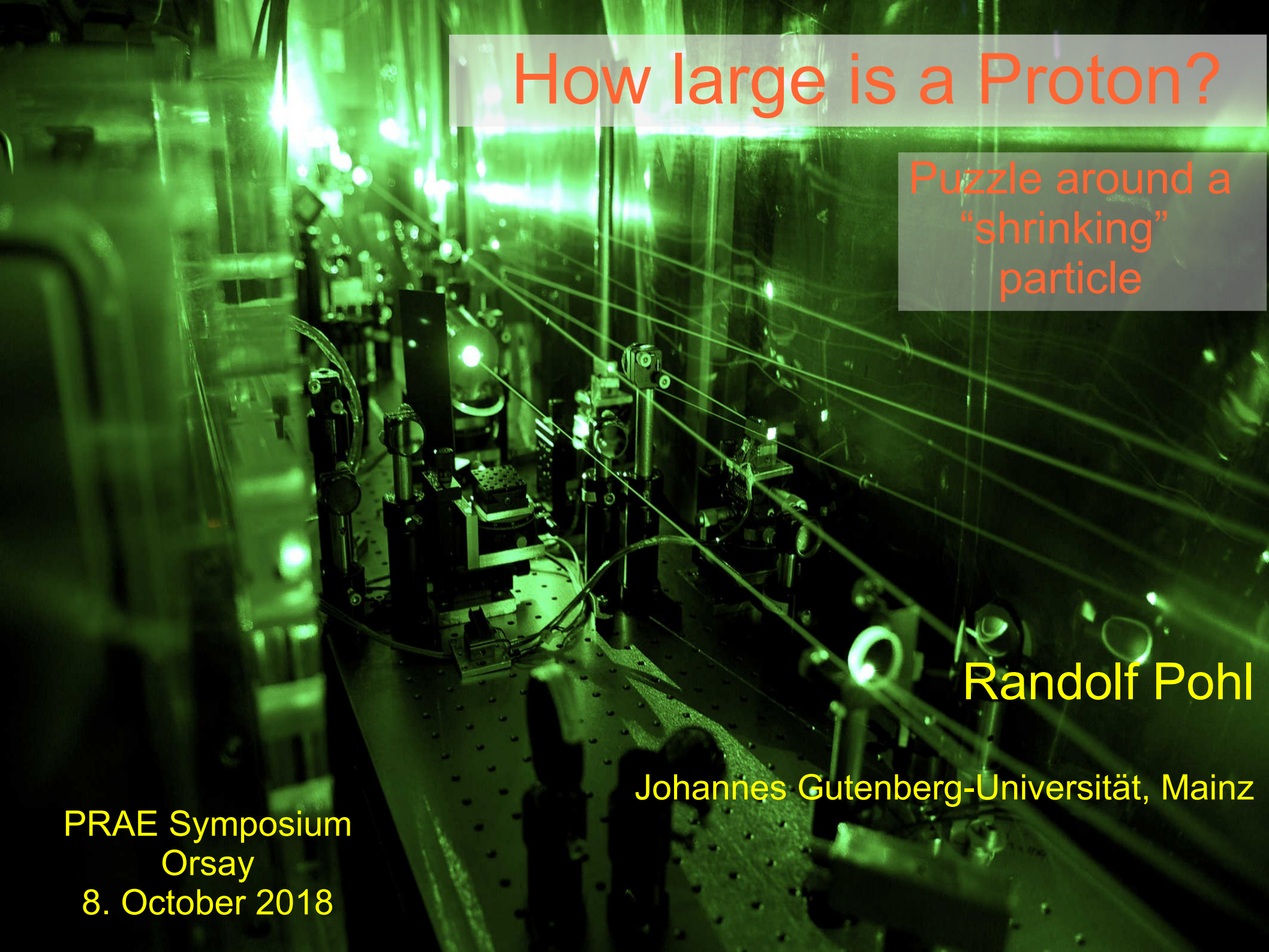


How large is a Proton?

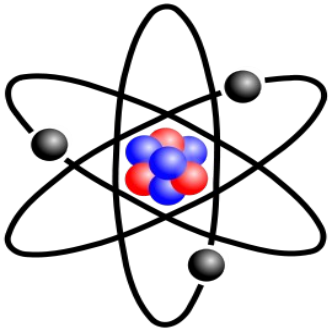
Puzzle around a "shrinking" particle

Randolf Pohl

Johannes Gutenberg-Universität, Mainz

PRAE Symposium
Orsay
8. October 2018

Today ....

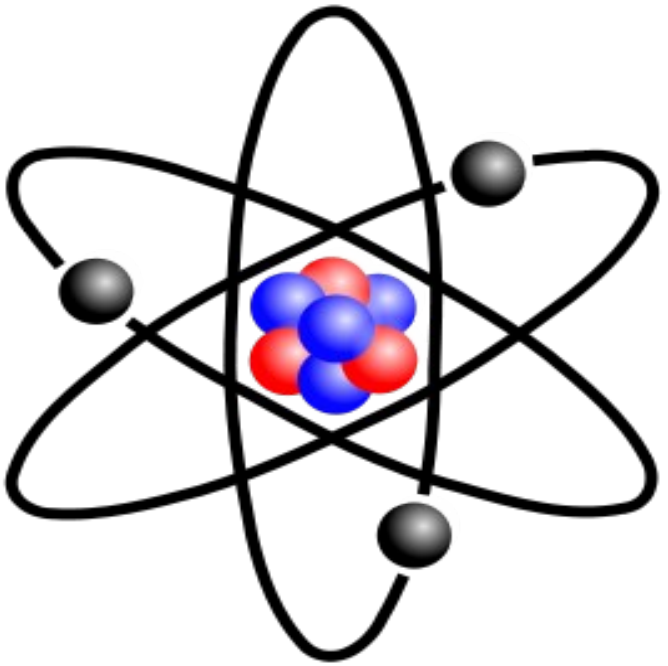


- Atoms
- Protons, Electrons
- Accelerators
- Particles: Muons
- Laser
- and (no) answer to the question:

  “How large is the proton?”
- Have fun!

Atom, Proton, Electron, Quarks, Muons!

- **Atoms** have a **Nucleus**, which is orbited by Electrons.



Atom, Proton, Electron, Quarks, Muons!

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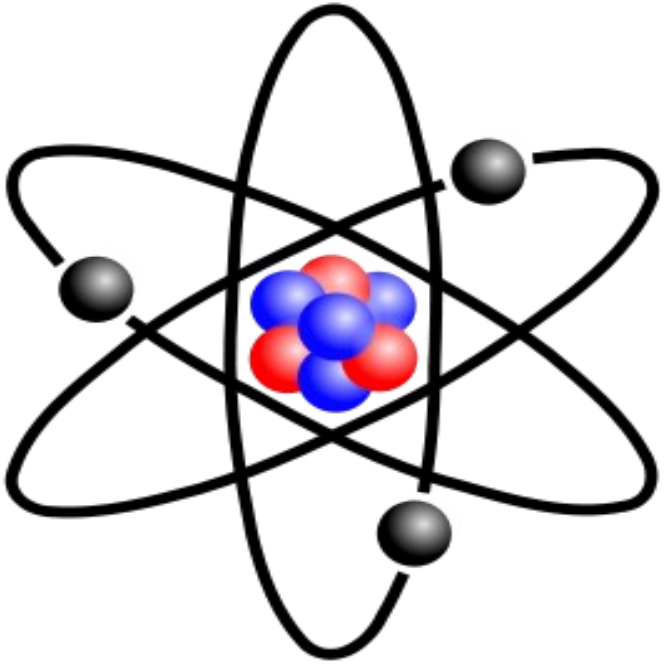
- The **Nucleus** consists of Protons and Neutrons.



Atom, Proton, Electron, Quarks, Muons!

- **Atoms** have a **Nucleus**, which is orbited by Electrons.
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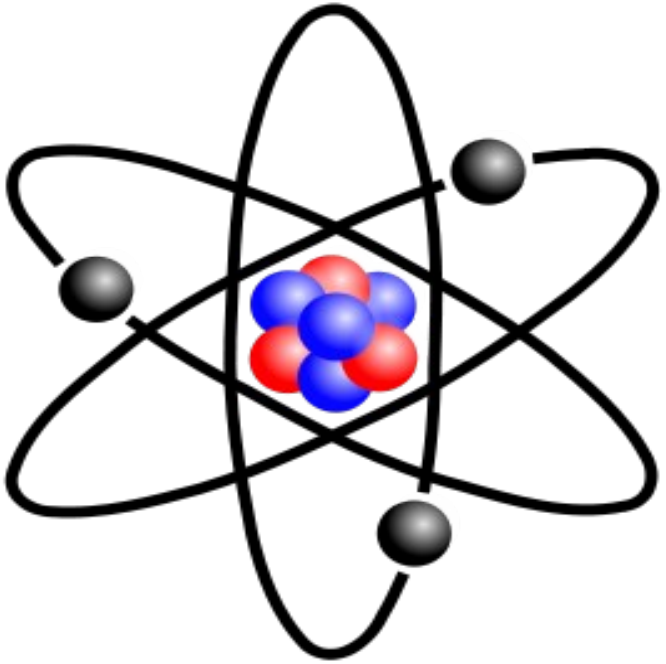
- Protons are made from Quarks, which are held together by Gluons.



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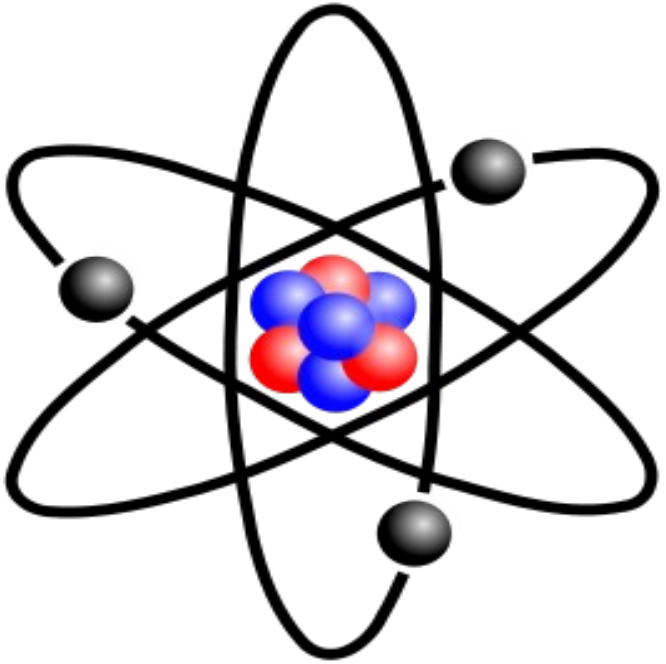

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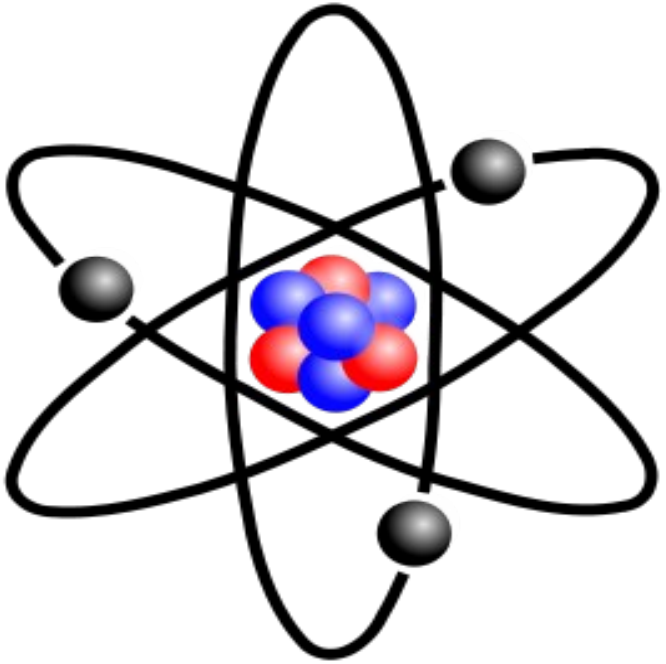
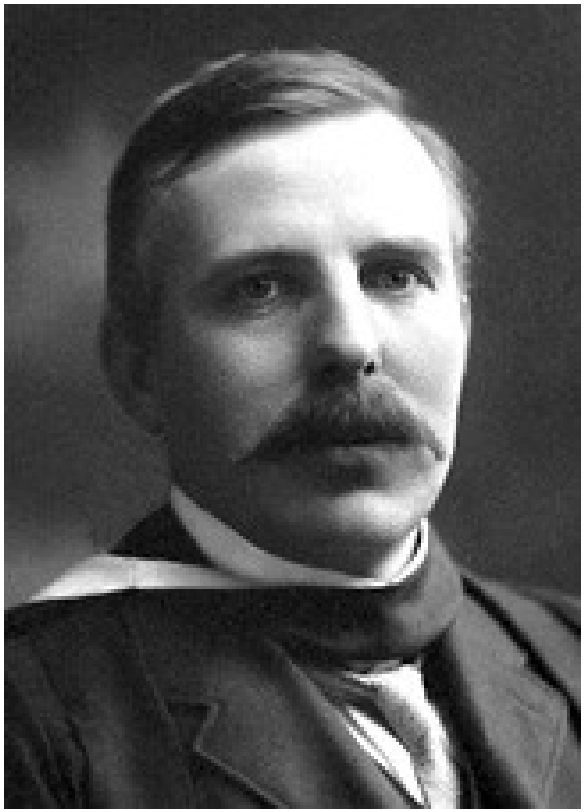
- Protons are thus extended objects
- Electrons are **point-like**

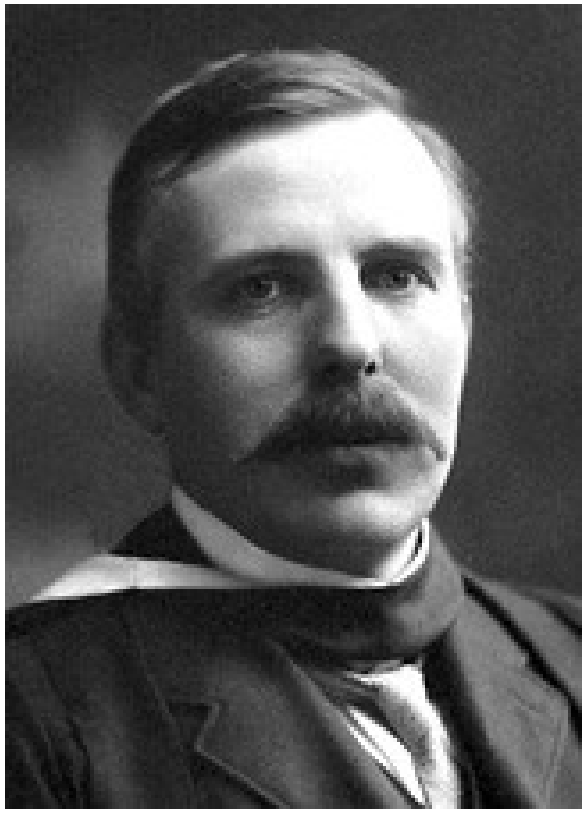


Ernest Rutherford – 1911



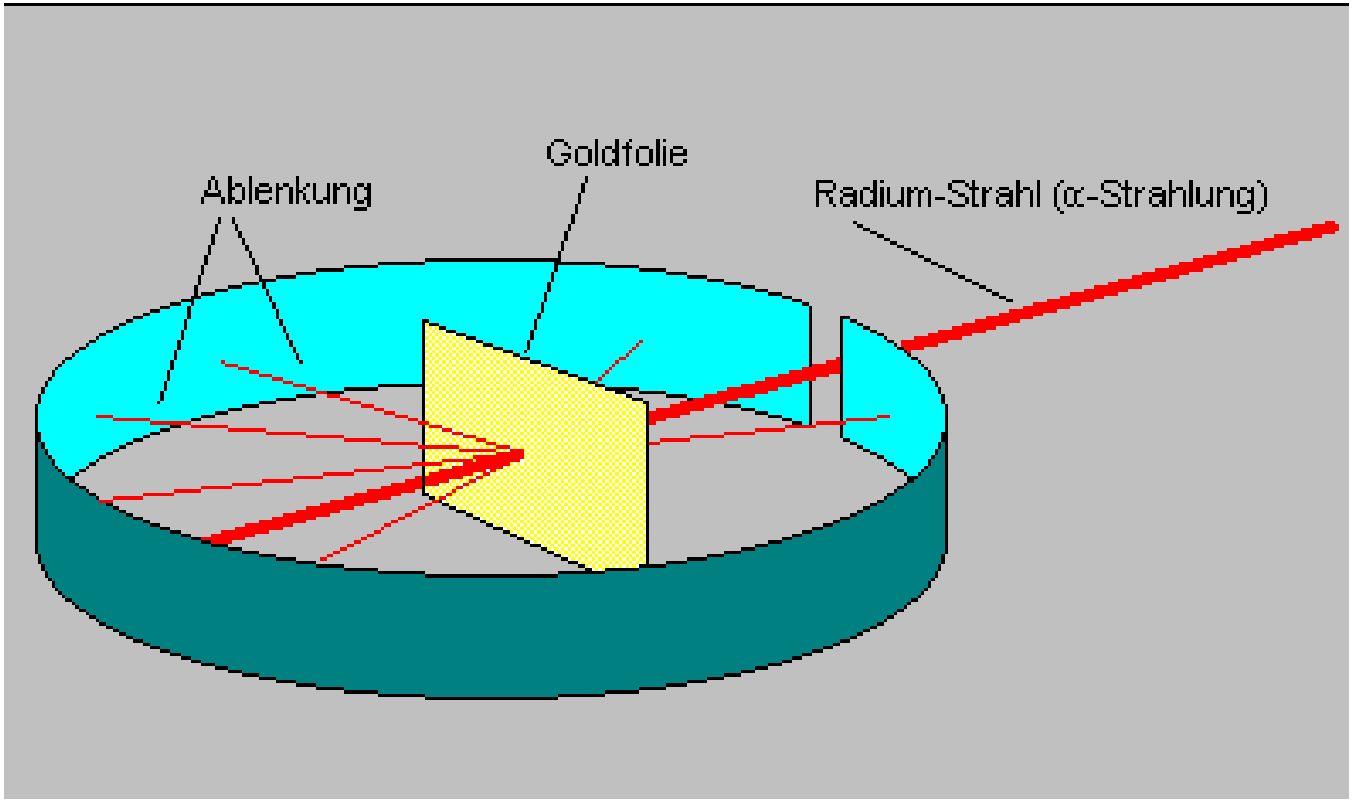
1871 – 1937
Nobel prize 1908

Ernest Rutherford – 1911



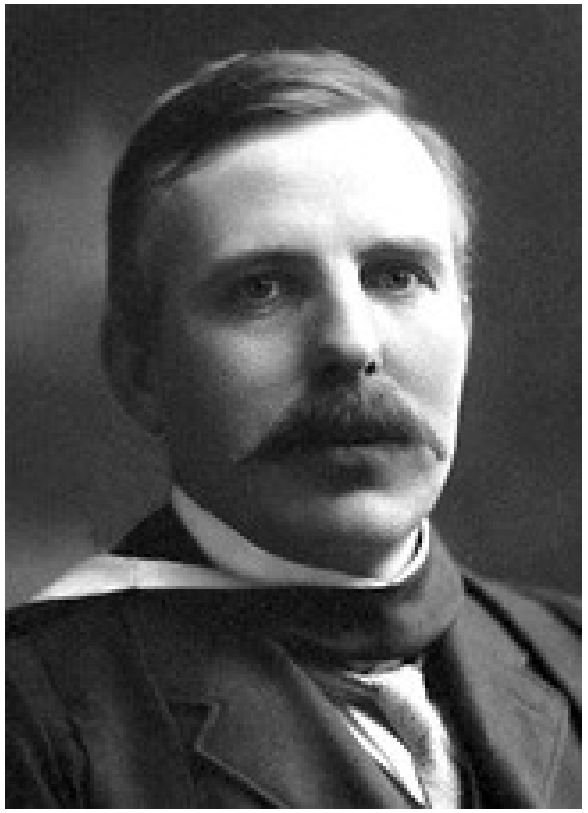
1871 – 1937
Nobel prize 1908

Rutherford shoots alpha particles onto a thin gold foil



Most alpha particles pass the thin gold foil unaffected.
A few are however deflected at large angles.

Ernest Rutherford – 1911



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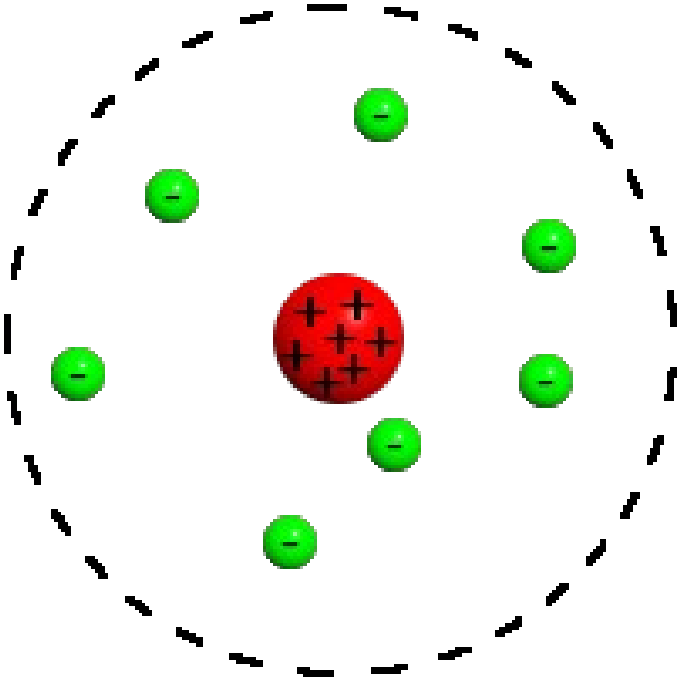
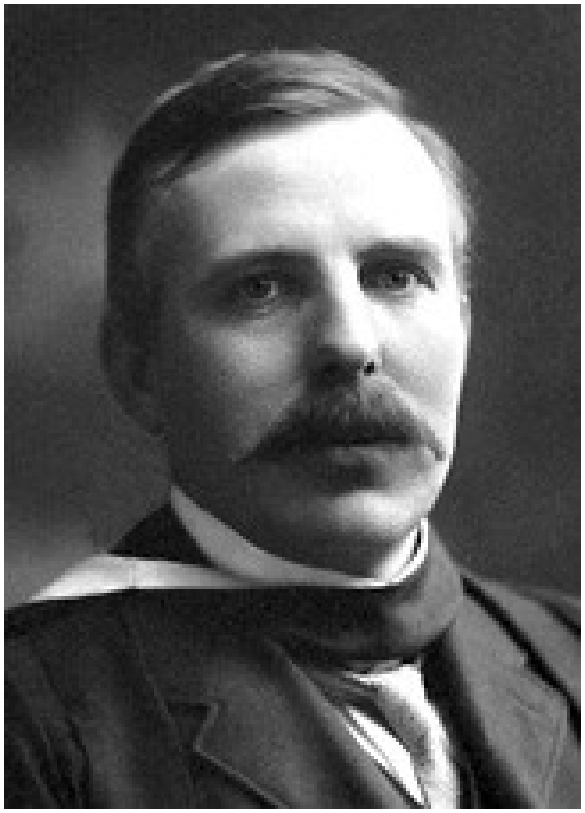


The Atom is a

very small, heavy, positively charged **Nucleus**

orbited by negatively charged **Electrons**

Ernest Rutherford – 1917

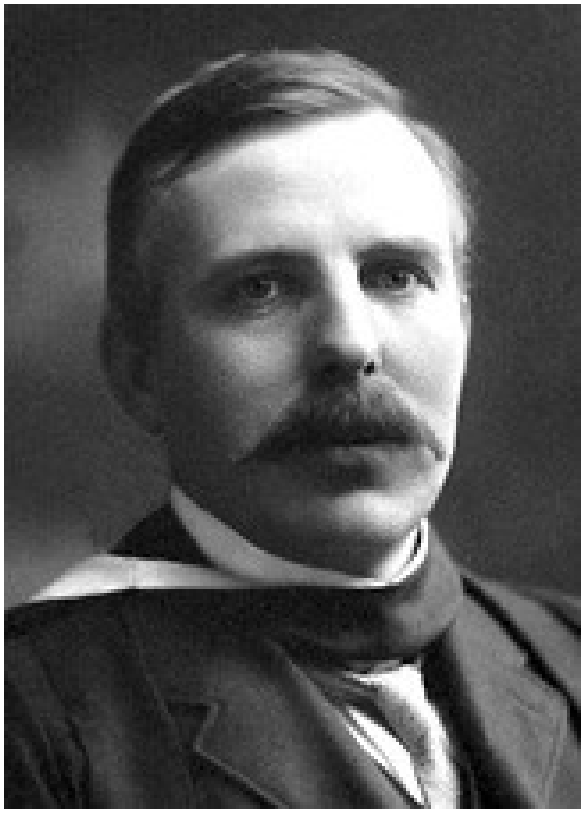


$^{14}N + \alpha \rightarrow {}^{17}O + p$

Rutherford achieves first man-made nuclear reaction.

Thereby he discovers the **Proton**.

Ernest Rutherford – 1917



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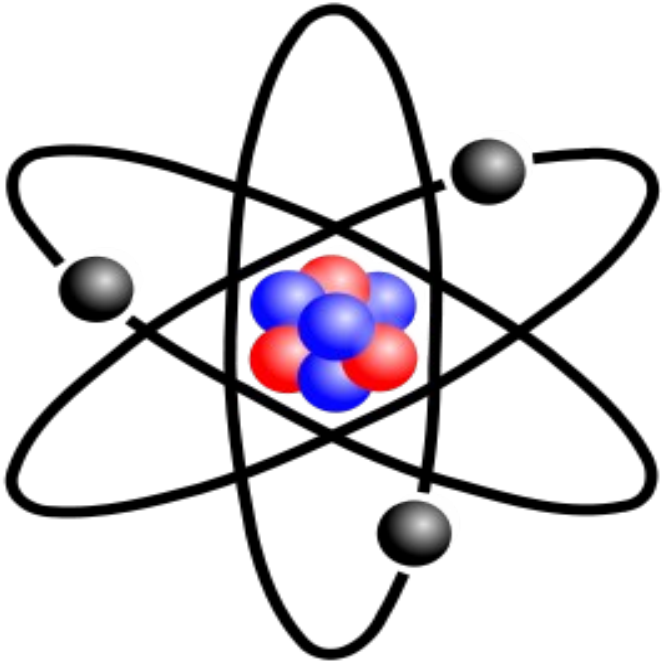
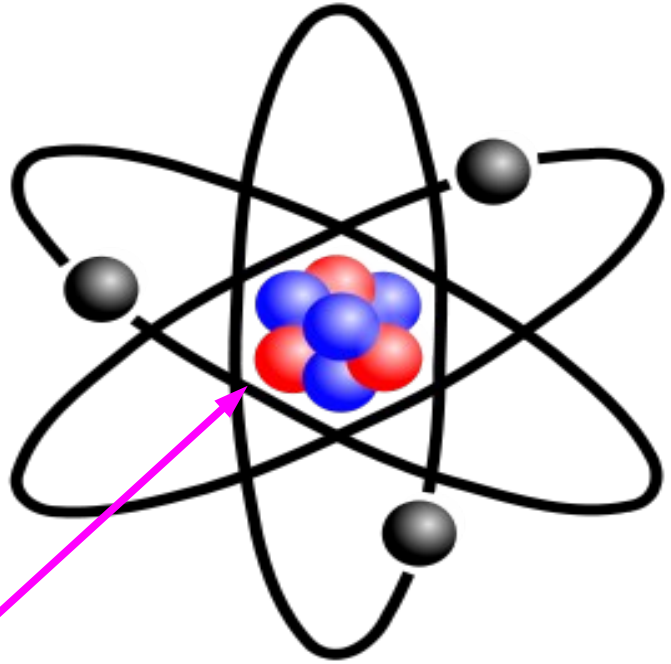
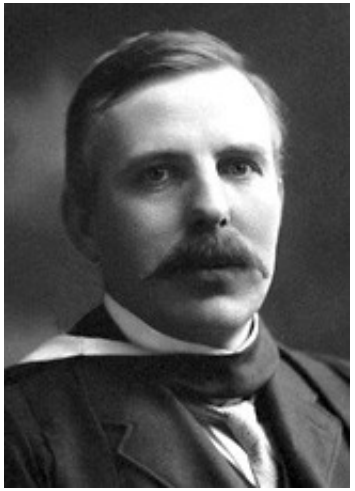
101 years of the proton !!!

Building blocks of matter



Building blocks of matter

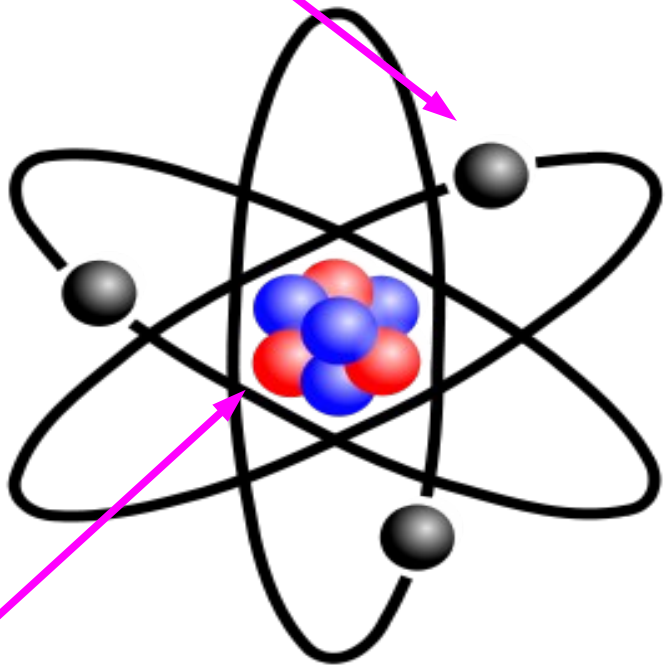


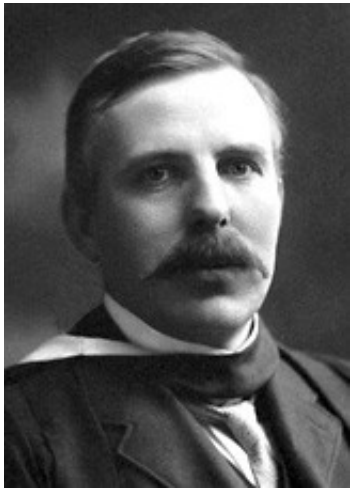


Proton: Ernest Rutherford
(1917)

Building blocks of matter

Electron: Joseph John Thomson
(1897)





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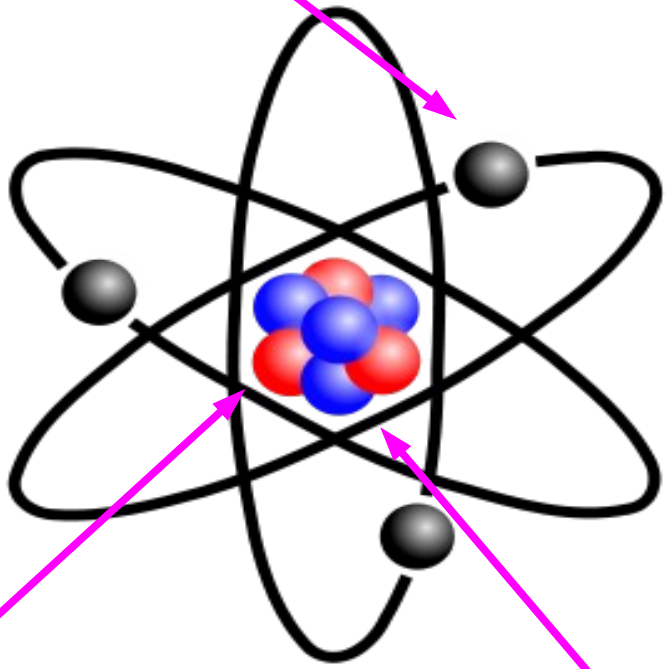
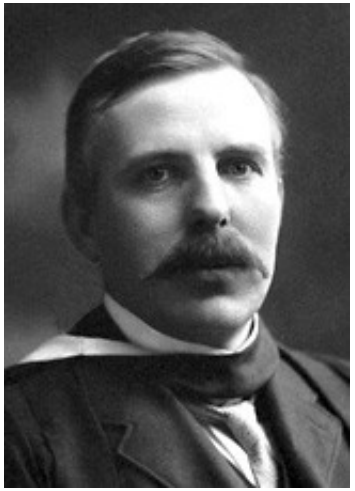
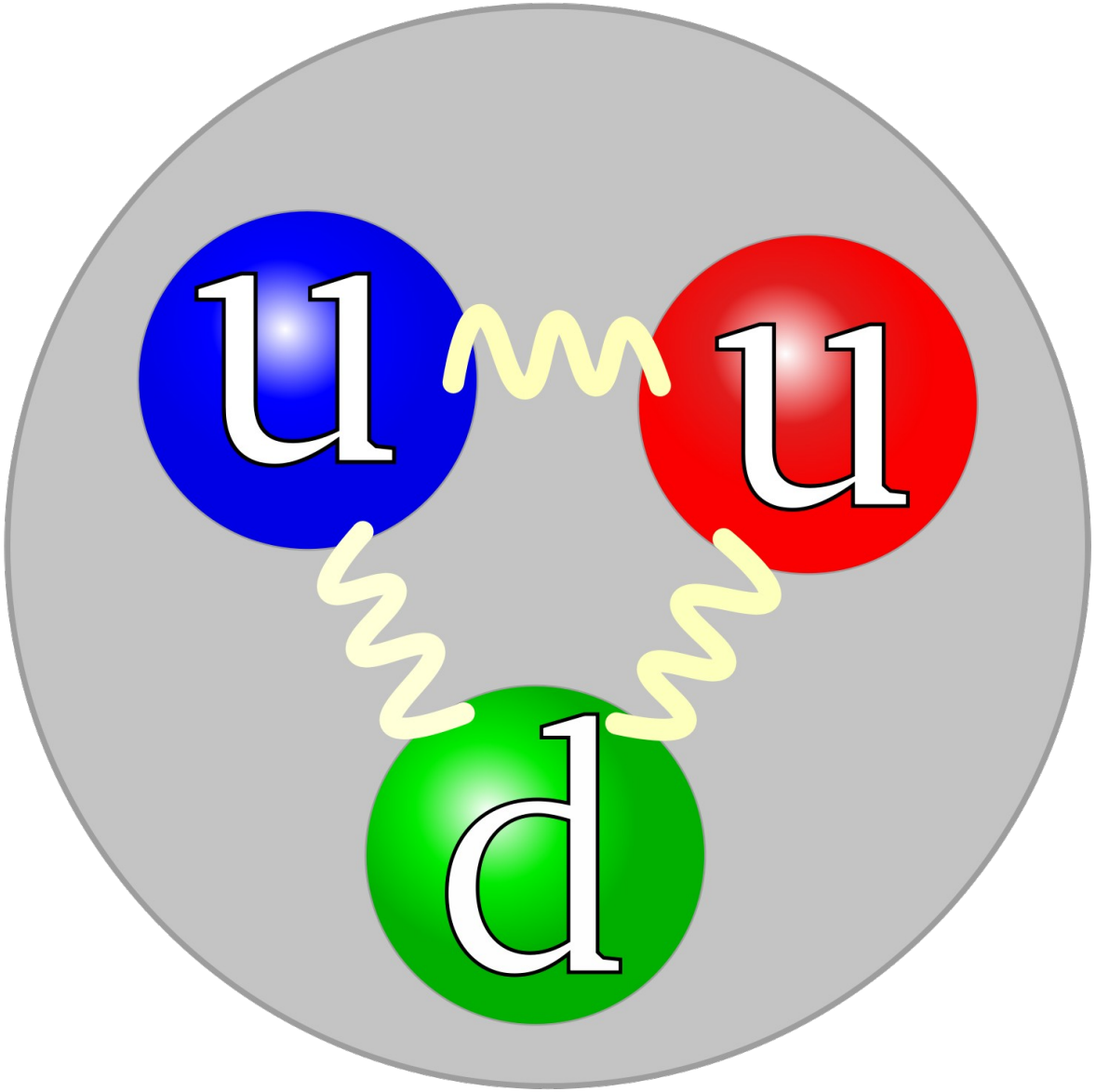




