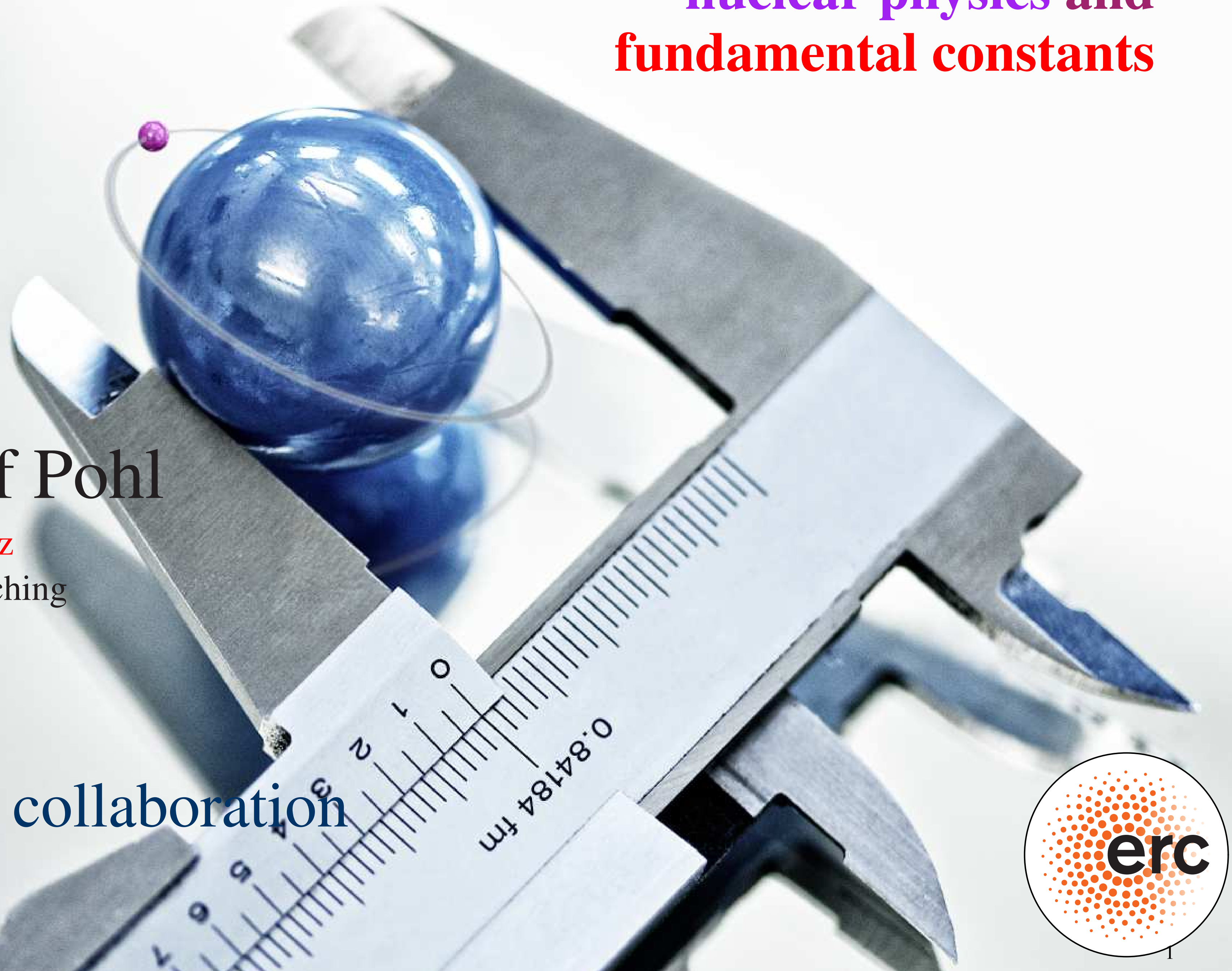
Shrinking the Proton

Laser spectroscopy 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

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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
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M. Abdou Ahmed, T. Graf, A. Voss, B. Weichelt	IFSW, Uni Stuttgart, Germany
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P. Amaro, J.P. Santos	Uni Lisbon, Portugal
L. Ludhova, P.E. Knowles, L.A. Schaller	Uni Fribourg, Switzerland
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P. Rabinowitz	Uni Princeton, USA

Hydrogen group at MPQ

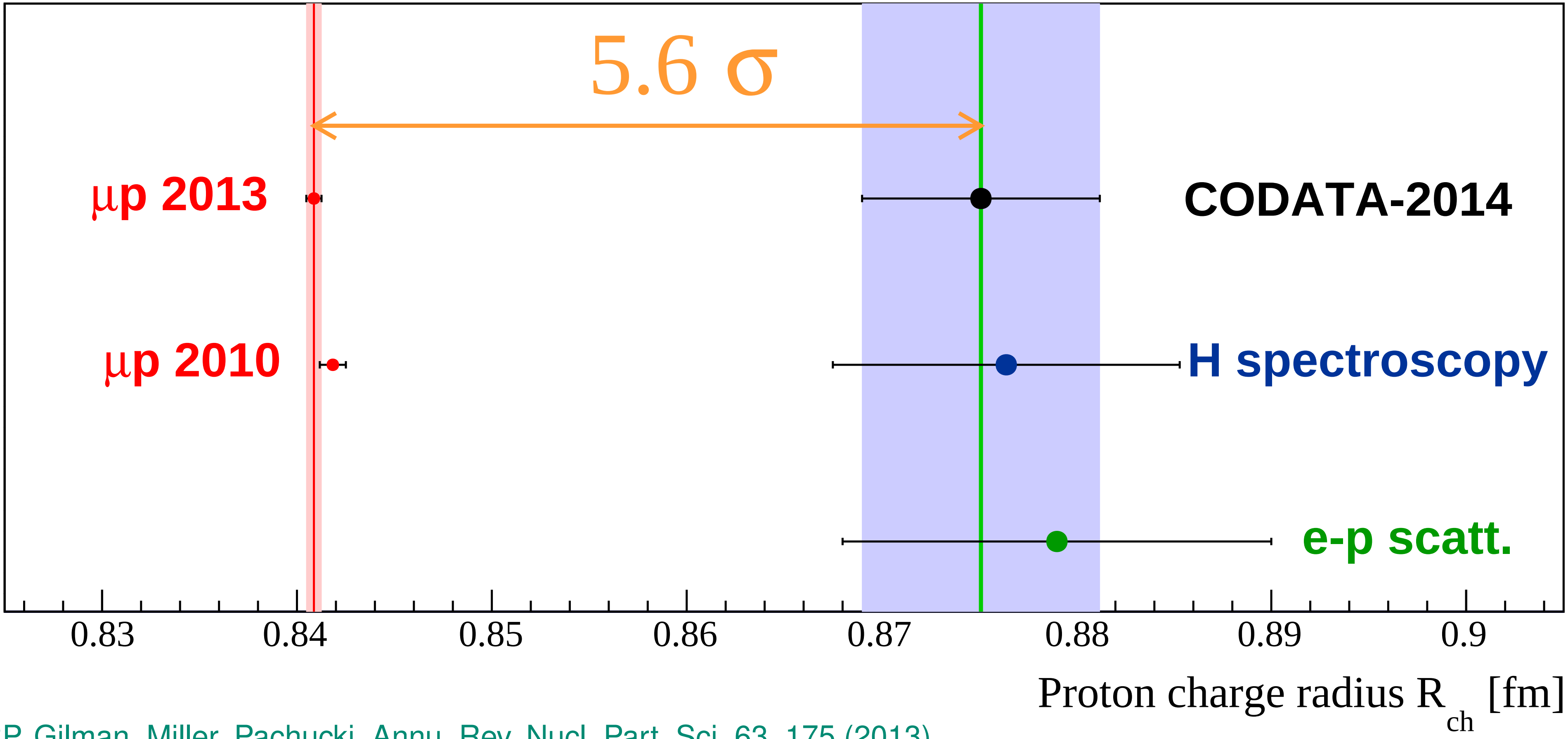
A. Beyer, A. Grinin, L. Maisenbacher, A. Matveev, C.G. Parthey, J. Alnis, D.C. Yost, E. Peters, R. Pohl, Th. Udem, T.W. Hänsch	MPQ, Garching, Germany
K. Khabarova, N. Kolachevksy	Lebedev Inst., Moscow, Russia

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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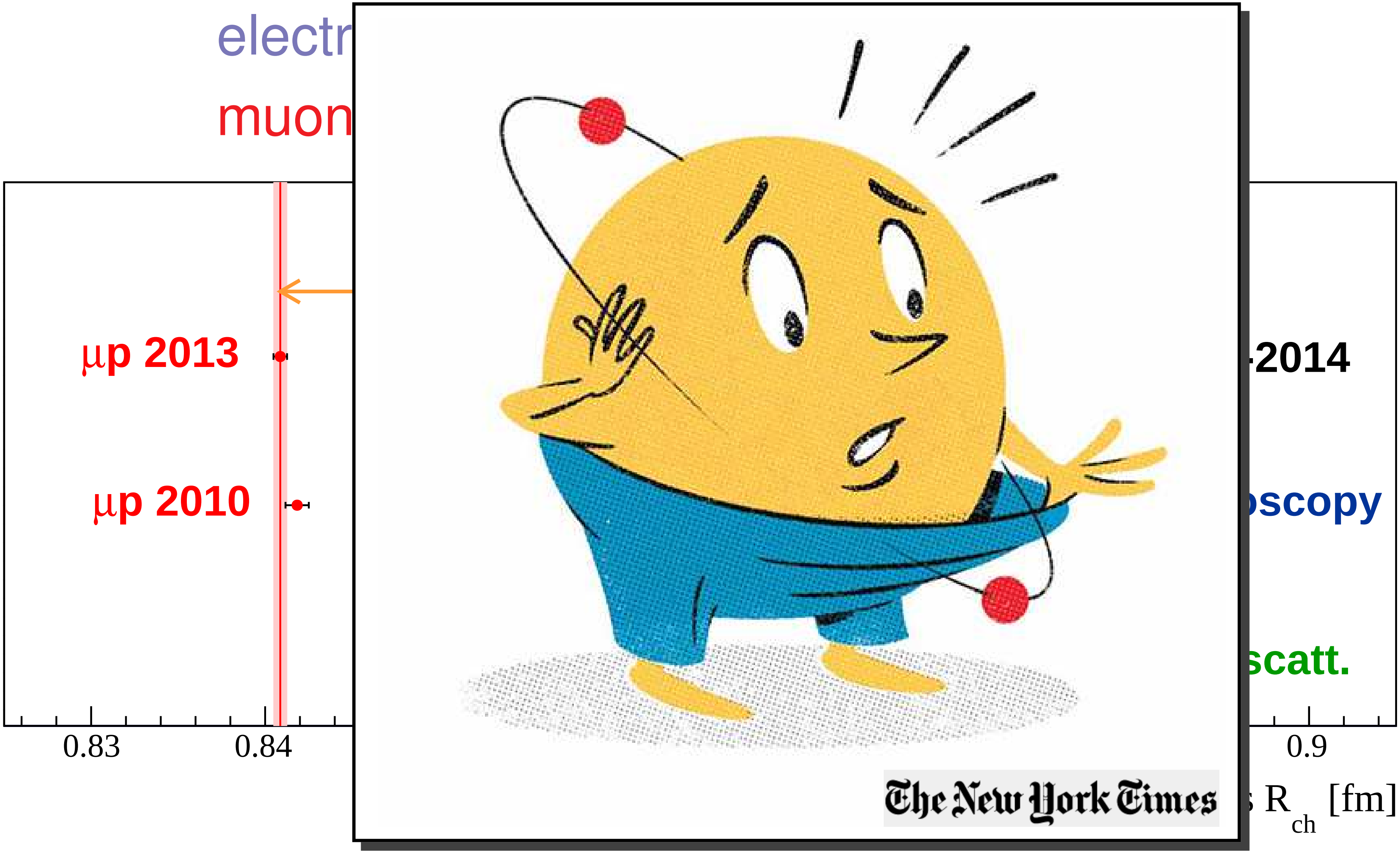
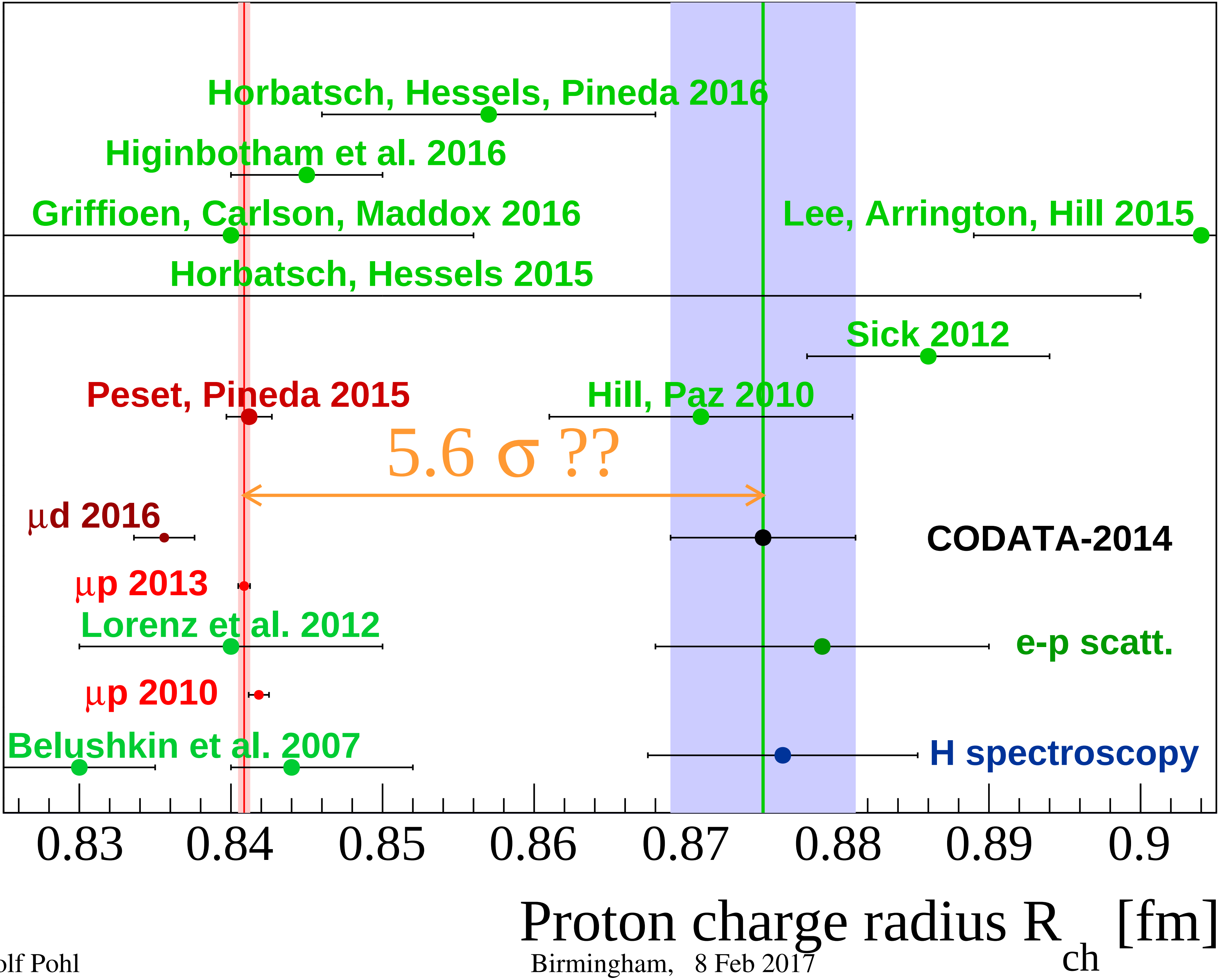


The proton radius puzzle???



Muons in the news

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

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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

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AAPPS

Volume 23 | Number 2 | APRIL 2013 **Bulletin**

Proton Size Puzzle Reinforced

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Feature Articles
- Neutrino Oscillation and Mixing
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Institutes in Asia Pacific
- Department of Physics Yonsei University
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INSIDE THE NEANDERTHAL BRAIN
First hints of how their minds differed from ours

NewScientist

WEEKLY July 20 - 26, 2013

TINY PARTICLE BIG PROBLEM

The humble proton is nothing like we expected

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EVOLUTION IN MINIATURE
It works differently if you're small

CAR HACKING
Could cyberattackers arrange a crash?

LONG STORY
How the Diplodocus got its neck

WINDS OF CHANGE
Gale-force warnings from Antarctica

Science and technology news www.newscientist.com US jobs in science

Muons in the news

J. Bernauer, RP

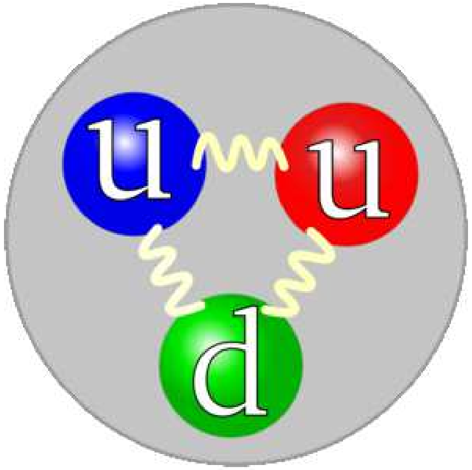
Muons in the news

J. Bernauer, RP

Outline

- Introduction:
  How large are the proton, deuteron, helion, alpha...?
  Atomic vs. nuclear physics
- Muonic hydrogen:
  Size does matter!
- Laser spectroscopy of muonic atoms/ions
- New measurements:
  - Muonic deuterium → Another puzzle!
  - Muonic helium
  - Regular hydrogen → New Rydberg constant!
- Future:
  - HFS in muonic hydrogen and helium-3
  - X-ray spectroscopy of radium etc.
  - Lamb shift in muonic Li, Be, ...
  - 1S-2S in regular tritium (triton radius)
  - ...

The Proton



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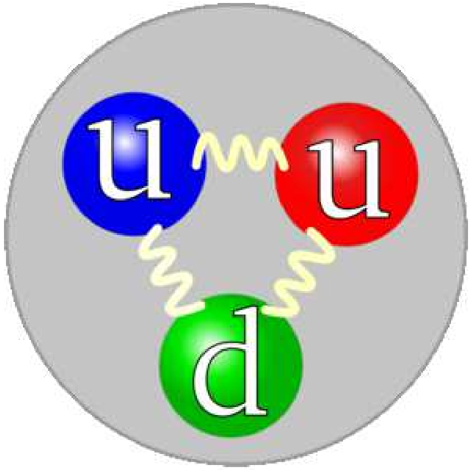

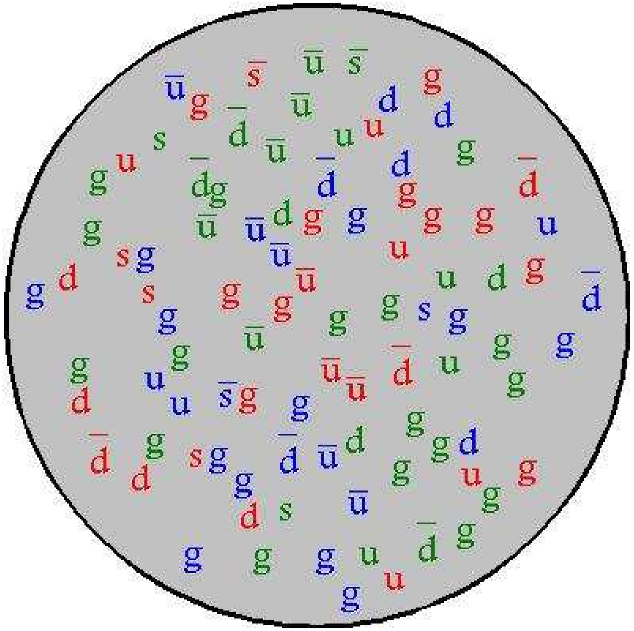

Ernest Rutherford (1871 - 1937)

half-life; α and β rays

1908: Nobel prize Chemistry:

"for his investigations into the disintegration of the elements, and the chemistry of radioactive substances"

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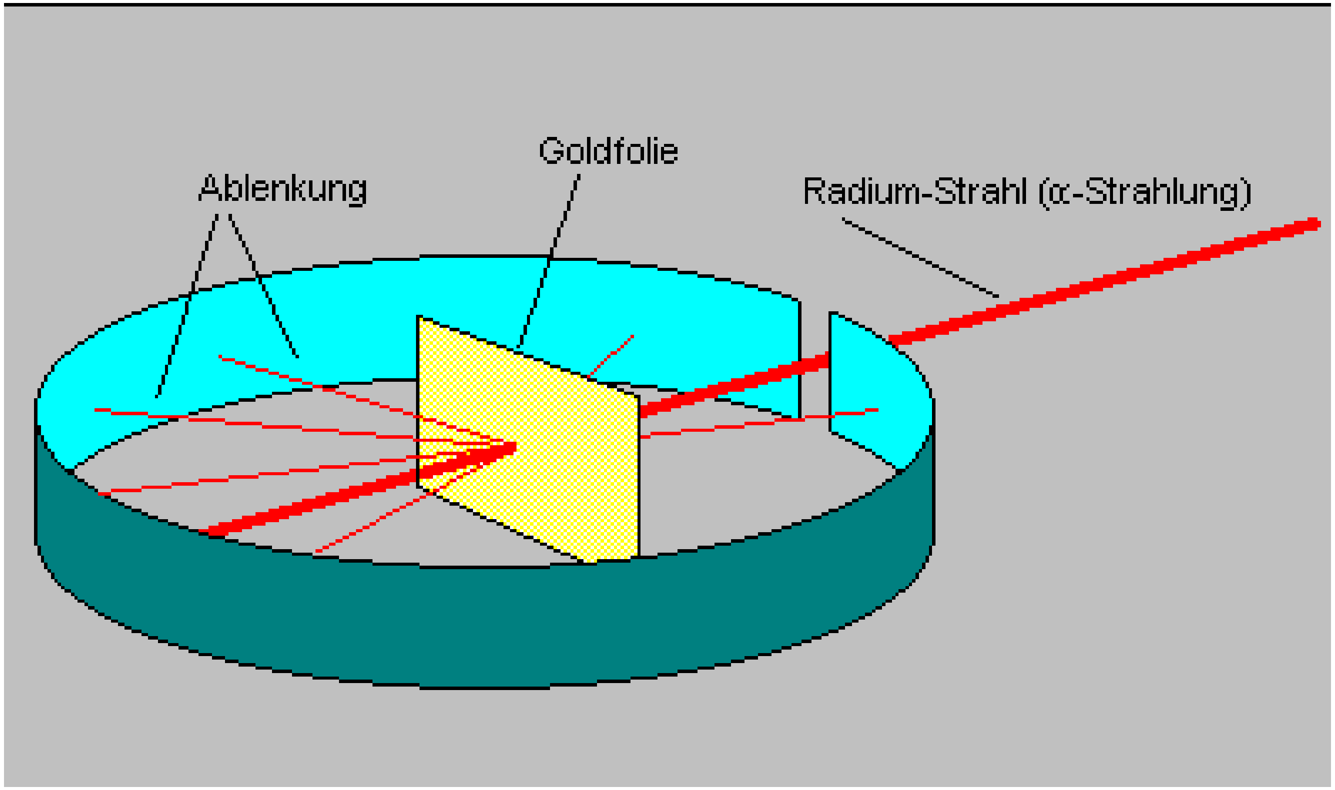

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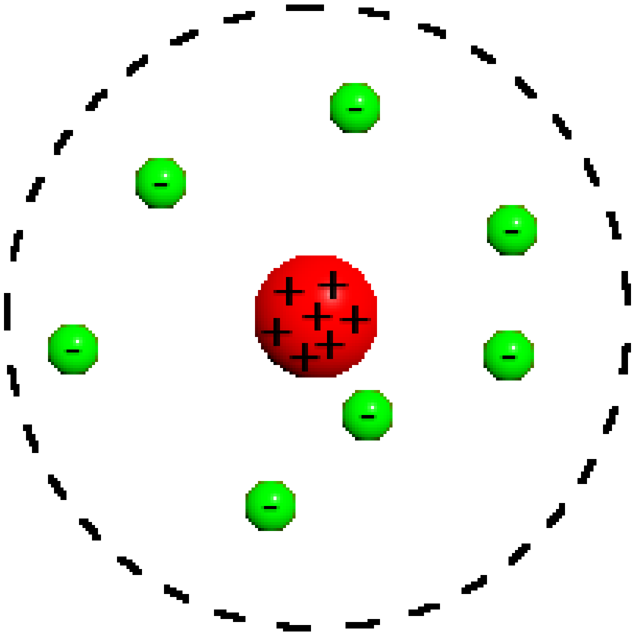
$\Rightarrow$ Atom = small, heavy, positive nucleus + electrons.



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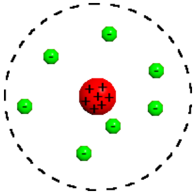

1917: Discovery of the proton.

$$^{14}\text{N} + \alpha \rightarrow {}^{17}\text{O} + \text{p}$$

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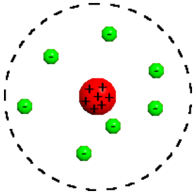

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100 years of protons!

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1961: Nobel prize Physics (with Rudolf Mössbauer):

"for his pioneering studies of **electron scattering** in atomic nuclei and for his consequent discoveries concerning the **structure of nucleons**"

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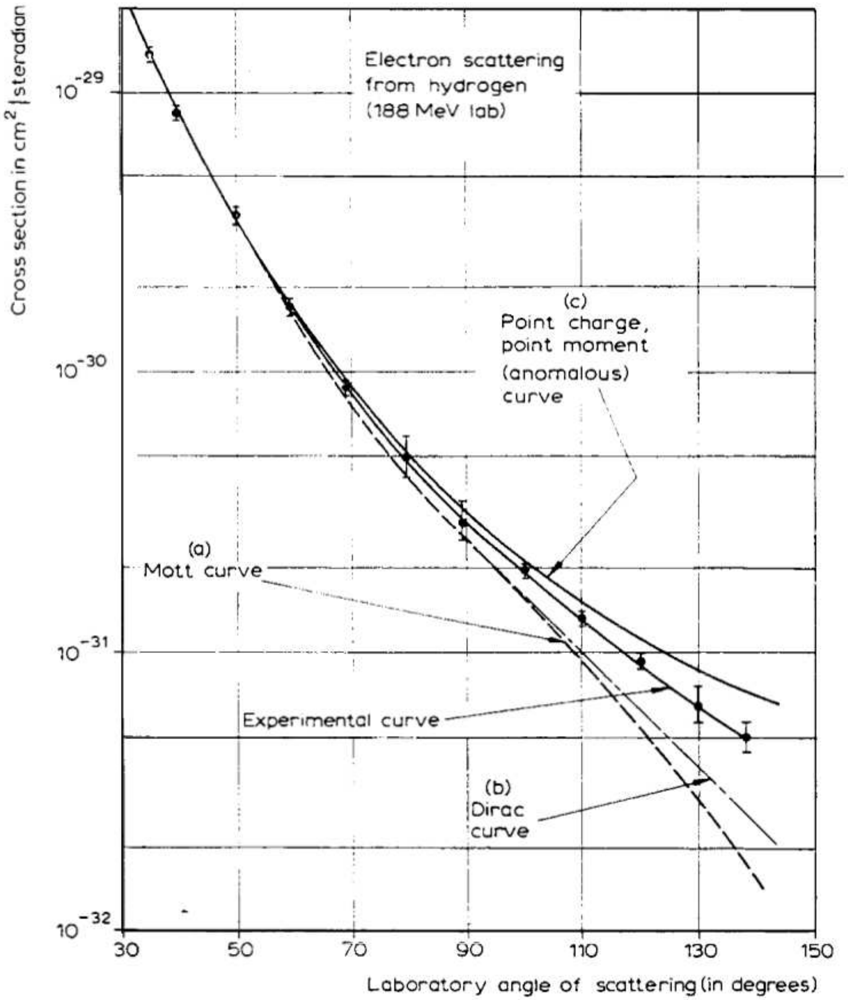

Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).

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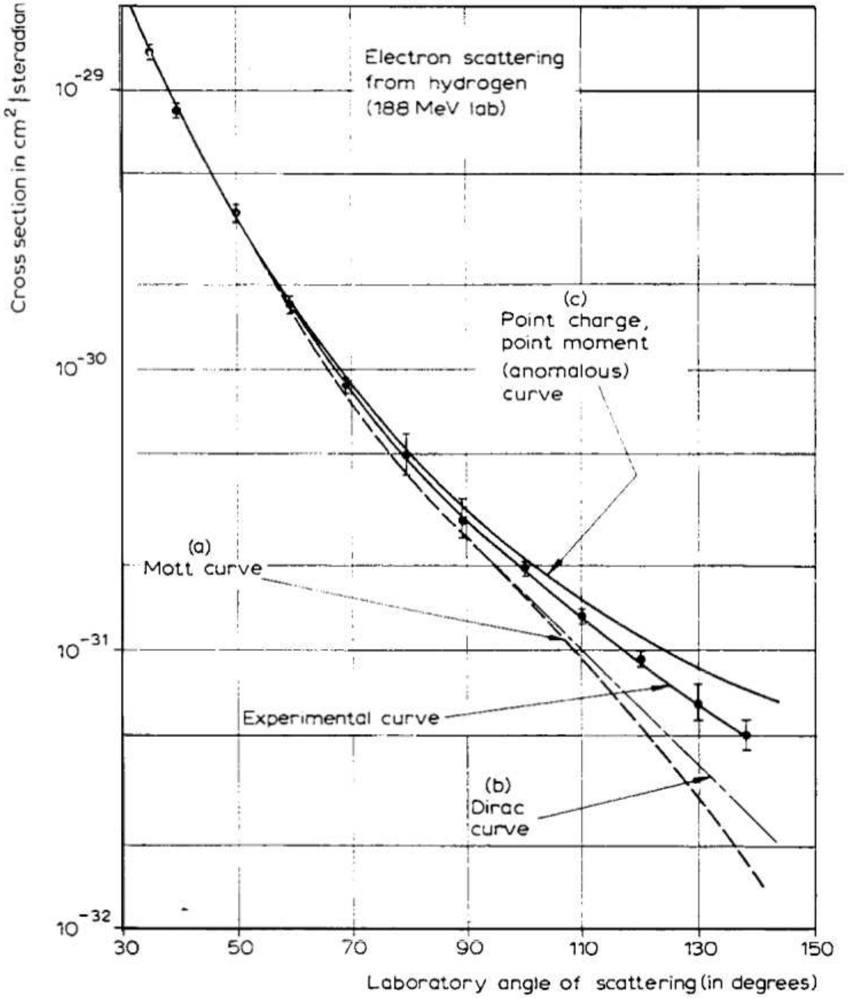

“Proton has a

diameter of 0.7×10^{-13} cm”

Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).

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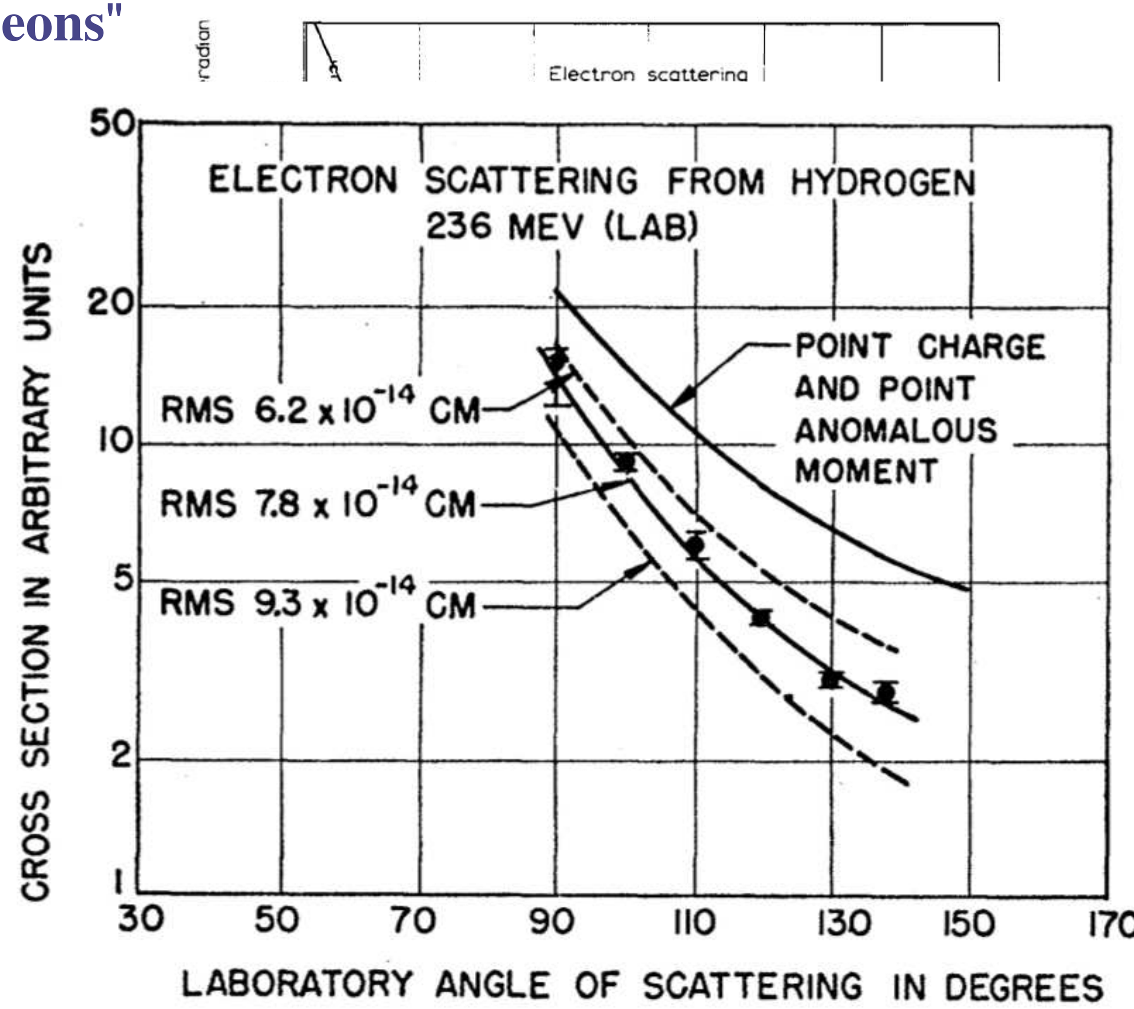


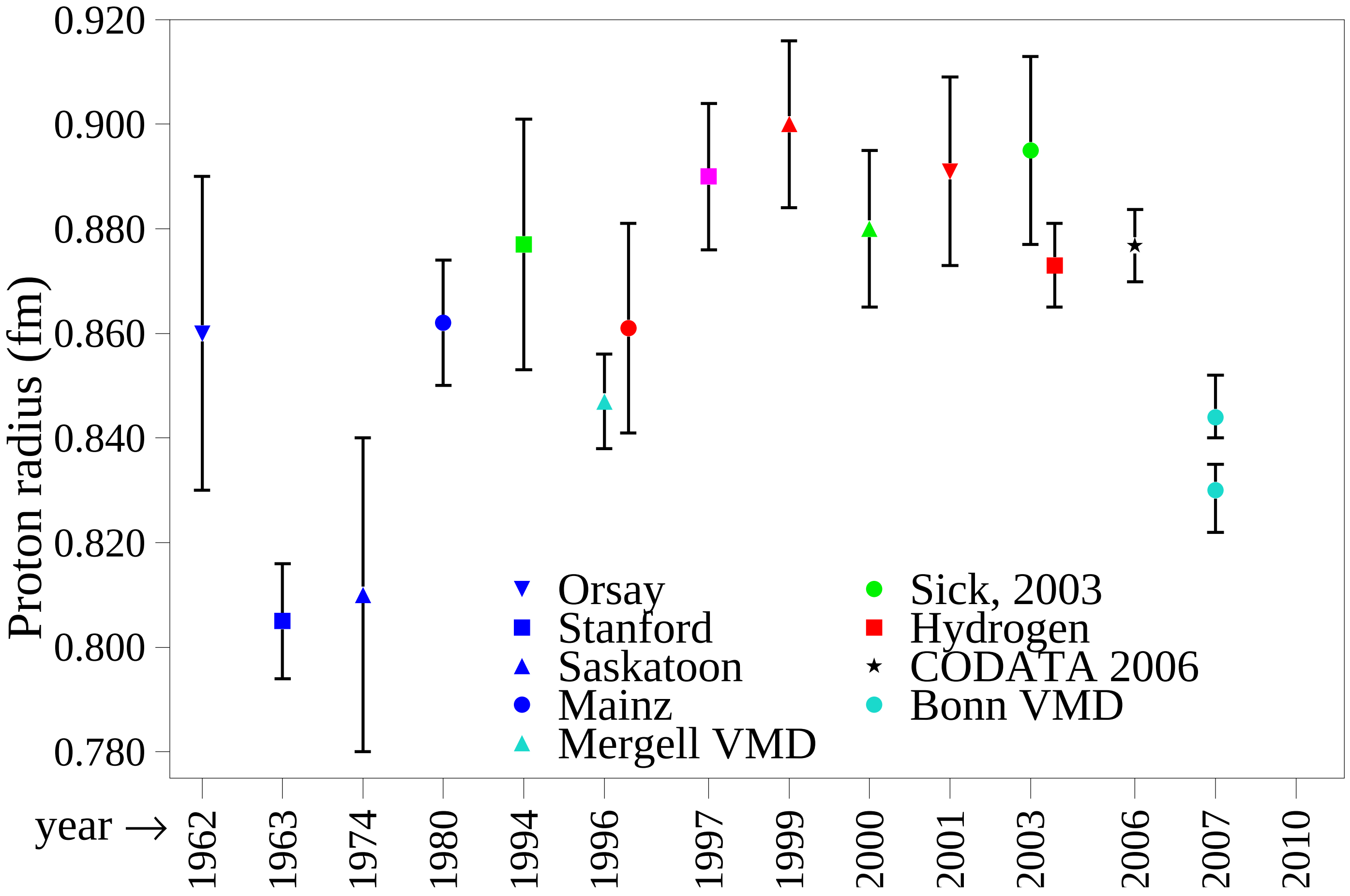
"The best fit lies near

diameter of 0.78×10^{-13} cm"

Hofstadter, McAllister, Phys. Rev. 98, 217 (1955).
Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).

Proton radius vs. time

The proton rms charge radius over the last 50 years.



● ● ● electron scattering

slope of G_E at $Q^2 = 0$

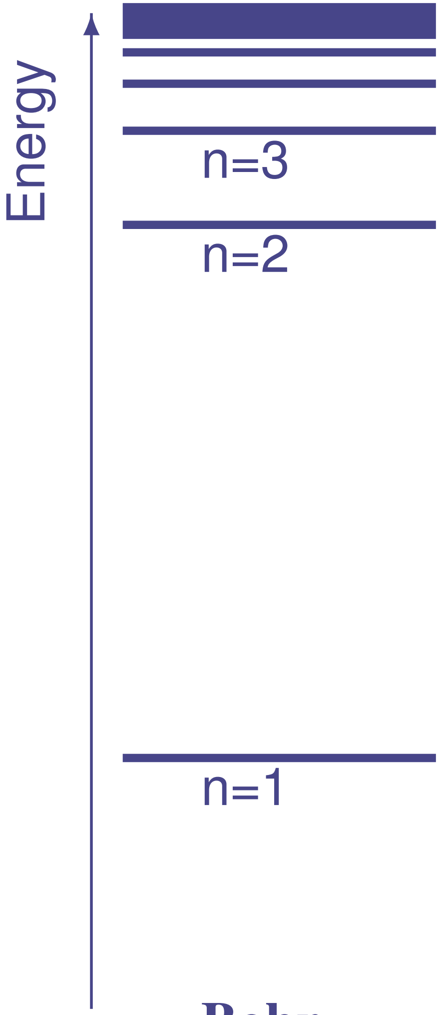
● ● hydrogen spectr.

