Reflection from attractive Casimir-Polder potential at $\sim 100\ \mathrm{nm}$
- Potential can be modelled with $V_4 = -{}^{C_4}/_{r^4}$
- Probability given by: $R \ \approx\ \exp\left(-4mv\sqrt{2mC_4}/\hbar^2\right)$
- Reflection Probability depends on:
  - Atom properties
  - Surface properties



Crépin, P.-P. *et al.* 2023.

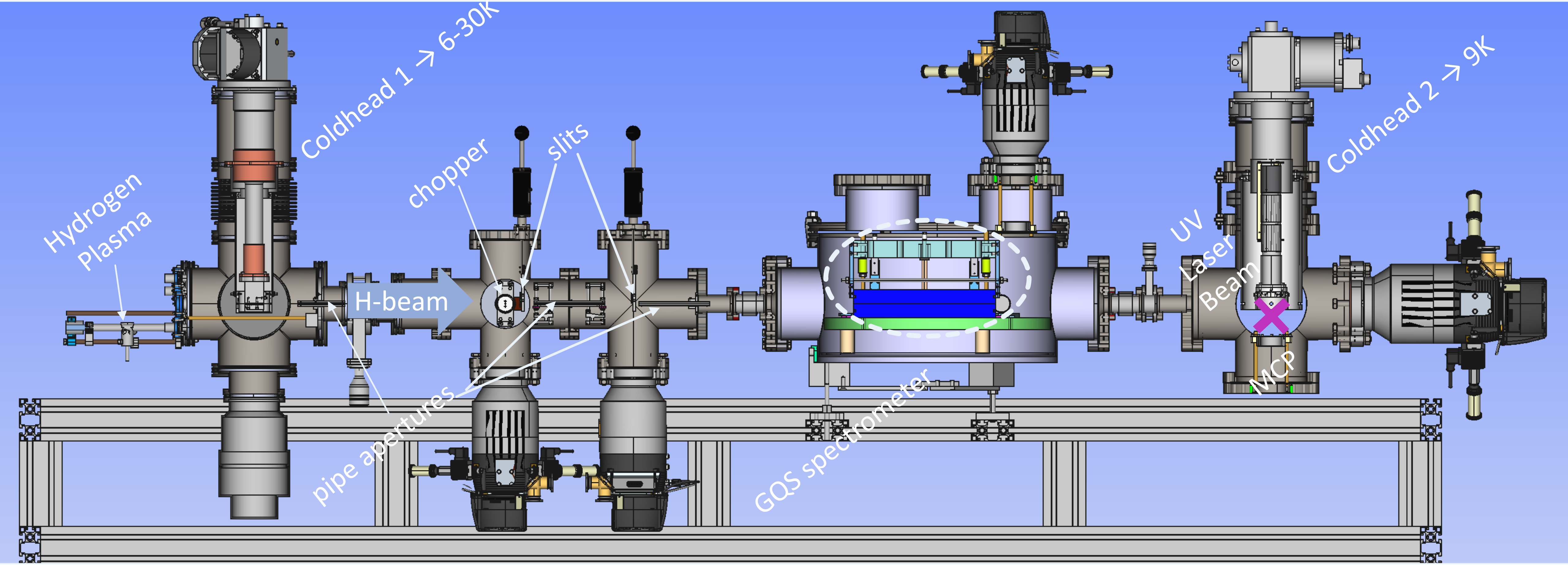
Quantum Reflections

- Observed for H atoms over liquid He-surface
- Observed for heavier atoms above solid surfaces
- H above silicon (Si) surface:
  - Never measured before!
  - Higher QR probabilities expected than for heavier atoms!
  - QR probability > 90 % for $v_{\perp}$< 7 cm/s above Si surface

