The proton radius from atomic/molecular spectroscopy : Current status and perspectives

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5th French-Ukrainian workshop
Instrumentation developments for high energy physics
LAL, Orsay, 7 November 2017

Metrology at Lab. Kastler Brossel

4 research axes

- Quantum gases
- Atoms and light in dense or complex media
- Quantum optics and quantum information
- Test of fundamental interactions and metrology

2 research teams

Metrology of simple systems and fundamental tests

- H atom spectroscopy $\rightarrow R_\infty, r_p$ (F. Nez)
- Heavy ions and exotic ions (P. Indelicato)
- Atom interferometry $\rightarrow \alpha$ (S. Guellati, P. Cladé)

Metrology of trapped ions

- H_2^+ spectroscopy (L. Hilico) $\rightarrow m_p / m_e$
- HMI theory (JPK) R_∞, r_p

International collaborations

- CREMA (Muonic Atom spectroscopy)
- GBAR (Gravitational Behaviour of Anti-hydrogen at Rest)

Outline

I. Introduction

Atomic energy levels, and the proton radius

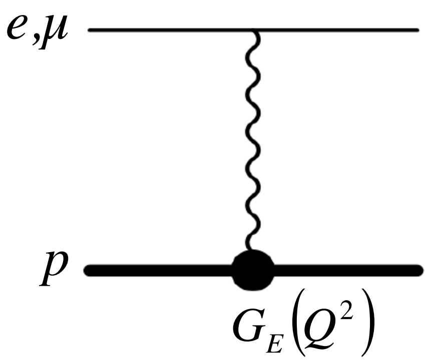
II. Current status of the "puzzle"

After recent measurements in hydrogen

III. New experiments

Focus on the hydrogen molecular ions

Finite-size shift of atomic energy levels



The proton radius is defined as

$$r_p^2 \equiv -6 \left.\frac{dG_E}{dQ^2}\right|_{Q^2=0}$$

G_E : Sachs electric form factor

- Modification of the Coulomb potential w.r.t. a point-like proton:

$$\delta V(\mathbf{r}) = -4\pi\alpha \int \frac{d^3q}{(2\pi)^3} \frac{\left[G_E\left(\mathbf{q}^2\right)-1\right]e^{-i\mathbf{q}\cdot\mathbf{r}}}{\mathbf{q}^2}$$

Leading order: $G_E\left(\mathbf{q}^2\right)-1 \approx -\frac{\mathbf{q}^2 r_p^2}{6}$ In atomic physics: $r_p q \sim r_p / a_0 \sim 10^{-5}$

$$\Rightarrow \quad \delta V(\mathbf{r}) = \frac{2\pi\alpha}{3} r_p^2\, \delta(\mathbf{r})$$

Finite-size shift of atomic energy levels

Shift of an atomic bound state: $\Delta E = \langle \psi | \delta V | \psi \rangle = \frac{2}{3} \pi \alpha |\psi(0)|^2 r_p^2$

Hydrogen-like atom, nl state: $\Delta E = \frac{2\alpha^4}{3n^3} m_r^3 r_p^2 \, \delta_{l0}$

Orders of magnitude

Hydrogen atom, 1S state: $\Delta E / h \approx 1.2\,\mathrm{MHz} \approx \mathbf{5.10^{-10}}\ \nu_{1S\text{-}2S}$

Exp. accuracy $\approx 10\,\mathrm{kHz} \Rightarrow \approx \mathbf{1\%}$ on r_p

Muonic hydrogen, 2S state: $\Delta E / h \approx 0.96\,\mathrm{THz} \approx \mathbf{2\%}$ of $\nu_{2S\text{-}2P}$

Exp. / theor. accuracy $\approx 0.5\,GHz \Rightarrow \approx \mathbf{5.10^{-4}}$ on r_p

Hydrogen atom energy levels

- Main dependences on fundamental constants

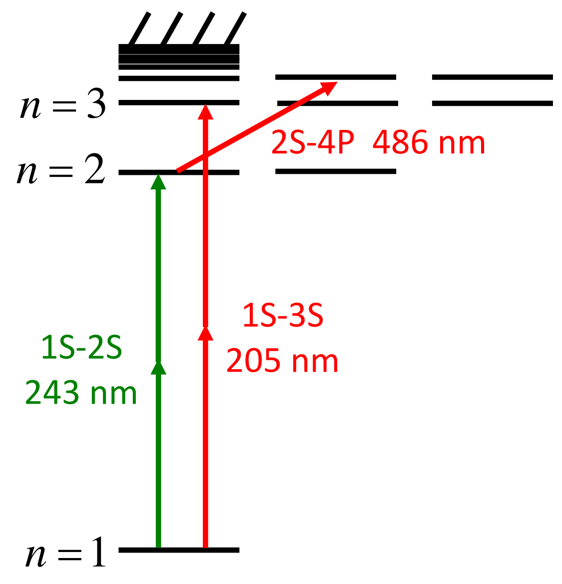
$$E_{n,l,j} = hcR_\infty \left[-\frac{1}{n^2}\frac{1}{1+1/\mu_{pe}} + \alpha^2 A(n,l,j) + \frac{4}{3n^3}\left(\frac{r_p}{a_0}\right)^2 \delta_{l0} + \dots \right]$$

Schrödinger — Relativistic and QED corr. — Finite nuclear size corr.

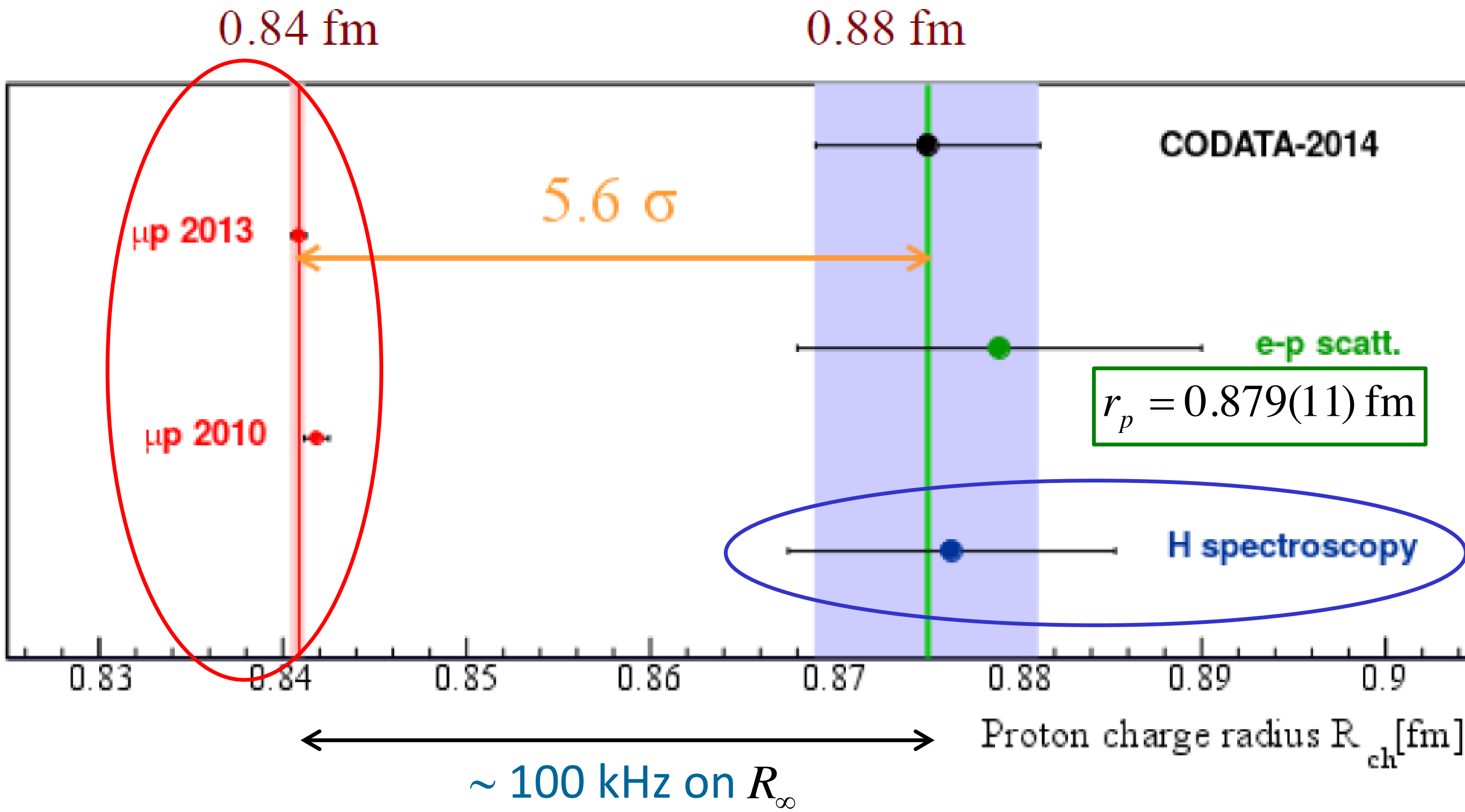
- $\mu_{pe} = m_p / m_e$ and α determined by other experiments

- 2 measurements required to determine R_∞ and r_p
  - A **single** narrow transition: 1S-2S ($\Delta\nu$ = 1.3 Hz) measured with high accuracy.
  - Other transitions: natural width ~ MHz.

  Each measurement, combined with 1S-2S, yields a correlated pair (R_∞, r_p).



