MPQ

Precision spectroscopy of the 2S-6P transitions in atomic hydrogen and deuterium

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R. Pohl, T. W. Hänsch and Th. Udem

FFK Conference, May 2023

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

α fine-structure constant

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

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QED effects with point-like nucleus

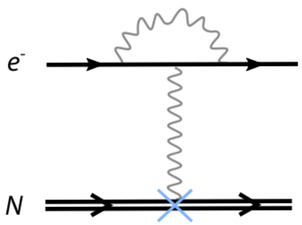
Nuclear effects

1st order elastic effect

1st order inelastic

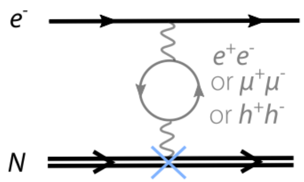
1-loop QED: self-energy

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



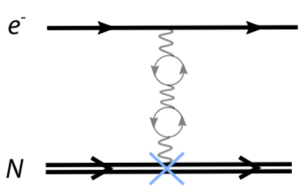
1-loop QED: vac.-pol.

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



2-loop QED: vac.-pol.

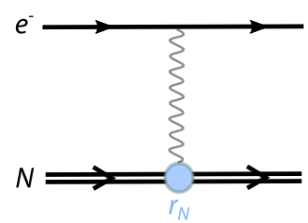
$\propto \alpha^2 \times \alpha^4$



+ other terms

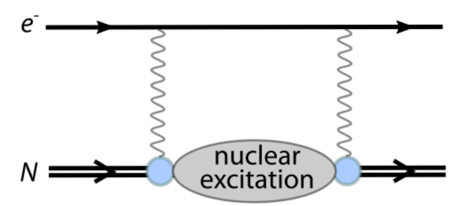
finite nuclear size

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



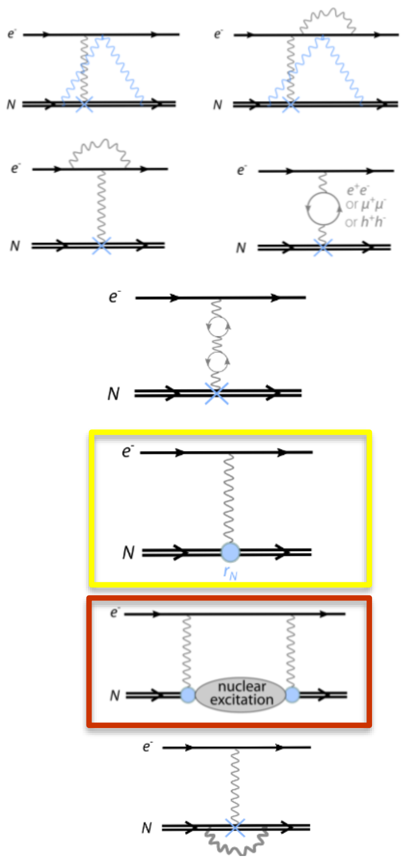
nuclear polarizabiliy

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



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

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 $m_e \to m_{\mathrm{red}}$)	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

Motivation for hydrogen and deuterium spectroscopy

Hydrogen/deuterium energy levels including QED and nuclear effects:

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

Precise *expressions* as a function of theory *parameters* (constants)

Motivation: metrology, test QED and consistency of Standard Model, nuclear physics

Constants $\alpha, m_e/m_N, \cdots$ from e.g. Penning traps, atom interferometry

Two constants left for us:

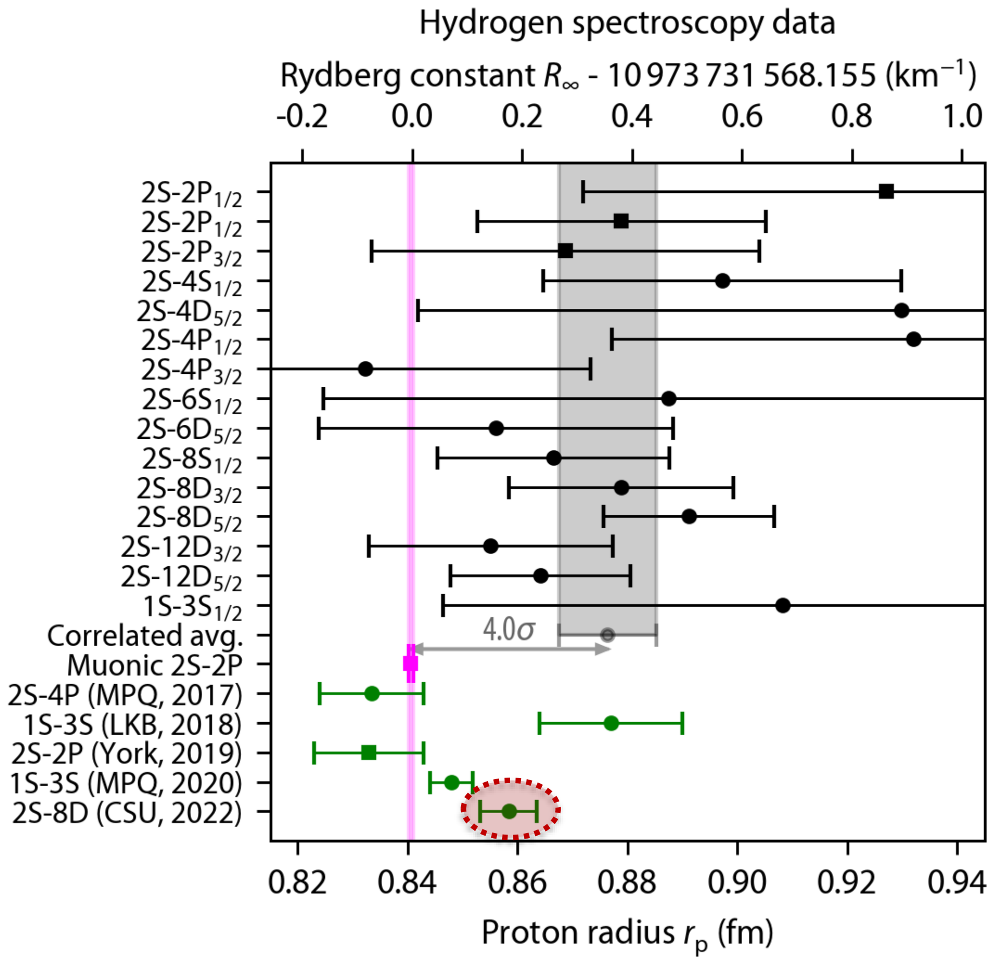
Rydberg constant R_∞ and RMS charge radius r_N^2

➔ need **at least 2 measurements**, more for tests

Measurement 1): e.g. narrow **1S-2S transition** using Doppler-free two-photon spectroscopy in hydrogen [1] and deuterium [2-3]

[1] C. G. Parthey *et al.*, PRL **107**, 203001 (2011); [2] C. G. Parthey *et al.*, PRL **104**, 233001 (2011); [3] R. Pohl *et al.*, Metrologia **54**, L1 (2017)

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



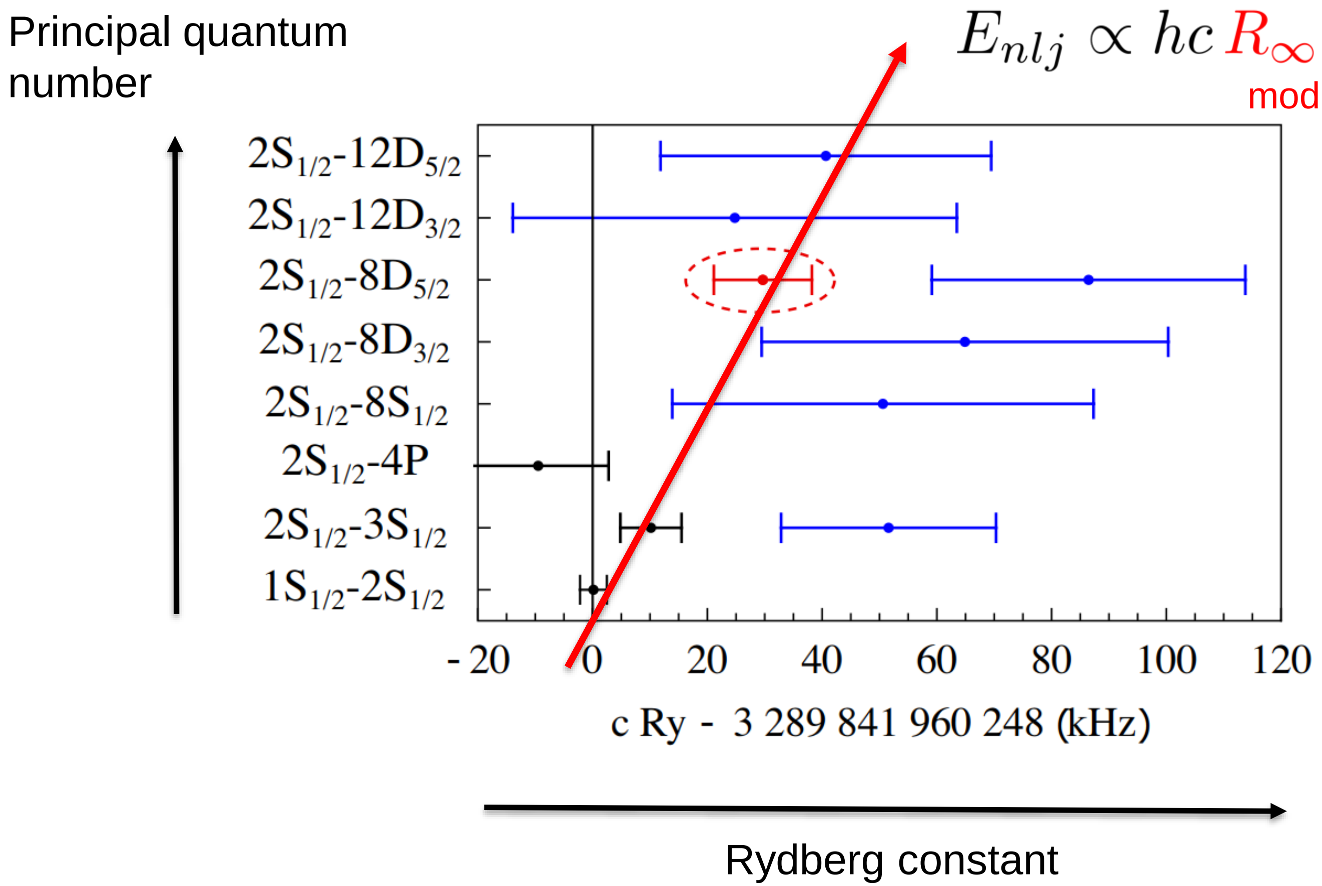
‚New Physics‘?

