Photonics
Q-Ex-2

Randolf Pohl

SoSe 2023

Tue 12:15-13:45 HS KPH

Thu 12:15-13:45 HS KPH

Thu Apr. 27: Sem 1 KPH

pohl@uni-mainz.de

Contents of this lecture

(dynamic, this is just a proposal!)

- Intro (Refresh)
  - Atomic physics, light-atom interaction (optical Bloch equations, Rabi oscillations, Ramsey method)
- Absorption and Emission of light
  - Black body radiation, Einstein coefficients
  - classical and semi-classical description
- Spectral lines:
  - natural line width, line strength
  - AC Stark shift (light shift), DC Stark shift, Zeeman shift, ….
  - broadening mechanisms: Doppler, time-of-flight, pressure, …
- Lasers
  - types of lasers: Ruby, HeNe, YAG, Ti:Sapphire, diode laser, fiber laser, …
  - principles of operation, technical realization
- Resonators / Cavities
- Gaussian optics
- Laser stabilization
  - locking techniques: side-of-fringe, Hänsch-Couillaud, Pound-Drever-Hall, ...
- Optical devices: EOM, AOM, beat signals, mixer, spectrum analyzer, ...
- Frequency comb
- Non-linear optics: SHG, THG, SFG, DFG, OPO, ...
- Laser spectroscopy: (Saturated) absorption spectroscopy, Doppler-free spectroscopy,
- Trapping of atoms and ions (MOT, Penning traps, ….)
- Precision measurements and fundamental constants
- ……...
- And whatever else YOU want to hear about

Literature

* W. Demtröder, Laser Spectroscopy 1 & 2
(German version online on library web site)

* C.J. Foot: Atomic Physics

* H.J. Metcalf & P. van der Straten: Laser Cooling and Trapping

* P. van der Straten & H.J. Metcalf: Atoms and Molecules Interacting with Light

* A. Siegman: Lasers

* R. Boyd: Nonlinear Optics

* Saleh & Teich: Fundamentals of Photonics

* M. Fox: Quantum Optics – an Introduction

I will try to mention which book I used to prepare a topic

Proton radius and Rydberg constant from electronic and muonic atoms

Randolf Pohl

Johannes Gutenberg-Universität Mainz
Institut für Physik, QUANTUM und PRISMA

Max-Planck Institute of Quantum Optics

Photonics, 18. Apr. 2023

Outline

- Muonic atoms

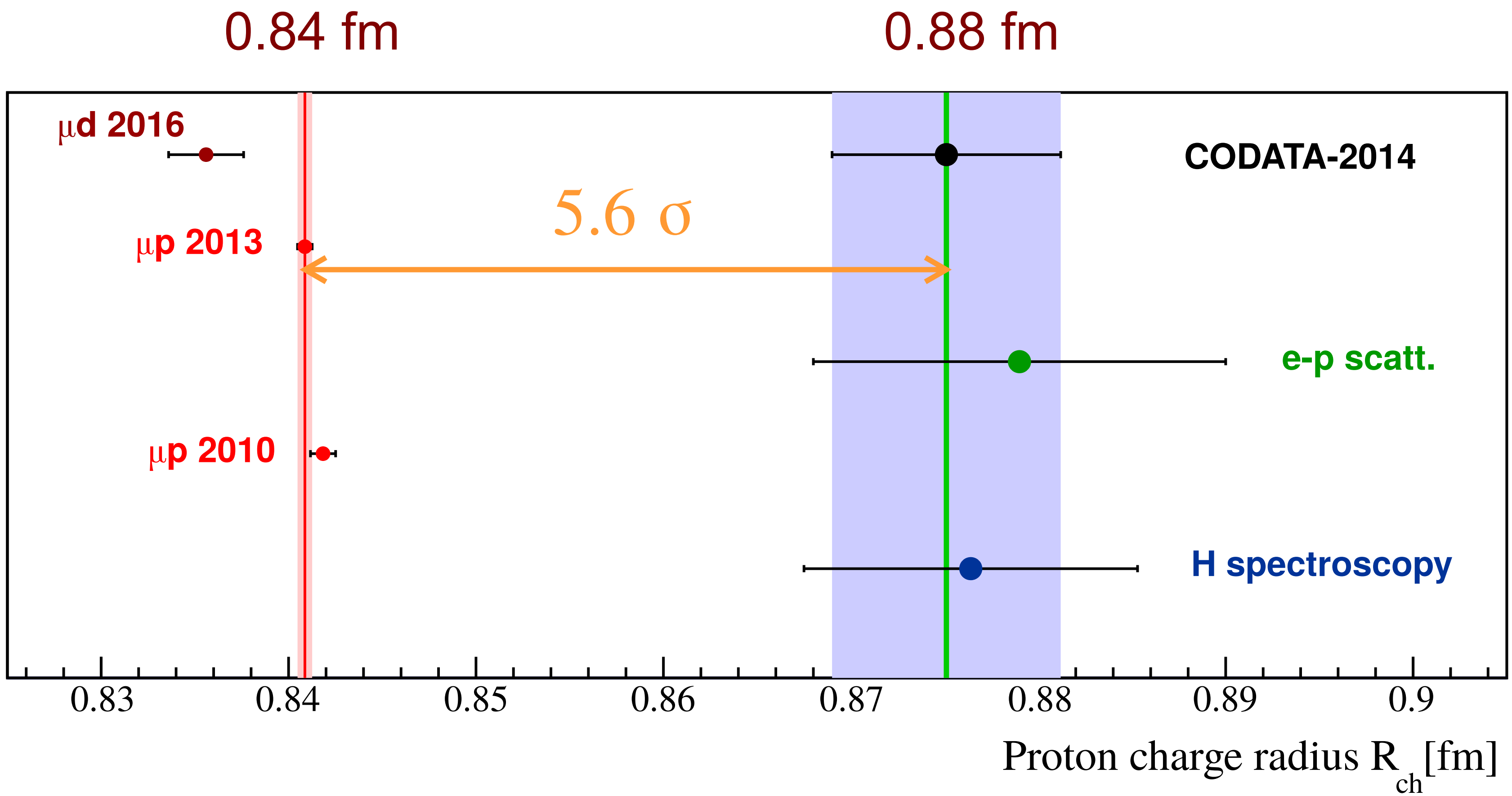
  as a probe of nuclear physics (**charge radii**, magnetization radii, polarizabilities, …)

- The "Proton Radius Puzzle"
- Rydberg constant

  key parameter to check **atomic physics** part of the discrepancy

- Muonic helium, later Li, Be, T?

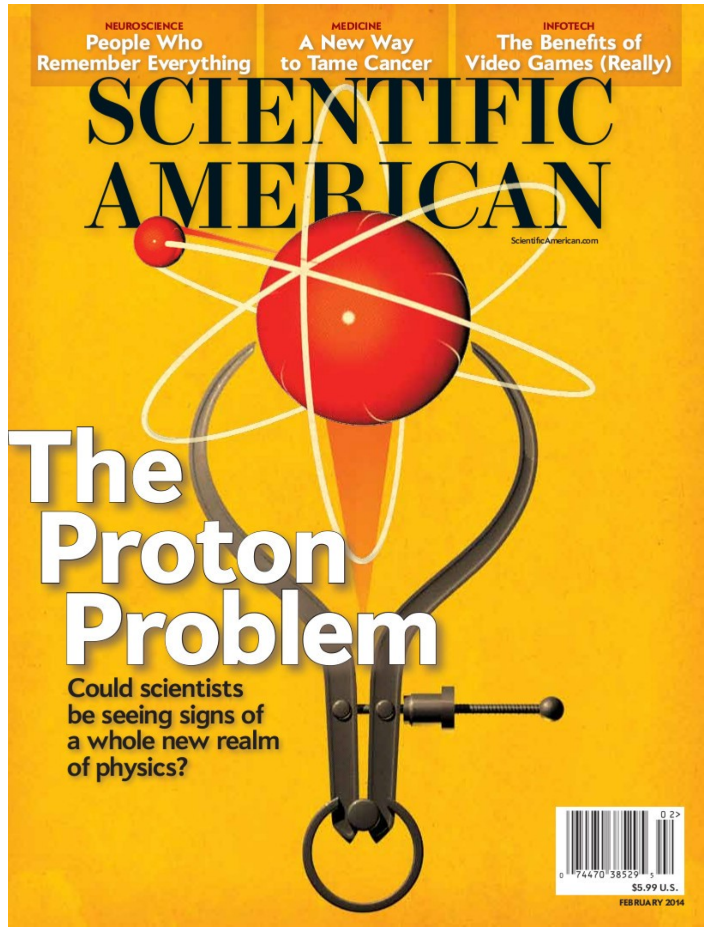
The “Proton Radius Puzzle”



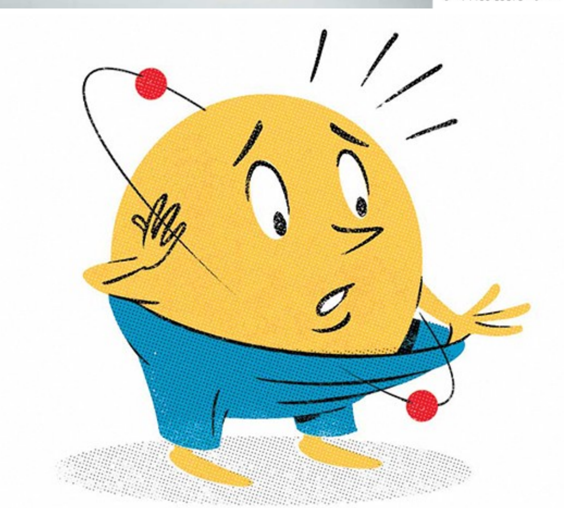
Measuring R_p using electrons: 0.88 fm (+- 0.7%)
using muons: 0.84 fm (+- 0.05%)

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

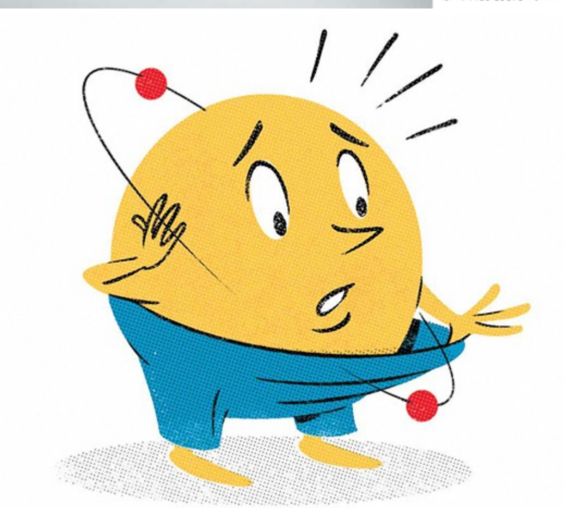

8 July 2010 | www.nature.com/nature | $10
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
nature
OIL SPILLS
There's more to come
PLAGIARISM
It's worse than you think
CHIMPANZEES
The battle for survival
0.84184 fm
SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent
NATUREJOBS
Researchers for hire


NEUROSCIENCE
People Who Remember Everything
MEDICINE
A New Way to Tame Cancer
INFOTECH
The Benefits of Video Games (Really)
SCIENTIFIC AMERICAN
ScientificAmerican.com
The Proton Problem
Could scientists be seeing signs of a whole new realm of physics?
$5.99 U.S.
FEBRUARY 2014


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
No2926 US$5.95 CAN$5.95
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



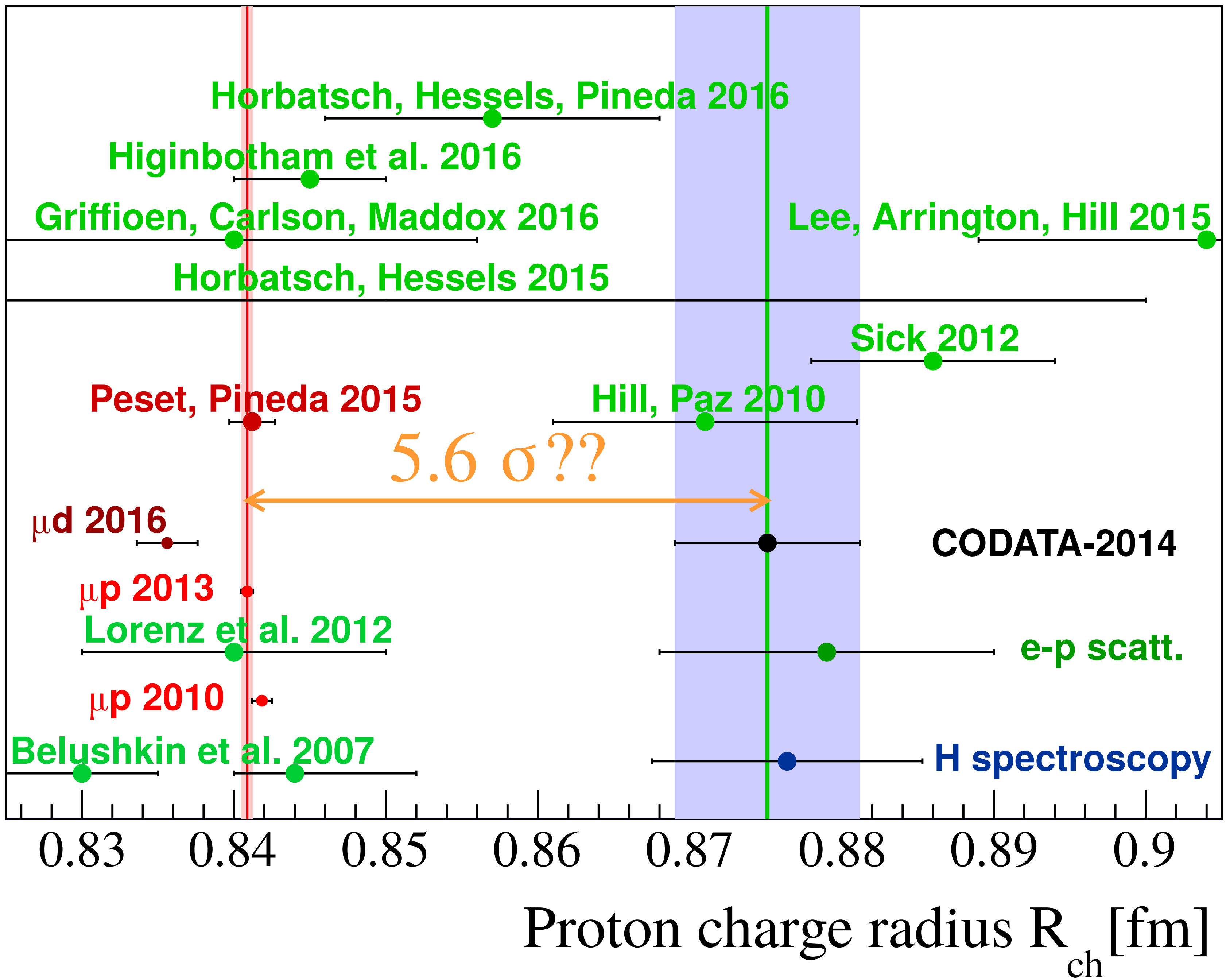
NY Times



NY Times

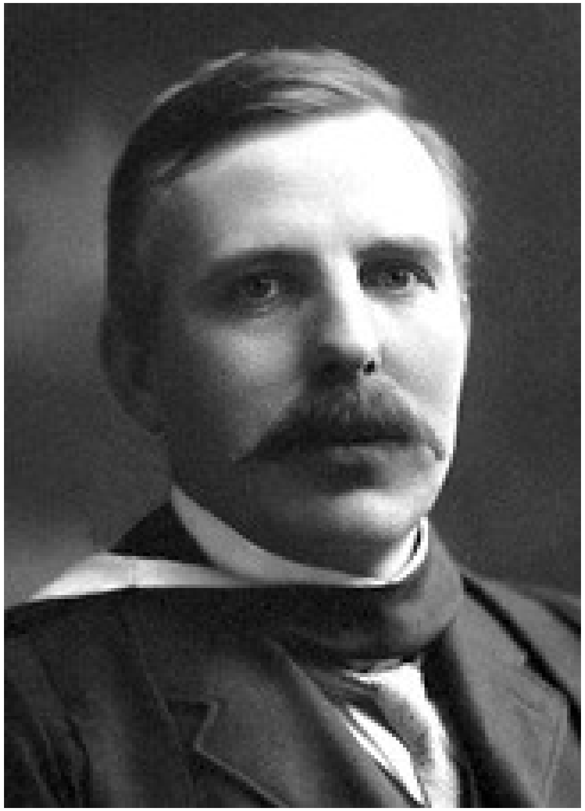
Jan Bernauer & RP,
April 2014

A "Proton Radius **Puzzle**" ??

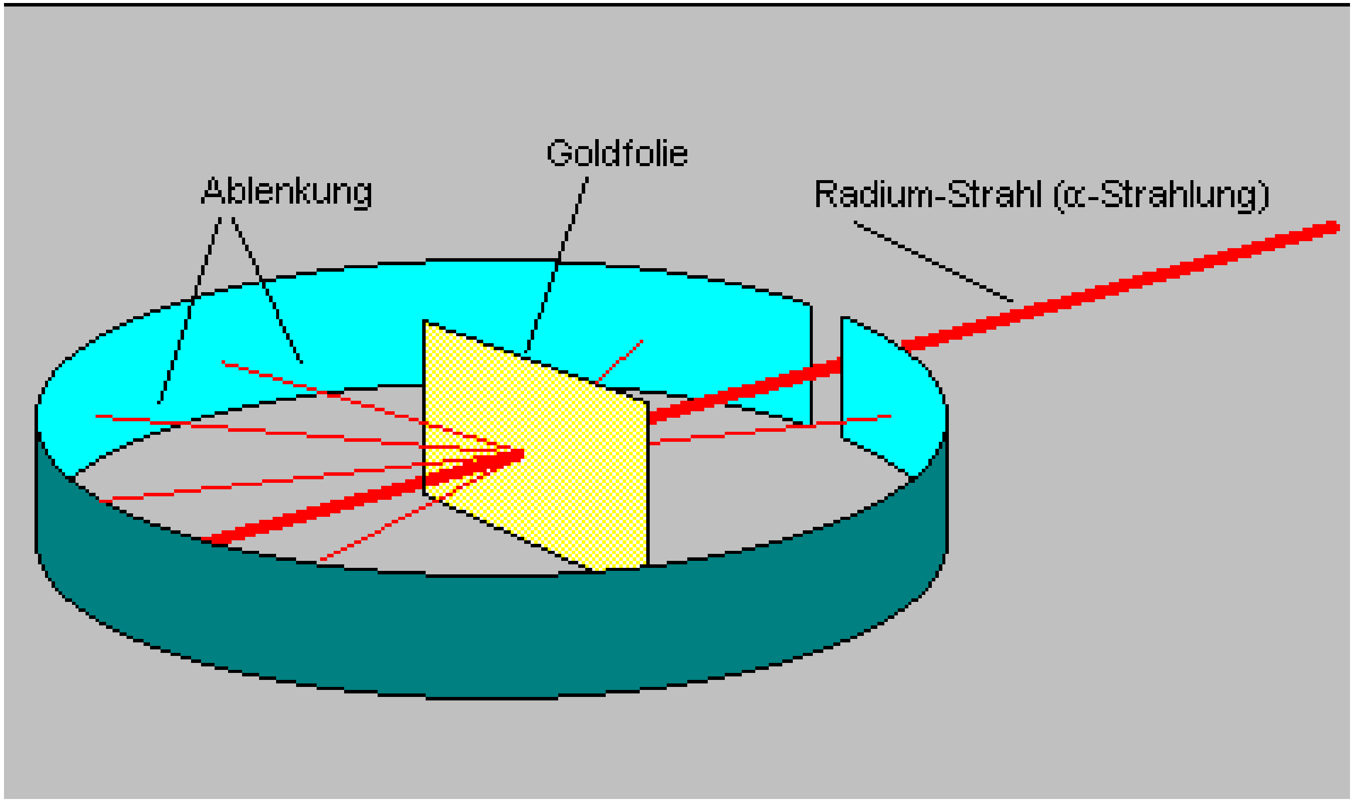


Intro: Atomic and nuclear physics

Ernest Rutherford – 1911



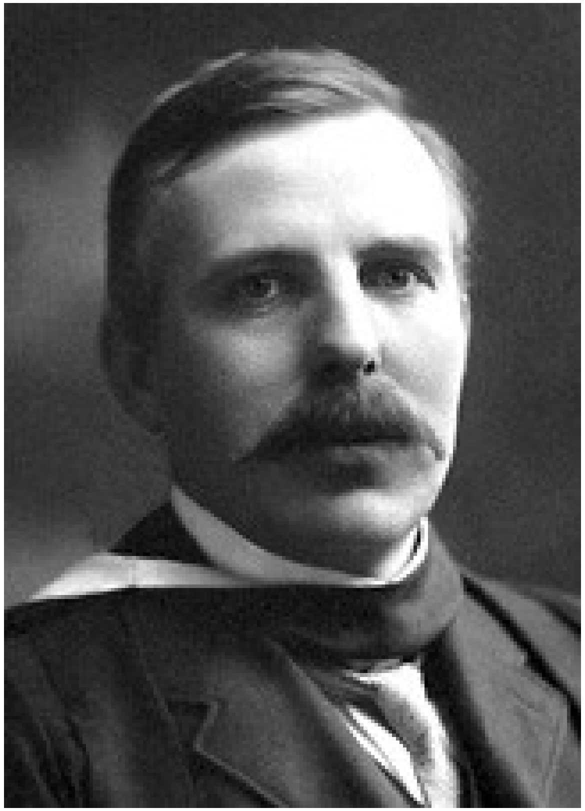
Rutherford shoots alpha particles onto a thin gold foil.



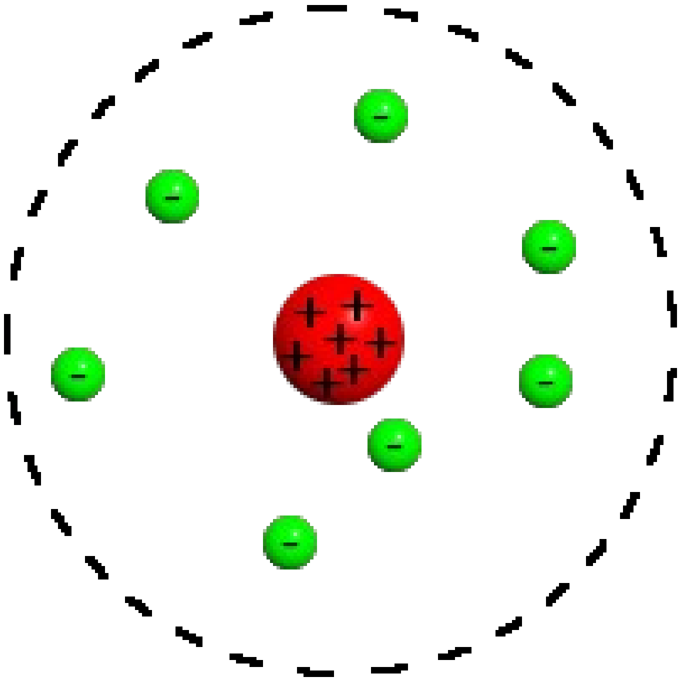
1871 – 1937
Nobel prize 1908

Most of the alpha particles pass the gold foil.
A few, however, are deflected by very large angles.

Ernest Rutherford – 1911



1871 – 1937
Nobel prize 1908

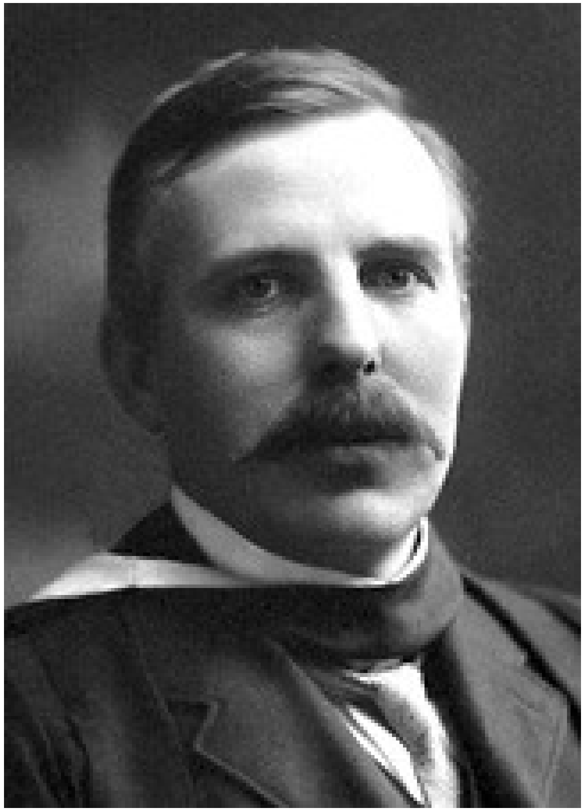


The Atom ist a

very small, heavy, positively charged **nucleus**

surrounded by negatively charged **electrons**

Ernest Rutherford – 1917

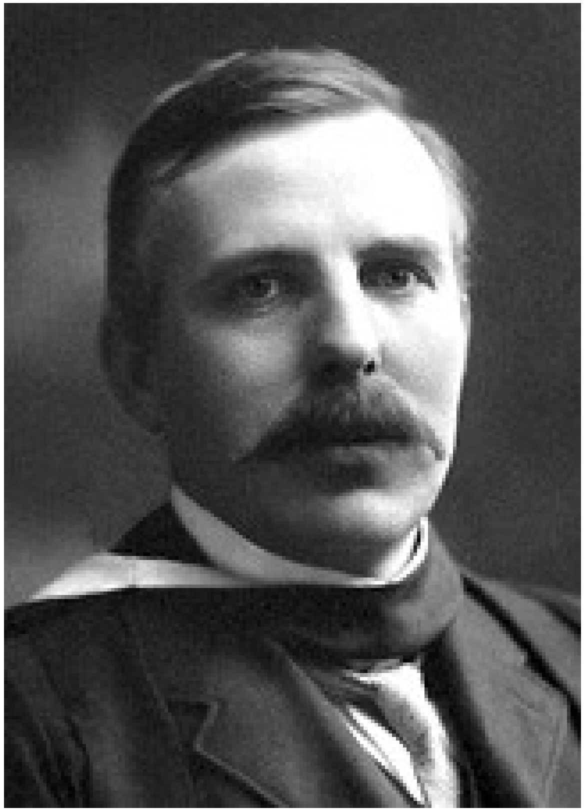


$^{14}N + \alpha \rightarrow {}^{17}O + p$

Rutherford shoots alpha particles at nitrogen. This creates the first man-made nuclear reaction.

He thereby discovers the **proton**.

Ernest Rutherford – 1917



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

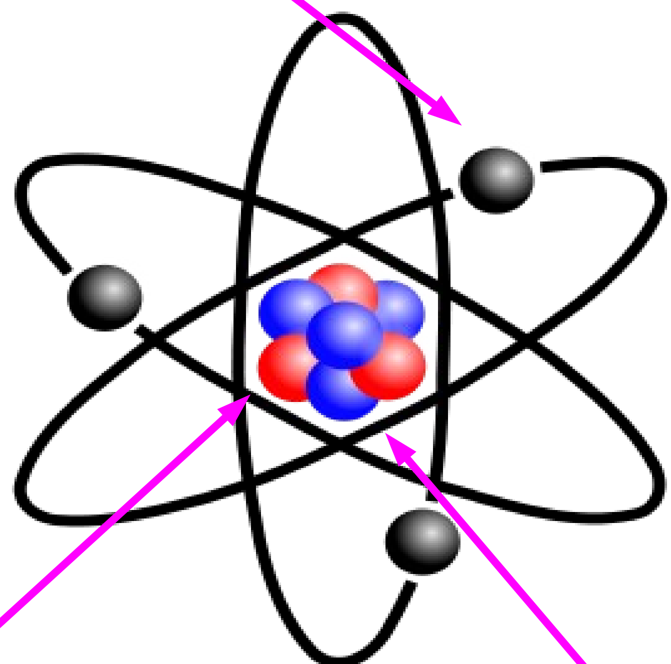
Rutherford shoots alpha particles at nitrogen. This creates the first man-made nuclear reaction.

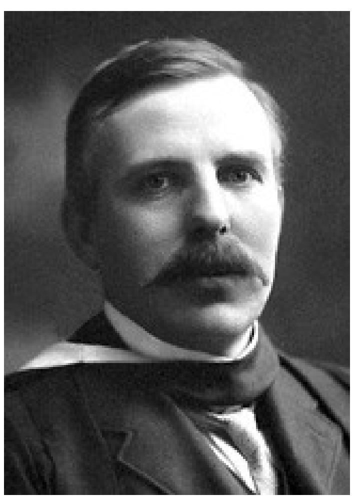
He thereby discovers the **proton**.

102nd birthday of the proton !!!

Constituents of matter

Electron: Joseph John Thomson
(1897)



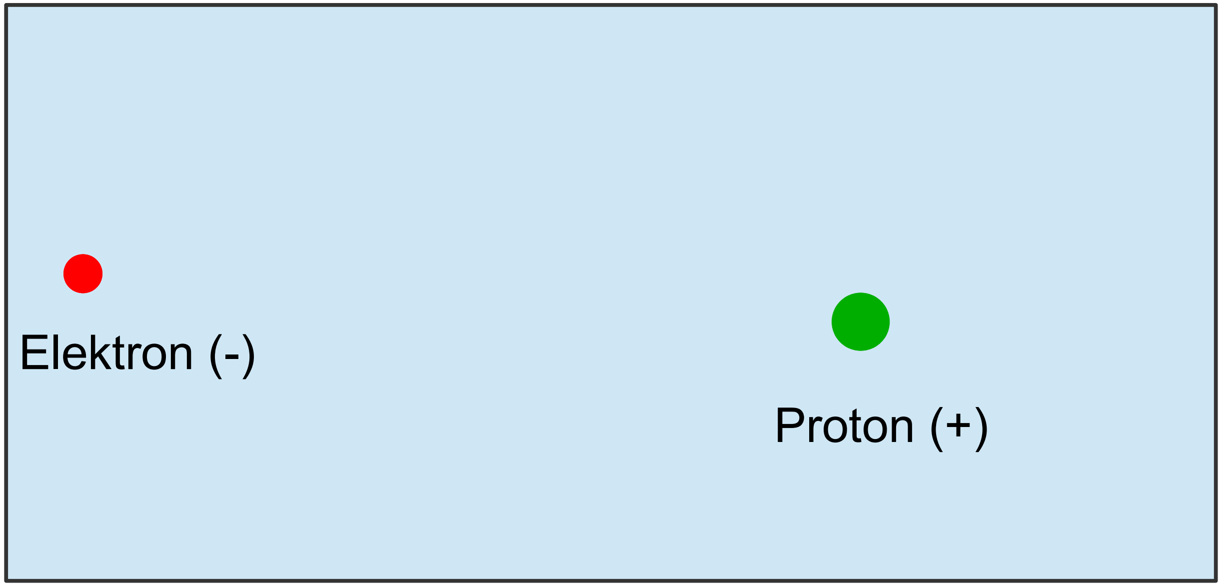


Proton: Ernest Rutherford
(1917)

Neutron: James Chadwick
(1932)

Robert Hofstadter – 1955

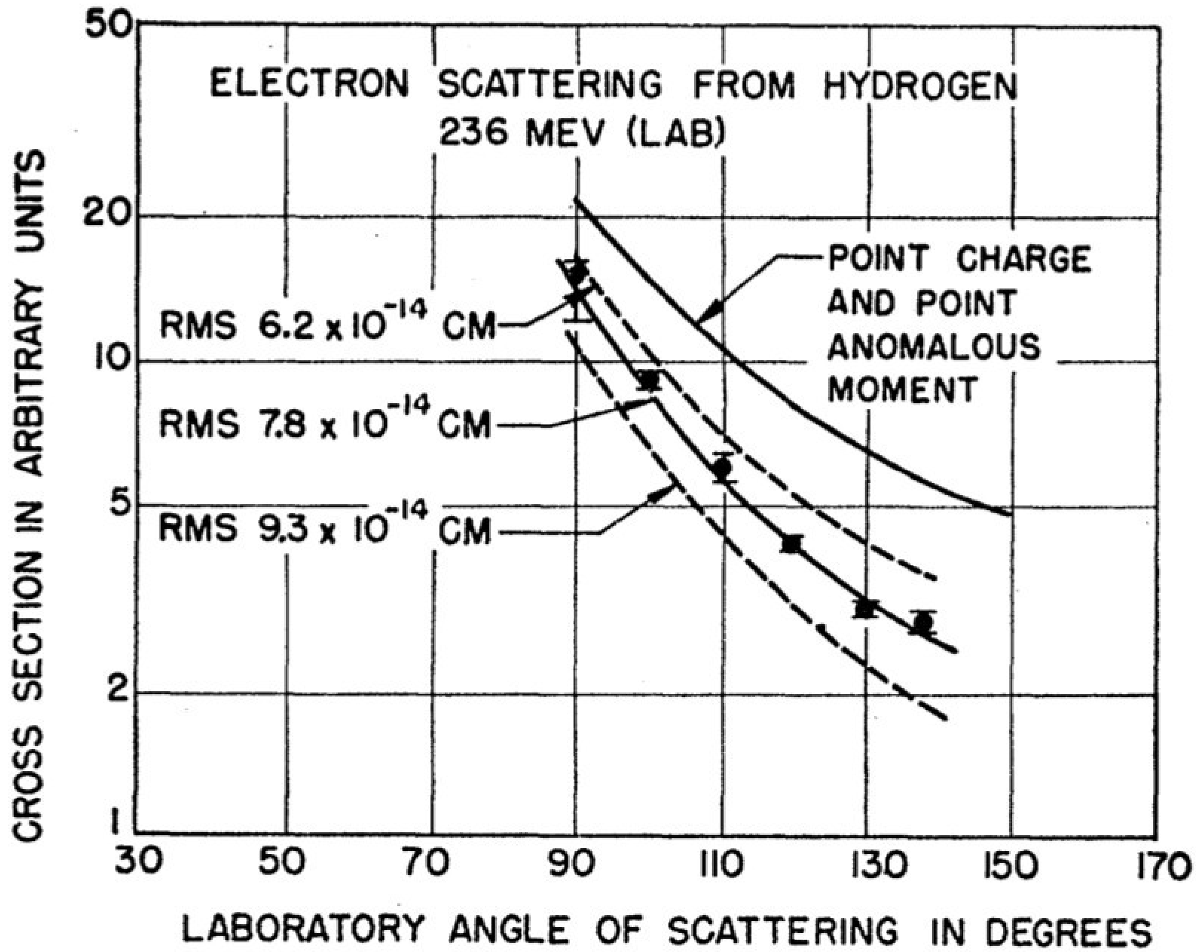
1915 – 1990
Nobelpreis 1961



Streuung von (negativ geladenen) Elektronen an (positiv geladenen) Protonen.

Robert Hofstadter – 1955

1915 – 1990
Nobelpreis 1961



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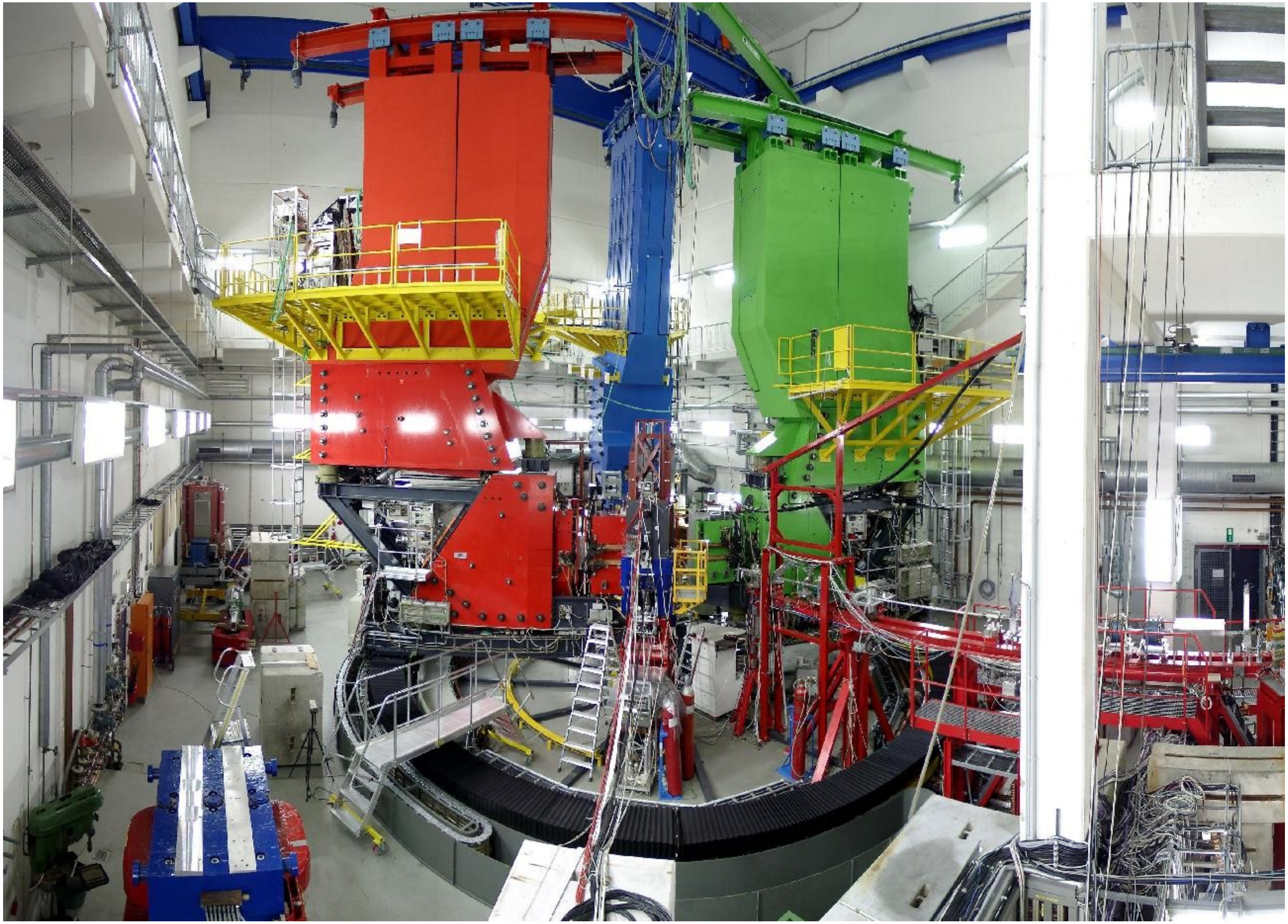
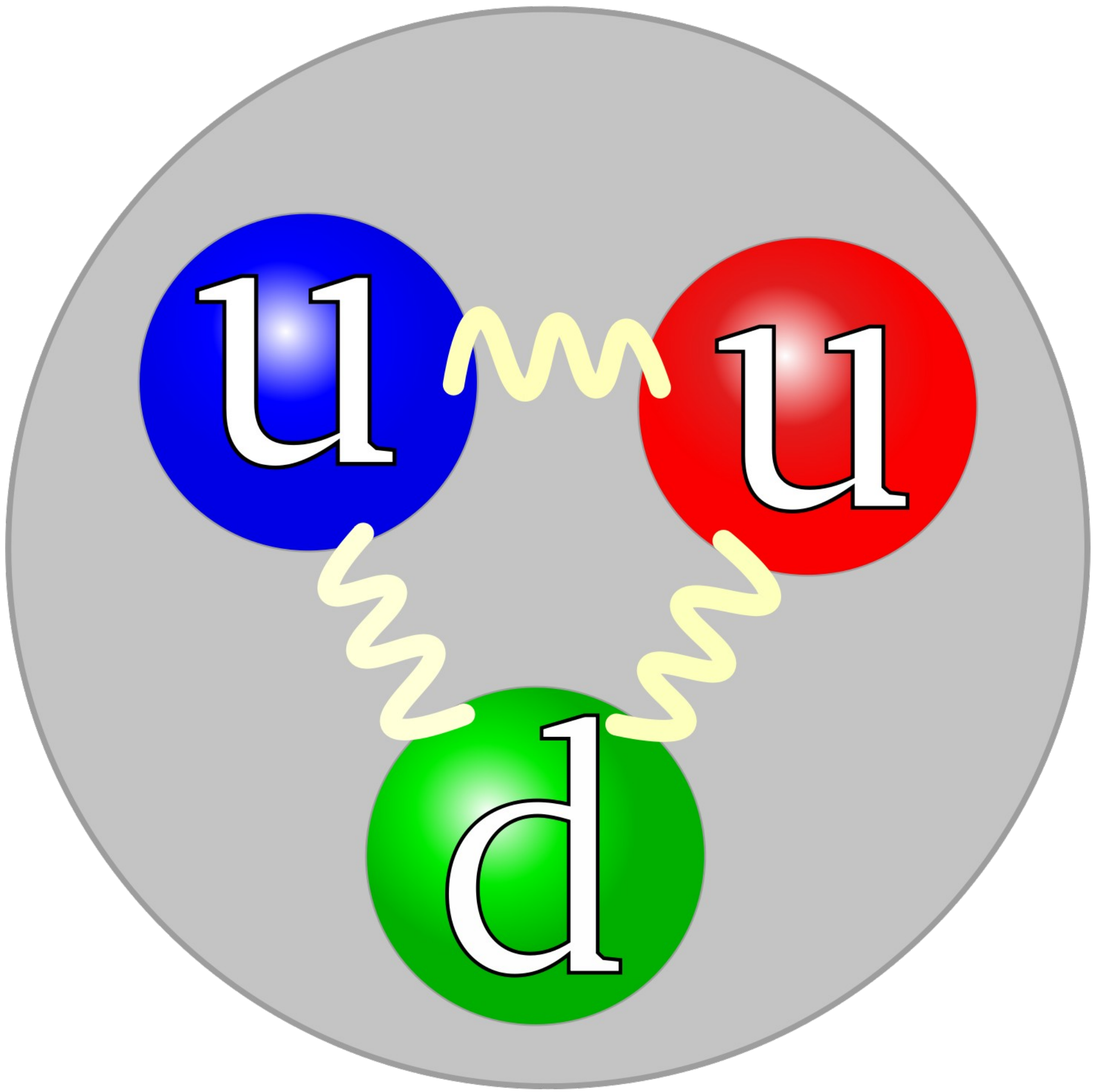
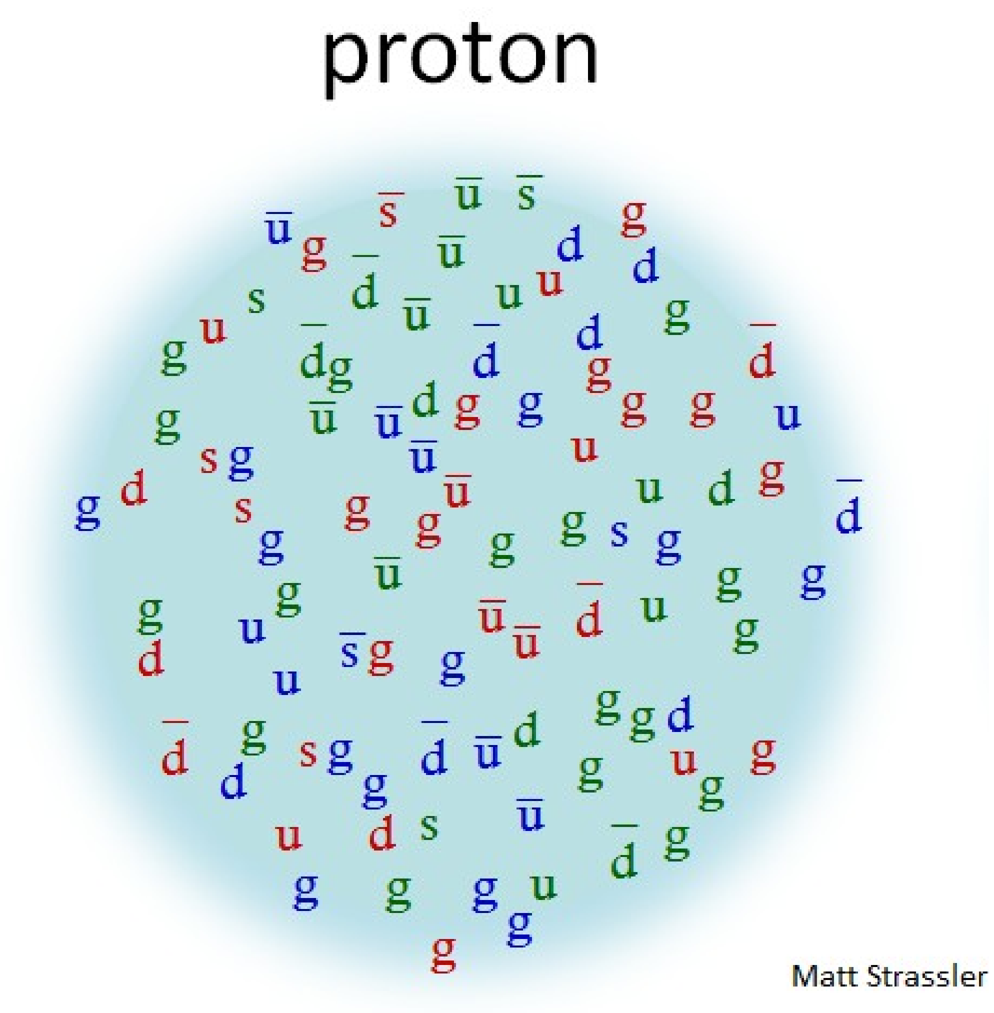
Mainzer Microtron MAMI



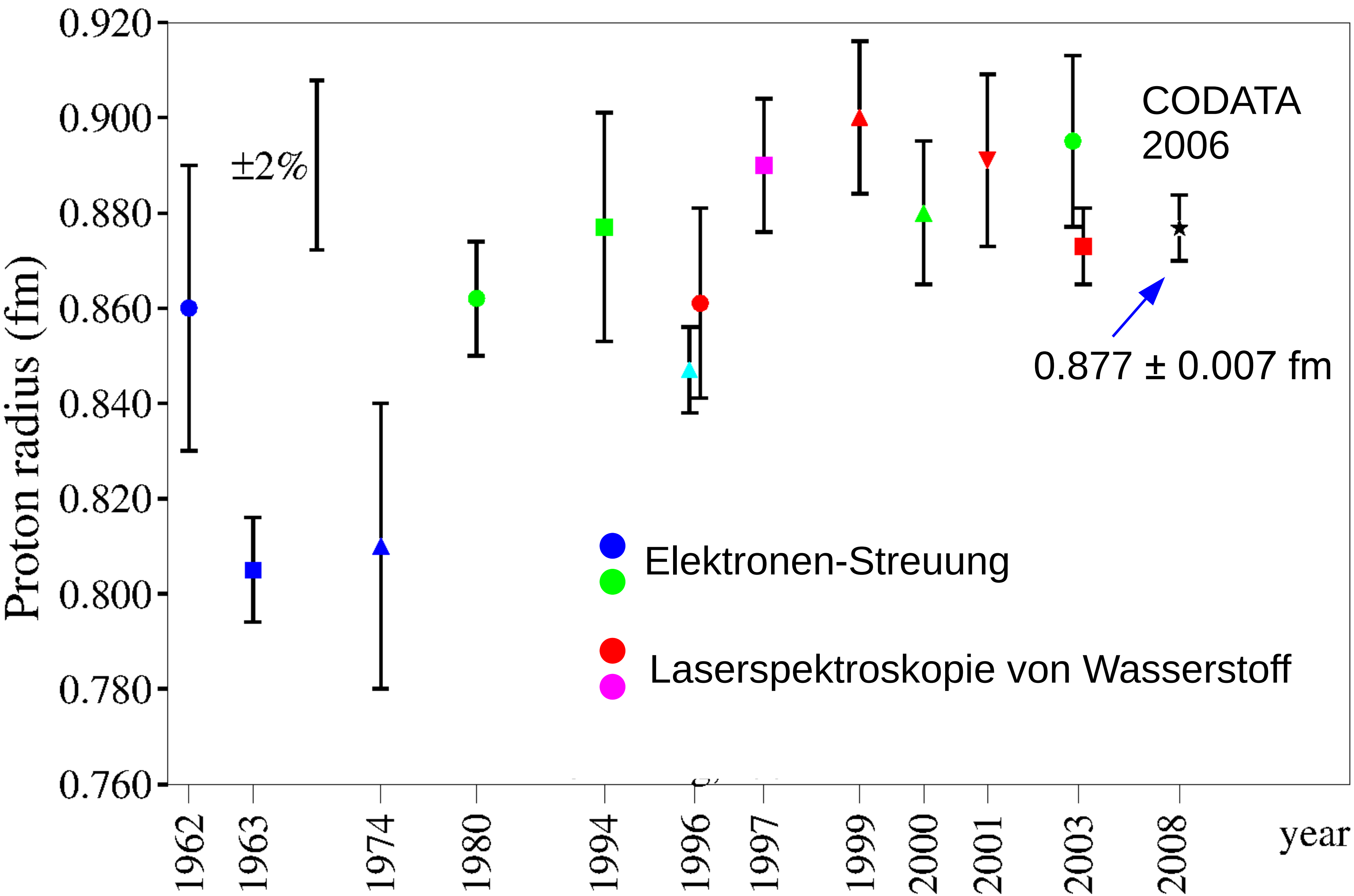
Proton – 3 Quarks



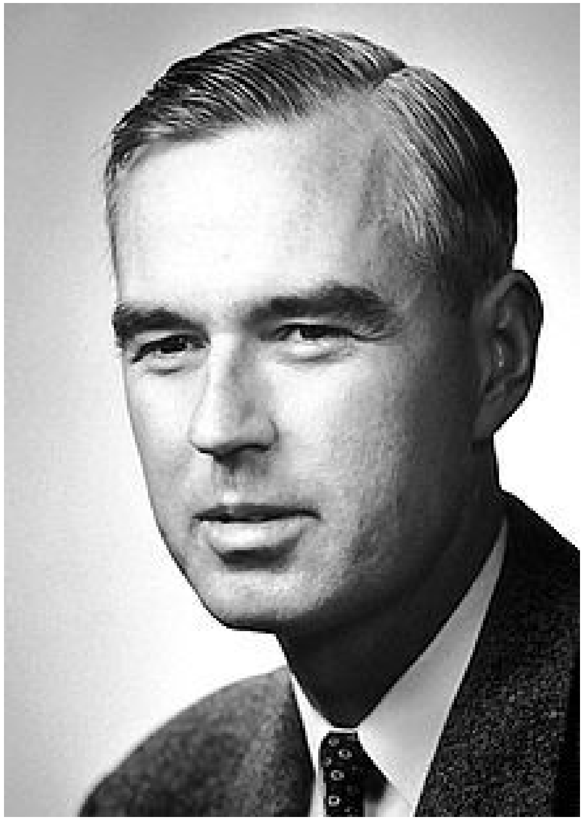
Proton – >>3 Quarks



Wie gross ist das Proton?



The Hydrogen Atom



Willis E. Lamb, Jr.

