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

L. Maisenbacher[1,4] , V. Wirthl[1] , A. Matveev[1], A. Grinin[1,5], R. Pohl[2] , T.W. Hänsch[1,3], and Th. Udem[1,3]

[1] Max-Planck-Institut für Quantenoptik, Garching, Germany.
[2] Johannes Gutenberg-Universität Mainz, Mainz, Germany.
[3] Ludwig-Maximilians-Universität München, Munich, Germany.
[4] Present address: University of California, Berkeley, CA, USA.
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ICAP 29
Wuhan 18.06.2026

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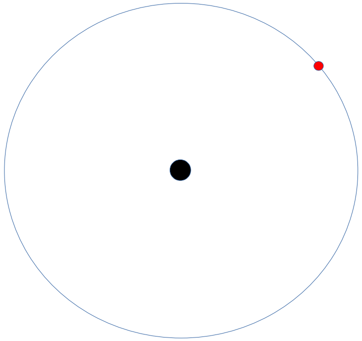
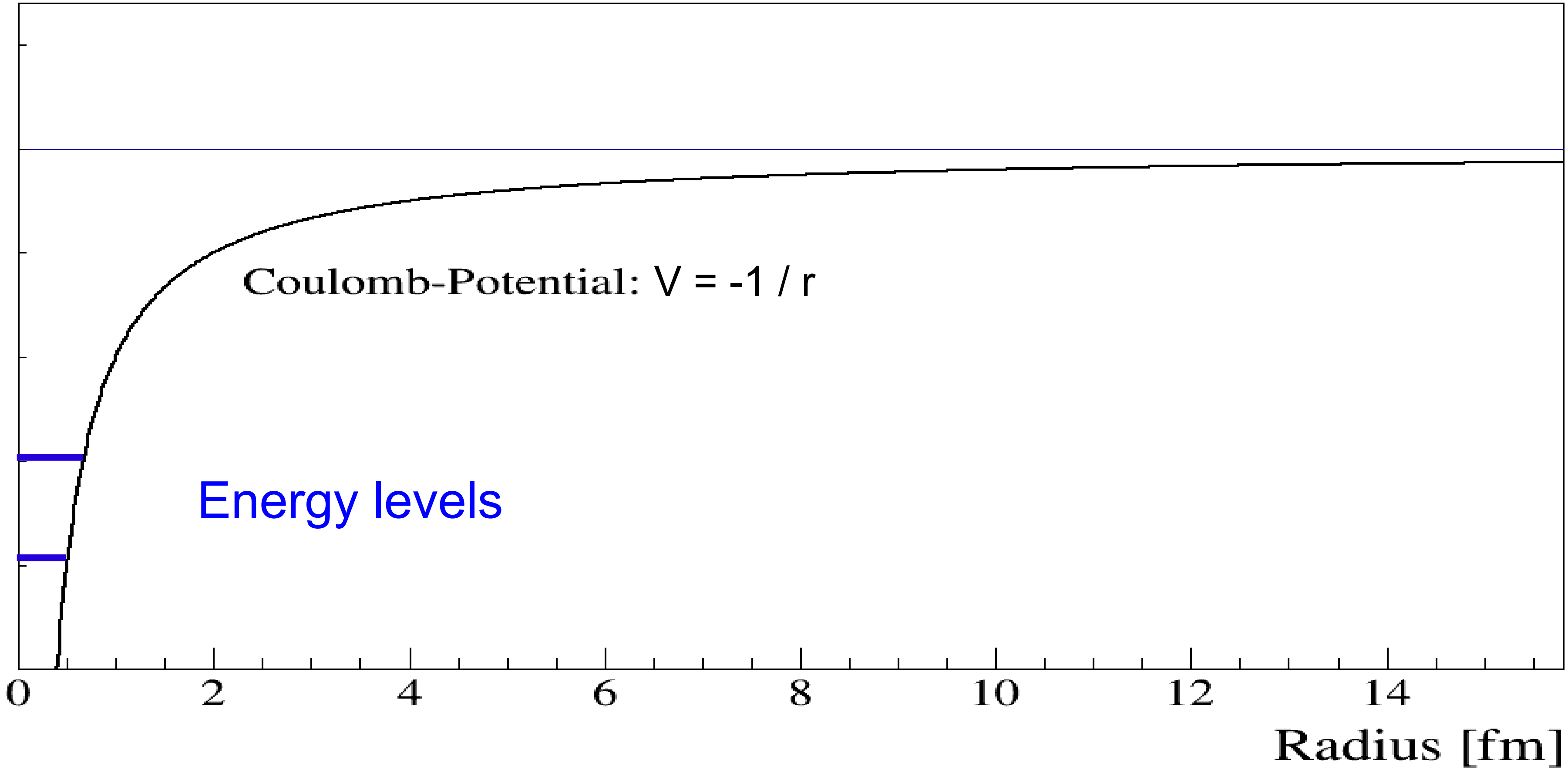
Hydrogen (-like atoms)



"There's a reason physicists are so successful with what they do, and that is they study the hydrogen atom and the helium ion and then they stop."

- Richard Feynman

Proton Radius and Hydrogen



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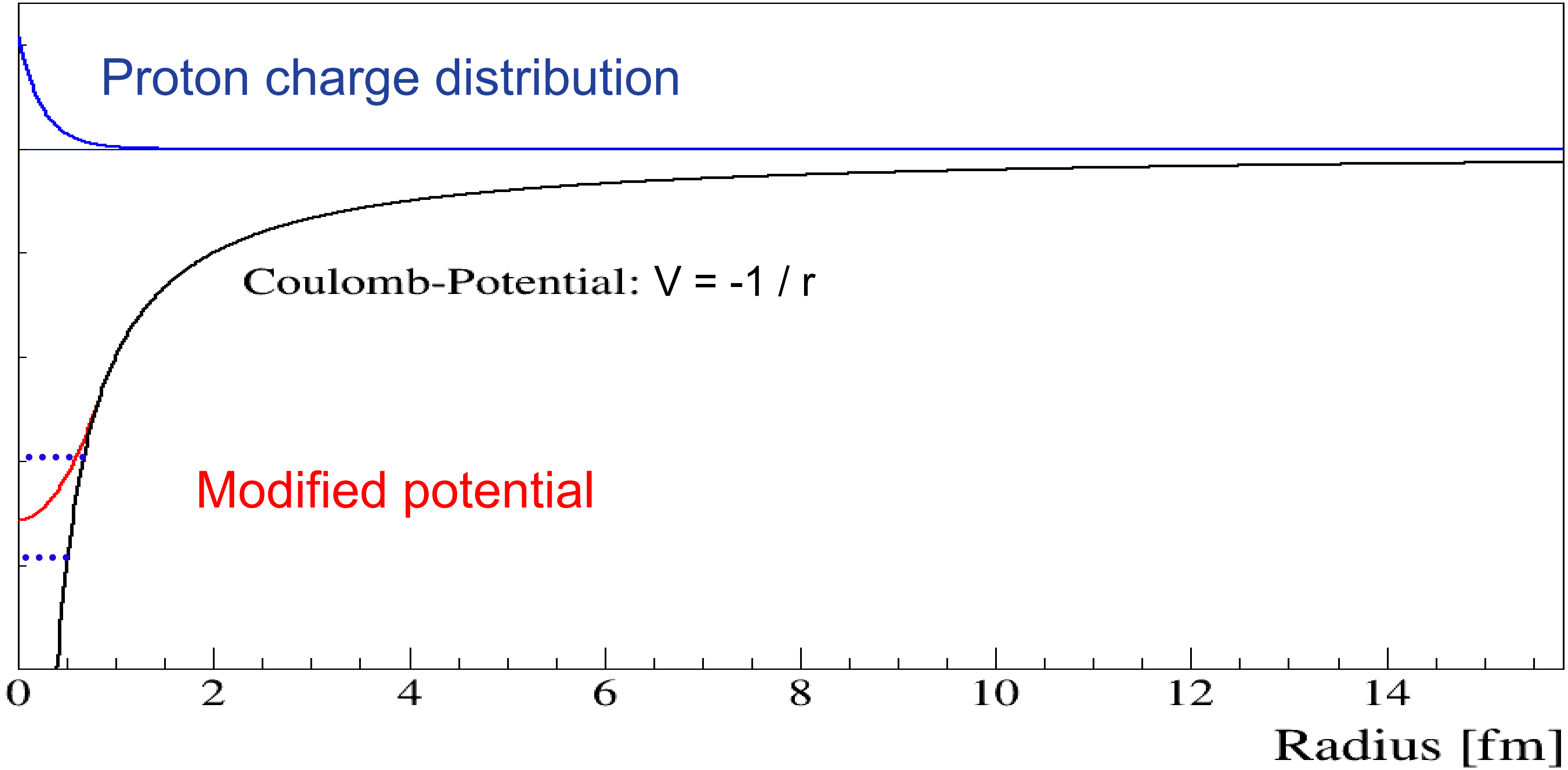

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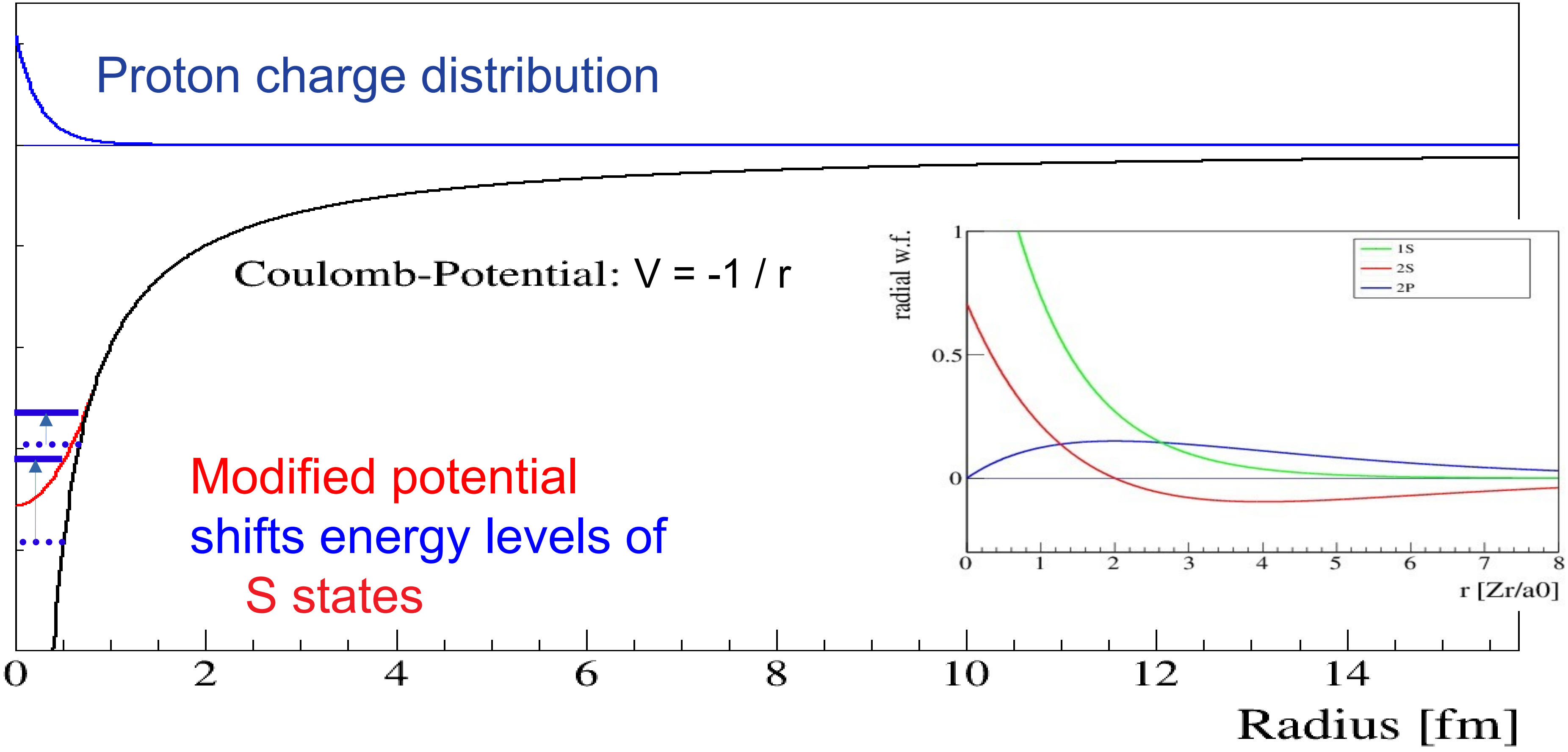


Muonic Atoms

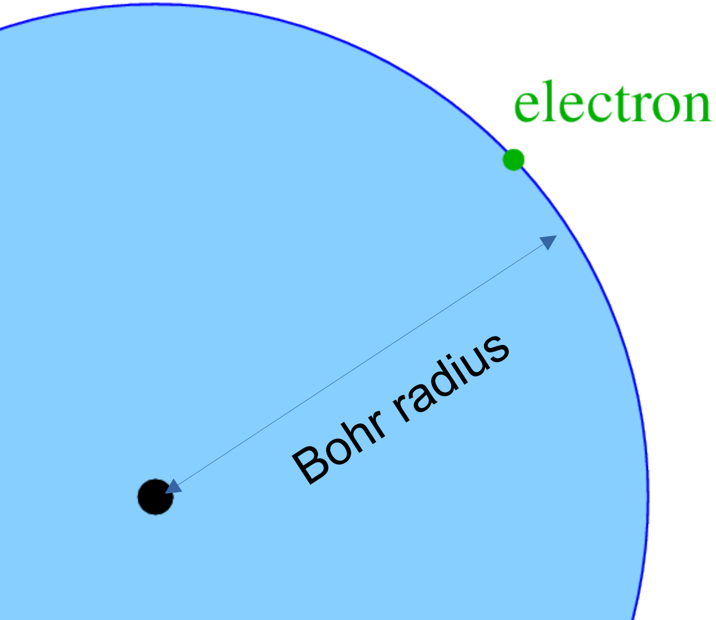
A **bare** nucleus, orbited by **one negative muon.**

Hydrogen theory!

Muonic atoms in a nutshell

Regular hydrogen:

Bohr radius ~ 50’000 x nuclear radius



Muonic hydrogen:

Muon **mass** = **200** * electron mass

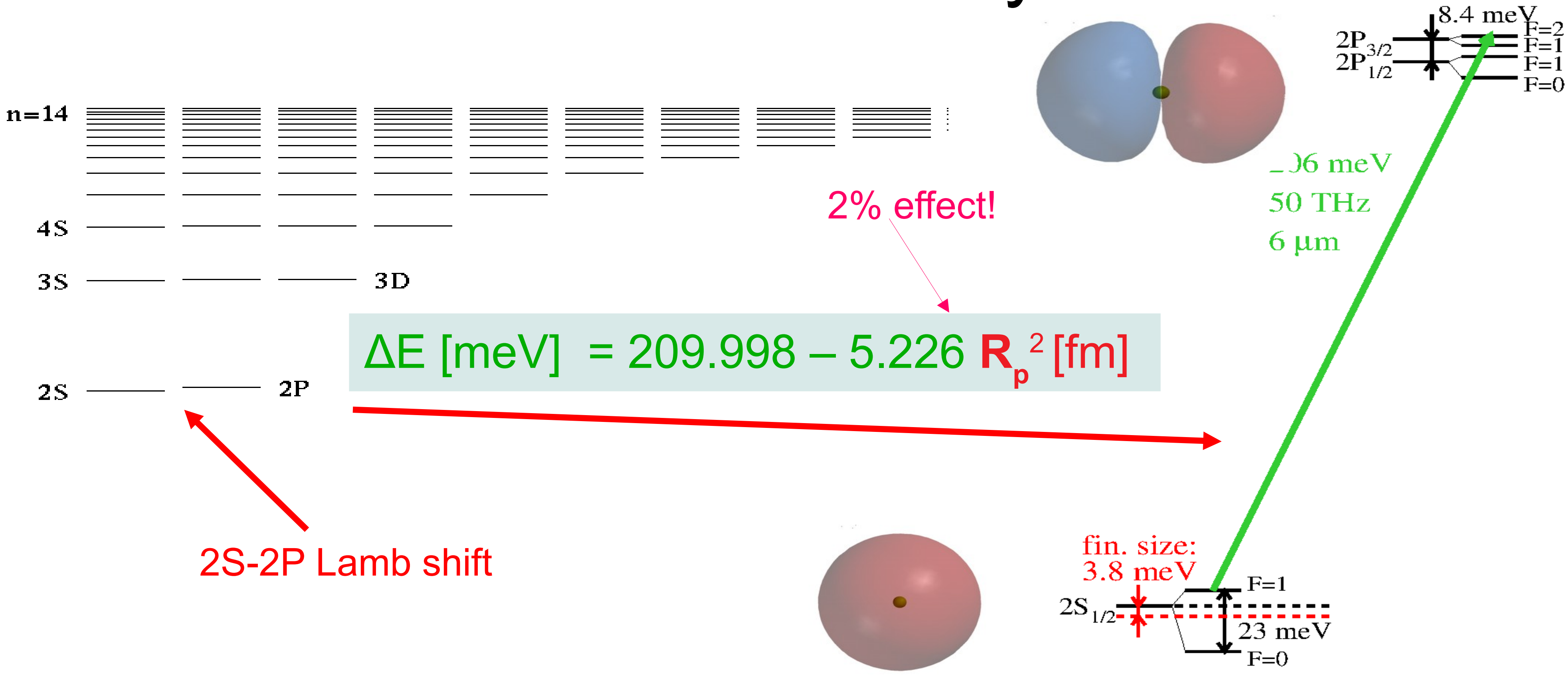
Bohr **radius** = **1/200** of H

200^3 = a **ten million times** more sensitive to nuclear size & structure

==> Our (laser) spectroscopy at **10^{-5}** level can compete with **10^{-12}** from normal atoms

Vastly not to scale!!

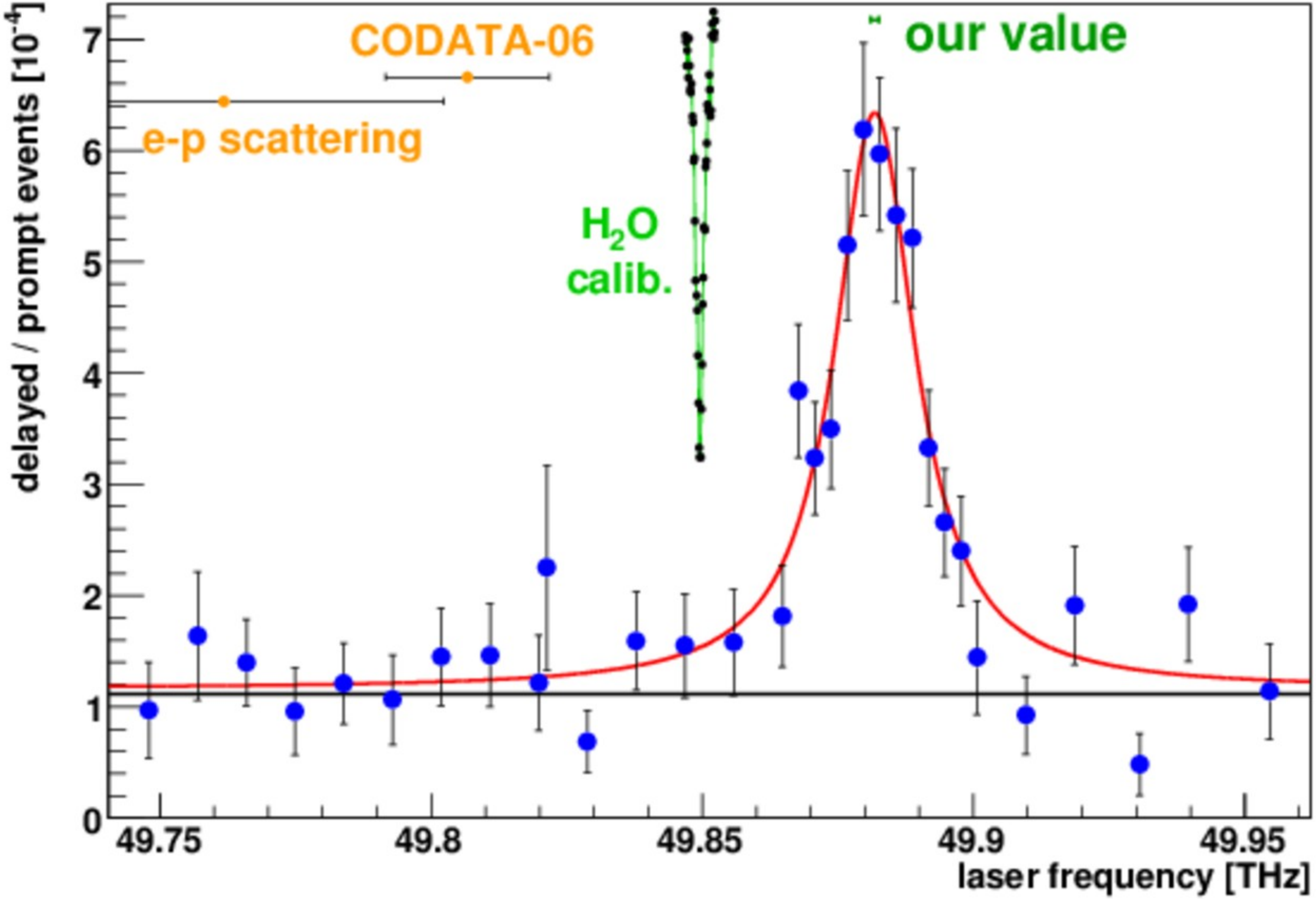
Lamb shift in Muonic Hydrogen



$$\Delta E\ [\text{meV}] = 209.998 - 5.226\ \mathbf{R_p}^2\ [\text{fm}]$$

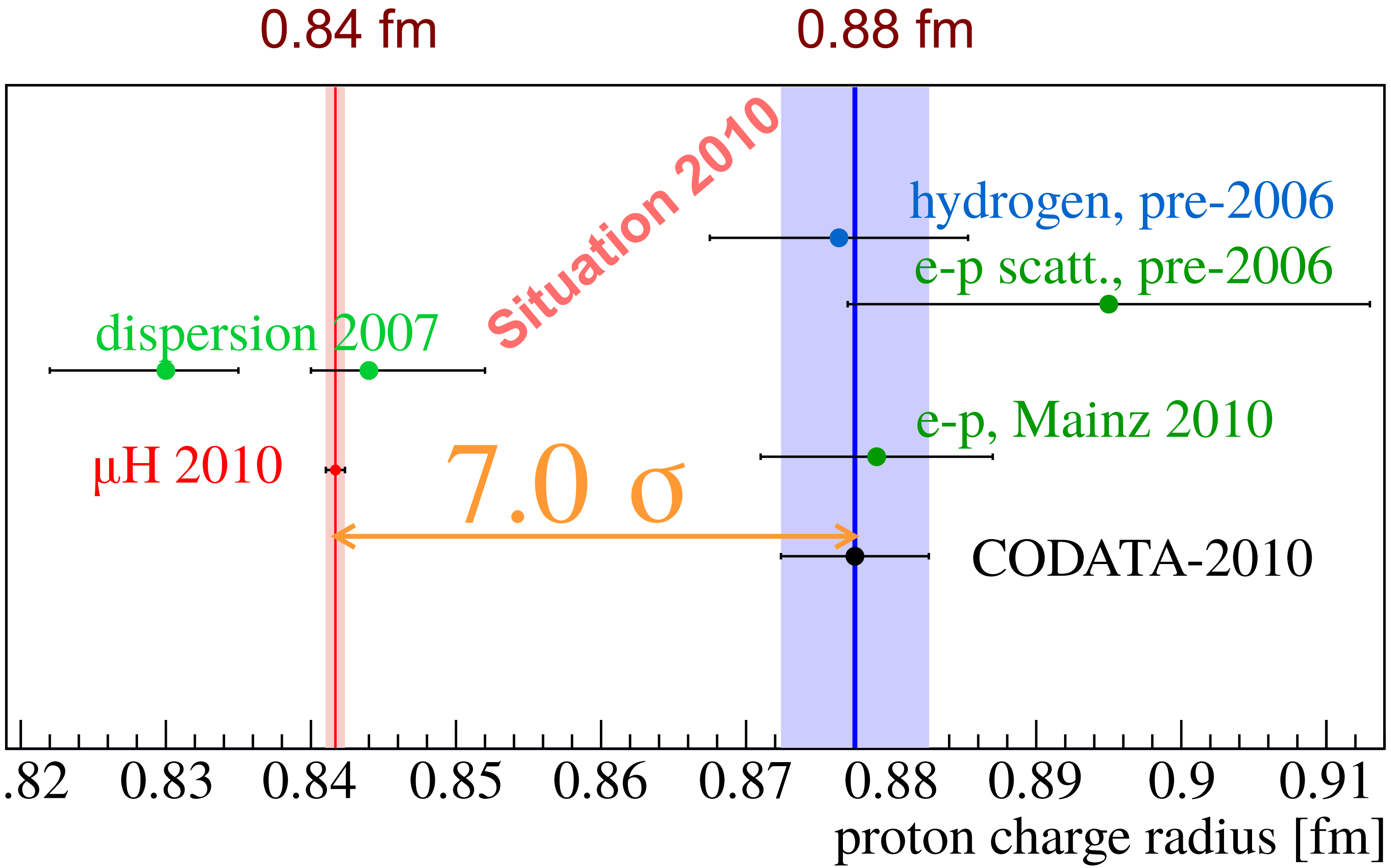
2S state is sensitive to the proton size.

Resonance



CODATA-06
our value
e-p scattering
H_2O
calib.
delayed / prompt events [10^{-4}]
laser frequency [THz]
0
1
2
3
4
5
6
7
49.75
49.8
49.85
49.9
49.95

The "Proton Radius Puzzle"



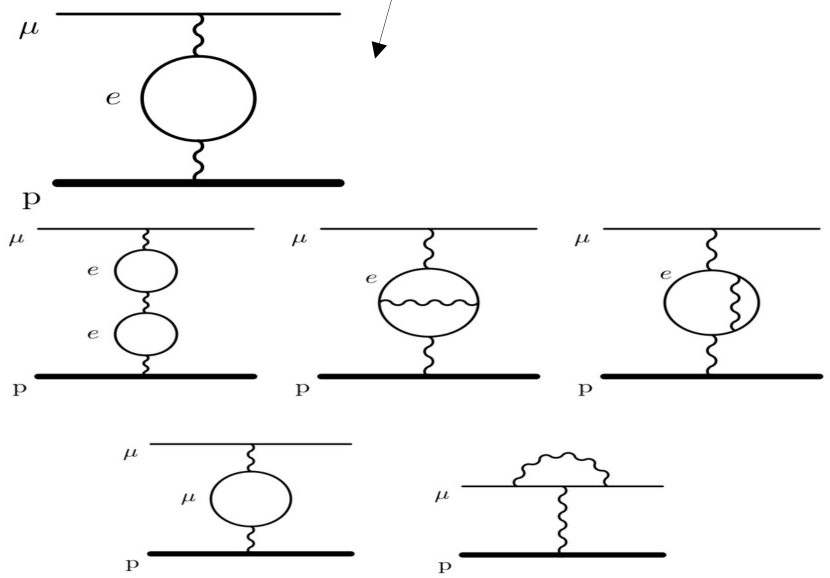
Theory in muonic H (D, $^{3,4}He^+$ similar)

$$\Delta E_{Lamb} = 206.0344\,(3)\ \mathrm{meV}_{QED} + 0.0289\,(25)\ \mathrm{meV}_{TPE} - 5.2259\,(1)\ \mathrm{meV/fm^2} * \mathbf{R_p}^{\mathbf{2}}$$

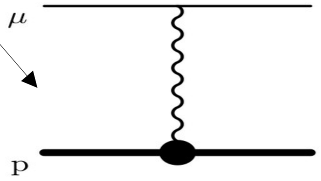
Uehling

Källen-Sabry

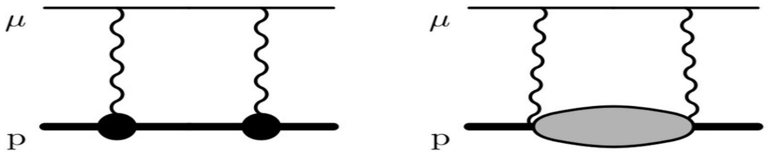
Muon SE+VP



and 20+ more….

