

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

L. Maisenbacher^{1,4} , V. Wirthl¹ , A. Matveev¹, A. Grinin^{1,5}, R. Pohl² , 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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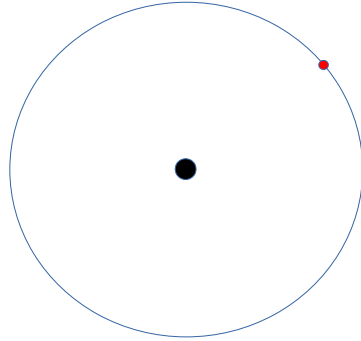
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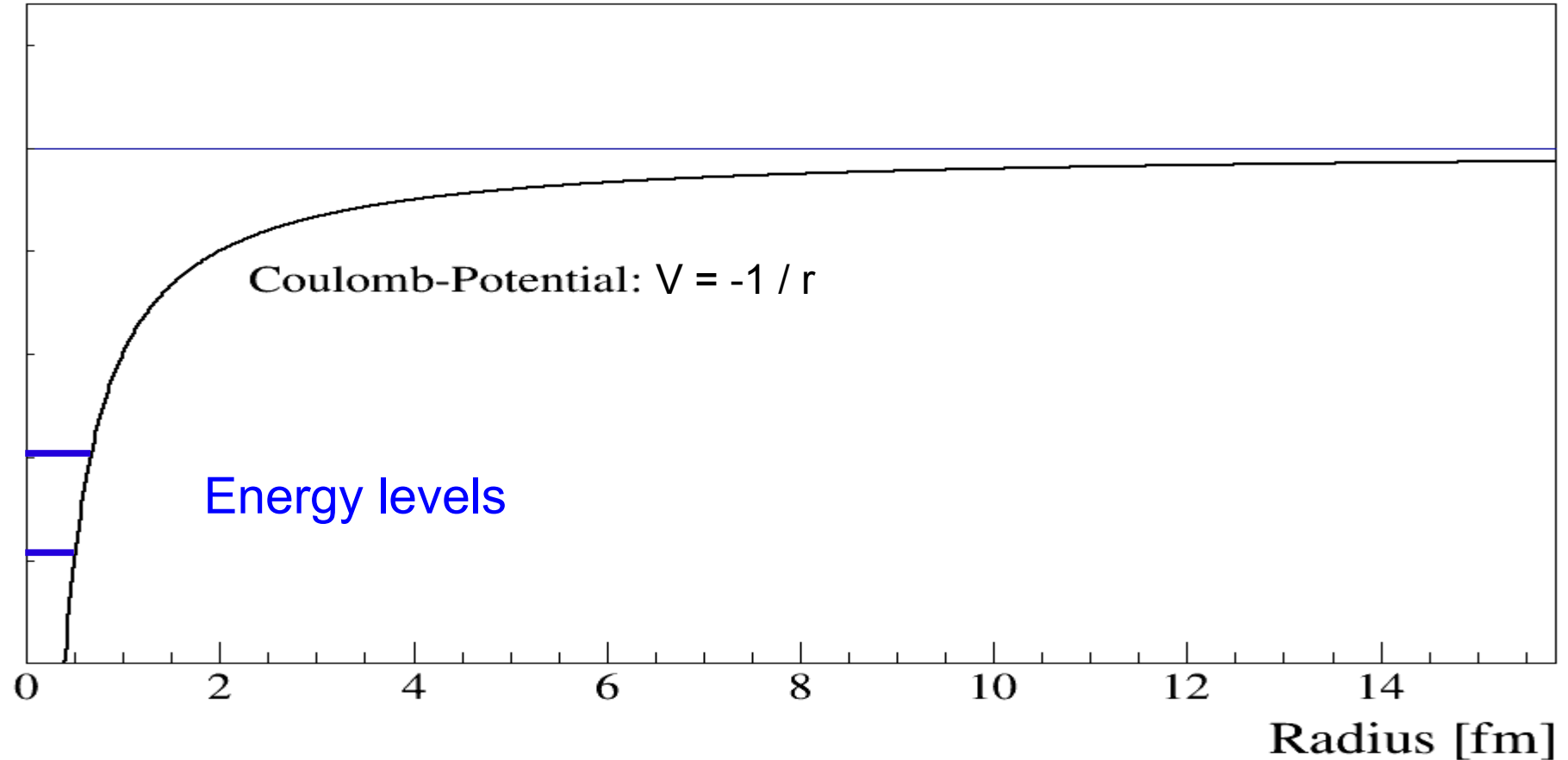
Hydrogen (-like atoms)



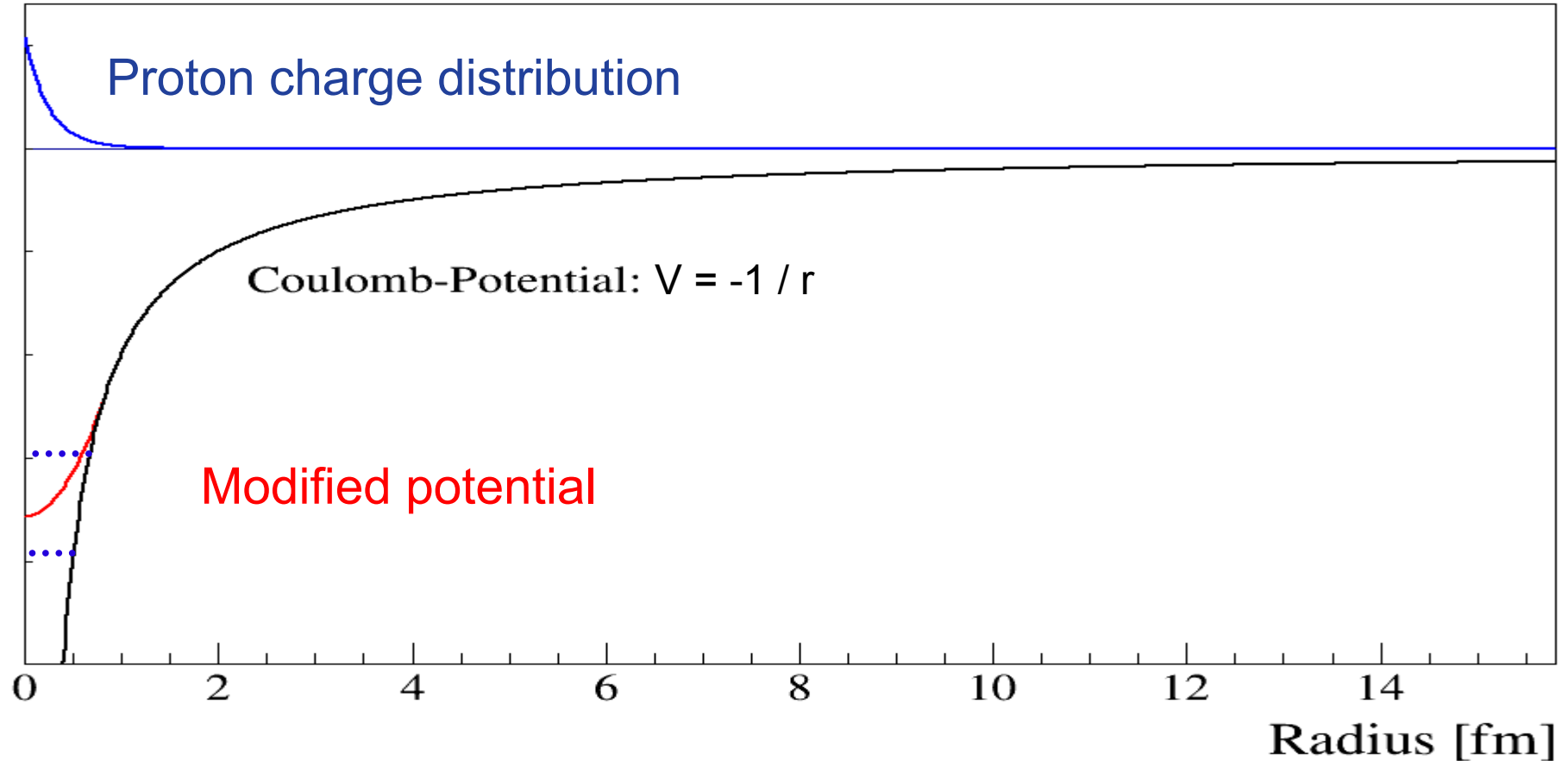
“There's a reason physicists are so successful with what they do,
and that is they study the hydrogen atom and the helium ion
and then they stop.”

- Richard Feynman

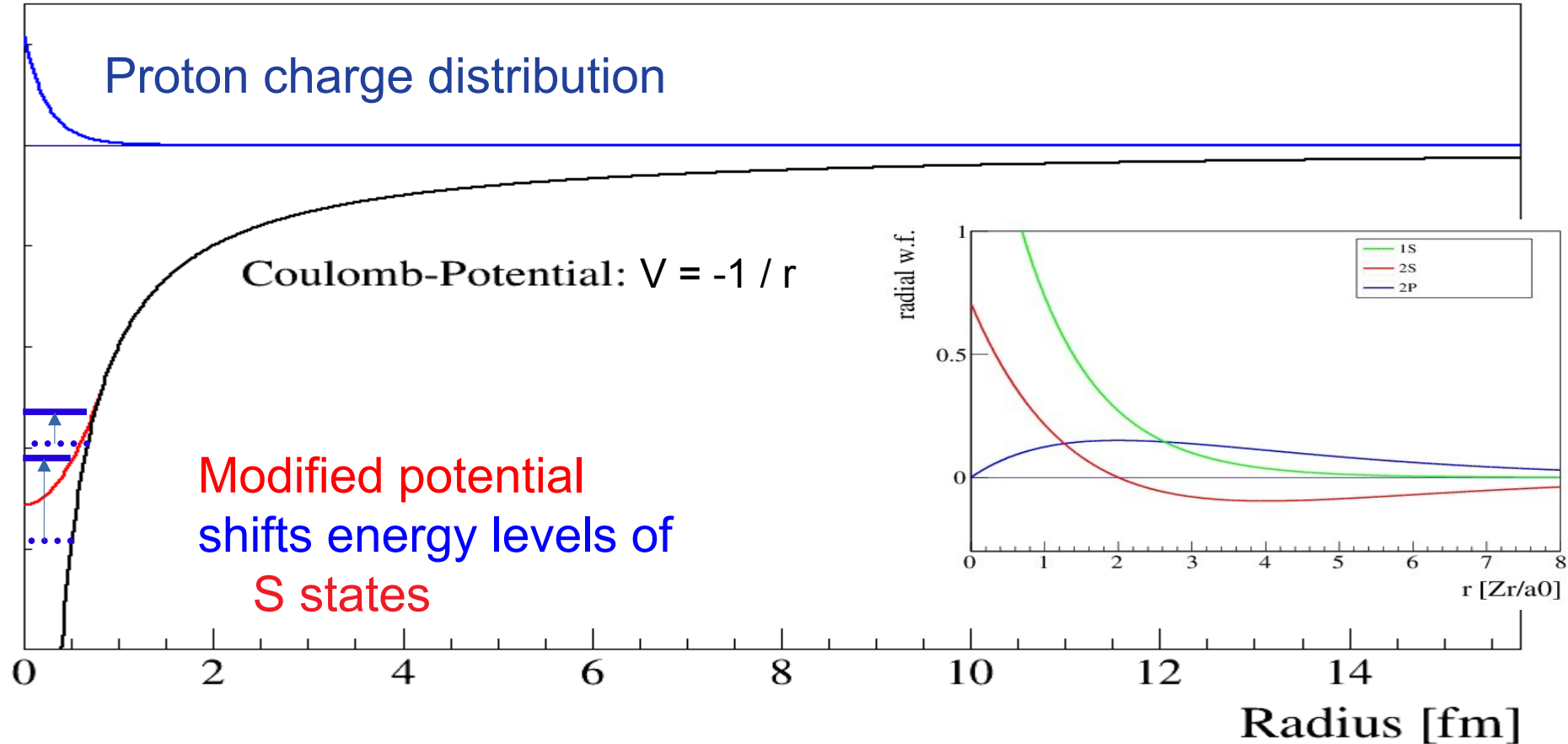
Proton Radius and Hydrogen



Proton Radius and Hydrogen



Proton Radius and Hydrogen



Muonic Atoms

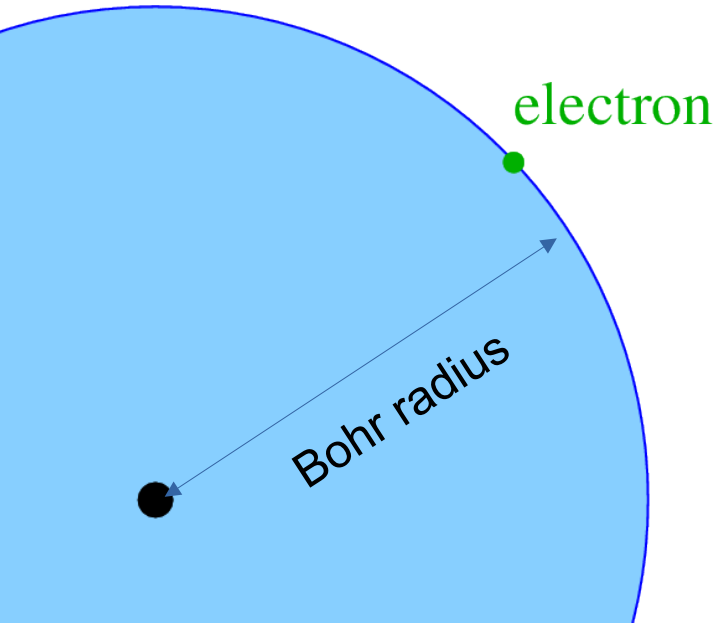
A **bare** nucleus, orbited by **one negative muon**.

Hydrogen theory!

Muonic atoms in a nutshell

Regular hydrogen:

Bohr radius $\sim 50'000$ x nuclear radius



Muonic hydrogen:



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

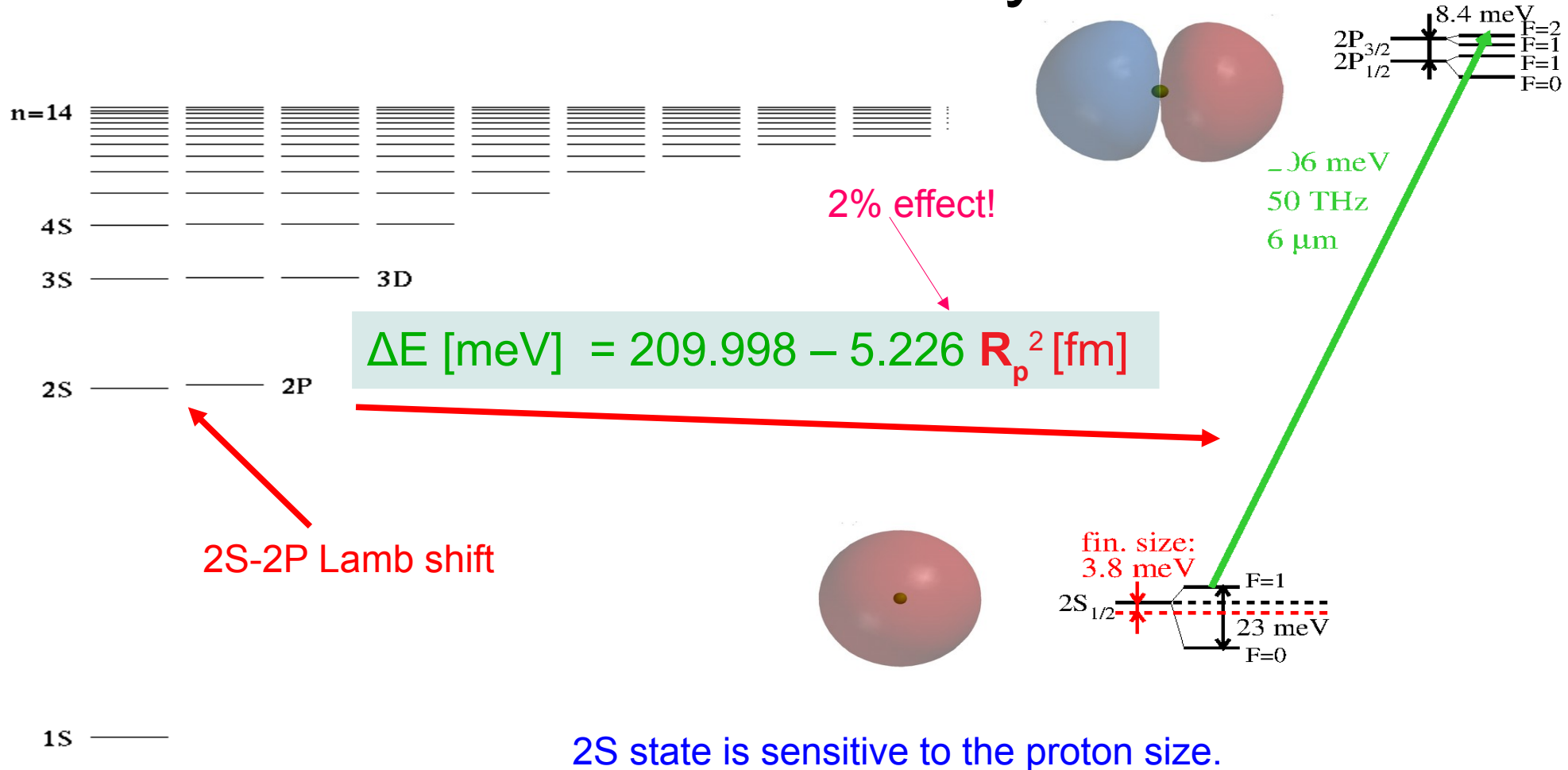
Bohr **radius** = **1/200** of H

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

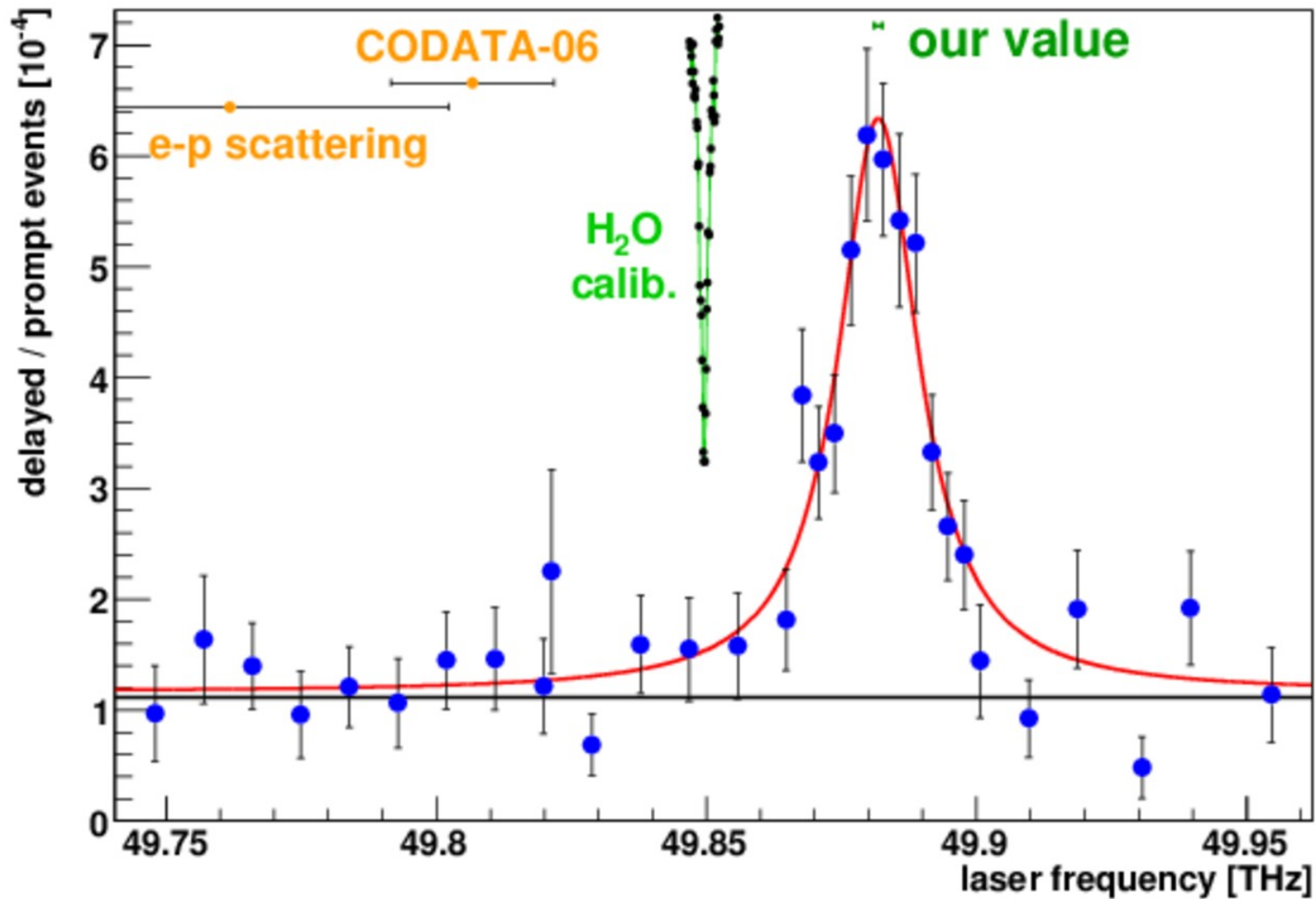
==> Our (laser) spectroscopy at **10^{-5}** level
can compete with **10^{-12}** from normal atoms

Vastly not to scale!!

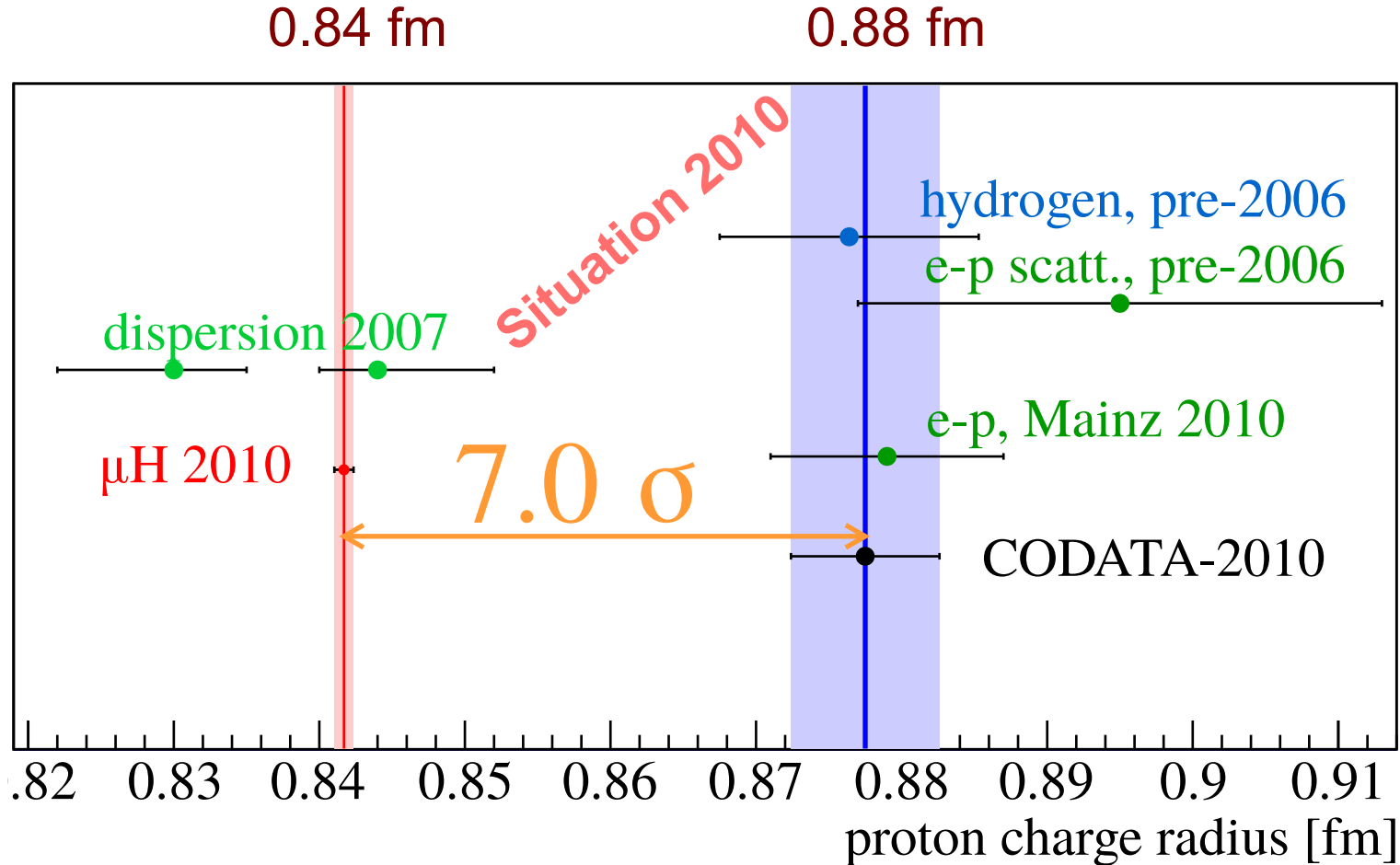
Lamb shift in Muonic Hydrogen



Resonance



The “Proton Radius Puzzle”

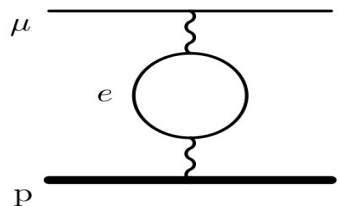


Theory in muonic H

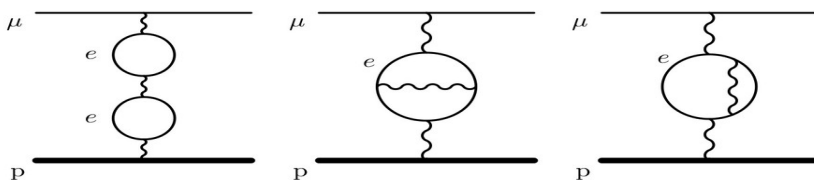
(D, $^3,^4\text{He}^+$ similar)

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

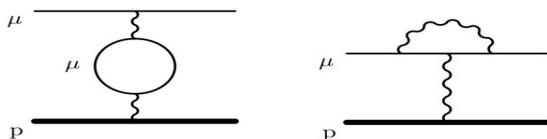
Uehling



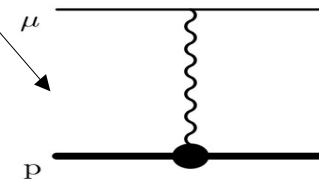
Källen-Sabry



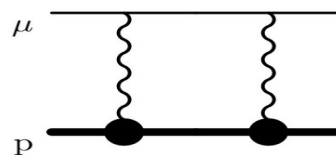
Muon SE+VP



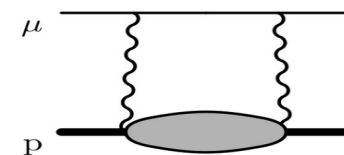
and 20+ more....



