Muonic and other atoms for the radii of the lightest nuclei

Randolf Pohl

Uni Mainz

EINN 2019
30 October 2019

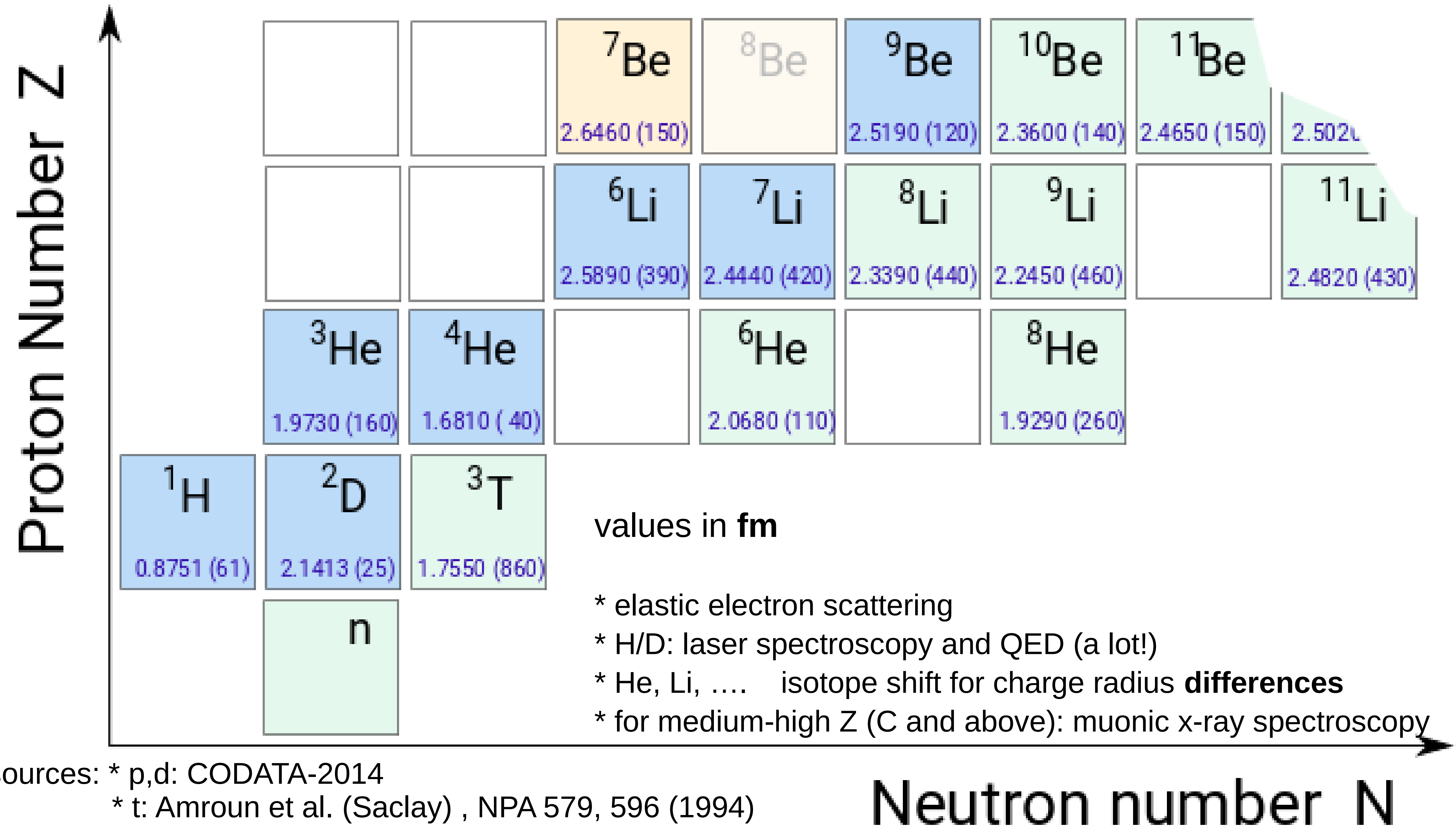
Outline

- Muonic hydrogen, deuterium and the Proton Radius Puzzle
  New results from H spectroscopy, e-p scattering
- Muonic helium-3 and -4
  Charge radii and the isotope shift
- Muonic **present**: HFS in μH, μ^3He
  10x better (magnetic) Zemach radii
- Muonic **future**: muonic Li, Be
  10-100x better charge radii
- **Ongoing**: Triton charge radius from atomic T(1S-2S)
  400fold improved triton charge radius

The Past

Nuclear rms charge radii

from measurements with **electrons**



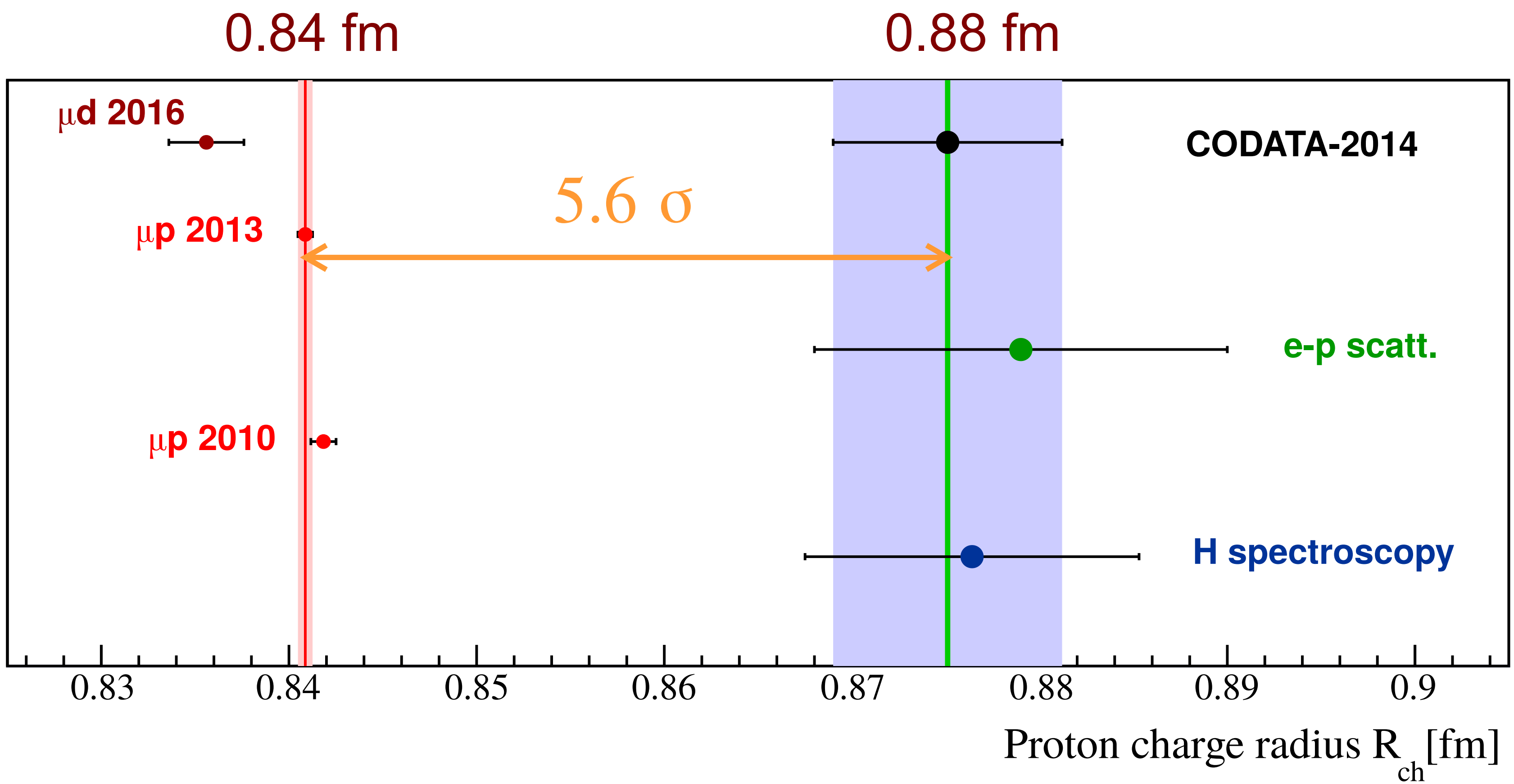
values in **fm**

* elastic electron scattering
* H/D: laser spectroscopy and QED (a lot!)
* He, Li, …. isotope shift for charge radius **differences**
* for medium-high Z (C and above): muonic x-ray spectroscopy

sources: * p,d: CODATA-2014
* t: Amroun et al. (Saclay) , NPA 579, 596 (1994)
* ^{3,4}He: Sick, J.Phys.Chem.Ref Data 44, 031213 (2015)
* Angeli, At. Data Nucl. Data Tab. 99, 69 (2013)

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)

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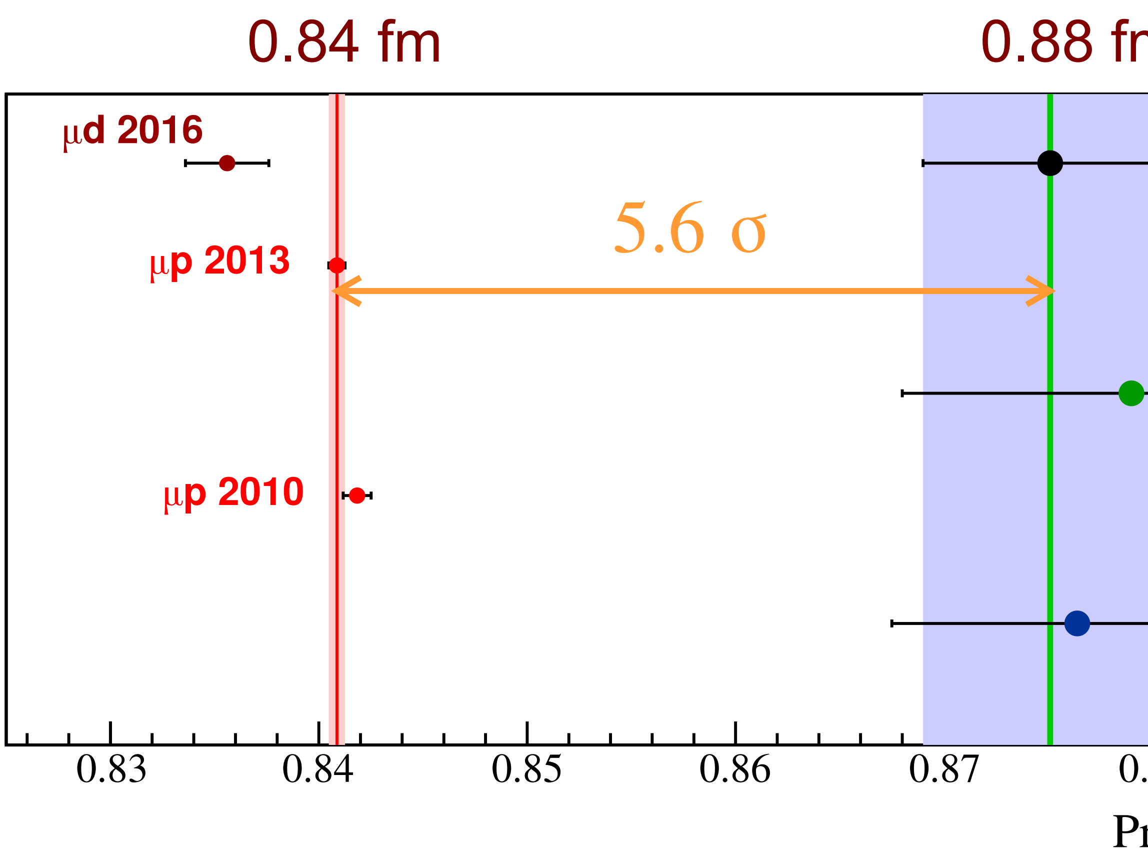

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The “Proton Radius Puzzle”

Measuring

'%)

5%)

0.

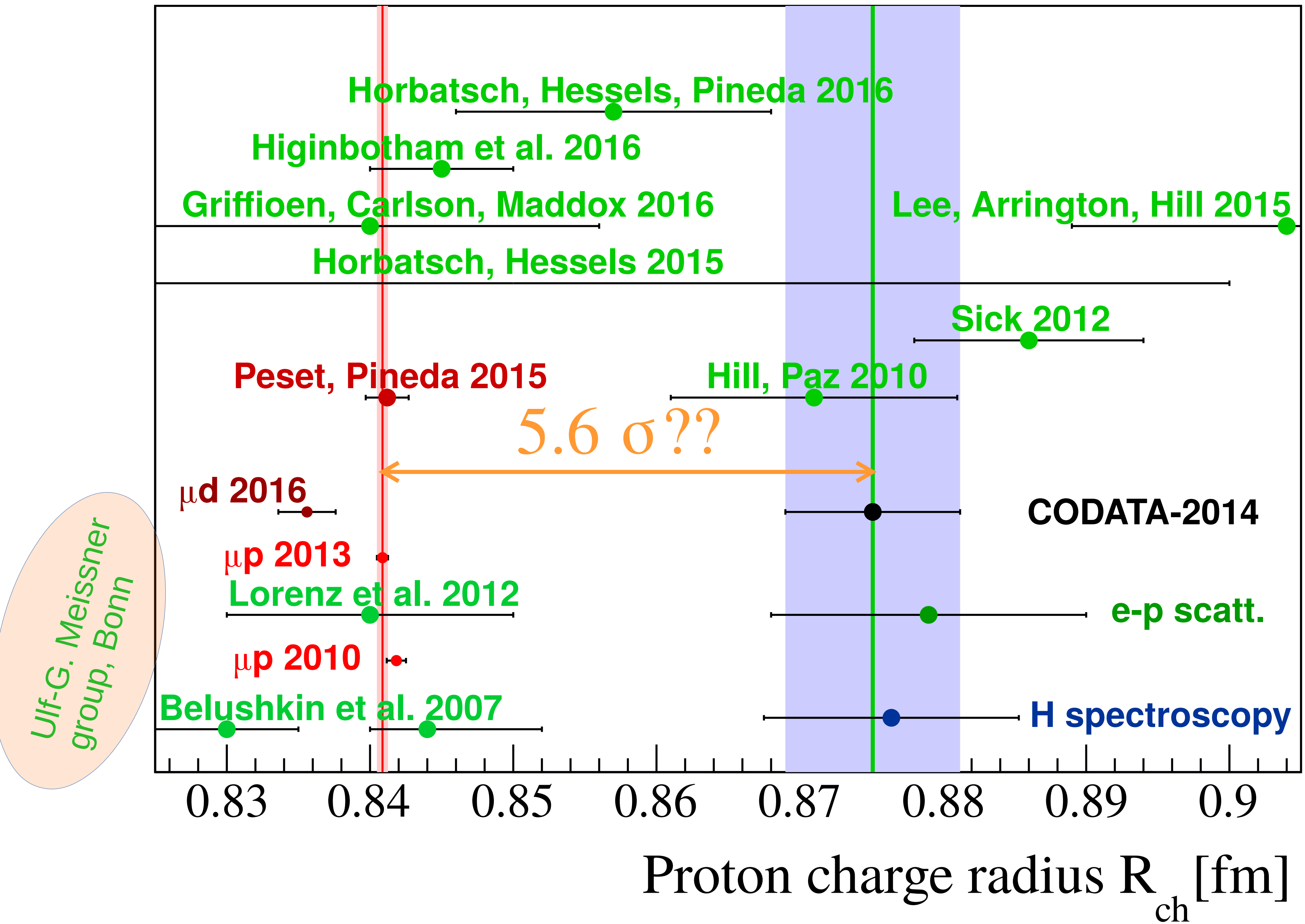
The New York Tim

cn

μd 2016: RP et al (CF

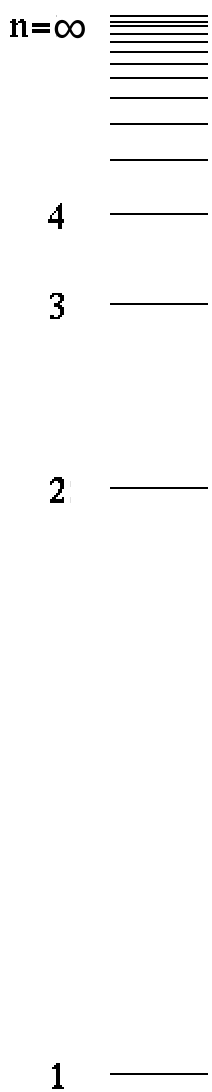
μp 2013: A. Antognini

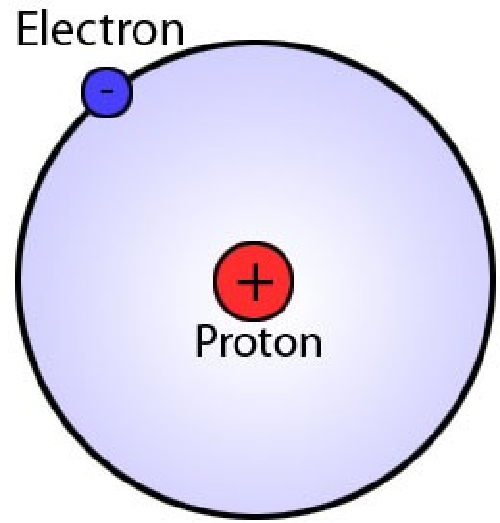
A “Proton Radius **Puzzle**” ??



Hydrogen

Energy levels of hydrogen

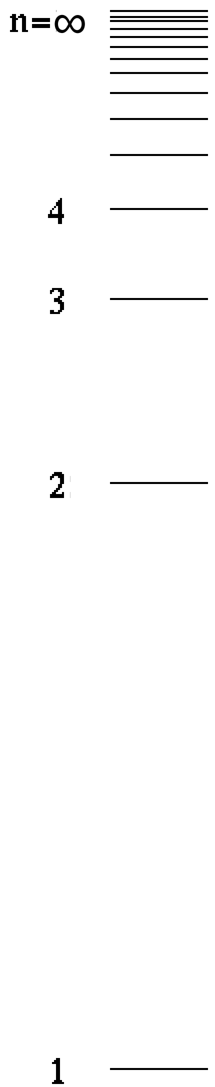




$$E_n \approx -\frac{R_\infty}{n^2}$$

Bohr formula

Energy levels of hydrogen



Rydberg constant

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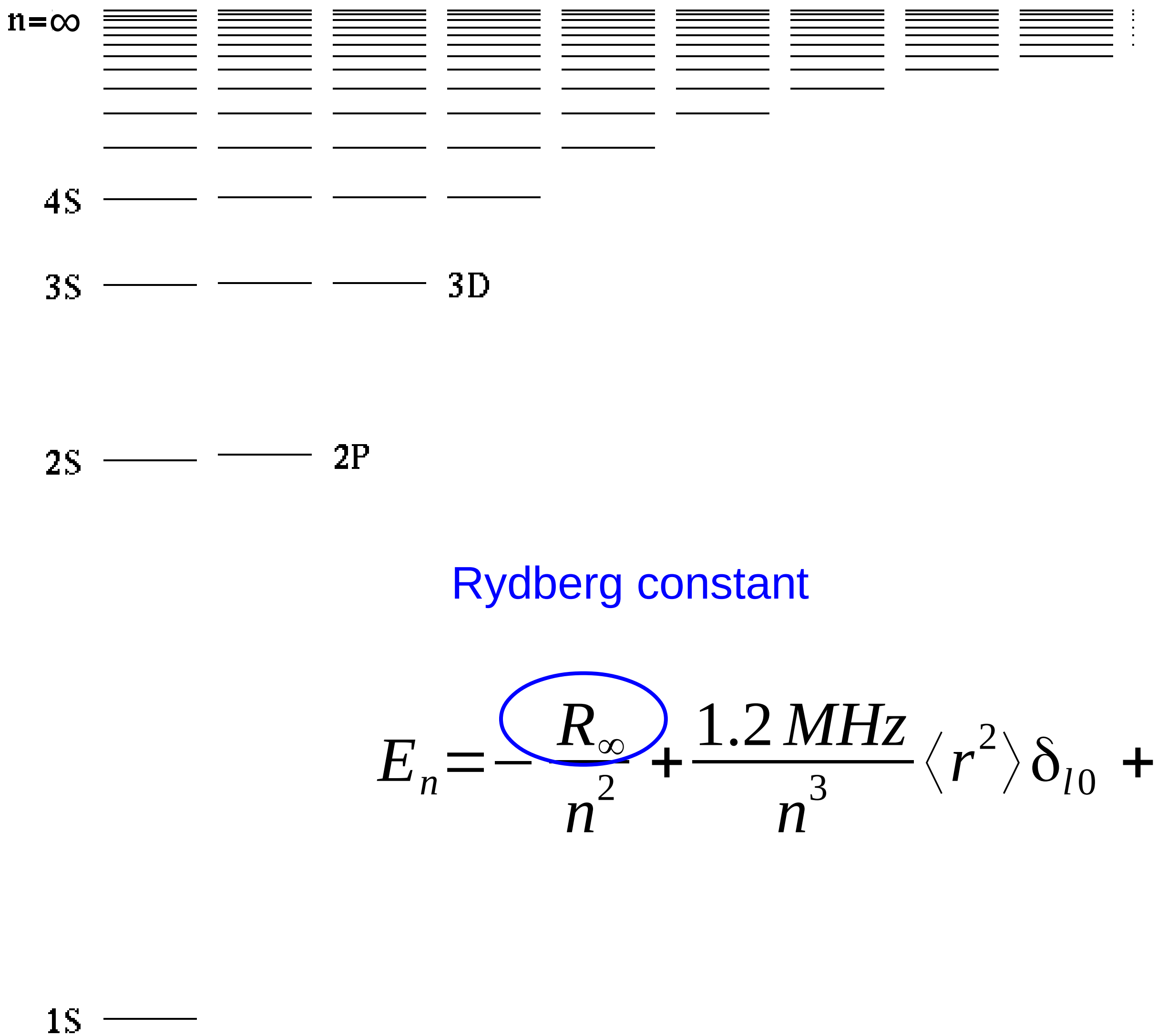
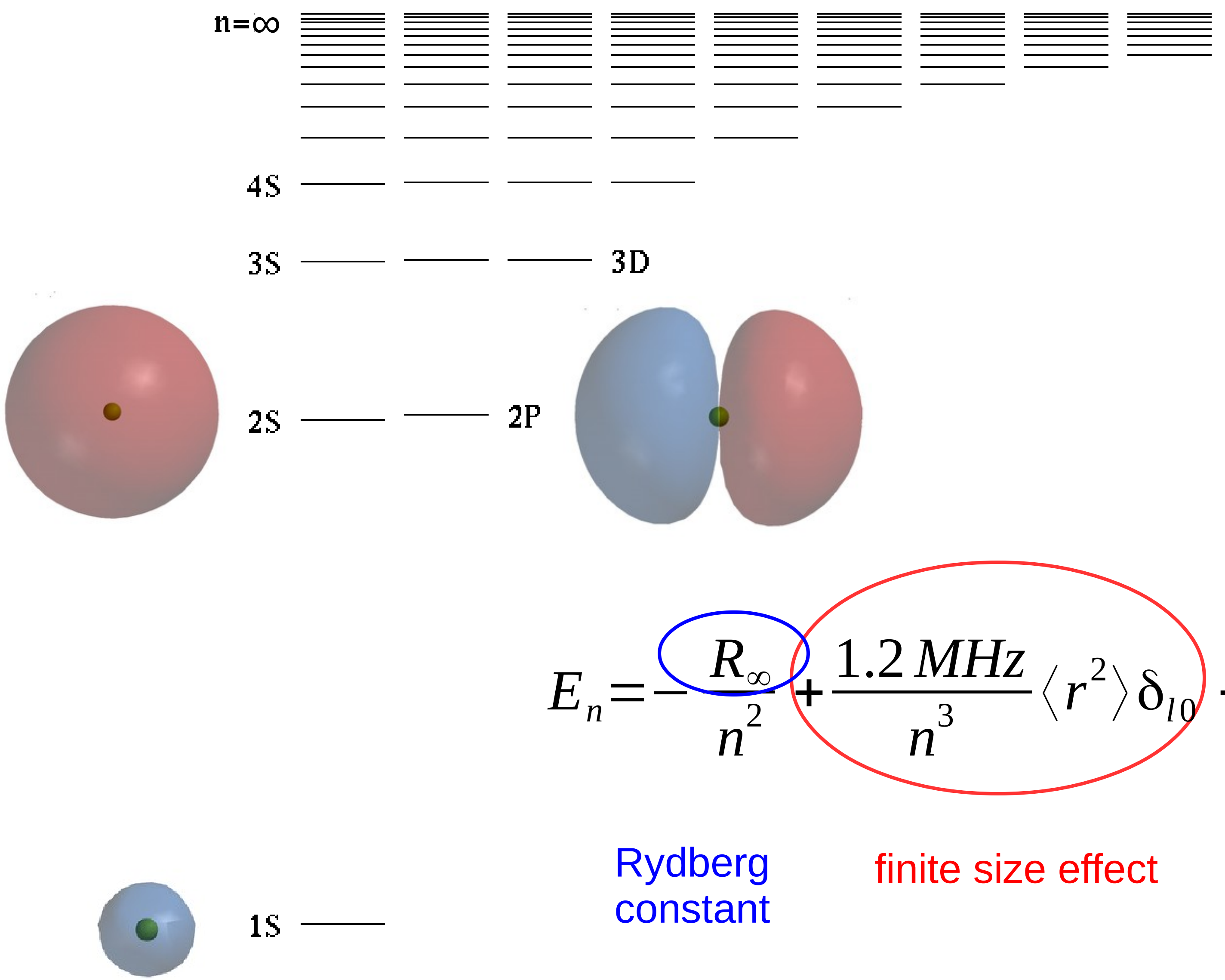


Rydberg constant

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

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

Energy levels of hydrogen



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Rydberg constant

finite size effect

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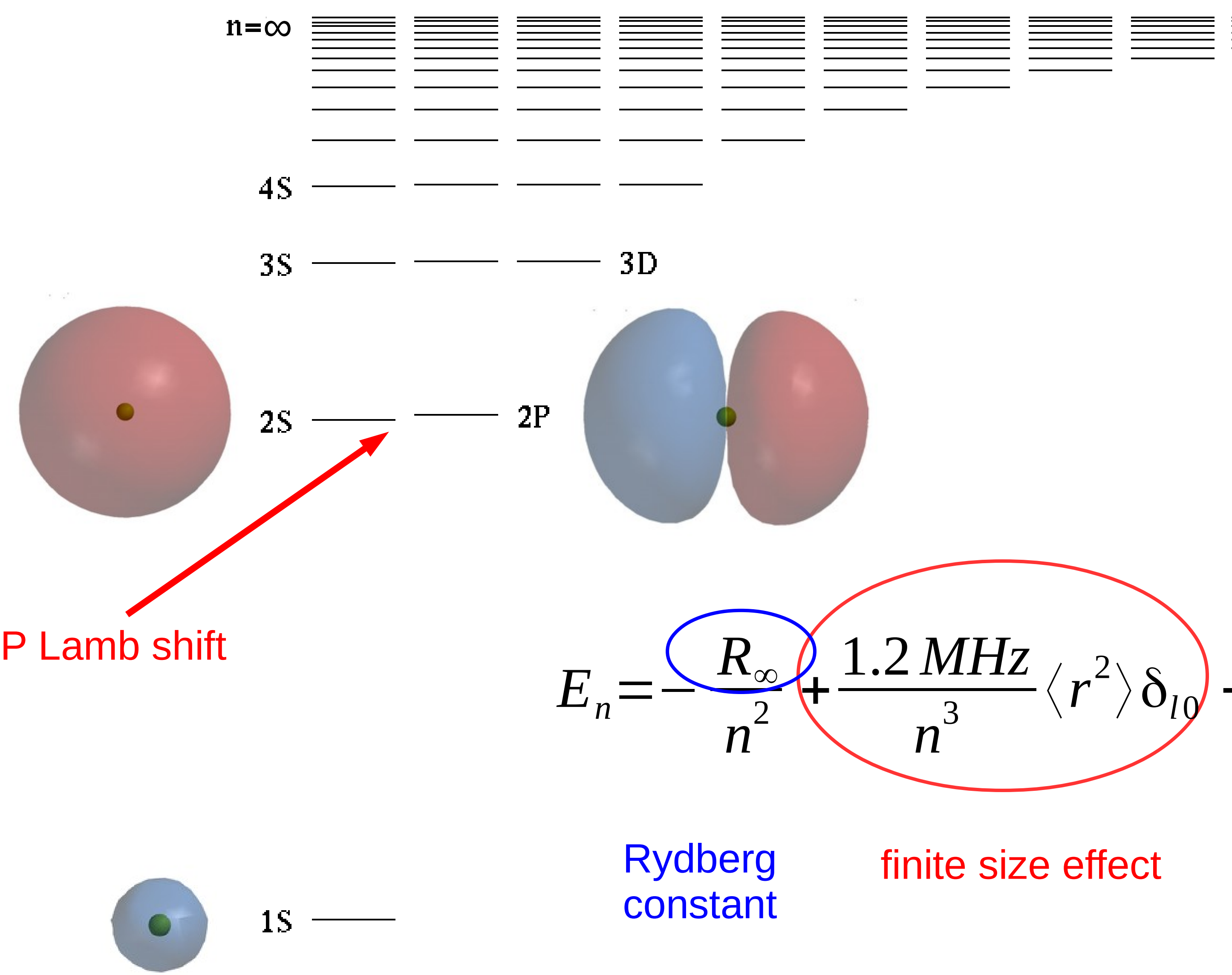

2S-2P Lamb shift

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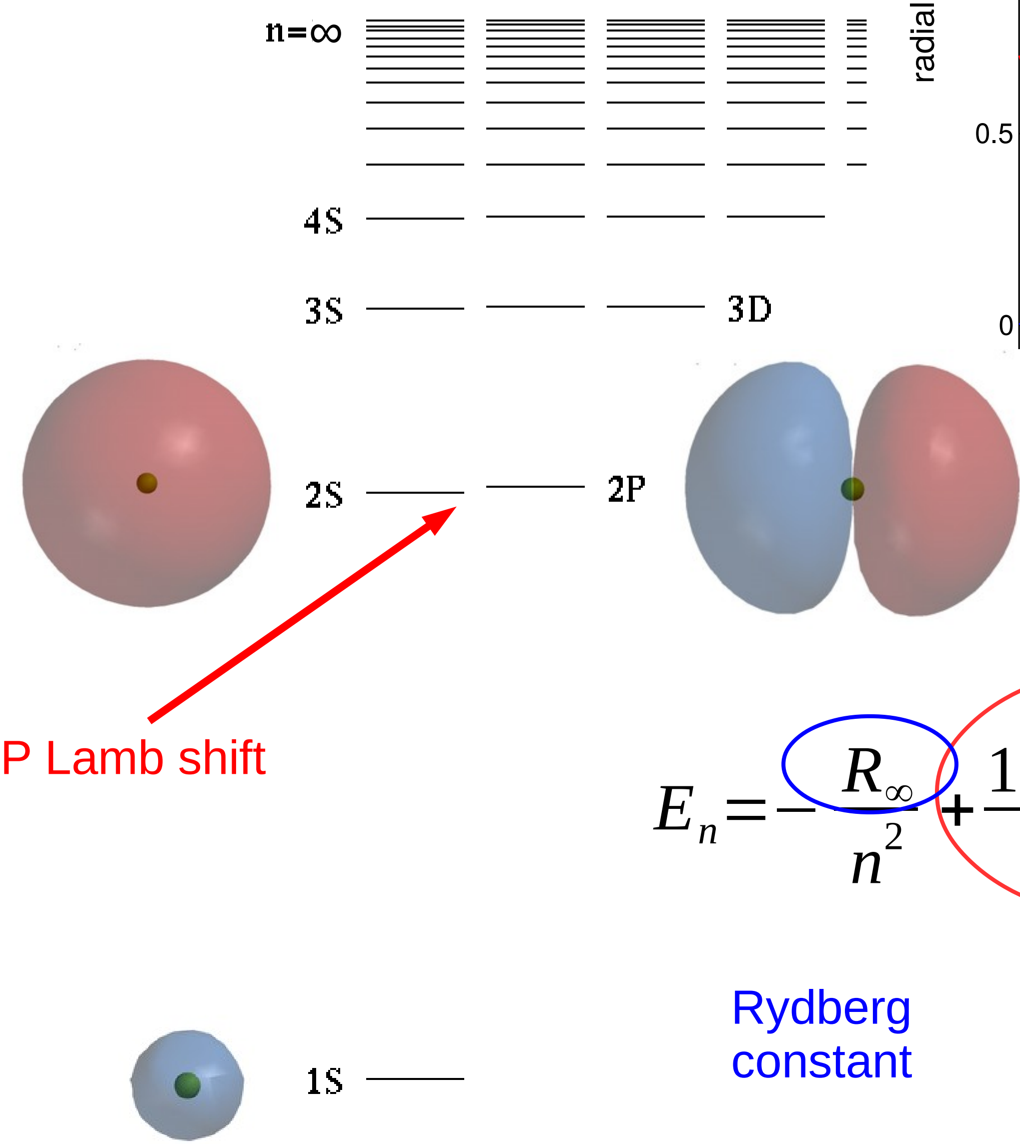

