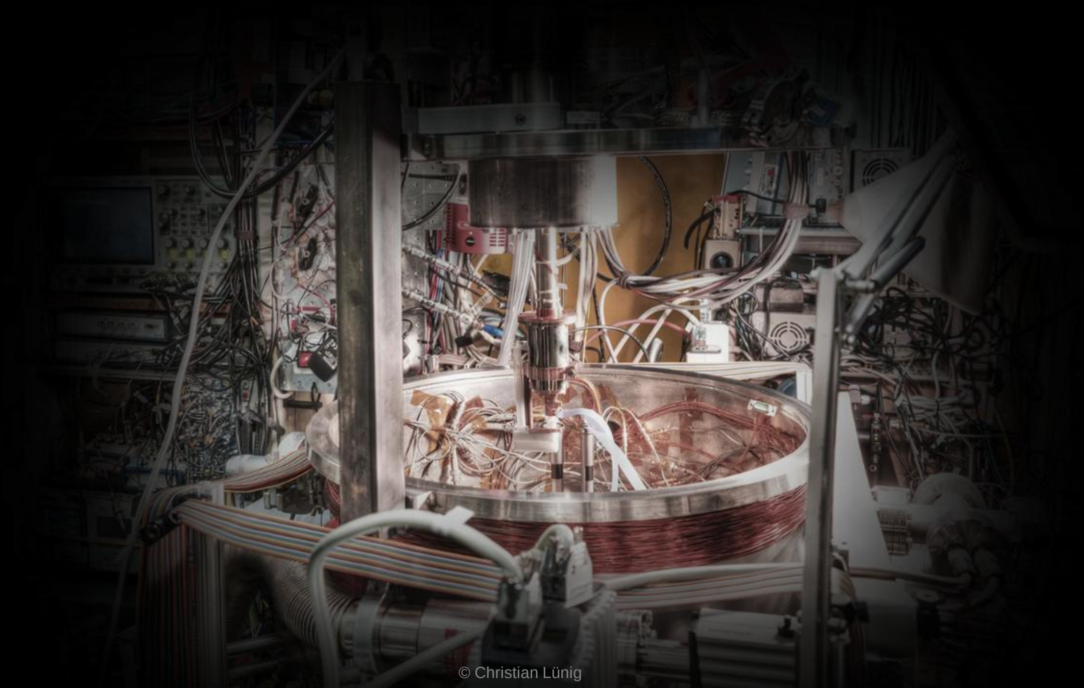
Sub-part-per-trillion test of the Standard Model in atomic hydrogen



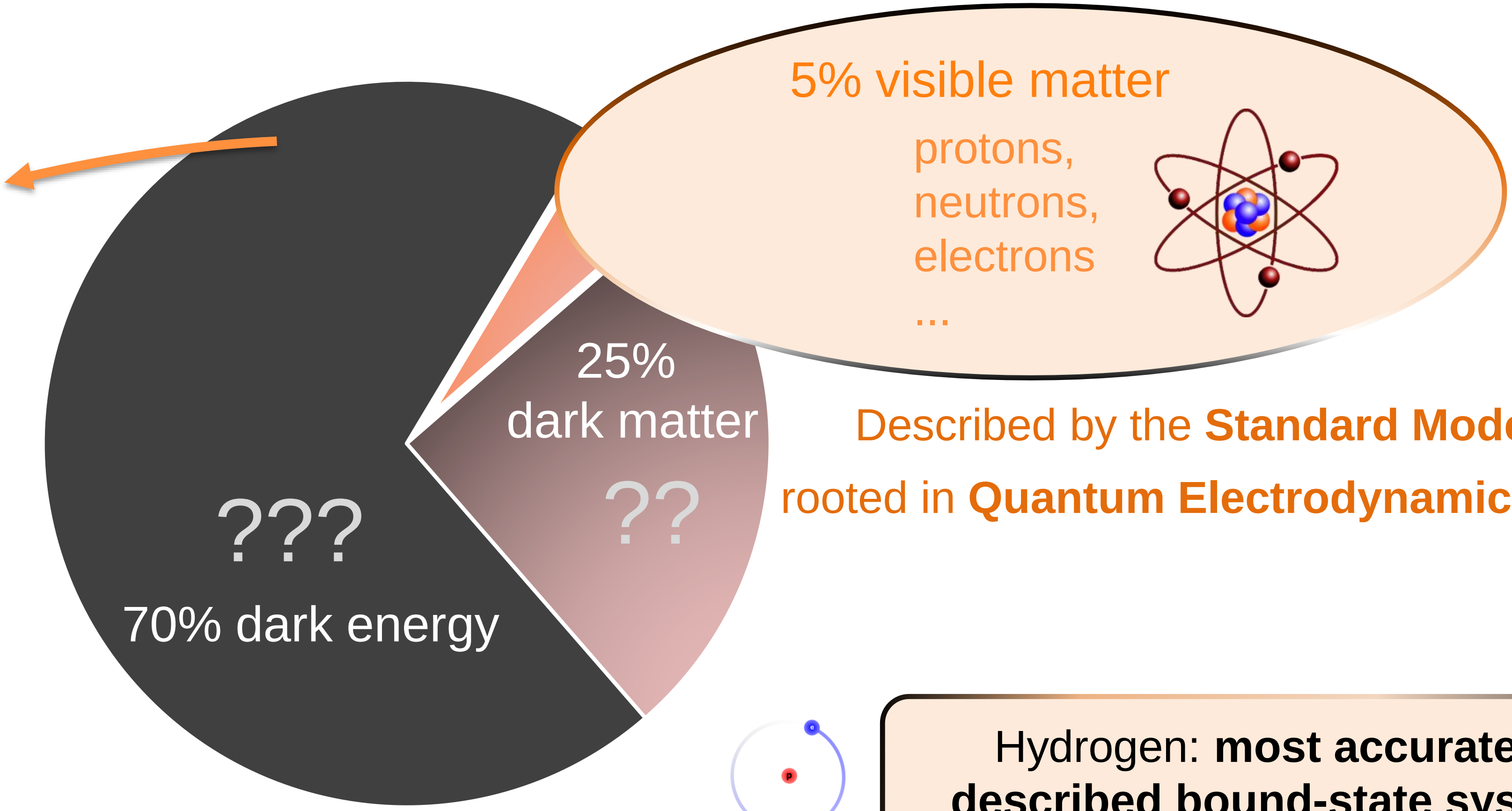
© Christian Lünig

Vitaly Wirthl
L. Maisenbacher, A. Matveev, A. Grinin,
R. Pohl, T. W. Hänsch and Th. Udem
Max Planck Institute of Quantum Optics, Garching, Germany

PSAS Conference Vienna
May 22, 2026

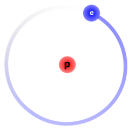
There must be New Physics!

Why no antimatter?



Described by the **Standard Model**

rooted in **Quantum Electrodynamics** (QED)



Hydrogen: **most accurately described bound-state system**

100%

~~95%~~ of energy and matter in our universe are not understood!

→ There must be „New Physics“!

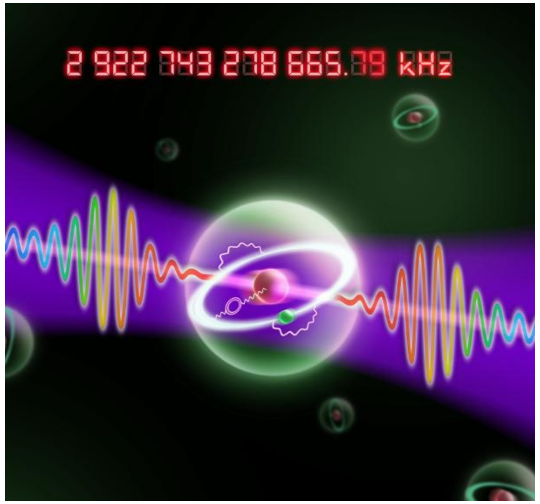
New Physics searches: complementary approaches

High-energy frontier

Direct production
of new particles

e.g. particle accelerators

Precision frontier



Virtual particles: tiny deviations
from theoretical predictions

e.g. precision spectroscopy

Hydrogen spectroscopy can probe
New Physics inaccessible to accelerators

Hydrogen: extraordinary probe of the quantum vacuum

Hydrogen energy levels based on bound-state Quantum Electrodynamics:*

$$E_n = hc R_\infty \left(-\frac{1}{n^2} - \frac{4n-3}{4n^4}\alpha^2 - \frac{2n^3+6n^2-12n+5}{8n^6}\alpha^4 \ldots \right) \frac{1}{1+m_e/m}$$

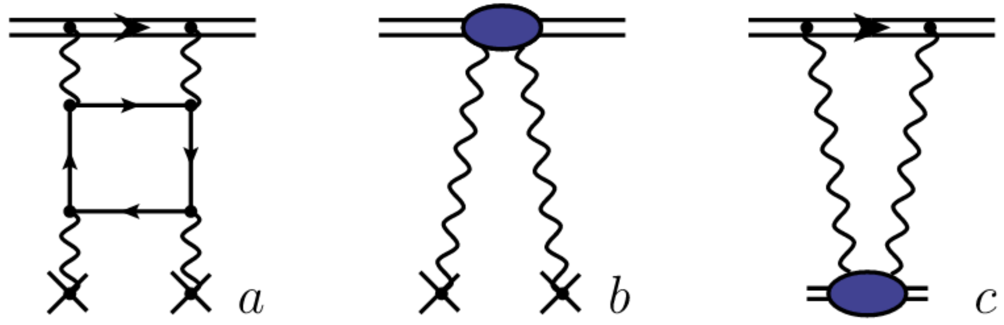
$$2n+29 \, \alpha^6 \ldots \Big) \frac{m_e}{m_p} \frac{1}{(1+m_e/m_p)^3}$$

This is wrong,
should be
709/3456 π^2

Physics Letters B 795 (2019) 432–437

The Lamb shift of the 1*s* state in hydrogen: Two-loop and three-loop contributions

Savely G. Karshenboim[a,b,c], Akira Ozawa[b], Valery A. Shelyuto[d,c], Robert Szafron[e], Vladimir G. Ivanov[c]



publication, the diagrams with the light-by-light (LbL) scattering block (see Fig. 1*a*) have been studied, and a correction to the previous result was found [8] due to the LbL diagrams overlooked in [18,19]. The LbL contributions are the most difficult for the numer-

Corrected (CODATA 2022):

$$-\ln(n) - \ldots + \ldots \Big) \alpha^2 \ln\left(\frac{1+m_e/m_p}{\alpha^2}\right)$$

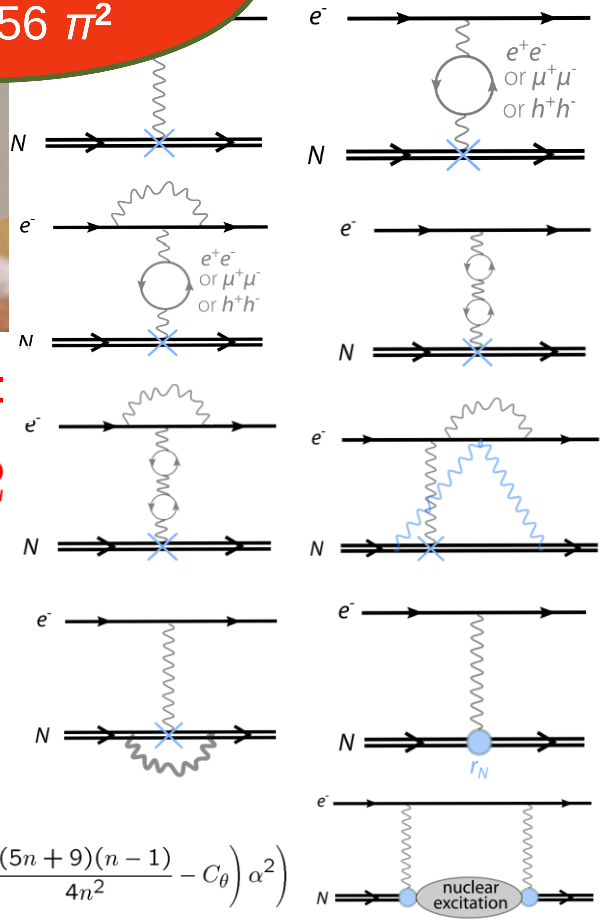
$$\cancel{+\frac{133}{864}\pi \Big) \alpha^2 \ln \Big(} + \frac{709}{3456}\pi^2$$

$$+B_{60} \ldots + \Delta B_{71}\alpha^3 \ln\left(\frac{1+m_e/m_p}{\alpha^2}\right)\Big)\Big)$$

$$+\frac{1591\pi^4}{3240} - \frac{252251\pi^2}{9720} + \frac{679441}{93312}\Big)$$

$$\frac{+m_p/m_e}{\alpha^2}\Big) - \ln k_0(n)\Big) - \frac{140h}{m_e c^2 \alpha^2 n^3}$$

$$C_\theta\Big)\alpha^2\Big) \quad -\left(\ln\left(\frac{1}{1+m_e/m_p}\frac{2\pi m_e c\alpha}{nh}r_p\right) + \Psi(n) - \frac{(5n+9)(n-1)}{4n^2} - C_\theta\right)\alpha^2\Big)$$



*for S-states ($l = 0, j = 1/2$)

Hydrogen: extraordinary probe of the quantum vacuum

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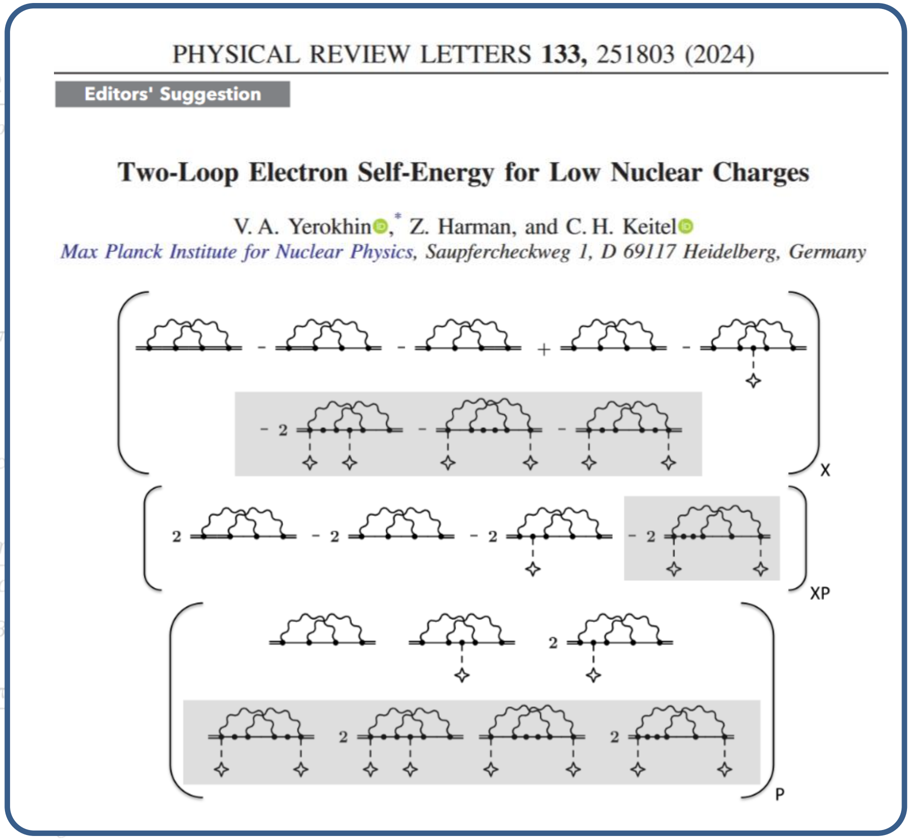


PHYSICAL REVIEW LETTERS **133**, 251803 (2024)

Editors' Suggestion

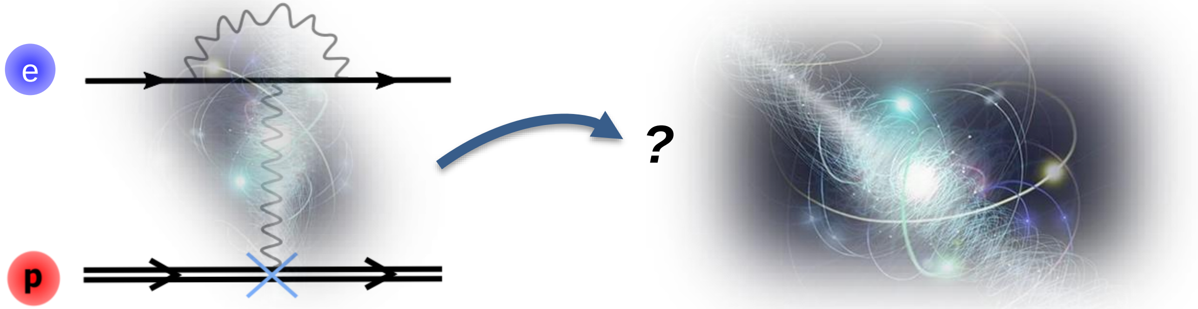
Two-Loop Electron Self-Energy for Low Nuclear Charges

V. A. Yerokhin,* Z. Harman, and C. H. Keitel

Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D 69117 Heidelberg, Germany

Current research: calculation of bound-state QED effects in hydrogen below $\sim 3 \times 10^{-13}$ of transition energies

Hydrogen is an **extraordinary probe** of the **quantum vacuum:** at some level **New Physics could be there**!



*for S-states ($l = 0, j = 1/2$)

Hydrogen spectroscopy: background

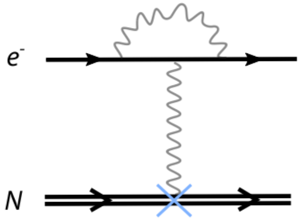
Hydrogen energy levels based on bound-state Quantum Electrodynamics:

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

QED effects with point-like nucleus

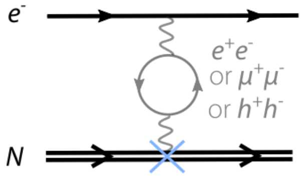
1-loop QED: self-energy

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



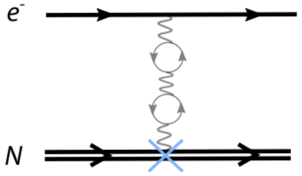
1-loop QED: vac.-pol.

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



2-loop QED: vac.-pol.

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



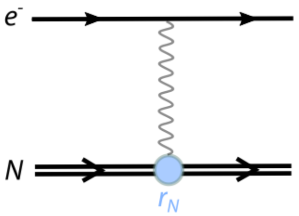
+ other terms

Nuclear effects

1st order elastic effect

finite nuclear size

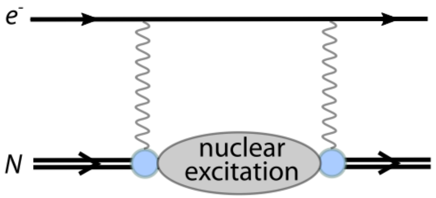
$\propto \alpha^2 \times \alpha^2\, r_N^2$



1st order inelastic

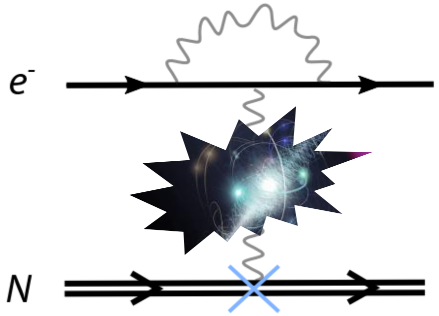
nuclear polarizabiliy

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



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

New physics?