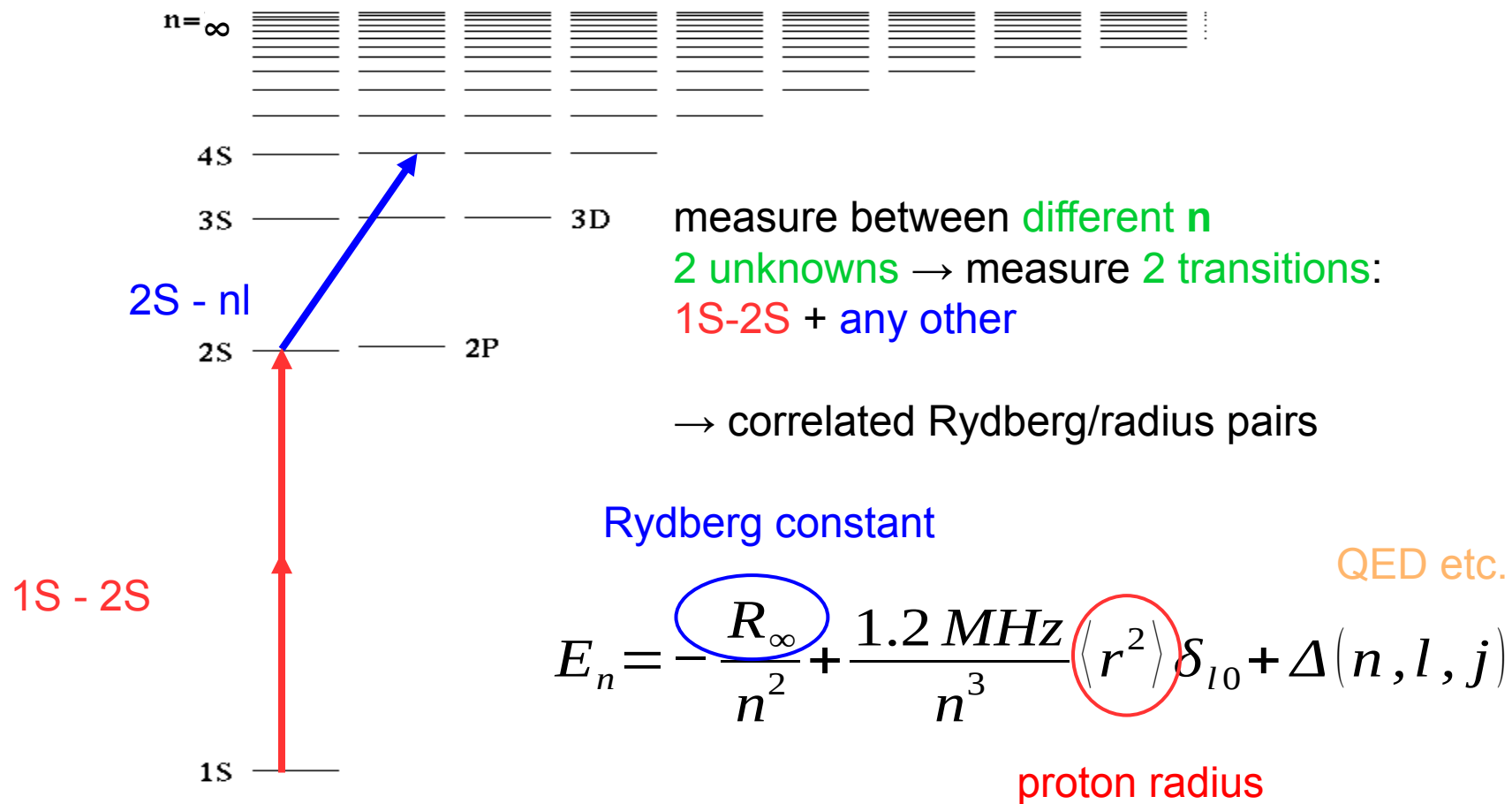
Proton form factor



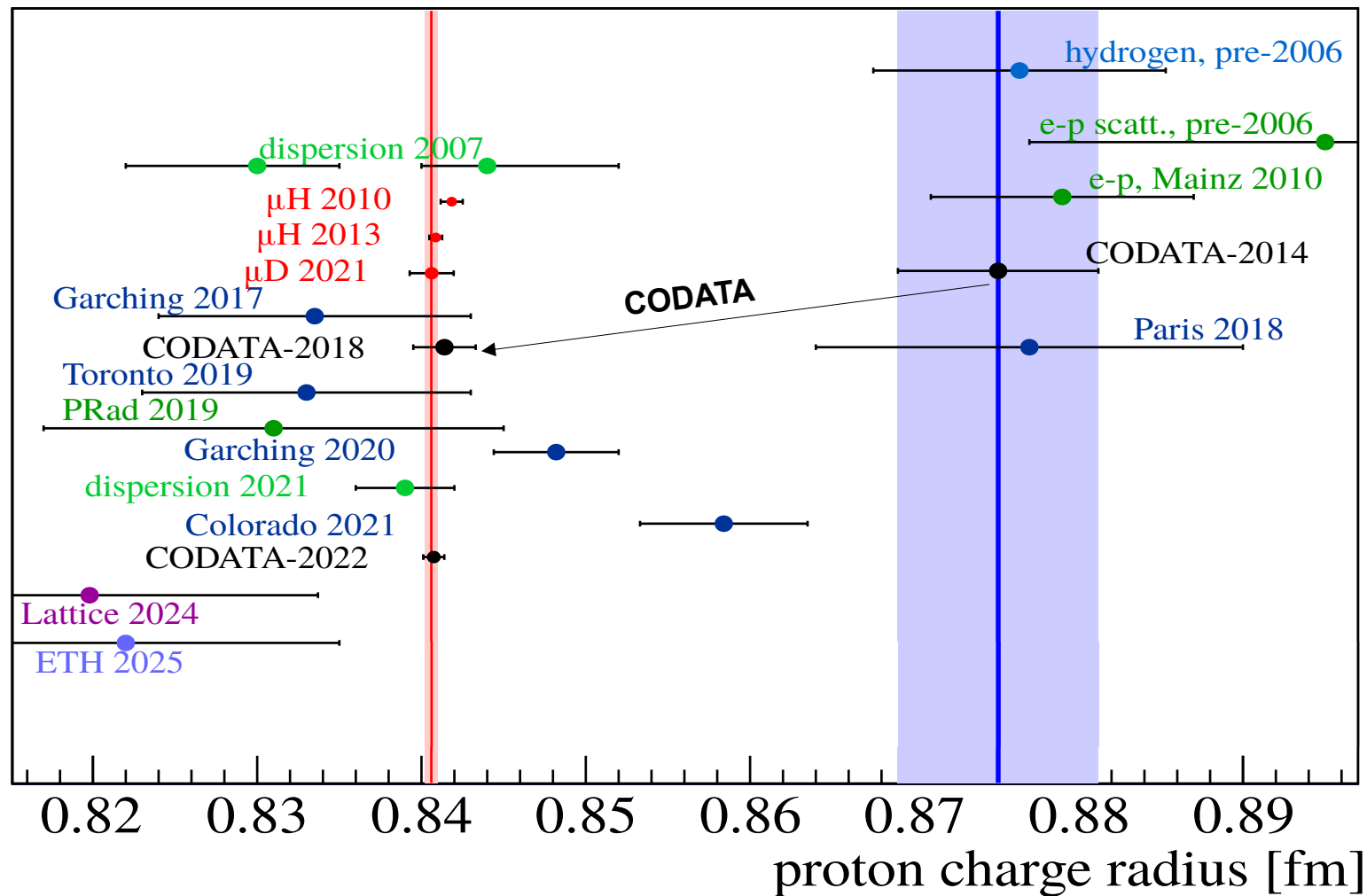
elastic and inelastic two-photon exchange
(Friar moment and polarizability)



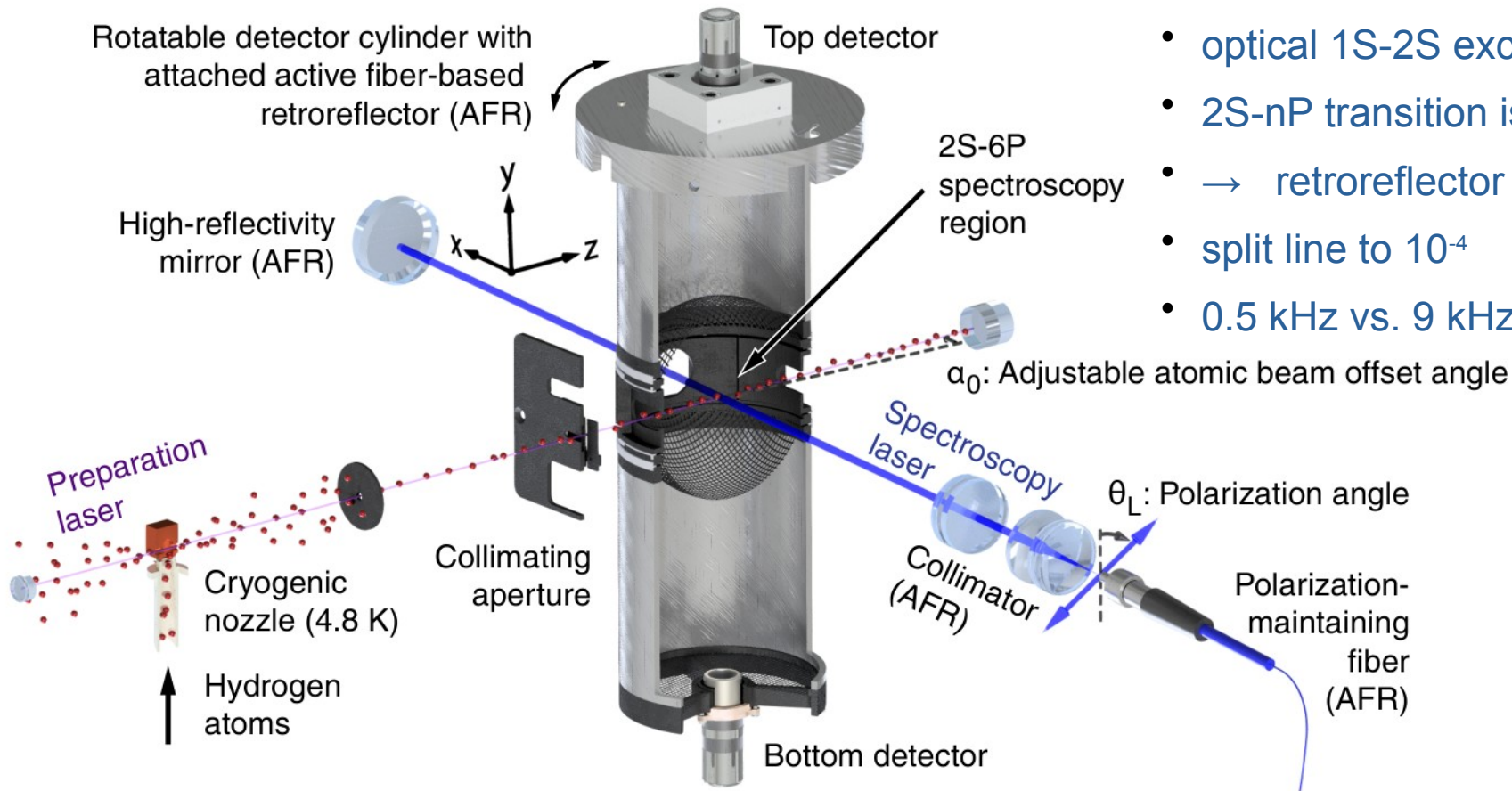
Proton radius from **ordinary** hydrogen



The proton radius situation last year

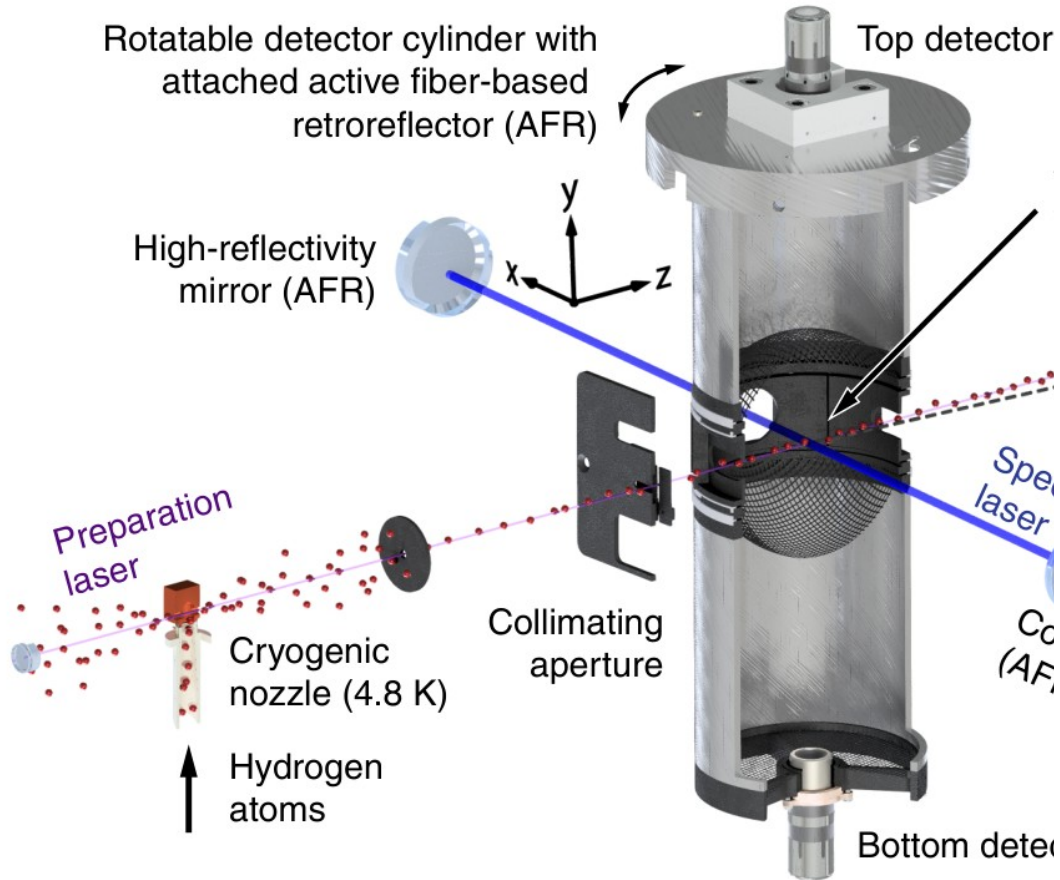


(Normal) Hydrogen 2S-nP in Garching

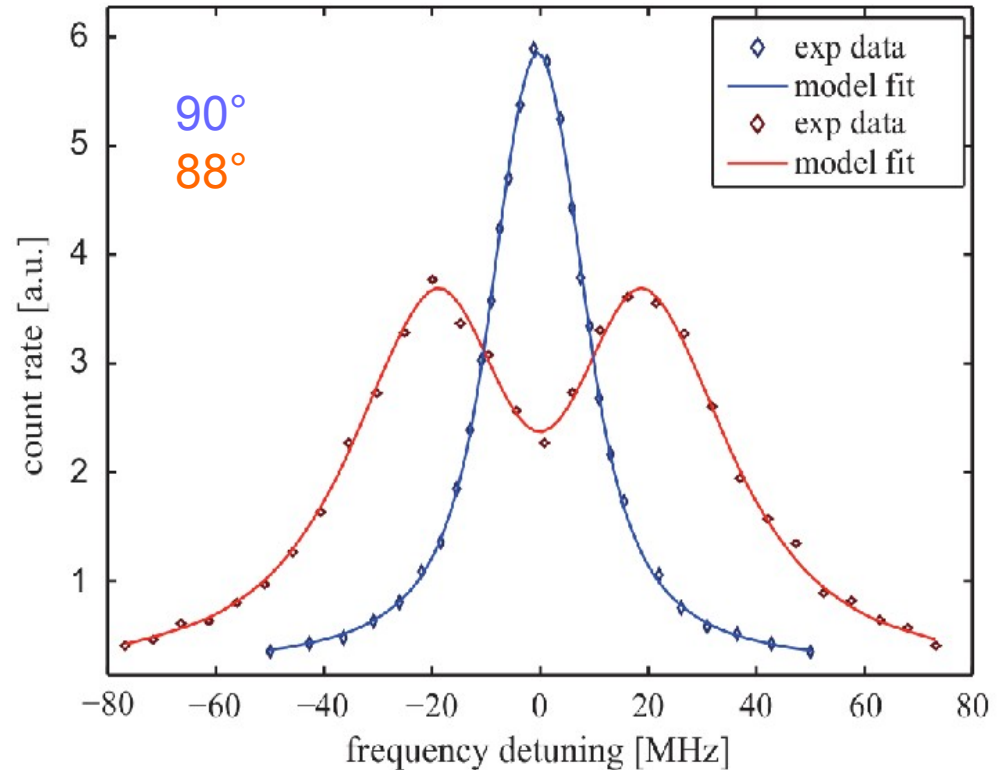


- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, $F=0$)
- 2S-nP transition is 1-photon
- → retroreflector (“AFR”)
- split line to 10^{-4}
- 0.5 kHz vs. 9 kHz PRP

Hydrogen 2S-nP in Garching



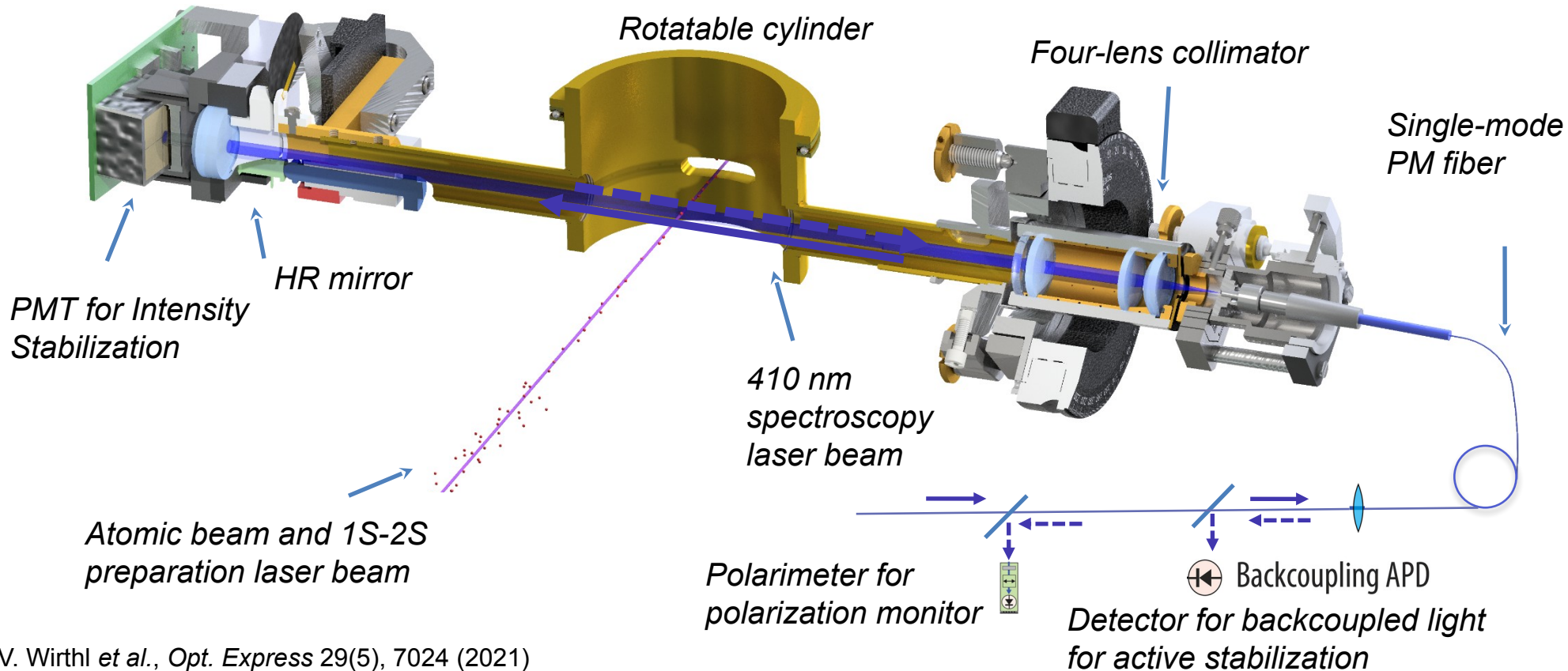
1st order Doppler cancellation (2S-4P)



Doppler shift suppression: Active Fiber-based Retroreflector



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

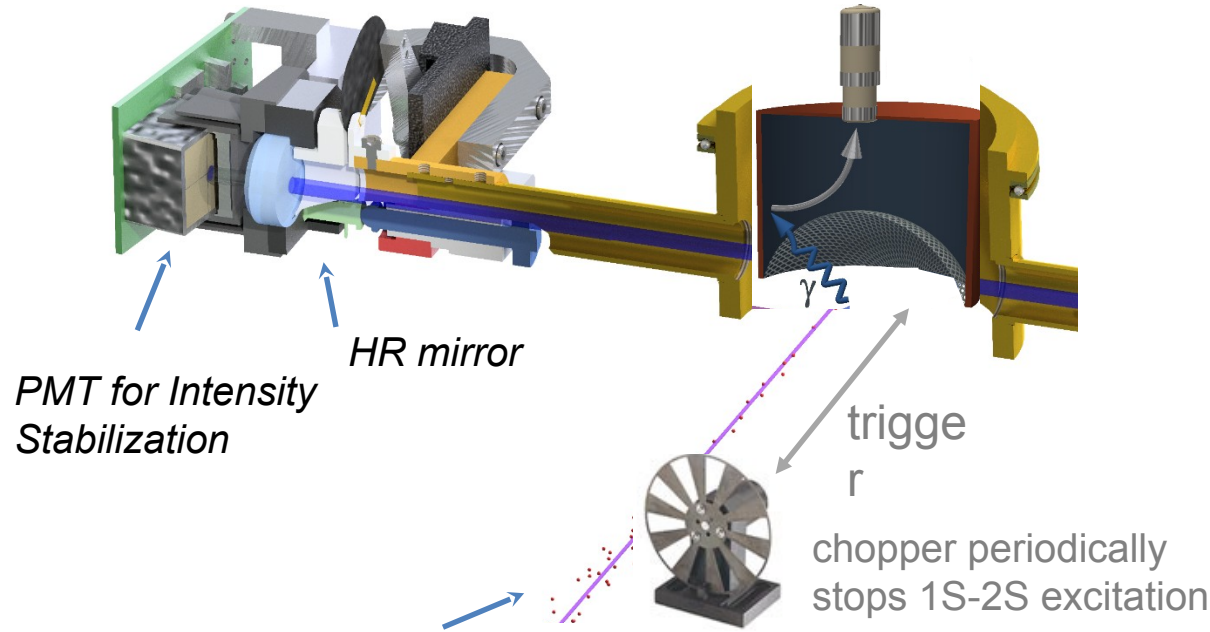


V. Wirthl et al., *Opt. Express* 29(5), 7024 (2021)

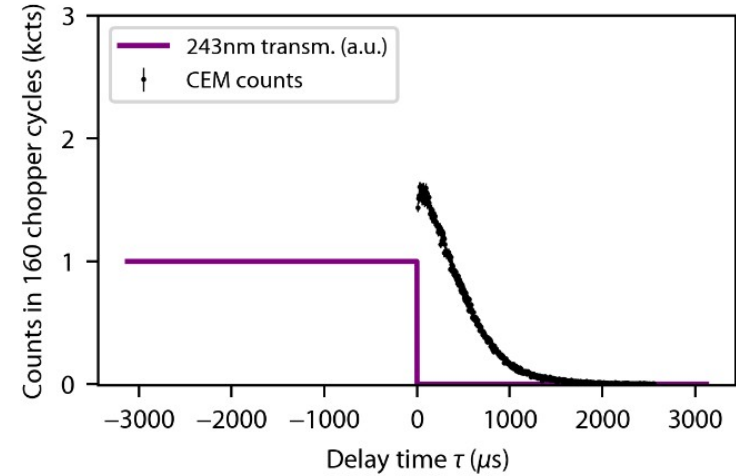
Time-resolved detection: velocity-dependent signal