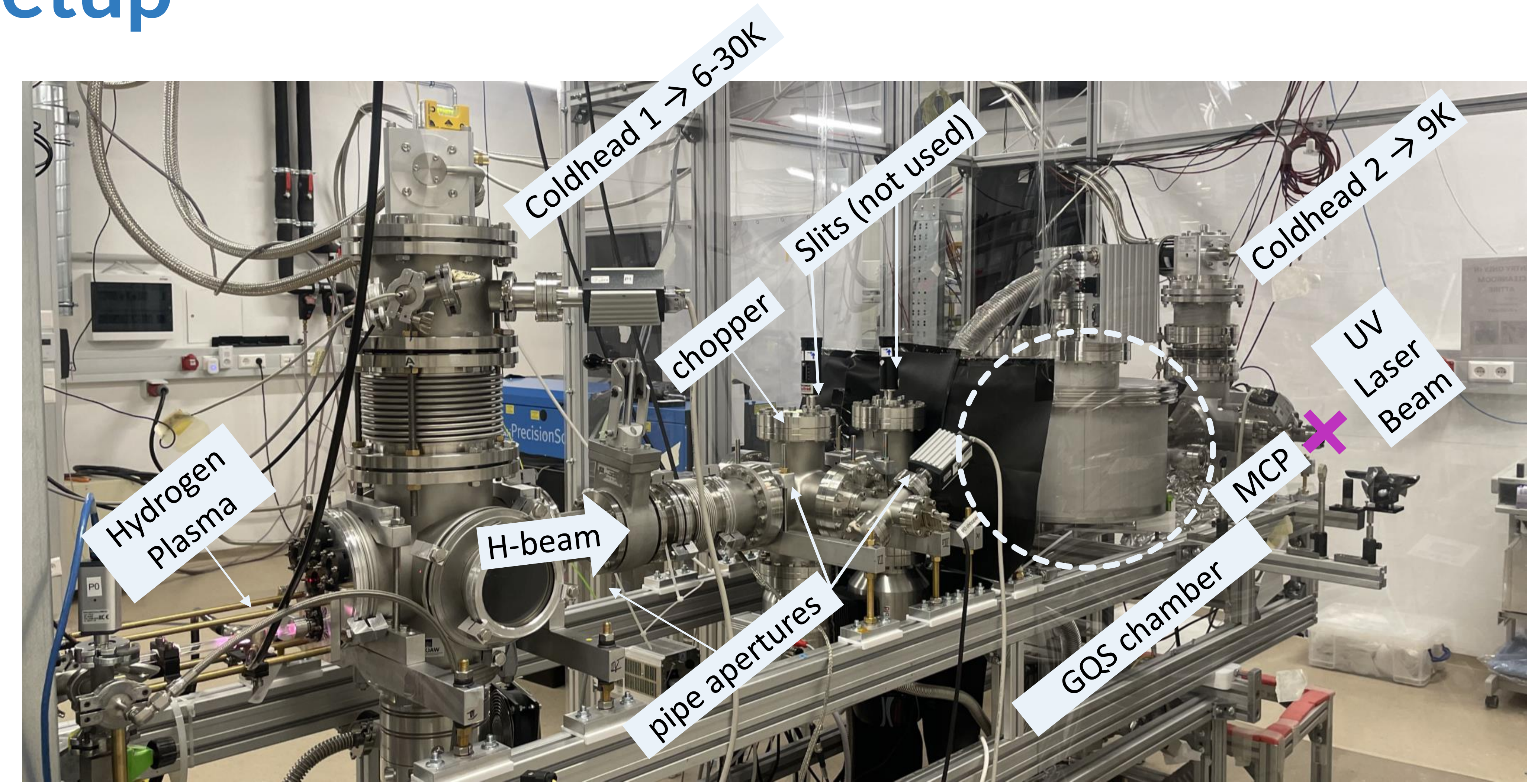


Quantum reflection probability R (calculated from model potential) as a function of the incident velocity for hydrogen above different surfaces (top) and different atoms above silicon (bottom).