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Rydberg constant

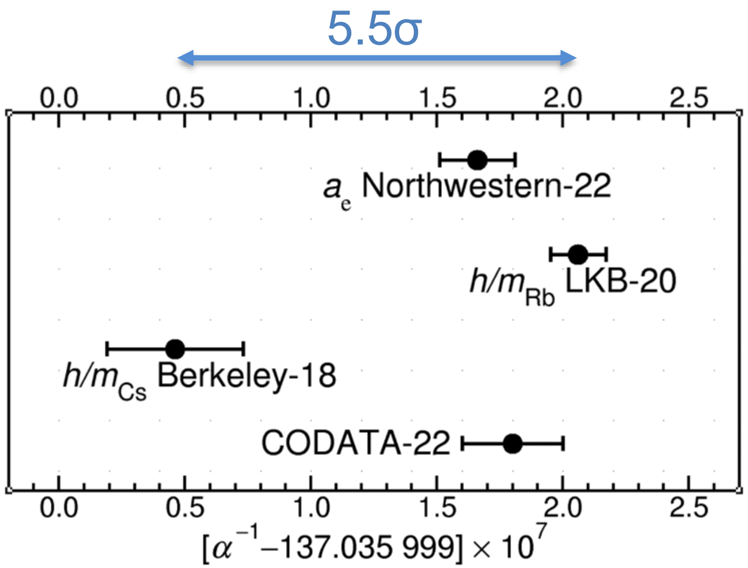
H spectroscopy

Penning traps

Atom interferometer

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

Link to atom interferometry: $R_\infty = \frac{m_e}{m_X}\frac{m_X}{h} c \times \frac{\alpha^2}{2} \Rightarrow \alpha$



P. Mohr et al., Rev. Mod. Phys 97 (2025)

5.5σ discrepancy in α determination between Cs and Rb atom interferometry experiments

Hydrogen spectroscopy not affected by the discrepancy since sensitive to α only in second-order

Hydrogen spectroscopy: background

Hydrogen energy levels based on bound-state Quantum Electrodynamics:

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

Rydberg constant

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

α fine-structure constant

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

…from other precision measurements,
e.g. Penning traps, atom interferometry
state-of-the-art uncertainty not required

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

For spectroscopy 2 theory parameters left for determination:

Rydberg constant R_∞ and RMS charge radius r_N^2

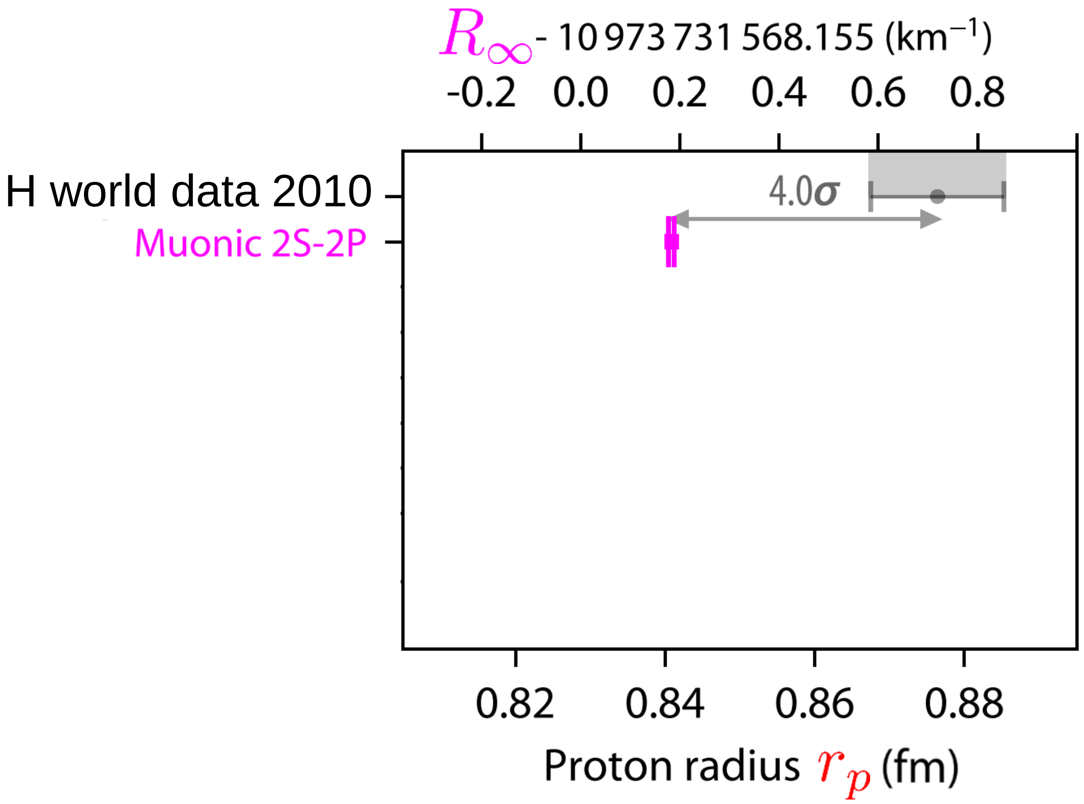
➔ need **at least 3 independent measurements** to test theory

1st measurement: narrow **1S-2S transition** using Doppler-free two-photon spectroscopy [1-3]

[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)

Proton radius puzzle

1S-2S transition measurement in hydrogen combined with 2nd transition measurement:



2010: Proton radius puzzle
muonic hydrogen yields a precise
but discrepant value to previous data

8 July 2010 | www.nature.com/nature | £10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

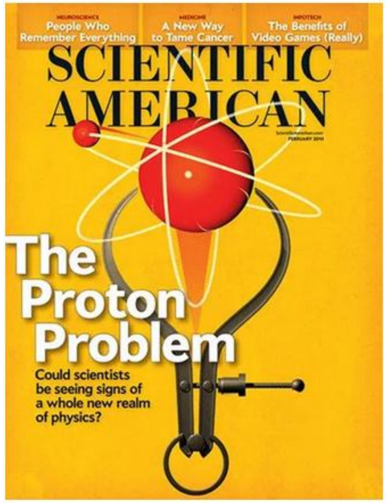
nature

MARINE OIL SPILLS
Get it right next time

BIODIVERSITY AND BUSINESS
The importance of costing the Earth

EARLY EUROPEANS
Venturing north in the early Pleistocene

SHRINKING THE PROTON
New value for charge radius of key subatomic particle



People Who Remember Everything

A New Way to Tame Cancer

The Benefits of Video Games (Really)

SCIENTIFIC AMERICAN

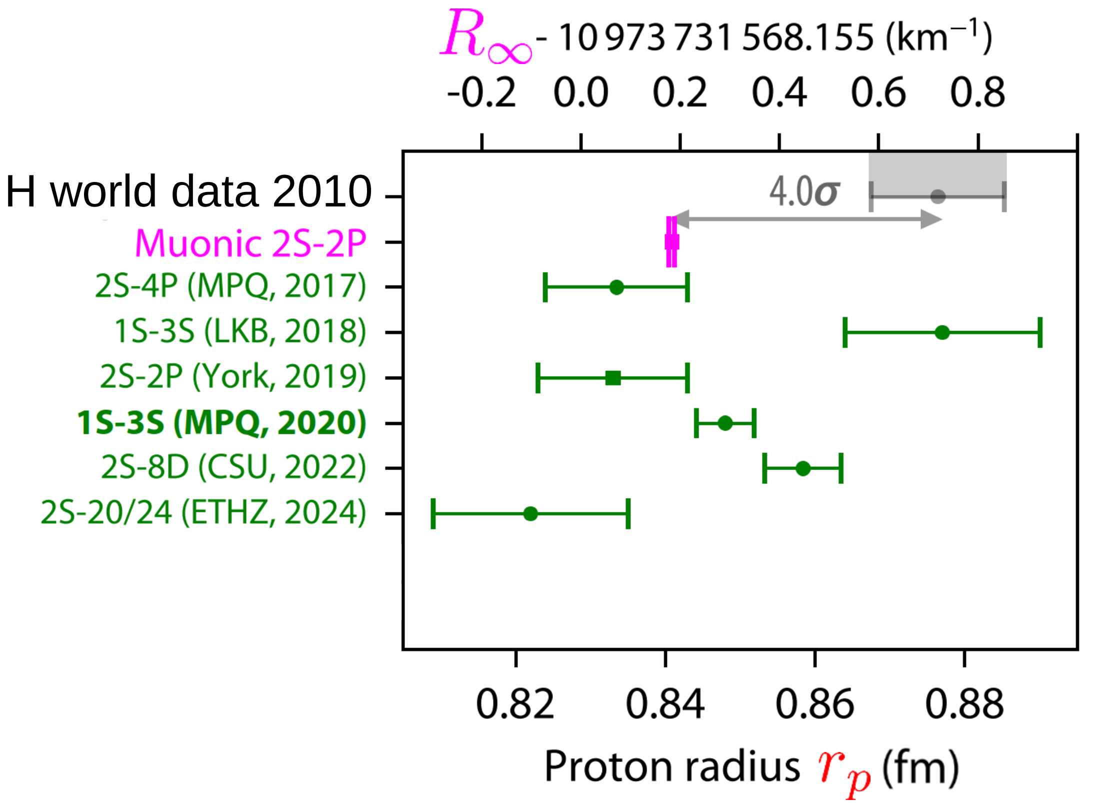
The Proton Problem

Could scientists be seeing signs of a whole new realm of physics?

R. Pohl et. al, Nature 466 (2010)

Proton radius puzzle

1S-2S transition measurement in hydrogen combined with 2nd transition measurement:



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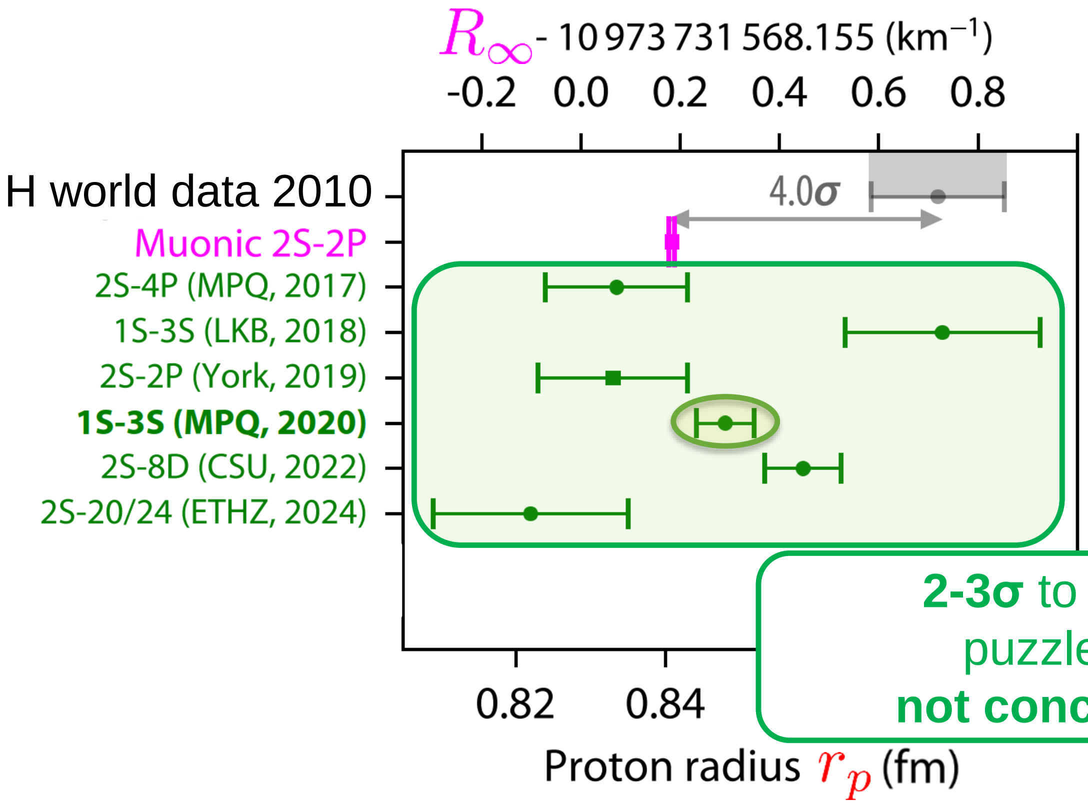
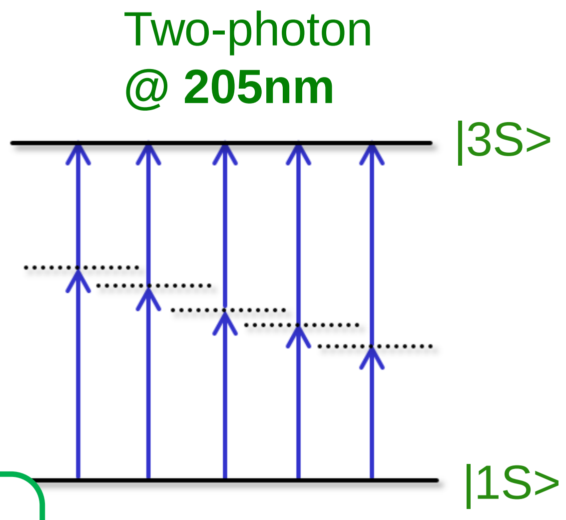


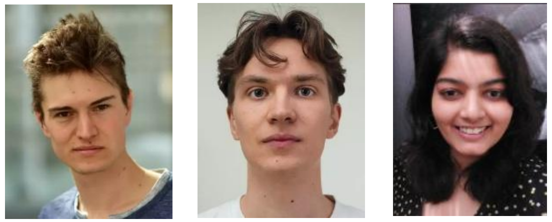
2-3σ to discrepant value:
puzzle weakened but
not conclusively resolved

1S-3S experiment



A. Grinin, et al. Science 370 (2020)

Current work on 1S-3S at MPQ:
Derya Taray, Vincent Weis, Surabhi Deshpande



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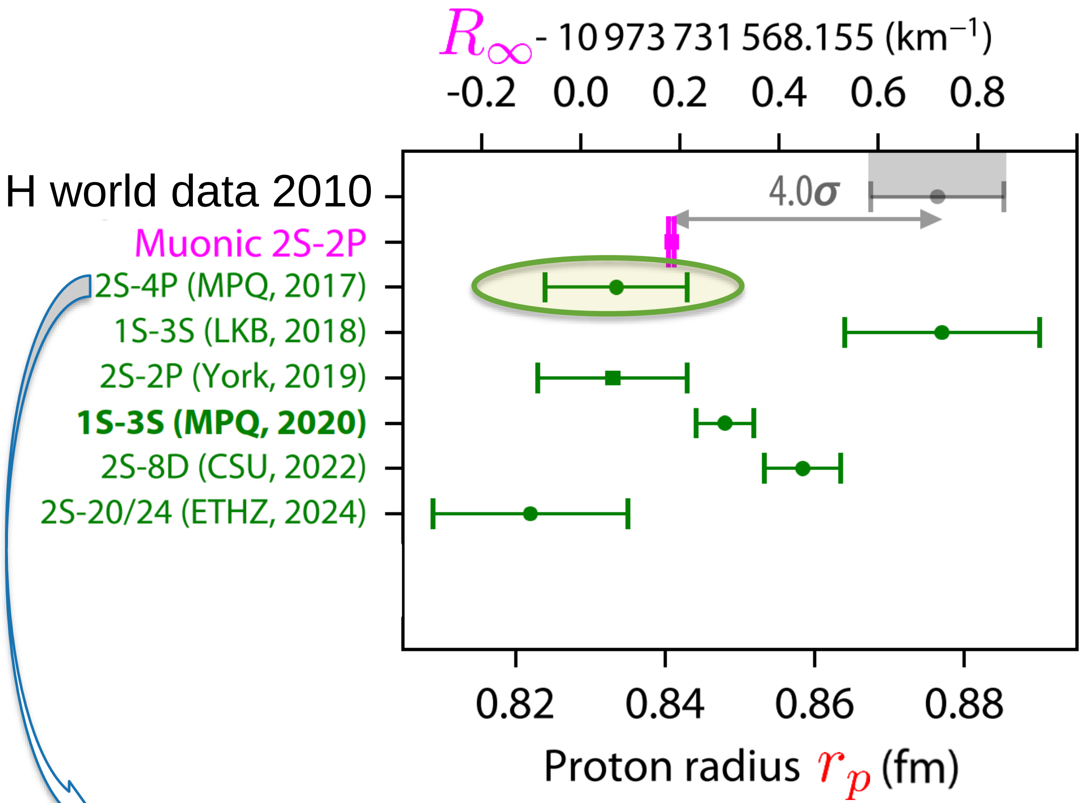
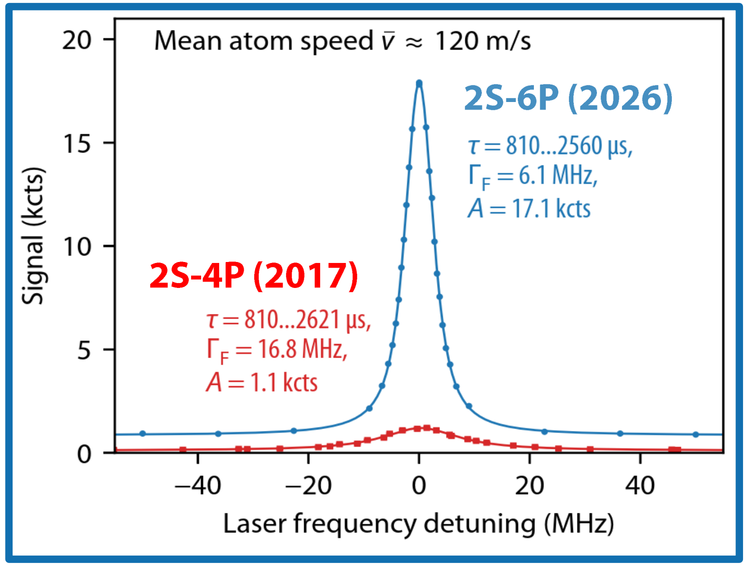
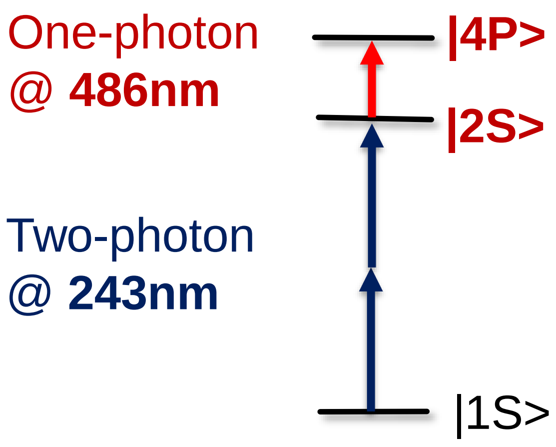




2S-4P experiment



One-photon
@ **486nm**

Two-photon
@ **243nm**

2S-6P (this work):

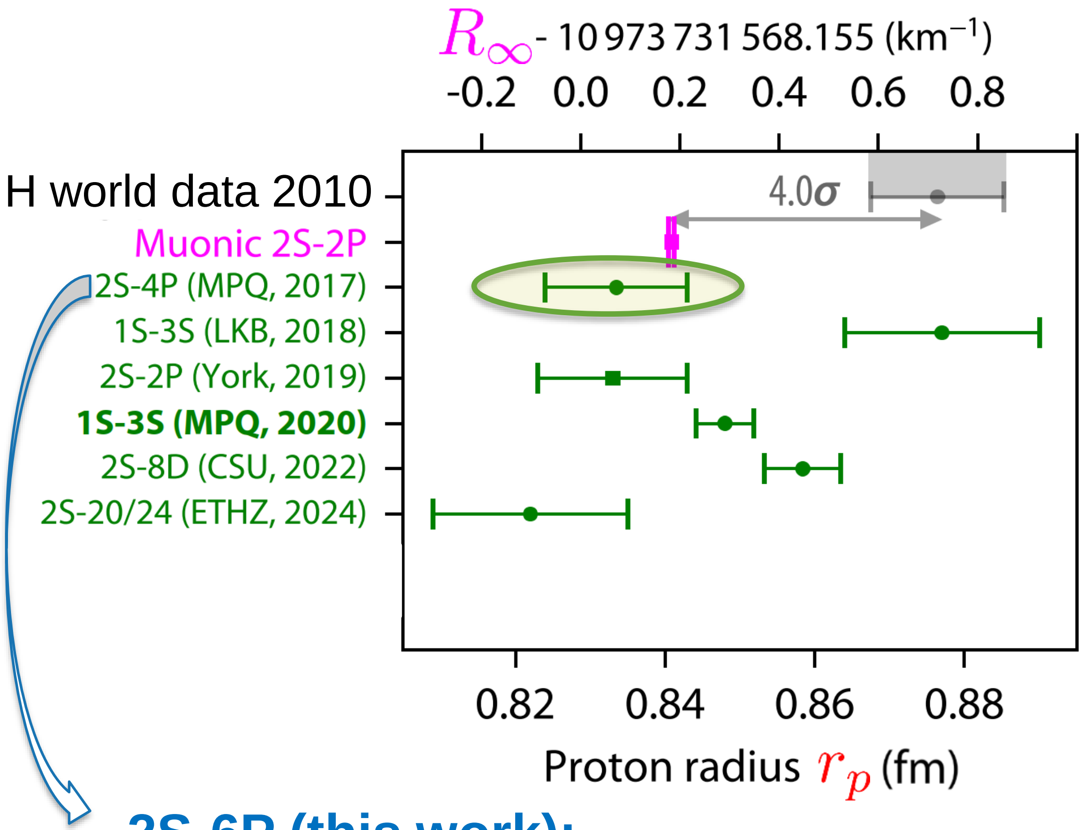
followup of 2S-4P experiment

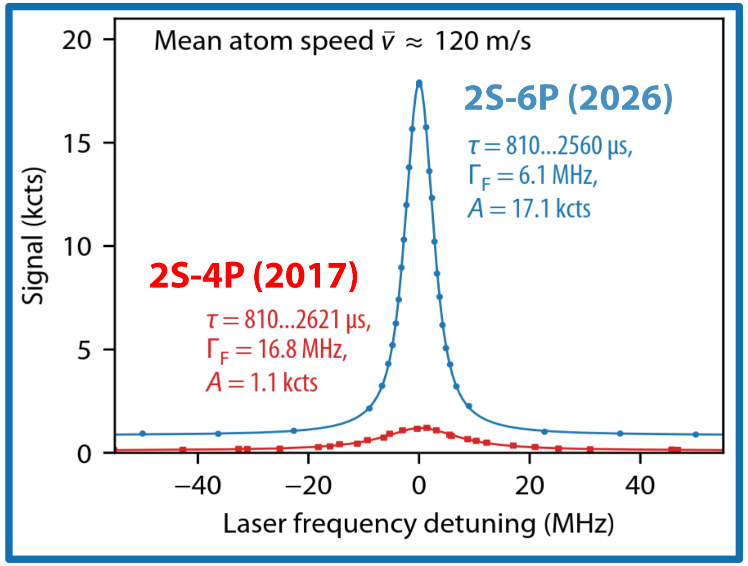
up to 16x **higher signal**

And 3x **lower linewidth**

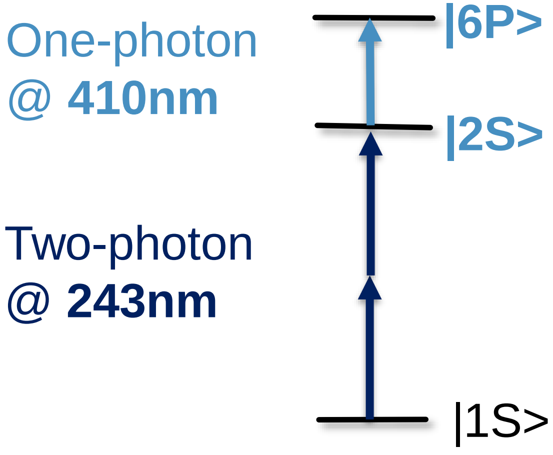
Proton radius puzzle

1S-2S transition measurement in hydrogen combined with 2nd transition measurement:





2S-6P experiment



One-photon @ **410nm**

Two-photon @ **243nm**

|6P>

|2S>

|1S>

2S-6P (this work):

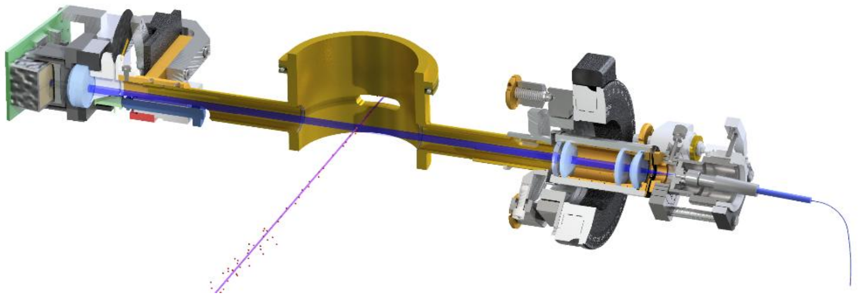
followup of 2S-4P experiment

up to 16x **higher signal**

And 3x **lower linewidth**

Technique for ***Doppler-free one-photon spectroscopy***:

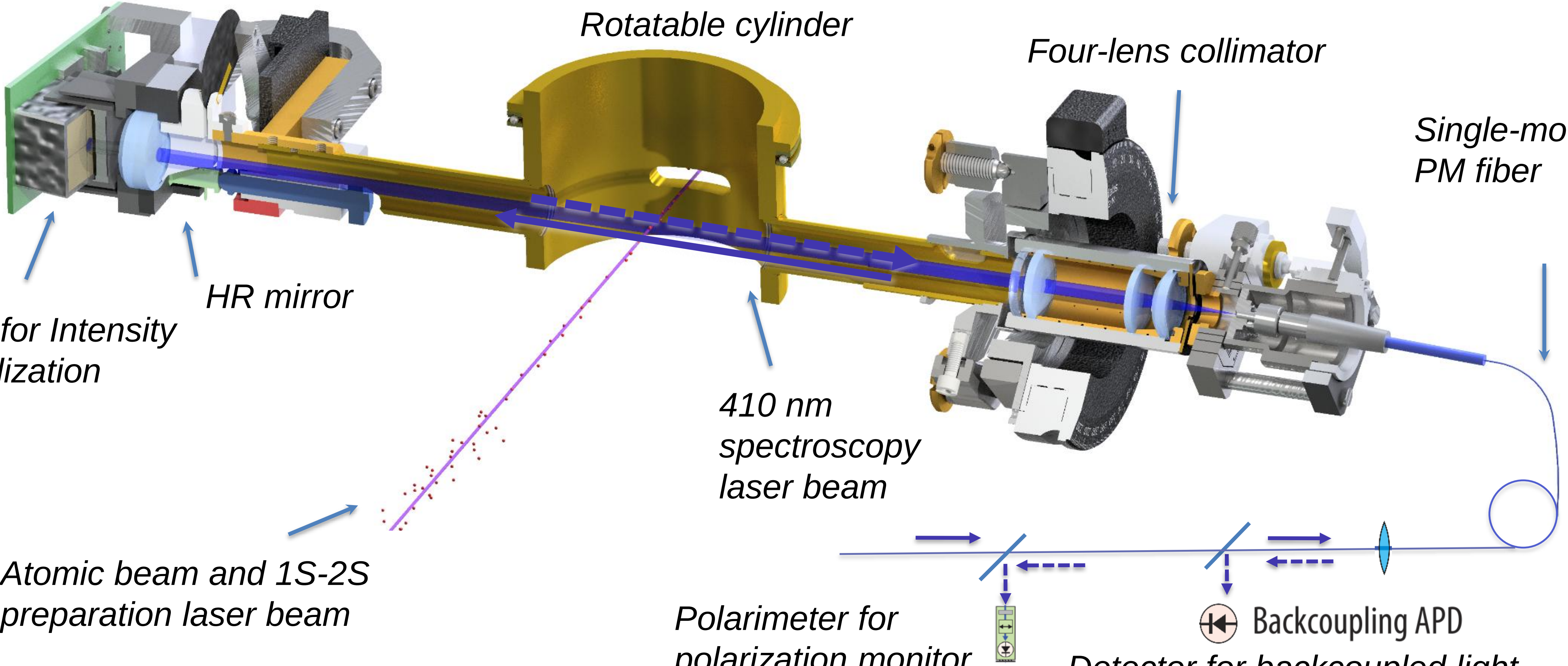
“Improved active-fiber based retroreflector for the near UV”



V. Wirthl et al, Opt. Express 29 (2021)

Doppler shift suppression: Active Fiber-based Retrorefector

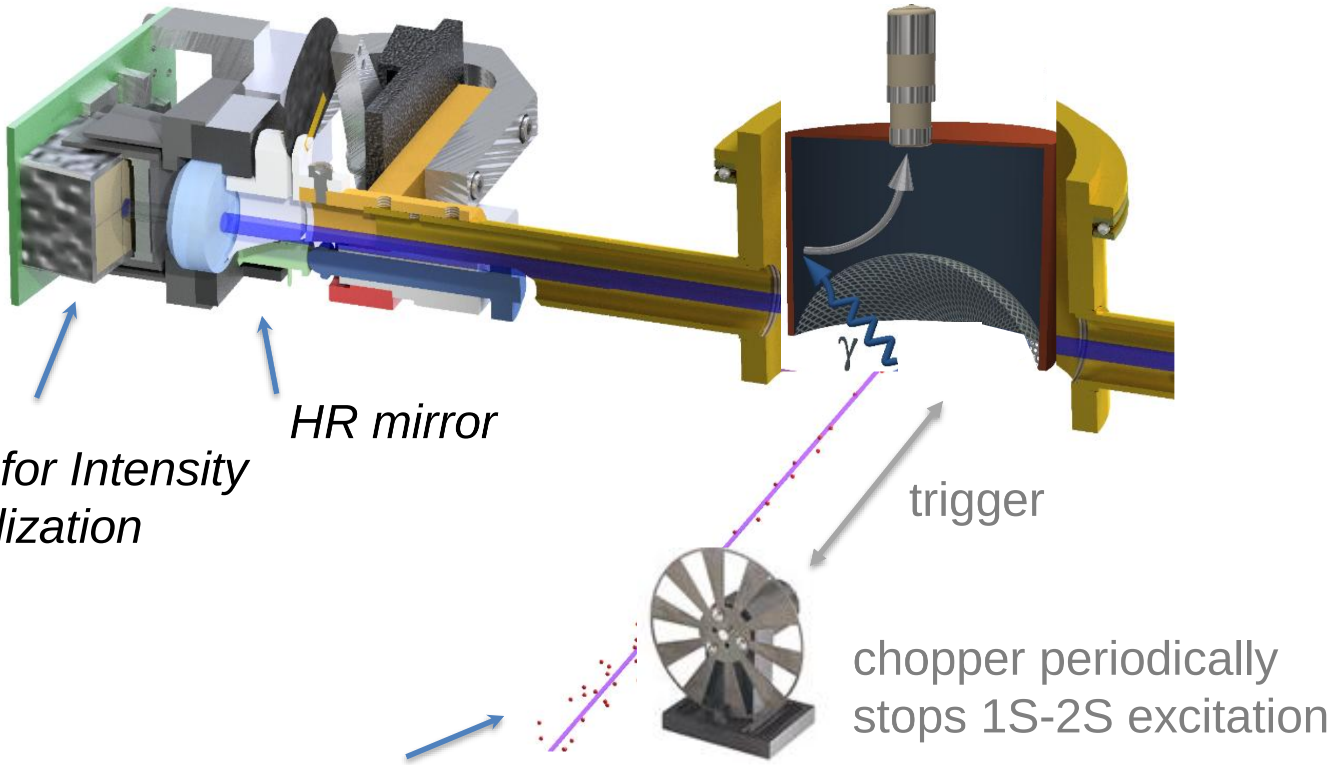
Improved active fiber-based retroreflector for near UV provides high-quality wavefront-retracing laser beams:



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

Time-resolved detection: velocity-dependent signal

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



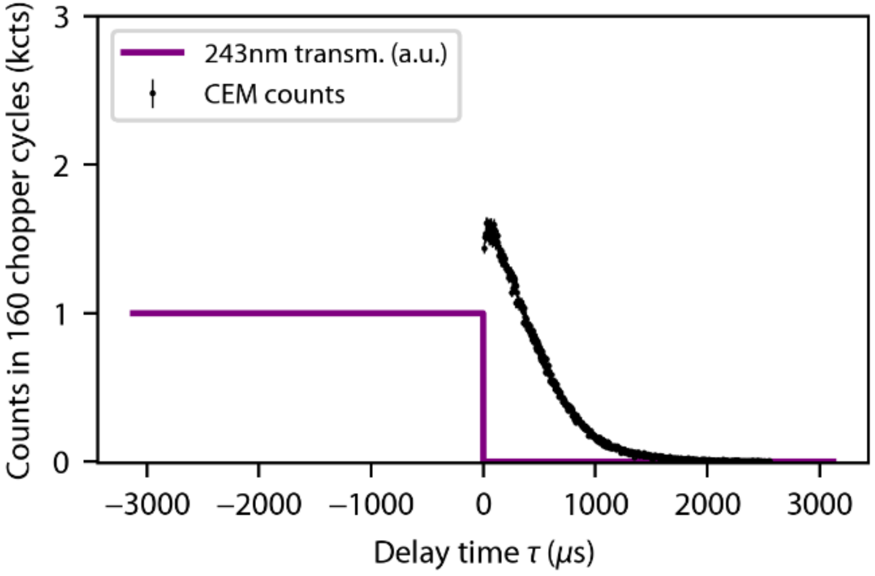
HR mirror

PMT for Intensity Stabilization

trigger

chopper periodically stops 1S-2S excitation

Atomic beam and 1S-2S preparation laser beam



➔ signal is recorded as a function of **delay time after 243nm light is blocked**

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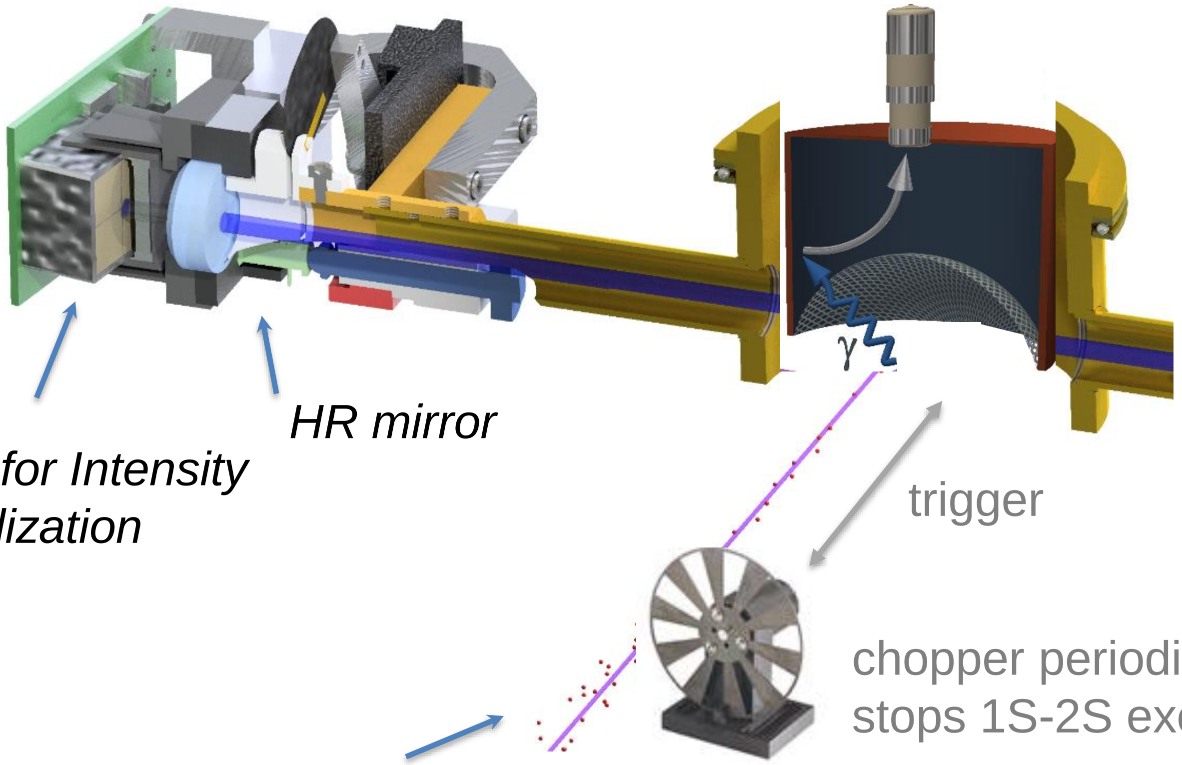
Time-resolved detection allows to access different velocity groups of atoms to **study velocity-dependent effects**



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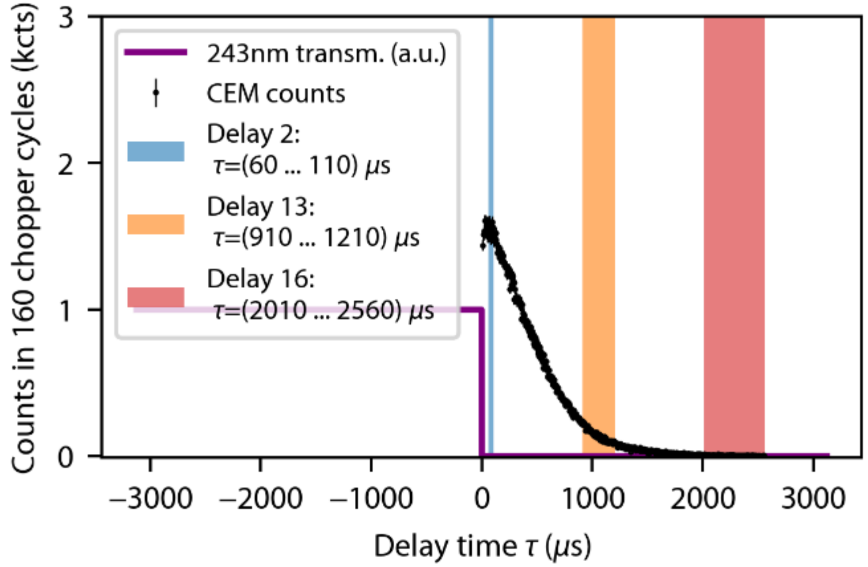

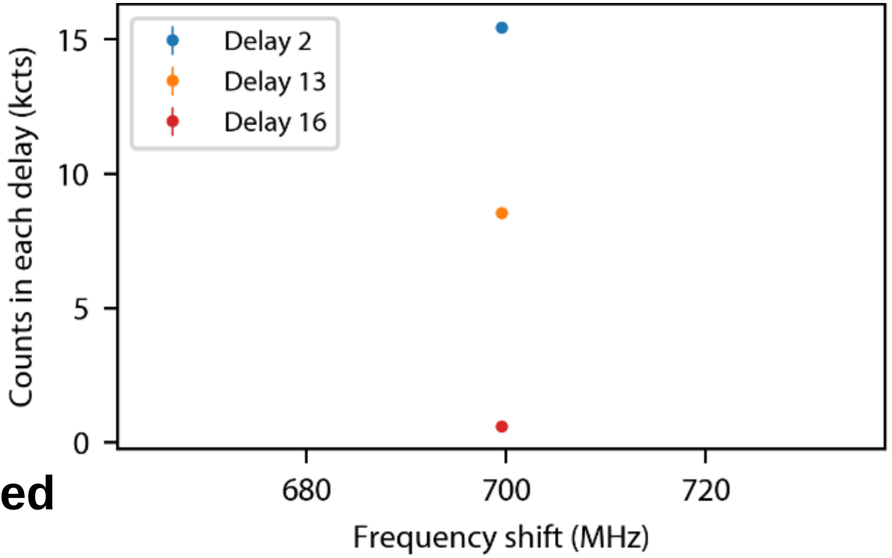

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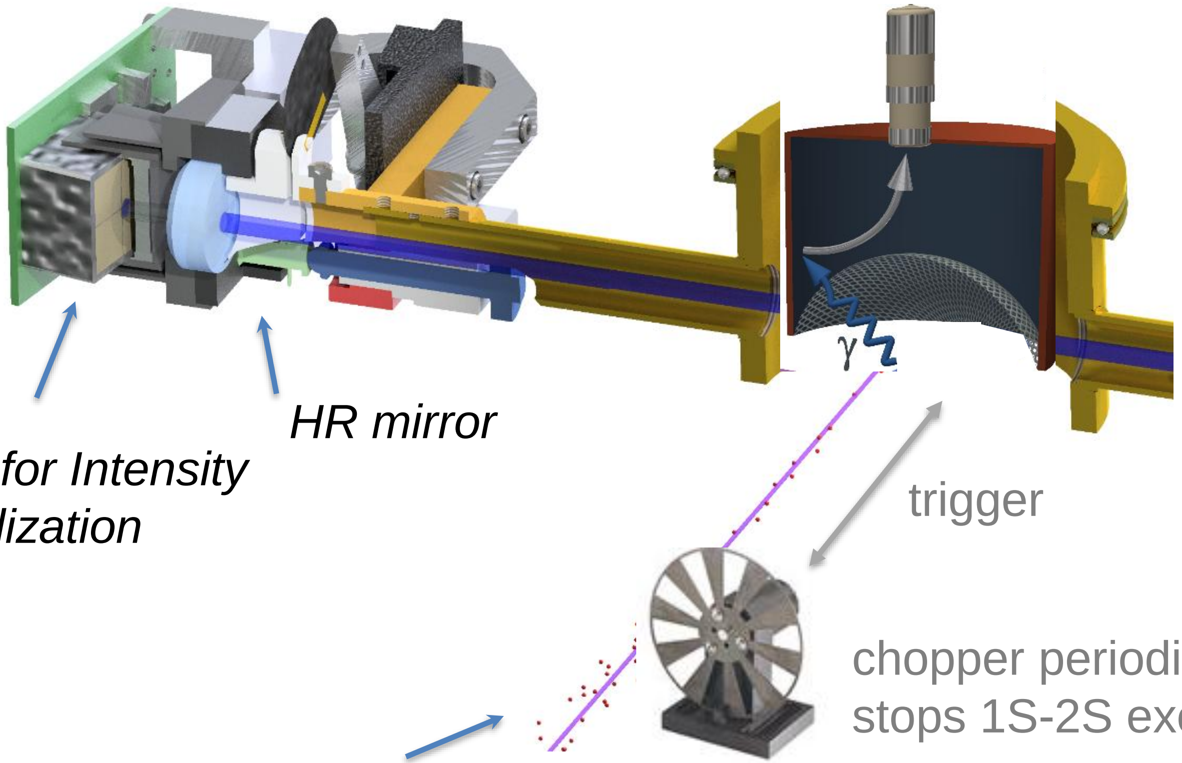

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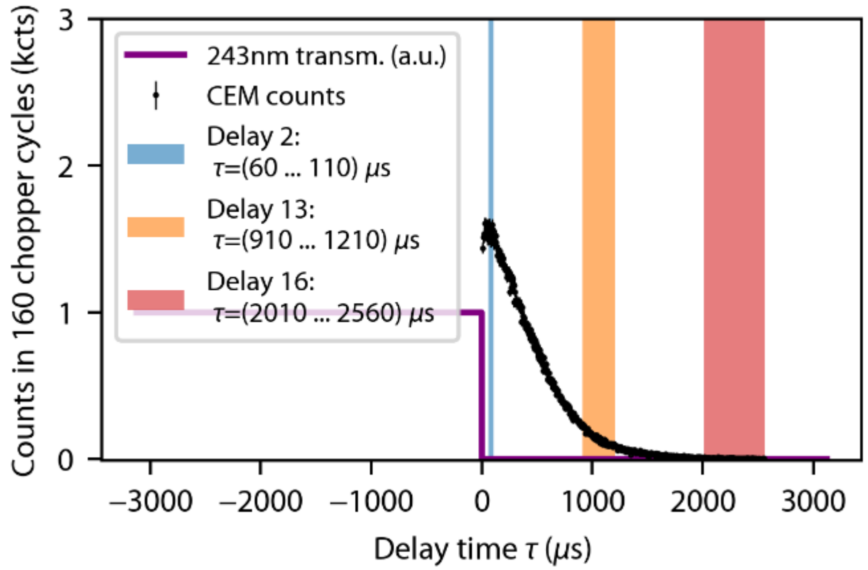

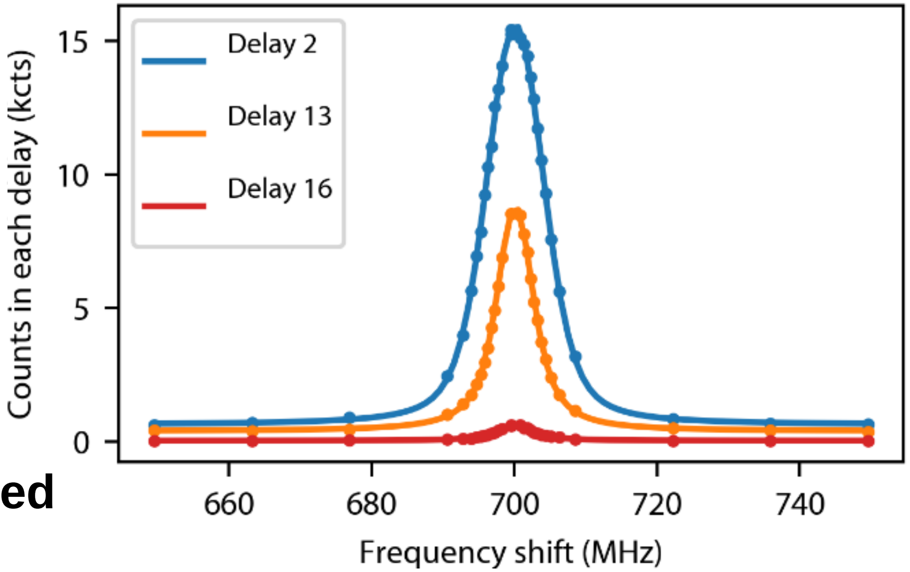

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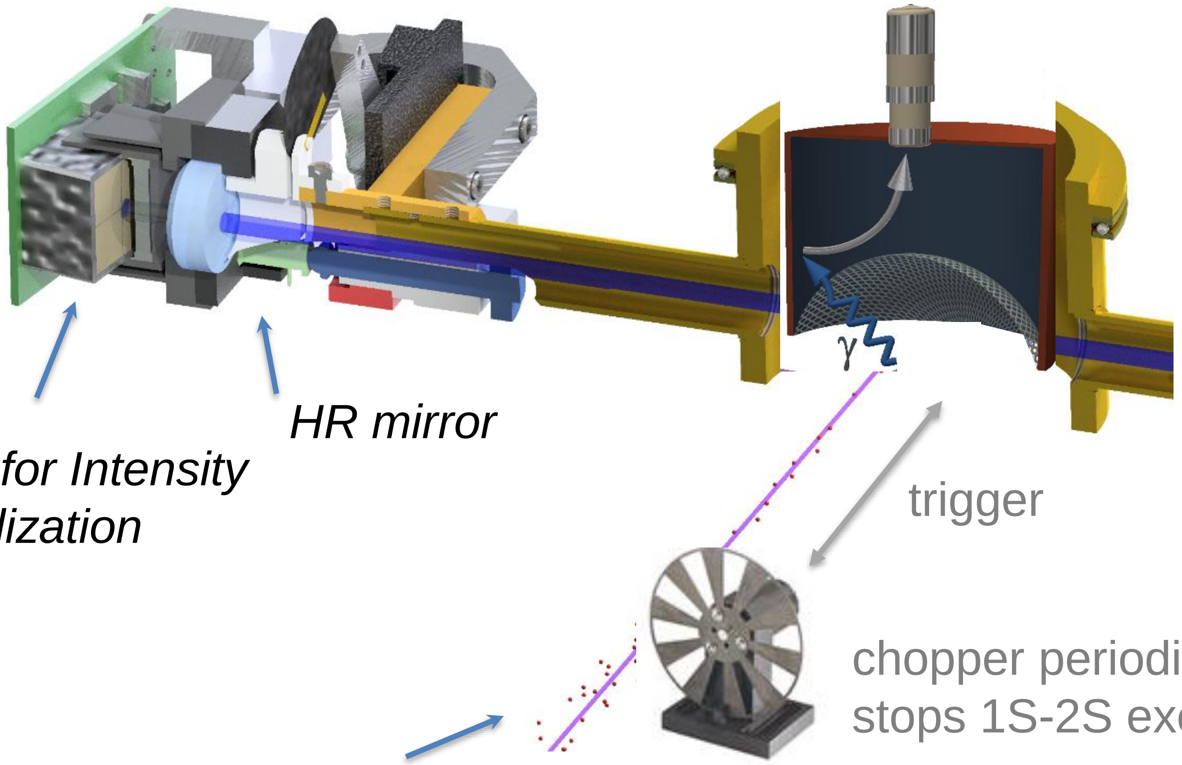

