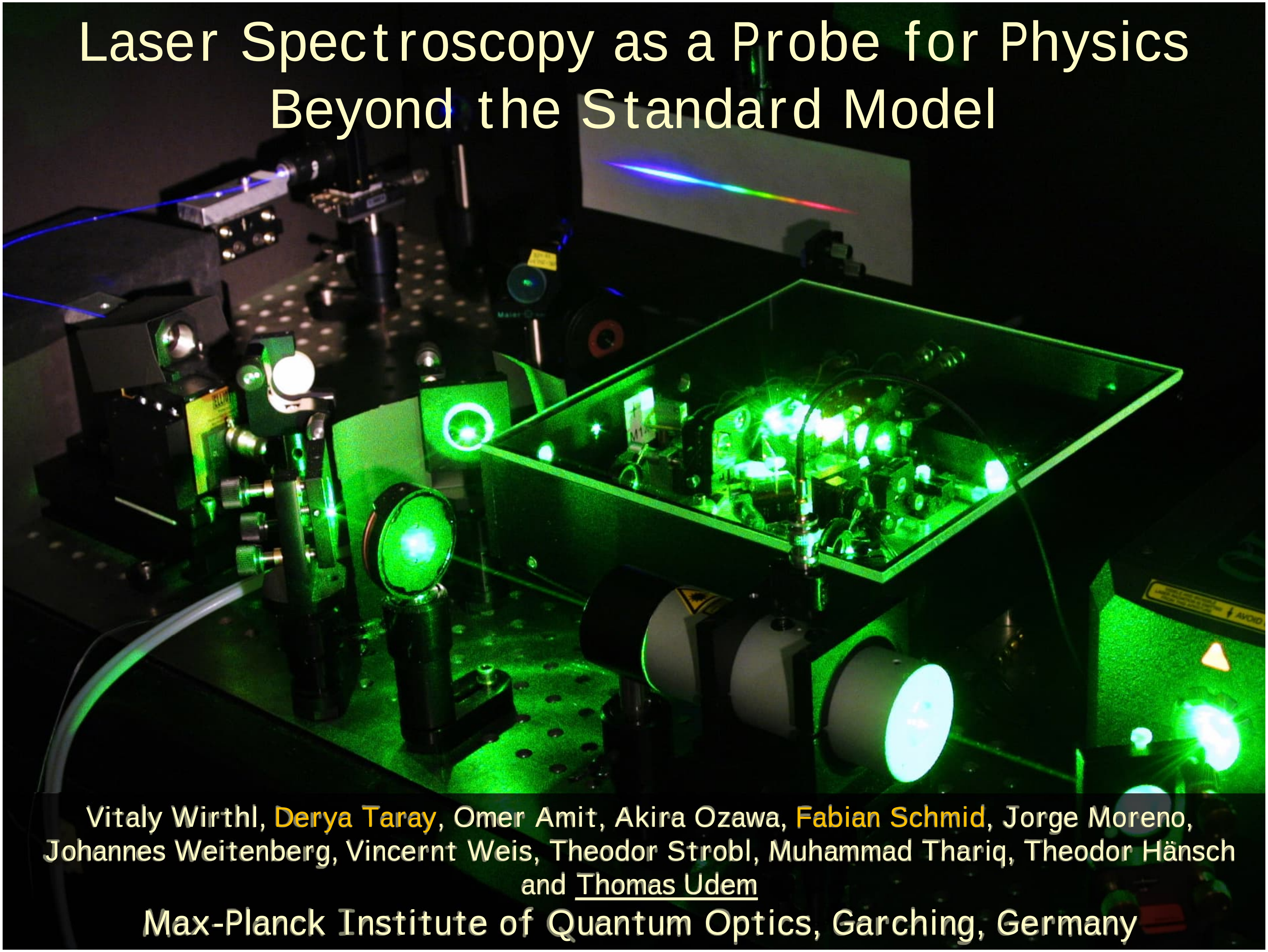
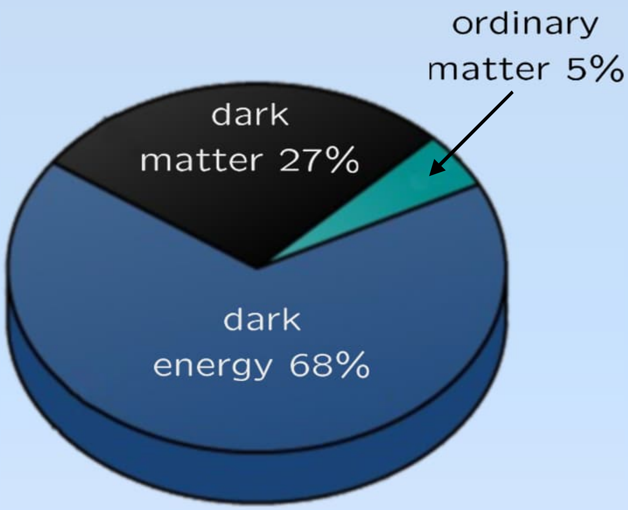
Laser Spectroscopy as a Probe for Physics Beyond the Standard Model



Vitaly Wirthl, Derya Taray, Omer Amit, Akira Ozawa, Fabian Schmid, Jorge Moreno,
Johannes Weitenberg, Vincernt Weis, Theodor Strobl, Muhammad Thariq, Theodor Hänsch
and Thomas Udem
Max-Planck Institute of Quantum Optics, Garching, Germany

New Physics



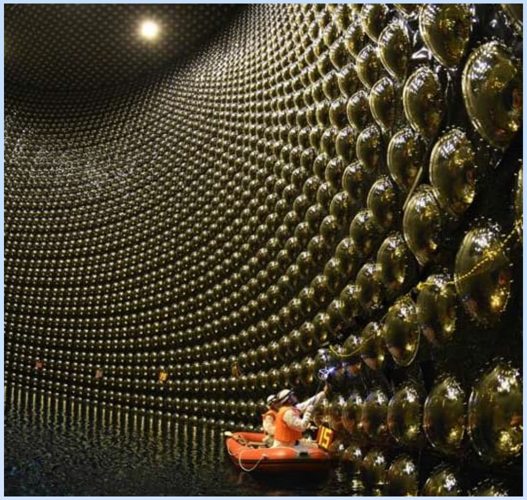
- 95% of the Universe is made of unknown *stuff*
- Matter-antimatter asymmetry problem
- Physics beyond the Planck scale unknown
- Quantum mechanics and General Relativity at conflict

How to find new Physics?

Energy frontier

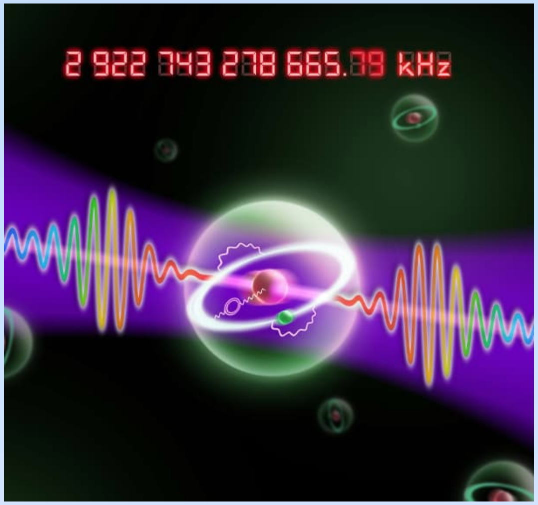
new particles (Higgs)

Sensitivity frontier



forbidden (rare) events

Precision frontier



tiny deviations

- Fundamental physics based on Quantum Field Theory (QFT)
- QFT is rooted in Quantum Electrodynamics (QED)
- Hydrogen-like systems are the simplest bound-state QED systems

1. Theory
2. Experiment
3. Comparison theory and experiment
4. More data

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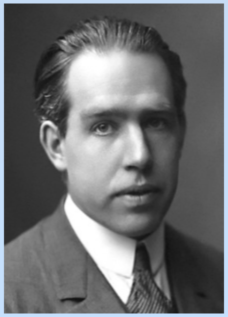
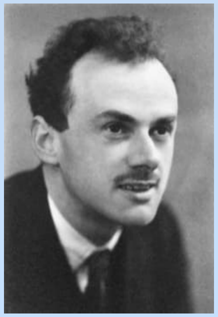
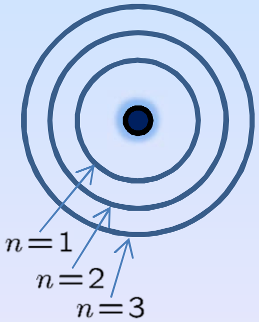
Evolution of the Theory

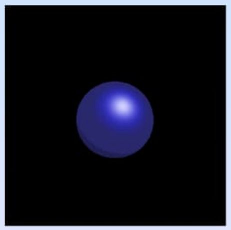




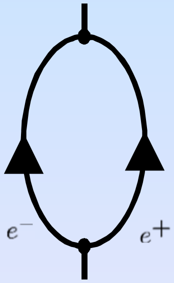
Bethe
Tomonaga
Schwinger
Feynman
Dyson
. . . .

