Nucleon and nuclear structure from muonic and normal atoms

Is the proton radius puzzle solved?

Randolf Pohl

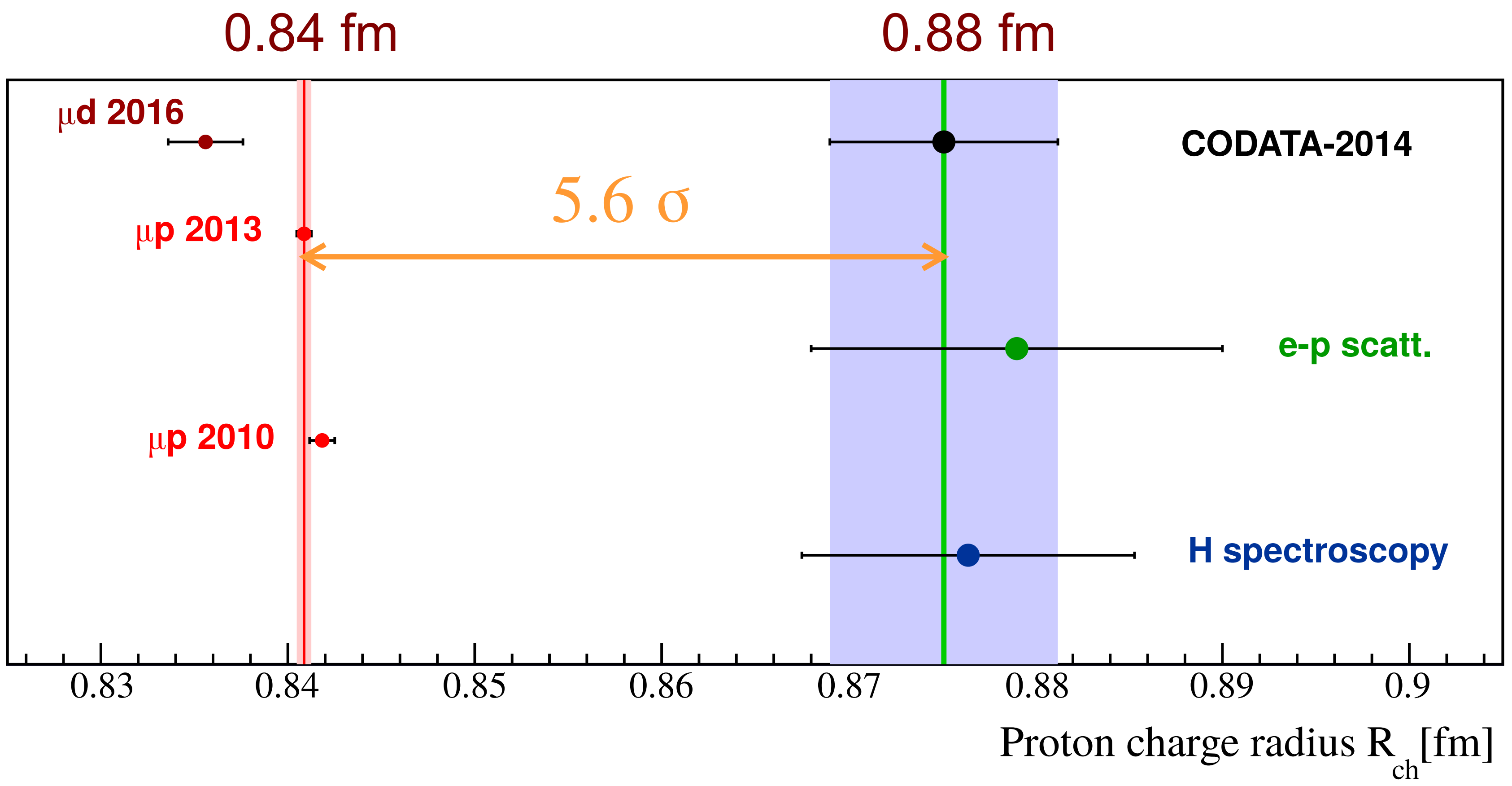
Johannes Gutenberg
Universität Mainz

Chiral Dynamics Beijing
(virtual)
19. Nov. 2021

Group at JGU Mainz

The “Proton Radius Puzzle”

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

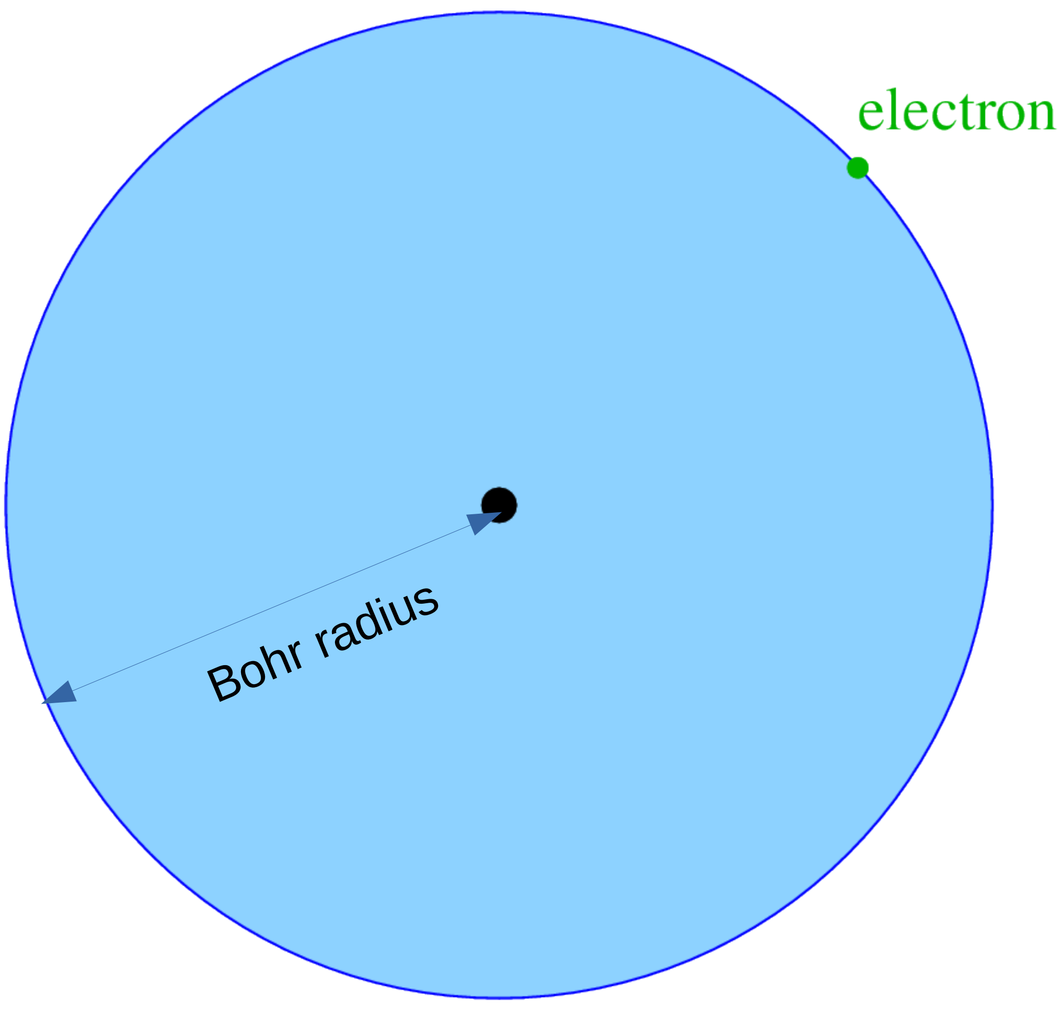


μd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
μp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

Electronic and muonic atoms

Regular hydrogen:

Proton + Electron



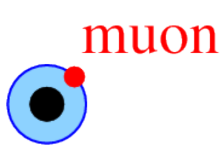
Muonic hydrogen:

Proton + Muon

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

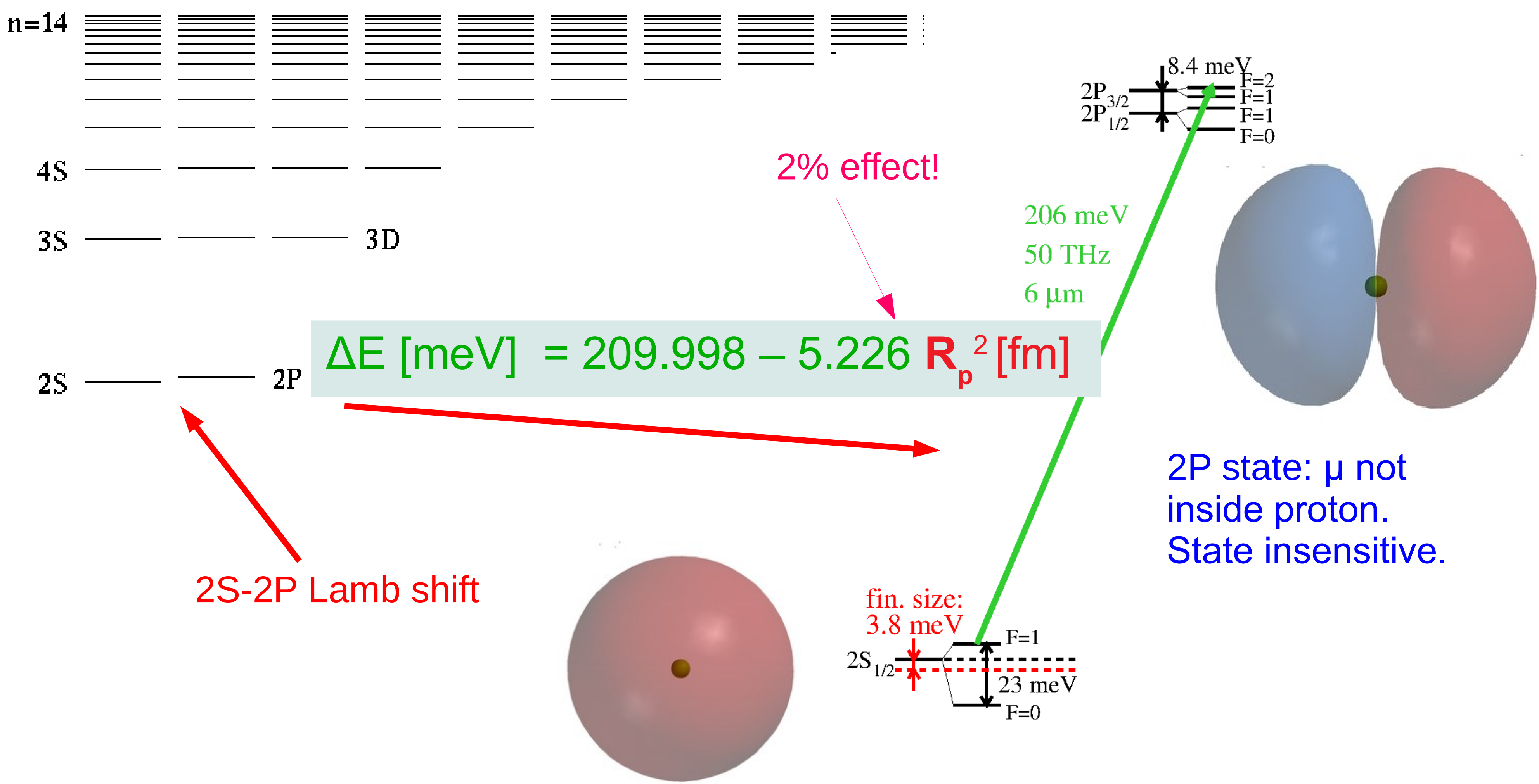
Bohr **radius** = **1/200** of H

200^3 = a **few million times** larger wave function overlap
==
more sensitive to proton size



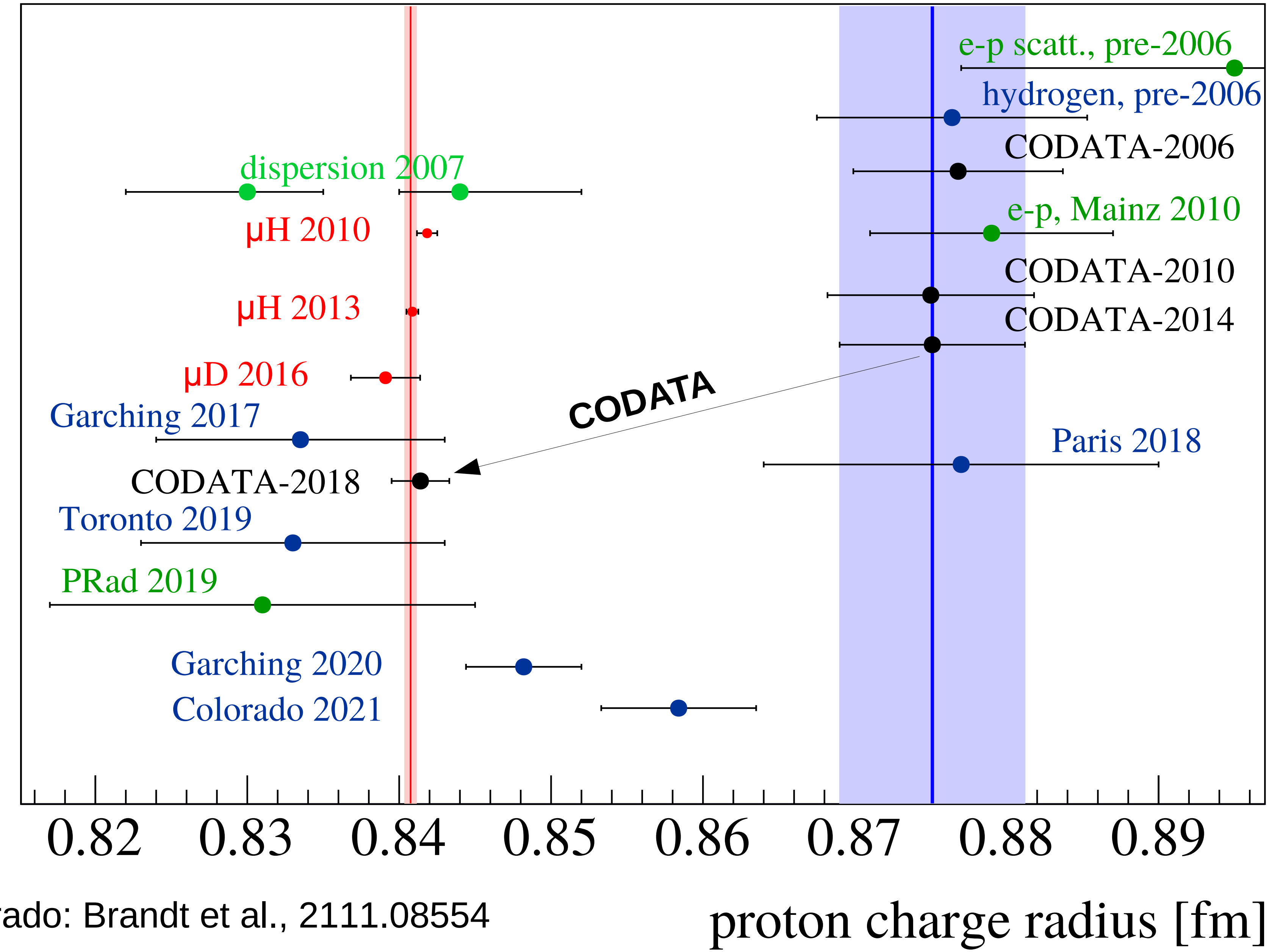
Vastly not to scale!!

