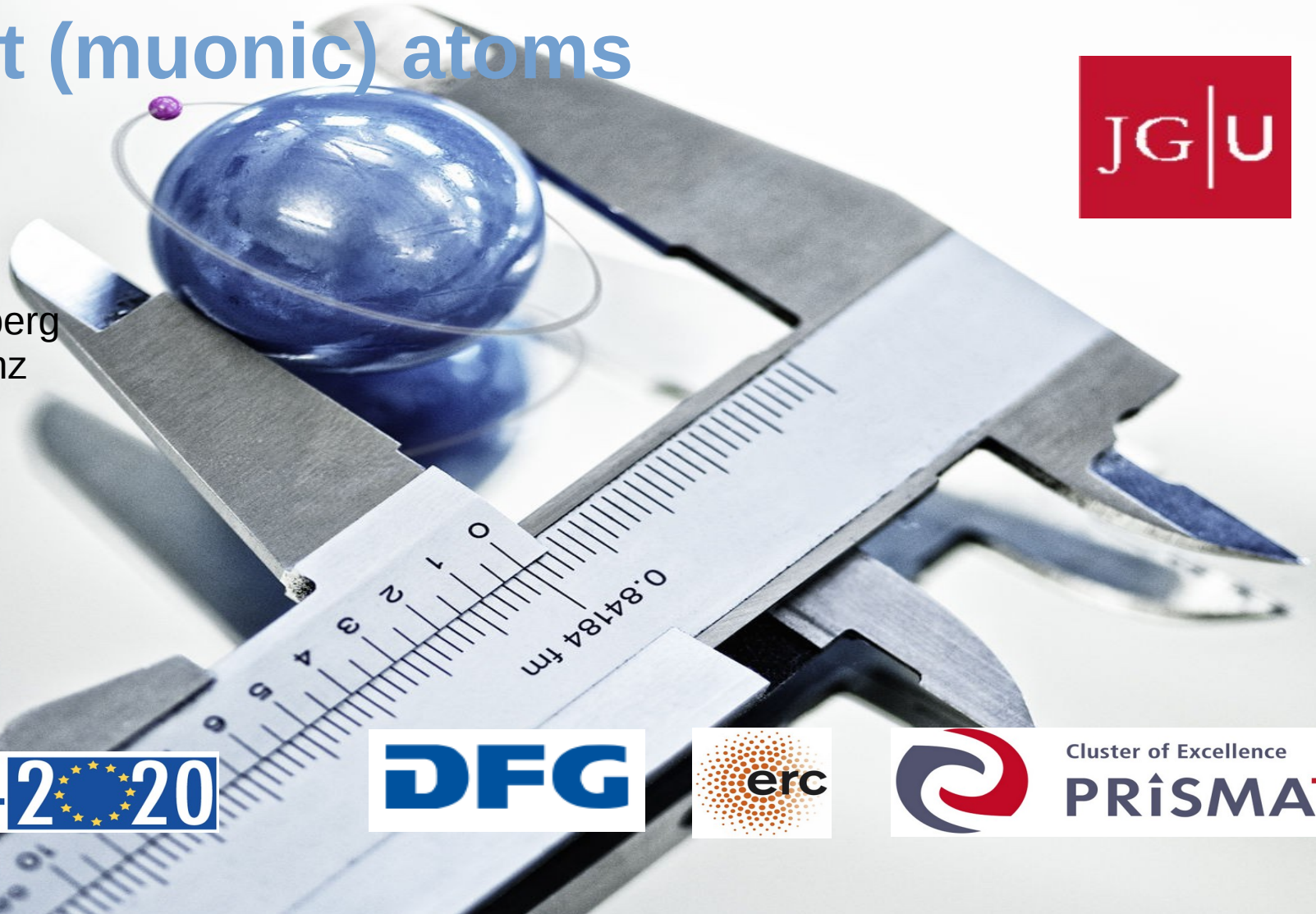
Precision nucleon and nuclear structure from light (muonic) atoms

Randolf Pohl

Johannes Gutenberg
Universität Mainz

ECT* Trento
28.07.25



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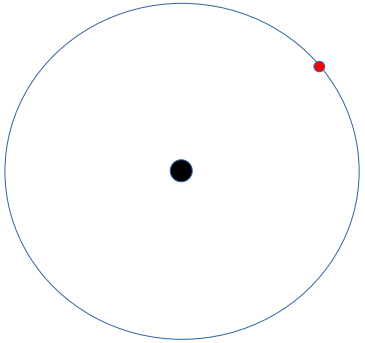
Hydrogen-like atoms

“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

Hydrogen-like atoms



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Welcome to ECT* Trento

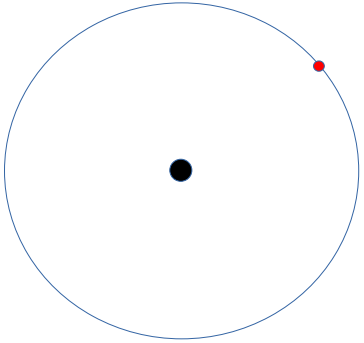
FONDAZIONE BRUNO KESSLER

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

New perspectives in the charge radii determination for light nuclei

July 28, 2025 to August 1, 2025
ECT*
Europe/Rome timezone

Cool muonic stuff



EURO-LABS
EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

INFN
Istituto Nazionale di Fisica Nucleare

FRIB Theory Alliance

Randolf Pohl, JGU Mainz

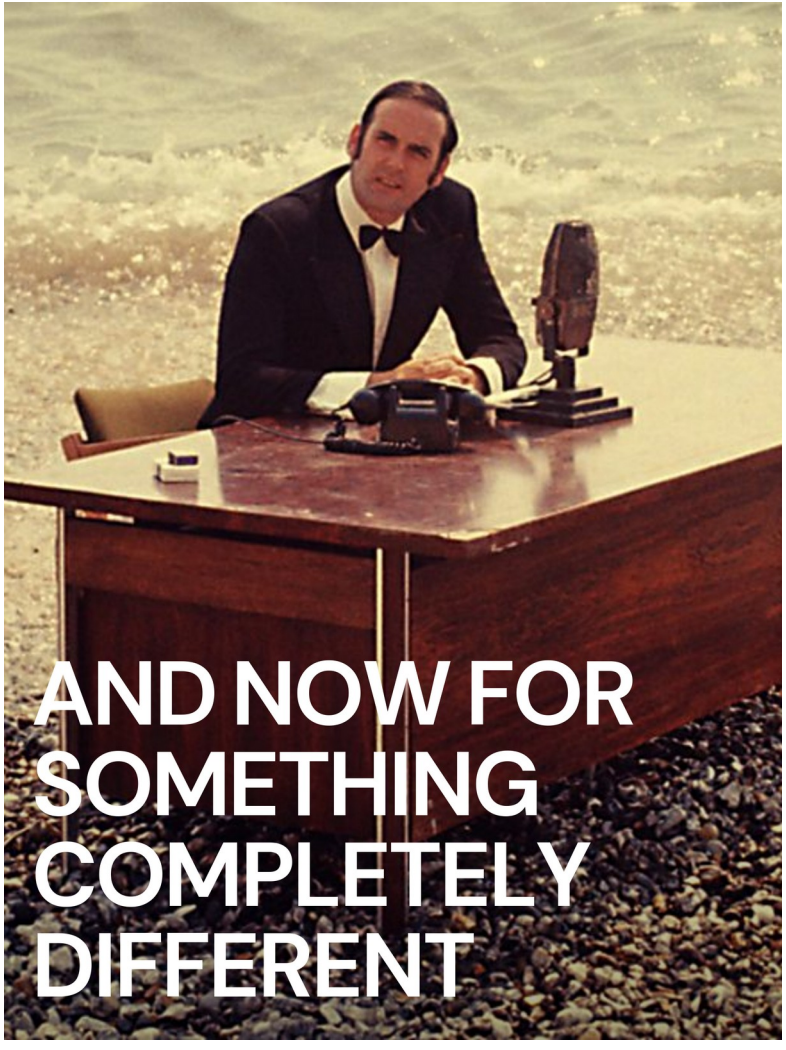
Organizers: Loredana **Gastaldo**
Franziska **Hagelstein**
Nancy **Paul**
Randolf **Pohl**

Main topics:

- High-resolution X-ray and laser spectroscopy
- Microcalorimeter X-ray detector technology
- Experimental progress: target preparation, background suppression, calibration
- Theory of muonic atoms
- Nuclear and nucleon structure effects
- Searches for physics beyond the Standard model (BSM)

Welcome to ECT* Trento

		Monday	Tuesday	Wednesday	Thursday	Friday
9:40 – 10:20	30 + 10	van Kolck	Ohayon	Bacca	Gasparian	Craig
10:20 – 11:00	30 + 10	Pohl	Peset	Drissi	Ouf	Potvliege
11:00 – 11:30	Coffee					
11:30 – 12:10	30 + 10	Gorshteyn	Harman	Pastore	Pitelis	Feng
12:10 – 12:50	30 + 10	Fleischmann	Nörtershäuser	Oreshkina	Lensky	Closing
13:00 – 15:00	Lunch					
15:00 – 15:40	30 + 10	Kreuzberger	Weber	Excursion	Ji	
15:40 – 16:20	30 + 10	Godhino	Rathi		Egert	
16:20 – 16:50		Coffee				
16:50 – 17:30	30 + 10	Baptista	Cocolios			
17:30 – 18:10	30 + 10	Heiße (Zoom)	Deseyn			
18:10 – 18:30	Discussions					


AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT

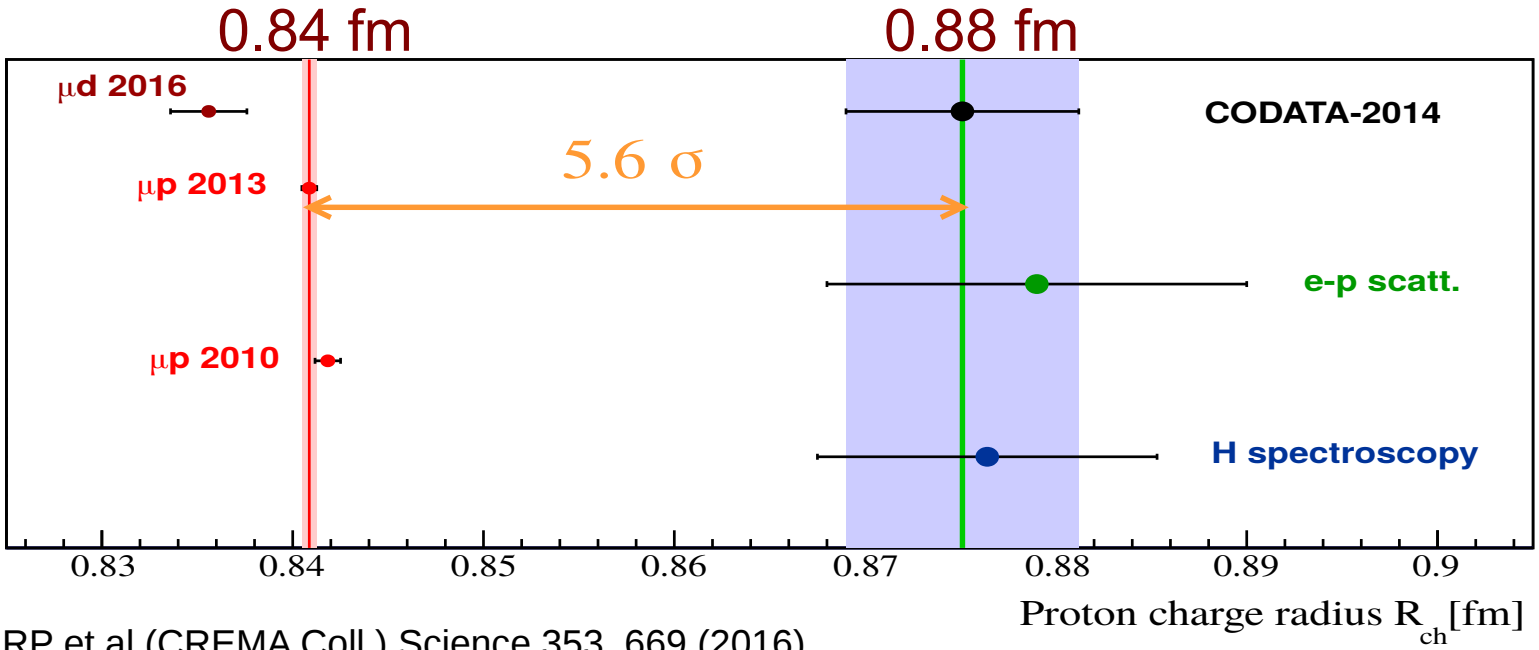
Stuff with lasers

ECT*, 28.7.2025

Randolf Pohl, JGU Mainz

The “Proton Radius Puzzle”

Measuring R_p using electrons: 0.88 fm (+- 0.7%)
using muons: 0.84 fm (+- 0.05%)



μd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
μp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

The “Proton Radius Puzzle”

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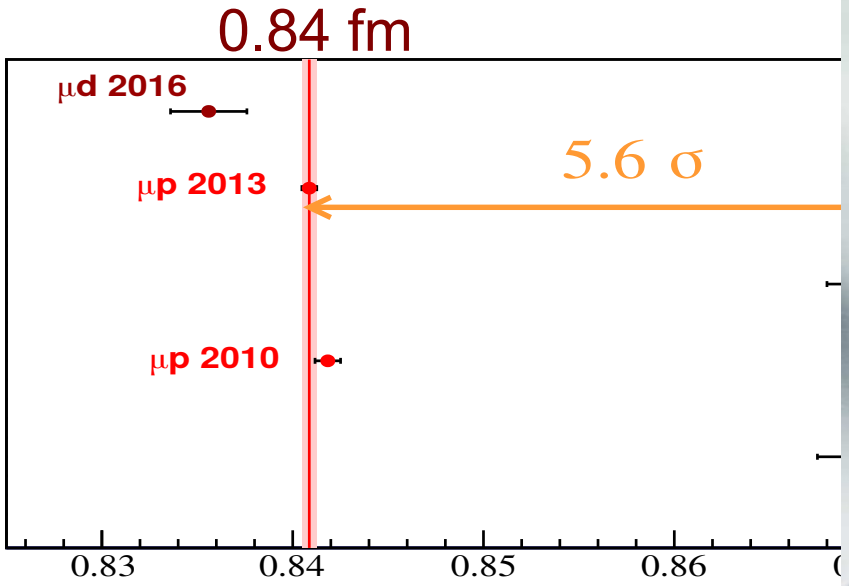

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The “Proton Radius Puzzle”

The “Proton Radius Puzzle”

Muonic Atoms

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

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

Hydrogen theory!

What is a Muon?

Carl David Anderson

Nobel prize 1936
(for the Positron!)

Seth Neddermeyer

Muons are **heavy electrons**:

200x the mass of an electron.

Discovered in 1936 by Carl D. Anderson and Seth Neddermeyer as part of the cosmic radiation.

Muon have a lifetime of 2 microseconds. (millionths of a second).

Isidor Isaac Rabi

What i

Carl David Anderson

Seth Neddermeyer

Nobel prize 1936
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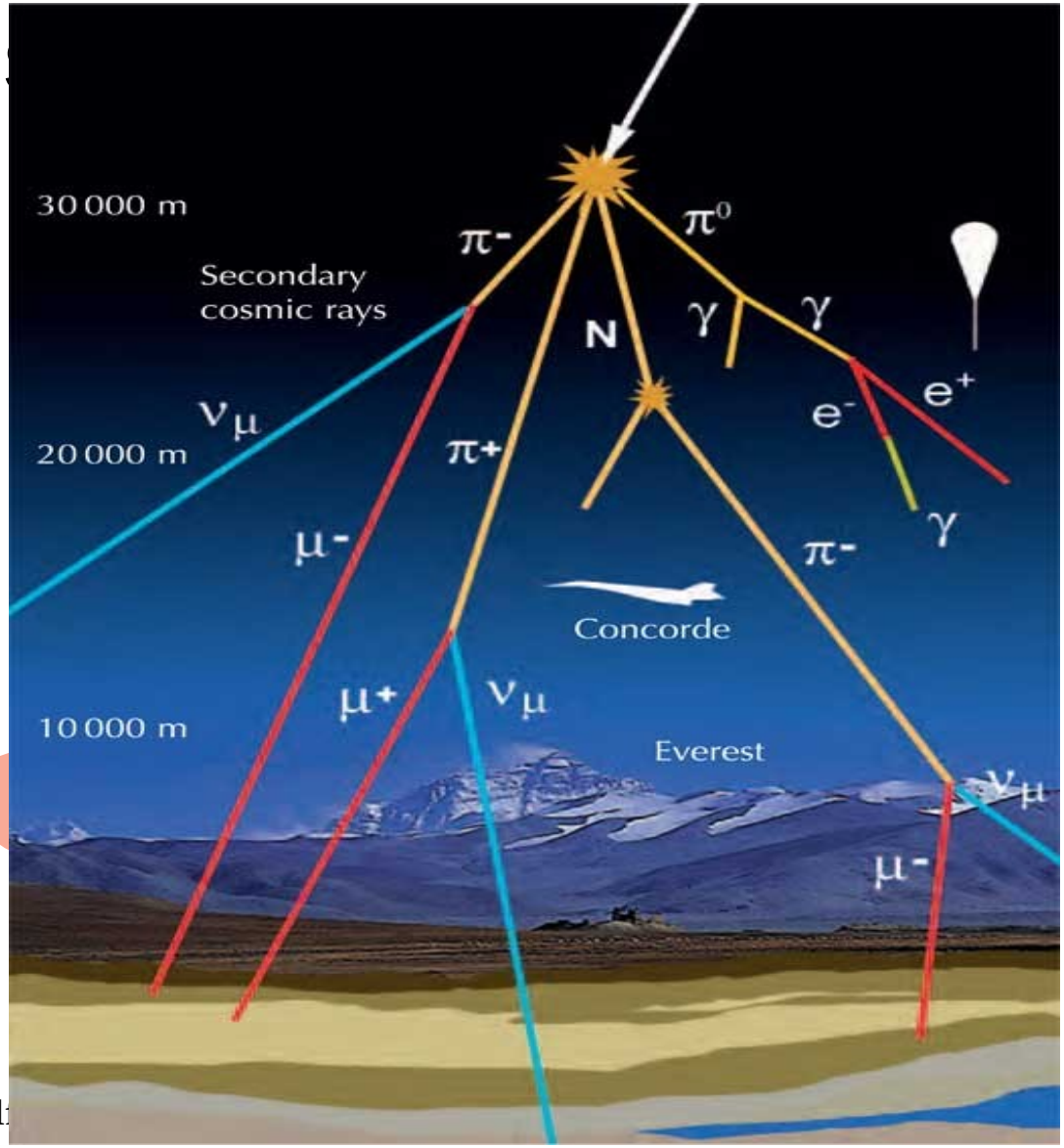

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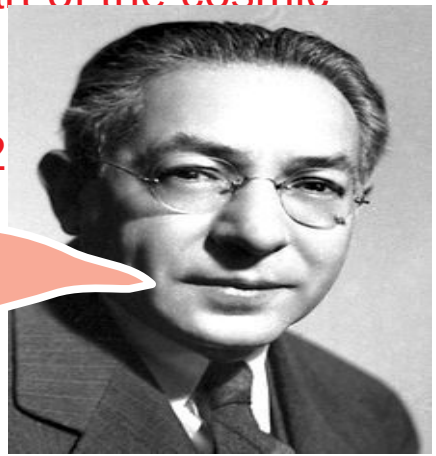
Muon have a lifetime of 2

Who ordered that?!

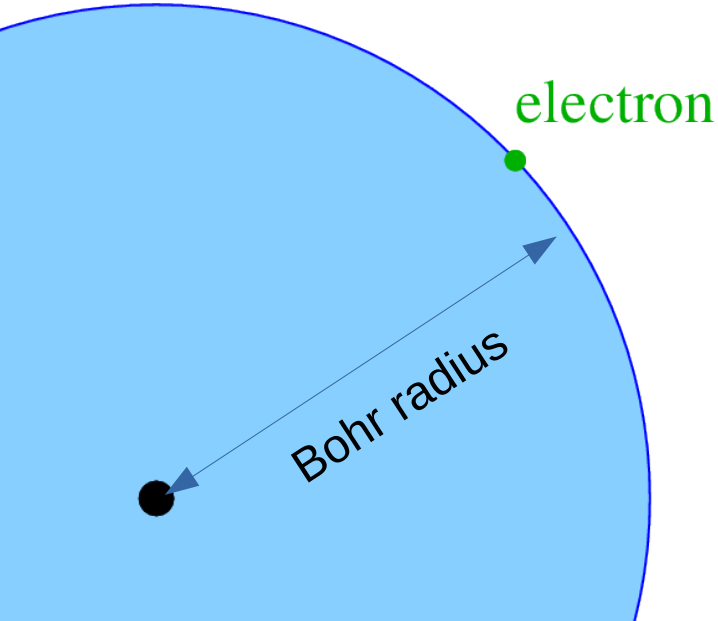


Isidor Isaac Rabi

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

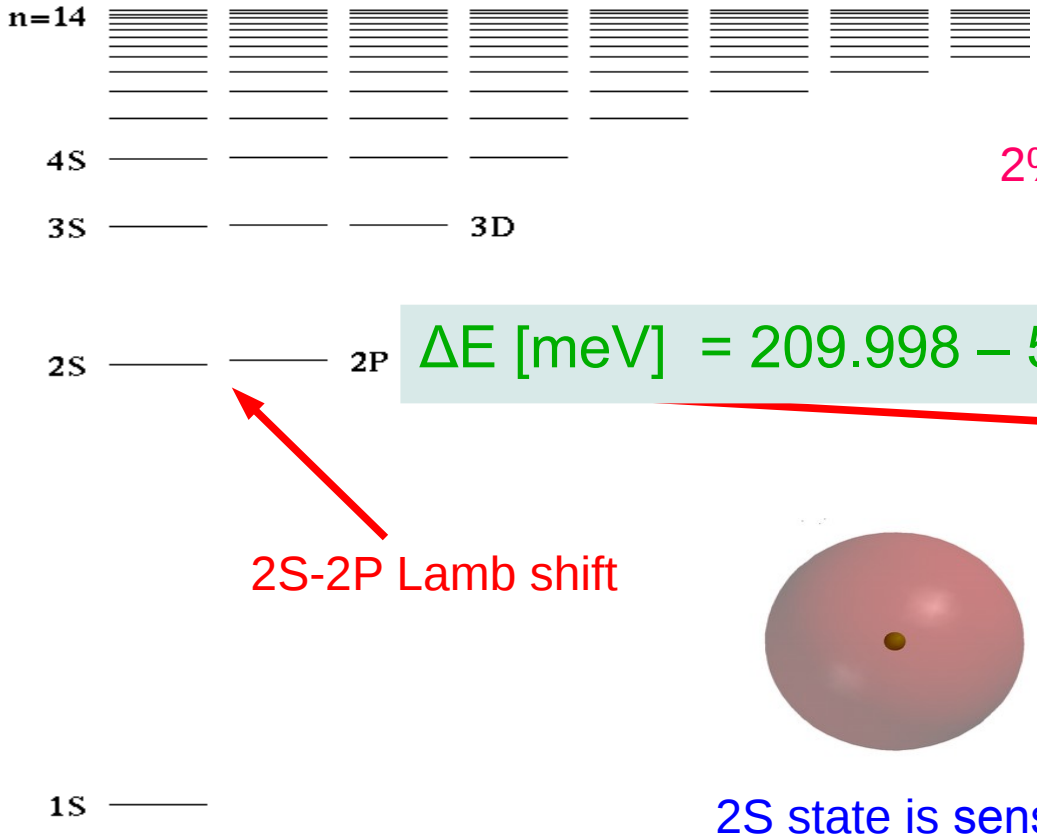
==> Our (laser) spectroscopy at **10^{-5}** level

can compete with **10^{-12}** from normal atoms

$$\Delta E_{\mathrm{FNS}}(n,l) = \frac{2c^4}{3\hbar^2}\frac{(Z\alpha)^4}{n^3} m_r^3 r^2 \delta_{l0}$$

Vastly not to scale!!

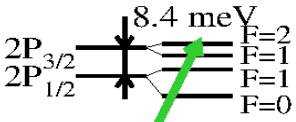
Lamb shift in Muonic Hydrogen



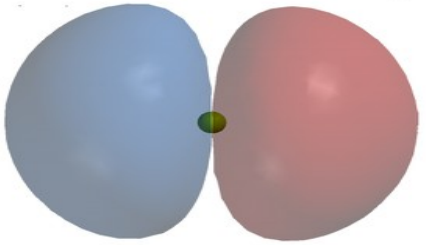
$$\Delta E\ [\text{meV}] = 209.998 - 5.226\ R_p^{\,2}\ [\text{fm}]$$

2% effect!

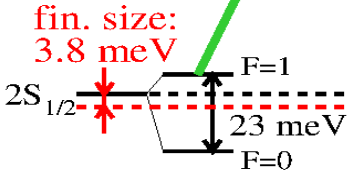
2S-2P Lamb shift



206 meV
50 THz
6 µm



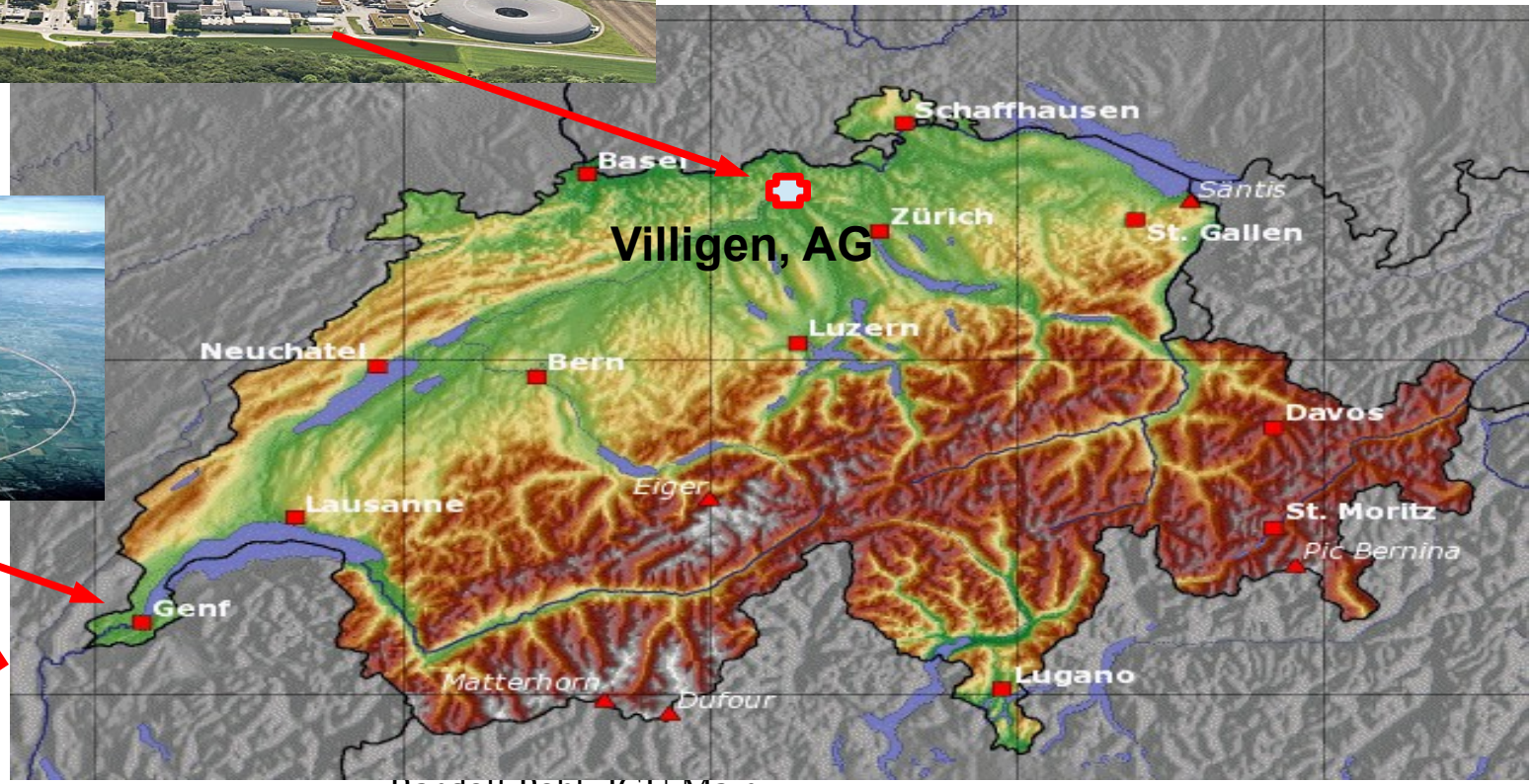
2P state: not sensitive to proton structure



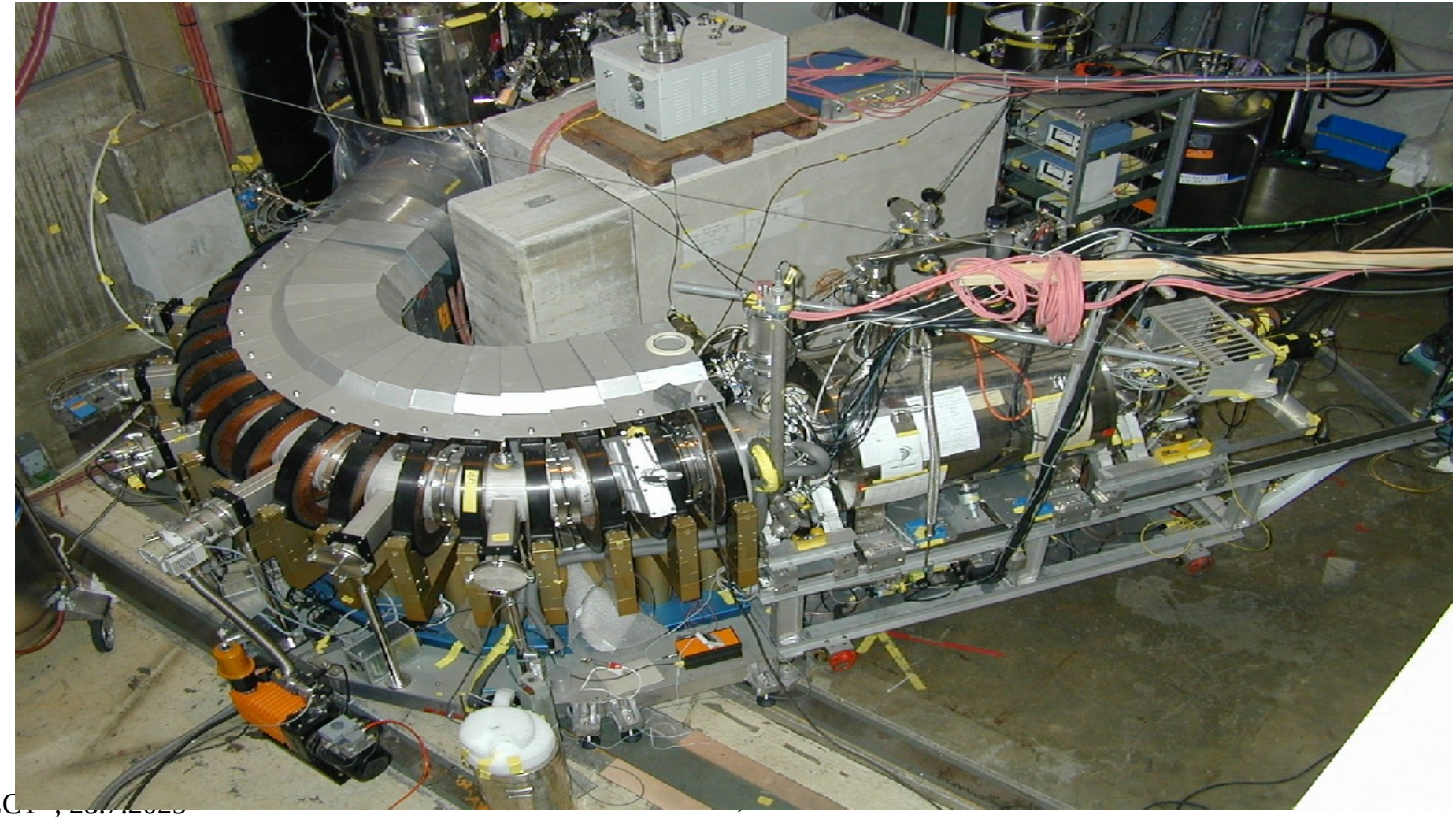
2S state is sensitive to the proton size.