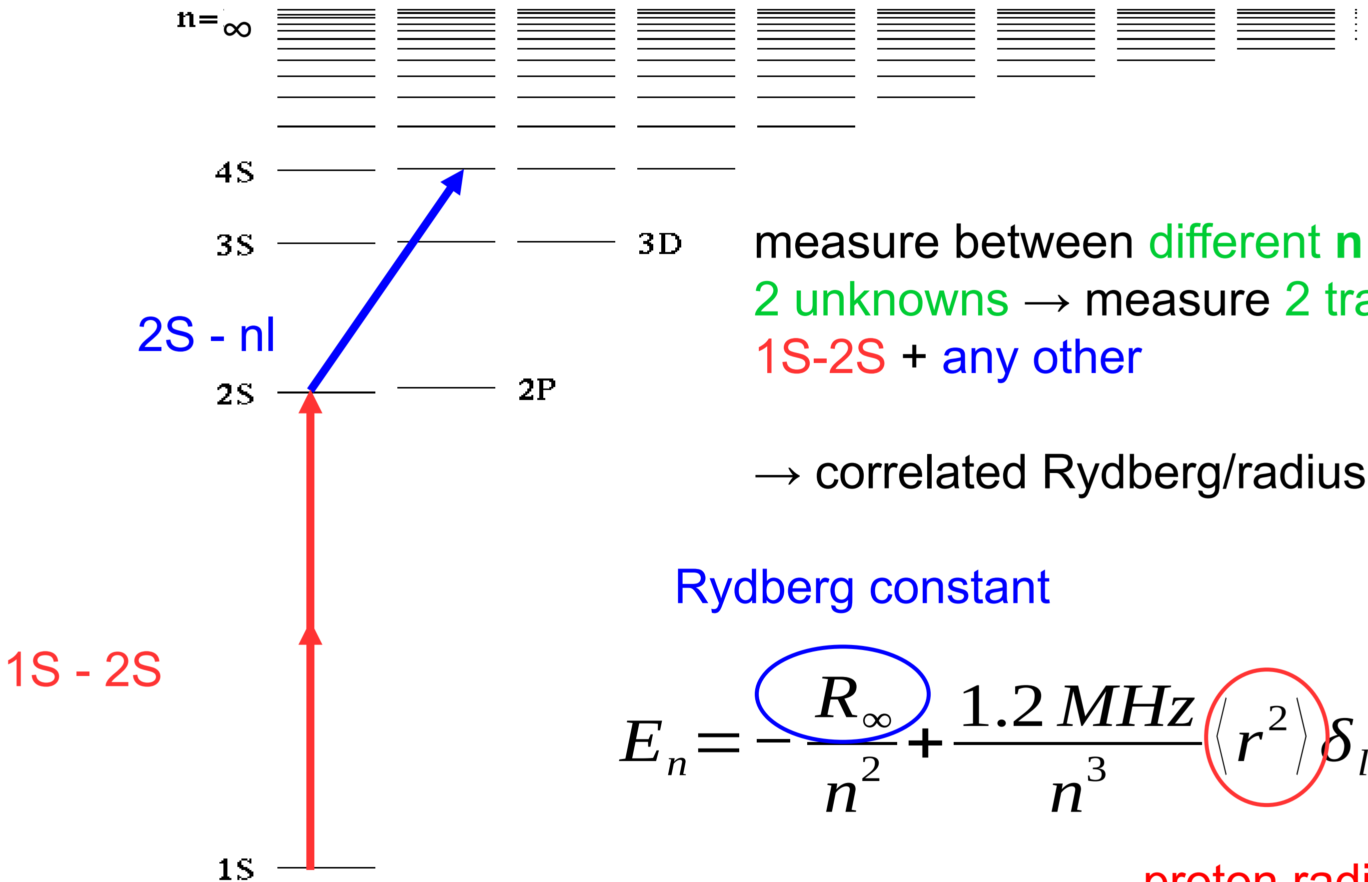


Proton form factor



elastic and inelastic two-photon exchange
(Friar moment and polarizability)

Proton radius from **ordinary hydrogen**



measure between different **n**
2 unknowns → measure 2 transitions:
1S-2S + any other

→ correlated Rydberg/radius pairs

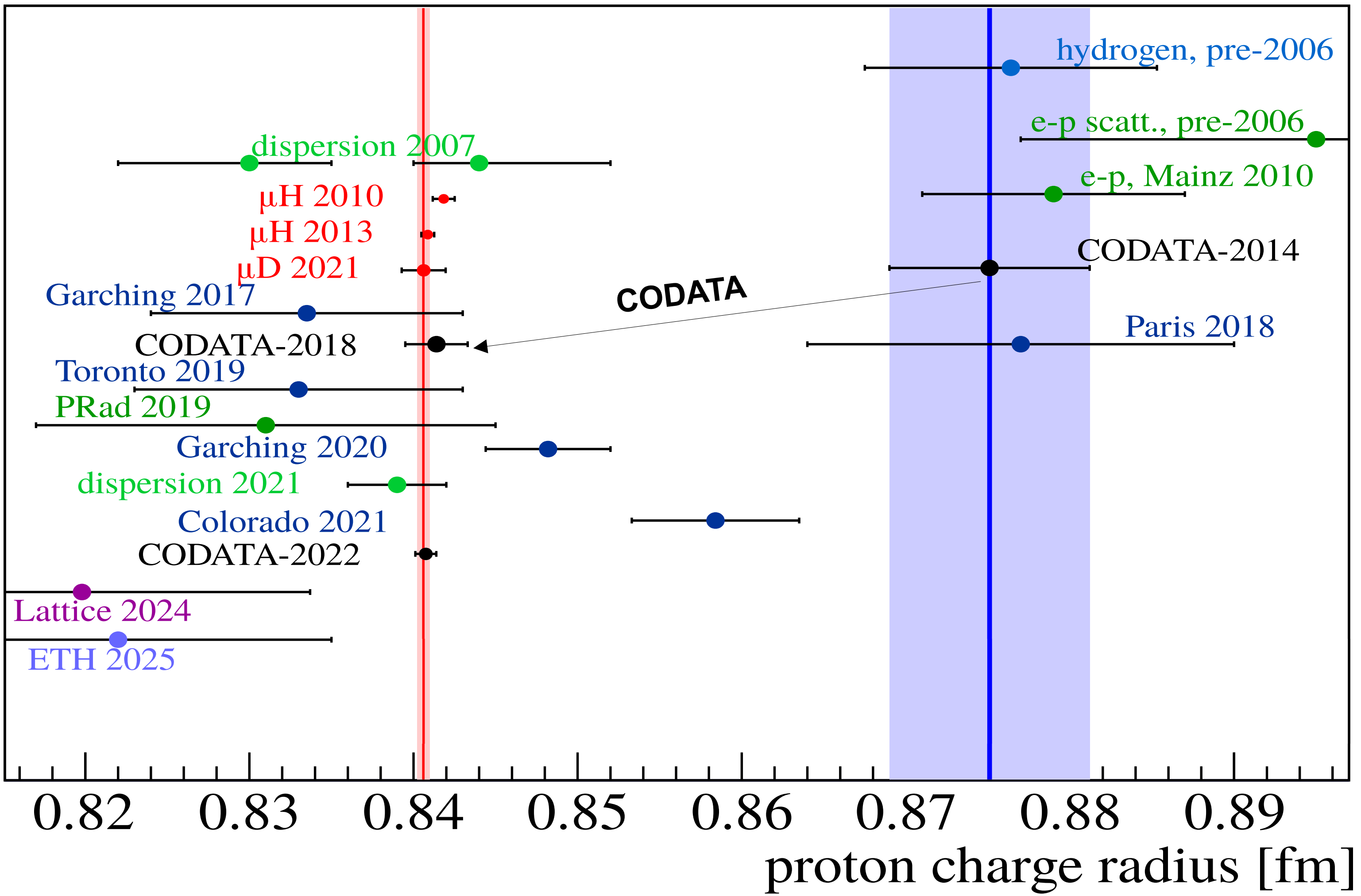
Rydberg constant

QED etc.

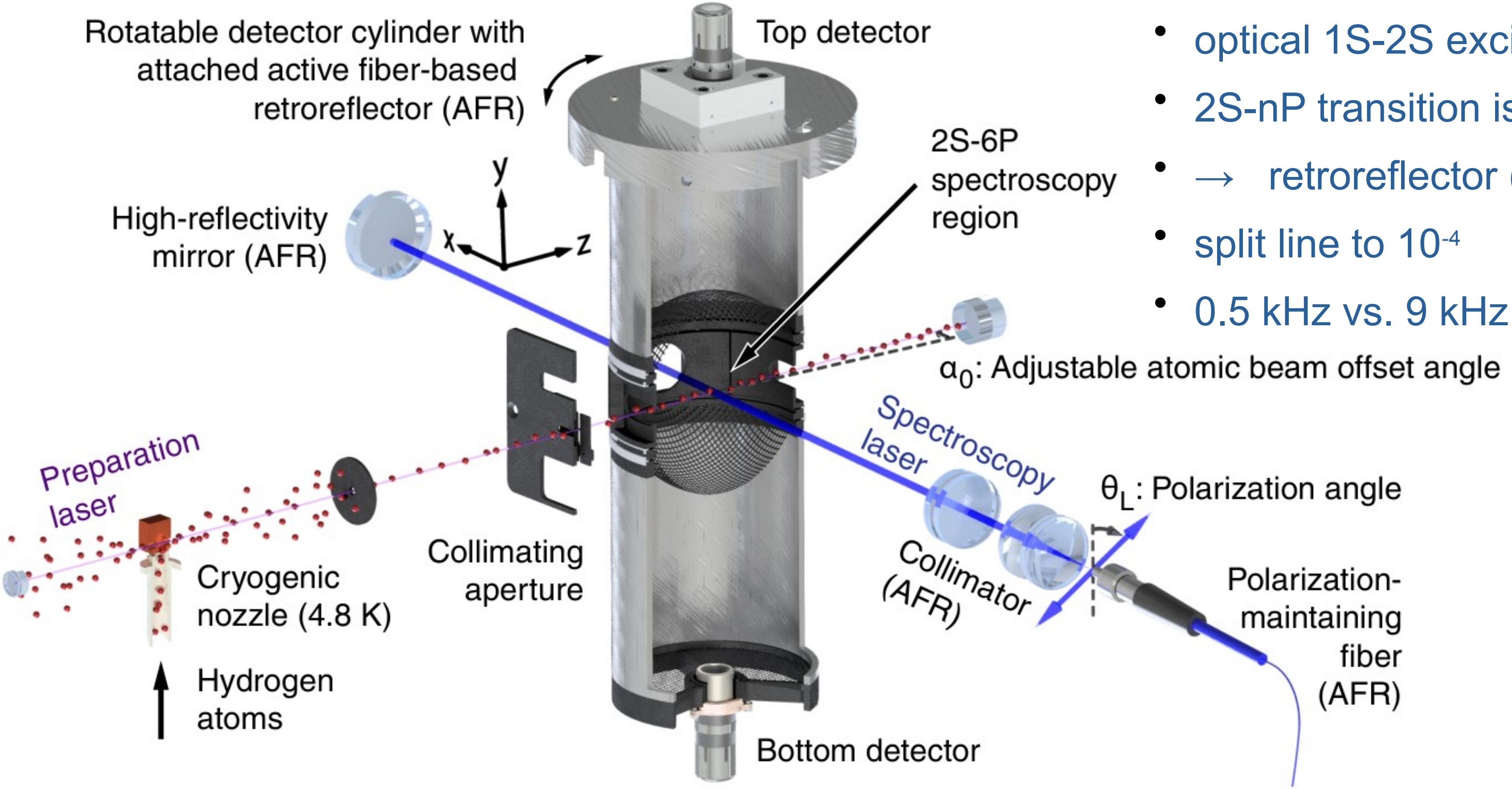
$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

proton radius

The proton radius situation last year



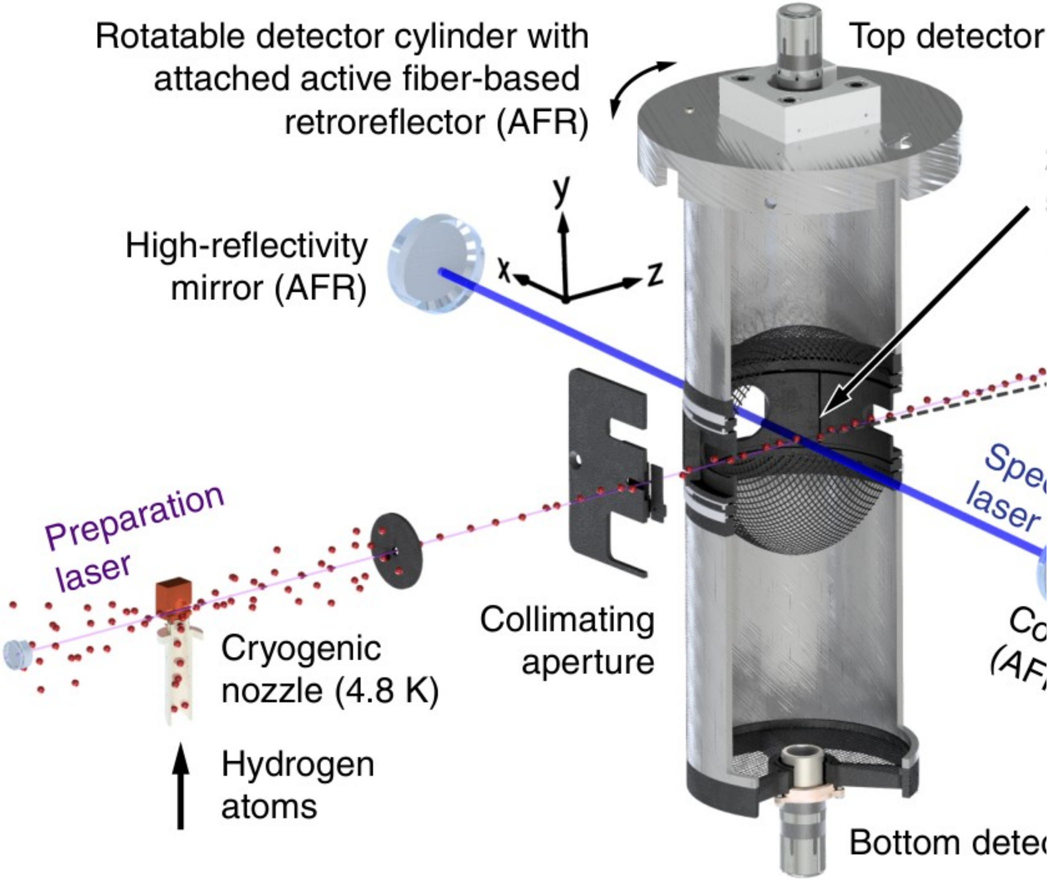
(Normal) Hydrogen 2S-nP in Garching



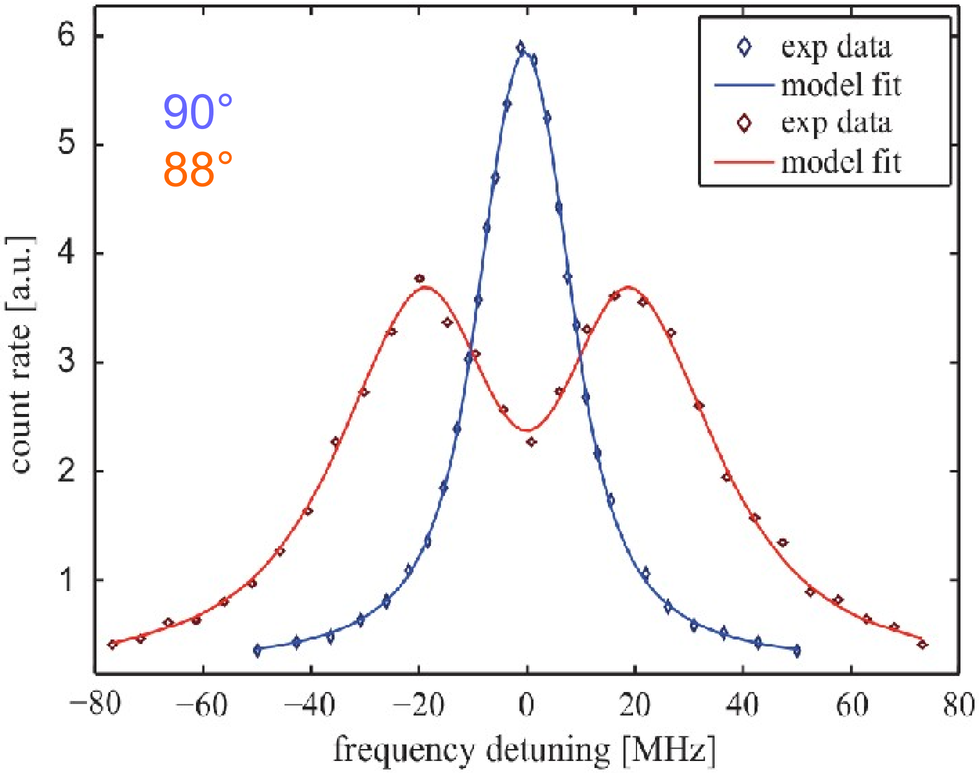
- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-nP transition is 1-photon
- → retroreflector ("AFR")
- split line to 10^{-4}
- 0.5 kHz vs. 9 kHz PRP

Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

Hydrogen 2S-nP in Garching



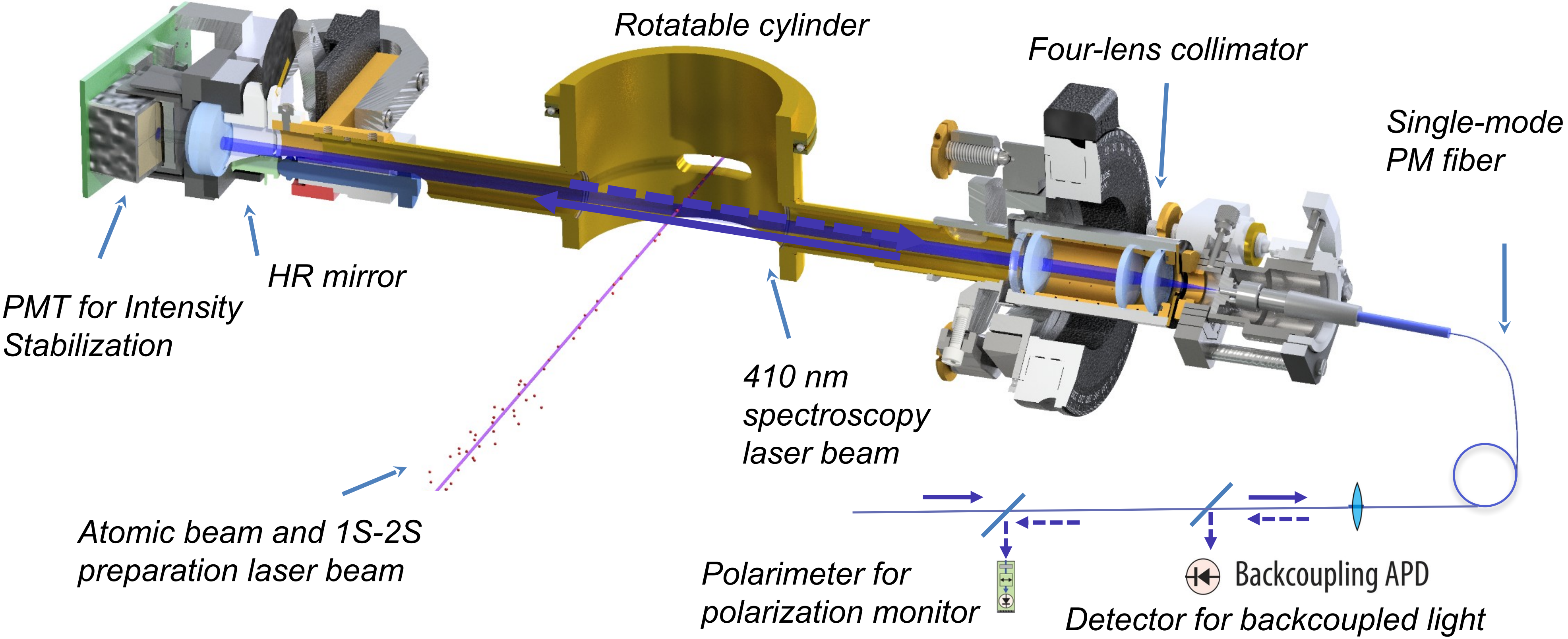
1st order Doppler cancellation (2S-4P)



Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

Doppler shift suppression: Active Fiber-based Retrorefector

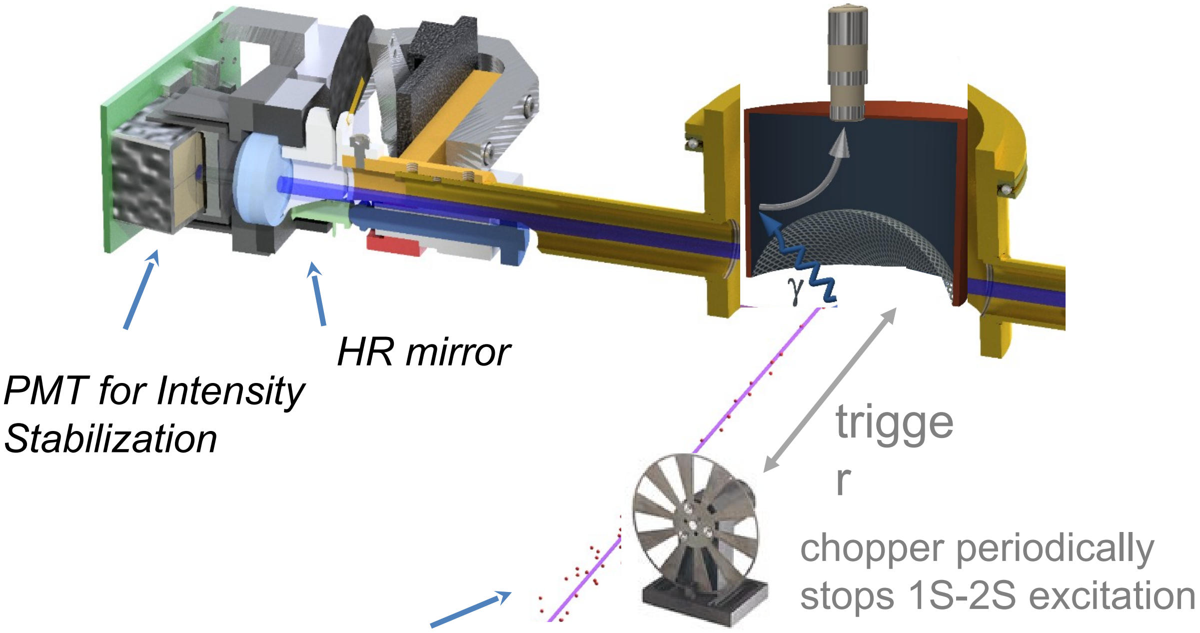
Improved active fiber-based retroreflector for near UV provides high-quality wavefront-retracing laser beams:

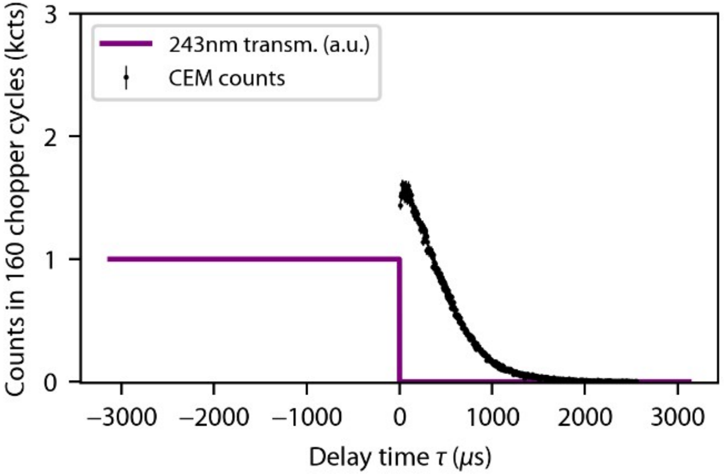


V. Wirthl *et al.*, *Opt. Express* 29(5), 7024 (2021)

Time-resolved detection: velocity-dependent signal

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





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

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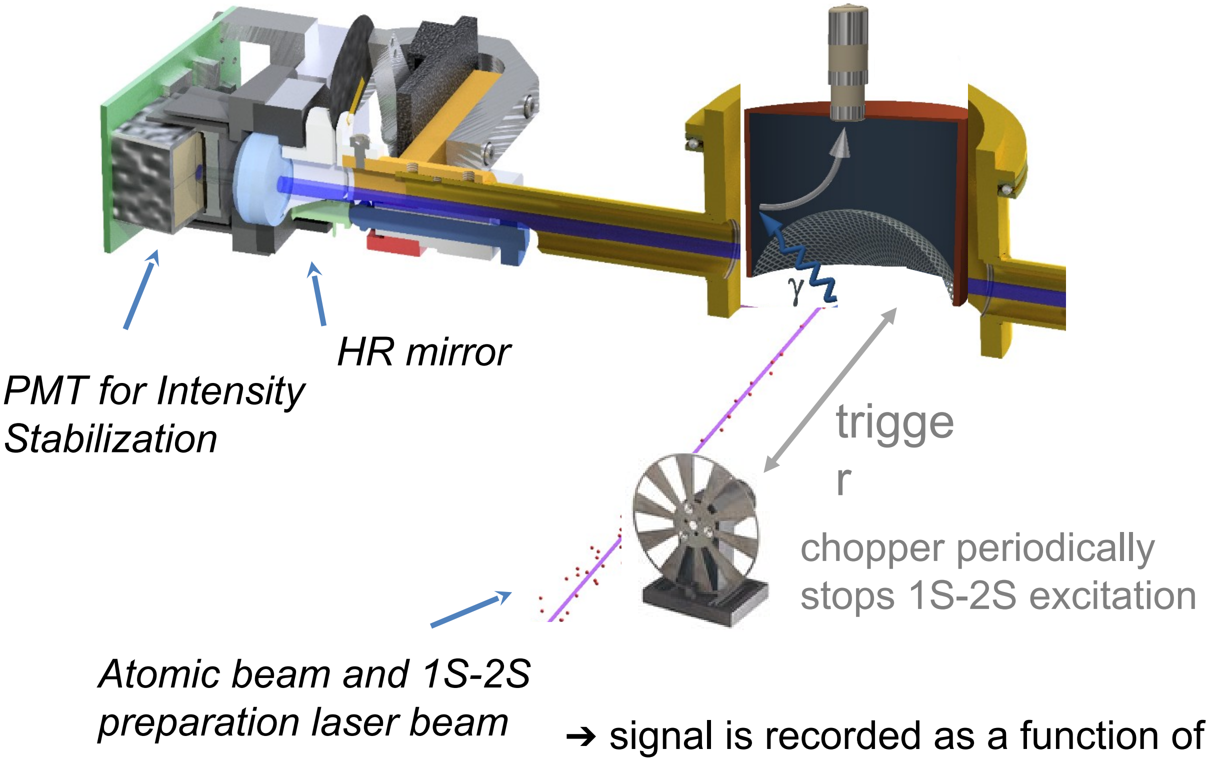