Lamb shift in Muonic Hydrogen



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

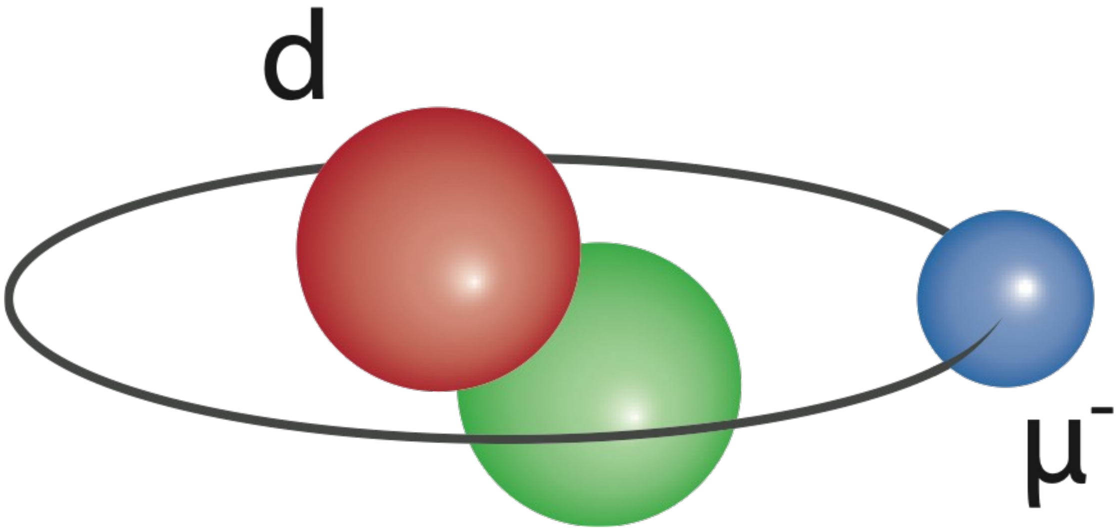
The situation in 2021



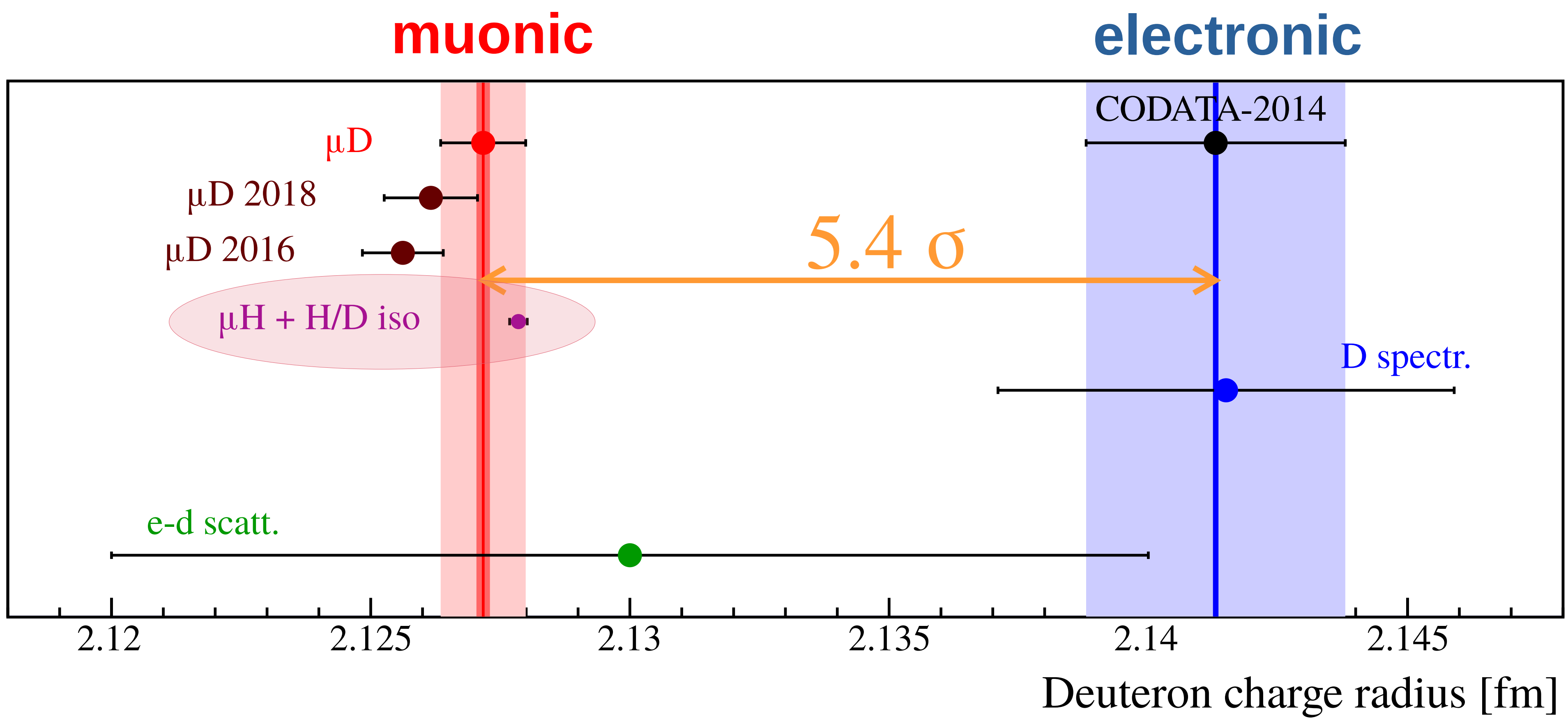
Colorado: Brandt et al., 2111.08554

Proton charge radius puzzle “solved”?

Muonic Deuterium



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:
$r_d^2 - r_p^2 = 3.82070(31)\ \text{fm}^2$

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

μD: RP et al. (CREMA) Science 353, 669 (2016)

H/D 1S-2S. Parthey, RP et al., 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

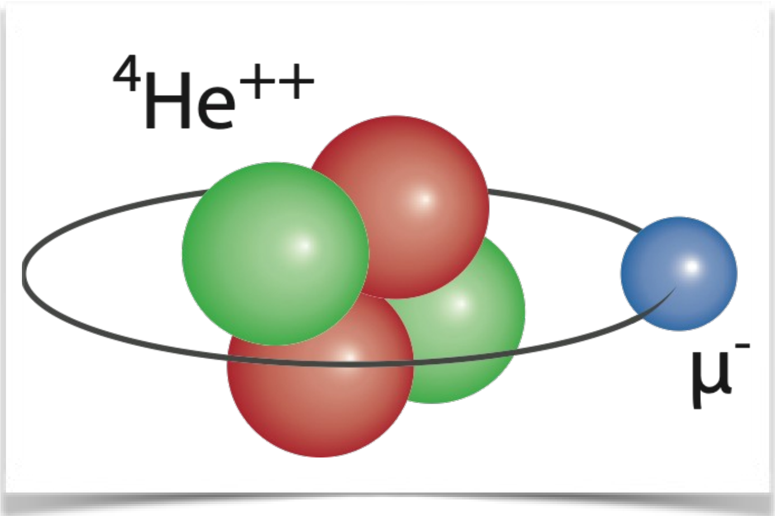
(2) **polarizability**, using **charge radius from isotope shift**

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

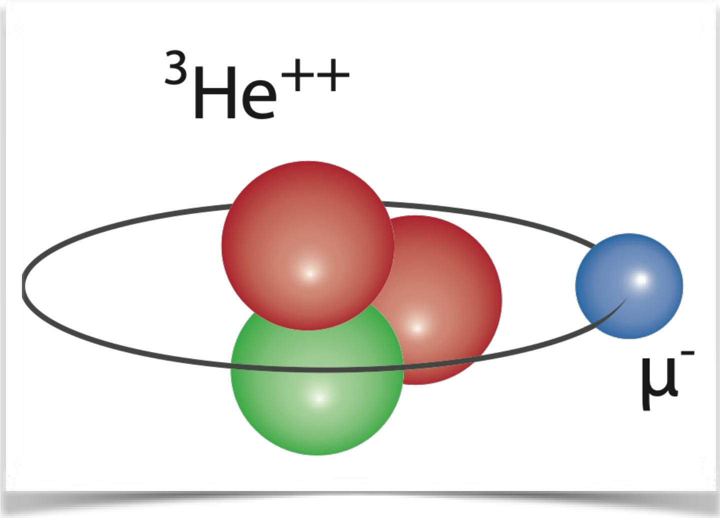
ΔE_{TPE} (exp) = 1.7591 (59) meV 3.5x more accurate

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

Muonic Helium



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



Measured

Theory in muonic He-3

$$\Delta E^{\mu^3He}_{Lamb} = 1644.4820(149)_{QED} + 15.3000(\mathbf{5200})_{TPE} - 103.5184(10) * \mathbf{R_h}^{\mathbf{2}} /fm^2 \quad [meV]$$

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

$$\Delta E^{\mu H}_{Lamb} = 206.0336\,(15)\ _{QED} + 0.0332(\ \ 20)_{TPE} - 5.2275(10) * \mathbf{R_p}^{\mathbf{2}} /fm^2 \quad [meV]$$

Annals of Physics 331 (2013) 127–145

Annals of Physics 366 (2016) 168–196

Contents lists available at ScienceDirect

ELSEVIER

Theory of the 2
splitting in mu

Aldo Antognini[a,*],
François Nez[b], Ra

[a] Institute for Particle Physics, E
[b] Laboratoire Kastler Brossel, Éc
[c] Max-Planck-Institut für Quant

ELSEVIER

Theory of t

Julian J. Kraut
Aldo Antogni

Eur. Phys. J. D (2017) 71: 341
DOI: 10.1140/epjd/e2017-80296-1

THE EUROPEAN PHYSICAL JOURNAL D

Topical Review

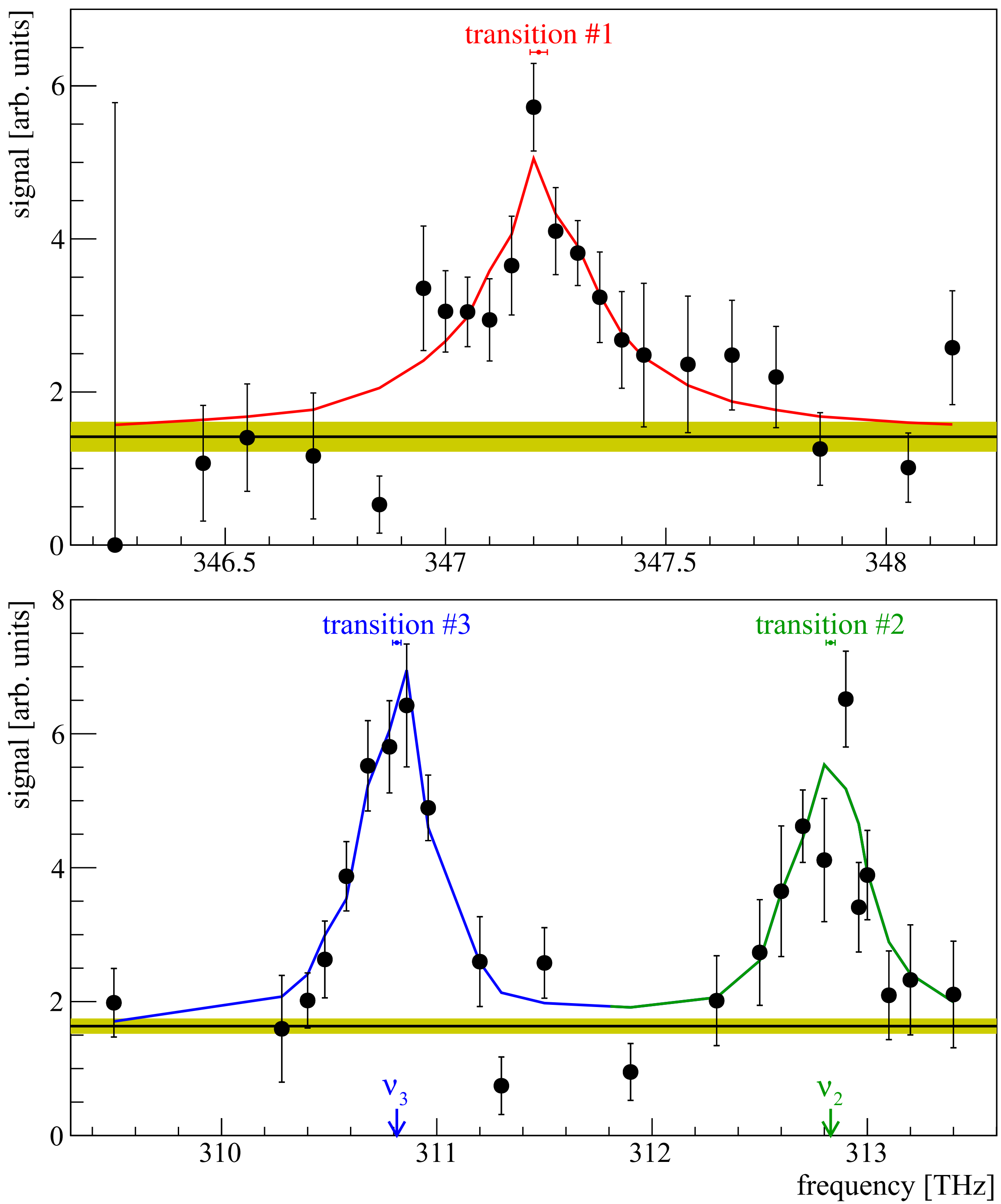
Theory of the $n = 2$ levels in muonic helium-3 ions

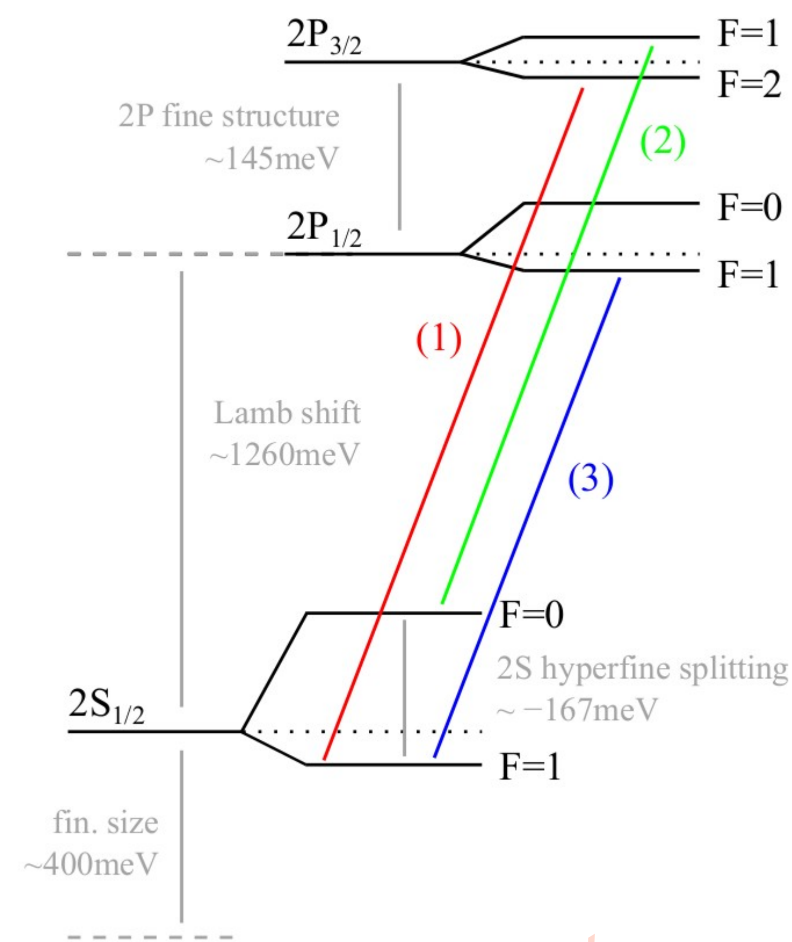
Beatrice Franke[1,2,a], Julian J. Krauth[1,3,b], Aldo Antognini[4,5], Marc Diepold[1], Franz Kottmann[4], and Randolf Pohl[3,1,c]

[1] Max–Planck–Institut für Quantenoptik, 85748 Garching, Germany
[2] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada
[3] Johannes Gutenberg-Universität Mainz, QUANTUM, Institut für Physik & Exzellenzcluster PRISMA, 55099 Mainz, Germany
[4] Institute for Particle Physics and Astrophysics, ETH Zurich, 8093 Zurich, Switzerland
[5] Paul Scherrer Institute, 5232 Villigen, Switzerland