Hydrogen Beam Experimental Setup

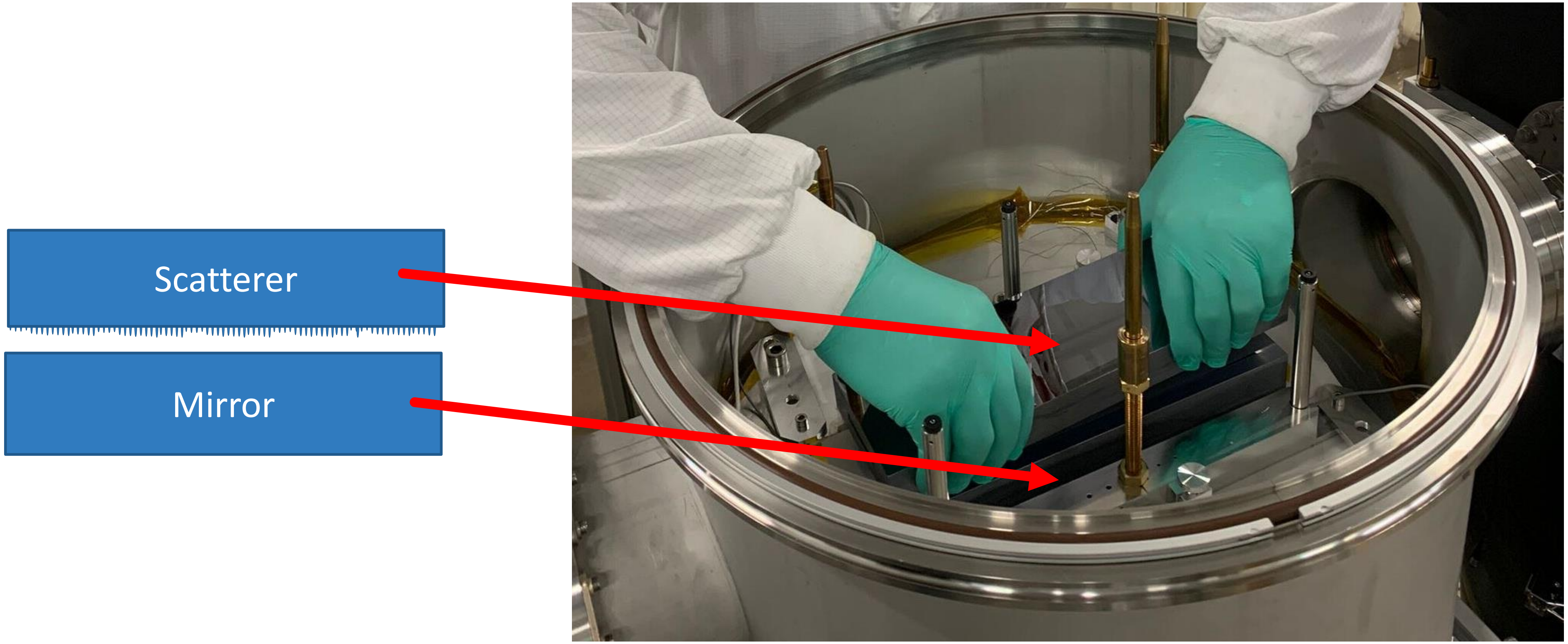


Hydrogen Beam Experimental Setup



Installation of GQS Spectrometer – July 2025

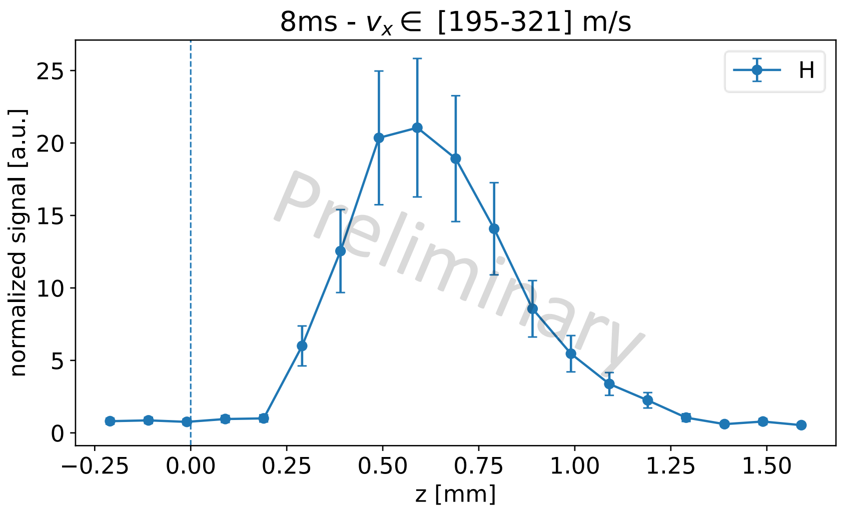
Silicon Mirror + Absorber separated by 200 µm spacers were inserted