Proton: Ernest Rutherford
(1917)

Neutron: James Chadwick
(1932)

Proton – 3 Quarks



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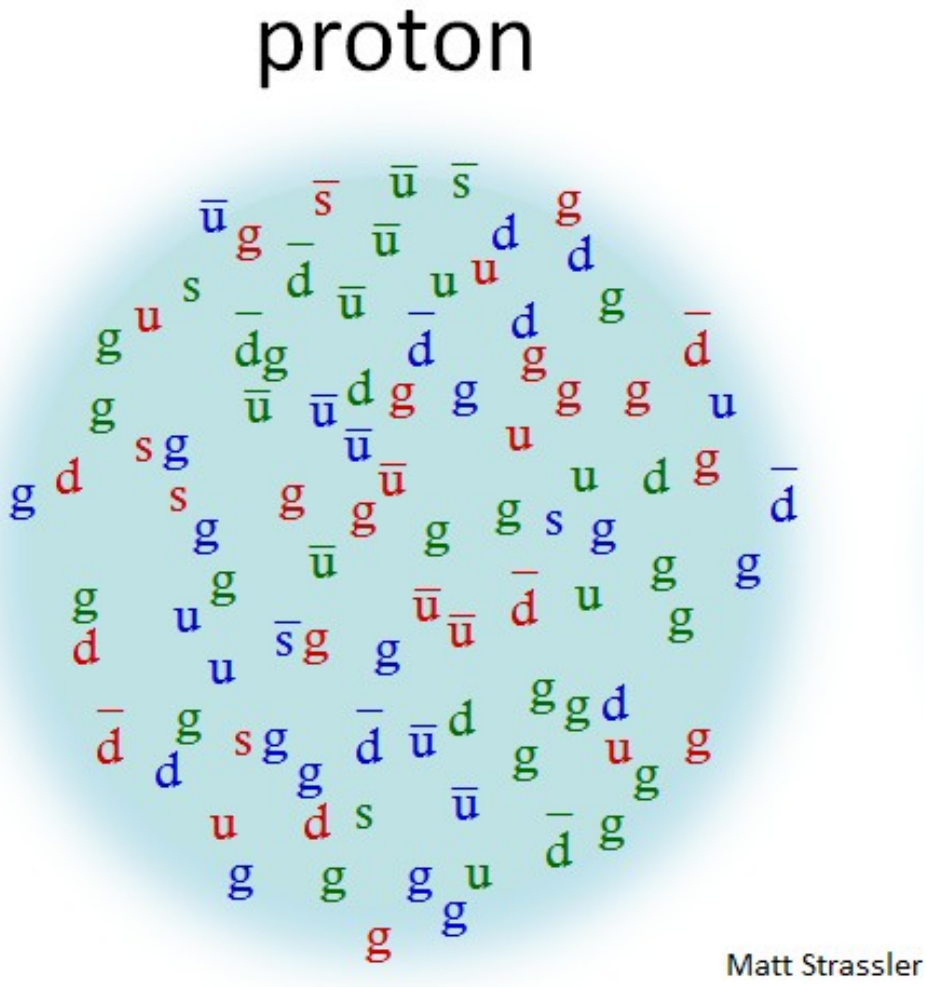
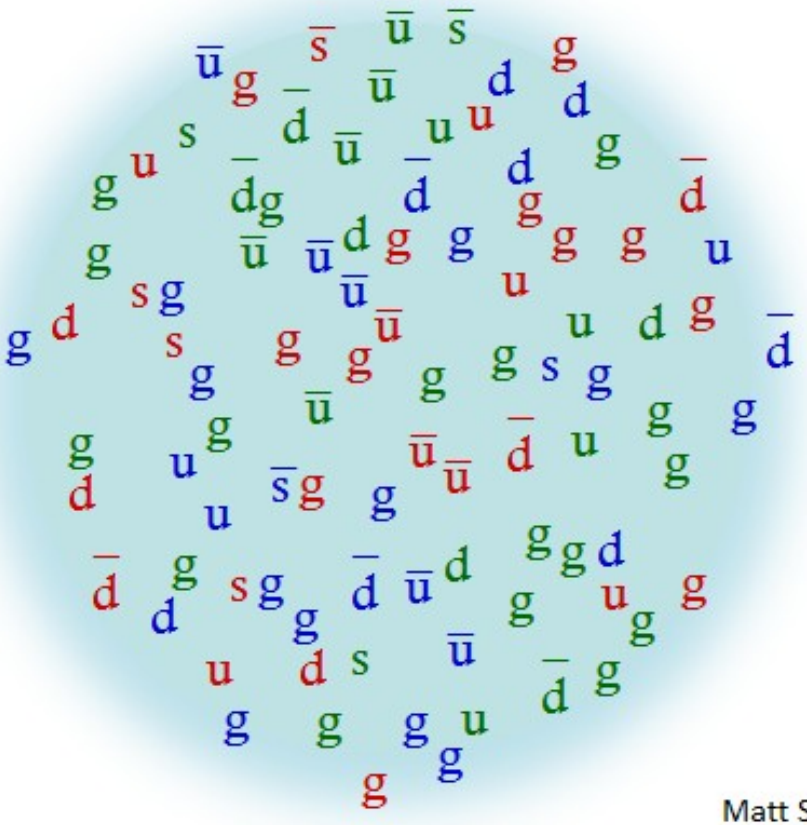
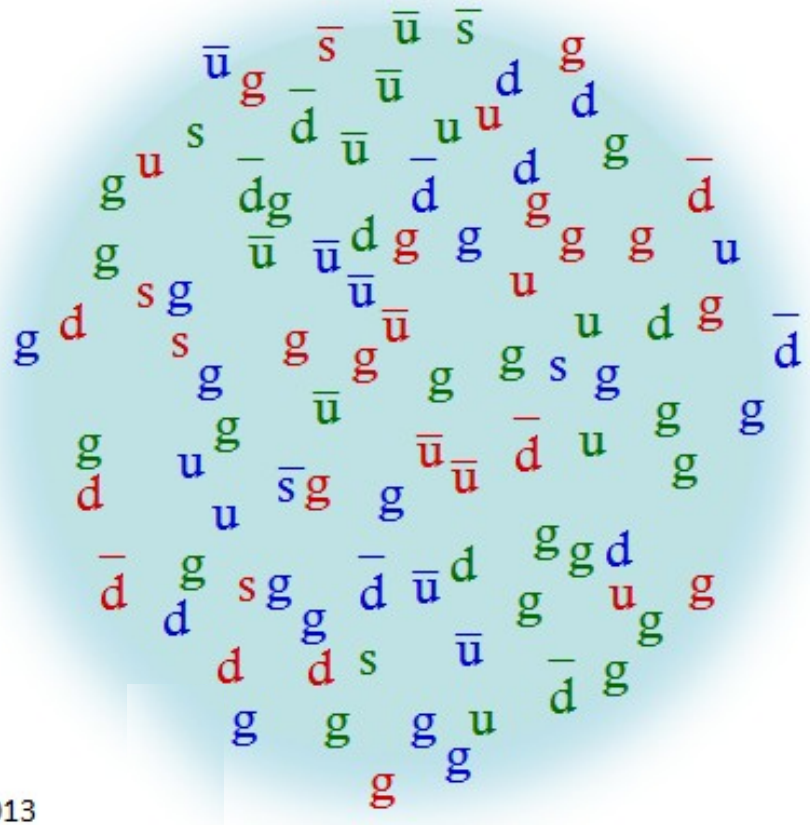


Proton – >>3 Quarks

proton

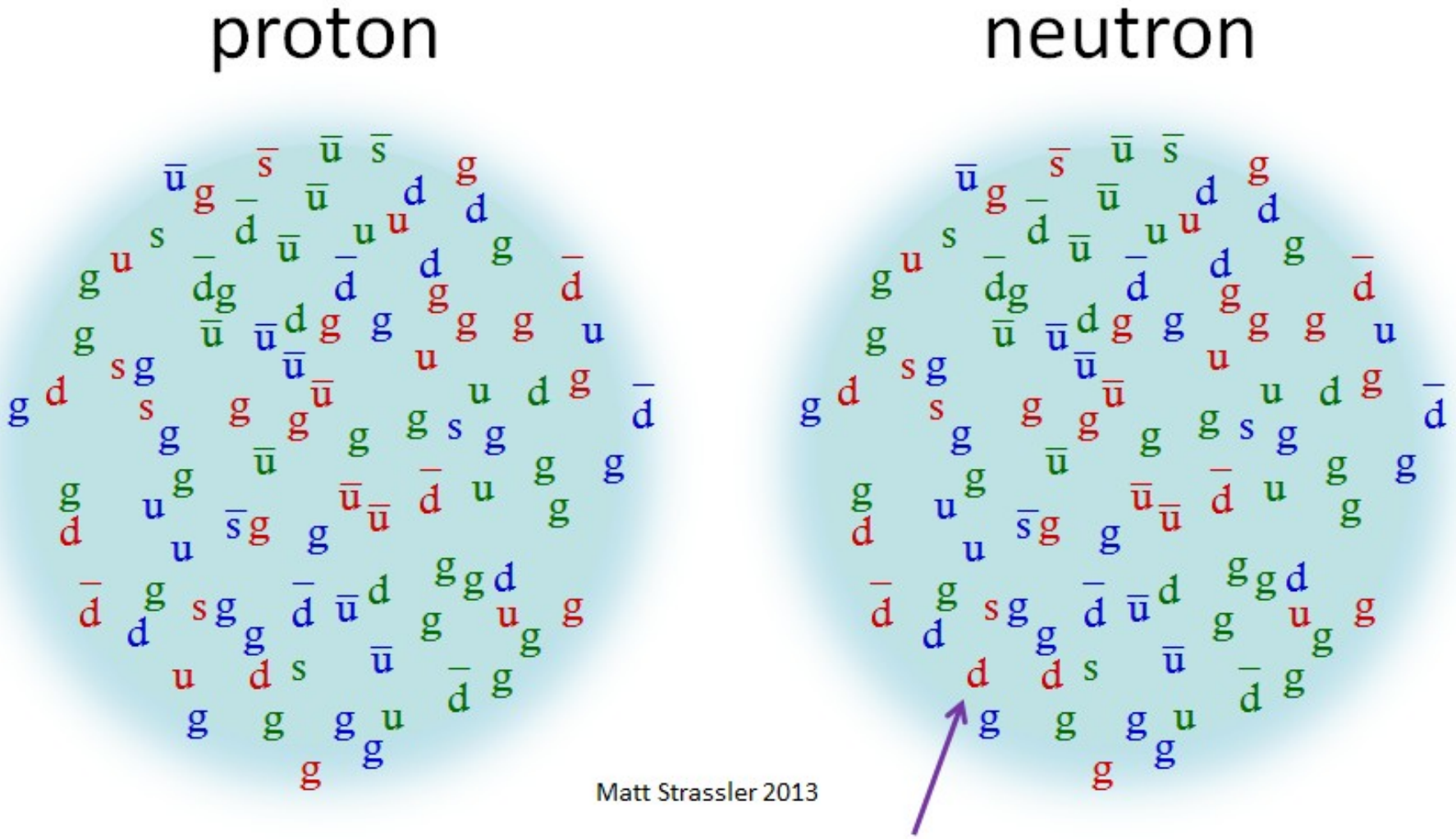


neutron



Matt Strassler 2013

Proton – >>3 Quarks



Robert Hofstadter – 1955

1915 – 1990
Nobel prize 1961

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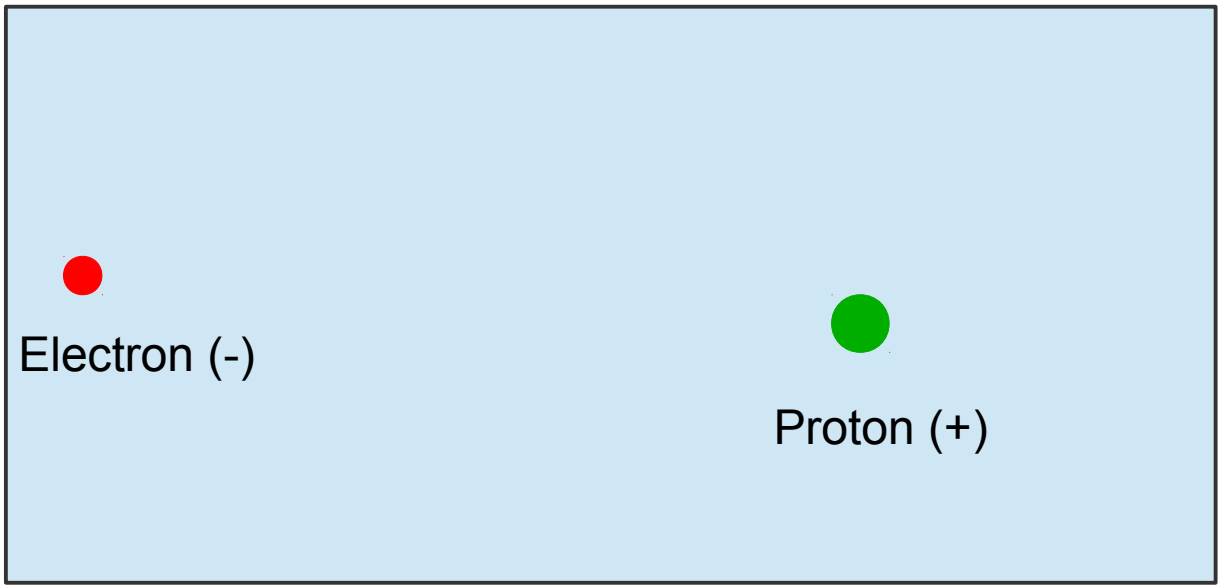

Scattering of (negatively charged) Electrons off (positively charged) Protons.

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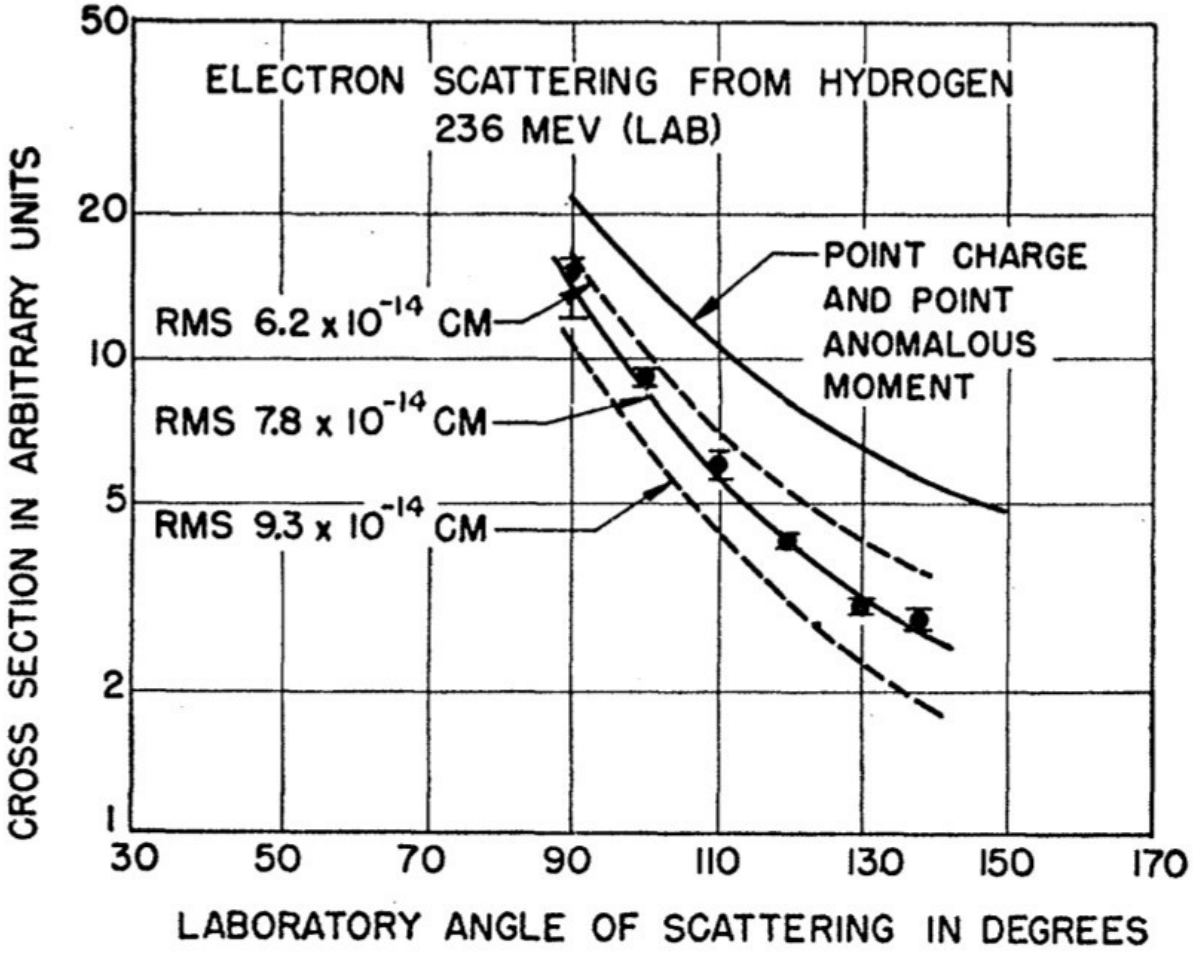
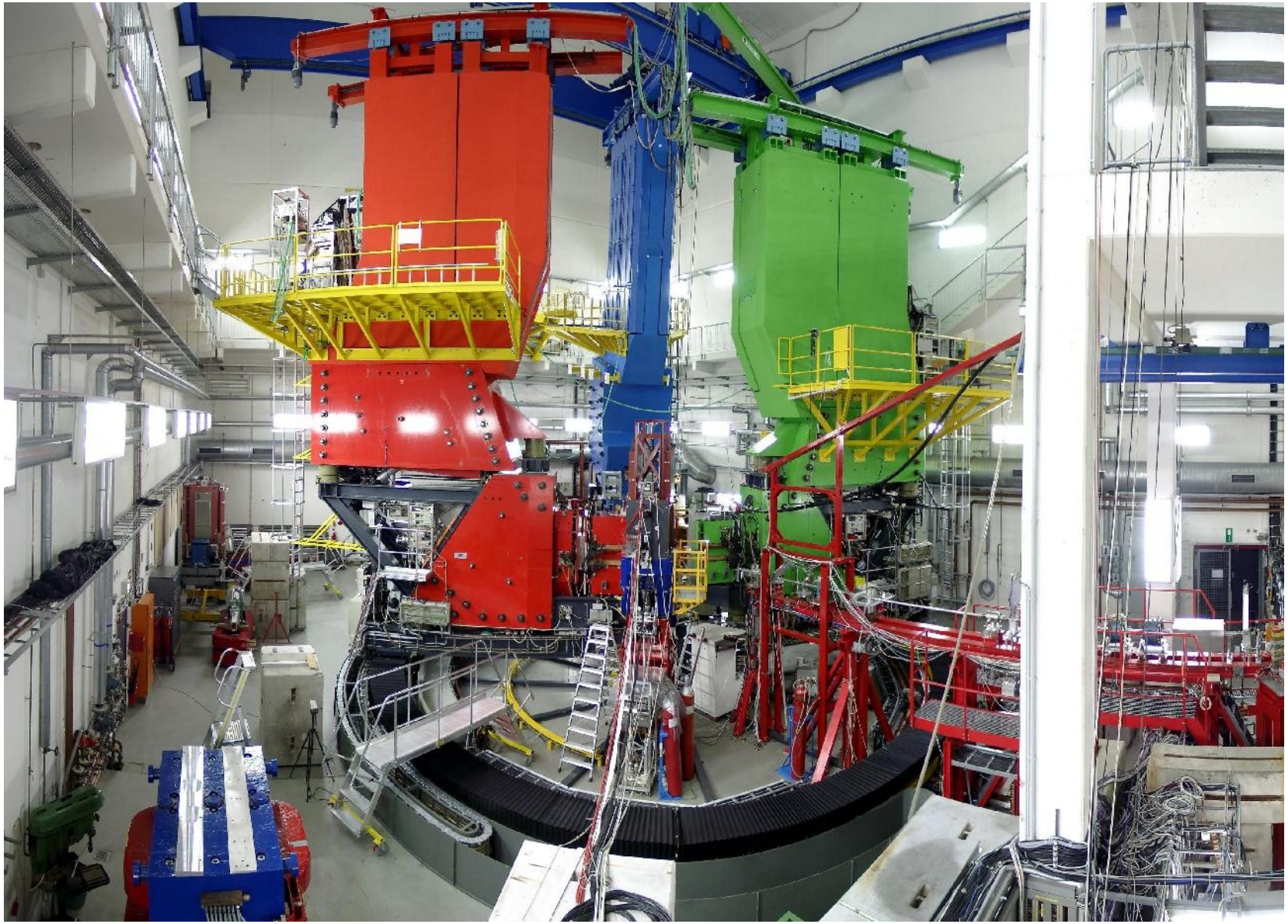


The Proton has a diameter of "$0{,}7 \cdot 10^{-13}$ cm"

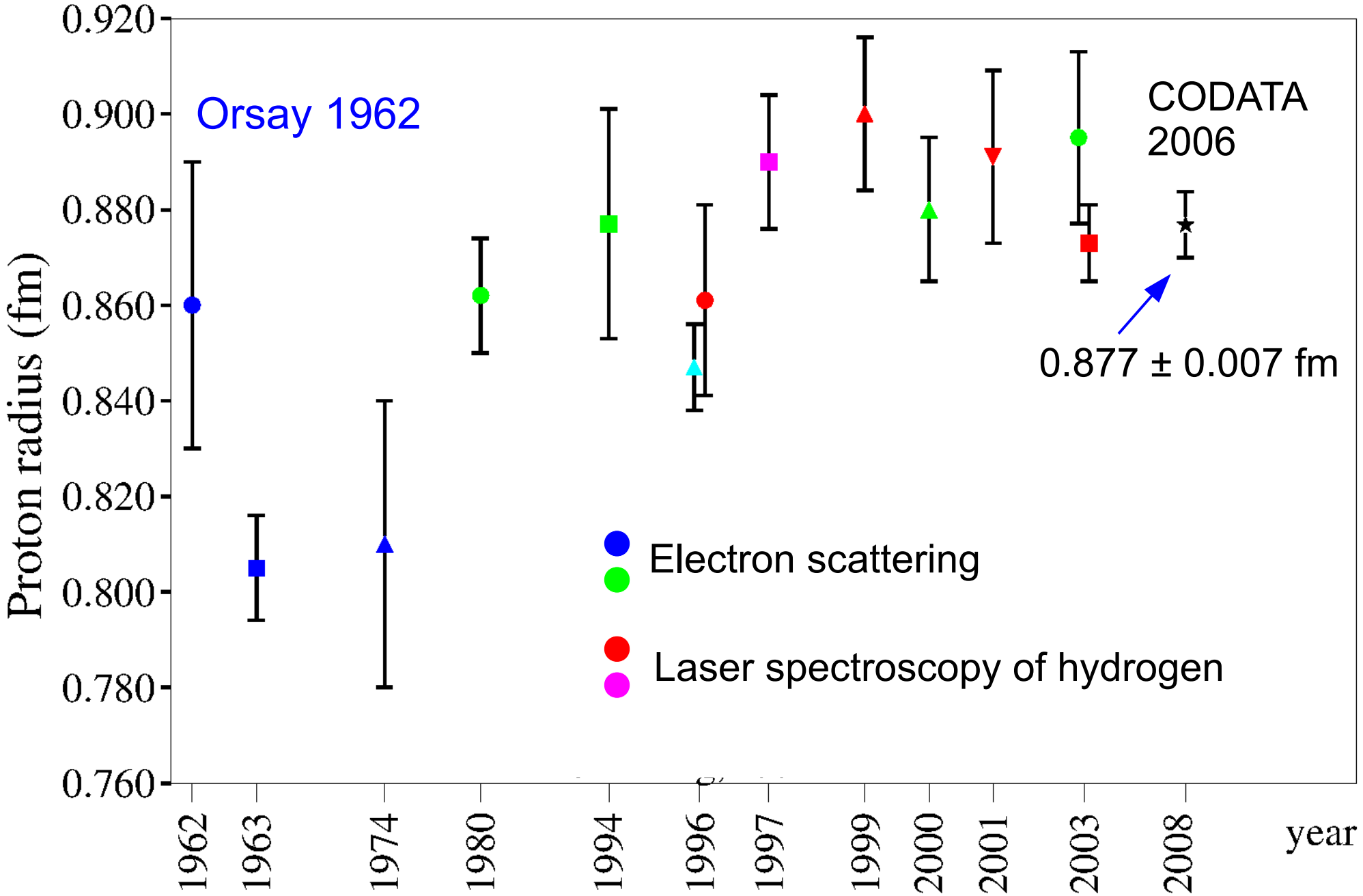
Mainzer Microtron MAMI



Mainzer Microtron MAMI

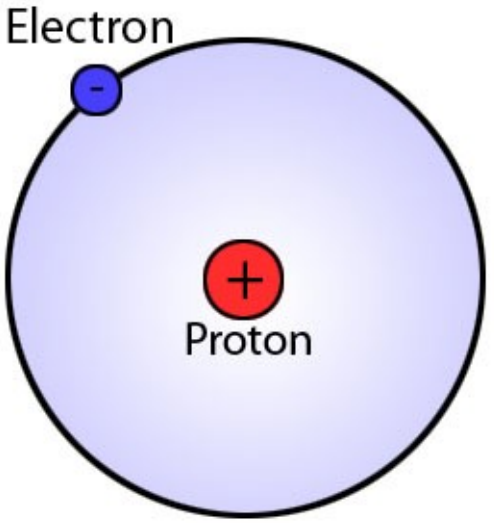
Mainzer Microtron MAMI

How large is a Proton?



The Hydrogen Atom

One Proton, orbited by *one* Electron.



The Hydrogen Atom

Nils Bohr

1885 – 1962
Nobel prize 1922

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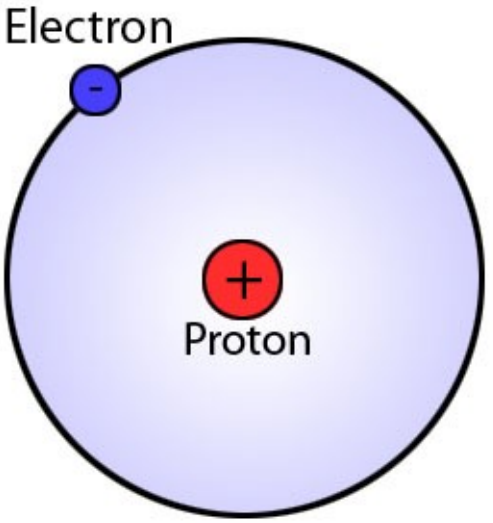

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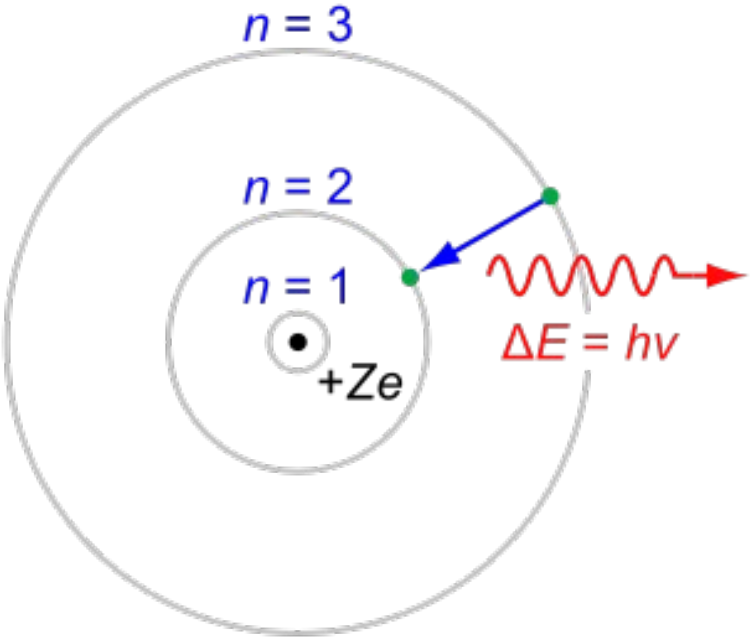

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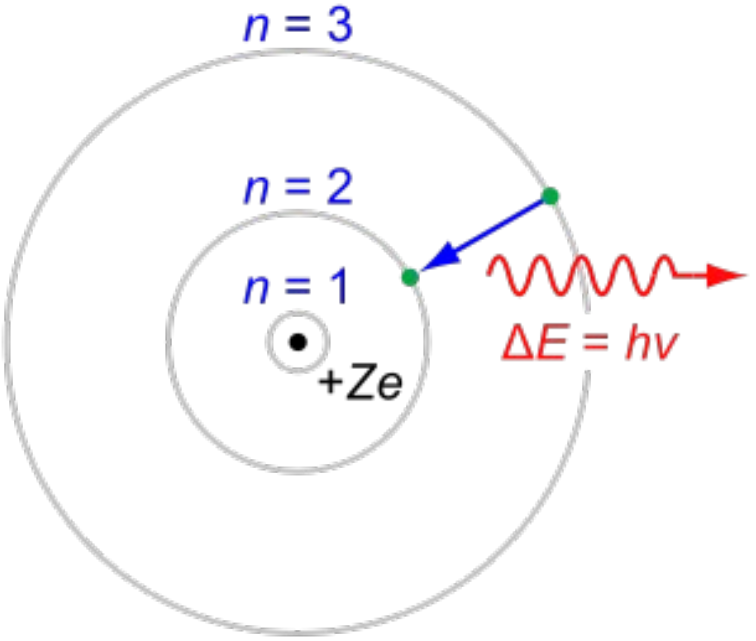
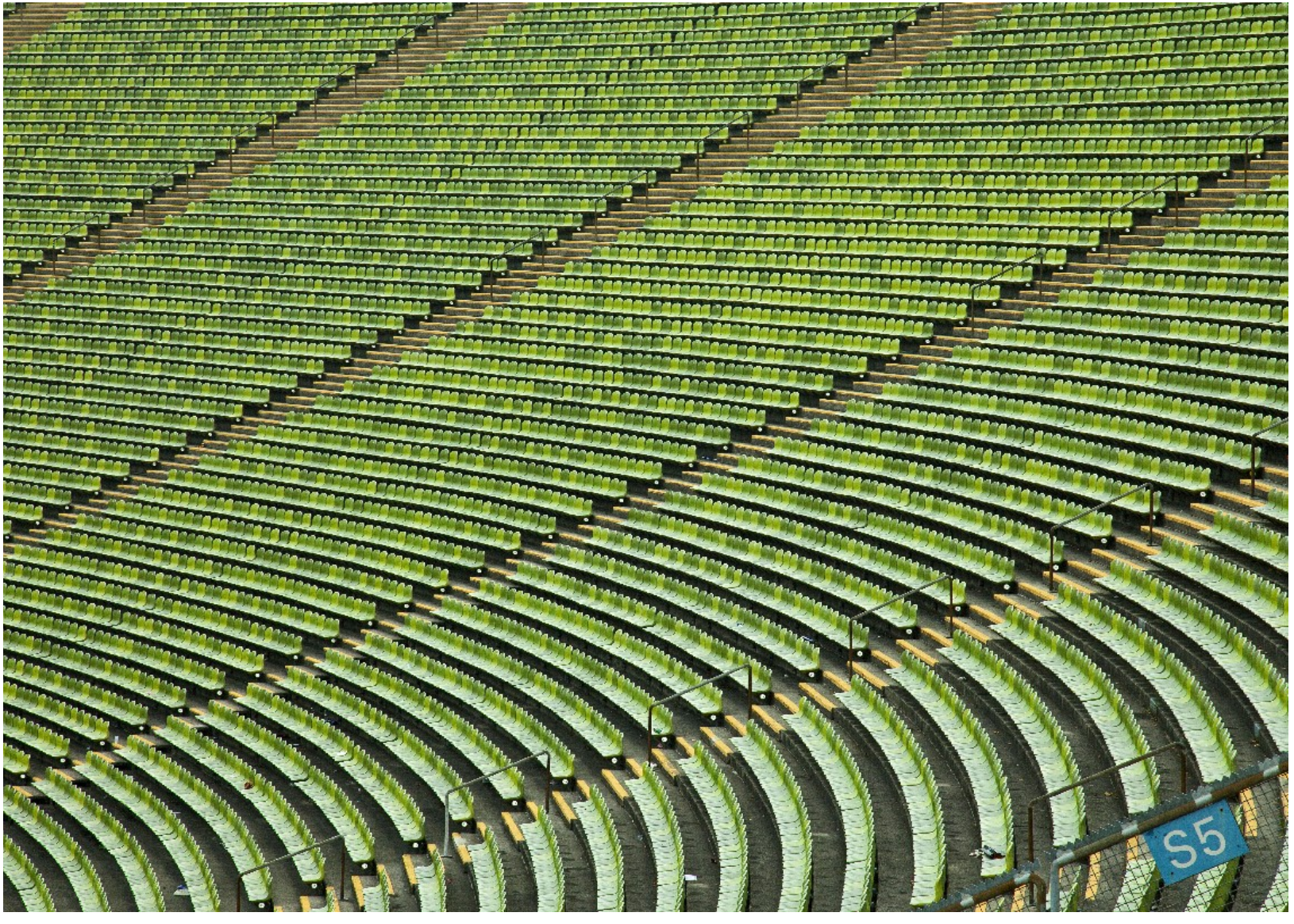