Balmer → Bohr → Schrödinger → Dirac → QED





$\alpha \approx \frac{1}{137}$ finestructure constant



Energy Levels of atomic Hydrogen

Bohr & Schrödinger & Dirac & recoil & relativistic recoil

$$E = \left(-\frac{1}{n^2} - \frac{4n-3}{4n^2}\alpha^2 - \frac{2n^3+6n^2-12n+5}{8n^6}\alpha^4 \ldots\right)\frac{1}{1+m_e/m_p}$$

$$+\left(\frac{1}{n^4}\alpha^2 - \frac{4n-3}{8n^6}\alpha^4 + \frac{8n^3+40n^2-72n+29}{64n^6}\alpha^6 \ldots\right)\frac{m_e}{m_p}\frac{1}{(1+m_e/m_p)^3}$$

$$+\frac{2\alpha^3 m_e}{\pi n^3 m_p (1+m_e/m_p)^3}\left(-\frac{2}{3}\ln(\alpha) - \frac{8}{3}\ln k_0(n) - \frac{1}{9} + \frac{14}{3}\left(\ln(\frac{2}{n}) + \sum_{m=1}^{n}\frac{1}{m}\right.\right.$$

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

$$+\frac{2\alpha^4 m_e}{m_p n^3}\left(4\ln(2) - \frac{7}{2} - \frac{44\alpha}{60\pi}\ln(\alpha)^2\right)$$

Energy Levels of atomic Hydrogen

(only S-states)

Bohr & Schrödinger & Dirac & recoil & relativistic recoil

$$E = \left(-\frac{1}{n^2} - \frac{4n-3}{4n^2}\alpha^2 - \frac{2n^3+6n^2-12n+5}{8n^6}\alpha^4 \ldots \right) \frac{1}{1+m_e/m_p}$$

$$+ \left(\frac{1}{n^4}\alpha^2 - \frac{4n-3}{8n^6}\alpha^4 + \frac{8n^3+40n^2-72n+29}{64n^6}\alpha^6 \ldots \right) \frac{m_e}{m_p} \frac{1}{(1+m_e/m_p)^3}$$

$$+ \frac{2\alpha^3 m_e}{\pi n^3 m_p (1+m_e/m_p)^3} \left(-\frac{2}{3}\ln(\alpha) - \frac{8}{3}\ln k_0(n) - \frac{1}{9} + \frac{14}{3} \left(\ln(\frac{2}{n}) + \sum_{m=1}^{n} \frac{1}{m} \right.\right.$$

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

$$+ \frac{2\alpha^4 m_e}{m_p n^3} \left(4\ln(2) - \frac{7}{2} - \frac{44\alpha}{60\pi} \ln(\alpha)^2 \right)$$

Energy Levels of atomic Hydrogen

Full recoil and QED in SI units:

$$E_{nlj} = R_\infty \left(-\frac{1}{n^2} + f_{nlj}\left(\alpha, \frac{m_e}{m_p}, \ldots\right) + \frac{16\pi^2 m_e^2 c^2 \alpha^2}{3n^3h^2}\, r_p^2 \right)$$

E. Tiesinga *et al.* Rev. Mod. Phys. 93, 025010 (2021) CODATA 2018
M. Horbatsch and E. A. Hessels, Phys. Rev. A 93, 022513 (2016)
M. Eides *et al.* Theory of Light Hydrogenic Bound States, Springer 2007

1. Theory
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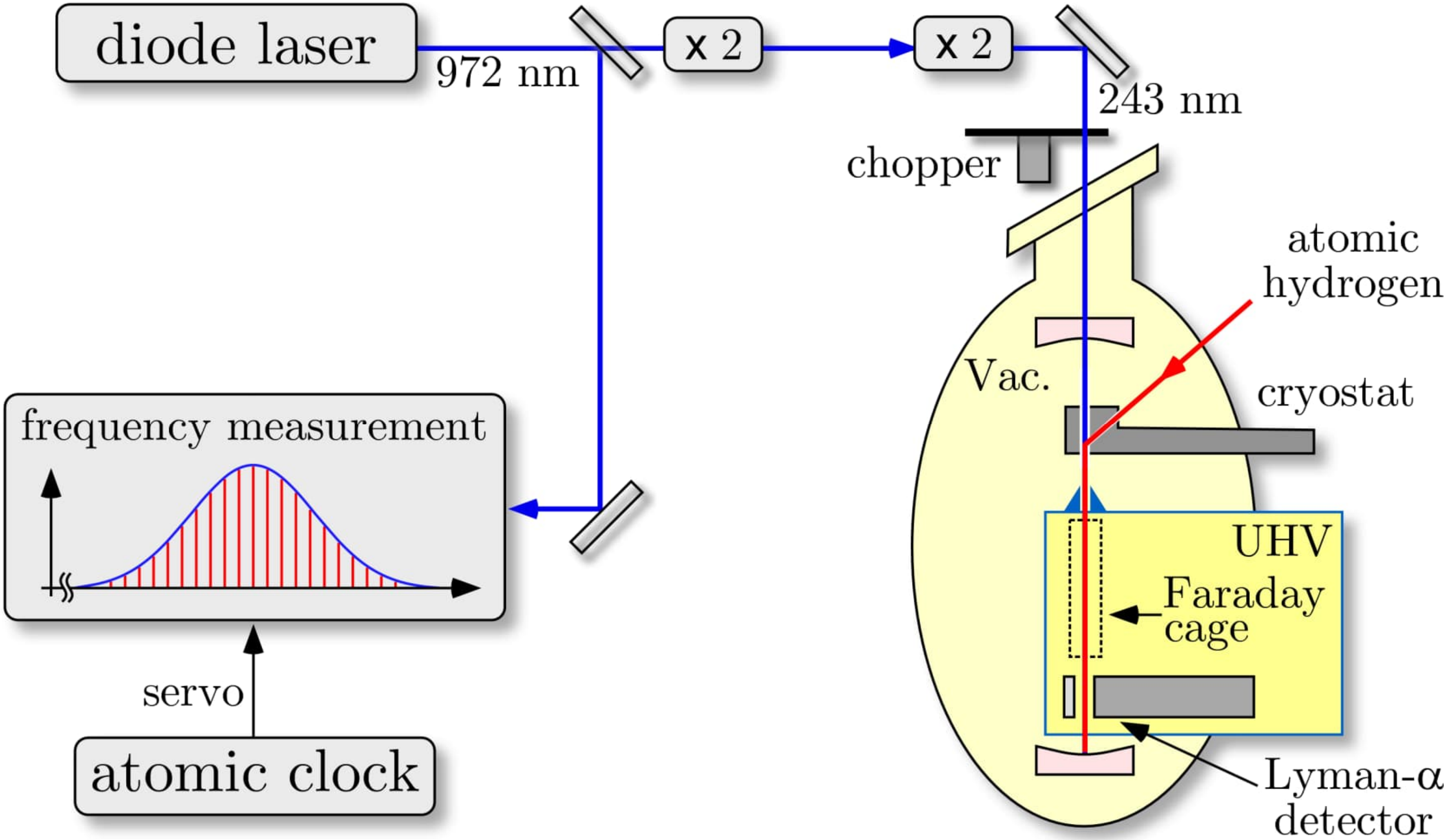
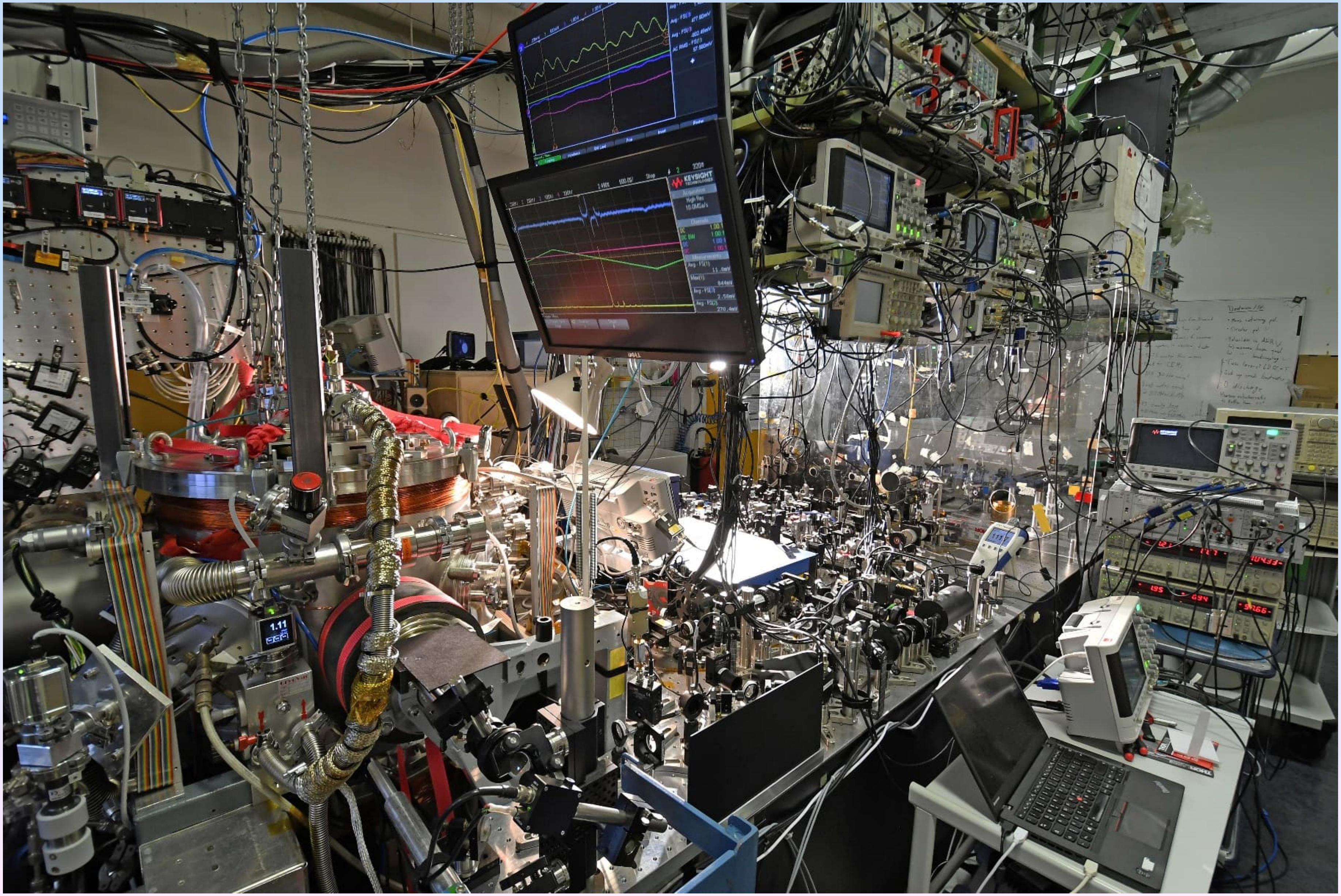
Hydrogen 1S-2S Spectrometer