Lamb shift (S-states)

e-p scattering: r_p = 0.895(18) fm ($u_r = 2\,\%$)

Hydrogen: r_p = 0.8760(78) fm ($u_r = 0.9\,\%$)

Hydrogen

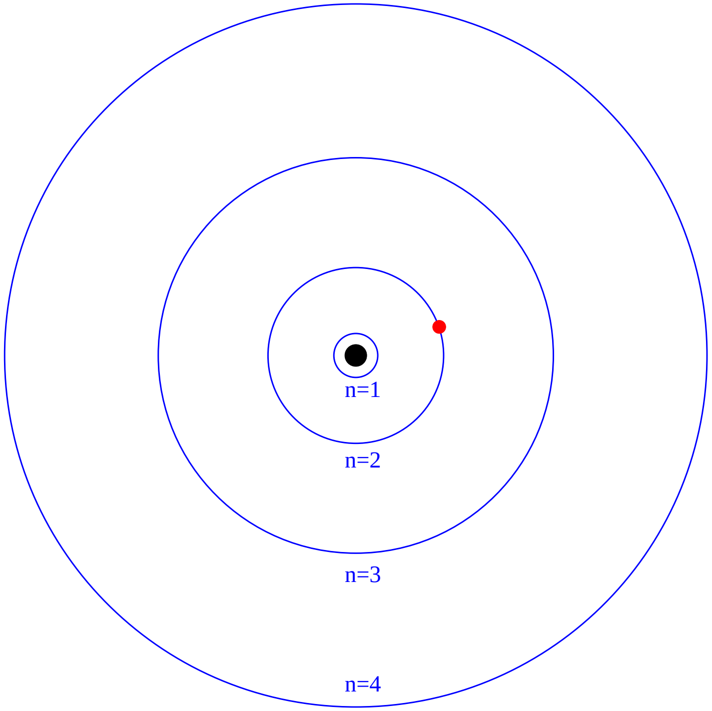


Bohr

$$E = R_\infty / n^2$$

$$V \sim 1/r$$

Bohr model of the hydrogen atom



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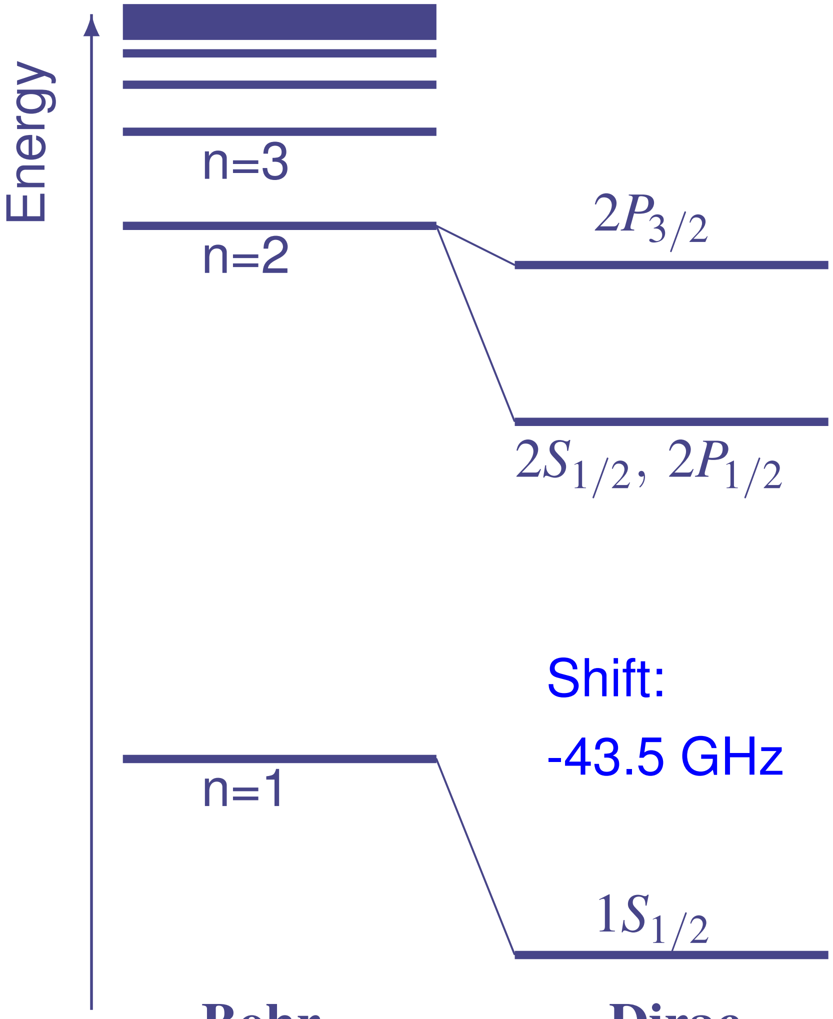


Energy

n=3

n=2

n=1

$2P_{3/2}$

$2S_{1/2},\ 2P_{1/2}$

$1S_{1/2}$

Shift:

-43.5 GHz

Bohr

Dirac

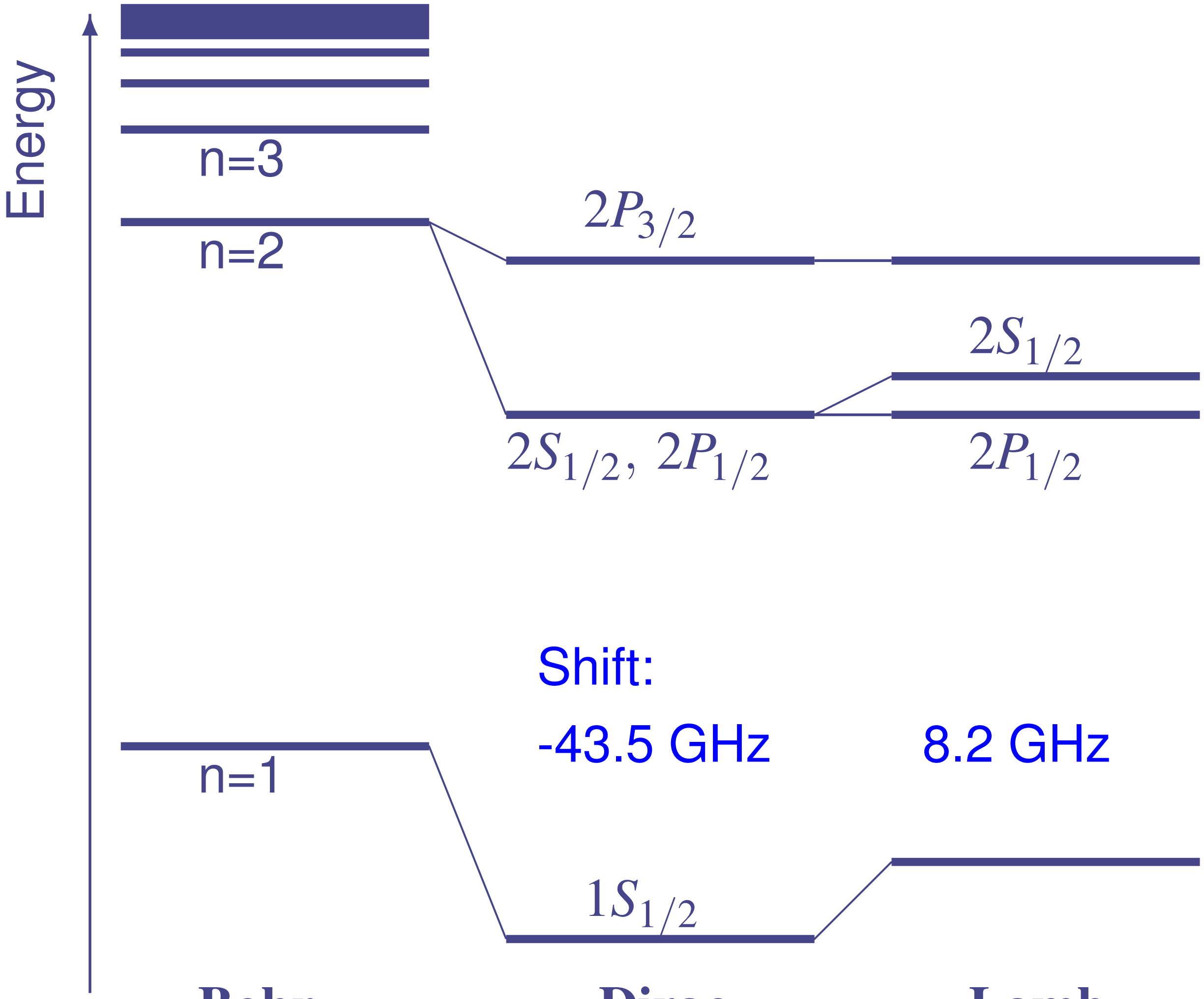
$E = R_\infty / n^2$

$V \sim 1/r$

e^- spin

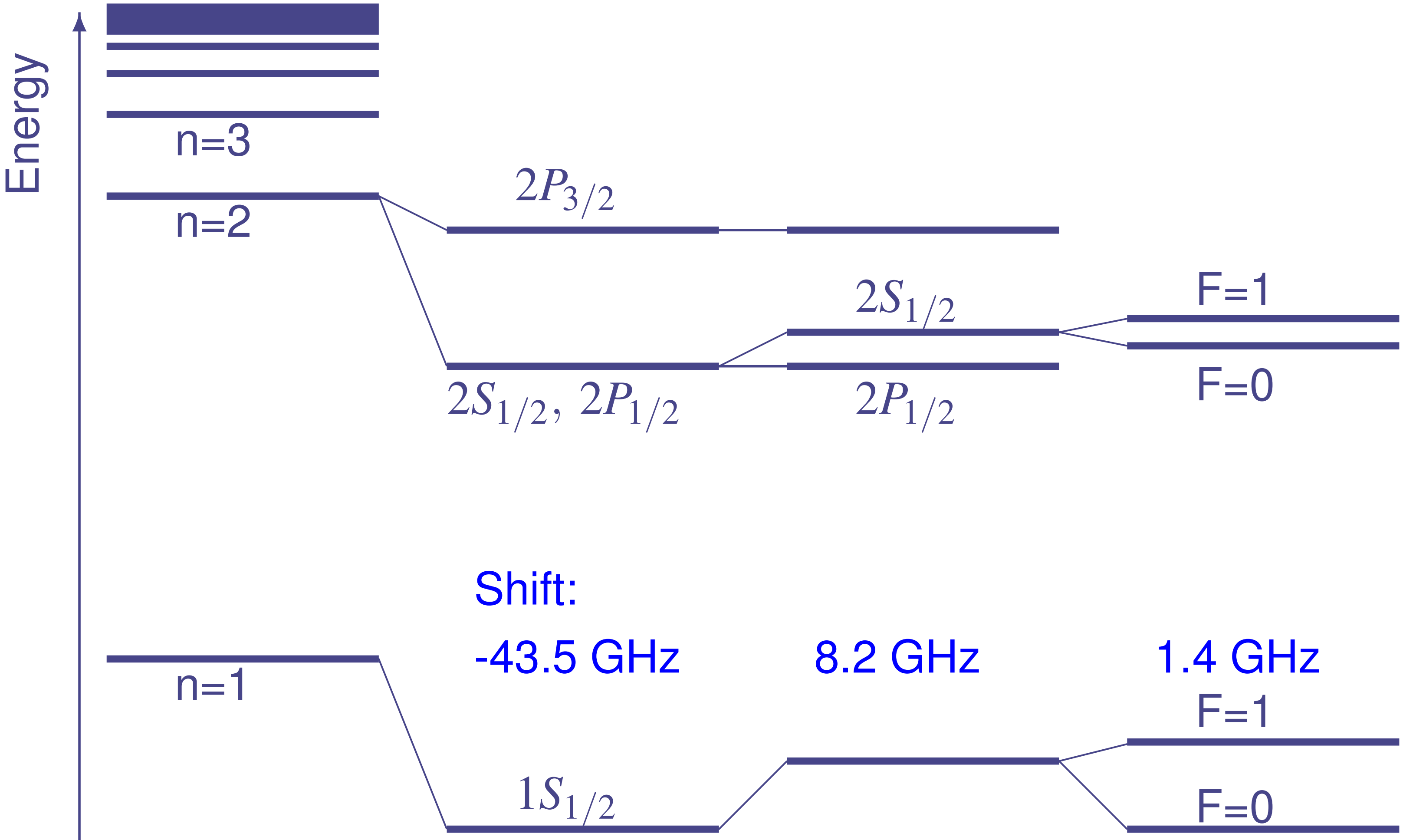
relativity

Hydrogen



Bohr	**Dirac**	**Lamb**
$E = R_\infty / n^2$ $V \sim 1/r$	e$^-$ spin relativity	QED

Hydrogen



Energy

n=3

n=2

$2P_{3/2}$

$2S_{1/2}$

F=1

$2S_{1/2},\ 2P_{1/2}$

$2P_{1/2}$

F=0

Shift:

-43.5 GHz

8.2 GHz

1.4 GHz

n=1

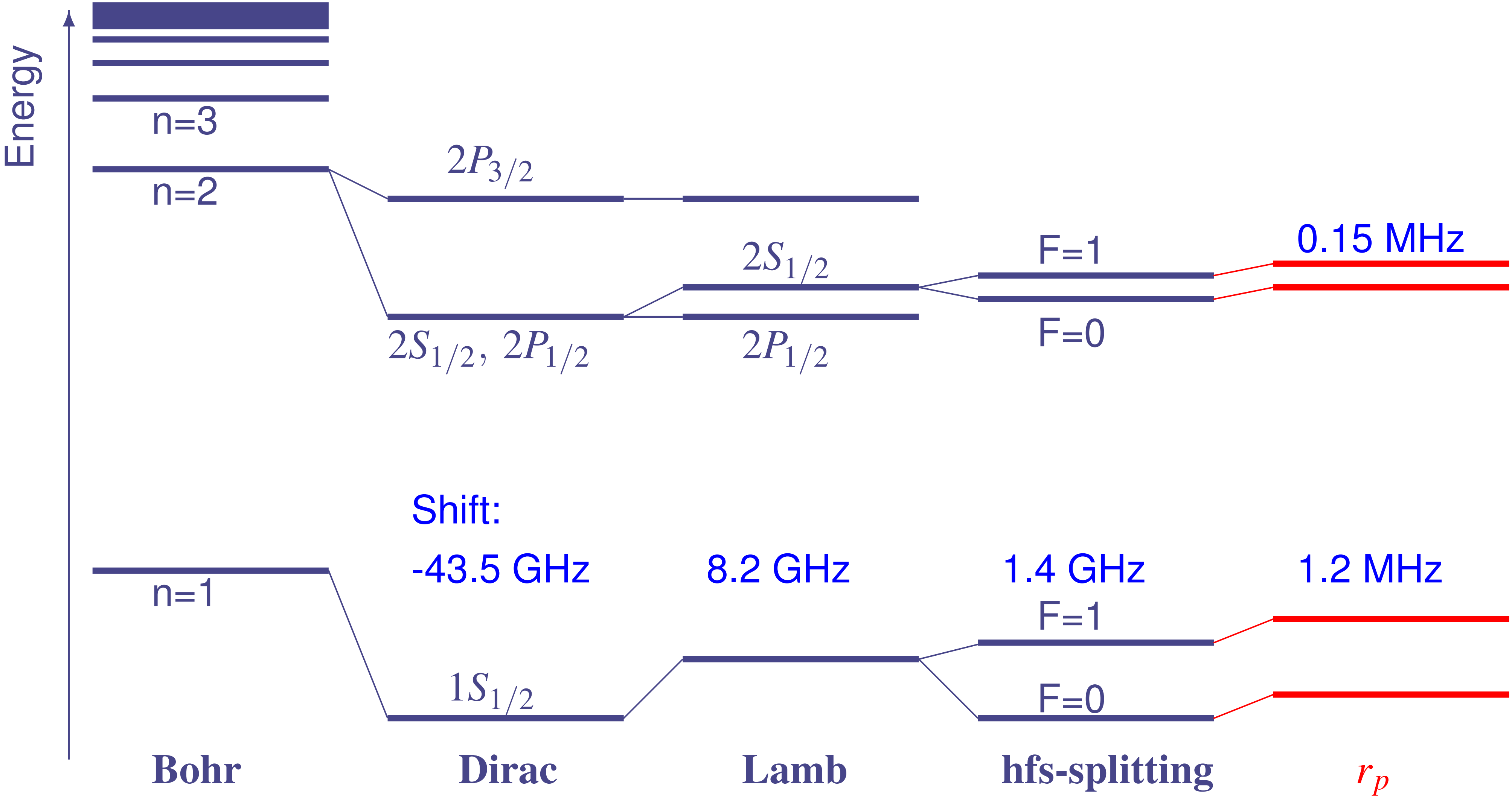
F=1

$1S_{1/2}$

F=0

Bohr	**Dirac**	**Lamb**	**hfs-splitting**
$E = R_\infty / n^2$ $V \sim 1/r$	e^- spin relativity	QED	proton-spin $H^{\text{hfs}} \sim \vec{\mu}_p \cdot \vec{\mu}_e$

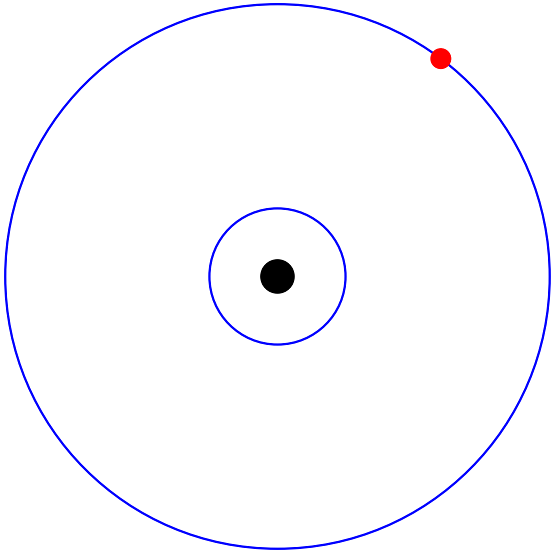
Hydrogen



Bohr	Dirac	Lamb	hfs-splitting	r_p
$E = R_\infty / n^2$ $V \sim 1/r$	e^- spin relativity	QED	proton-spin $H^{\text{hfs}} \sim \vec{\mu}_p \cdot \vec{\mu}_e$	proton size $V \not\sim 1/r$

Atomic physics

Bohr model of the atom



- Electrons orbit the nucleus

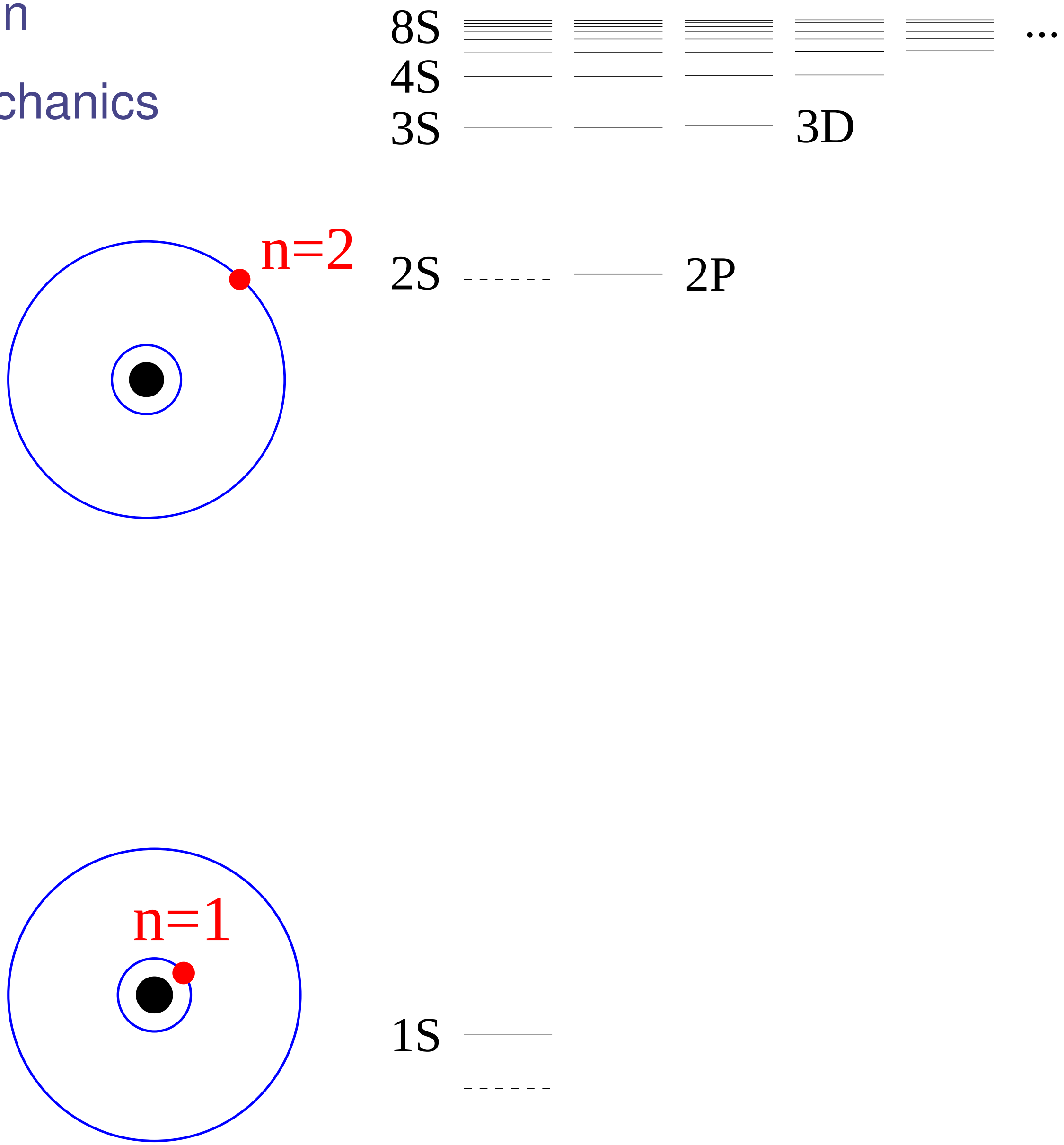
  “Planetary system”

- Hydrogen: 1 electron + 1 proton

Atomic physics

Spectrum of atomic hydrogen

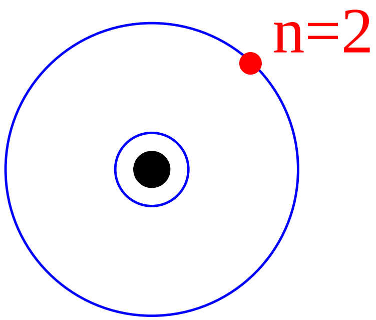
Bohr model → quantum mechanics

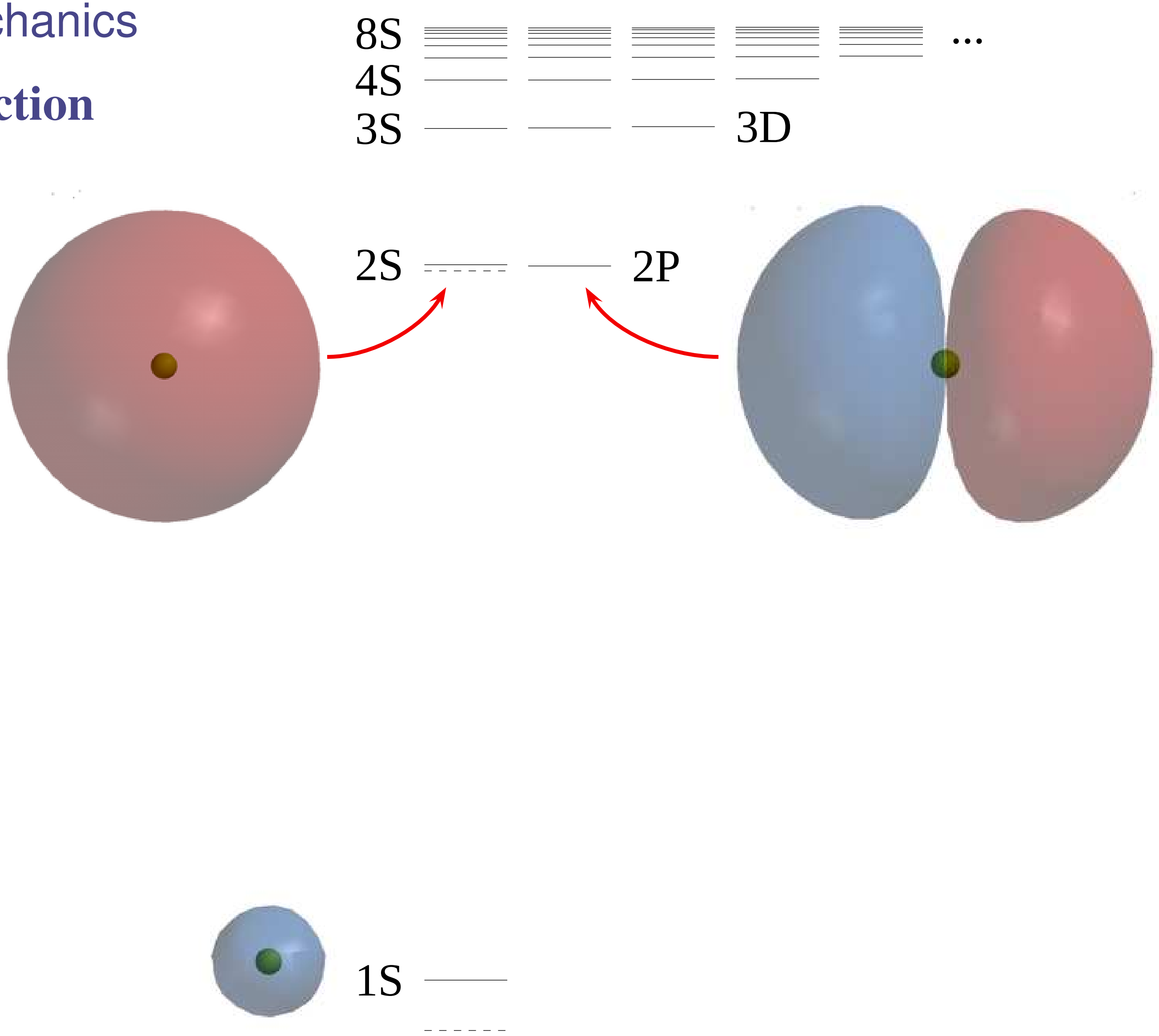


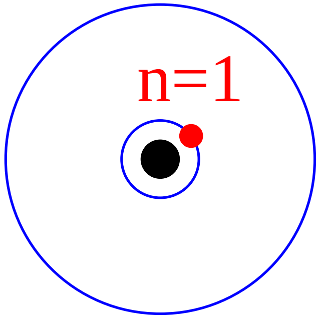
Atomic physics

Bohr model → quantum mechanics

planetary orbits → **wave function**



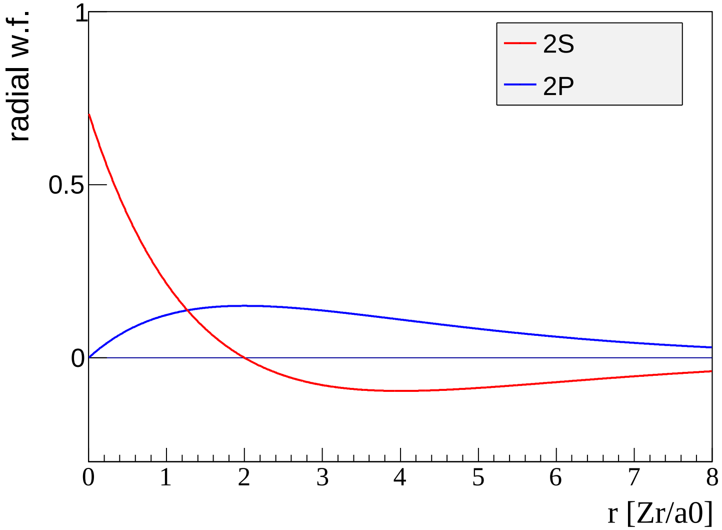


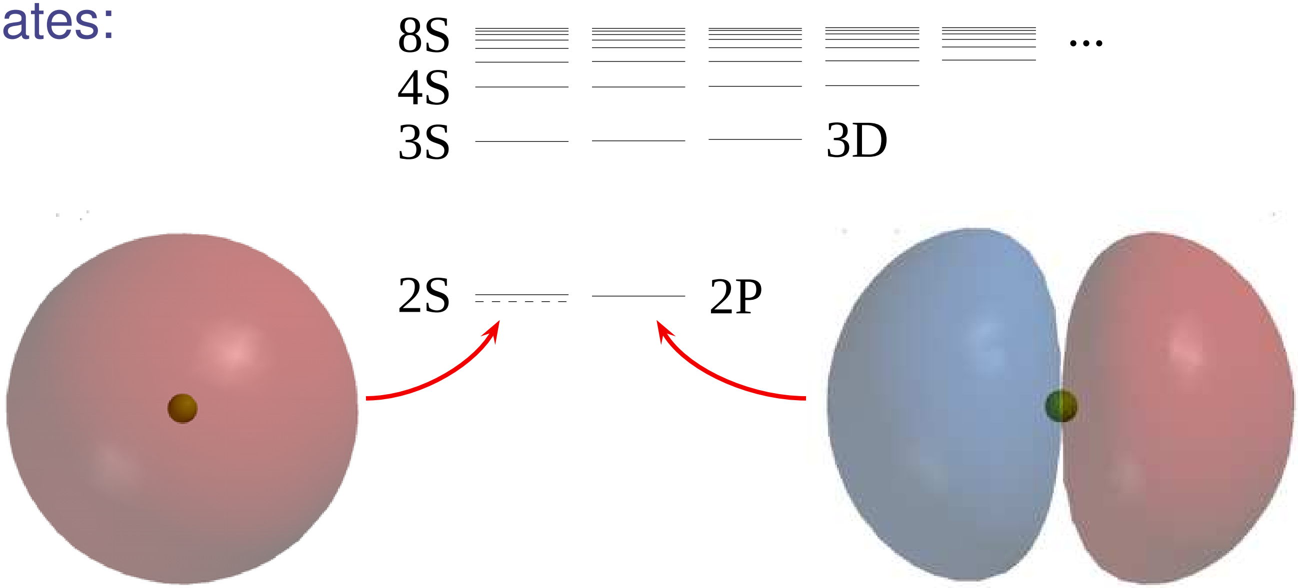


Orbital pictures from Wikipedia

Atomic and nuclear physics

Wave functions of S and P states:





S states: max. at r=0

Electron sometimes inside the proton.

S states are shifted.

Shift ist proportional to the

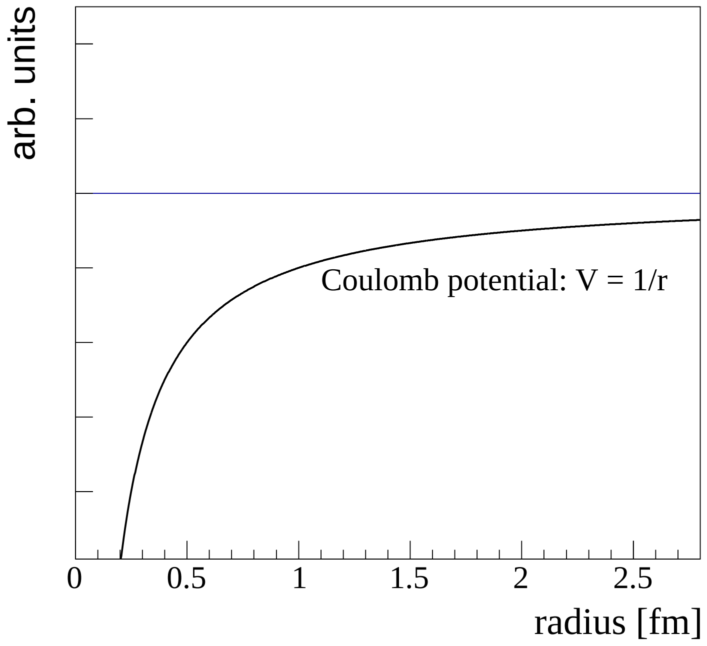
size of the proton

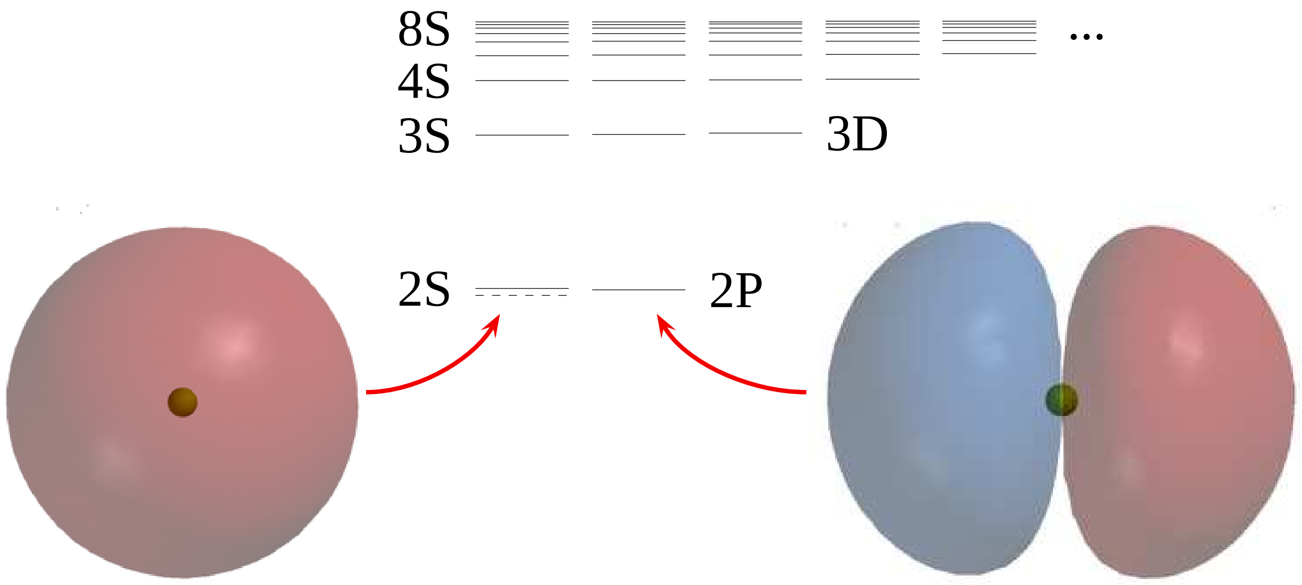
P states: zero at r=0

Electron is not inside the proton.

Orbital pictures from Wikipedia

Atomic and nuclear physics





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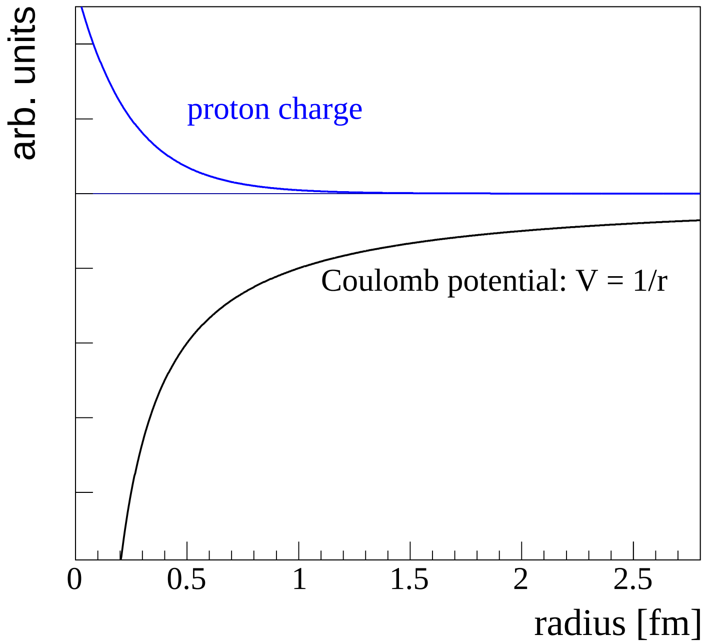

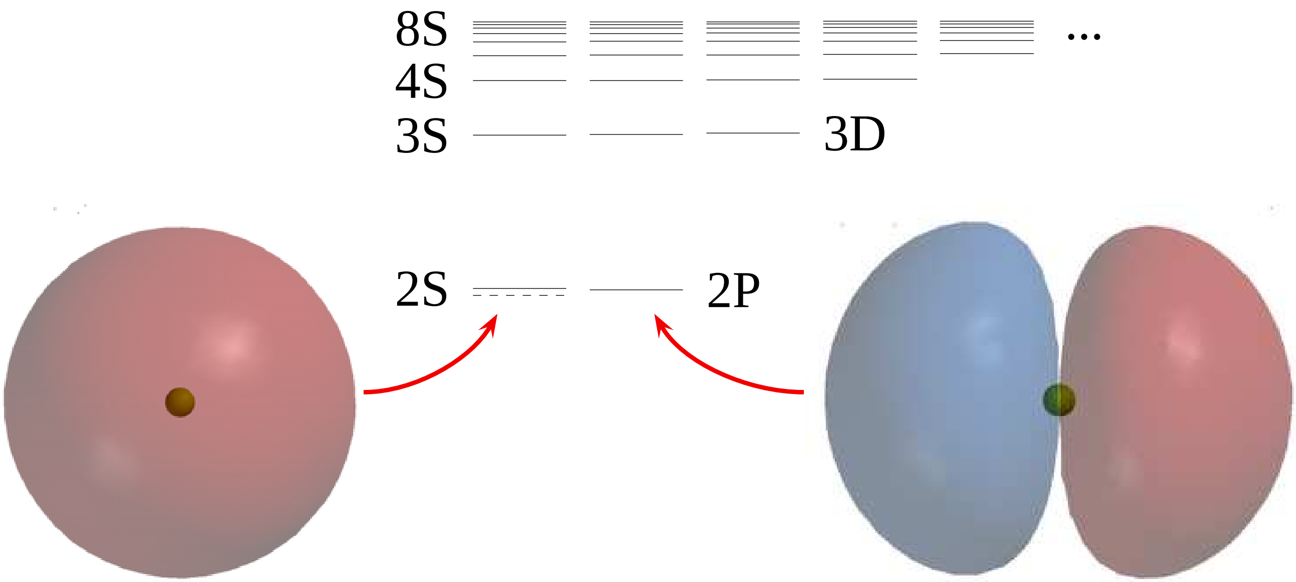

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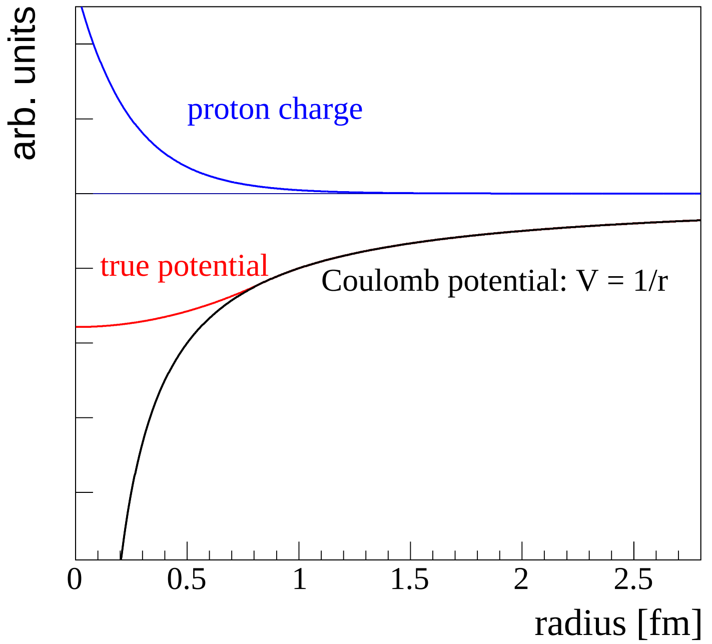

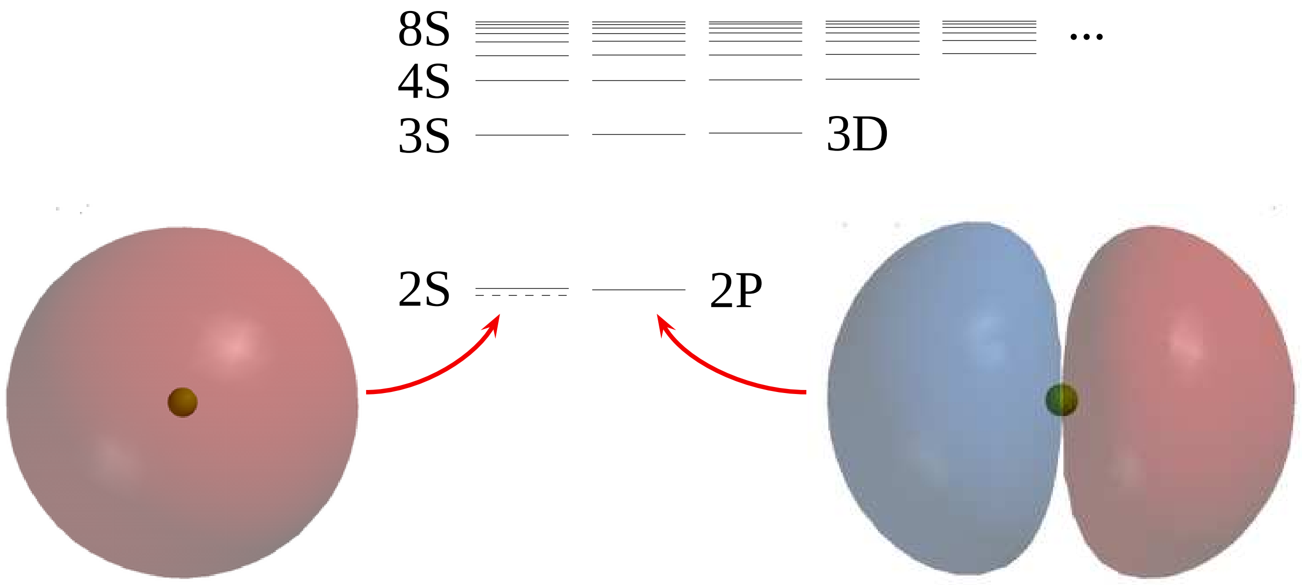

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Electron sometimes inside the proton.

S states are shifted.

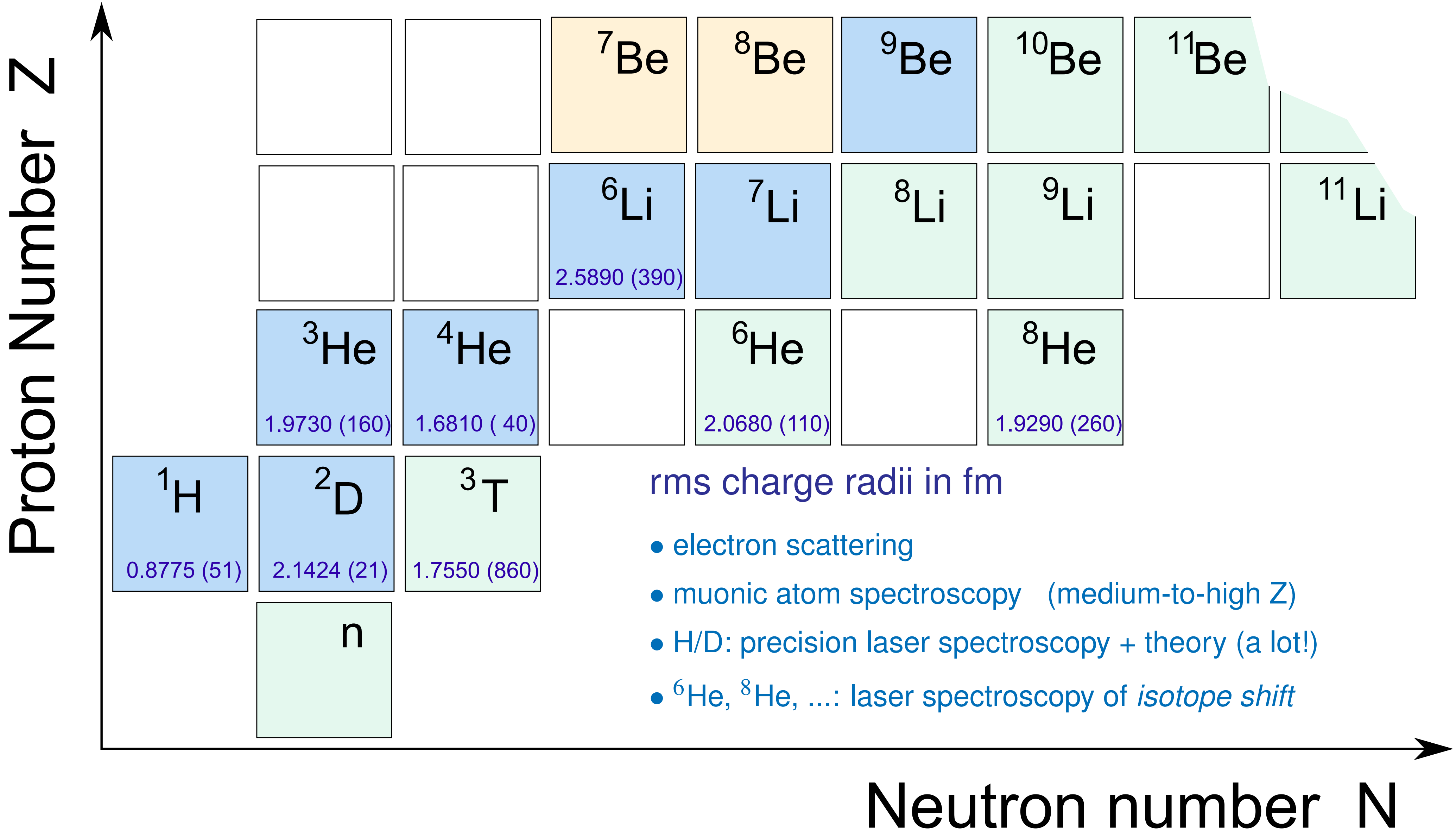
Shift ist proportional to the

size of the proton

Electron is not inside the proton.