- Discrete orbits
- “Quantum leaps”

The Hydrogen Atom

The Hydrogen Atom



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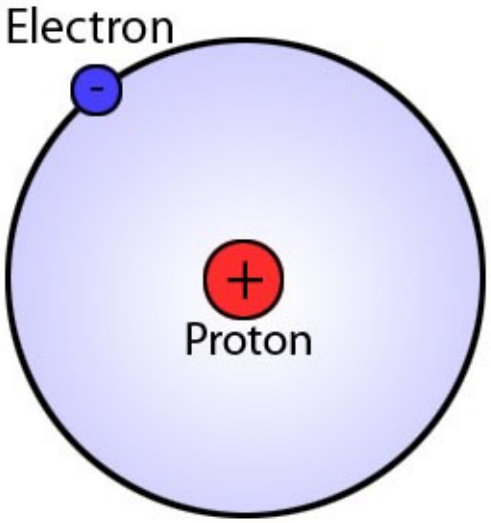

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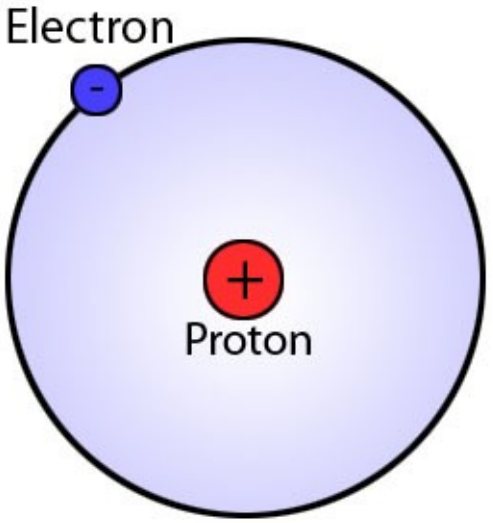

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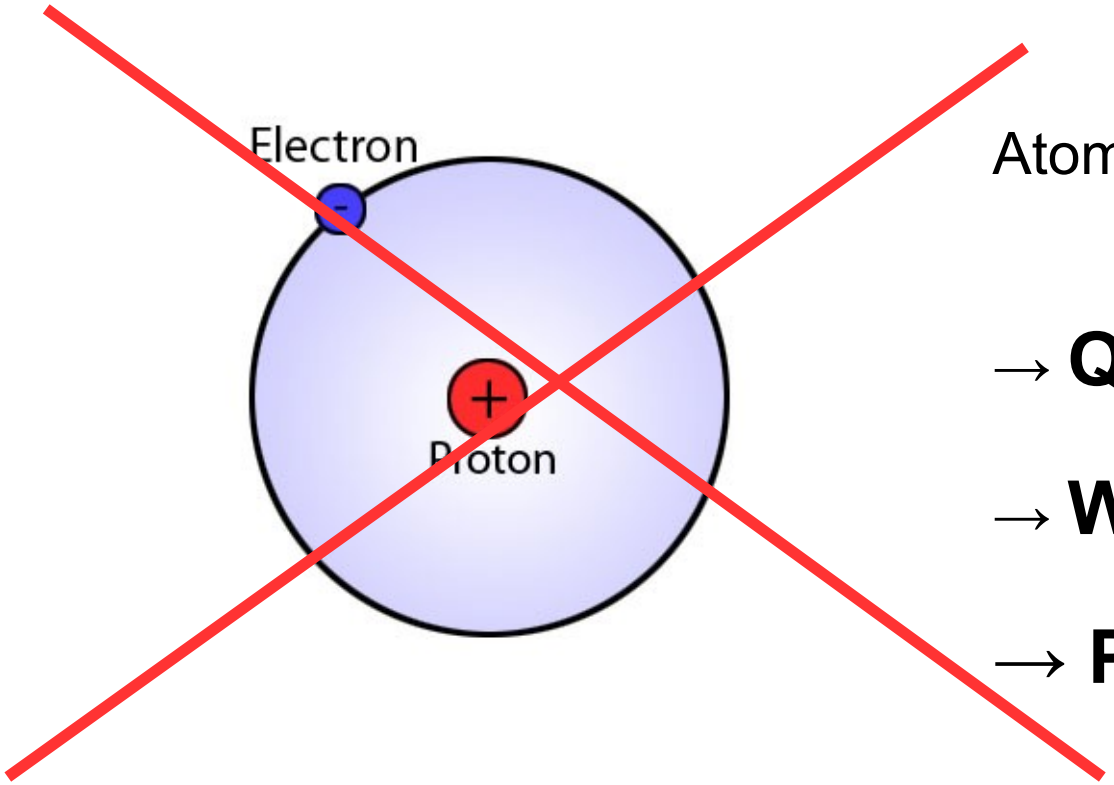


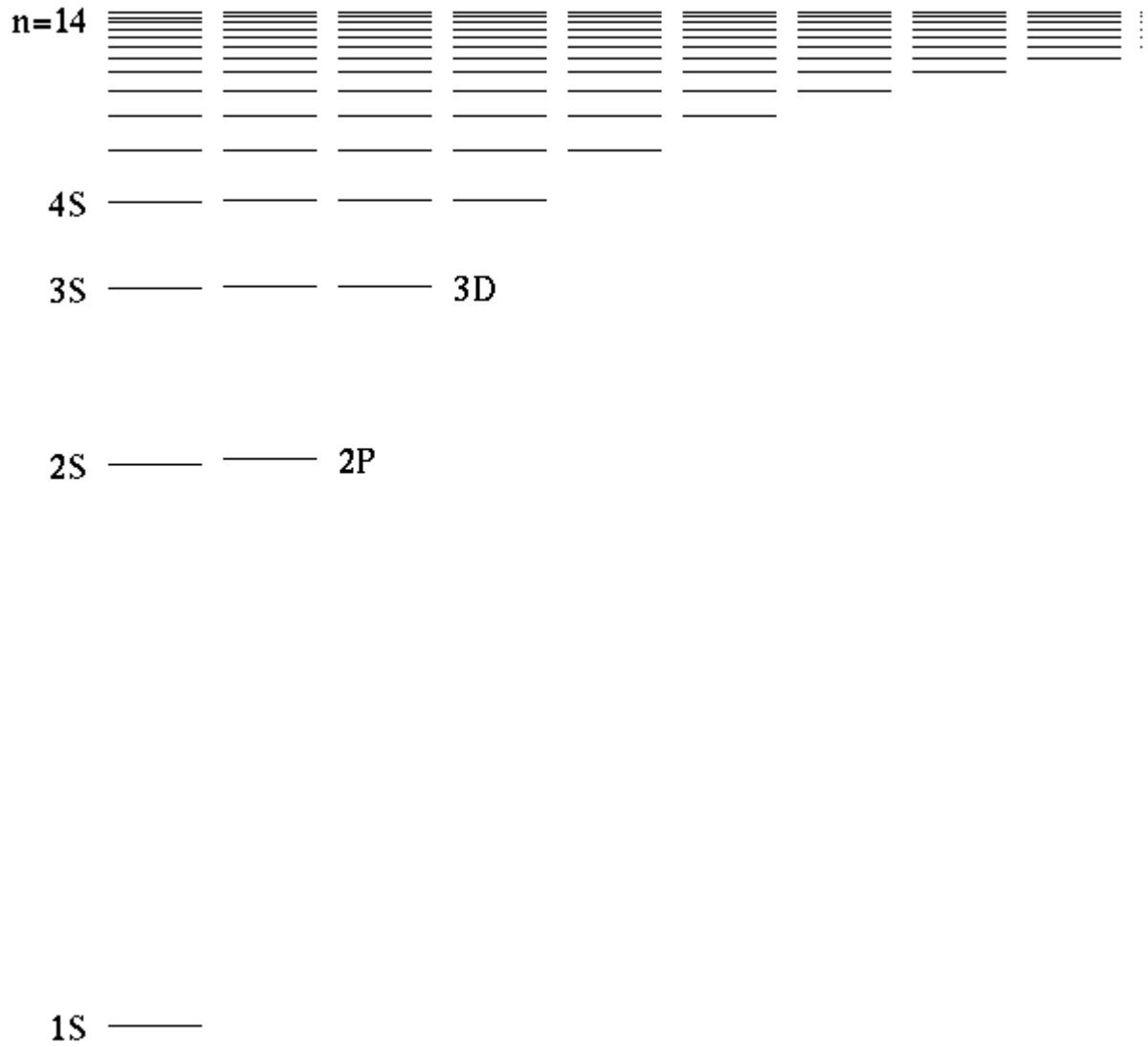
Atom is NO Planetary System.

→ **Quantum mechanics**

→ **Wave functions**

→ **Probabilities**

Energy levels of Hydrogen



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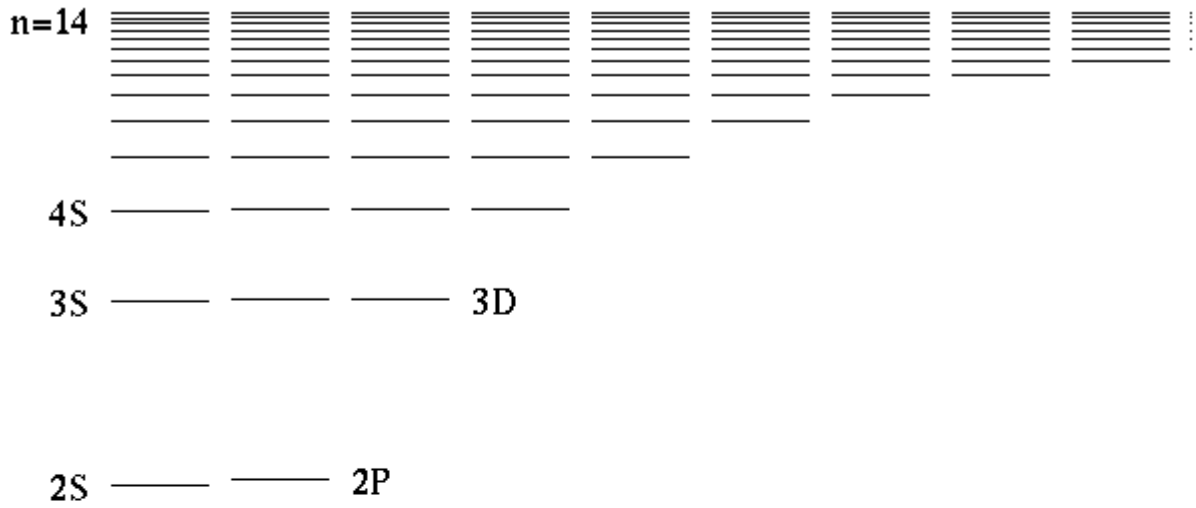
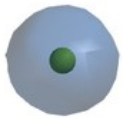
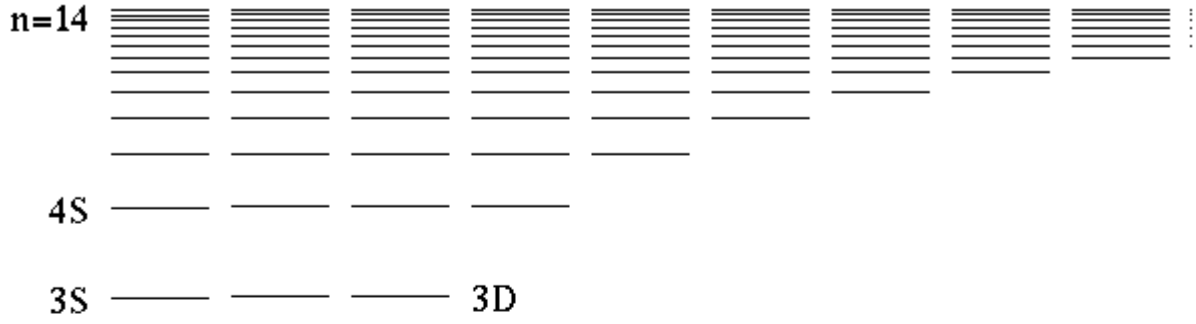
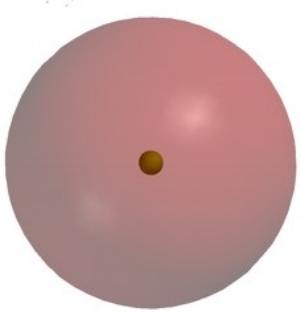


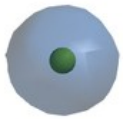


Electron probability density
(Square of the wave function)

Energy levels of Hydrogen





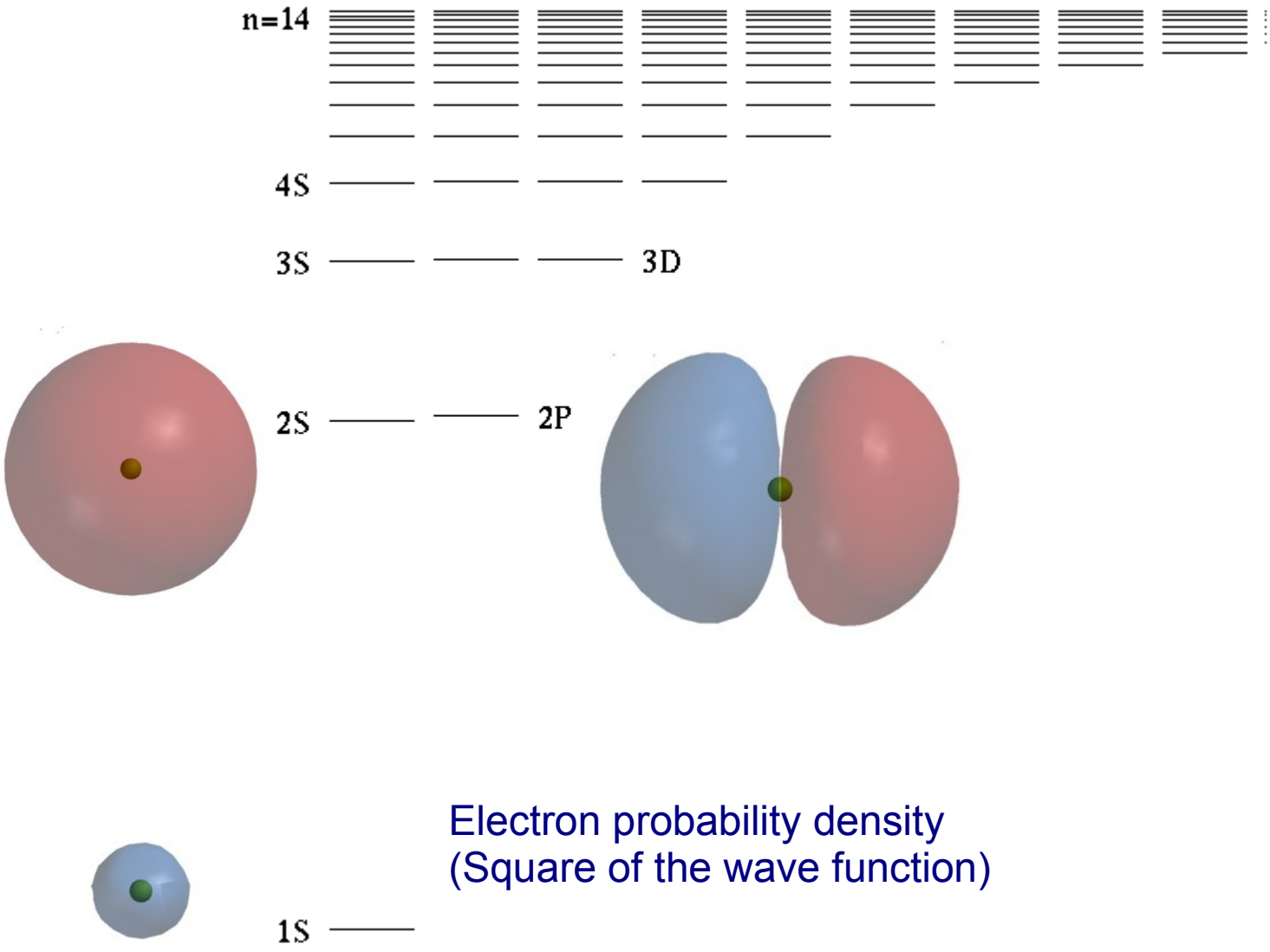


2S 2P

1S

Electron probability density
(Square of the wave function)

Energy levels of Hydrogen



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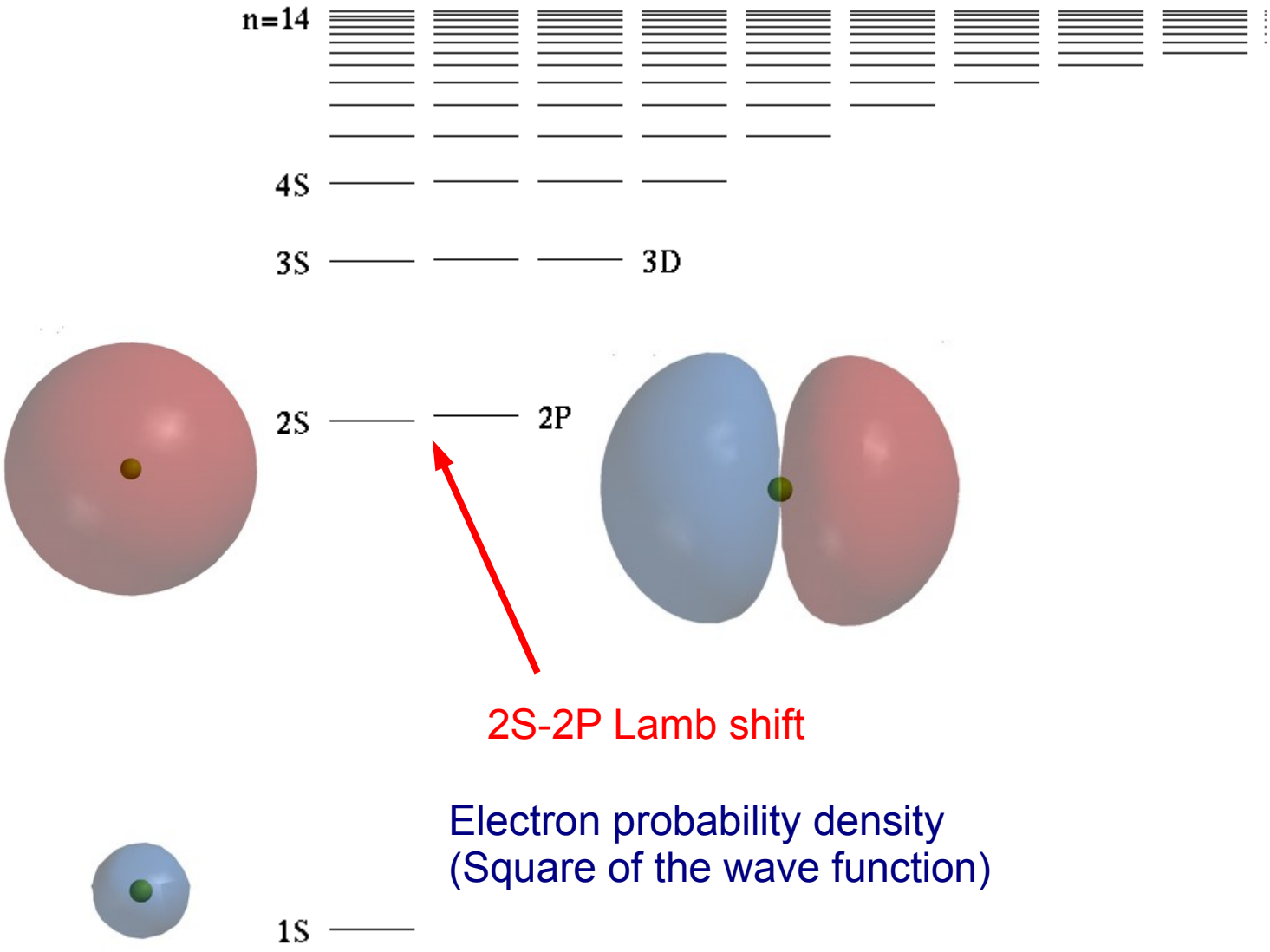
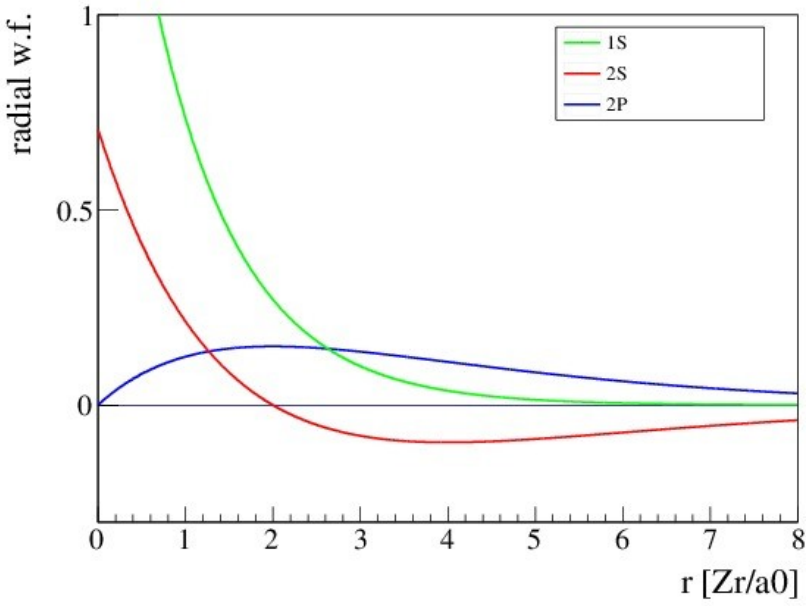
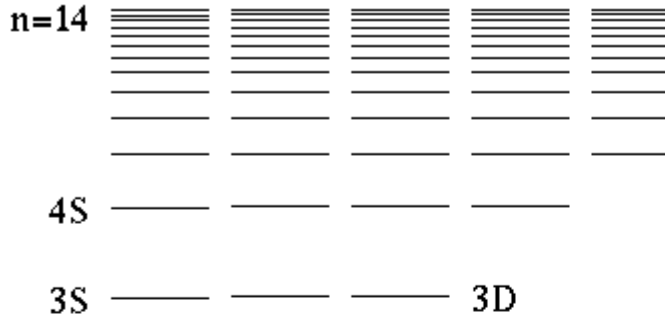
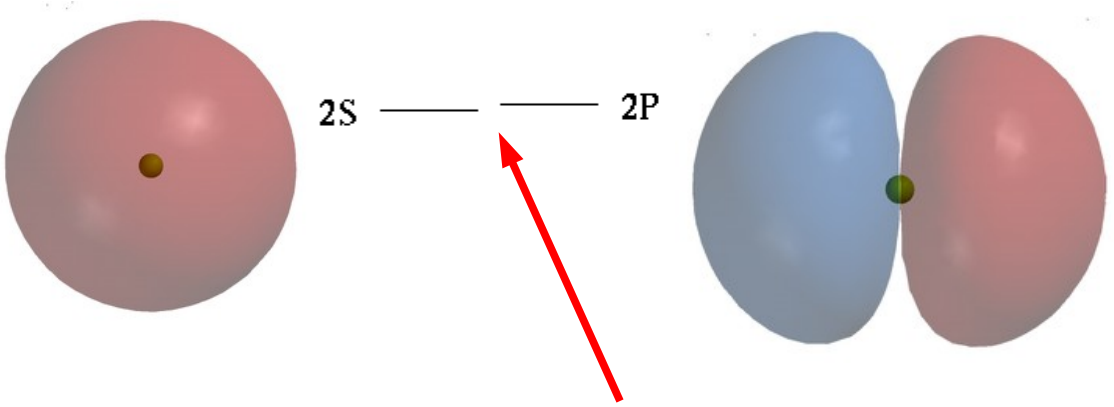


Energy levels of I

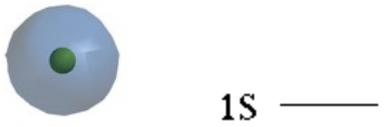




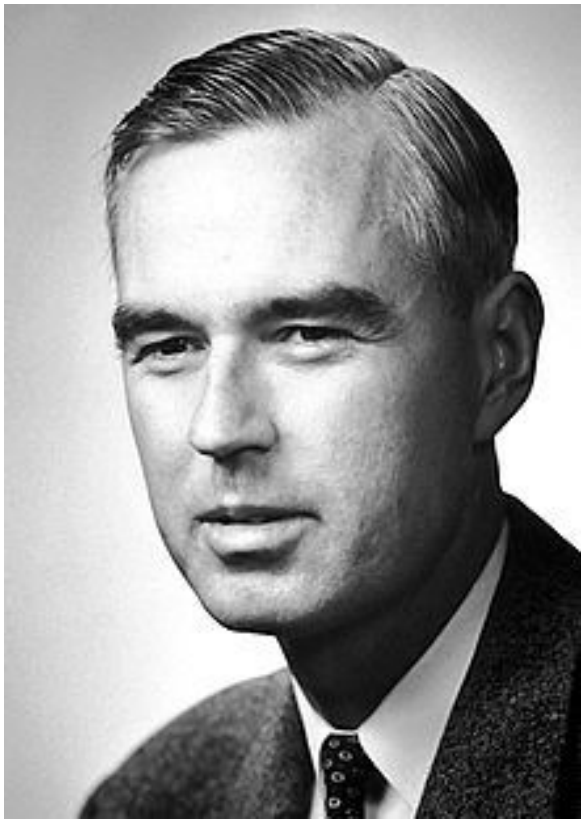


2S-2P Lamb shift

Electron probability density
(Square of the wave function)



The Hydrogen Atom



Discovers in 1947 (with Robert Retherford):

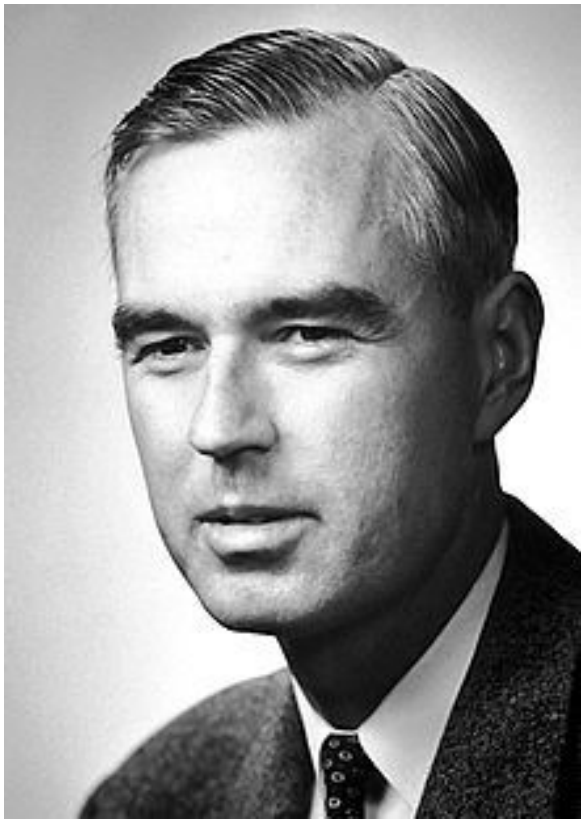
Energy levels “2S” and “2P” in hydrogen

Do NOT have the same energy

Willis E. Lamb, Jr.

1913 – 2008
Nobel prize 1955

The Hydrogen Atom



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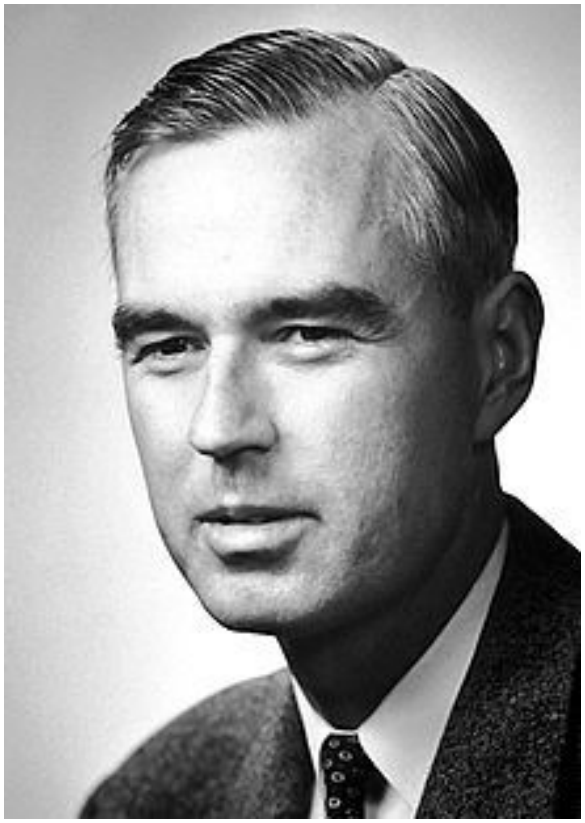

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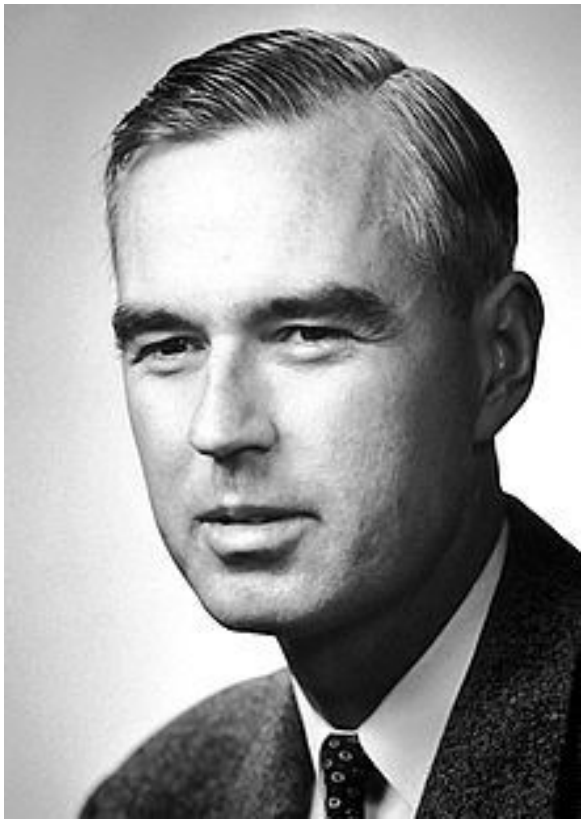

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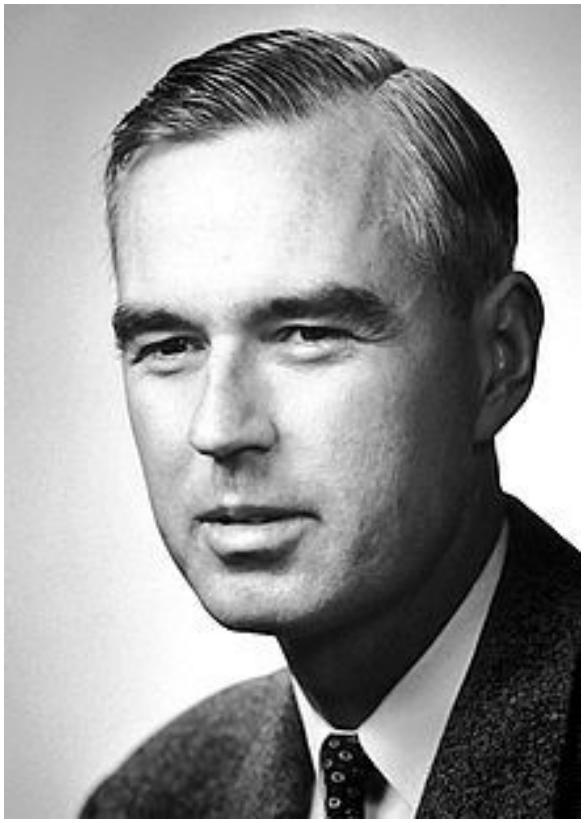

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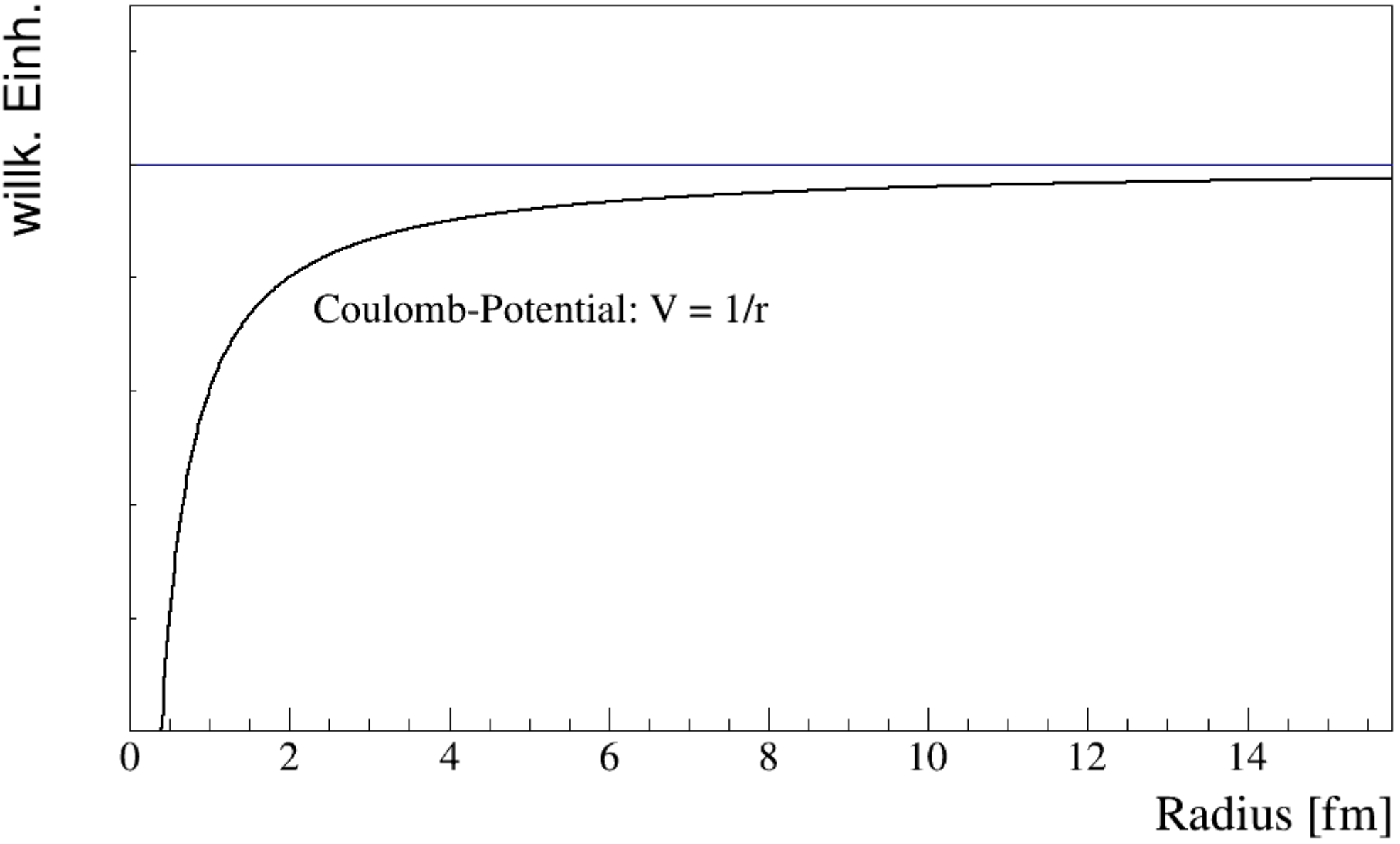
→ Development of