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



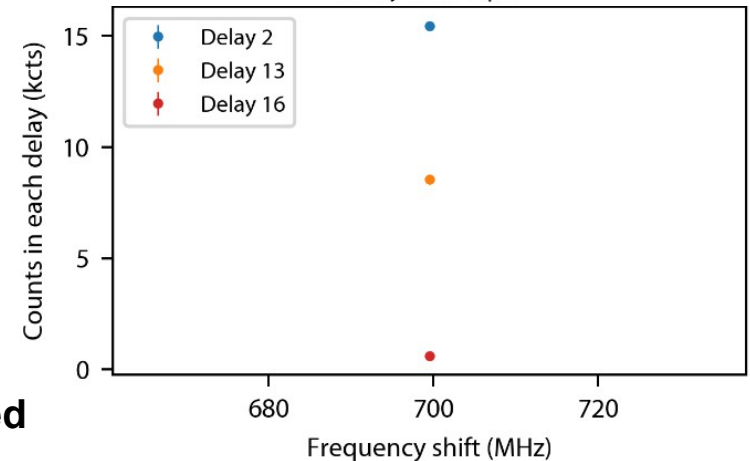
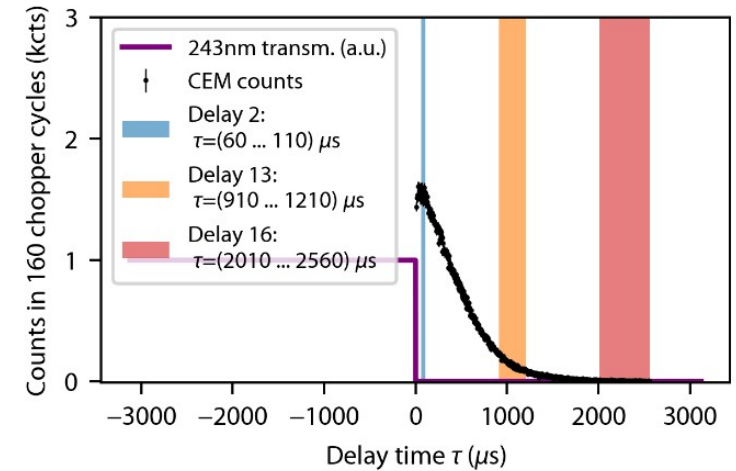
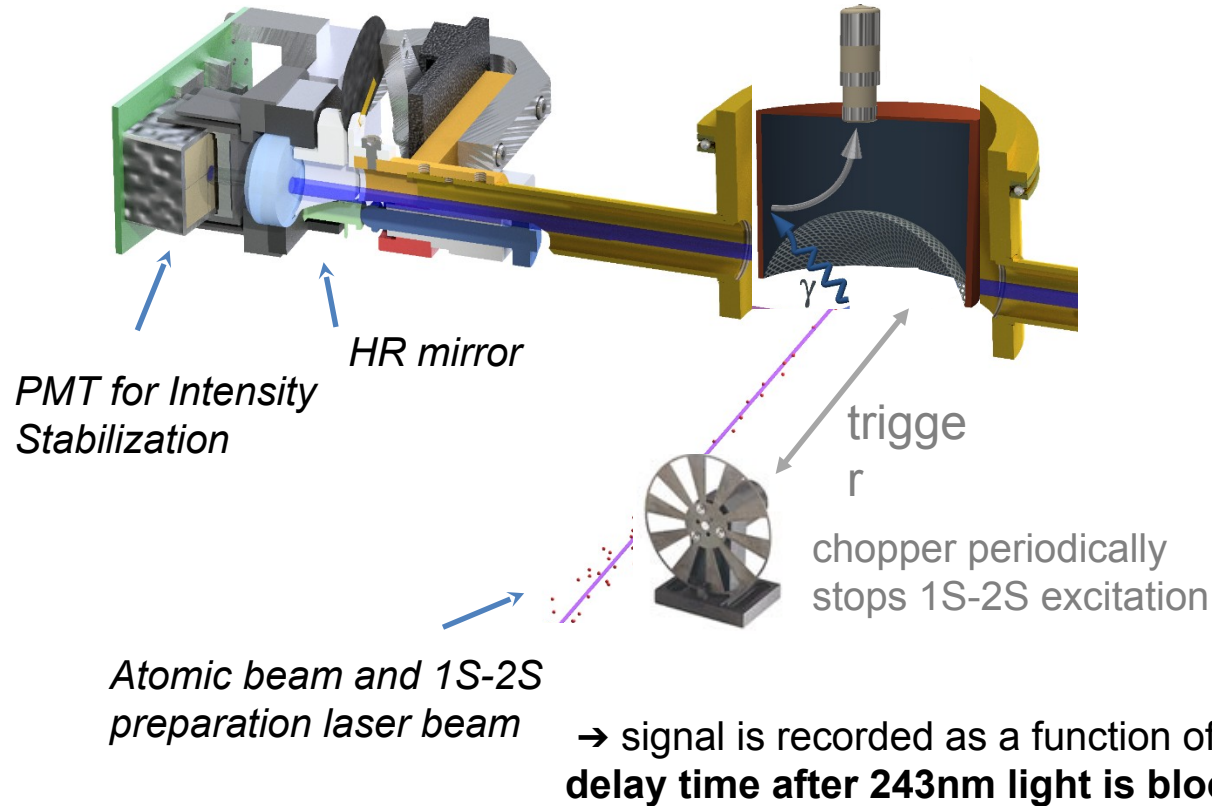
→ signal is recorded as a function of delay time after 243nm light is blocked



Time-resolved detection: velocity-dependent signal



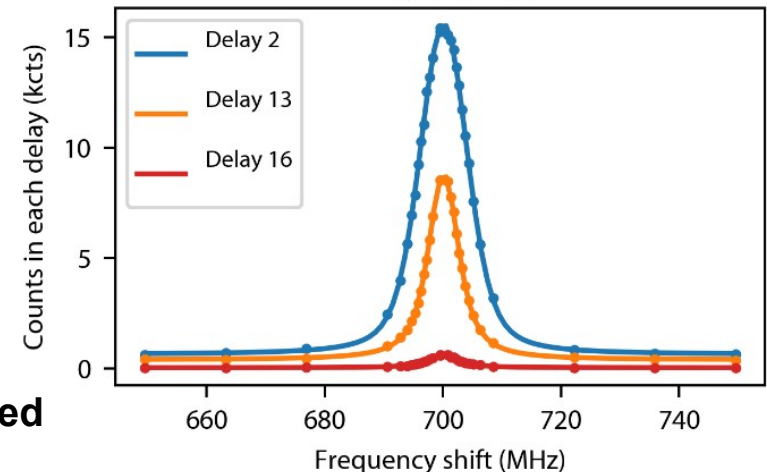
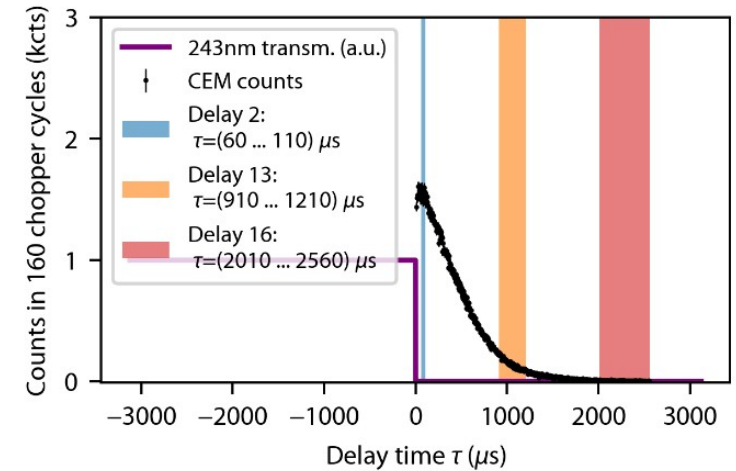
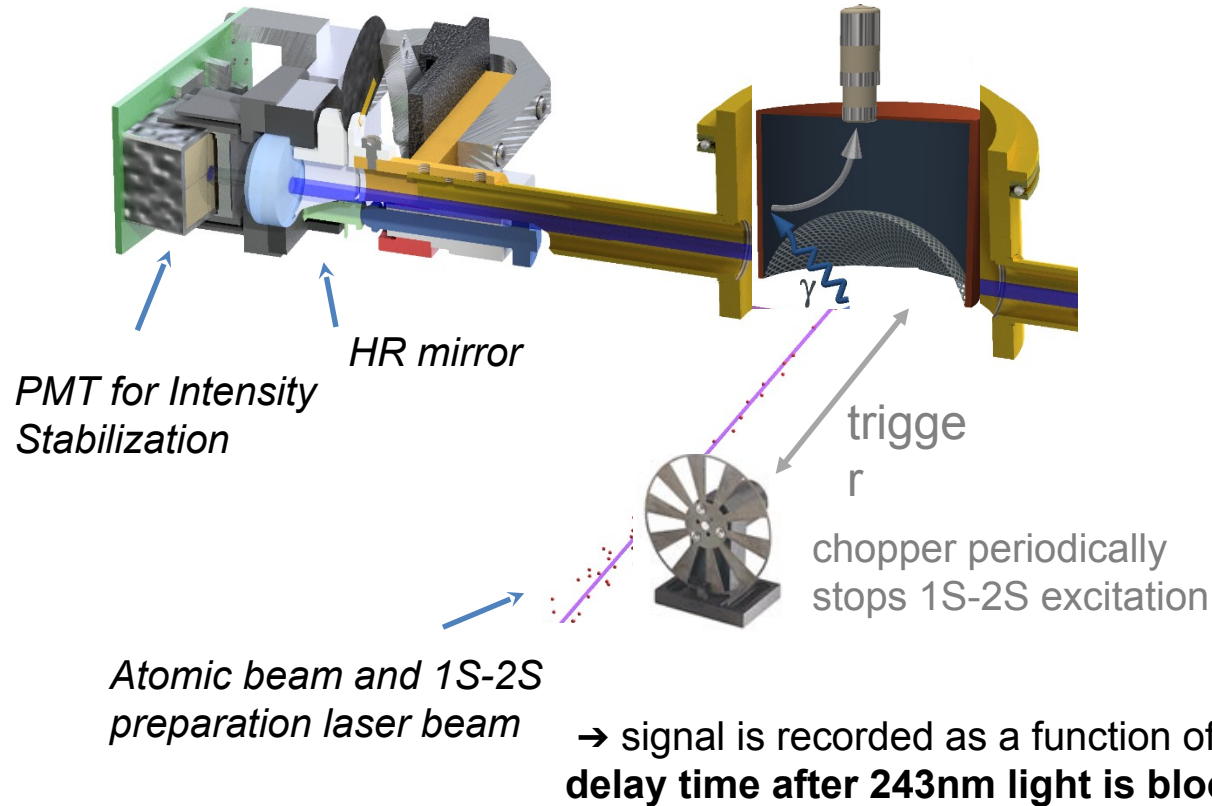
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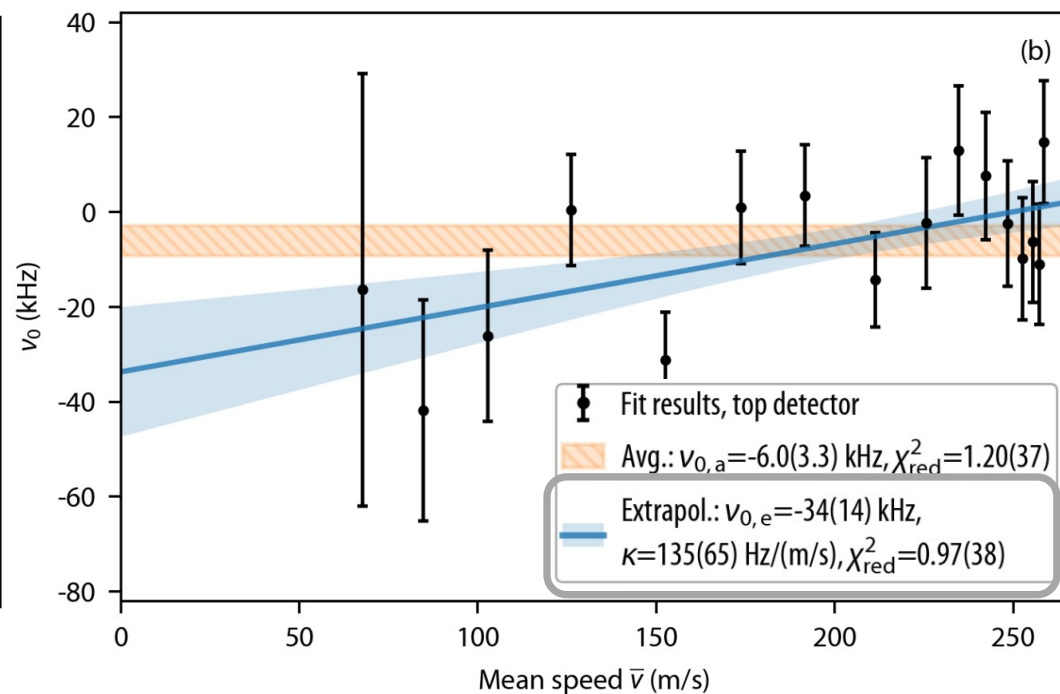
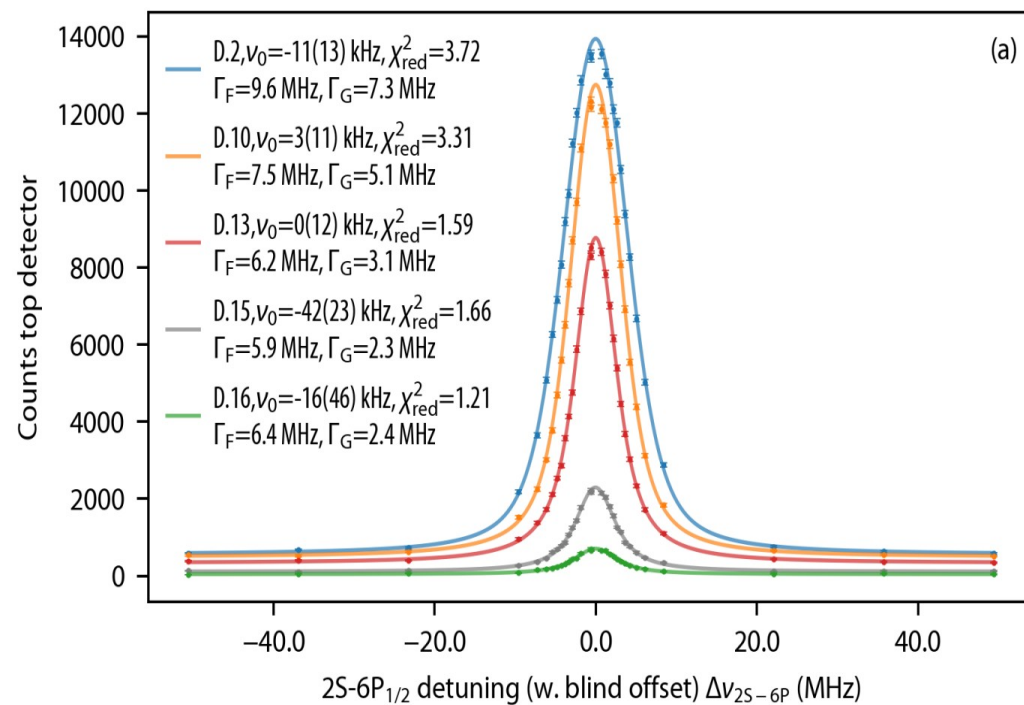
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Time-resolved detection: velocity-dependent signal



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

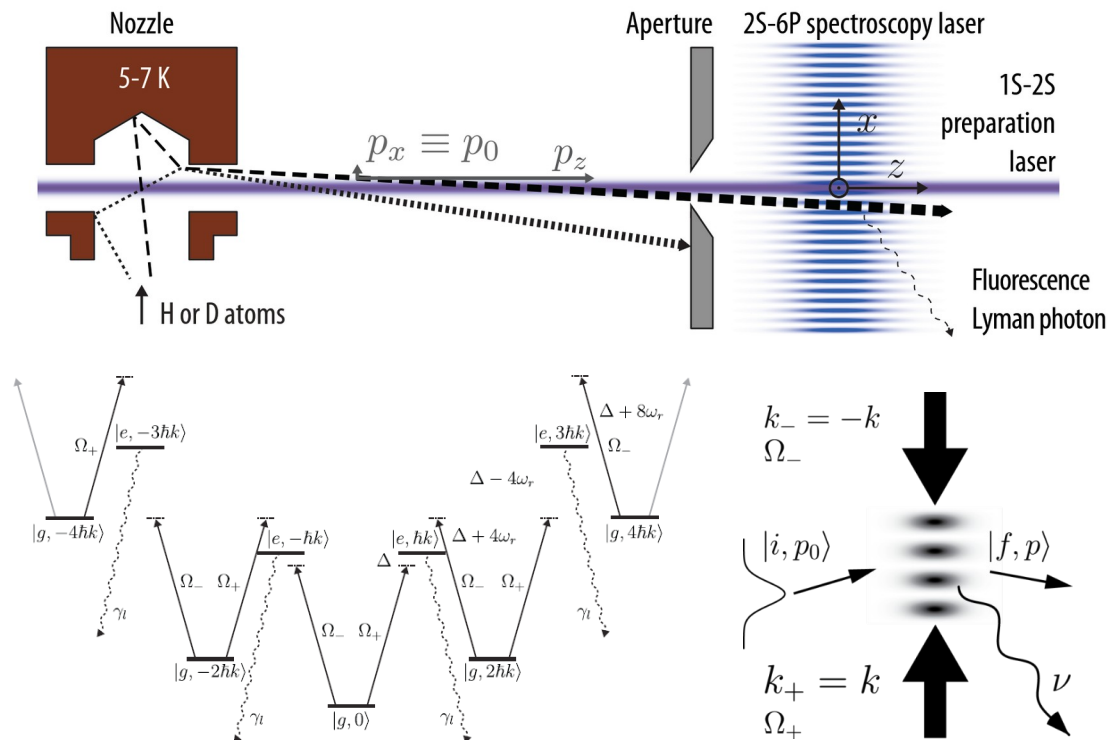


L. Maisenbacher, V. Wirthl, RP et al, *Nature* 650 (2026)

Contribution	$\Delta\nu$ (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 $\Delta\nu_{\text{HFS}}(\nu_{2\text{S-6P}})$	-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



Corrections and uncertainties for hydrogen 2S-6P measurement

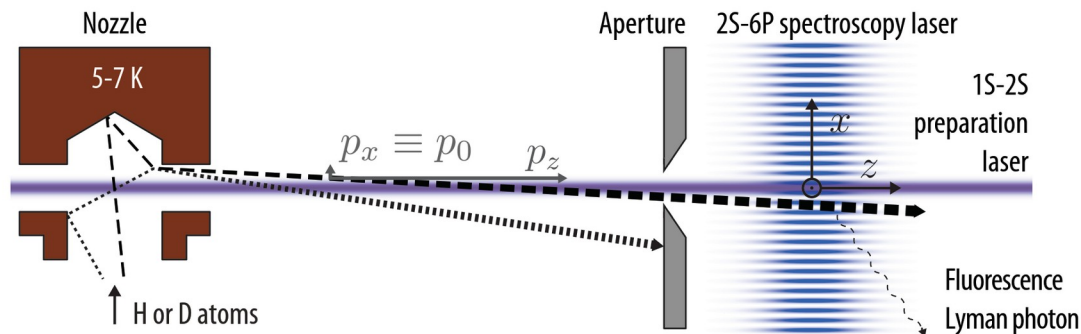


L. Maisenbacher, V. Wirthl, RP et al, *Nature* 650 (2026)

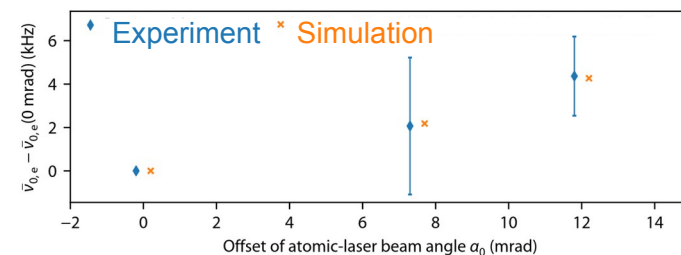
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Light Force Shift measured by rotating atomic beam



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

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



Corrections and uncertainties for hydrogen 2S-6P measurement



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

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

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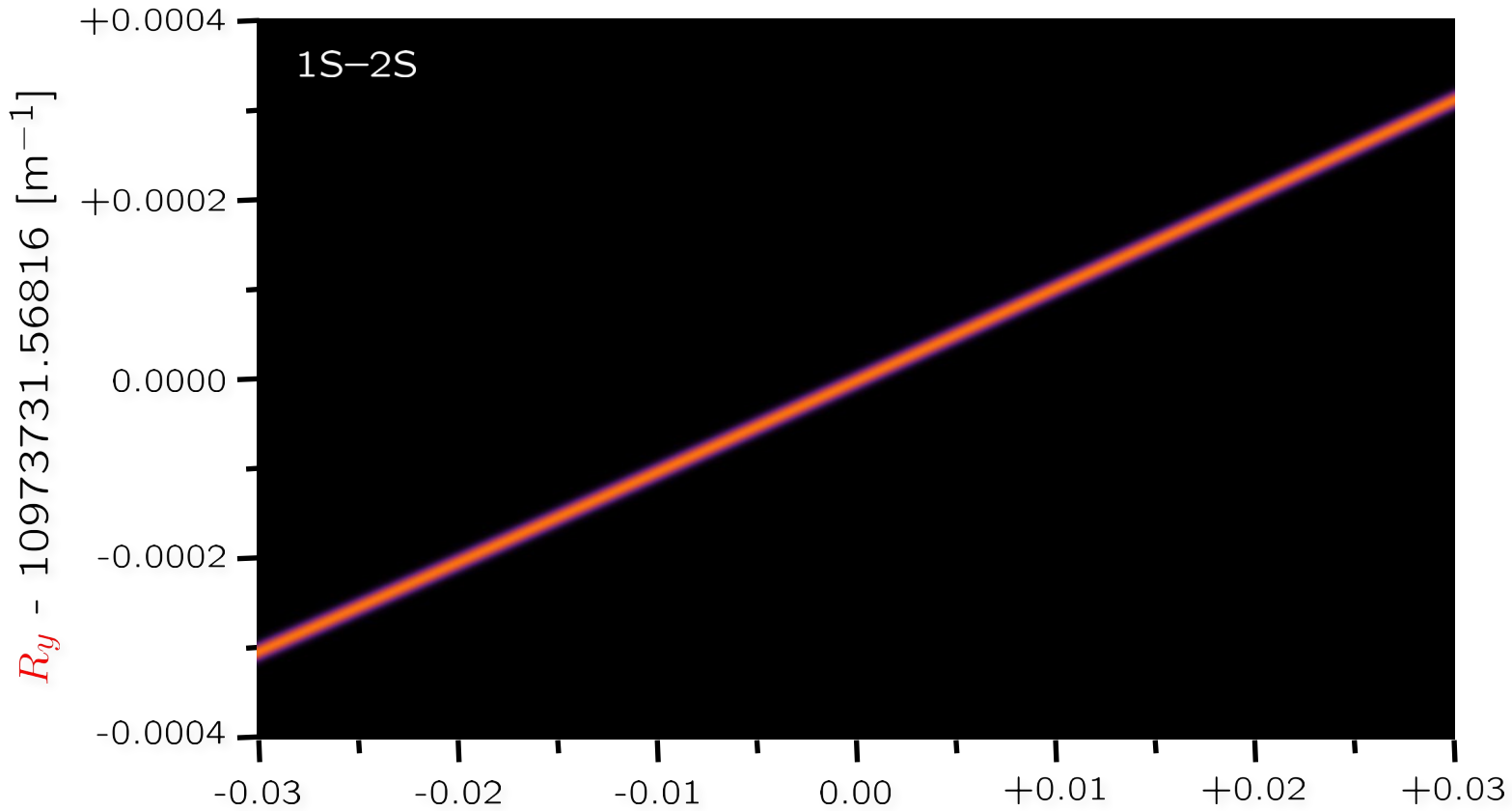
Largest individual uncertainty: Statistical uncertainty of Doppler-free (extrapolated) transition frequency

Largest systematic correction: Light force shift

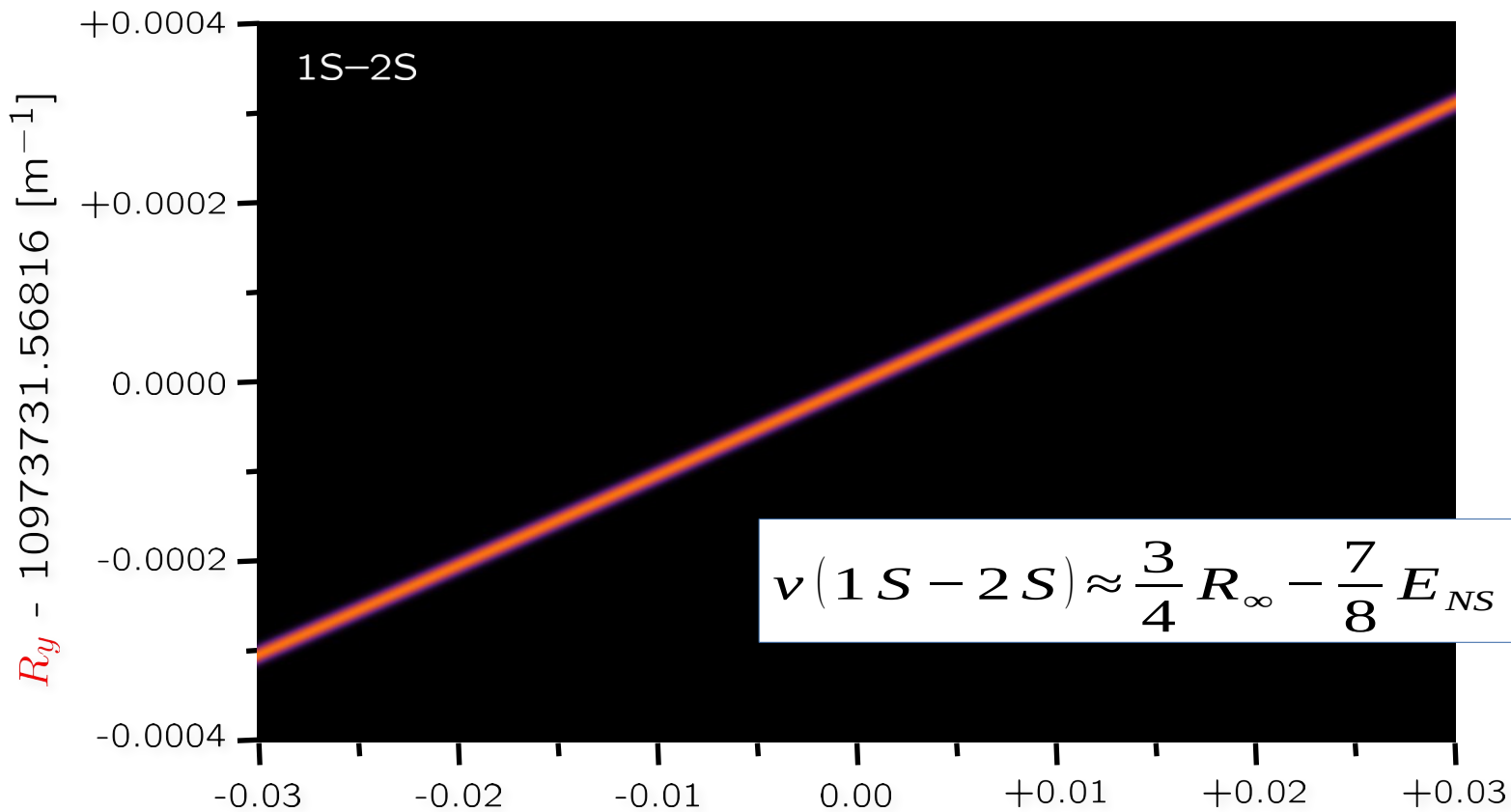
All corrections other than LFS individually contribute less than 100 Hz to uncertainty