Three-photon contribution still missing (Pachucki et al., PRA 97, 052511 (2018))

muonic ^{3}He ions

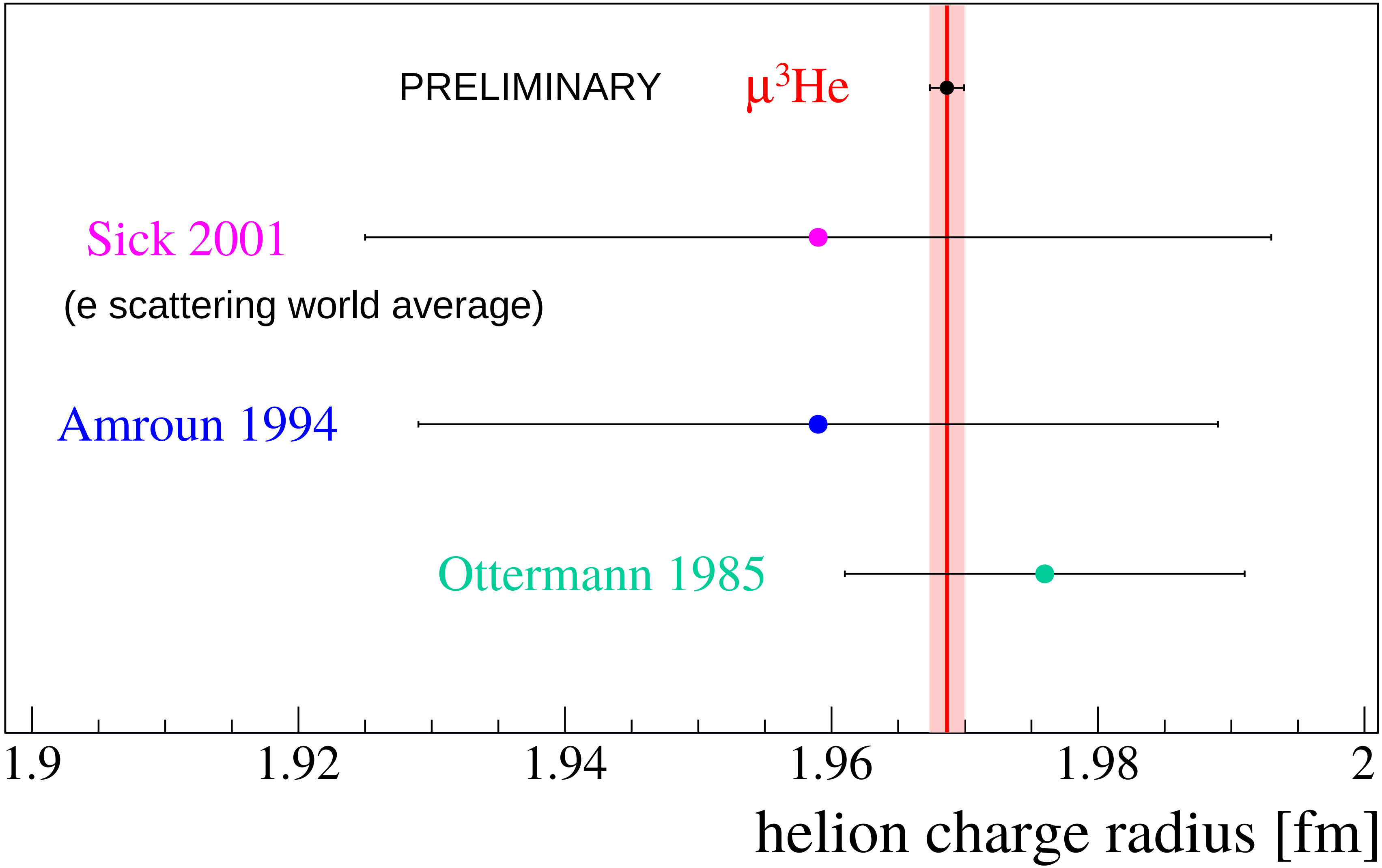




$R(^3He) = 1.96866\ (12)_{exp}\ (128)_{theo}$ fm

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]

Theory in muonic He-4

$$\Delta E^{\mu^4He}_{Lamb} = 1668.5670(178)_{QED} + 9.9000(\mathbf{2800})_{TPE} - 106.3540(80) * \mathbf{R_\alpha}^{\mathbf{2}} /fm^2 \quad [meV]$$

$$\Delta E^{\mu^3He}_{Lamb} = 1644.4820(149)_{QED} + 15.3000(5200)_{TPE} - 103.5184(10) * \mathbf{R_h}^{\mathbf{2}} /fm^2 \quad [meV]$$

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

$$\Delta E^{\mu H}_{Lamb} = 206.0336\,(15)_{QED} + 0.0332(\;20)_{TPE} - 5.2275(10) * \mathbf{R_p}^{\mathbf{2}} /fm^2 \quad [meV]$$

Annals of Physics 331 (2013) 127–145

Annals of Physics 396 (2018) 220–244

ELSEVIER

Theory of the
splitting in mu

Aldo Antognini [a,*],
François Nez [b], Ra
[a] Institute for Particle Physics, E
[b] Laboratoire Kastler Brossel, Éc
[c] Max-Planck-Institut für Quan

Annals o

ELSEVIER

Theory of t

Julian J. Kraut
Aldo Antogni

Eur. Phys. J. D (2017) 71: 34
DOI: 10.1140/epjd/e2017-802

Topical Review

Theory of the

Beatrice Franke[1,2,a], Julian
and Randolf Pohl[3,1,c]
[1] Max–Planck–Institut für Qu
[2] TRIUMF, 4004 Wesbrook M
[3] Johannes Gutenberg-Unive
55099 Mainz, Germany
[4] Institute for Particle Physic
[5] Paul Scherrer Institute, 523

ELSEVIER

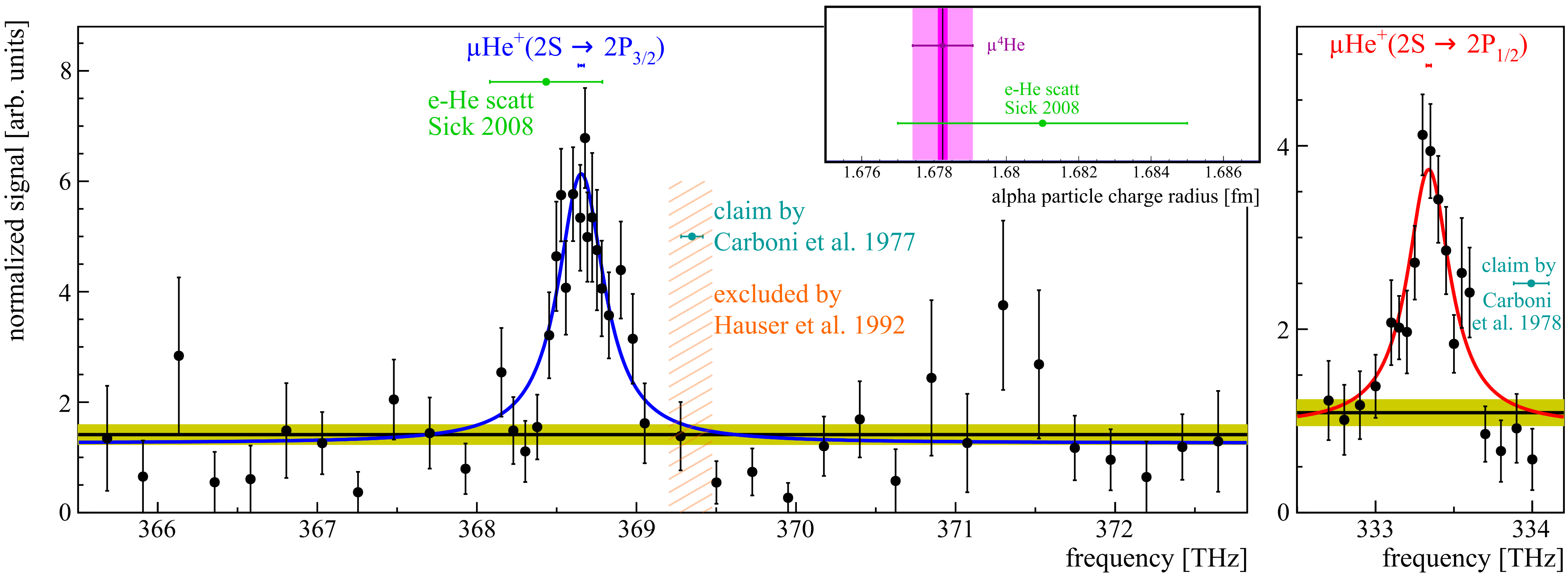
Contents lists available at ScienceDirect
Annals of Physics
journal homepage: www.elsevier.com/locate/aop

Theory of the Lamb Shift and fine structure in muonic ^{4}He ions and the muonic ^{3}He–^{4}He Isotope Shift

Marc Diepold [a], Beatrice Franke [a,b], Julian J. Krauth [a,c,*], Aldo Antognini [d,e], Franz Kottmann [d], Randolf Pohl [c,a]

Three-photon contribution estimation included (Pachucki et al., PRA 97, 052511 (2018))

muonic ^{4}He ions



$2P_{3/2}$: ±17 GHz **$2P_{1/2}$: ±15 GHz**

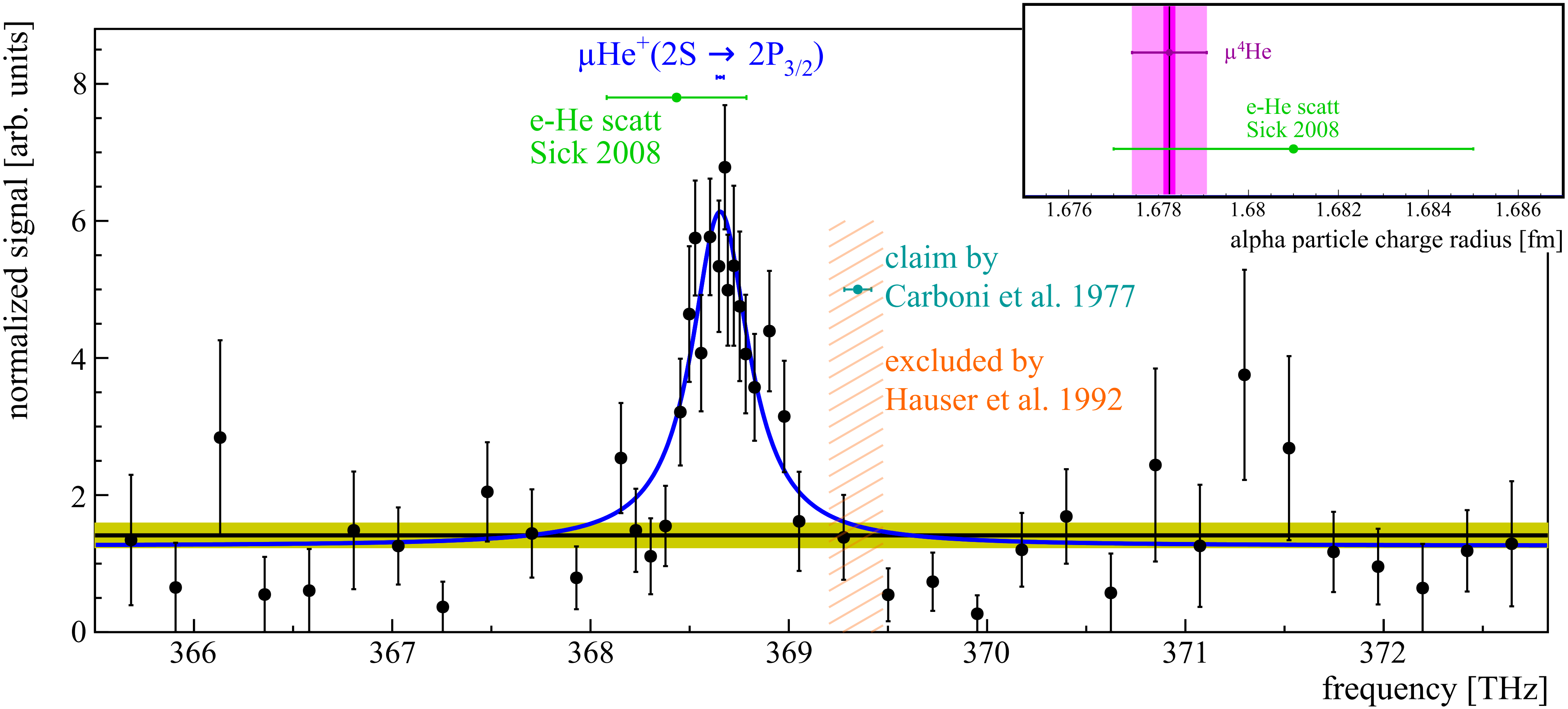
$$R(^4\mathrm{He}) = 1.67824\ (13)_{exp}\ (82)_{theo}\ \mathrm{fm}$$

$$(82)_{theo} = (70)_{2PE}\ \ (42)_{3PE}$$

Krauth, RP et al. (CREMA Coll.)
Nature 589, 527 (2021)

Theory: Diepold et al., Ann. Phys. (2018)
incl. 3-photon nuclear polarizability (Pachucki, 2018)

muonic ^{4}He ions



$R(^4He) = 1.67824\ (13)_{exp}\ (82)_{theo}$ fm

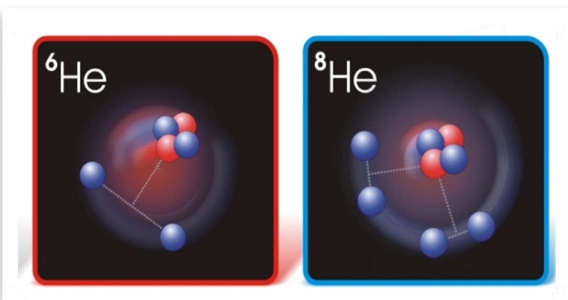
Krauth, RP et al. (CREMA Coll.)
Nature 589, 527 (2021)

Theory: Diepold et al., Ann. Phys. (2018)
incl. 3-photon nuclear polarizability (Pachucki, 2018)

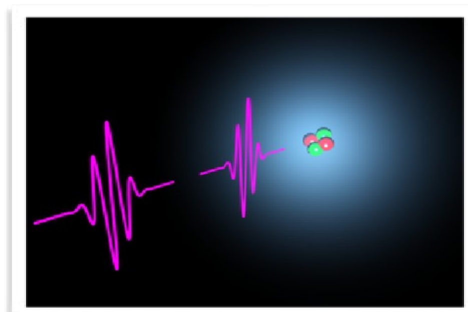
Impact of μ^4He^+ measurements

Few-nucleon theories
- r_α represents a benchmark for few-nucleon theories.
- r_α can be used also to fix a low-energy constant of nuclear potential.
- r_α improves ^6He and ^8He radii

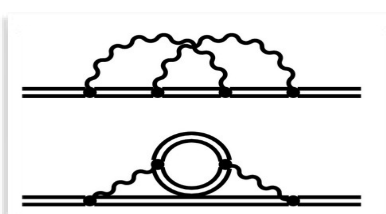
BSM physics
- Agreement constrains BSM models suggested to explain the R_p puzzle



Müller, Lu



Udem, MPQ
Eikema, LaserLab



Combined with upcoming He^+ (He) exp.
- bound-state QED test He^+(1S-2S):
  60 kHz, $u_r = 6x10^{-12}$
- Rydberg constant: 24 kHz
- **2PE+3PE in μHe with 0.1 meV uncertainty**

from A. Antognini

Conclusions

Muonic atoms / ions provide:

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

Conclusions

Muonic atoms / ions provide:

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

	^{3}He	^{4}He
	1.9687* (13)	1.6782 (8)
	~~1.9730 (160)~~	~~1.6810 (40)~~

^{1}H	^{2}D	^{3}T
0.8409 (4)	2.1277 (2)	
~~0.8751 (61)~~	~~2.1413 (25)~~	1.7550 (860)

*** = preliminary**

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!

