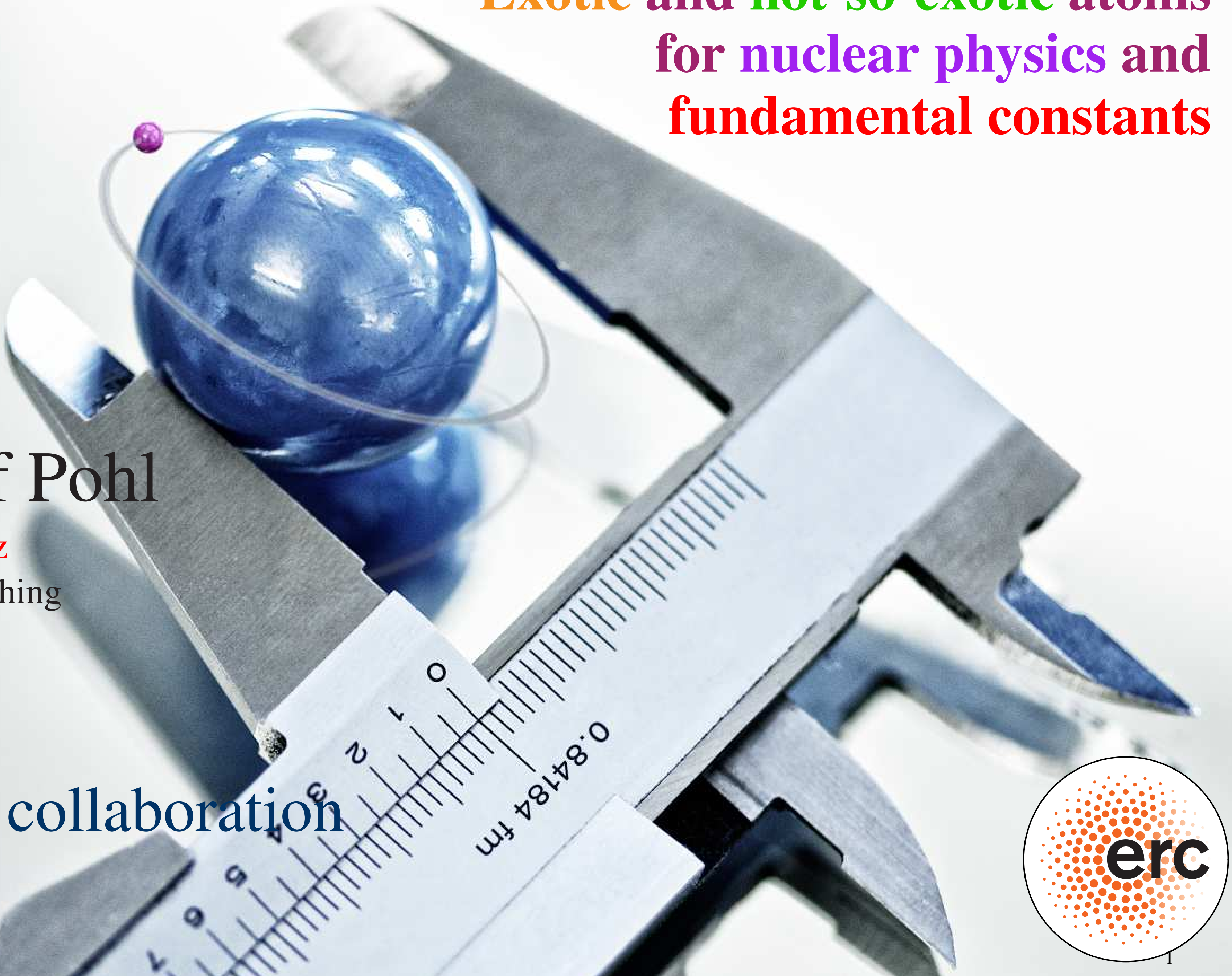
Shrinking the Proton

Exotic and not-so-exotic atoms for nuclear physics and fundamental constants



Randolf Pohl

JGU, Mainz

MPQ, Garching

for the

CREMA collaboration

Collaborators

CREMA (Charge Radius Experiment with Muonic Atoms) at PSI

A. Antognini, K. Kirch, F. Kottmann, B. Naar, K. Schuhmann, D. Taqqu	ETH Zürich, Switzerland
M. Diepold, B. Franke, J. Götzfried, T.W. Hänsch, J. Hartmann, T. Kohlert, J. Krauth, F. Mulhauser, T. Nebel, R. Pohl	MPQ, Garching, Germany → JGU, Mainz, Germany
M. Hildebrandt, A. Knecht, A. Dax	PSI, Switzerland
F. Biraben, P. Indelicato, E.-O. Le Bigot, S. Galtier, L. Julien, F. Nez, C. Szabo-Foster	Laboratoire Kastler Brossel, Paris, France
F.D. Amaro, J.M.R. Cardoso, L.M.P. Fernandes, A.L. Gouvea, J.A.M. Lopez, C.M.B. Monteiro, J.M.F. dos Santos	Uni Coimbra, Portugal
D.S. Covita, J.F.C.A. Veloso	Uni Aveiro, Portugal
M. Abdou Ahmed, T. Graf, A. Voss, B. Weichelt	IFSW, Uni Stuttgart, Germany
T.-L. Chen, C.-Y. Kao, Y.-W. Liu	Nat. Tsing Hua Uni, Hsinchu, Taiwan
P. Amaro, J.P. Santos	Uni Lisbon, Portugal
L. Ludhova, P.E. Knowles, L.A. Schaller	Uni Fribourg, Switzerland
A. Giesen	Dausinger & Giesen GmbH, Stuttgart, Germany
P. Rabinowitz	Uni Princeton, USA

Hydrogen group at MPQ

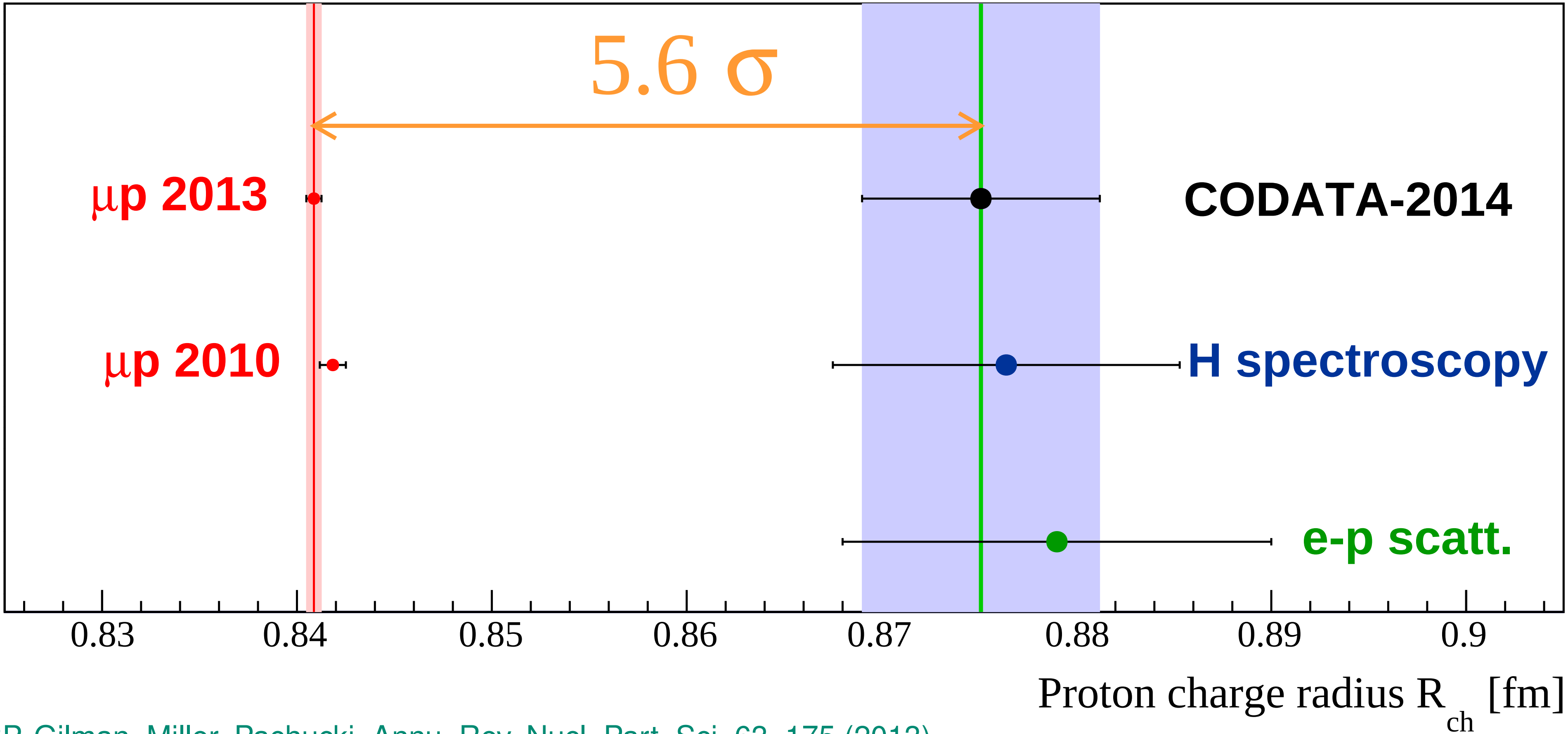
A. Beyer, A. Grinin, L. Maisenbacher, A. Matveev, C.G. Parthey, J. Alnis, D.C. Yost, E. Peters, R. Pohl, Th. Udem, T.W. Hänsch	MPQ, Garching, Germany
K. Khabarova, N. Kolachevksy	Lebedev Inst., Moscow, Russia

The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8751 ± 0.0061 fm

muons: 0.8409 ± 0.0004 fm



RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

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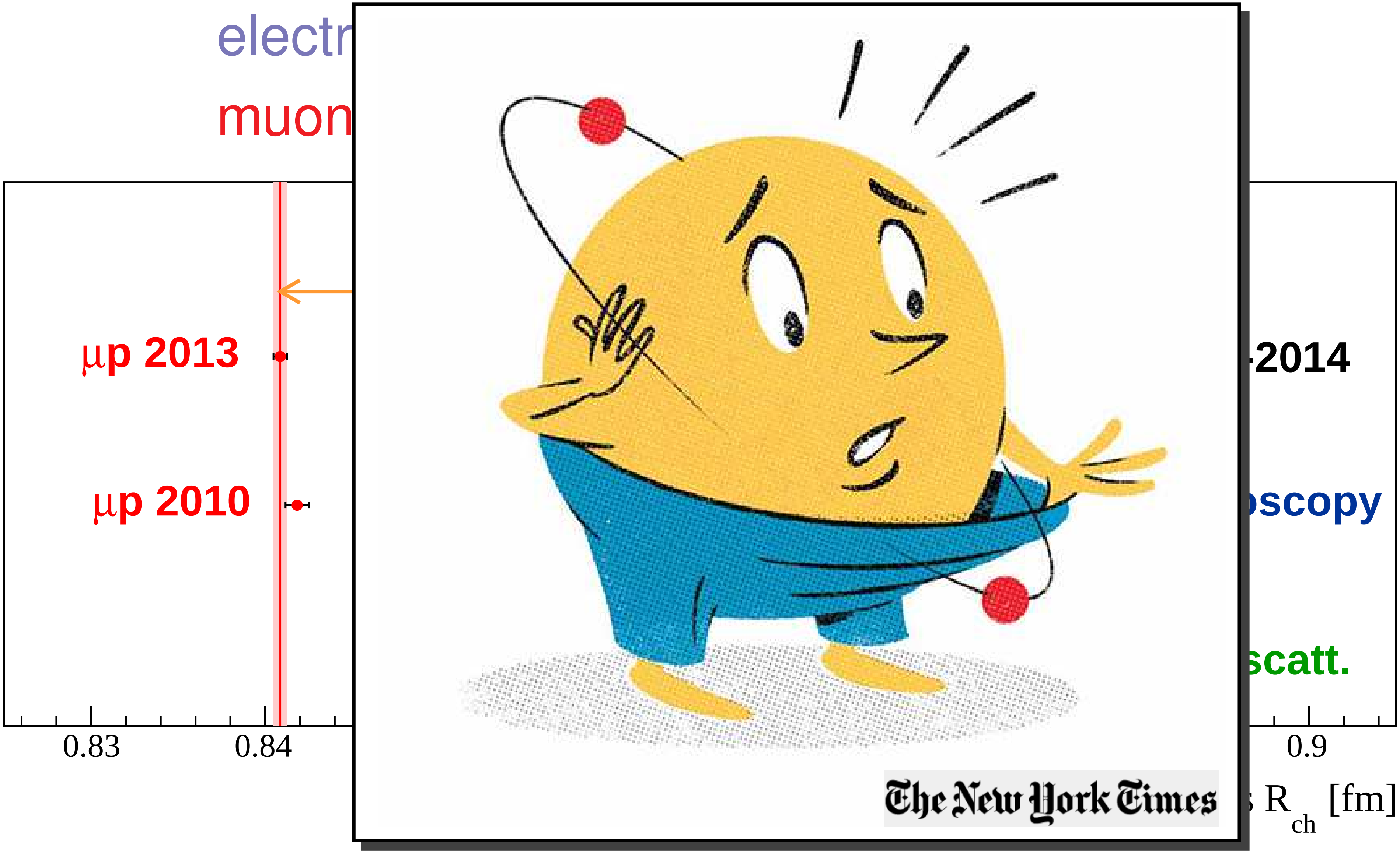
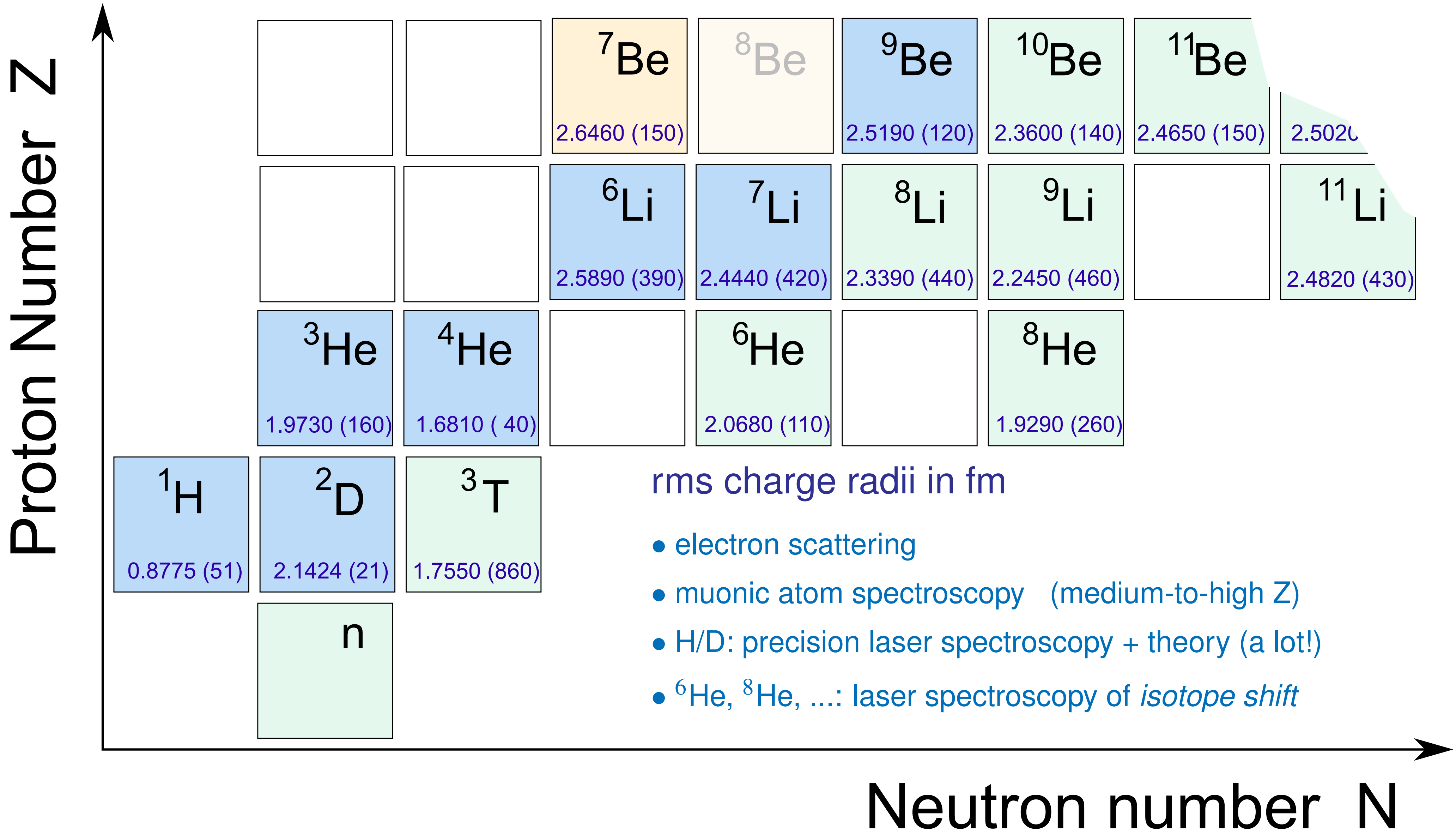


Outline

- Introduction
- Measurements
  - Muonic hydrogen
  - Muonic deuterium $\rightarrow 6\sigma$ discrepancy to CODATA!
  - Muonic helium-3 and -4 ions
  - Regular hydrogen $\rightarrow$ New Rydberg constant!
- Future:
  - HFS in muonic hydrogen and helium-3
  - X-ray spectroscopy of muonic radium etc.
  - Lamb shift in muonic Li, Be, ...
  - 1S-2S in regular tritium (triton radius)
  - ...

Charge radii of light nuclei



rms charge radii in fm

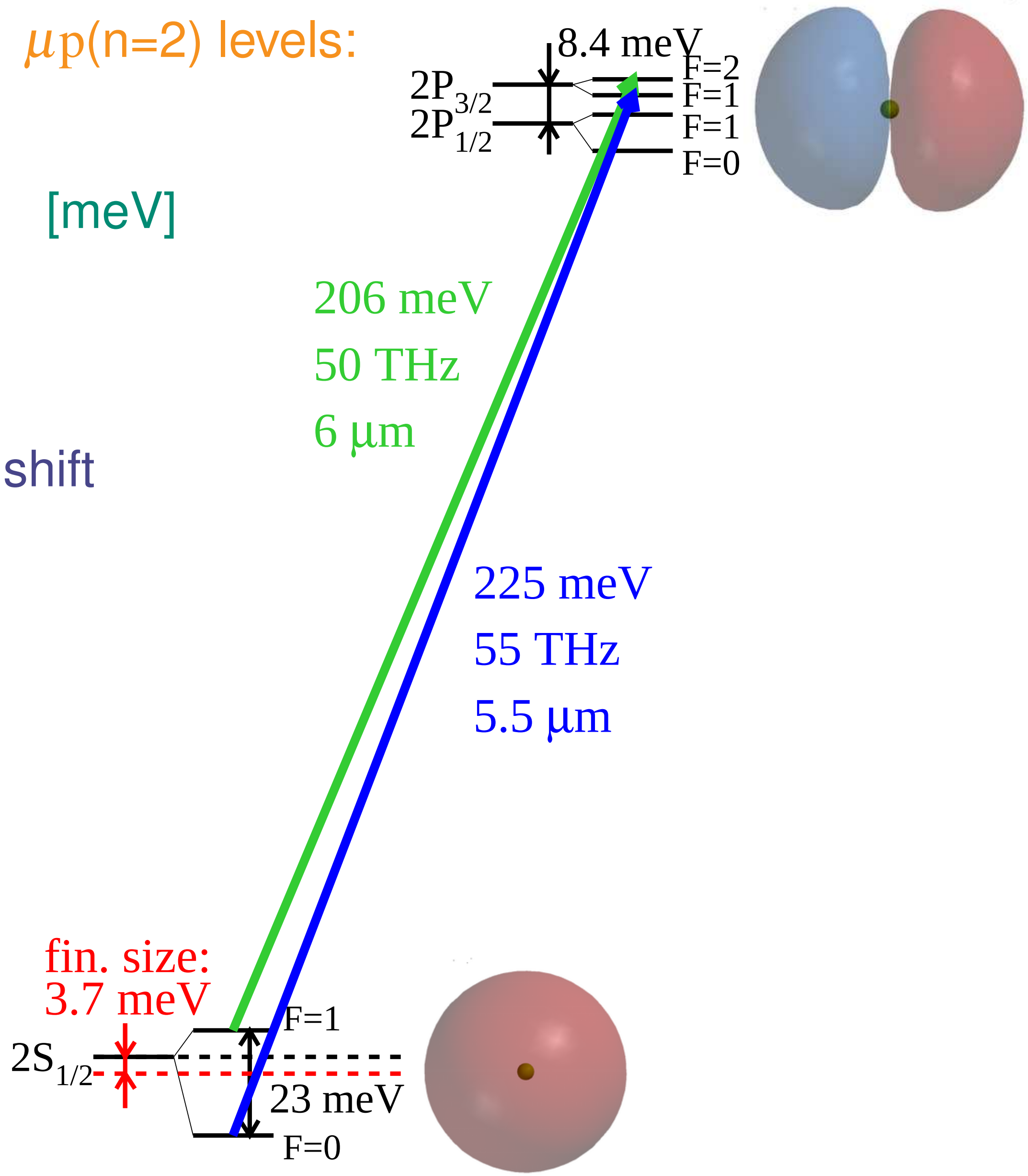
- electron scattering
- muonic atom spectroscopy (medium-to-high Z)
- H/D: precision laser spectroscopy + theory (a lot!)
- ^{6}He, ^{8}He, ...: laser spectroscopy of *isotope shift*

Proton charge radius and muonic hydrogen

Lamb shift in μp [meV]:

$$\Delta E = 206.0668(25) - 5.2275(10)\, r_{\mathrm{p}}^2 \quad \text{[meV]}$$

μp(n=2) levels:



Proton size effect is 2% of the μp Lamb shift

Measure to 10^{-5} $\Rightarrow$ r_{p} to 0.05 %

Experiment:

R. Pohl *et al.*, Nature 466, 213 (2010).

A. Antognini, RP *et al.*, Science 339, 417 (2013).

Theory summary:

A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

A nice hierarchy

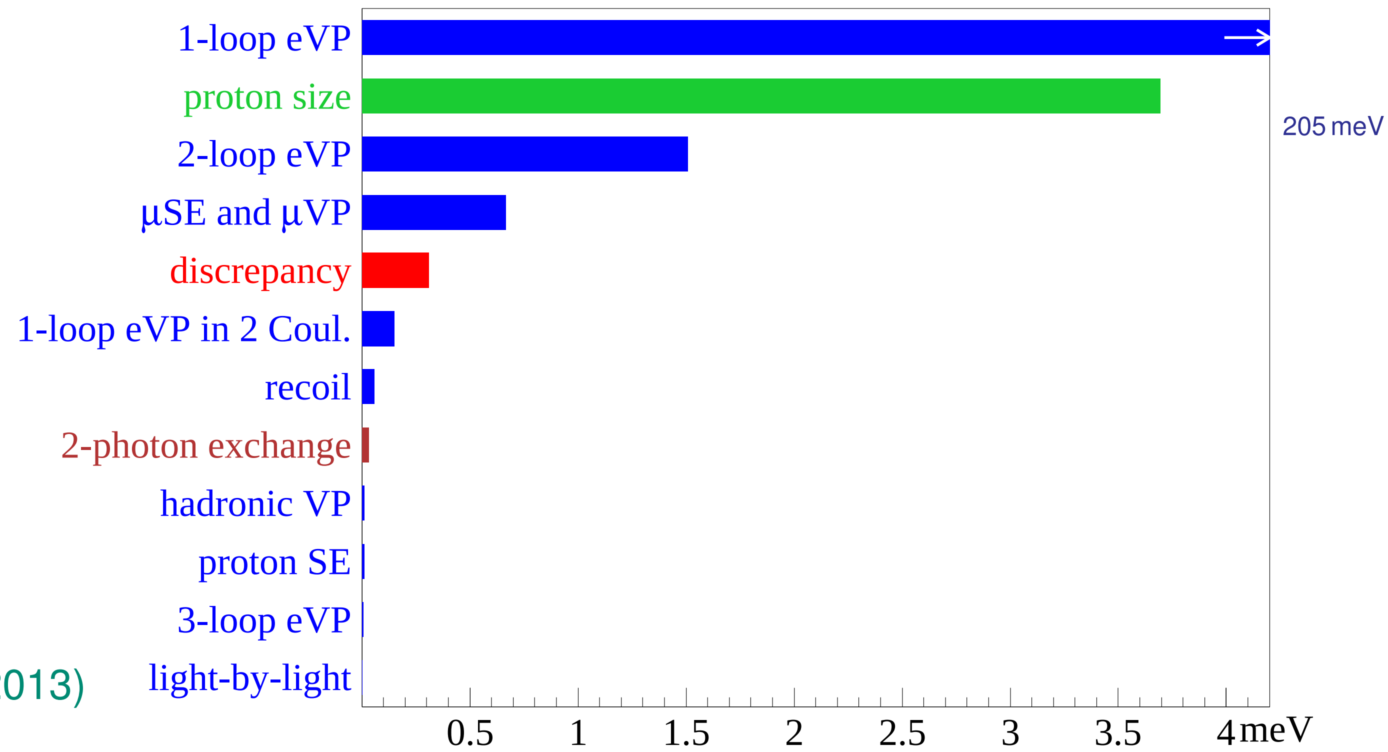
$$\Delta E = 206.0668(25) - 5.2275(10)\, r_p^2 \ \text{[meV]}$$

Discrepancy = 0.33 meV
Theory uncert. = 0.0025 meV

$\Longrightarrow$ 120δ(theory) deviation

Some contributions to the μp Lamb shift

double-checked by many groups



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Annals of Physics 331, 127 (2013)

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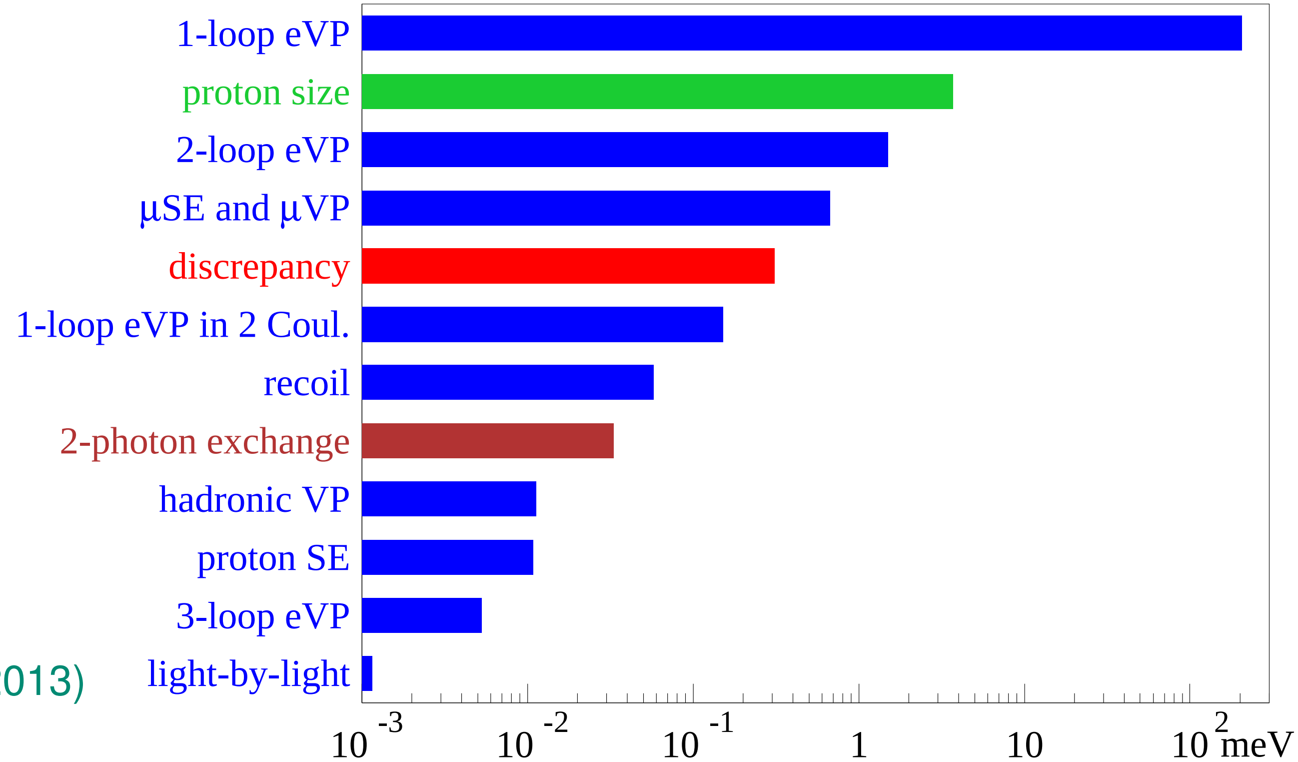

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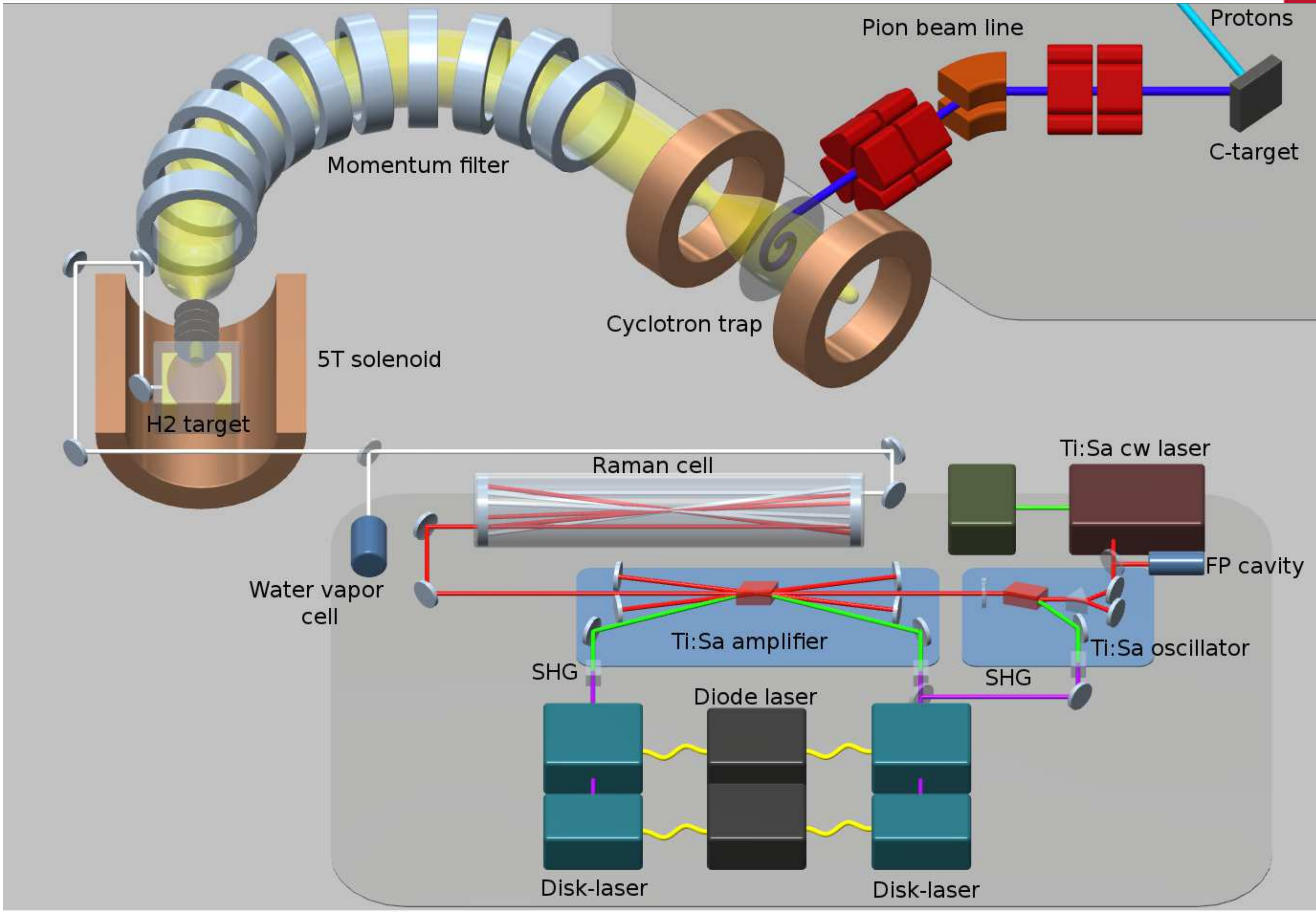
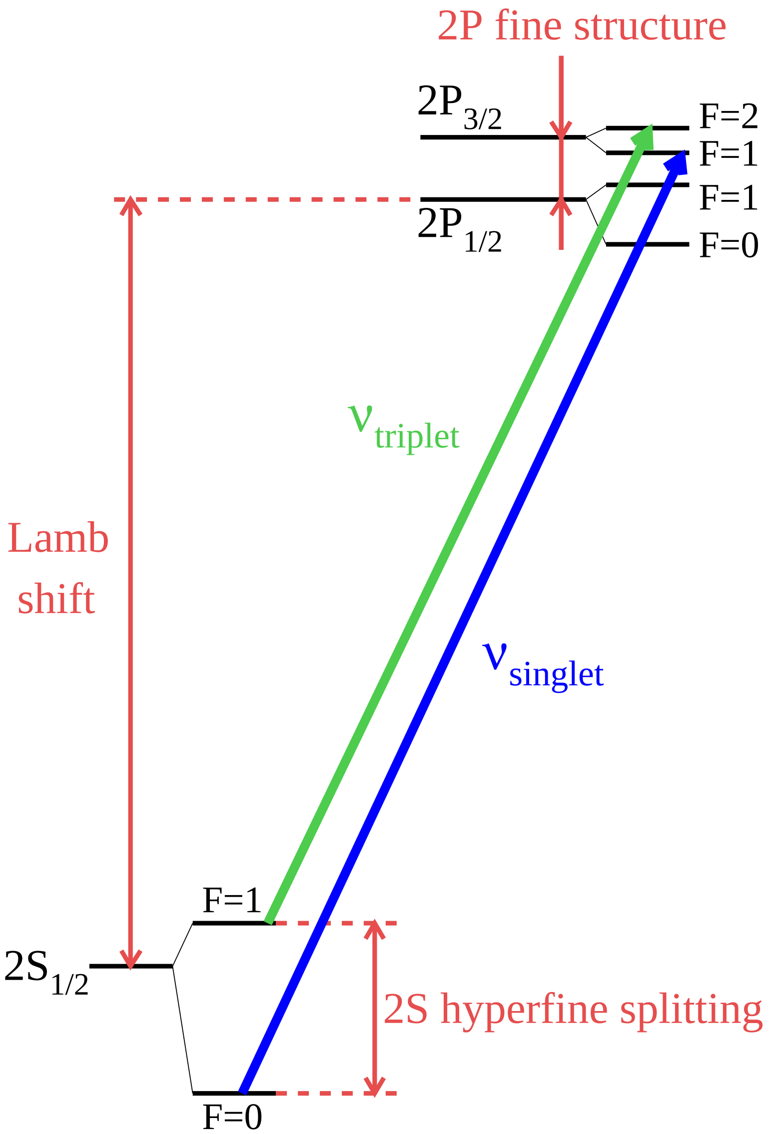
Setup

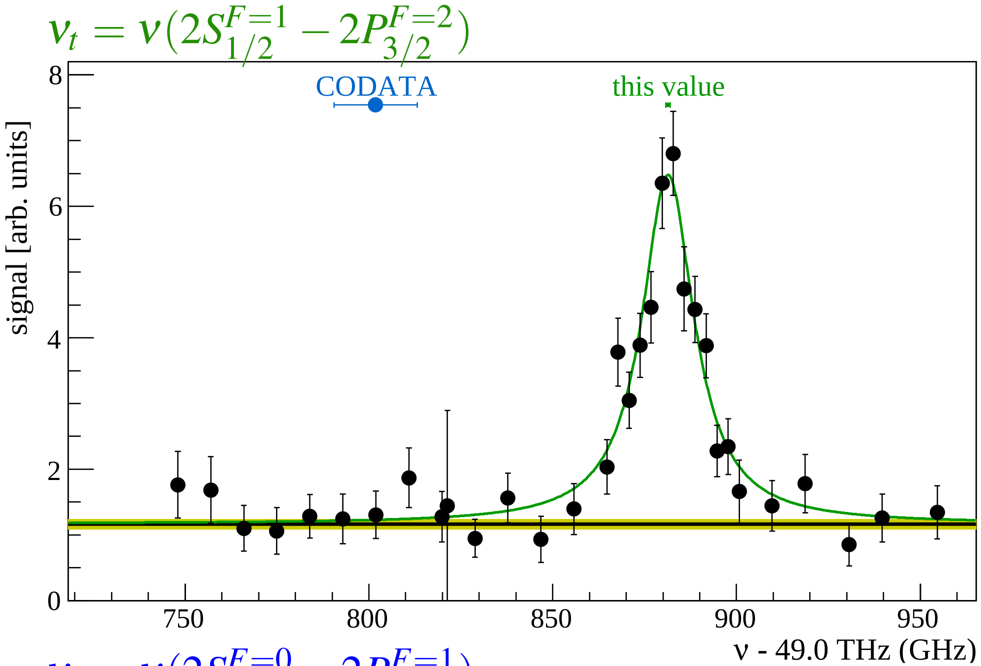


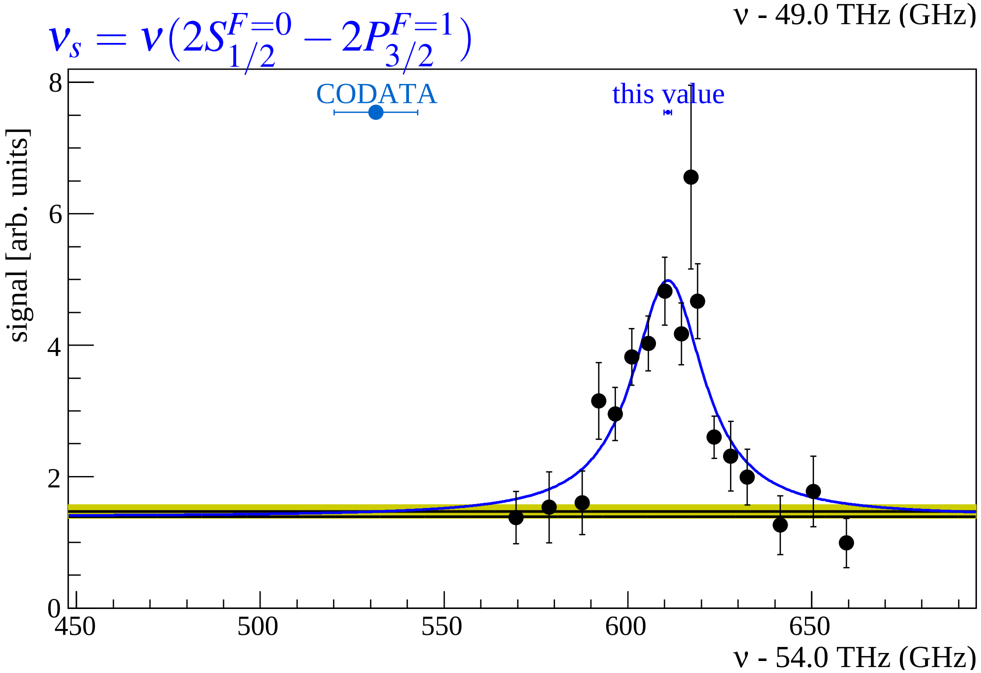
Protons
Pion beam line
C-target
Momentum filter
Cyclotron trap
5T solenoid
H2 target
Raman cell
Ti:Sa cw laser
FP cavity
Water vapor
cell
Ti:Sa amplifier
Ti:Sa oscillator
SHG
SHG
Diode laser
Disk-laser
Disk-laser

Muonic hydrogen

Muonic hydrogen results







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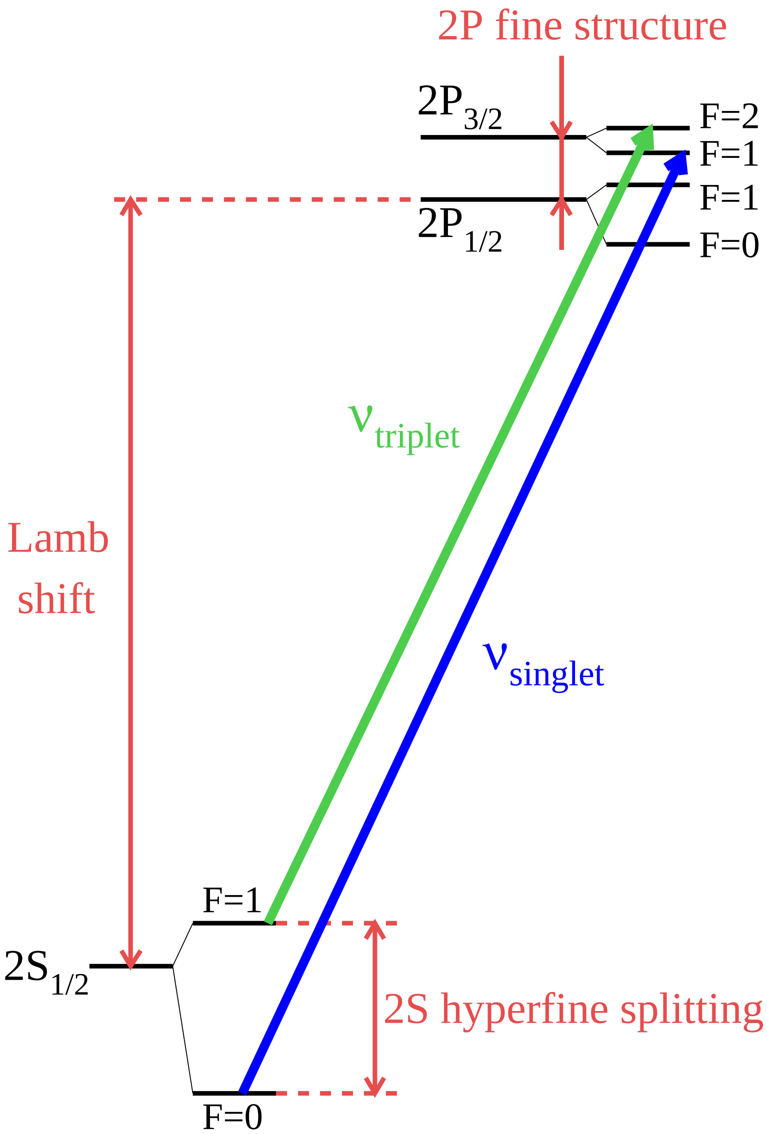
Muonic hydrogen results



- two transitions measured

ν_t = 49881.35(65) GHz

ν_s = 54611.16(1.05) GHz

- Lamb shift ⇒ **charge radius**

$$\Delta E_{LS} = 206.0668(25) - 5.2275(10)\; r_E^2 \quad \text{[meV, fm]}$$

$$r_E^2 = \int d^3r\, r^2\, \rho_E(r)$$

$r_E = 0.84087\,(26)_{exp}\,(29)_{th}$ fm = 0.84087 (39) fm

10x more precise than CODATA-2010

4% smaller (7σ)

proton radius puzzle

Exp.: R. Pohl *et al.*, Nature 466, 213 (2010).
A. Antognini, RP *et al.*, Science 339, 417 (2013).
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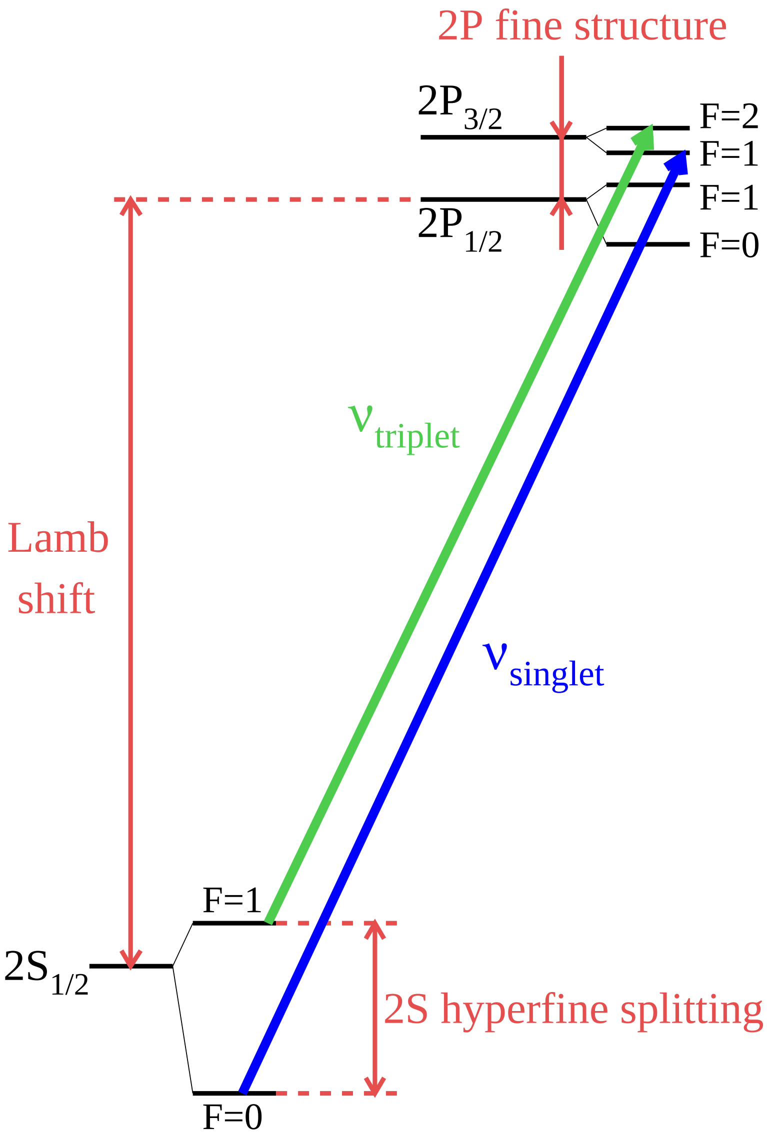

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- 2S-HFS ⇒ **Zemach radius**

$$\Delta E_{HFS} = 22.9843(30) - 0.1621(10)\, r_Z \quad \text{[meV, fm]}$$

$$r_Z = \int d^3r \int d^3r'\, r\, \rho_E(r)\, \rho_M(r - r')$$

$$r_Z = 1.082\,(31)_{exp}\,(20)_{th}\ \text{fm} = 1.082\,(37)\ \text{fm}$$

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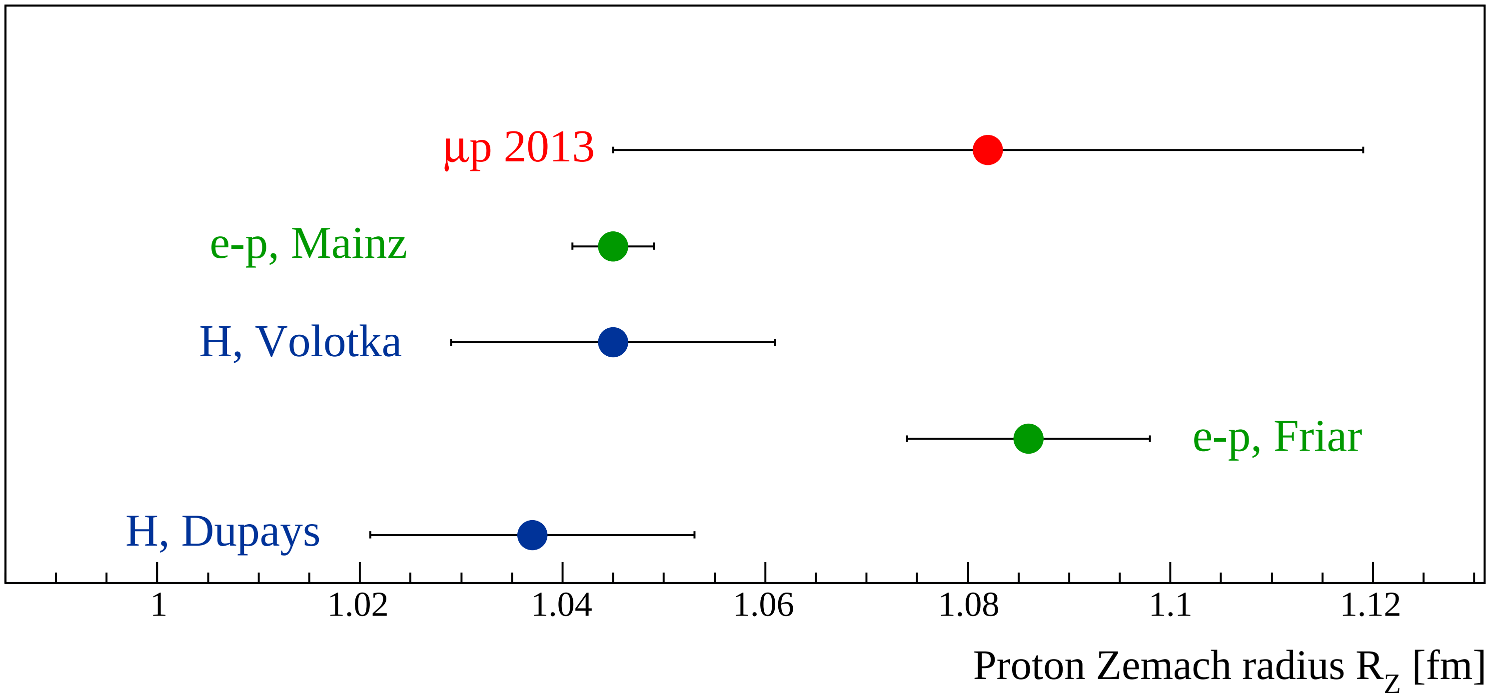
Proton Zemach radius

2S hyperfine splitting in μp is: $\Delta E_{\rm HFS} = 22.9843(30) - 0.1621(10)\, r_Z\, [\rm fm]$ meV

with $r_Z = \int d^3r \int d^3r'\, r\, \rho_E(r)\, \rho_M(r - r')$

We measured $\Delta E_{\rm HFS} = 22.8089(51)$ meV

This gives a proton Zemach radius $r_Z = 1.082\ (31)_{\rm exp}\ (20)_{\rm th} = 1.082\ (37)$ fm



A. Antognini, RP *et al.*, Science 339, 417 (2013)

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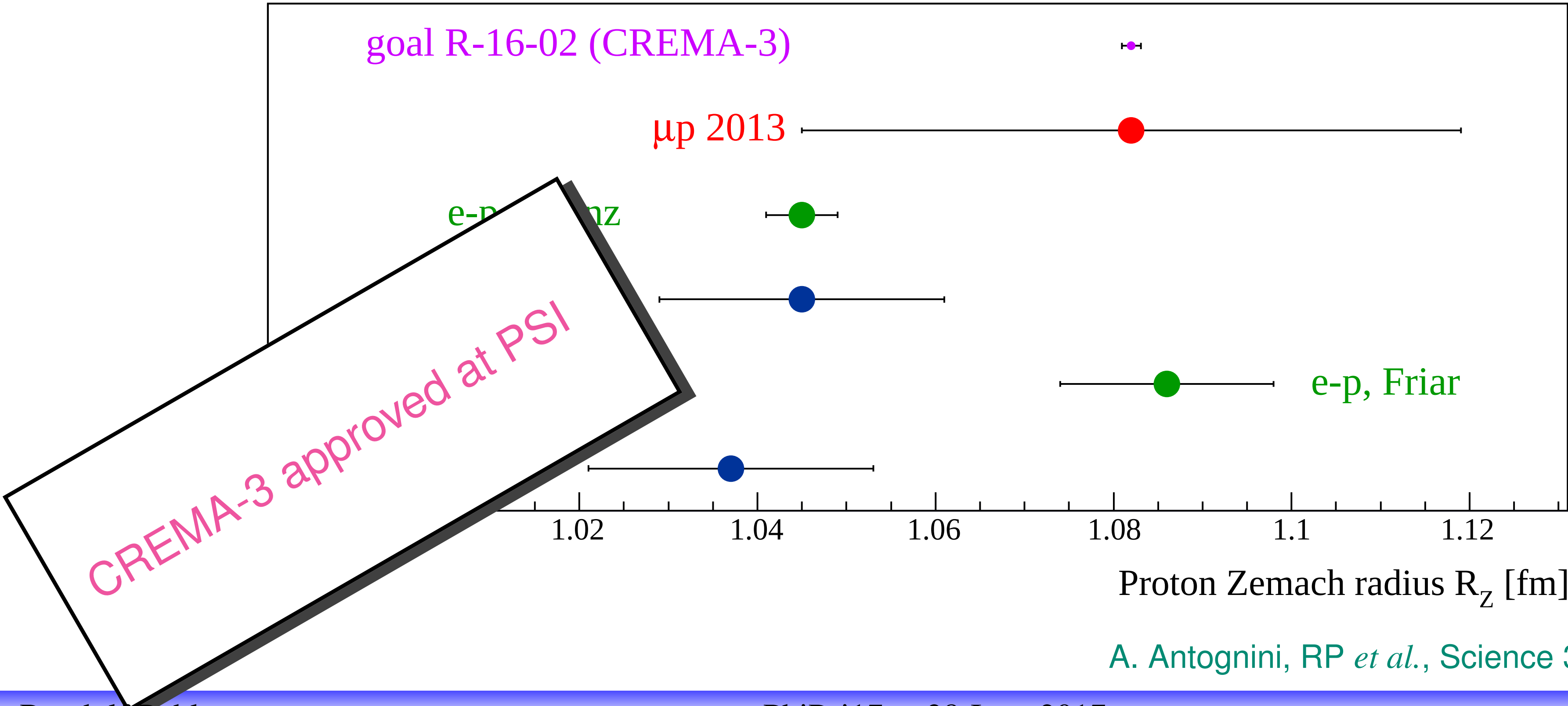

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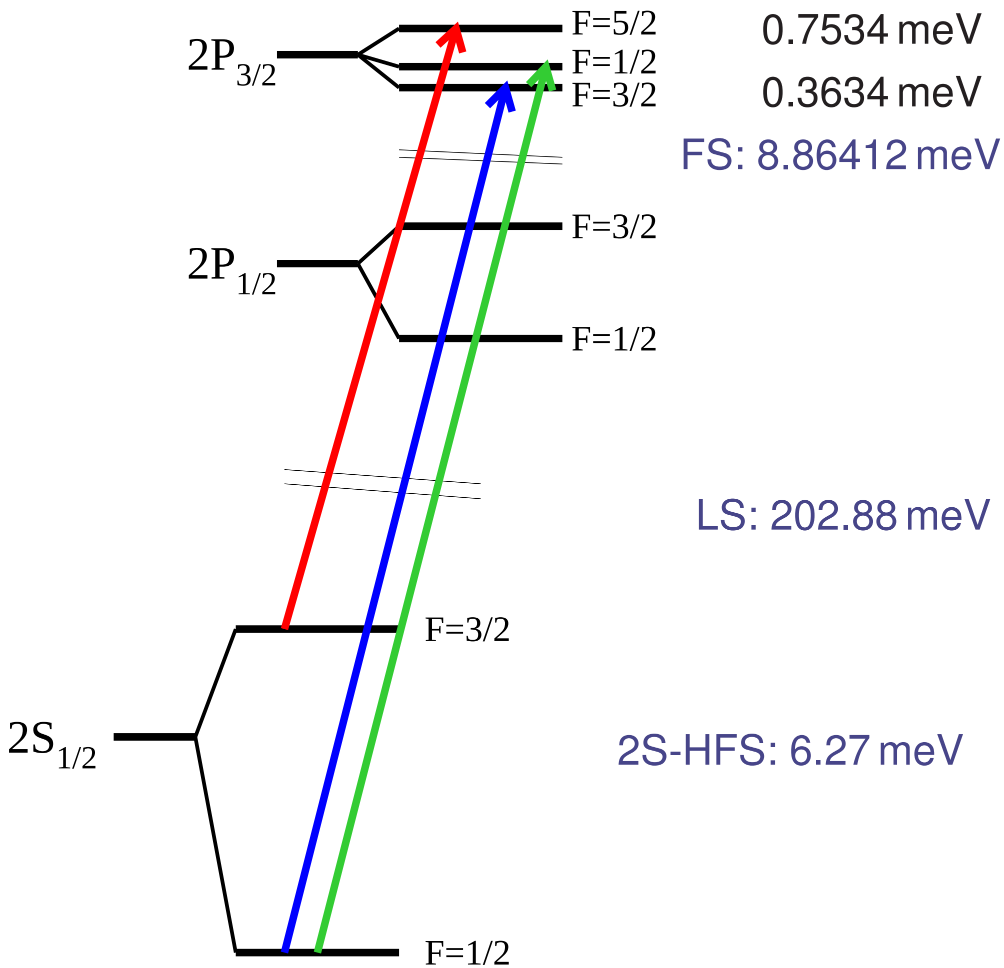
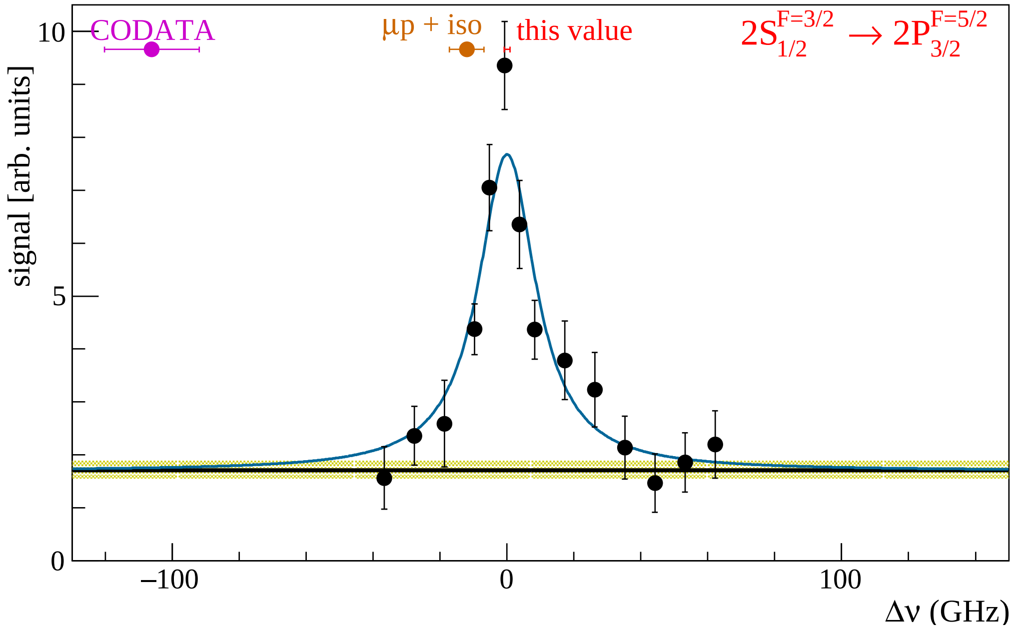
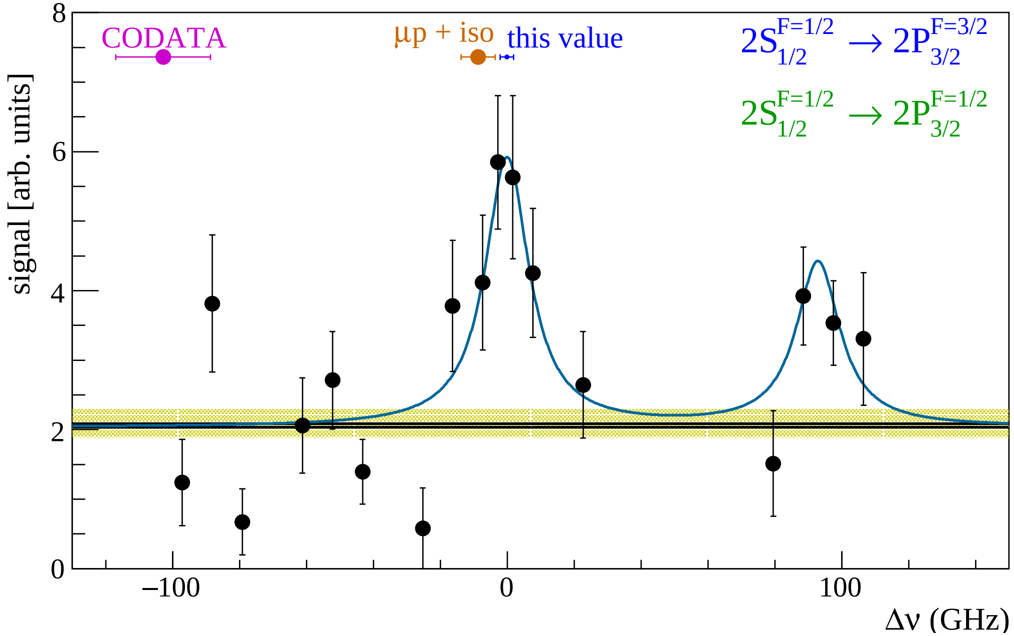
Muonic deuterium



Muonic DEUTERIUM



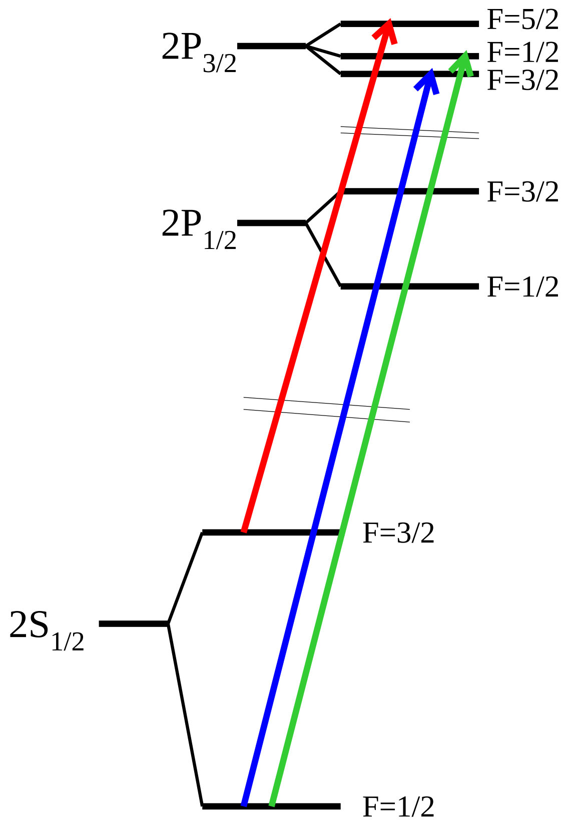


Experiment:

RP *et al.* (CREMA), Science **353**, 417 (2016).

