MPQ

# Precision spectroscopy of the 2S-6P transition in atomic deuterium

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# Hydrogen and deuterium energy levels theory

Hydrogen/deuterium energy levels based on bound-state Quantum Electrodynamics:

$$E_{nlj} = hc\,R_\infty \left( -\frac{1}{n^2} + f_{nlj}(\alpha, \frac{m_e}{m_N}) + \frac{\delta_{l0}}{n^3} \left( C_{\mathrm{NS}} r_N^2 + C_{\mathrm{pol}} + \mathrm{h.o.n.e.} \right) \right)$$

Rydberg constant

$$hcR_\infty = m_e c^2 \times \frac{\alpha^2}{2}$$

*..related to the electron mass and the fine-structure constant*

$r_N^2$ r.m.s. nuclear charge radius

$\alpha$ fine-structure constant

$\frac{m_e}{m_N}$ electron-to-nucleus mass ratio

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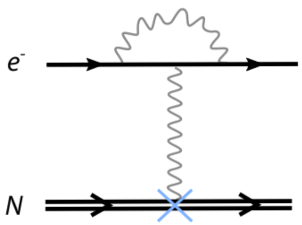
## QED effects with point-like nucleus

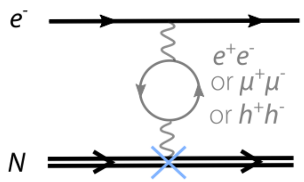
1-loop QED: self-energy

$\propto \alpha^2 \times \alpha^3 \ln(\alpha^2)$



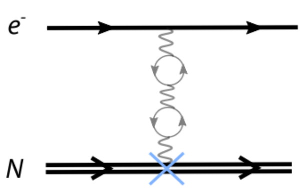

1-loop QED: vac.-pol.

$\propto \alpha^2 \times \alpha^3$




2-loop QED: vac.-pol.

$\propto \alpha^2 \times \alpha^4$



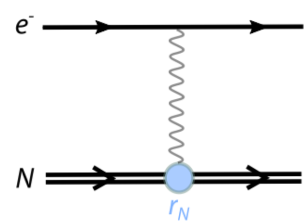

+ other terms

## Nuclear effects

### 1st order elastic effect

finite nuclear size

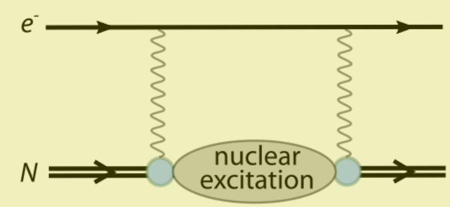
$\propto \alpha^2 \times \alpha^2\, r_N^2$




### 1st order inelastic

nuclear polarizabiliy

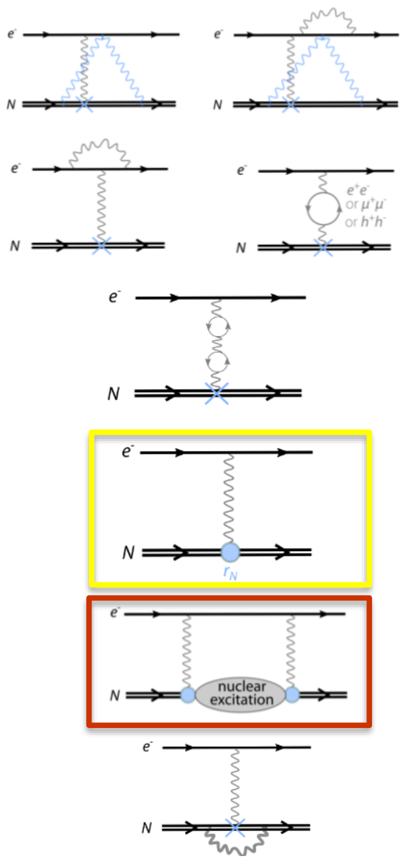
$\propto \alpha^2 \times \alpha^3\, \tilde{C}_{\mathrm{pol}}$




+ higher order nuclear effects (h.o.n.e.)

non-negligible for 2S-6P in deuterium

# H 2S-6P vs D 2S-6P: contributions to transition frequency



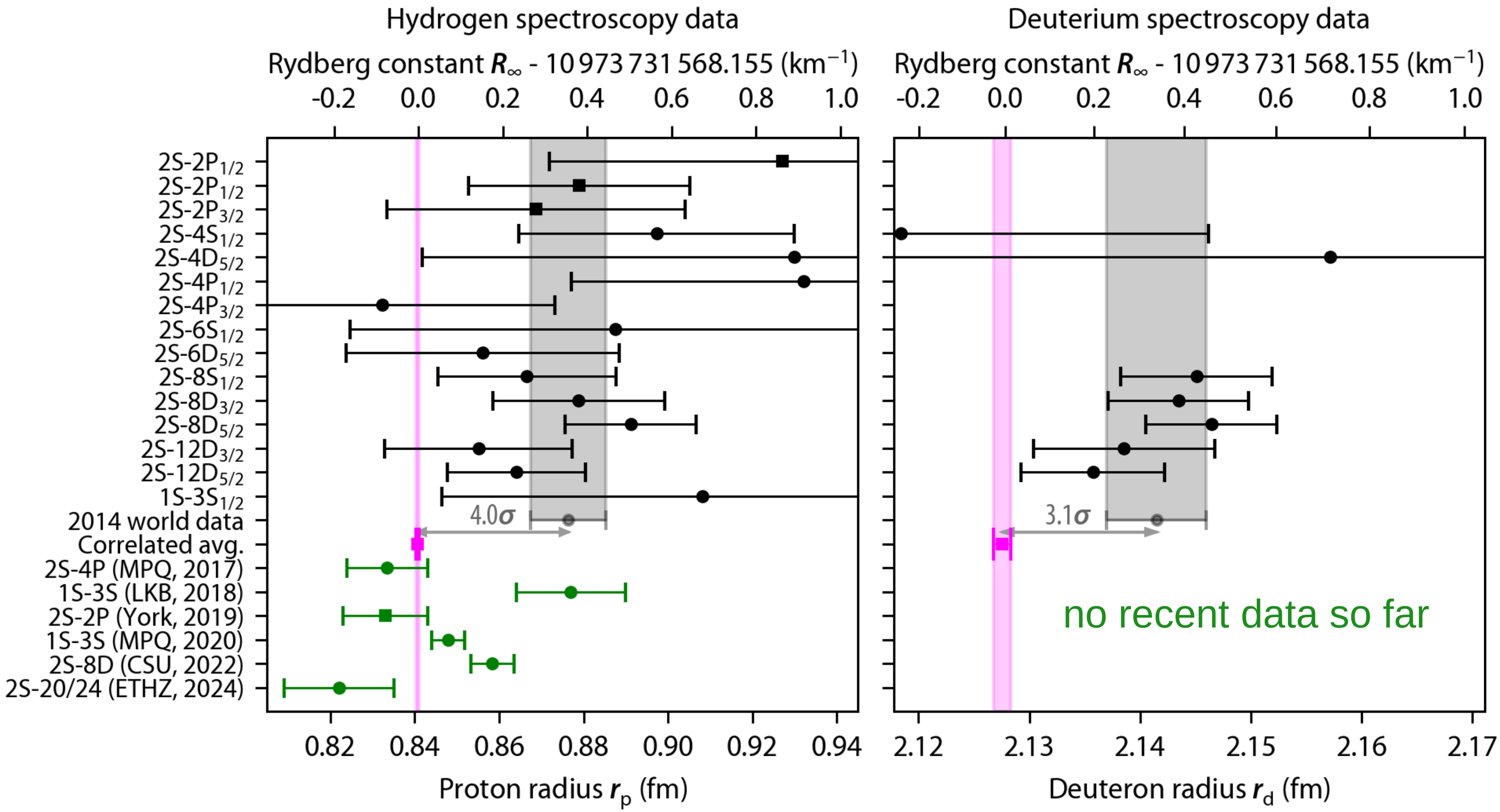

| | Hydrogen $2S_{1/2}$-$6P_{1/2}$ (Hz) | Deuterium $2S_{1/2}$-$6P_{1/2}$ (Hz) |
|---|---|---|
| Dirac (with $m_e \to m_{\text{red}}$) | 730 691 021 696 054 | 730 889 842 123 184 |
| Rel. nuclear recoil | 1 129 173 | 566 917 |
| Radiative recoil | 1540 | 771 |
| 1-loop QED | | |
| self-energy | −1 071 679 859 | −1 072 517 882 |
| vacuum-polarization | 26 853 088 | 26 875 014 |
| $\mu^+\mu^-$ vacuum-pol. | 634 | 634 |
| hadronic vacuum-pol. | 425 | 425 |
| 2-loop QED | −90 477 | −90 551 |
| 3-loop QED | −236 | −236 |
| Finite nuclear size | | |
| $\propto \alpha^4$ | −138 394 | −885 943 |
| $\propto \alpha^5$ | 5 | 19 |
| $\propto \alpha^6$ | −74 | −433 |
| Nuclear polarizability | | |
| $\propto \alpha^5$ | 8 | 2722 |
| $\propto \alpha^6$ | −49 | 68 |
| Nuclear self-energy | −584 | −153 |
| Total | 730 689 977 771 255 | 730 888 796 074 559 |
| Theory uncertainty | 199 | 181 |
| Uncert. from constants | 1532 | 1529 |
| Total uncertainty | 1545 | 1539 |

