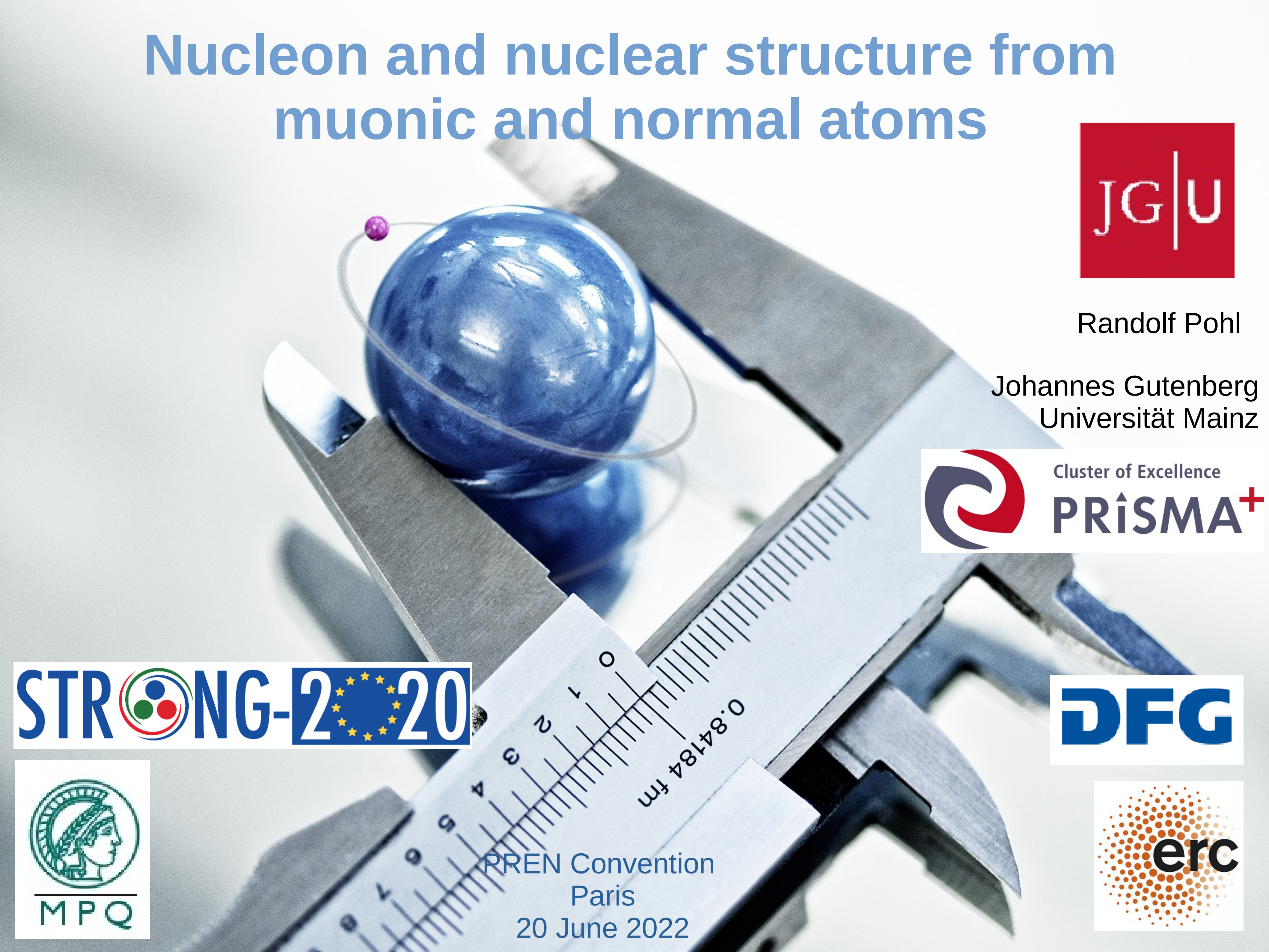
Nucleon and nuclear structure from muonic and normal atoms



Randolf Pohl

Johannes Gutenberg
Universität Mainz

PREN Convention
Paris
20 June 2022

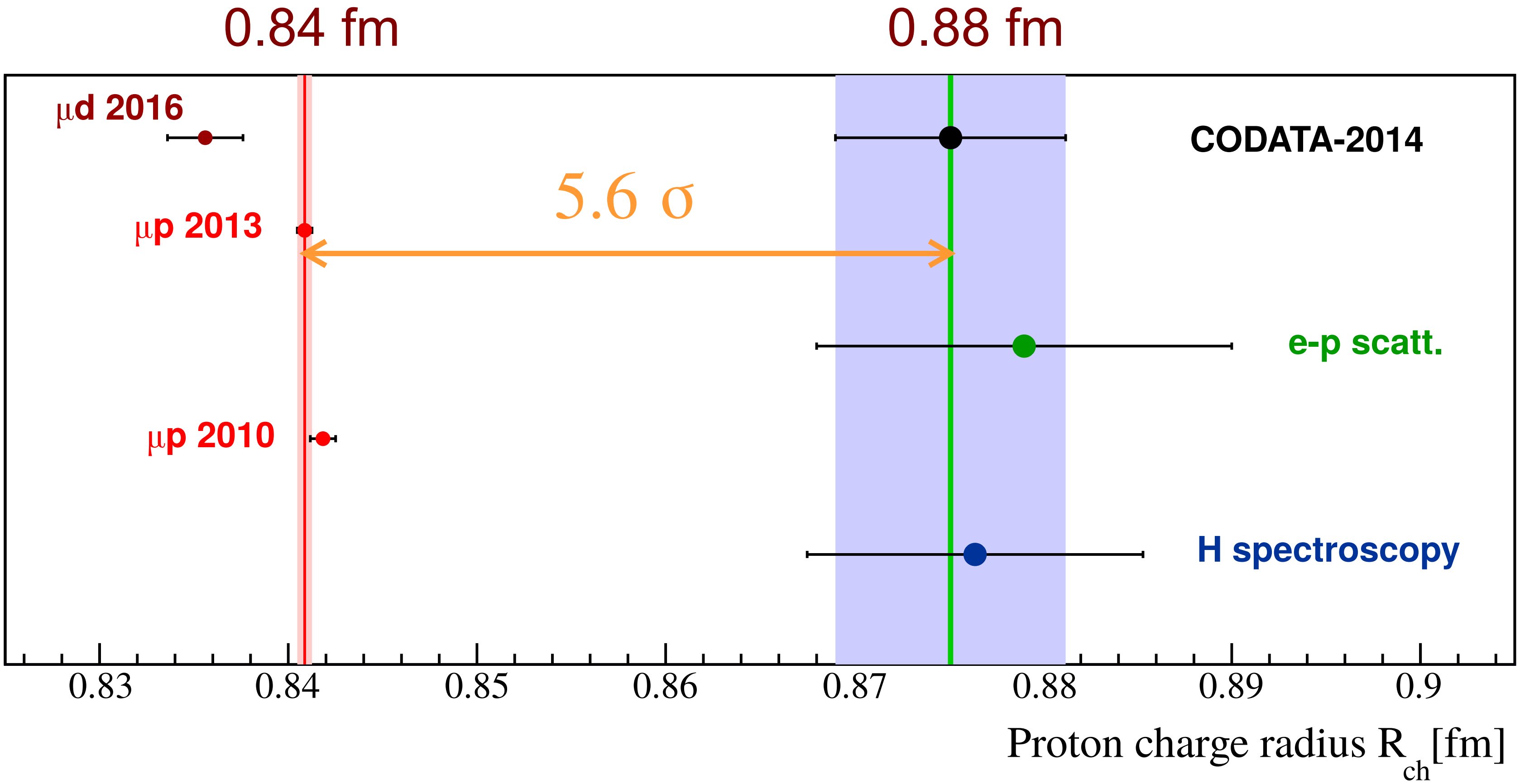
PSAS 2010 Conference

June 1st, 2010

ÉCOLE DE
PHYSIQUE
DES HOUCHES

The “Proton Radius Puzzle”

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

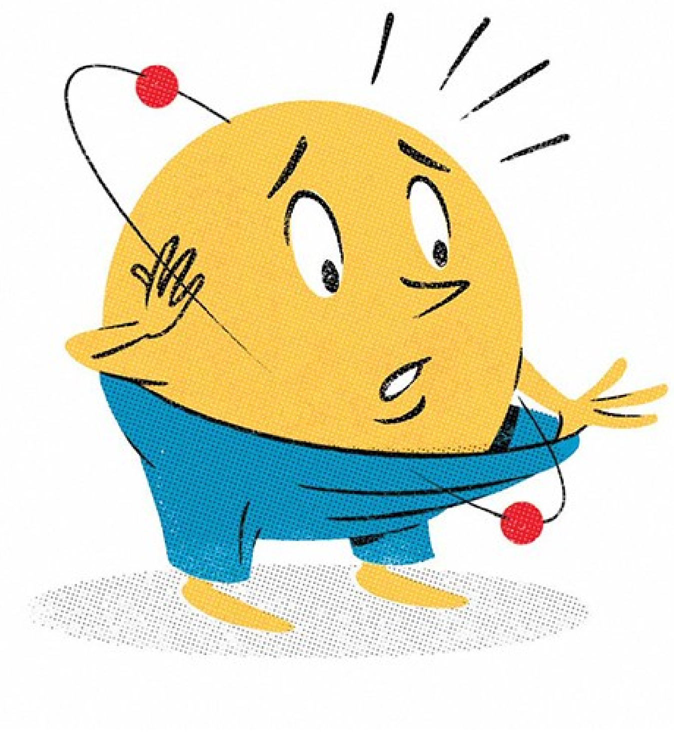


μd 2016: RP et al (CREMA Coll.) Science 353, 669 (2016)
μp 2013: A. Antognini, RP et al (CREMA Coll.) Science 339, 417 (2013)

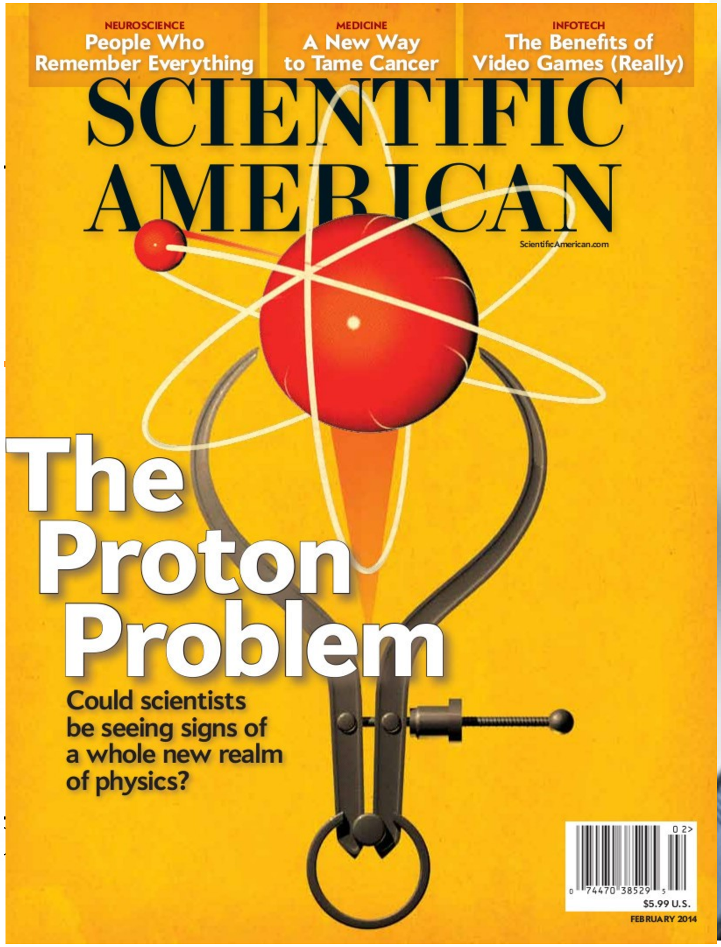
The “Proton Radius Puzzle”

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

0.84 fm



The New York Times



NEUROSCIENCE
People Who Remember Everything

MEDICINE
A New Way to Tame Cancer

INFOTECH
The Benefits of Video Games (Really)

SCIENTIFIC AMERICAN

ScientificAmerican.com

The Proton Problem

Could scientists be seeing signs of a whole new realm of physics?

$5.99 U.S.
FEBRUARY 2014

8 July 2010 | www.nature.com/nature | $10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

nature

OIL SPILLS
There's more to come

PLAGIARISM
It's worse than you think

CHIMPANZEES
The battle for survival

SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent

NATUREJOBS
Researchers for hire

$10.00US $12.99CAN

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

Workshop: The “Proton Radius Puzzle”

ECT* Trento, Italy, Oct. 2012

47 participants
 Theory + Experiment
 Atomic physics
 Nuclear physics
 Particle physics
 Electron scattering
 “Beyond Standard Model”

38 Talks
3 “Fighting Sessions”

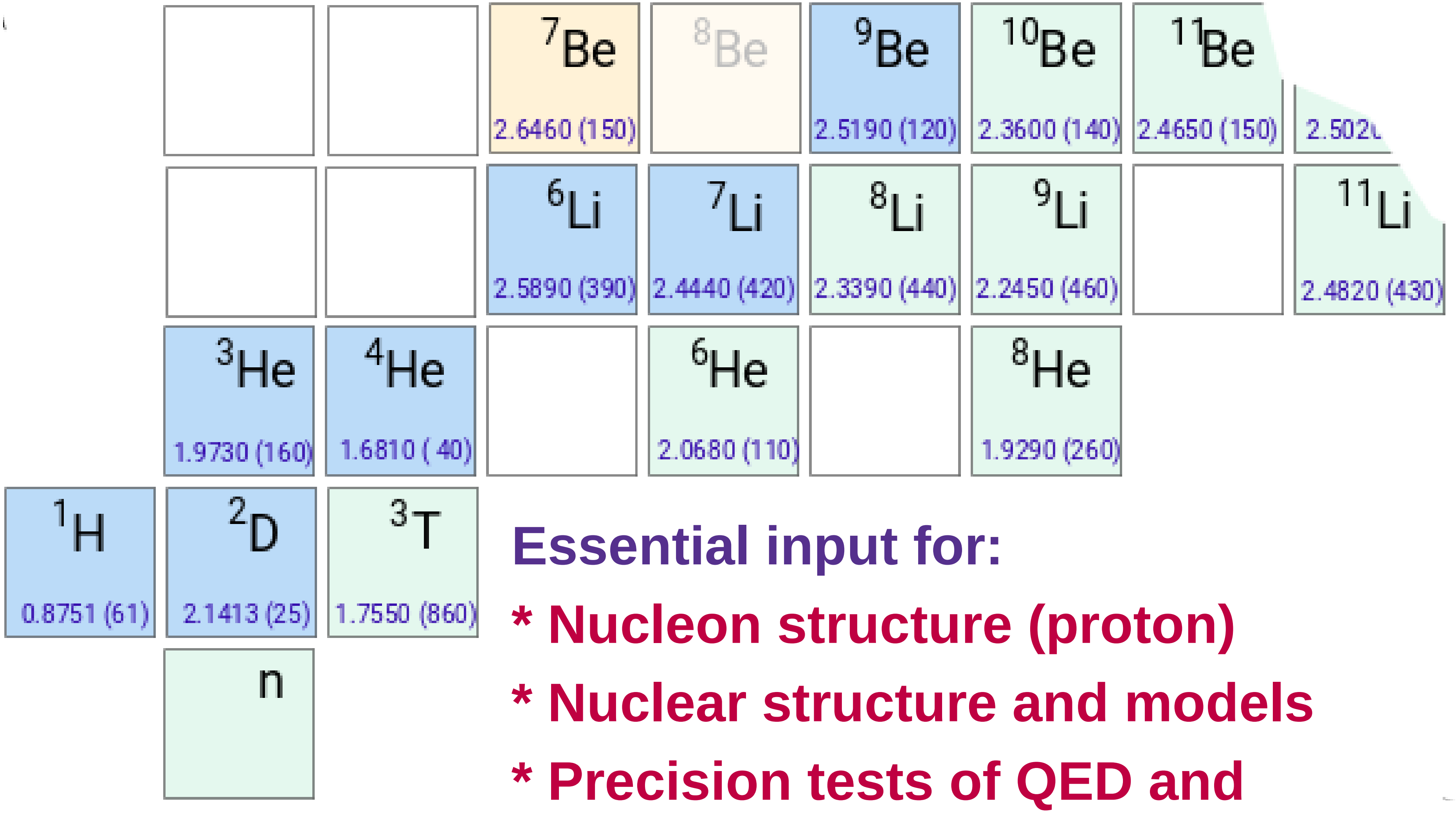
Finally: **Vote (!)**

→ Measurement problem

We need **more data**.

Follow-up conferences
*** Mainz 2014**
*** Trento 2016**
*** Mainz 2018**

Nuclear radii



			^{7}Be 2.6460 (150)	^{8}Be	^{9}Be 2.5190 (120)	^{10}Be 2.3600 (140)	^{11}Be 2.4650 (150)	2.502
			^{6}Li 2.5890 (390)	^{7}Li 2.4440 (420)	^{8}Li 2.3390 (440)	^{9}Li 2.2450 (460)		^{11}Li 2.4820 (430)
	^{3}He 1.9730 (160)	^{4}He 1.6810 (40)		^{6}He 2.0680 (110)		^{8}He 1.9290 (260)		
^{1}H 0.8751 (61)	^{2}D 2.1413 (25)	^{3}T 1.7550 (860)						
	n							

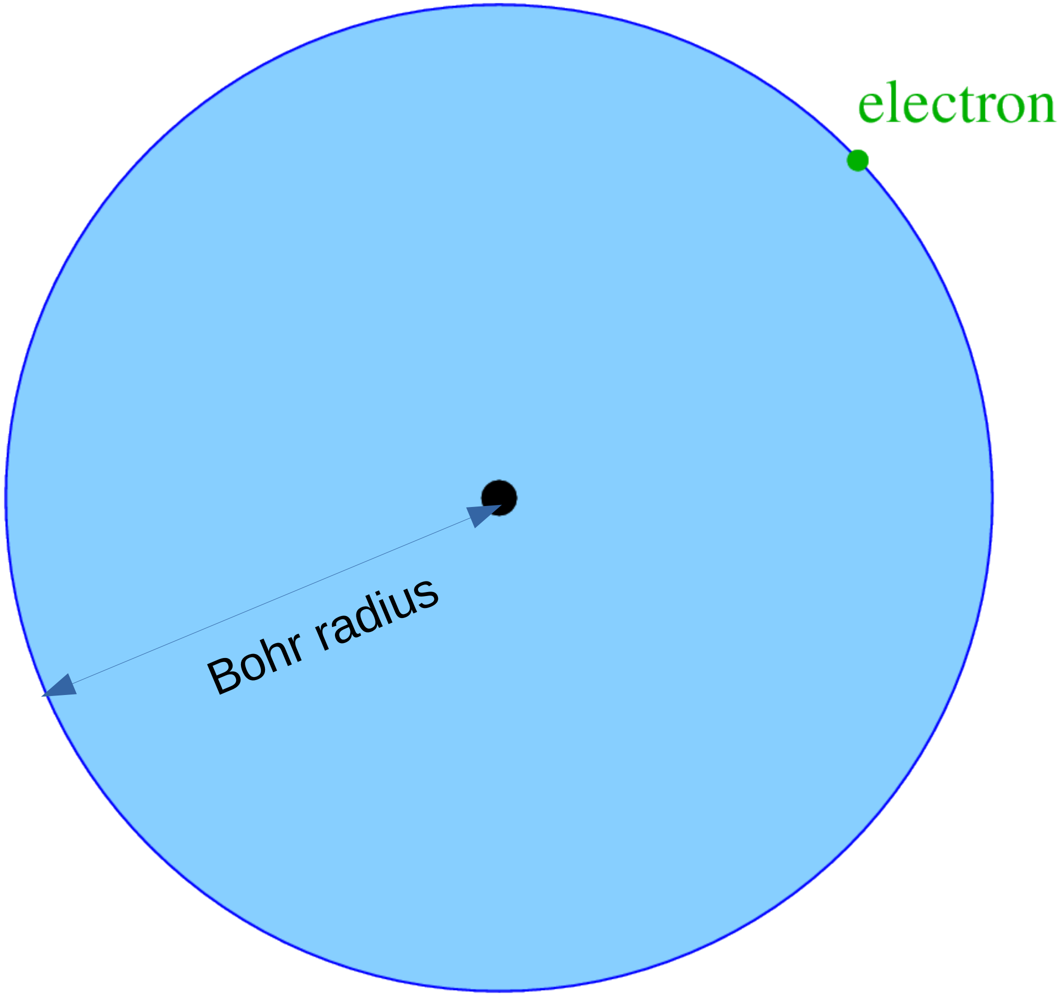
Essential input for:

- * Nucleon structure (proton)
- * Nuclear structure and models
- * Precision tests of QED and the Standard Model
- * Fundamental constants (CODATA)

Electronic and muonic atoms

Regular hydrogen:

Proton + Electron



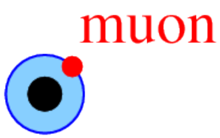
Muonic hydrogen:

Proton + Muon

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

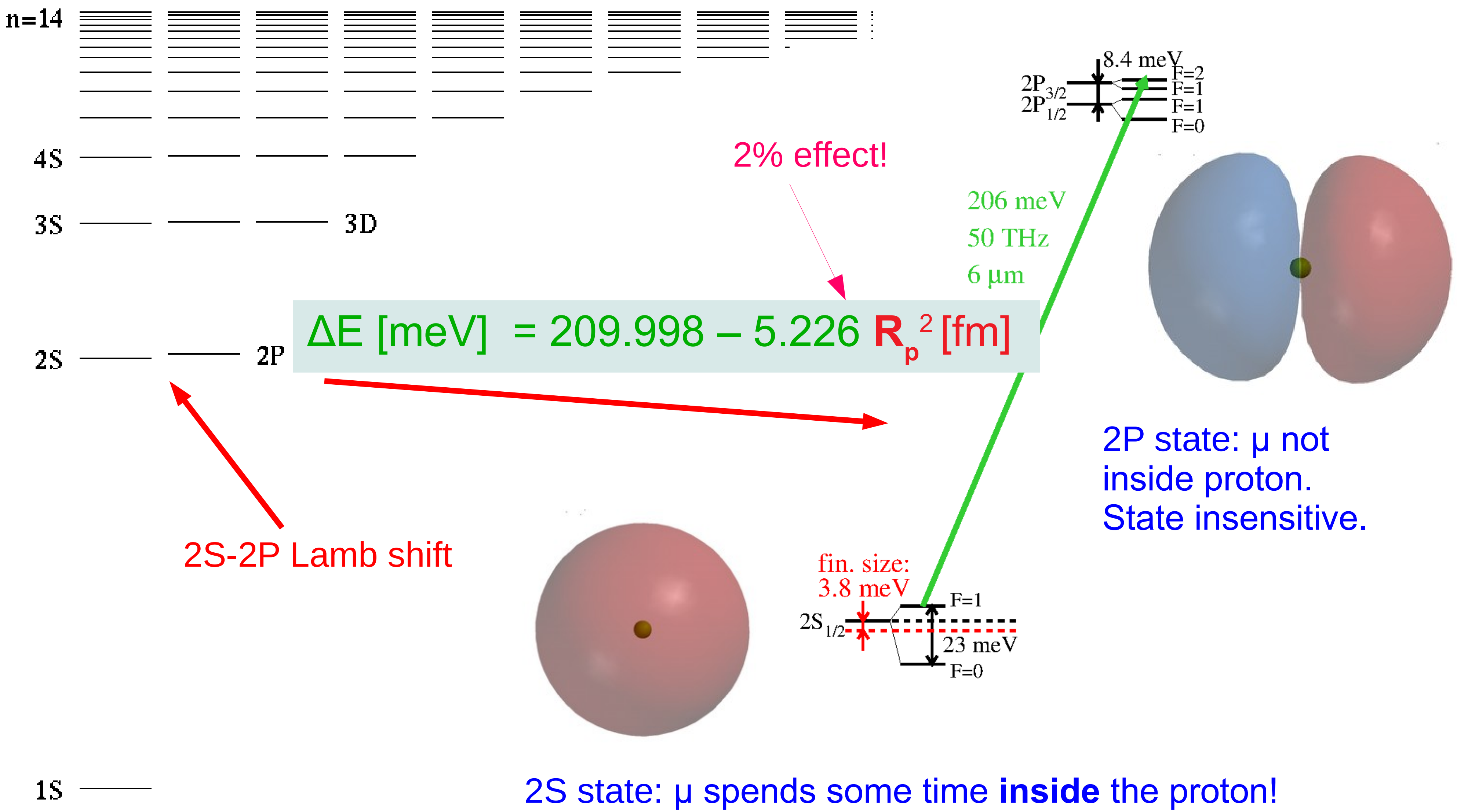
Bohr **radius** = **1/200** of H

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



Vastly not to scale!!

Lamb shift in Muonic Hydrogen



2% effect!

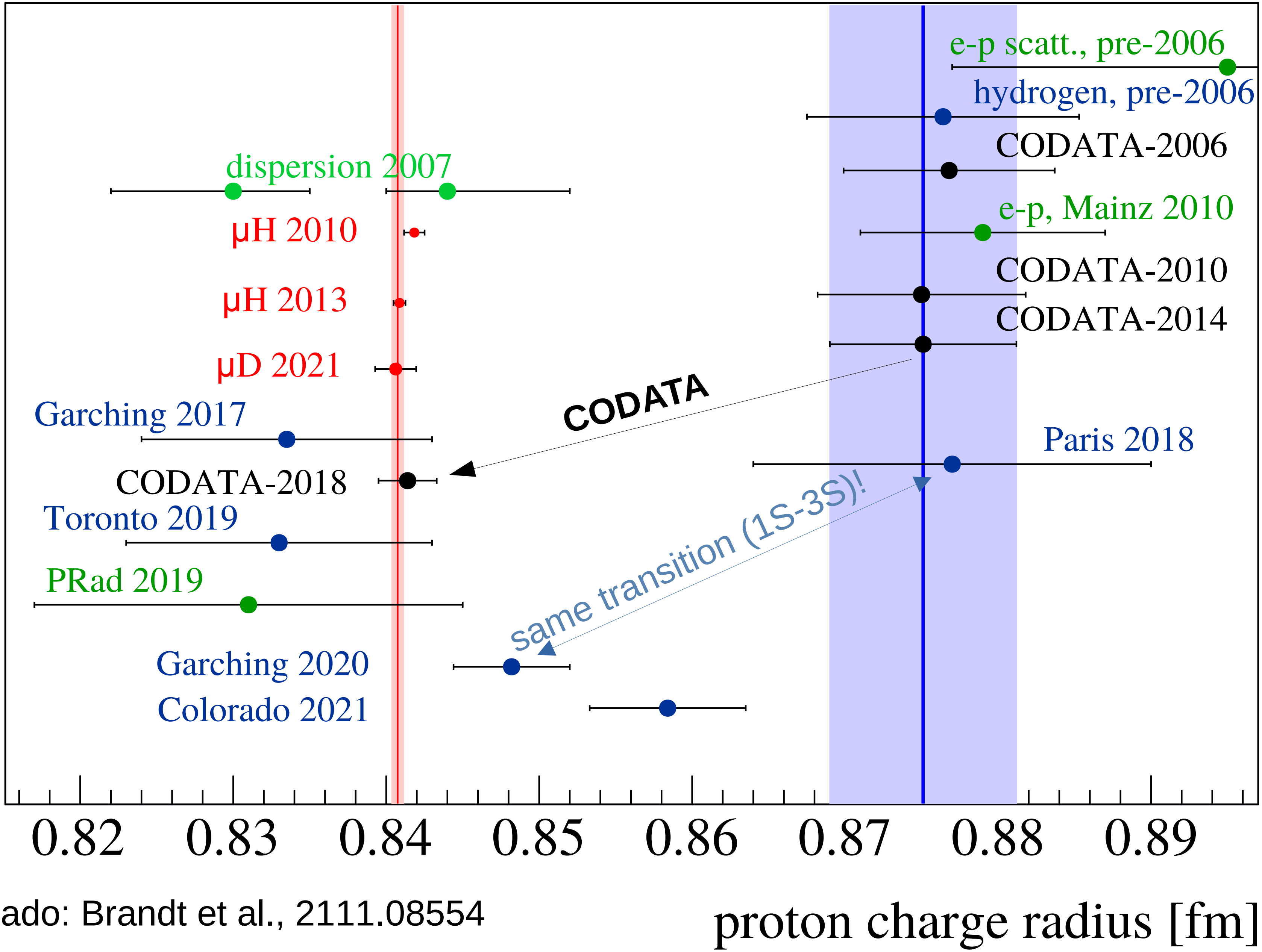
$$\Delta E\ [\text{meV}] = 209.998 - 5.226\ \mathbf{R_p}^2\ [\text{fm}]$$

2S-2P Lamb shift

2P state: μ not
inside proton.
State insensitive.