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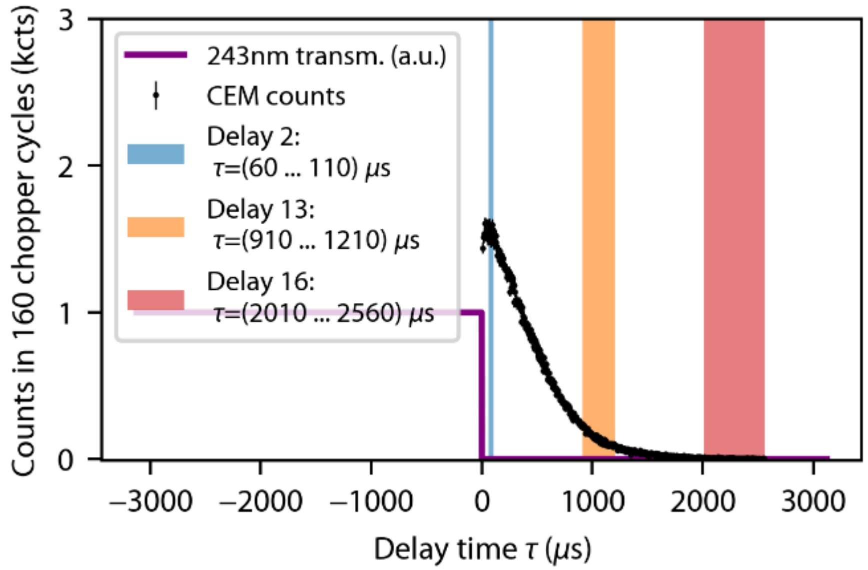
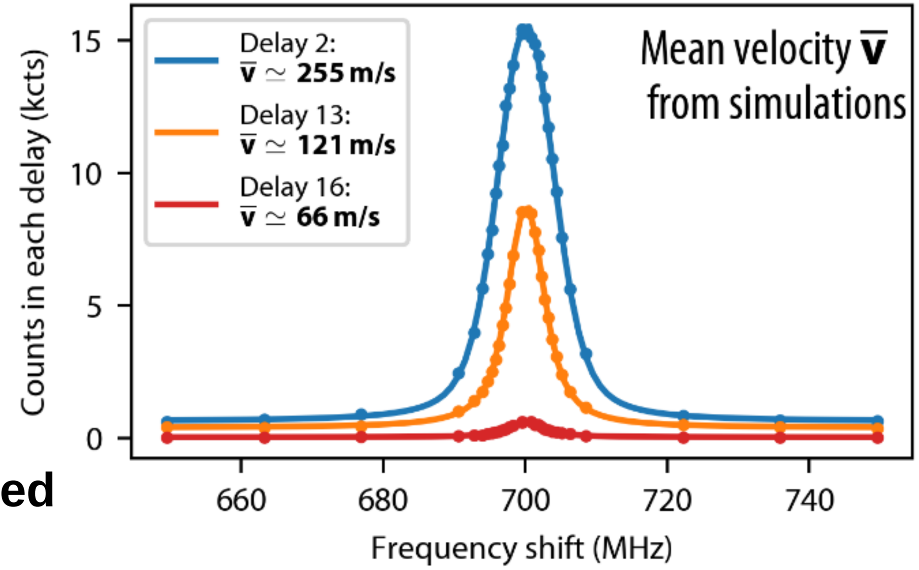
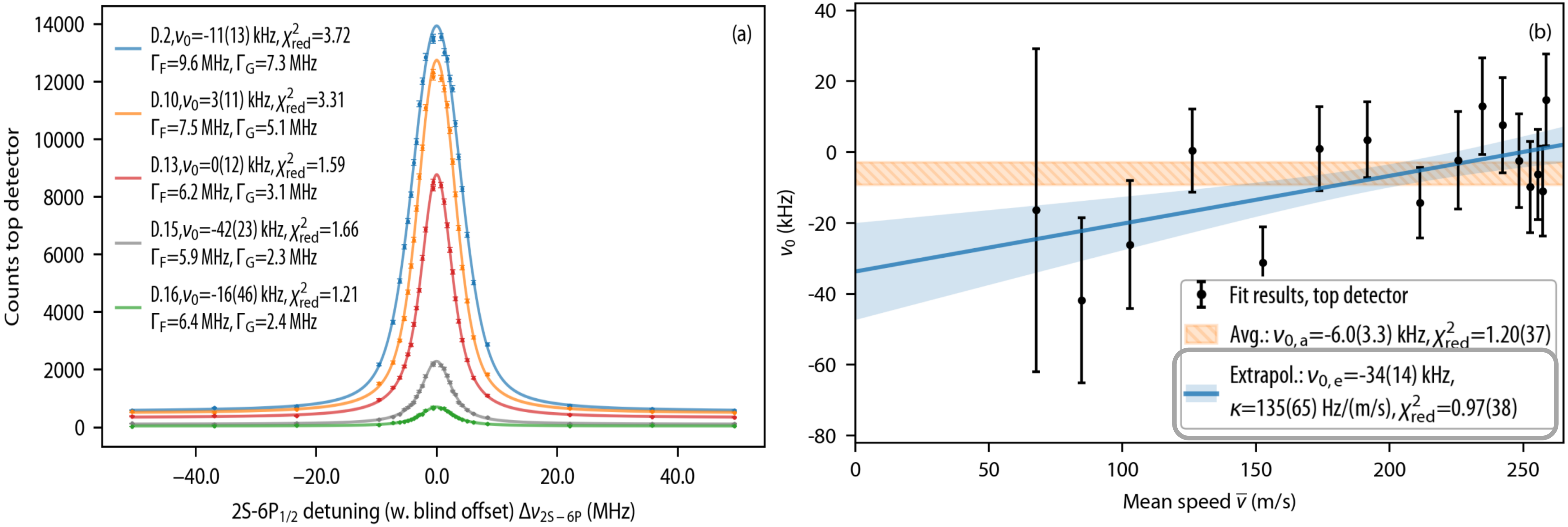




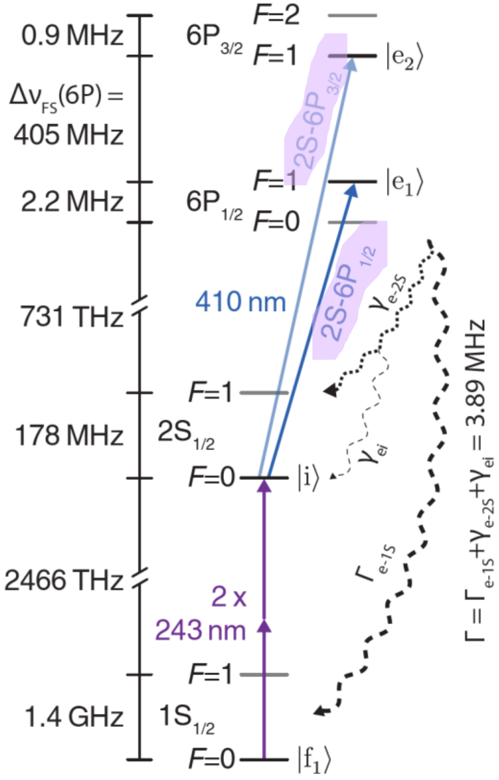
Time-resolved detection: velocity-dependent signal

Example of a single 2S-6P spectroscopy line scan

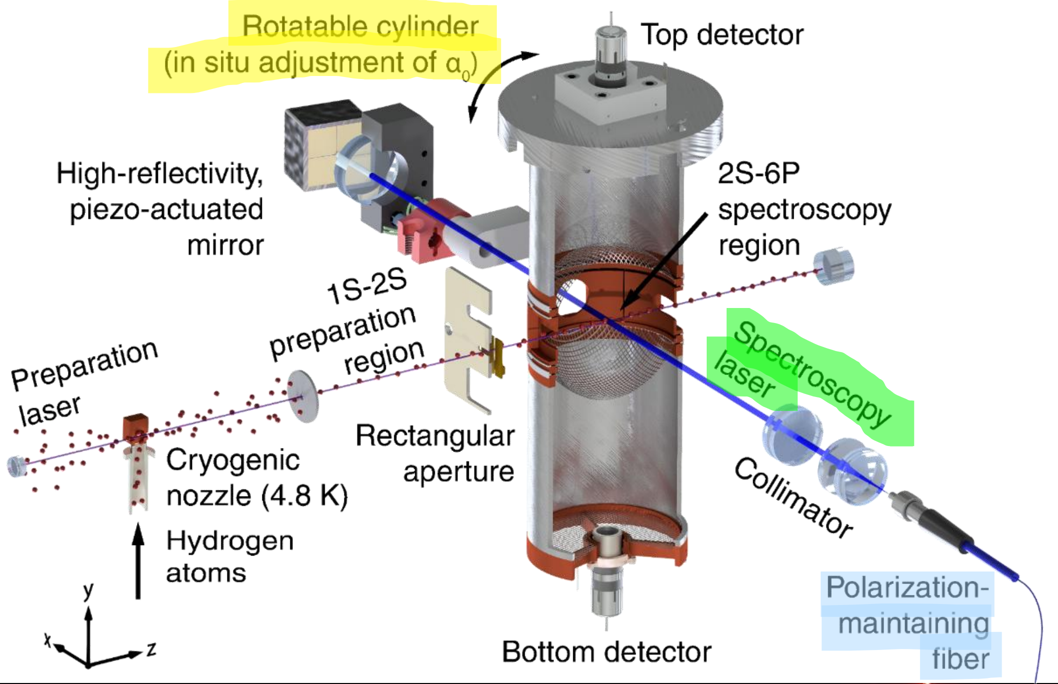


Time-resolved detection tests velocity-dependent effects and extracts the zero-velocity frequency

Hydrogen 2S-6P measurement runs and groups



Meas. run	Time period (2019)	α_0 (mrad)	θ_L (°)	$P_{1S\text{-}2S}$ (W)	Detector blocking meshes	FS	$P_{2S\text{-}6P}$ (µW)	FCs	Valid line scans
A	24.3.–3.4. (6 days)	0	56.5	1.0 – 1.7	Installed	$6P_{1/2}$	30	13	285
						$6P_{3/2}$	15	3	162
B	23.5.–9.6. (14 days)	0	56.5, 146.5	1.0 – 1.3	Removed	$6P_{1/2}$	10, 20, 30	21	1093
						$6P_{3/2}$	5, 10, 15	20	992
C	29.7.–7.8. (5 days)	0, ±7.5, ±12.0	56.5	1.0 – 1.1	Removed	$6P_{1/2}$	30	16	623
Total								73	3155



We form the 2S-6P fine-structure (FS) centroid by combining the measured $2S\text{-}6P_{12}$ and $2S\text{-}6P_{3/2}$ transition frequencies.

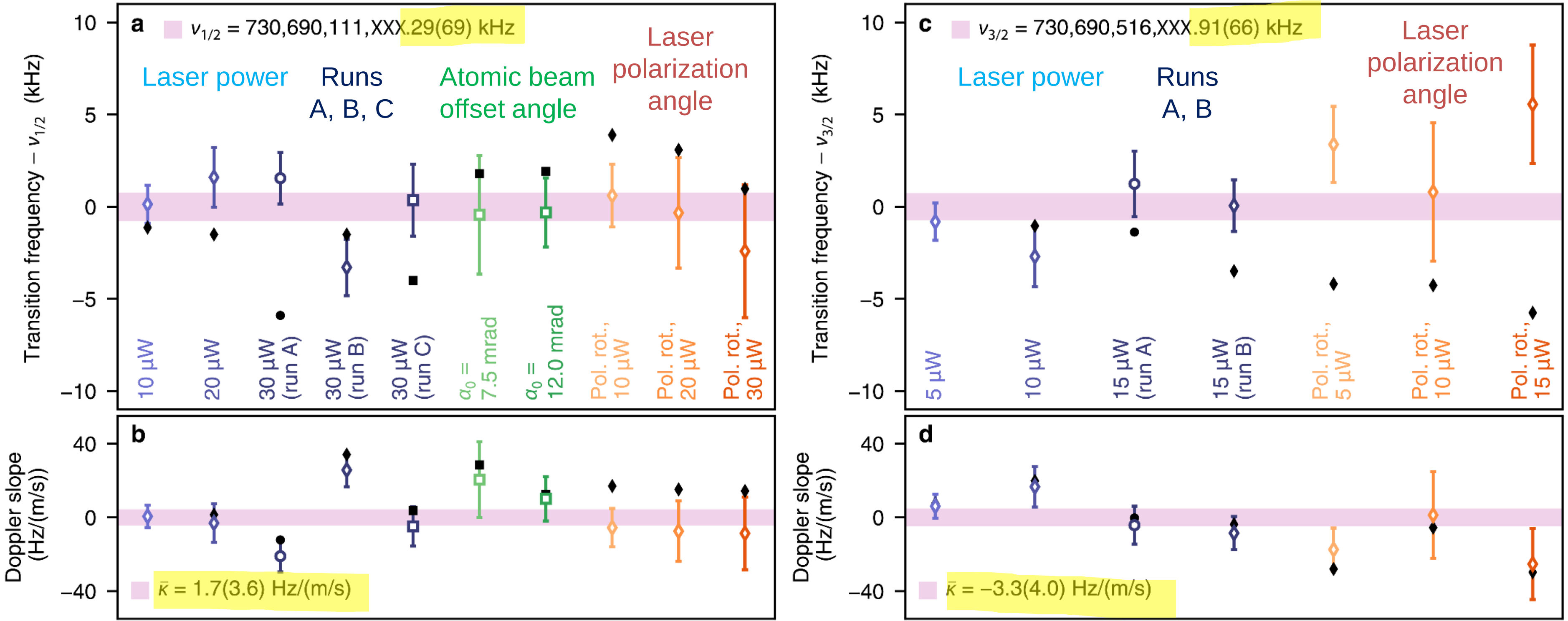
2S-6P measurement results by parameter combination

All 2S-6P data:

- Two transitions (2S-6P$_{1/2}$ and -6P$_{3/2}$)
- 3155 line scans
- 73 freezing cycles, each with atomic beam realignment
- Grouped by parameter combination into 14 data groups

Meas. run	Time period (2019)	α_0 (mrad)	θ_L (°)	$P_{1S\text{-}2S}$ (W)	Detector blocking meshes	FS	$P_{2S\text{-}6P}$ (μW)	FCs	Valid line scans
A	24.3.–3.4. (6 days)	0	56.5	1.0 – 1.7	Installed	6P$_{1/2}$	30	13	285
						6P$_{3/2}$	15	3	162
B	23.5.–9.6. (14 days)	0	56.5, 146.5	1.0 – 1.3	Removed	6P$_{1/2}$	10, 20, 30	21	1093
						6P$_{3/2}$	5, 10, 15	20	992
C	29.7.–7.8. (5 days)	0, ±7.5, ±12.0	56.5	1.0 – 1.1	Removed	6P$_{1/2}$	30	16	623
Total								73	3155

2S-6P$_{1/2}$ **Including all corrections** 2S-6P$_{3/2}$



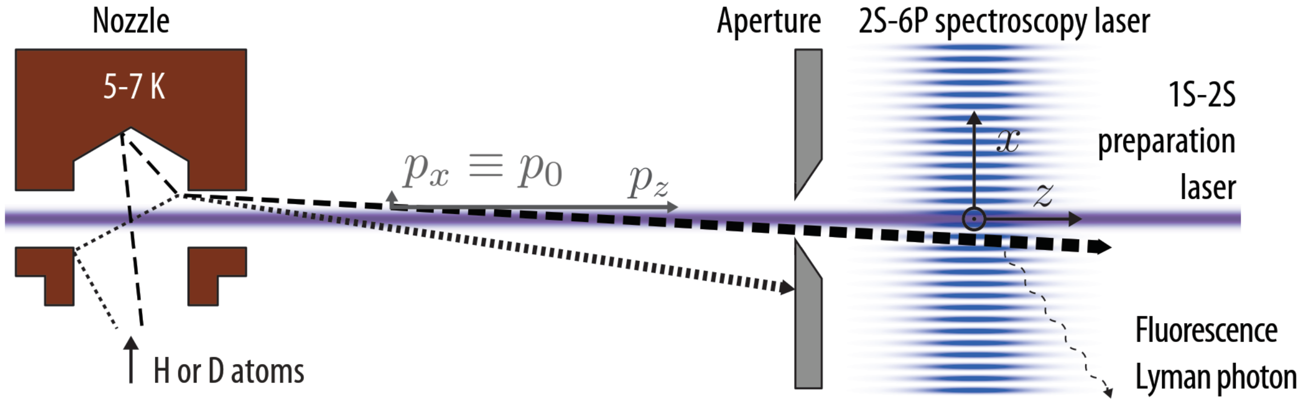
Corrections and uncertainties for hydrogen 2S-6P measurement

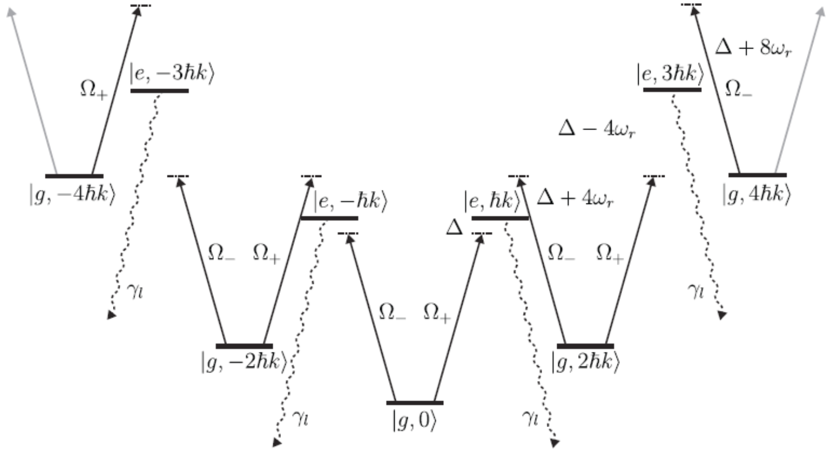
L. Maisenbacher, V. Wirthl et al, *Nature* 650 (2026)

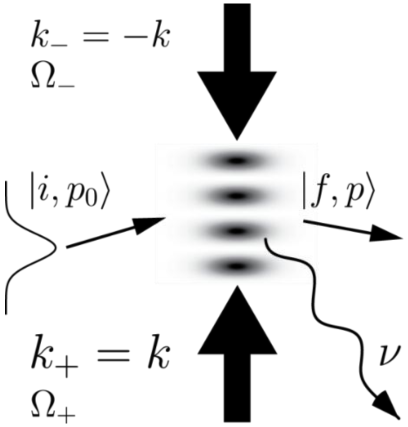
	Correction	Uncertainty
Contribution	$\Delta\nu$ (kHz)	σ (kHz)
Doppler shift extrapolation	0.34	0.43
Statistics	0.34	0.43
Simulation of atom speeds	—	0.01
Simulation corrections	1.05	0.17
Light force shift	1.15	0.17
Quantum interference shift	0.05	0.02
Second-order Doppler shift	−0.14	0.01
Sampling bias	0.00	0.06
Signal background	0.00	0.03
dc-Stark shift	0.05	0.07
BBR-induced shift	0.29	0.03
Zeeman shift	0.00	0.08
Pressure shift	0.00	0.01
Frequency standard	0.00	0.07
Total corrections (excl. recoil & HFS)	1.73	0.49
Recoil shift	−1176.03	0.00
HFS corrections $\Delta\nu_{\mathrm{HFS}}(\nu_{\text{2S-6P}})$	−132985.252	0.007
Total	−134159.552	0.49

Largest individual uncertainty: Statistical uncertainty of Doppler-free (extrapolated) transition frequency

Largest systematic correction: Light force shift







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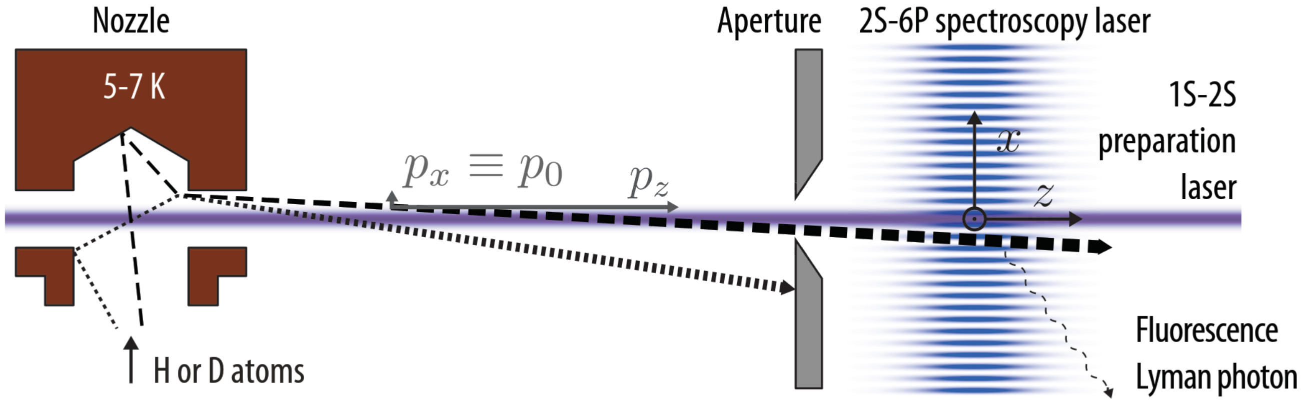
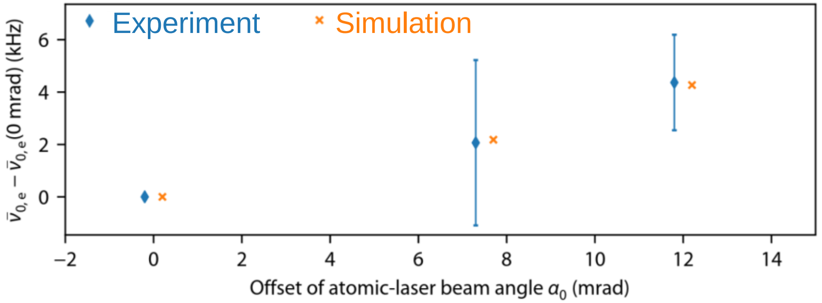