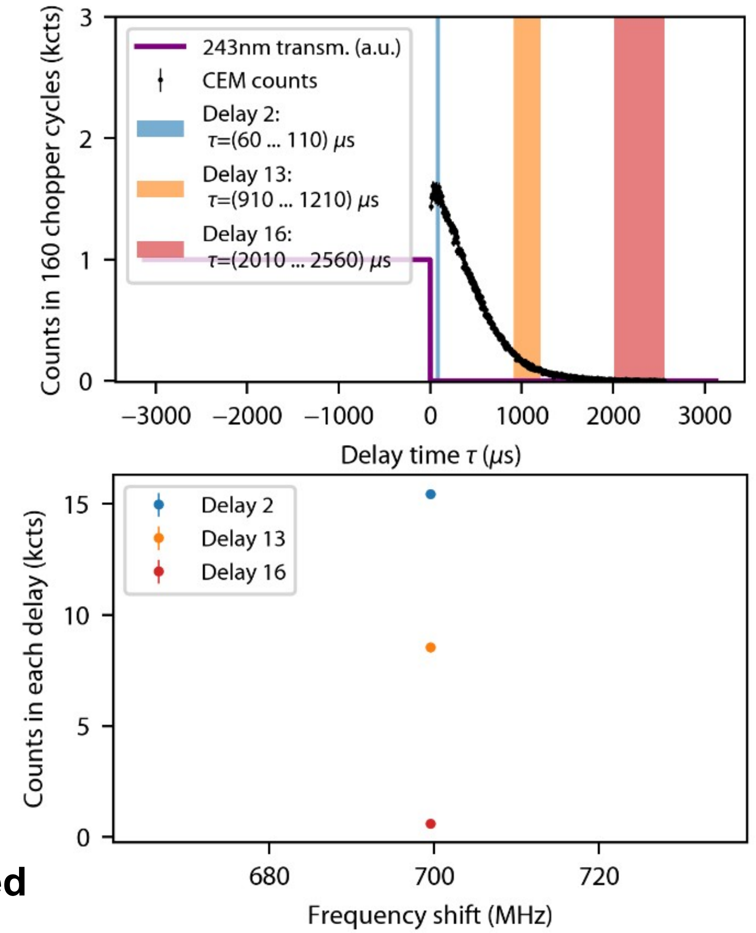

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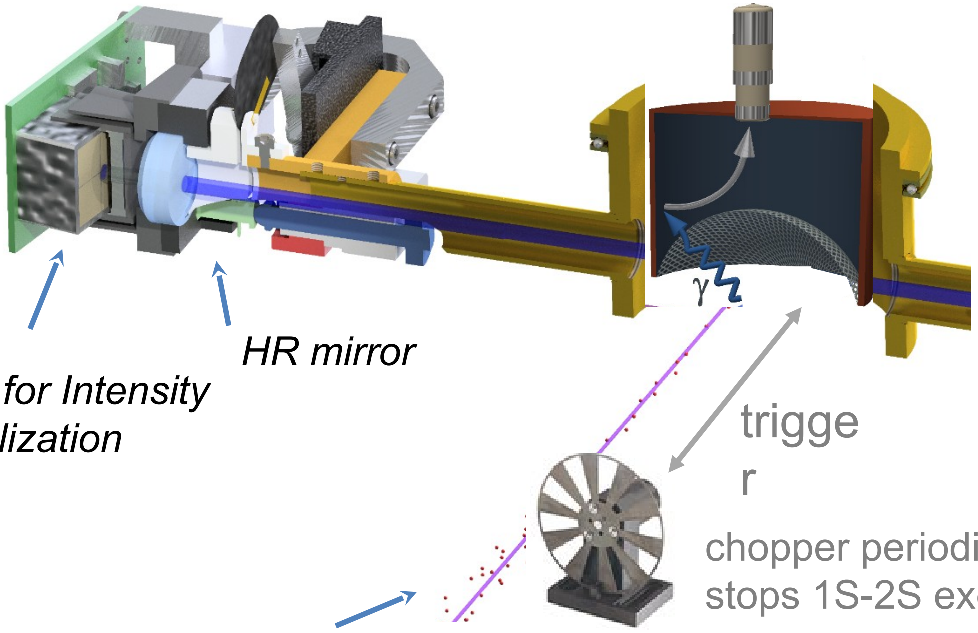

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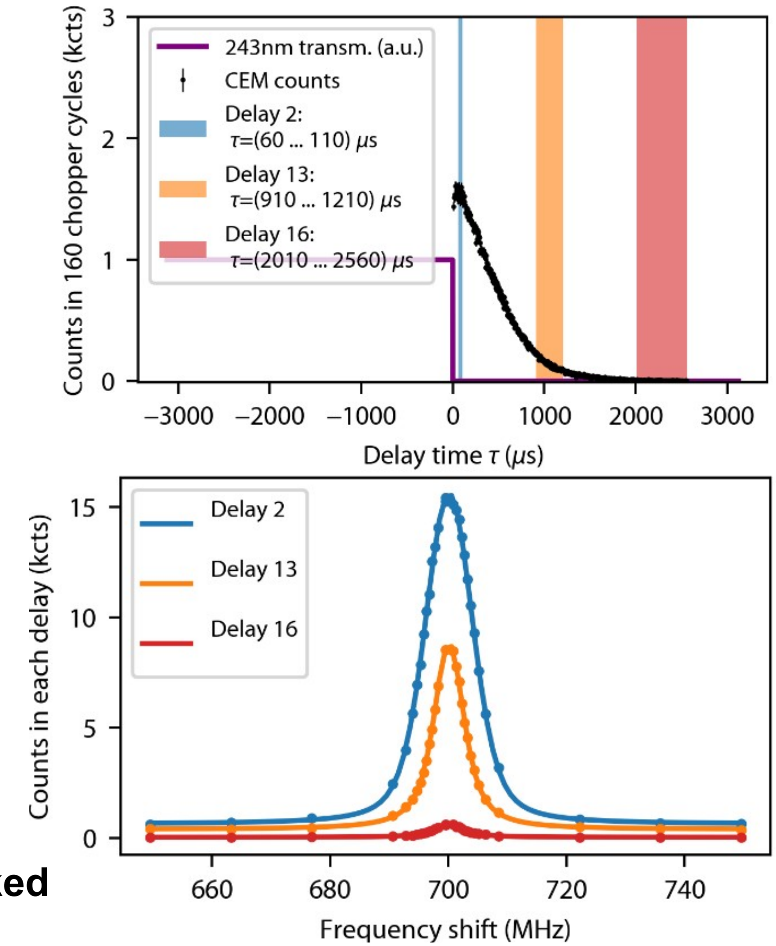
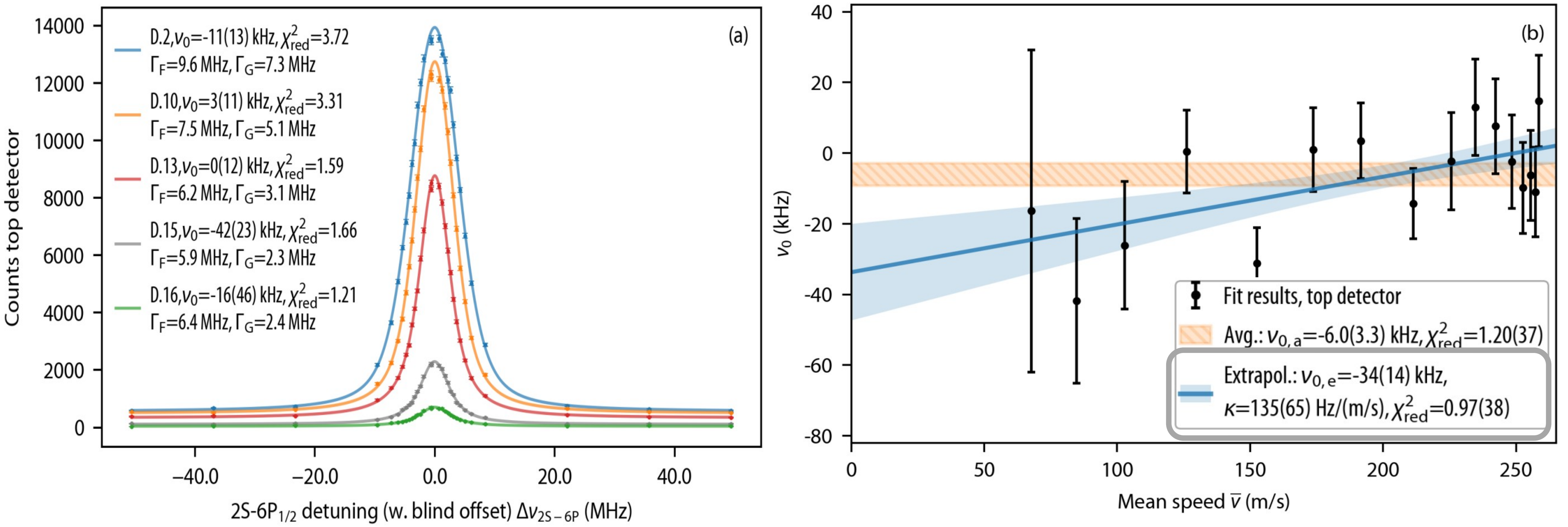


Time-resolved detection: velocity-dependent signal

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



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

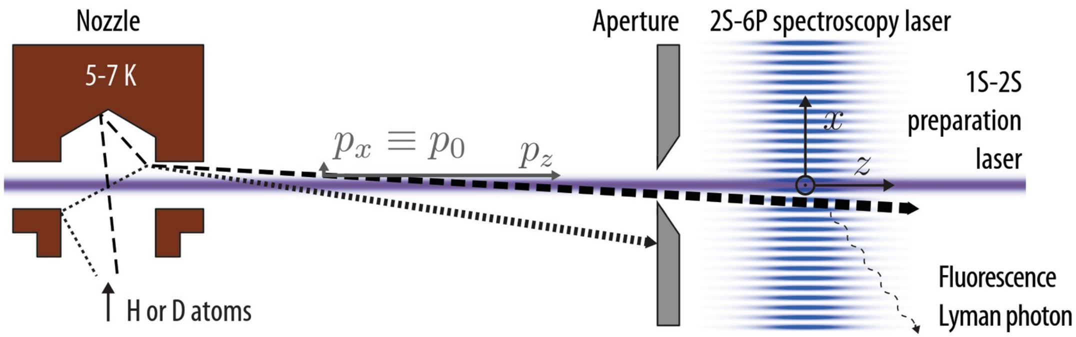
Corrections and uncertainties for hydrogen 2S-6P measurement

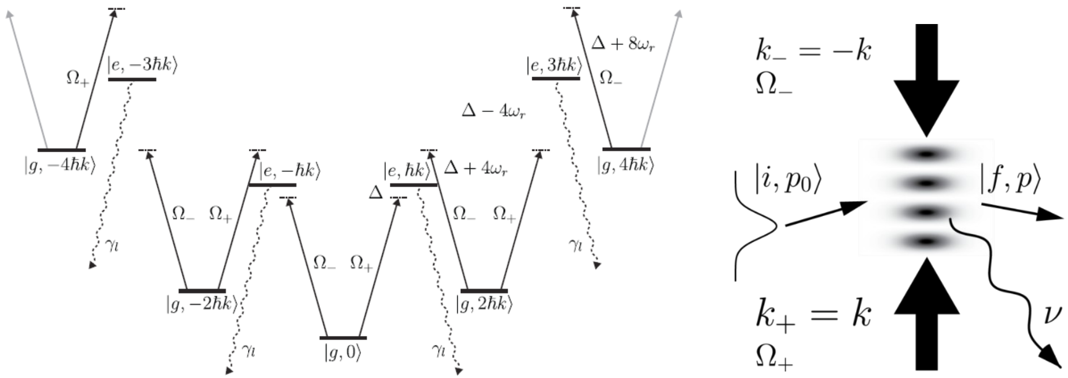
L. Maisenbacher, V. Wirthl, RP et al, *Nature* 650 (2026)

Contribution	Correction $\Delta\nu$ (kHz)	Uncertainty 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 $\Delta\nu_{\mathrm{HFS}}(\nu_{\mathrm{2S\text{-}6P}})$	−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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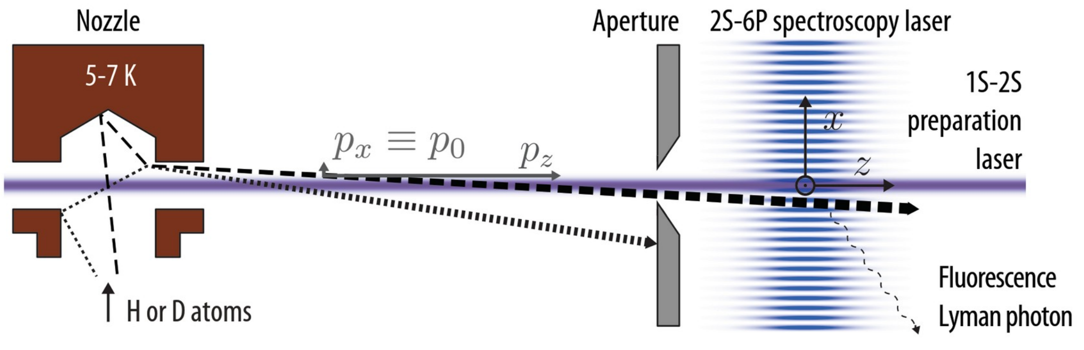
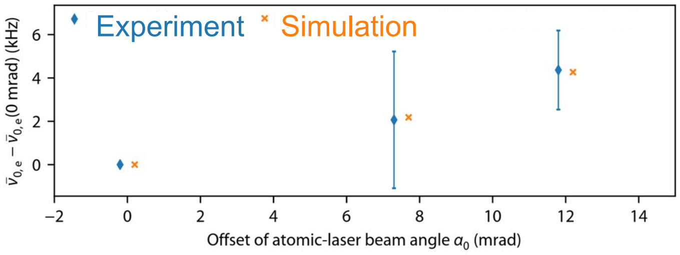


Light Force Shift measured by rotating atomic beam



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

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

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Largest systematic correction: Light force shift

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

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

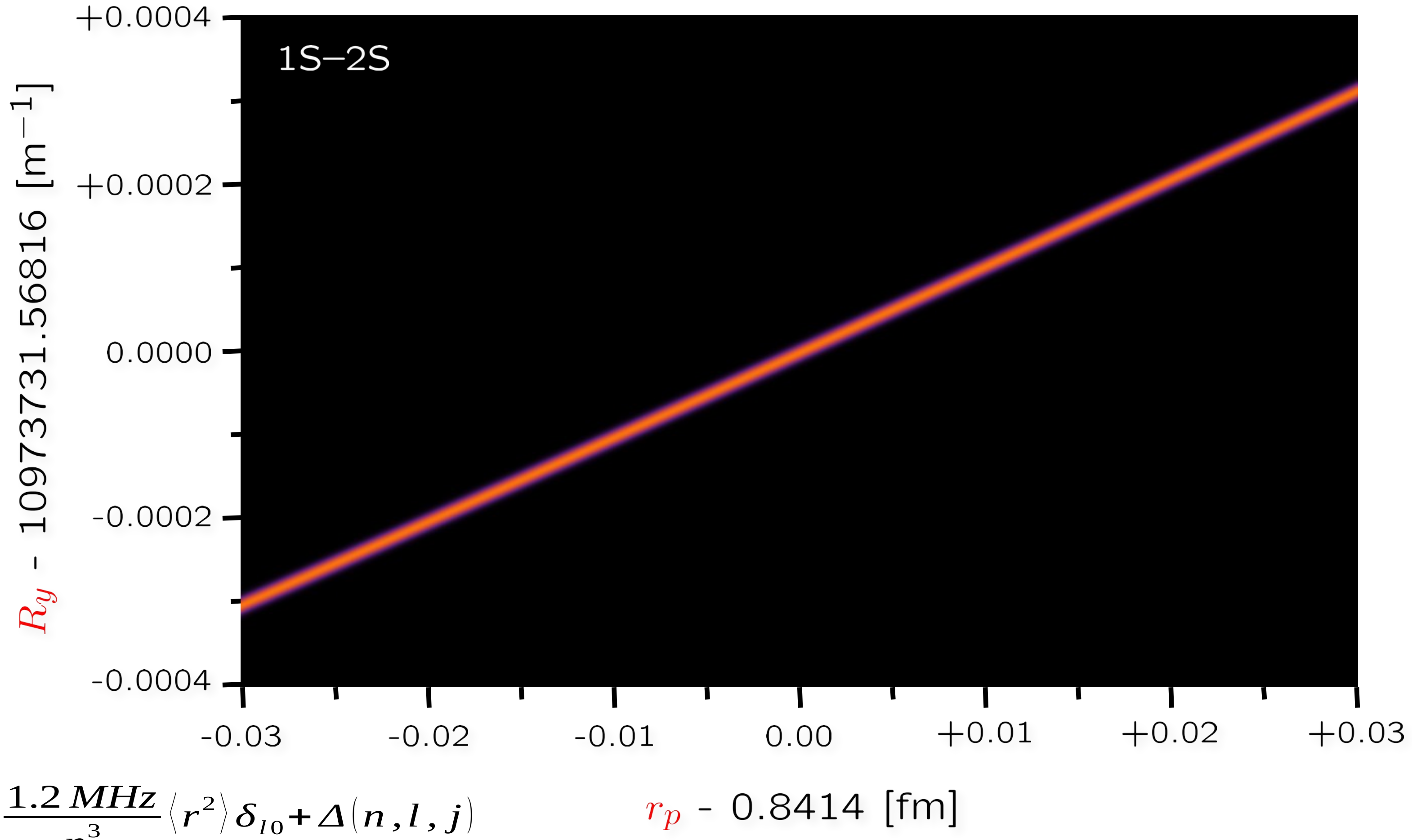
Largest systematic correction: Light force shift

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

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

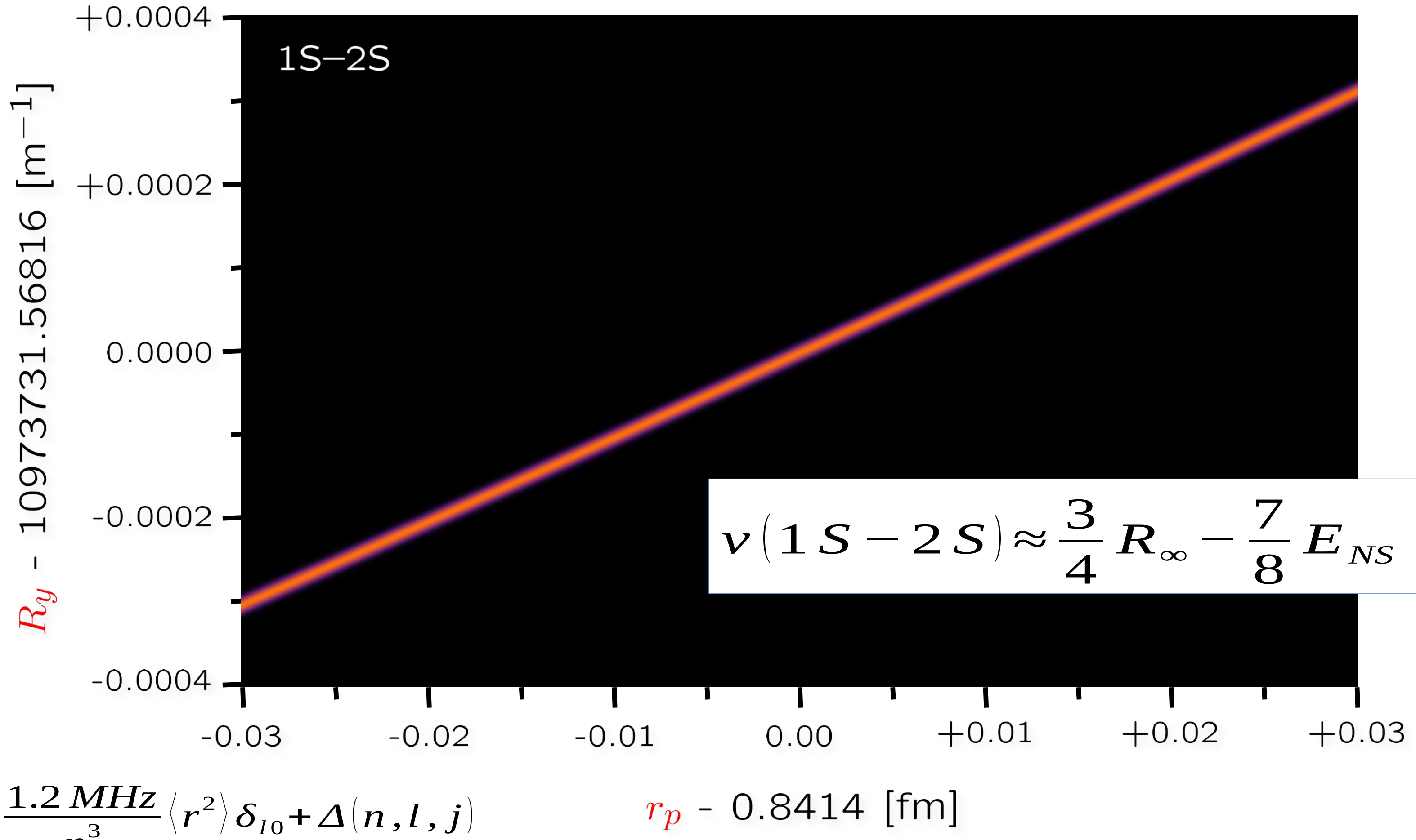
Recoil shift and hyperfine (HFS) corrections are large, but known extremely well

QED Test



$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n,l,j)$$

QED Test



$$\nu(1S-2S) \approx \frac{3}{4} R_\infty - \frac{7}{8} E_{NS}$$

$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3} \langle r^2 \rangle \delta_{l0} + \Delta(n,l,j)$$

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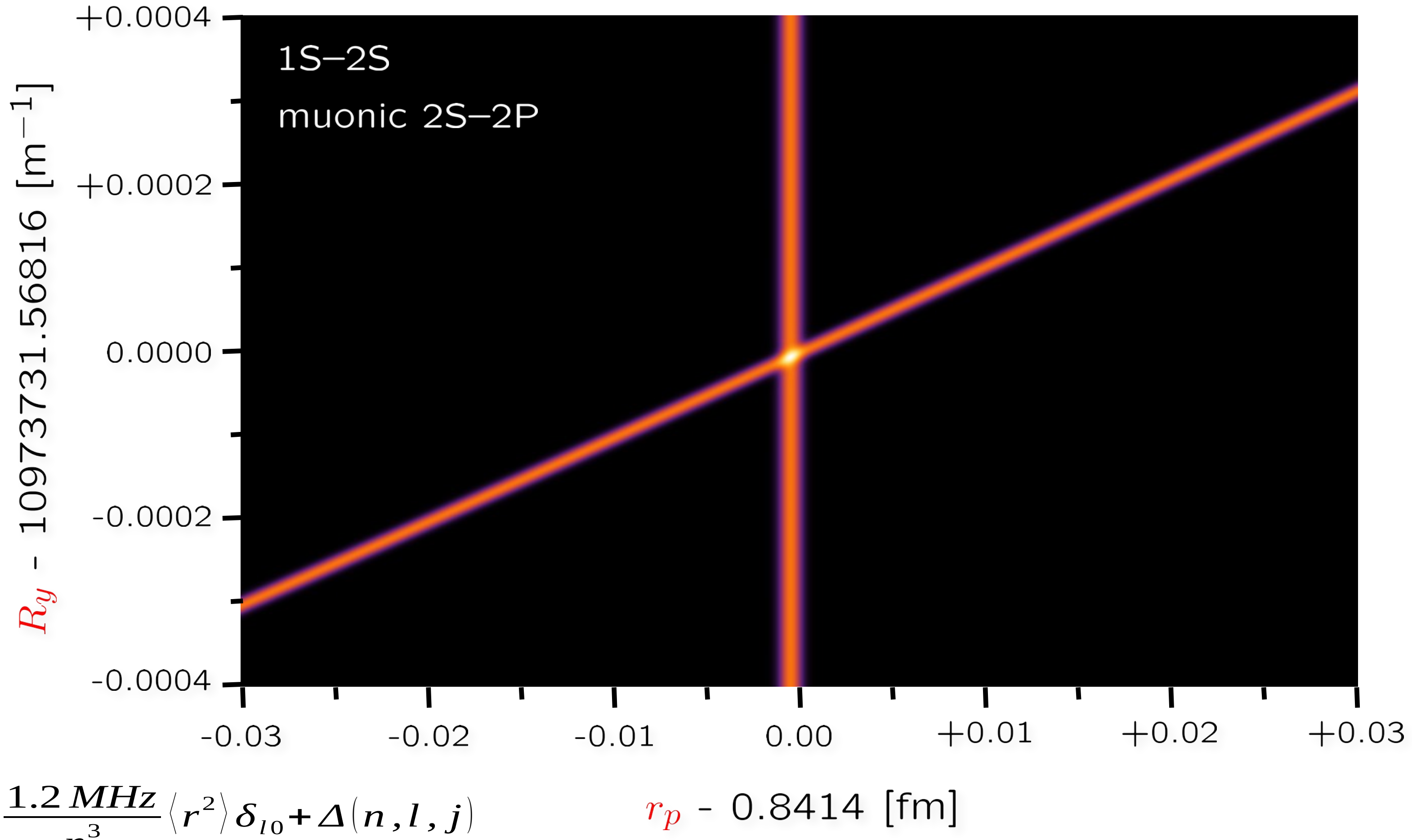