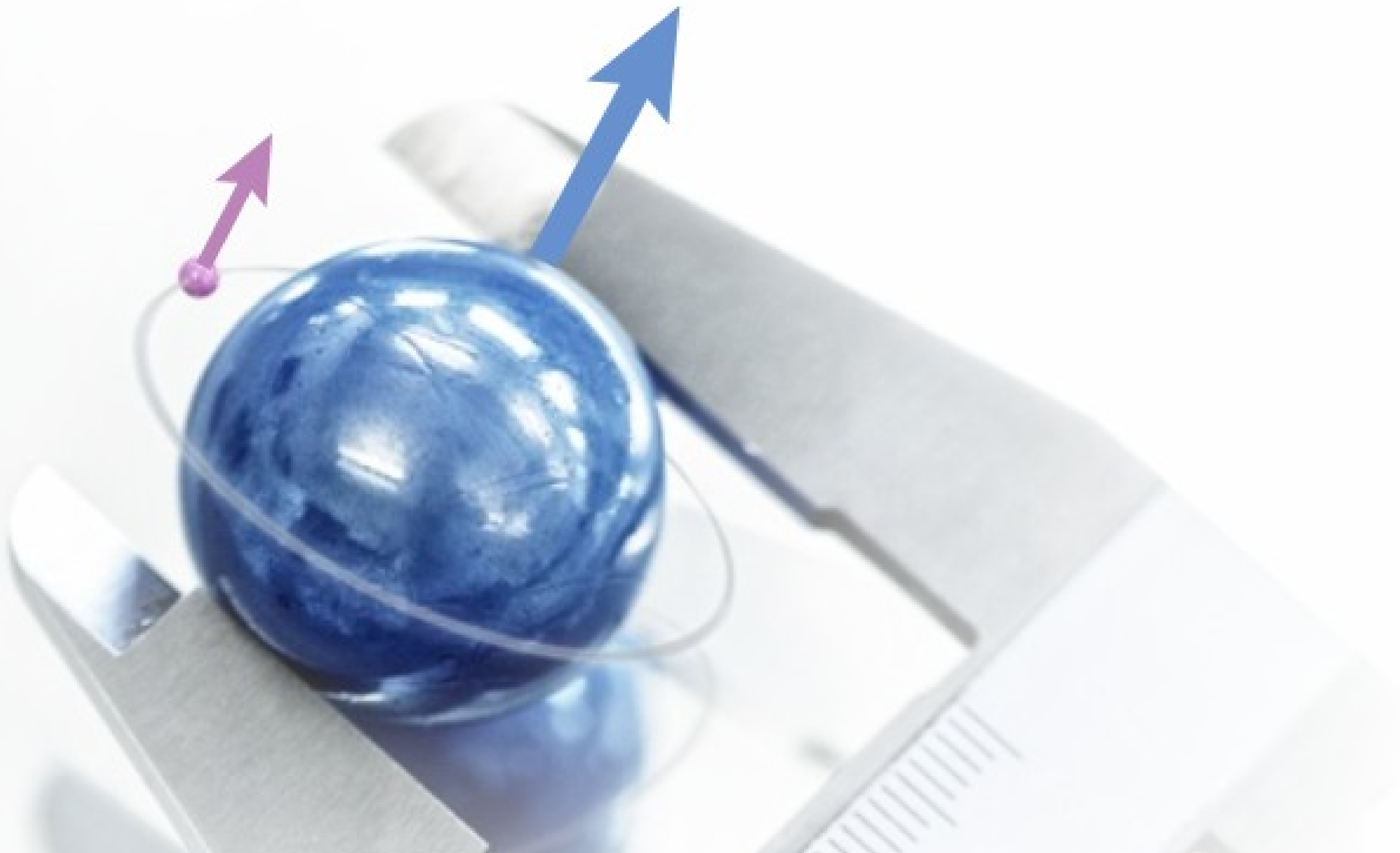
- H(2S – 6P, 8P, 9P, …) and D(2S-nl) underway in Garching and Colorado
- H(1S – 3S, 4S, ..) and D(1S-3S) underway in Paris and Garching
- Muonium at PSI, J-PARC
- Positronium (Cassidy @ UCL, Crivelli @ ETH)
- He^+(1S-2S) underway in Garching (Udem) and Amsterdam (Eikema)
- HD^+, H_2, etc. in Amsterdam (Ubachs), Paris (Hilico, Karr), Zurich (Merkt)
- He (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 / AMBER @ CERN
-

Compare Rydberg values to test QED and SM

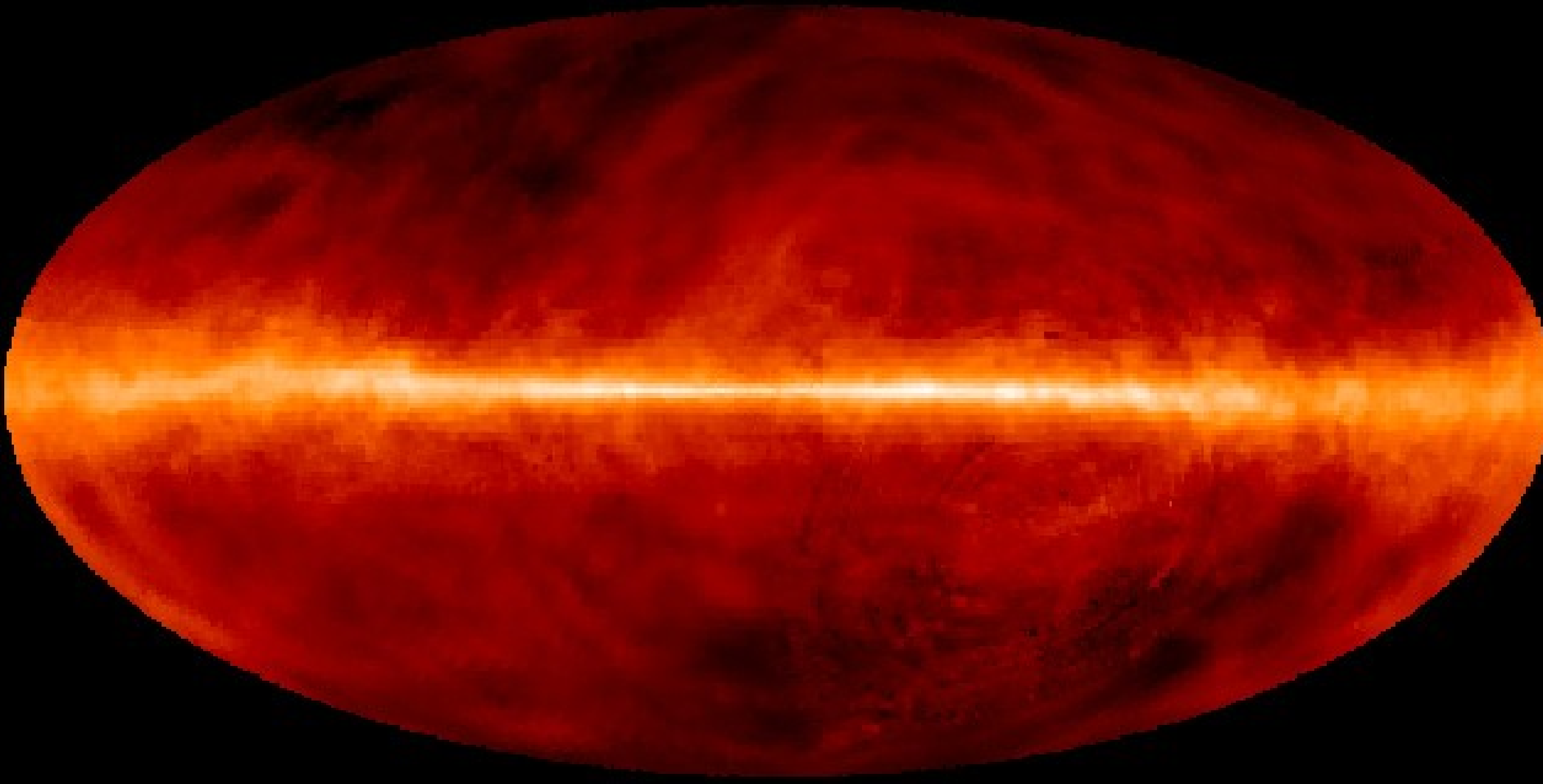
The Present

Hyperfine structure in muonic H

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

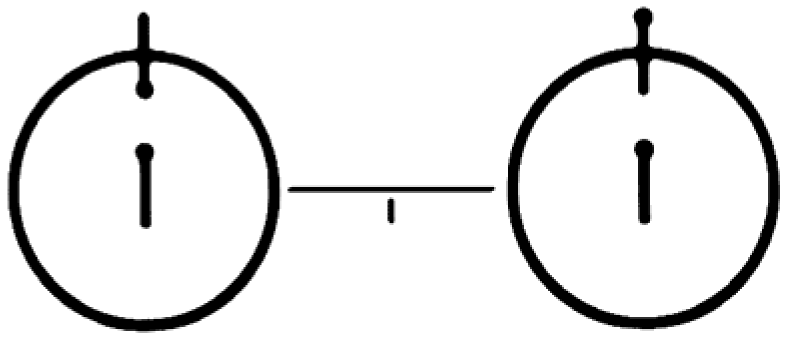


The sky in hydrogen



Hyperfine structure in H / μp

The 21 cm line in hydrogen (1S hyperfine splitting)



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:

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

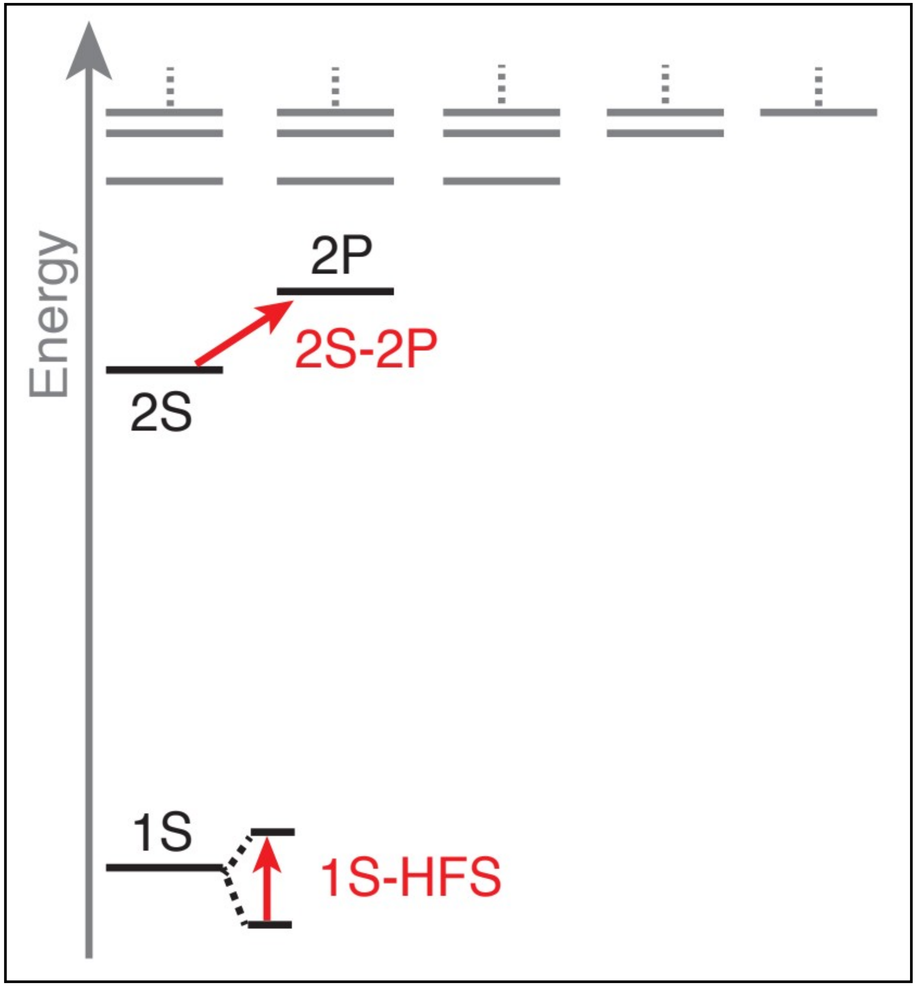
$$\langle r \rangle_{(2)} = \int d^3r \, d^3r' \rho_E(r) \rho_M(r') |r - r'|$$