The accelerator at PSI

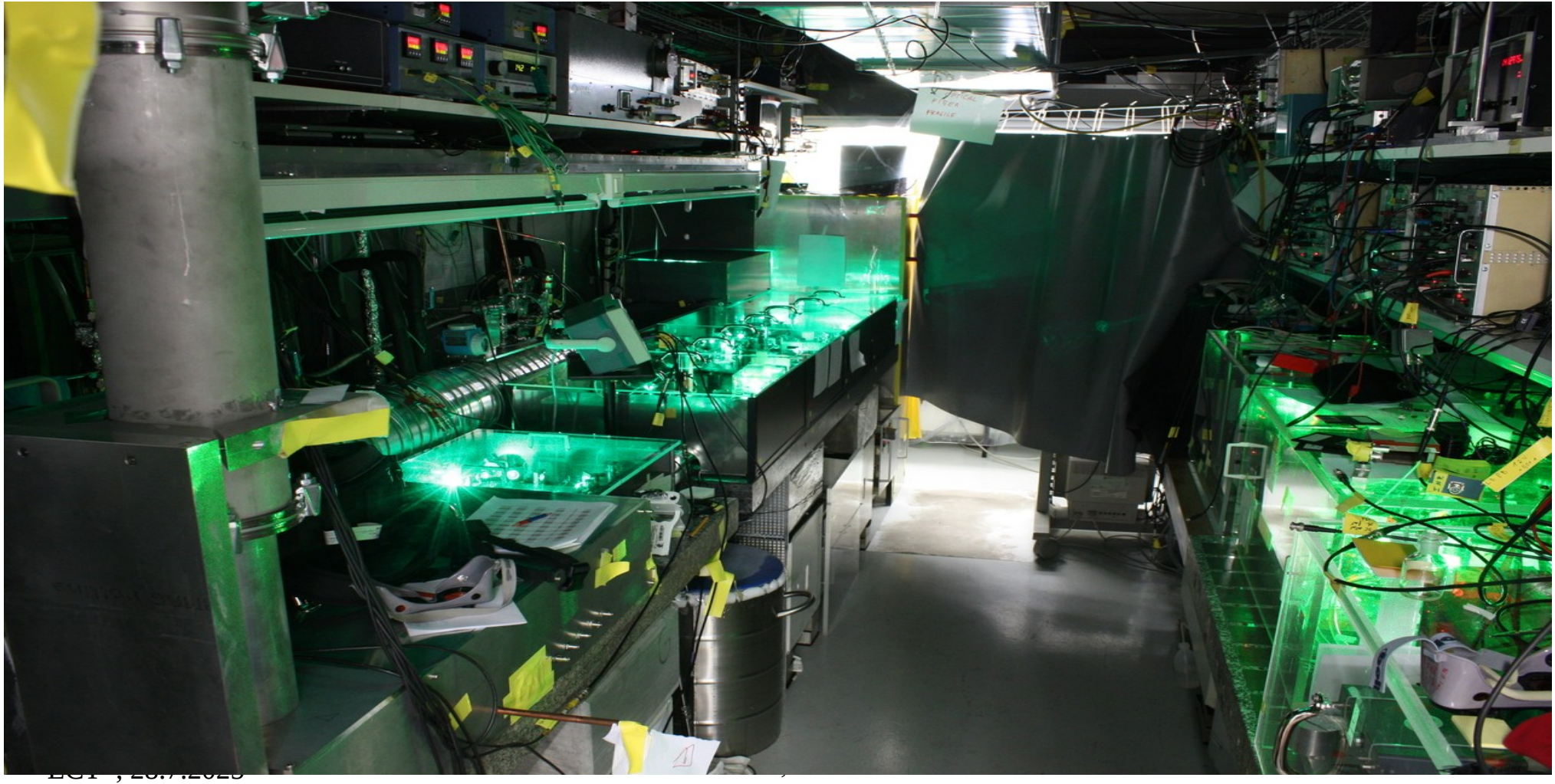
PAUL SCHERRER INSTITUT



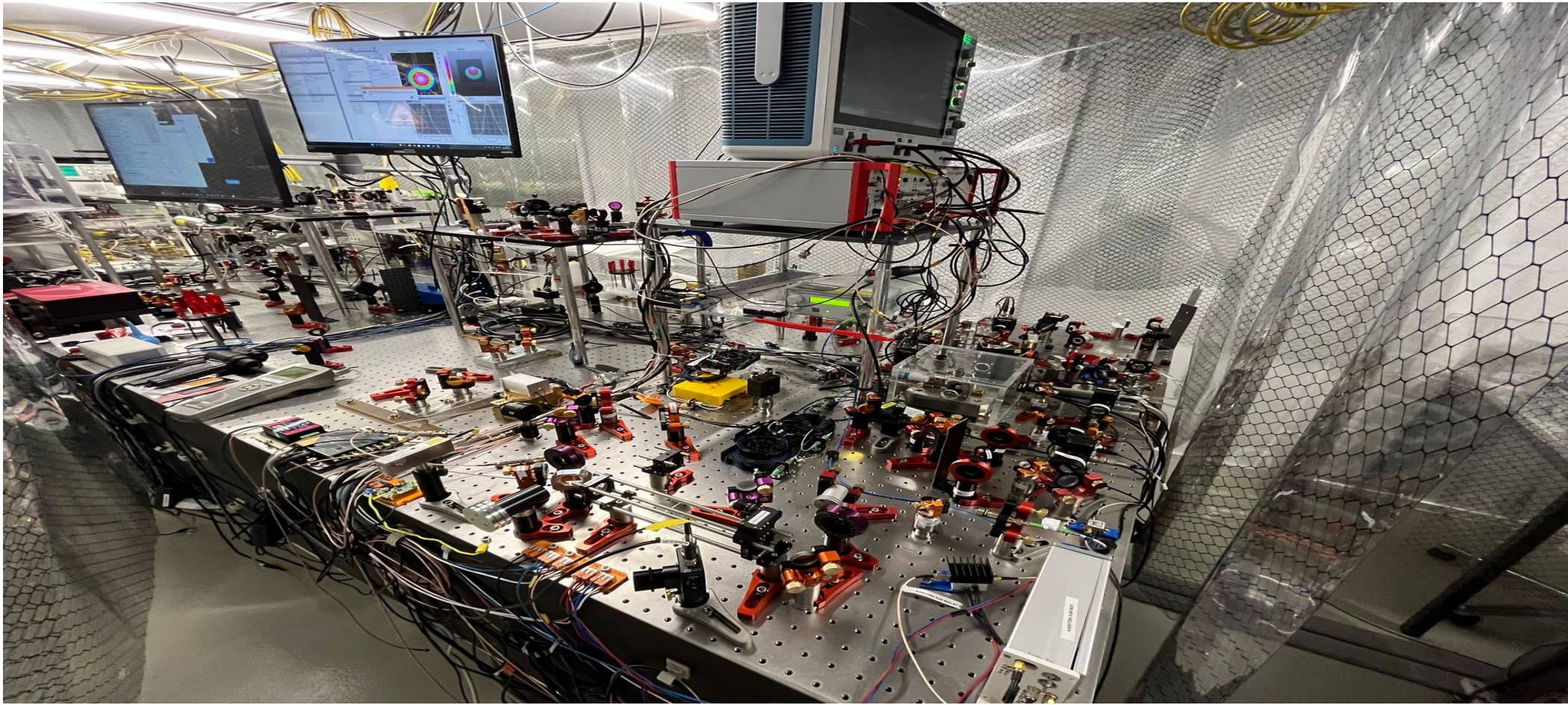
The muon beam line in πE5



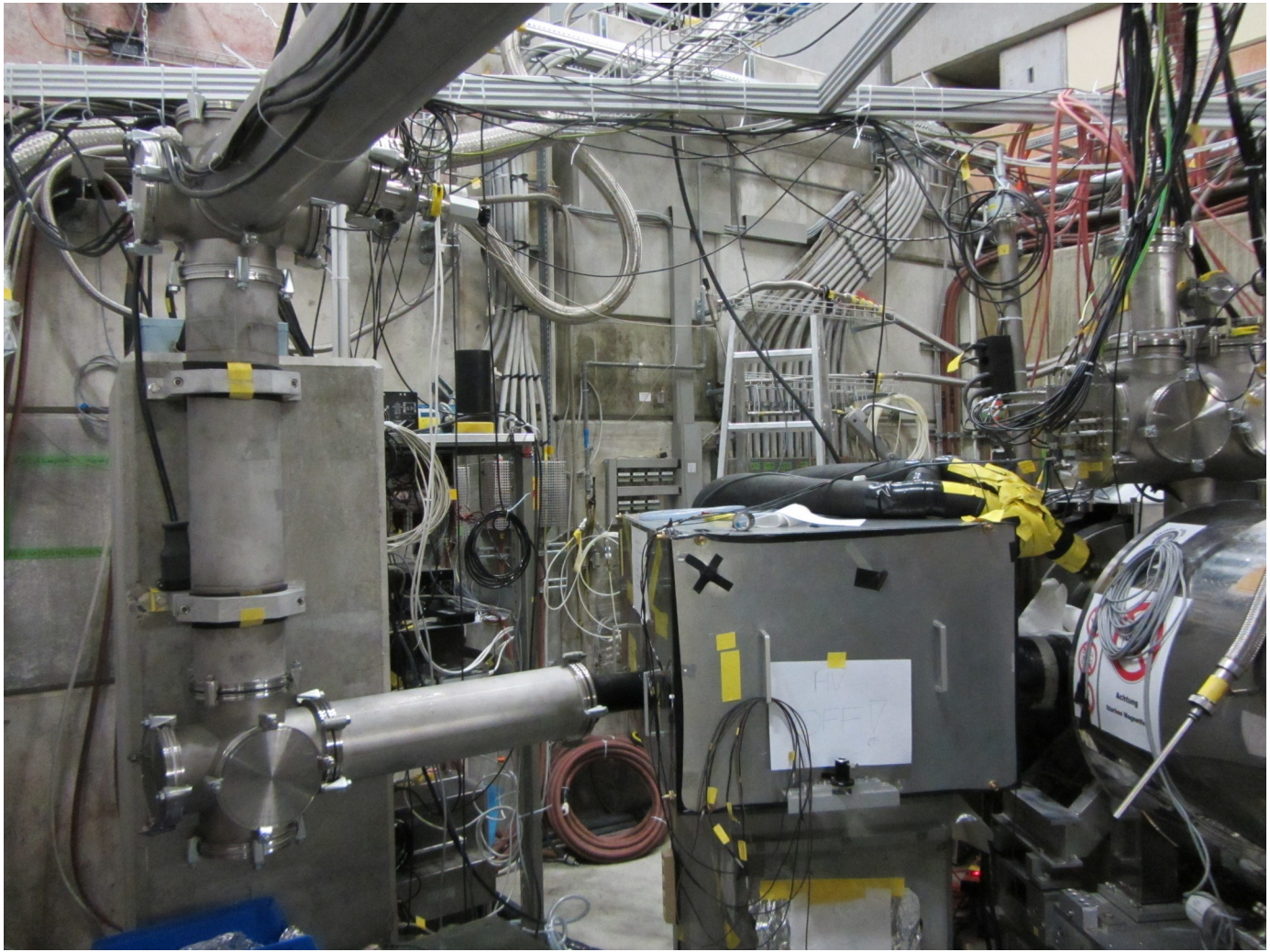
Inside the laser hut



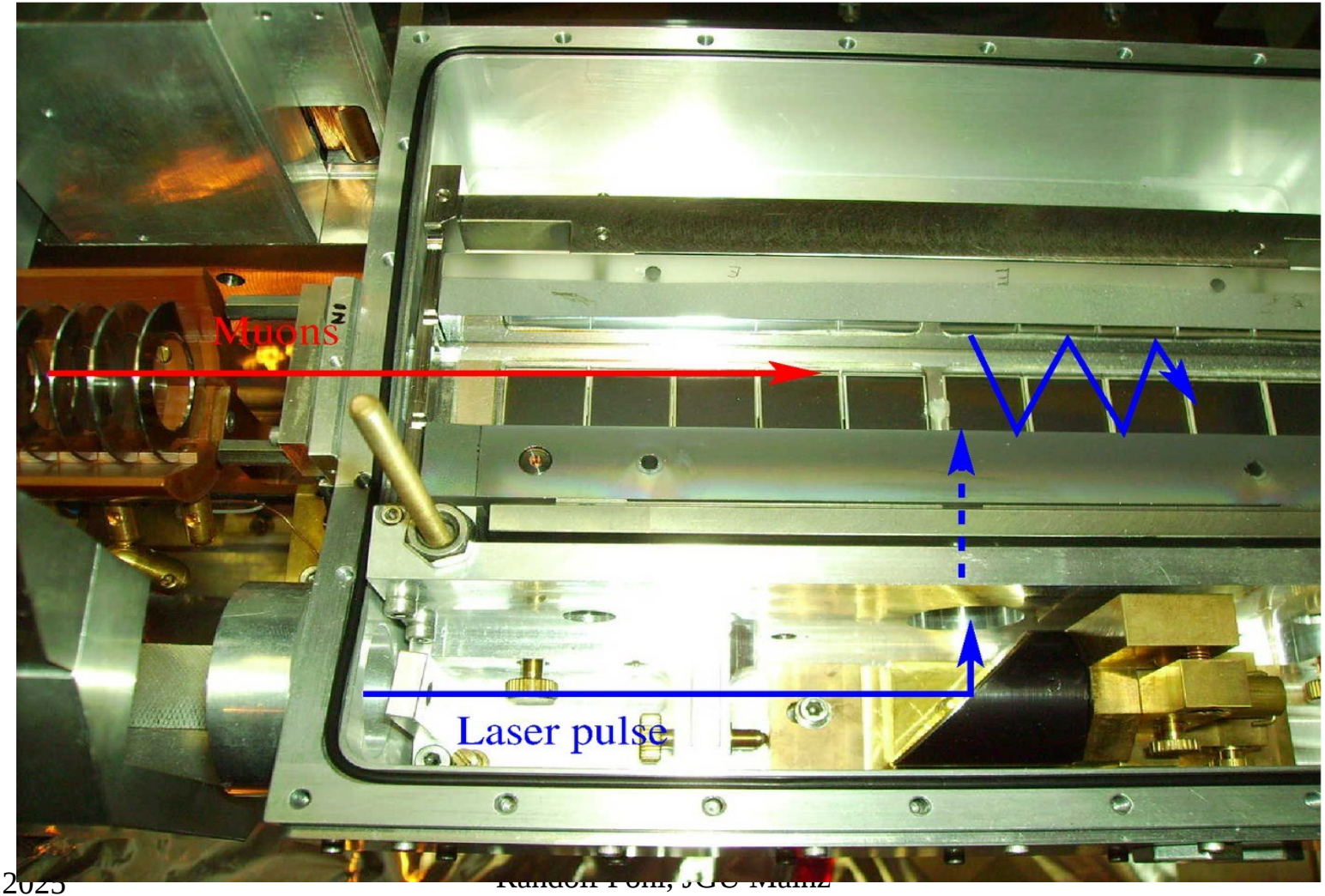
Inside the laser hut



Laser beam line

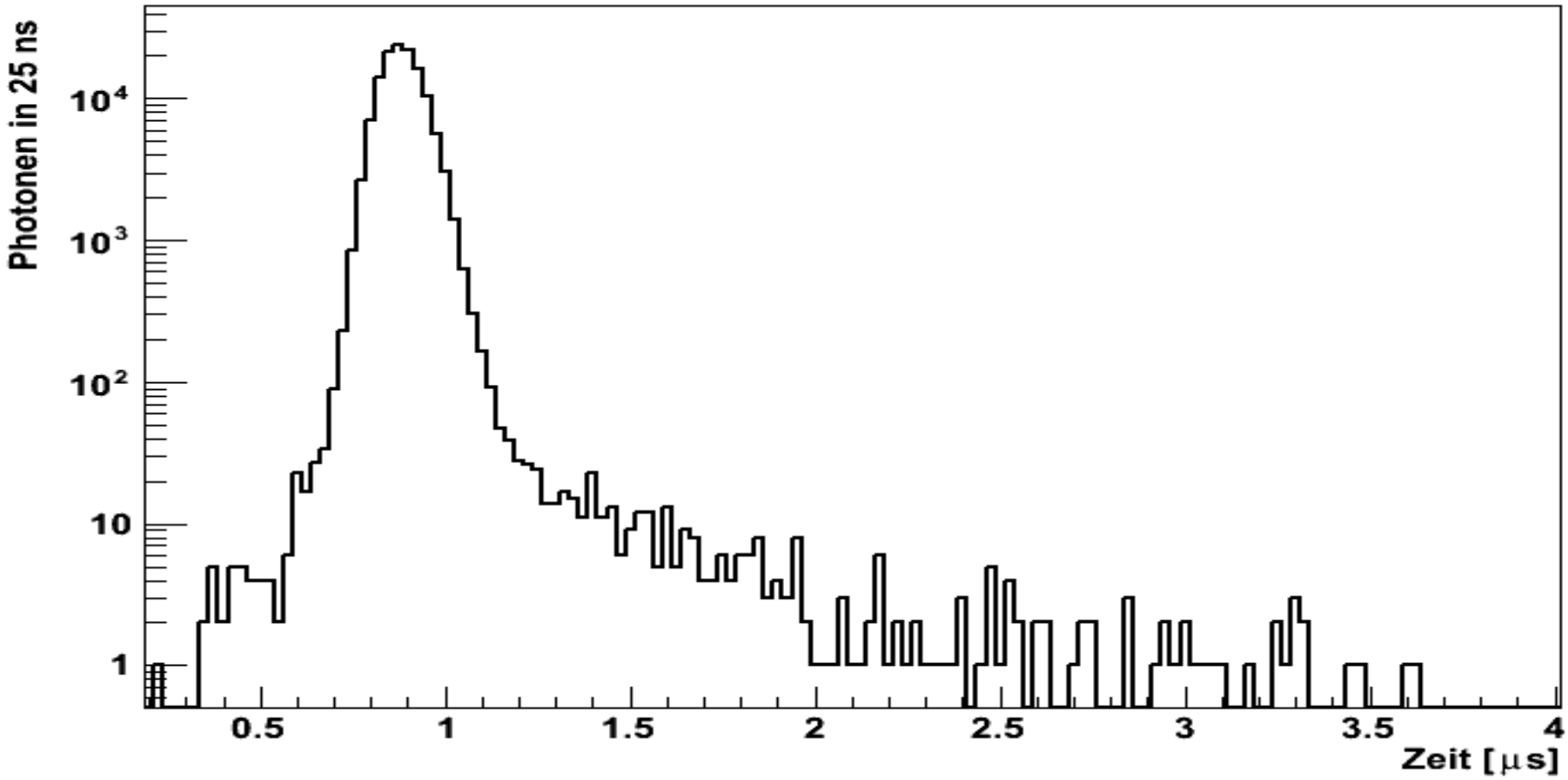


The hydrogen target



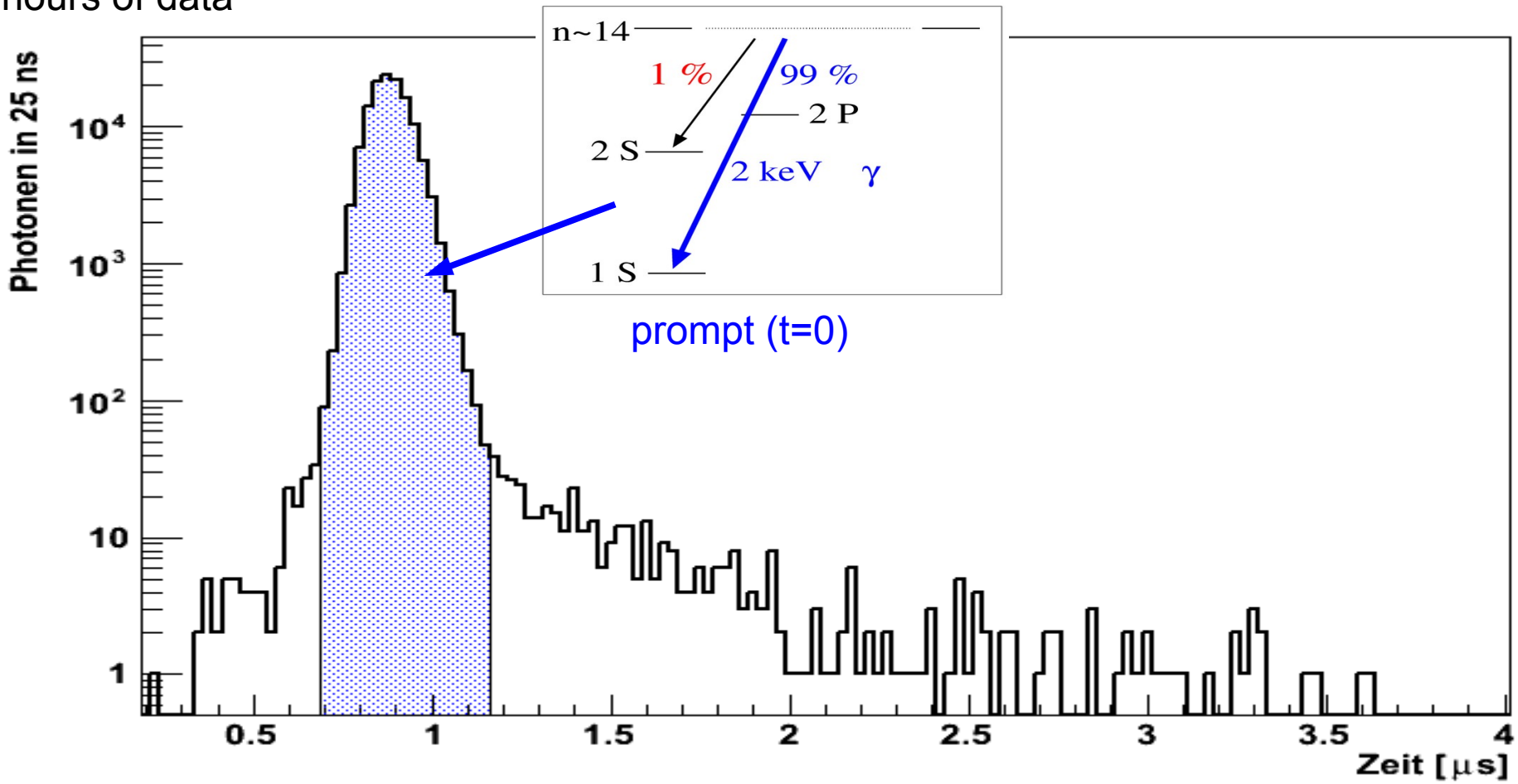
Time Spectra

13 hours of data

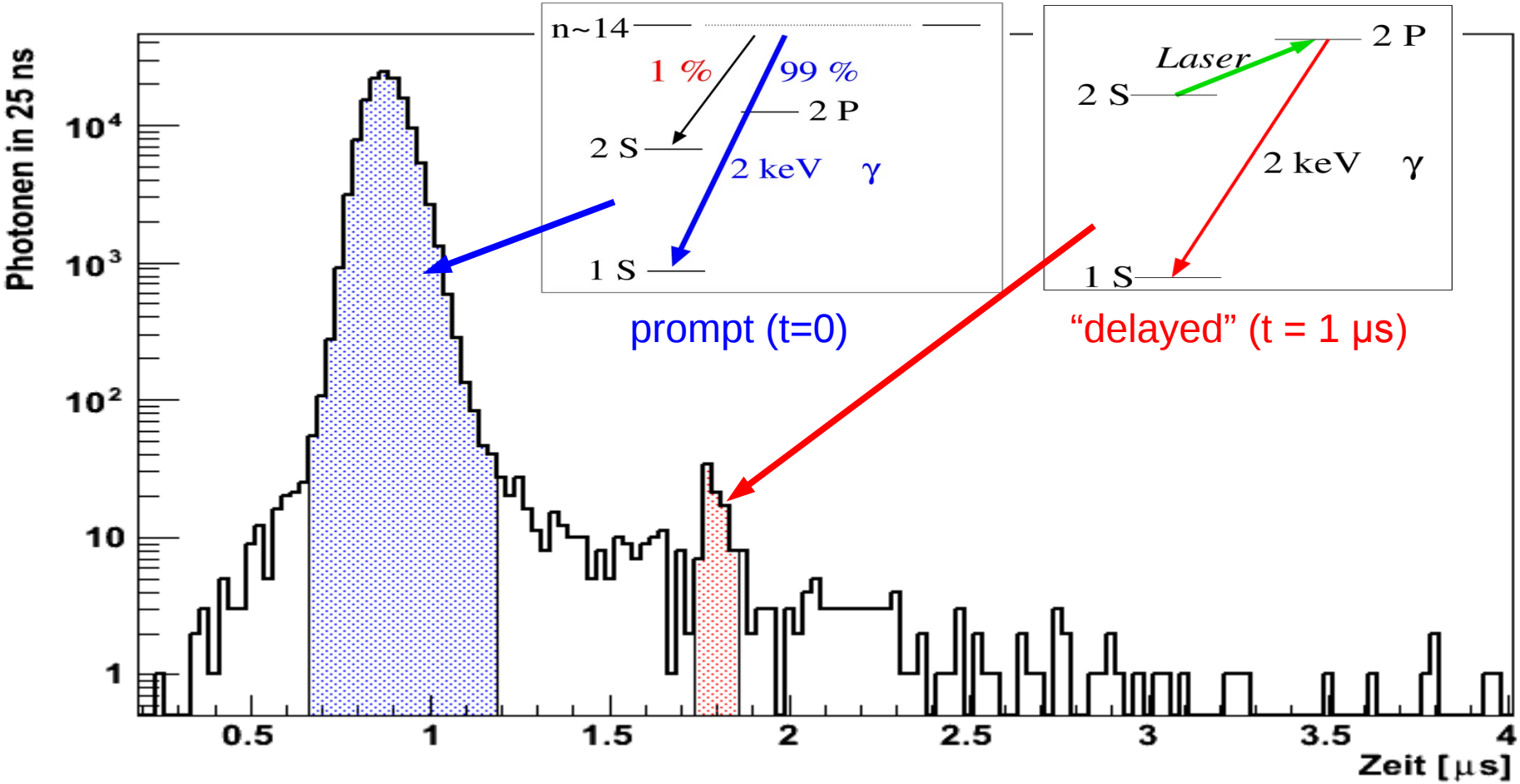


Time Spectra

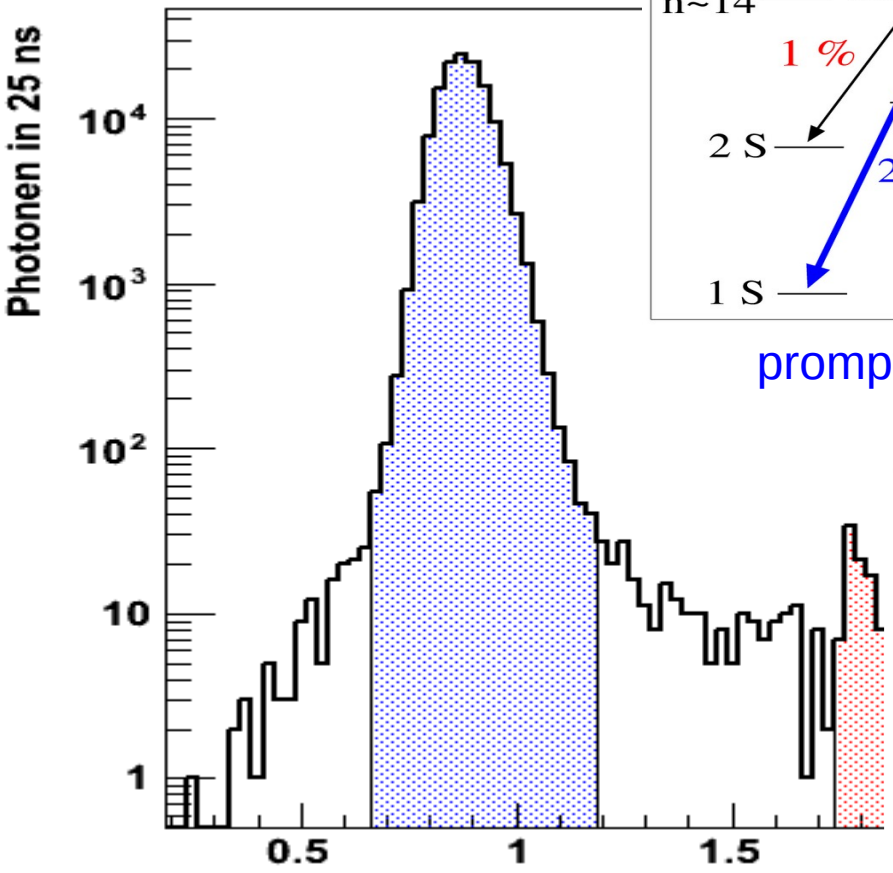
13 hours of data

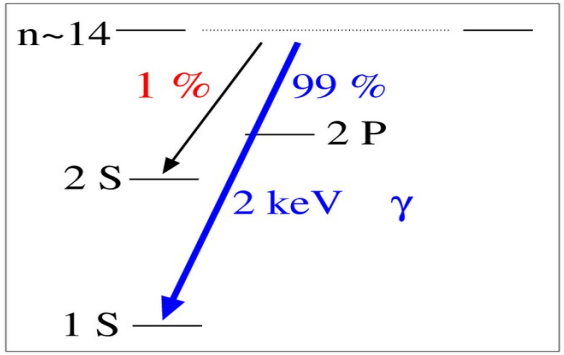


Time Spectra

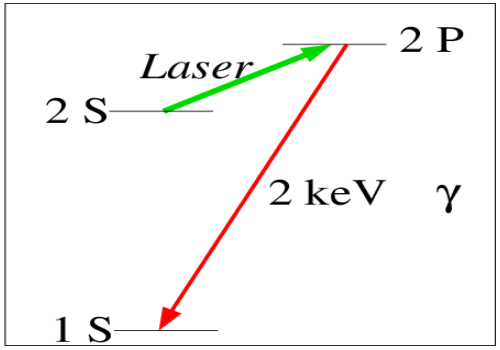


Time Spectra



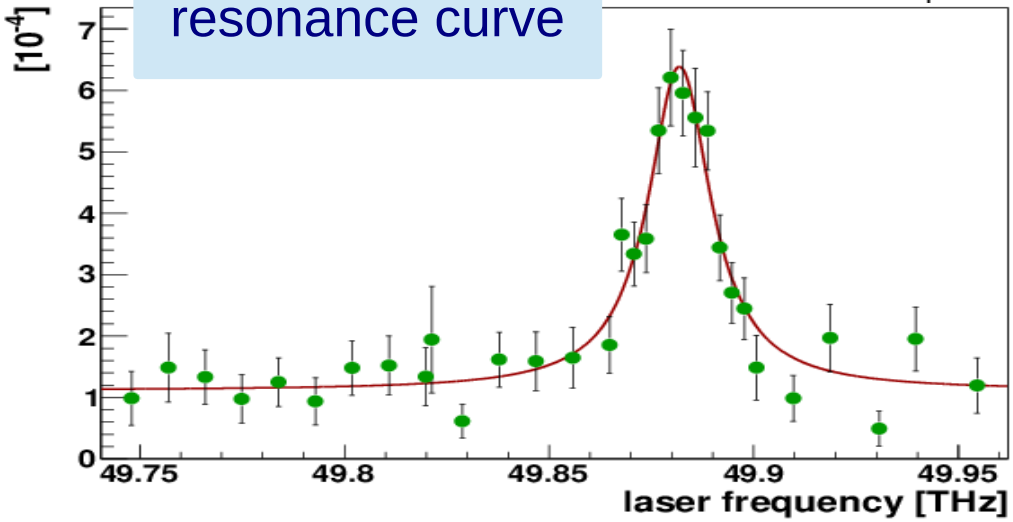


prompt (t=0)

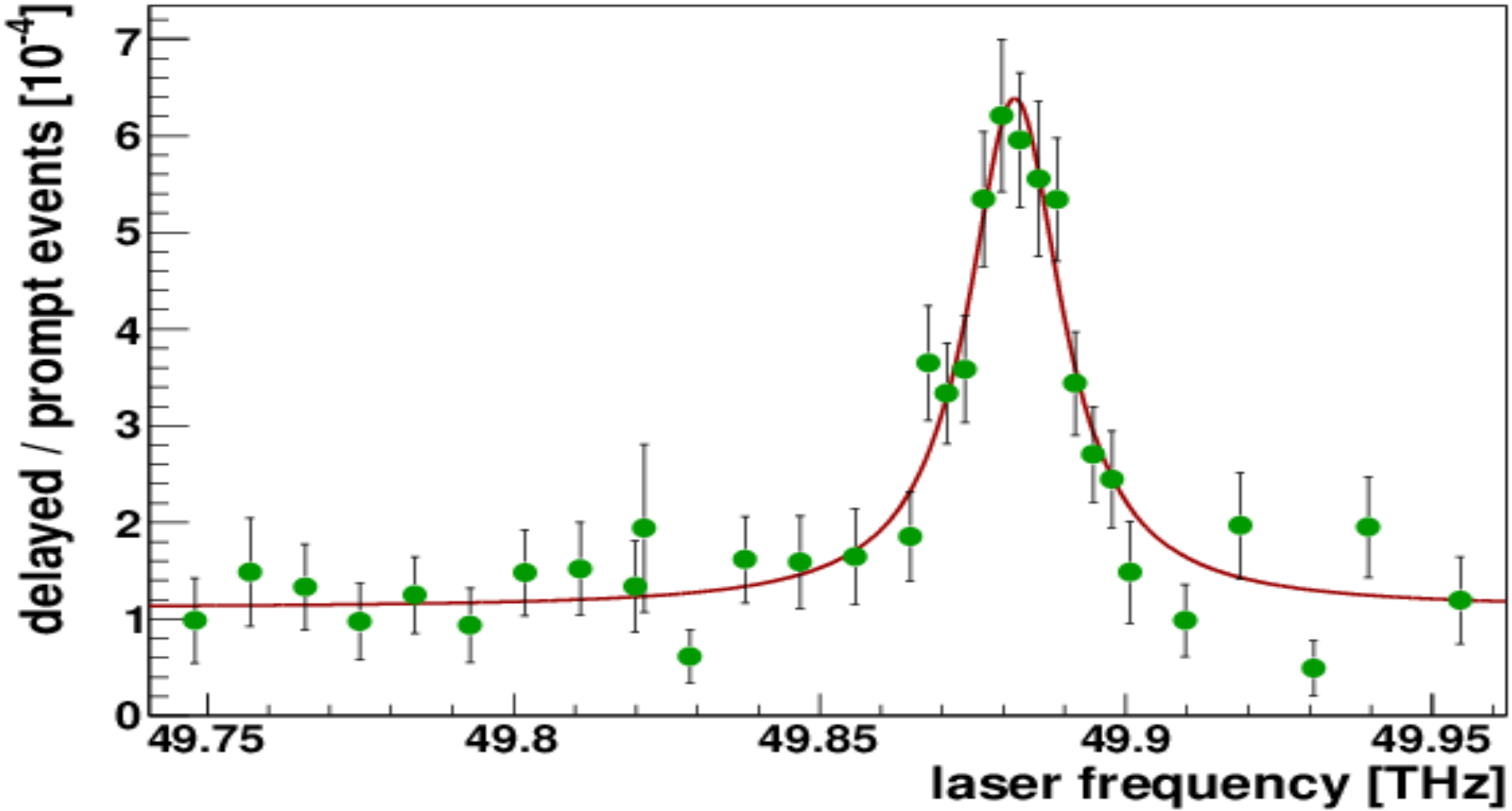


“delayed” (t = 1 μs)

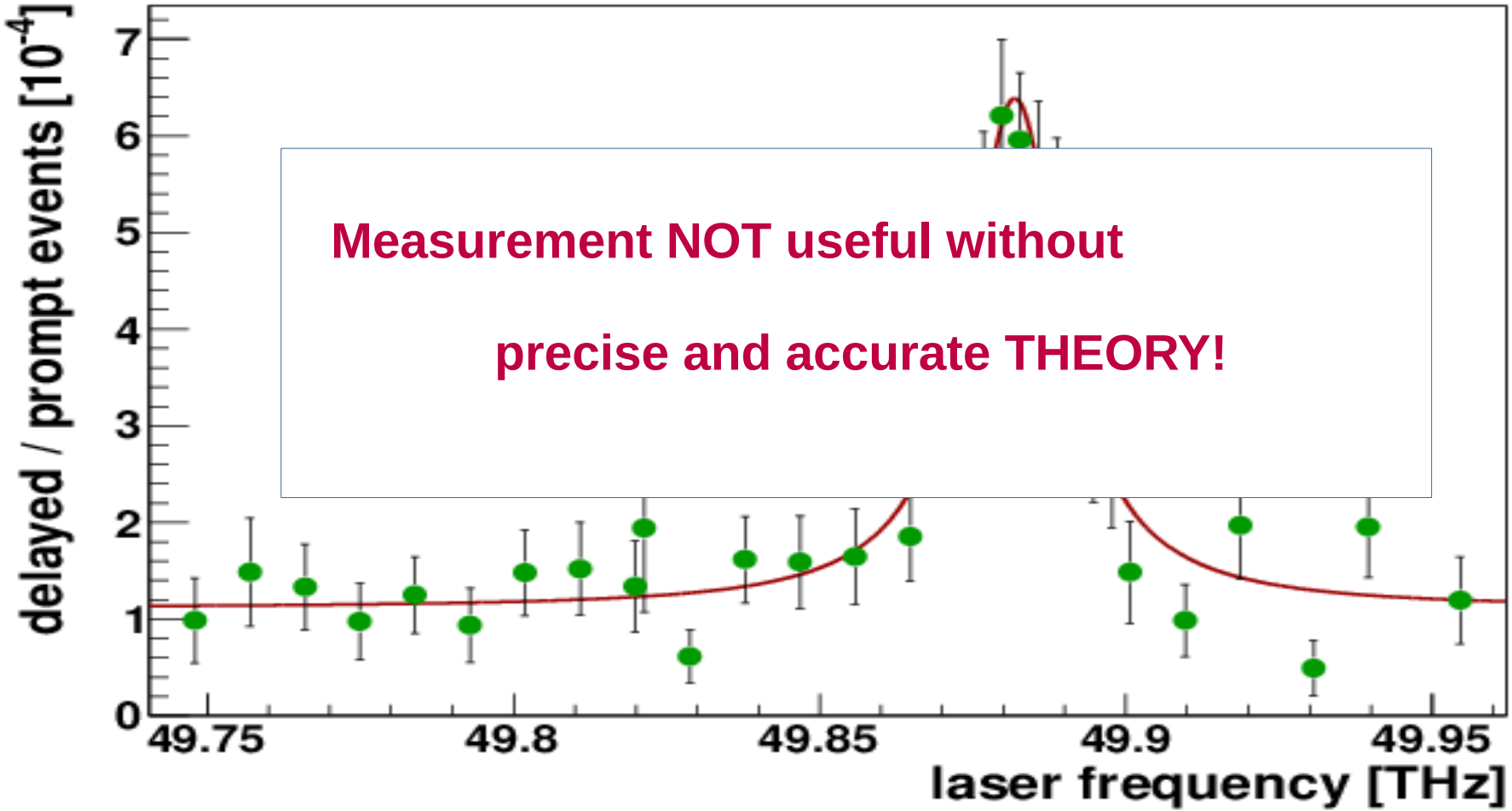
resonance curve



Resonance


delayed / prompt events [10^-4]
0
1
2
3
4
5
6
7
49.75
49.8
49.85
49.9
49.95
laser frequency [THz]

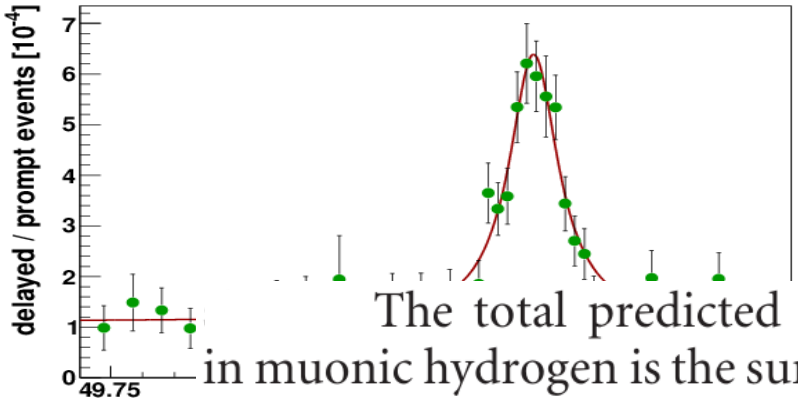
Resonance vs Result



Measurement NOT useful without

precise and accurate THEORY!

Resonance vs Result



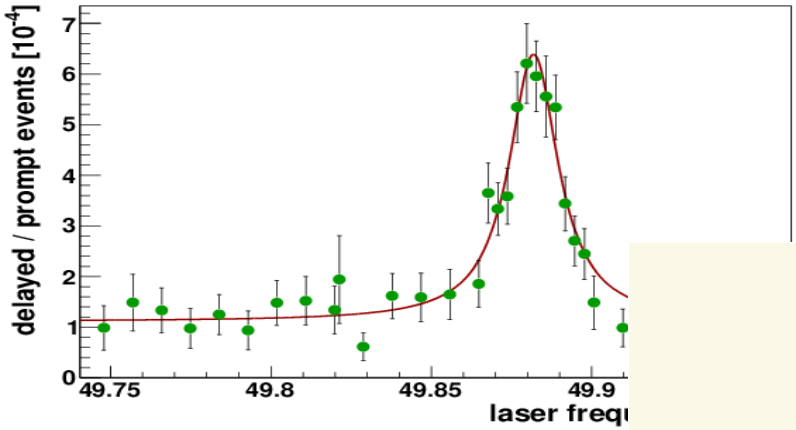
The total predicted $2S_{1/2}^{F=1} - 2P_{3/2}^{F=2}$ energy difference, $\Delta\tilde{E}$, in muonic hydrogen is the sum of radiative, recoil, and proton structure contributions, and the fine and hyperfine splittings for our particular transition, and it is given[8,11–15] by

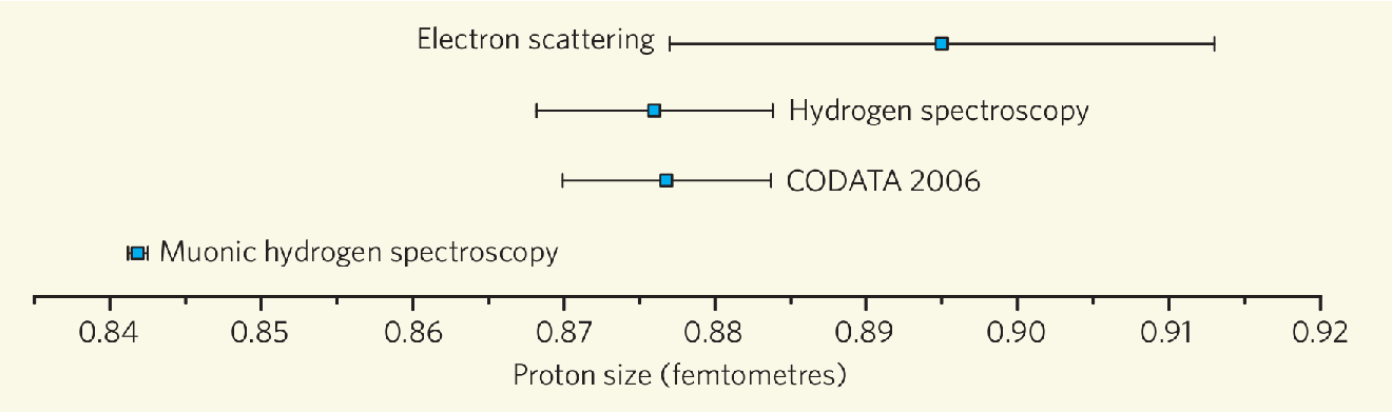
$$\boxed{\Delta\tilde{E} = 209.9779(49) - 5.2262\ r_p^2 + 0.0347\ r_p^3\ \text{meV}} \qquad (1)$$

where $r_p = \sqrt{\langle r_p^2 \rangle}$ is given in fm. A detailed derivation of equation (1) is given in Supplementary Information.

Measurement NOT useful without THEORY!

Resonance vs Result





$$\Delta\tilde{E} = 209.9779(49) - 5.2262\ r_p^2 + 0.0347\ r_p^3\ \text{meV} \qquad (1)$$

Measurement NOT useful without THEORY!

Theory in muonic H

$$\Delta E_{Lamb} = 206.0336\ (15)\ \text{meV}_{QED} + 0.0332\ (20)\ \text{meV}_{TPE} - 5.2275\ (10)\ \text{meV/fm}^2 * \mathbf{R_p^2}$$

Annals of Physics 331 (2013) 127–145

Contents lists available at SciVerse ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Theory of the 2S–2P Lamb shift and 2S hyperfine splitting in muonic hydrogen

Aldo Antognini [a,*], Franz Kottmann [a], François Biraben [b], Paul Indelicato [b], François Nez [b], Randolf Pohl [c]

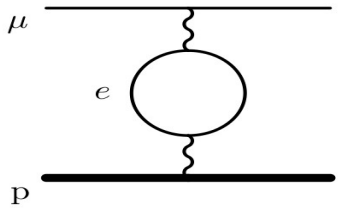
[a] Institute for Particle Physics, ETH Zurich, 8093 Zurich, Switzerland
[b] Laboratoire Kastler Brossel, École Normale Supérieure, CNRS and Université P. et M. Curie, 75252 Paris, CEDEX 05, France
[c] Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

Our attempt to summarize all the original work by many theorists….

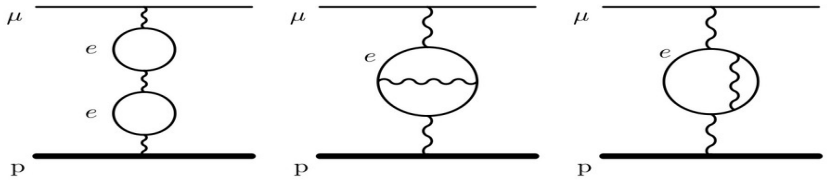
Theory in muonic H

ΔE_{Lamb} = 206.0344 (3) meV_{QED} + 0.0289 (25) meV_{TPE} – 5.2259 (1) meV/fm^2 * $\mathbf{R_p^2}$

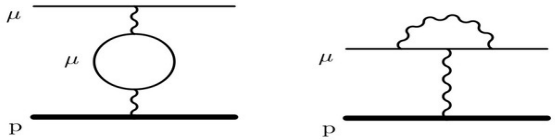
Uehling



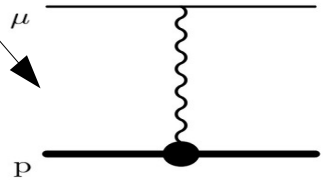
Källen-Sabry



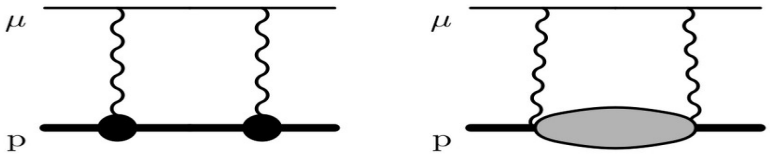
Muon SE+VP



and 20+ more….



Proton form factor



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

Theory I: “pure” QED

Table 1
All known radius-*independent* contributions to the Lamb shift in μp from different authors, and the one we selected. Values are in meV. The entry # in the first column refers to Table 1 in Ref. [13]. The “finite-size to relativistic recoil correction” (entry #18 in [13]), which depends on the proton structure, has been shifted to Table 2, together with the small terms #26 and #27, and the proton polarizability term #25. SE: self-energy, VP: vacuum polarization, LBL: light-by-light scattering, Rel: relativistic, NR: non-relativistic, RC: recoil correction.

#	Contribution	Pachucki [10,11]	Nature [13]	Borie-v6 [79]	Indelicato [80]	Our choice	Ref.
1	NR one-loop electron VP (eVP)	205.0074					
2	Rel. corr. (Breit–Pauli)	0.0169[a]					
3	Rel. one-loop eVP		205.0282	205.0282	205.02821	205.02821	[80] Eq. (54)
19	Rel. RC to eVP, $\alpha(Z\alpha)^4$	(incl. in #2)[b]	−0.0041	−0.0041		−0.00208[c]	[77,78]
4	Two-loop eVP (Källén–Sabry)	1.5079	1.5081	1.5081	1.50810	1.50810	[80] Eq. (57)
5	One-loop eVP in 2-Coulomb lines $\alpha^2(Z\alpha)^5$	0.1509	0.1509	0.1507	0.15102	0.15102	[80] Eq. (60)
7	eVP corr. to Källén–Sabry	0.0023	0.00223	0.00223	0.00215	0.00215	[80] Eq. (62), [87]
6	NR three-loop eVP	0.0053	0.00529	0.00529		0.00529	[87,88]
9	Wichmann–Kroll, “1:3” LBL		−0.00103	−0.00102	−0.00102	−0.00102	[80] Eq. (64), [89]
10	Virtual Delbrück, “2:2” LBL		0.00135	0.00115		0.00115	[74,89]
New	“3:1” LBL			−0.00102		−0.00102	[89]
20	μSE and μVP	−0.6677	−0.66770	−0.66788	−0.66761	−0.66761	[80] Eqs. (72) + (76)
11	Muon SE corr. to eVP $\alpha^2(Z\alpha)^4$	−0.005(1)	−0.00500	−0.004924[d]		−0.00254	[85] Eq. (29a)[e]
12	eVP loop in self-energy $\alpha^2(Z\alpha)^4$	−0.001	−0.00150			[f]	[74,90–92]
21	Higher order corr. to μSE and μVP		−0.00169	−0.00171[g]		−0.00171	[86] Eq. (177)
13	Mixed eVP + μVP		0.00007	0.00007		0.00007	[74]
New	eVP and μVP in two Coulomb lines				0.00005	0.00005	[80] Eq. (78)
14	Hadronic VP $\alpha(Z\alpha)^4 m_r$	0.0113(3)	0.01077(38)	0.011(1)		0.01121(44)	[93–95]
15	Hadronic VP $\alpha(Z\alpha)^5 m_r$		0.000047			0.000047	[94,95]
16	Rad corr. to hadronic VP		−0.000015			−0.000015	[94,95]
17	Recoil corr.	0.0575	0.05750	0.0575	0.05747	0.05747	[80] Eq. (88)
22	Rel. RC $(Z\alpha)^5$	−0.045	−0.04497	−0.04497	−0.04497	−0.04497	[80] Eq. (88), [74]
23	Rel. RC $(Z\alpha)^6$	0.0003	0.00030		0.0002475	0.0002475	[80] Eq. (86)+Tab.II
New	Rad. (only eVP) RC $\alpha(Z\alpha)^5$					0.000136	[85] Eq. (64a)
24	Rad. RC $\alpha(Z\alpha)^n$ (proton SE)	−0.0099	−0.00960	−0.0100		−0.01080(100)	[43][h] [74]
	Sum	206.0312	206.02915	206.02862		206.03339(109)	

Antognini, RP at al., Ann. Phys. (N.Y.) 331, 127 (2013)

Theory

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, RP, RMP 96 (2024)

REVIEWS OF MODERN PHYSICS, VOLUME 96, JANUARY–MARCH 2024

Comprehensive theory of the Lamb shift in light muonic atoms

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(published 24 January 2024)

A comprehensive theory of the Lamb shift in light muonic atoms such as μH, μD, μ^3He$^+$, and μ^4He$^+$ is presented, with all quantum electrodynamic corrections included at the precision level constrained by the uncertainty of nuclear structure effects. This analysis can be used in the global adjustment of fundamental constants and in the determination of nuclear charge radii. Further improvements in the understanding of electromagnetic interactions of light nuclei will allow for a promising test of fundamental interactions by comparison with "normal" atomic spectroscopy, in particular, with H-D and ^{3}He-^{4}He isotope shifts.