Speculation about ‘new physics’ in the recent paper of 2S-8D measurement [1]:

$$E_{nlj} \propto hc\, R_\infty(n)$$

modified Coulomb potential:

$$-\frac{\alpha}{r} \rightarrow -\frac{\alpha_{\mathrm{eff}}(r)}{r}$$

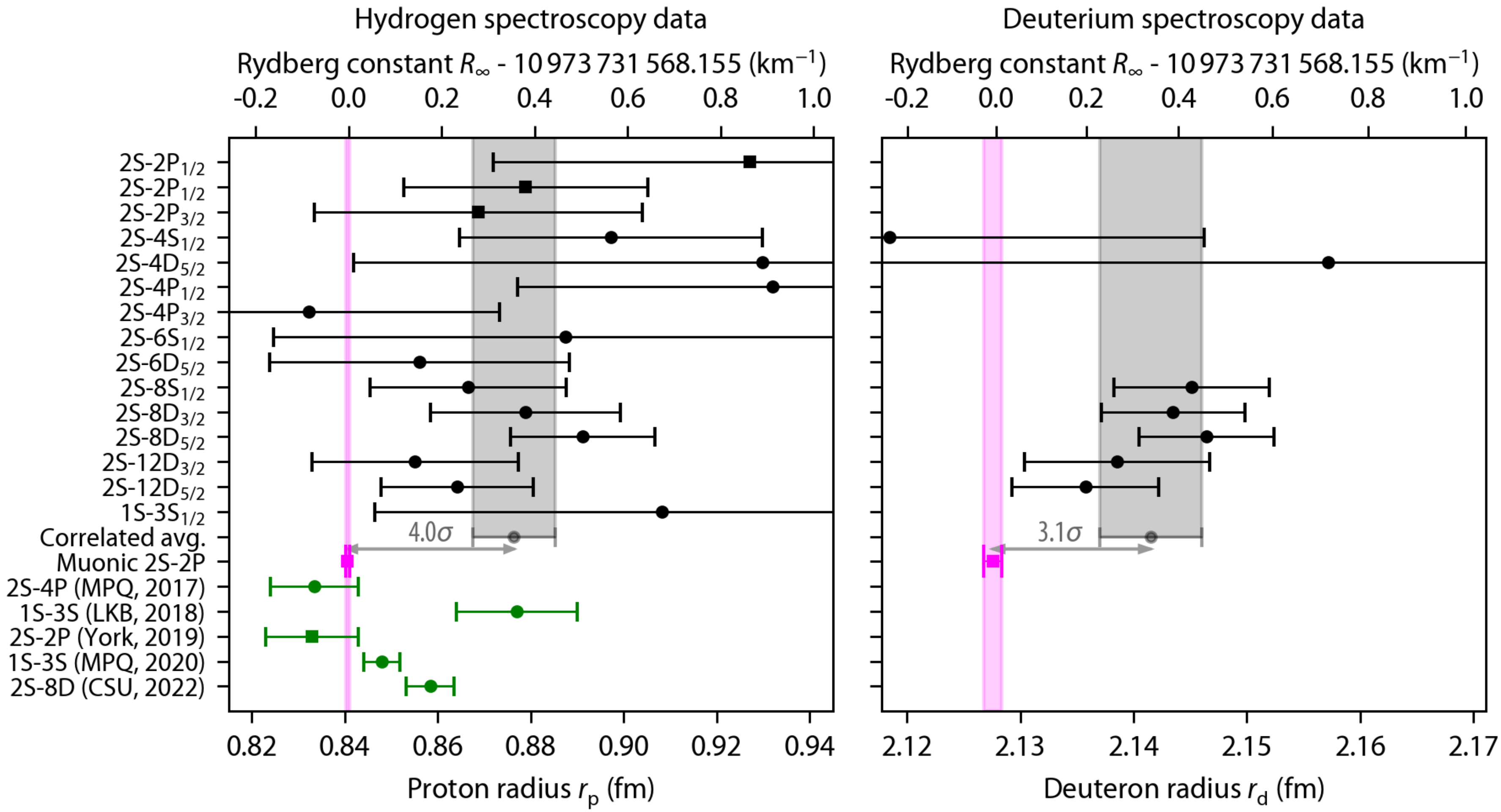


2S-*n*P spectroscopy provides test for *n*-dependent Rydberg constant
(undiscovered bosons can provide additional coupling between nucleus and electron)

[1] A. D. Brandt et al., PRL 128, 023001 (2022)

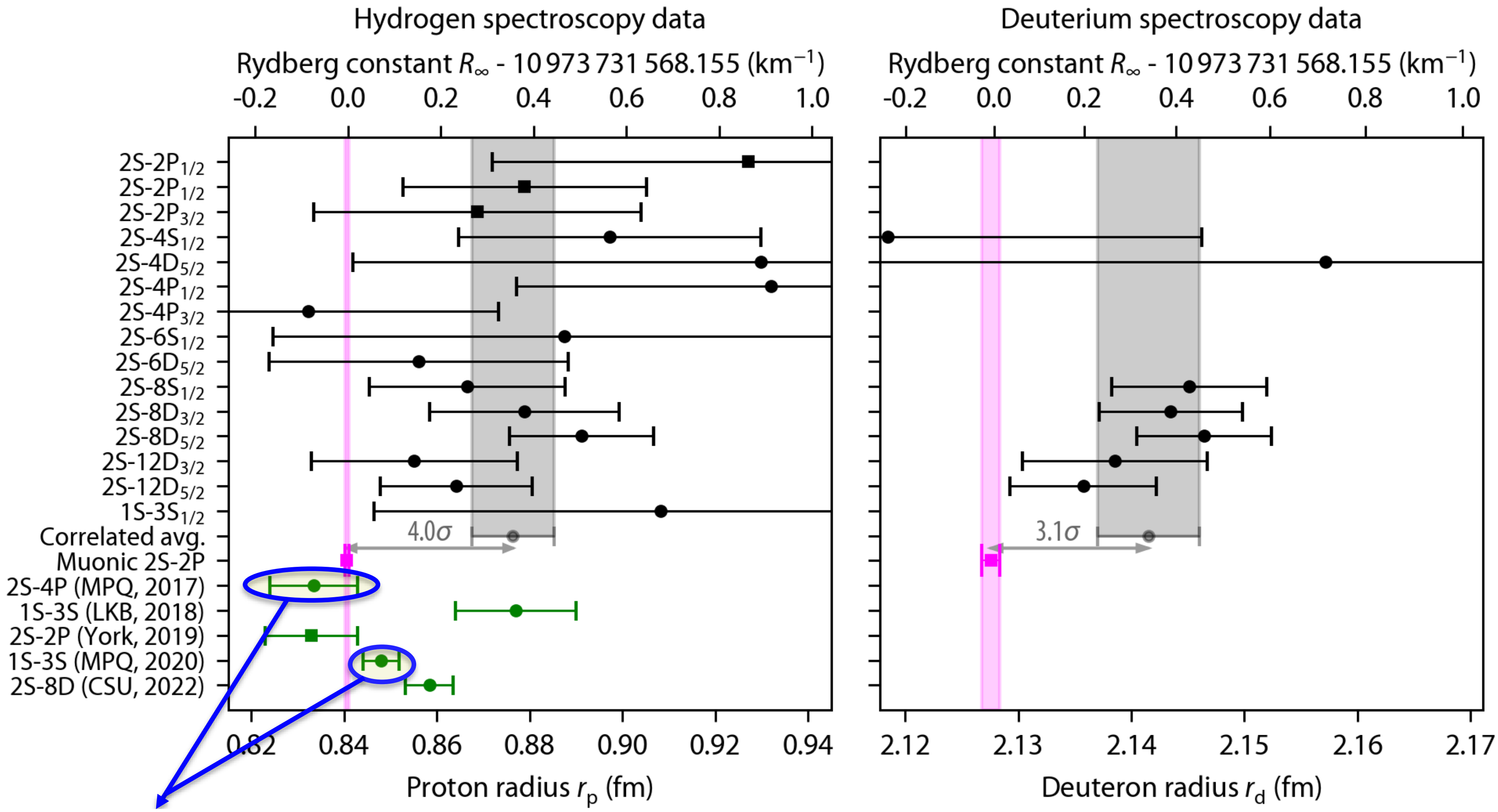
Hydrogen and deuterium spectroscopy data overview

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

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



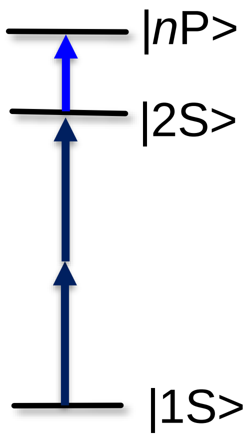
Hydrogen @ MPQ:
2 running experiments + 1 experiment in preparation (see poster by Omer Amit)