Hydrogen 2S-6P: higher-order nuclear size effects and polarizability < 0.1 kHz

Deuterium 2S-6P: higher-order nuclear size 0.4 kHz, polarizability 2.7 kHz

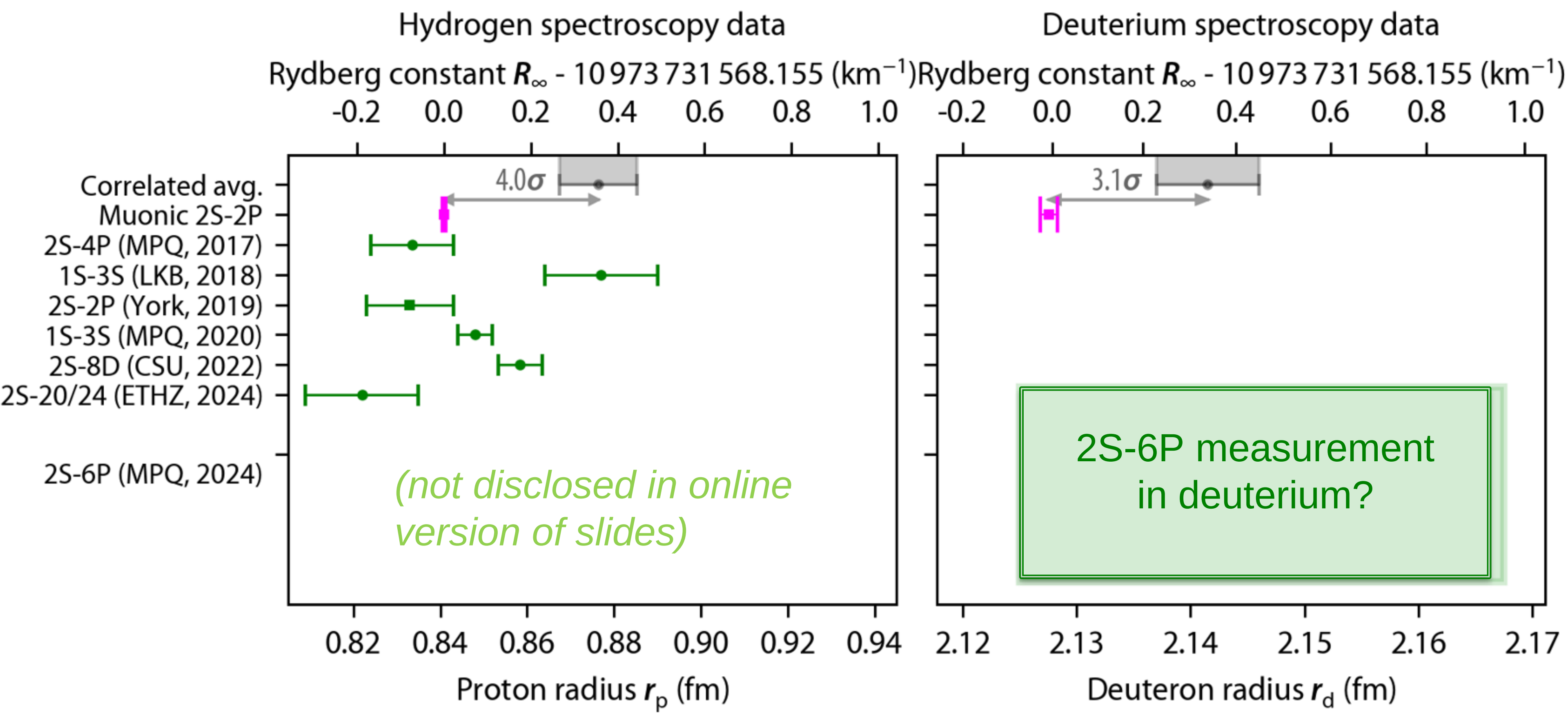
# Hydrogen and deuterium spectroscopy data overview

**Considering hydrogen and deuterium separately**: 1S-2S transition measurement in hydrogen or deuterium combined with other transition measurement:

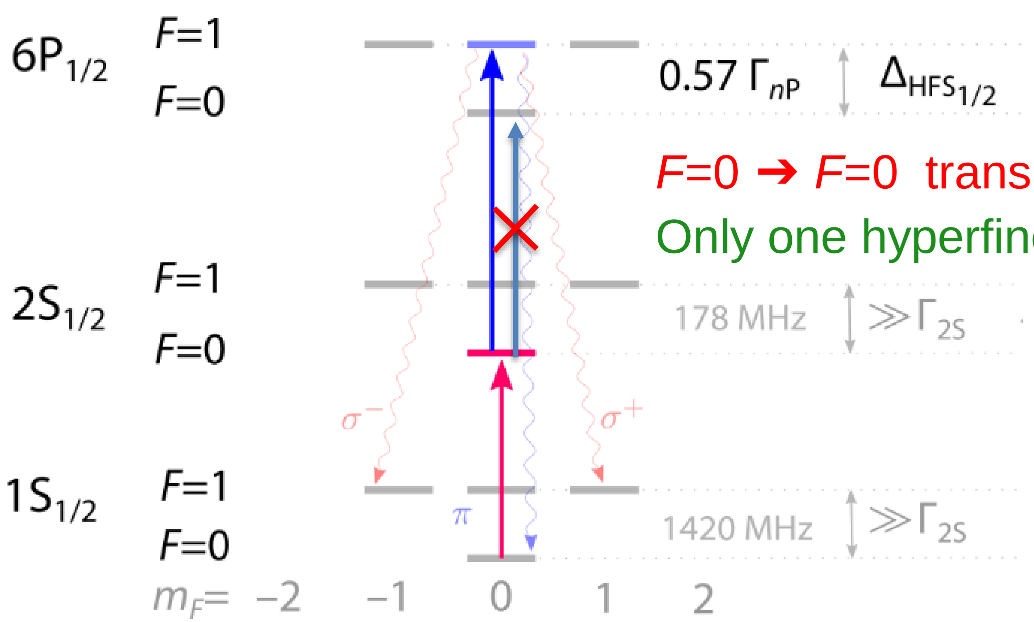



Similar discrepancy for the muonic and electronic deuterium, but so far no recent data from deuterium spectroscopy