Quantum electrodynamics(QED)

Proton Radius and Hydrogen



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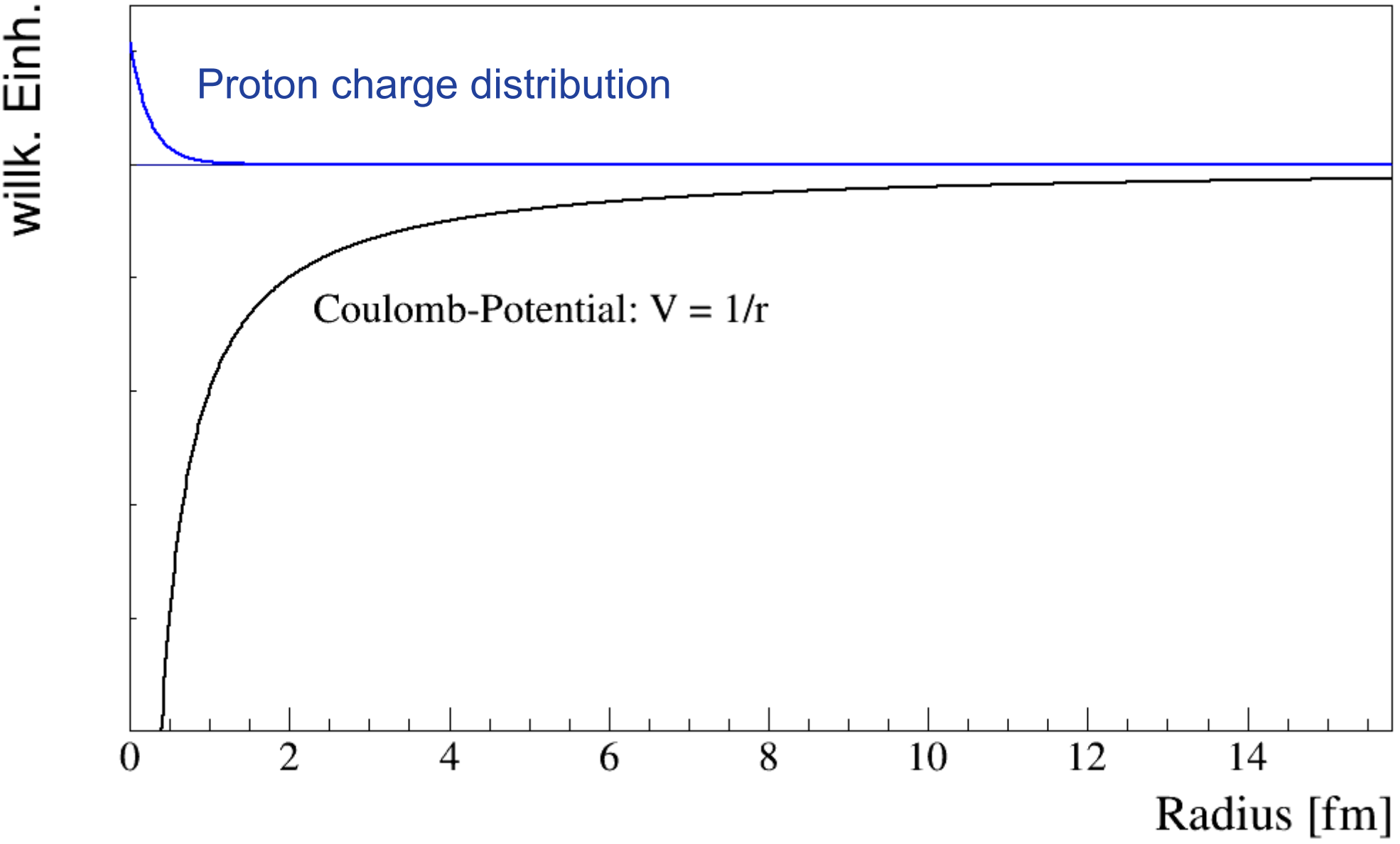

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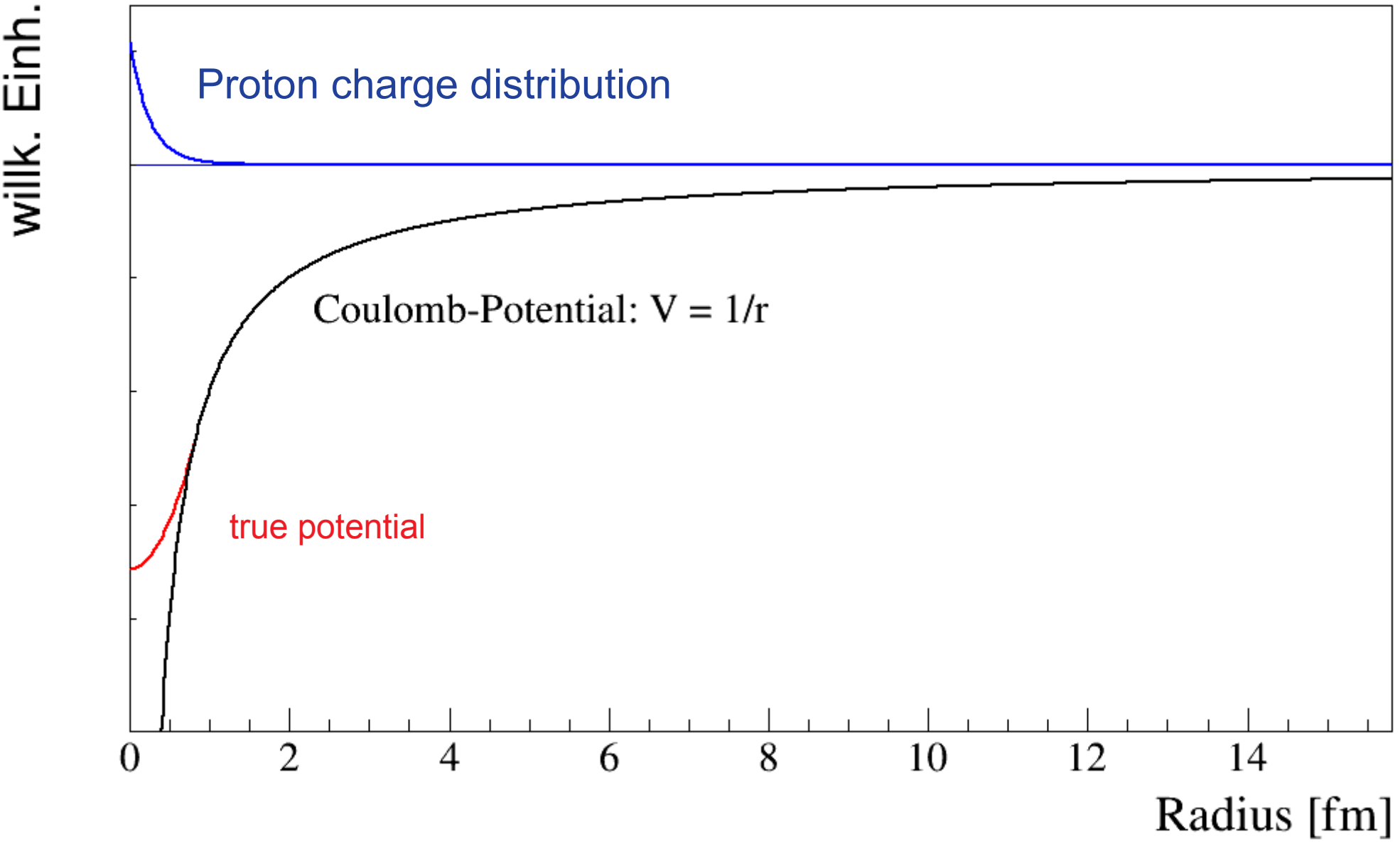

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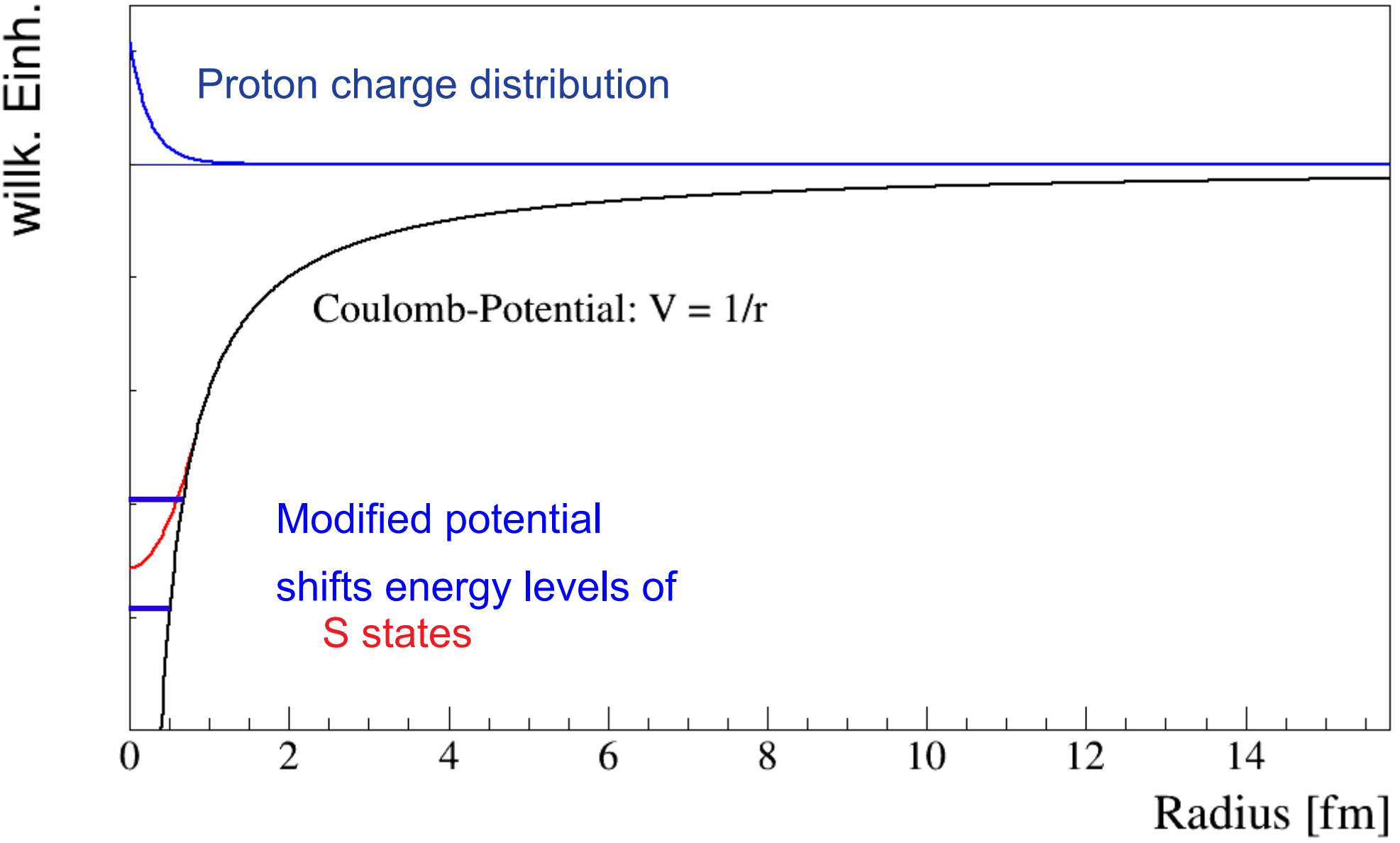
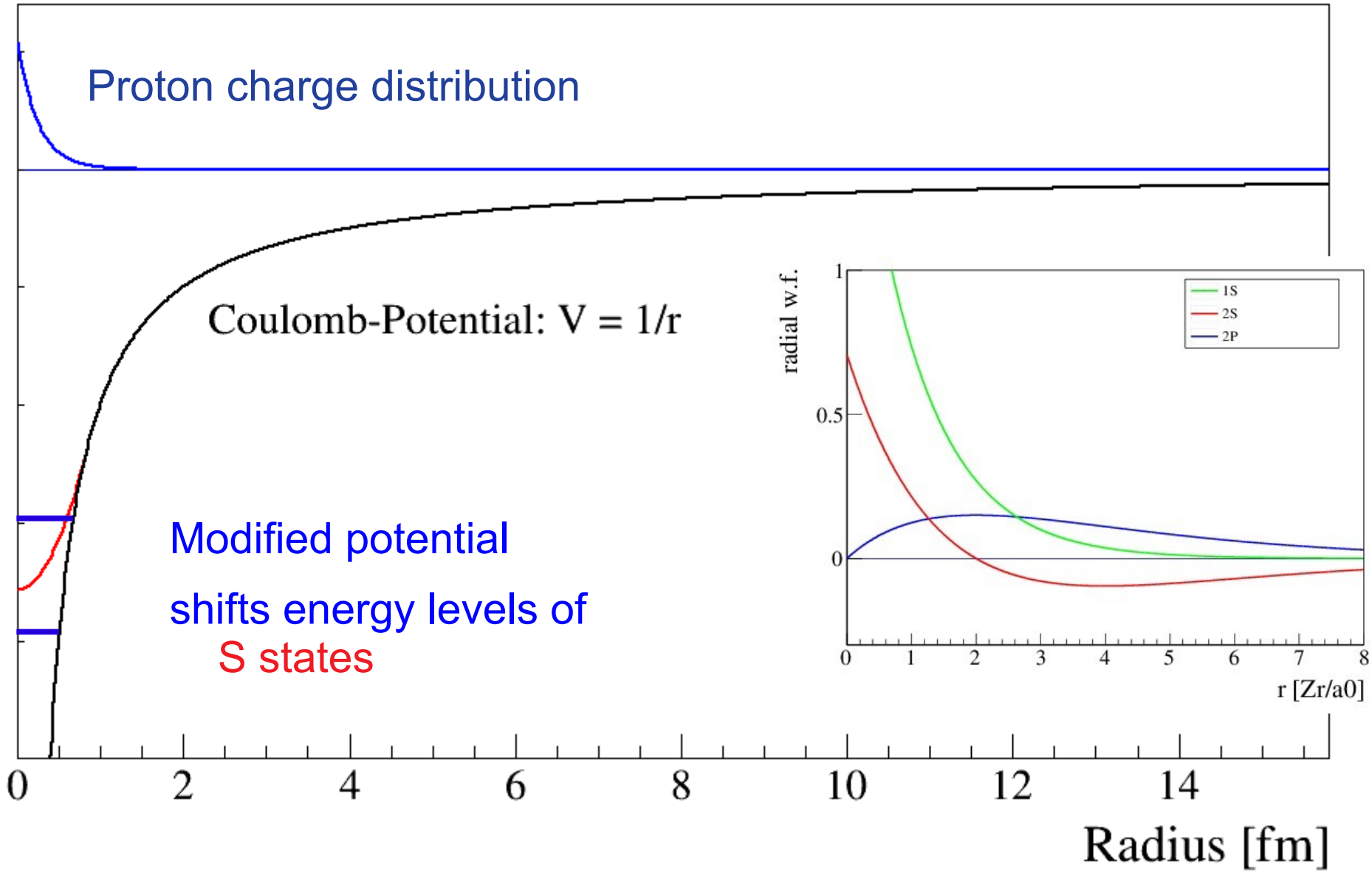
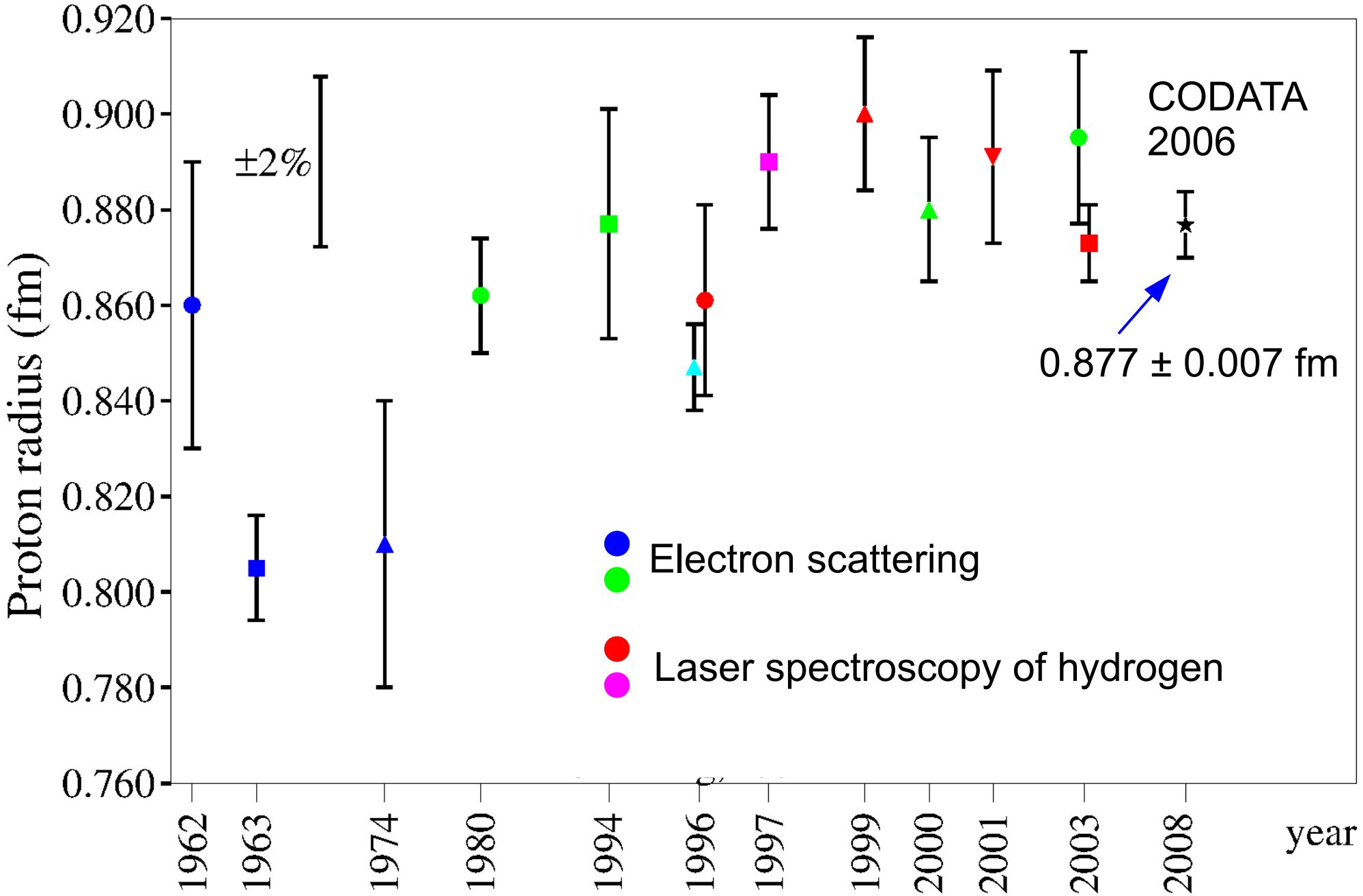


Proton Radius and Hydrogen

willk. Einh.



How large is a Proton?



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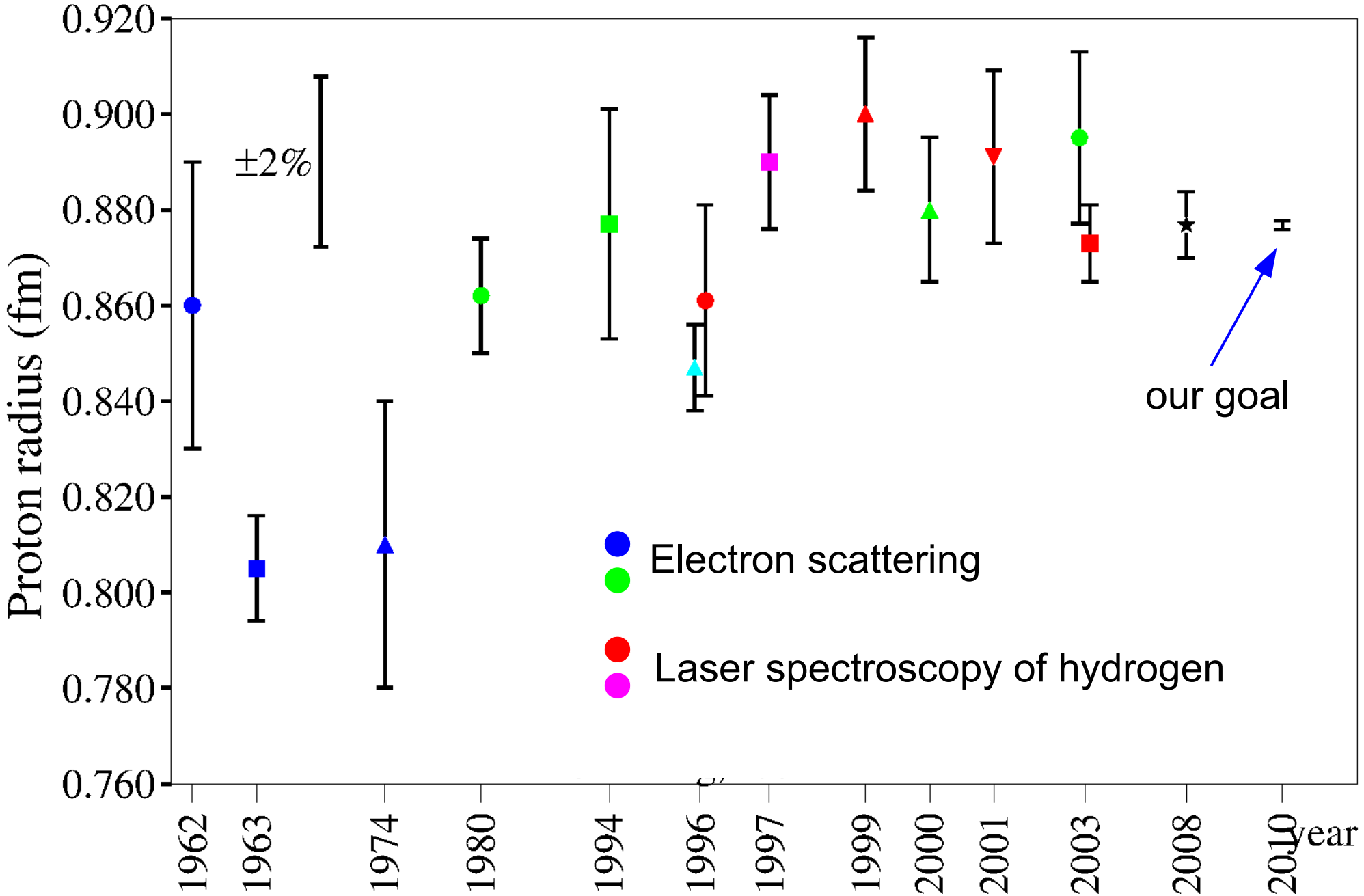

A 10fold more precise measurement of the proton radius!?

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Precision since **1963**: 1%

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
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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:

Measure the

Lamb shift

in

muonic hydrogen

Goal:

10 time more precise

Muonic Hydrogen

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

What is a Muon?

Carl David Anderson

Nobel prize 1936
(for the Positron!)

Seth Neddermeyer

Muons are **heavy electrons**:

200x the mass of an electron.

Discovered in 1936 by Carl D. Anderson and Seth Neddermeyer as part of the cosmic radiation.

Muon have a lifetime of 2 microseconds. (millionths of a second).

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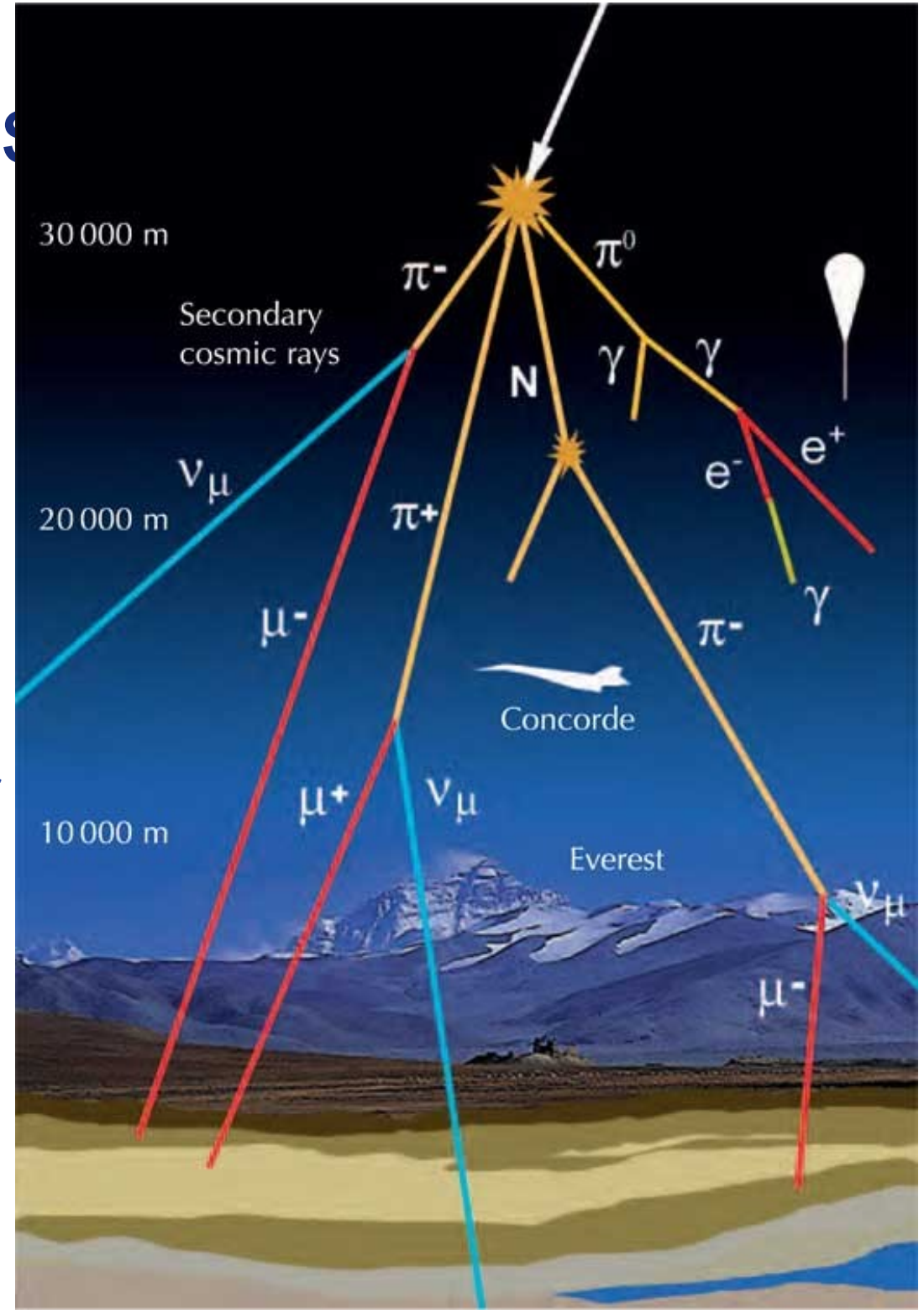

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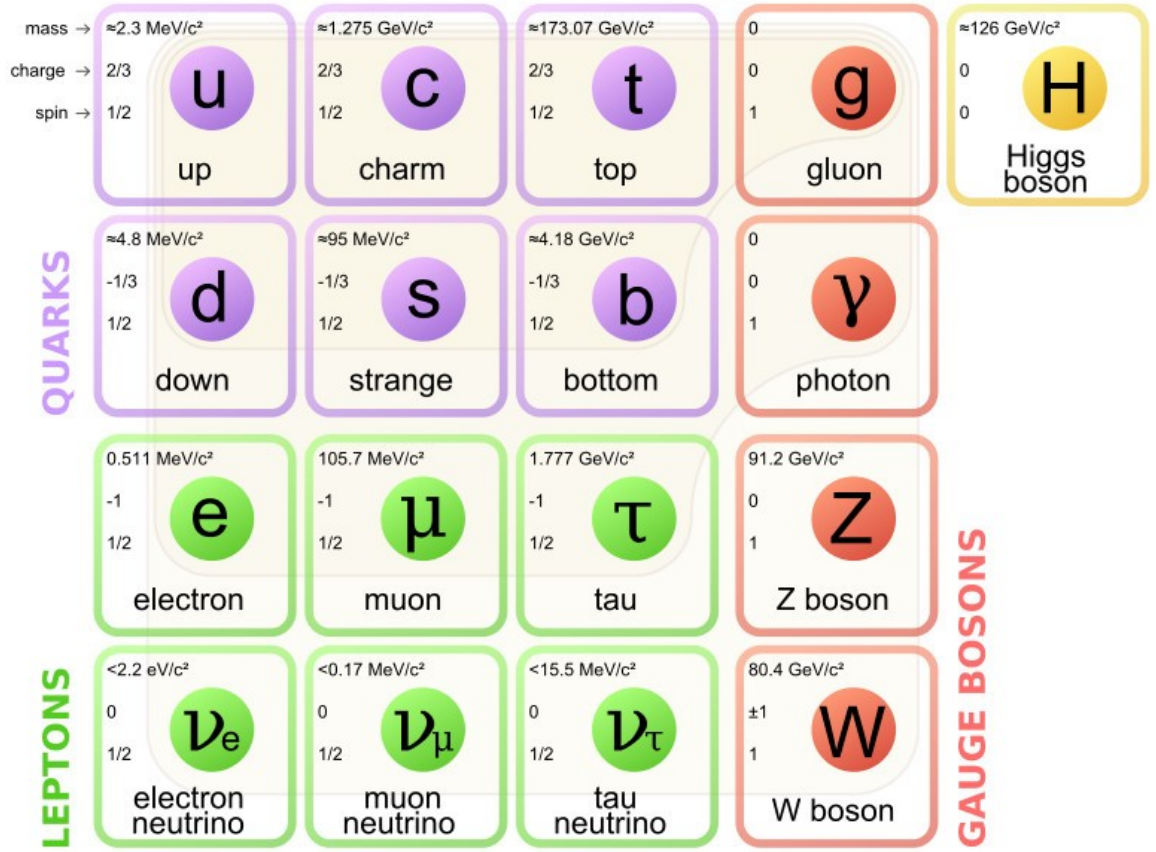
Isidor Isaac Rabi

The muon and its place in the world

Standard Modell of Particle Physics



The muon and its place in the world

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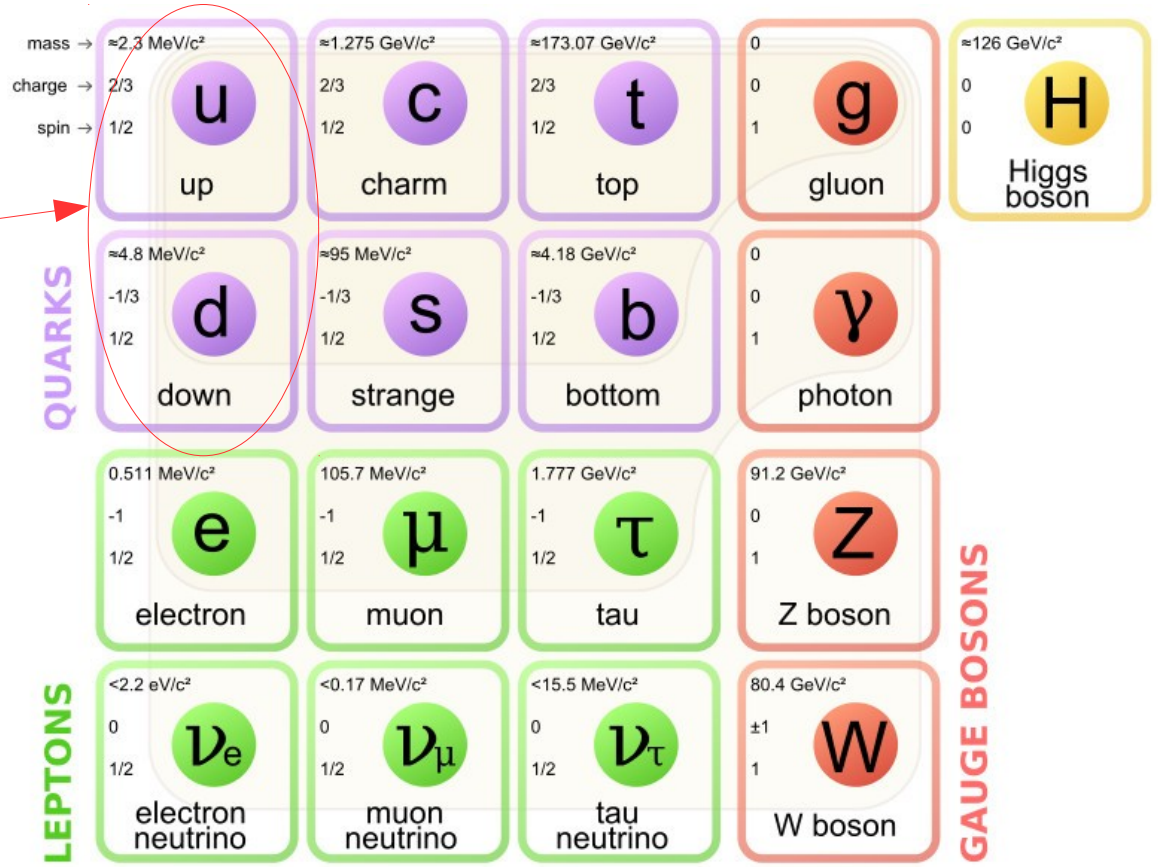