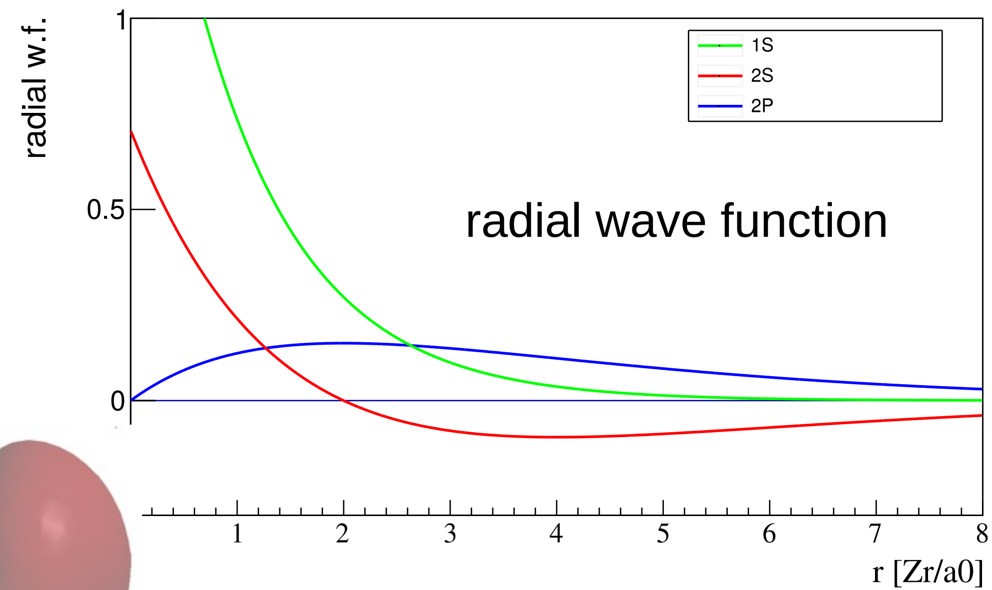

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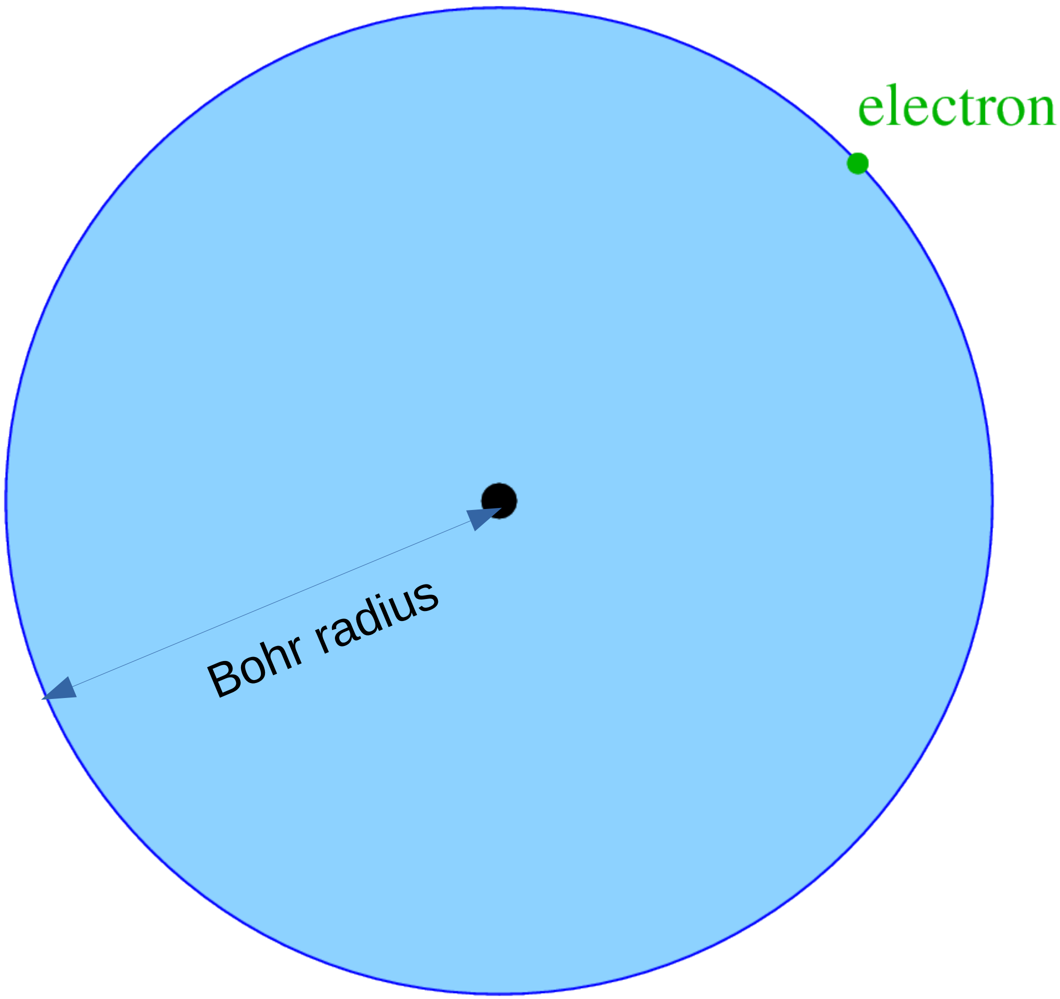
Muonic Hydrogen

A proton, orbited by a **negative muon.**

Electronic and muonic atoms

Regular hydrogen:

Proton + Electron



Muonic hydrogen:

Proton + Muon

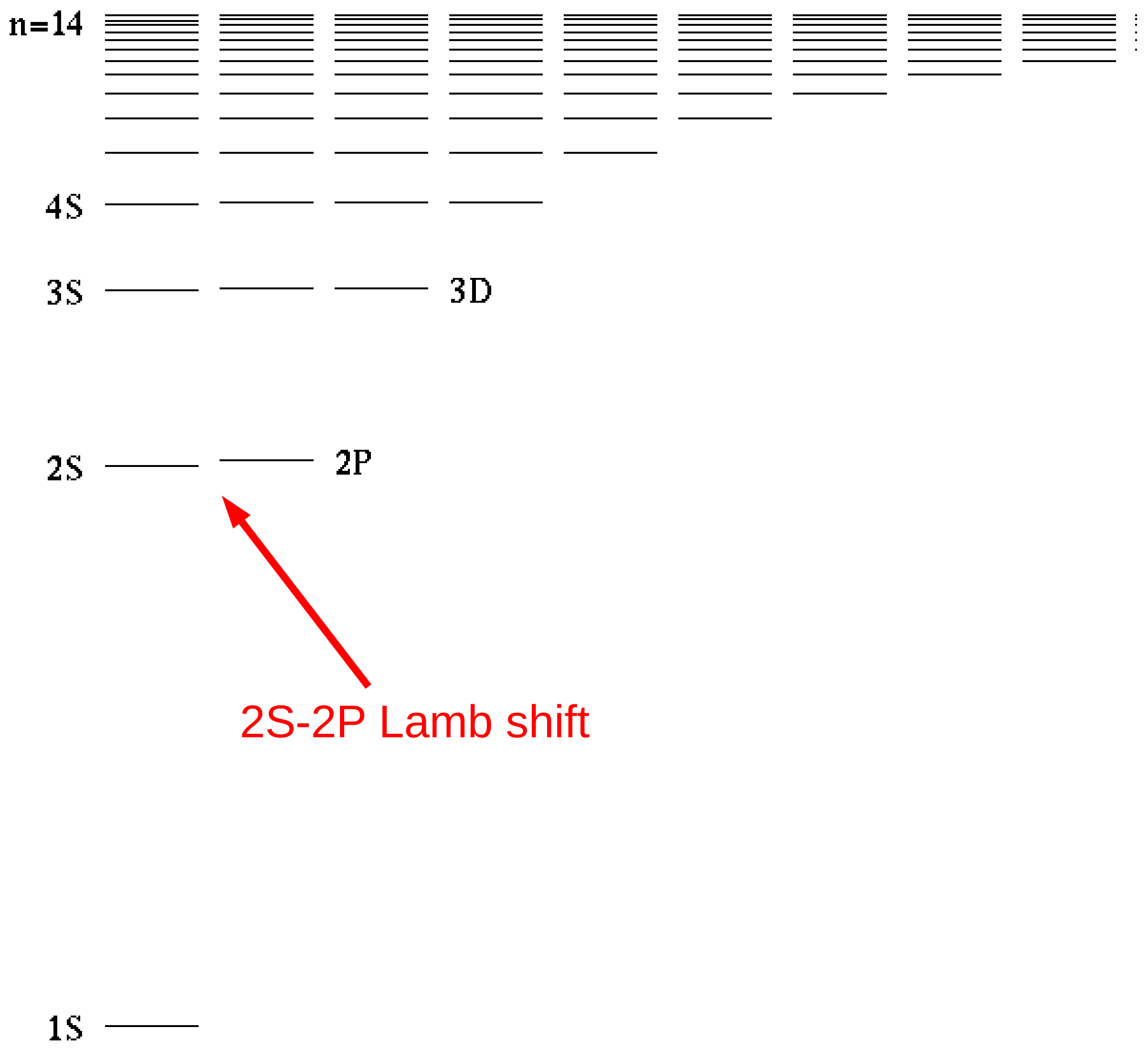
Muon **mass** = **200** * electron mass

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

$\mathbf{200^3}$ = a **few million times** more sensitive to proton size

Vastly not to scale!!

Muonic Hydrogen



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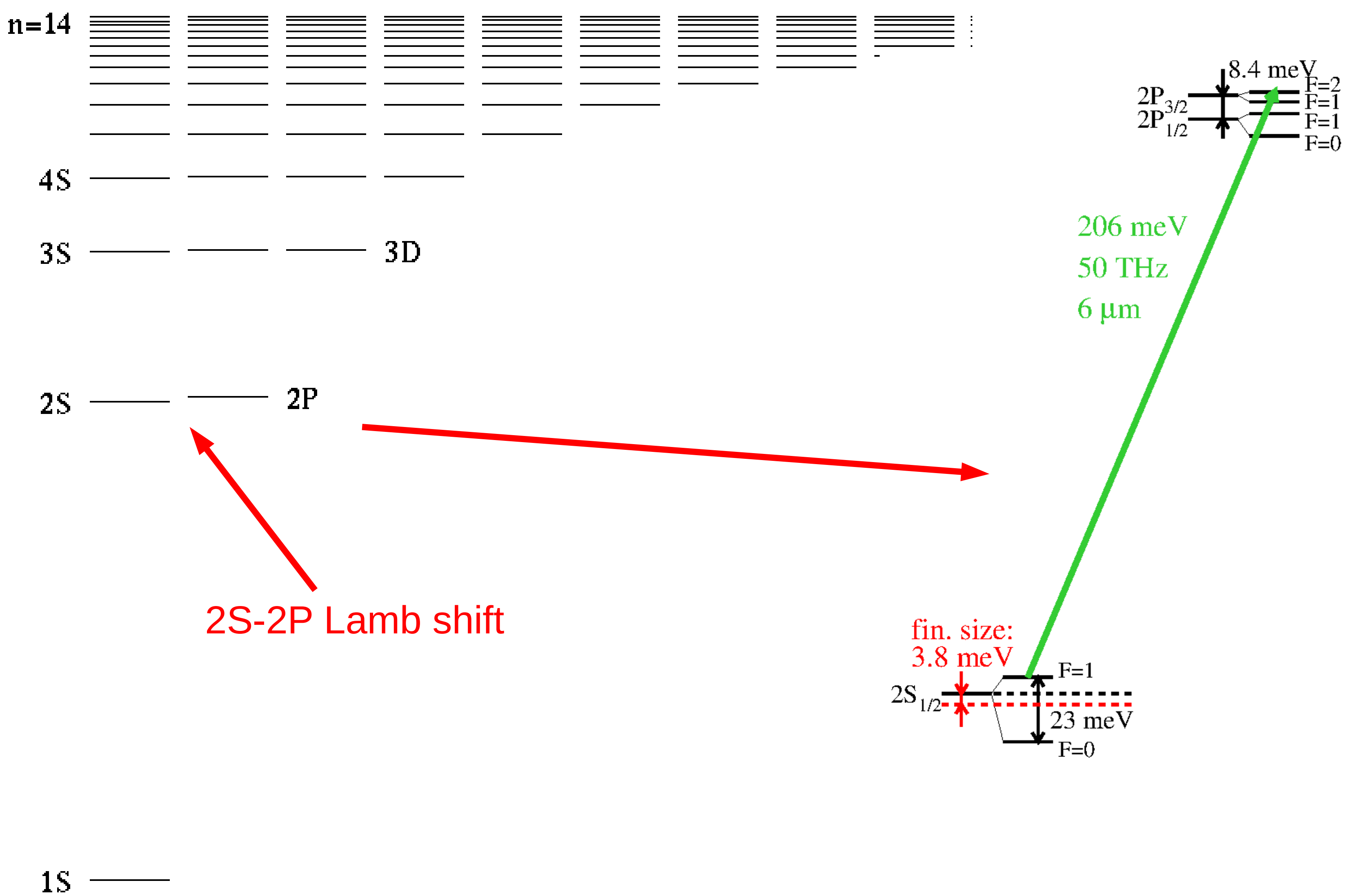

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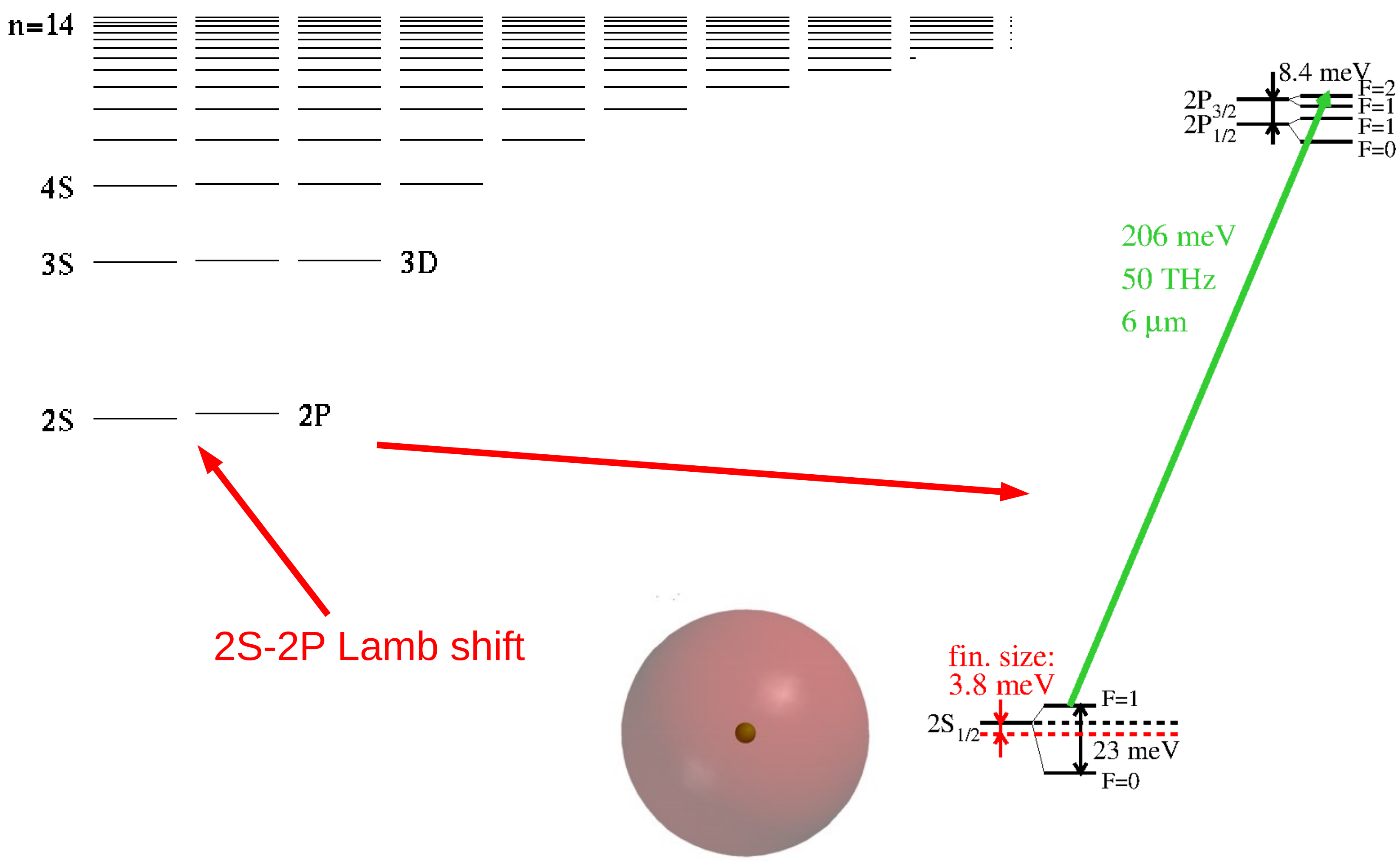
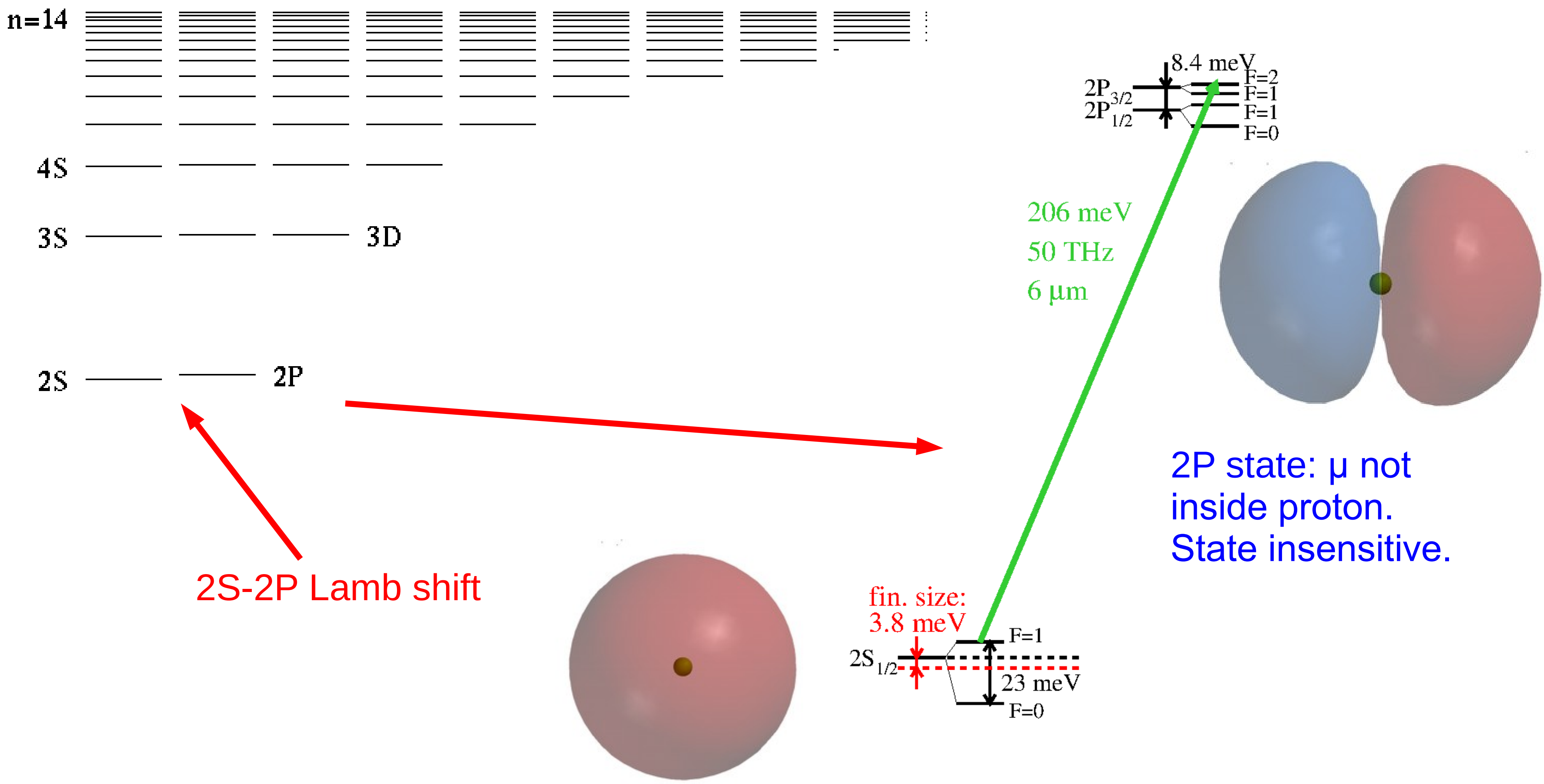


2S state: μ spends some time **inside** the proton!
State is sensitive to the proton size.

Muonic Hydrogen



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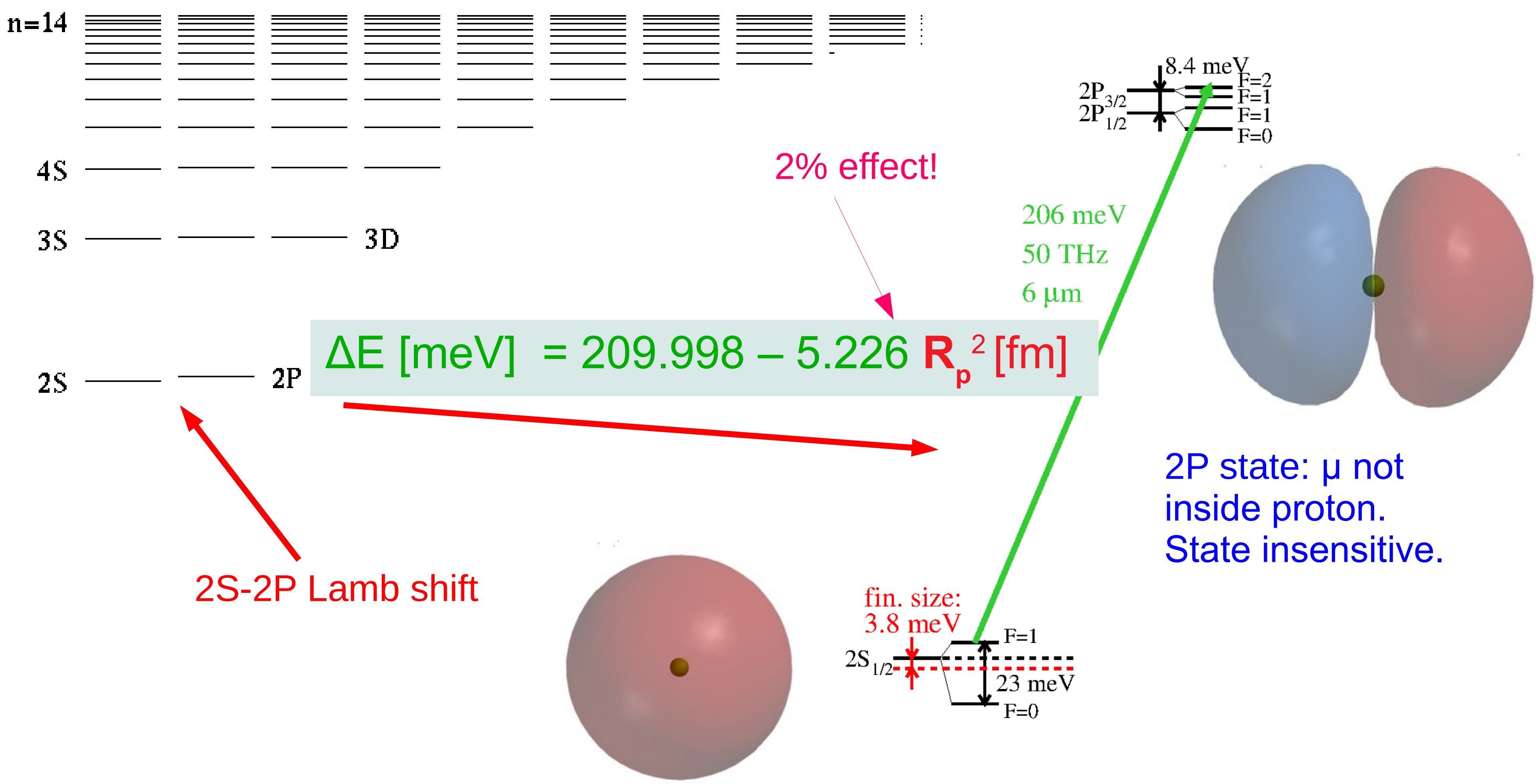

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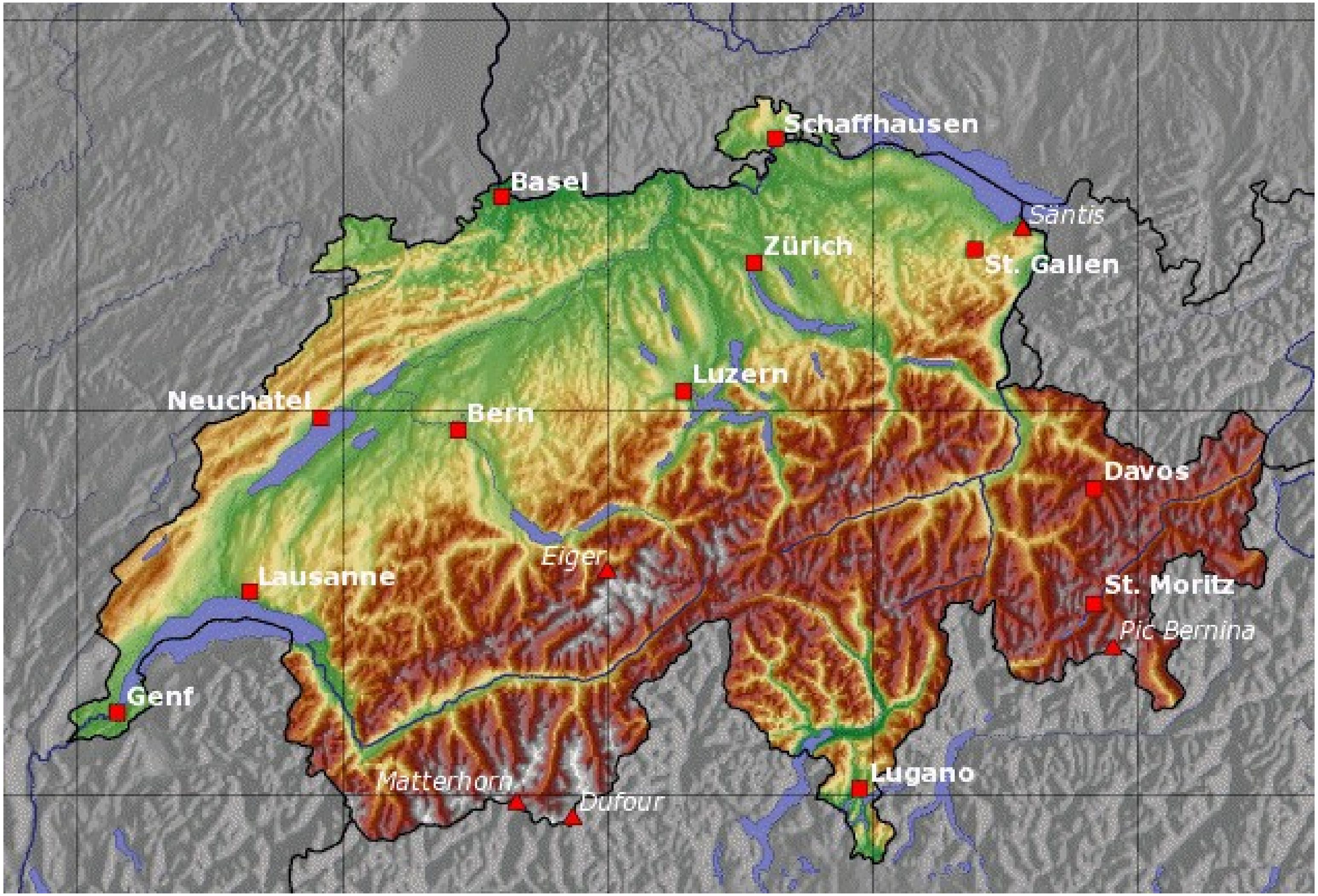
The accelerator at PSI



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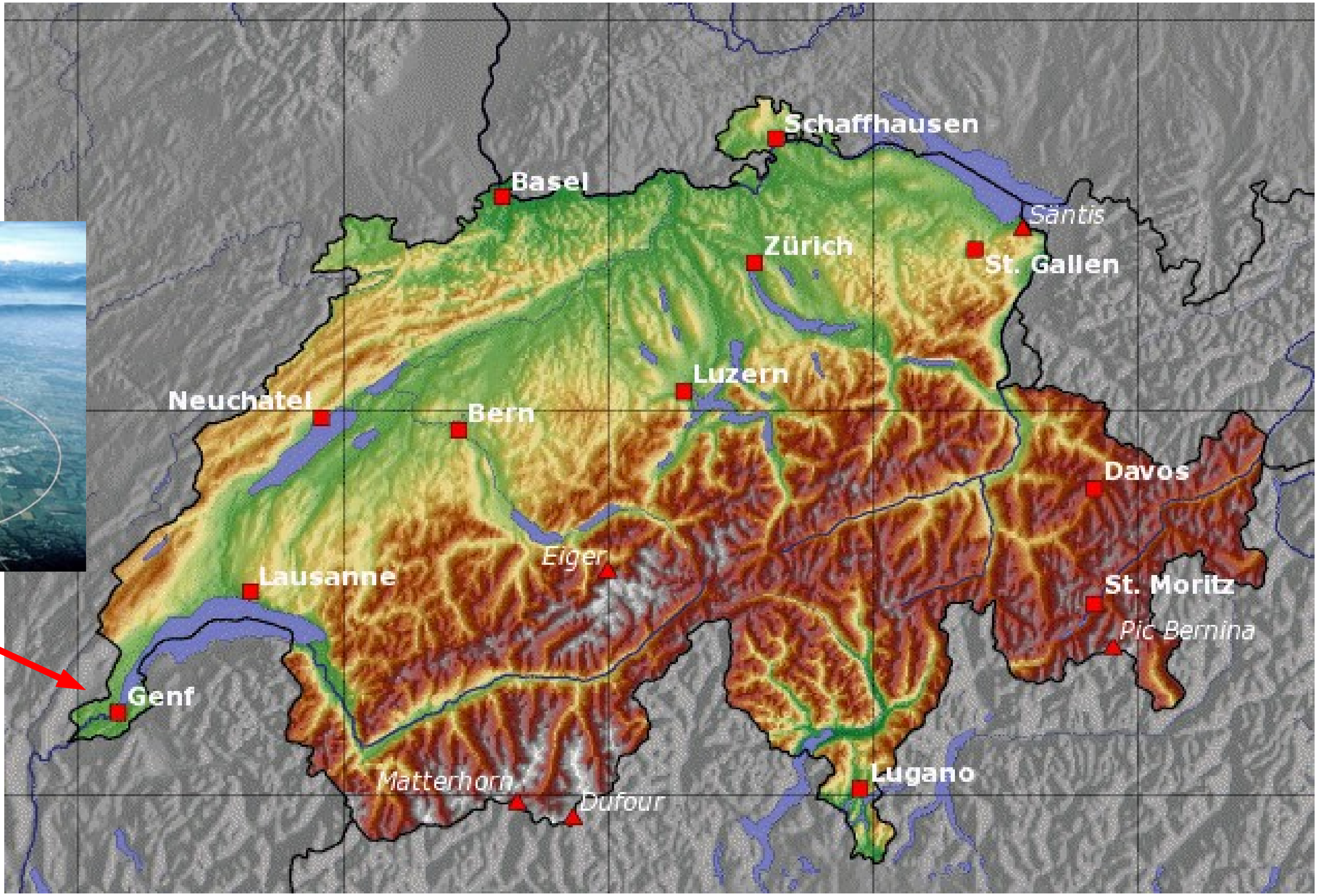