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

$$\Rightarrow r_d = 2.12562(13)_{exp}(77)_{theo}\ \text{fm}$$



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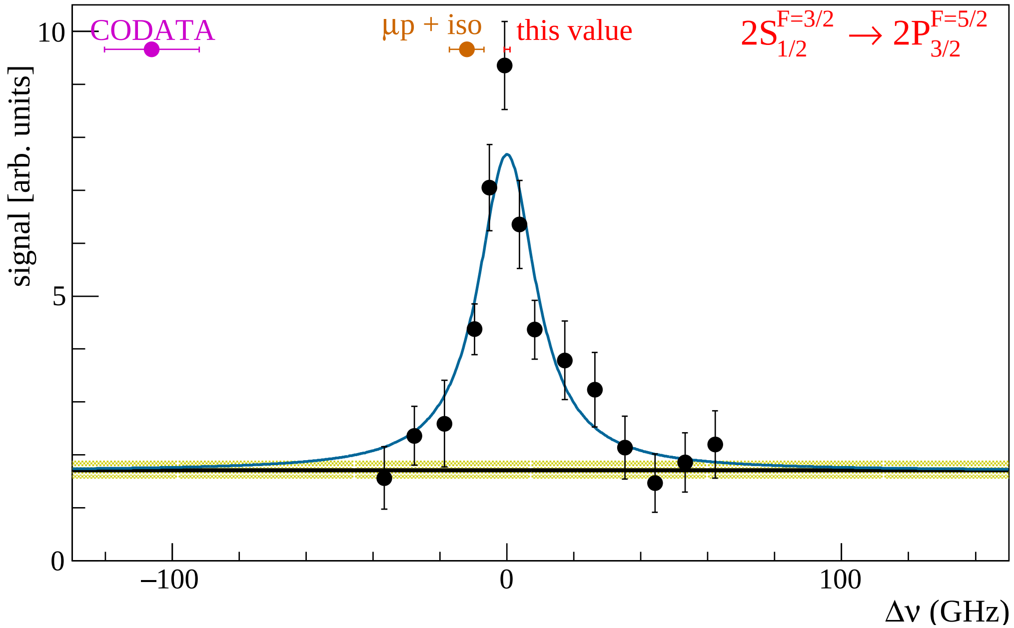

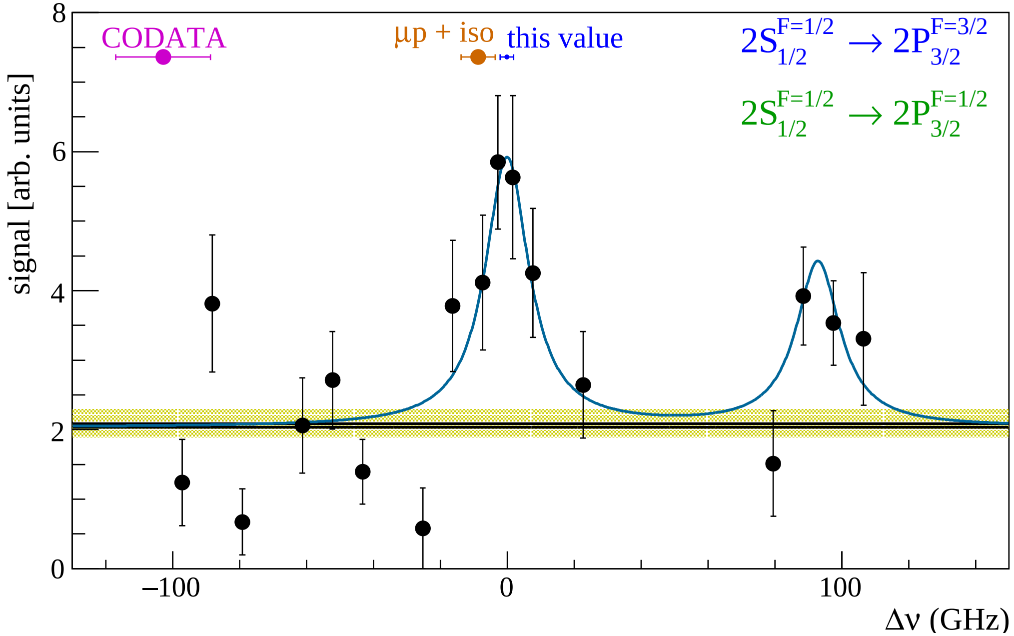

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Theory:

$$\begin{aligned}\Delta E_{LS}^{theo} = {} & 228.7766(\ \ 10)\,\text{meV}\ \text{(QED)} \\ & +1.7096(200)\,\text{meV}\ \text{(TPE)} \\ & -6.1103(\ \ \ 3)\,r_d^2\ \text{meV}/\text{fm}^2,\end{aligned}$$

Krauth, RP *et al.*, Ann. Phys. **366**, 168 (2016) [arXiv 1506.01298]

based on papers and communication from

Bacca, Barnea, Birse, Borie, Carlson, Eides, Faustov, Friar, Gorchtein, Hernandez, Ivanov, Jentschura, Ji, Karshenboim, Korzinin, Krutov, Martynenko, McGovern, Nevo Dinur, Pachucki, Shelyuto, Sick, Vanderhaeghen *et al.*

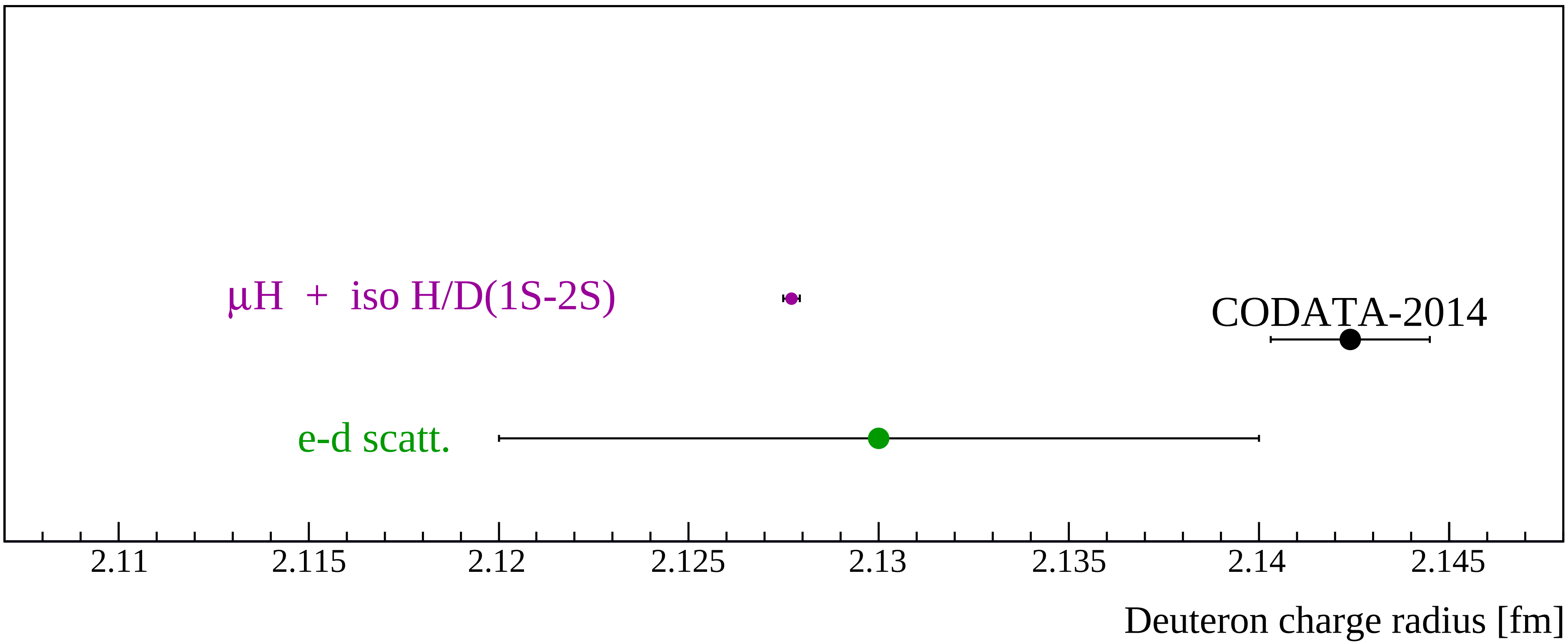
THANK YOU!

Deuteron charge radius

H/D isotope shift: $r_\mathrm{d}^2 - r_\mathrm{p}^2 = 3.82007(65)$ fm^2 C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2014 $r_\mathrm{d} = 2.14130(250)$ fm

r_p from μH gives $r_\mathrm{d} = 2.12771(\ \ 22)$ fm $\leftarrow 5.4\sigma$ from r_p



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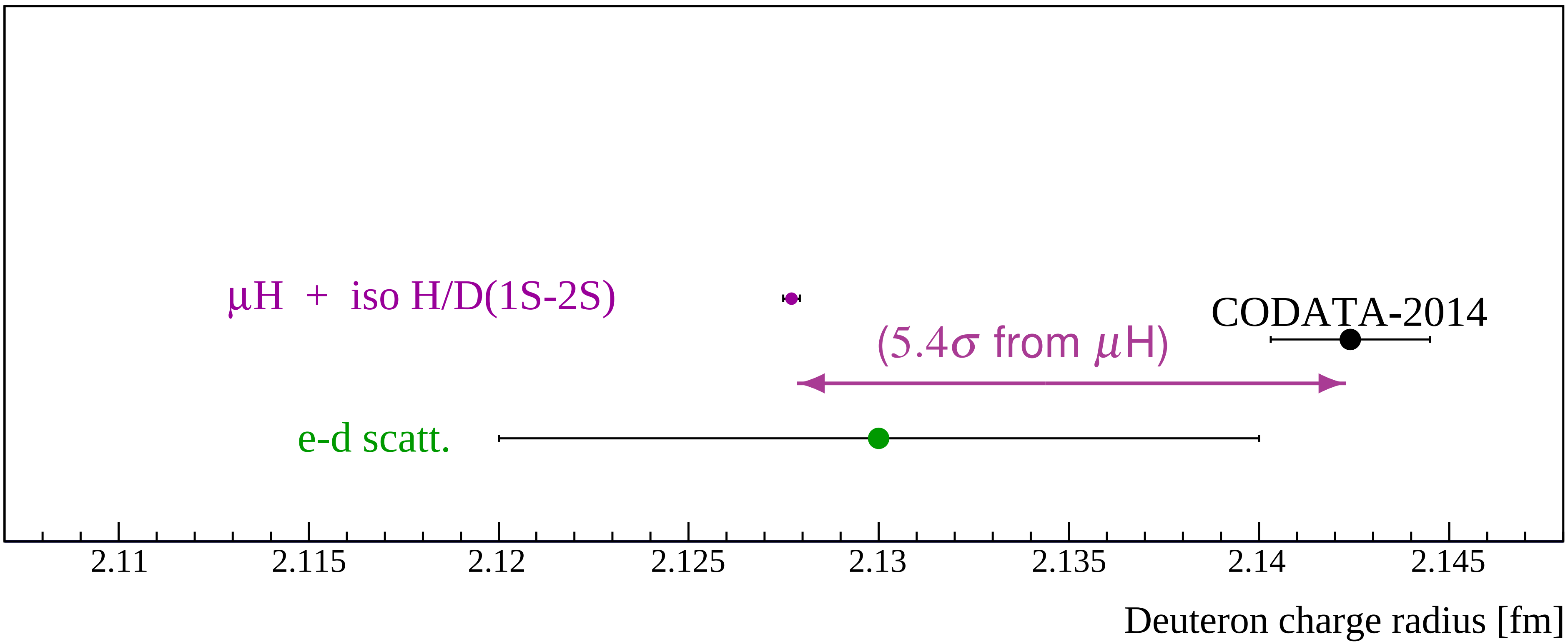

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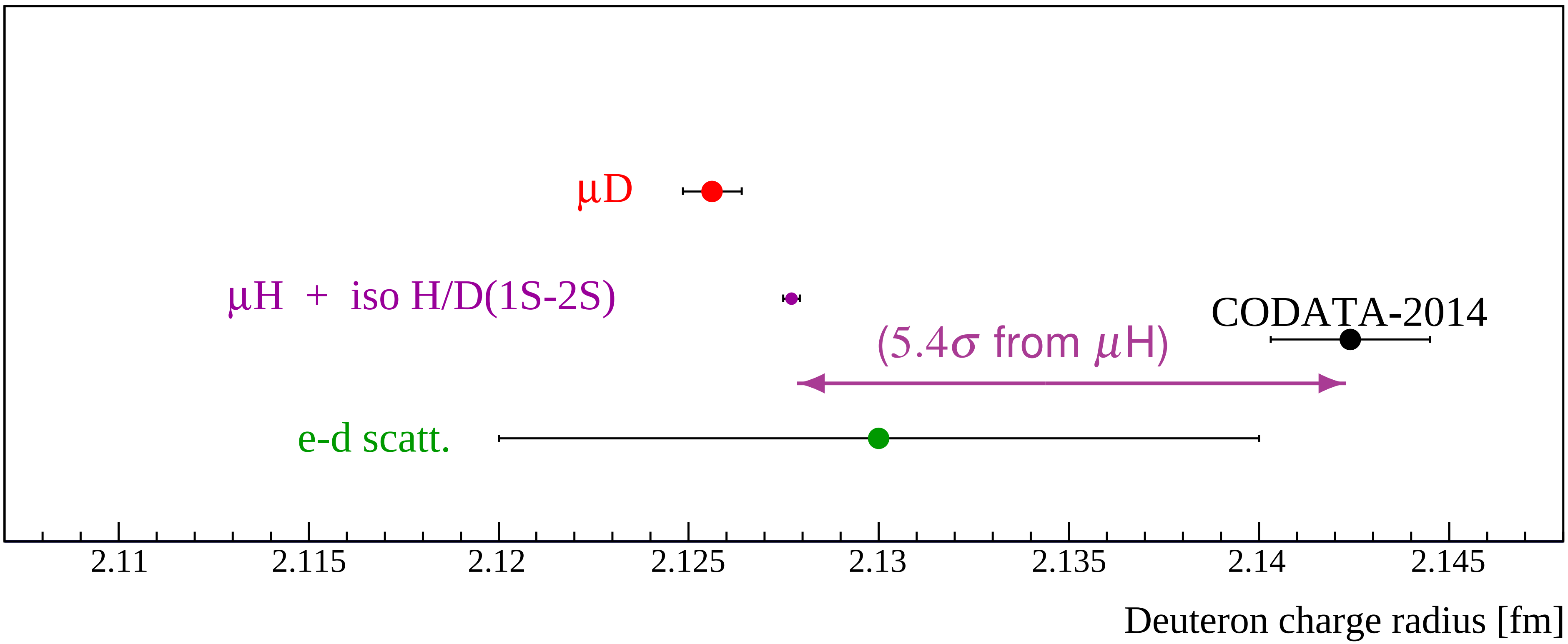

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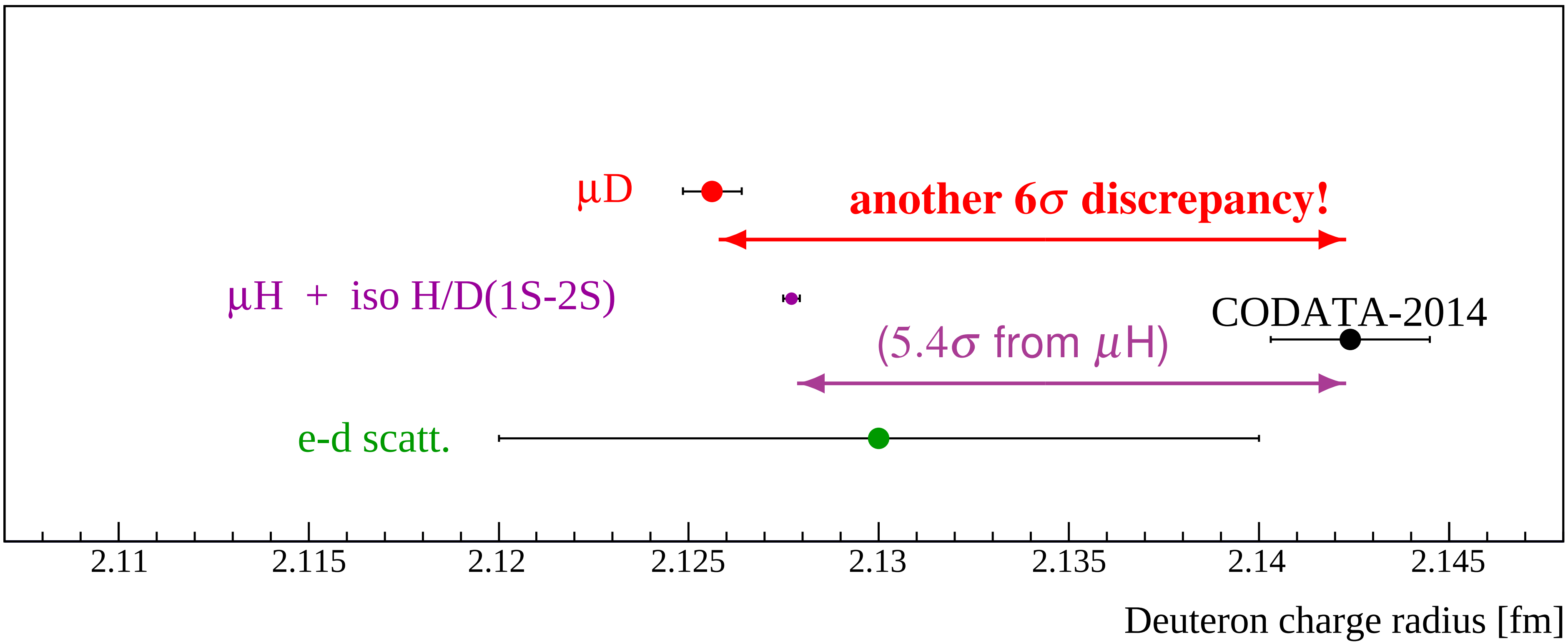

Conclusions μp and μd

Pohl *et al.*, Nature 466, 213 (2010).
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- Proton charge radius: r_p= 0.84087 (39) fm
- Proton Zemach radius: R_Z = 1.082 (37) fm
- Rydberg constant, using H(1S-2S):
  $R_\infty = 3.289\,841\,960\,249\,5\ (10)^{\text{radius}}\ (25)^{\text{QED}}\ \times 10^{15}\ \text{Hz/c}$
- Deuteron charge radius: r_d= 2.12771 (22) fm using H/D(1S-2S)

- r_p is 5.6σ smaller than CODATA-2014
  4.0σ smaller than r_p(H spectrosopy)

- r_d is 5.4σ smaller than CODATA-2014 (99% correlated with r_p!)
  3.5σ smaller than r_d(D spectrosopy)

- Proton and deuteron are consistently too small:

$$r_d^2 = r_{\text{struct}}^2 + r_p^2 + r_n^2 + \frac{3\hbar^2}{4m_p^2c^2}$$

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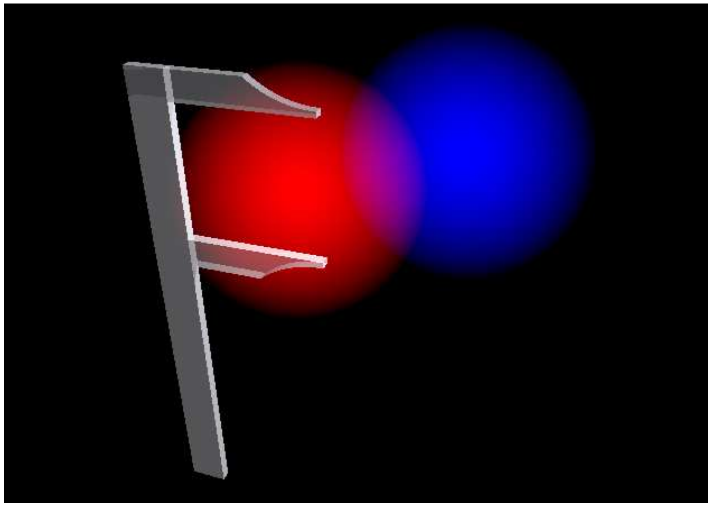
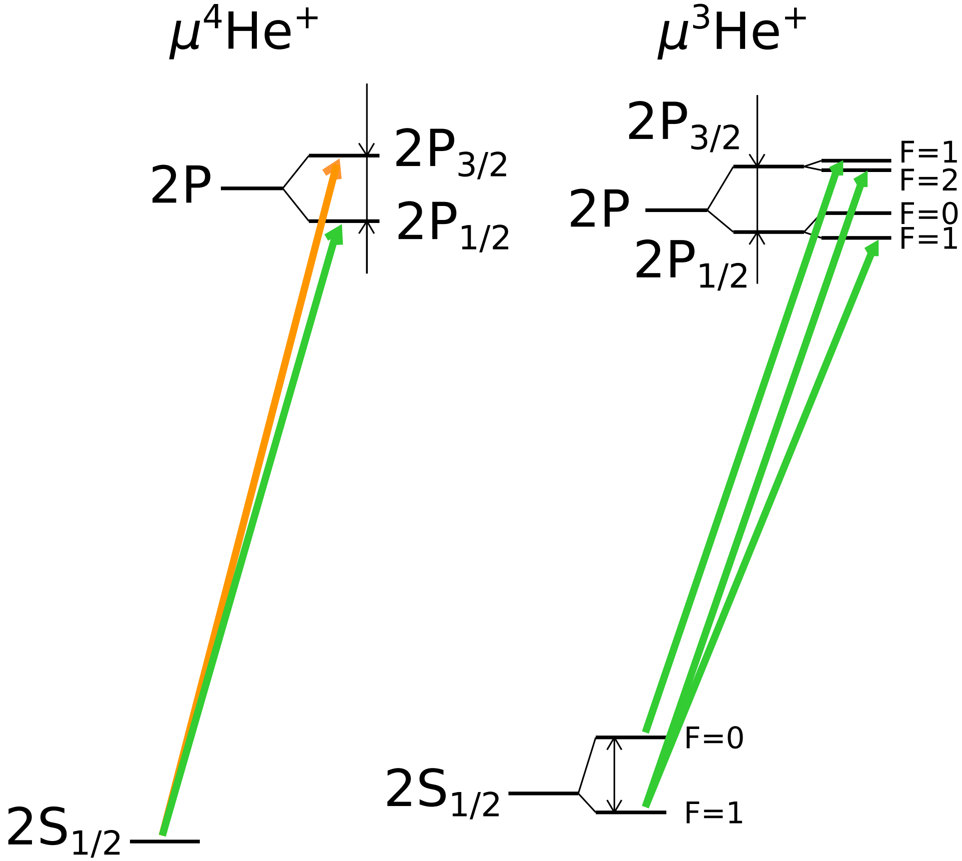
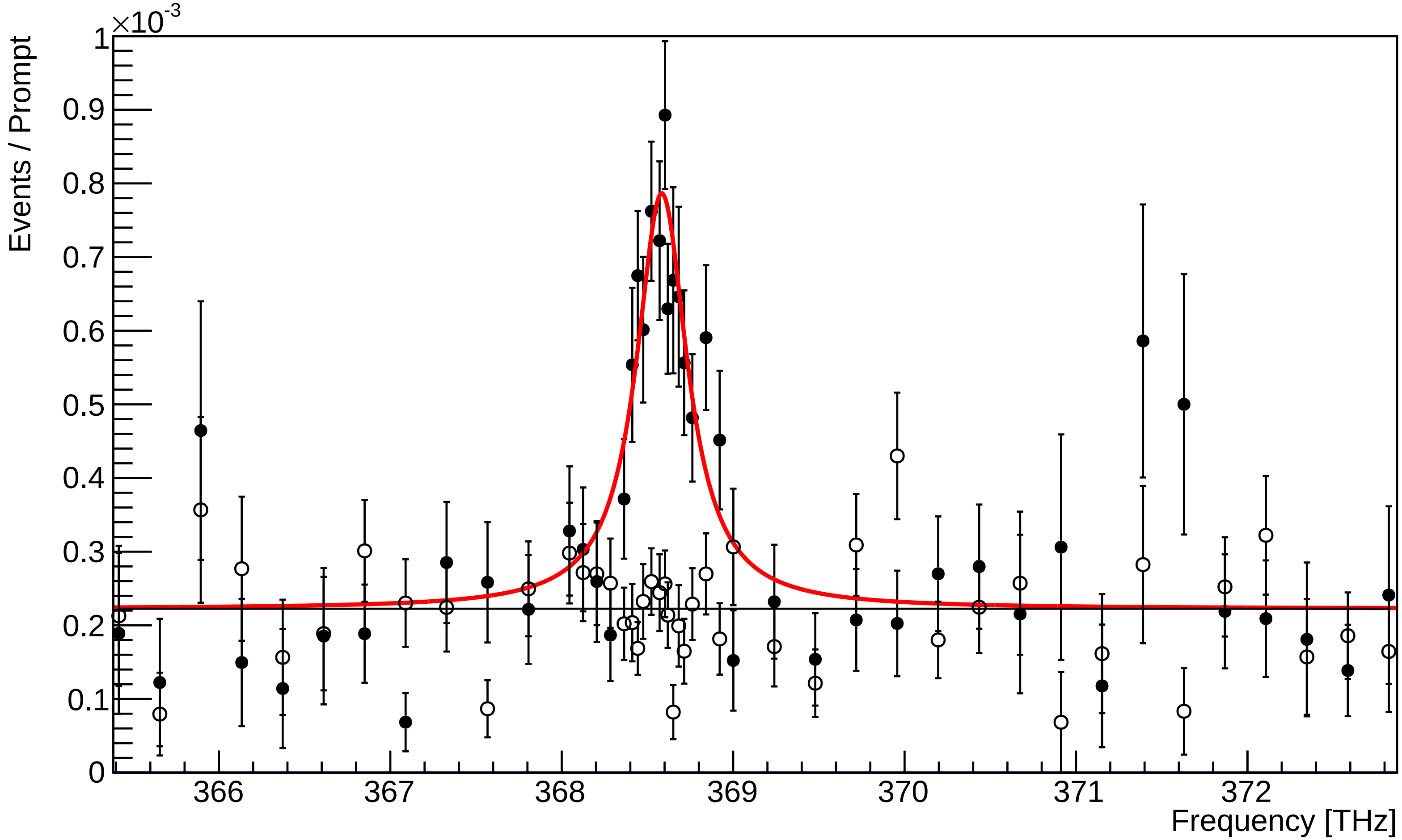


Muonic helium ions



$\mu^4He^+(2S_{1/2} \to 2P_{3/2})$

1st μ^4He-ion resonance at $\sim$ 812 nm wavelength



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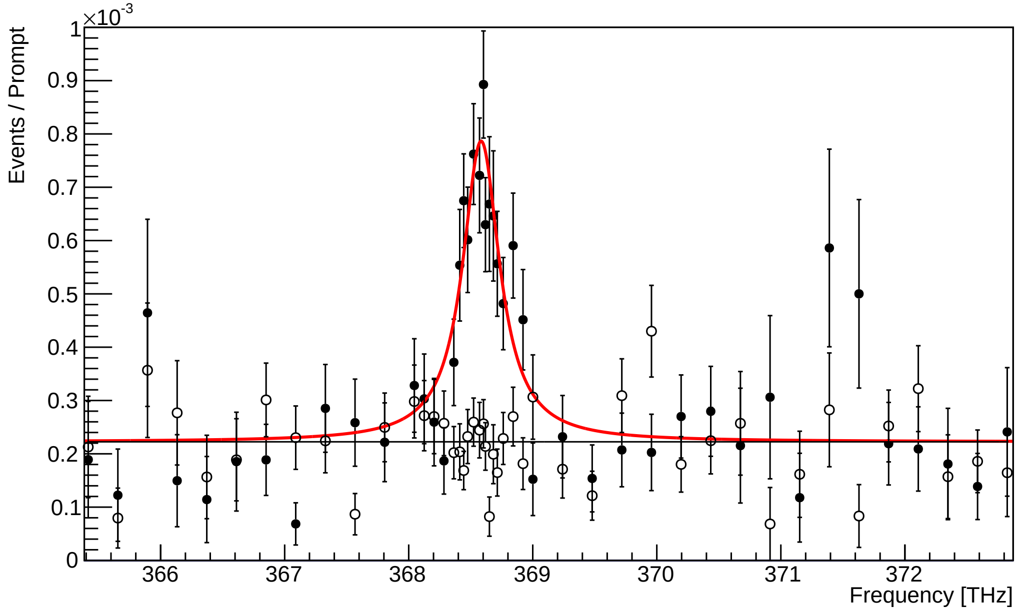


$$\Delta E(2S-2P) = 1668.487(\ \ 14)\,\text{meV}_{(\text{QED})}$$
$$-106.358(\ \ 7)\,\text{meV/fm}^2 \cdot \langle r^2 \rangle$$
$$+6.761(\ \ 77)\,\text{meV}_{(\text{Friar})}$$
$$+3.296(189)\,\text{meV}_{(\text{polarizability})}$$
$$+146.197(\ \ 12)\,\text{meV}_{(\text{fine structure})}$$

Diepold et al., 1606.05231

Thanks to the theorists!

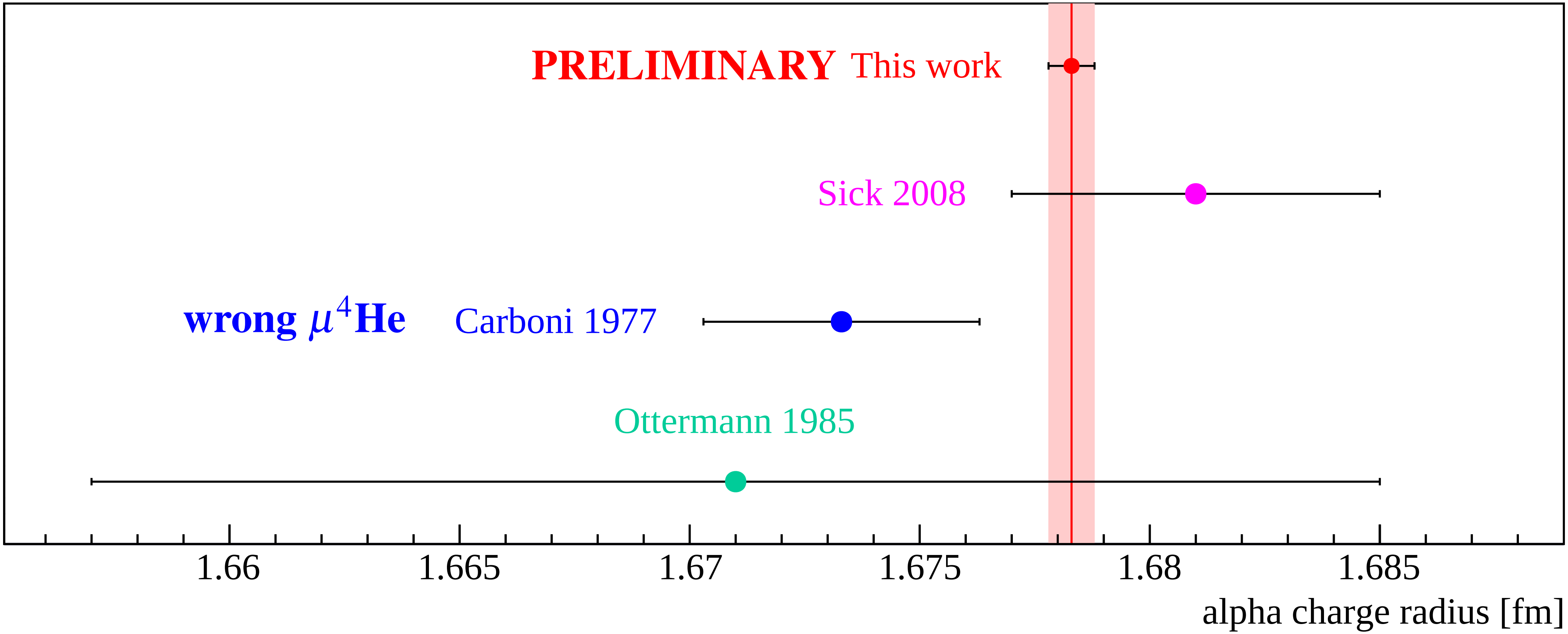
expt'l accuracy: 17 GHz $\equiv$ 0.066 meV

r(^{4}He) = 1.68xxx (19)$_{\text{exp}}$ (58)$_{\text{theo}}$ fm **PRELIMINARY**

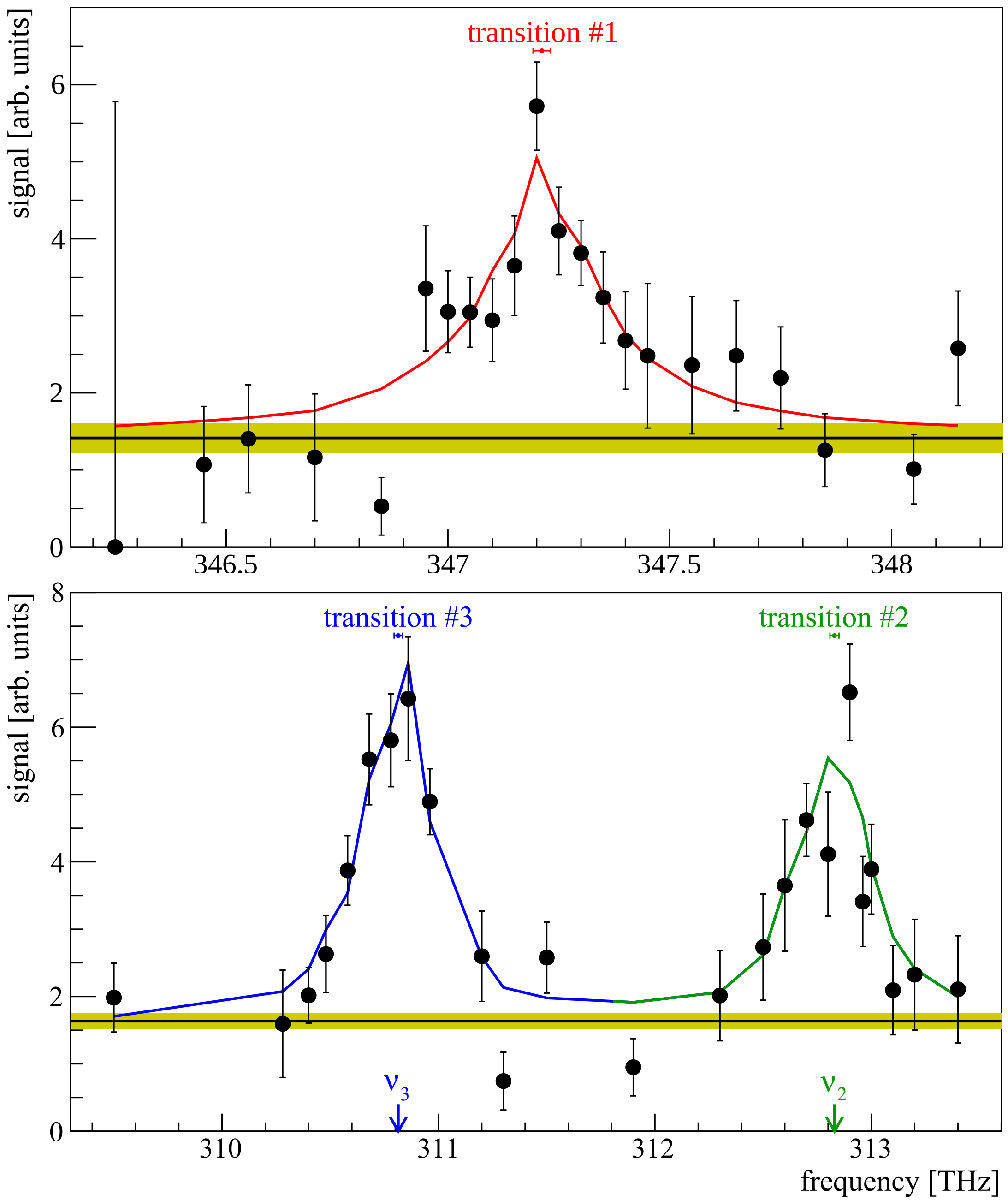
vs. 1.68100 (400) fm from e-He scattering

(plus the other transition $\mu^4He^+(2S_{1/2} \to 2P_{1/2})$)

^{4}He charge radii



μ^3He^+ resonances



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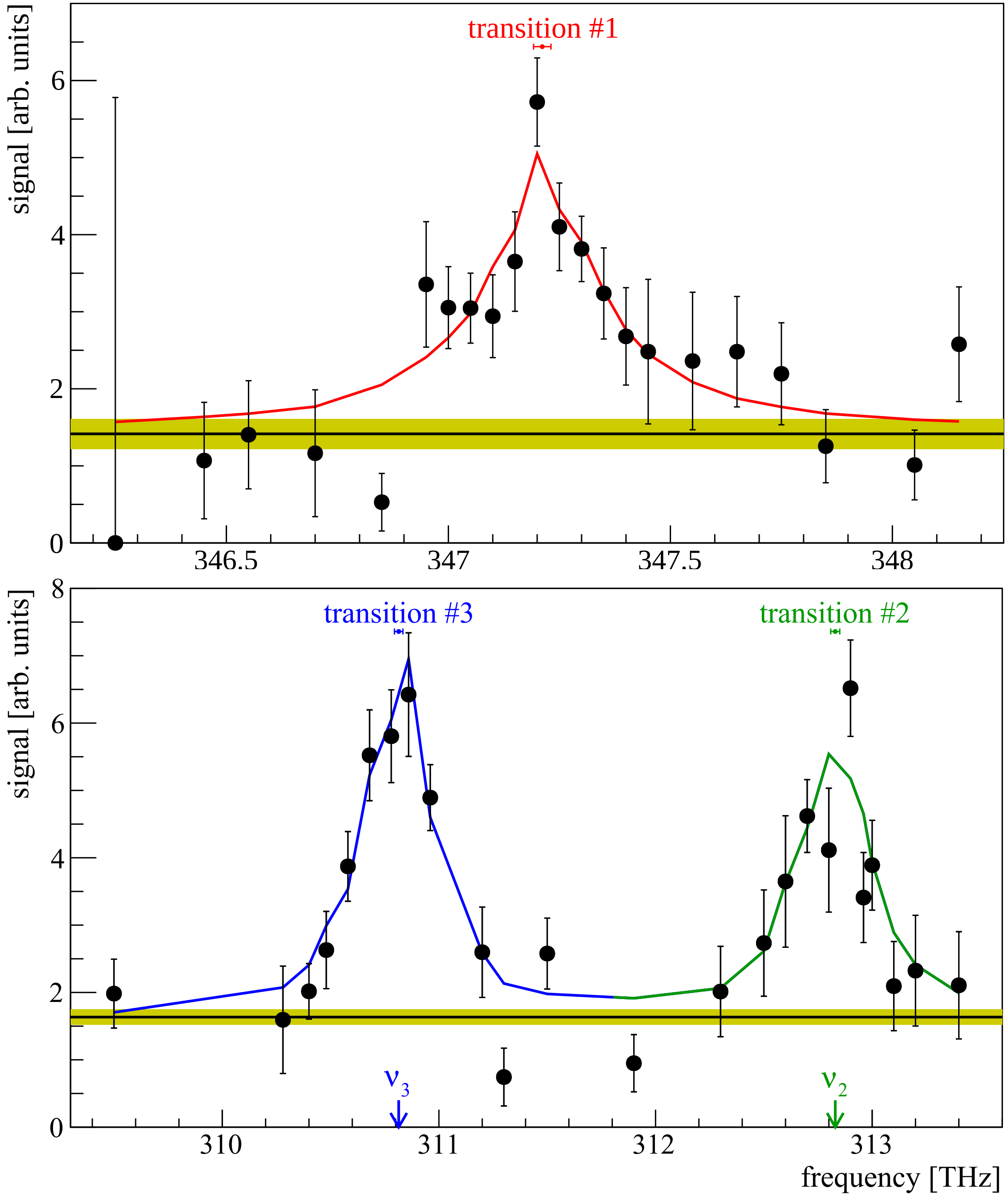


$$\Delta E(2S - 2P_{1/2}) =$$

$$\begin{aligned} & 1644.347\ (\ 15)\ \mathrm{meV}_{(QED)} \\ - & 103.518\ (\ 10)\ \mathrm{meV/fm^2} \cdot \langle r^2 \rangle \\ + & 0.118\ (\ 3)\ \mathrm{meV}_{(radius)} \\ + & 15.300\ (520)\ \mathrm{meV}_{(polarizability)} \end{aligned}$$

Franke, Krauth et al., 1705.00352

Thanks to the theorists!

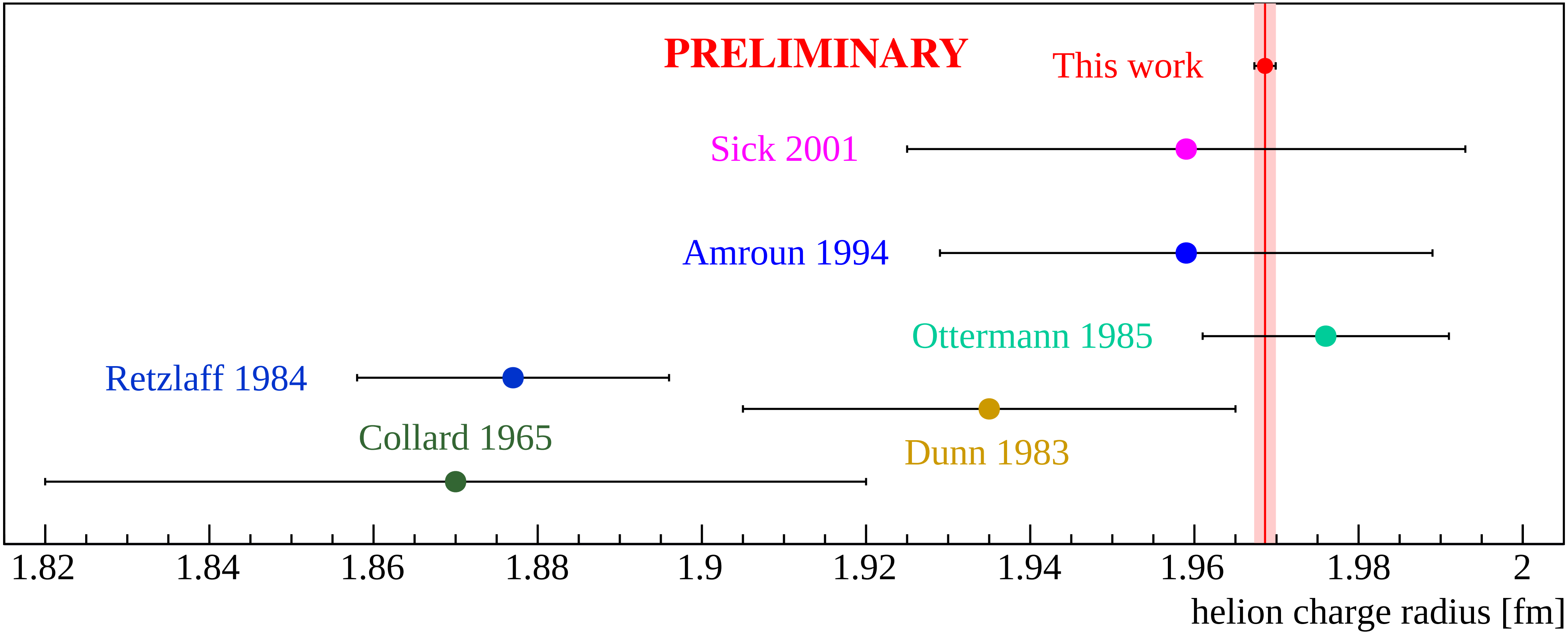
expt'l accuracy: each ~ 20 GHz

$\Rightarrow 0.082/\sqrt{3}\,\mathrm{meV} \;=\; 0.050\,\mathrm{meV}$

$r(^3He) = 1.97xxx\ (\ 12)_{exp}\ (128)_{theo}$ fm

PRELIMINARY

^{3}He charge radii



Muonic summary

- Muonic hydrogen gives:
  - Proton charge radius: r_{p}= 0.84087 (39) fm

    7σ away from electronic average (CODATA: H, e-p scatt.)
  - Deuteron charge radius: $r_d = 2.12771\,(22)$ fm from μH + H/D(1S-2S)
- Muonic deuterium:
  - Deuteron charge radius: $r_d = 2.12562\,(13)_{\mathrm{exp}}\,(77)_{\mathrm{theo}}$ fm

    consistent with muonic proton radius, but

    again 7σ away from CODATA: $2.14240\,(210)$ fm
- “Proton” Radius Puzzle is in fact “Z=1 Radius Puzzle”
- muonic helium-3 and -4 ions: No big discrepancy (PRELIMINARY)

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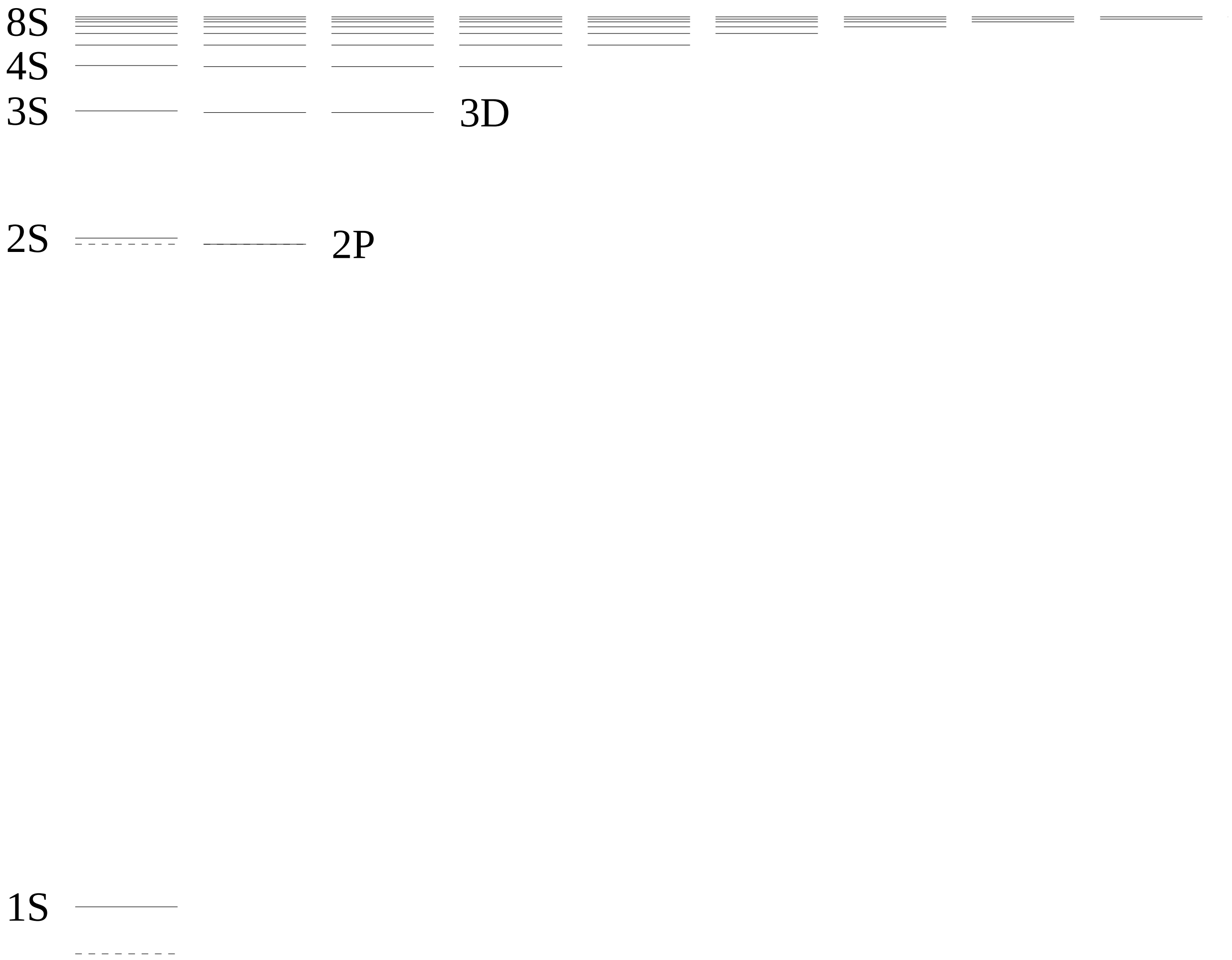
- "Proton" Radius Puzzle is in fact "Z=1 Radius Puzzle"
- muonic helium-3 and -4 ions: No big discrepancy (PRELIMINARY)
- Could **ALL** be solved if the **Rydberg constant** [and hence the (electronic) proton radius] was wrong.
  Plus $\sim 2.6\sigma$ change in deuteron polarizabililty.
  Plus: accept dispersion fits of e-p scattering
- Or: BSM physics, e.g. Tucker-Smith & Yavin (2011)

(Electronic) hydrogen.