DOI: 10.1103/RevModPhys.96.015001

Theory

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, RP, RMP 96 (2024)

TABLE I. Contributions to the $2P_{1/2} - 2S_{1/2}$ energy difference E_L in meV, with the charge radii r_C given in fm. All corrections larger than 3% of the overall uncertainty are included. Theoretical predictions for E_L are $E_L(\text{theo}) = E_{\text{QED}} + \mathcal{C}r_C^2 + E_{\text{NS}}$. The last two rows show the values of r_C determined from a comparison of $E_L(\text{theo})$ to $E_L(\text{exp})$.

Section	Order	Correction	μH	μD	μ^3He$^+$	μ^4He$^+$
III.A	$\alpha(Z\alpha)^2$	eVP$^{(1)}$	205.007 38	227.634 70	1641.886 2	1665.773 1
III.A	$\alpha^2(Z\alpha)^2$	eVP$^{(2)}$	1.658 85	1.838 04	13.084 3	13.276 9
III.A	$\alpha^3(Z\alpha)^2$	eVP$^{(3)}$	0.007 52	0.008 42(7)	0.073 0(30)	0.074 0(30)
III.B	$(Z, Z^2, Z^3)\alpha^5$	Light-by-light eVP	−0.000 89(2)	−0.000 96(2)	−0.013 4(6)	−0.013 6(6)
III.C	$(Z\alpha)^4$	Recoil	0.057 47	0.067 22	0.126 5	0.295 2
III.D	$\alpha(Z\alpha)^4$	Relativistic with eVP$^{(1)}$	0.018 76	0.021 78	0.509 3	0.521 1
III.E	$\alpha^2(Z\alpha)^4$	Relativistic with eVP$^{(2)}$	0.000 17	0.000 20	0.005 6	0.005 7
III.F	$\alpha(Z\alpha)^4$	μSE$^{(1)}$ + μVP$^{(1)}$, LO	−0.663 45	−0.769 43	−10.652 5	−10.926 0
III.G	$\alpha(Z\alpha)^5$	μSE$^{(1)}$ + μVP$^{(1)}$, NLO	−0.004 43	−0.005 18	−0.174 9	−0.179 7
III.H	$\alpha^2(Z\alpha)^4$	μVP$^{(1)}$ with eVP$^{(1)}$	0.000 13	0.000 15	0.003 8	0.003 9
III.I	$\alpha^2(Z\alpha)^4$	μSE$^{(1)}$ with eVP$^{(1)}$	−0.002 54	−0.003 06	−0.062 7	−0.064 6
III.J	$(Z\alpha)^5$	Recoil	−0.044 97	−0.026 60	−0.558 1	−0.433 0
III.K	$\alpha(Z\alpha)^5$	Recoil with eVP$^{(1)}$	0.000 14(14)	0.000 09(9)	0.004 9(49)	0.003 9(39)
III.L	$Z^2\alpha(Z\alpha)^4$	nSE$^{(1)}$	−0.009 92	−0.003 10	−0.084 0	−0.050 5
III.M	$\alpha^2(Z\alpha)^4$	$\mu F_1^{(2)}$, $\mu F_2^{(2)}$, μVP$^{(2)}$	−0.001 58	−0.001 84	−0.031 1	−0.031 9
III.N	$(Z\alpha)^6$	Pure recoil	0.000 09	0.000 04	0.001 9	0.001 4
III.O	$\alpha(Z\alpha)^5$	Radiative recoil	0.000 22	0.000 13	0.002 9	0.002 3
III.P	$\alpha(Z\alpha)^4$	hVP	0.011 36(27)	0.013 28(32)	0.224 1(53)	0.230 3(54)
III.Q	$\alpha^2(Z\alpha)^4$	hVP with eVP$^{(1)}$	0.000 09	0.000 10	0.002 6(1)	0.002 7(1)
IV.A	$(Z\alpha)^4$	r_C^2	$-5.197\,5r_p^2$	$-6.073\,2r_d^2$	$-102.523r_h^2$	$-105.322r_\alpha^2$
IV.B	$\alpha(Z\alpha)^4$	eVP$^{(1)}$ with r_C^2	$-0.028\,2r_p^2$	$-0.034\,0r_d^2$	$-0.851r_h^2$	$-0.878r_\alpha^2$
IV.C	$\alpha^2(Z\alpha)^4$	eVP$^{(2)}$ with r_C^2	$-0.000\,2r_p^2$	$-0.000\,2r_d^2$	$-0.009(1)r_h^2$	$-0.009(1)r_\alpha^2$
V.A	$(Z\alpha)^5$	TPE	0.029 2(25)	1.979(20)	16.38(31)	9.76(40)
V.B	$\alpha^2(Z\alpha)^4$	Coulomb distortion	0.0	−0.261	−1.010	−0.536
V.C	$(Z\alpha)^6$	3PE	−0.001 3(3)	0.002 2(9)	−0.214(214)	−0.165(165)
V.D	$\alpha(Z\alpha)^5$	eVP$^{(1)}$ with TPE	0.000 6(1)	0.027 5(4)	0.266(24)	0.158(12)
V.E	$\alpha(Z\alpha)^5$	μSE$^{(1)}$ + μVP$^{(1)}$ with TPE	0.000 4	0.002 6(3)	0.077(8)	0.059(6)
III	E_{QED}	Point nucleus	206.034 4(3)	228.774 0(3)	1644.348(8)	1668.491(7)
IV	$\mathcal{C}r_C^2$	Finite size	$-5.225\,9r_p^2$	$-6.107\,4r_d^2$	$-103.383r_h^2$	$-106.209r_\alpha^2$
V	E_{NS}	Nuclear structure	0.028 9(25)	1.750 3(200)	15.499(378)	9.276(433)
	E_L (exp)	Experiment[a]	202.370 6(23)	202.878 5(34)	1258.598(48)	1378.521(48)
	r_C	This review	0.840 60(39)	2.127 58(78)	1.970 07(94)	1.678 6(12)
	r_C	Previous work[a]	0.840 87(39)	2.125 62(78)	1.970 07(94)	1.678 24(83)

Theory

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, RP, RMP 96 (2024)

TABLE I. Contributions to the $2P_{1/2} - 2S_{1/2}$ energy difference E_L in meV, with the charge radii r_C given in fm. All corrections larger than 3% of the overall uncertainty are included. Theoretical predictions for E_L are $E_L(\text{theo}) = E_{\text{QED}} + \mathcal{C}r_C^2 + E_{\text{NS}}$. The last two rows show the values of r_C determined from a comparison of $E_L(\text{theo})$ to $E_L(\text{exp})$.

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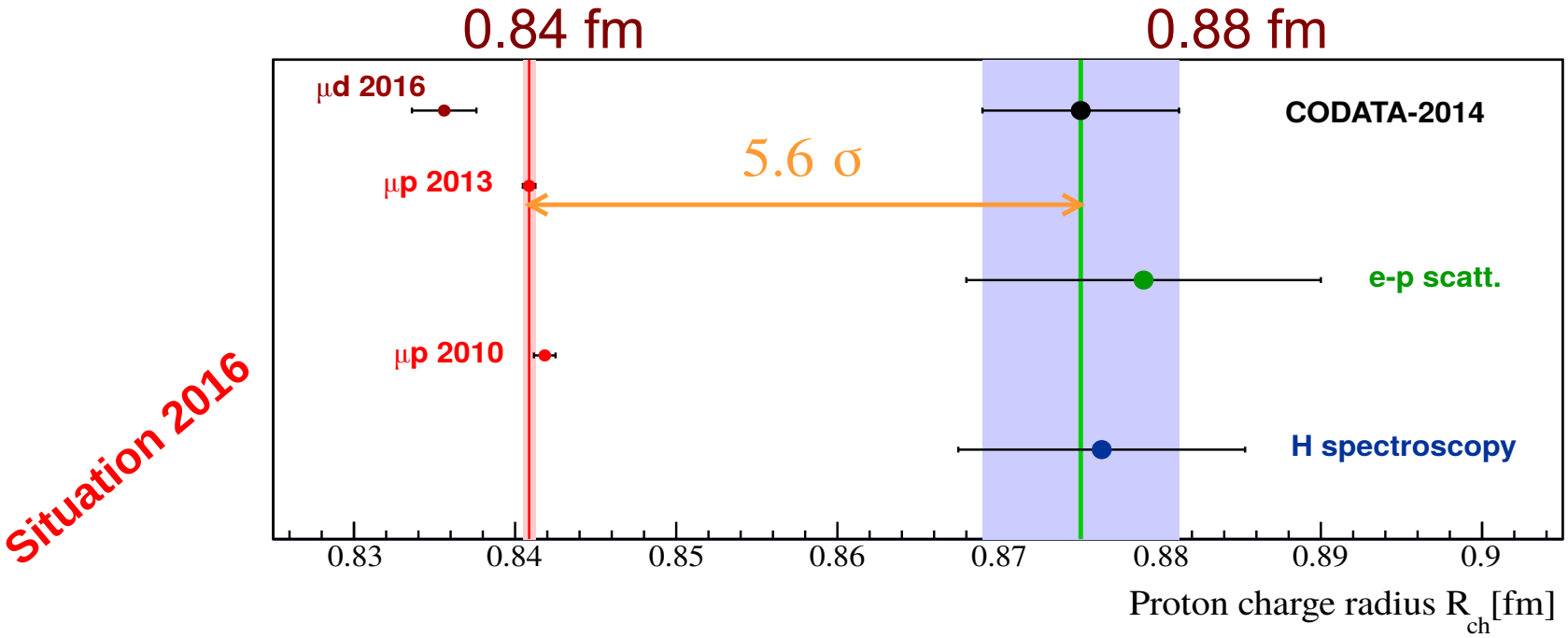
The “Proton Radius Puzzle“

Measuring R_p using electrons: 0.88 fm (+- 0.7%)
using muons: 0.84 fm (+- 0.05%)



μd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
μp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

ECT* Workshop 2012

“Fitting wars”

TPE and The Subtraction Term

Missing QED contributions?

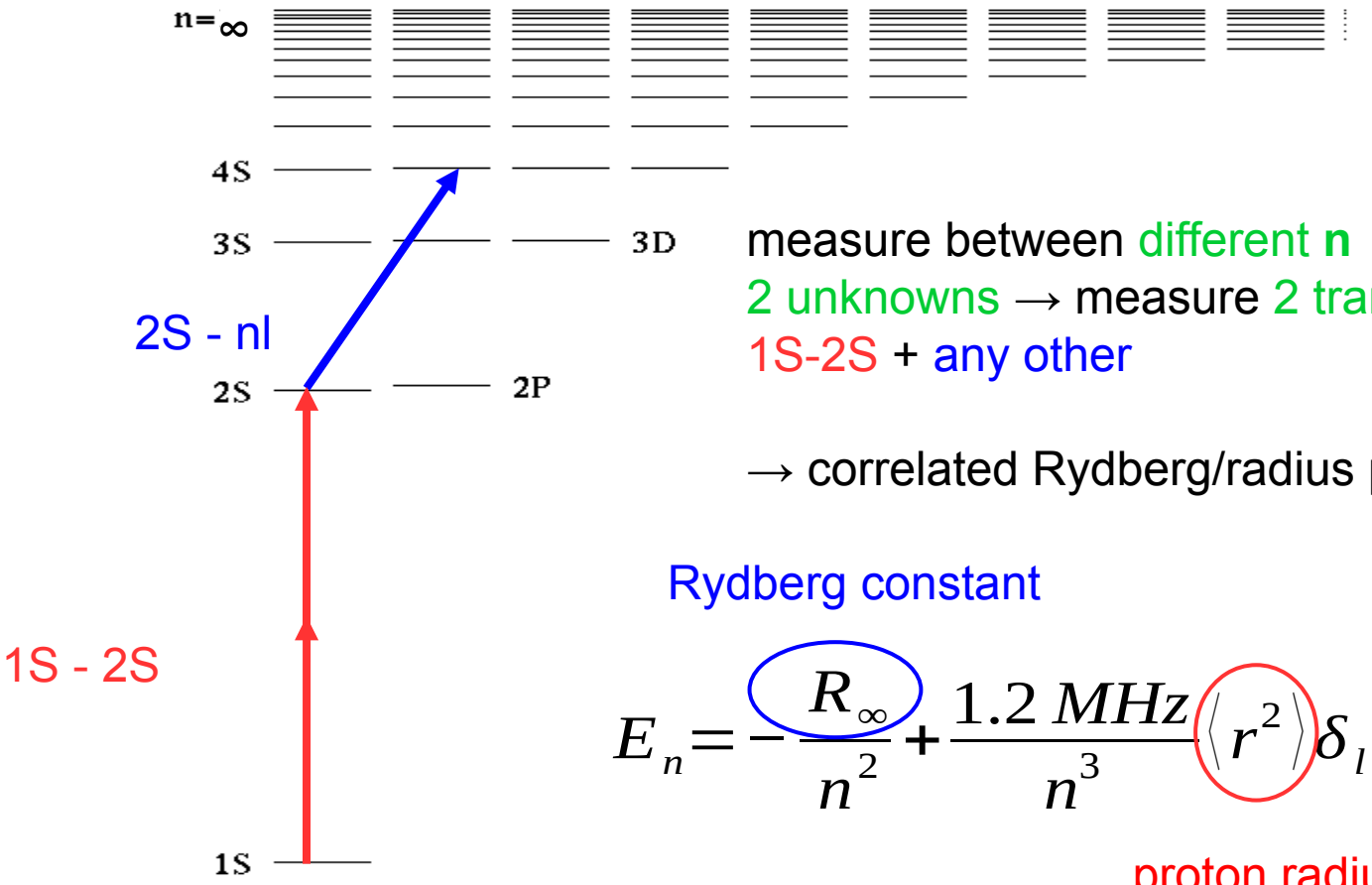
Form factors vs. charge density

BSM Physics

Muon Scattering

muH-HFS

Hydrogen energy levels



measure between different **n**

2 unknowns → measure 2 transitions:

1S-2S + any other

→ correlated Rydberg/radius pairs

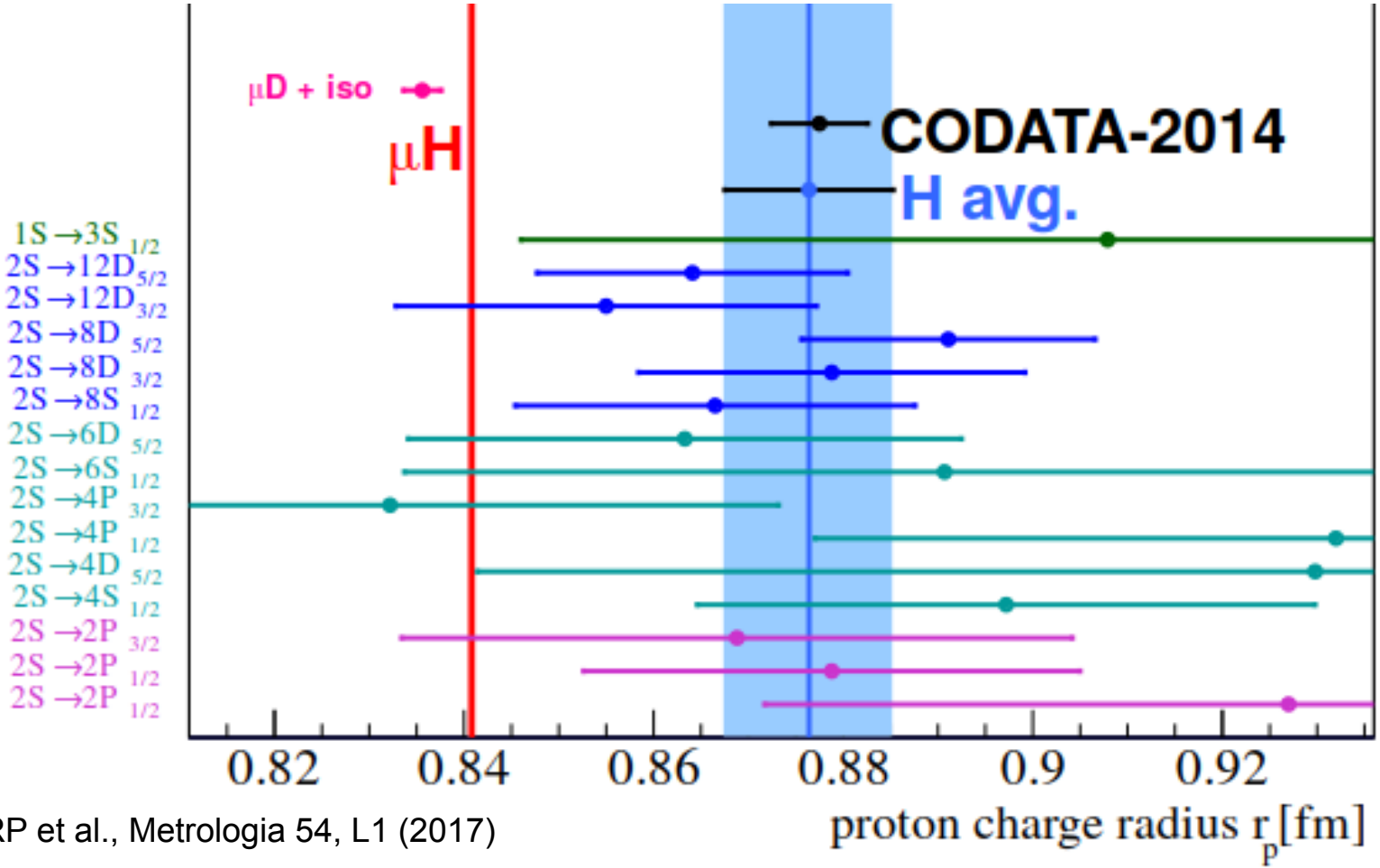
Rydberg constant

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

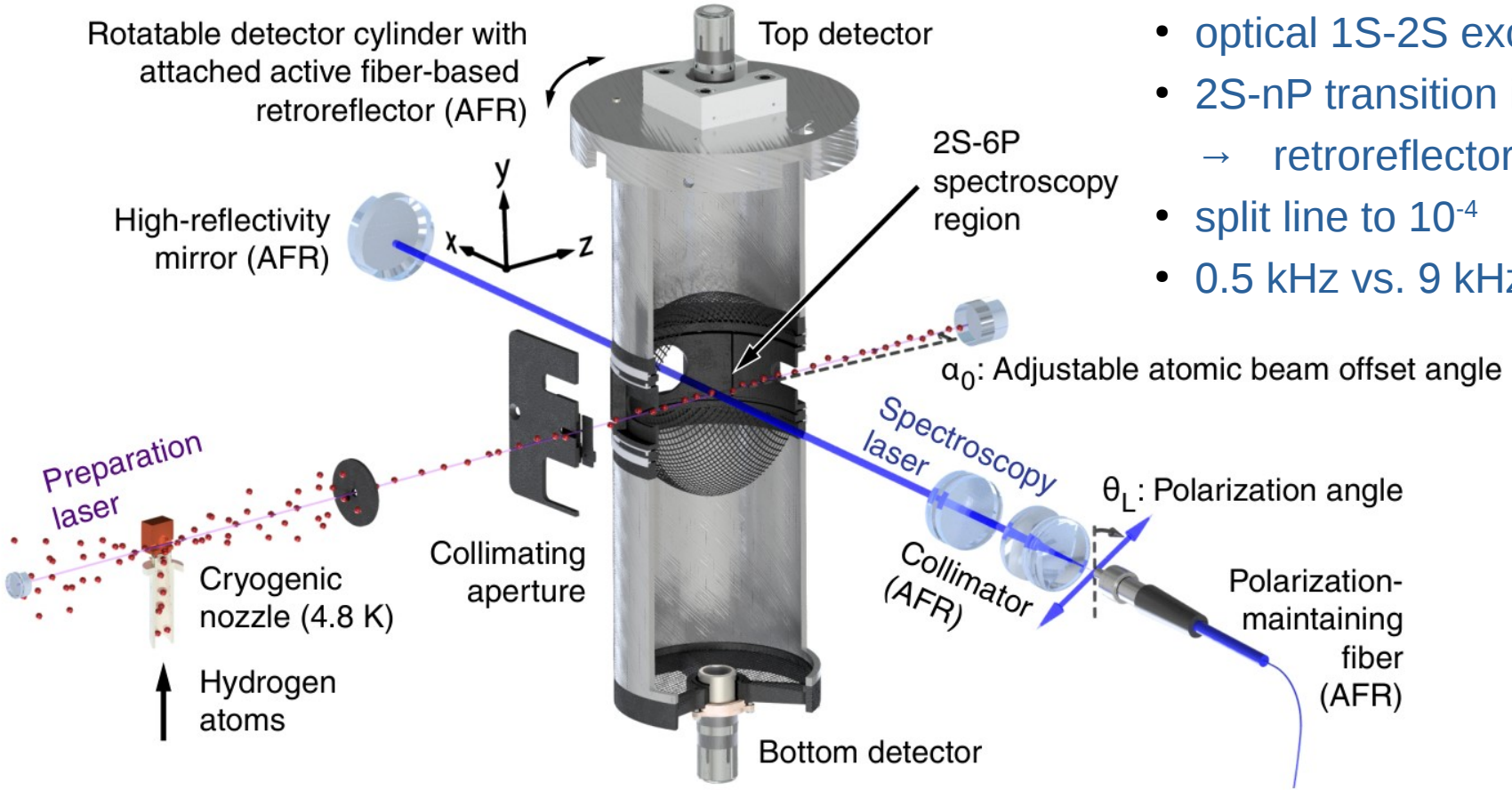
Rp from H spectroscopy



Situation 2016

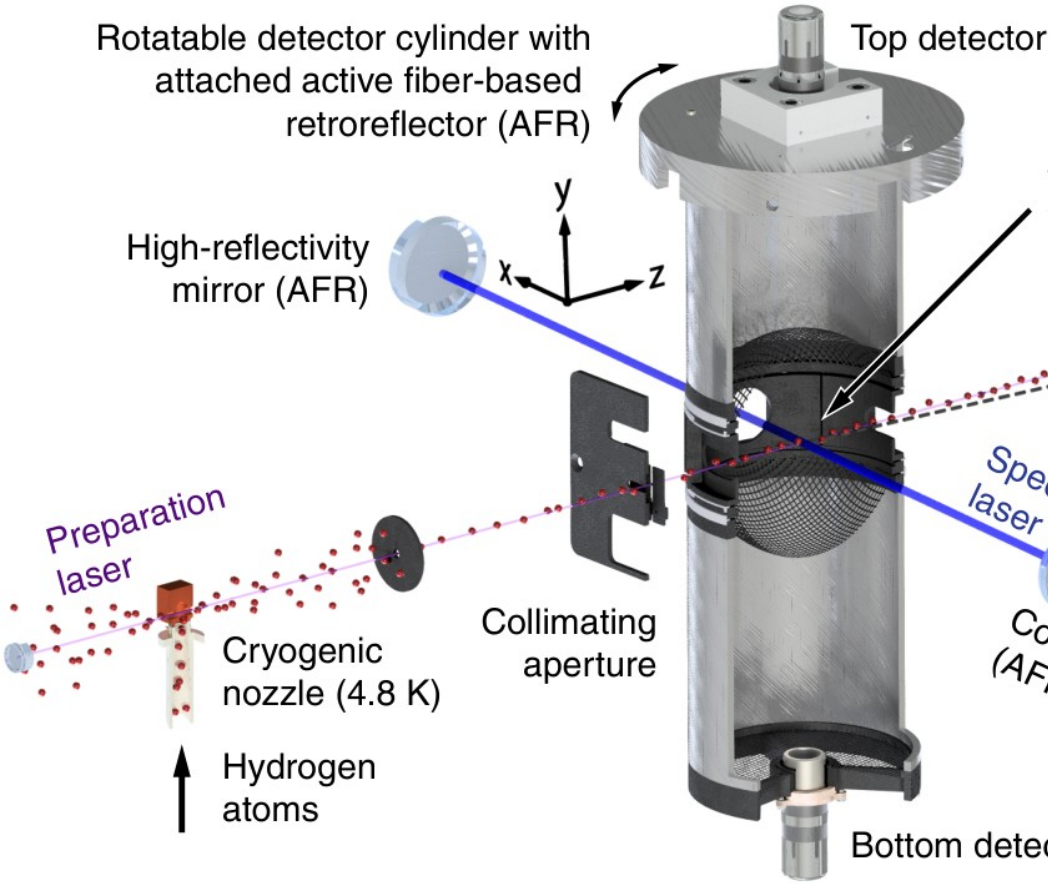
RP et al., Metrologia 54, L1 (2017)

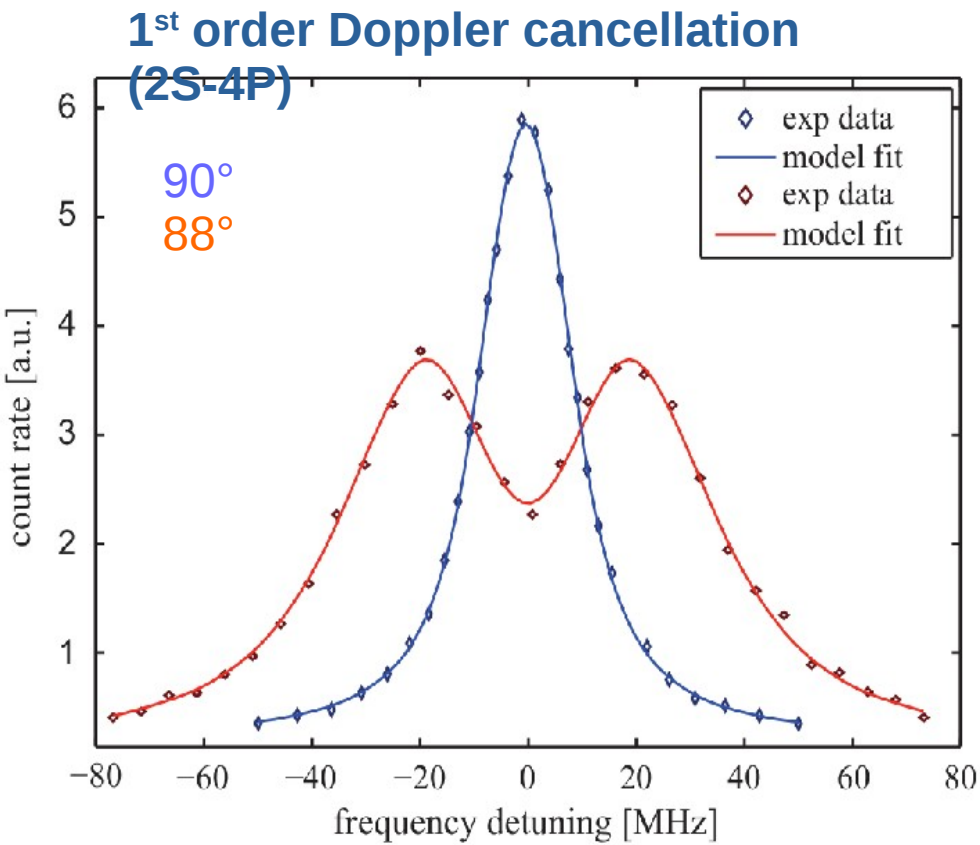
2S-nP in Garching



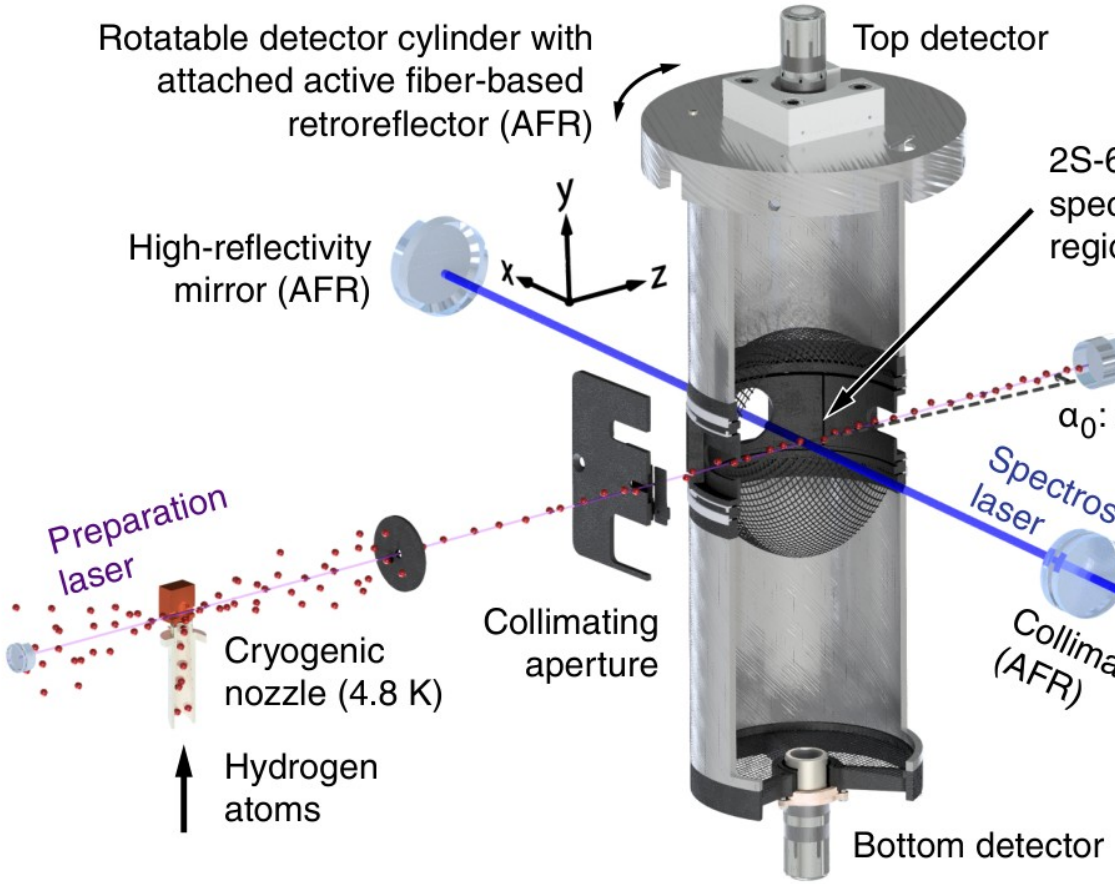
- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-nP transition is 1-photon
  → retroreflector ("AFR")
- split line to 10^{-4}
- 0.5 kHz vs. 9 kHz PRP

2S-nP in Garching





2S-nP in Garching

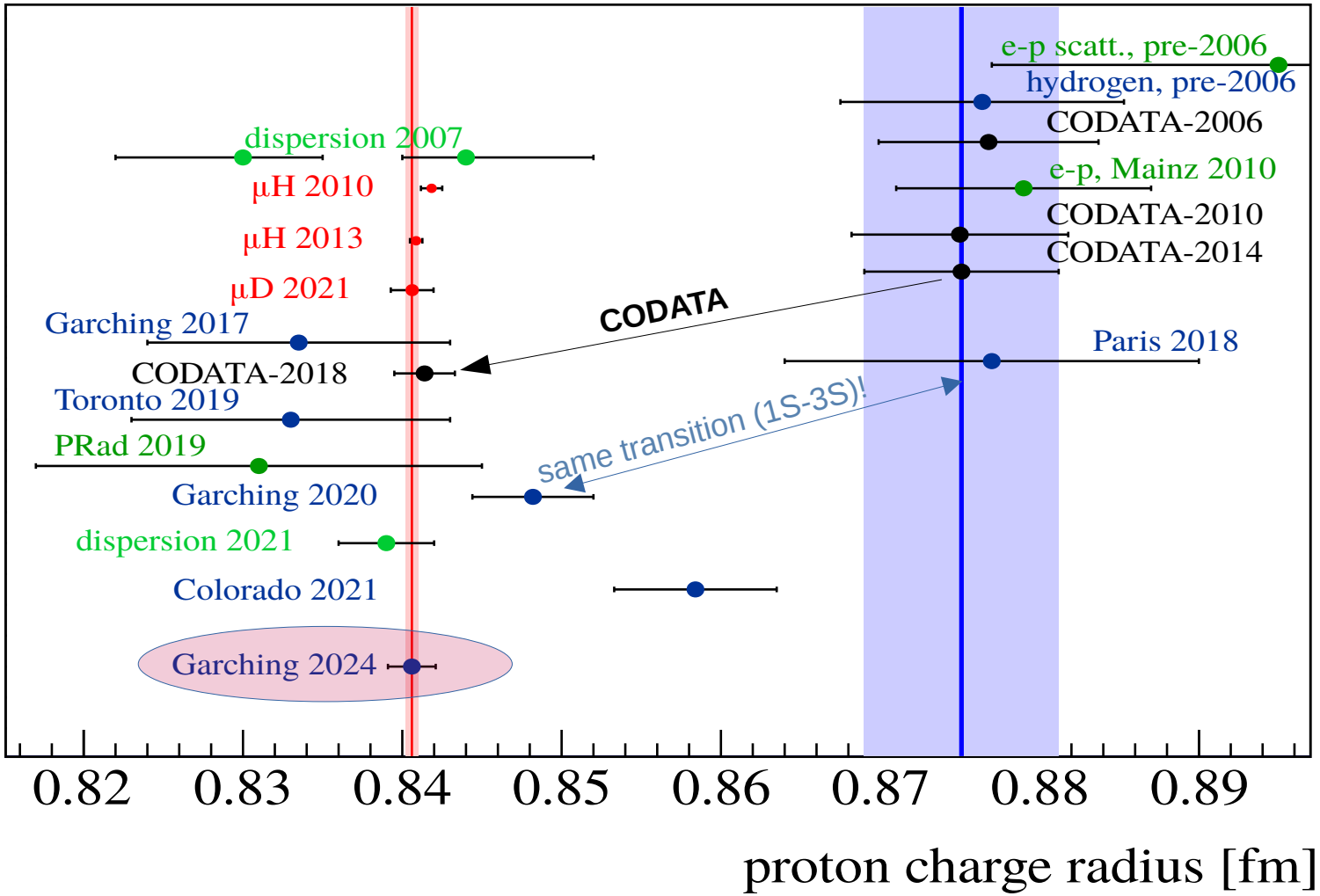


Systematics (2S-6P)

Contribution	$\Delta\nu$ (kHz)	σ (kHz)
First-order Doppler shift	0.34	0.43
Extrapolation (statistical)	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
dc-Stark shift	0.05	0.07
BBR-induced shift	0.28	0.01
Zeeman shift	0.00	0.08
Pressure shift	0.00	0.02
Sampling bias	0.00	0.06
Signal background	0.00	0.03
Laser spectrum	0.00	0.07
Frequency standard	0.02	0.01
Subtotal (experiment-specific contributions)	1.74	0.48
Recoil shift	−1 176.03	0.00
HFS correction $\Delta\nu_{\mathrm{HFS}}(\nu_{\mathrm{2S\text{-}6P}})$	−132 985.25	0.01
Total (all contributions)	−134 159.54	0.48

Maisenbacher et al., submitted

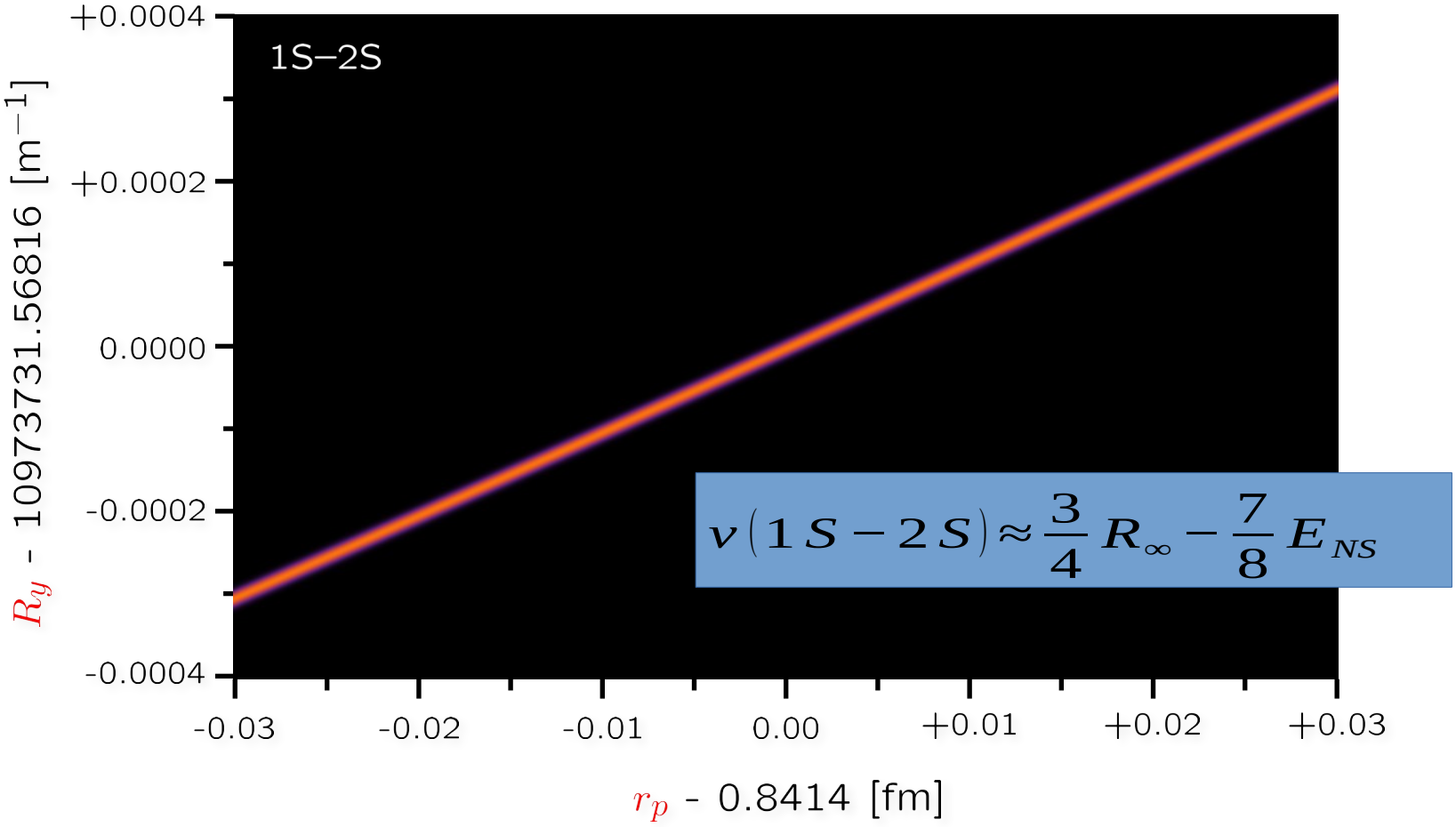
The proton radius situation today



Not really “solved”