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

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



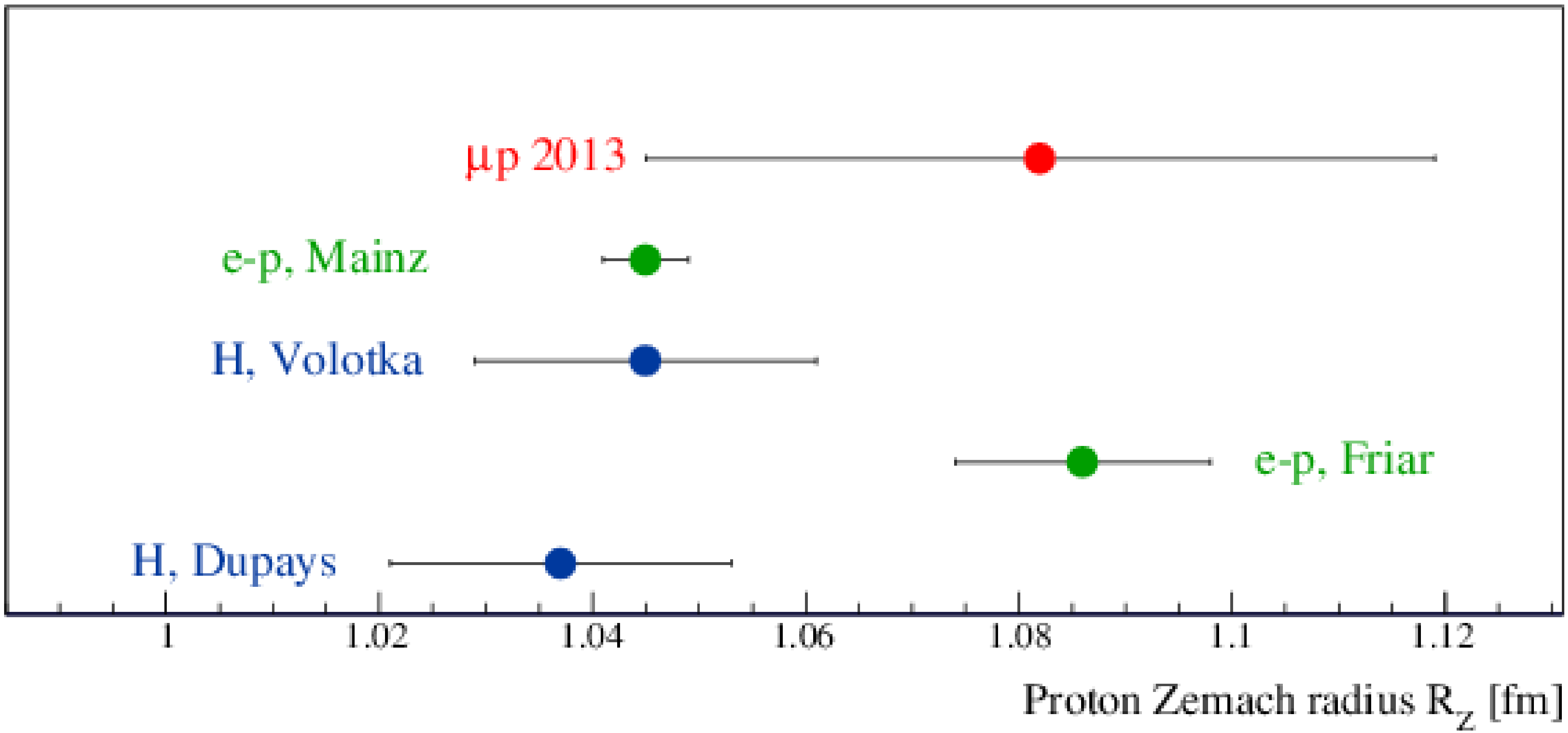
2S-2P = Lamb shift

is sensitive to CHARGE radius

1S-HFS = Hyperfine splitting

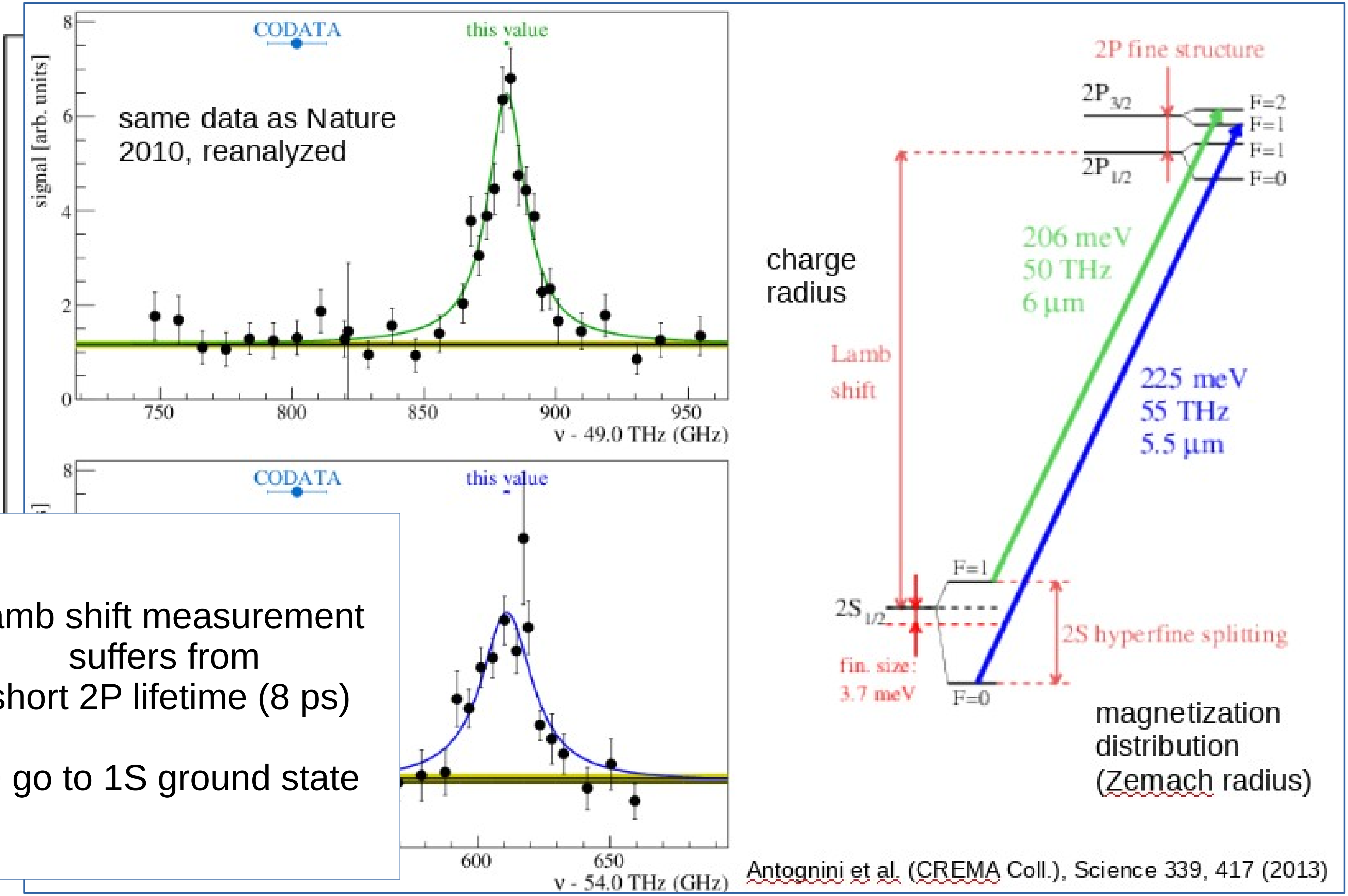
is sensitive to ZEMACH radius

Proton Zemach radius from μp



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

Proton Zemach radius from μp



same data as Nature 2010, reanalyzed

charge radius

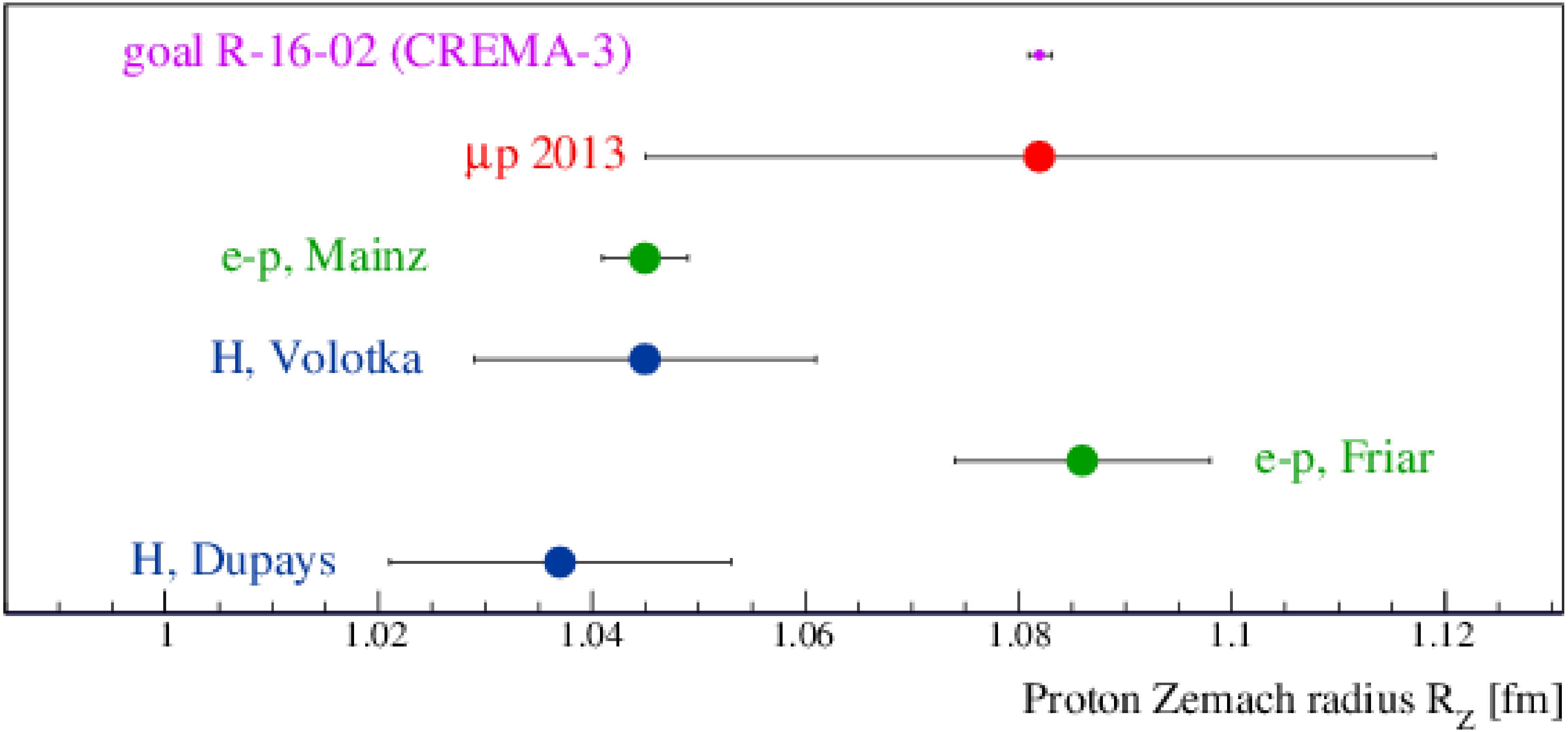
magnetization distribution (Zemach radius)

Lamb shift measurement suffers from short 2P lifetime (8 ps)

-> go to 1S ground state

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

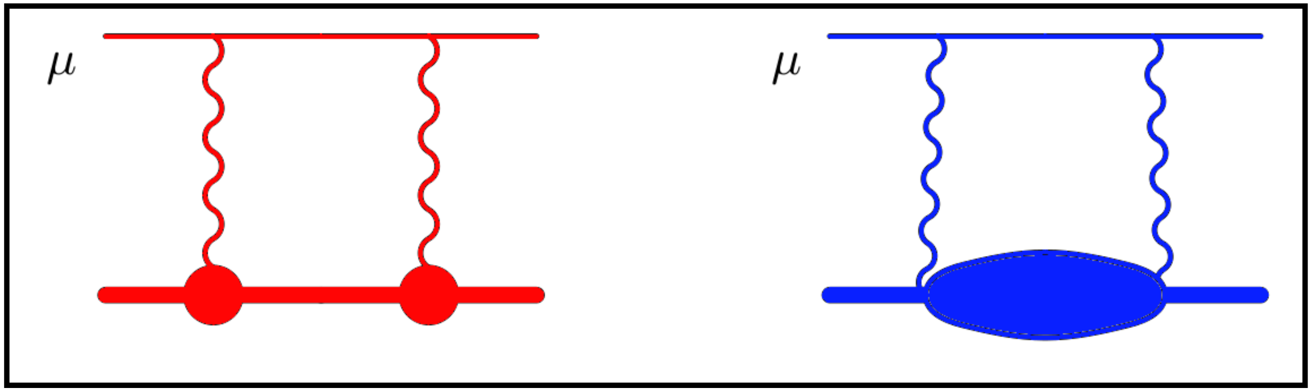
also: FAMU @ RIKEN/RAL, and a Collaboration at J-PARC

HFS in μp

$$\Delta E^{\rm th}_{\rm HFS} = 182.819(10) - \underbrace{1.301 R_Z + 0.064(21)}_{\rm TPE} + \cdots \quad {\rm meV}$$

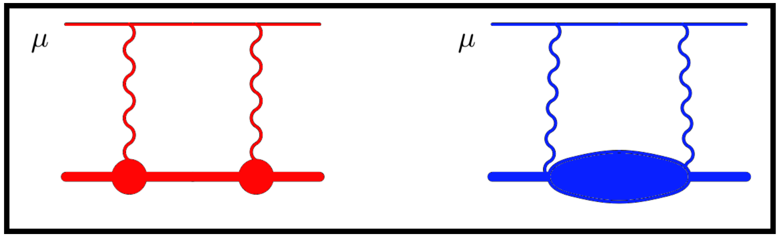
goal: measure HFS with 1 ppm relative accuracy

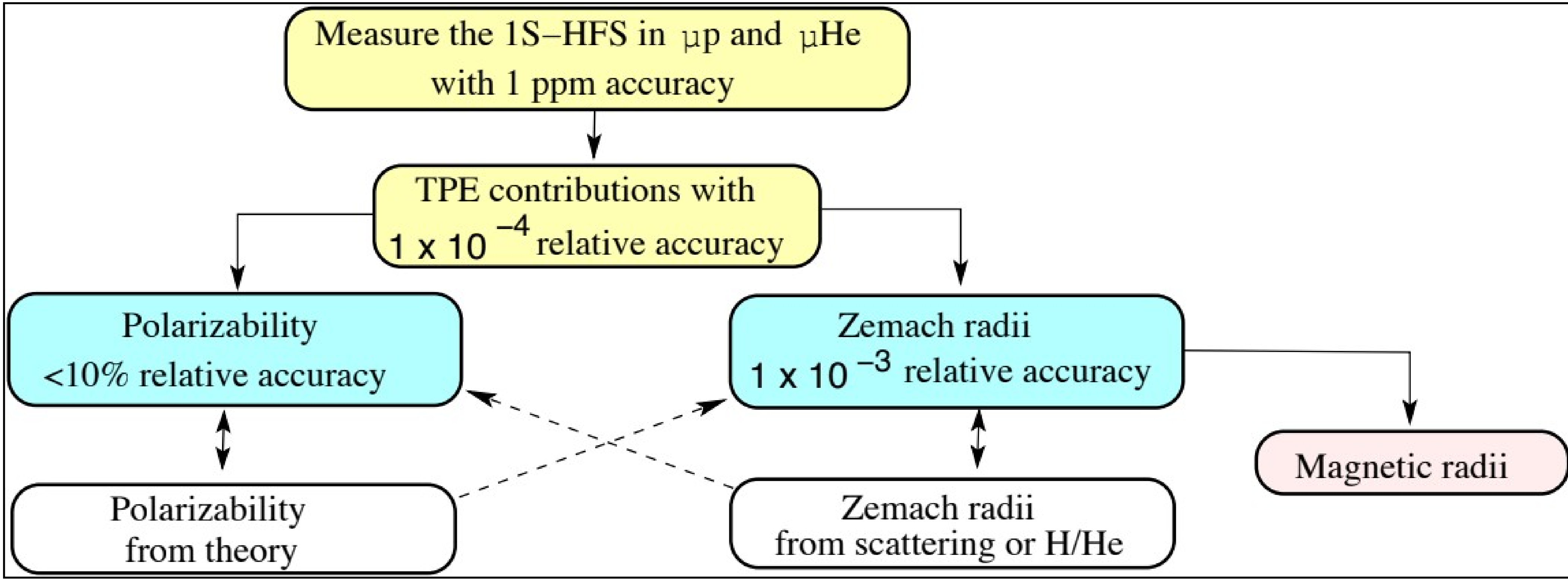
obtain TPE with 3×10^{-4} rel. accuracy



HFS in μp

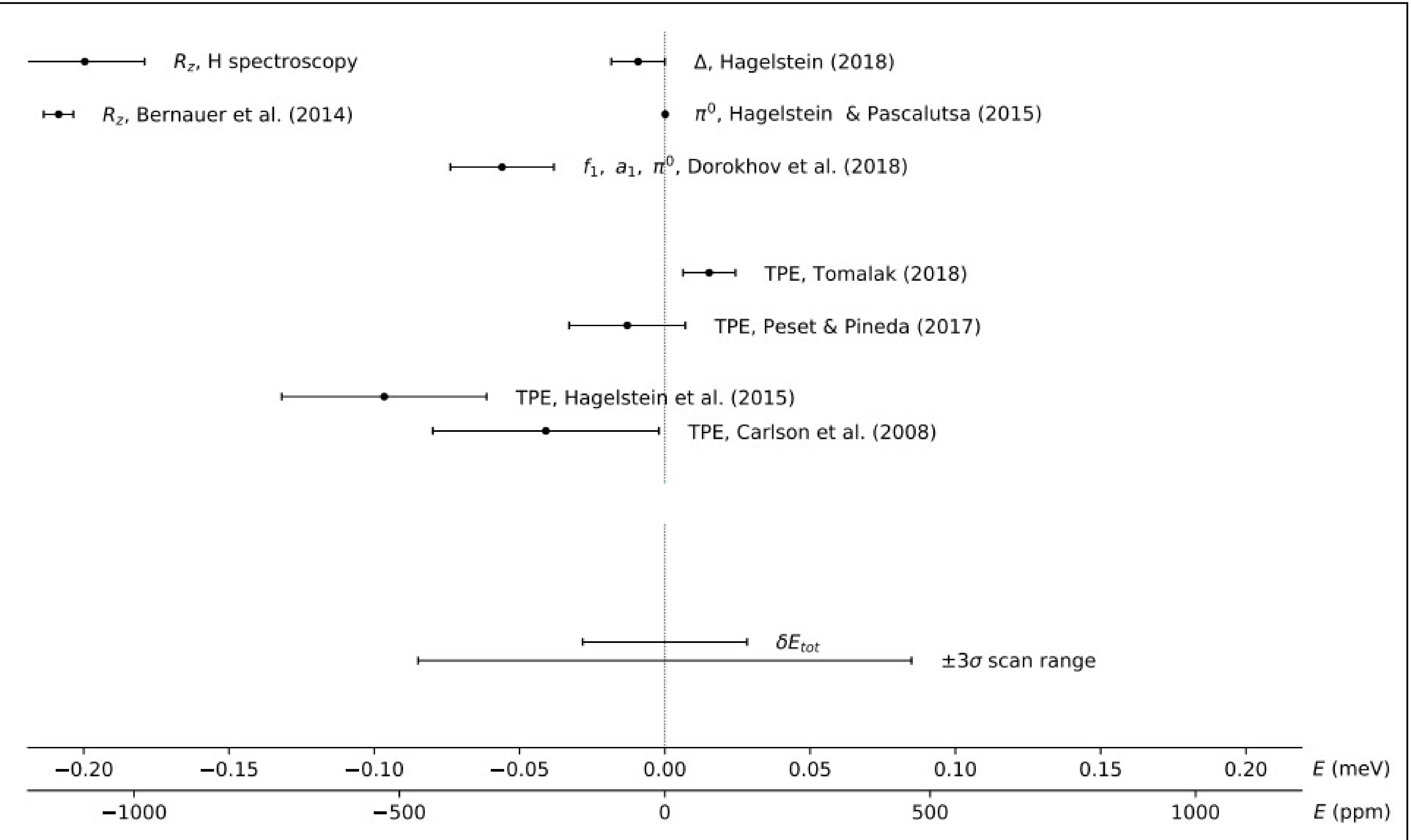
$$\Delta E^{\mathrm{th}}_{\mathrm{HFS}} = 182.819(10) - \underbrace{1.301 R_Z + 0.064(21)}_{\mathrm{TPE}} + \cdots \quad \mathrm{meV}$$