1913 – 2008
Nobel prize 1955

Discovers in 1947 (with Robert Retherford):

Energy levels “2S” and “2P” in hydrogen

do NOT have the same energy

Reason for Lamb-Shift

* Quantum fluctuations of the vacuum

* Proton charge radius

→ Development of

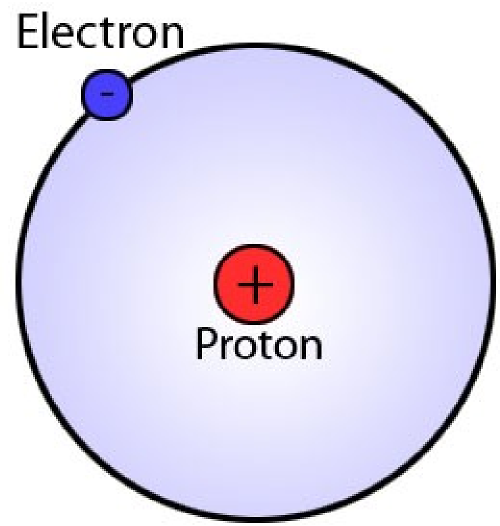
Quantum electrodynamics(QED)

The hydrogen atom

Nils Bohr

1885 – 1962
Nobel prize 1922

One Proton, orbited by *one* Electron.



The hydrogen atom

Nils Bohr

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Nobel prize 1922

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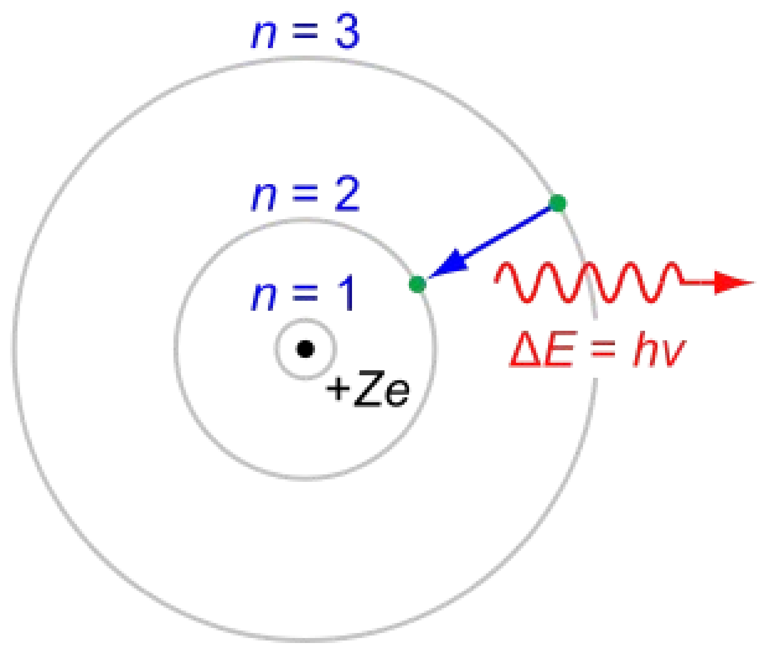
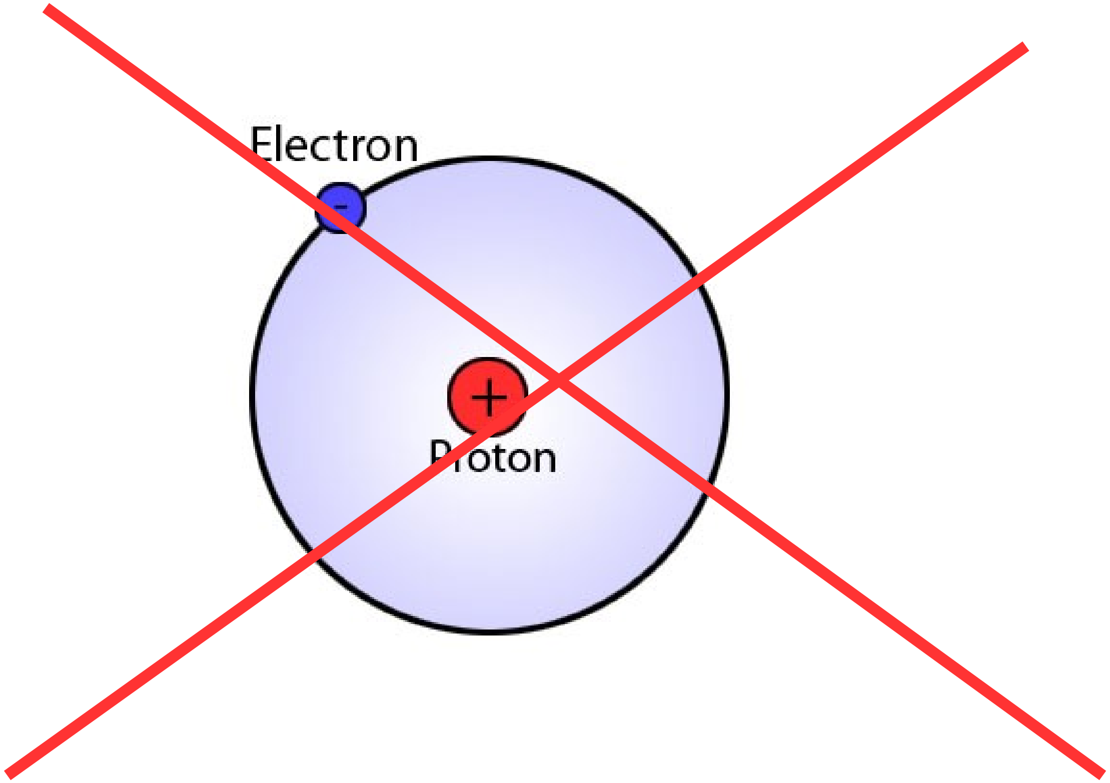


The hydrogen atom



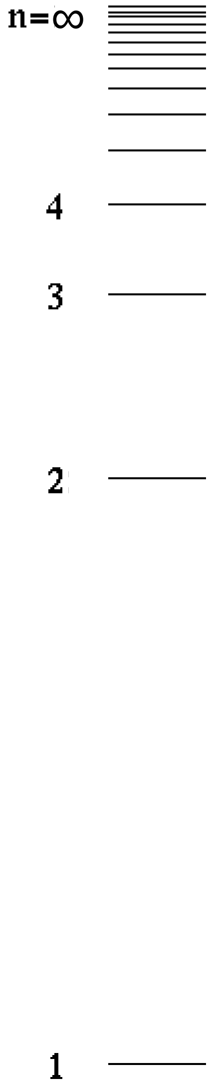
The atom is NOT a planetary system.

→ Quantum mechanics

→ Wave functions

→ Probability amplitudes

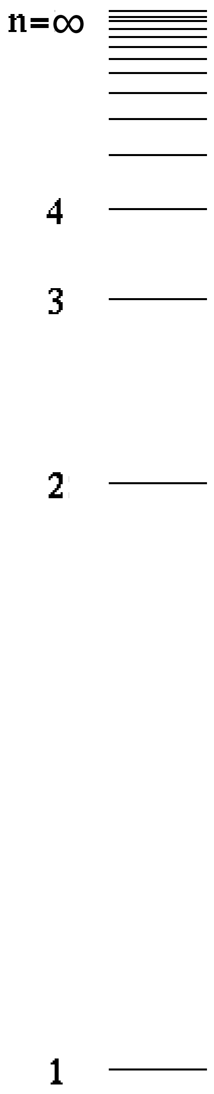
Energy levels of hydrogen



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

Bohr formula

Energy levels of hydrogen

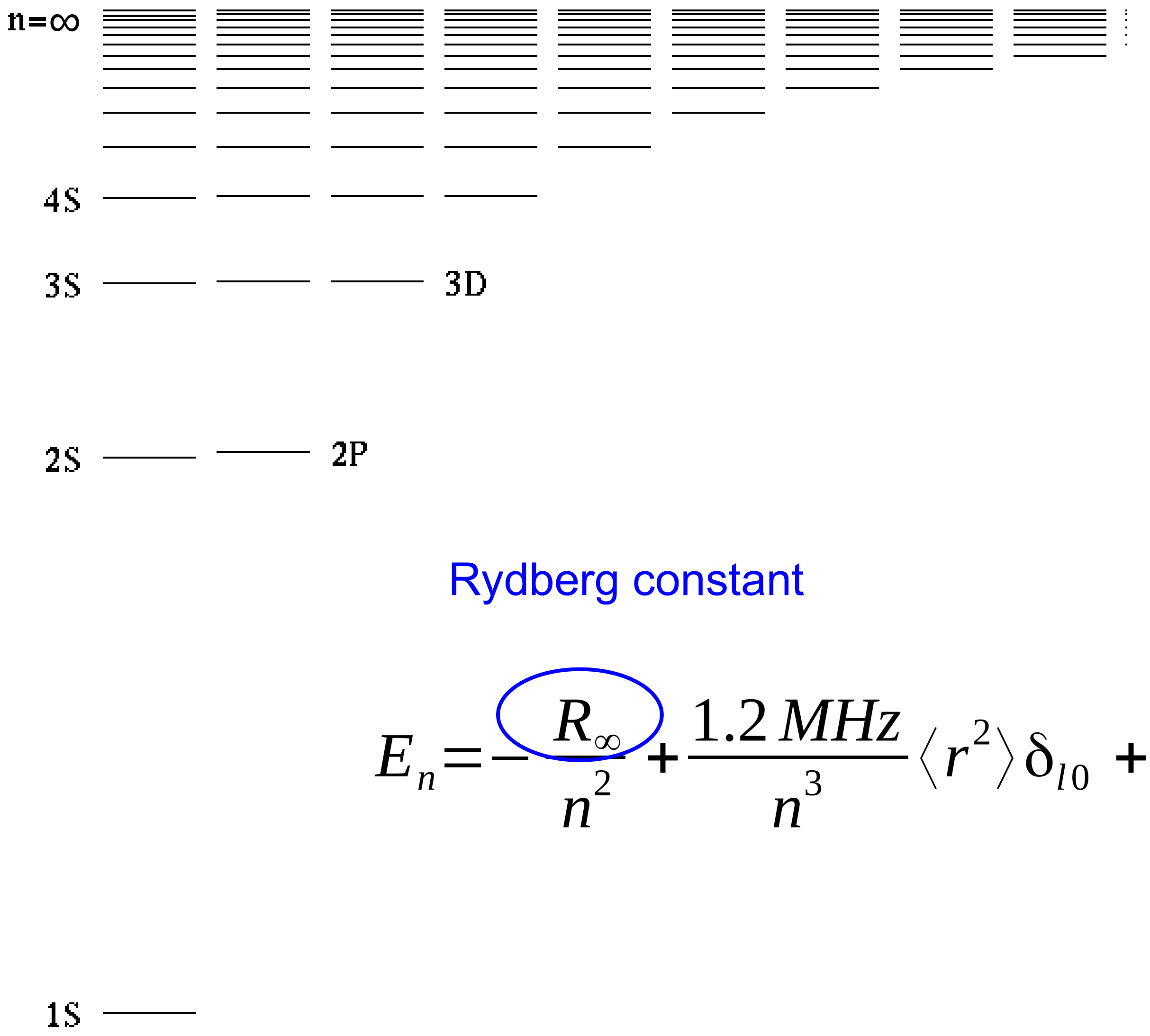


Rydberg constant

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

Bohr formula

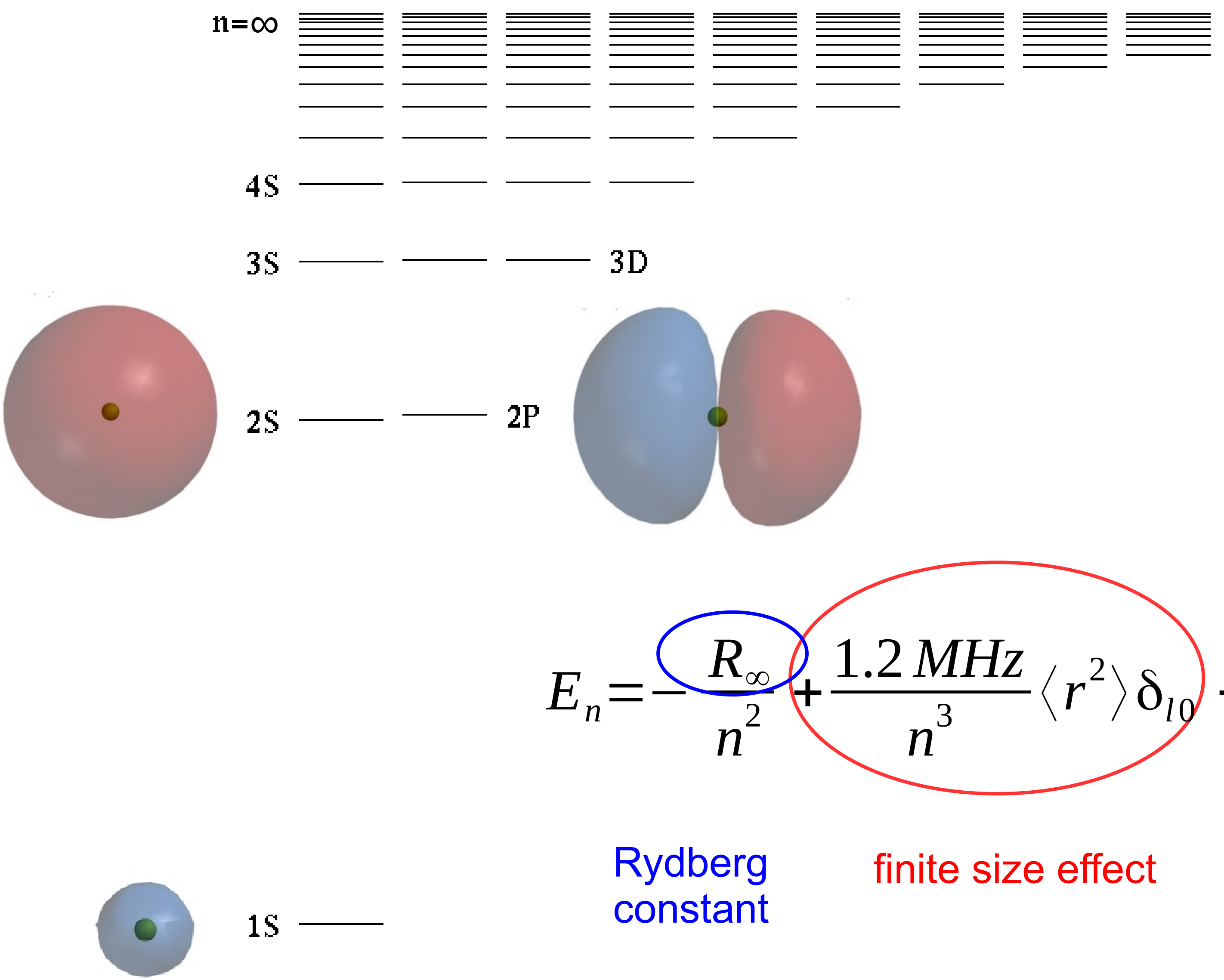
Energy levels of hydrogen



Rydberg constant

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

Energy levels of hydrogen

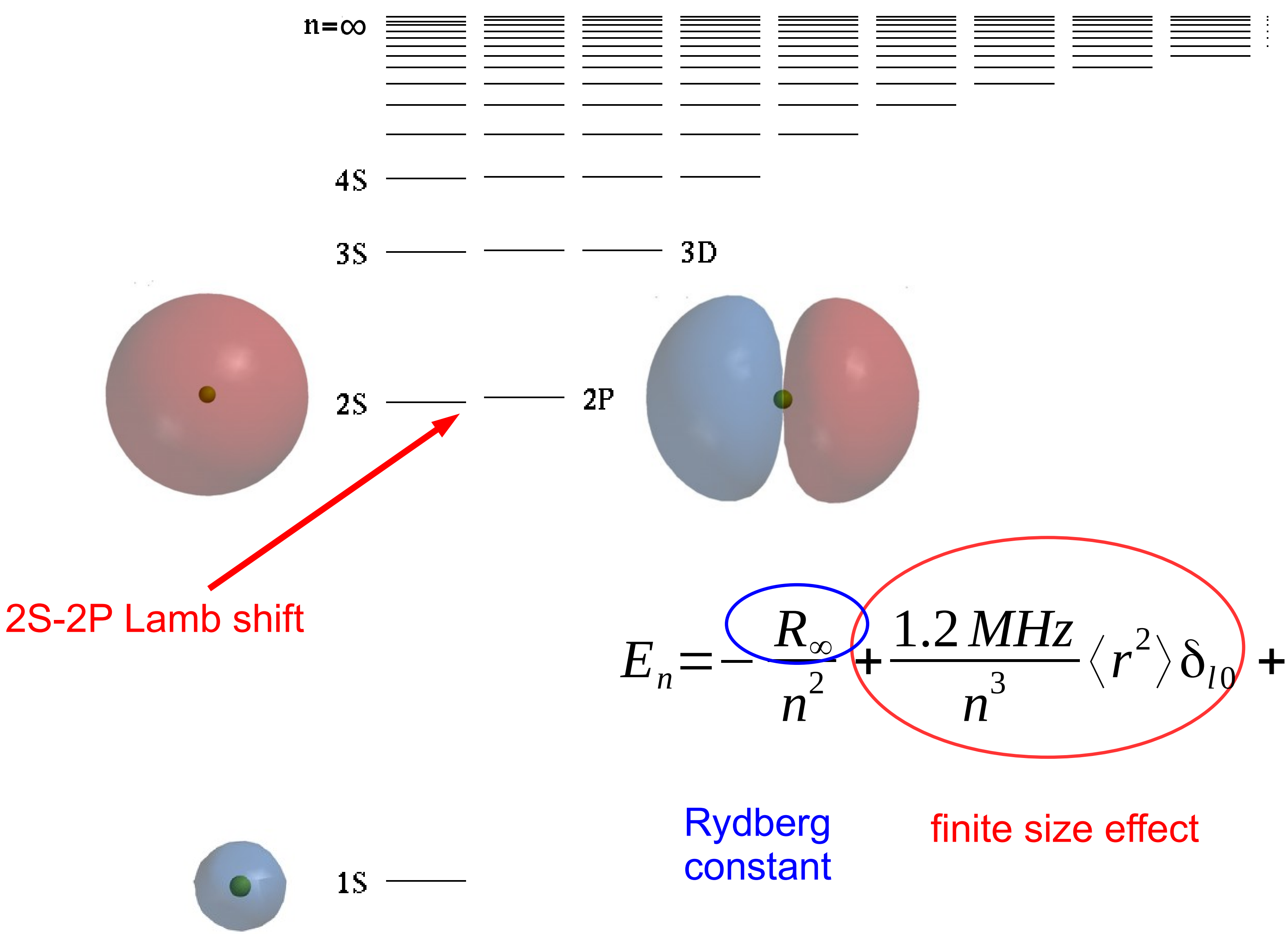


$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2\rangle \delta_{l0} + \Delta(n, l, j)$$

Rydberg constant

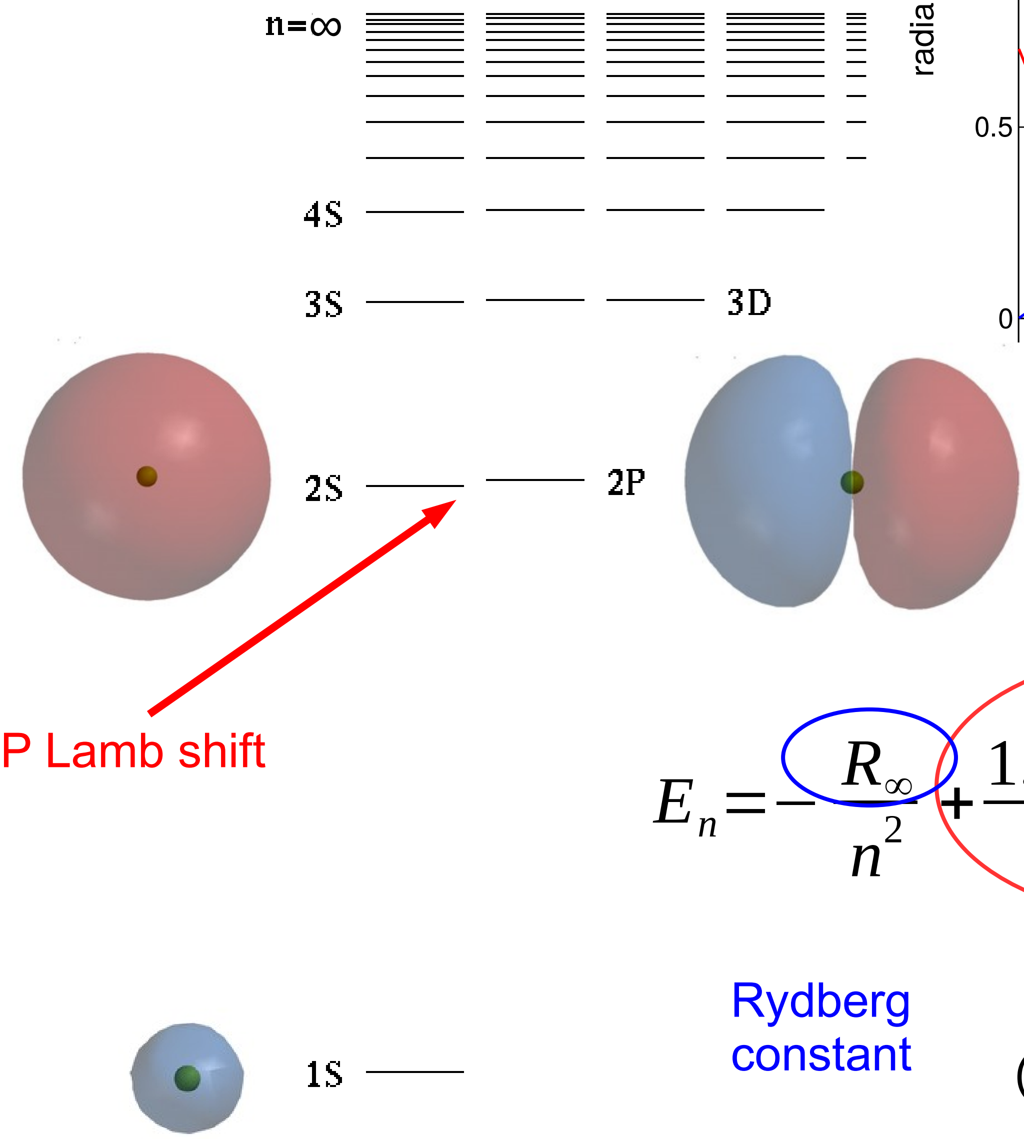
finite size effect

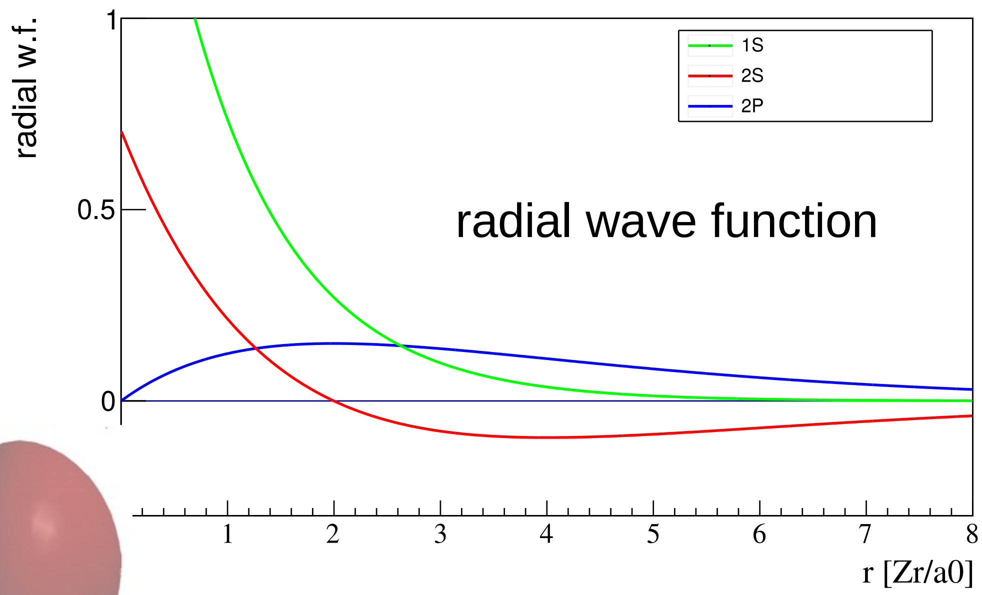
Energy levels of hydrogen



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

Energy levels of hydrogen





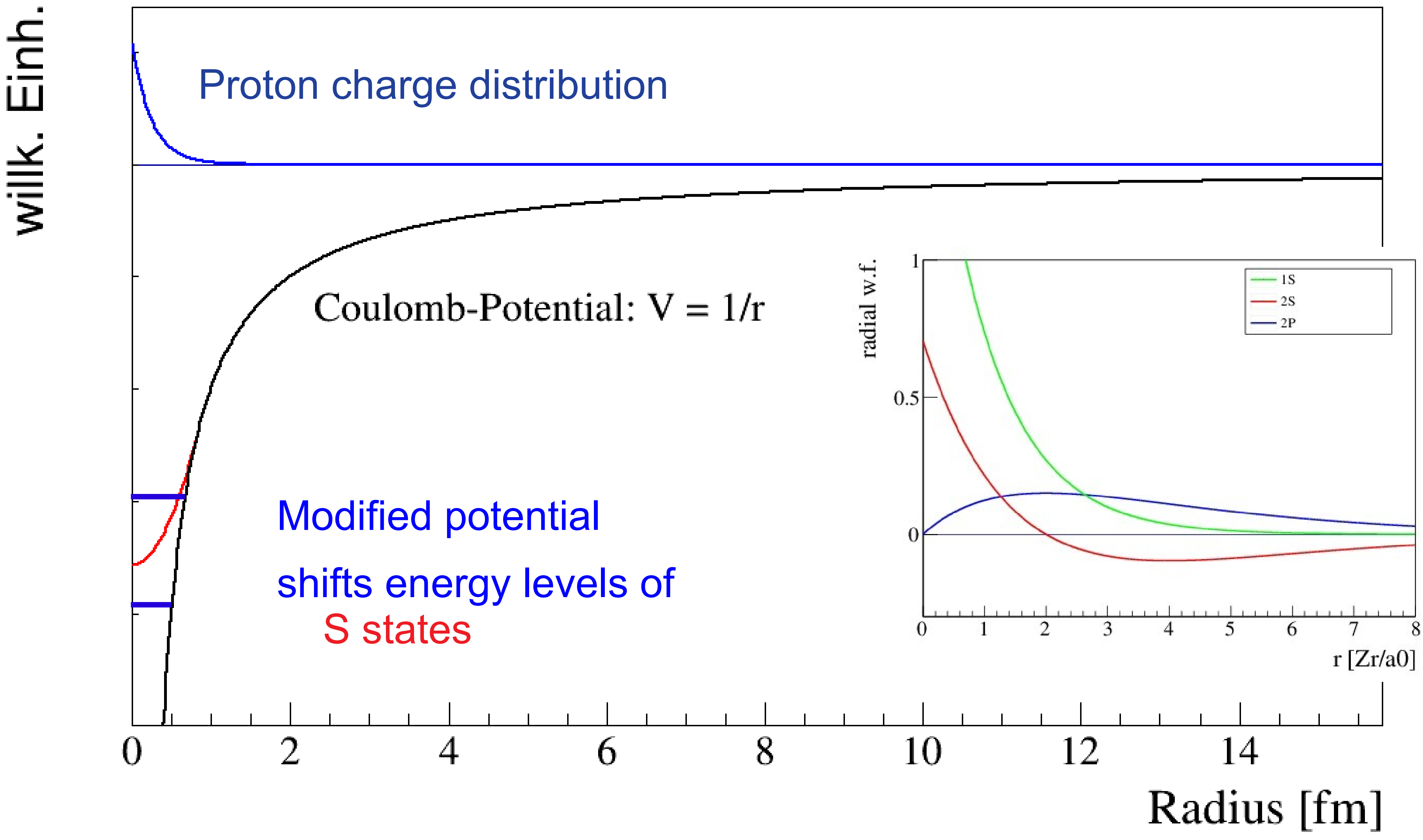
2S-2P Lamb shift

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

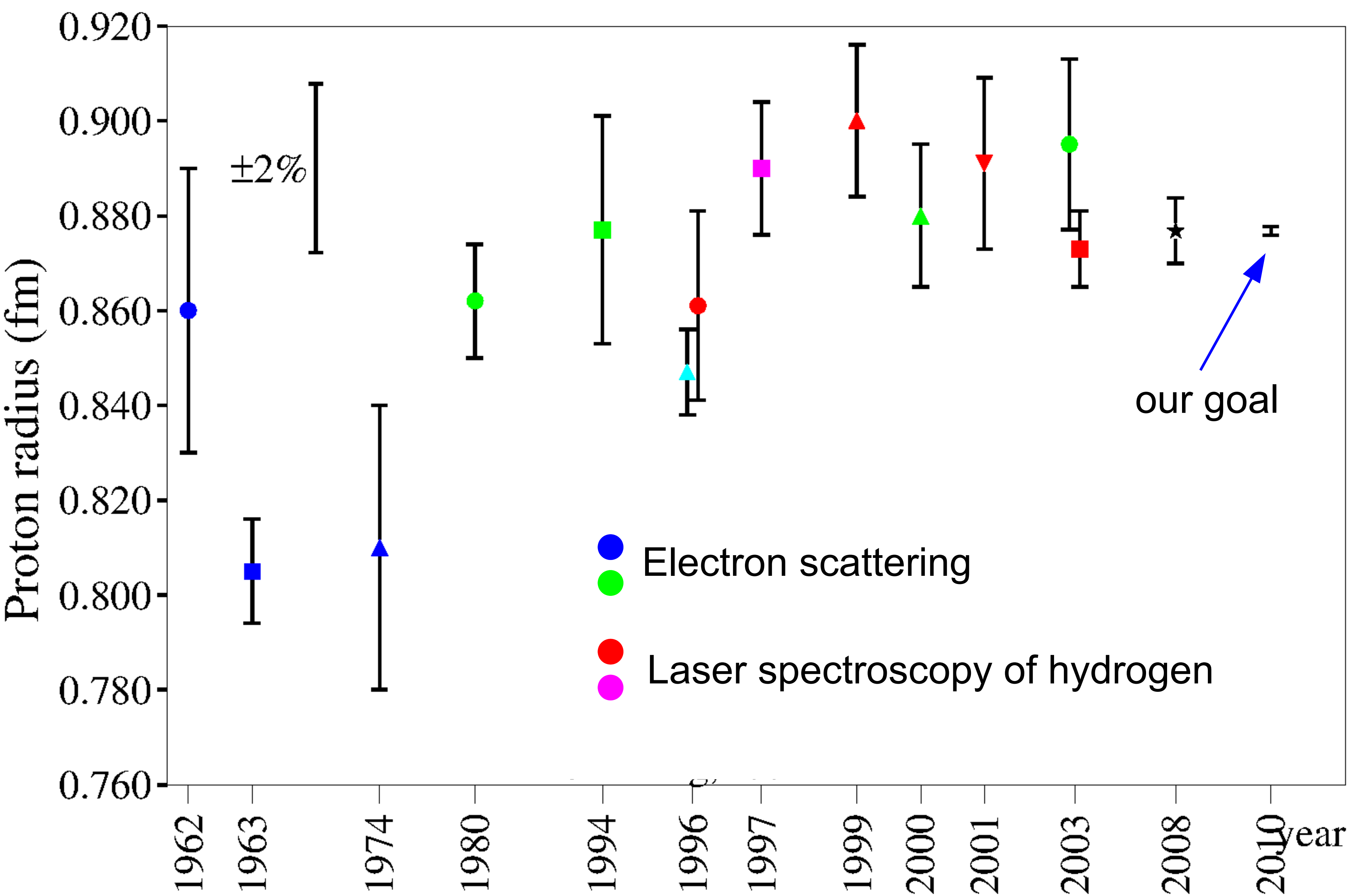
Rydberg constant

finite size effect (enters at the 10th digit)

Proton radius and hydrogen



How large is a Proton?



A 10fold more precise measurement of the proton radius!?

Proposal for an experiment at PSI

Laser spectroscopy of the Lamb Shift in muonic hydrogen

P. Hauser, C. Petitjean, L.M. Simons, D. Taqqu
Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

F. Kottmann, R. Pohl
Institut für Teilchenphysik, ETHZ, CH-8093 Zürich, Switzerland

C. Donche-Gay, O. Huot, P. Knowles, F. Mulhauser, L.A. Schaller, H. Schneuwly
Institut de Physique de l'Université, CH-1700 Fribourg, Switzerland

F.J. Hartmann, W. Schott
Physik-Department, Technische Universität München, D-85747 Garching, Germany

F. Biraben, F. Nez, P. Indelicato
Laboratoire Kastler Brossel, F-75252 Paris CEDEX 05, France

C.A.N. Conde, J.M.F. Santos, J.F.C.A. Veloso
Department of Physics, Coimbra University, P-3000 Coimbra, Portugal

T.W. Hänsch
Max-Planck-Institut für Quantenoptik, D-85747 Garching, Germany

P. Rabinowitz
Department of Chemistry, Princeton University, Princeton, NJ08544-1009, USA

Proposal 1998:

3: 1%

Measure the

Lamb shift

in

muonic hydrogen

Goal:

10 time more precise

Muonic Hydrogen

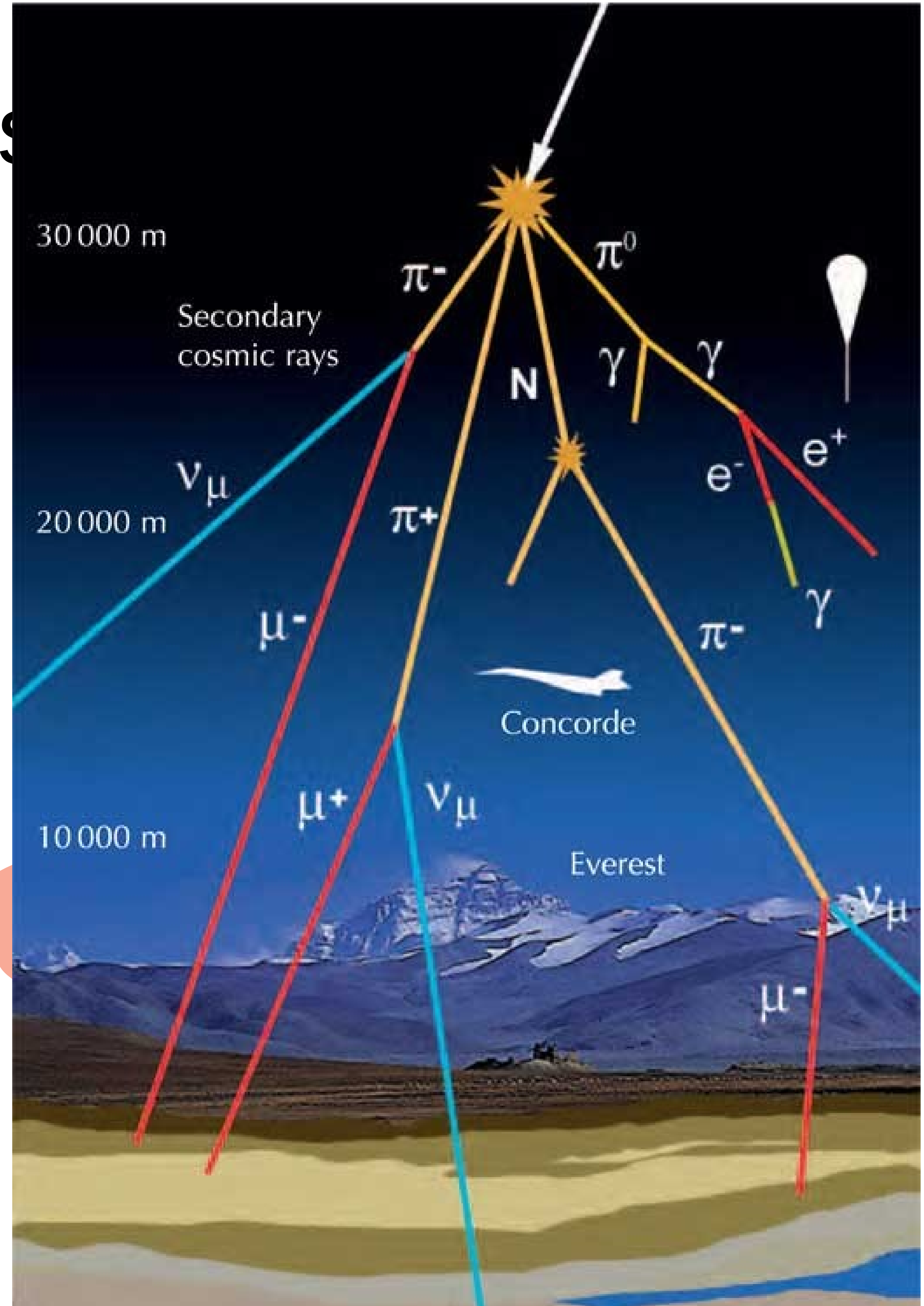
A proton, orbited by a **negative muon.**

What is

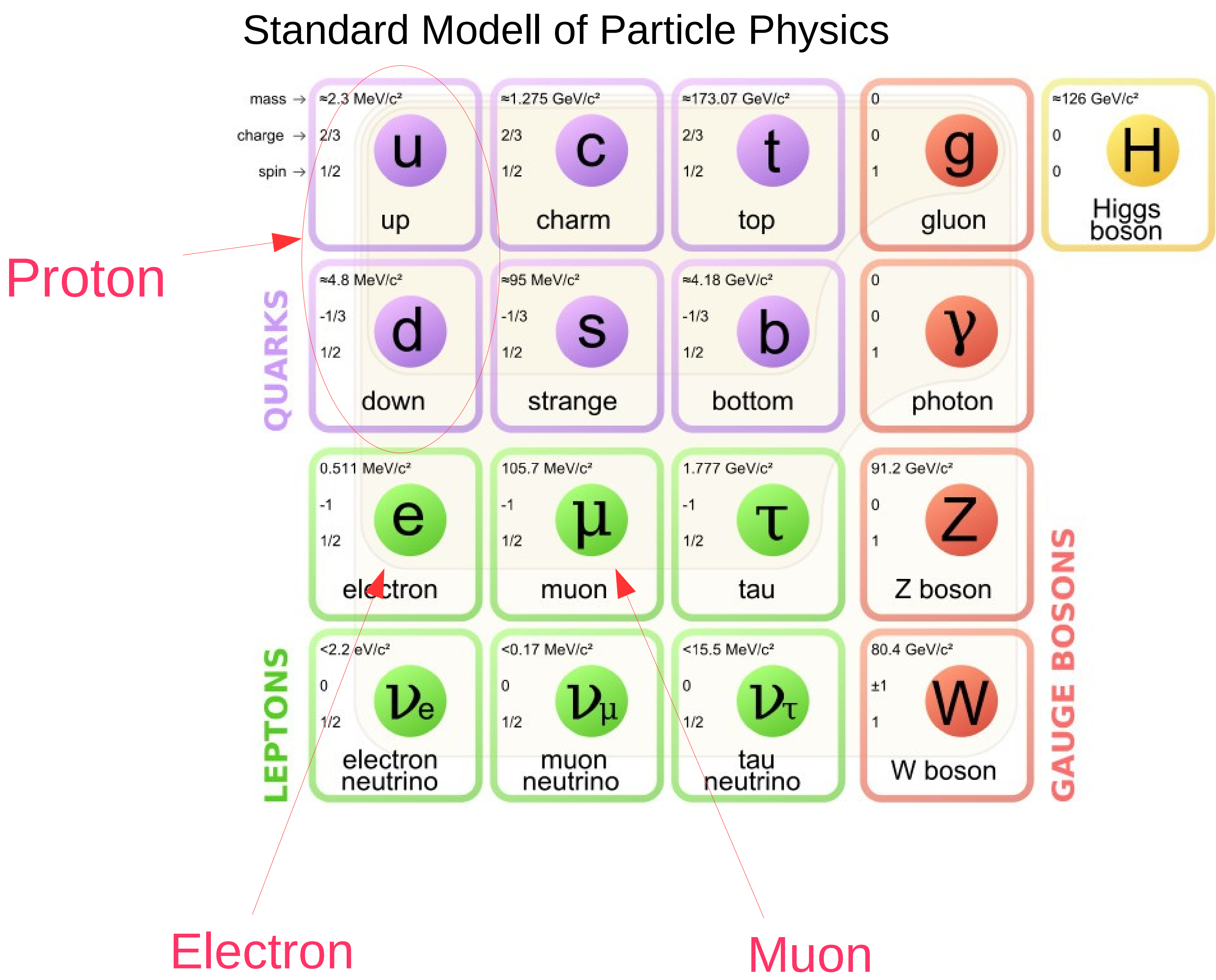
Carl David Anderson

Seth Neddermeyer

Nobel prize 1936
(for the Positron!)



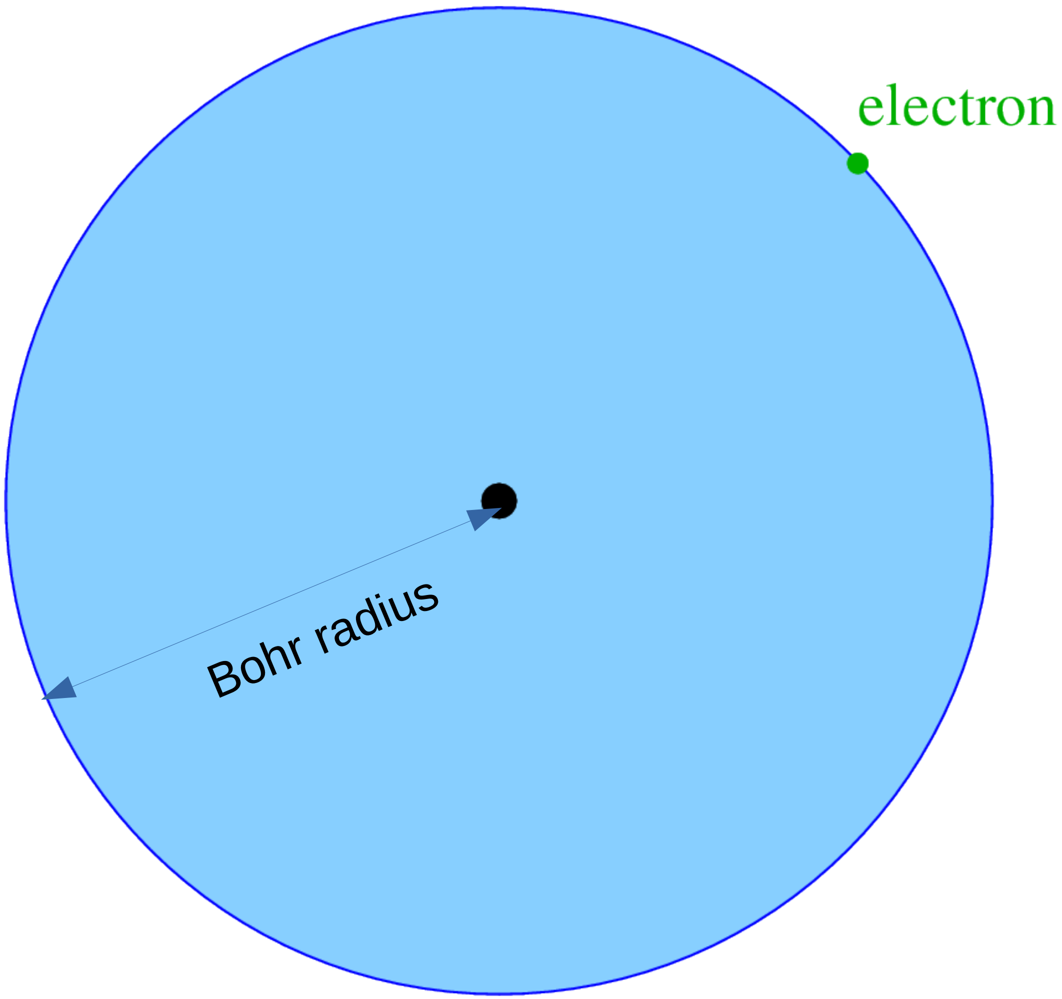
The muon and its place in the world



Electronic and muonic atoms

Regular hydrogen:

Proton + Electron



Muonic hydrogen:

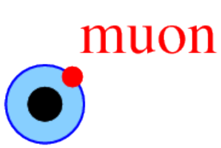
Proton + Muon

Muon **mass** = 200 * electron mass

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

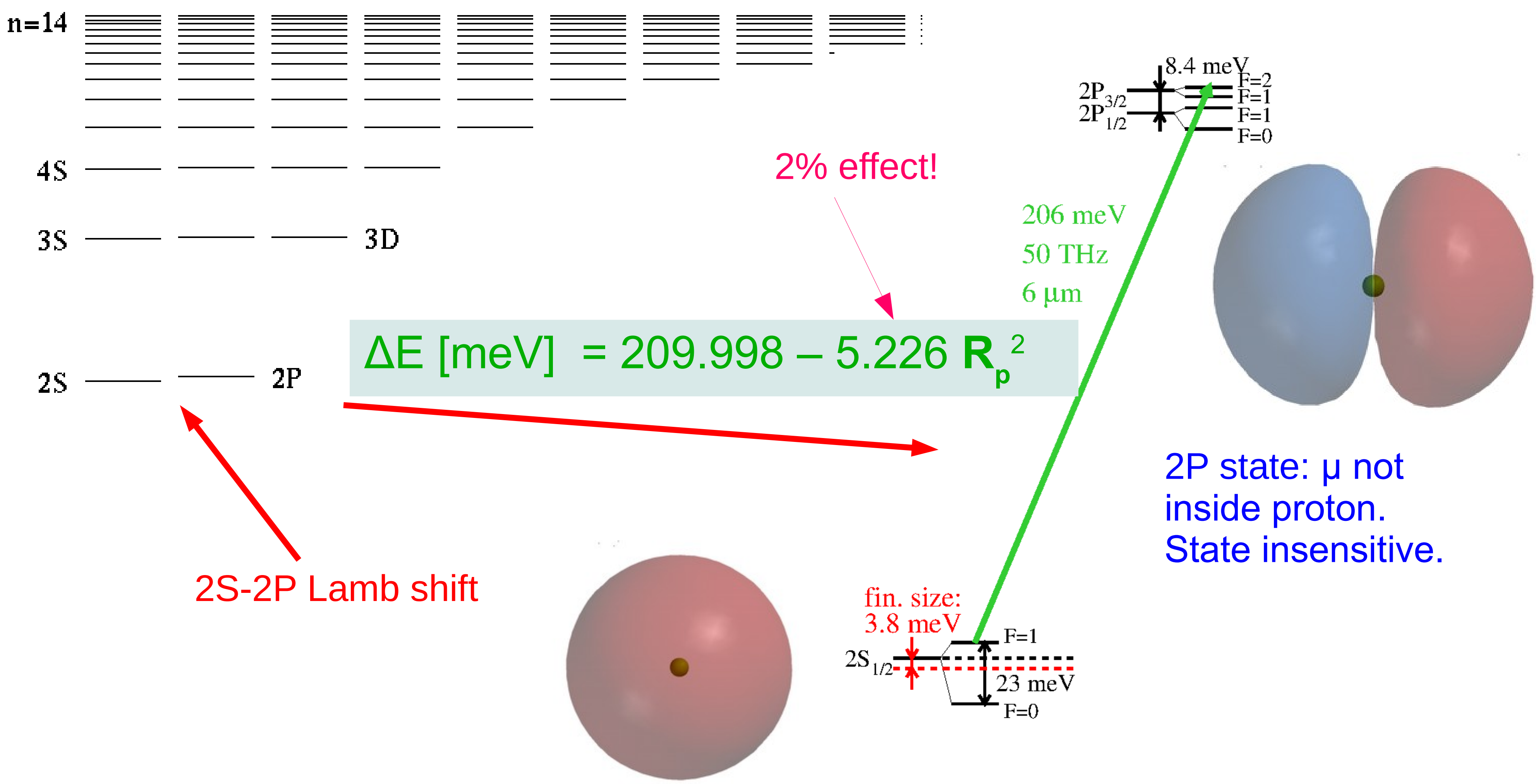
Wave function overlap:

200^3 = 10 million !