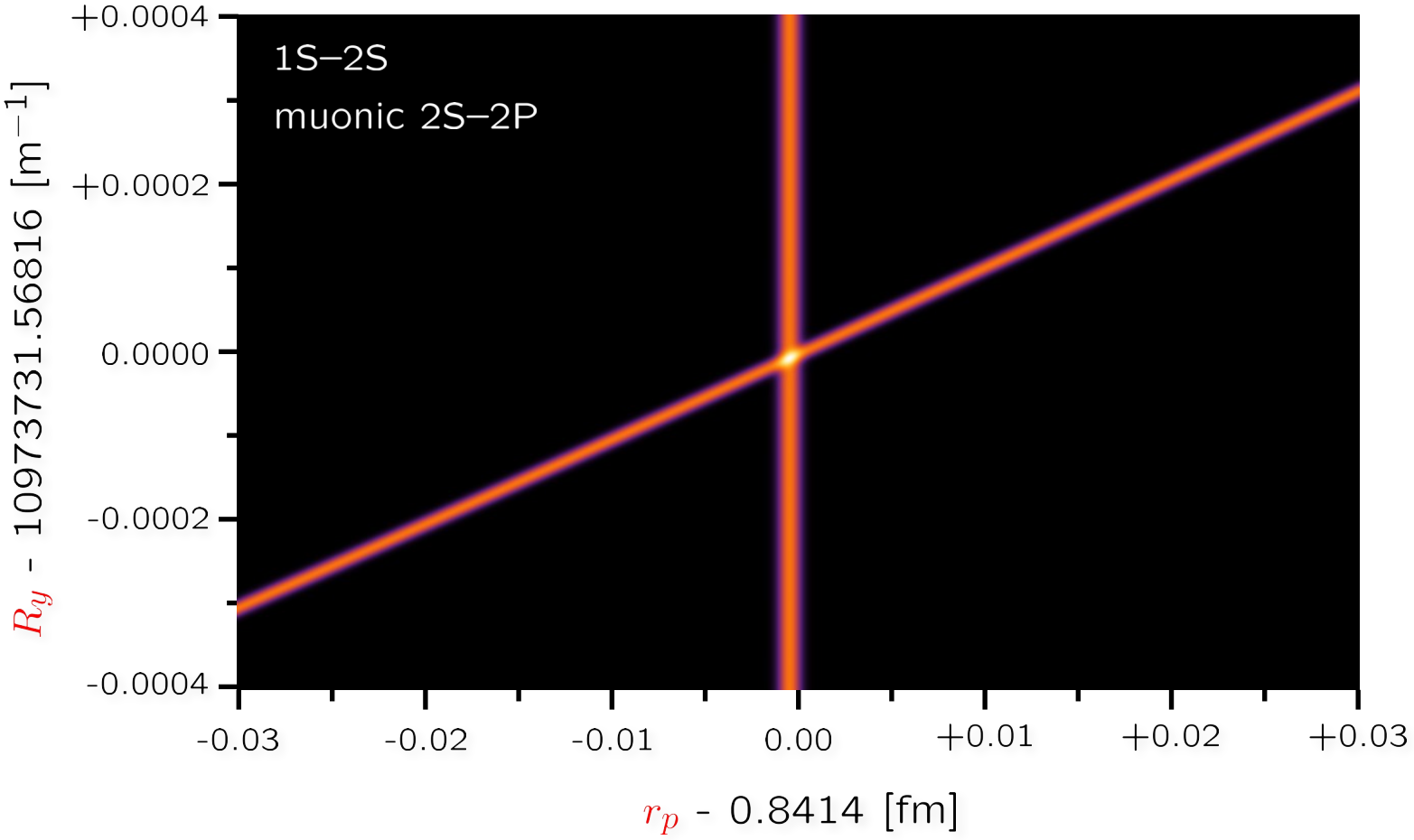
H (2S-6P)
preliminary

QED Test

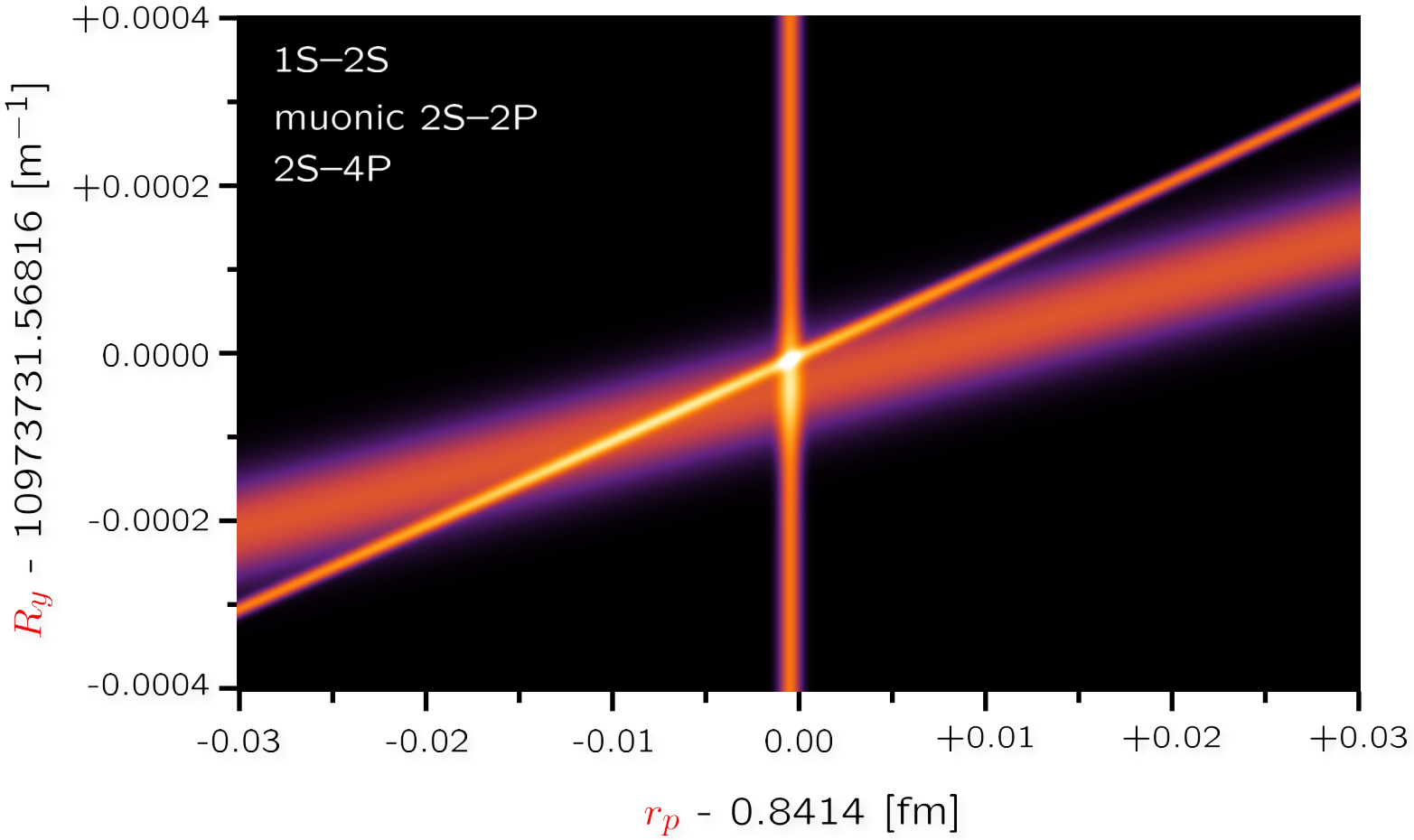


$$\nu(1S-2S) \approx \frac{3}{4} R_\infty - \frac{7}{8} E_{NS}$$

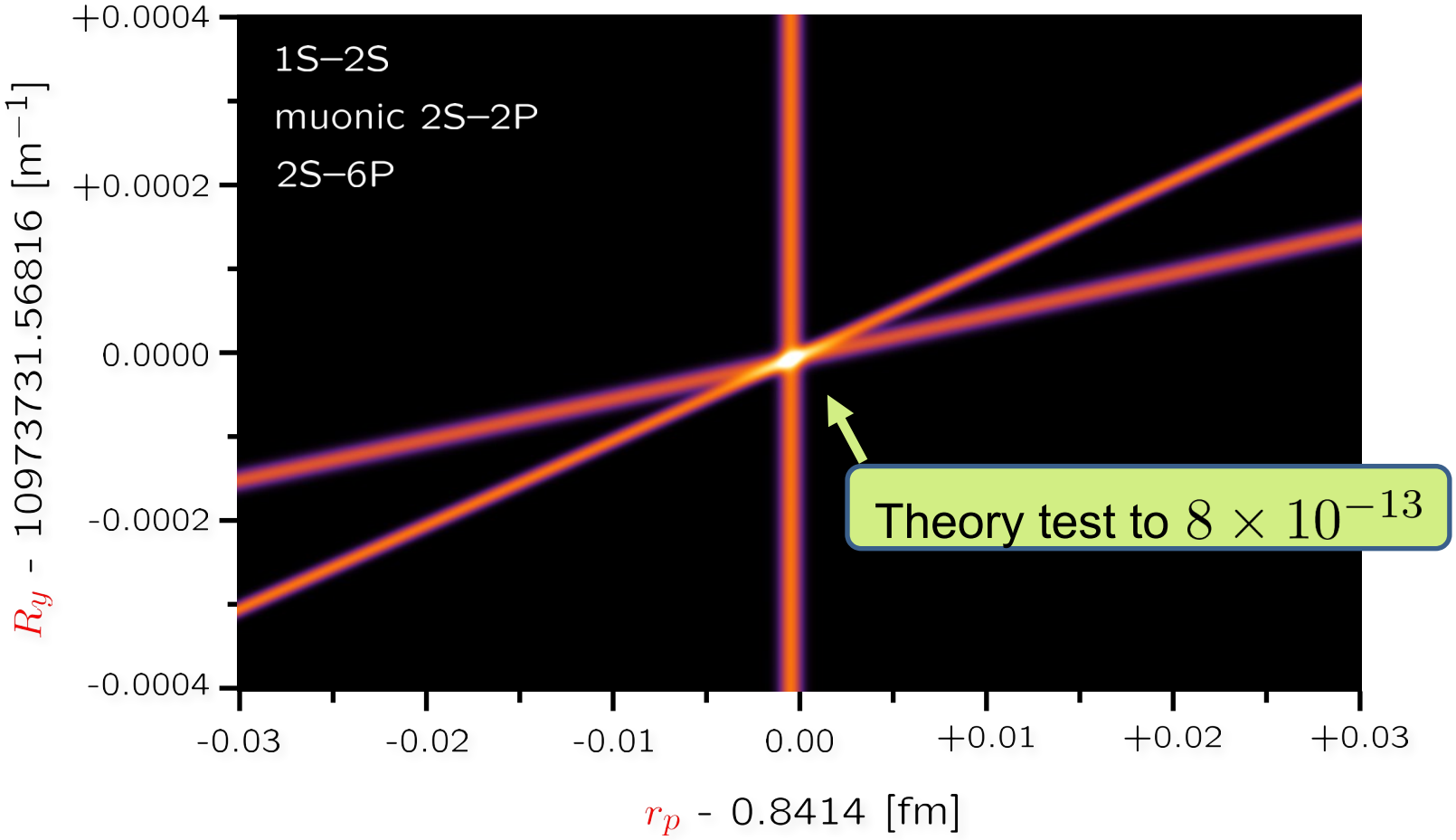
QED Test


1S–2S
muonic 2S–2P
+0.0004
+0.0002
0.0000
-0.0002
-0.0004
R_y - 10973731.56816 [m^{-1}]
-0.03
-0.02
-0.01
0.00
+0.01
+0.02
+0.03
r_p - 0.8414 [fm]

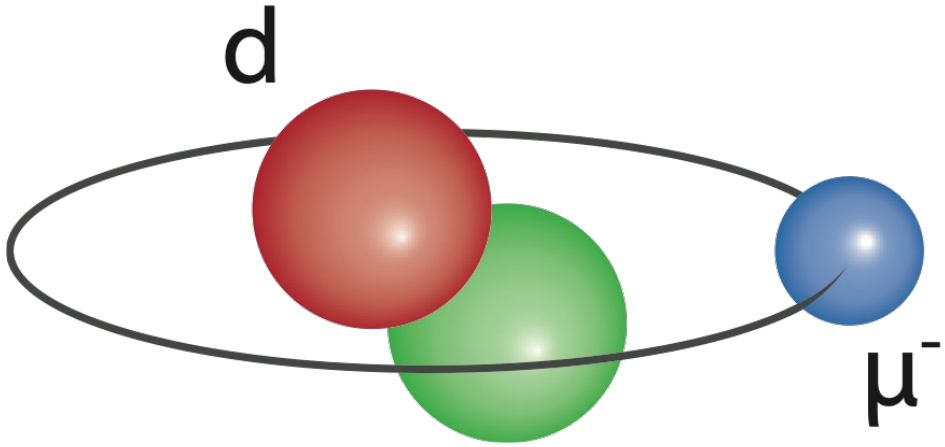
QED Test


1S–2S
muonic 2S–2P
2S–4P
+0.0004
+0.0002
0.0000
-0.0002
-0.0004
R_y - 10973731.56816 [m^{-1}]
-0.03
-0.02
-0.01
0.00
+0.01
+0.02
+0.03
r_p - 0.8414 [fm]

QED Test

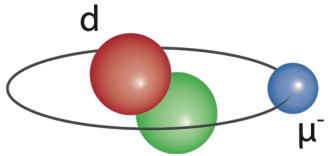

1S–2S
muonic 2S–2P
2S–6P
+0.0004
+0.0002
0.0000
-0.0002
-0.0004
R_y - 10973731.56816 [m^{-1}]
-0.03
-0.02
-0.01
0.00
+0.01
+0.02
+0.03
r_p - 0.8414 [fm]
Theory test to 8×10^{-13}

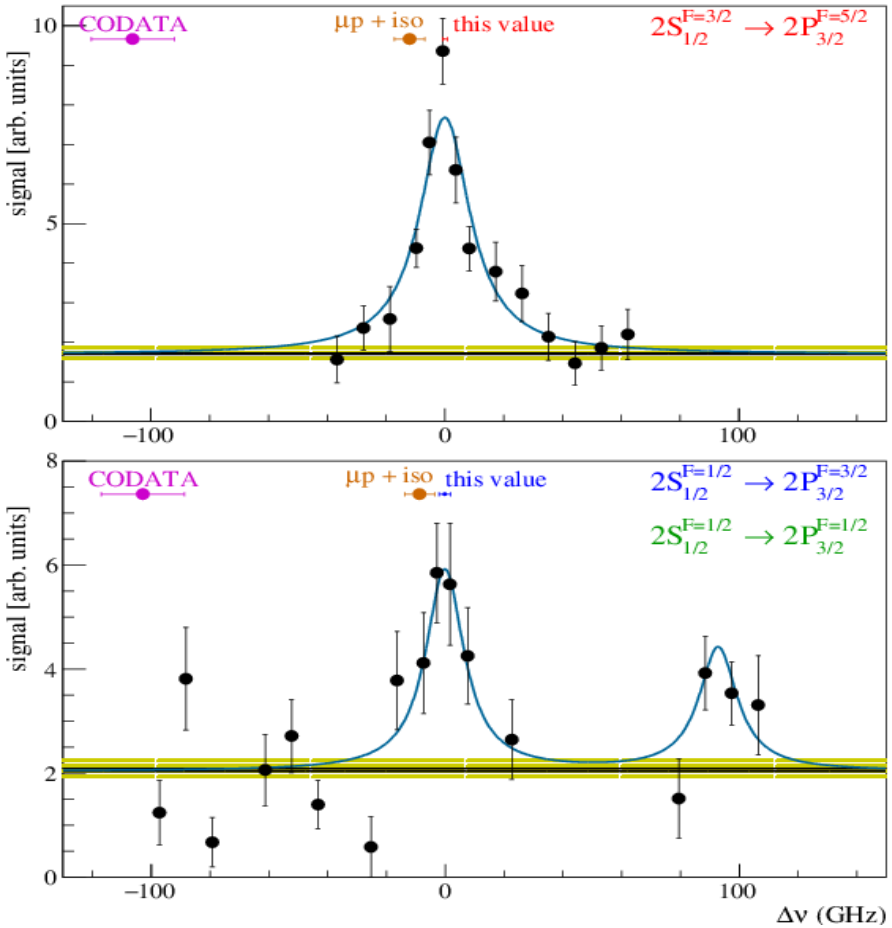
Muonic Deuterium

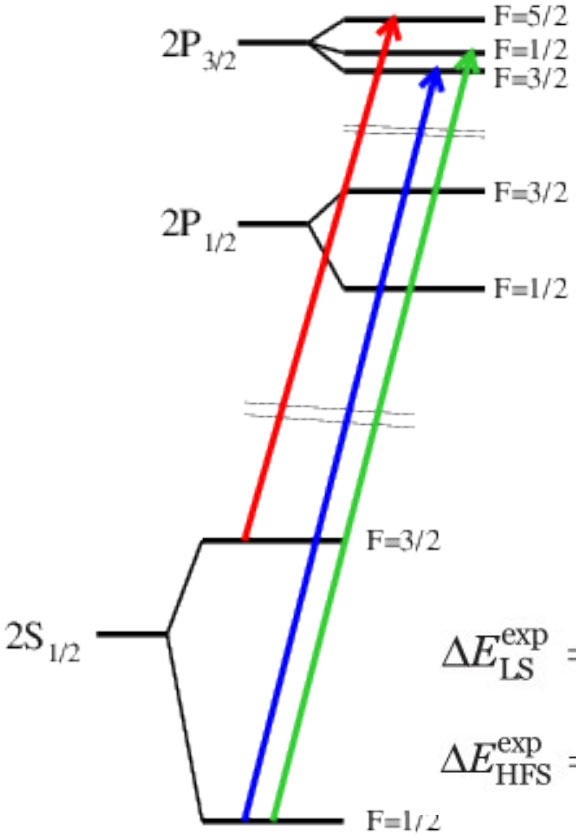


Pohl et al. (CREMA), Science (2016)

2.5 transitions in muonic D







$$\Delta E_{LS}^{exp} = 202.8785(31)_{stat}(14)_{syst}\,\text{meV}$$

$$\Delta E_{HFS}^{exp} = 6.2747(70)_{stat}(20)_{syst}\,\text{meV}$$

Pohl et al. (CREMA Coll.), Science 353, 669 (2016)

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)\ meV_{QED} + 1.7150\ (\mathbf{230})\ meV_{TPE} - 6.1103\ (3)\ meV/fm^2 * \mathbf{R_d^2}$$

Nuclear structure contributions to the Lamb shift in muonic deuterium.

Item	Contribution	Pachucki [55] AV18		Friar [60] ZRA		Hernandez *et al.* [58] AV18	N^{3}LO †		Pach.& Wienczek [65] AV18		Carlson *et al.* [64] data	Our choice value	source
	Source	1		2		3	4		5		6		
p1	Dipole	1.910	$\delta_0 E$	1.925	Leading C1	1.907	1.926	$\delta^{(0)}_{D1}$	1.910	$\delta_0 E$		1.9165 ± 0.0095	3-5
p2	Rel. corr. to p1, longitudinal part	−0.035	$\delta_R E$	−0.037	Subleading C1	−0.029	−0.030	$\delta^{(0)}_L$	−0.026	$\delta_R E$			
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta^{(0)}_T$					
p4	Rel. corr. to p1, higher-order								0.004	$\delta_{HO} E$			
sum	Total rel. corr., p2+p3+p4	−0.035		−0.037		−0.017	−0.017		−0.022			−0.0195 ± 0.0025	3-5
p5	Coulomb distortion, leading	−0.255	$\delta_{C1} E$						−0.255	$\delta_{C1} E$			
p6	Coul. distortion, next order	−0.006	$\delta_{C2} E$						−0.006	$\delta_{C2} E$			
sum	Total Coulomb distortion, p5+p6	−0.261				−0.262	−0.264	$\delta^{(0)}_C$	−0.261			−0.2625 ± 0.0015	3-5
p7	El. monopole excitation	−0.045	$\delta_{Q0} E$	−0.042	C0	−0.042	−0.041	$\delta^{(2)}_{R2}$	−0.042	$\delta_{Q0} E$			
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta^{(2)}_{D1D3}$	0.139	$\delta_{Q1} E$			
p9	El. quadrupole excitation	−0.066	$\delta_{Q2} E$	−0.061	C2	−0.061	−0.061	$\delta^{(2)}_Q$	−0.061	$\delta_{Q2} E$			
sum	Tot. nuclear excitation, p7+p8+p9	0.040		0.034	C0 + ret-C1 + C2	0.036	0.038		0.036			0.0360 ± 0.0020	2-5
p10	Magnetic	−0.008 $^{\diamond a}$	$\delta_M E$	−0.011	M1	−0.008	−0.007	$\delta^{(0)}_M$	−0.008	$\delta_M E$		−0.0090 ± 0.0020	2-5
SUM_1	Total nuclear (corrected)	1.646		1.648 ^{b}		1.656	1.676		1.655			1.6615 ± 0.0103	
p11	Finite nucleon size			0.021	Retarded C1 f.s.	0.020 $^{\diamond c}$	0.021 $^{\diamond c}$	$\delta^{(2)}_{NS}$	0.020	$\delta_{FS} E$			
p12	n p charge correlation			−0.023	pn correl. f.s.	−0.017	−0.017	$\delta^{(1)}_{np}$	−0.018	$\delta_{FZ} E$			
sum	p11+p12			−0.002		0.003	0.004		0.002			0.0010 ± 0.0030	2-5
p13	Proton elastic 3rd Zemach moment	} 0.043(3)	$\delta_P E$	0.030	$\langle r^3 \rangle^{pp}_{(2)}$				} 0.043(3)	$\delta_P E$		0.0289 ± 0.0015	Eq.(13)^d
p14	Proton inelastic polarizab.					} 0.027(2)		δ^N_{pol} [64]			} 0.028(2) ΔE^{hadr}	} 0.0280 ± 0.0020	6
p15	Neutron inelastic polarizab.								0.016(8)	$\delta_N E$			
p16	Proton & neutron subtraction term											−0.0098 ± 0.0098	Eq.(15)^e
sum	Nucleon TPE, p13+p14+p15+p16	0.043(3)		0.030		0.027(2)			0.059(9)			0.0471 ± 0.0101	^{f}
SUM_2	Total nucleon contrib.	0.043(3)		0.028		0.030(2)			0.061(9)			0.0476 ± 0.0105	
	Sum, published	1.680(16)		1.941(19)		1.690(20)			1.717(20)		2.011(740)		
	Sum, corrected			1.697(19) ^{g}		1.714(20) ^{h}			1.707(20) ^{i}		1.748(740) ^{j}	**1.7096 ± 0.0147**	

Krauth, RP at al., Ann. Phys. (N.Y.) 366, 168 (2016)

+ Pachucki et al., PRA 97, 062511 (2018)
+ Hernandez et al., PLB 778, 377 (2018)

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)\ meV_{QED} + 1.7150\ (\mathbf{230})\ meV_{TPE} - 6.1103\ (3)\ meV/fm^2 * \mathbf{R_d^2}$$

Nuclear structure contributions to the Lamb shift in muonic deuterium.

Table 3
Nuclear polarization contributions to the 2S–2P Lamb shift ΔE [meV] in μD with different potentials.

		Ref. [29]	AV18	N^{3}LO-EM	N^{3}LO-EGM
$\delta^{(0)}$	$\delta^{(0)}_{D1}$	−1.910	−1.907	−1.912	(−1.911, −1.926)
	$\delta^{(0)}_{L}$	0.035	0.029	0.029	(0.029, 0.030)
	$\delta^{(0)}_{T}$	–	−0.012	−0.012	−0.013
	$\delta^{(0)}_{C}$	0.261	0.262	0.262	(0.262, 0.264)
	$\delta^{(0)}_{M}$	0.016	0.008	0.007	0.007
$\delta^{(1)}$	$\delta^{(1)}_{Z3}$	–	0.357	0.359	(0.359, 0.363)
$\delta^{(2)}$	$\delta^{(2)}_{R2}$	0.045	0.042	0.041	0.041
	$\delta^{(2)}_{Q}$	0.066	0.061	0.061	0.061
	$\delta^{(2)}_{D1D3}$	−0.151	−0.139	−0.139	(−0.139, −0.140)
δ_{NS}	$\delta^{(1)}_{Z1}$	–	0.064	0.064	(0.064, 0.065)
	$\delta^{(1)}_{np}$	–	0.017	0.017	0.017
	$\delta^{(2)}_{NS}$	–	−0.015	−0.015	−0.015
δ^{A}_{pol}		–	−1.235	−1.237	(−1.236, −1.246)
δ_{Zem}		–	−0.421	−0.423	(−0.424, −0.428)
$\delta^{A}_{pol} + \delta_{Zem}$		−1.638	−1.656	−1.661	(−1.660, −1.674)

Item	Hernandez *et al.* [58] N^{3}LO †		Pach.& Wienczek [65] AV18		Carlson *et al.* [64] data	Our choice value		source
	4		5		6			
p1	1.926	$\delta^{(0)}_{D1}$	1.910	$\delta_0 E$		1.9165	± 0.0095	3-5
p2	−0.030	$\delta^{(0)}_{L}$	−0.026	$\delta_R E$				
p3	0.013	$\delta^{(0)}_{T}$						
p4			0.004	$\delta_{HO} E$				
sum	−0.017		−0.022			−0.0195	± 0.0025	3-5
p5			−0.255	$\delta_{C1} E$				
p6			−0.006	$\delta_{C2} E$				
sum	−0.264	$\delta^{(0)}_{C}$	−0.261			−0.2625	± 0.0015	3-5
p7								
p8								
p9								
sum								
p10								
SUM_1								
p11								
p12								
sum								
p13			} 0.043(3)	$\delta_P E$		0.0289	± 0.0015	Eq.(13)[a]
p14	0.027(2)	δ^{N}_{pol} [64]			} 0.028(2) ΔE^{hadr}	} 0.0280	± 0.0020	6
p15			0.016(8)	$\delta_N E$				
p16						−0.0098	± 0.0098	Eq.(15)[e]
sum	0.027(2)		0.059(9)			0.0471	± 0.0101	[f]
SUM_2	0.030(2)		0.061(9)			0.0476	± 0.0105	
	1.690(20)		1.717(20)		2.011(740)			
	1.714(20) [h]		1.707(20) [i]		1.748(740) [j]	**1.7096**	**± 0.0147**	

O.J. Hernandez et al. / Physics Letters B 736 (2014) 344–349

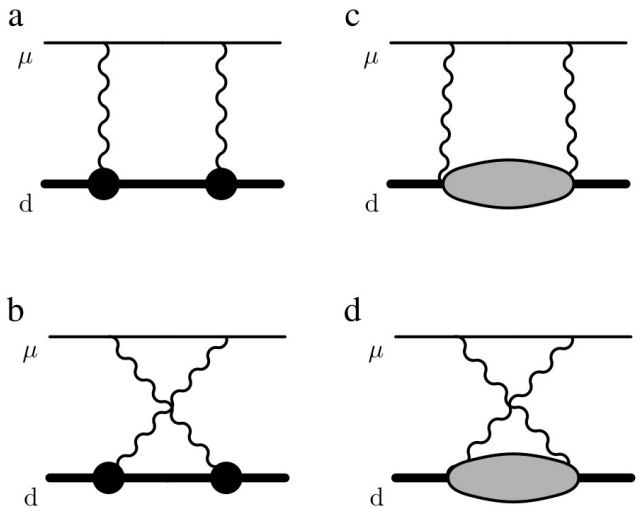
nuclear structure theory with error bars!

Theory: Lamb shift in muonic D

$$\Delta E_{\text{Lamb}}^{\mu D} = 228.7740\,(3)\ \text{meV}_{\text{QED}} + 1.7503\,(\mathbf{200})\ \text{meV}_{\text{TPE}} - 6.1074\ \text{meV/fm}^2 * \mathbf{R_d^2}$$

$$\Delta E_{\text{LS}}^{\text{exp}} = 202.8785(31)_{\text{stat}}(14)_{\text{syst}}\ \text{meV}$$

Nuclear structure two (and three!)-photon contributions to the Lamb shift in muonic deuterium.



Pachucki, RP et al, arXiv 2212.13782

see also Krauth, RP et al. (2016) using calculations from Pachucki (2011), Friar (2013), Carlson, Gorchtein, Vanderhaeghen (2014), Hernandez et al. (2014), Pachucki + Wienczek (2015)

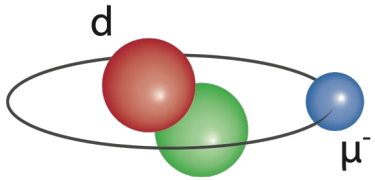
+ Pachucki et al., PRA 97, 062511 (2018): Sizeable three-photon !!

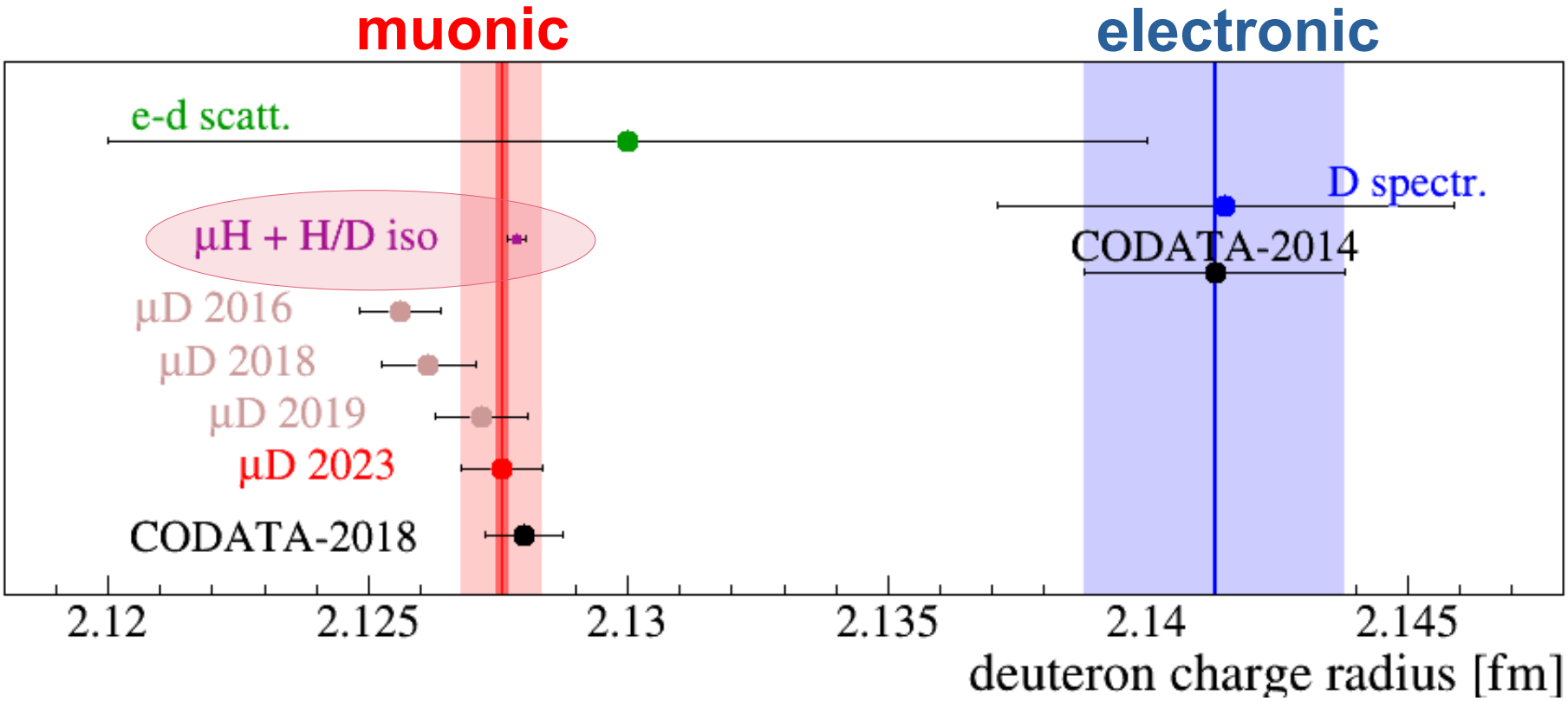
+ Hernandez et al., PLB 778, 377 (2018): χEFT

+ Kalinowski (2019): eVP to nucl. struct.

+ Acharya et al., PRC 103, 024001 (2021)
χEFT + Disperson relations

Muonic Deuterium





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

μH + H/D(1S-2S): 2.12785 (17) fm

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7740\ (3)\ meV_{QED} + 1.7503\ (\mathbf{200})\ meV_{TPE} - 6.1074\ \ meV/fm^2 * \mathbf{R_d^2}$$

ΔE_{TPE} (theo) = 1.7503 +- 0.0200 meV Bacca group

vs. +- 0.0034 meV experimental uncertainty

(1) **charge radius**, using **calculated TPE**

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

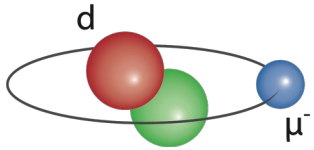
(2) **polarizability**, using **charge radius from isotope shift**

ΔE_{TPE} (theo) = 1.7503 (200) meV vs.

ΔE_{TPE} (exp) = 1.7591 (59) meV 3x more accurate

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, Pohl, RMP (2024)

Muonic Deuterium



muonic **old electronic**

e-d scatt.

D spectr.

μH + H/D iso

CODATA-2014

μD 2016

μD 2018

μD 2019

μD 2023

CODATA-2018

perfect agreement
between eH / eD
and μH / μD

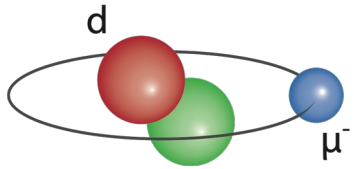
2.12 2.125 2.13 2.135 2.14 2.145

deuteron charge radius [fm]

$r_d^2 - r_p^2$ = 3.82070(31) fm² H / D 1S-2S isotope shift

3.82028(232) fm² μH / μD 2S-2P isotope shift (0.18 σ)

H/D isotope shift

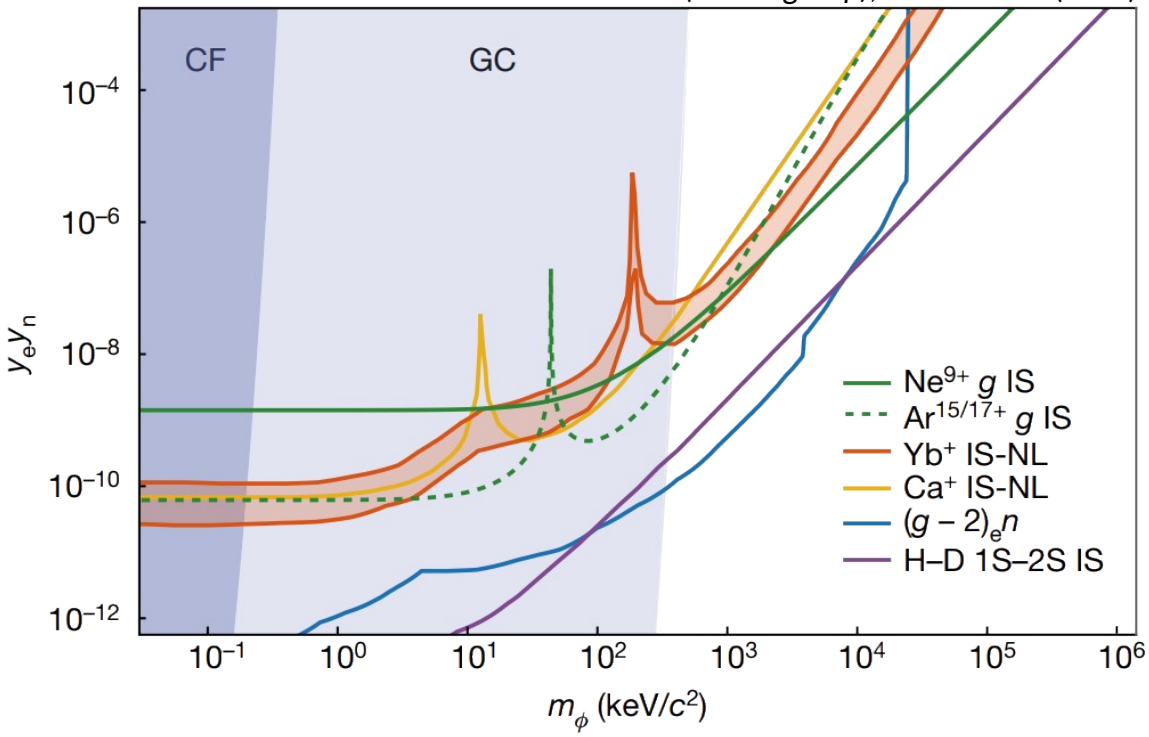


electronic H/D (1S-2S): $r_d^2 - r_p^2 = 3.8207(3)_{theo}$ fm^2

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

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

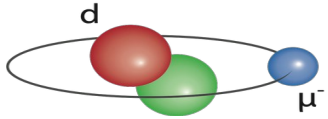
→ Best bound on 5th force

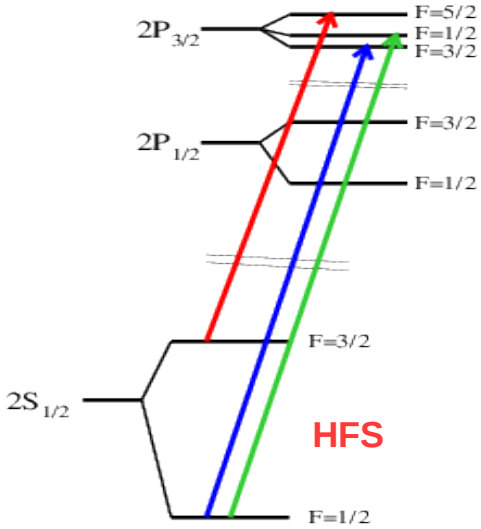


K. Blaum, S. Sturm:
tomorrow

B. Ohayon (QUARTET)
μLi … μNe
Wednesday

HFS in muonic D





PHYSICAL REVIEW A **98**, 062513 (2018)

Nuclear-structure corrections to the hyperfine splitting in muonic deuterium

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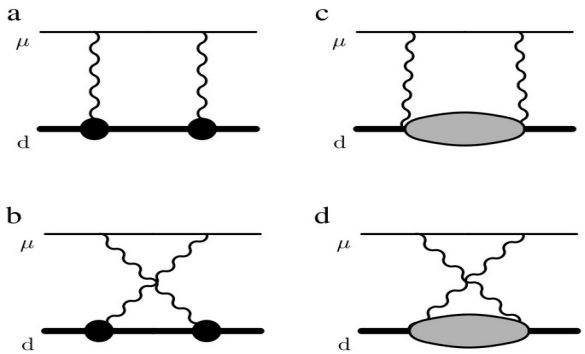
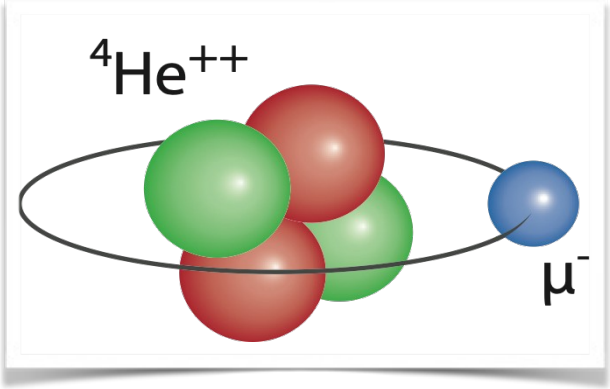
(Received 15 October 2018; revised manuscript received 7 November 2018; published 17 December 2018)

Nuclear structure corrections of orders $Z\alpha\, E_F$ and $(Z\alpha)^2 E_F$ are calculated for the hyperfine splitting of the muonic deuterium. The obtained results disagree with previous calculations and lead to a $5\,\sigma$ disagreement with the current experimental value of the $2S$ hyperfine splitting in muonic deuterium.

5σ disagreement between theory and experiment !!!

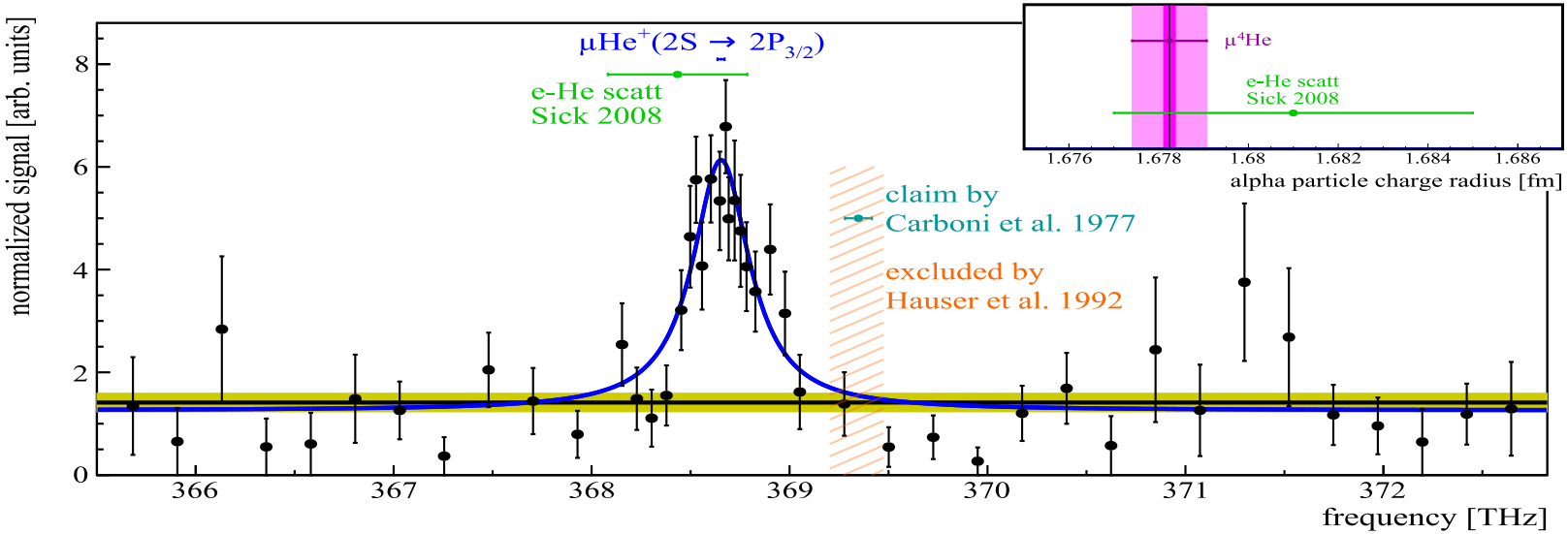


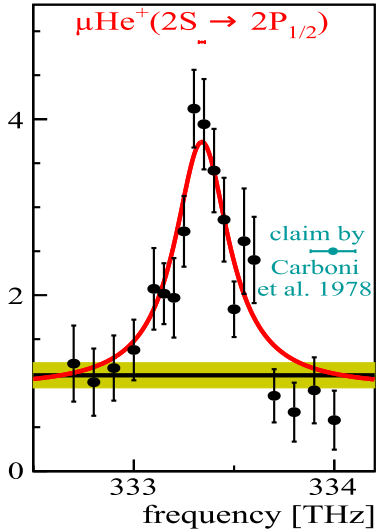
Muonic Helium-4



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

muonic ^{4}He ions





$2P_{3/2}$: ±17 GHz

$2P_{1/2}$: ±15 GHz

$$R(^4\mathrm{He}) = 1.67854\ (13)_{exp}\ (120)_{theo}\ \mathrm{fm}$$

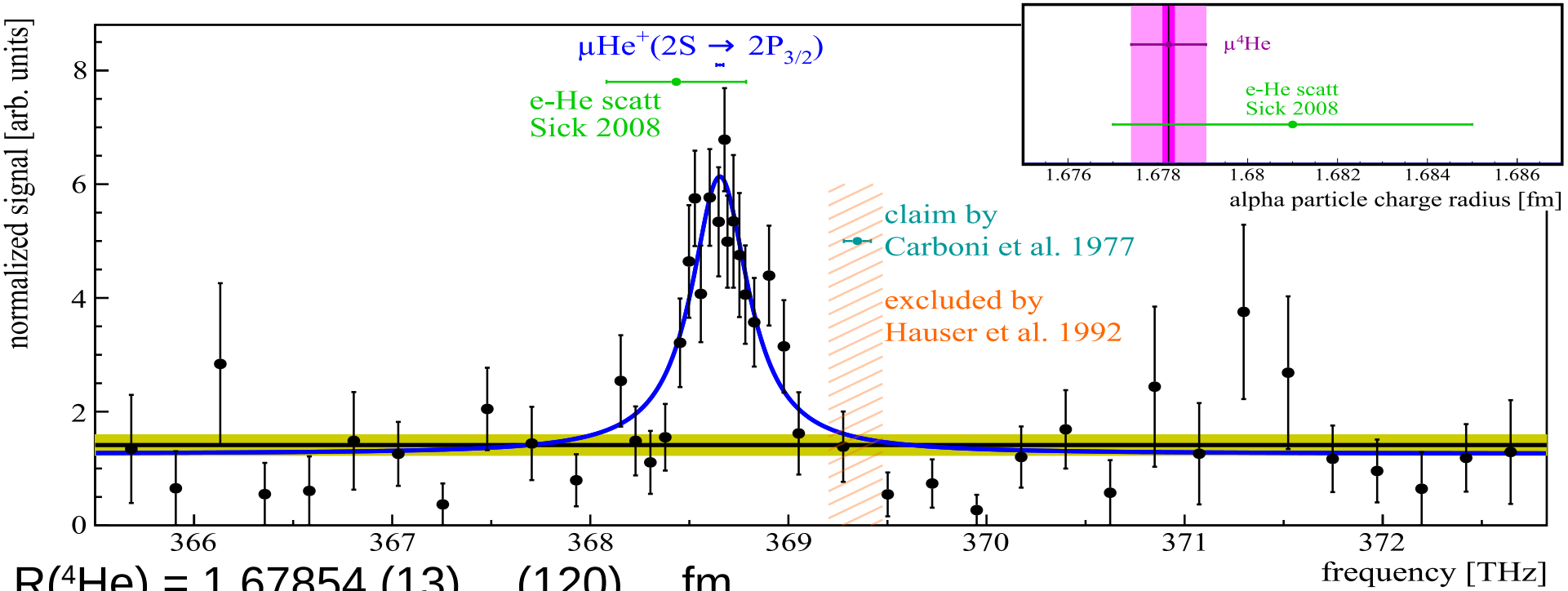
$$(120)_{theo} = (112)_{2PE}\ \ (46)_{3PE}$$

2-photon exchange: Bacca group

3-photon exchange: our educated guess based on Pachucki et al.