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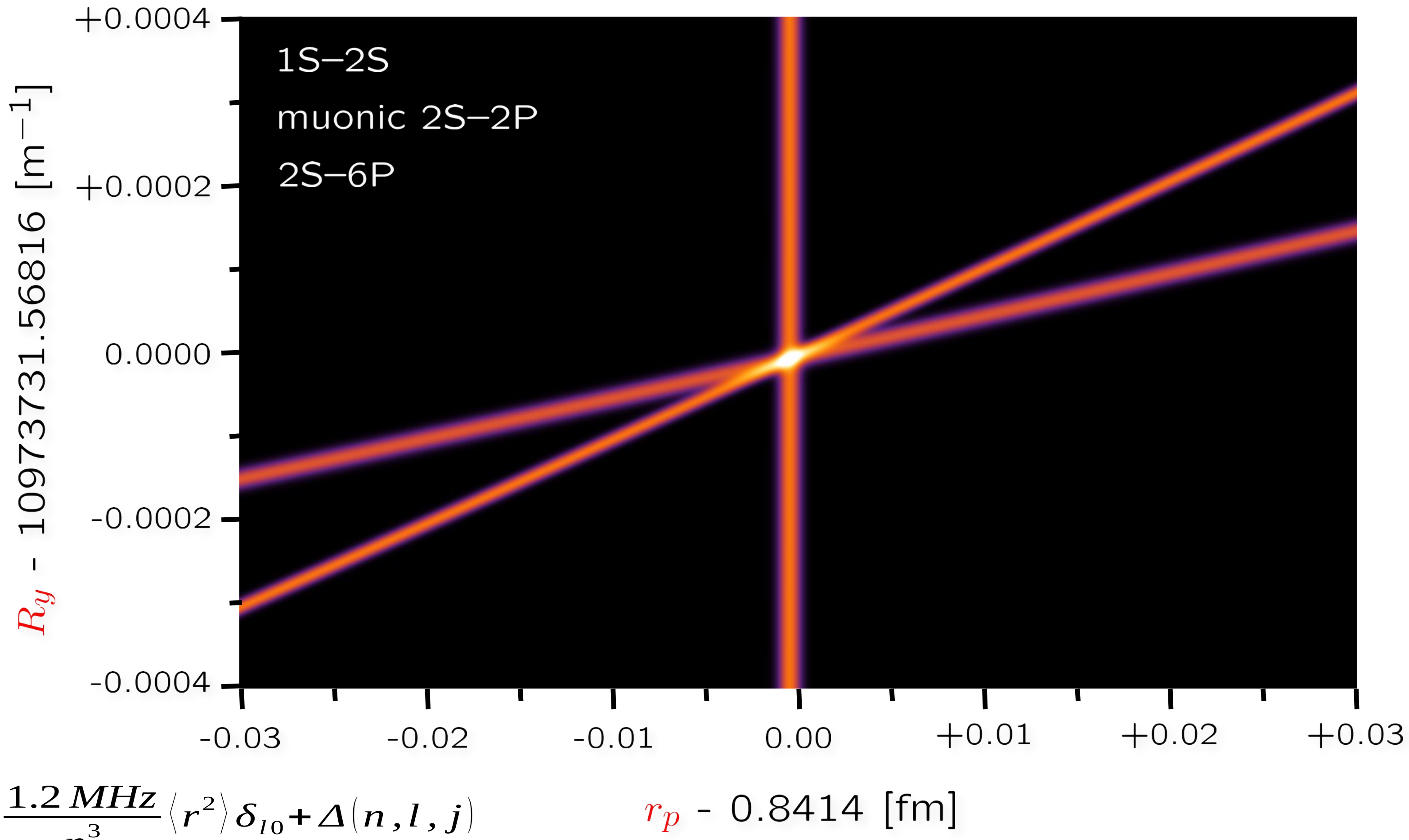

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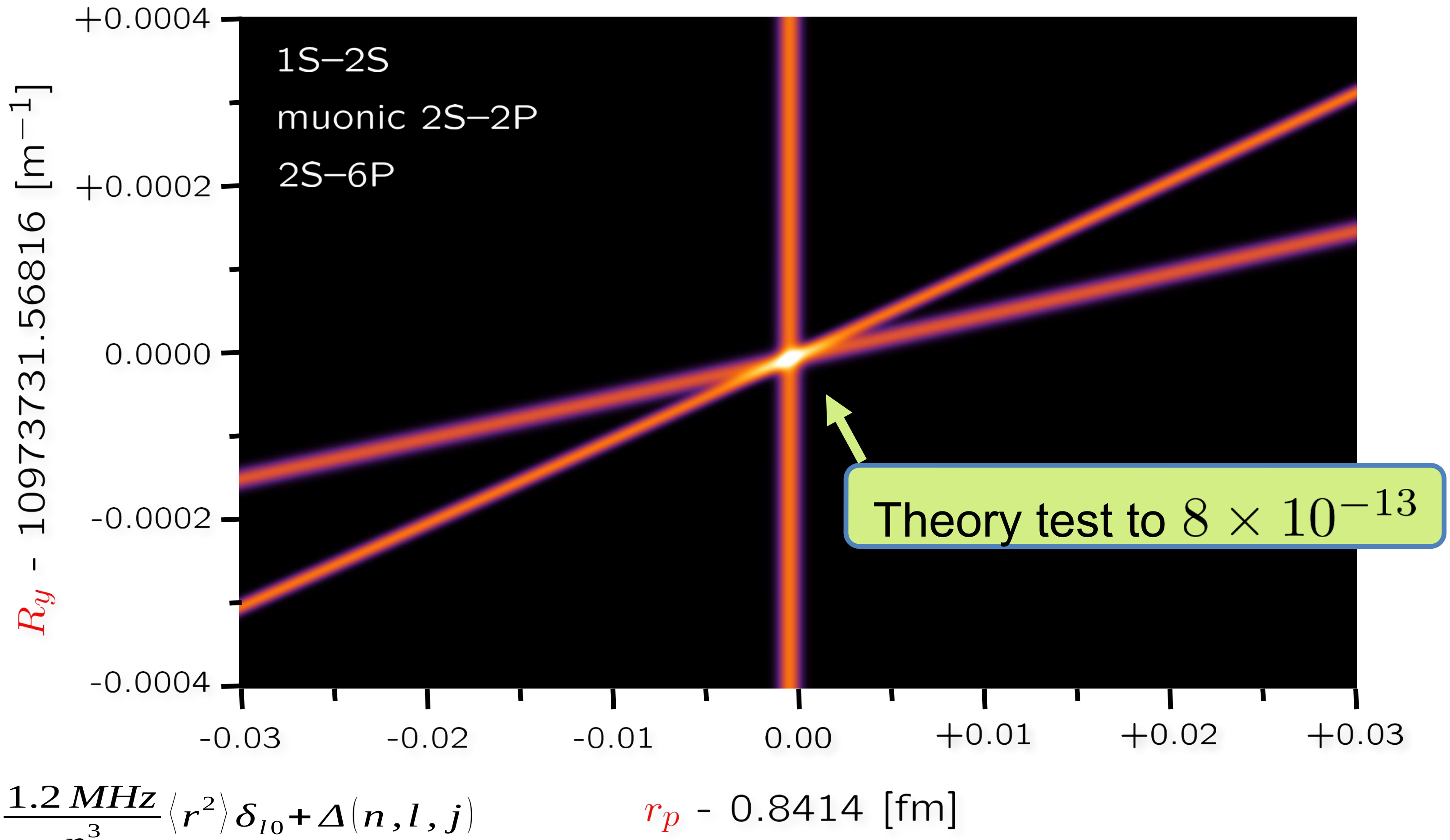

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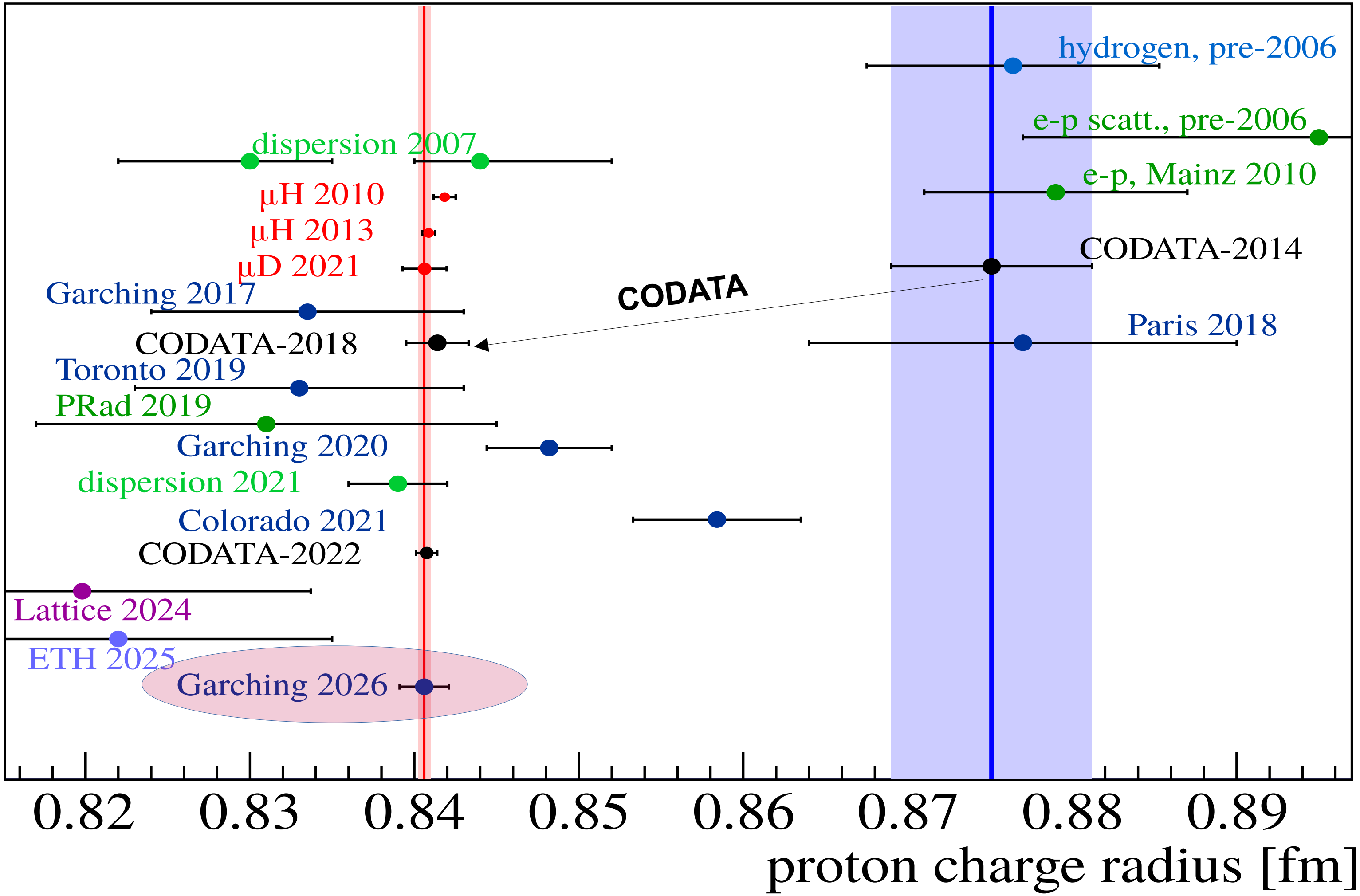
The proton radius situation now



But what about the old H data?

H (2S-6P)

Solving the “Proton Radius Puzzle”

PHYSICAL REVIEW A **110**, 052807 (2024)

But what about the old H data?

Narrow resonances in Rydberg hydrogen spectroscopy

R. G. Bullis, W. L. Tavis, M. R. Weiss, and D. C. Yost
Department of Physics, Colorado State University, Fort Collins, Colorado 80523, USA

(Received 5 July 2024; revised 8 September 2024; accepted 4 November 2024; published 18 November 2024)

We present the recovery of six $2S_{1/2}$-$nS_{1/2}$ two-photon resonances in atomic hydrogen with $8 \leqslant n \leqslant 16$. For each transition, we obtain quality factors $\geqslant 4 \times 10^9$, which we believe are the highest obtained in hydrogen laser spectroscopy excepting the singular $1S_{1/2}$-$2S_{1/2}$ two-photon transition. To the best of our knowledge, the transitions with $n \geqslant 13$ have not been previously observed. These results are enabled by a tightly constrained atomic beam geometry, and by mitigation of the light shift caused by the spectroscopy laser field.

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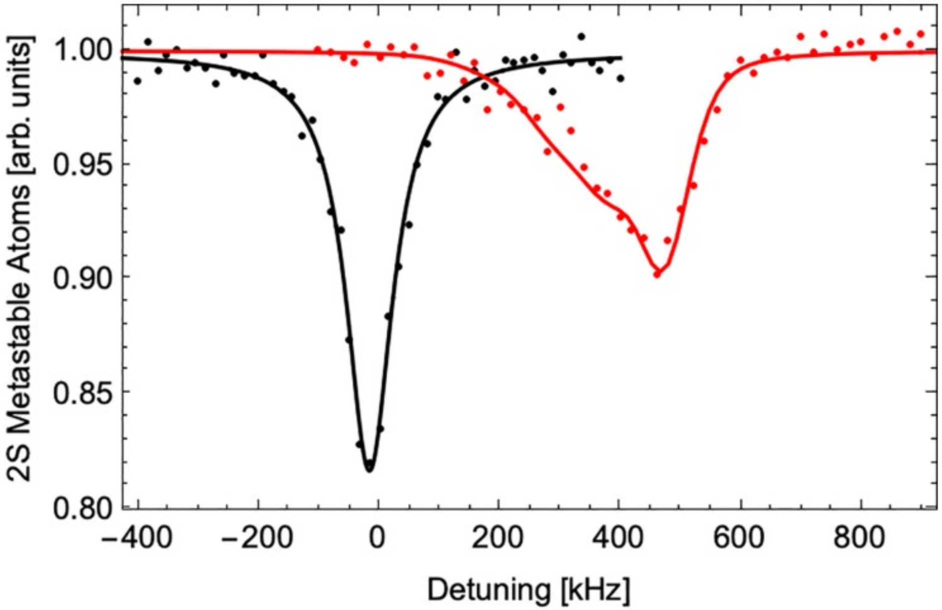

FIG. 2. Experimentally recovered lineshapes for the $2S_{1/2}$-$12S_{1/2}$ transition with ac Stark shift mitigation (black) and without (red).

But what about the old H data?

Solving the "Proton Radius Puzzle"

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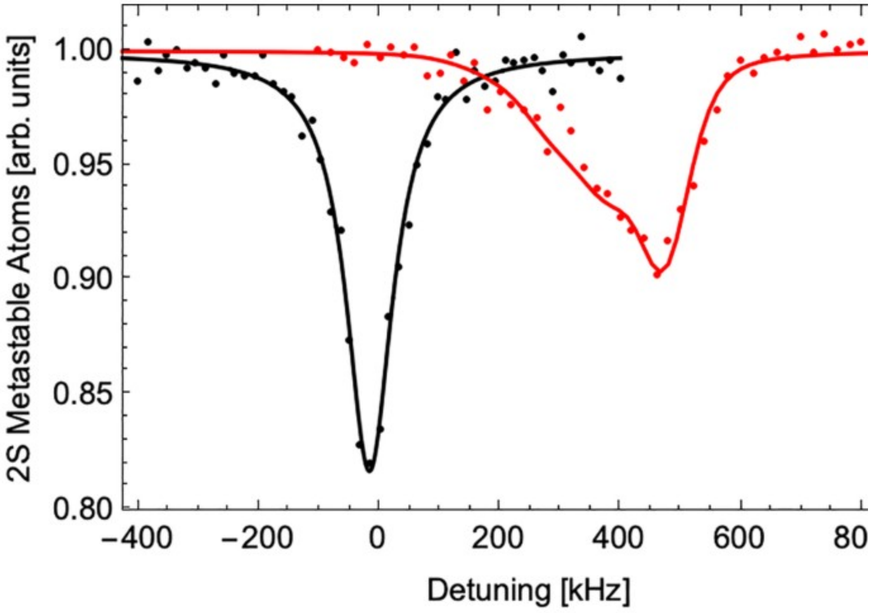

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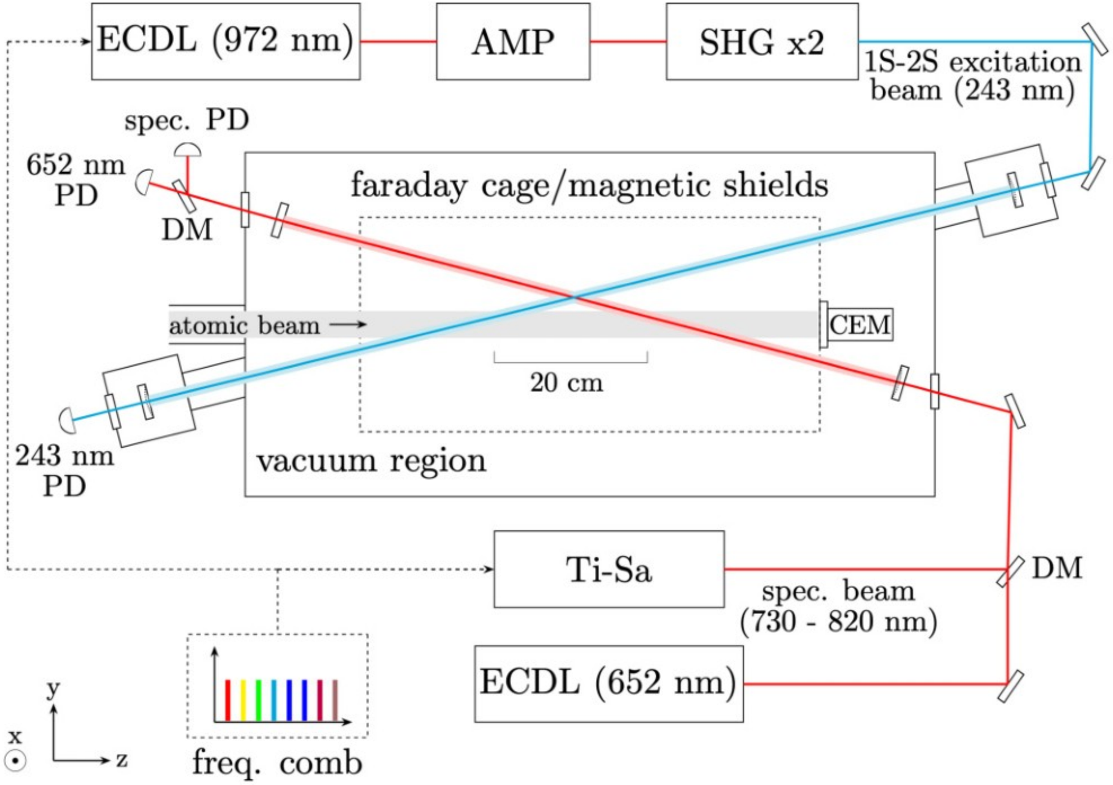

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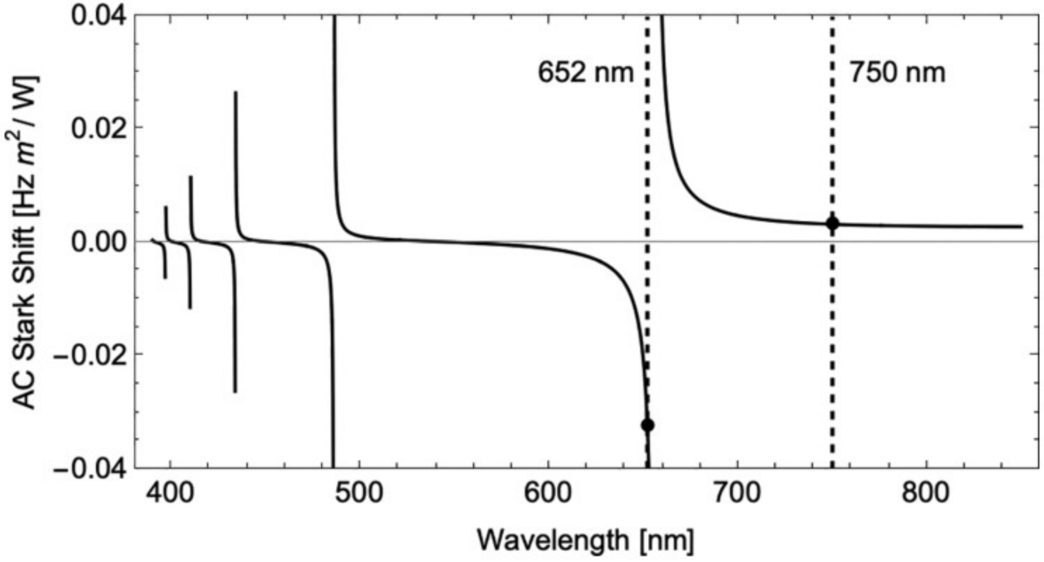

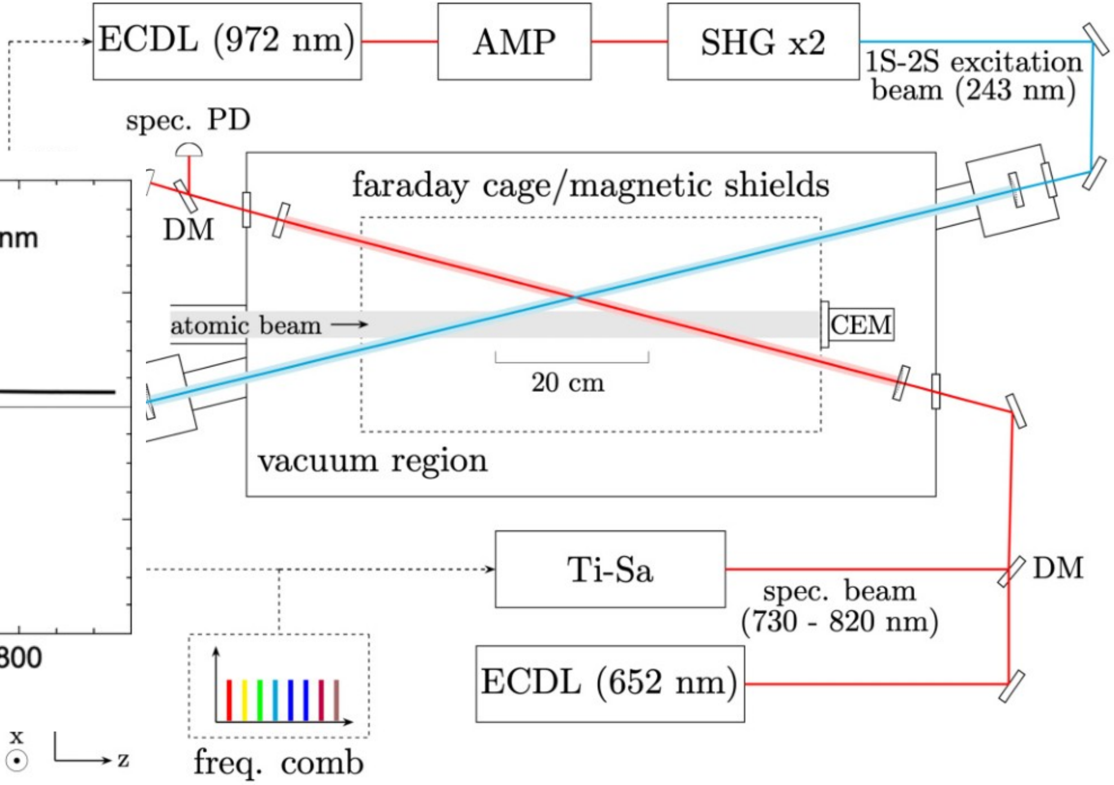

Solving the "Proton Radius Puzzle"

But what about the old H data?

Narrow resonances in Rydberg hydrogen spectroscopy

R. G. Bullis, W. L. Tavis, M. R. Weiss, and D. C. Yost
Department of Physics, Colorado State University, Fort Collins, Colorado 80523, USA

PHYSICAL REVIEW LETTERS **136,** 123001 (2026)

Editors' Suggestion

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

R. G. Bullis,[1] W. L. Tavis,[1] M. R. Weiss,[1] J. Orellana Cisneros,[1] A. J. Cheeseman,[1] U. D. Jentschura,[2] and D. C. Yost[1]
[1]*Department of Physics, Colorado State University, Fort Collins, Colorado 80523, USA*
[2]*Department of Physics and LAMOR, Missouri University of Science and Technology, Rolla, Missouri 65409, USA*

(Received 5 December 2025; accepted 20 February 2026; published 23 March 2026)

We present absolute frequency measurements of $2S_{1/2}$-$nS_{1/2}$ two-photon transitions with $n = 8$, 9, and 10 in a cryogenic beam of atomic hydrogen. Each transition has been measured with a fractional uncertainty of $\approx 2.6 \times 10^{-12}$. Combining the results from this Letter and the $1S_{1/2}$-$2S_{1/2}$ transition frequency, we extract a root-mean-square proton radius of $r_p = 0.8433(31)$ fm and a Rydberg frequency of $cR_\infty = 3\,289\,841\,960\,252.9(9.7)$ kHz. These are in good agreement with the CODATA 2022 recommended values.