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

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



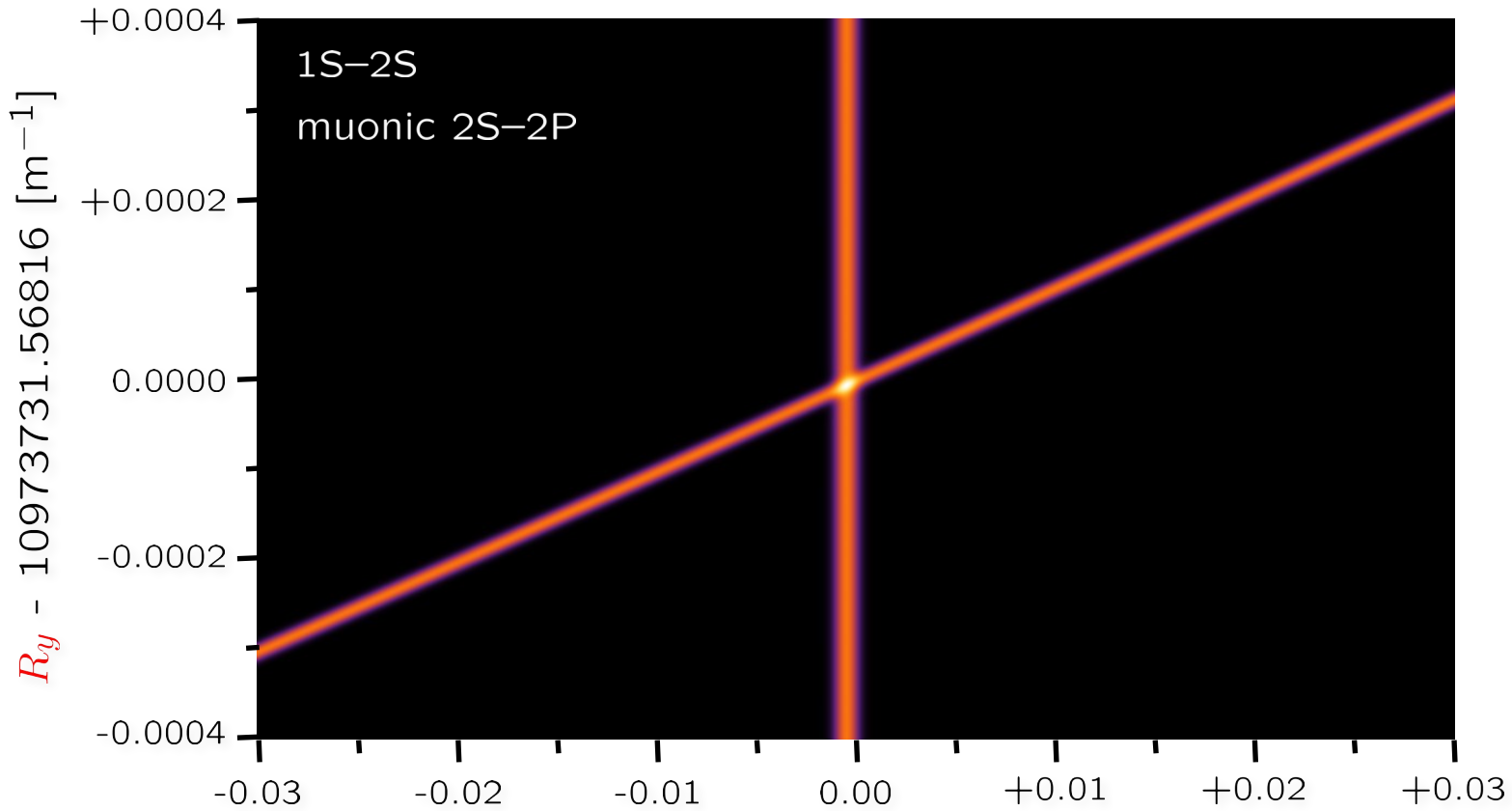
$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2 \text{ MHz}}{n^3} \langle r^2 \rangle \delta_{l0} + \Delta(n, l, j)$$



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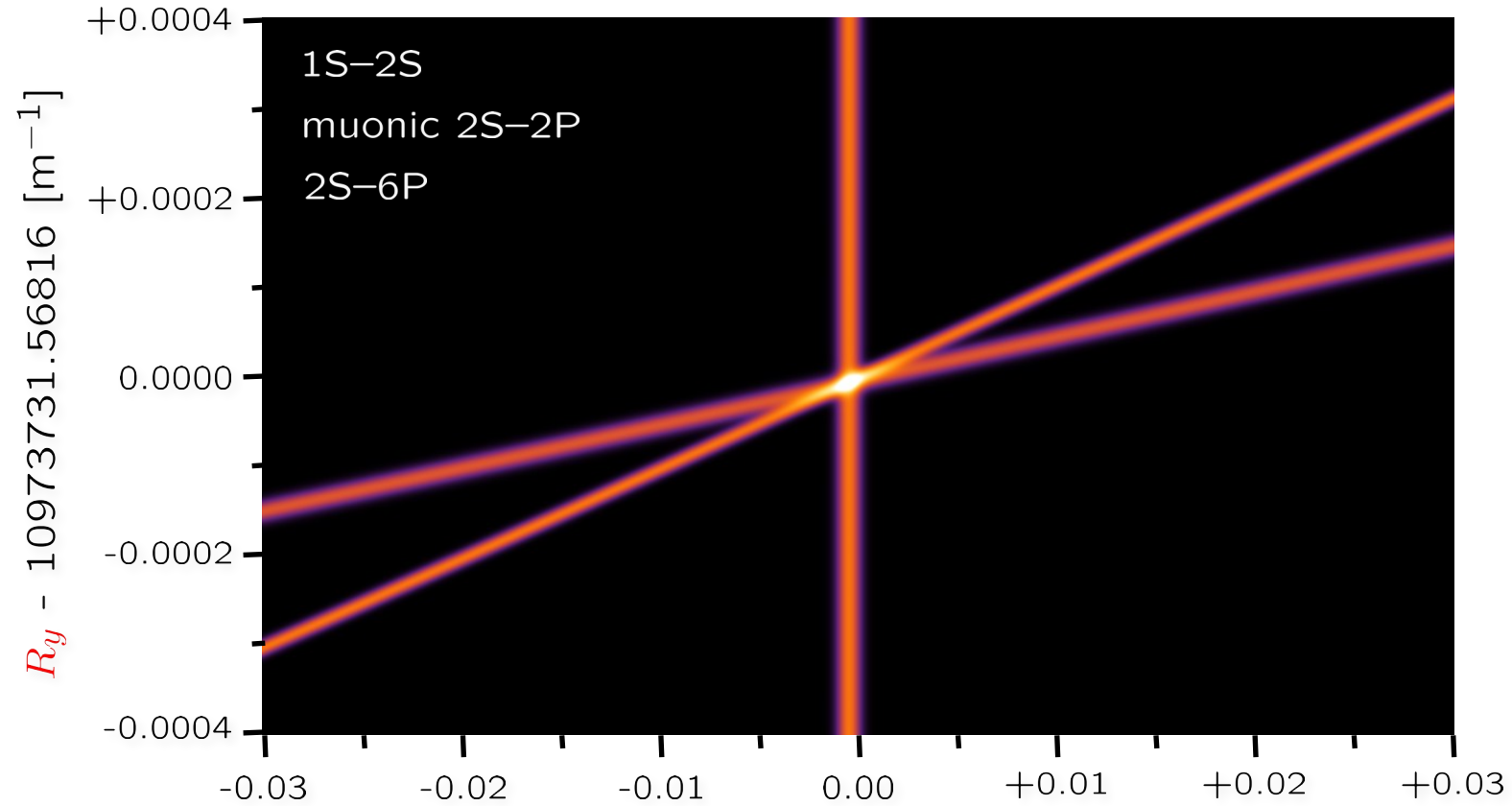
$r_p - 0.8414 \text{ [fm]}$

QED Test



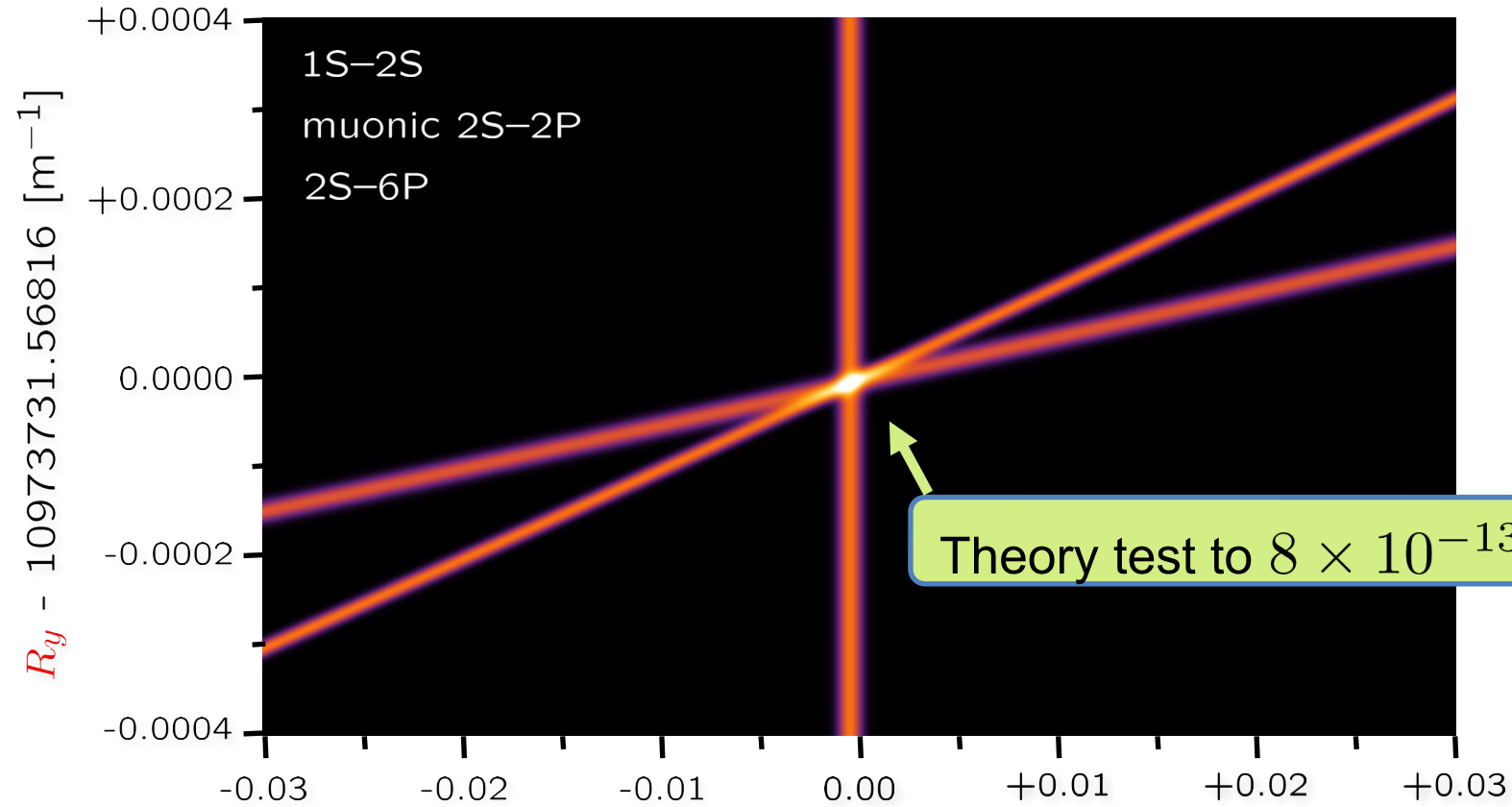
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QED Test



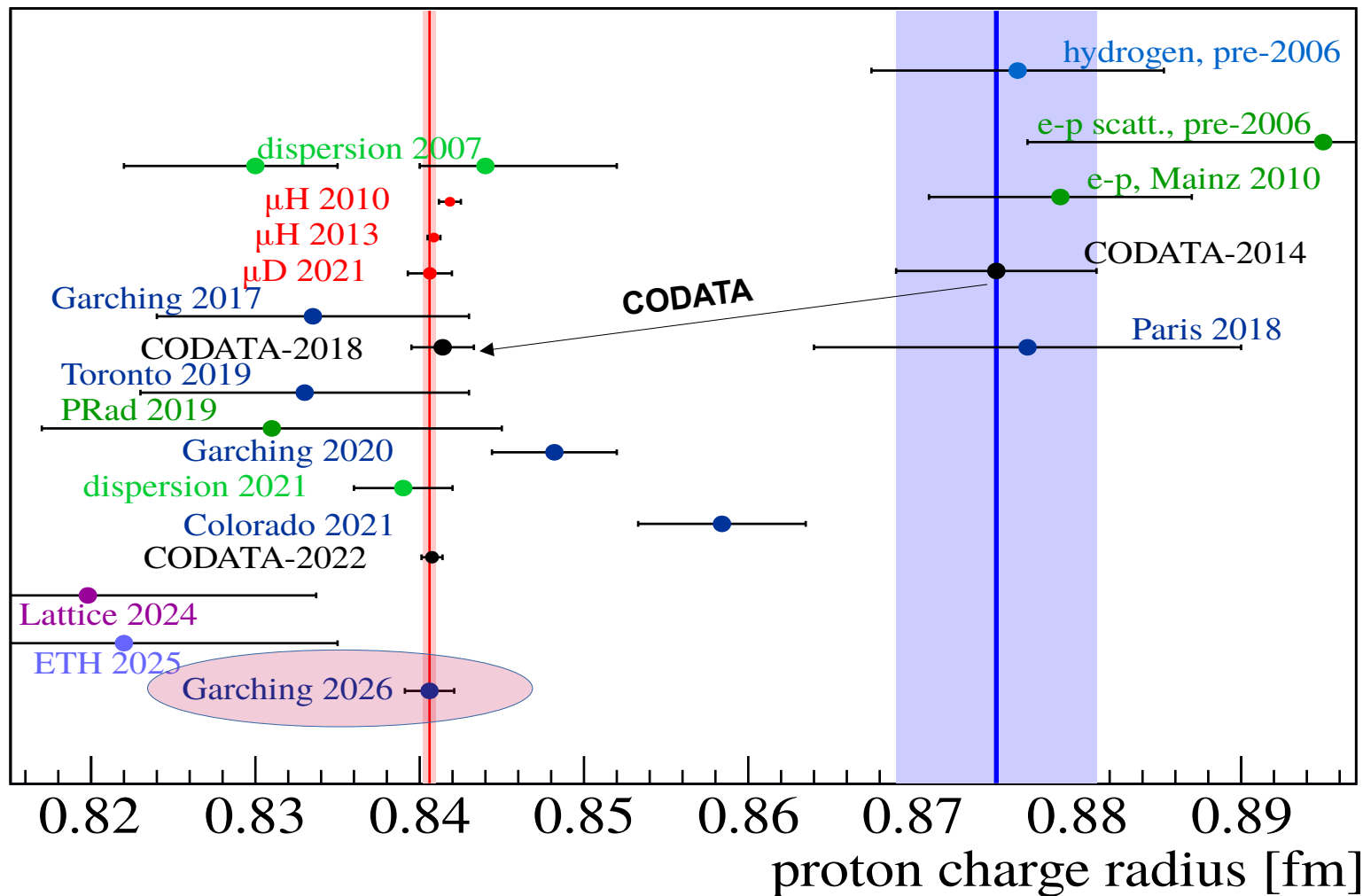
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QED Test



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

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 $8 \leq n \leq 16$. For each transition, we obtain quality factors $\geq 4 \times 10^9$, 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 $n \geq 13$ 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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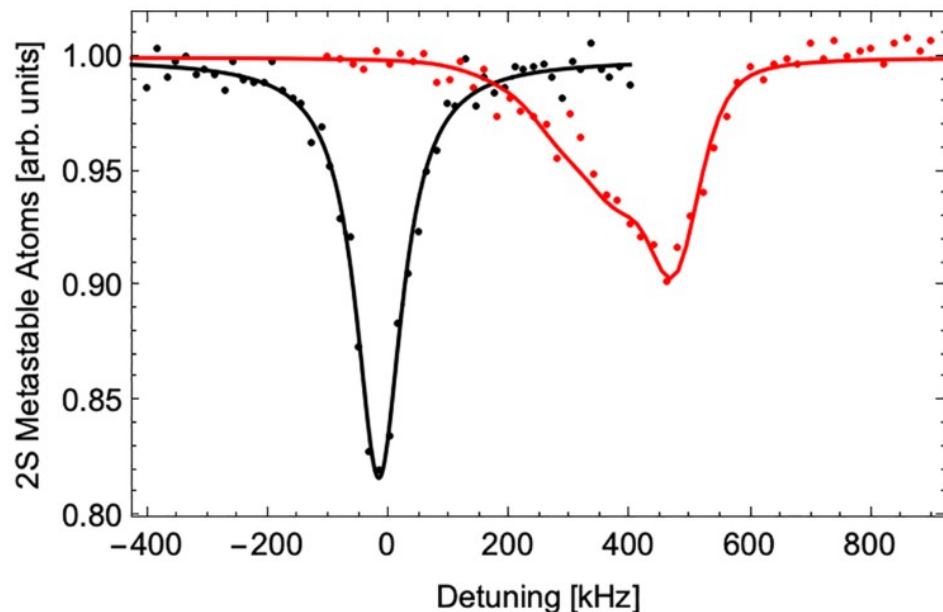


FIG. 2. Experimentally recovered lineshapes for the $2S_{1/2}$ - $12S_{1/2}$ transition with ac Stark shift mitigation (black) and without (red).

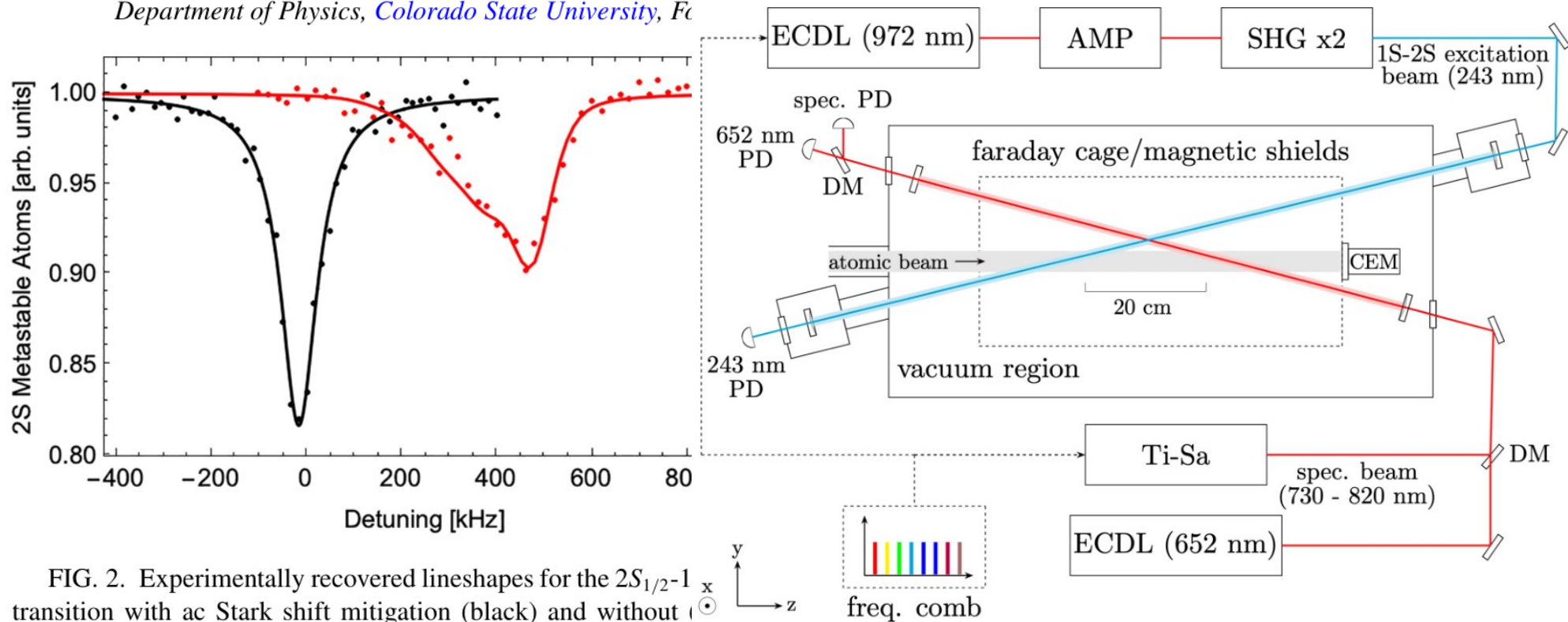
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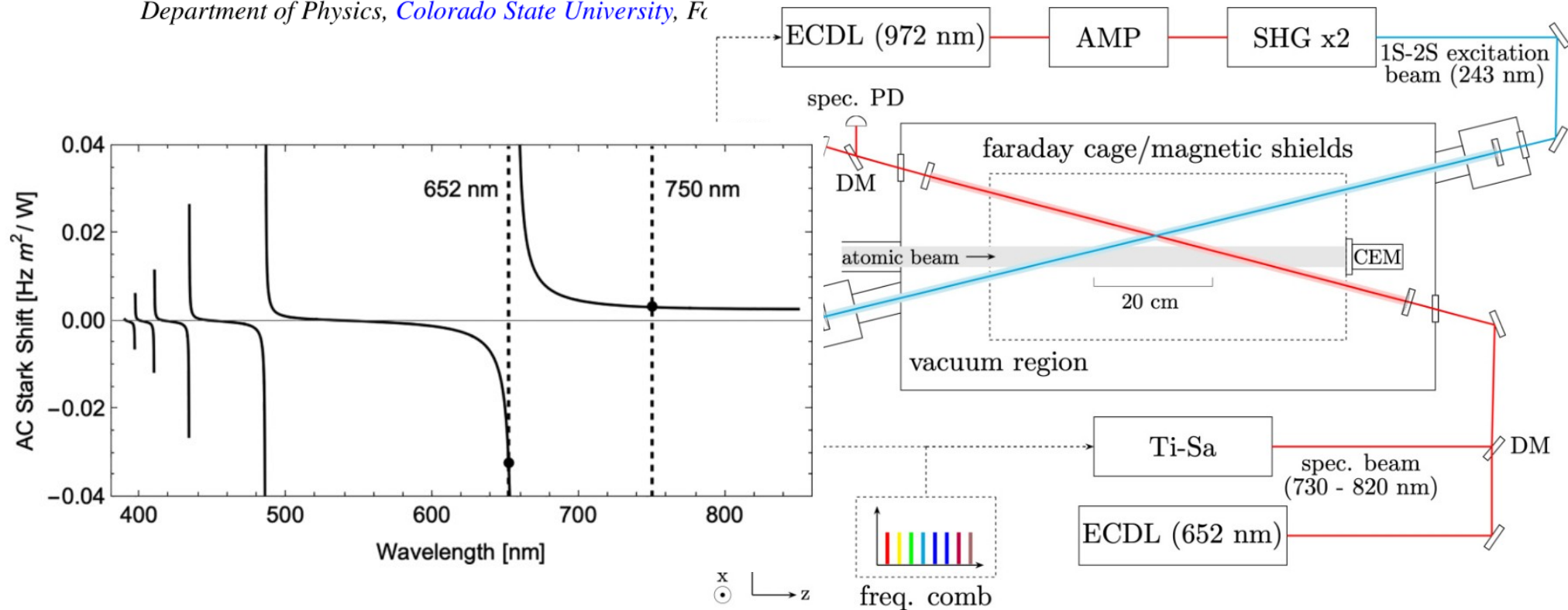
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PHYSICAL REVIEW LETTERS **136**, 123001 (2026)

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.