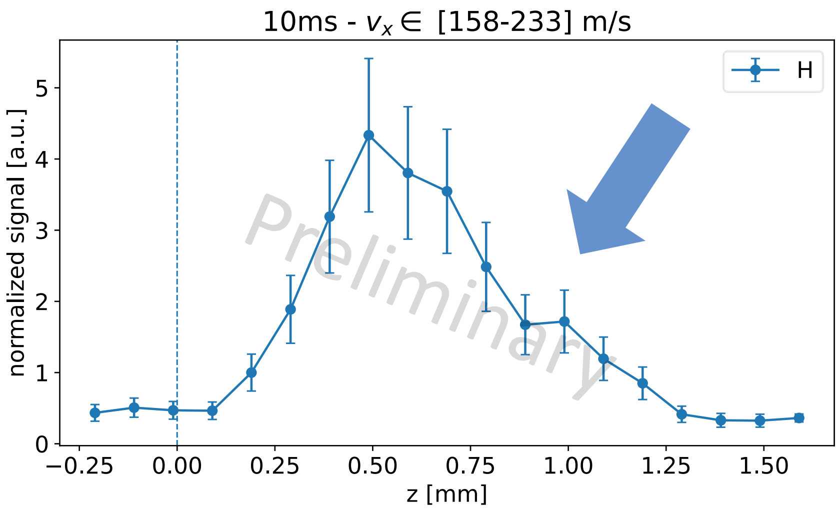


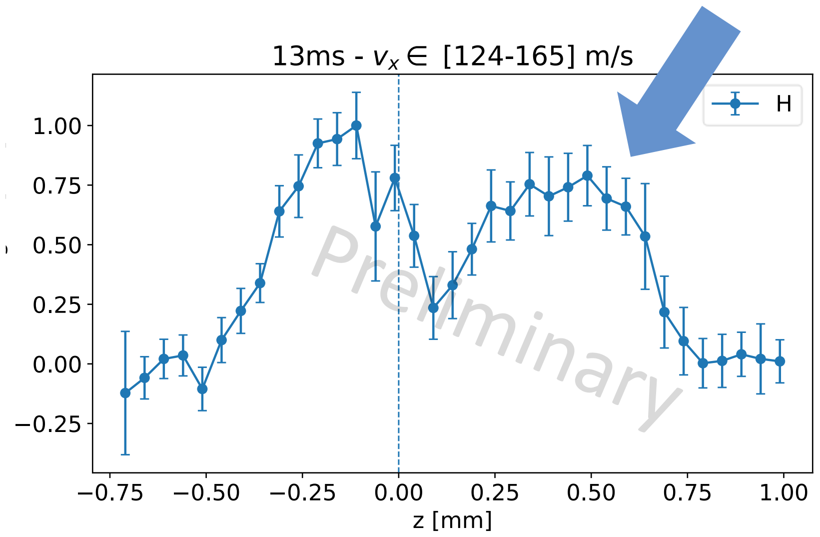
First Measurements with Spectrometer

Recorded vertical profiles for different ToF (horizontal velocity v_x)

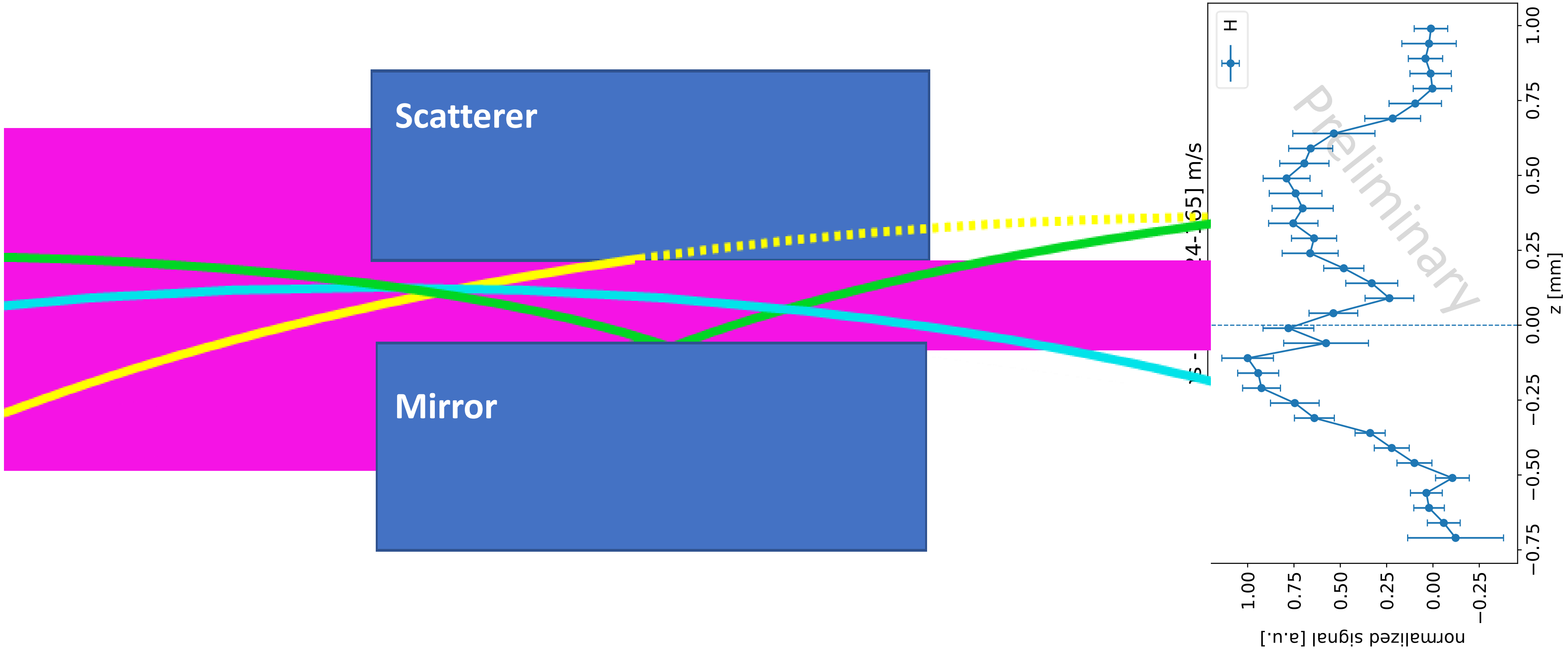
Double peak structure appeared for low v_x