muonic hydrogen is a few million times more sensitive to proton size

Muonic Hydrogen

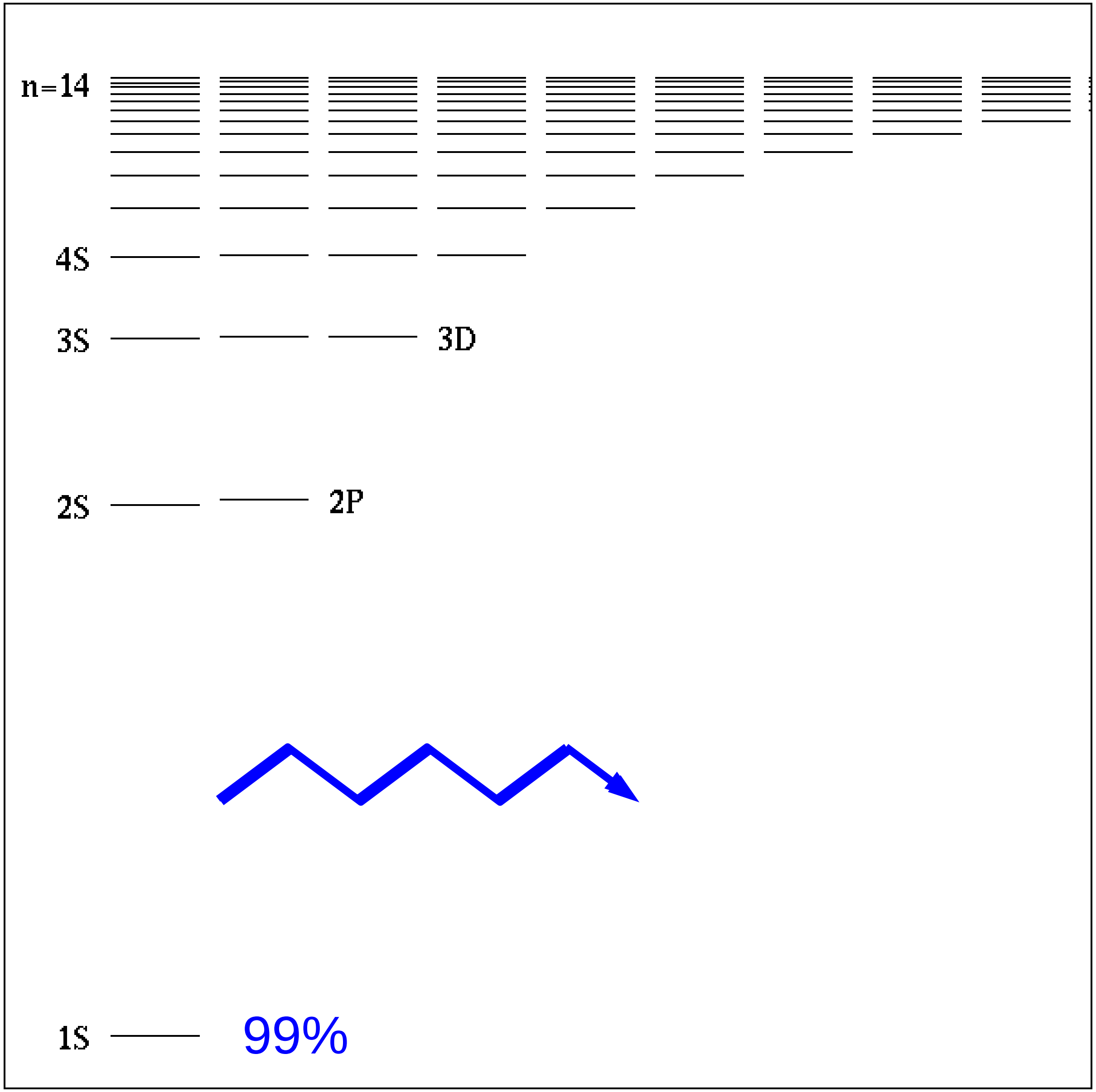


$$\Delta E\ [\mathrm{meV}] = 209.998 - 5.226\ \mathbf{R_p}^2$$

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

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

Principle of the measurement



* Muons stop in H_2

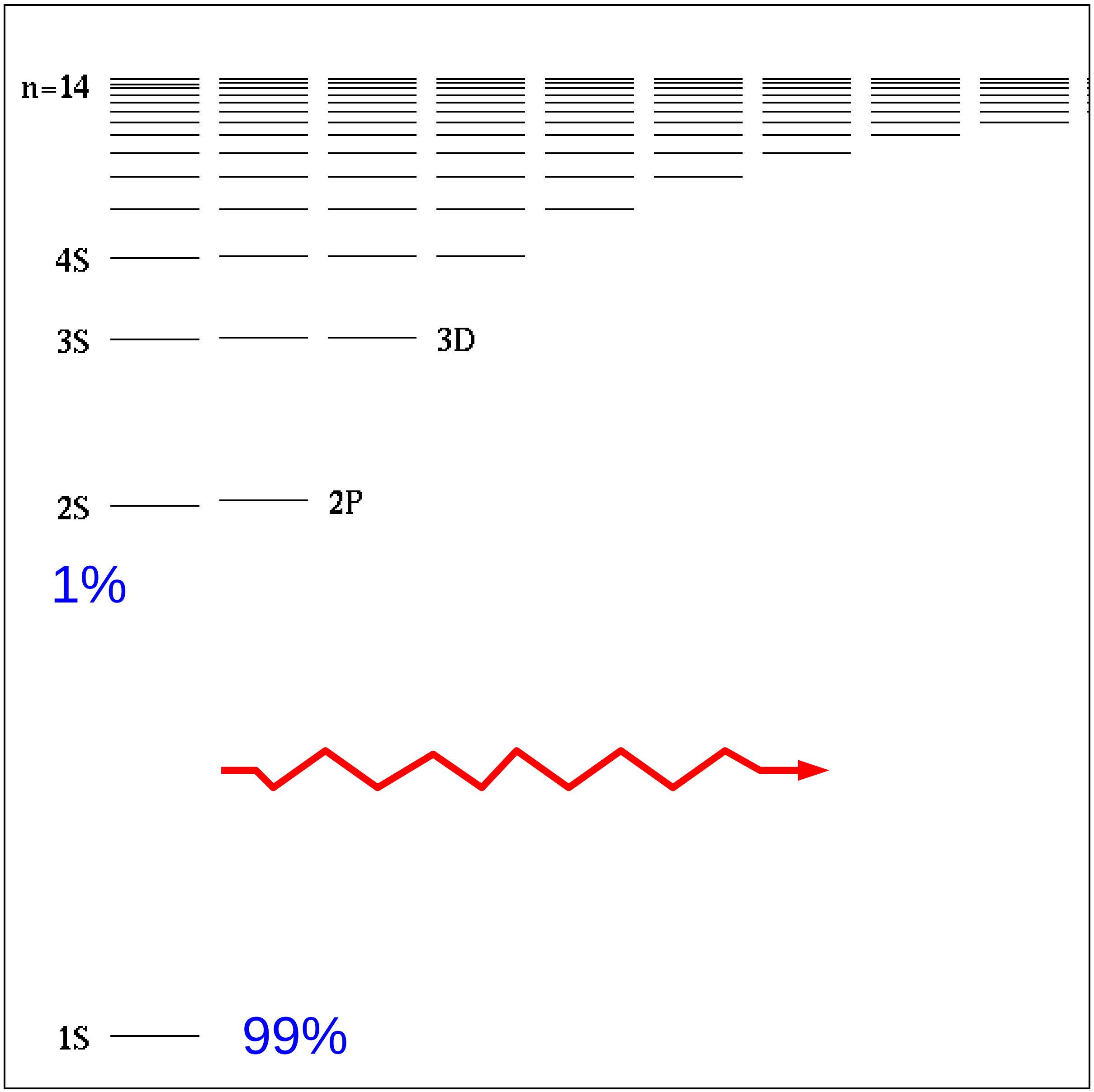
* Initial capture into states with n~14

* cascade to lower n

* 99% end in 1S ground-state

* X-ray photons

Principle of the measurement



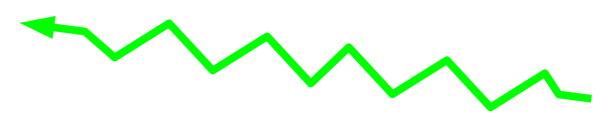
* Muons stop in H_2

* Initial capture into states with n~14

* cascade to lower n

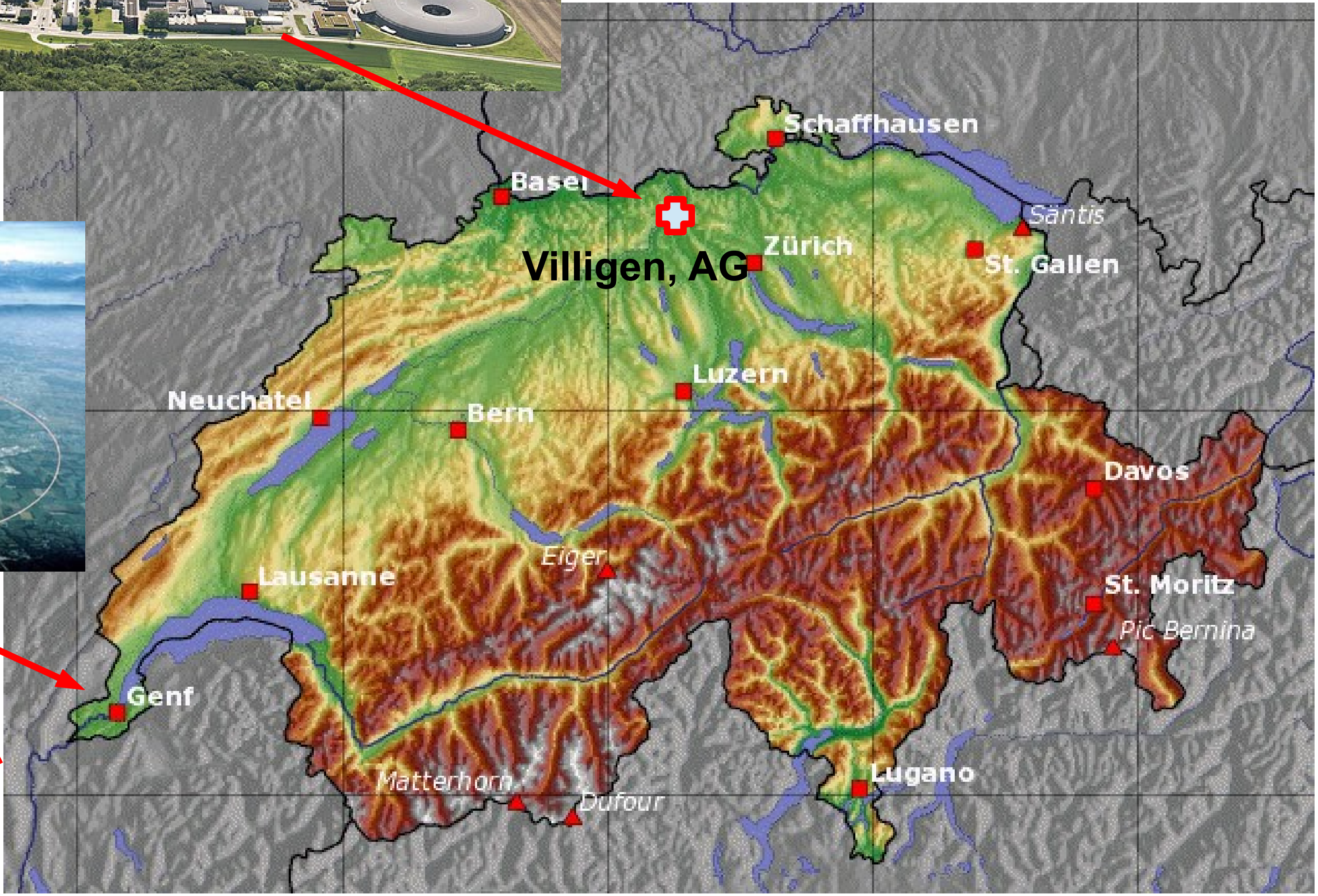
* 1% reach the long-lived 2S state

* Laser on resonance



The accelerator at PSI

PAUL SCHERRER INSTITUT PSI

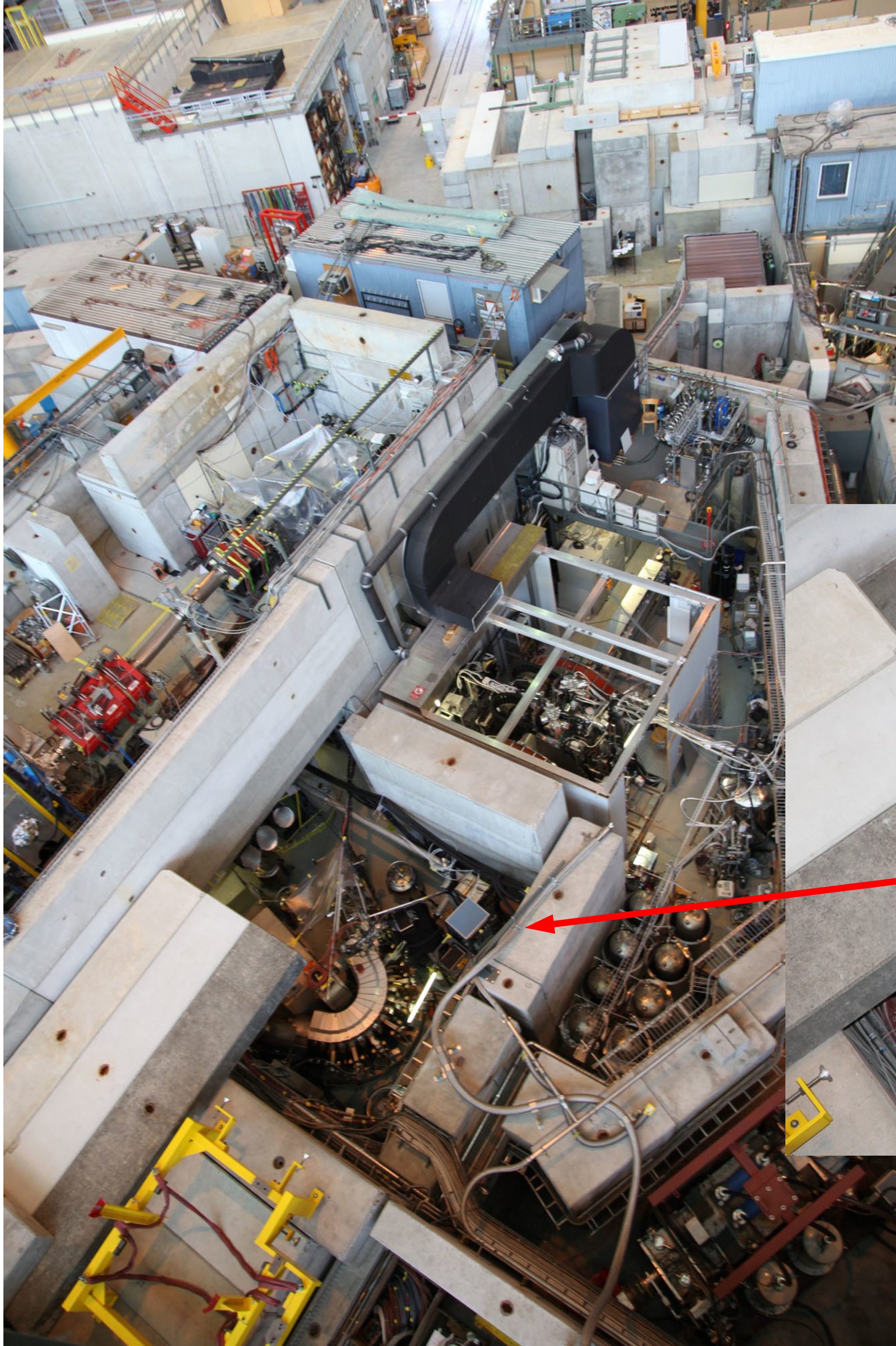


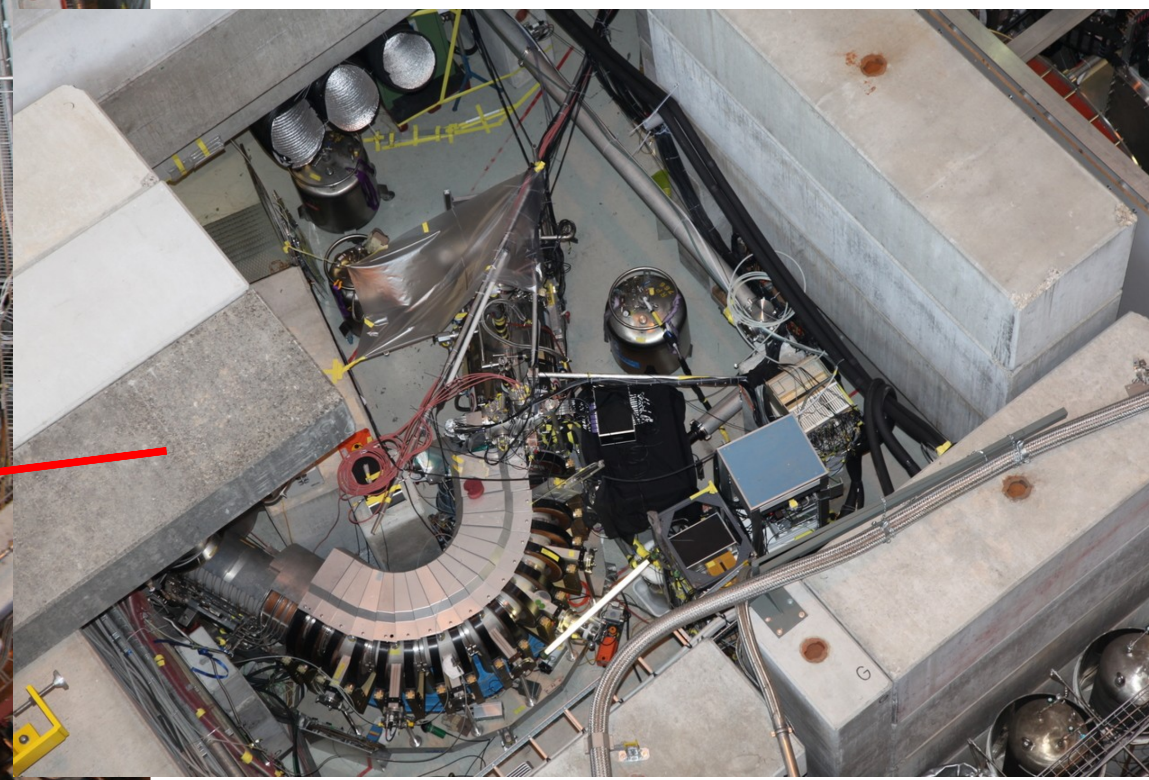
Paul-Scherrer-Institut

Paul-Scherrer-Institut

Experimental hall

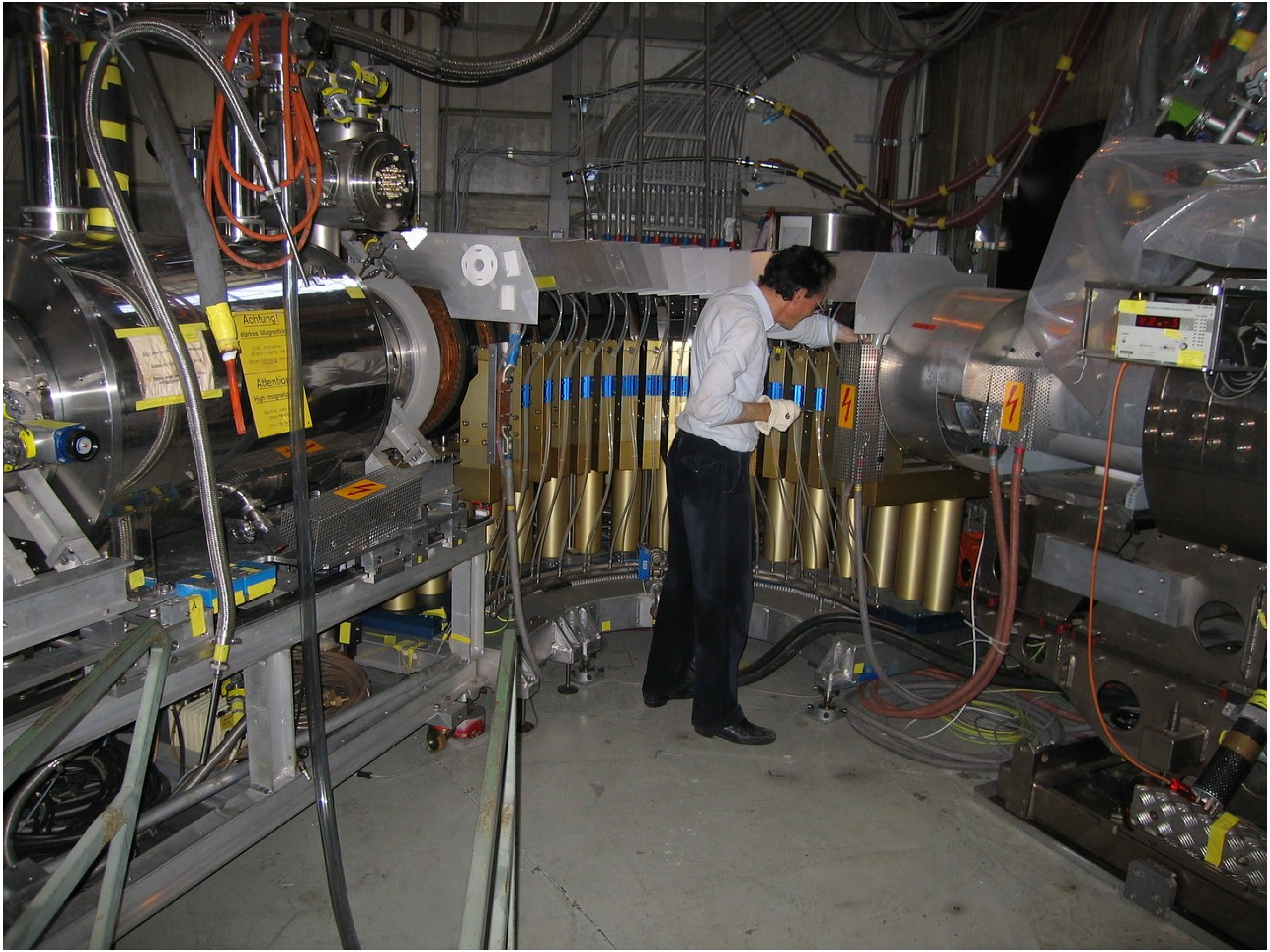
Experimental hall from above



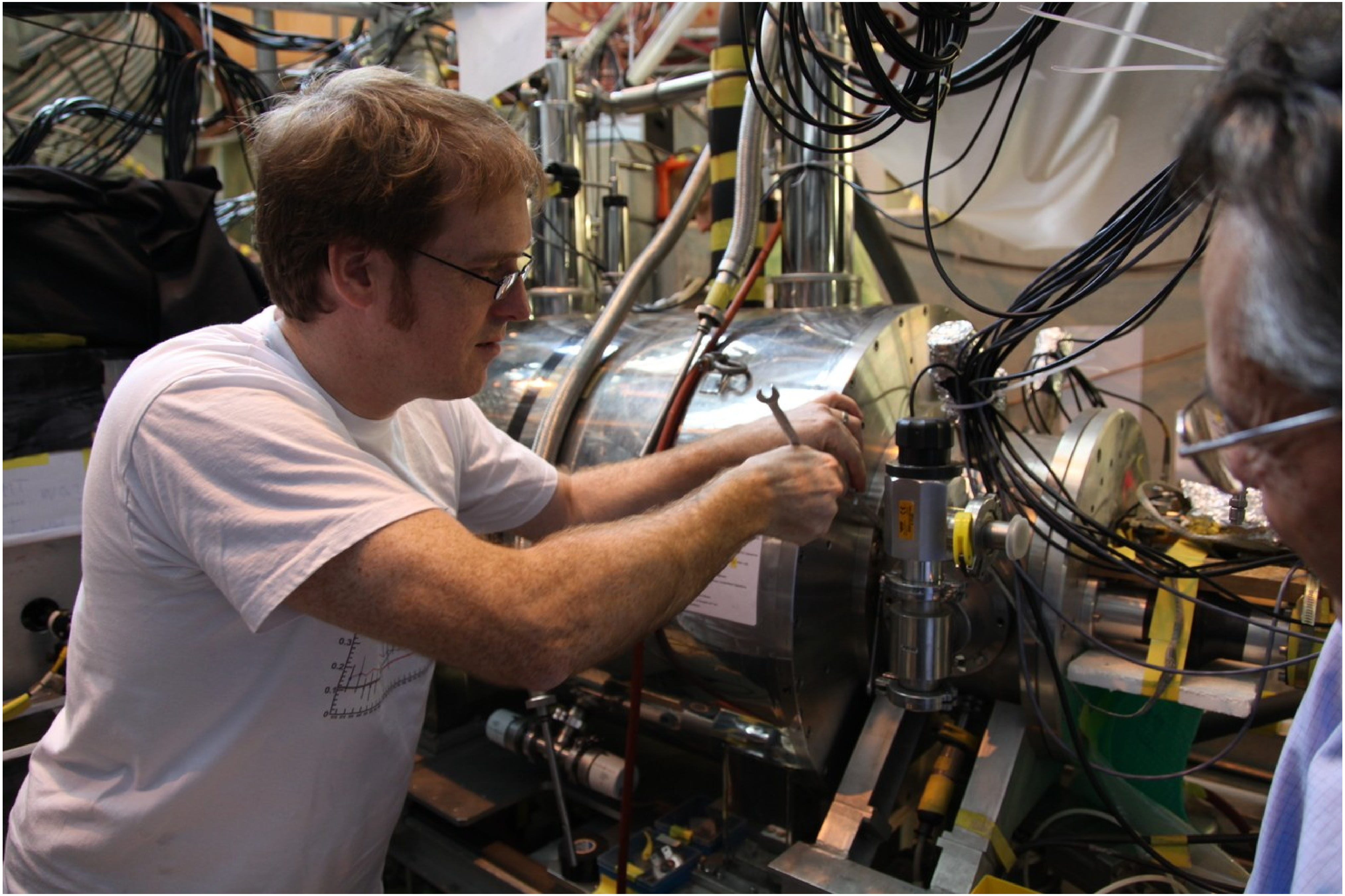


Beam area πE5

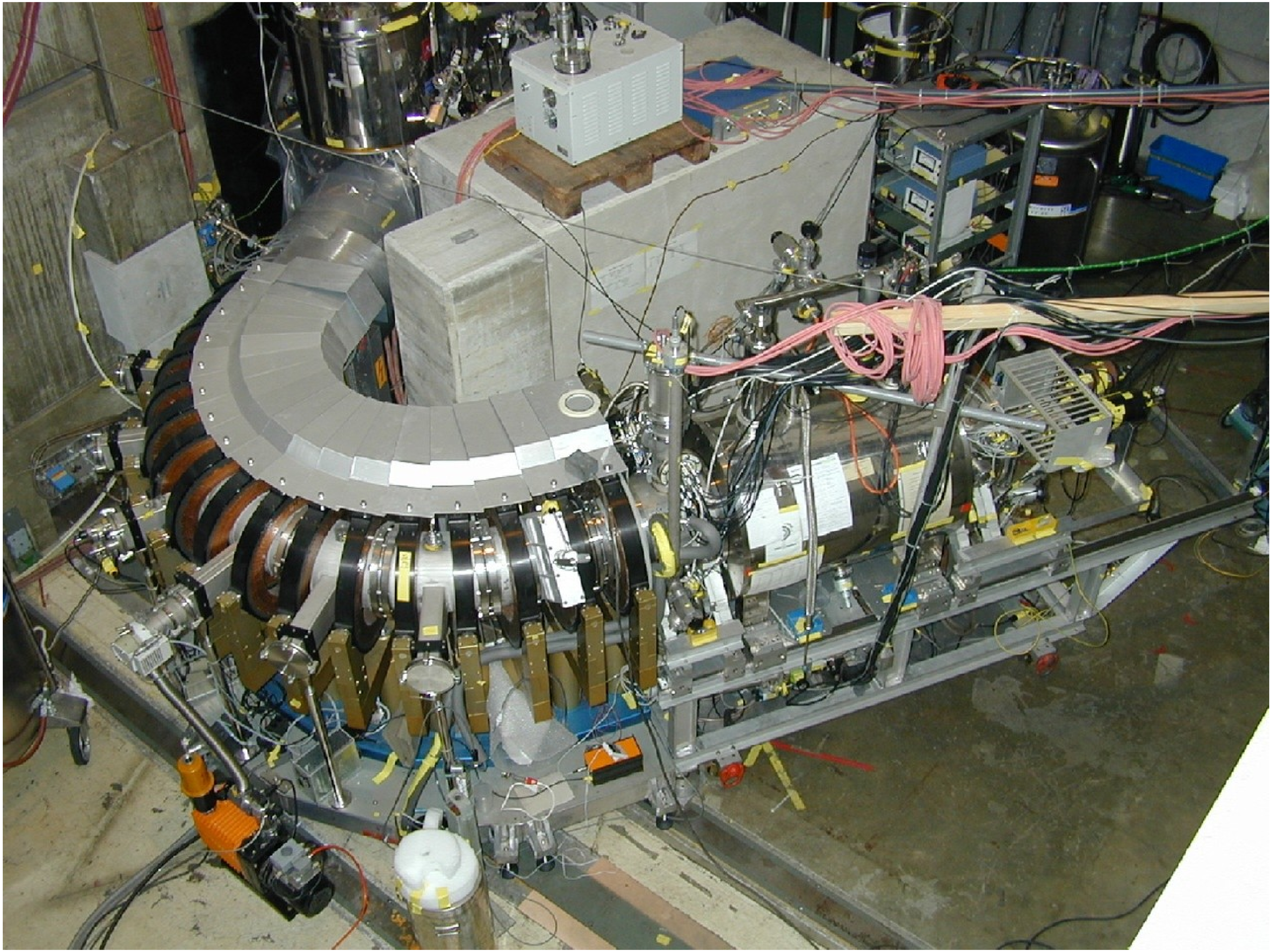
Muon beam line in πE5



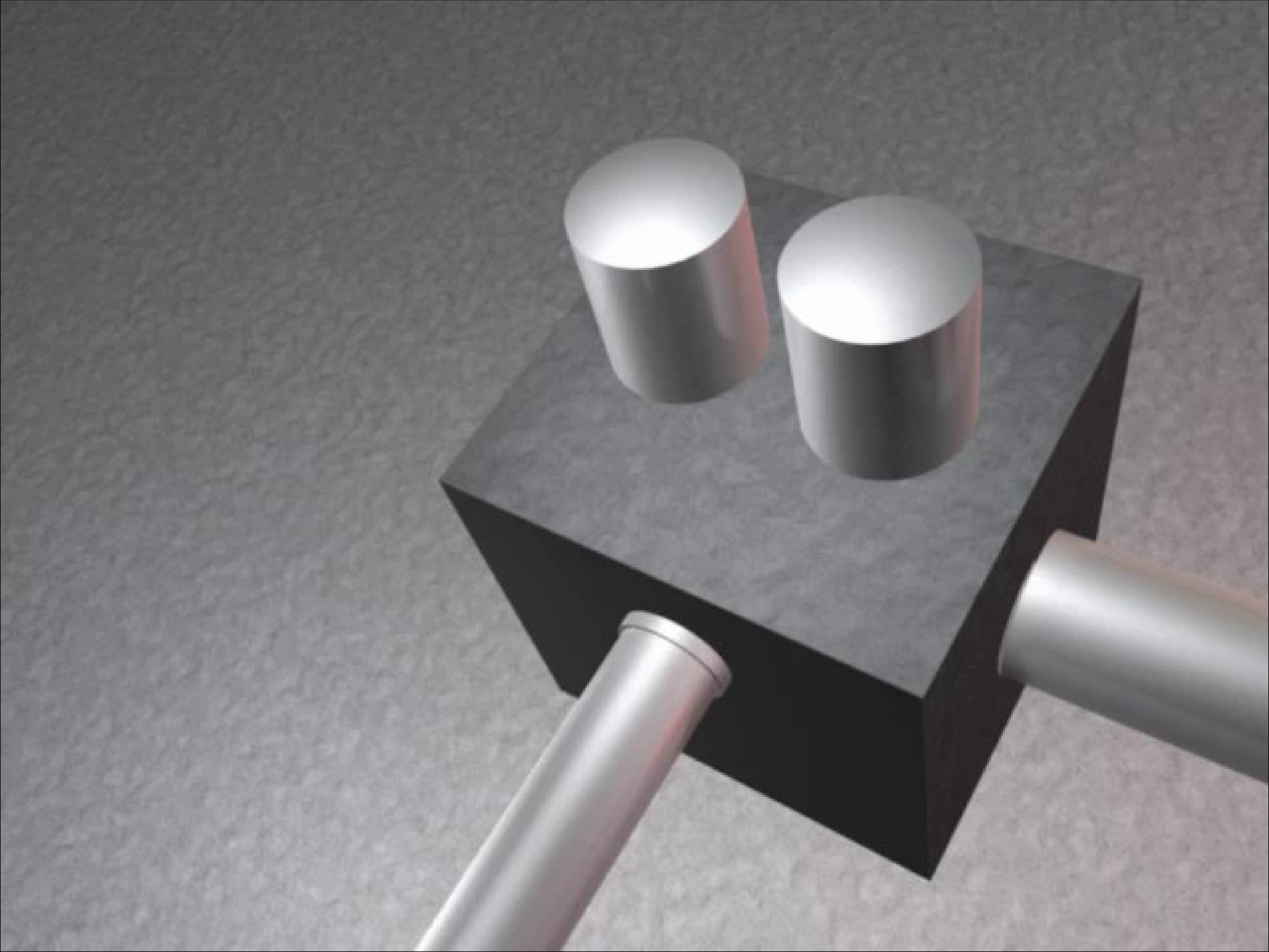
Final preparations



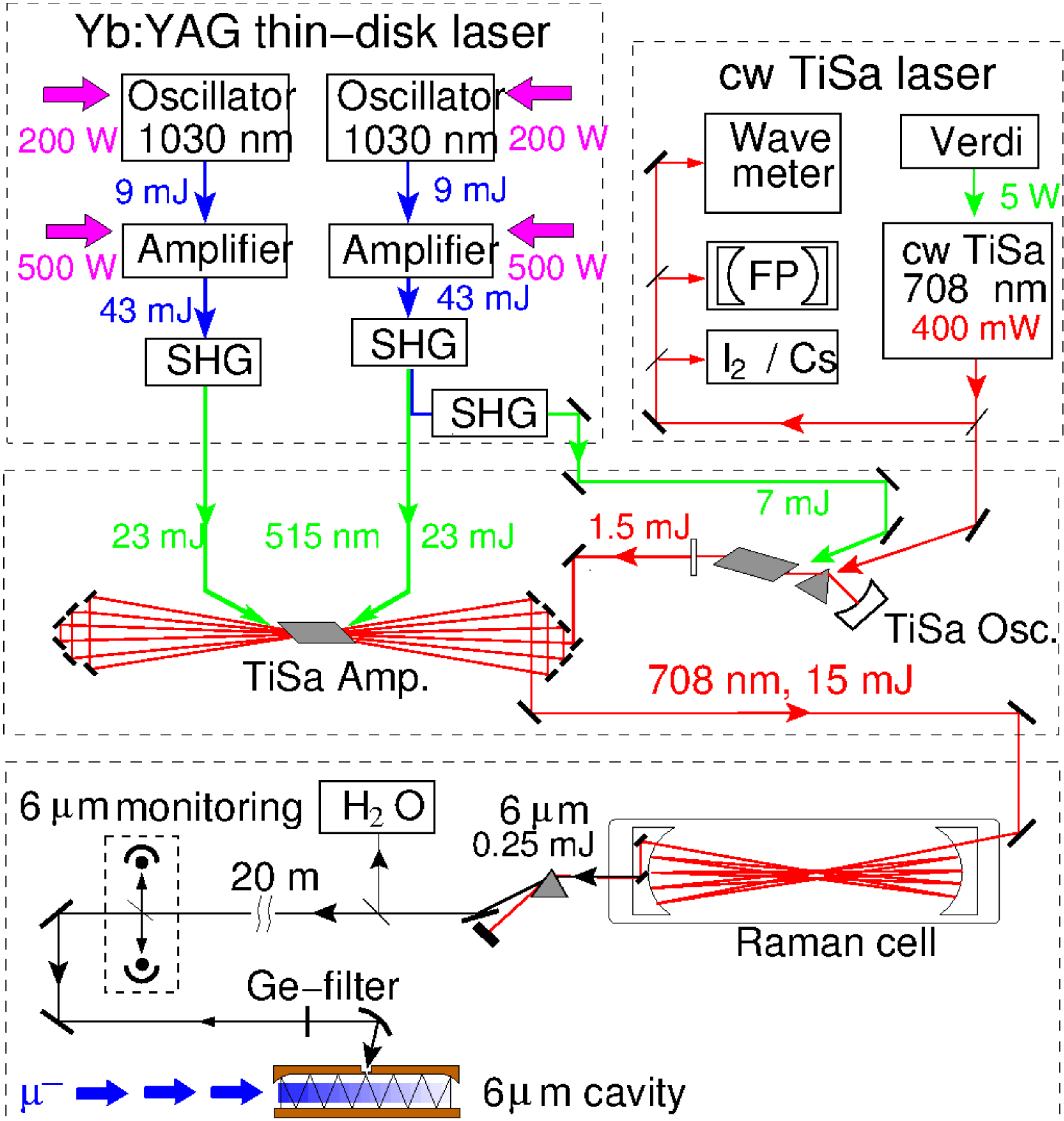
The muon beam line in πE5



Movie: Beam Line



The laser system



Yb:YAG Disk laser
→ fast response on µ

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

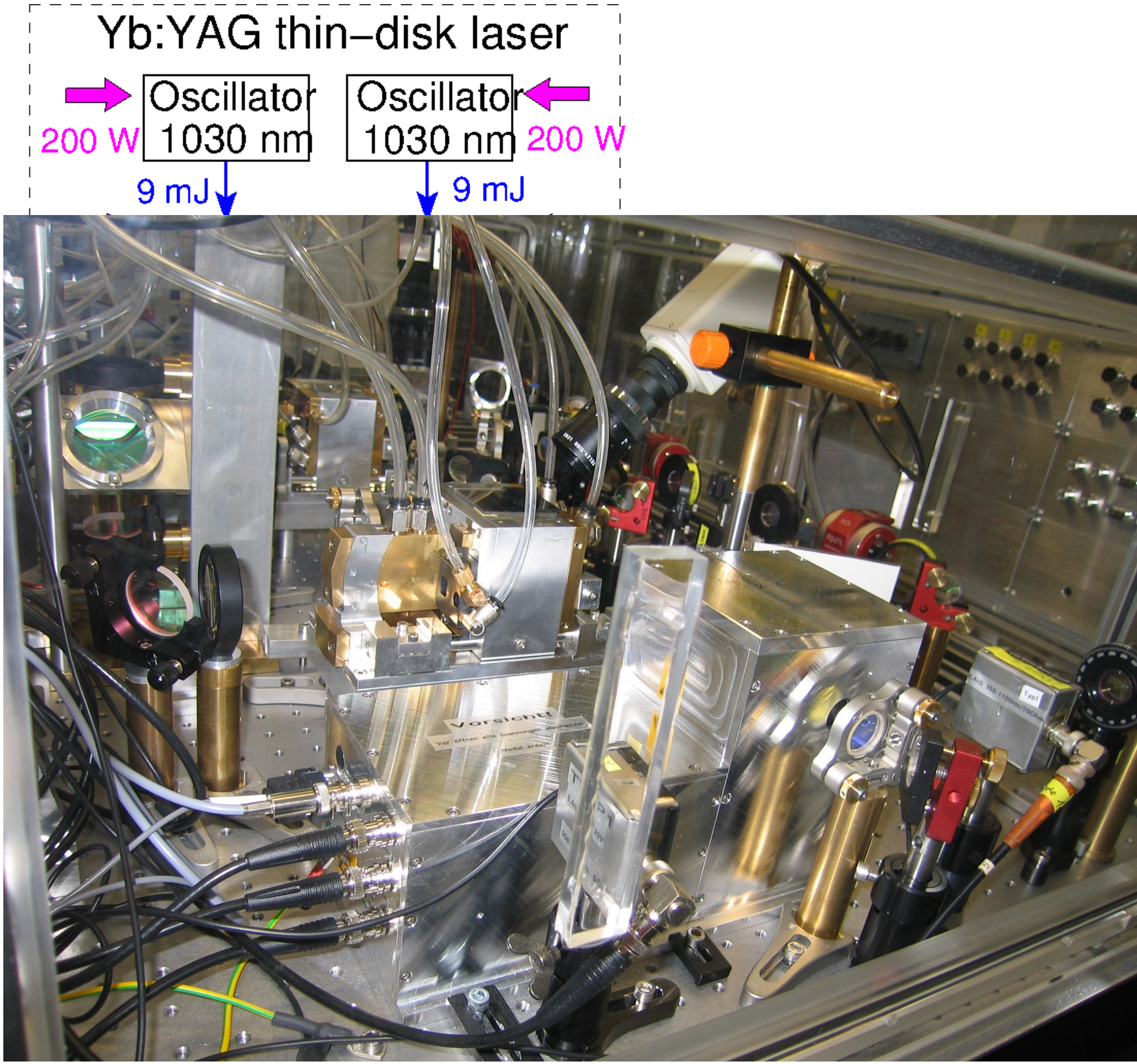
Ti:sapphire cw laser
→ determines laser frequency

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

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

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

Laser system: Yb:YAG Disk Osci



Yb:YAG Disk laser
 → fast response on μ

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

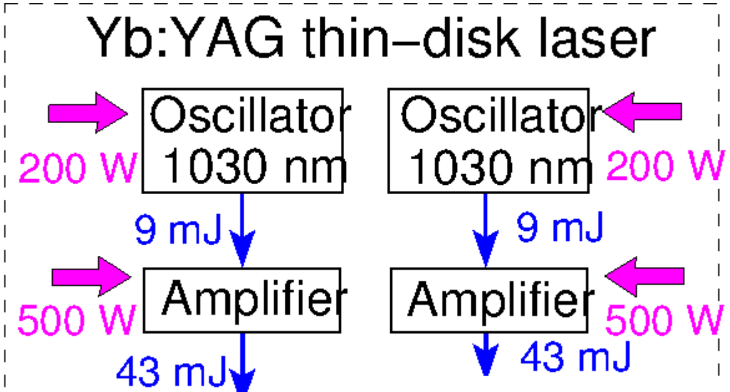
Ti:sapphire cw laser
 → determines laser frequency

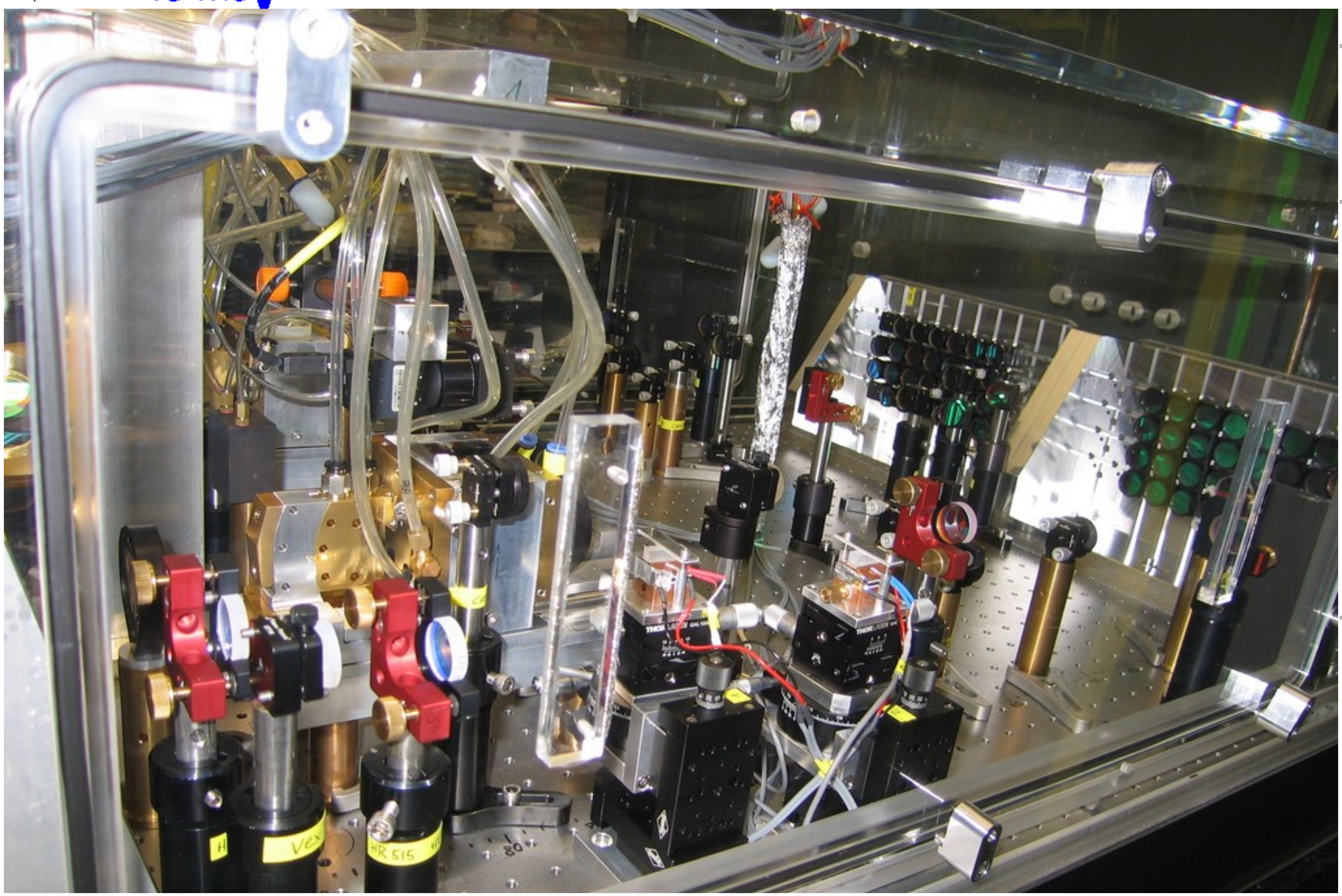
Ti:sapphire MOPA
 → high pulse energy (15 mJ)

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

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

Laser system: Yb:YAG Disk Ampli





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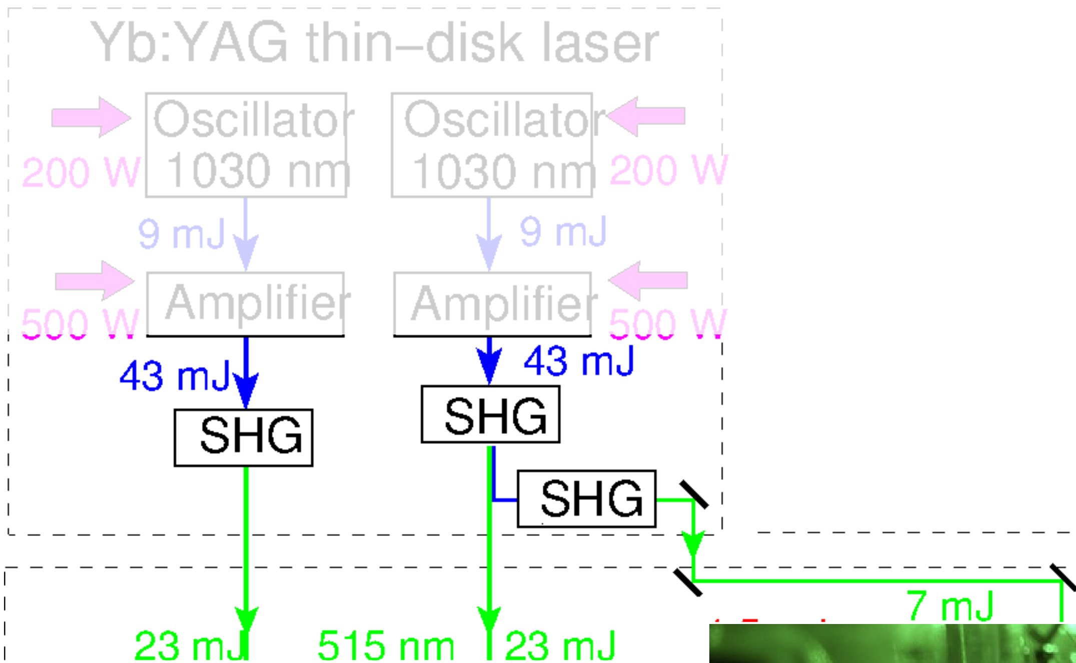
Raman cell
→ 3 sequential stimulated
Raman Stokes shifts
Laser wave length → 6 μm

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

Laser system: SHG



Yb:YAG Disk laser
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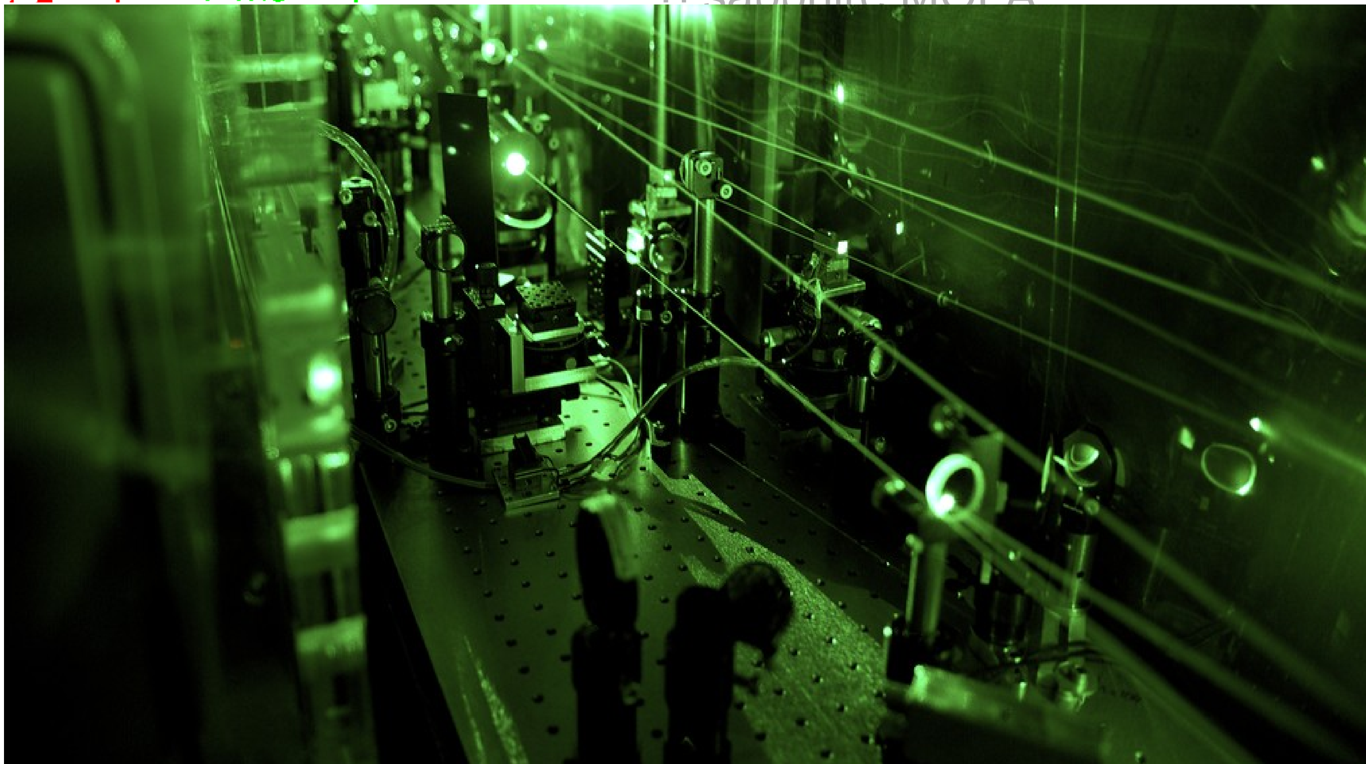
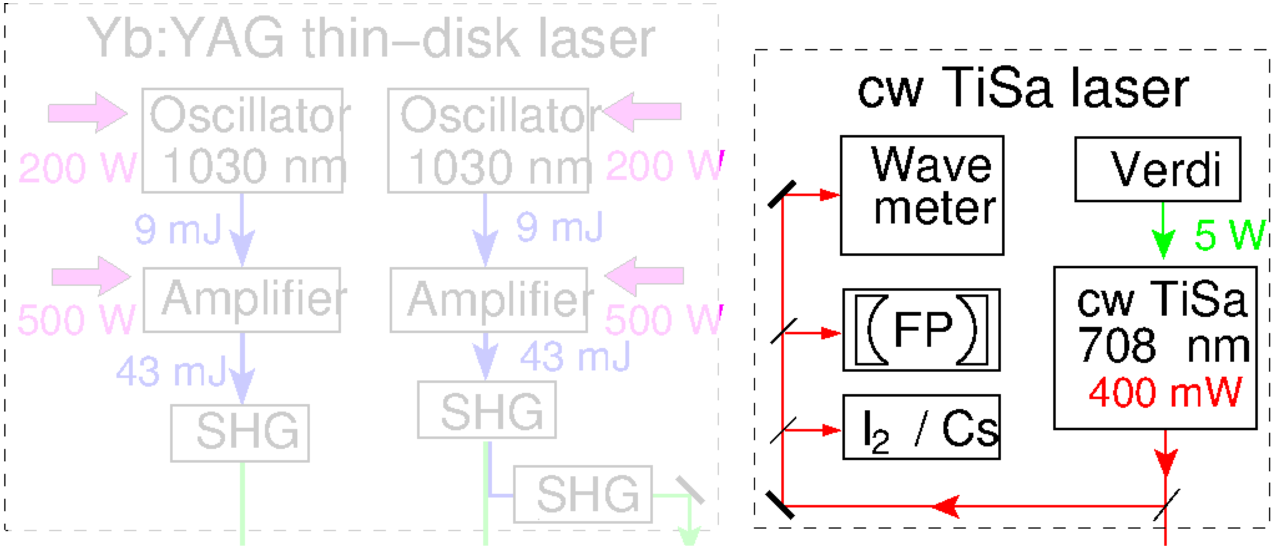
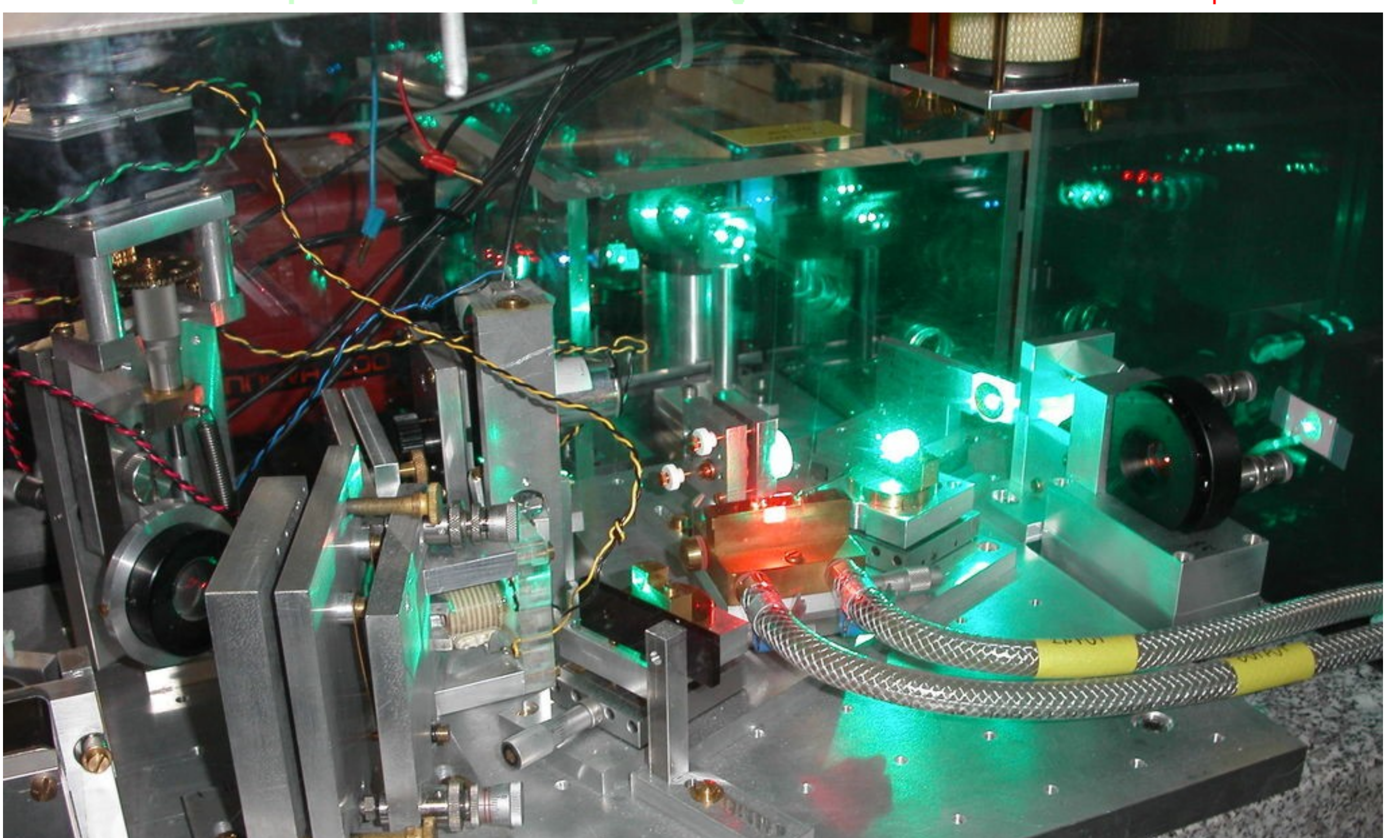