Exp: Krauth, RP et al. (CREMA Coll.) Nature 589, 527 (2021) Theory updated in Pachucki, RP et al., arXiv 2212.13782

muonic ^{4}He ions



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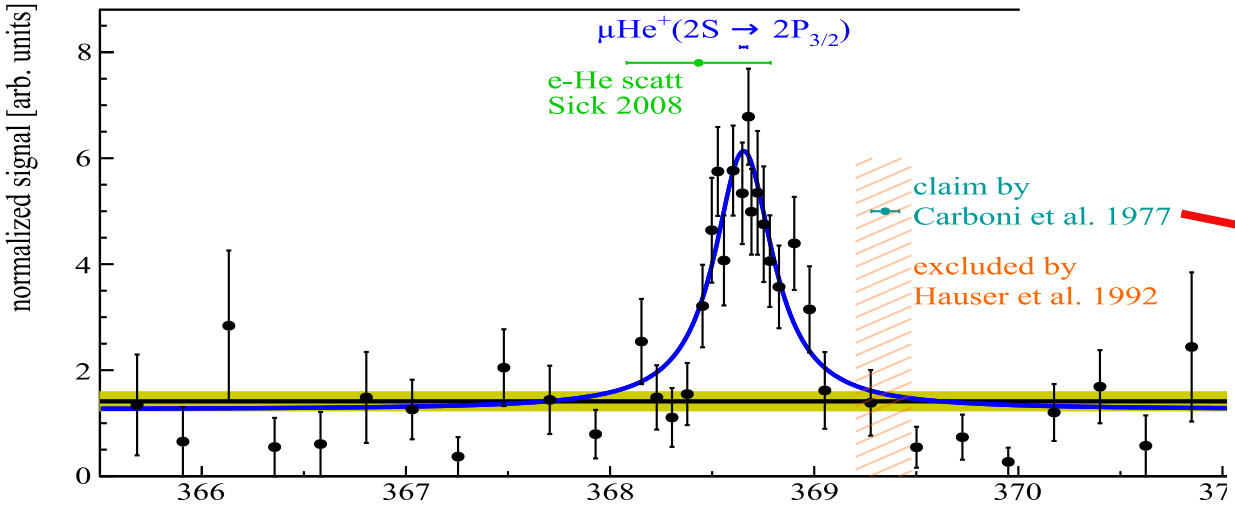
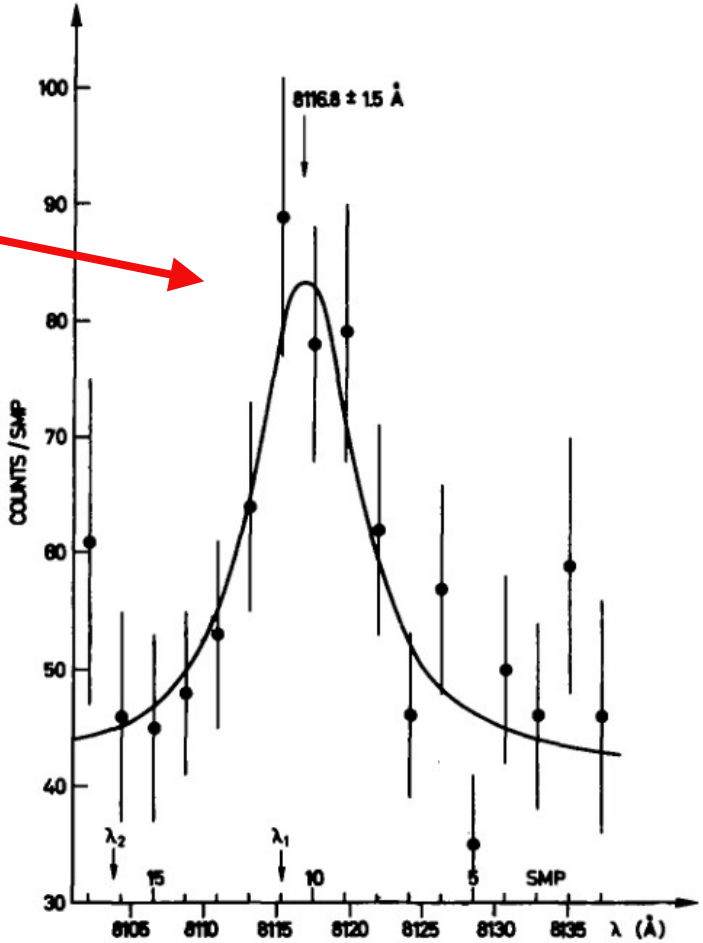
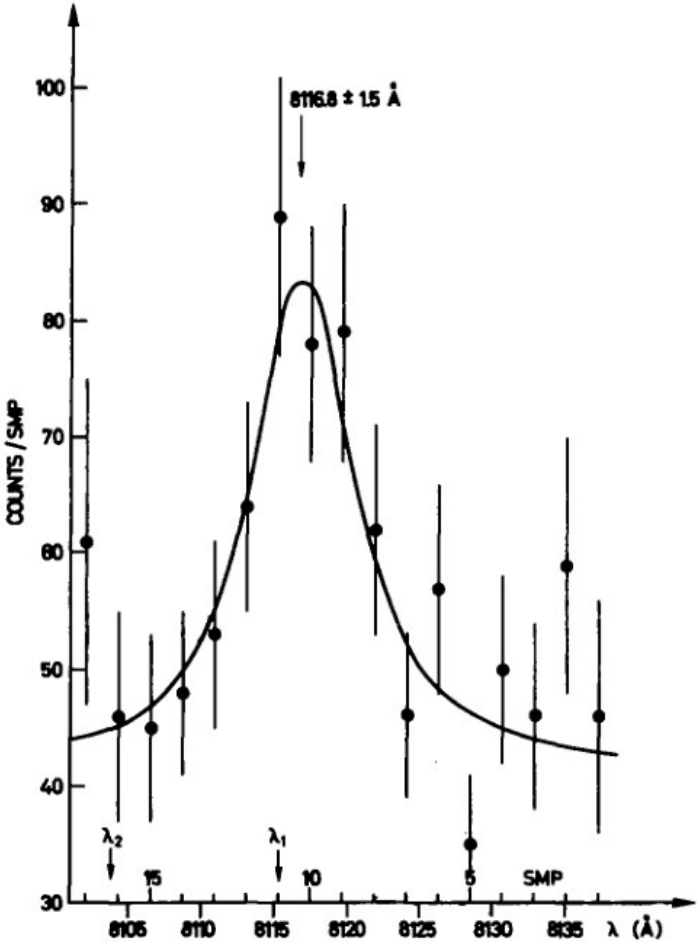
muonic ^{4}He ions

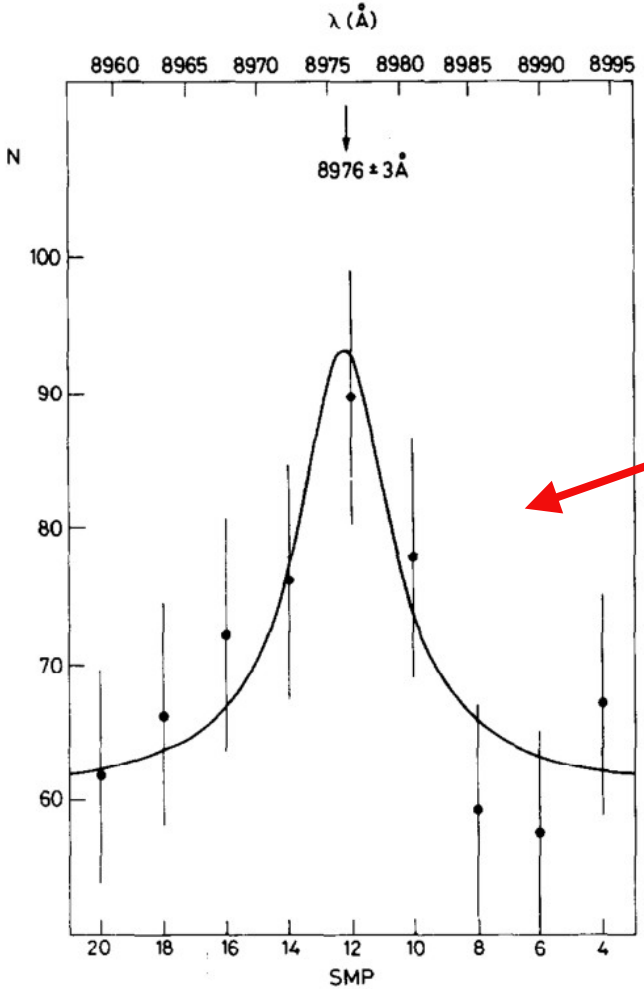


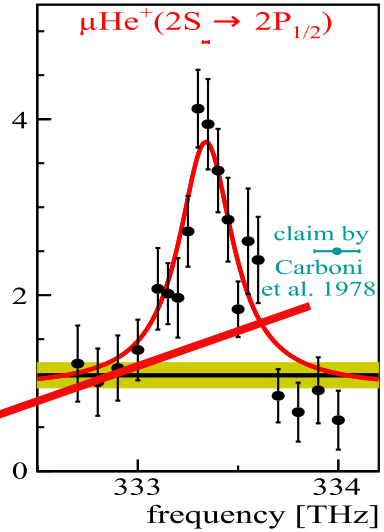


$2P_{3/2}$: ±17 GHz

muonic ^{4}He ions

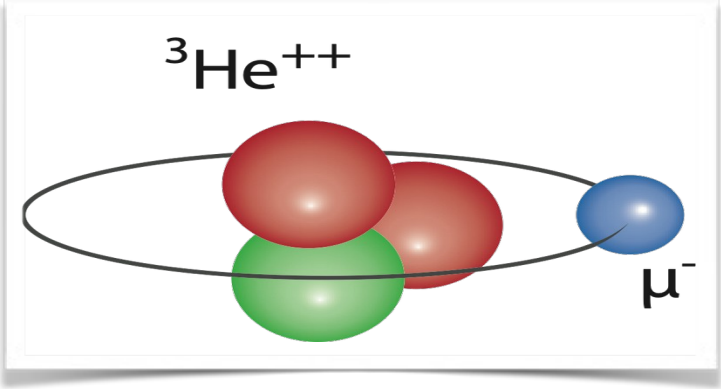






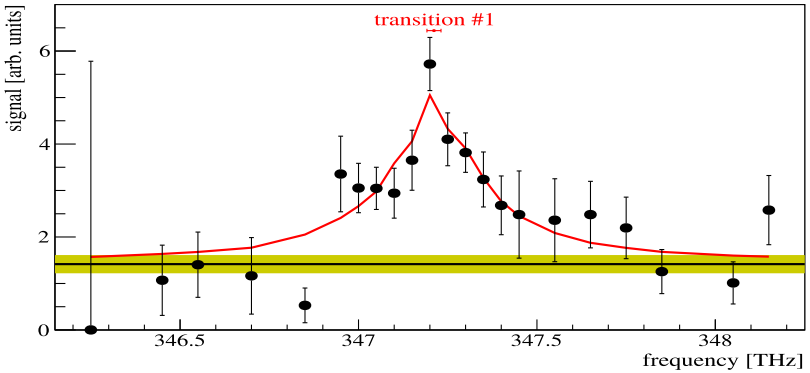
$2P_{1/2}$: ±15 GHz

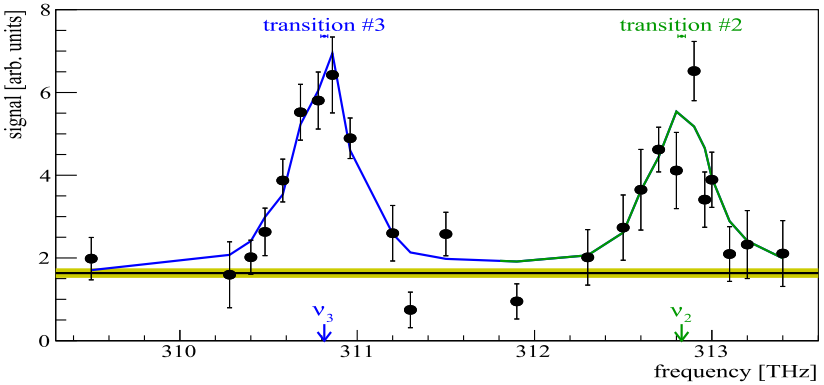
Muonic Helium-3

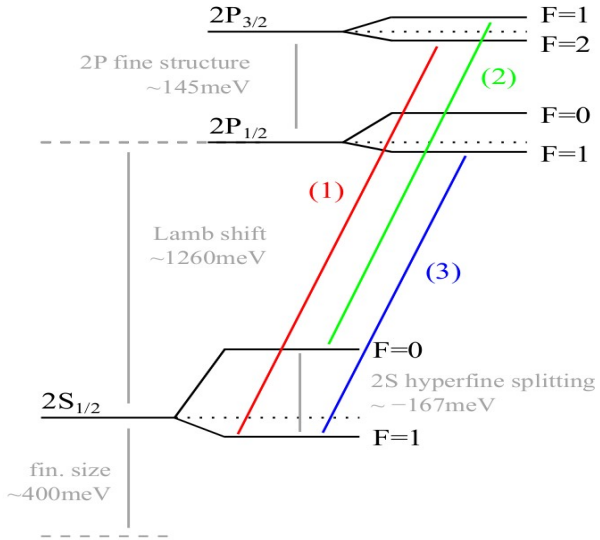


Schuhmann et al. (CREMA), Science (2025)
arXiv 2305.11679

muonic ^{3}He ions







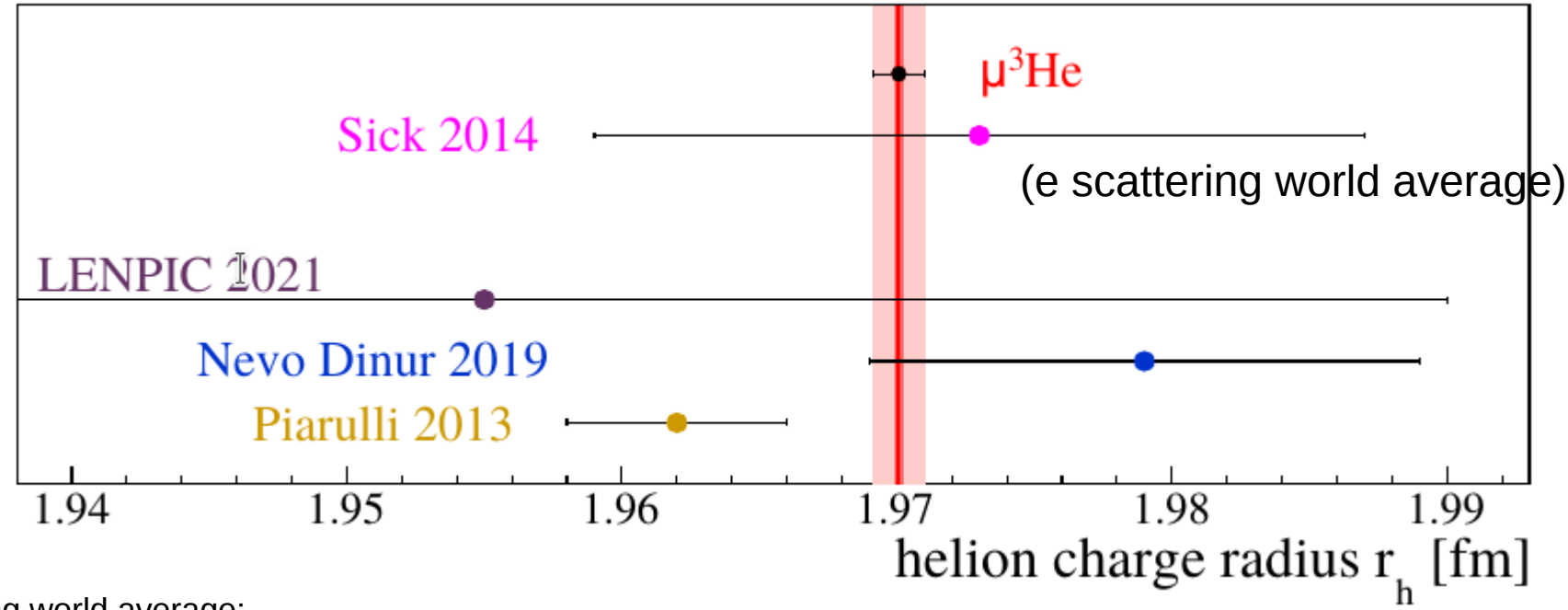
exp: each line has +-20 GHz(stat) +- 1 GHz (syst)

$$R(^3\mathrm{He}) = 1.97007\ (12)_{exp}\ (93)_{theo}\ \mathrm{fm}$$

theo = +- 0.00076 fm 2PE
+- 0.00052 fm 3PE
+- 0.00001 fm R^2 coeff.
+- 0.00002 fm QED

CREMA Coll., arXiv 2305.11679

Muonic Helium-3

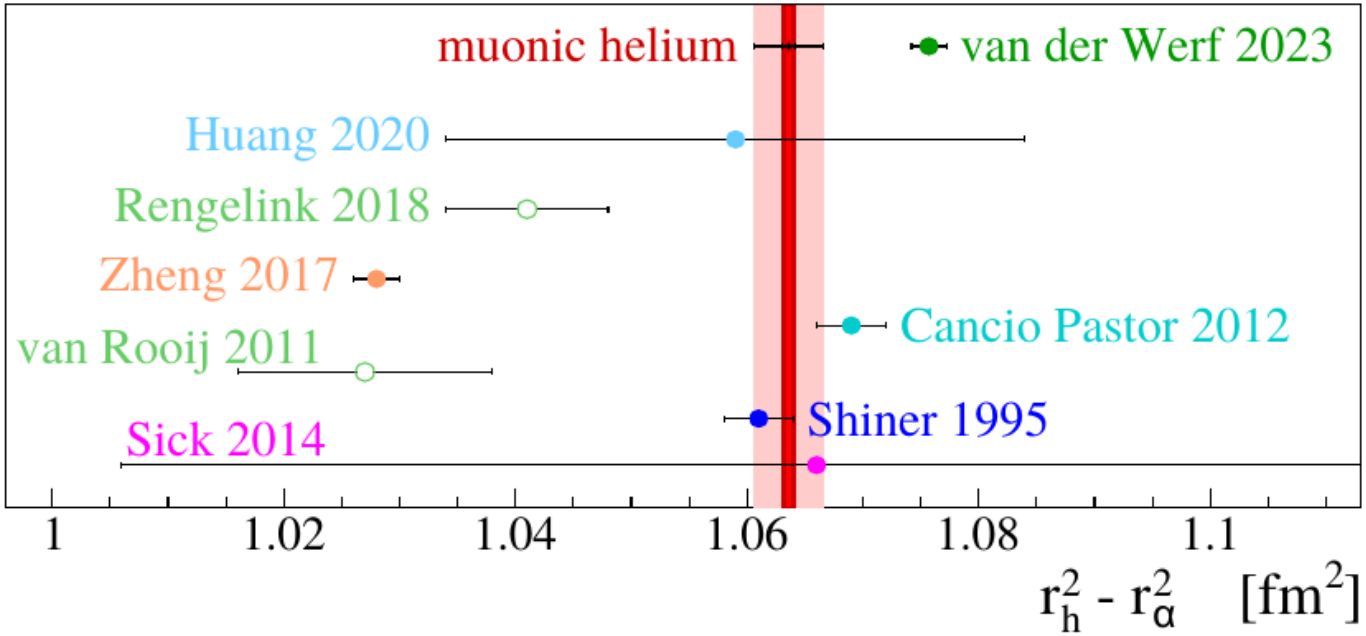


e-scattering world average:
Sick 2014: PRC 90, 064002 (2014)

nuclear theory:
LENPIC: Maris et al., PRC 106, 064002 (2022)
Nevo Dinur et al., PRC 99, 034004 (2019)
Piarulli et al., PRC 87, 014006 (2013)

CREMA Coll., Science (2025)

Helium-3 – Helium-4 Isotope Shift

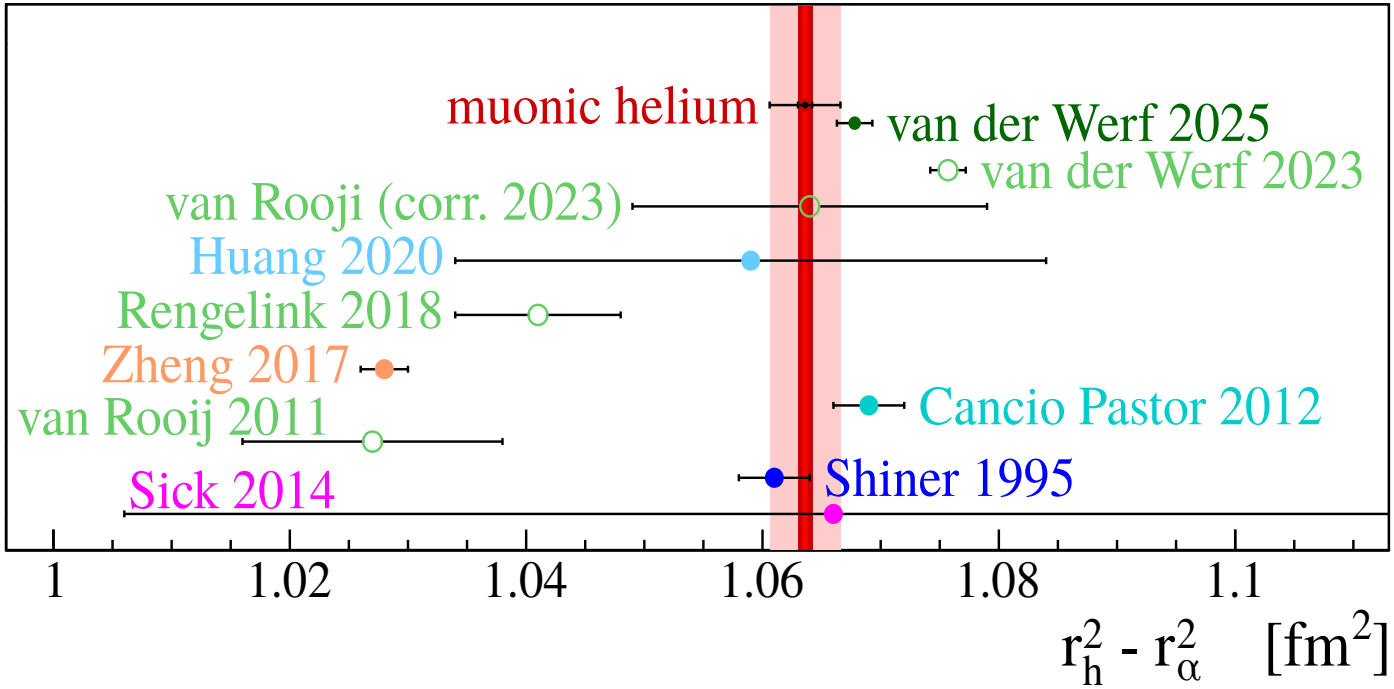


3.6σ !

CREMA Coll., arXiv 2305.11679

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)

Helium-3 – Helium-4 Isotope Shift



2nd order hyperfine mixing

Qi et al, 2024
Pachucki et al. 2024

CREMA Coll., Science (2025)

Huang: PRA 101, 062507 (2020)
Rengelink: Nature Physics 14, 1132 (2018)
Zheng: PRL 119, 263002 (2017)
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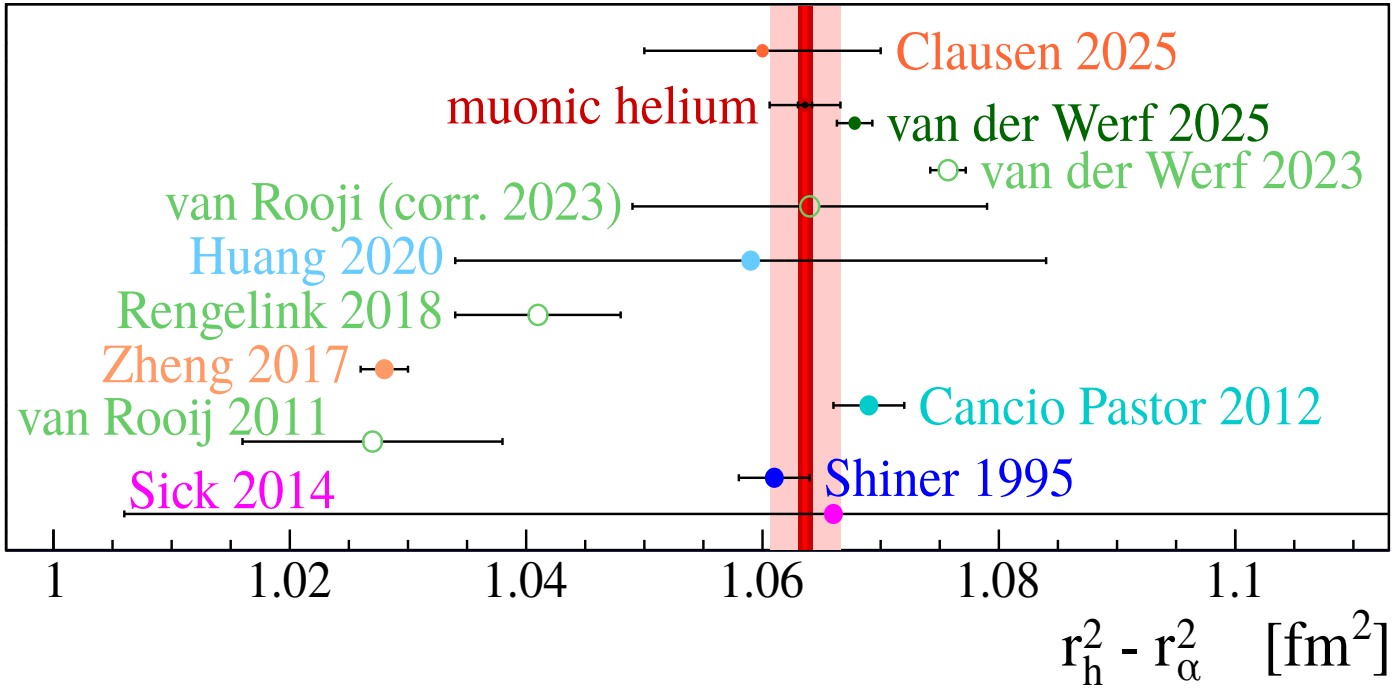
Helium-3 – Helium-4 Isotope Shift



CREMA Coll., Science (2025)

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)

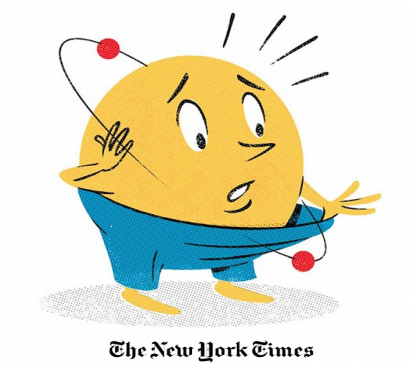
Intermediate conclusions

Muonic atoms / ions provide:

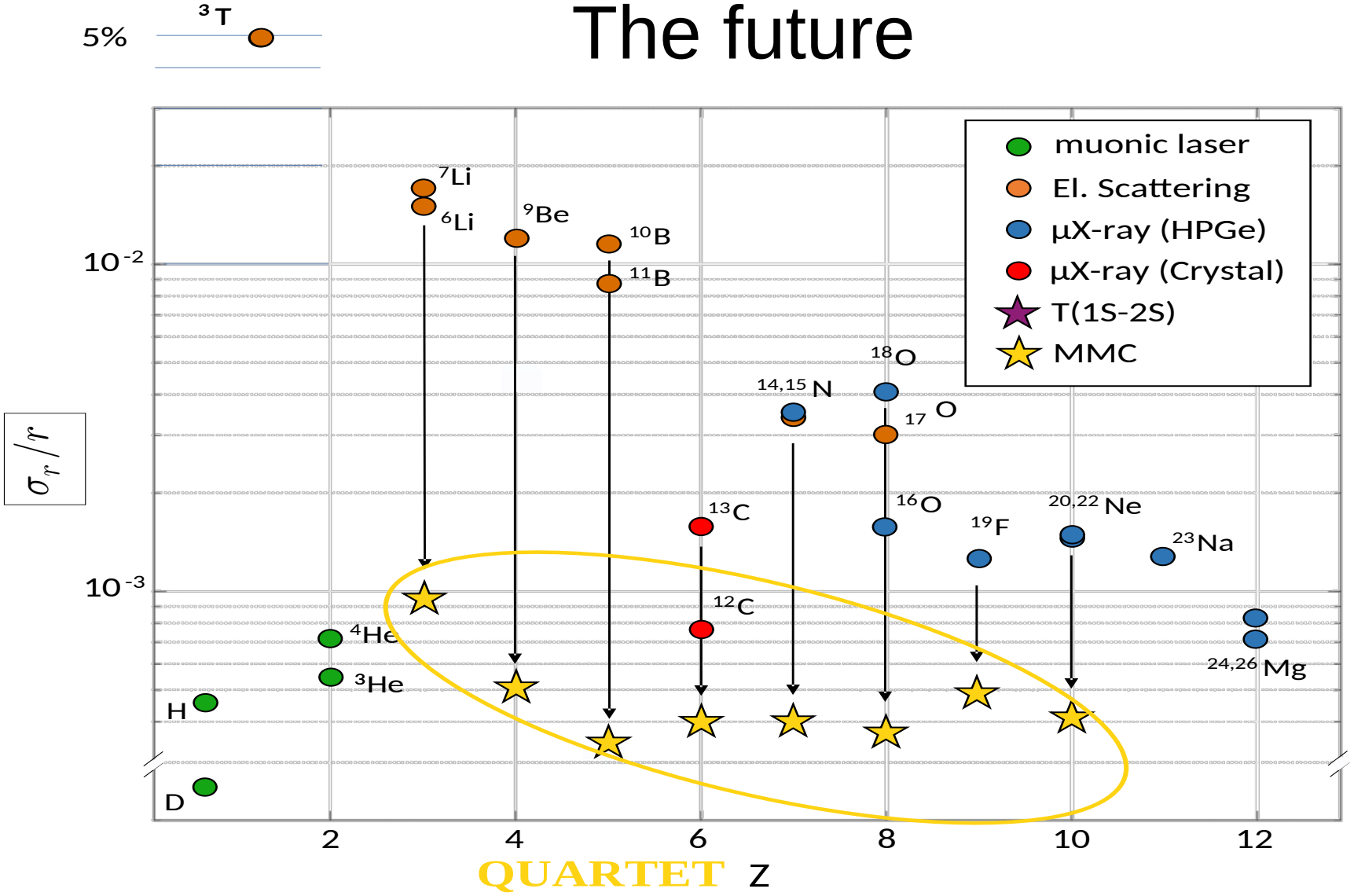
- **~10x more accurate charge radii**, when combined with

calculated polarizability

	^{3}He 1.9701*(10) ~~1.9730 (160)~~	^{4}He 1.6786 (12) ~~1.6810 (40)~~
^{1}H 0.8406 (4) ~~0.8751 (61)~~	^{2}D 2.1279 (2) ~~2.1413 (25)~~	^{3}T 1.7550 (860)



The future

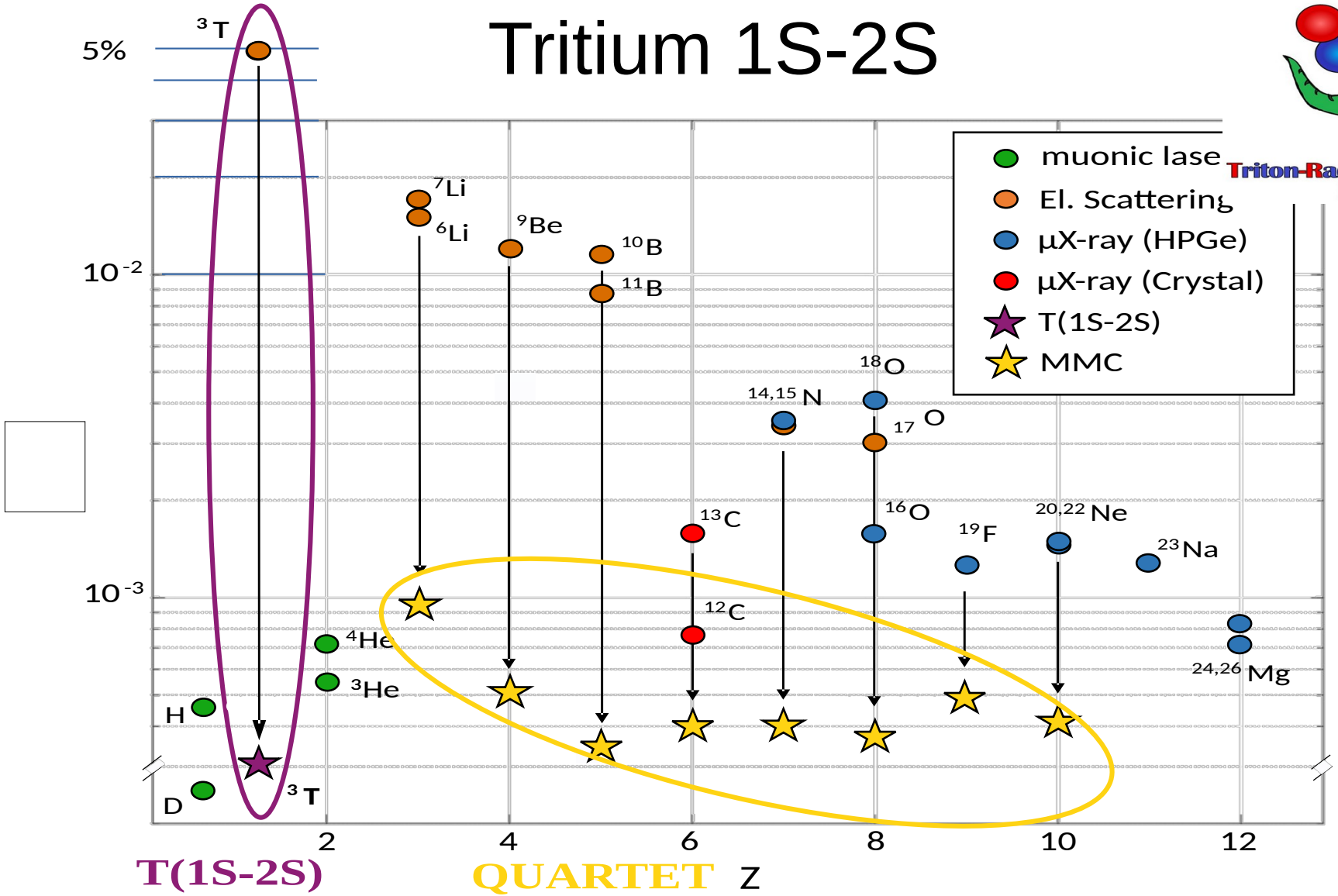

5%
³T
muonic laser
El. Scattering
μX-ray (HPGe)
μX-ray (Crystal)
T(1S-2S)
MMC
σ_r/r
10^{-2}
10^{-3}
⁷Li
⁶Li
⁹Be
¹⁰B
¹¹B
¹⁸O
¹⁴,¹⁵N
¹⁷O
¹³C
¹⁶O
¹⁹F
²⁰,²²Ne
²³Na
¹²C
⁴He
³He
H
D
²⁴,²⁶Mg
2
4
6
8
10
12
QUARTET
Z