# Preliminary hydrogen 2S-6P measurement result



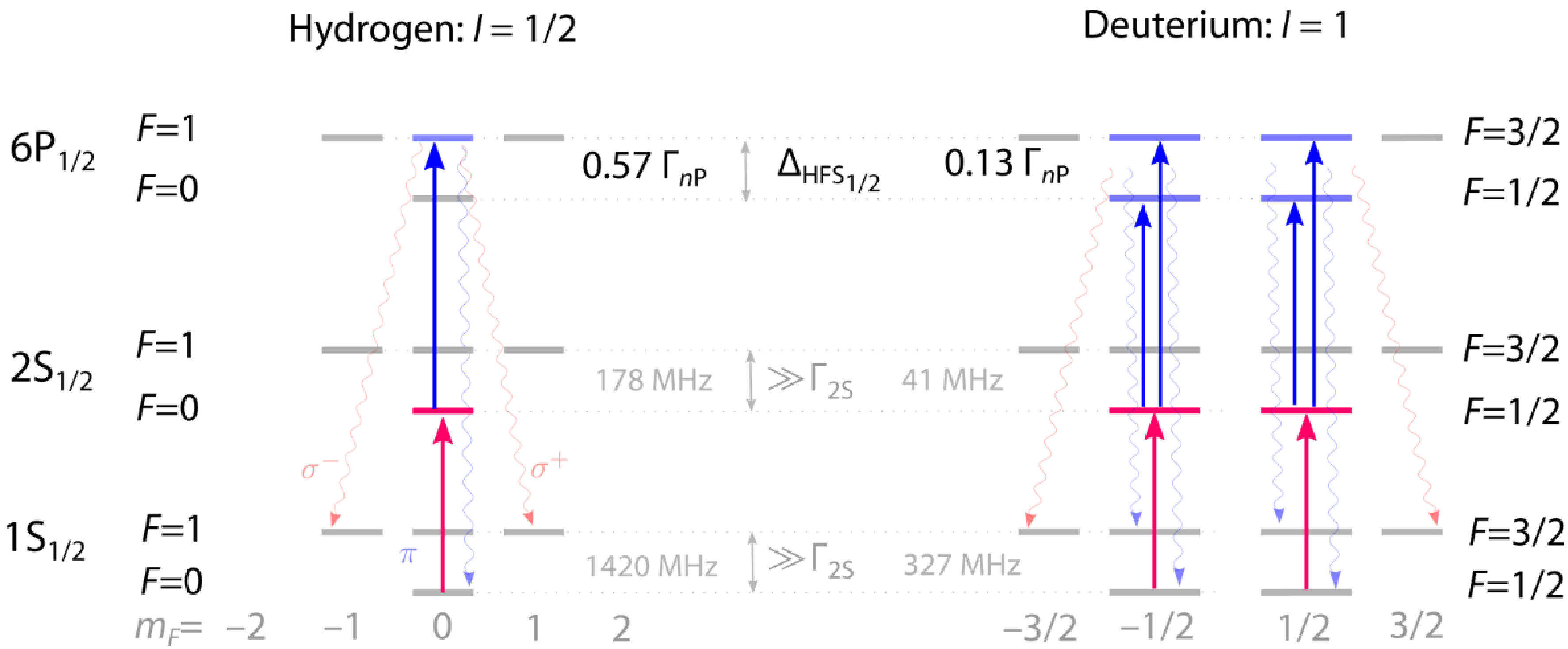
Hydrogen: $I = 1/2$




$F$=0 ➔ $F$=0 transitions forbidden

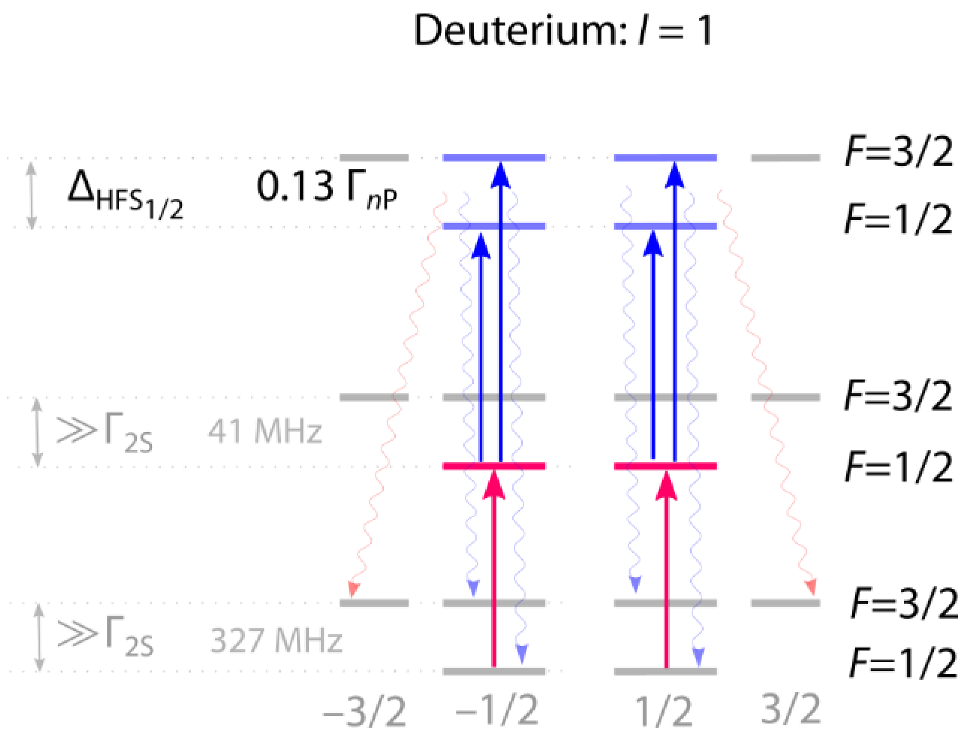
Only one hyperfine manifold excited

# 2S-6P in deuterium: complications



**Additionally allowed transitions** compared to hydrogen require to consider:

1) simultaneous excitation of different hyperfine levels



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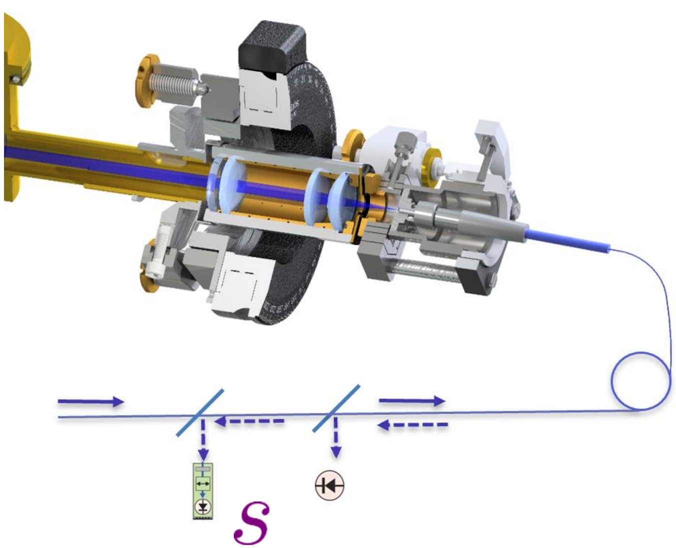
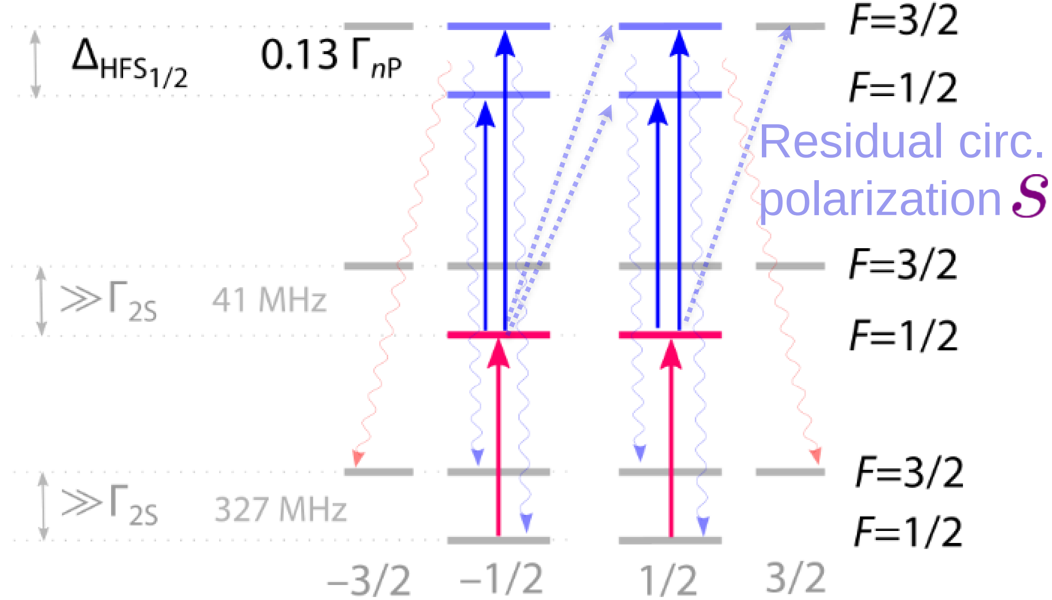



Deuterium: $I = 1$




Residual circular polarization $S$ changes the dipole ratio of excited hyperfine state manifolds

Introduced **polarization monitor** in our improved active fiber-based retroreflector [1]

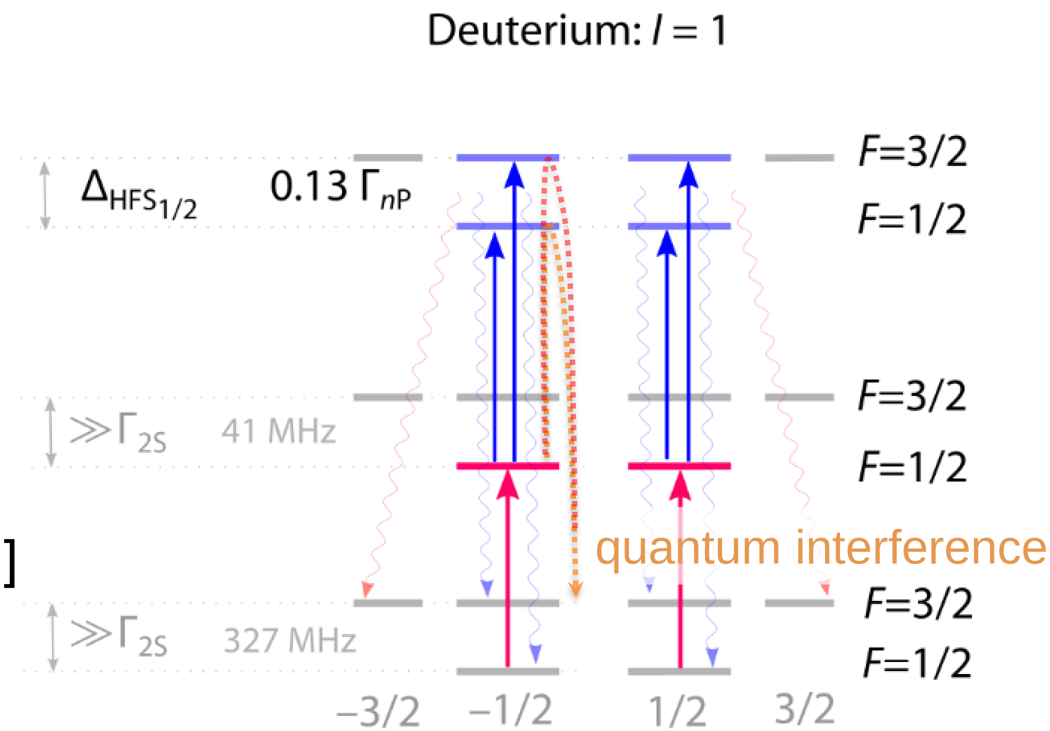
Shift from non-zero circular polarization **cancels for equal population of initial states**

[1] V. Wirthl *et al.*, *Opt. Express* 29(5), 7024 (2021)

**Additionally allowed transitions** compared to hydrogen require to consider:

1) simultaneous excitation of different hyperfine levels

2) quantum interference between unresolved hyperfine transitions [1]




[1] Th. Udem *et al.*, *Ann. Phys. 531*(5), 1900044 (2019)