Orbital pictures from Wikipedia

Charge radii of light nuclei



			^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	
			^{6}Li 2.5890 (390)	^{7}Li	^{8}Li	^{9}Li		^{11}Li
	^{3}He 1.9730 (160)	^{4}He 1.6810 (40)		^{6}He 2.0680 (110)		^{8}He 1.9290 (260)		
^{1}H 0.8775 (51)	^{2}D 2.1424 (21)	^{3}T 1.7550 (860)						
	n							

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*

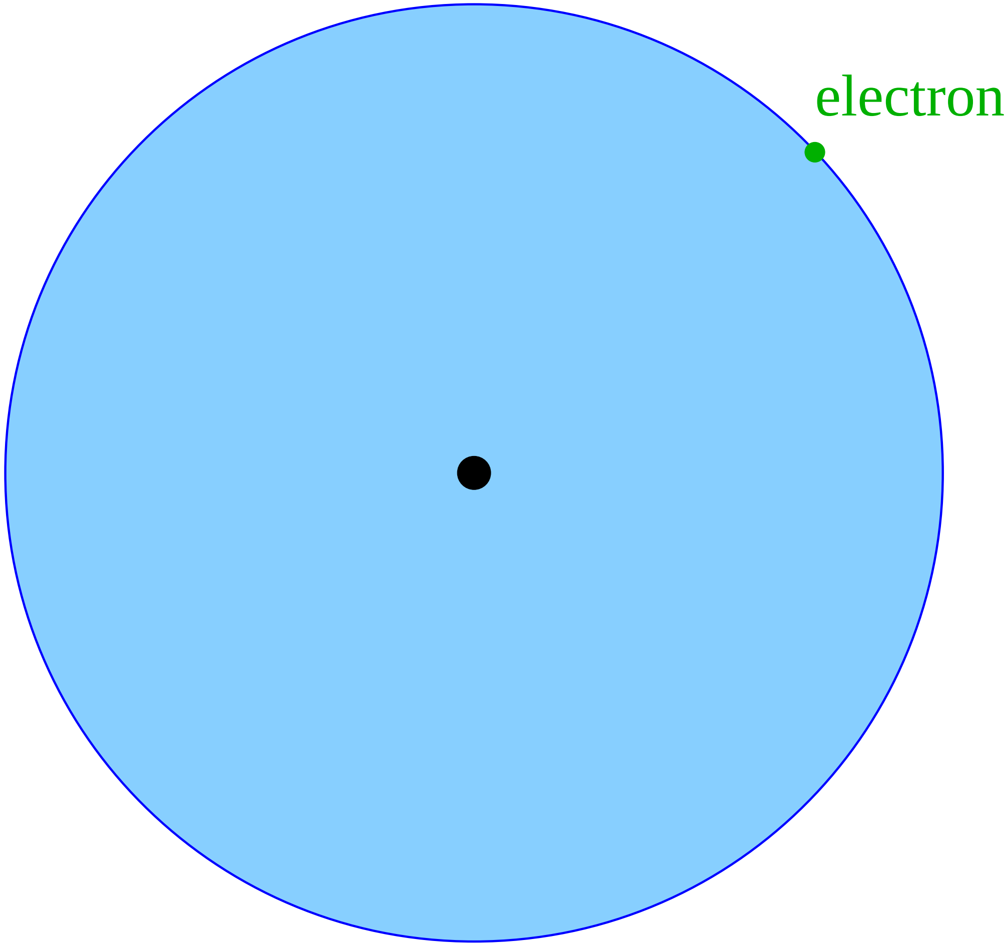
Muonic hydrogen

Regular hydrogen:

electron e^- + proton p

Muonic hydrogen:

muon μ^- + proton p



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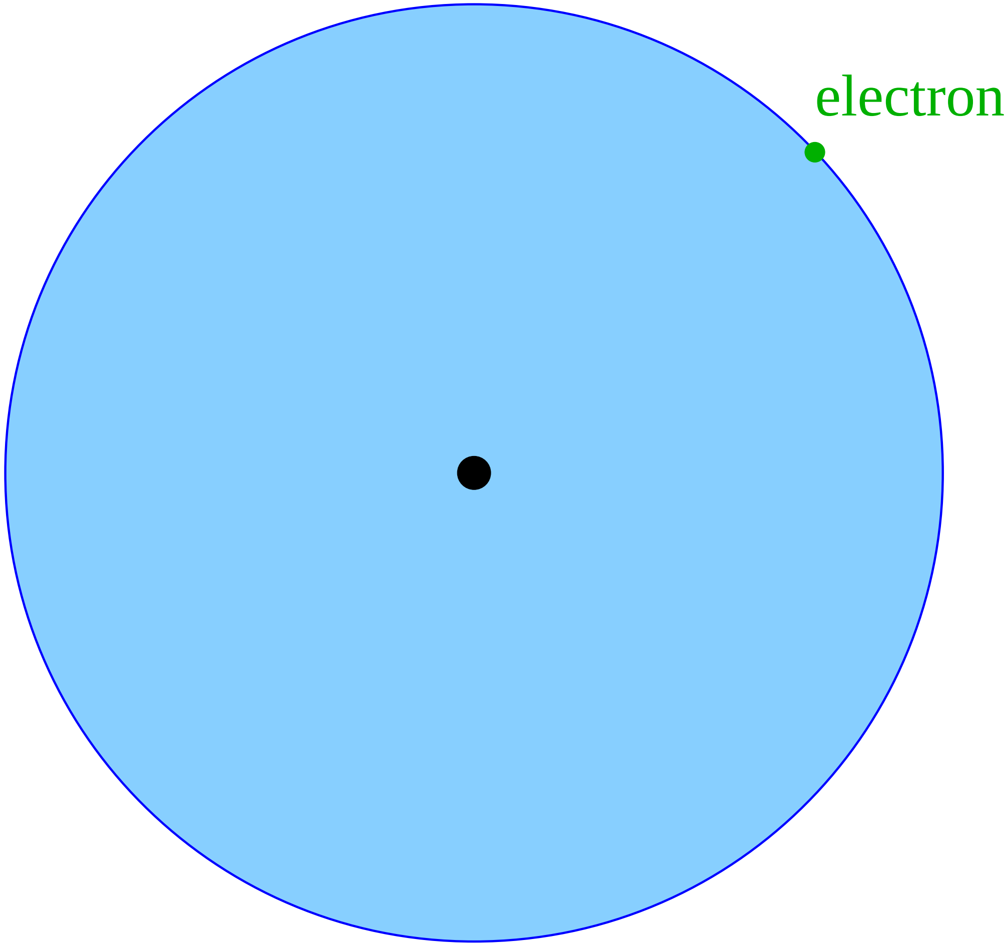

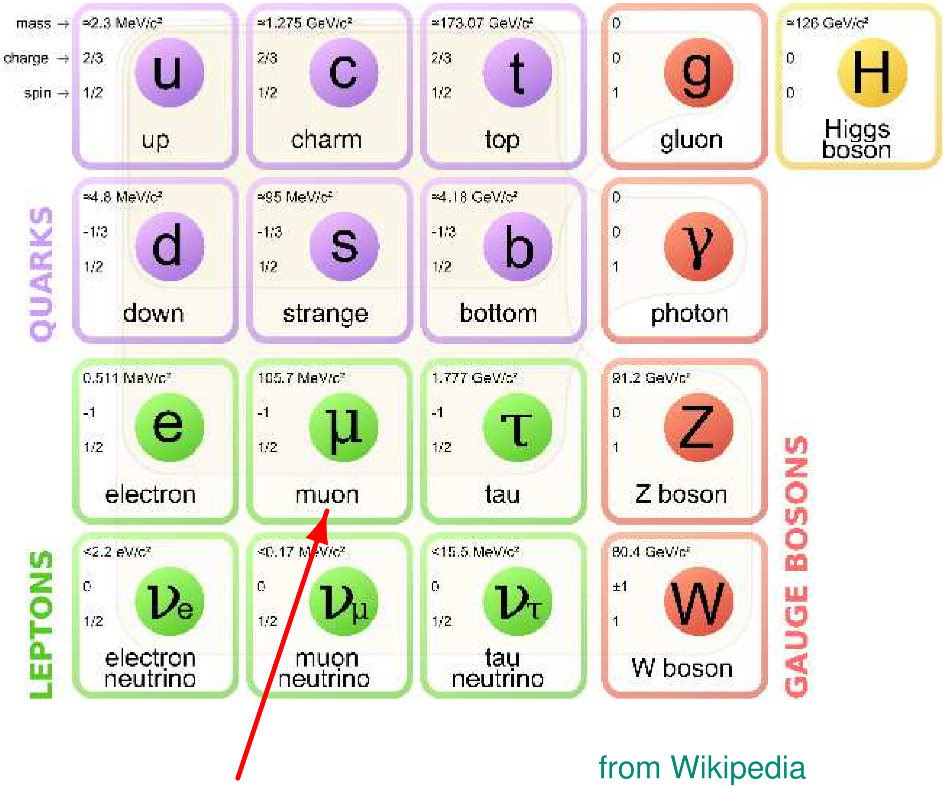

from Wikipedia

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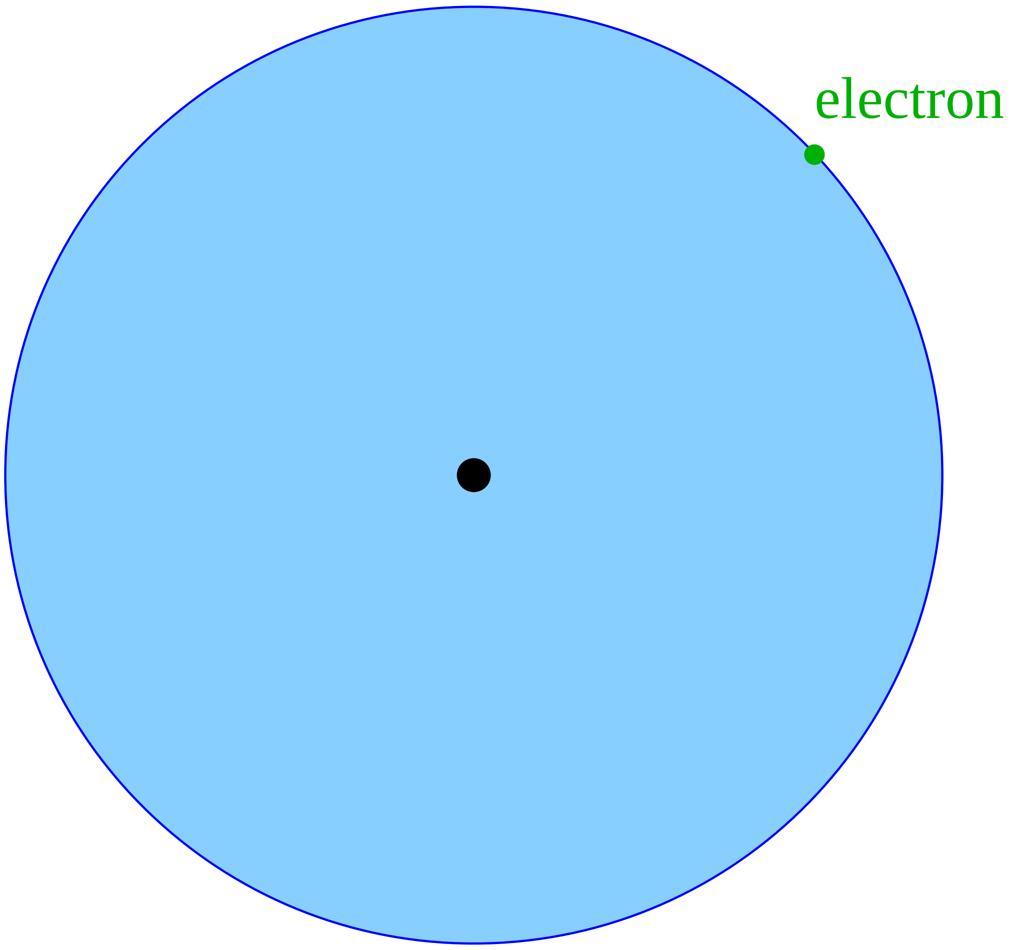


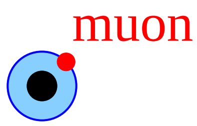
Muonic hydrogen:

muon μ^- + proton p

muon mass $m_\mu \approx 200 \times m_e$

Bohr radius $r_\mu \approx 1/200 \times r_e$

μ inside the proton: $200^3 \approx 10^7$



muon **much** is more sensitive to r_p

Proton charge radius and muonic hydrogen

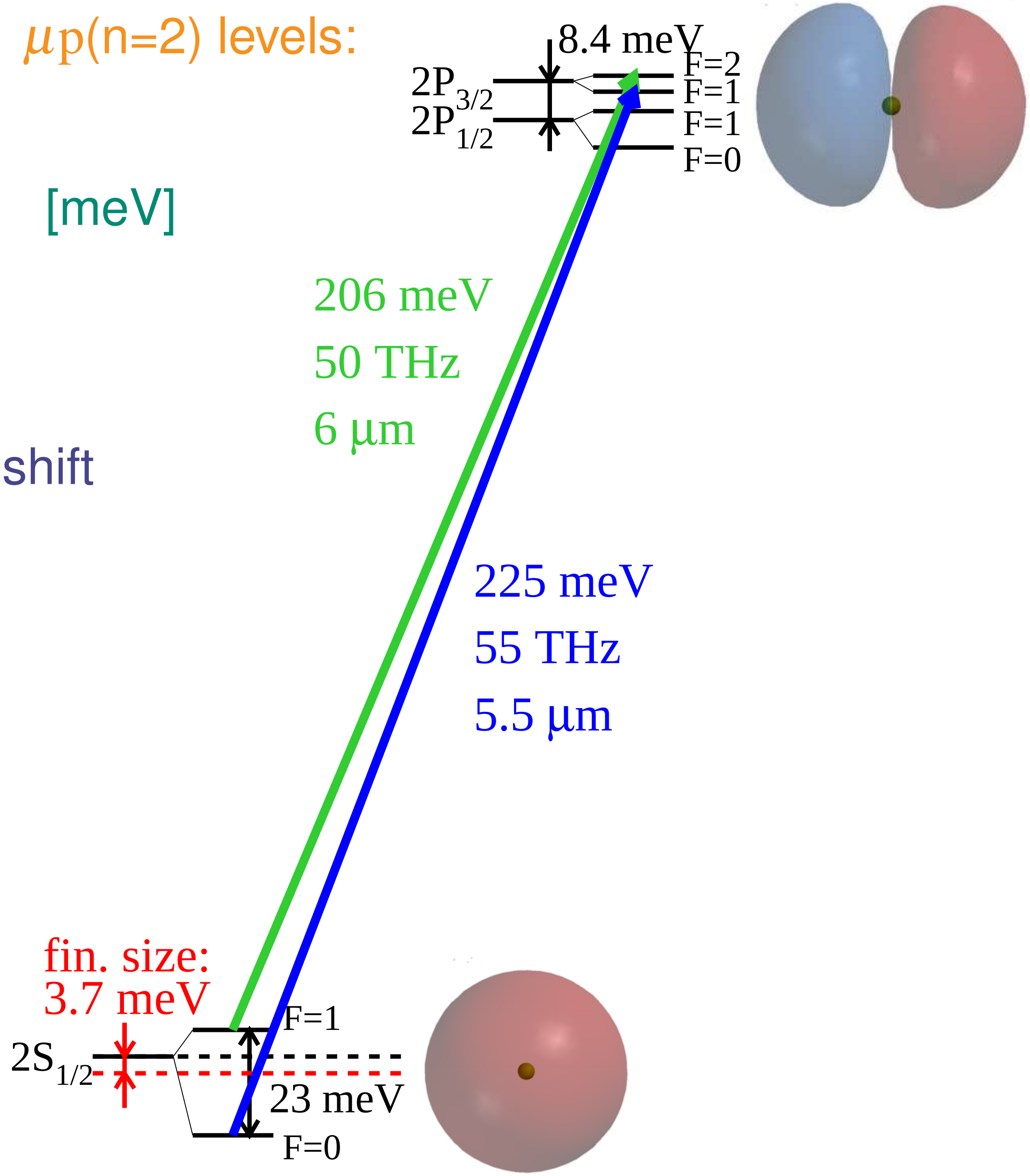
Lamb shift in μp [meV]:

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

Proton size effect is 2% of the μp Lamb shift

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

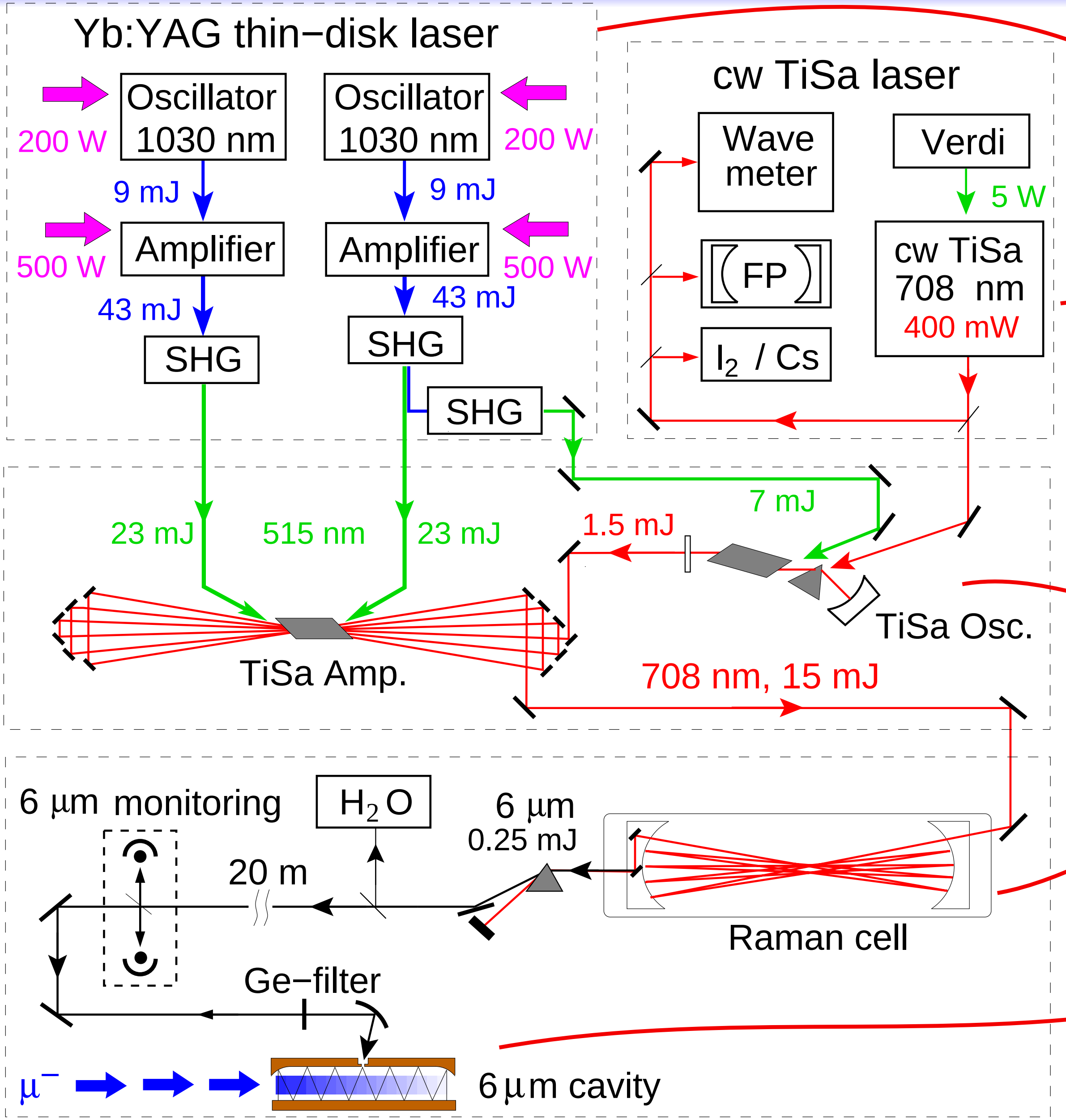
μp(n=2) levels:



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).

The laser system



Main components:

- Thin-disk laser

  fast response to detected μ^-
- Frequency doubling
- TiSa laser:

  frequency stabilized cw laser

  injection seeded oscillator

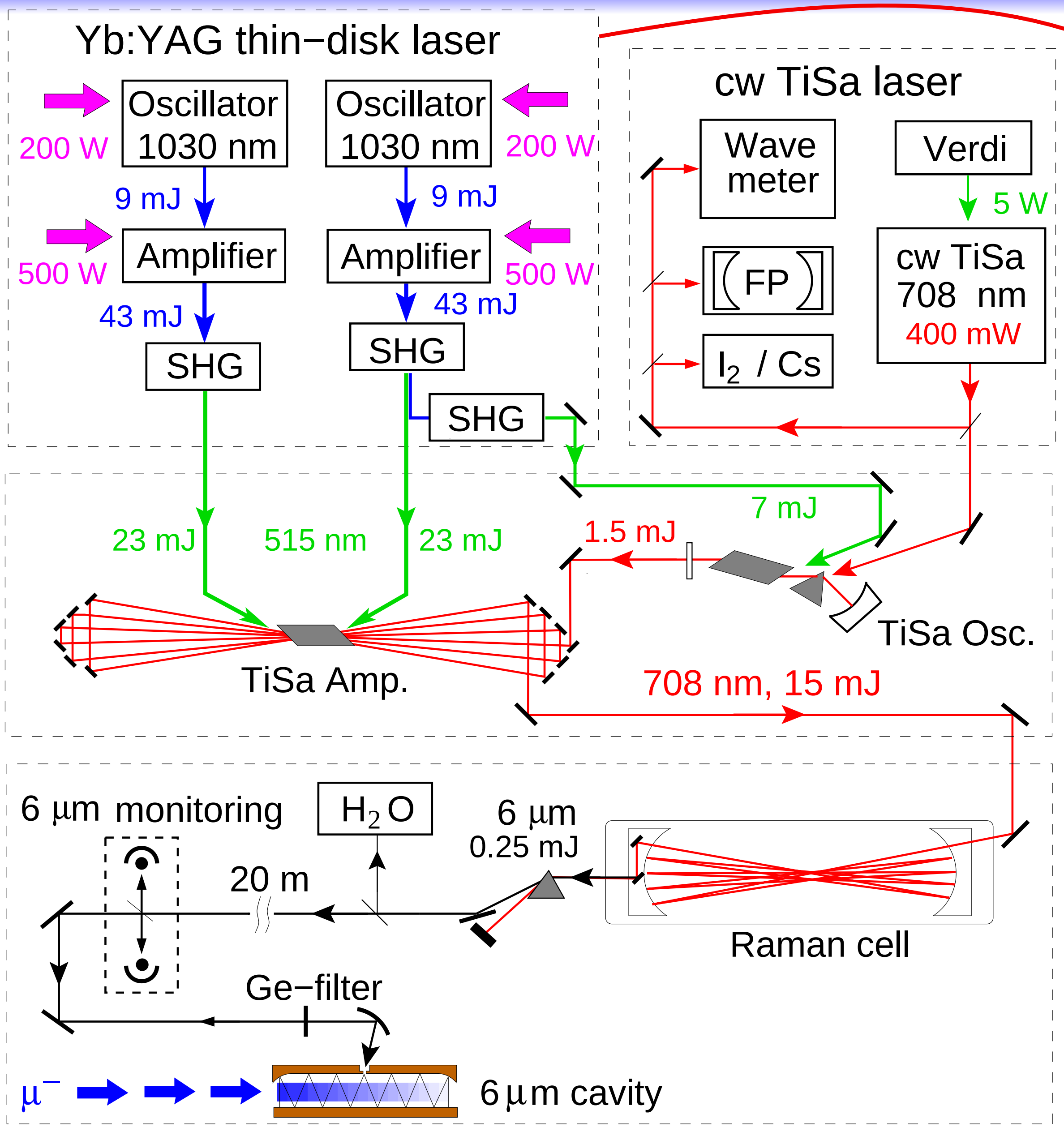
  multipass amplifier
- Raman cell

  3 Stokes: 708 nm → 6 μm

  λ calibration @ 6 μm
- Target cavity

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

The laser system



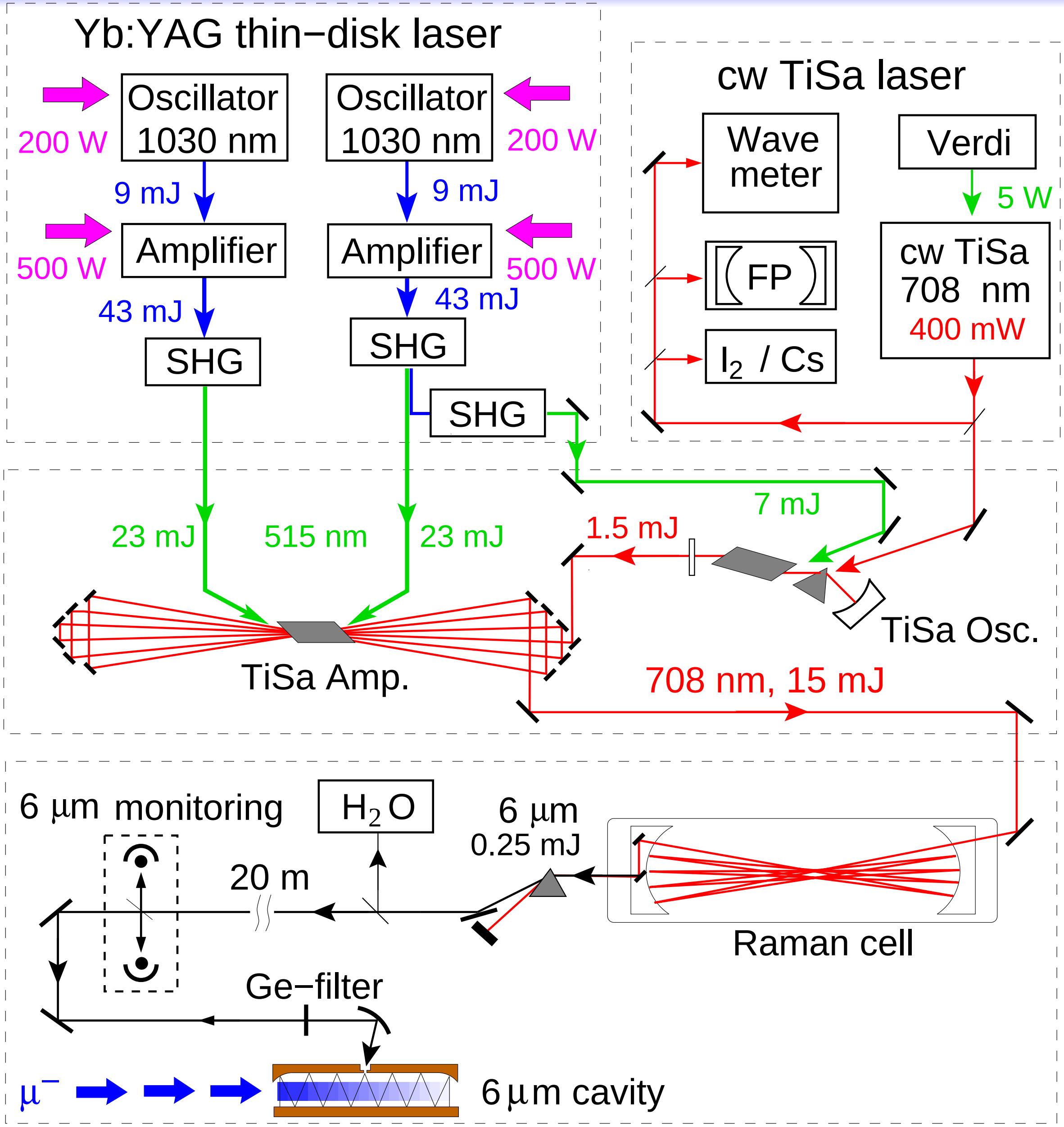
Thin-disk laser

- 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

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

$FSR = 1497.344(6)$ MHz

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

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

Seeded oscillator

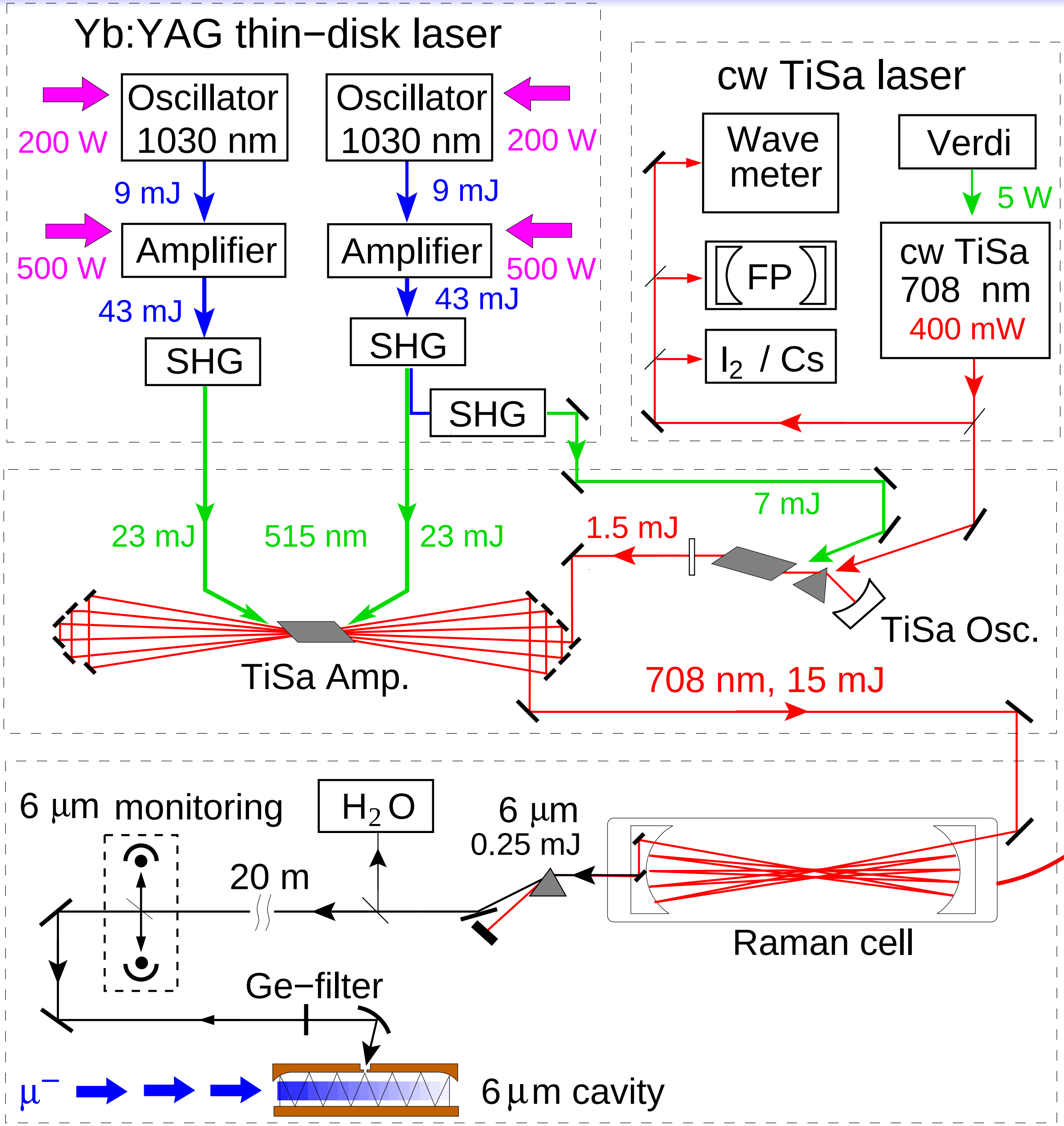
$\rightarrow \nu^{\text{pulsed}}_{\text{TiSa}} = \nu^{\text{cw}}_{\text{TiSa}}$

(frequency chirp ≤ 200 MHz)

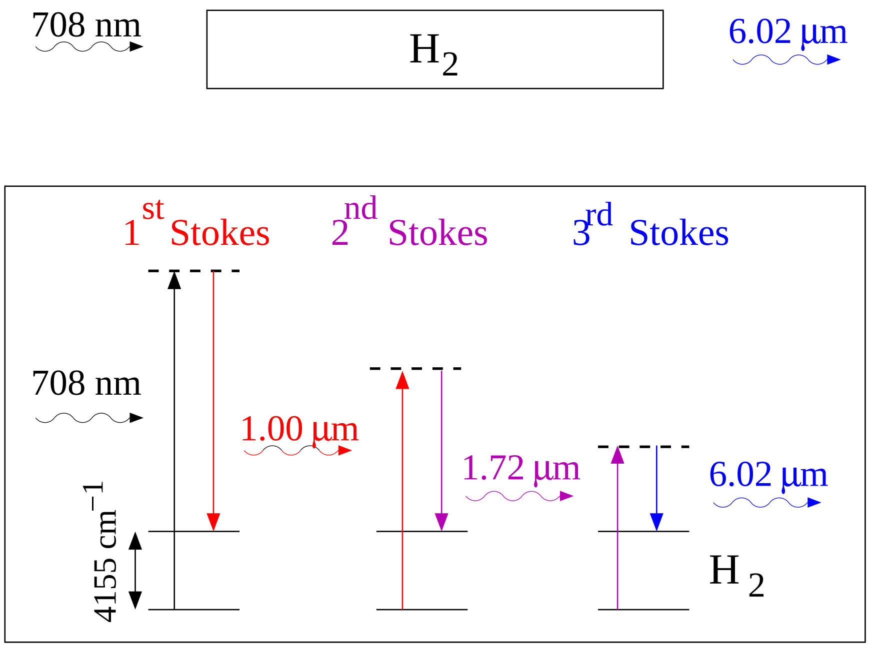
Multipass amplifier (2f- configuration)

gain=10

The laser system



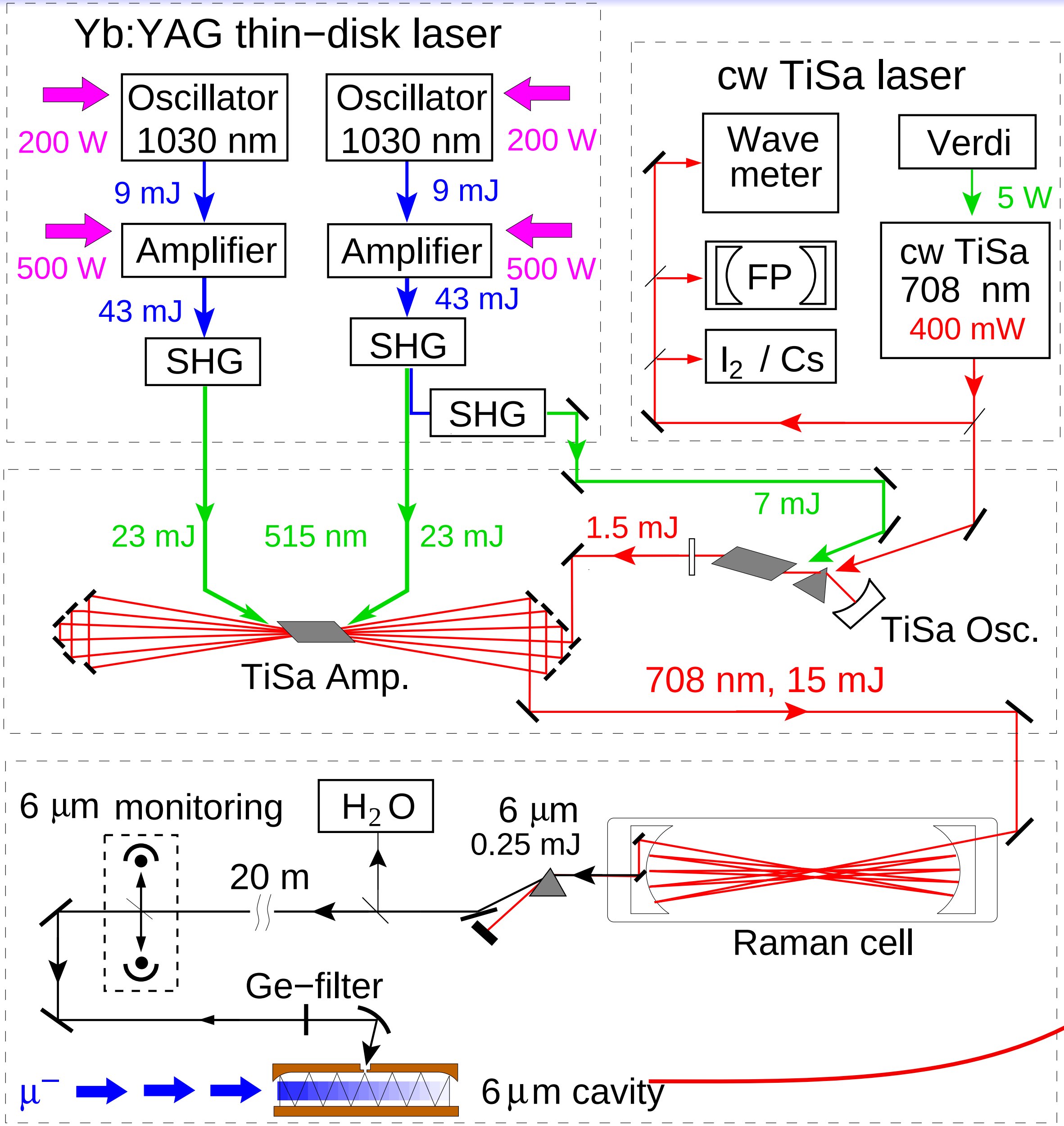
Raman cell:

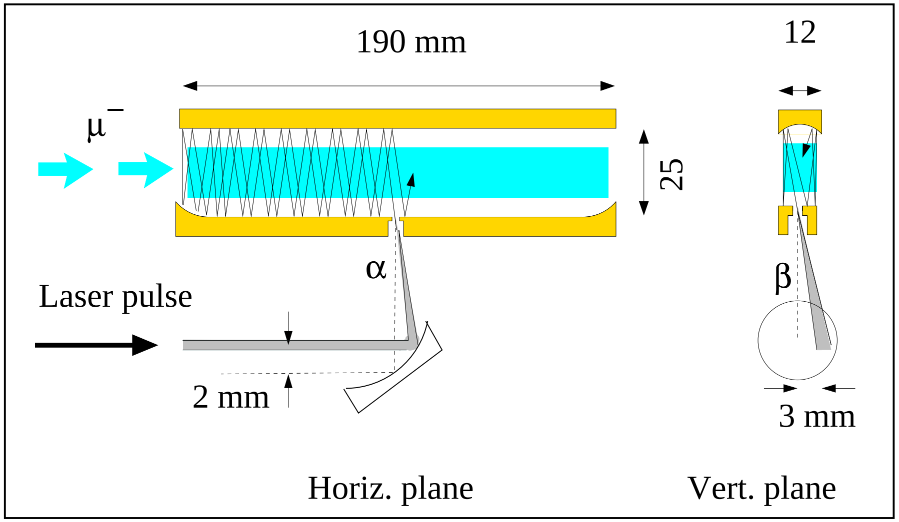


$$\nu^{6\mu m} = \underbrace{\nu^{708nm}}_{\text{tunable}} - 3\cdot\hbar\underbrace{\omega_{vib}}_{\omega_{vib}(p,T)\,=\,\text{const}}$$

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)