Light Force Shift measured by rotating atomic beam



✓

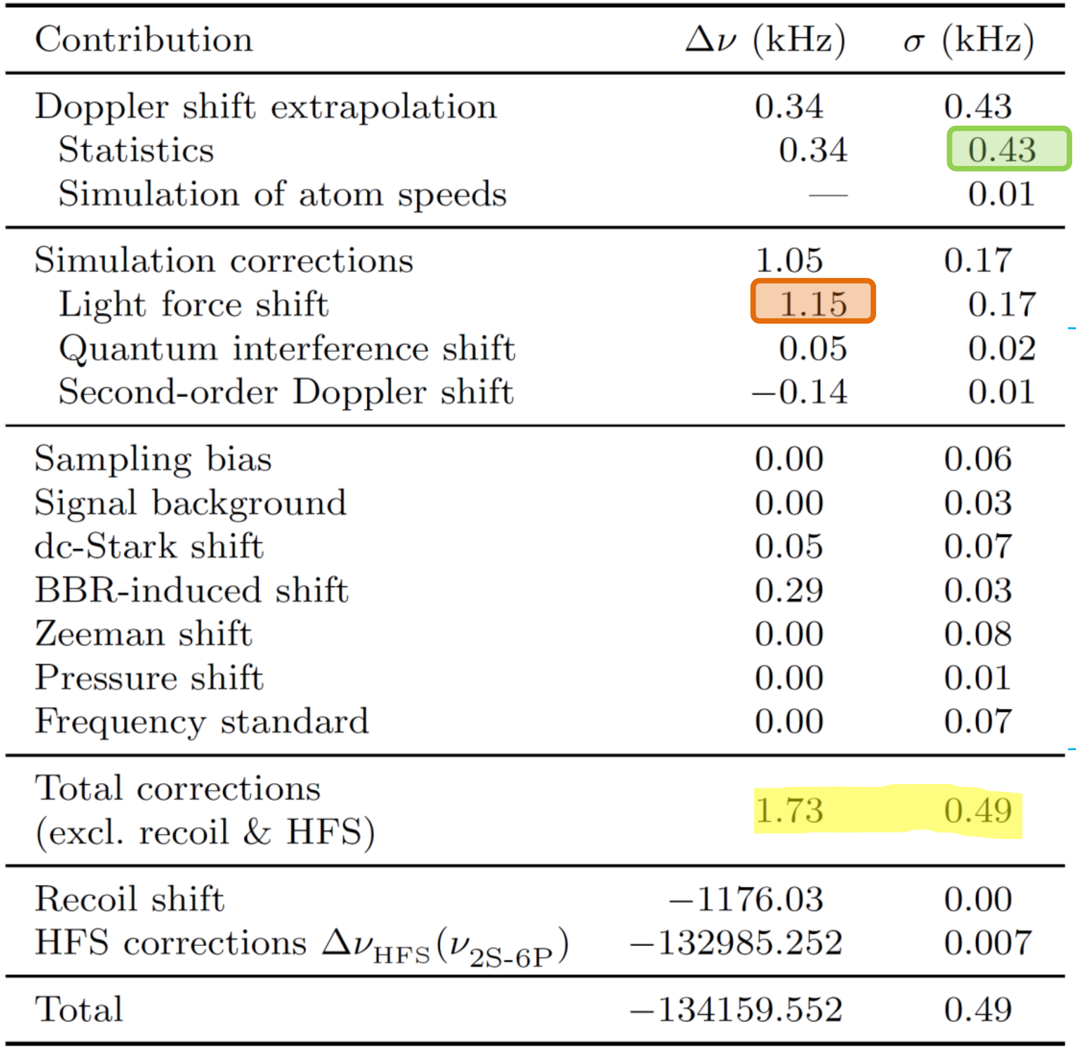
Experiment: $\bar{\nu}_{0,\mathrm{e}}(12.0\,\mathrm{mrad}) - \bar{\nu}_{0,\mathrm{e}}(0\,\mathrm{mrad}) = 4.37(1.82)\,\mathrm{kHz}$

Simulation: $\nu_{0,\mathrm{e}}(12.0\,\mathrm{mrad}) - \nu_{0,\mathrm{e}}(0\,\mathrm{mrad}) = 4.27\,\mathrm{kHz}.$

Corrections and uncertainties for hydrogen 2S-6P measurement

L. Maisenbacher, V. Wirthl et al, *Nature* 650 (2026)

Correction Uncertainty



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Total	−134159.552	0.49

Largest individual uncertainty: Statistical uncertainty of Doppler-free (extrapolated) transition frequency

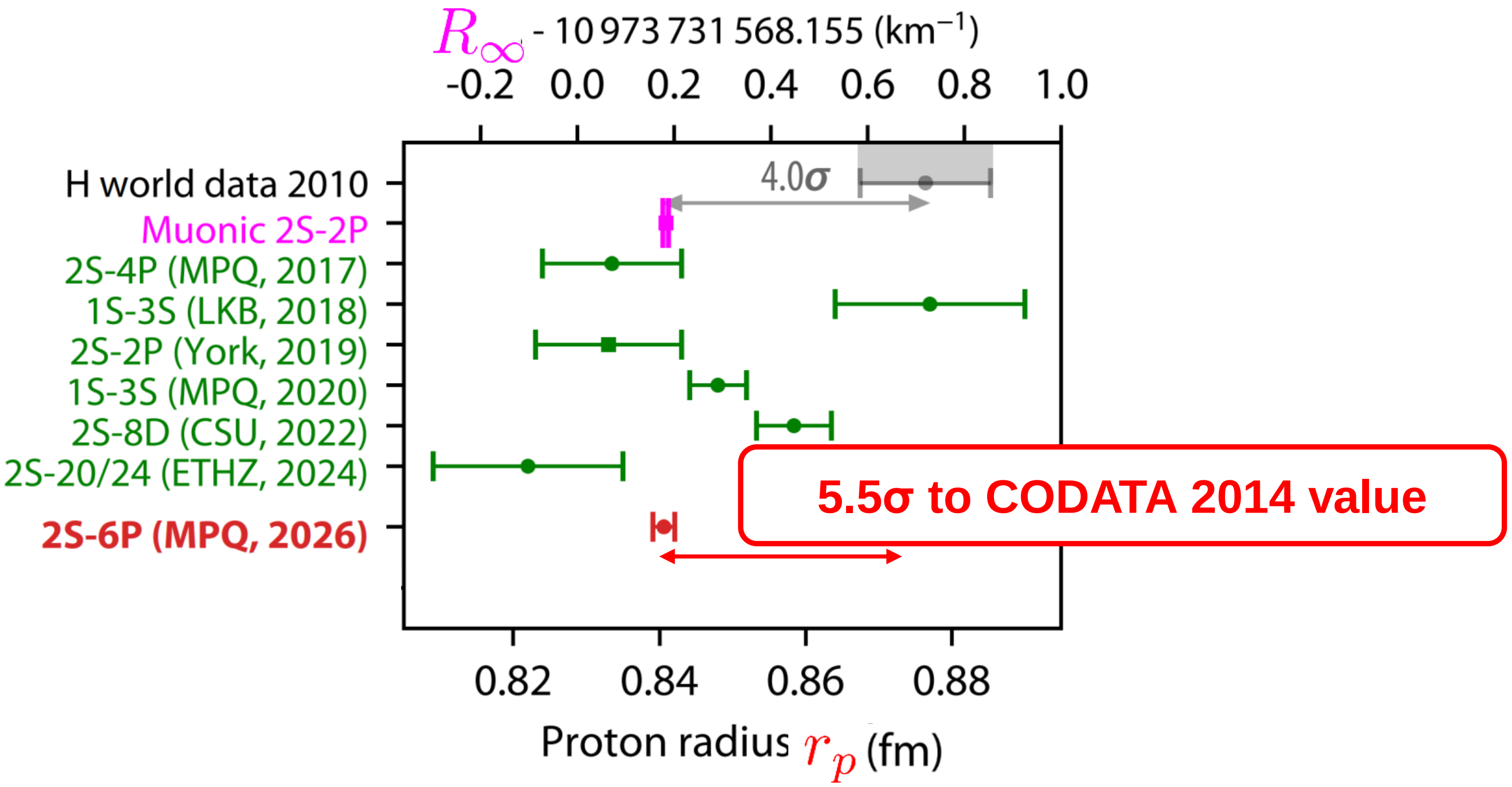
Largest systematic correction: Light force shift

All corrections other than LFS individually contribute less than 100 Hz to uncertainty

Total correction (excl. recoil and HFS) only 3.5 σ

Recoil shift and hyperfine (HFS) corrections are large, but known extremely well

Proton radius puzzle resolved

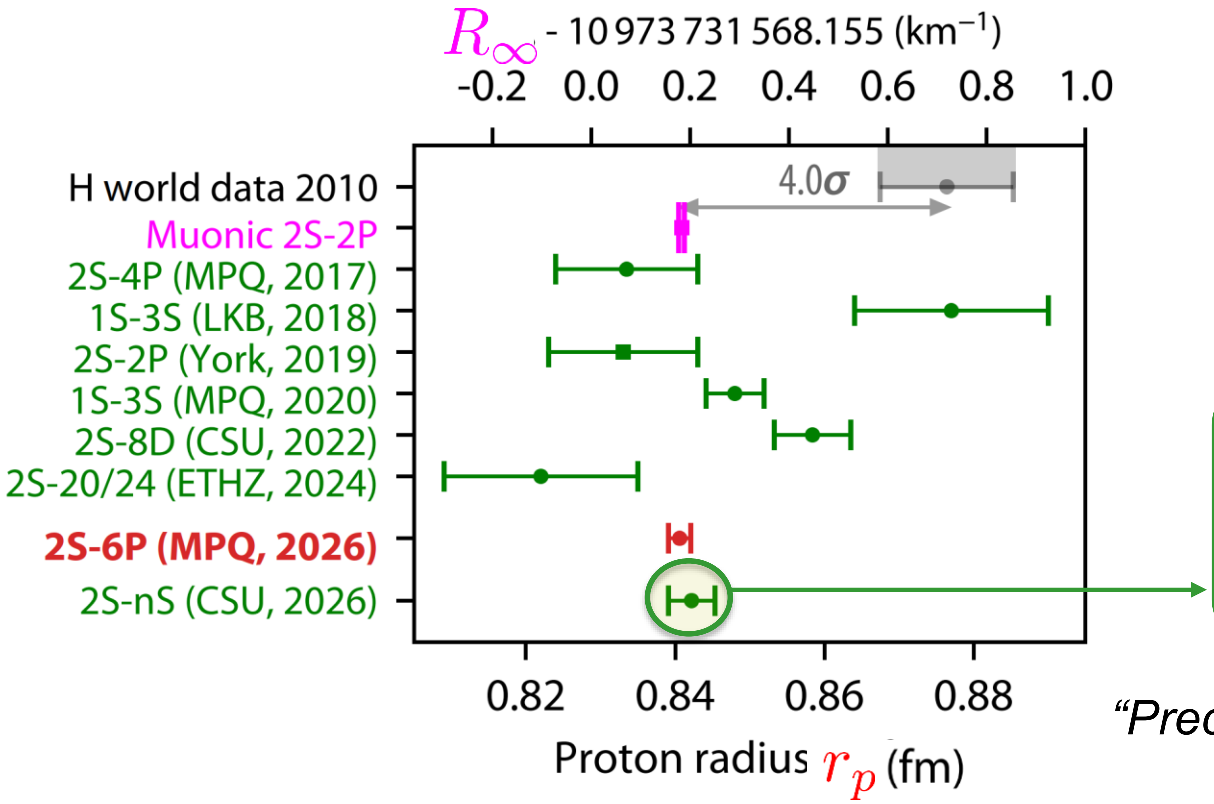


5.5σ to CODATA 2014 value

“Sub-part-per-trillion test of the Standard Model with atomic hydrogen”

L. Maisenbacher, V. Wirthl et al, *Nature* 650 (2026)

Proton radius puzzle resolved



Agreement with muonic hydrogen also from 2S-nS transitions, which contributed significantly to "H world data 2010" and CODATA 2014

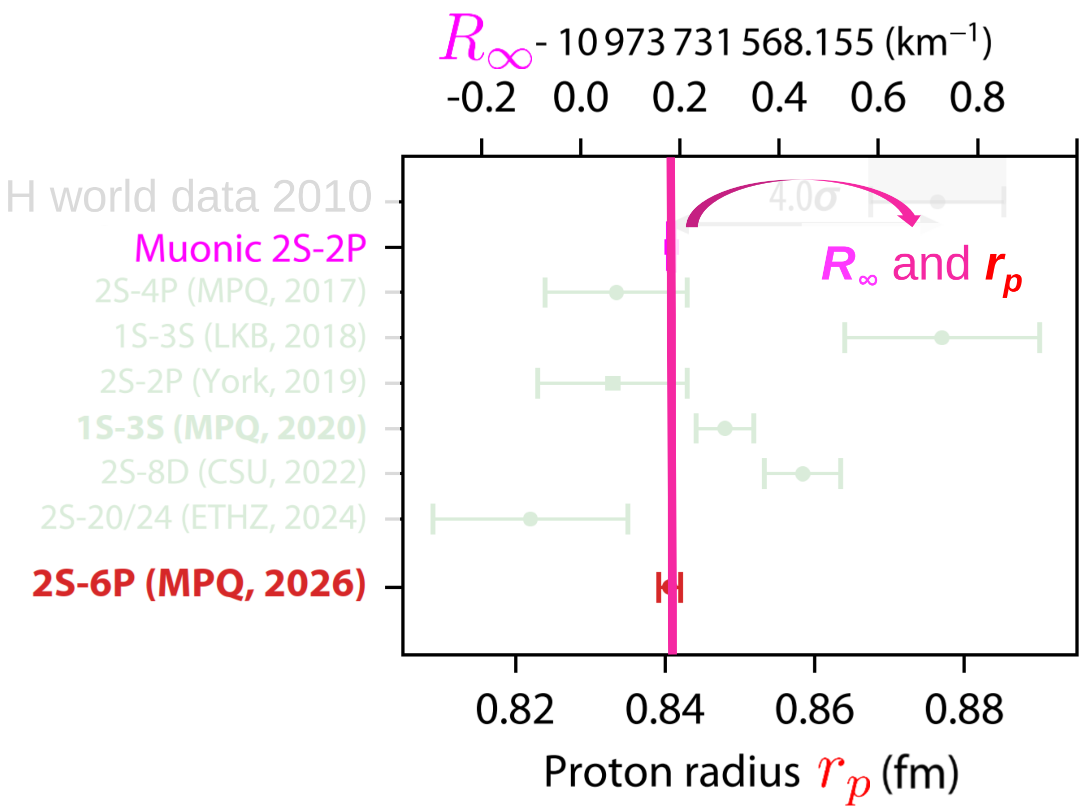
"Precision Spectroscopy of 2S-nS Transitions in Atomic Hydrogen: A Determination of the Proton Charge Radius"

R. G. Bullis et al, *PRL* 136 (2026)

"Sub-part-per-trillion test of the Standard Model with atomic hydrogen"

L. Maisenbacher, V. Wirthl et al, *Nature* 650 (2026)

New “gold standard” of Standard Model tests



“Sub-part-per-trillion test of the Standard Model with atomic hydrogen”

L. Maisenbacher, V. Wirthl et al, *Nature* 650 (2026)

Theory with R_∞ and r_p [0.31 ppt]:

$$\nu_{\text{2S-6P,QED}} = 730690248610.79(18)_{\text{QED}}(14)_{r_p}\ \text{kHz}$$

$$\nu_{\text{2S-6P,QED}} - \nu_{\text{2S-6P,exp}} = 0.00(55)\ \text{kHz}$$ **[0.74 ppt]**

Experiment [0.66 ppt]:

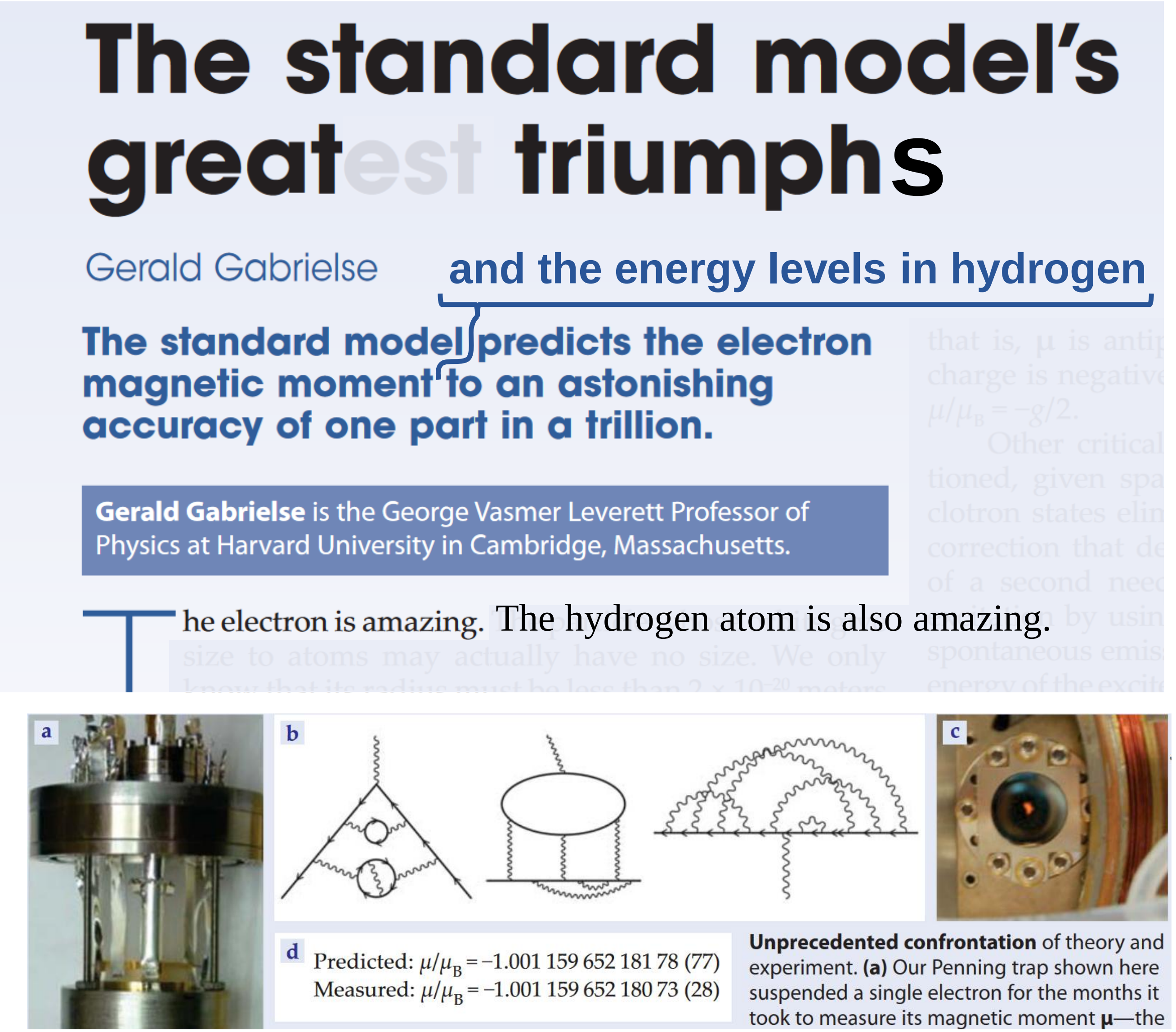
$$\nu_{\text{2S-6P,exp}} = 730690248610.79(48)\ \text{kHz}$$

Most accurate bound-state QED test to date

Standard Model test to 7×10^{-13}

New "gold standard" of Standard Model tests

Physics Today 66 (12), 64–65 (2013)



The standard model's greatest triumphs

and the energy levels in hydrogen

Gerald Gabrielse

The standard model predicts the electron magnetic moment to an astonishing accuracy of one part in a trillion.

Gerald Gabrielse is the George Vasmer Leverett Professor of Physics at Harvard University in Cambridge, Massachusetts.

The electron is amazing. The hydrogen atom is also amazing.