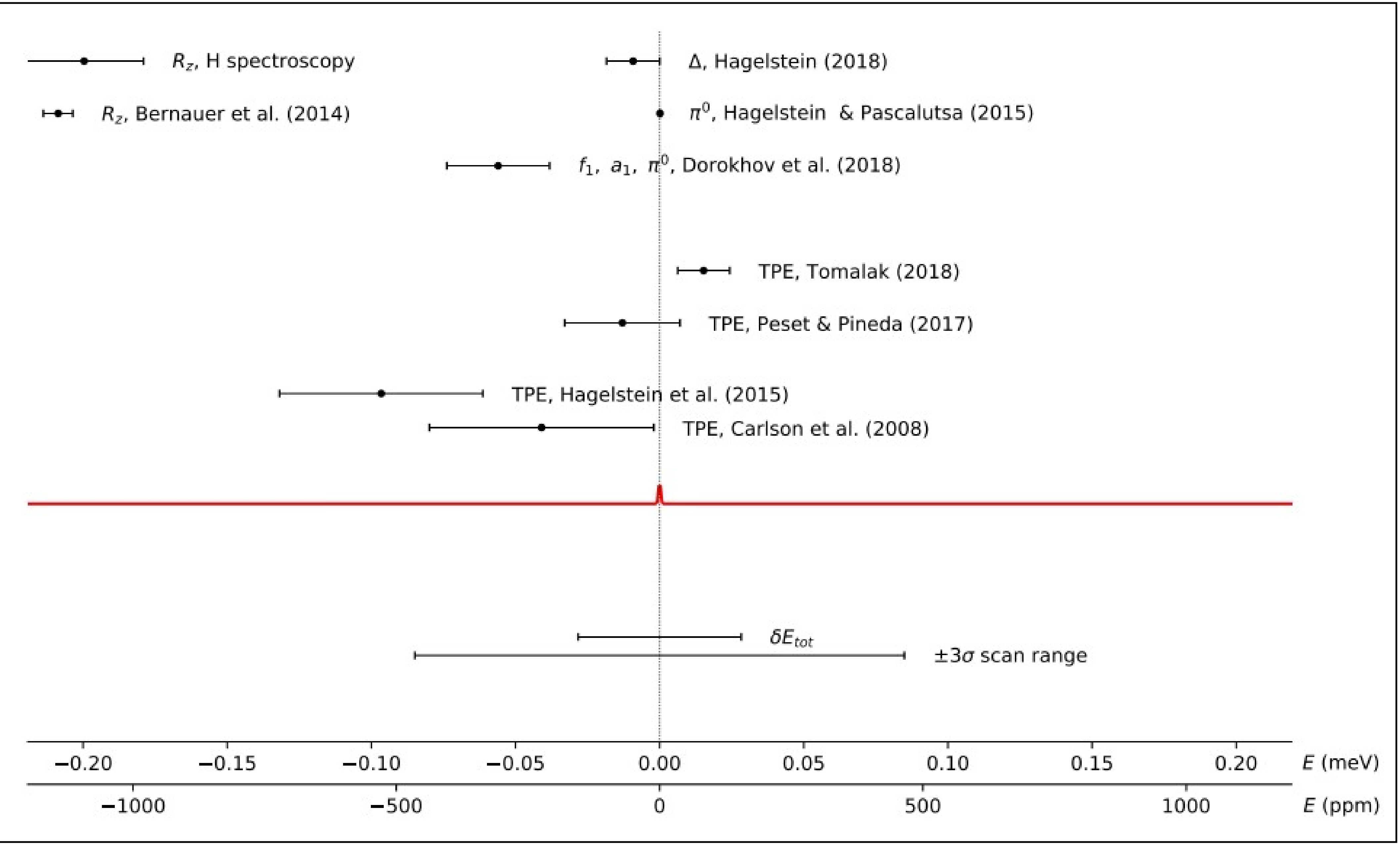


related propsals: FAMU at RIKEN/RAL,   muonic H at J-PARC

Predicting the resonance position

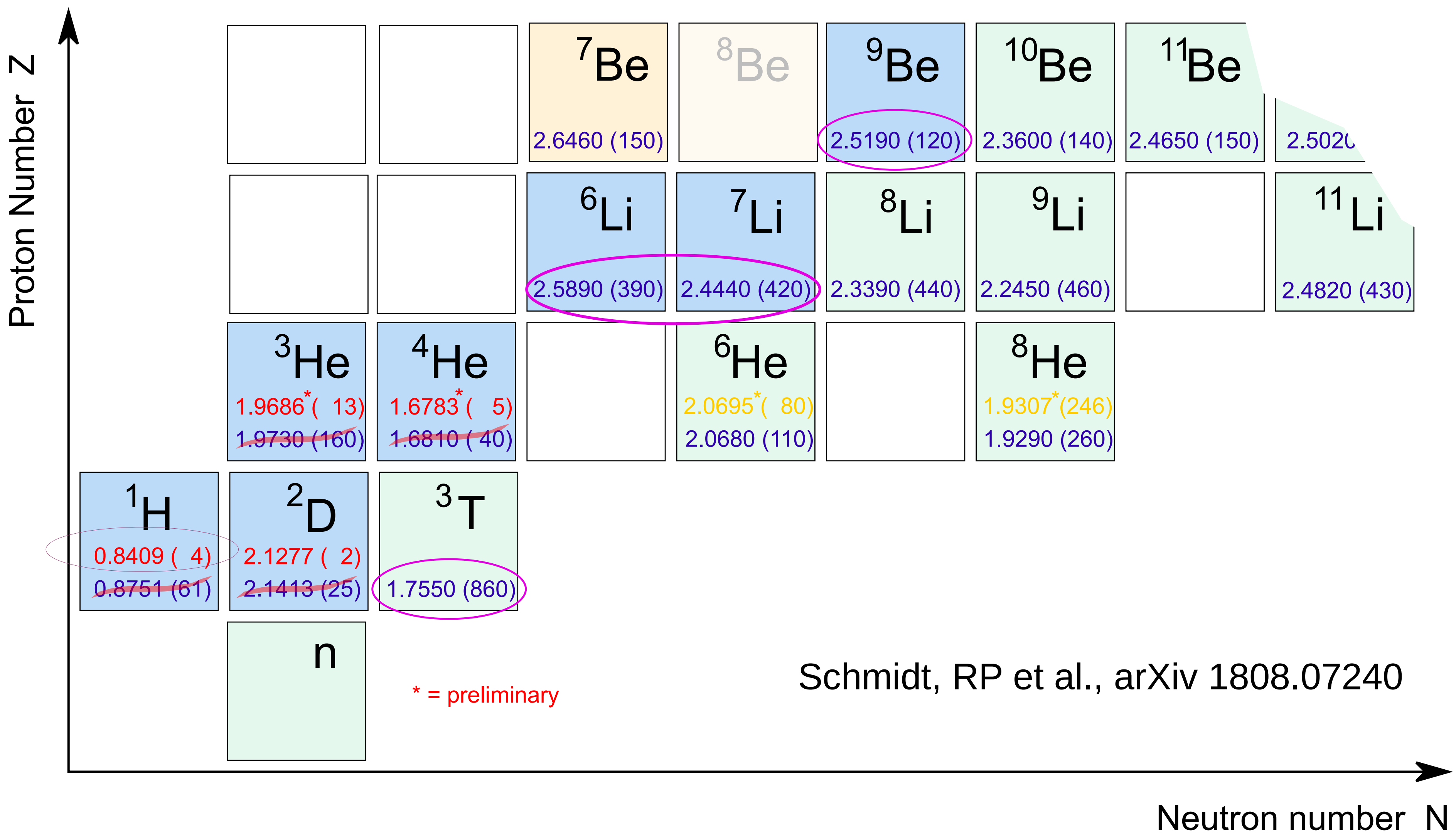


The resonance position



The Future

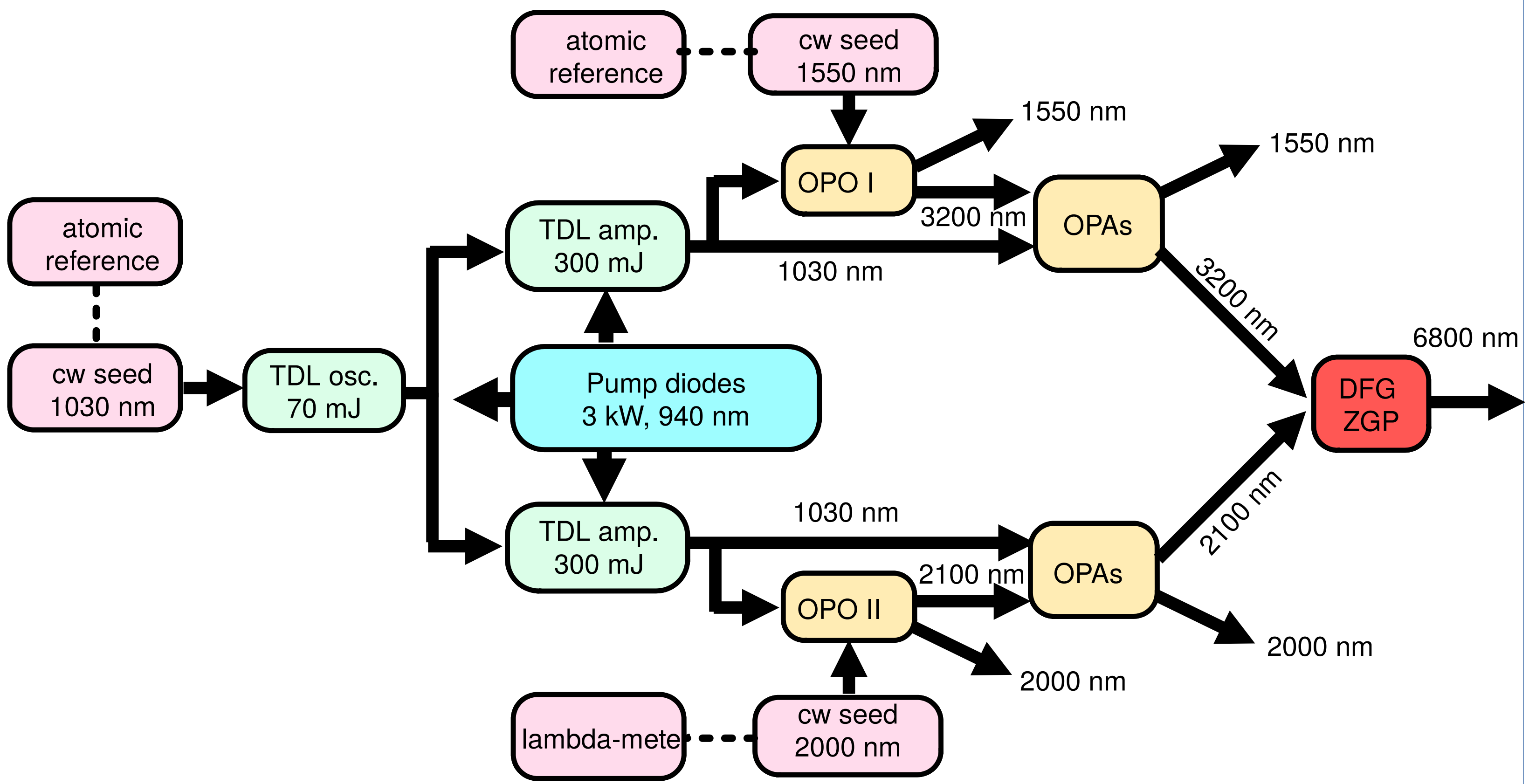
Charge radii: The future

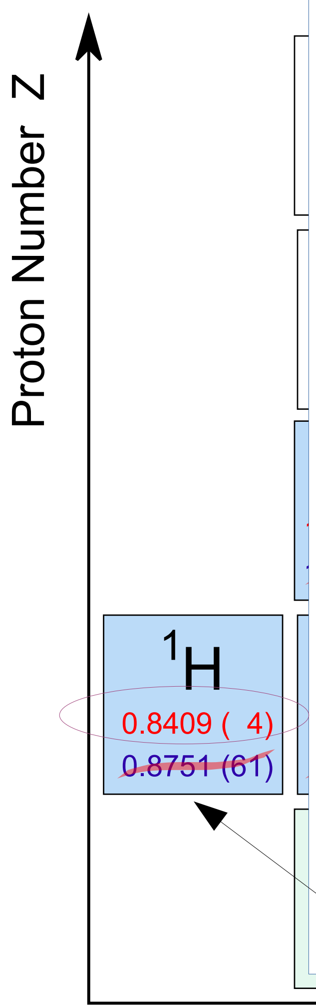


Schmidt, RP et al., arXiv 1808.07240

Charge radii: The future

Laser system for 6.8 µm for **hyperfine** measurement



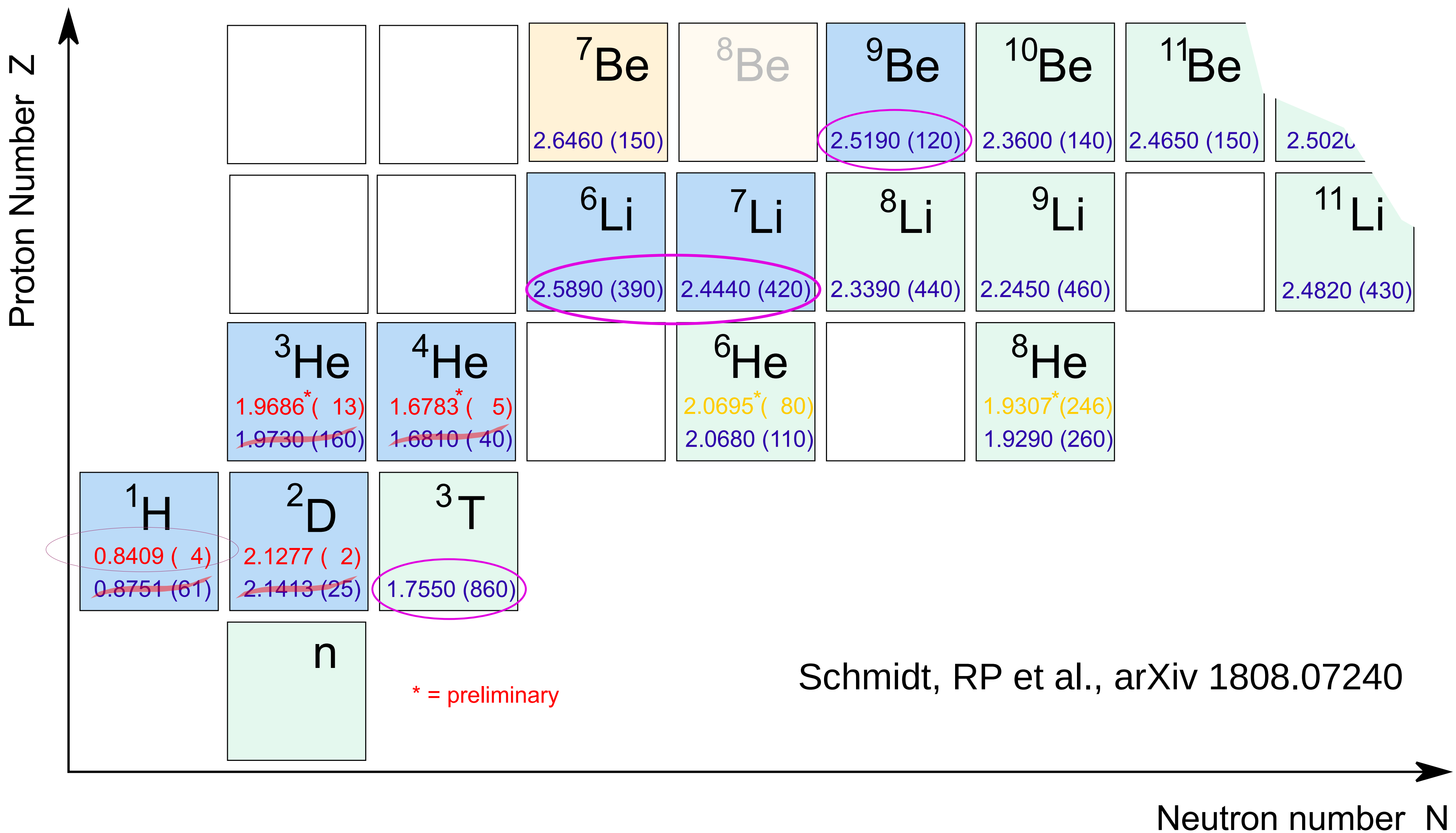


can be used to improve **Lamb shift** in muonic hydrogen

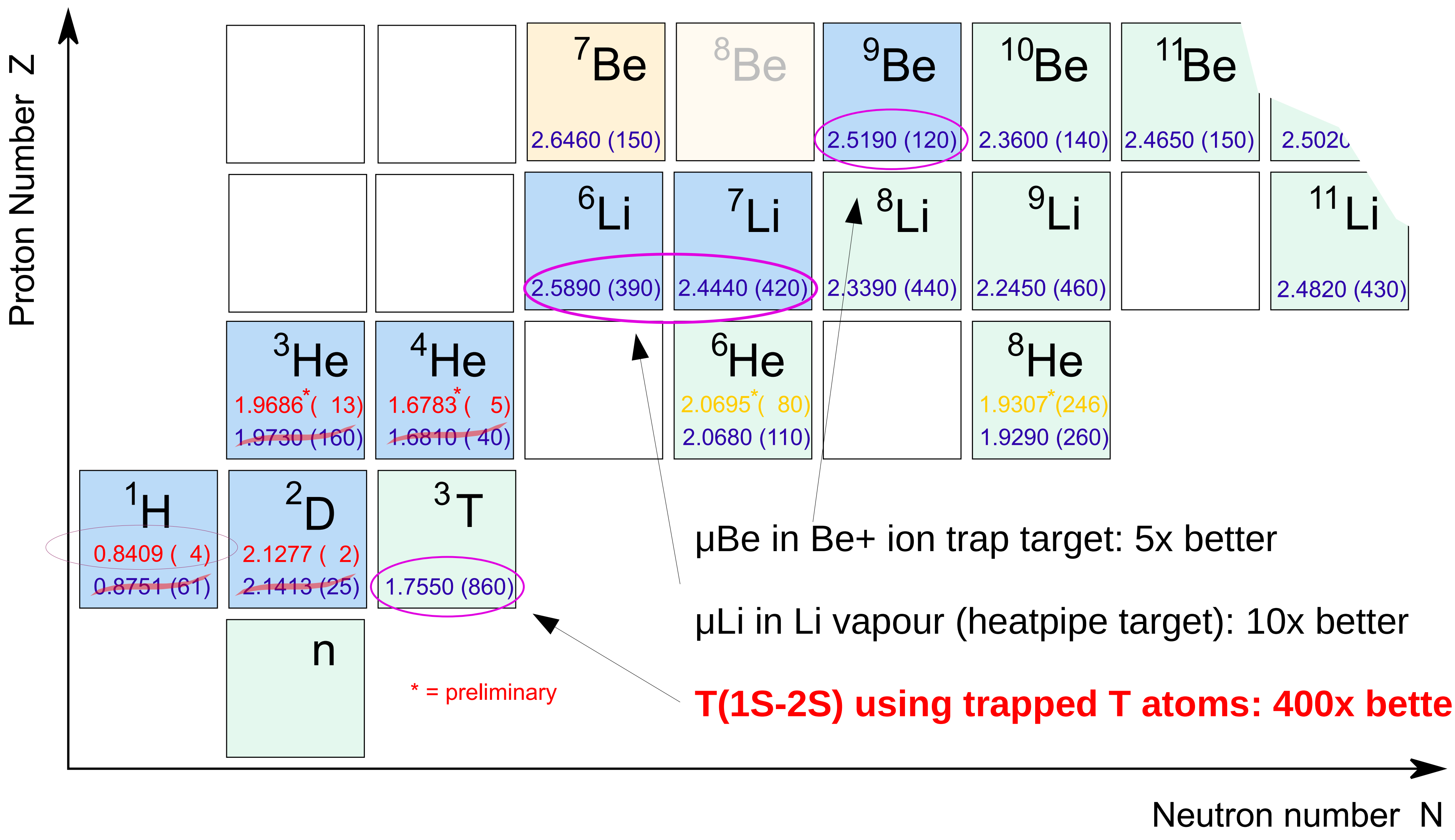
-> 5x better proton charge radius (if TPE improves)