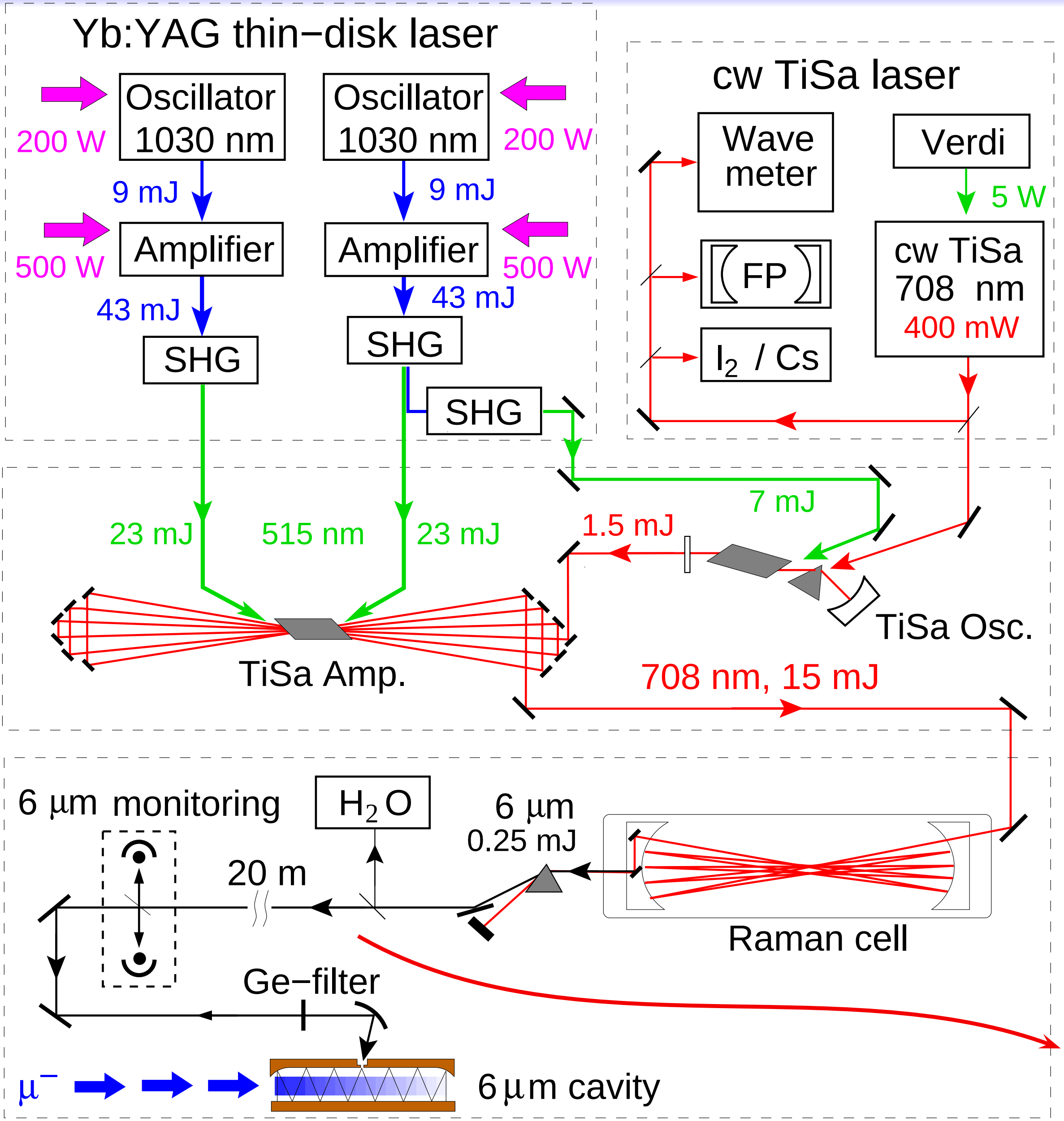
→ Light makes 1000 reflections

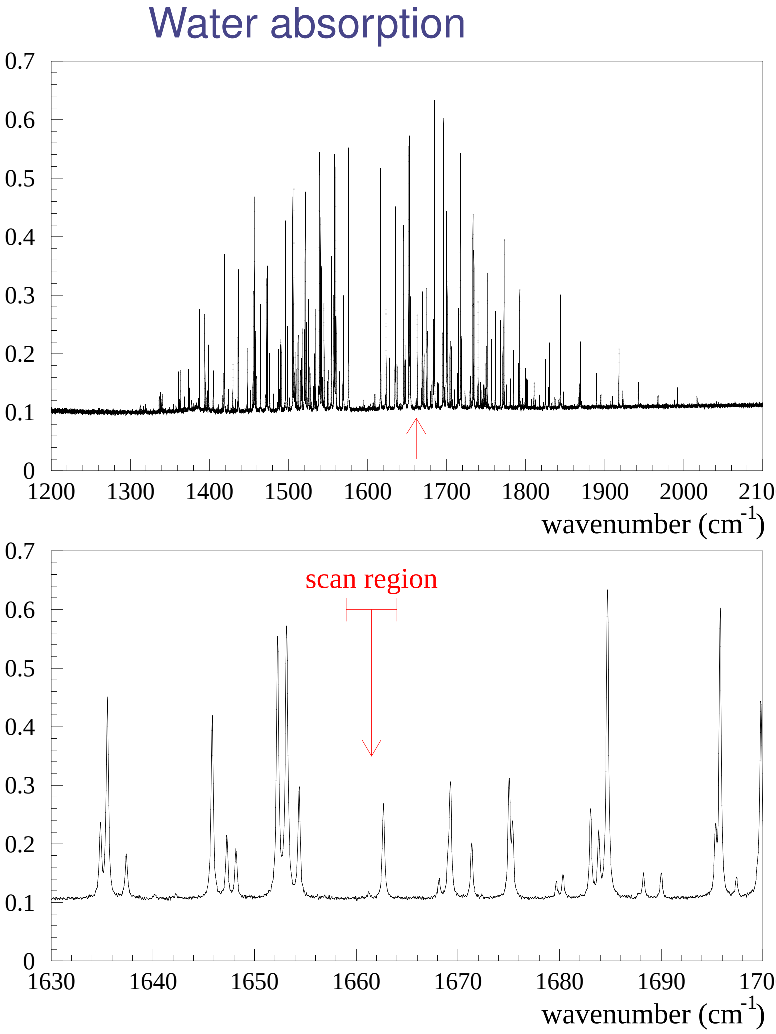
→ Light is confined for τ=50 ns

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

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

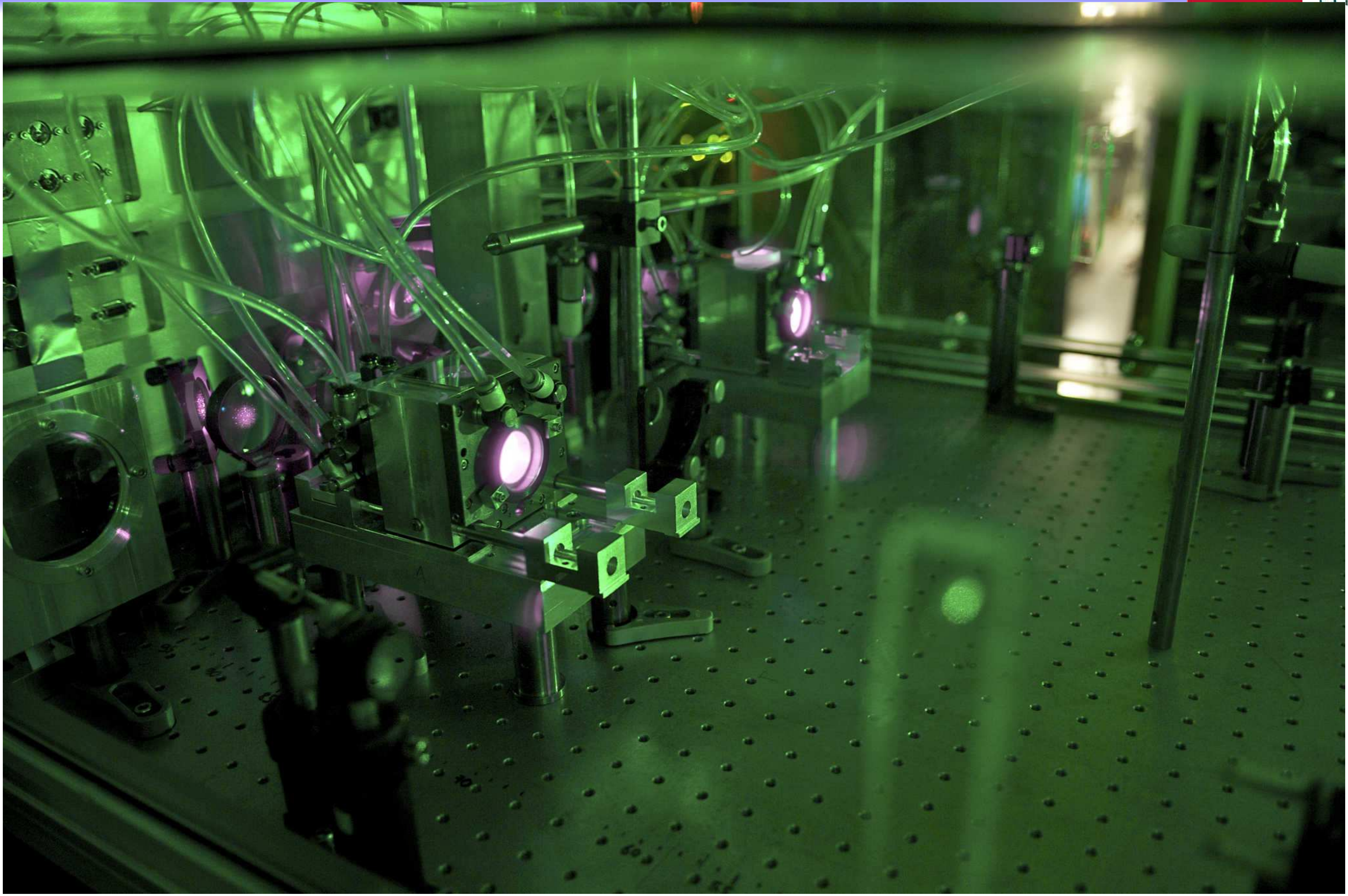
The laser system



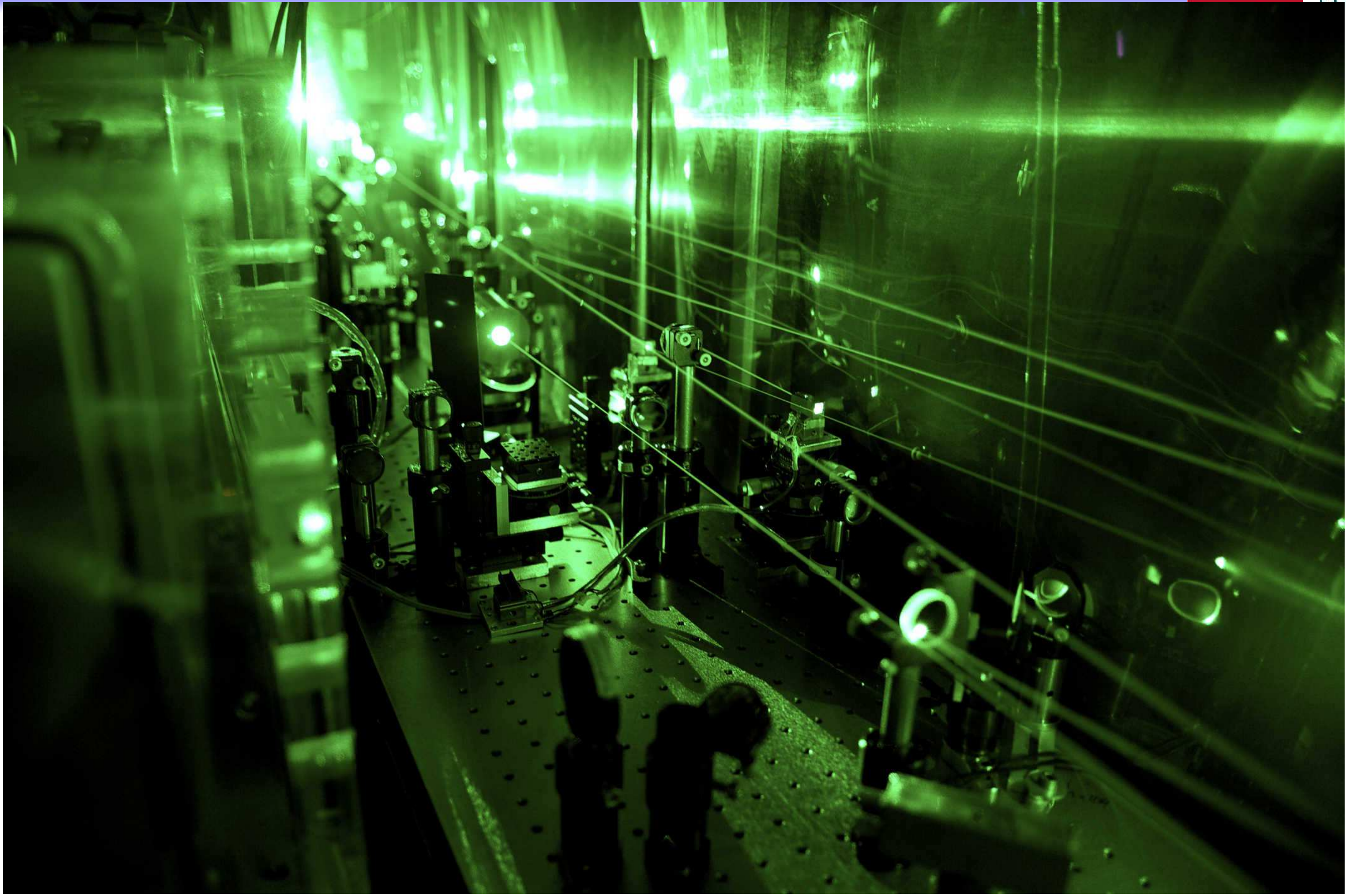

Water absorption

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

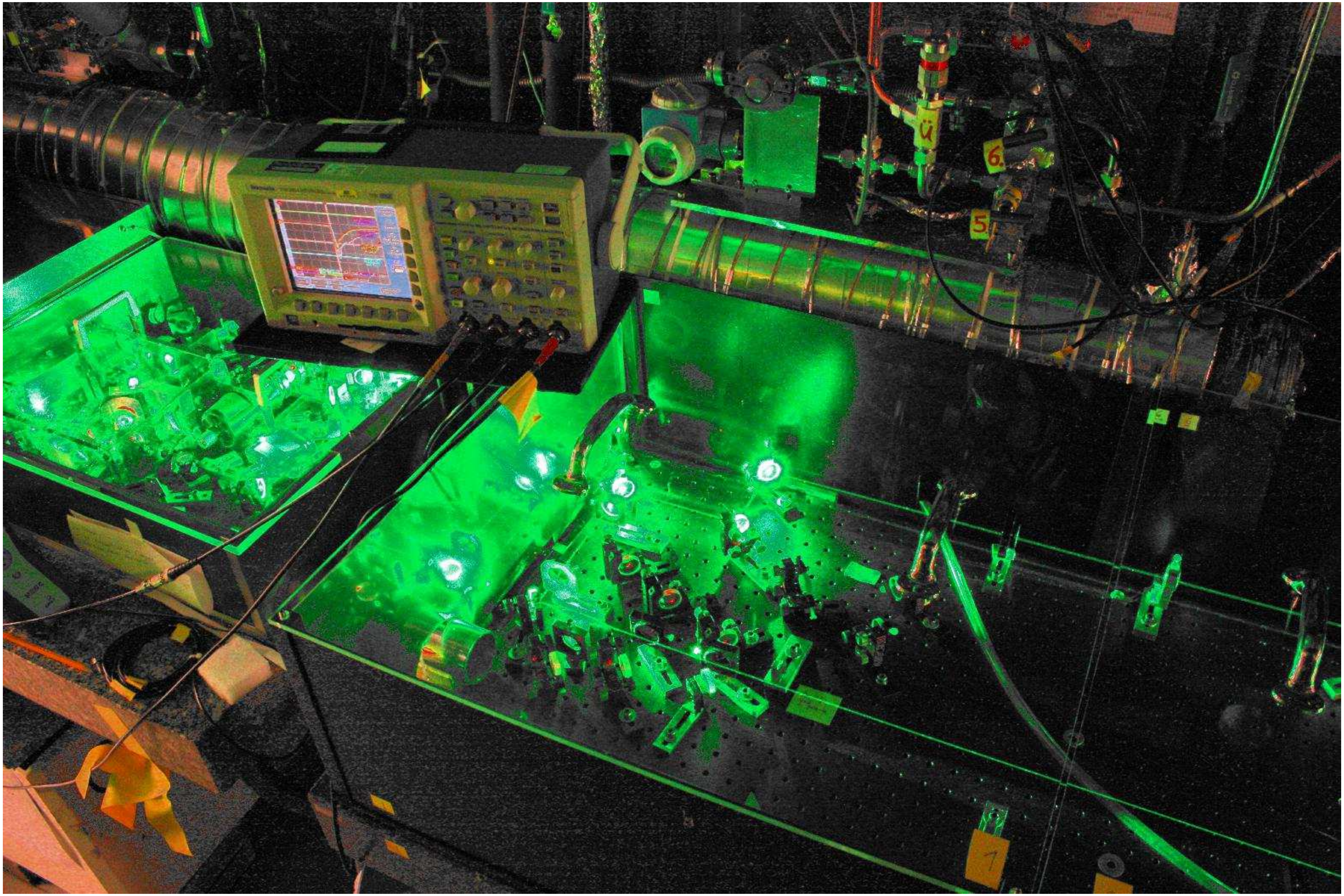
Disk amplifier laser heads



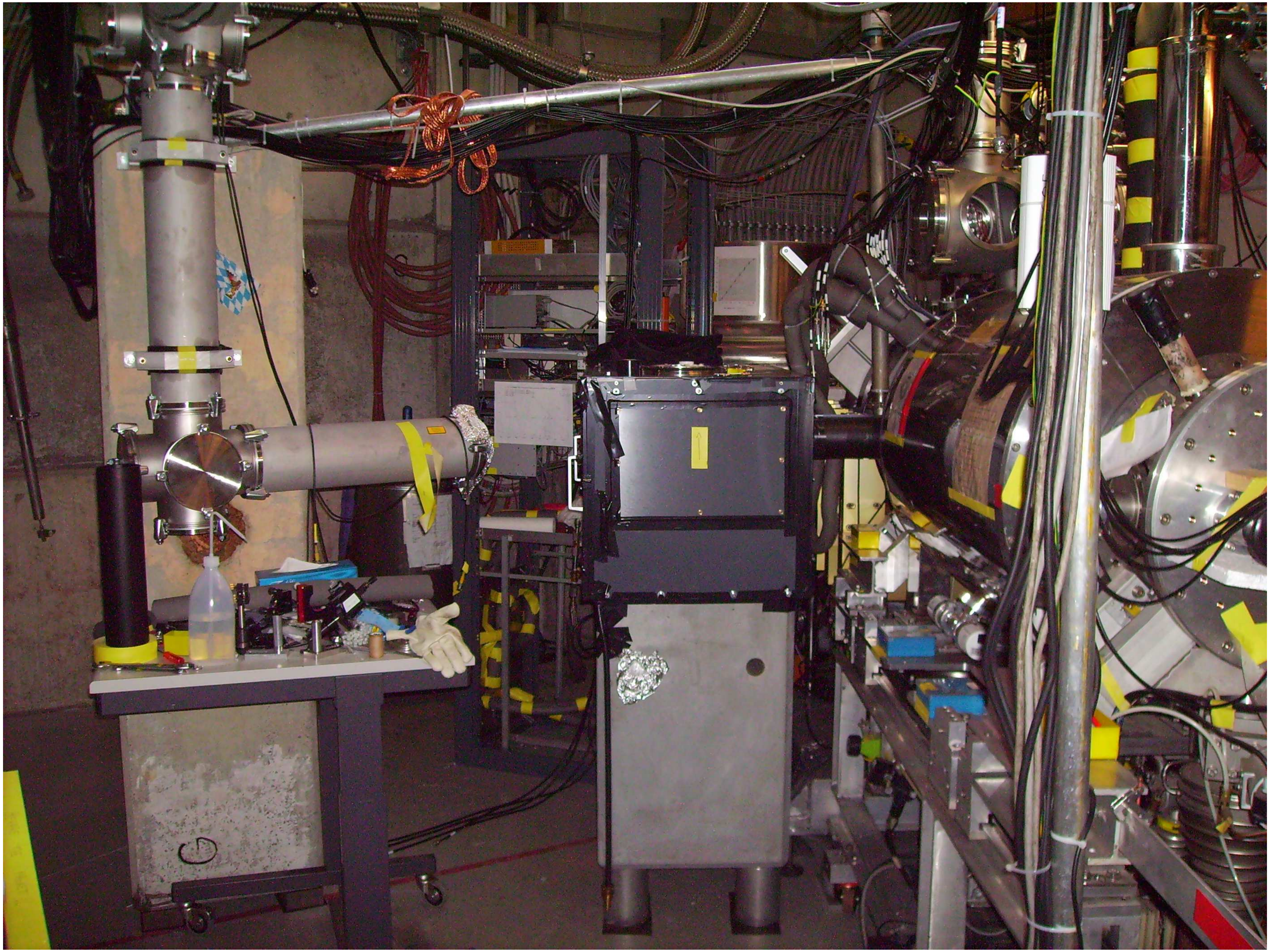
Disk laser doubling stages



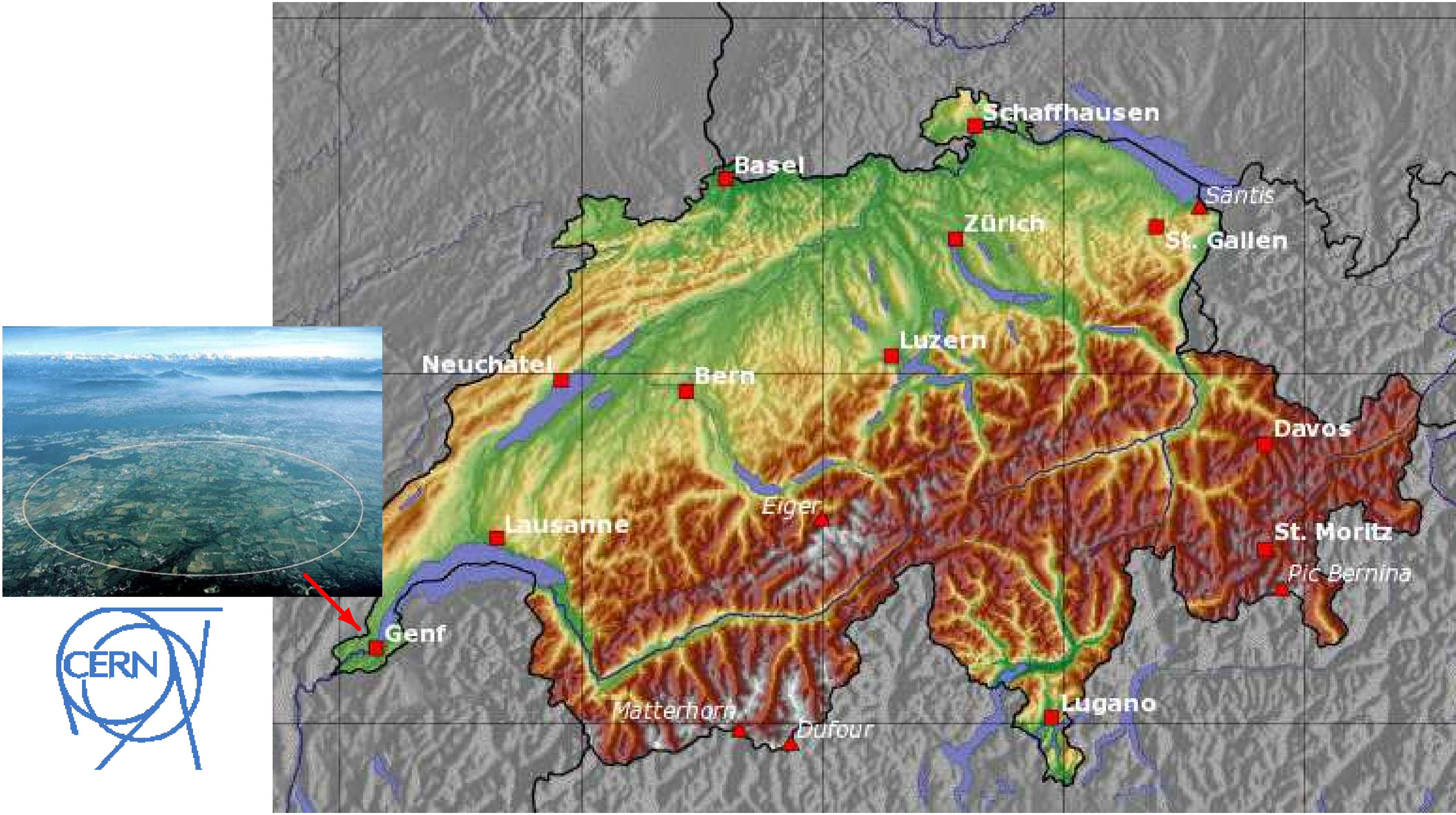
TiSa lasers and Raman cell



Laser beam tube

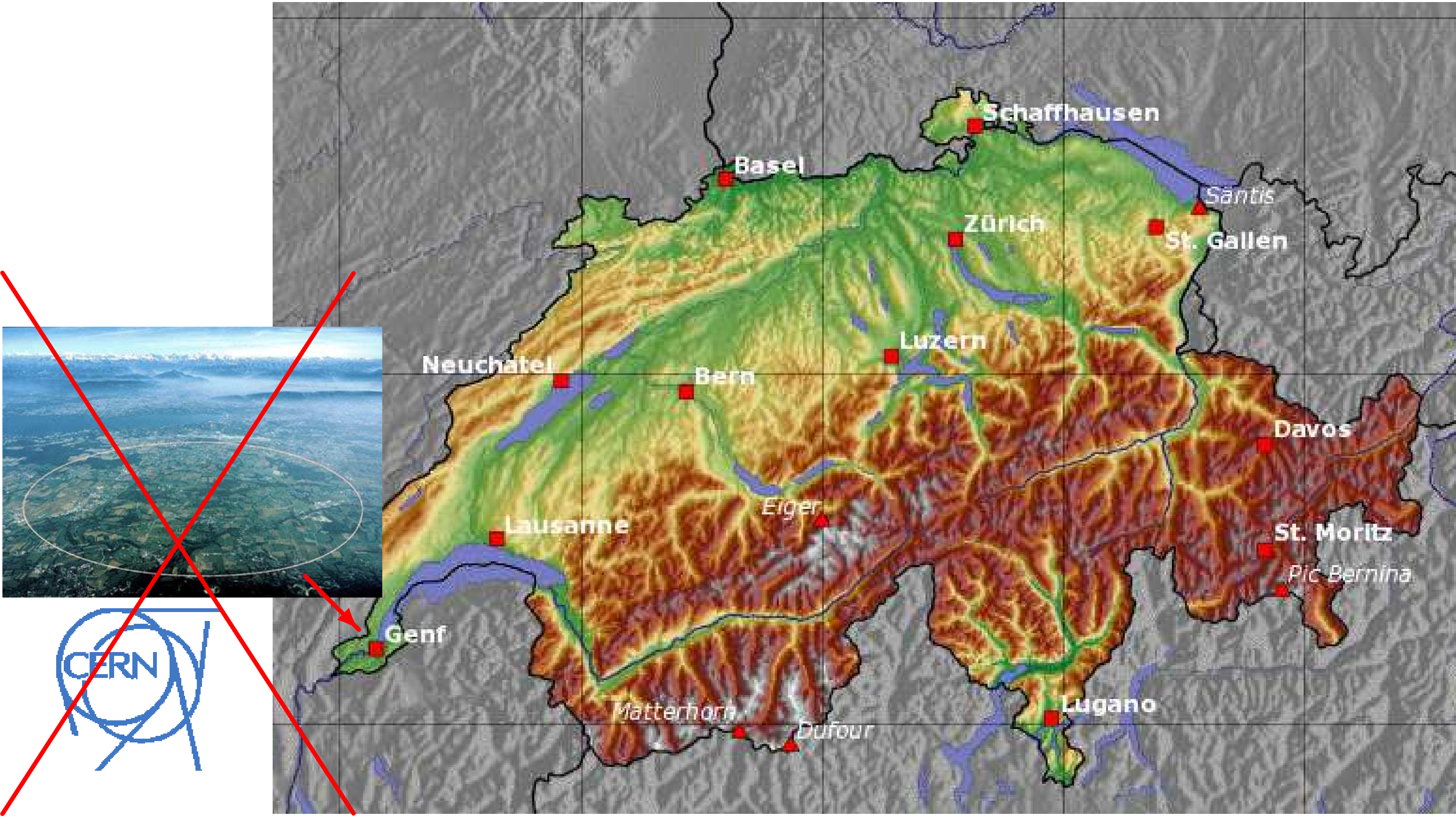


Swiss muons

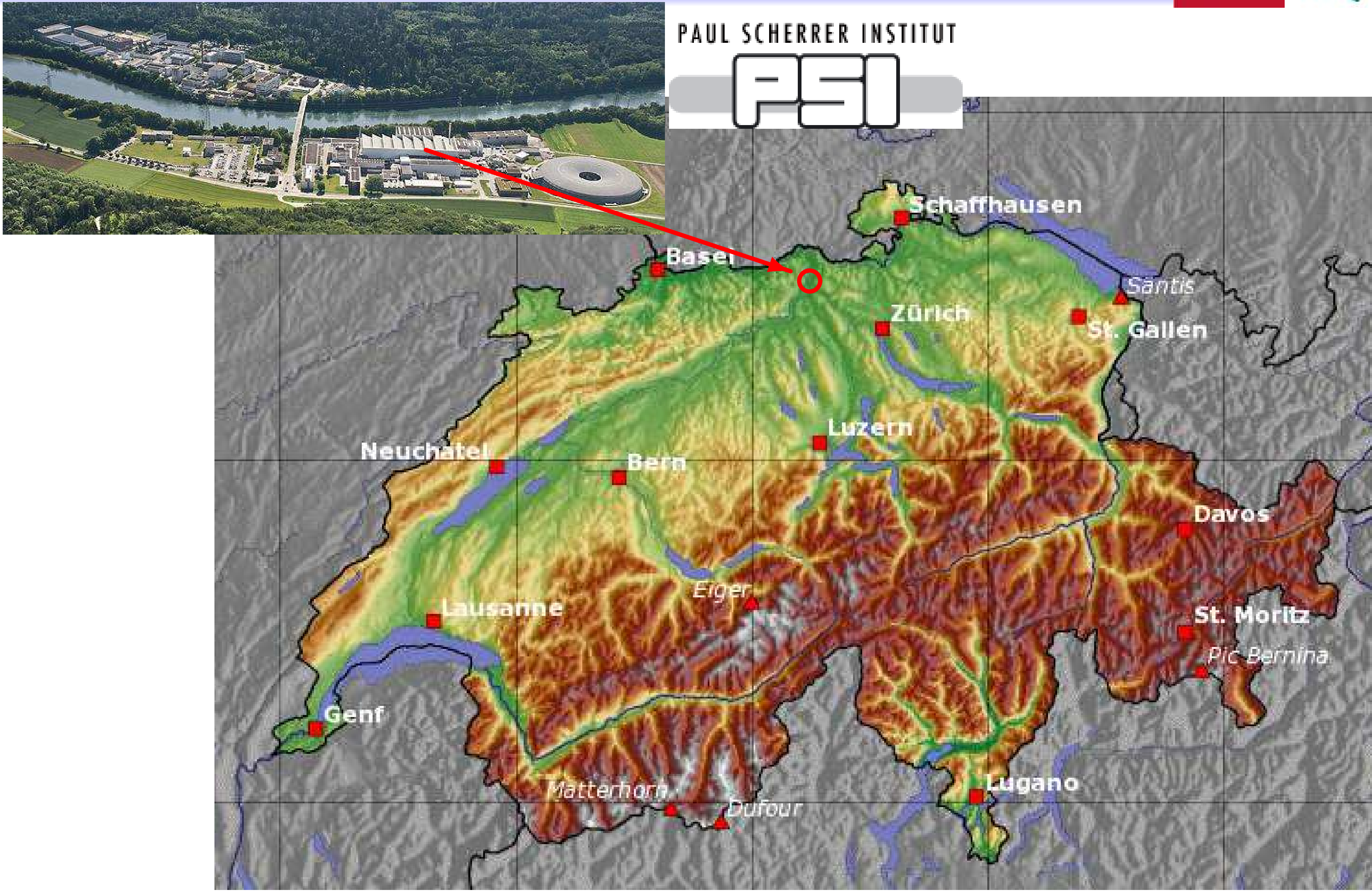


CERN

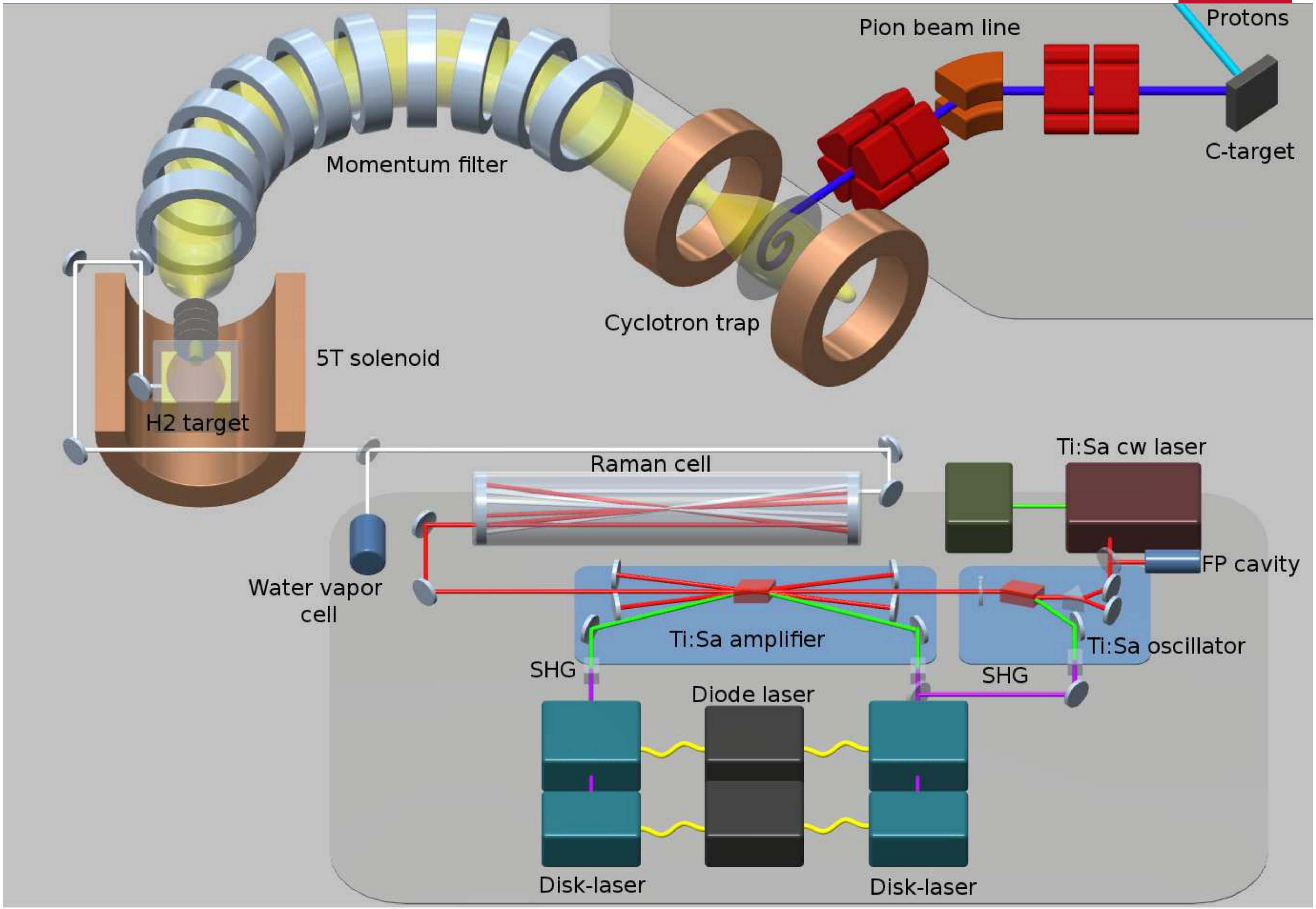
Swiss muons


Schaffhausen
Basel
Säntis
Zürich
St. Gallen
Luzern
Neuchâtel
Bern
Davos
Eiger
Lausanne
St. Moritz
Piz Bernina
Genf
CERN
Lugano
Matterhorn
Dufour

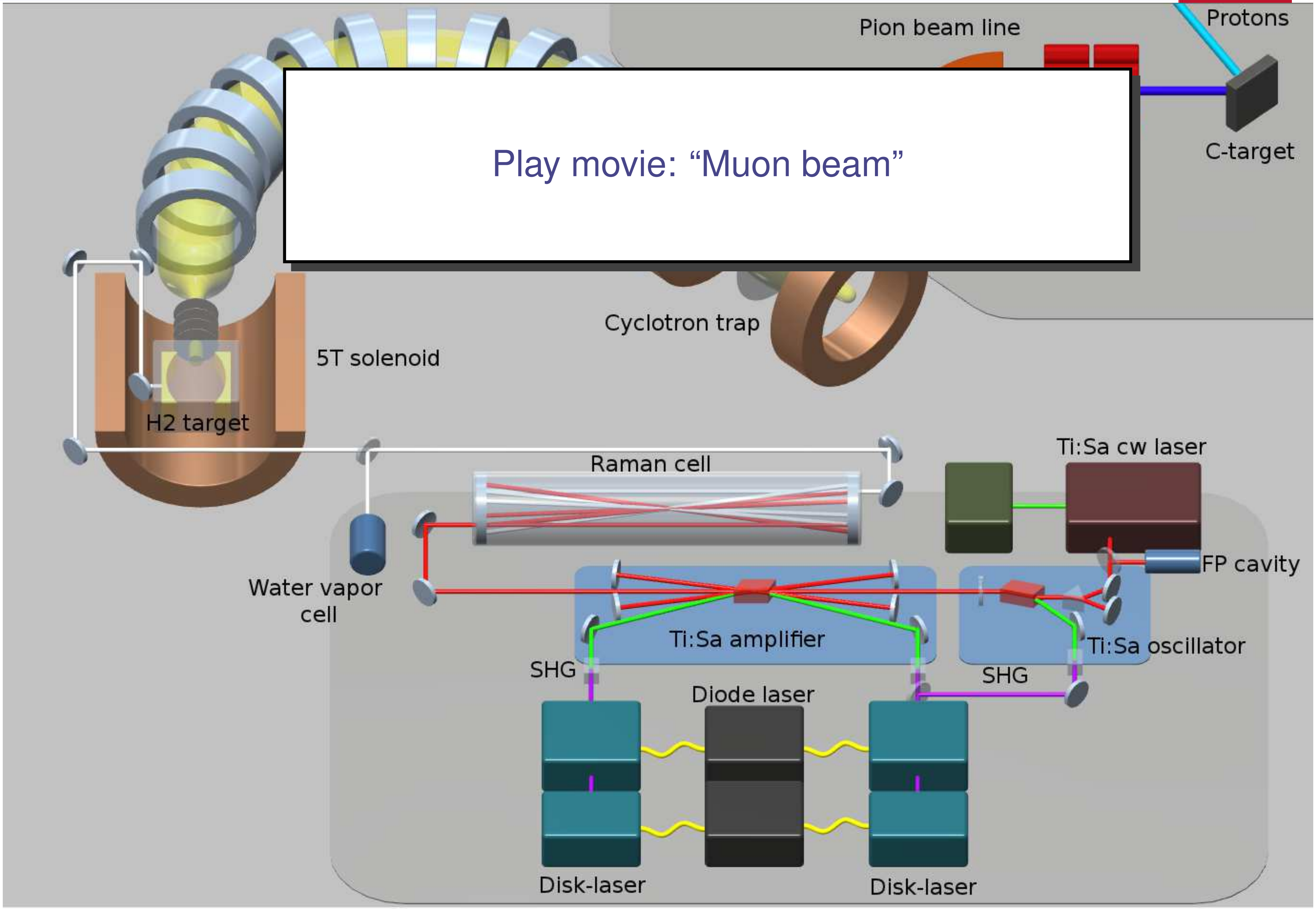
Swiss muons


PAUL SCHERRER INSTITUT
PSI
Schaffhausen
Basel
Zürich
Santis
St. Gallen
Luzern
Neuchatel
Bern
Davos
Eiger
Lausanne
St. Moritz
Pic Bernina
Genf
Matterhorn
Dufour
Lugano

Setup


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

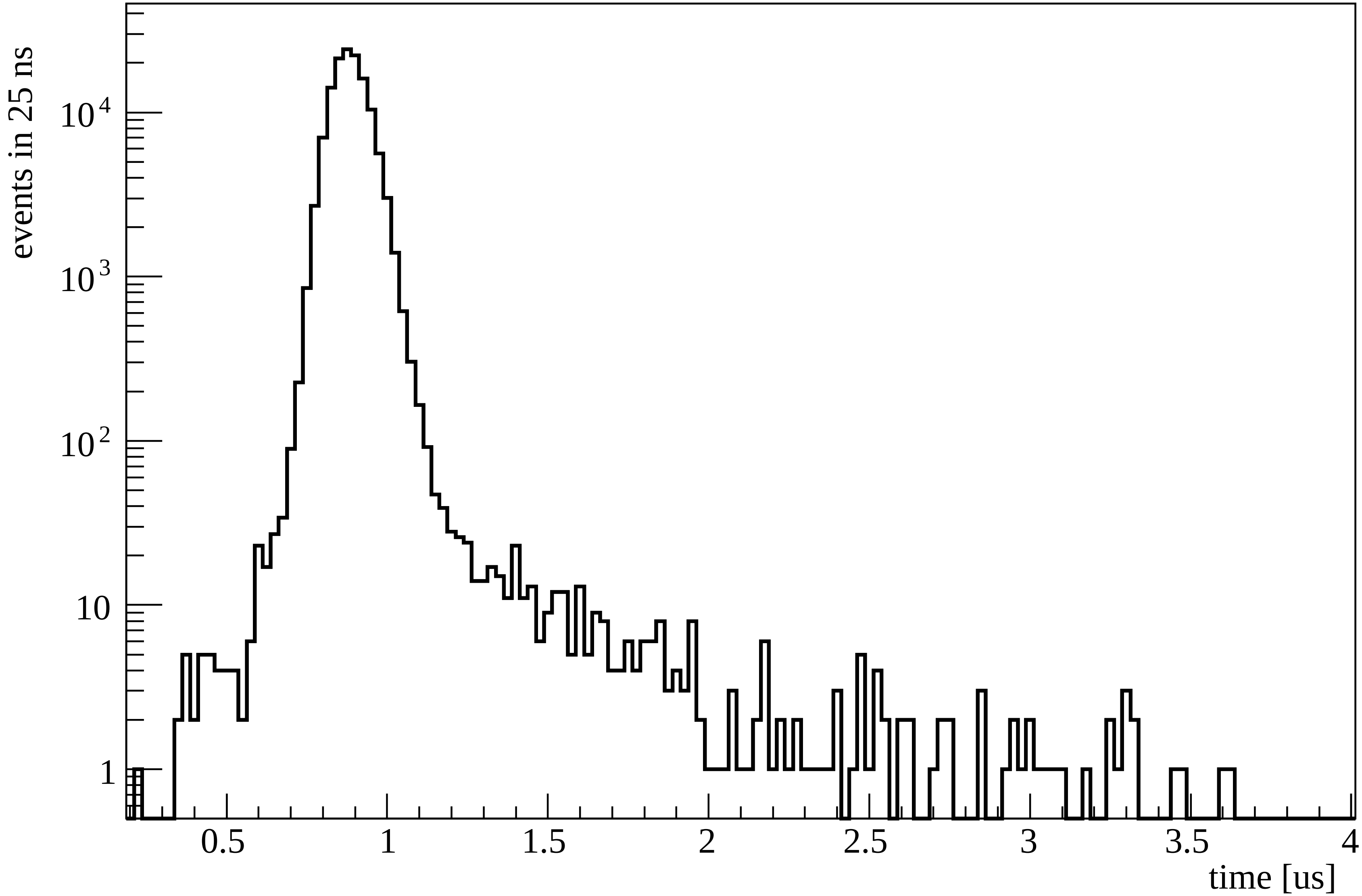
Setup



Play movie: “Muon beam”

μp Lamb shift experiment: Principle

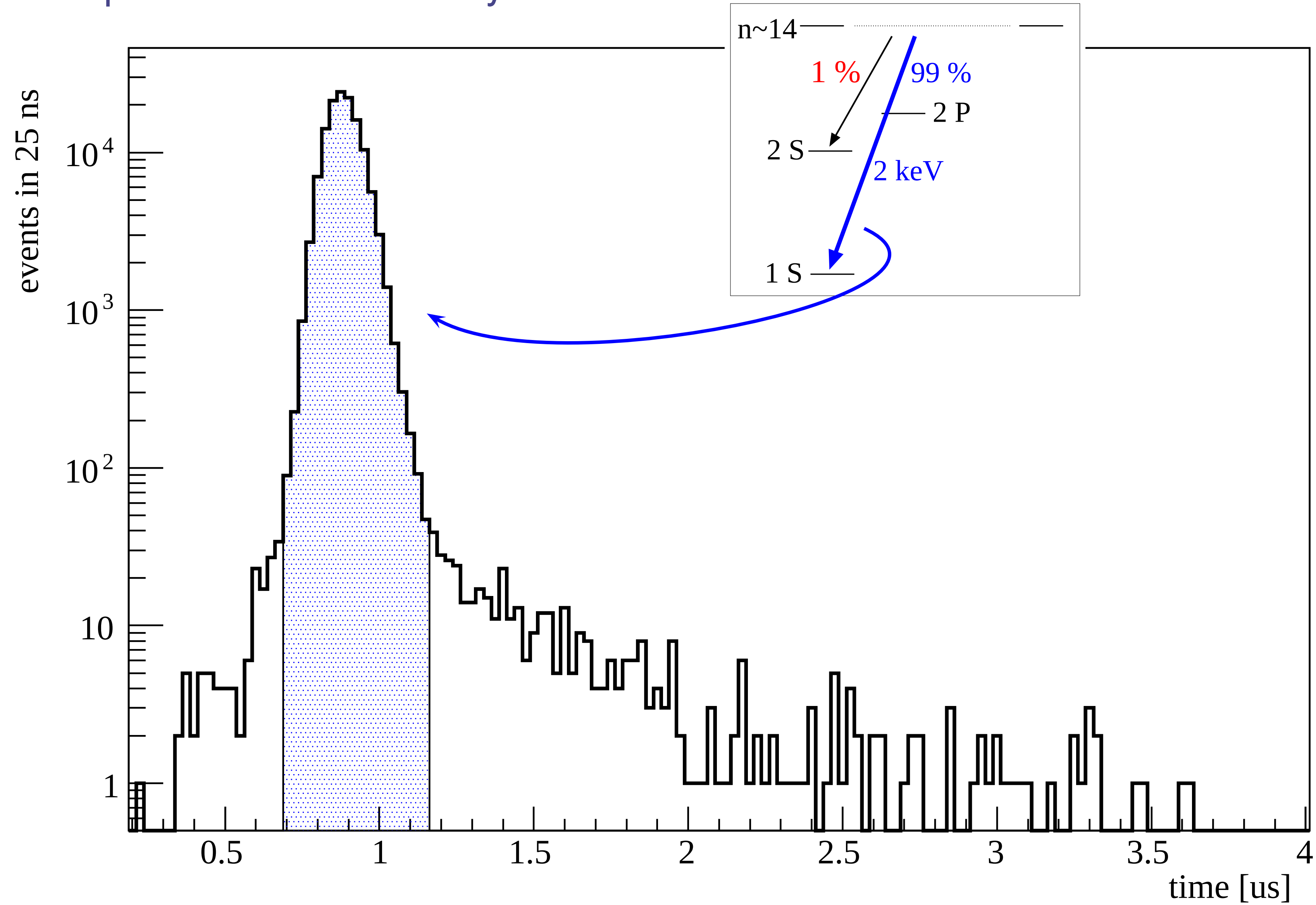
time spectrum of 2 keV x-rays (~ 13 hours of data @ 1 laser wavelength)



μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays

“prompt” ($t \sim 0$)

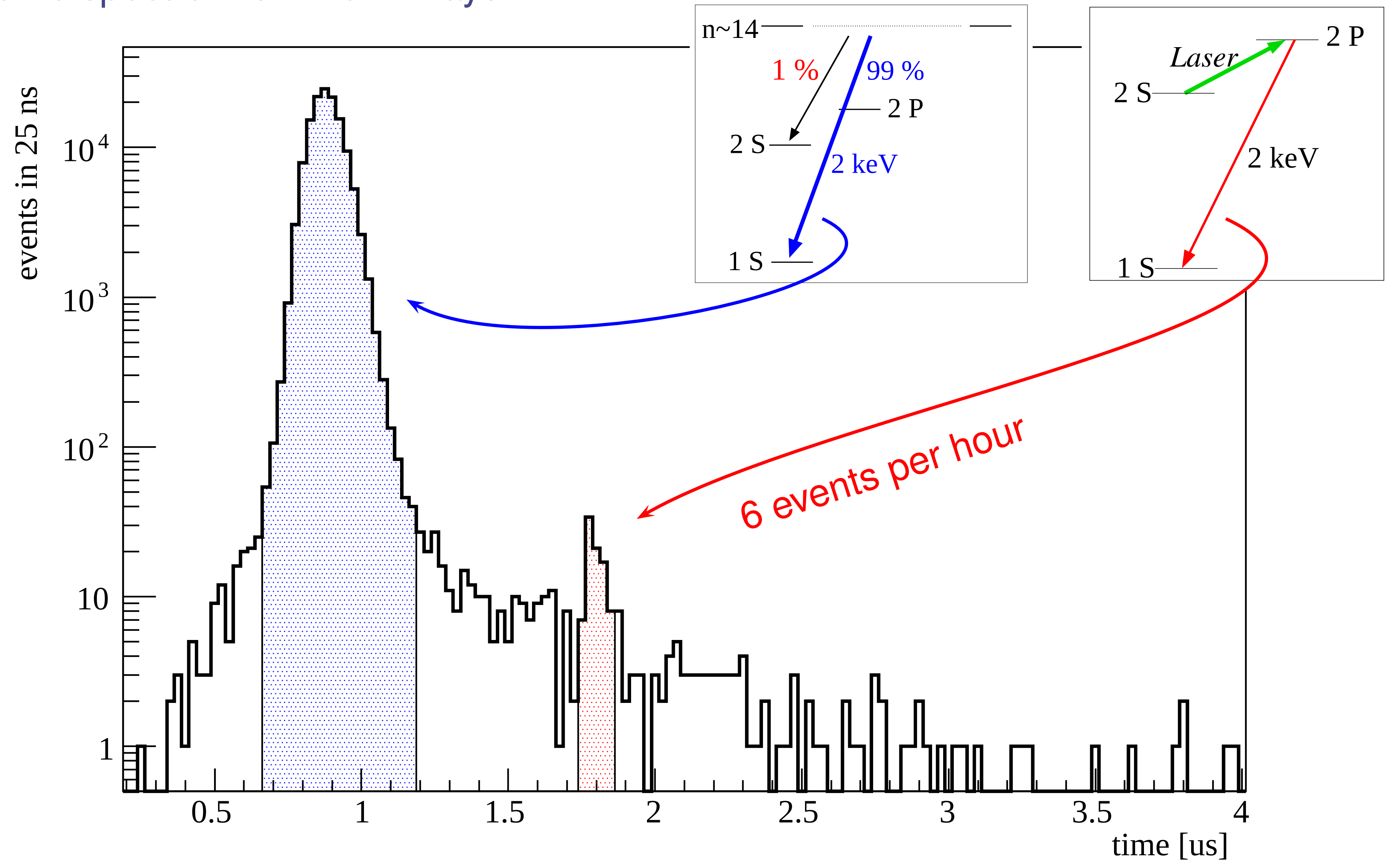


μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays

“prompt” ($t \sim 0$)

“delayed” ($t \sim 1\ \mu s$)



μp Lamb shift experiment: Principle

time spectrum of 2 keV x-rays

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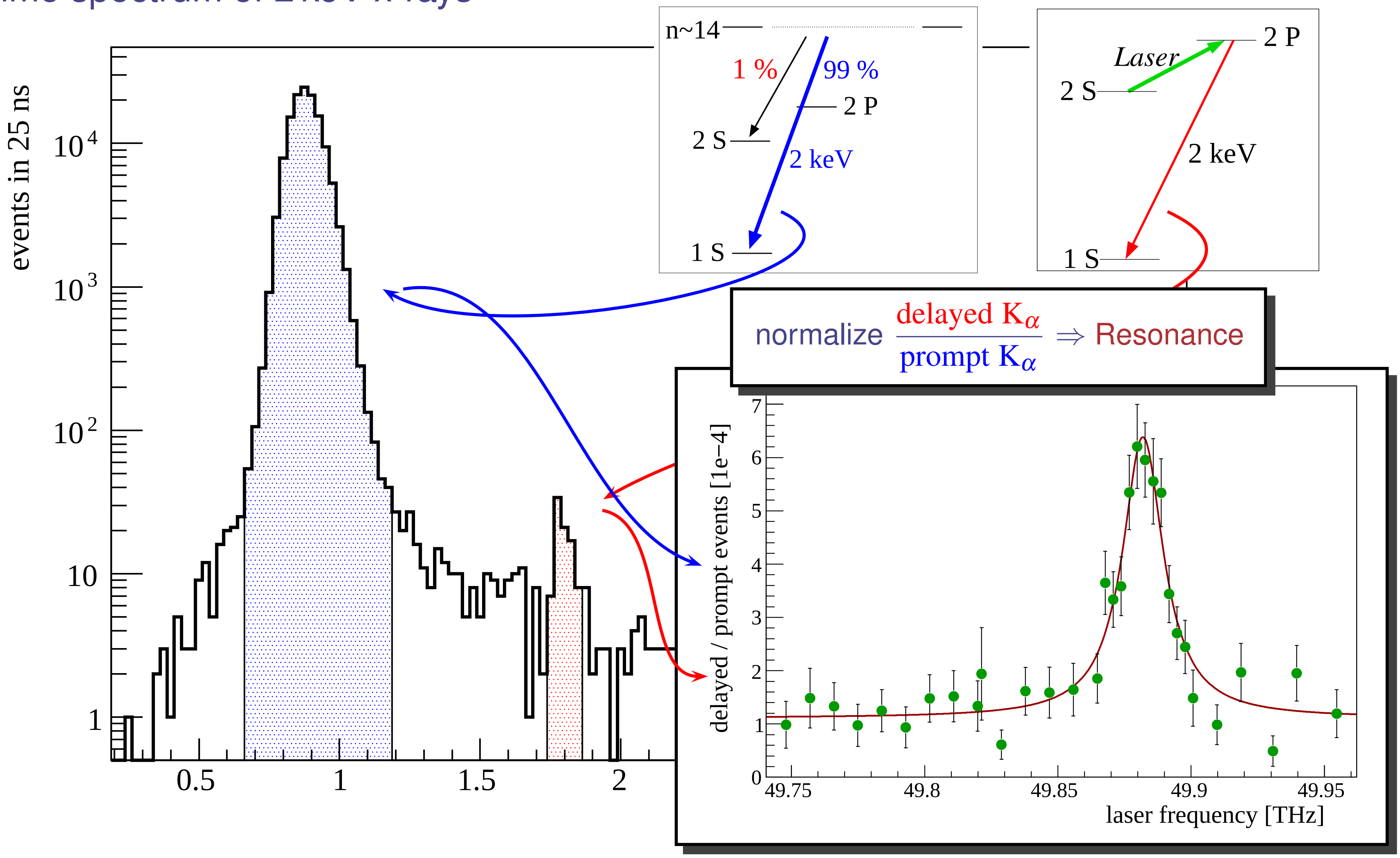
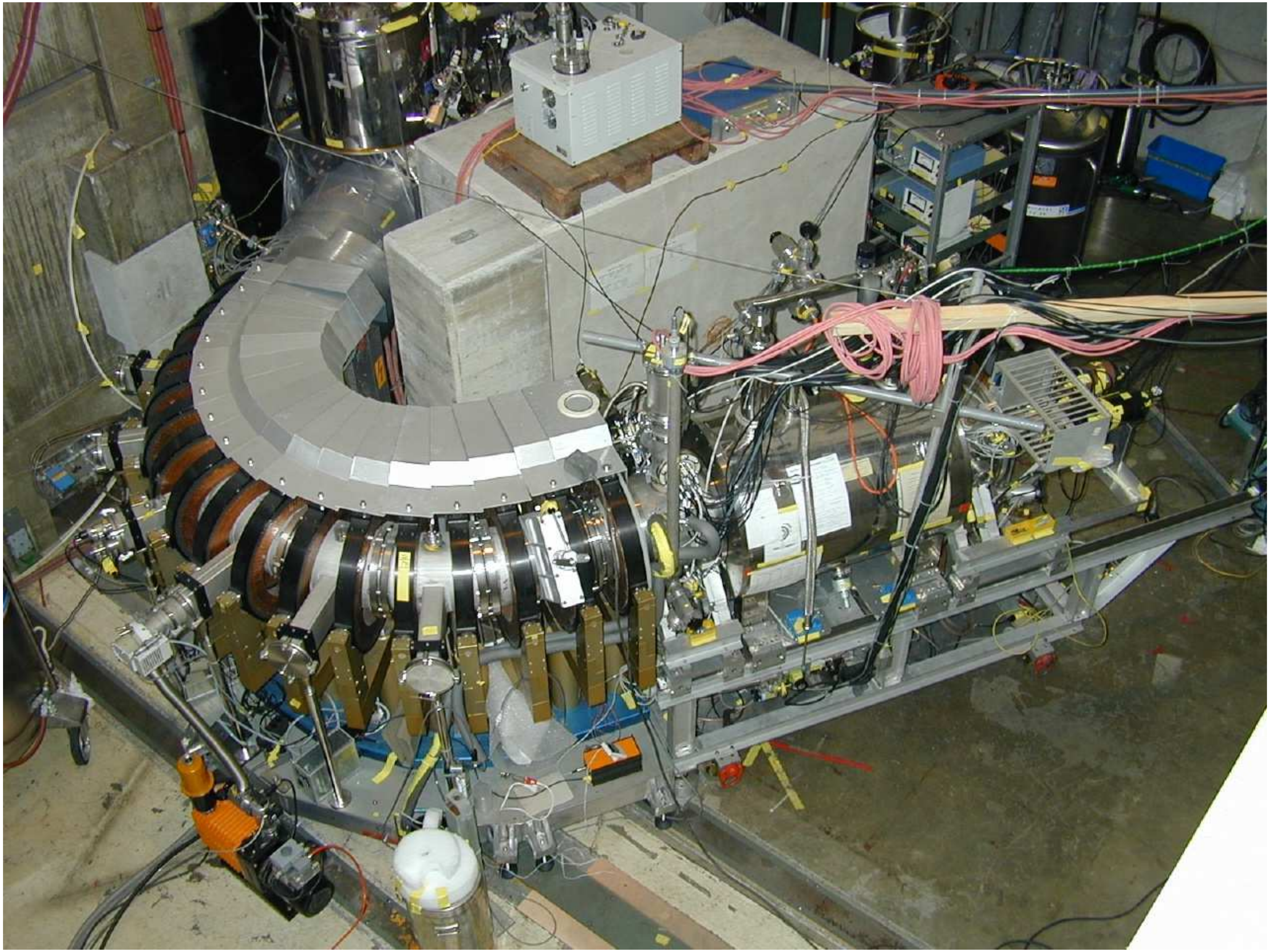
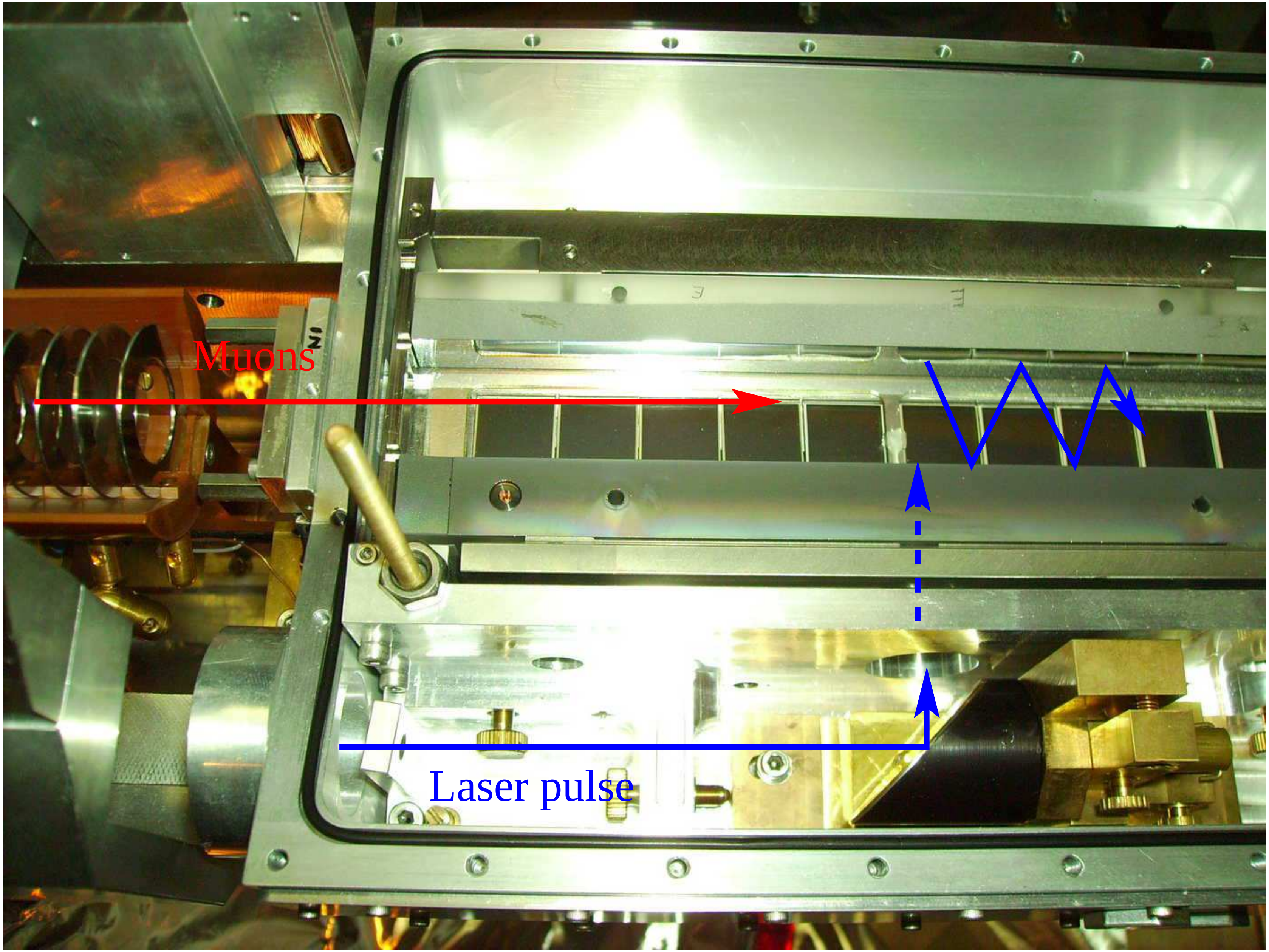


$$\text{normalize}\ \frac{\text{delayed } K_\alpha}{\text{prompt } K_\alpha} \Rightarrow \text{Resonance}$$