The proton-radius puzzle



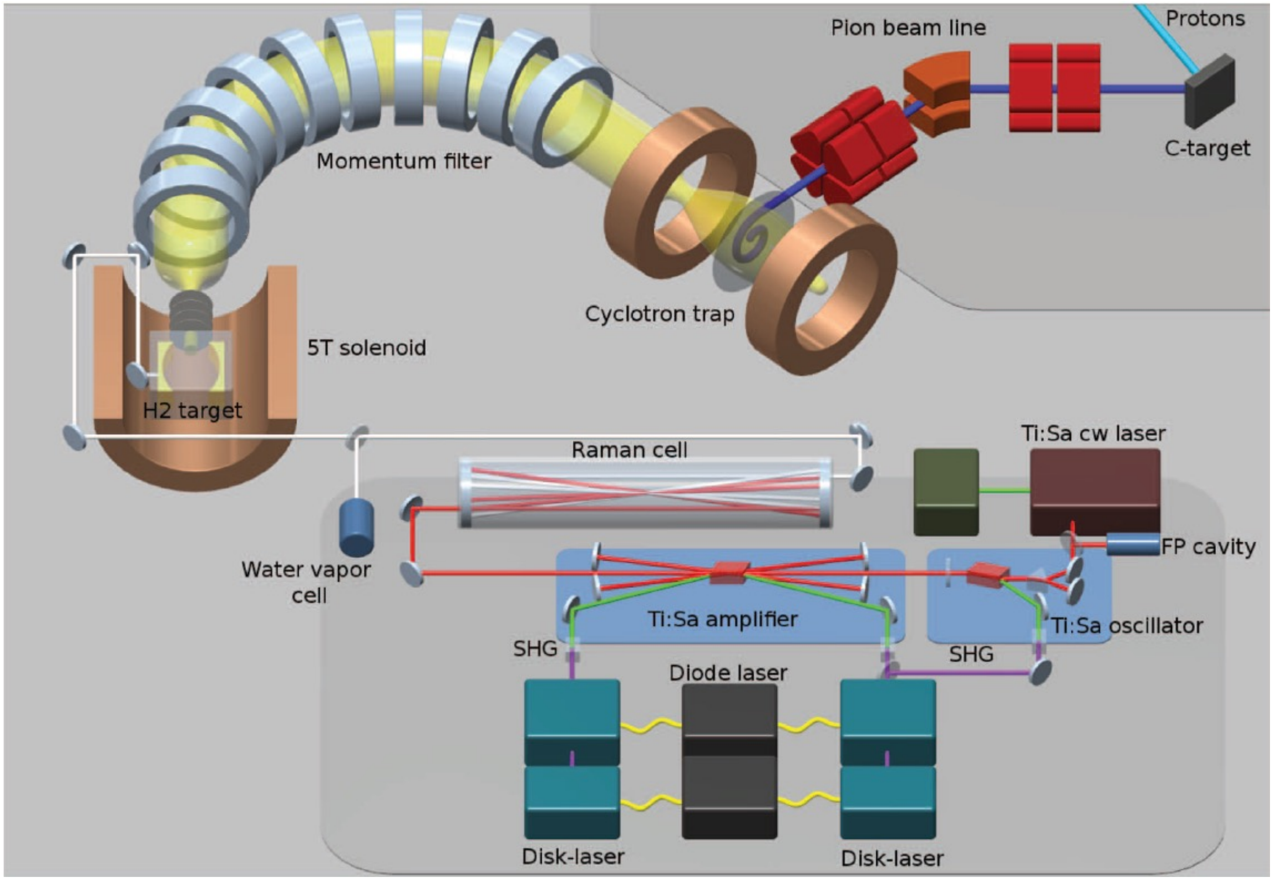
CODATA 2014: P.J. Mohr, D.B. Newell, and B.N. Taylor, Rev. Mod. Phys. **88**, 035009 (2016)

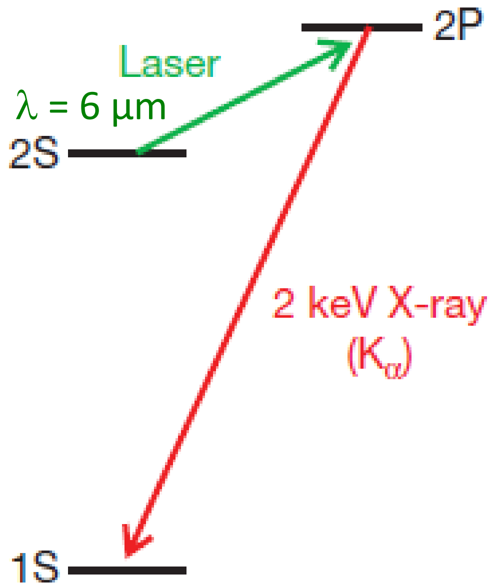
e-p scattering: J. Arrington and I. Sick., J. Phys. Chem. Ref. Data 44, 031204 (2015)