Hydrogen spectroscopy

$$\text{Lamb shift}: \quad L_{1S}(r_\mathrm{p}) = 8171.636(4) + 1.5645 \, \langle r_\mathrm{p}^2 \rangle \ \mathrm{MHz}$$

$$L_{nS} \simeq \frac{L_{1S}}{n^3}$$



RP *et al.* arXiv 1607.03165

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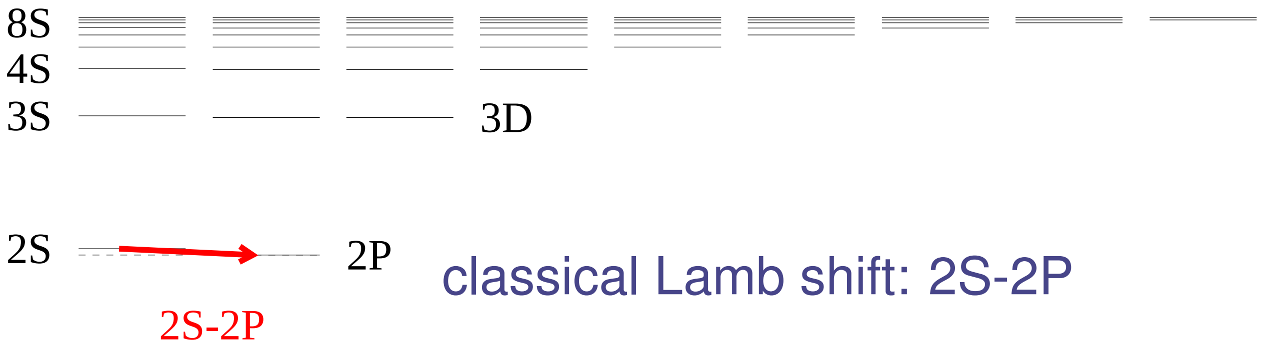
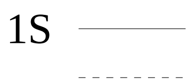
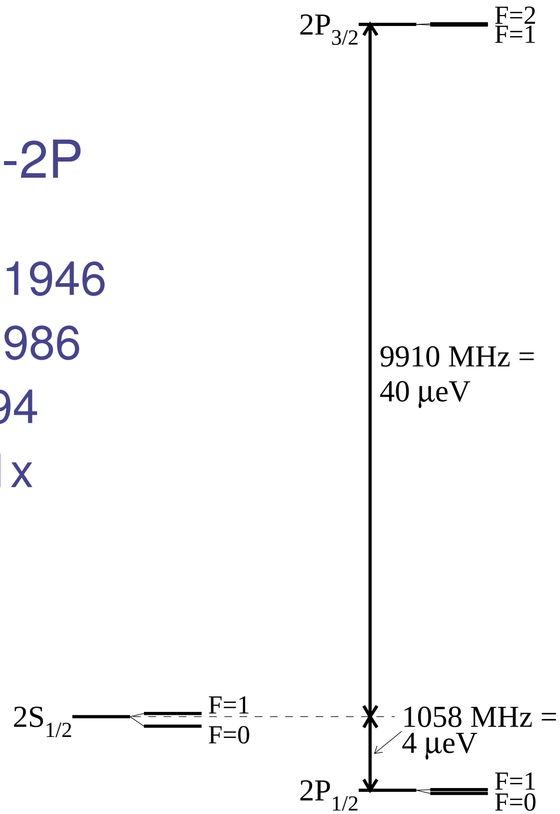




classical Lamb shift: 2S-2P

- Lamb, Retherford 1946
- Lundeen, Pipkin 1986
- Hagley, Pipkin 1994
- Hessels *et al.*, 201x



RP *et al.* arXiv 1607.03165

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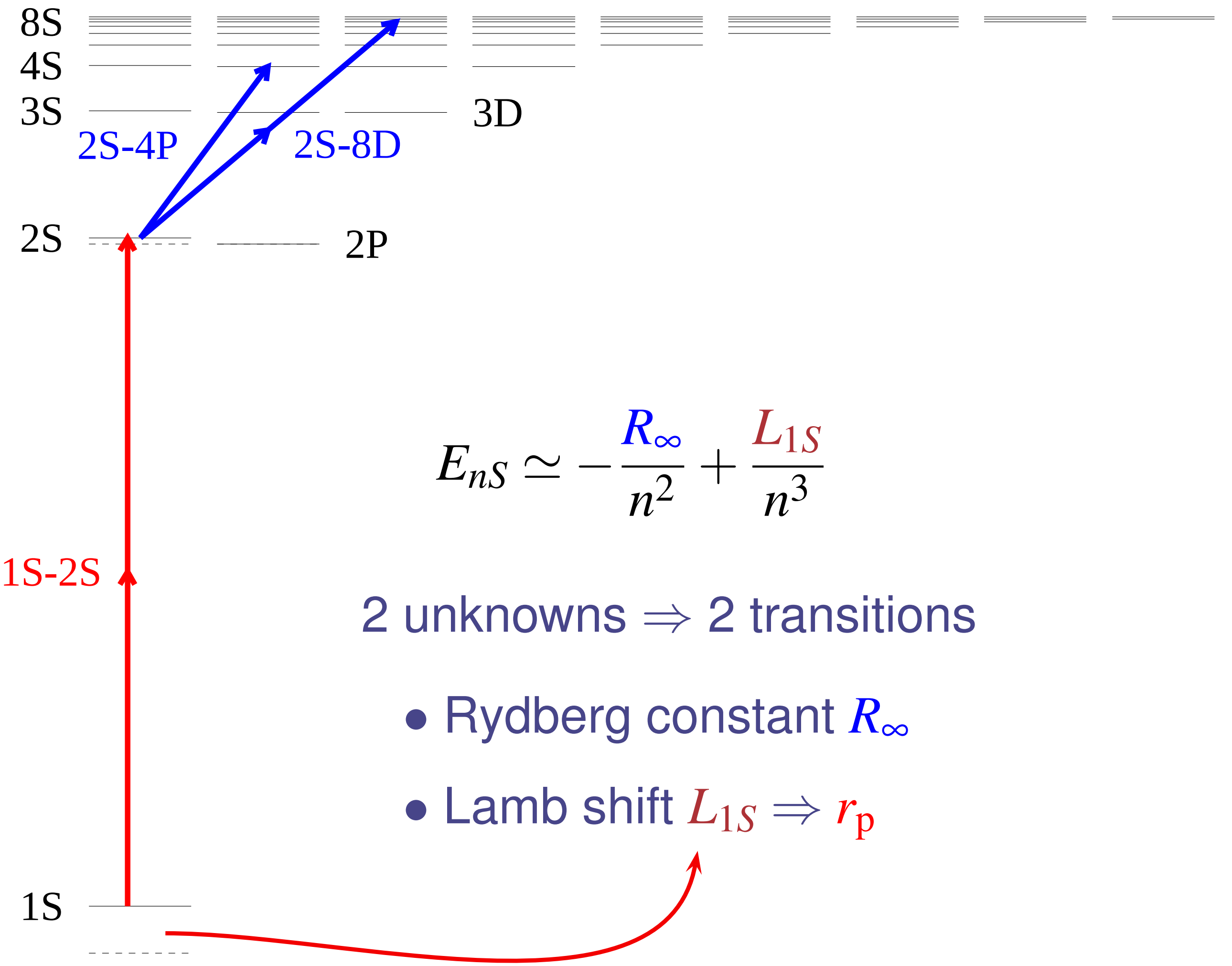


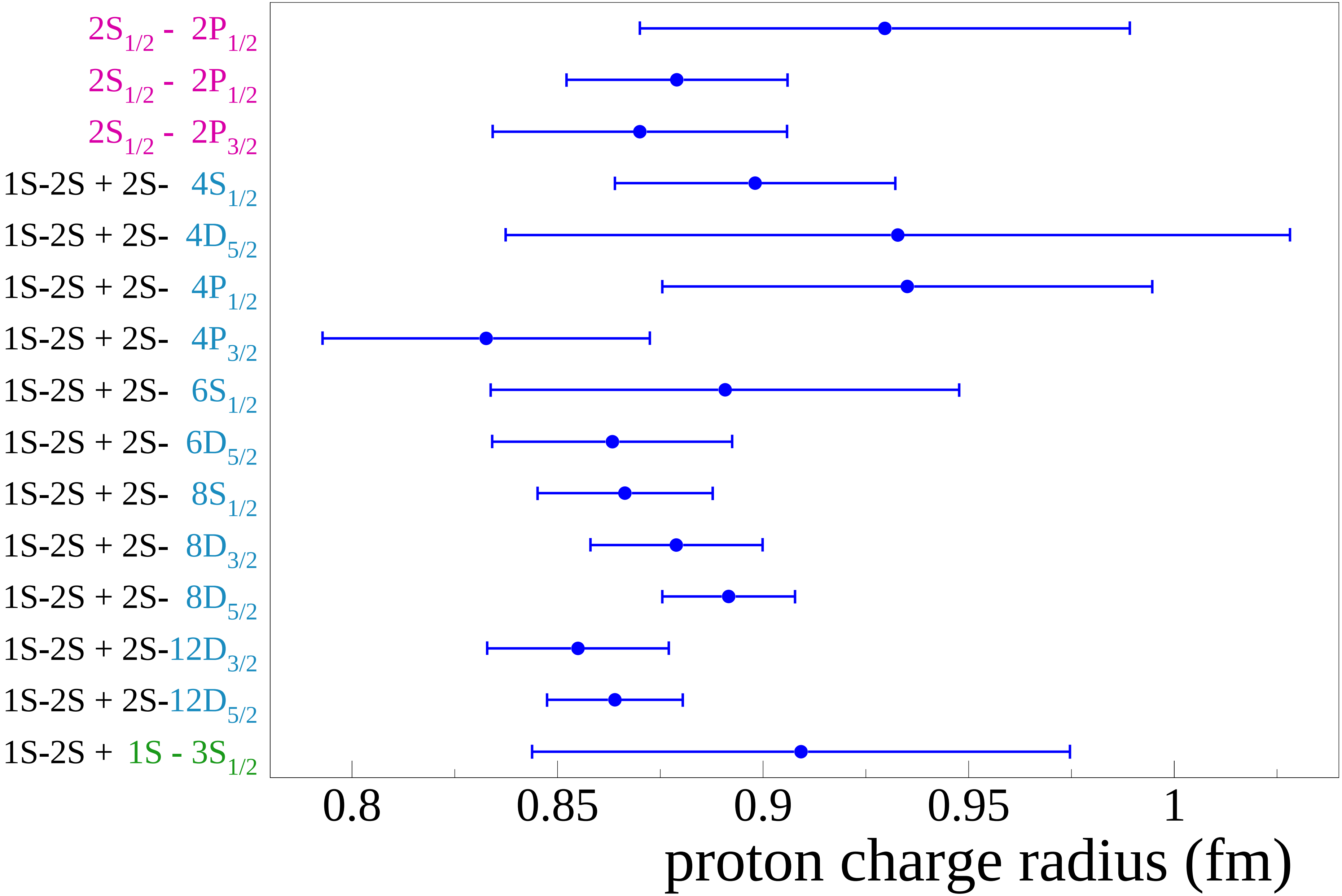
$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns $\Rightarrow$ 2 transitions

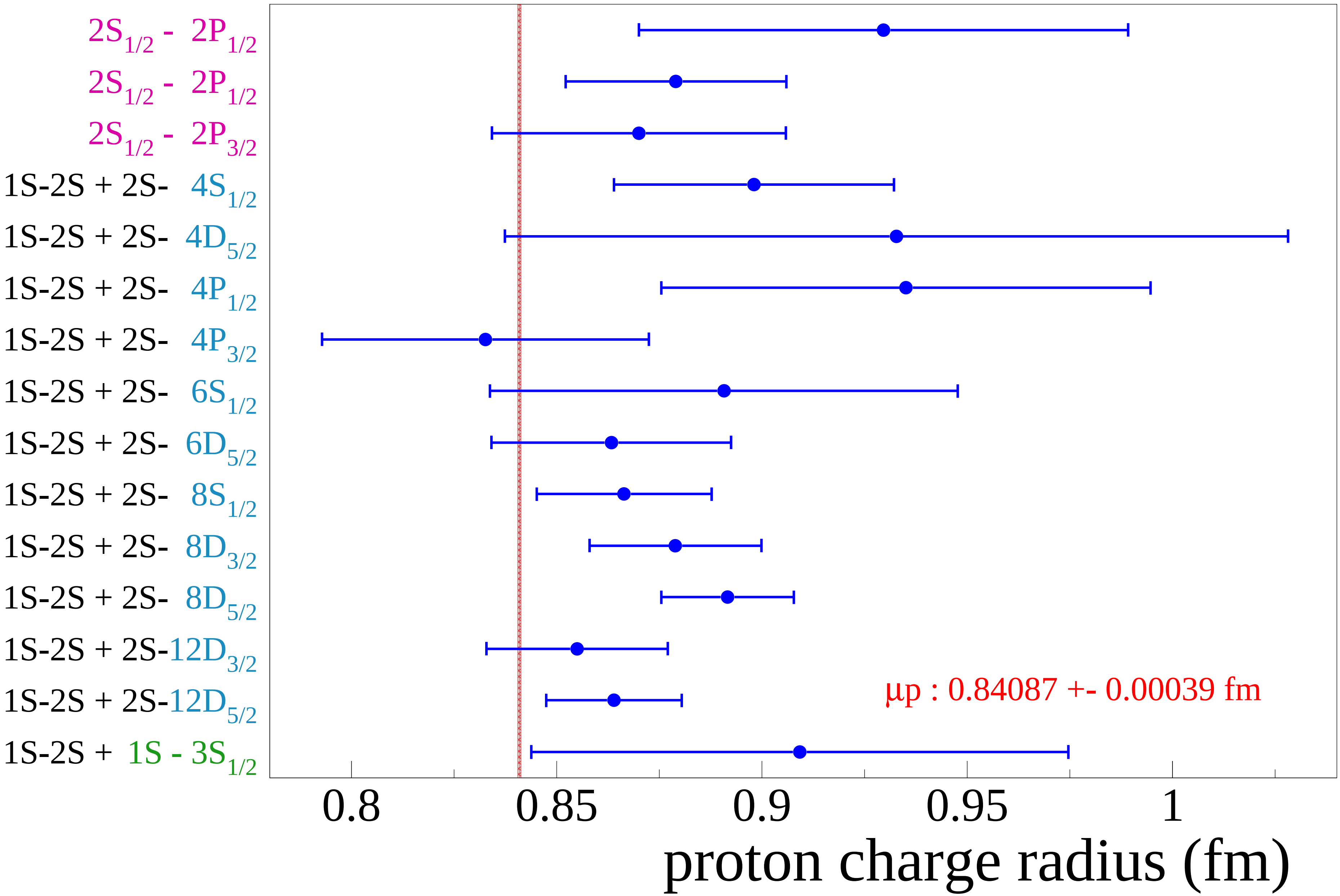
- Rydberg constant R_∞
- Lamb shift $L_{1S} \Rightarrow r_p$

RP *et al.* arXiv 1607.03165

Hydrogen spectroscopy



Hydrogen spectroscopy



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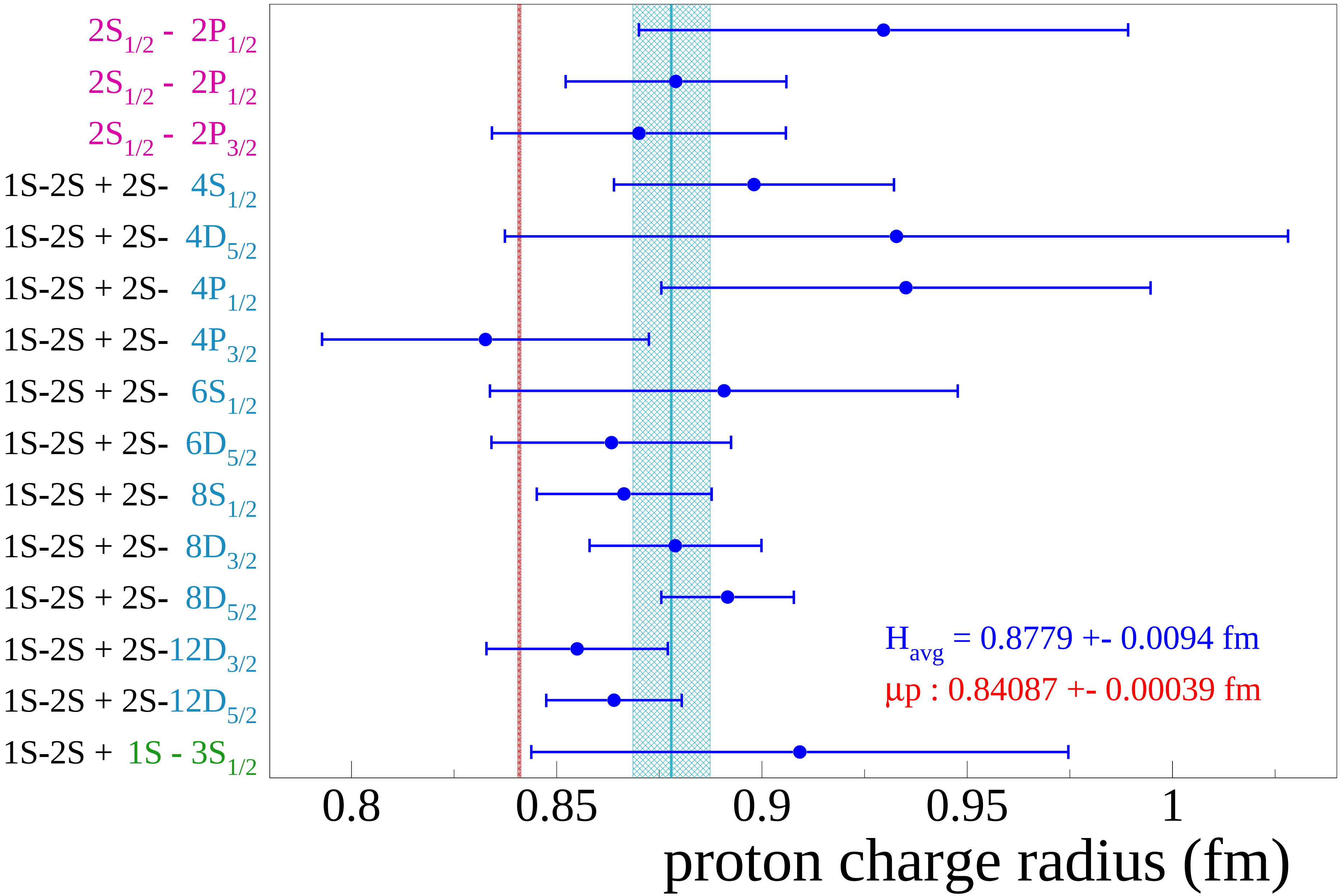

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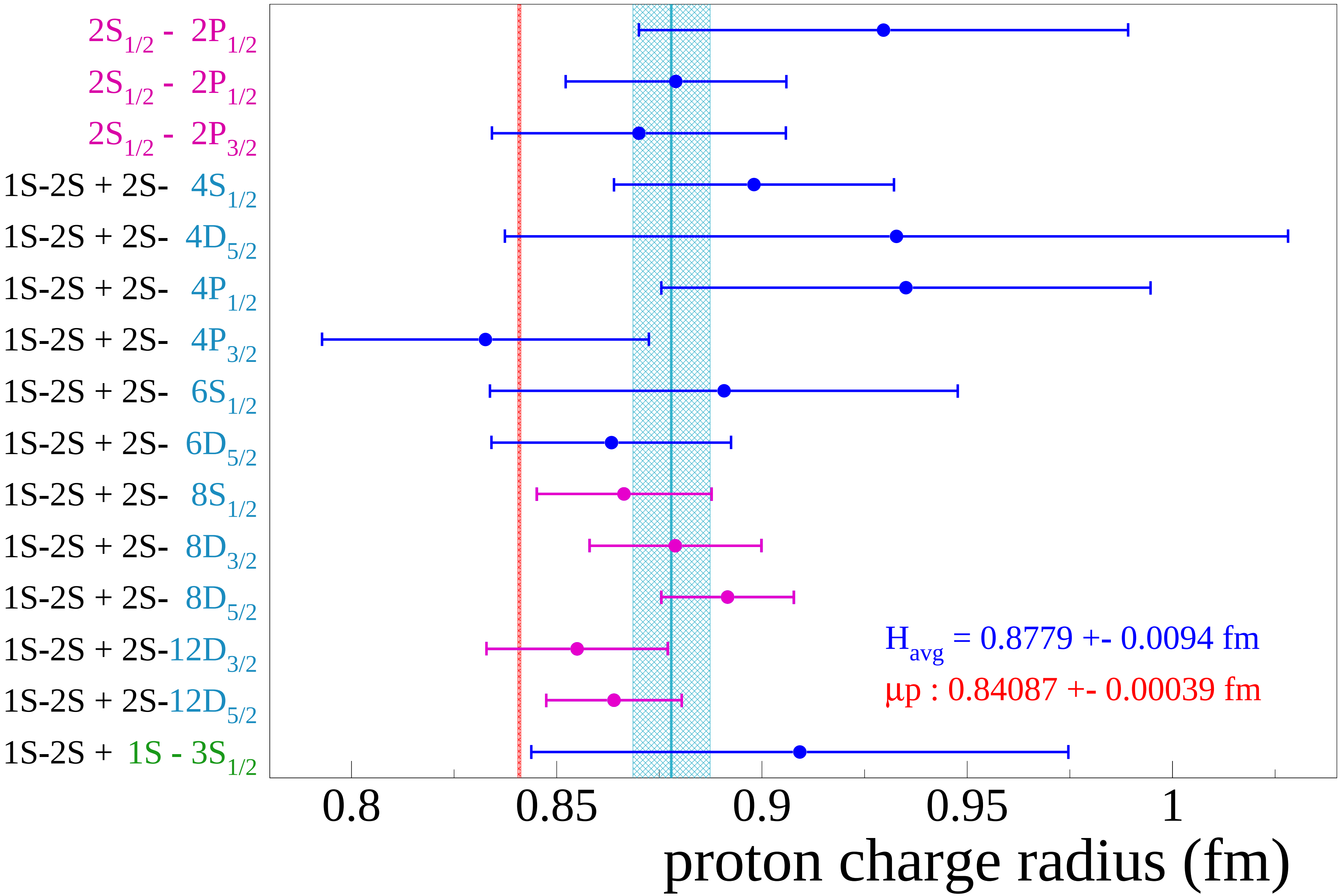
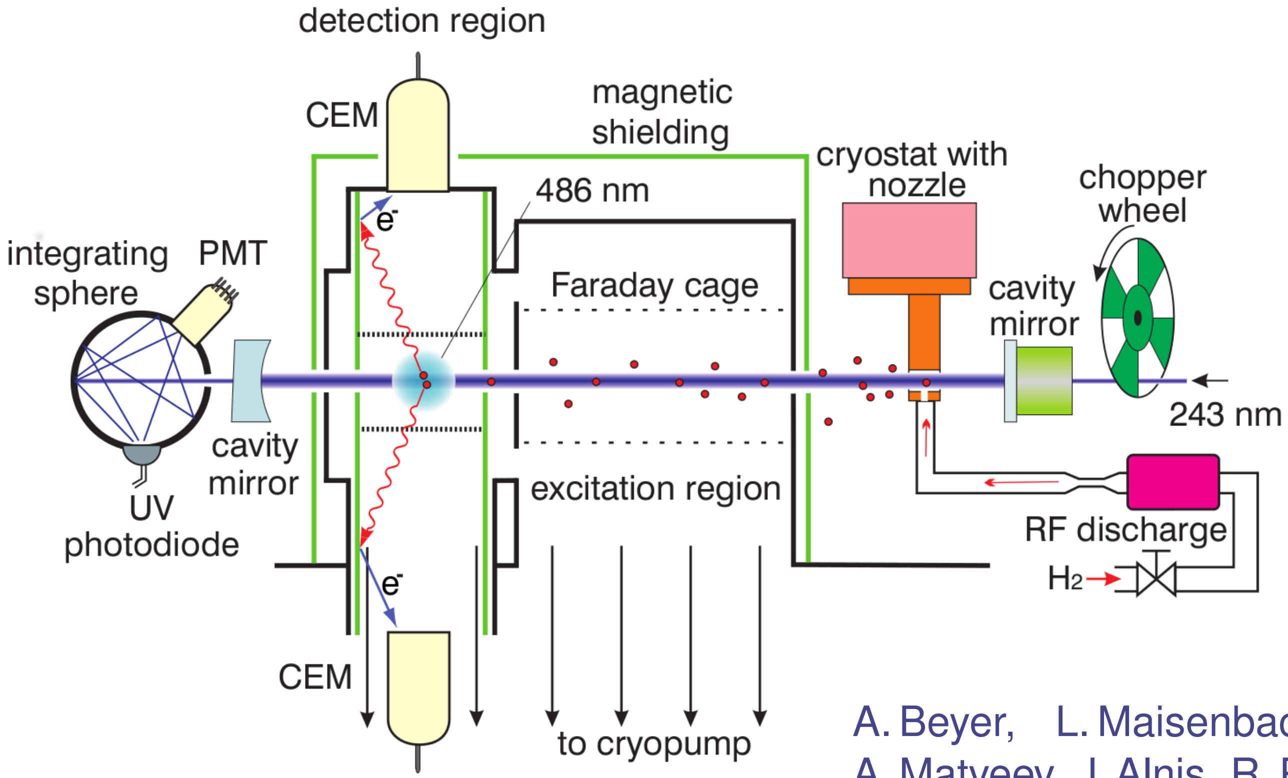
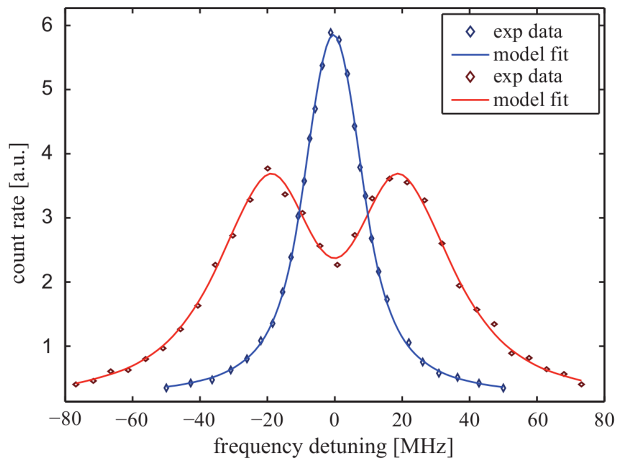


Rydberg constant from hydrogen



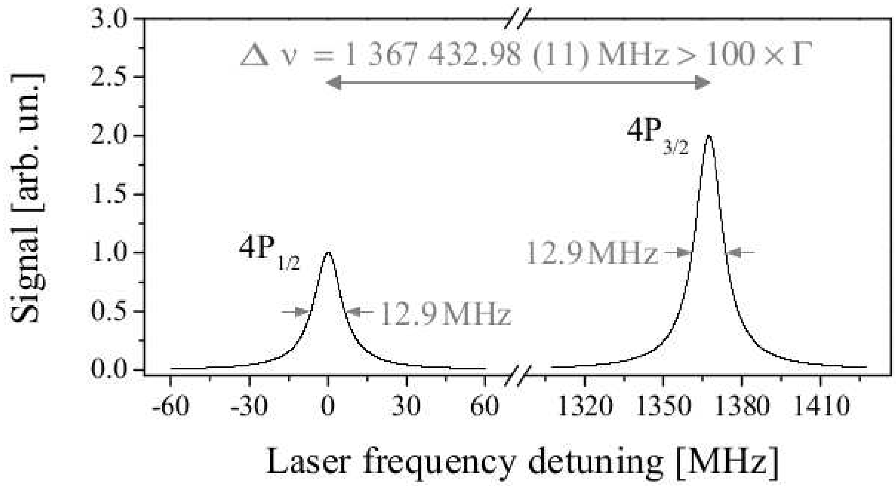


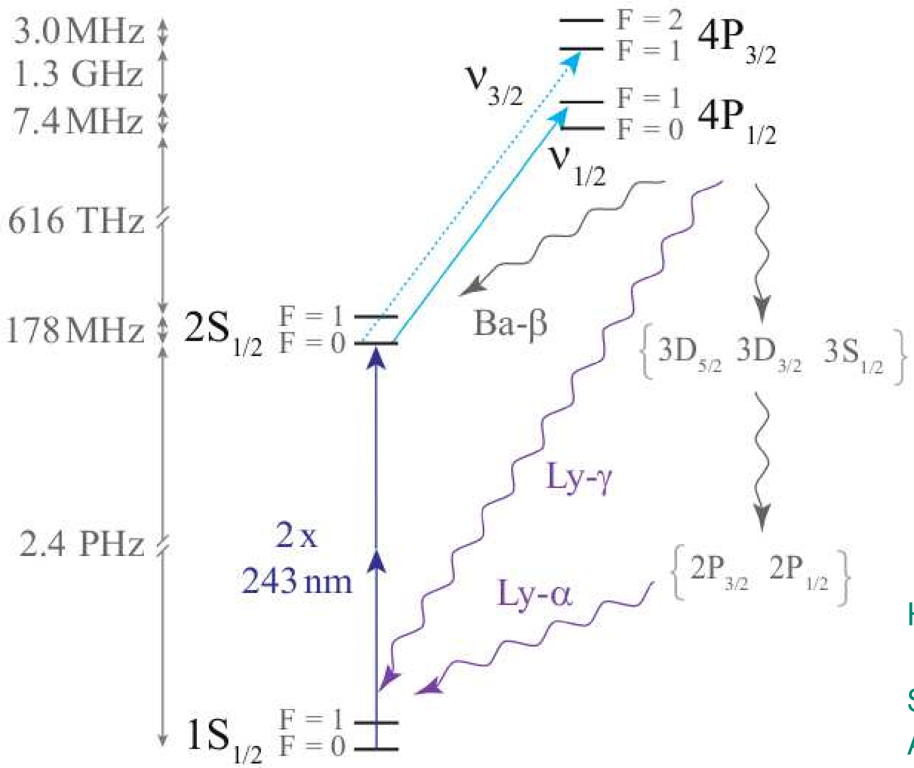
2S – 4P resonance at
$88 \pm 0.5\,^\circ$ and $90 \pm 0.08\,^\circ$

A. Beyer, L. Maisenbacher, K. Khabarova, C.G. Parthey, A. Matveev, J. Alnis, R. Pohl, N. Kolachevsky, Th. Udem and T.W. Hänsch

- Apparatus used for H/D(1S-2S) — C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010); C.G. Parthey, RP *et al.*, PRL **107**, 203001 (2011)
- 486 nm at 90° + Retroreflector $\Rightarrow$ Doppler-free 2S-4P excitation
- 1st oder Doppler vs. ac-Stark shift
- ~ 2.5 kHz accuracy (vs. 15 kHz Yale, 1995)
- **cryogenic** H beam, **optical** excitation to 2S — A. Beyer, RP *et al.*, Ann. d. Phys. **525**, 671 (2013)

Quantum interference shifts





Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011), PRA 86, 040501 (2012), etc.

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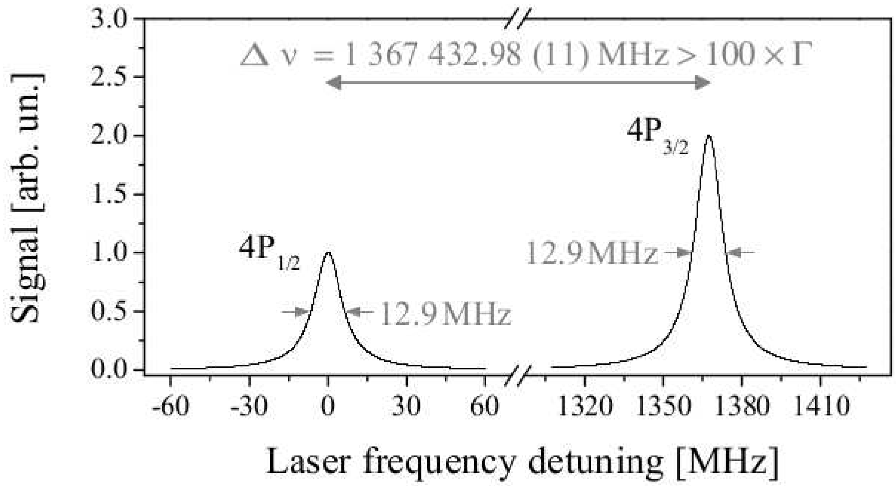

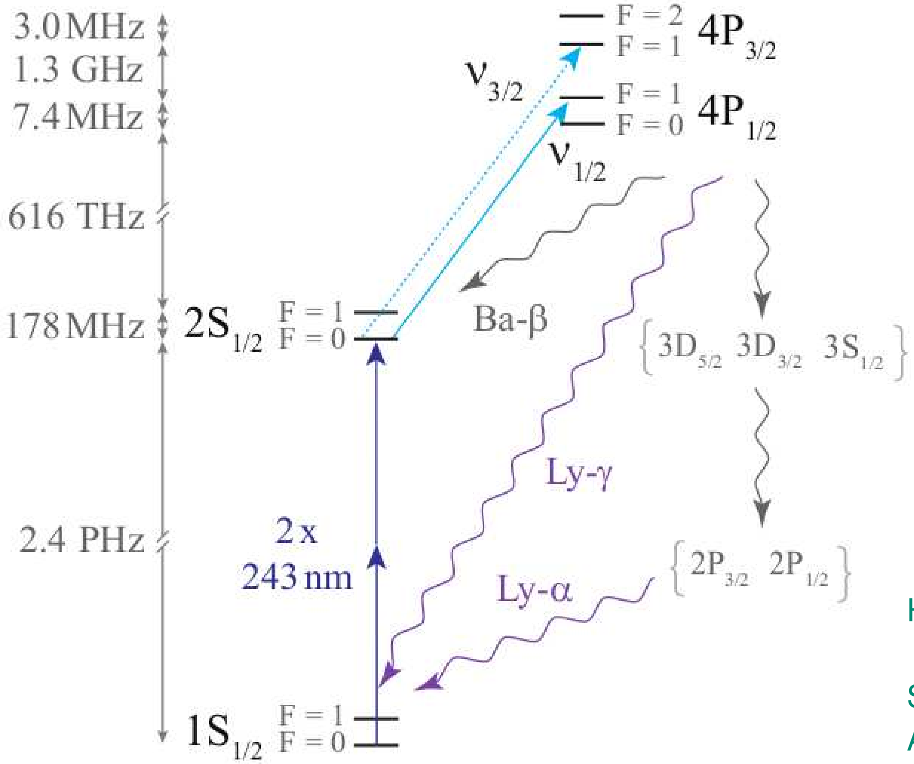

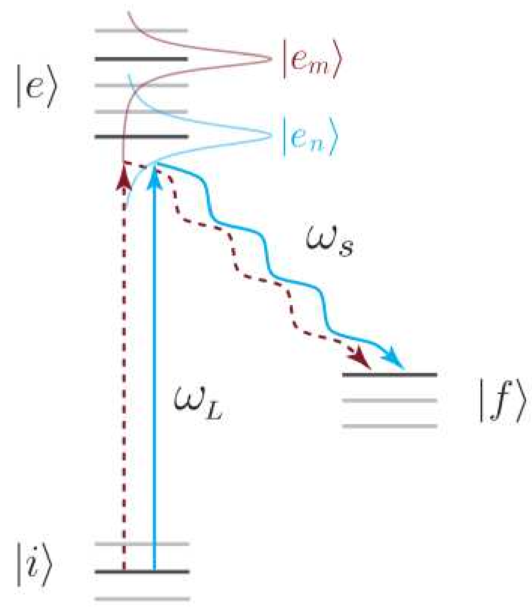

$$P(\omega) \propto \left| \frac{(\vec{d}_1 \cdot \vec{E}_0)\vec{d}_1}{\omega_1 - \omega_L + i\gamma_1/2} + \frac{(\vec{d}_2 \cdot \vec{E}_0)\vec{d}_2 e^{i\Delta\phi}}{\omega_2 - \omega_L + i\gamma_2/2} \right|^2$$

= Lorentzian(1) + Lorentzian(2) +

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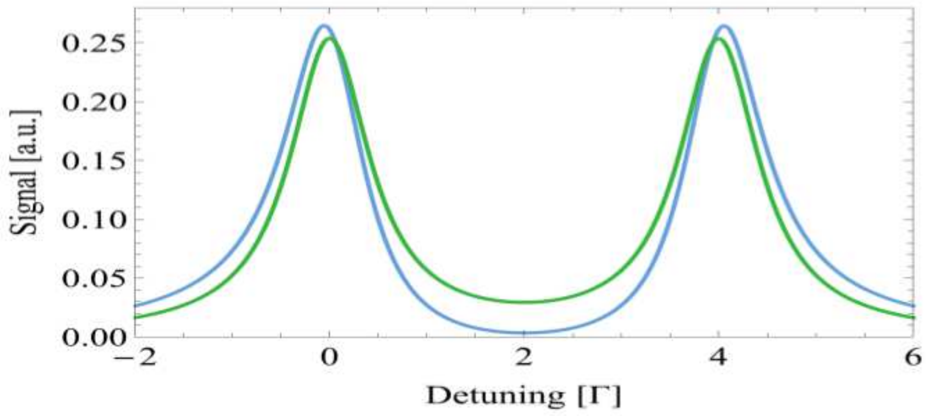

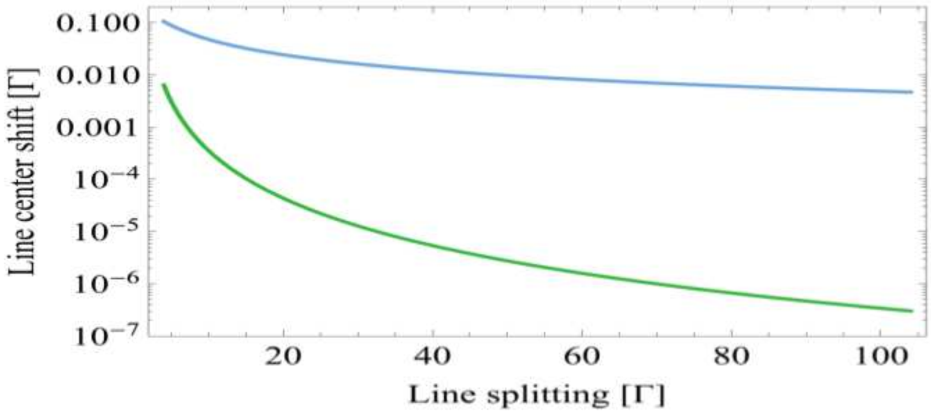

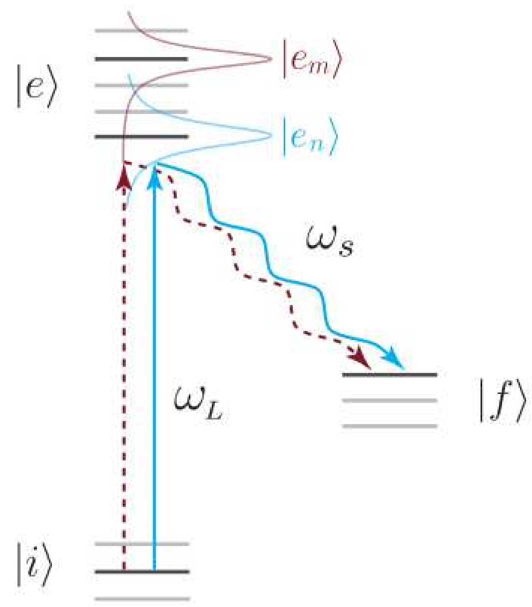

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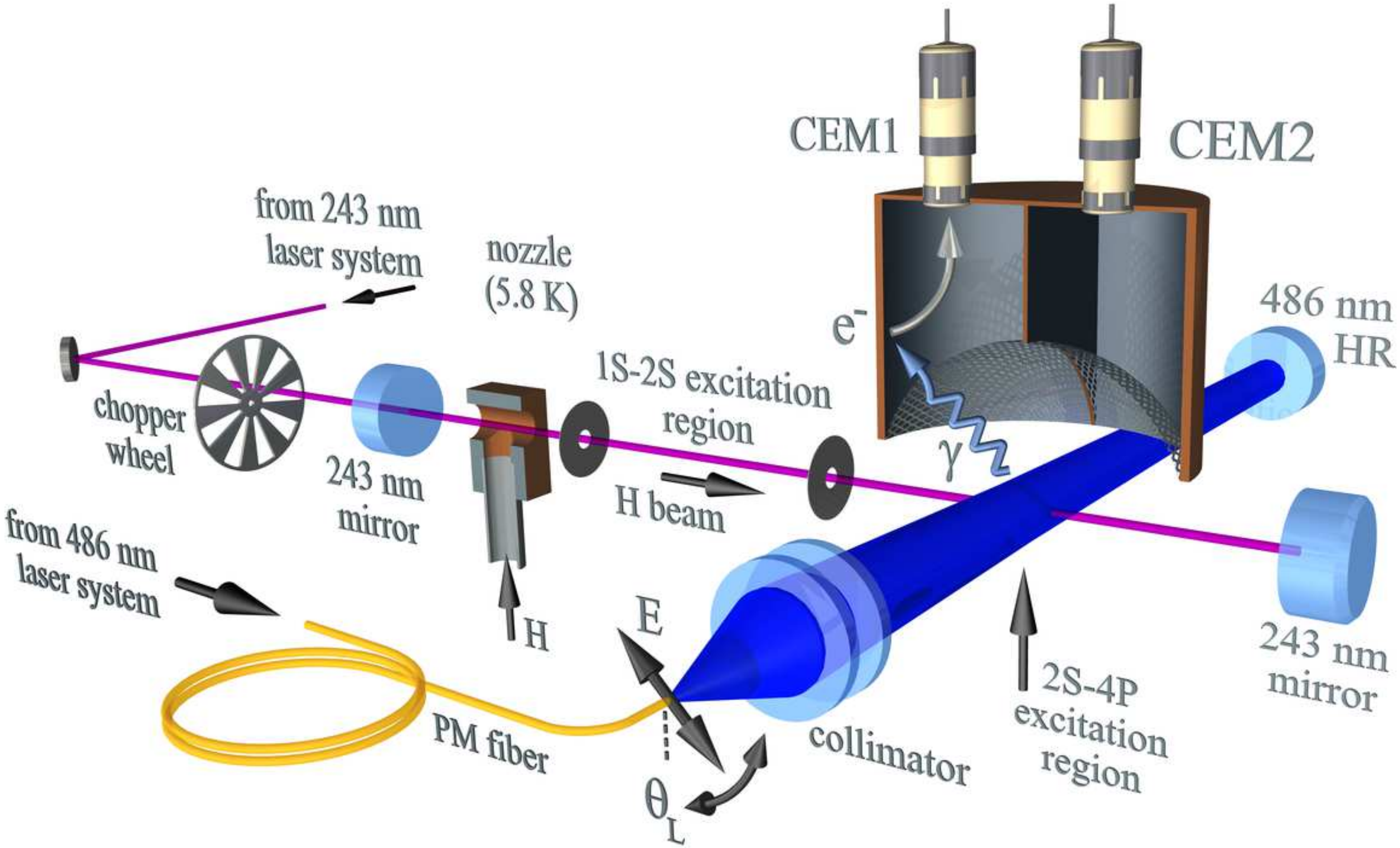
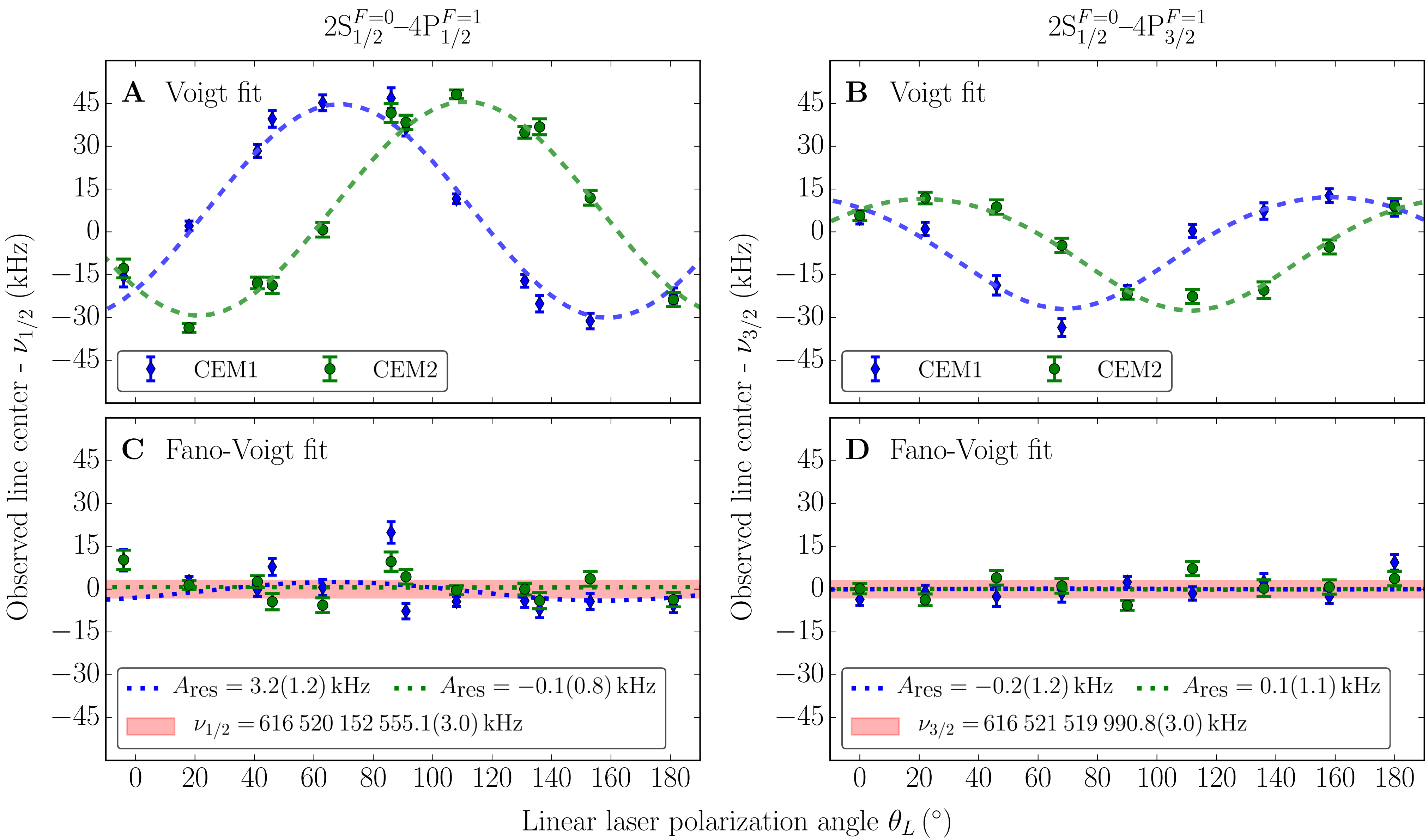
2S-4P setup



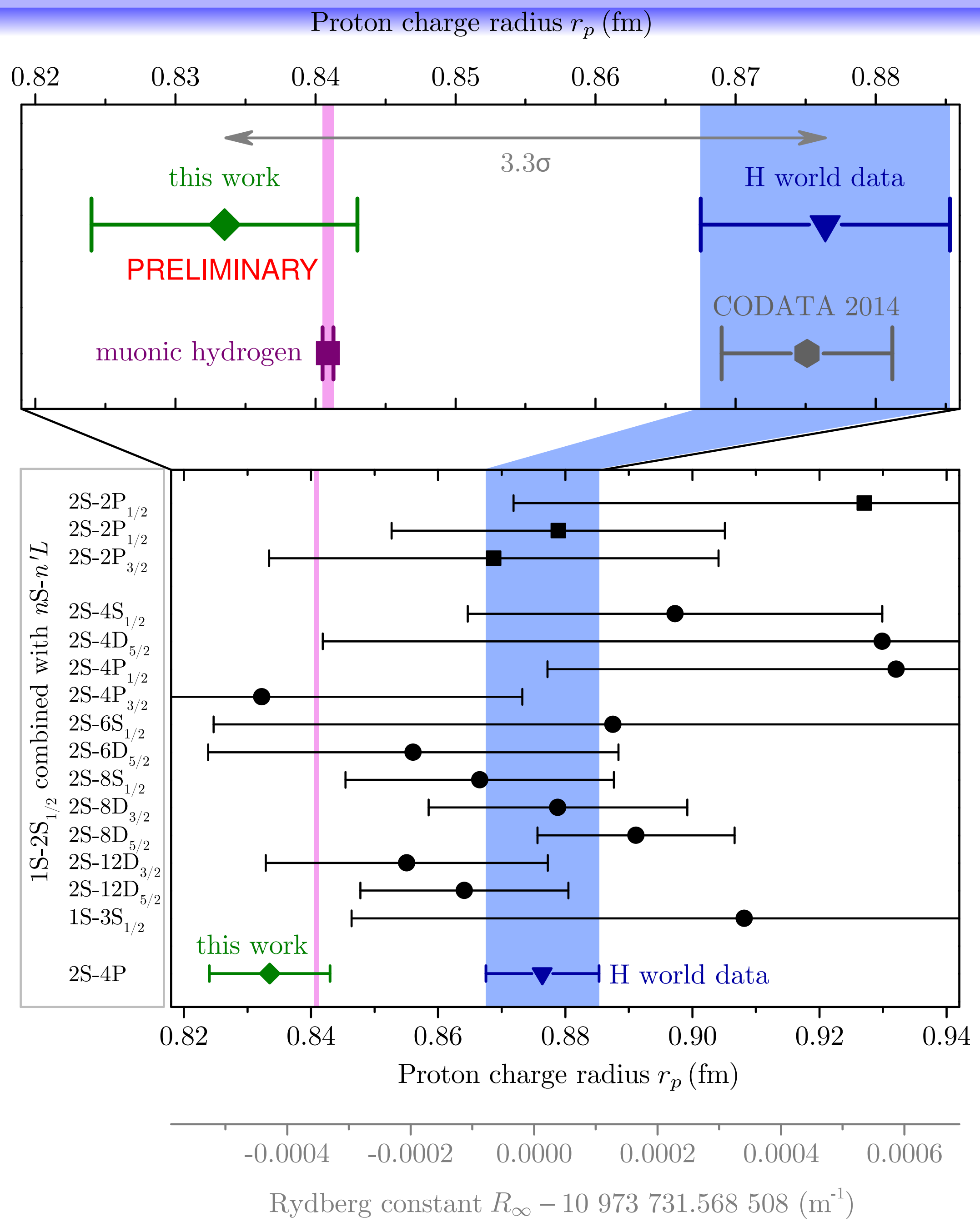
Beyer, RP *et al.*, submitted (2016)

Cross-damping



A. Beyer, RP *et al.*, submitted.

2S – 4P results



PRELIMINARY

A. Beyer, RP *et al.*, submitted.

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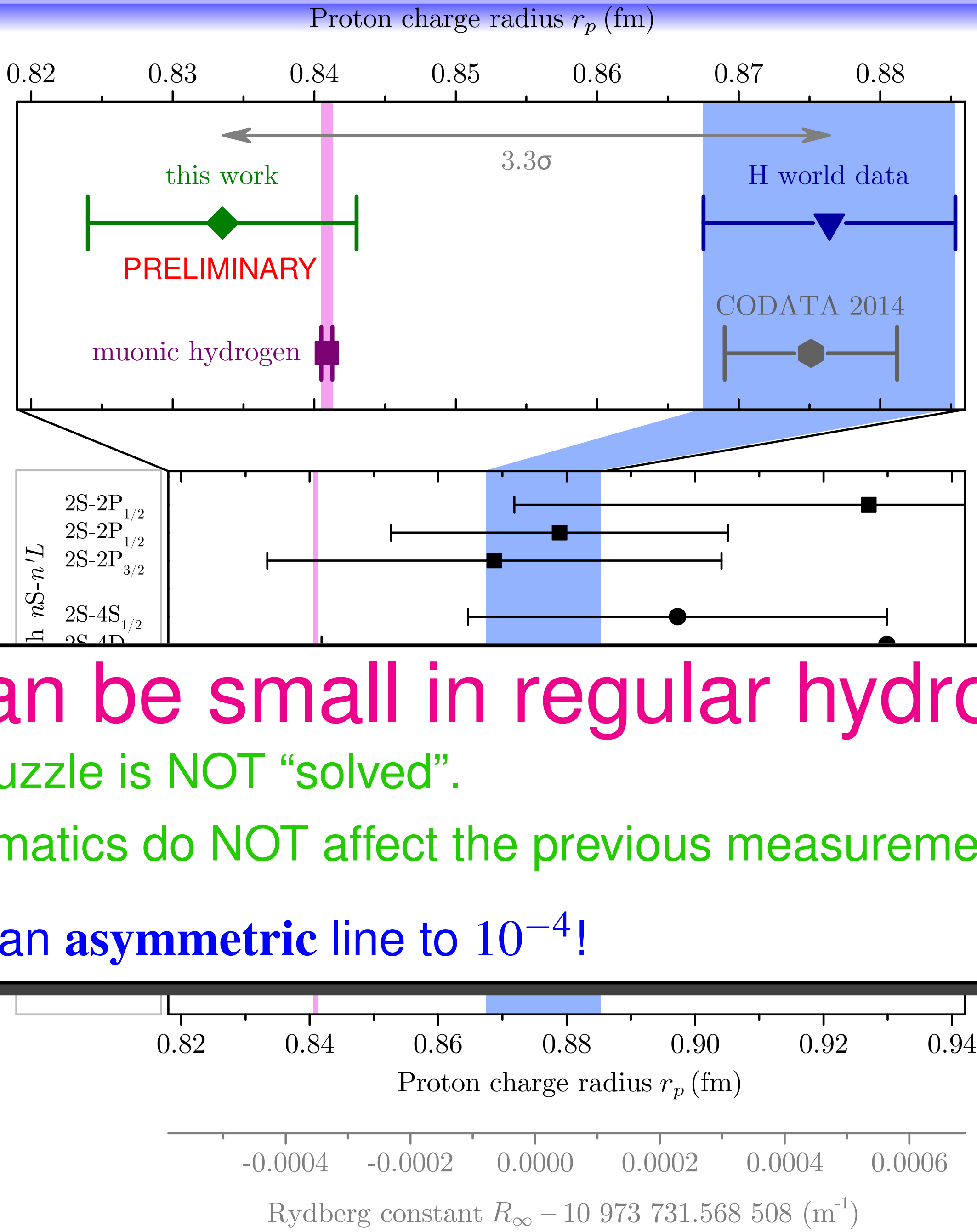


PRELIMINARY

Proton can be small in regular hydrogen, too!

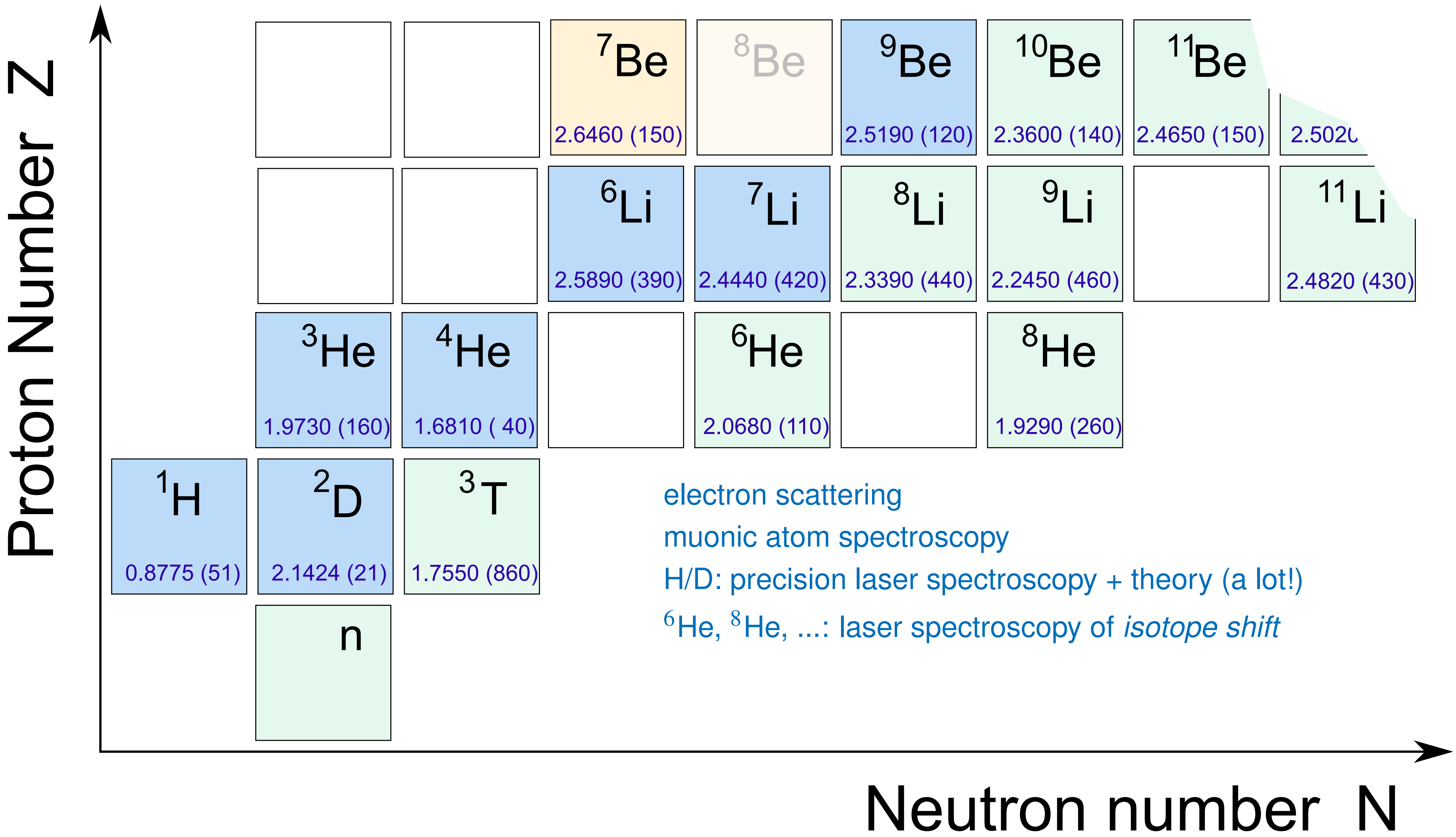
Proton radius puzzle is NOT "solved".