1S – 2S in (ordinary) atomic tritium

Triton-Radius EXperiment
Mainz

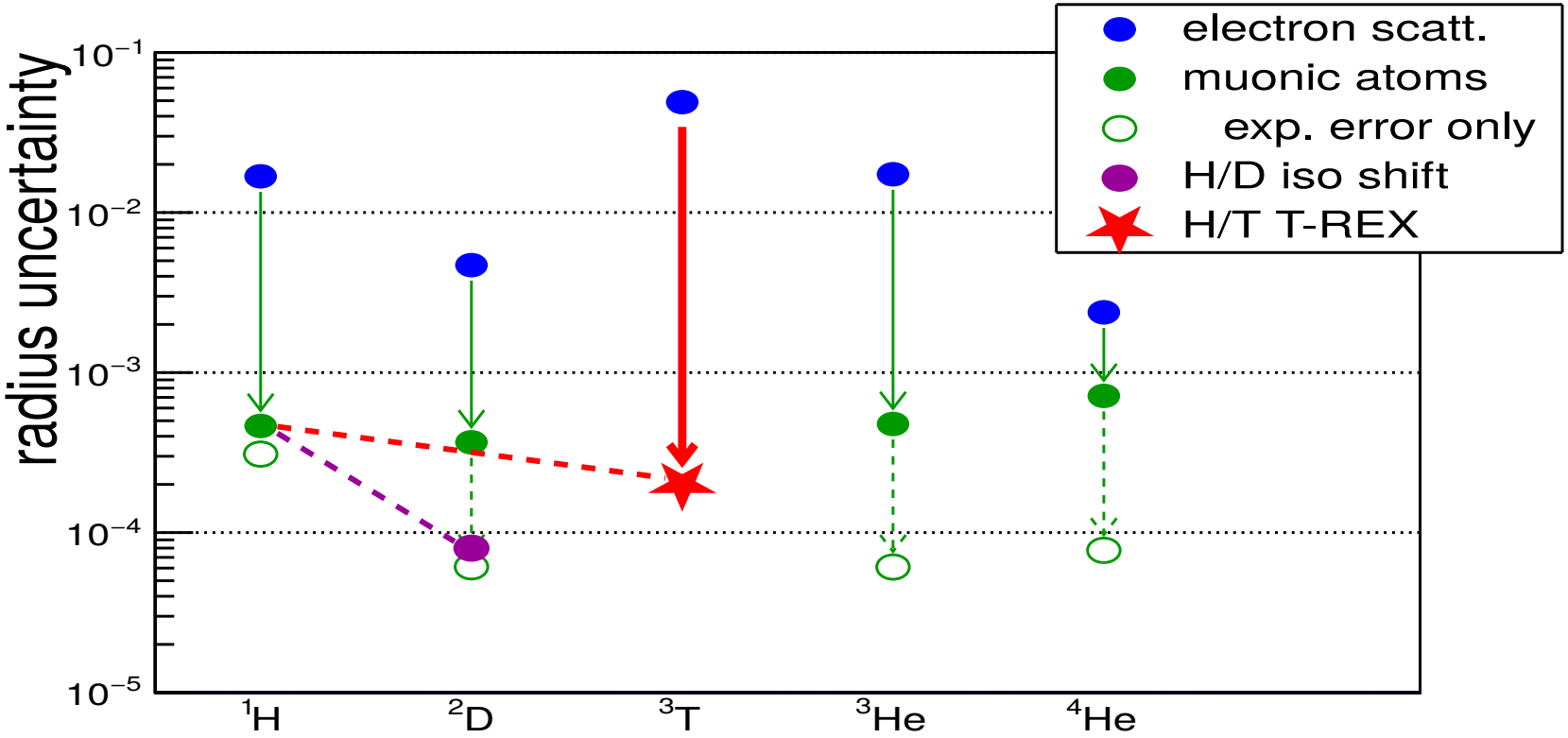
Randolf Pohl, JGU Mainz

Tritium 1S-2S

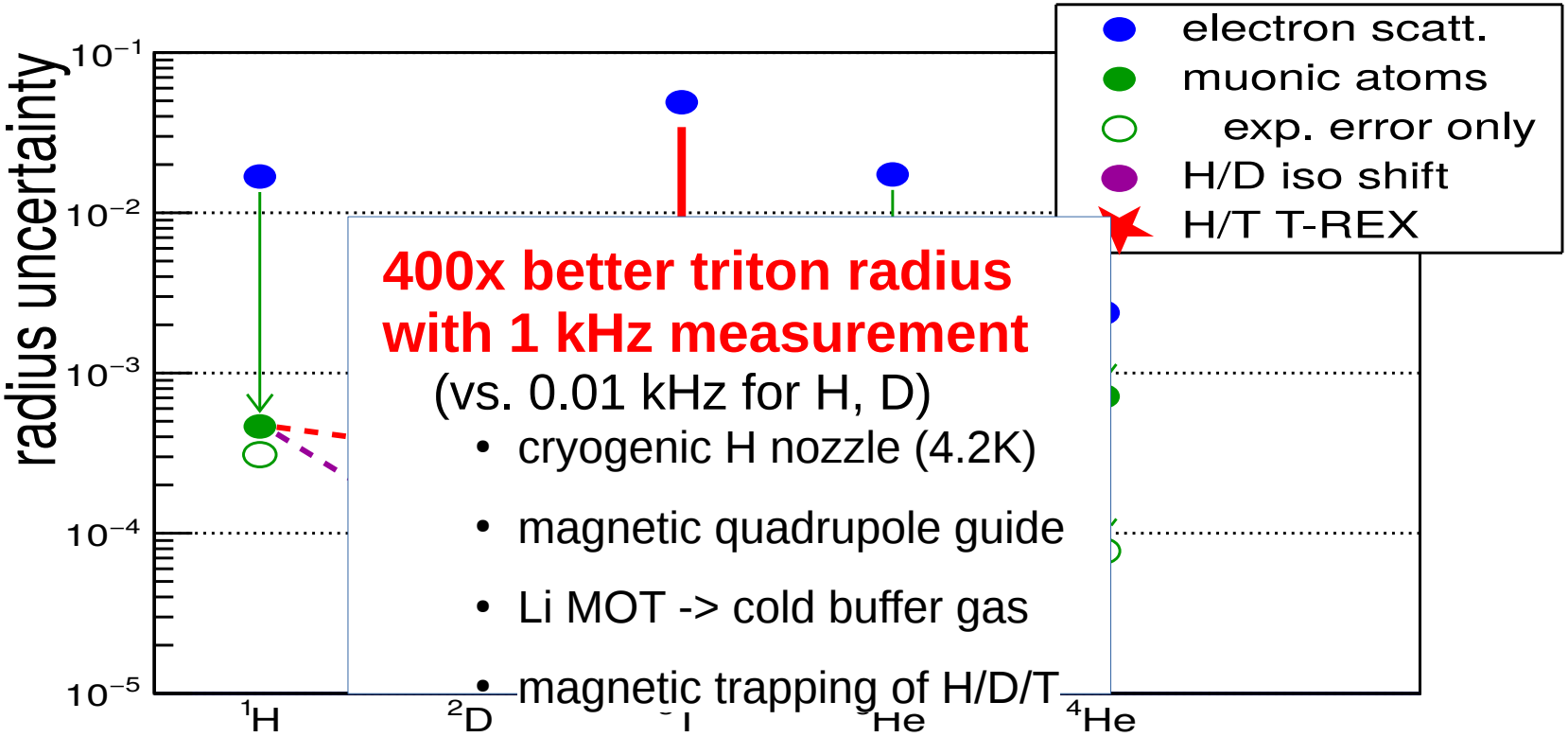


Triton-Radius EXperiment
Mainz

Tritium 1S-2S



Tritium 1S-2S

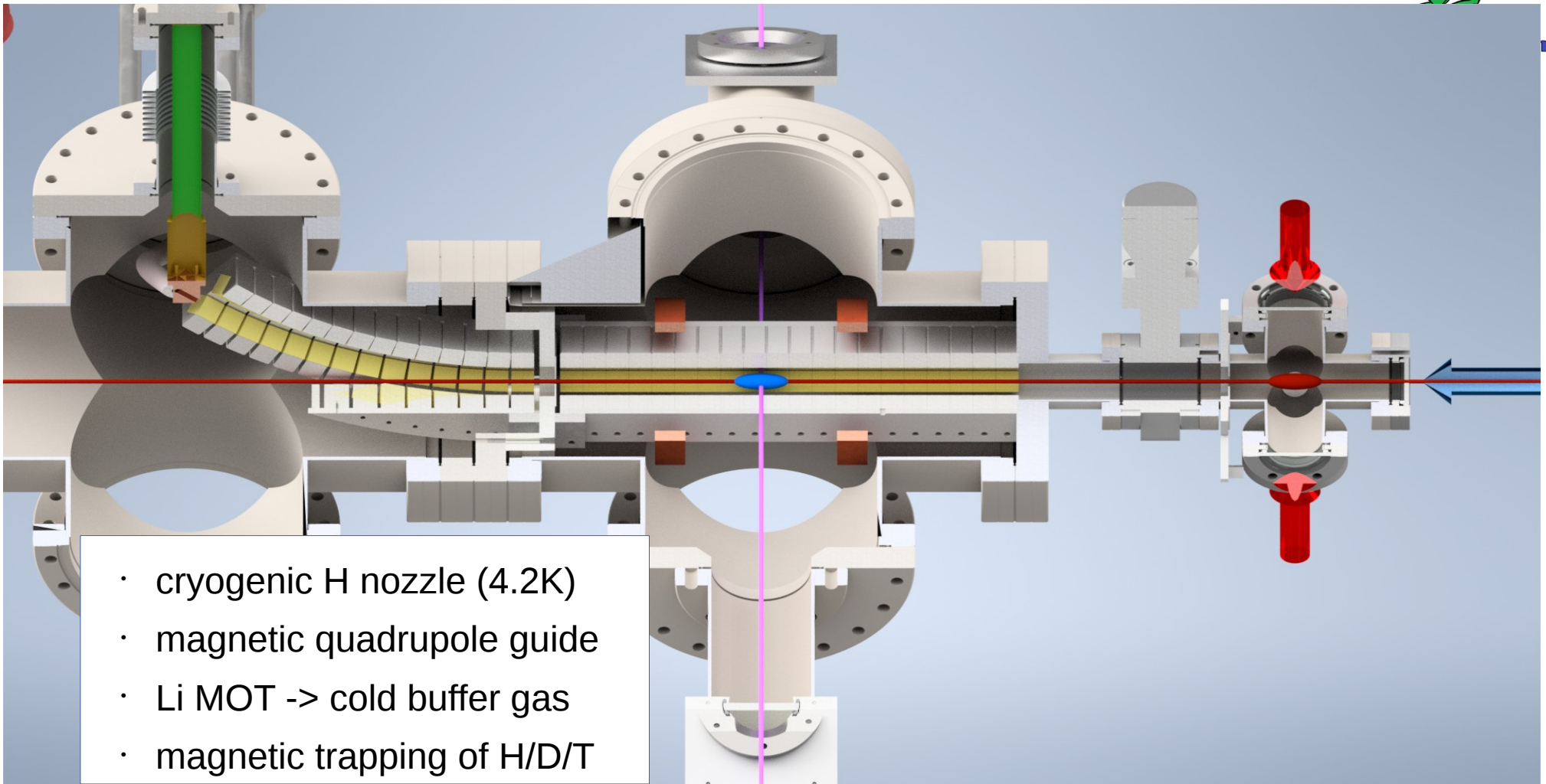


400x better triton radius with 1 kHz measurement

(vs. 0.01 kHz for H, D)

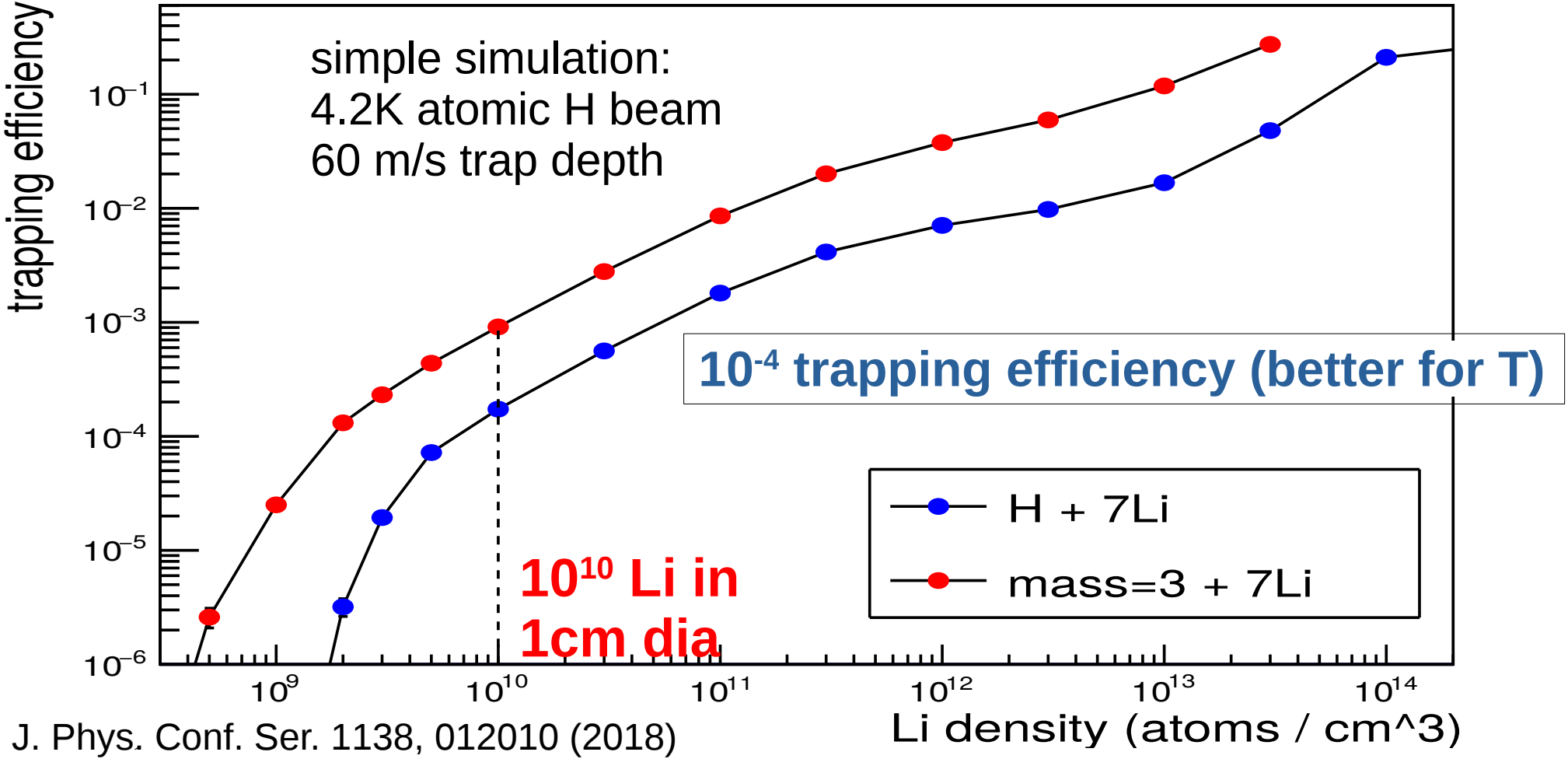
- cryogenic H nozzle (4.2K)
- magnetic quadrupole guide
- Li MOT -> cold buffer gas
- magnetic trapping of H/D/T

Trapping and spectroscopy



- cryogenic H nozzle (4.2K)
- magnetic quadrupole guide
- Li MOT -> cold buffer gas
- magnetic trapping of H/D/T

Simulated trapping efficiency



J. Phys. Conf. Ser. 1138, 012010 (2018)

Triton charge radius from Tritium 1S-2S

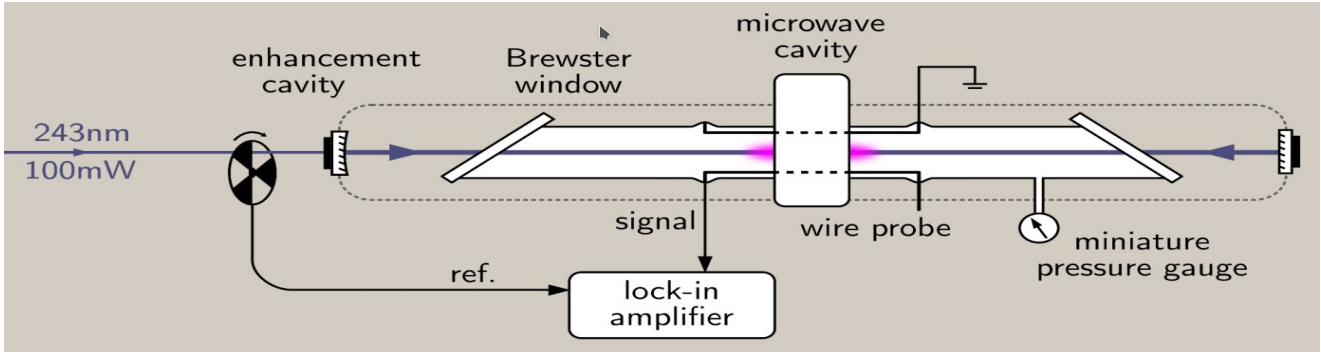
^{3}He 1.9679*(14) ~~1.9730 (160)~~	^{4}He 1.6782 (8) ~~1.6810 (40)~~	
^{1}H 0.8409 (4) ~~0.8751 (61)~~	^{2}D 2.1279 (2) ~~2.1413 (25)~~	^{3}T **1.7xxx (200)** 1.7550 (860)

Triton-Radius EXperiment Mainz

4x better radius with 100 kHz measurement

(vs. 0.01 kHz for H, D)

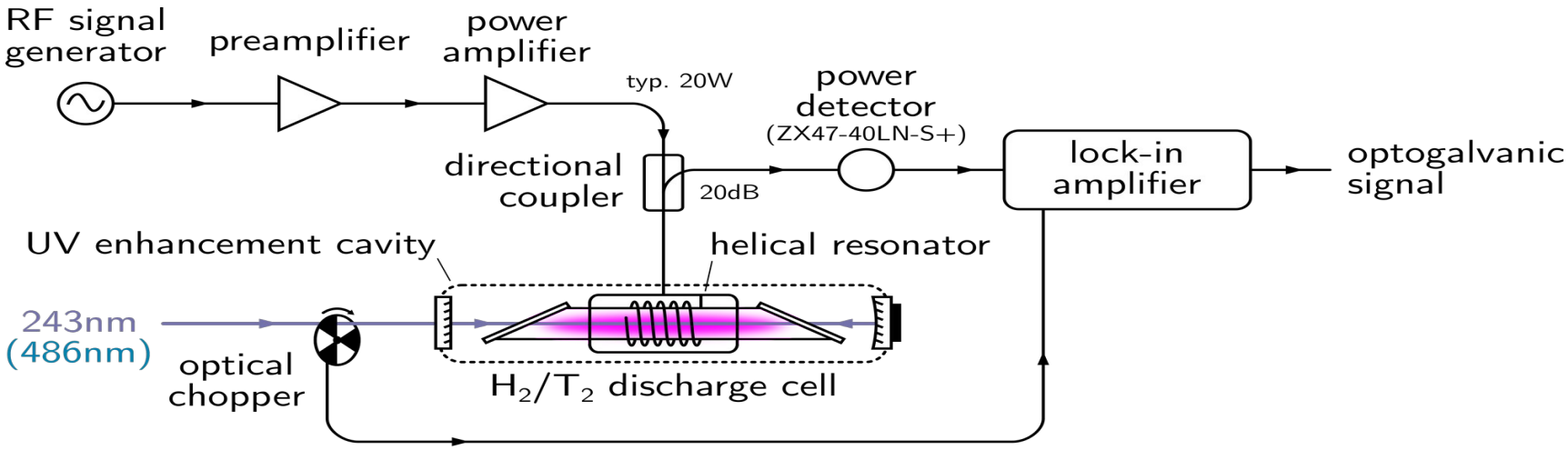
- Optogalvanic spectroscopy in a cell
- Syst. extrapolation w/ H,D
- Tritium confined.



staged approach

Hydrogen/Tritium Laser Spectroscopy in RF Discharge Cell

Spectroscopy Setup



optogalvanic detection → laser-induced impedance change of the plasma

- monitoring reflected (or forward) RF power via directional coupler (shown above)
- pickup-coil around plasma tube

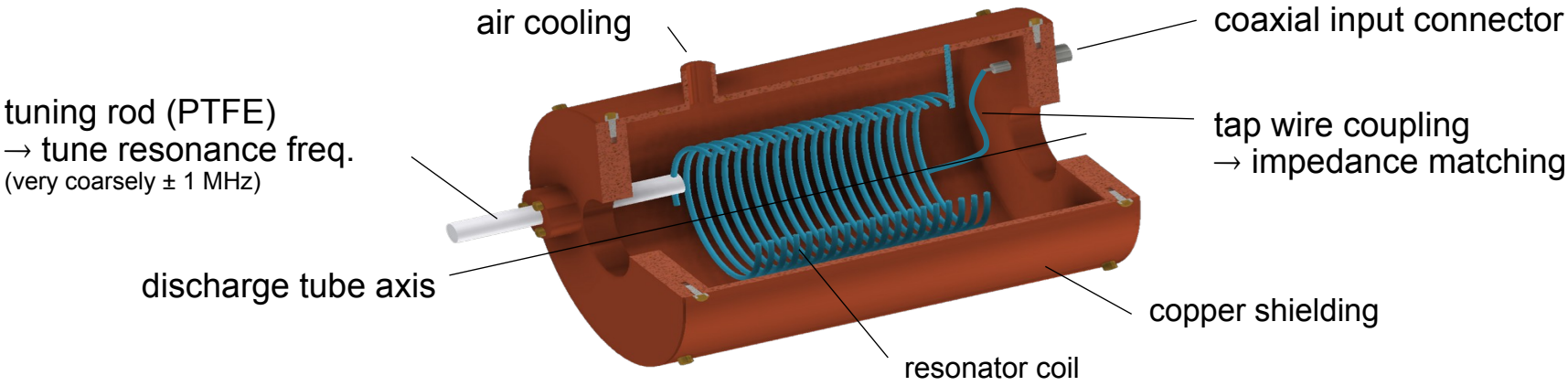
\+ avoid optical detection within the fluorescence background of the discharge glow

\+ containment of radioactive tritium samples in a compact sealed glass cell

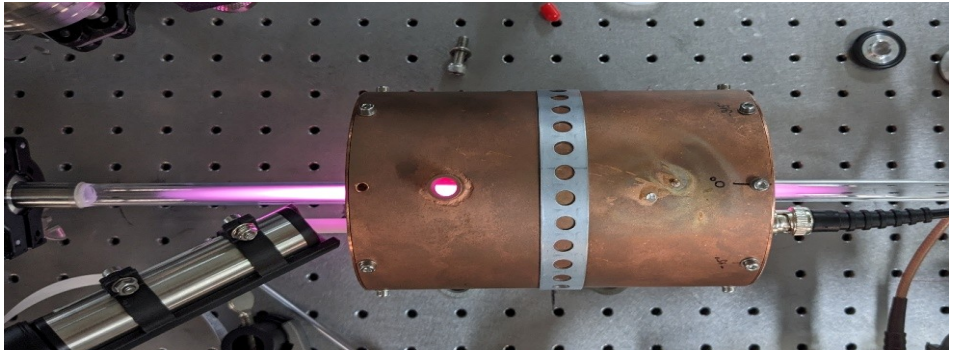
− large systematic effects expected due to electric fields and collision processes

Hydrogen/Tritium Laser Spectroscopy in RF Discharge Cell

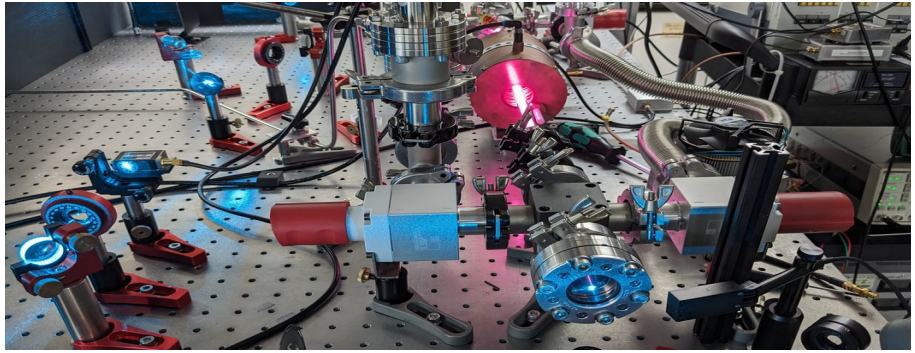
Spectroscopy Setup



Resonator design inspired by [Tate, *Investigations of simple atomic systems by laser spectroscopy*, Phd thesis, Oxford (1987)]



▲ discharge tube (reduced power)



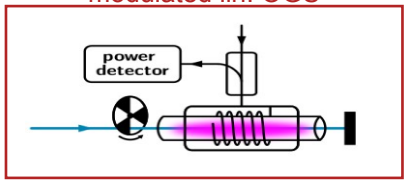
overview ▲

Hydrogen/Tritium Laser Spectroscopy in RF Discharge Cell

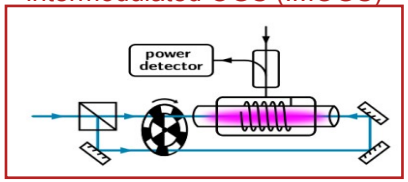
Balmer-β Transition / Overview

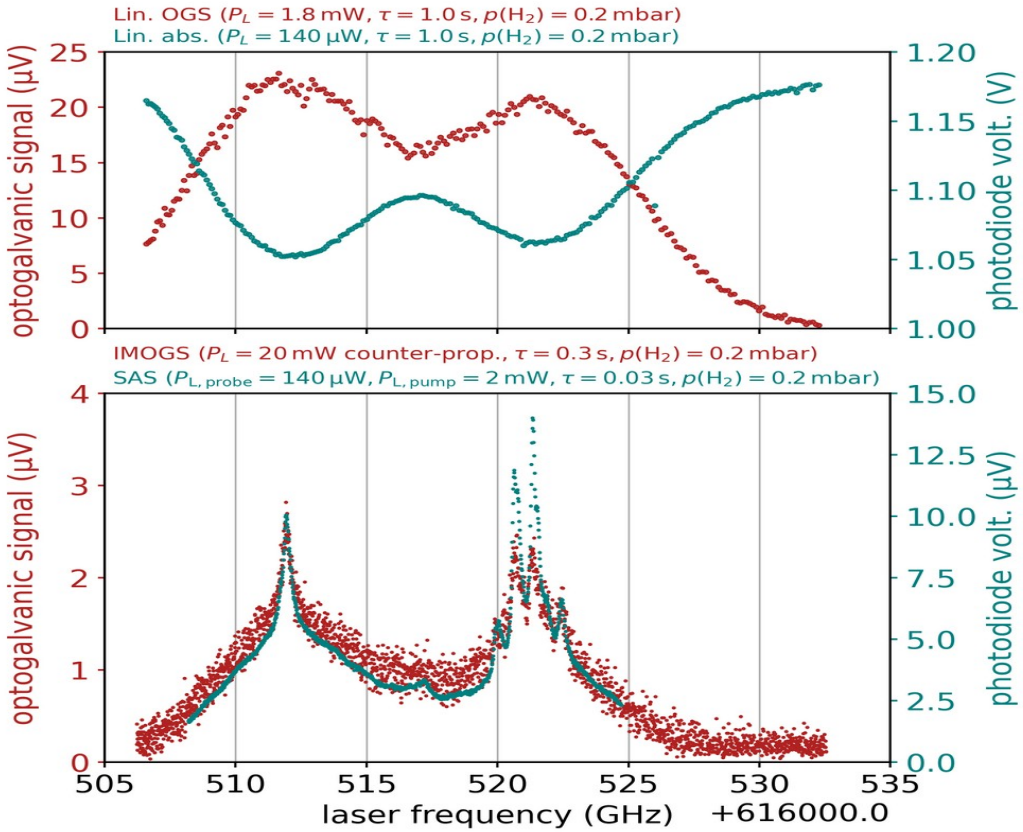
optogalvanic spectroscopy (OGS)

modulated lin. OGS



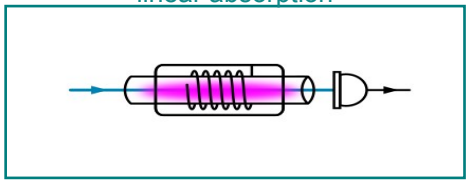
intermodulated OGS (IMOGS)



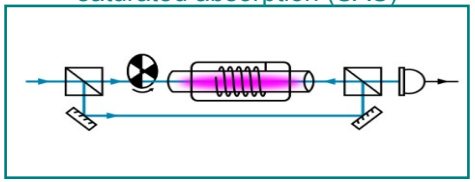


absorption spectroscopy

linear absorption

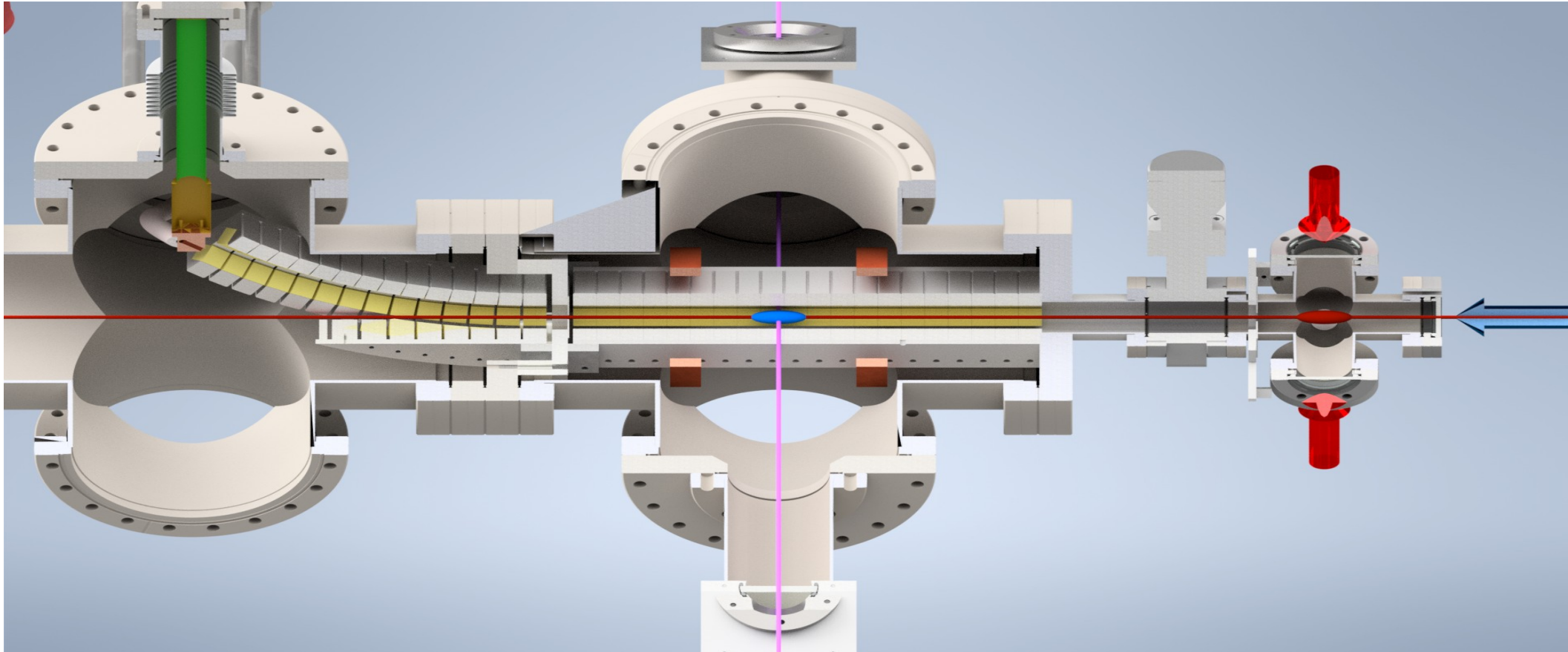


saturated absorption (SAS)



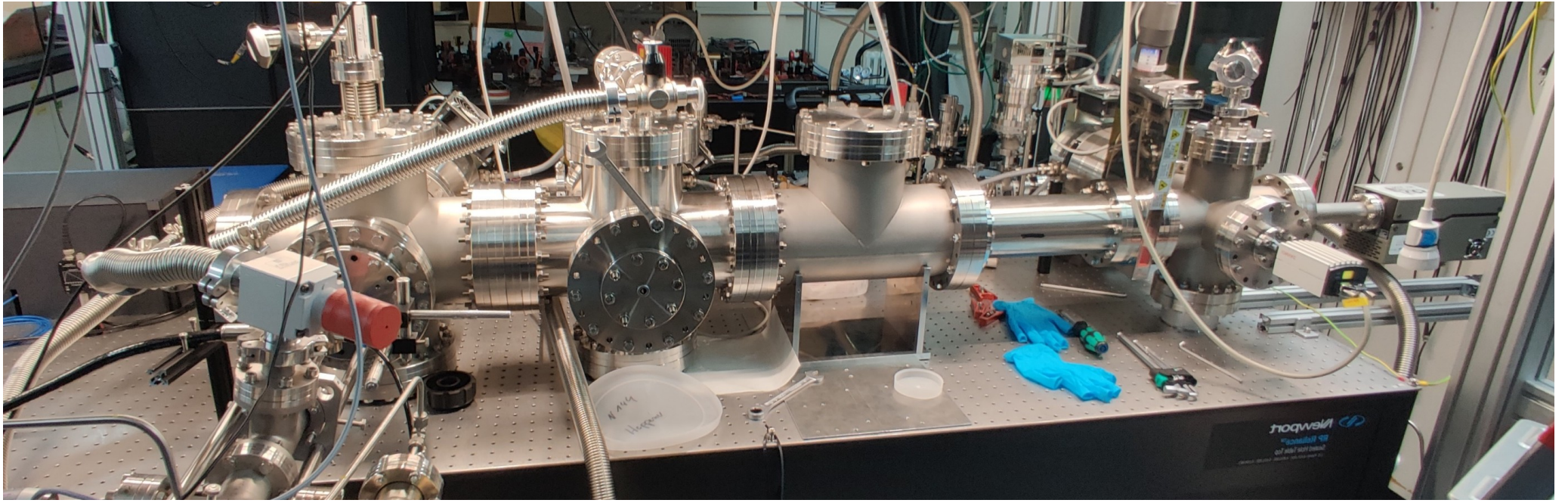
Towards trapping and spectroscopy

Triton-Radius EXperiment
Mainz

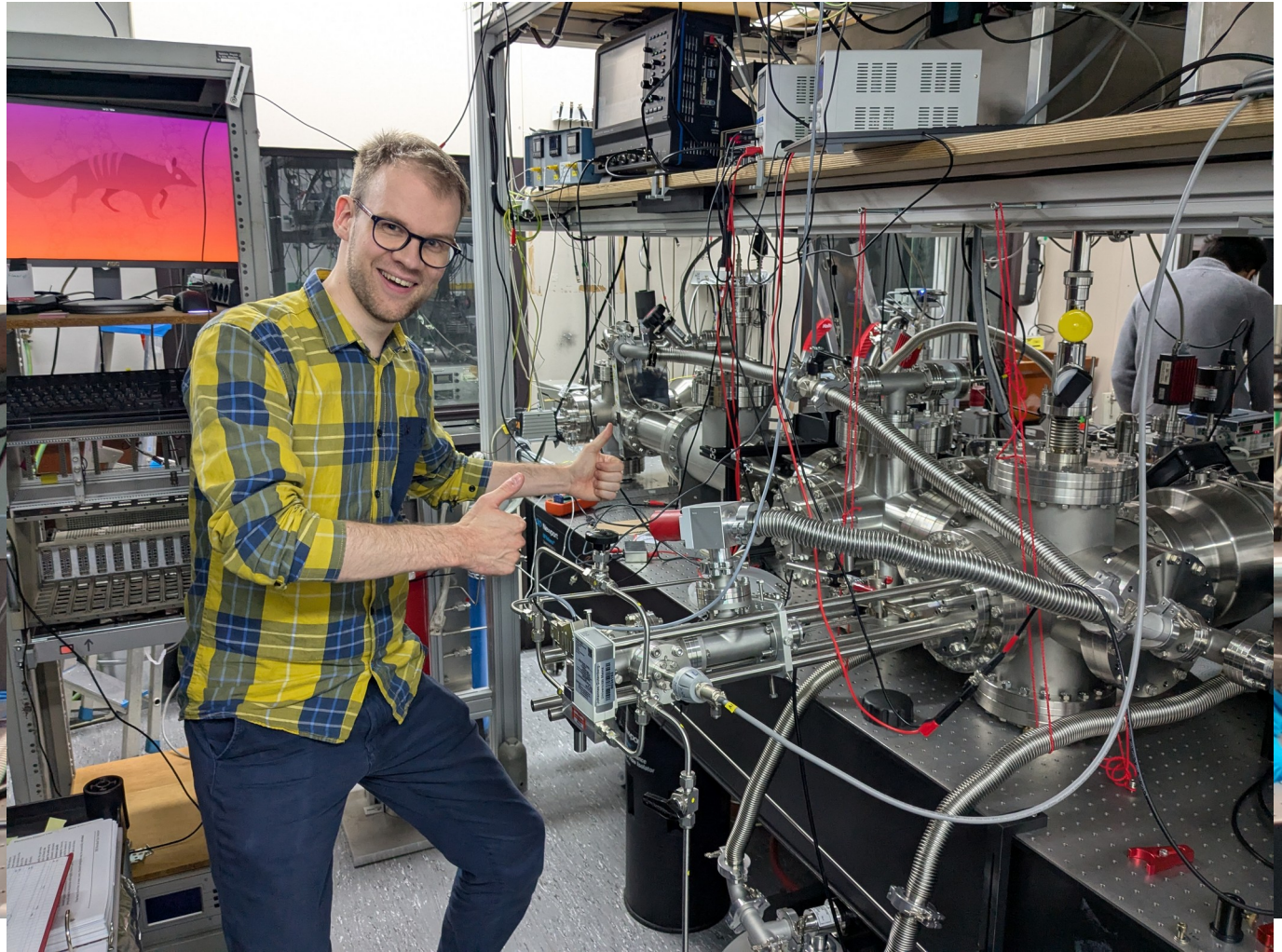


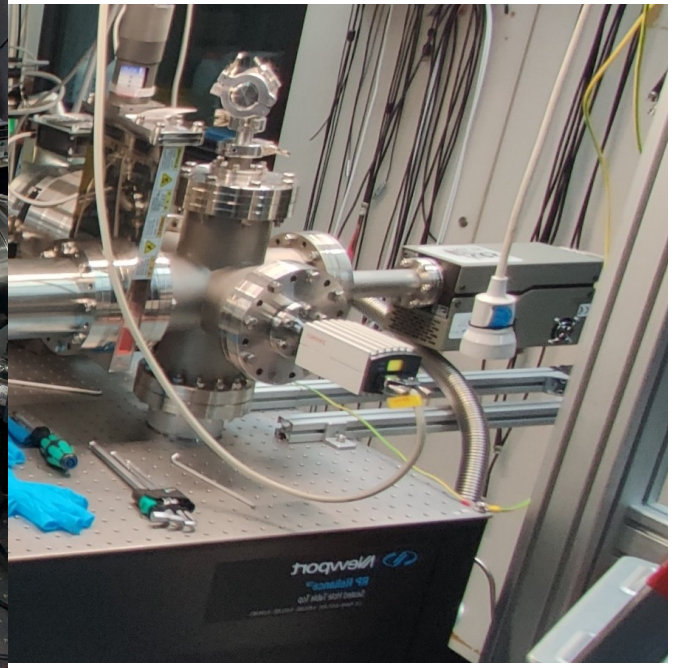
Towards H Beam Characterization

- Hydrogen beam dissociation
- Cryogenic nozzle design and atom beam shape
- Quadrupole cut-off velocity