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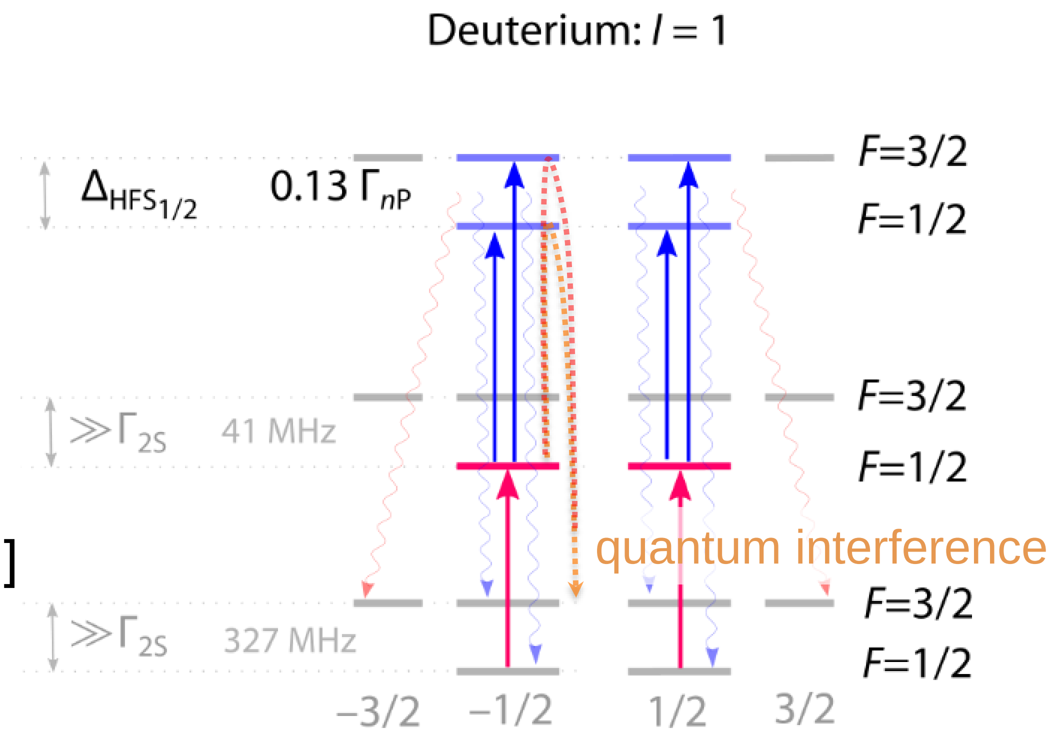
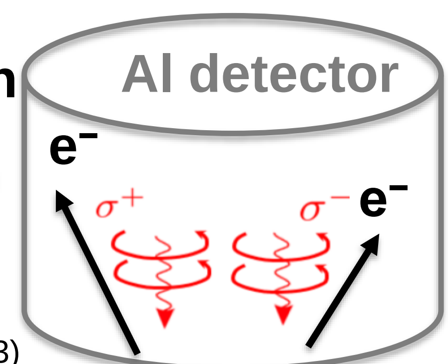



- for $\pi$ decays q. i. effect cancels [2] for each initial state

- for $\sigma^{\pm}$ decays q. i. effect **cancels** [2] **for equal population of initial states or equal detection** of $\sigma^{+}$ and $\sigma^{-}$ decays

possible sensitivity $\xi_{\circ}$ of e⁻ yield upon **circular polarization**




[1] Th. Udem *et al.*, *Ann. Phys. 531*(5), 1900044 (2019)
[2] V. Wirthl, *PhD Thesis, LMU Munich* (2023)

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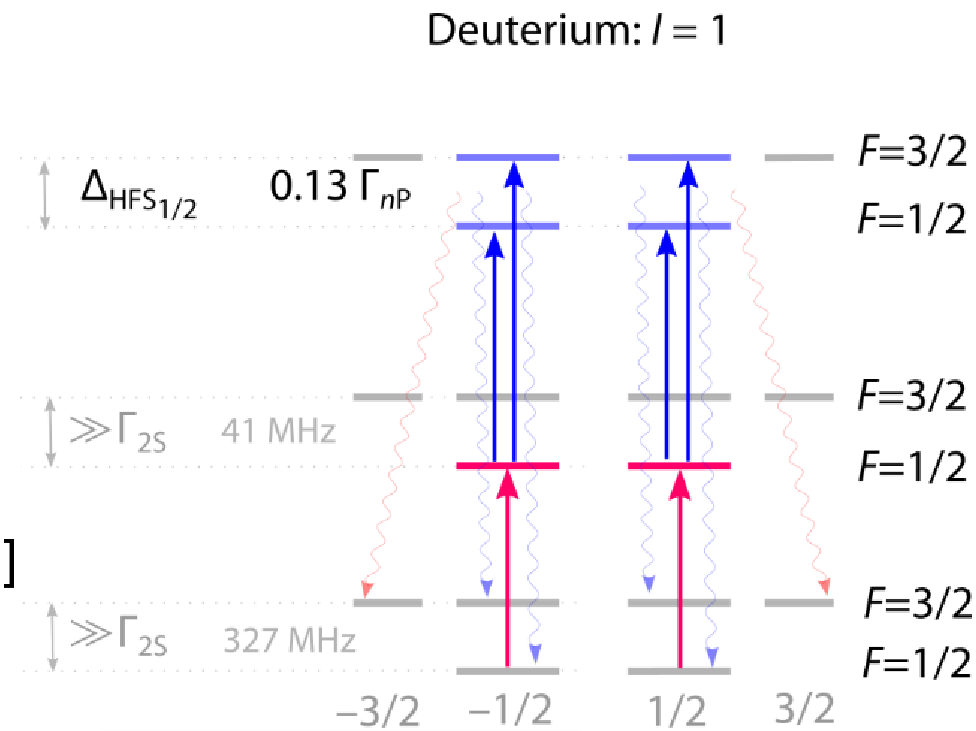



| | Circ. polar. sensitivity of the detector $\xi_0$ | Initital state population asymmetry $l$ | Residual circular polarization $S$ |
|---|---|---|---|
| 1) Shift from dipole ratio | | x | |
| 2) Unresolved Q.I. | | x | |

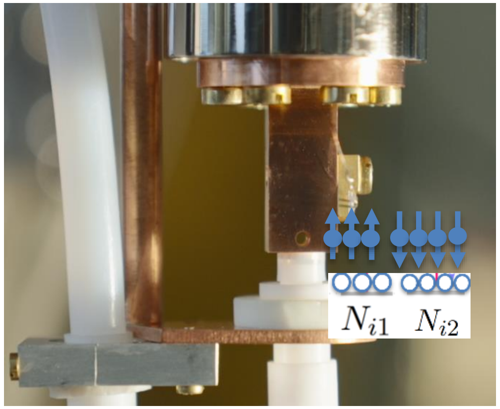
Both effects from additional transitions in deuterium **doubly suppressed**

[1] Th. Udem *et al.*, *Ann. Phys. 531*(5), 1900044 (2019)

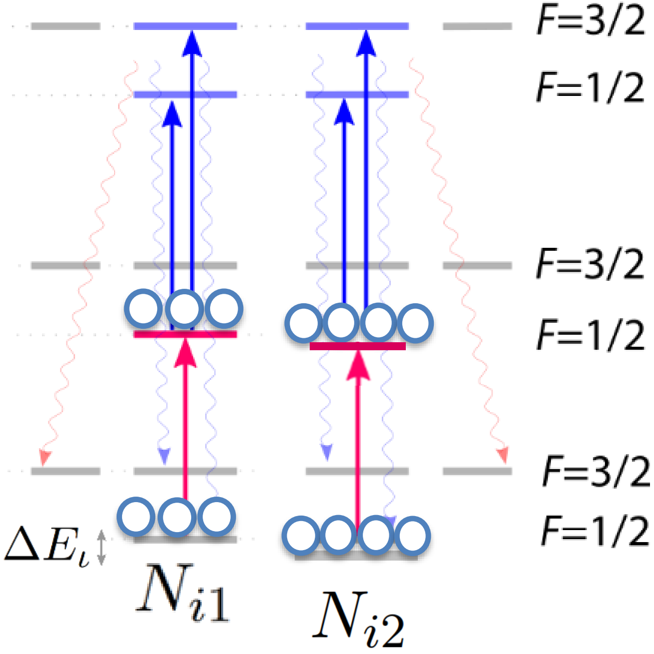
Both effects from additional transitions in deuterium depends on the **initial state population asymmetry**:

$$\iota = \frac{N_{i2} - N_{i1}}{N_{i2} + N_{i1}}$$

**Spin-polarizing effects in the nozzle?**




Deuterium: $I = 1$

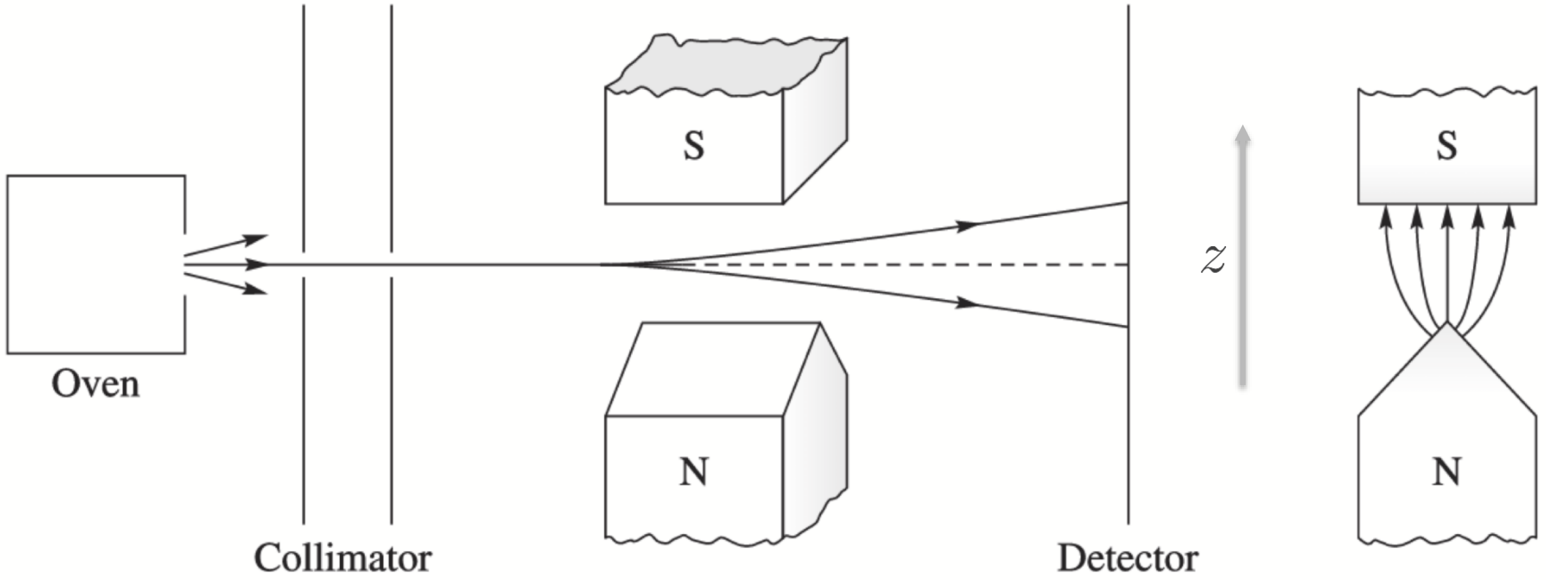


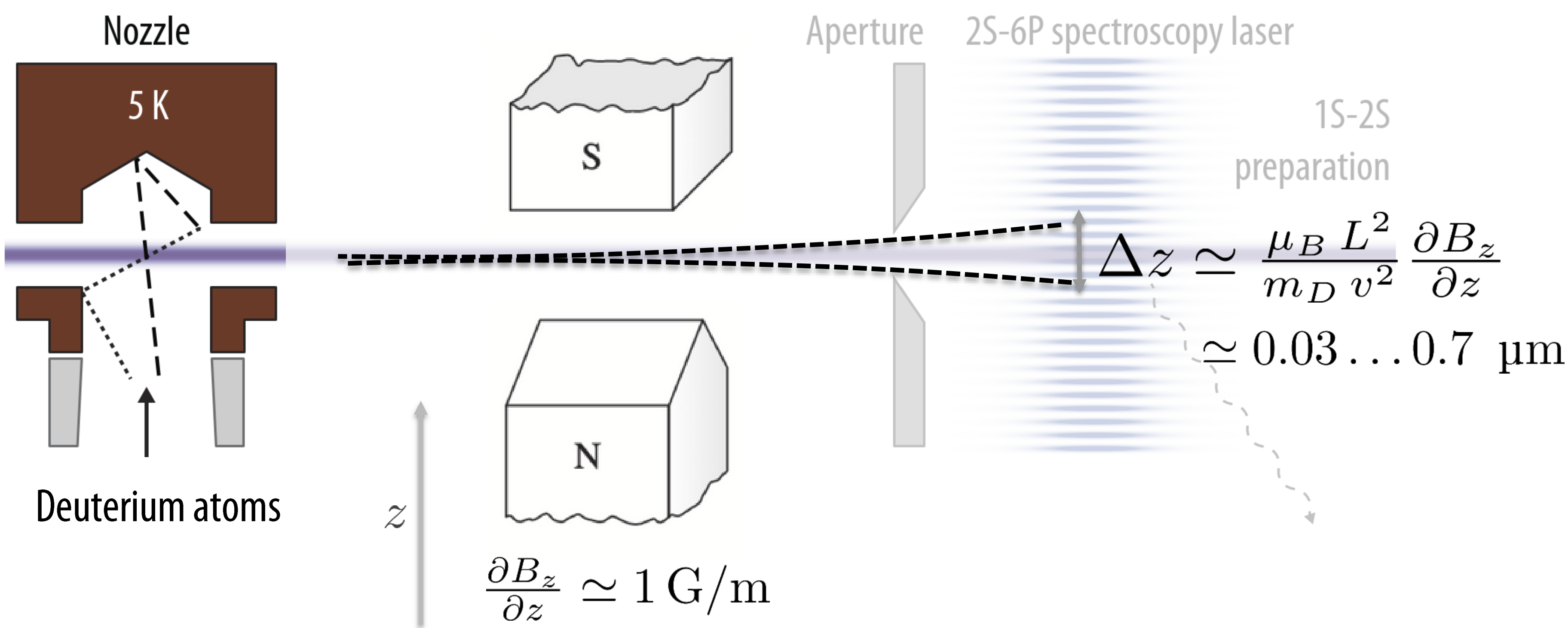

Symmetric nozzle: **symmetry breaking induced by magnetic field**, which leads to the energy difference $\Delta E_\iota = \frac{2}{3}\mu_B B$ between the two initial states.
Estimate assuming thermalization (Boltzmann distribution):

$$\frac{N_{i1}}{N_{i2}} = \exp\left(-\frac{\Delta E_\iota}{k_B T_N}\right) \quad \Rightarrow \quad \iota \simeq \frac{\mu_B B}{3 k_B T_N} \sim 3 \times 10^{-7}$$

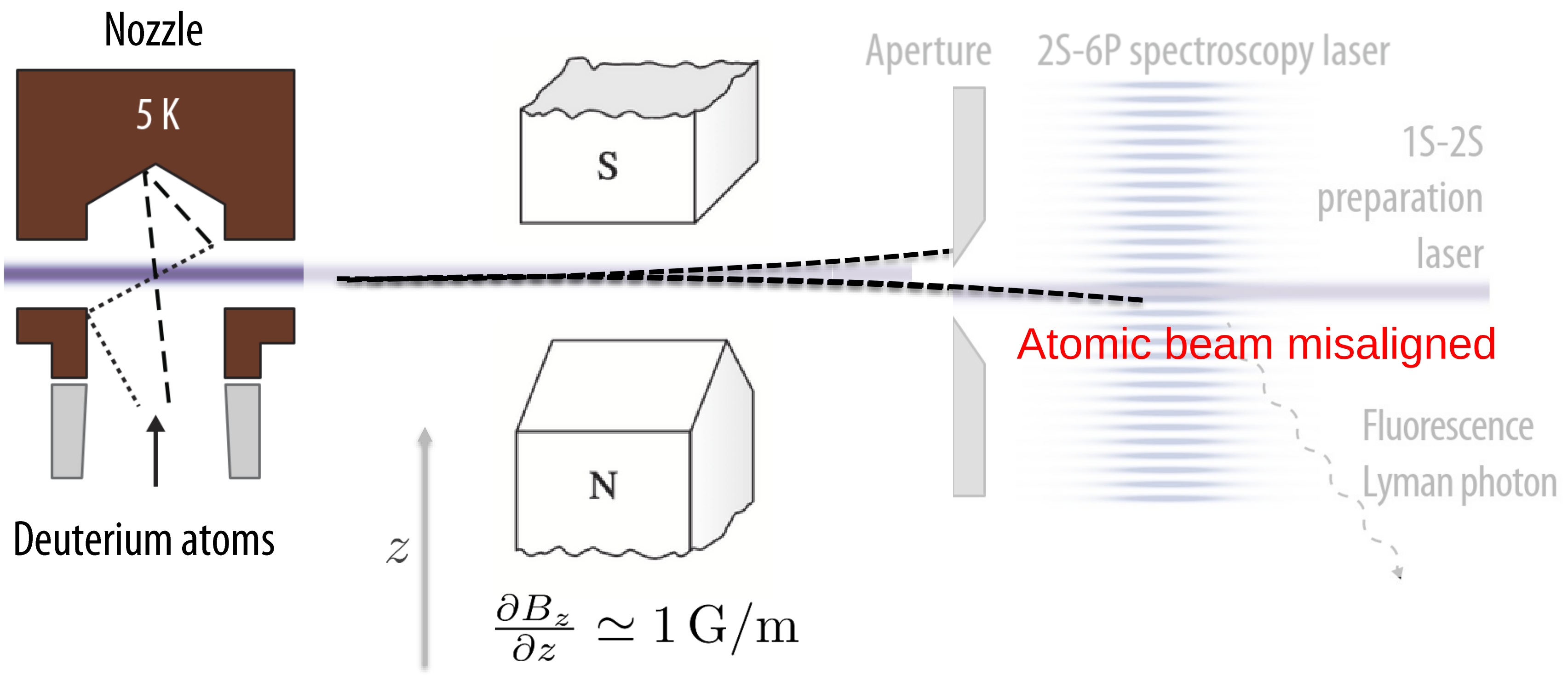
Magnetic field gradient leads to separation of spins

$$F_z \simeq \mu_B \frac{\partial B_z}{\partial z}$$




Nozzle
5 K
Deuterium atoms
S
N
$z$
Aperture
2S-6P spectroscopy laser
1S-2S
preparation
$\frac{\partial B_z}{\partial z} \simeq 1\,\mathrm{G/m}$
$\Delta z \simeq \frac{\mu_B L^2}{m_D v^2} \frac{\partial B_z}{\partial z}$
$\simeq 0.03 \ldots 0.7\ \mu\mathrm{m}$

# Initial state population asymmetry: Stern-Gerlach effect




Initial state asymmetry originates only from asymmetries in the apparatus

Estimate of initial state asymmetry from Stern-Gerlach effect in the atomic beam:

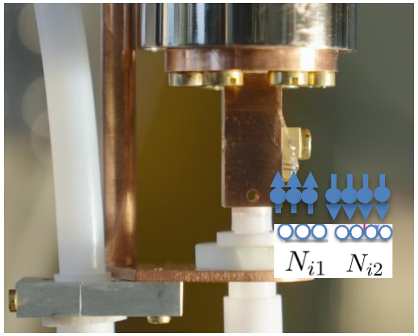
$$\iota \simeq 10^{-6} \ldots 5 \times 10^{-5}$$