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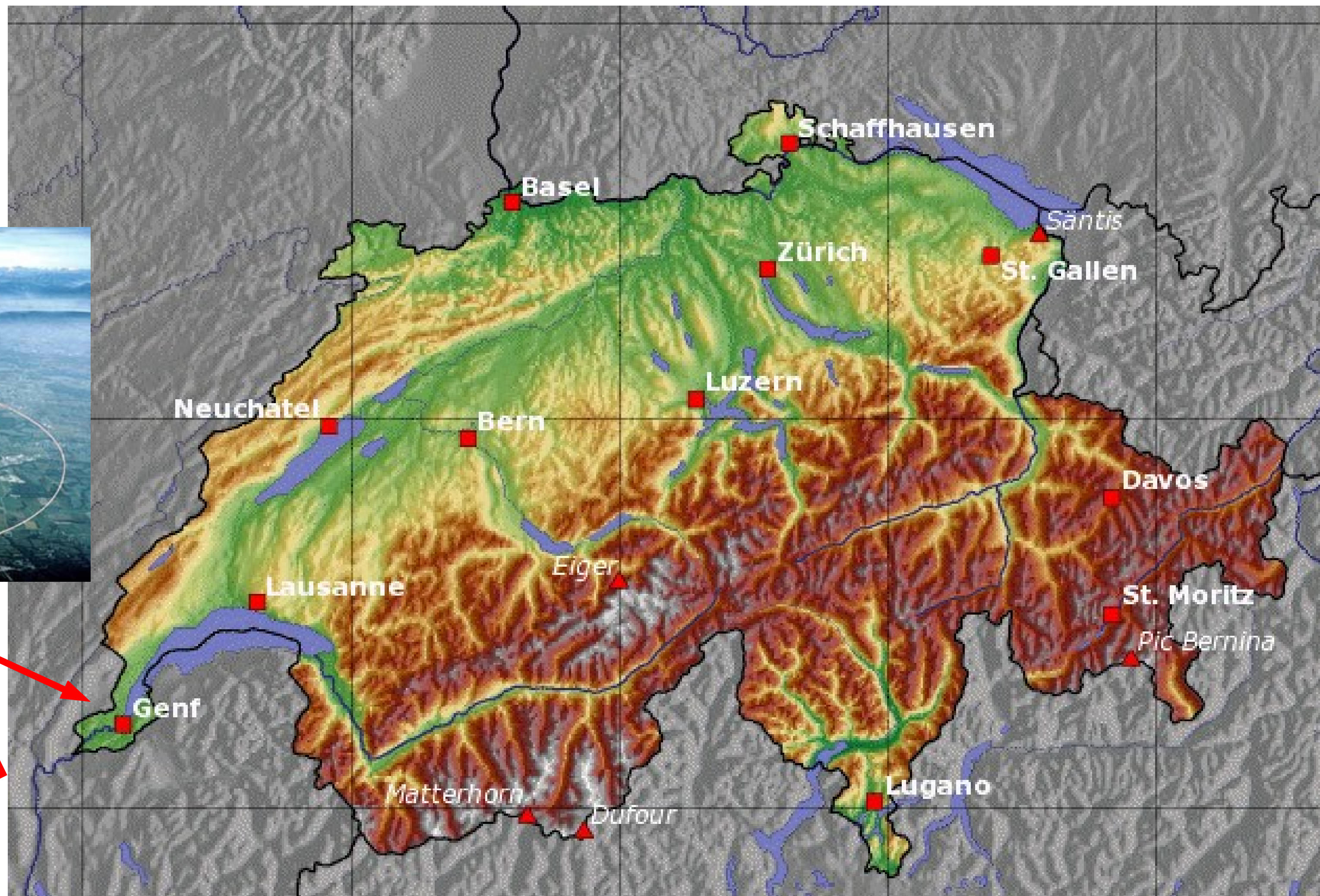

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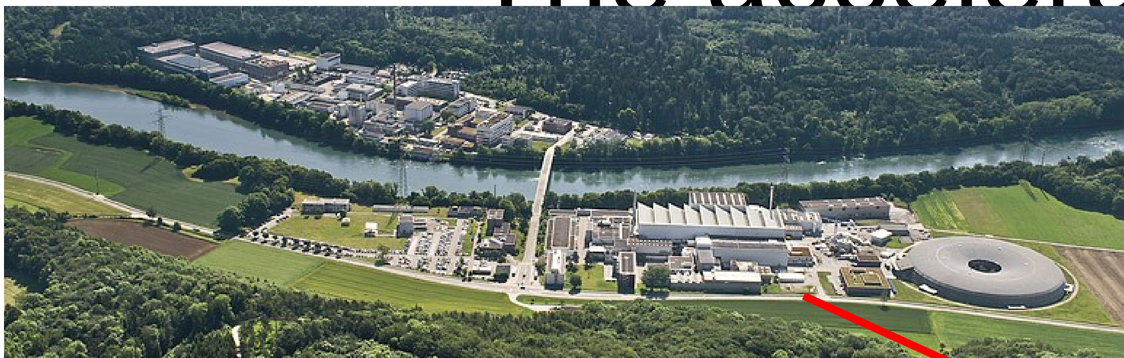
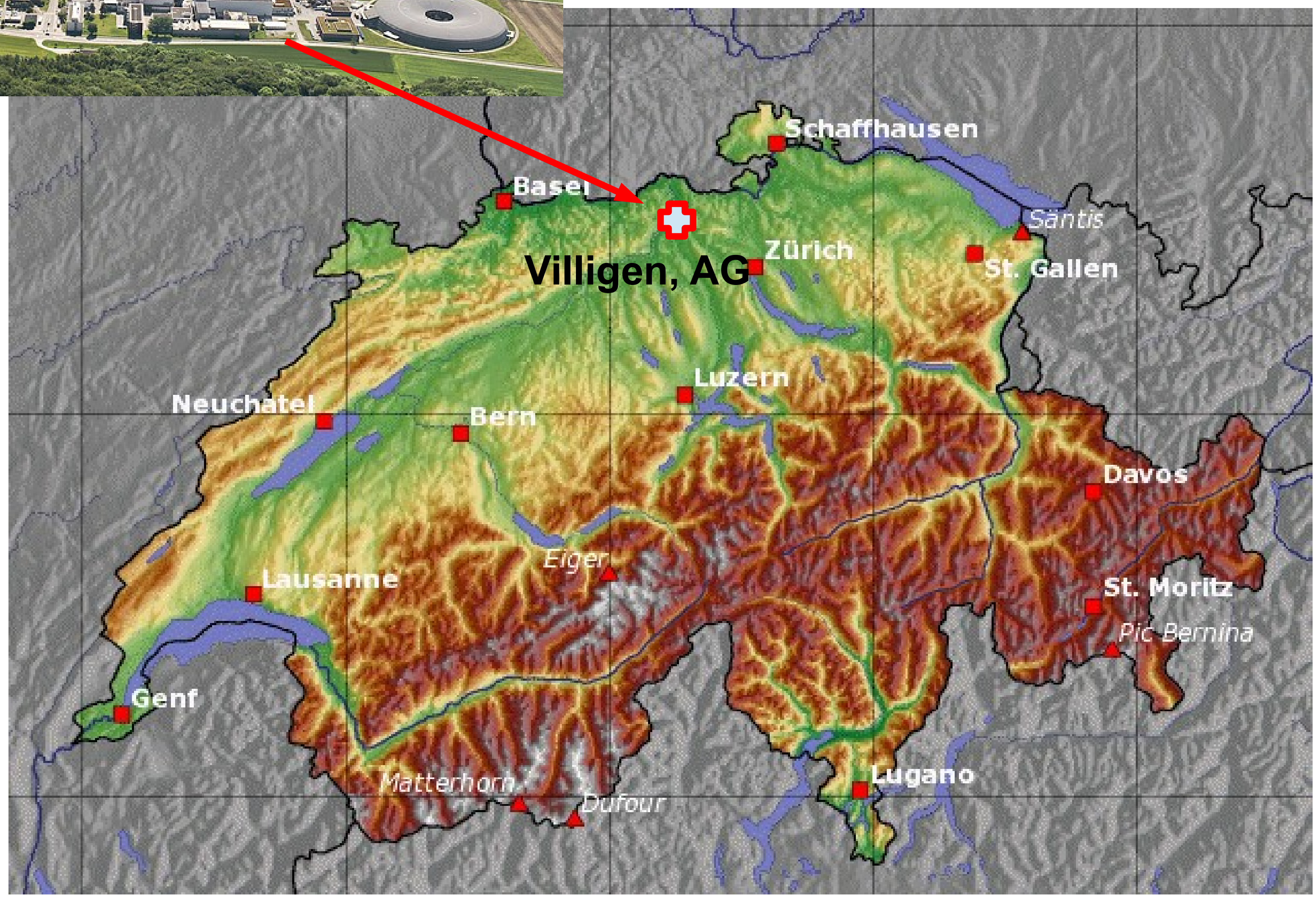
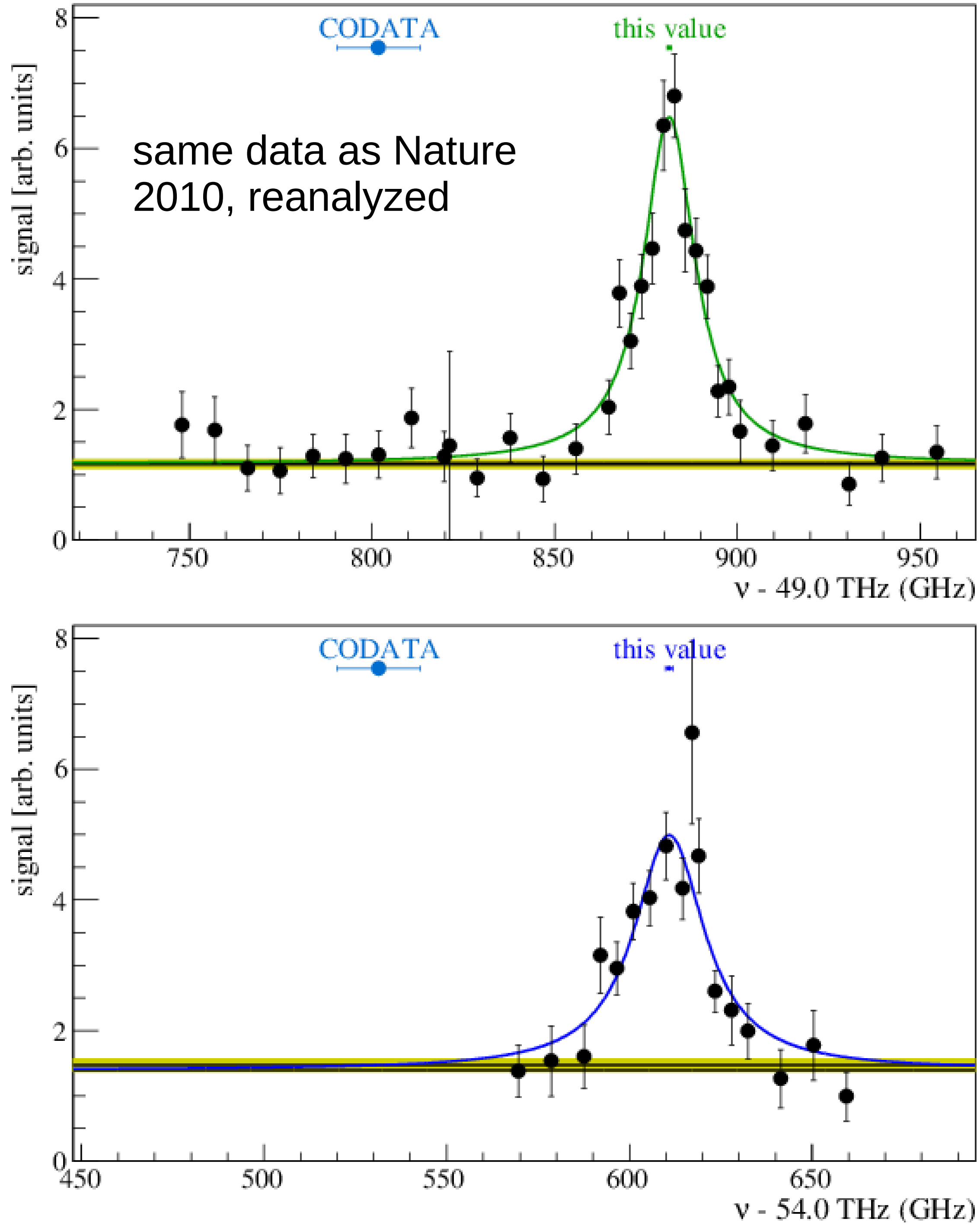


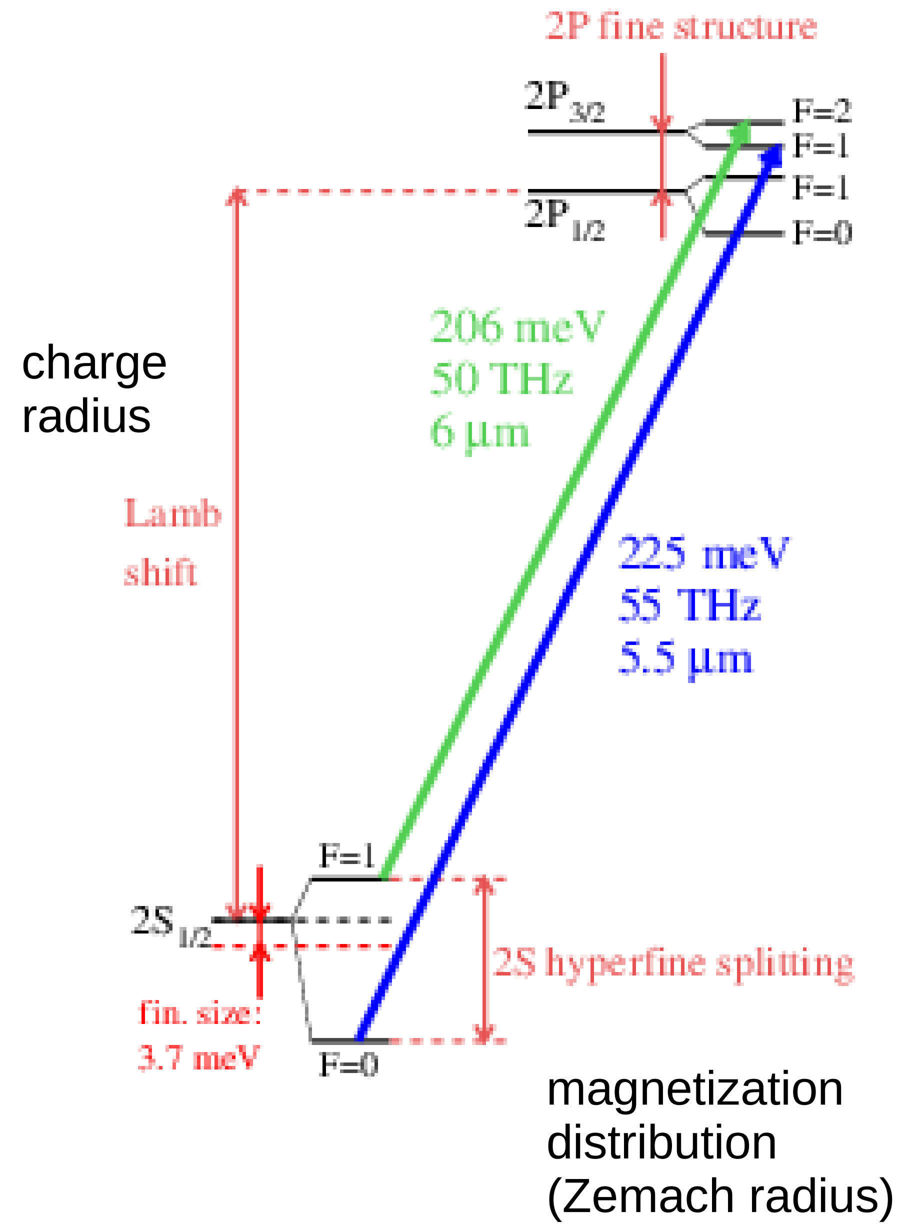
PAUL SCHERRER INSTITUT

PSI



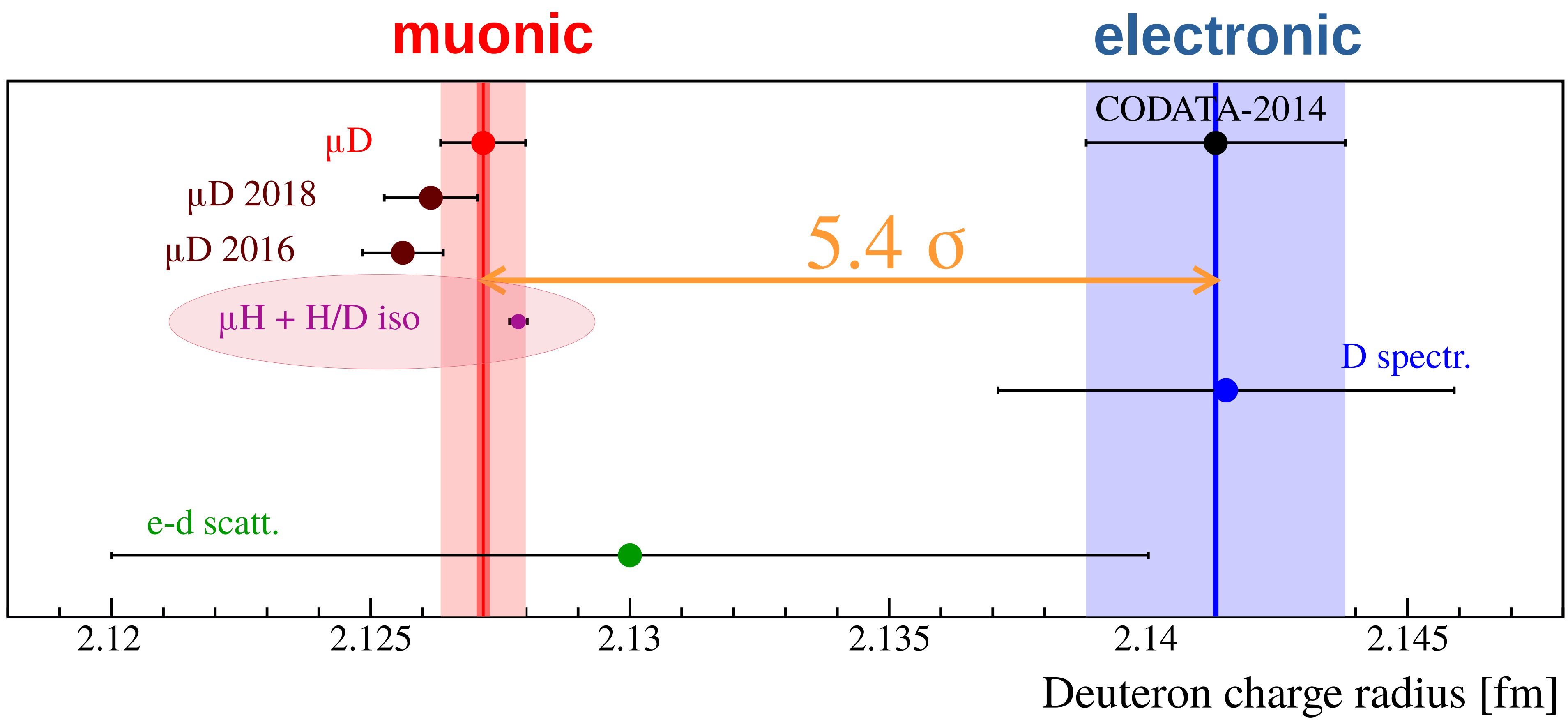
2 transitions in muonic H





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

Muonic Deuterium



μD: 2.12717 $(13)_{exp}$ $(82)_{theo}$ fm (theo = nucl. polarizability)

μH + H/D(1S-2S): 2.12785 (17) fm

CODATA-2014: 2.1**4**130 (250) fm

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

Pachucki et al., PRA 97, 062511 (2018)

H/D 1S-2S. Parthey, RP et al. (MPQ Garching), PRL 104, 233001 (2010)
PRL 107, 203001 (2011)

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\,(13)\ \text{meV}_{QED} + 1.7500\,(\mathbf{210})\ \text{meV}_{TPE} - 6.1103\,(3)\ \text{meV/fm}^2 * \mathbf{R_d}^{\mathbf{2}}$$

ΔE_{TPE} (theo) = 1.7500 +- 0.0210 meV (Kalinowski, 2018)

vs. **+- 0.0034 meV experimental uncertainty**

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

r_d (μD) = 2.12717 (13) $_{exp}$ (82) $_{theo}$ fm vs.

r_d (CODATA-14) = 2.1**4**130 (250) fm

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

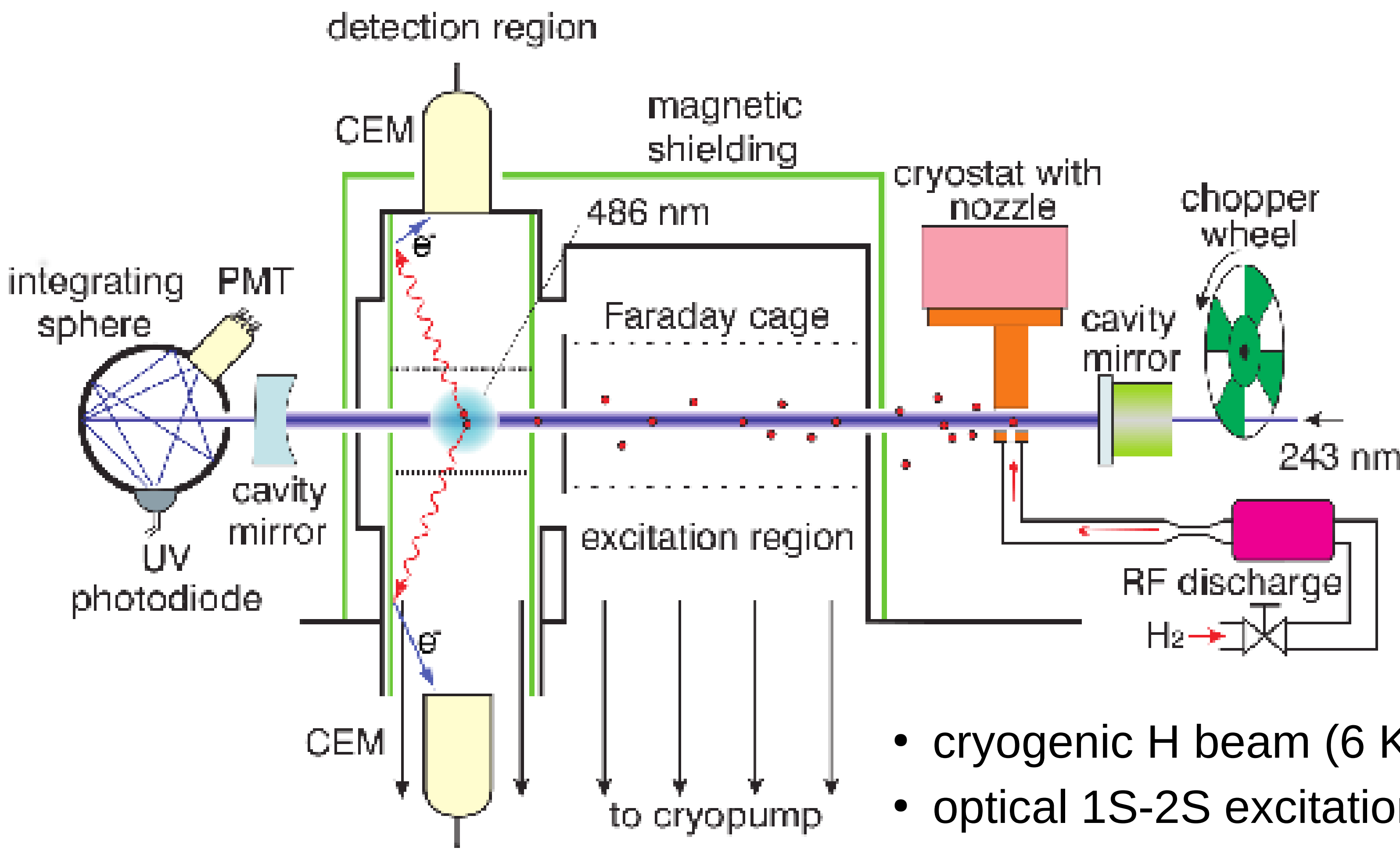
ΔE_{TPE} (theo) = 1.7500 (210) meV vs.

ΔE_{TPE} (exp) = 1.7591 (59) meV 3.5x more accurate

Krauth et al. (2016) + Pachucki et al. (2018) + Hernandez et al. (2018) + Kalinowski (2018)

Hydrogen

Garching H(2S-4P)



- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-4P transition is 1-photon: retroreflector
- split line to 10^{-4} !!!
- 2.3 kHz vs. 9 kHz PRP
- large systematics

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

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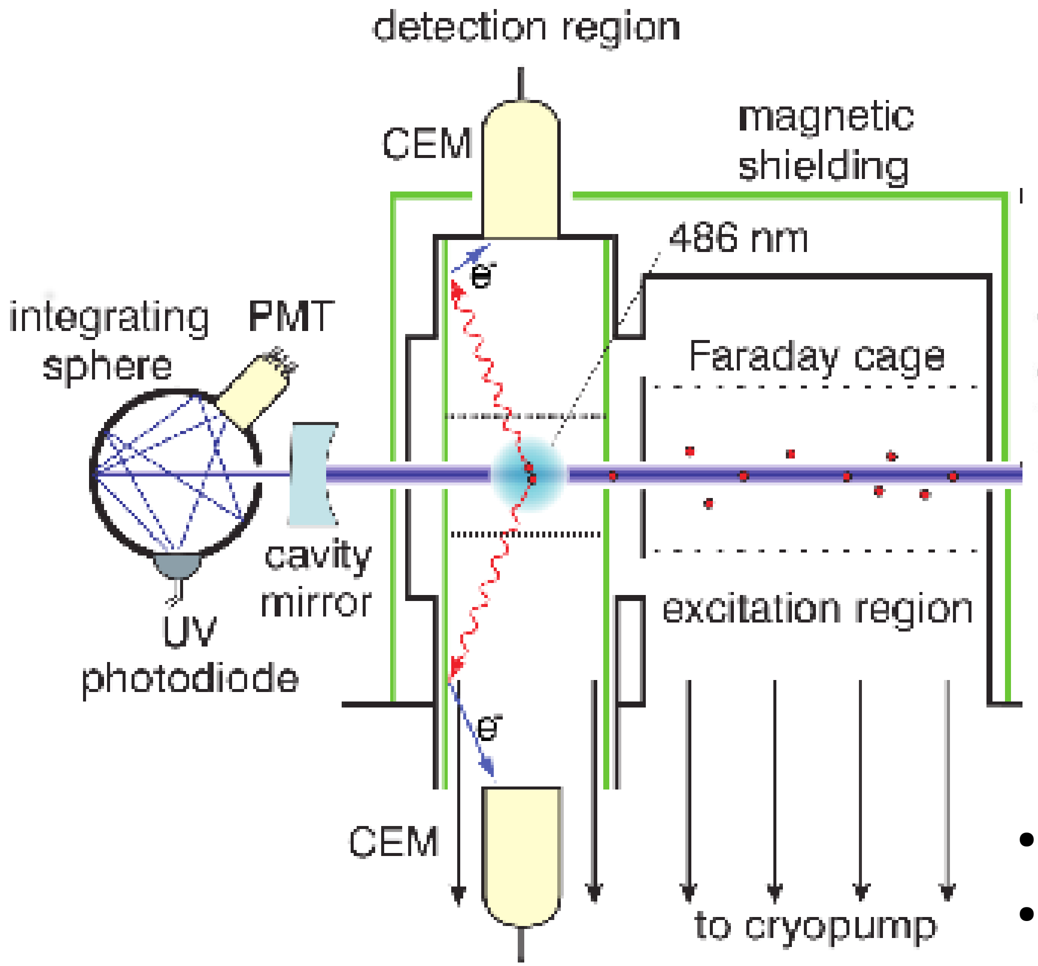
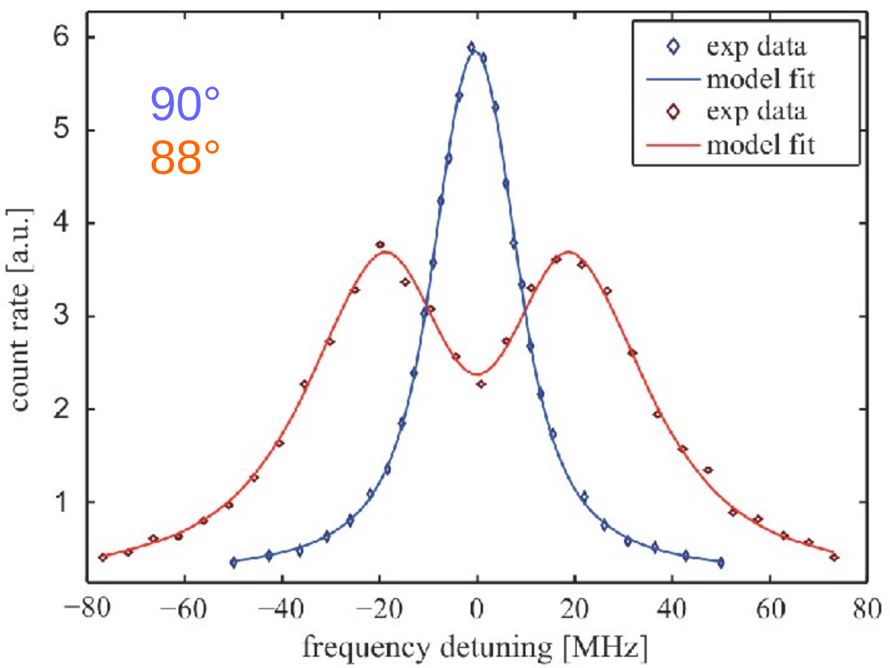