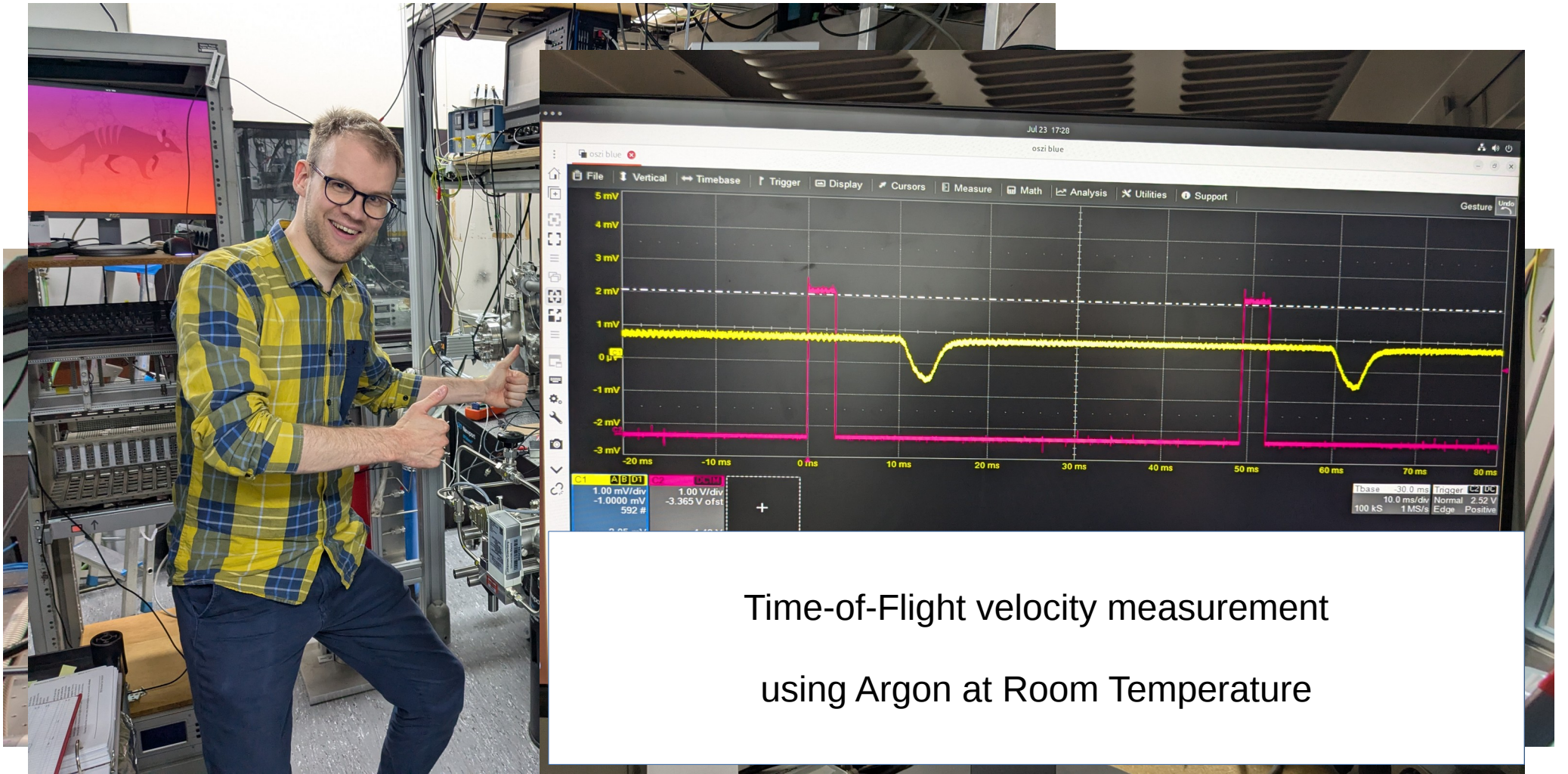


Towards H Beam Characterization





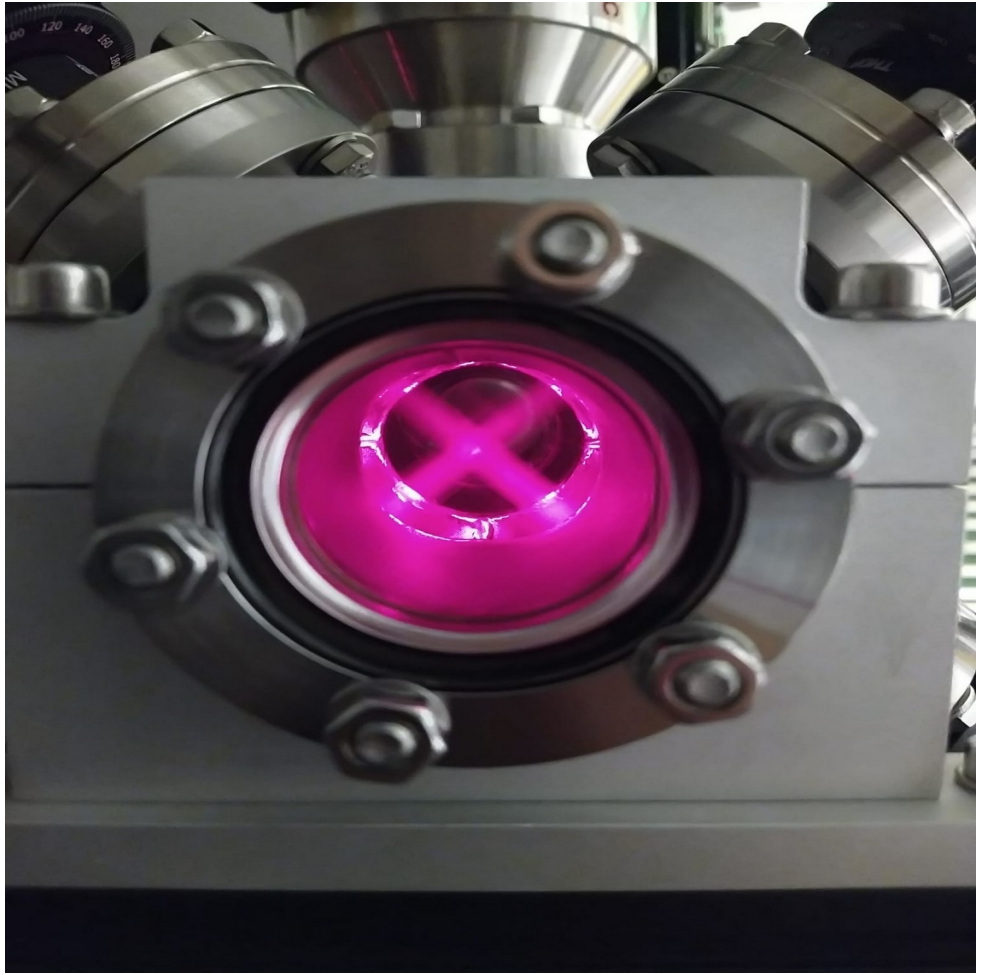
Towards H Beam Characterization

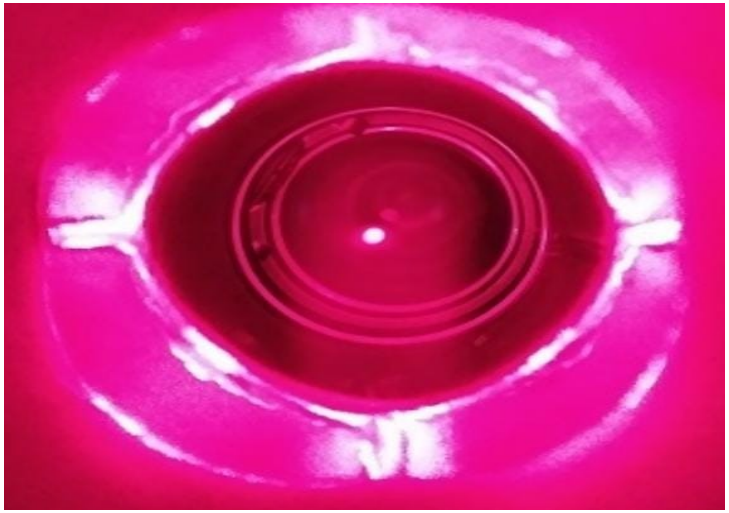


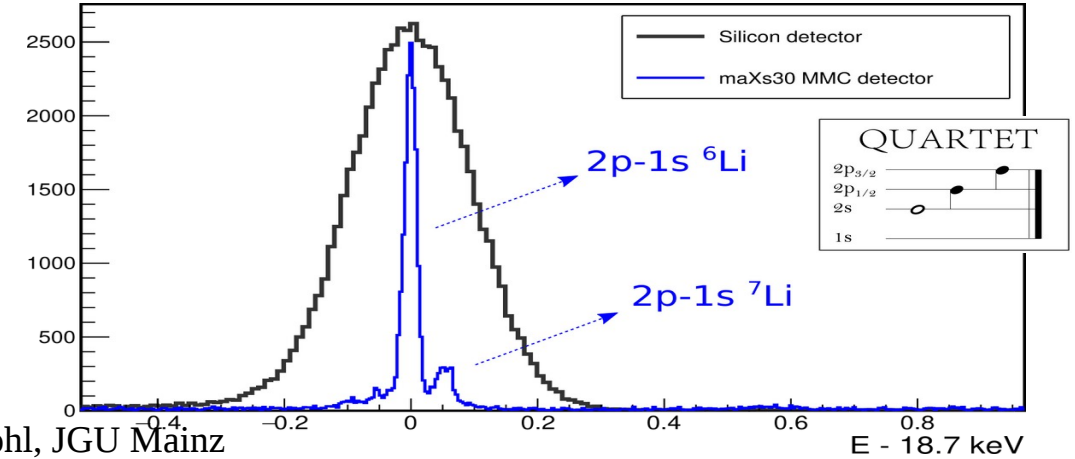
Time-of-Flight velocity measurement

using Argon at Room Temperature

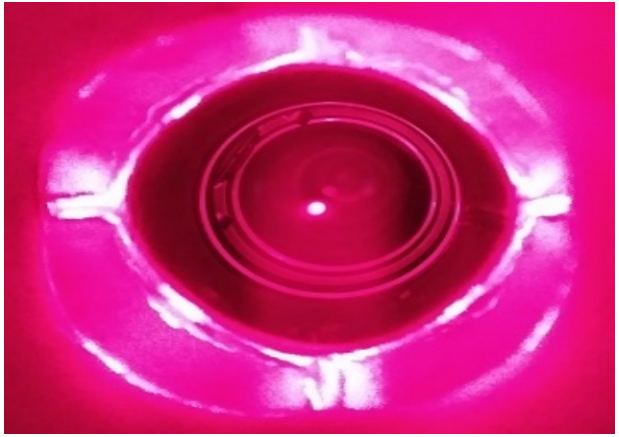
Atomic Lithium

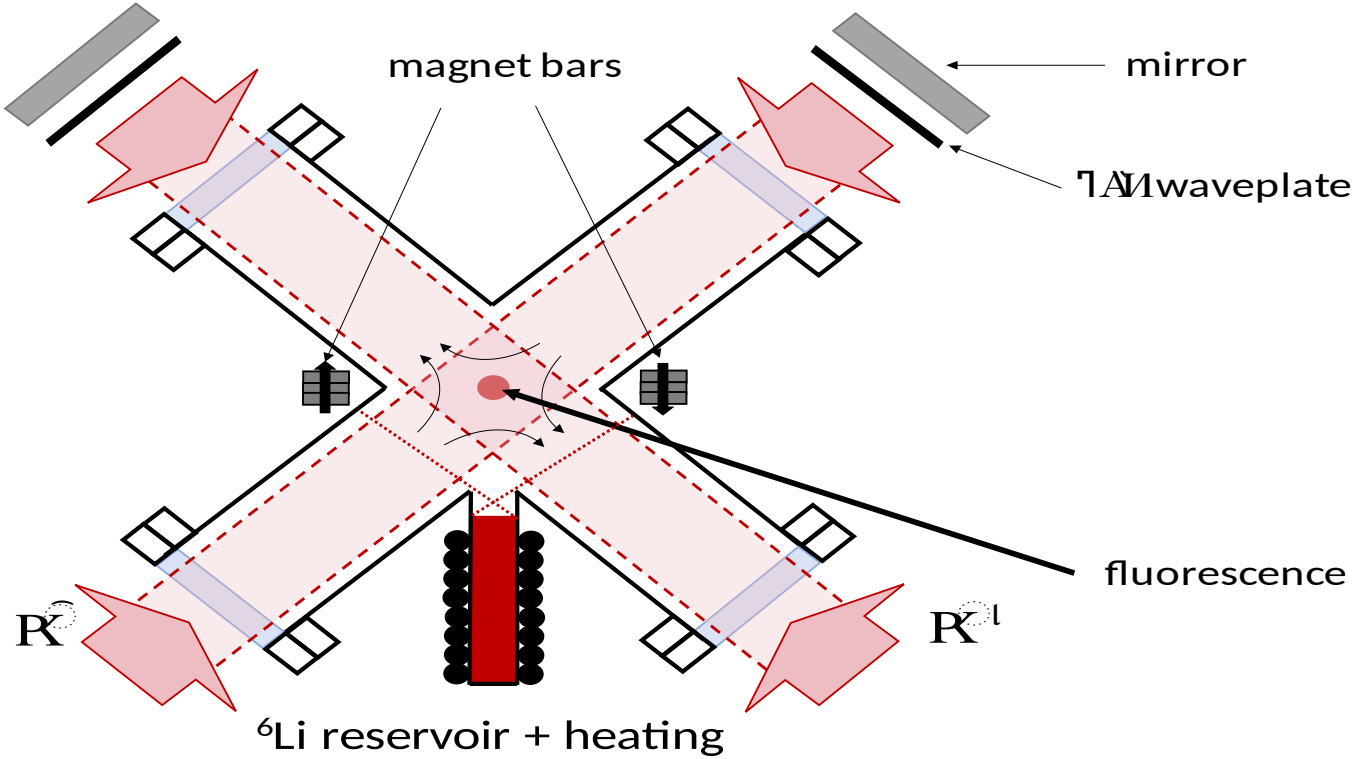






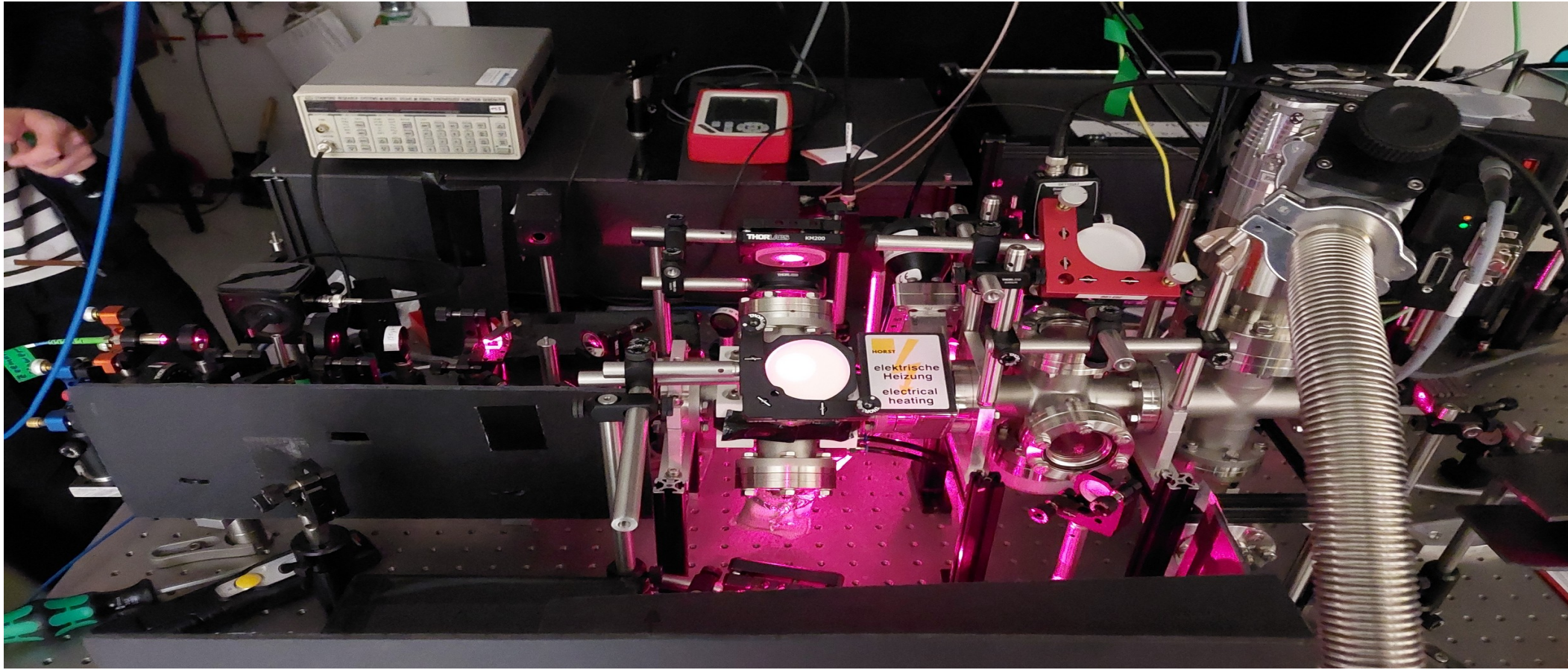
2D MOT as cold Li beam source





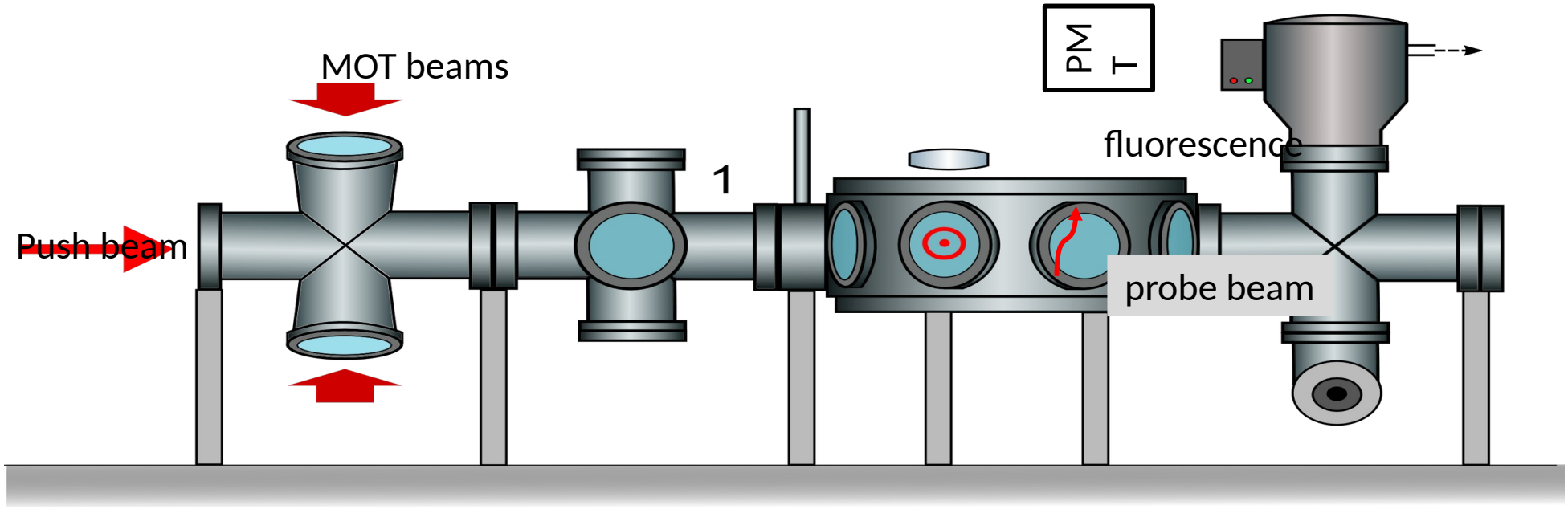
2D-MOT design: Tiecke, Walraven et al, PRA 80, 013409 (2009)

2D MOT for cold Li (old)



2D-MOT design: Tiecke, Walraven et al, PRA 80, 013409 (2009)

Vacuum Setup / Beamline



Our 1st spectroscopy on cold Li

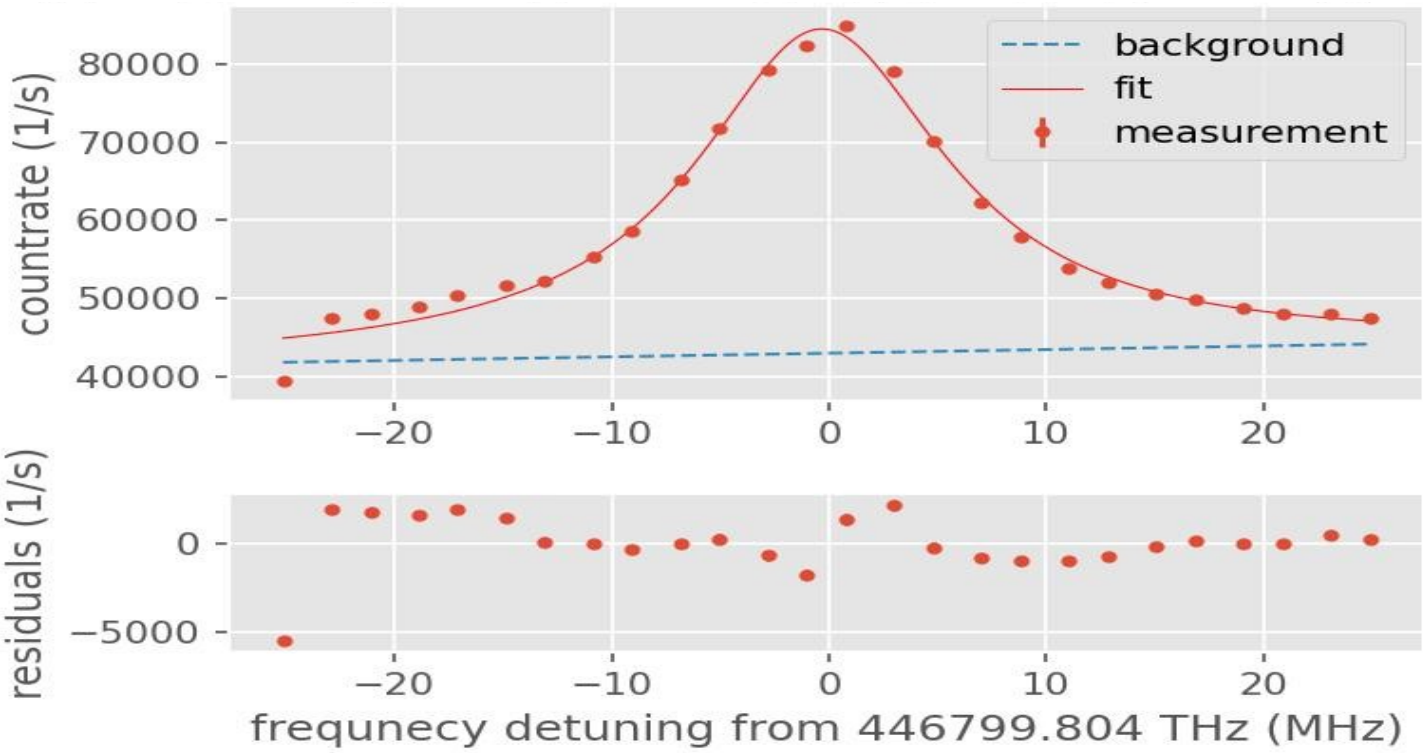
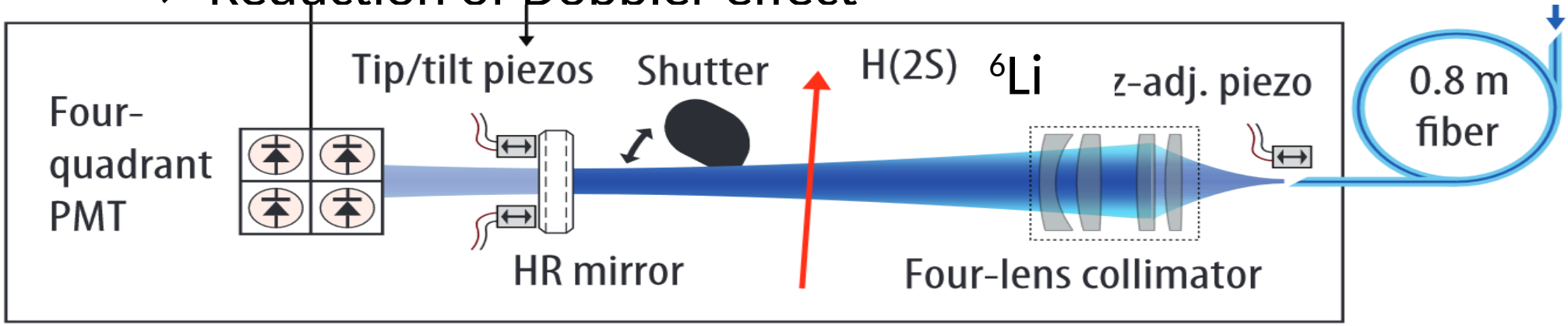


Fig.1: Fluorescence spectrum with a probe beam power µW measured over 1 s.

Next up: AFR

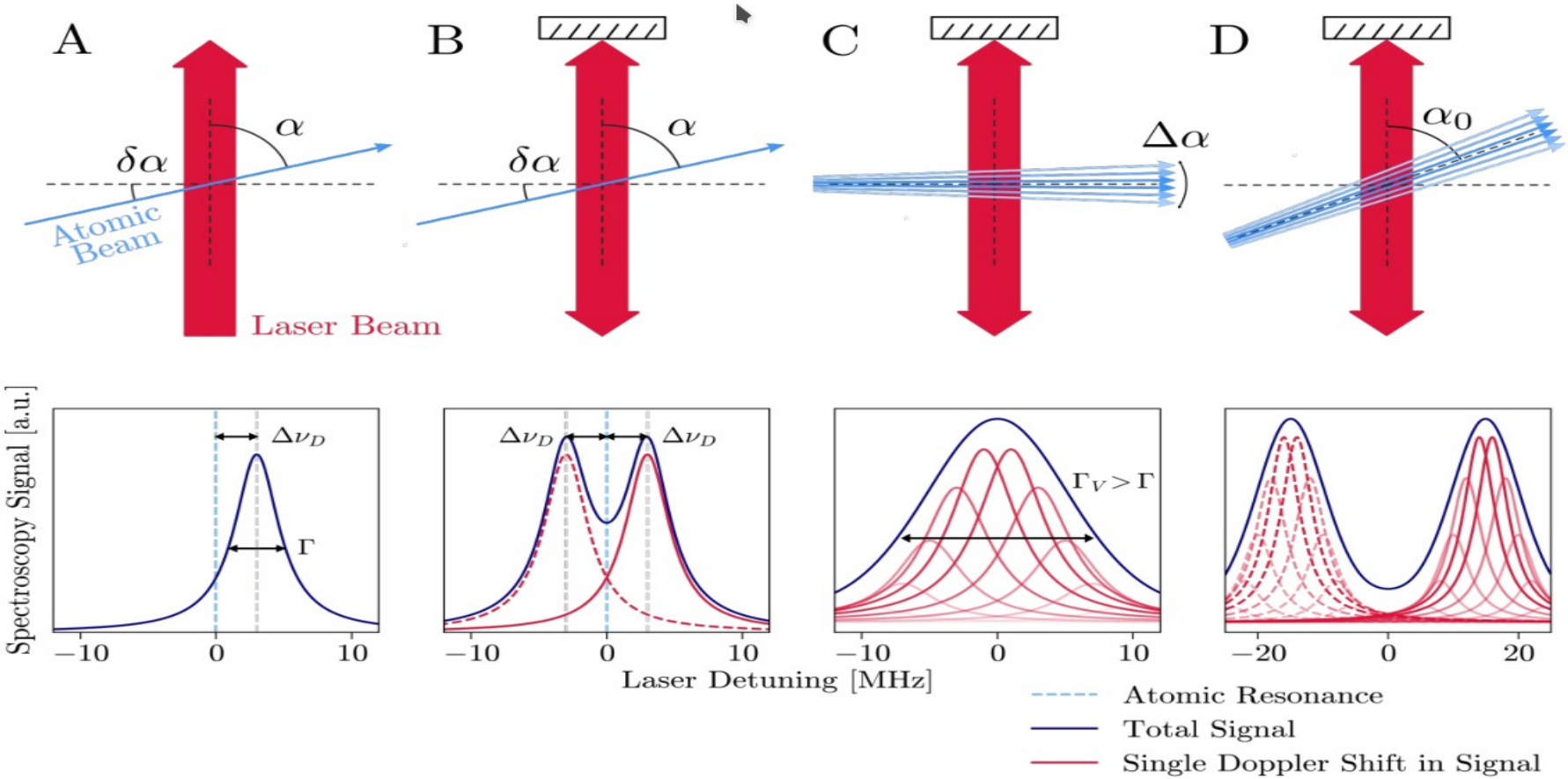
- Use of Active fiber-based Retroreflector:

  → Reduction of Doppler effect

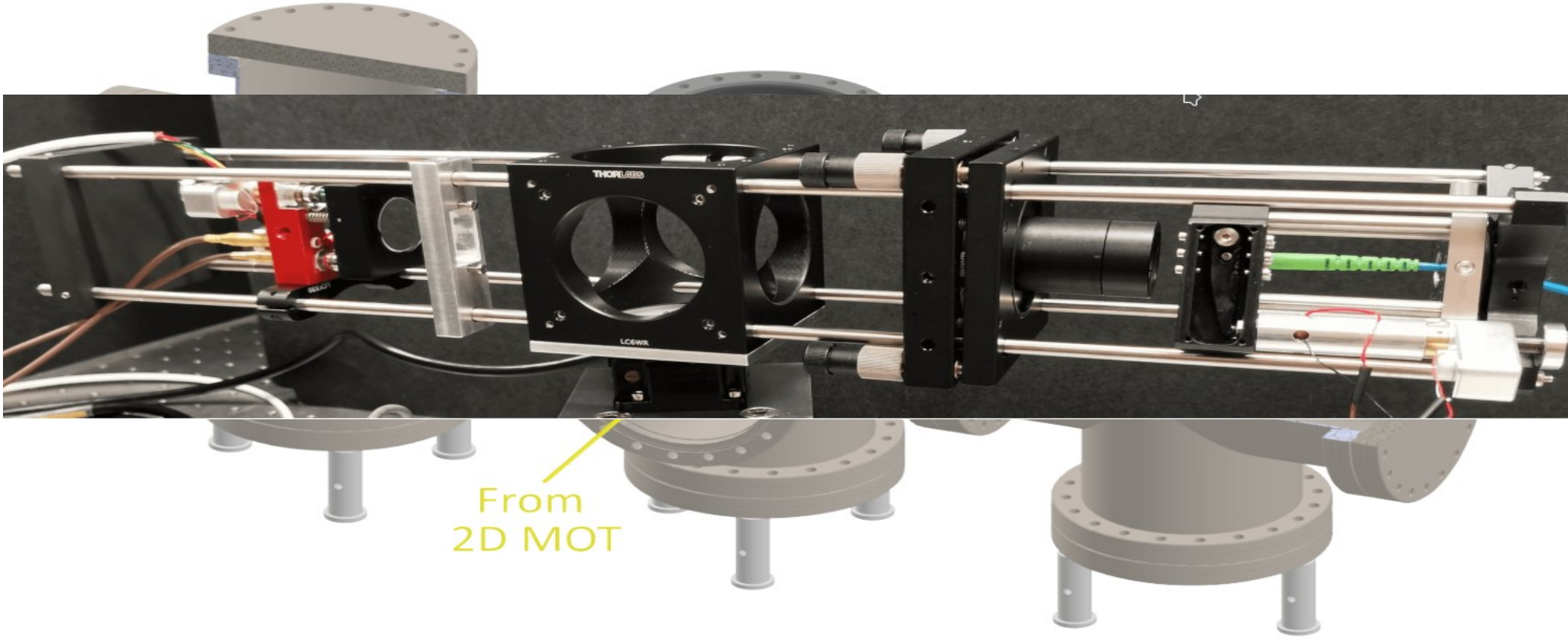


[A. Beyer, "Active fiber-based retroreflector providing phase-retracing anti-parallel laser beams for precision spectroscopy", 2016]
[V. Wirthl, "Improved active fiber-based retroreflector with intensity stabilization and a polarization monitor for the near UV", 2022]

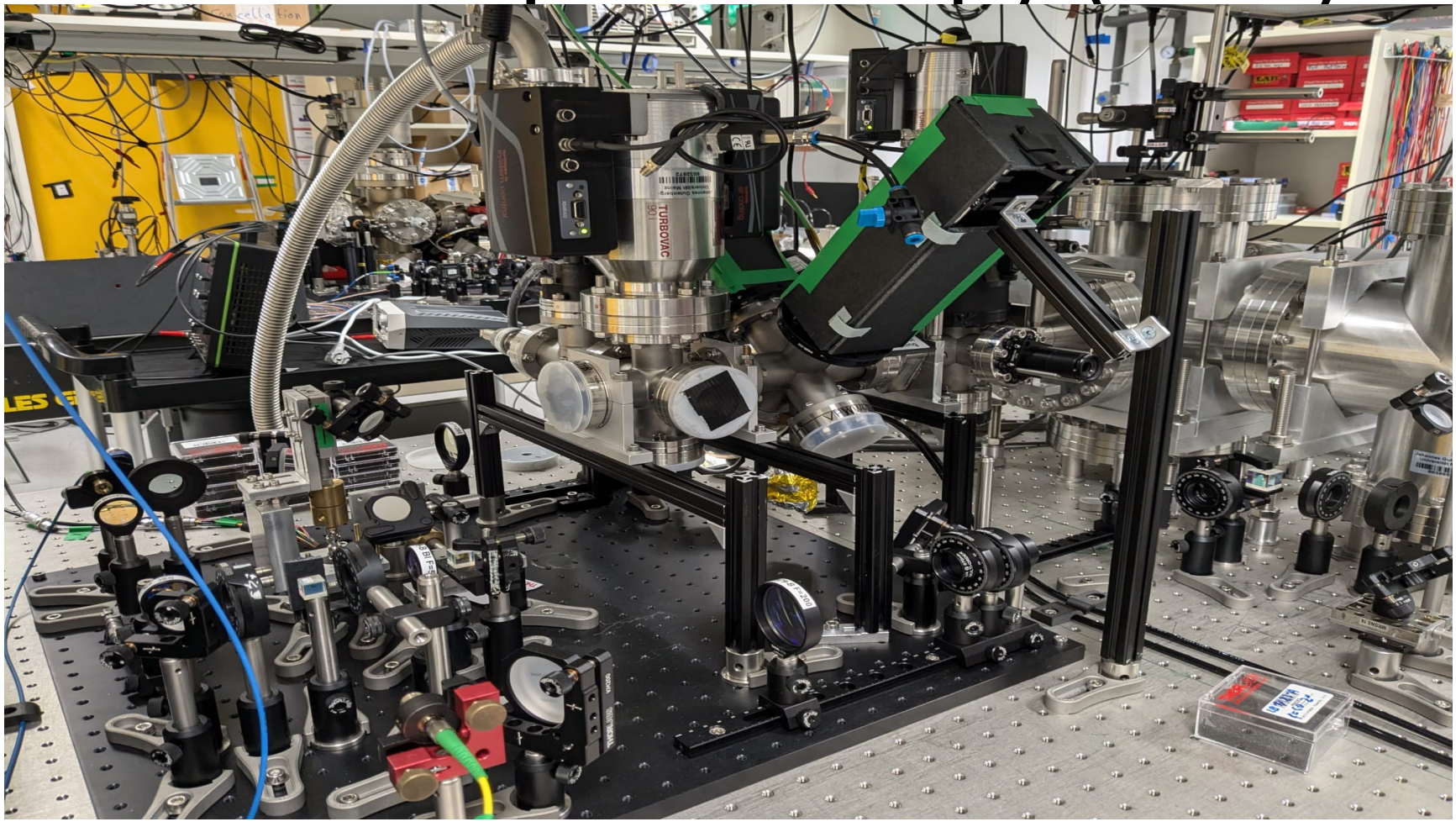
AFR: Actively stabilized Fiber-based Retro-Reflector



AFR: Actively stabilized Fiber-based Retro-Reflector



2D MOT + spectroscopy (AFR)



2D-MOT design: Tiecke, Walraven et al, PRA 80, 013409 (2009)

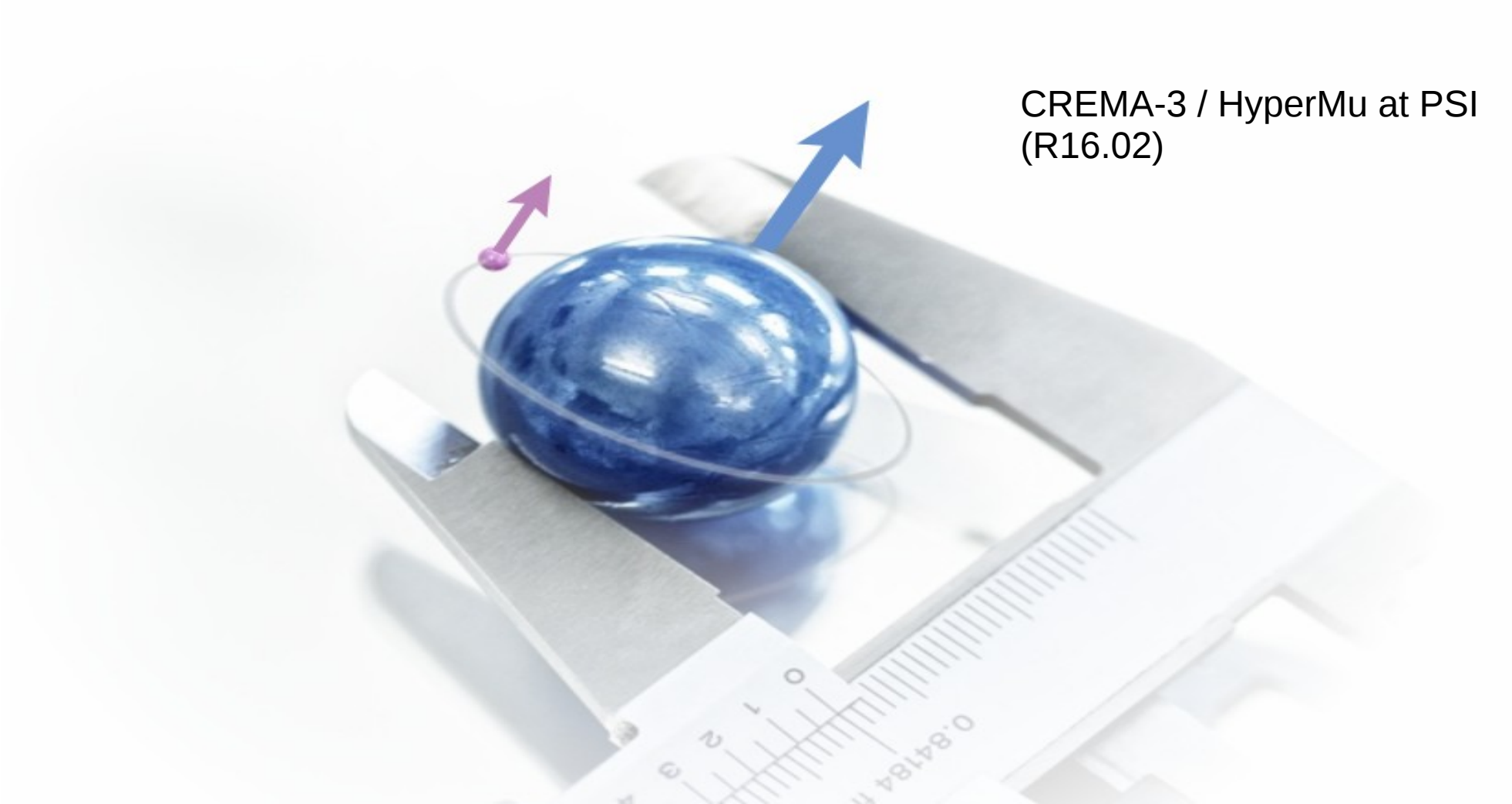
Thanks a lot for your attention

Thanks a lot for your attention

Welcome to ECT* Trento

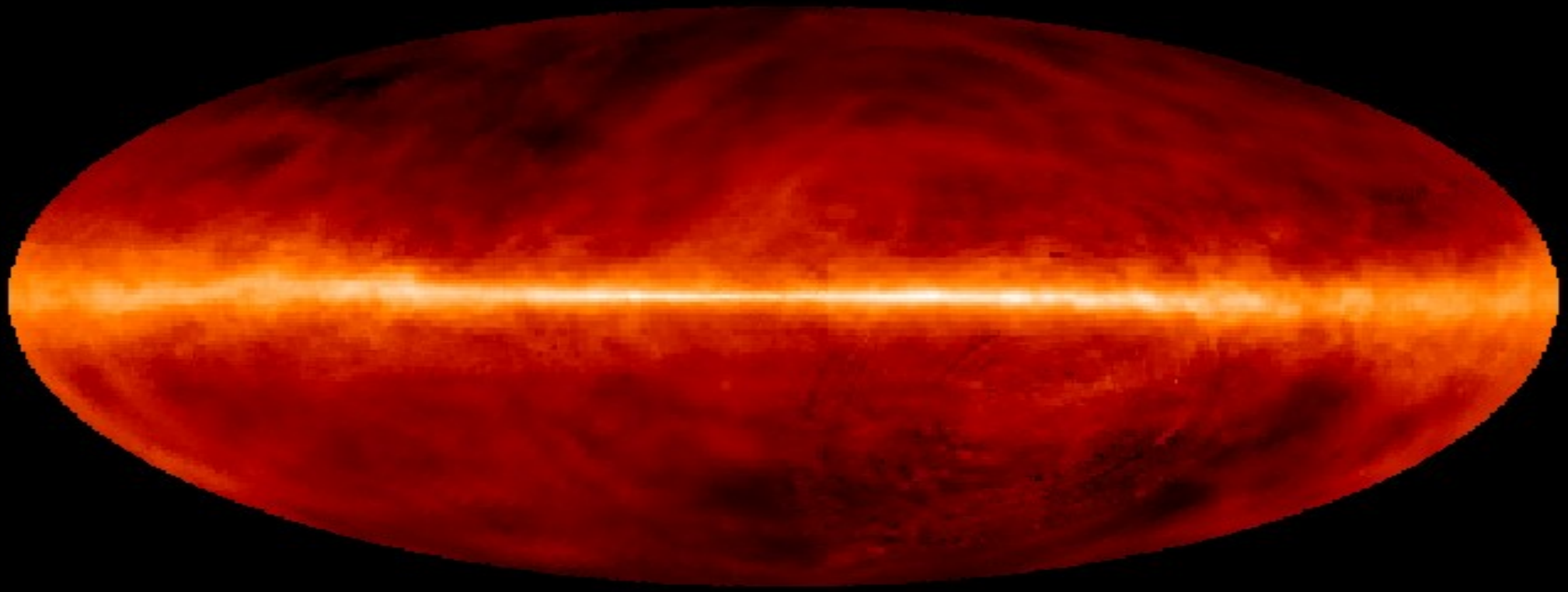
		Monday	Tuesday	Wednesday	Thursday	Friday
9:40 – 10:20	30 + 10	van Kolck	Ohayon	Bacca	Gasparian	Craig
10:20 – 11:00	30 + 10	Pohl	Peset	Drissi	Ouf	Potvliege
11:00 – 11:30	Coffee					
11:30 – 12:10	30 + 10	Gorshteyn	Harman	Pastore	Pitelis	Feng
12:10 – 12:50	30 + 10	Fleischmann	Nörtershäuser	Oreshkina	Lensky	Closing
13:00 – 15:00	Lunch					
15:00 – 15:40	30 + 10	Kreuzberger	Weber	Excursion	Ji	
15:40 – 16:20	30 + 10	Godhino	Rathi		Egert	
16:20 – 16:50		Coffee				
16:50 – 17:30	30 + 10	Baptista	Cocolios			
17:30 – 18:10	30 + 10	Heiße (Zoom)	Deseyn			
18:10 – 18:30	Discussions					

Hyperfine structure in muonic H

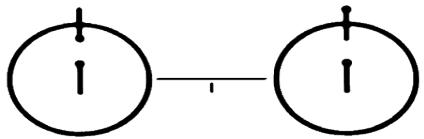


CREMA-3 / HyperMu at PSI
(R16.02)

The sky in hydrogen



Hyperfine structure in H / μp



The 21 cm line in hydrogen (1S hyperfine splitting) has been **measured** to 12 digits (0.001 Hz) in 1971:

$$\nu_{exp} = 1\,420\,405.\,751\,766\,7 \pm 0.000\,001 \text{ kHz}$$

Essen et al., Nature 229, 110 (1971)

QED test is limited to 6 digits (800 Hz) because of proton structure effects:

$$\nu_{theo} = 1\,420\,403.\,1 \pm 0.6_{\text{proton size}} \pm 0.4_{\text{polarizability}} \text{ kHz}$$

Eides et al., Springer Tracts 222, 217 (2007)

Proton Zemach radius

HFS depends on “Zemach” radius:

$$\Delta E = -2(Z\alpha)m\langle r\rangle_{(2)} E_F$$

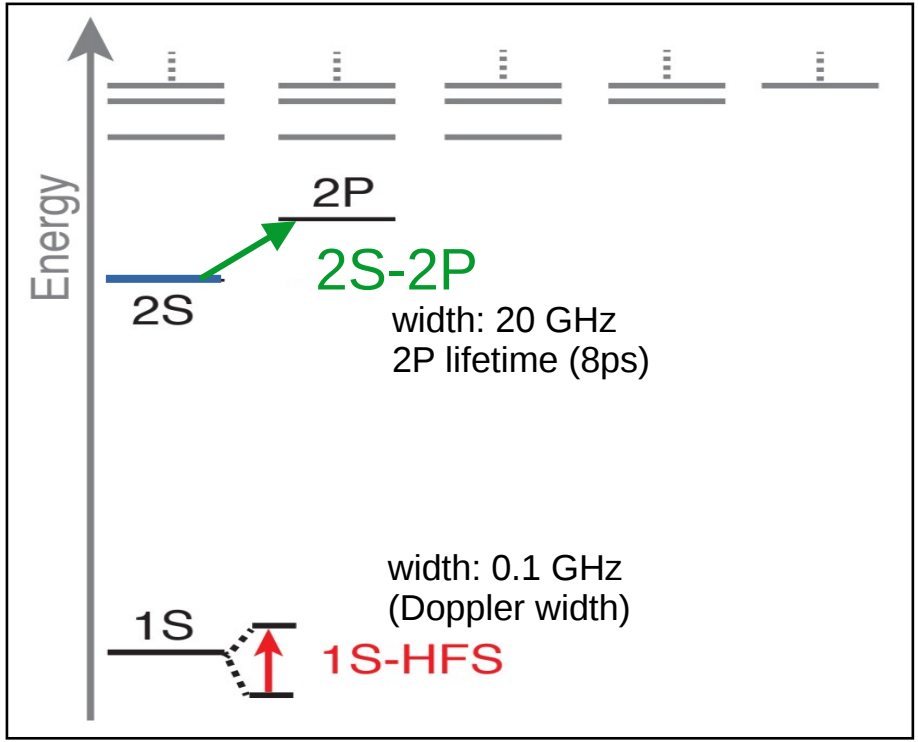
$$\langle r\rangle_{(2)} = \int d^3r\, d^3r'\, \rho_E(r)\rho_M(r')|r-r'|$$

Zemach, Phys. Rev. 104, 1771 (1956)

$$\Delta E = \frac{8(Z\alpha)m}{\pi n^3} E_F \int_0^\infty \frac{dk}{k^2}\left[\frac{G_E(-k^2)G_M(-k^2)}{1+\kappa}\right]$$