Solving the “Proton Radius Puzzle”

PHYSICAL REVIEW LETTERS **136,** 123001 (2026)

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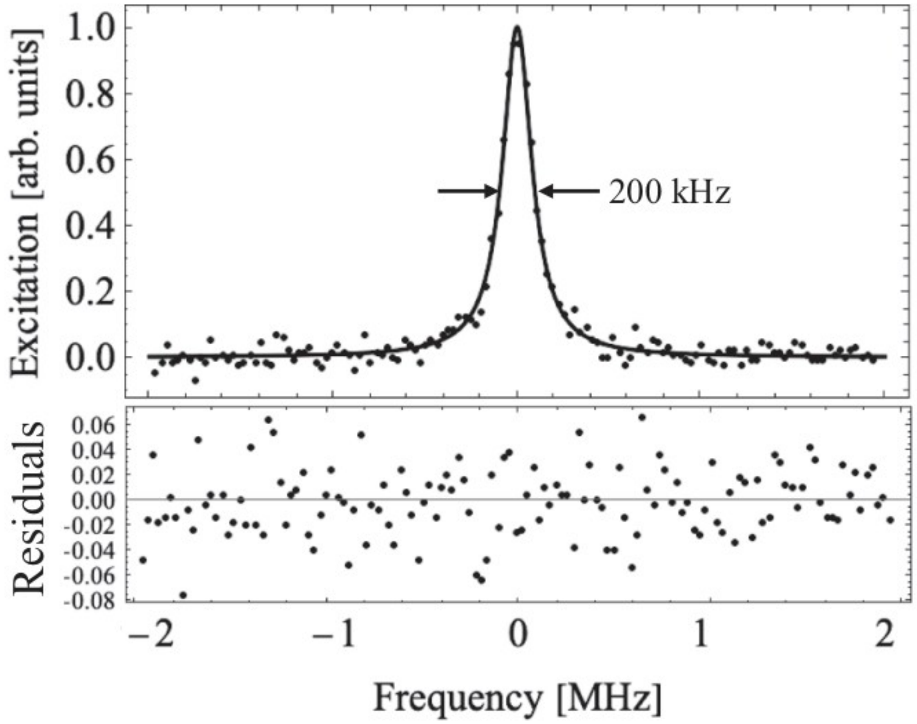
Precision Spectroscopy of 2S-nS Transitions in Atomic Hydrogen: A Determination of the Proton Charge Radius



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Solving the “Proton Radius Puzzle”

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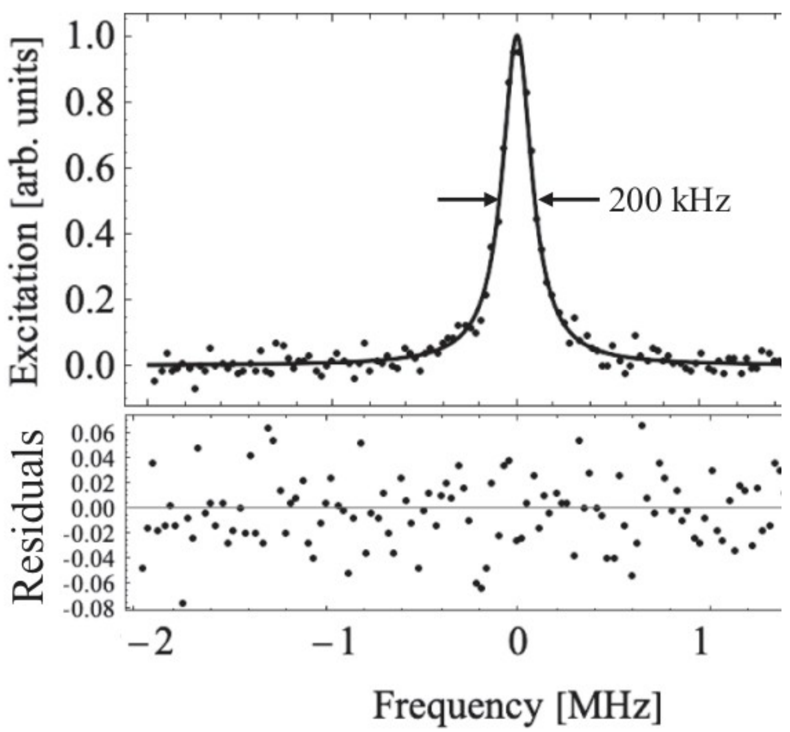
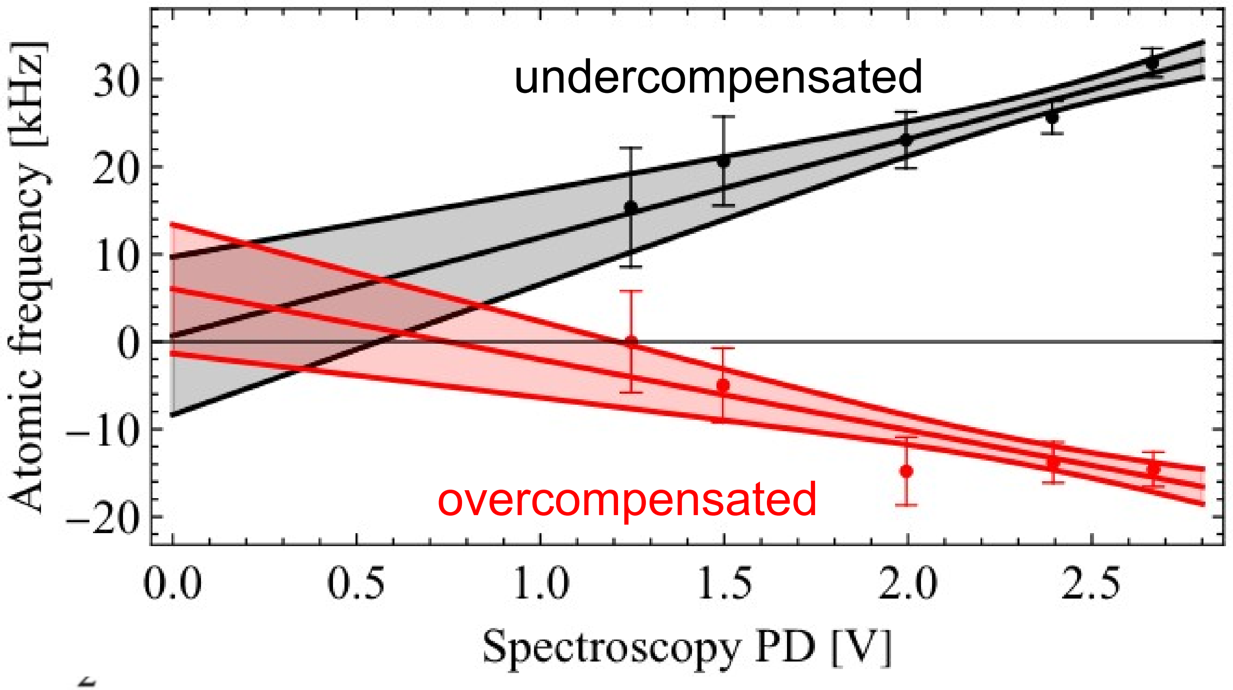
Precision Spectroscopy of 2S-nS Transitions in Atomic Hydrogen:
A Determination of th





Solving the “Proton Radius Puzzle”

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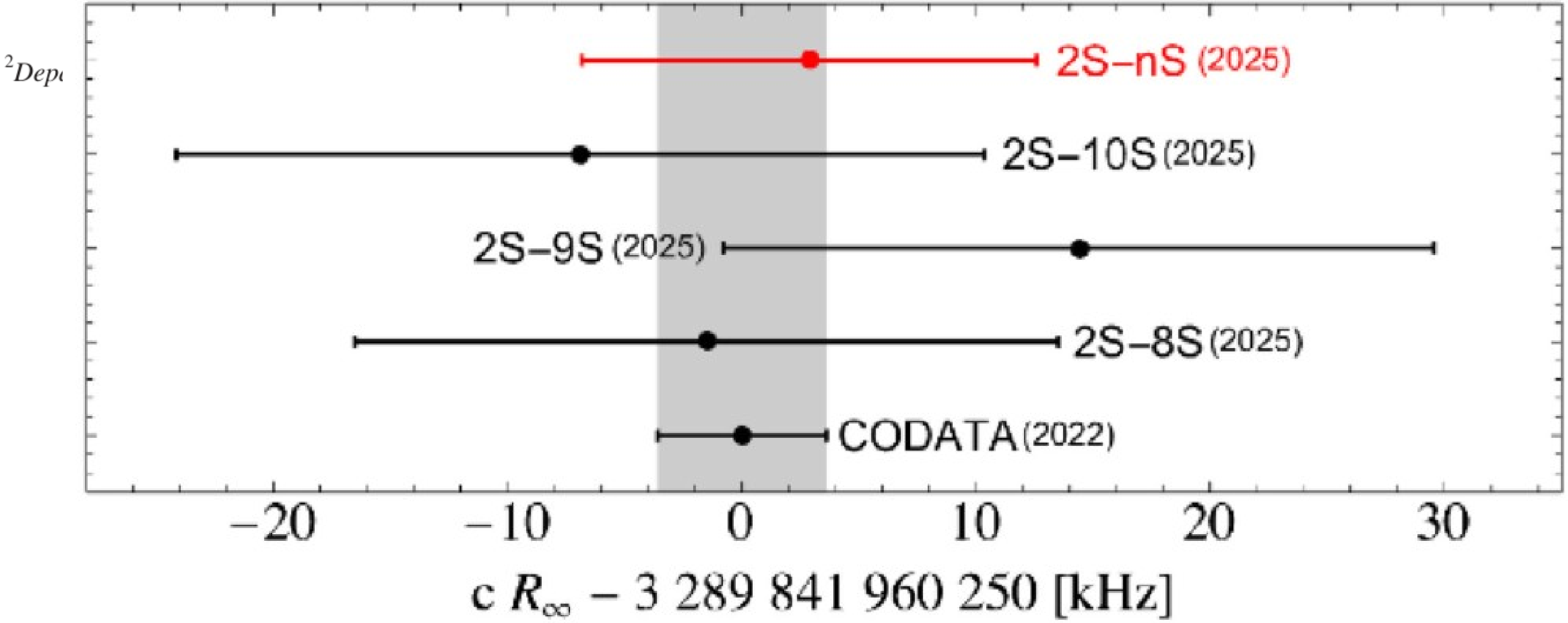
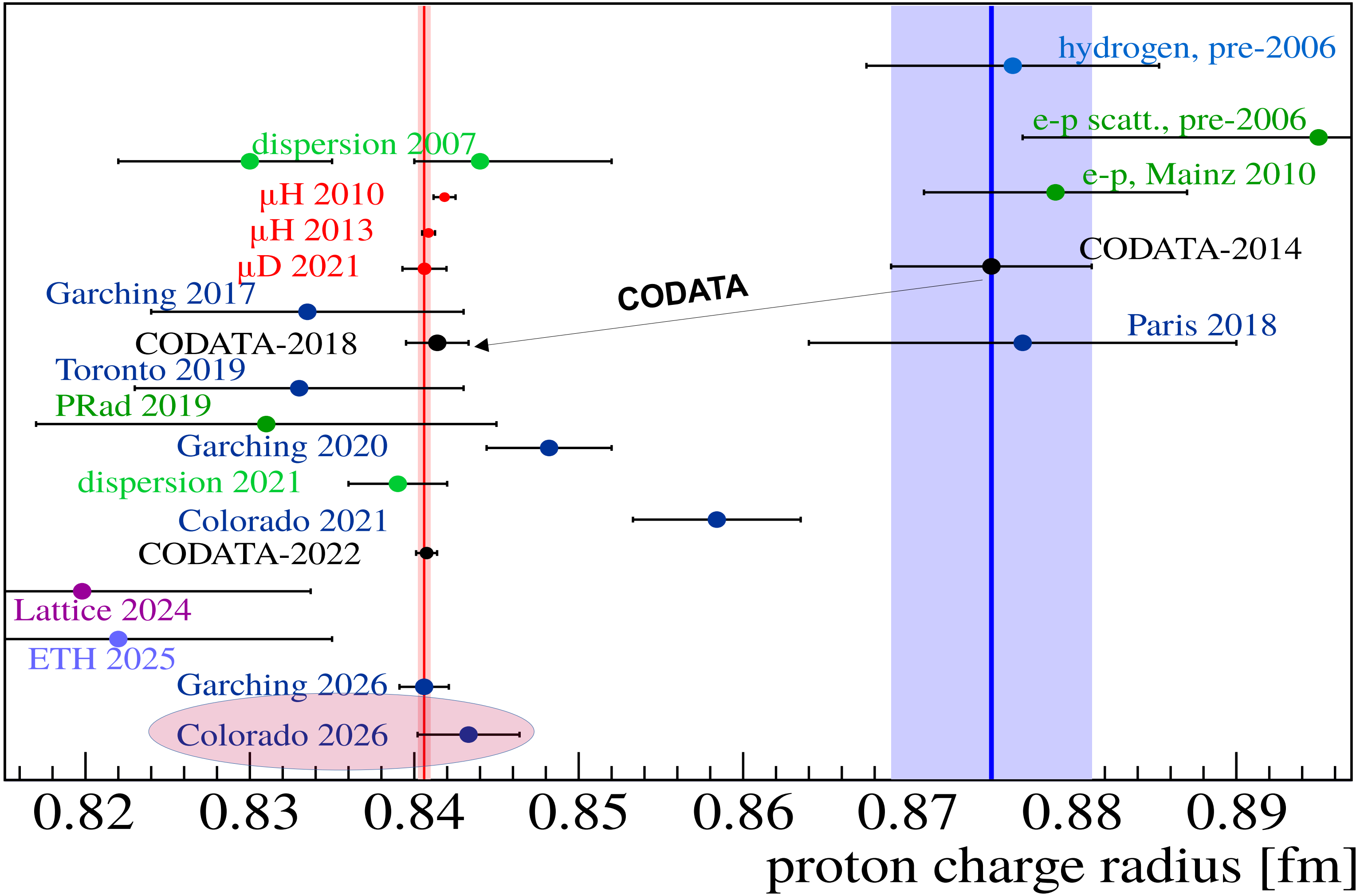


Solving the "Proton Radius Puzzle"

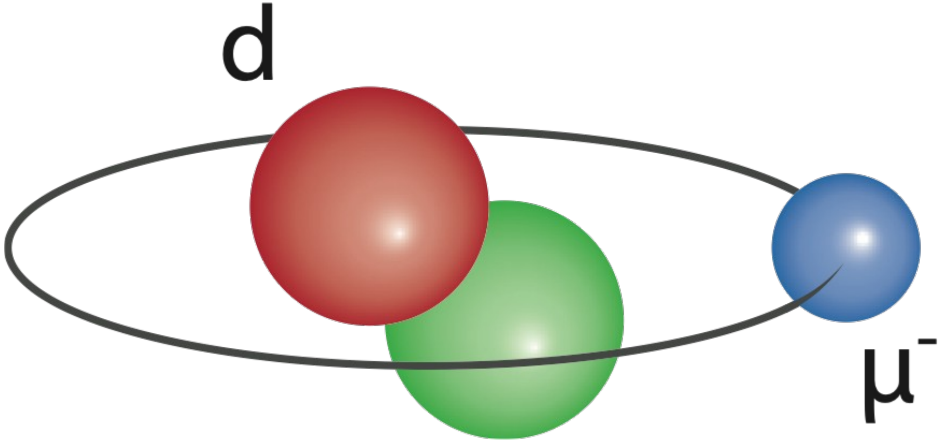


But what about the old H data?

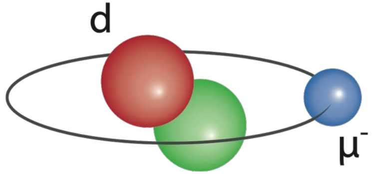
H (2S - 6P)

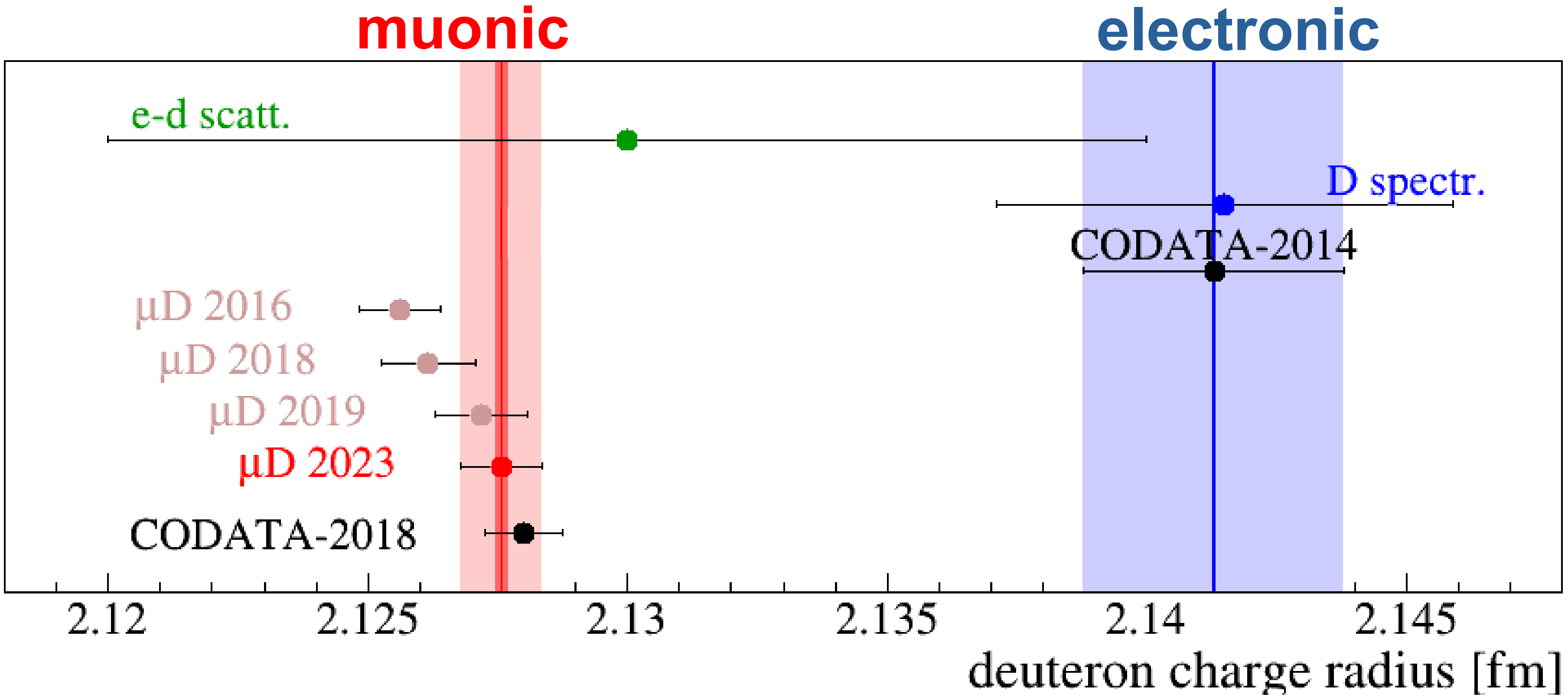
H (2S – **8/9/10S**)

Muonic Deuterium



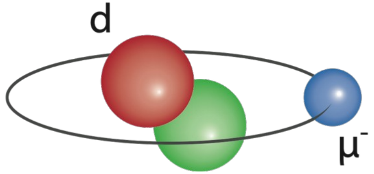
Muonic Deuterium

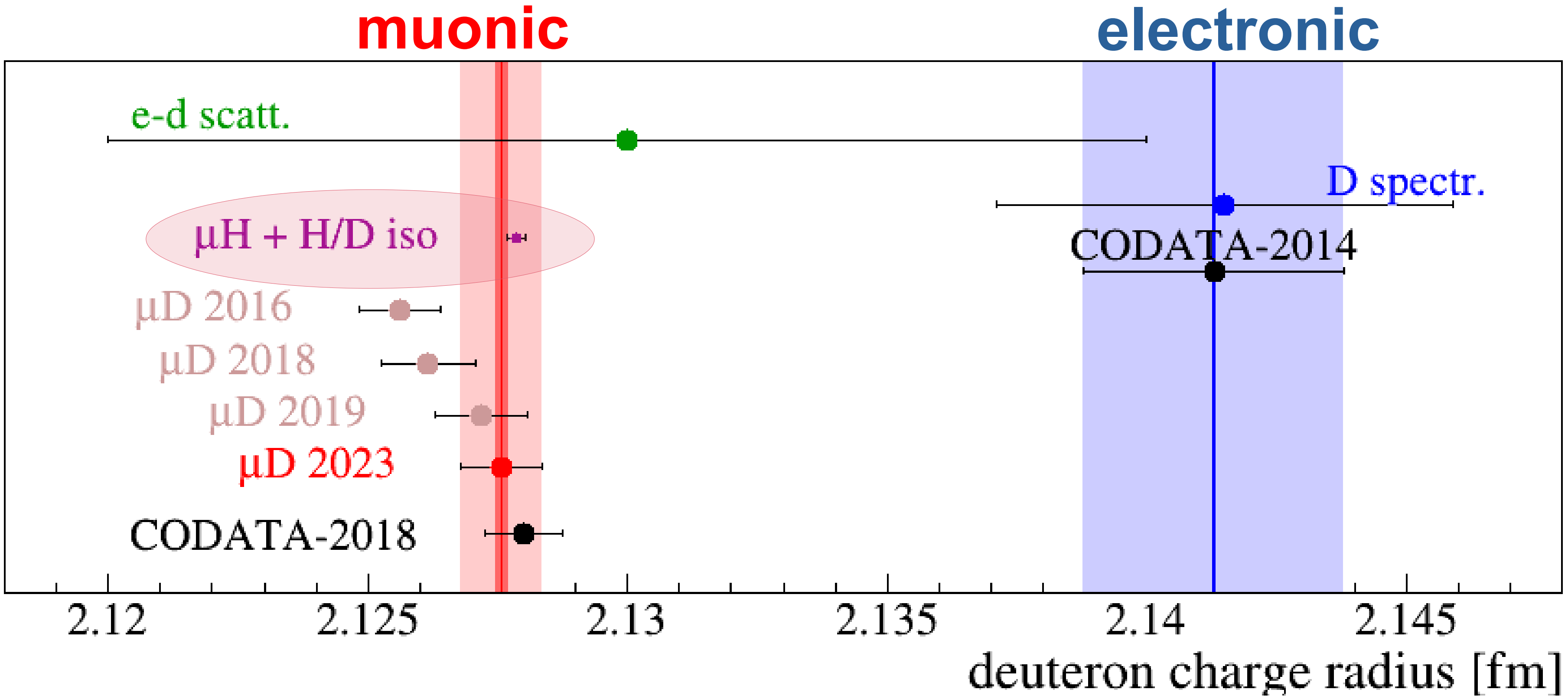




μD: $2.12758\ (13)_{exp}\ (78)_{theo}$ fm

Muonic Deuterium



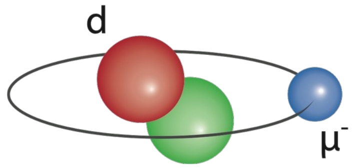


μD: 2.12758 $(13)_{exp}$ $(78)_{theo}$ fm

μH + H/D(1S-2S): 2.12785 (17) fm

$r_d^2 - r_p^2 = 3.8207(3)_{theo}\ fm^2$

H/D isotope shift

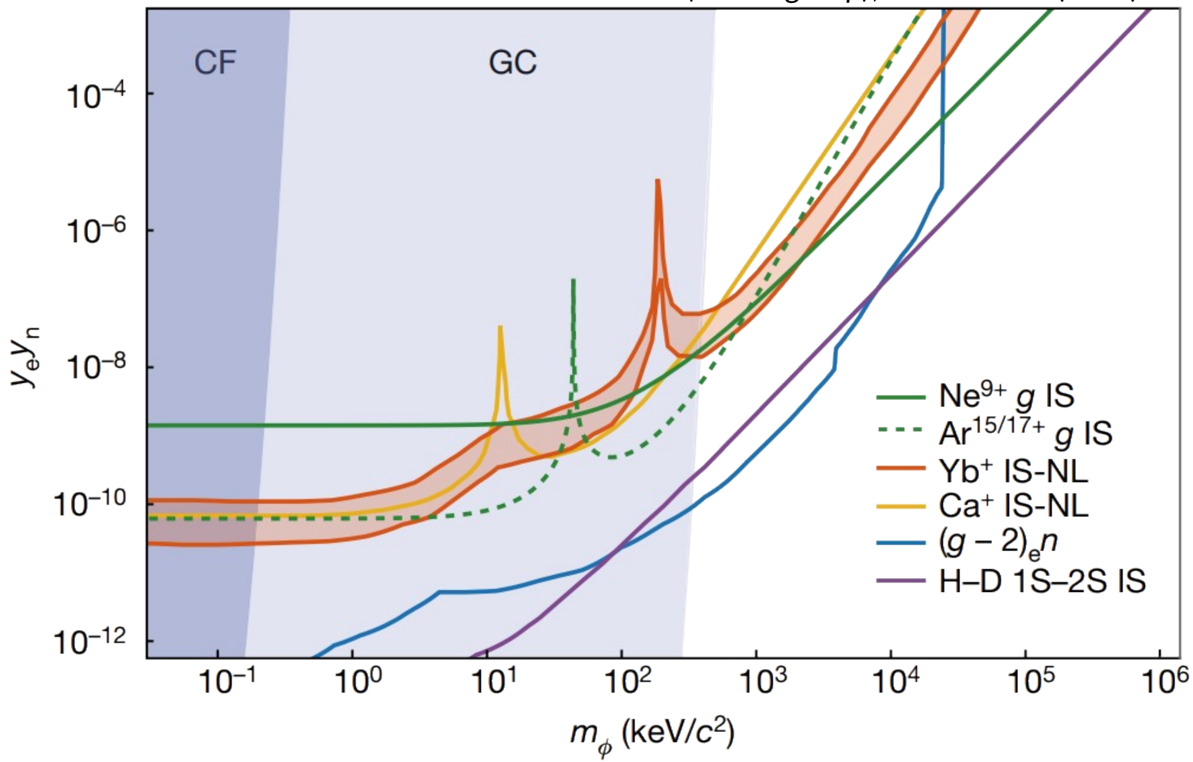


electronic H/D (1S-2S): $r_d^2 - r_p^2 = 3.8207(3)_{theo}\ fm^2$

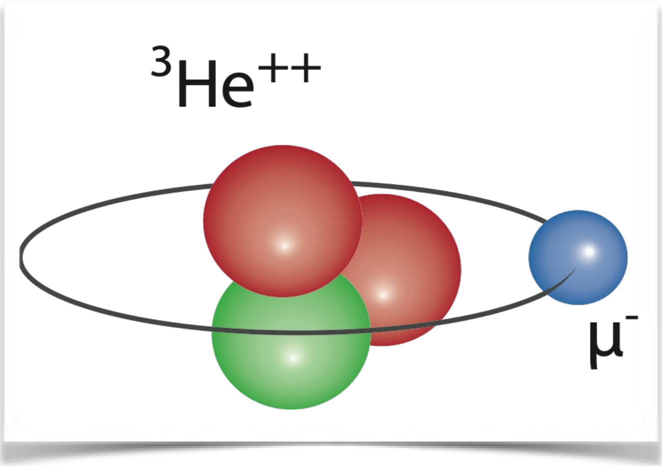
muonic H/D (2S-2P): $r_d^2 - r_p^2 = 3.8200(7)_{exp}(30)_{theo}\ fm^2$

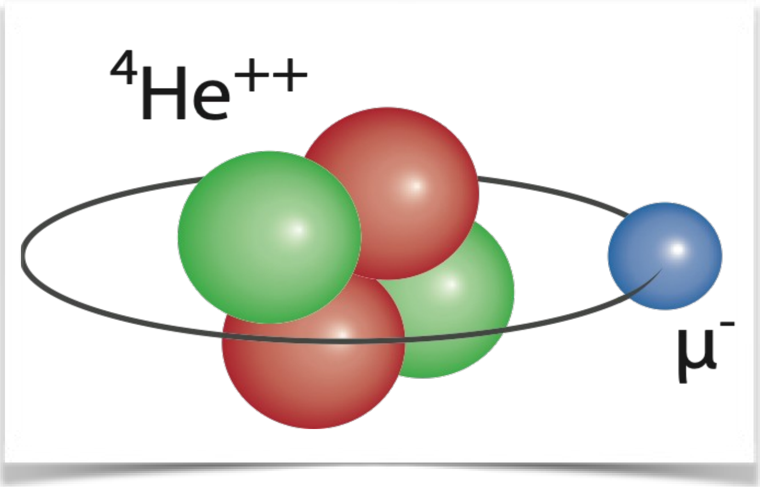
→ Best bound on 5^{th} force

T. Sailer *et. al.* (*Blaum group*), Nature 606 (2022)



Muonic Helium

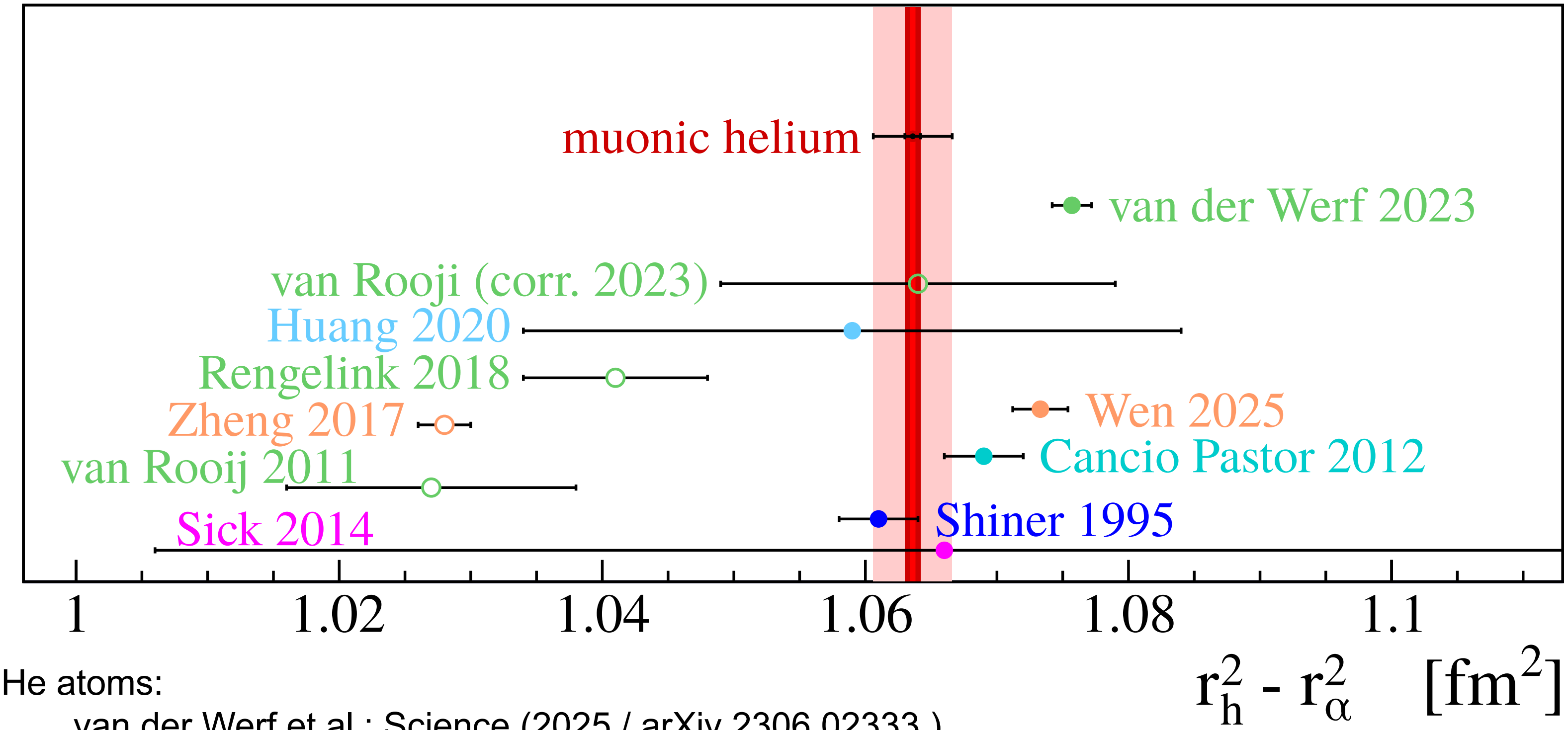




Schuhmann et al. (CREMA), Science 388, 854 (2025) ; arXiv 2305.11679

Krauth et al. (CREMA), Nature (2021)