Hydrogen Spectrometer



1S-2S Transition Frequency

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

C. G. Parthey *et al.*, Phys. Rev. Lett. 107, 203001 (2011); A. Matveev *et al.* PRL 110, 230801 (2013)

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Constants and Parameters

$$E_{nlj} = R_\infty \left(-\frac{1}{n^2} + f_{nlj}\left(\alpha, \frac{m_e}{m_p}, \ldots\right) + \frac{16\pi^2 m_e^2 c^2 \alpha^2}{3n^3 h^2}\, r_p^2 \right)$$

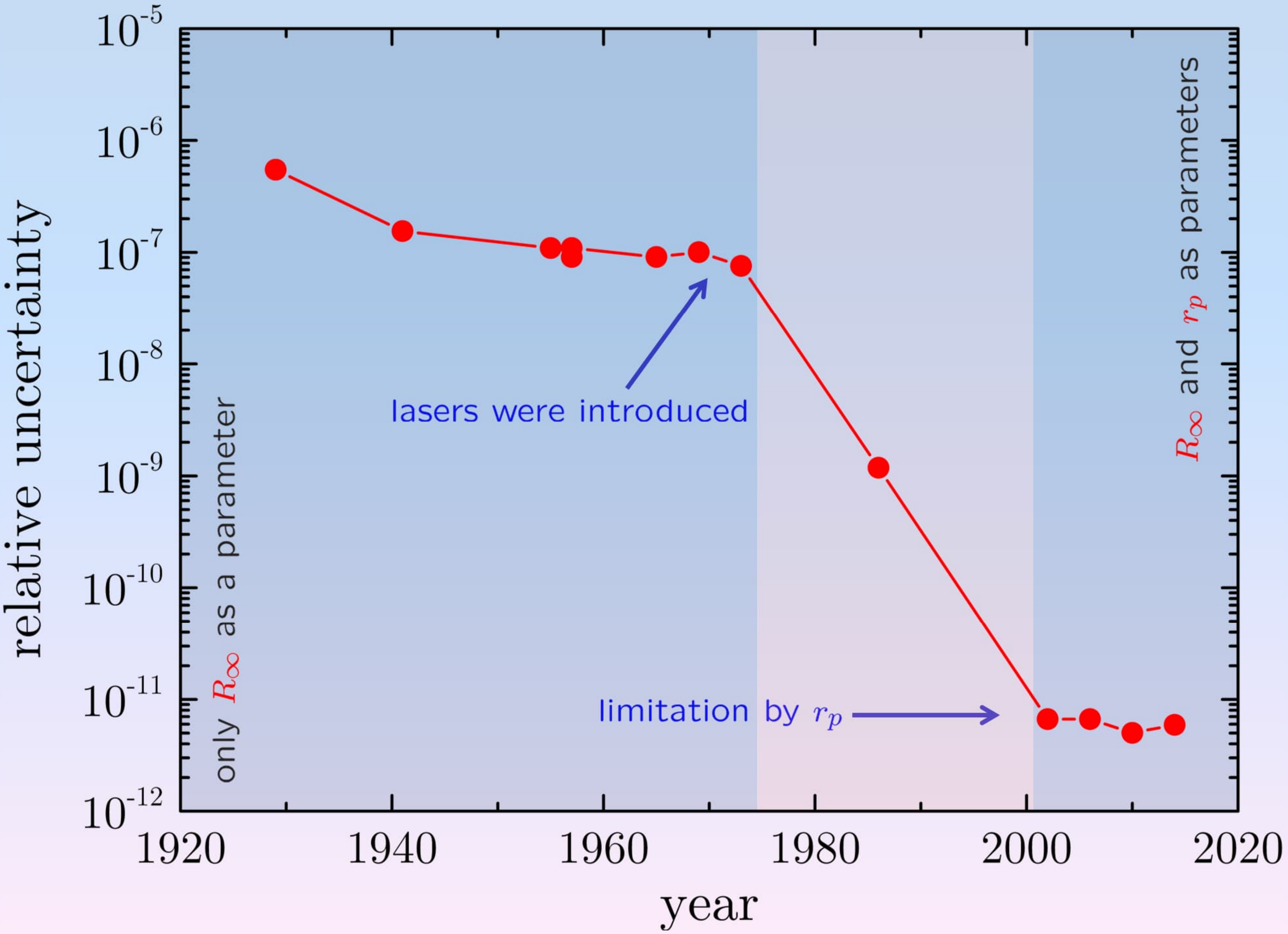
Constants and Parameters

$$E_{nlj} = R_\infty \left(-\frac{1}{n^2} + f_{nlj}\left(\alpha, \frac{m_e}{m_p}, \ldots\right) + \frac{16\pi^2 m_e^2 c^2 \alpha^2}{3n^3 h^2}\, r_p^2 \right)$$

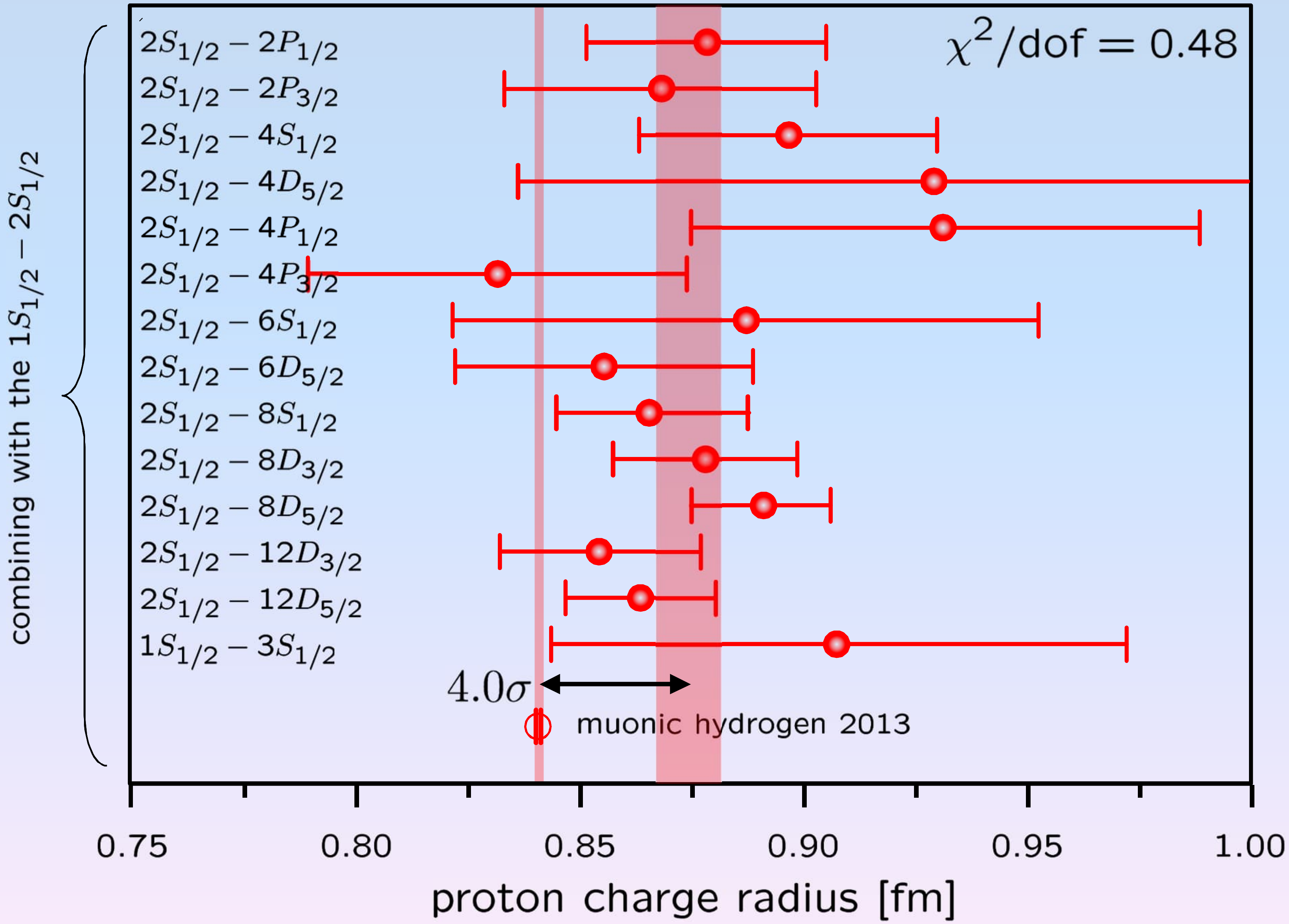
- effective number of parameters depends on the requested accuarcy
- α, m_e/m_p and m_e/h are obtained from other experiments
- R_∞ and r_p are left as adjustable parameters
- need two transitions to determine the values of R_∞ and r_p