Neutron number N

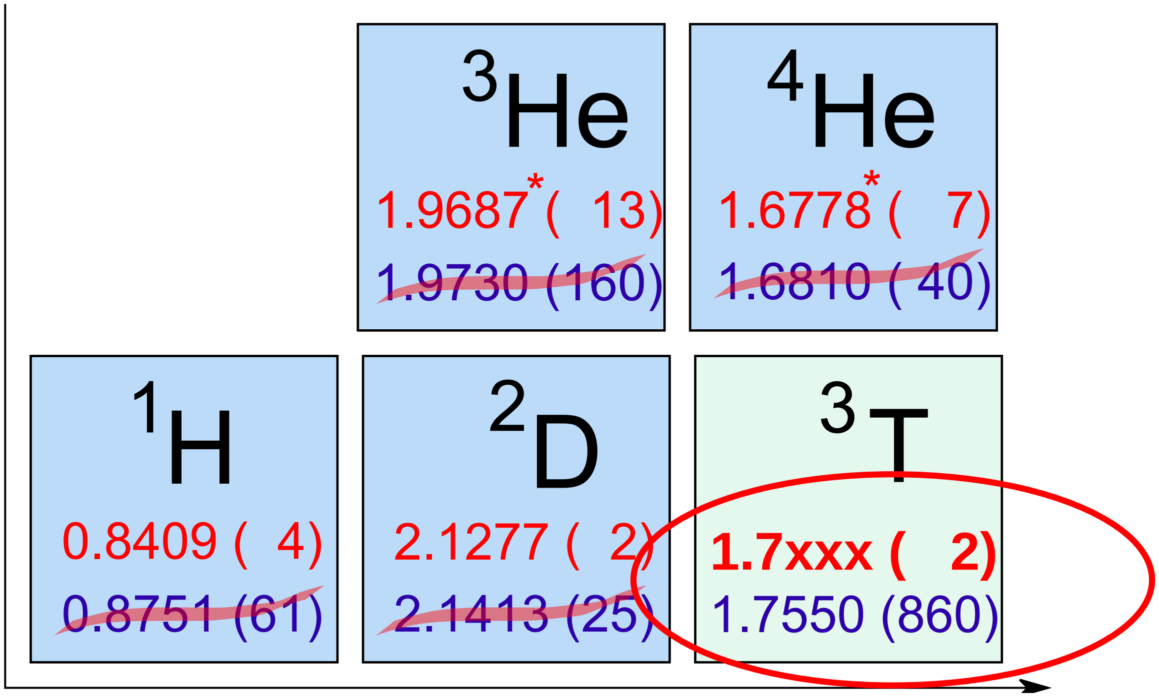
Charge radii: The future



Charge radii: The future

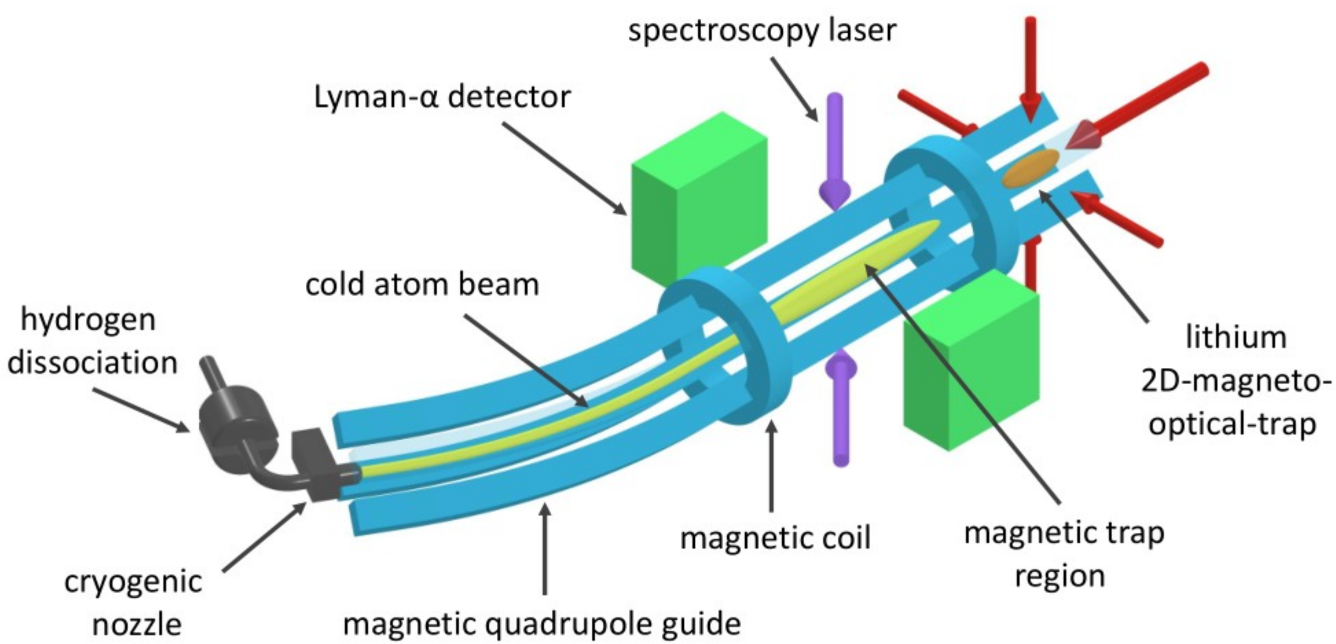


Tritium 1S-2S in a trap



Triton-Radius EXperiment
Mainz

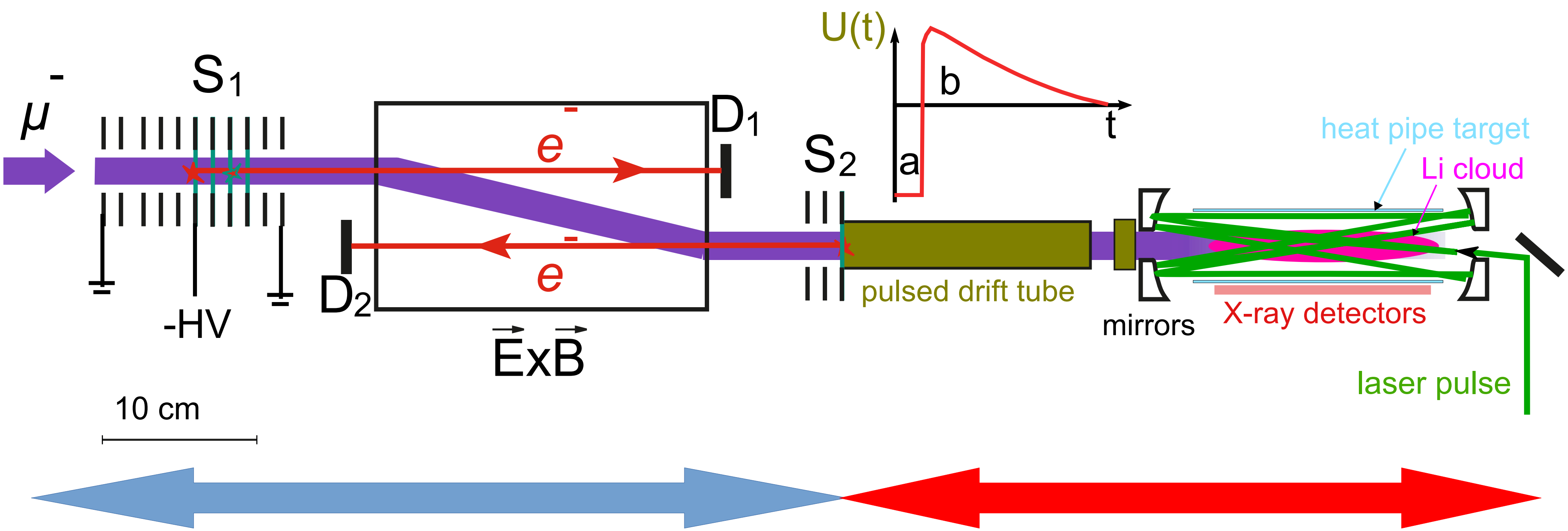
400x better radius
with 1 kHz measurement
(vs. 0.01 kHz for H, D)



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

muonic Li with heat pipe target

difficult

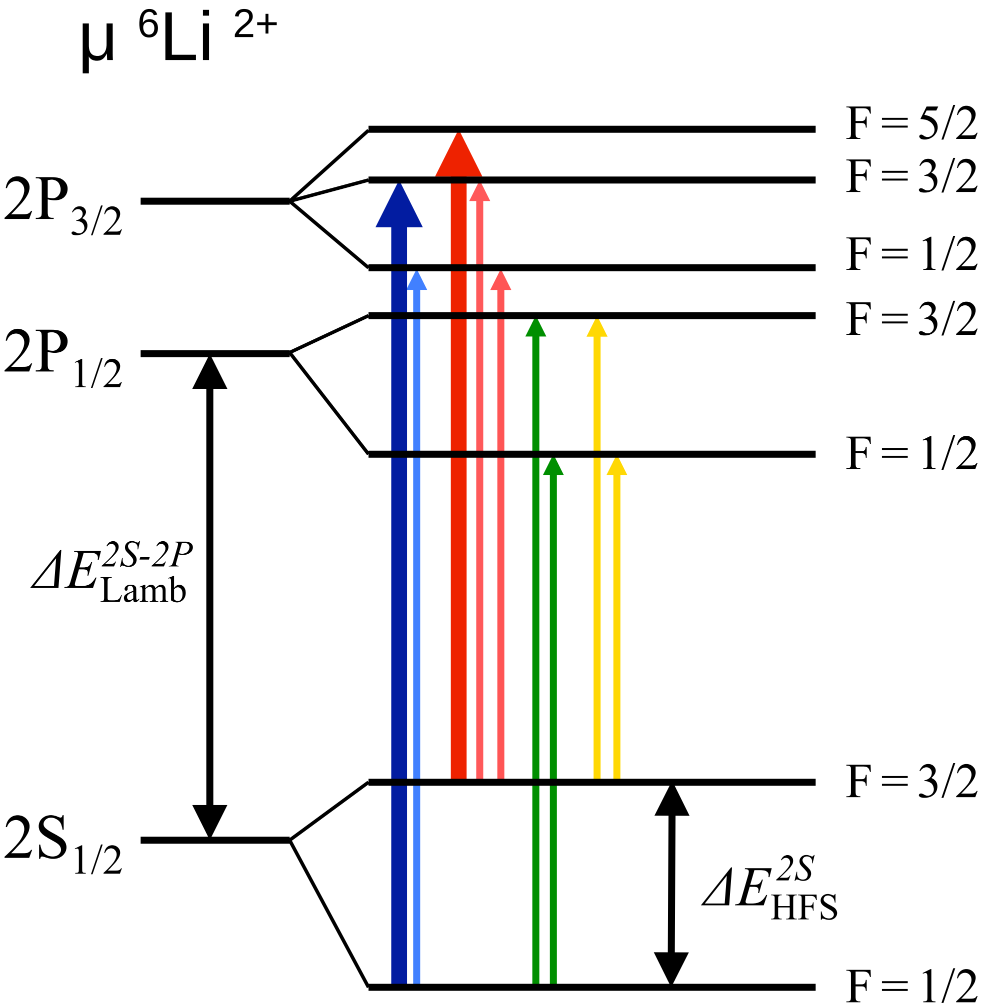


existing beam line:
1000/s at ~1 keV

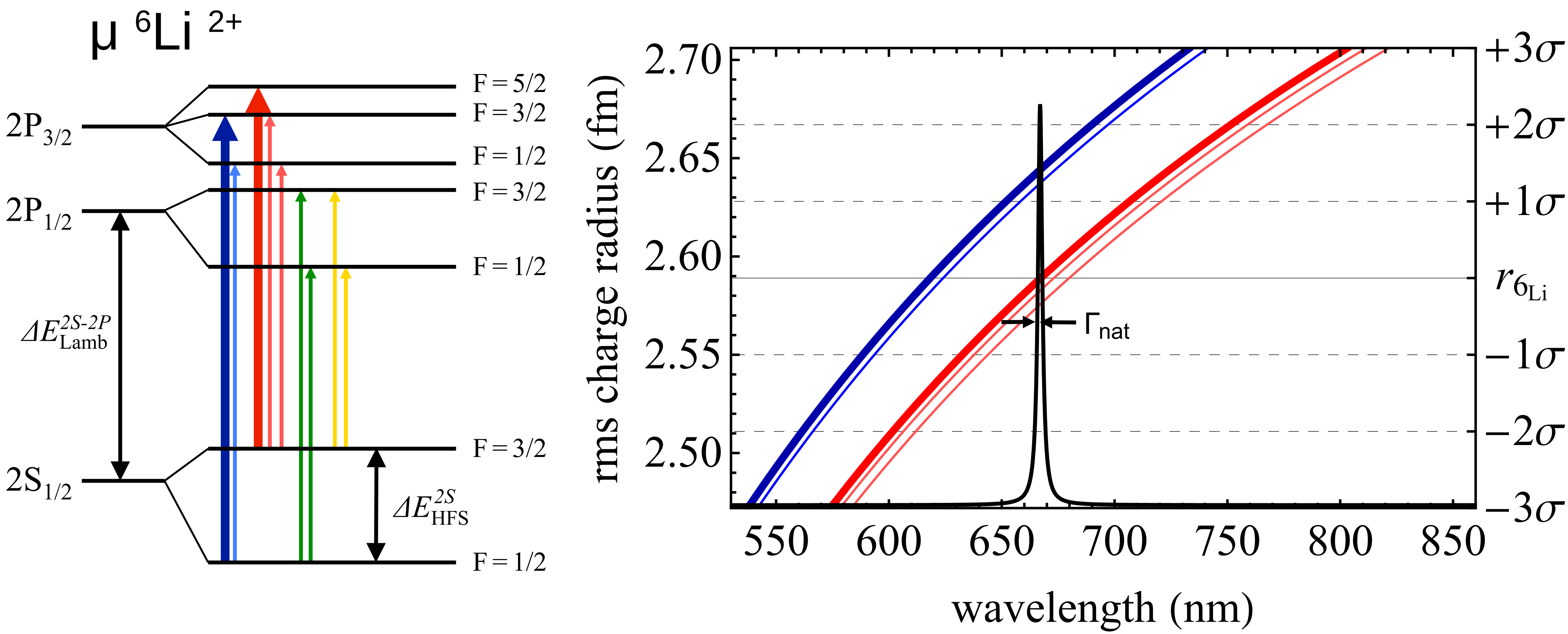
to be built:

drift tube to 100 .. 10 eV
lasers
detectors (easy)