Two running hydrogen experiments at MPQ

1S-2S and 2S-*n*P experiment

One-photon
@ 380-486 nm

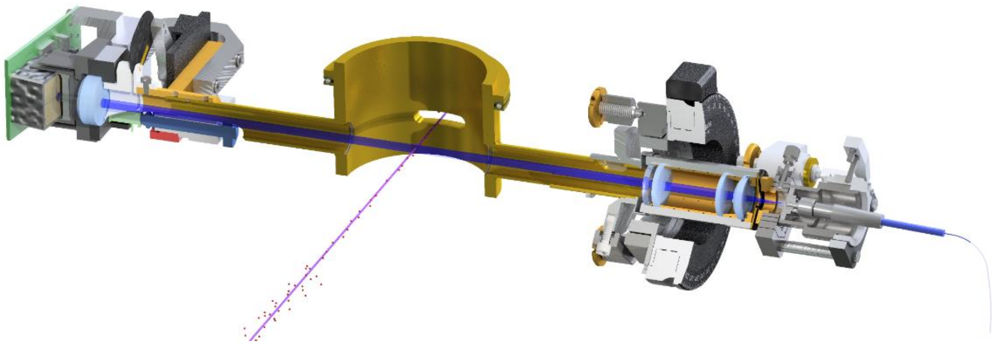
Two-photon
@ 243nm



1S-3S experiment

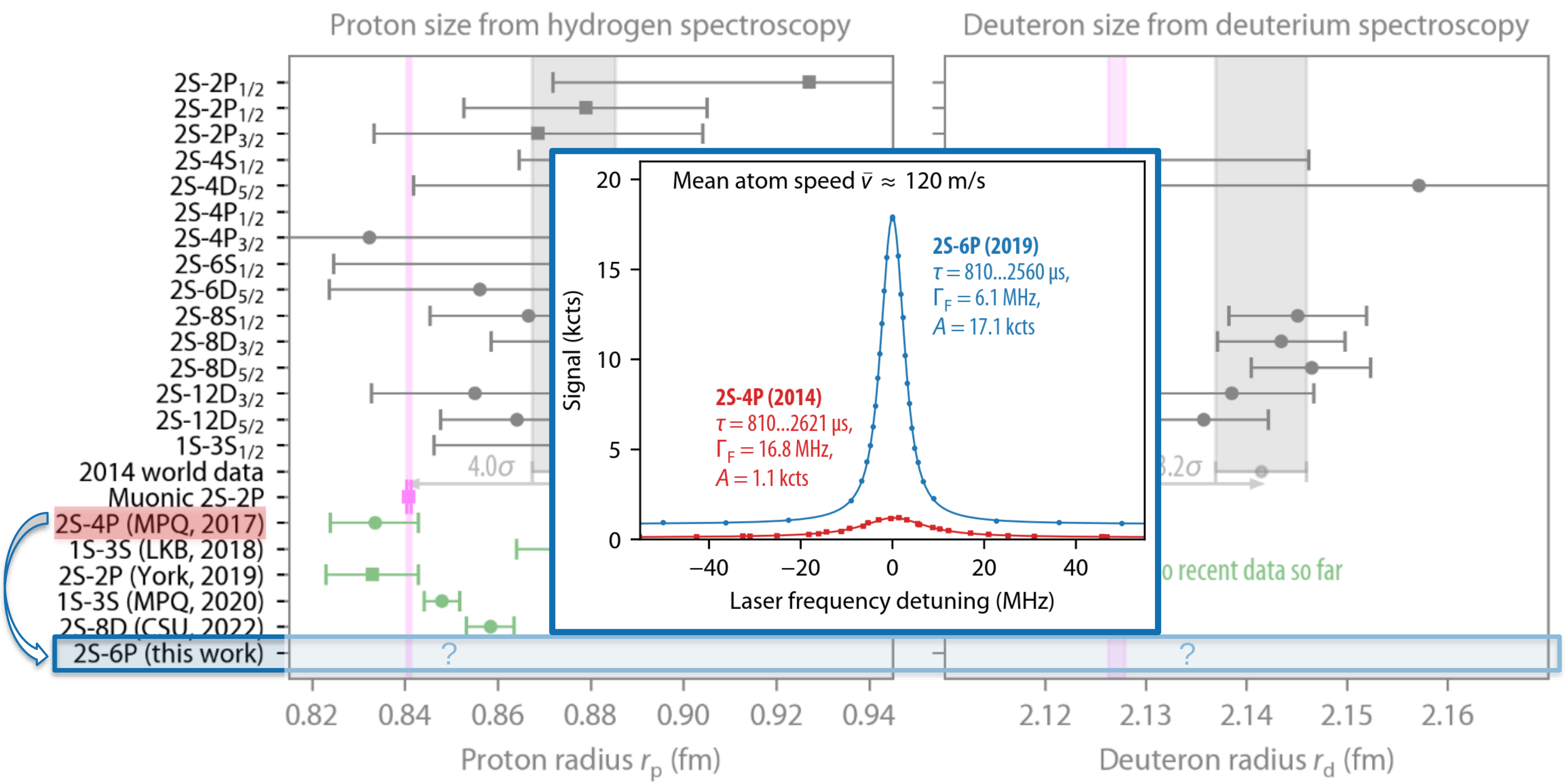
Two-photon
@ 205nm

CW laser spectroscopy



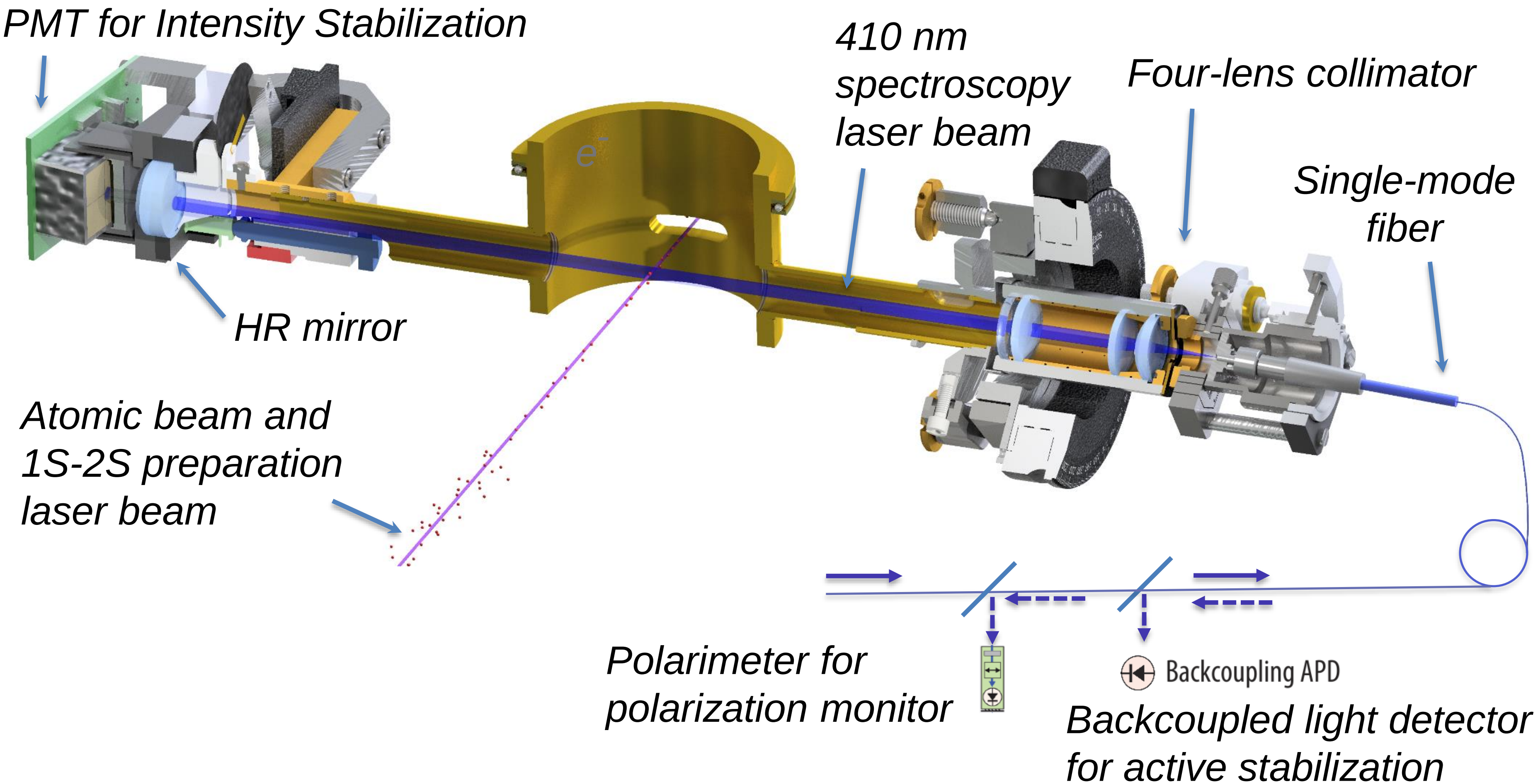
Direct frequency comb spectroscopy

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



This work: 2S-6P transition measurement in hydrogen and deuterium (improves 2S-4P experiment: up to 16x higher signal and 3x lower linewidth)