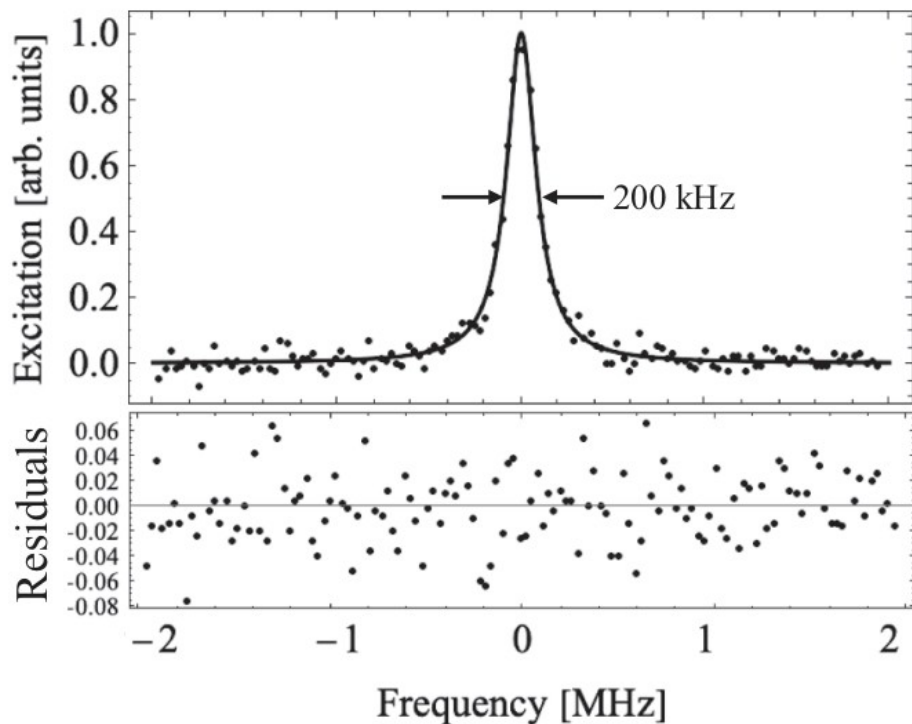
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,¹ A. J. Cheeseman ,¹

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gy, Rolla, Missouri 65409, USA

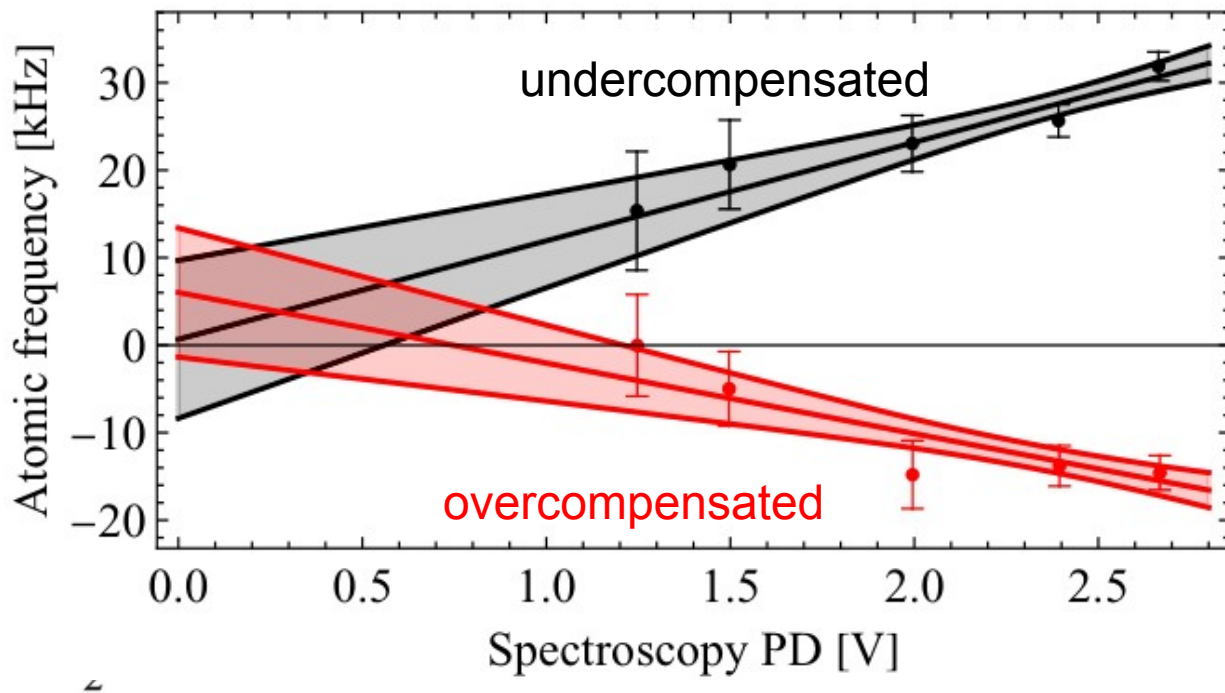
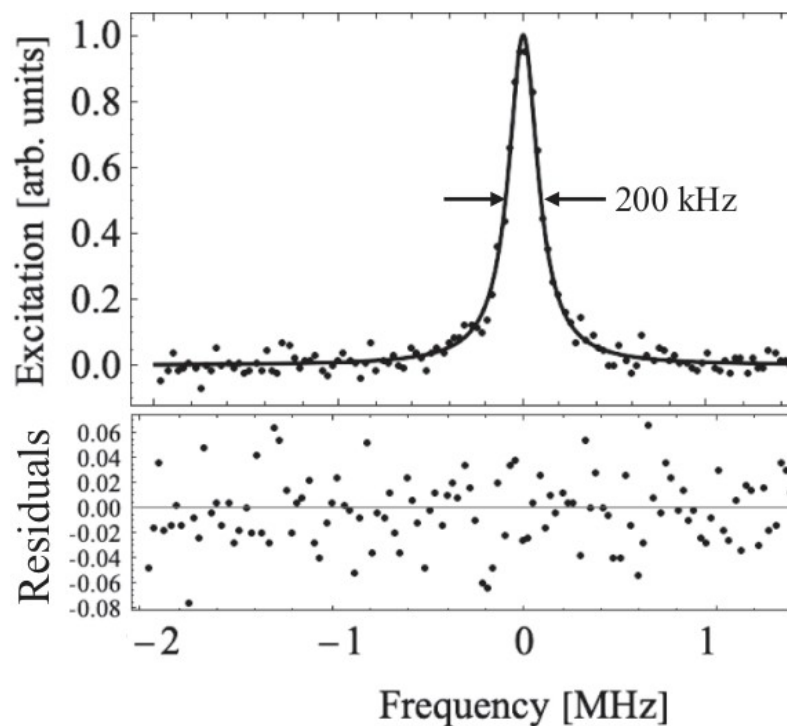
Solving the “Proton Radius Puzzle”

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

Editors' Suggestion

But what about the
old H data?

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



Solving the “Proton Radius Puzzle”

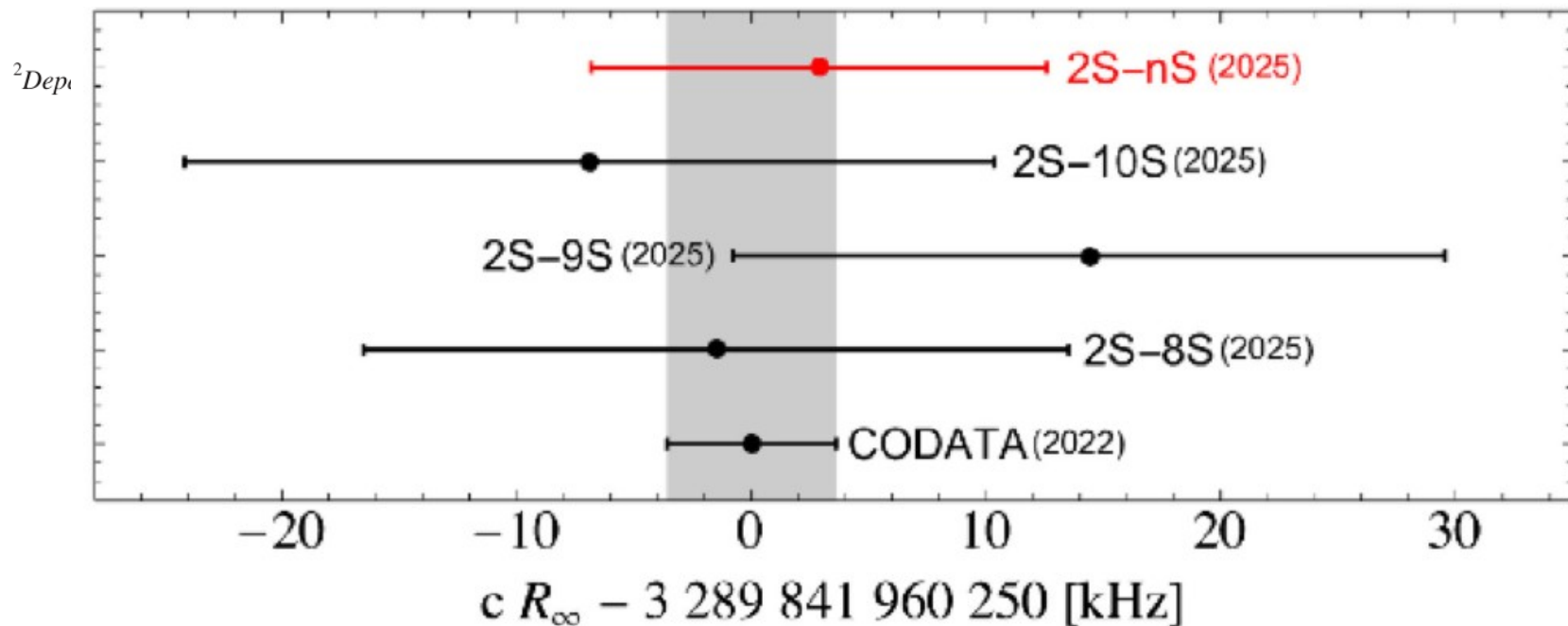
PHYSICAL REVIEW LETTERS **136**, 123001 (2026)

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

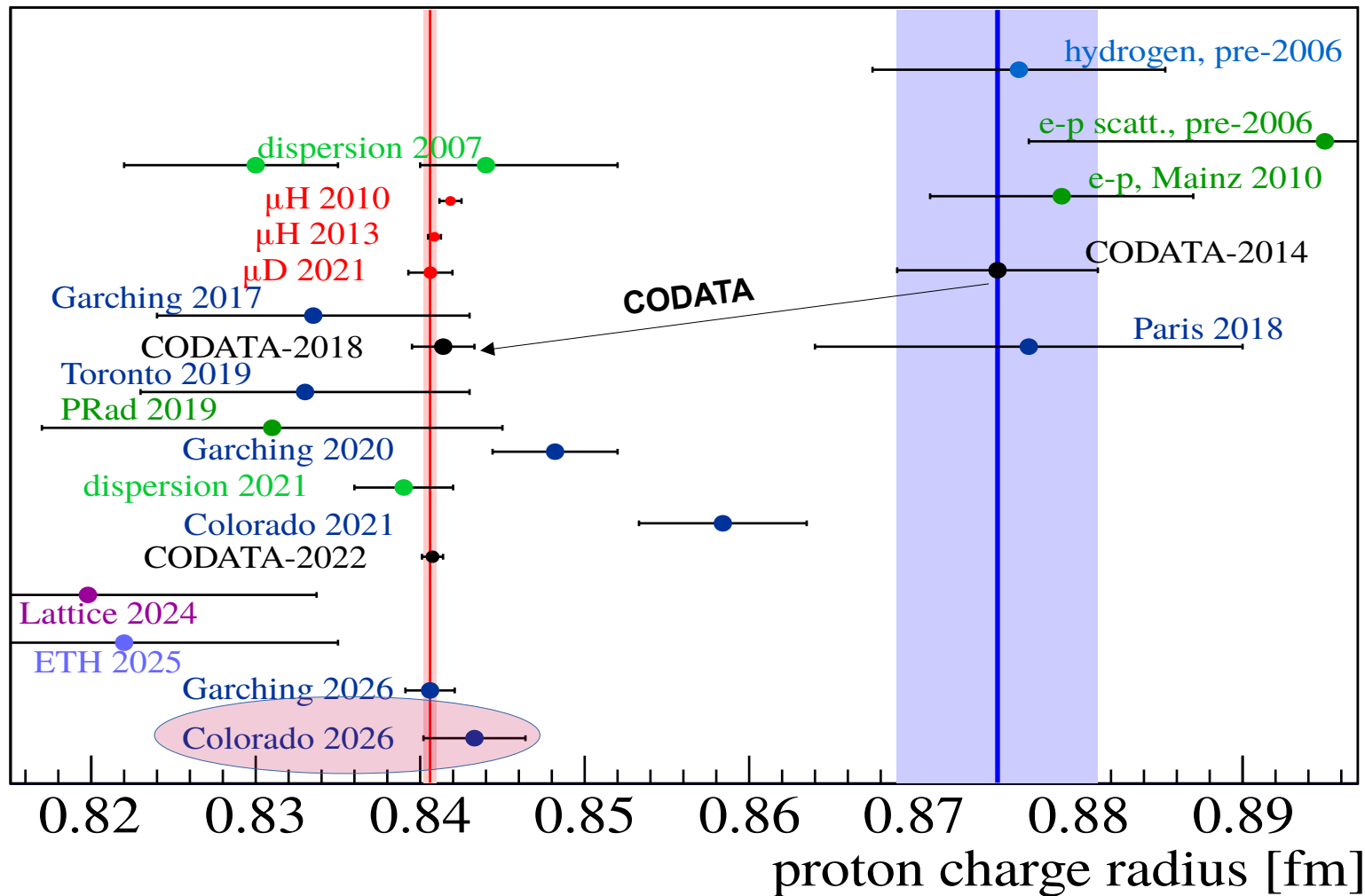
R. G. Bullis¹, W. L. Tavis¹, M. R. Weiss¹, J. Orellana Cisneros¹, A. J. Cheeseman¹,
U. D. Jentschura², and D. C. Yost¹

¹Department of Physics, *Colorado State University*, Fort Collins, Colorado 80523, USA

²Department of Physics and LAMOR, *Missouri University of Science and Technology*, Rolla, Missouri 65409, USA



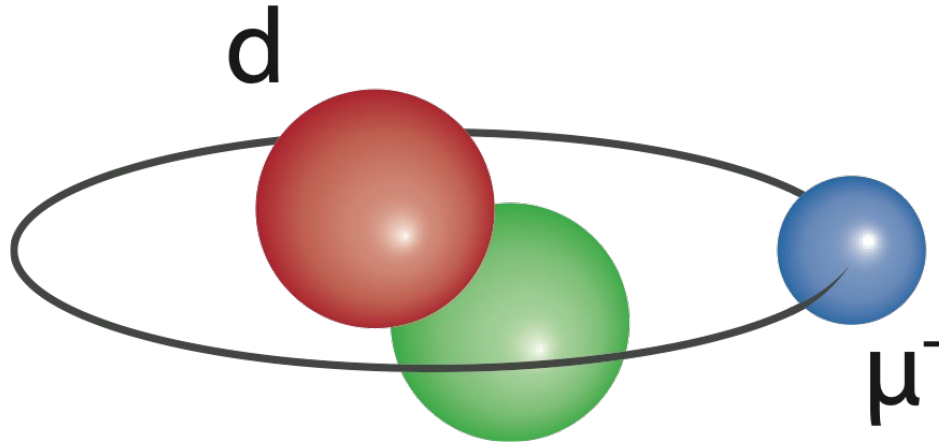
Solving the “Proton Radius Puzzle”



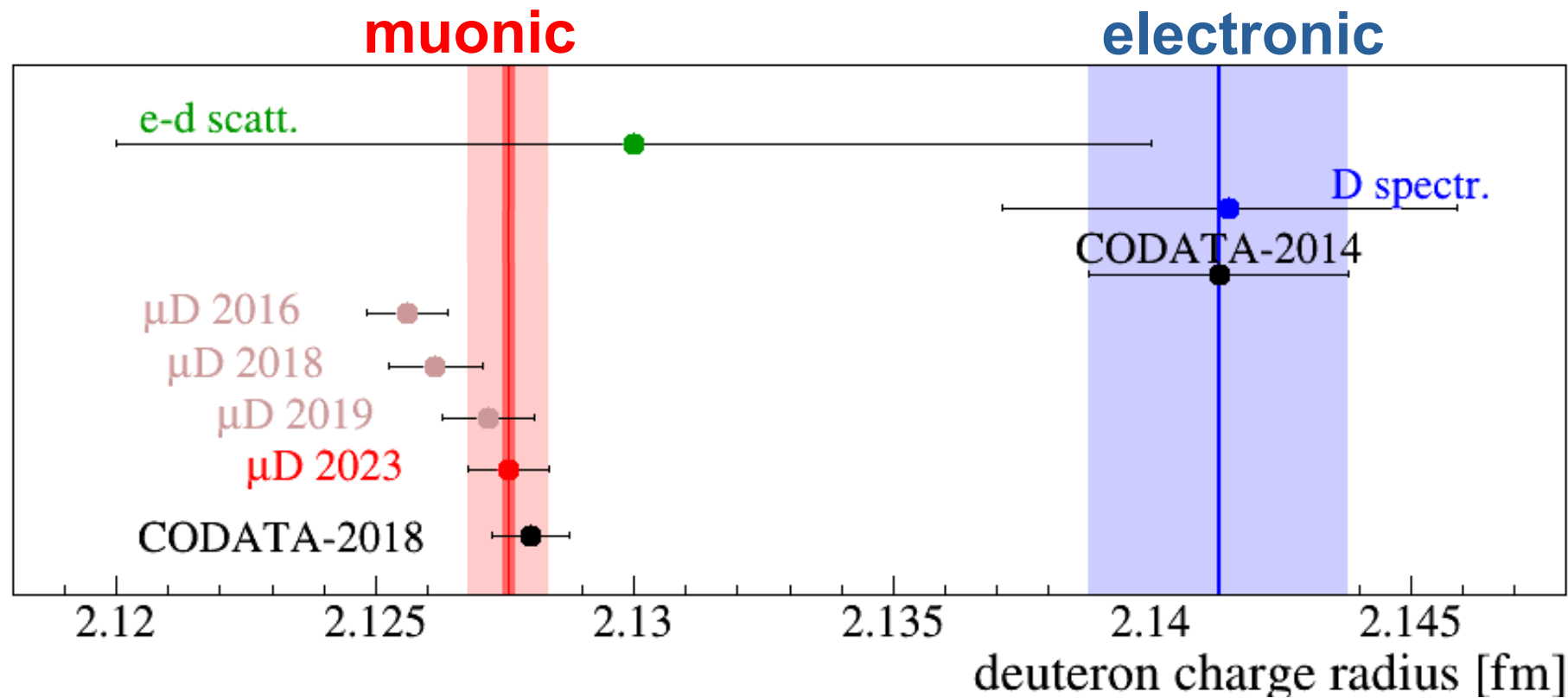
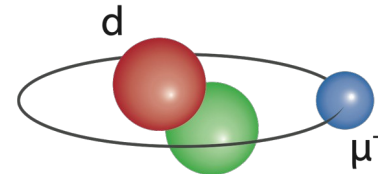
But what about the
old H data?

H (2S - 6P)
H (2S - 8/9/10S)

Muonic Deuterium

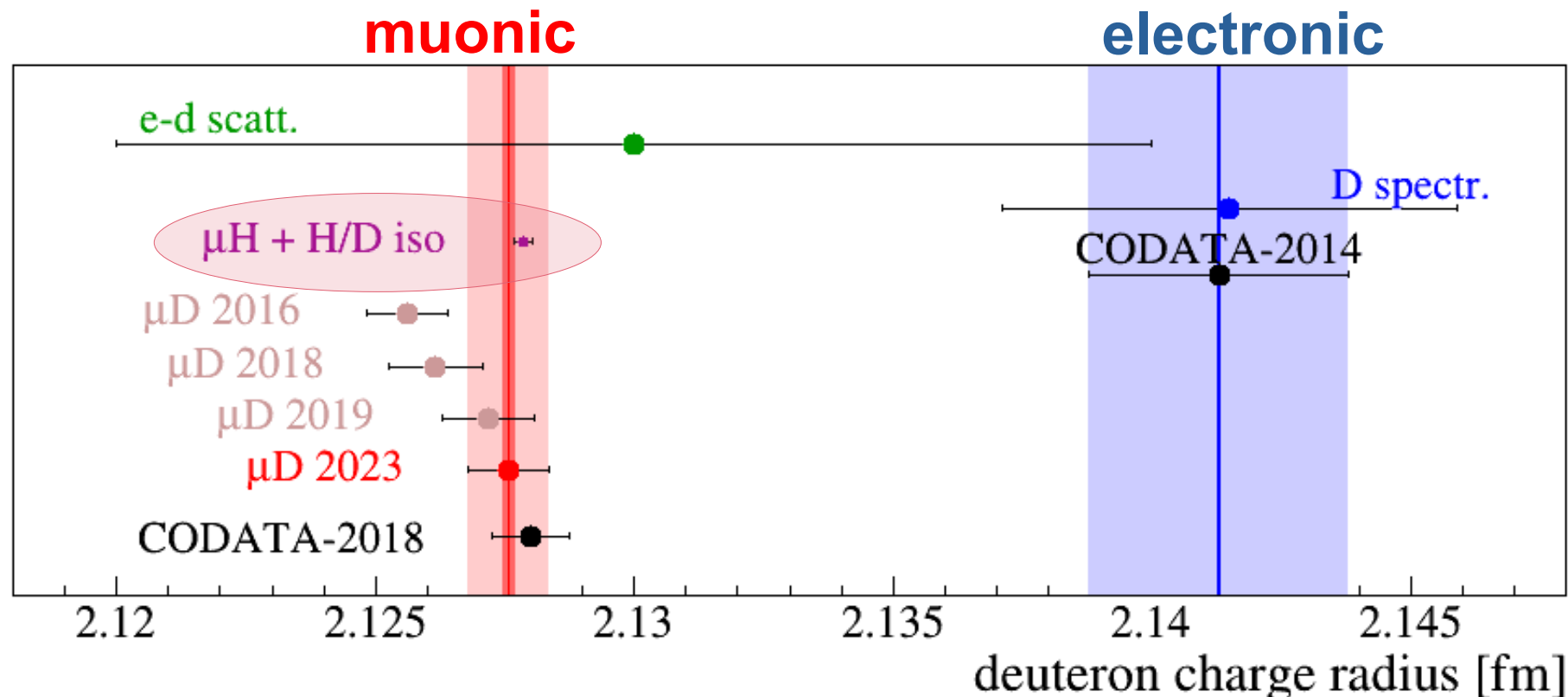
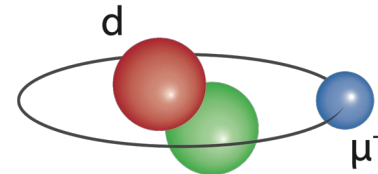


Muonic Deuterium



μ D: 2.12758 (13)_{exp} (78)_{theo} fm

Muonic Deuterium

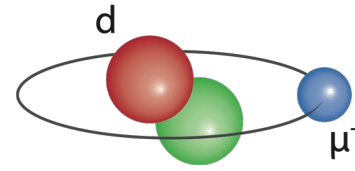


μD : $2.12758 \quad (13)_{\text{exp}} \quad (78)_{\text{theo}} \text{ fm}$

$\mu\text{H} + \text{H/D}(1\text{S}-2\text{S})$: $2.12785 \quad (17) \text{ fm}$

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

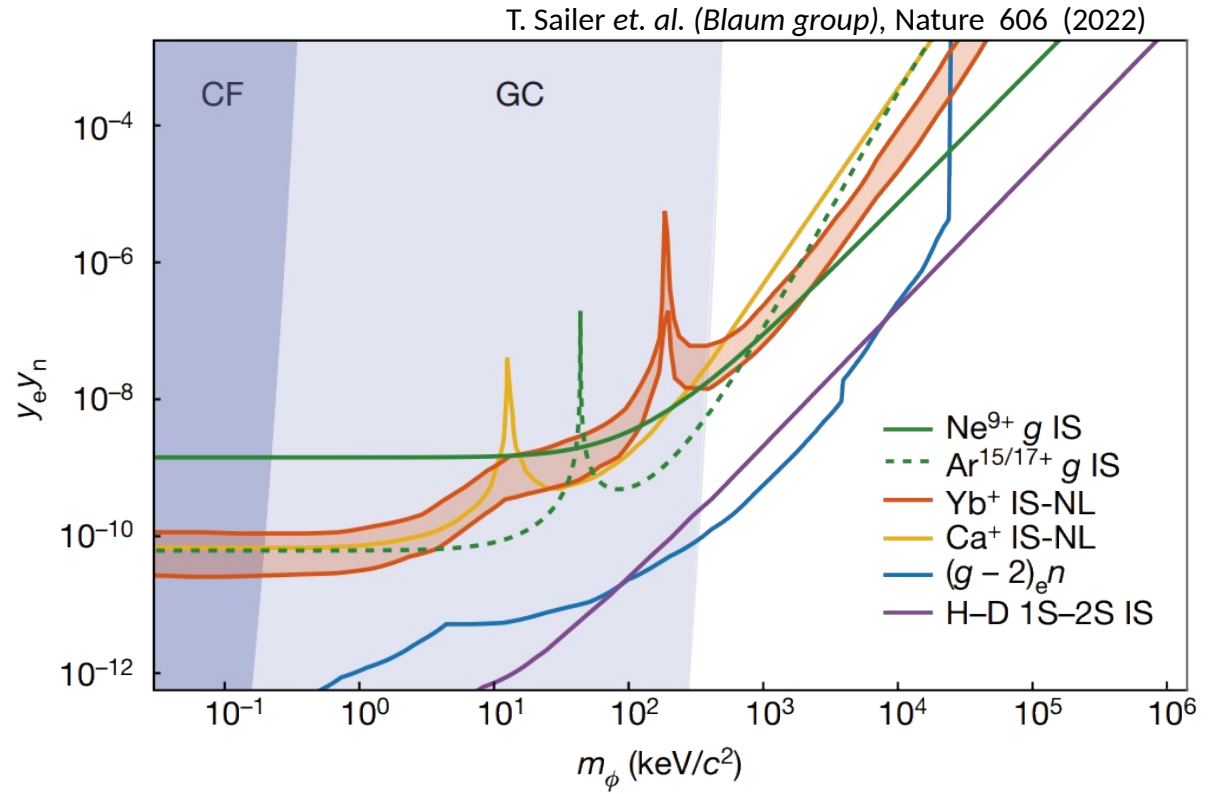
H/D isotope shift



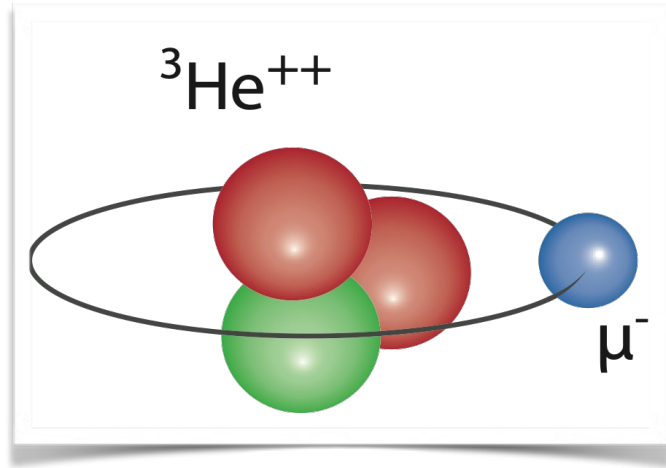
electronic H/D (1S-2S): $r_d^2 - r_p^2 = 3.8207(3)_{\text{theo}} \text{ fm}^2$