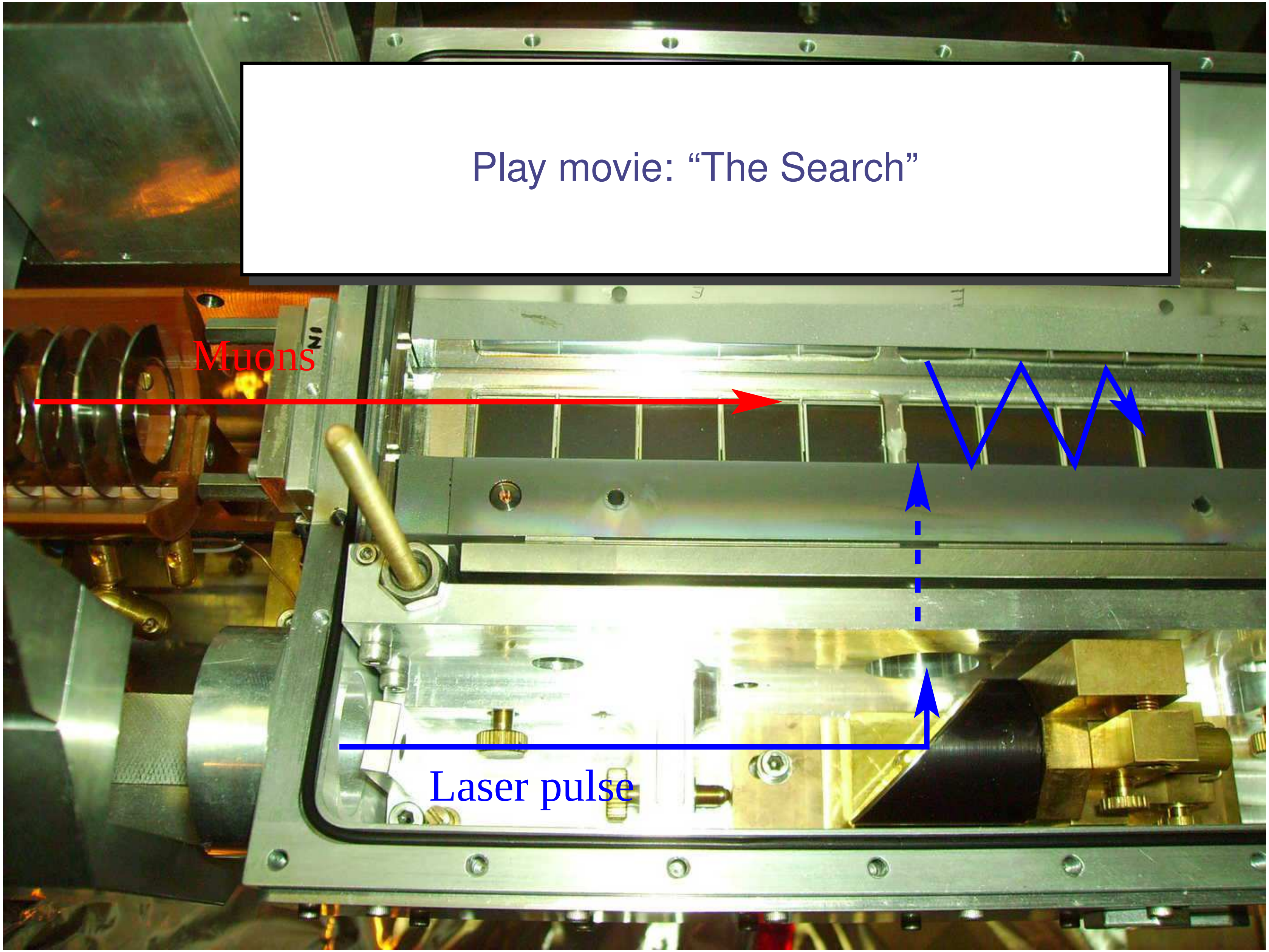
Muon beam line



Target, cavity and detectors



Target, cavity and detectors



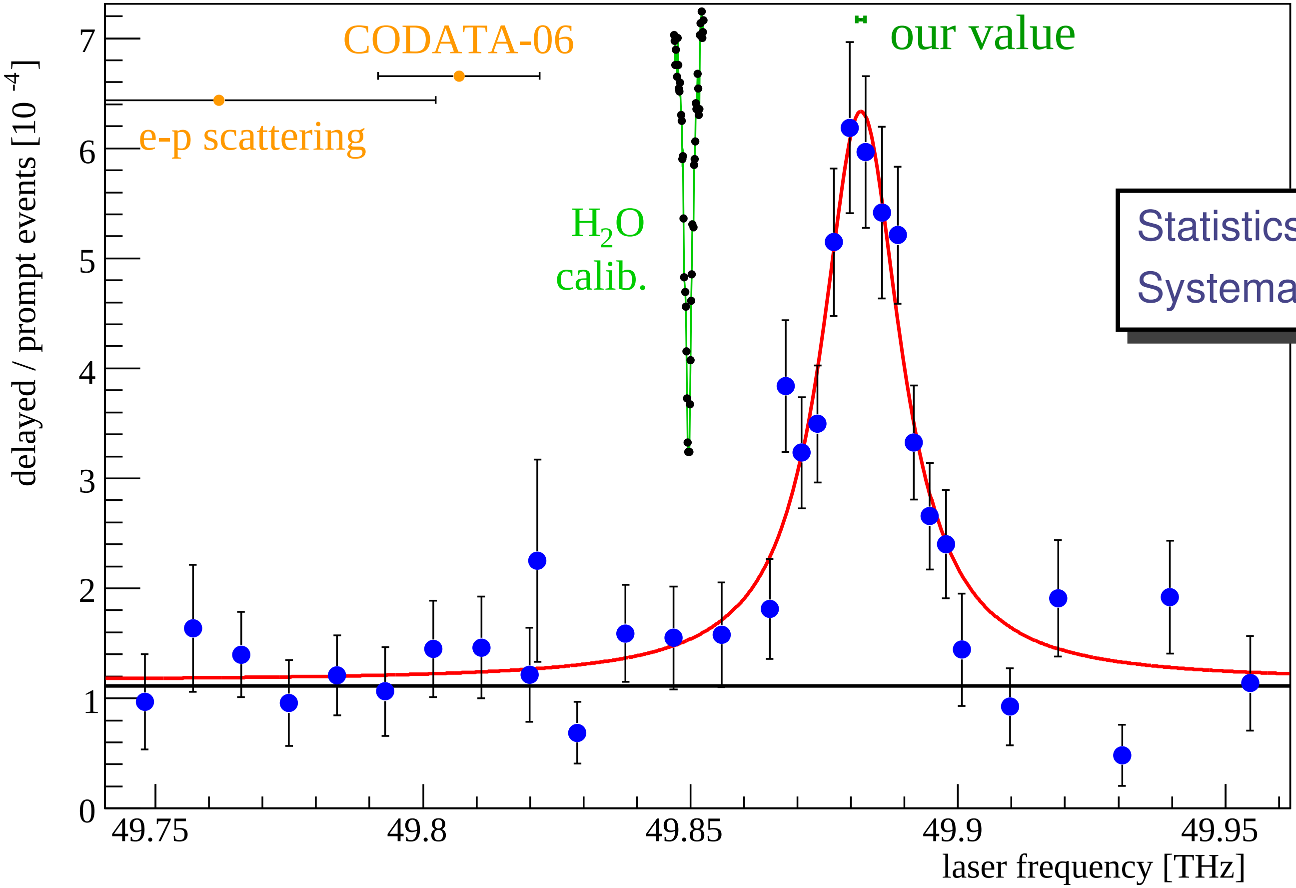
Play movie: “The Search”

Yeah!

The resonance: discrepancy, sys., stat.

Water-line/laser wavelength:
300 MHz uncertainty

$\Delta\nu$ water-line to resonance:
200 kHz uncertainty

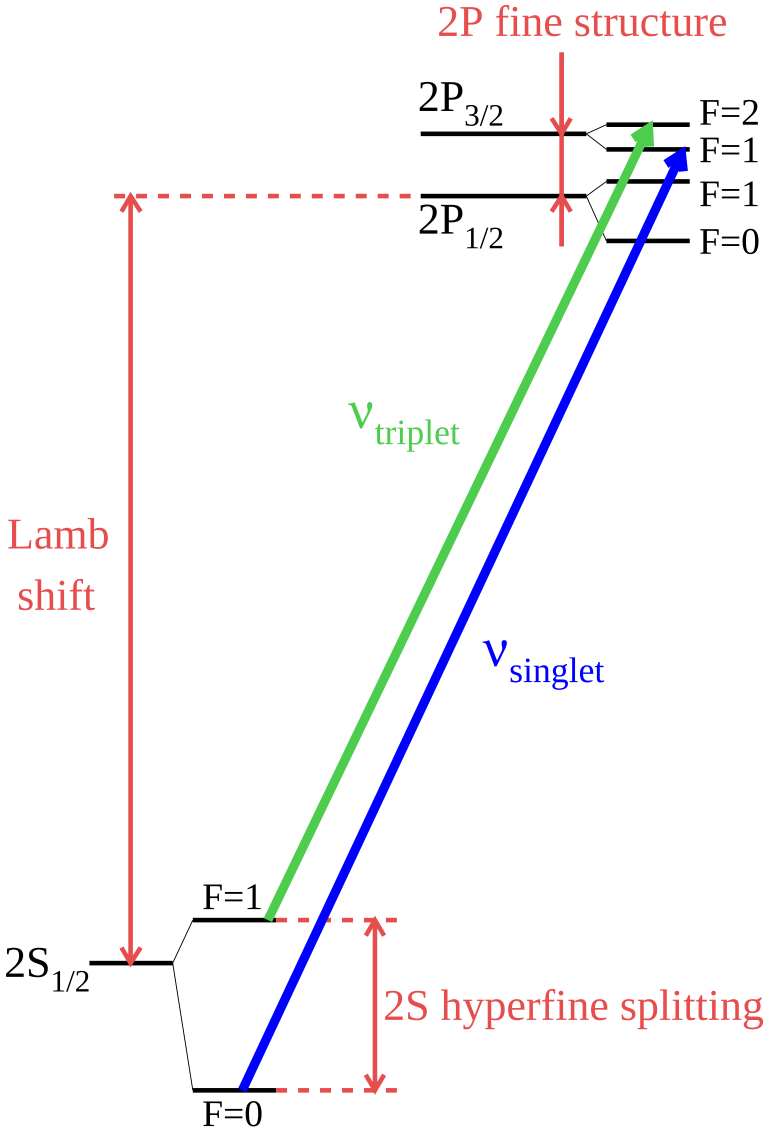


Statistics: 700 MHz
Systematics: 300 MHz

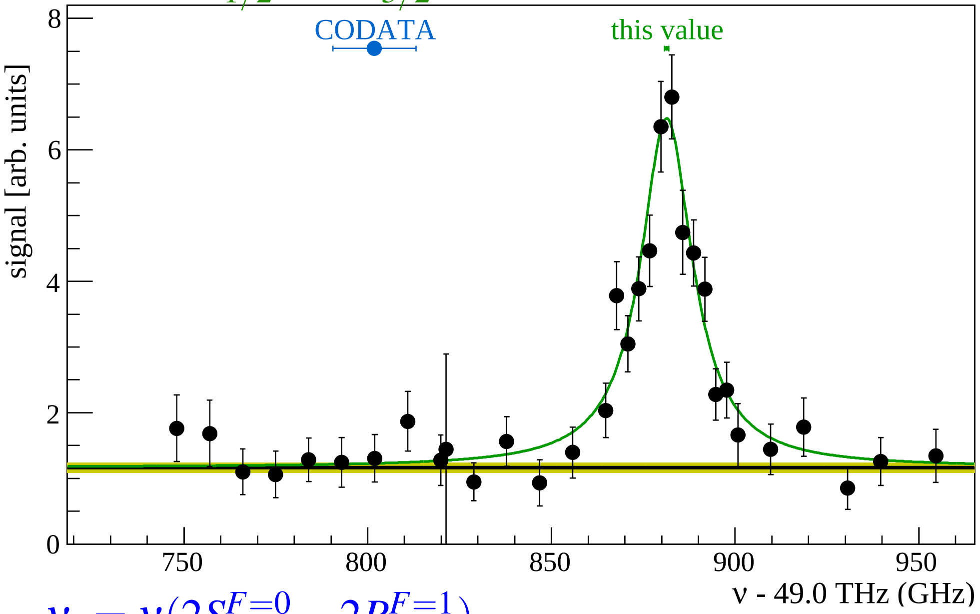
Discrepancy:
$5.0\sigma \leftrightarrow$ **80 GHz** $\leftrightarrow \delta\nu/\nu = 1.5 \times 10^{-3}$

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

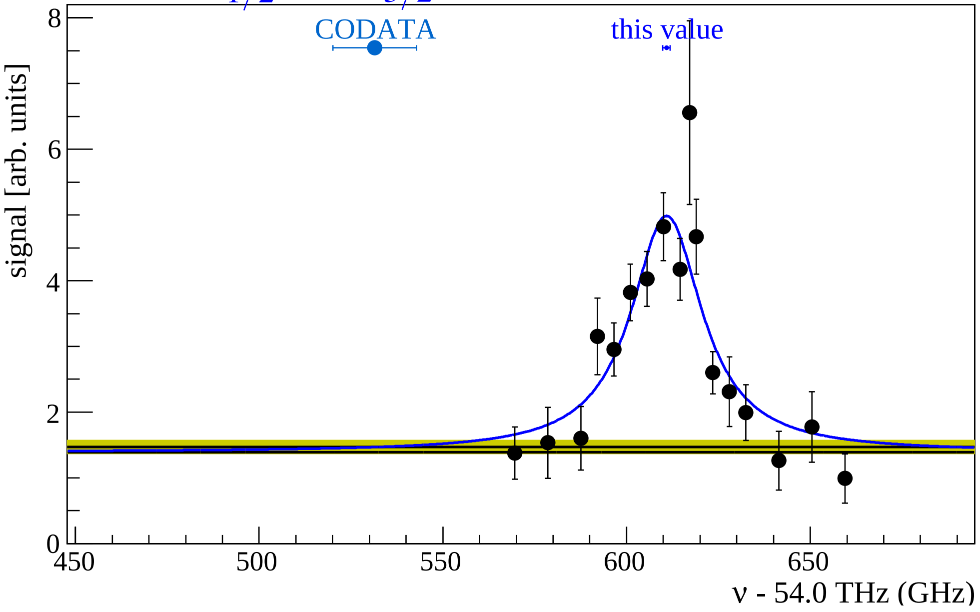
Muonic hydrogen results



$\nu_t = \nu(2S_{1/2}^{F=1} - 2P_{3/2}^{F=2})$



$\nu_s = \nu(2S_{1/2}^{F=0} - 2P_{3/2}^{F=1})$



Exp.: R. Pohl *et al.*, Nature 466, 213 (2010).
A. Antognini, RP *et al.*, Science 339, 417 (2013).
Theo: A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

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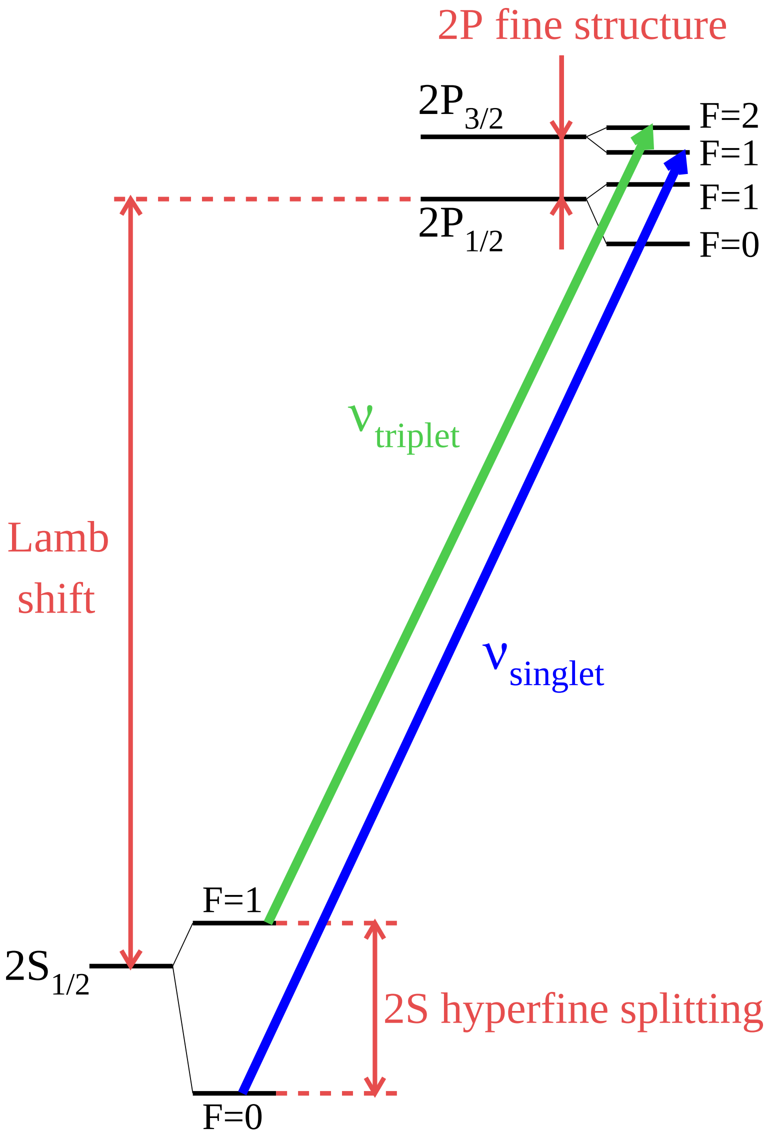


- two transitions measured

ν_t = 49881.35(65) GHz

ν_s = 54611.16(1.05) GHz

- Lamb shift ⇒ **charge radius**

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

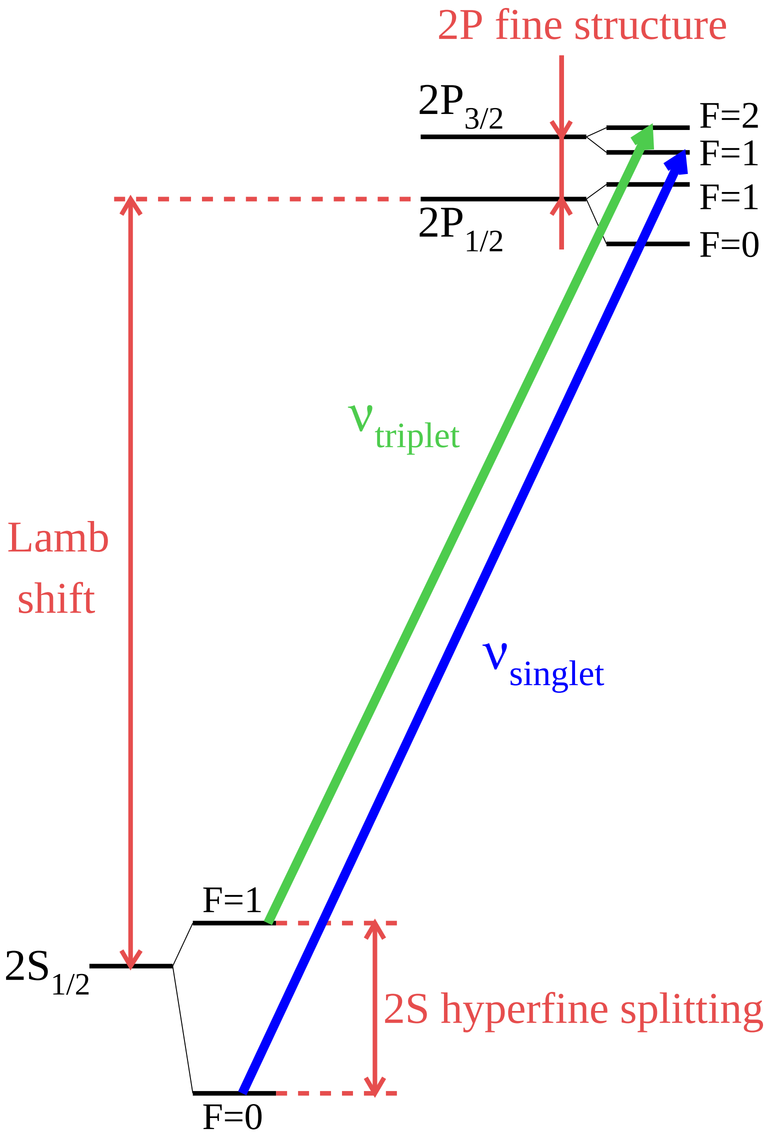
$$r_{\text{E}}^2 = \int d^3r\, r^2\, \rho_E(r)$$

$$\boxed{r_{\text{E}} = 0.84087\,(26)_{\text{exp}}\,(29)_{\text{th}}\ \text{fm} = 0.84087\ (39)\ \text{fm}}$$

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

Muonic hydrogen results



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- 2S-HFS ⇒ **Zemach radius**

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

$$r_{\text{Z}} = \int d^3r \int d^3r'\, r\, \rho_E(r)\, \rho_M(r - r')$$

$$\boxed{r_{\text{Z}} = 1.082\ (31)_{\text{exp}}\ (20)_{\text{th}}\ \text{fm} = 1.082\ (37)\ \text{fm}}$$

Exp.: R. Pohl *et al.*, Nature 466, 213 (2010).
A. Antognini, RP *et al.*, Science 339, 417 (2013).
Theo: A. Antognini, RP *et al.*, Ann. Phys. 331, 127 (2013).

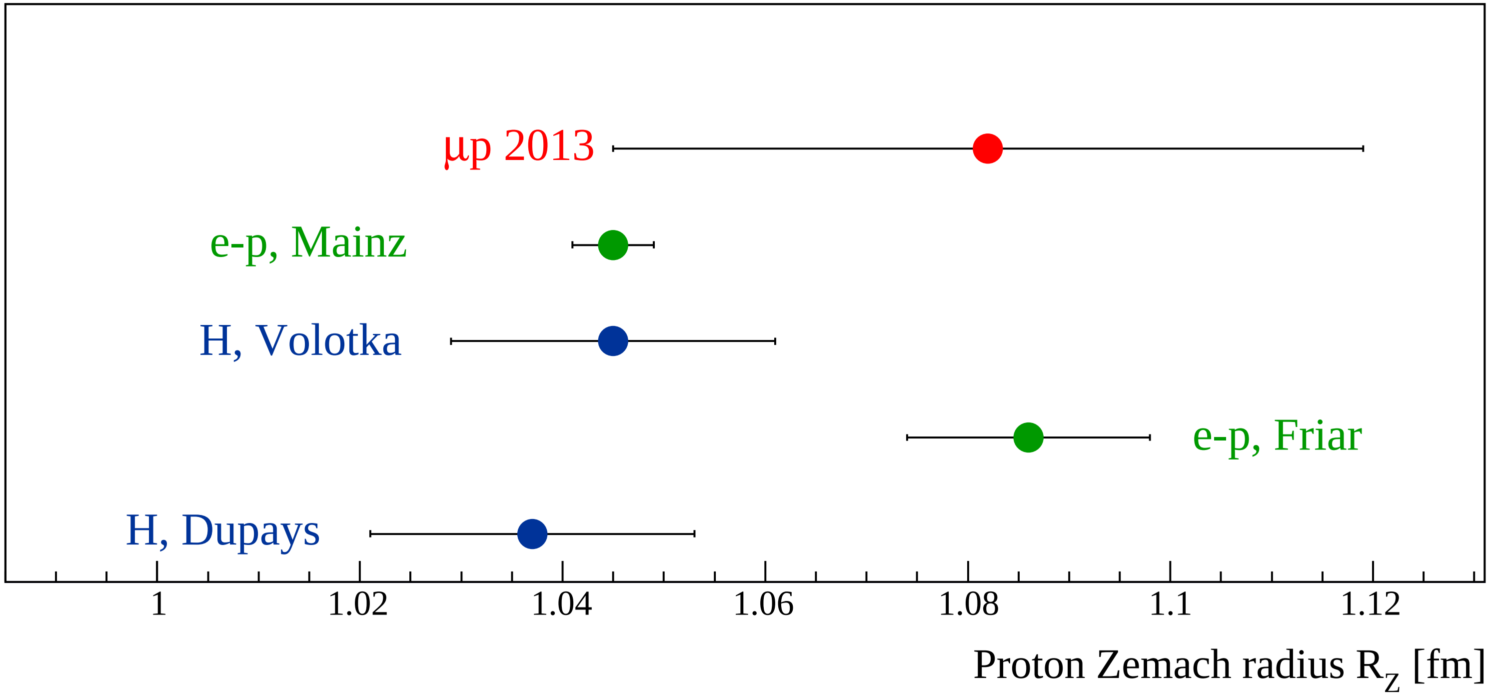
Proton Zemach radius

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

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

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

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



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

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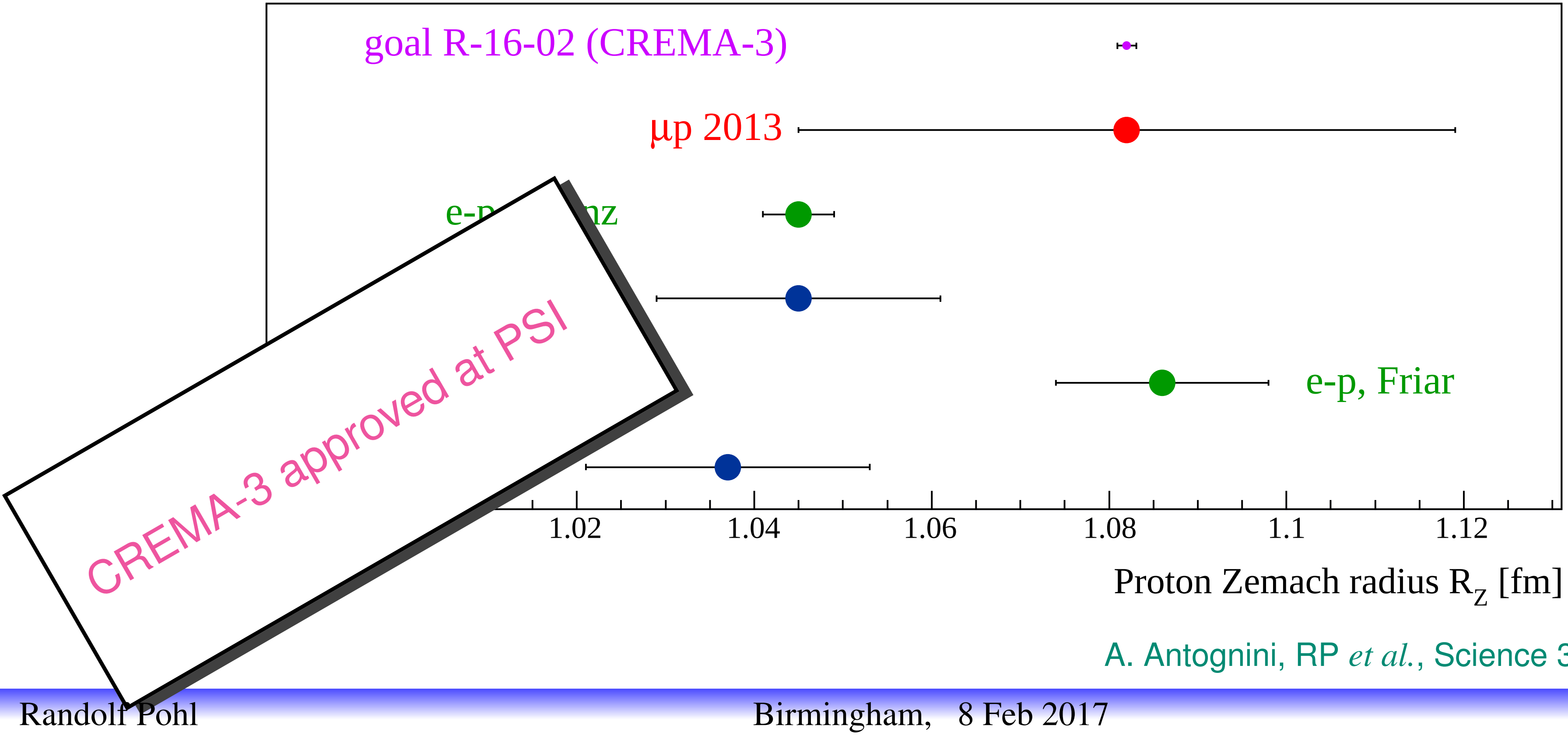
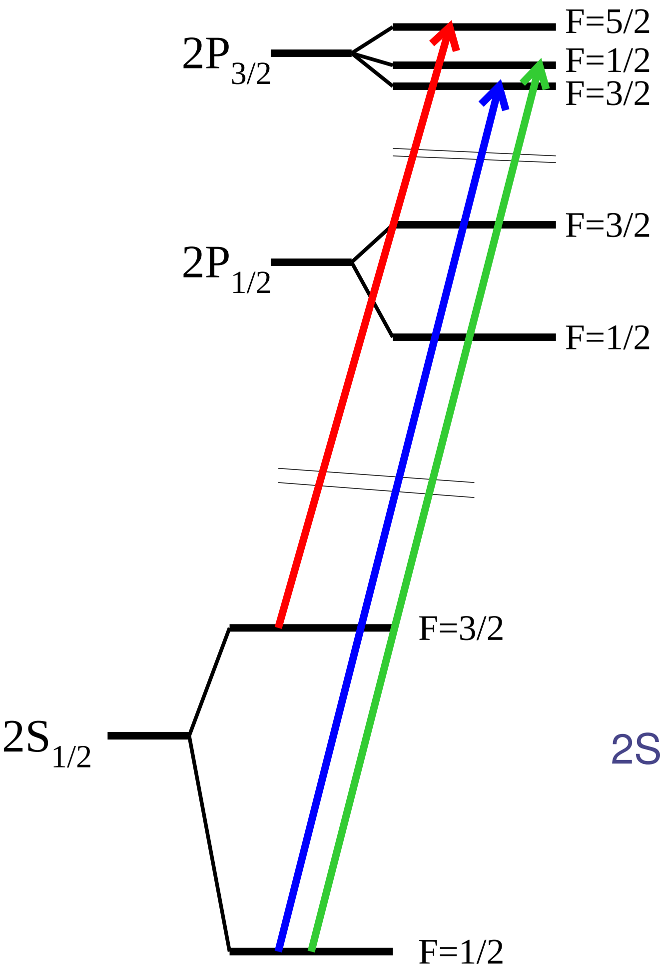


A. Antognini, RP *et al.*, Science 339, 417 (2013)

Muonic deuterium



0.7534 meV

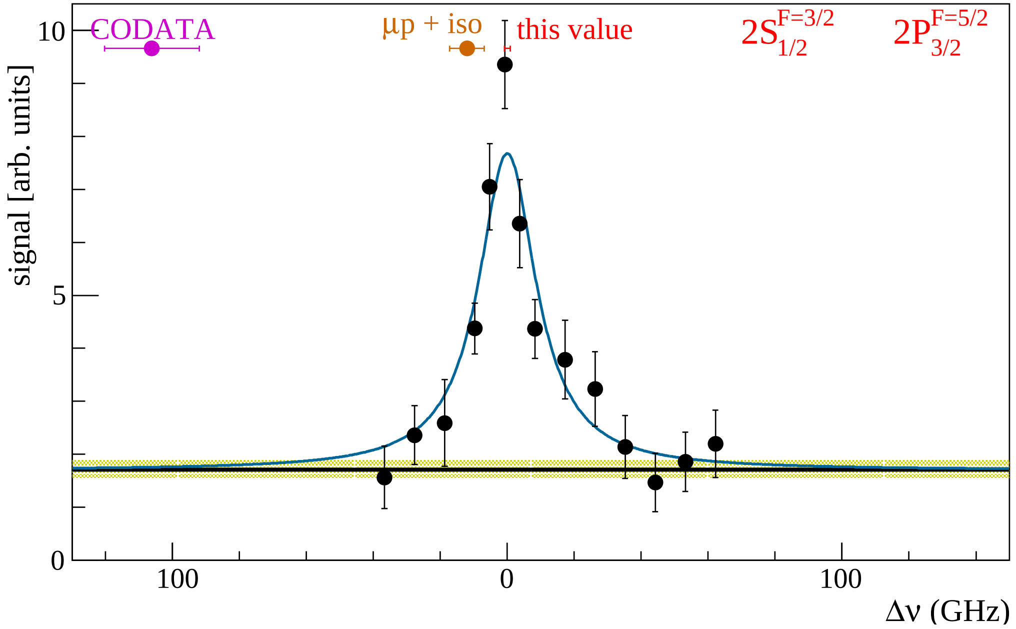
0.3634 meV

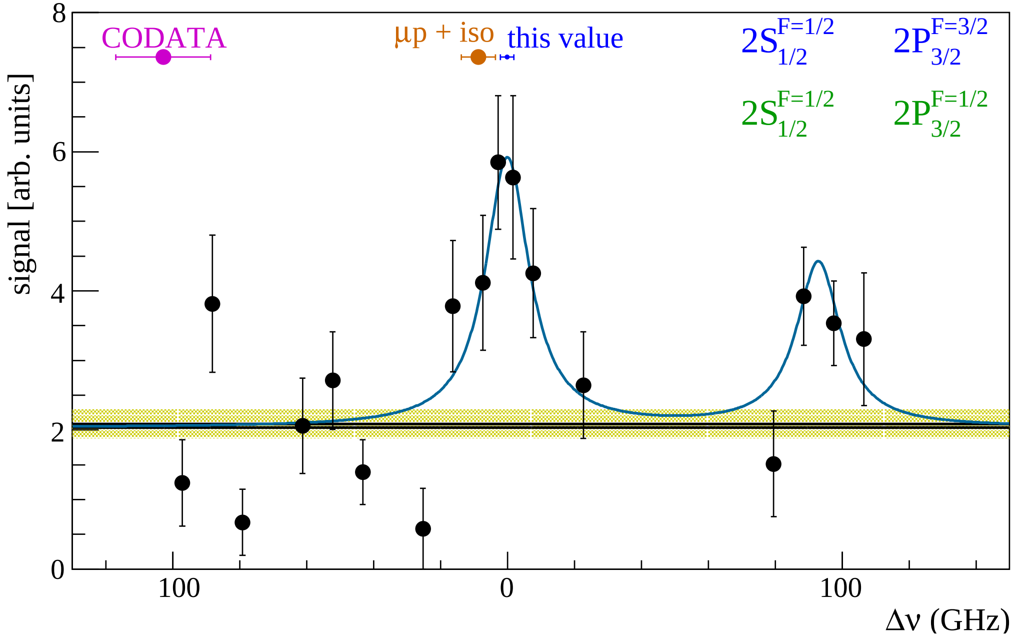
FS: 8.86412 meV

LS: 202.88 meV

2S-HFS: 6.27 meV

Muonic DEUTERIUM



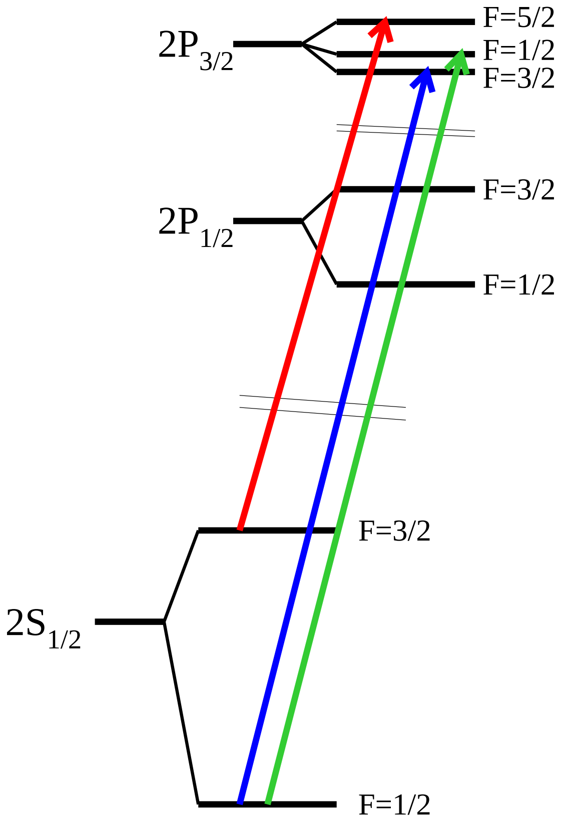


Experiment:

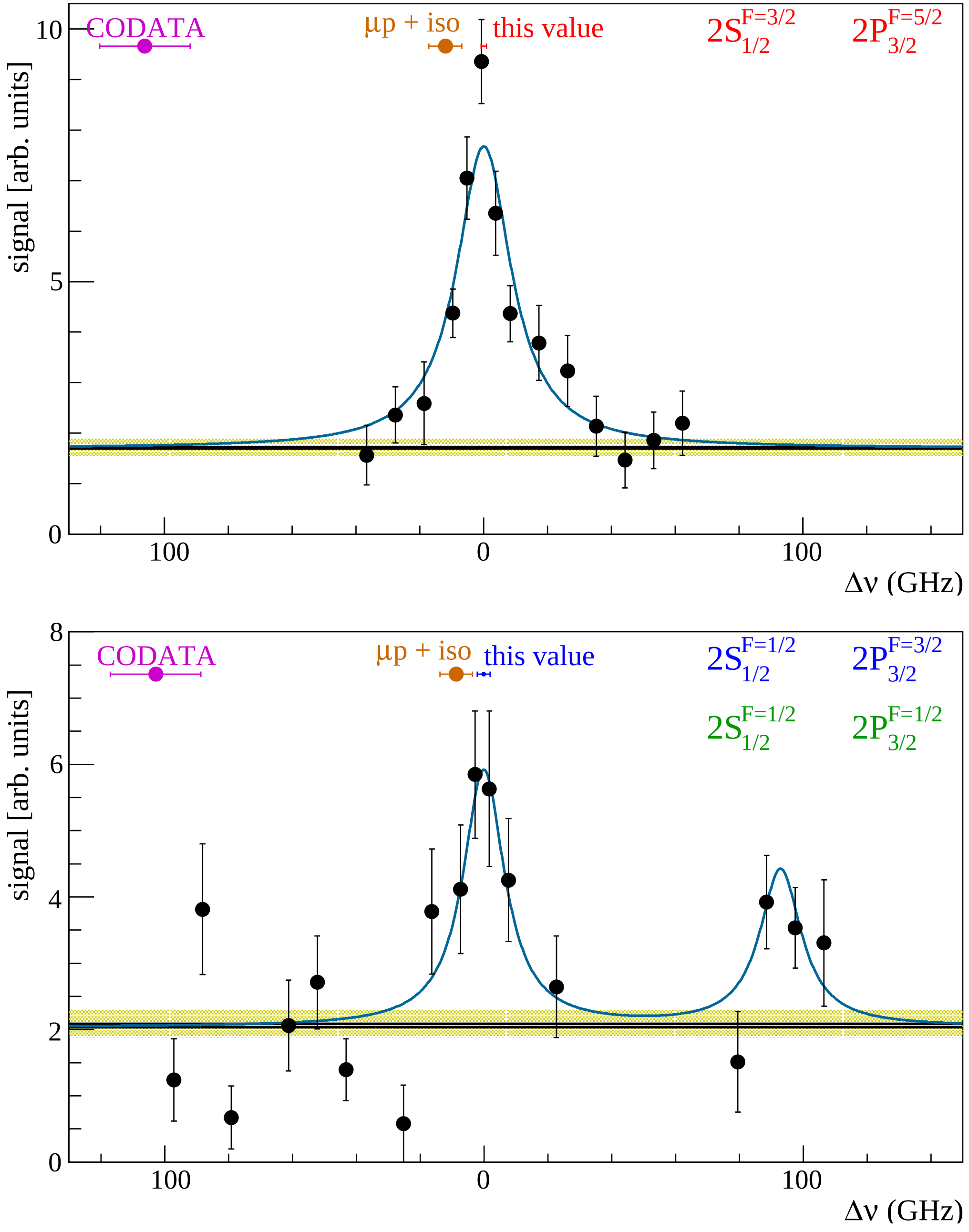
RP *et al.* (CREMA), Science **353**, 417 (2016).