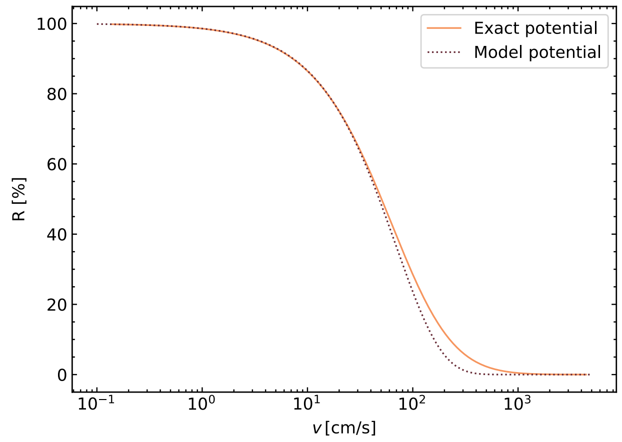
First Observation of QR!



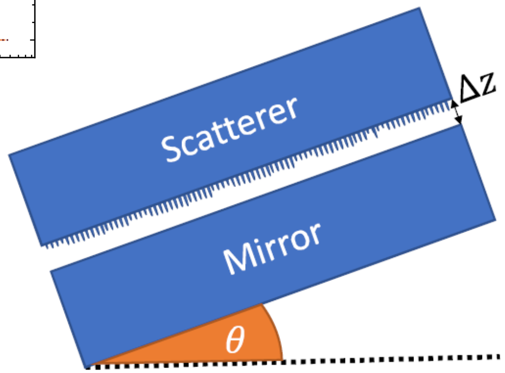
Measurement of the Reflection Coefficient R

Goal: Measure R at different perpendicular velocities $v_\perp$

- ➢ Vary the delay between chopper opening and laser pulse (longitudinal velocities)



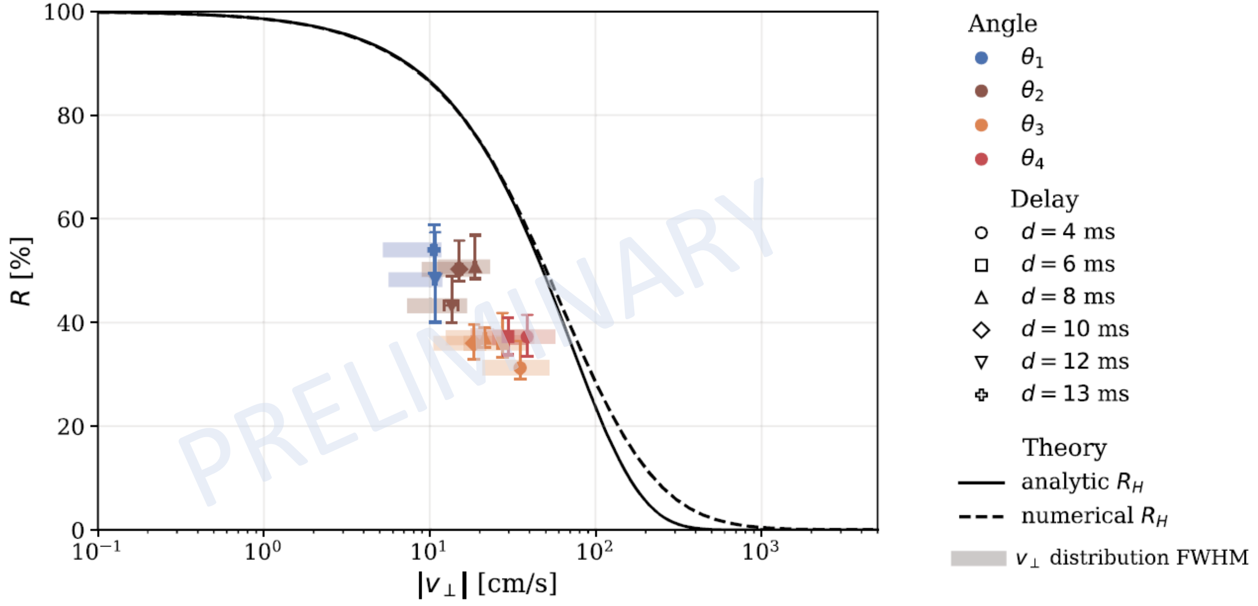
- ➢ Vary the angle of incidence (perpendicular velocities)