Th. Udem Nat. Phys. 14, 632 (2018)

History of the Rydberg Constant



Proton Charge Radius until 2017



1. Theory
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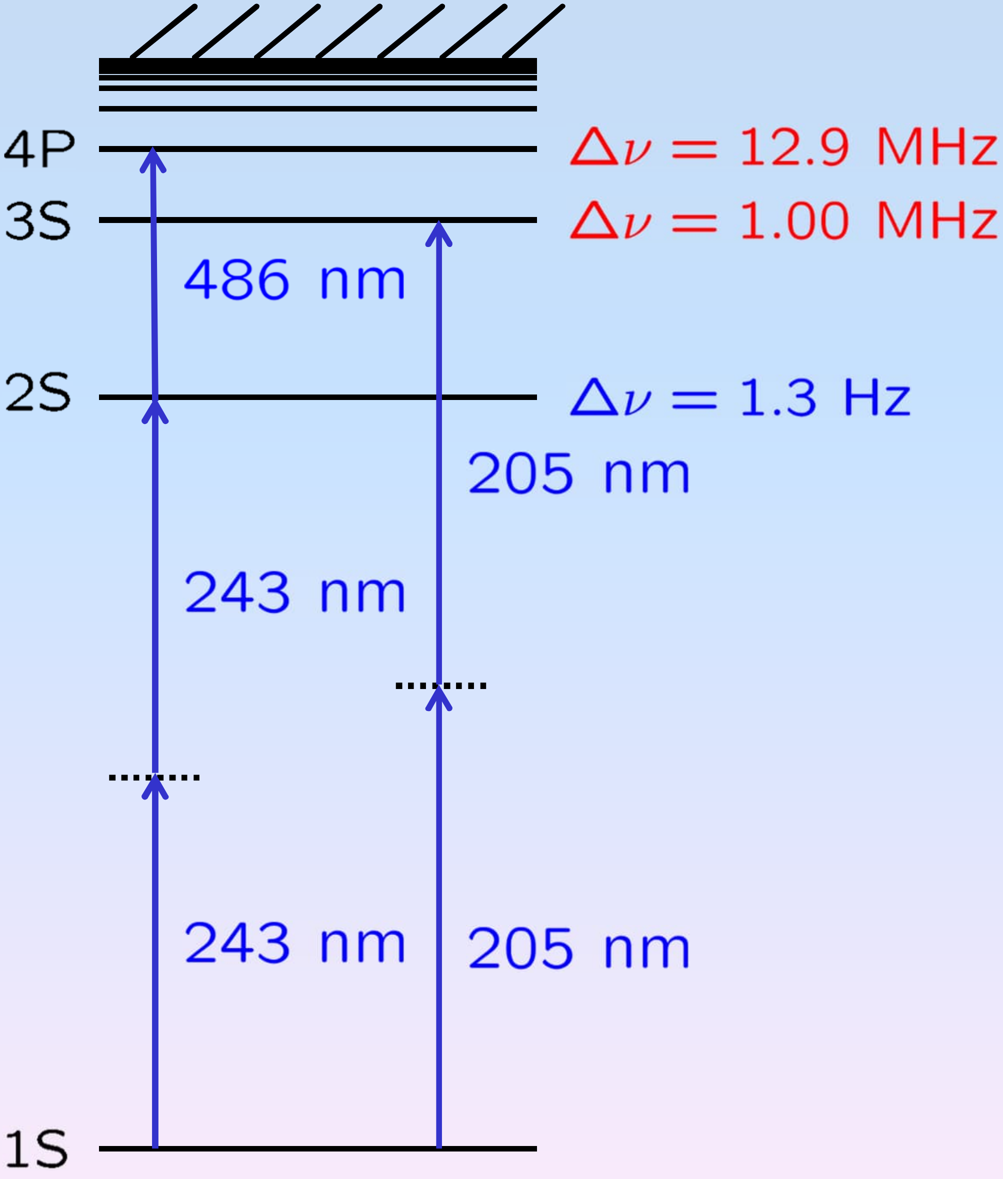
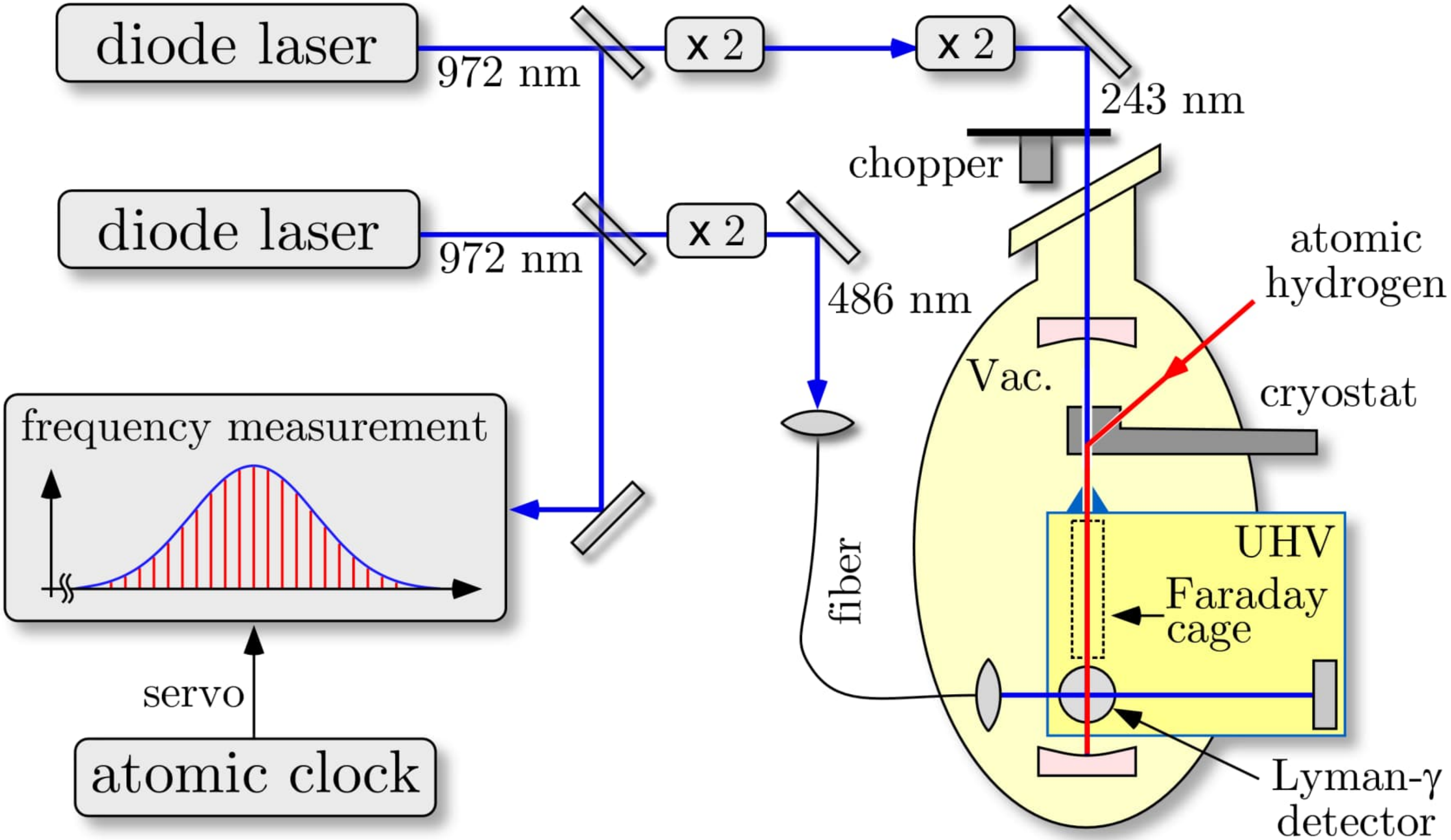
Natural Lifetimes