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

The situation in 2021



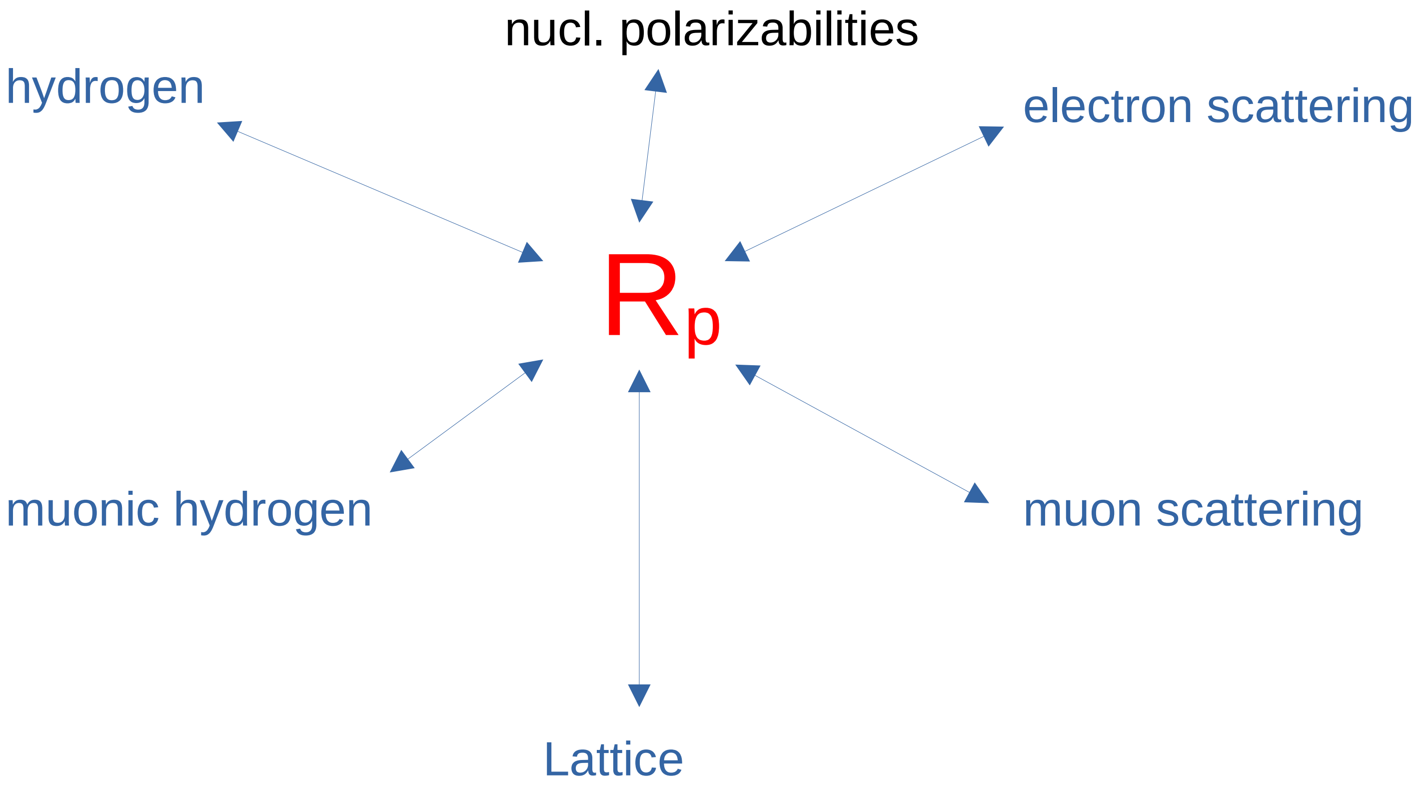
Colorado: Brandt et al., 2111.08554

Proton charge radius puzzle “solved”?

Why was the proton radius so interesting?

QED

Standard Model



nucl. polarizabilities

hydrogen

electron scattering

R_p

muonic hydrogen

muon scattering

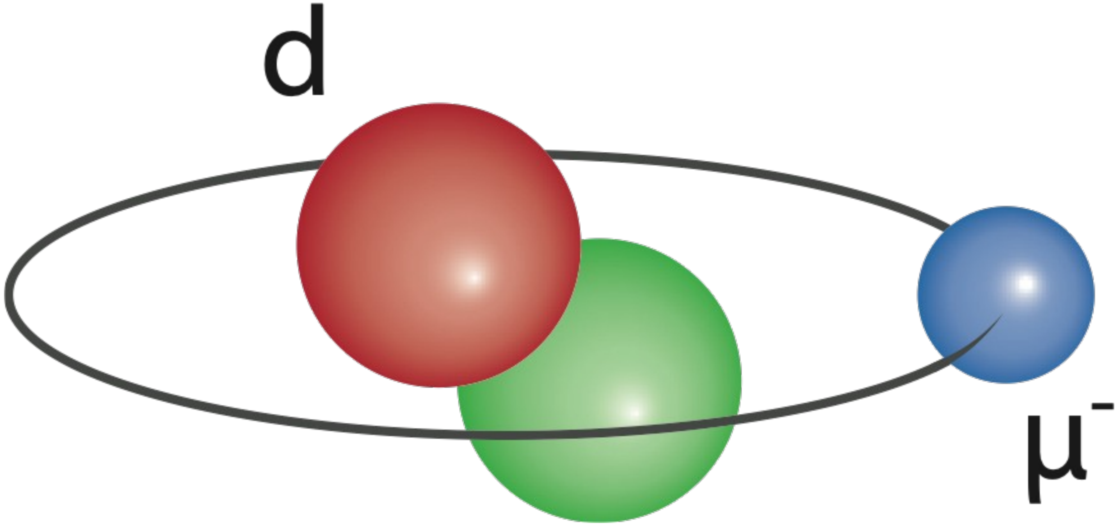
Lattice

Hyperfine structure in muonic H

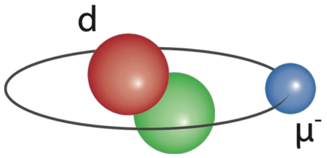
CREMA-3 / HyperMu at PSI
(R16.02)

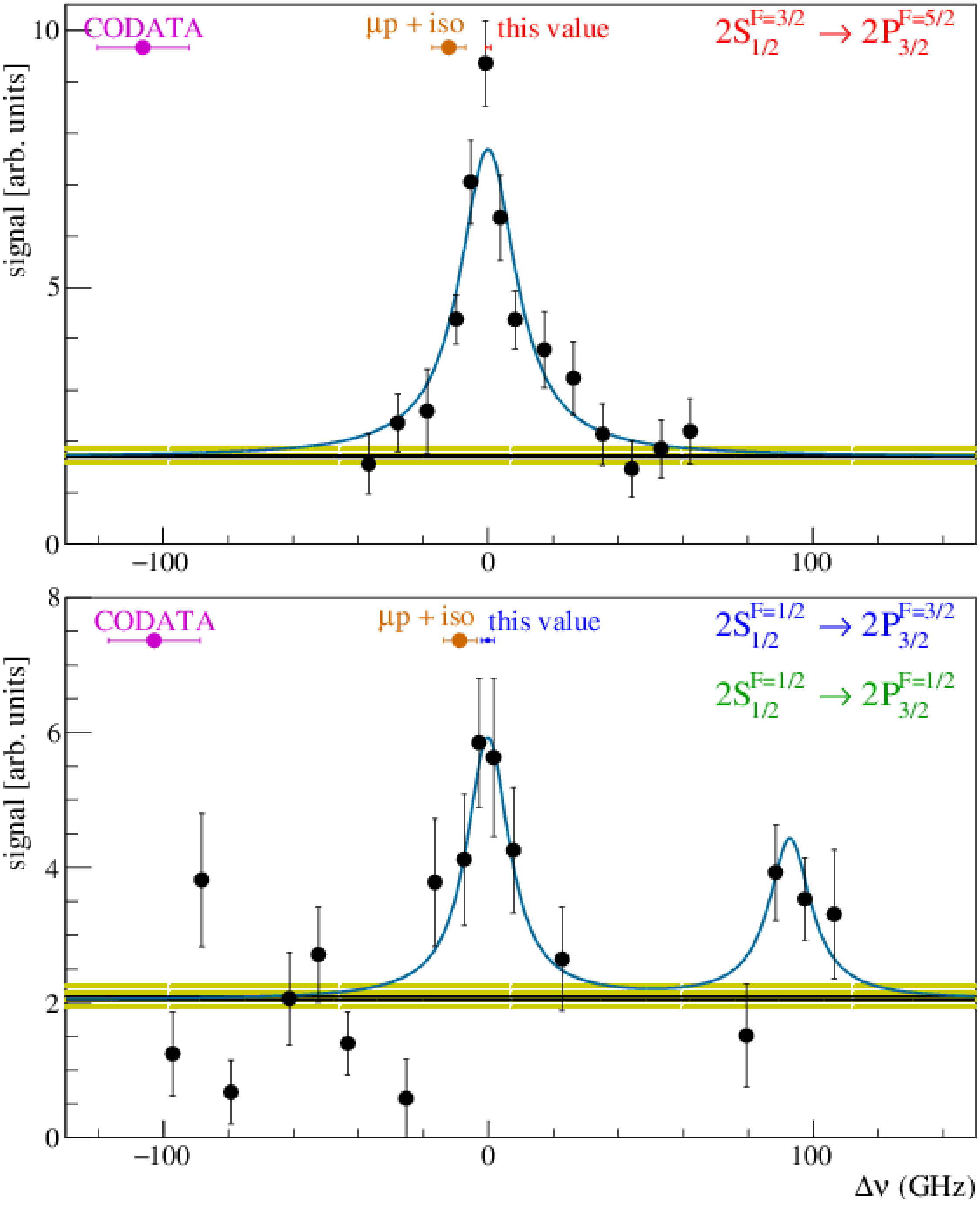
talk by Aldo

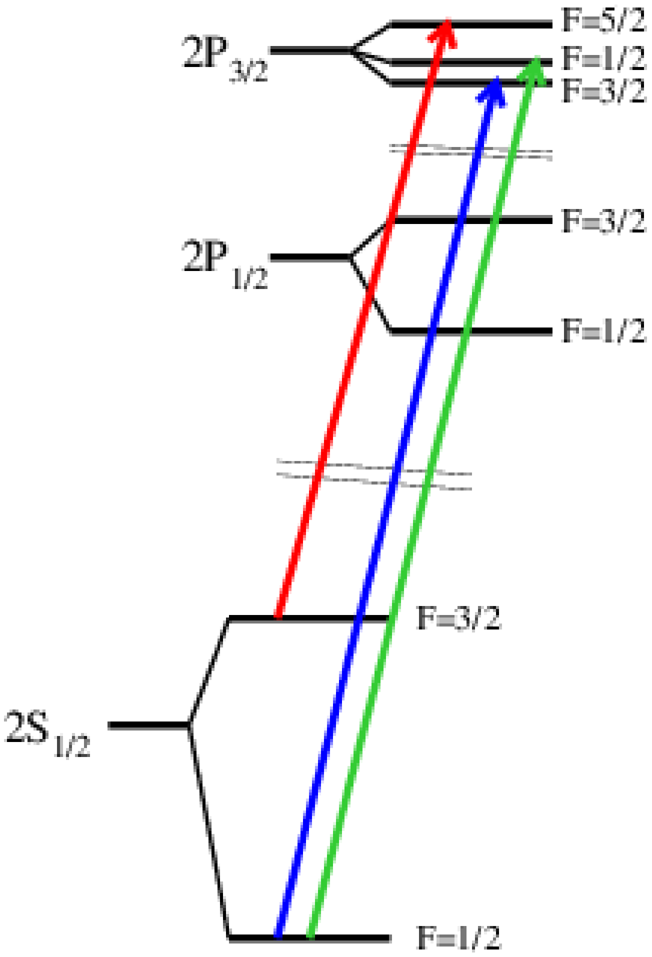
Muonic Deuterium



2.5 transitions in muonic D







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

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

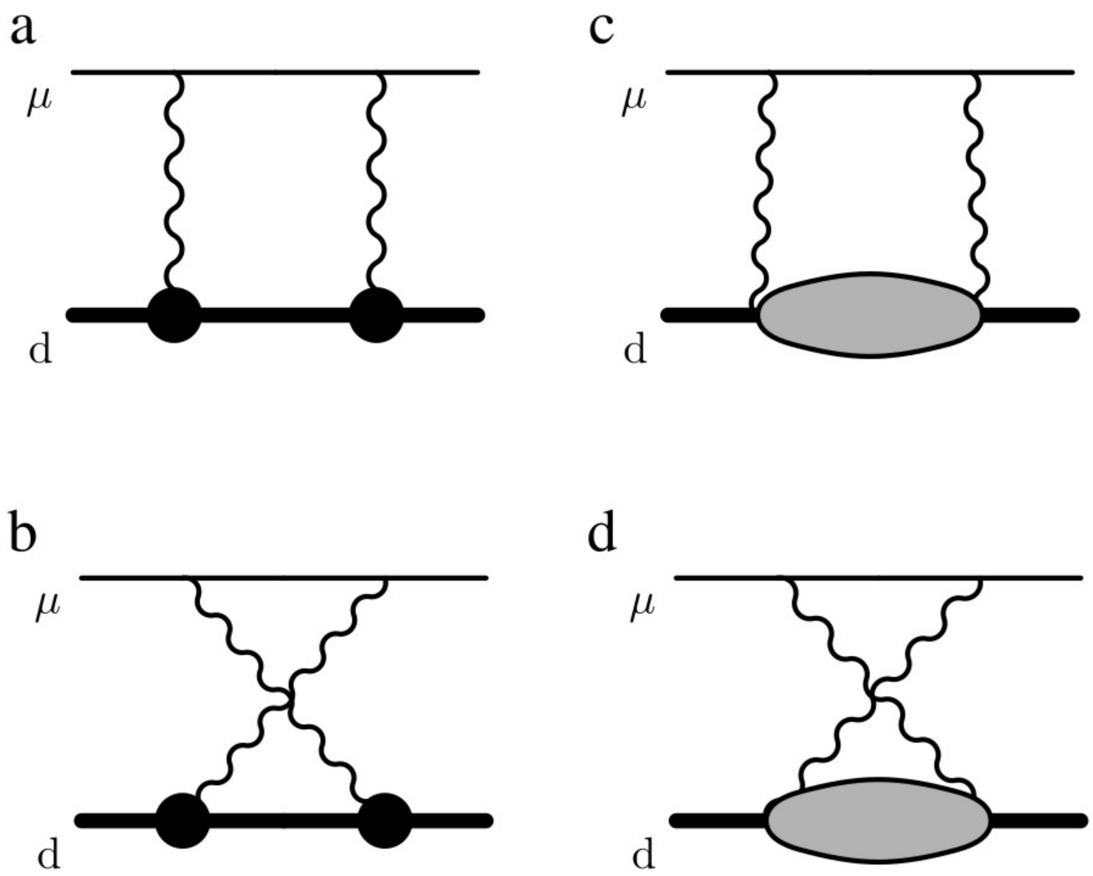
Pohl et al. (CREMA Coll.), Science 353, 669 (2016)

Theory: Lamb shift in muonic D

$$\Delta E^{\mu D}_{\mathrm{Lamb}} = 228.7854\,(13)\ \mathrm{meV}_{\mathrm{QED}} + 1.7653\,(\mathbf{130})\ \mathrm{meV}_{\mathrm{TPE}} - 6.1103\,(3)\ \mathrm{meV/fm}^2 * \mathbf{R_d}^{\mathbf{2}}$$

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

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



Krauth, RP et al. (2016) using calculations from

* Pachucki (2011)
* Friar (2013)
* Carlson, Gorchtein, Vanderhaeghen (2014)
* Hernandez et al. (2014)
* Pachucki + Wienczek (2015)

plus new refinements

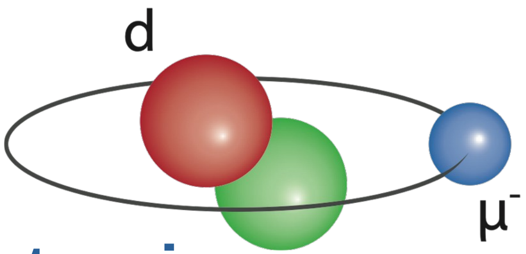
\+ Pachucki et al., PRA 97, 062511 (2018)
Sizeable three-photon contribution!

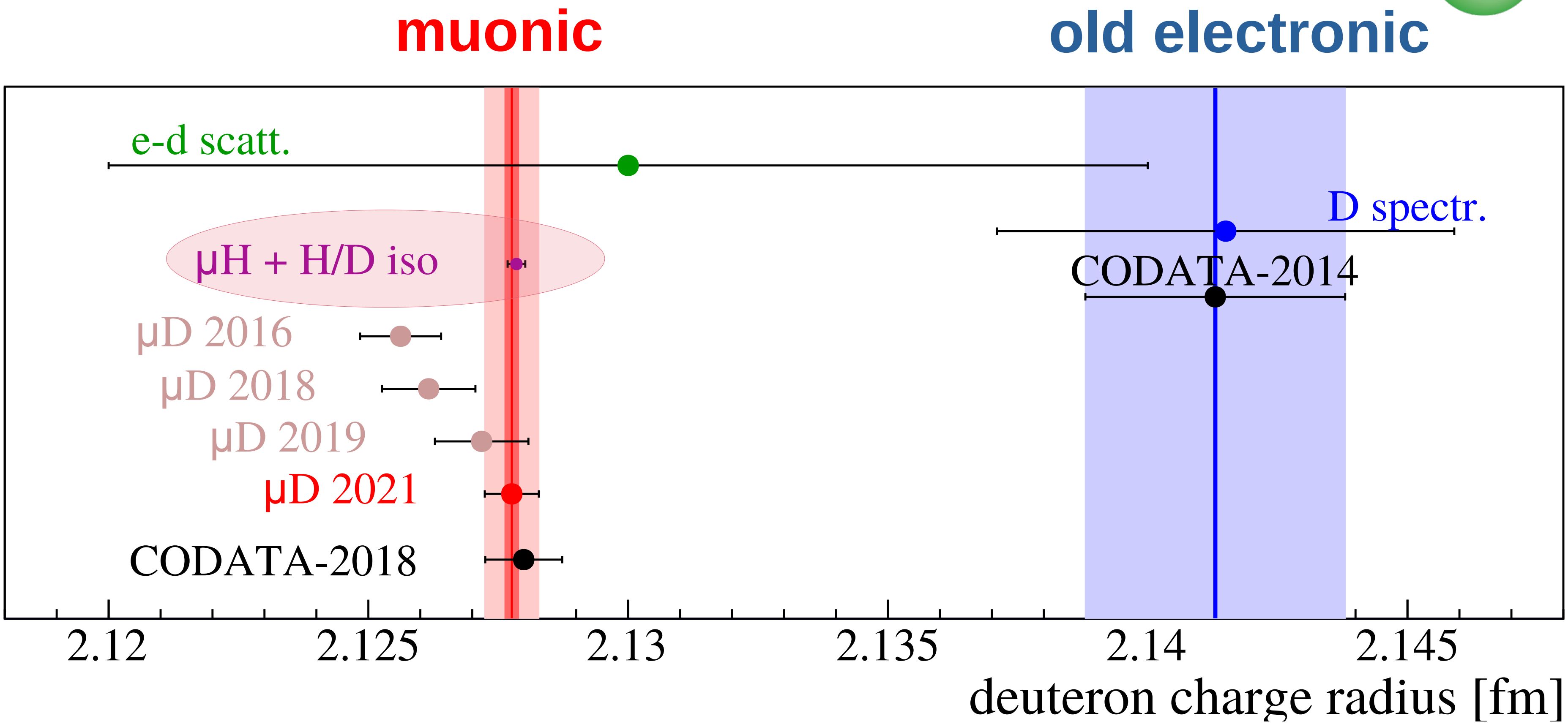
\+ Hernandez et al., PLB 778, 377 (2018)
χEFT

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

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

Muonic Deuterium





μD: 2.12776 $(13)_{exp}$ $(50)_{theo}$ fm

nucl. polarizability = 2- and **3-photon** exchange: Bacca, Pachucki, Vanderhaeghen, Carlson, Hernandez, Acharya, Kalinowski, …

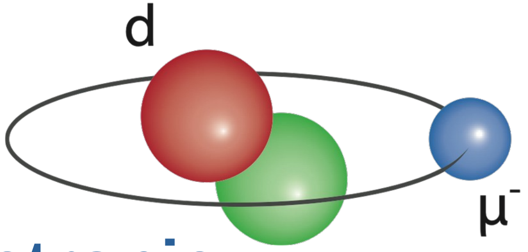
μH + H/D(1S-2S): 2.12785 (17) fm

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

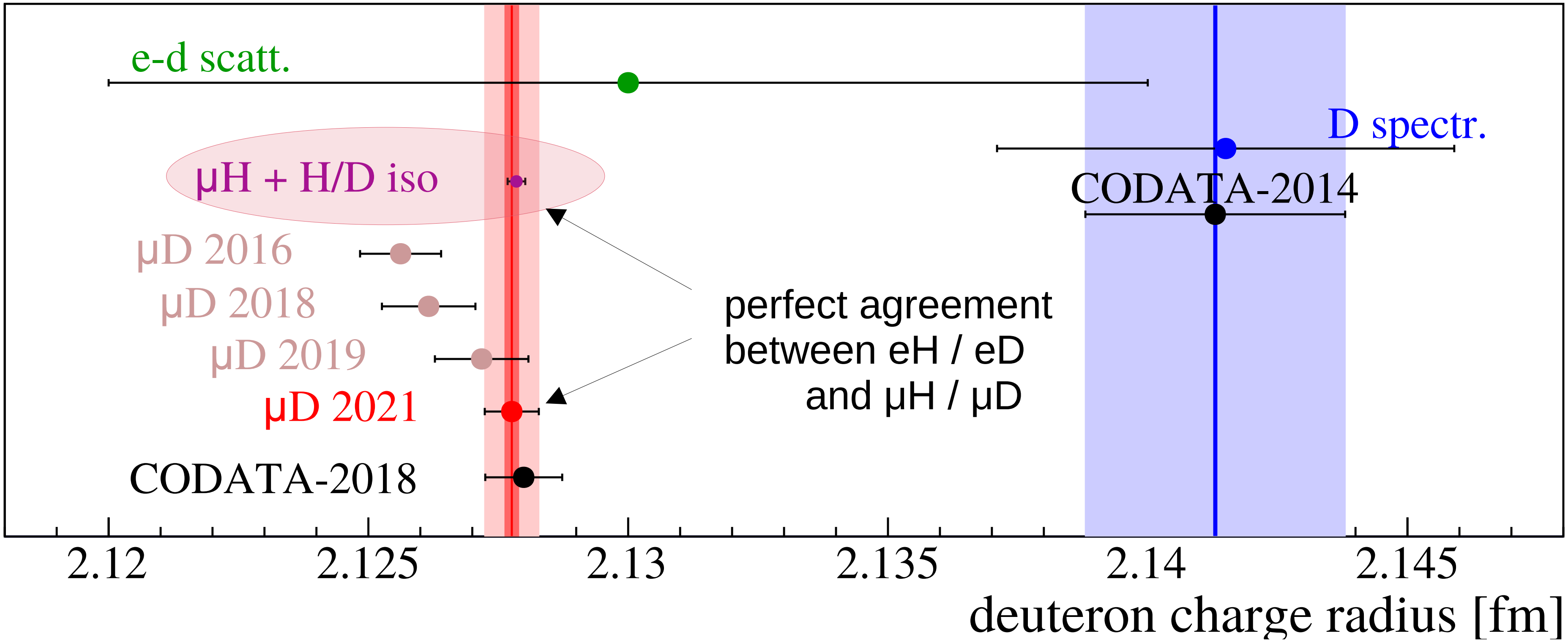
H/D 1S-2S isotope shift:
$r_d^2 - r_p^2 = 3.82070(31)\ \mathrm{fm}^2$

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

Muonic Deuterium



muonic **old electronic**



perfect agreement
between eH / eD
and μH / μD

$r_d^2 - r_p^2 =$ 3.82070(31) fm^2 H / D 1S-2S isotope shift   Pachucki et al., PRA 97, 062511 (2018)

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

TPE in muonic D

$\Delta E^{\mu D}_{\mathrm{Lamb}}$ = 228.7854 (13) $\mathrm{meV}_{\mathrm{QED}}$ + 1.7653 (**130**) $\mathrm{meV}_{\mathrm{TPE}}$ – 6.1103 (3) $\mathrm{meV/fm}^2$ * $\mathbf{R_d}^{\mathbf{2}}$

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

ΔE_{TPE} (theo) = 1.7653 +- 0.0130 meV

vs. +- 0.0034 meV experimental uncertainty

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

r_d (μD) = 2.12776 (13) $_{\mathrm{exp}}$ (51) $_{\mathrm{theo}}$ fm vs.

r_d (μH + H/D iso) = 2.12785 (17) fm

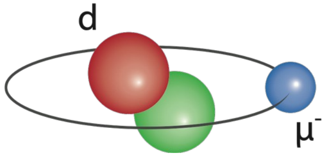
(2) **polarizability**, using **charge radius from isotope shift**

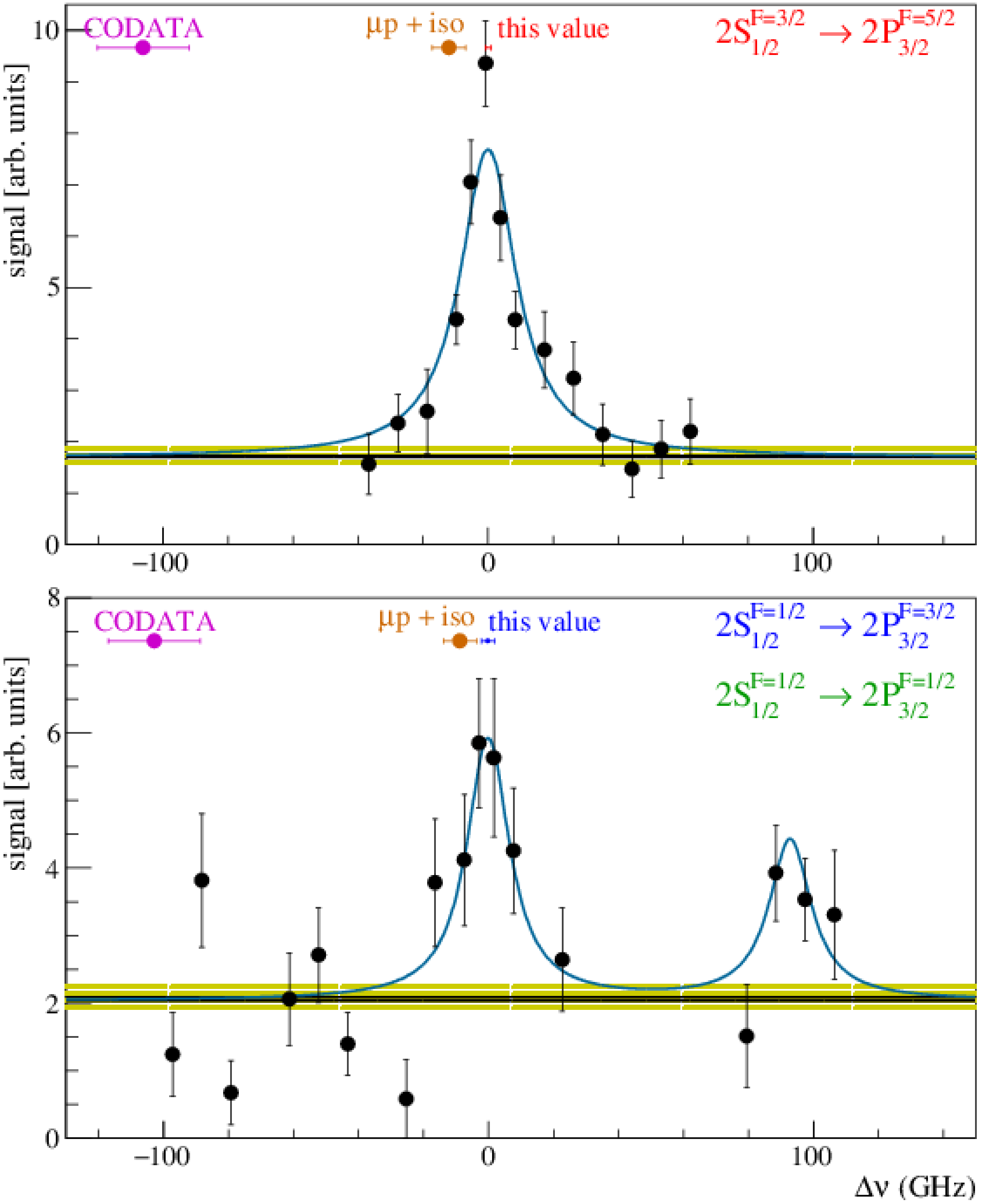
ΔE_{TPE} (theo) = 1.7653 (130) meV vs.