Proton

The muon and its place in the world

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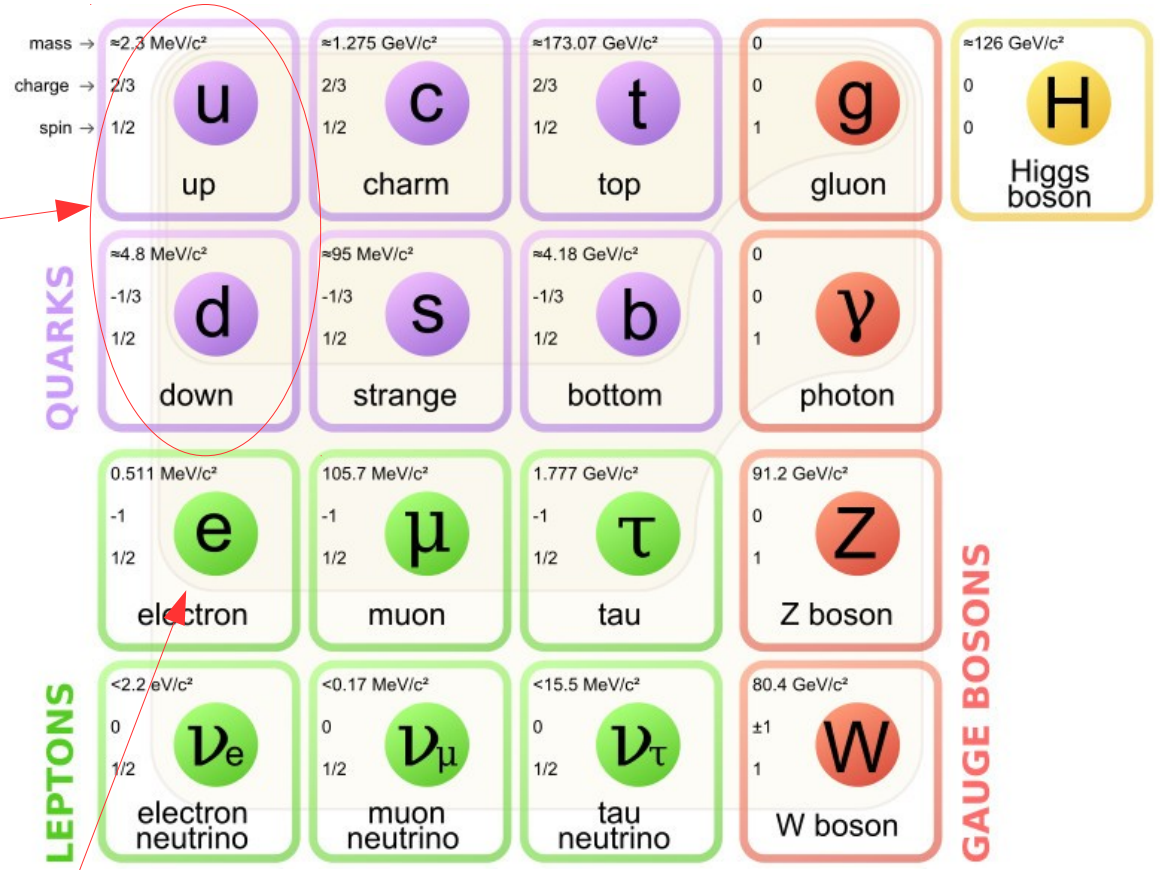

Proton

Electron

The muon and its place in the world

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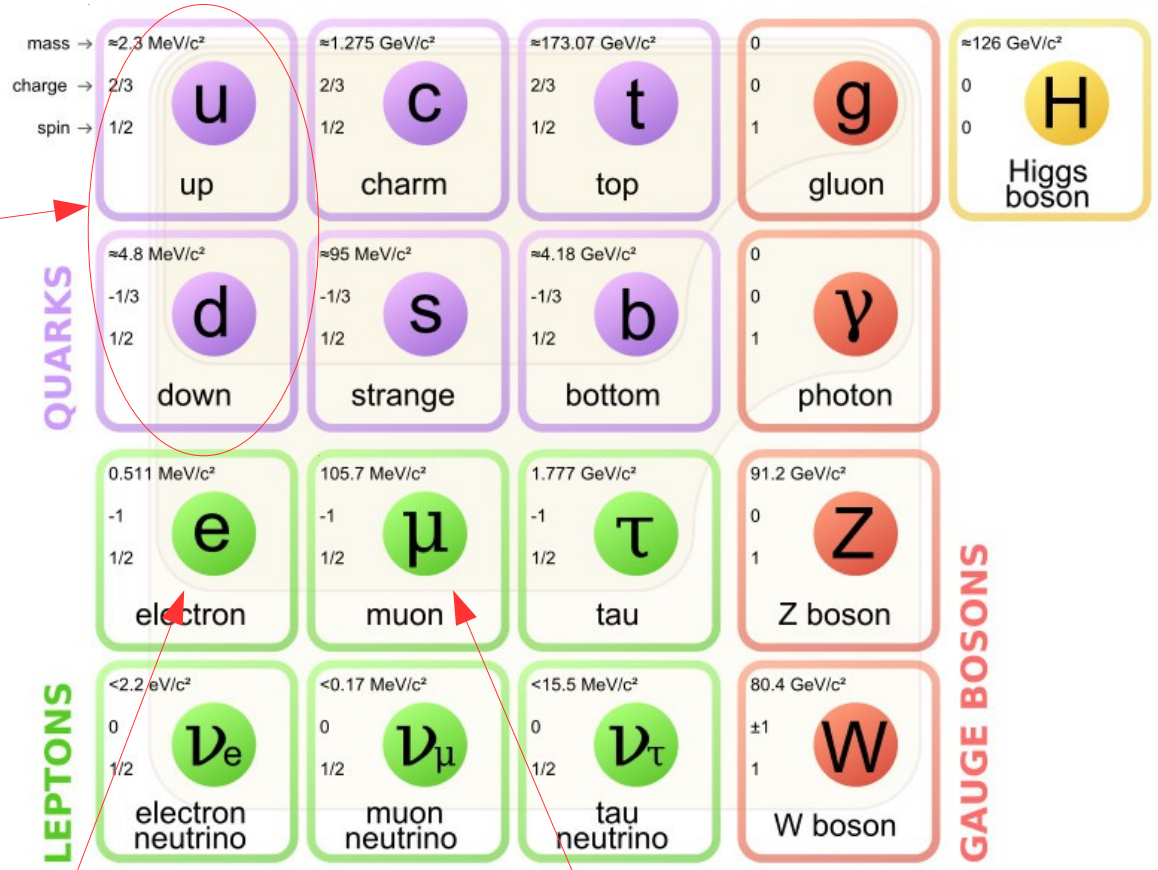


Proton

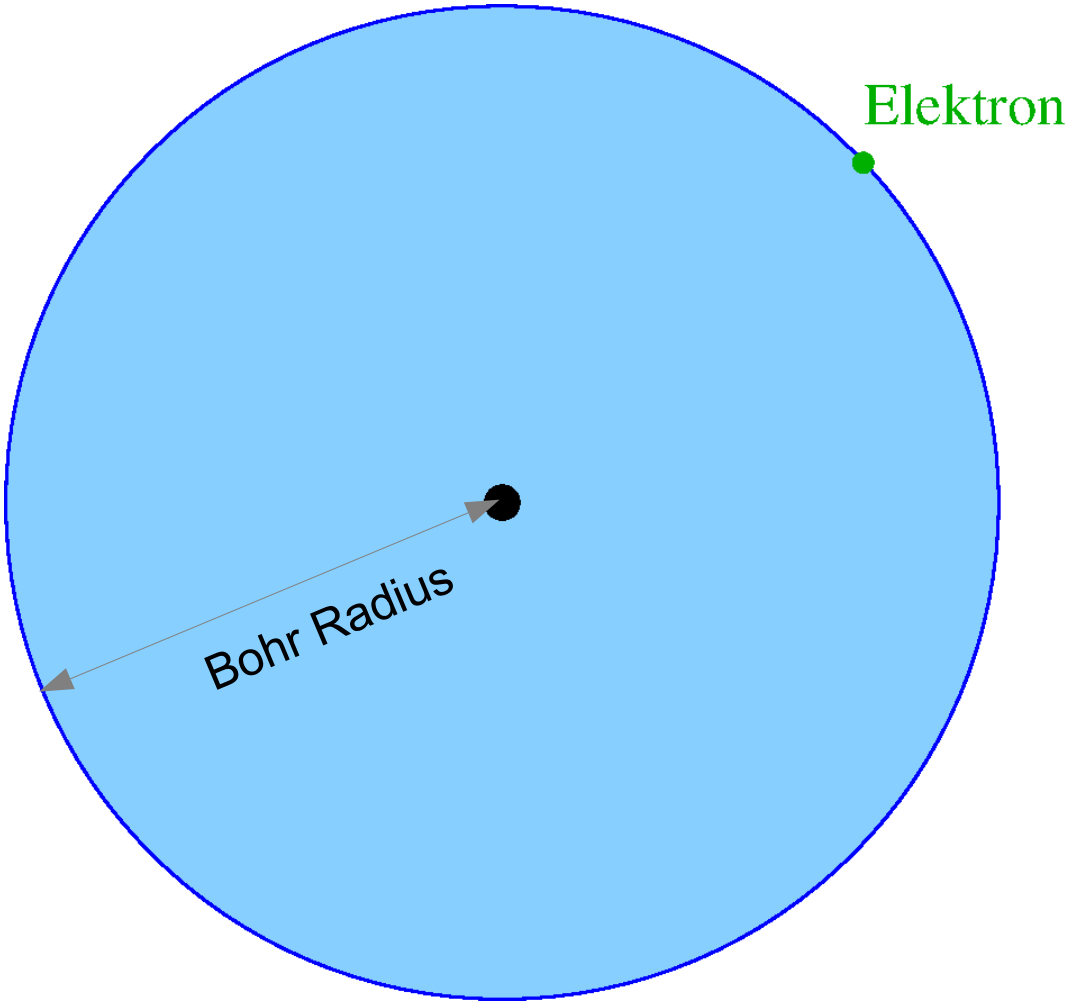
Electron

Muon

Normal and muonic hydrogen

normal hydrogen:

Proton + Electron



muonic hydrogen:

Proton + Muon

Mass = **200 *** Electron mass

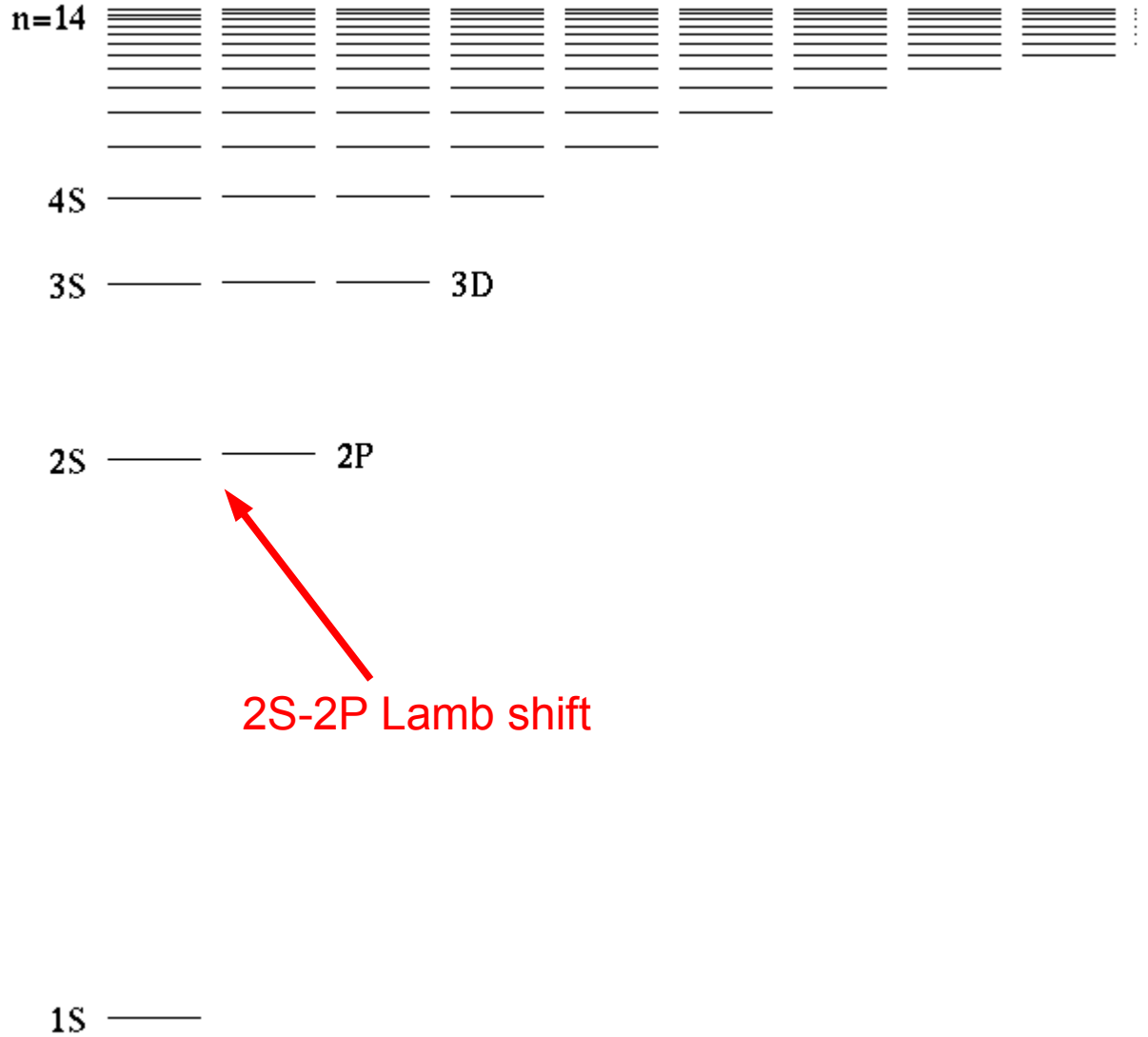
Bohr **Radius** = **1/200** of hydrogen

200^3 = 10 Million

times more sensitive

To the size of the proton

Muonic Hydrogen



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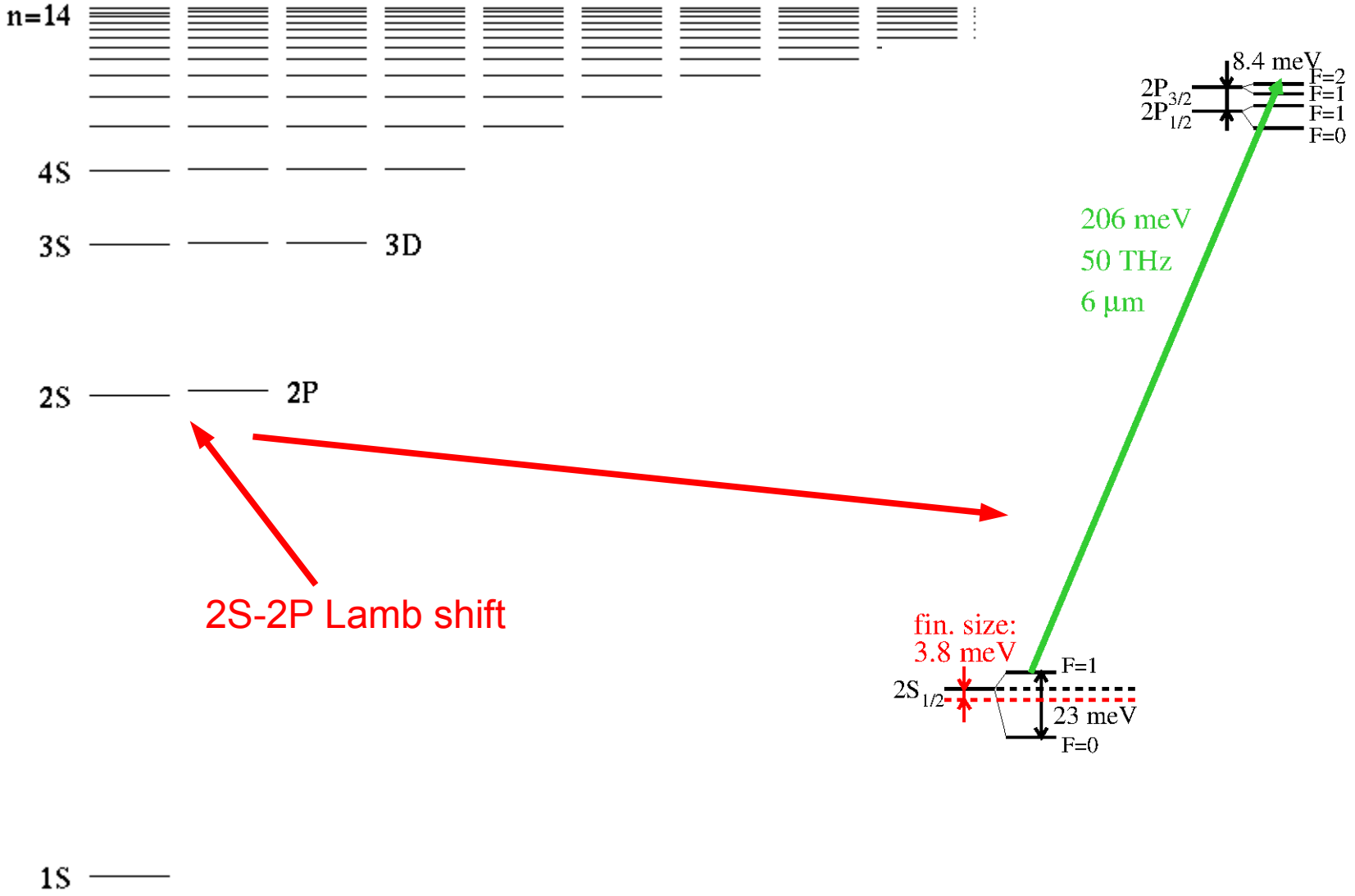

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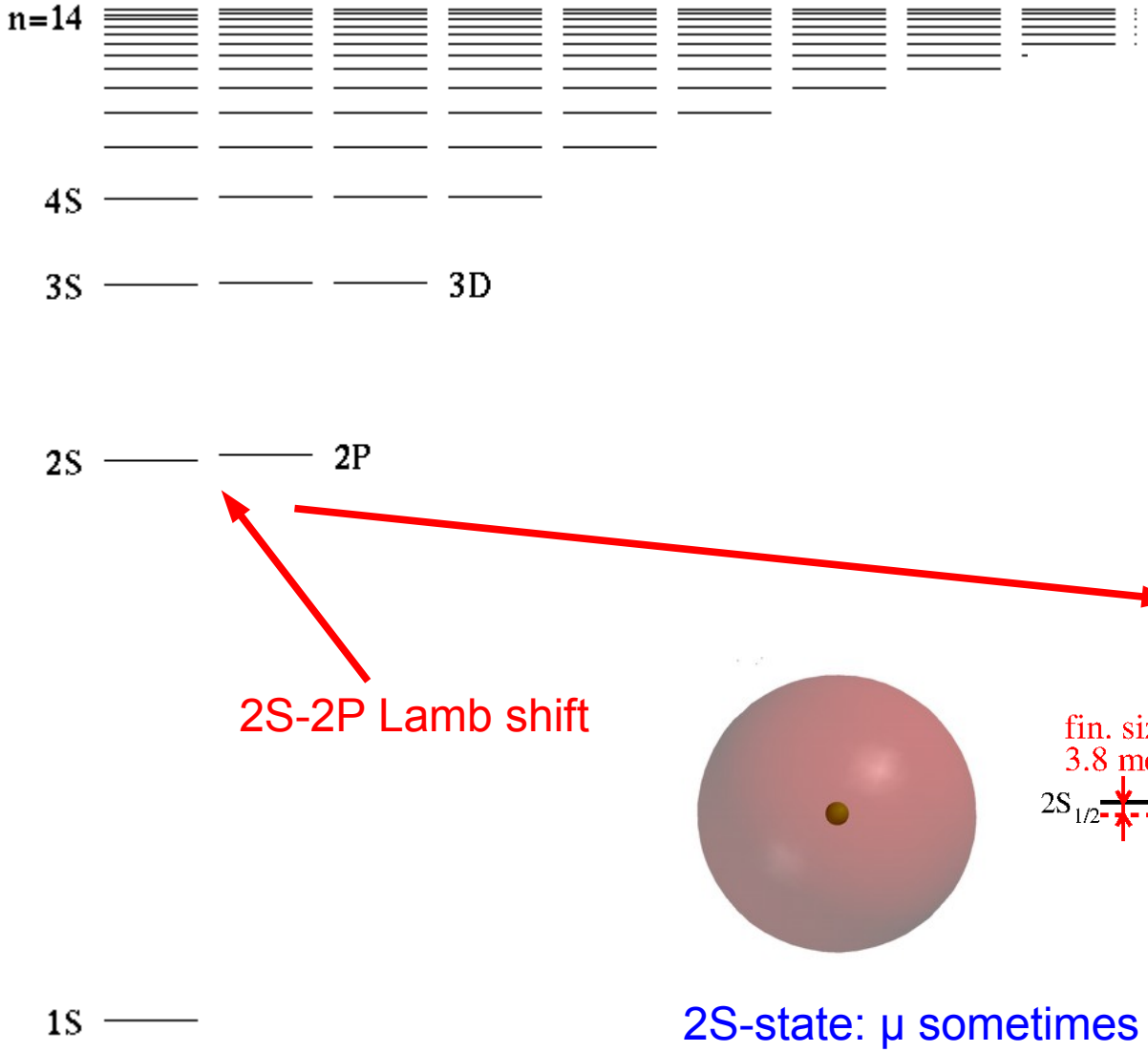
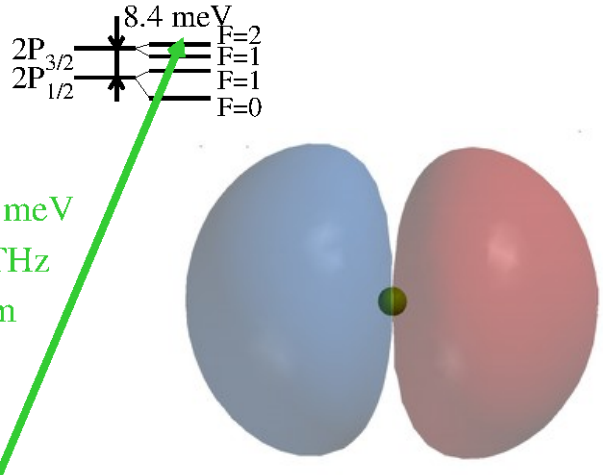
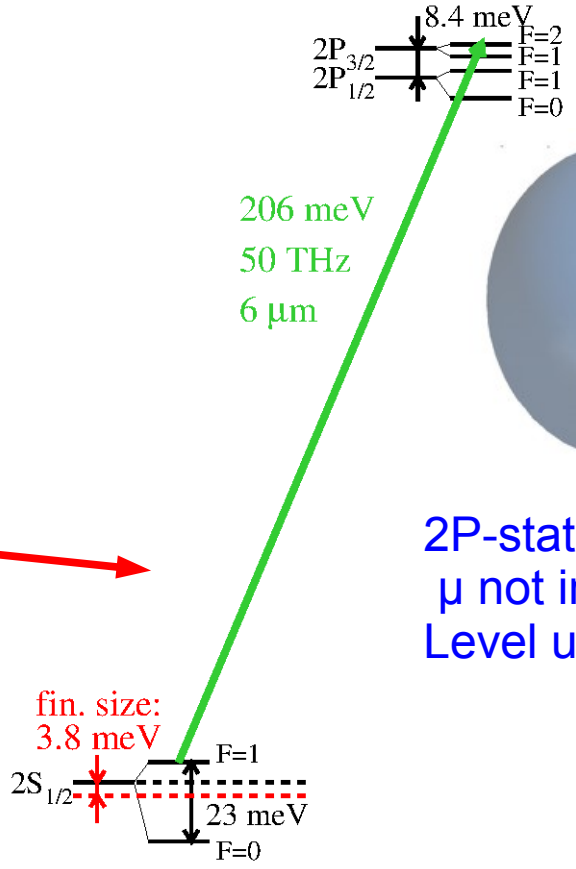




2P-state:
μ not inside proton
Level unaffected.

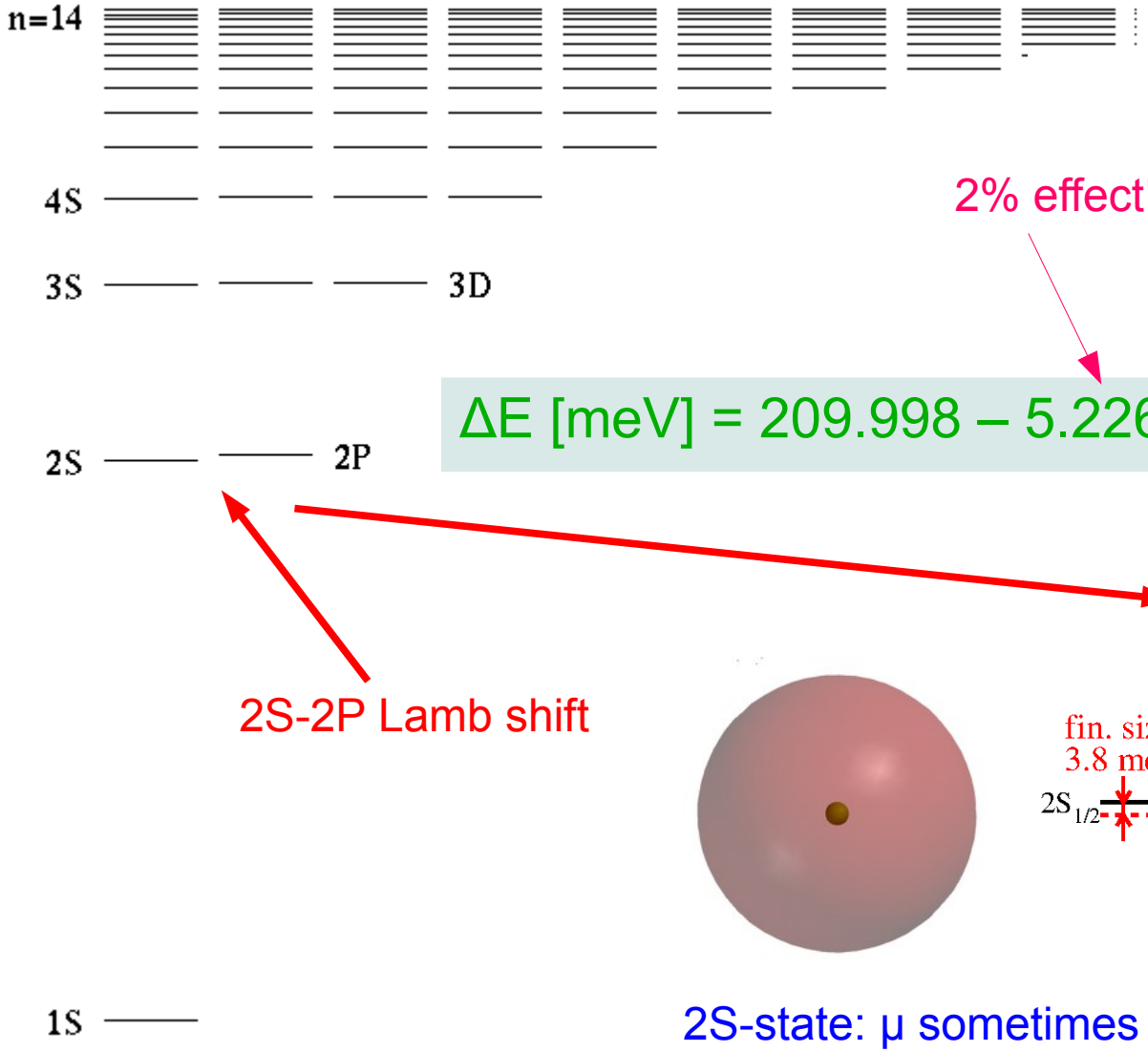
206 meV
50 THz
6 μm

2S-2P Lamb shift



2S-state: μ sometimes inside the Proton!
Level sensitive to Proton Size

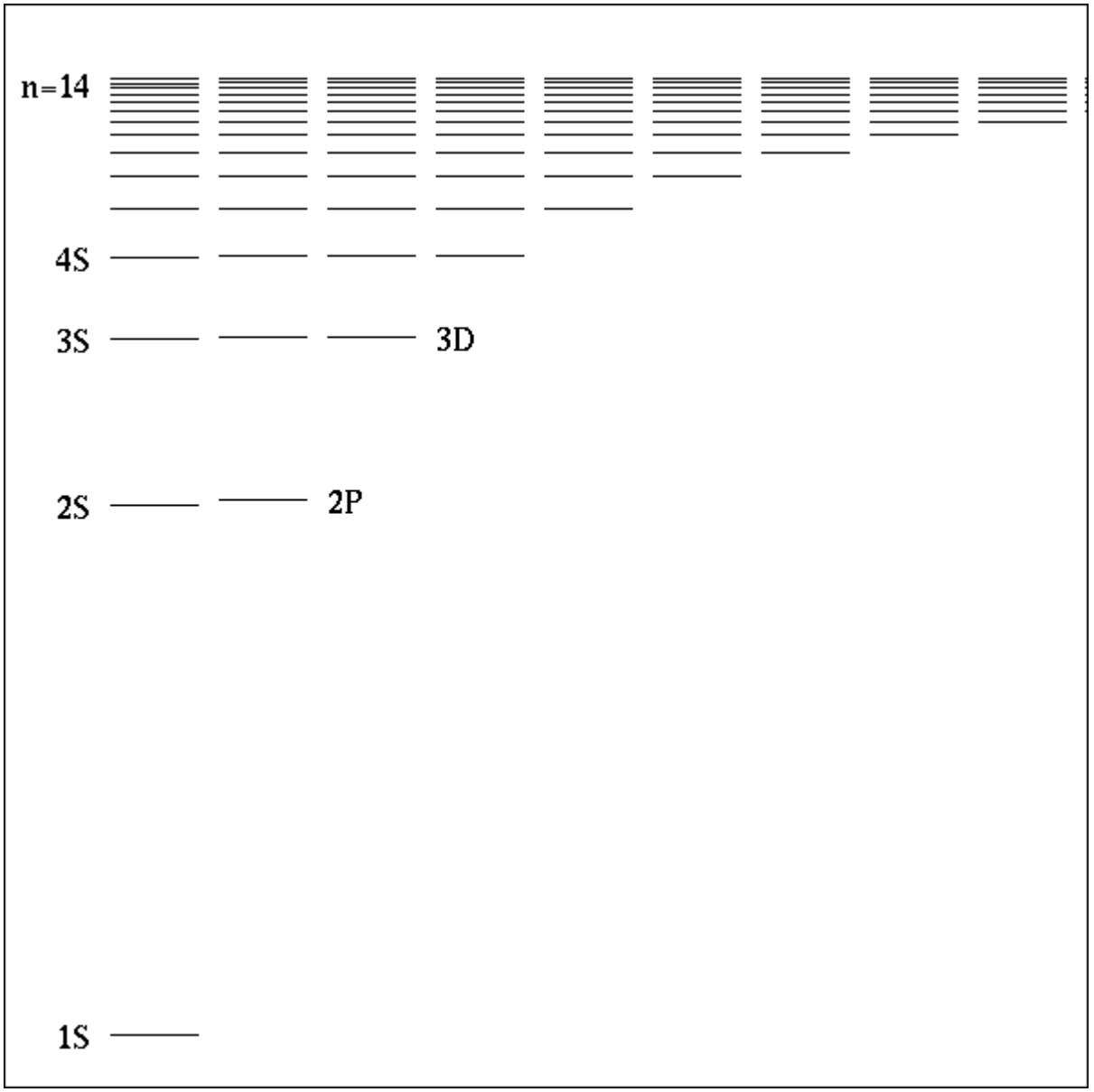
Muonic Hydrogen



2P-state:
µ not inside proton
Level unaffected.