Our main systematics do NOT affect the previous measurements.

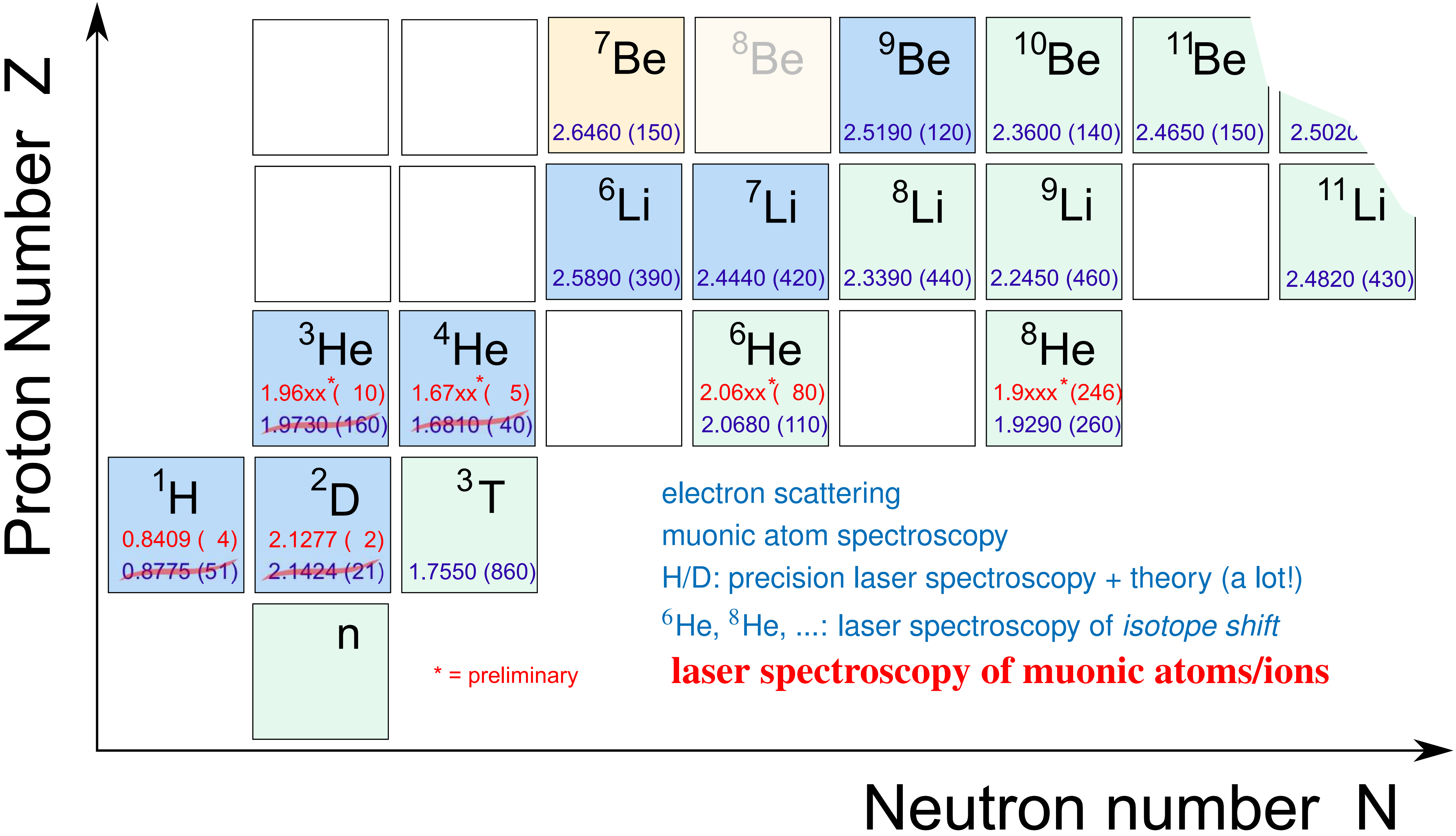
Note: We split an **asymmetric** line to 10^{-4}!

A. Beyer, RP *et al.*, submitted.

The nuclear chart



The nuclear chart - new charge radii

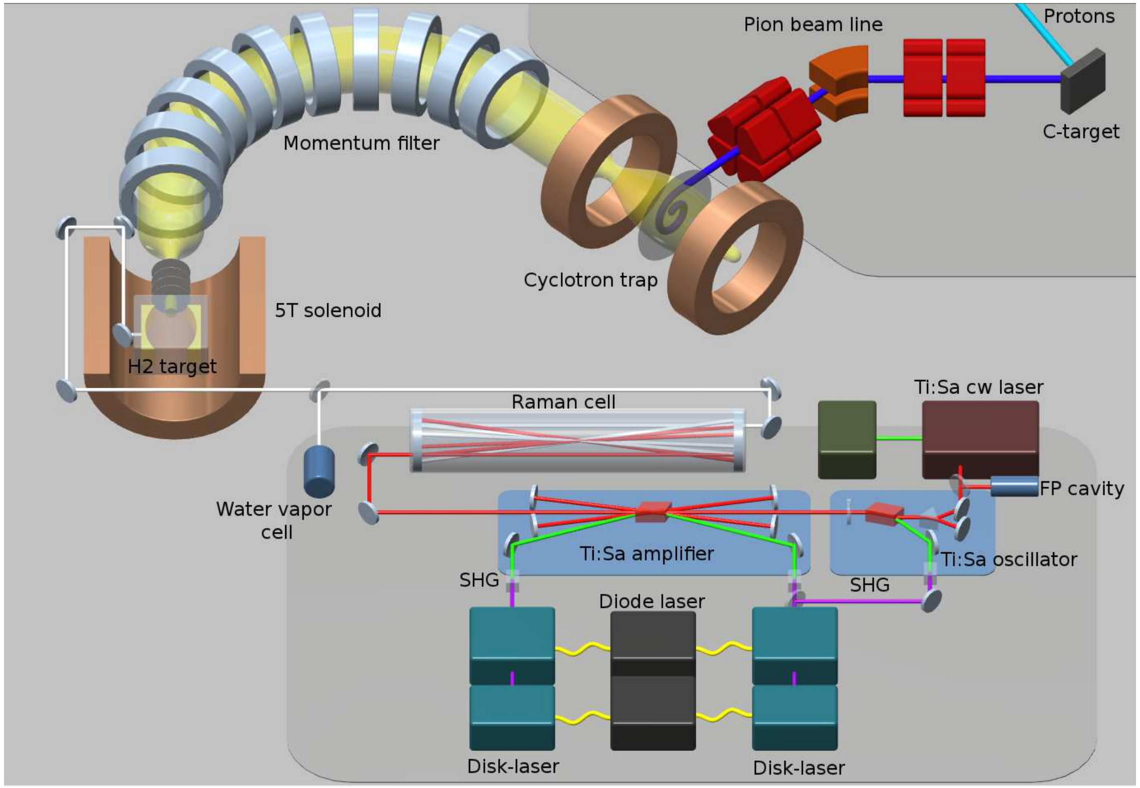


Summary

- Results from muonic hydrogen and deuterium:
  - Proton charge radius: r_p= 0.84087 (39) fm
  - Proton Zemach radius: R_Z = 1.082 (37) fm
  - Rydberg constant: $R_\infty = 3.289\,841\,960\,249\,5\ (10)^{r_p}\ (25)^{\mathrm{QED}}\ \times 10^{15}$ Hz/c
  - Deuteron charge radius: r_d = 2.12771 (22) fm from μH + H/D(1S-2S)
  - The “Proton radius puzzle”
- muonic helium-3 and -4: charge radius 10x more precise. No big discrepancy
- H(2S-4P) gives revised Rydberg $\Rightarrow$ small r_p PRELIMINARY
- New projects:
  - 1S-HFS in muonic hydrogen / ^{3}He $\Leftarrow$ PSI, J-PARC, RIKEN-RAL, ...
  - LS in muonic Li, Be, B, T, ...; muonic high-Z, ...
  - 1S-2S and 2S-$n\ell$ in Hydrogen/Deuterium/Tritium, He^+
  - He, H_2, HD^+,...
  - Positronium $\equiv e^+e^-$, Muonium $\equiv \mu^+e^-$
  - Electron scattering: H at lower Q^2, D, He
  - Muon scattering: MUSE @ PSI
  - ...

Future: Muonic

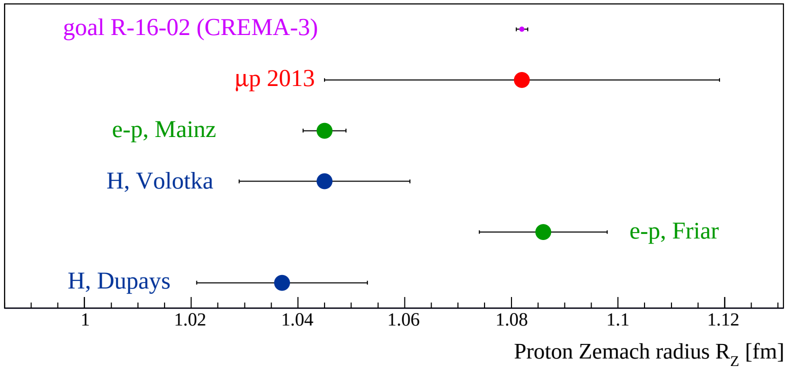
The **world's most intense beam** for **low-energy μ^-**



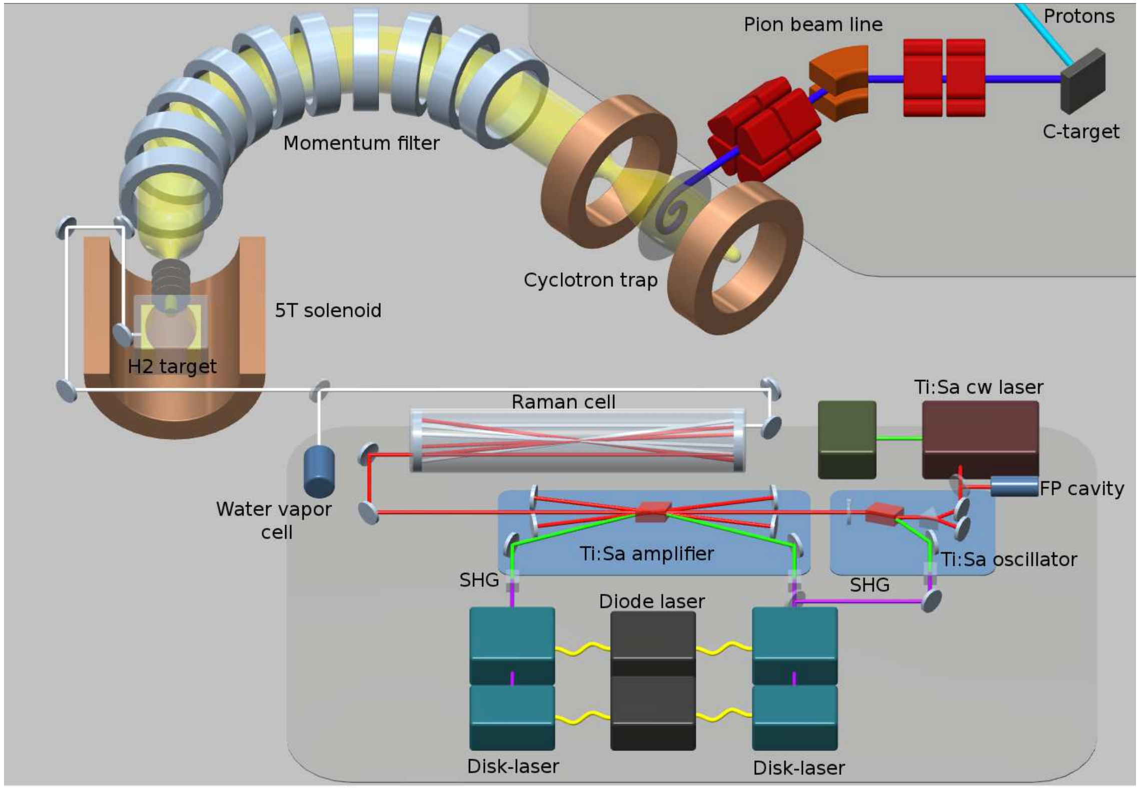
Future: Muonic

1S-HFS in μp, μ^3He

$\rightarrow$ Zemach (magnetic) radius



The **world's most intense beam** for **low-energy** μ^-



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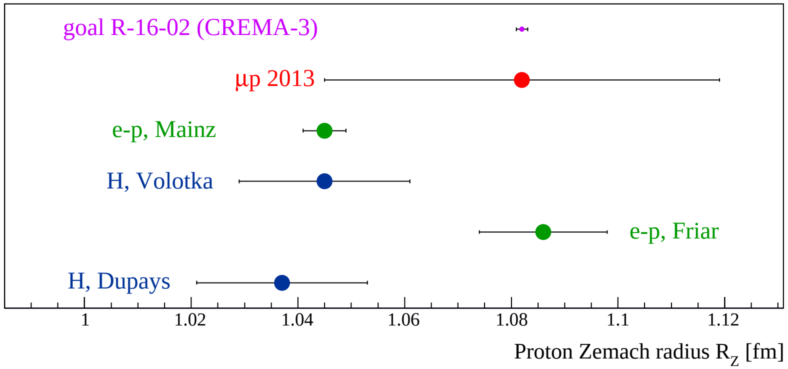
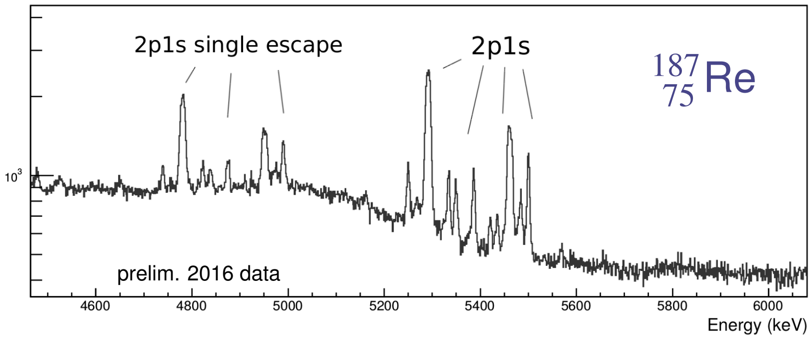
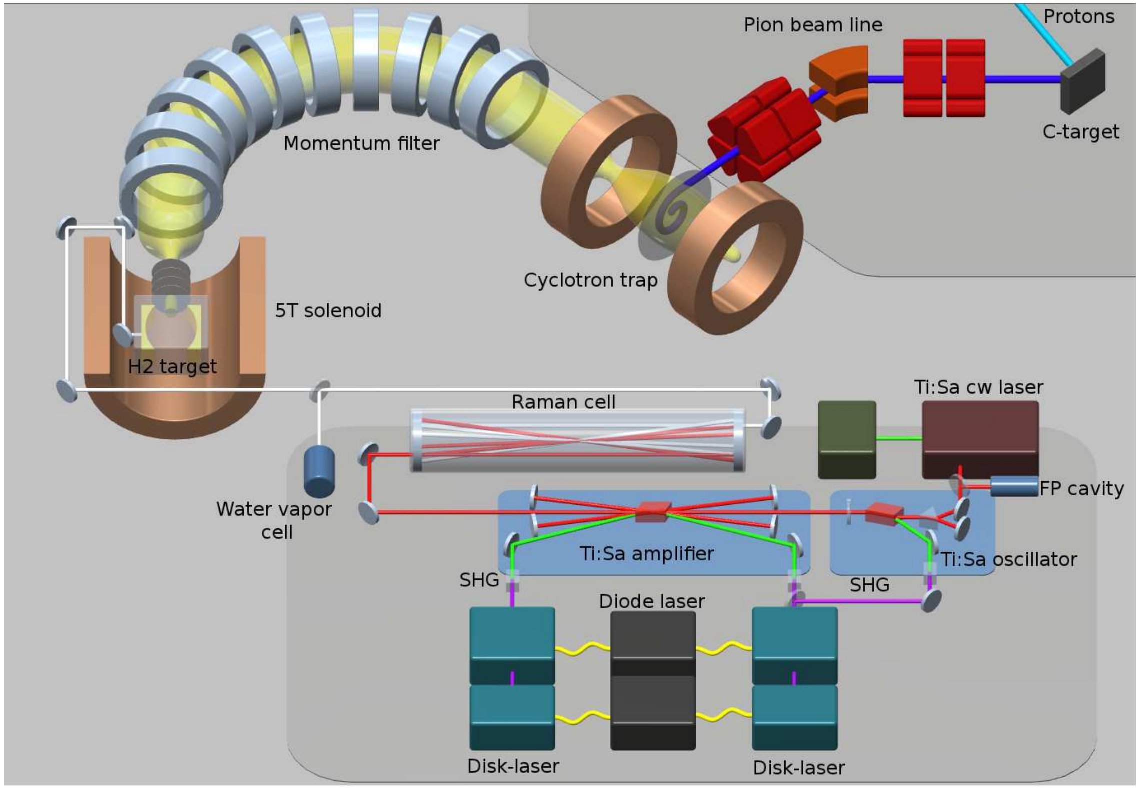
1S-HFS in μp, μ^3He
→ Zemach (magnetic) radius



stop in μg of (radioactive) material
→ charge radii of higher Z

muX Collab @ PSI





Future: Muonic

1S-HFS in μp, μ^3He
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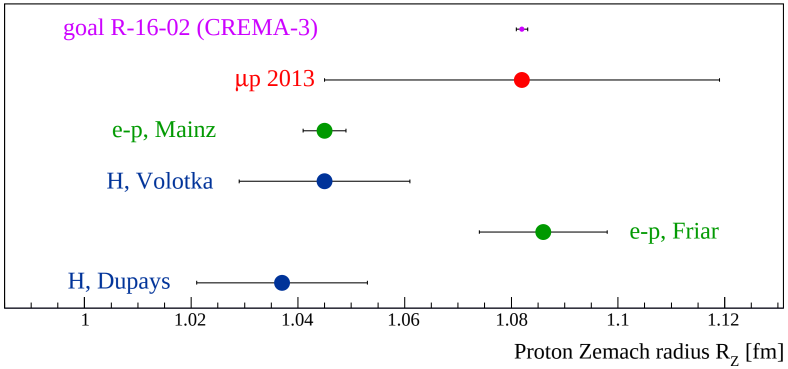

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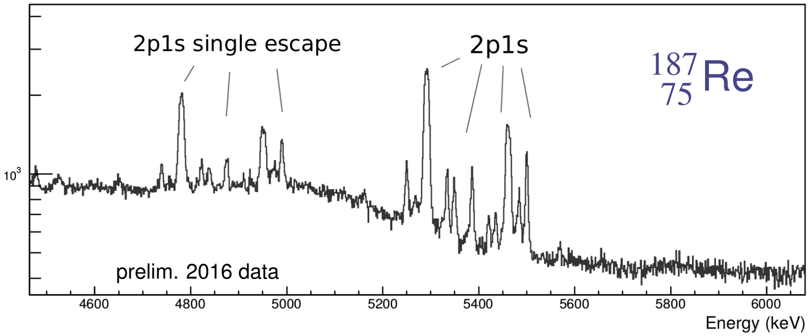
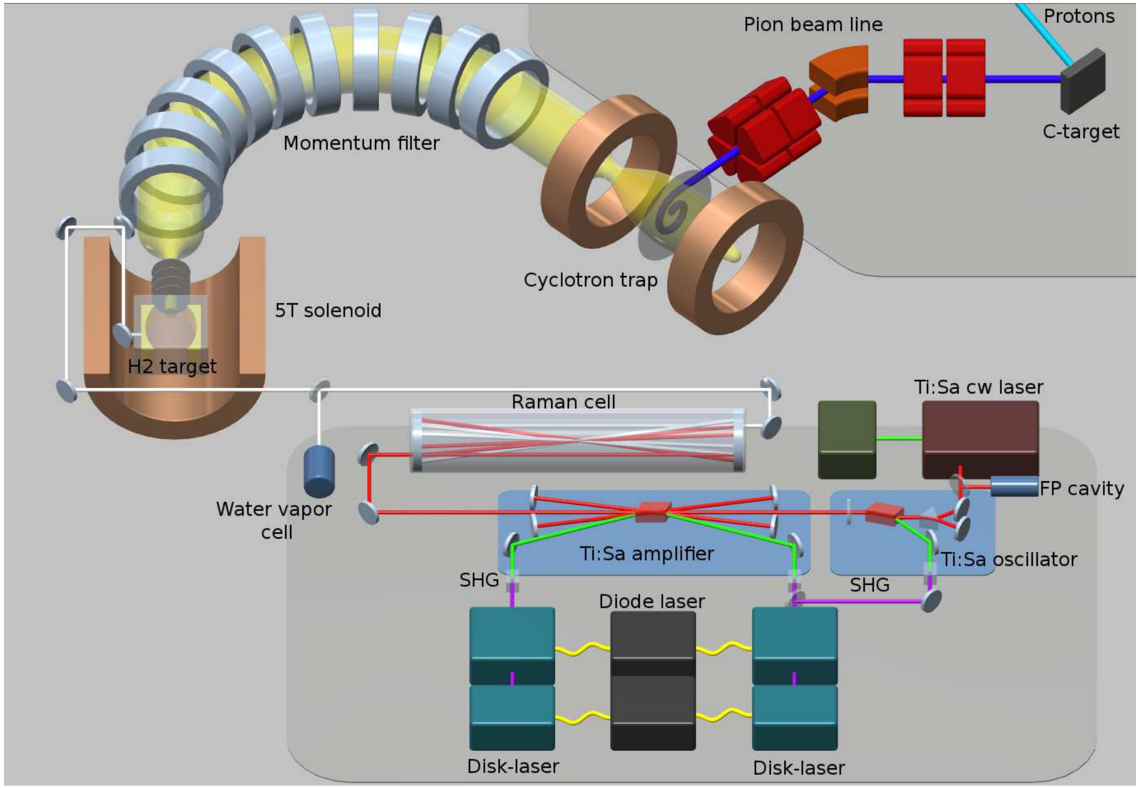
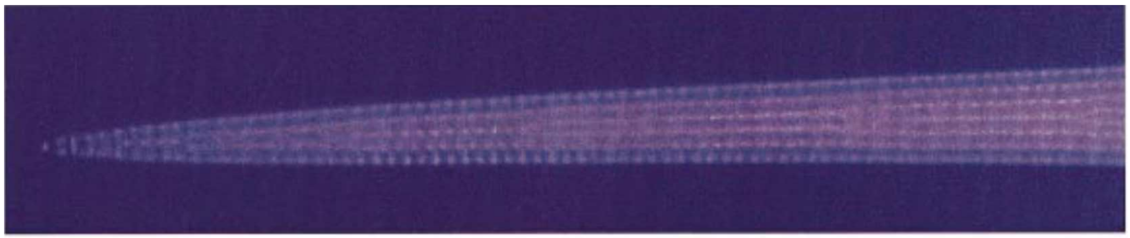


The **world's most intense beam** for **low-energy μ^-**

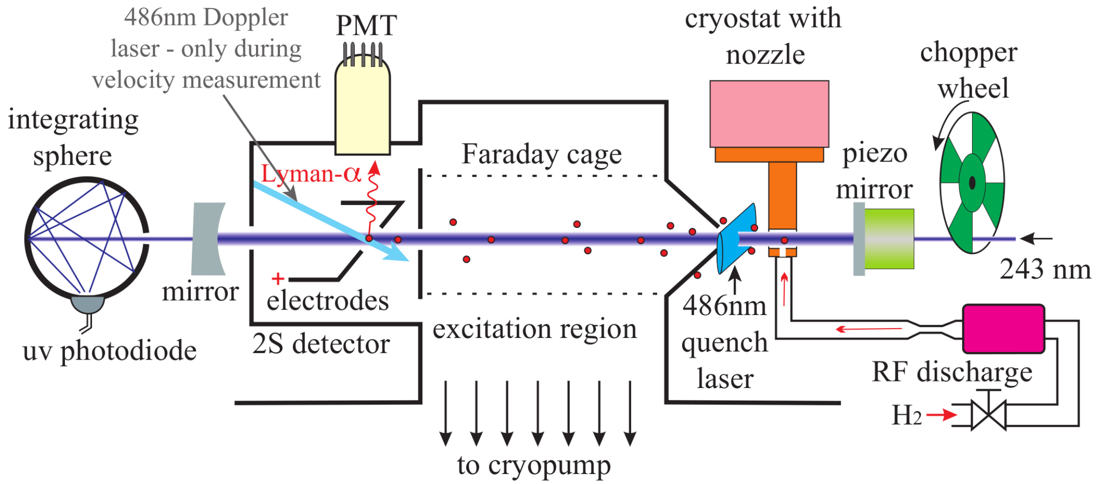


stop μ^- in Penning trap
$\rightarrow$ charge radii of Li, Be, B, T



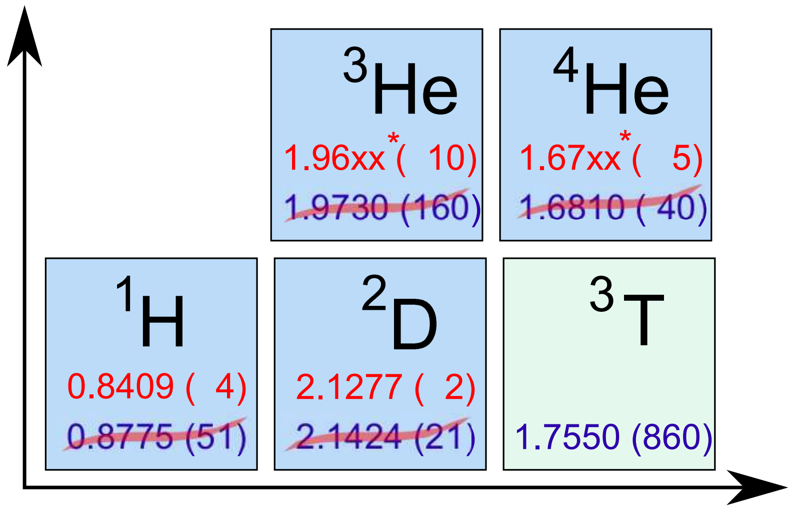
Future: Electronic

Hydrogen apparatus in Garching

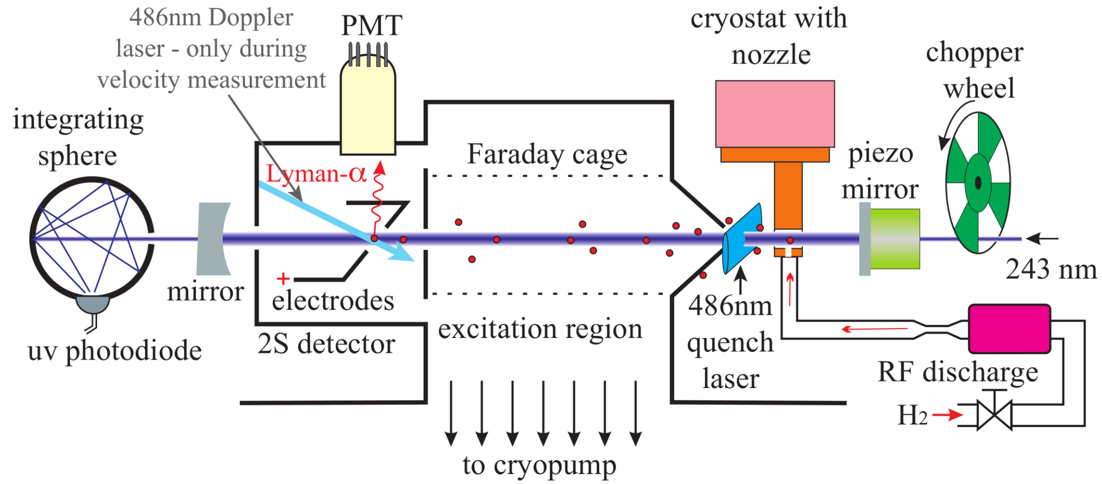


Future: Electronic

Tritium = “missing link”



Hydrogen apparatus in Garching



r_p = 0.8775(51) fm → 0.8409(4) fm

r_d = 2.1424(21) fm → 2.1277(2) fm

r_t = 1.7550(860) fm ⇒ potential improvement by 400!

$r_d^2 - r_p^2 = 3.82007(65)$ fm^2 H/D(1S-2S) isotope shift to 15 Hz

limit from **theory**: 1 kHz

r_t from T(1S-2S) to 10 kHz, later 1 kHz

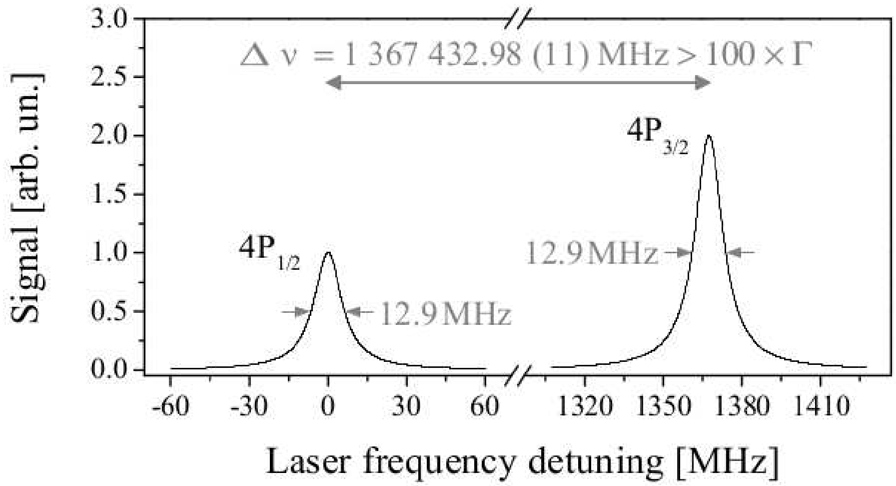
CREMA in 2009...

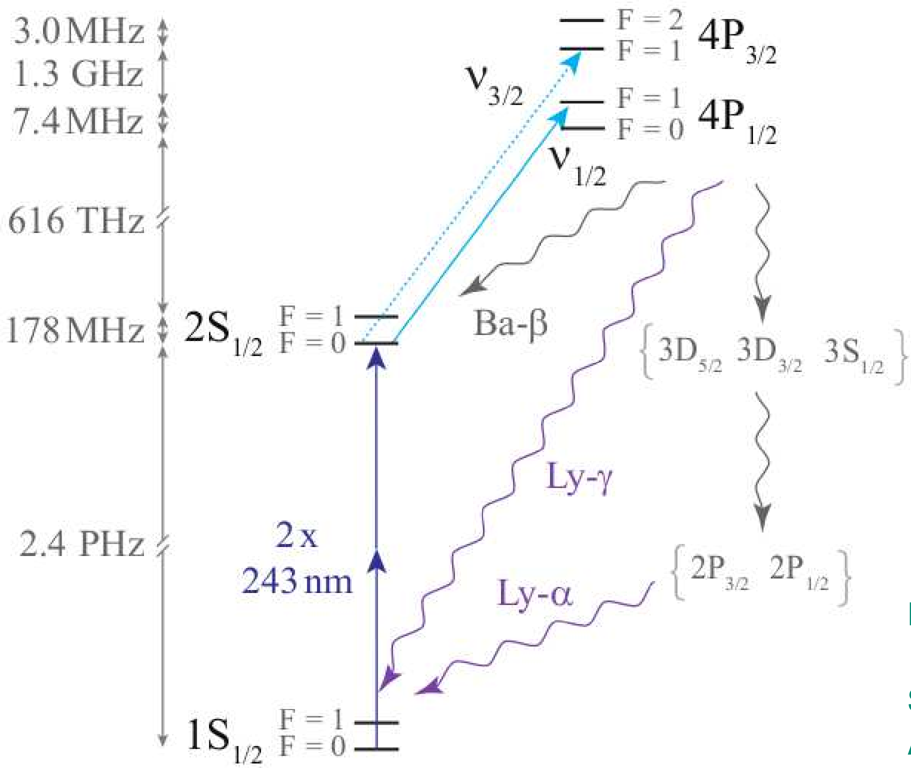
... and 2014

... and 2017

Backup slides.

Quantum interference shifts





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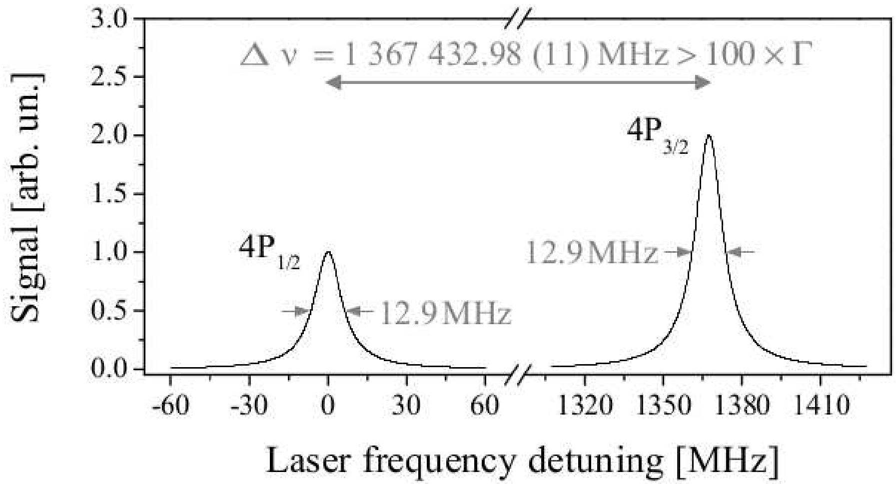
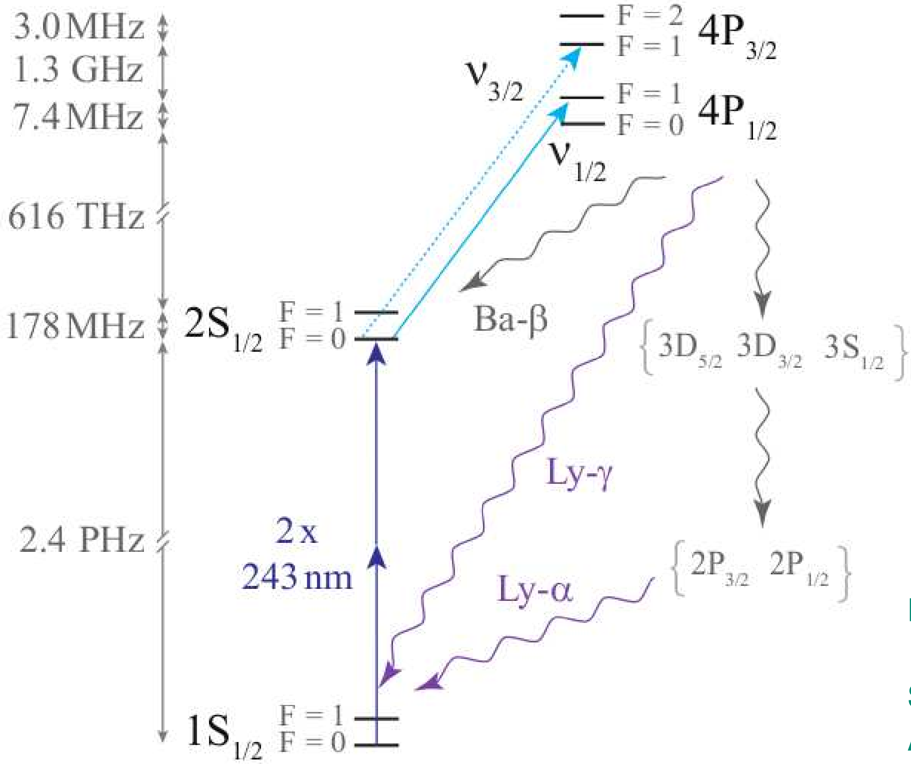
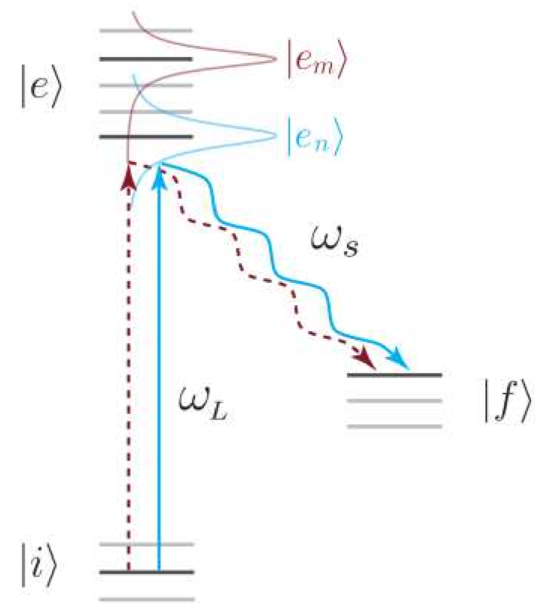
Quantum interference shifts







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

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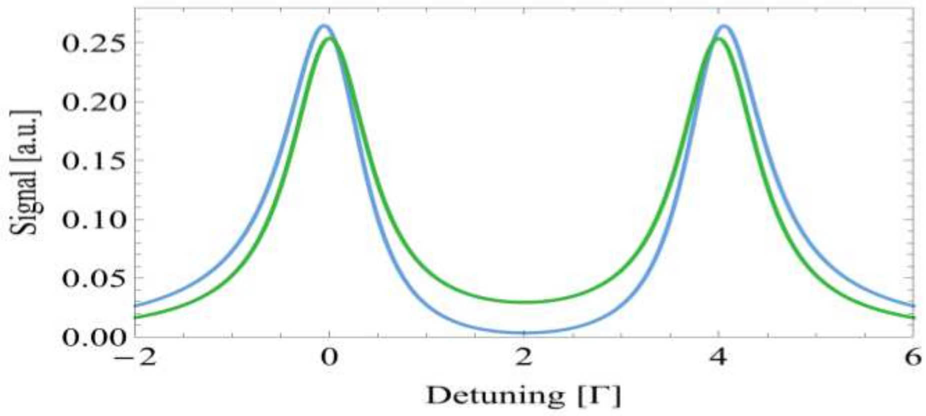
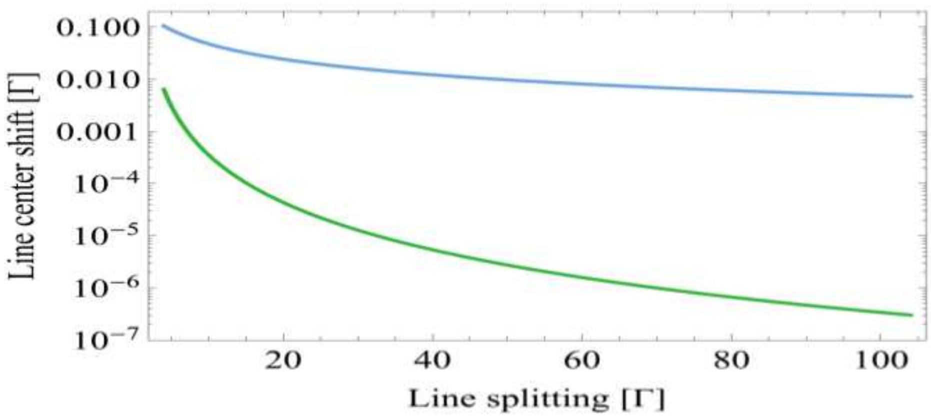
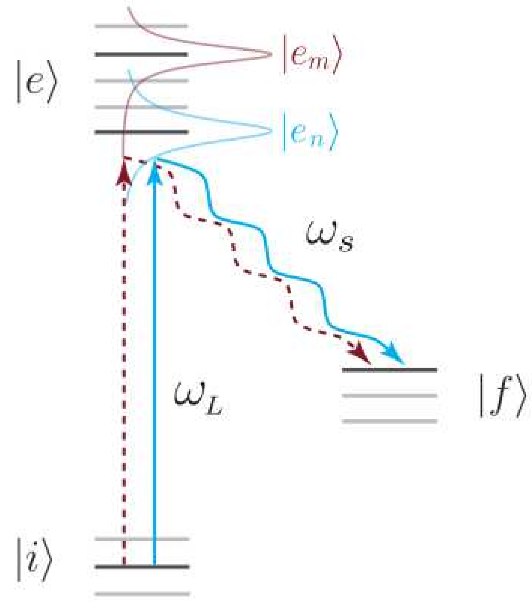






$$P(\omega) \propto \left| \frac{(\vec{d}_1 \cdot \vec{E}_0)\vec{d}_1}{\omega_1 - \omega_L + i\gamma_1/2} + \frac{(\vec{d}_2 \cdot \vec{E}_0)\vec{d}_2 e^{i\Delta\phi}}{\omega_2 - \omega_L + i\gamma_2/2} \right|^2$$

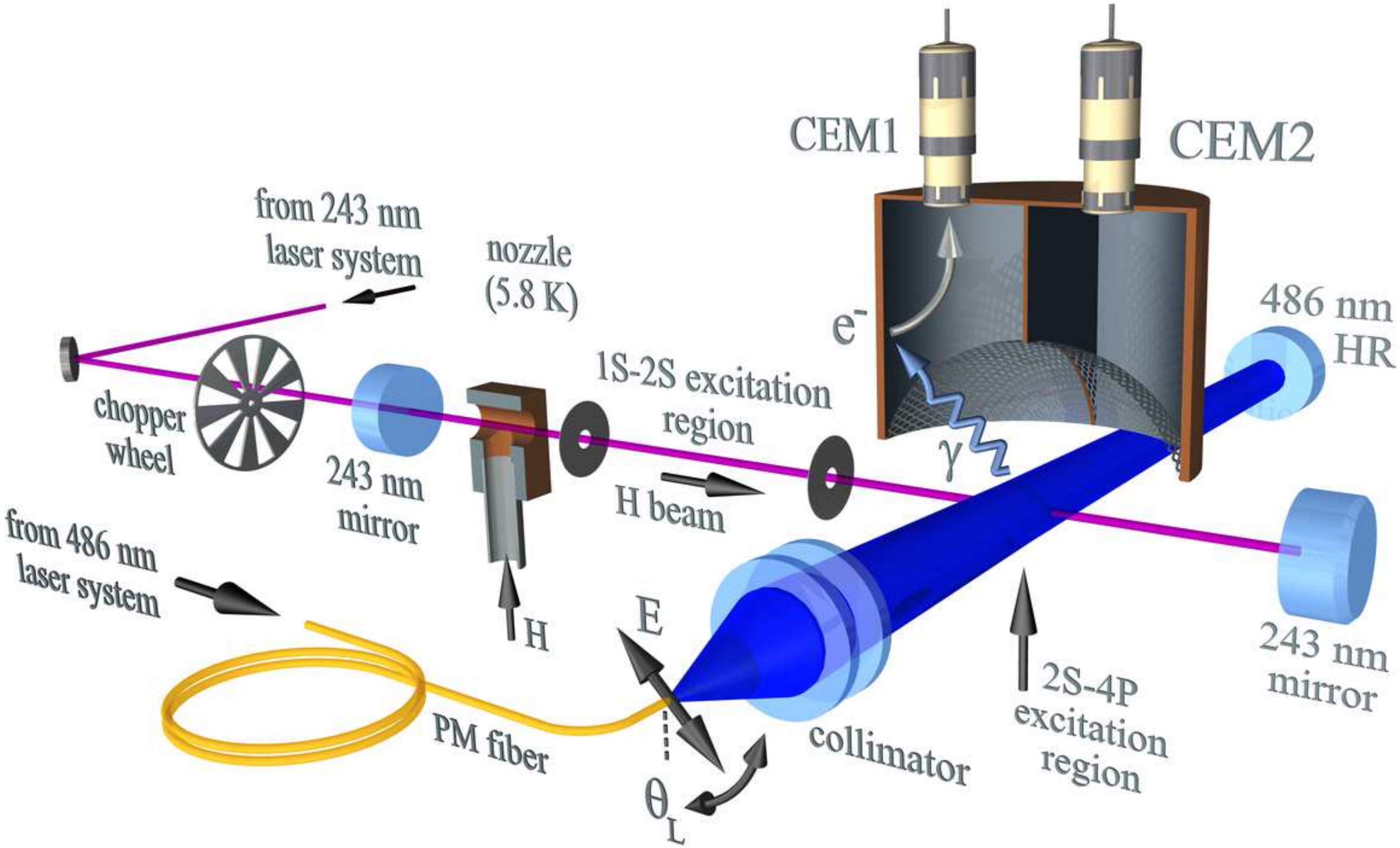
= Lorentzian(1) + Lorentzian(2) +

cross-term (QI)

Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011), PRA 86, 040501 (2012), etc.
Sansonetti *et al.*, PRL 107, 023001 (2011); Brown *et al.*, PRA 87, 032504 (2013)
Amaro, RP *et al.*, PRA 92, 022514 (2015); PRA 92, 062506 (2015)

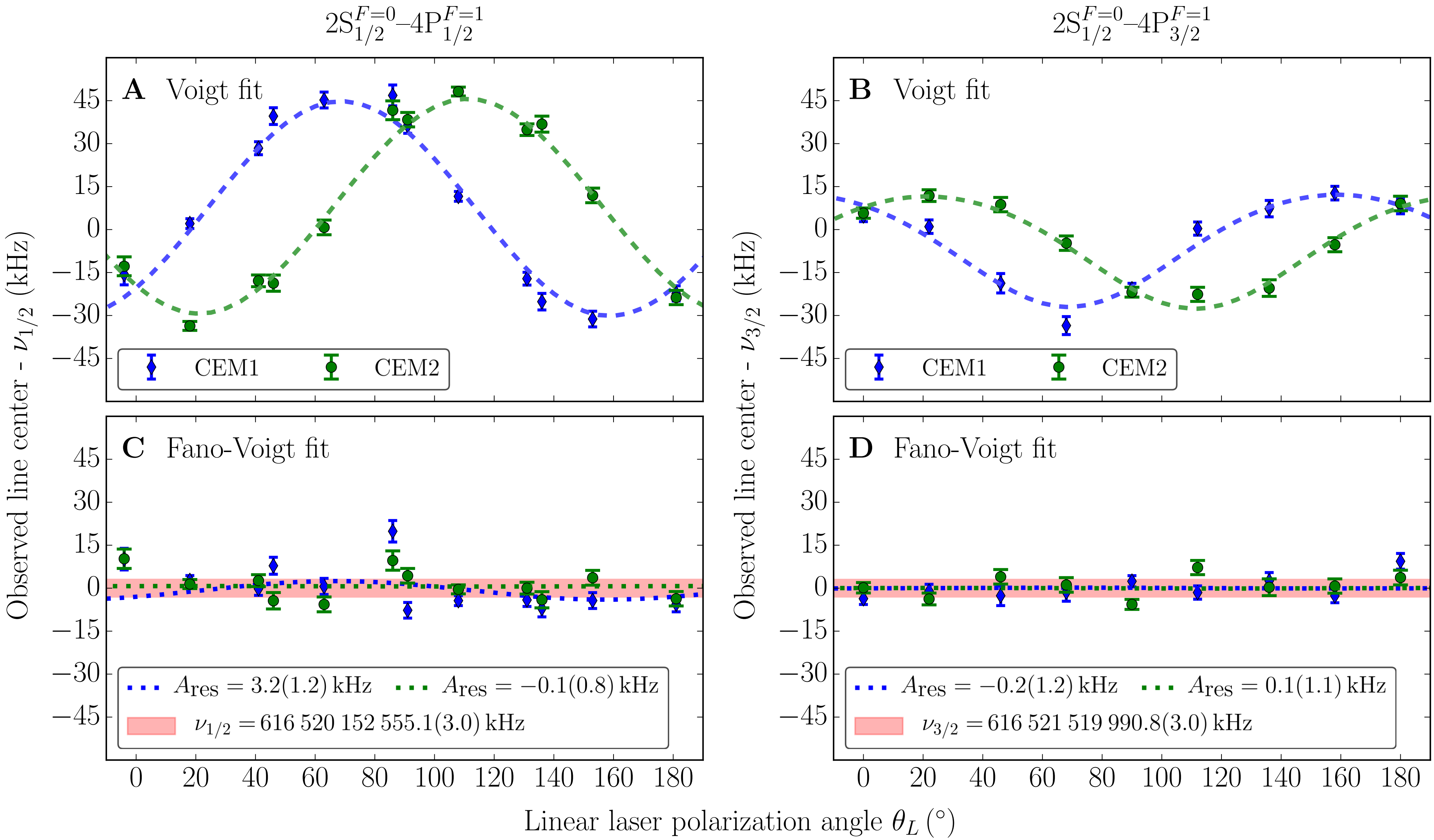
Quantum interference shifts

2S-4P setup



Beyer, RP *et al.*, submitted (2016)

Cross-damping



A. Beyer, RP *et al.*, submitted.

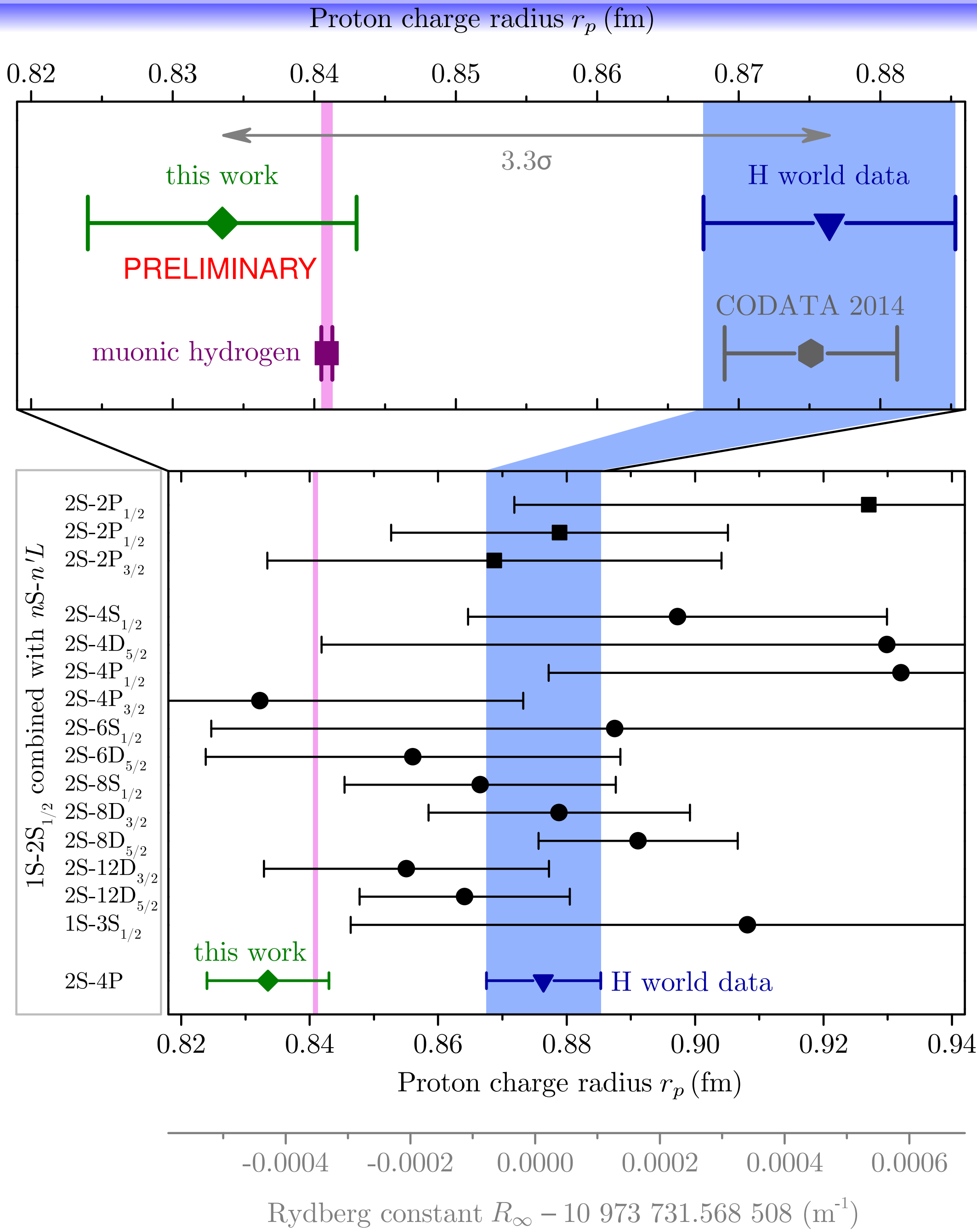
2S – 4P uncertainties

	$\Delta\nu$ (kHz)	σ (kHz)
Statistics	0.0	0.40
First-order Doppler shift	0.0	2.13
Quantum interference shift	0.0	0.20
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	0.0	0.20
Zeeman shift	0.0	0.22
Pressure shift	0.0	0.008
Laser spectrum	0.0	0.1
Laser frequency determination	0.0	0.1
Frequency standard (H maser)	0.0	0.06
Recoil shift	-837.23	0.00
Hyperfine structure (HFS) corrections	-132552.092	0.075
Total	-133388.9	2.3

A. Beyer, RP *et al.*, submitted.

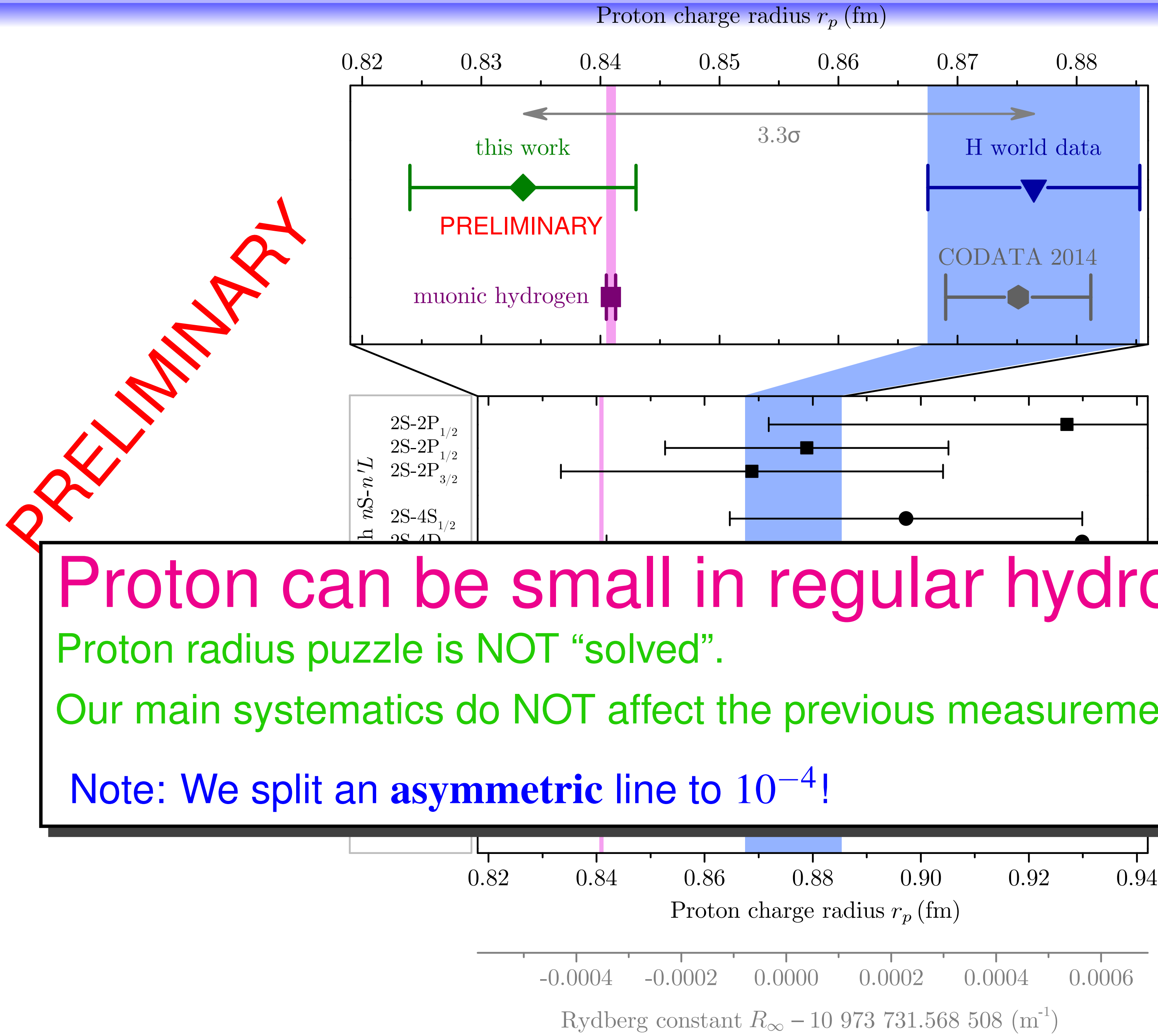
2S – 4P results

PRELIMINARY



A. Beyer, RP *et al.*, submitted.

2S – 4P results



Proton can be small in regular hydrogen, too!