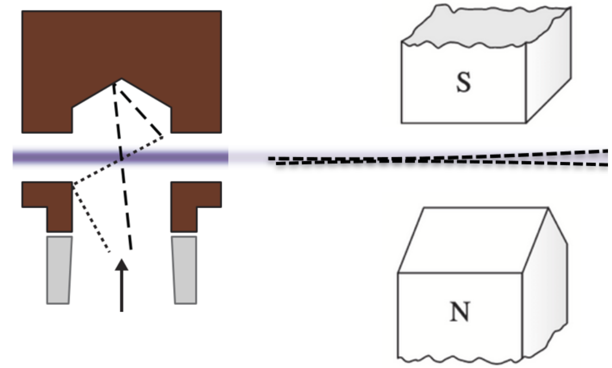
Depends on velocity of atoms:
**velocity-resolved detection** sensitive to this effect

# Estimates of line shifts due to initial state population asymmetry

Estimates of initial state asymmetry:

…from nozzle $\iota < 10^{-6}$ …from atomic beam $\iota < 10^{-4}$



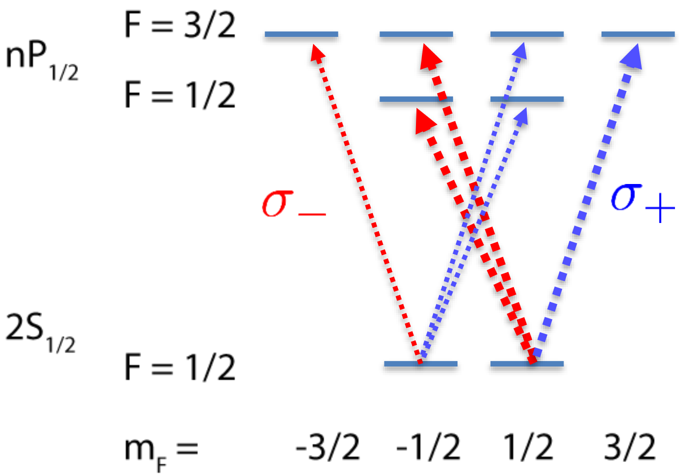

Calculation of systematic shifts coupled to population asymmetry yields [1]:

| | 2S-6P$_{1/2}$ : | 2S-6P$_{3/2}$ : |
|---|---|---|
| Shift due to simultaneous excitation with residual circular polarization fraction $s$ : | $\Delta\nu_{\iota s} \simeq \iota s \times 75\,\mathrm{kHz}$ | $\iota s \times 37\,\mathrm{kHz}$ |
| Shift due to unresolved Q.I. with circular polarization sensitivity of the detector $\xi_\circ$ : | $\Delta\nu_{\iota\xi_\circ} \simeq \iota\xi_\circ \times 100\,\mathrm{kHz}$ | $\iota\xi_\circ \times 5\,\mathrm{kHz}$ |

With the estimated initial state population asymmetry of < $10^{-4}$, both effects lead to shifts < 1 Hz even for the worst case of other imperfections

+ sensitive to velocity-resolved detection + different for 2S-6P$_{1/2}$ and 2S-6P$_{3/2}$

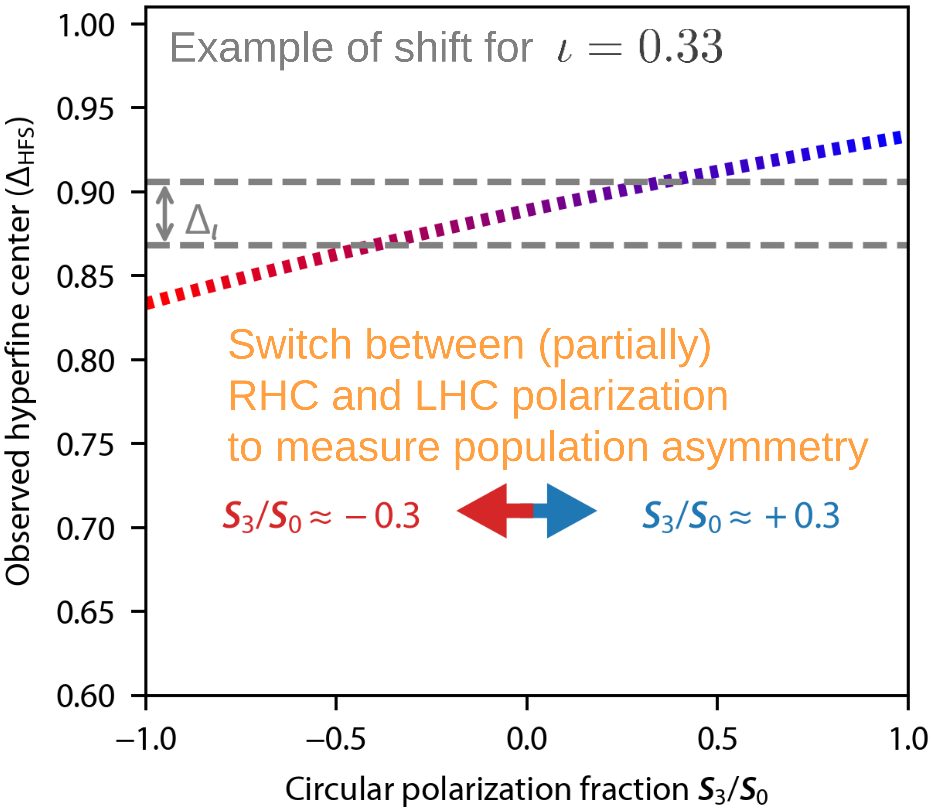
[1] V. Wirthl, *PhD Thesis, LMU Munich* (2023)




Induced shift from switching between (20% partial) RHC and LHC polarization:

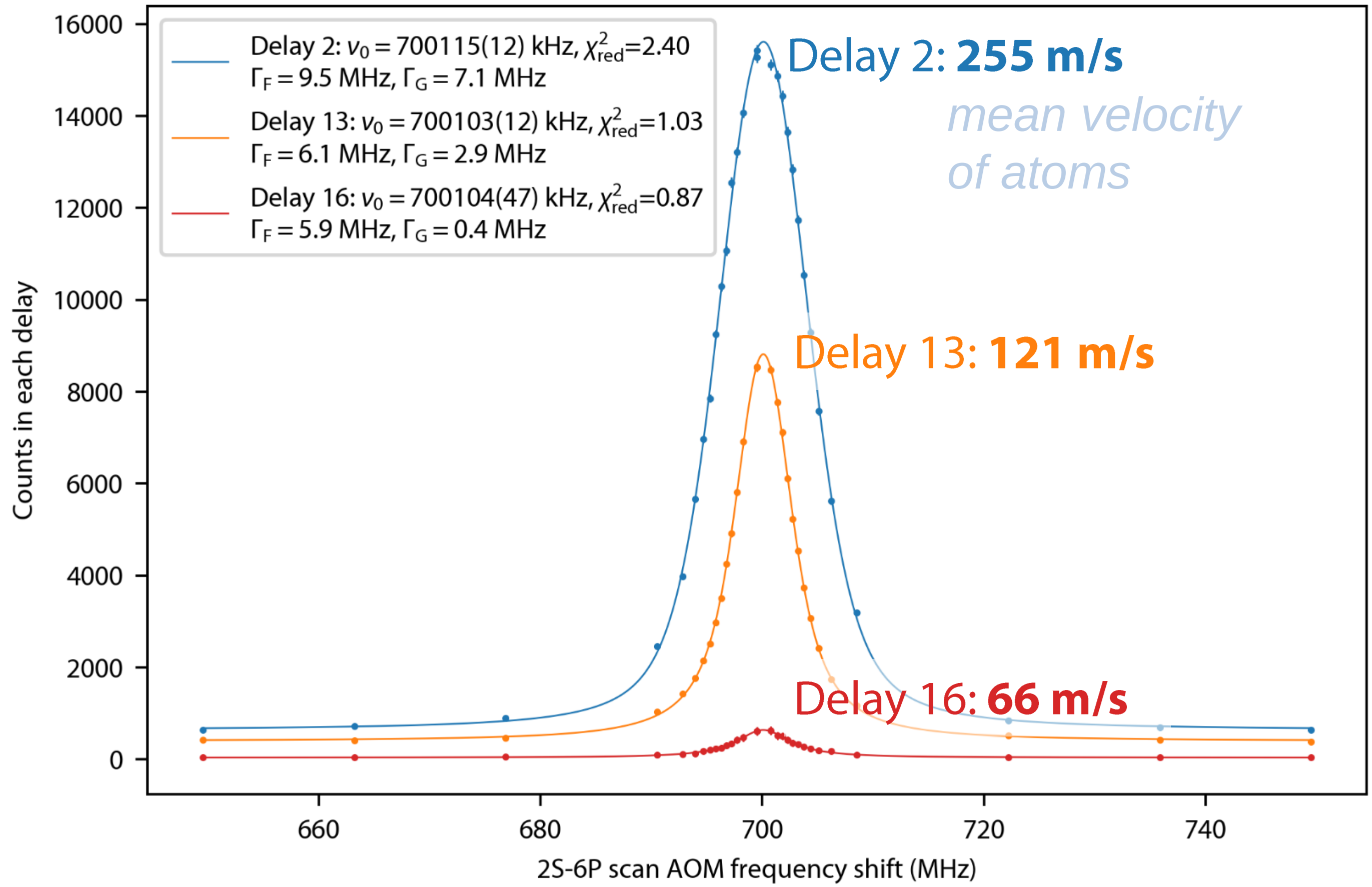
$$\Delta_\iota \simeq \iota \times 50\,\mathrm{kHz}$$