1) μp spectroscopy

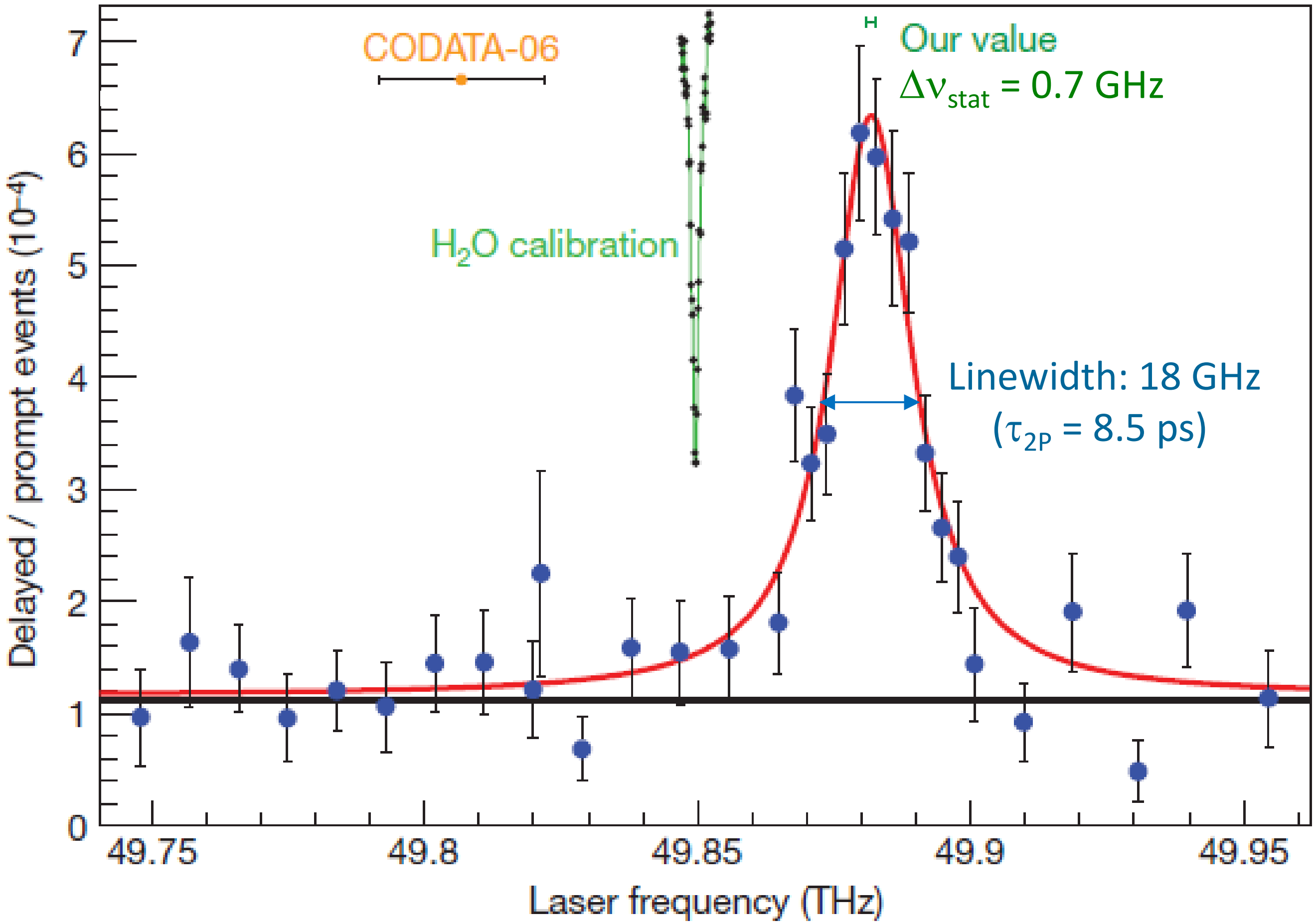
2) H spectroscopy

Muonic hydrogen spectroscopy at PSI





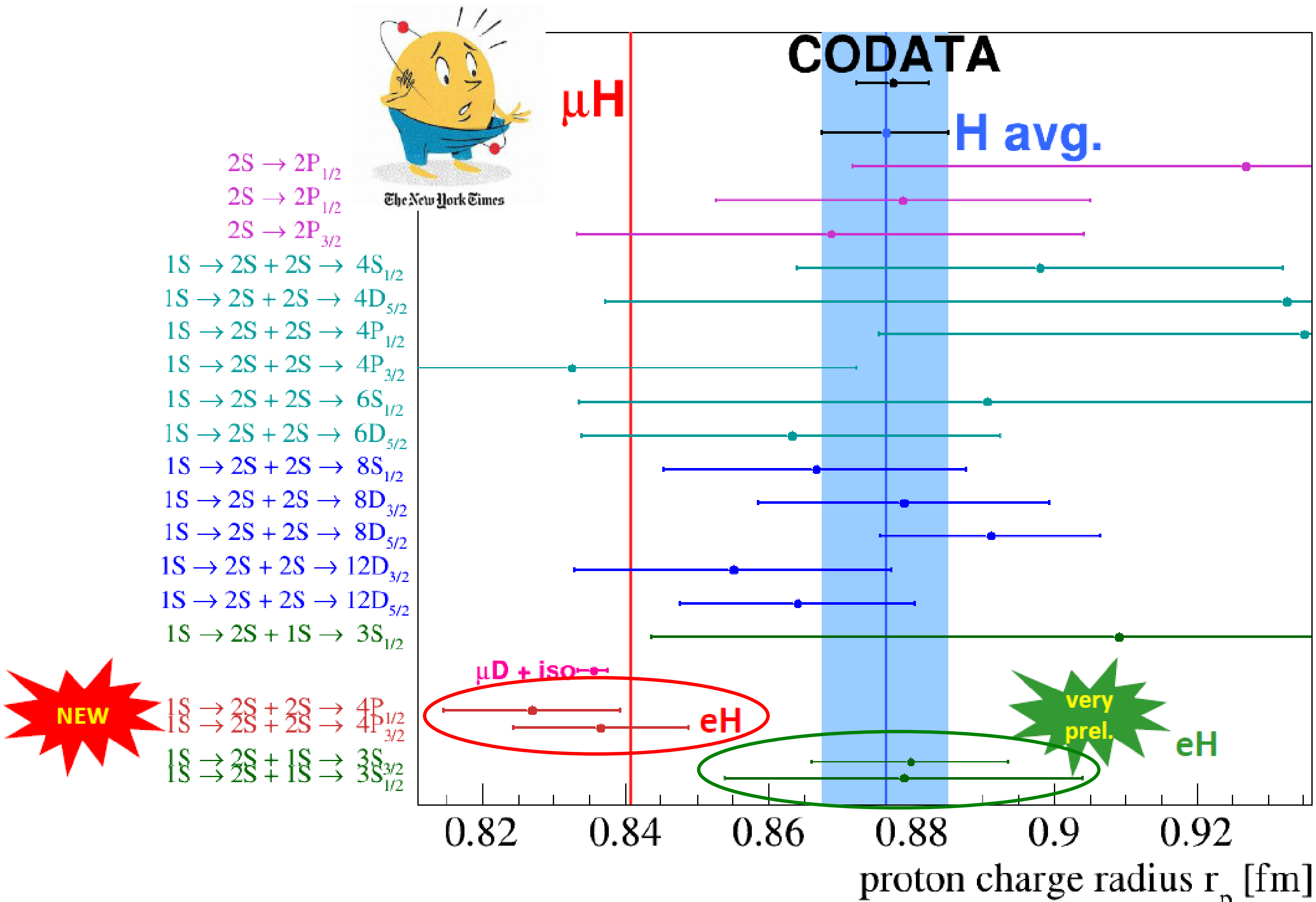
Muonic hydrogen spectroscopy at PSI



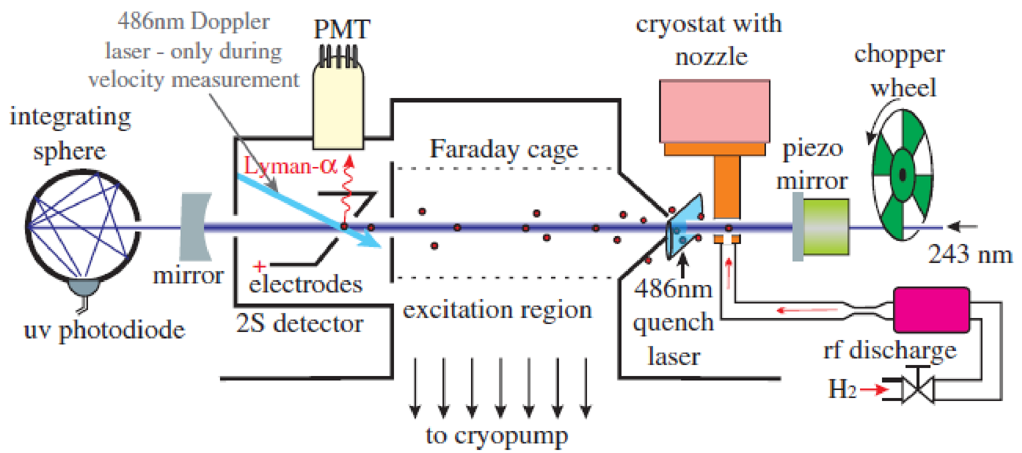
$$r_p = 0.84087(39)\ \text{fm}$$

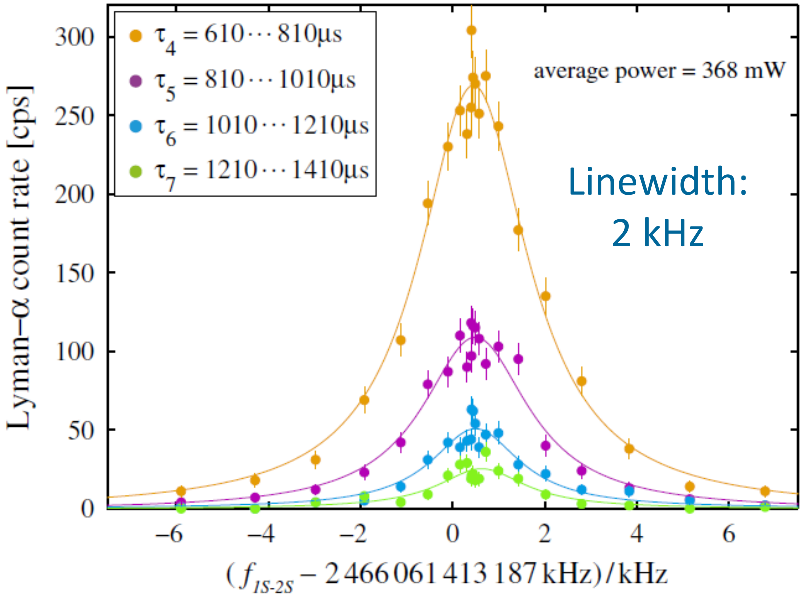
R. Pohl et al., Nature **466**, 213 (2010)
A. Antognini et al., Science **339**, 417 (2013)

H atom spectroscopy



1S-2S transition (MPQ Garching)





$$f_{1S\text{-}2S} = 2\ 466\ 061\ 413\ 187\ 035\ (10)\ \text{Hz}$$

C.G. Parthey et al., PRL **107**, 203001 (2011)

$$f_{1S\text{-}2S} = 2\ 466\ 061\ 413\ 187\ 018\ (11)\ \text{Hz}$$

A. Matveev et al., PRL **110**, 230801 (2013)

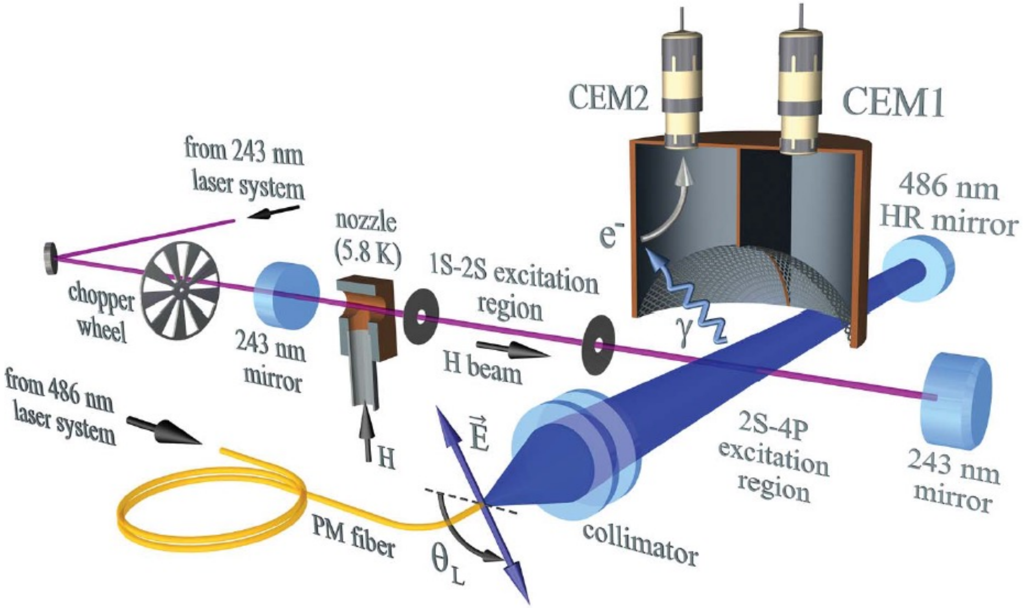
Challenges in high-resolution spectroscopy of H

- Determine the center of a line to a small fraction (10^{-3}-10^{-4}) of its width

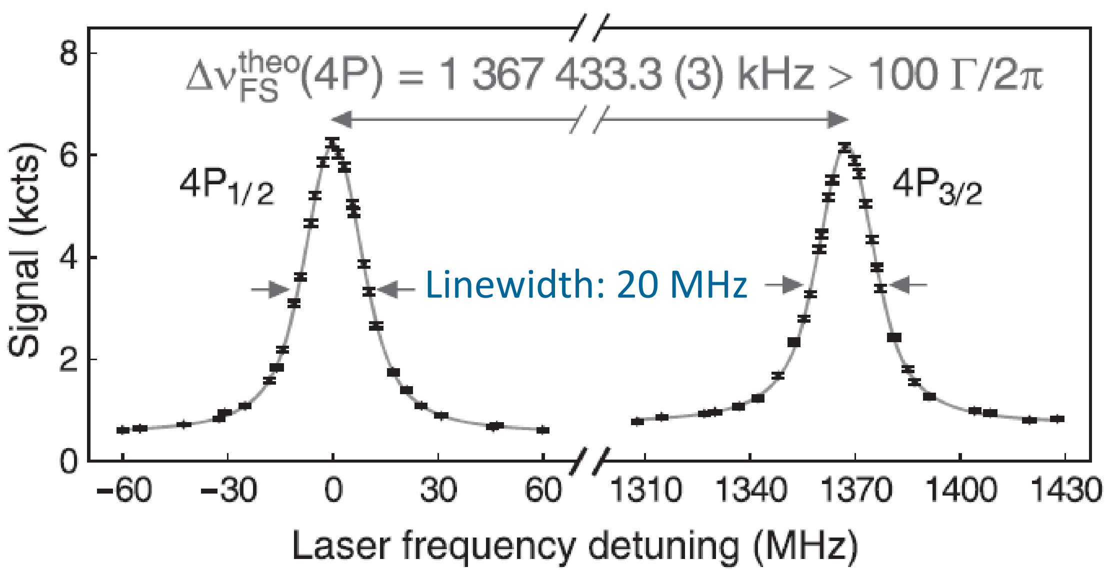
- High statistics
- Precise understanding of lineshape and systematic effects:

  - 1^{st} or 2^{nd}-order Doppler effect: velocity distribution in atomic beam
  - AC Stark shift (especially for two-photon transitions)
  - Pressure (collision) shift
  - Quantum interference effect
  - …

New! 2S-4P transition (MPQ Garching)



- Cold (5.8 K) H(2S) atoms
- Single hyperfine level populated:$2S_{1/2}$ F=0

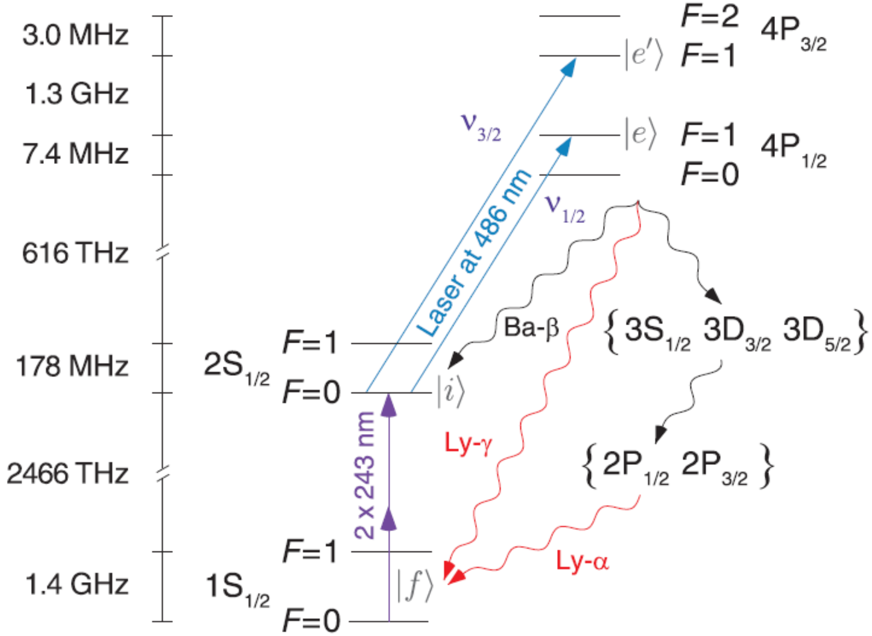


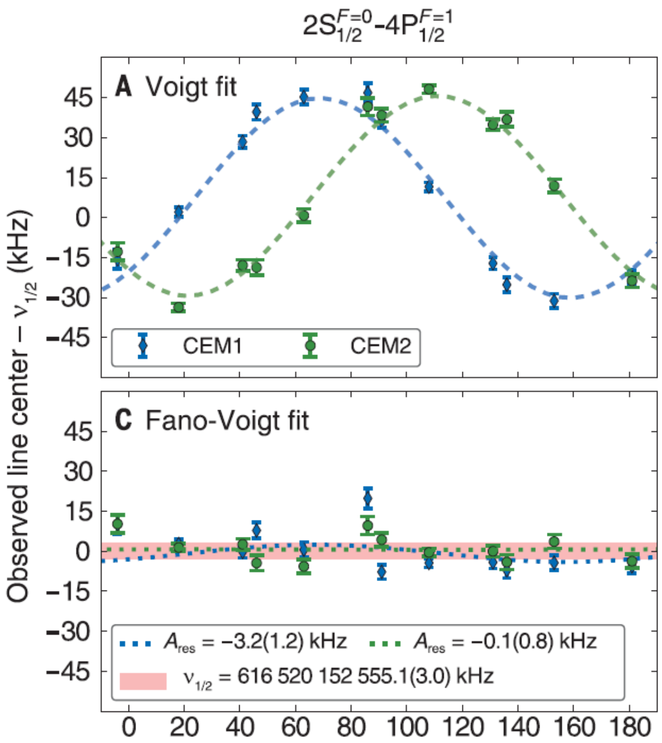
Natural linewidth: 12.9 MHz

+ Doppler broadening, power broadening

New! 2S-4P transition (MPQ Garching)

Quantum interference effect



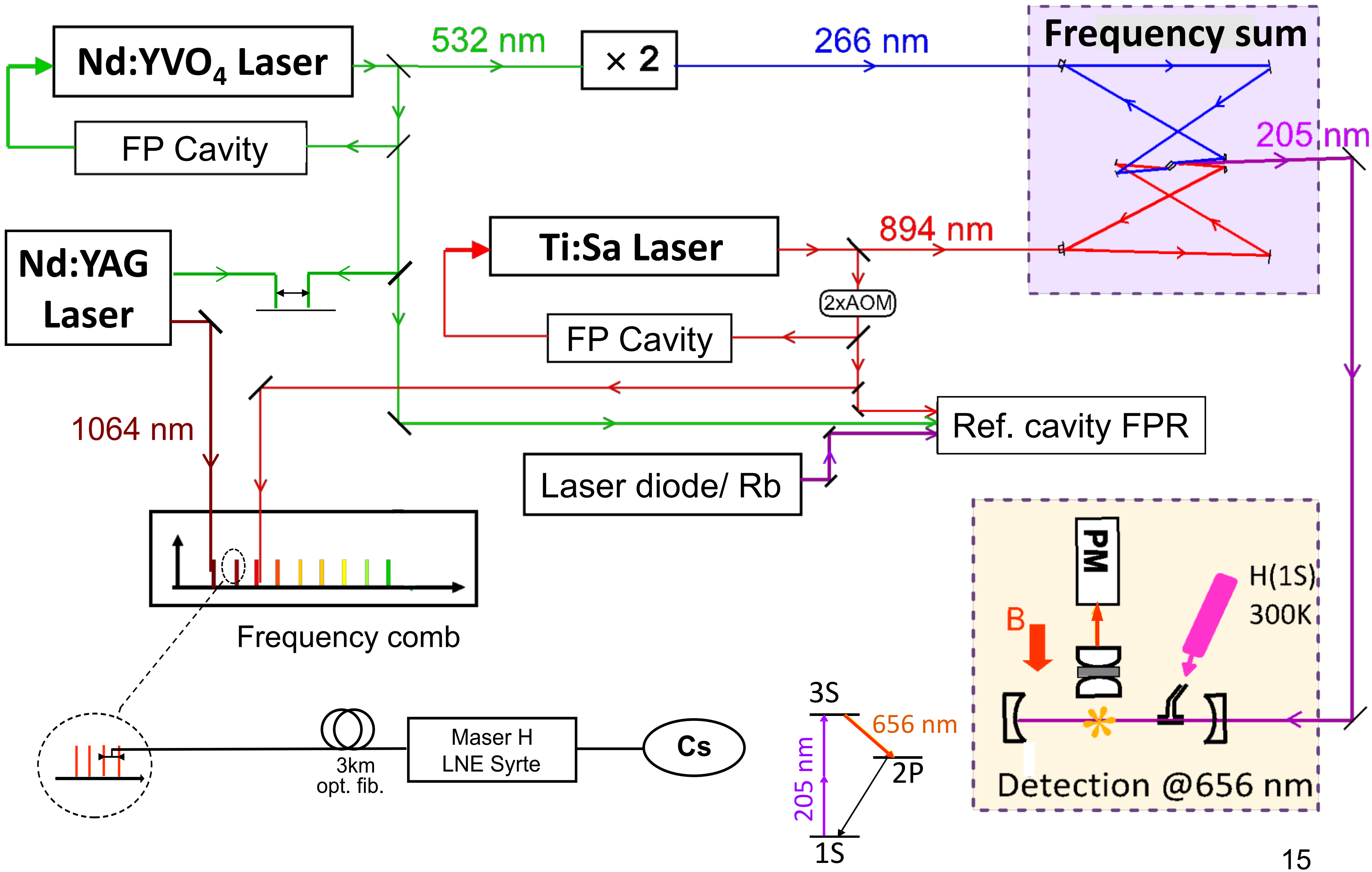


$f_{\text{2S-4P}}$ = 616 520 931 626.8(2.3) kHz $\Delta f \sim 10^{-4}\,\Gamma$!

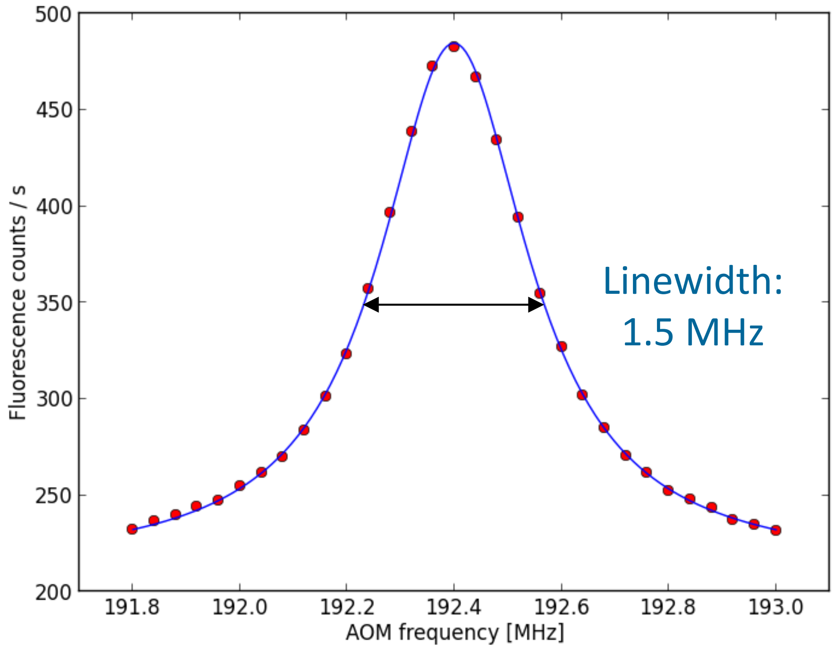
Main source of uncertainty: 1st-order Doppler shift