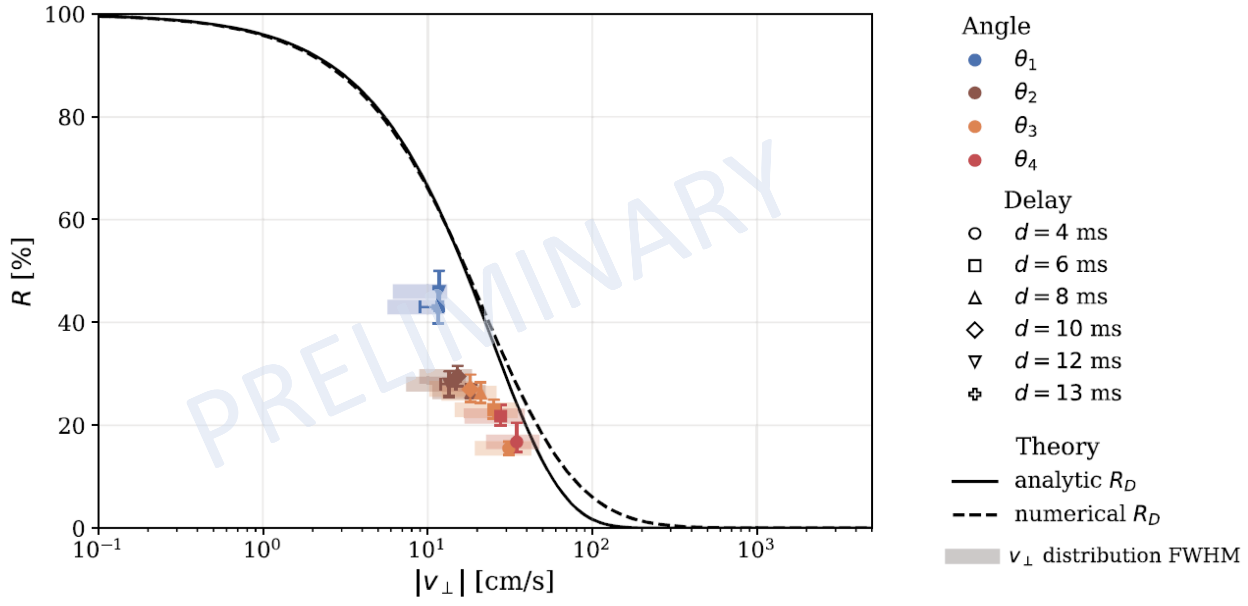
Use measurement matrix to extract R!