requires separate measurement campaign



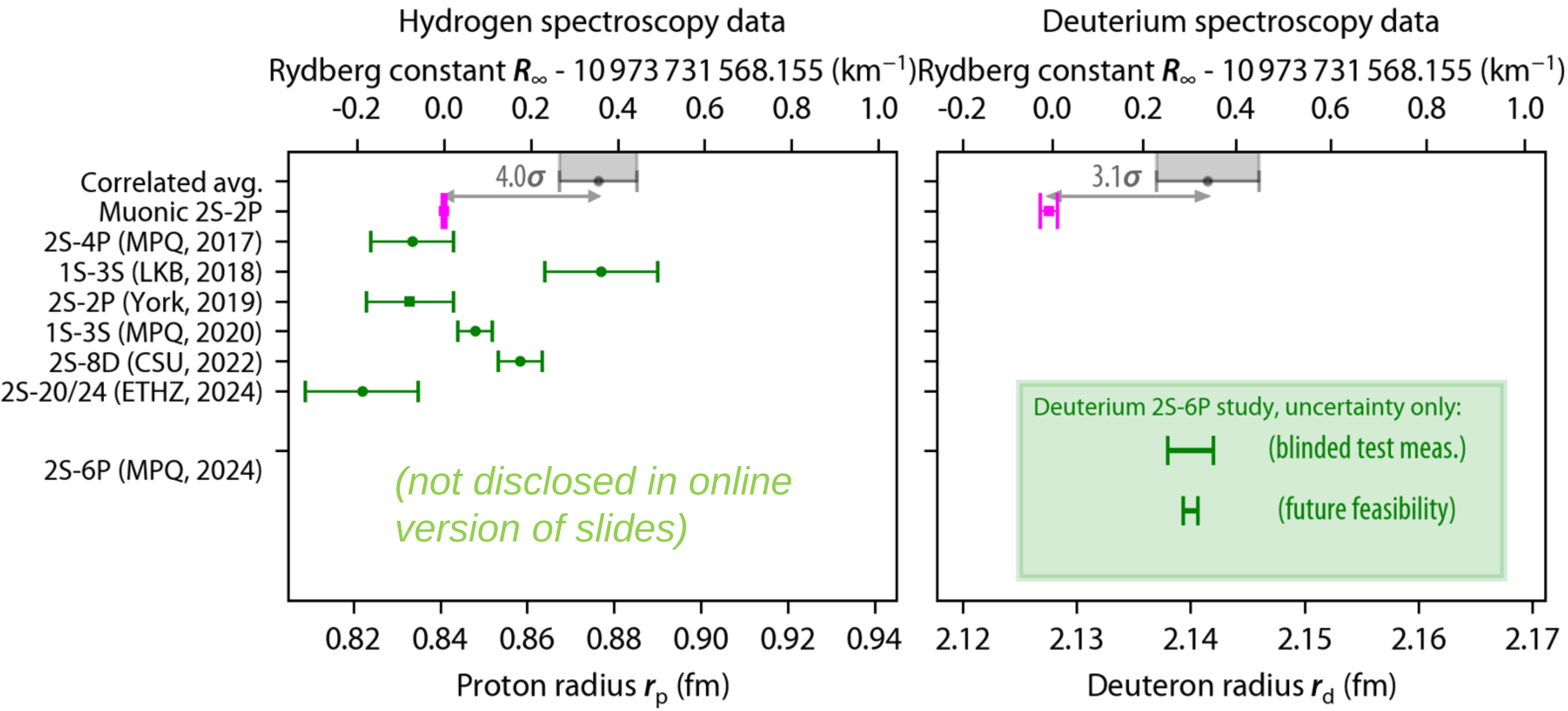

For our measurement uncertainty of $\Delta_\iota \sim 0.5\,\mathrm{kHz}$ we could determine the population asymmetry to $\iota \sim 10^{-2}$, which allows to place a limit of < 100 Hz for systematic effects arising from non-zero $\iota$ .

Observed deuterium 2S-6P transition signal with a high count rate, low background:




Test measurement: ~ 300 deuterium 2S-6P precision line scans

## Preliminary deuterium 2S-6P measurement campaign result:

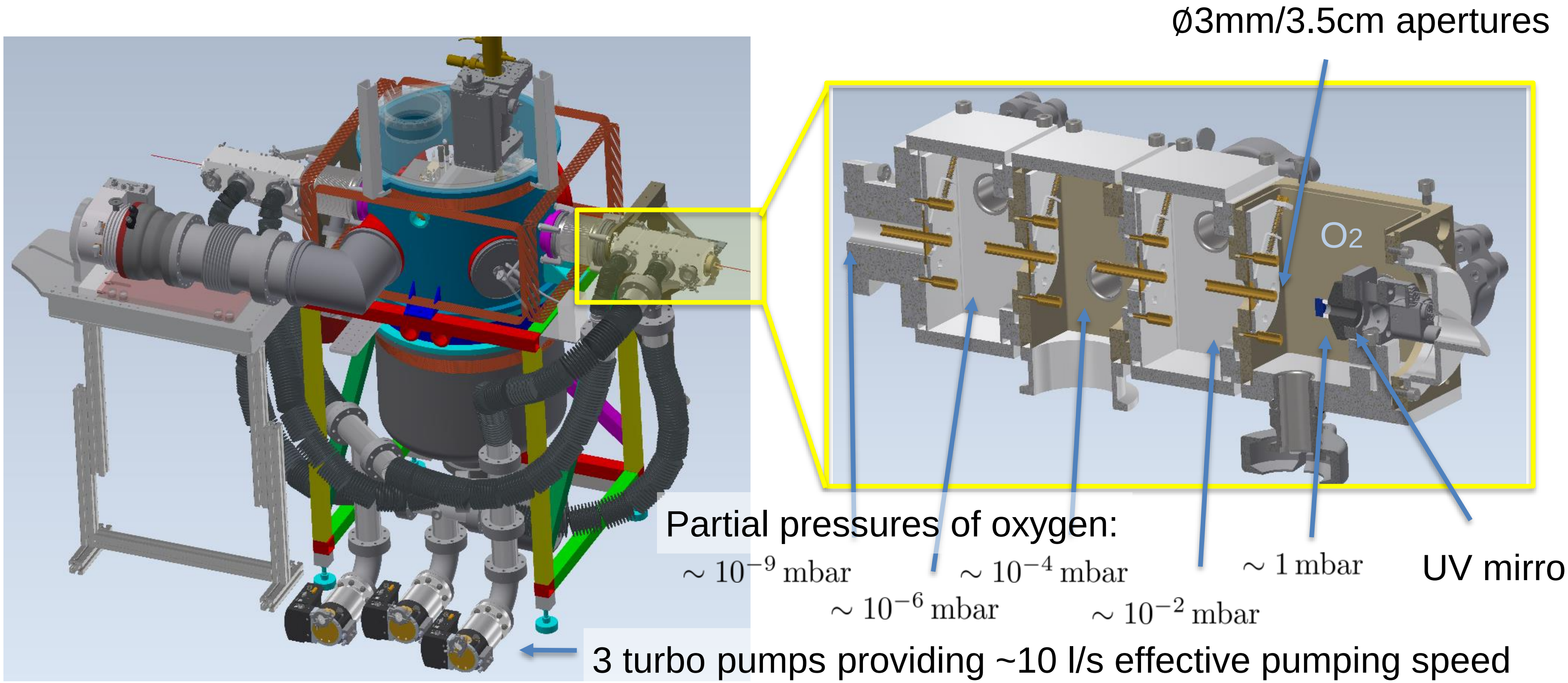


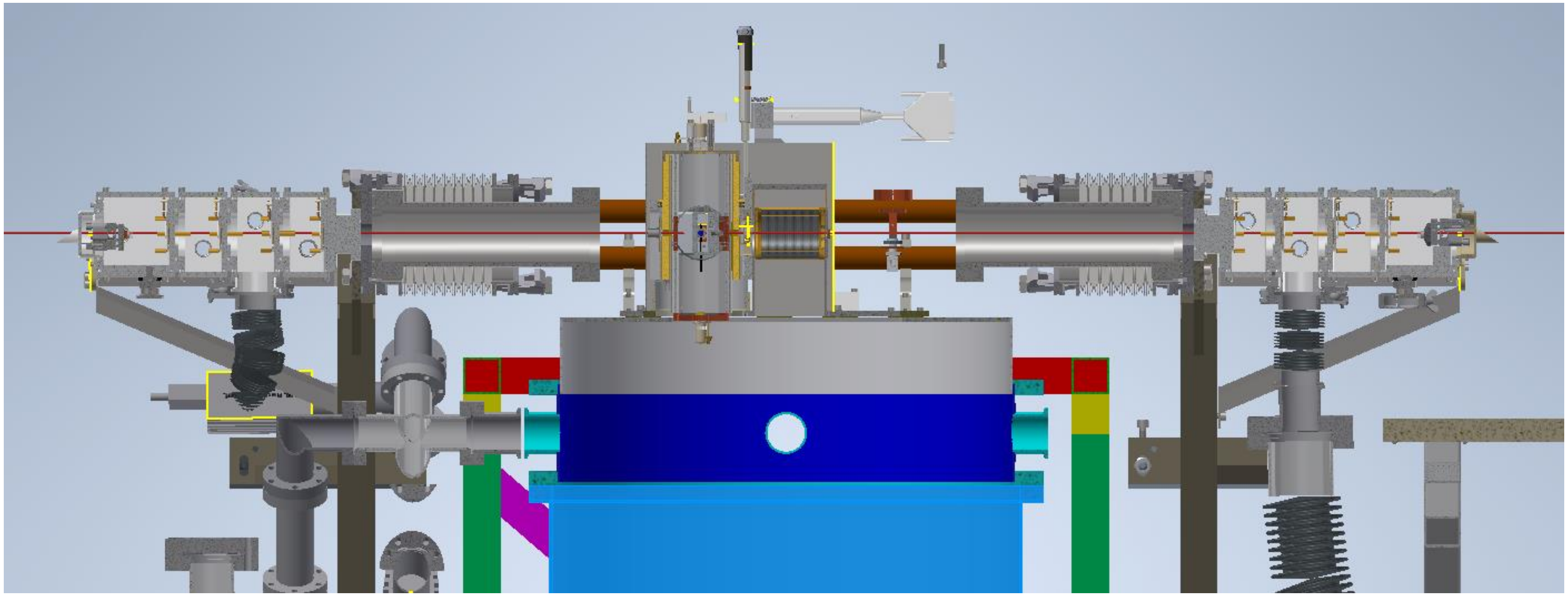

Deuterium 2S-6P measurement campaign currently in preparation
➔ feasible with a similar precision as in hydrogen