1st order Doppler cancellation



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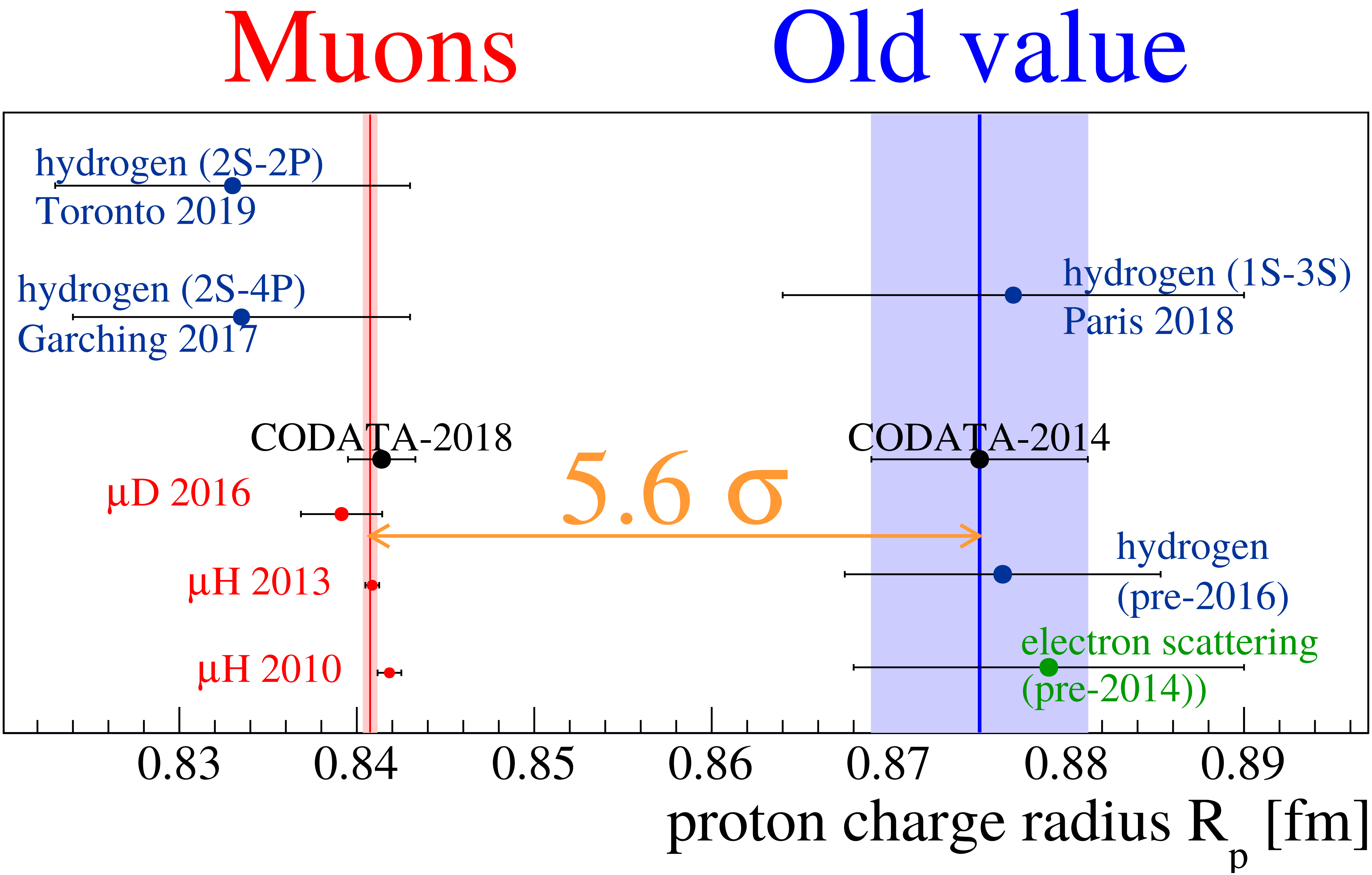
Systematics

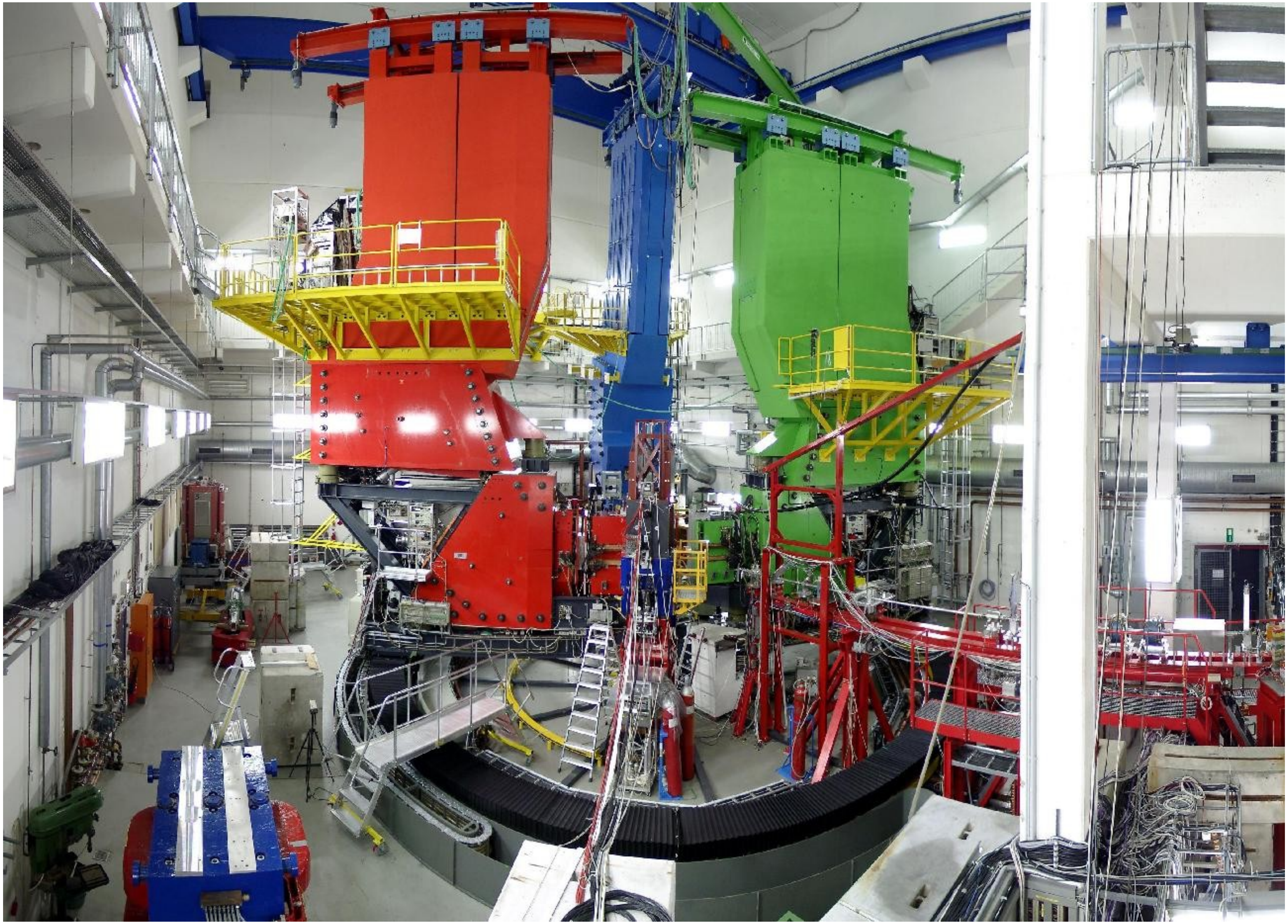
Contribution	$\Delta\nu$ (kHz)	σ (kHz)
Statistics	0.00	0.41
First-order Doppler shift	0.00	2.13
Quantum interference shift	0.00	0.21
Light force shift	–0.32	0.30
Model corrections	0.11	0.06
Sampling bias	0.44	0.49
Second-order Doppler shift	0.22	0.05
dc-Stark shift	0.00	0.20
Zeeman shift	0.00	0.22
Pressure shift	0.00	0.02
Laser spectrum	0.00	0.10
Frequency standard (hydrogen maser)	0.00	0.06
Recoil shift	–837.23	0.00
Hyperfine structure corrections	–132,552.092	0.075
Total	–133,388.9	2.3

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

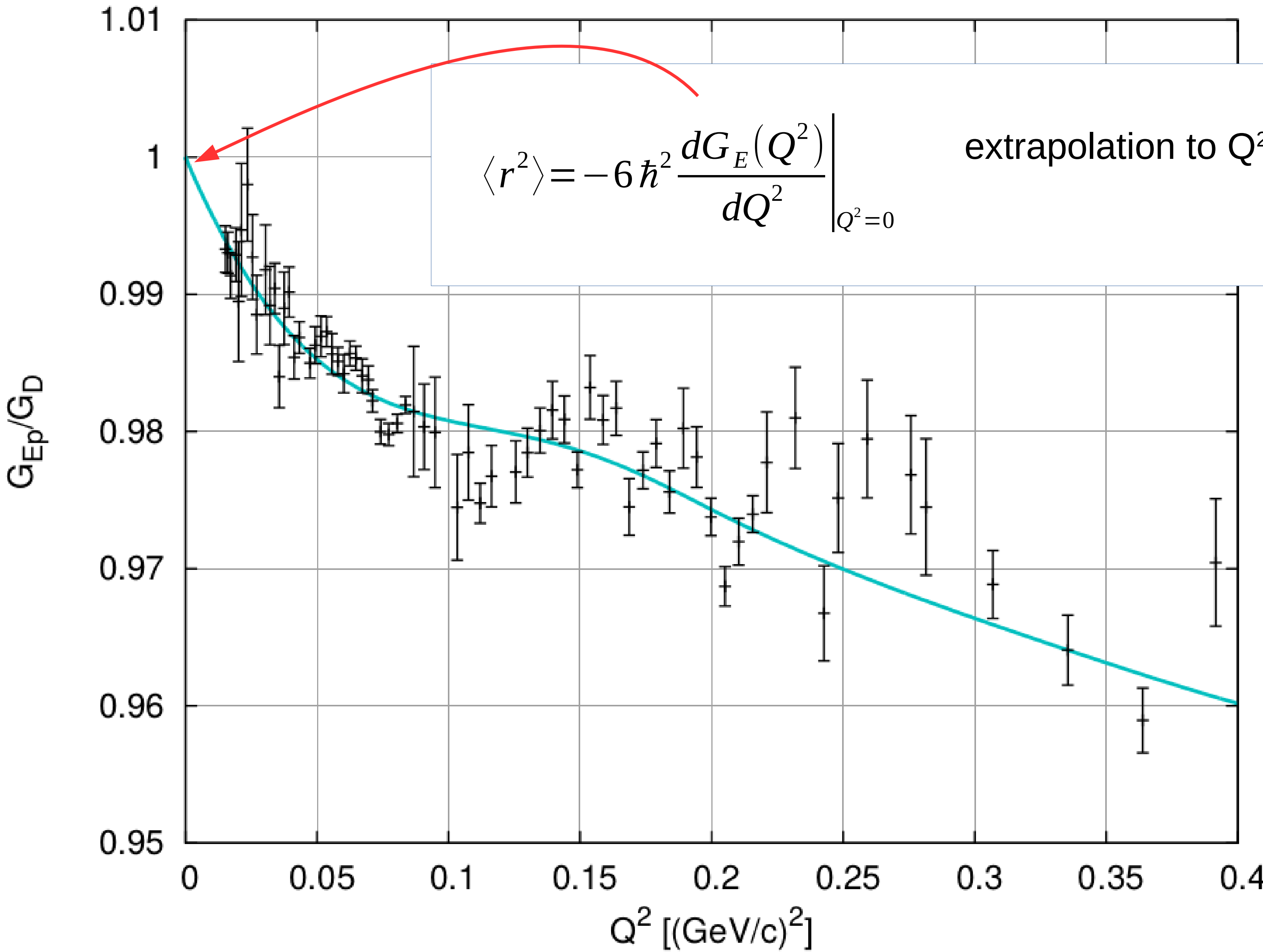
The “Proton Radius Puzzle”



Mainzer Microtron MAMI



Electron scattering



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

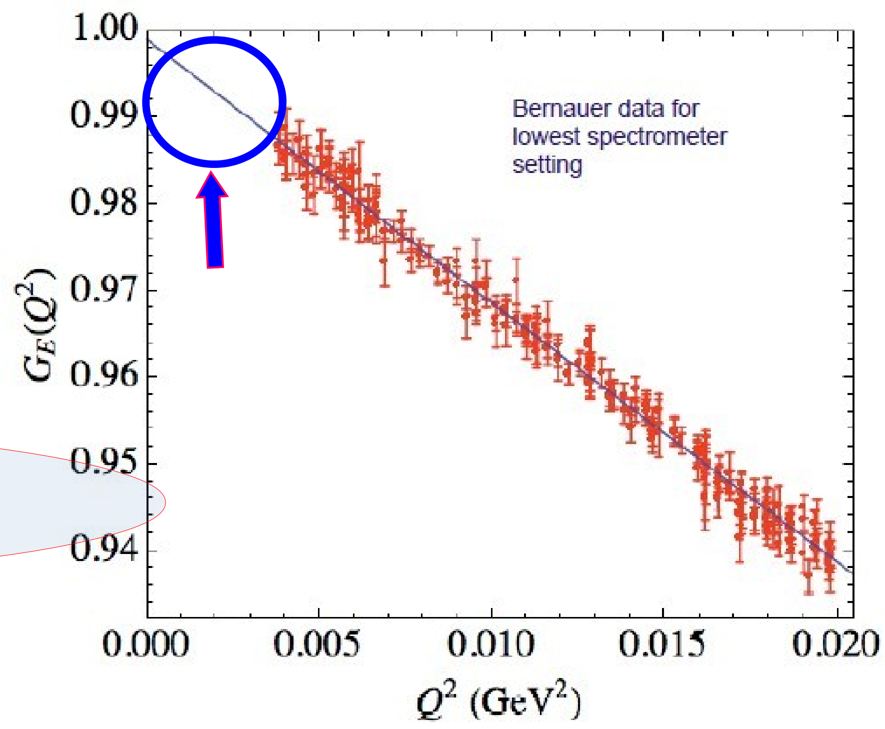
extrapolation to $Q^2 = 0$ required

Mainz MAMI data 2010

Vanderhaeghen, Walcher: 1008.4225

The PRad Experimental Approach

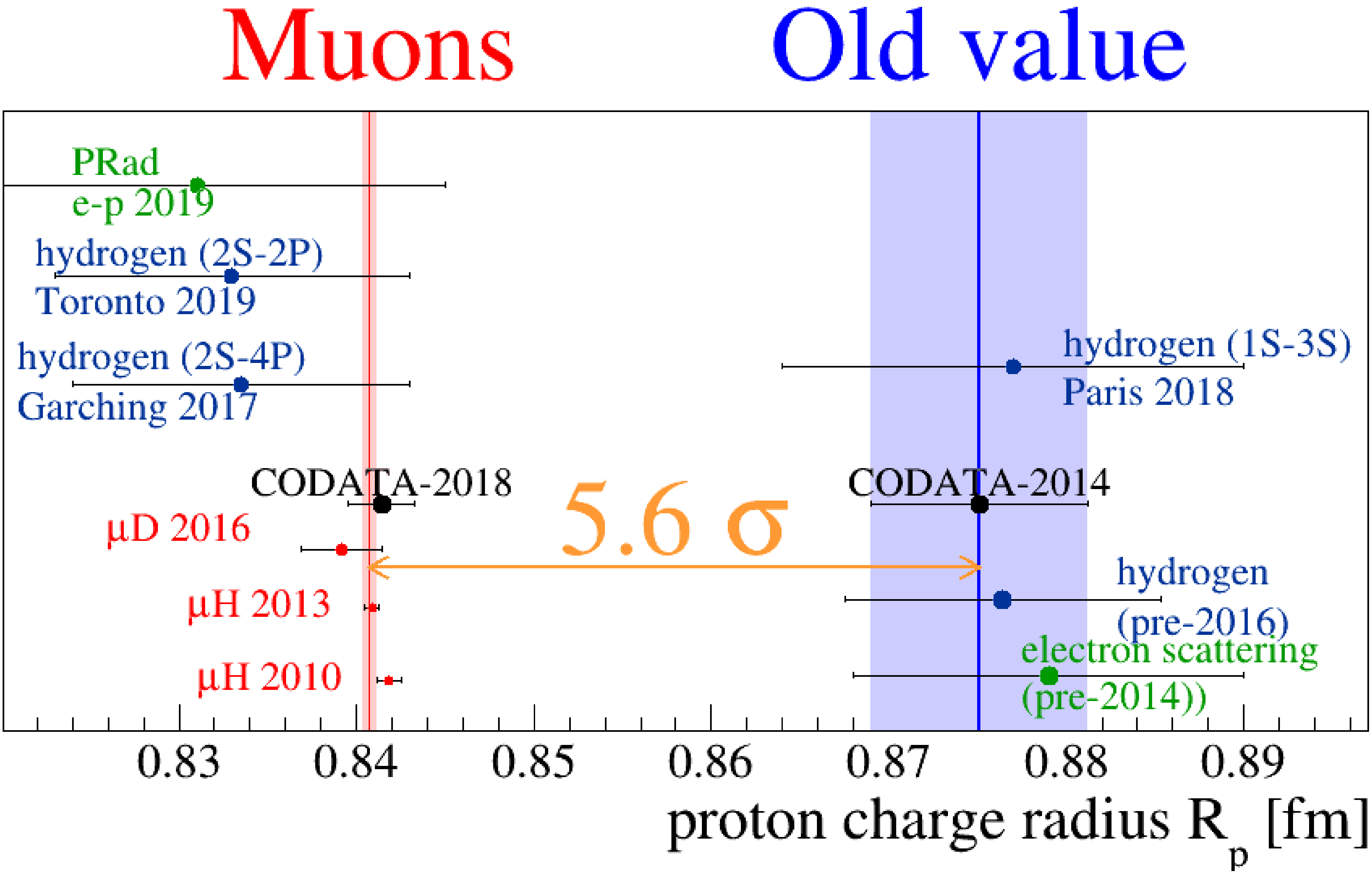
- PRad initial goals:
  - large Q^2 range in one experimental setting
  - reach to very low Q^2 range (~ 10^{-4} GeV/C^2)
  - reach to sub-percent precision in cross section
- PRad suggested solutions:
  - use high resolution high acceptance calorimeter:
    - ✓ reach smaller scattering angles: ($\theta_e = 0.7^0 – 7.0^0$)
($Q^2 = 2x10^{-4} \div 6x10^{-2}$) GeV/c^2 ;
    - ✓ large Q^2 range in one experimental setting!;
    - ✓ simultaneous detection of *ee* → *ee* Moller scattering (best known control of systematics).
  - use high density windowless H_2 gas flow target:
    - ✓ beam background under control;
    - ✓ minimize experimental background.



Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

- Two beam energies: E_0 = 1.1 GeV and 2.2 GeV to increase Q^2 range.
- Approved by JLab PAC39 (June, 2012) with high “A” scientific rating.

New Measurements: PRad

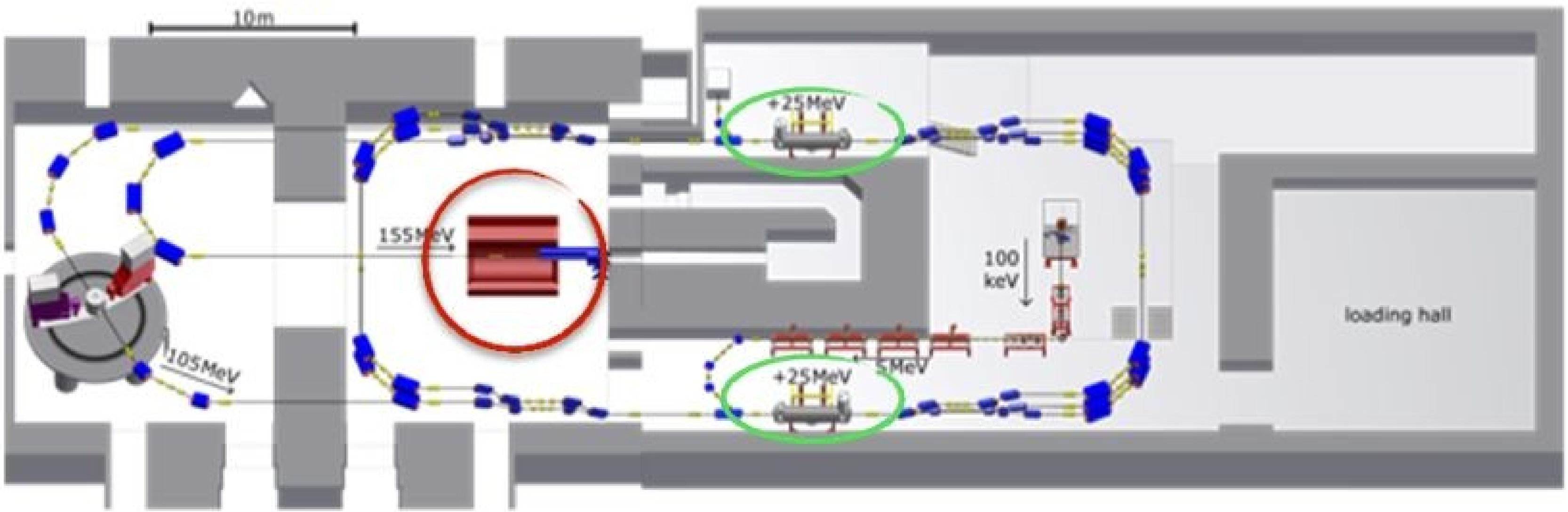


New Mainz electron accelerator **MESA**

Kurt Aulenbacher

MESA — "**M**ainz **E**nergy-Recovering **S**uperconducting **A**ccelerator

Beam energy: 105 MeV / 155 MeV Current: 1–2 mA

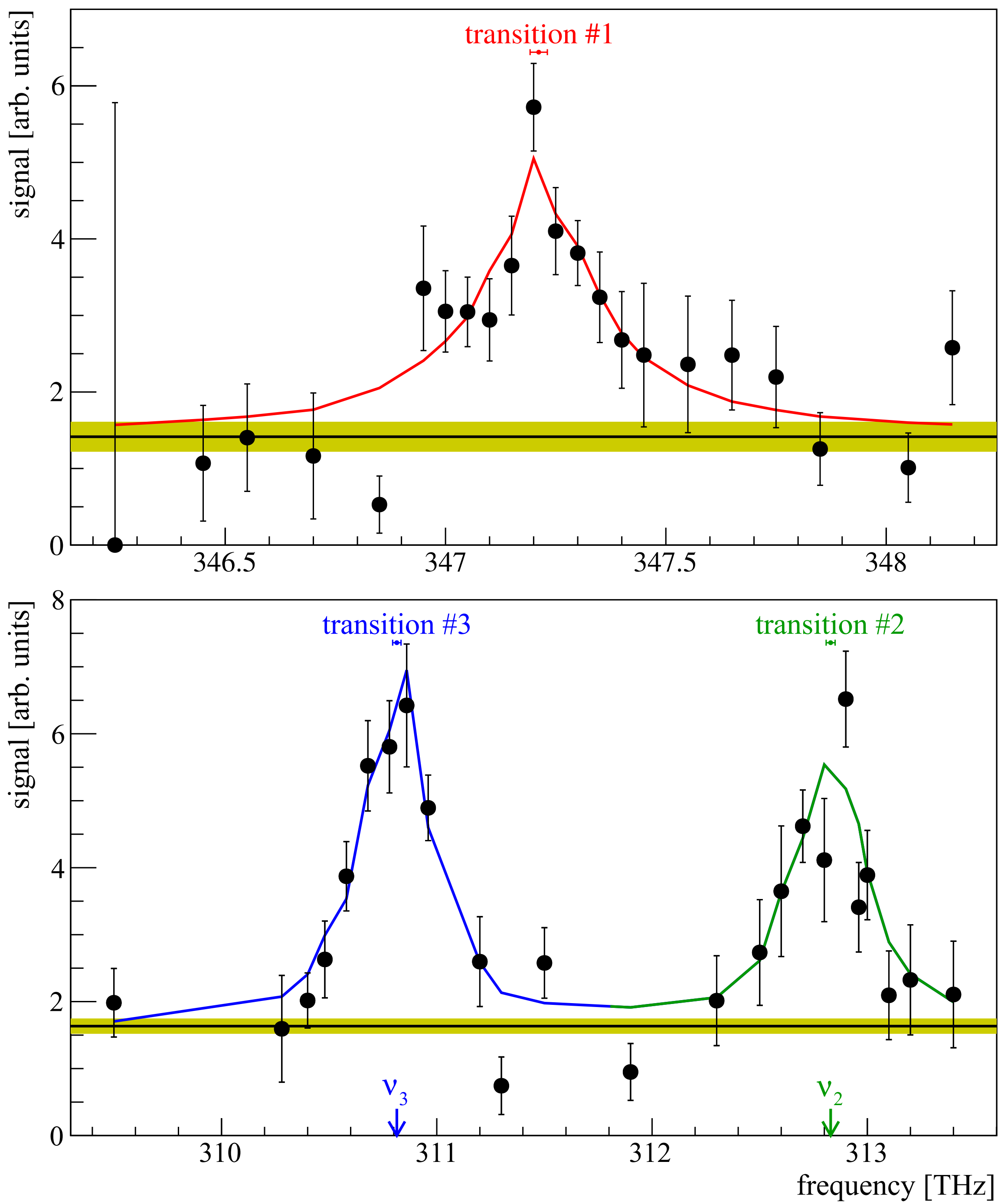


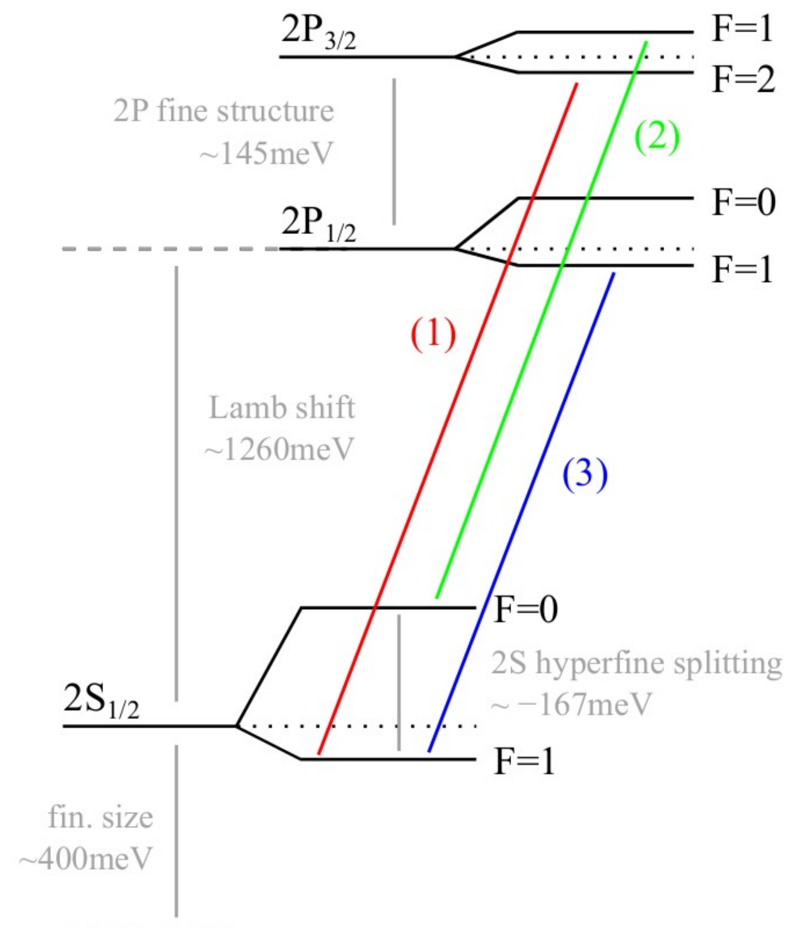
Being built on **Campus of JGU Mainz**

MAGIX: windowless (gas-jet) target, lowest Q^2

Muonic Helium-3 and -4

muonic ^{3}He ions



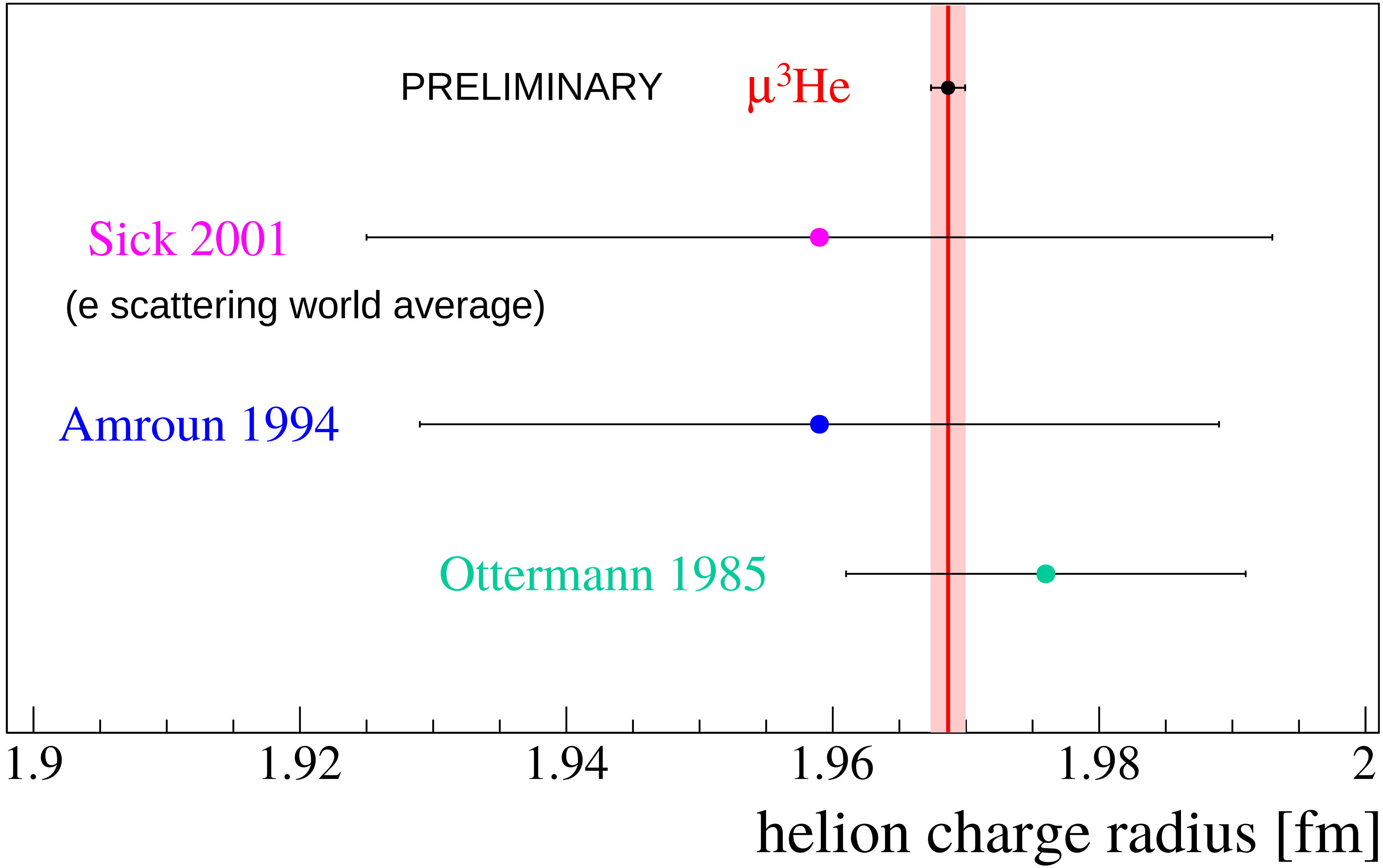


$R(^3He) = 1.96866\,(12)_{exp}\,(128)_{theo}$ fm

PRELIMINARY

Theory: Franke et al., EPJD (2017),
but 3-photon (Pachucki et al.) ?!?!