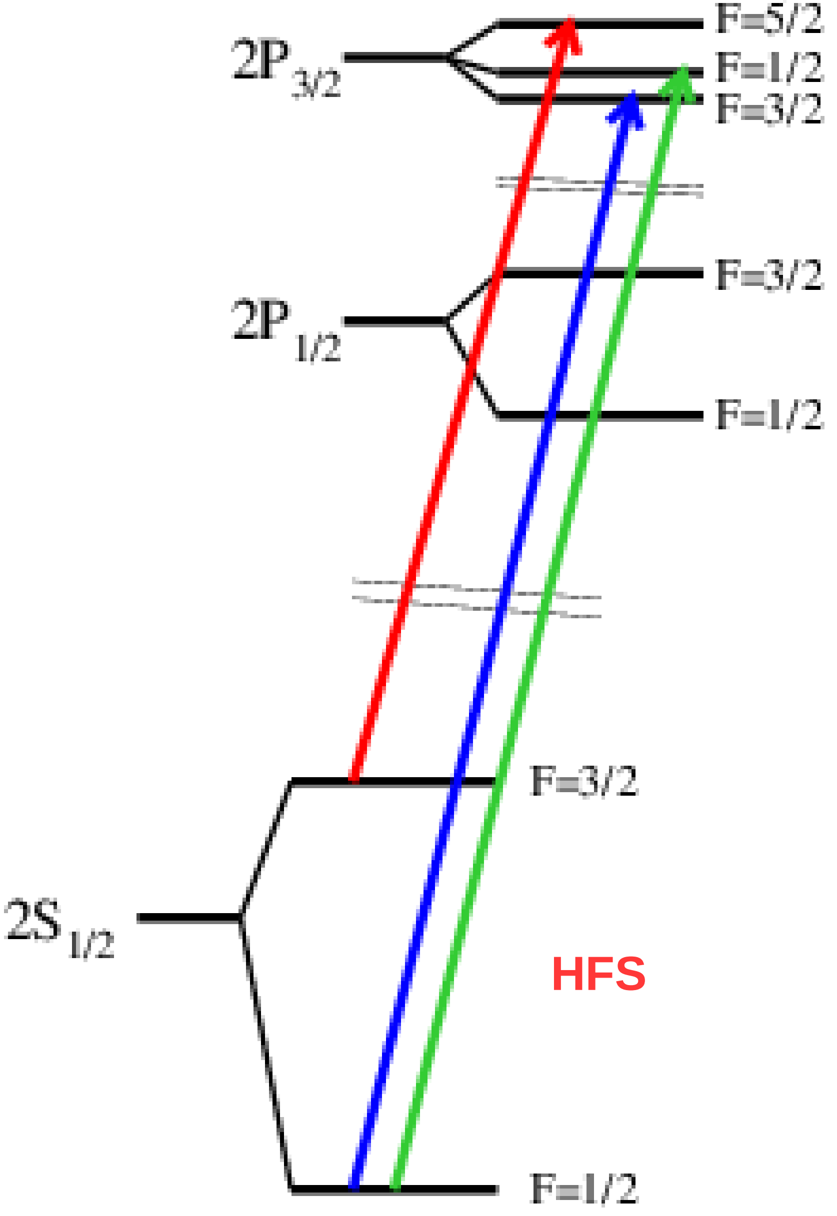
ΔE_{TPE} (exp) = 1.7591 (59) meV 2x more accurate

Krauth et al. (2016) + Pachucki et al. (2018) + Hernandez et al. (2018) + Kalinowski (2019) + Acharya (2021)

HFS in muonic D

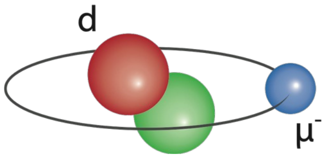


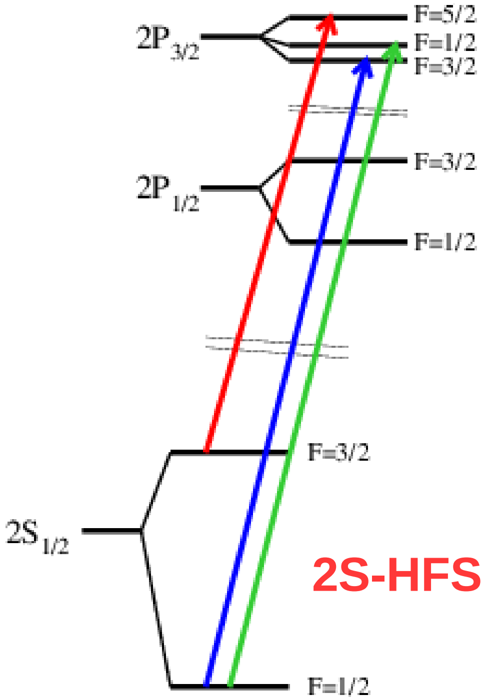




Pohl et al. (CREMA Coll.), Science 353, 669 (2016)

HFS in muonic D





nucl. TPE scaled from electronic D

$$\begin{aligned}\Delta E^{\mathrm{th}}_{\mathrm{HFS}} &= 6.17420(73)\ \mathrm{meV} + 0.22260(490)\ \mathrm{meV} - 0.04539\, r_Z\ \mathrm{meV/fm}\\ &= 6.39680(494)\ \mathrm{meV} - 0.04539\, r_Z\ \mathrm{meV/fm}.\end{aligned}$$

Using the Zemach radius $r_Z = (2.593 \pm 0.016)$ fm [78] we get:

$$\Delta E^{\mathrm{th}}_{\mathrm{HFS}} = 6.2791(50)\ \mathrm{meV}$$

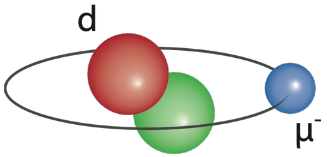
Krauth et al., Ann. Phys. (N.Y.) 366, 168 (2016)

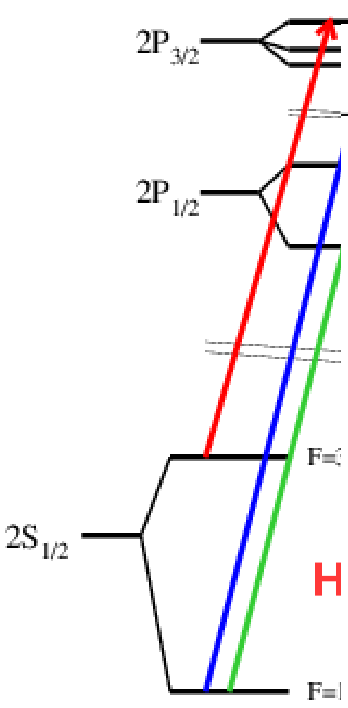
$$\Delta E^{\mathrm{exp}}_{\mathrm{HFS}} = 6.2747(70)_{\mathrm{stat}}(20)_{\mathrm{syst}}\ \mathrm{meV} \qquad (6)$$

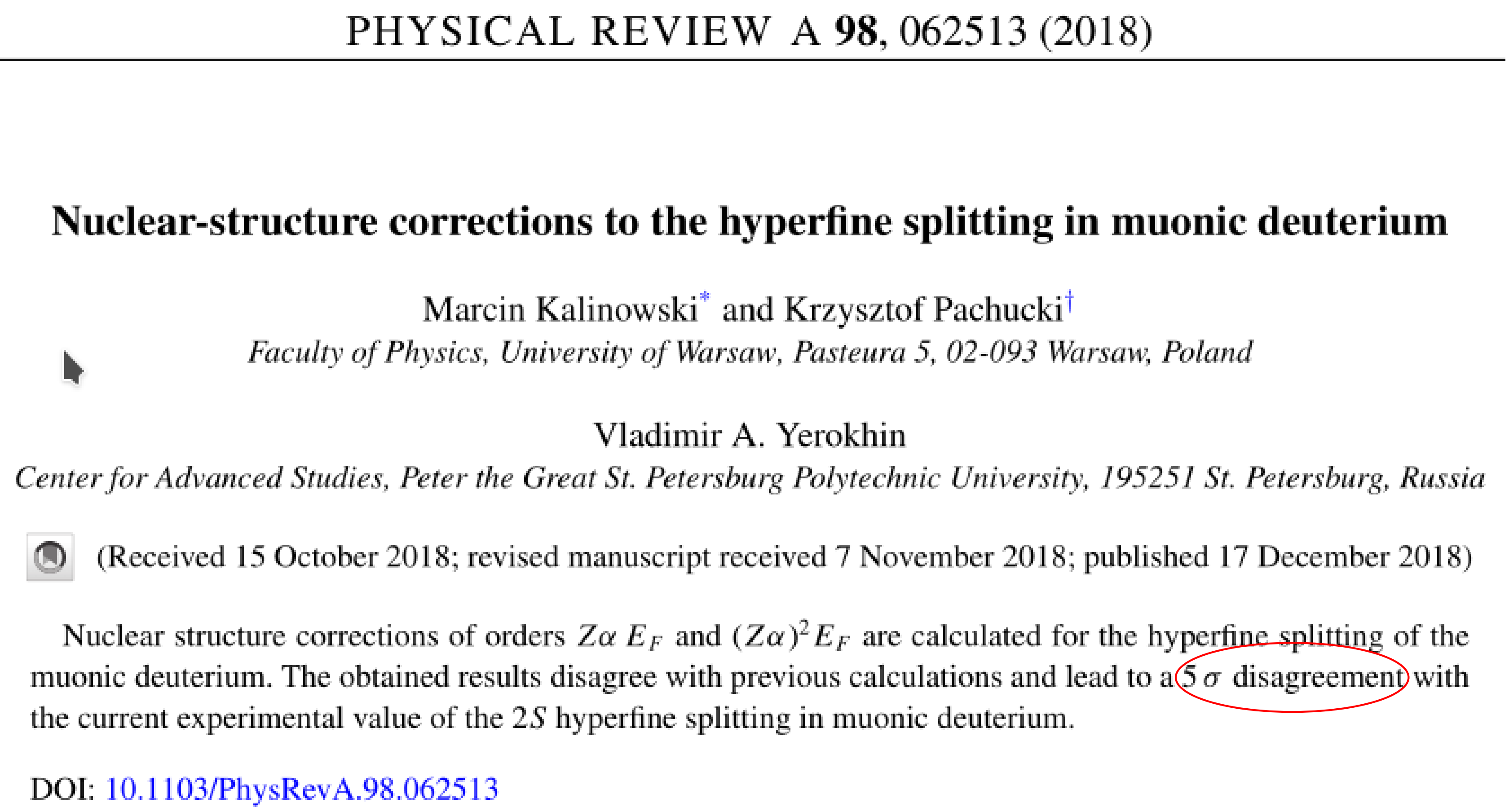
Pohl et al. (CREMA Coll.), Science 353, 669 (2016)

perfect agreement between theory and experiment !!???

HFS in muonic D






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

Nuclear-structure corrections to the hyperfine splitting in muonic deuterium

Marcin Kalinowski* and Krzysztof Pachucki†
Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland

Vladimir A. Yerokhin
Center for Advanced Studies, Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia

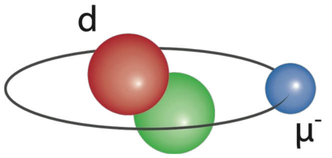
(Received 15 October 2018; revised manuscript received 7 November 2018; published 17 December 2018)

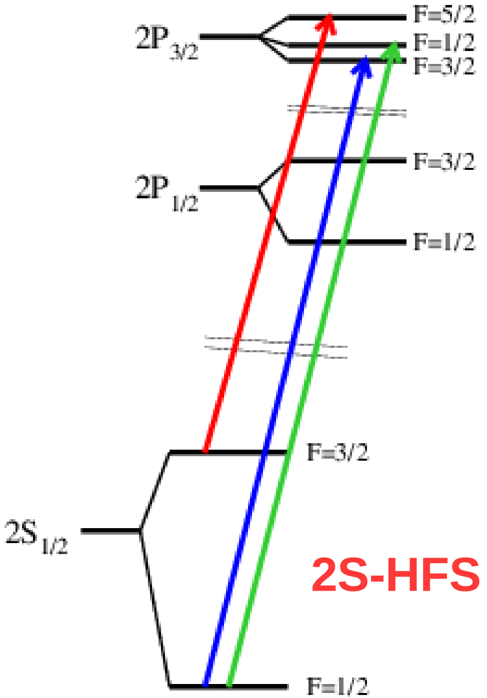
Nuclear structure corrections of orders $Z\alpha\, E_F$ and $(Z\alpha)^2 E_F$ are calculated for the hyperfine splitting of the muonic deuterium. The obtained results disagree with previous calculations and lead to a $5\,\sigma$ disagreement with the current experimental value of the 2S hyperfine splitting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

DOI: 10.1103/PhysRevA.98.062513

Another 5σ disagreement between theory and experiment !!

HFS in muonic D





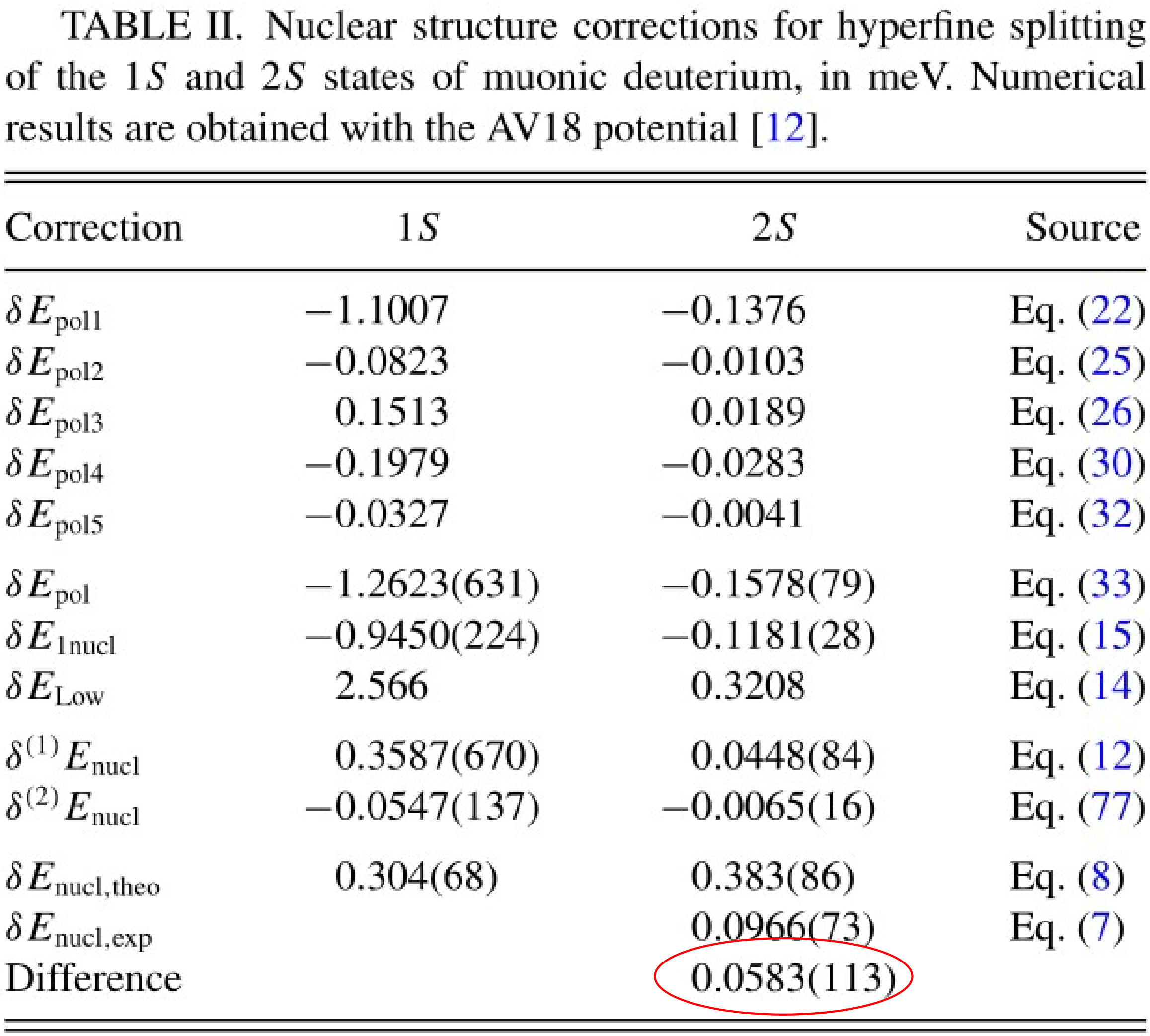


TABLE II. Nuclear structure corrections for hyperfine splitting of the 1S and 2S states of muonic deuterium, in meV. Numerical results are obtained with the AV18 potential [12].

Correction	1S	2S	Source
$\delta E_{\rm pol1}$	−1.1007	−0.1376	Eq. (22)
$\delta E_{\rm pol2}$	−0.0823	−0.0103	Eq. (25)
$\delta E_{\rm pol3}$	0.1513	0.0189	Eq. (26)
$\delta E_{\rm pol4}$	−0.1979	−0.0283	Eq. (30)
$\delta E_{\rm pol5}$	−0.0327	−0.0041	Eq. (32)
$\delta E_{\rm pol}$	−1.2623(631)	−0.1578(79)	Eq. (33)
$\delta E_{\rm 1nucl}$	−0.9450(224)	−0.1181(28)	Eq. (15)
$\delta E_{\rm Low}$	2.566	0.3208	Eq. (14)
$\delta^{(1)} E_{\rm nucl}$	0.3587(670)	0.0448(84)	Eq. (12)
$\delta^{(2)} E_{\rm nucl}$	−0.0547(137)	−0.0065(16)	Eq. (77)
$\delta E_{\rm nucl,theo}$	0.304(68)	0.383(86)	Eq. (8)
$\delta E_{\rm nucl,exp}$		0.0966(73)	Eq. (7)
Difference		0.0583(113)	

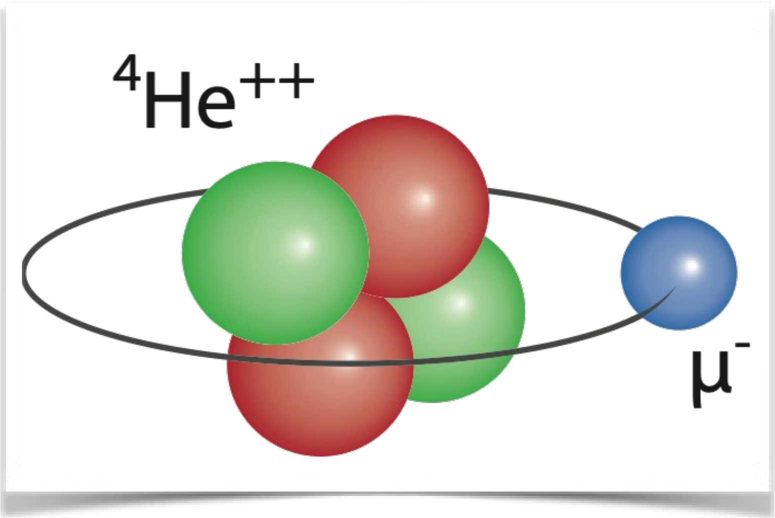
nucl. 3-photon →

Exp – QED(point nucleus) =

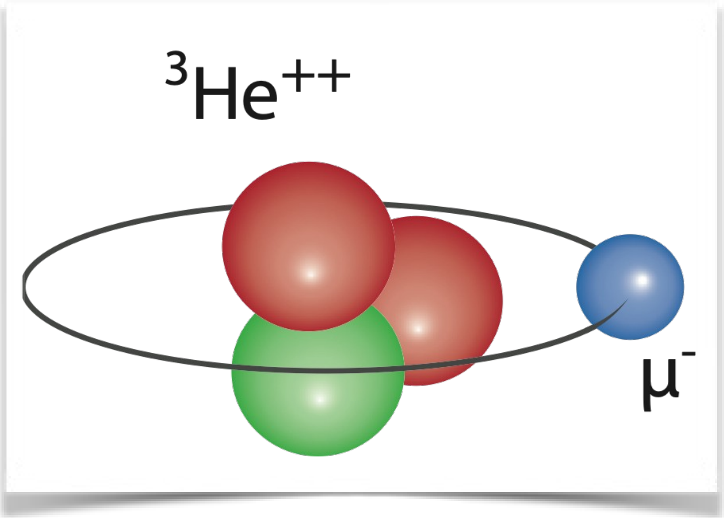
5σ

Kalinowski, Pachucki, Yerokhin, PRA 98, 062513 (2018)

Muonic Helium



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



Measured

Theory in muonic He-4

$$\Delta E^{\mu^4\mathrm{He}}_{\mathrm{Lamb}} = 1668.5002(140)_{\mathrm{QED}} + 9.1900(\mathbf{2900})_{\mathrm{TPE}} - 106.2200(80) * \mathbf{R}_{\boldsymbol{\alpha}}^{\mathbf{2}}\,/\mathrm{fm}^2 \quad [\mathrm{meV}]$$

$$\Delta E^{\mu\mathrm{D}}_{\mathrm{Lamb}} = 228.7854\,(13)_{\mathrm{QED}} + 1.7653\,(130)_{\mathrm{TPE}} - 6.1103\,(\ \ 3) * \mathbf{R}_{\mathbf{d}}^{\mathbf{2}}\,/\mathrm{fm}^2 \quad [\mathrm{meV}]$$

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

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

Theory in muonic He-4

$$\Delta E^{\mu^4\mathrm{He}} = 1668.5002(140)_{\mathrm{QED}} + 9.1900(\mathbf{2900})_{\mathrm{TPE}} - 106.2200(80) * \mathbf{R}_{\alpha}^{2} /\mathrm{fm}^2 \quad [\mathrm{meV}]$$

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

$9.1900(\mathbf{2900})_{\mathrm{TPE}} = 9.340(250)_{\mathrm{2PE}}$ nucl. 2-photon exchange

$-0.150(150)_{\mathrm{3PE}}$ nucl. 3-photon guesstimate

Reasoning: inelastic 3PE = 0 …. (minus elastic 3PE)
= 0 in “hard” proton,
cancels elastic 3PE in “soft” deuteron

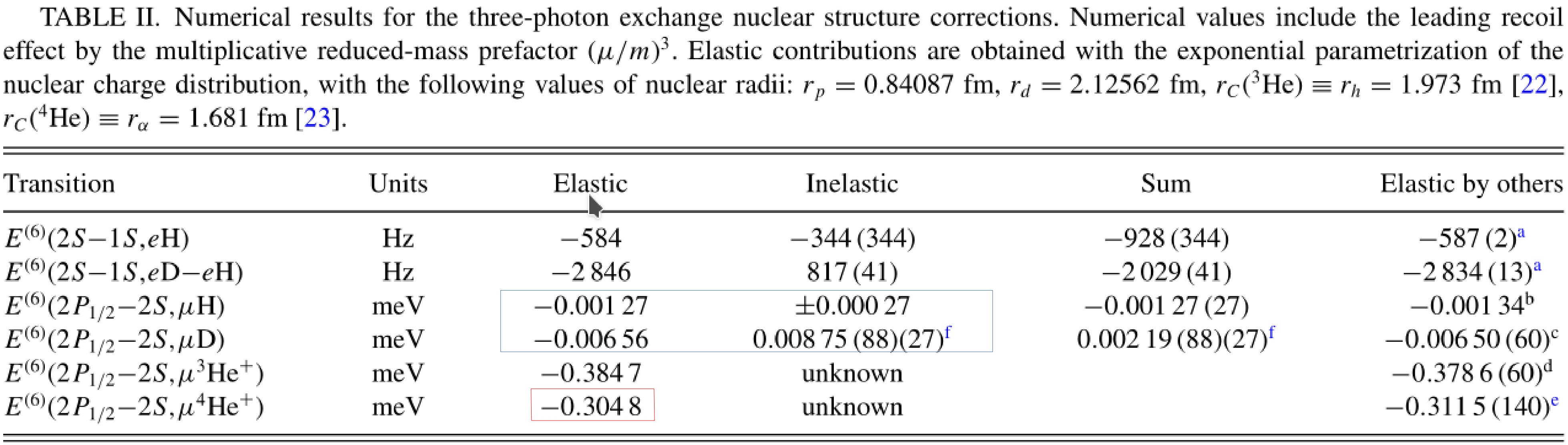


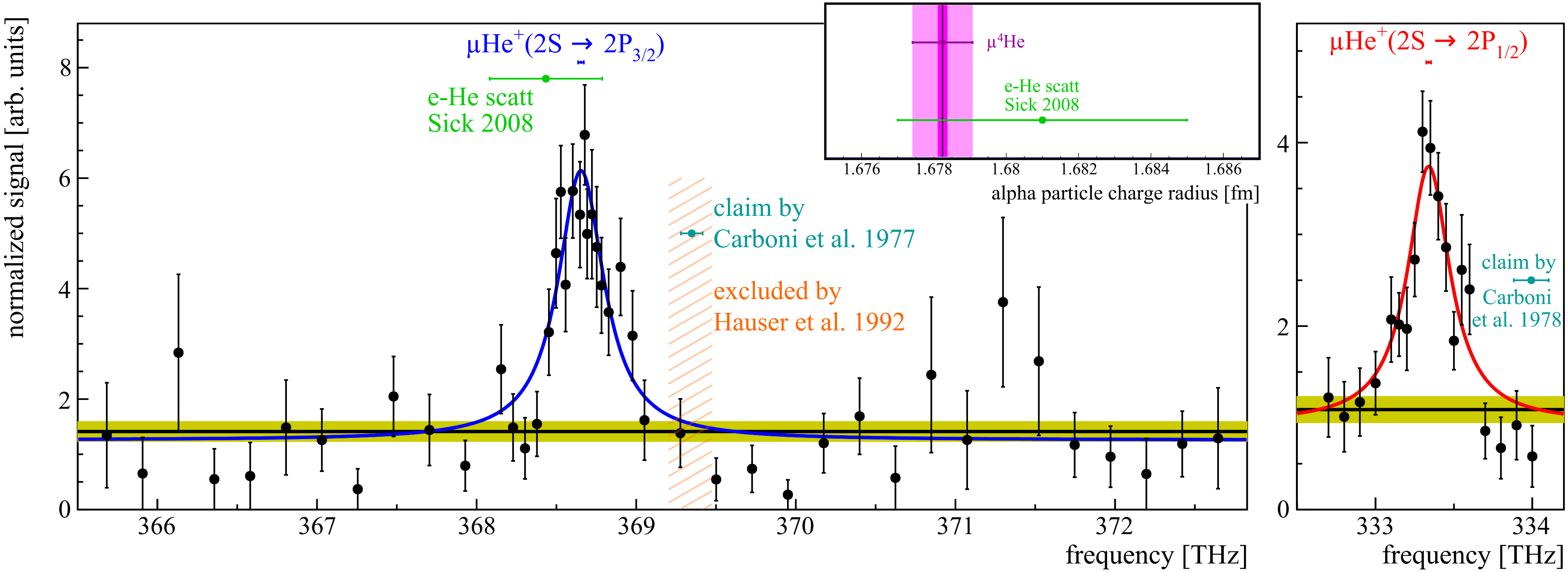
TABLE II. Numerical results for the three-photon exchange nuclear structure corrections. Numerical values include the leading recoil effect by the multiplicative reduced-mass prefactor $(\mu/m)^3$. Elastic contributions are obtained with the exponential parametrization of the nuclear charge distribution, with the following values of nuclear radii: $r_p = 0.84087$ fm, $r_d = 2.12562$ fm, $r_C(^3\mathrm{He}) \equiv r_h = 1.973$ fm [22], $r_C(^4\mathrm{He}) \equiv r_\alpha = 1.681$ fm [23].