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

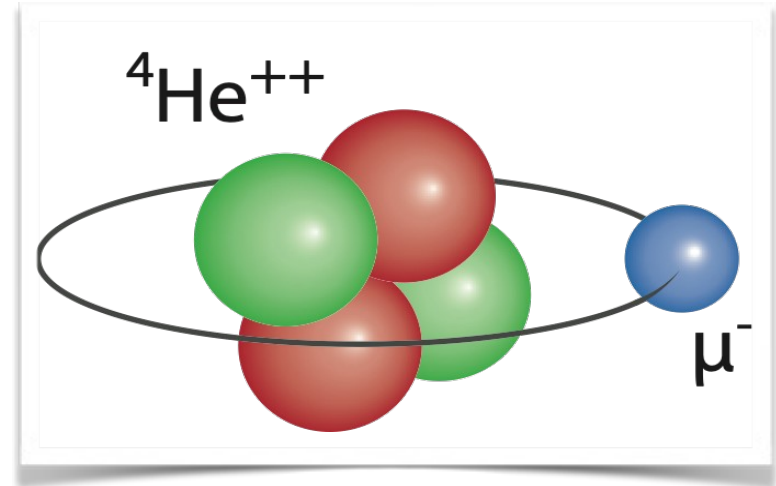
→ Best bound on 5th force



Muonic Helium

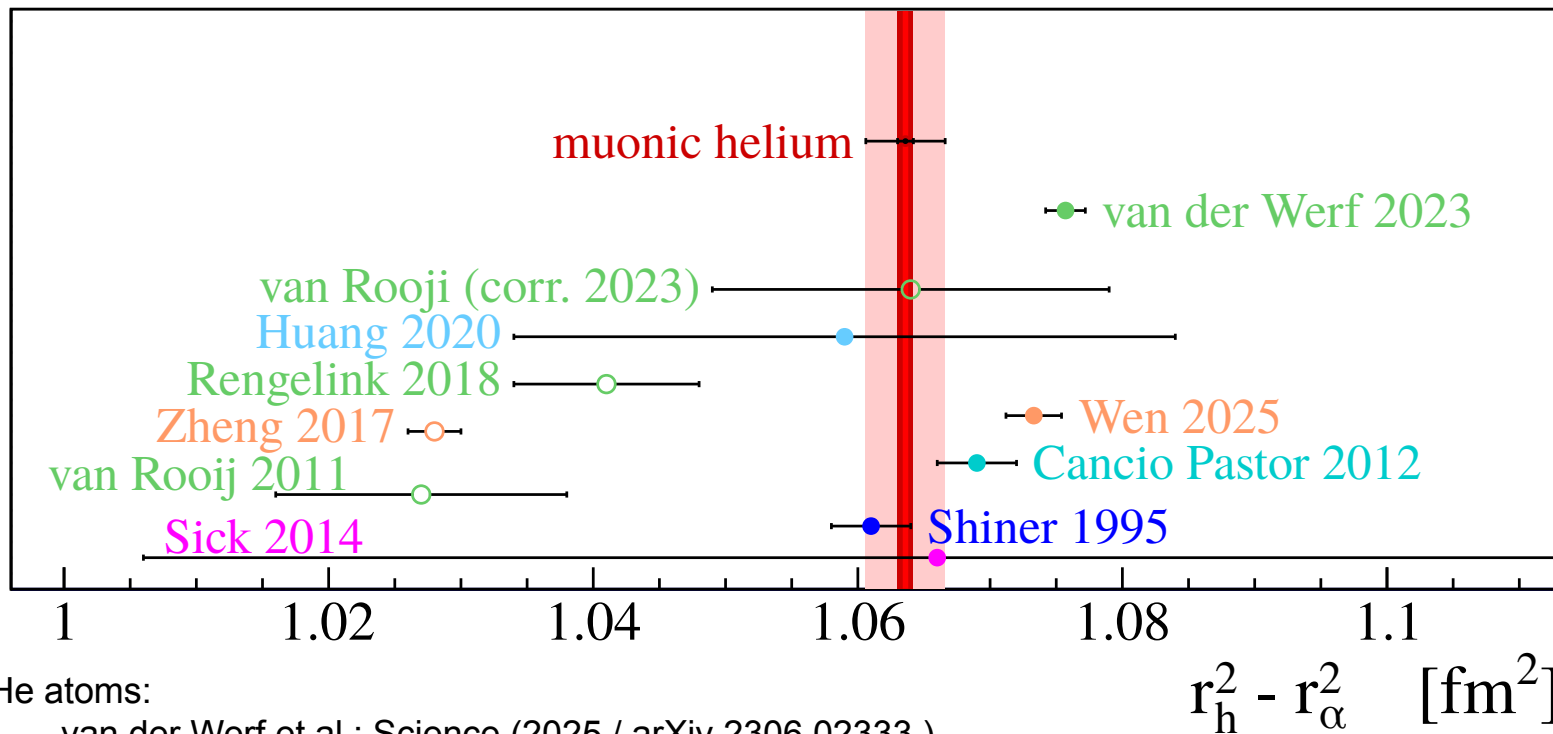


Schuhmann et al. (CREMA),
Science 388, 854 (2025) ; arXiv 2305.11679



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

Helium-3 – Helium-4 Isotope Shift



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

muonic helium

● Qi + v.d. Werf 2024
○ van der Werf 2023

~~3.6σ !~~

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*

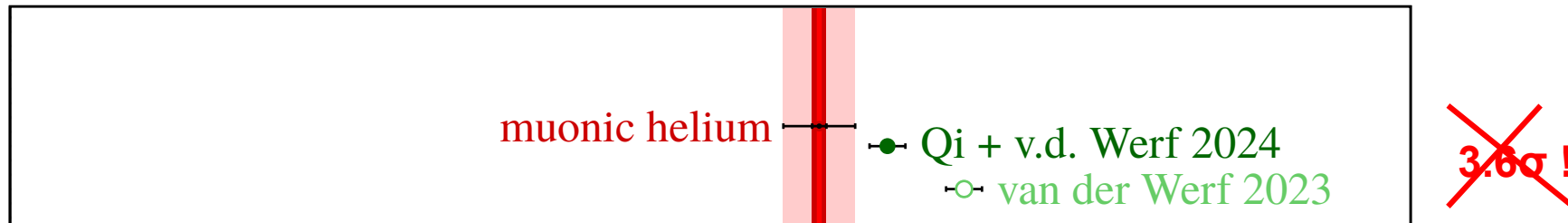
³*Department of Physics, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3*

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

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,†}

The discrepancy in the squared nuclear charge radius difference, ΔR^2 , between ^3He and ^4He , 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 ^3He 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 $1.0757(15) \text{ fm}^2$ to $1.0693(15) \text{ fm}^2$, as initially reported by Werf *et al.* [[arXiv:2306.02333](#)]. This brings ΔR^2 closer to the value of $1.0636(31) \text{ fm}^2$ 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 $1.069(3) \text{ fm}^2$ 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

muonic helium



- Pachucki v.d. Werf 2025
- Qi + v.d. Werf 2024
- van der Werf 2023

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

Krzysztof Pachucki,¹ Vojtěch Patkóš,² and Vladimir A. Yerokhin³

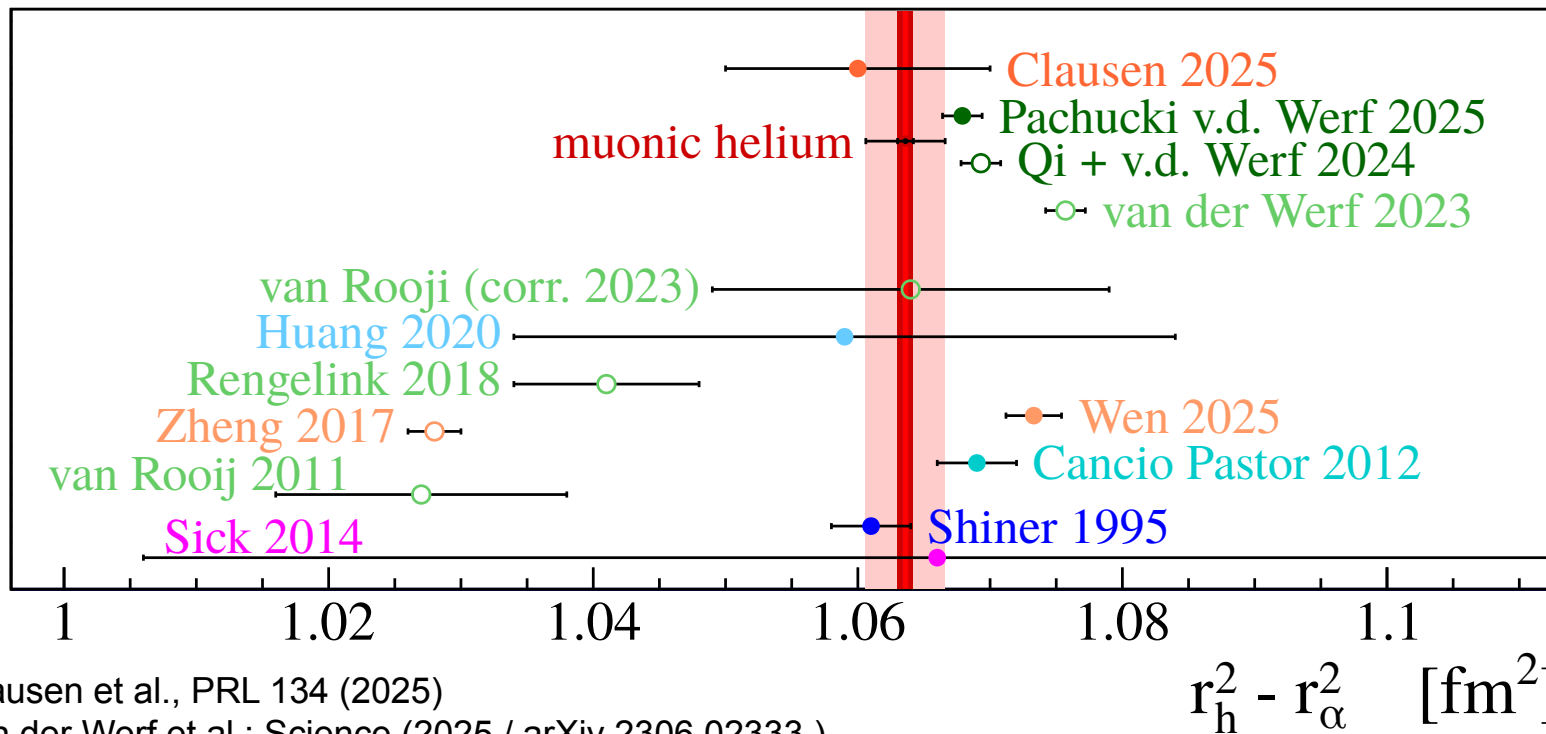
¹*Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*

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 ^3He atoms. For ^3He , 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 ^3He – ^4He 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)

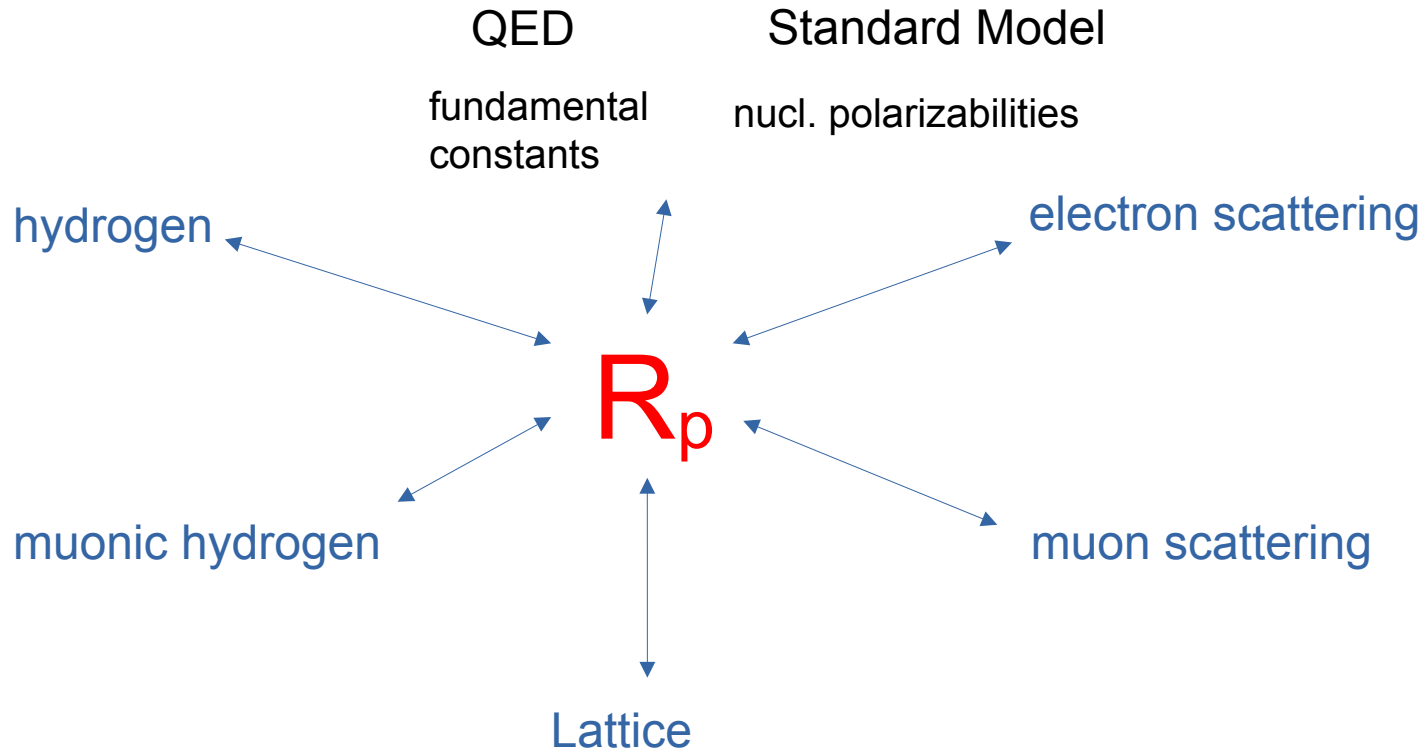
Qi et al., Phys. Rev. Research 7, L022020 (2025), arXiv 2409.09279

Pachucki et al, arXiv 2411.04621

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

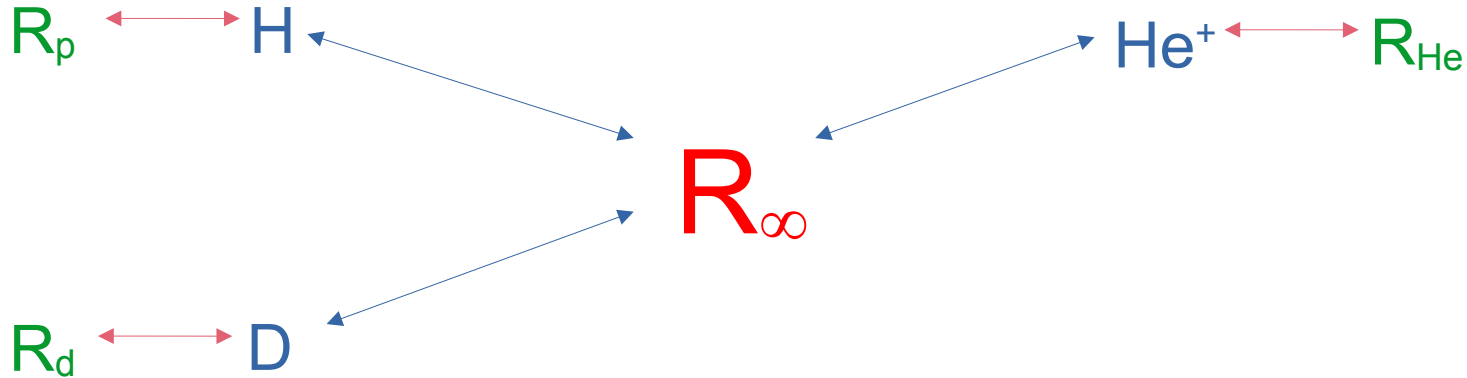
CREMA Coll. Science 2025 (arXiv 2305.11679)

Why was the proton radius so interesting?



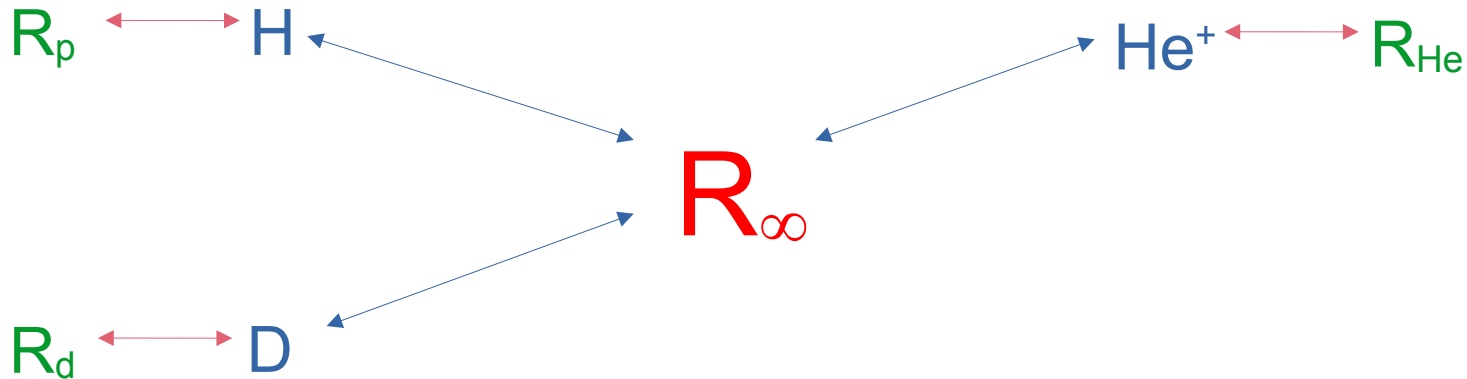
The Rydberg constant

→ Test QED and SM



2-body QED calculations

The Rydberg constant

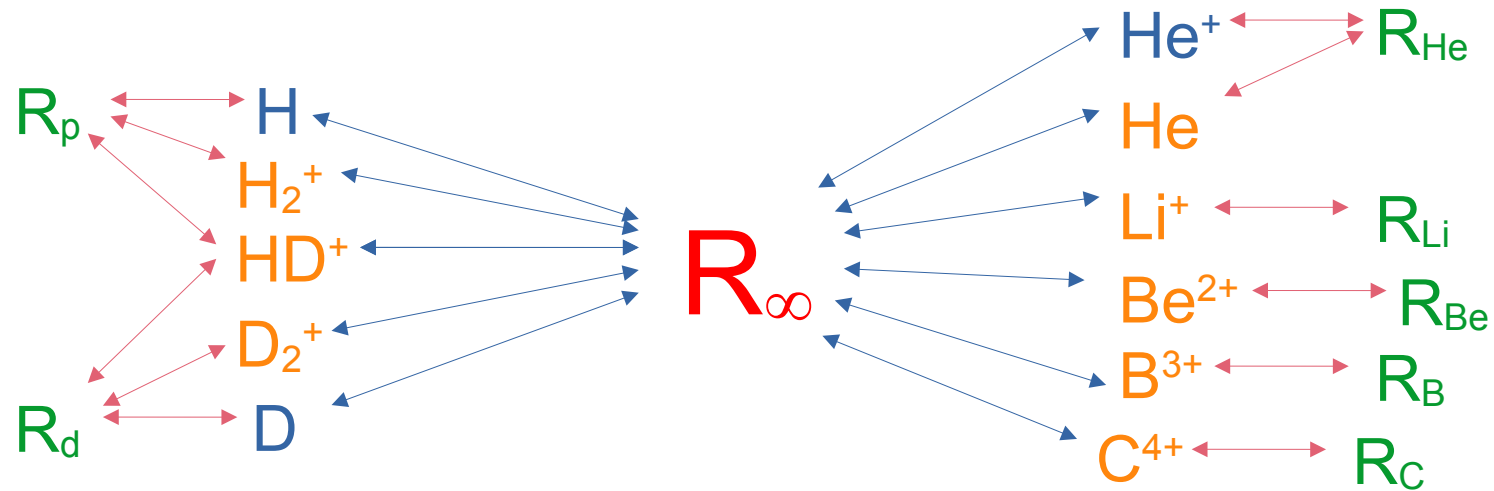


2-body QED calculations

Exp: Amsterdam, Garching,
Paris, Colorado, Mainz

...

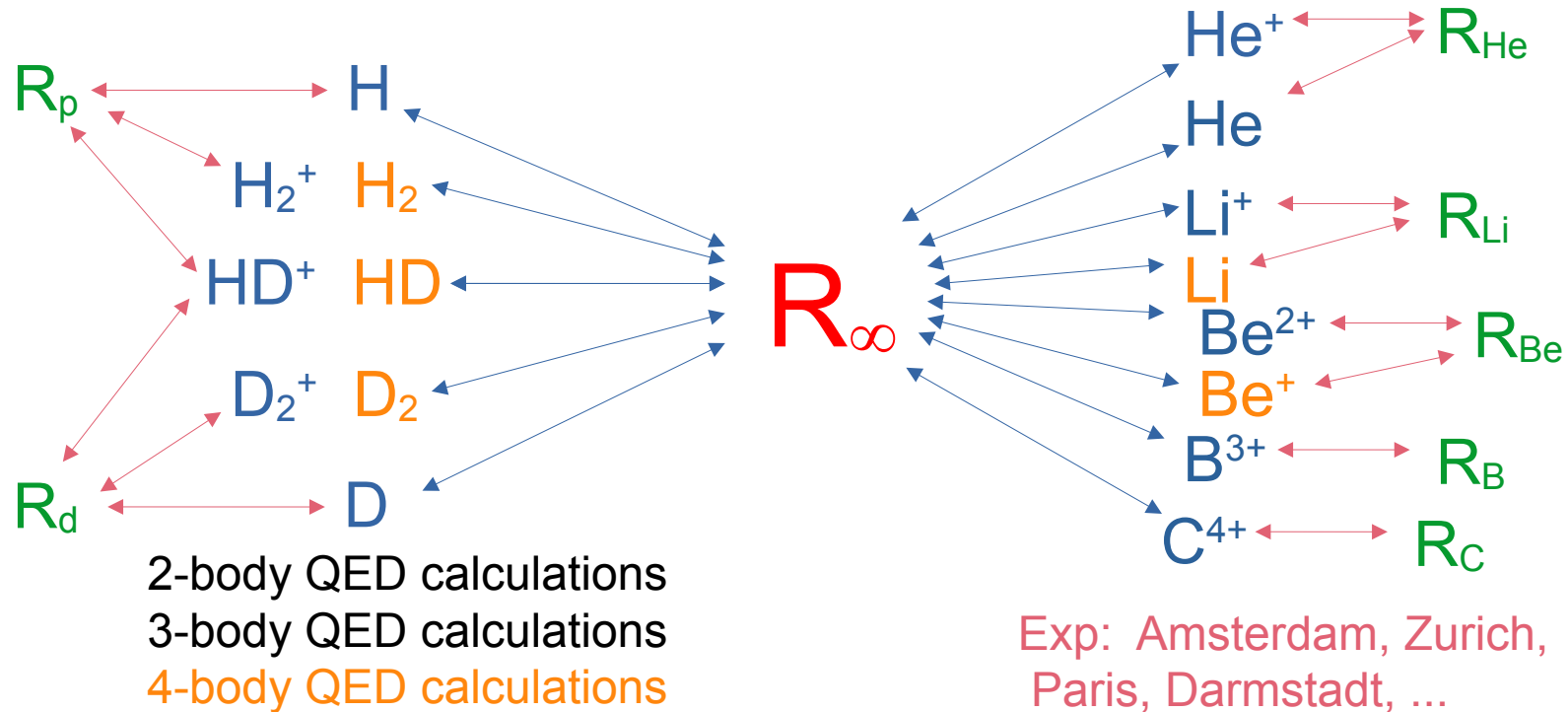
The Rydberg constant



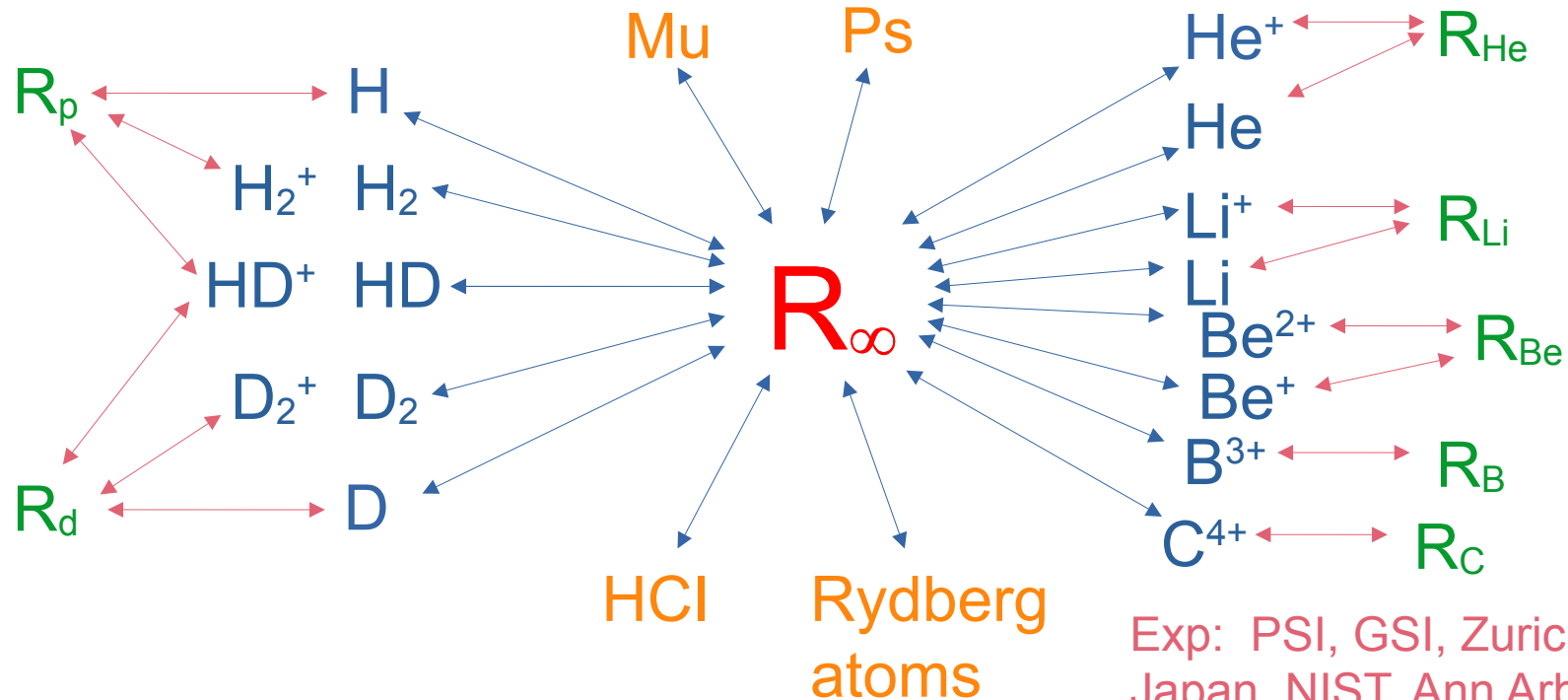
2-body QED calculations
3-body QED calculations