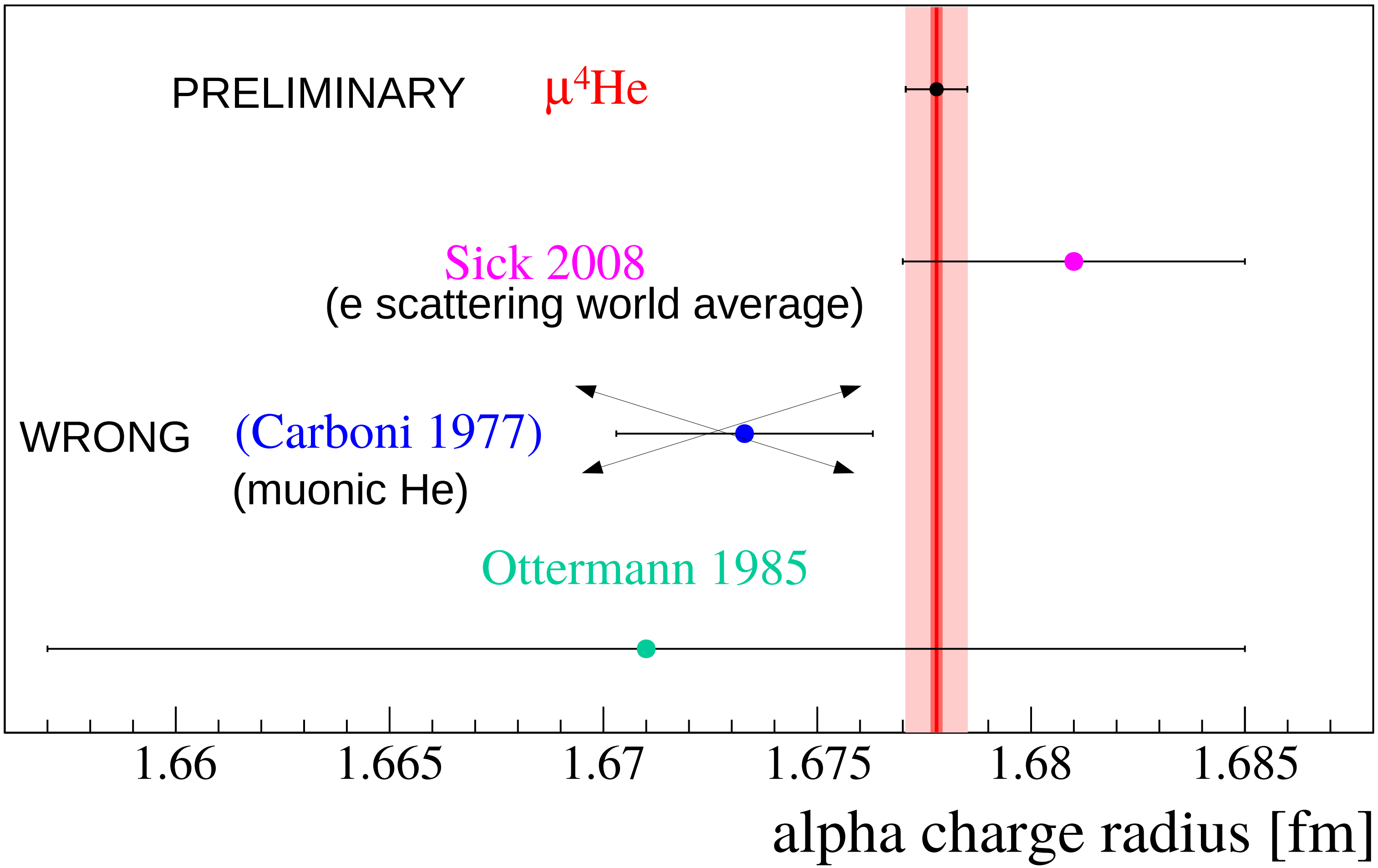
Muonic Helium-3



prel. accuracy: exp **+- 0.00012** fm, theo **+- 0.00128** fm (nucl. polarizability)

Theory: see Franke et al. EPJ D 71, 341 (2017) [1705.00352]

Muonic Helium-4



prel. accuracy: exp **+- 0.00019** fm, theo **+- 0.00058** fm (nucl. polarizability)

Theory: M. Diepold, RP et al. Ann. Phys. (N.Y.) 396, 220 (2018)
(arxiv 1606.05231 (sic!))

Conclusions

Muonic atoms / ions provide:

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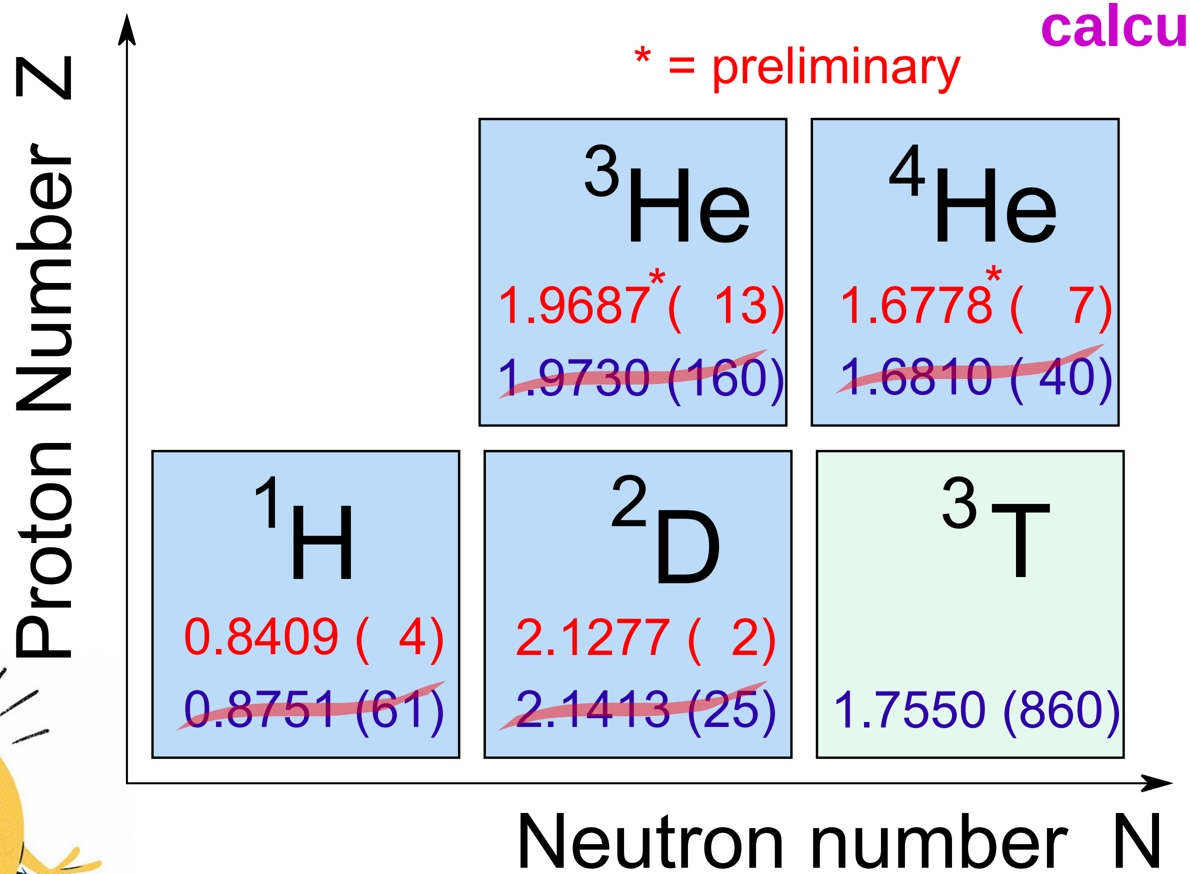


Intermediate conclusions

Muonic atoms / ions provide:

- **~10x more accurate charge radii**, when combined with **calculated polarizability**
- few times more accurate **nuclear polarizability**, when combined with **charge radius from regular atoms**

Muonic atoms are a novel tool for proton and new-nucleon properties!

Intermediate conclusions

Proton radius situation:

- smaller radii from muonic **hydrogen** and **deuterium** imply a smaller Rydberg constant
- new H(2S-4P), H(2S-2P), H(1S-3S) give a smaller proton radius
- new H(1S-3S) however confirms large proton radius

More data coming in!

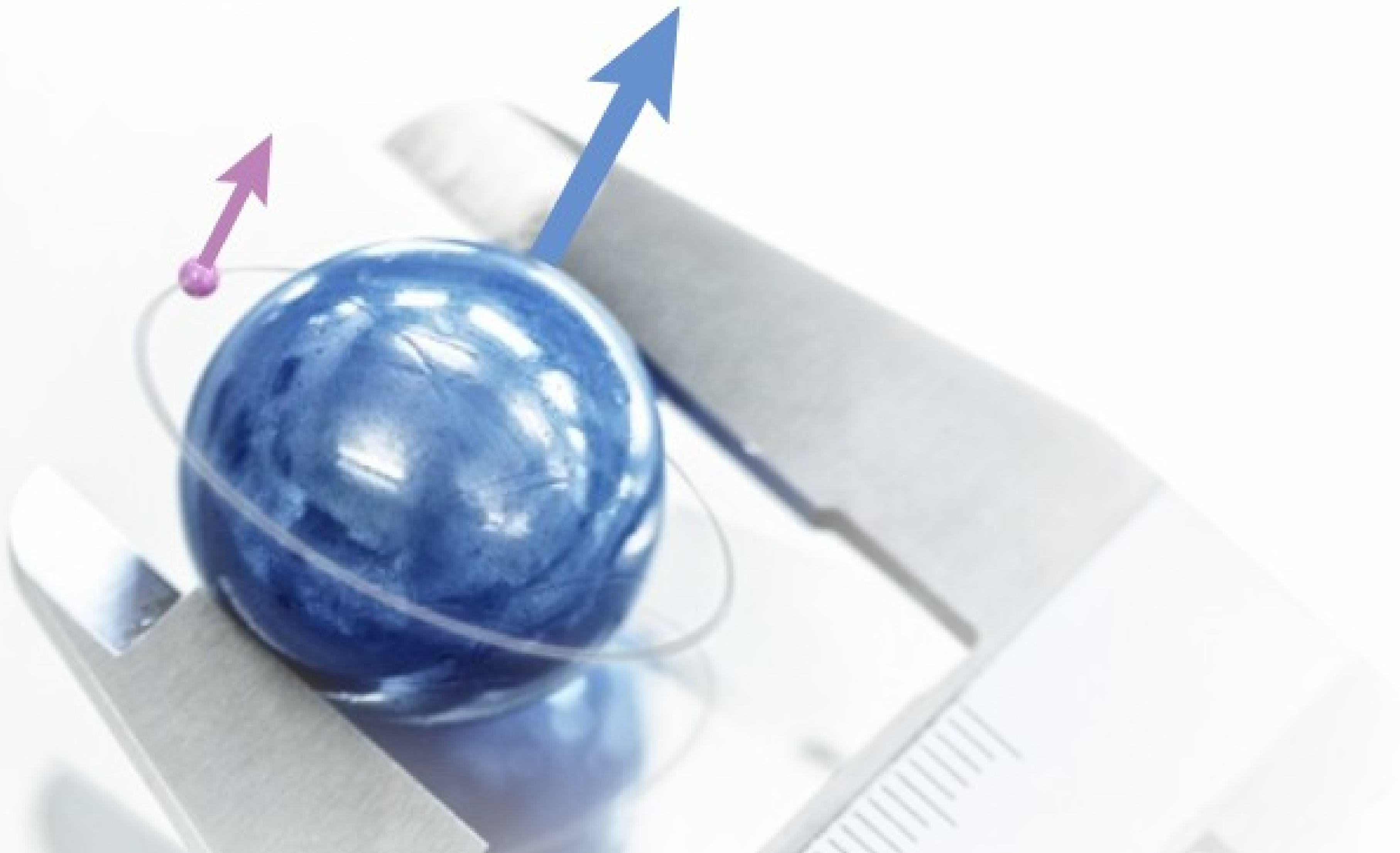
- H(2S – 6P, 8P, 9P, …) and D(2S-nl) underway in Garching and Colorado
- H(1S – 3S, 4S, ..) underway in Paris and Garching
- H(2S-2P) (Hessels @ Toronto)
- Muonium at PSI, J-PARC
- Positronium (Cassidy @ UCL, Crivelli @ ETH)
- He^+(1S-2S) underway in Garching (Udem) and Amsterdam (Eikema)
- HD^+, H_2, etc. in Amsterdam (Ubachs) and Paris (Hilico, Karr)
- He (Vassen @ Amsterdam), Li^+ (Udem @ Garching)
- HCI, e.g. H-like Ne (Tan @ NIST)
- Rydberg-atoms, e.g. Rb (Raithel @ Ann Arbor)
- new low-Q^2 electron scattering at MAMI, JLab, MESA
- muon scattering: MUSE @ PSI, COMPASS @ CERN

Compare Rydberg values to test QED and SM

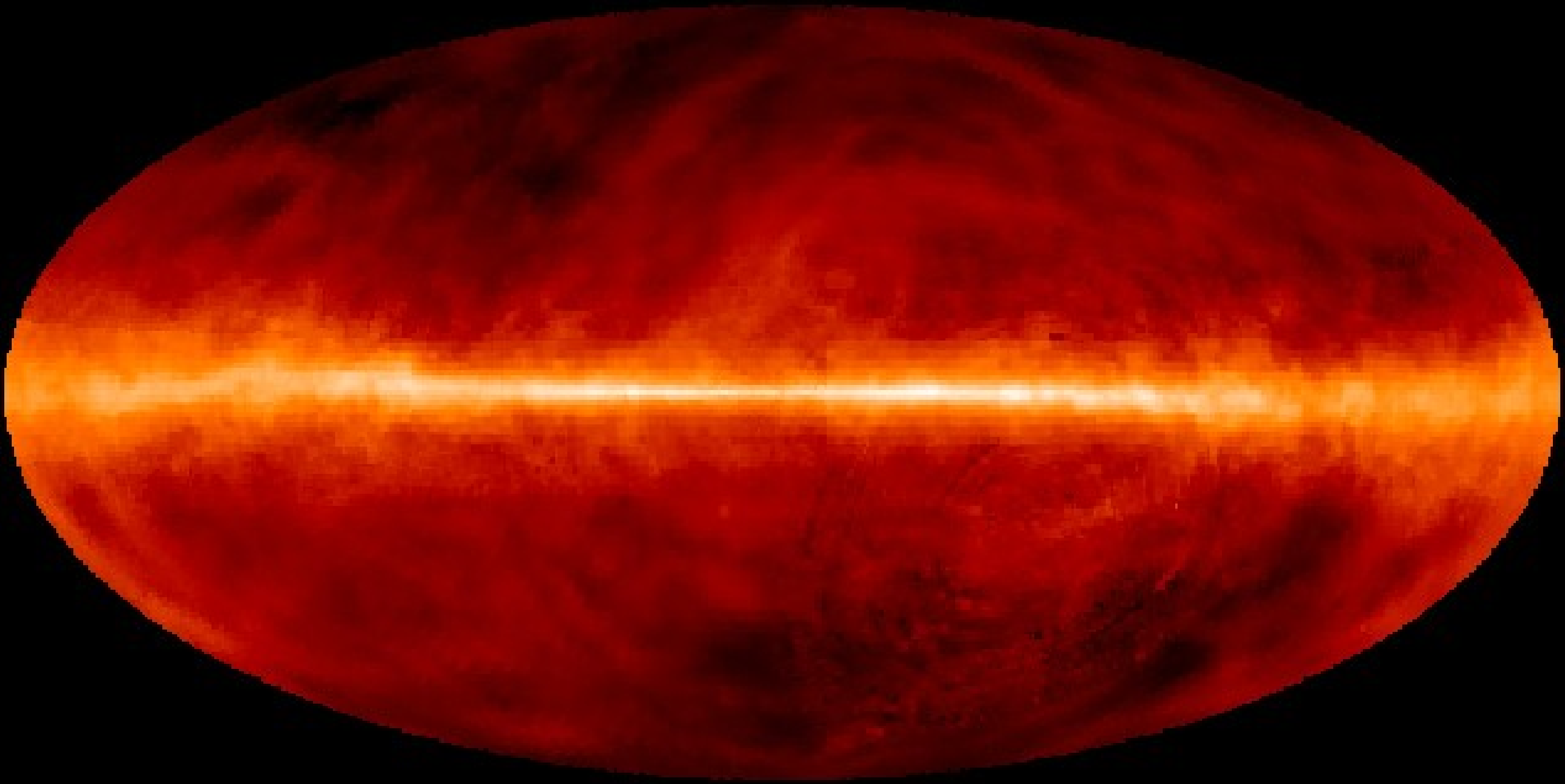
The Present

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)

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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:

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

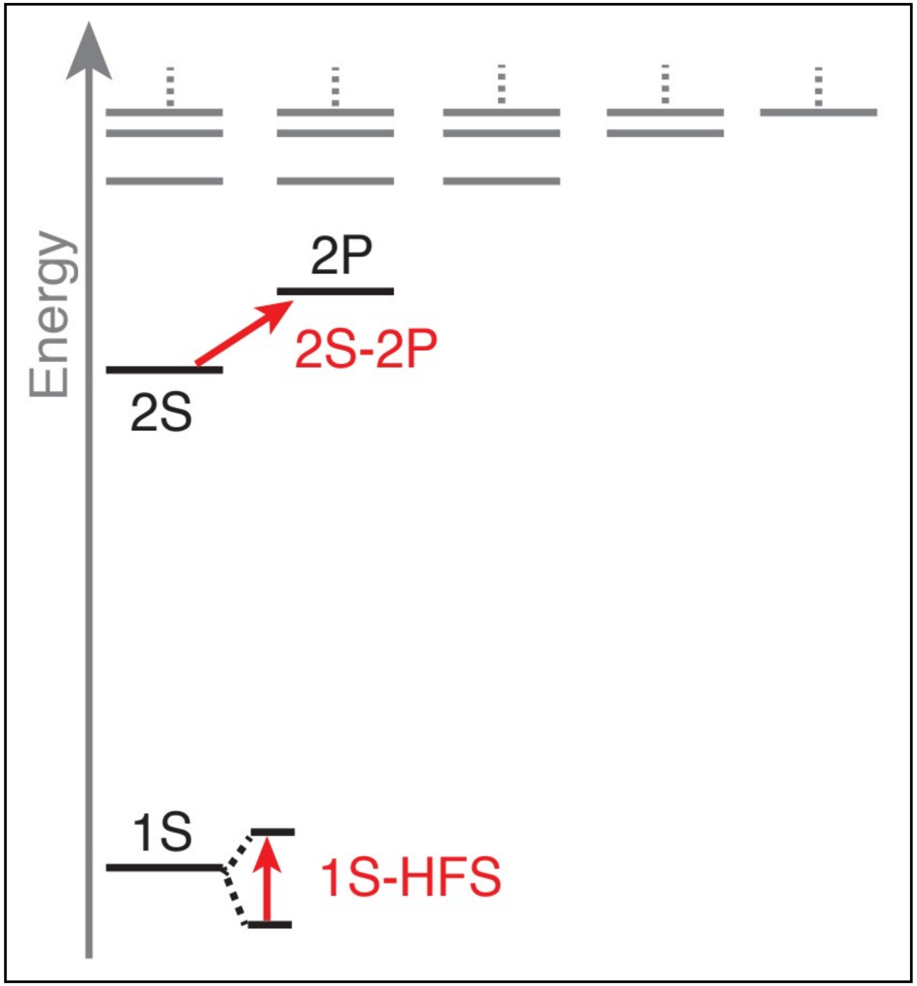
$$\langle r \rangle_{(2)} = \int d^3 r\, d^3 r' \rho_E(r) \rho_M(r') |r - r'|$$

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

Form factors and momentum space

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

From charge to magnetic properties



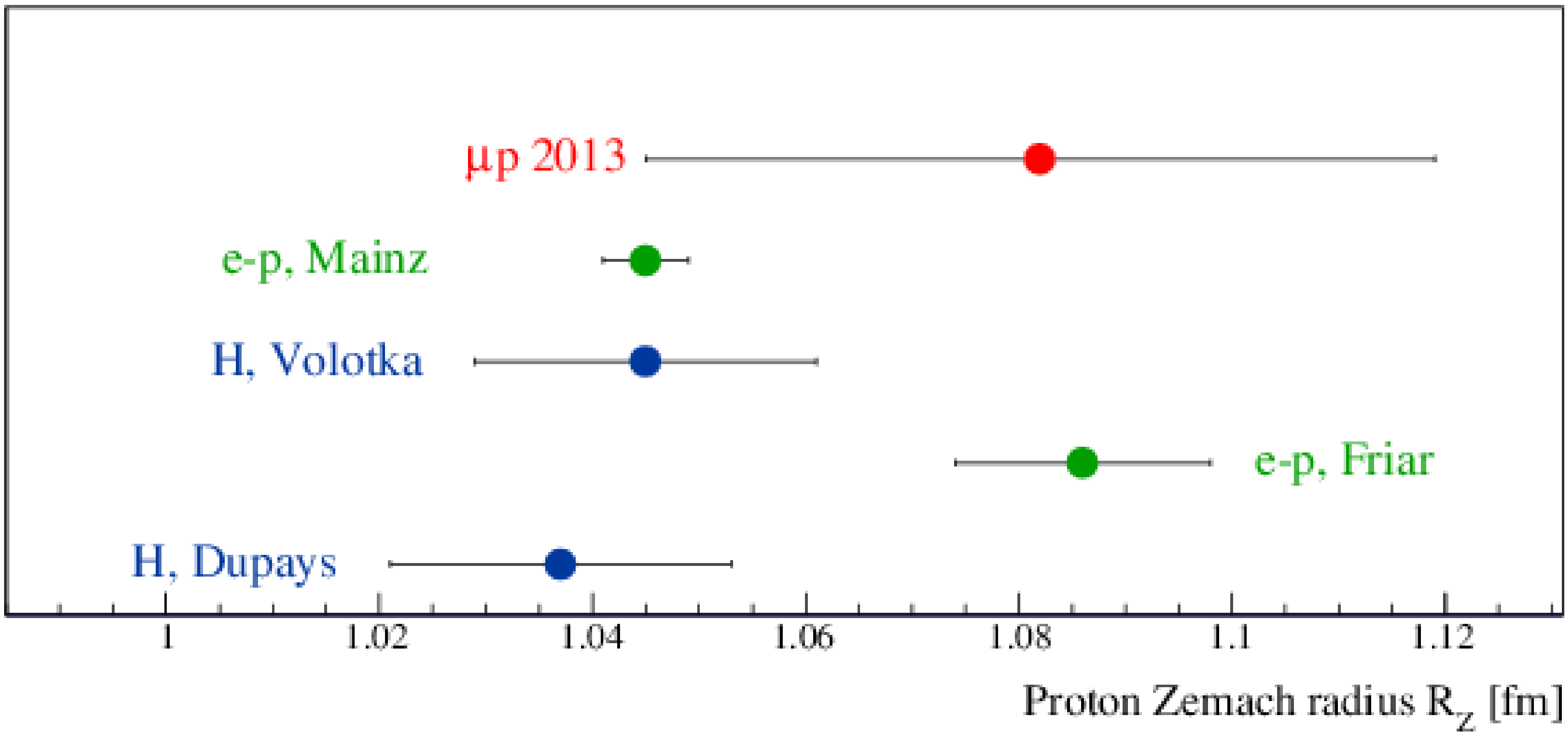
2S-2P = Lamb shift

is sensitive to CHARGE radius

1S-HFS = Hyperfine splitting

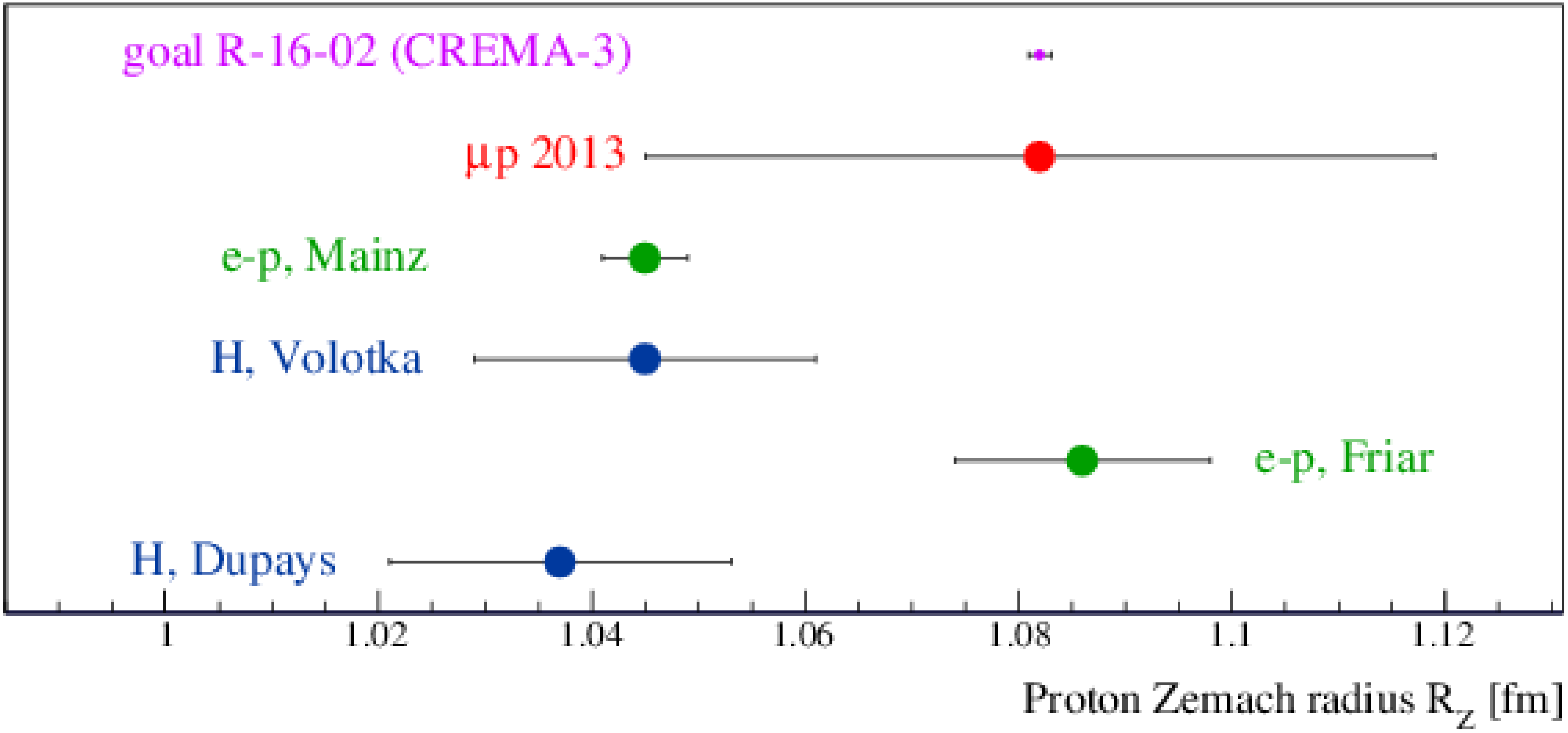
is sensitive to ZEMACH radius

Proton Zemach radius from μp



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

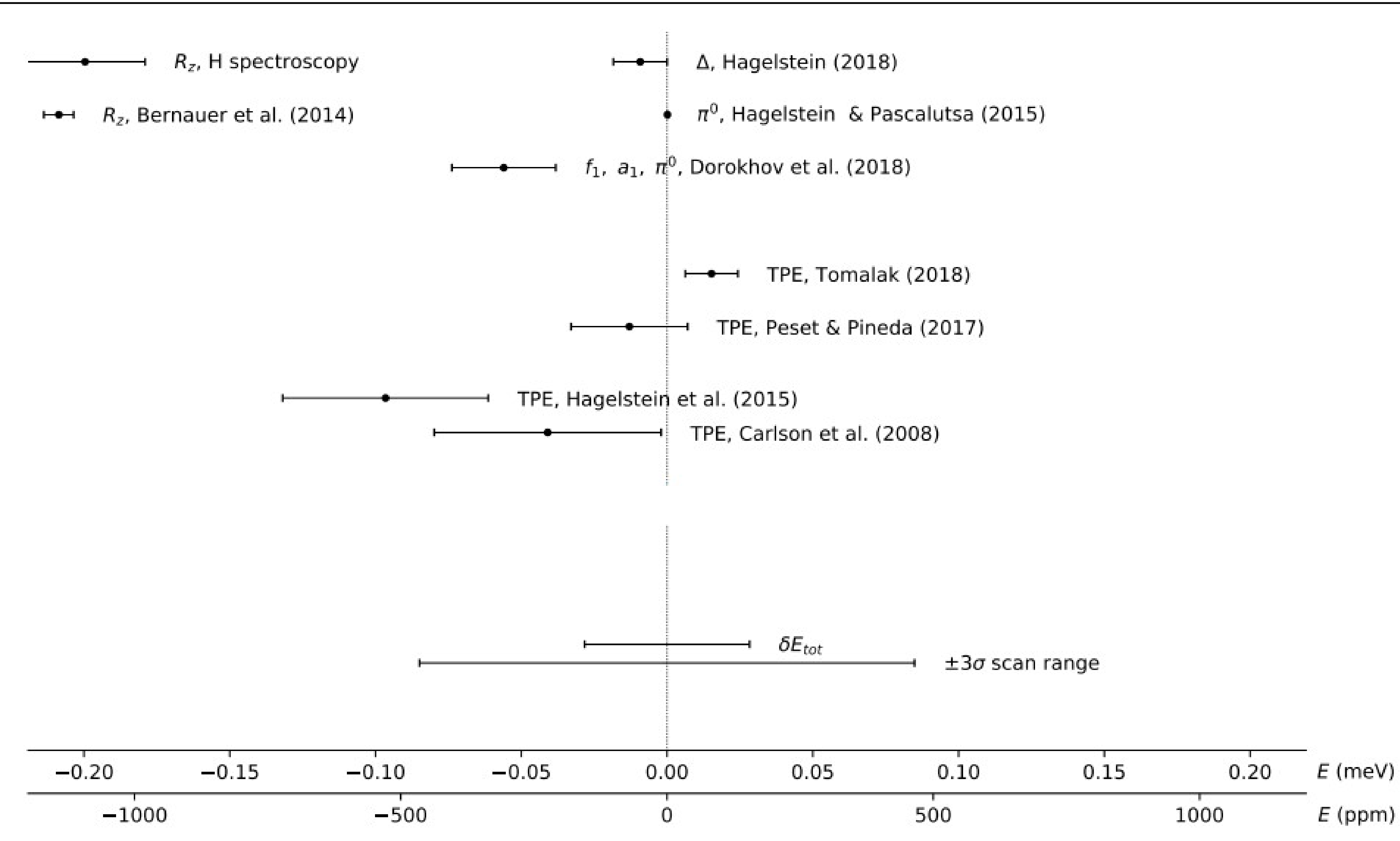
Proton Zemach radius from μp



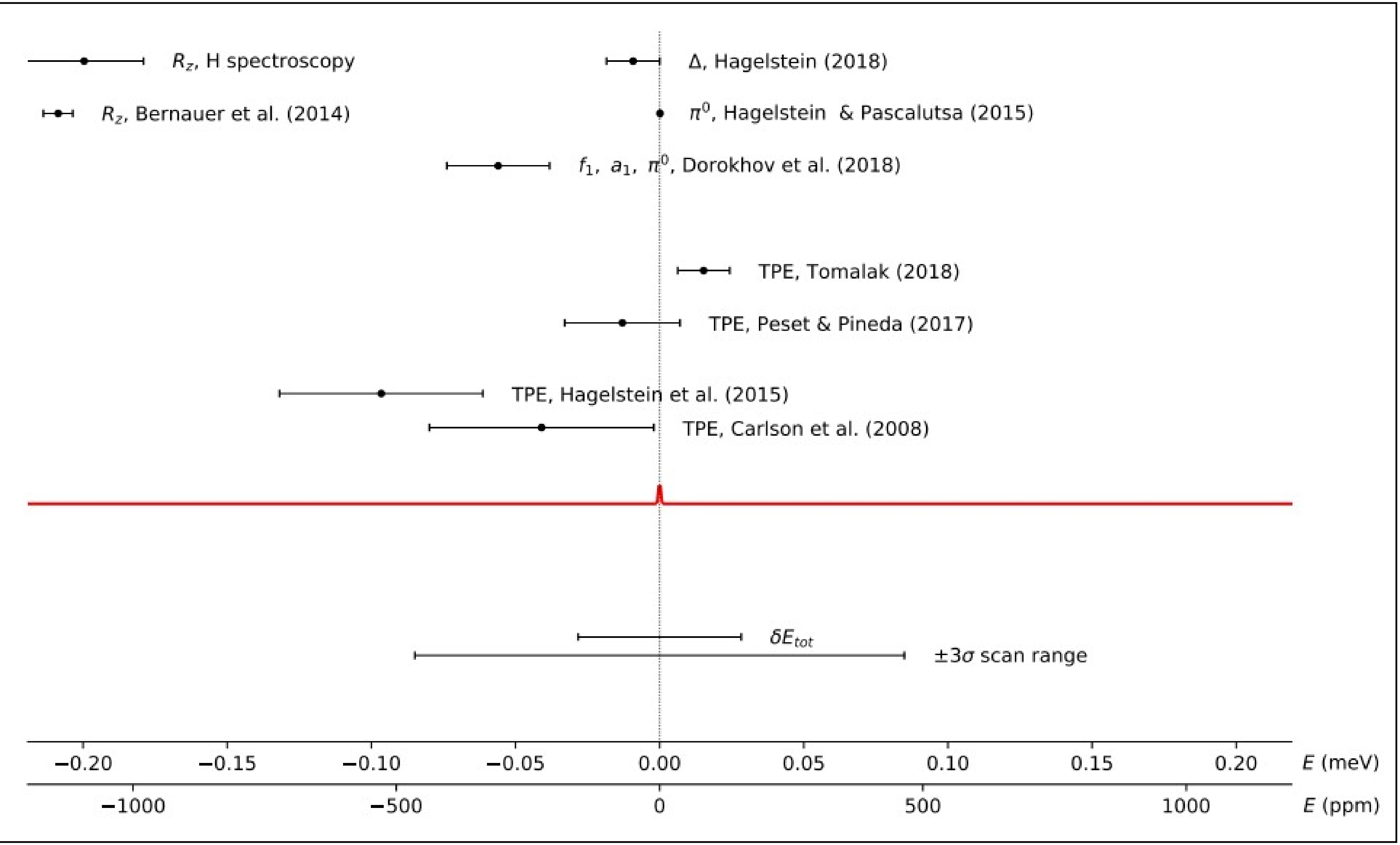
PSI Exp. R-16-02: Antognini, RP et al. (CREMA-3 / HyperMu)

see e.g. Schmidt, RP et al., J. Phys. Conf. Ser 1138, 012010 (2018); arXiv 1808.07240