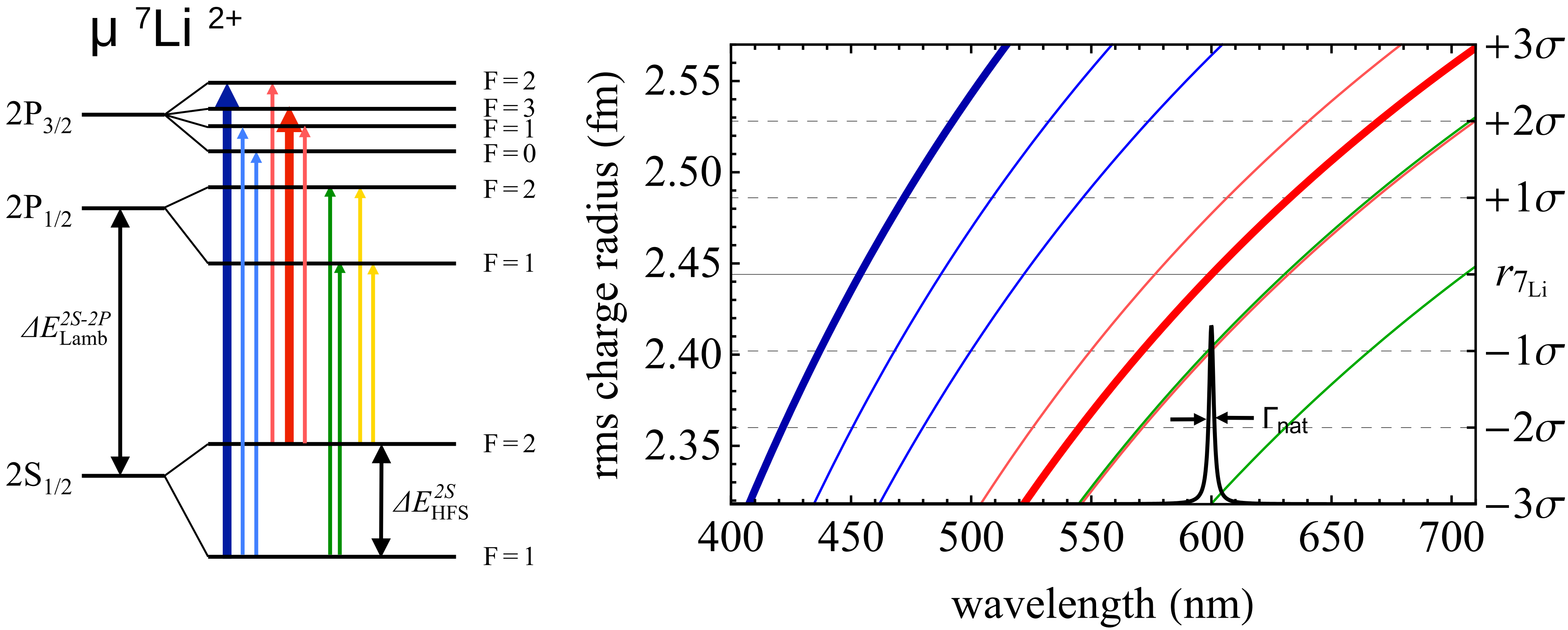
muonic Li with heat pipe target



muonic Li with heat pipe target



muonic Li with heat pipe target



muonic Li: theory and accuracy

Item	$(\mu\,^6\text{Li})^{2+}$	$(\mu\,^7\text{Li})^{2+}$
QED Lamb shift [meV]	4654.4(0.1)	4671.4(0.1)
finite size [meV]	-3712(112)	-3335(117)
nucl. shape (Friar moment) [meV]	223(9)	191(9)
nucl. polarizability [meV]	15(4)	21(4)
total Lamb shift [meV]	1162(112)(10)	1532(117)(10)
experimental accuracy goal ($\Gamma/10$) [meV]	0.7	0.7
wavelengths ($\pm 3\sigma$ in charge radius)	575-800 nm	520-710 nm

line width Γ (nm/meV)	2.3 nm $\equiv$ 6.8 meV
K_α energy	18.7 keV
2S lifetime $\tau(2S)$	830 ns

$$\boldsymbol{r}(^6\mathbf{Li}) = 2.58900(\mathbf{3900})\text{ fm [31]} \quad \rightarrow \quad 2.58xxx(\;\mathbf{40})^{\text{exp}}(\mathbf{400})^{\text{th}}\text{ fm} \qquad (\mu\,^6\text{Li})^{2+}$$

$$\boldsymbol{r}(^7\mathbf{Li}) = 2.44400(\mathbf{4200})\text{ fm [31]} \quad \rightarrow \quad 2.44xxx(\;\mathbf{40})^{\text{exp}}(\mathbf{400})^{\text{th}}\text{ fm} \qquad (\mu\,^7\text{Li})^{2+}$$

exp: 100x better radius, but polarizability -> “only” 10x better

muonic Li and Li^+

Item	$(\mu\,^6Li)^{2+}$	$(\mu\,^7Li)^{2+}$
QED Lamb shift [meV]	4654.4(0.1)	4671.4(0.1)
finite size [meV]	-3712(112)	-3335(117)
nucl. shape (Friar moment) [meV]	223(9)	191(9)
nucl. polarizability [meV]	15(4)	21(4)
total Lamb shift [meV]	1162(112)(10)	1532(117)(10)
experimental accuracy goal ($\Gamma/10$) [meV]	0.7	0.7

$\boldsymbol{r}(^6\mathbf{Li}) = 2.58900(\mathbf{3900})$ fm [31] $\rightarrow$ $2.58xxx(\,\mathbf{40})^{\mathrm{exp}}(\mathbf{400})^{\mathrm{th}}$ fm $(\mu\,^6Li)^{2+}$

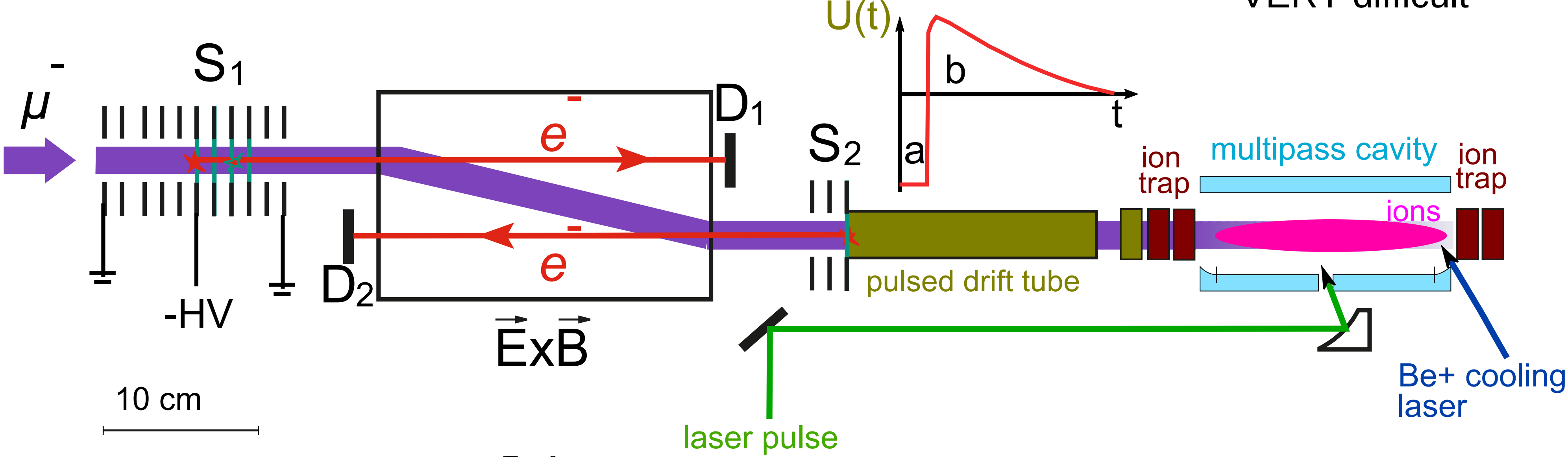
$\boldsymbol{r}(^7\mathbf{Li}) = 2.44400(\mathbf{4200})$ fm [31] $\rightarrow$ $2.44xxx(\,\mathbf{40})^{\mathrm{exp}}(\mathbf{400})^{\mathrm{th}}$ fm $(\mu\,^7Li)^{2+}$

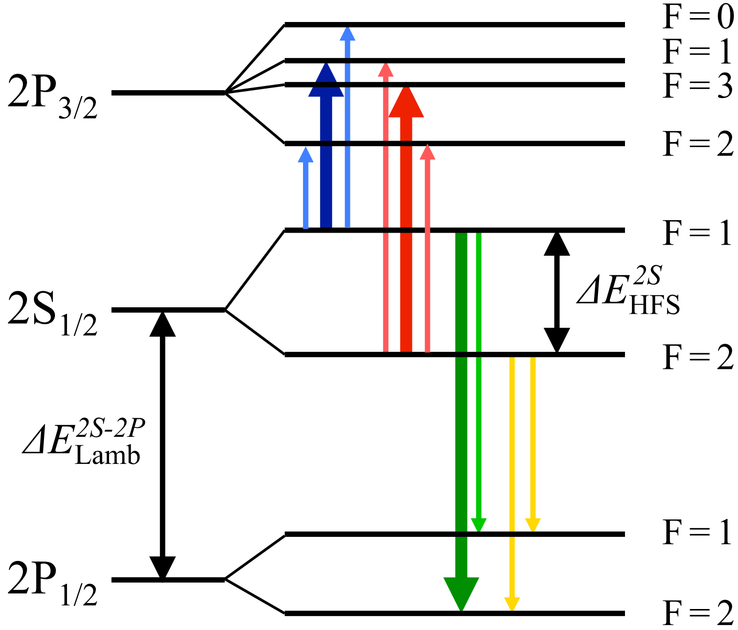
when combined with normal Li^+ (Th. Udem)

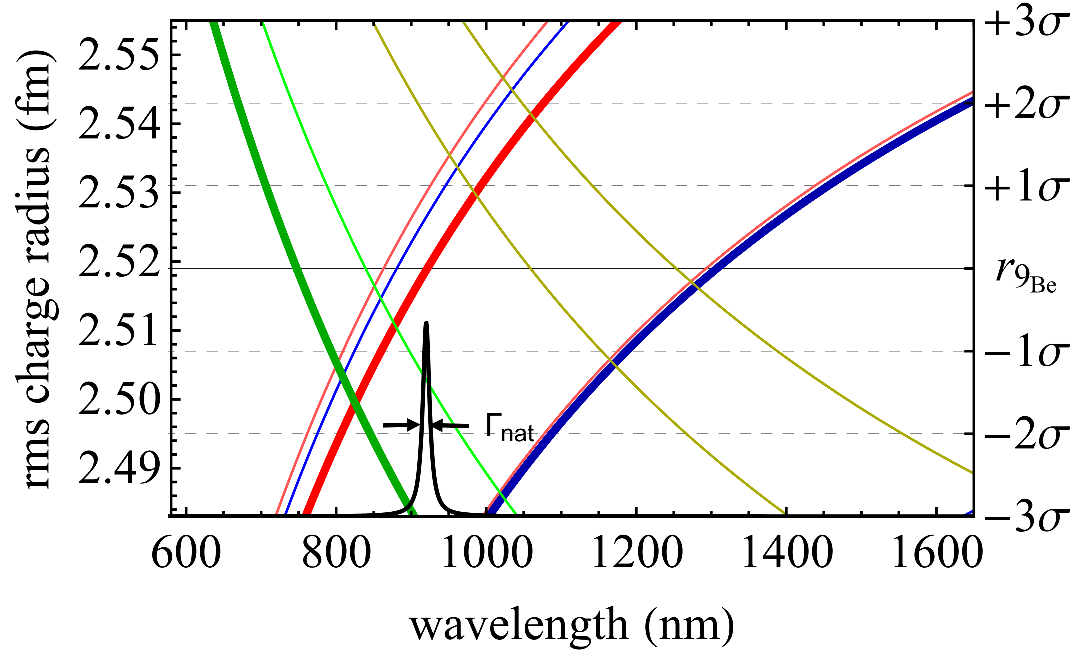
-> QED test: He/μHe vs. Li^+/μLi and
H/μH vs. He^+/μHe
Rydberg constant H, He, Li, ...
100x better radius AND 10x better polarisability,

muonic Be with Penning trap target

VERY difficult







muonic Li and Be ions

VERY difficult

$$\boldsymbol{r}(\mathbf{^6Li}) = 2.58900(\mathbf{3900})\ \mathrm{fm}\ [31] \quad \rightarrow \quad 2.58xxx(\ \mathbf{40})^{\mathrm{exp}}(\mathbf{400})^{\mathrm{th}}\ \mathrm{fm} \qquad (\mu\,^6\mathrm{Li})^{2+}$$

$$\boldsymbol{r}(\mathbf{^7Li}) = 2.44400(\mathbf{4200})\ \mathrm{fm}\ [31] \quad \rightarrow \quad 2.44xxx(\ \mathbf{40})^{\mathrm{exp}}(\mathbf{400})^{\mathrm{th}}\ \mathrm{fm} \qquad (\mu\,^7\mathrm{Li})^{2+}$$

$$\boldsymbol{r}(\mathbf{^9Be}) = 2.51900(\mathbf{1200})\ \mathrm{fm}\ [31] \quad \rightarrow \quad 2.51xxx(\ \mathbf{25})^{\mathrm{exp}}(\mathbf{230})^{\mathrm{th}}\ \mathrm{fm} \qquad (\mu\,^9\mathrm{Be})^{3+}$$

Thanks a lot for your attention

My Mainz group:

Konrad Franz, Lukas Görner, Jan Haack, Merten Heppener, Jonas Klingelhöfer, Ahmed Ouf, Siddarth Rajamohanan, Gregor Schwendler, Hendrik Schürg, Benedikt Tscharn, Andreas Westerhoff, Marcel Willig

The Garching Hydrogen Team:

Axel Beyer, Lothar Maisenbacher, Vitaly Wirthl, Arthur Matveev, RP, Ksenia Khabarova, Alexey Grinin, Tobias Lamour, Derya Taray, 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

The CREMA Collaboration

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK GARCHING
MPQ

Laboratoire Kastler Brossel
Physique quantique et applications

國立清華大學
NATIONAL TSING HUA UNIVERSITY

PAUL SCHERRER INSTITUT
PSI

ETH

· U · C ·
UNIVERSIDADE DE COIMBRA

UNIVERSIDADE NOVA DE LISBOA

universidade de aveiro

IFSW
UNIVERSITÄT STUTTGART
INSTITUT FÜR STRAHLWERKZEUGE
STUTTGART LASER TECHNOLOGIES

IFJ PAN