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

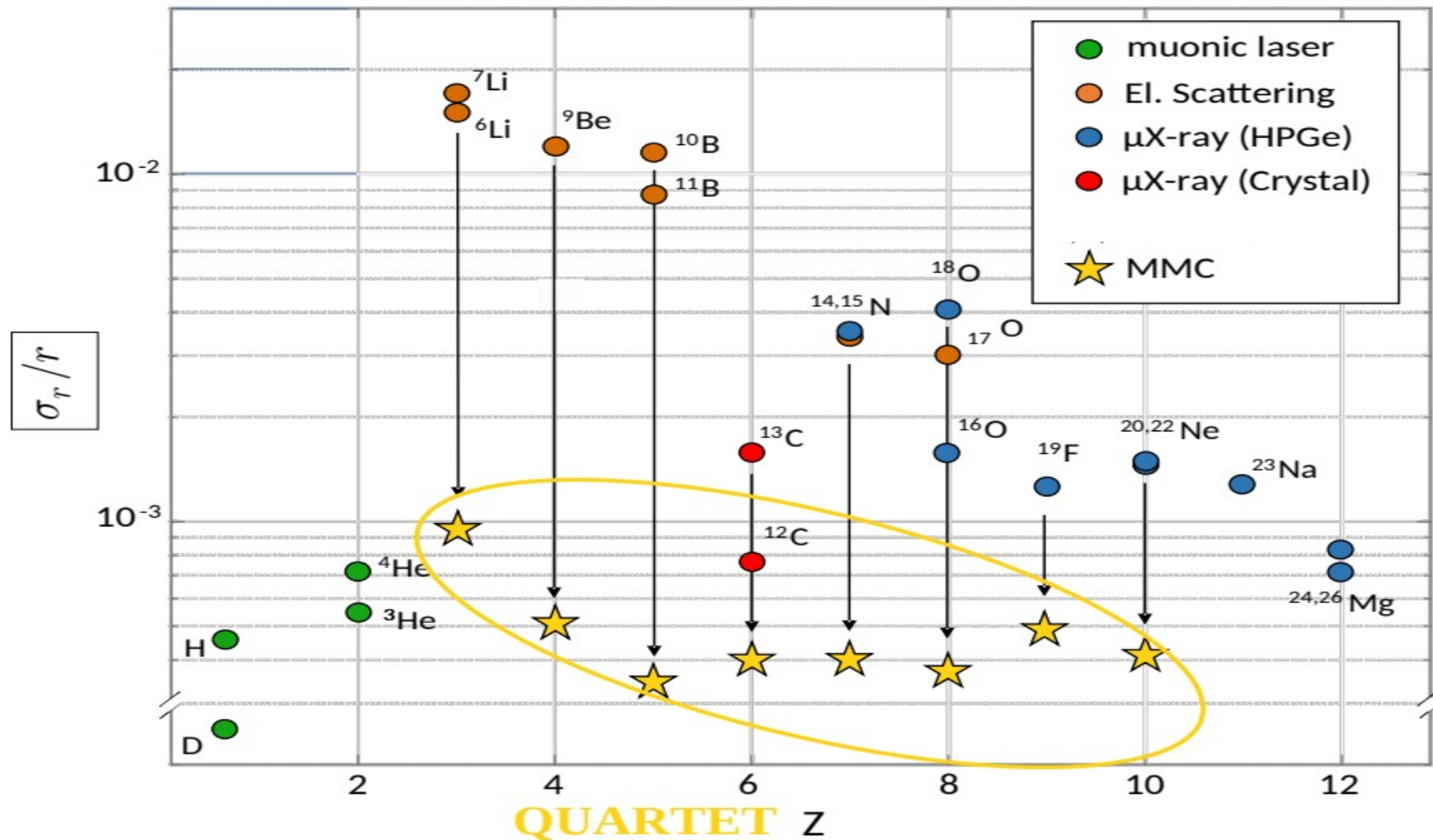
The Rydberg constant



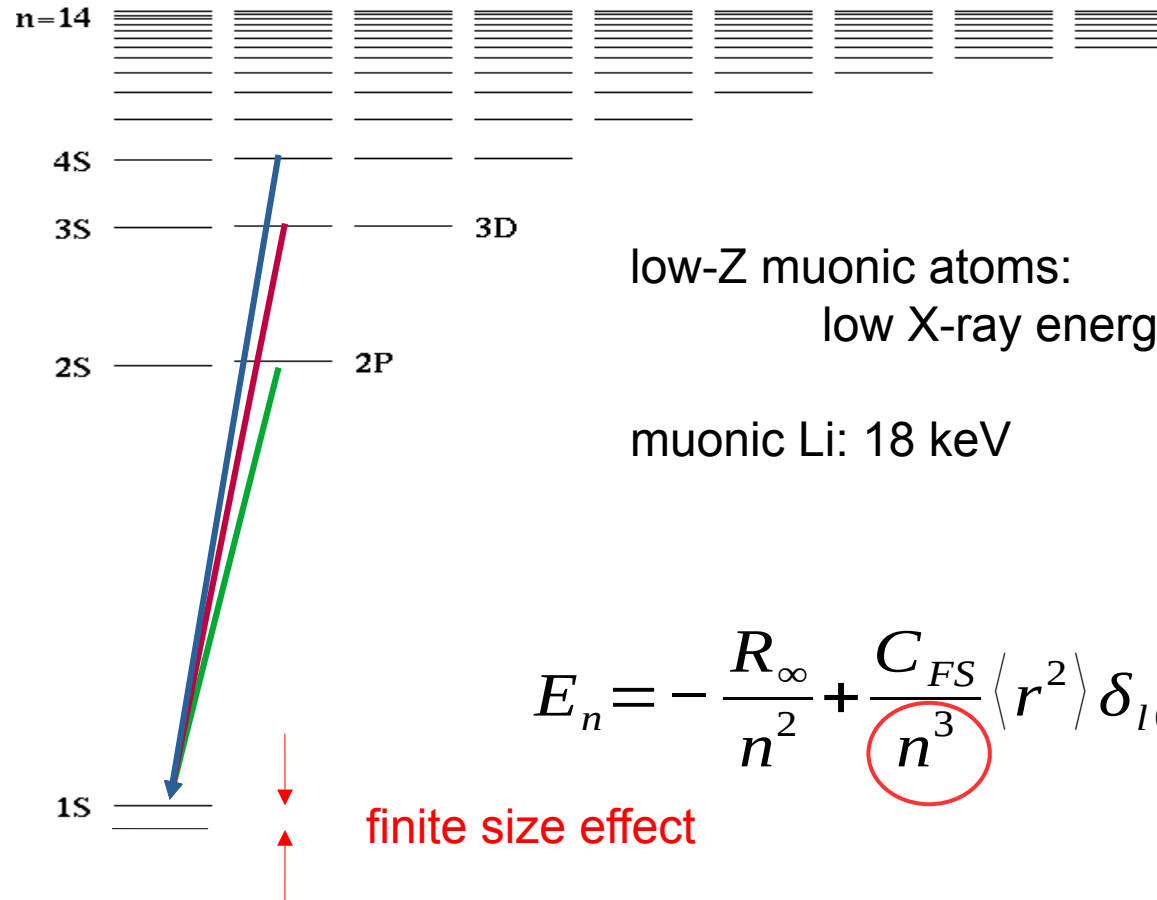
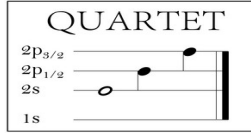
The Rydberg constant



QUARTET: X-ray spectroscopy of muonic atoms



Muonic X-ray spectroscopy



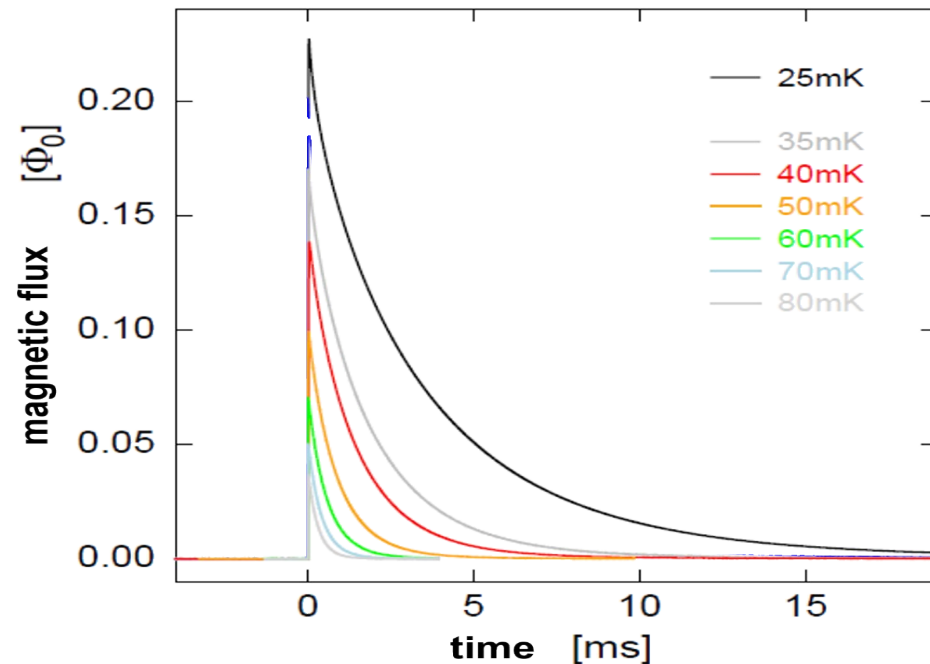
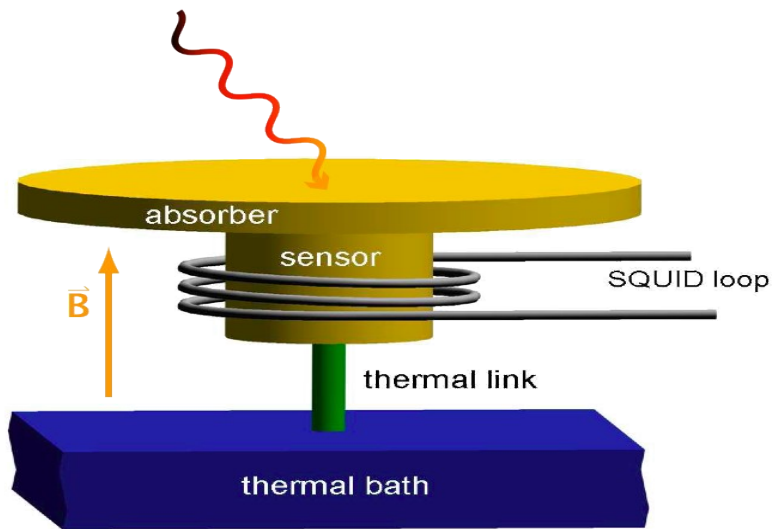
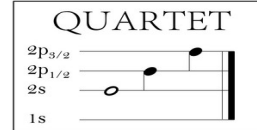
low-Z muonic atoms:
low X-ray energy $\rightarrow$ difficult!

muonic Li: 18 keV

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

finite size effect

Metallic Magnetic Calorimeters (MMCs)

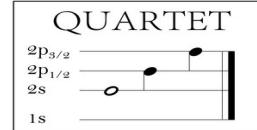


Magnetization of paramagnetic material:

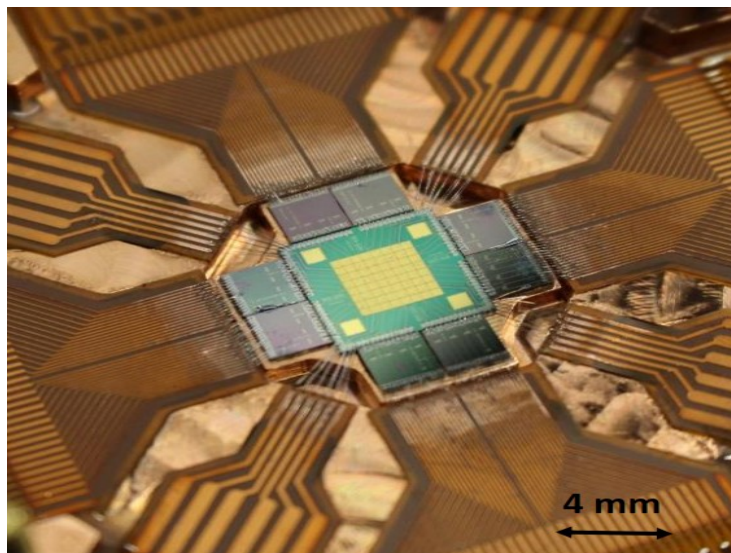


Decay time 3ms@30mK
Keep rates < 10 Hz
per pixel to avoid pileup

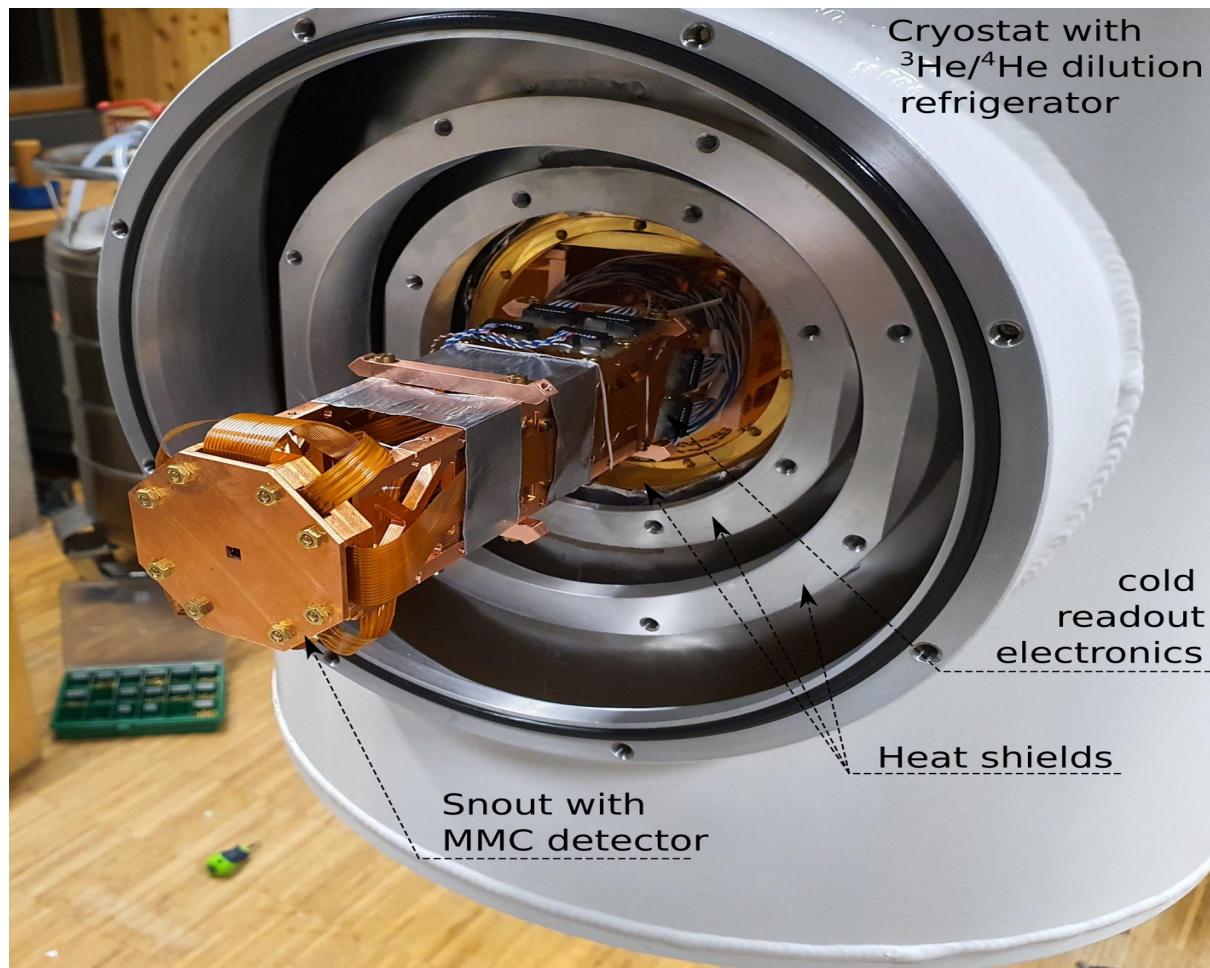
Metallic Magnetic Calorimeters (MMCs)



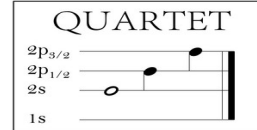
pixel array, area 16mm²



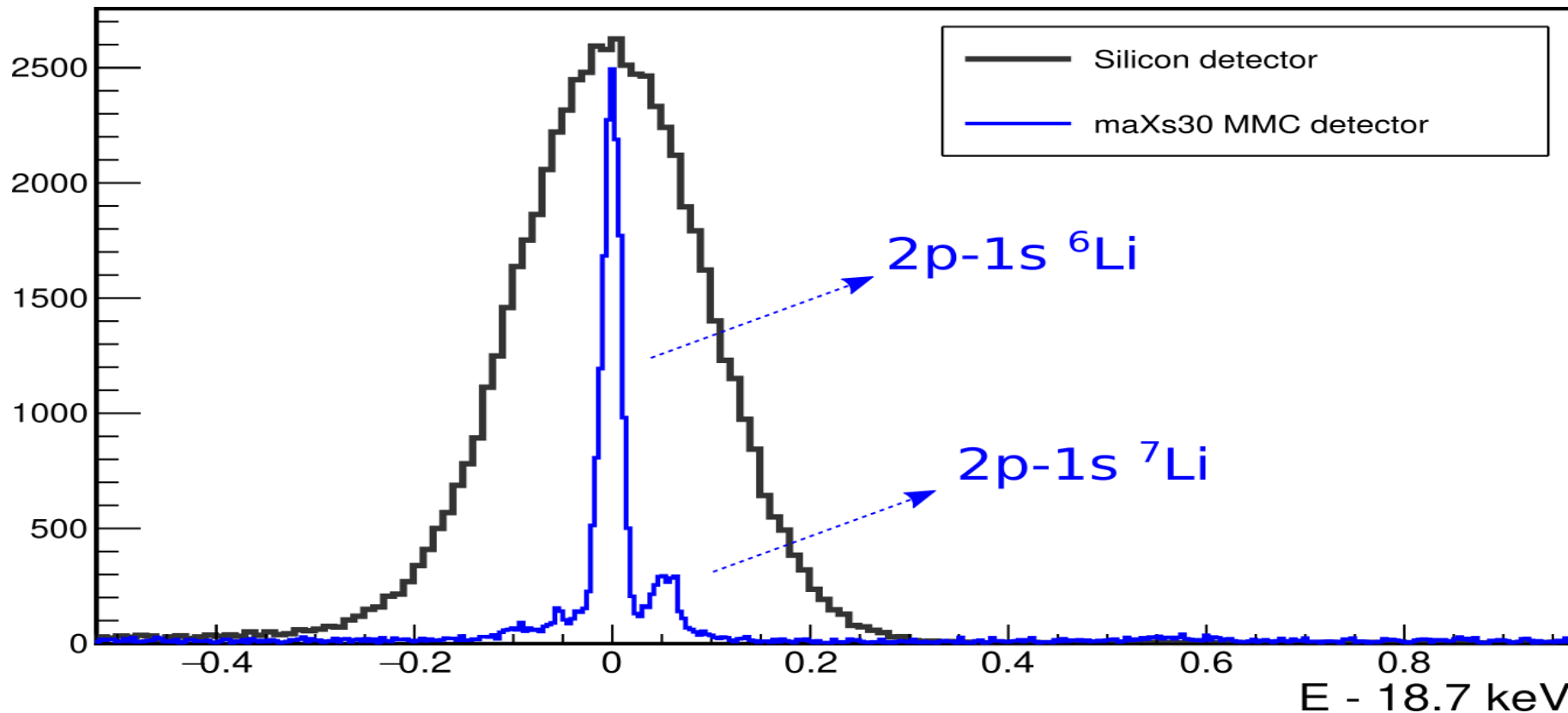
High efficiency (>90%) for
photons 10-60 keV



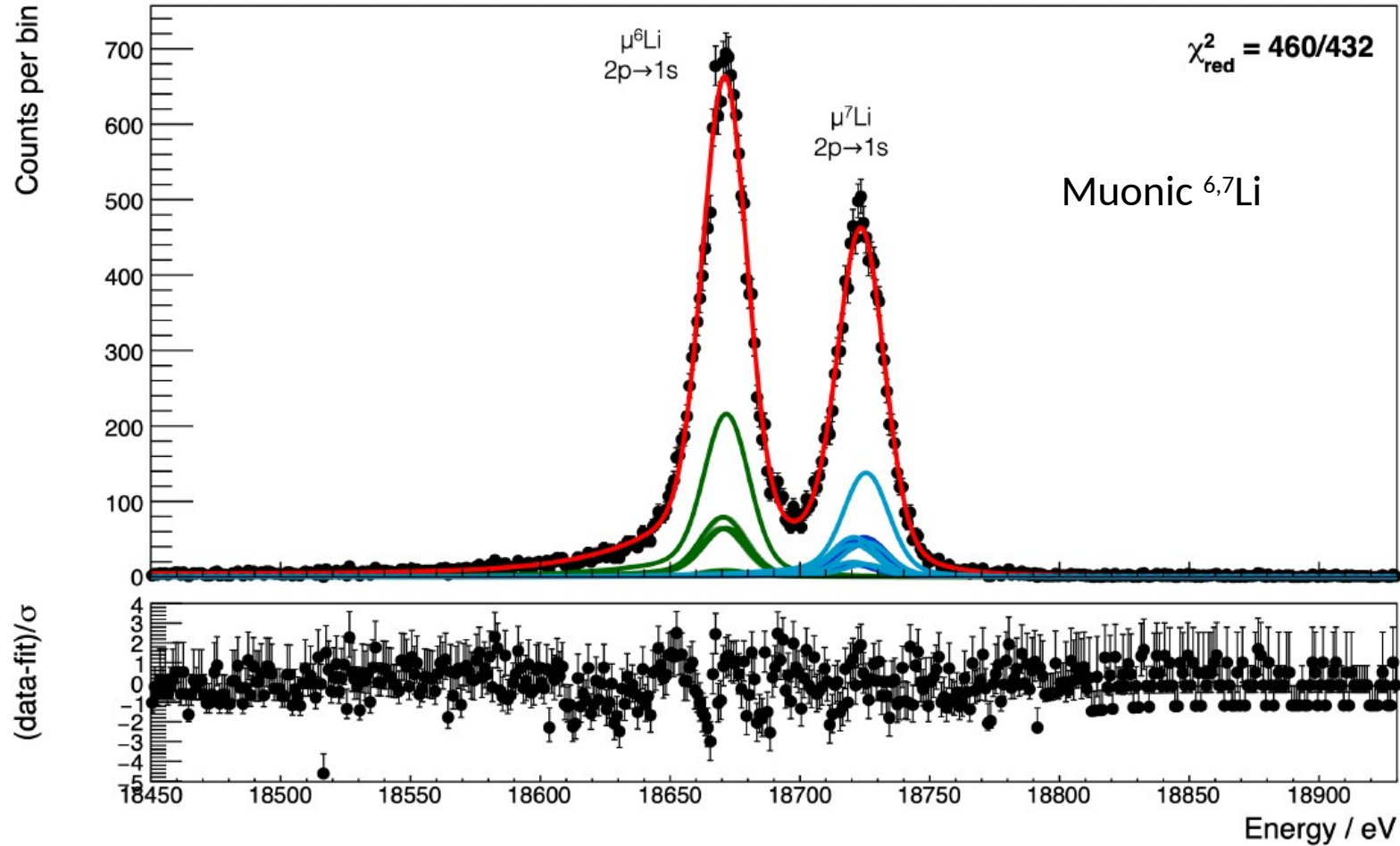
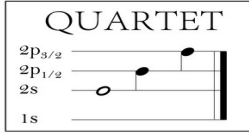
MMC have *excellent* energy resolution



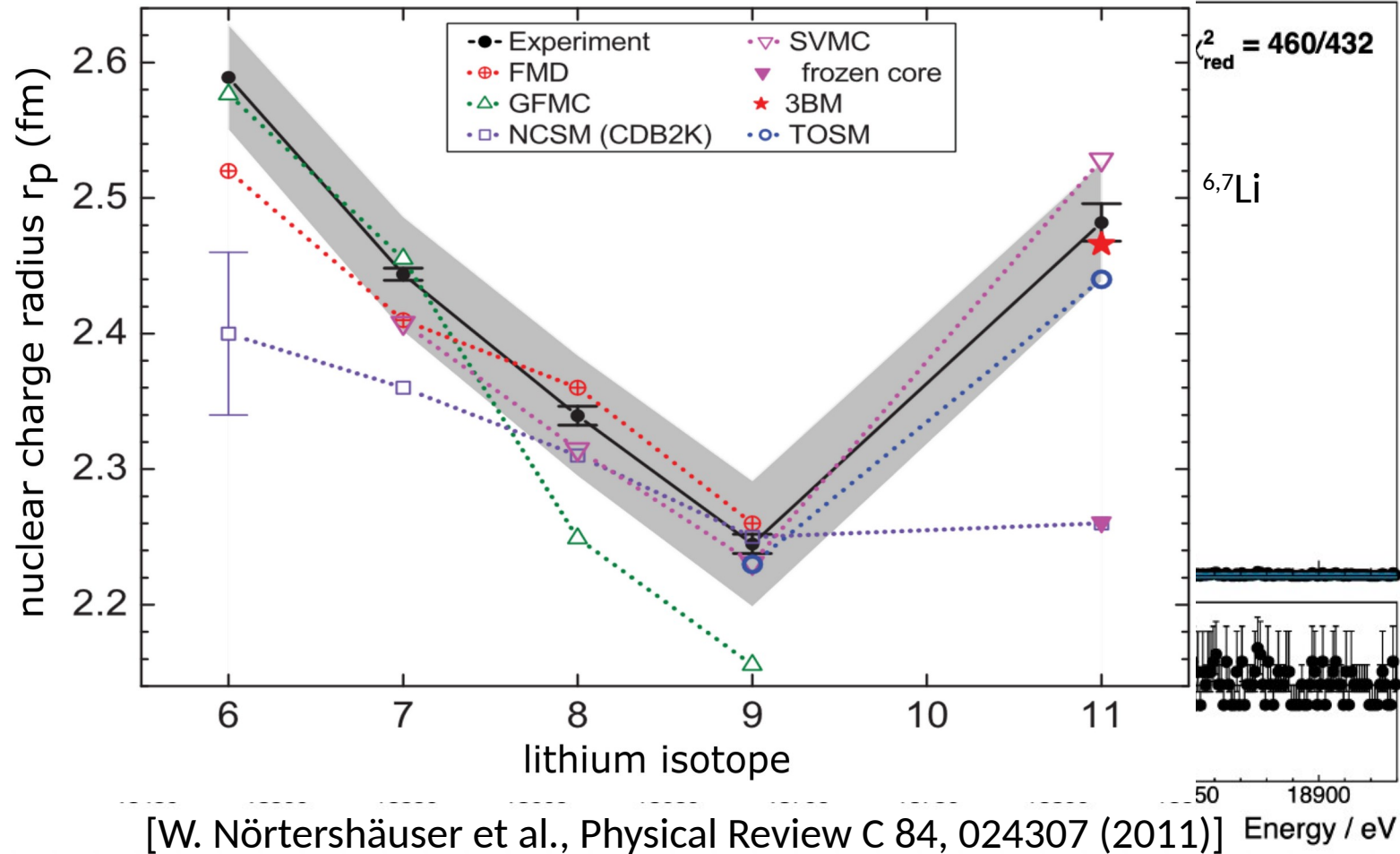
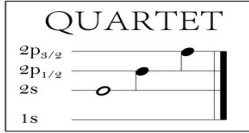
2023 pilot run muLi