Predicting the resonance position



The resonance position

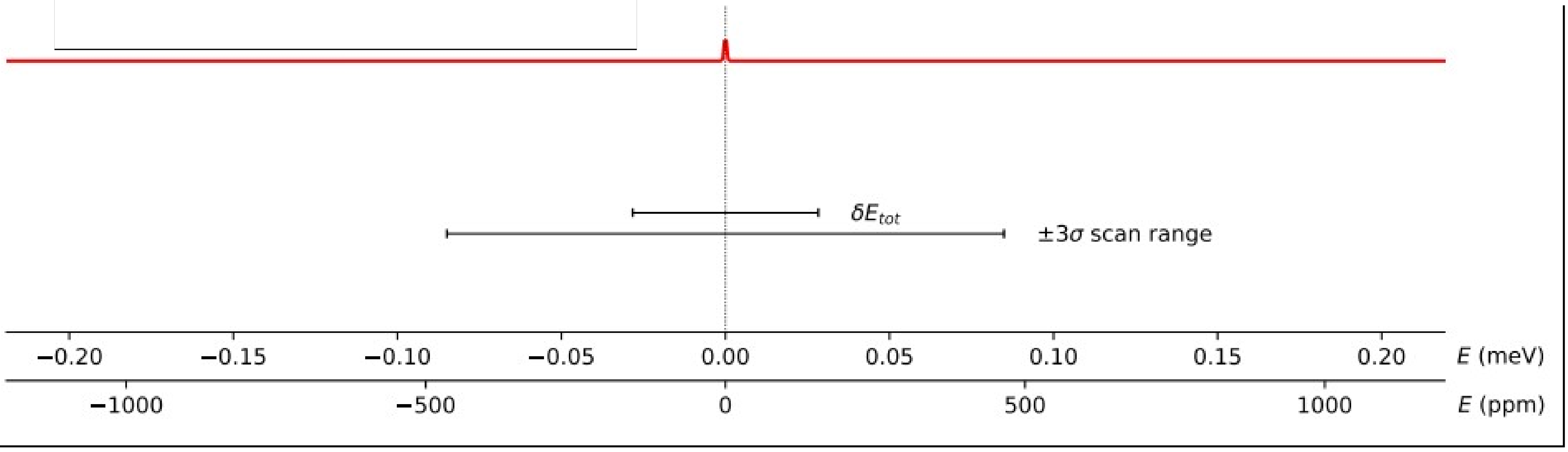


Searching the resonance

Need to search the line with steps of 0.1 GHz
(2 ppm of HFS)

BUT ∓3σ range = 0.17 meV
= 930 ppm
= 42 GHz

⇨ 450 points



Searching the resonance

Need to search the line with steps of 0.1 GHz (2 ppm of HFS)

BUT ∓3σ range = 0.17 meV
= 930 ppm
= 42 GHz

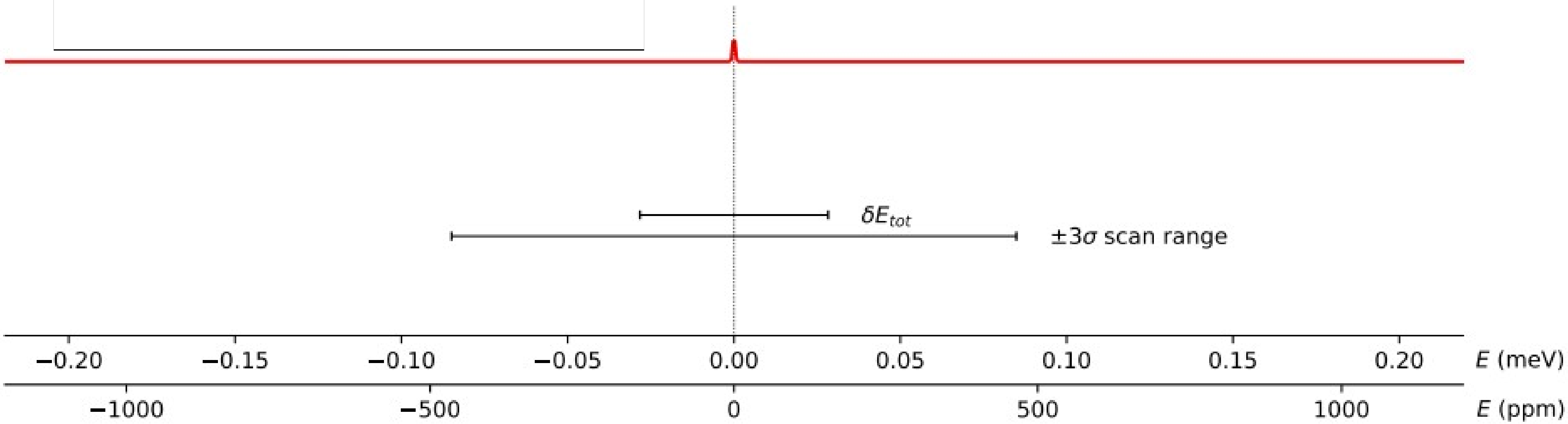
⇨ 450 points

Plans:

2019: muon beam tests done
target and detectors finished
cavity (already purchased)

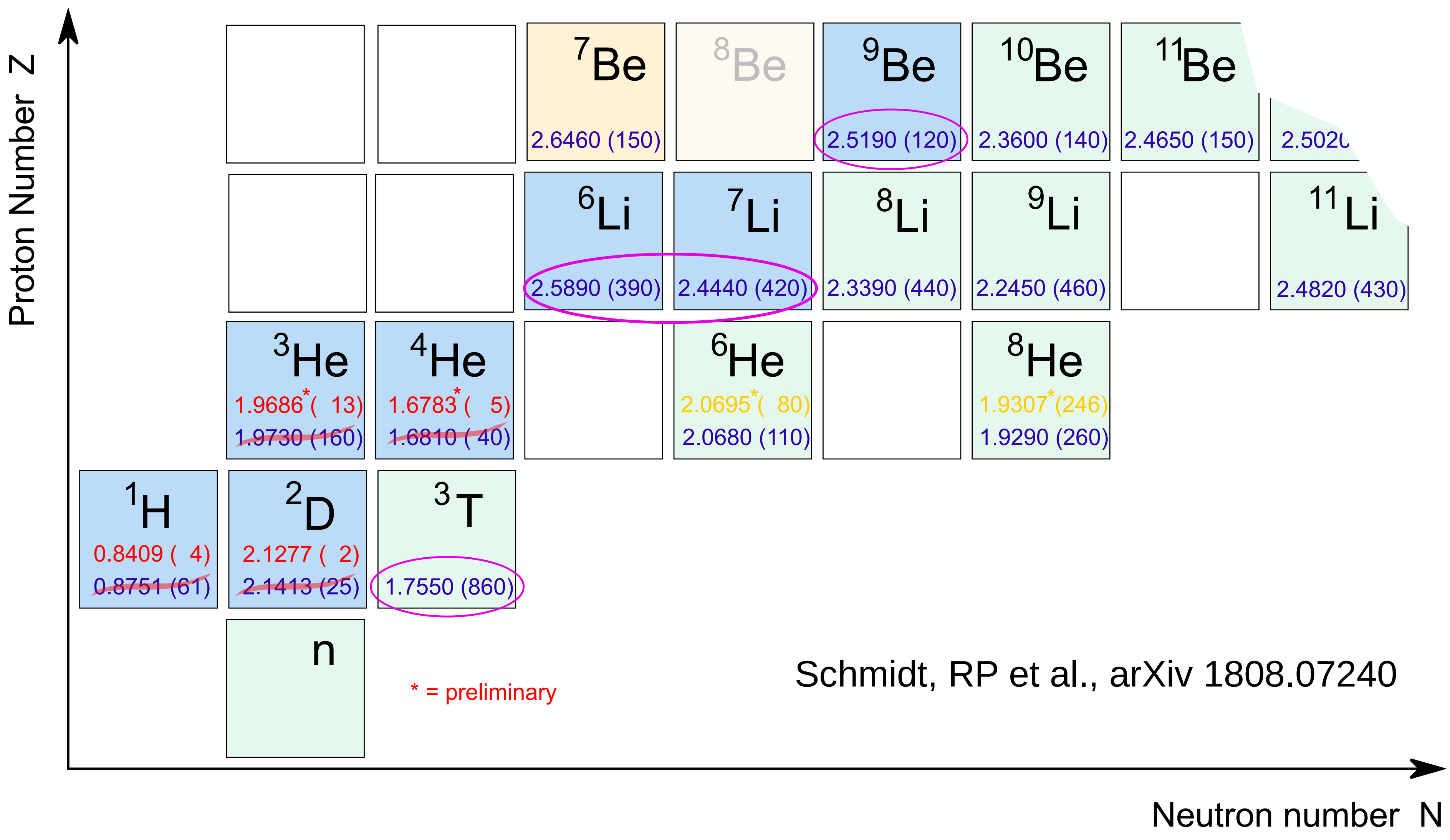
2020/21: find resonance and measure HFS

afterwards: μ^3He^+



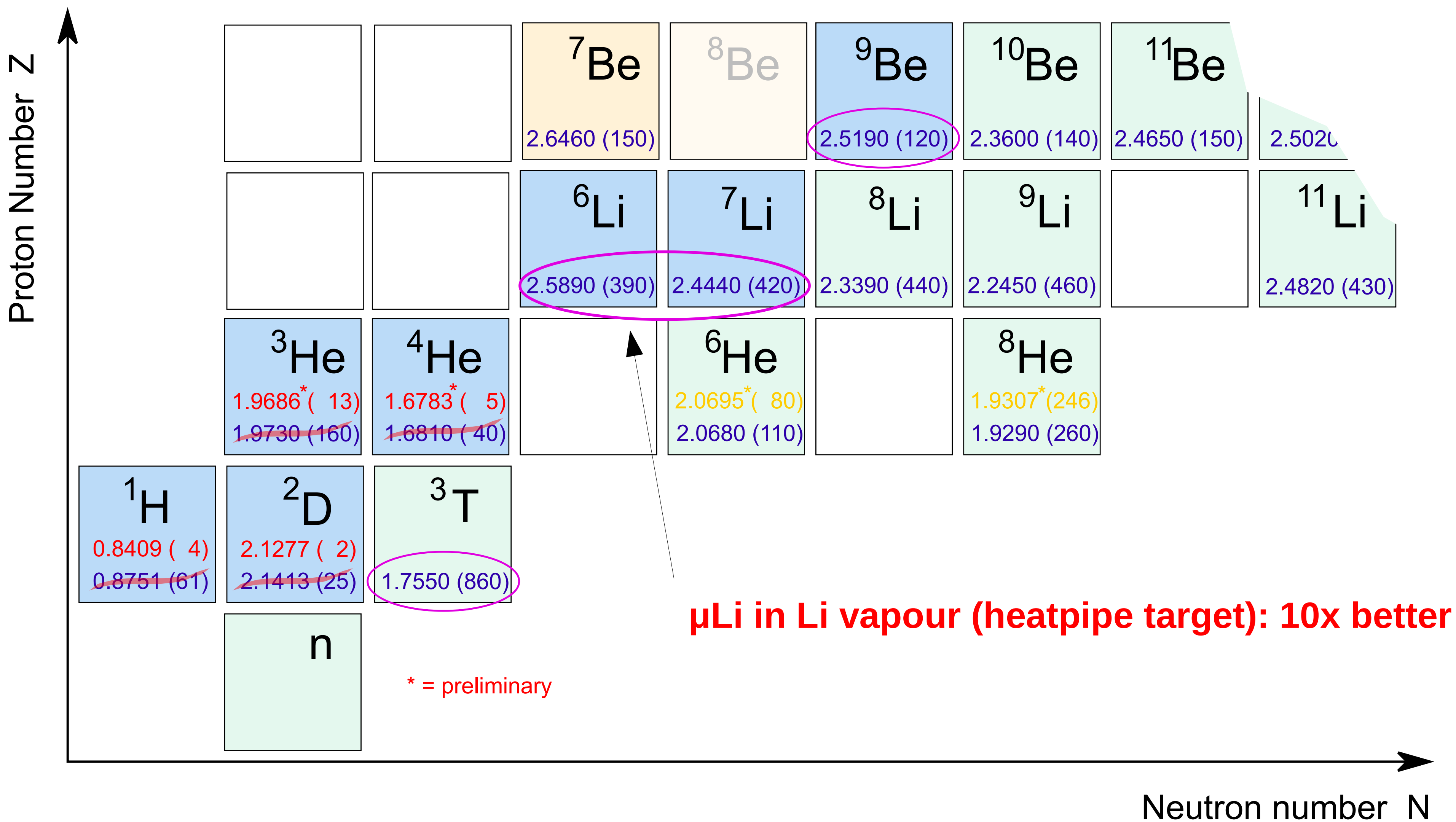
The Future

Charge radii: The future

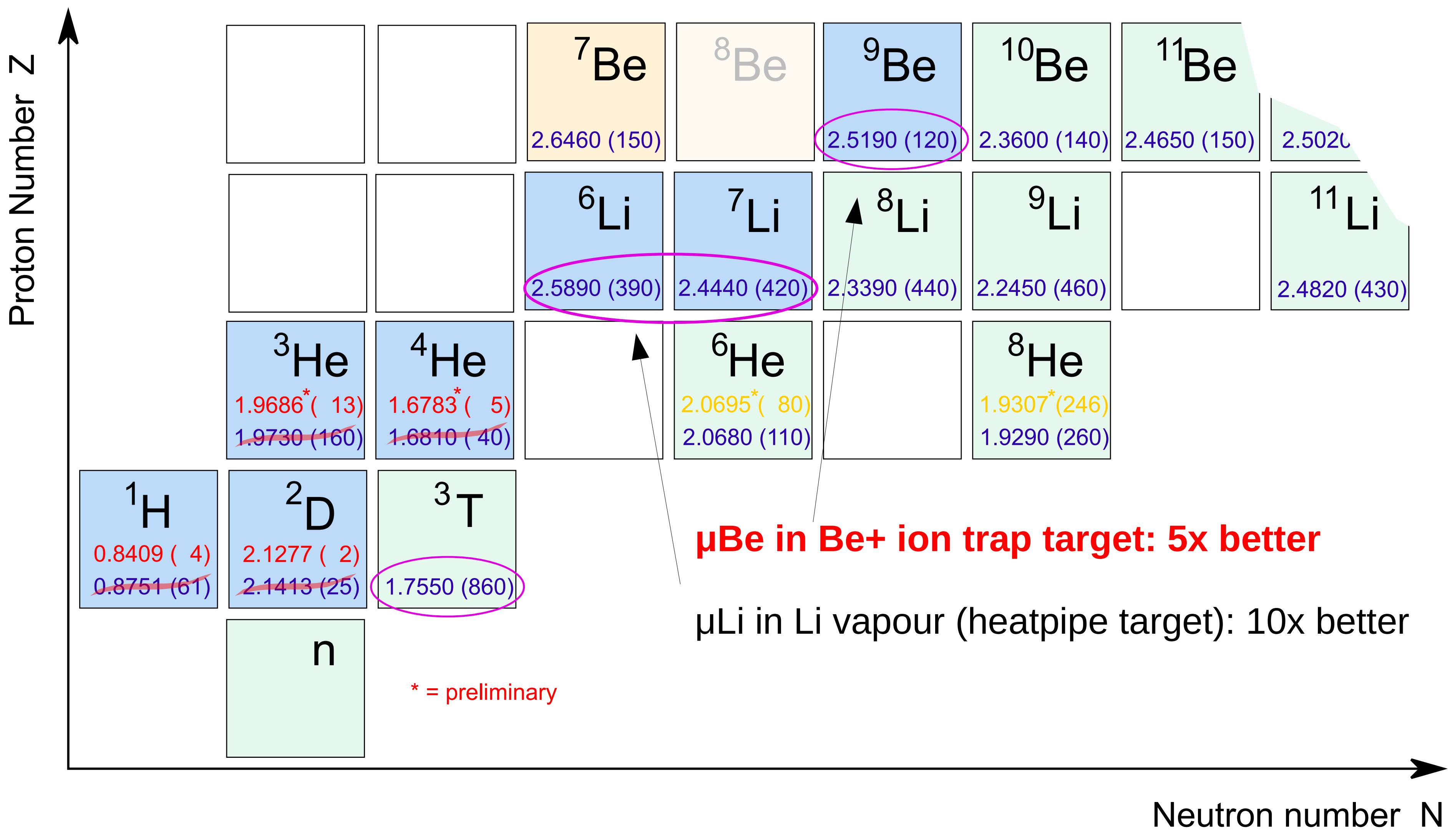


Schmidt, RP et al., arXiv 1808.07240

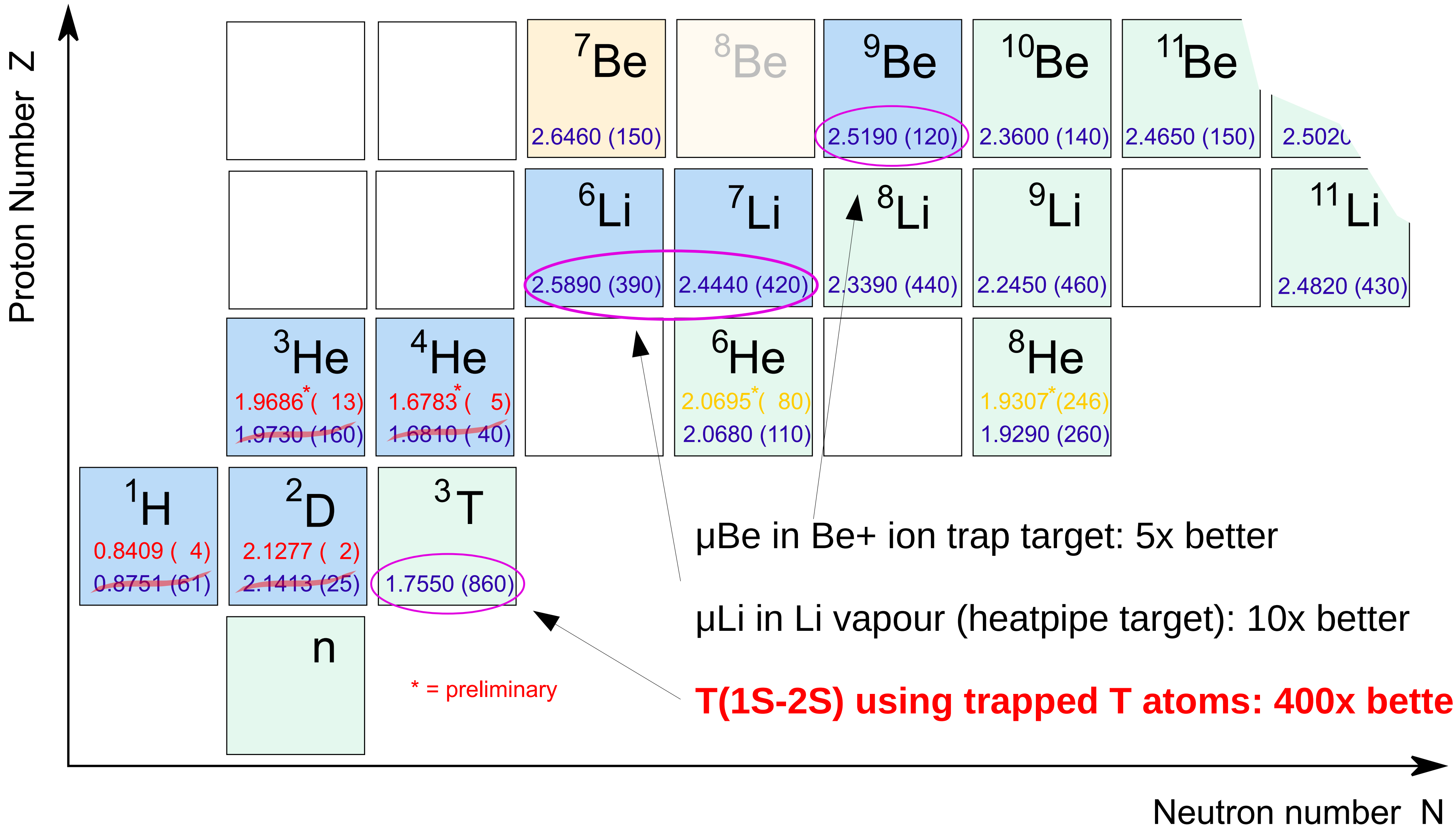
Charge radii: The future



Charge radii: The future



Charge radii: The future

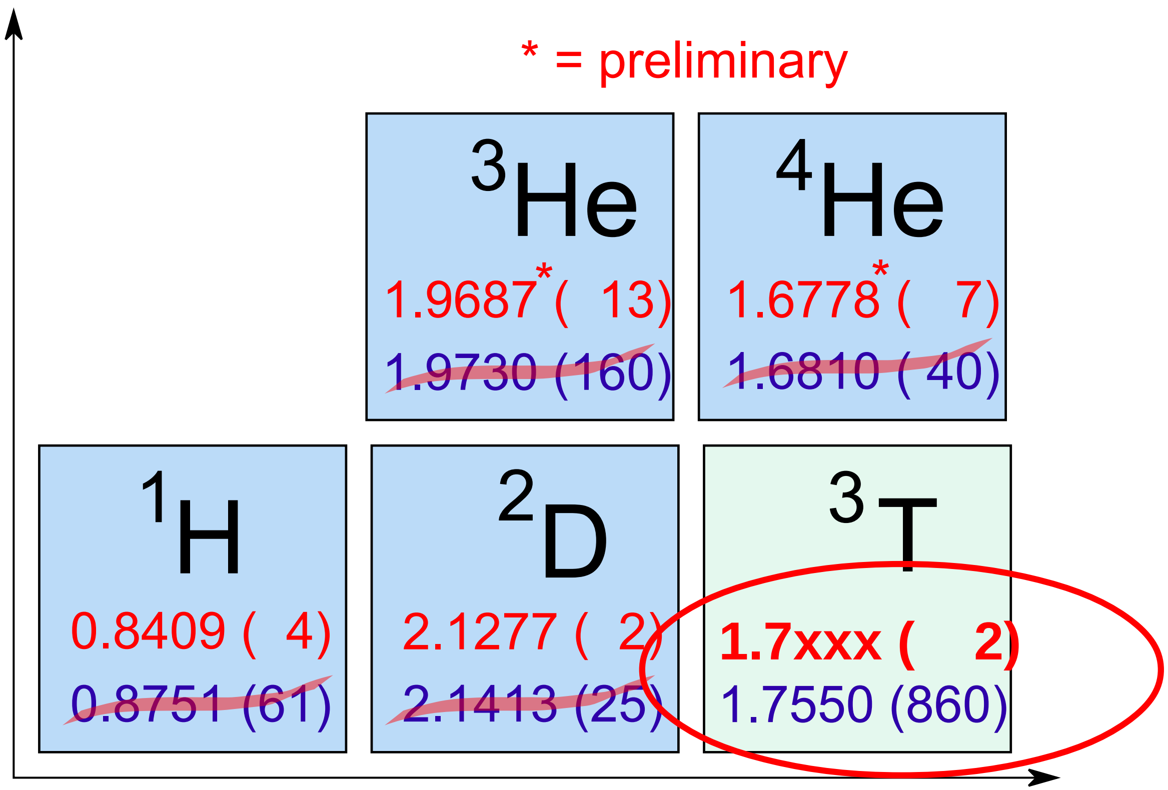


μBe in Be+ ion trap target: 5x better

μLi in Li vapour (heatpipe target): 10x better

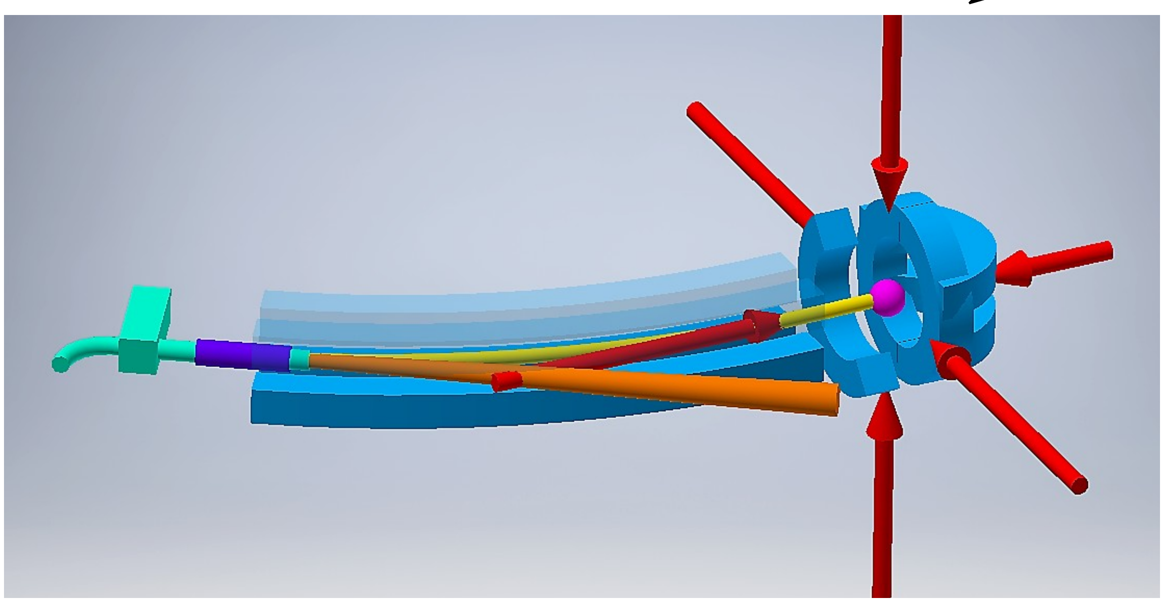
T(1S-2S) using trapped T atoms: 400x better

Tritium 1S-2S in a trap



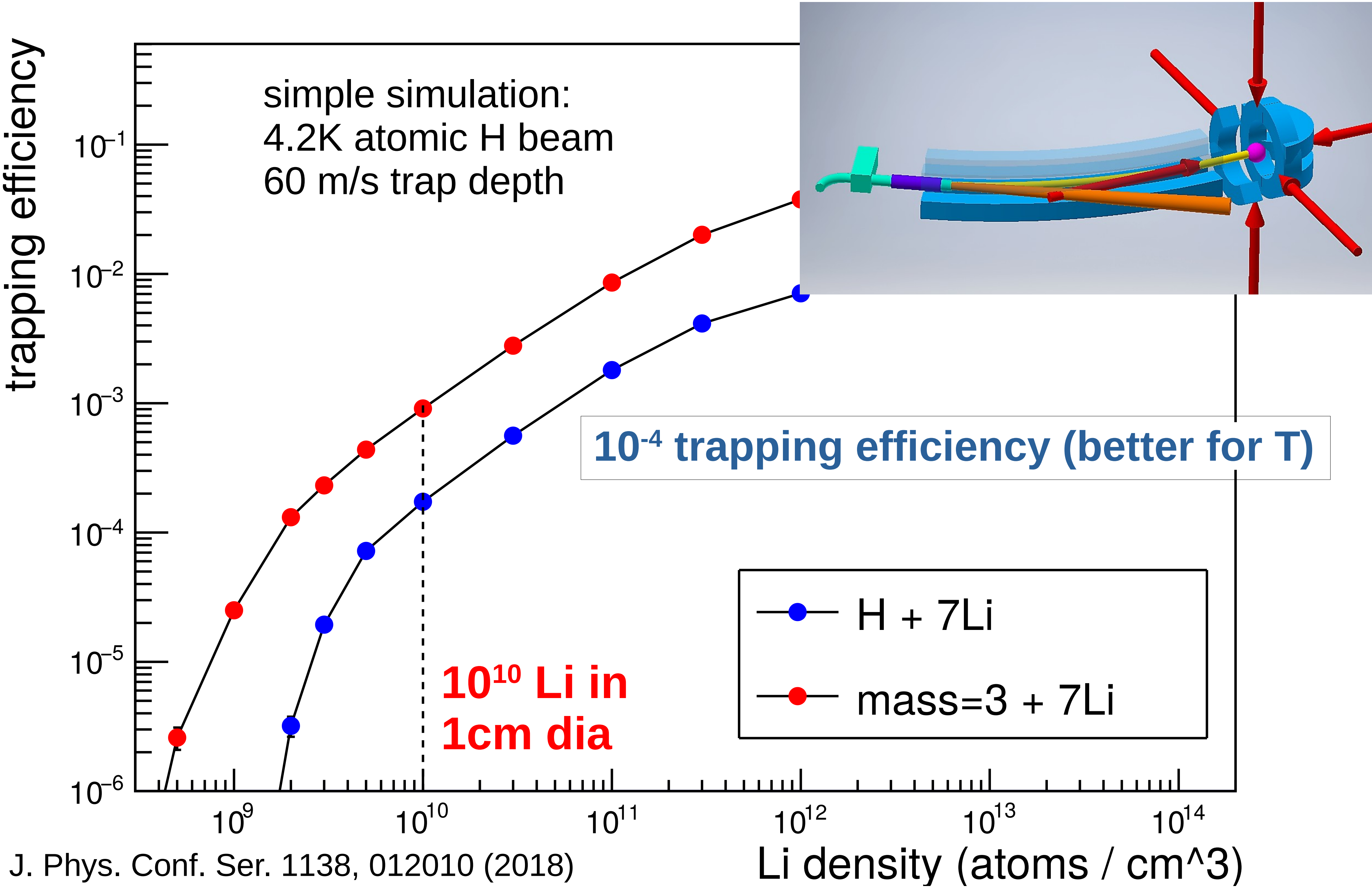
Triton-Radius EXperiment
Mainz

400x better radius
with 1 kHz measurement
(vs. 0.01 kHz for H, D)