Laser system: cw Ti:sapphire





Yb:YAG Disk laser
→ fast response on μ

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

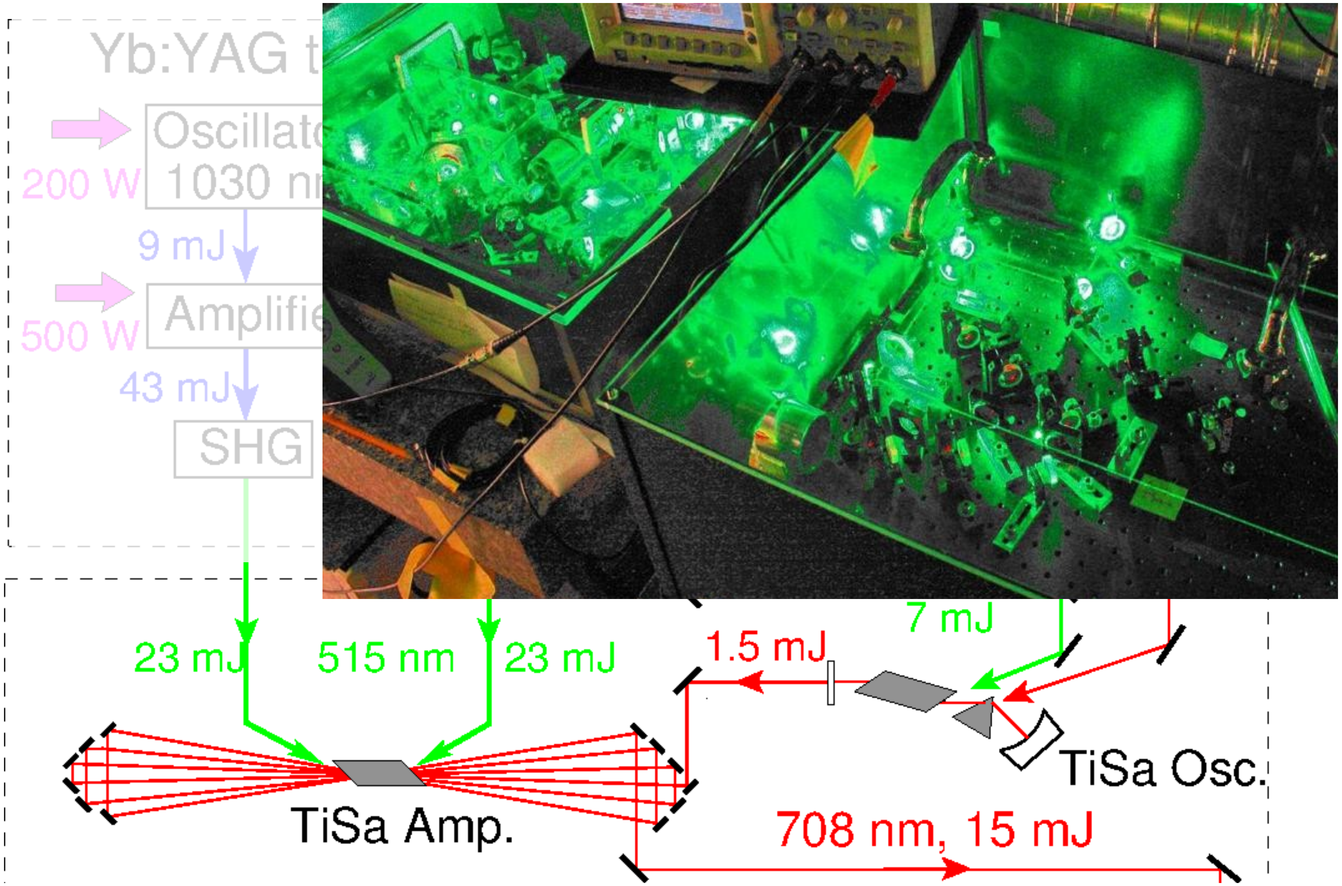
Ti:sapphire cw laser
→ determines laser frequency

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

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

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

Laser system: pulsed Ti:sapphire



Yb:YAG Disk laser
→ fast response on μ

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

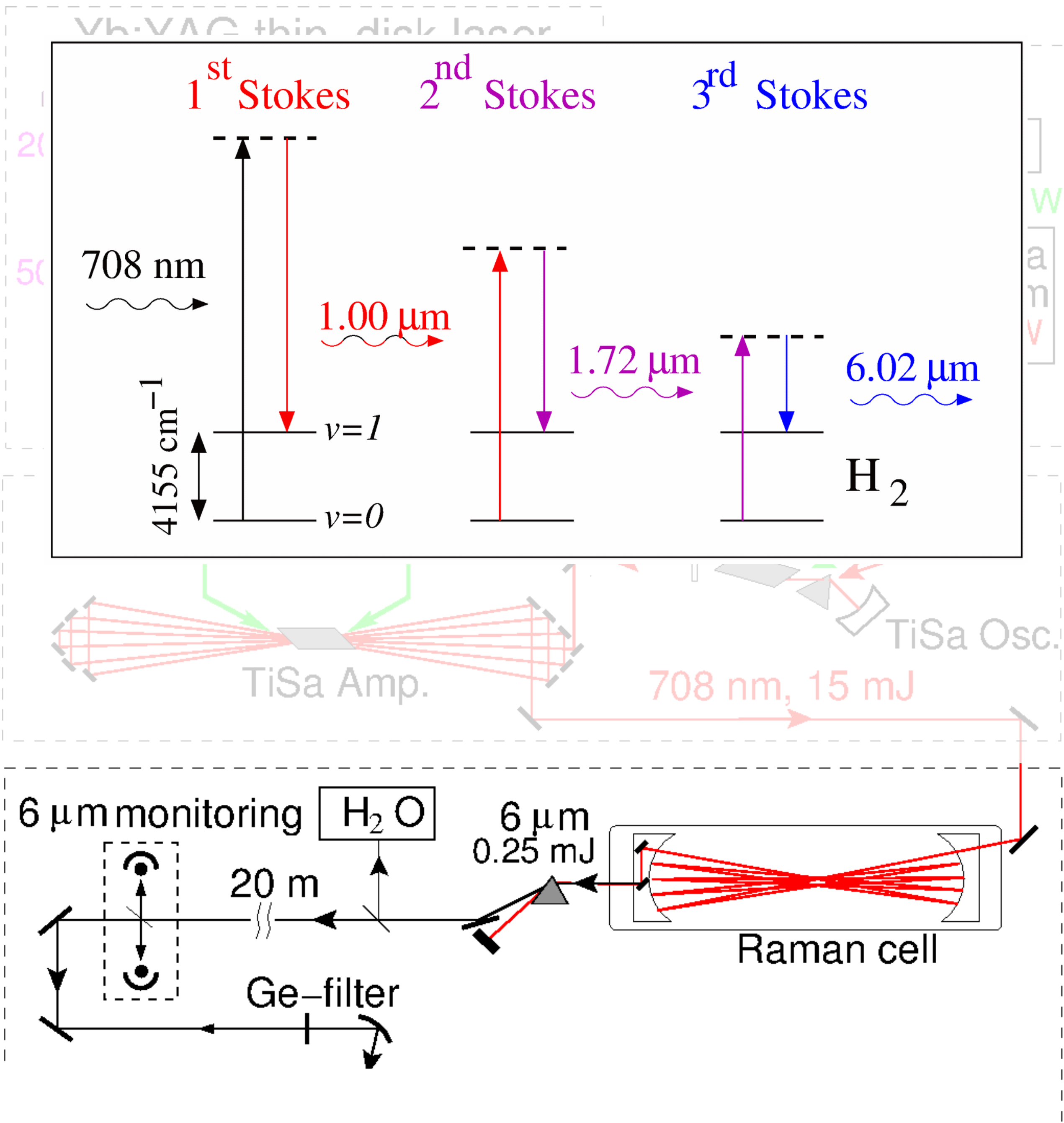
Ti:sapphire cw laser
→ determines laser frequency

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

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

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

Laser system: Raman cell



Yb:YAG Disk laser
→ fast response on µ

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

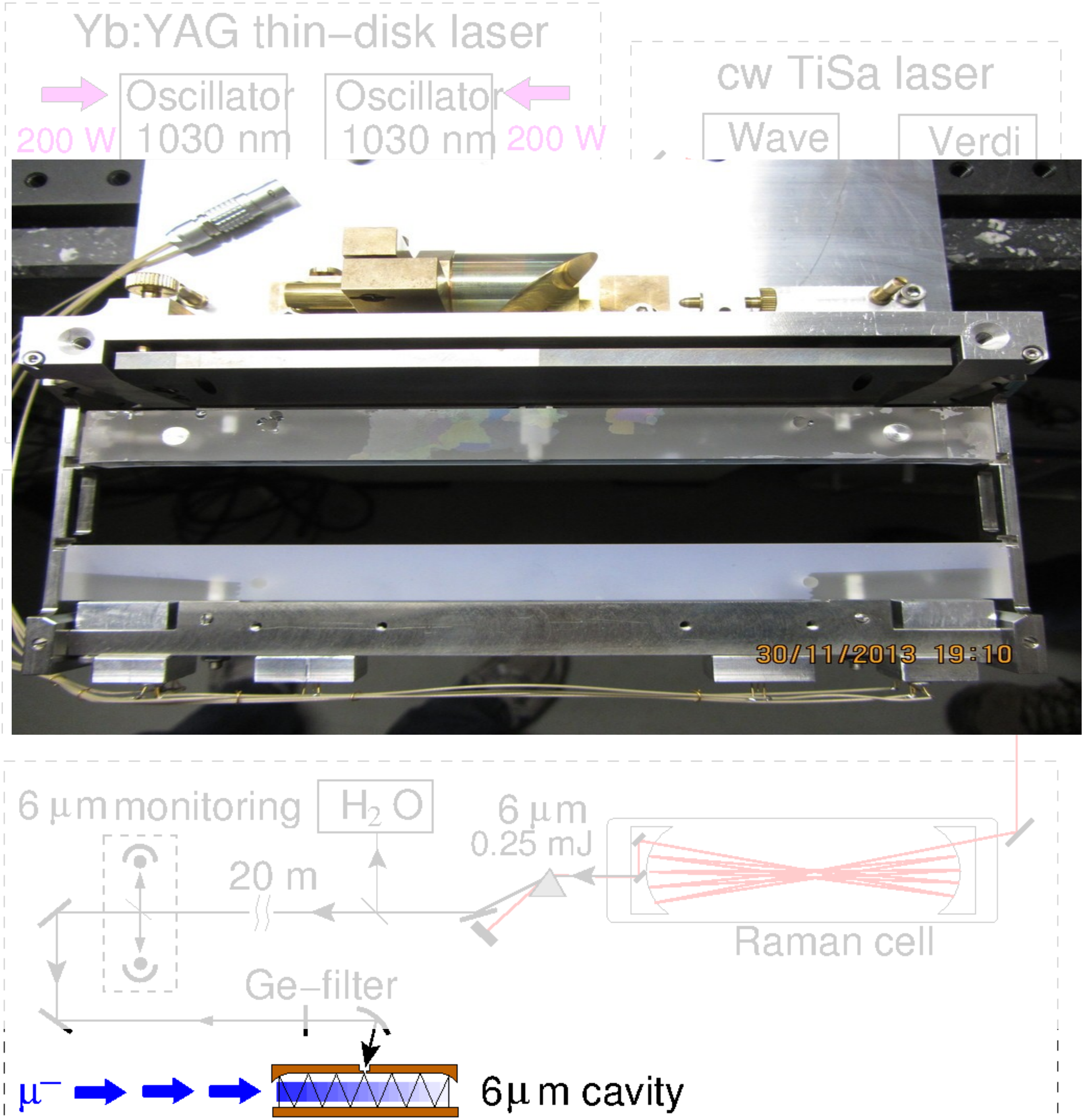
Ti:sapphire cw laser
→ determines laser frequency

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

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

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

Laser system: Target cavity



Yb:YAG Disk laser
→ fast response on µ

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

Ti:sapphire cw laser
→ determines laser frequency

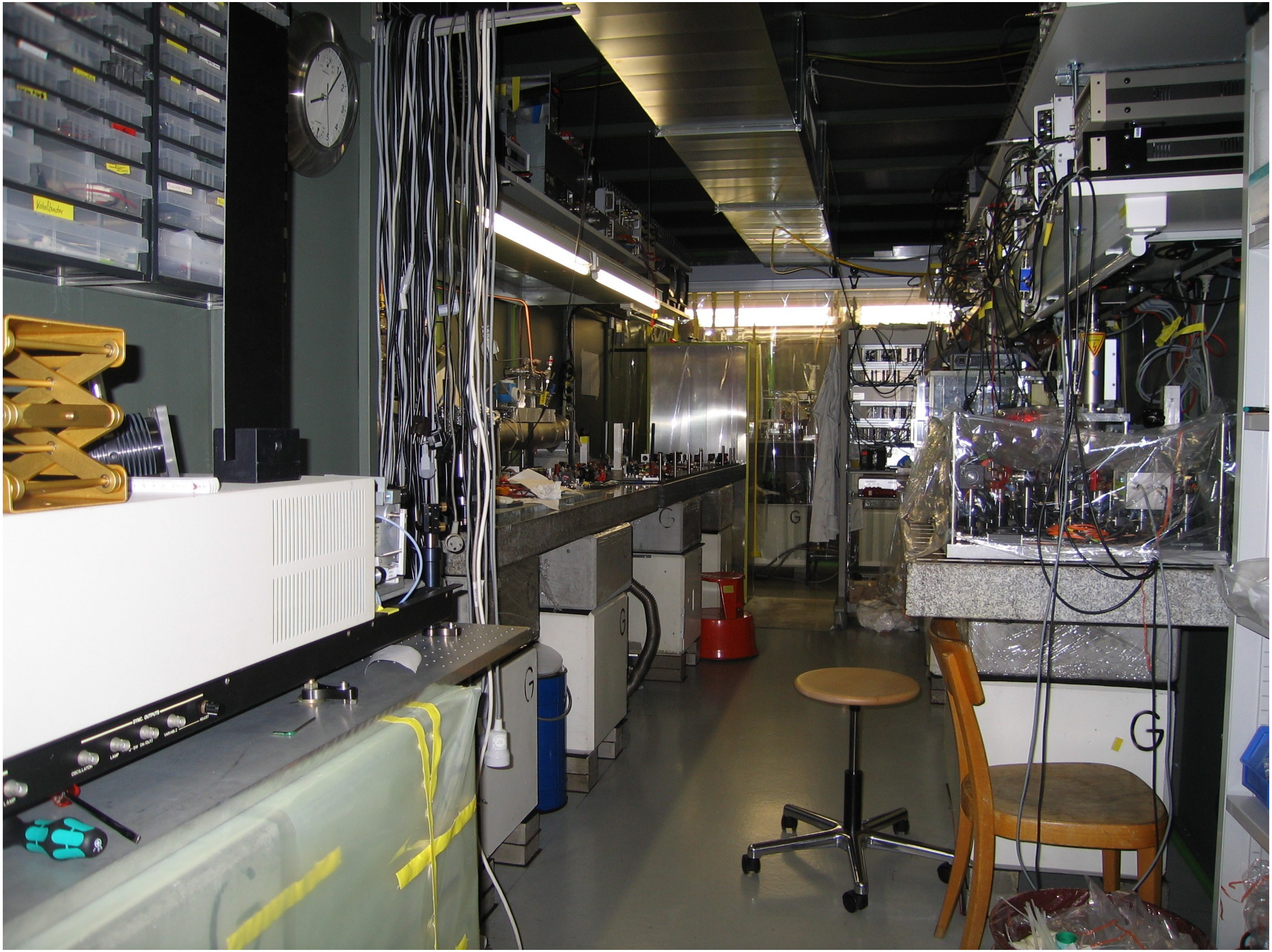
Ti:sapphire MOPA
→ high pulse energy (15 mJ)

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

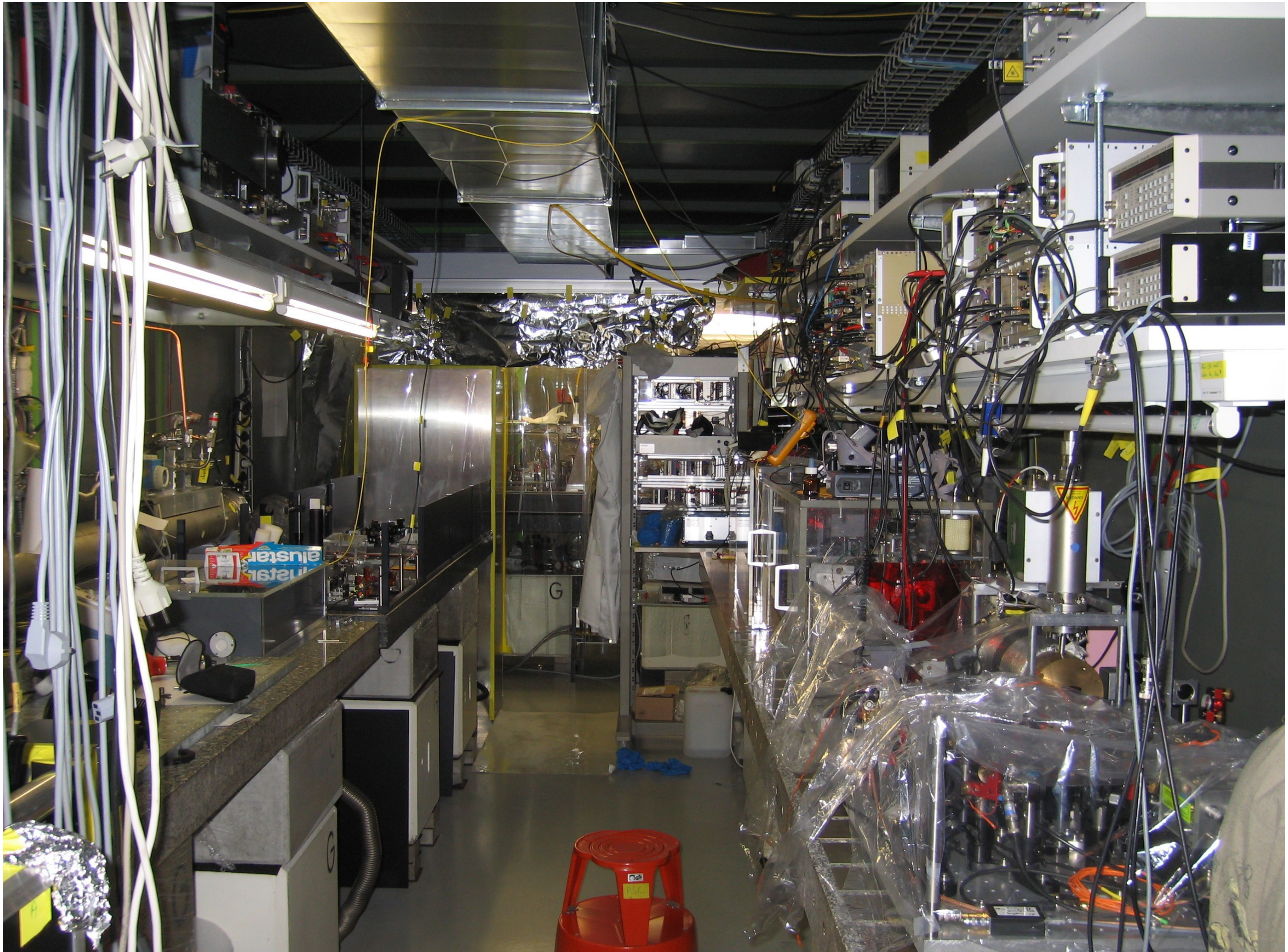
Target Cavity
→ Mirror system to fill the muon stop volume (H_2)

In der Laserhütte

In der Laserhütte

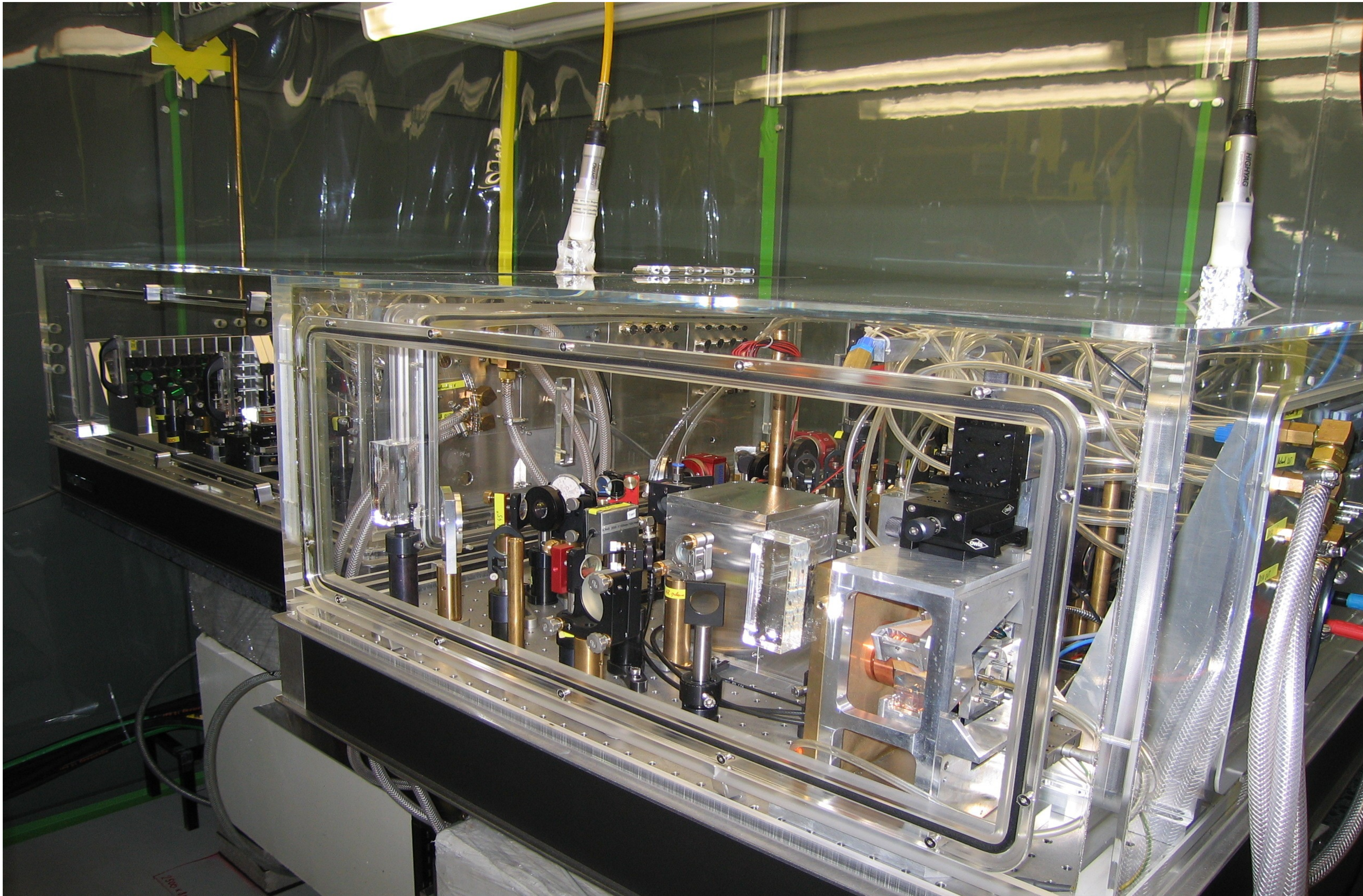


Inside the laser hut at PSI

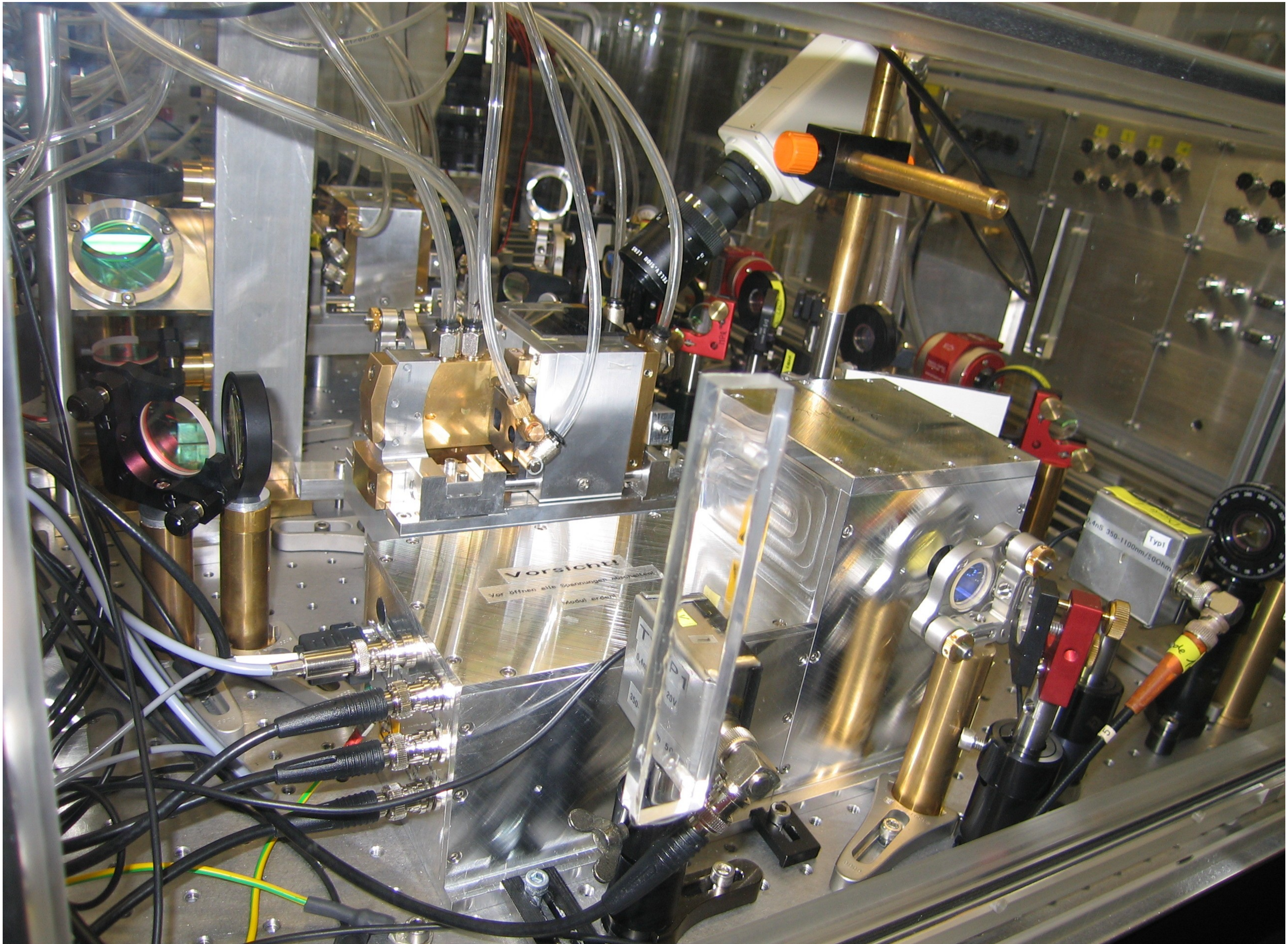


The laser hut at PSI

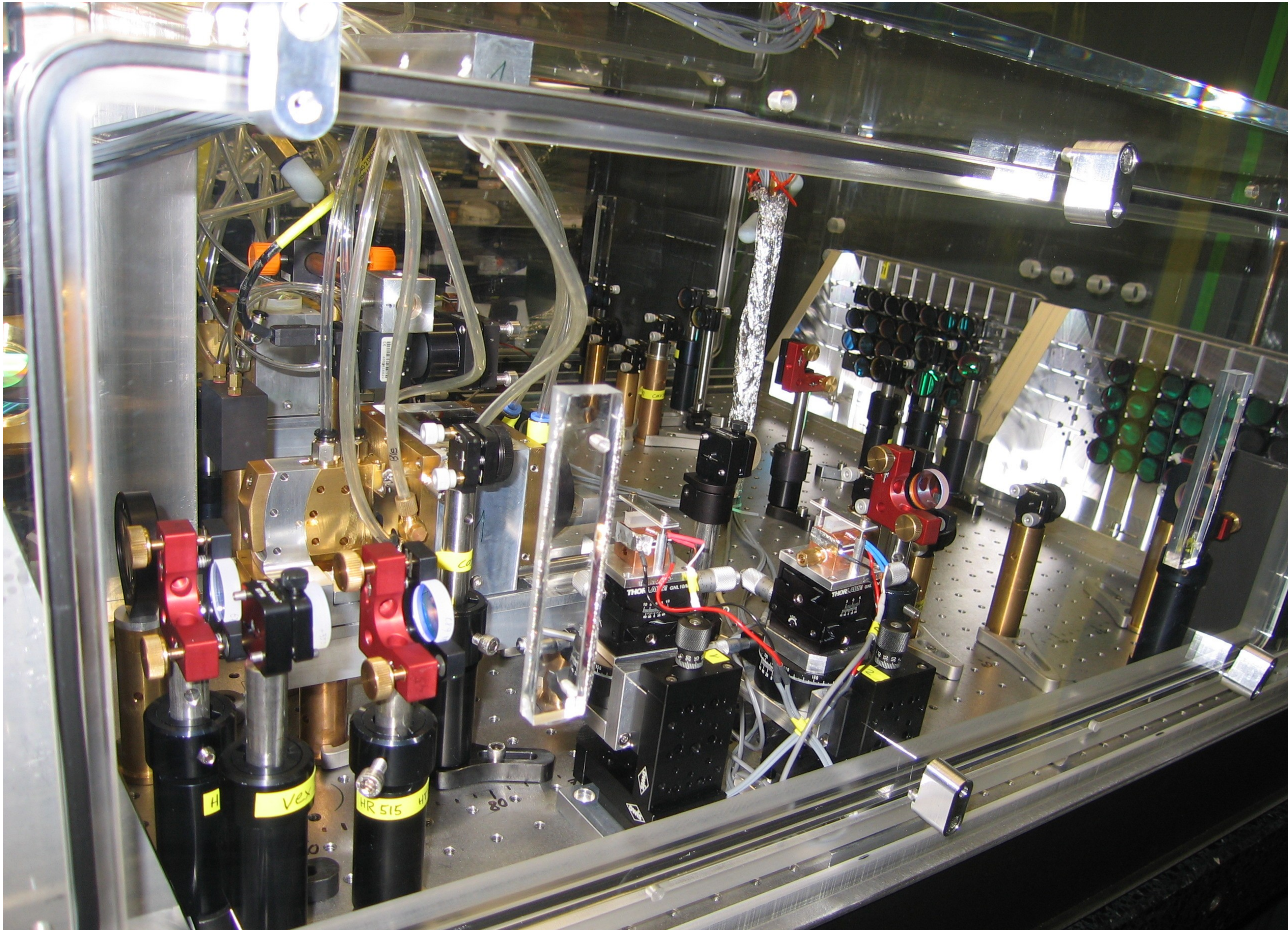
Yb:YAG thin-disk lasers



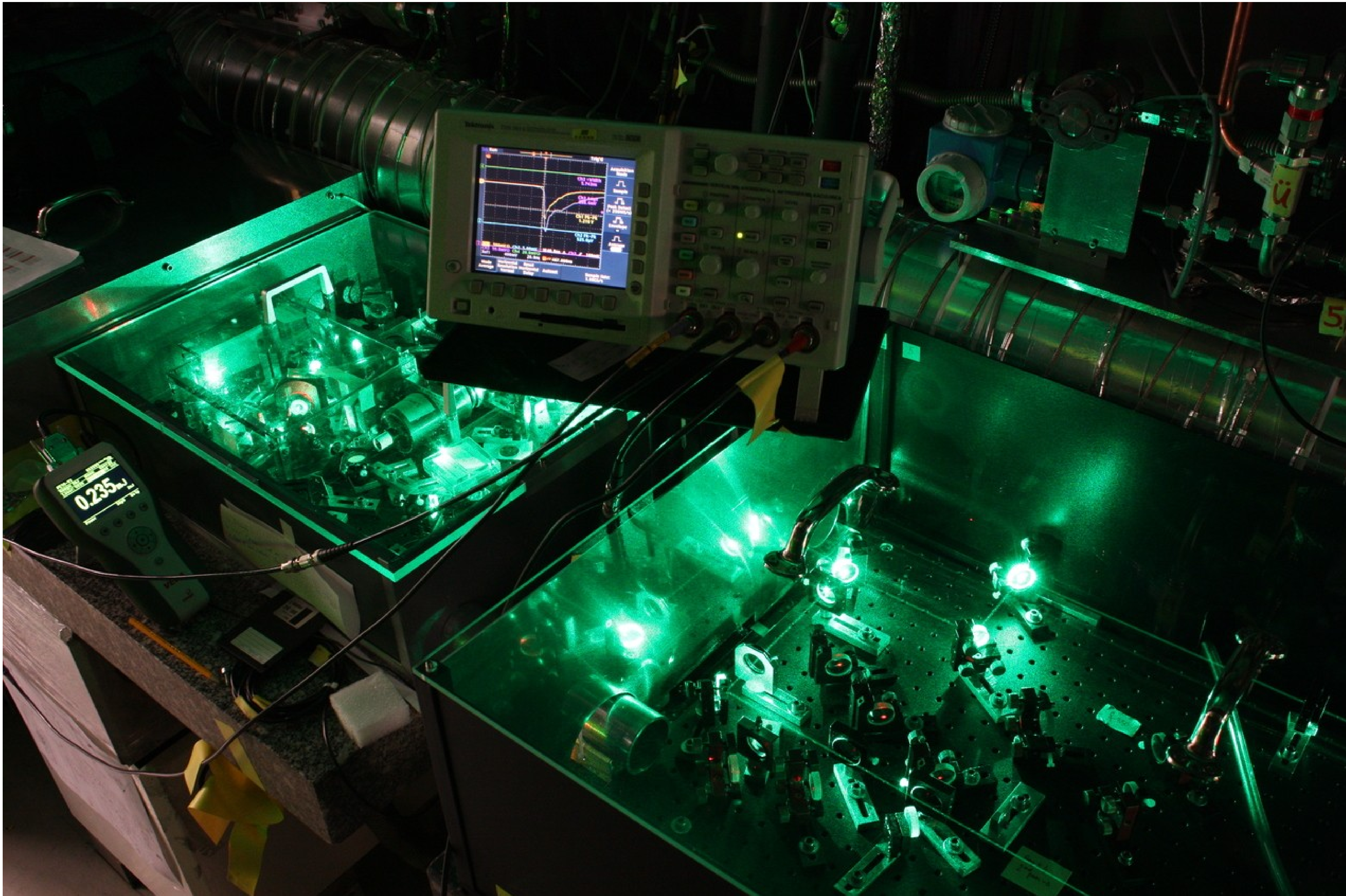
Yb:YAG Disk Oscillators



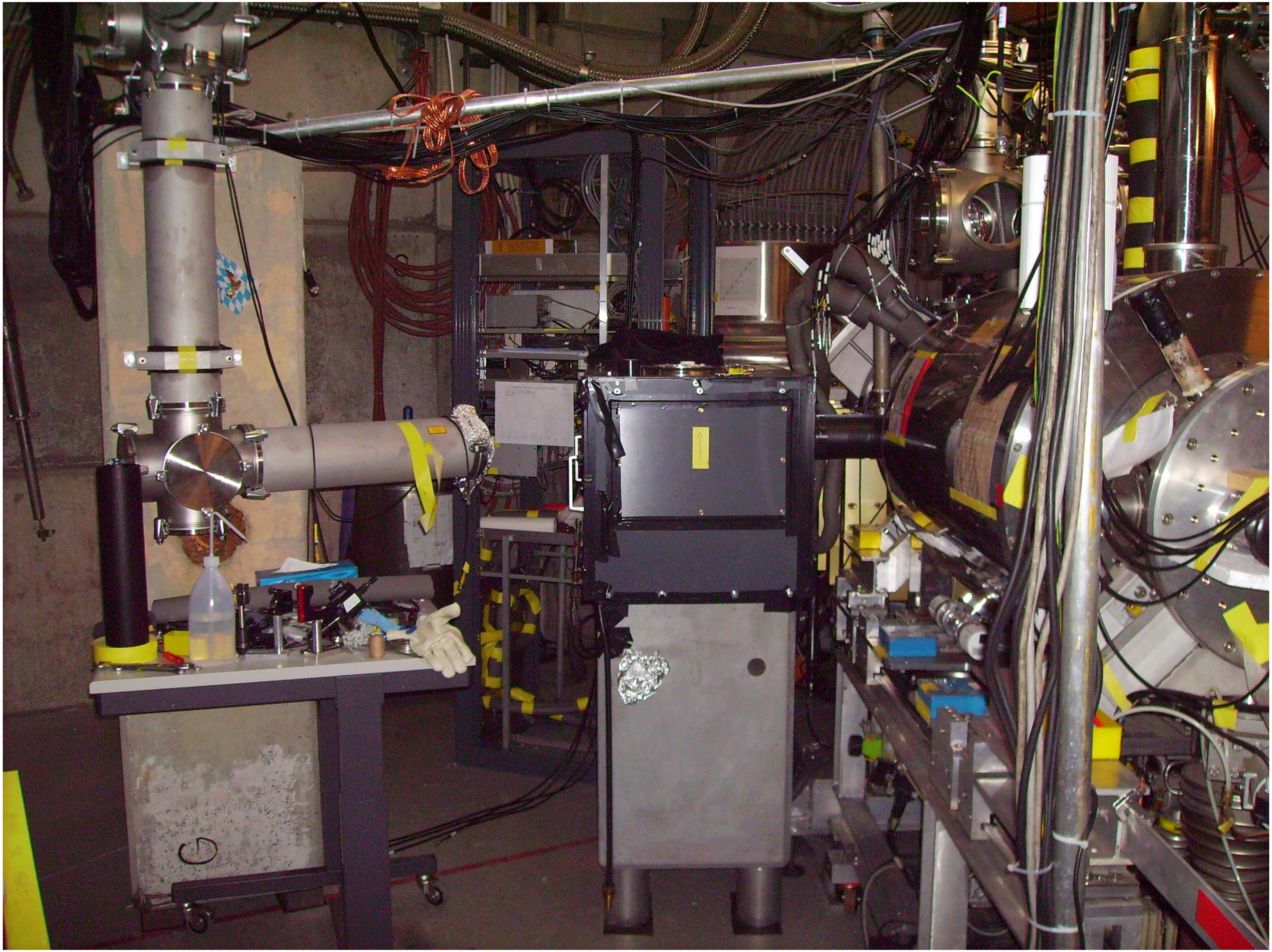
Yb:YAG Disk Amplifiers



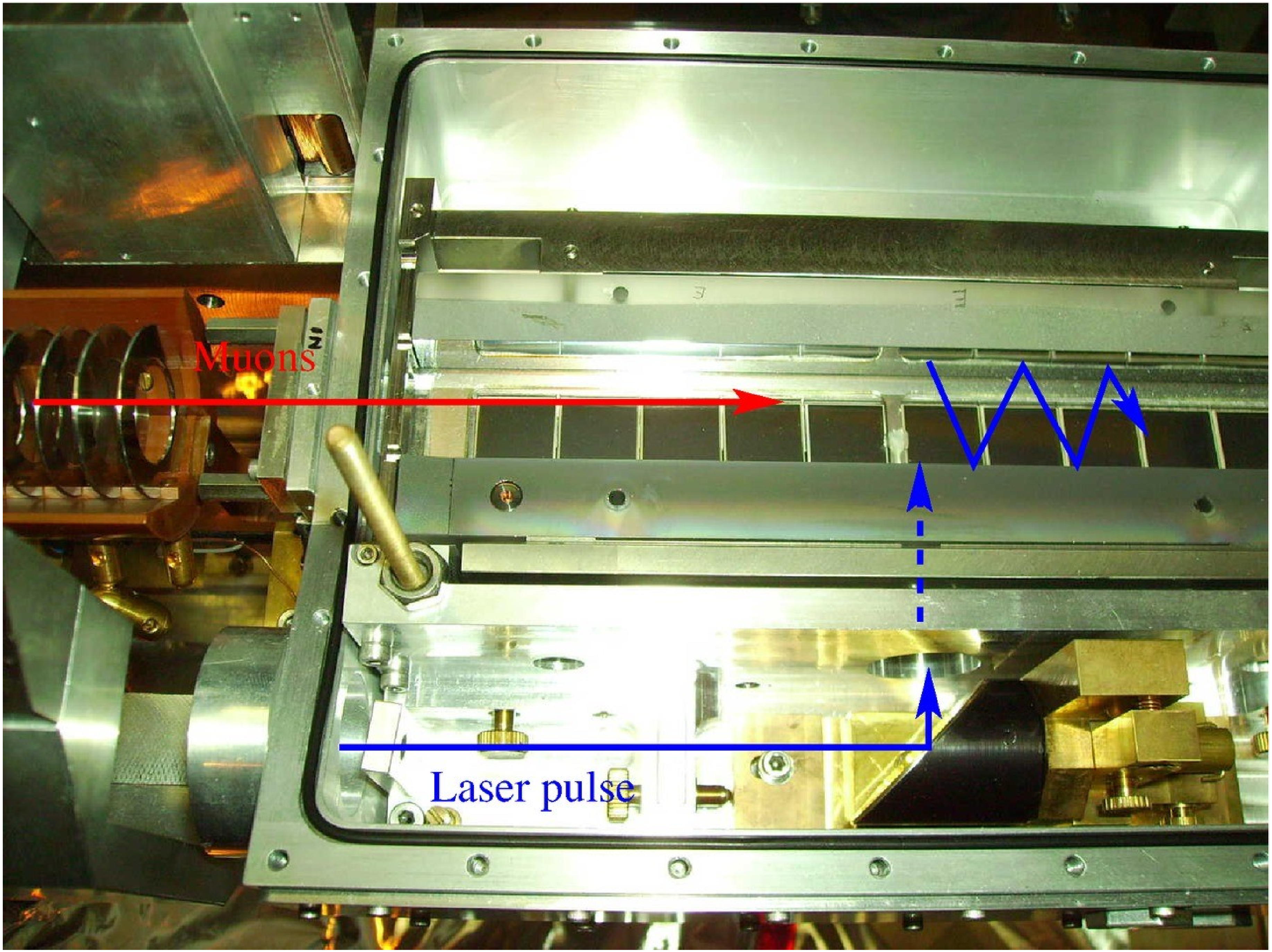
Ti:sapphire lasers



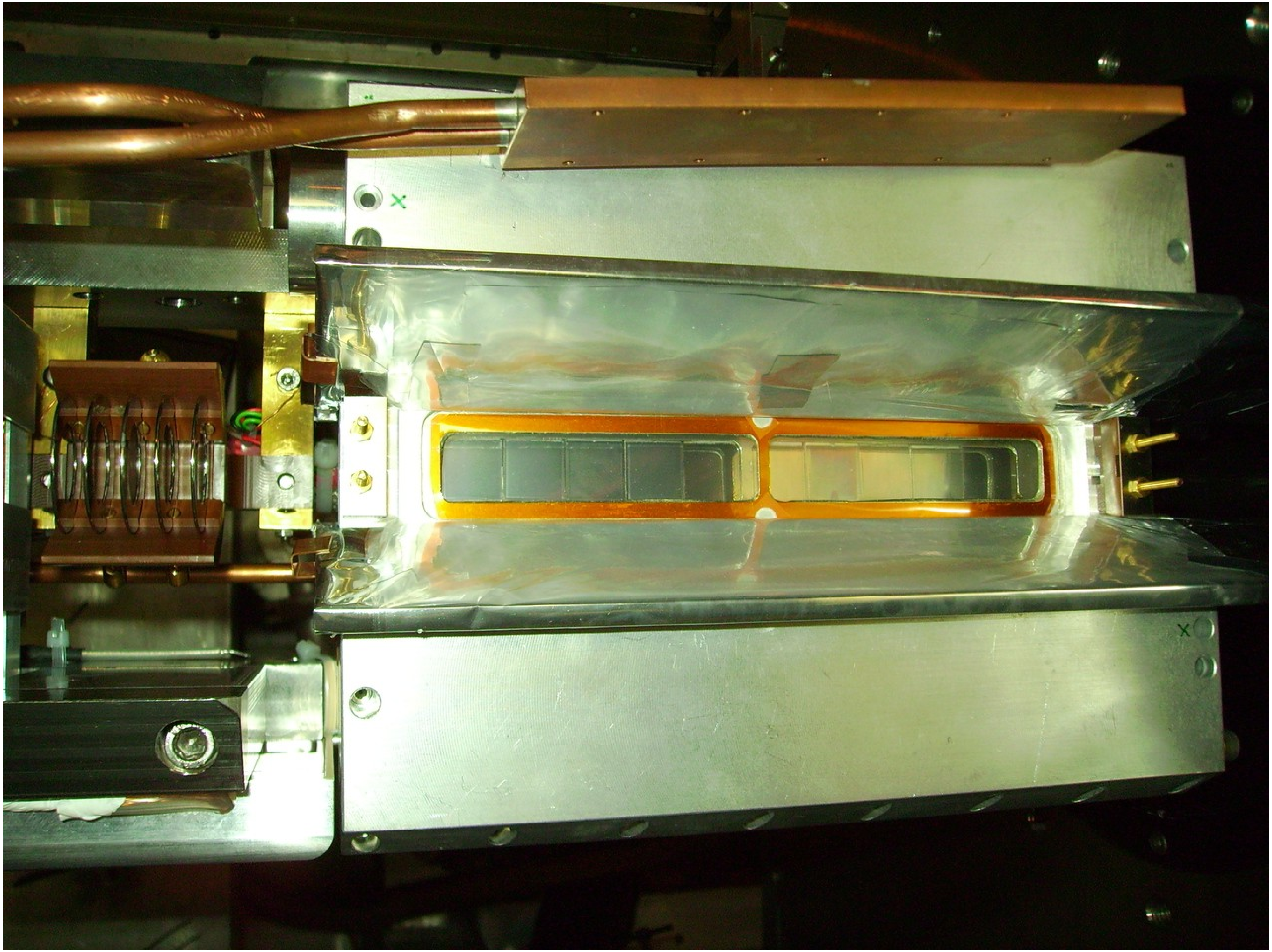
Light at the end of the tunnel



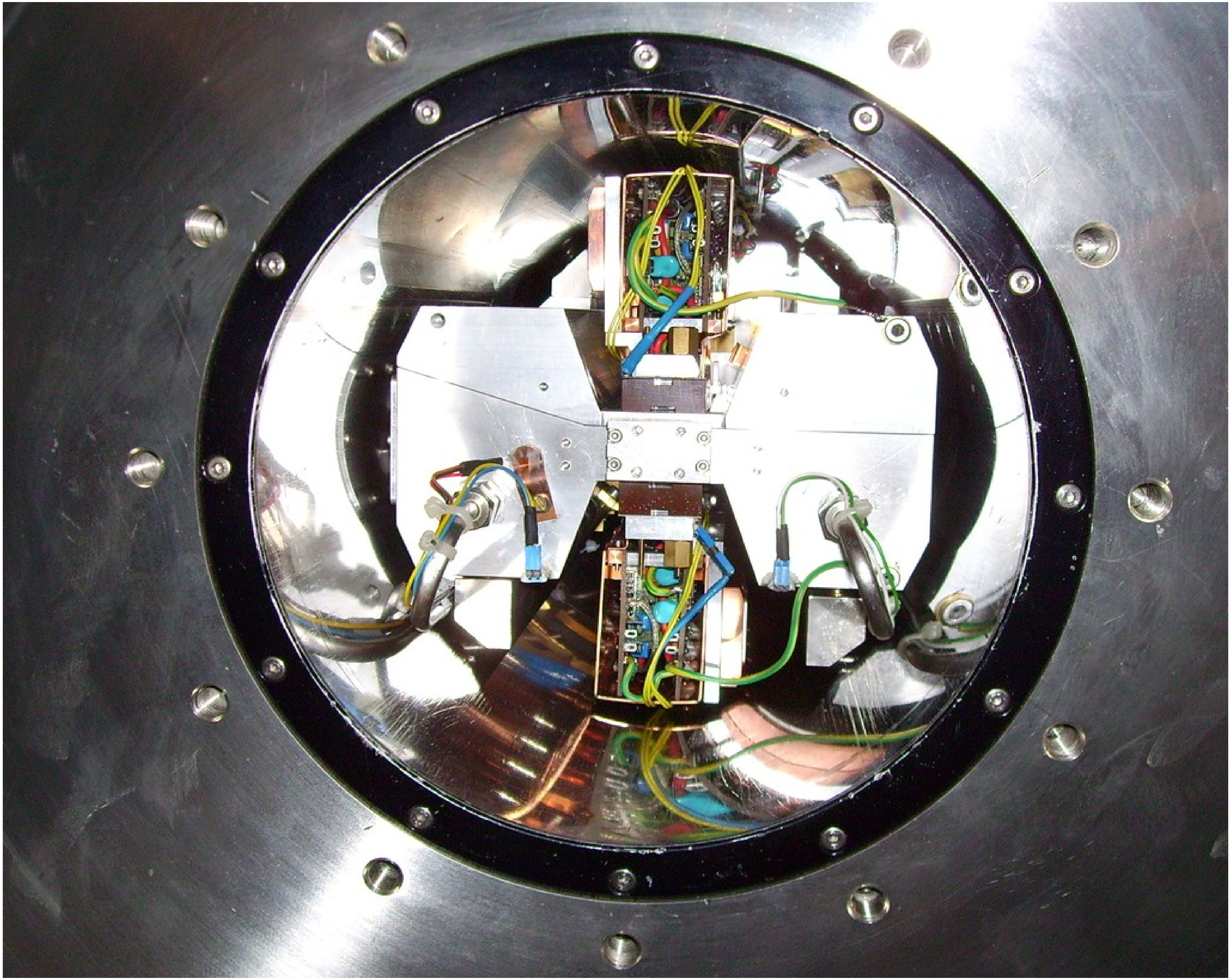
The hydrogen target



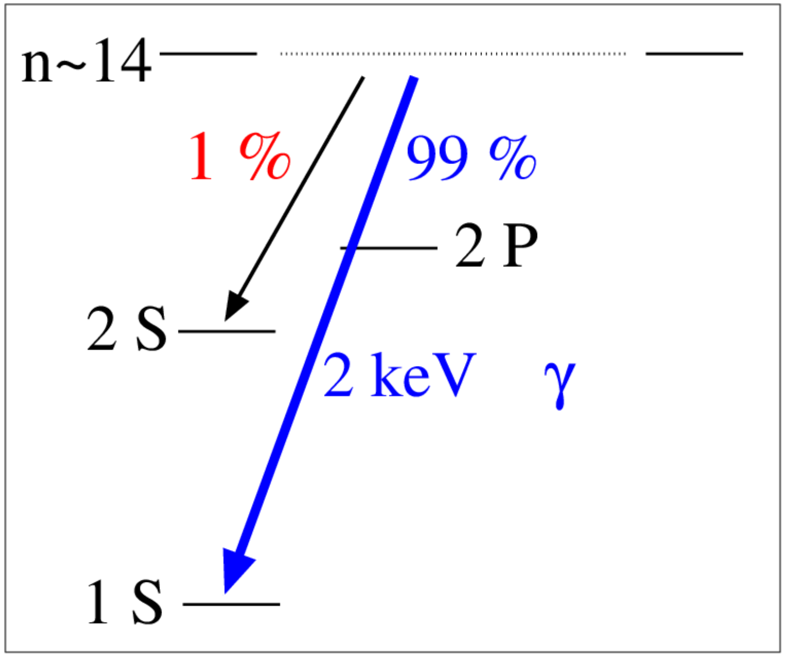
Das Herzstück -- Target

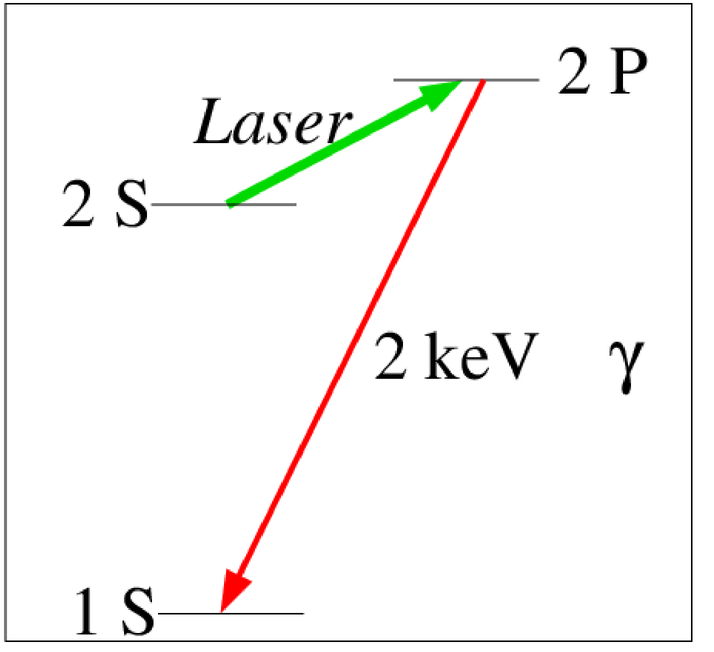


Das Herzstück -- Target



Prinzip der Messung





"prompt" (t=0):