Helium-3 – Helium-4 Isotope Shift



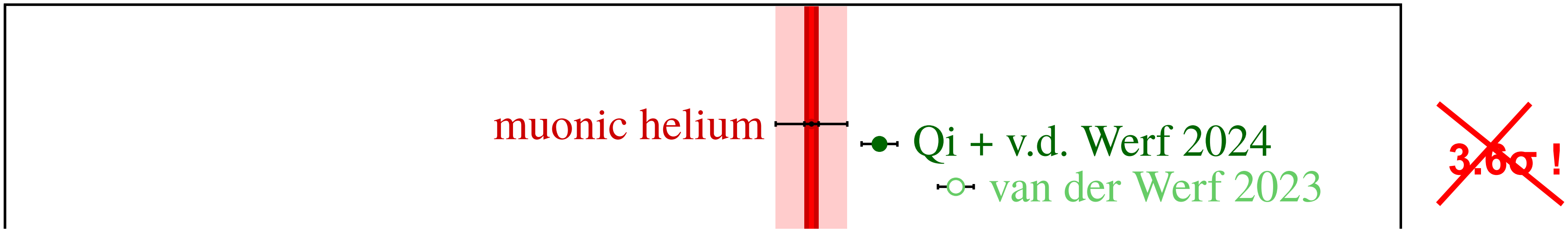
3.6σ !

normal He atoms:

van der Werf et al.: Science (2025 / arXiv 2306.02333)
Huang: PRA 101, 062507 (2020)
Rengelink: Nature Physics 14, 1132 (2018)
Zheng: PRL 119, 263002 (2017)
van Rooij: Science 333, 196 (2011)
Cancio Pastor: PRL 108, 143001 (2012)
Shiner: PRL 74, 3553 (1995)

CREMA Coll., Science 388, 852 (2025)

Helium-3 – Helium-4 Isotope Shift



PHYSICAL REVIEW RESEARCH **7**, L022020 (2025)

Letter

Toward resolving the discrepancy in helium-3 and helium-4 nuclear charge radii

Xiao-Qiu Qi,[1,2] Pei-Pei Zhang,[2] Zong-Chao Yan,[3,2] Li-Yan Tang,[2] Ai-Xi Chen,[1]
Ting-Yun Shi,[2,*] and Zhen-Xiang Zhong[4,2,†]

[1]*Department of Physics, Zhejiang Sci-Tech University, Hangzhou 310018, China*

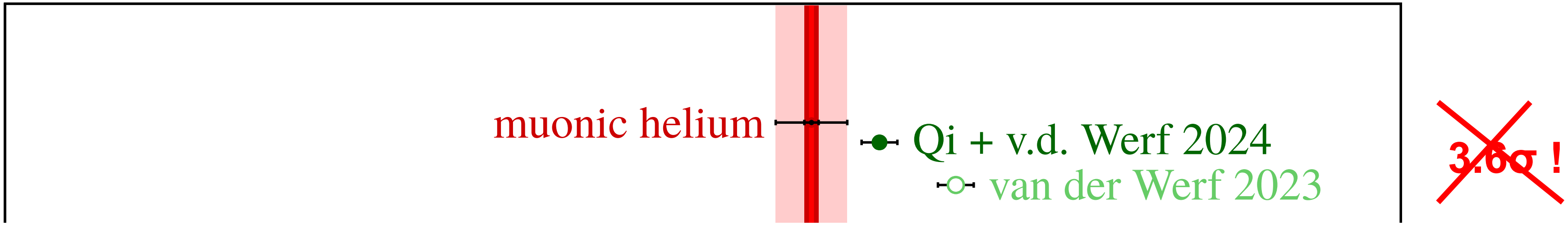
[2]*State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, Wuhan 430071, China*

[3]*Department of Physics, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3*

[4]*Center for Theoretical Physics, School of Physics and Optoelectronic Engineering, Hainan University, Haikou 570228, China*

(Received 31 August 2024; accepted 25 March 2025; published 21 April 2025)

Helium-3 – Helium-4 Isotope Shift



Toward resolving the discrepancy in helium-3 and helium-4 nuclear charge radii

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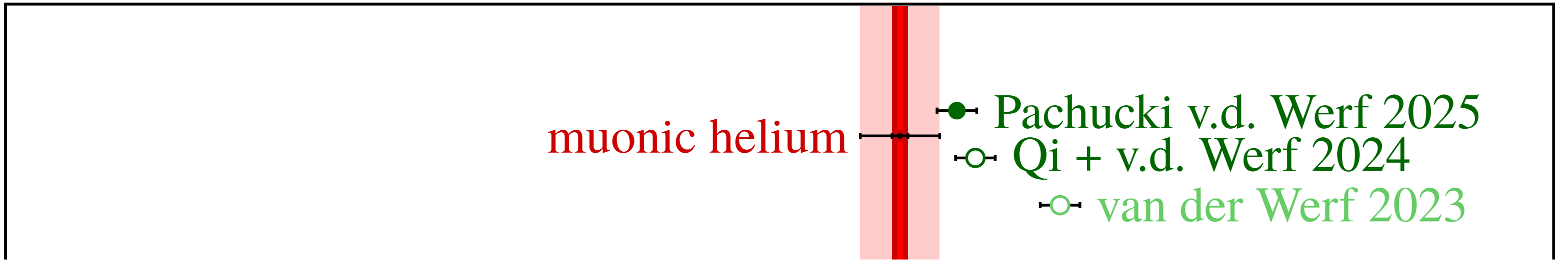
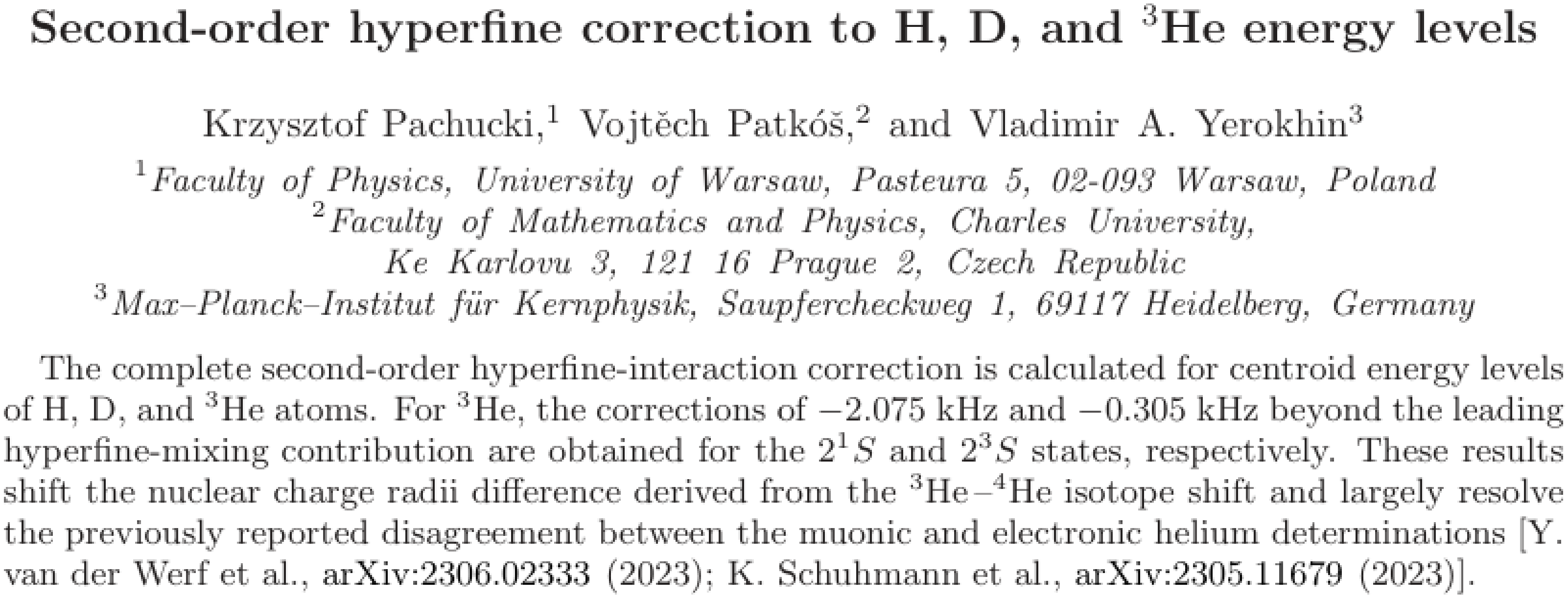
Ting-Yun Shi,[2,*] and Zhen-Xiang Zhong[4,2,†]

The discrepancy in the squared nuclear charge radius difference, ΔR^2, between ^{3}He and ^{4}He, as determined from electronic and muonic atom energy levels, presents an unresolved puzzle. This paper shows that accounting for off-diagonal hyperfine mixing effects can substantially reduce this discrepancy. We find that hyperfine mixing with the $n\,^3S$ and $n\,^1S$ states ($n > 2$) in ^{3}He introduces a correction of -1.37 kHz to the isotope shift of the $2\,^1S - 2\,^3S$ transition, a factor of seven times larger than the current uncertainty. This correction modifies ΔR^2 by -0.0064 fm^2, shifting it from 1.0757(15) fm^2 to 1.0693(15) fm^2, as initially reported by Werf *et al.* [arXiv:2306.02333]. This brings ΔR^2 closer to the value of 1.0636(31) fm^2 obtained from muonic helium μHe$^+$ by Schuhmann *et al.* [arXiv:2305.11679], narrowing the existing discrepancy from 3.6σ to 1.7σ. The adjusted value ΔR^2 also agrees well with the result of 1.069(3) fm^2 derived from the helium $2\,^3S - 2\,^3P$ transitions, as analyzed by Patkóš *et al.* [Phys. Rev. A **94**, 052508 (2016)]. Our results provide key insights for resolving the discrepancy in ΔR^2.

Helium-3 – Helium-4 Isotope Shift





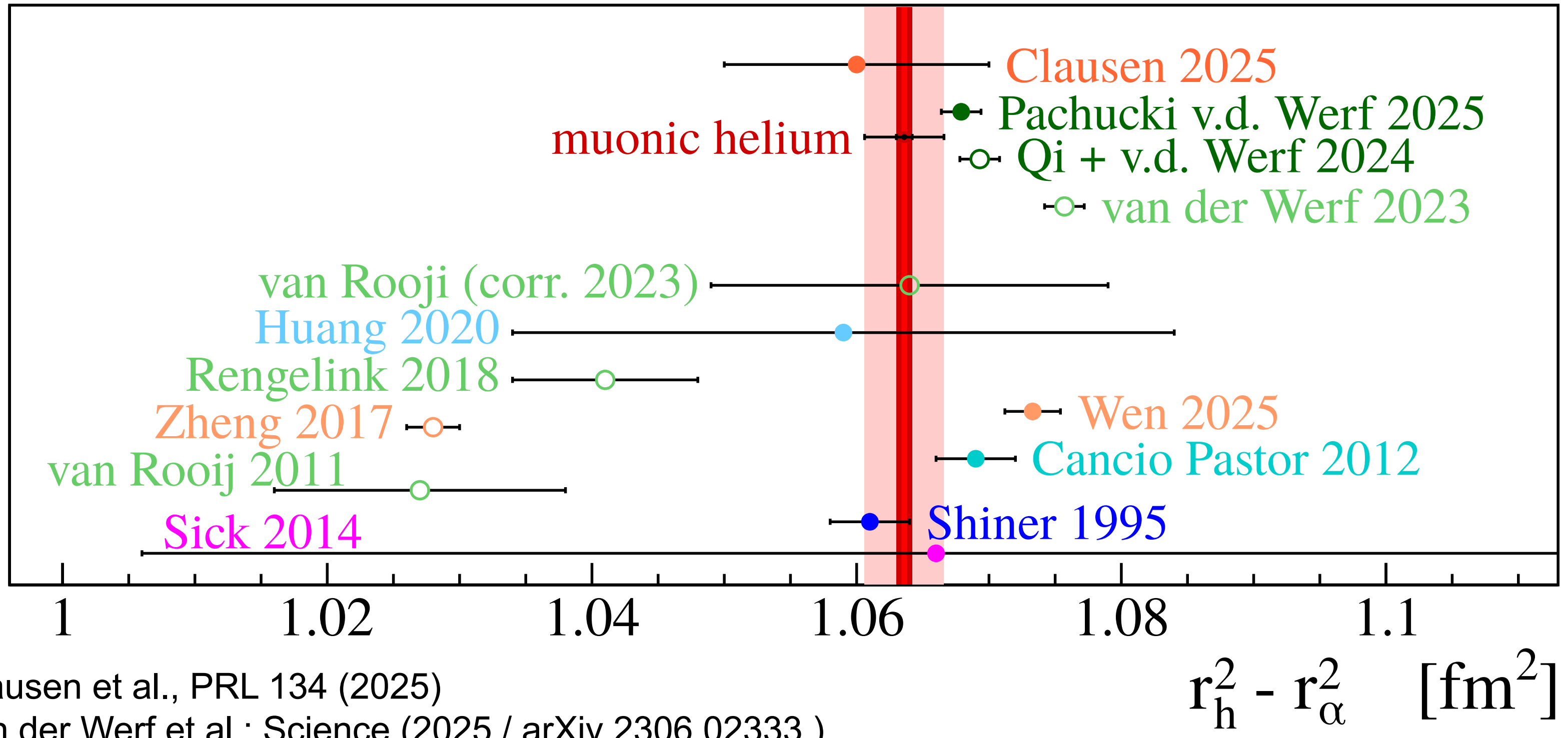
Second-order hyperfine correction to H, D, and ^{3}He energy levels

Krzysztof Pachucki,[1] Vojtěch Patkóš,[2] and Vladimir A. Yerokhin[3]

[1] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[2] *Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Prague 2, Czech Republic*
[3] *Max–Planck–Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

The complete second-order hyperfine-interaction correction is calculated for centroid energy levels of H, D, and ^{3}He atoms. For ^{3}He, the corrections of -2.075 kHz and -0.305 kHz beyond the leading hyperfine-mixing contribution are obtained for the 2^1S and 2^3S states, respectively. These results shift the nuclear charge radii difference derived from the ^{3}He–^{4}He isotope shift and largely resolve the previously reported disagreement between the muonic and electronic helium determinations [Y. van der Werf et al., arXiv:2306.02333 (2023); K. Schuhmann et al., arXiv:2305.11679 (2023)].

Helium-3 – Helium-4 Isotope Shift



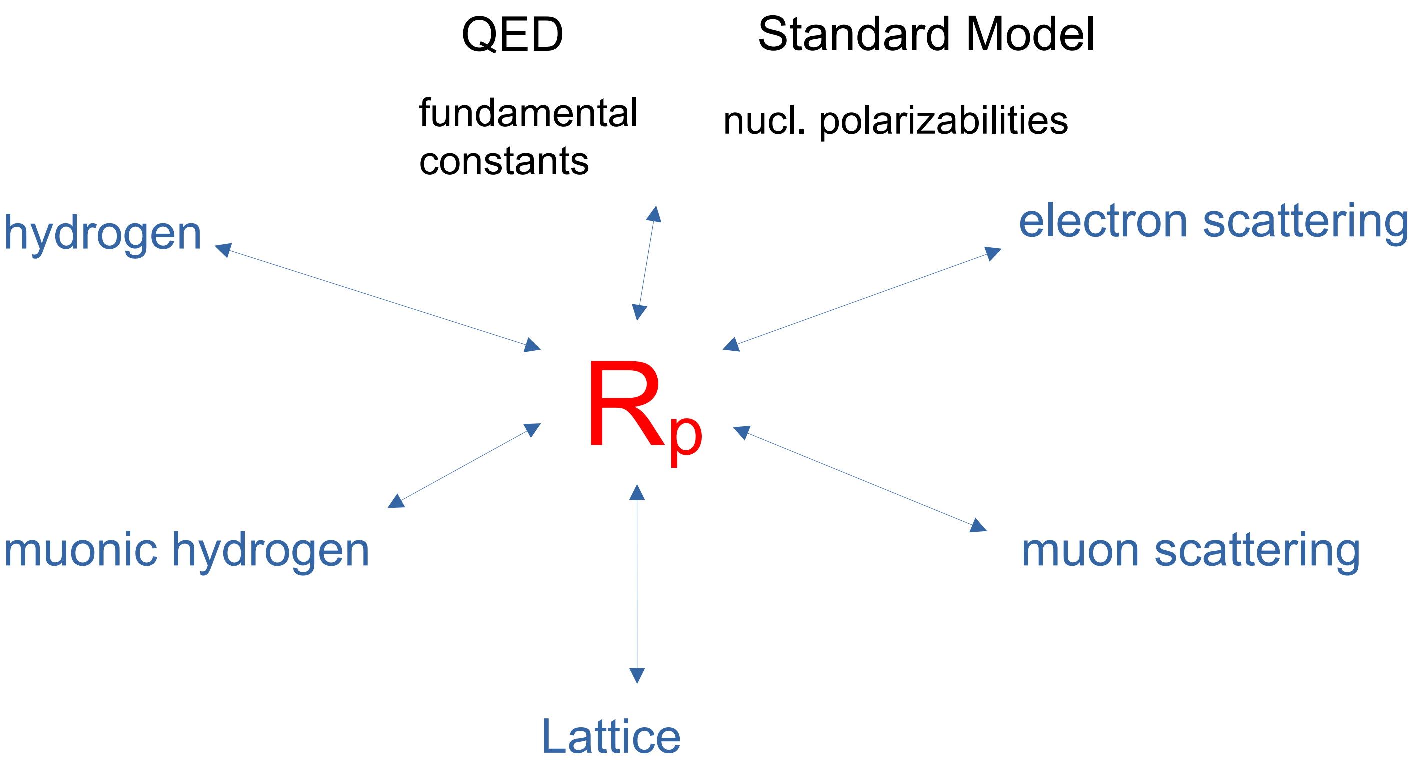
Clausen et al., PRL 134 (2025)
van der Werf et al.: Science (2025 / arXiv 2306.02333)
Huang: PRA 101, 062507 (2020)
Rengelink: Nature Physics 14, 1132 (2018)
Zheng: PRL 119, 263002 (2017)
van Rooij: Science 333, 196 (2011)
Cancio Pastor: PRL 108, 143001 (2012)
Shiner: PRL 74, 3553 (1995)

Qi et al., Phys. Rev. Research 7, L022020 (2025), arXiv 2409.09279
Pachucki et al, arXiv 2411.04621

Wen et al., Sci. Adv. 11 (2025)

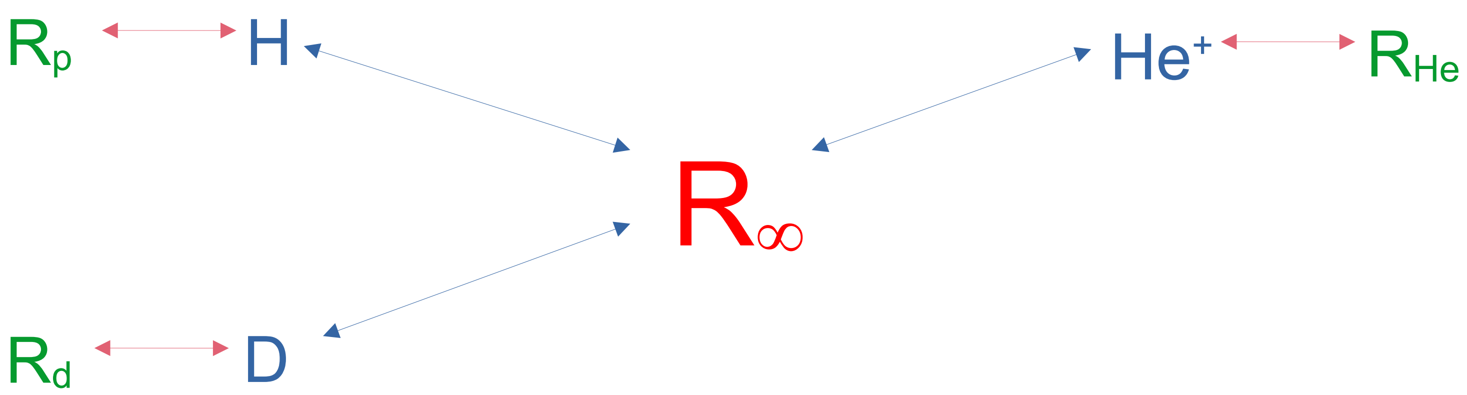
CREMA Coll. Science 2025 (arXiv 2305.11679)

Why was the proton radius so interesting?



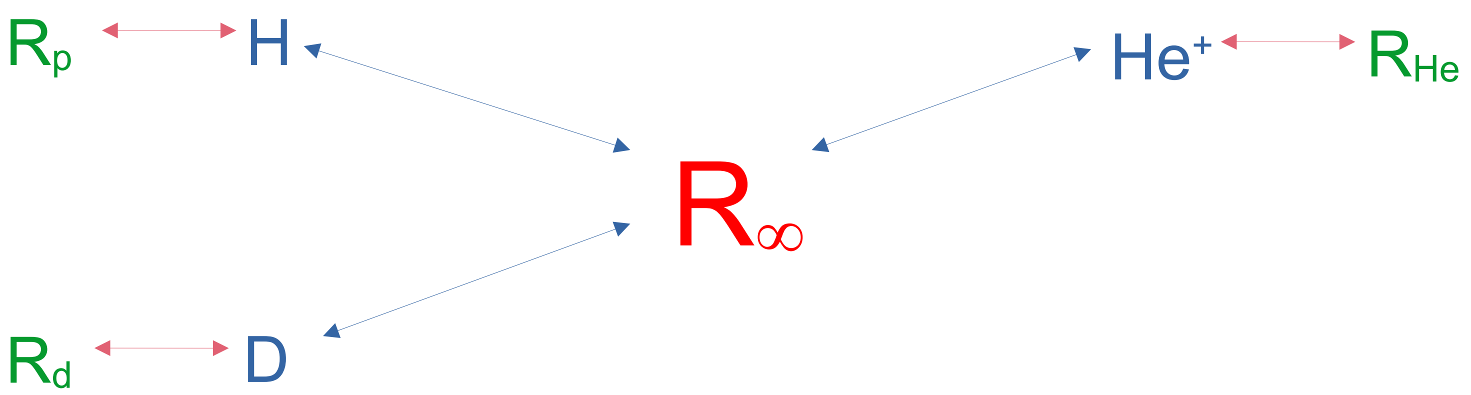
The Rydberg constant

→ Test QED and SM



2-body QED calculations

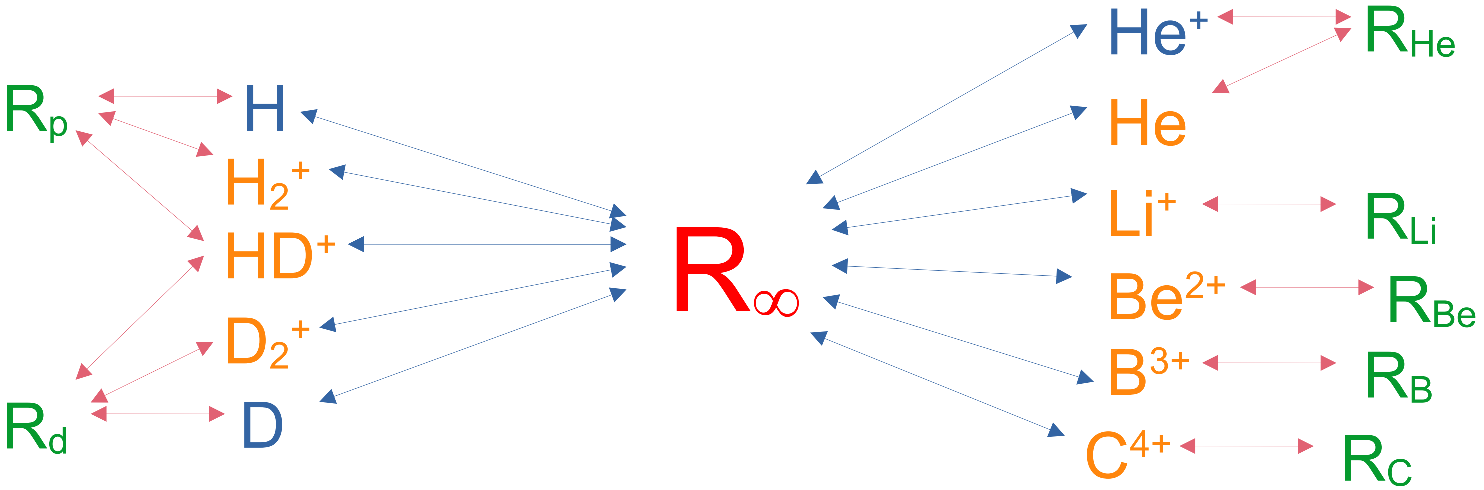
The Rydberg constant



2-body QED calculations

Exp: Amsterdam, Garching,
Paris, Colorado, Mainz
...

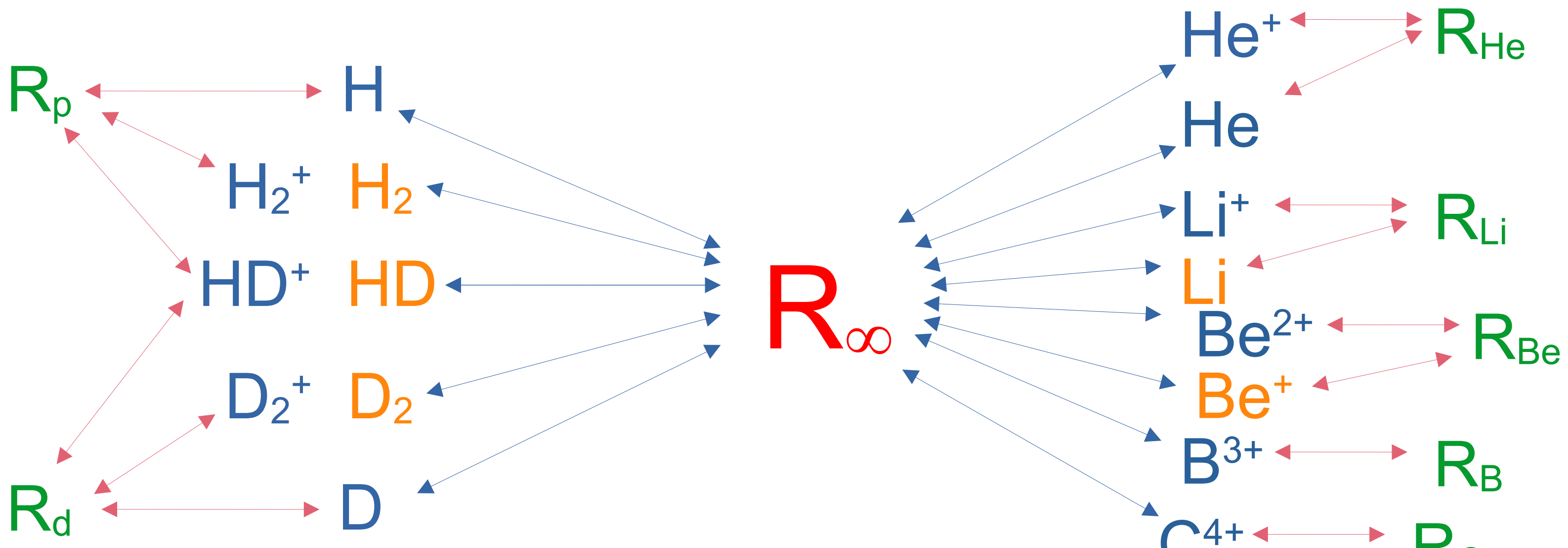
The Rydberg constant



2-body QED calculations
3-body QED calculations

Exp: Amsterdam, Zurich, Düsseldorf, Garching, Paris, Darmstadt, Wuhan, ...