Predicted: $\mu/\mu_B = -1.001\,159\,652\,181\,78\ (77)$
Measured: $\mu/\mu_B = -1.001\,159\,652\,180\,73\ (28)$

Unprecedented confrontation of theory and experiment. **(a)** Our Penning trap shown here suspended a single electron for the months it took to measure its magnetic moment **μ**—the

Theory with R_∞ and r_p [0.31 ppt]:

$$\nu_{\text{2S-6P,QED}} = 730690248610.79(18)_{\text{QED}}(14)_{r_p}\ \text{kHz}$$

$$\nu_{\text{2S-6P,QED}} - \nu_{\text{2S-6P,exp}} = 0.00(55)\ \text{kHz}$$ **[0.74 ppt]**

Experiment [0.66 ppt]:

$$\nu_{\text{2S-6P,exp}} = 730690248610.79(48)\ \text{kHz}$$

Most accurate bound-state QED test to date

Standard Model test to 7×10^{-13}

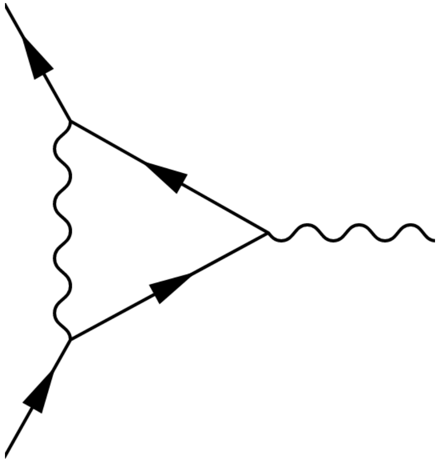
Same precision as the Standard Model test with the anomalous magnetic moment of the electron ("g-2"):

$$-\mu/\mu_B = g/2 = 1.00115965218059(13)$$

Bound-state QED vs. free QED: complementary tests of the Standard Model

Free electron one-loop QED

1 simple diagram

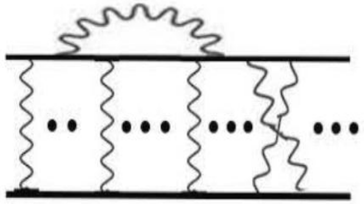


$$\frac{\alpha}{2\pi}$$

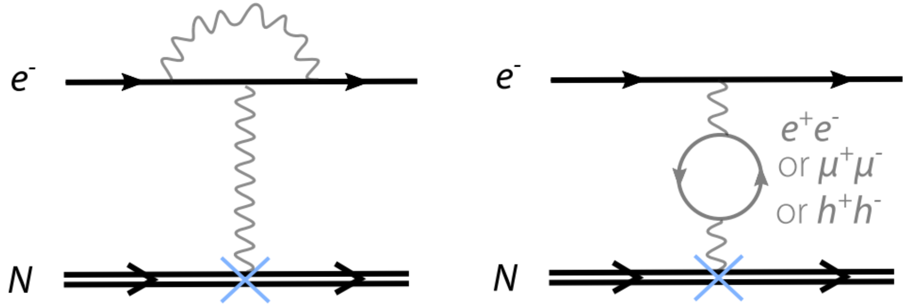
Bound-state QED is different from free QED: complementary tests of the Standard Model

Bound-state one-loop QED

electron constantly interacting



2 *classes* of diagrams



$$\frac{2\alpha^3}{\pi n^3(1+m_e/m_p)^3} \Bigg(\bigg(\frac{4}{3}-\alpha^2+\bigg(4\sum_m^n\frac{1}{m}+\frac{28}{3}\ln(2)-4\ln(n)-\frac{781}{180}$$

$$-\frac{77}{45n^2}\bigg)\bigg)\ln\bigg(\frac{1+m_e/m_p}{\alpha^2}\bigg)-\frac{4}{3}\ln k_0(n)+\frac{10}{9}+\bigg(\frac{139}{32}-2\ln(2)\bigg)\pi+\alpha^2 G_{SE}(n)\bigg)$$

$$+\frac{2\alpha^3}{\pi n^3(1+m_e/m_p)^3}\Bigg(-\frac{4}{15}+\frac{5}{48}\pi\alpha-\frac{2}{15}\alpha^2\ln\bigg(\frac{1+m_e/m_p}{\alpha^2}\bigg)$$

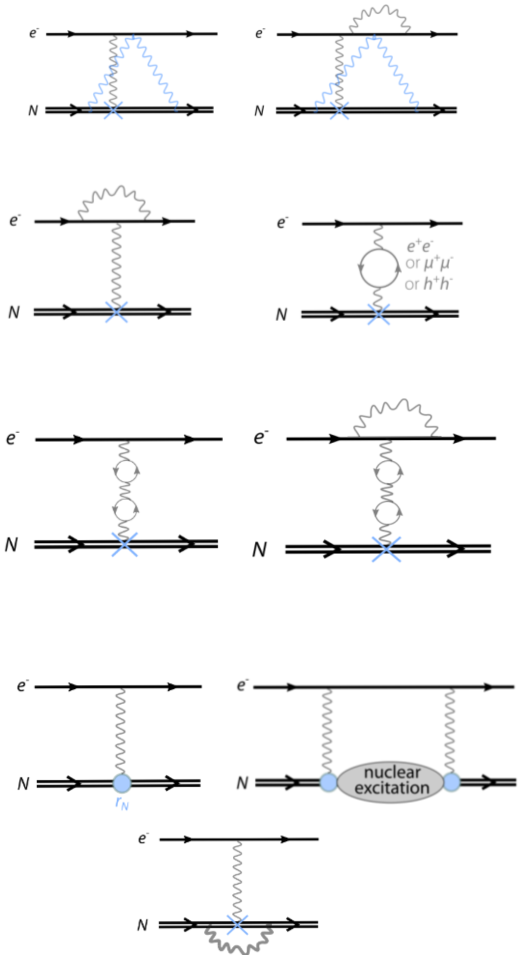
$$+\bigg(\frac{19}{45}-\frac{\pi^2}{27}\bigg)\alpha^2+\bigg(\frac{1}{60}-\frac{31\pi^2}{2880}\bigg)\pi\alpha^3+G_{VP}^{(1)}(\alpha)\Bigg)$$

Bound-state QED vs. free QED: complementary tests of the Standard Model

Theory	Free electron QED	Bound-state QED
Quantity	$\mu_e/\mu_\mathrm{B} = -g/2$	$\nu_{2\mathrm{S}\text{-}6\mathrm{P}}$
Required constants	α from $R_\infty, \frac{m_e}{m_X}, \frac{m_X}{h}$	$R_\infty, r_p, \frac{m_e}{m_p}, \alpha$
QED prediction to	1.4×10^{-12} (discrepancy)	3.6×10^{-13}
Prediction from		
…Schrödinger	0.5 no correct digits…	7306**8…** kHz **4** digits correct
…Dirac	1.00**0…** 2 digits correct	73069**1…** kHz **5** digits correct
Largest "pure" QED term at the level of	$\alpha/2\pi = 1.2 \times 10^{-3}$	1.5×10^{-6}
QED theory up to order of	α^5 "5-loop"	$\alpha^2 \times \alpha^5$ "3-loop"

Measurement accuracy	1.3×10^{-13}	6.7×10^{-13}
Theory test to	$\sim 1.4 \times 10^{-12}$	8×10^{-13}
"Pure" QED part test to	$\sim 10^{-9}$	5×10^{-7}

Hydrogen 2S-6P: which contributions are being tested



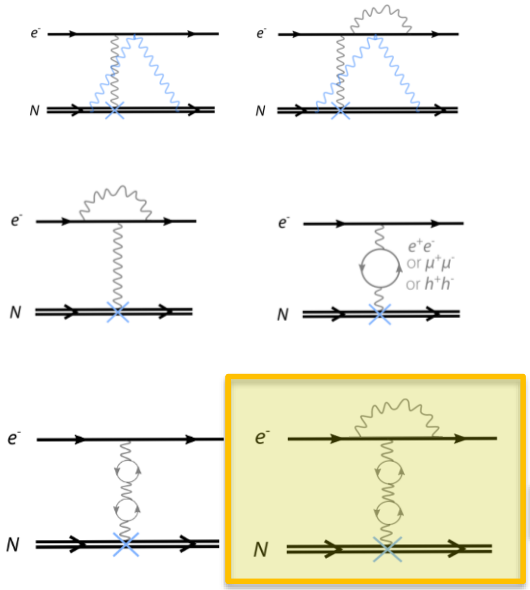
Contribution (Hz)	Value (Hz)	Theory σ (Hz)
Dirac	730 691 293 379 480	0
Rel. nuclear recoil	−340 940	0
Radiative recoil	1540	102
1-loop QED		
self-energy	−1 071 052 911	1
vacuum-polarization	26 853 096	0
$\mu^+\mu^-$ vacuum-pol.	634	0
hadronic vacuum-pol.	425	10
2-loop QED	−91 497	126
3-loop QED	−215	46
Finite nuclear size and polarizability		
$\propto \alpha^4$	−138 131	0
$\propto \alpha^5$	14	2
$\propto \alpha^6$	−124	53
$\propto \alpha^7$	<1	0
Nuclear self-energy	−584	22
Total theory prediction	730 690 248 610 787	179

Experiment uncert.:

490 Hz

experimental input contributions to the prediction: 138 Hz *(r_p)*, 3 Hz *(1S-2S)*, 2 Hz *(α)*, < 1Hz *(m_p/m_e)*

Hydrogen 2S-6P: which contributions are being tested



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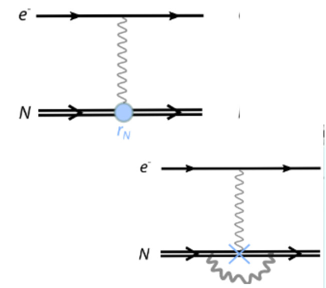
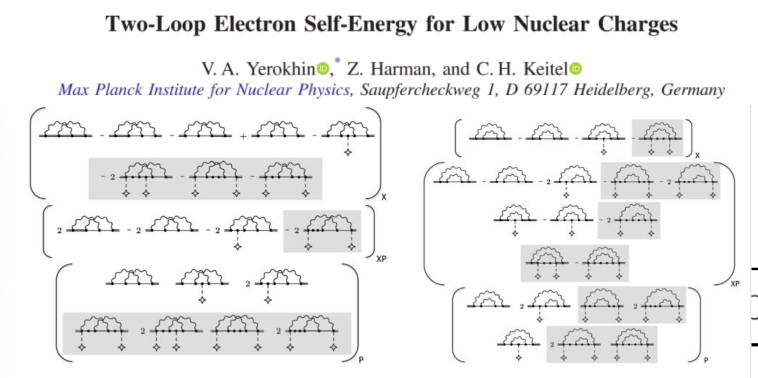


PHYSICAL REVIEW LETTERS **133**, 251803 (2024)

Editors' Suggestion



Two-Loop Electron Self-Energy for Low Nuclear Charges

V. A. Yerokhin,* Z. Harman, and C. H. Keitel

Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D 69117 Heidelberg, Germany

Experiment uncert.:

490 Hz

Approaching level of 3-loop QED

Level of current 2-loop QED research

CODATA theory uncertainty claimed 180 Hz, but recent recalculation **shifted theory value by ~ 500 Hz (~ 3σ)**

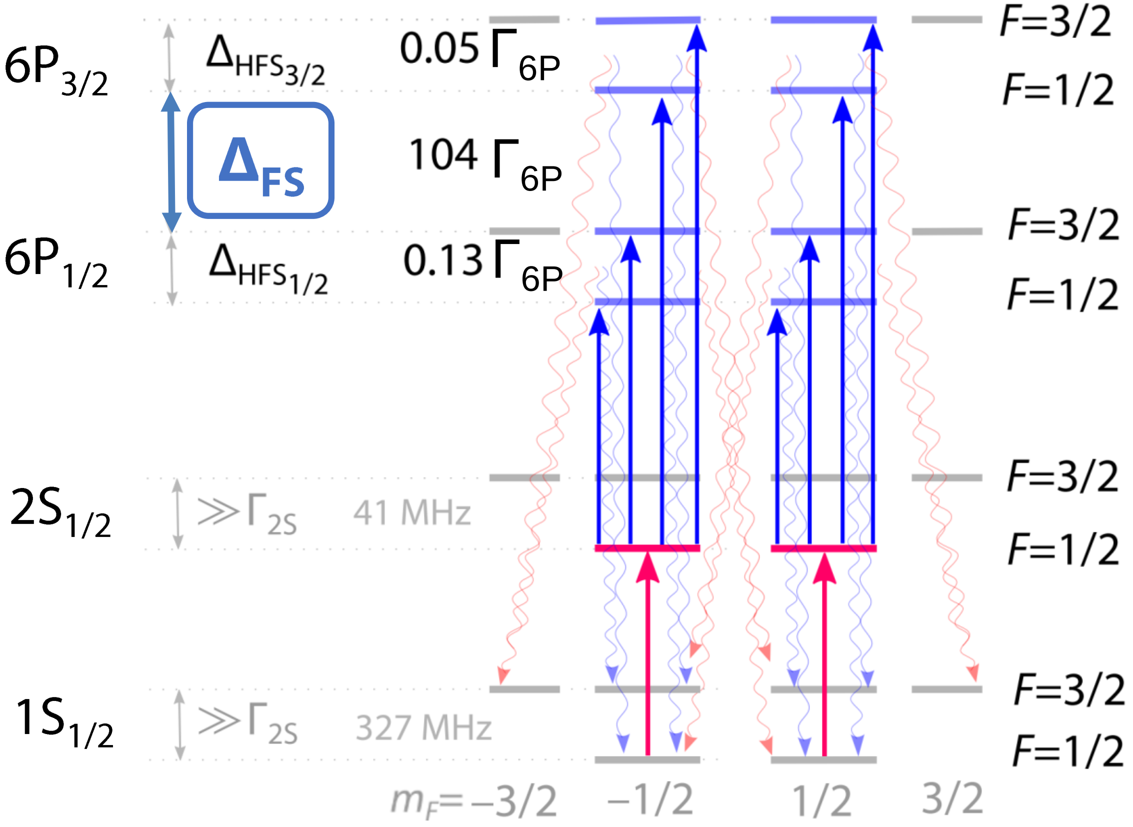
experimental input contributions to the prediction: 138 Hz *(r_p)*, 3 Hz *(1S-2S)*, 2 Hz *(α)*, < 1Hz *(m_p/m_e)*

Current and future plans

Deuterium 2S-6P vs Hydrogen 2S-6P

Higher nuclear spin ➔ 2S-6P excitation scheme more complicated in deuterium

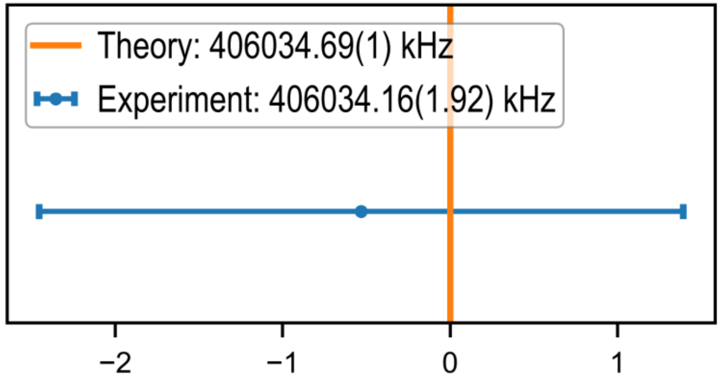
Γ_{6P} = 3.9 MHz (natural linewidth)



Systematic effect due to unresolved hyperfine structure **different for 2S-6P$_{1/2}$ vs 2S-6P$_{3/2}$**

➔ **fine-structure splitting Δ_{FS}** provides a **powerful test** for systematic uncertainties from **unresolved transitions**

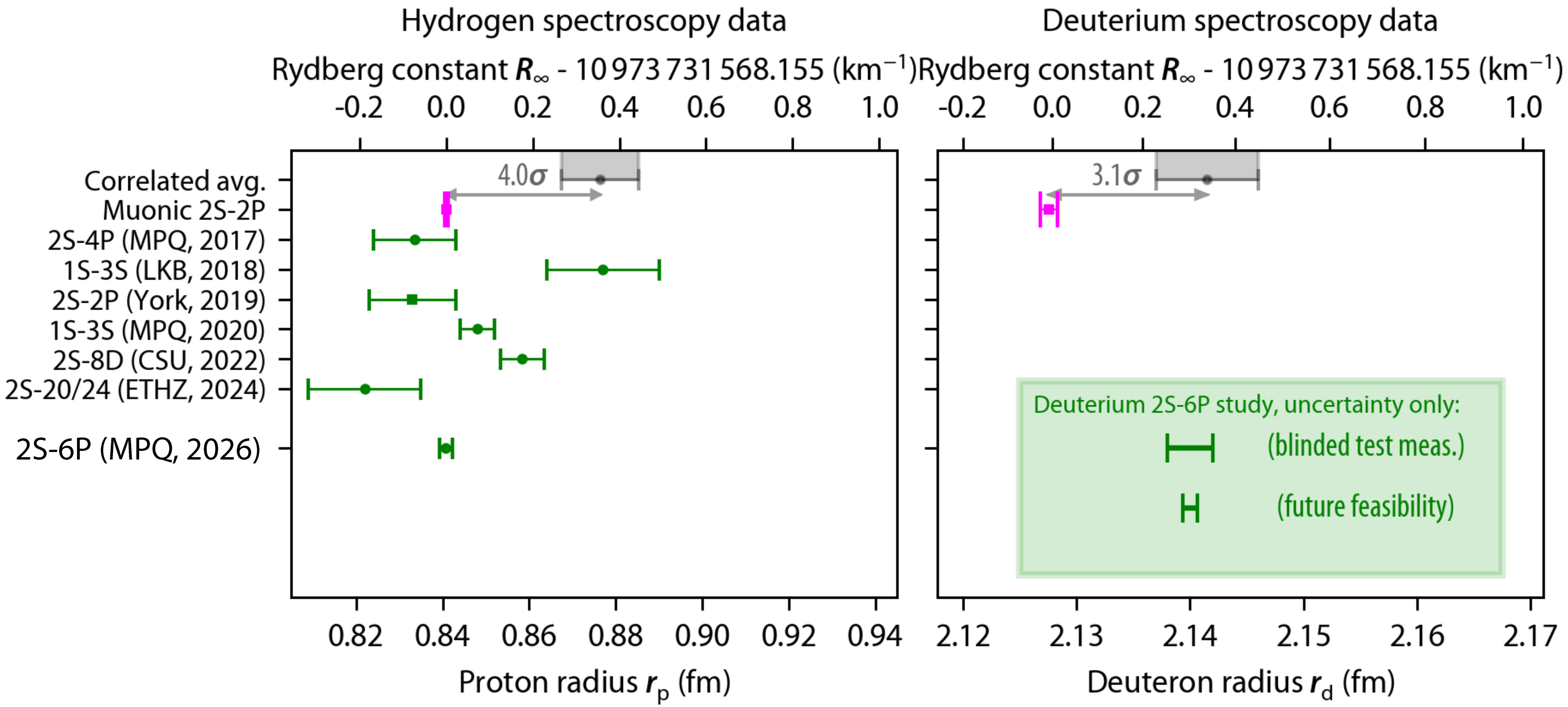
➔ successful test in prelim. measurement



Deuterium 6P fine-structure splitting Δ_{FS} (kHz, 406 034 692 Hz offset)

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

Deuterium 2S-6P: measurement campaign in progress



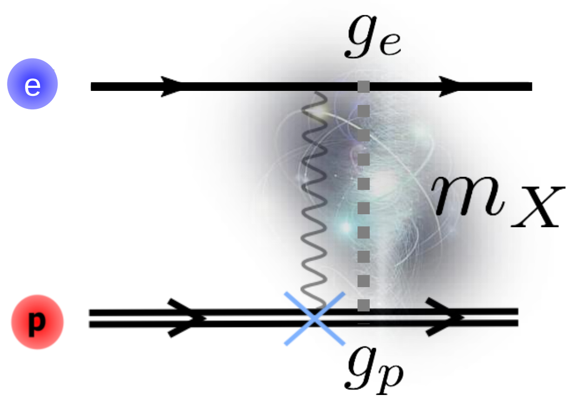
Deuterium 2S-6P measurement is feasible with a similar uncertainty as in hydrogen

Successful fine-structure splitting test was performed, measurement campaign is currently ongoing

New Physics constraints

Unique New Physics constraints from hydrogen

New **spin-independent coupling** between proton and electron leads to:



Modified Coulomb potential with Yukawa term (in *natural units*)

$$V(r) = \frac{\alpha + \alpha' \exp(-m_X r)}{r}$$ where $$\alpha' \propto |g_p g_e| \ll 1$$

very weak
electron-proton
coupling

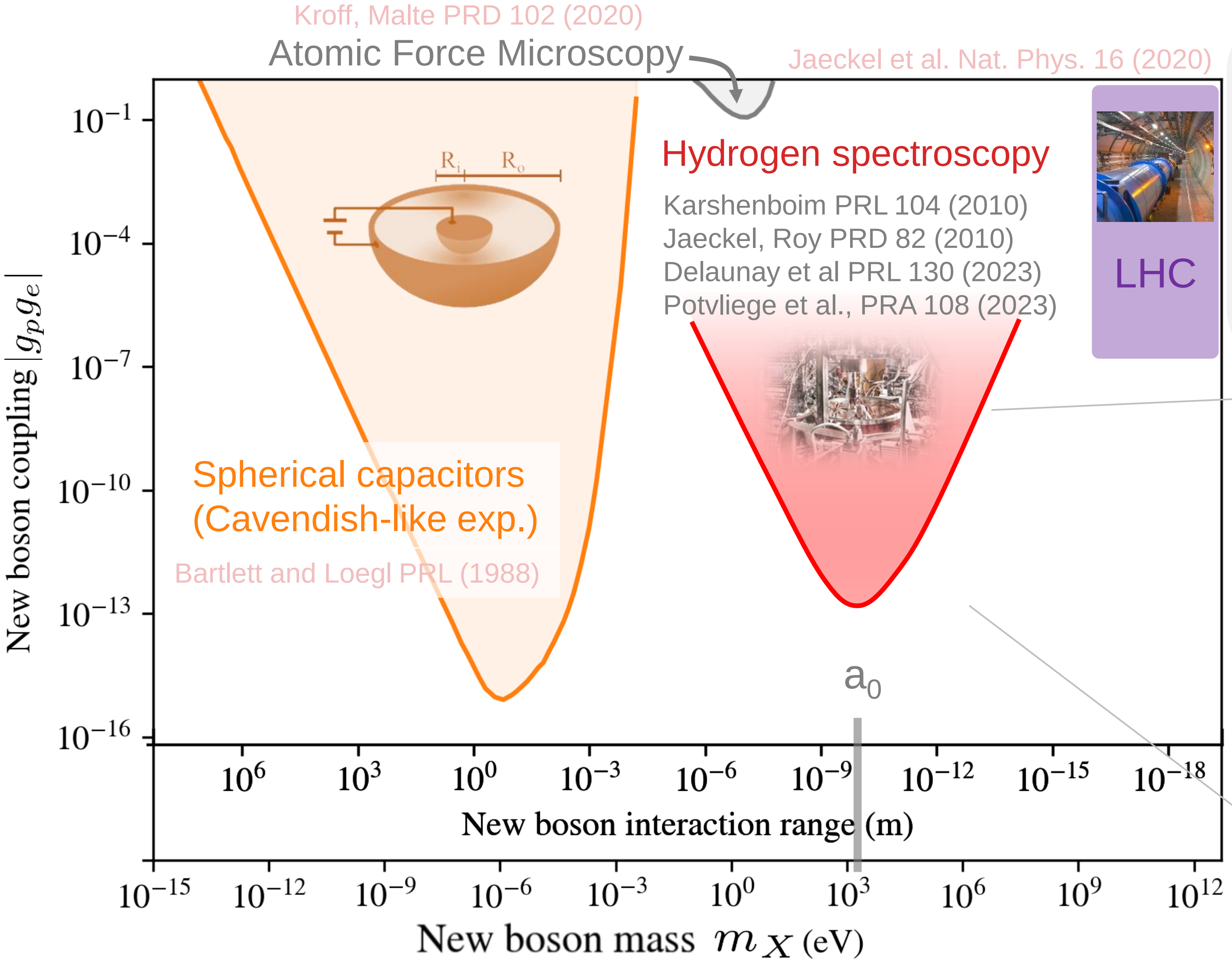
Bohr radius mass scale:
a_0 = 0.5 Å = 4 keV

Hydrogen spectroscopy
tests the Coulomb law
at distances **> 0.5 Å (Bohr radius)**

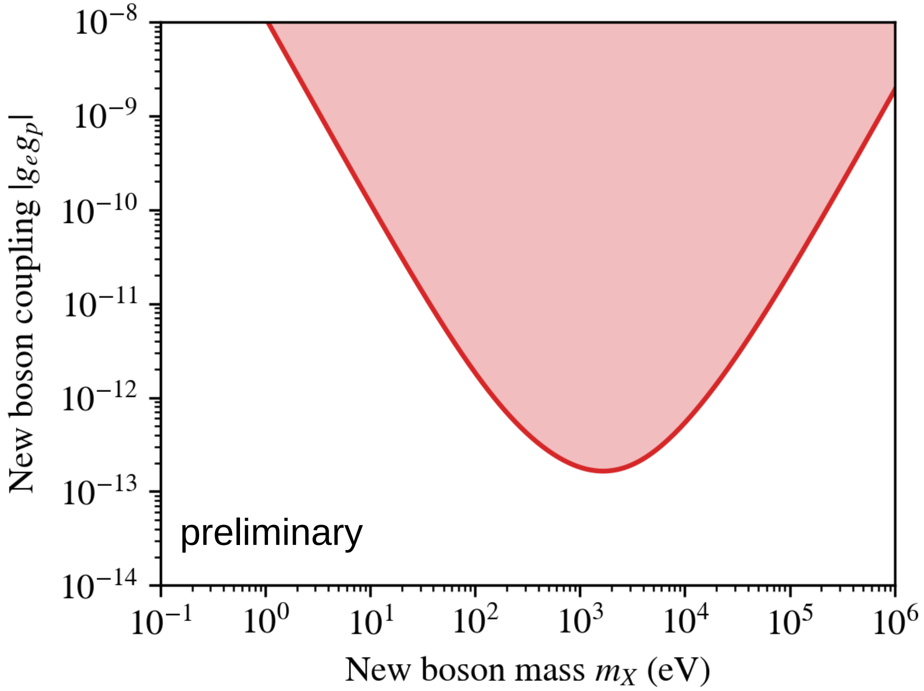
≡

Hydrogen spectroscopy probes
new bosons with masses $\boldsymbol{m_X}$ **< keV**
‘5th force search’, ‘hidden photon’, ‘kinetic mixing’