Transition	Units	Elastic	Inelastic	Sum	Elastic by others
$E^{(6)}(2S-1S, e\mathrm{H})$	Hz	−584	−344 (344)	−928 (344)	−587 (2)[a]
$E^{(6)}(2S-1S, e\mathrm{D}-e\mathrm{H})$	Hz	−2 846	817 (41)	−2 029 (41)	−2 834 (13)[a]
$E^{(6)}(2P_{1/2}-2S, \mu\mathrm{H})$	meV	−0.001 27	±0.000 27	−0.001 27 (27)	−0.001 34[b]
$E^{(6)}(2P_{1/2}-2S, \mu\mathrm{D})$	meV	−0.006 56	0.008 75 (88)(27)[f]	0.002 19 (88)(27)[f]	−0.006 50 (60)[c]
$E^{(6)}(2P_{1/2}-2S, \mu^3\mathrm{He}^+)$	meV	−0.384 7	unknown		−0.378 6 (60)[d]
$E^{(6)}(2P_{1/2}-2S, \mu^4\mathrm{He}^+)$	meV	−0.304 8	unknown		−0.311 5 (140)[e]

Pachucki, Patkos, Yerokhin, PRA 97, 052511 (2018)

Three-photon contribution estimation included (a la Pachucki et al., PRA 97)

muonic ^{4}He ions



$2P_{3/2}$: ±17 GHz

$2P_{1/2}$: ±15 GHz

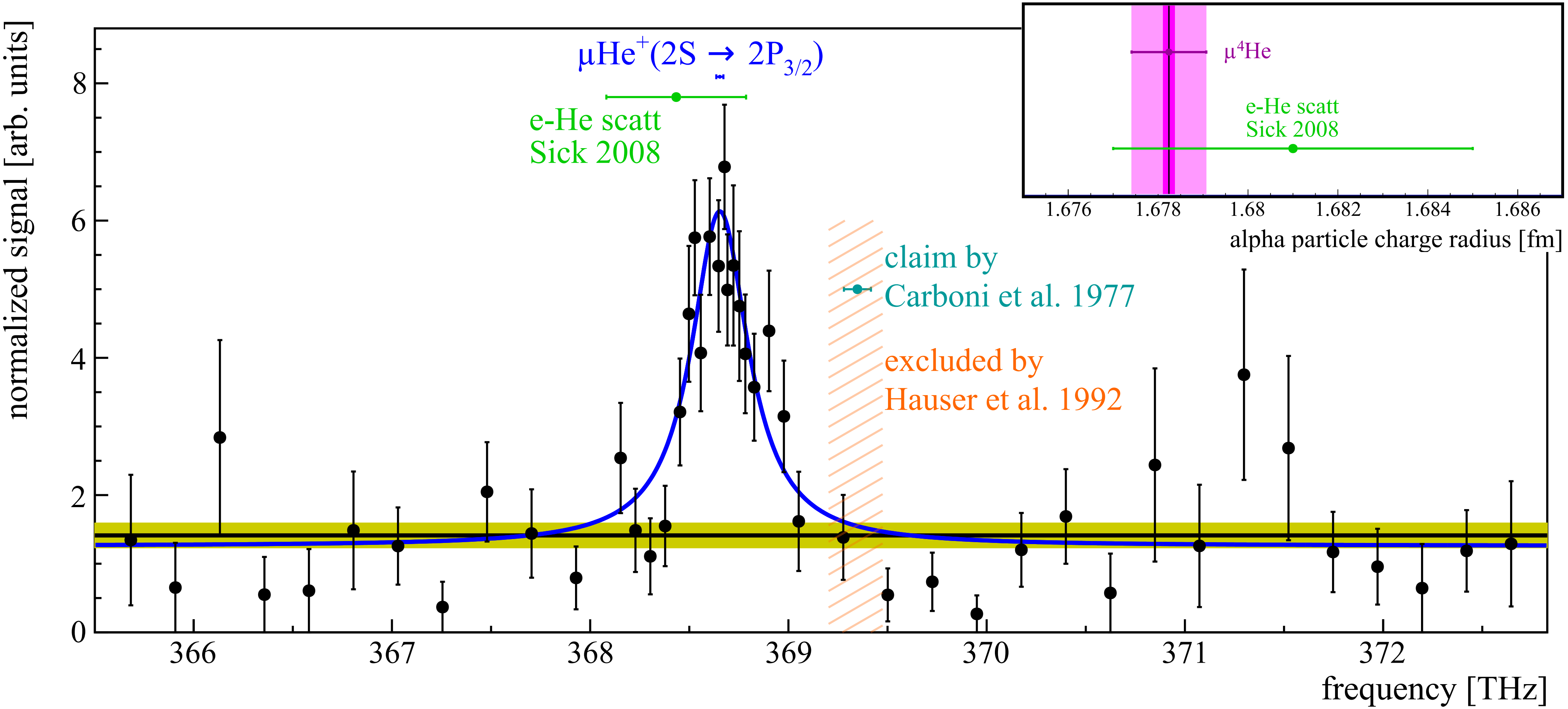
$R(^4He) = 1.67824\ (13)_{exp}\ (82)_{theo}$ fm

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

2-photon exchange: Bacca group
3-photon exchange: our educated(?) guess based on Pachucki et al.

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

muonic ^{4}He ions



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

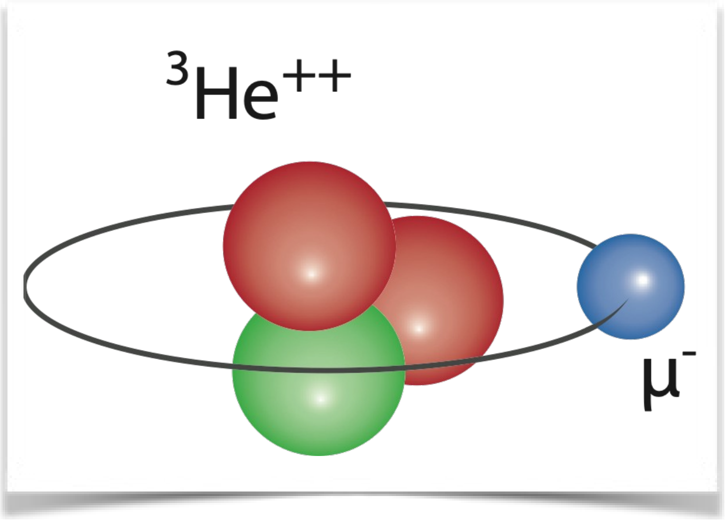
$(82)_{\mathrm{theo}} = (70)_{\mathrm{2PE}}\ \ (42)_{\mathrm{3PE}}$

2-photon exchange: Bacca group

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

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

Muonic Helium-3



Preliminary results

Theory in muonic He-3

$$\Delta E^{\mu^4\mathrm{He}} = 1668.5002(140)_{\mathrm{QED}} + 9.1900(\mathbf{2900})_{\mathrm{TPE}} - 106.2200(\ 80) * \mathbf{R_{\alpha}^{2}}\ /\mathrm{fm}^2 \quad [\mathrm{meV}]$$

$$\Delta E^{\mu^3\mathrm{He}} = 1644.3466(149)_{\mathrm{QED}} + 15.1000(\mathbf{5600})_{\mathrm{TPE}} - 103.5180(100) * \mathbf{R_{h}^{2}}\ /\mathrm{fm}^2 \quad [\mathrm{meV}]$$

Following the same recipe as for μ4He:

$15.10(\mathbf{56})_{\mathrm{TPE}} = 15.30(52)_{\mathrm{2PE}}$ nucl. 2-photon exchange

$- 0.20(20)_{\mathrm{3PE}}$ nucl. 3-photon guesstimate

Reasoning: inelastic 3PE = 0 …. (minus elastic 3PE)
= 0 in “hard” proton,
cancels elastic 3PE in “soft” deuteron

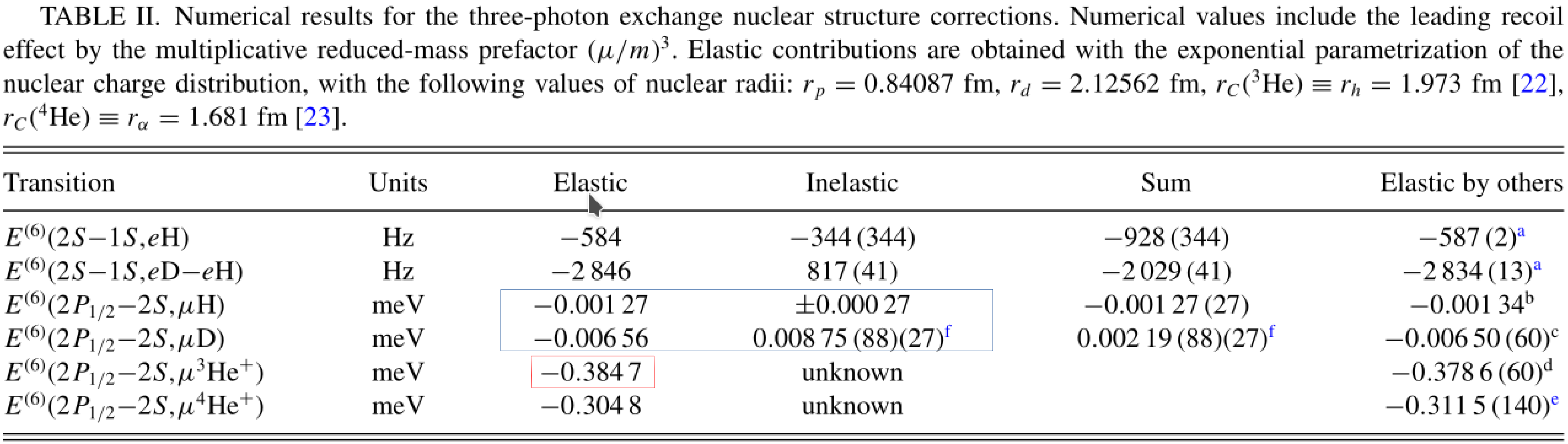
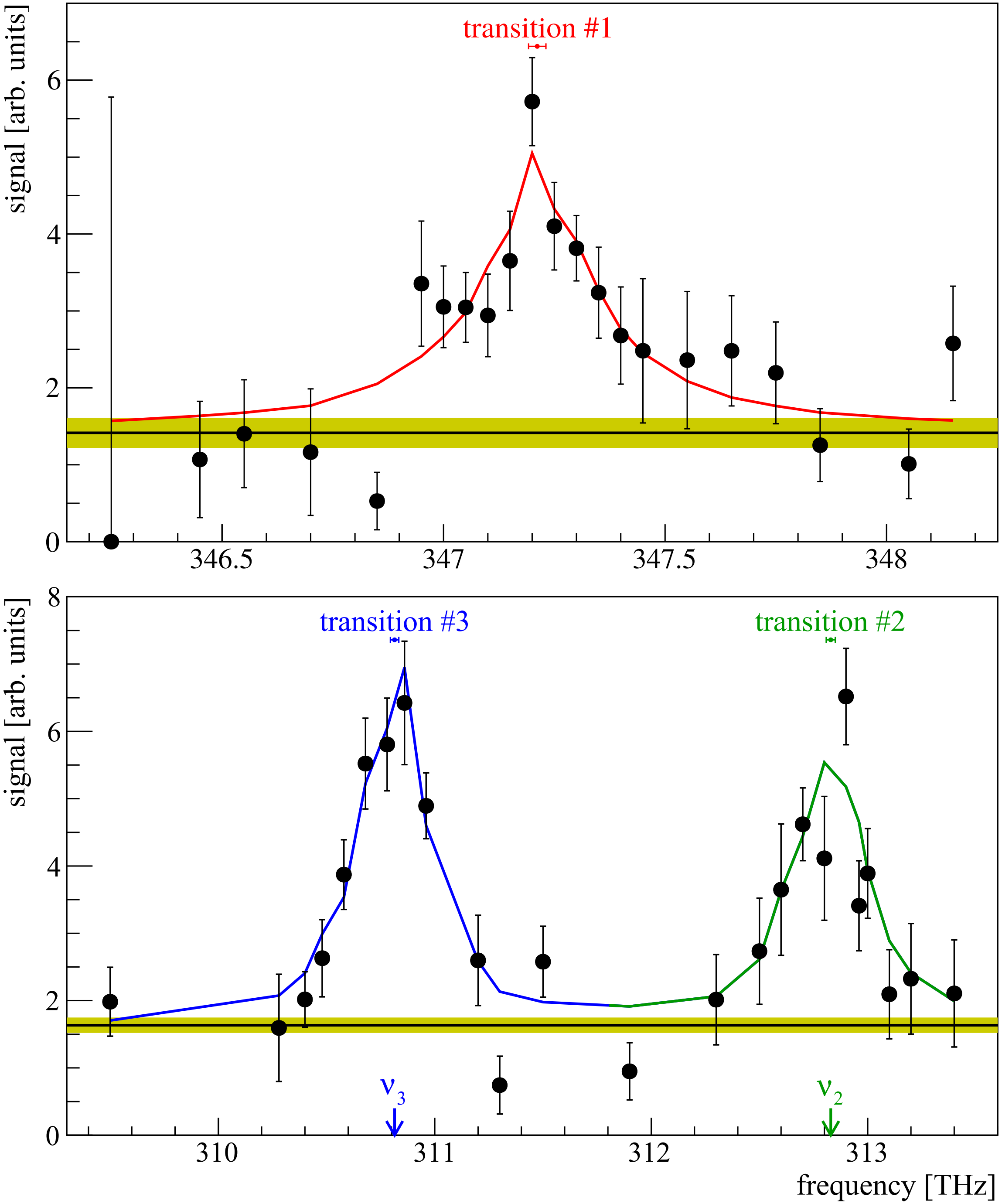


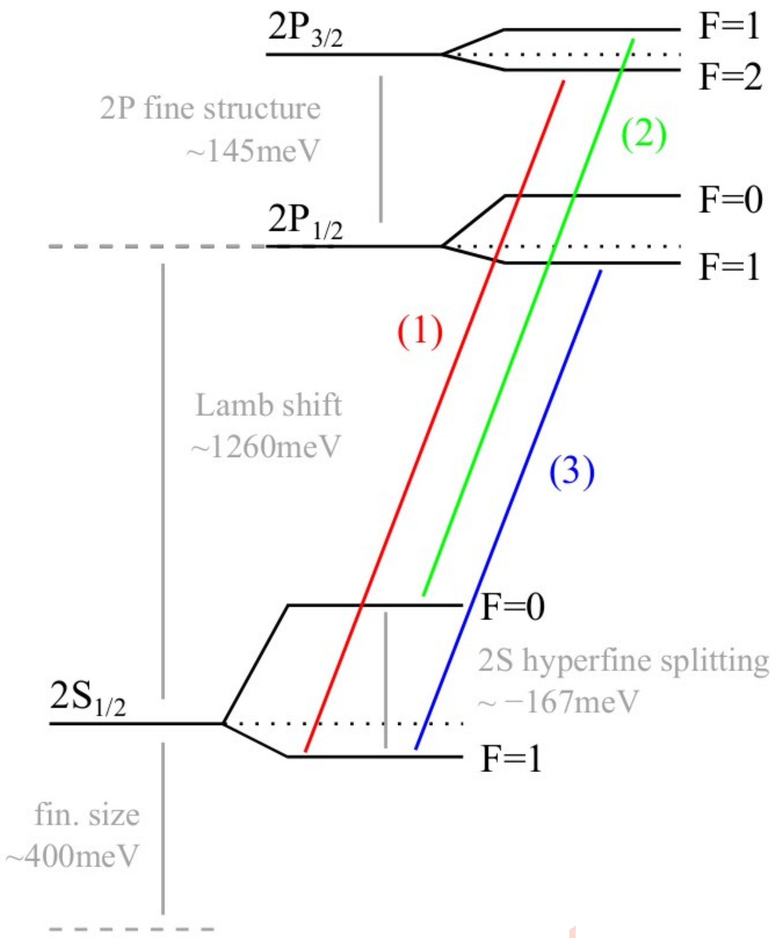
TABLE II. Numerical results for the three-photon exchange nuclear structure corrections. Numerical values include the leading recoil effect by the multiplicative reduced-mass prefactor $(\mu/m)^3$. Elastic contributions are obtained with the exponential parametrization of the nuclear charge distribution, with the following values of nuclear radii: $r_p = 0.84087$ fm, $r_d = 2.12562$ fm, $r_C(^3\mathrm{He}) \equiv r_h = 1.973$ fm [22], $r_C(^4\mathrm{He}) \equiv r_\alpha = 1.681$ fm [23].

Transition	Units	Elastic	Inelastic	Sum	Elastic by others
$E^{(6)}(2S-1S, e\mathrm{H})$	Hz	−584	−344 (344)	−928 (344)	−587 (2)[a]
$E^{(6)}(2S-1S, e\mathrm{D}-e\mathrm{H})$	Hz	−2 846	817 (41)	−2 029 (41)	−2 834 (13)[a]
$E^{(6)}(2P_{1/2}-2S, \mu\mathrm{H})$	meV	−0.001 27	±0.000 27	−0.001 27 (27)	−0.001 34[b]
$E^{(6)}(2P_{1/2}-2S, \mu\mathrm{D})$	meV	−0.006 56	0.008 75 (88)(27)[f]	0.002 19 (88)(27)[f]	−0.006 50 (60)[c]
$E^{(6)}(2P_{1/2}-2S, \mu^3\mathrm{He}^+)$	meV	−0.384 7	unknown		−0.378 6 (60)[d]
$E^{(6)}(2P_{1/2}-2S, \mu^4\mathrm{He}^+)$	meV	−0.304 8	unknown		−0.311 5 (140)[e]

Pachucki, Patkos, Yerokhin, PRA 97, 052511 (2018)

muonic ^{3}He ions



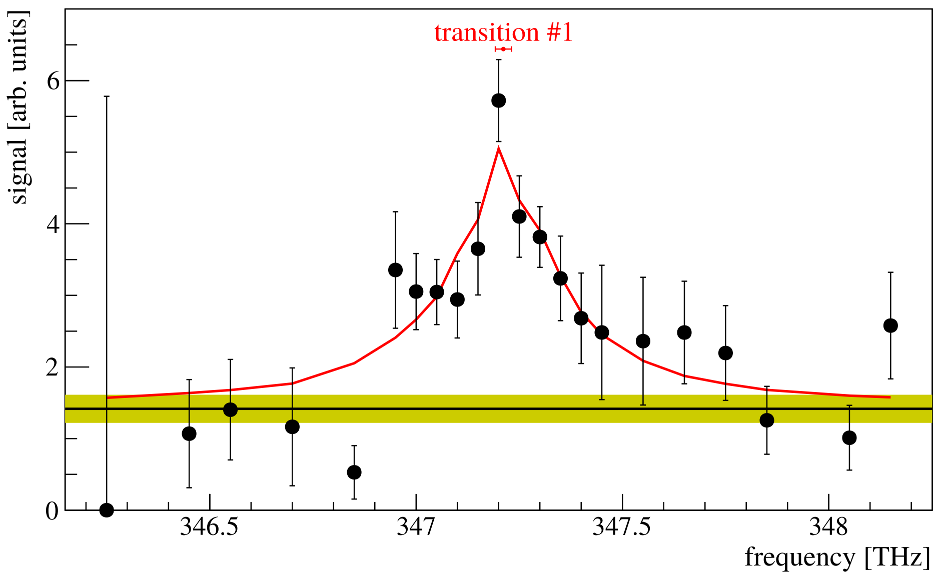


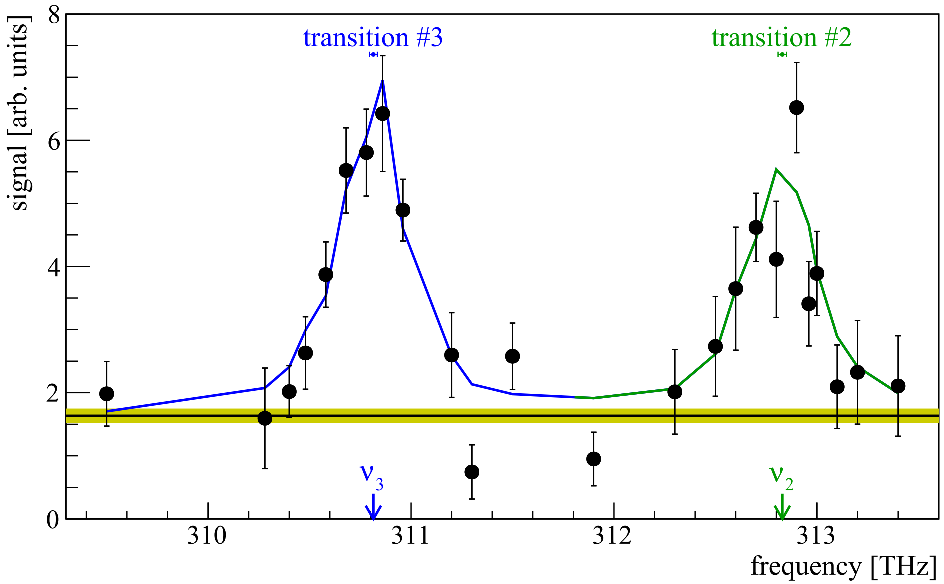
$$R(^3\mathrm{He}) = 1.96792\,(12)_{\mathrm{exp}}\,(137)_{\mathrm{theo}}\ \mathrm{fm}$$

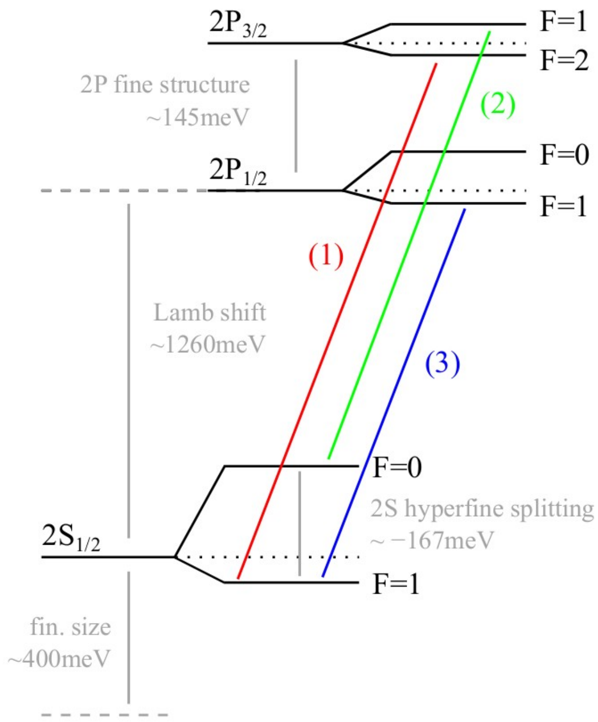
also:

$$E^{\mathrm{TPE}}_{\mathrm{HFS}}(2S) \;=\; 6.25(10)\ \mathrm{meV}$$

muonic ^{3}He ions





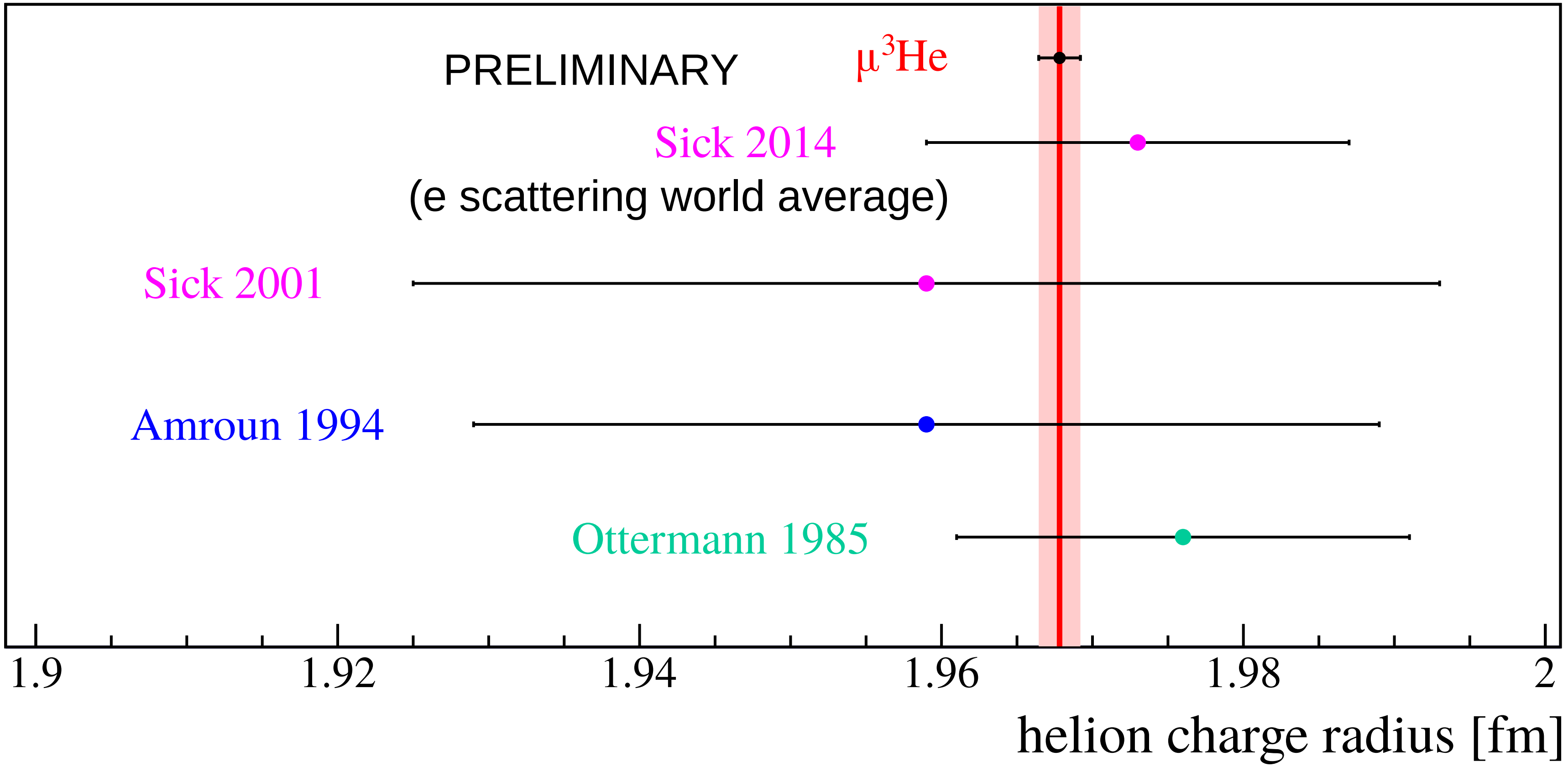


exp: each line has +-20 GHz(stat) +- 0.2 GHz (syst)

R(^{3}He) = 1.96782 $(12)_{exp}$ $(137)_{theo}$ fm preliminary!