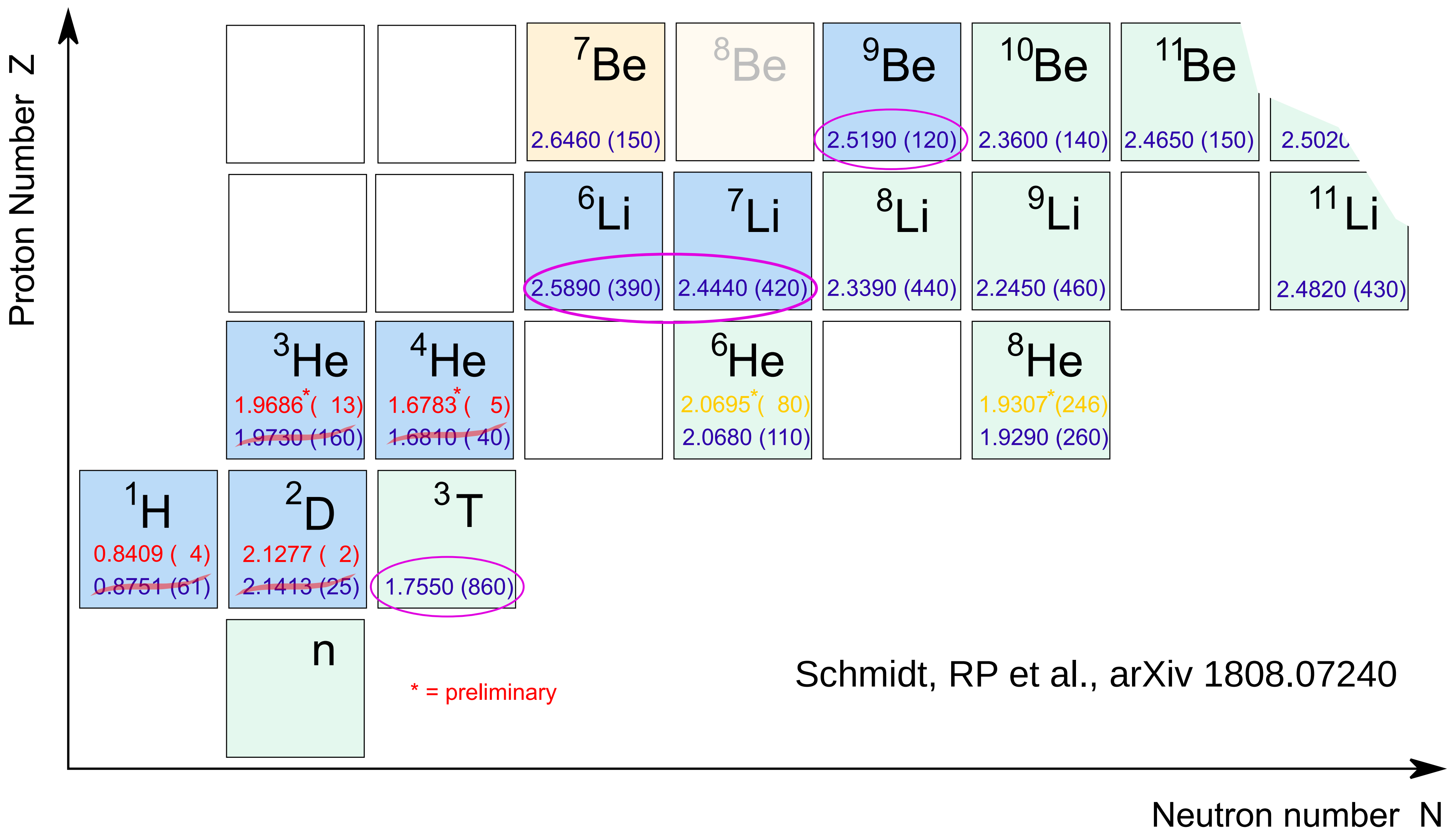
- cryogenic H nozzle (4.2K)
- magnetic quadrupole guide
- Li MOT -> cold buffer gas
- magnetic trapping of H/D/T

Simulated trapping efficiency



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

Charge radii: The future



Schmidt, RP et al., arXiv 1808.07240

Thanks a lot for your attention

My new Mainz group:

Reinhard Alexander, Adrian Dick, Lukas Görner, Jan Haack, Merten Heppener, Rishi Horn, Ahmed Ouf, Gregor Schwendler, Lukas Schumacher, Benedikt Tscharn, Julia Winter, Katharina Wolk, Marcel Willig

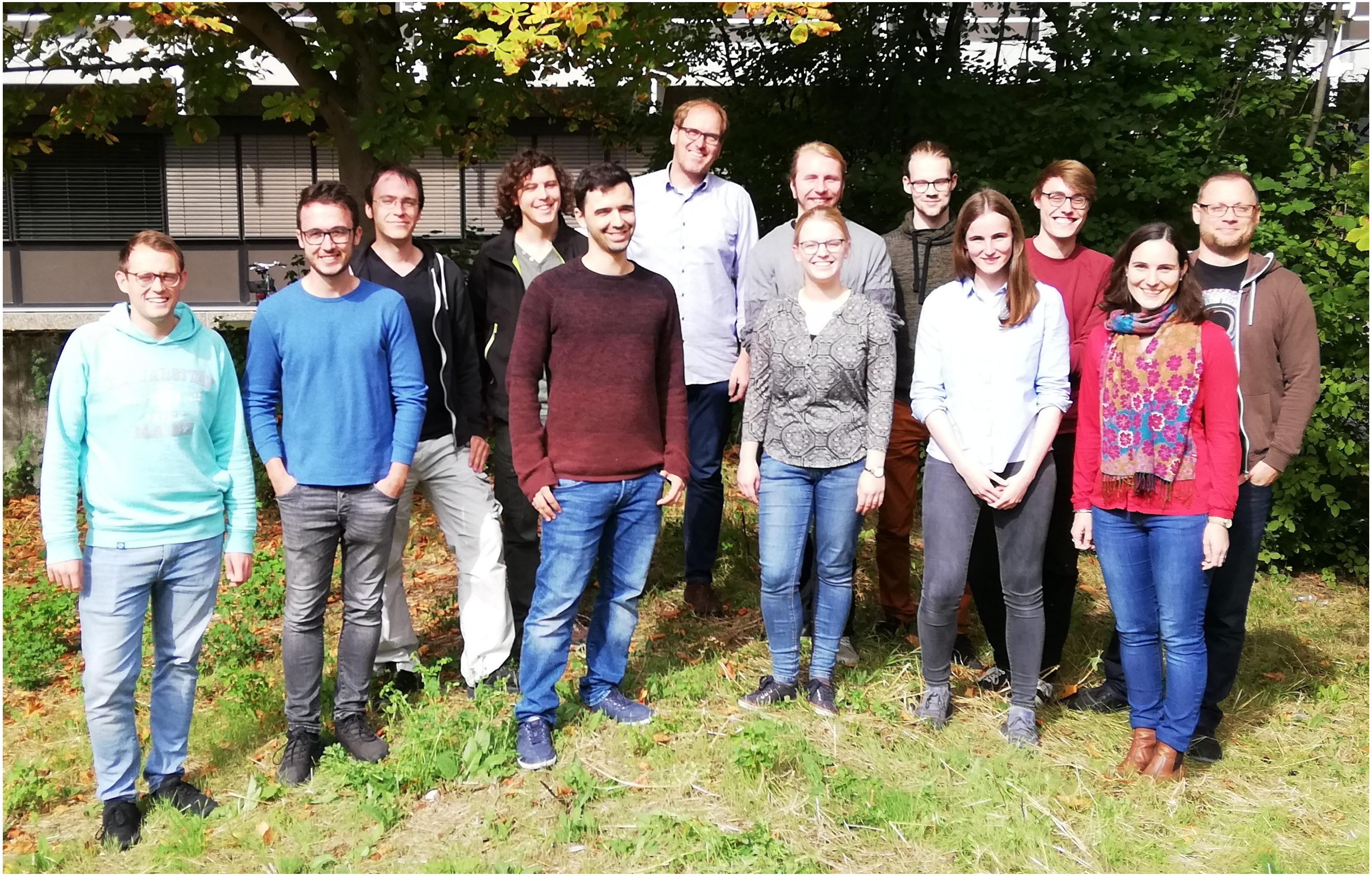
The Garching Hydrogen Team:

Axel Beyer, Lothar Maisenbacher, Arthur Matveev, RP, Ksenia Khabarova, Alexey Grinin, Tobias Lamour, Dylan C. Yost, Theodor W. Hänsch, Nikolai Kolachevsky, Thomas Udem

The CREMA Collaboration:

Aldo Antognini, Fernando D. Amaro, François Biraben, João M. R. Cardoso, Daniel S. Covita, Andreas Dax, Satish Dhawan, Marc Diepold, Luis M. P. Fernandes, Adolf Giesen, Andrea L. Gouvea, Thomas Graf, Theodor W. Hänsch, Paul Indelicato, Lucile Julien, Paul Knowles,Franz Kottmann, Juilian J. Krauth, Eric-Olivier Le Bigot, Yi-Wei Liu, José A. M. Lopes, Livia Ludhova, Cristina M. B. Monteiro, Françoise Mulhauser, Tobias Nebel, François Nez, Paul Rabinowitz, Joaquim M. F. dos Santos, Lukas A. Schaller, Karsten Schuhmann, Catherine Schwob, David Taqqu, João F. C. A. Veloso, RP

Group at JGU Mainz



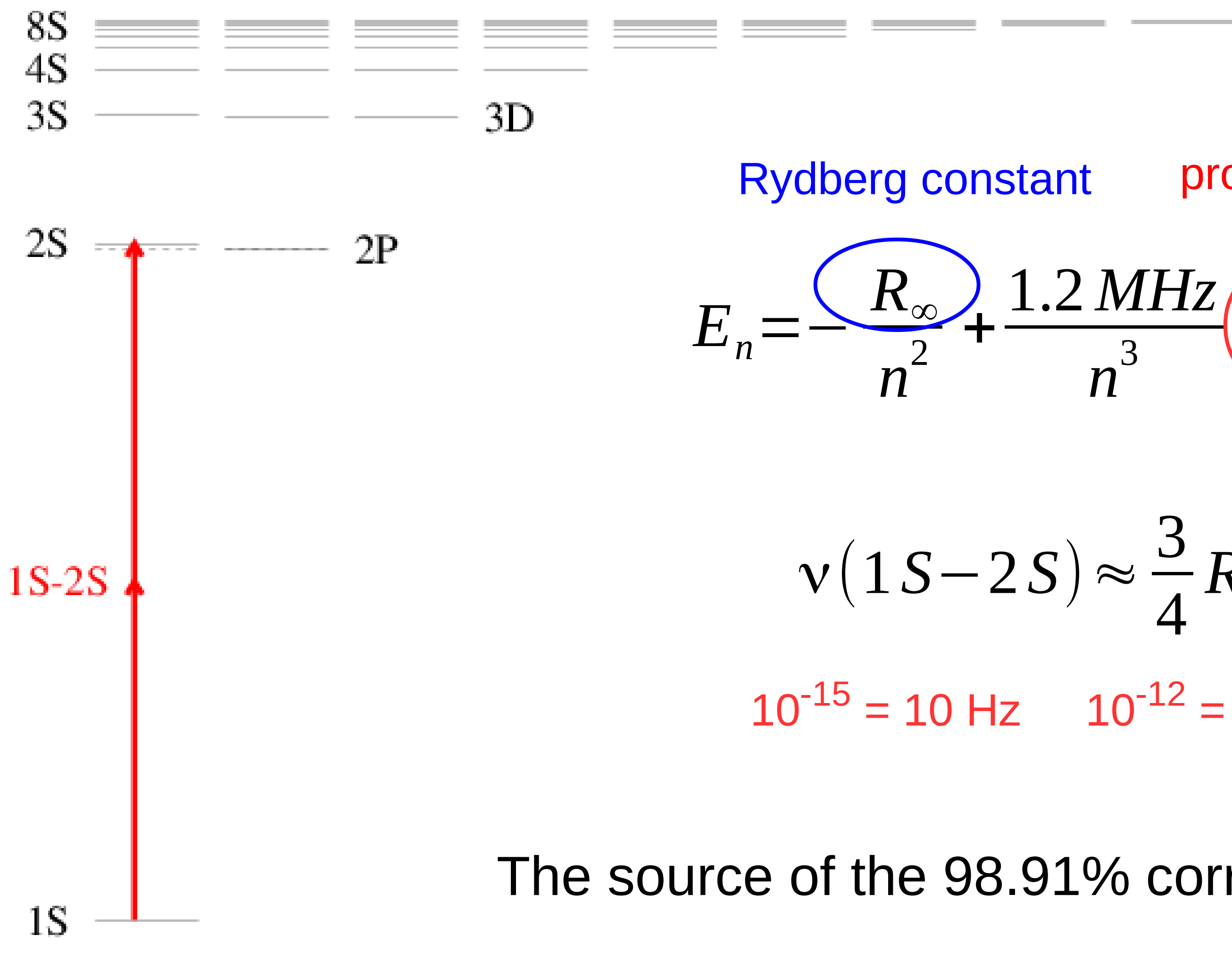
Group at JGU Mainz

Open Positions!

pohl @ uni-mainz.de

...

Correlation between R_∞ and R_p / R_d



Rydberg constant   proton radius

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

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

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

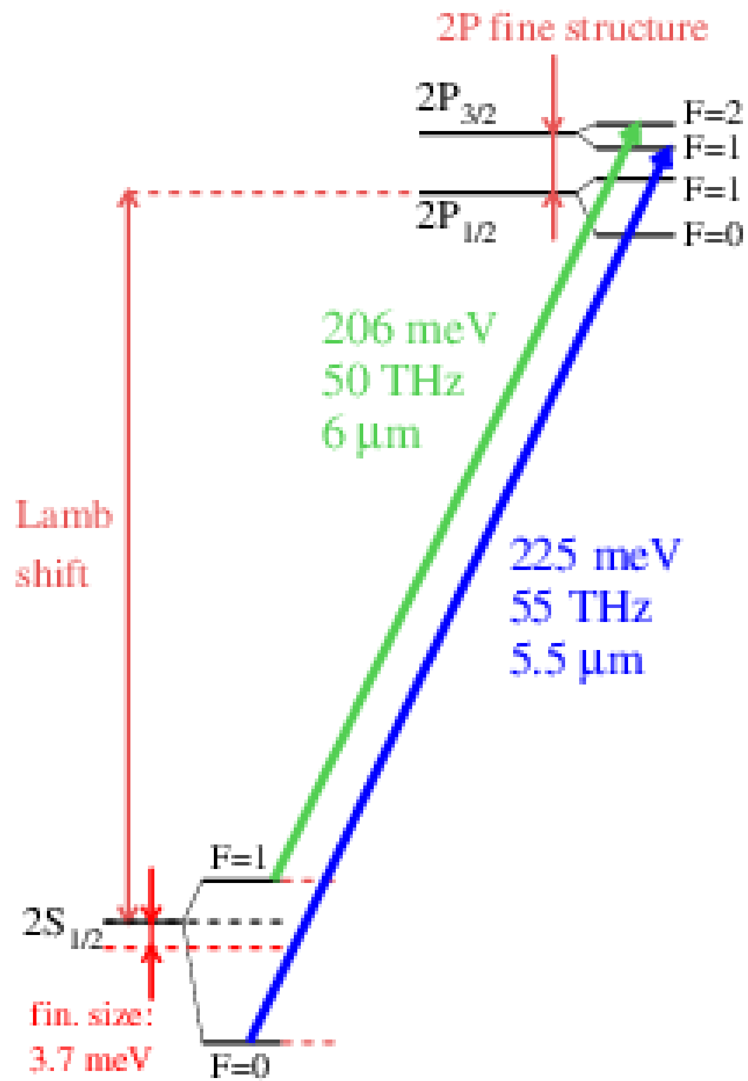
The source of the 98.91% correlation of R_∞ and R_p

1S-2S: Parthey, RP et al., PRL 107, 203001 (2011)

Theory in muonic H

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

Simple-looking formula
based on decades of work by
E. Borie, M.C. Birse, P. Blunden, C.E. Carlson,
M.I. Eides, R. Faustov, J.L. Friar, G. Paz,
A. Pineda, J. McGovern, K. Griffioen, H. Grotch,
F. Hagelstein, H.-W. Hammer, R.J Hill, P.Indelicato,
U.D. Jentschura, S.G. Karshenboim, E.Y. Korzinin,
V.G. Ivanov, I.T. Lorenz, A.P. Martynenko,
G.A. Miller, U.-G. Meissner, P.J. Mohr,
K. Pachucki, V. Pascalutsa, J. Rafelski,
V.A. Shelyuto, I. Sick, A.W. Thomas,
M. Vanderhaeghen, V. Yerokhin,
…..
(shout if I missed your name!)



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

Theory in muonic H

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

Annals of Physics 331 (2013) 127–145

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

CrossMark

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[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 I: “pure” QED

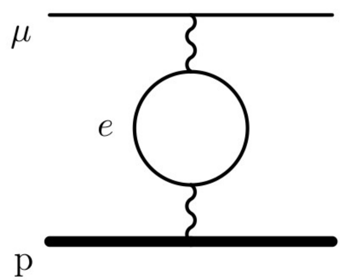
Table 1
All known radius-*independent* contributions to the Lamb shift in μp from different authors, and the one we selected. Values are in meV. The entry # in the first column refers to Table 1 in Ref. [13]. The “finite-size to relativistic recoil correction” (entry #18 in [13]), which depends on the 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.

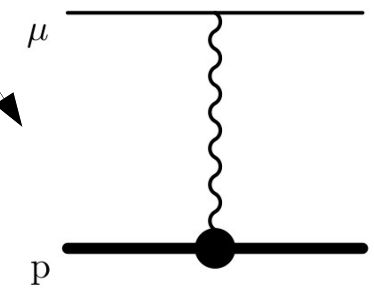
#	Contribution	Pachucki [10,11]	Nature [13]	Borie-v6 [79]	Indelicato [80]	Our choice	Ref.
1	NR one-loop electron VP (eVP)	205.0074					
2	Rel. corr. (Breit–Pauli)	0.0169[a]					
3	Rel. one-loop eVP		205.0282	205.0282	205.02821	205.02821	[80] Eq. (54)
19	Rel. RC to eVP, $\alpha(Z\alpha)^4$	(incl. in #2)[b]	−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)	

Theory in muonic H

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

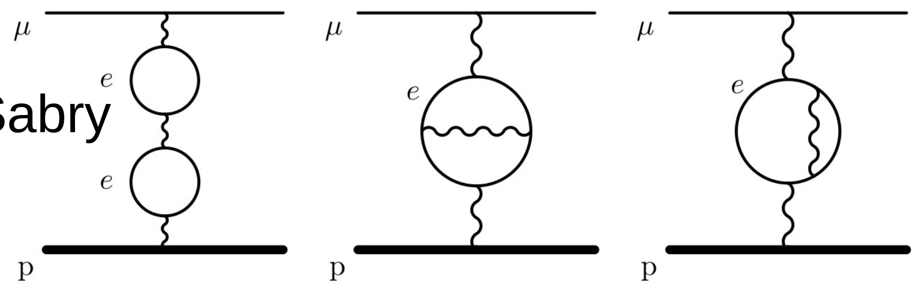
Uehling



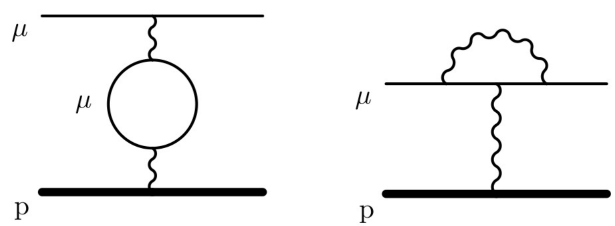


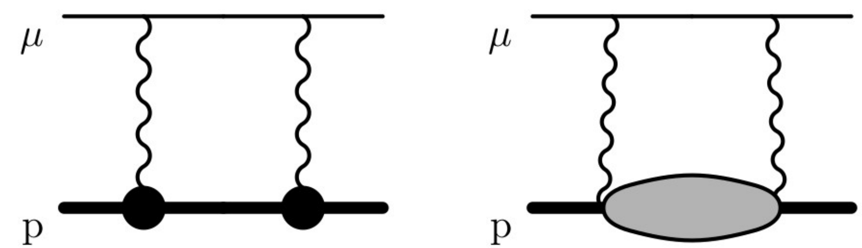
Proton form factor

Källen-Sabry



Muon SE+VP





and 20+ more….

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

Theory in muonic D

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

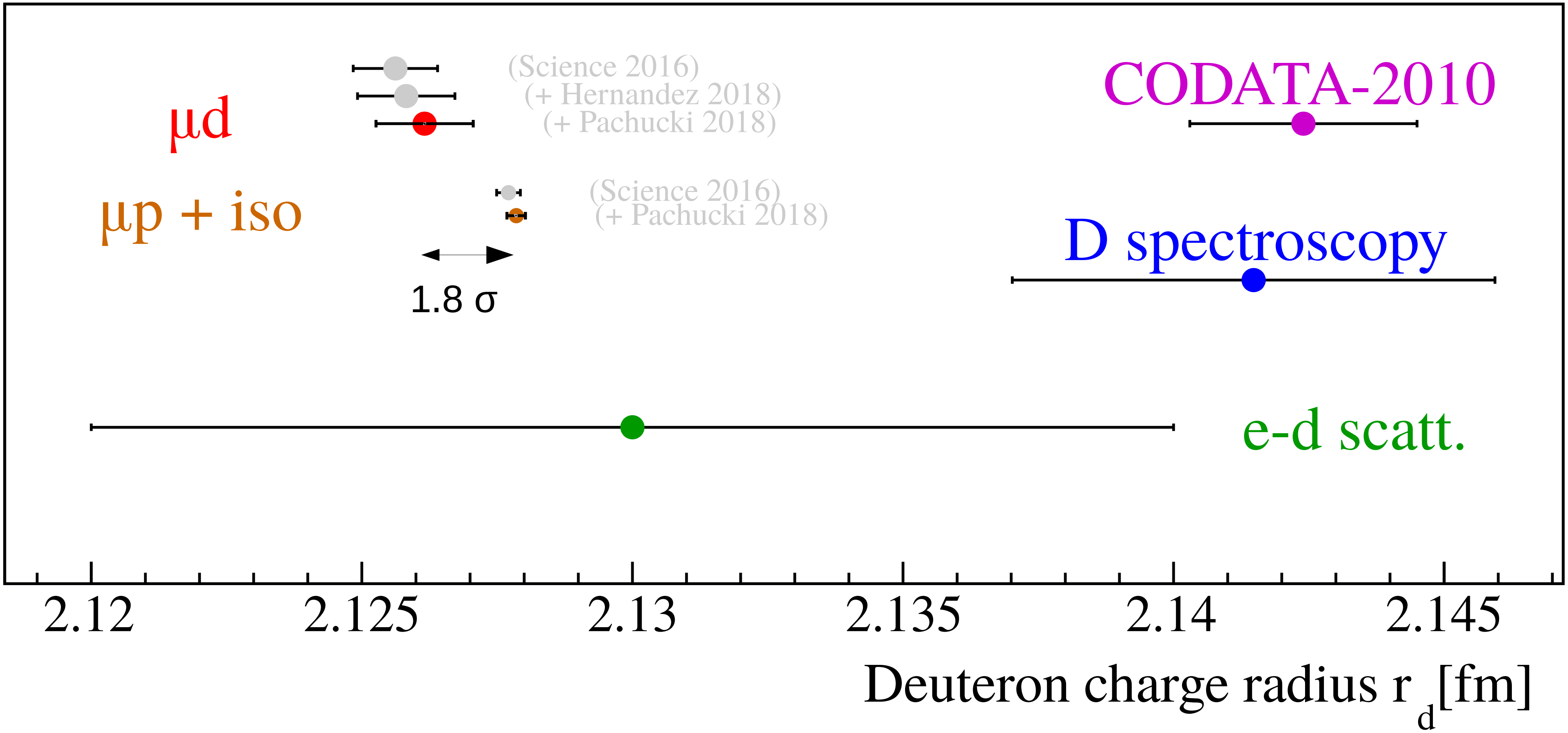
Nuclear structure contributions to the Lamb shift in muonic deuterium.

Item	Contribution	Pachucki [55]		Friar [60]		Hernandez *et al.* [58]			Pach.& Wienczek [65]		Carlson *et al.* [64]		Our choice		
		AV18		ZRA		AV18	N^3LO †		AV18		data		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 ◇ [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 ◇ [c]	0.021 ◇ [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)		$\delta^{N}_{\mathrm{pol}}$ [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)

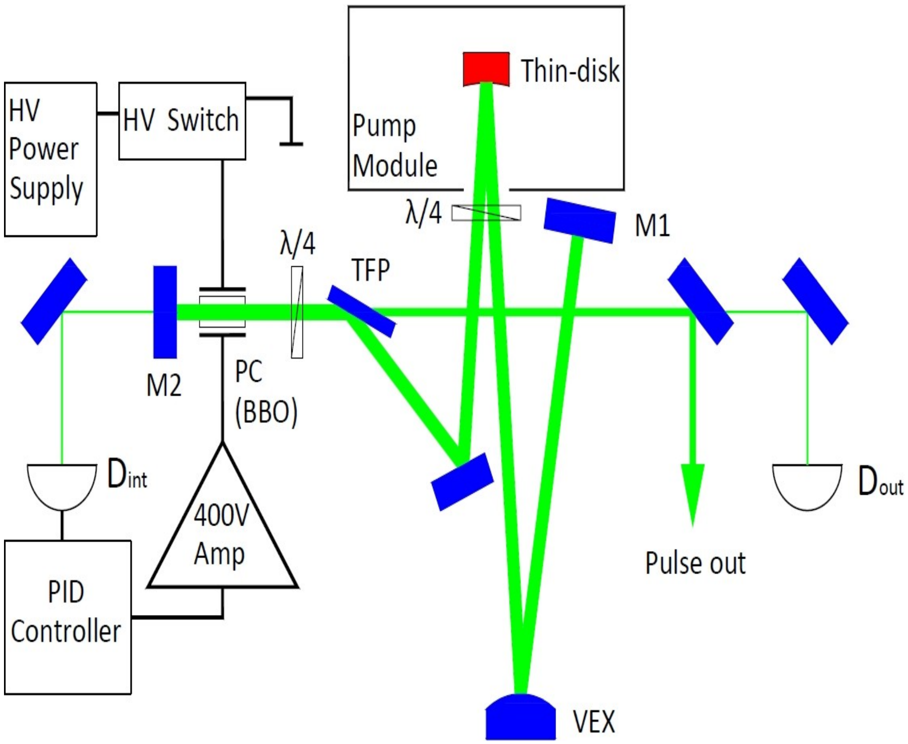
+ Pachucki et al., PRA 97, 062511 (2018)
+ Hernandez et al., PLB 778, 377 (2018)

Deuteron radius



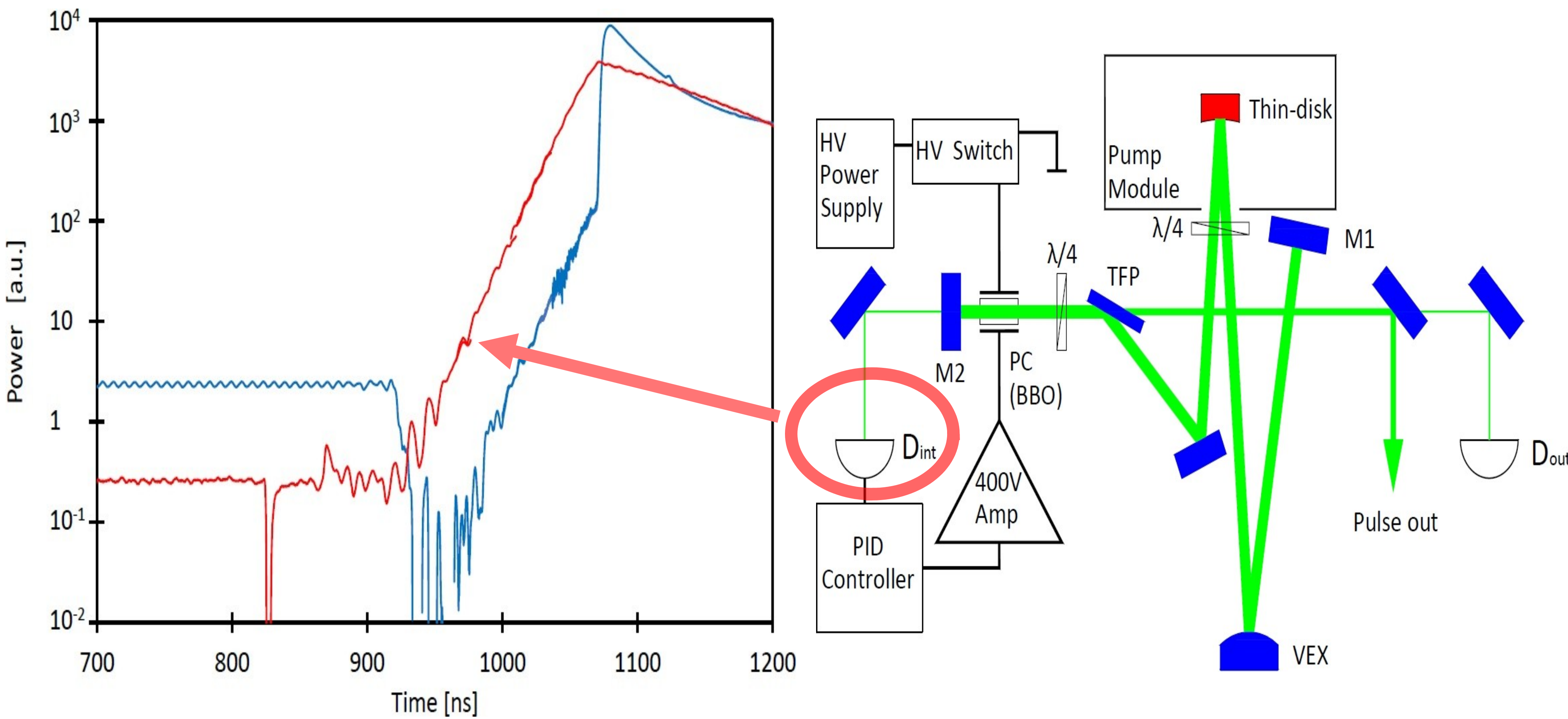
Hernandez et al, Phys. Lett. B 778, 377 (2018)
Pachucki et al., PRA 97, 062511 (2018)