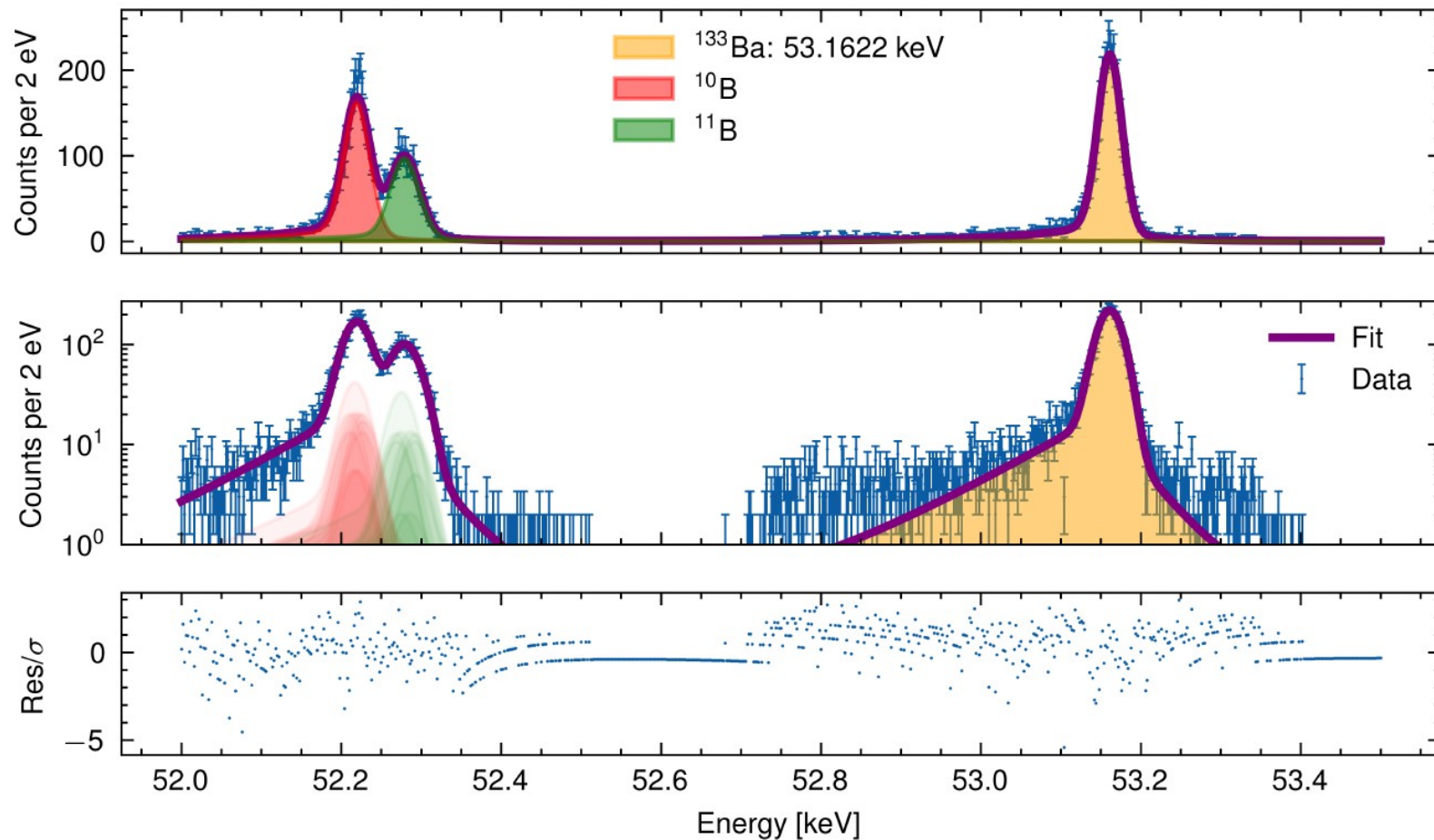
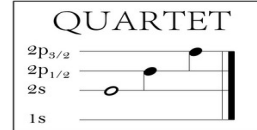
2024: Li, Be, B



2024: Li, Be, B

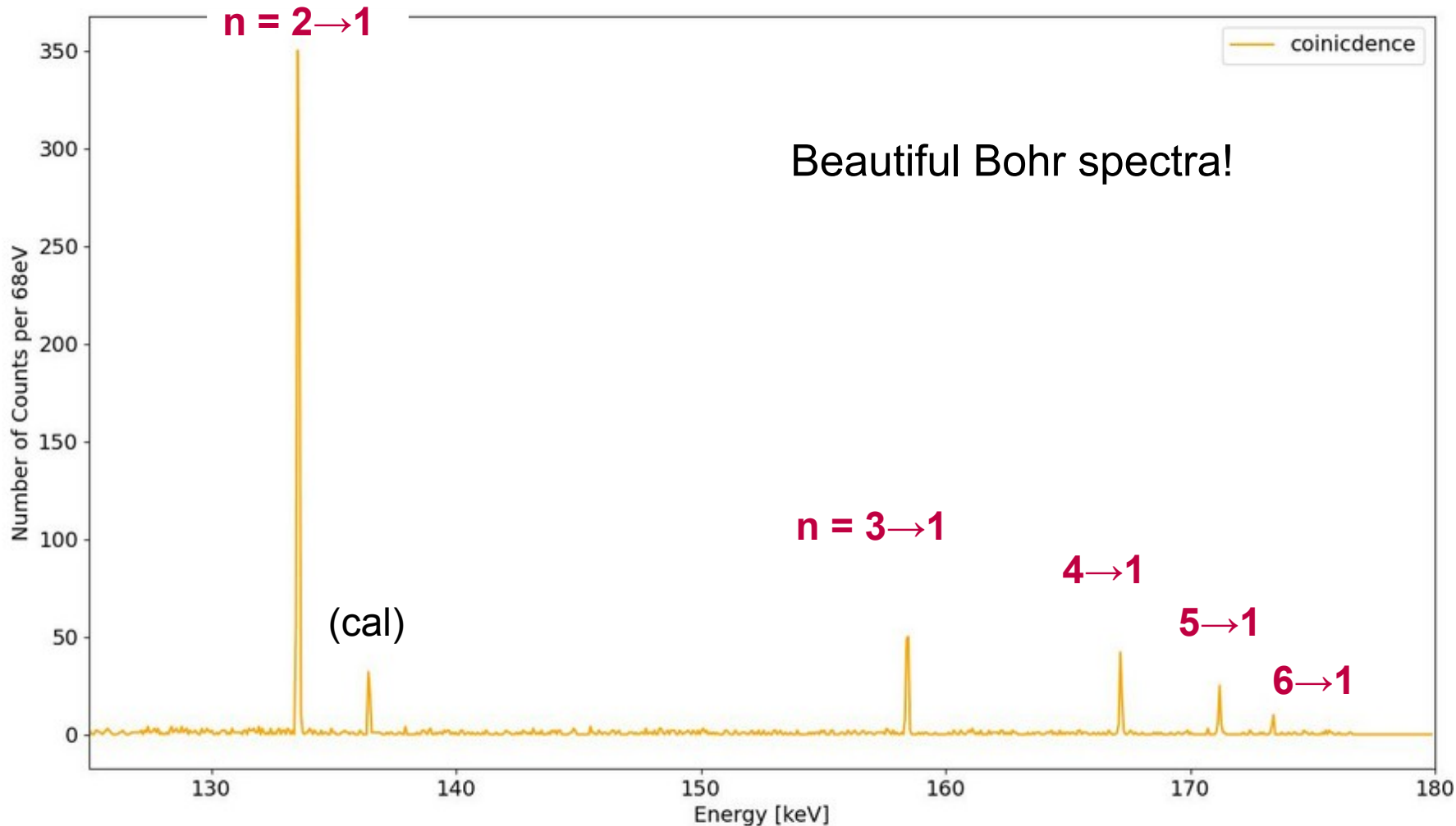
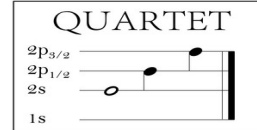


2024: Li, Be, B

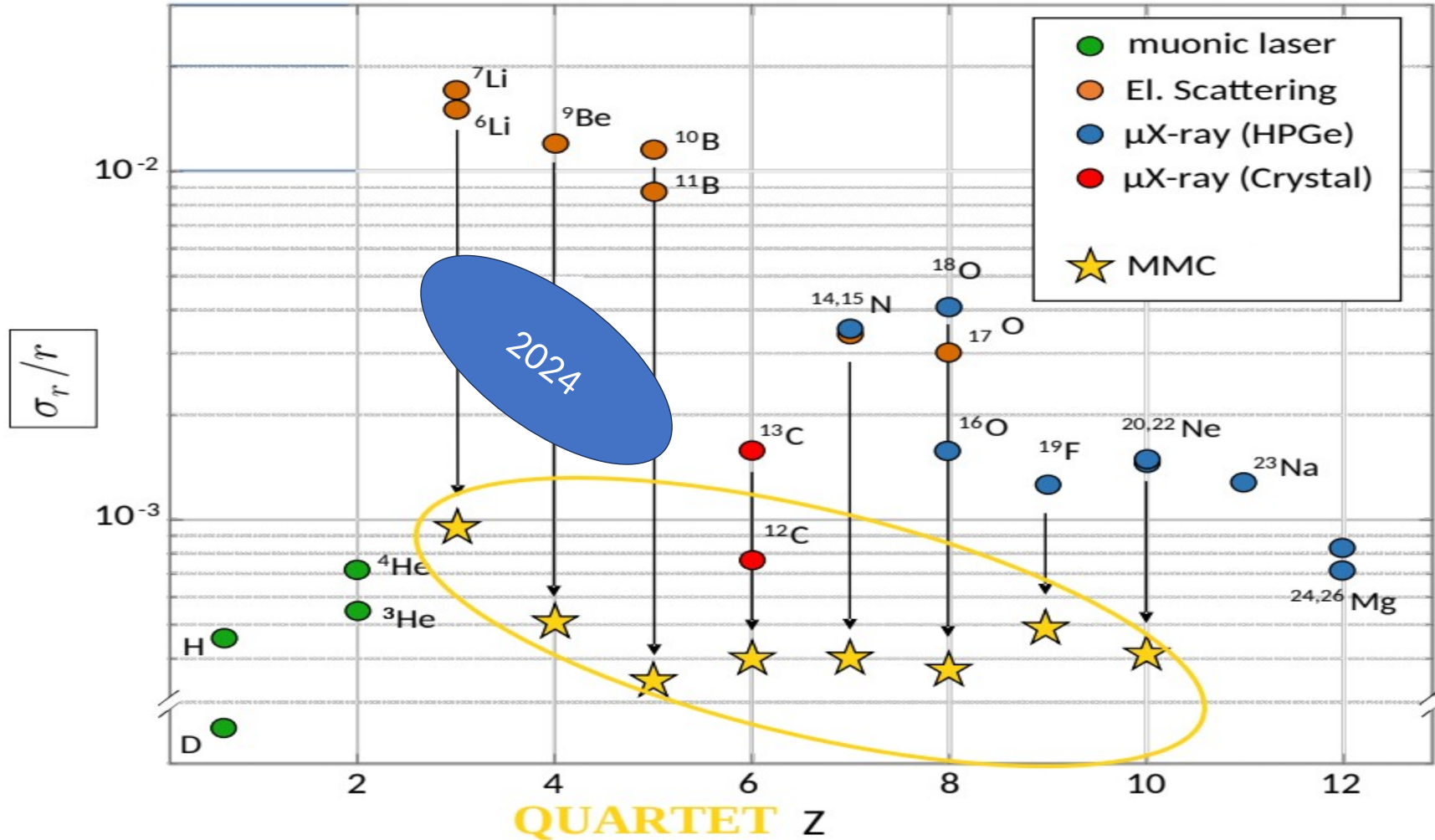


Muonic ^{10,11}B

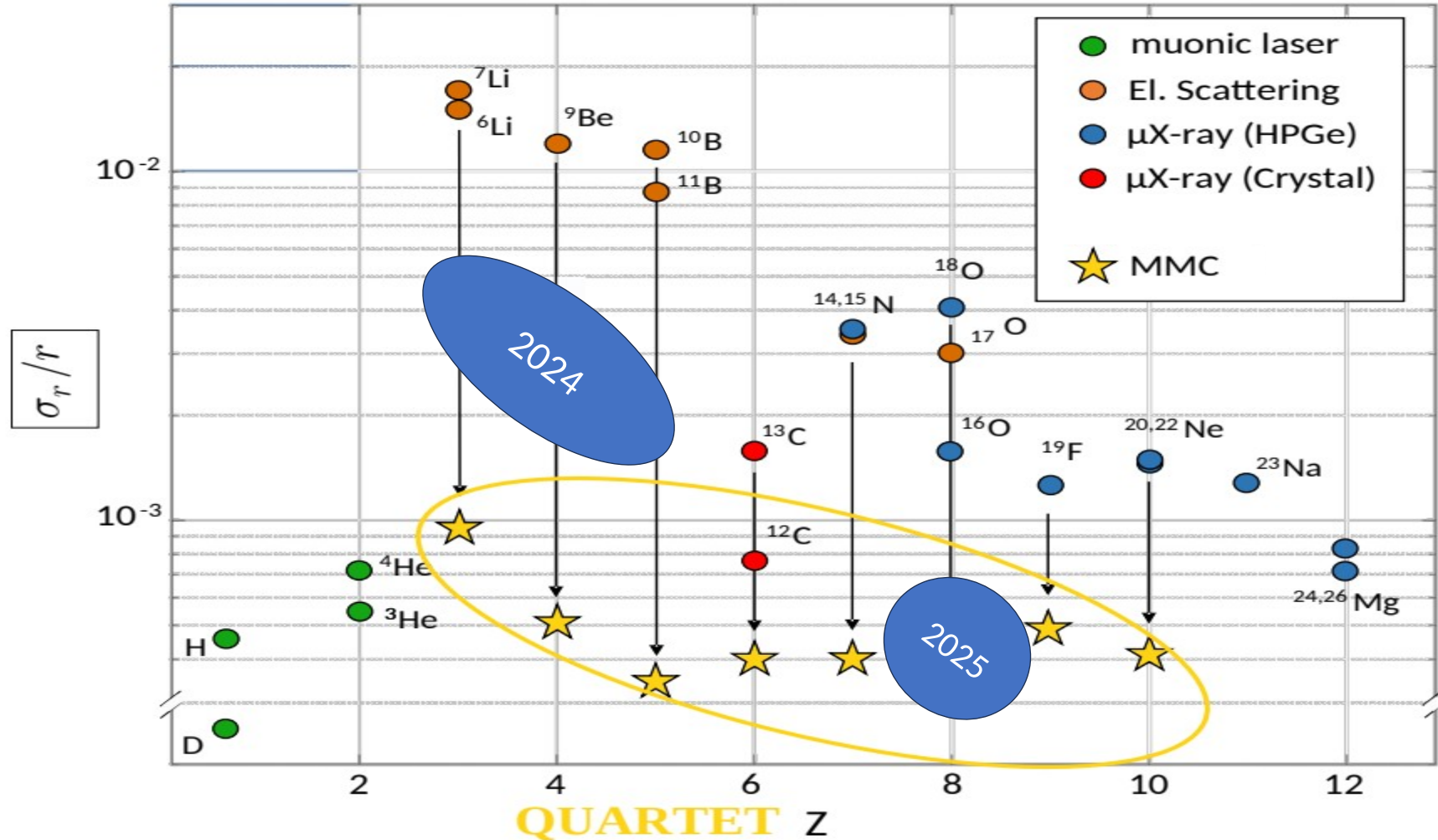
muonic ^{17}O , online spectrum 2025



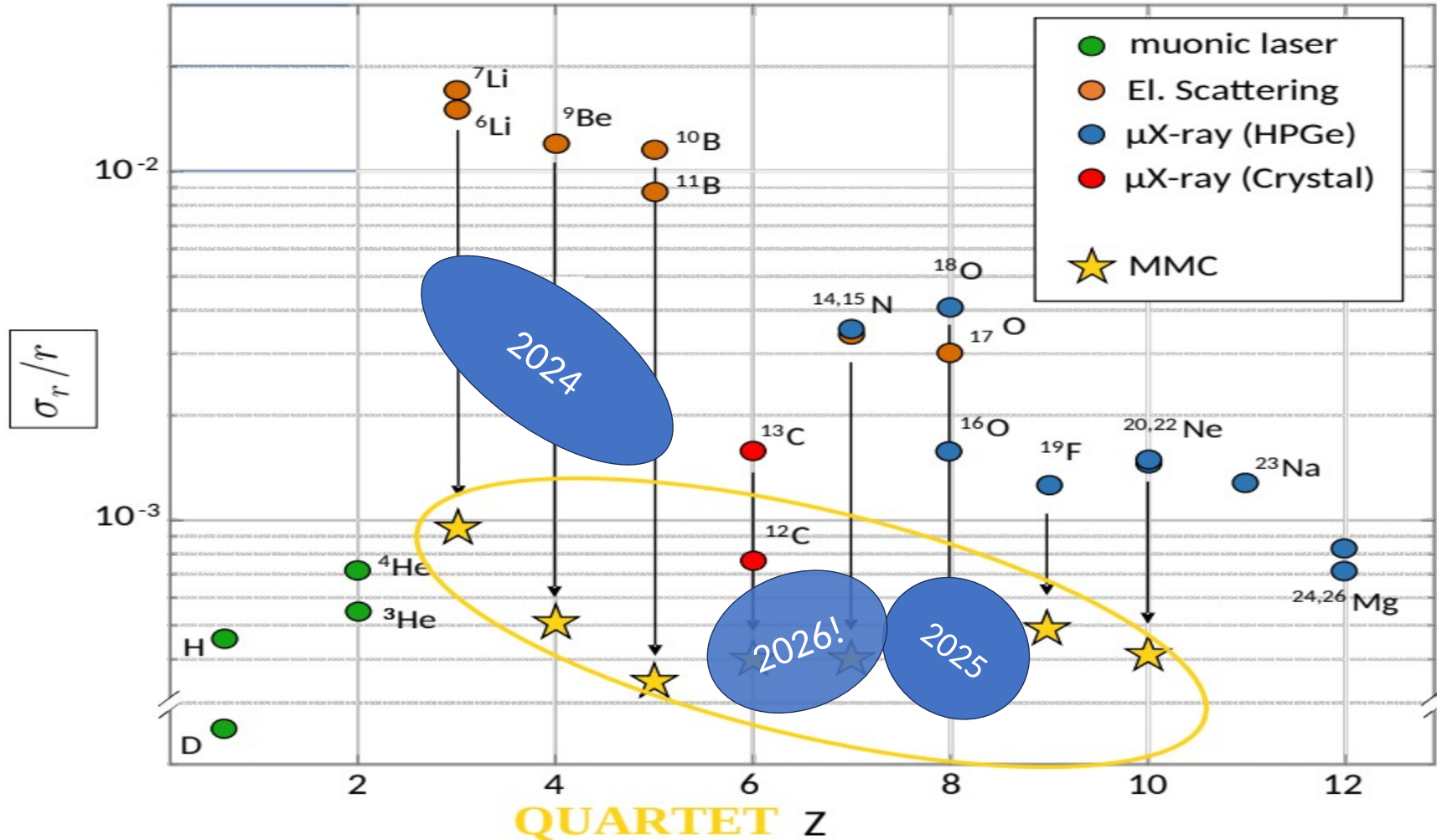
QUARTET: X-ray spectroscopy



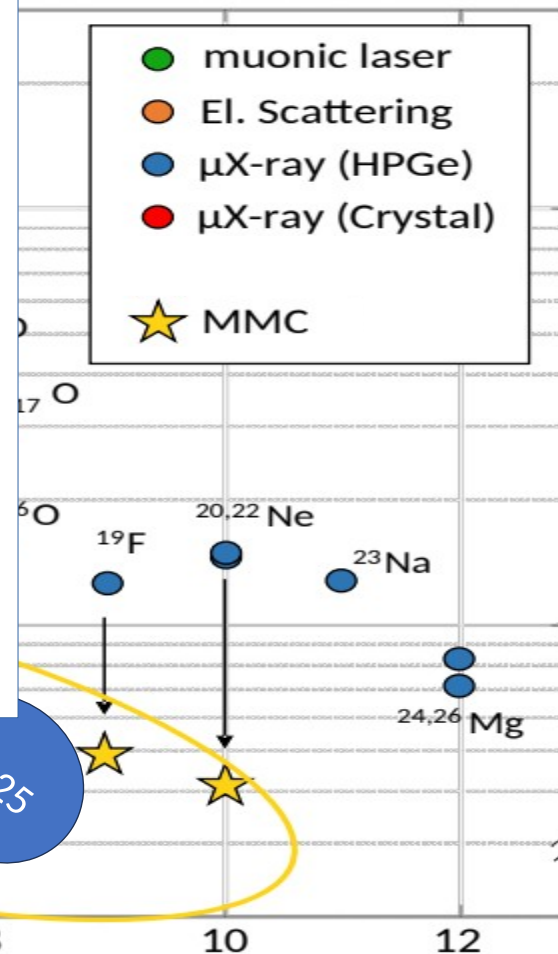
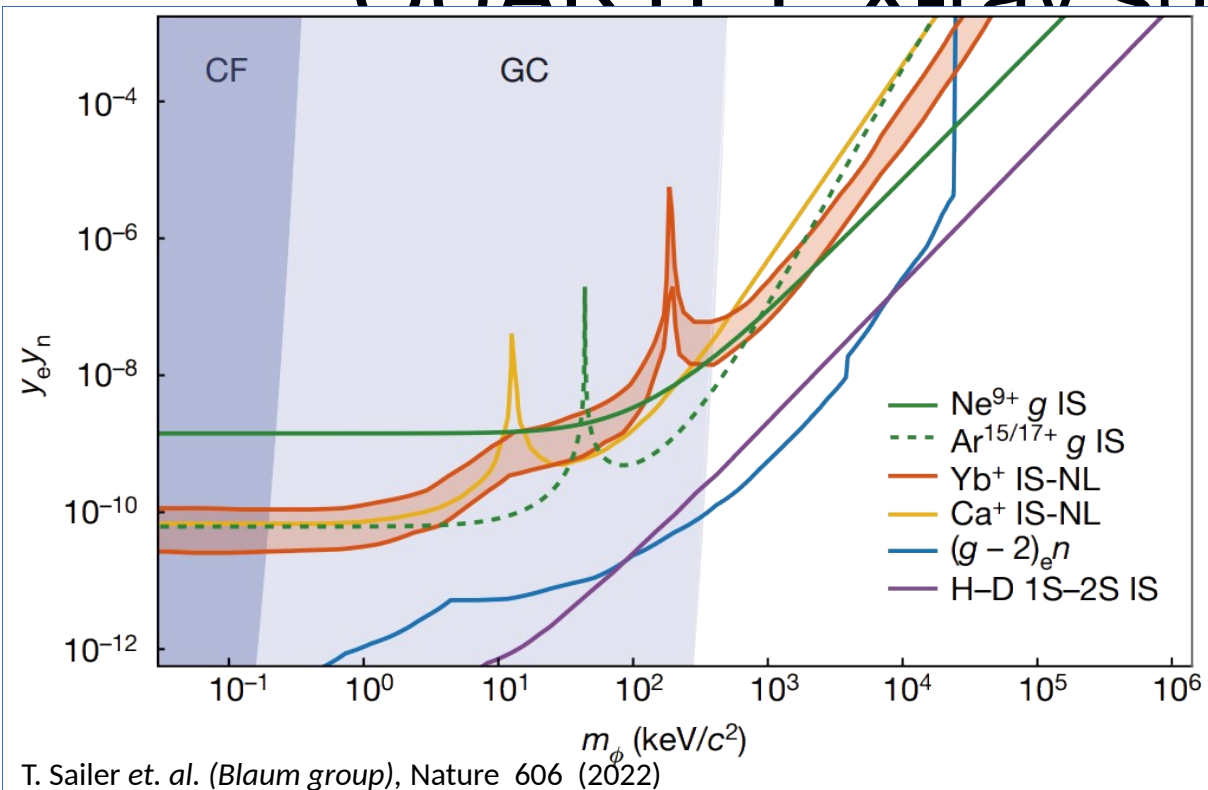
QUARTET: X-ray spectroscopy



QUARTET: X-ray spectroscopy



QUARTET: X-ray spectroscopy



QUARTET Z

Conclusions

muonic H, D, ^3He , ^4He by laser done $\rightarrow$ 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, $\rightarrow$ better charge radii by QUARTET X-rays and MMCs

muonic high-Z , also for rare or radioactive nuclei! $\rightarrow$ muX

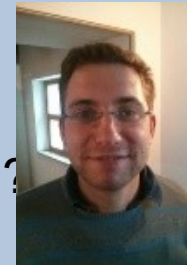
Thanks a lot
for your attention



Lothar
Maisenbacher



Vitaly
Wirthl



Alexey
Grinin



Arthur
Matveev