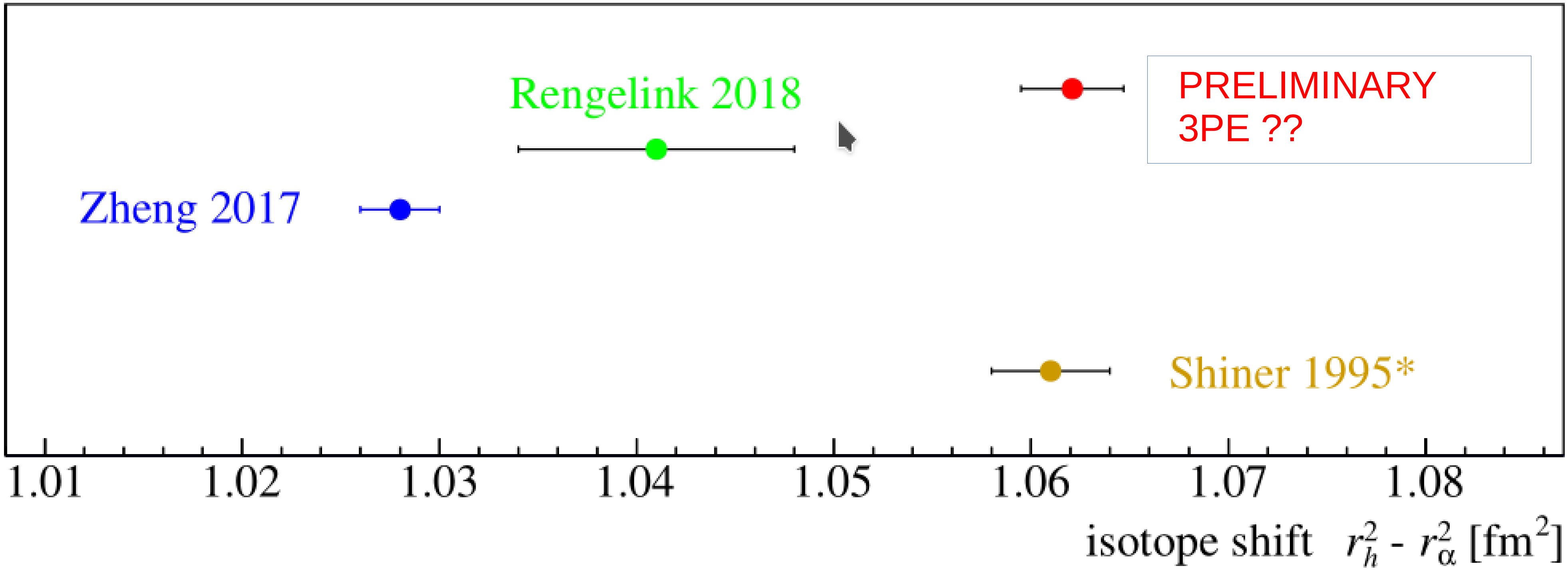
theo = +- 0.00128 meV 2PE
+- 0.00049 meV 3PE
+- 0.00010 meV R^2 coeff.
+- 0.00004 meV QED

Muonic Helium-3



Sick, PRC 90, 064002 (2014)

Helium-3 – Helium-4 Isotope Shift



assumption: the (uncalculated) inelastic 3PE terms are correlated

Shiner	PRL 74, corrected by Marsmann et al., (Hessels group)
Zheng	PRL 119
Rengelink	Nature Physics

Cancio Pastor not shown, too large Quantum Interference (per Hessels)

Intermediate conclusions

Muonic atoms / ions provide:

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

calculated polarizability

$^{3}\mathrm{He}$
1.9687* (13)
~~1.9730 (160)~~

$^{4}\mathrm{He}$
1.6782 (8)
~~1.6810 (40)~~

$^{1}\mathrm{H}$
0.8409 (4)
~~0.8751 (61)~~

$^{2}\mathrm{D}$
2.1277 (2)
~~2.1413 (25)~~

$^{3}\mathrm{T}$
1.7550 (860)

*** = preliminary**


The New York Times

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!

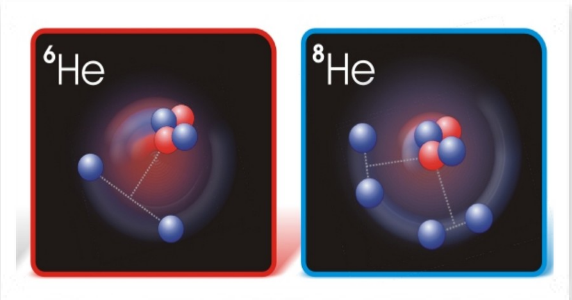
Impact of μ^4He^+ measurements

Few-nucleon theories

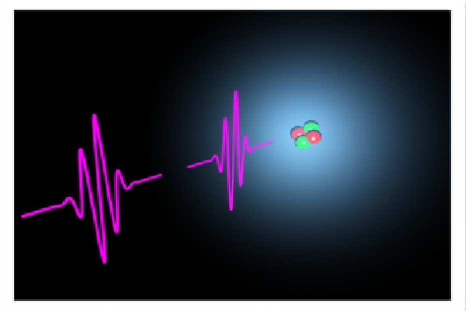
- r_α represents a benchmark for few-nucleon theories.
- r_α can be used also to fix a low-energy constant of nuclear potential.
- r_α improves ^{6}He and ^{8}He radii (slightly)

BSM physics

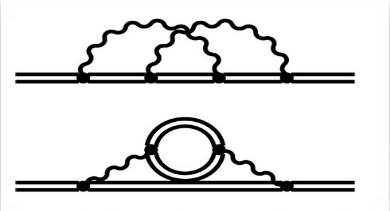
- Agreement constrains BSM models suggested to explain the R_p puzzle



Müller, Lu



Udem, MPQ
Eikema, LaserLab

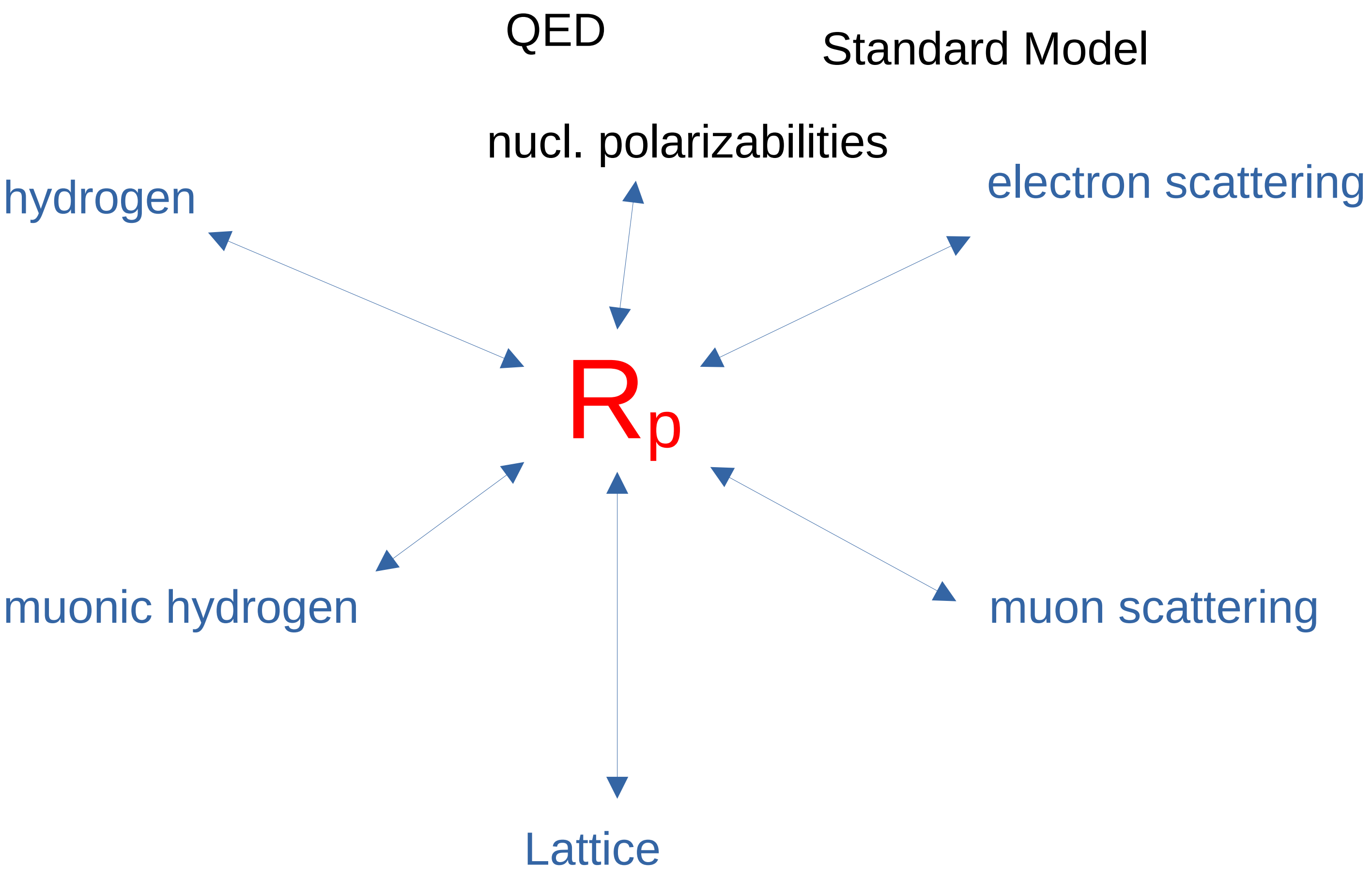


Combined with upcoming He⁺ (He) exp.

- 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

Why was the proton radius so interesting?



QED

Standard Model

nucl. polarizabilities

hydrogen

electron scattering

R_p

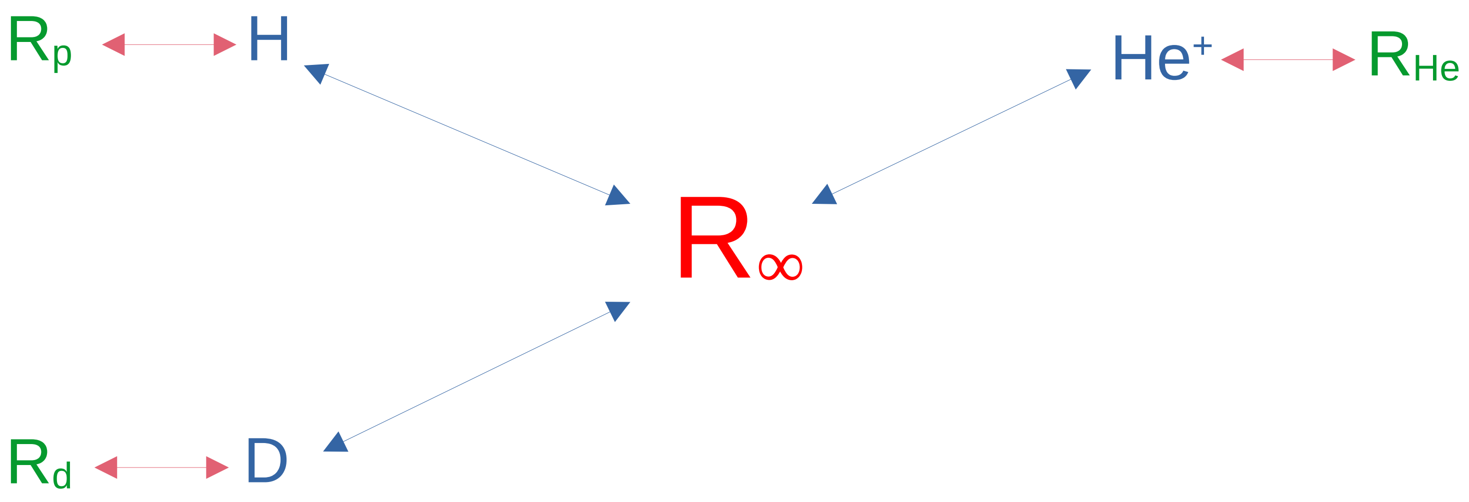
muonic hydrogen

muon scattering

Lattice

The Rydberg constant

→ Test QED and SM



R_p ↔ H

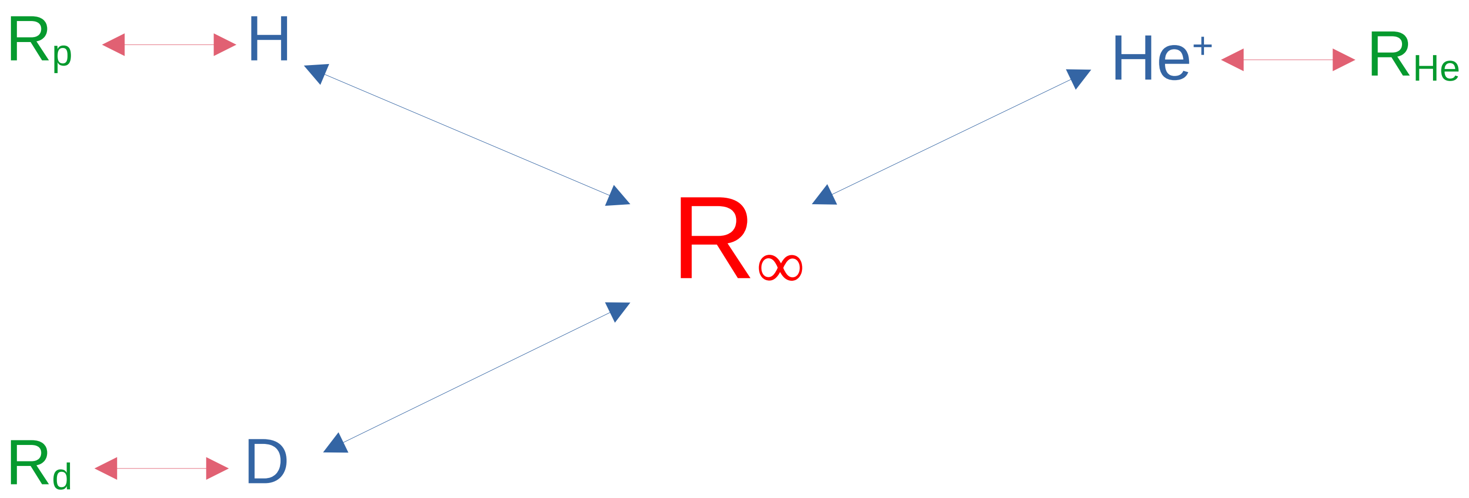
He^+ ↔ R_{He}

R_∞

R_d ↔ D

2-body QED calculations

The Rydberg constant



R_p H

He$^+$ R_{He}

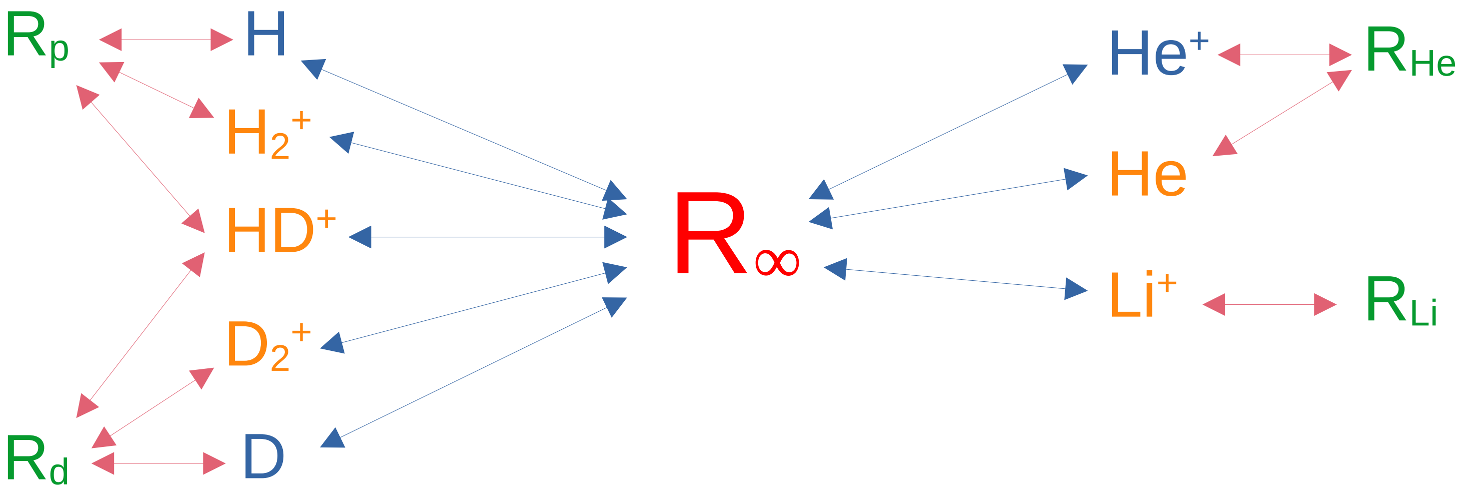
R_∞

R_d D

2-body QED calculations

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

The Rydberg constant



R_p H

H_2^+

HD^+

D_2^+

R_d D

R_∞

He^+ R_{He}

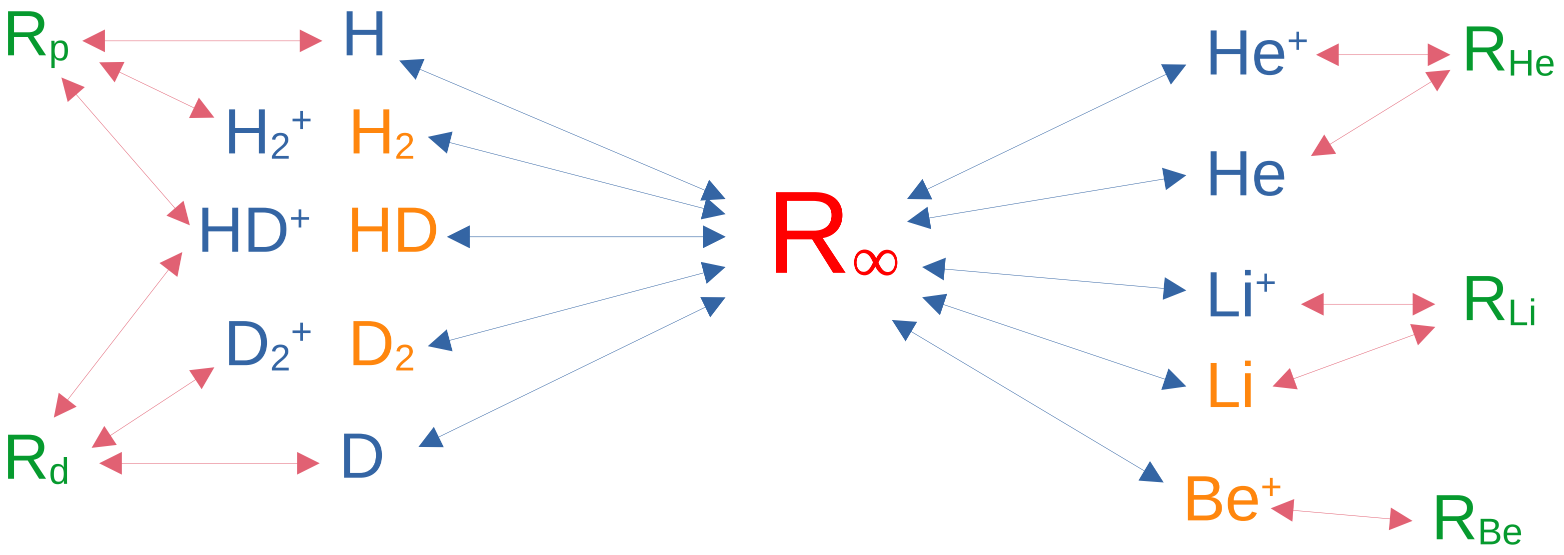
He

Li^+ R_{Li}

2-body QED calculations
3-body QED calculations

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

The Rydberg constant



R_p H

H_2^+ H_2

HD^+ HD

D_2^+ D_2

R_d D

R_∞

He^+ R_{He}

He

Li^+ R_{Li}

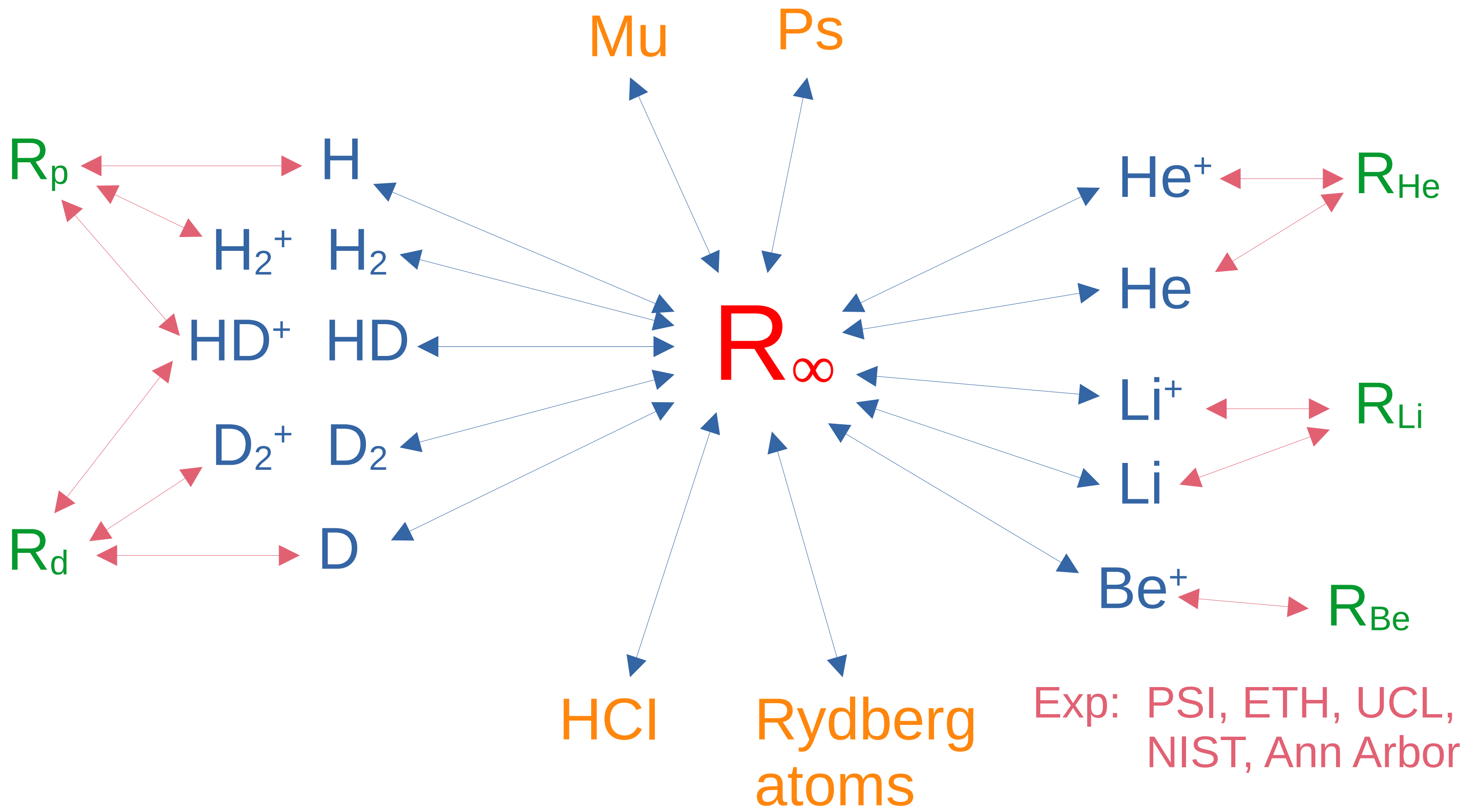
Li

Be^+ R_{Be}

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

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

The Rydberg constant



Mu Ps

R_p H

H_2^+ H_2

HD^+ HD

D_2^+ D_2

R_d D

R_∞

He^+ R_{He}

He

Li^+ R_{Li}

Li

Be^+ R_{Be}

HCl

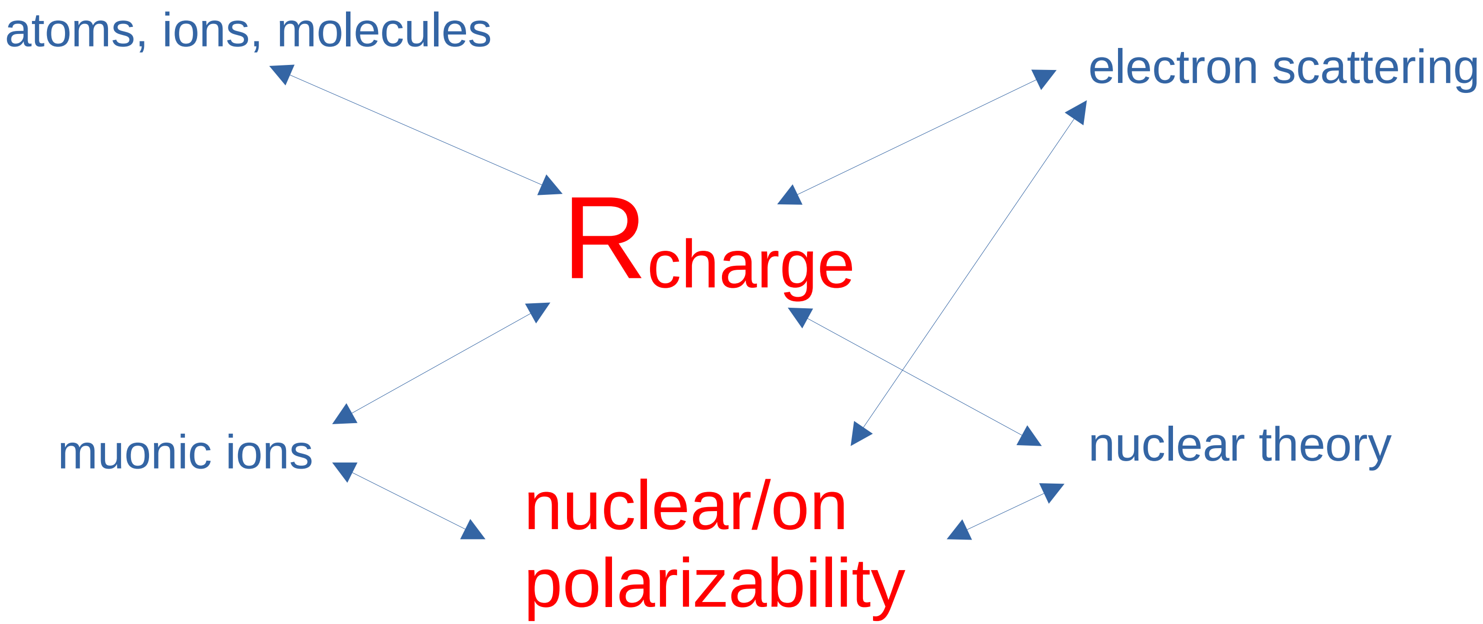
Rydberg atoms

Exp: PSI, ETH, UCL, Japan,
NIST, Ann Arbor, …

The Rydberg constant

Determine Rydberg constant with various means → Test QED and SM

absolutely requires nuclear charge radii + polarizabilities



atoms, ions, molecules

electron scattering

R_{charge}

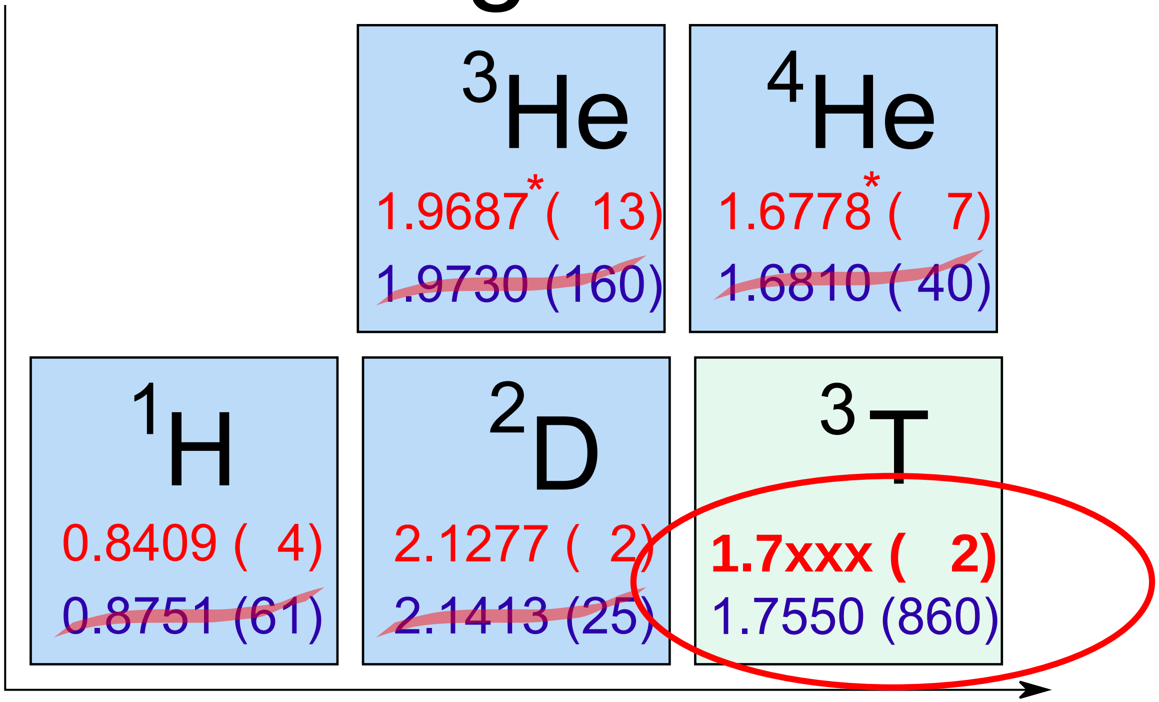
muonic ions

nuclear theory

nuclear/on polarizability

What’s next?