* Einfang des Myons bei n~14
* Kaskade
* 99% enden im Grundzustand

→ "prompte" Röntgenquanten

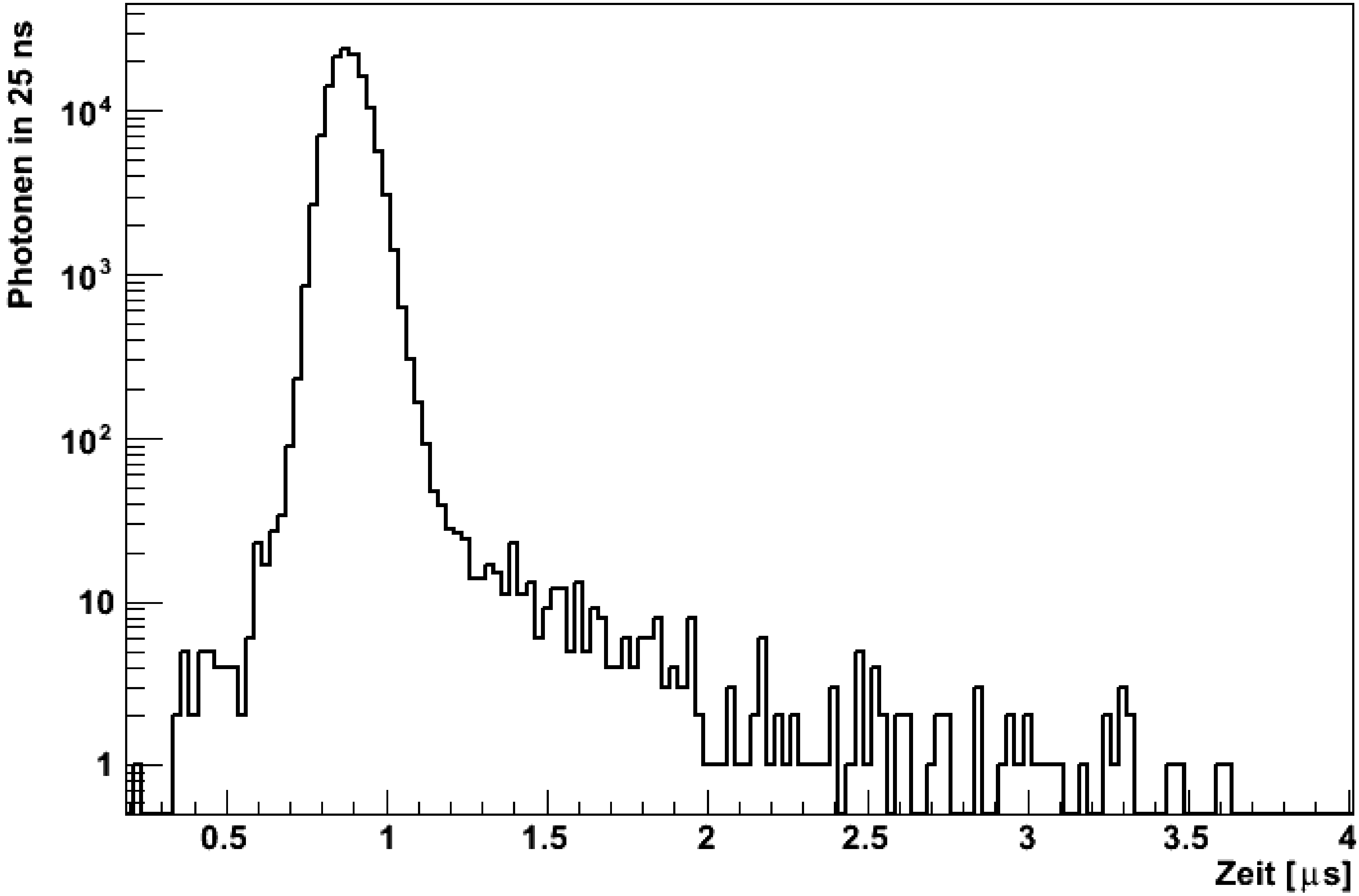
"später" (t ~ 1μs):

* 1% der Myonen sind im 2S-Zustand
* Laser auf Resonanz (λ=6μm)
* 2S → 2P → 1S

→ "verzögerte" Röntgenquanten

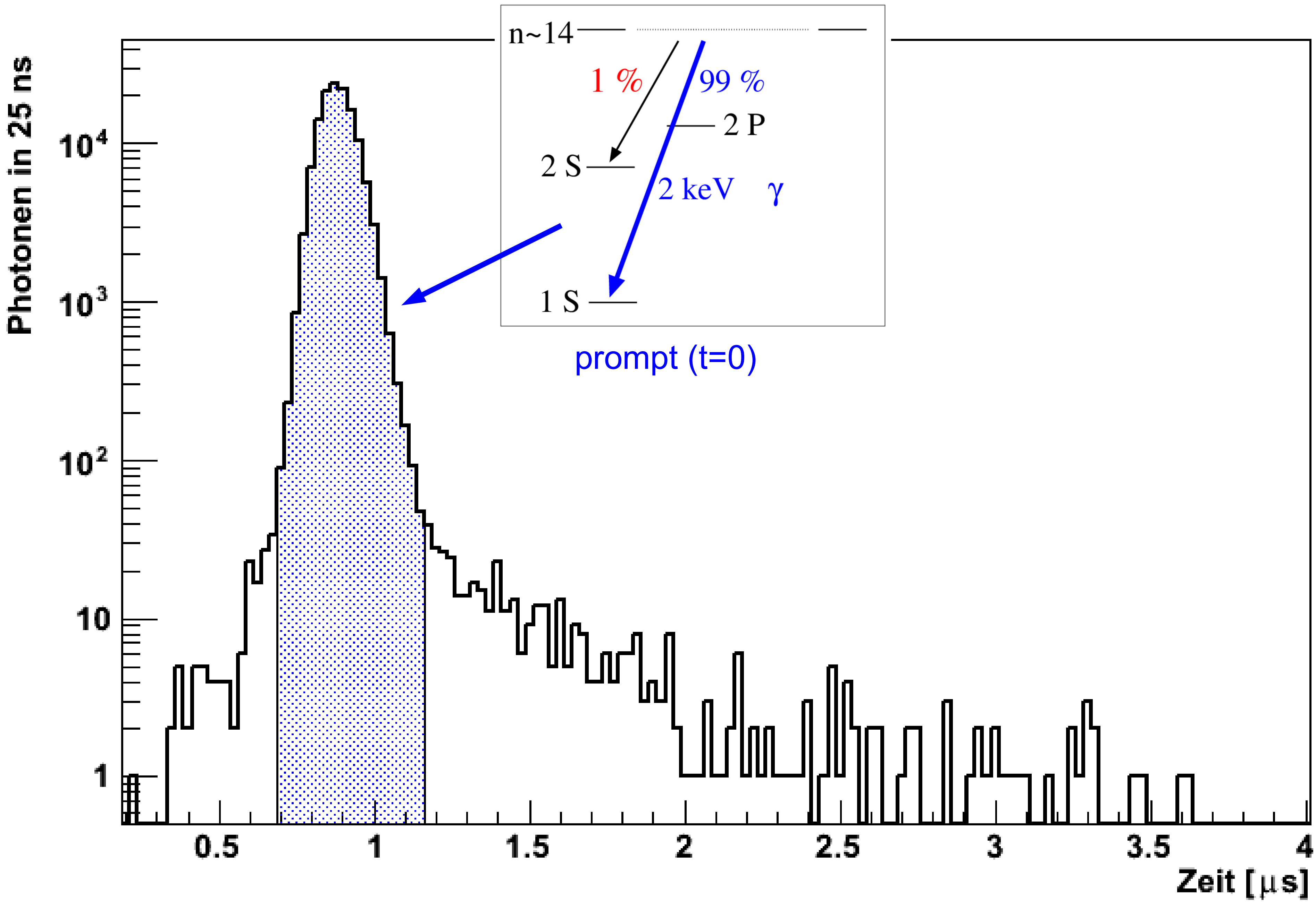
Time Spectra

13 hours of data

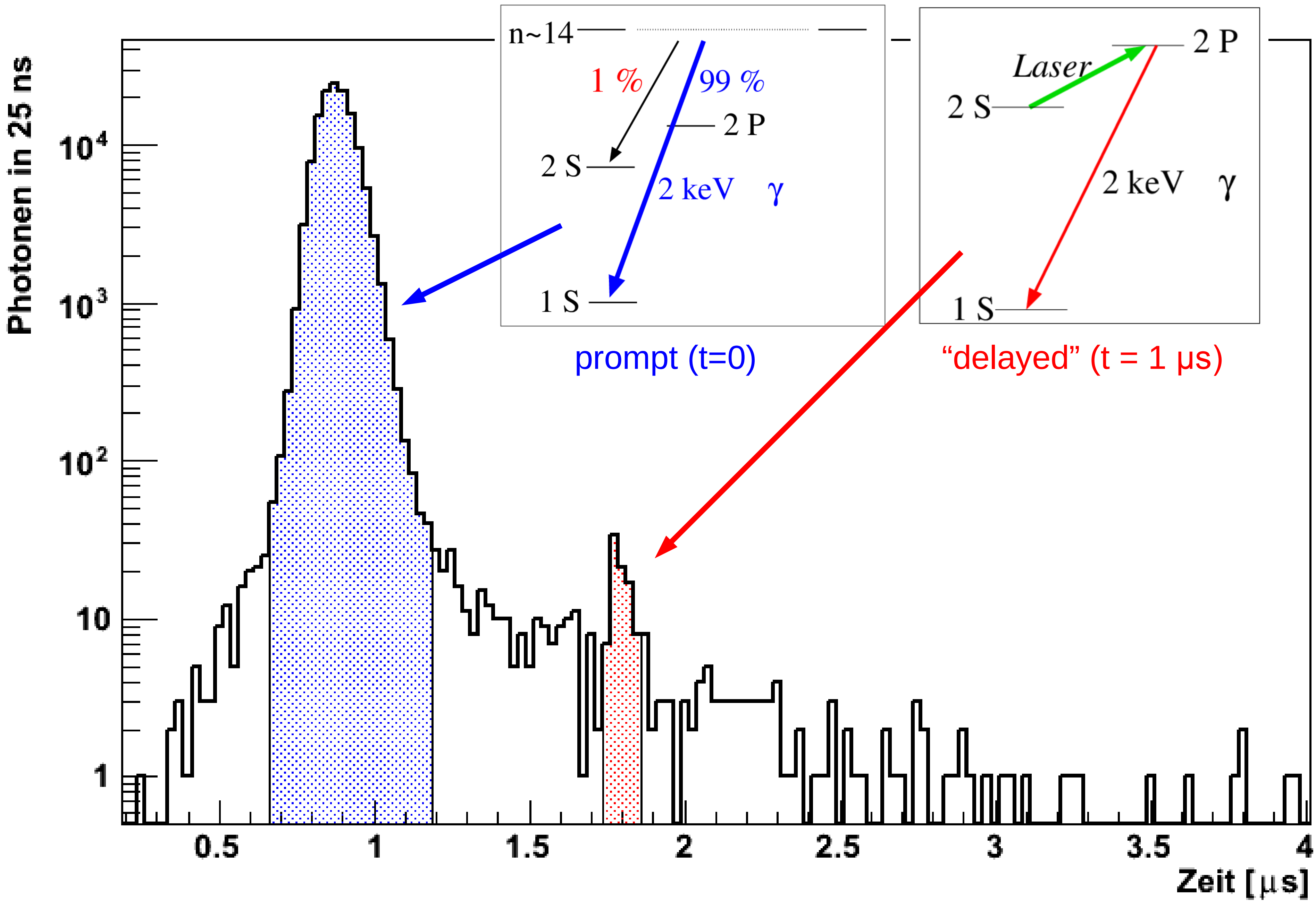


Time Spectra

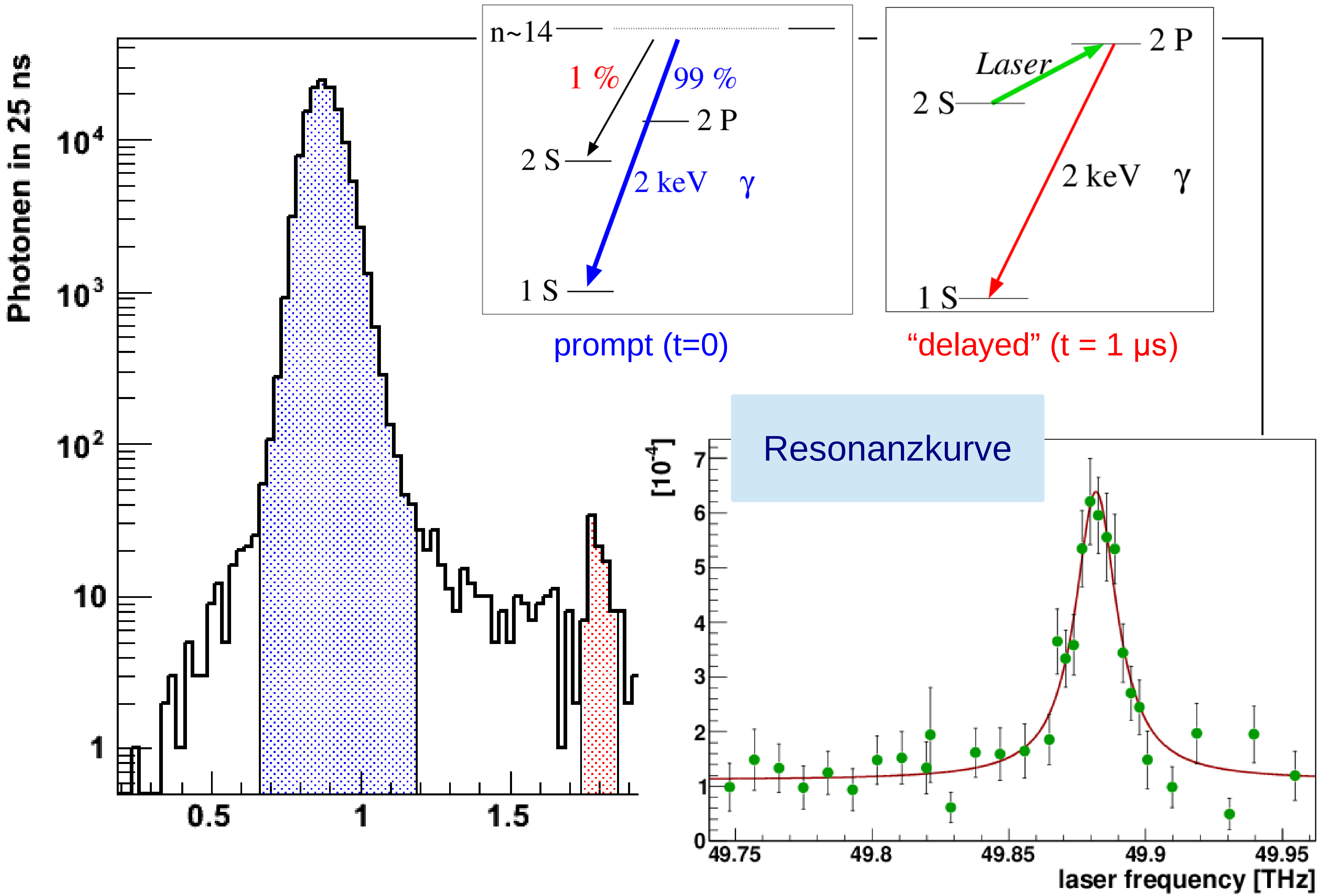
13 hours of data



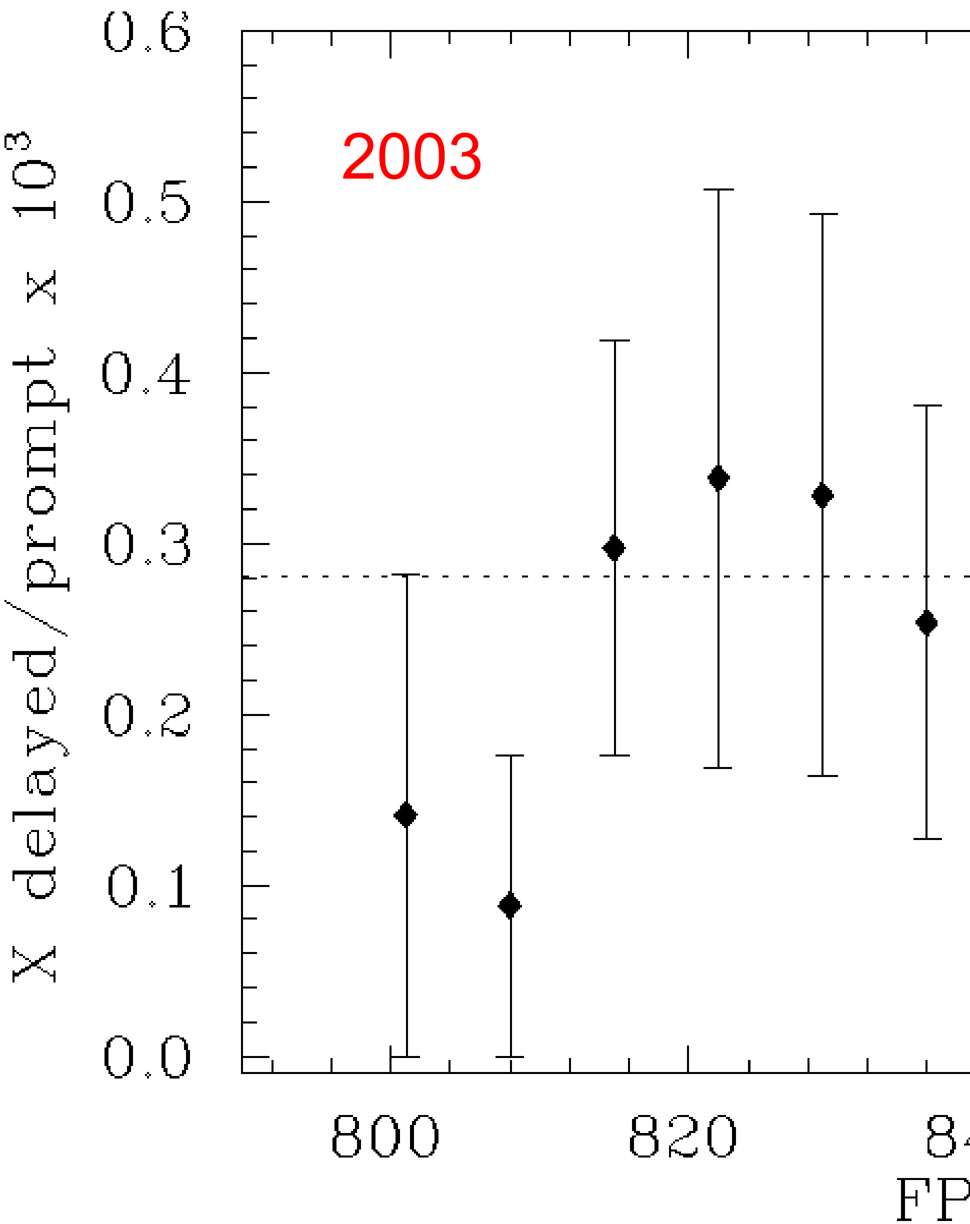
Time Spectra



Time Spectra



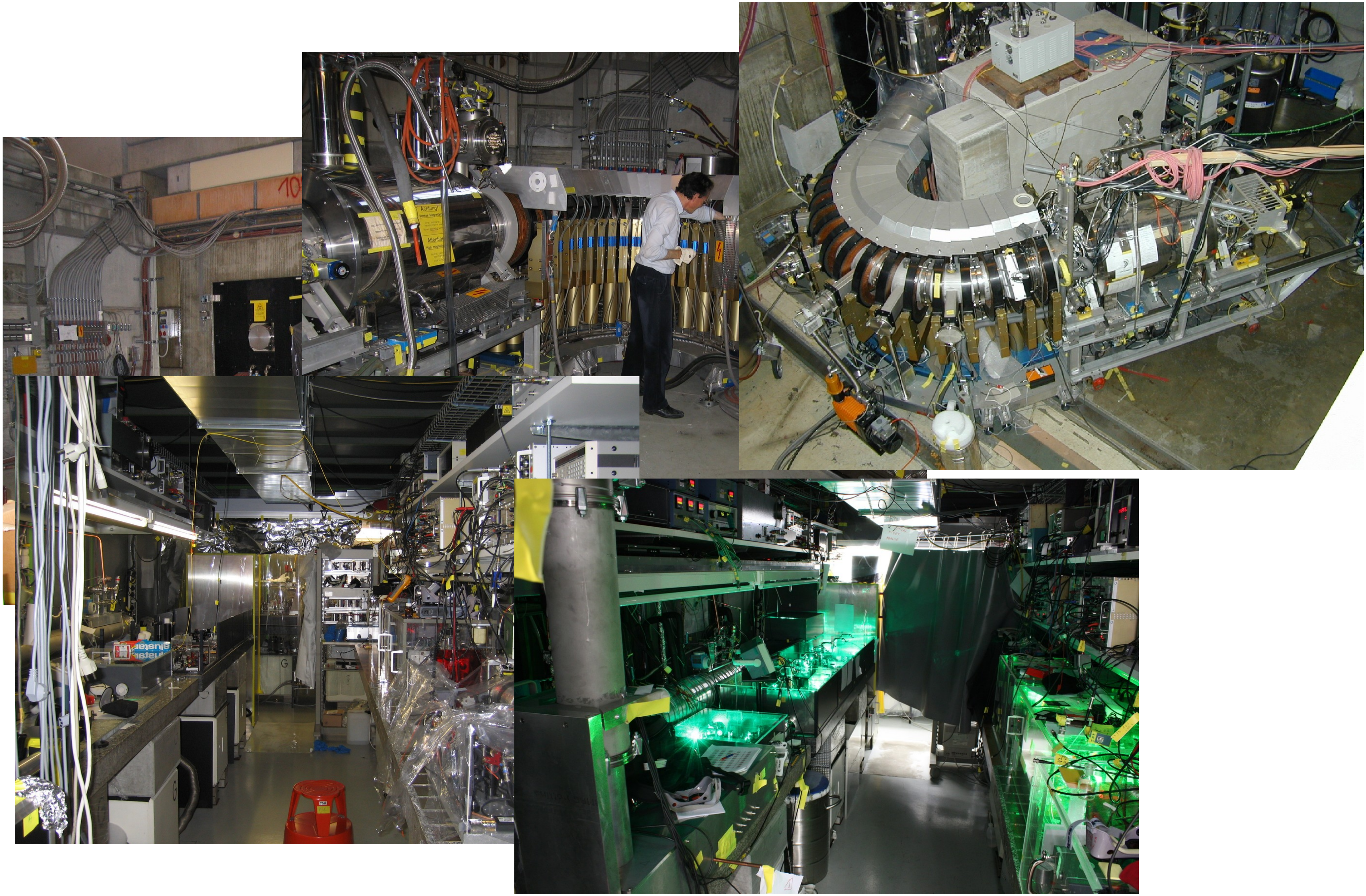
Eine lange



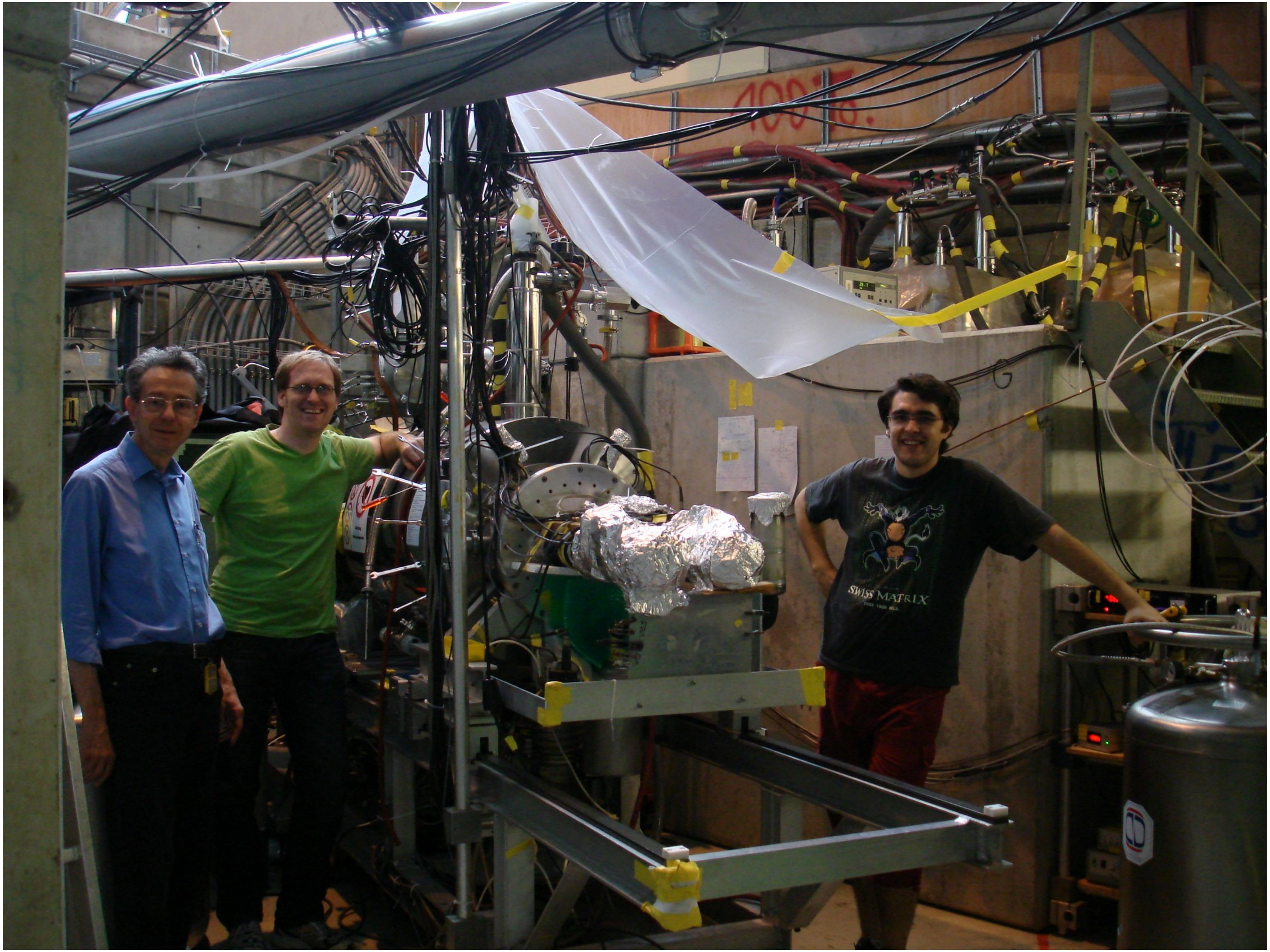
0.6
0.5
0.4
0.3
0.2
0.1
0.0
X delayed/prompt x 10³
2003
800
820
84
FP

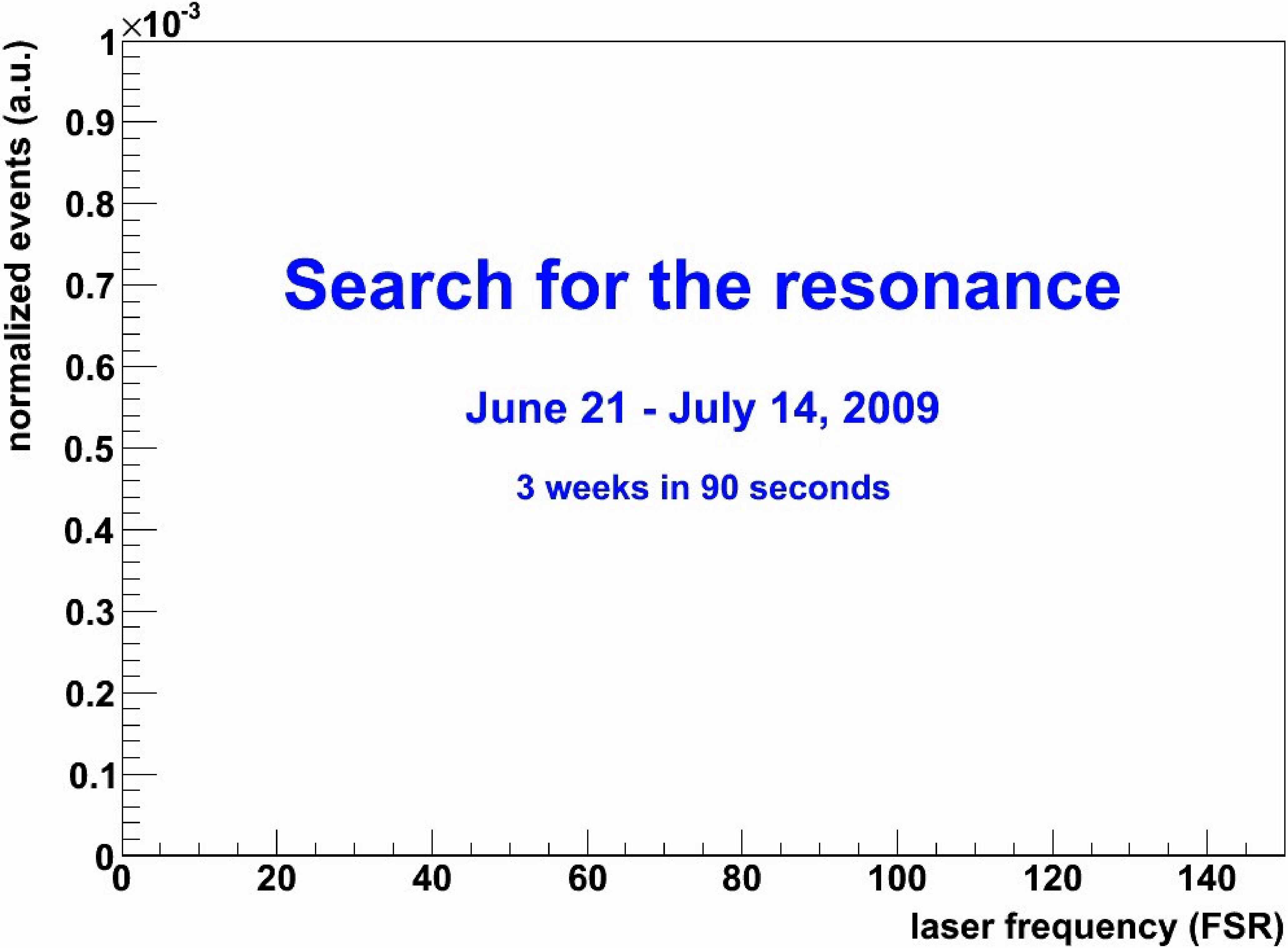
8 July 2010 | www.nature.com/nature $10
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
nature
OIL SPILLS
There's more to come
PLAGIARISM
It's worse than you think
CHIMPANZEES
The battle for survival
0.84184 fm
SHRINKING THE PROTON
New value from exotic atom trims radius by four per cent
NATUREJOBS
Researchers for hire

Run 2009

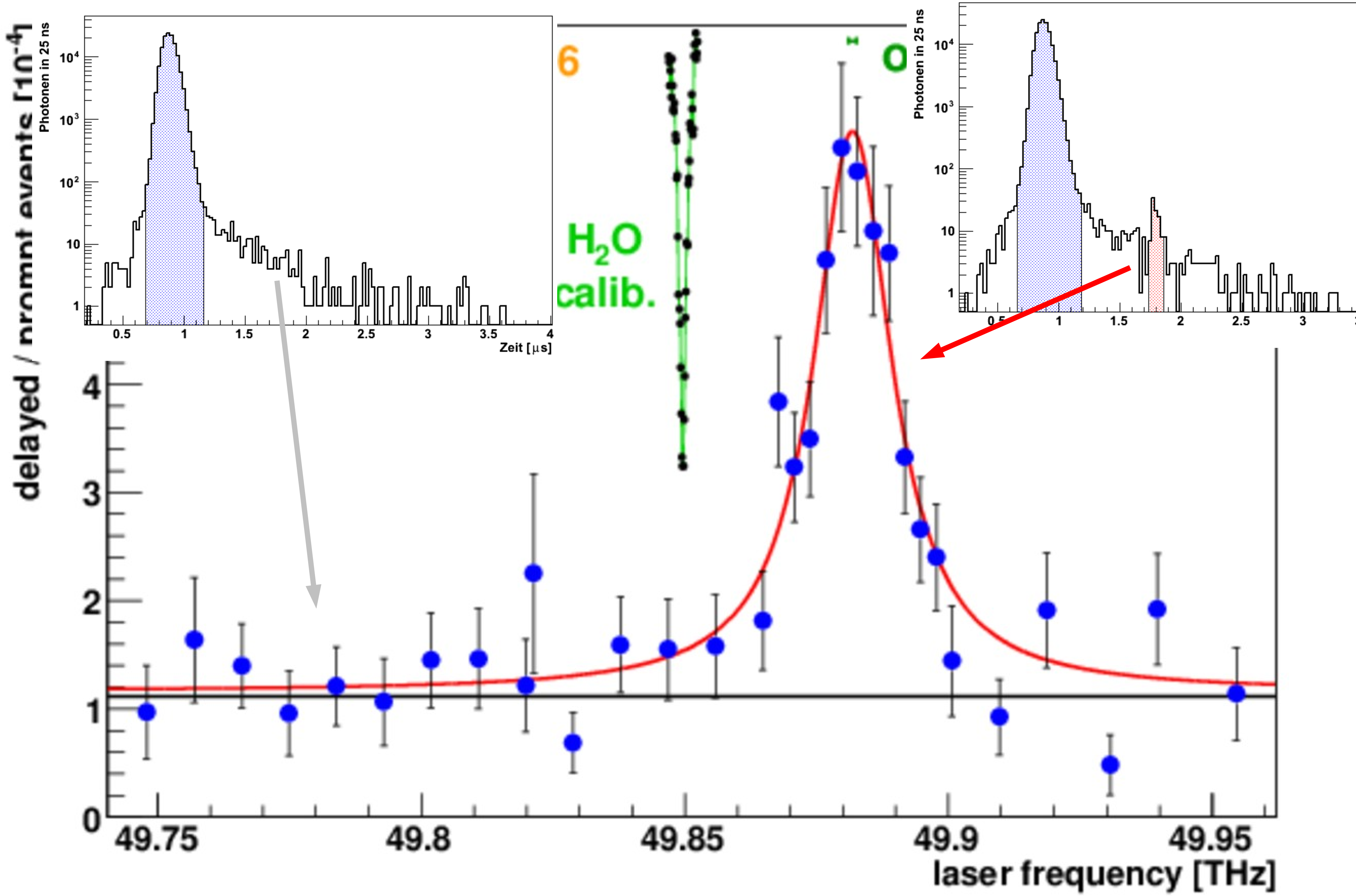


Fertig aufgebaut




Search for the resonance
June 21 - July 14, 2009
3 weeks in 90 seconds
normalized events (a.u.)
×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
120
140
laser frequency (FSR)

Die Resonanzlinie



Yeah!

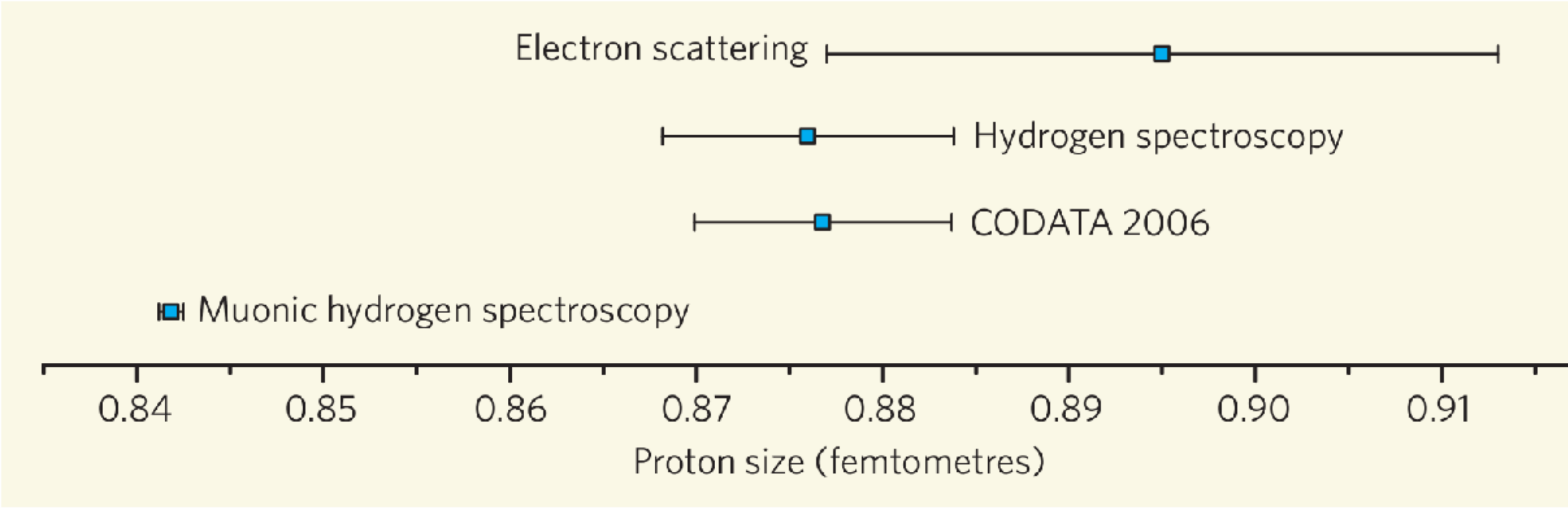
Auf die Resonanz!

Die Resonanz auf die Linie

Das Proton ist 4% kleiner als gedacht!