Quantum refection of H and D

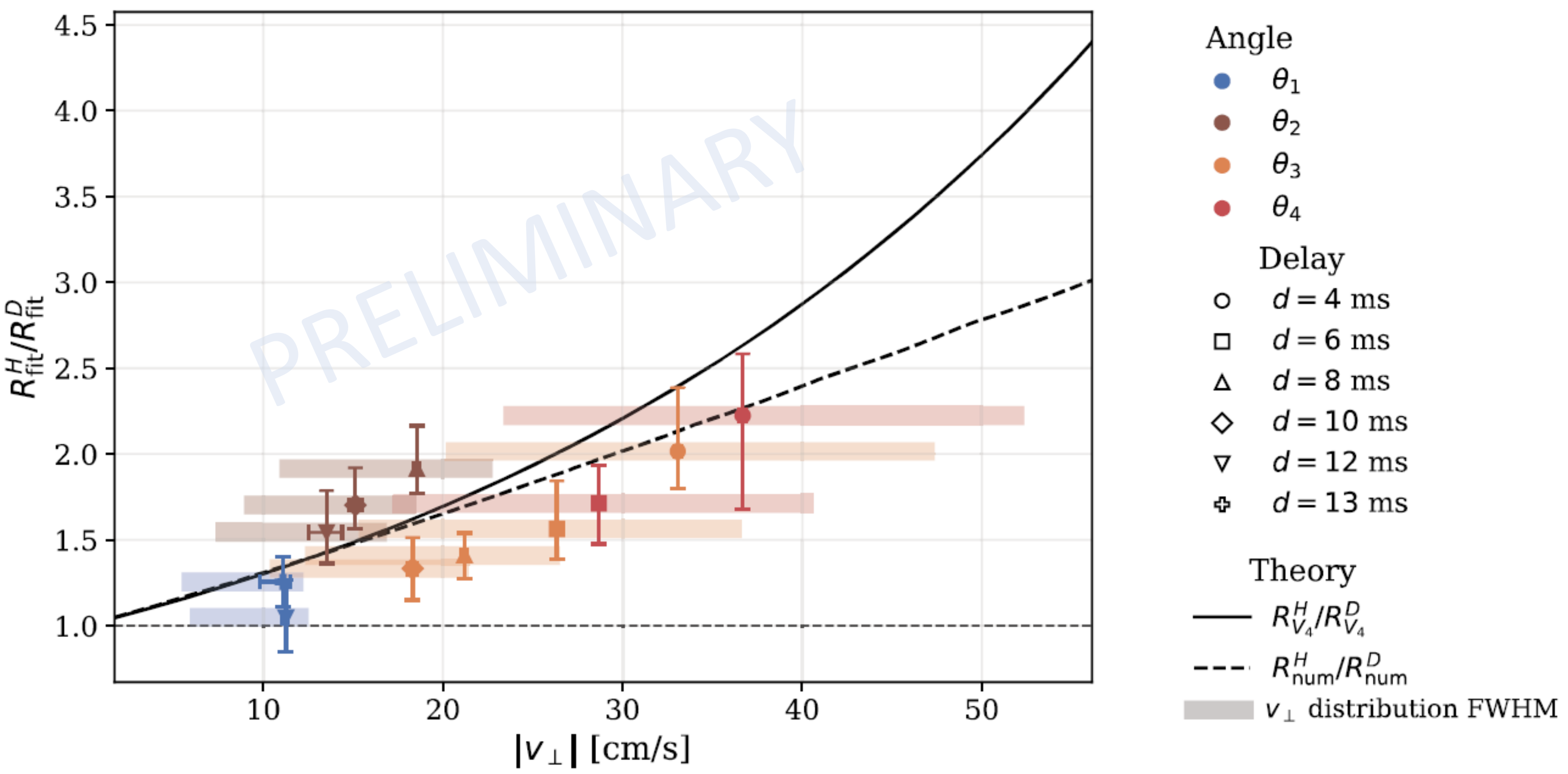
Hydrogen



Deuterium

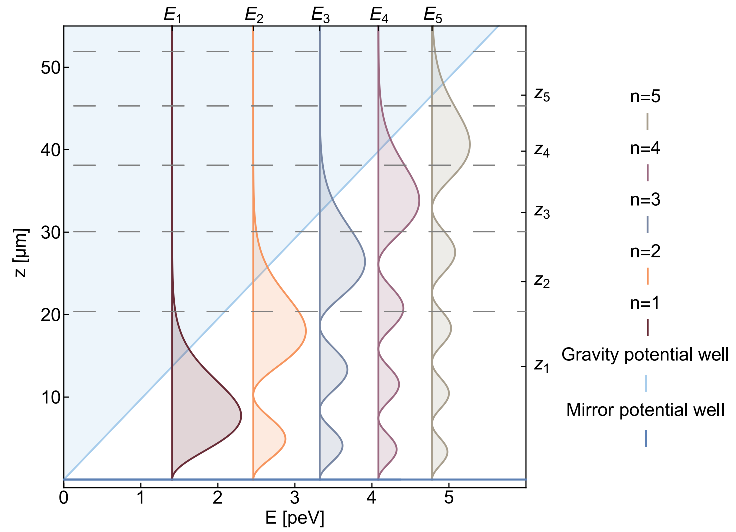


Isotope Shift of R



Summary & Outlook

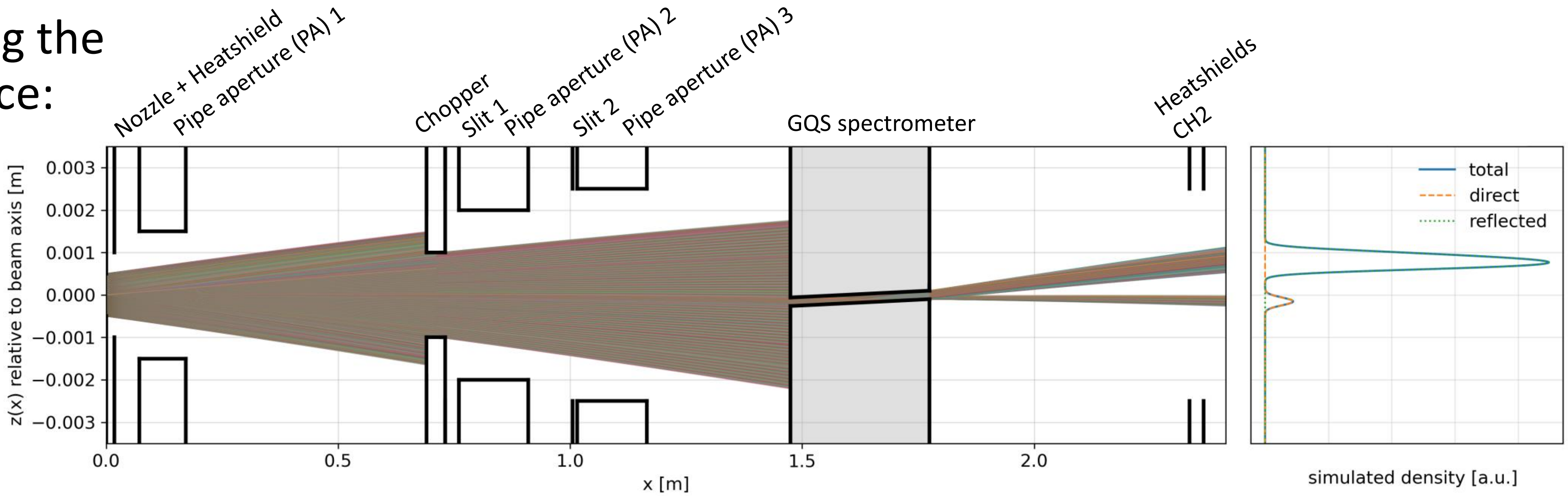
- Quantum reflection of H and D off Si surface for the first time
- Reflection coefficients smaller than predicted by theory
- First ever isotope comparison for R
  - Agreement with theory
- For future GQS measurements
  - Increased statistics
  - Understand reduced QR
  - Reduce vertical velocity