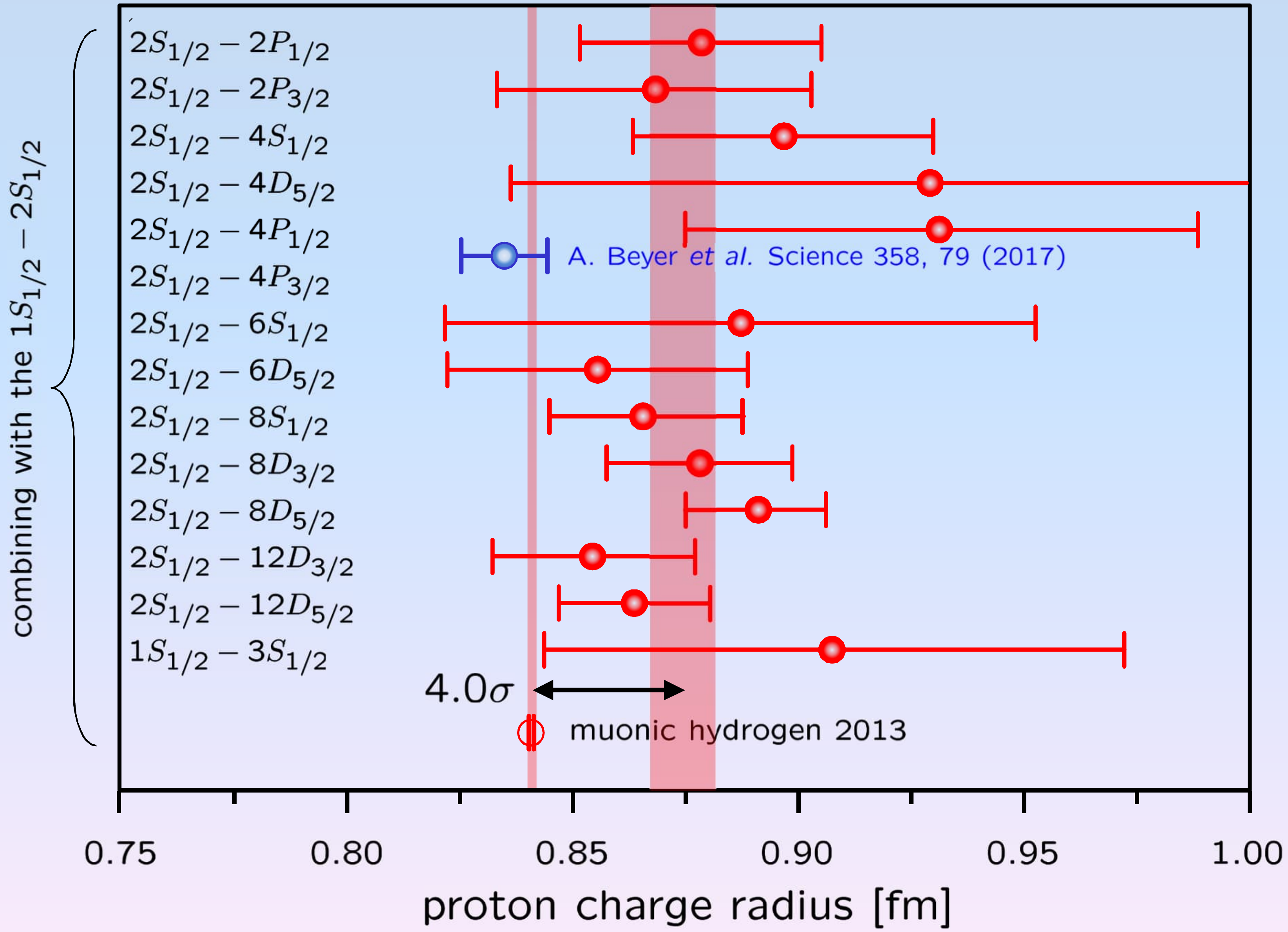


Hydrogen 2S-4P Transition

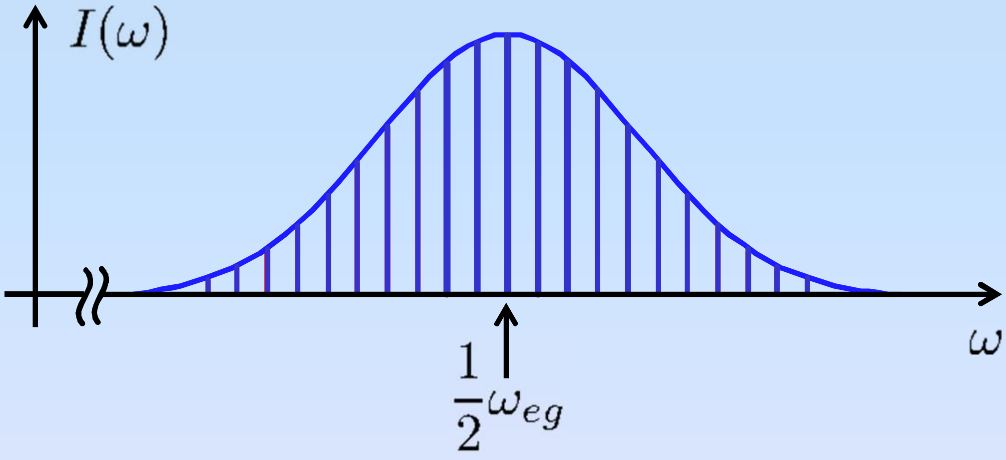


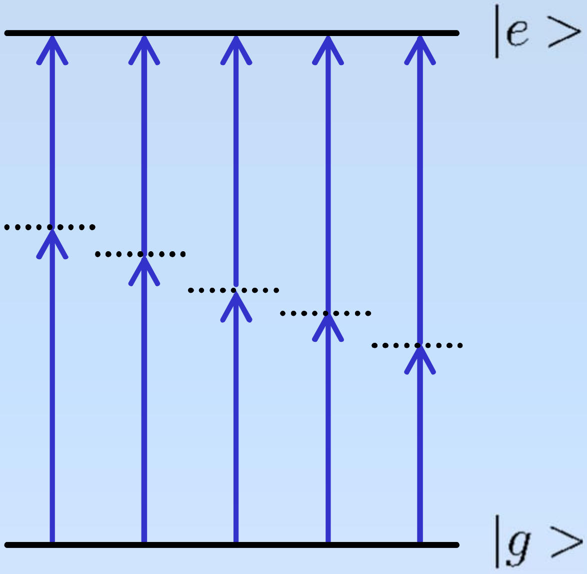
A. Beyer *et al.* Science 358, 79 (2017)

Proton Charge Radius



Two-Photon Comb Spectroscopy

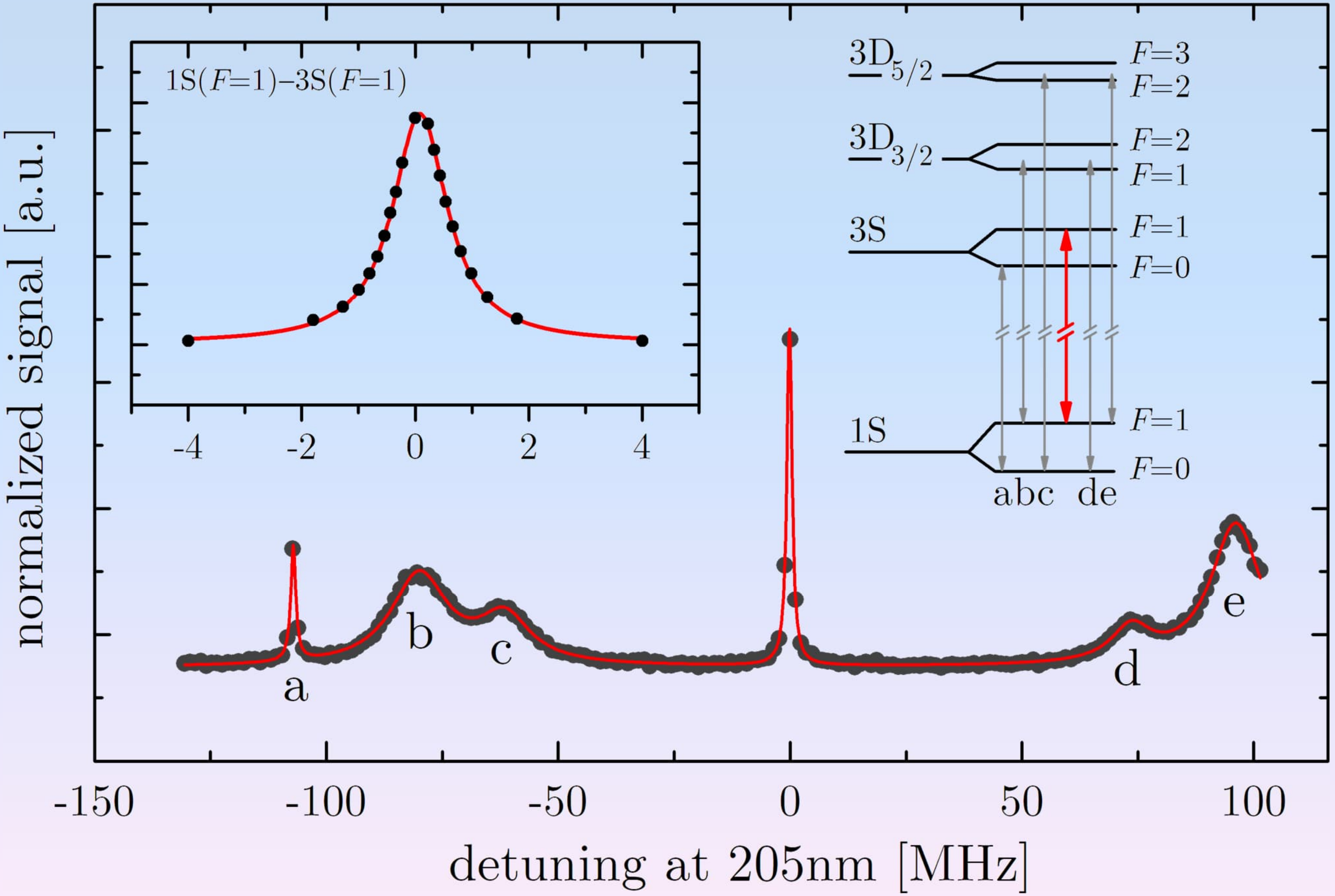




- Transition rate with power from all modes combined.
- Line width from a single mode.
- AC Stark shift from time averaged intensity.