A. Beyer et al., Science **358**, 79 (2017)

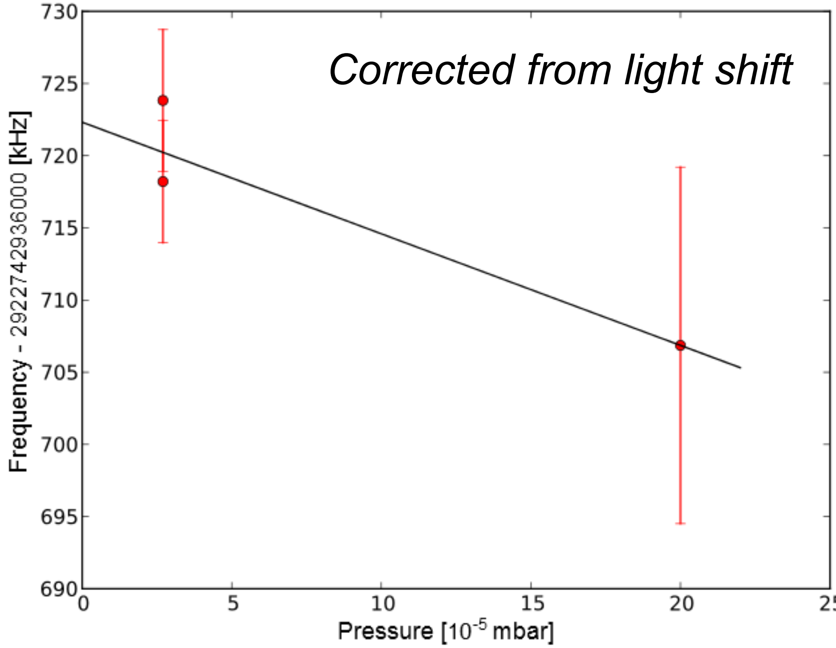
Preliminary! 1S-3S transition (LKB Paris)



Preliminary! 1S-3S transition (LKB Paris)



Pressure shift

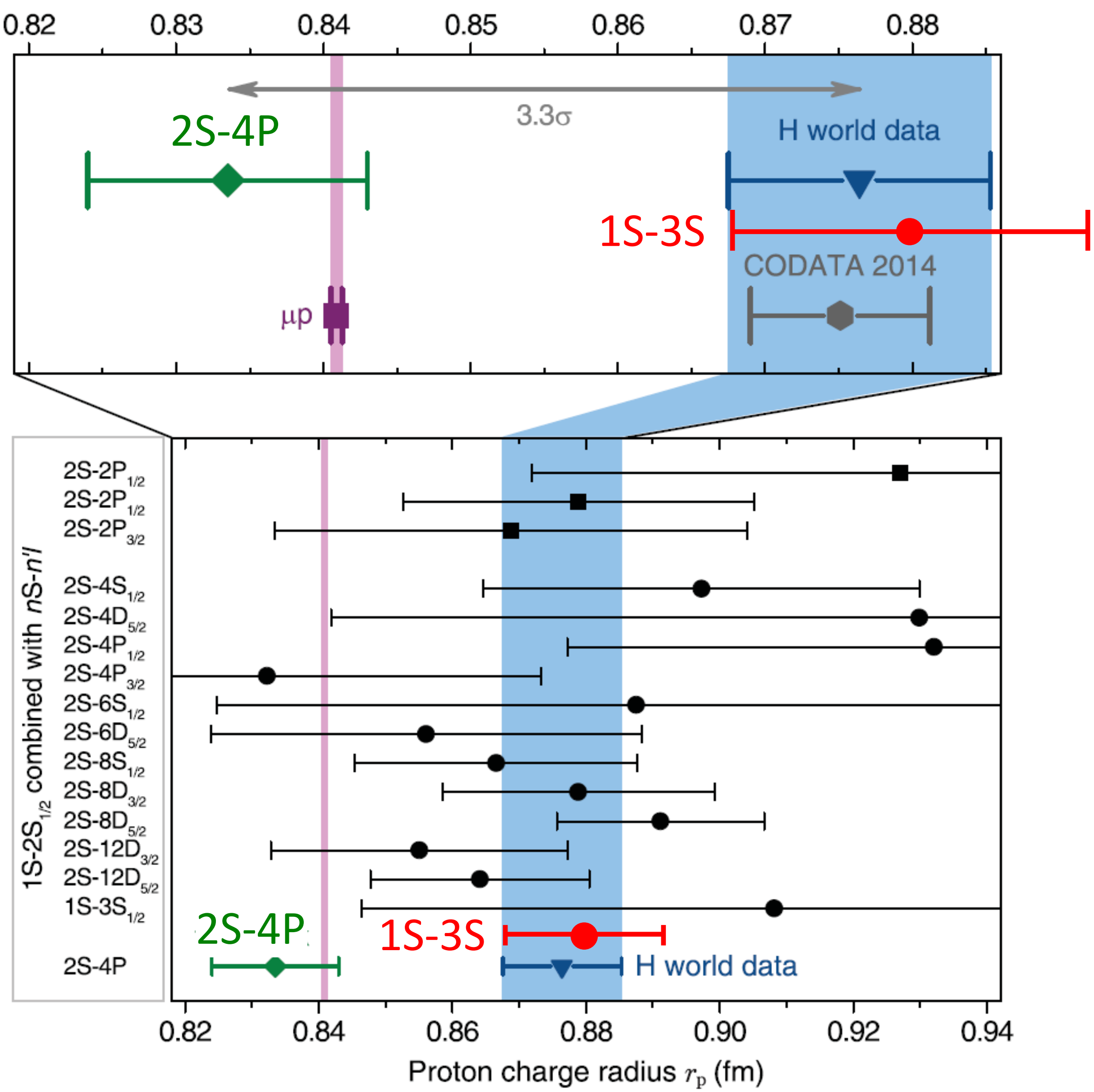


$$f_{1S\text{-}3S} = 2\ 922\ 743\ 278\ \text{xxx.x}\ (2.4)\ \text{kHz}$$

S. Galtier et al., J. Phys. Chem. Ref. Data **44**, 031201 (2015)
<u>QI effect</u>: H. Fleurbaey, F. Biraben, L. Julien, JPK, F. Nez, PRA **95**, 052503 (2017)
H. Fleurbaey et al., *in preparation*

➢ Next step : cold (77K) H beam

Overview



0.82
0.83
0.84
0.85
0.86
0.87
0.88
3.3σ
2S-4P
H world data
1S-3S
CODATA 2014
μp
1S-2S1/2 combined with nS-n'l'
2S-2P1/2
2S-2P1/2
2S-2P3/2
2S-4S1/2
2S-4D5/2
2S-4P1/2
2S-4P3/2
2S-6S1/2
2S-6D5/2
2S-8S1/2
2S-8D3/2
2S-8D5/2
2S-12D3/2
2S-12D5/2
1S-3S1/2
2S-4P
2S-4P
1S-3S
H world data
0.82
0.84
0.86
0.88
0.90
0.92
0.94
Proton charge radius rp (fm)

What to do now ?

“To summarize, the possibilities are:
*1. The **electronic hydrogen experiments** are almost, but not quite, as accurate as stated.*
*2. The **QED calculations in μp** are almost, but not quite, as accurate as stated.*
*3. The two-photon exchange term that depends on **proton polarizability** has not been correctly evaluated.*
*4. The electron and the muon really do have different interactions with the proton so there is **physics beyond the Standard Model**.*
None of these possibilities seem very likely, but all must be pursued.”

R. Pohl et al., Annu. Rev. Nucl. Part. Sci. **63**, 175 (2013)
C.E. Carlson, Progr. Part. Nucl. Phys. **82**, 59 (2015)

“Beyer *et al.* **do not claim to have solved the proton-size puzzle**. After all, it is only one measurement, and the data analysis was very complicated. Moreover, one would need to understand why other measurements in hydrogen are so far off or, possibly, exhibit a systematic shift in the same direction. There is presently no explanation for that. Also, the proton size deduced from electron-proton scattering disagrees. **Thus, more measurements are what is needed**.”

W. Vassen, Science (Pespective) **358**, 39 (2017)

Spectroscopy projects

- Hydrogen-like systems

electronic

2S-2P in ***H*** (YU Toronto) $\Rightarrow r_p$
1S-2S in ***He***$^{+}$ (VU Amsterdam + MPQ Garching) $\Rightarrow R_\infty, r_\alpha$
Rydberg states in High-Z ions (NIST Gaithersburg) $\Rightarrow R_\infty$

muonic

2S-2P in ***μHe***$^{+}$ (PSI) $\Rightarrow r_\alpha$

leptonic

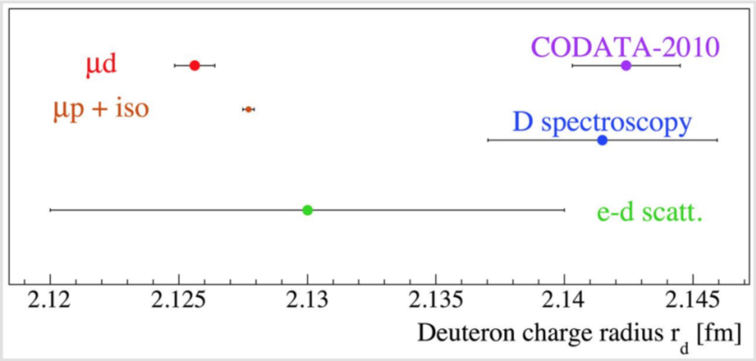
1S-2S in ***Positronium*** e^+e^- (ETH Zürich + UC London) $\Rightarrow R_\infty$
1S-2S in ***Muonium*** μ^+e^- (PSI + ETH Zürich) $\Rightarrow$ μ-specific forces ?