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

$$\boxed{\Rightarrow r_{\mathrm{d}} = 2.12562(13)_{\mathrm{exp}}(77)_{\mathrm{theo}}\ \text{fm}}$$



Muonic DEUTERIUM



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Theory:

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

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.*

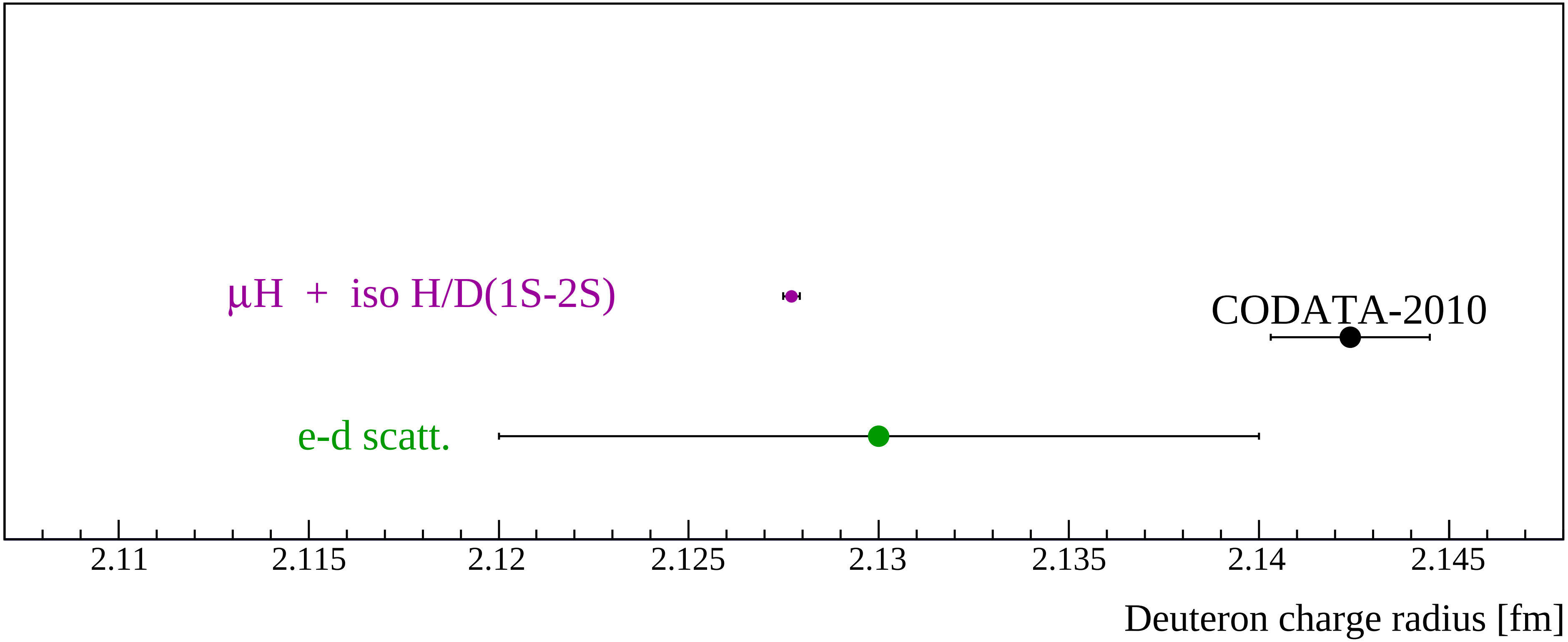
THANK YOU!

Deuteron charge radius

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

CODATA 2010 $r_\mathrm{d} = 2.14240(210)$ fm

r_p from μH gives $r_\mathrm{d} = 2.12771(\ \ 22)$ fm ← 7σ from r_p



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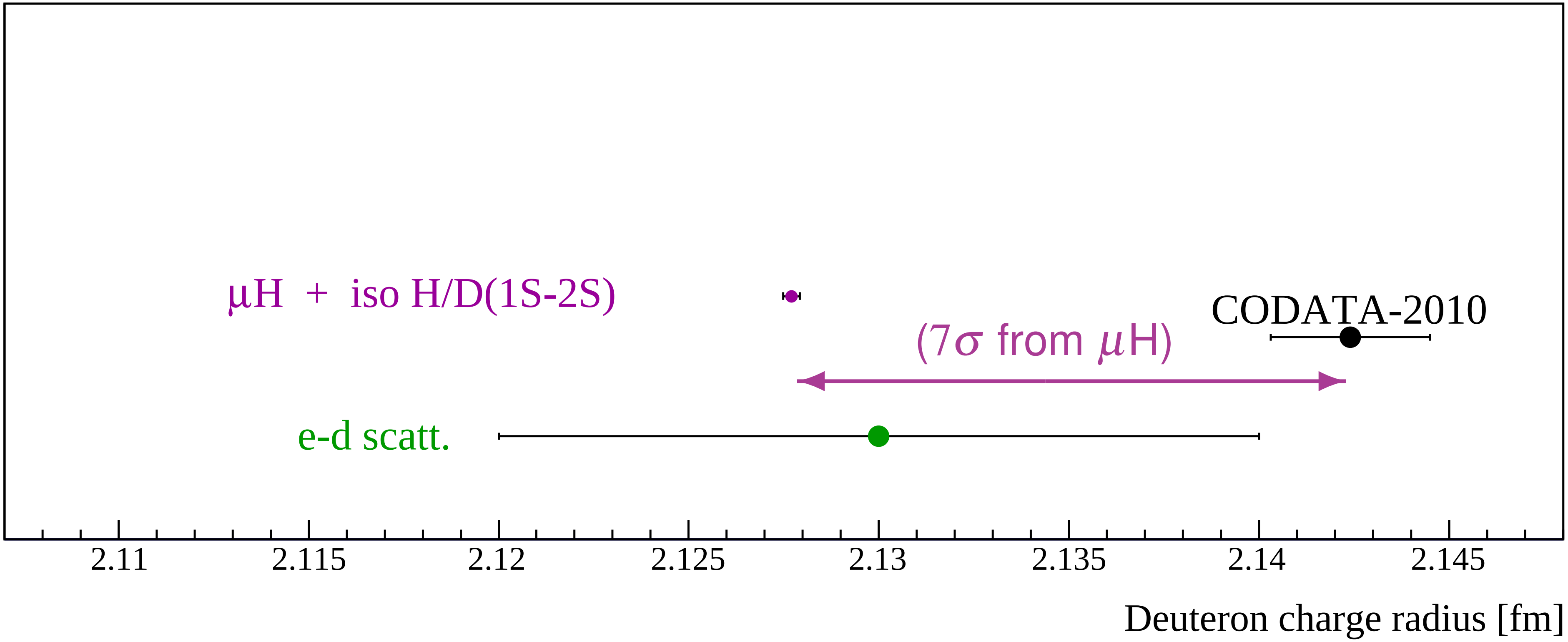

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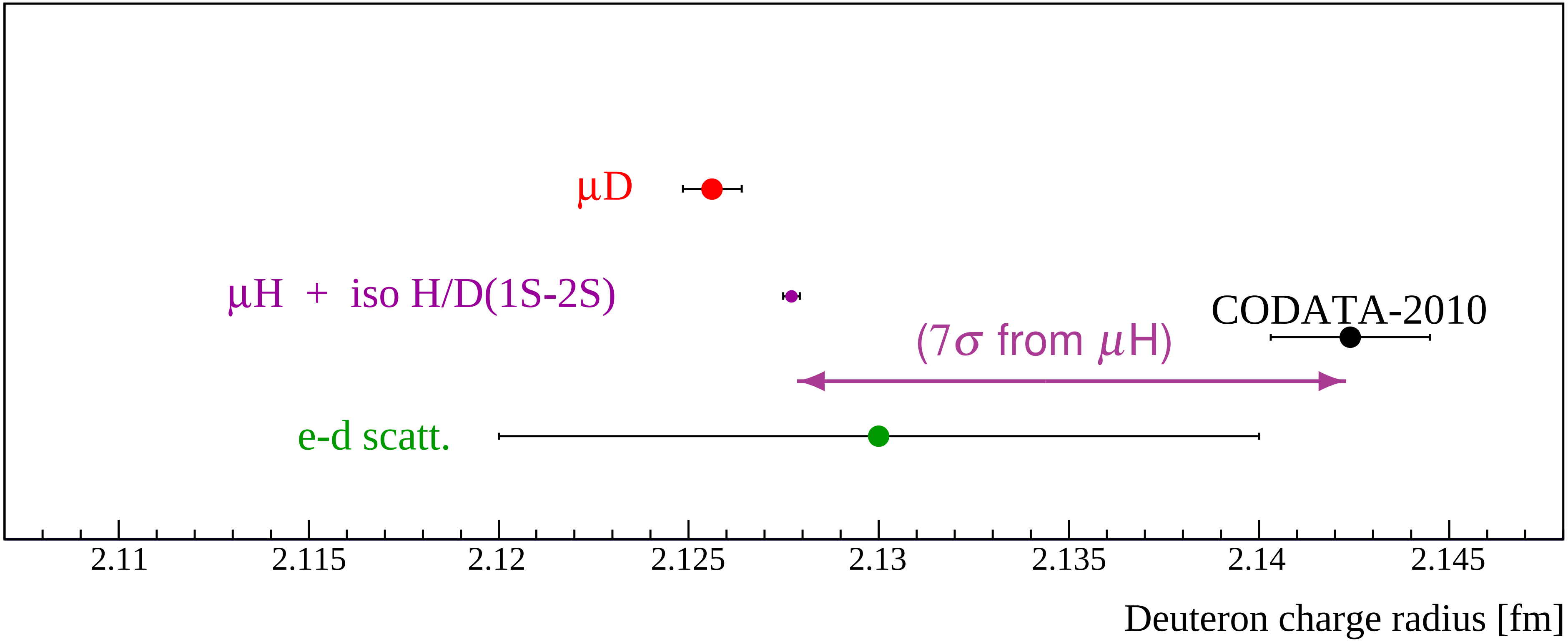

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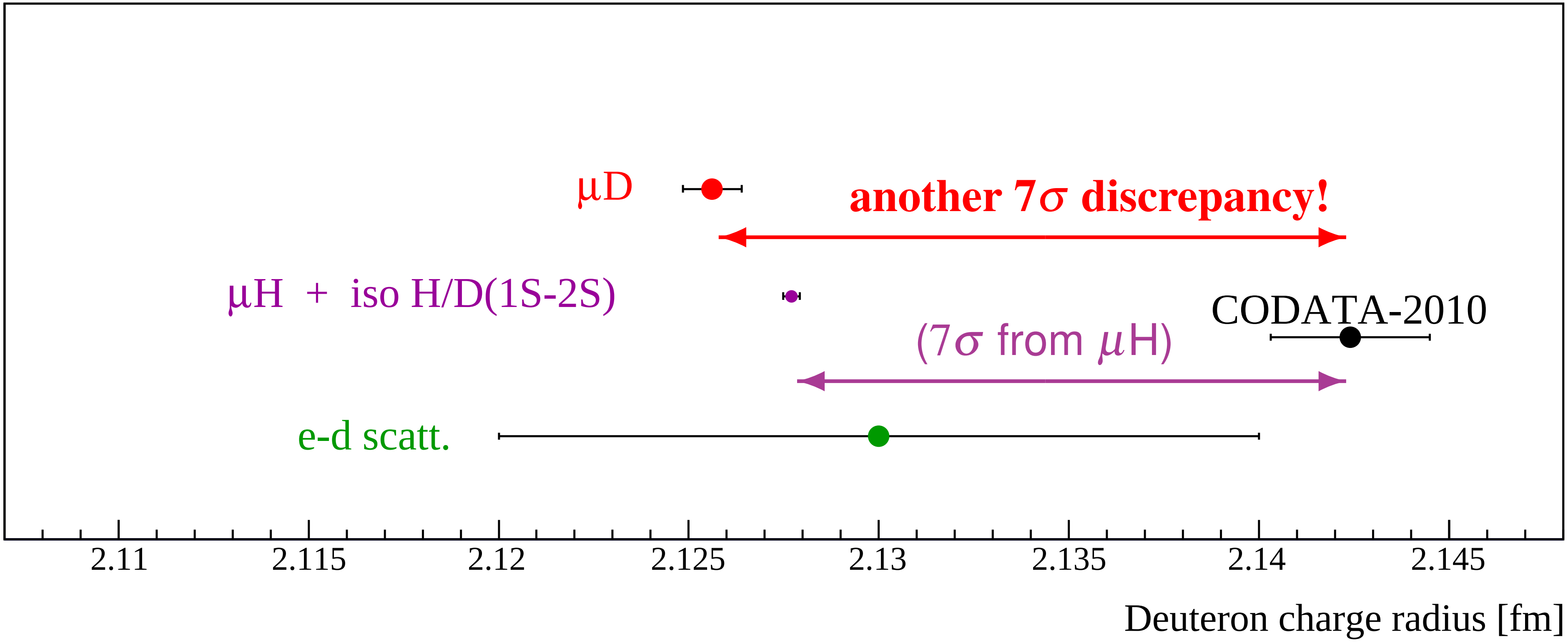
r_{p} from μH gives $r_{\mathrm{d}} = 2.12771(\ 22)\ \mathrm{fm}$ ← 7σ from r_{p}

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



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)

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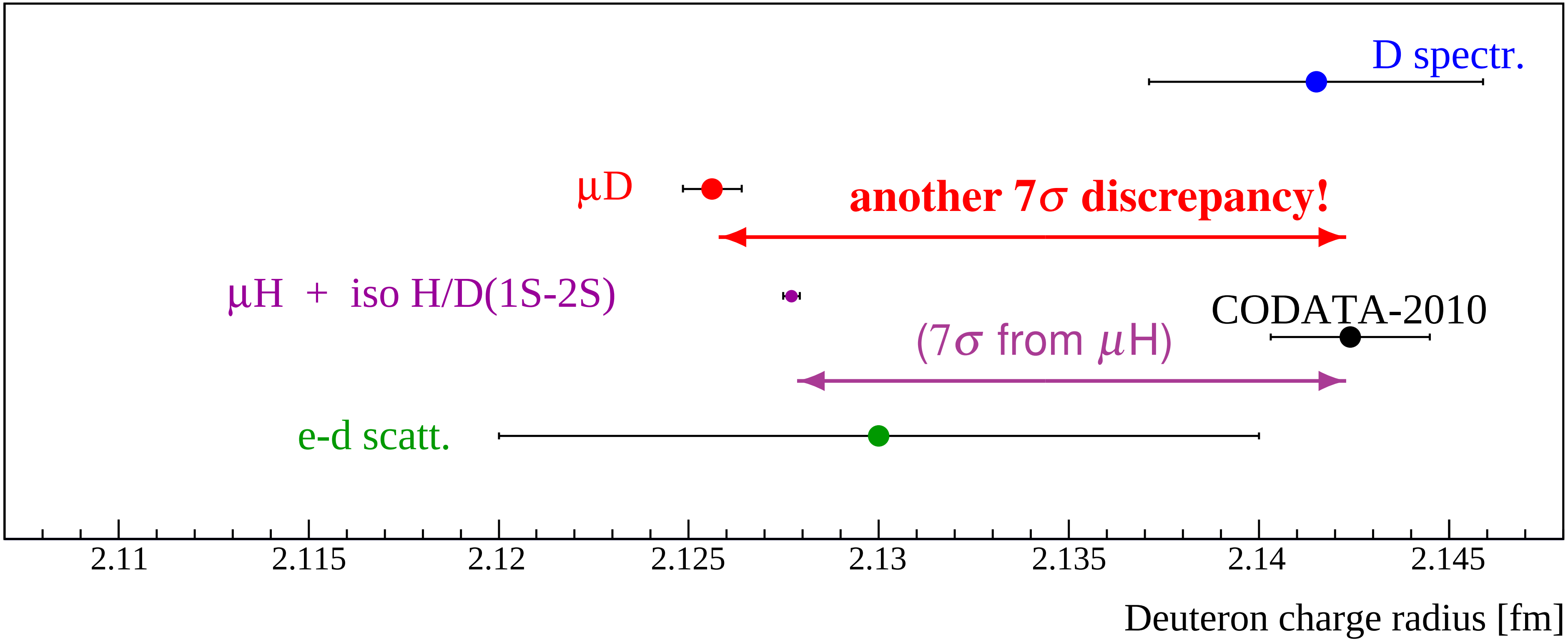
electronic D (r_p indep.) $r_\mathrm{d} = 2.14150(450)$ fm RP *et al.* arXiv 1607.03165



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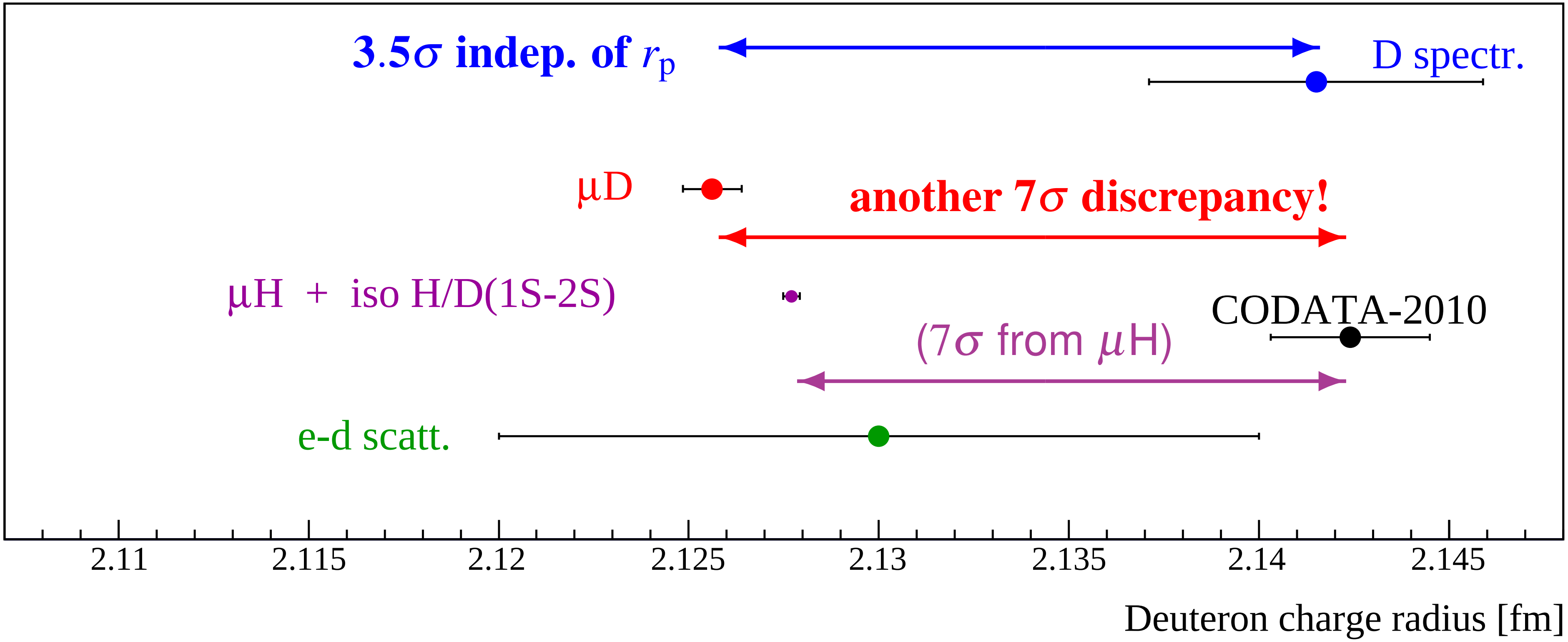


Results from muonic deuterium (prel.)

Lamb shift in muonic deuterium:

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

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

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

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

$r_d(\mu\mathrm{d}) = 2.12562\,(13)_{\mathrm{exp}}\,(77)_{\mathrm{theo}}\ \mathrm{fm}$ (preliminary)

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

$r_d(\mathrm{CODATA}) = 2.14240\,(210)\ \mathrm{fm}$ 7.5σ

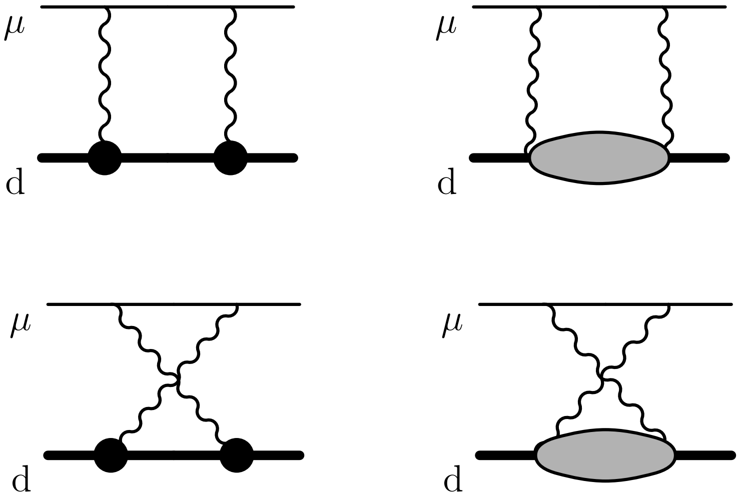
Disprepancy to $\Delta E_{\mathrm{LS}}(\,r_d(\mathrm{CODATA})\,)$ = 0.438(59) meV

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

Theory in μd: TPE

$\boxed{r_\mathrm{d} = 2.12562(13)_\mathrm{exp}(77)_\mathrm{theo}\ \text{fm},}$ 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]		Friar [60]		Hernandez *et al.* [58]			Pach.& Wienczek [65]		Carlson *et al.* [64]	Our choice		
		AV18		ZRA		AV18	N^{3}LO †		AV18		data	value		source
	Source	1		2		3	4		5		6			
p1	Dipole	1.910	$\delta_0 E$	1.925	Leading C1	1.907	1.926	$\delta^{(0)}_{D1}$	1.910	$\delta_0 E$		1.9165	± 0.0095	3-5
p2	Rel. corr. to p1, longitudinal part	−0.035	$\delta_R E$	−0.037	Subleading C1	−0.029	−0.030	$\delta^{(0)}_{L}$	−0.026	$\delta_R E$				
p3	Rel. corr. to p1, transverse part					0.012	0.013	$\delta^{(0)}_{T}$						
p4	Rel. corr. to p1, higher order								0.004	$\delta_{HO} E$				
sum	Total rel. corr., p2+p3+p4	−0.035		−0.037		−0.017	−0.017		−0.022			−0.0195	± 0.0025	3-5
p5	Coulomb distortion, leading	−0.255	$\delta_{C1} E$						−0.255	$\delta_{C1} E$				
p6	Coul. distortion, next order	−0.006	$\delta_{C2} E$						−0.006	$\delta_{C2} E$				
sum	Total Coulomb distortion, p5+p6	−0.261				−0.262	−0.264	$\delta^{(0)}_{C}$	−0.261			−0.2625	± 0.0015	3-5
p7	El. monopole excitation	−0.045	$\delta_{Q0} E$	−0.042	C0	−0.042	−0.041	$\delta^{(2)}_{R2}$	−0.042	$\delta_{Q0} E$				
p8	El. dipole excitation	0.151	$\delta_{Q1} E$	0.137	Retarded C1	0.139	0.140	$\delta^{(2)}_{D1D3}$	0.139	$\delta_{Q1} E$				
p9	El. quadrupole excitation	−0.066	$\delta_{Q2} E$	−0.061	C2	−0.061	−0.061	$\delta^{(2)}_{Q}$	−0.061	$\delta_{Q2} E$				
sum	Tot. nuclear excitation, p7+p8+p9	0.040		0.034	C0 + ret-C1 + C2	0.036	0.038		0.036			0.0360	± 0.0020	2-5
p10	Magnetic	−0.008 ◇	$\delta_M E$	−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	$\langle r^3 \rangle^{\mathrm{pp}}_{(2)}$				} 0.043(3)	$\delta_P E$		0.0289	± 0.0015	Eq.(13)
p14	Proton inelastic polarizab.					} 0.027(2)		δ^N_{pol} [64]			} 0.028(2)ΔE^{hadr}	} 0.0280	± 0.0020	6
p15	Neutron inelastic polarizab.								0.016(8)	$\delta_N E$				
p16	Proton & neutron subtraction term											−0.0098	± 0.0098	Eq.(15)
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]

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

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Experimental TPE in μd

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

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

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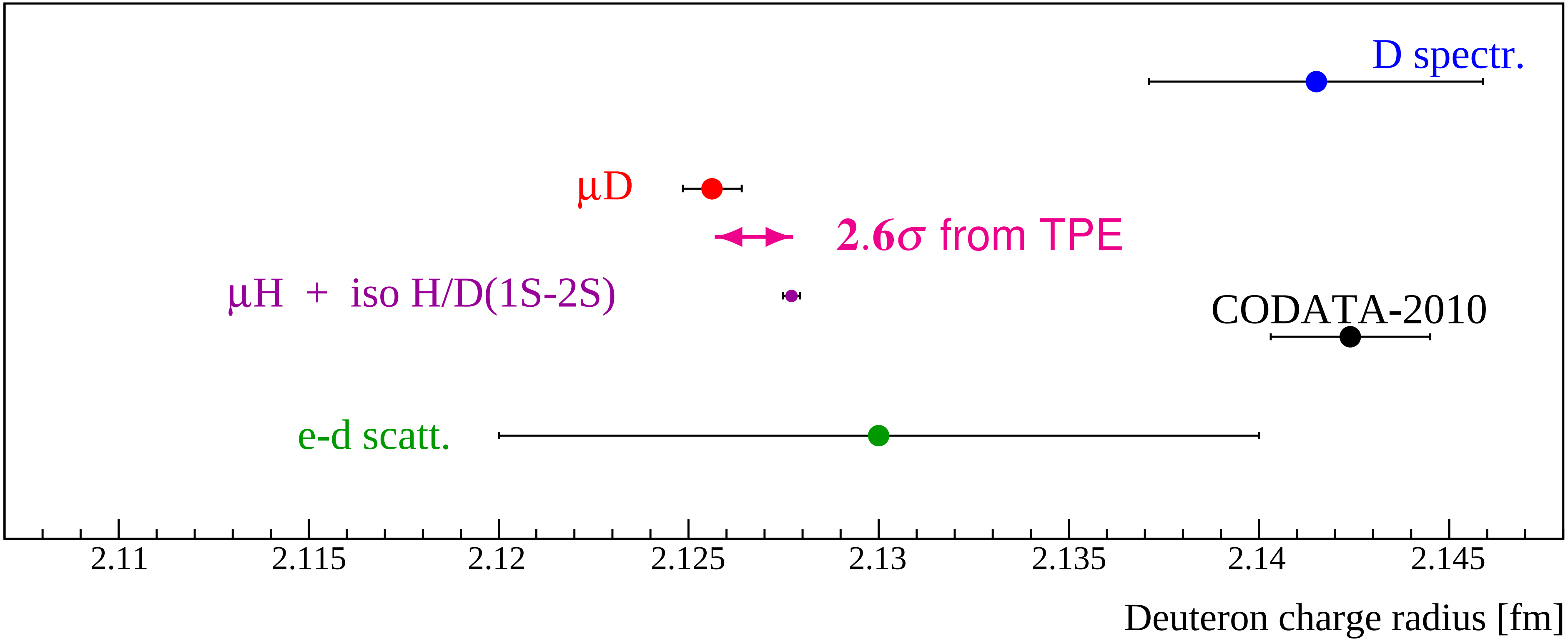
- $\Delta E_{\mathrm{LS}}^{\mathrm{exp}} = 202.8785\,(31)_{\mathrm{stat}}(14)_{\mathrm{syst}}$ meV from μD exp.
- $r_d = 2.12771(22)$ fm

from $r_{\mathrm{d}}^2 - r_{\mathrm{p}}^2 = 3.82007(65)\ \mathrm{fm}^2$ [H/D(1S-2S) isotope shift]
using $r_{\mathrm{p}}(\mu\mathrm{H})$ = 0.84087(39) fm



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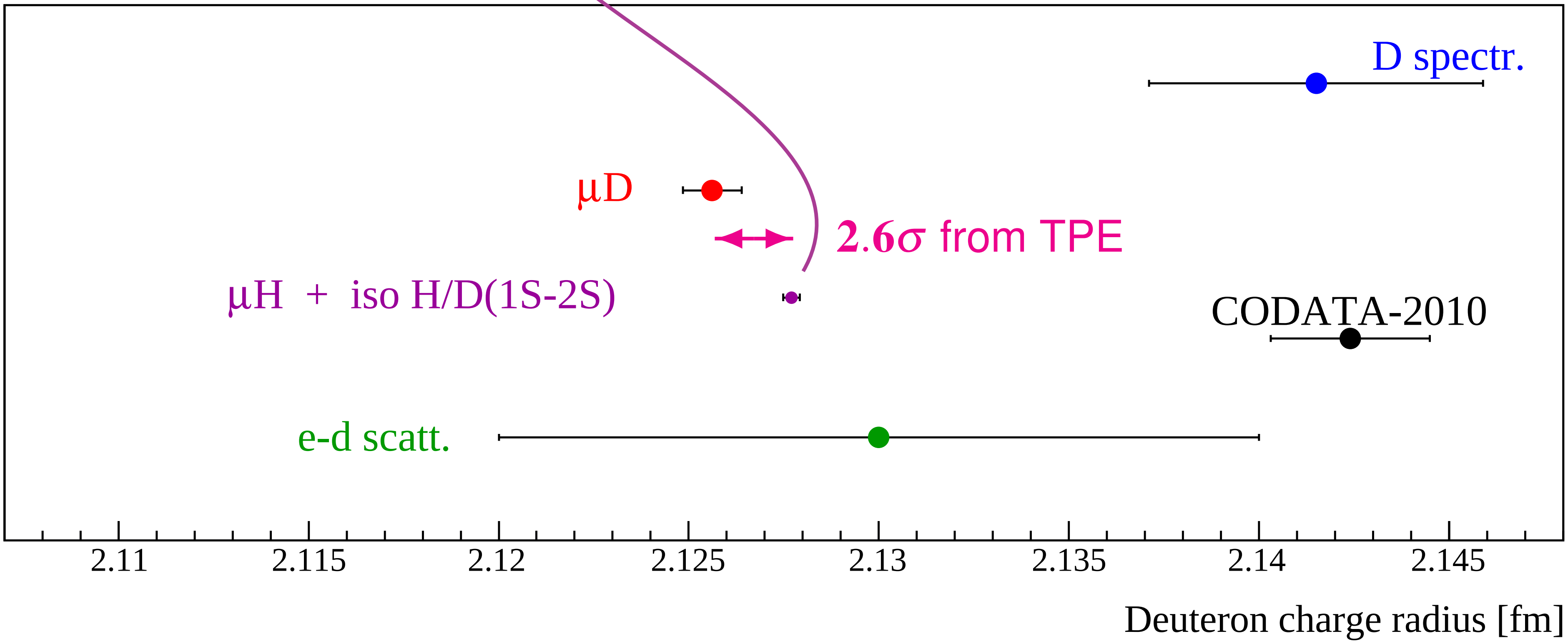

Conclusions μp and μd

Pohl *et al.*, Nature 466, 213 (2010).
Antognini *et al.*, Science 339, 417 (2013).
Pohl *et al.*, Science 353, 669 (2016).
Antognini *et al.*, Ann. Phys. 331, 127 (2013).
Krauth *et al.*, Ann. Phys. 366, 168 (2016).
Pohl *et al.*, Metrologia (accepted 2016).

- Proton charge radius: r_p= 0.84087 (39) fm
- Proton Zemach radius: R_Z = 1.082 (37) fm
- Rydberg constant, using H(1S-2S):
  $R_\infty = 3.289\,841\,960\,249\,5\ (10)^\mathrm{radius}\ (25)^\mathrm{QED}\ \times 10^{15}\ \mathrm{Hz/c}$
- Deuteron charge radius: r_d= 2.12771 (22) fm using H/D(1S-2S)
- r_p is $\sim 7\sigma$ smaller than CODATA-2010
  4.0σ smaller than r_p(H spectrosopy)
- r_d is 7.5σ smaller than CODATA-2010 (99% correlated with r_p!)
  3.5σ smaller than r_d(D spectrosopy)
- Proton and deuteron are consistently too small:

$$r_\mathrm{d}^2 = r_\mathrm{struct}^2 + r_\mathrm{p}^2 + r_n^2 + \frac{3\hbar^2}{4m_p^2c^2}$$

Conclusions μp and μd

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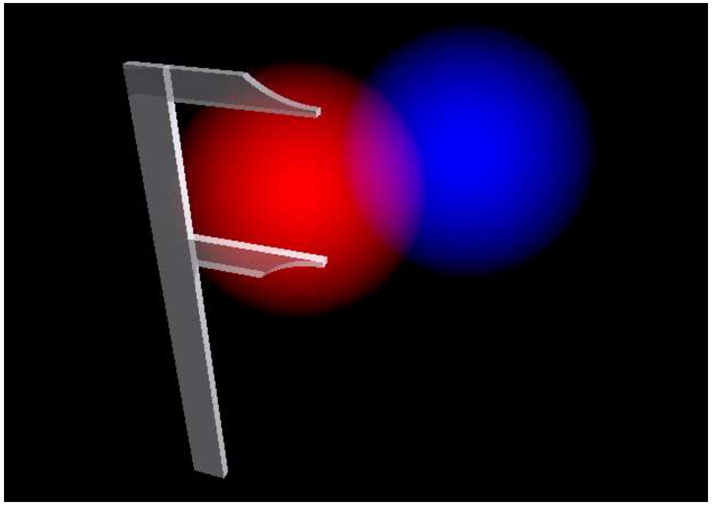
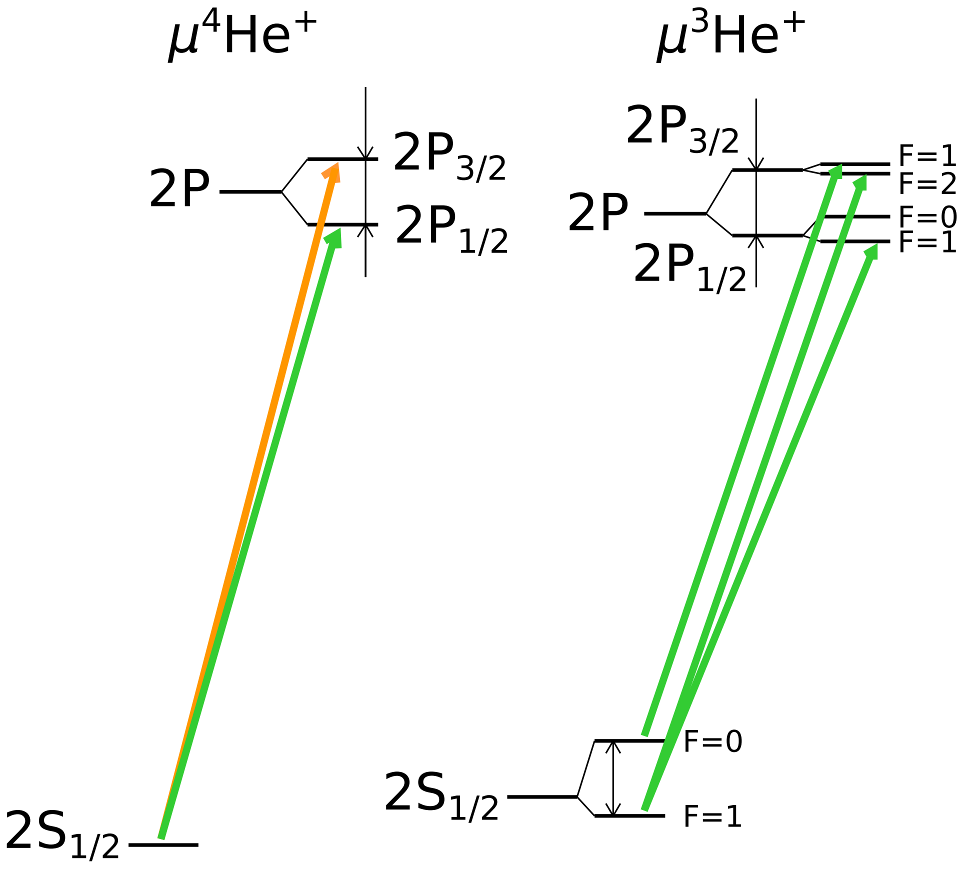


Muonic helium ions



Lamb shift in muonic helium

- Goal: Measure ΔE(2S-2P) in $\mu\,^4$He, $\mu\,^3$He to ~ 50 ppm
- ⇒ alpha particle and helion charge radius to 3×10^{-4} (± 0.0005 fm),

  This is **10 times better** than from electron scattering.
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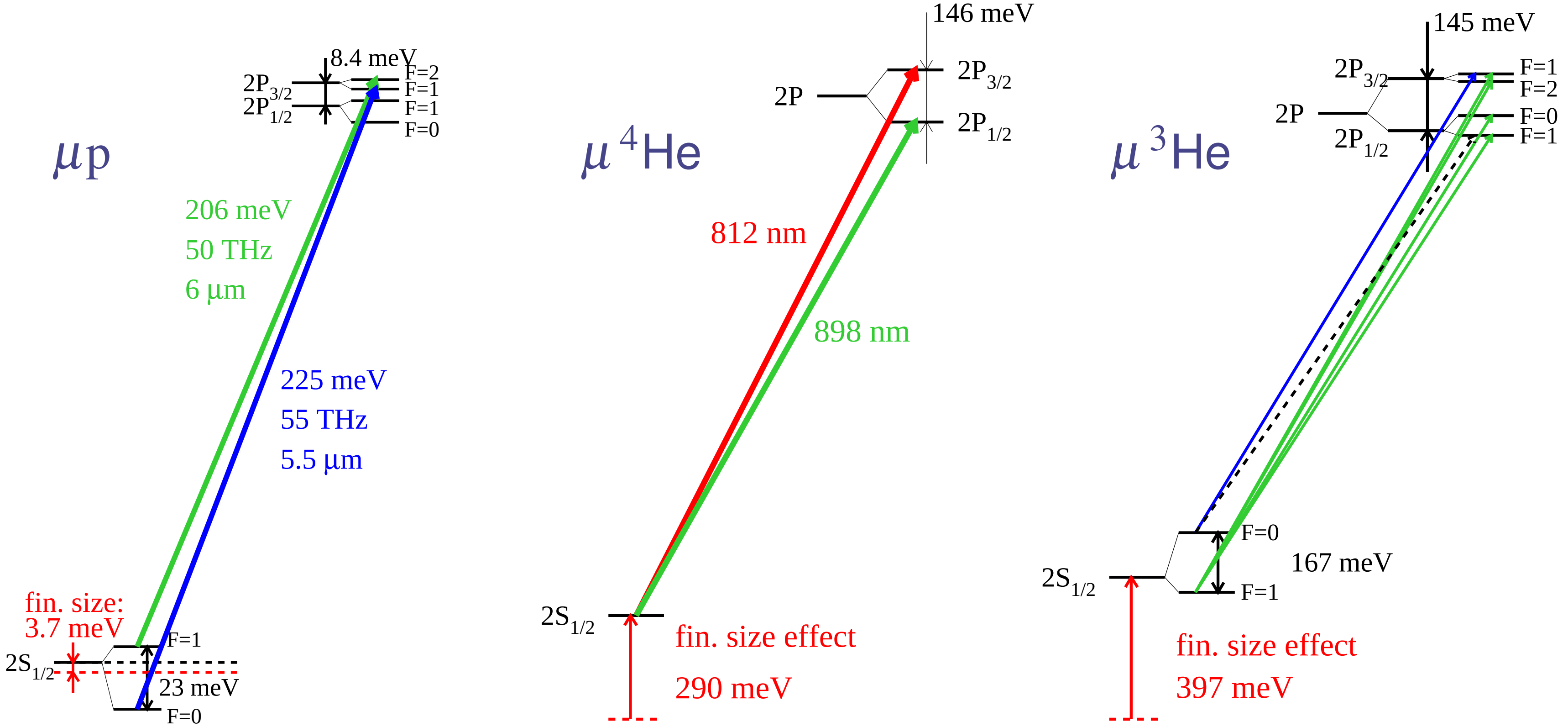
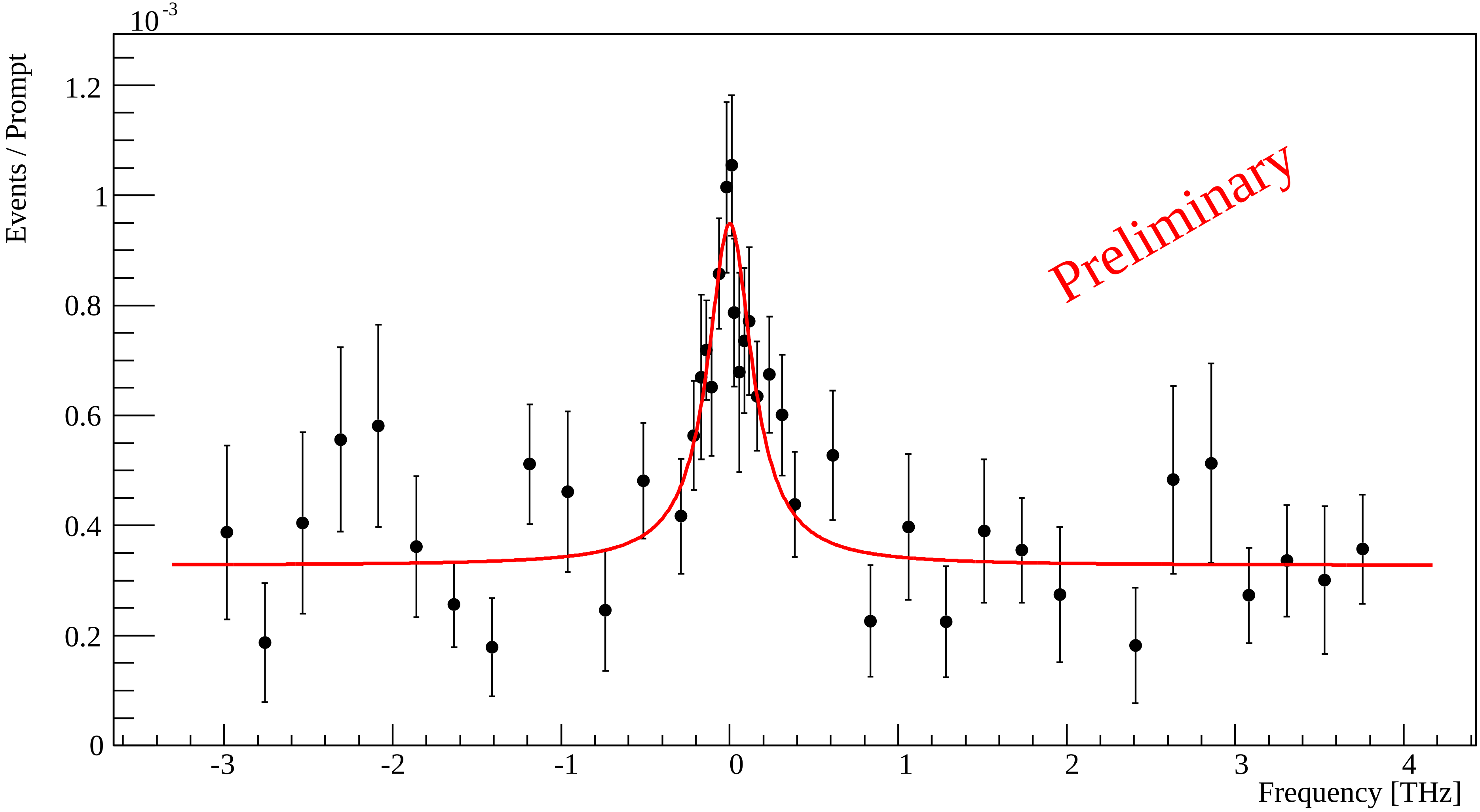


1st resonance in muonic He-4

$\mu^4\mathrm{He}(2S_{1/2} \rightarrow 2P_{3/2})$ at ~ 813 nm wavelength



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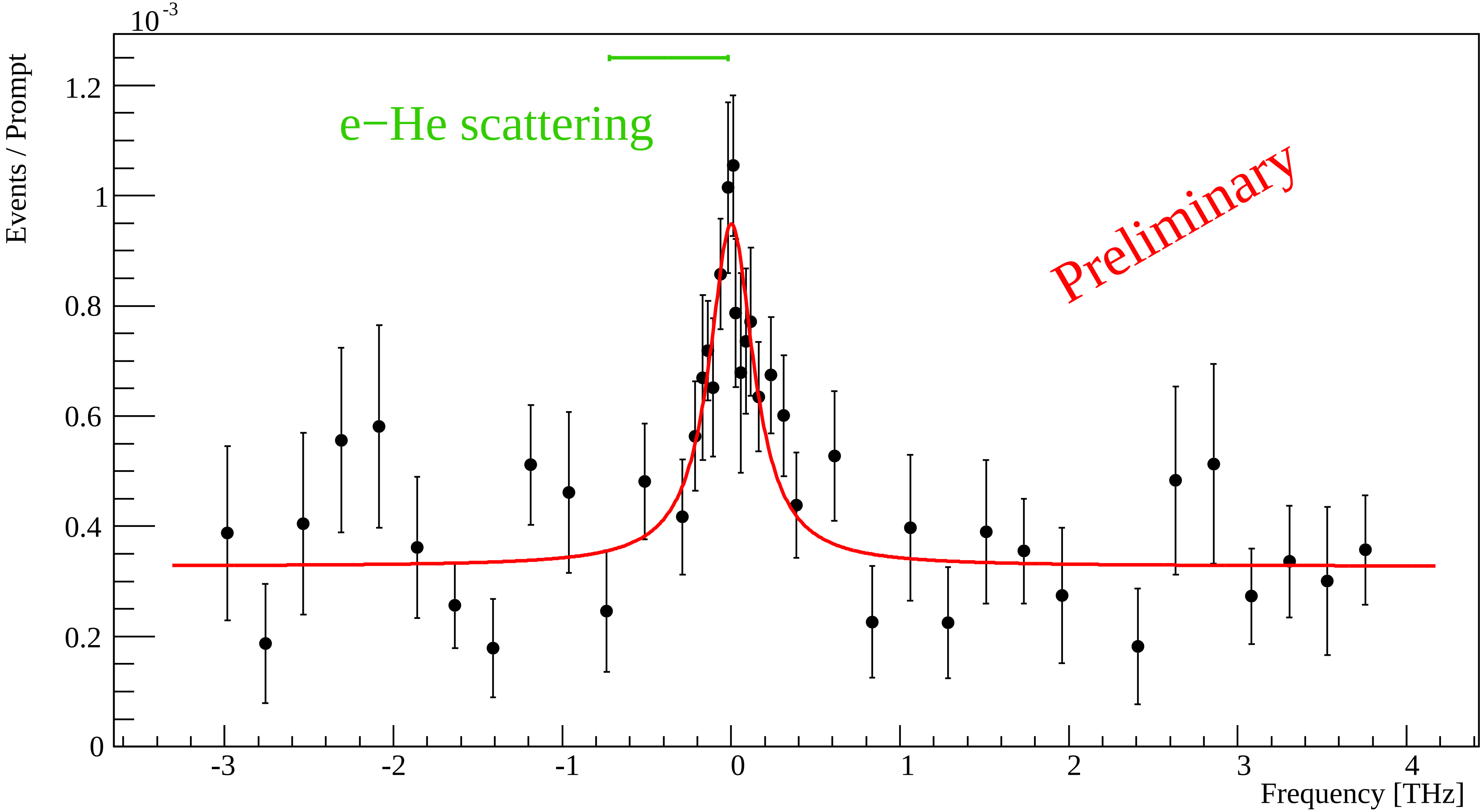