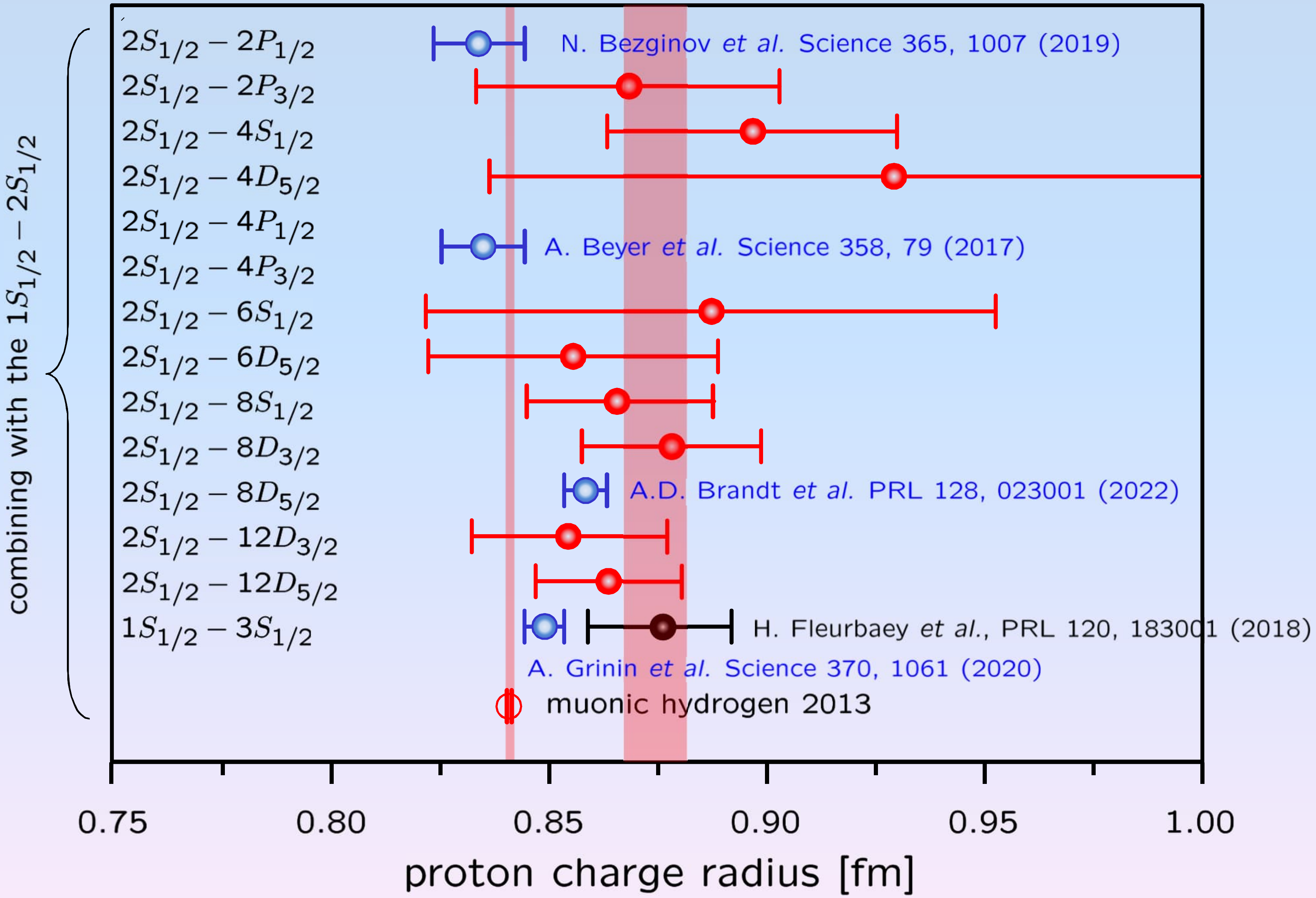
Ye.V.Baklanov and V.P.Chebotayev, Appl. Phys 12, 97 (1977)

Hydrogen 1S-3S Transition



A. Grinin *et al.* Science 370, 1061, (2020)

Proton Charge Radius



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5. Even more data

The Better Hydrogen: He$^+$

theory:

- QED power series in $(Z\alpha)$.
- nuclear radius better unter control from electron scattering.
- muonic Lamb shift has already been measured.

experiment:

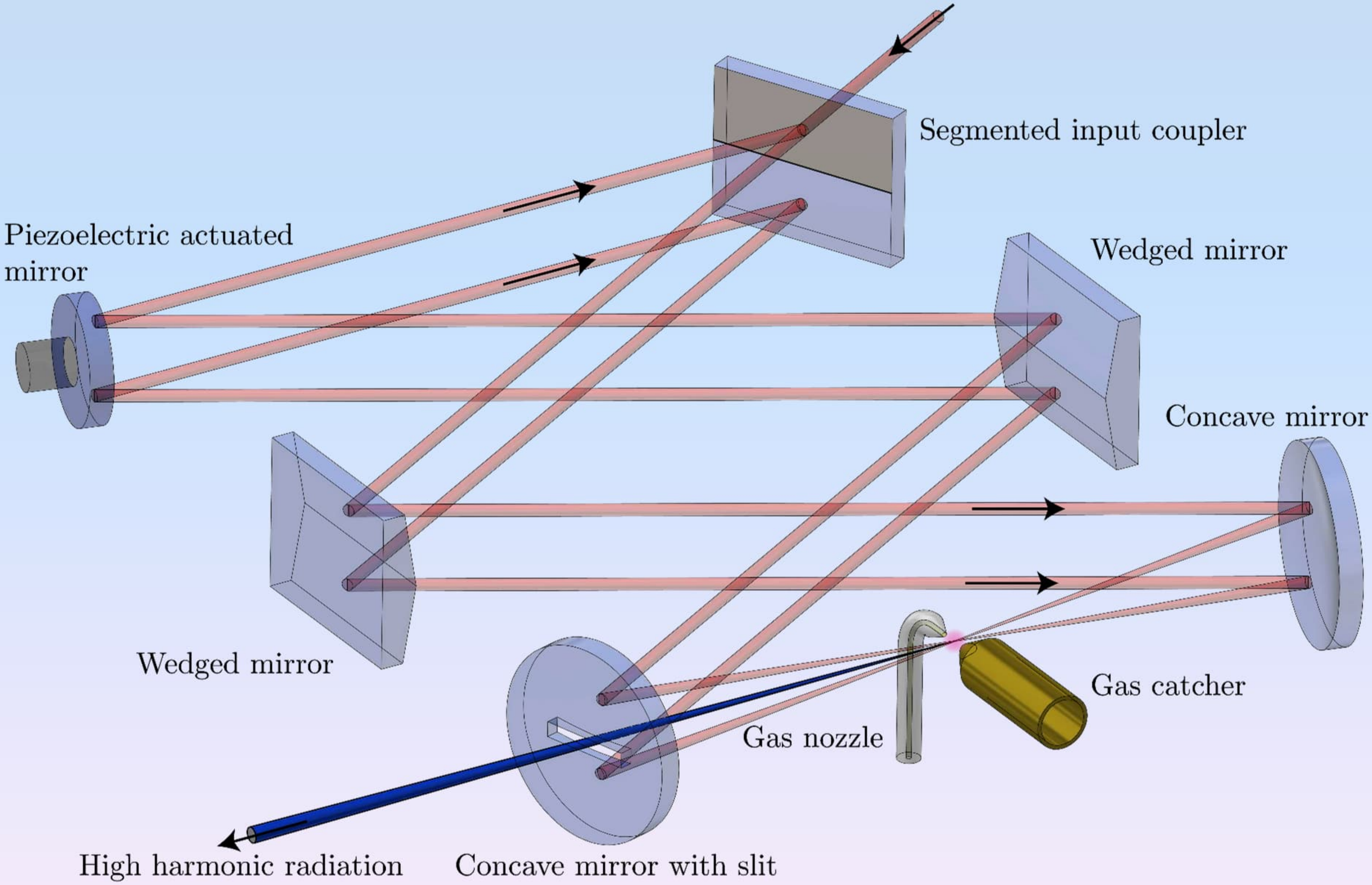
- can be trapped and sympathetically cooled.
- second order Doppler and AC-Stark largely eliminated.
- no HFS in ^{4}He.

the challenge:

- needs a narrow band laser at 60.8nm with ~10µW power!
- narrow band XUV lasers will find many other applications.