2S-state: µ sometimes inside the Proton!
Level sensitive to Proton Size

Measurement Principle



* Muons stop in H_2

* Capture into high states with n~14

* Cascade to lower n

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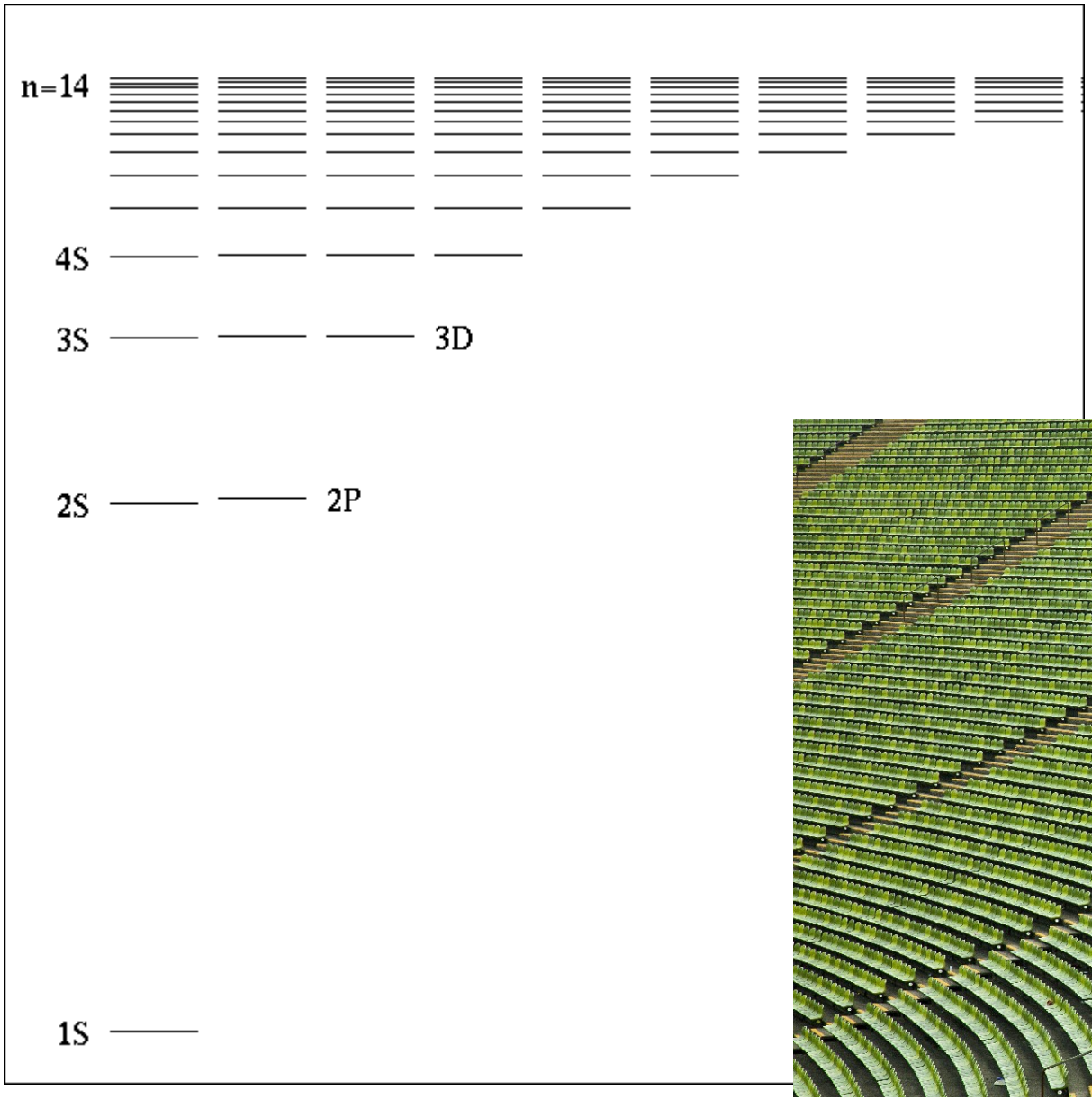

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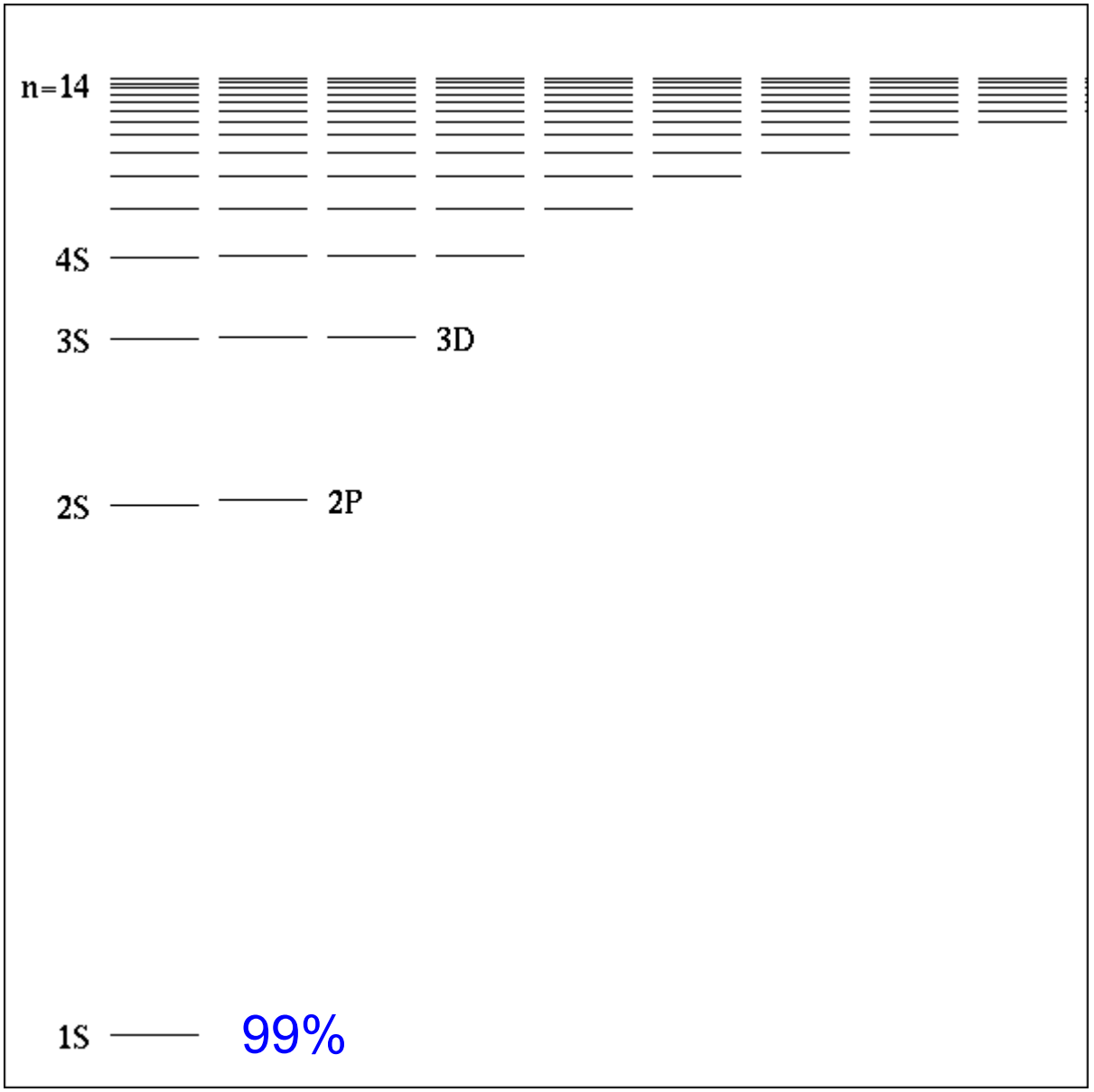

* Muons stop in H_2

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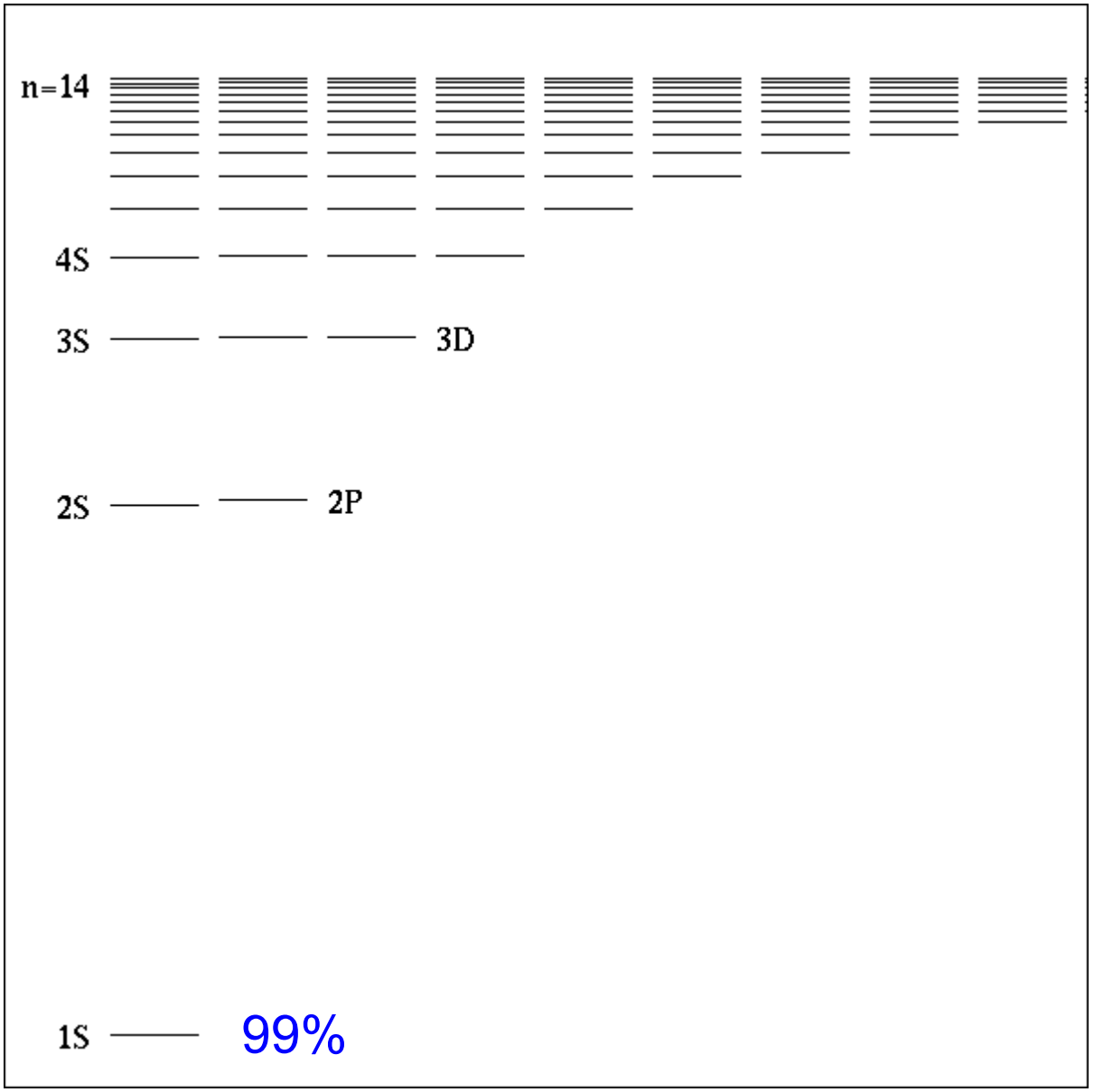
* 99% end in 1S ground-state

* X-ray photons

Measurement Principle



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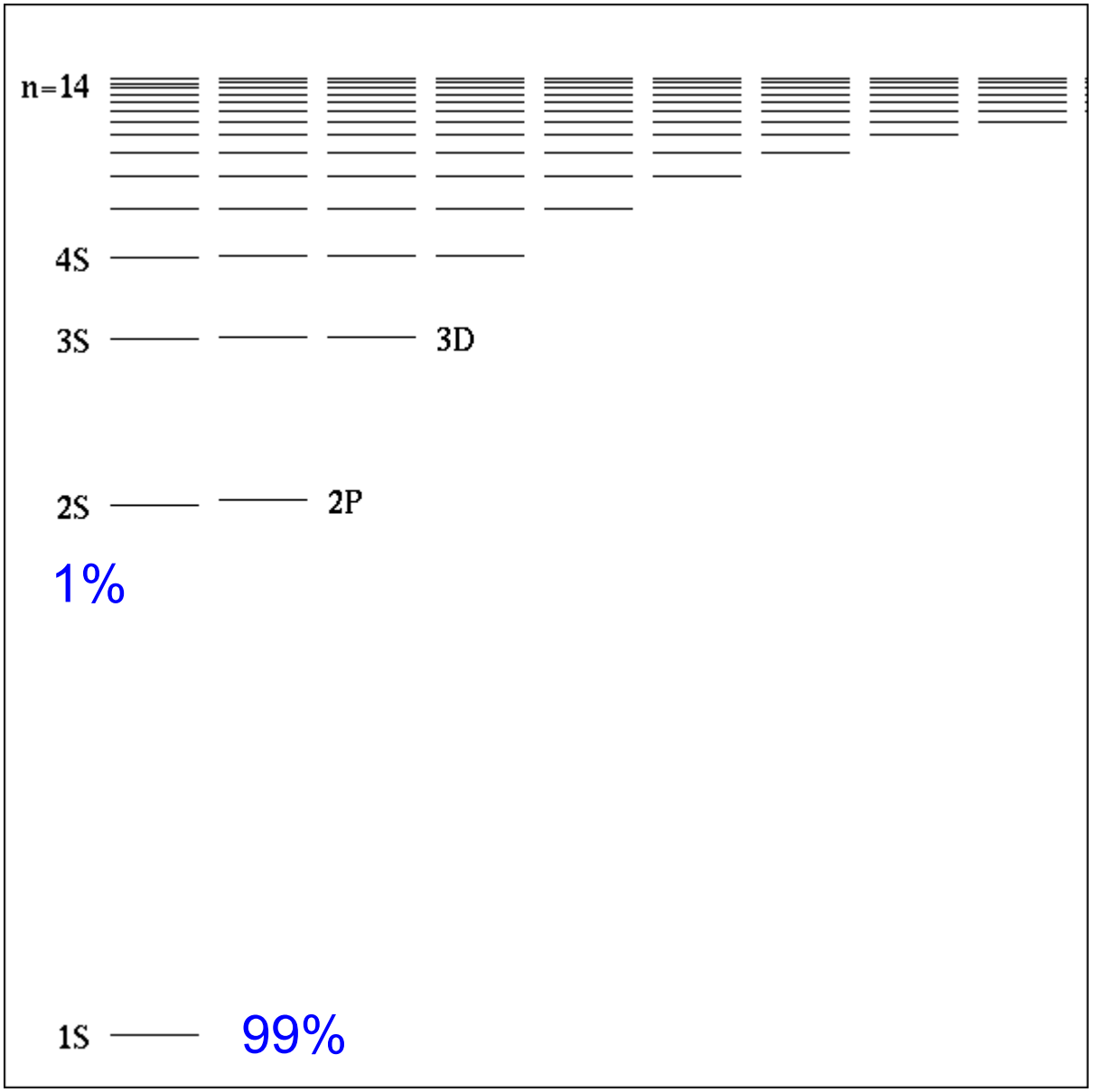


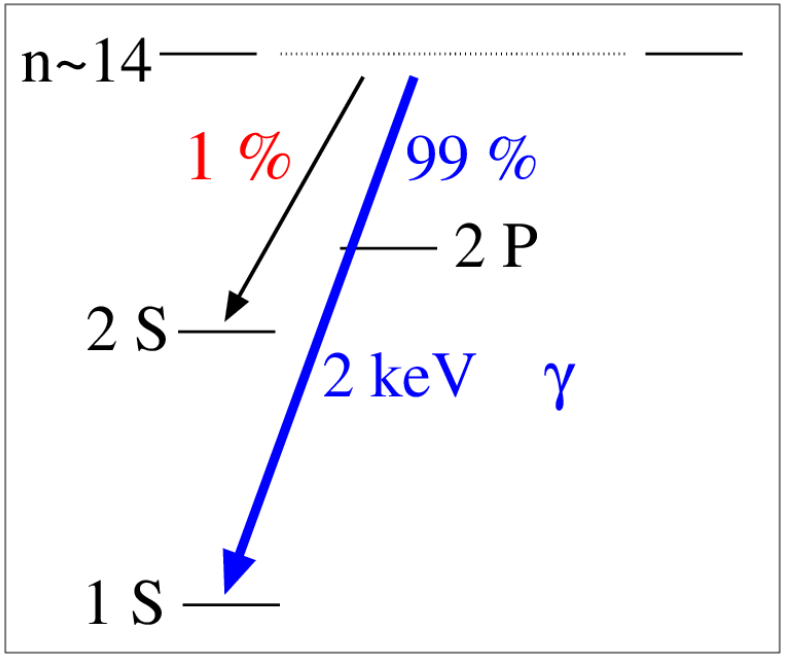
* Muons stop in H_2

* Capture into high states with n~14

* Cascade to lower n

* 1% end in long-lived 2S state

Measurement Principle

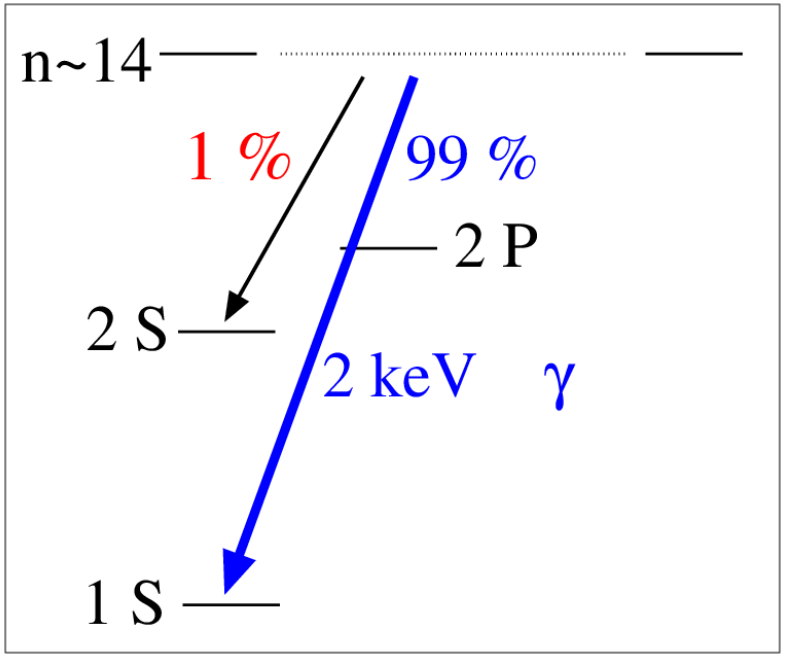


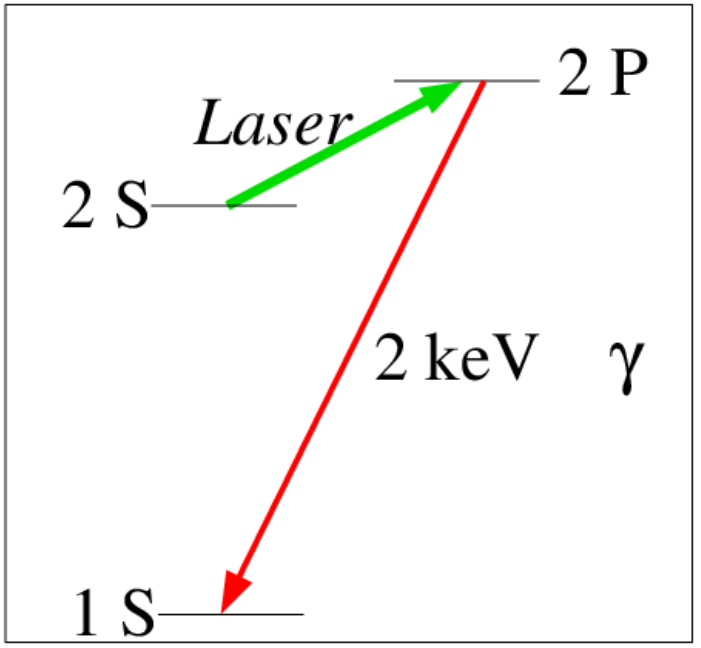
“prompt” (t=0):

* Muon capture into n~14
* Cascade
* 99% end in ground state

→ “prompt” X-ray photons

Measurement Principle





"prompt" (t=0):

* Muon capture into n~14
* Cascade
* 99% end in ground state

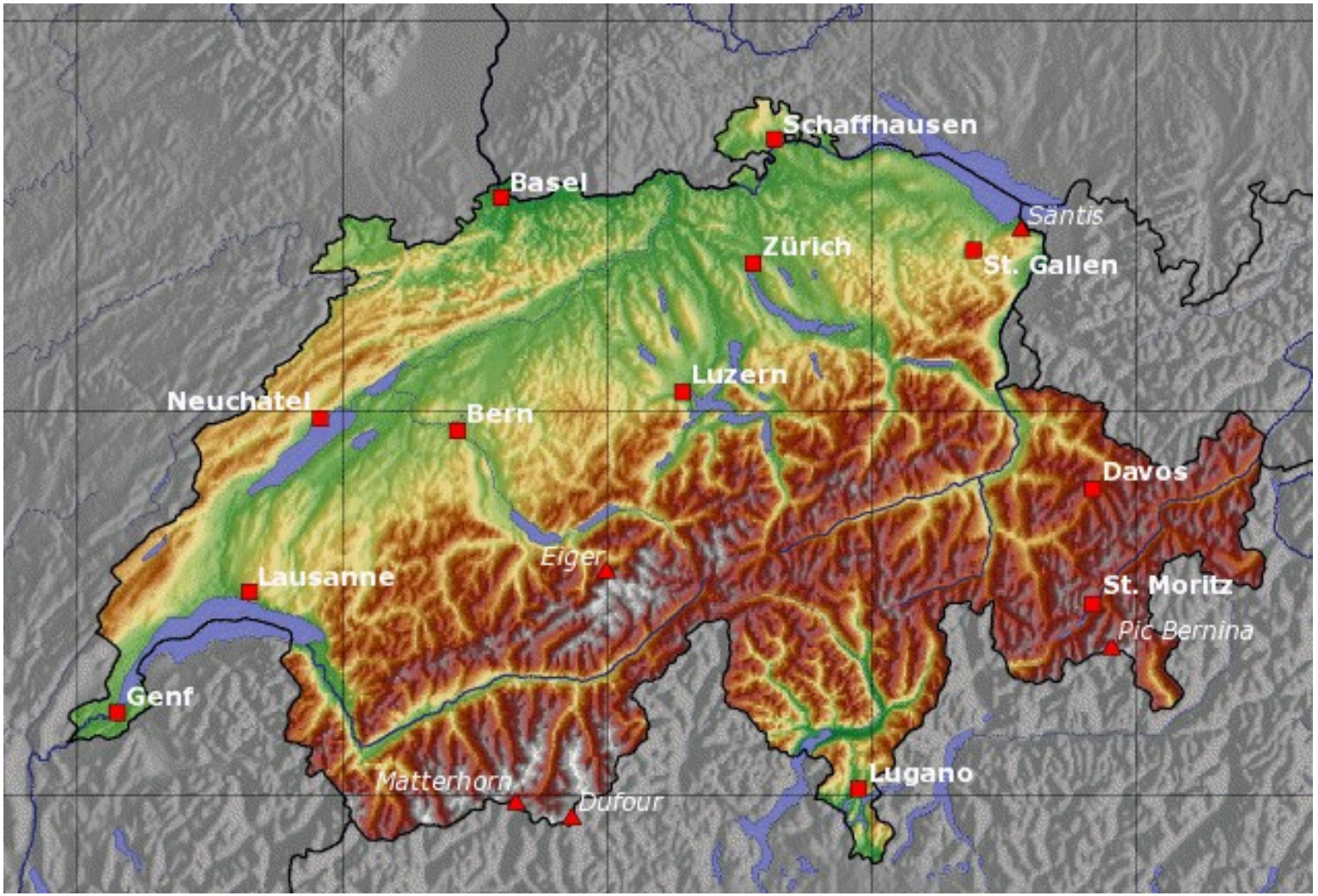
→ "prompt" X-ray photons

"delayed" (t ~ 1μs):

* 1% of the Muons in 2S state
* Laser on resonance (λ=6μm)
* 2S → 2P → 1S

→ "delayed" X-ray photons

The accelerator at PSI



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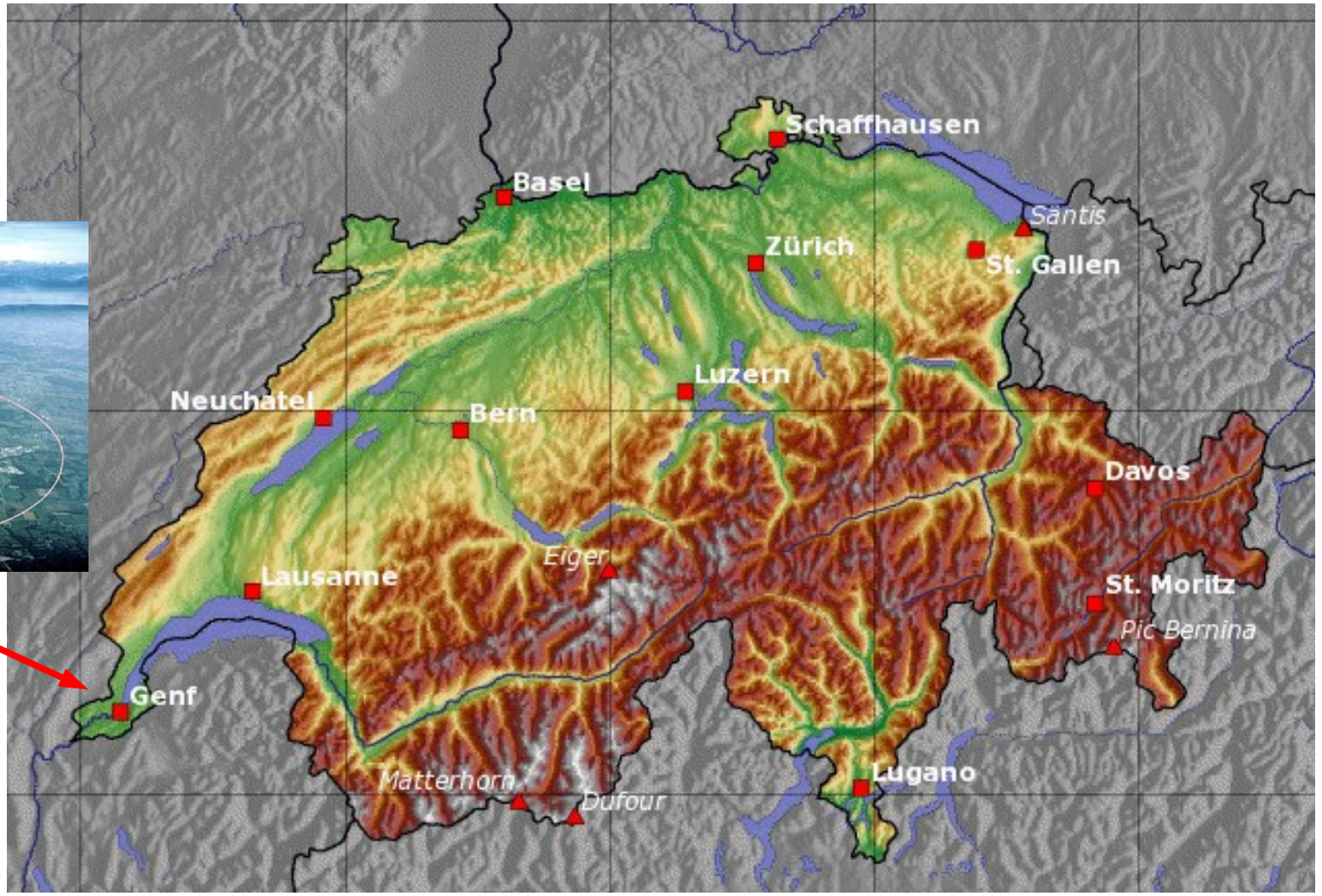

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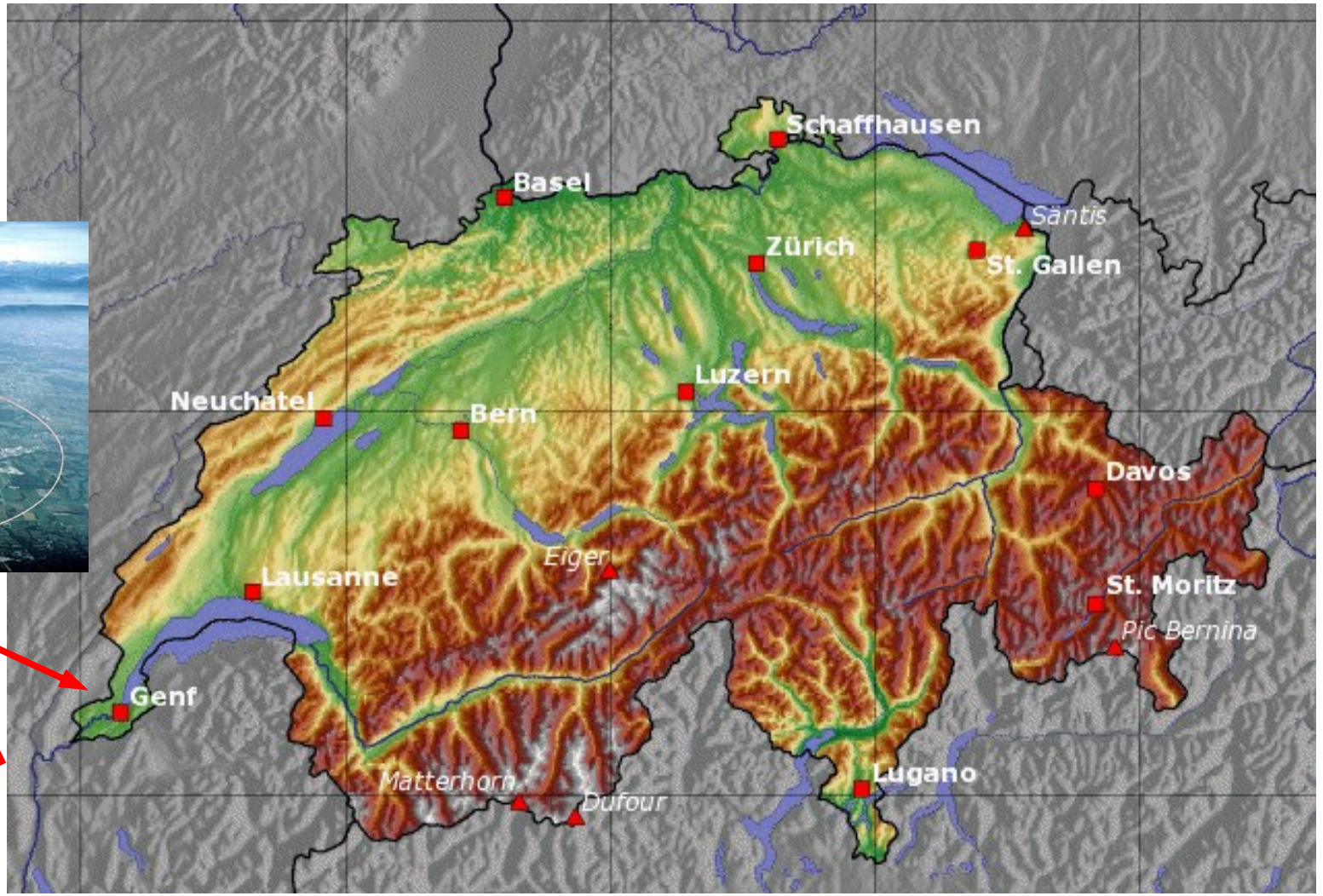
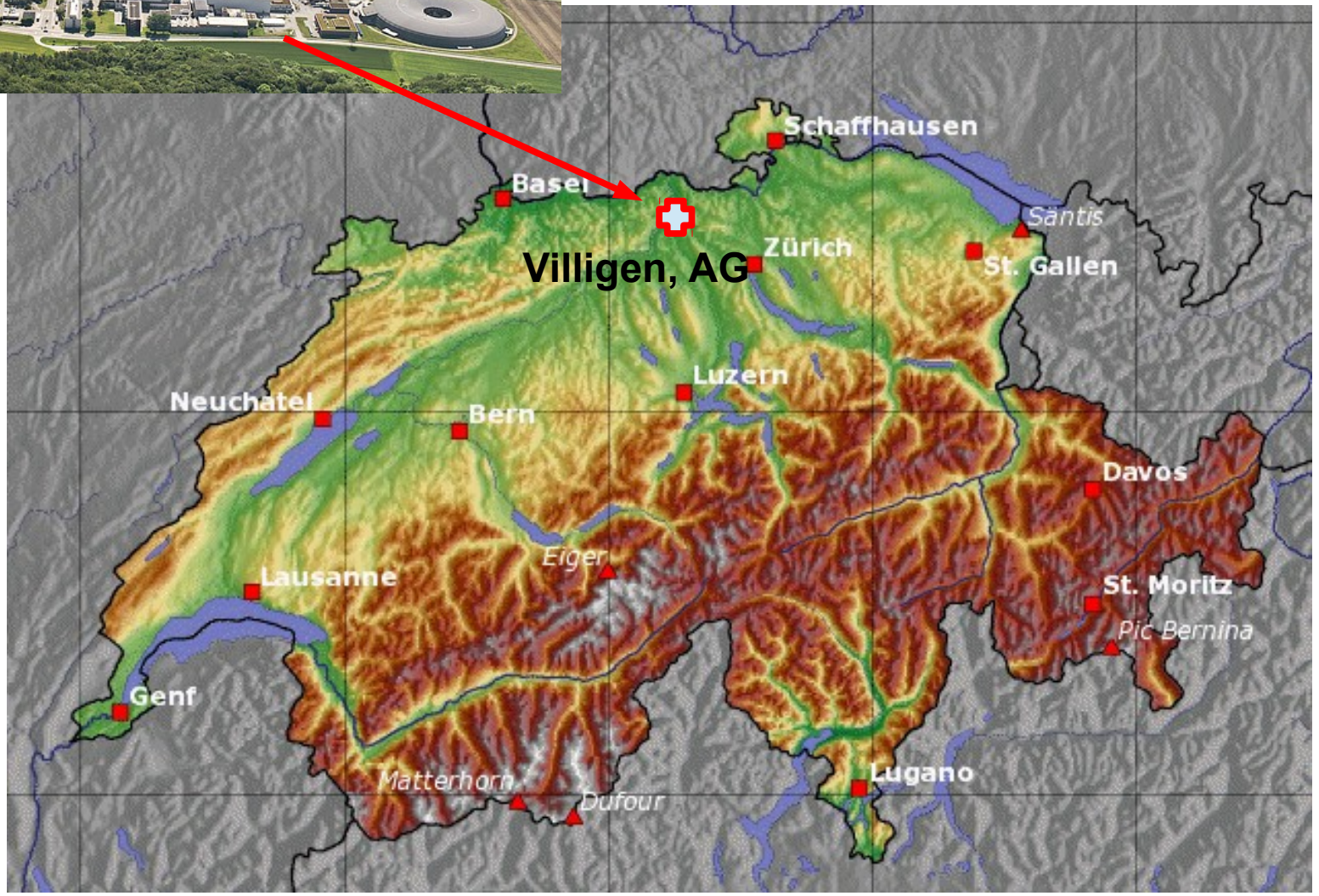