- One-electron molecules $\Rightarrow R_\infty, r_p, m_p/m_e$ $(+r_d, m_d/m_e)$
  H₂⁺ / HD⁺ (VU Amsterdam + Düsseldorf + LKB Paris)
- Two-electron atoms
  He (VU Amsterdam + Hefei) α, r_α
- Two-electron molecules $\Rightarrow R_\infty, r_p, m_p/m_e$ $(+r_d, m_d/m_e)$
  H_2 / HD (VU Amsterdam + ETH Zürich)
- Muonic Li, Be … (JGU Mainz + PSI)

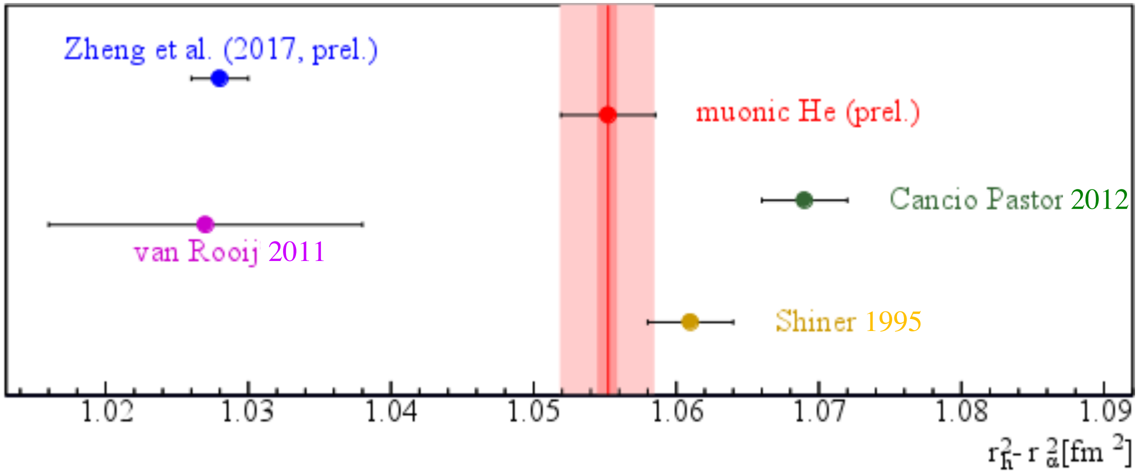
D / μD discrepancy

Other nuclei

Deuteron radius



^{3}He/^{4}He isotope shift (preliminary)

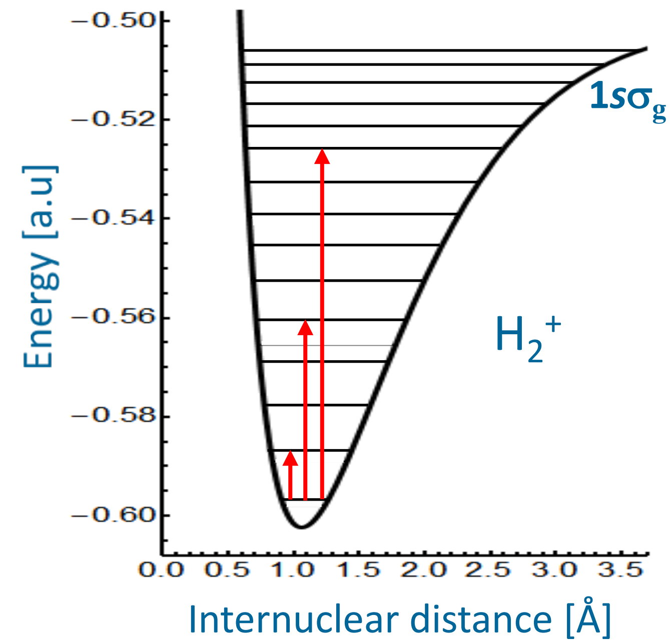


Another >5σ discrepancy ?

Hydrogen molecular ions

Dependence of ro-vibrational transition frequencies on fundamental constants :

$$\nu = cR_\infty \left[\varepsilon_{nr}(\mu_n) + \alpha^2 F_{QED}(\alpha) + \sum_n A_n^{fs} (r_n / a_0)^2 \right]$$



1. Strong dependence on μ_n : $\varepsilon_{nr} \propto 1/\sqrt{m_r}$

$\Rightarrow$ Determination of μ_{pe} and μ_{dp} by laser spectroscopy of H_2^+/HD^+

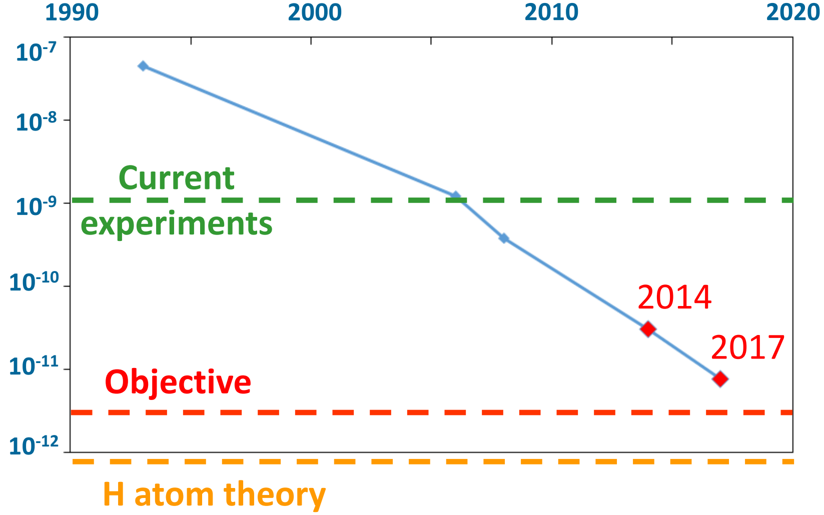
W.H. Wing, G.A. Ruff, W.E. Lamb Jr., J.J. Spezeski, PRL **36**, 1488 (1976)

2. *All* ro-vibrational transitions in $1s\sigma_g$ electronic state are *very narrow*

$\Rightarrow$ Measuring several transitions in H_2^+/HD^+ could provide a reliable determination of R_∞ , r_p , r_d , cross-checking H/D results and shedding light on the proton-radius puzzle.

J.Ph. Karr, L. Hilico, J.CJ. Koelemeij, V.I. Korobov, PRA **94**, 050501(R) (2016)

Status of theory



H_2^+ (v = 0, L=0) → (v'=1, L'=0) interval in kHz

ν_{nr}	65 687 511 047.0
ν_{α^2}	1091 040.5
ν_{α^3}	−276 545.1
ν_{α^4}	−1952.0(1)
ν_{α^5}	121.8(1)
ν_{α^6}	−2.3(5)
ν_{tot}	65 688 323 710.1(5)(29)(11)

Theoretical uncertainty **7.6 10^{-12}**

Uncert. on μ_{pe}

Discrepancies on R_∞ and r_p

V.I. Korobov, L. Hilico, J.-Ph. Karr, PRL **118**, 233001 (2017)

- Further improvement by a factor of 2-3 would allow discriminating between conflicting measurements of R_∞, r_p, r_d from a well-chosen set of ro-vibrational transitions.

Experimental state of art

One-photon ro-vibrational transitions in HD^+

- Sympathetic cooling by laser-cooled Be^+ (T~10 mK)
- Detection by selective dissociation of the excited state (REMPD)
- Measurement of HD^+ ion number by motional excitation

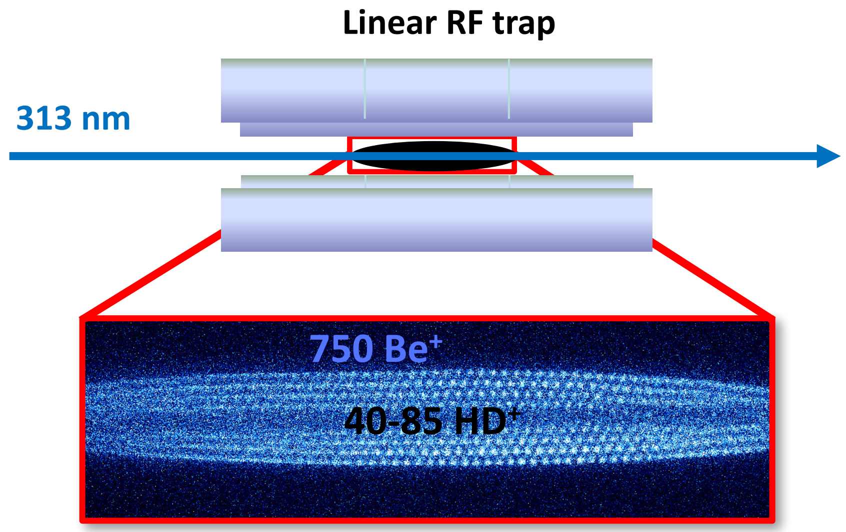
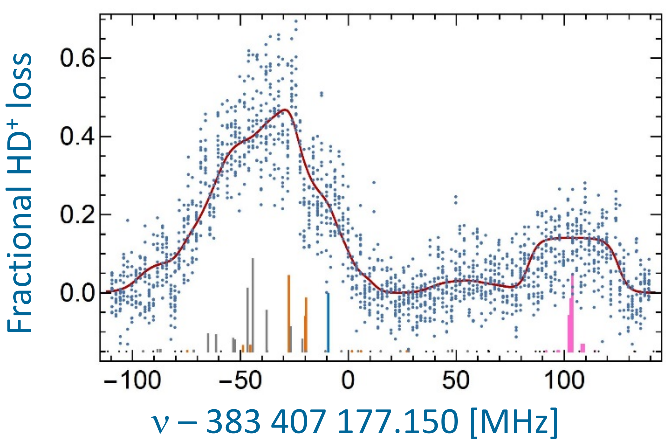