0.84184 ± 0.00067 fm anstatt

0.8768 ± 0.0069 fm



Die Resonanz auf die Linie

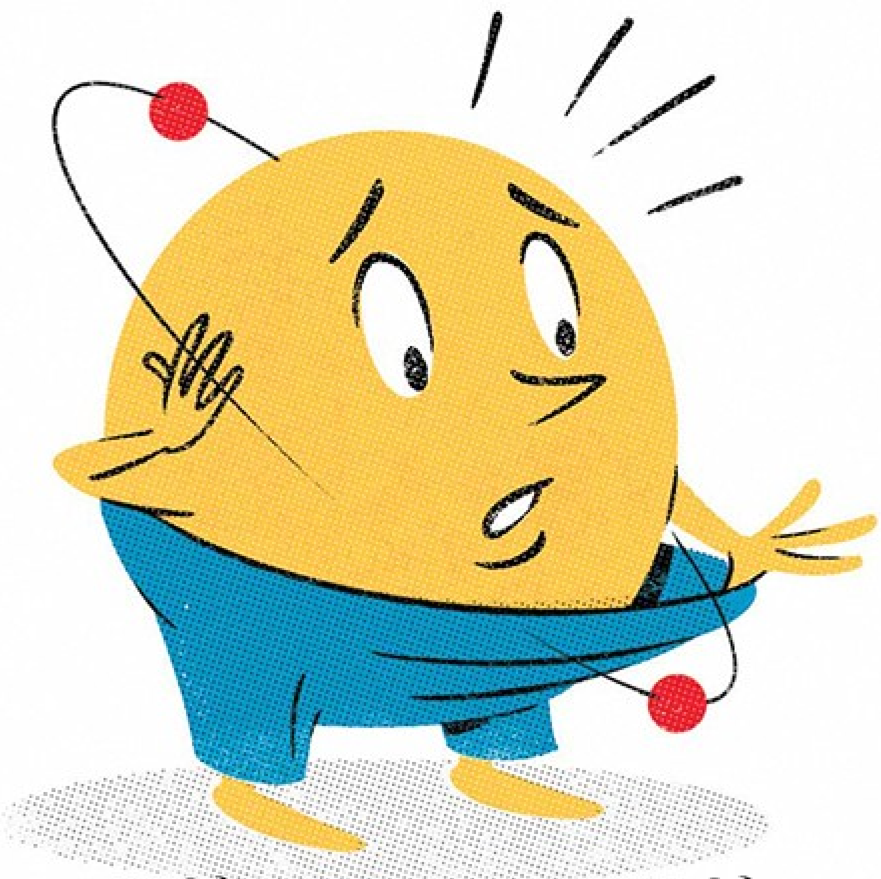
DRS 1

SPIEGEL

DIE

la Repubbli

NATIONAL GEOGRAPHIC

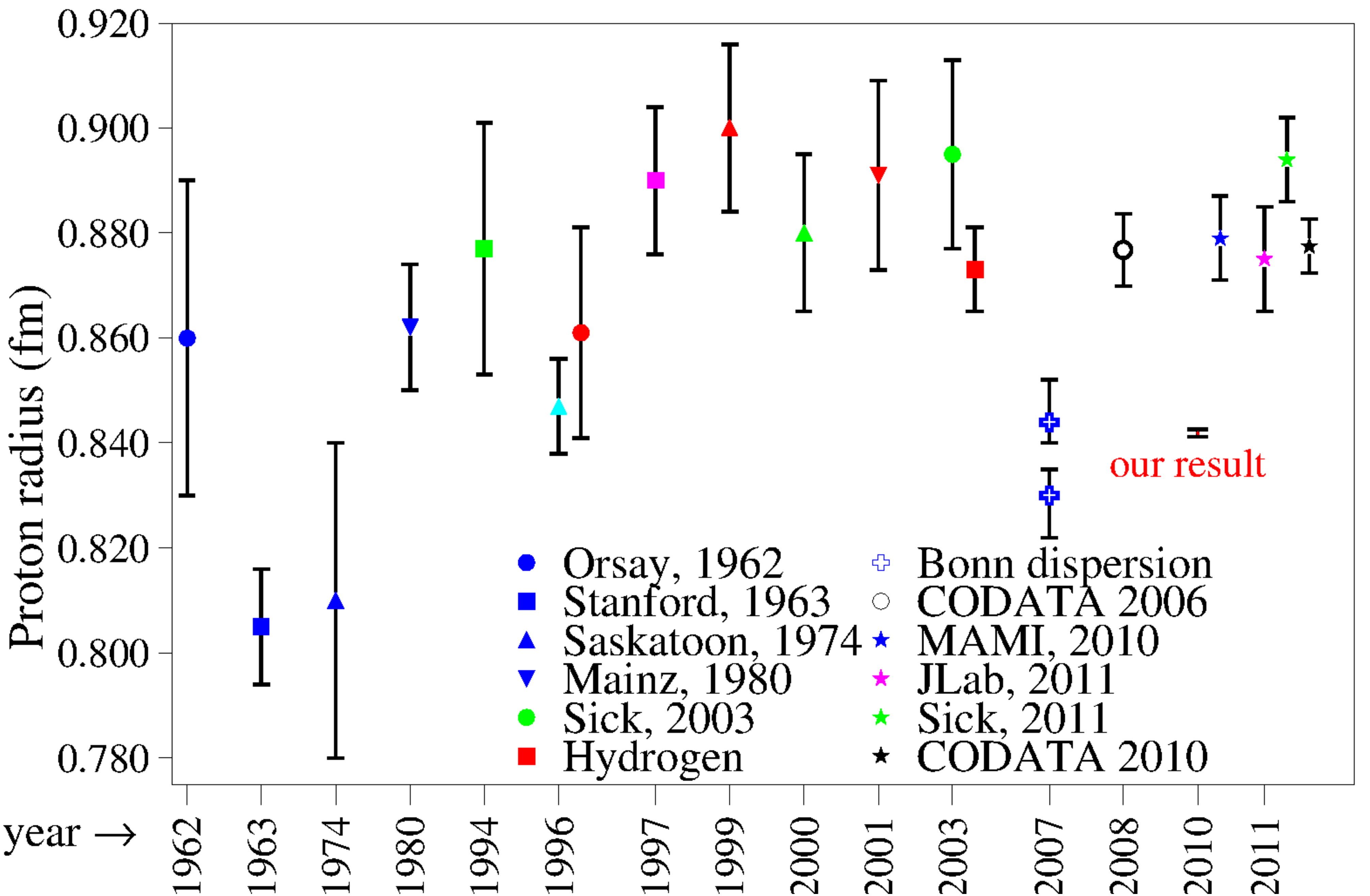


The New York Times

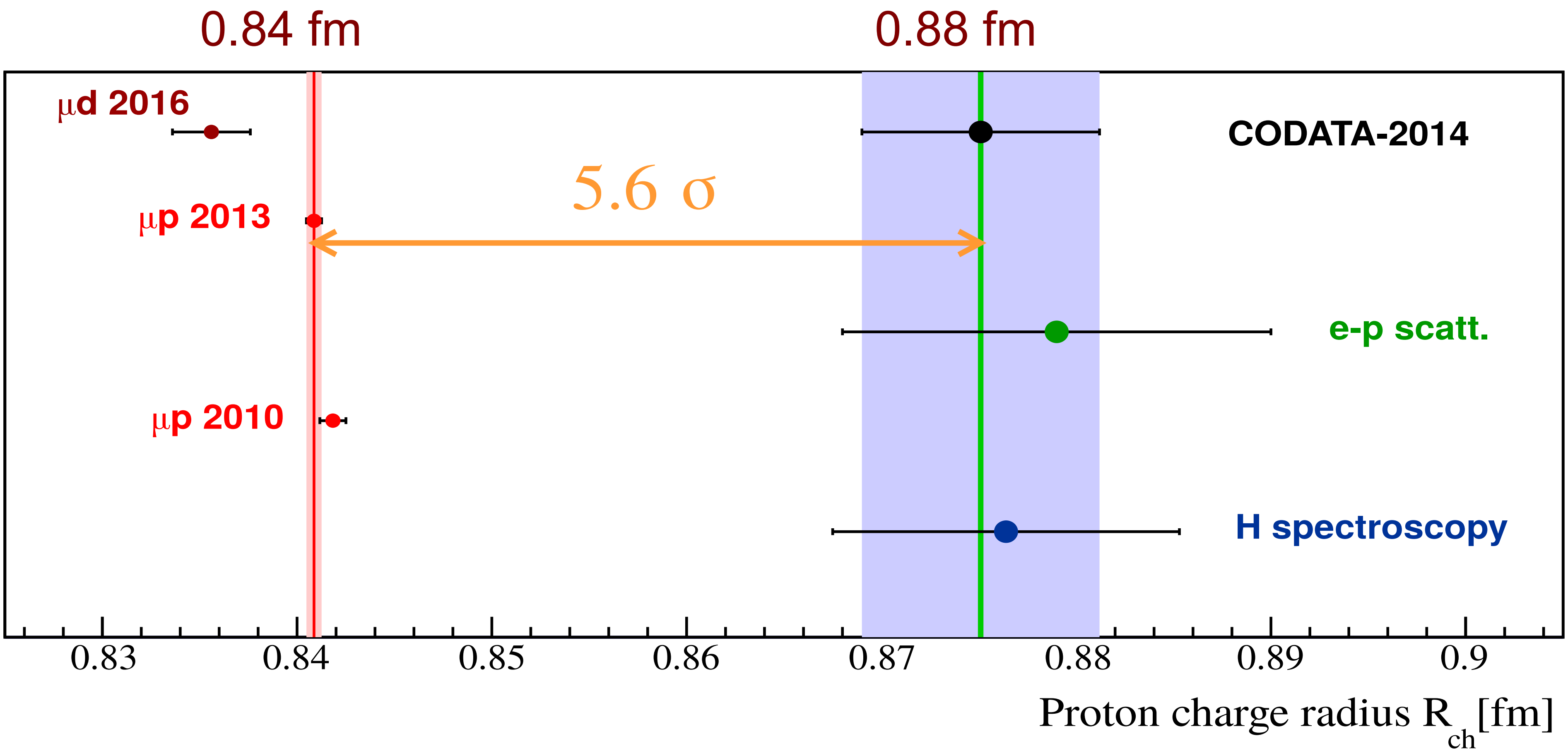
Los Angeles Times

Movie: In the News

Das "Proton Radius Puzzle"



Muonic Hydrogen



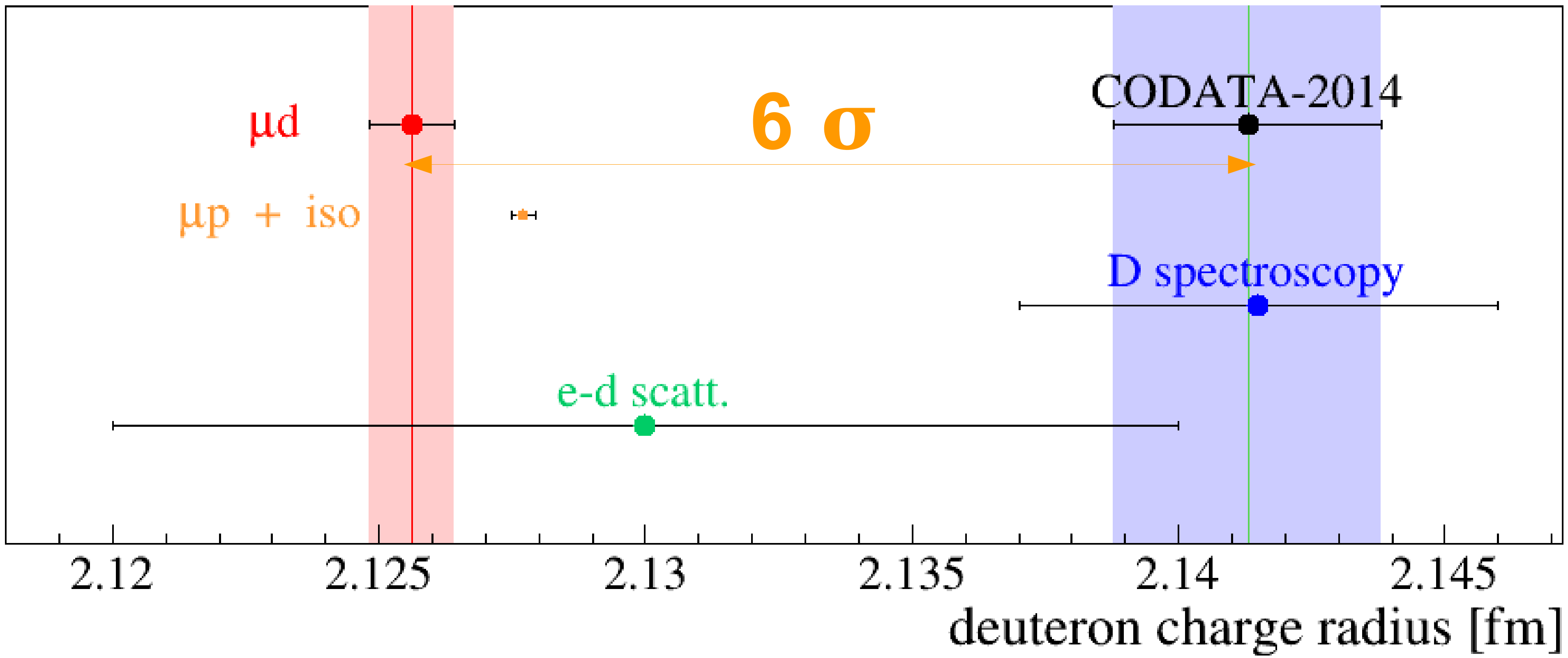
muonic hydrogen: 0.8409 ± 0.0004 fm

electronic hydrogen: 0.876 ± 0.008 fm

electron scattering 0.879 ± 0.011 fm

20x more accurate

Muonic Deuterium



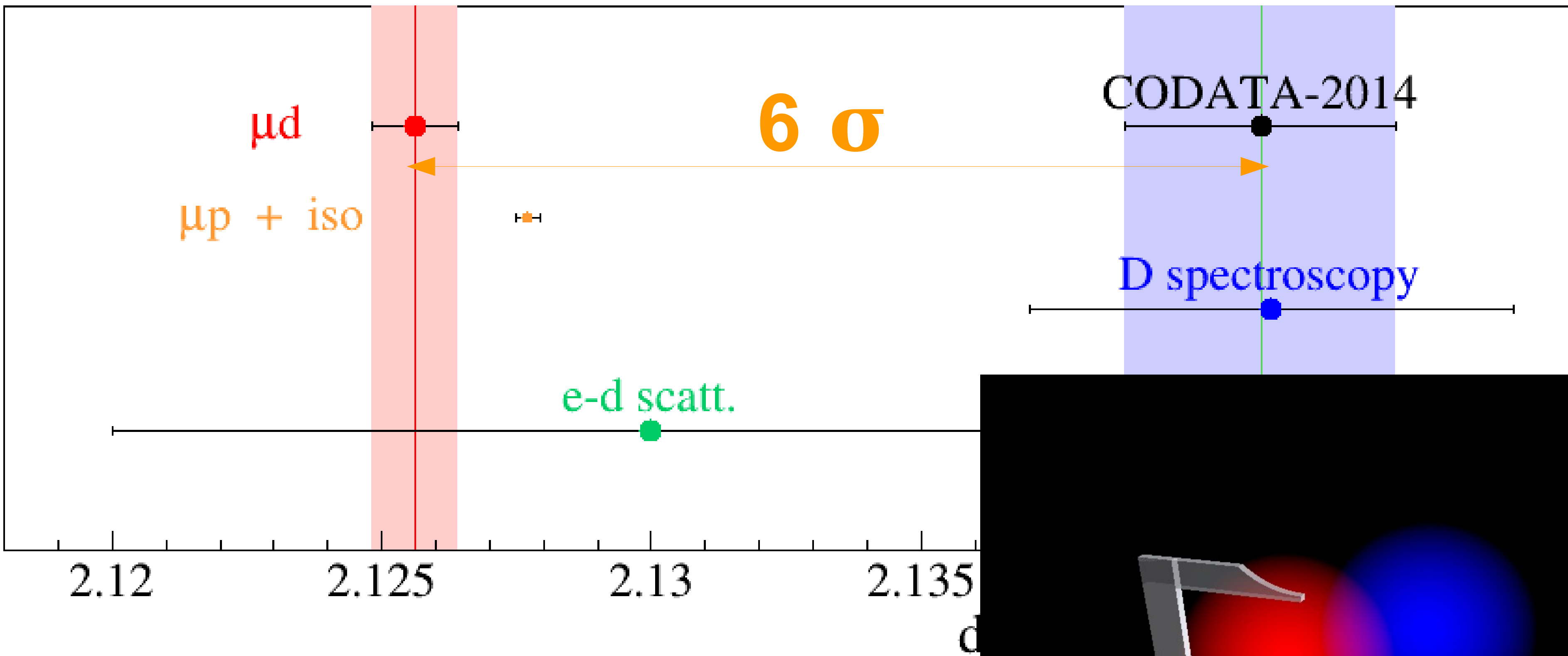
μD: 2.12562 $(13)_{exp}$ $(77)_{theo}$ fm (nucl. polarizability)

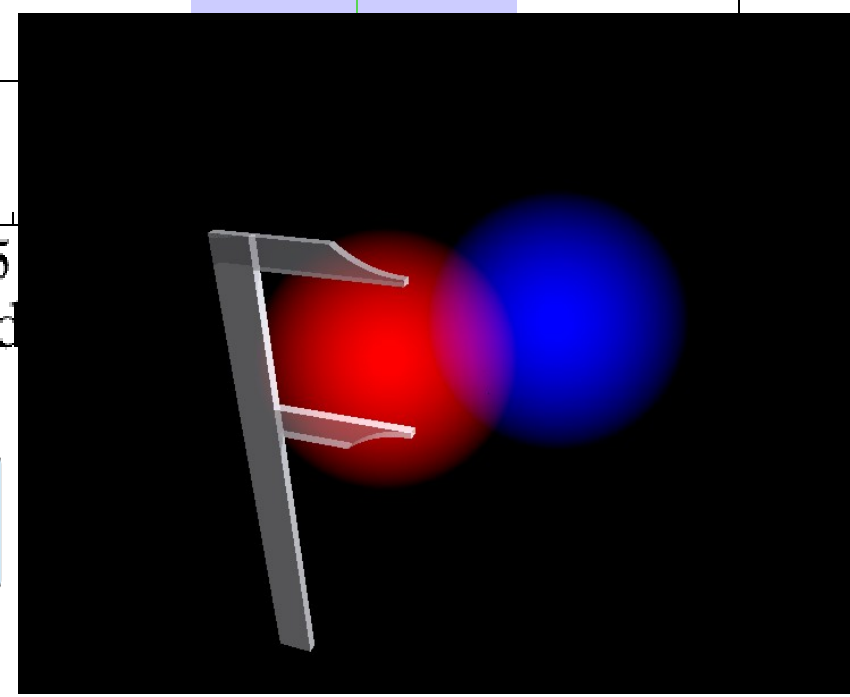
μH + H/D(1S-2S): 2.12771 (22) fm

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

RP et al. (CREMA Coll.), Science 353, 559 (2016)

Deuteron radius



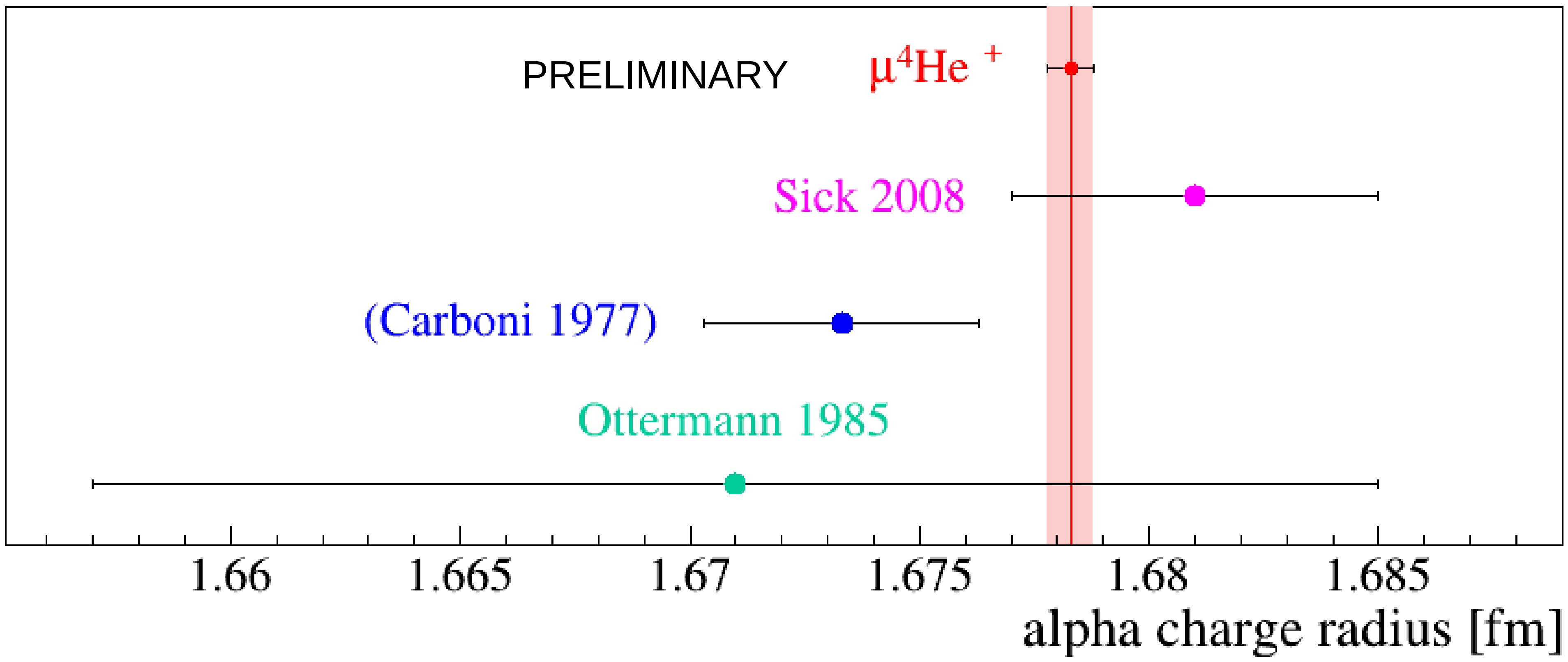


Deuteron is CONSISTENTLY smaller!

$$R_d^{\,2} = R^2_{struct} + R_p^{\,2} + R_n^{\,2} \text{ (+ DF)}$$

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

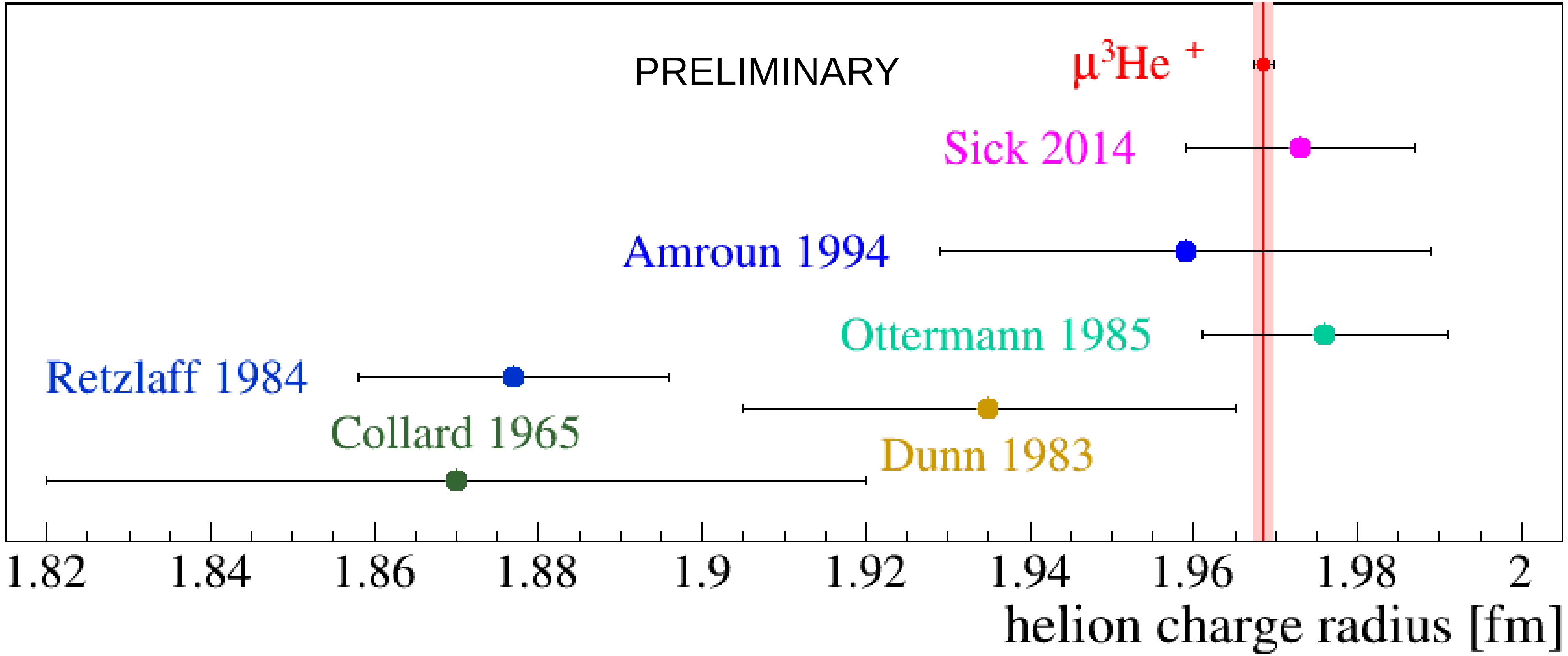
Muonic Helium-4



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

Theory: see Diepold et al. arxiv 1606.05231

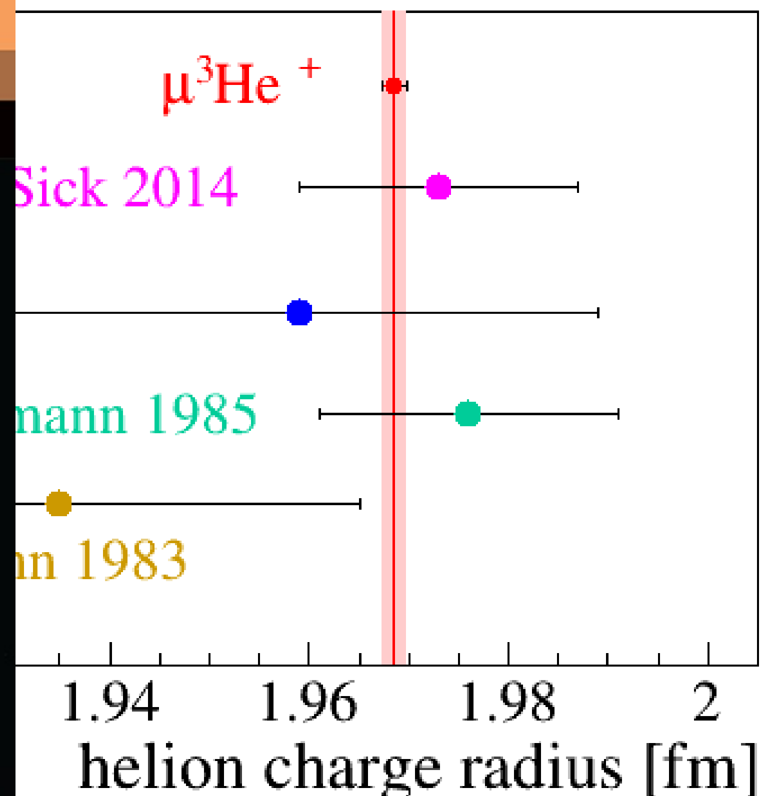
Muonic Helium-3

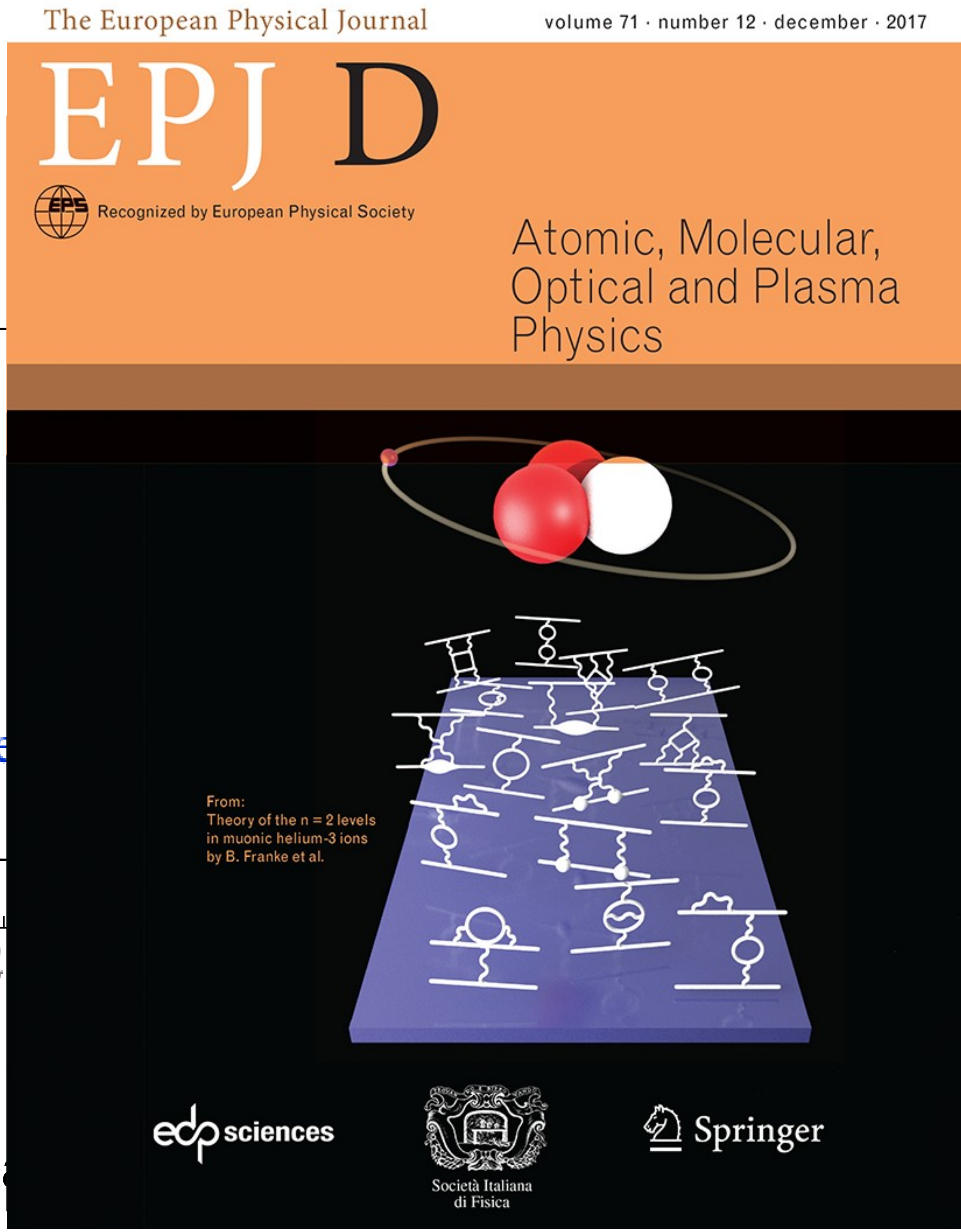


prel. accuracy: exp +- 0.00012 fm, theo +- 0.00128 fm (nucl. polarizability)

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

um-3





prel. … 0.00128 fm (nucl. polarizability)

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

Muonic conclusions

- The proton radius is 0.84087 (26)$_{exp}$ (29)$_{theo}$ fm
- The deuteron radius is 2.12771 (22) fm
- both are >5σ smaller than CODATA values
- No discrepancy for helion and alpha particle

Part 2: The Rydberg constant

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

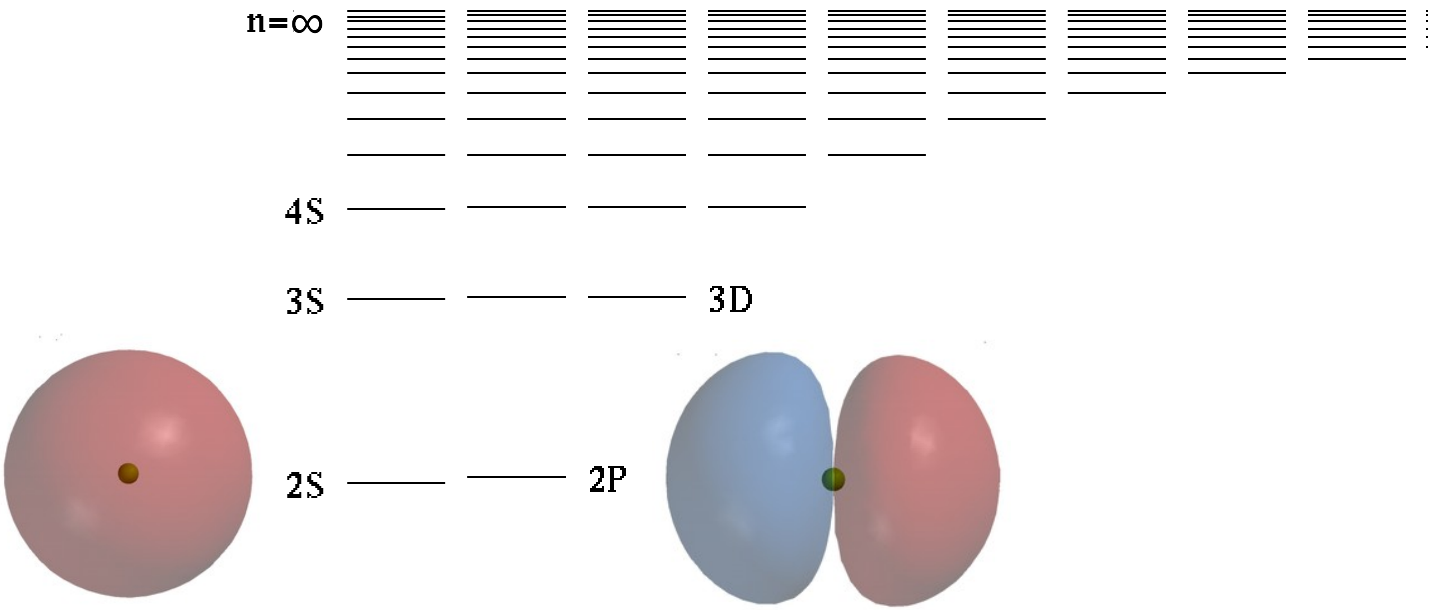
- most accurately determined fundamental constant $u_r = 5.9 * 10^{-12}$
- corner stone of the CODATA LSA of fundamental constants

  links fine structure constant α, electron mass m_e, velocity of light c and Planck's constant *h*
- correlation coefficient with proton radius: 0.9891

  → The “proton radius puzzle” could be a “Rydberg puzzle”

- R_∞ is a “unit converter”: atomic units → SI (Hertz)

Energy levels of hydrogen

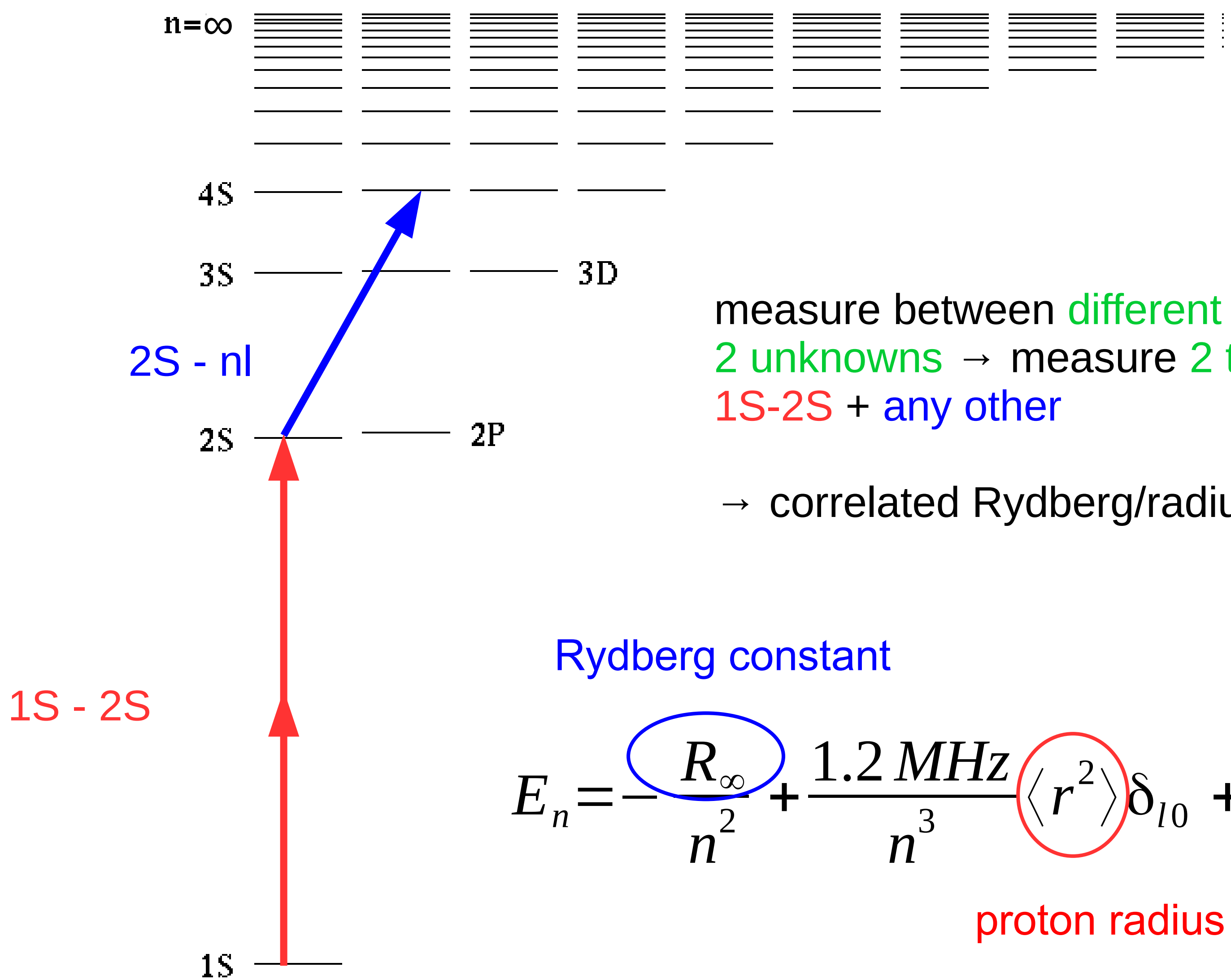


Rydberg constant

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

proton radius

Energy levels of hydrogen



measure between different **n**
2 unknowns → measure 2 transitions:
1S-2S + any other

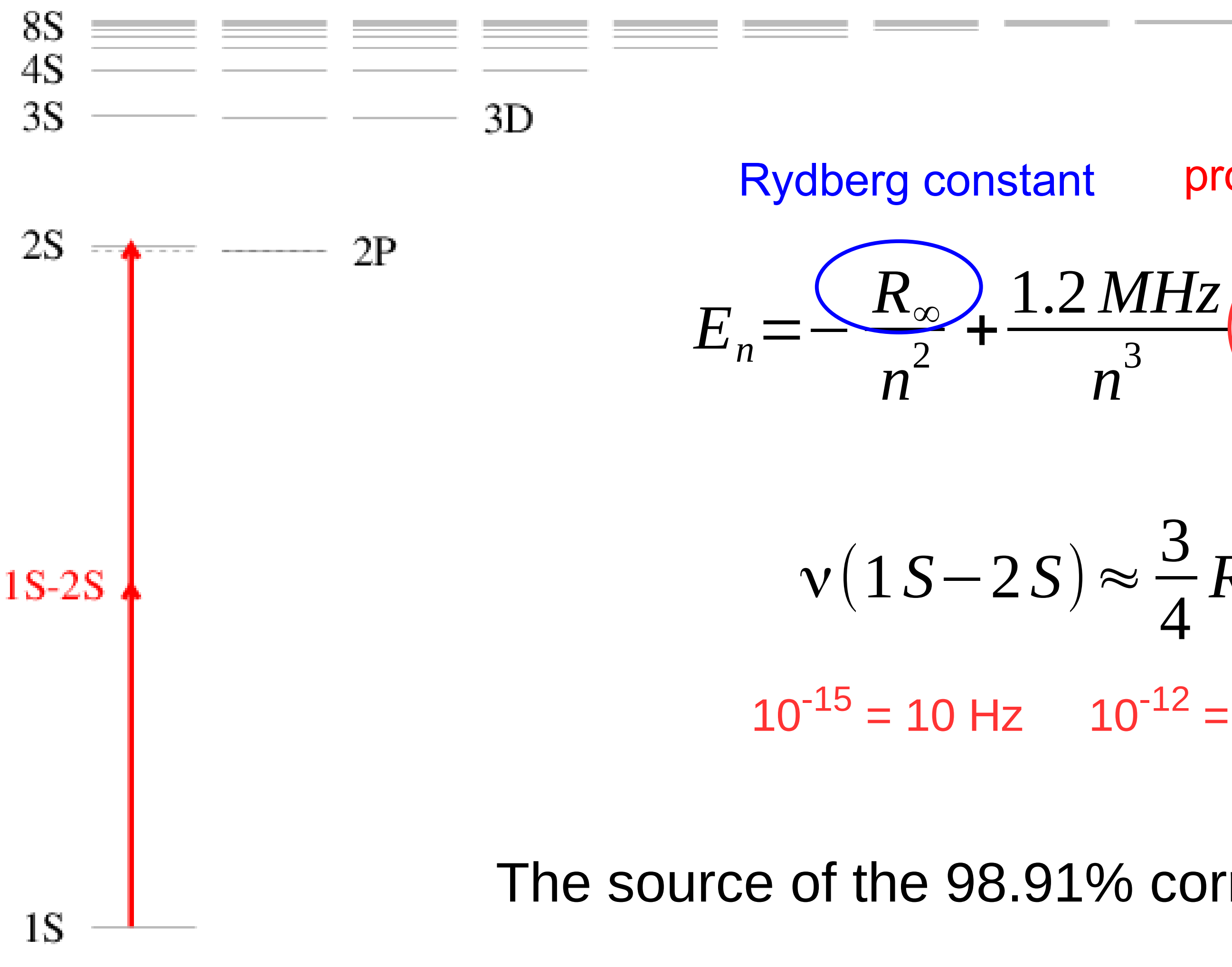
→ correlated Rydberg/radius pairs

Rydberg constant

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

proton radius

Correlation between R_∞ and R_p / R_d



Rydberg constant   proton radius

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

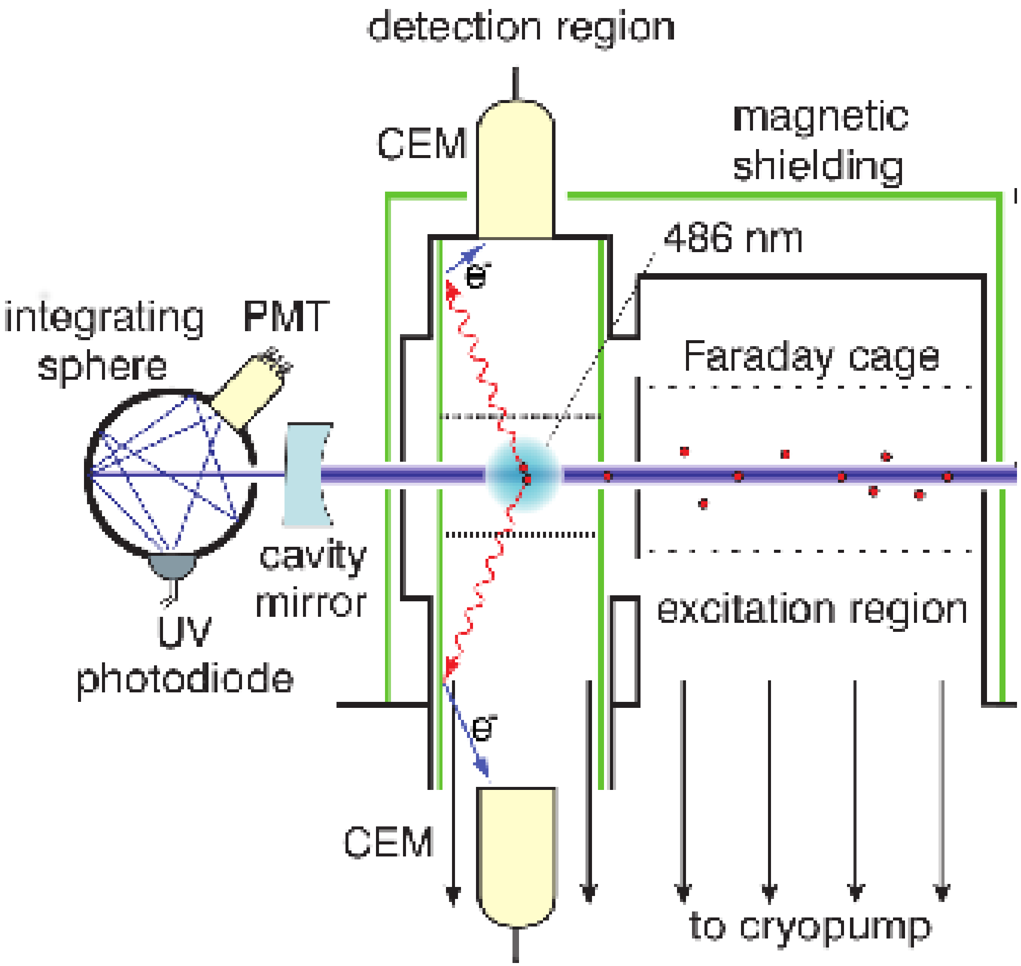
$$\nu(1S-2S) \approx \frac{3}{4}R_\infty - \frac{7}{8}E_{NS}$$

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

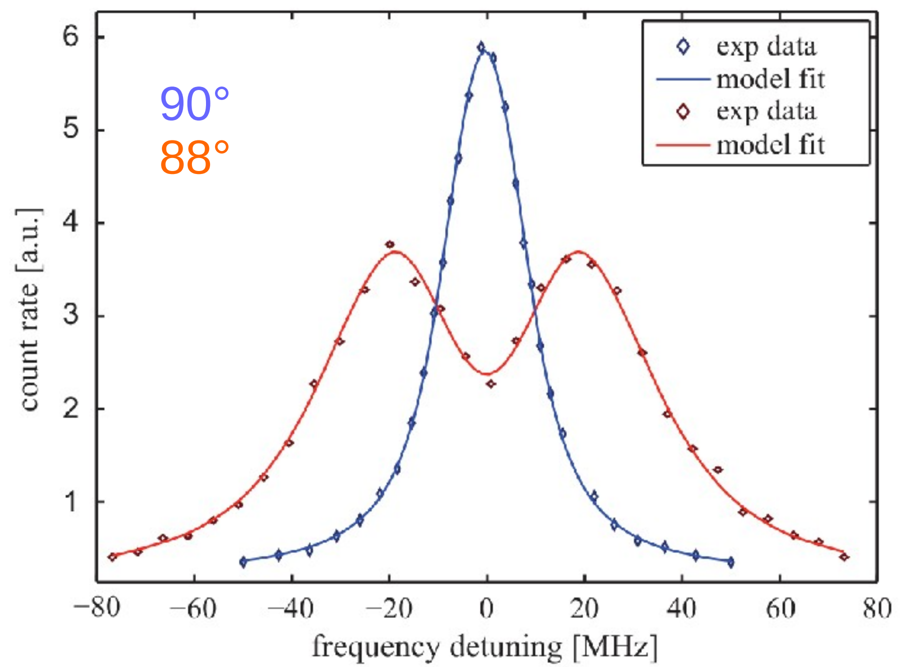
The source of the 98.91% correlation of R_∞ and R_p

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

Garching H(2S-4P)



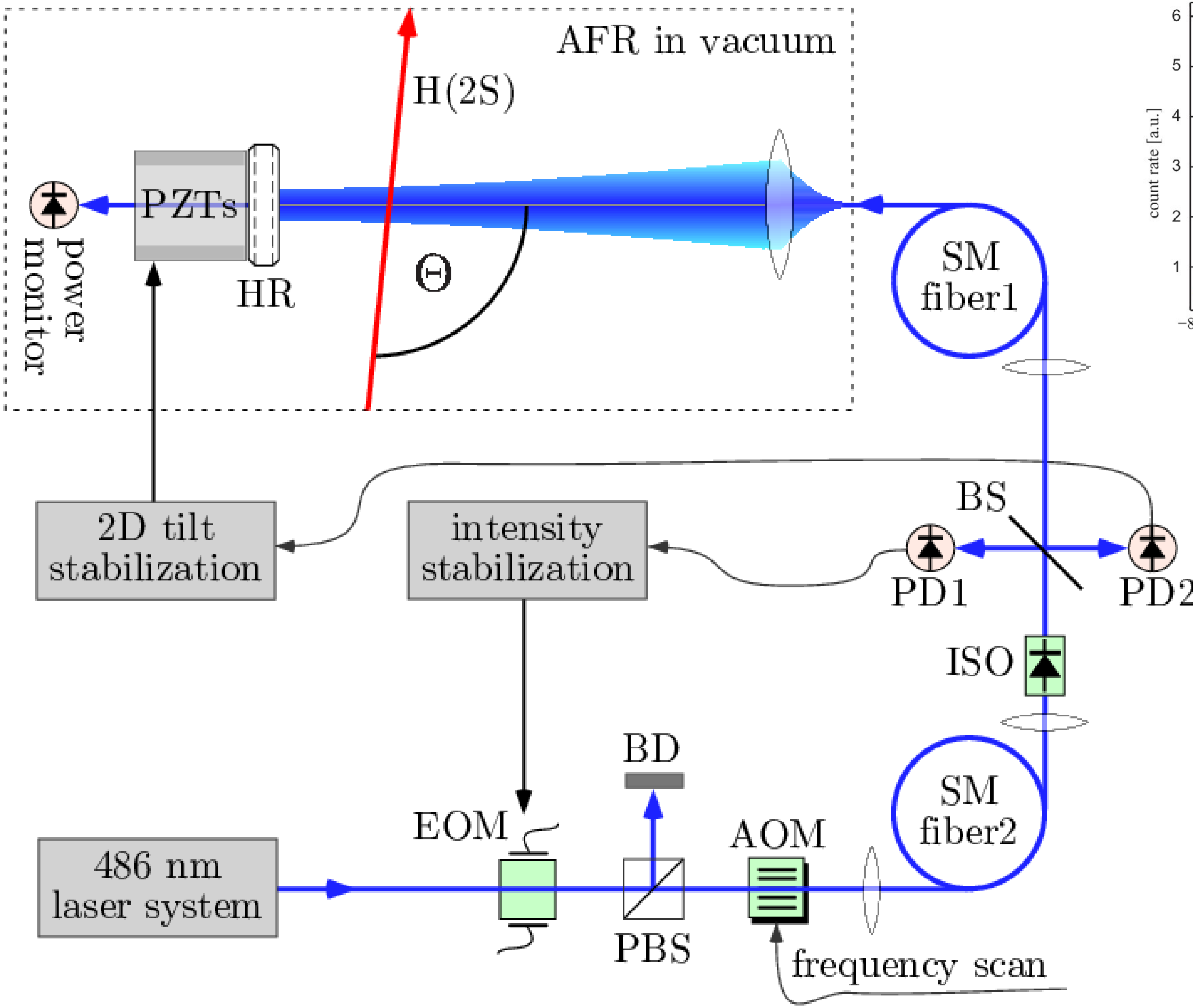
1st order Doppler cancellation

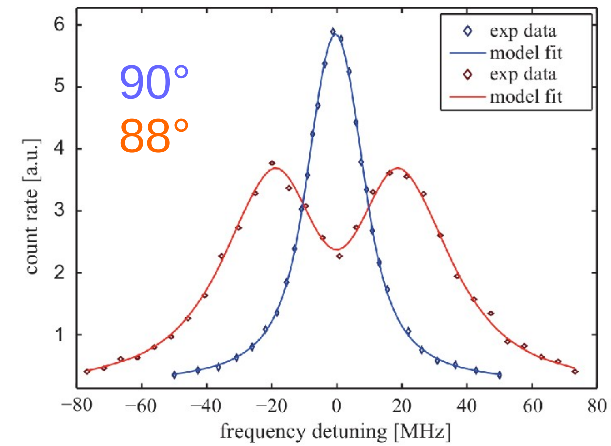


- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-4P transition is 1-photon: retroreflector
- split line to 10^{-4} !!!
- 2.3 kHz vs. 9 kHz PRP
- large systematics

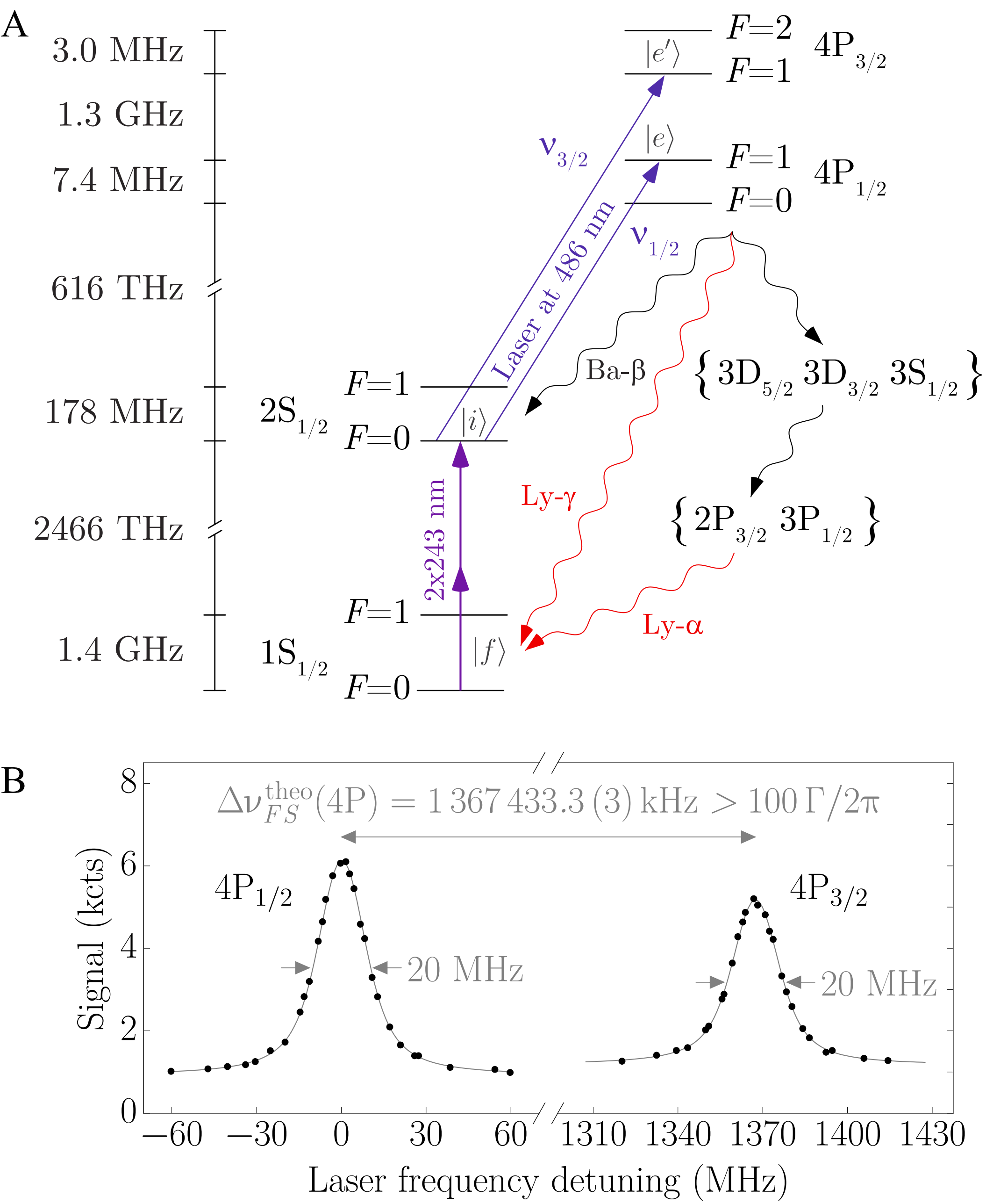
Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