Q-switched thin-disk laser oscillator

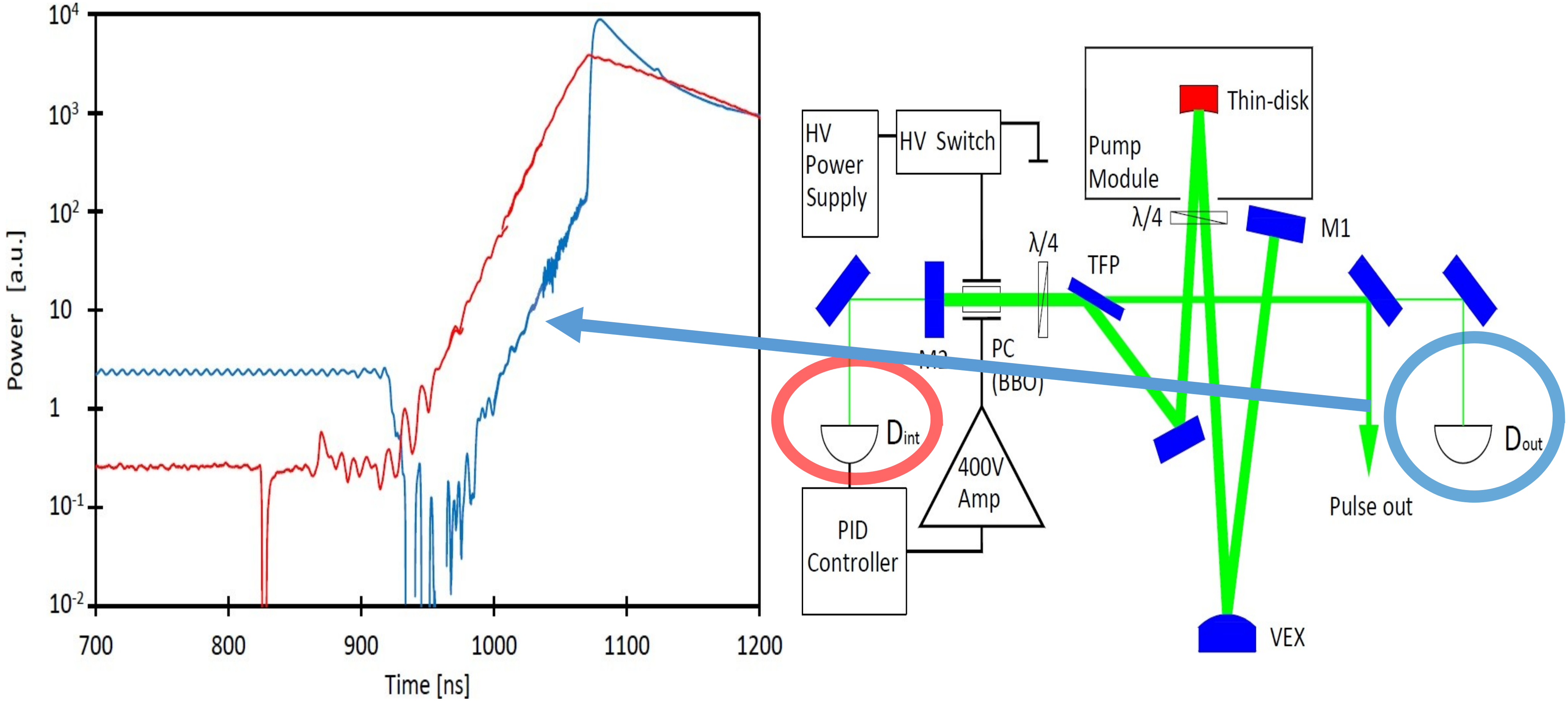


- Prelasing
- Close the laser cavity
- Exponential pulse build up
- Open the cavity
- Extraction of the laser pulse

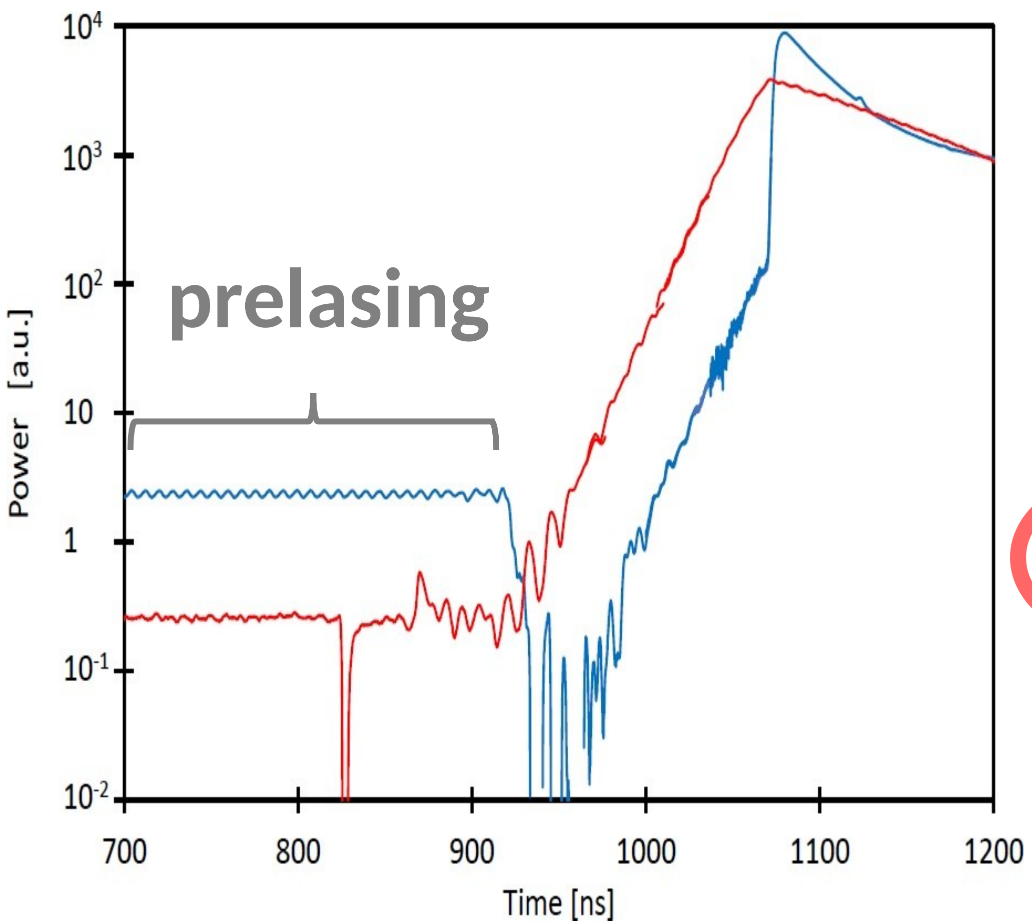
Thin disk laser with prelasing: Pulse build up

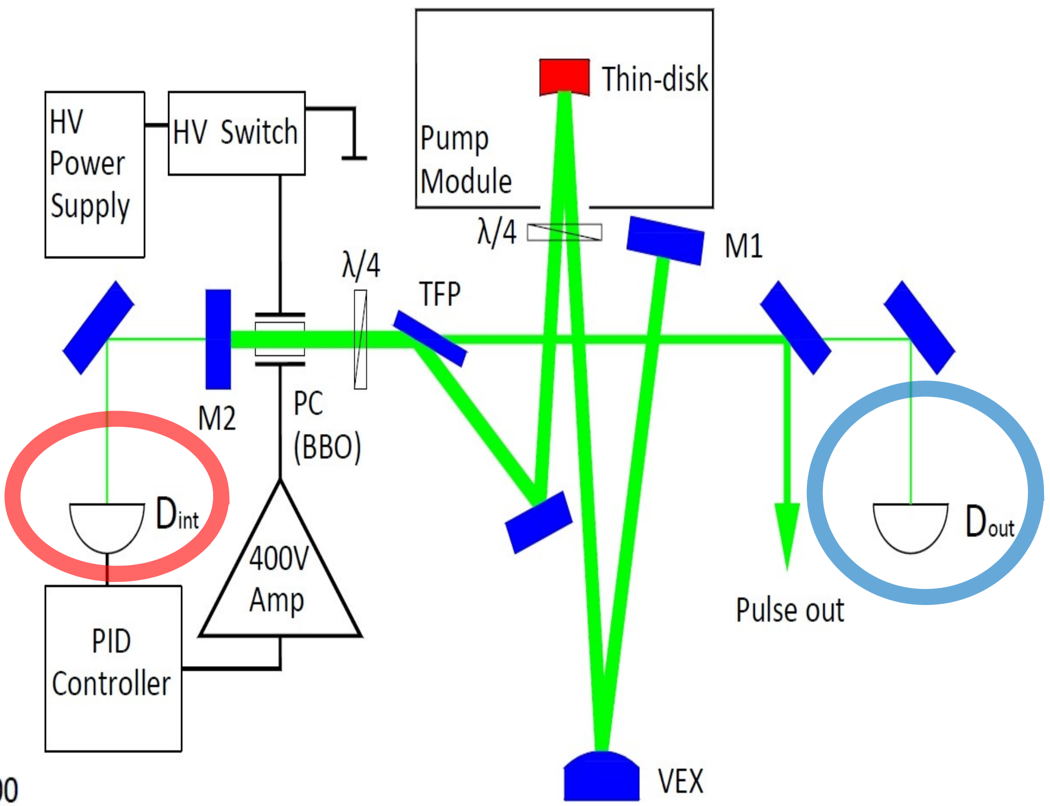


Thin disk laser with prelasing: Pulse build up

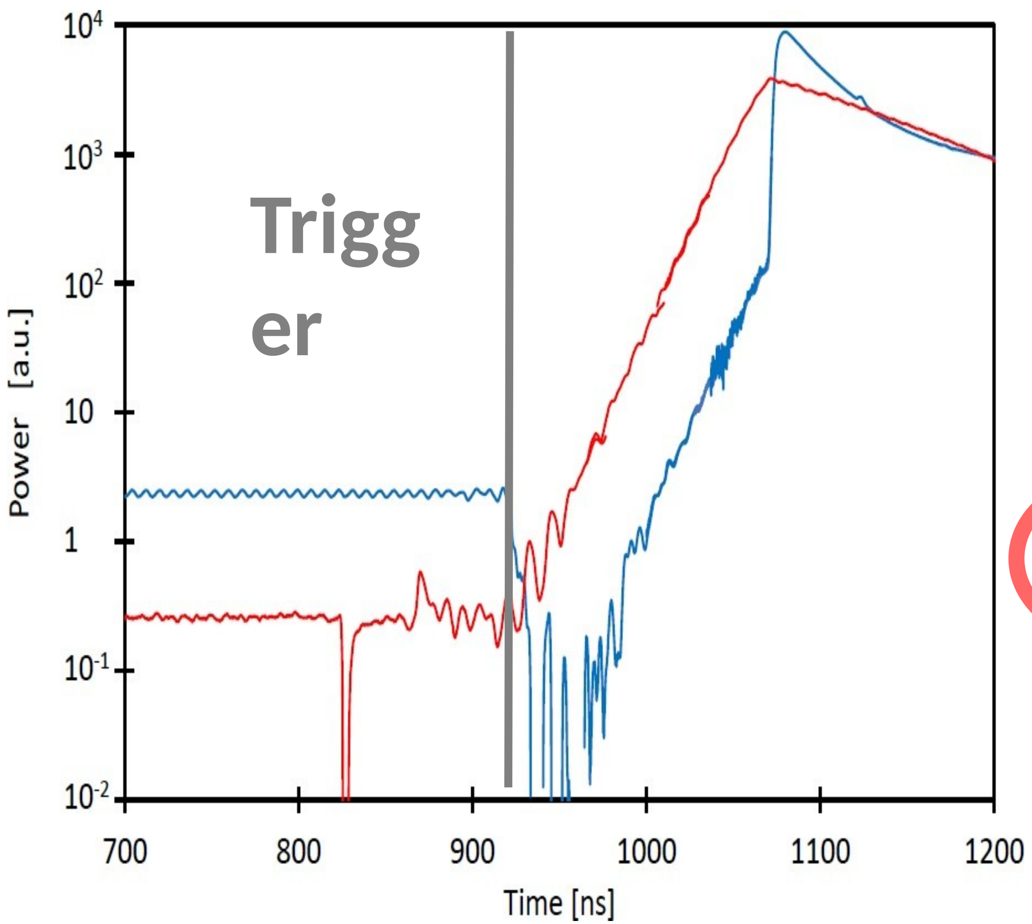


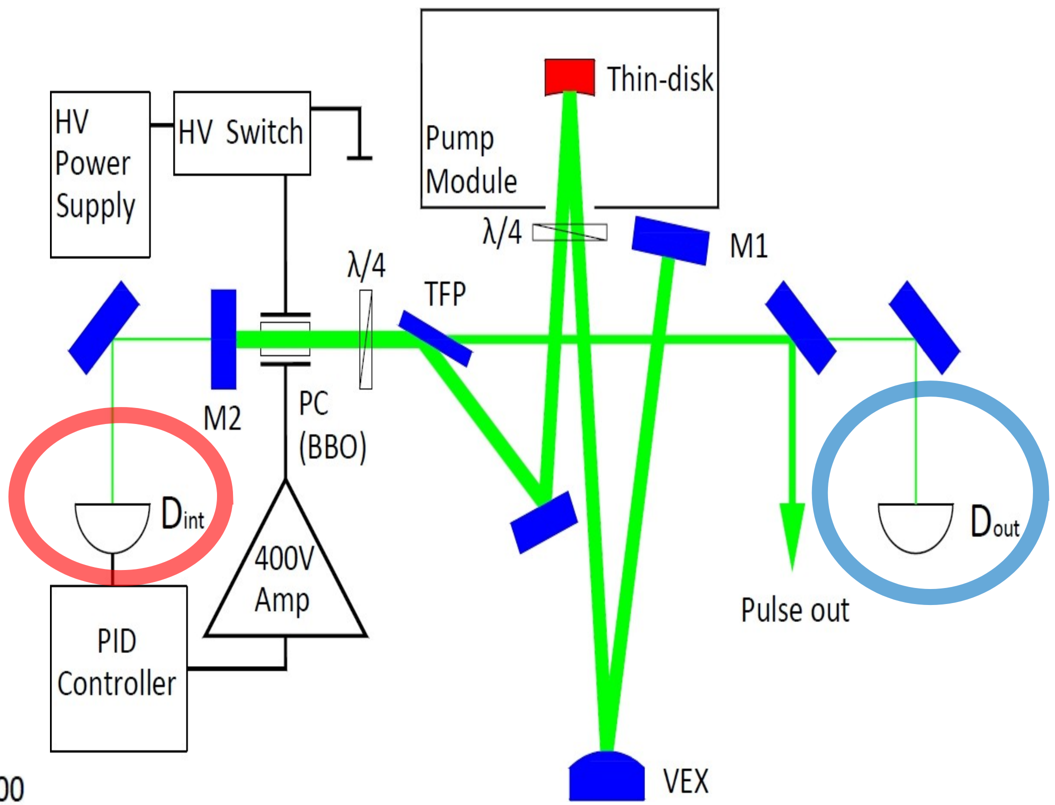
Thin disk laser with prelasing: Pulse build up



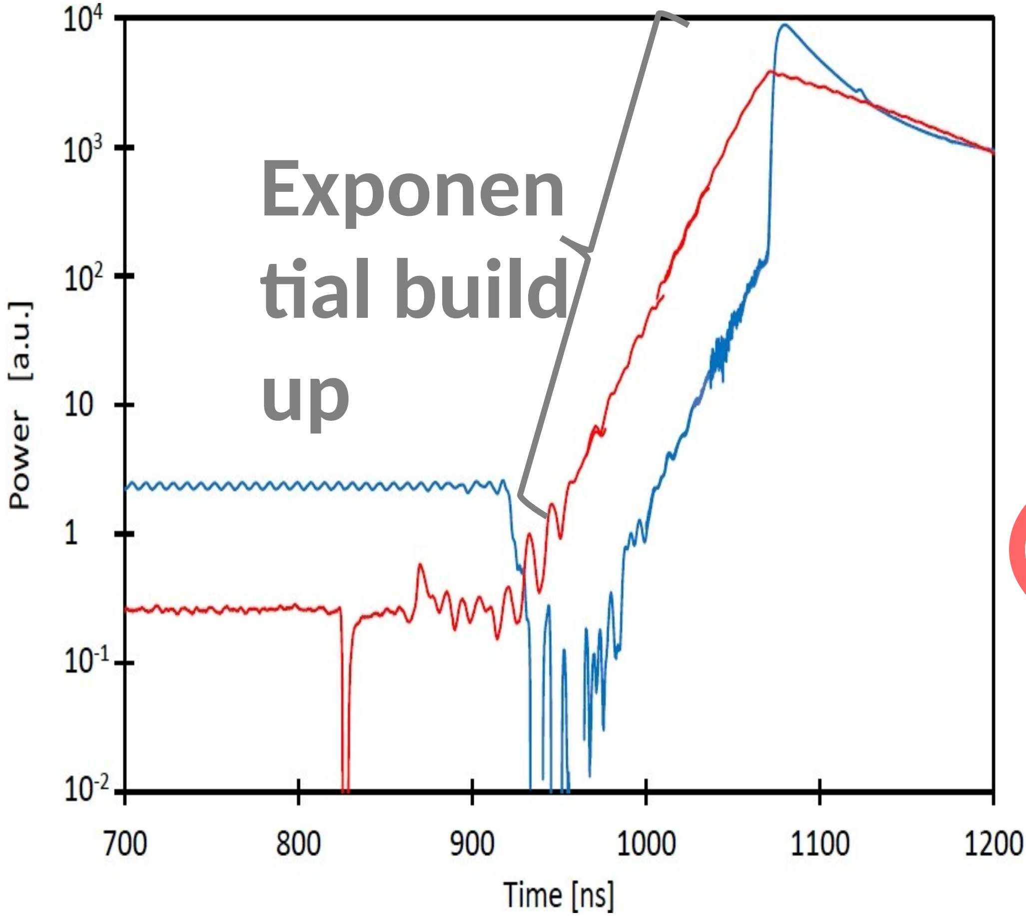


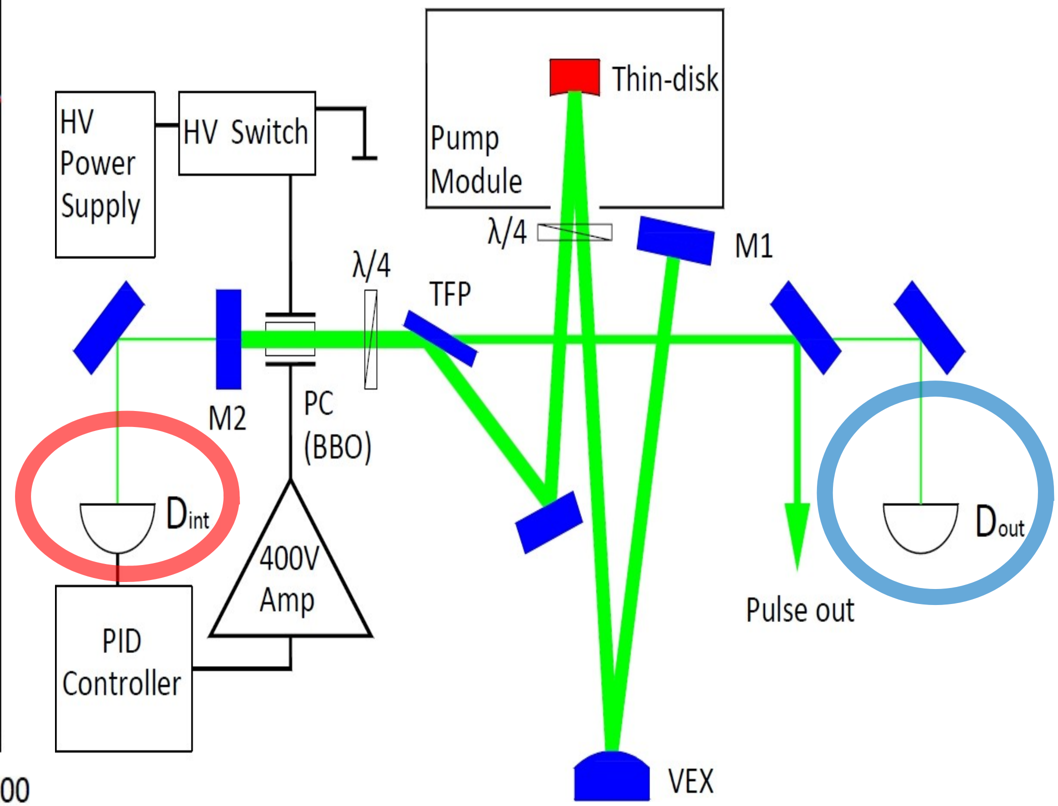
Thin disk laser with prelasing: Pulse build up



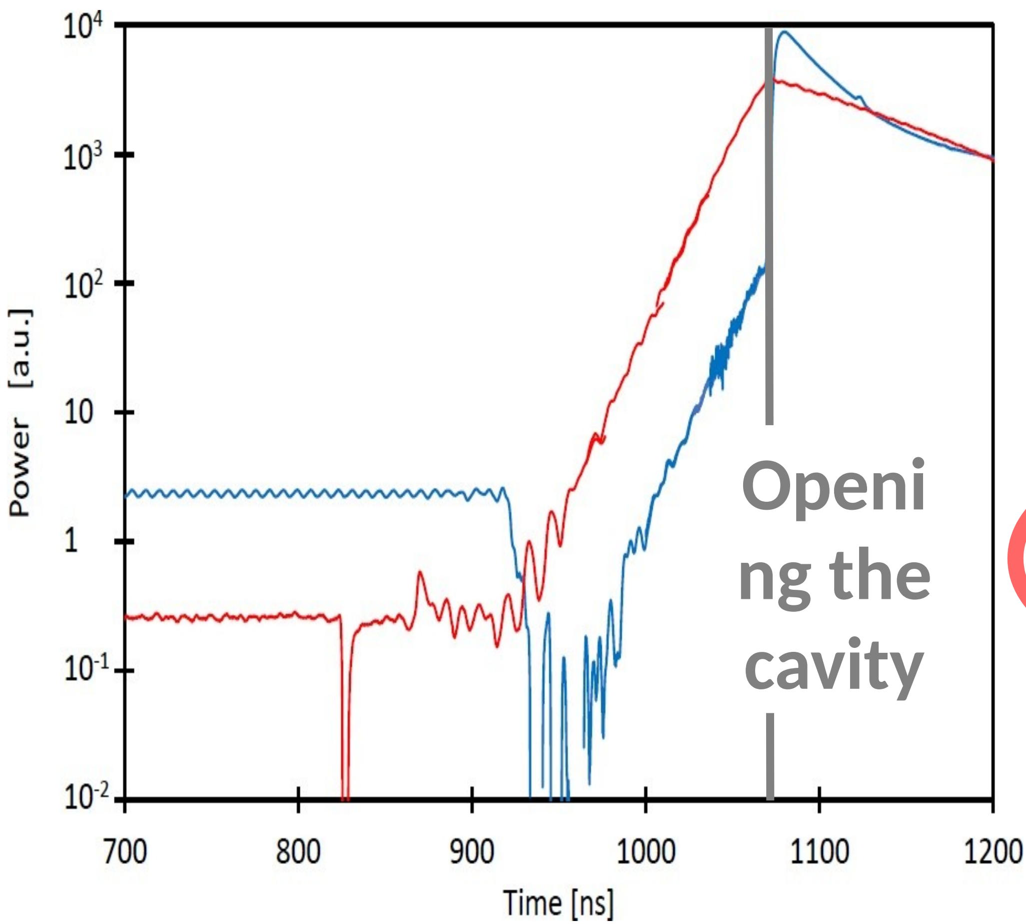


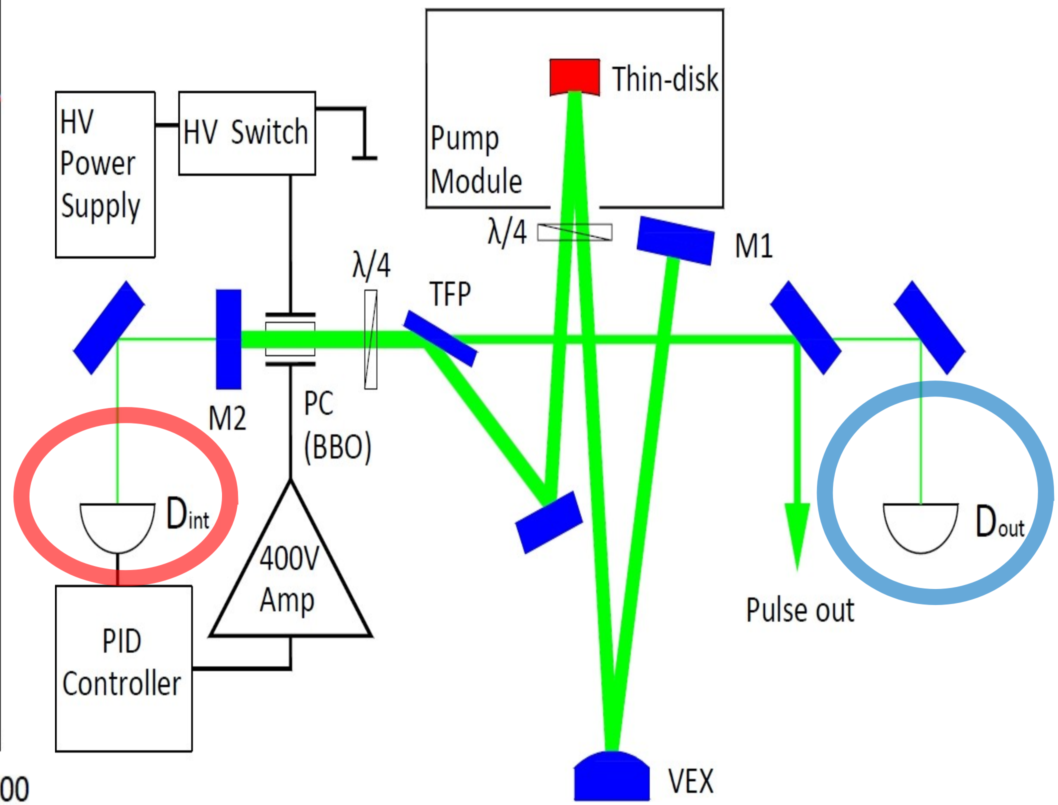
Thin disk laser with prelasing: Pulse build up



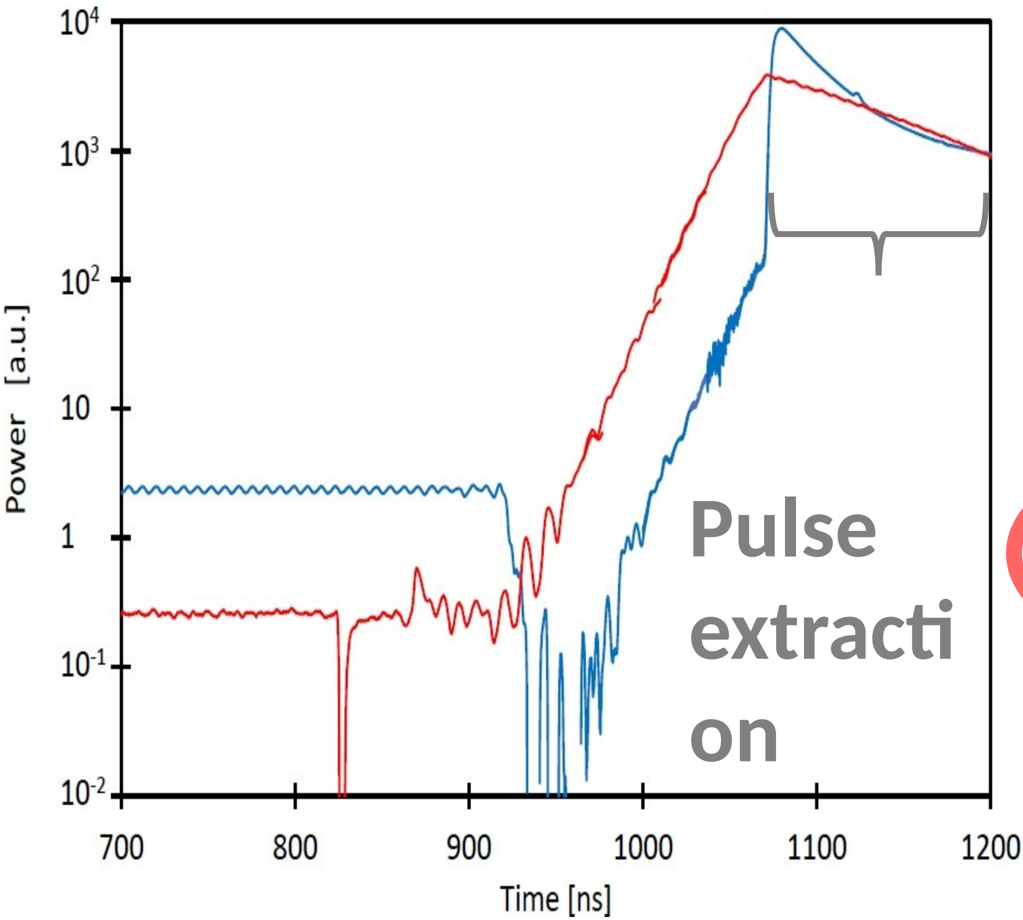


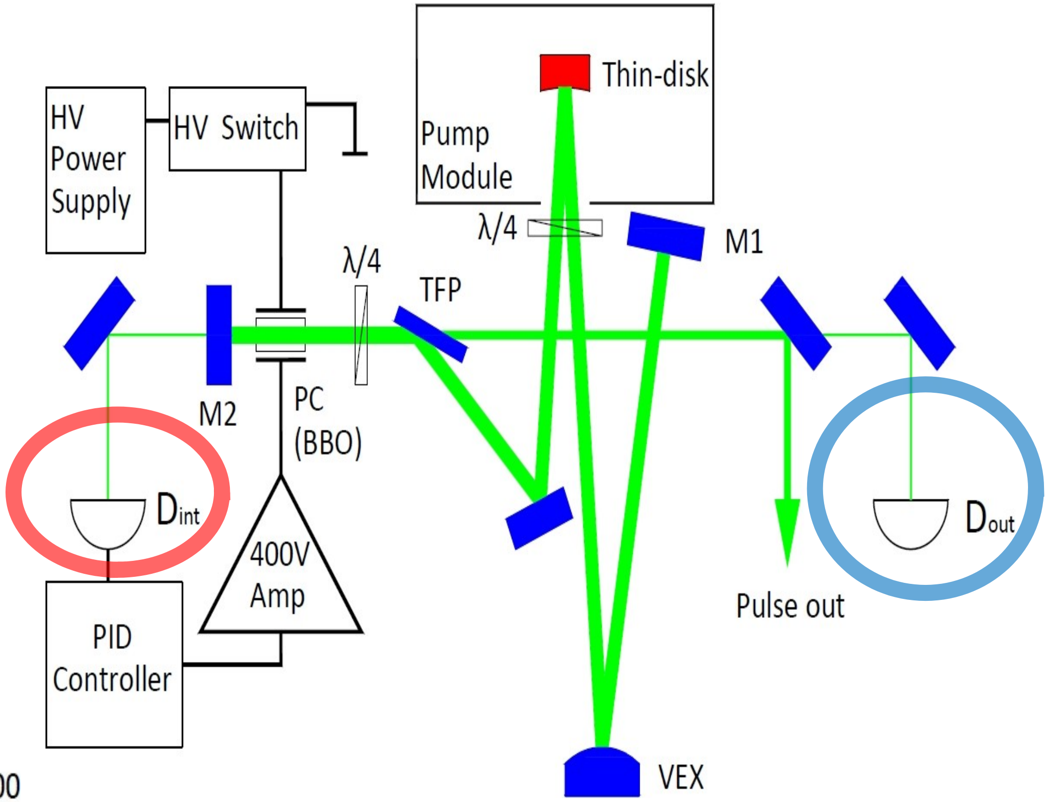
Thin disk laser with prelasing: Pulse build up





Thin disk laser with prelasing: Pulse build up





Thin disk laser with prelasing: Stabilization of the prelasing operation