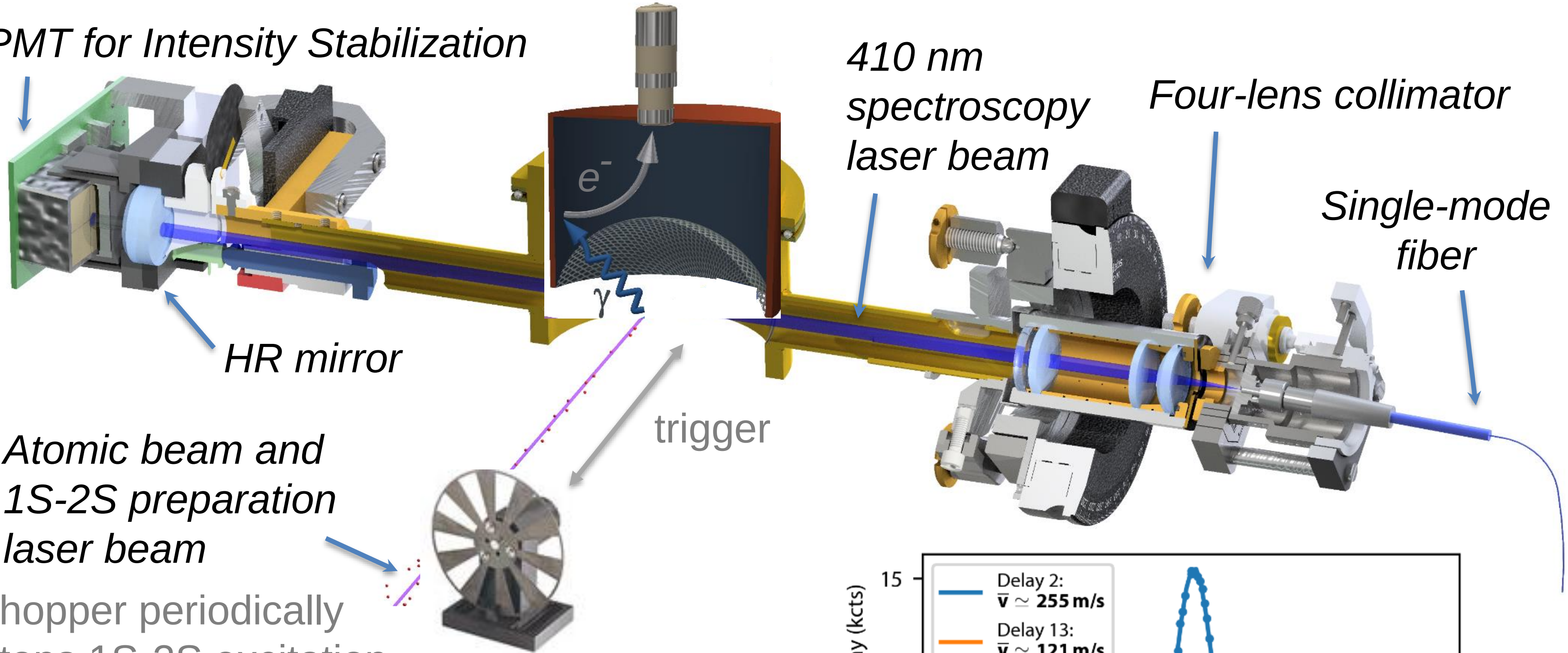
Improved active fiber-based retroreflector for near UV [1] provides high-quality wavefront-retracing anti-parallel laser beams:



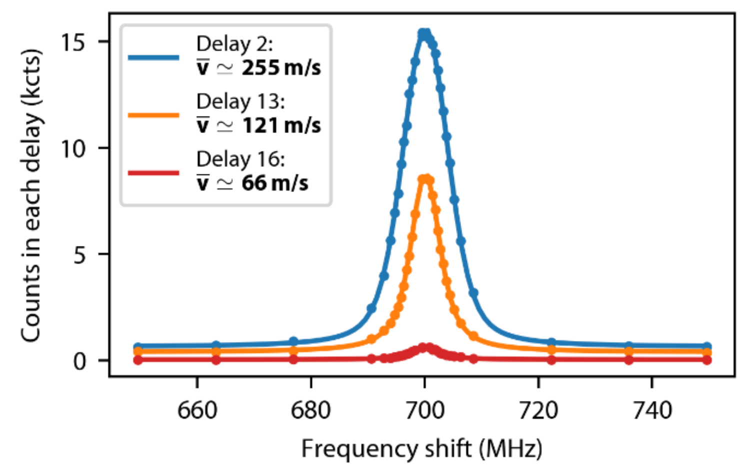
[1] V. Wirthl *et al.*, *Opt. Express* 29(5), 7024 (2021)

First-order Doppler shift suppression

Improved active fiber-based retroreflector for near UV [1] provides high-quality wavefront-retracing anti-parallel laser beams:



Time-resolved detection allows to access different velocity groups of atoms to **study velocity-dependent effects**



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

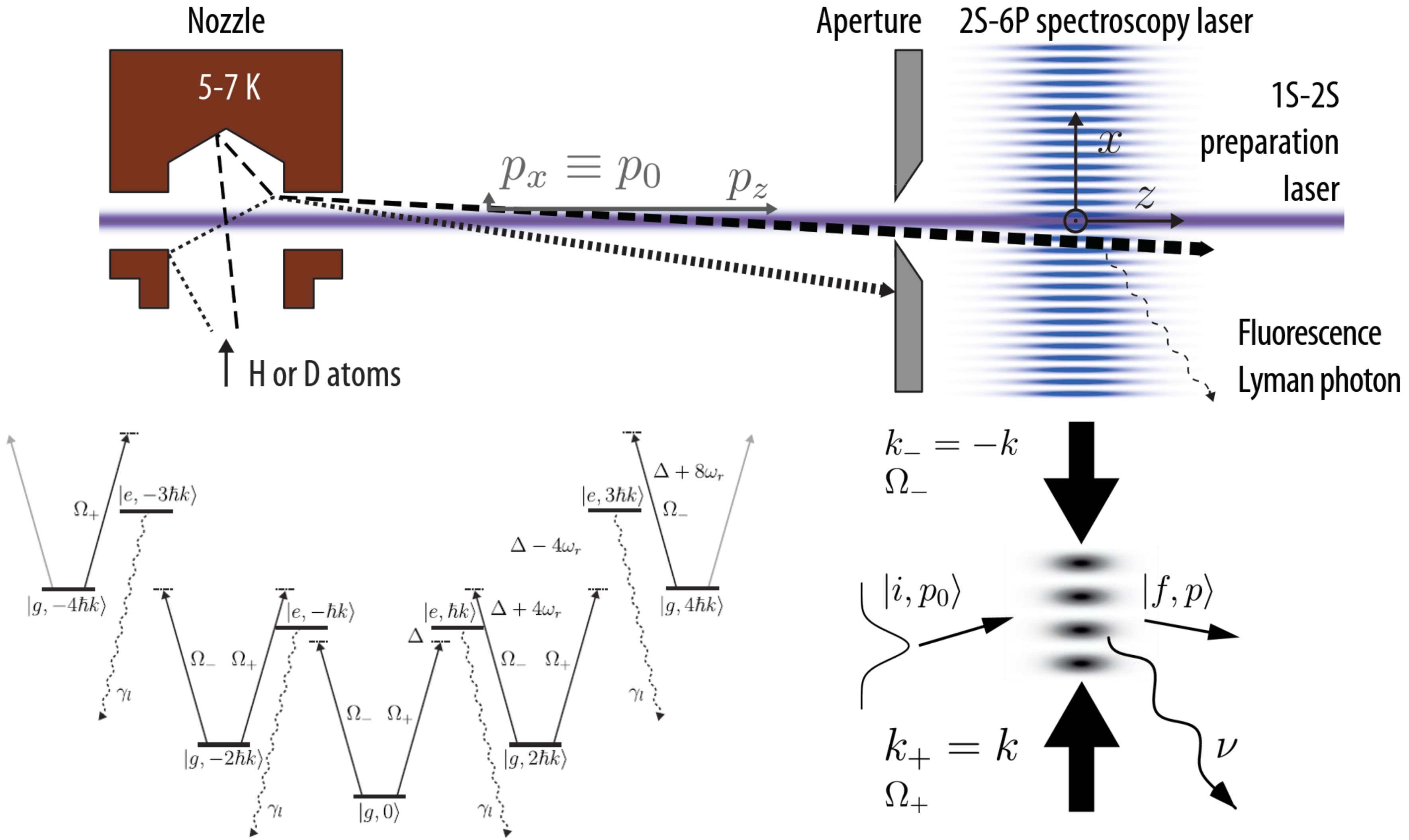
Preliminary uncertainty of hydrogen 2S-6P measurement

Table 2.3: List of corrections $\Delta\nu$ and uncertainties σ for the determination of the 2S-6P$_{1/2}$ ($\nu_{1/2}$) and the 2S-6P$_{3/2}$ ($\nu_{3/2}$) transition frequencies, as well as of the the 2S-6P fine-structure centroid $\nu_{2S\text{-}6P}$, formed by combining $\nu_{1/2}$ and $\nu_{3/2}$. All values are given in units of kHz. BBR: blackbody radiation, HFS: hyperfine structure, FS: fine structure.

	$2S_{1/2}^{F=0}-6P_{1/2}^{F=1}$ ($\nu_{1/2}$)		$2S_{1/2}^{F=0}-6P_{3/2}^{F=1}$ ($\nu_{3/2}$)		2S-6P FS centroid ($\nu_{2S\text{-}6P}$)	
Contribution (kHz)	$\Delta\nu$	σ	$\Delta\nu$	σ	$\Delta\nu$	σ
Statistics (incl. Doppler shift)	—	0.49	—	0.60	—	0.43
Light force shift	0.70	0.21	1.31	0.39	1.11	0.33
				0.29	0.05	0.05
				0.02	-0.14	0.02
dc-Stark shift	0.20	0.20	0.05	0.05	0.10	0.10
BBR-induced shift	0.29	0.03	0.29	0.03	0.29	0.03
Zeeman shift	0.00	0.05	0.00	0.23	0.00	0.17
Pressure shift	0.00	0.01	0.00	0.01	0.00	0.01
Frequency standard	0.00	0.07	0.00	0.07	0.00	0.07
Total without recoil & HFS corr.	1.25	0.82	1.49	0.81	1.41	0.58
Recoil shift	-1176.03	0.00	-1176.03	0.00	-1176.03	0.00
Hyperfine structure corrections	—	—	—	—	-132985.252	0.007
Total	-1174.78	0.82	-1174.54	0.81	-134159.872	0.58

Largest systematic effect: light force shift

Light force shift



Atoms delocalized over standing wave (205 nm periodicity) and can be described as plane wave with defined transverse momentum p_0

Preliminary hydrogen 2S-6P measurement result

Table 2.3: List of corrections $\Delta\nu$ and uncertainties σ for the determination of the 2S-6P$_{1/2}$ ($\nu_{1/2}$) and the 2S-6P$_{3/2}$ ($\nu_{3/2}$) transition frequencies, as well as of the the 2S-6P fine-structure centroid $\nu_{\text{2S-6P}}$, formed by combining $\nu_{1/2}$ and $\nu_{3/2}$. All values are given in units of kHz. BBR: blackbody radiation, HFS: hyperfine structure, FS: fine structure.