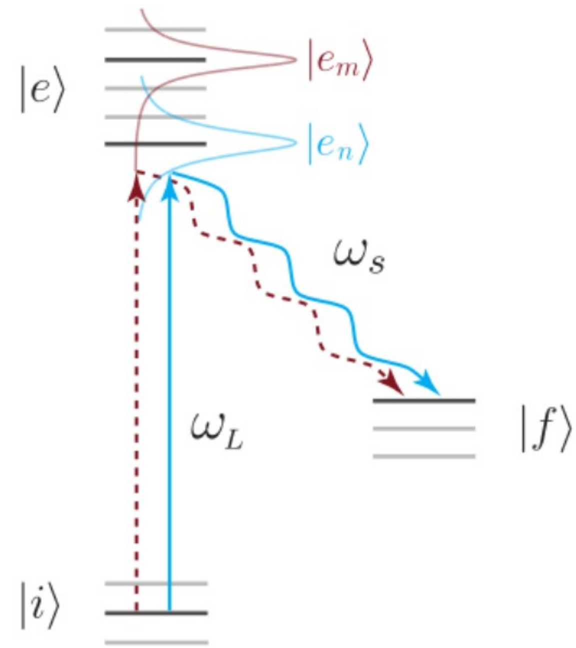
1st order Doppler shift





Quantum interference shifts





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

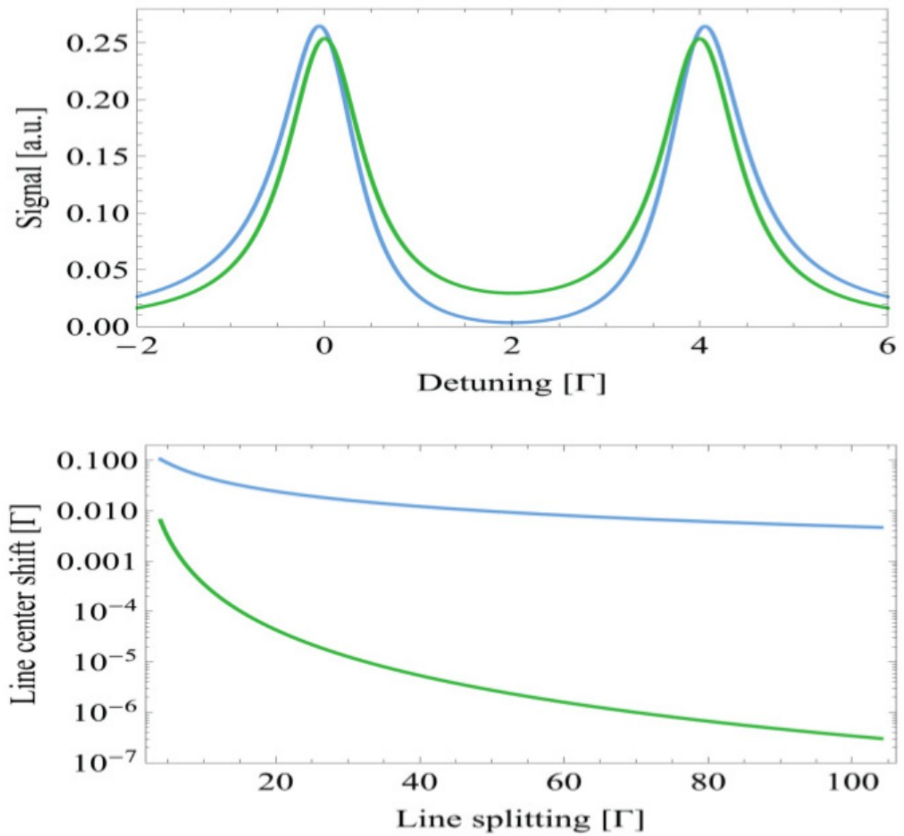
= Lorentzian(1) + Lorentzian(2)

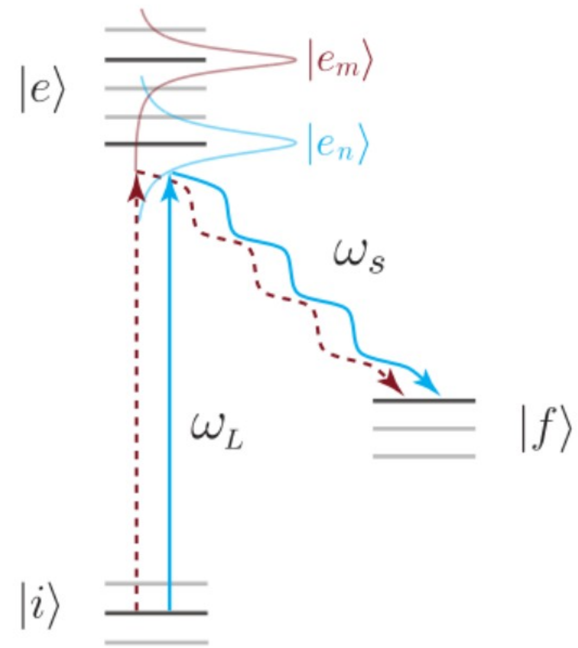
+ cross-term (QI)

see

Horbatsch, Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011); PRA 86 040501 (2012)
Sansonetti et al., PRL 107, 021001 (2011)
Brown et al., PRA 87, 032504 (2013)

Quantum interference shifts





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

= Lorentzian(1) + Lorentzian(2)

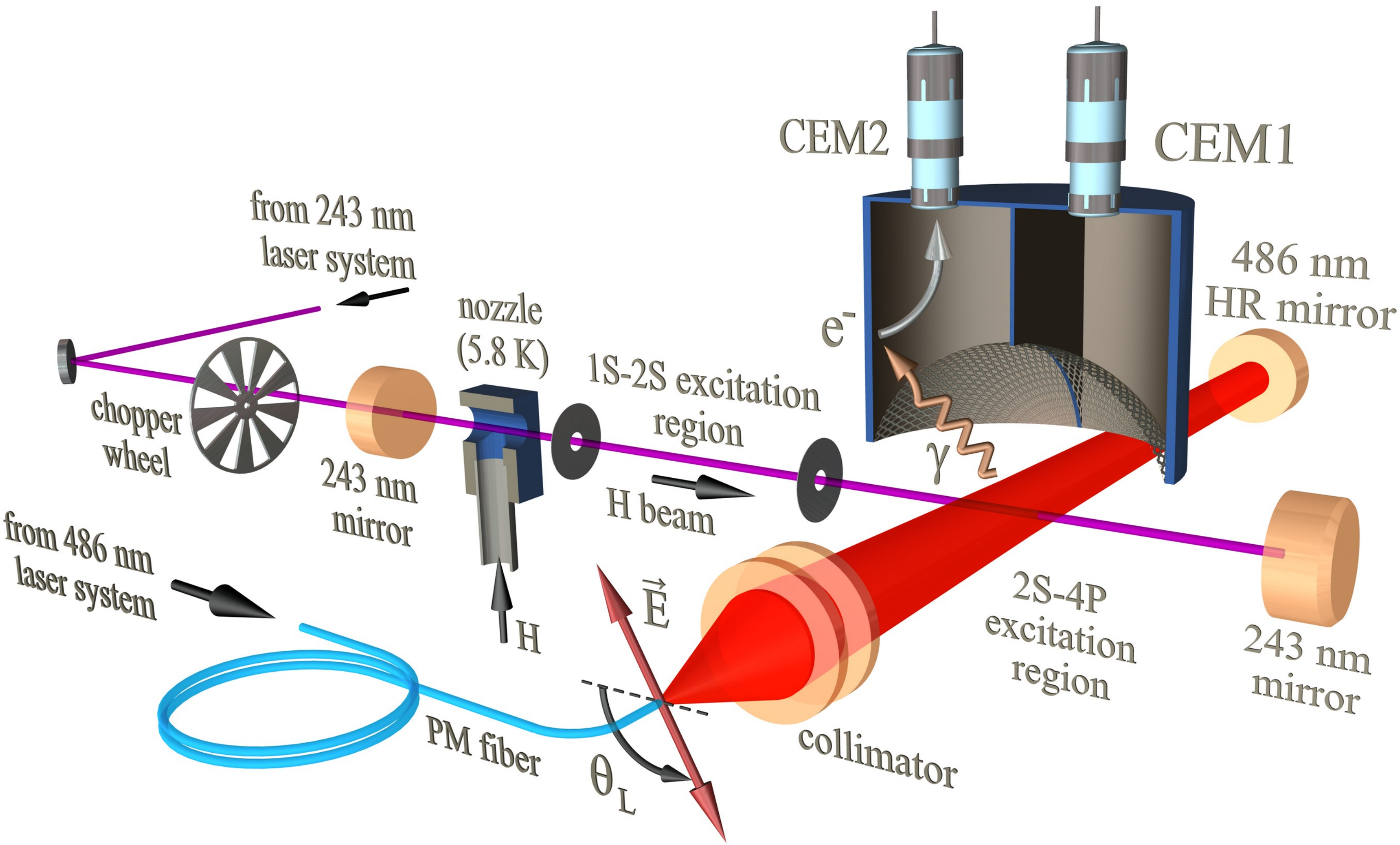
+ cross-term (QI)

Fitting this with 2 Lorentzians creates

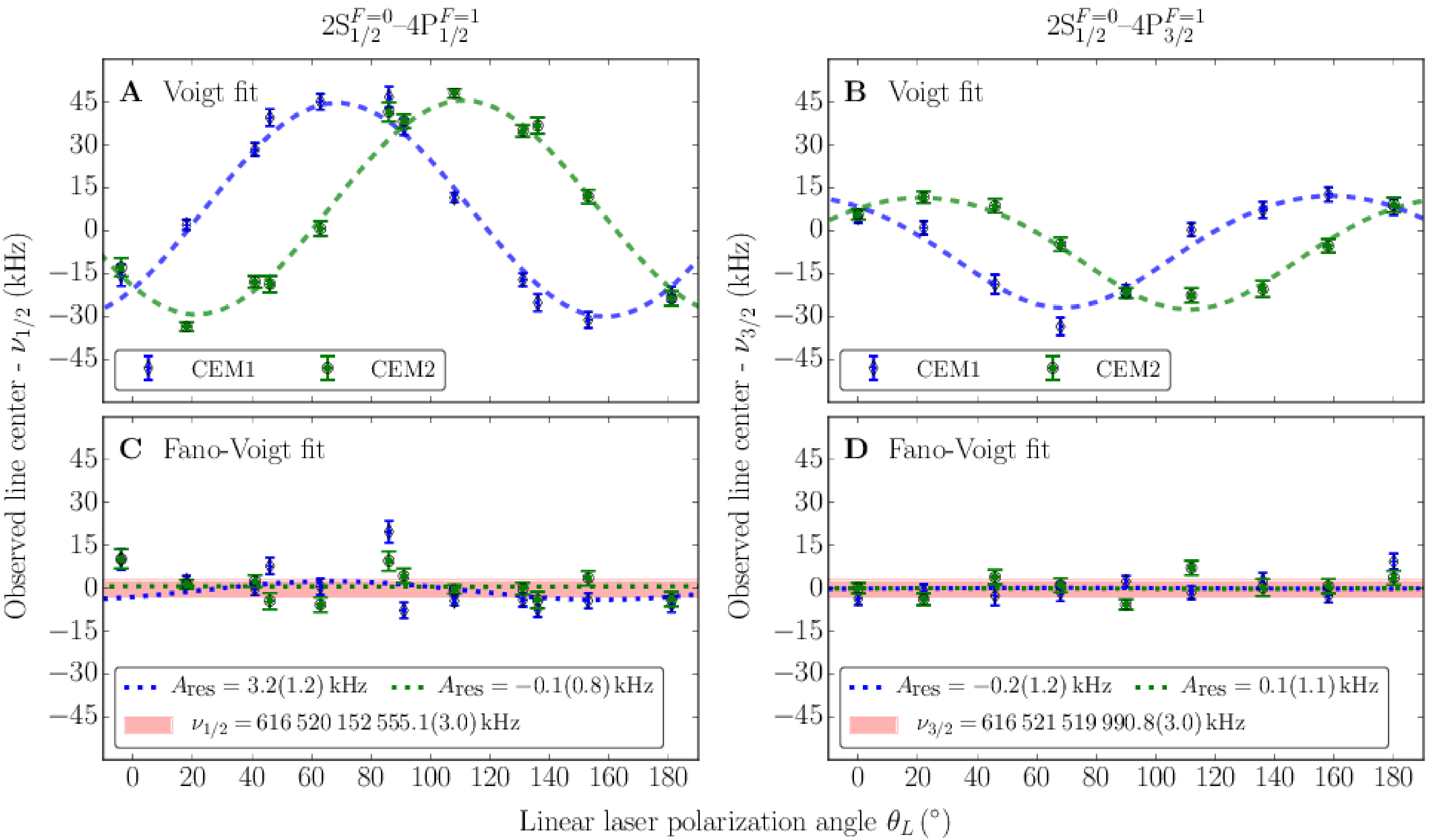
line shifts

see
Horbatsch, Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011); PRA 86 040501 (2012)
Sansonetti et al., PRL 107, 021001 (2011)
Brown et al., PRA 87, 032504 (2013)

Studying QI in 2S-4P



QI in hydrogen   (Δ = 100 Γ)

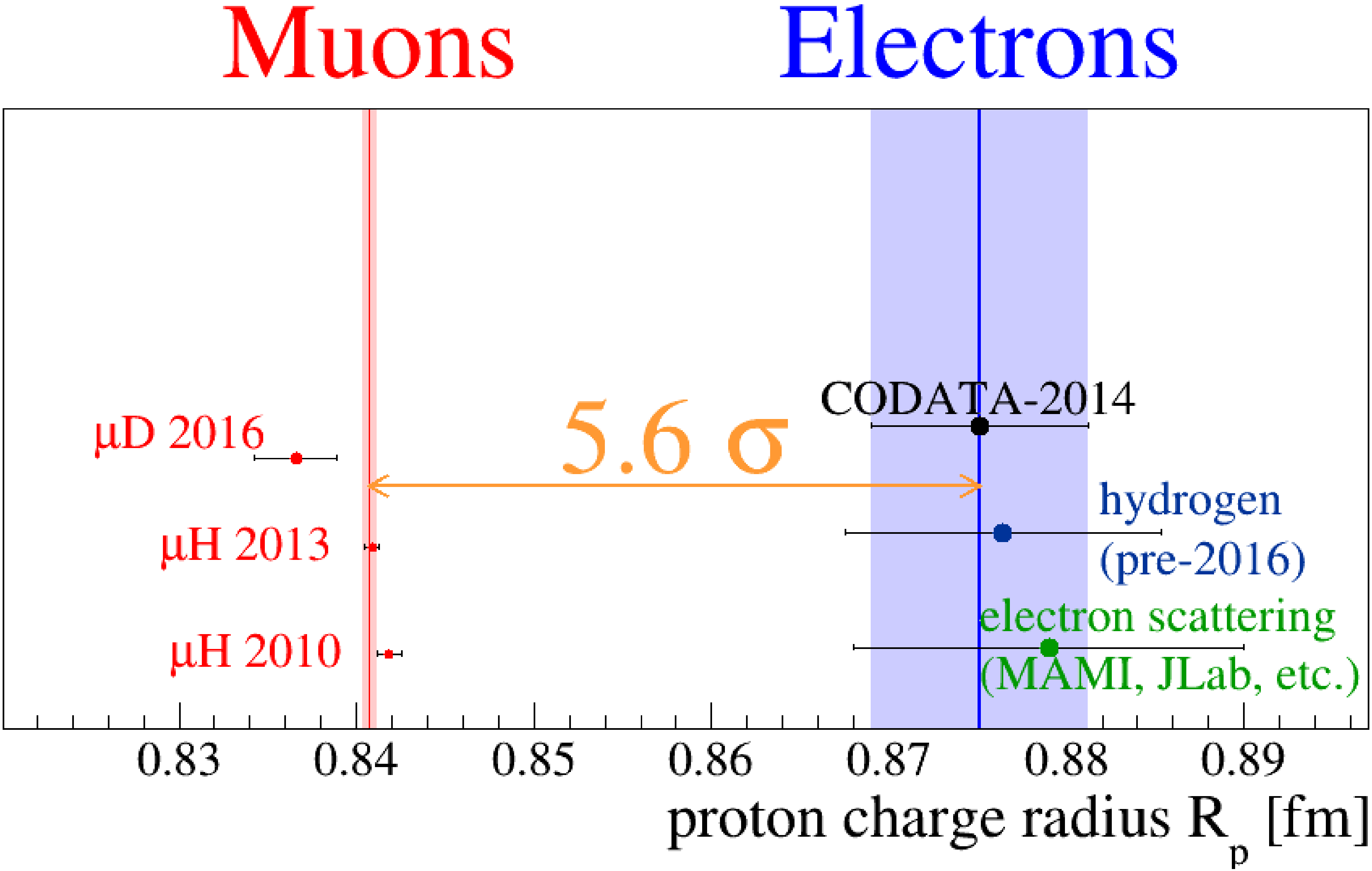


Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

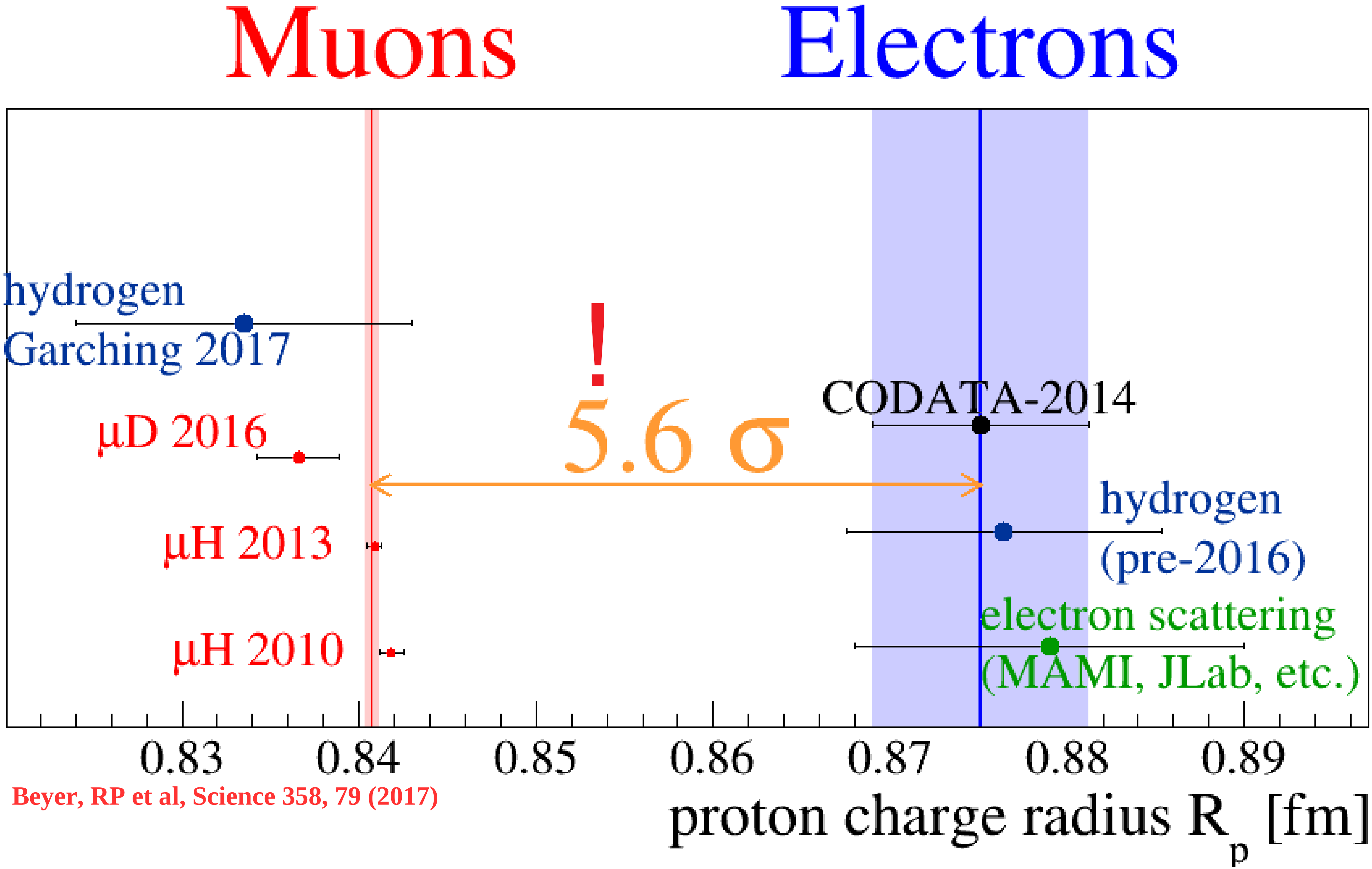
Systematics

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

The "Proton Radius Puzzle"

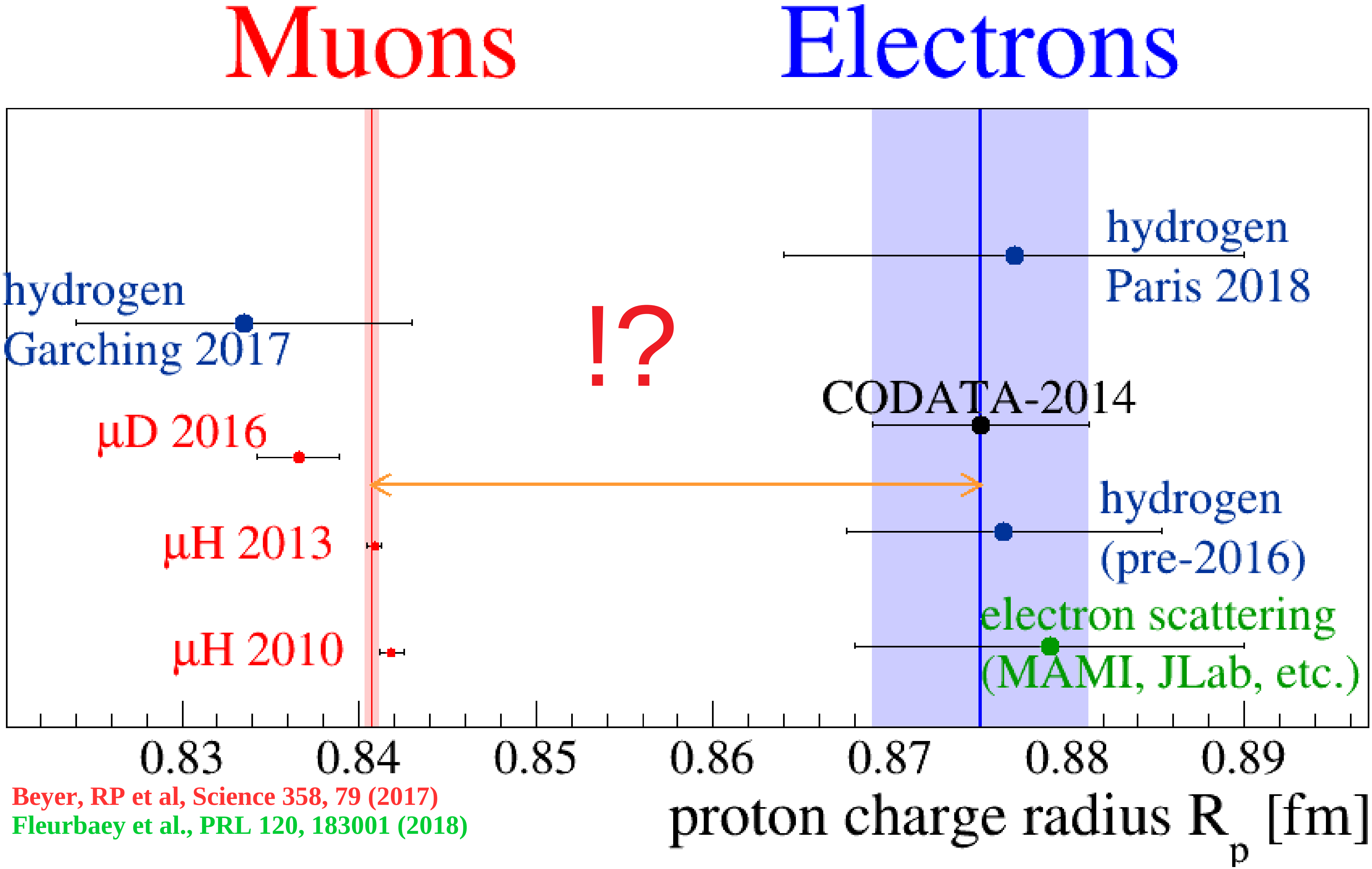


New Measurements: Garching 2S-4P



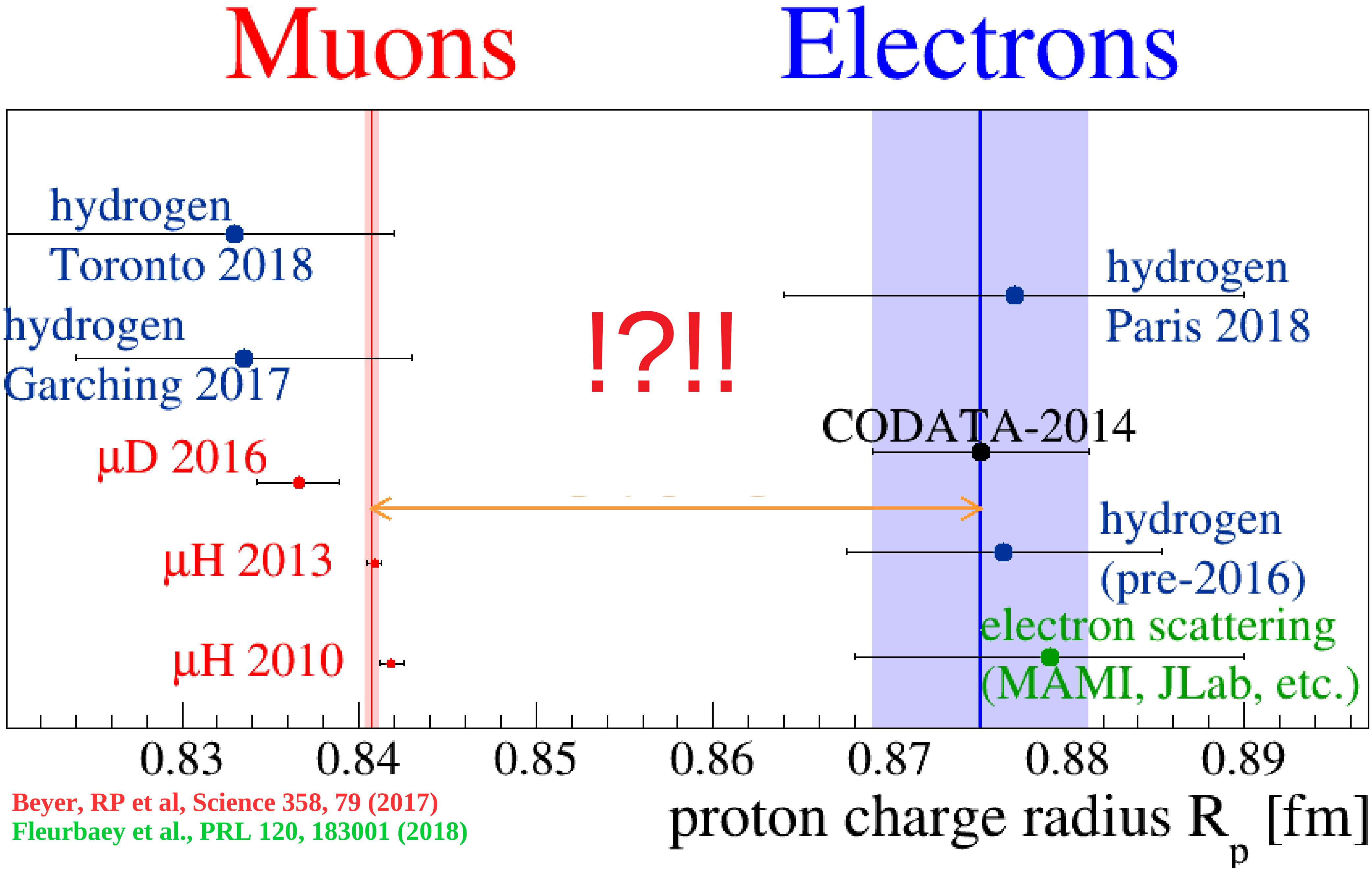
Beyer, RP et al, Science 358, 79 (2017)

New Measurements: Paris 1S-3S



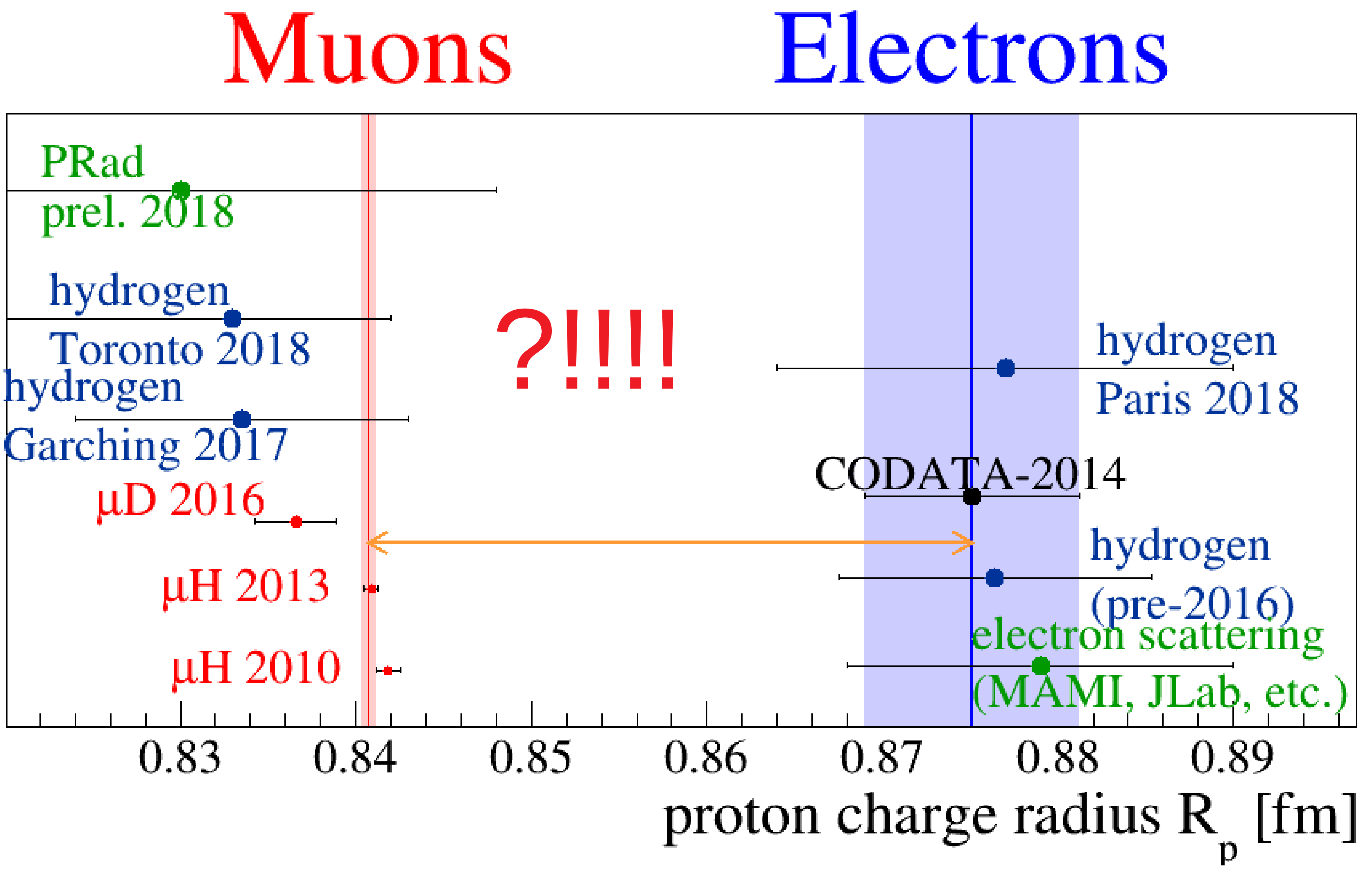
Beyer, RP et al, Science 358, 79 (2017)
Fleurbaey et al., PRL 120, 183001 (2018)

New Measurements: Toronto 2S-2P

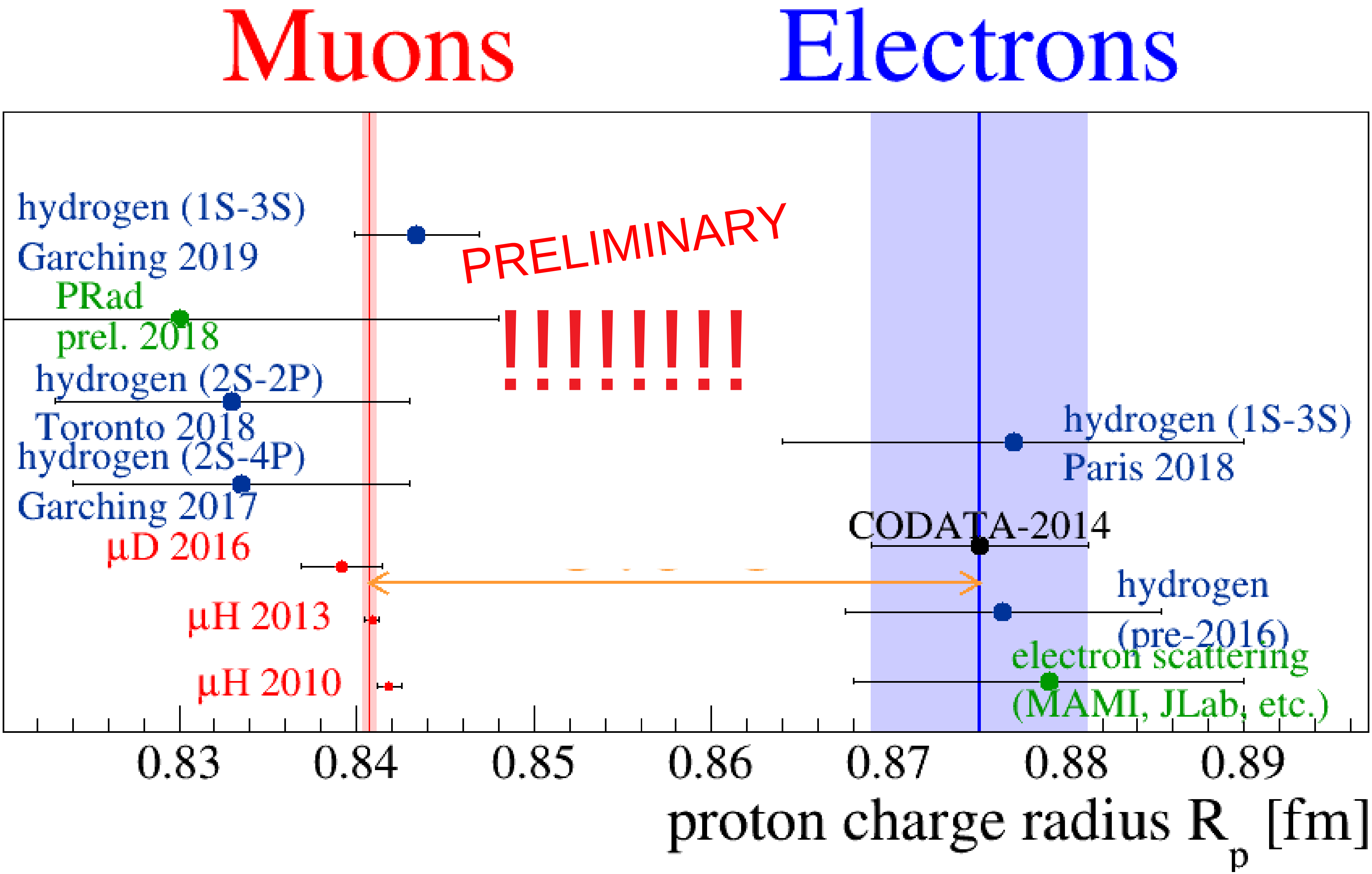


Beyer, RP et al, Science 358, 79 (2017)
Fleurbaey et al., PRL 120, 183001 (2018)

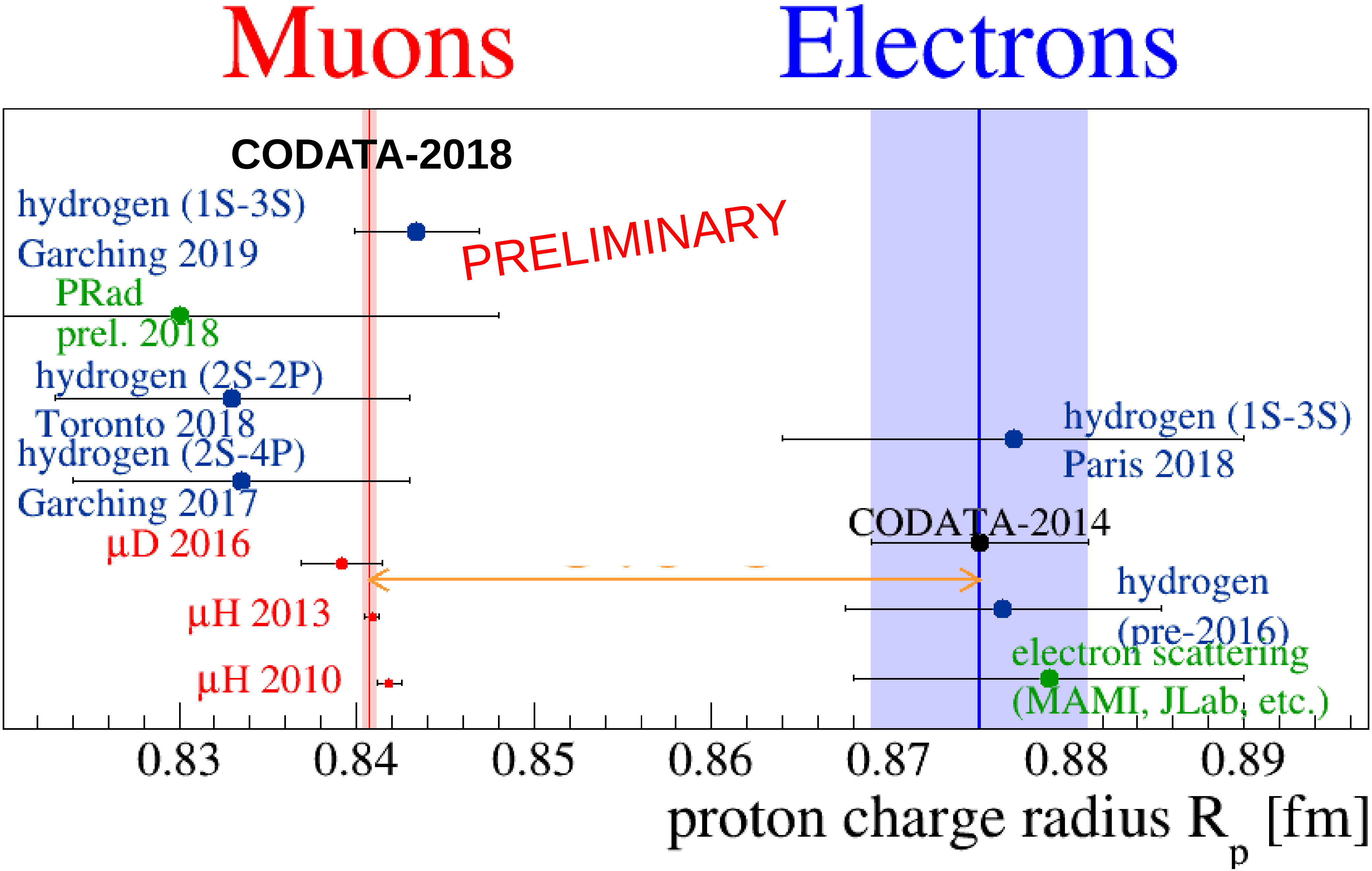
New Measurements: PRad



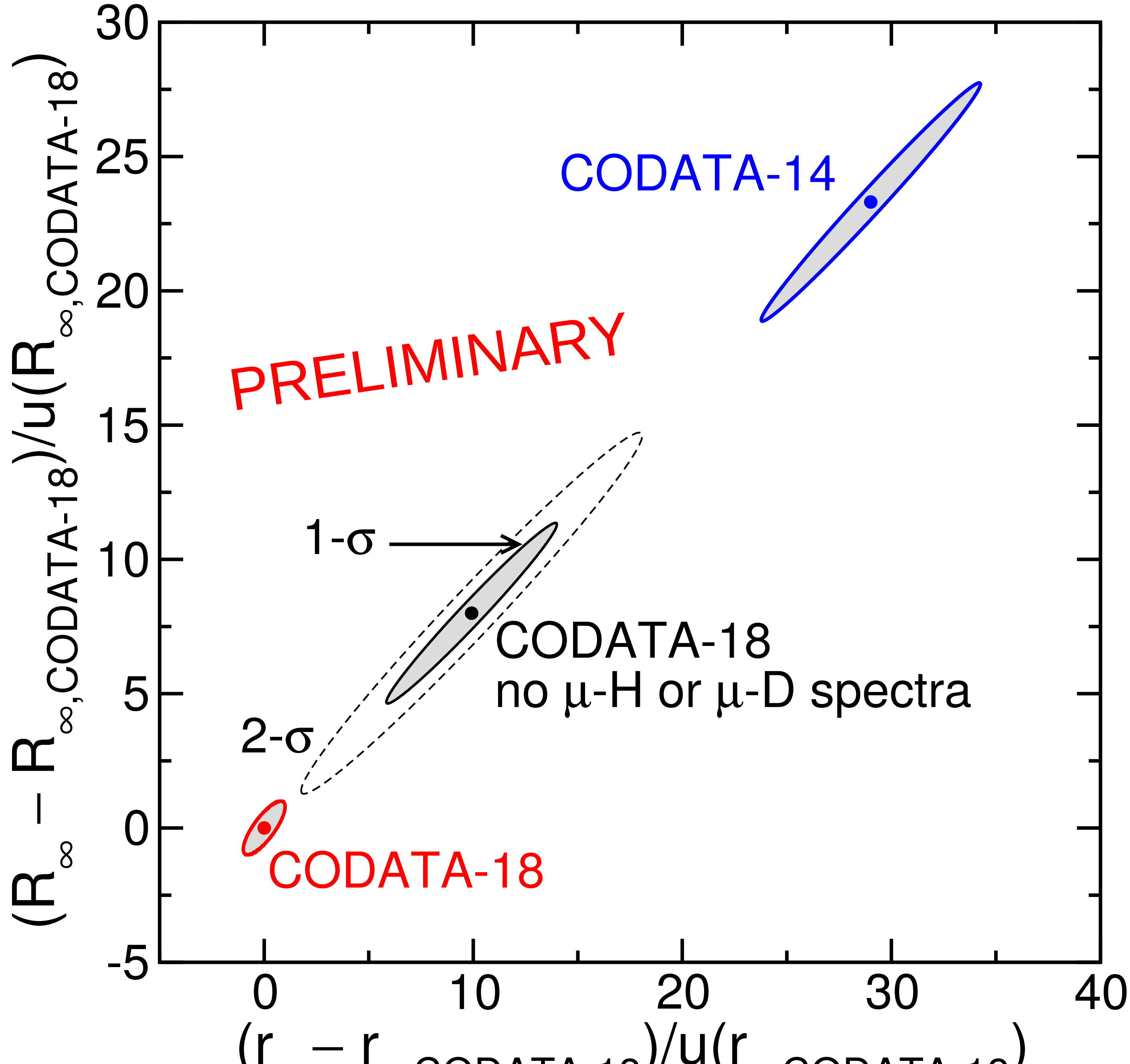
New Measurements: Garching 1S-3S



New: CODATA-2018



New: CODATA-2018



Proton radius,

Deuteron radius

and

Rydberg constant

smaller by >5σ

☺

Conclusions

- smaller radii from muonic **hydrogen** and **deuterium** imply a smaller Rydberg constant
- new H(2S-4P) gives small Rydberg constant in agreement with muonic values
- new H(2S-4P) gives thus a smaller proton radius, too
- new H(1S-3S) however confirms large proton radius

More data needed:

- H(2S – 6P, 8P, 9P, …) and D(2S-nl) underway in Garching and Colorado
- H(1S – 3S, 4S, ..) underway in Paris and Garching
- H(2S-2P) in Toronto (Hessels)
- Muonium
- Positronium (Cassidy, Crivelli)
- He^+(1S-2S) underway in Garching (Udem) and Amsterdam (Eikema)
- HD^+, H_2, etc. in Paris, Amsterdam

- new low-Q^2 electron scattering at MAMI, JLab, MESA
- muon scattering: MUSE @ PSI, COMPASS @ CERN

Workshop: The “Proton Radius Puzzle”

ECT* Trento, Okt. 2012

47 Teilnehmer
- Theorie + Experiment
- Atomphysik
- Kernphysik
- Teilchenphysik
- Elektronenstreuung
- “Beyond Standard Model”

38 Vorträge
3 “Fighting Sessions”

Am Schluss: Abstimmung

→ Meßfehler

Wir brauchen neue Daten.

Erklärungsversuche

Meßfehler

myonischer Wasserstoff

oder

Wasserstoff UND Elektronenstreuung

Theoriefehler

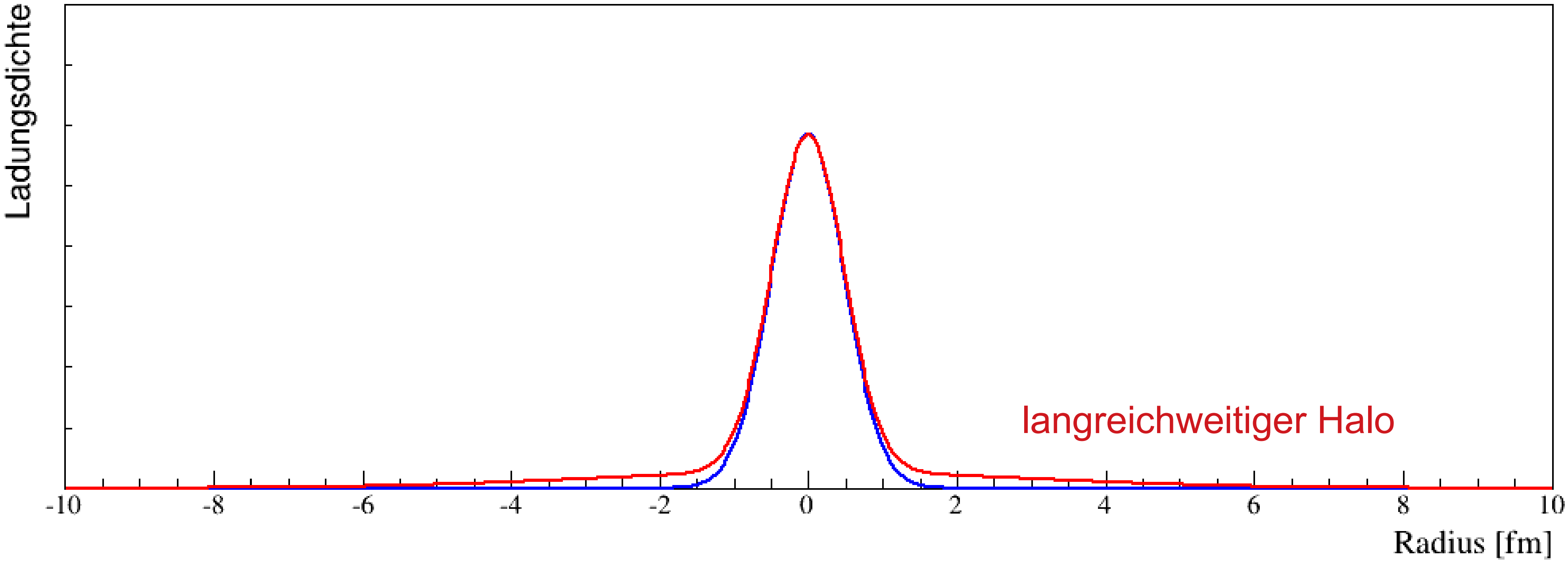
$$\Delta E = 209.998 - 5.226\, \mathbf{R_p}^2$$

Fehler im Standard-Modell der Teilchenphysik!

Das Proton schaut anders aus!

Das Proton ist keine feste Kugel.

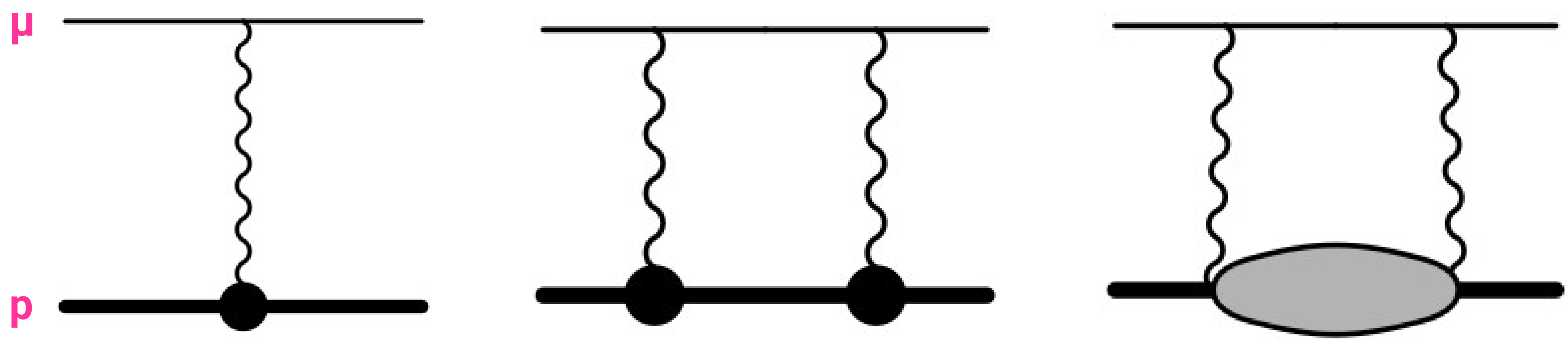
Die (radiale) Ladungsverteilung schaut anders aus!



Würde die Diskrepanz erklären!
Ist jedoch im Widerspruch zu Messungen des Halos (e-p Streuung).