Triton charge radius from Tritium 1S-2S



^{3}He
1.9687* (13)
~~1.9730 (160)~~

^{4}He
1.6778* (7)
~~1.6810 (40)~~

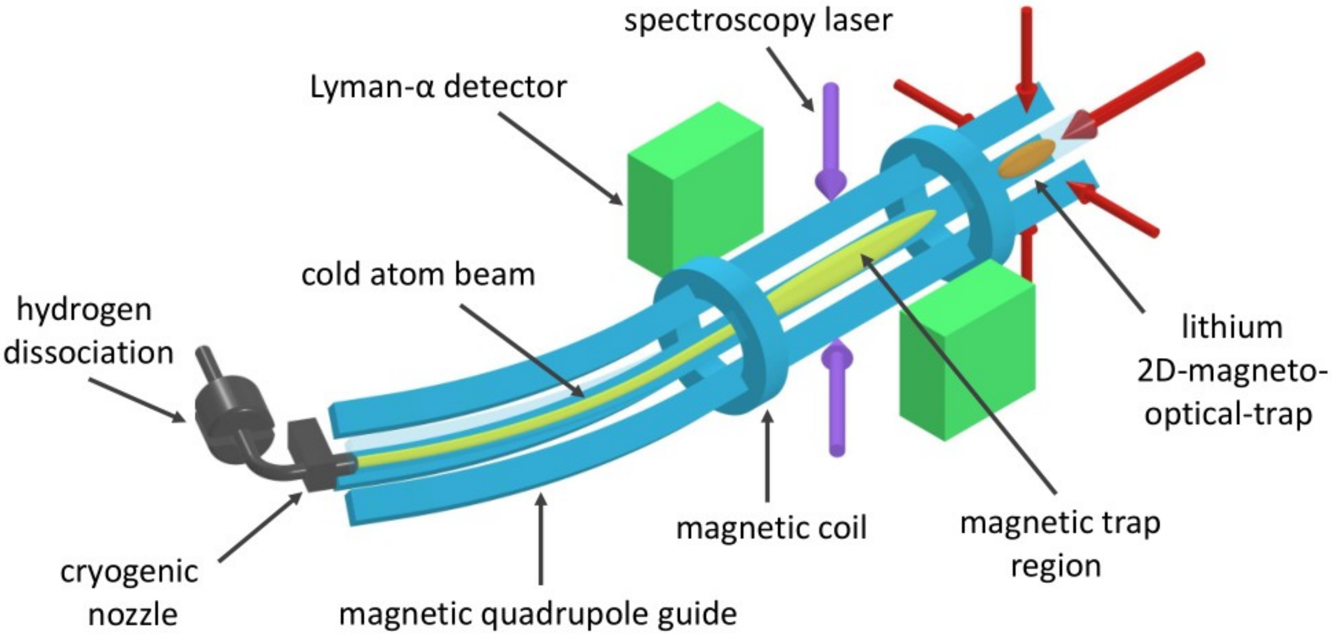
^{1}H
0.8409 (4)
~~0.8751 (61)~~

^{2}D
2.1277 (2)
~~2.1413 (25)~~

^{3}T
1.7xxx (2)
1.7550 (860)

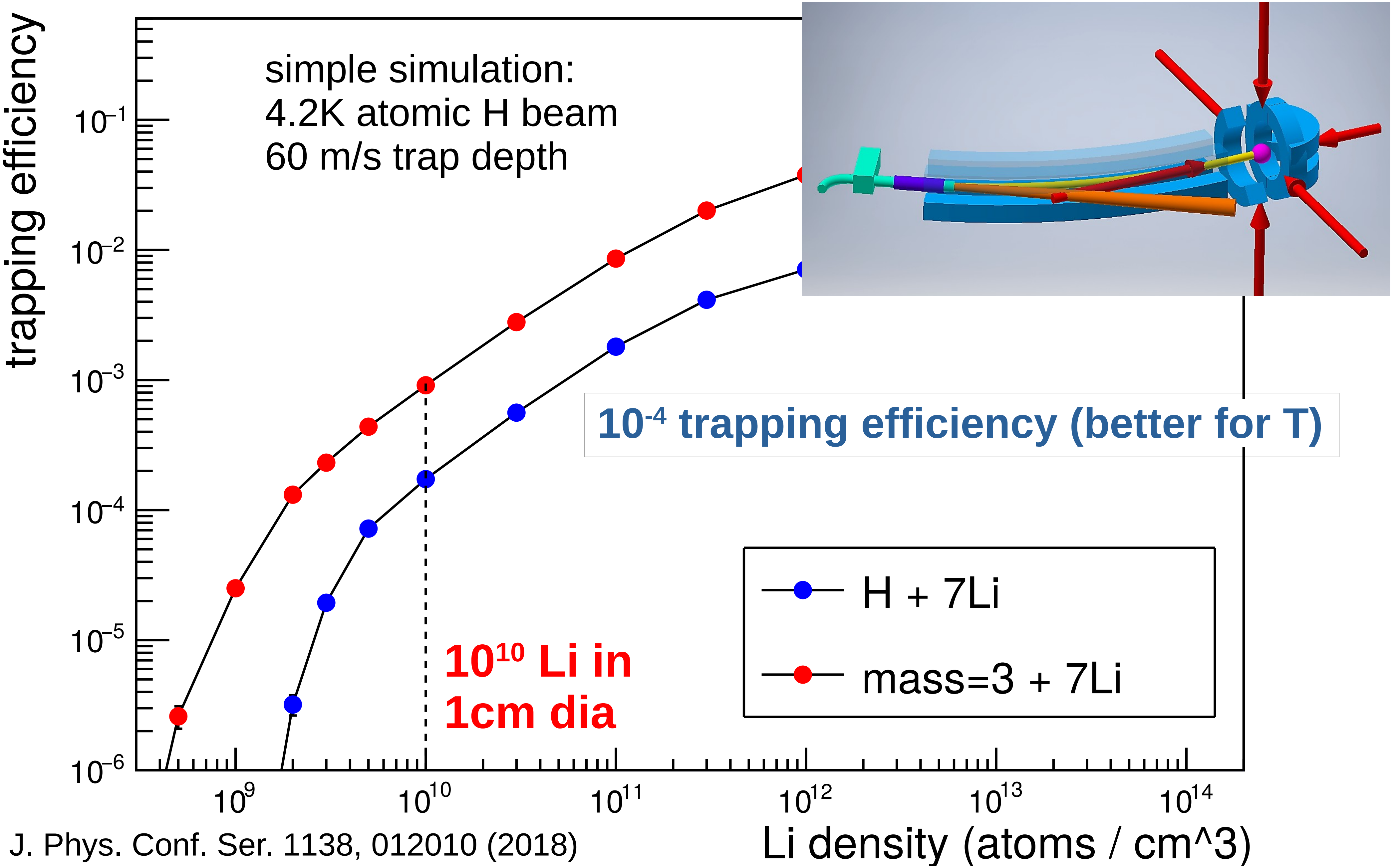
Triton-Radius EXperiment
Mainz

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



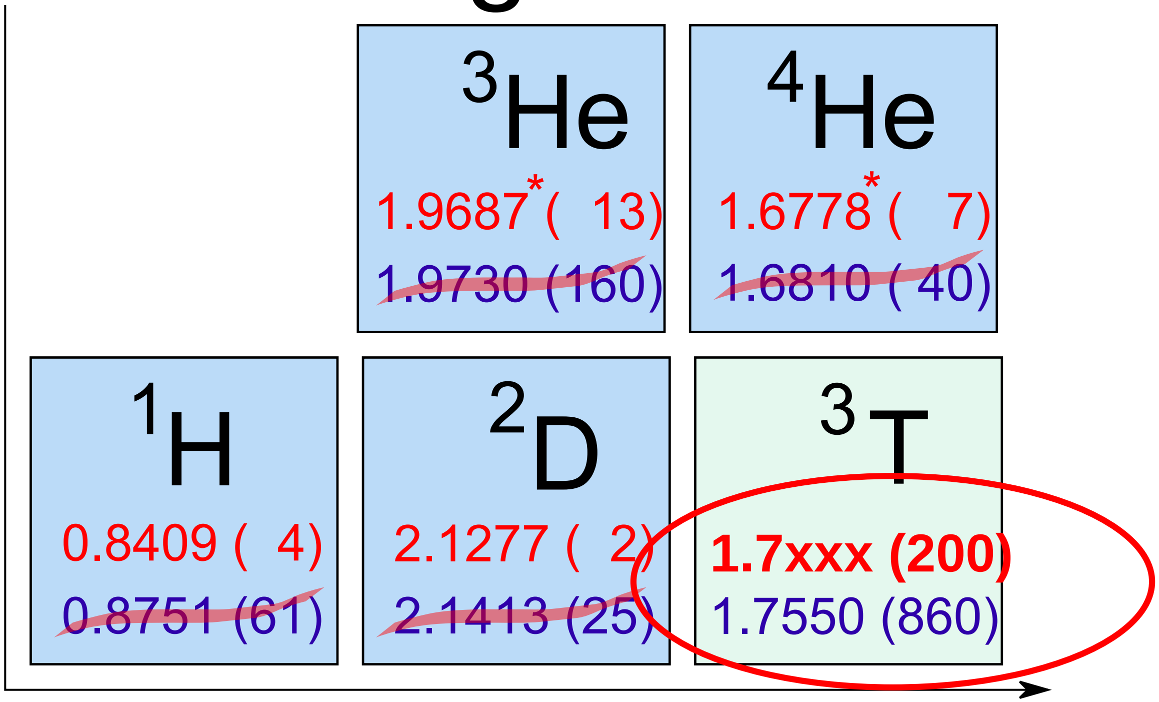
simple simulation:
4.2K atomic H beam
60 m/s trap depth

10^{-4} trapping efficiency (better for T)

10^{10} Li in
1cm dia

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

Triton charge radius from Tritium 1S-2S



^{3}He
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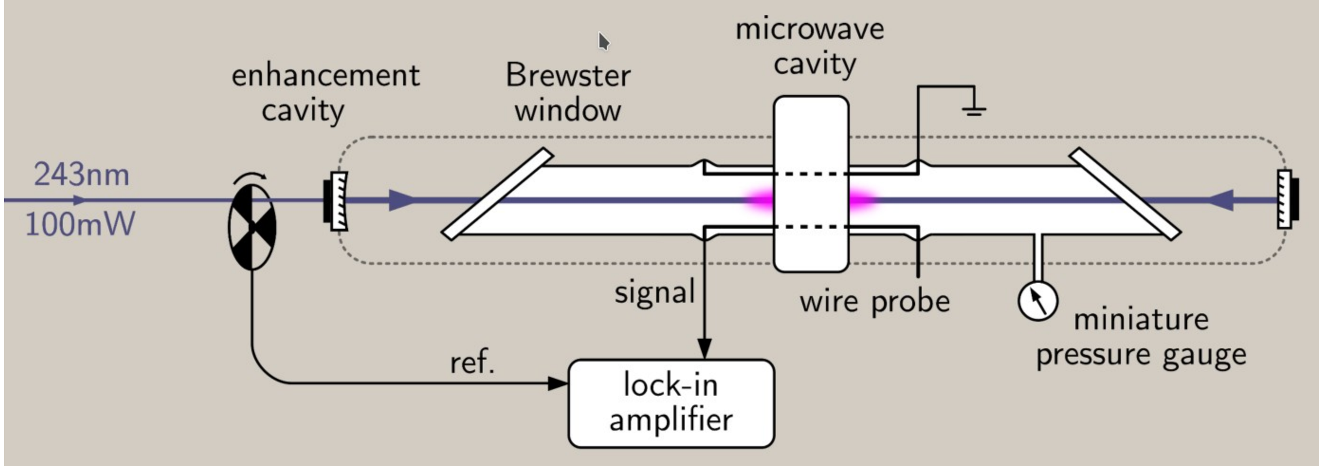
^{2}D
2.1277 (2)
~~2.1413 (25)~~

^{3}T
1.7xxx (200)
1.7550 (860)

Triton-Radius EXperiment
Mainz

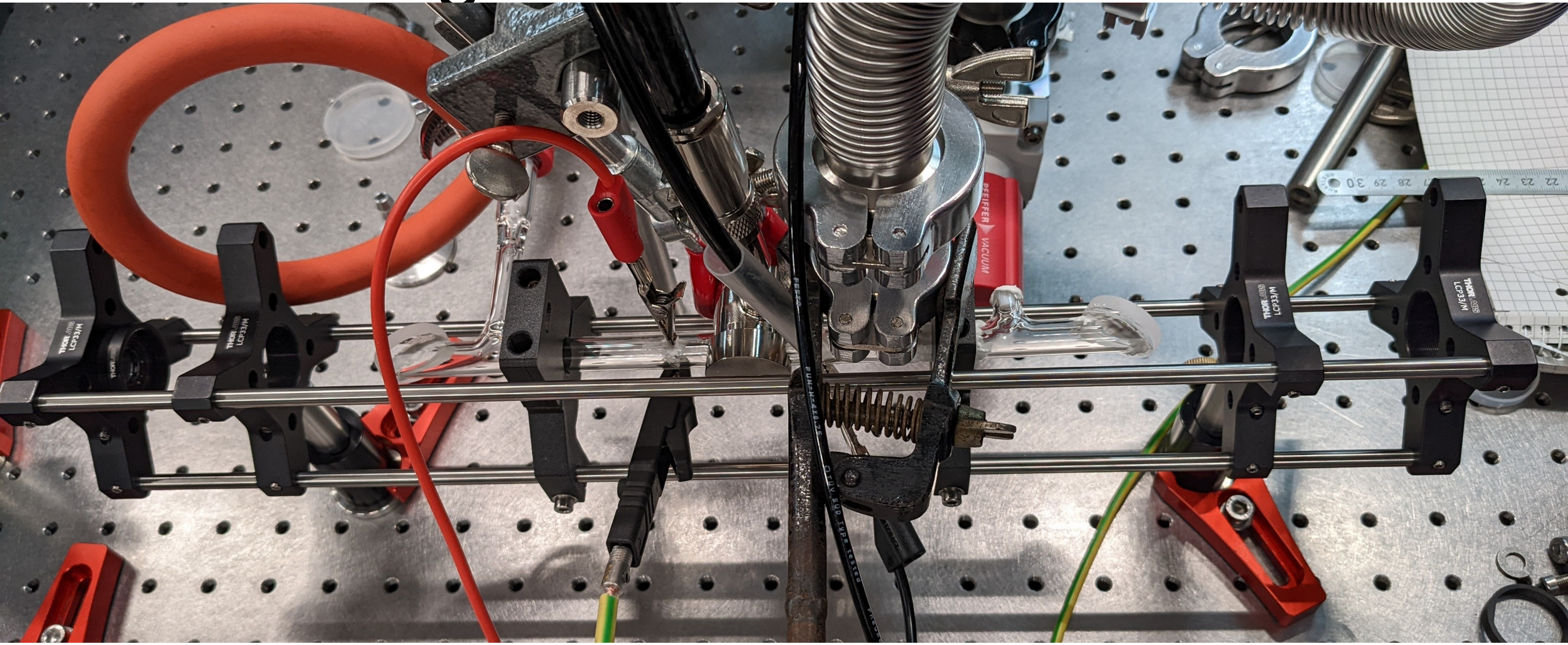
4x better radius
with 100 kHz measurement
(vs. 0.01 kHz for H, D)

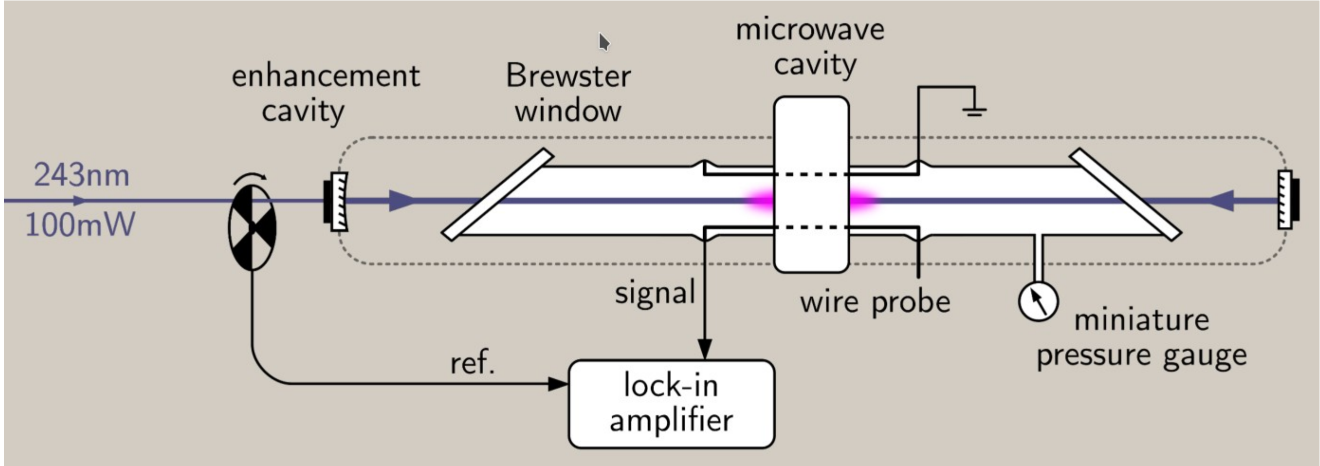


- Optogalvanic spectroscopy in a cell
- Syst. extrapolation w/ H,D
- Tritium confined.

staged approach

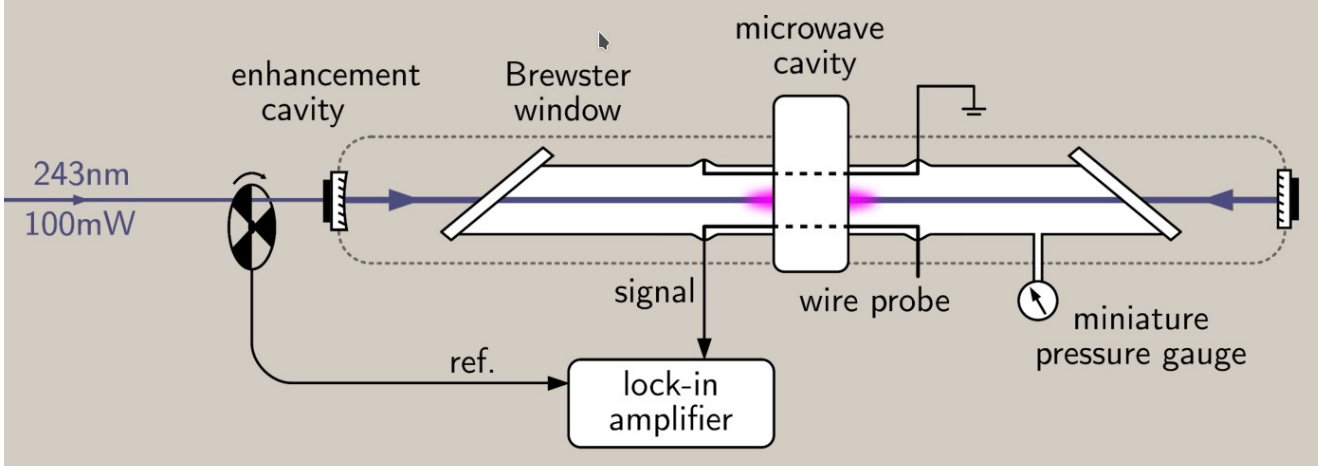
Triton charge radius from Tritium 1S-2S

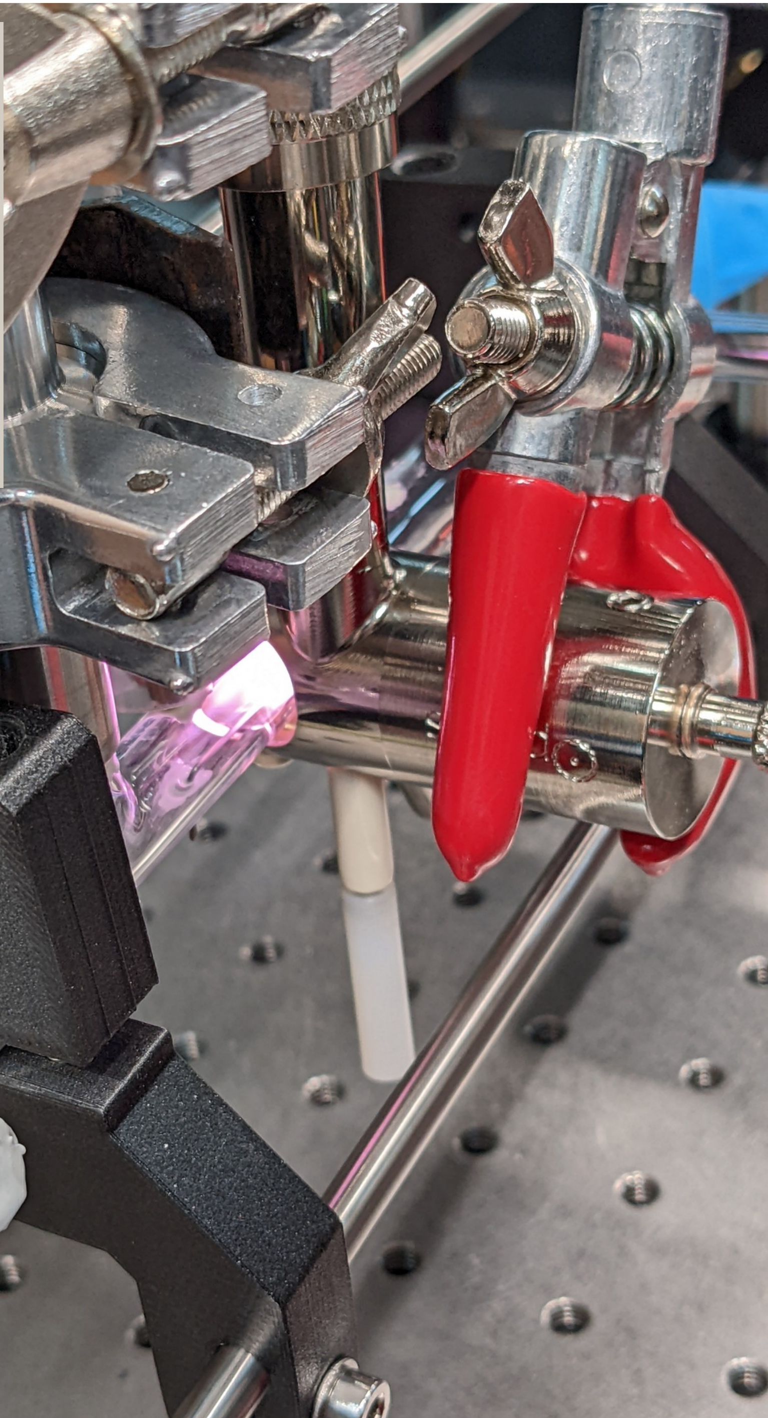




- Optogalvanic spectroscopy in a cell
- Syst. extrapolation w/ H,D
- Tritium confined.