	$2S_{1/2}^{F=0}-6P_{1/2}^{F=1}$ ($\nu_{1/2}$)		$2S_{1/2}^{F=0}-6P_{3/2}^{F=1}$ ($\nu_{3/2}$)		2S-6P FS centroid ($\nu_{\text{2S-6P}}$)	
Contribution (kHz)	$\Delta\nu$	σ	$\Delta\nu$	σ	$\Delta\nu$	σ
Statistics (incl. Doppler shift)	—	0.49	—	0.60	—	0.43
Light force shift	0.70	0.21	1.31	0.39	1.11	0.33
Quantum interference shifts	0.21	0.58	-0.02	0.29	0.05	0.05
Second-order Doppler shift	-0.15	0.02	-0.14	0.02	-0.14	0.02
dc-Stark shift	0.20	0.20	0.05	0.05	0.10	0.10
BBR-in					0.29	0.03
Zeeman					0.00	0.17
Pressur					0.00	0.01
Frequen					0.00	0.07
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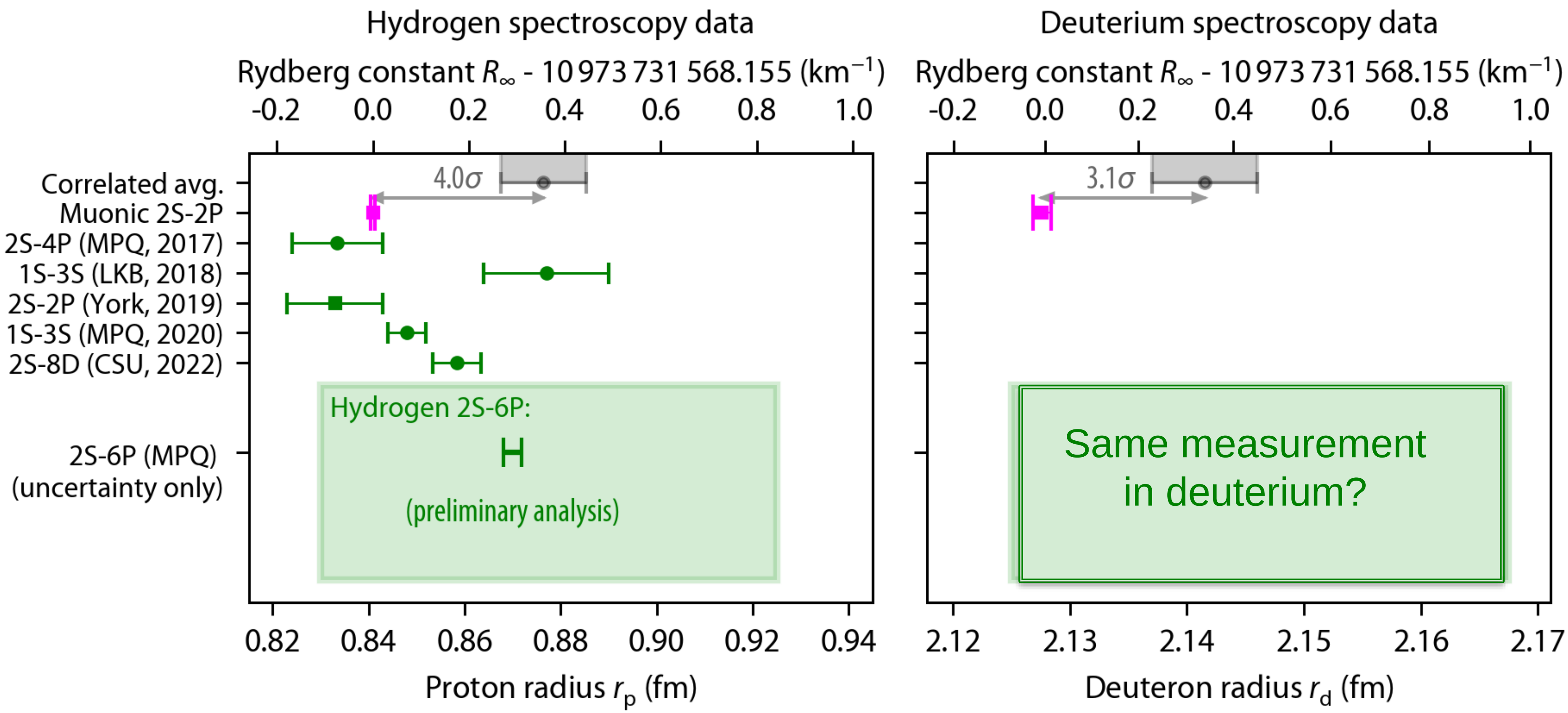
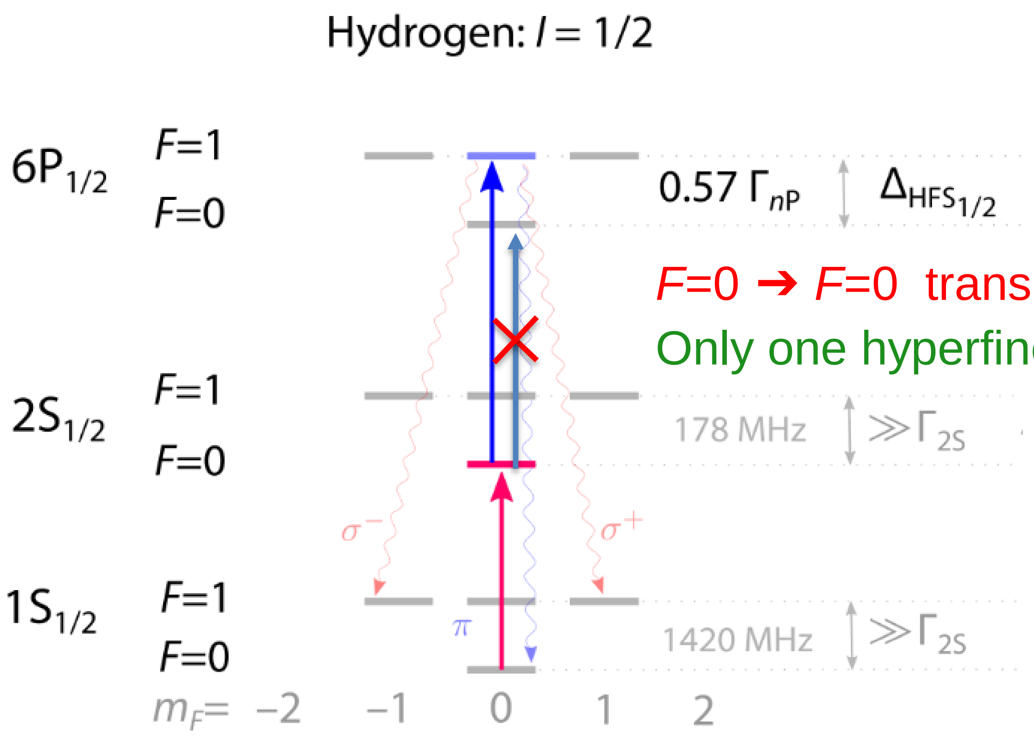
Preliminary Hydrogen 2S-6P uncertainty:
0.6 kHz with only 1.4 kHz corrections

Preliminary hydrogen 2S-6P measurement result

Data analysis of our hydrogen 2S-6P measurement campaign currently ongoing (with blind offset), preliminary uncertainty result:

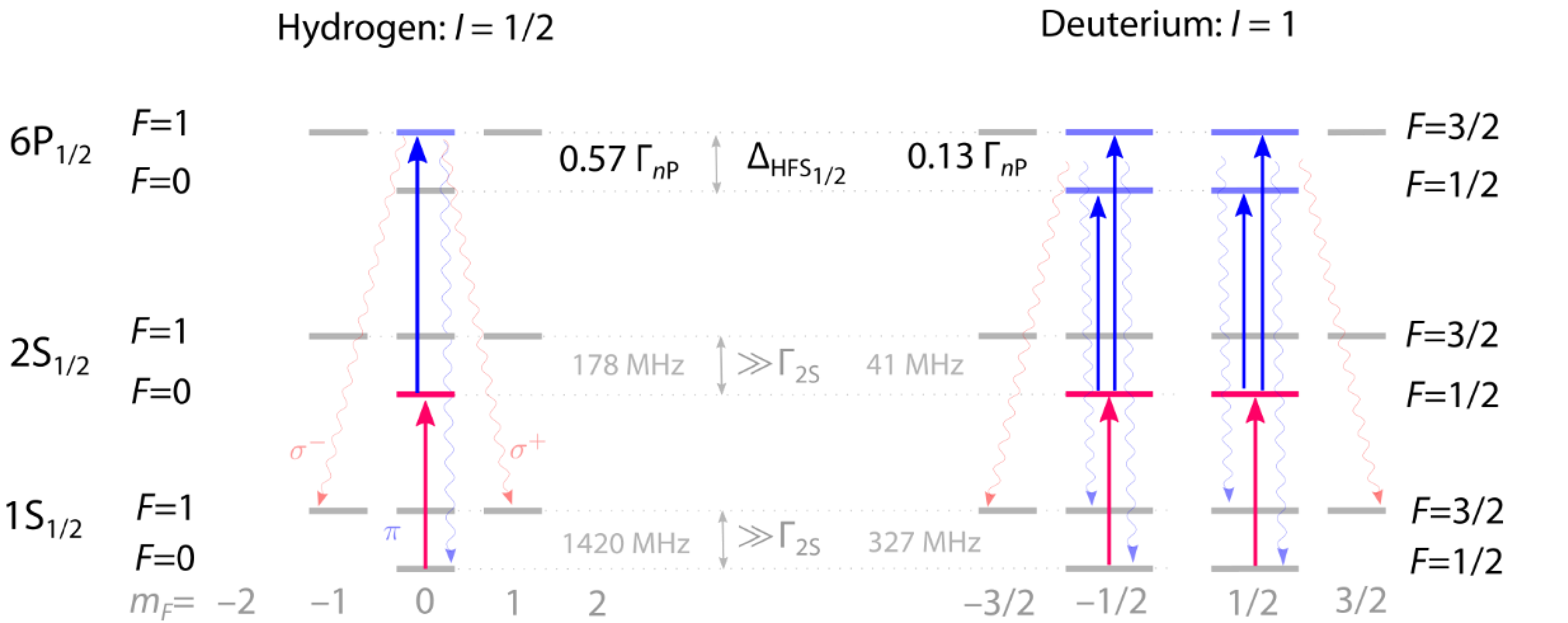




F=0 ➔ *F*=0 transitions forbidden

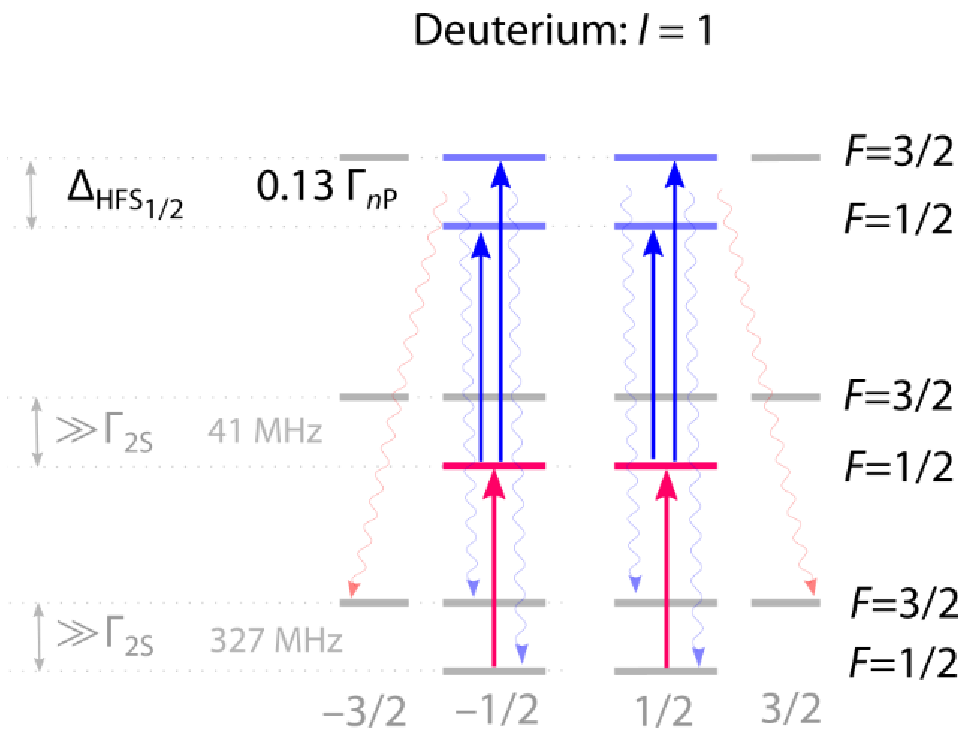
Only one hyperfine manifold excited

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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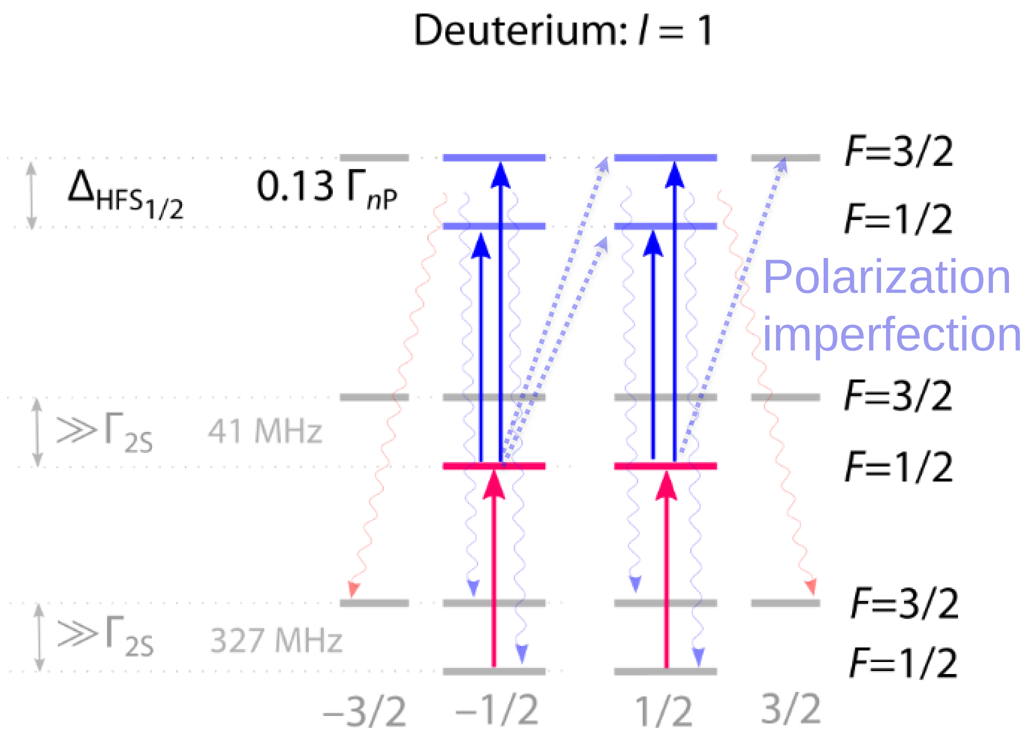
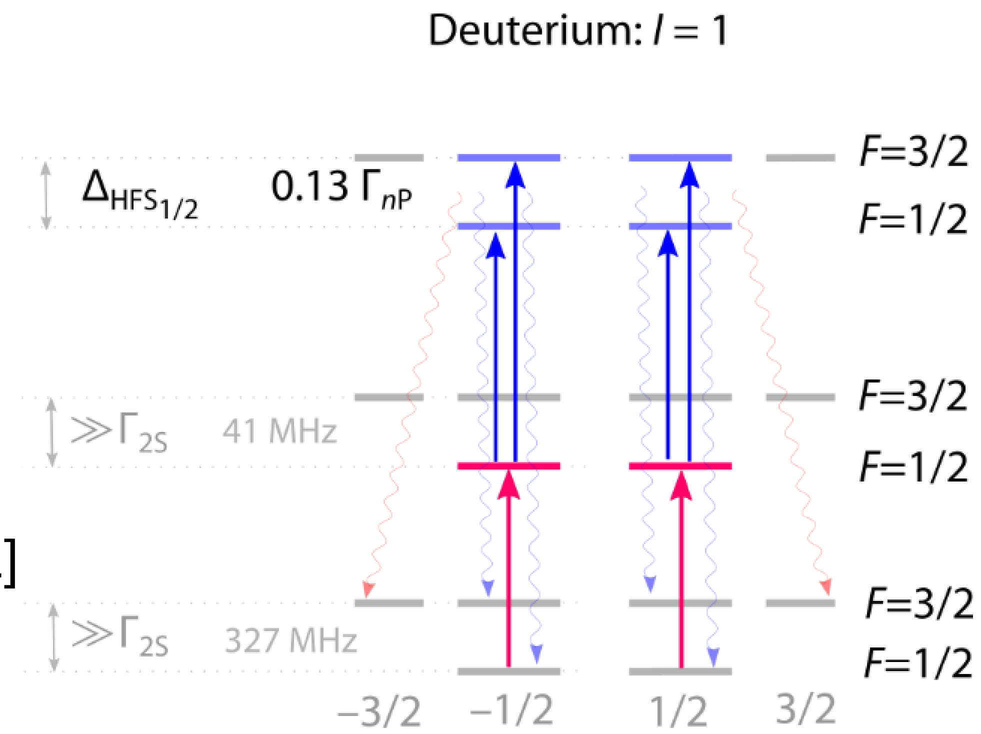


Residual circular polarization changes the dipole ratio of excited hyperfine state manifolds

Additionally allowed transitions compared to hydrogen require to consider:

1) simultaneous excitation of different hyperfine levels

2) quantum interference between unresolved hyperfine transitions [1]