The accelerator at PSI

PAUL SCHERRER INSTITUT

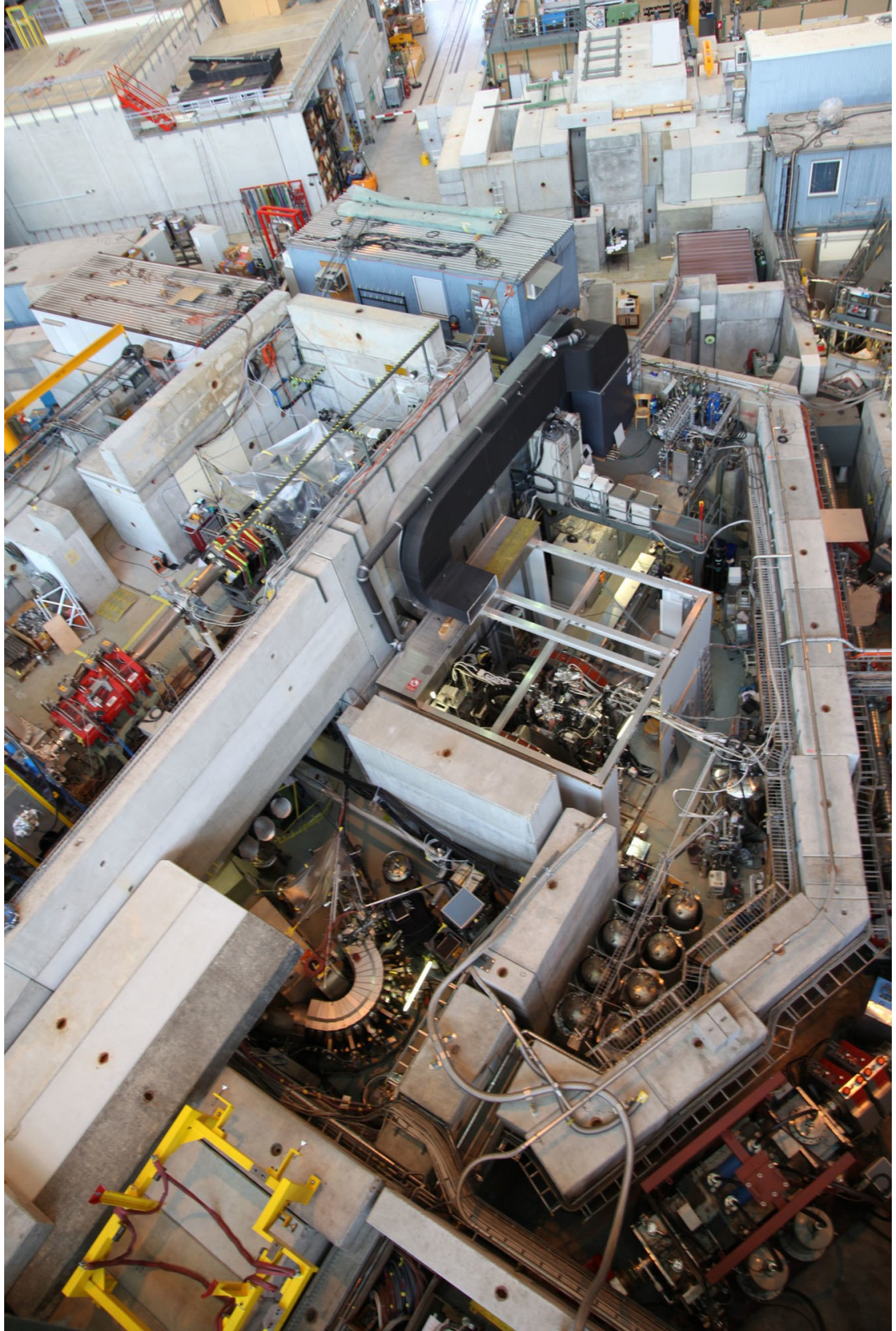
PSI



Paul Scherrer Institute

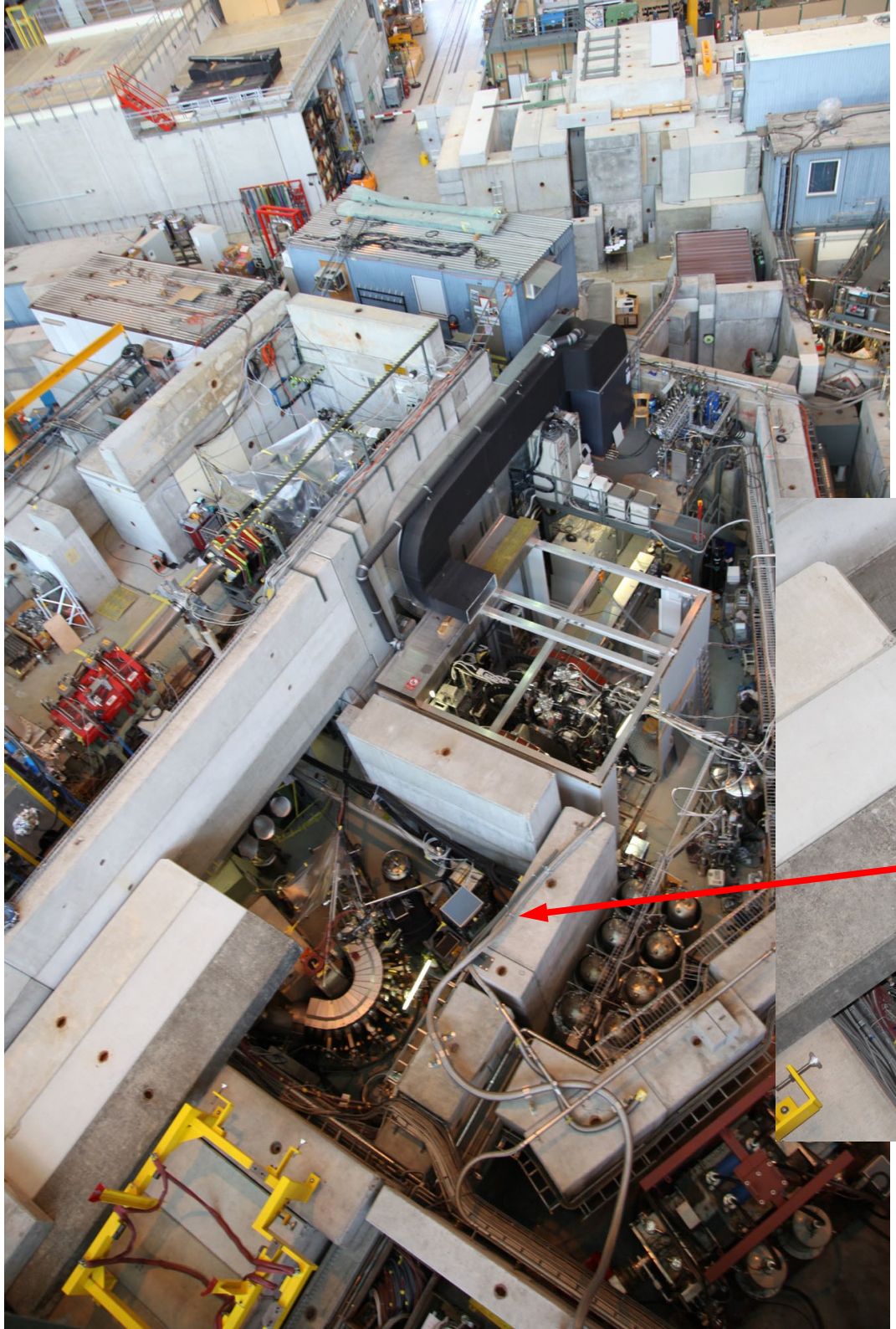
Paul Scherrer Institute

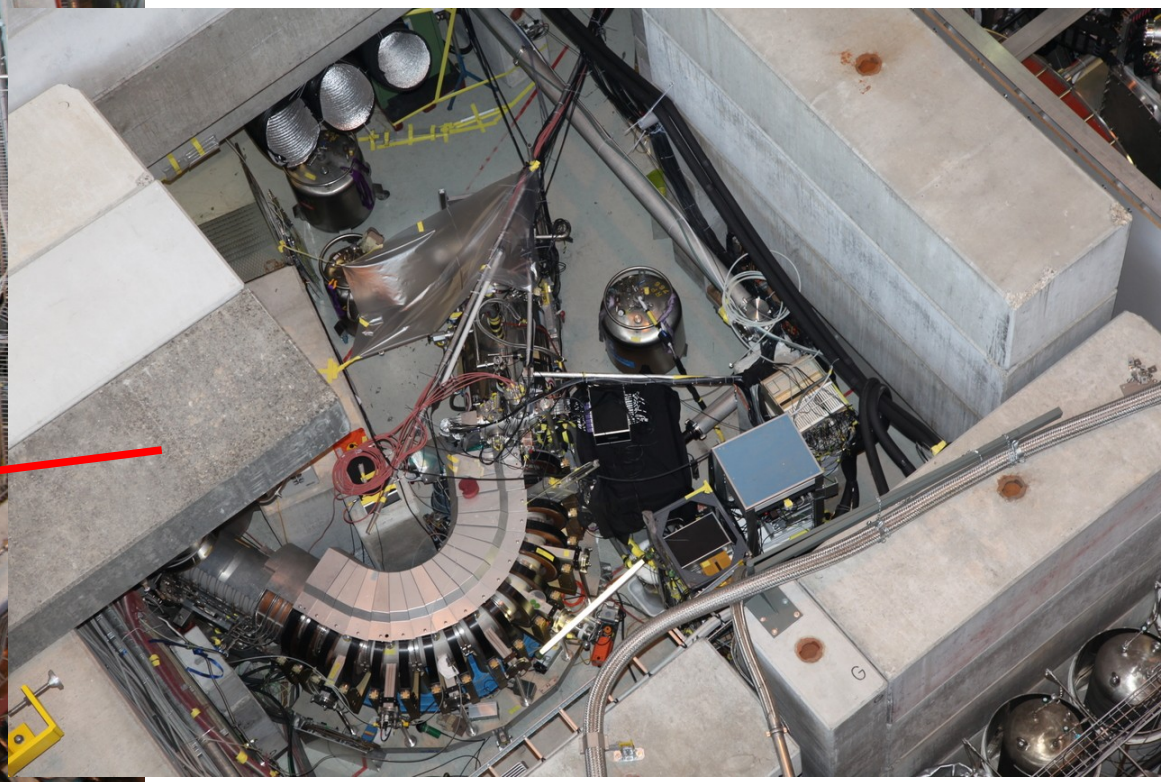
Experimental Hall



Experimental Hall from above

Experimental Hall from above





Beam Area πE5

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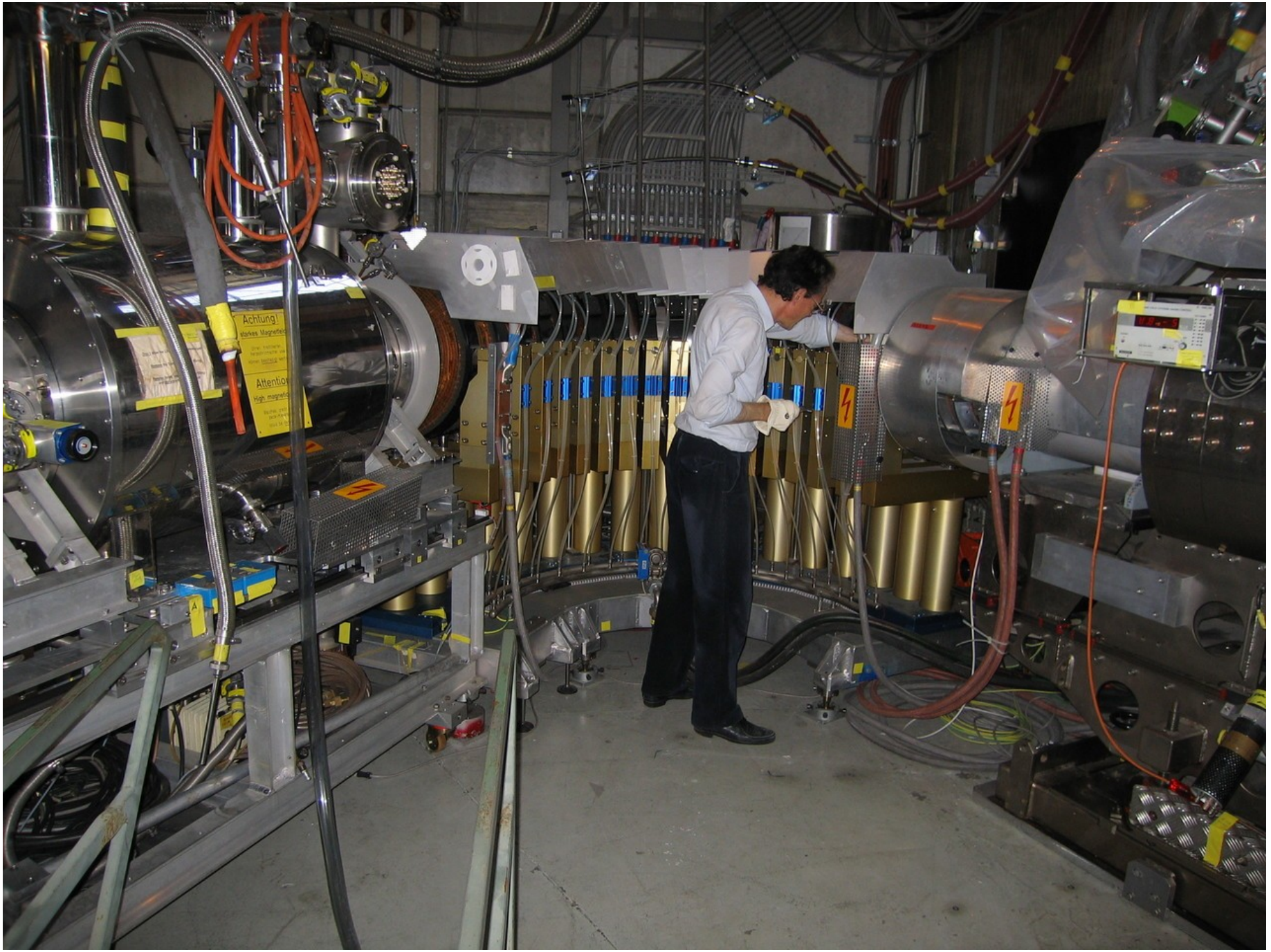
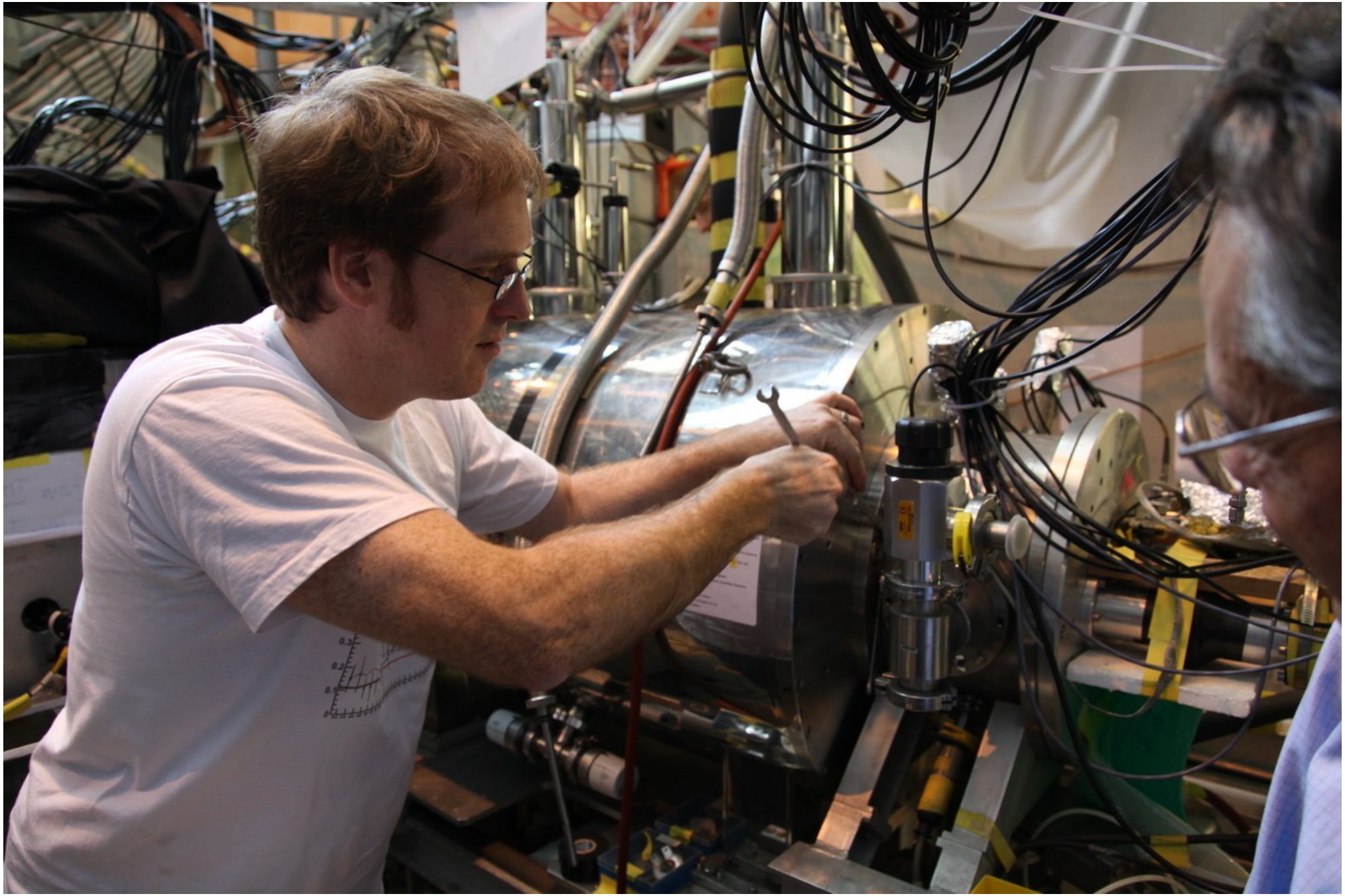
Beam Area πE5

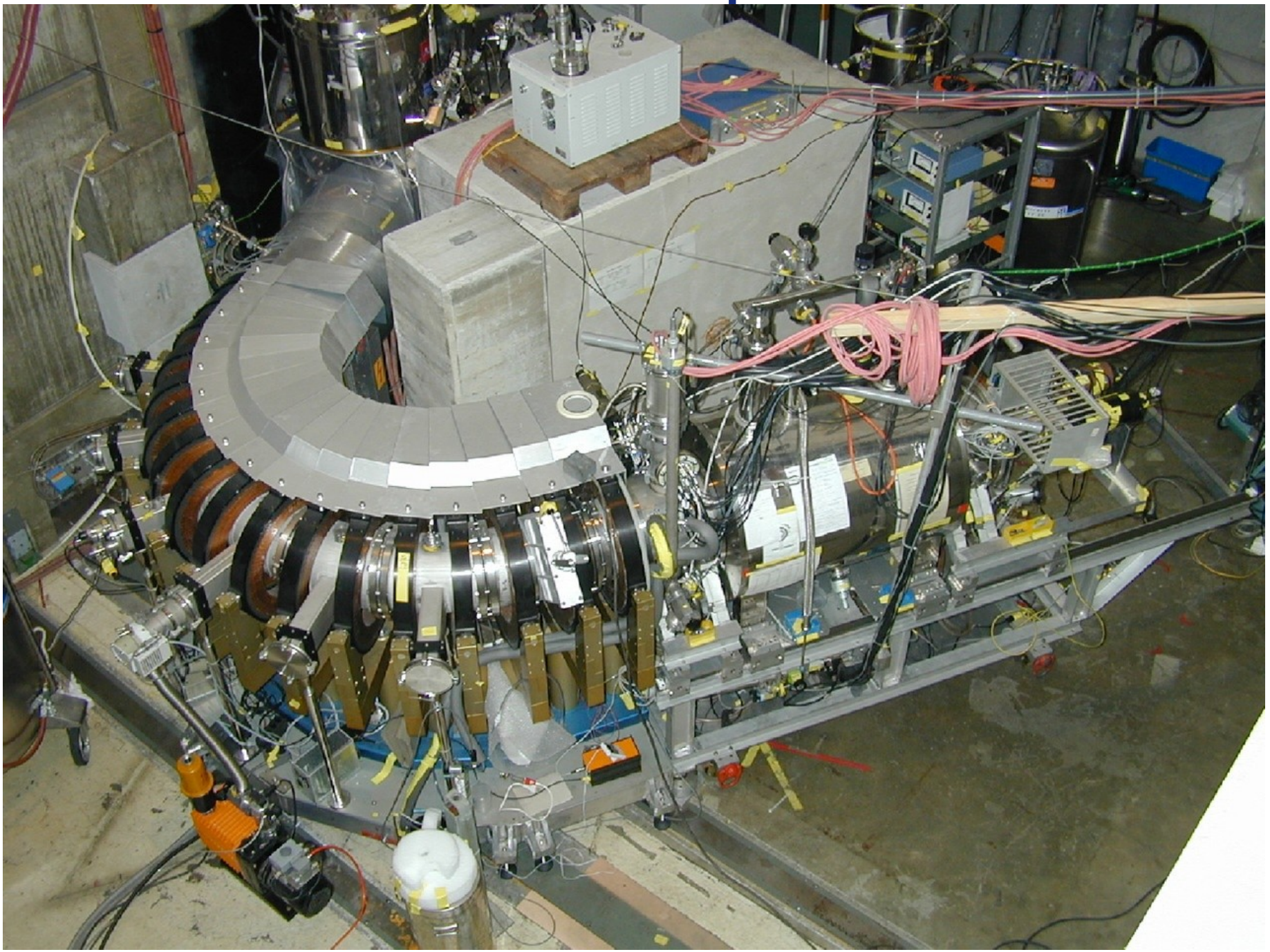
Our Muon Beam inside πE5



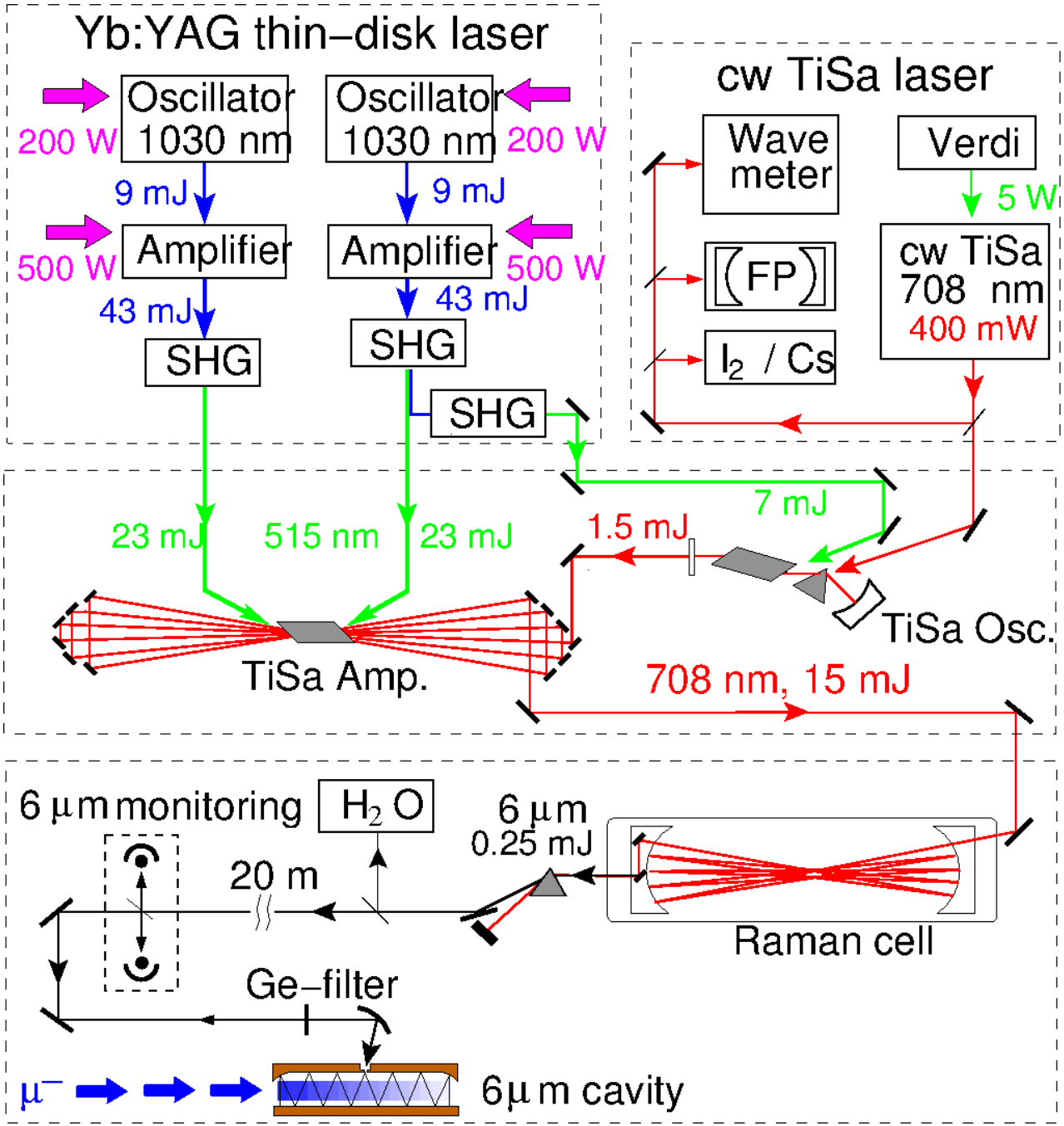
Getting ready….



Muon Beam Setup inside πE5



The Laser System



Yb:YAG Thin-Disk laser
→ quick response to µ

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

Ti:sapphire cw laser
→ controls laser wavelength

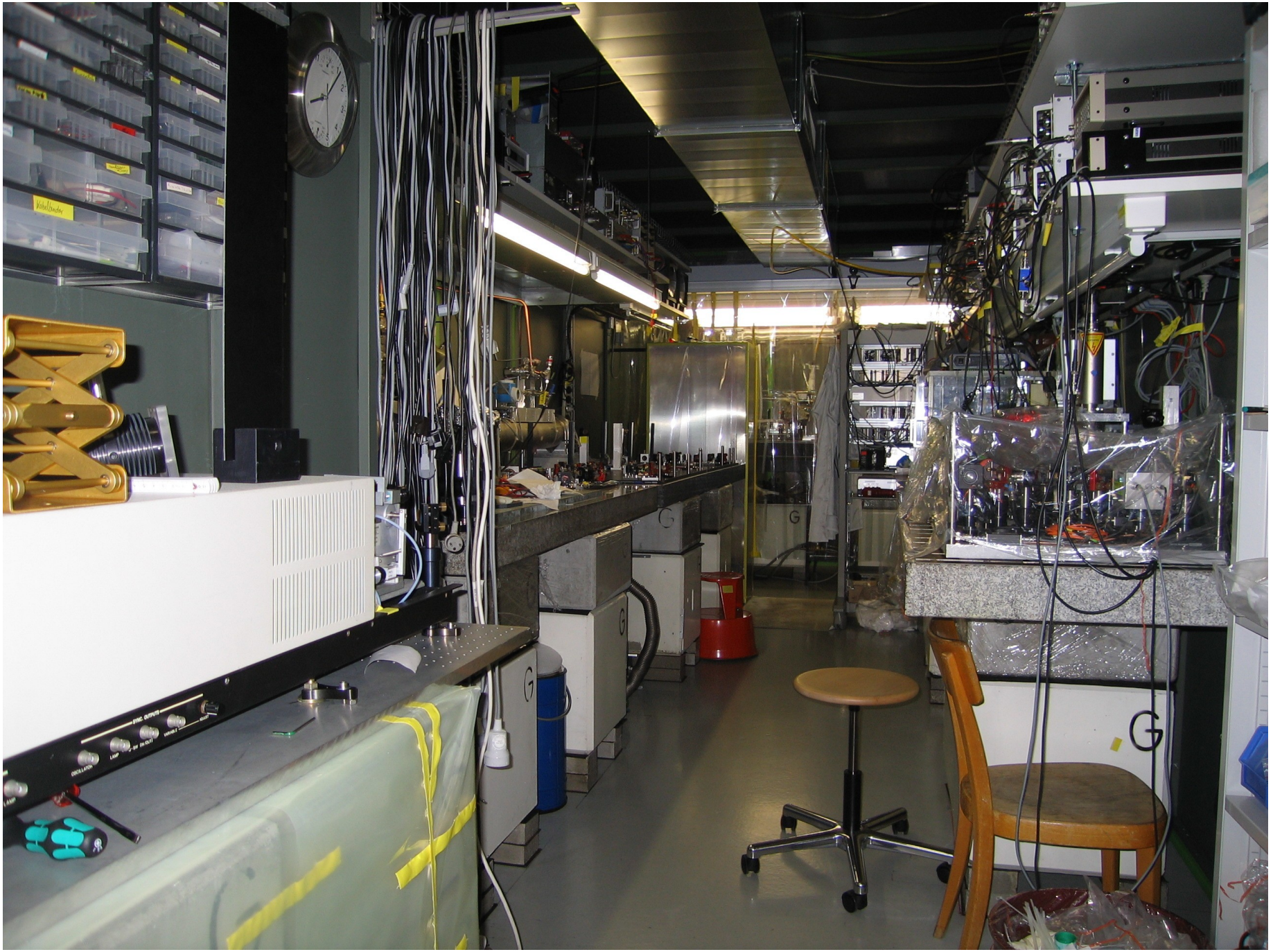
Ti:sapphire oscillator/amplifier
→ large pulse energy (15 mJ)

Raman cell
→ 3fold wavelength change → 6 µm

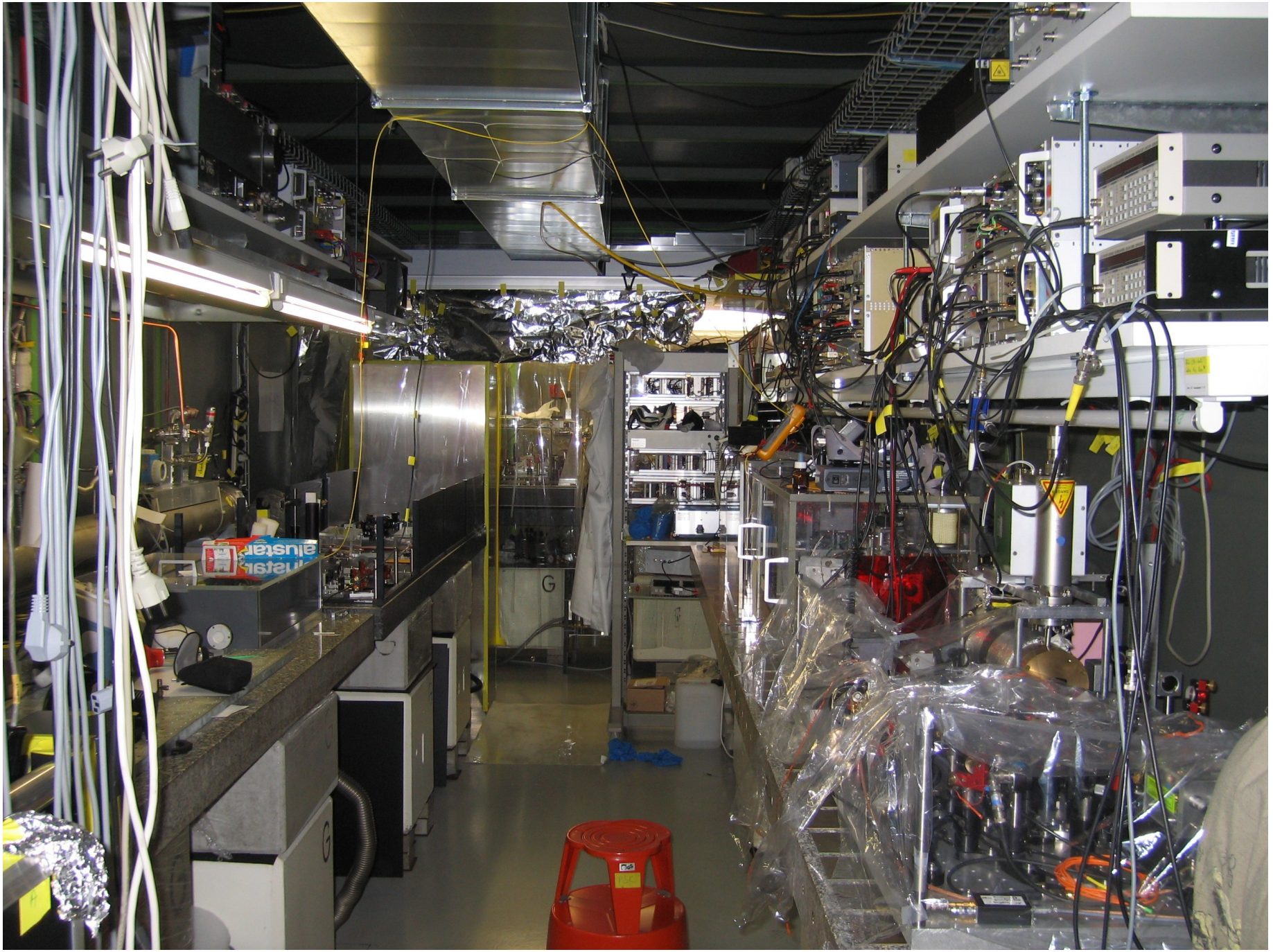
Target Cavity
→ Mirror system surrounds muon stop volume