Sick, PRD 77, 040302(R) (2008) Borie, Ann. Phys. 327, 733 (2012)

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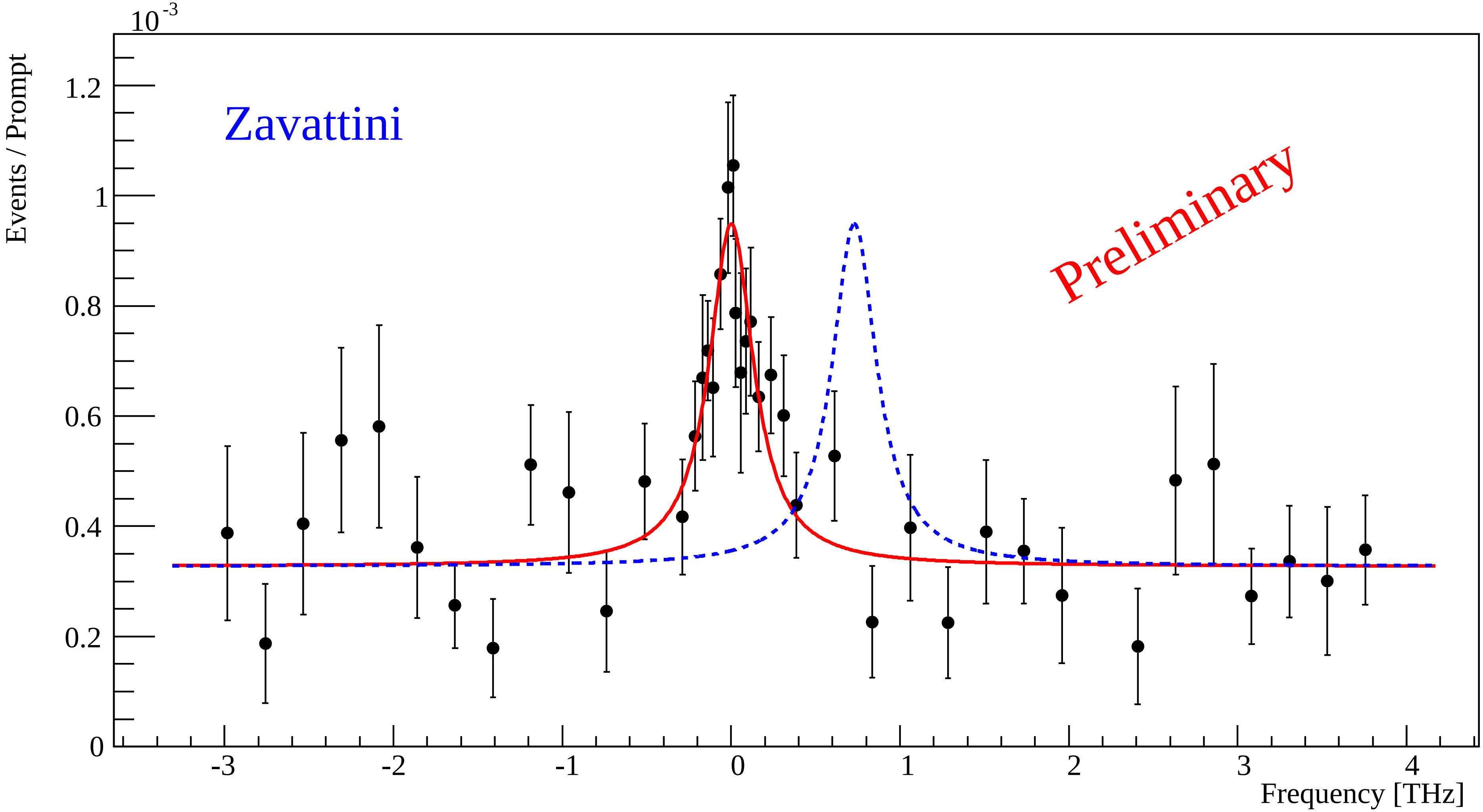

Carboni et al, Nucl. Phys. A273, 381 (1977)

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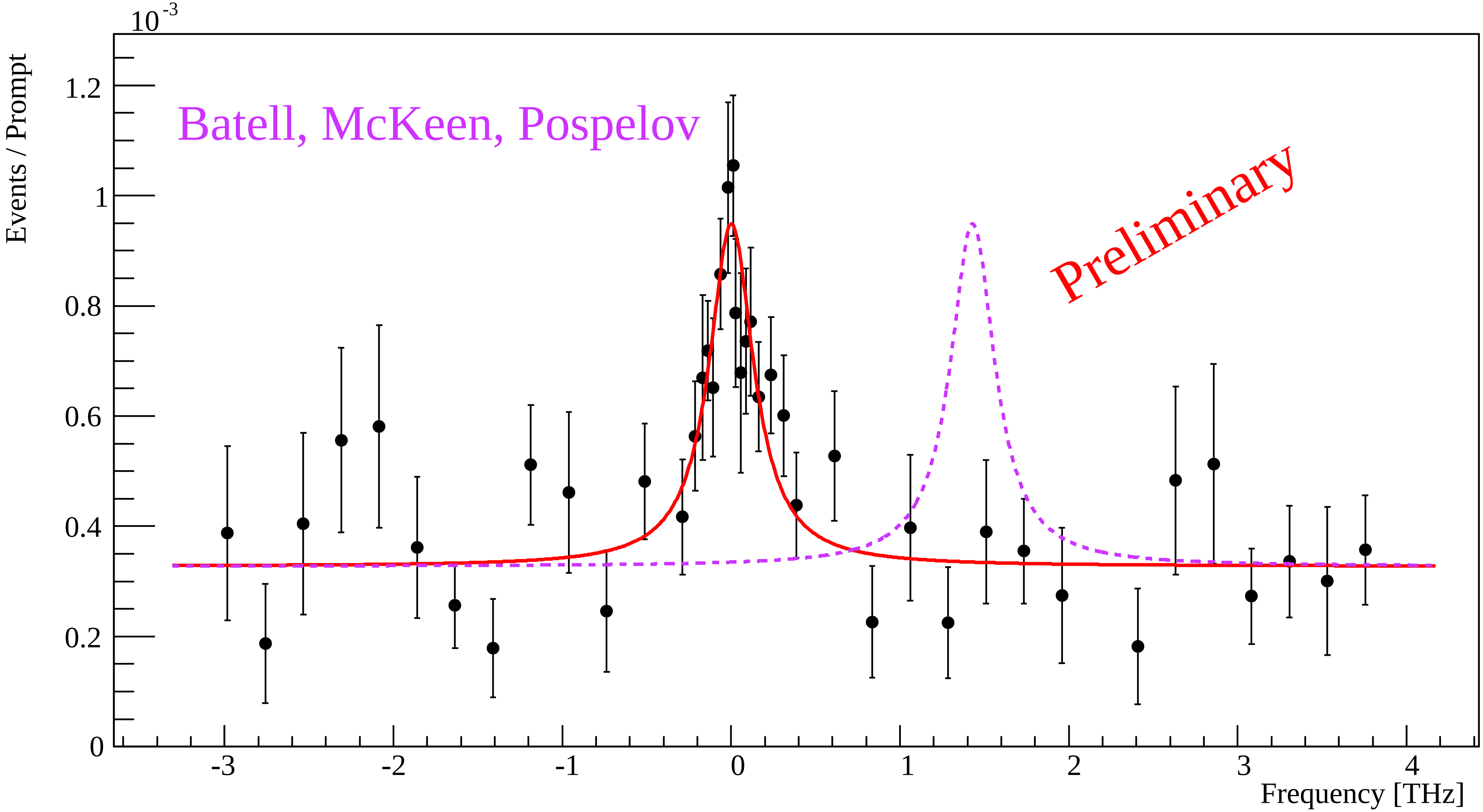

Batell, McKeen, Pospelov, PRL 107, 011803 (2011)

Muonic summary

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    7σ away from electronic average (CODATA: H, e-p scatt.)
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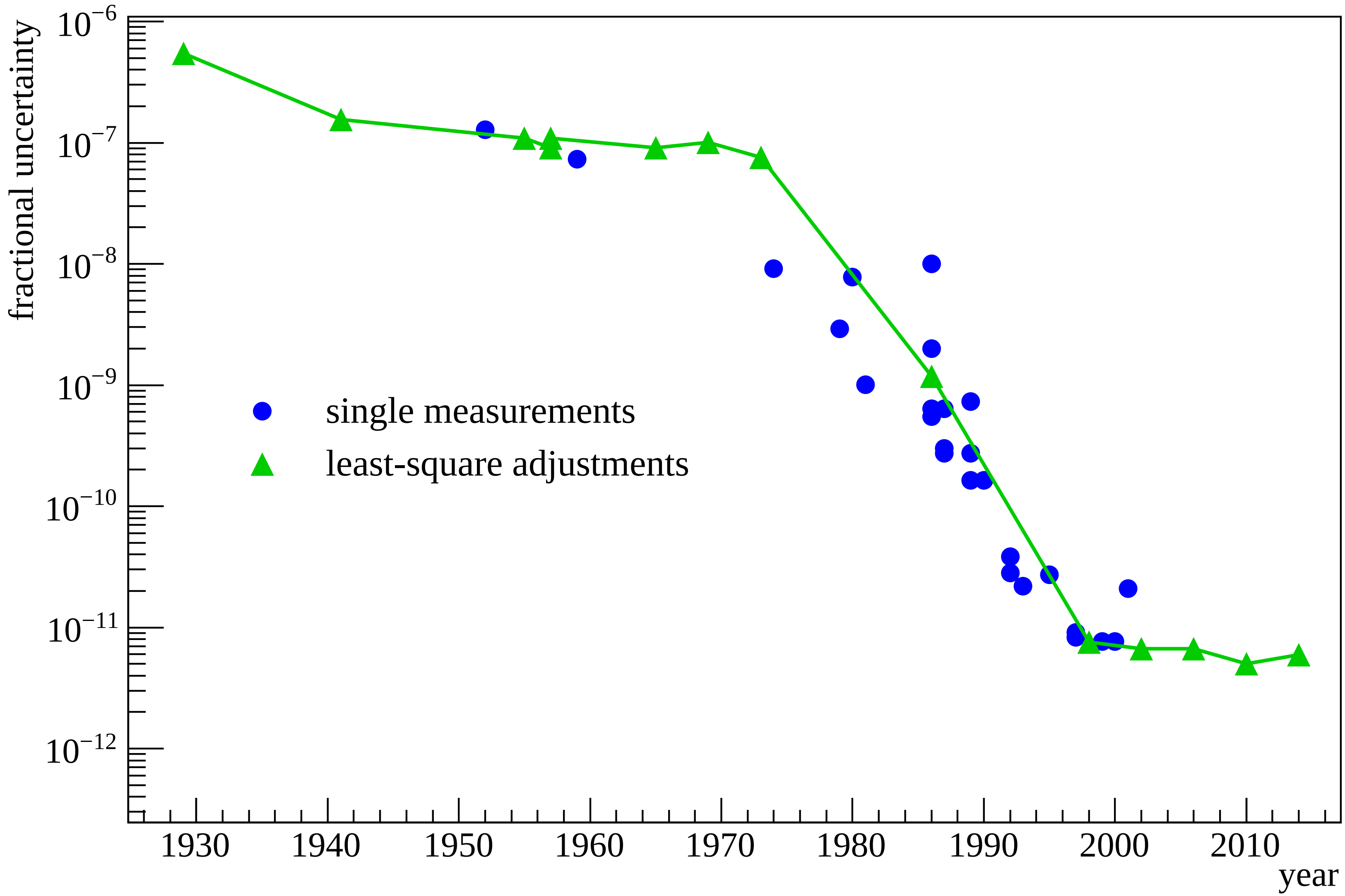
- Could **ALL** be solved if the **Rydberg constant** [and hence the (electronic) proton radius] was wrong.
  Plus $\sim 2.6\sigma$ change in deuteron polarizabililty.
  Plus: accept dispersion fits of e-p scattering
- Or: BSM physics, e.g. Tucker-Smith & Yavin (2011)

(Electronic) hydrogen.

Rydberg constant

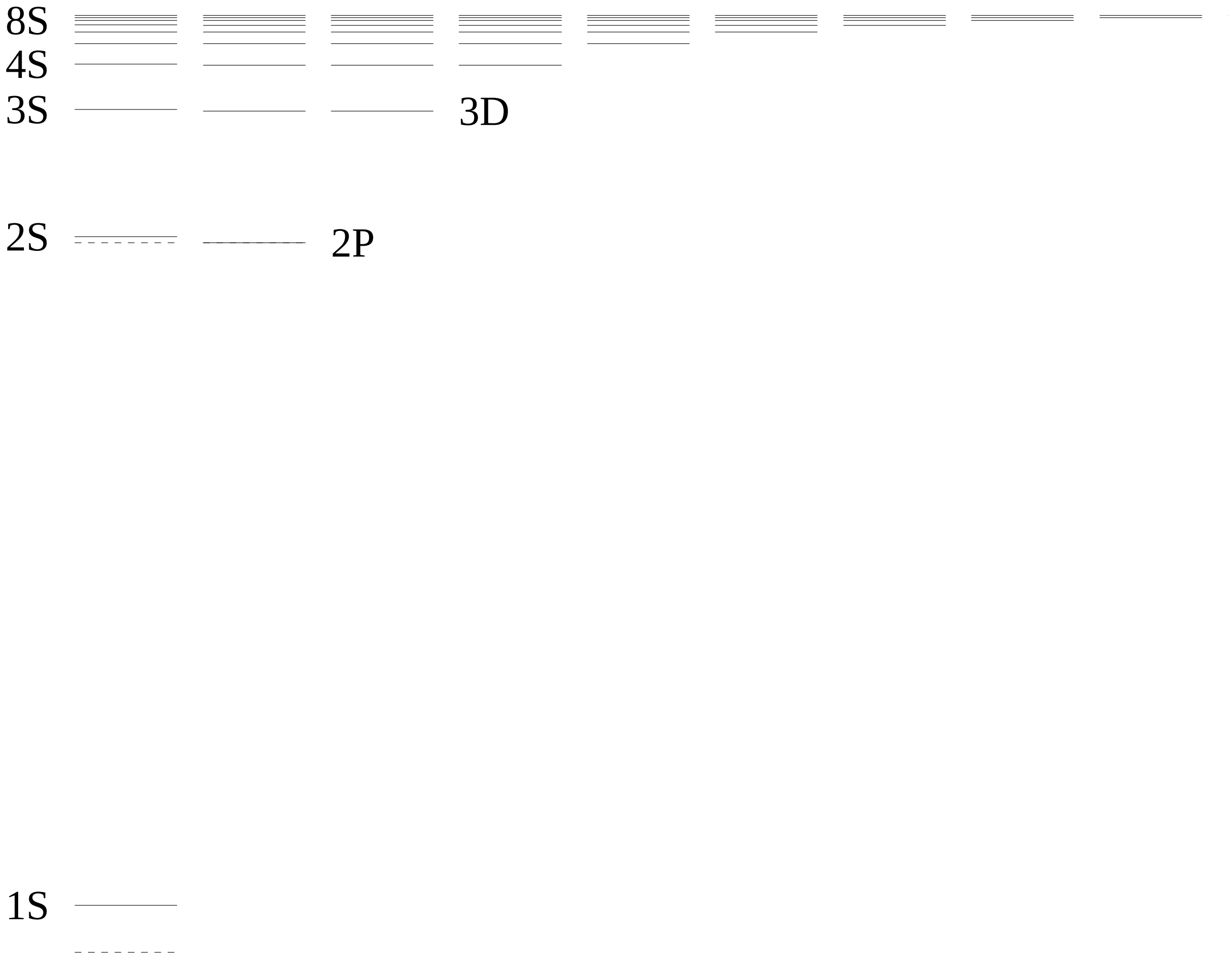
$$R_\infty = \frac{\alpha^2 m_e c}{2h}$$



Hydrogen spectroscopy

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

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



RP *et al.* arXiv 1607.03165

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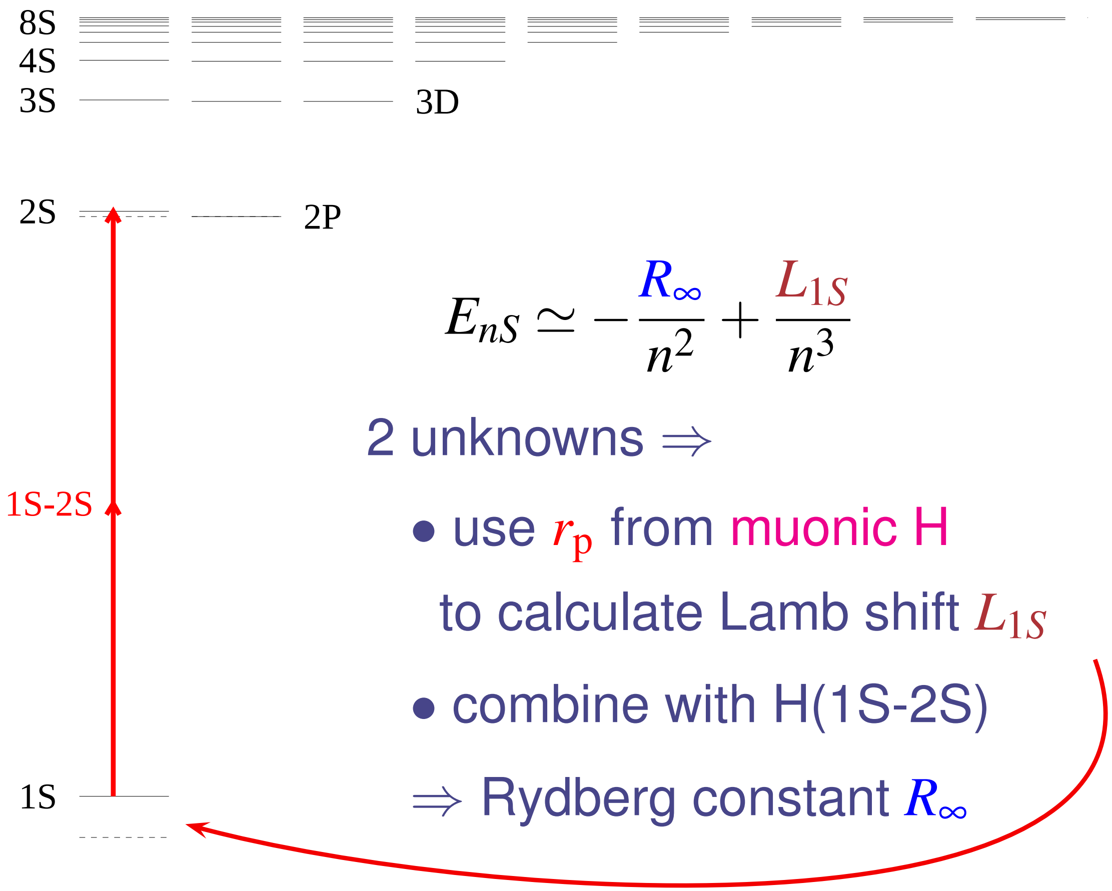

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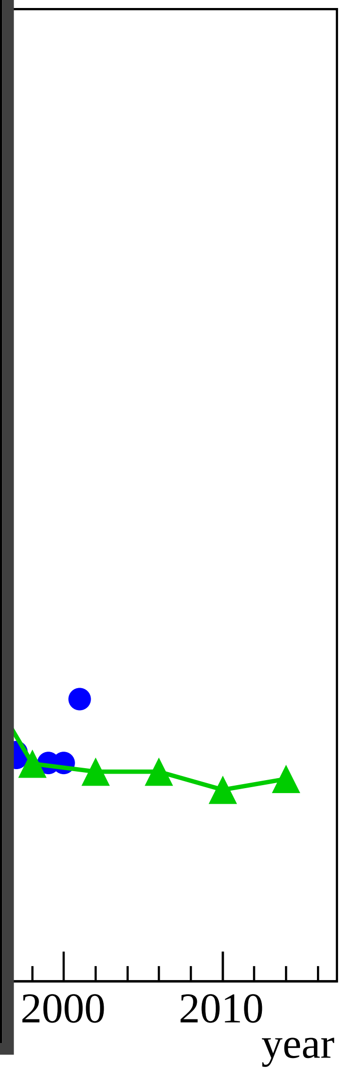
2 unknowns ⇒

- use r_p from muonic H to calculate Lamb shift L_{1S}
- combine with H(1S-2S)

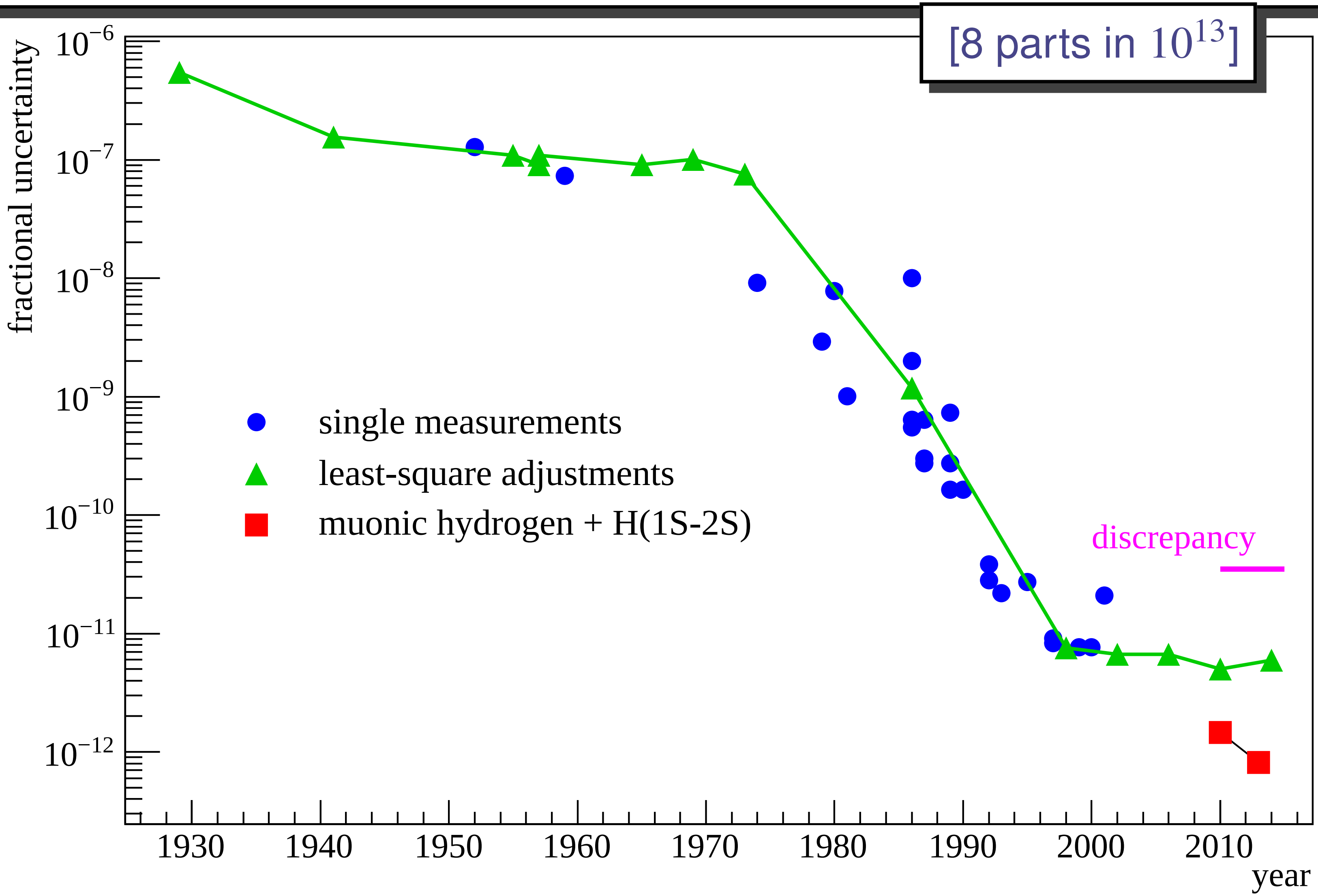
⇒ Rydberg constant R_∞



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}]



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

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

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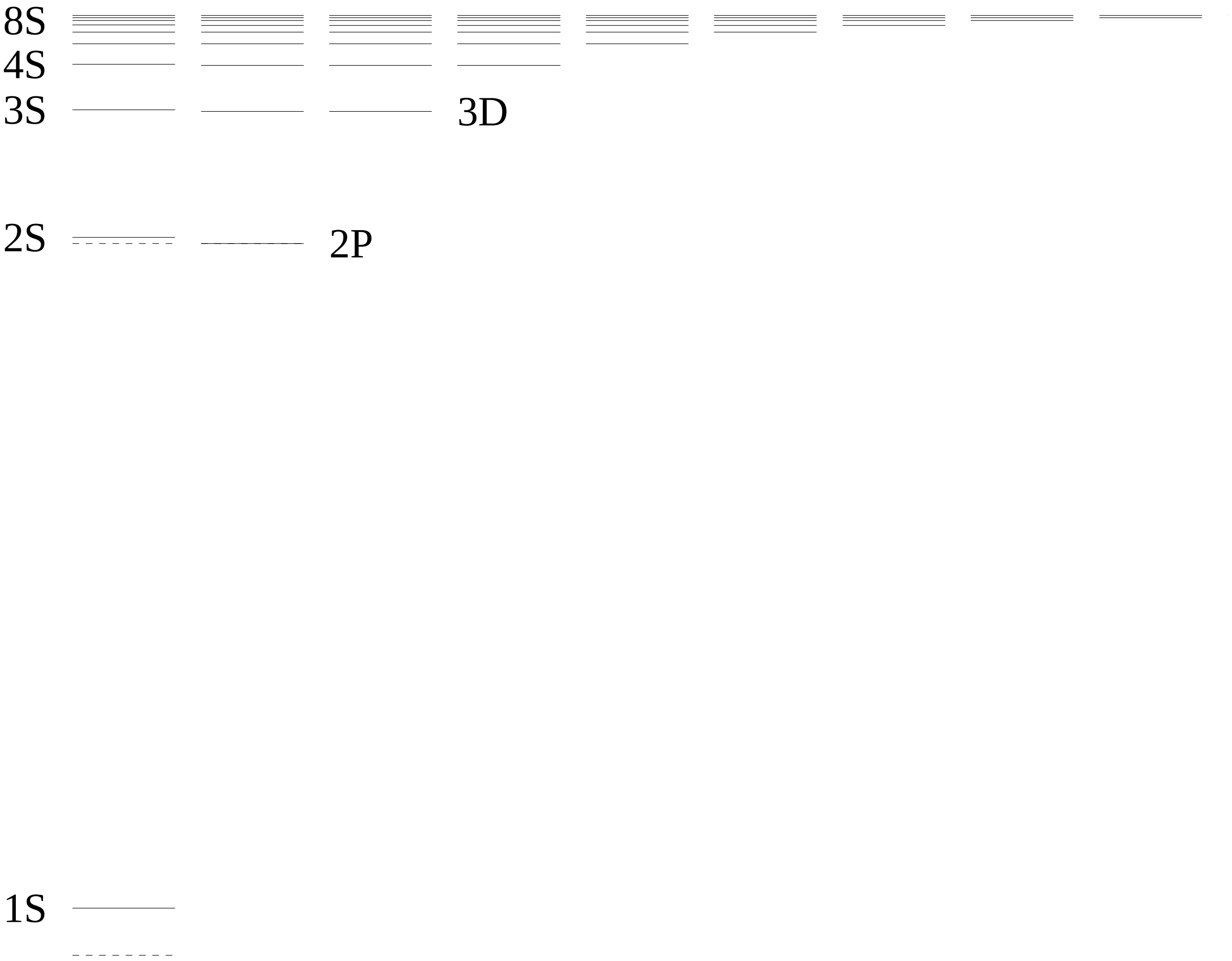

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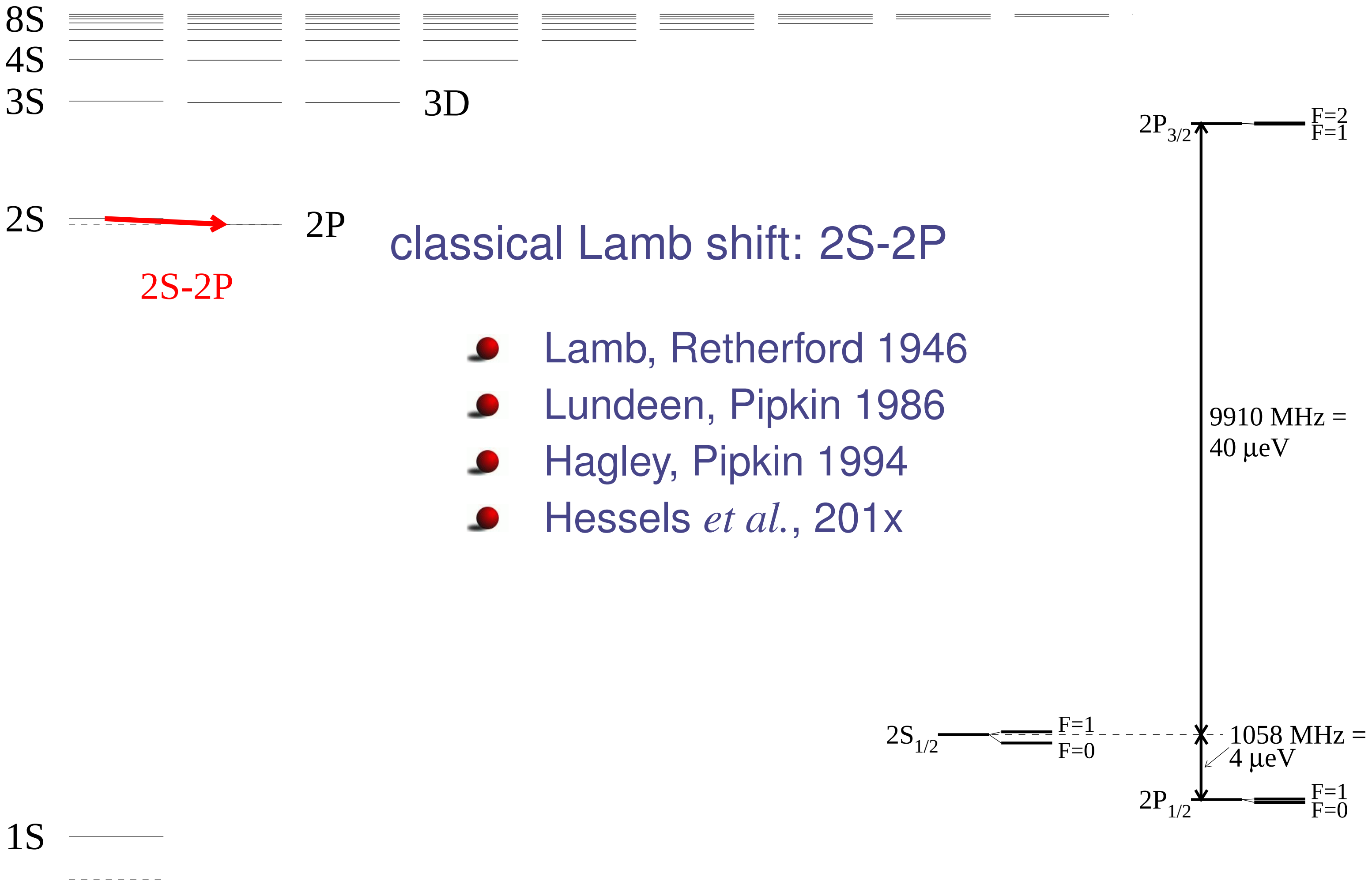

classical Lamb shift: 2S-2P

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

RP *et al.* arXiv 1607.03165

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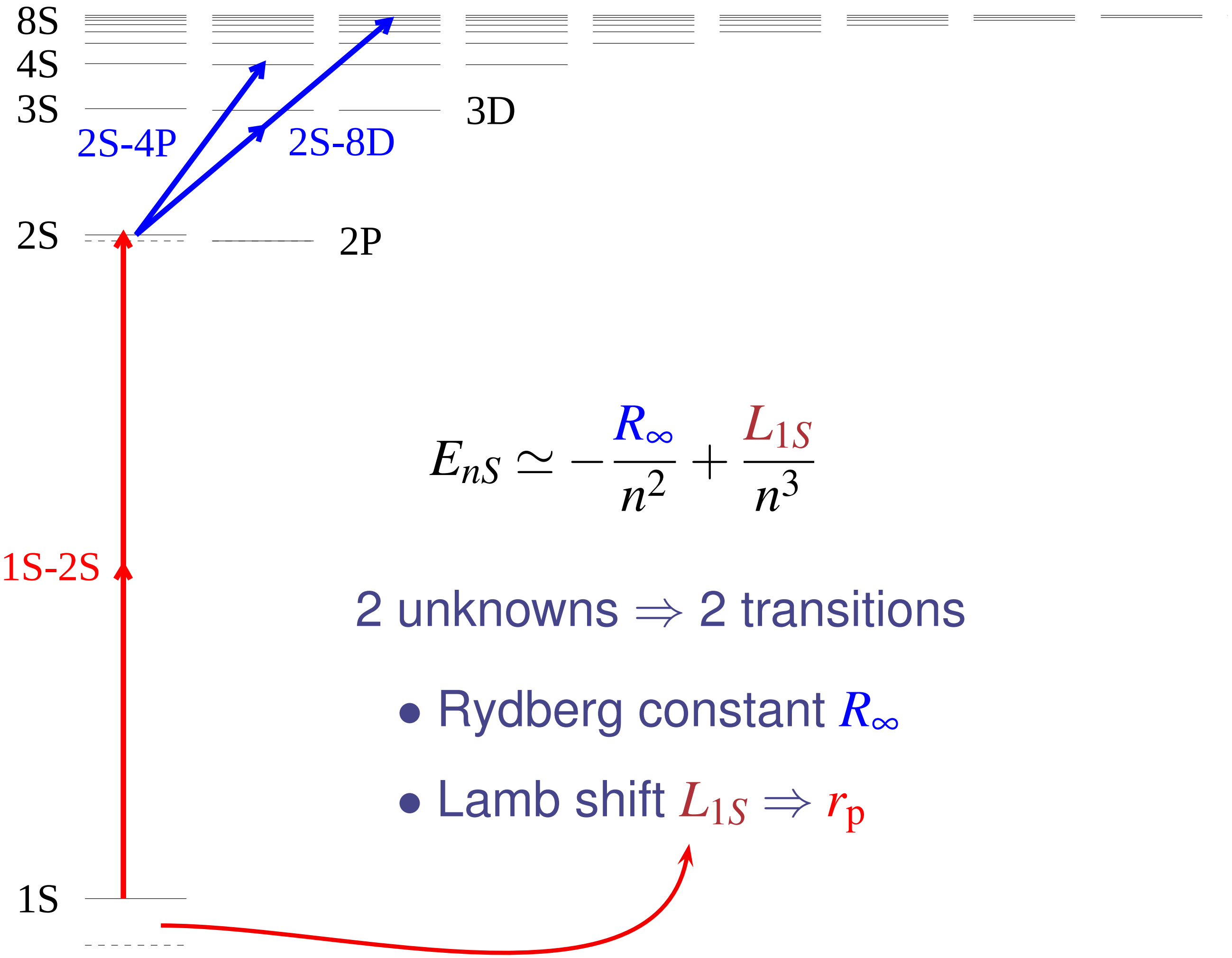
$$L_{nS} \simeq \frac{L_{1S}}{n^3}$$



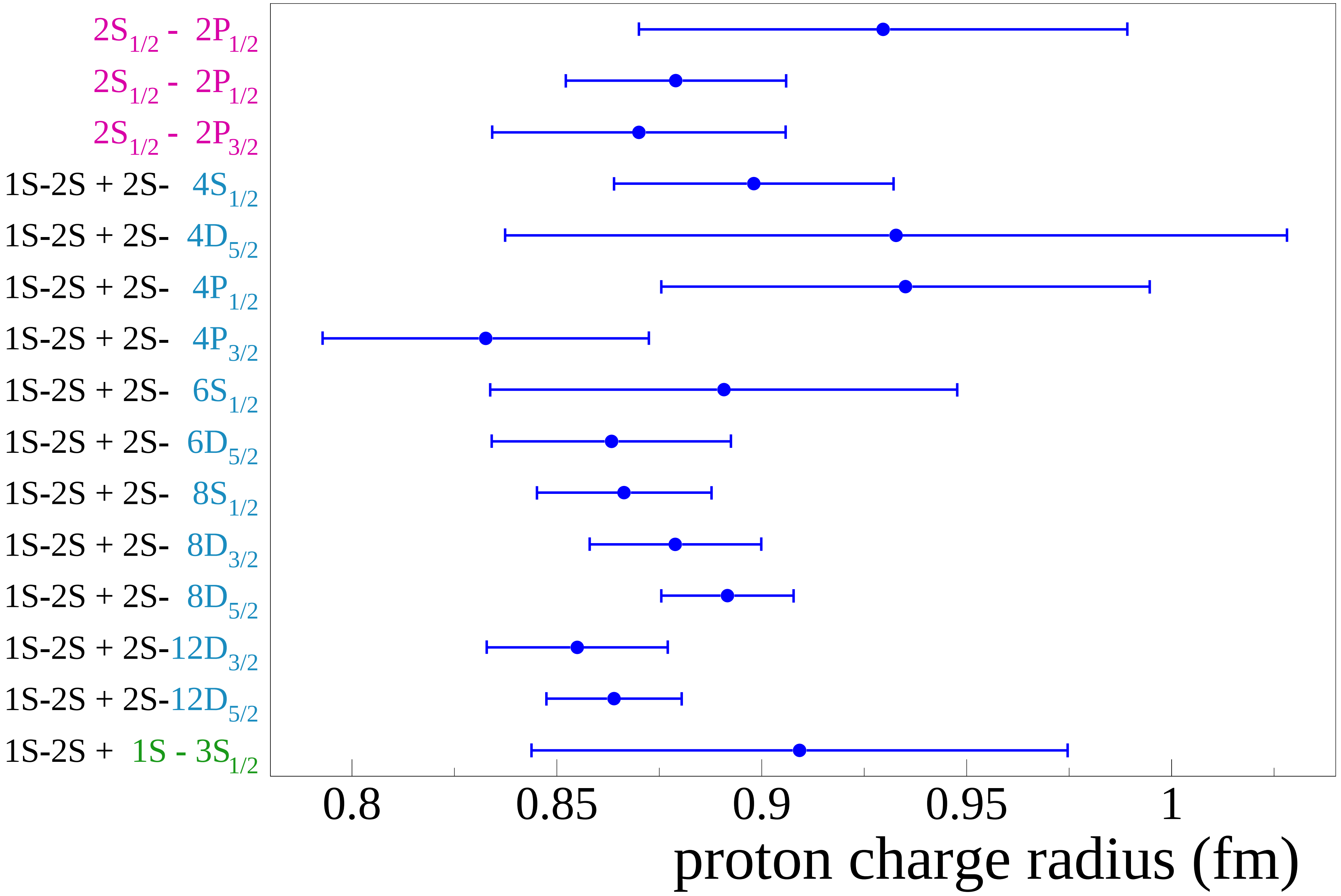
$$E_{nS} \simeq -\frac{R_\infty}{n^2} + \frac{L_{1S}}{n^3}$$

2 unknowns ⇒ 2 transitions

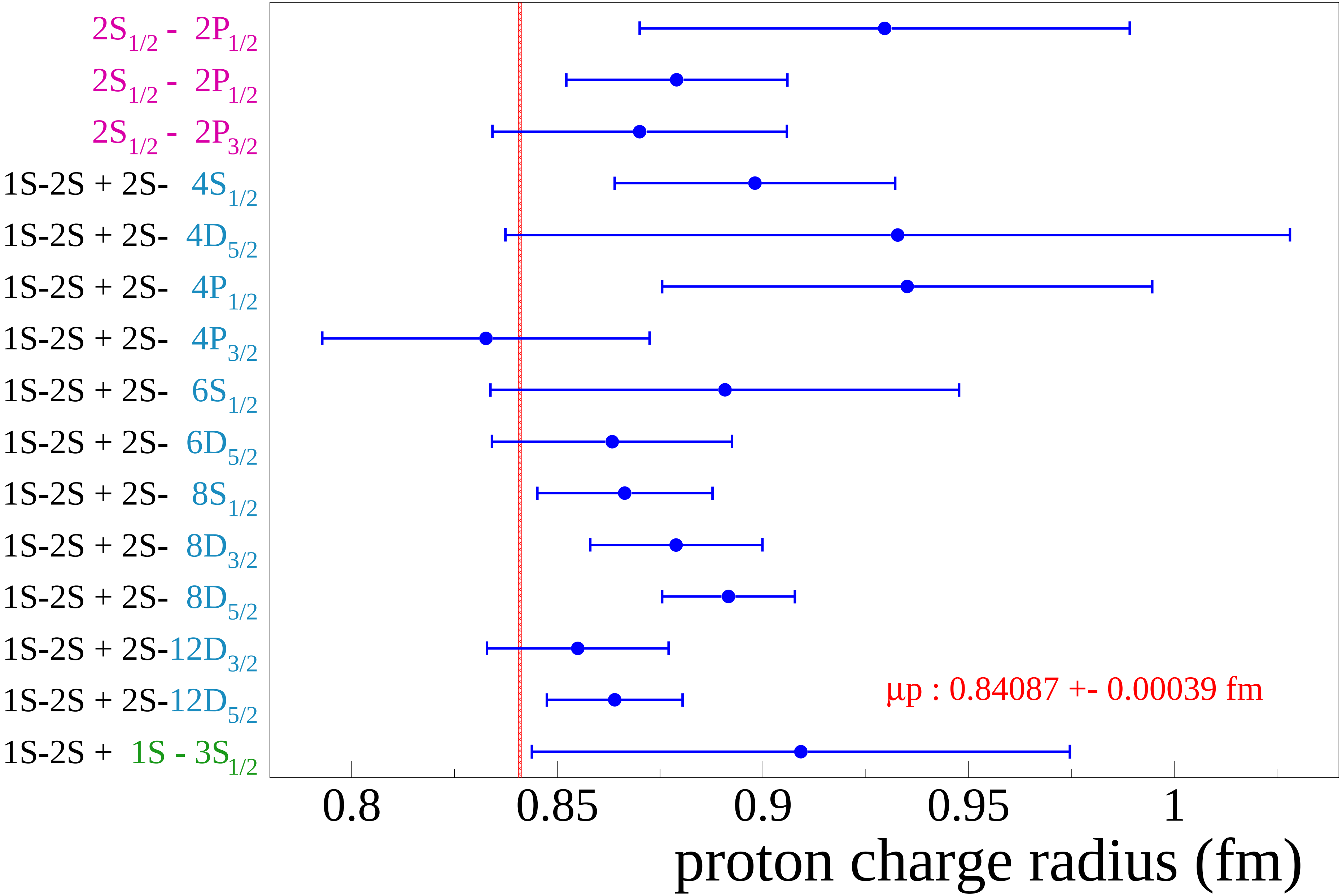
- Rydberg constant R_∞
- Lamb shift $L_{1S} \Rightarrow r_p$