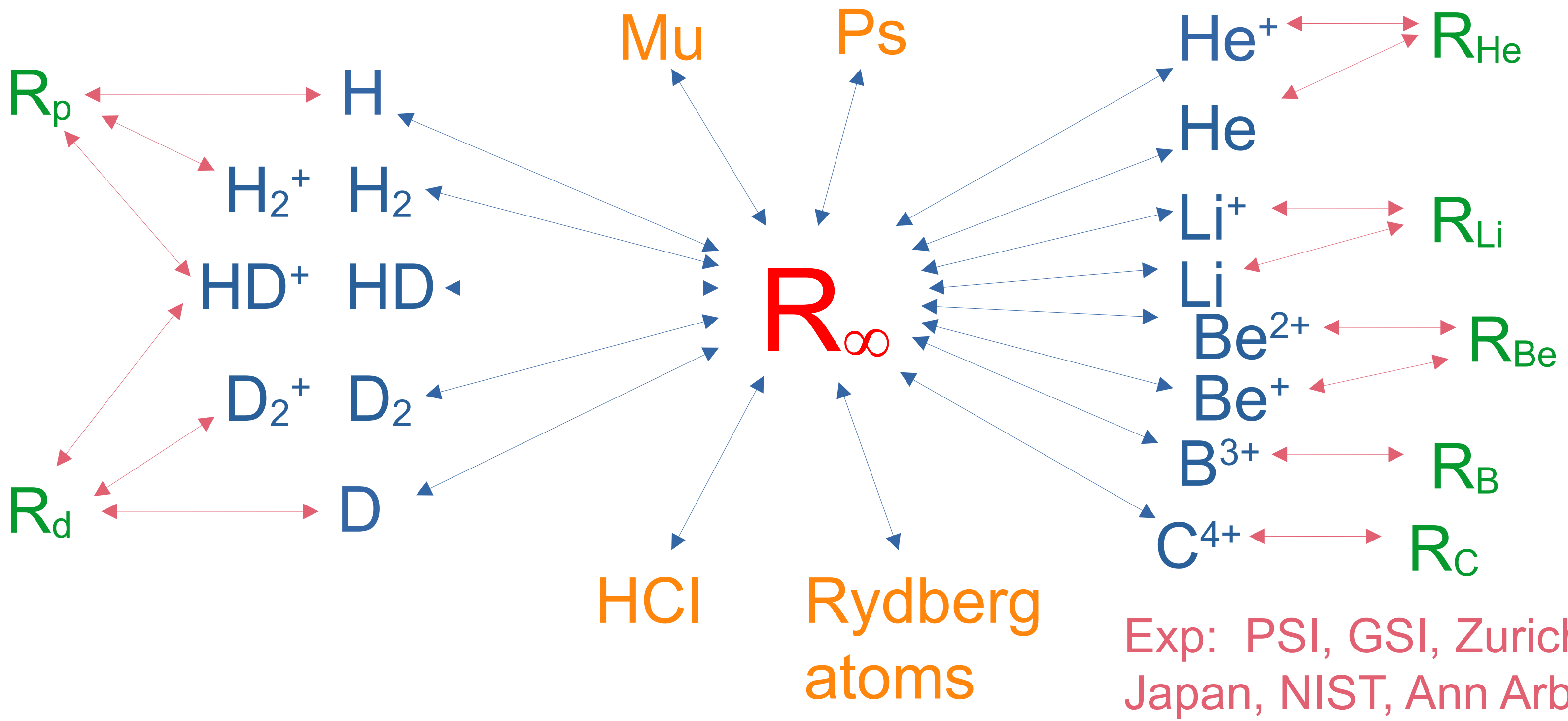
The Rydberg constant



2-body QED calculations
3-body QED calculations
4-body QED calculations

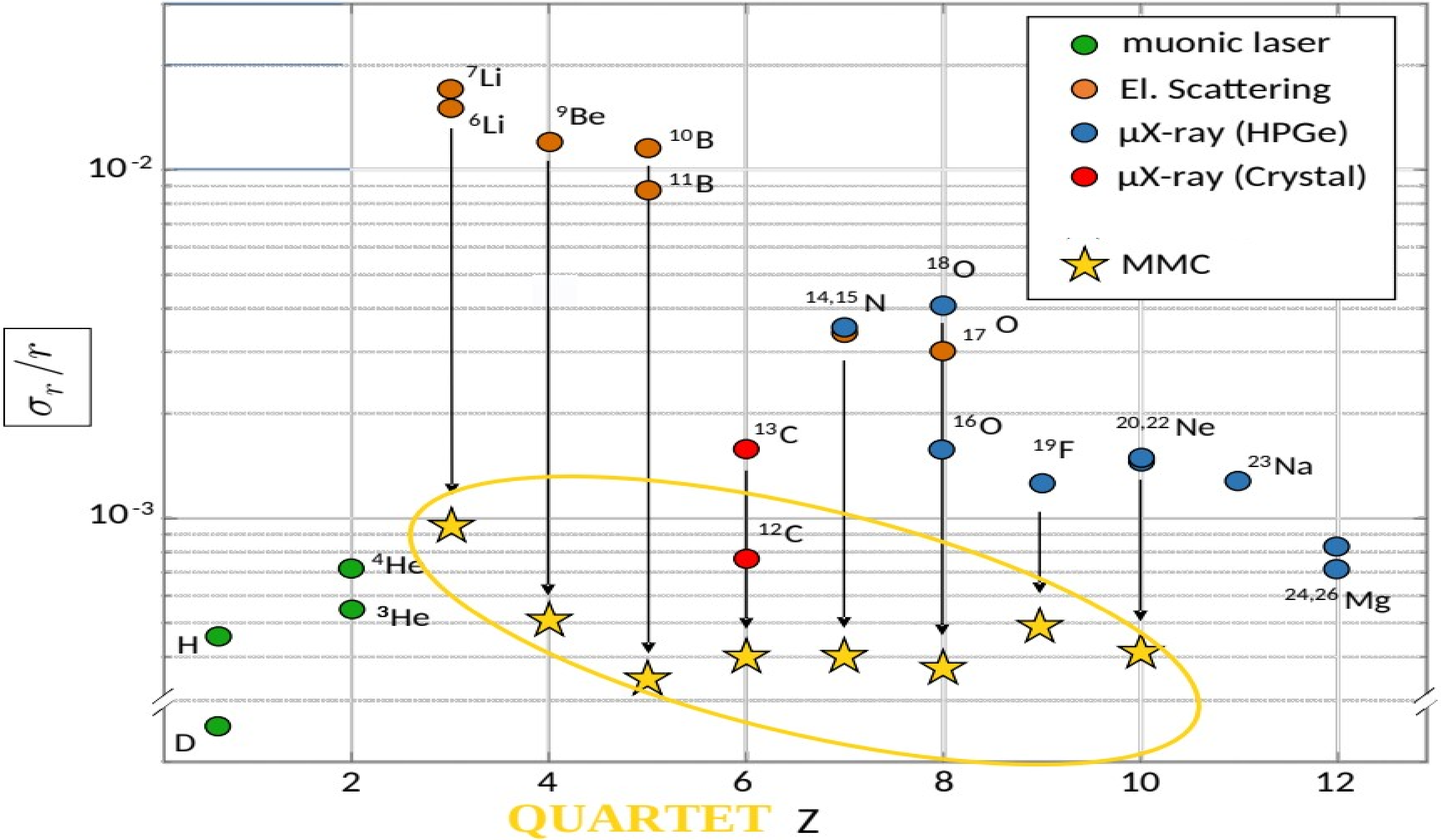
Exp: Amsterdam, Zurich, Paris, Darmstadt, ...

The Rydberg constant



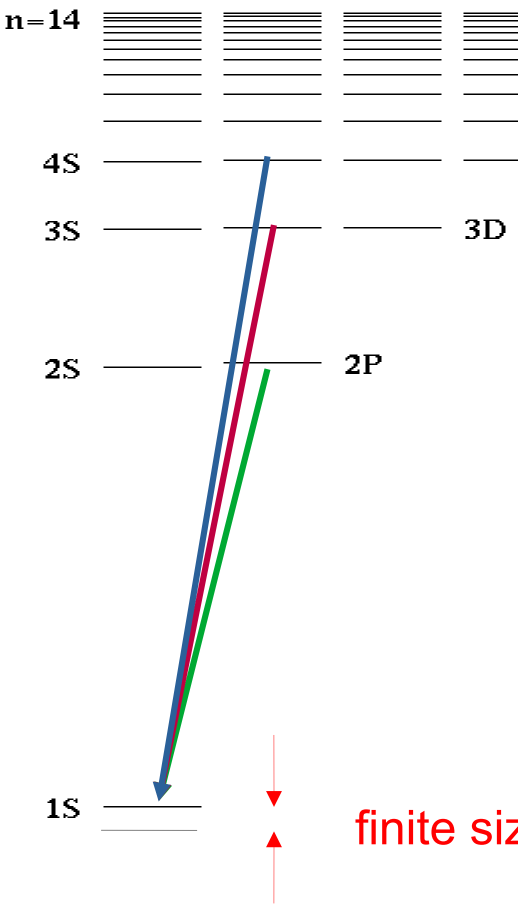
Exp: PSI, GSI, Zurich, Heidelberg, Japan, NIST, Ann Arbor, …

QUARTET: X-ray spectroscopy of muonic atoms



QUARTET

Muonic X-ray spectroscopy



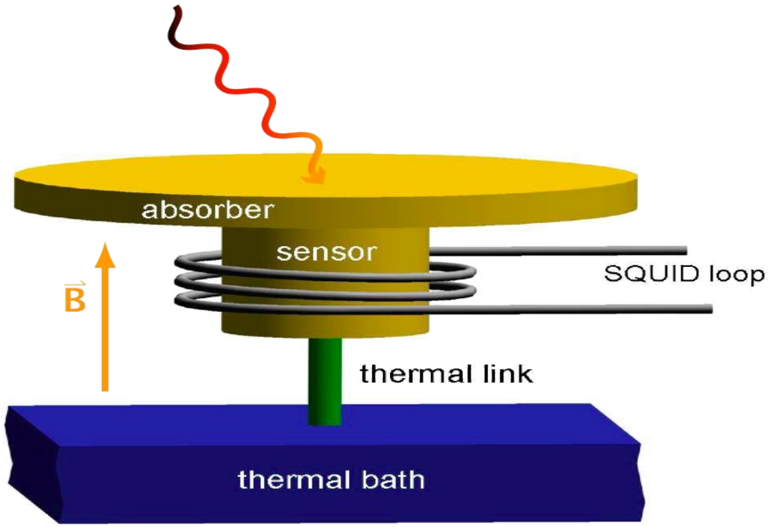
low-Z muonic atoms:

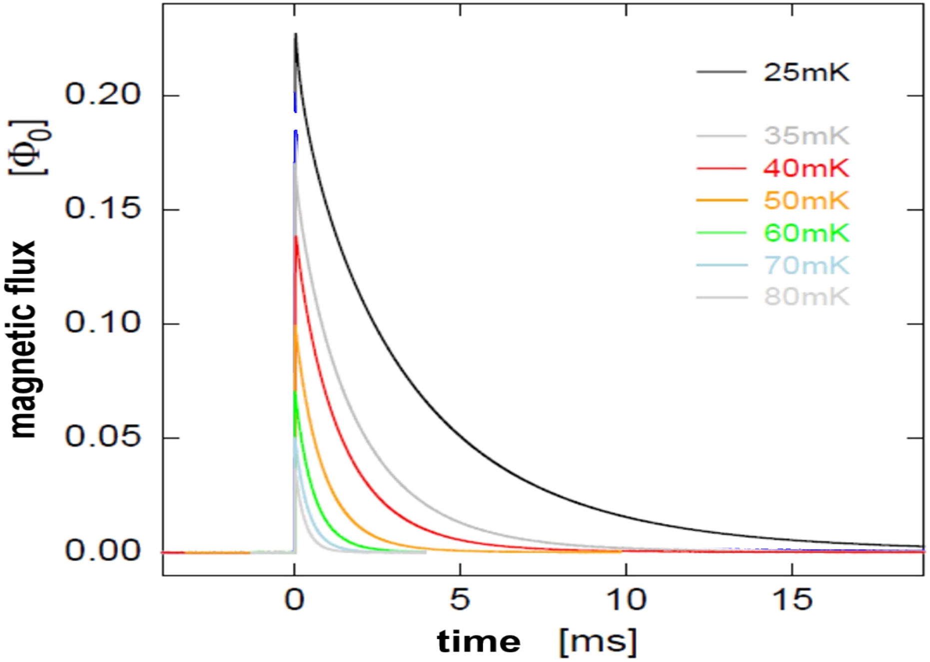
low X-ray energy → difficult!

muonic Li: 18 keV

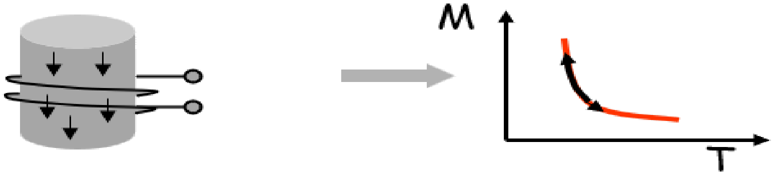
$$E_n = -\frac{R_\infty}{n^2} + \frac{C_{FS}}{n^3} \langle r^2 \rangle \delta_{l0} + \Delta(n, l, j)$$

Metallic Magnetic Calorimeters (MMCs)





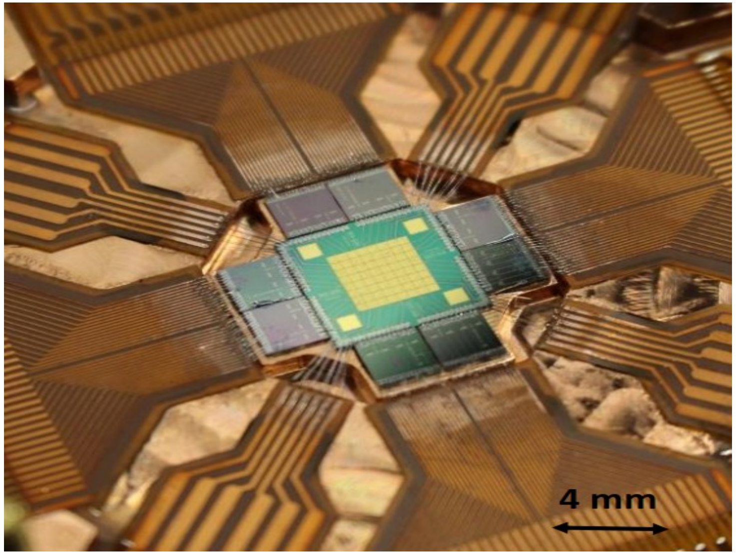
Magnetization of paramagnetic material:



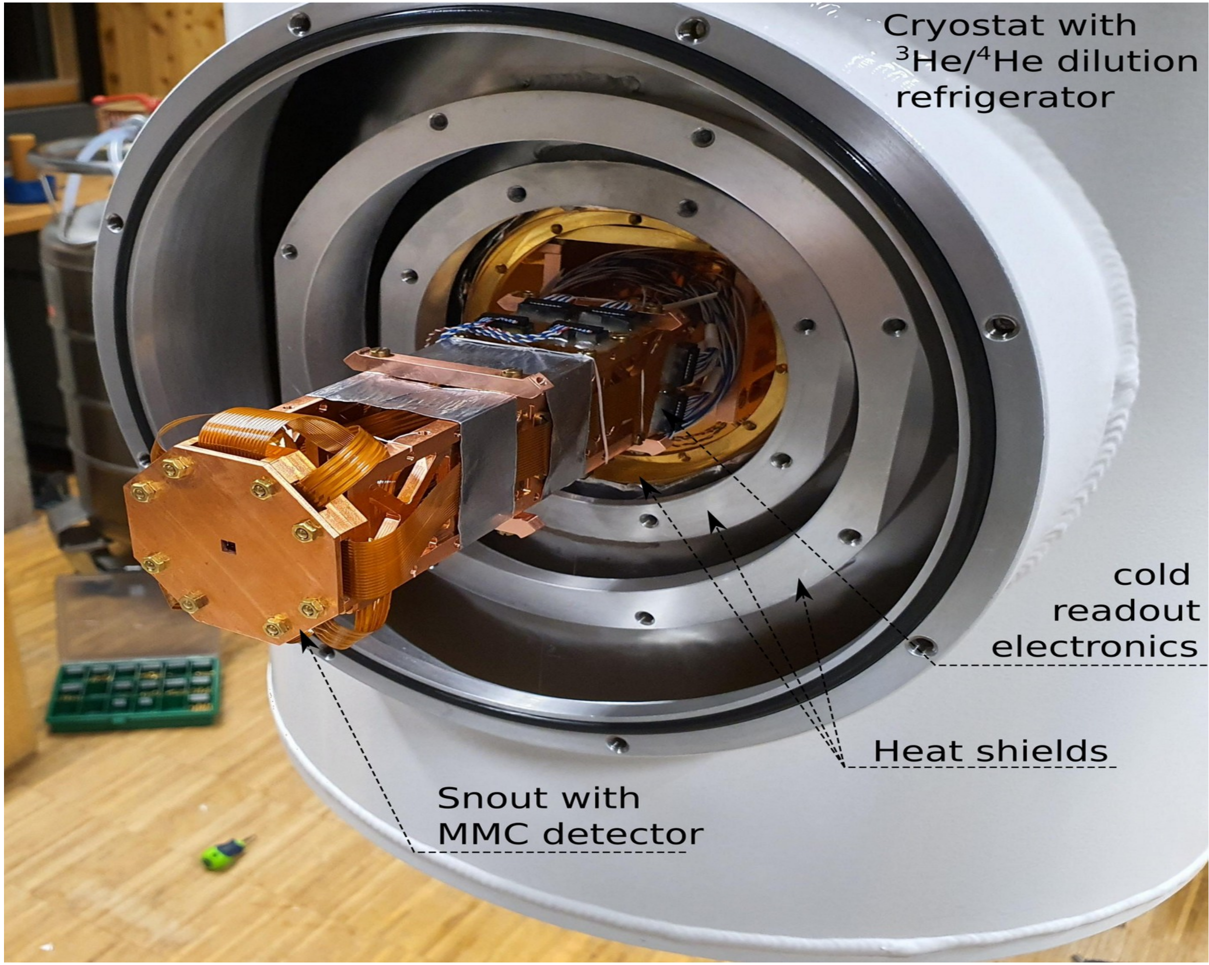
Decay time 3ms@30mK
Keep rates < 10 Hz
per pixel to avoid pileup

Metallic Magnetic Calorimeters (MMCs)

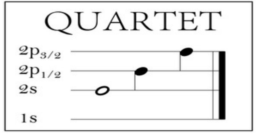
pixel array, area 16mm^2



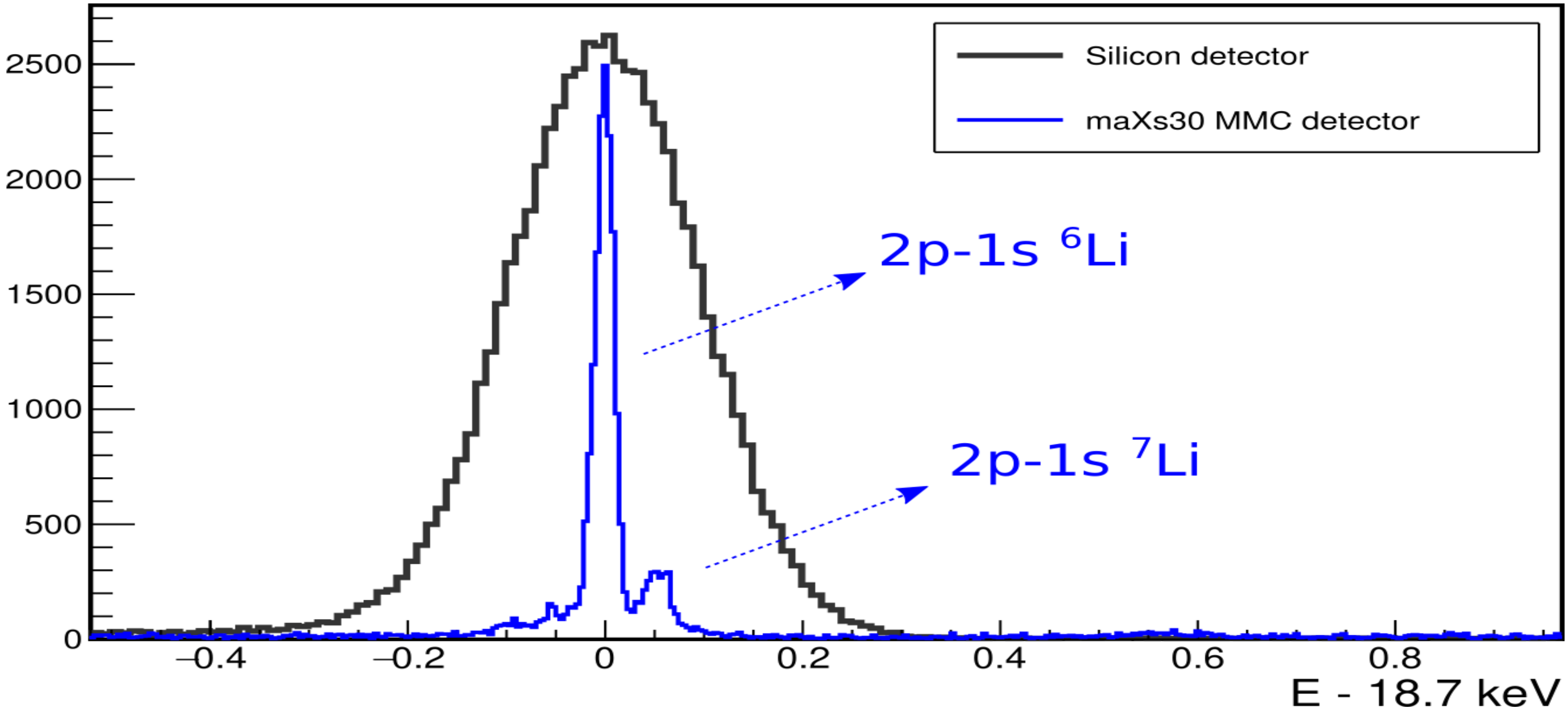
High efficiency (>90%) for photons 10-60 keV