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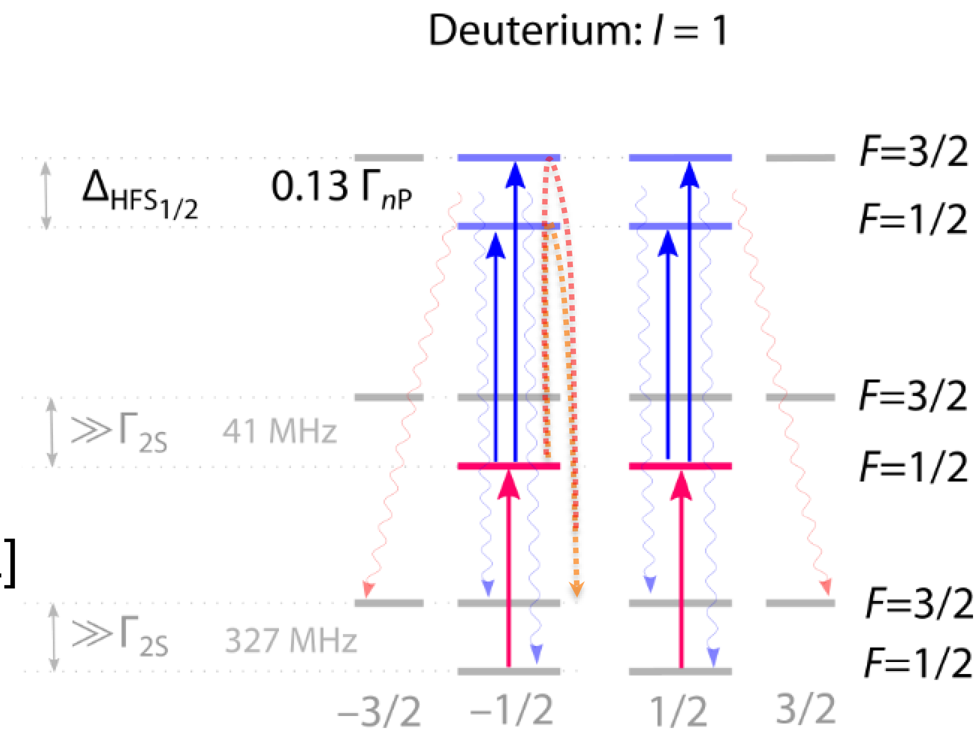


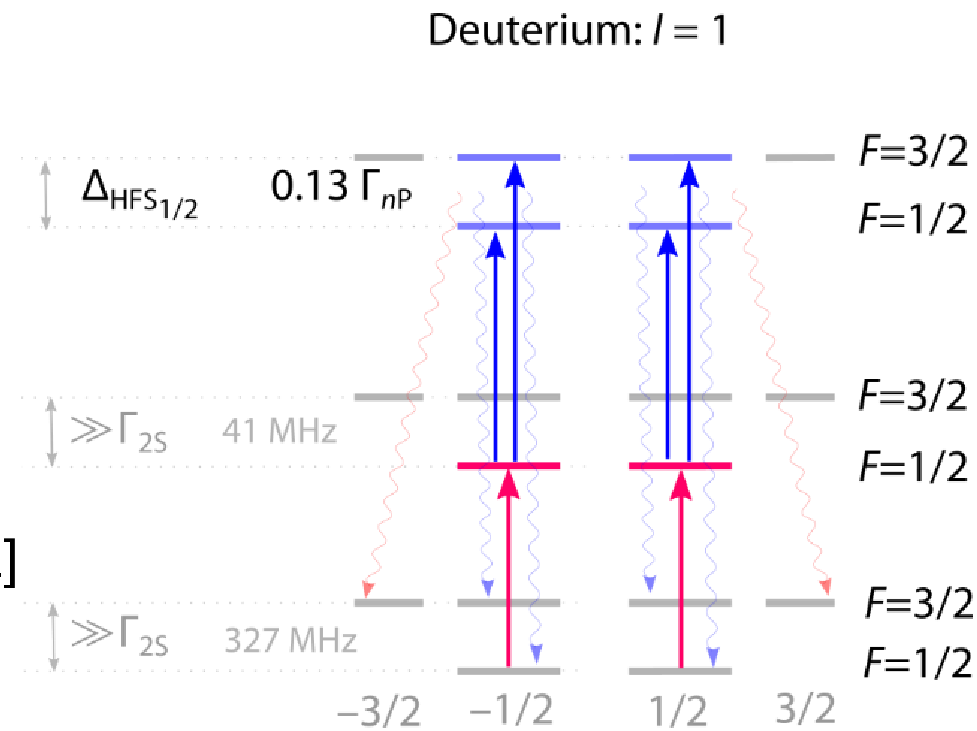
Possible quantum interference between the different signal paths from the two hyperfine manifolds

2S-6P in deuterium: complications

Additionally allowed transitions compared to hydrogen require to consider:

1) simultaneous excitation of different hyperfine levels

2) quantum interference between unresolved hyperfine transitions [1]

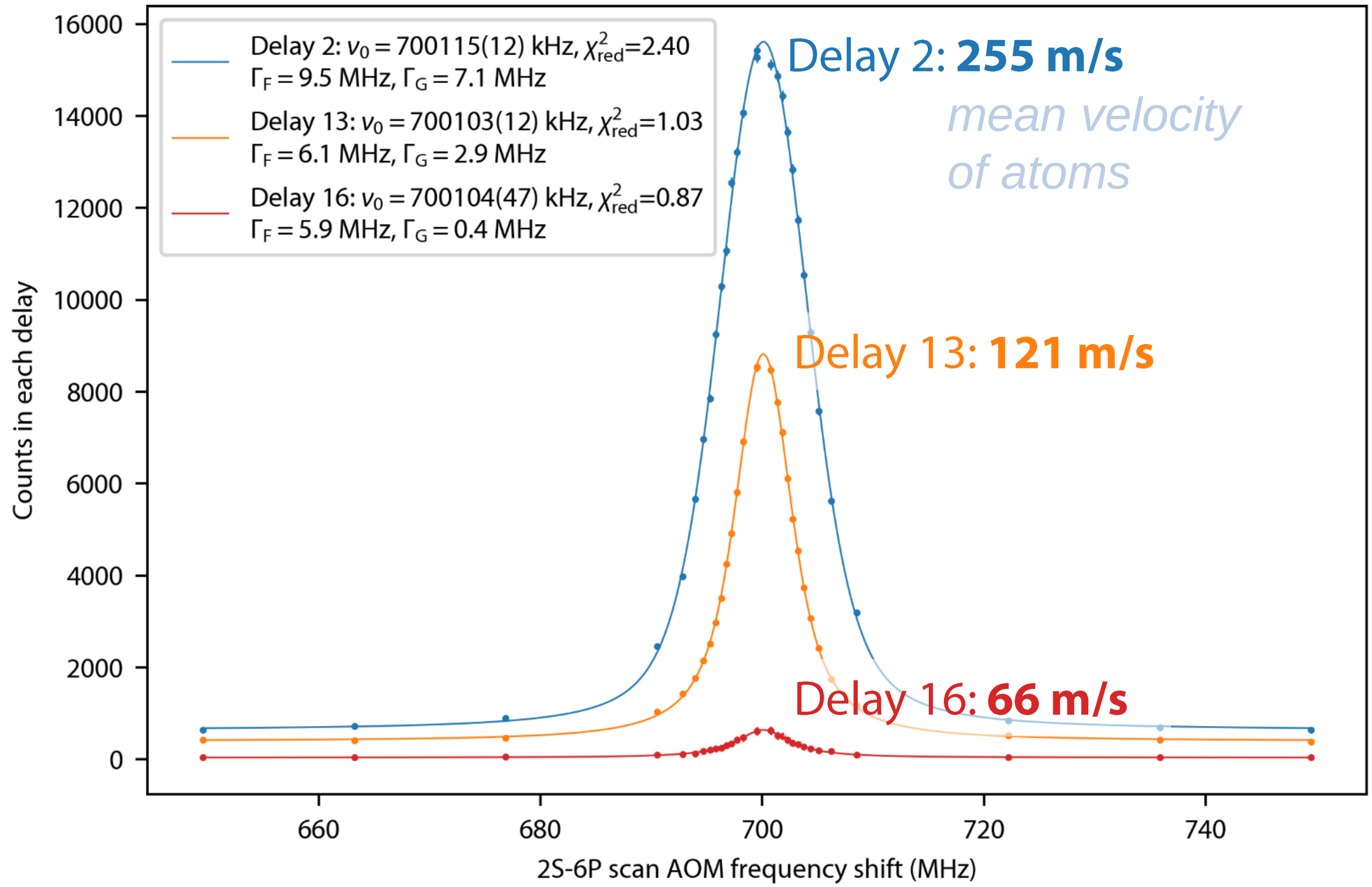


<table>
<tr><th></th><th>Detection different for LH/RH circular pol.</th><th>Initital state population asymmetry</th><th>Residual circular polarization</th></tr>
<tr><td>1) Shift from dipole ratio</td><td></td><td colspan="2">x</td></tr>
<tr><td>2) Unresolved Q.I.</td><td colspan="2">x</td><td></td></tr>
</table>

We find that both effects from additional transitions in deuterium **doubly suppressed**