Triton charge radius from Tritium 1S-2S



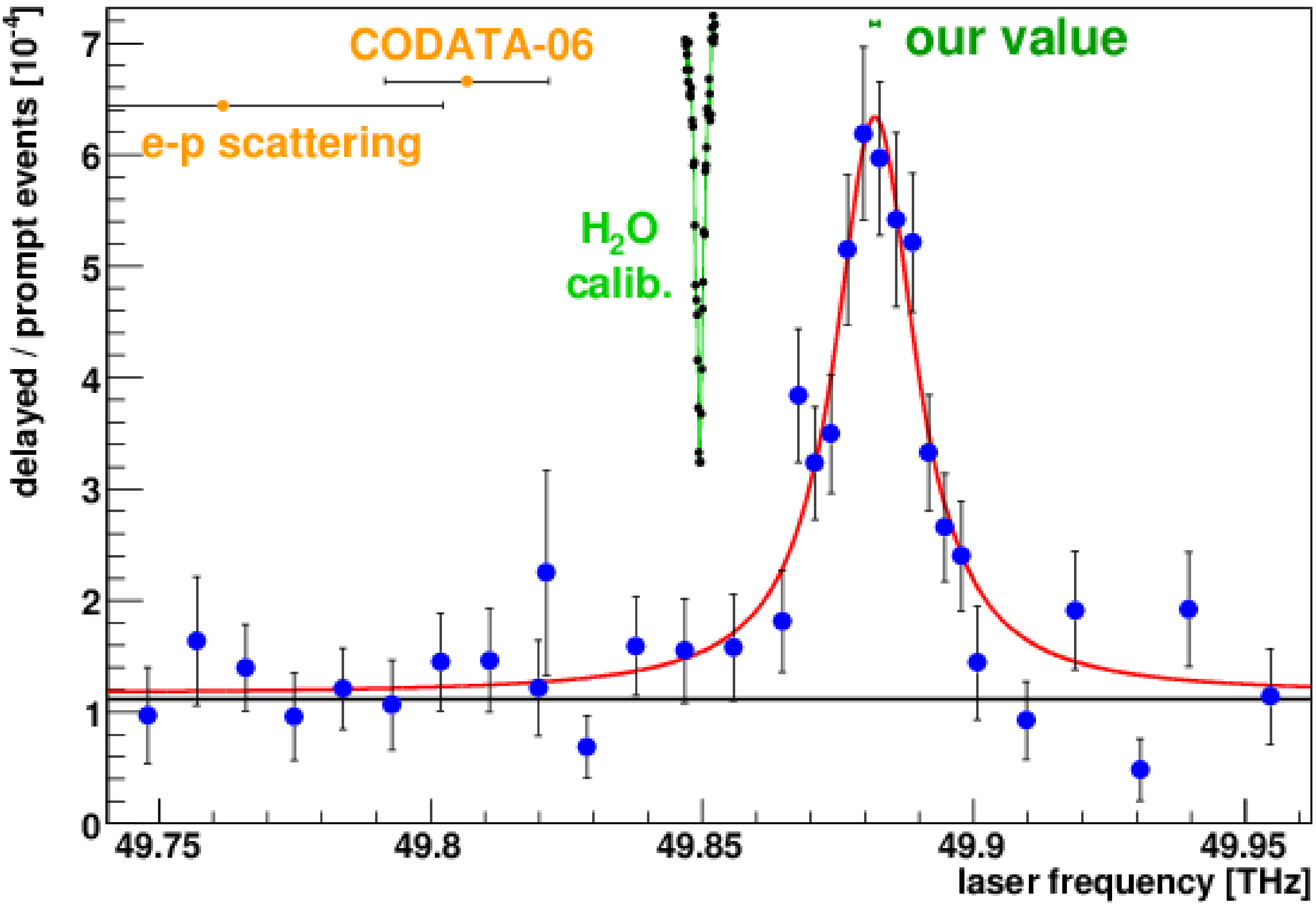


Status:
Hunting for the signal in H

further future:

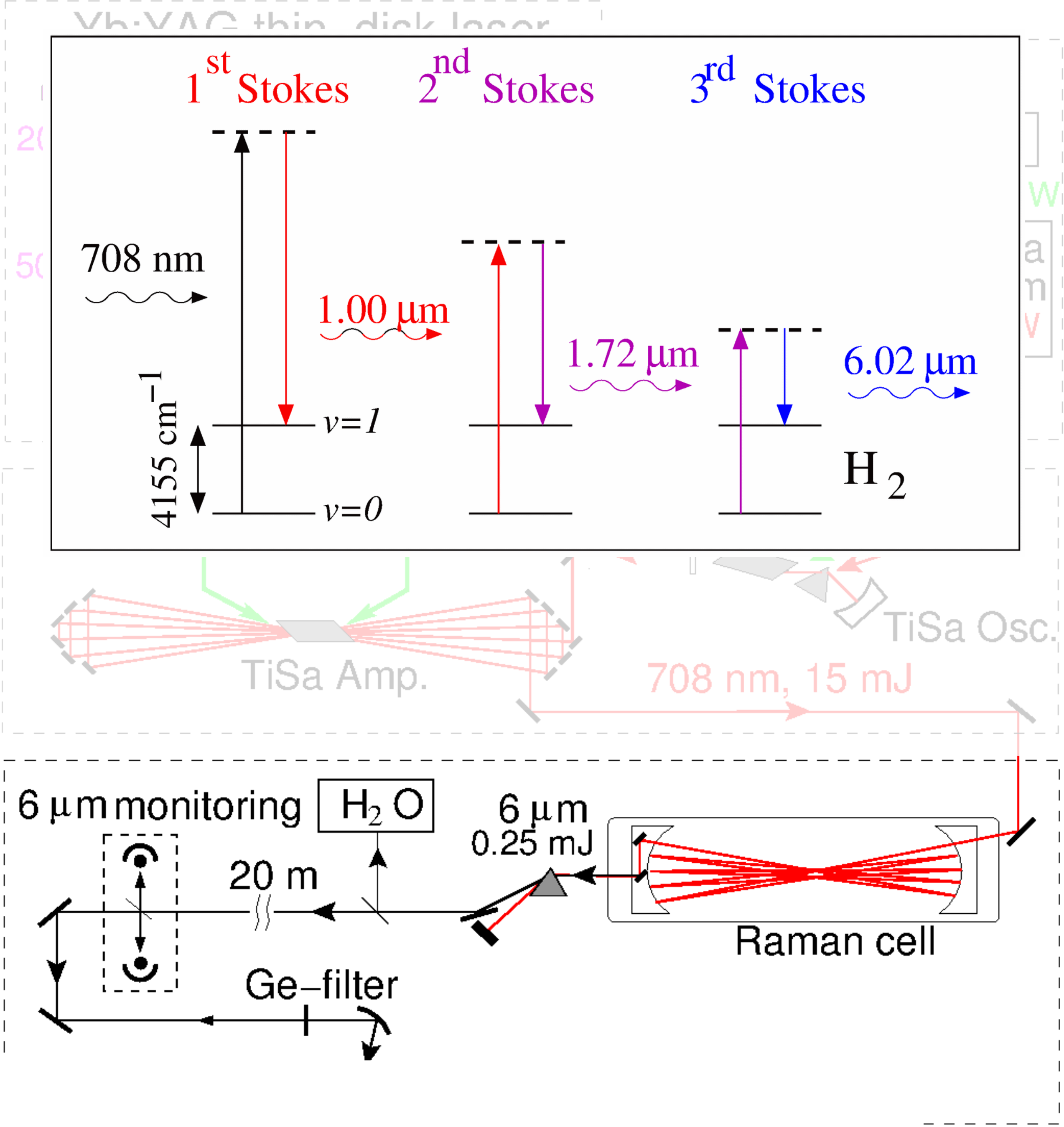
5x better Lamb shift in muonic hydrogen

Resonance in muonic hydrogen



Pohl et al. (CREMA Coll.), Nature 466, 213 (2010)

Laser system: Raman cell



Yb:YAG Disk laser
→ fast response on μ

Frequency doubling (SHG)
→ green light to pump
Ti:sapphire laser

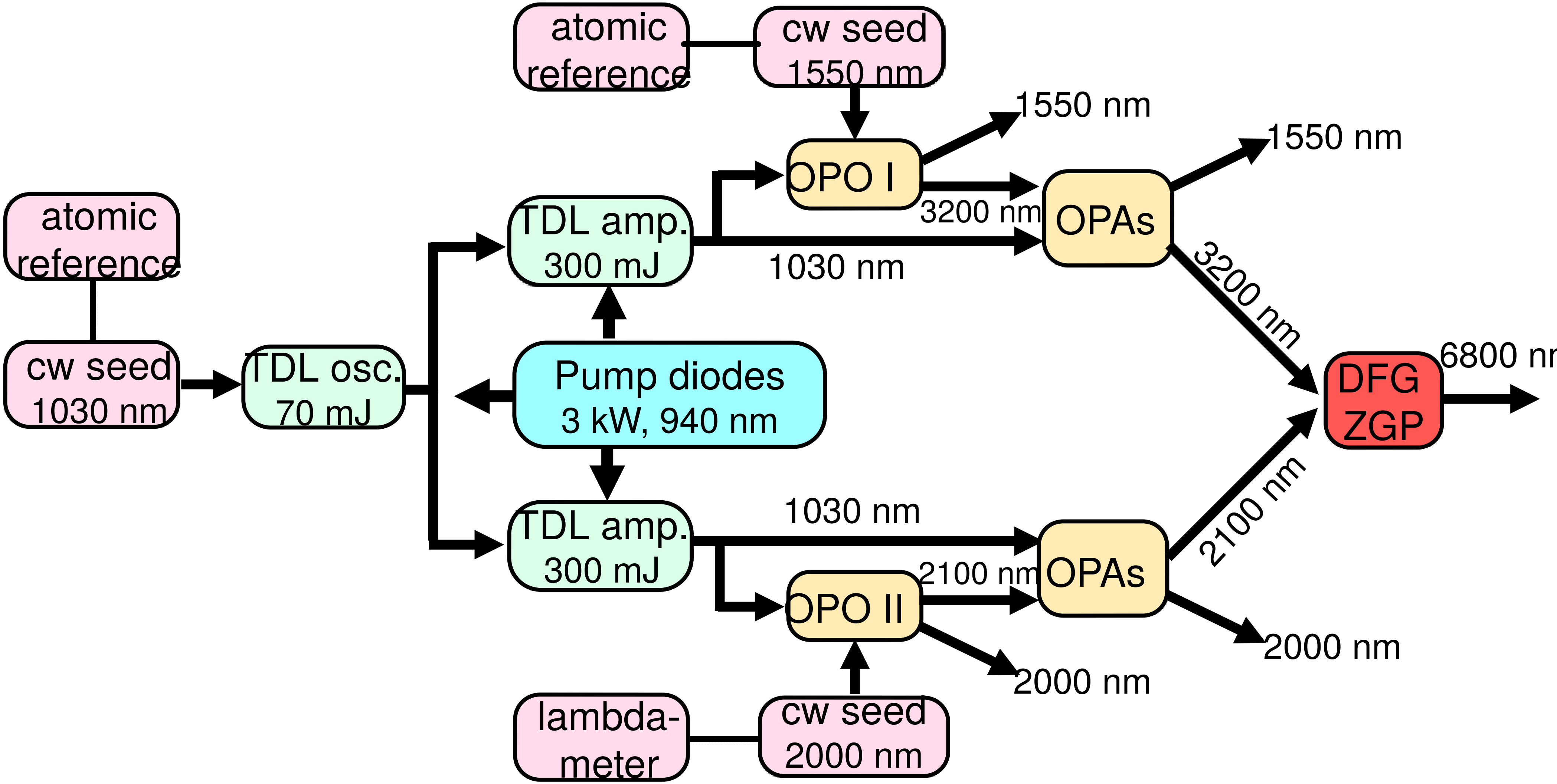
Ti:sapphire cw laser
→ determines laser frequency

Ti:sapphire MOPA
→ high pulse energy (15 mJ)

Raman cell
→ 3 sequential stimulated
Raman Stokes shifts
Laser wave length → 6 μm

Target Cavity
→ Mirror system to fill the
muon stop volume (H_2)

The laser



atomic reference
cw seed 1030 nm
TDL osc. 70 mJ
Pump diodes 3 kW, 940 nm
TDL amp. 300 mJ
TDL amp. 300 mJ
atomic reference
cw seed 1550 nm
OPO I
1550 nm
3200 nm
1030 nm
OPAs
1550 nm
3200 nm
DFG ZGP
6800 nr
1030 nm
2100 nm
OPO II
OPAs
2100 nm
2000 nm
2000 nm
lambda-meter
cw seed 2000 nm

Thanks a lot for your attention

The CREMA Collaboration

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Physique quantique et applications

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IFSW
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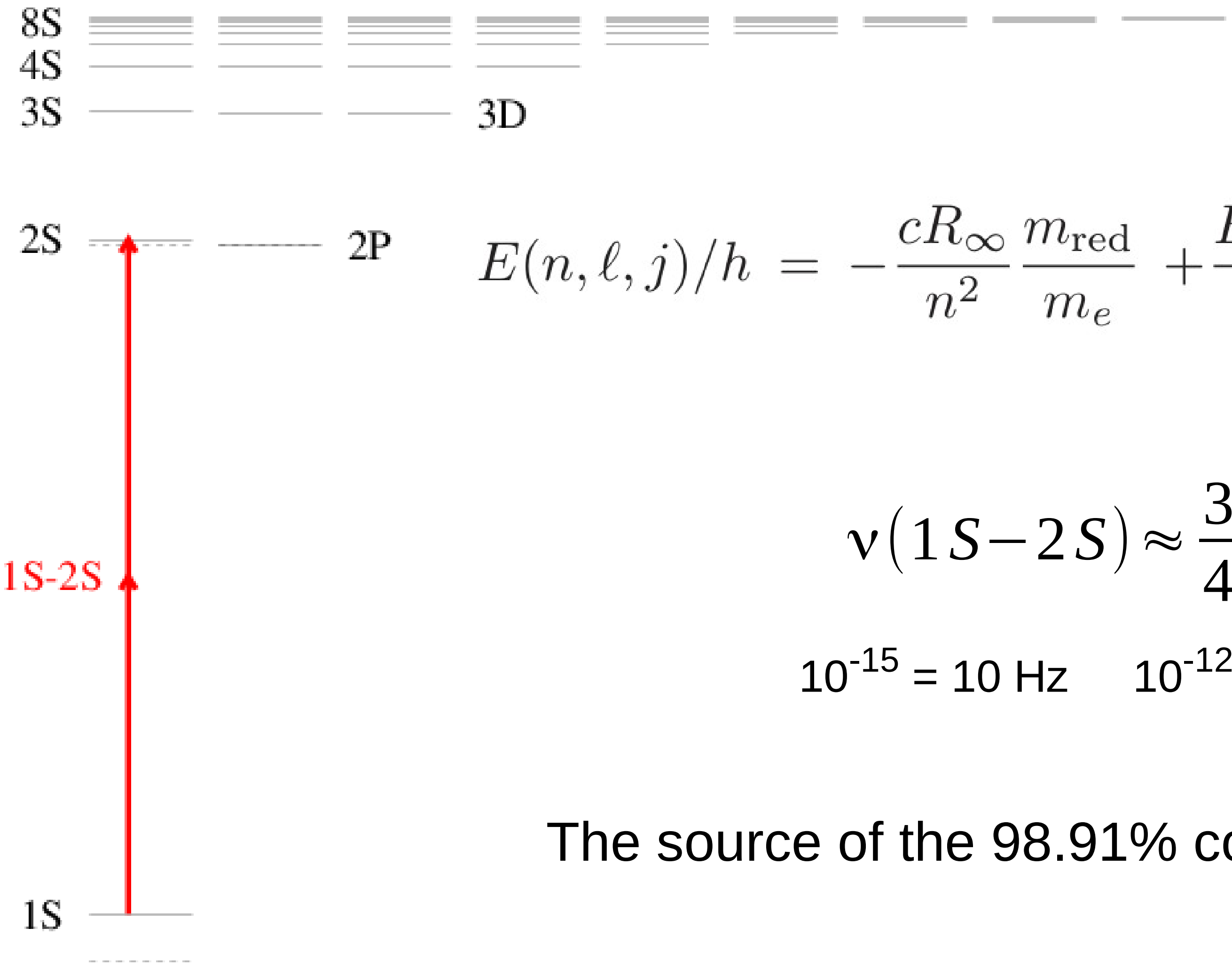
INSTITUT FÜR STRAHLWERKZEUGE
STUTTGART LASER TECHNOLOGIES

IFJ PAN

Correlation between R_∞ and R_p / R_d



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

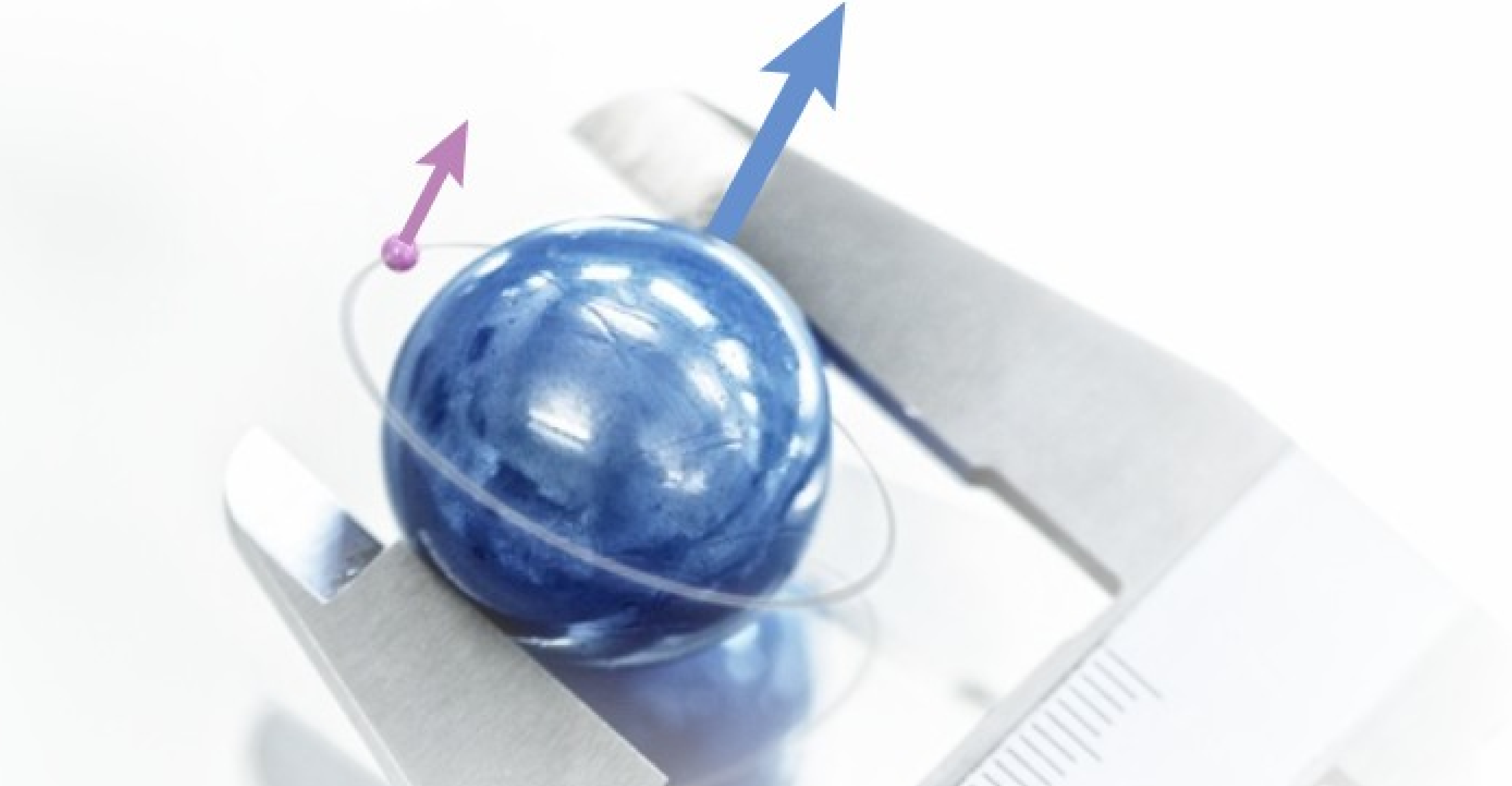
$$\nu(1S-2S) \approx \frac{3}{4}R_\infty - \frac{7}{8}E_{NS}$$

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

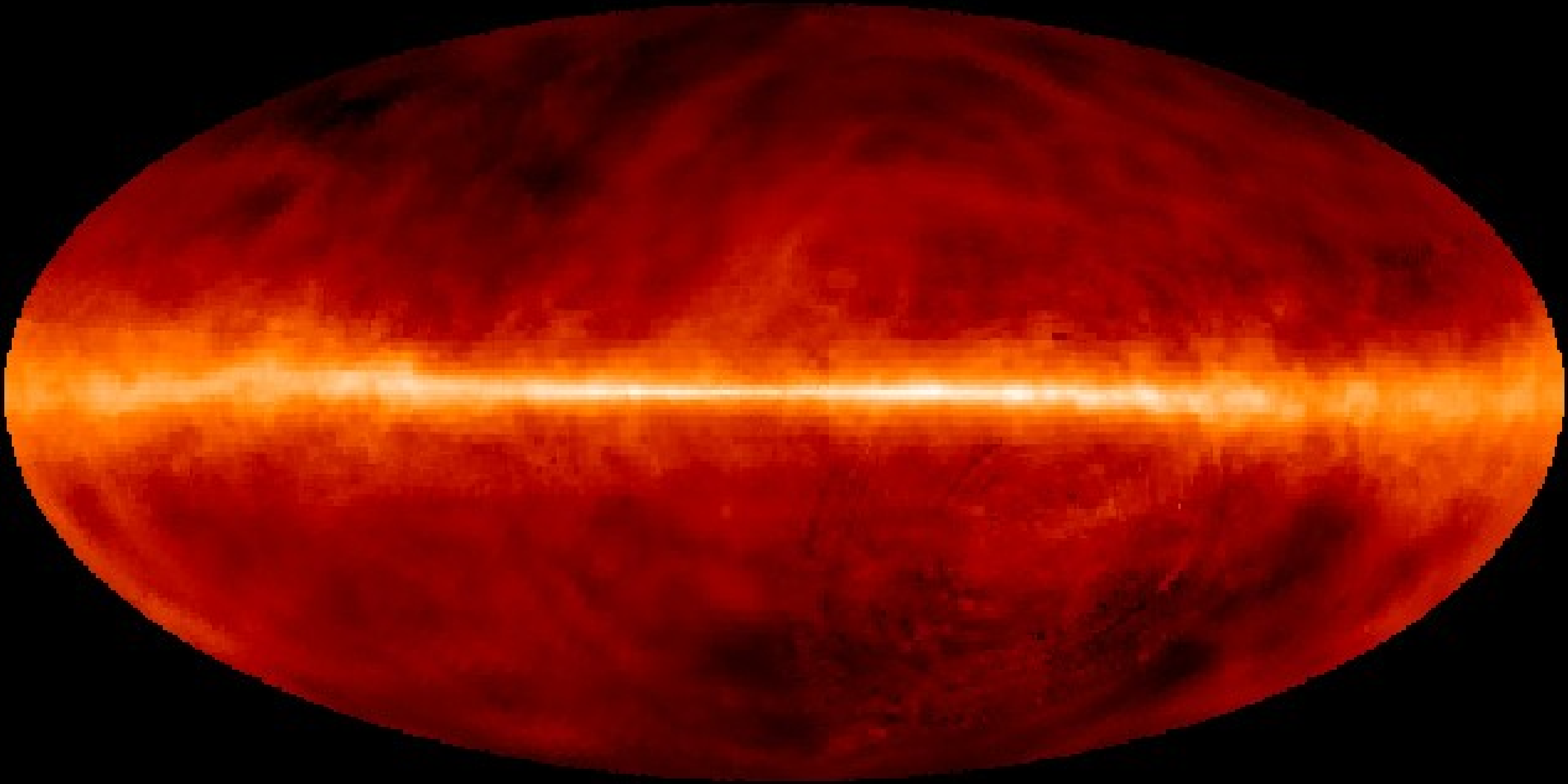
The source of the 98.91% correlation of R_∞ and R_p

Hyperfine structure in muonic H

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

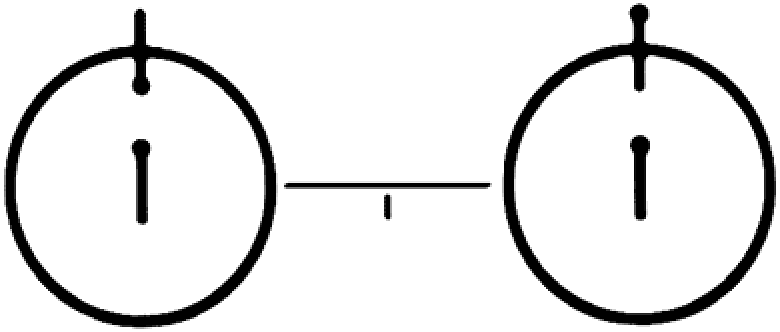


The sky in hydrogen



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:

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

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

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

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

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

Proton Zemach radius

HFS depends on “Zemach” radius:

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

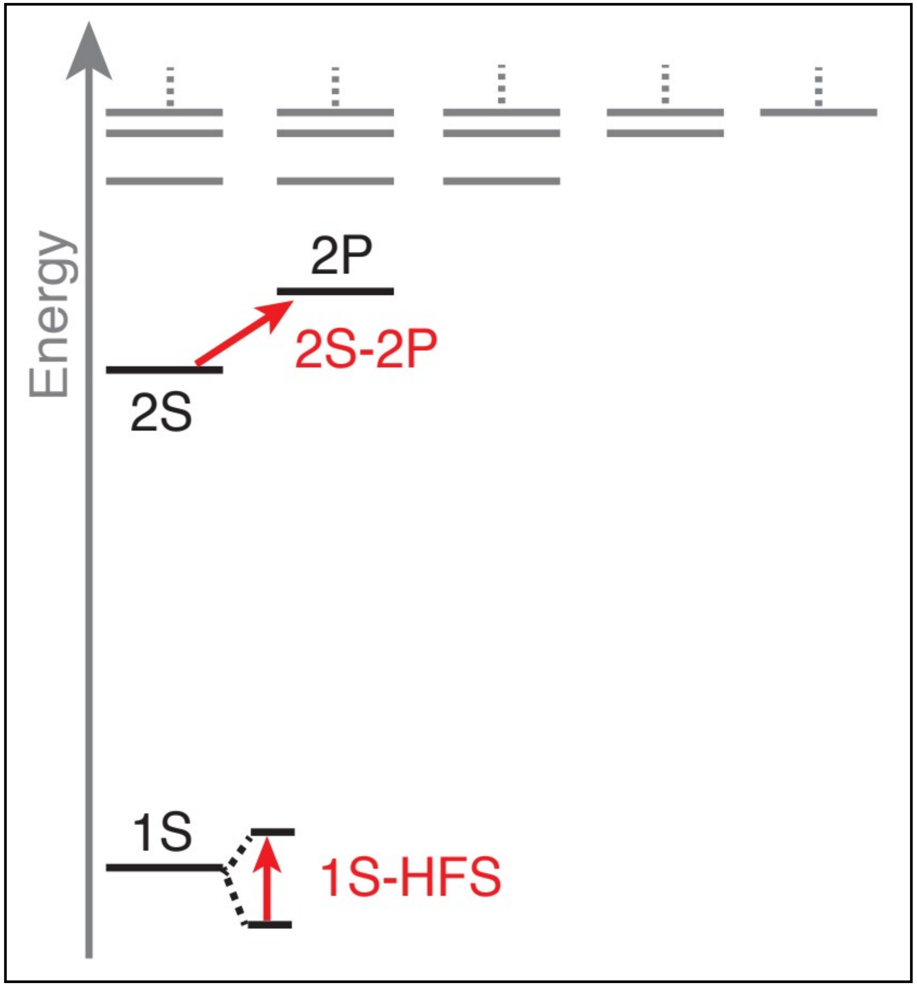
$$\langle r \rangle_{(2)} = \int d^3r\, d^3r'\, \rho_E(r)\, \rho_M(r')\, |r - r'|$$