Proton radius puzzle is NOT “solved”.

Our main systematics do NOT affect the previous measurements.

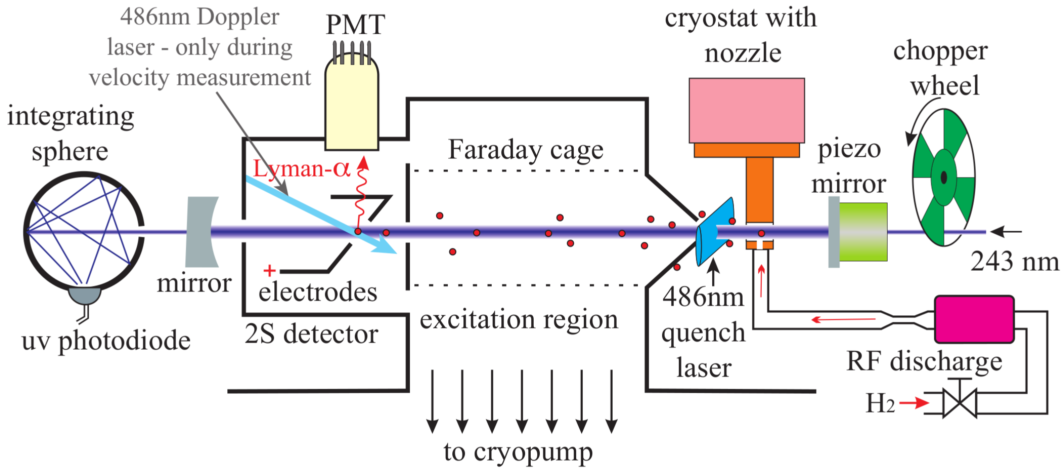
Note: We split an **asymmetric** line to 10^{-4}!

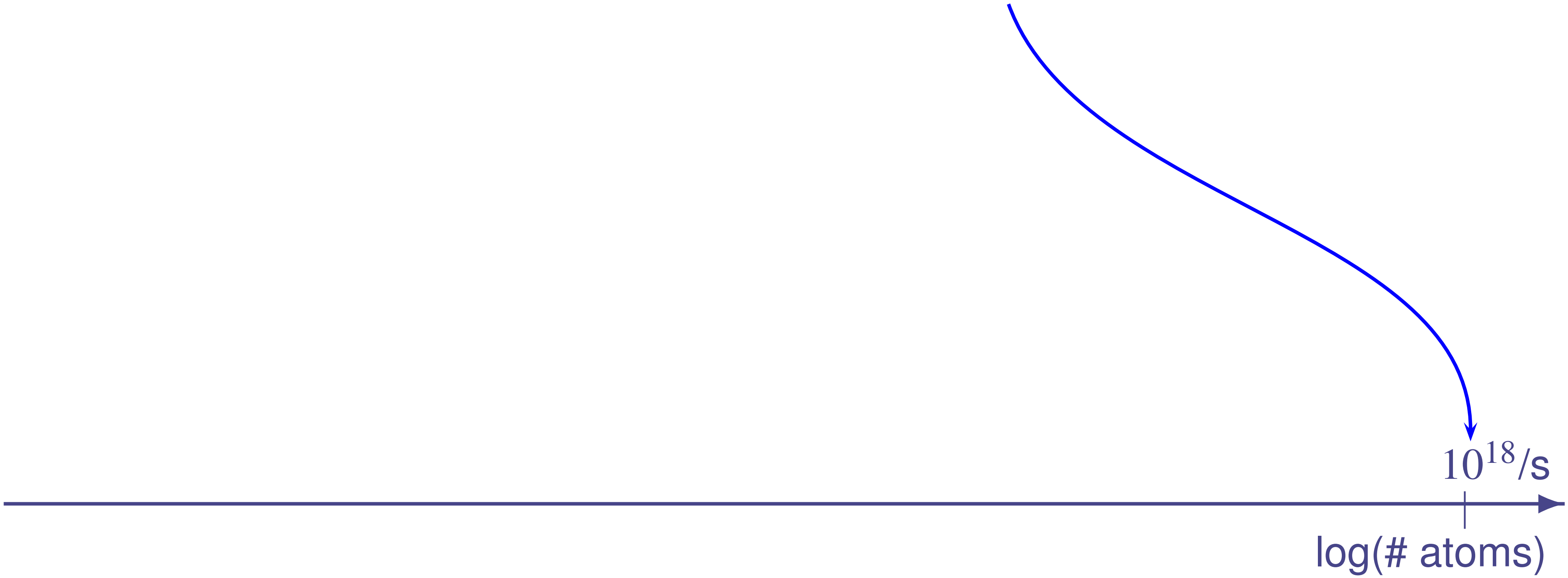
A. Beyer, RP *et al.*, submitted.

Hydrogen(-like) 1S-2S

Hydrogen(-like) 1S-2S

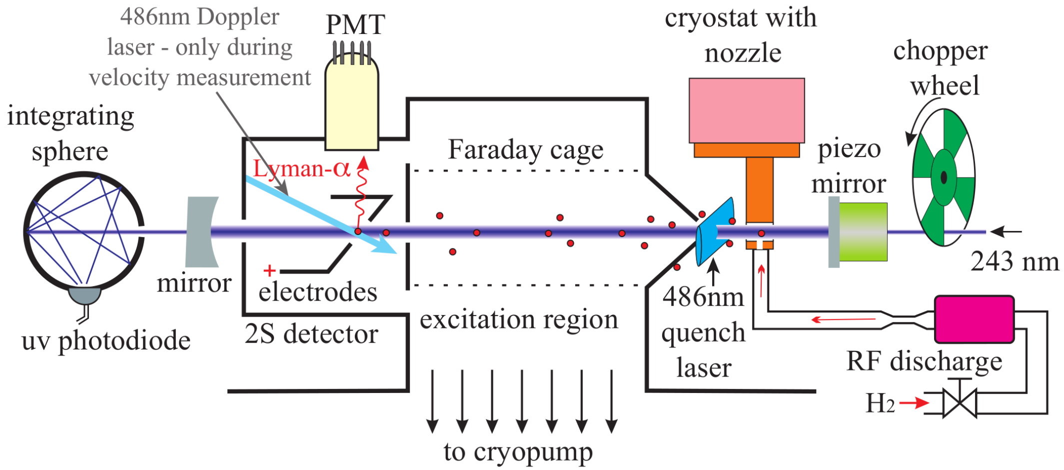
Hydrogen apparatus in Garching



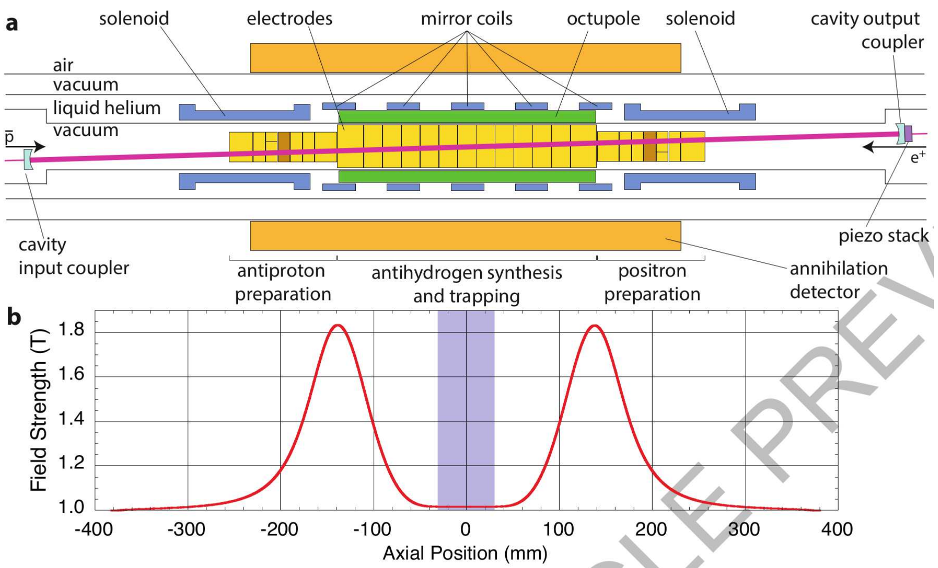


Hydrogen(-like) 1S-2S

Hydrogen apparatus in Garching



ALPHA Antihydrogen 1S-2S



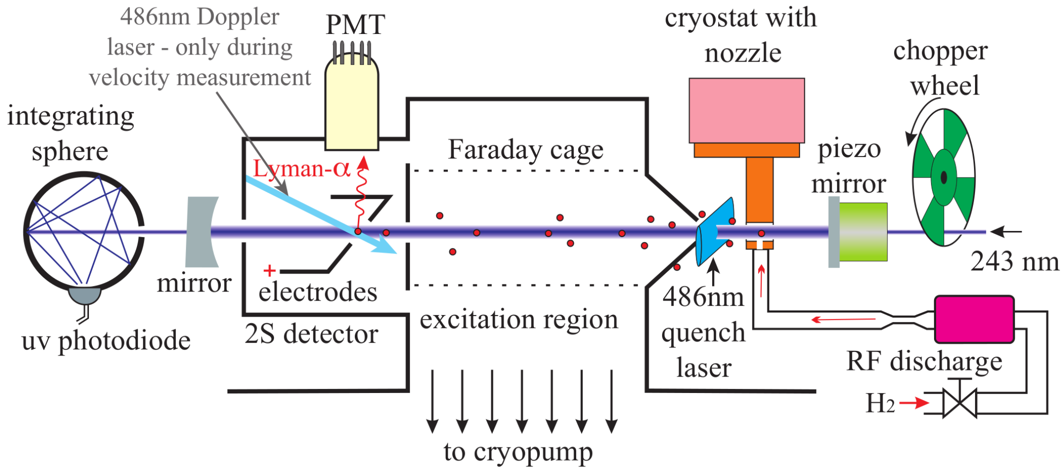
10^0/s

10^{18}/s

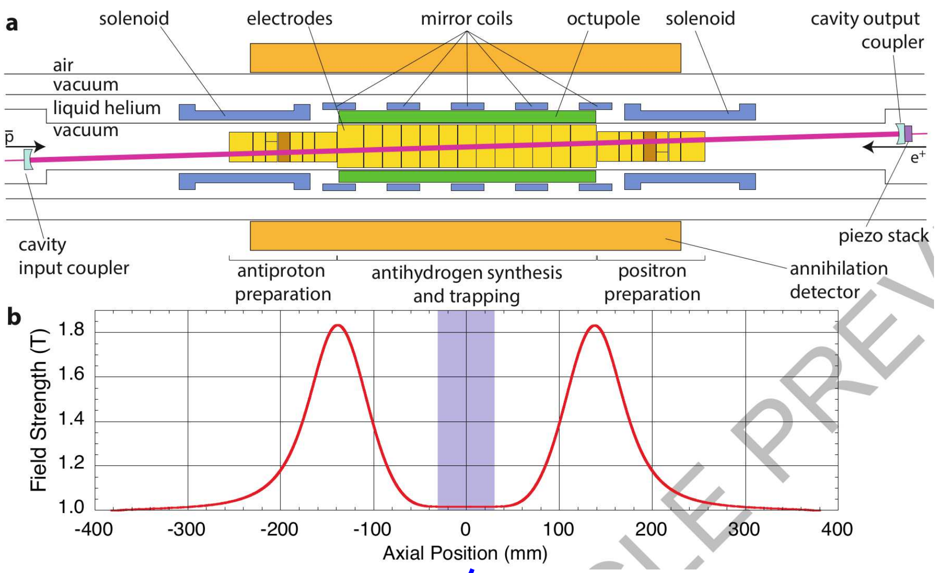
log(# atoms)

Hydrogen(-like) 1S-2S

Hydrogen apparatus in Garching



ALPHA Antihydrogen 1S-2S



work here!

10^0/s

10^9/trial

10^{18}/s

log(# atoms)

Towards T(1S-2S) I: Trapped H (BEC)

PRL 70, 544 (1993), Walraven group

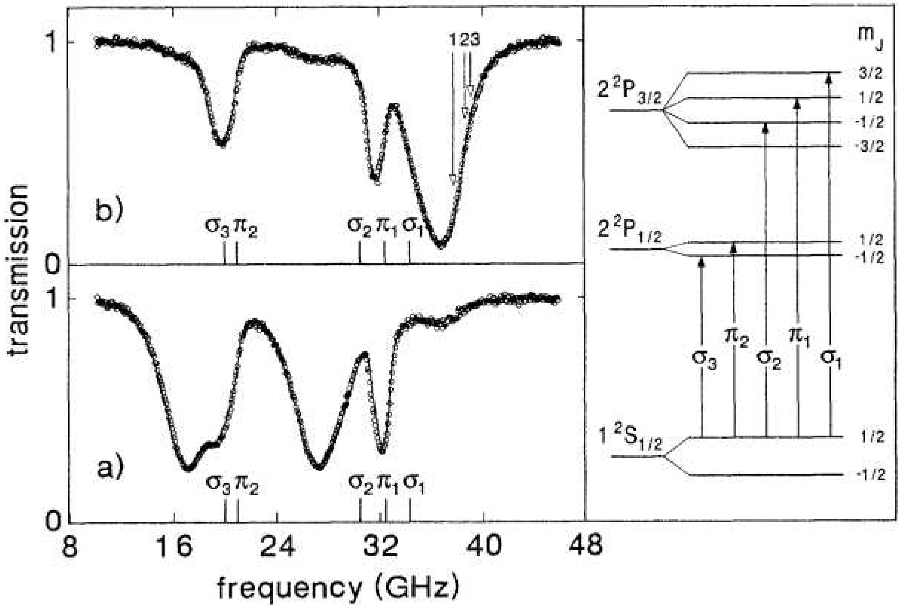


FIG. 2. Transmission spectra, recorded with (a) right- and (b) left-circularly polarized light, and energy level diagram defining the five allowed transitions. The scan time for each spectrum is 30 s. The solid lines are calculated spectra for $T = 51(12)$ mK and (a) $n_0 = 4.4(1.0) \times 10^{12}\,\mathrm{cm}^{-3}$ and (b) $n_0 = 3.3(0.8) \times 10^{12}\,\mathrm{cm}^{-3}$. The frequency is relative to $\frac{3}{4}R_\infty(1 + m_e/m_p)^{-1}$. The vertical bars denote the resonant frequencies of the five allowed transitions for $B = B_0$. The arrows in (b) indicate the three AOM frequencies.

Towards T(1S-2S) I: Trapped H (BEC)

PRL 70, 544 (1993), Walraven group

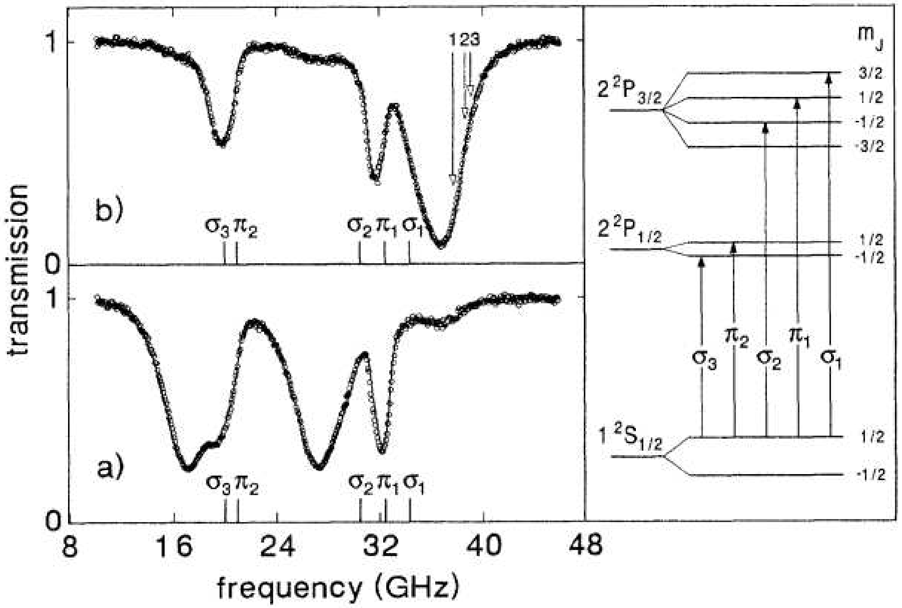


FIG. 2. Transmission spectra, recorded with (a) right- and (b) left-circularly polarized light, and energy level diagram defining the five allowed transitions. The scan time for each spectrum is 30 s. The solid lines are calculated spectra for $T = 51(12)$ mK and (a) $n_0 = 4.4(1.0) \times 10^{12}\,\mathrm{cm}^{-3}$ and (b) $n_0 = 3.3(0.8) \times 10^{12}\,\mathrm{cm}^{-3}$. The frequency is relative to $\frac{3}{4} R_\infty (1 + m_e/m_p)^{-1}$. The vertical bars denote the resonant frequencies of the five allowed transitions for $B = B_0$. The arrows in (b) indicate the three AOM frequencies.

PRL 77, 255 (1996), Kleppner group

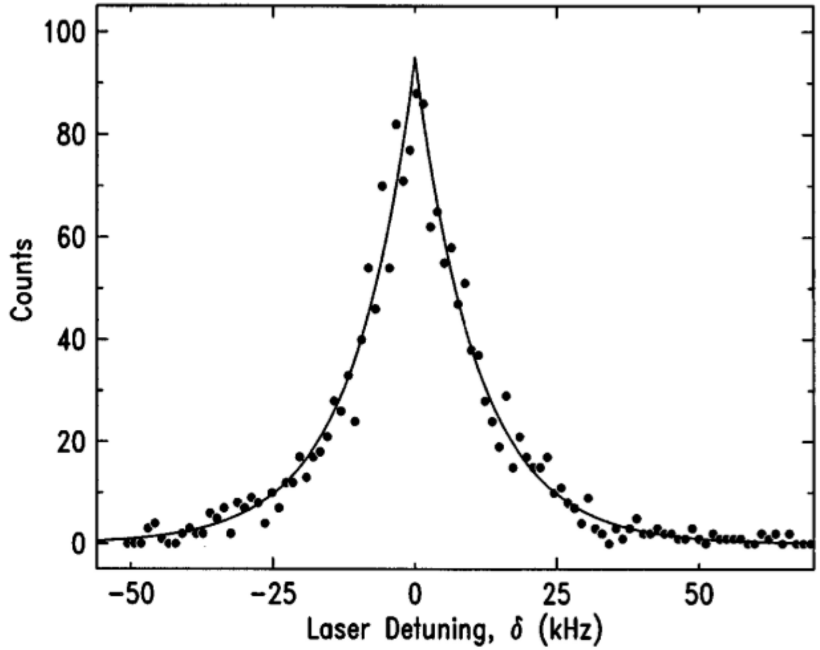


FIG. 2. 1*S*-2*S* excitation spectrum displaying a time of flight profile. The UV detuning (at 243 nm) is δ. The density is 3×10^{12} cm^{-3}, the temperature is 1.7 mK, and the UV power is ≈1.5 mW. The total UV exposure time at each point is 2.7 s. Here the dominant source of broadening is the finite interaction time of an atom moving across the UV beam, which leads to an exponential spectrum: $\exp(-|\delta|/\delta_0)$. The solid line corresponds to $\delta_0 = 11$ kHz, which yields a full width at half maximum of 15 kHz.

Towards T(1S-2S) I: Trapped H (BEC)

PRL 70, 544 (1993), Walraven group

PRL 77, 255 (1996), Kleppner group
PRL 81, 3811 (1998)

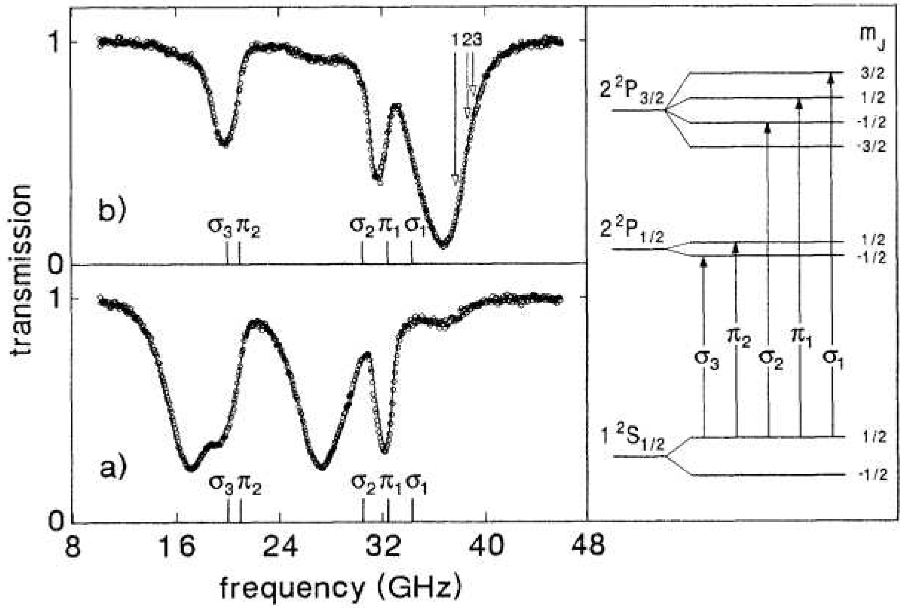


FIG. 2. Transmission spectra, recorded with (a) right- and (b) left-circularly polarized light, and energy level diagram defining the five allowed transitions. The scan time for each spectrum is 30 s. The solid lines are calculated spectra for $T = 51(12)$ mK and (a) $n_0 = 4.4(1.0) \times 10^{12}\,\mathrm{cm}^{-3}$ and (b) $n_0 = 3.3(0.8) \times 10^{12}\,\mathrm{cm}^{-3}$. The frequency is relative to $\frac{3}{4}R_\infty(1 + m_e/m_p)^{-1}$. The vertical bars denote the resonant frequencies of the five allowed transitions for $B = B_0$. The arrows in (b) indicate the three AOM frequencies.

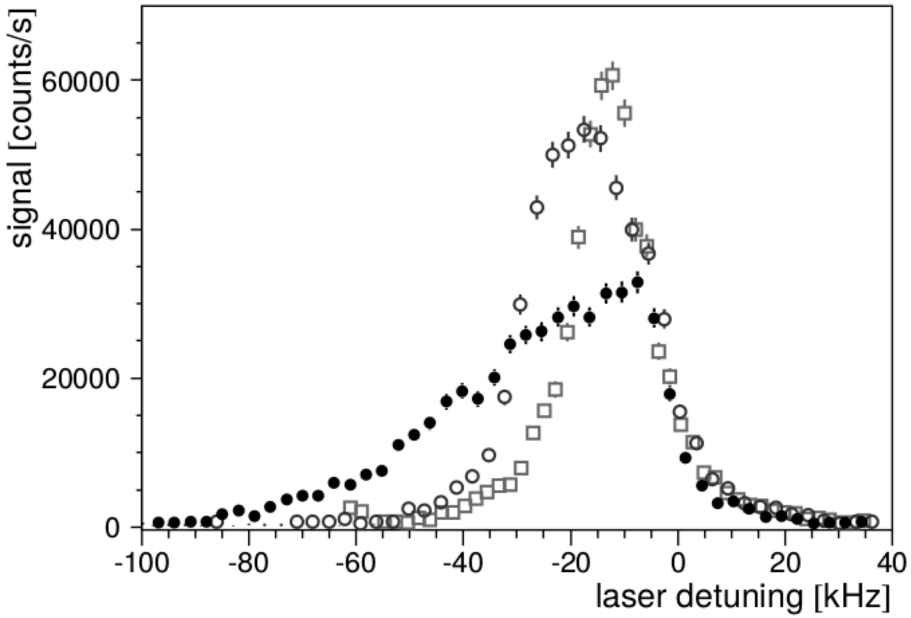
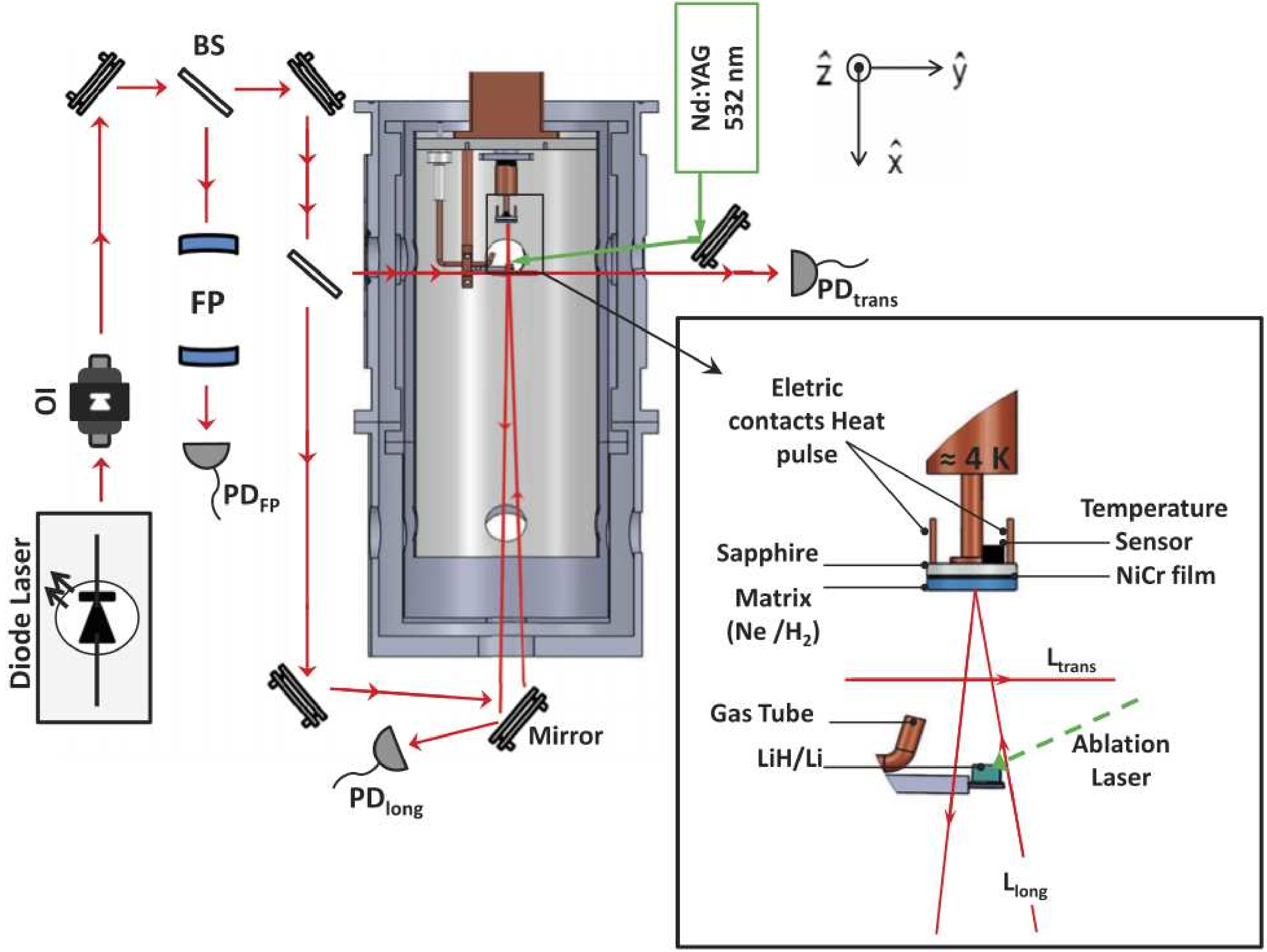


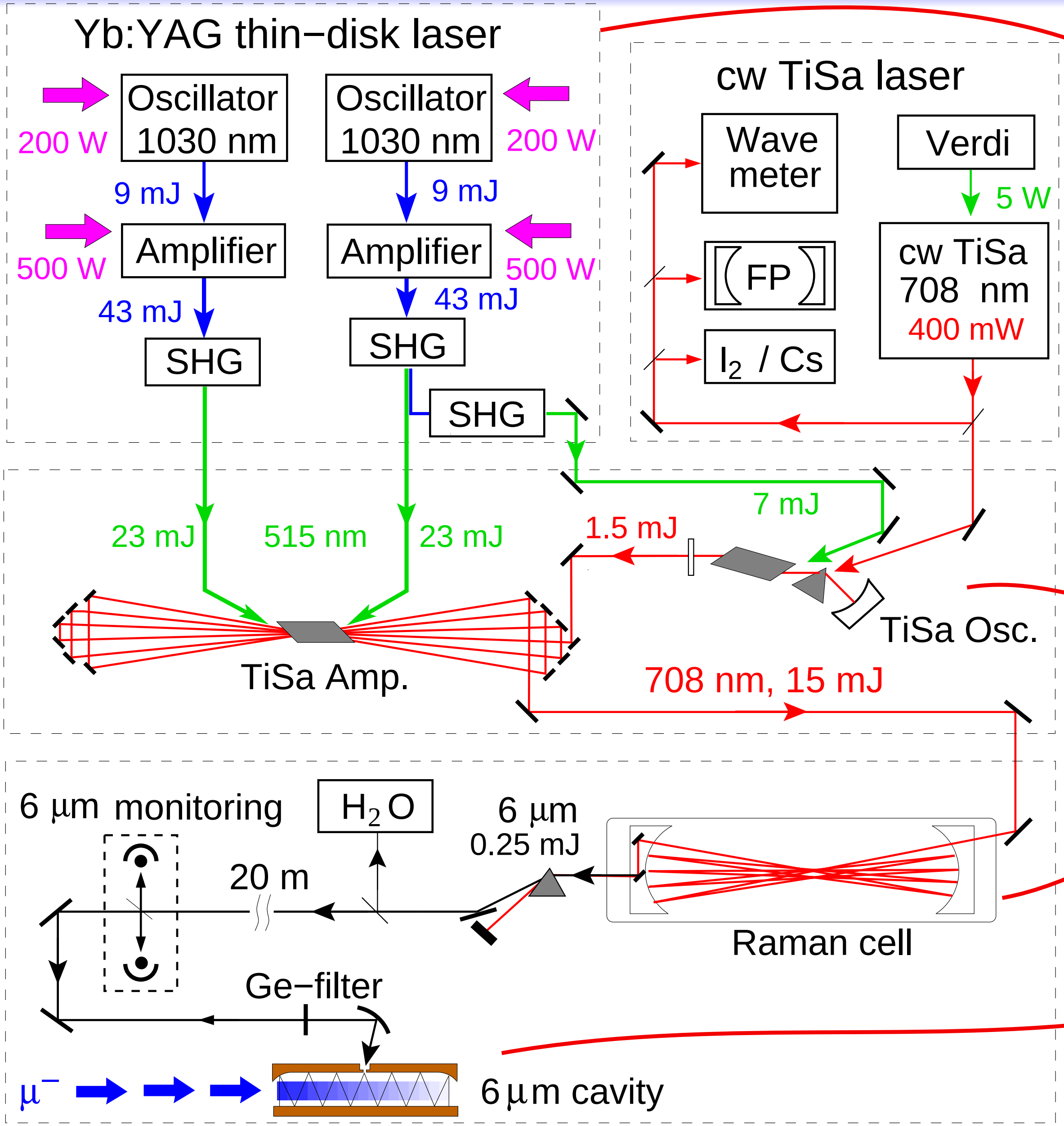
FIG. 4. Doppler-free spectrum of normal fraction above and below the onset of BEC. The symmetric spectrum (above T_c, open symbols) suddenly becomes asymmetric (solid symbols) when the condensate forms. Temperatures for the three spectra are about 120 μK (open squares), 53 μK (open circles), and 44 μK (solid circles).

Towards T(1S-2S) II: Matrix sublimation

Rev. Sci. Instr. 86, 073109 (2015)
C.L. Cesar (Kleppner @ MIT, 1990s) et al.



The laser system

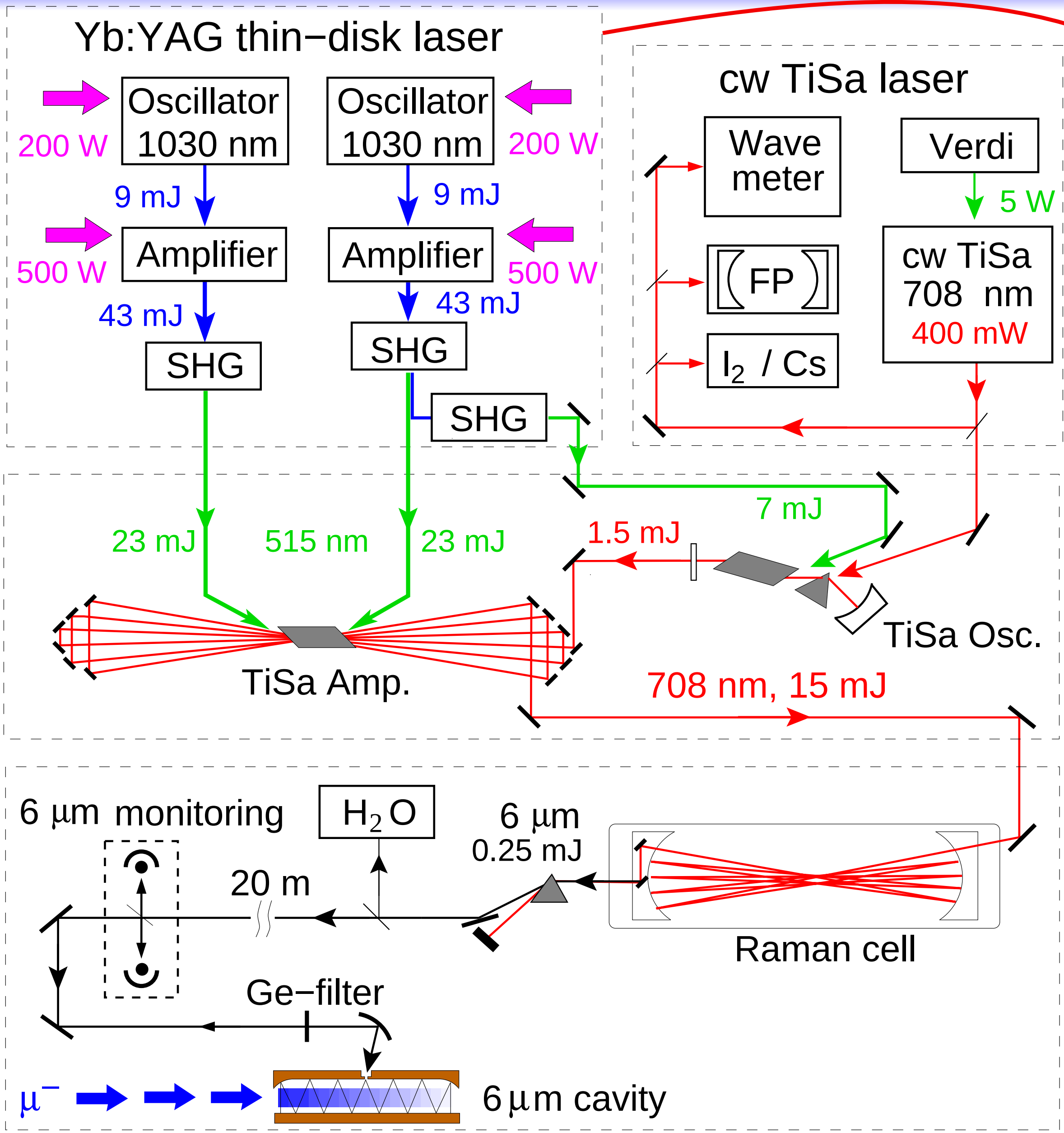


Main components:

- Thin-disk laser
  - fast response to detected μ^-
- Frequency doubling
- TiSa laser:
  - frequency stabilized cw laser
  - injection seeded oscillator
  - multipass amplifier
- Raman cell
  - 3 Stokes: 708 nm $\rightarrow$ 6 μm
  - λ calibration @ 6 μm
- Target cavity

A. Antognini, RP *et. al.*, Opt. Comm. 253, 362 (2005).

The laser system



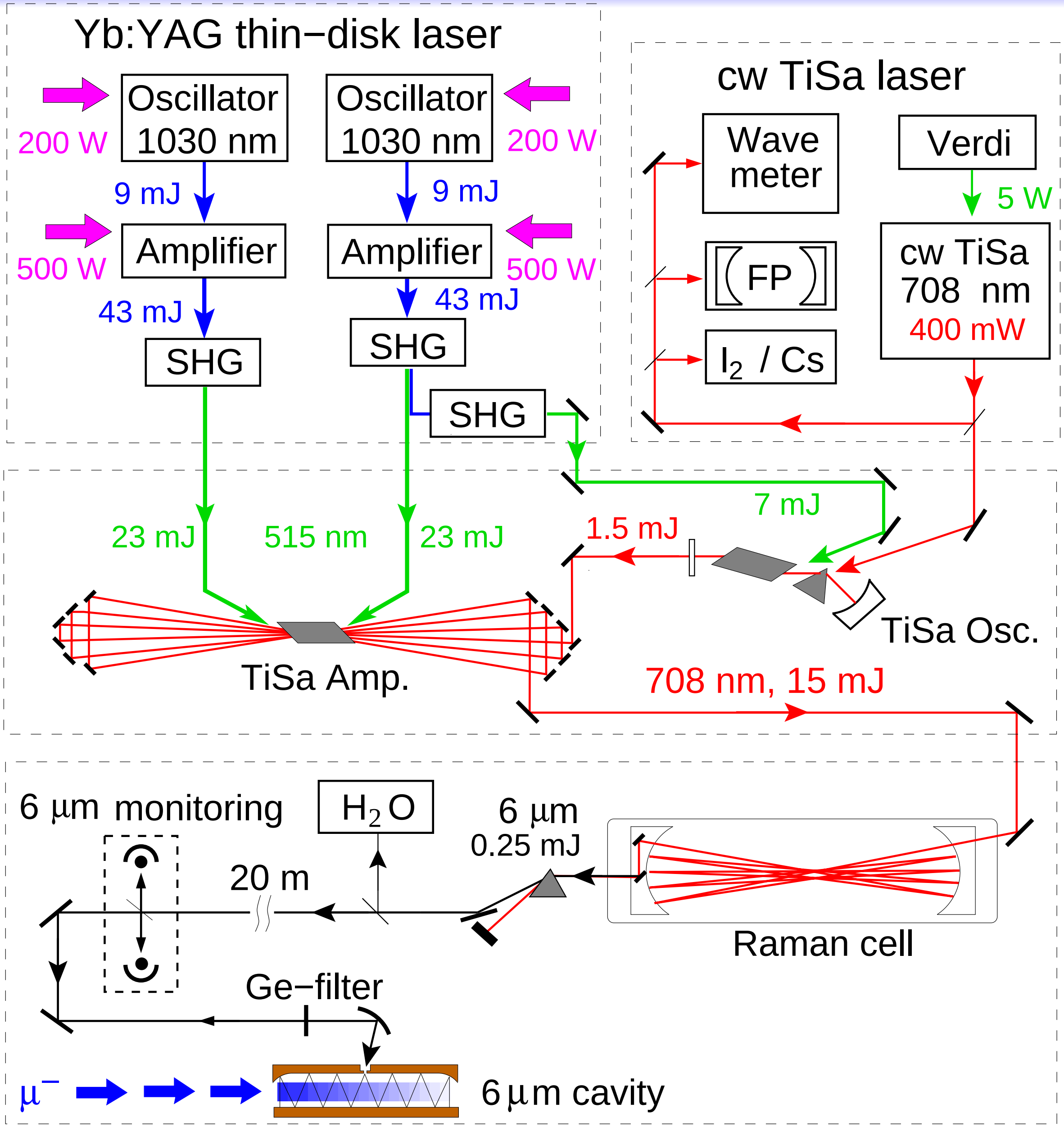
Thin-disk laser

- Large pulse energy: 85 (160) mJ
- Short trigger-to-pulse delay: $\lesssim 400$ ns
- Random trigger
- Pulse-to-pulse delays down to 2 ms (rep. rate $\gtrsim 500$ Hz)

- Each single μ^- triggers the laser system
- $2S$ lifetime $\approx 1\ \mu s \rightarrow$ short laser delay

A. Antognini, RP *et. al.*,
IEEE J. Quant. Electr. 45, 993 (2009).

The laser system



MOPA TiSa laser:

cw laser, frequency stabilized

- referenced to a stable FP cavity
- FP cavity calibrated with I_2, Rb, Cs lines

$\nu_{\rm FP} = N \cdot FSR$

$FSR = 1497.344(6)$ MHz

$\nu^{\rm cw}_{\rm TiSa}$ absolutely known to 30 MHz

$\Gamma_{\rm 2P-2S} = 18.6$ GHz

Seeded oscillator

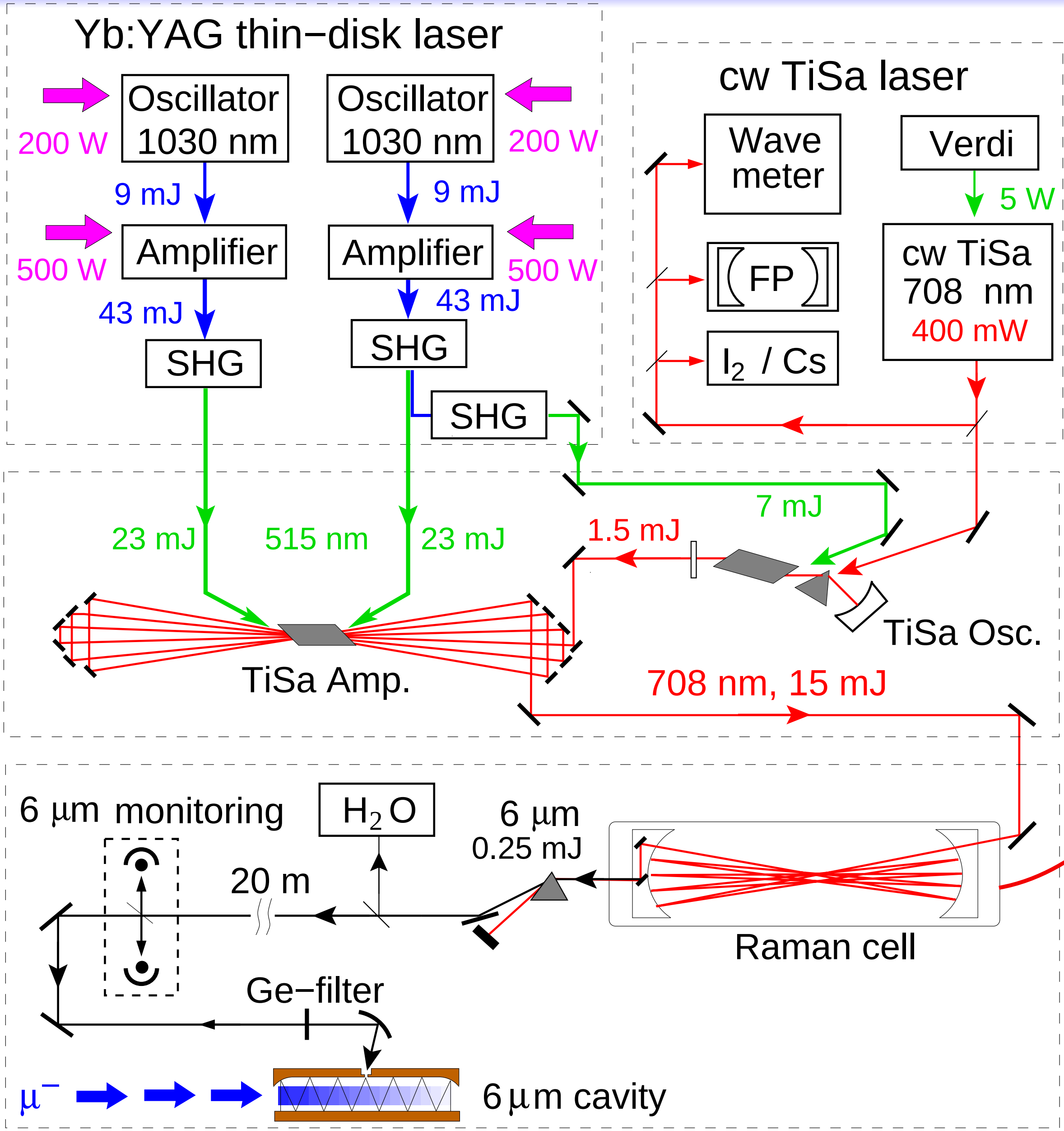
$\rightarrow \nu^{\rm pulsed}_{\rm TiSa} = \nu^{\rm cw}_{\rm TiSa}$

(frequency chirp ≤ 200 MHz)

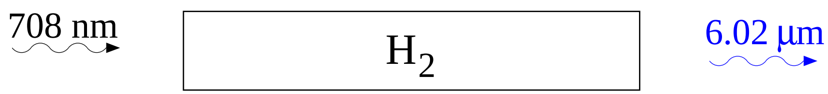
Multipass amplifier (2f- configuration)

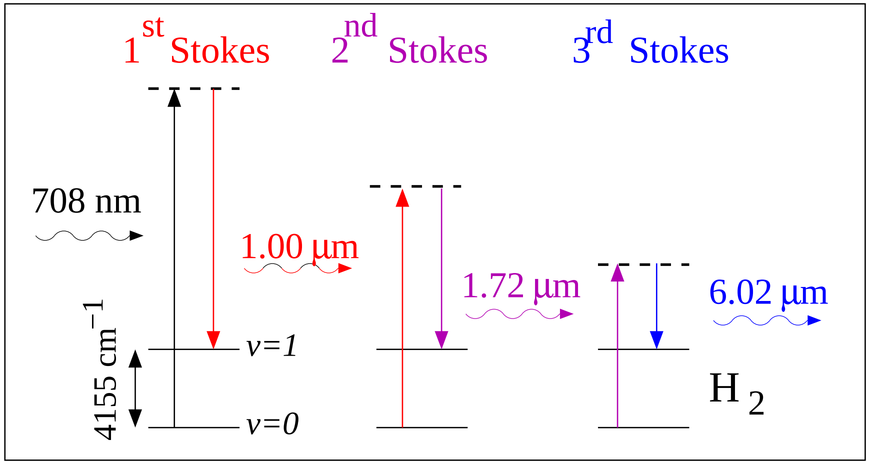
gain=10

The laser system



Raman cell:





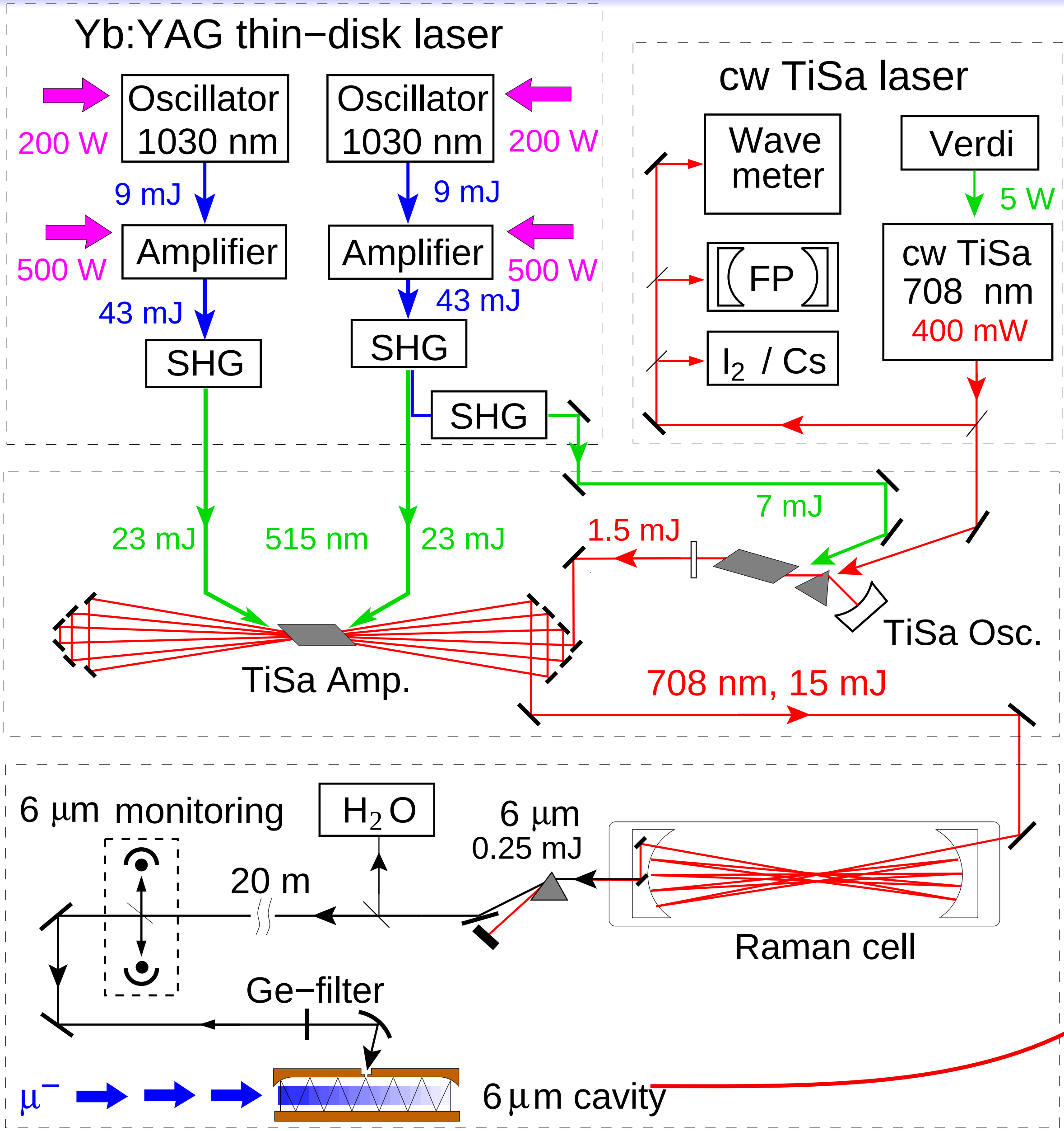
$$\nu^{6\mu m} = \nu^{708nm} - 3 \cdot \hbar\omega_{vib}$$

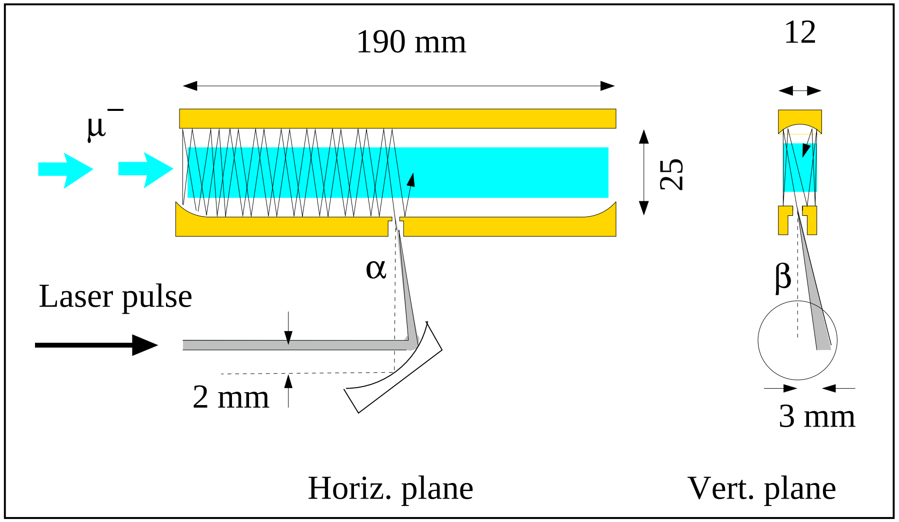
tunable

$\omega_{vib}(p,T) = \text{const}$

P. Rabinowitz *et. al.*, IEEE J. QE **22**, 797 (1986)

The laser system





Design: insensitive to misalignment

Transverse illumination

Large volume

Dielectric coating with $R \geq 99.9\%$ (at 6 μm)

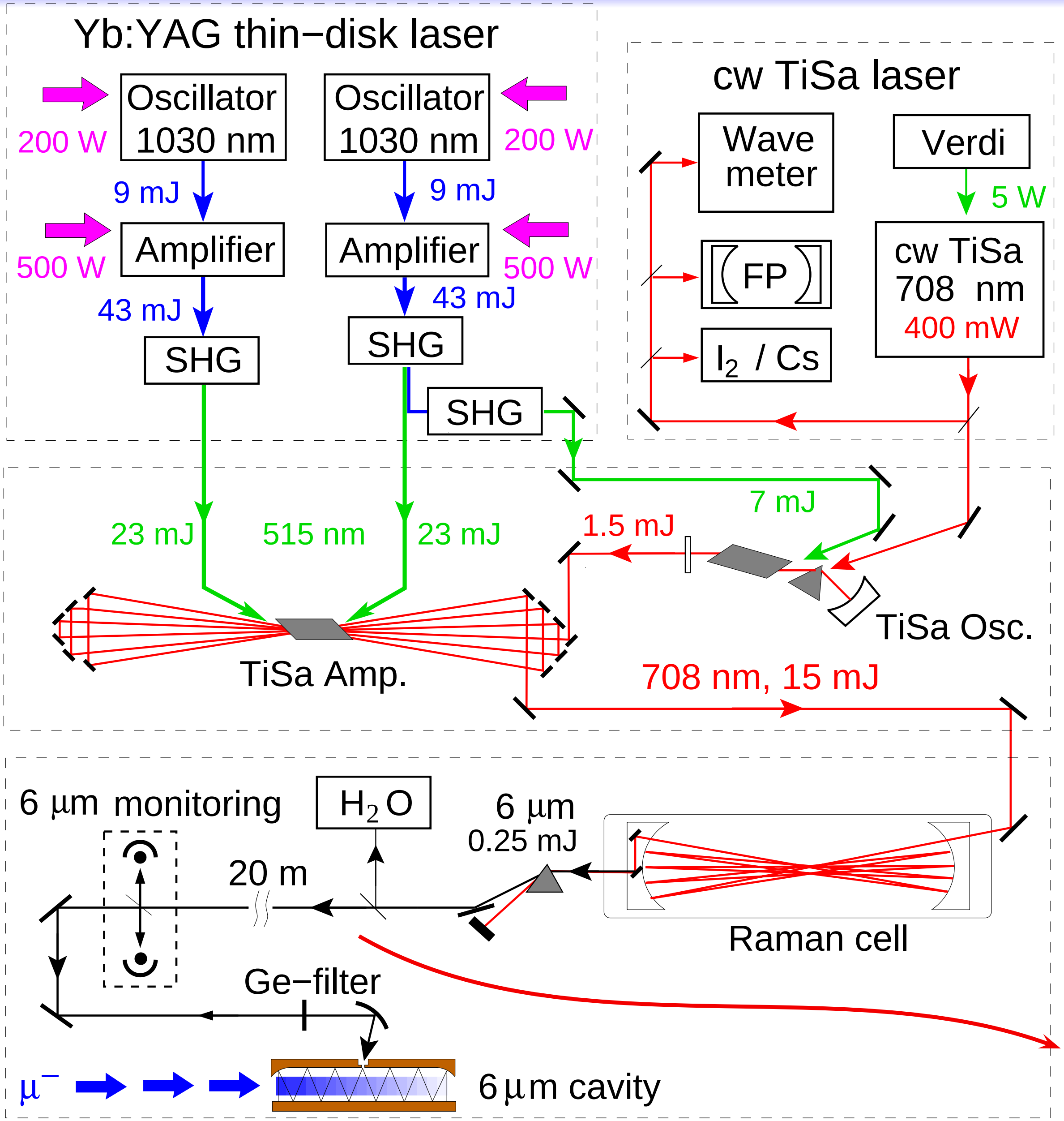
→ Light makes 1000 reflections

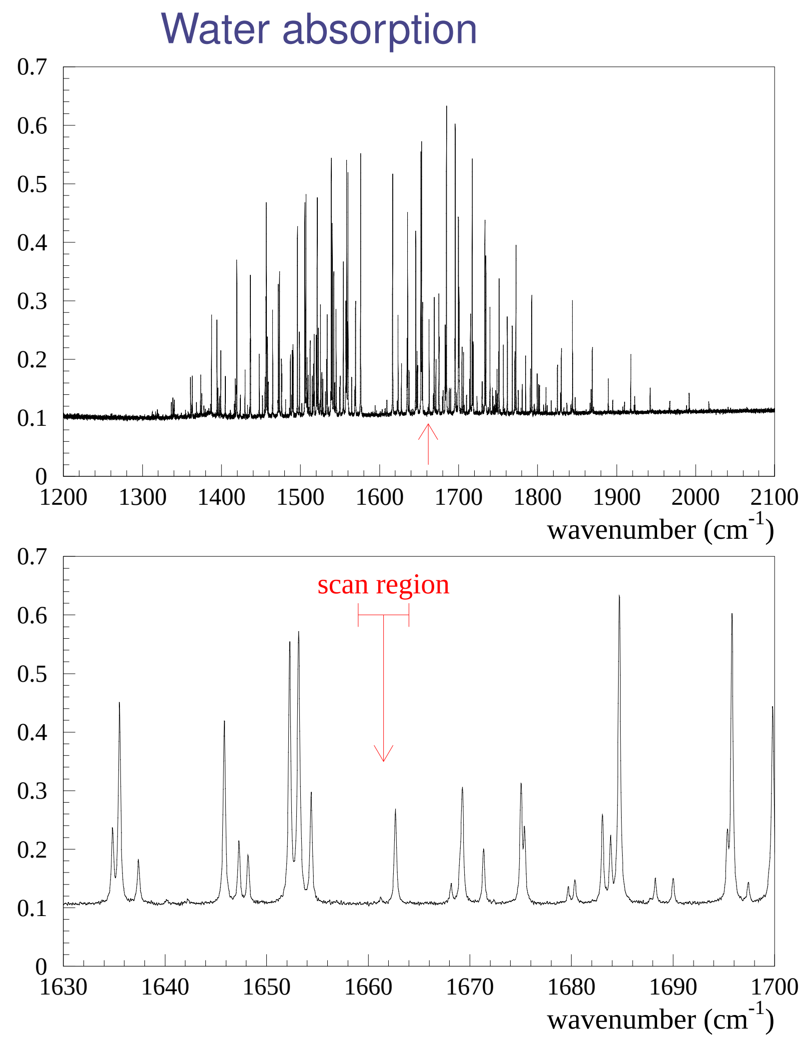
→ Light is confined for τ=50 ns

→ 0.15 mJ saturates the $2S - 2P$ transition

J. Vogelsang, RP *et. al.*, Opt. Expr. **22**, 13050 (2014)

The laser system

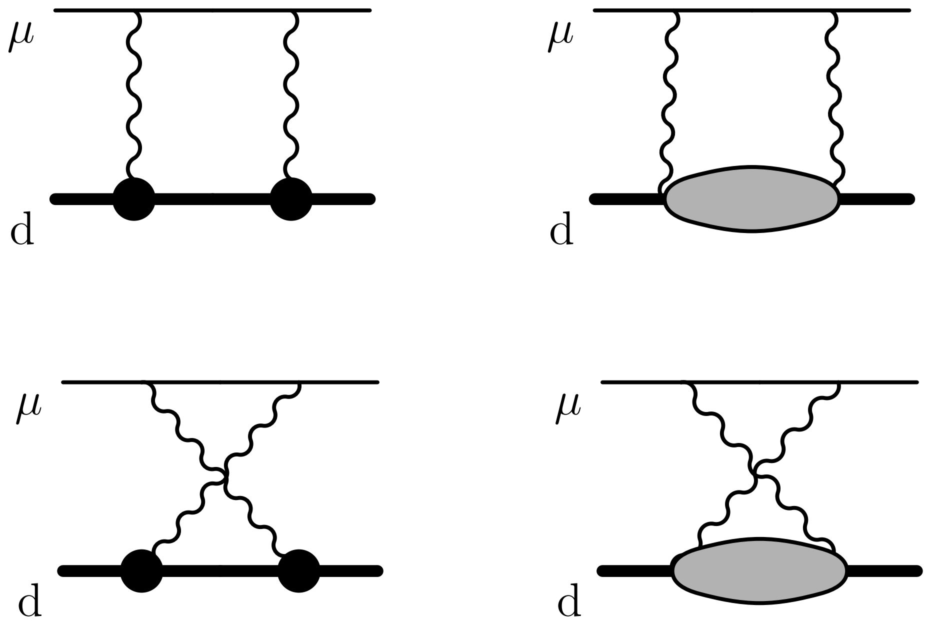




- Vacuum tube for 6 μm beam transport.
- Direct frequency calibration at 6 μm.