Form factors and momentum space

From charge to magnetic properties



2S-2P = Lamb shift

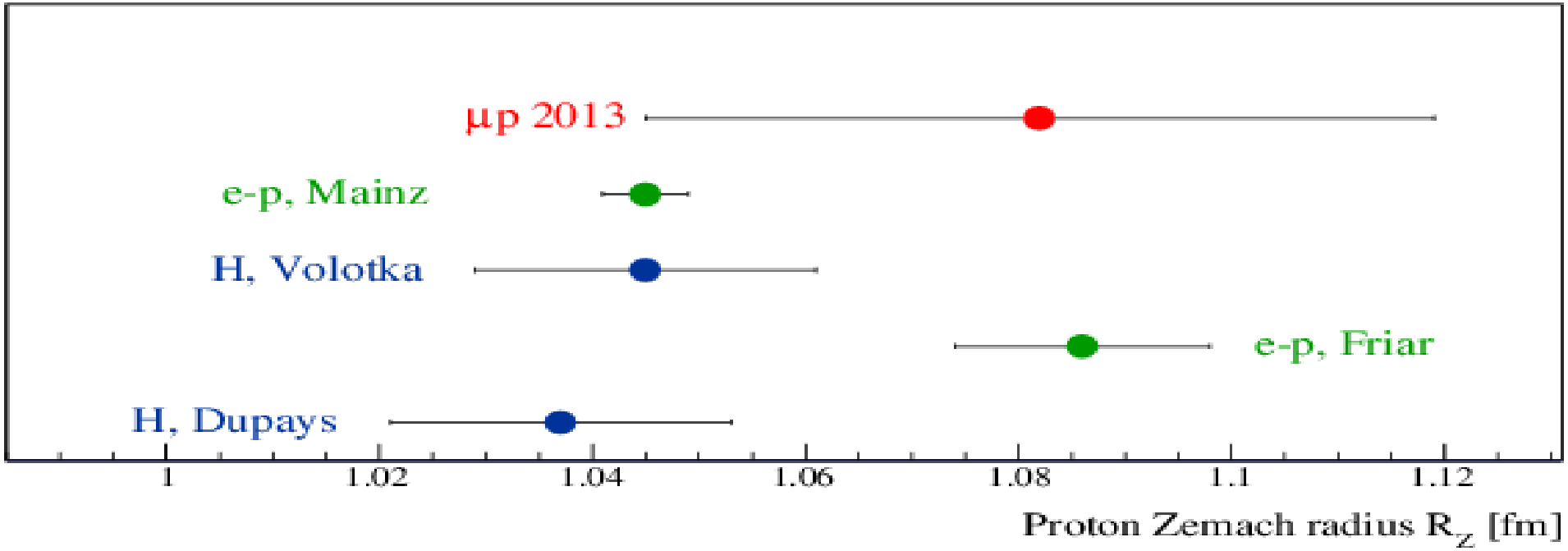
is sensitive to CHARGE radius

1S-HFS = Hyperfine splitting

is sensitive to ZEMACH radius

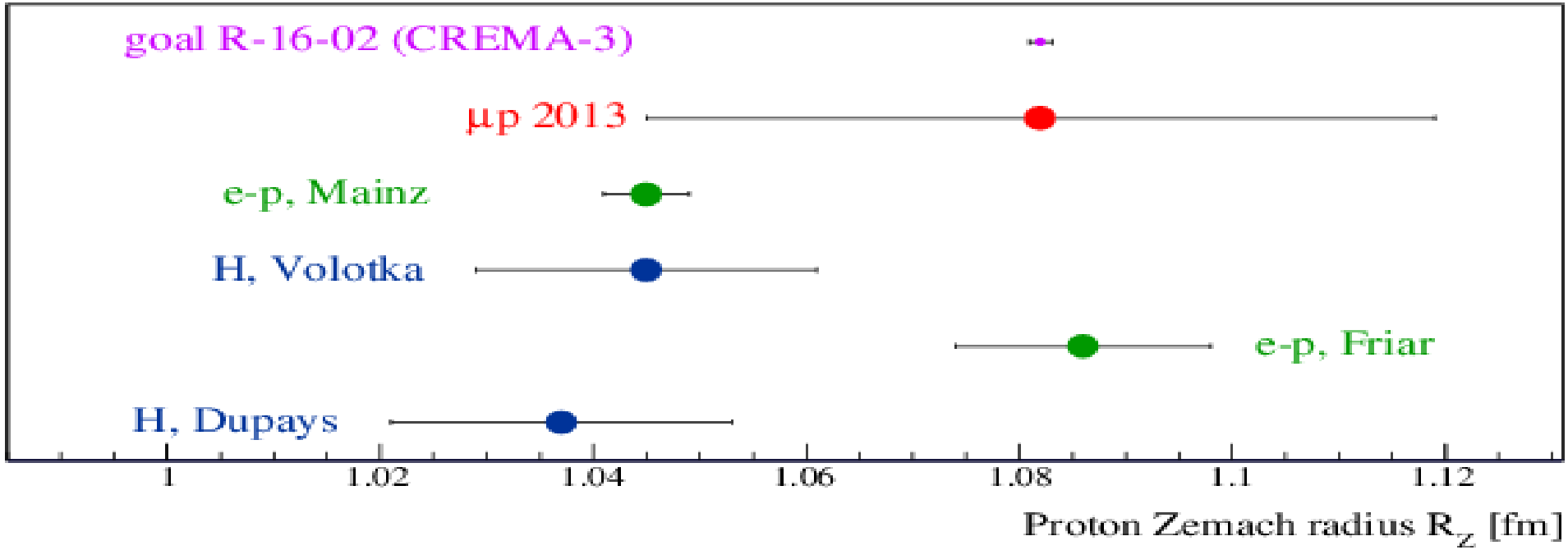
Amaro et al [CREMA], 2112.00138

Proton Zemach radius from μp



μp 2013: Antognini et al. (CREMA Coll.), Science 339, 417 (2013)

Proton Zemach radius from μp

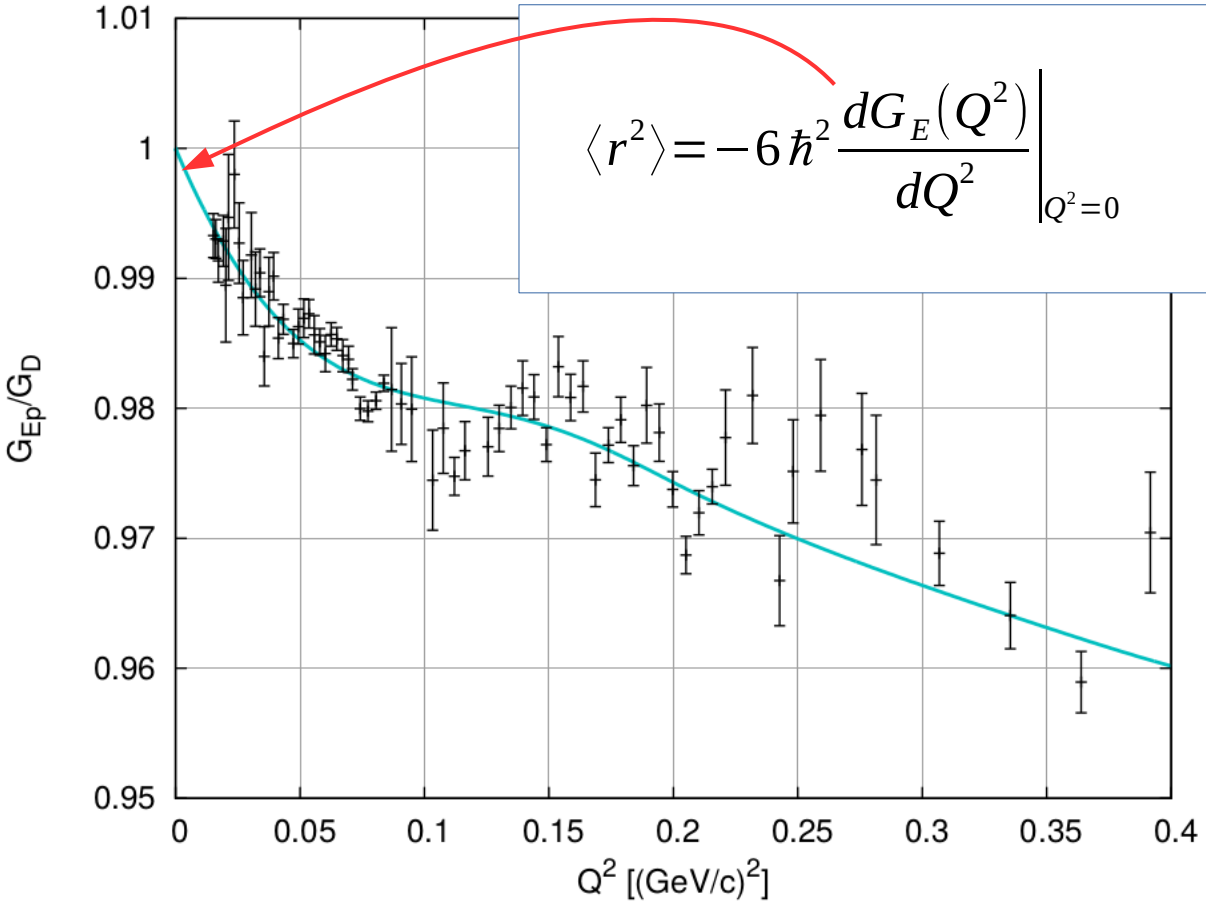


PSI Exp. R-16-02: Antognini, RP et al. (CREMA-3 / HyperMu)
see e.g. Schmidt, RP et al., J. Phys. Conf. Ser 1138, 012010 (2018); arXiv 1808.07240

also: FAMU @ RIKEN/RAL, and a Collaboration at J-PARC

Backup

Electron scattering



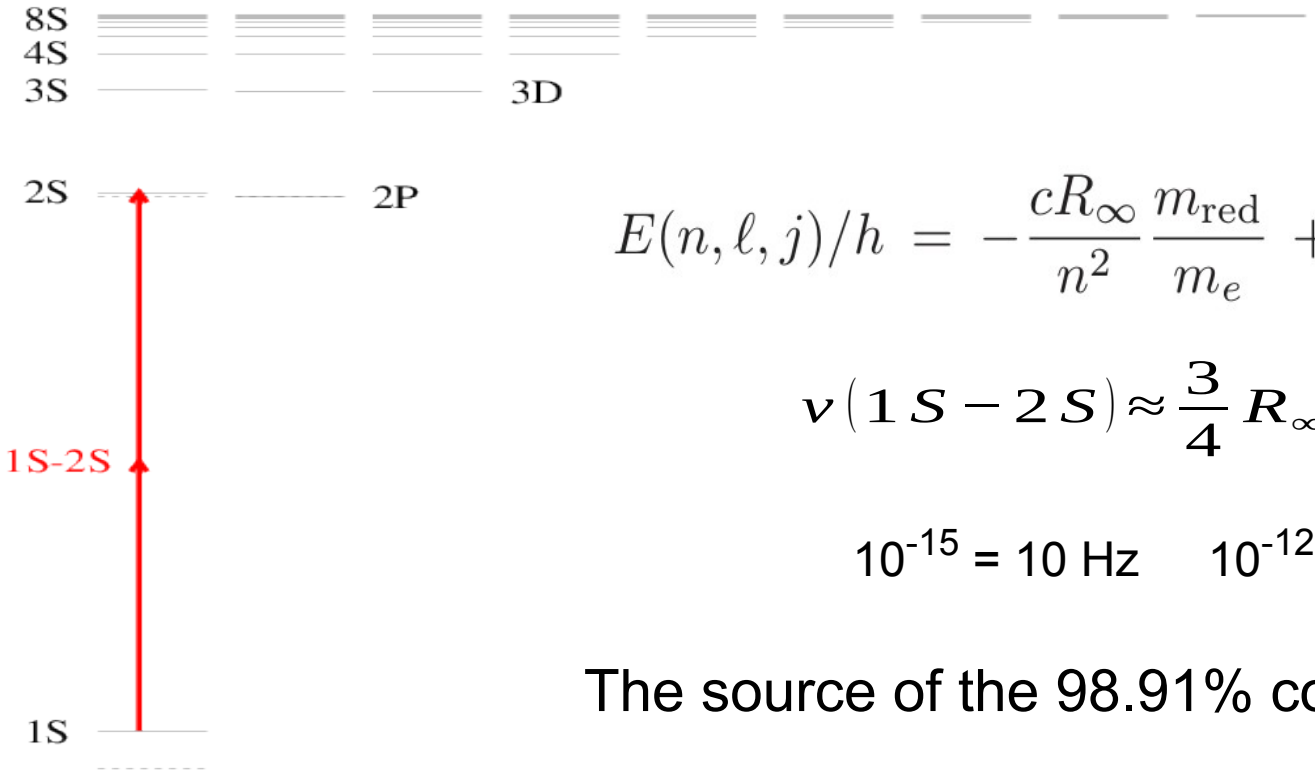
$$\langle r^2 \rangle = -6\hbar^2 \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

extrapolation to $Q^2 = 0$ required

Vanderhaeghen, Walcher: 1008.4225

Mainz MAMI data 2010

Correlation between R_∞ and R_p / R_d



$$E(n,\ell,j)/h = -\frac{cR_\infty}{n^2}\frac{m_{\mathrm{red}}}{m_e} + \frac{E_{NS}}{n^3}\delta_{\ell 0} + \Delta(n,\ell,j). \quad (7)$$

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

10^{-15} = 10 Hz 10^{-12} = 20 kHz

The source of the 98.91% correlation of R_∞ and R_p

[Pohl et al., Metrologia 54, L1 (2017)]

‚New Physics constraints

PRL **104,** 220406 (2010) PHYSICAL REVIEW LETTERS week ending 4 JUNE 2010

Precision Physics of Simple Atoms and Constraints on a Light Boson with Ultraweak Coupling

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(Received 12 April 2010; published 4 June 2010)

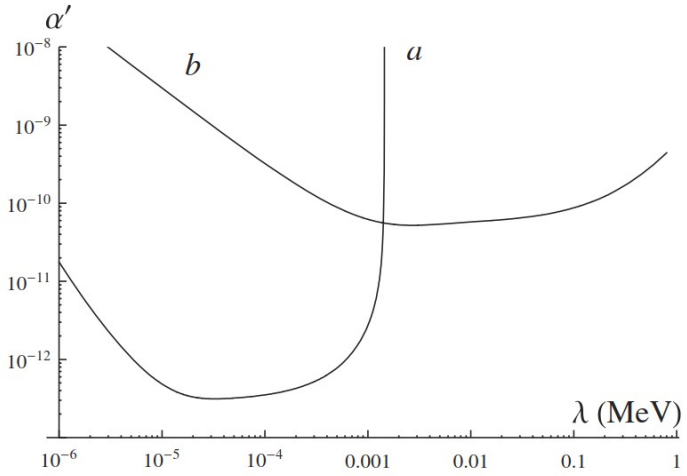


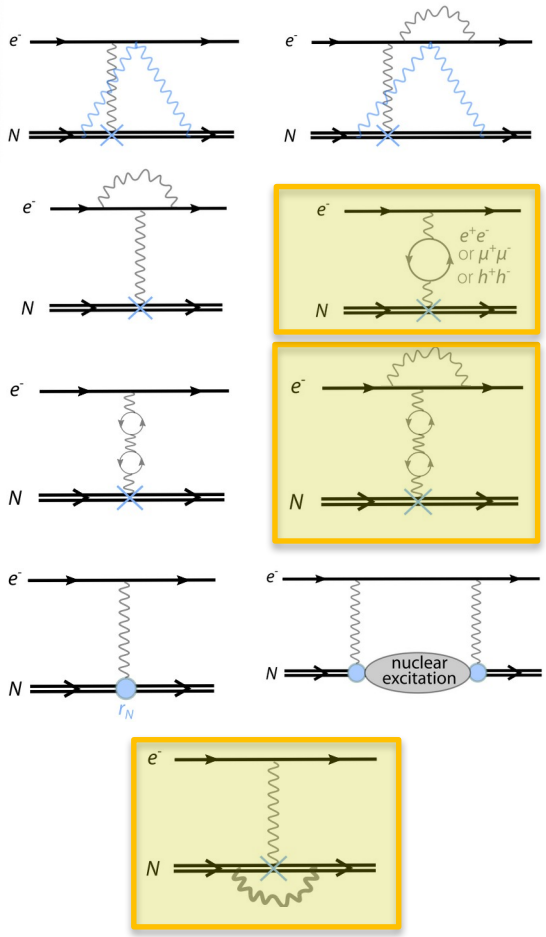
FIG. 1. Constraints on a long-range spin-independent interaction from hydrogen spectroscopy and $g_e - 2$, including a con-

modified Coulomb potential:

$$-\frac{\alpha}{r} \rightarrow -\frac{\alpha_{\mathrm{eff}}(r)}{r}$$

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

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



	Hydrogen $2S_{1/2}$-$6P_{1/2}$ (Hz)
Dirac (with $m_e \to m_{\mathrm{red}}$)	730 691 021 696 054
Rel. nuclear recoil	1 129 173
Radiative recoil	1540
1-loop QED	
self-energy	−1 071 679 859
vacuum-polarization	26 853 088
$\mu^+\mu^-$ vacuum-pol.	634
hadronic vacuum-pol.	425
2-loop QED	−90 477
3-loop QED	−236
Finite nuclear size	
$\propto \alpha^4$	−138 394
$\propto \alpha^5$	5
$\propto \alpha^6$	−74
Nuclear polarizability	
$\propto \alpha^5$	8
$\propto \alpha^6$	−49
Nuclear self-energy	−584
Total	730 689 977 771 255
Theory uncertainty	199

Our 2S-6P meas. uncert.:
490 Hz

Start seeing muons and hadrons in vacuum

Start seeing 3-loop bound-state vacuum effects

Start seeing Nuclear self-energy

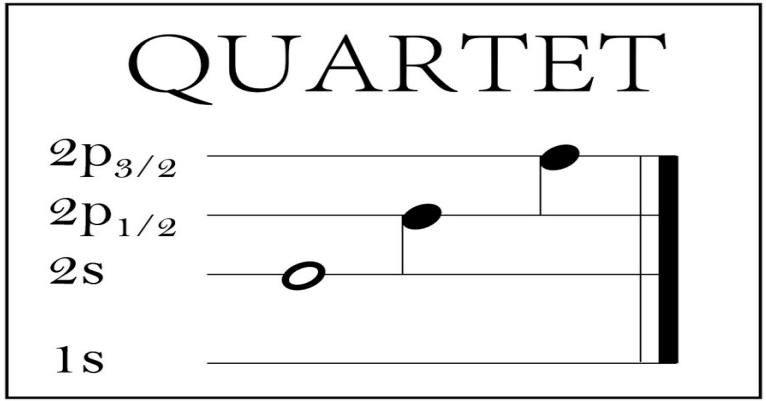
CREMA:
Laser spectroscopy of light muonic atoms

Randolf Pohl, JGU Mainz

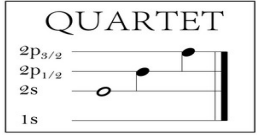
Radii of Z=3 …. 10

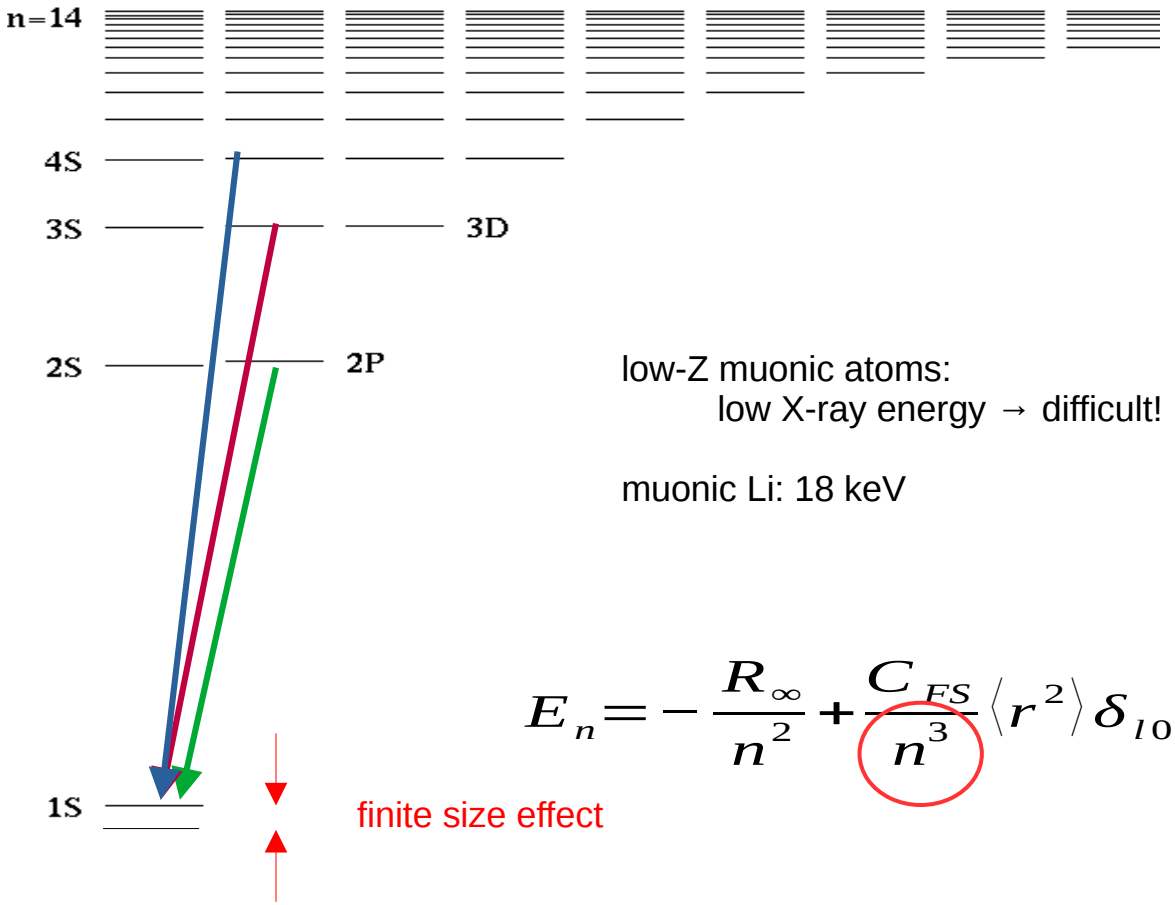
Xray spectroscopy

of muonic atoms



X-ray spectroscopy



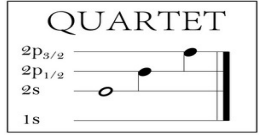


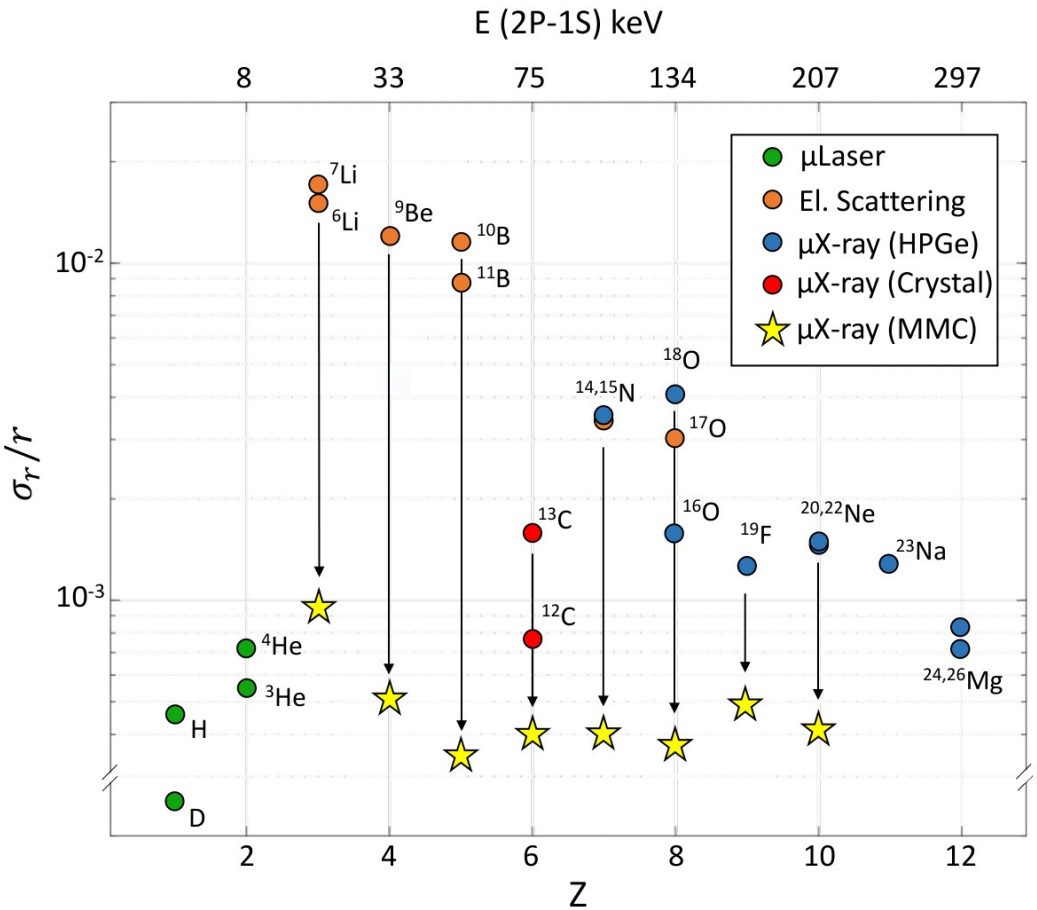
low-Z muonic atoms:
low X-ray energy → difficult!

muonic Li: 18 keV

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

QUARTET Goals





10x improved nuclear charge radii → challenging nuclear few-body calculations

Current knowledge on radii of the lightest nuclei:

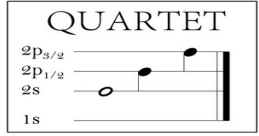
Z=1,2: muonic atom laser spectroscopy

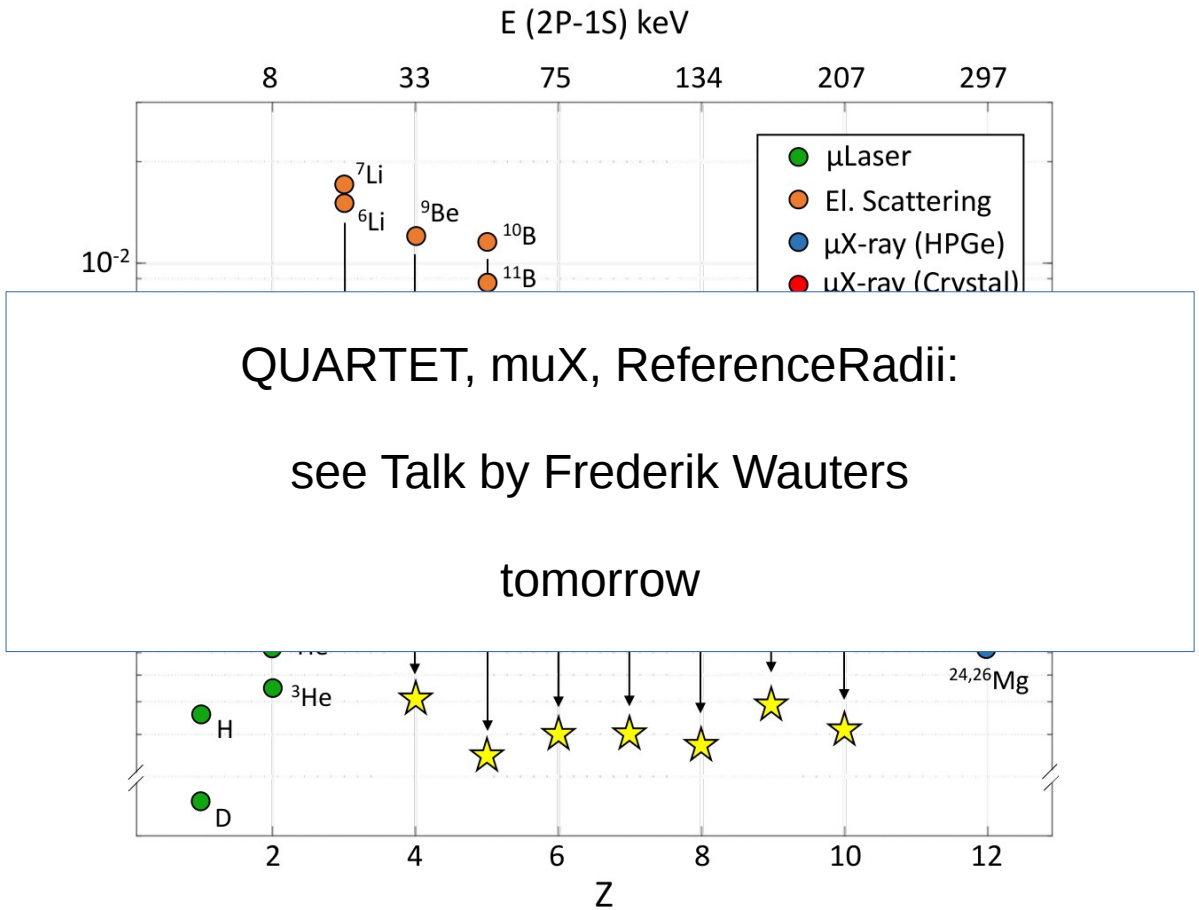
Z>3: mostly e-scattering

Z=6: some muonic X-rays (crystal spectrometer)

Z>8: muonic X-rays (Ge detectors)

QUARTET Goals





QUARTET, muX, ReferenceRadii:

see Talk by Frederik Wauters

tomorrow

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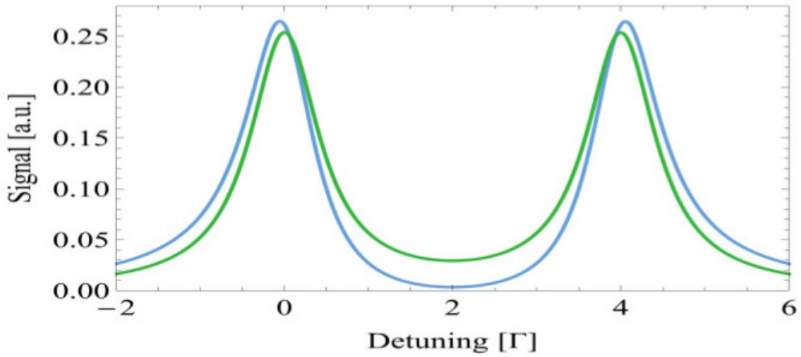
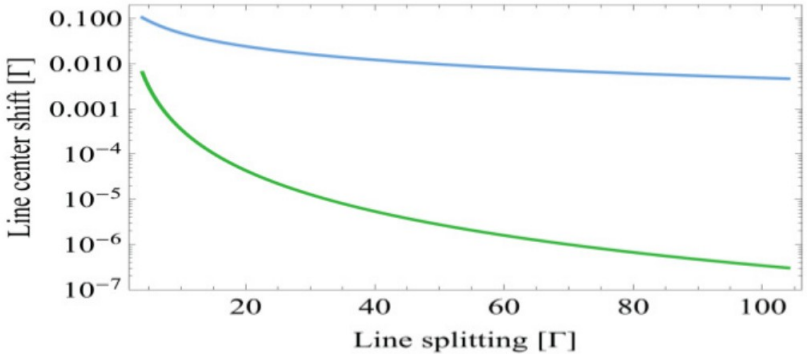
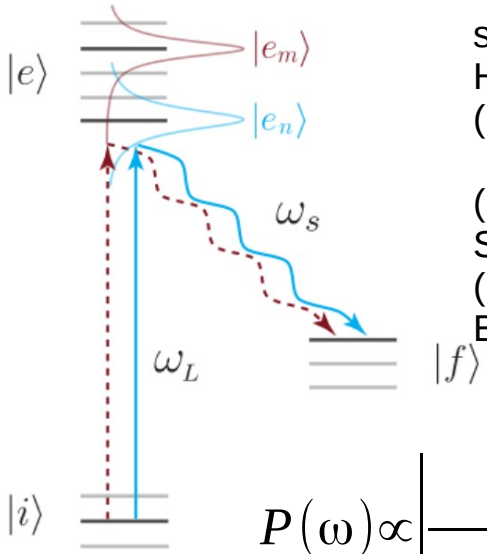
Quantum Interference in 2S-nP







see
Horbatsch, Hessels, PRA 82, 052519 (2010);
PRA 84, 032508 ('11); PRA 86 040501 ('12)
Sansonetti et al., PRL 107, 021001 (2011)
Brown et al., PRA 87, 032504 (2013)

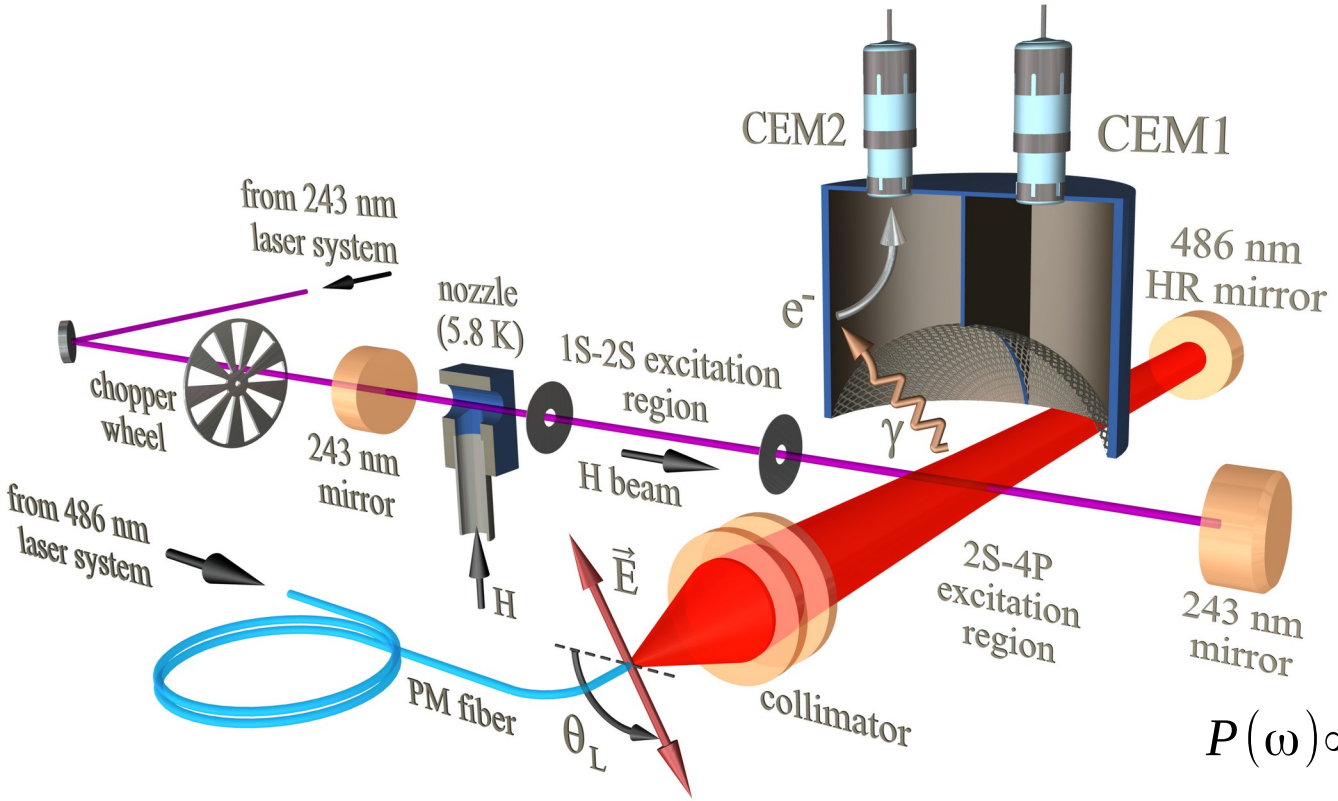
$$P(\omega) \propto \left| \frac{(\vec{d}_1 \vec{E}_0)\vec{d}_1}{\omega_1 - \omega_L + i\gamma_1/2} + \frac{(\vec{d}_2 \vec{E}_0)\vec{d}_2 e^{i\Delta\Phi}}{\omega_2 - \omega_L + i\gamma_2/2} \right|^2$$

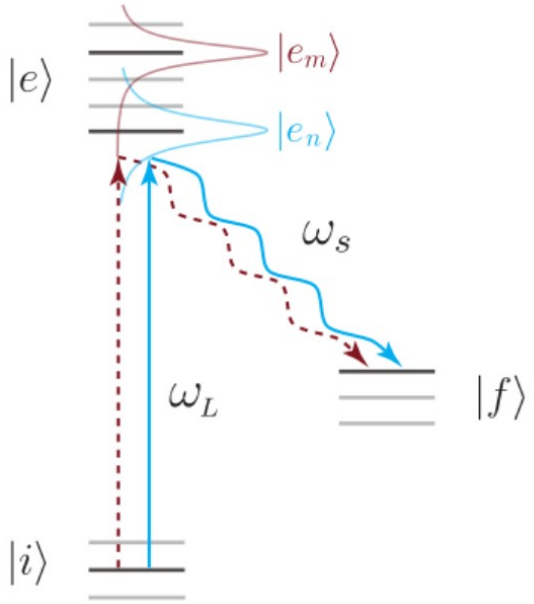
= Lorentzian(1) + Lorentzian(2)

+ cross-term (QI)

Fitting this with 2 Lorentzians creates
line shifts

Studying Quantum Interference in 2S-4P





$$P(\omega) \propto \left| \frac{(\vec{d}_1 \vec{E}_0)\vec{d}_1}{\omega_1 - \omega_L + i\gamma_1/2} + \frac{(\vec{d}_2 \vec{E}_0)\vec{d}_2 e^{i\Delta\Phi}}{\omega_2 - \omega_L + i\gamma_2/2} \right|^2$$

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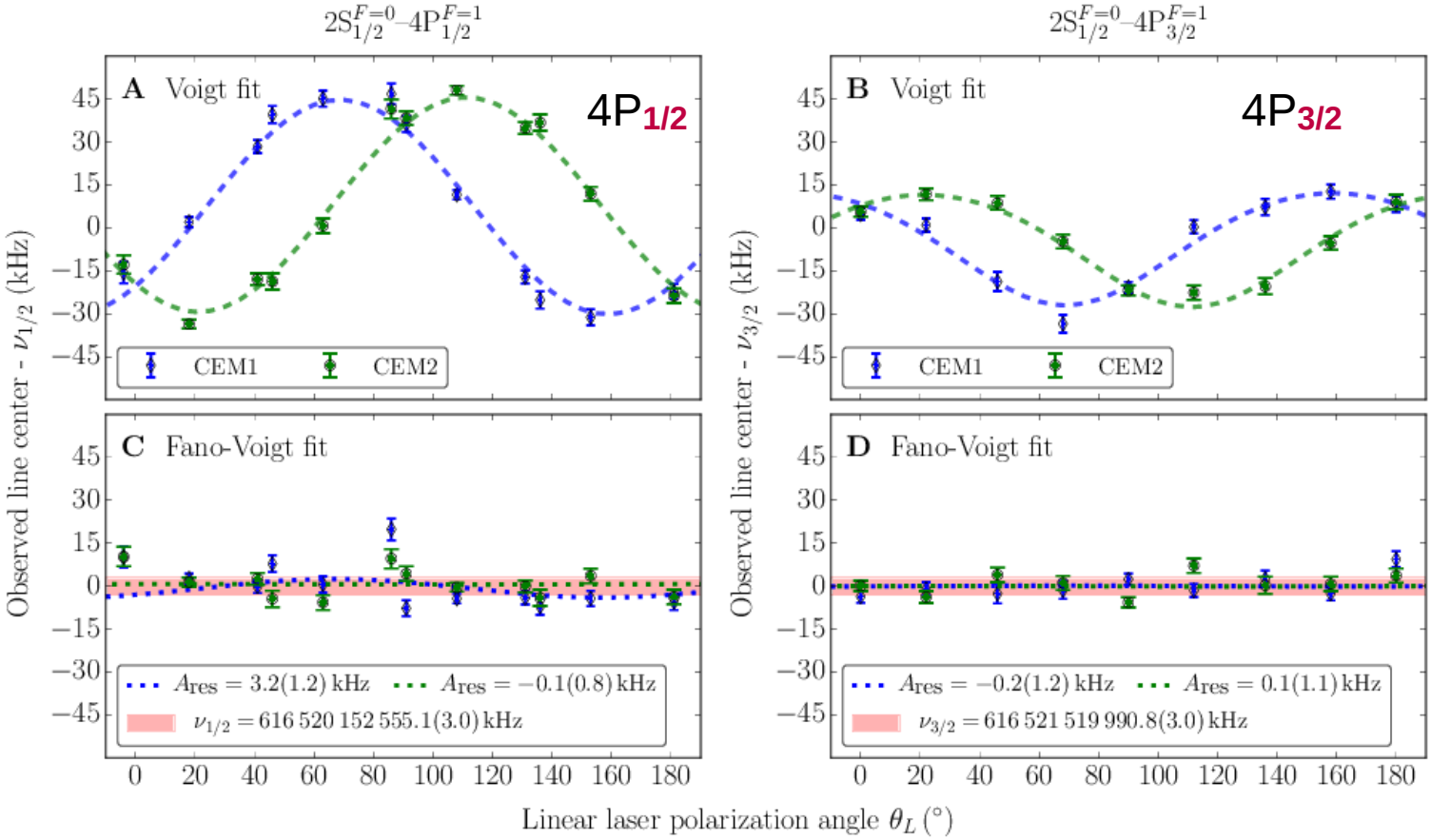
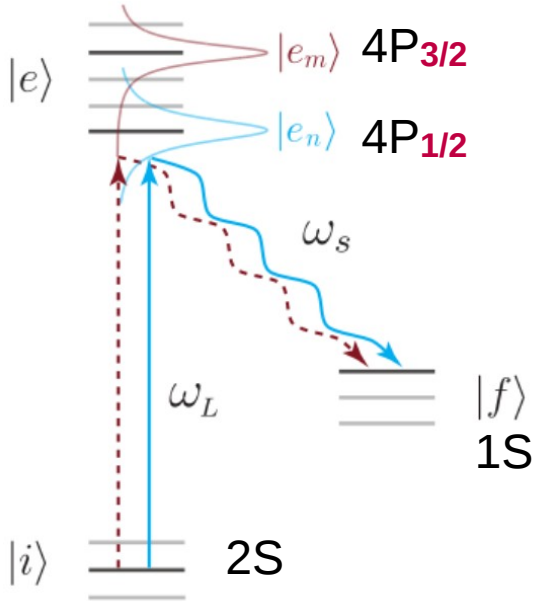
Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

Studying Quantum Interference in 2S-4P





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