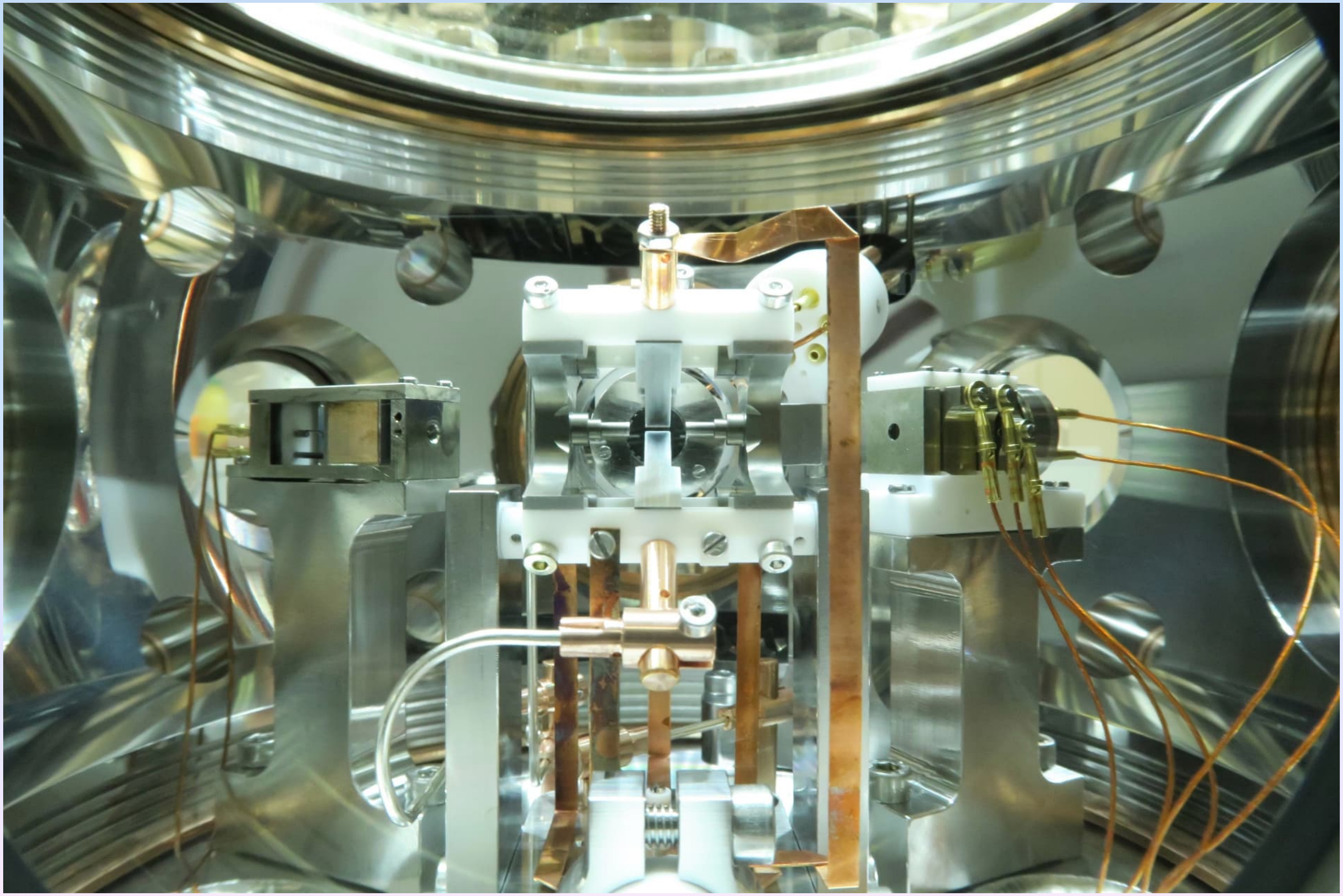
J. Moreno *et al.* Eur. Phys. J. D (2023)77:67