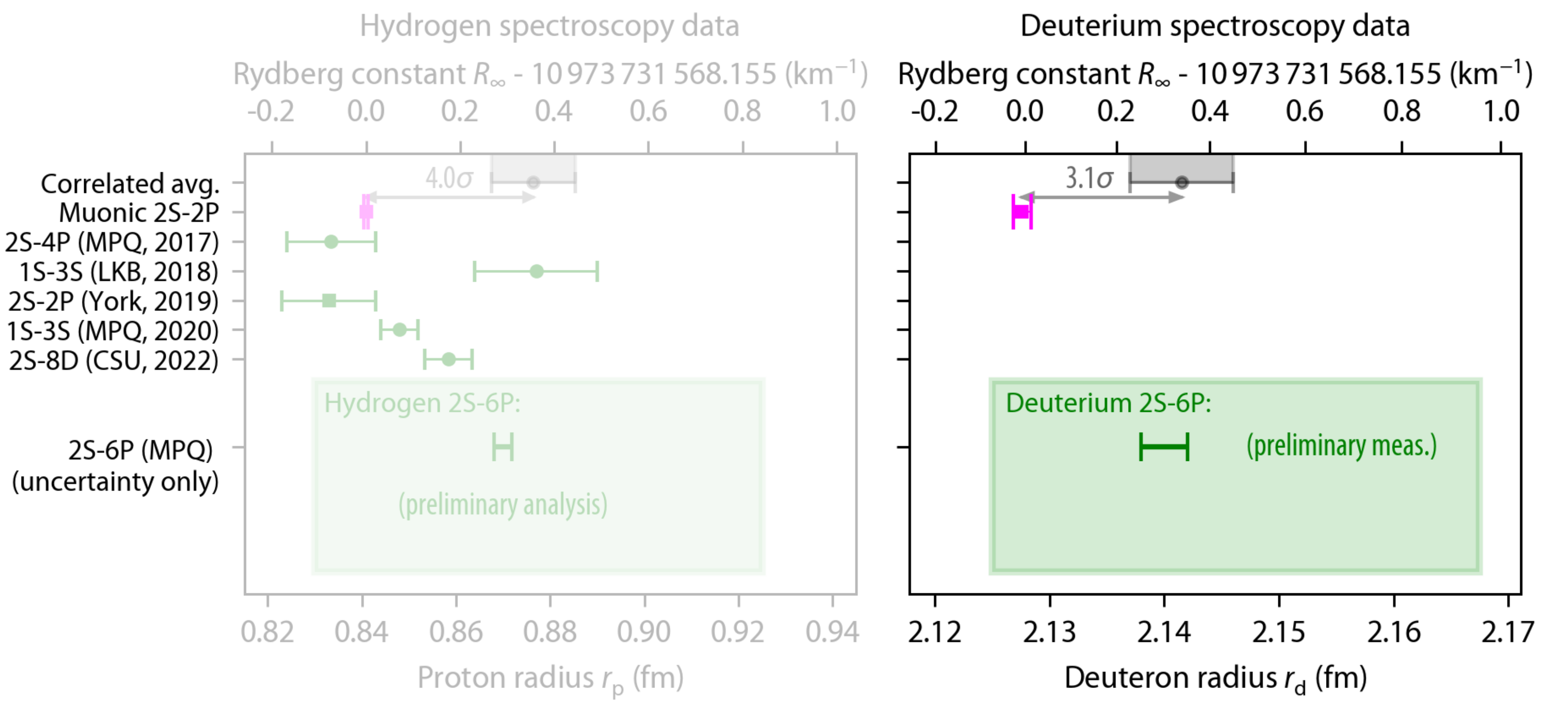
[1] Th. Udem *et al.*, *Ann. Phys. 531*(5), 1900044 (2019)

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

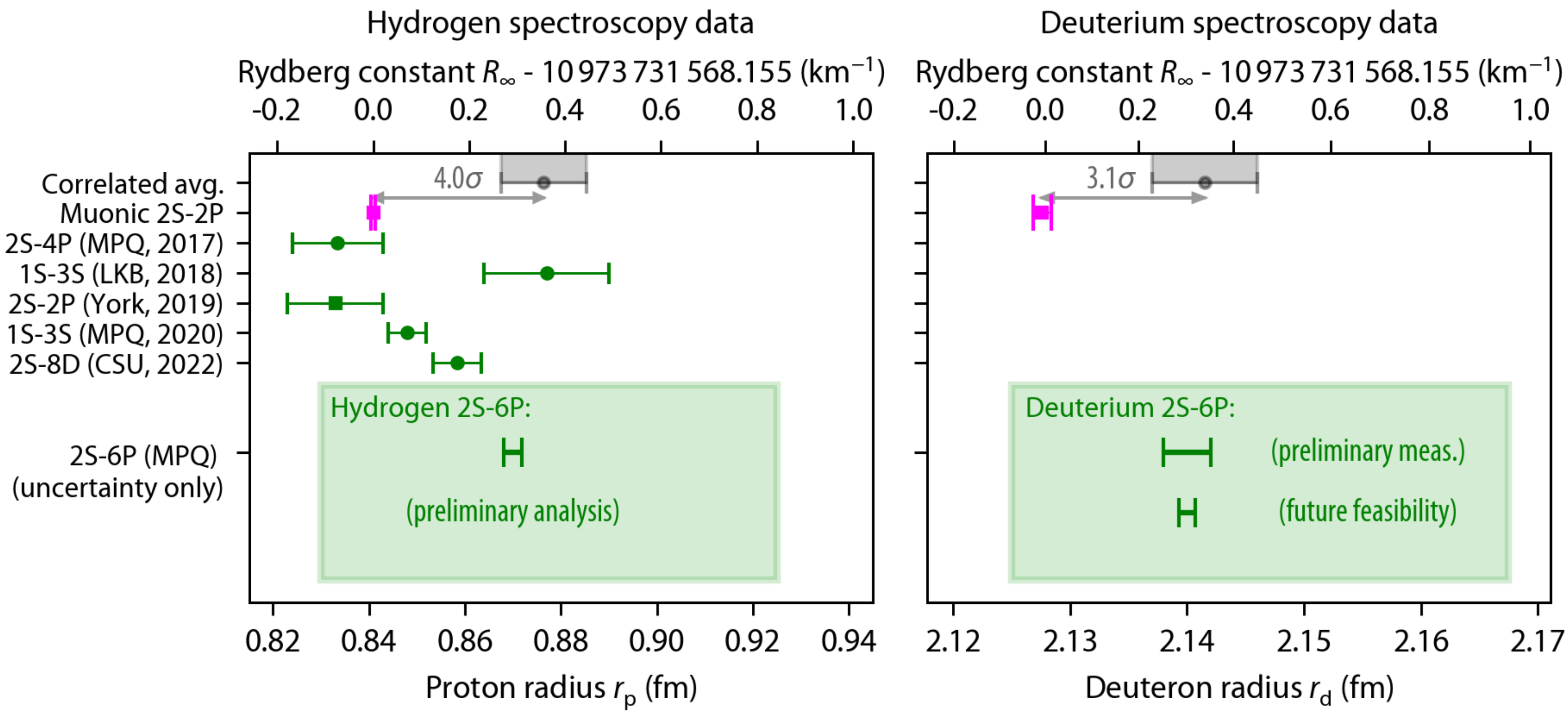


Preliminary measurement: ~ 300 deuterium 2S-6P precision line scans

Preliminary deuterium 2S-6P measurement campaign result:



Preliminary deuterium 2S-6P measurement campaign result:

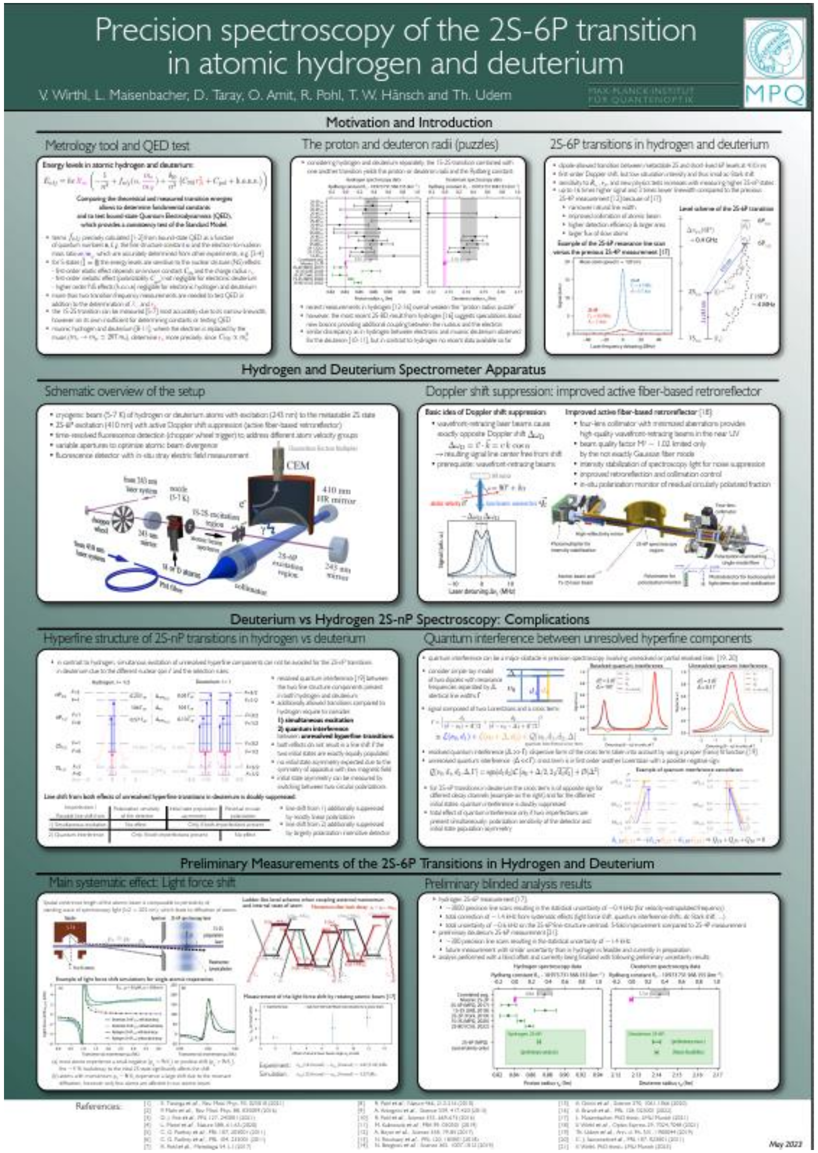


Deuterium 2S-6P measurement campaign currently in preparation
➔ feasible with a similar precision as in hydrogen

See poster

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

for more details!



Thank you for your attention!

Hydrogen team

Derya Taray

Omer Amit

Vitaly Wirthl

Lothar Maisenbacher (UC Berkeley)

Looking for new PhD students!

Randolf Pohl

Thomas Udem

Theodor W. Hänsch