Unique New Physics constraints from hydrogen



Hydrogen: unique probe for a model-independent **Coulomb law test at 1 Å** (= new boson search in the **keV range**), our 2S-6P result pushes bounds to relative **couplings down to 10^{-13}**

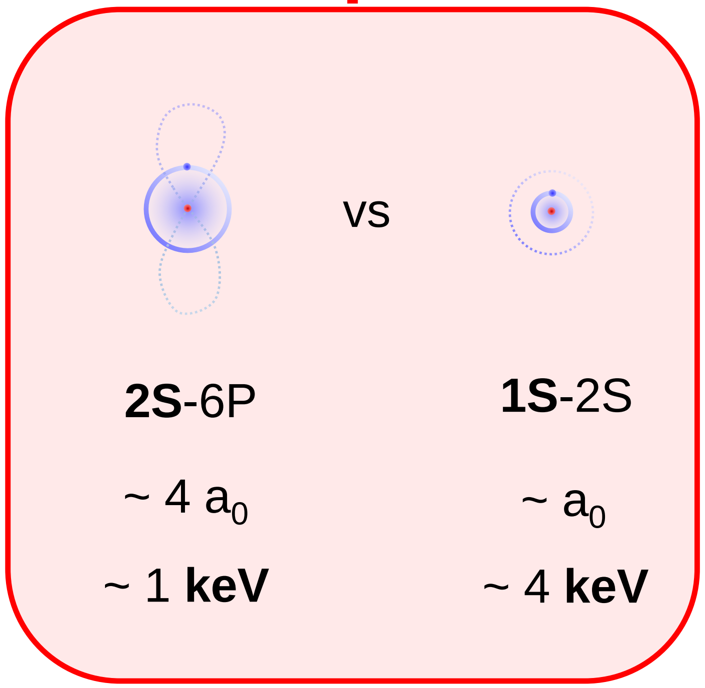


Note: model-dependent astrophysical bounds not shown, see e.g. A. Caputo et al., PRD 104 (2021)

review: V. Wirthl et al., in prep. for Rep. Prog. Phys (2026)
V. Wirthl and R. Potvliege, publication in preparation

Unique New Physics constraints from hydrogen

2S-6P:
tightest constraint for the
keV–scale



2S-6P

~ 4 a_0

~ 1 **keV**

1S-2S

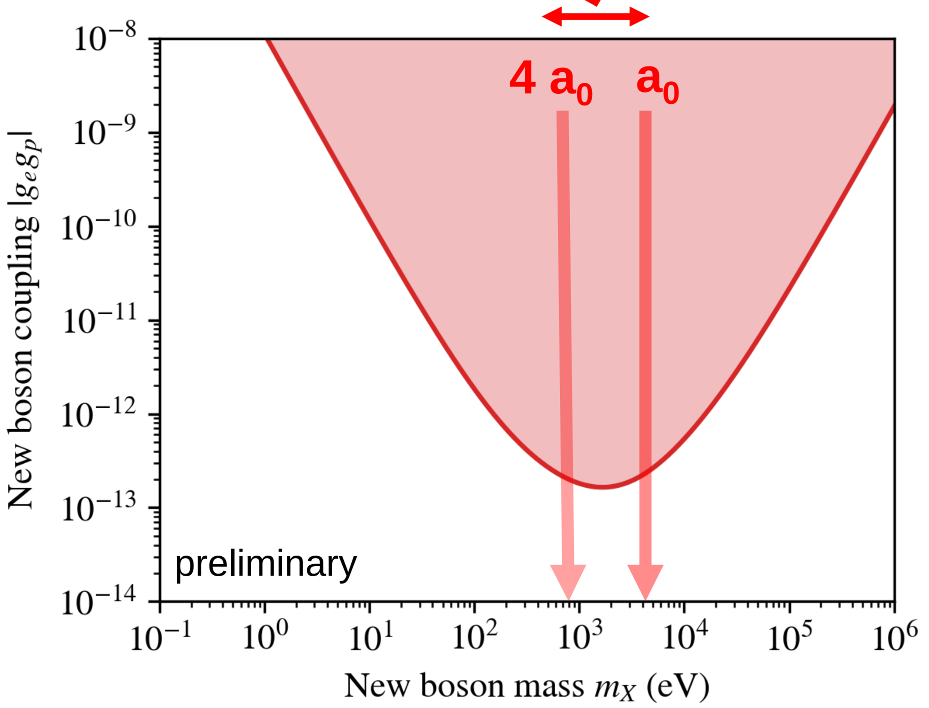
~ a_0

~ 4 **keV**

$$V(r) = \frac{\alpha + \alpha' \exp(-m_X \boxed{r})}{\boxed{r}}$$

Constraint on $g_p g_e$
(electron-proton coupling)

Hydrogen 2S-6P
provides
tightest constraint
for **keV-scale**
dark photons



Consistency of Coulomb potential (→ R_∞)
at different length scales

review: V. Wirthl et al., in prep. for Rep. Prog. Phys (2026)
V. Wirthl and R. Potvliege, publication in preparation

S. Karshenboim PRL 104 (2010), R. M. Potvliege et al., PRA 108 052825 (2023)
C. Delaunay et al., PRL 130 121801 (2023), arXiv:2602.20750 (2026)

Planned future:
Improved New physics constraints

MCQST START Fellowship Junior Research Group

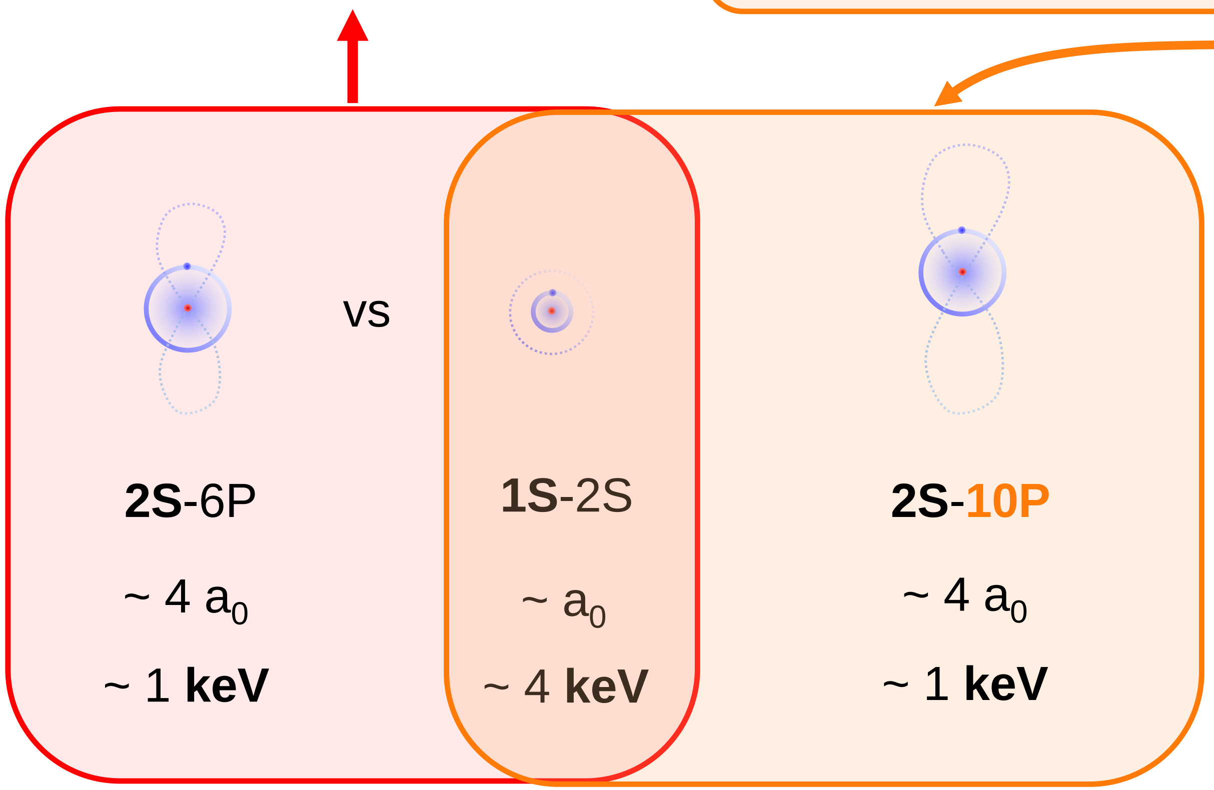
Vitaly Wirthl

Unique New Physics constraints from hydrogen

2S-6P:
tightest constraint for the
keV–scale

Our planned **higher 2S-nP**
measurements **improve bounds,**
but not much

Constraint on $g_p g_e$
(electron-proton coupling)



2S-6P

~ 4 a_0

~ 1 **keV**

vs

1S-2S

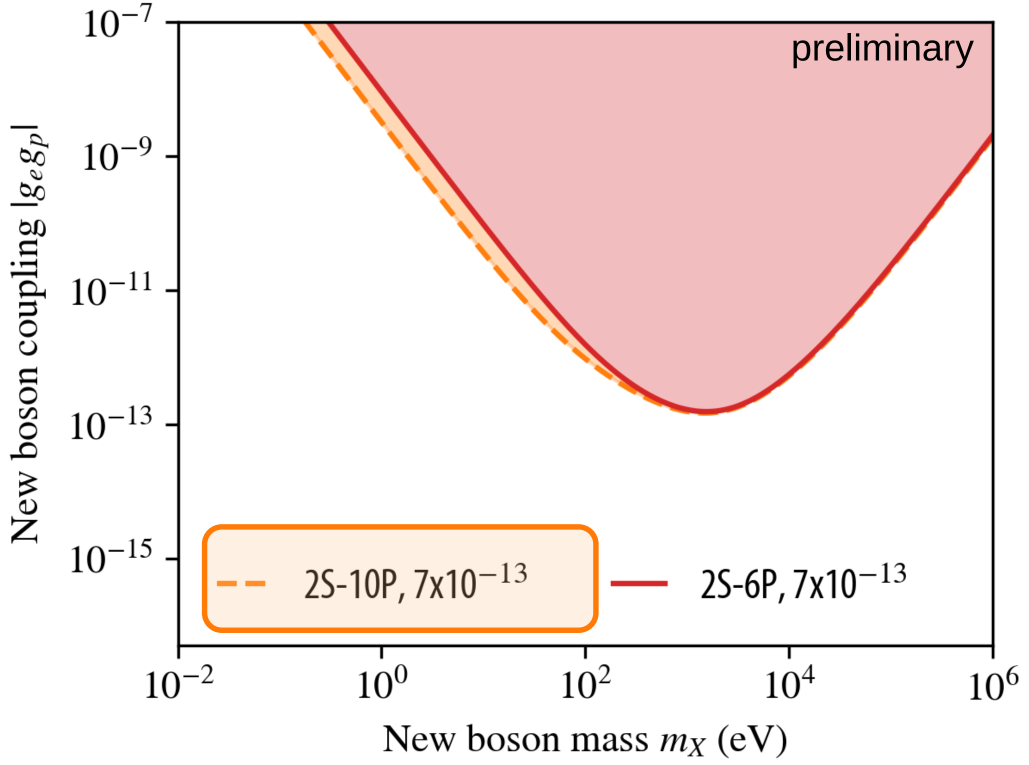
~ a_0

~ 4 **keV**

2S-**10P**

~ 4 a_0

~ 1 **keV**



Consistency of Coulomb potential ($\rightarrow R_\infty$)
at different length scales

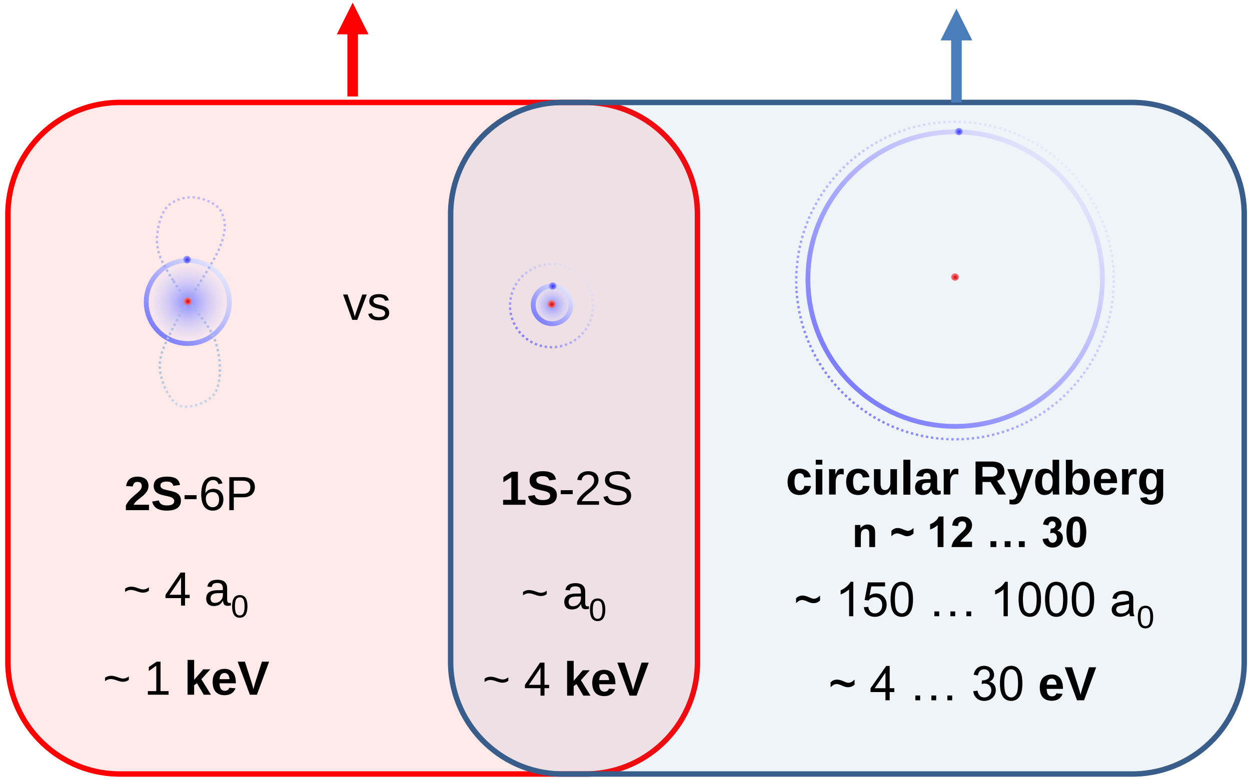
V. Wirthl and R. Potvliege, publication in preparation

Circular Rydberg spectroscopy for improved New Physics constraints

2S-6P: **tightest constraint** for the keV–scale

Circular Rydberg transitions: constraints with **widest mass range**

…essentially **free from nuclear and QED effets,** robust theory, suppressed cross-damping
U. Jentschura and D. Yost PRA 108 (2023)



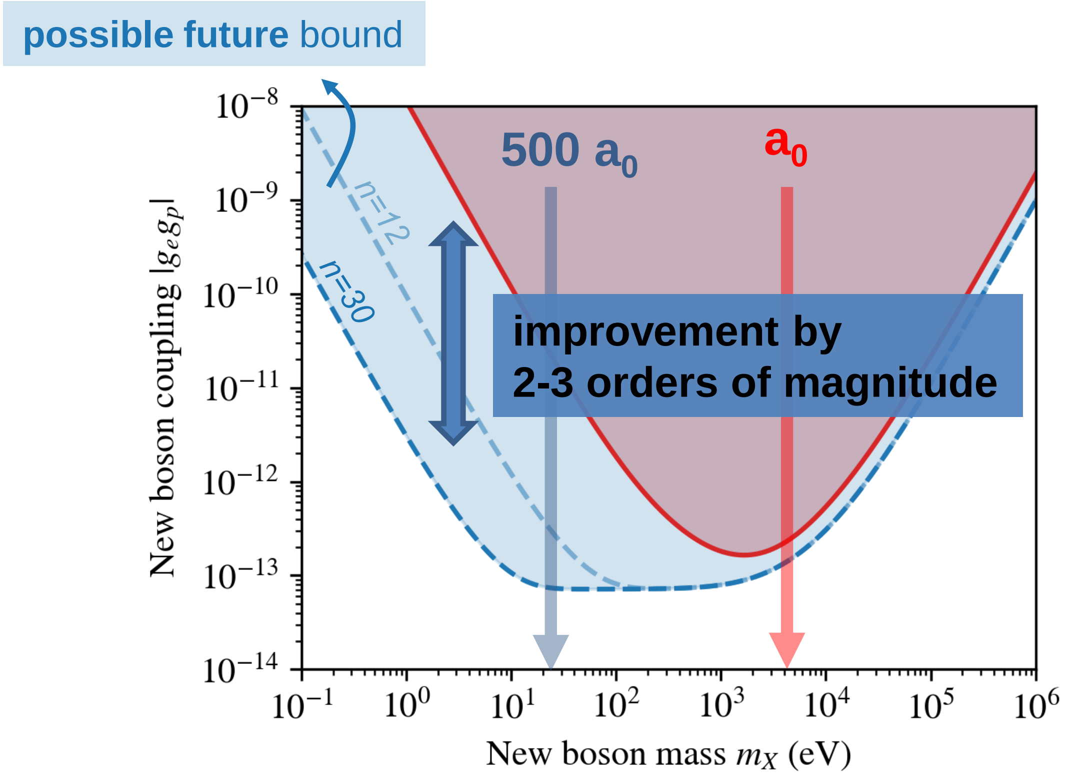
2S-6P
~ 4 a_0
~ 1 **keV**

vs

1S-2S
~ a_0
~ 4 **keV**

circular Rydberg
n ~ 12 … 30
~ 150 … 1000 a_0
~ 4 … 30 **eV**

Consistency of Coulomb potential ($\rightarrow R_\infty$)
at different length scales



V. Wirthl and R. Potvliege, publication in preparation

Circular Rydberg spectroscopy for improved New Physics constraints

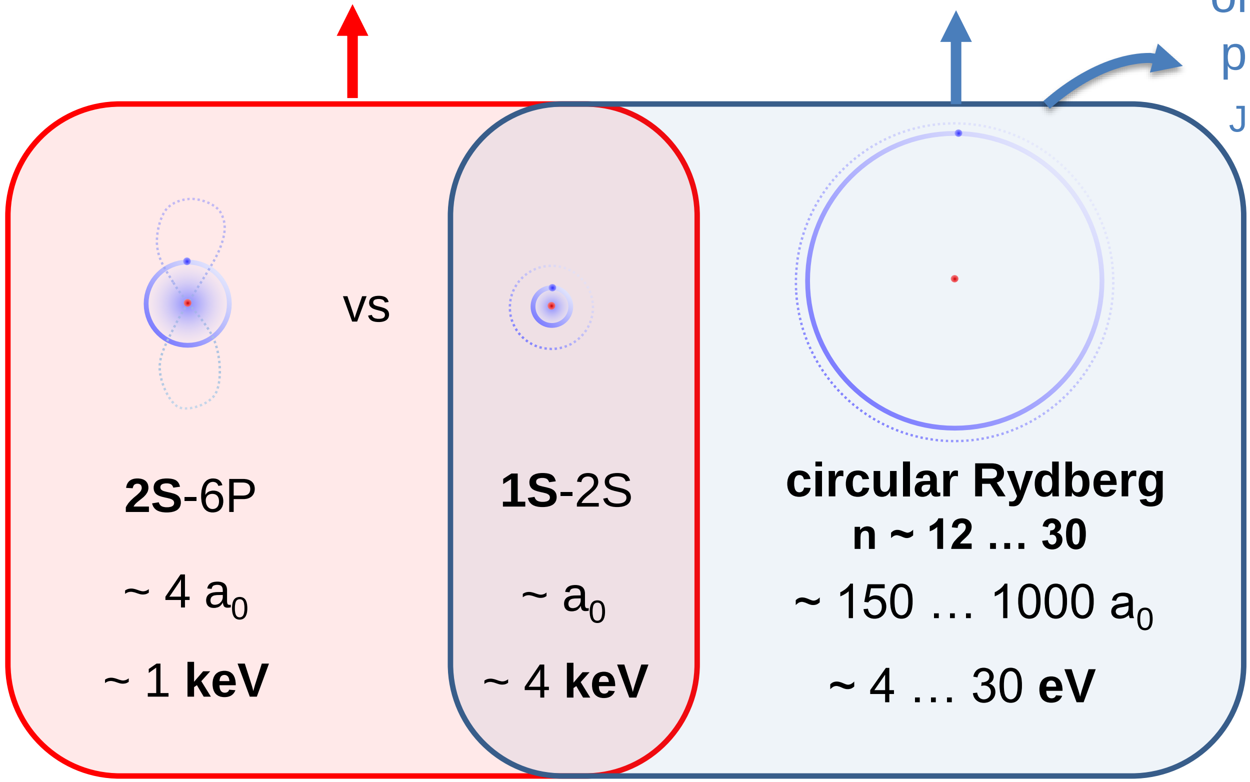
2S-6P:
tightest constraint for the
keV–scale

Circular Rydberg transitions:
constraints with
widest mass range

only a single 25-year-old
preliminary result exists

J. De Vries, PhD thesis MIT (2001)

..paper not published, uncertainty unreliable


vs

2S-6P
~ 4 a_0
~ 1 **keV**

1S-2S
~ a_0
~ 4 **keV**

circular Rydberg
n ~ 12 … 30
~ 150 … 1000 a_0
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Consistency of Coulomb potential ($\rightarrow R_\infty$)
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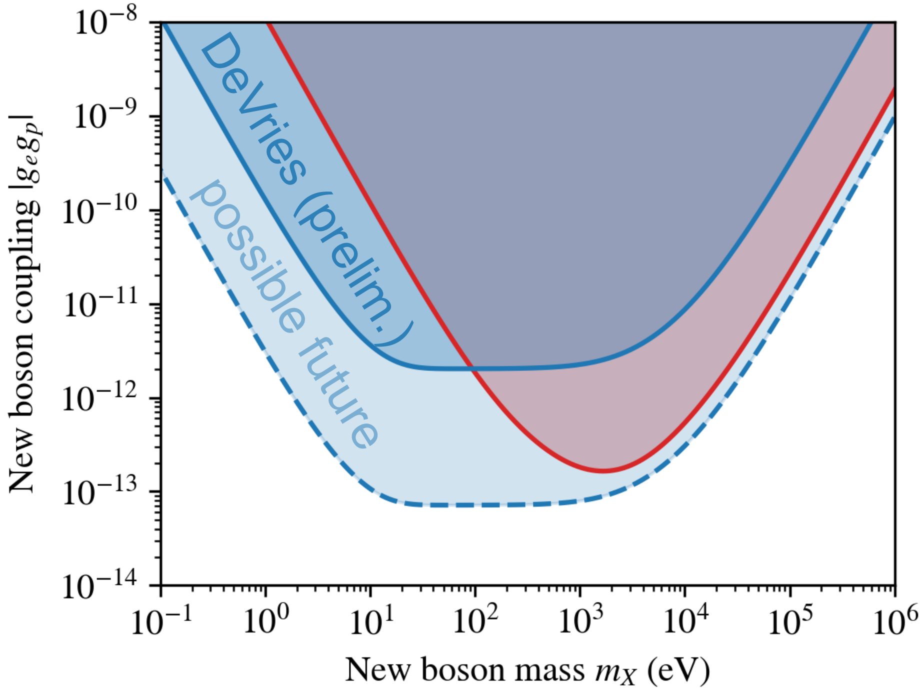


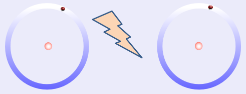
V. Wirthl and R. Potvliege, publication in preparation

Why has prior work remained incomplete?