Theory in μd: TPE

Deuteron structure contributions to the Lamb shift in muonic deuterium.



Cancellation between elastic "Friar" (a.k.a. 3rd Zemach) terms and part of inelastic "polarizability" contributions.

Friar & Payne, PRA 56, 5173 (1997) ; Pachucki, PRL 106, 193007 (2011) ; Friar, PRC 88, 034003 (2013) ; Hernandez *et al.*, PLB 736, 344 (2014)

J.J. Krauth, RP *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

Theory in μd: TPE

Table 3: Deuteron structure contributions to the Lamb shift in muonic deuterium. Values are in meV.

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	$\delta_{D1}^{(0)}$	1.910	$\delta_0 E$		1.9165	$\pm$ 0.0095	3-5
p2	Rel. corr. to p1, longitudinal part	−0.035	$\delta_R E$	−0.037	Subleading C1	−0.029	−0.030	$\delta_L^{(0)}$	−0.026	$\delta_R E$				
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta_T^{(0)}$						
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	$\pm$ 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	$\delta_C^{(0)}$	−0.261			−0.2625	$\pm$ 0.0015	3-5
p7	El. monopole excitation	−0.045	$\delta_{Q0} E$	−0.042	C0	−0.042	−0.041	$\delta_{R2}^{(2)}$	−0.042	$\delta_{Q0} E$				
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta_{D1D3}^{(2)}$	0.139	$\delta_{Q1} E$				
p9	El. quadrupole excitation	−0.066	$\delta_{Q2} E$	−0.061	C2	−0.061	−0.061	$\delta_Q^{(2)}$	−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	$\pm$ 0.0020	2-5
p10	Magnetic	−0.008 ◇	$\delta_M E$	−0.011	M1	−0.008	−0.007	$\delta_M^{(0)}$	−0.008	$\delta_M E$		−0.0090	$\pm$ 0.0020	2-5
SUM_1	Total nuclear (corrected)	1.646		1.648		1.656	1.676		1.655			1.6615	$\pm$ 0.0103	
p11	Finite nucleon size			0.021	Retarded C1 f.s.	0.020 ◇	0.021 ◇??	$\delta_{NS}^{(2)}$	0.020	$\delta_{FS} E$				
p12	n p charge correlation			−0.023	pn correl. f.s.	−0.017	−0.017	$\delta_{np}^{(1)}$	−0.018	$\delta_{FZ} E$				
sum	p11+p12			−0.002		0.003	0.004		0.002			0.0010	$\pm$ 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	$\pm$ 0.0015	Eq.(13)
p14	Proton inelastic polarizab.					} 0.027(2)		δ^N_{pol} [64]			} 0.028(2)ΔE^{hadr}	} 0.0280	$\pm$ 0.0020	6
p15	Neutron inelastic polarizab.								0.016(8)	$\delta_N E$				
p16	Proton & neutron subtraction term											−0.0098	$\pm$ 0.0098	Eq.(15)
sum	Nucleon TPE, p13+p14+p15+p16	0.043(3)		0.030		0.027(2)			0.059(9)			0.0471	$\pm$ 0.0101	
SUM_2	Total nucleon contrib.	0.043(3)		0.028		0.030(2)			0.061(9)			0.0476	$\pm$ 0.0105	
	Sum, published	1.680(16)		1.941(19)		1.690(20)			1.717(20)		2.011(740)			
	Sum, corrected			1.697(19)		1.714(20)			1.707(20)		1.748(740)	**1.7096**	$\pm$ **0.0147**	

J.J. Krauth *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

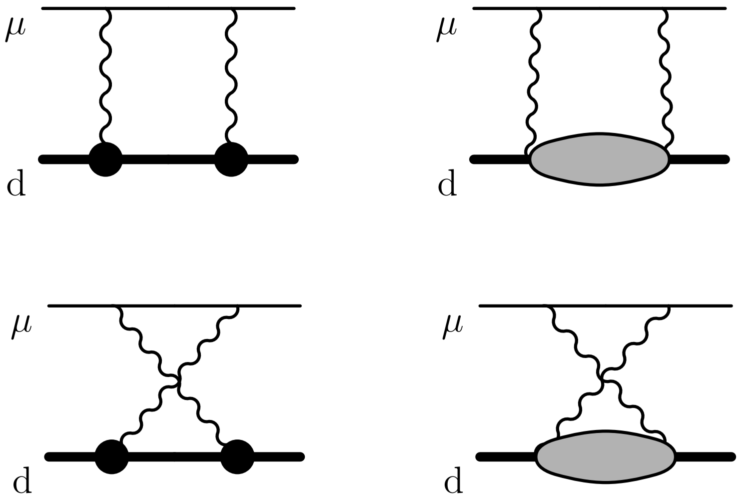
$$\Delta E^{TPE}(\text{theo}) = 1.7096 \pm 0.0200 \text{ meV}$$

vs. $\pm\, 0.0034$ meV exp. uncertainty

Theory in μd: TPE

$r_\mathrm{d} = 2.12562(13)_\mathrm{exp}(77)_\mathrm{theo}$ fm, using $\Delta E^\mathrm{theo}_\mathrm{TPE} = 1.7096(200)\,\mathrm{meV}$

limited by **deuteron structure** (TPE) contributions to the μd LS



Cancellation between elastic "Friar" (a.k.a. 3rd Zemach) terms and part of inelastic "polarizability" contributions.

Nucleon structure adds relevant contributions (and uncertainty).

Friar & Payne, PRA 56, 5173 (1997) ; Pachucki, PRL 106, 193007 (2011) ; Friar, PRC 88, 034003 (2013) ;
Hernandez *et al.*, PLB 736, 344 (2014) ; Pachucki & Wienczek, PRA 91, 040503(R) (2015) ;
Carlson, Gorchtein, Vanderhaeghen, PRA 89, 022504 (2014) ; Birse & McGovern *et al.*

J.J. Krauth, RP *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

Theory in μd: TPE

Table 3: Deuteron structure contributions to the Lamb shift in muonic deuterium. Values are in meV.

Item	Contribution	Pachucki [55] AV18		Friar [60] ZRA		Hernandez *et al.* [58] AV18	N^{3}LO †		Pach.& Wienczek [65] AV18		Carlson *et al.* [64] data	Our choice value		source
	Source	1		2		3	4		5		6			
p1	Dipole	1.910	$\delta_0 E$	1.925	Leading C1	1.907	1.926	$\delta^{(0)}_{D1}$	1.910	$\delta_0 E$		1.9165	± 0.0095	3-5
p2	Rel. corr. to p1, longitudinal part	−0.035	$\delta_R E$	−0.037	Subleading C1	−0.029	−0.030	$\delta^{(0)}_{L}$	−0.026	$\delta_R E$				
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta^{(0)}_{T}$						
p4	Rel. corr. to p1, higher order								0.004	$\delta_{HO} E$				
sum	Total rel. corr., p2+p3+p4	−0.035		−0.037		−0.017	−0.017		−0.022			−0.0195	± 0.0025	3-5
p5	Coulomb distortion, leading	−0.255	$\delta_{C1} E$						−0.255	$\delta_{C1} E$				
p6	Coul. distortion, next order	−0.006	$\delta_{C2} E$						−0.006	$\delta_{C2} E$				
sum	Total Coulomb distortion, p5+p6	−0.261				−0.262	−0.264	$\delta^{(0)}_{C}$	−0.261			−0.2625	± 0.0015	3-5
p7	El. monopole excitation	−0.045	$\delta_{Q0} E$	−0.042	C0	−0.042	−0.041	$\delta^{(2)}_{R2}$	−0.042	$\delta_{Q0} E$				
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta^{(2)}_{D1D3}$	0.139	$\delta_{Q1} E$				
p9	El. quadrupole excitation	−0.066	$\delta_{Q2} E$	−0.061	C2	−0.061	−0.061	$\delta^{(2)}_{Q}$	−0.061	$\delta_{Q2} E$				
sum	Tot. nuclear excitation, p7+p8+p9	0.040		0.034	C0 + ret-C1 + C2	0.036	0.038		0.036			0.0360	± 0.0020	2-5
p10	Magnetic	−0.008 ◇	$\delta_M E$	−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		1.656	1.676		1.655			1.6615	± 0.0103	
p11	Finite nucleon size			0.021	Retarded C1 f.s.	0.020 ◇	0.021 ◇??	$\delta^{(2)}_{NS}$	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)
p14	Proton inelastic polarizab.					}	0.027(2)	$\delta^N_{\rm pol}$ [64]			} 0.028(2) $\Delta E^{\rm hadr}$	} 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)
sum	Nucleon TPE, p13+p14+p15+p16	0.043(3)		0.030		0.027(2)			0.059(9)			0.0471	± 0.0101	
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)		1.714(20)			1.707(20)		1.748(740)	**1.7096**	**± 0.0147**	

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$$\Delta E^{\rm TPE}(\text{theo}) = 1.7096 \pm 0.0200\ \text{meV}$$

$$\Delta E^{\rm TPE}(\text{exp}) = 1.7638 \pm 0.0068\ \text{meV}$$

Experimental TPE in μd

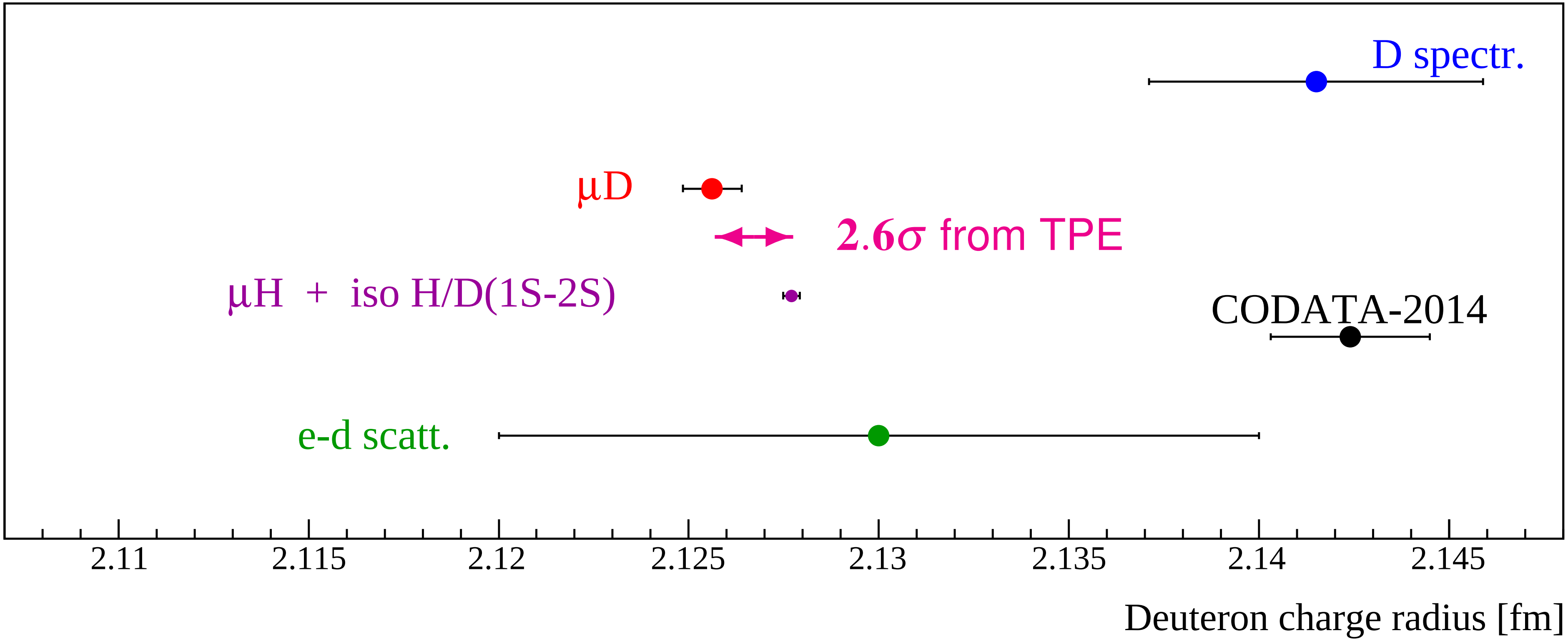
$$\Delta E^{\rm TPE}({\rm theo}) = 1.7096 \pm 0.0200 \text{ meV}$$

$$\Delta E^{\rm TPE}({\rm exp}) = 1.7638 \pm 0.0068 \text{ meV}$$

2.6σ, 3x more accurate

$$\Delta E_{\rm LS} = 228.7766(10)\,{\rm meV}\ ({\rm QED}) + \Delta E^{\rm TPE} - 6.1103(3)\ r_{\rm d}^2\ {\rm meV/fm}^2,$$

- $\Delta E_{\rm LS}^{\rm exp} = 202.8785\,(31)_{\rm stat}(14)_{\rm syst}$ meV from μD exp.
- $r_d = 2.12771(22)$ fm — from $r_{\rm d}^2 - r_{\rm p}^2 = 3.82007(65)\,{\rm fm}^2$ [H/D(1S-2S) isotope shift] using $r_{\rm p}(\mu{\rm H})$ = 0.84087(39) fm



Experimental TPE in μd

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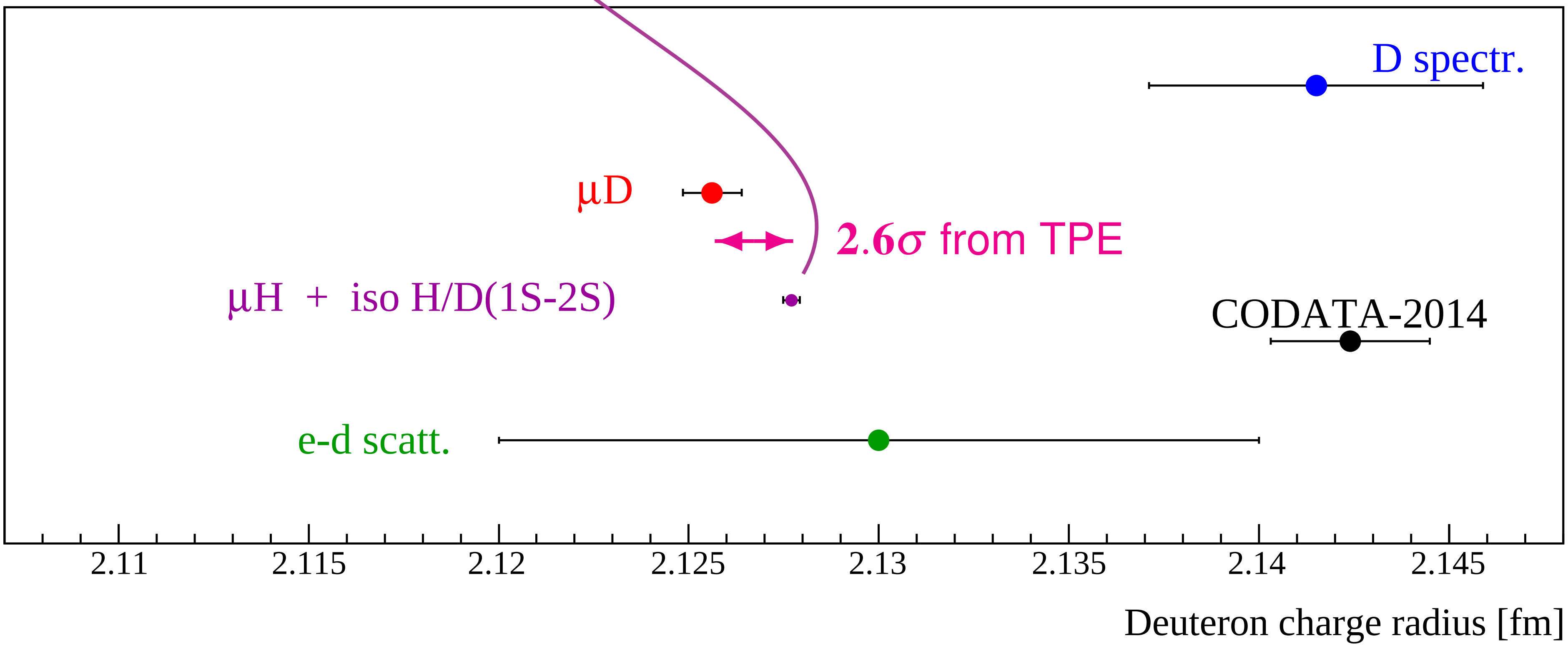
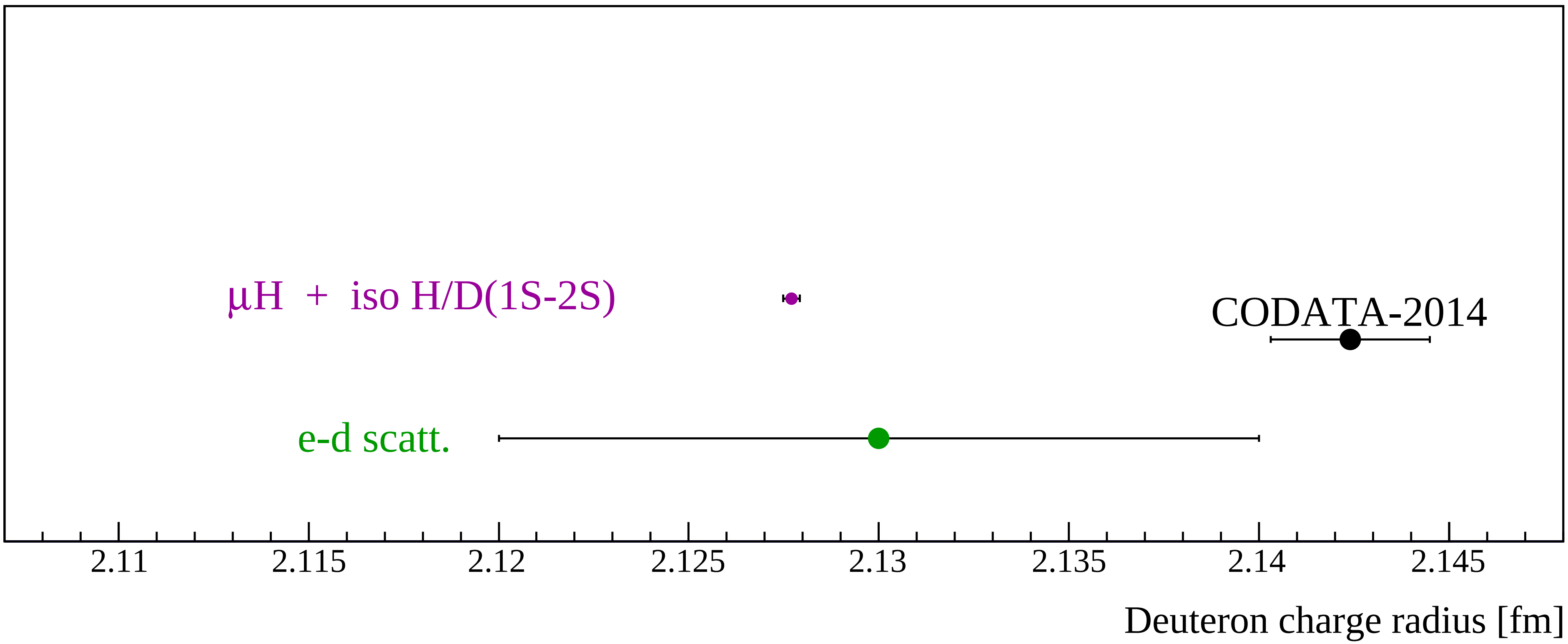


Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)\ \mathrm{fm}^2$ C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2014 $r_d = 2.14130(250)$ fm

$r_p$from μH gives $r_d = 2.12771(\ \ 22)$ fm $\leftarrow$ 5.4σ from r_p

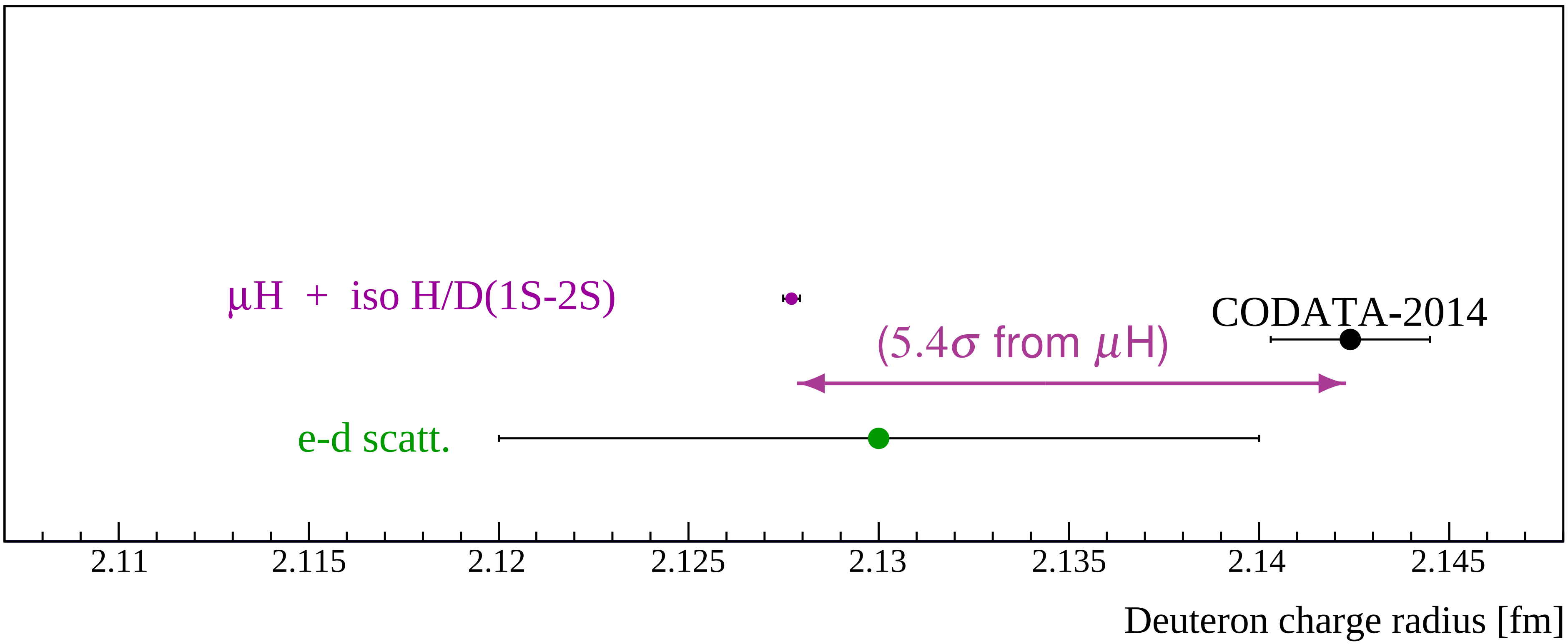


Deuteron charge radius

H/D isotope shift: $r_\mathrm{d}^2 - r_\mathrm{p}^2 = 3.82007(65)$ fm^2 C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2014 $r_\mathrm{d} = 2.14130(250)$ fm

r_p from μH gives $r_\mathrm{d} = 2.12771(\ \ 22)$ fm $\leftarrow 5.4\sigma$ from r_p



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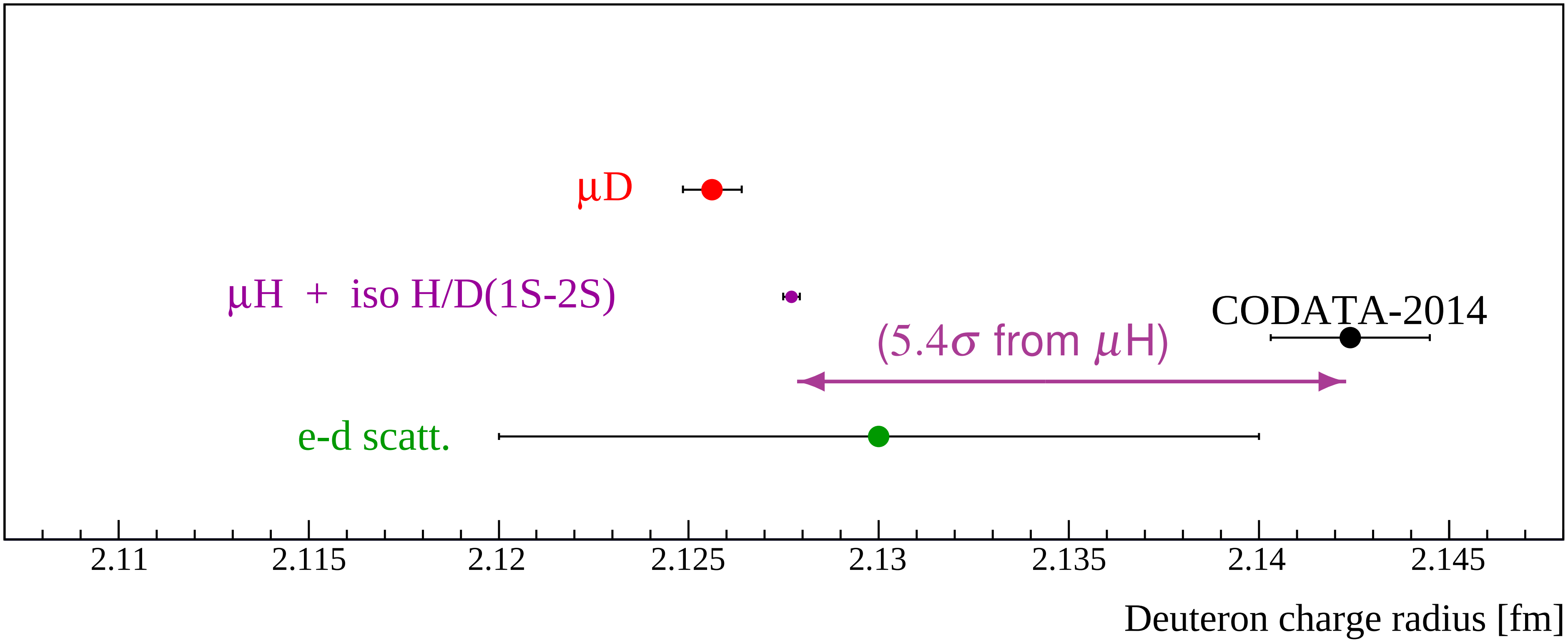
CODATA 2014	$r_d = 2.14130(250)$ fm
r_p from μH gives	$r_d = 2.12771(\ 22)$ fm $\leftarrow 5.4\sigma$ from r_p
Muonic DEUTERIUM	$r_d = 2.12562(\ 13)_{exp}\ (77)_{theo}$ fm RP *et al.*, Science **353**, 417 (2016)



Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)\ \mathrm{fm}^2$ C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2014 $r_d = 2.14130(250)$ fm

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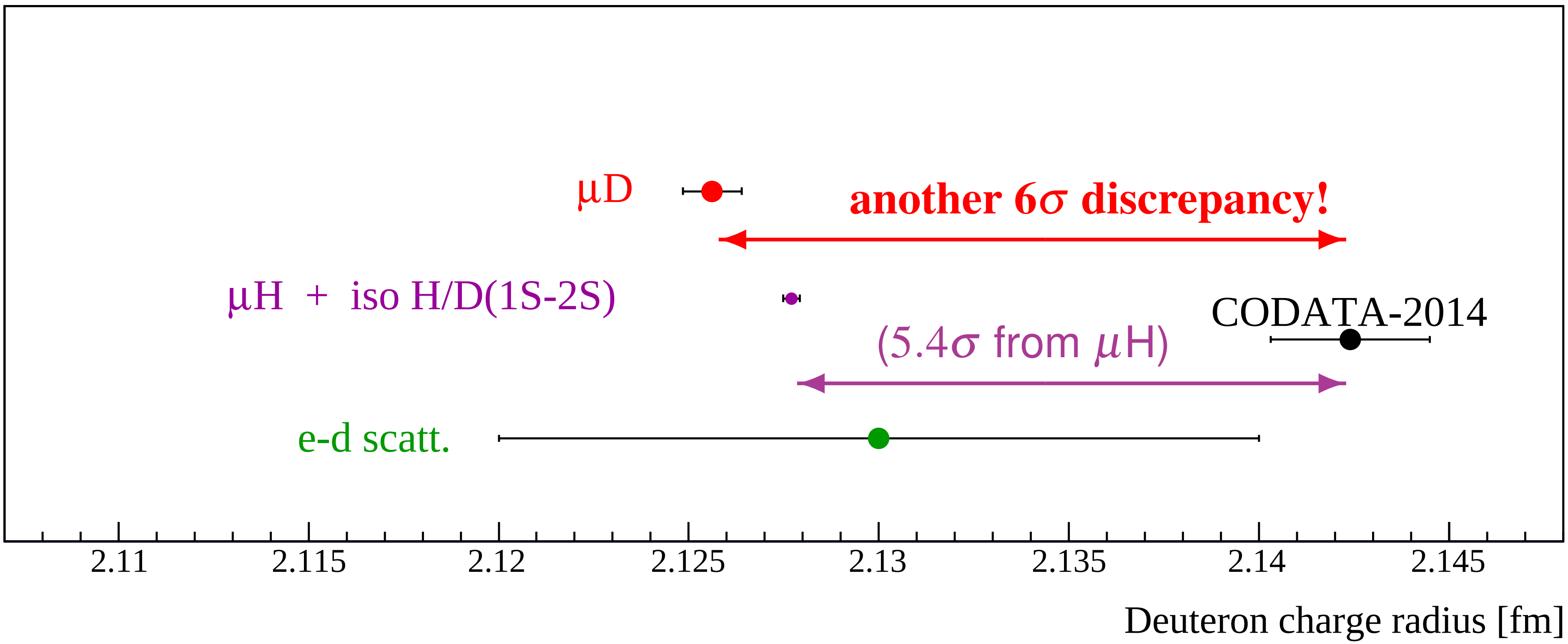

Deuteron charge radius

H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)$ fm^2 C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

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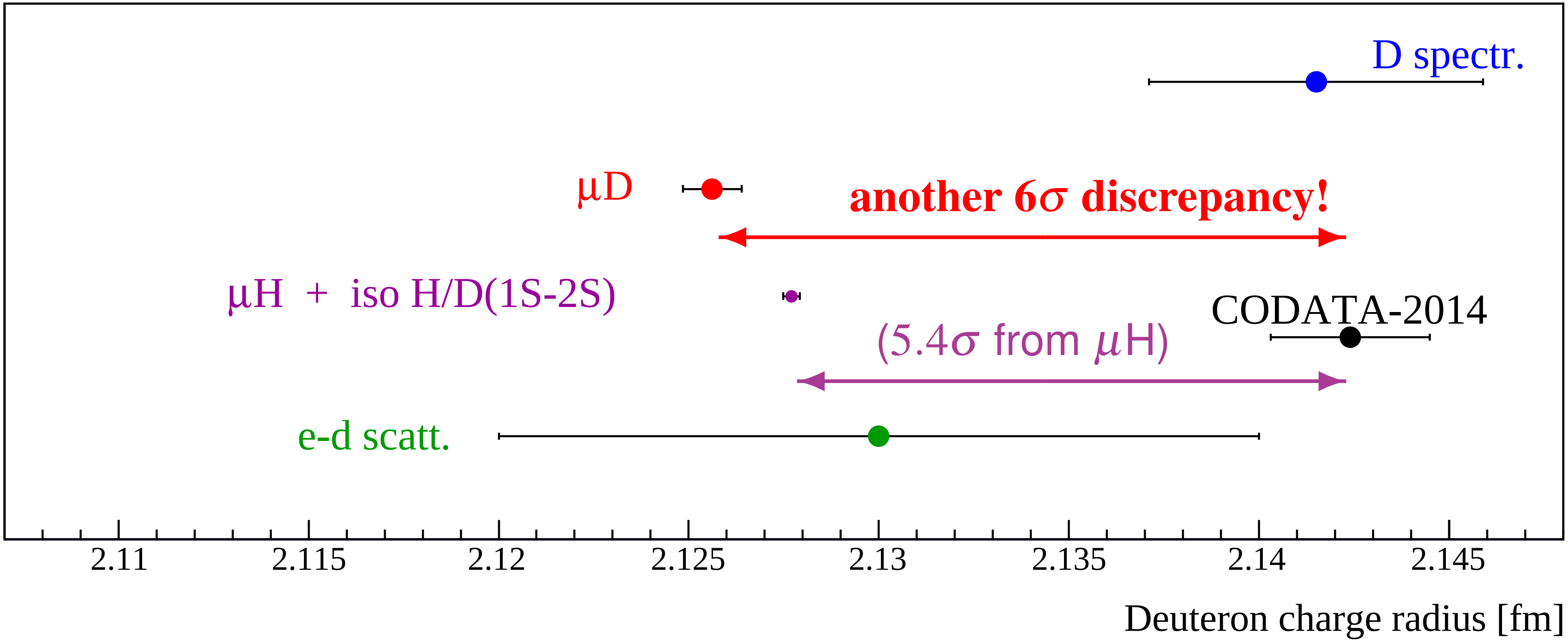
Muonic DEUTERIUM $r_d = 2.12562(\ 13)_{exp}\,(77)_{theo}$ fm RP *et al.*, Science **353**, 417 (2016)

electronic D (r_p indep.) $r_d = 2.14150(450)$ fm RP *et al.* Metrologia **54**, L1 (2017)



Deuteron charge radius

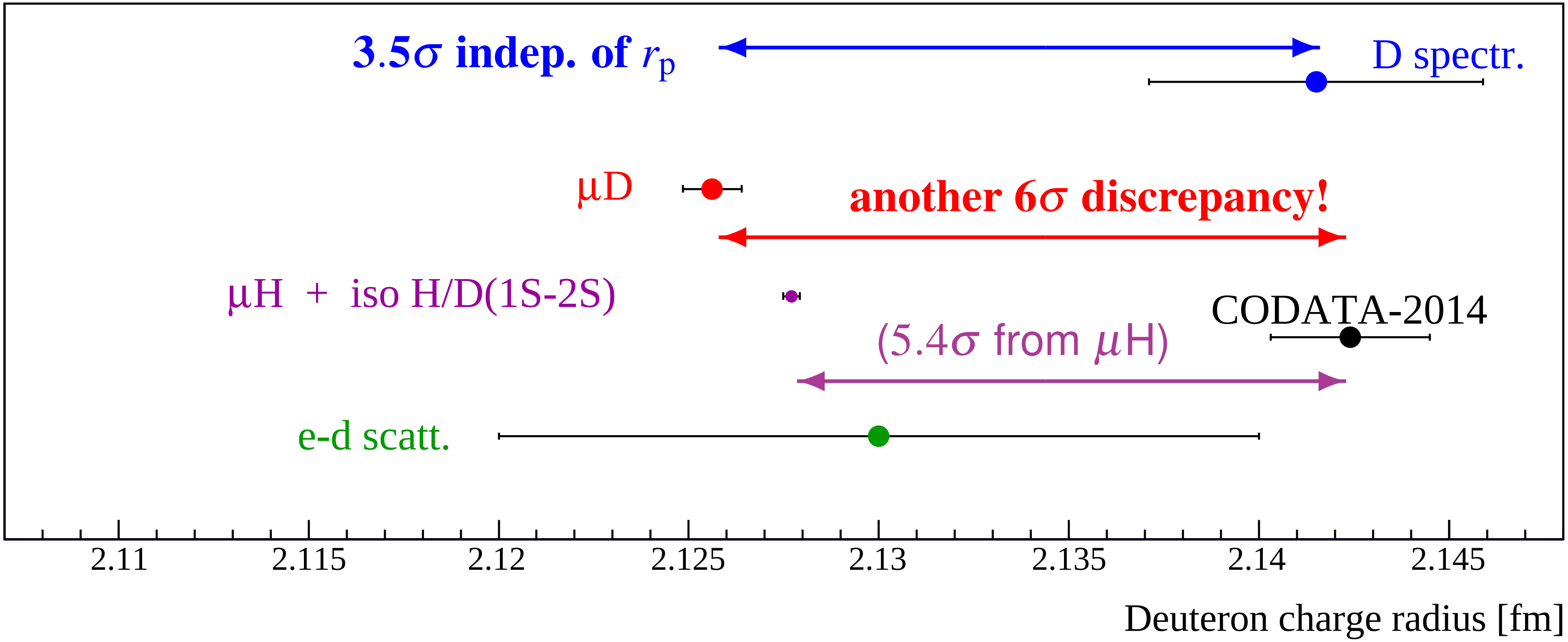
H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)$ fm^2 C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2014 $r_d = 2.14130(250)$ fm

r_p from μH gives $r_d = 2.12771(\ 22)$ fm $\leftarrow 5.4\sigma$ from r_p

Muonic DEUTERIUM $r_d = 2.12562(\ 13)_{exp}\,(77)_{theo}$ fm RP *et al.*, Science **353**, 417 (2016)

electronic D (r_p indep.) $r_d = 2.14150(450)$ fm $\leftarrow 3.5\sigma$ RP *et al.* Metrologia **54**, L1 (2017)



Results from muonic deuterium

Lamb shift in muonic deuterium:

$$\Delta E_{\rm LS}^{\rm theo} = 228.7766(10)\,{\rm meV} + \Delta E^{\rm TPE} - 6.1103(3)\; r_{\rm d}^2\ {\rm meV/fm}^2$$

with deuteron polarizability (TPE) $\Delta E^{\rm TPE}({\rm theo}) = 1.7096(200)\,{\rm meV}$

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compilation of original results from:
Borie, Martynenko *et al.*, Karshenboim *et al.*, Jentschura, Bacca, Barnea, Nevo Dinur *et al.*, Pachucki *et al.*, Friar, Carlson, Gorchtein, Vanderhaeghen, and others

$r_d(\mu{\rm d}) = 2.12562(\ 13)_{\rm exp}(77)_{\rm theo}$ fm RP *et al.*, Science **353**, 417 (2016)

$r_d(\mu{\rm p}+{\rm iso}) = 2.12771(\ 22)$ fm from $r_{\rm p}(\mu{\rm p})$ and H/D(1S-2S) 2.6σ

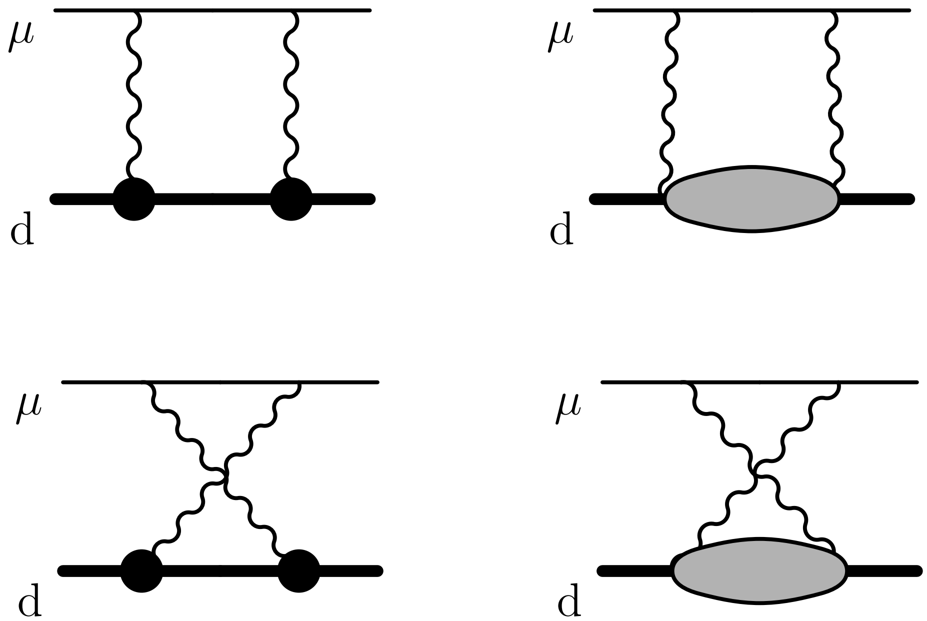
$r_d({\rm CODATA}) = 2.14130(250)$ fm 6.0σ

Disprepancy to $\Delta E_{\rm LS}(r_d({\rm CODATA}))$ = 0.409(68) meV

(“proton radius puzzle” (μp discrepancy) = 0.329(47) meV)

Theory in μd: TPE

Deuteron structure contributions to the Lamb shift in muonic deuterium.



Cancellation between elastic "Friar" (a.k.a. 3rd Zemach) terms and part of inelastic "polarizability" contributions.

Friar & Payne, PRA 56, 5173 (1997) ; Pachucki, PRL 106, 193007 (2011) ; Friar, PRC 88, 034003 (2013) ; Hernandez *et al.*, PLB 736, 344 (2014)

J.J. Krauth, RP *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

Theory in μd: TPE

JG|U

Table 3: Deuteron structure contributions to the Lamb shift in muonic deuterium. Values are in meV.

Item	Contribution	Pachucki [55] AV18		Friar [60] ZRA		Hernandez *et al.* [58] AV18	N^{3}LO †		Pach.& Wienczek [65] AV18		Carlson *et al.* [64] data	Our choice value		source
	Source	1		2		3	4		5		6			
p1	Dipole	1.910	$\delta_0 E$	1.925	Leading C1	1.907	1.926	$\delta_{D1}^{(0)}$	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	$\delta_L^{(0)}$	−0.026	$\delta_R E$				
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta_T^{(0)}$						
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	$\delta_C^{(0)}$	−0.261			−0.2625	± 0.0015	3-5
p7	El. monopole excitation	−0.045	$\delta_{Q0} E$	−0.042	C0	−0.042	−0.041	$\delta_{R2}^{(2)}$	−0.042	$\delta_{Q0} E$				
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta_{D1D3}^{(2)}$	0.139	$\delta_{Q1} E$				
p9	El. quadrupole excitation	−0.066	$\delta_{Q2} E$	−0.061	C2	−0.061	−0.061	$\delta_Q^{(2)}$	−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 ◇	$\delta_M E$	−0.011	M1	−0.008	−0.007	$\delta_M^{(0)}$	−0.008	$\delta_M E$		−0.0090	± 0.0020	2-5
SUM_1	Total nuclear (corrected)	1.646		1.648		1.656	1.676		1.655			1.6615	± 0.0103	
p11	Finite nucleon size			0.021	Retarded C1 f.s.	0.020 ◇	0.021 ◇??	$\delta_{NS}^{(2)}$	0.020	$\delta_{FS} E$				
p12	n p charge correlation			−0.023	pn correl. f.s.	−0.017	−0.017	$\delta_{np}^{(1)}$	−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	$\langle r^3\rangle_{(2)}^{pp}$				} 0.043(3)	$\delta_P E$		0.0289	± 0.0015	Eq.(13)
p14	Proton inelastic polarizab.					} 0.027(2)		$\delta_{\rm pol}^N$ [64]			} 0.028(2) $\Delta E^{\rm hadr}$	} 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)
sum	Nucleon TPE, p13+p14+p15+p16	0.043(3)		0.030		0.027(2)			0.059(9)			0.0471	± 0.0101	
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)		1.714(20)			1.707(20)		1.748(740)	**1.7096**	**± 0.0147**	

J.J. Krauth *et al.*, Ann. Phys. **366**, 168 (2016) [1506.01298]

$$\Delta E^{\rm TPE}({\rm theo}) = 1.7096 \pm 0.0200\ {\rm meV}$$

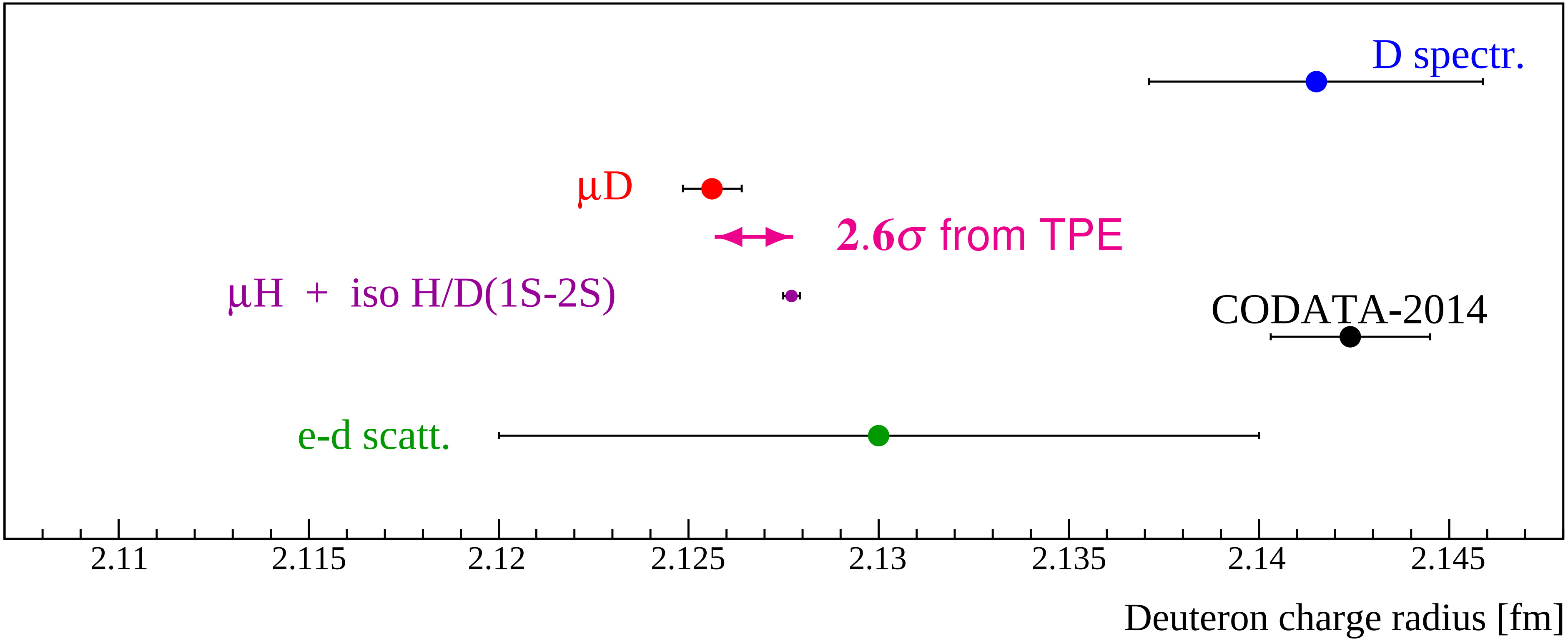
vs. $\pm\, 0.0034$ meV exp. uncertainty

Experimental TPE in μd

$$\Delta E^{\rm TPE}(\text{theo}) = 1.7096 \pm 0.0200 \text{ meV}$$
$$\Delta E^{\rm TPE}(\text{exp}) = 1.7638 \pm 0.0068 \text{ meV}$$ **2.6σ**, 3x more accurate

$$\Delta E_{\rm LS} = 228.7766(10)\,\text{meV (QED)} + \Delta E^{\rm TPE} - 6.1103(3)\ r_{\rm d}^2\ \text{meV/fm}^2,$$

- $\Delta E_{\rm LS}^{\rm exp} = 202.8785\,(31)_{\rm stat}(14)_{\rm syst}$ meV from μD exp.
- $r_d = 2.12771(22)$ fm from $r_{\rm d}^2 - r_{\rm p}^2 = 3.82007(65)$ fm^2 [H/D(1S-2S) isotope shift] using $r_{\rm p}(\mu\text{H})$ = 0.84087(39) fm



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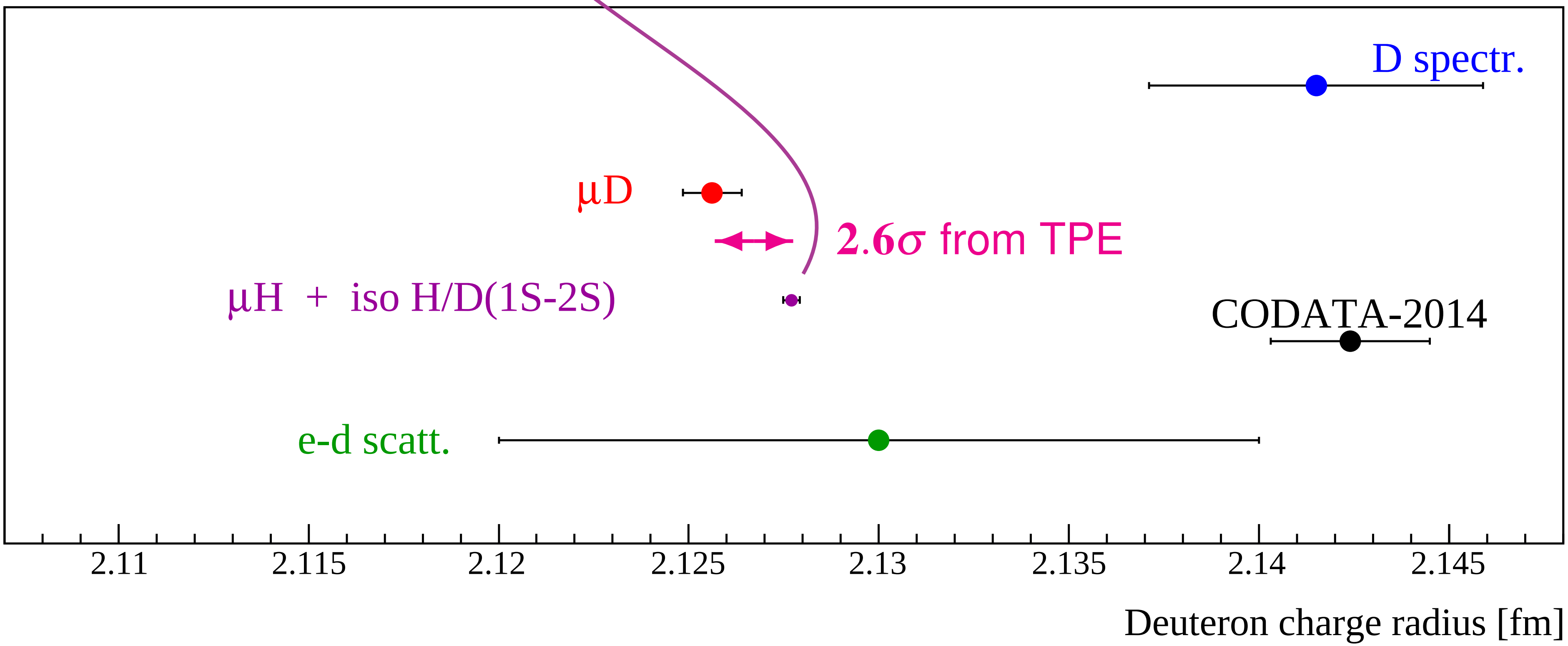
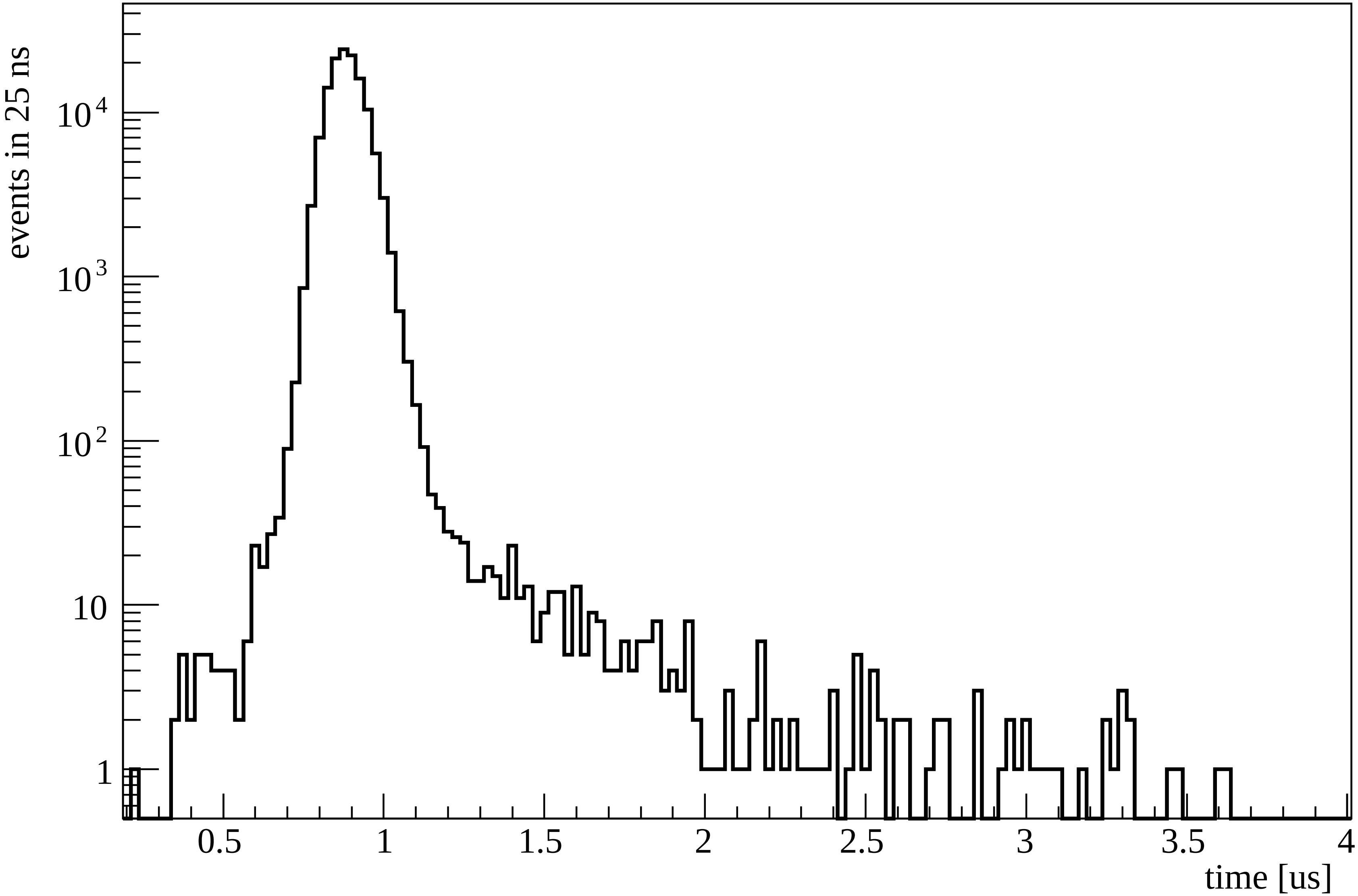