# Setup upgrade for $O_2$ flushing of UV mirrors: differential pumping

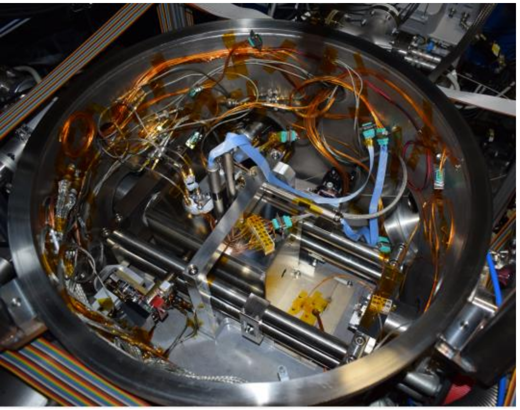
Main problem for continuos operation of the experiment: **UV mirror degradation** for the 243nm enhancement cavity

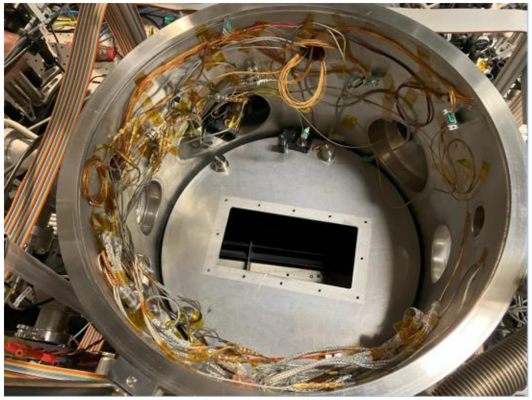
➔ Solution: in the future planned to rebuild setup for differential pumping to **flush mirrors with ~1mbar of oxygen**

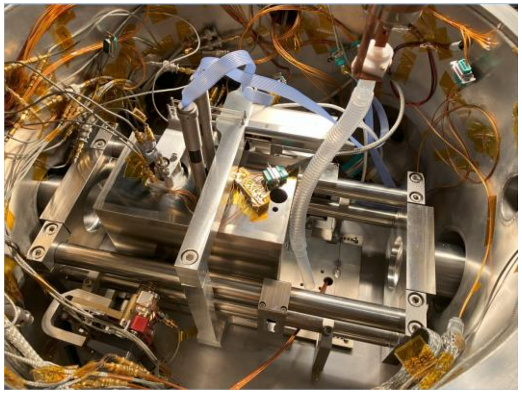




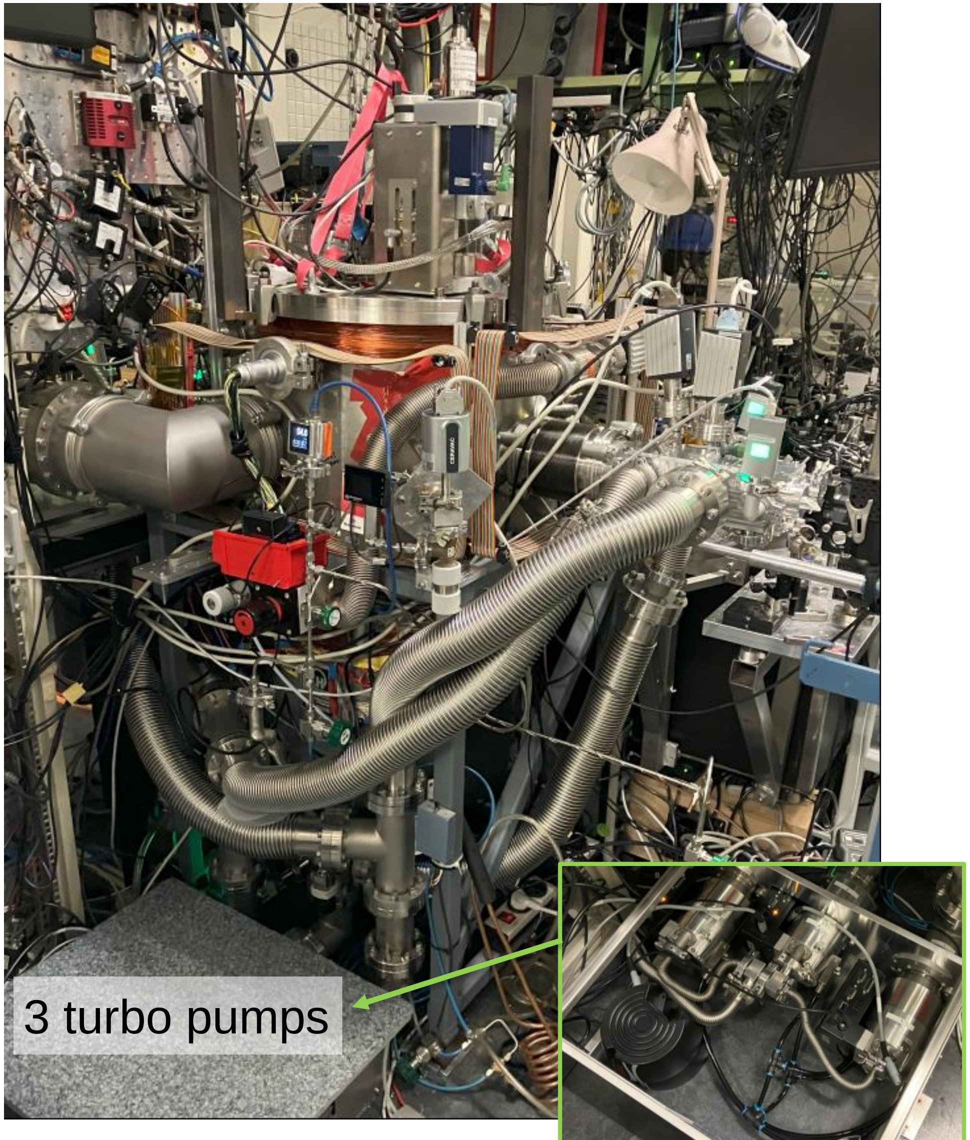
Upgrade to differential pumping required to disassemble the whole apparatus

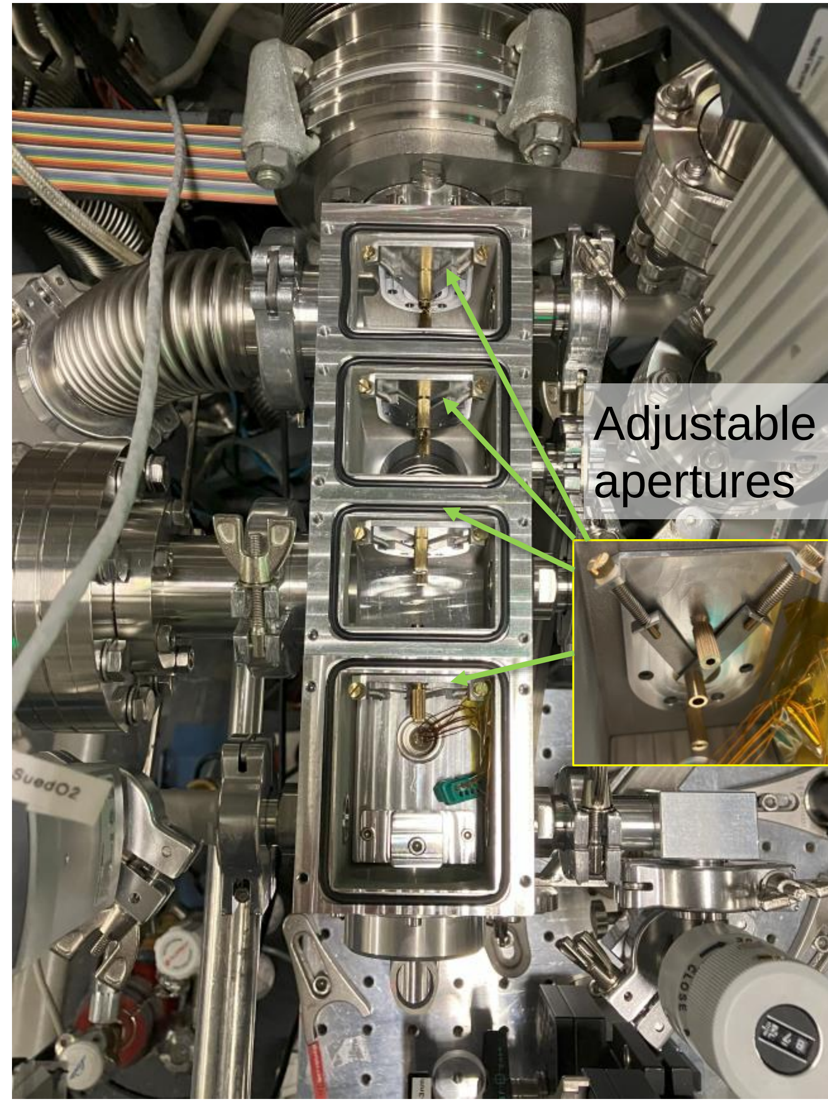






# Setup upgrade for $O_2$ flushing of UV mirrors: differential pumping



# Thank you for your attention!

## Hydrogen team

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Looking for new PhD students!

Randolf Pohl

Thomas Udem

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