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



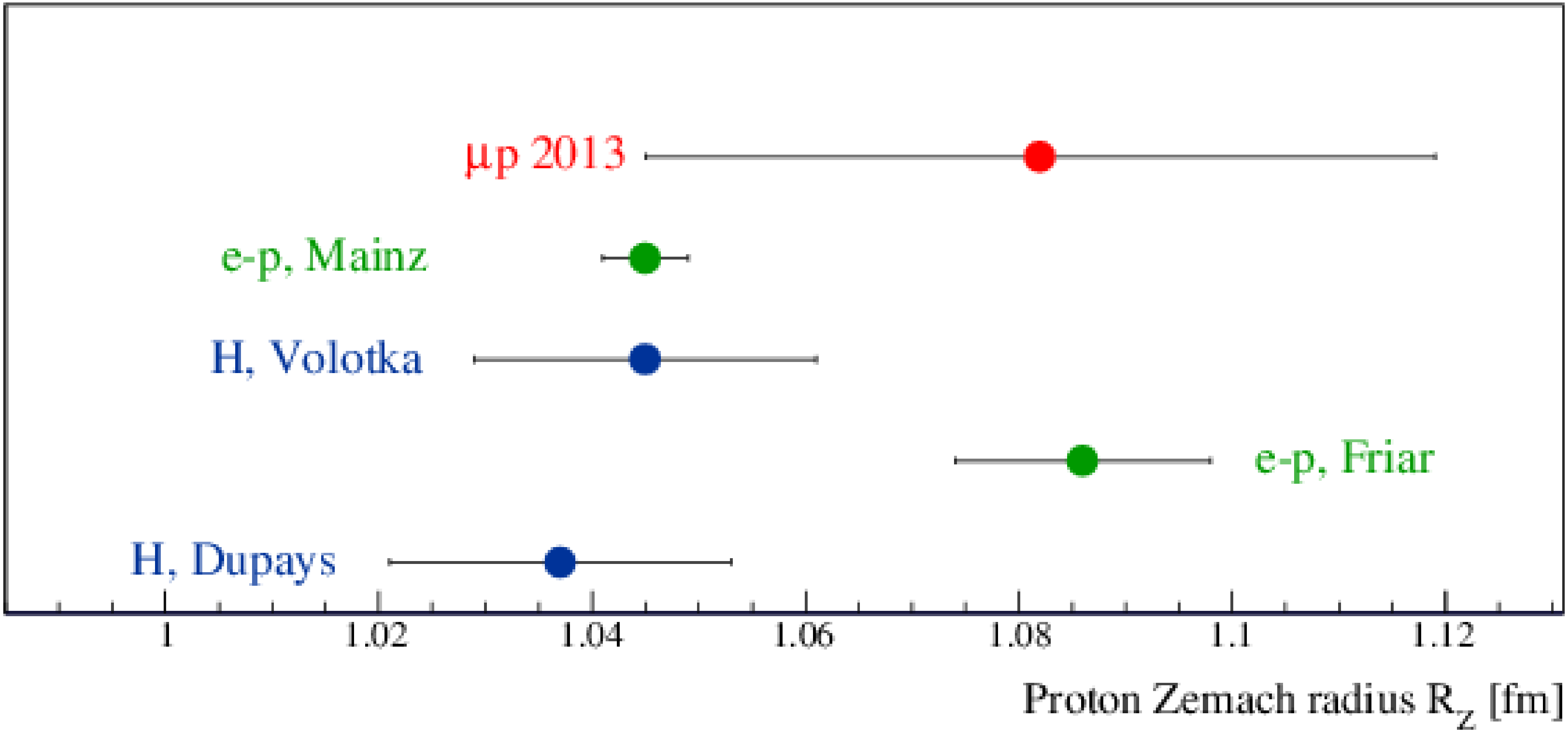
2S-2P = Lamb shift

is sensitive to CHARGE radius

1S-HFS = Hyperfine splitting

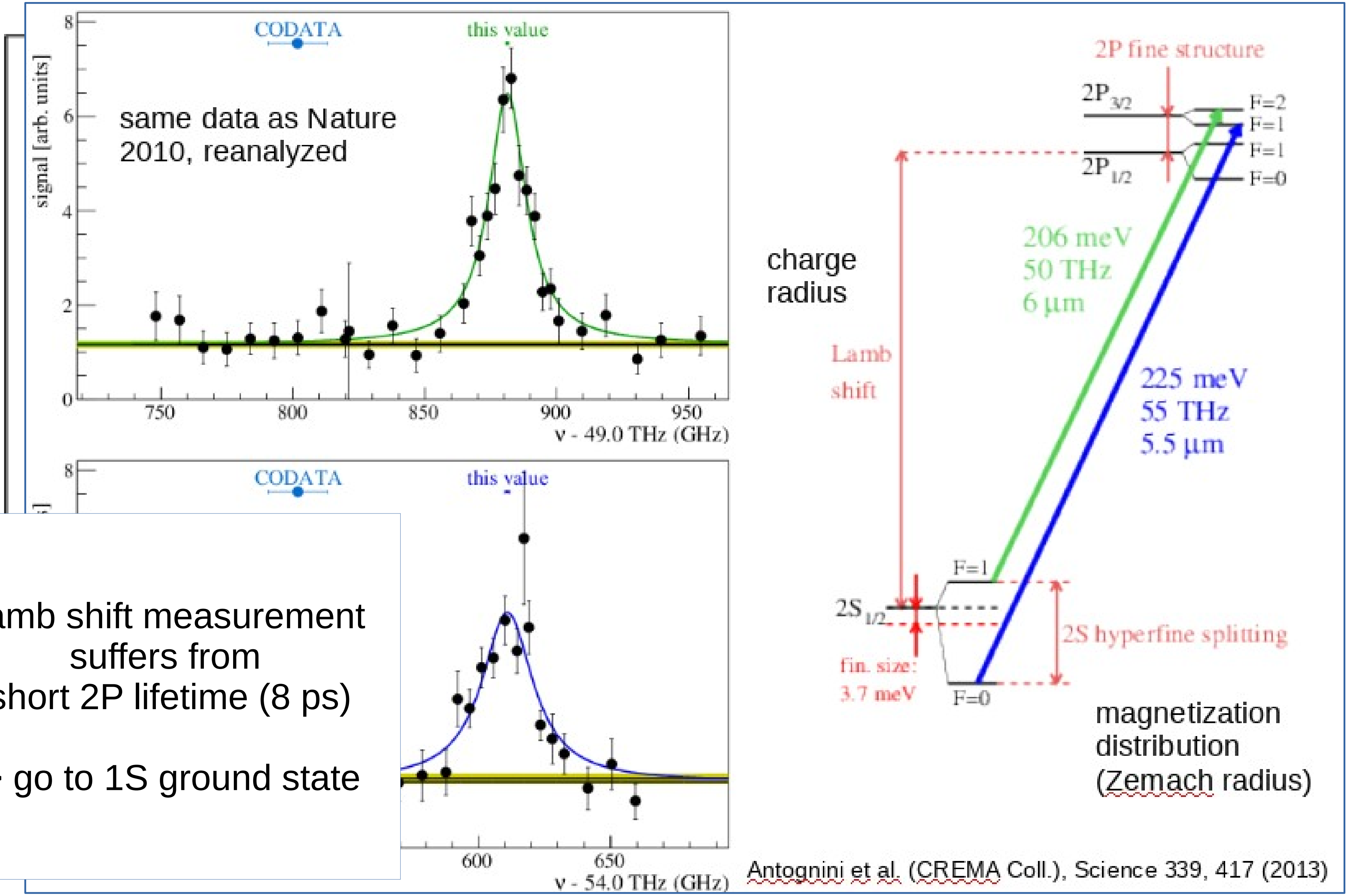
is sensitive to ZEMACH radius

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

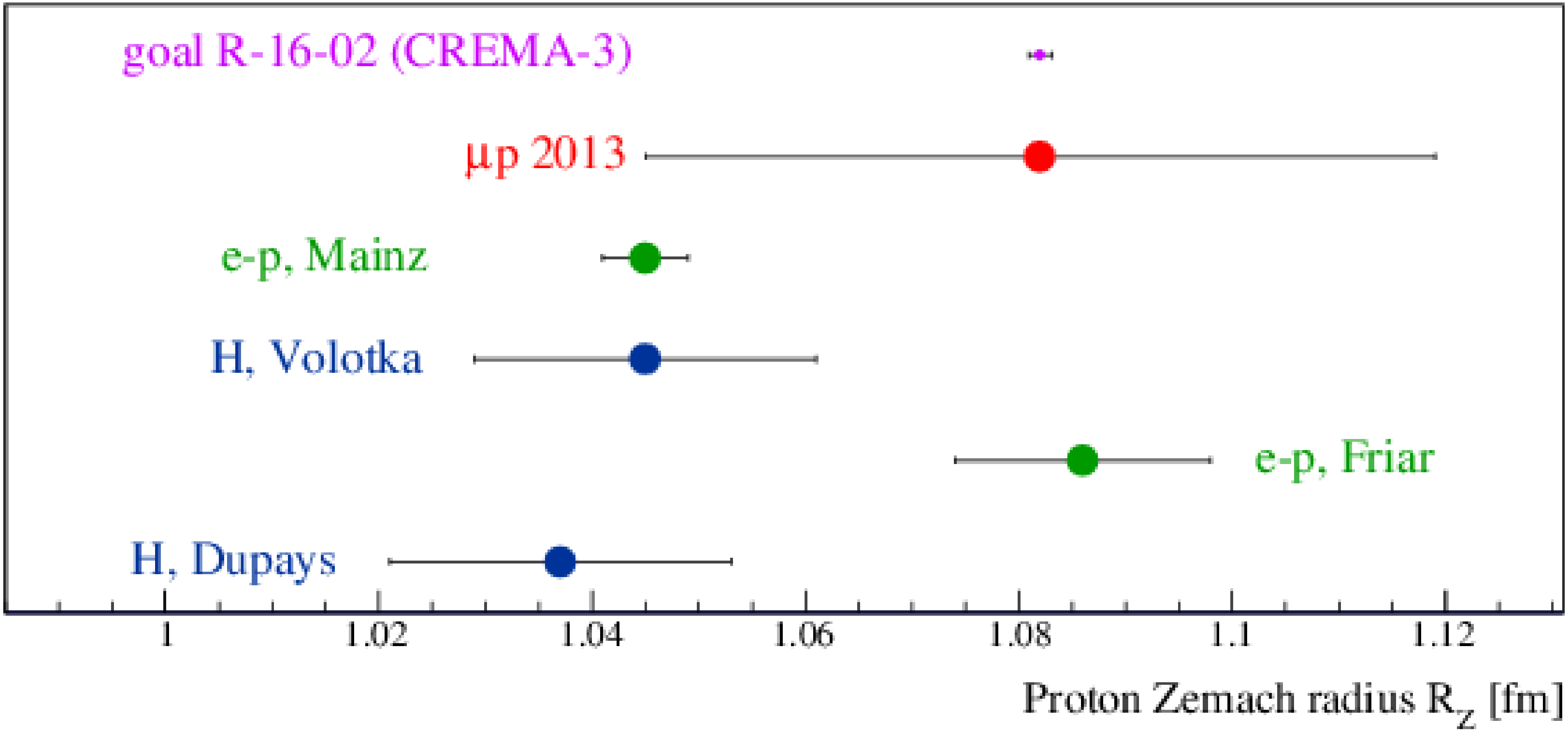
magnetization distribution (Zemach radius)

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

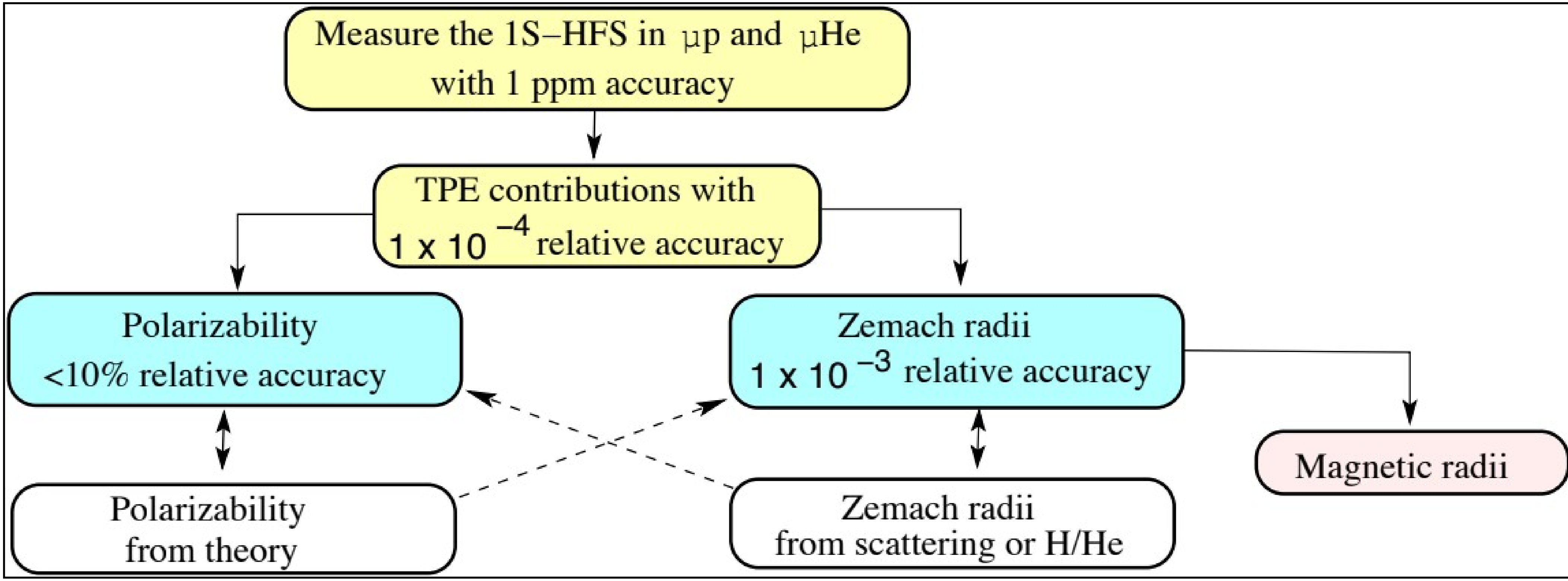
also: FAMU @ RIKEN/RAL, and a Collaboration at J-PARC

HFS in μp

goal: measure HFS with 1 ppm relative accuracy

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

HFS in μp



Measure the 1S–HFS in μp and μHe with 1 ppm accuracy

TPE contributions with 1×10^{-4} relative accuracy

Polarizability <10% relative accuracy

Zemach radii 1×10^{-3} relative accuracy

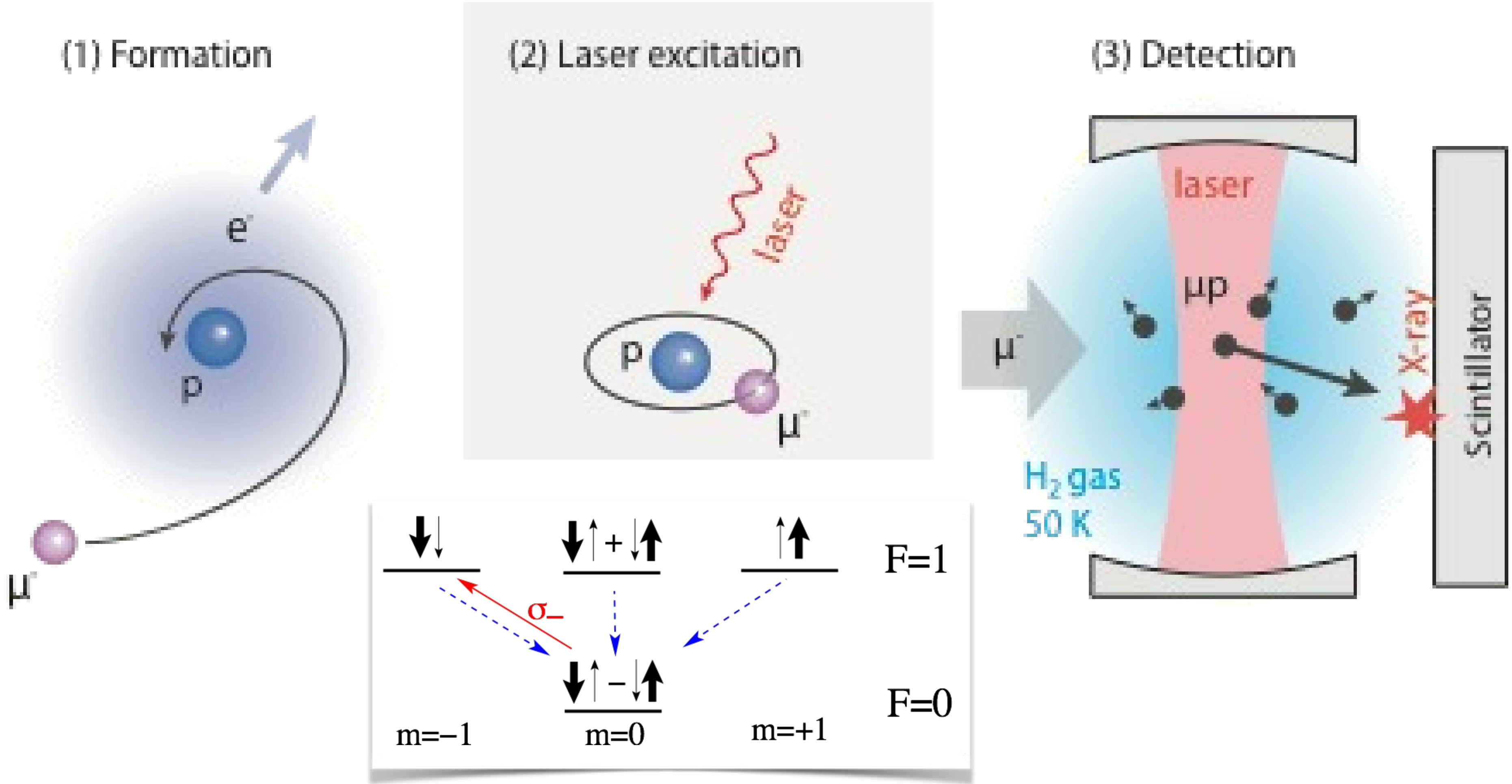
Magnetic radii

Polarizability from theory

Zemach radii from scattering or H/He

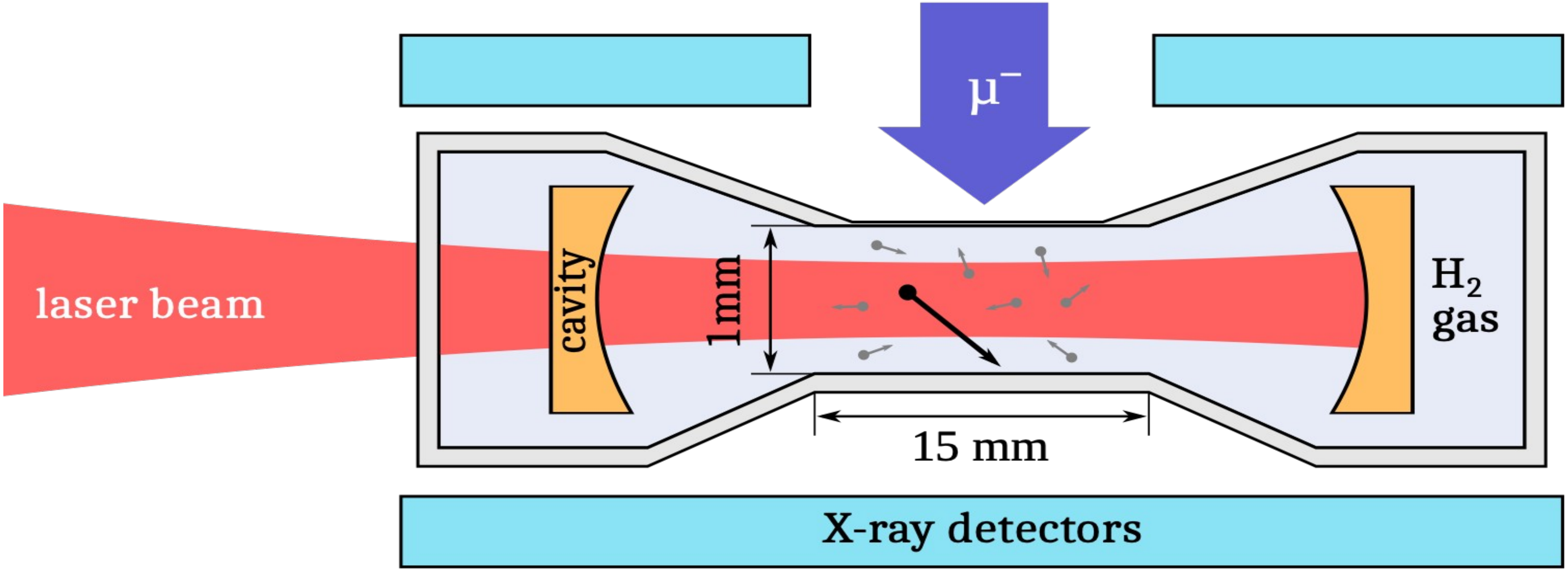
related propsals: FAMU at RIKEN/RAL, muonic H at J-PARC

CREMA-3/HyperMu @ PSI

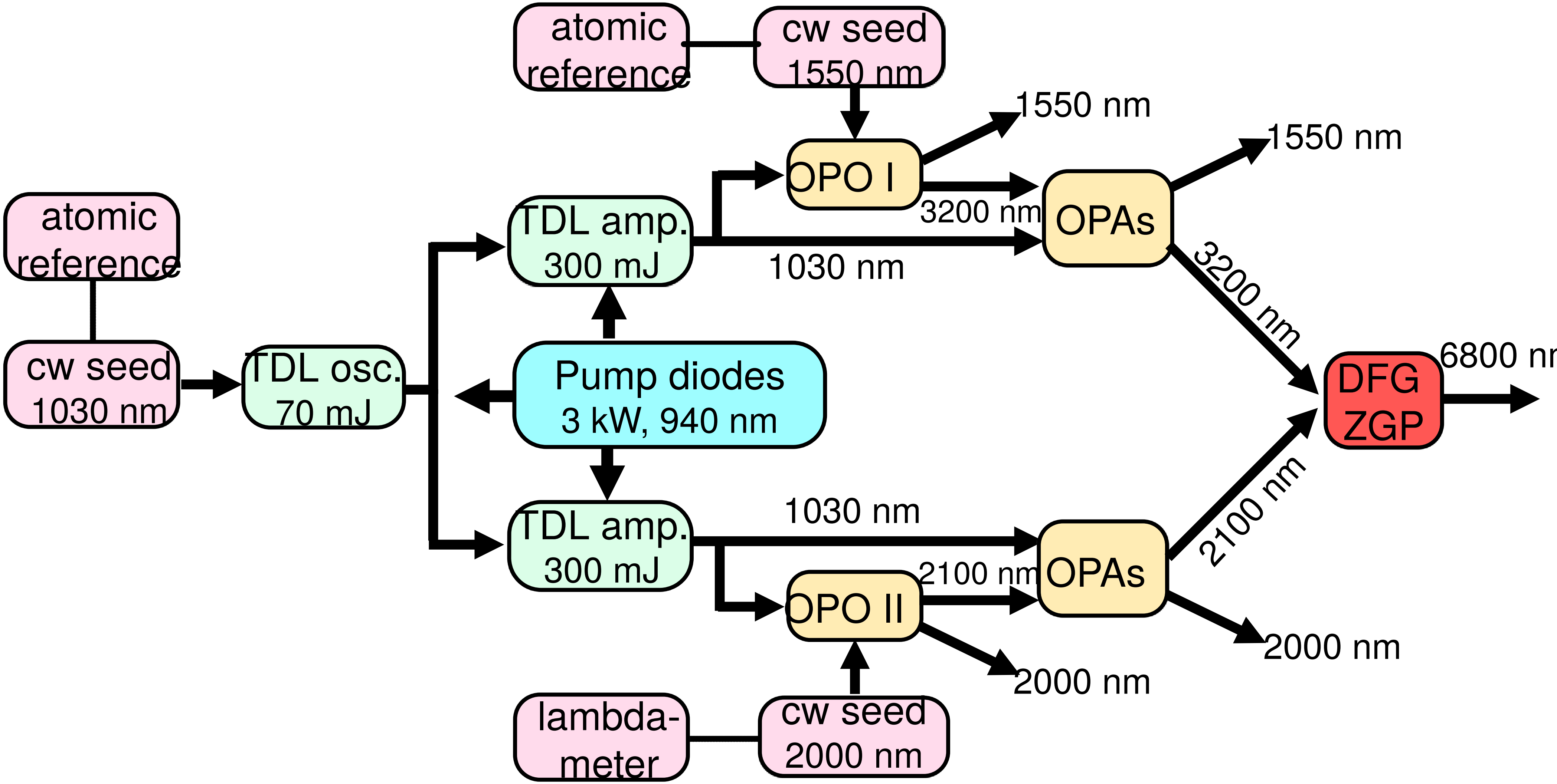


- Laser pulse: μp(F=0) + γ → μp(F=1)
- De-excitation: μp(F=1) + H_2 → μp(F=0) + H_2 + E_{kin}
- Diffusion: X-rays produced at target walls
- Resonance: Number of X-rays vs laser freq.

Detection



The laser



atomic reference

cw seed 1550 nm

1550 nm

OPO I

3200 nm

OPAs

1550 nm

atomic reference

cw seed 1030 nm

TDL osc. 70 mJ

TDL amp. 300 mJ

1030 nm

3200 nm

Pump diodes 3 kW, 940 nm

DFG ZGP

6800 n

TDL amp. 300 mJ

1030 nm

2100 nm

OPAs

2100 nm

OPO II

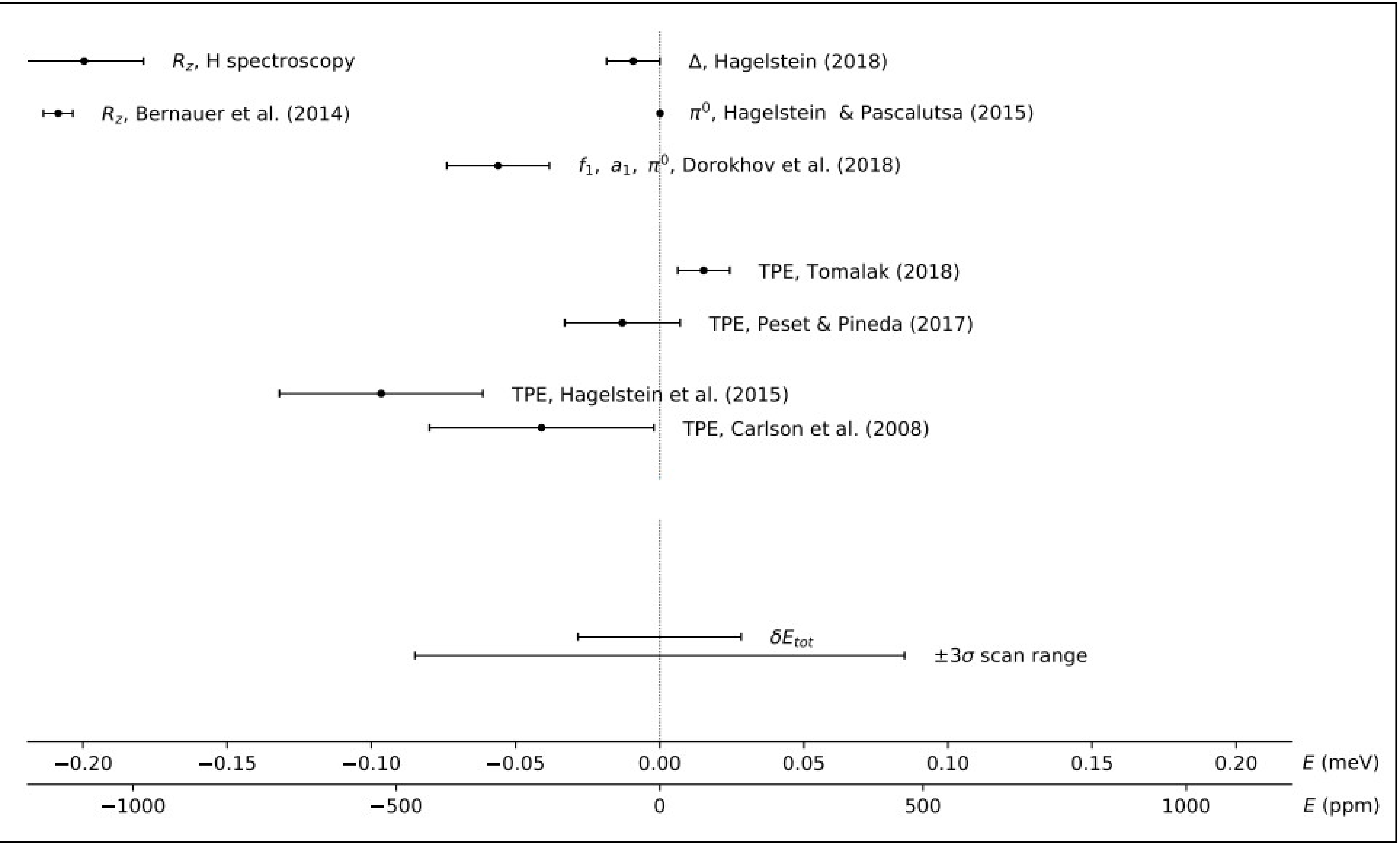
2000 nm

2000 nm

lambda-meter

cw seed 2000 nm

Predicting the resonance position



The resonance position