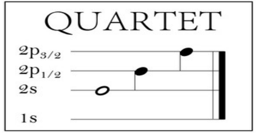
MMC have *excellent* energy resolution

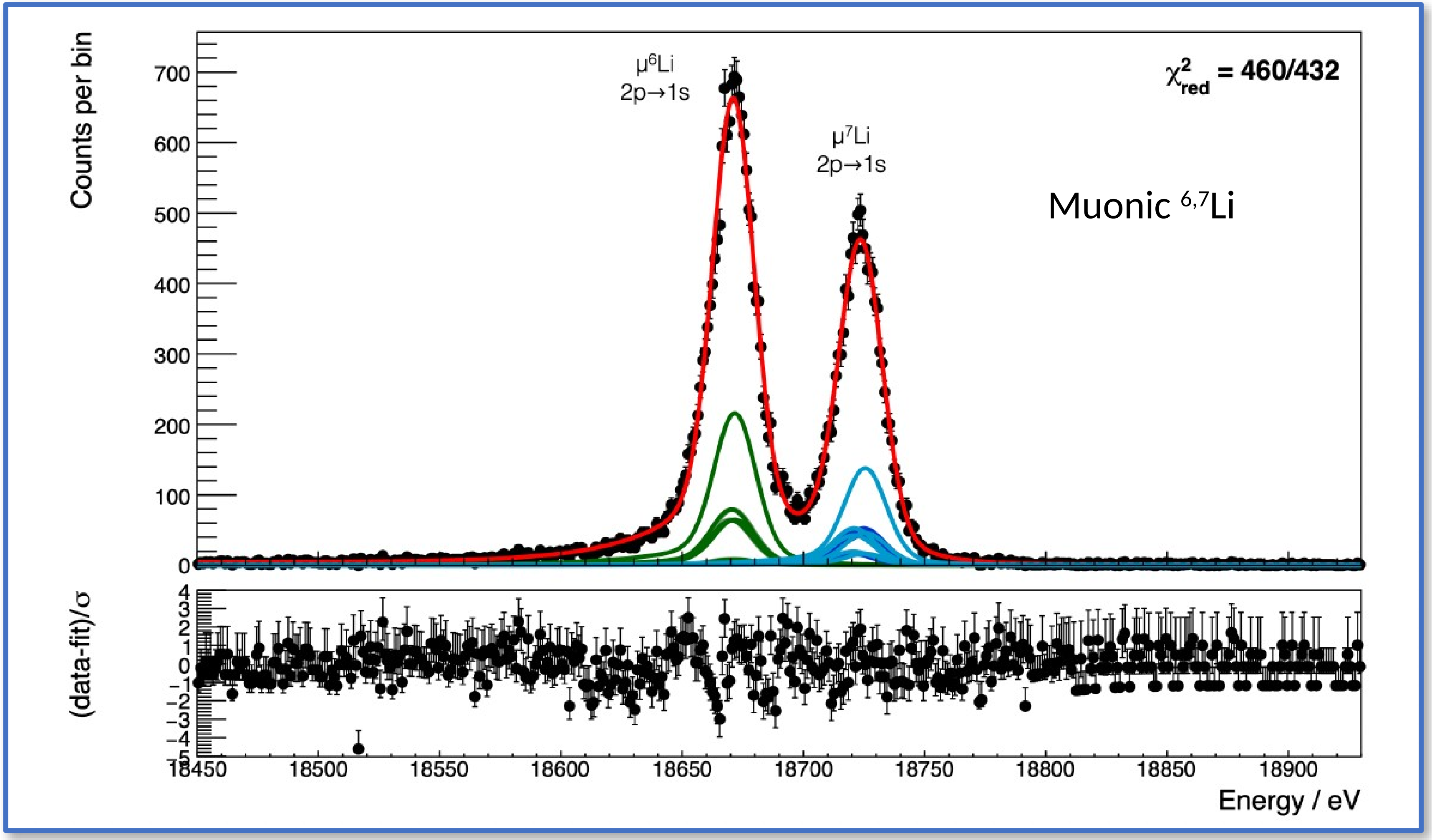


2023 pilot run muLi

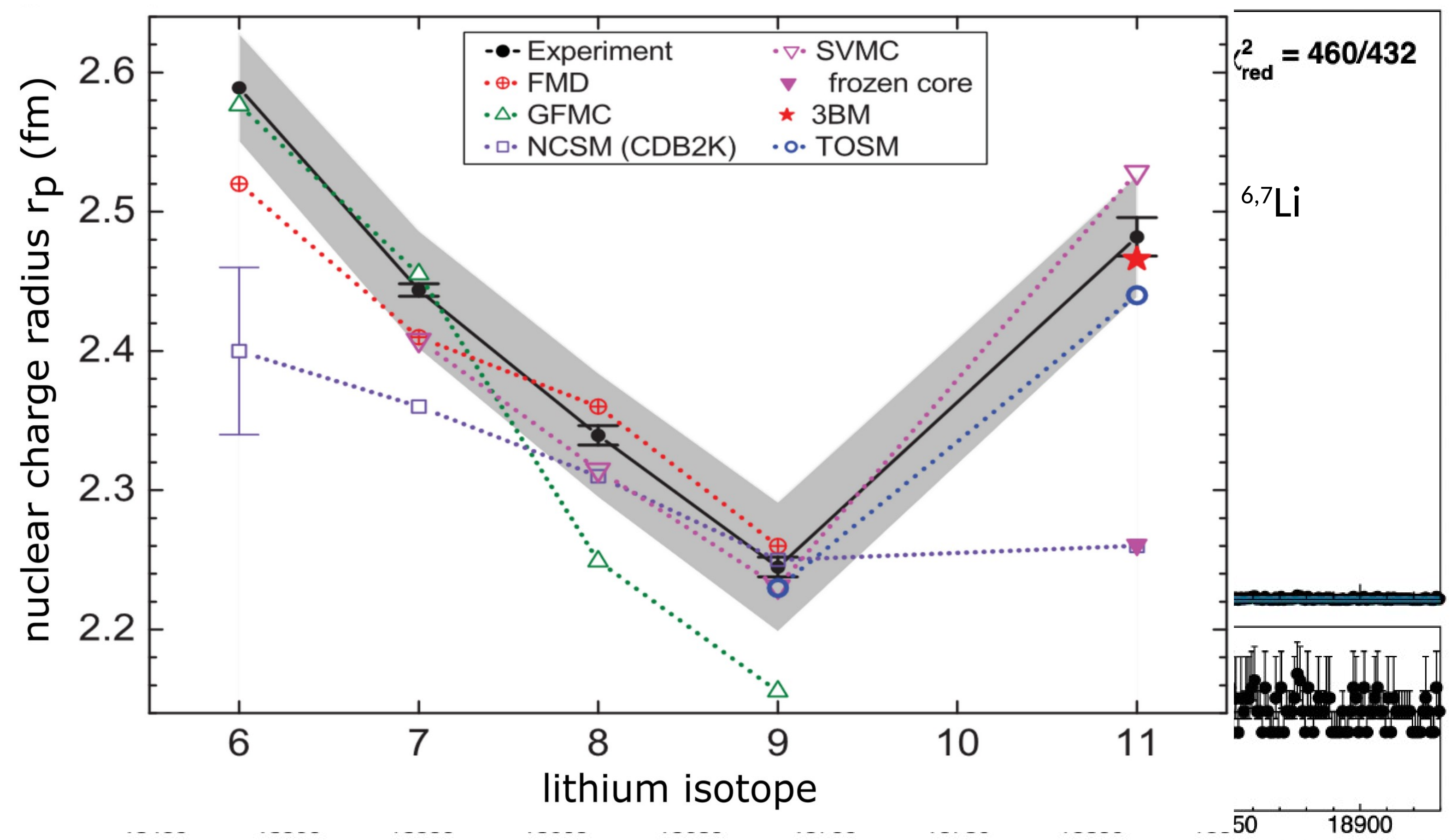


2024: Li, Be, B


QUARTET
2p3/2
2p1/2
2s
1s

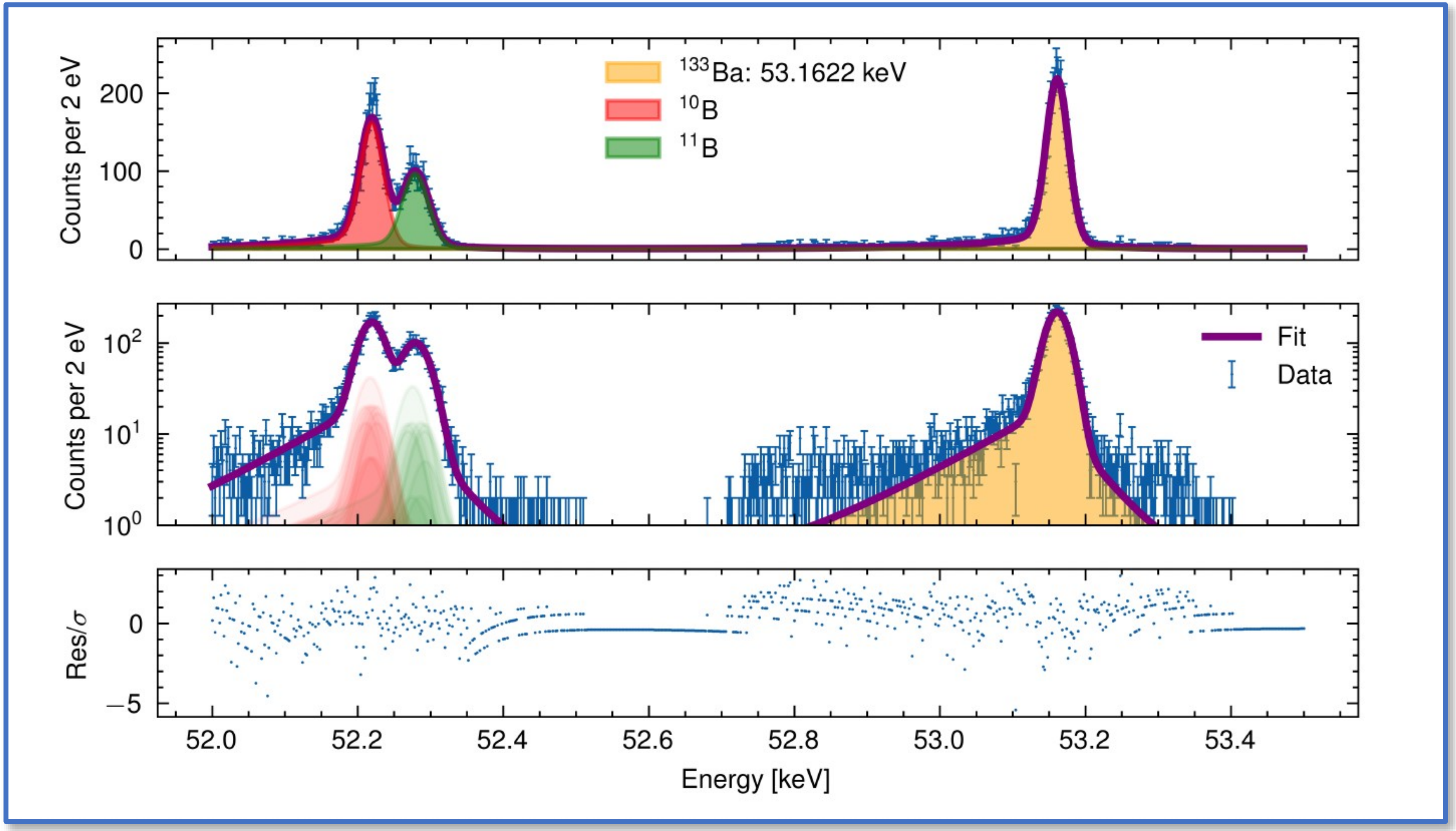

Counts per bin
μ6Li
2p→1s
μ7Li
2p→1s
χ2red = 460/432
Muonic 6,7Li
(data-fit)/σ
Energy / eV
18450
18500
18550
18600
18650
18700
18750
18800
18850
18900

2024: Li, Be, B



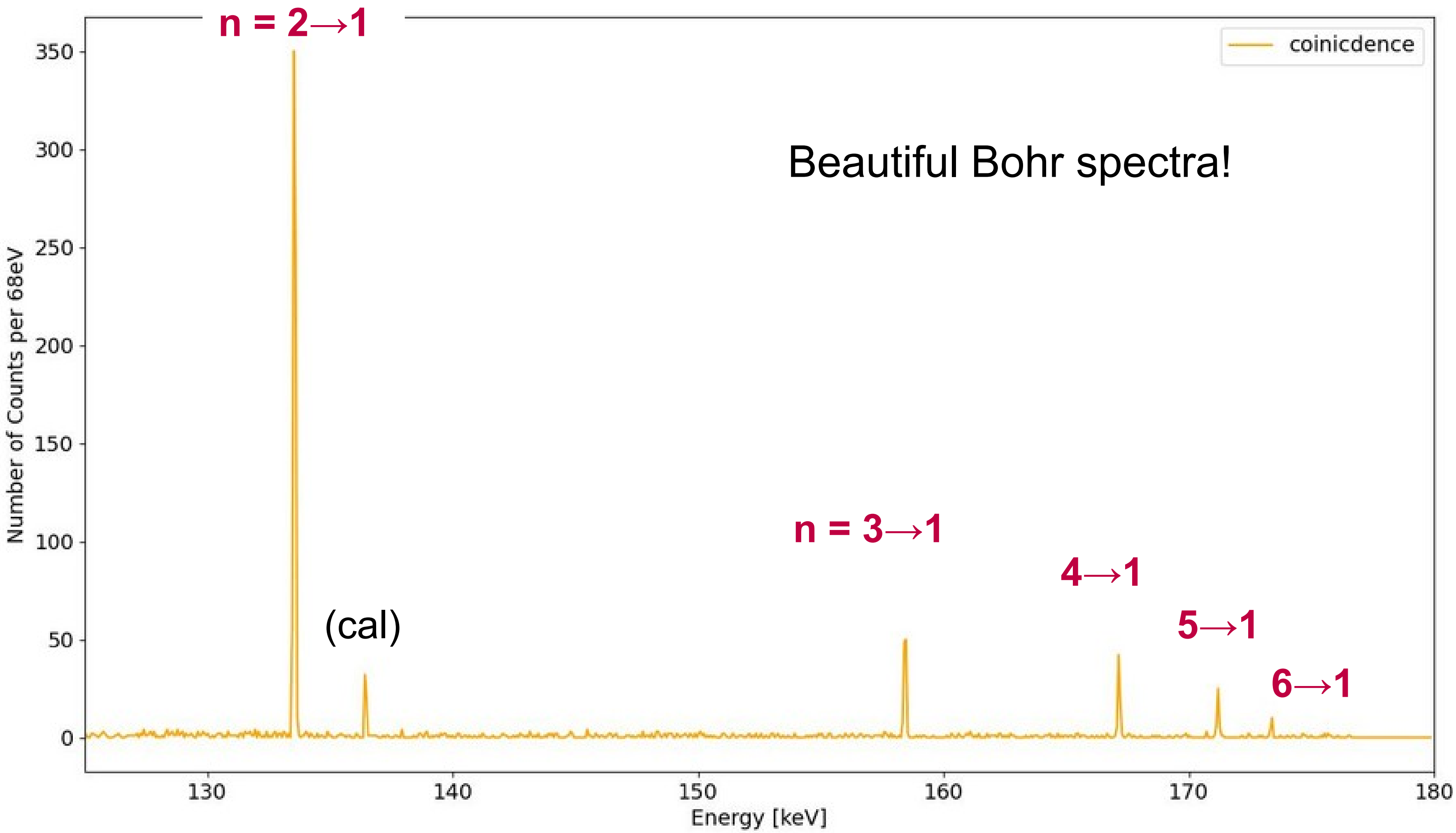
[W. Nörtershäuser et al., Physical Review C 84, 024307 (2011)]

2024: Li, Be, B

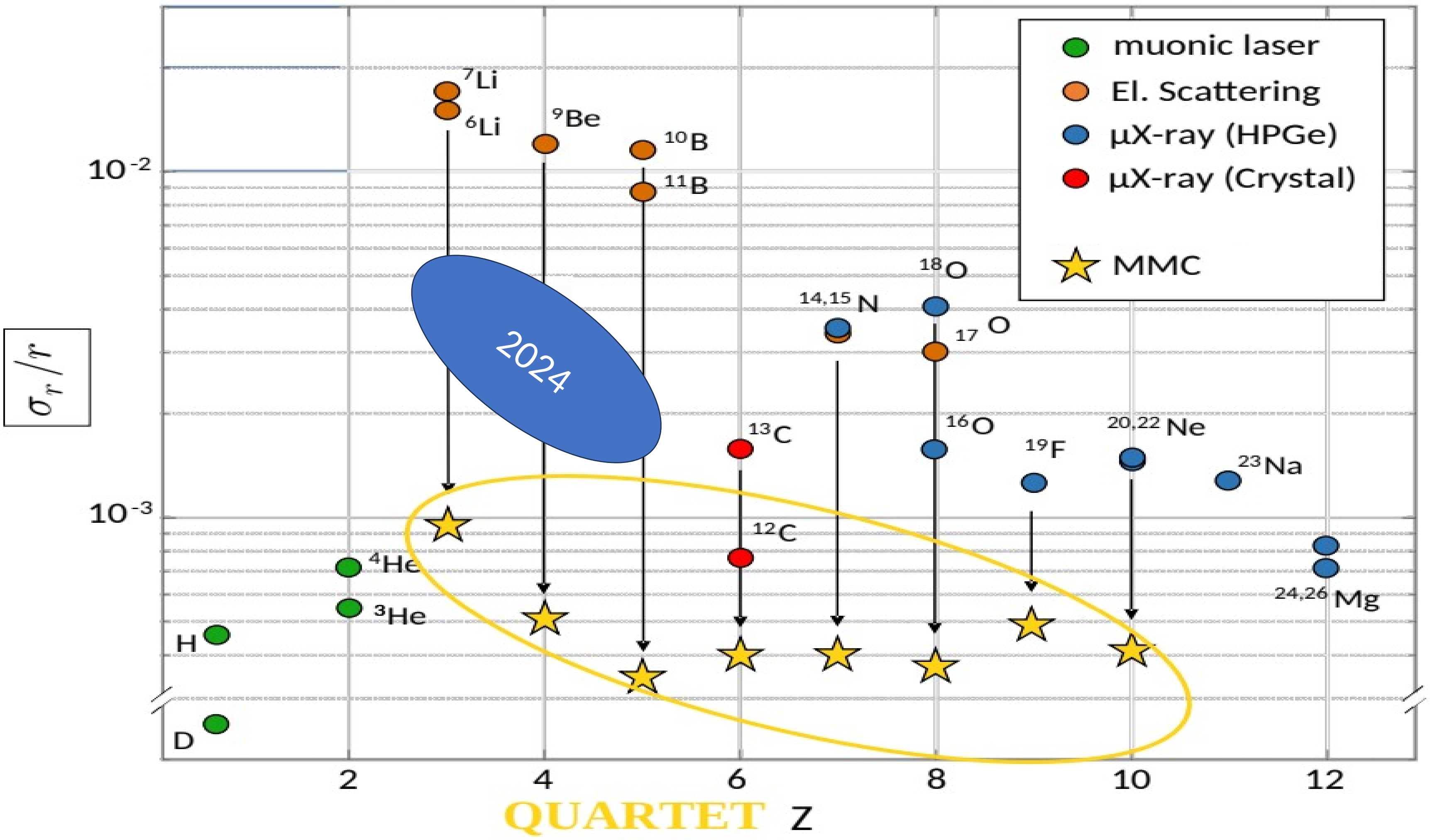


Muonic ^{10,11}B

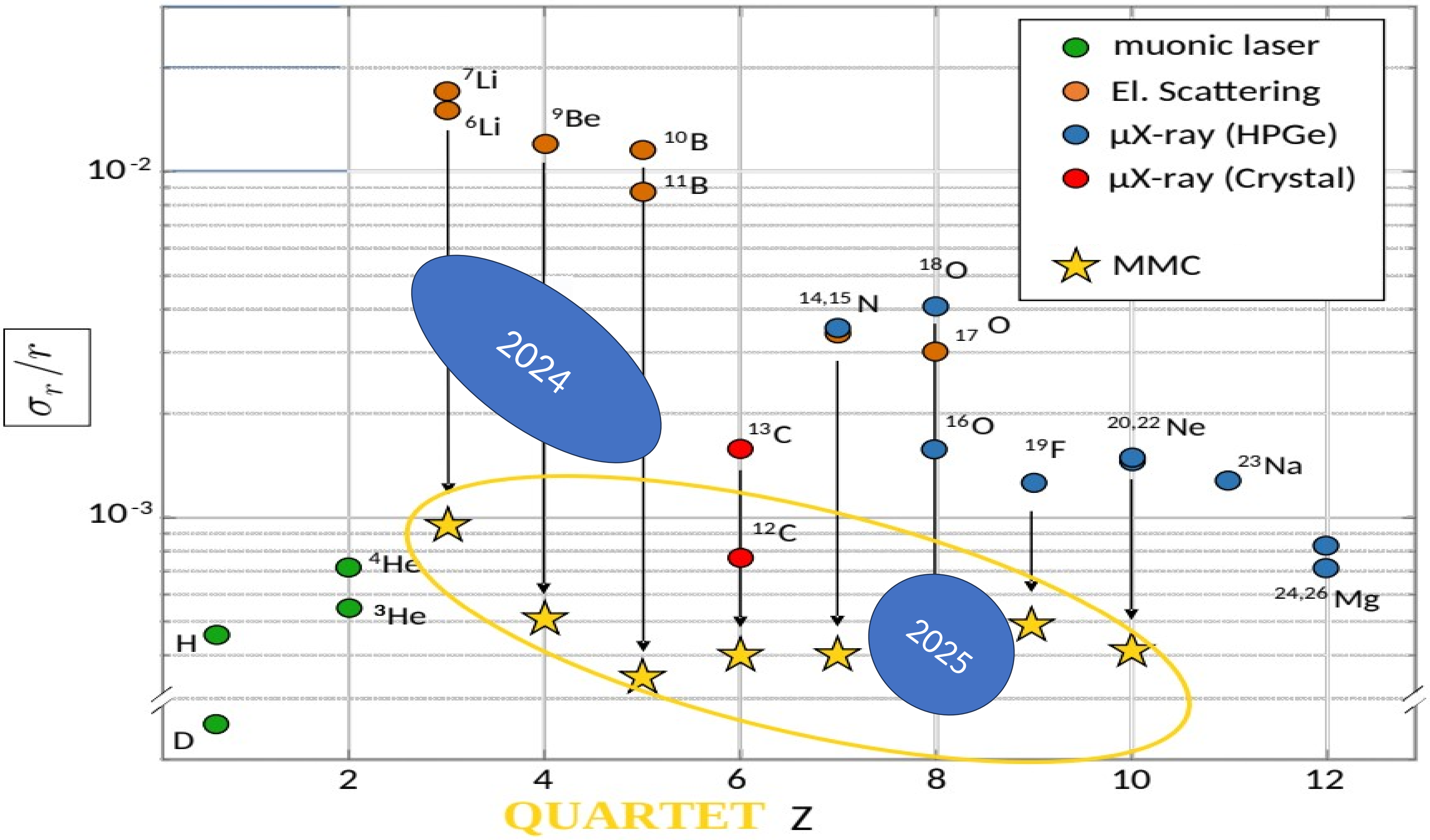
muonic ^{17}O, online spectrum 2025



QUARTET: X-ray spectroscopy



QUARTET: X-ray spectroscopy



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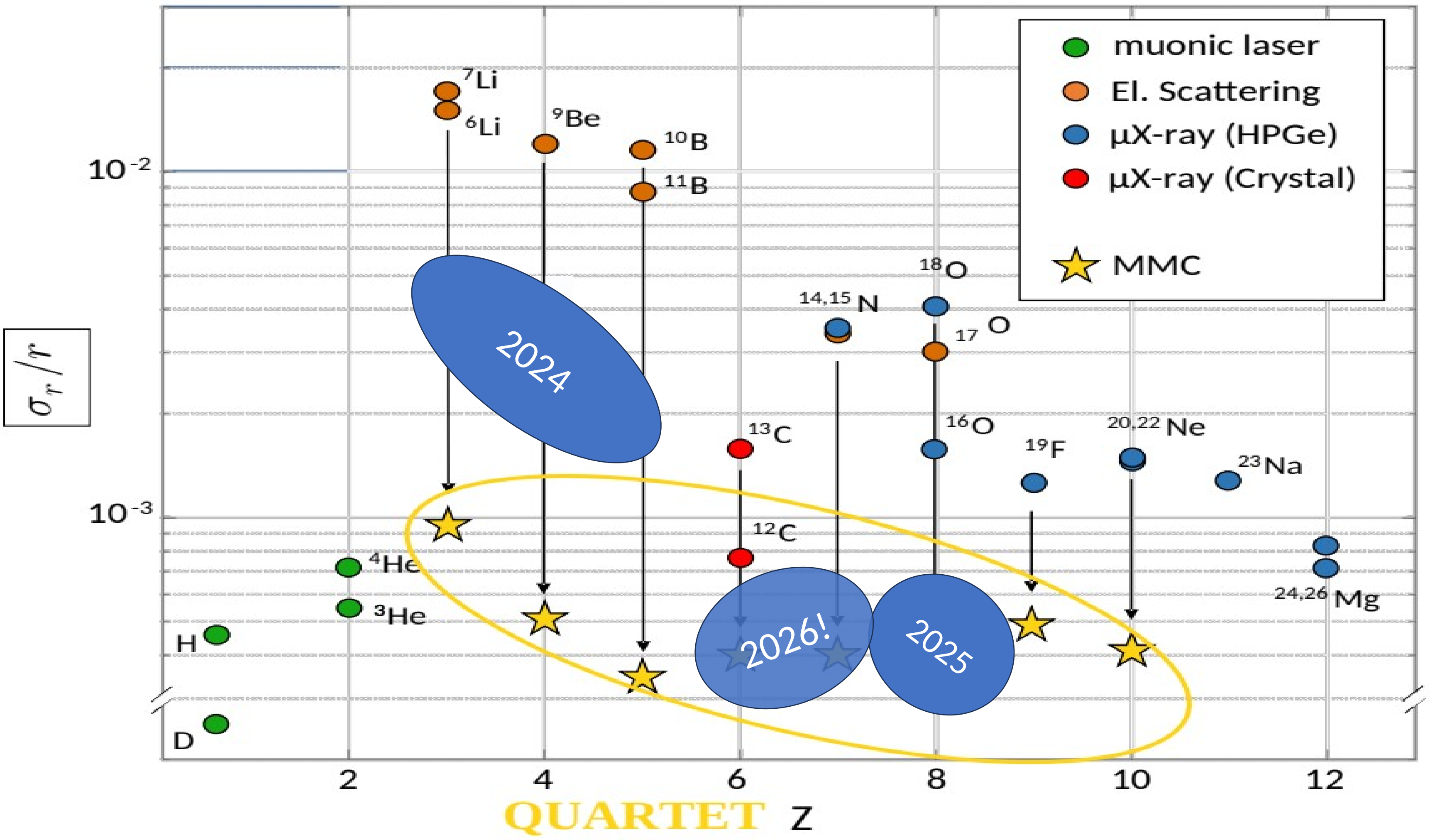
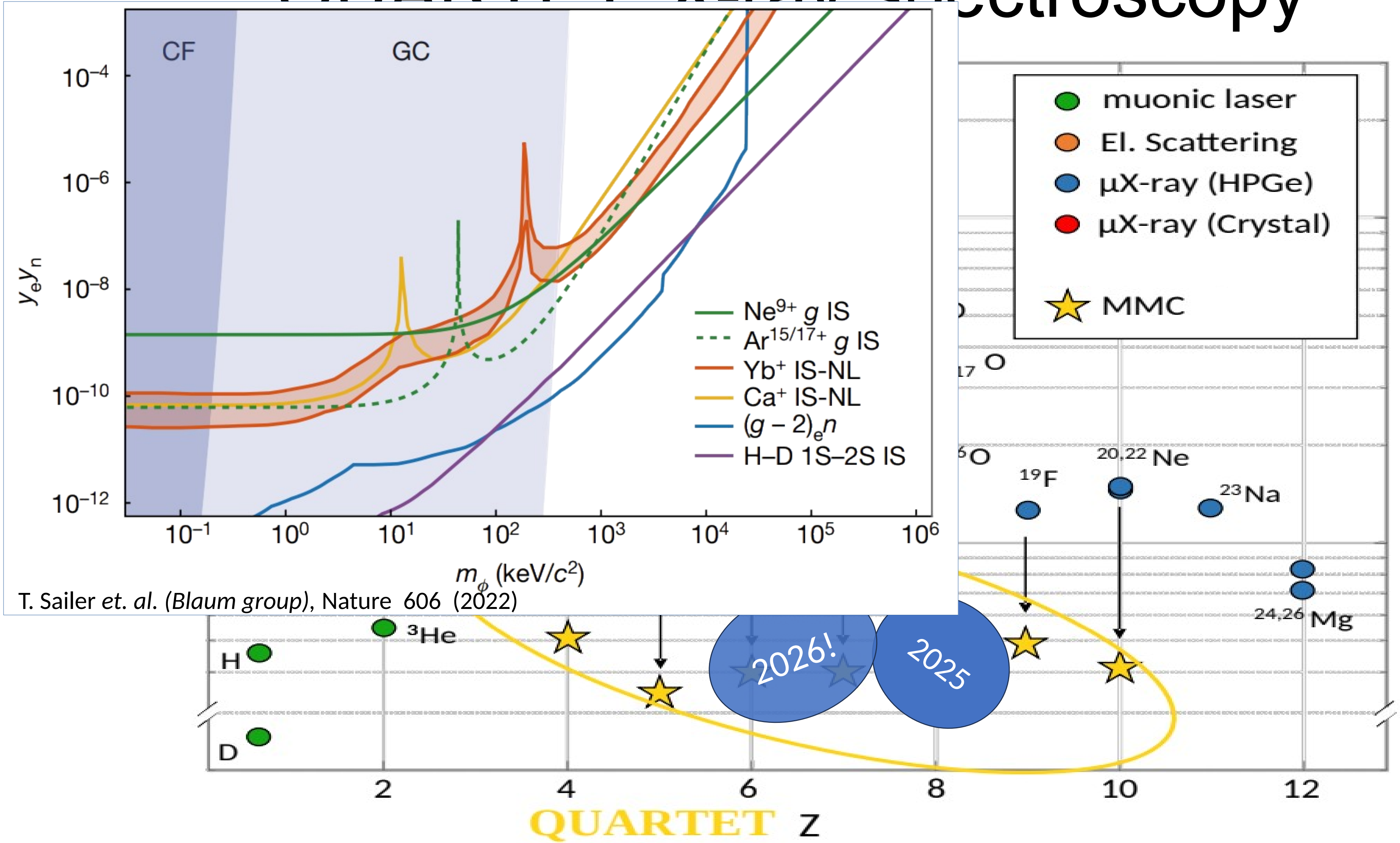


QUARTET: X-ray spectroscopy



T. Sailer *et. al. (Blaum group)*, Nature 606 (2022)

Conclusions

muonic H, D, ^{3}He, ^{4}He by laser done → improved charge radii

nuclear polarizability

Proton radius puzzle solved

He isotope shift solved

→ Muonic atoms provide reliable charge radii

QED/SM Test to 8×10^{-13}

muonic Li, Be, …. → better charge radii by QUARTET X-rays and MMCs

muonic high-Z , also for rare or radioactive nuclei! → muX

Thanks a lot for your attention

Lothar Maisenbacher

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