The Better Hydrogen: He^+

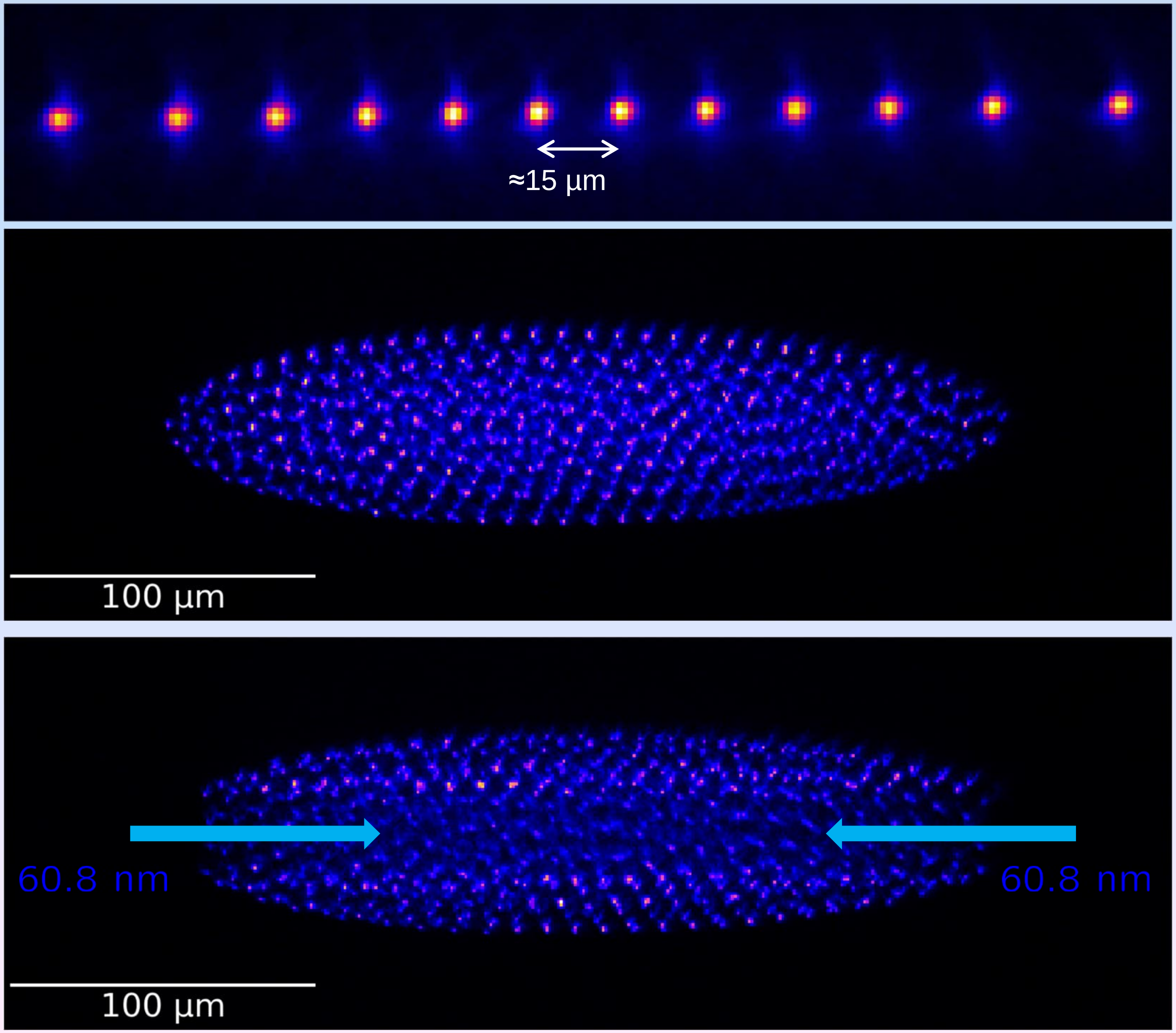


J. Moreno *et al.* Eur. Phys. J. D (2023)77:67

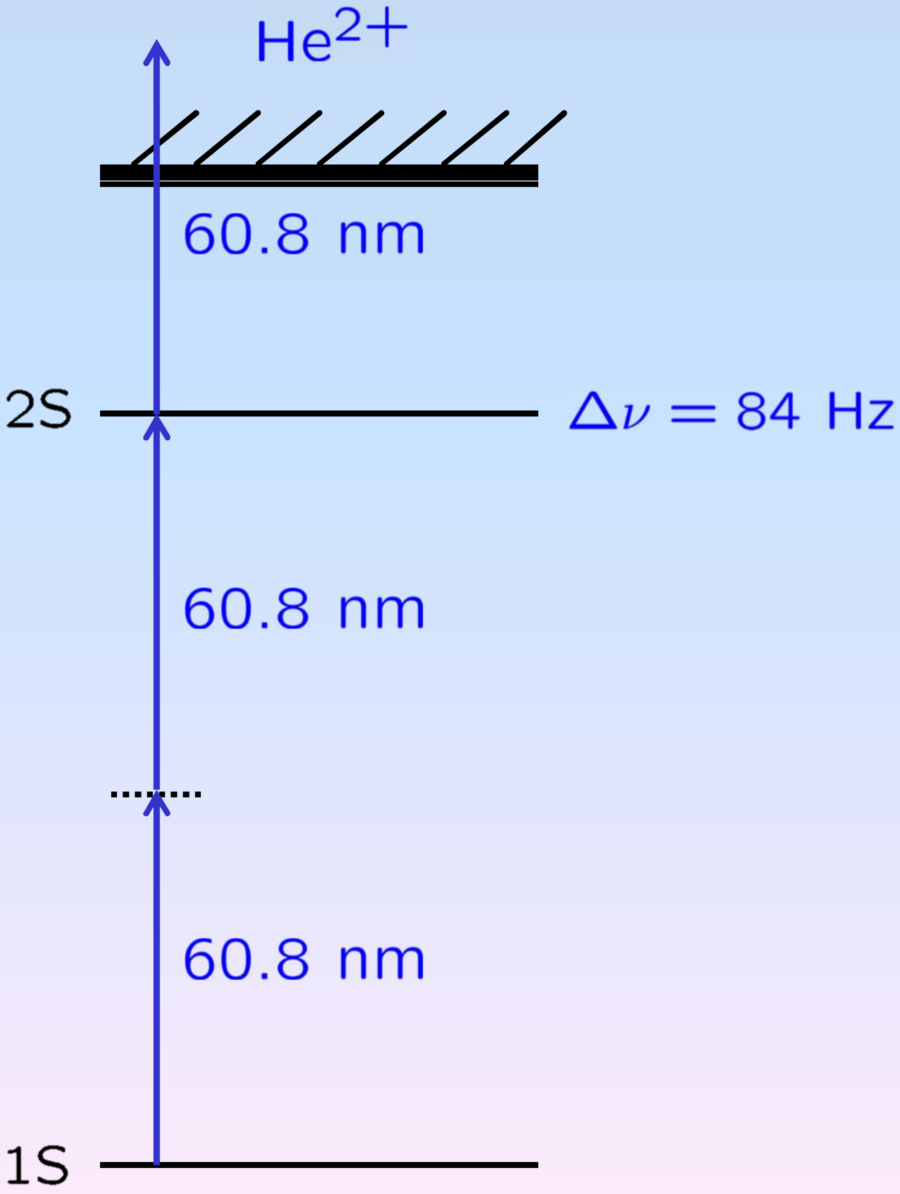
He^+ Be^+



Ion Crystals

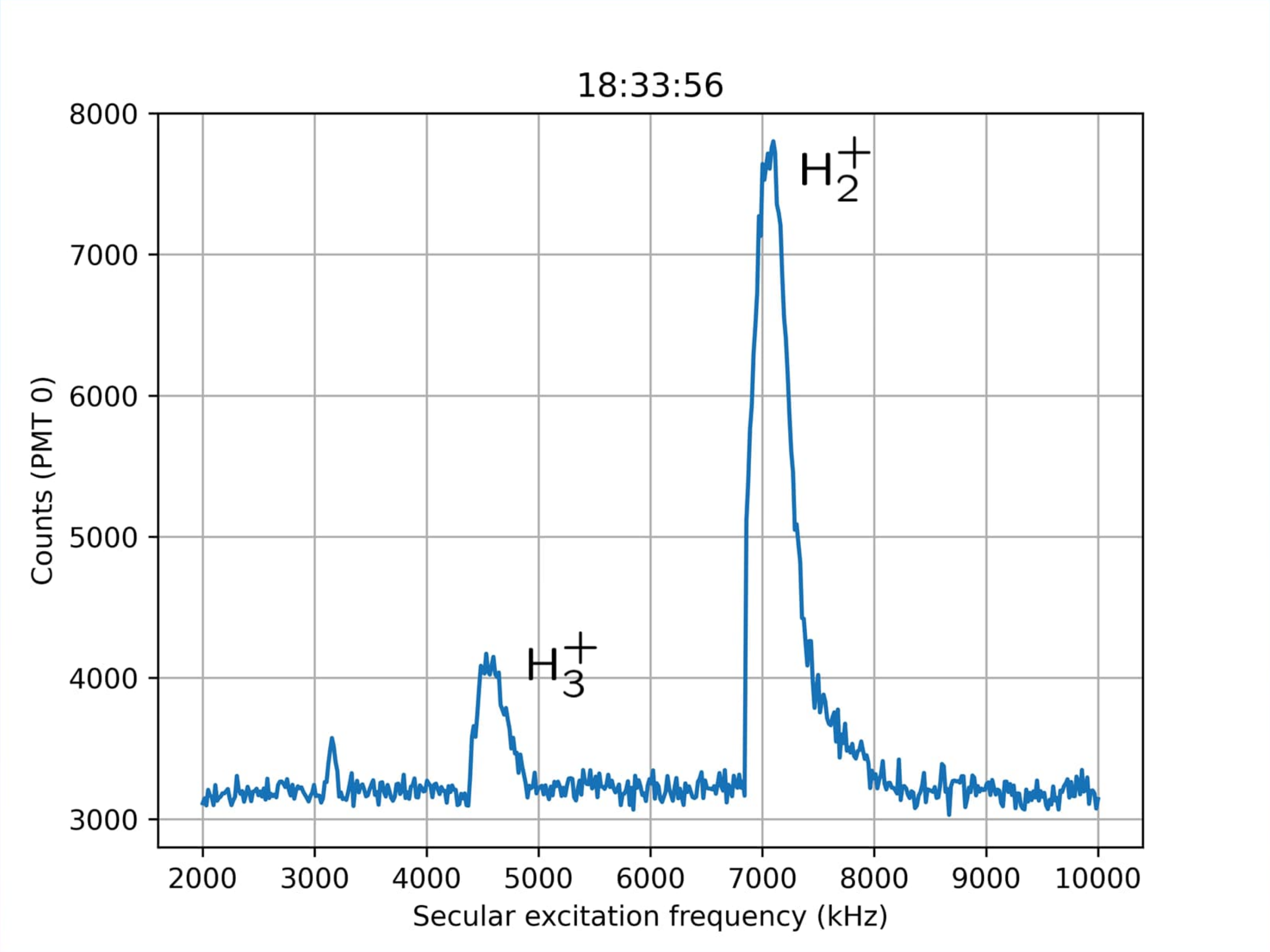


He^+



Single Ion Detection

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$



F. Schmid *et al.* Phys. Rev. A 106, L041101 (2022)

Single Ion Detection

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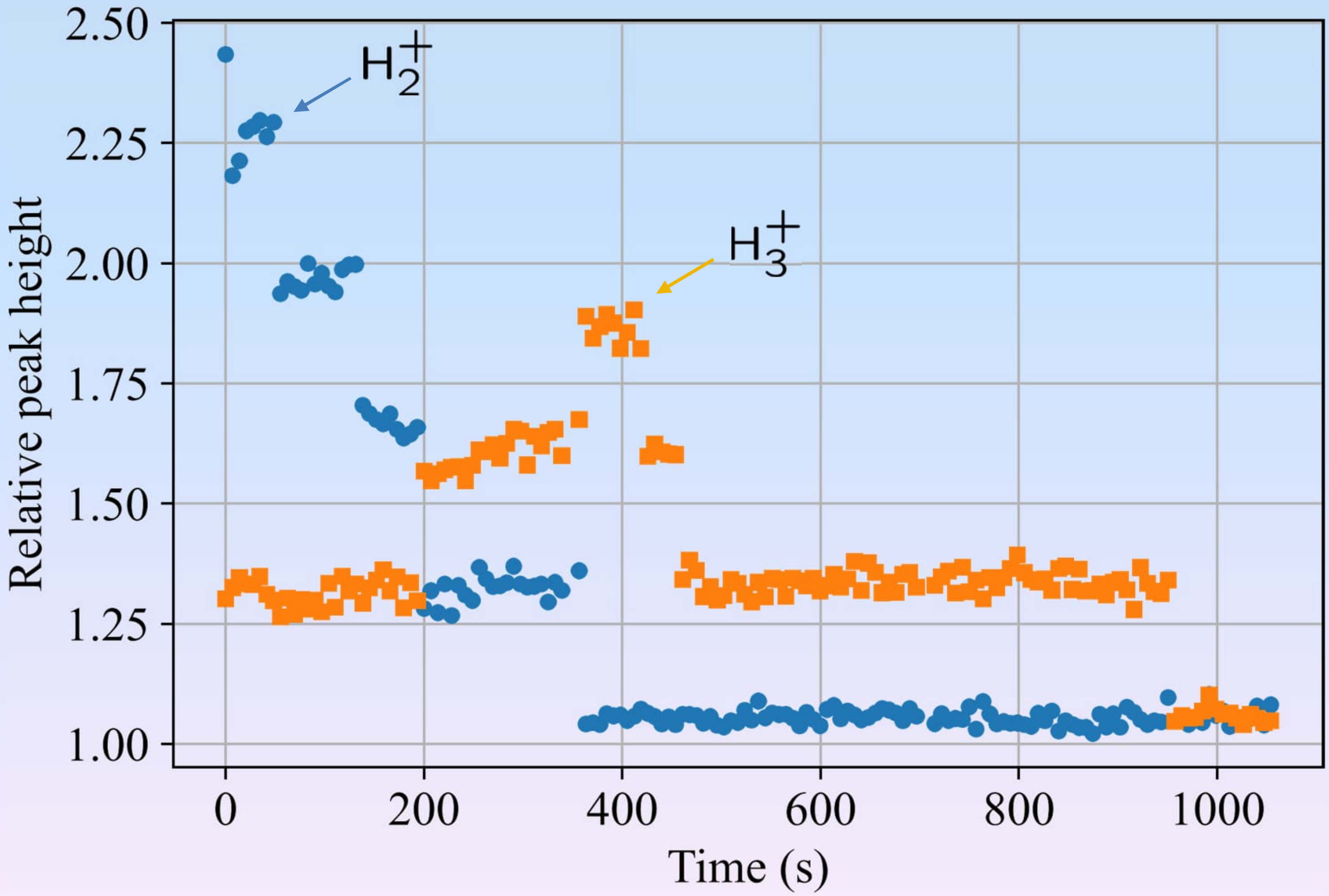

F. Schmid *et al.* Phys. Rev. A 106, L041101 (2022)

Summary / Outlook

- two measurements deterimine r_p **and** R_∞ (if QED is correct)
- 1S-2S the only (metrologically relevant) narrow line
- additional measurements test QED by comparing parameters

- Next:
  - identify 1S-3S Paris/Garching problem
  - measure the 2S-6P transition
  - take more deuterium data
  - three body systems: H_2^+, He, Li^+ . . .
  - measure 1S-2S transition frequency in He^+ (60.8 nm)

Thank you for your Attention