Image: J.C.J. Koelemeij (VU Amsterdam)

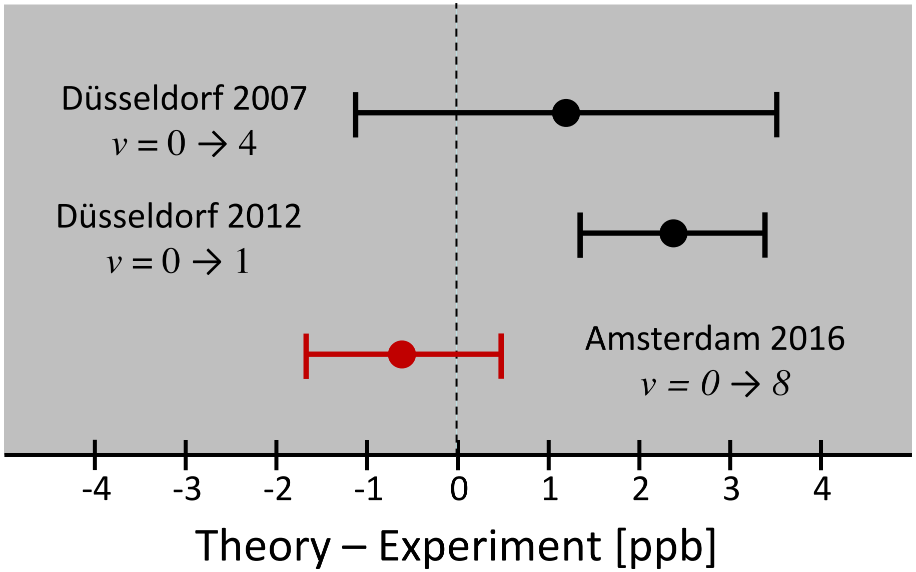
HD^+ $v = 0 \rightarrow 8$ transition



Main limitation: Doppler broadening

J.Biesheuvel, J.-Ph. Karr, L. Hilico, K.S.E. Eikema, W. Ubachs, J.C.J. Koelemeij, Nature Comm. **7**, 10385 (2016)

Experimental state of art



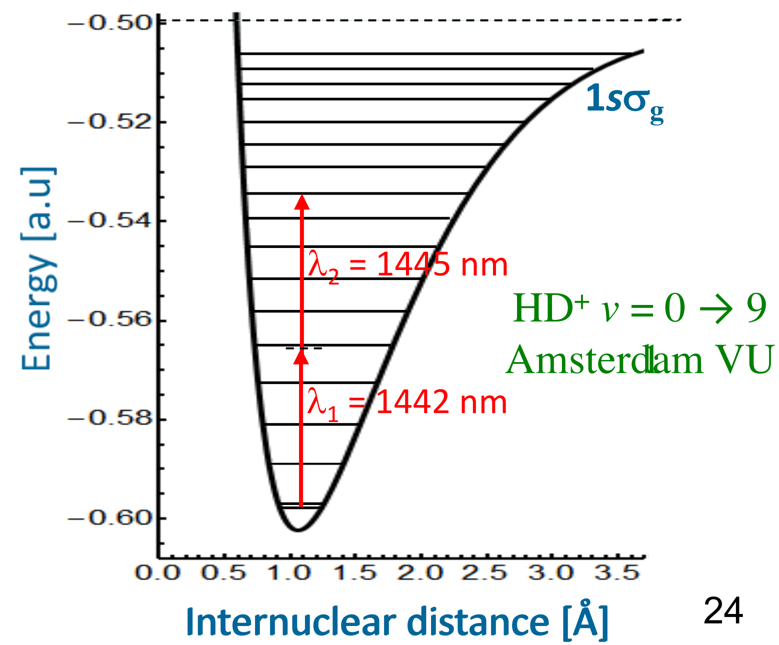
$\Rightarrow$ Determination of μ_{pe} with 2.5 ppb accuracy

S. Patra, J.-Ph. Karr, L. Hilico, M. Germann, V.I. Korobov, J.C.J. Koelemeij, arXiv:1710.11537, to appear in J. Phys. B

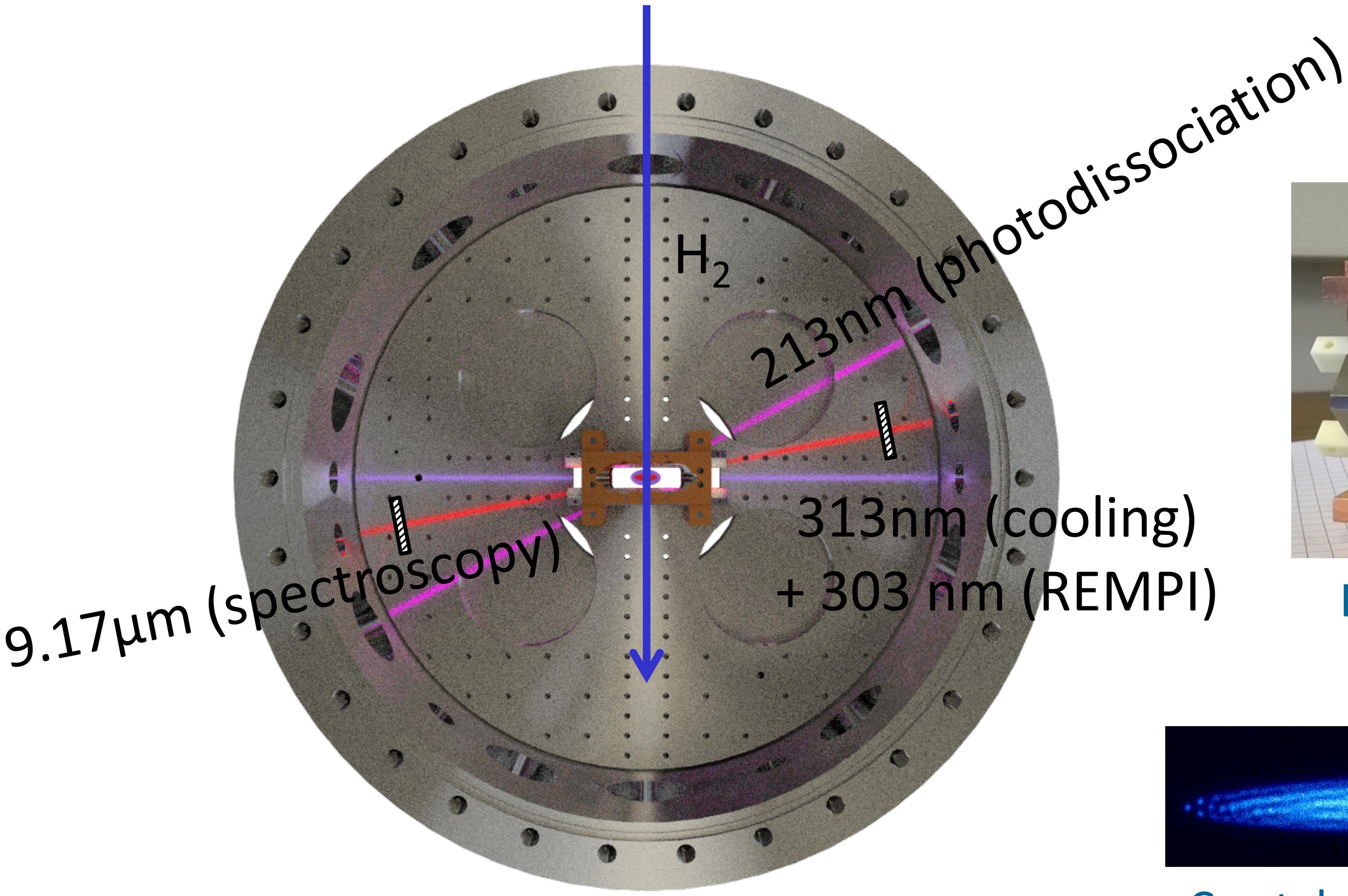
Next step:

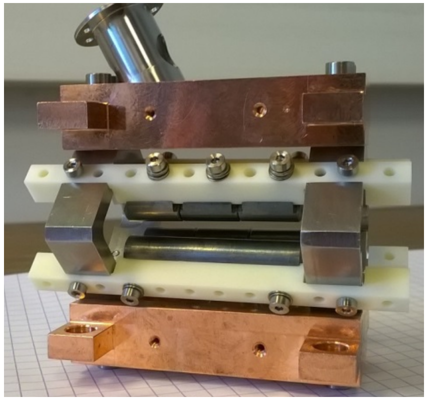
Doppler-free two-photon transitions

Goal accuracy : 10^{-12}

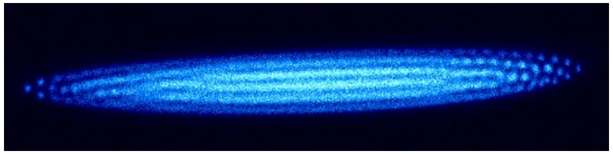


H_2^+ two-photon spectroscopy setup





Linear ion trap



Crystal of laser-cooled Be^+

Acknowledgements

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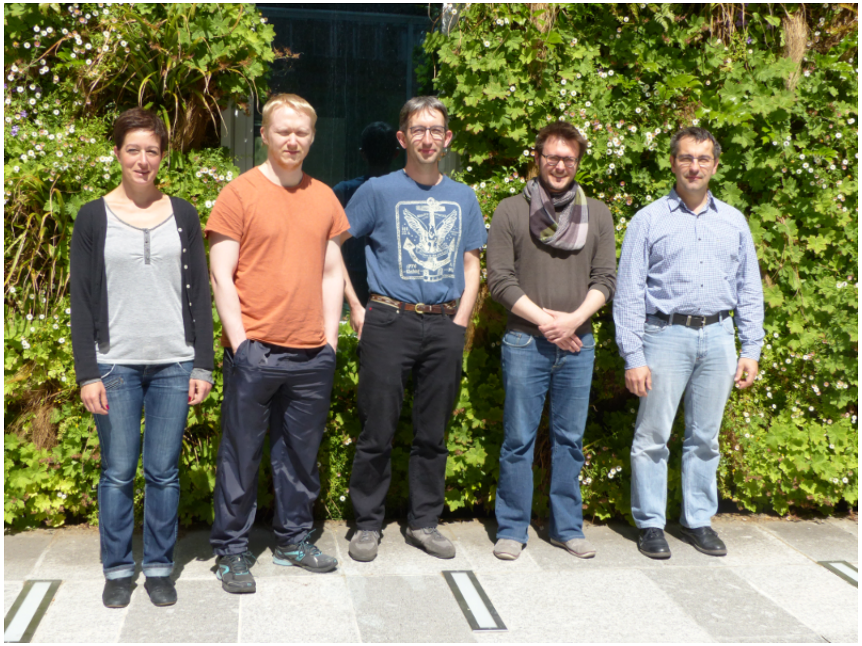