RP *et al.* arXiv 1607.03165

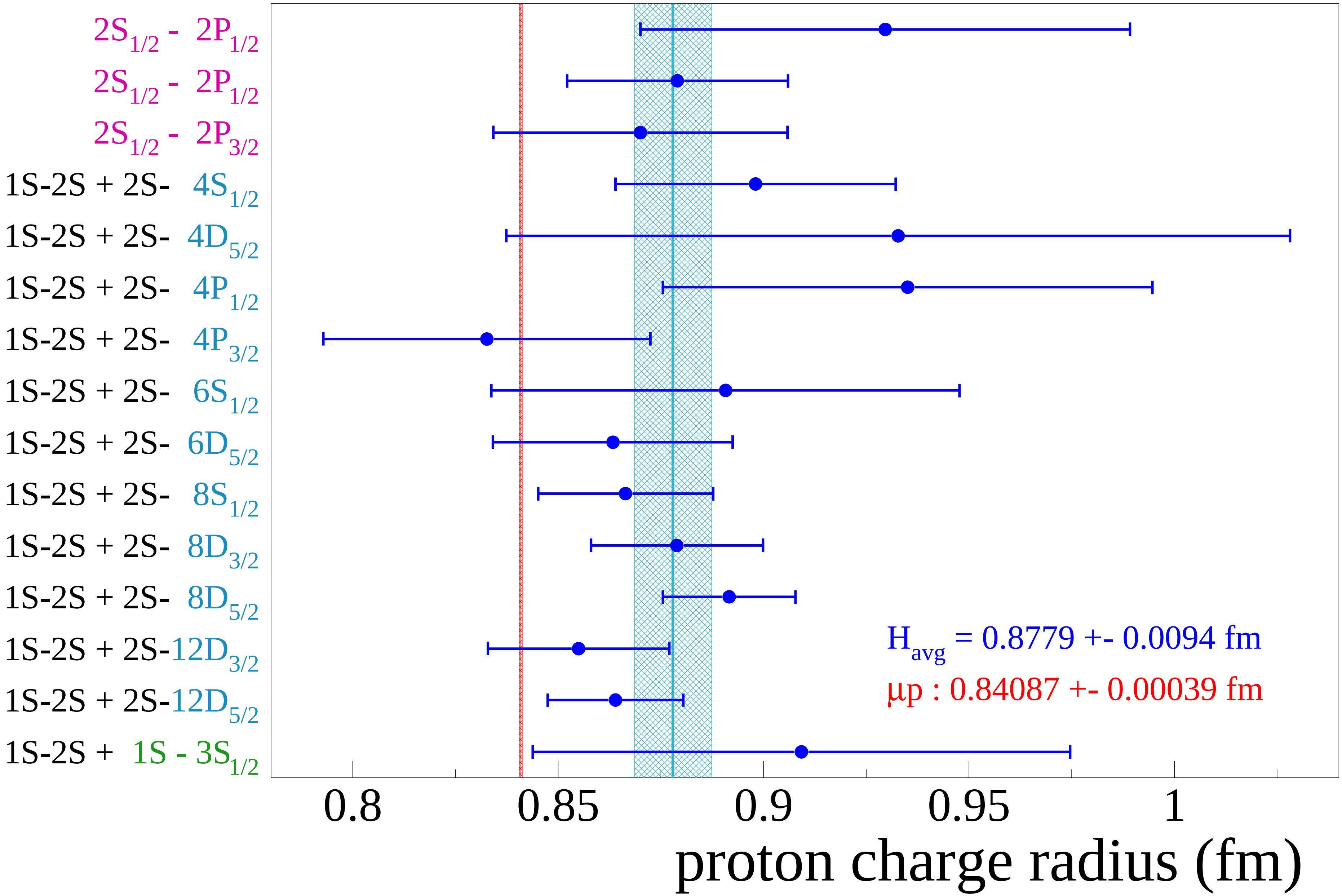
Hydrogen spectroscopy



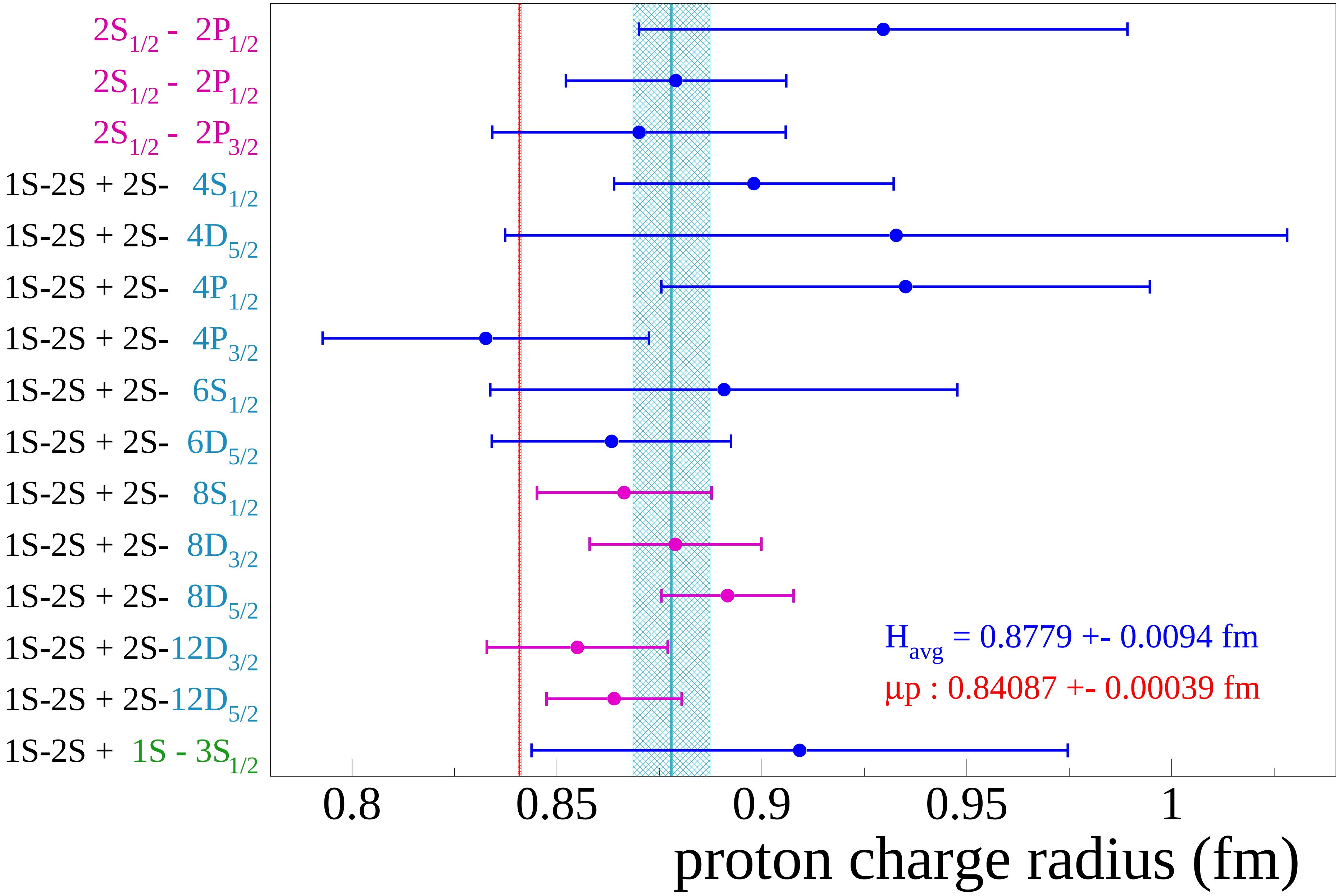
Hydrogen spectroscopy



Hydrogen spectroscopy



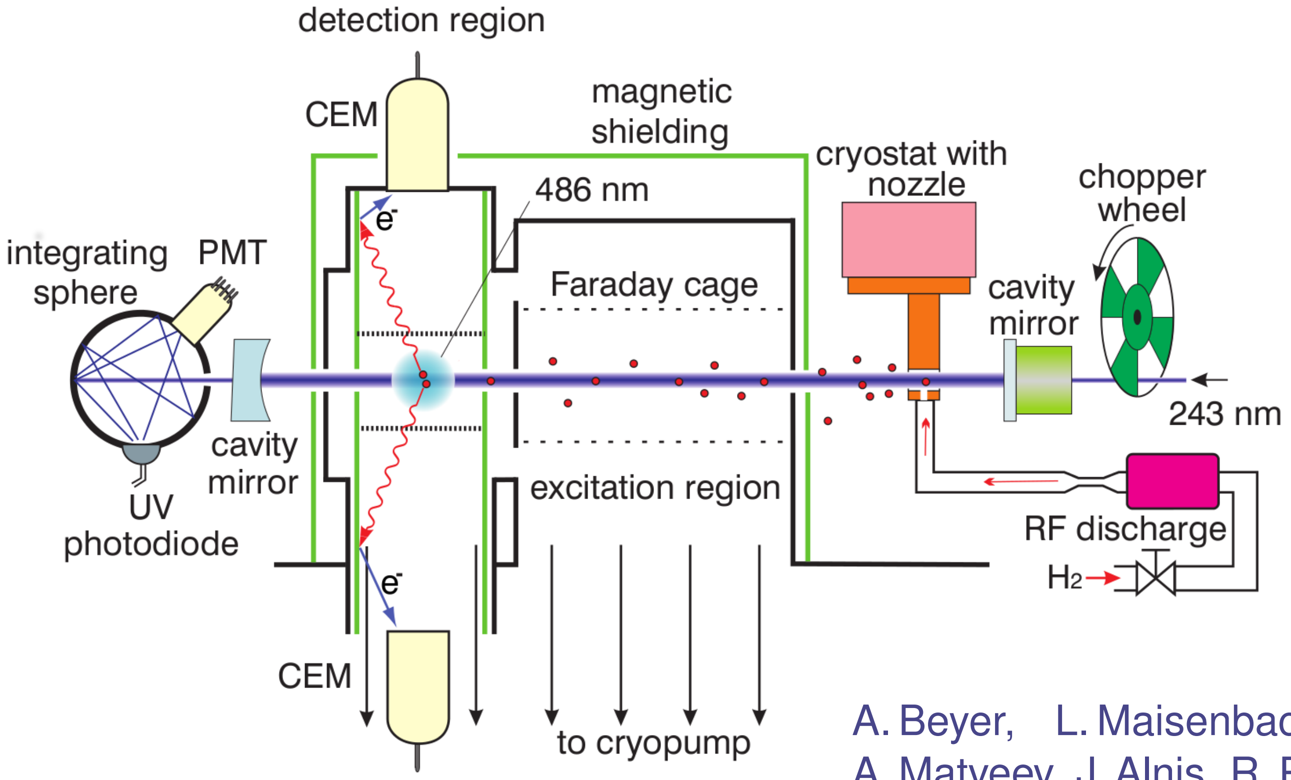
Hydrogen spectroscopy

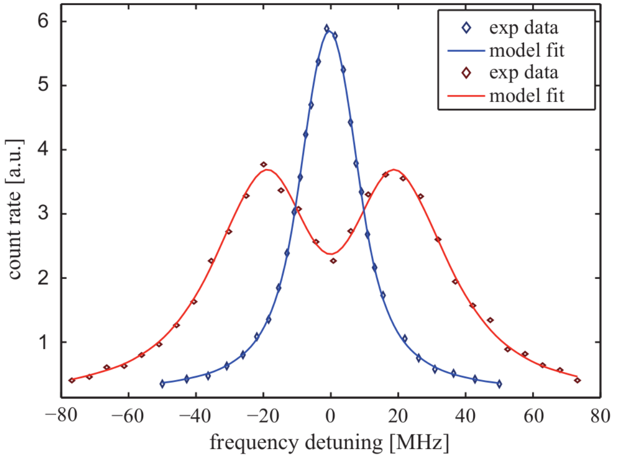


H_{avg} = 0.8779 +- 0.0094 fm

μp : 0.84087 +- 0.00039 fm

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)

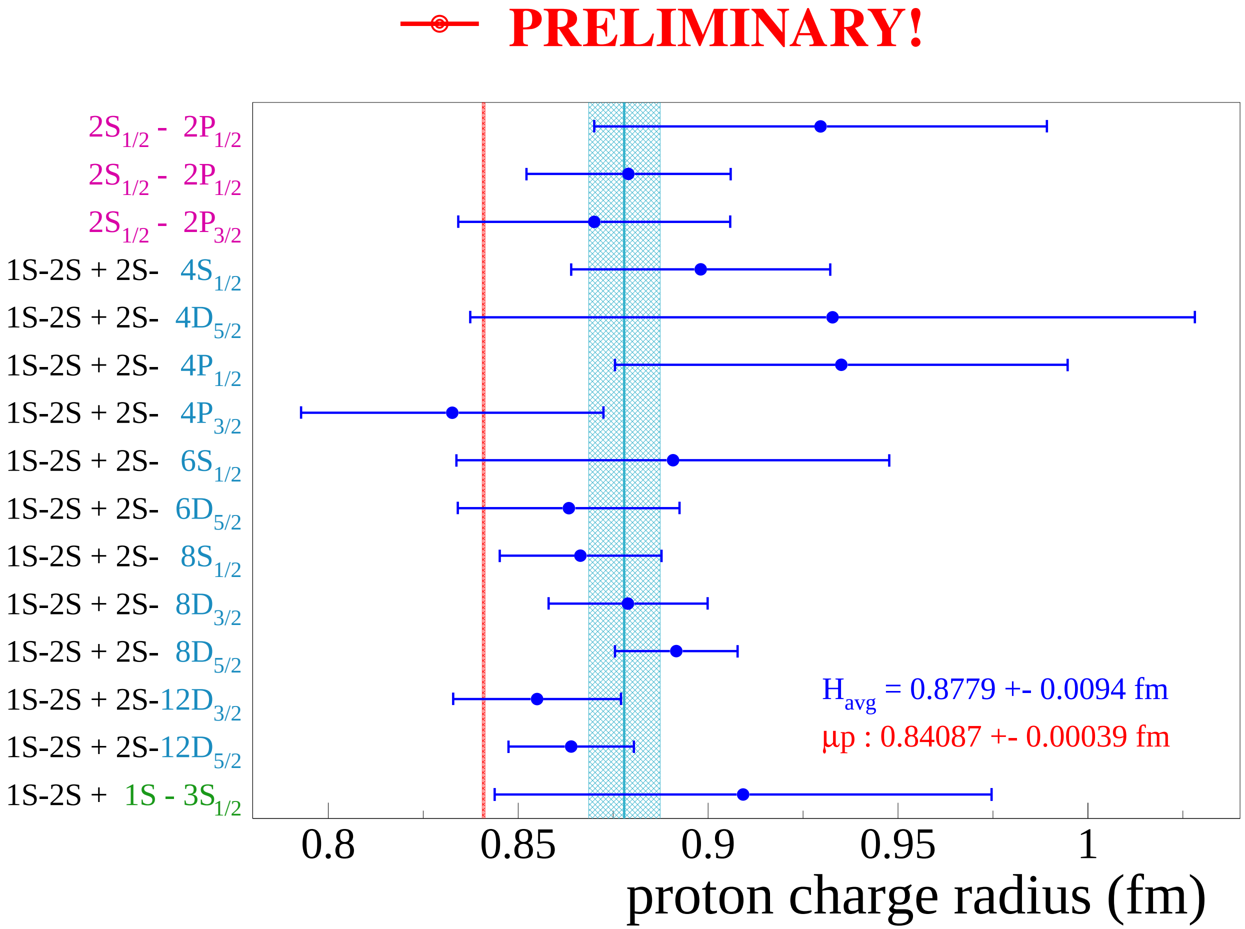
  C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)
  C.G. Parthey, RP *et al.*, PRL **107**, 203001 (2011)
- 486 nm at 90° + Retroreflector ⇒ Doppler-free 2S-4P excitation
- 1st oder Doppler vs. ac-Stark shift
- ~ 2.5 kHz accuracy (vs. 15 kHz Yale, 1995)
- **cryogenic** H beam, **optical** excitation to 2S

  A. Beyer, RP *et al.*, Ann. d. Phys. **525**, 671 (2013)

New hydrogen 2S→4P at MPQ!

Proton is small in regular hydrogen, too!

Proton radius puzzle is NOT “solved”.
Our main systematics do NOT affect the previous measurements.



$2S \rightarrow 4P_{1/2}$ and $4P_{3/2}$

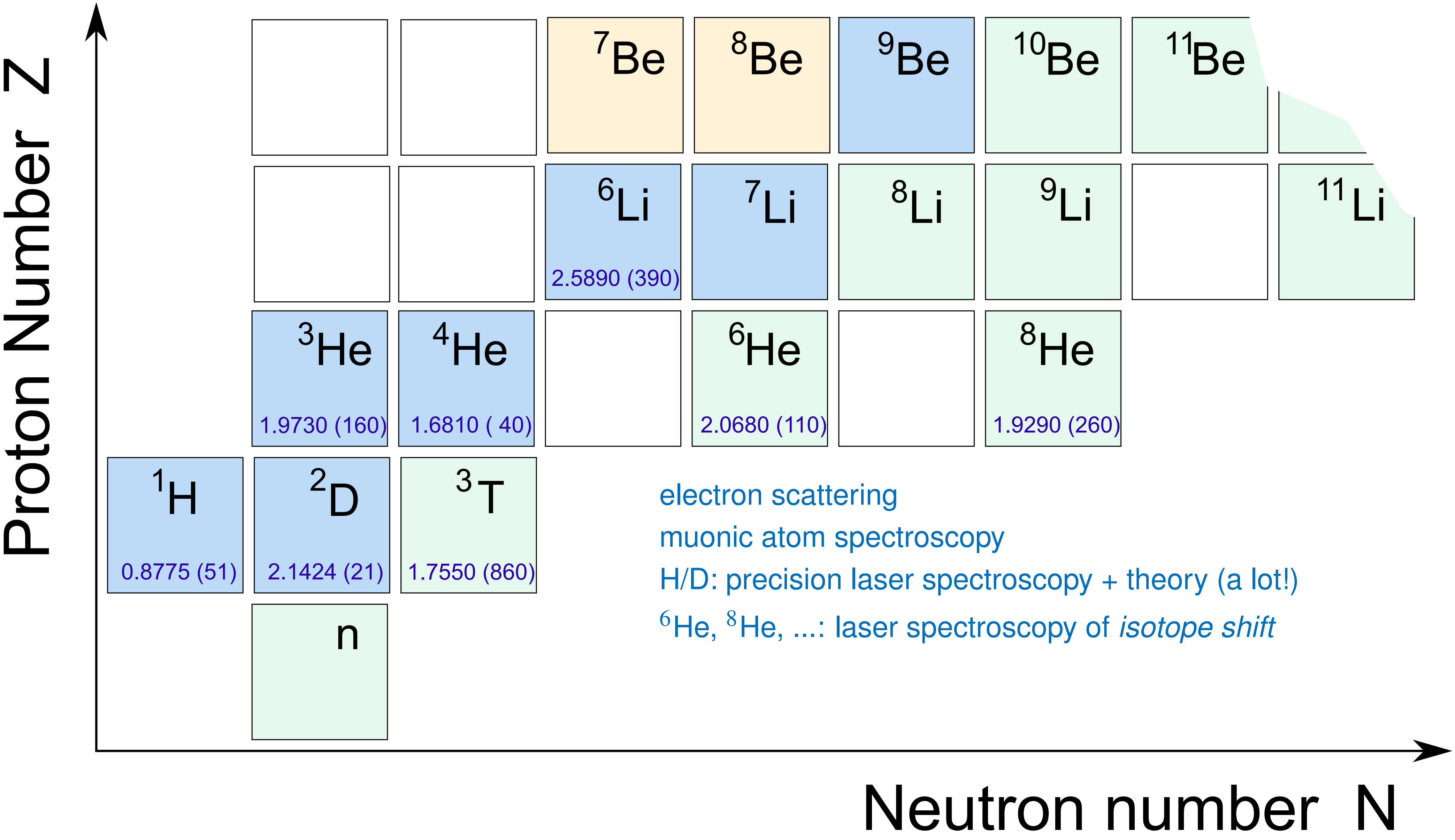
cold H(2S) beam

optically excited $(1S \rightarrow 2S)$

$\Delta\nu \sim 2\,\mathrm{kHz} \quad \equiv \Gamma/10'000$!!!

Beyer, Maisenbacher, Matveev, RP,
Khabarova, Grinin, Lamour, Yost,
Hänsch, Kolachevsky, Udem,
submitted (2016)

The nuclear chart



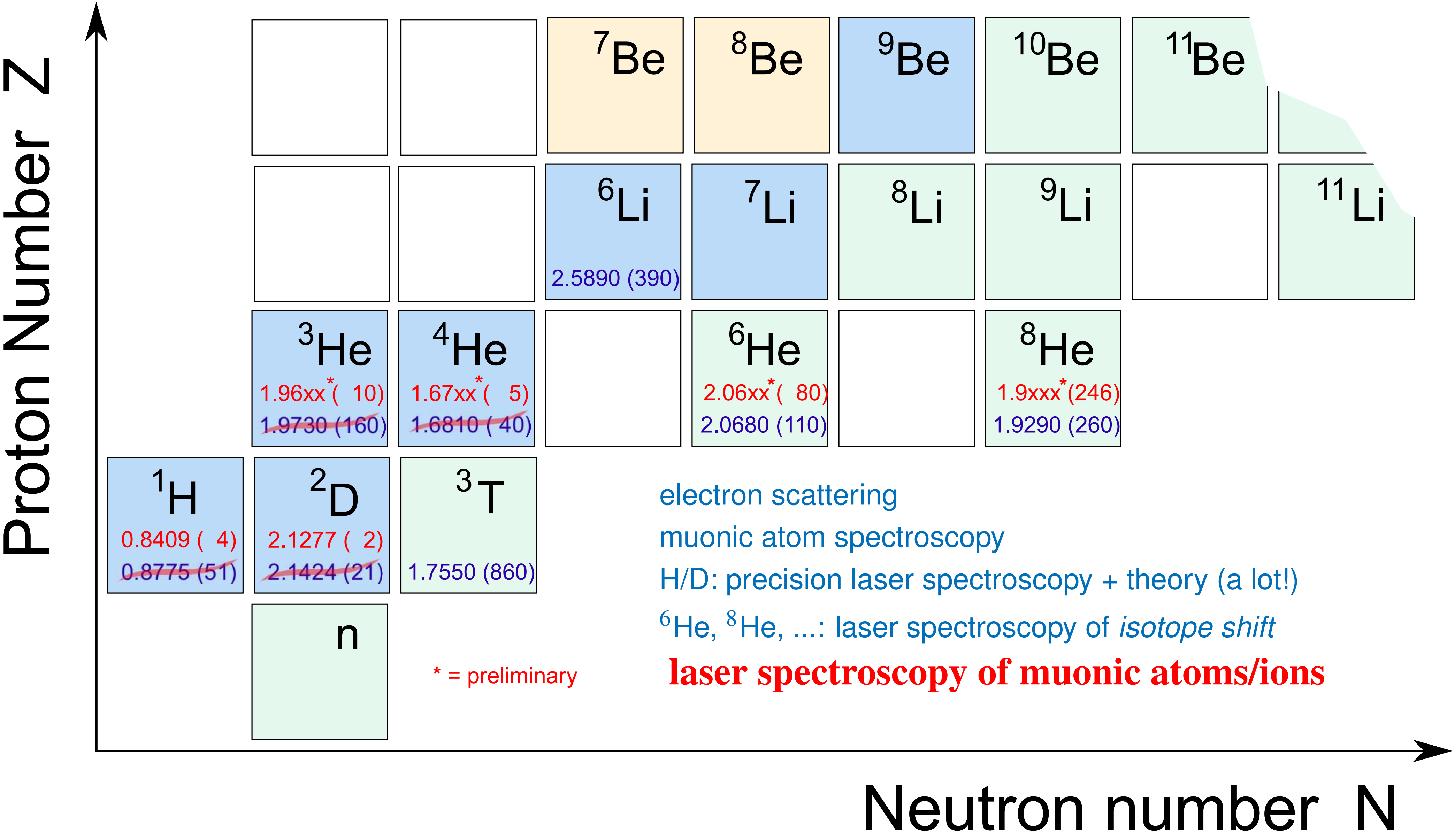
electron scattering

muonic atom spectroscopy

H/D: precision laser spectroscopy + theory (a lot!)

^{6}He, ^{8}He, ...: laser spectroscopy of *isotope shift*

The nuclear chart - new charge radii



* = preliminary

electron scattering

muonic atom spectroscopy

H/D: precision laser spectroscopy + theory (a lot!)

^{6}He, ^{8}He, ...: laser spectroscopy of *isotope shift*

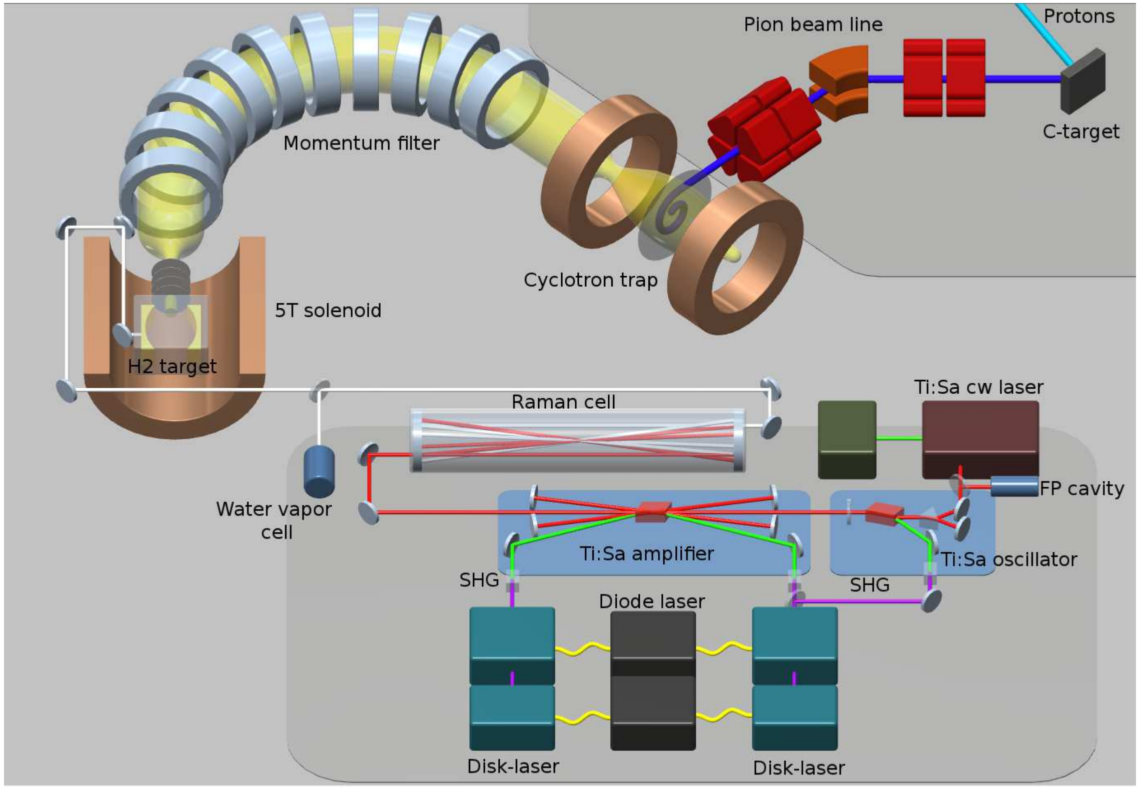
laser spectroscopy of muonic atoms/ions

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: $R_\infty = 3.289\,841\,960\,249\,5\ (10)^{r_\mathrm{p}}\ (25)^{\mathrm{QED}}\ \times 10^{15}\ \mathrm{Hz/c}$
  - 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 ⇒ small r_p PRELIMINARY
- New projects:
  - 1S-HFS in muonic hydrogen / ^{3}He ⇐ 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^-**

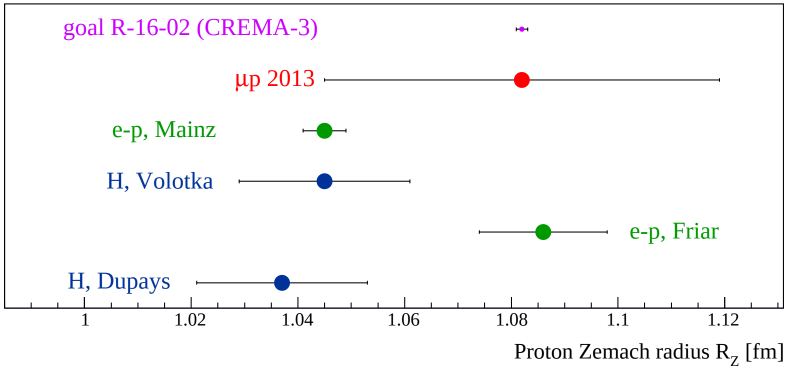


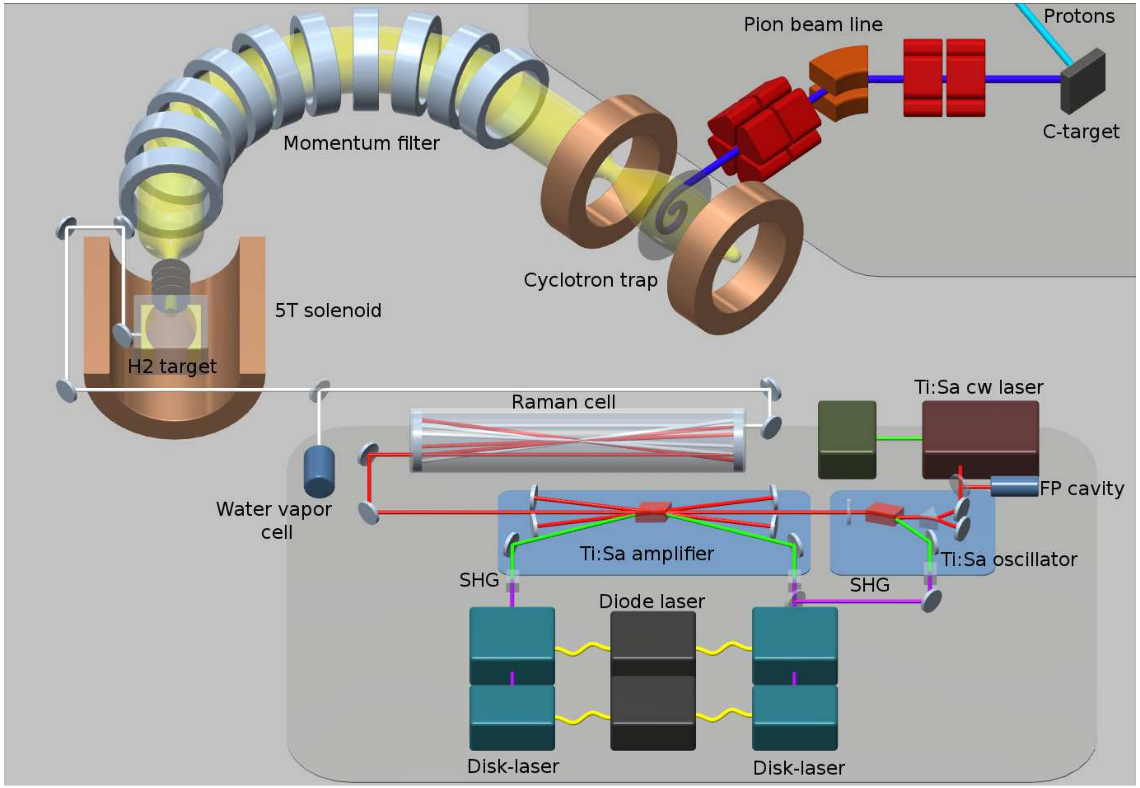
Future: Muonic

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

1S-HFS in μp, μ^3He

$\rightarrow$ Zemach (magnetic) radius

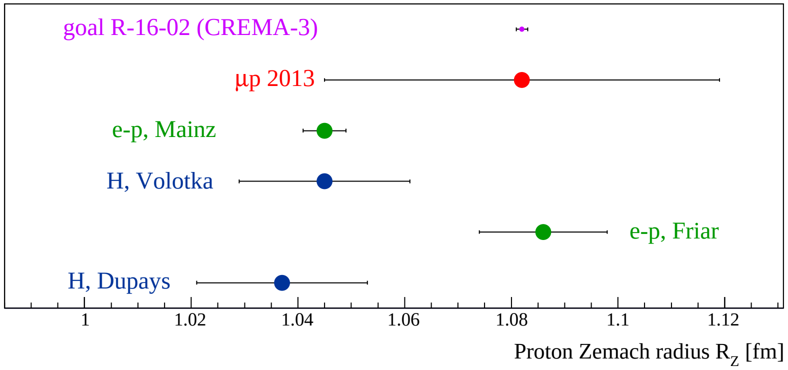




Future: Muonic

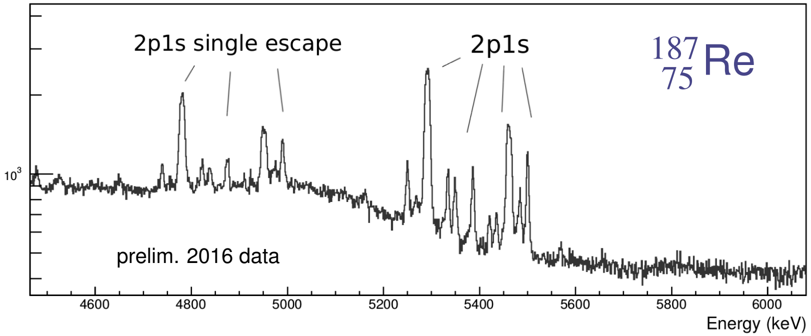
1S-HFS in μp, μ^3He

→ Zemach (magnetic) radius

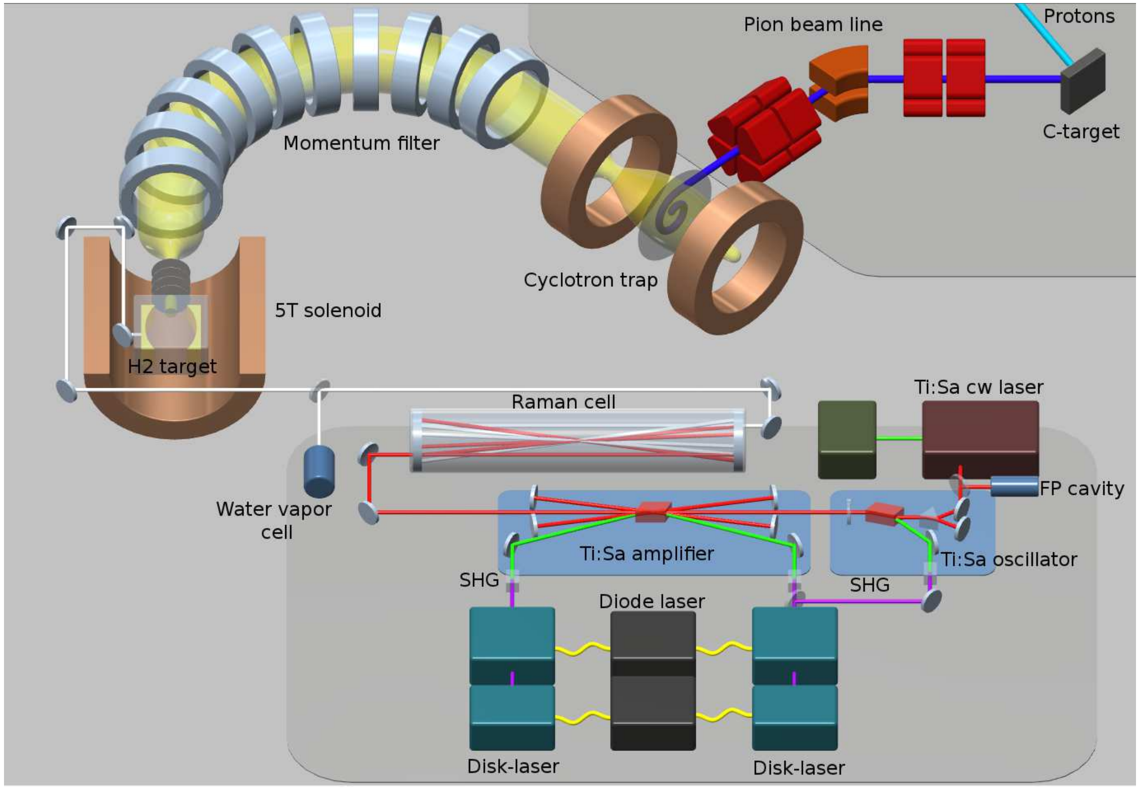


stop in μg of (radioactive) material

→ charge radii of higher Z



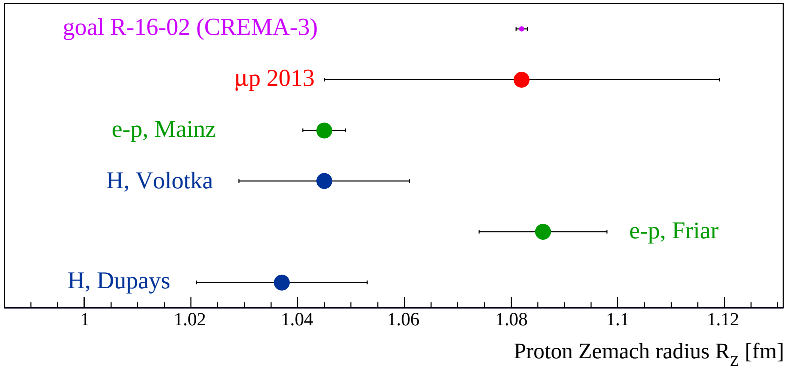
The **world's most intense beam** for **low-energy μ^-**



Future: Muonic

1S-HFS in μp, μ^3He

$\rightarrow$ Zemach (magnetic) radius



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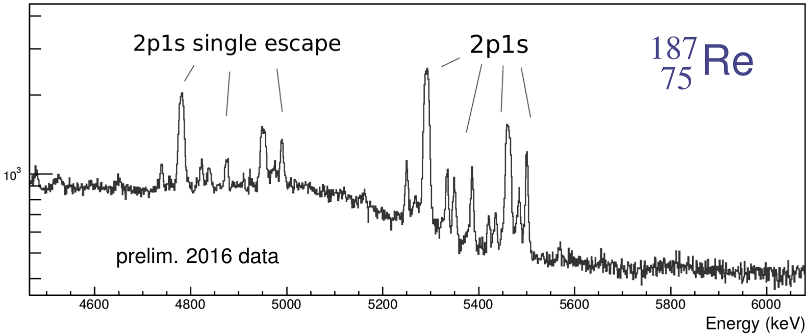
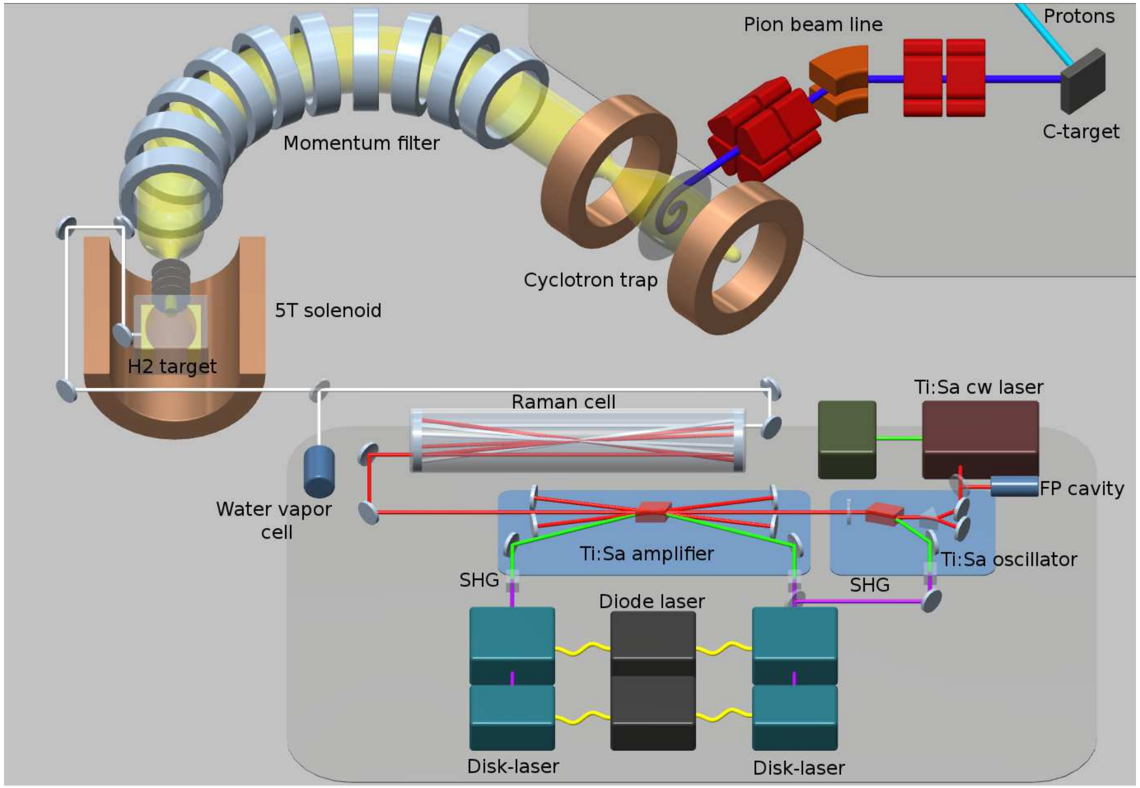
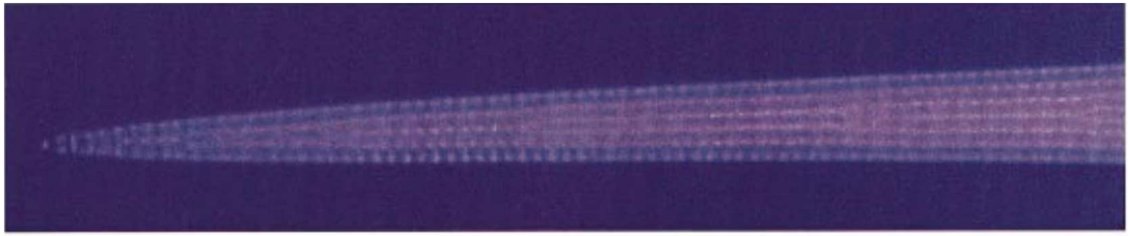


The **world's most intense beam** for **low-energy μ^-**



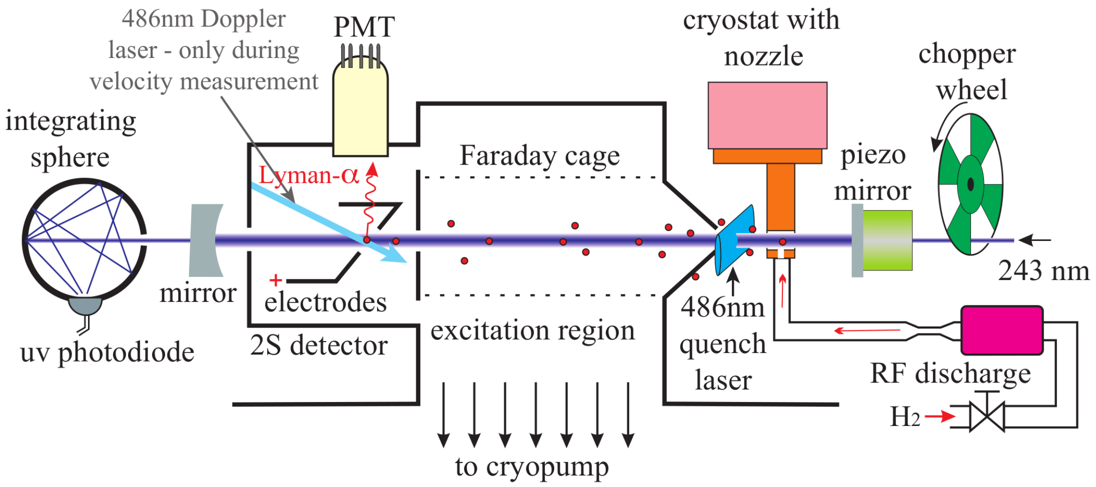
stop μ^- in Penning trap

$\rightarrow$ charge radii of Li, Be, B, T



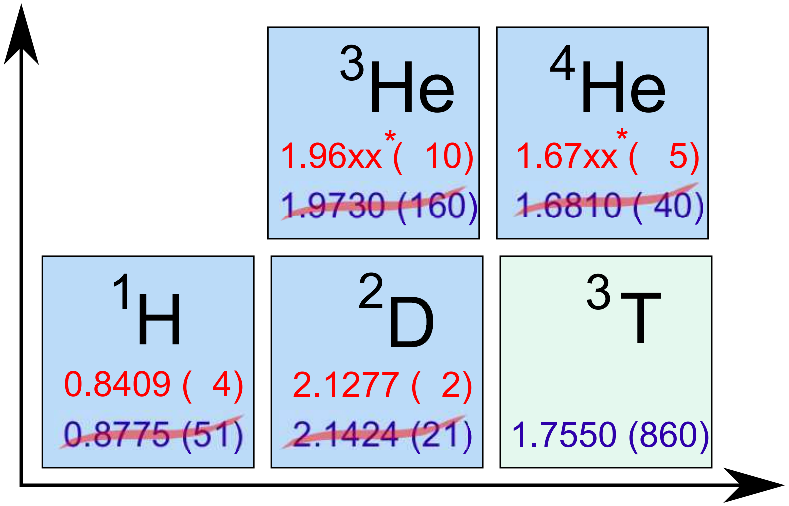
Future: Electronic

Hydrogen apparatus in Garching

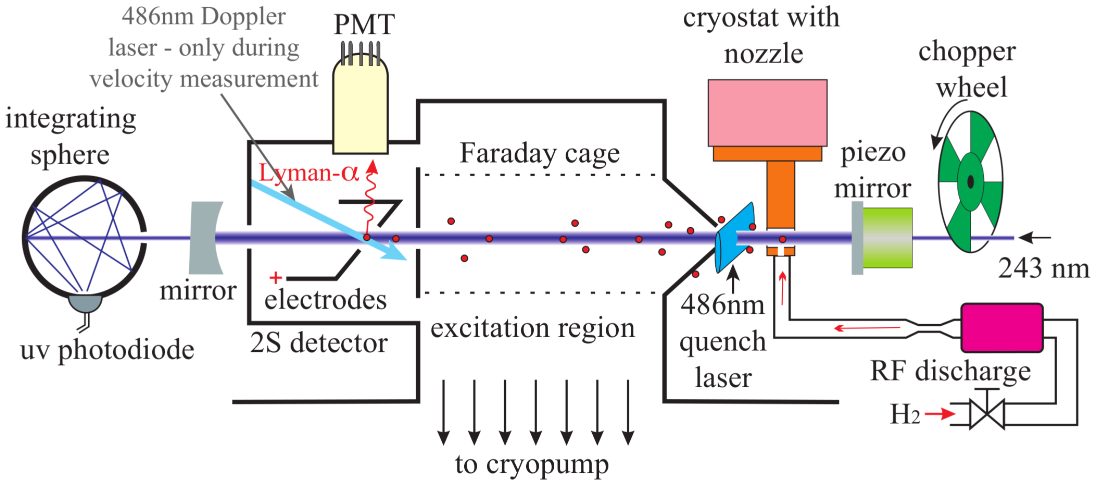


Future: Electronic

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!

$r_\mathrm{d}^2 - r_\mathrm{p}^2 = 3.82007(65)$ fm^2 H/D(1S-2S) isoshift to 10 Hz

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

CREMA in 2009...

Proton Size Investigators thank you for your attention

... and 2014

The cost for LHC

According to **Forbes** (Jul. 2012), the Higgs discovery cost

13.25 billion USD.

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Cost increase for Higgs discovery: 1.06 billion USD.

The cost for LHC

My aplogies.

:-)