μp Lamb shift experiment: Principle

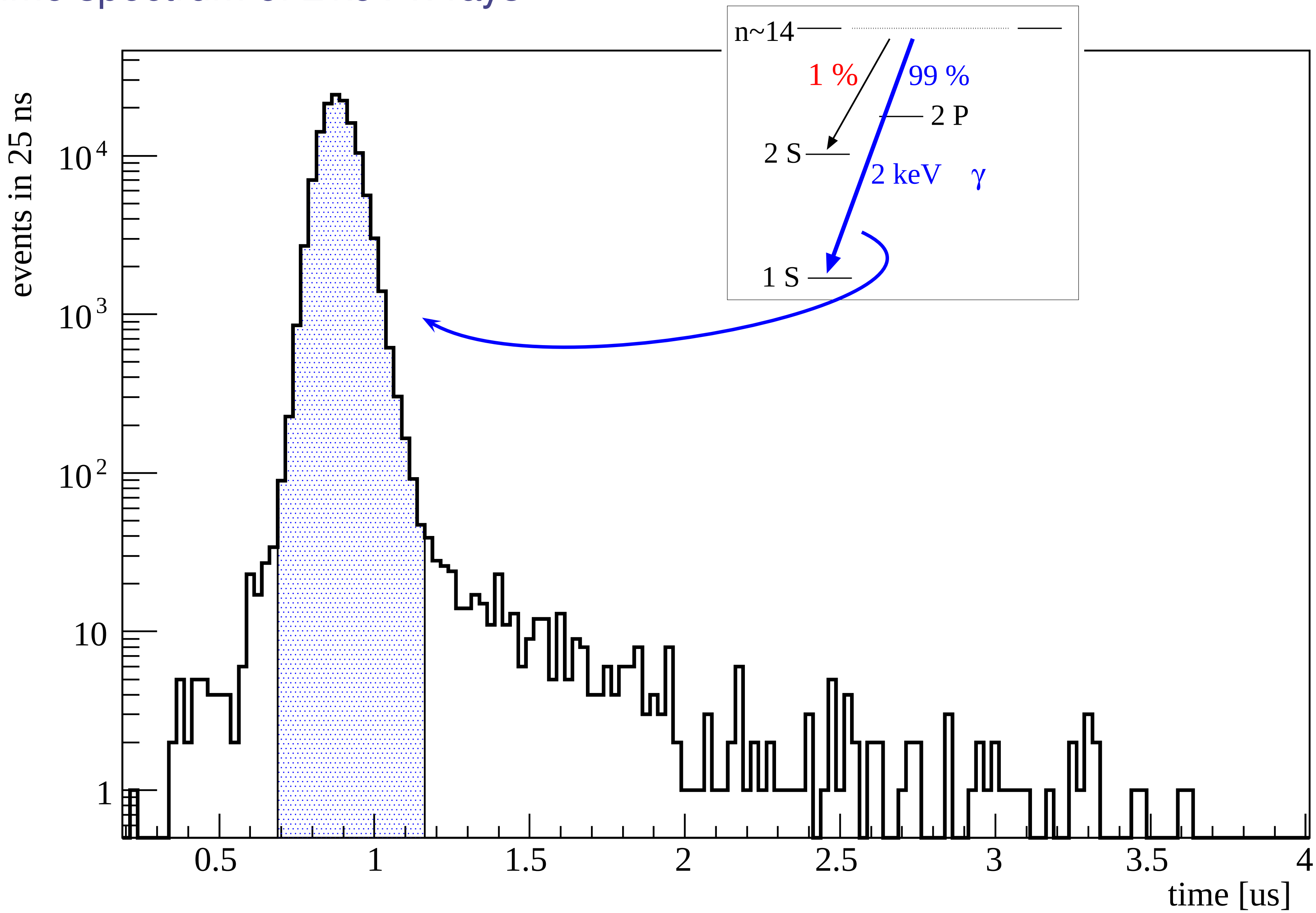
time spectrum of 2 keV x-rays (~ 13 hours of data @ 1 laser wavelength)



μp Lamb shift experiment: Principle

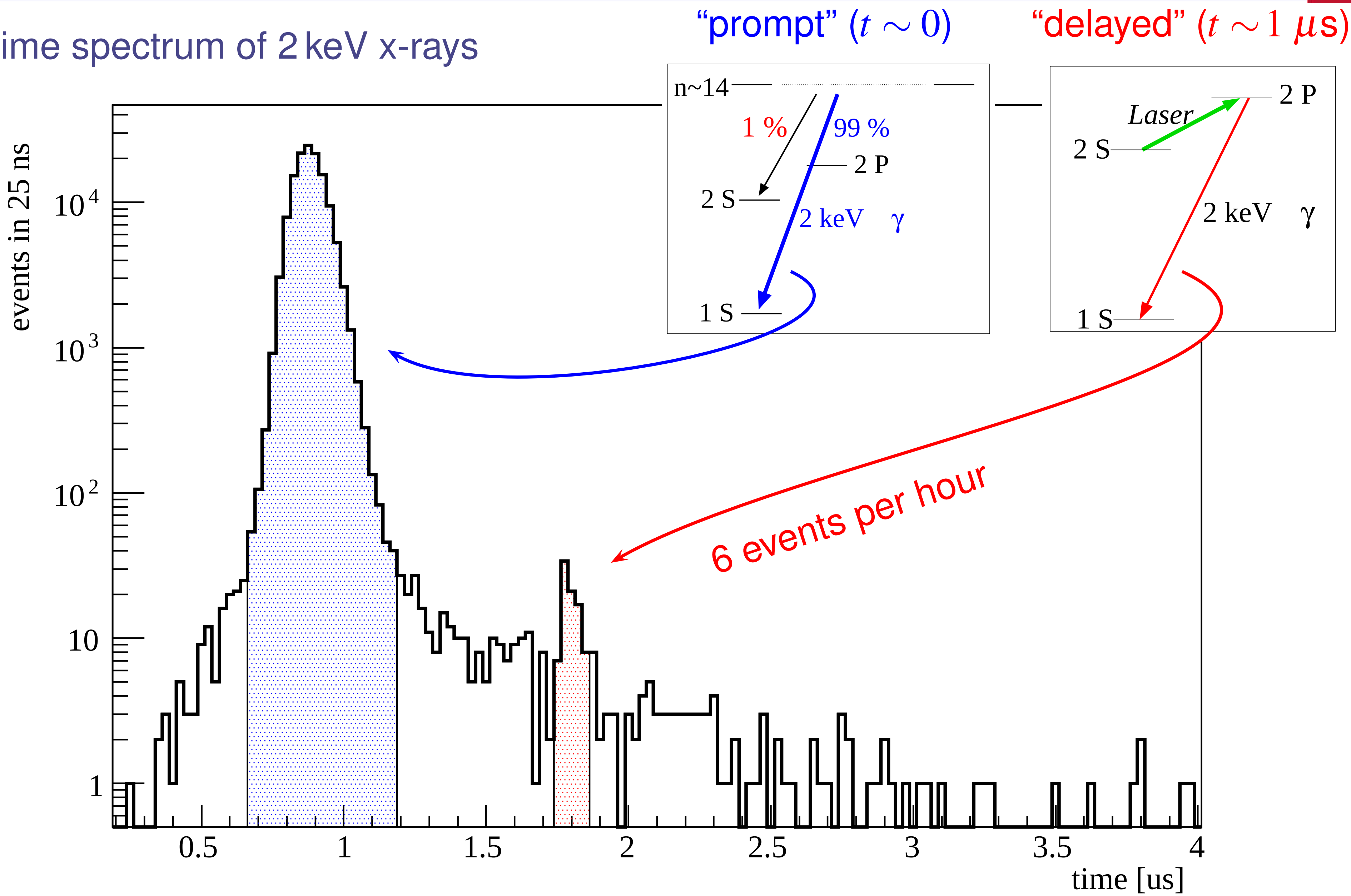
time spectrum of 2 keV x-rays

“prompt” ($t \sim 0$)

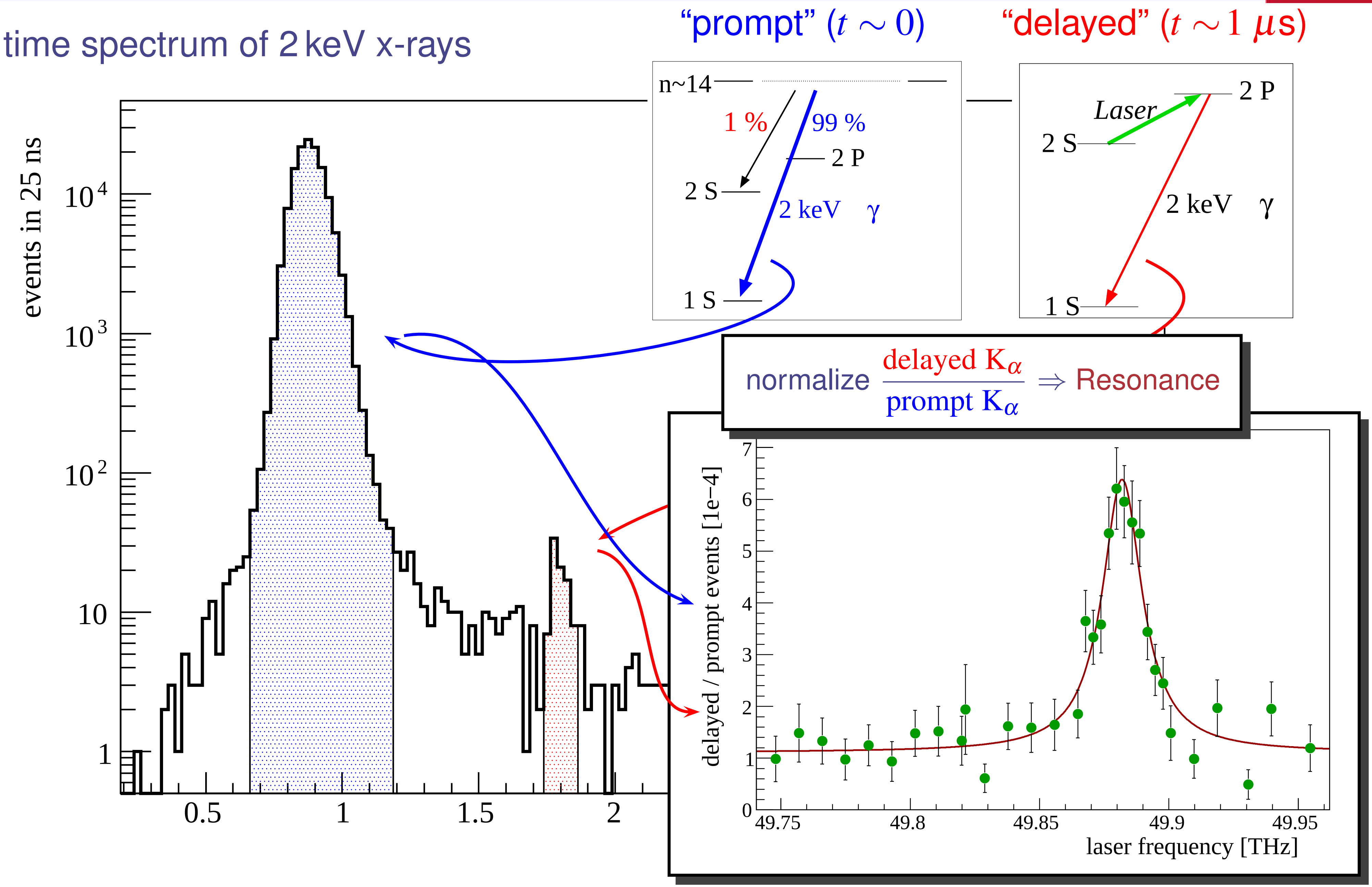


μp Lamb shift experiment: Principle

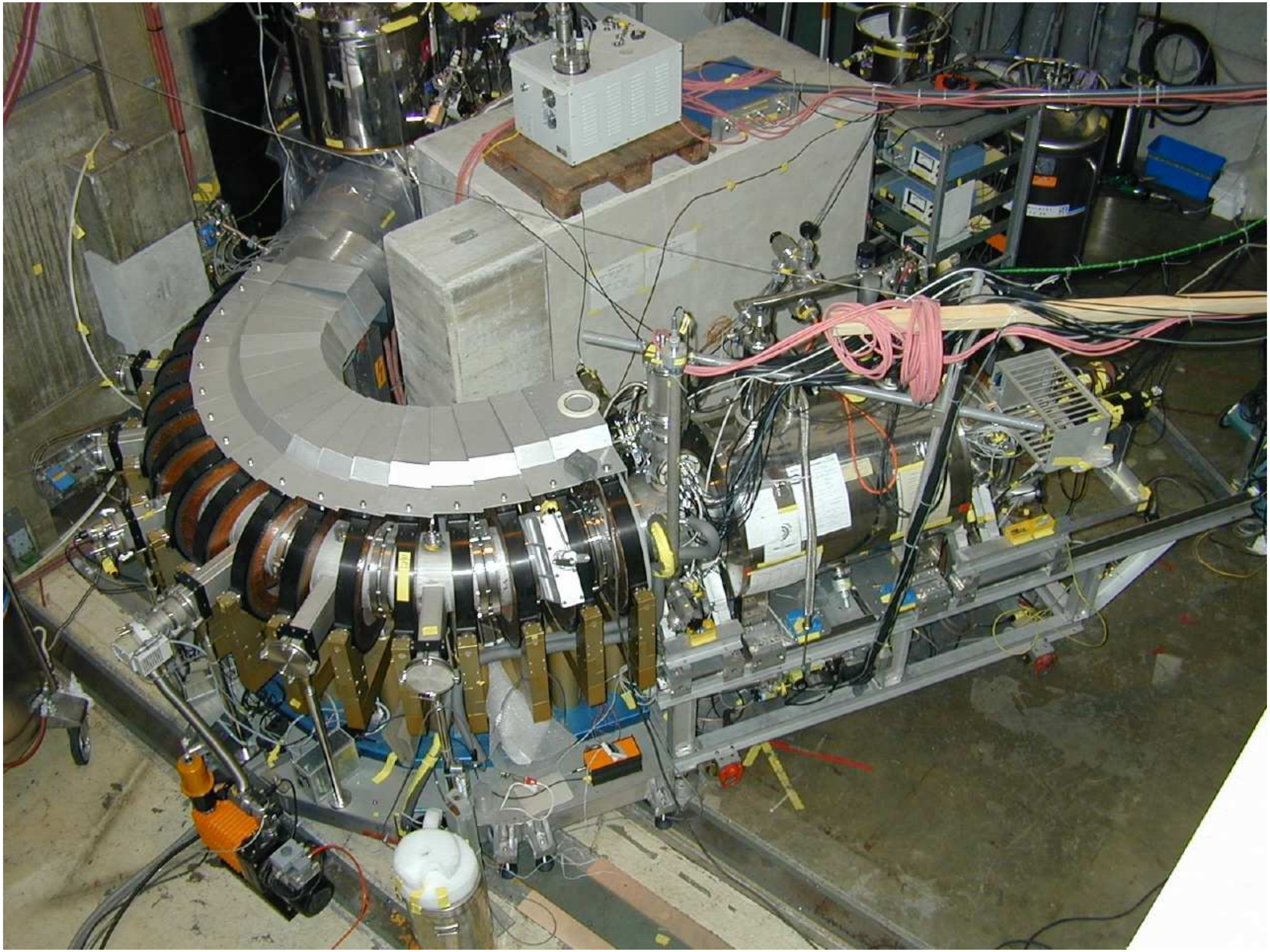
time spectrum of 2 keV x-rays



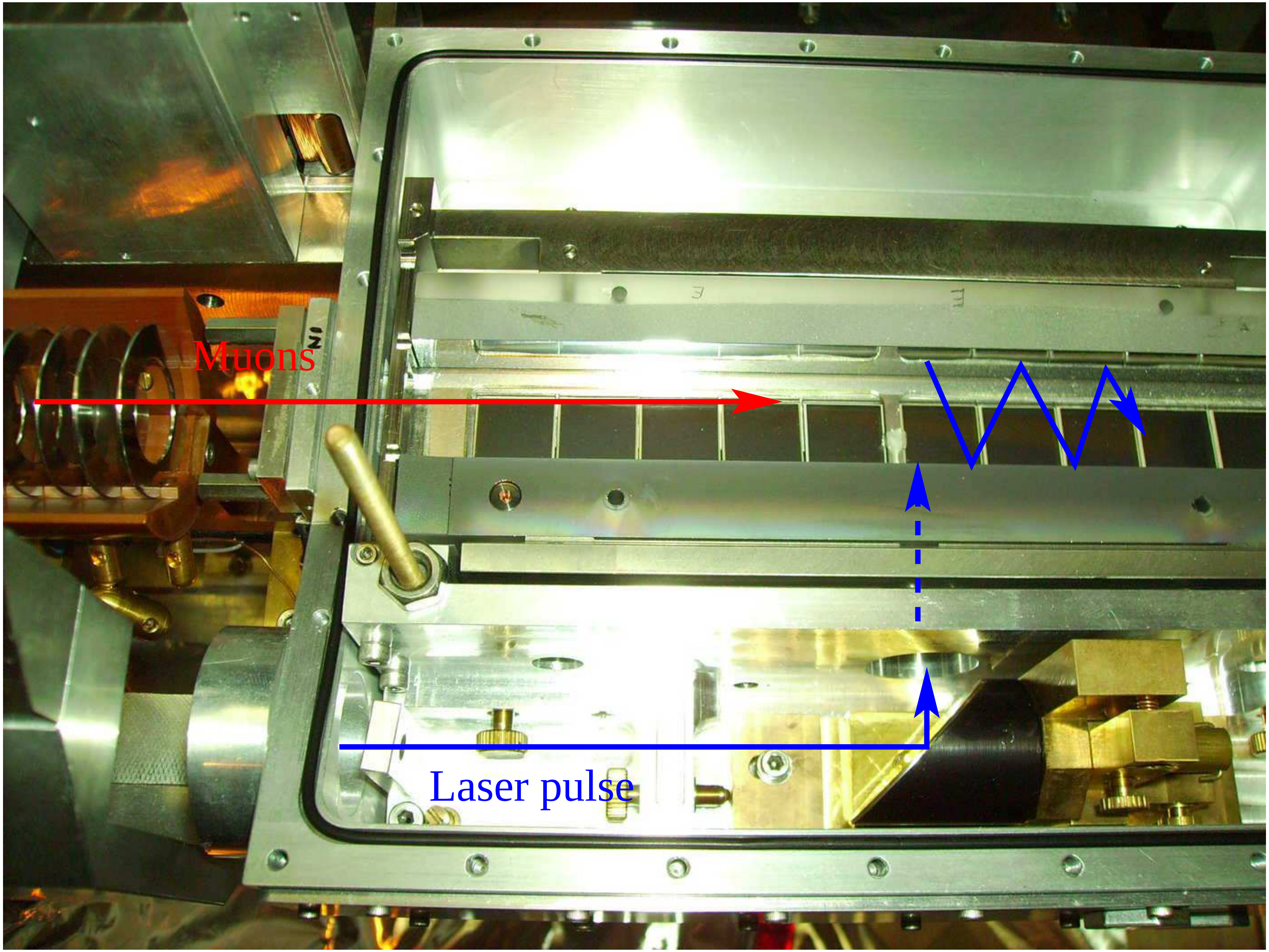
μp Lamb shift experiment: Principle



Muon beam line

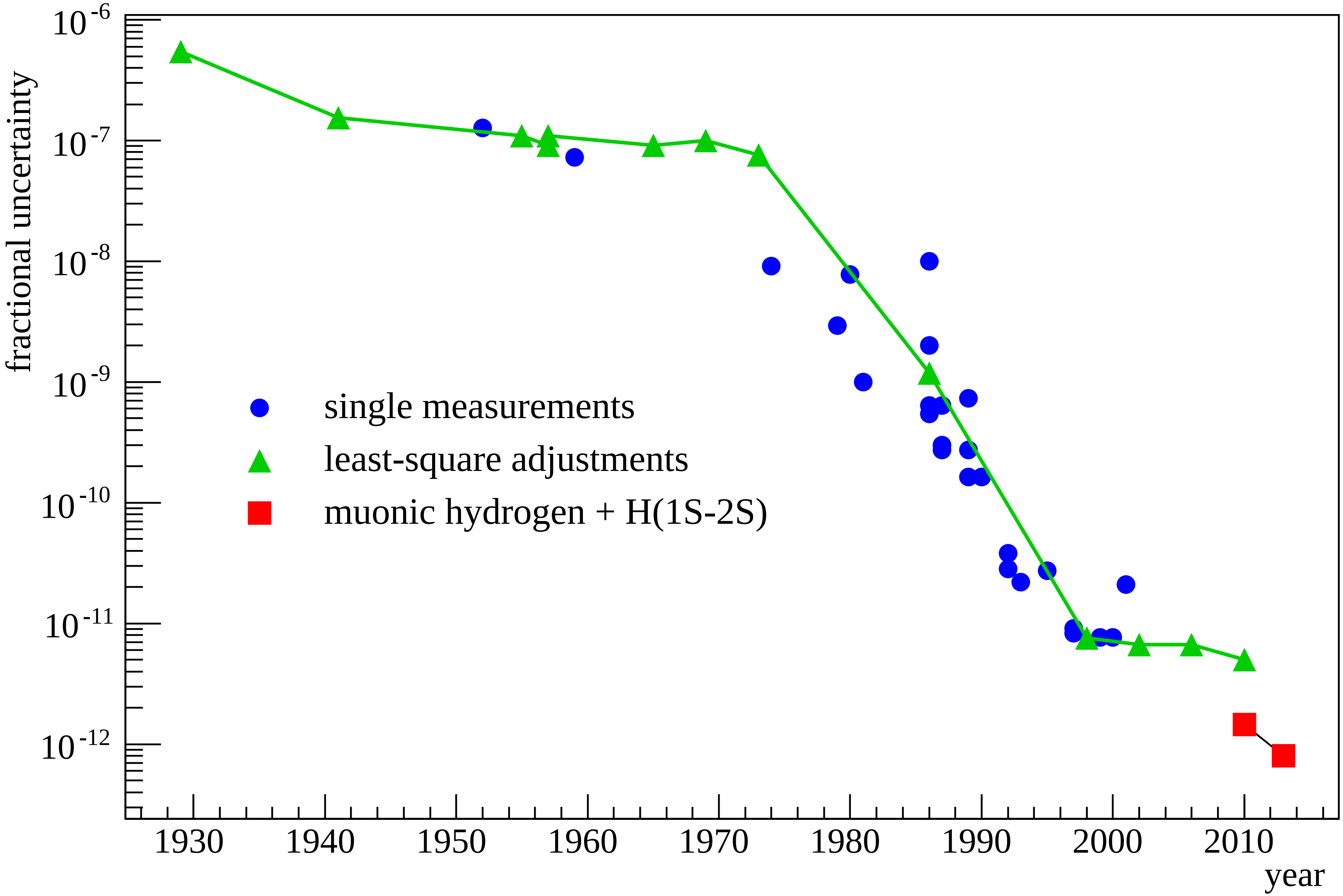


Target, cavity and detectors



Rydberg constant

$$R_\infty = \frac{\alpha^2 m_e c}{2h}$$

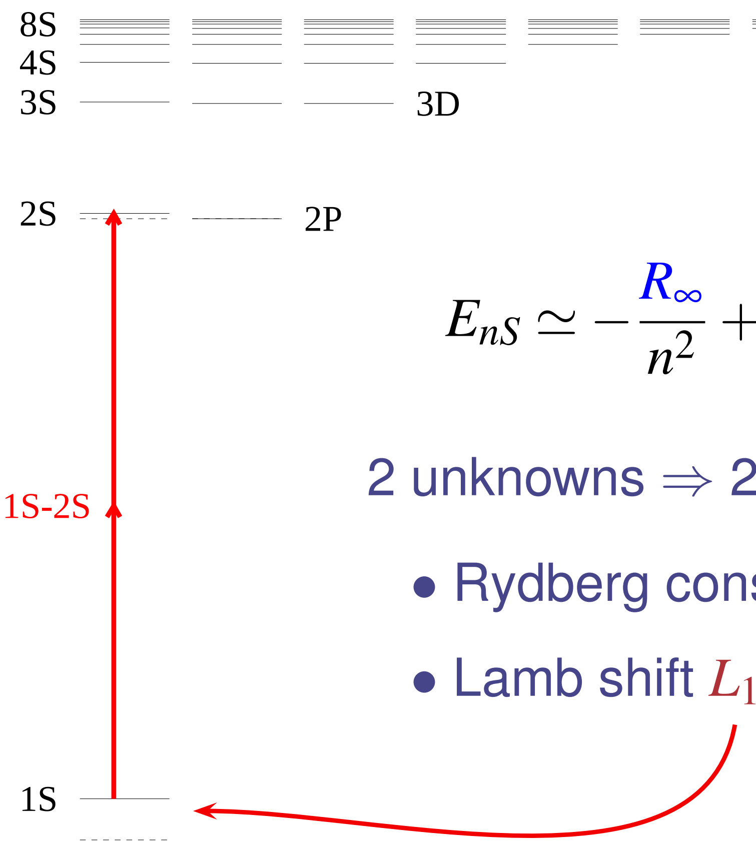


H(1S-2S): C.G. Parthey, RP *et al.*, PRL 107, 203001 (2011). r_p: A. Antognini, RP *et al.*, Science 339, 417 (2013).

Rydberg constant

Hydrogen spectroscopy (Lamb shift):

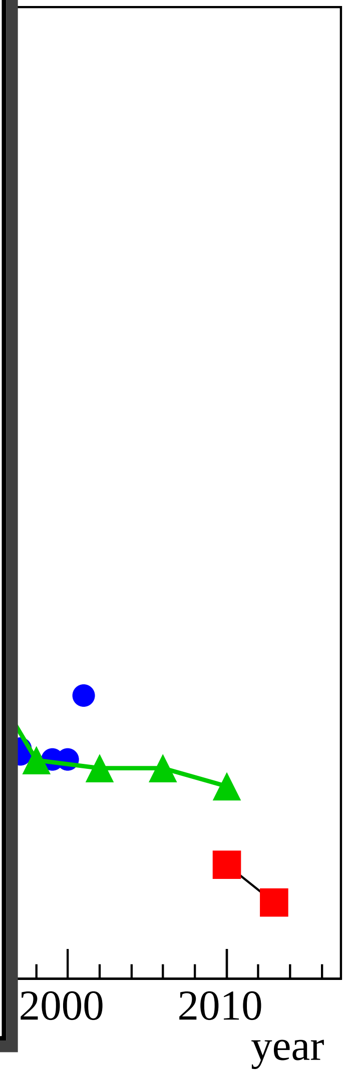
$$L_{1S}(r_p) = 8171.636(4) + 1.5645 \langle r_p^2 \rangle \quad \text{MHz}$$



$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns $\Rightarrow$ 2 transitions

- Rydberg constant R_∞
- Lamb shift $L_{1S} \leftarrow r_p$



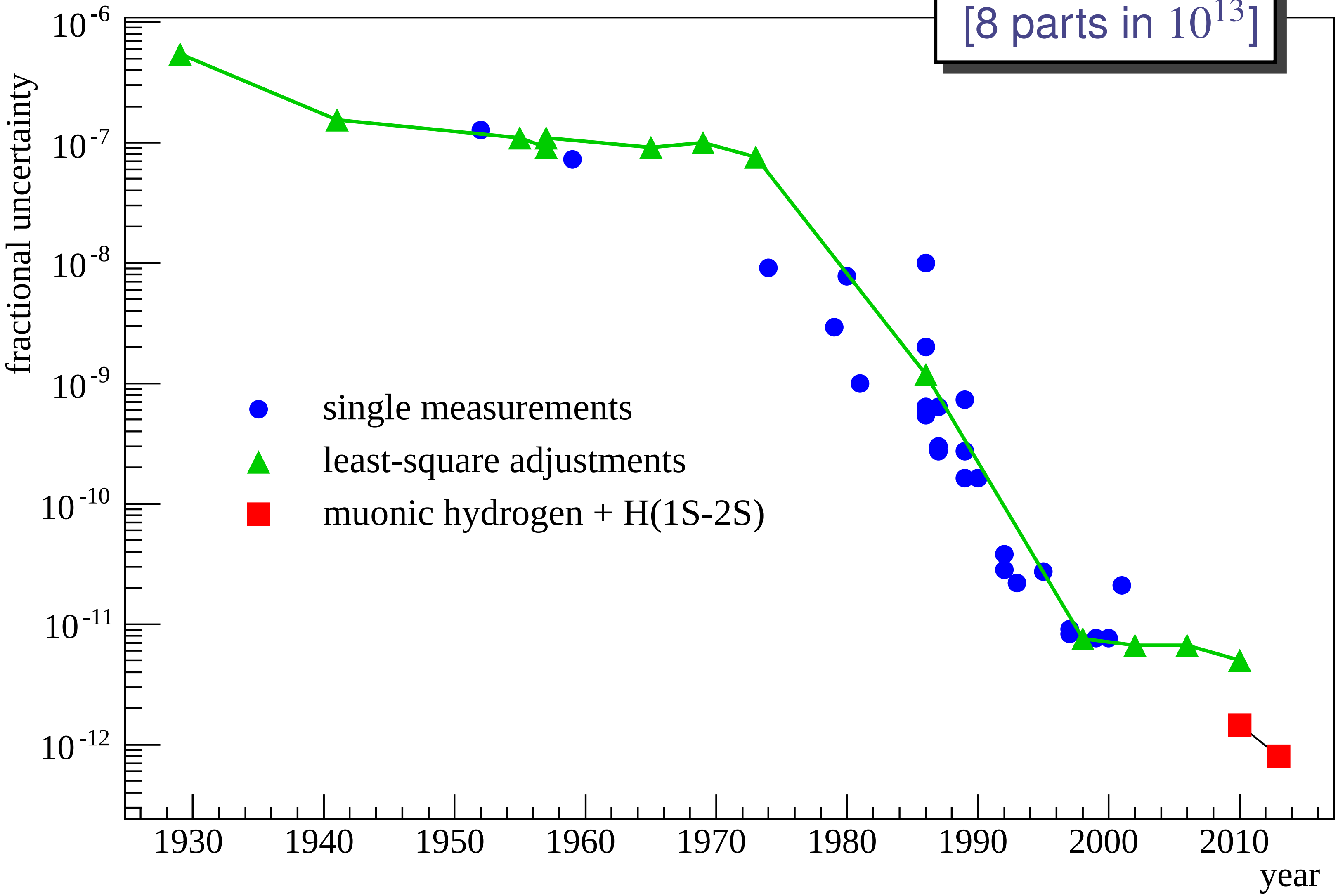
H(1S-2S): C.G. Parthey, RP *et al.*, PRL 107, 203001 (2011).

r_p: A. Antognini, RP *et al.*, Science 339, 417 (2013).

Rydberg constant

$$R_\infty = 3.289\,841\,960\,249\,5\,(10)^{r_p}\,(25)^{\text{QED}} \times 10^{15}\ \text{Hz/c}$$

[8 parts in 10^{13}]



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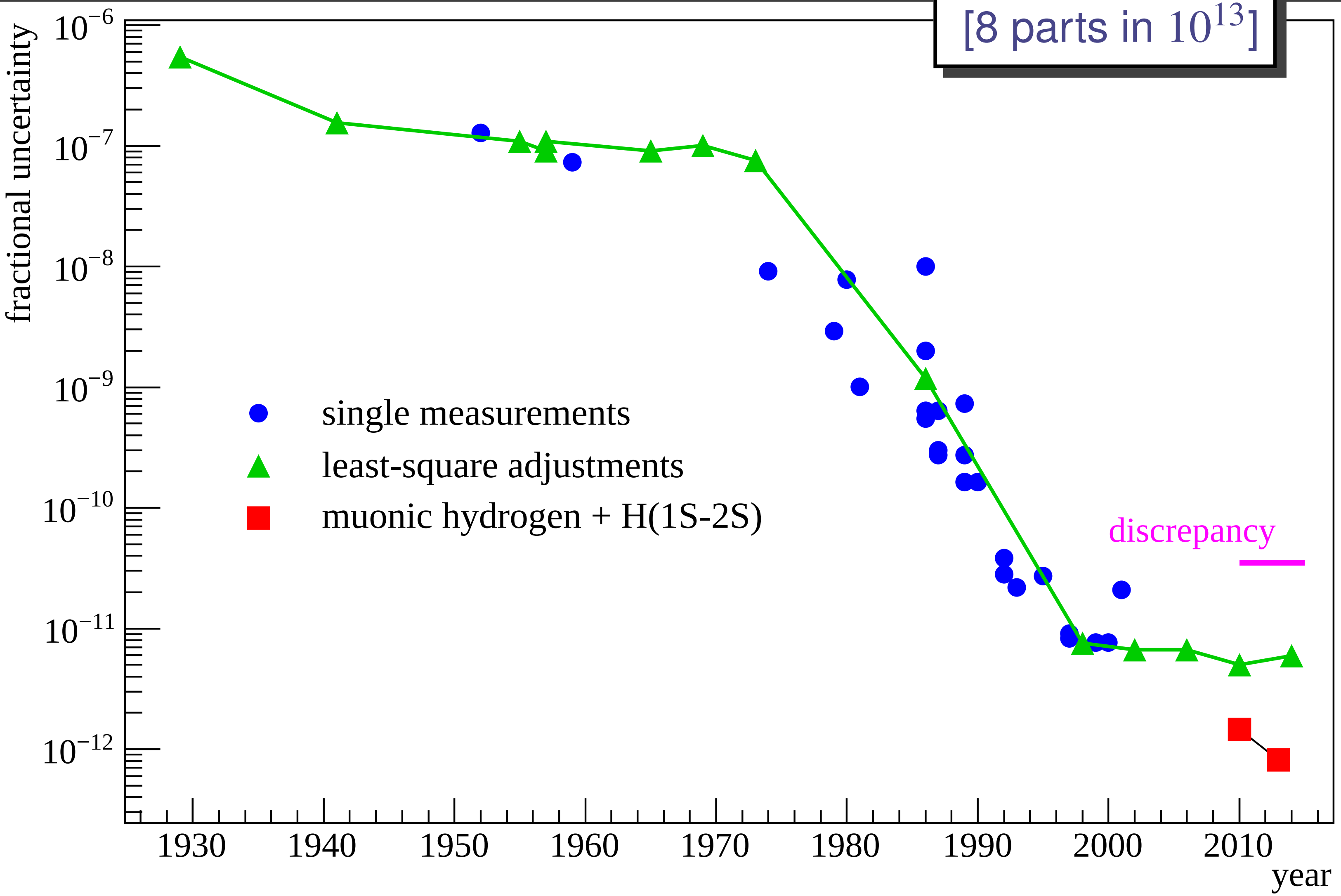

H(1S-2S): C.G. Parthey, RP *et al.*, PRL 107, 203001 (2011). r_p: A. Antognini, RP *et al.*, Science 339, 417 (2013).

Lamb shift in μp 1: r_{p} independent

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

(*continued on next page*)

A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013), Tab 1

Lamb shift in μp 1: r_p independent

Table 1 (*continued*)

#	Contribution	Pachucki [10,11]	Nature [13]	Borie-v6 [79]	Indelicato [80]	Our choice	Ref.
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)	

[a] This value has been recalculated to be 0.018759 meV [77].
[b] This correction is not necessary here because in #2 the Breit–Pauli contribution has been calculated using a Coulomb potential modified by eVP.
[c] Difference between Eqs. (6) and (4) in [78]: $E^{(\mathrm{rel})}_{\mathrm{VP}}(2P_{1/2}–2S_{1/2}) - E^{(0)}_{\mathrm{VP}}(2P_{1/2}–2S_{1/2}) = 0.018759 - 0.020843 = -0.002084$ meV (see also Table IV). Using these corrected values, the various approaches are consistent. Pachucki becomes $205.0074 + 0.018759 = 205.0262$ meV and Borie $205.0282 - 0.0020843 = 205.0261$ meV.
[d] In Appendix C, incomplete.
[e] Eq. (27) in [85] includes contributions beyond the logarithmic term with modification of the Bethe logarithm to the Uehling potential. The factor 10/9 should be replaced by 5/6.
[f] This term is part of #22, see Fig. 22 in [86].
[g] Borie includes wave-function corrections calculated in [87]. The actual difference between Ref. [13] and Borie-v6 [79] is given by the inclusion of the Källén–Sabry correction with muon loop.
[h] This was calculated in the framework of NRQED. It is related to the definition of the proton radius.

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A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013), Tab 1

Lamb shift in μp 2: r_p-dependent

Table 2

Proton-structure-dependent contributions to the Lamb shift in μp from different authors and the one we selected. Values are in meV, $\langle r^2 \rangle$ in fm^2. The entry # in the first column refers to Table 1 in Ref. [13] supplementary information [9]. Entry # 18 is under debate. TPE: two-photon exchange, VP: vacuum polarization, SE: self-energy, Rel: relativistic.

#	Contribution	Borie-v6 [79]	Karshenboim [78]	Pachucki [10,11]	Indelicato [80]	Carroll [84]	Our choice
	Non-rel. finite-size	$-5.1973\ \langle r^2\rangle$	$-5.1975\ \langle r^2\rangle$	$-5.1975\ \langle r^2\rangle$			
	Rel. corr. to non-rel. finite size	$-0.0018\ \langle r^2\rangle$		-0.0009 meV[a]			
	Rel. finite-size						
	Exponential				$-5.1994\ \langle r^2\rangle$	$-5.2001\ \langle r^2\rangle$	$-5.1994\ \langle r^2\rangle$
	Yukawa					$-5.2000\ \langle r^2\rangle$	
	Gaussian					$-5.2001\ \langle r^2\rangle$	
	Finite size corr. to one-loop eVP	$-0.0110\ \langle r^2\rangle$	$-0.0110\ \langle r^2\rangle$	$-0.010\ \langle r^2\rangle$	$-0.0282\ \langle r^2\rangle$		$-0.0282\ \langle r^2\rangle$
	Finite size to one-loop eVP-it.	$-0.0165\ \langle r^2\rangle$	$-0.0170\ \langle r^2\rangle$	$-0.017\ \langle r^2\rangle$	(incl. in -0.0282)		
	Finite-size corr. to Källén–Sabry	[b]			$-0.0002\ \langle r^2\rangle$		$-0.0002\ \langle r^2\rangle$
New	Finite size corr. to μ self-energy	(0.00699)[c]			$0.0008\ \langle r^2\rangle$		$0.0009(3)\ \langle r^2\rangle$[d]
	ΔE_TPE [46]						0.0332(20) meV
	Elastic (third Zemach)[e]						
	Measured $R^3_{(2)}$	$0.0365(18)\ \langle r^2\rangle^{3/2}$					(incl. above)
	Exponential			$0.0363\ \langle r^2\rangle^{3/2}$	$0.0353\ \langle r^2\rangle^{3/2}$ [f]	$0.0353\ \langle r^2\rangle^{3/2}$	
	Yukawa					$0.0378\ \langle r^2\rangle^{3/2}$	
	Gaussian					$0.0323\ \langle r^2\rangle^{3/2}$	
25	Inelastic (polarizability)	0.0129(5) meV [101]		0.012(2) meV			(incl. above)
New	Rad. corr. to TPE	$-0.00062\ \langle r^2\rangle$					$-0.00062\ \langle r^2\rangle$
26	eVP corr. to polarizability						0.00019 meV [95]

(*continued on next page*)

A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013), Tab 2

Lamb shift in μp 2: r_p-dependent

Table 2 (*continued*)

#	Contribution	Borie-v6 [79]	Karshenboim [78]	Pachucki [10,11]	Indelicato [80]	Carroll [84]	Our choice
27	SE corr. to polarizability						−0.00001 meV [95]
18	Finite-size to rel. recoil corr.	(0.013 meV)[g]		[h]			(incl. in ΔE_{TPE})
	Higher order finite-size corr.	−0.000123 meV			0.00001(10) meV		0.00001(10) meV
	$2P_{1/2}$ finite-size corr.	$-0.0000519\langle r^2\rangle$[i]			(incl. above)	(incl. above)	(incl. above)

[a] Corresponds to Eq. (6) in [11] which accounts only for the main terms in F_{REL} and F_{NREL}.
[b] This contribution has been accounted already in both the −0.0110 meV/fm^2 and −0.0165 meV/fm^2 coefficients.
[c] Given only in Appendix C. Bethe logarithm is not included.
[d] This uncertainty accounts for the difference between all-order in $Z\alpha$ and perturbative approaches [82].
[e] Corresponds to Eq. (20).
[f] This value is slightly different from Eq. (22) because here an all-order in finite-size and an all-order in eVP approaches were used.
[g] See Appendix F of [96]. This term is under debate.
[h] Included in ΔE_{TPE}. This correction of $0.018 - 0.021 = -0.003$ meV is given by Eq. (64) in [10] and Eq. (25) in [11]. This correction is also discussed in [76] where the 6/7 factor results from 0.018/0.021.
[i] Eq. (6a) in [79].

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A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013), Tab 2

Table 3
All known contributions to the 2S-HFS in μp from different authors and the one we selected. Values are in meV, radii in fm. SE: self-energy, VP: vacuum polarization, Rel: relativistic, RC: recoil correction, PT: perturbation theory, p: proton, int: interaction, AMM: anomalous magnetic moment.

	Contribution	Martynenko [72]	Borie-v6 [79]	Indelicato	Our choice [80]	Ref.
h1	Fermi energy, $(Z\alpha)^4$	22.8054	22.8054			
h2	Breit corr., $(Z\alpha)^6$	0.0026	0.00258			
h3	Dirac energy (+ Breit corr. in all-order)			22.807995	22.807995	Eq. (107) in [80]
h4	μ AMM corr., $\alpha(Z\alpha)^4$, $\alpha(Z\alpha)^4$	0.0266	0.02659		0.02659	
h5	eVP in 2nd-order PT, $\alpha(Z\alpha)^5$ (ϵ_{VP2})	0.0746	0.07443			
h6	All-order eVP corr.			0.07437	0.07437	Eq. (109) in [80]
h7	Two-loop corr. to Fermi-energy (ϵ_{VP2})		0.00056		0.00056	
h8	One-loop eVP in 1γ int., $\alpha(Z\alpha)^4$ (ϵ_{VP1})	0.0482	0.04818		0.04818	
h9	Two-loop eVP in 1γ int., $\alpha^2(Z\alpha)^4$ (ϵ_{VP1})	0.0003	0.00037		0.00037	
h10	Further two-loop eVP corr.		0.00037		0.00037	[113,114]
h11	μVP (similar to ϵ_{VP2})		0.00091		0.00091	
h12	μVP (similar to ϵ_{VP1})	0.0004	(incl. in h13)		(incl. in h13)	
h13	Vertex, $\alpha(Z\alpha)^5$		−0.00311		−0.00311	[a]
h14	Higher order corr. of (h13), (part with $\ln(\alpha)$)		−0.00017		−0.00017	[115]
h15	μ SE with p structure, $\alpha(Z\alpha)^5$	0.0010				
h16	Vertex corr. with proton structure, $\alpha(Z\alpha)^5$	−0.0018				
h17	"Jellyfish" corr. with p structure, $\alpha(Z\alpha)^5$	0.0005				
h18	Hadron VP, α^6	0.0005(1)	0.00060(10)		0.00060(10)	
h19	Weak interaction contribution	0.0003	0.00027		0.00027	[116]
h20	Finite-size (Zemach) corr. to ΔE_{Fermi}, $(Z\alpha)^5$	−0.1518[b]	$-0.16037\ r_Z$	$-0.16034\ r_Z$	$-0.16034\ r_Z$	Eq. (107) in [80]

(*continued on next page*)

A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013), Tab 3

Table 3 (*continued*)

	Contribution	Martynenko [72]	Borie-v6 [79]	Indelicato	Our choice [80]	Ref.
h21	Higher order finite-size corr. to ΔE_{Fermi}			$-0.0022\, r_E{}^2 + 0.0009$	$-0.0022\, r_E{}^2 + 0.0009$	Eq. (107) in [80]
h22	Proton polarizability, $(Z\alpha)^5$, $\Delta E^{\text{pol}}_{\text{HFS}}$	0.0105(18)	0.0080(26)		0.00801(260)	[117,118]
h23	Recoil corr.	(incl. in h20)	0.02123		0.02123	[112]
h24	eVP + proton structure corr., α^6	-0.0026				
h25	eVP corr. to finite-size (similar to ϵ_{VP2})		-0.00114	$-0.0018\, r_Z - 0.0001$	$-0.0018\, r_Z - 0.0001$	Eq. (109) in [80]
h26	eVP corr. to finite-size (similar to ϵ_{VP1})		-0.00114		$-0.00114(20)$	
h27	Proton structure corr., $\alpha(Z\alpha)^5$	-0.0017				
h28	Rel. + radiative RC with p AMM, α^6	0.0018				
	Sum	22.8148(20)[c]	22.9839(26) $- 0.1604\, r_Z$		22.9858(26) $- 0.1621(10)\, r_Z - 0.0022(5)\, r_E^2$	
	Sum with $r_E = 0.841$ fm, $r_Z = 1.045$ fm [28]	22.8148 meV	22.8163 meV		22.8149 meV	

[a] Includes a correction $\alpha(Z\alpha)^5$ due to μVP.
[b] Calculated using the Simon et al. form factor.
[c] The uncertainty is 0.0078 meV if the uncertainty of the Zemach term (h20) is included (see Table II of [72]).

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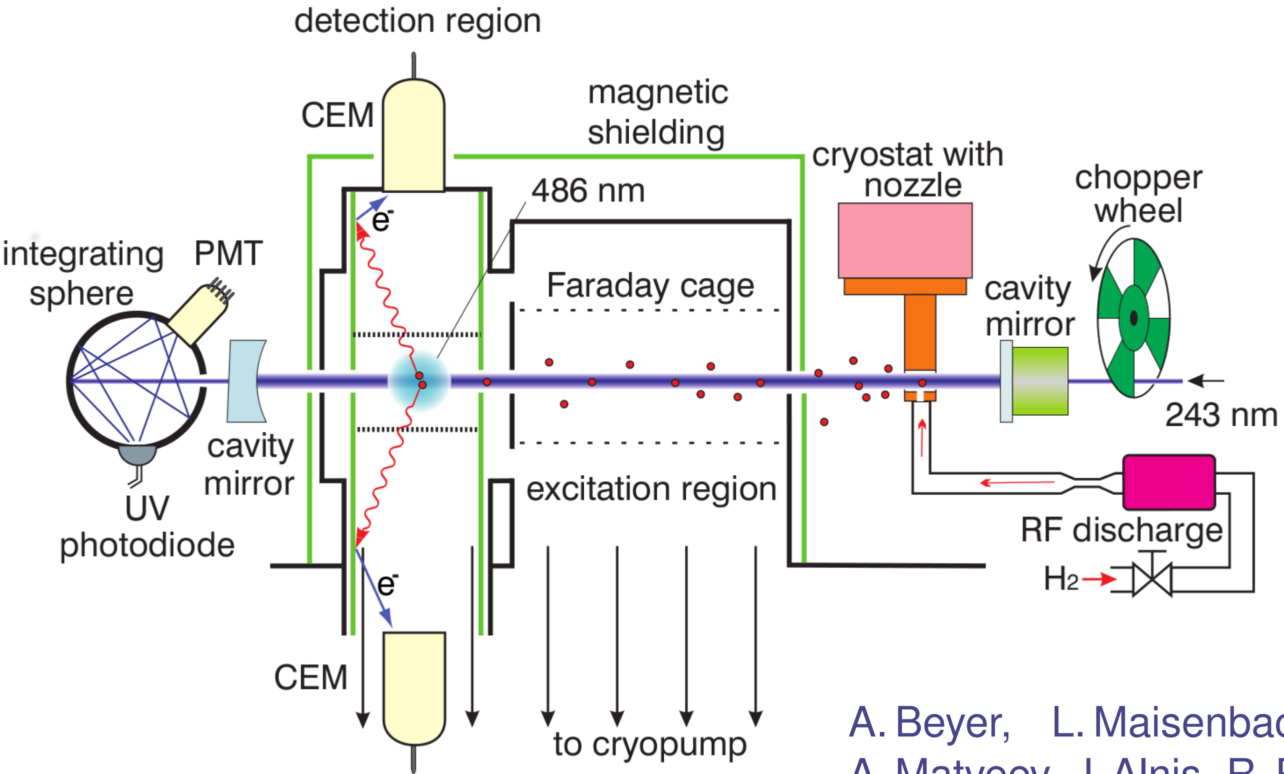
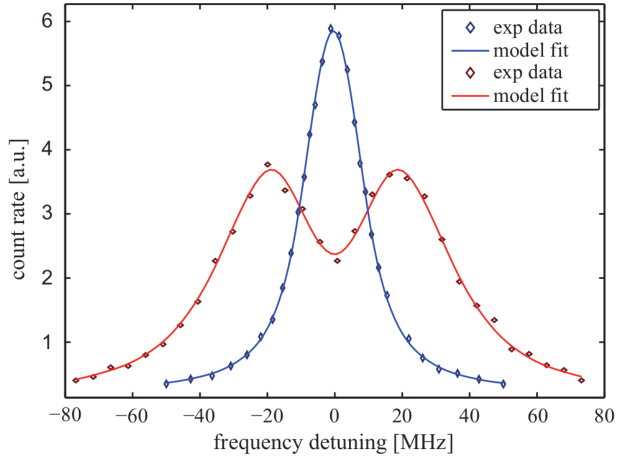
A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013), Tab 3

Rydberg constant from hydrogen





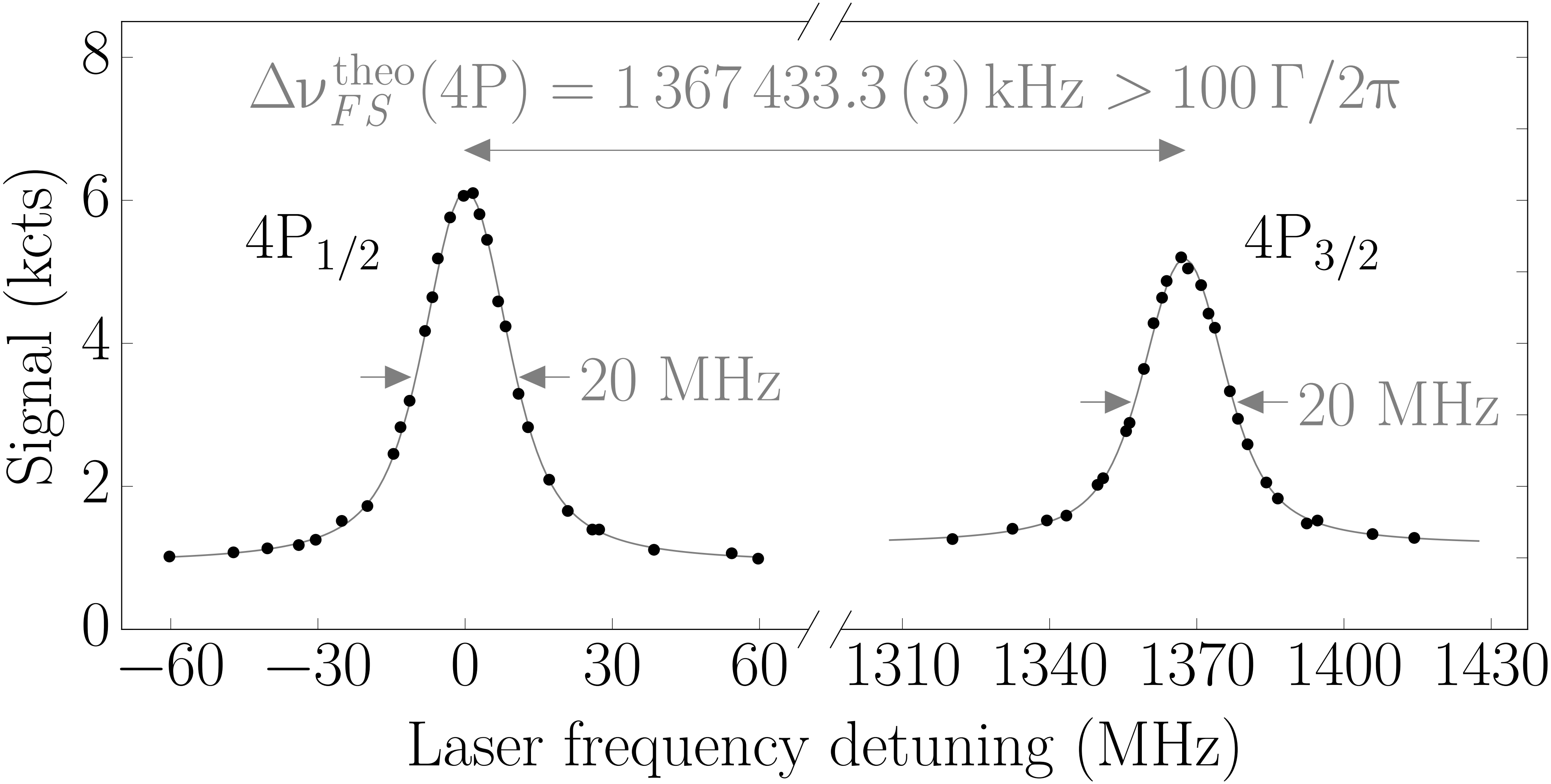
2S – 4P resonance at
$88 \pm 0.5\,^\circ$ and $90 \pm 0.08\,^\circ$

A. Beyer, L. Maisenbacher, K. Khabarova, C.G. Parthey, A. Matveev, J. Alnis, R. Pohl, N. Kolachevsky, Th. Udem and T.W. Hänsch

- Apparatus used for H/D(1S-2S) — C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010); C.G. Parthey, RP *et al.*, PRL **107**, 203001 (2011)
- 486 nm at 90° + Retroreflector $\Rightarrow$ Doppler-free 2S-4P excitation
- 1st oder Doppler vs. ac-Stark shift
- ~ 2.5 kHz accuracy (vs. 15 kHz Yale, 1995)
- **cryogenic** H beam, **optical** excitation to 2S — A. Beyer, RP *et al.*, Ann. d. Phys. **525**, 671 (2013)