3rd Zemach moment: 37 fm^3 vs. 2.7 ± 0.1 fm^3

Das Myon verändert das Proton



1-Photon-Austausch

2-Photonen-Austausch (elastisch)

2-Photonen-Austausch (inelastisch)

Ladungsradius

Proton-"Halo"

Protonen-Polarisierbarkeit

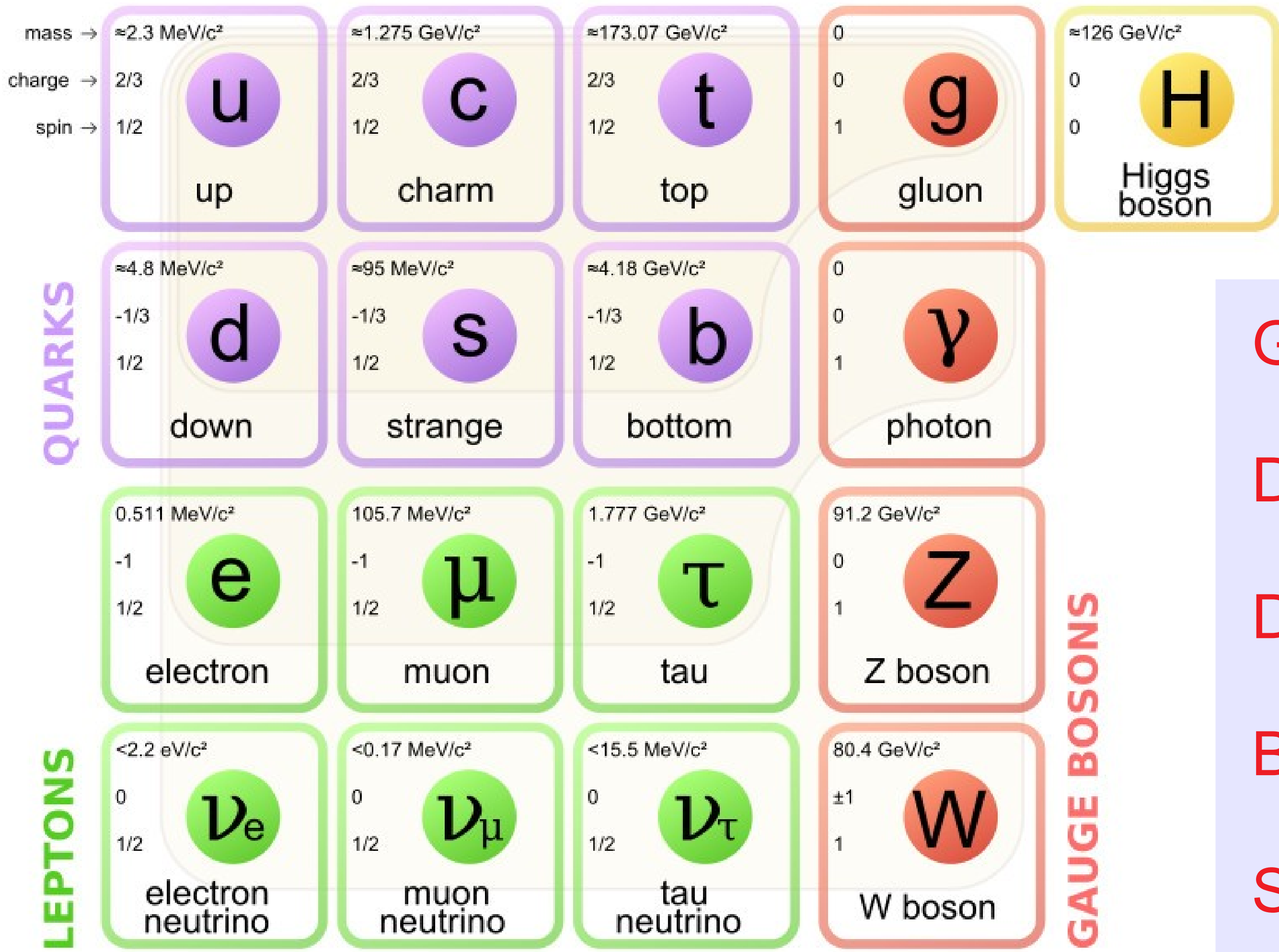
Ja! Die sog. "Polarisierbarkeit des Protons"

Aber der Effekt ist schon berücksichtigt und viel zu klein!

Diskrepanz: 0.31 meV

Polarisierbarkeit: 0.0127 ± 0.0005 meV

Ein neues Teilchen!



Gravitation!

Dunkle Materie?

Dunkle Energie?

Baryonen-Asymmetrie!

Starkes CP-Problem!

...

Ein neues Teilchen!

Physik jenseits des Standardmodells

könnte im Prinzip für die Diskrepanz verantwortlich sein!

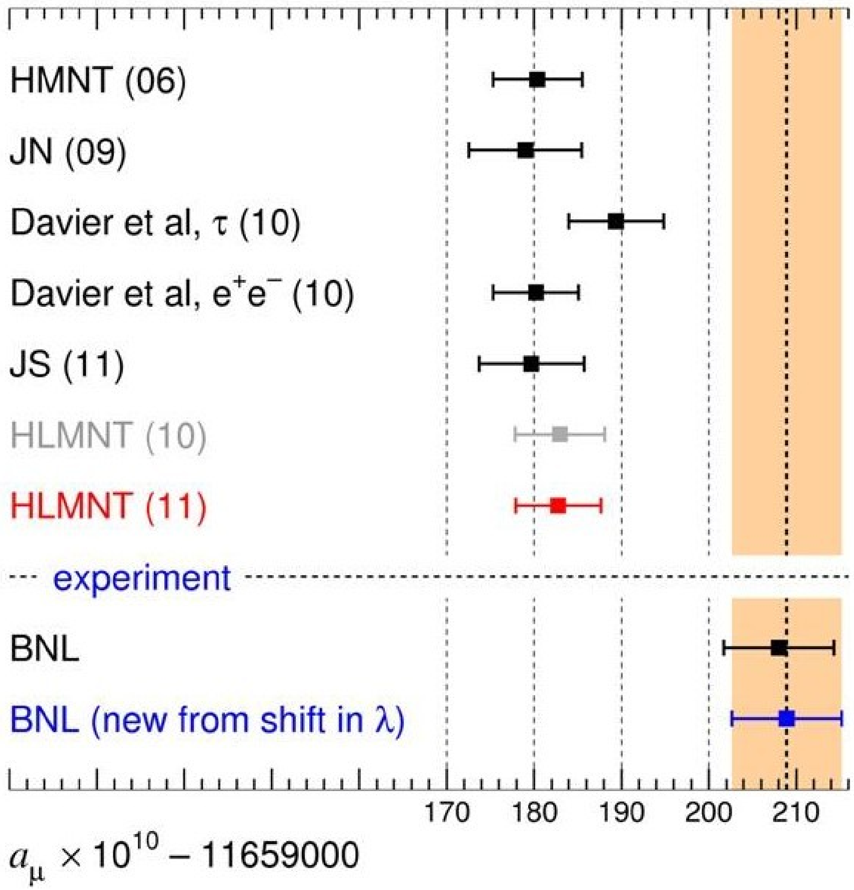
Das wäre ein neues Teilchen, das eine neue Kraft überträgt!

Diese Teilchen muß aber in das Korsett bestehender Messungen passen!

Schwierig.......

Das Myon macht uns **zwei** Probleme!

Anomales magnetisches Moment des Myons (g-2)

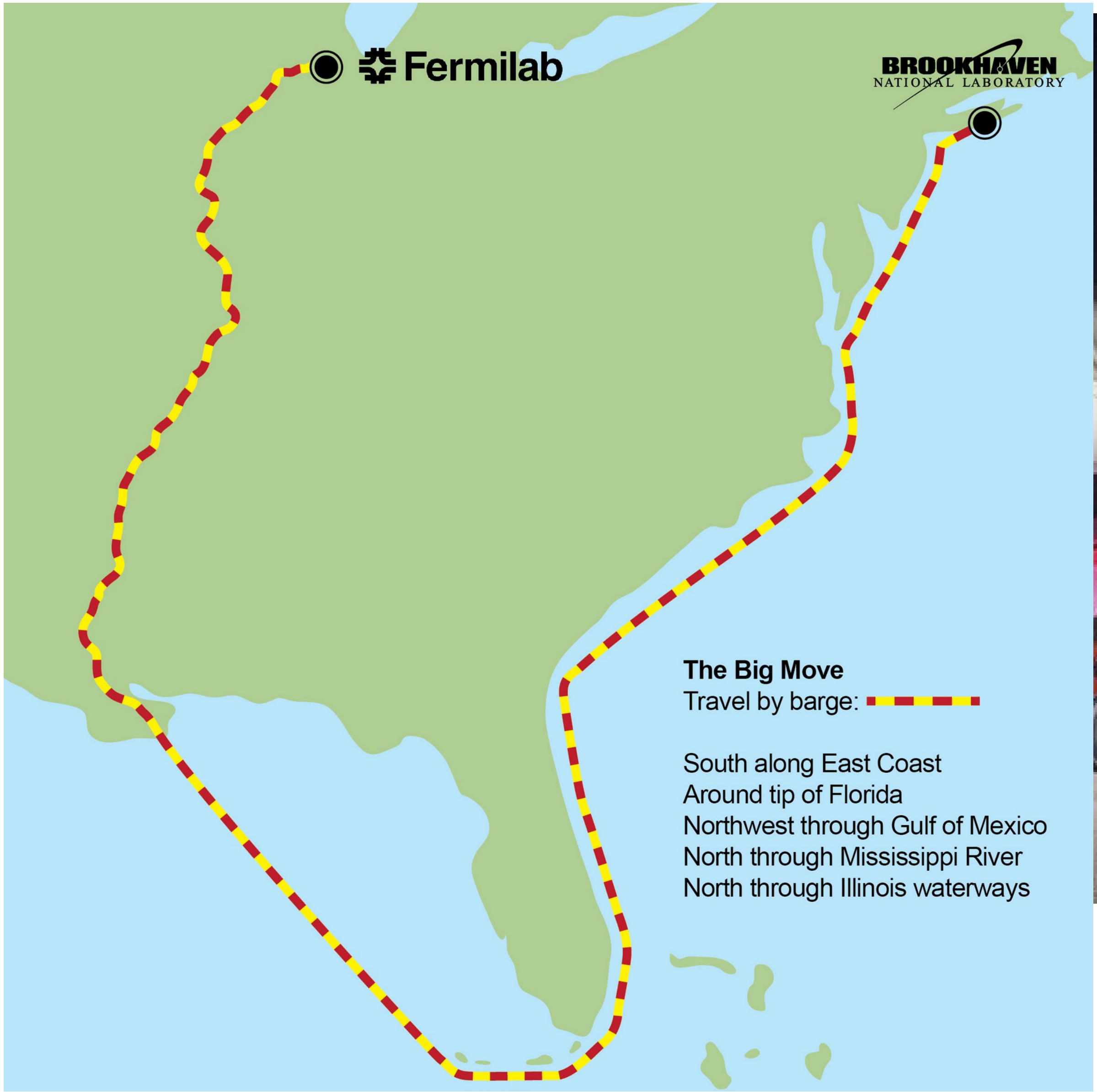


Theorie

Experiment

Seit 10 Jahren existiert eine ca. 3.6 σ Diskrepanz zum Standardmodell

Das neue Myon g-2 Experiment



Umzug: Sommer 2013
Messung: 2017/18

Zusammenfassung

Das Rätsel um das geschrumpfte Proton ist ungelöst.

Vielleicht will uns das Myon etwas sagen?

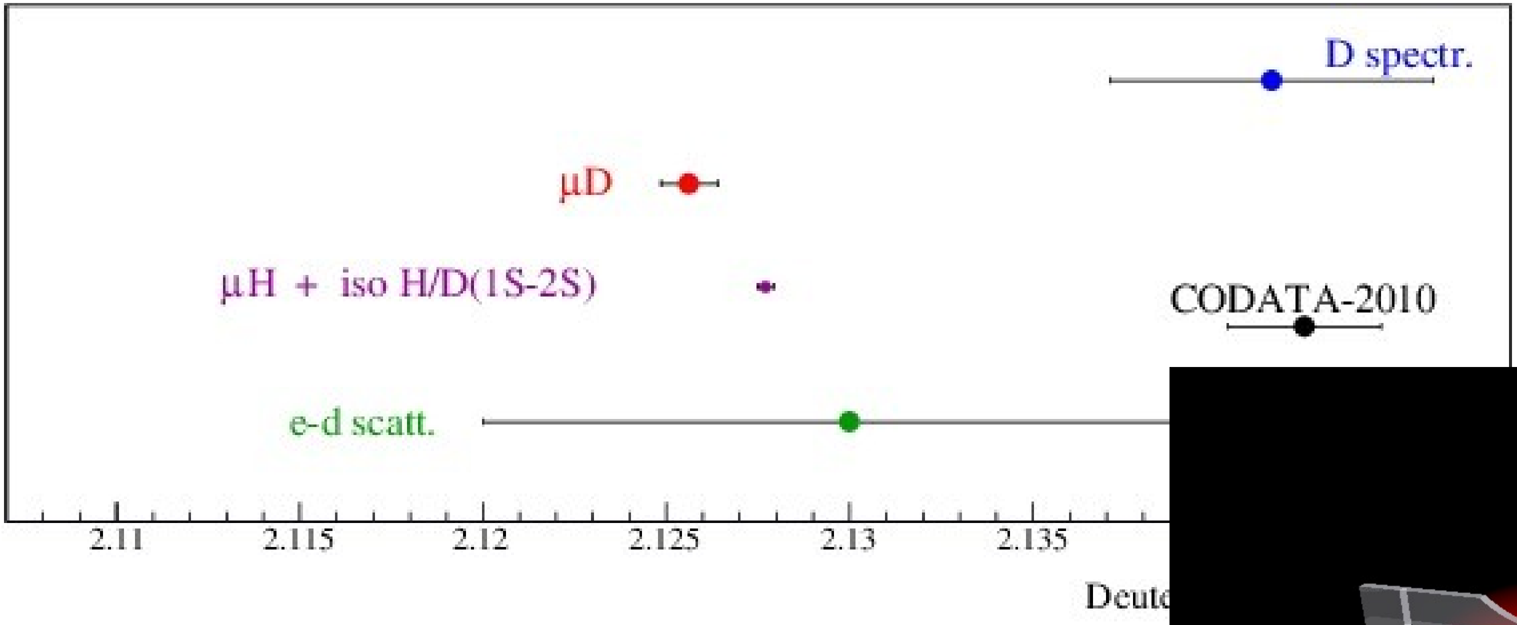
Oder ein Meßfehler?

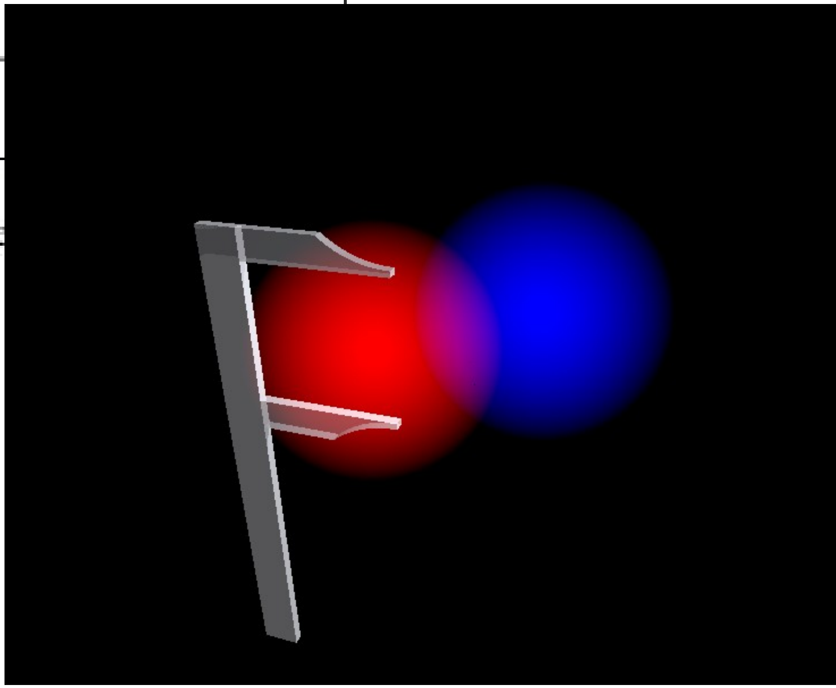
Eine Menge neuer Experimente sind auf dem Weg.

Zum Beispiel: Myonisches **Deuterium**

Radius des Deuterons

Lamb-Verschiebung in myonischem Deuterium





Deuteron is KONSISTENT zu klein!

$$R_d^2 = R^2_{struct} + R_p^2 + R_n^2 \ (+ DF)$$

Pohl et al. (CREMA), Science 353, 669 (2016)
RP, Physik in unserer Zeit 47, 266 (2016)

Zusammenfassung

Das Rätsel um das geschrumpfte Proton ist ungelöst.

Vielleicht will uns das Myon etwas sagen?

Oder ein Meßfehler?

Eine Menge neuer Experimente sind
auf dem Weg.

Es bleibt spannend.....

Jan Bernauer & RP,
April 2014

Proton Size Investigators thank you for your attention

Up next: Hyperfine structure in μp

The 21 cm line in hydrogen (1S hyperfine splitting) has been **measured** to 12 digits (1 mHz) in 1971:

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

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

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

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

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

Proton Zemach radius

HFS depends on “Zemach” radius:

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

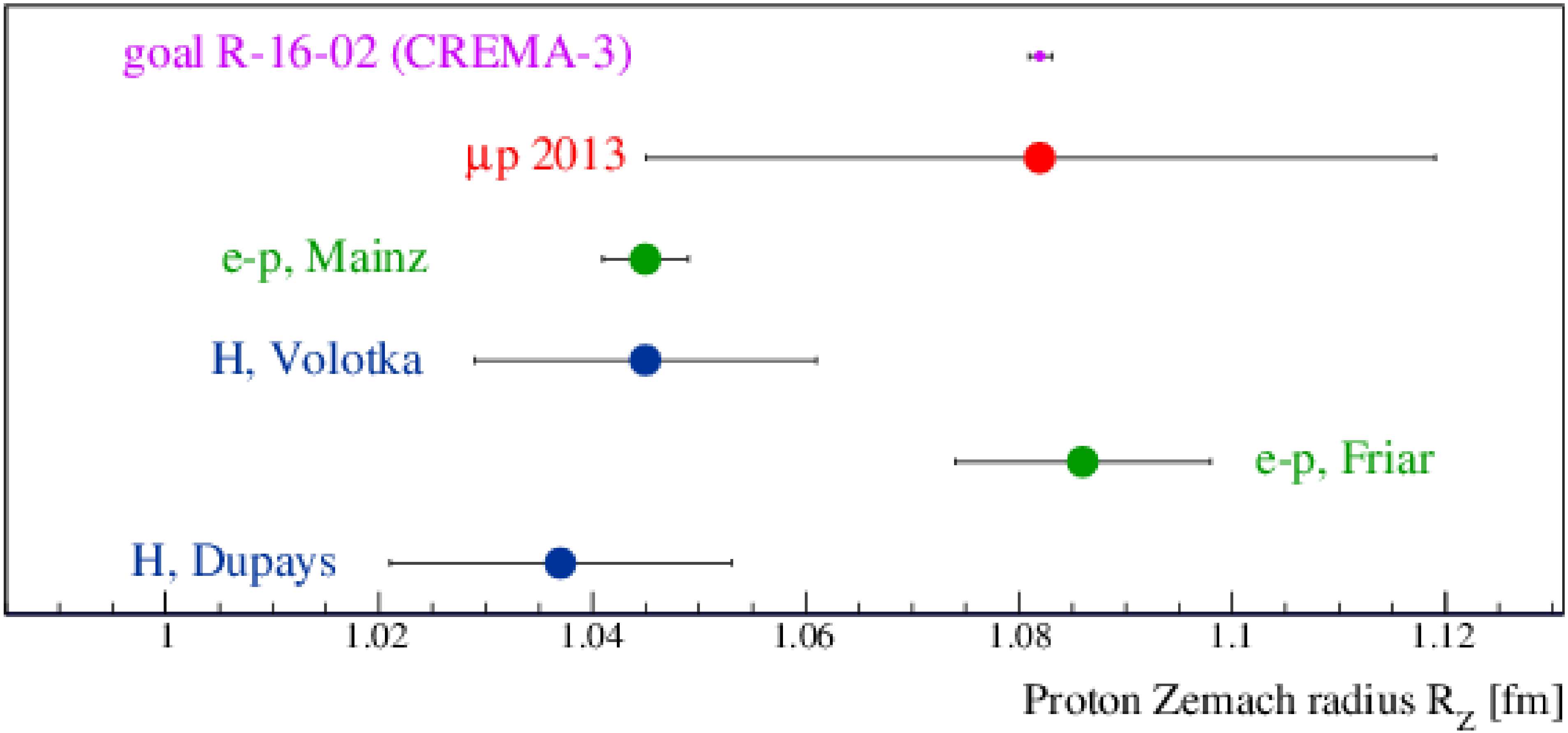
$$\langle r \rangle_{(2)} = \int d^3r\, d^3r'\, \rho_E(r)\, \rho_M(r')\, |r - r'|$$

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

Form factors and momentum space

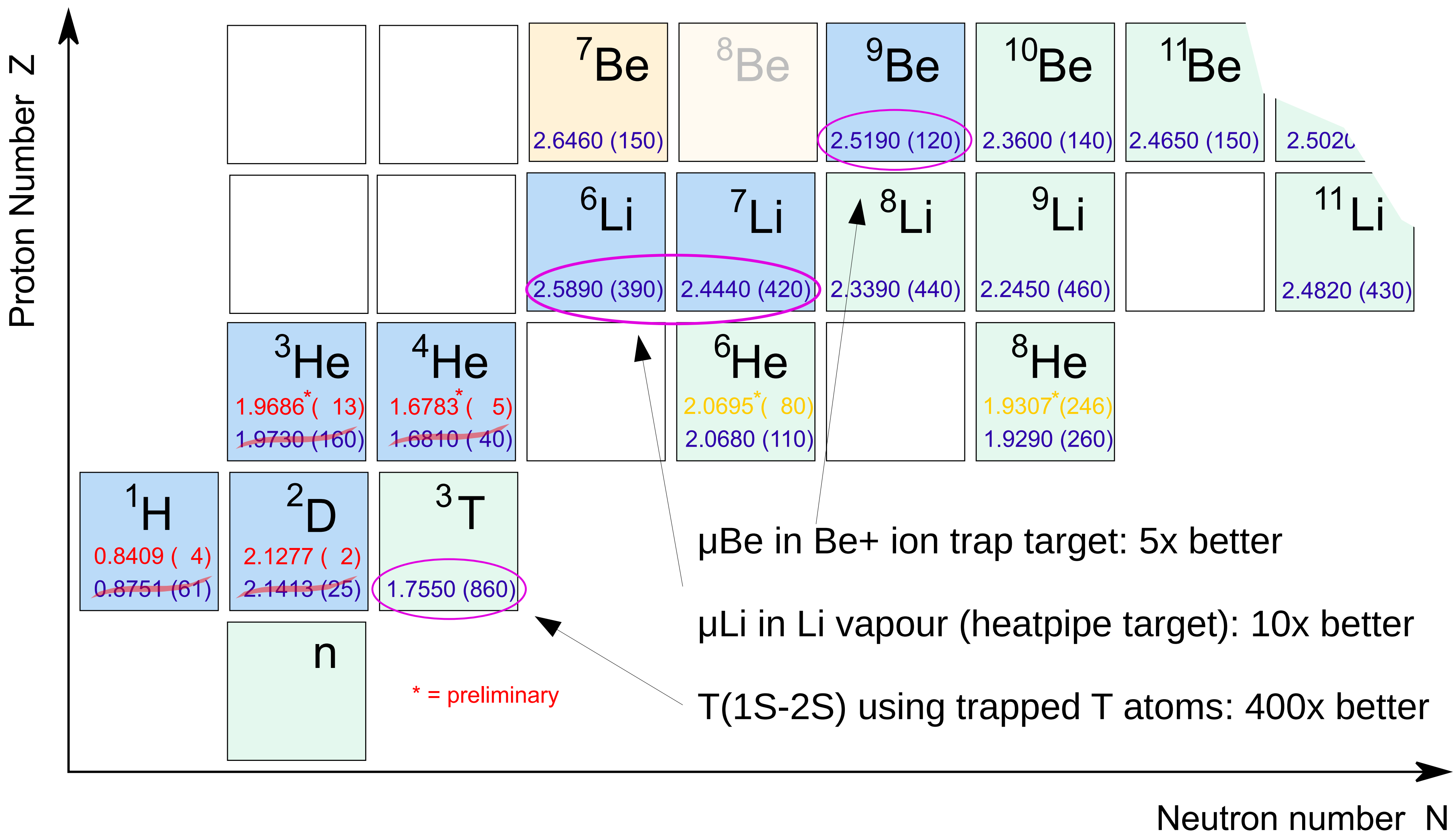
$$\Delta E = \frac{8(Z\alpha)m}{\pi n^3} E_F \int_0^\infty \frac{dk}{k^2} \left[\frac{G_E(-k^2)\, G_M(-k^2)}{1+\kappa} \right]$$

Proton Zemach radius from µp



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

Charge radii: The future



Thanks a lot for your attention

The Garching Hydrogen Team:

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

The CREMA Collaboration:

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

Thanks a lot for your attention

My new Mainz group:

Jan Haack, Rishi Horn, Ahmed Ouf, Stefan Schmidt, Lukas Schumacher, Gregor Schwendler, Andreas Wieltsch, Marcel Willig

The Garching Hydrogen Team:

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

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The Garchin

Ax ... ,
Ksenia ... . Yost,
Th ... em

The CREMA

Aldo Antogr ... R. Cardoso,
Daniel S. ... Luis M. P.
Fernande ... eodor W.
Hänsch, Pa ... mann, Eric-
Olivier Le B ... istina M. B.
Montei ... z, Paul
Rabino ... arsten
Schuhma ... eloso, RP

...

CODATA “sub-adjustments”

Adj. 3: “The Adjustment” (all data) Rp = 0.8775(51) fm, Rd = 2.1424(21) fm
Adj. 8: H spectroscopy only Rp = 0.8764(89) fm
Adj. 10: D spectroscopy only Rd = 2.1210(250) fm

TABLE XXXVIII. Summary of the results of some of the least-squares adjustments used to analyze the input data related to R_∞. The values of R_∞, r_p, and r_d are those obtained in the indicated adjustment, N is the number of input data, M is the number of adjusted constants, $\nu = N - M$ is the degrees of freedom, and $R_B = \sqrt{\chi^2/\nu}$ is the Birge ratio. See the text for an explanation and discussion of each adjustment. In brief, adjustment 6 is 3 but the scattering data for the nuclear radii are omitted; 7 is 3, but with only the hydrogen data included (no isotope shift); 8 is 7 with the r_p data deleted; 9 and 10 are similar to 7 and 8, but for the deuterium data; 11 is 3 with the muonic Lamb-shift value of r_p included; and 12 is 11, but without the scattering values of r_p and r_d.

Adj.	N	M	ν	χ^2	R_B	R_∞ (m^{-1})	$u_r(R_\infty)$	r_p (fm)	r_d (fm)
3	149	82	67	58.1	0.93	10 973 731.568 539(55)	5.0×10^{-12}	0.8775(51)	2.1424(21)
6	146	82	64	55.5	0.93	10 973 731.568 521(82)	7.4×10^{-12}	0.8758(77)	2.1417(31)
7	131	72	59	53.4	0.95	10 973 731.568 561(60)	5.5×10^{-12}	0.8796(56)	
8	129	72	57	52.5	0.96	10 973 731.568 528(94)	8.6×10^{-12}	0.8764(89)	
9	114	65	49	46.9	0.98	10 973 731.568 37(13)	1.1×10^{-11}		2.1288(93)
10	113	65	48	46.8	0.99	10 973 731.568 28(30)	2.7×10^{-11}		2.121(25)
11	150	82	68	104.9	1.24	10 973 731.568 175(12)	1.1×10^{-12}	0.842 25(65)	2.128 24(28)
12	147	82	65	74.3	1.07	10 973 731.568 171(12)	1.1×10^{-12}	0.841 93(66)	2.128 11(28)

Spectroscopy data in CODATA

TABLE XI. Summary of measured transition frequencies ν considered in the present work for the determination of the Rydberg constant R_∞ (H is hydrogen and D is deuterium).

Authors	Laboratory[a]	Frequency interval(s)	Reported value ν (kHz)	Rel. stand. uncert. u_r	
(Fischer *et al.*, 2004)	MPQ	$\nu_H(1S_{1/2} - 2S_{1/2})$	2 466 061 413 187.080(34)	1.4×10^{-14}	H(1S-2S)
(Weitz *et al.*, 1995)	MPQ	$\nu_H(2S_{1/2} - 4S_{1/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	4 797 338(10)	2.1×10^{-6}	
		$\nu_H(2S_{1/2} - 4D_{5/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	6 490 144(24)	3.7×10^{-6}	
		$\nu_D(2S_{1/2} - 4S_{1/2}) - \frac{1}{4}\nu_D(1S_{1/2} - 2S_{1/2})$	4 801 693(20)	4.2×10^{-6}	
		$\nu_D(2S_{1/2} - 4D_{5/2}) - \frac{1}{4}\nu_D(1S_{1/2} - 2S_{1/2})$	6 494 841(41)	6.3×10^{-6}	
(Parthey *et al.*, 2010)	MPQ	$\nu_D(1S_{1/2} - 2S_{1/2}) - \nu_H(1S_{1/2} - 2S_{1/2})$	670 994 334.606(15)	2.2×10^{-11}	D(1S-2S) –
(de Beauvoir *et al.*, 1997)	LKB/SYRTE	$\nu_H(2S_{1/2} - 8S_{1/2})$	770 649 350 012.0(8.6)	1.1×10^{-11}	H(1S-2S)
		$\nu_H(2S_{1/2} - 8D_{3/2})$	770 649 504 450.0(8.3)	1.1×10^{-11}	
		$\nu_H(2S_{1/2} - 8D_{5/2})$	770 649 561 584.2(6.4)	8.3×10^{-12}	(iso shift)
		$\nu_D(2S_{1/2} - 8S_{1/2})$	770 859 041 245.7(6.9)	8.9×10^{-12}	
		$\nu_D(2S_{1/2} - 8D_{3/2})$	770 859 195 701.8(6.3)	8.2×10^{-12}	
		$\nu_D(2S_{1/2} - 8D_{5/2})$	770 859 252 849.5(5.9)	7.7×10^{-12}	
(Schwob *et al.*, 1999)	LKB/SYRTE	$\nu_H(2S_{1/2} - 12D_{3/2})$	799 191 710 472.7(9.4)	1.2×10^{-11}	
		$\nu_H(2S_{1/2} - 12D_{5/2})$	799 191 727 403.7(7.0)	8.7×10^{-12}	
		$\nu_D(2S_{1/2} - 12D_{3/2})$	799 409 168 038.0(8.6)	1.1×10^{-11}	
		$\nu_D(2S_{1/2} - 12D_{5/2})$	799 409 184 966.8(6.8)	8.5×10^{-12}	
(Arnoult *et al.*, 2010)	LKB	$\nu_H(1S_{1/2} - 3S_{1/2})$	2 922 743 278 678(13)	4.4×10^{-12}	
(Bourzeix *et al.*, 1996)	LKB	$\nu_H(2S_{1/2} - 6S_{1/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 3S_{1/2})$	4 197 604(21)	4.9×10^{-6}	
		$\nu_H(2S_{1/2} - 6D_{5/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 3S_{1/2})$	4 699 099(10)	2.2×10^{-6}	
(Berkeland, Hinds, and Boshier, 1995)	Yale	$\nu_H(2S_{1/2} - 4P_{1/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	4 664 269(15)	3.2×10^{-6}	
		$\nu_H(2S_{1/2} - 4P_{3/2}) - \frac{1}{4}\nu_H(1S_{1/2} - 2S_{1/2})$	6 035 373(10)	1.7×10^{-6}	
(Hagley and Pipkin, 1994)	Harvard	$\nu_H(2S_{1/2} - 2P_{3/2})$	9 911 200(12)	1.2×10^{-6}	
(Lundeen and Pipkin, 1986)	Harvard	$\nu_H(2P_{1/2} - 2S_{1/2})$	1 057 845.0(9.0)	8.5×10^{-6}	
(Newton, Andrews, and Unsworth, 1979)	U. Sussex	$\nu_H(2P_{1/2} - 2S_{1/2})$	1 057 862(20)	1.9×10^{-5}	

[a]MPQ: Max-Planck-Institut für Quantenoptik, Garching. LKB: Laboratoire Kastler-Brossel, Paris. SYRTE: Systèmes de référence Temps Espace, Paris, formerly Laboratoire Primaire du Temps et des Fréquences (LPTF).

Spectroscopy data: H

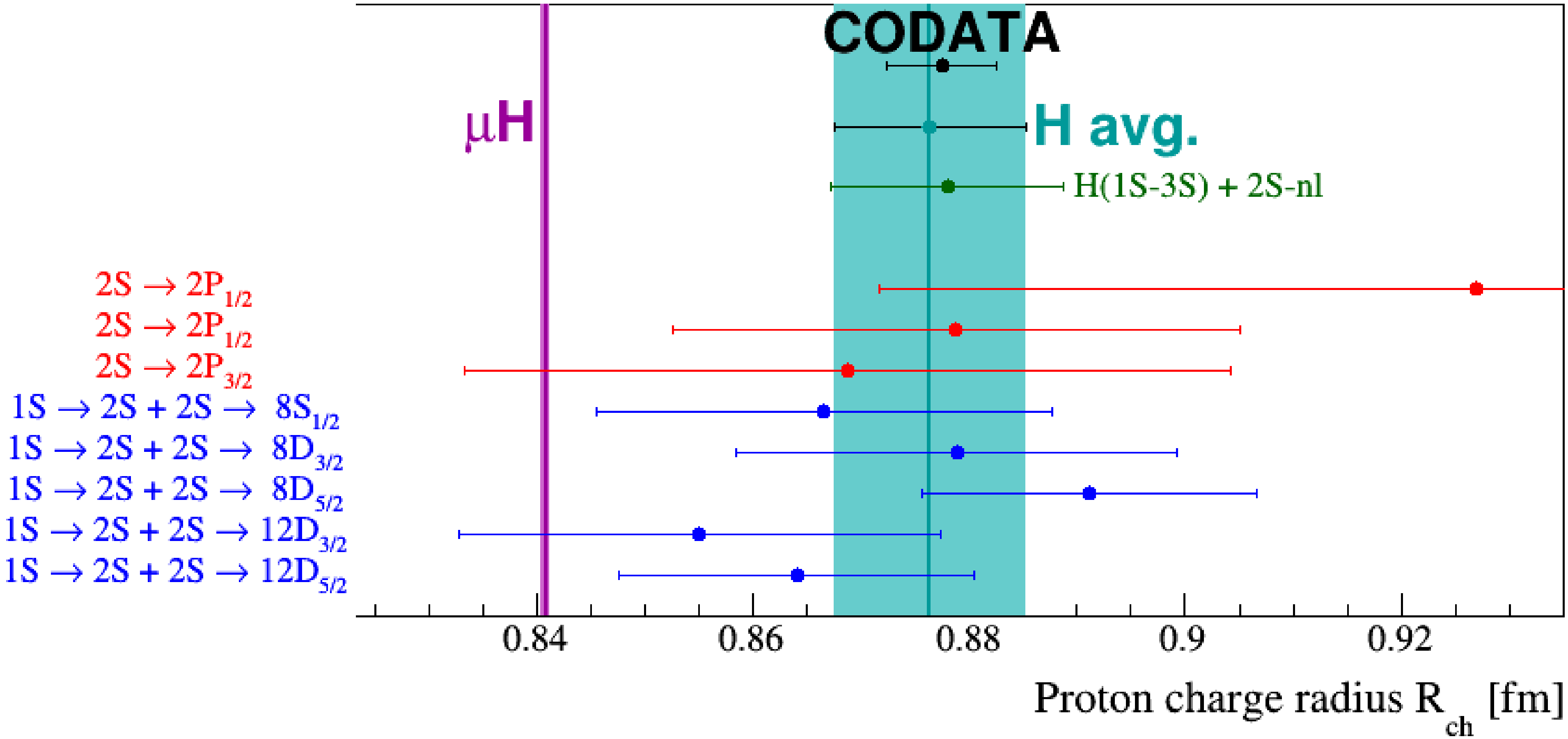
TABLE III: Some recent measurements in atomic hydrogen. An asterisk following the reference denotes items considered in the most recent CODATA-2010 report. Following our nomenclature, the $2S \to 2P_{1/2}$ transition must be assigned a negative frequency, because the final state $(n', \ell', j') = 2P_{1/2}$ is *lower* than the initial $(n, \ell, j) = 2S_{1/2}$ state.

#	$(n,\ell,j) - (n',\ell',j')$	ν_{meas} (kHz)	rel. unc.	Source	Ref.
H1	$2S_{1/2} \to 2P_{1/2}$	-1 057 862(20)	1.9×10^{-5}	Sussex 1979	[25] *
H2		-1 057 845.0(9.0)	8.5×10^{-6}	Harvard 1986	[26] *
H3	$2S_{1/2} \to 2P_{3/2}$	9 911 200(12)	1.2×10^{-6}	Harvard 1994	[27] *
H4	$2S_{1/2} \to 8S_{1/2}$	770 649 350 012.0(8.6)	1.1×10^{-11}	LKB 1997	[28] *
H5	$2S_{1/2} \to 8D_{3/2}$	770 649 504 450.0(8.3)	1.1×10^{-11}	LKB 1997	[28] *
H6	$2S_{1/2} \to 8D_{5/2}$	770 649 561 584.2(6.4)	8.3×10^{-12}	LKB 1997	[28] *
H7	$2S_{1/2} \to 12D_{3/2}$	799 191 710 472.7(9.4)	1.1×10^{-11}	LKB 1999	[29] *
H8	$2S_{1/2} \to 12D_{5/2}$	799 191 727 403.7(7.0)	8.7×10^{-12}	LKB 1999	[29] *
H9	$1S_{1/2} \to 2S_{1/2}$	2 466 061 413 187.103(46)	1.9×10^{-14}	MPQ 2000	[30]
H10		2 466 061 413 187.080(34)	1.4×10^{-14}	MPQ 2004	[31] *
H11		2 466 061 413 187.035(10)	4.2×10^{-15}	MPQ 2011	[32]
H12		2 466 061 413 187.018(11)	4.5×10^{-15}	MPQ 2013	[33]
H13	$1S_{1/2} \to 3S_{1/2}$	2 922 743 278 678(13)	4.4×10^{-12}	LKB 2010	[34] *
H14		2 922 743 278 659(17)	5.8×10^{-12}	MPQ 2016	[35]

Rp from H spectroscopy

#	Transition	r_p [fm]	
H1	$2S \to 2P_{1/2}$	0.9270 ± 0.0553	
H2	$2S \to 2P_{1/2}$	0.8788 ± 0.0262	
H3	$2S \to 2P_{3/2}$	0.8688 ± 0.0354	
H10 + H4	$1S \to 2S + 2S \to 8S_{1/2}$	0.8666 ± 0.0211	
H10 + H5	$1S \to 2S + 2S \to 8D_{3/2}$	0.8789 ± 0.0204	
H10 + H6	$1S \to 2S + 2S \to 8D_{5/2}$	0.8911 ± 0.0155	
H10 + H7	$1S \to 2S + 2S \to 12D_{3/2}$	0.8551 ± 0.0222	
H10 + H8	$1S \to 2S + 2S \to 12D_{5/2}$	0.8641 ± 0.0164	
$1S \to 2S$ (H10) + all H($2S \to n\ell$)		0.8747 ± 0.0091	avg.
$1S \to 3S$ (H13+H14) + all H($2S \to n\ell$)		0.8780 ± 0.0108	
CODATA Adj. 8		0.8764 ± 0.0089	Eq. (18)

Rp from H spectroscopy



Spectroscopy data: D

TABLE V: Some recent measurements of the H-D isotope shift. An asterisk following the reference denotes items considered in the most recent CODATA-2010 report.

#	Transition	Frequency (kHz)	rel. unc.	Source	Ref.
I1	$1S_{1/2} \rightarrow 2S_{1/2}$	670 994 334.64(15)	2.2×10^{-10}	MPQ 1998	[7]
I2		670 994 334.606(15)	2.2×10^{-11}	MPQ 2010	[8] *

TABLE VI: Some recent measurements in atomic deuterium. An asterisk following the reference denotes items considered in the most recent CODATA-2010 report. Items D9 and D10 are direct measurements, while D11 and D12 have been constructed as justified in the text.

#	$(n, \ell, j) - (n', \ell', j')$	ν_{meas} (kHz)	rel. unc.	Source	Ref.
D4	$2S_{1/2} \rightarrow 8S_{1/2}$	770 859 041 245.7(6.9)	8.9×10^{-12}	LKB 1997	[28] *
D5	$2S_{1/2} \rightarrow 8D_{3/2}$	770 859 195 701.8(6.3)	8.2×10^{-12}	LKB 1997	[28] *
D6	$2S_{1/2} \rightarrow 8D_{5/2}$	770 859 252 849.5(5.9)	7.7×10^{-12}	LKB 1997	[28] *
D7	$2S_{1/2} \rightarrow 12D_{3/2}$	799 409 168 038.0(8.6)	1.1×10^{-11}	LKB 1999	[29] *
D8	$2S_{1/2} \rightarrow 12D_{5/2}$	799 409 184 966.8(6.8)	8.5×10^{-12}	LKB 1999	[29] *
D9	$1S_{1/2} \rightarrow 2S_{1/2}$	2 466 732 407 521.8(1.5)	6.1×10^{-13}	MPQ 1997	[36]
D10		2 466 732 407 522.88(91)	3.7×10^{-13}	MPQ 1997	[36]
D11		2 466 732 407 521.74(20)	7.9×10^{-14}	MPQ 1998/2000	H9 +I1
D12		2 466 732 407 521.641(25)	1.0×10^{-14}	MPQ 2010/2011	H11+I2

D only

H + iso

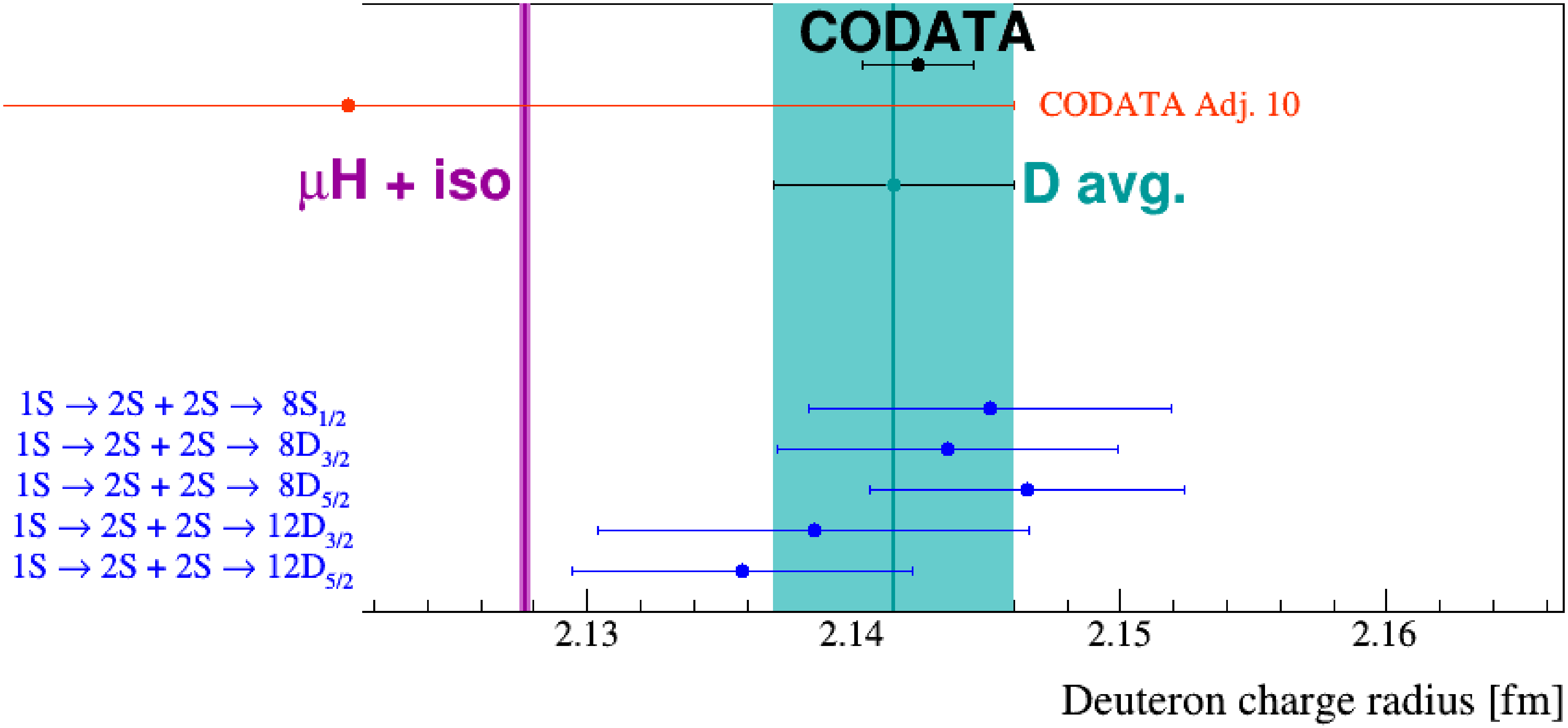
Rd from D spectroscopy

TABLE VII: Deuteron charge radii from deuterium. The value labelled "Eq. (19)" is our result. It is the average of the individual values above it, taking into account the known correlations between the $2S \rightarrow n\ell$ measurements. The next 2 values use items D9 and D10, which have not been measured using atomic hydrogen as a transfer oscillator (see text).

#	Transition	r_d [fm]	
D12 + D4	$1S \rightarrow 2S + 2S \rightarrow 8S_{1/2}$	2.1451 ± 0.0068	
D12 + D5	$1S \rightarrow 2S + 2S \rightarrow 8D_{3/2}$	2.1435 ± 0.0064	
D12 + D6	$1S \rightarrow 2S + 2S \rightarrow 8D_{5/2}$	2.1465 ± 0.0059	
D12 + D7	$1S \rightarrow 2S + 2S \rightarrow 12D_{3/2}$	2.1385 ± 0.0081	
D12 + D8	$1S \rightarrow 2S + 2S \rightarrow 12D_{5/2}$	2.1358 ± 0.0064	
	D12 + all D($2S \rightarrow n\ell$)	2.1415 ± 0.0045	Eq. (19)
	D9 + all D($2S \rightarrow n\ell$)	2.1414 ± 0.0045	
	D10 + all D($2S \rightarrow n\ell$)	2.1411 ± 0.0045	
	CODATA Adj. 10:	2.1214 ± 0.0253	

5.6 times more accurate!

Rd from D spectroscopy



Rd from D spectroscopy

WHICH 1S-2S we choose is IRRELEVANT!

#	Transition	r_d [fm]	
D12 + D4	$1S \to 2S + 2S \to 8S_{1/2}$	2.1451 ± 0.0068	
D12 + D5	$1S \to 2S + 2S \to 8D_{3/2}$	2.1435 ± 0.0064	
D12 + D6	$1S \to 2S + 2S \to 8D_{5/2}$	2.1465 ± 0.0059	
D12 + D7	$1S \to 2S + 2S \to 12D_{3/2}$	2.1385 ± 0.0081	
D12 + D8	$1S \to 2S + 2S \to 12D_{5/2}$	2.1358 ± 0.0064	
D12 + all D($2S \to n\ell$)		2.1415 ± 0.0045	Eq. (19)
D9 + all D($2S \to n\ell$)		2.1414 ± 0.0045	
D10 + all D($2S \to n\ell$)		2.1411 ± 0.0045	
CODATA Adj. 10:		2.1214 ± 0.0253	

Deuteron charge radius from spectroscopy data in atomic deuterium

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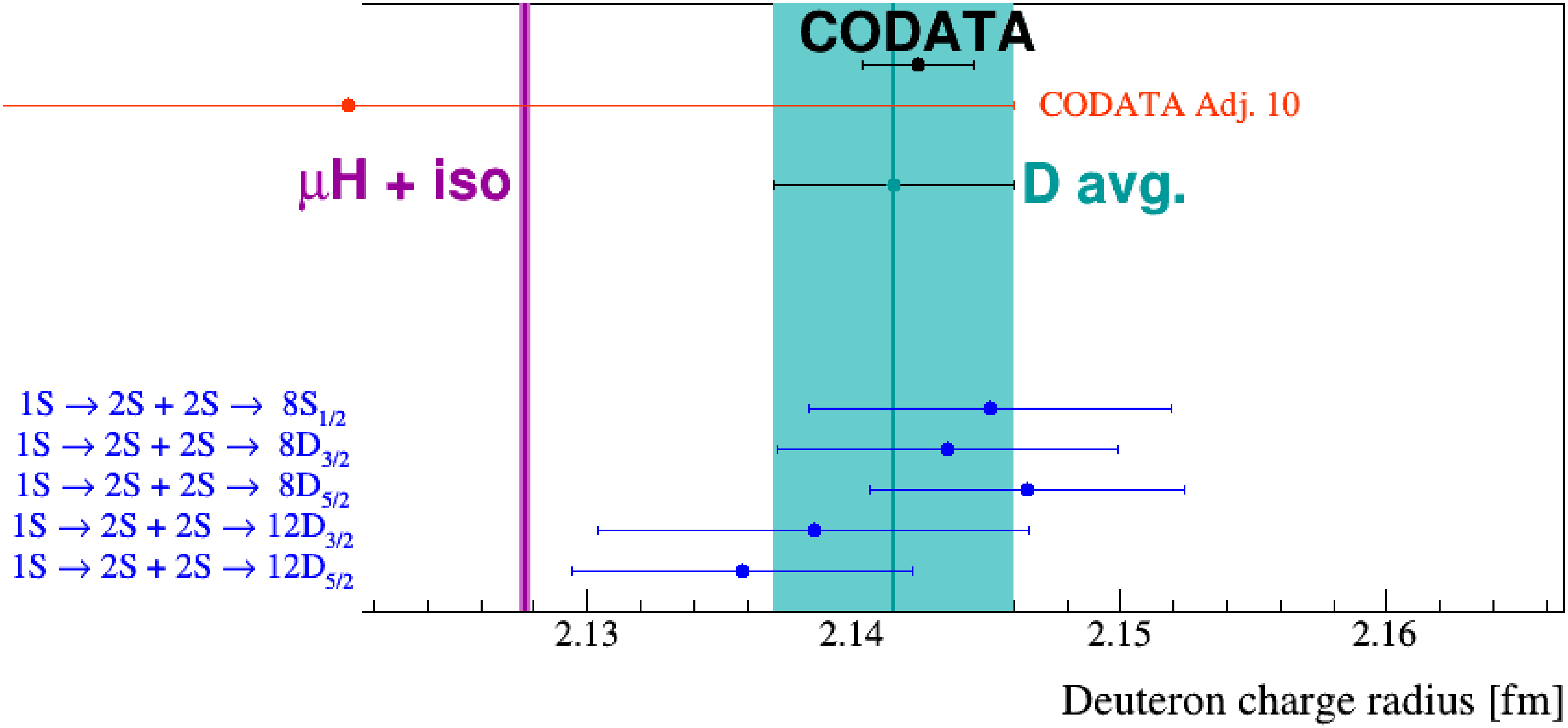
(Dated: July 11, 2016)

We give a pedagogical description of the method to extract the charge radii and Rydberg constant from laser spectroscopy in regular hydrogen (H) and deuterium (D) atoms, that is part of the CODATA least-squares adjustment (LSA) of the fundamental physical constants. We give a deuteron charge radius r_{d} from D spectroscopy alone of 2.1415(45) fm. This value is independent of the proton charge radius, and five times more accurate than the value found in the CODATA Adjustment 10.

arXiv 1607.03165

Related work:
* Horbatsch, Hessels, “Tabulation of bound-state energies of atomic hydrogen”,
  PRA 93, 022513 (2016) [1601.01057]
  (see Talk Wed.)

Rd from D spectroscopy



Summary

- Rp = 0.8775(51) fm CODATA-2010

  0.8747(91) fm H(1S-2S) + 2S-nl (*) uncorrel.

  0.8780(108) fm H(1S-3S) + 2S-nl

  0.8764(89) fm CODATA Adj. 8

  0.8409(4) fm muH 4.0 sigma
- Rd = 2.1424(21) fm CODATA-2010

  2.1415(45) fm Deuterium only (*) uncorrel.

  2.1XXX(8) fm muD → next talk