Backup

QR Analysis

- Based on classical trajectory simulations given by $z(x) = z_0 + \left(\frac{x v_{z0}}{v_x}\right) - g\,\left(\frac{x}{v_x}\right)^2$
- Trajectories hitting apertures are discarded
- Atoms hitting the mirror surface:
  $v_\perp \rightarrow -v_\perp$



QR Analysis: Initial Beam Properties

- Initialize an atomic ensemble with MB distributions for v_x, a Gaussian distribution for v_{z0}, and $v_y \sim 0$
  - $p(v) = v^3 \exp(\frac{-mv^2}{2kT})$
  - $v = \sqrt{v_x^2 + v_y^2 + v_{zo}^2}$

- The vertical distribution is defined as a Gaussian profile $p(z_0)$
  - $\sigma = S_0 \ * 10$
  - $S_0 = 1 \text{ mm}$ (nozzle opening)

QR Analysis: Trajectories

- Velocity distribution v_x is defined by chopper delay
  - $v_x \in [v_{x,min}, v_{x,max}]$, $dv_x = 5.0$ m/s
- Velocity distribution v_{z0} is defined by Gaussian distribution
  - $v_{z0} \in [v_{z0,min}, v_{z0,max}] = [-0.14, 0.16]$ m/s, $dv_{z0} = 0.005$ m/s
- Starting height is defined by the slit size
  - $z_0 \in \left[-\frac{s0}{2}, \frac{s0}{2}\right] = [-0.5, 0.5]$ mm, $dz_0 = 0.005$ mm
  - $p = p(v) * p(z_0)$

QR Analysis: Parameters

Geometrical parameters:

- Vertical offset of chopper from beam axis
- Vertical offset of GQS spectrometer compared to beam axis
- Exact horizontal position of GQS spectrometer along the beamline
- Angles of the different angle settings
- Pivot point of mirror rotation
- Tilts along third (“y”) axis

VARIED BY PARAMETER SCAN

Other parameters

- Mapping constant
- Laser beam waist
- Vertical velocity spread

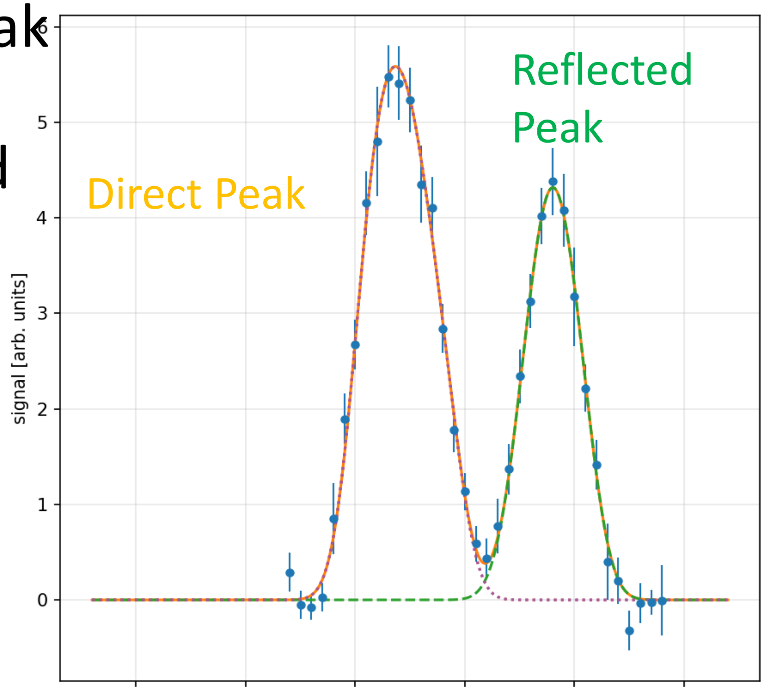
VARIED BY PARAMETER SCAN

Fit parameters

- Scaling of the curves
- QR probability

QR Analysis: Global Fit

- Combine all measurements performed for H or D
- Every trajectory simulation is fitted to the respective dataset with 2 parameters:
  - Overall scaling *A* : only applied to direct peak
  - Reflection probability *R*: only applied to reflected peak
- Variation of all parameters: Repeating the trajectory simulation for all parameter combinations, fitting *A* and *R* after every iteration
  Optimum at $\chi^2 = \min$
- Post processing: using exported parameter scans results
  to find parameter-uncertainty-dependent uncertainty of *R*



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