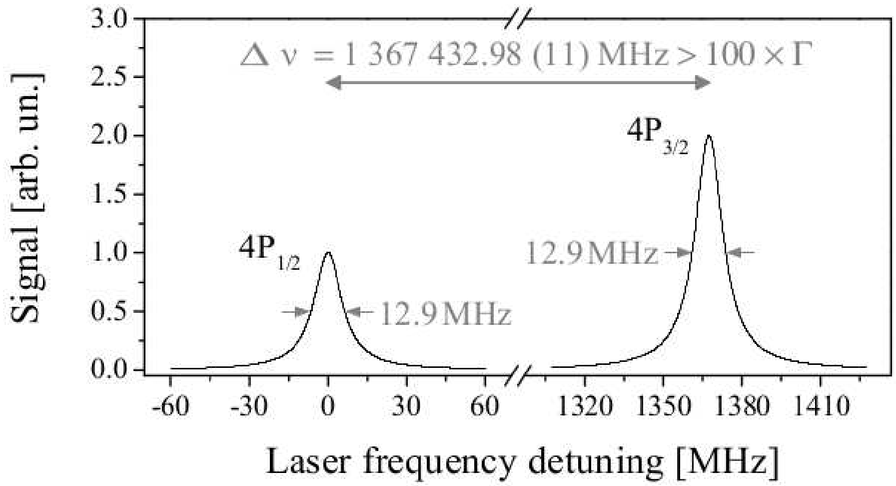
2S – 4P resonances

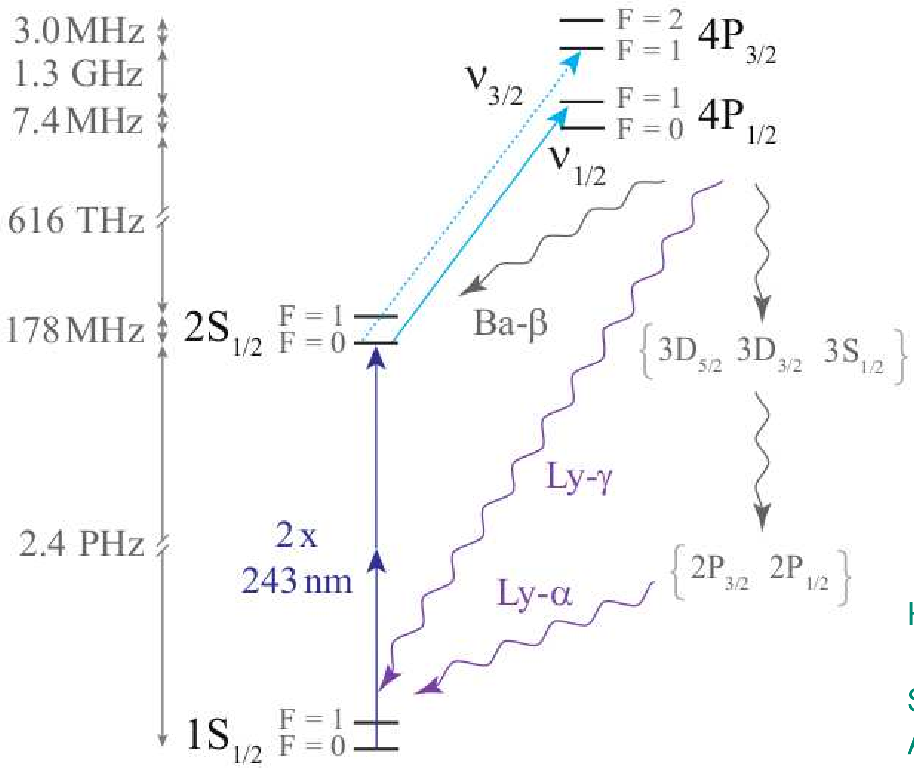
data (each a single scan of ~ 1 minute)



A. Beyer, RP *et al.*, submitted.

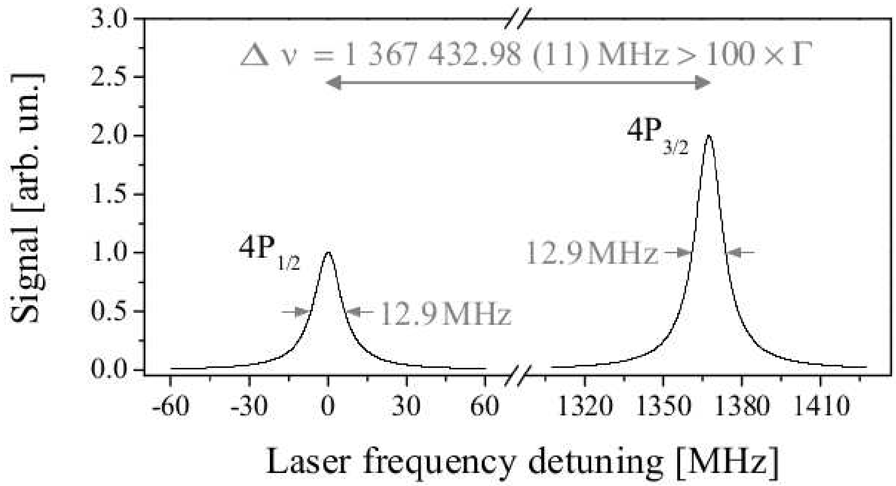
Quantum interference shifts

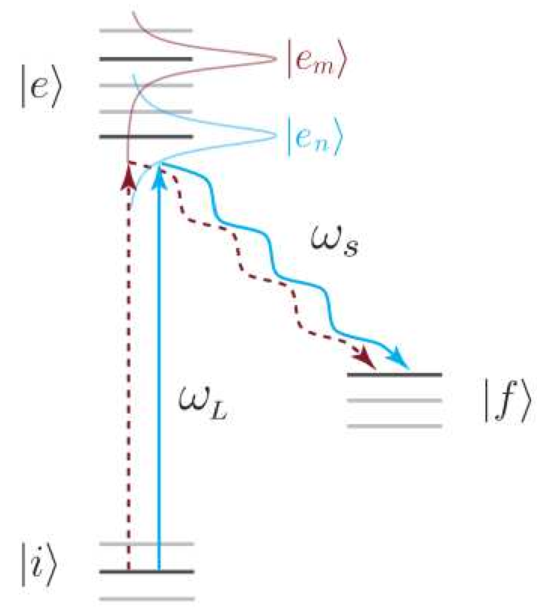


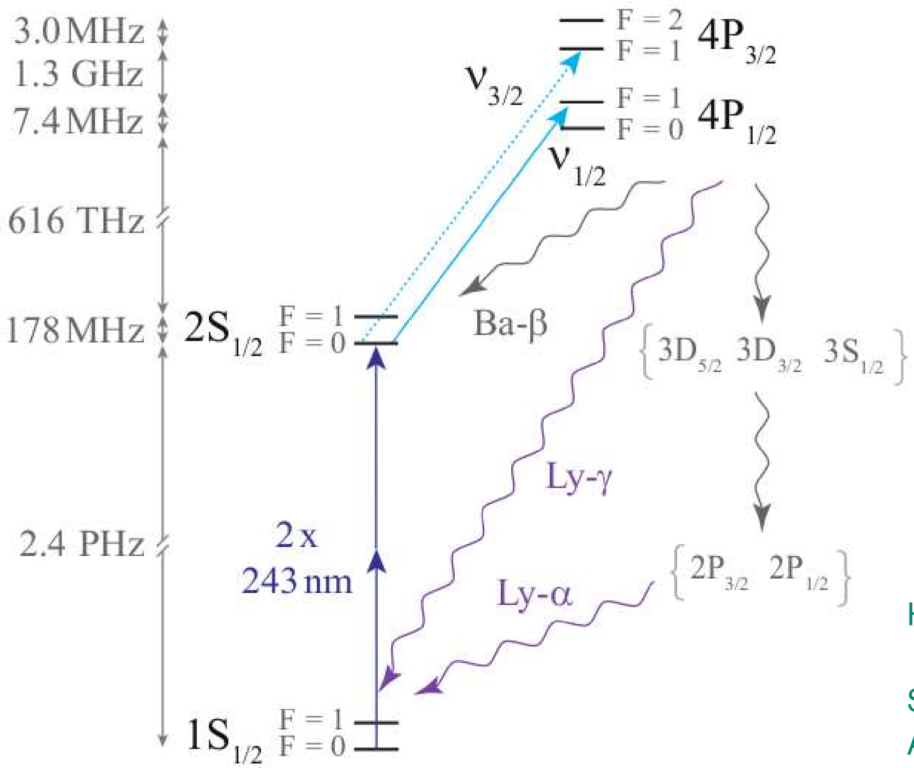


Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011),
PRA 86, 040501 (2012), etc.
Sansonetti *et al.*, PRL 107, 023001 (2011); Brown *et al.*, PRA 87, 032504 (2013)
Amaro, RP *et al.*, PRA 92, 022514 (2015); PRA 92, 062506 (2015)

Quantum interference shifts







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

= Lorentzian(1) + Lorentzian(2) +

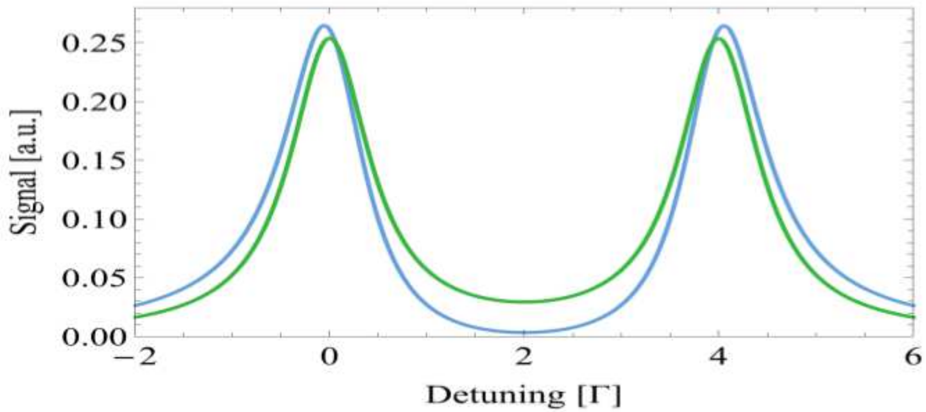
cross-term (QI)

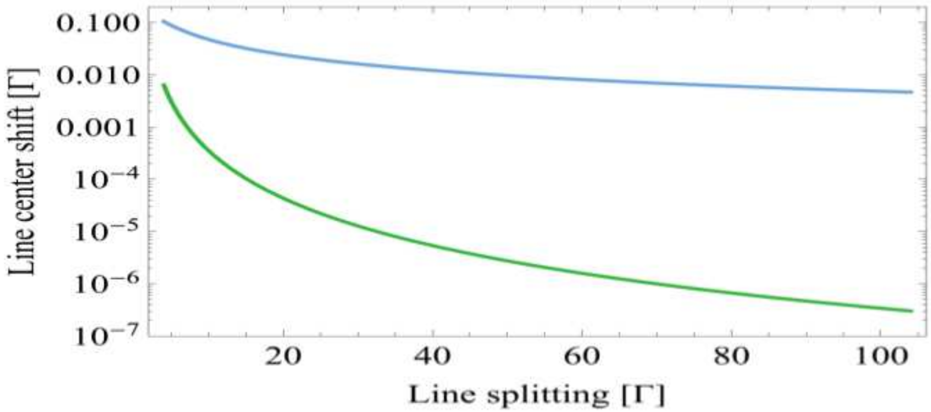
Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011), PRA 86, 040501 (2012), etc.

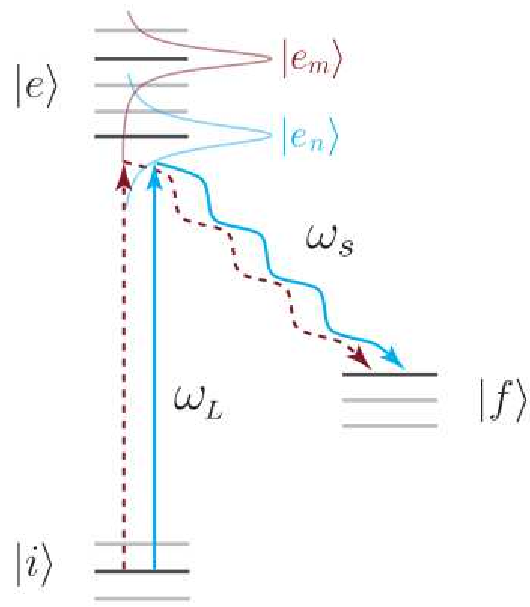
Sansonetti *et al.*, PRL 107, 023001 (2011); Brown *et al.*, PRA 87, 032504 (2013)

Amaro, RP *et al.*, PRA 92, 022514 (2015); PRA 92, 062506 (2015)

Quantum interference shifts







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

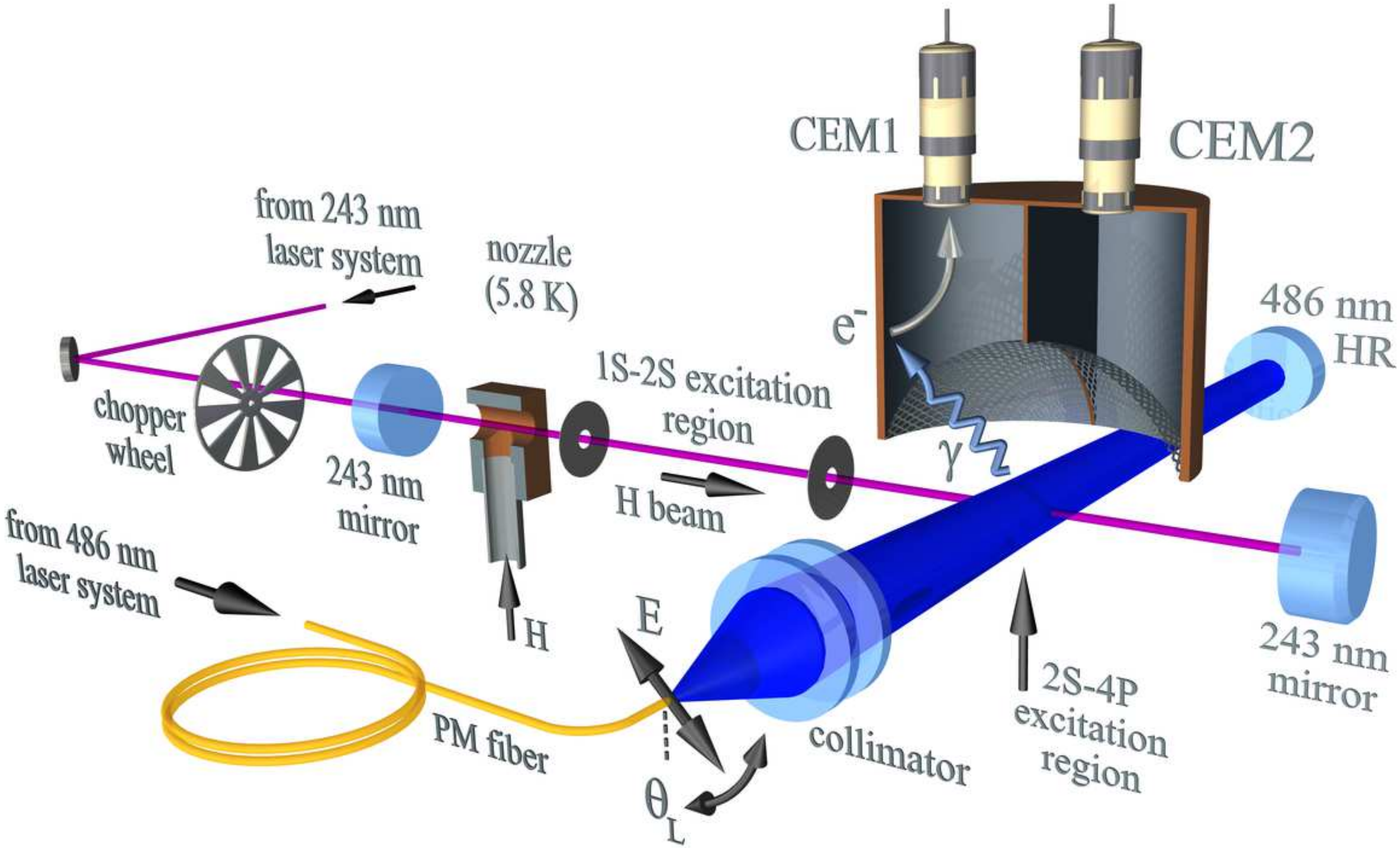
= Lorentzian(1) + Lorentzian(2) +

cross-term (QI)

Horbatsch & Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011), PRA 86, 040501 (2012), etc.
Sansonetti *et al.*, PRL 107, 023001 (2011); Brown *et al.*, PRA 87, 032504 (2013)
Amaro, RP *et al.*, PRA 92, 022514 (2015); PRA 92, 062506 (2015)

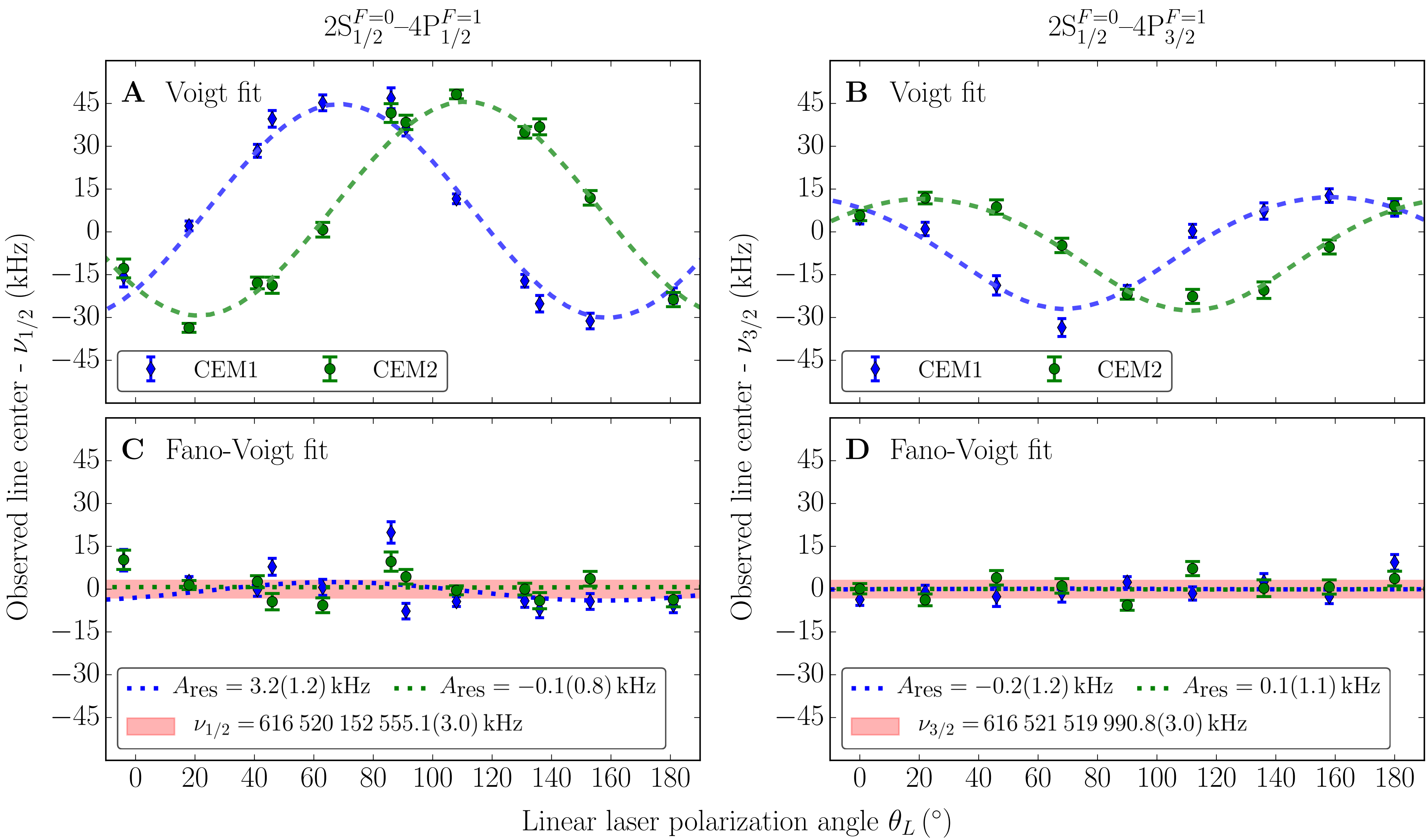
Quantum interference shifts

2S-4P setup



Beyer, RP *et al.*, submitted (2016)

Cross-damping



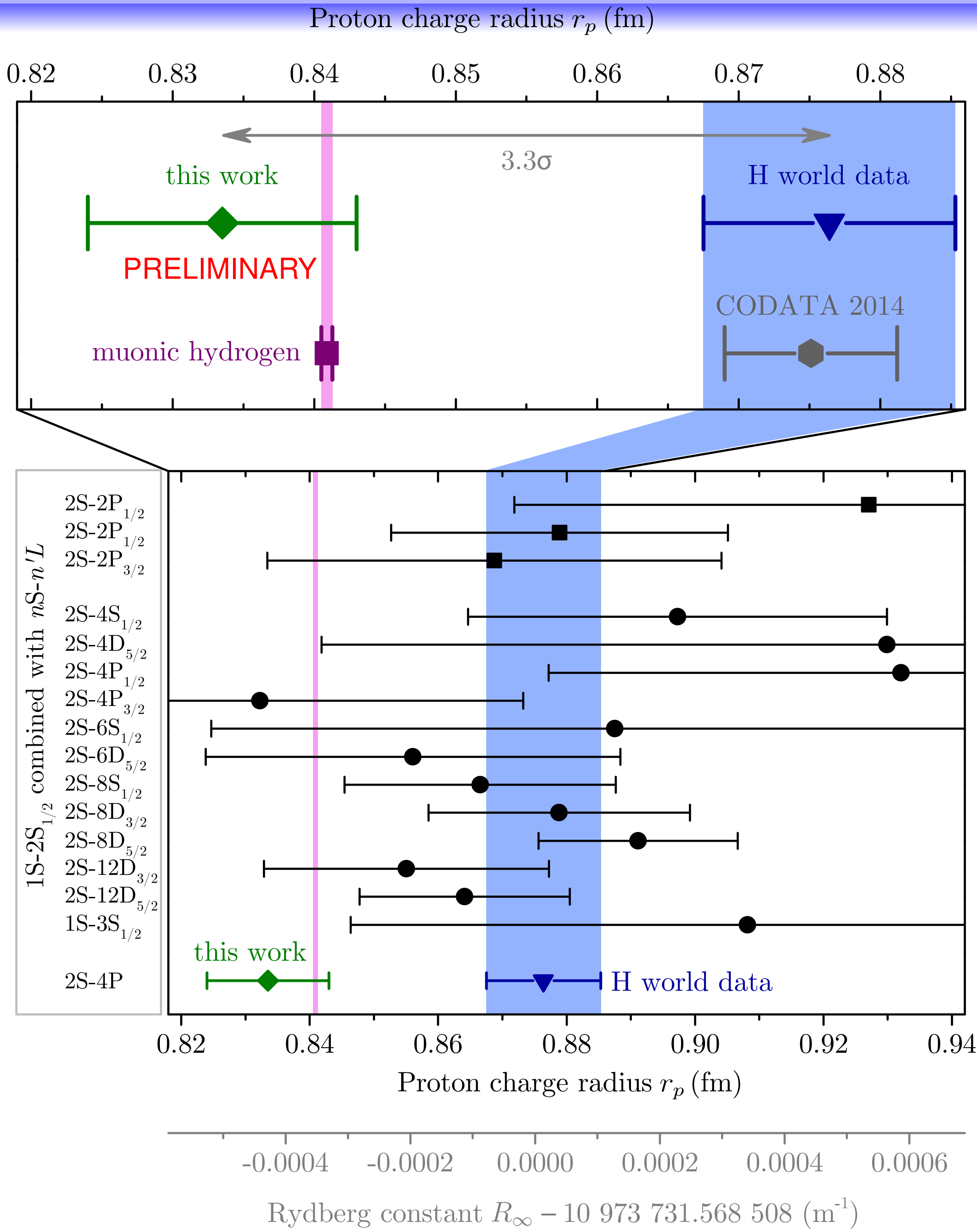
A. Beyer, RP *et al.*, submitted.

2S – 4P uncertainties

	$\Delta\nu$ (kHz)	σ (kHz)
Statistics	0.0	0.40
First-order Doppler shift	0.0	2.13
Quantum interference shift	0.0	0.20
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	0.0	0.20
Zeeman shift	0.0	0.22
Pressure shift	0.0	0.008
Laser spectrum	0.0	0.1
Laser frequency determination	0.0	0.1
Frequency standard (H maser)	0.0	0.06
Recoil shift	-837.23	0.00
Hyperfine structure (HFS) corrections	-132552.092	0.075
Total	-133388.9	2.3

A. Beyer, RP *et al.*, submitted.

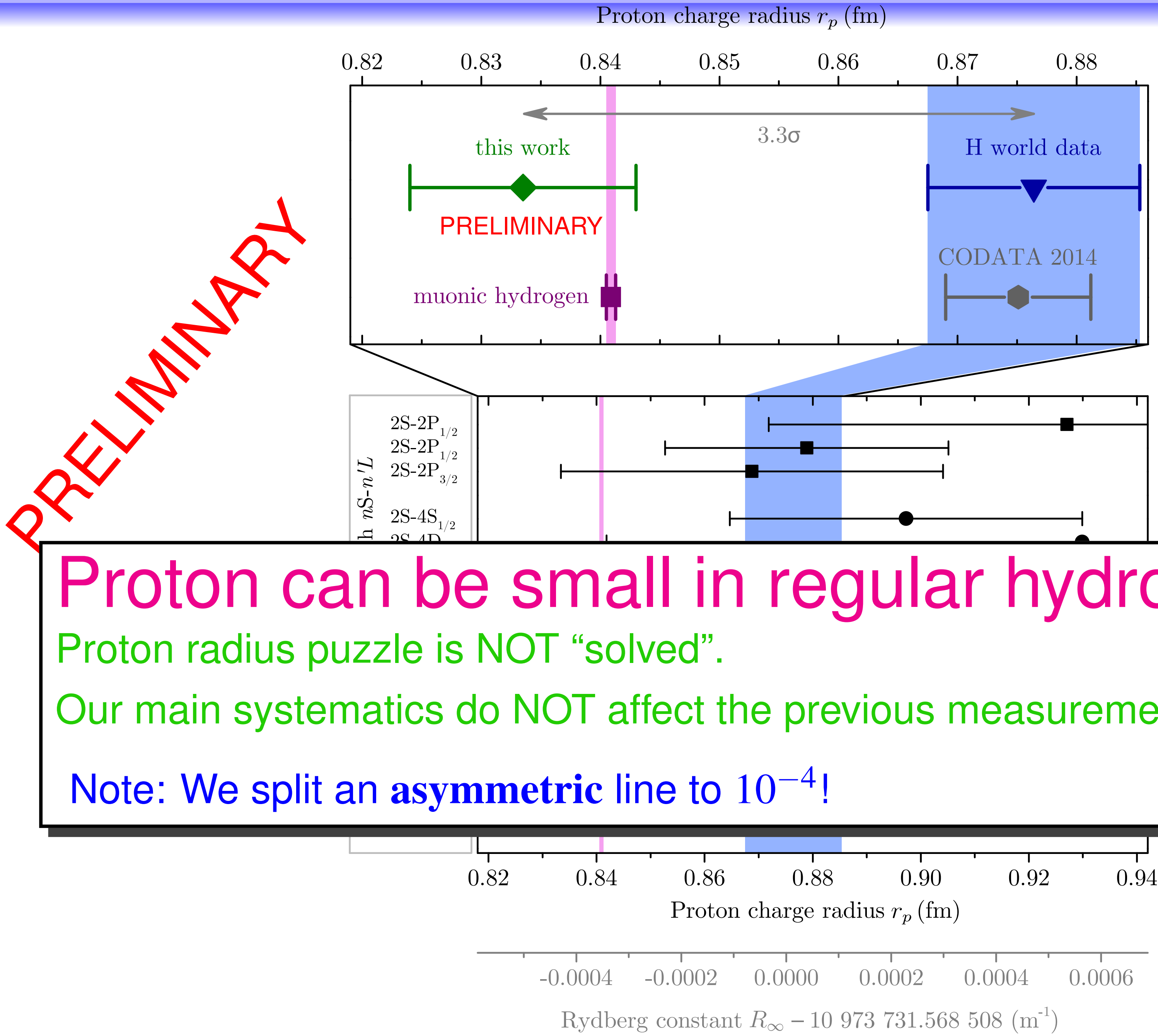
2S – 4P results



PRELIMINARY

A. Beyer, RP *et al.*, submitted.

2S – 4P results



Proton can be small in regular hydrogen, too!

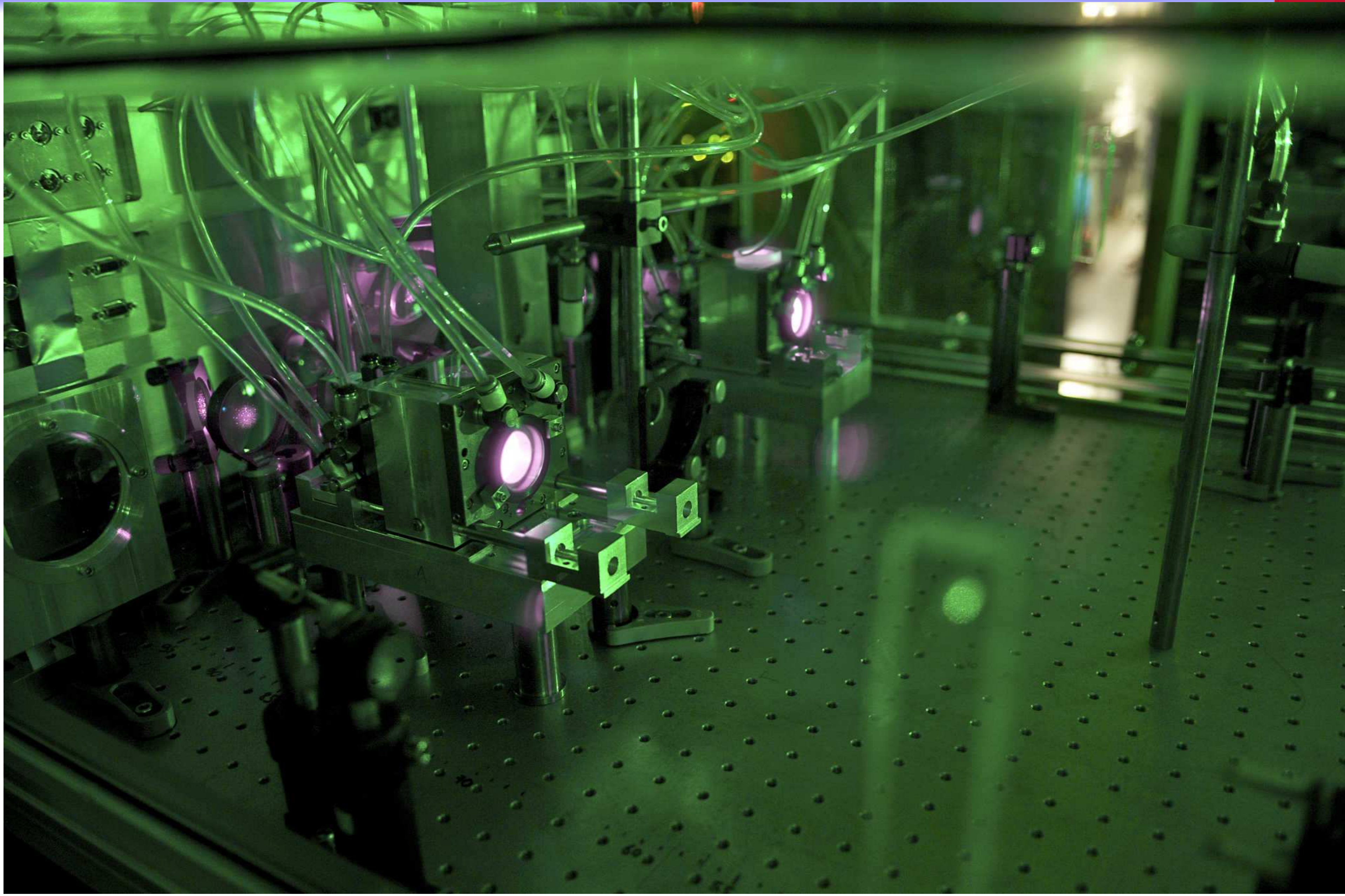
Proton radius puzzle is NOT “solved”.

Our main systematics do NOT affect the previous measurements.

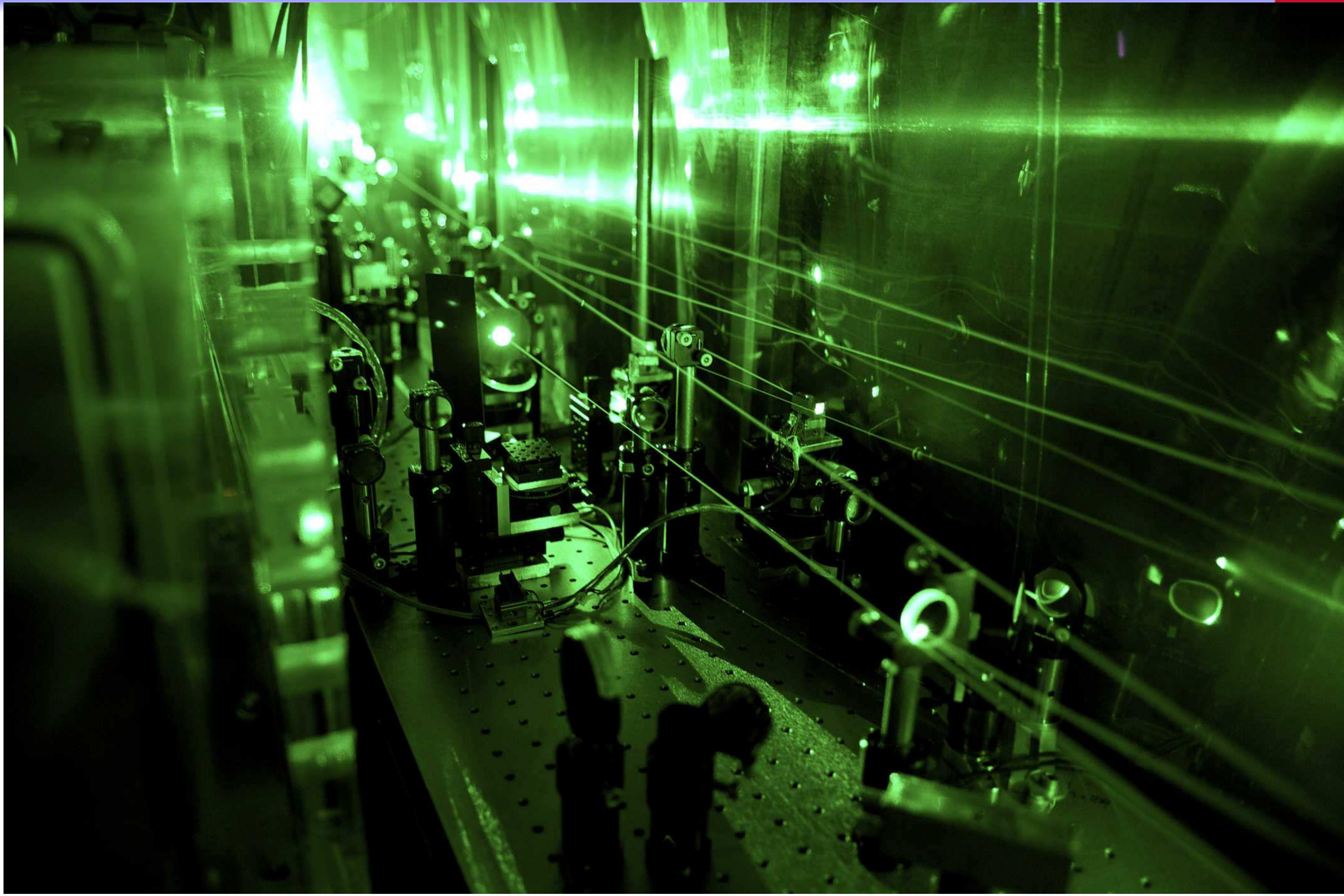
Note: We split an **asymmetric** line to 10^{-4}!

A. Beyer, RP *et al.*, submitted.

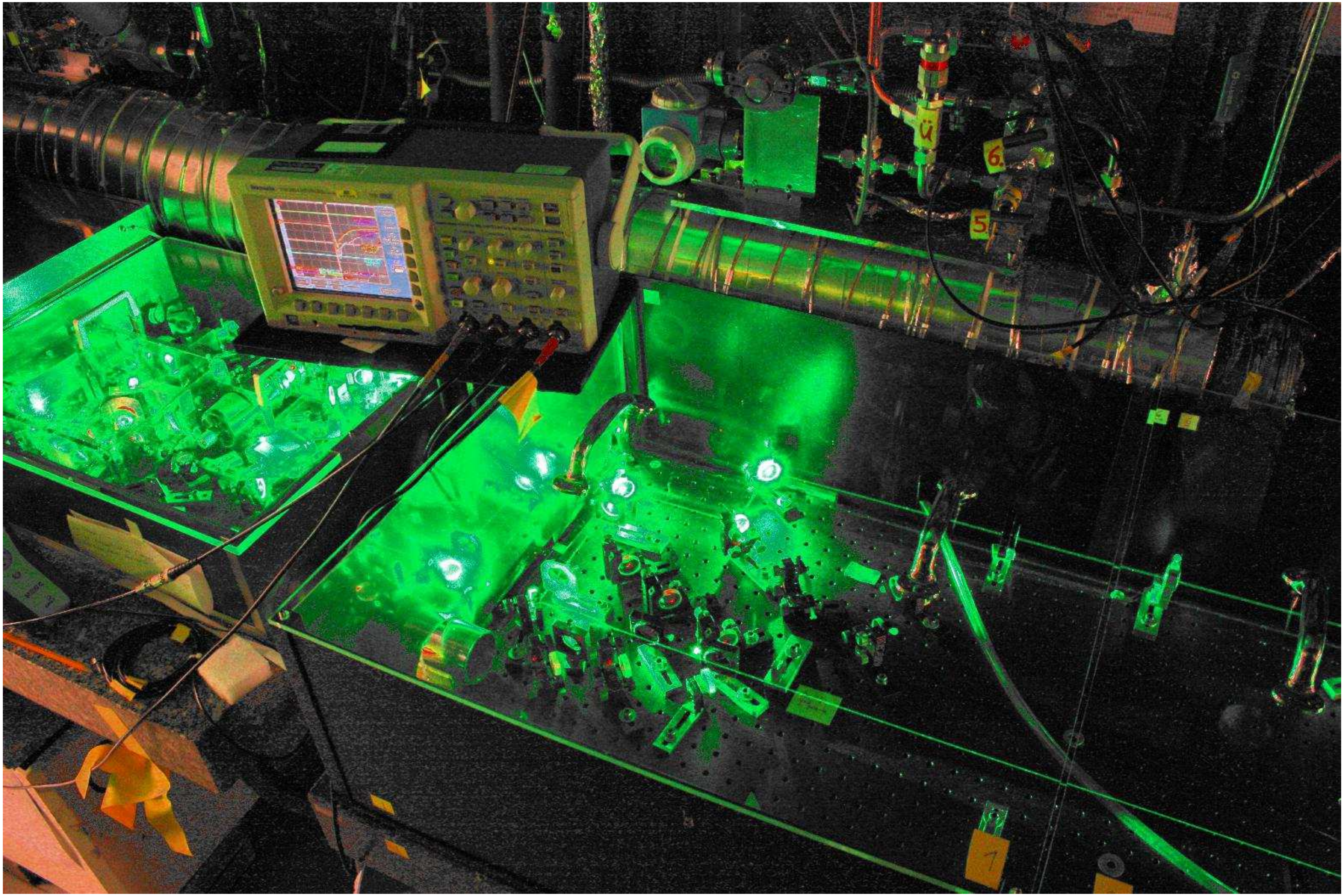
Disk amplifier laser heads



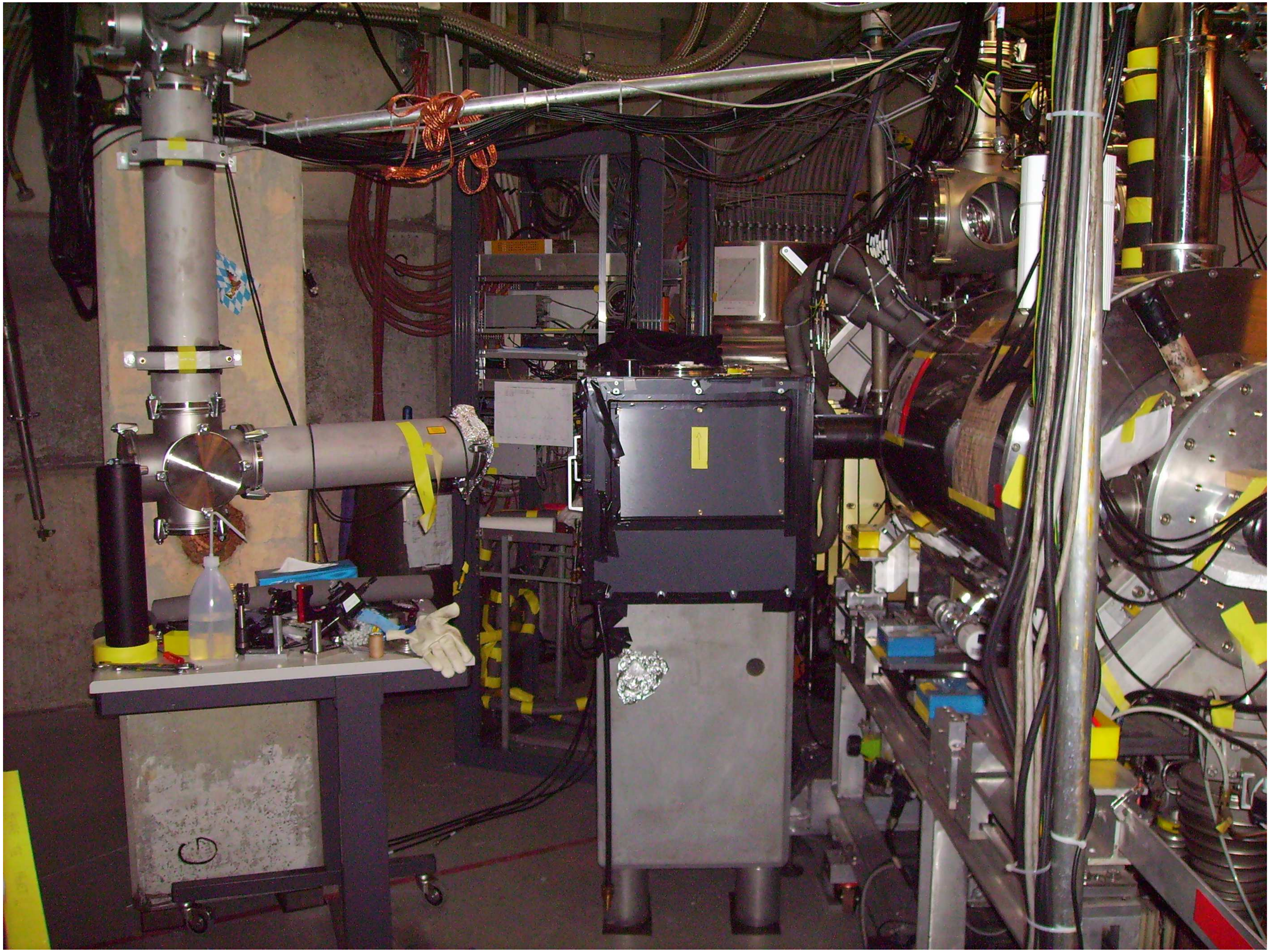
Disk laser doubling stages



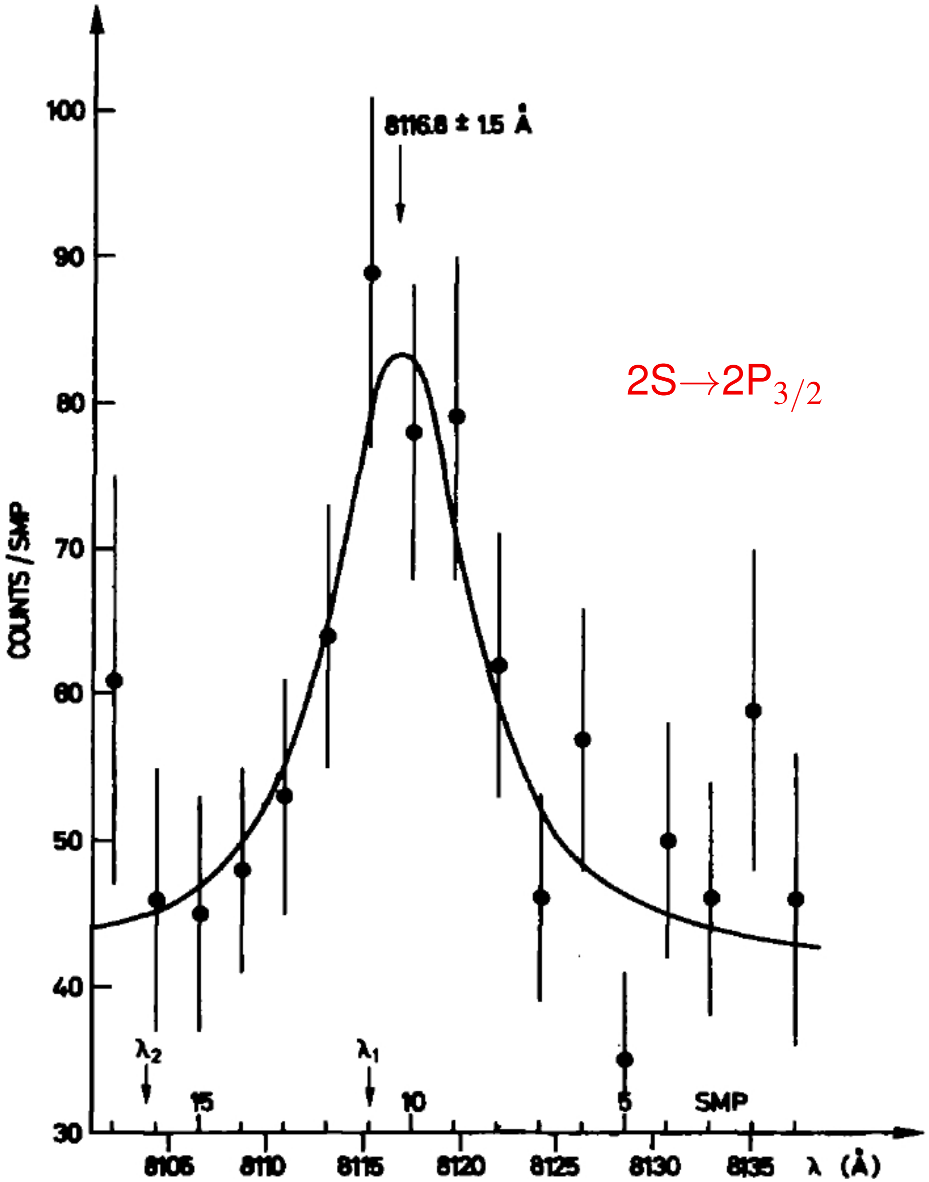
TiSa lasers and Raman cell



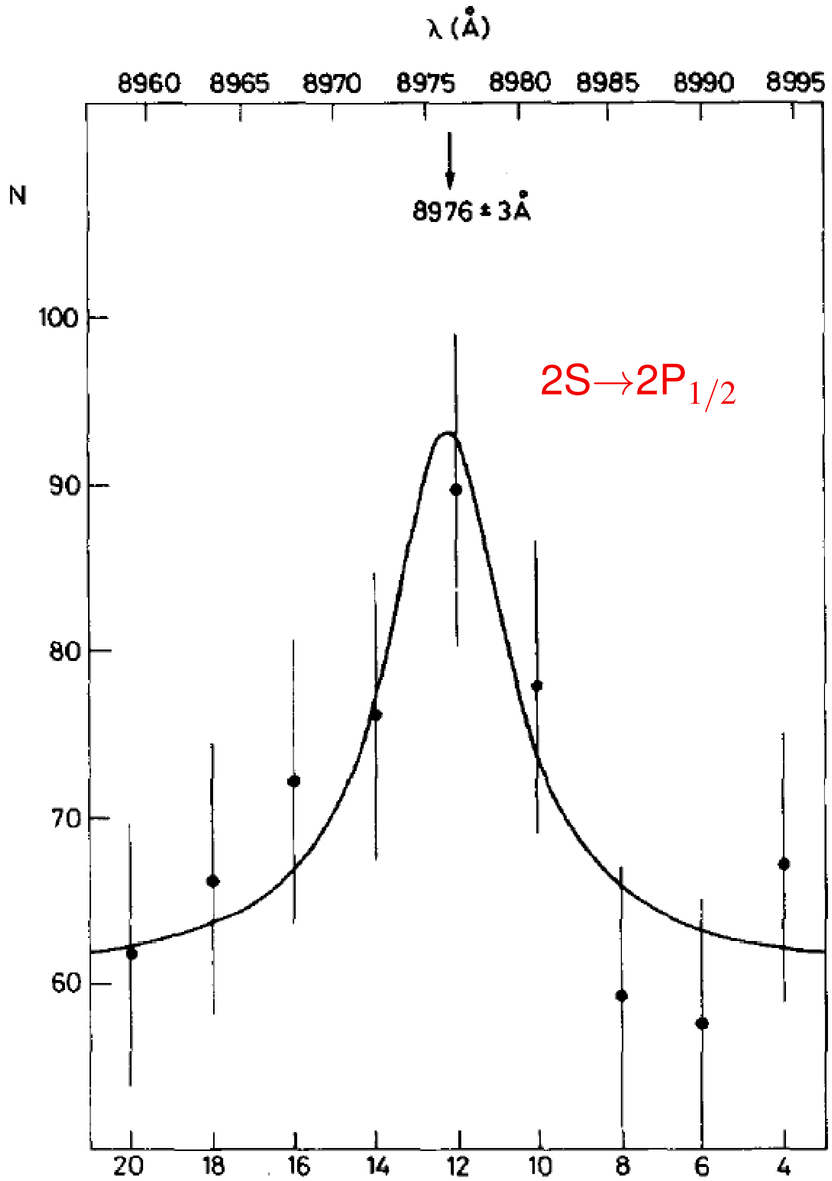
Laser beam tube



Old μHe^+ resonances

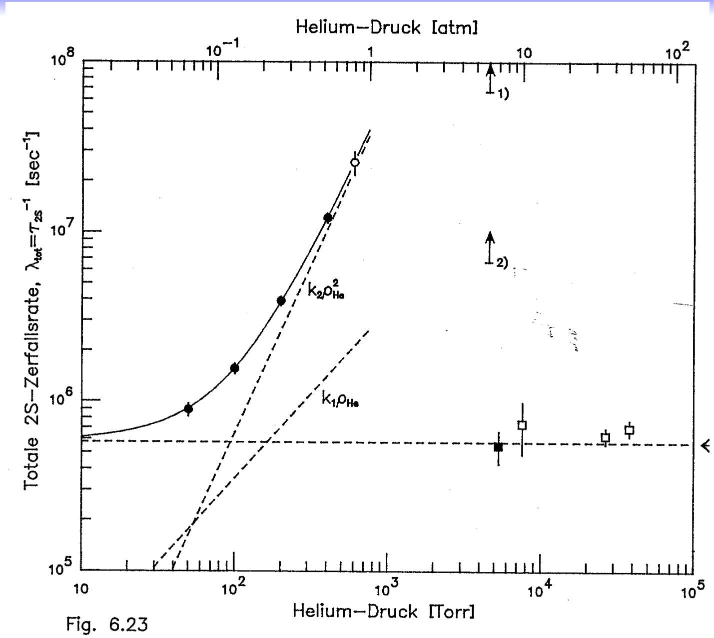


Carboni et al, Nucl. Phys. A273, 381 (1977)



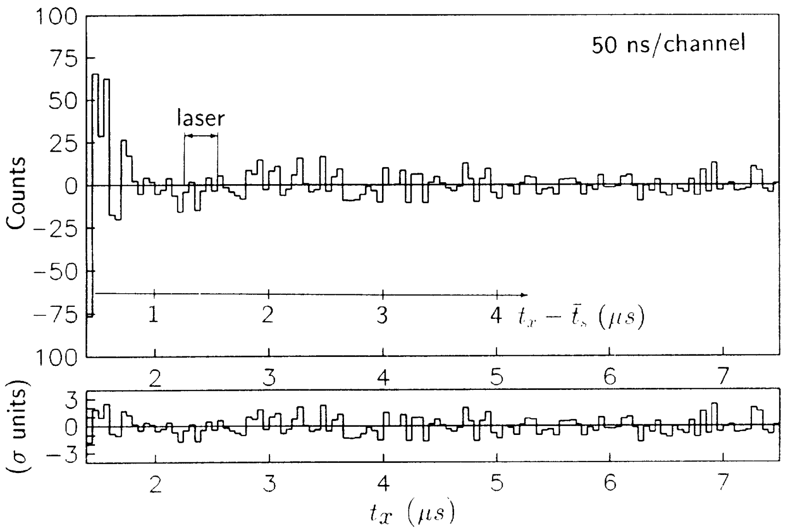
Carboni et al, Phys. Lett. 73B, 229 (1978)

$\mu He^+(2S)$ lifetime

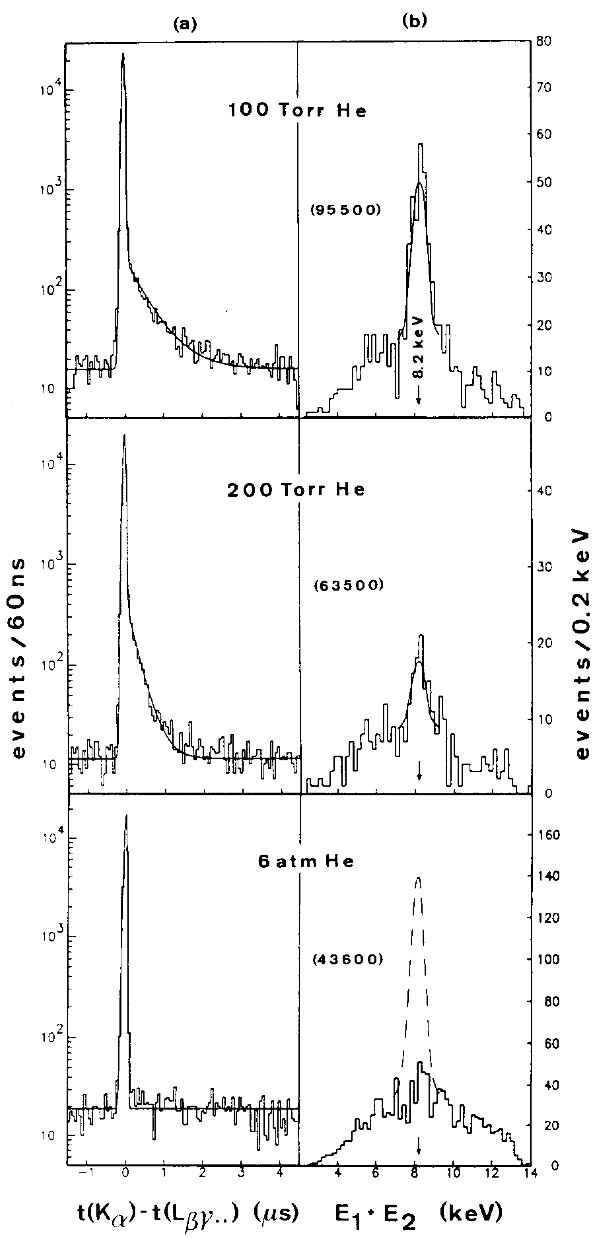


Dittus, PhD thesis ETH Zurich (1985)

laser exp.:



Hauser *et al.*, PRA 46, 2363 (1992)



von Arb *et al.*, PLB 136, 232 (1984)

1st resonance in muonic He-4