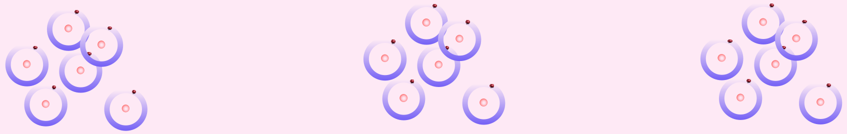
Prior work: J. De Vries, PhD thesis MIT (2001)

Why prior work remained incomplete?

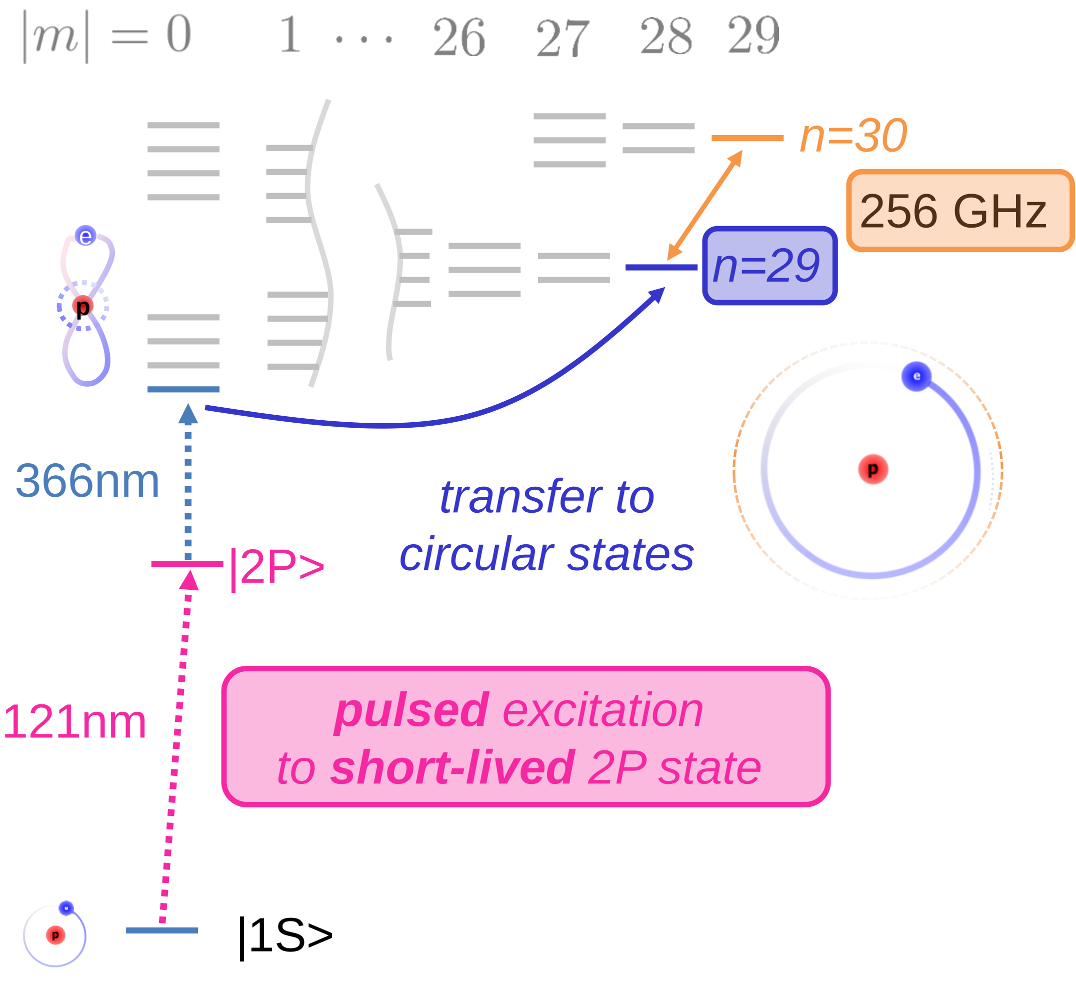
Systematic uncertainty **limited by dipole-dipole interactions**
➔ increases with **density**, scales as $\boldsymbol{n^4}$



Pulsed production of circ. Rydberg atoms
➔ **high peak density** + low statistics



No suitable laser–based THz sources available
➔ single electronic source for ~ **300 GHz**
➔ forced to probe very ***high n=27..30 states***



transfer to circular states

***pulsed** excitation to **short-lived** 2P state*

80K atomic beam

Future reliable and versatile circular Rydberg spectrometer

This work: **reliable** and **versatile circular Rydberg spectrometer**

Suppress and characterize dipole-dipole interactions

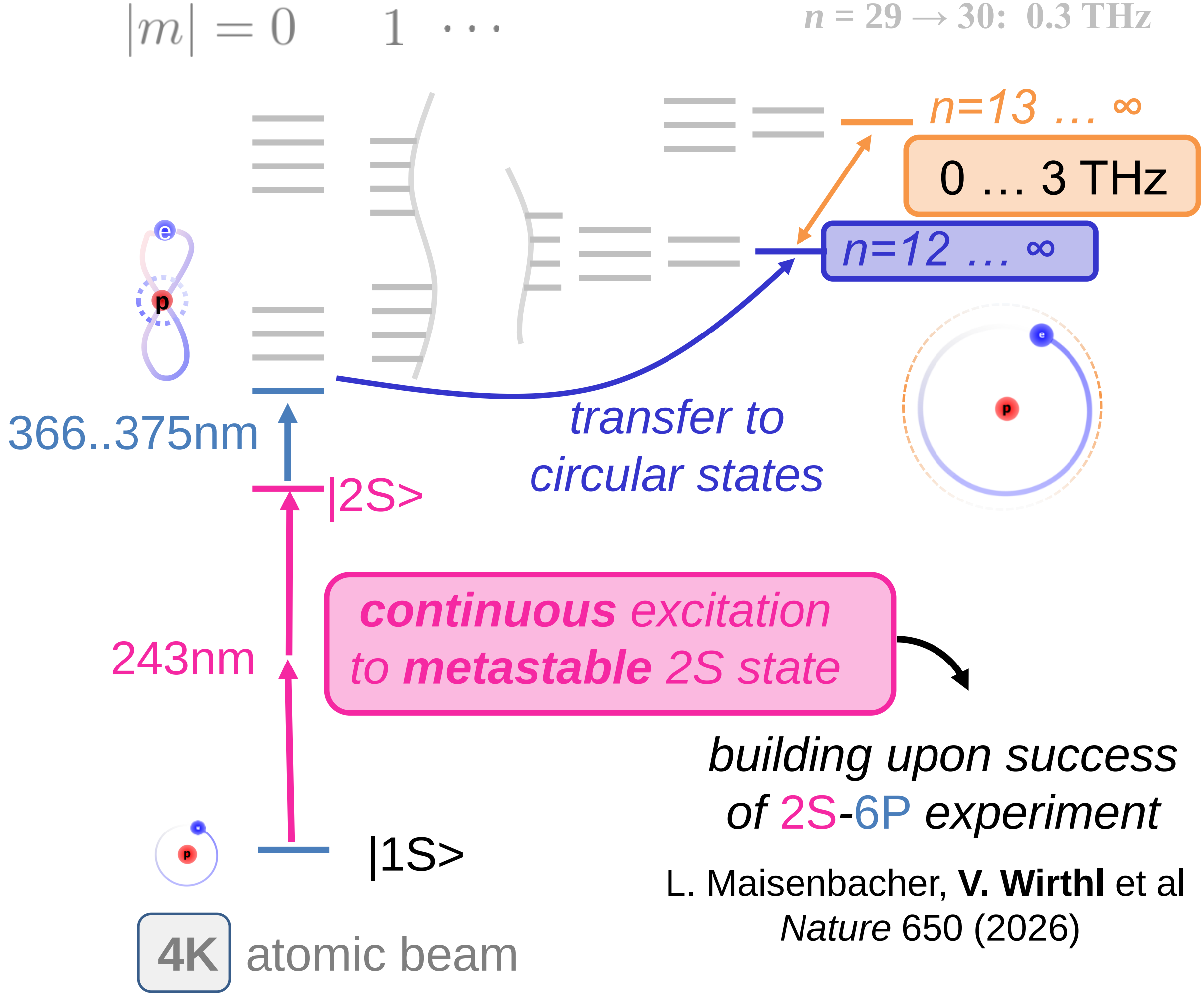
➔ up to 10^6 lower density

➔ lower ***n*** ➔ vary ***n***

Continuous production of circ. Rydberg atoms
➔ **low density** + high statistics

Exploit **novel laser–based THz sources**
➔ single compact system for **0…3 THz**
➔ flexible to probe ***all n = 12 …∞ circular states***

$n = 12 \rightarrow 13$: 3.3 THz
…
$n = 18 \rightarrow 19$: 1.0 THz
…
$n = 29 \rightarrow 30$: 0.3 THz



building upon success of 2S-6P experiment

L. Maisenbacher, **V. Wirthl** et al
Nature 650 (2026)

Leveraging cutting-edge THz technology

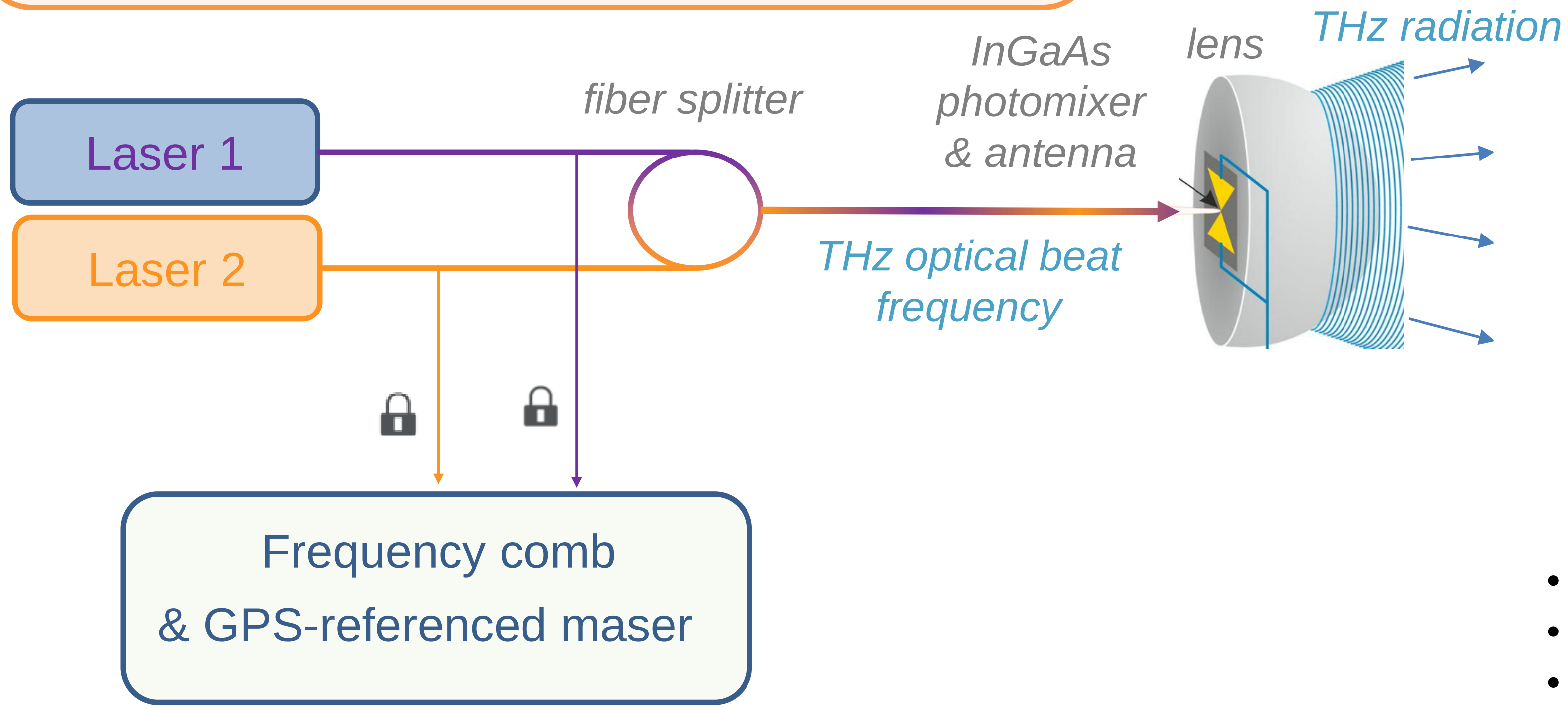
“Frequency-domain THz spectroscopy”

Laser–based cw THz precision spectroscopy
➔ demonstrate sub-Hz narrow THz radiation
➔ probe circular Rydberg state transitions

Novel THz technology based on **photomixers** and **frequency-comb** locked lasers

Lowest phase noise of any cw THz source!

Mueller et al, J. Infr. THz Waves (2025)
Krause et al, Nat. Comm 16 (2025)

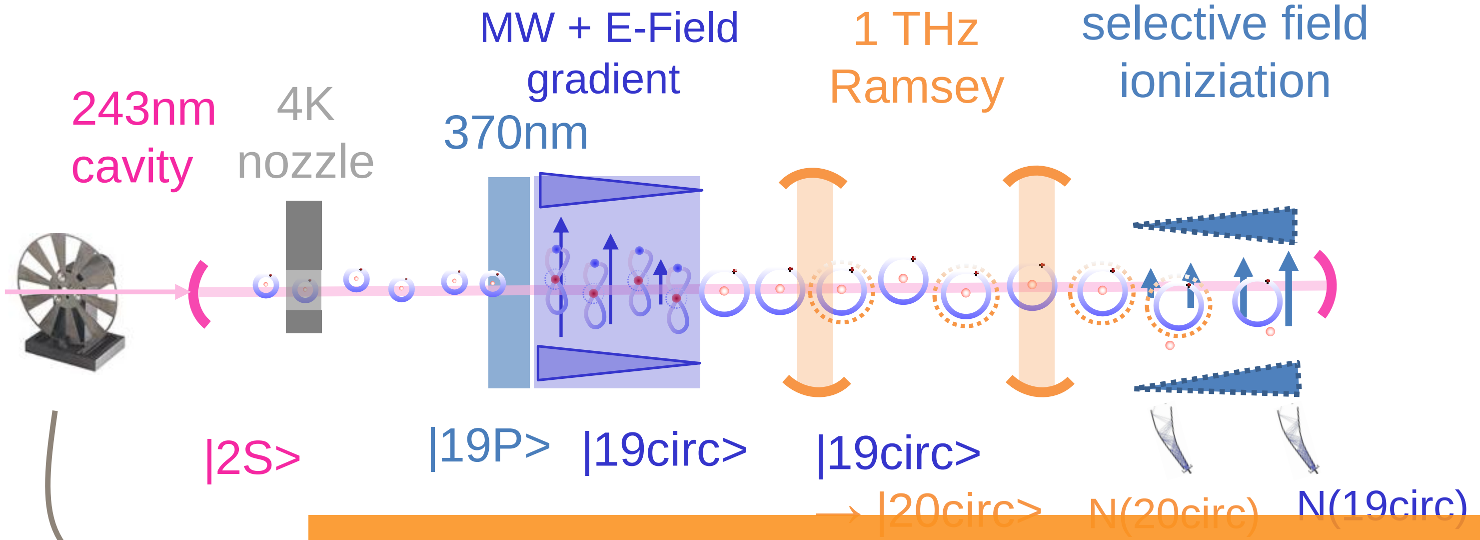


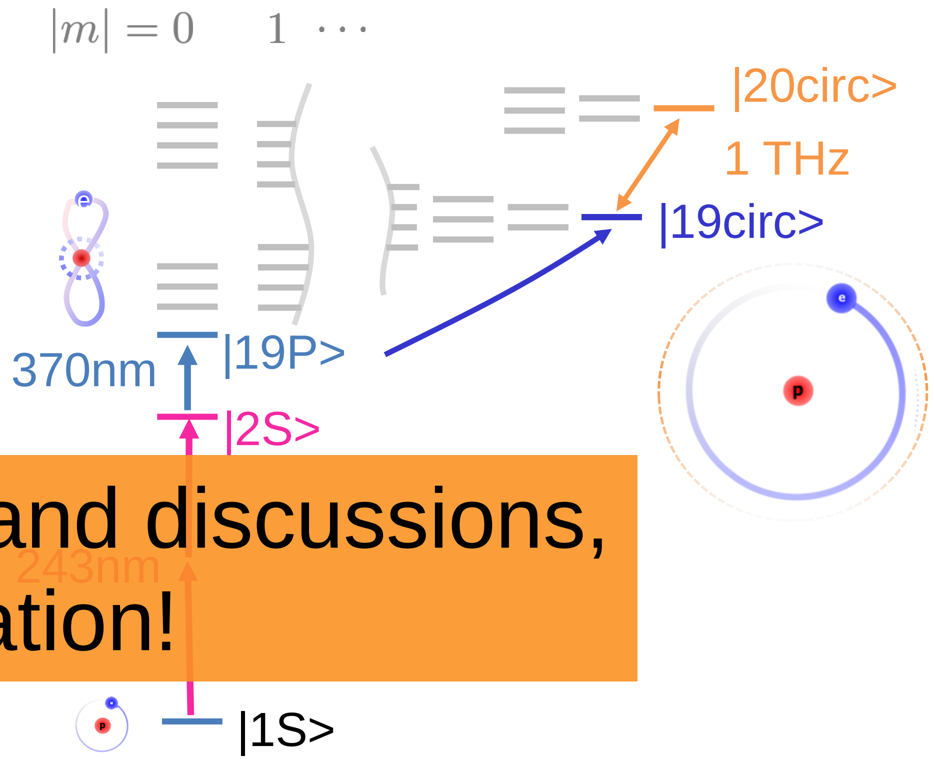
MPQ infrastructure

Toptica TeraScan1550 system

- 2 lasers + fiber combiner + THz mixer/antenna
- THz radiation : **DC … 3 THz**
- linewidth (comb-locked lasers): **< 1 Hz**

Circular Rydberg state spectroscopy: proposed experimental setup

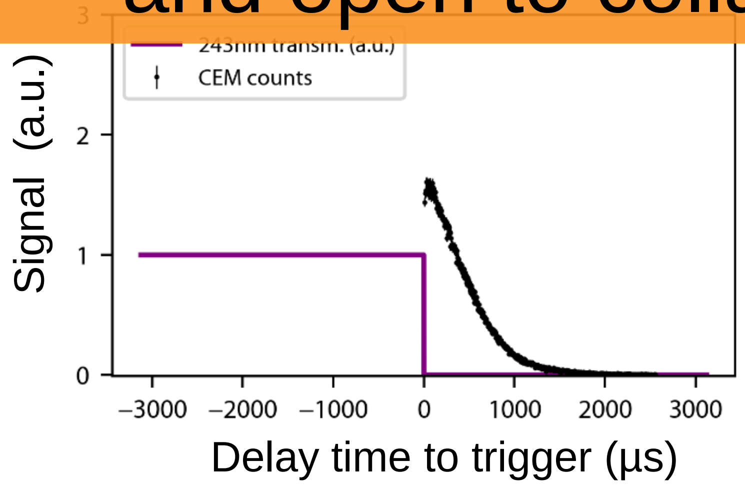




I am thankful for any comments and discussions, and open to collaboration!

chopper periodically stops 1S-2S excitation → trigger

Time-resolved signal: *study systematic uncertainties*



2S-6P Hydrogen Team 2015-2024


Lothar
Maisenbacher


Vitaly
Wirthl


Alexey
Grinin


Arthur
Matveev


Randolf
Pohl


Thomas
Udem

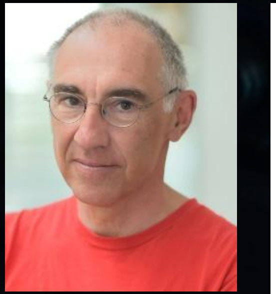

Theodor W.
Hänsch

Thank you for your attention!

Current MPQ Hydrogen Team


Randolf
Pohl


Theodor W.
Hänsch


**Thomas
Udem**

Advanced
Grant

2S-*n*P

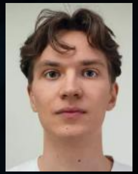

Vitaly
Wirthl


Alexander
Wilzewski


Sudhir
Suresh

1S-3S


Derya
Taray


Vincent
Weis


Surabhi
Deshpande

H-Trap


Omer
Amit


Patrick
Schaile


Mustafa
Syed


Andrew
Klug

Thank you for your attention!

Current MPQ Hydrogen Team

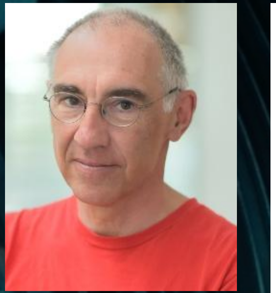
MCQST

START Fellowship Group

Vitaly
Wirthl

Randolf
Pohl

Theodor W.
Hänsch



**Thomas
Udem**

erc Advanced Grant

2S-*n*P and Circular Rydberg

Open positions!

?

?

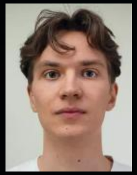
?

Alexander
Wilzewski

Sudhir
Suresh

1S-3S

Derya
Taray



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