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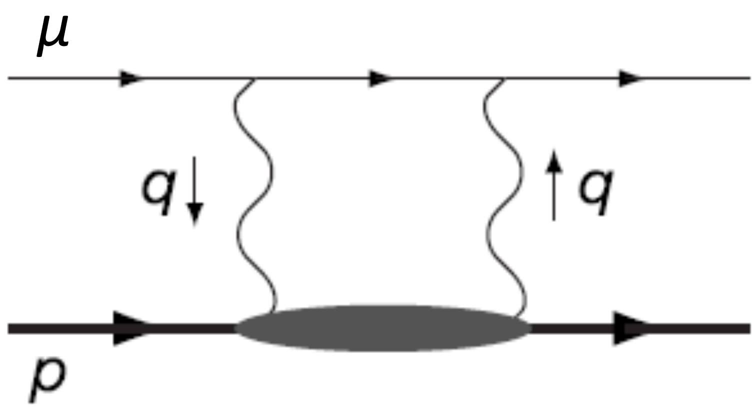
Sayan Patra
Matthias Germann
Juriaan Biesheuvel
Frank Cozijn
Kjeld Eikema
Wim Ubachs

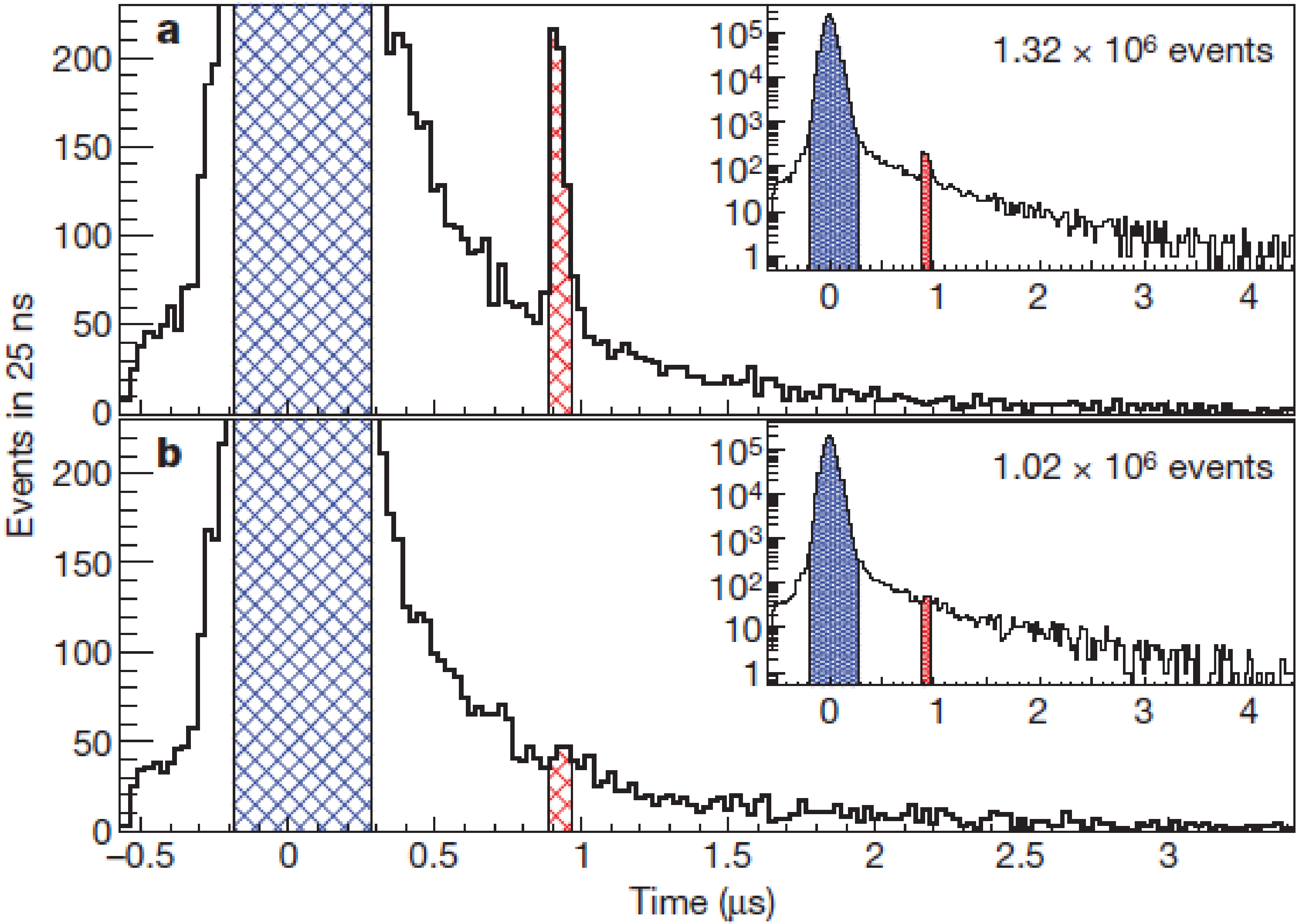
Finite-size corrections in muonic hydrogen

In addition to the leading term, higher-order QED corrections involving the proton structure have to be considered.

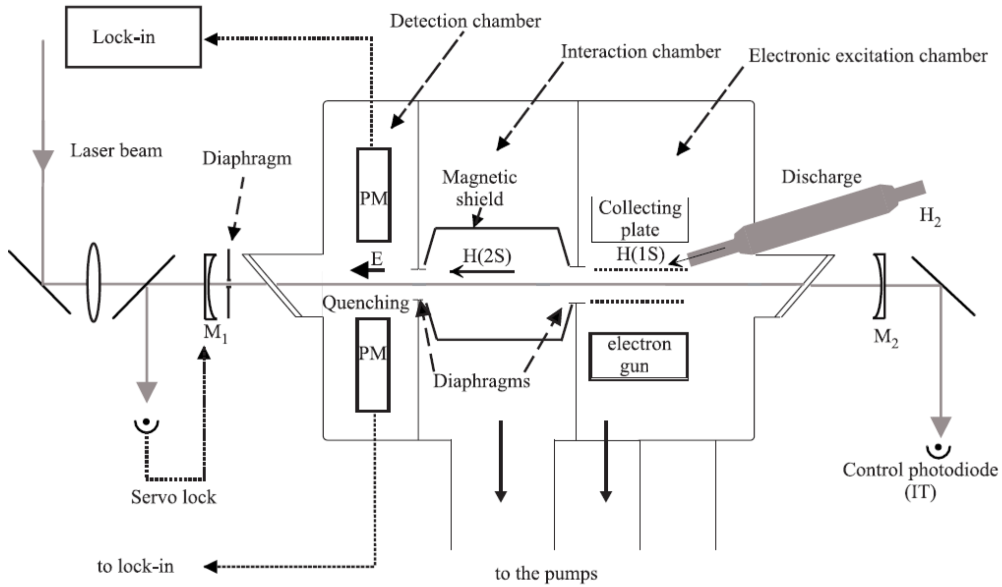


Two-photon exchange : - elastic
- inelastic : ***proton polarizability***
- subtraction of QED correction to proton radius

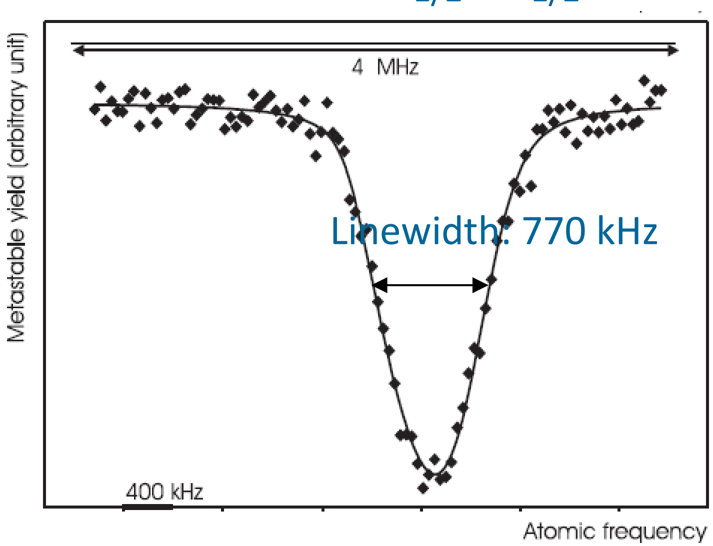
Muonic hydrogen spectroscopy at PSI



2S-nS(D) transitions (LKB Paris)



Example: $2S_{1/2}$-$8S_{1/2}$



$$f(2S_{1/2}\text{-}8S_{1/2}) = 770\ 649\ 350\ 012.0(8.6)\ \text{kHz}$$

(+ 4 other transitions)

Main source of uncertainty: AC Stark shift

B. De Beauvoir et al., PRL **78**, 440 (1997) and EPJD **12**, 61 (2000)
C. Schow et al., PRL **82**, 4960 (1999).