Inside the Laser Hut

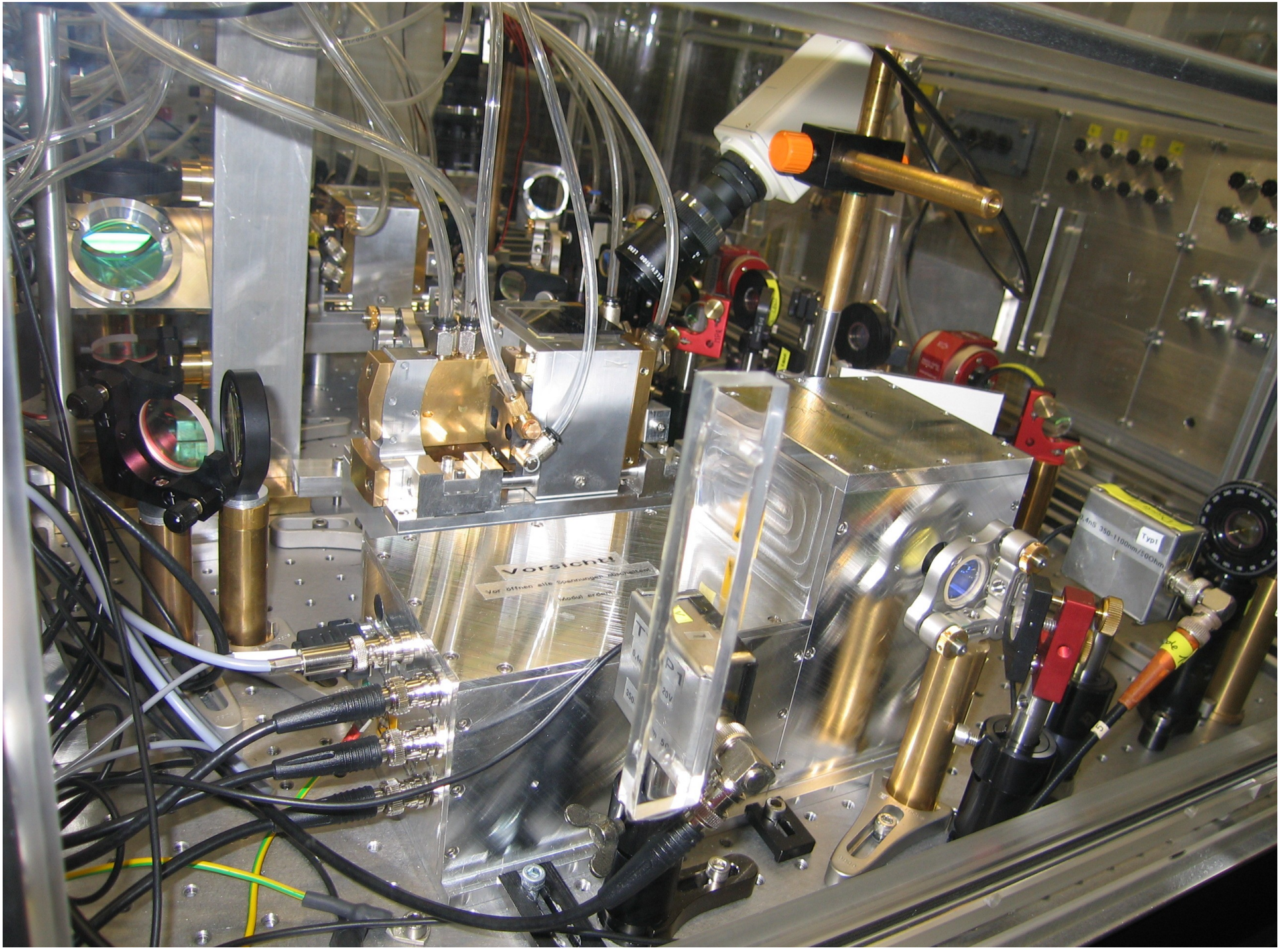
Inside the Laser Hut



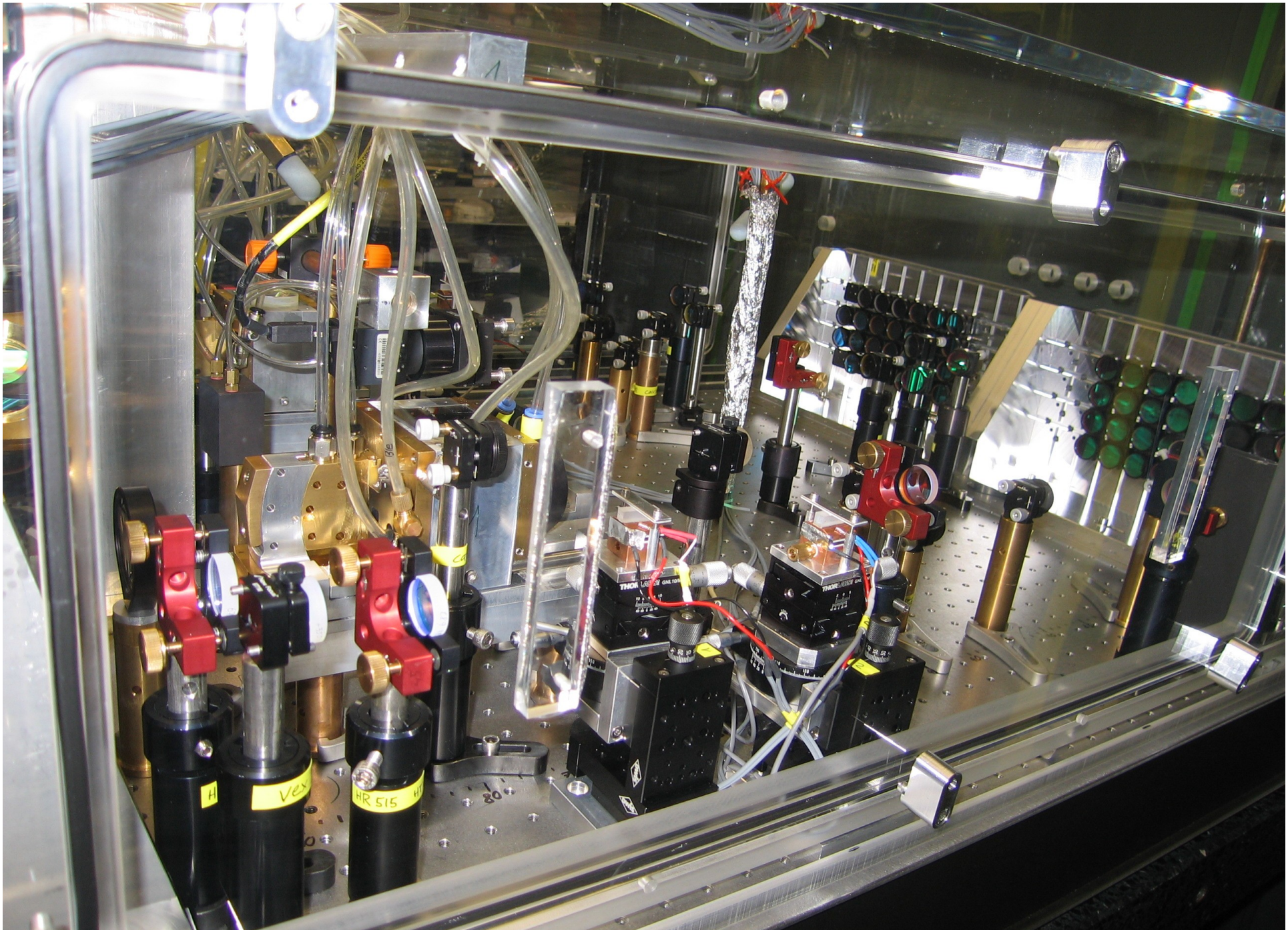
Inside the Laser Hut



Yb:YAG Oscillator



Yb:YAG Amplifier



Inside the Laser Hut

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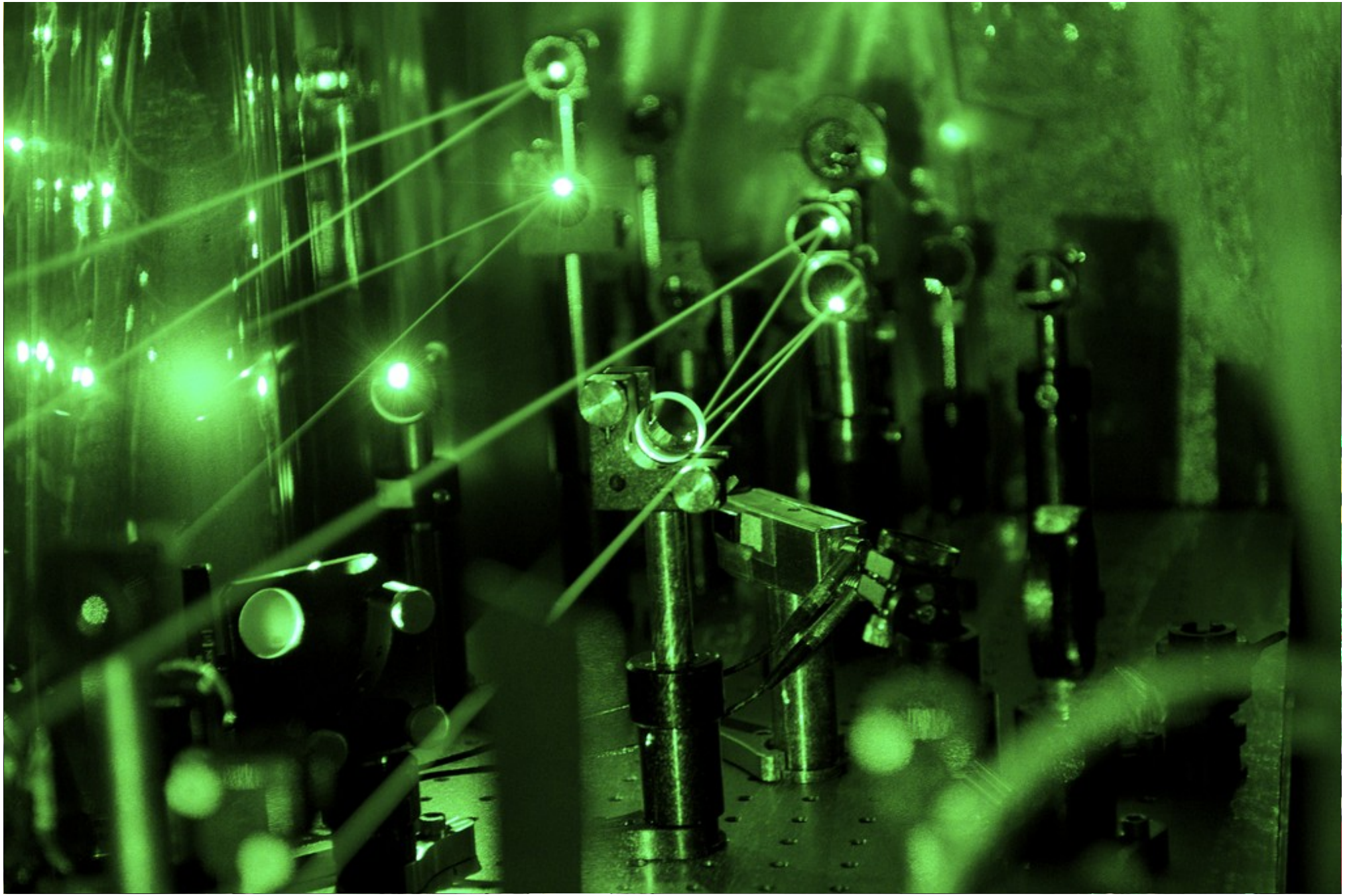

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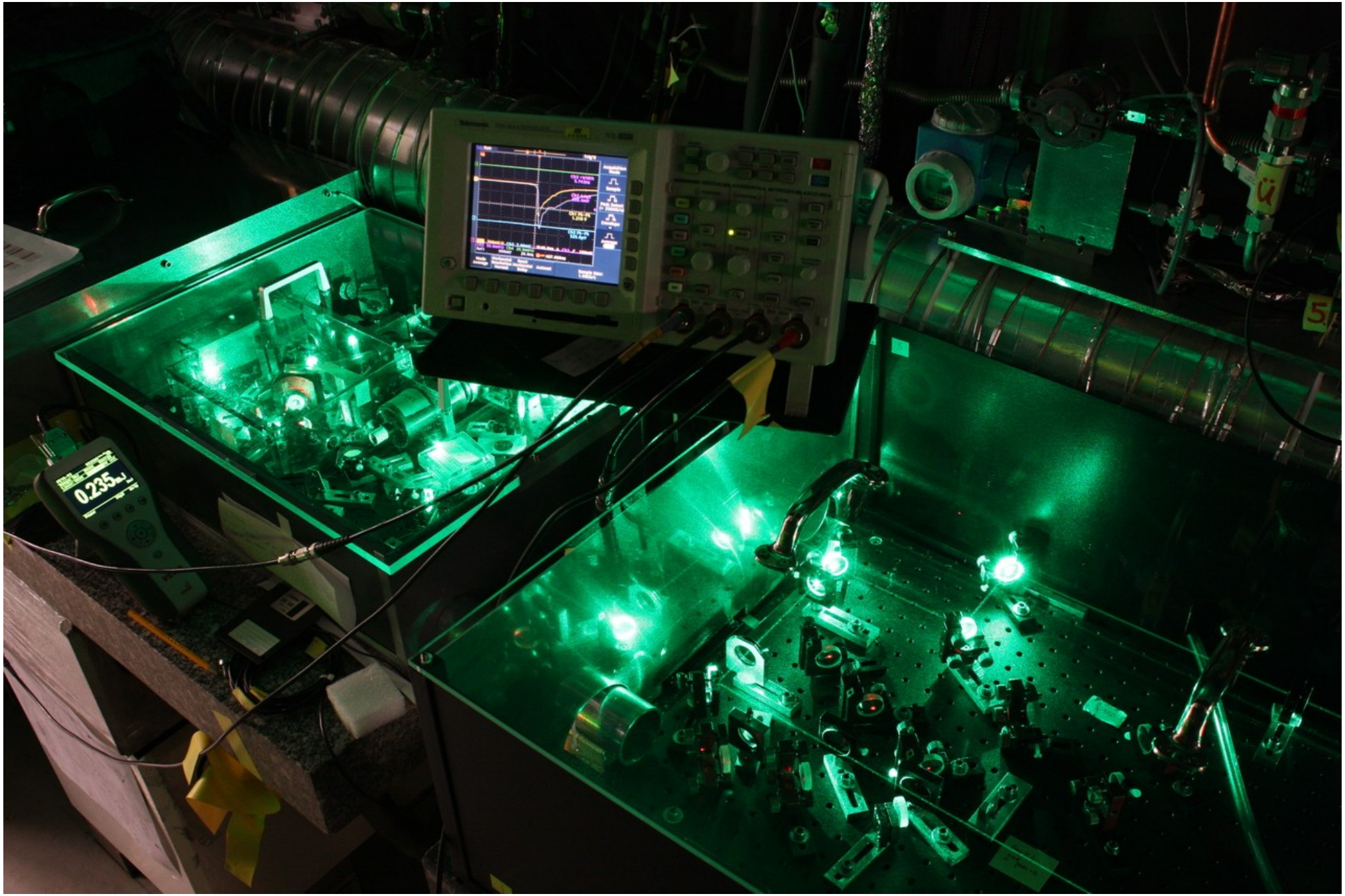
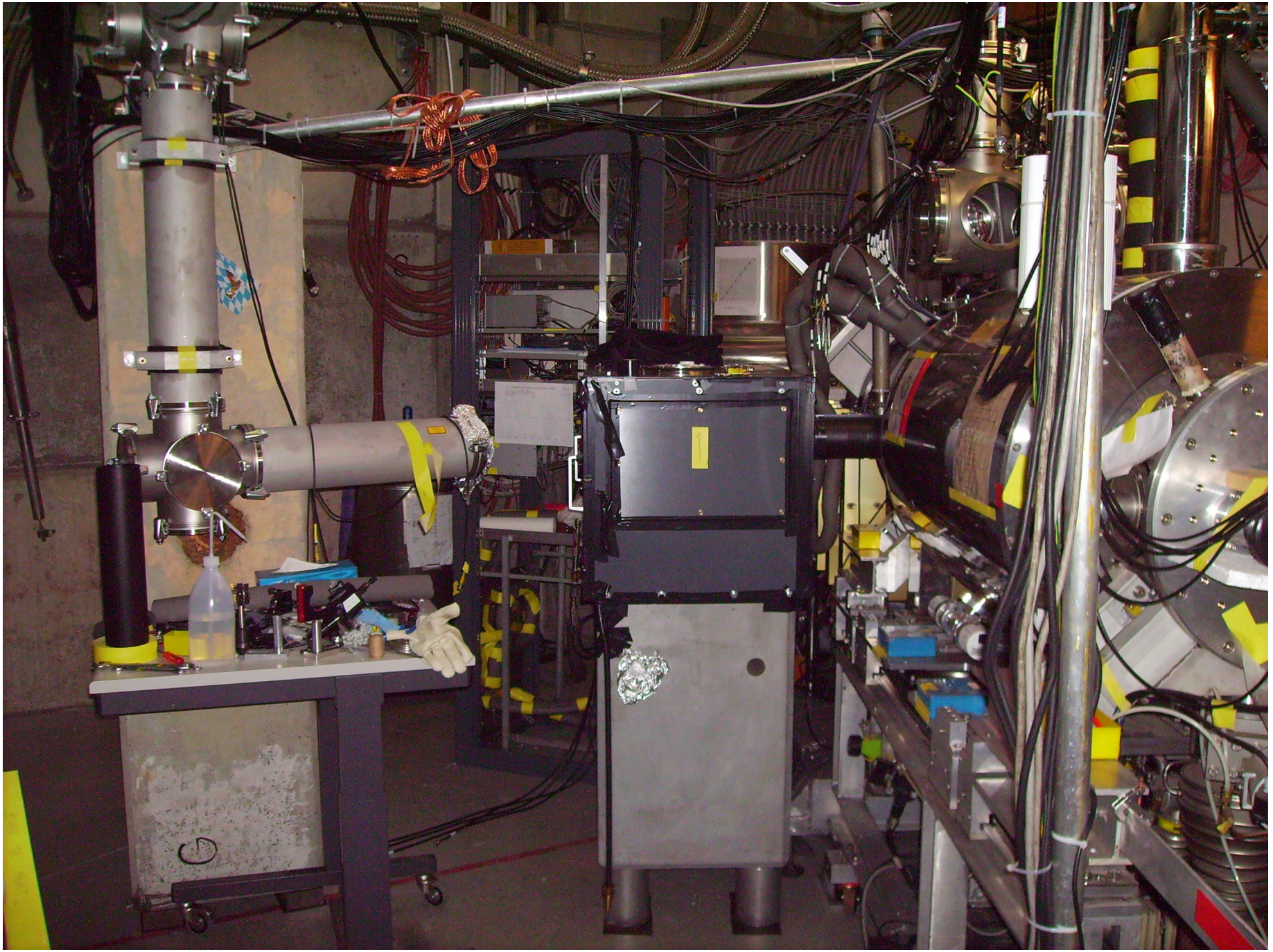
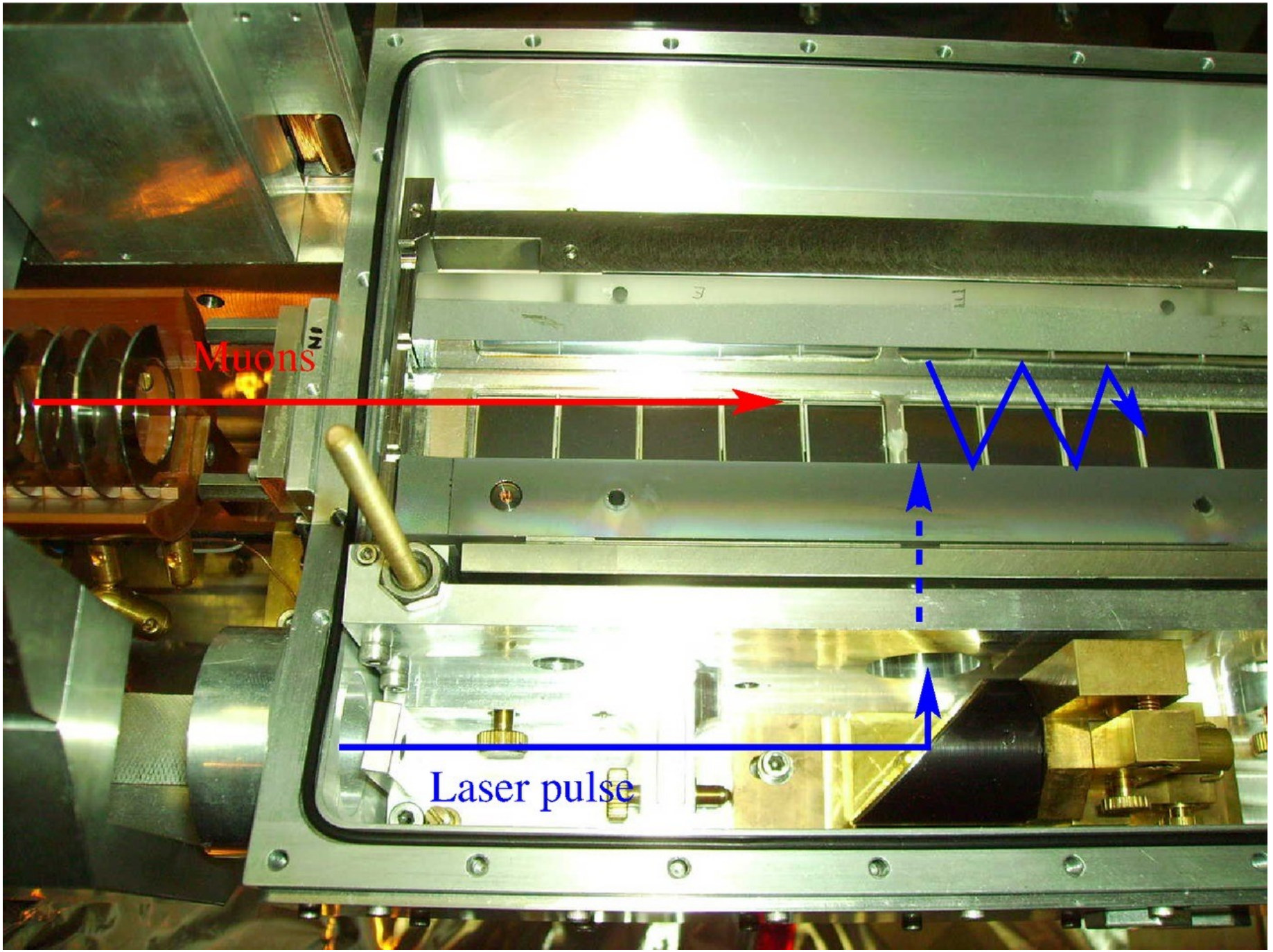


Light through the Tube



The Heart of the Setup -- Target



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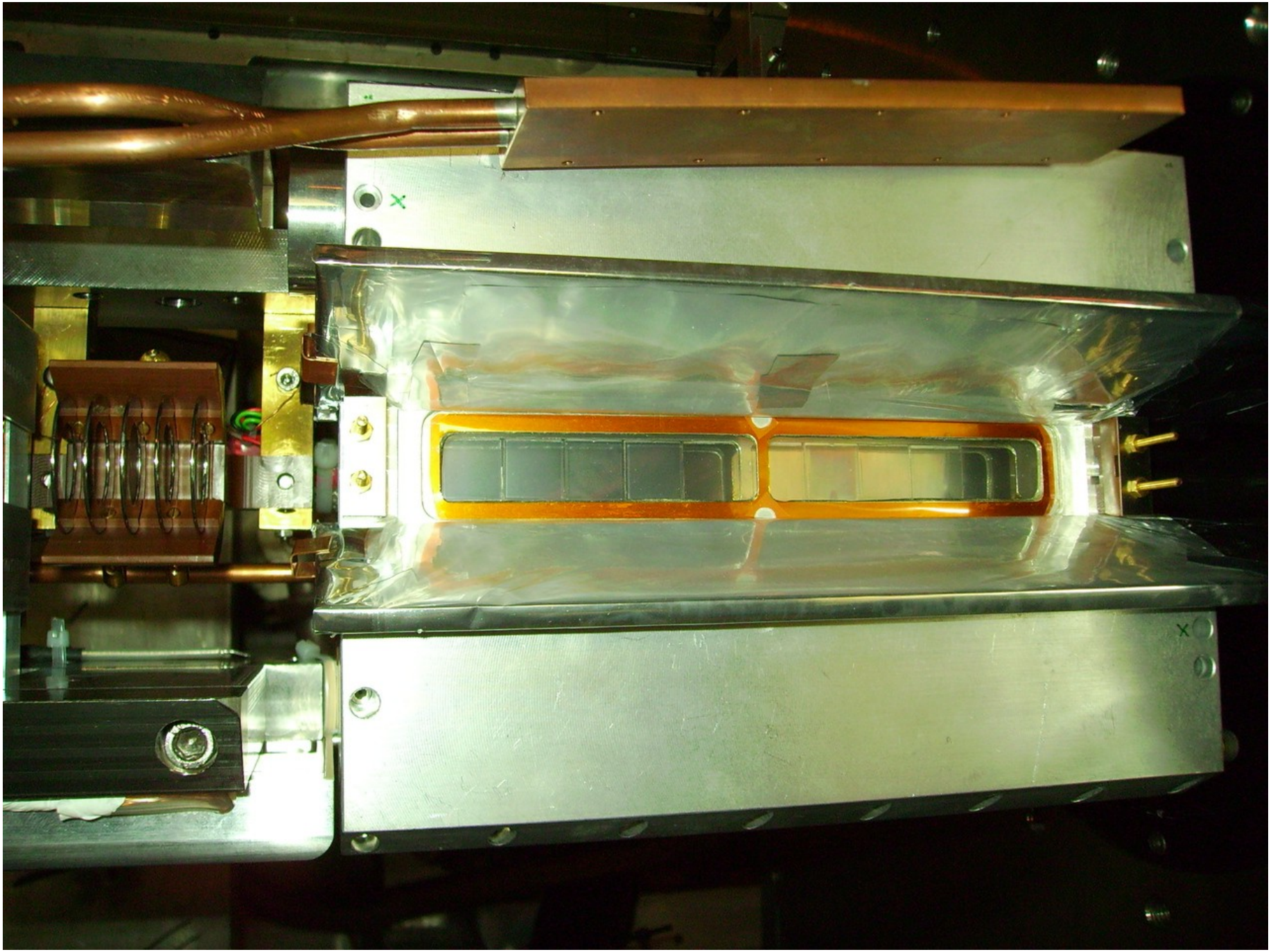

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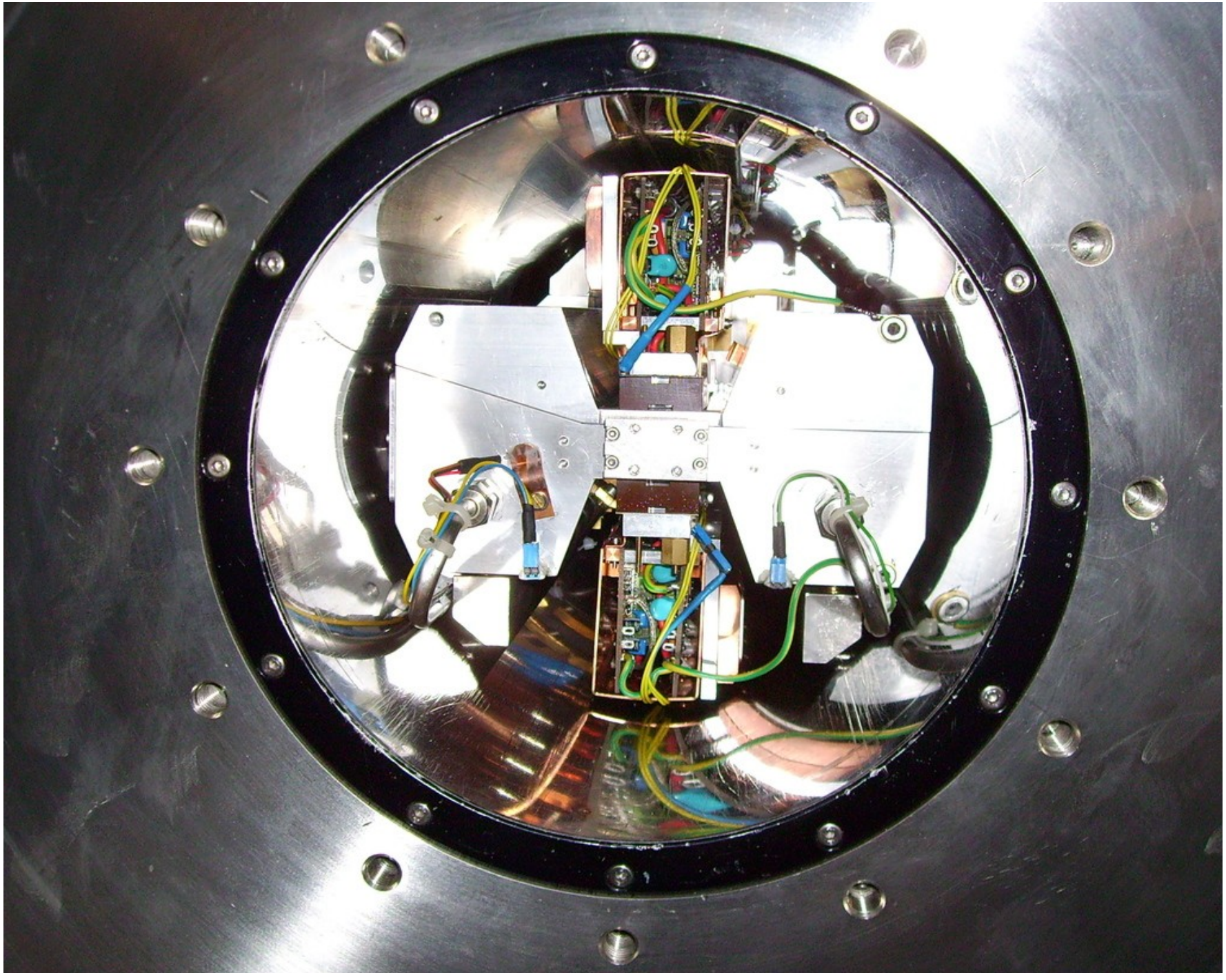
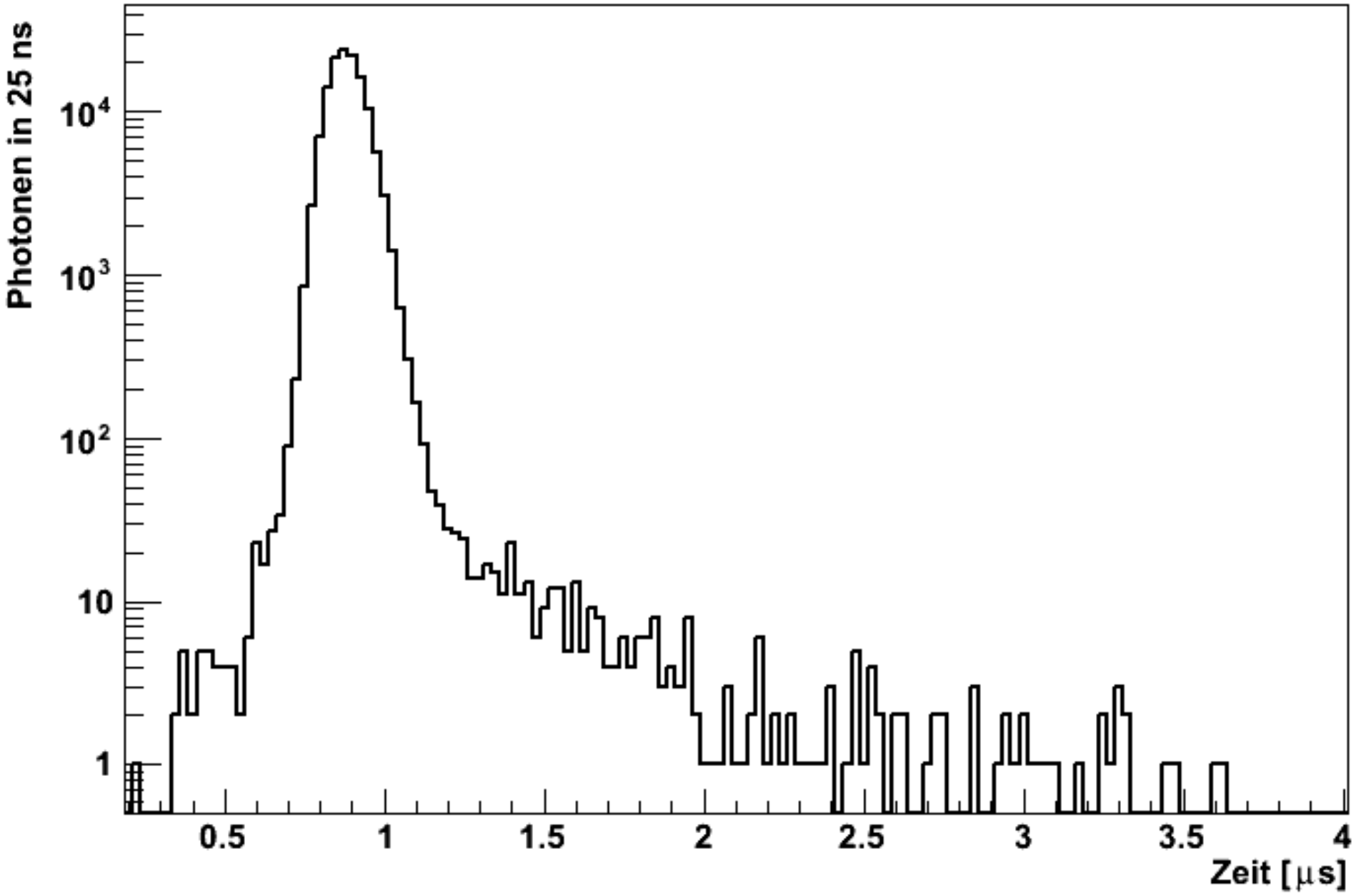


Time Spectra

13 hours of data



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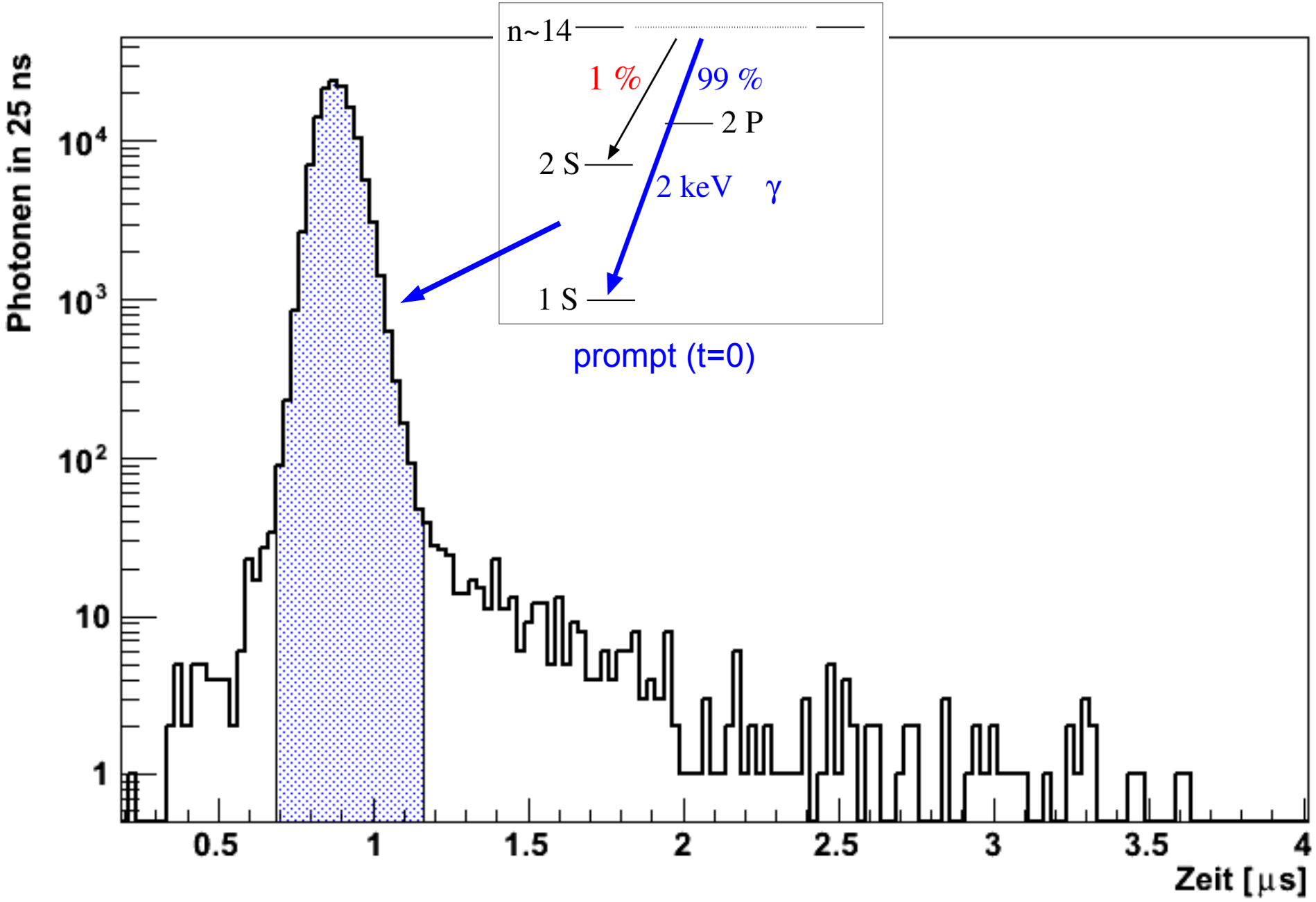
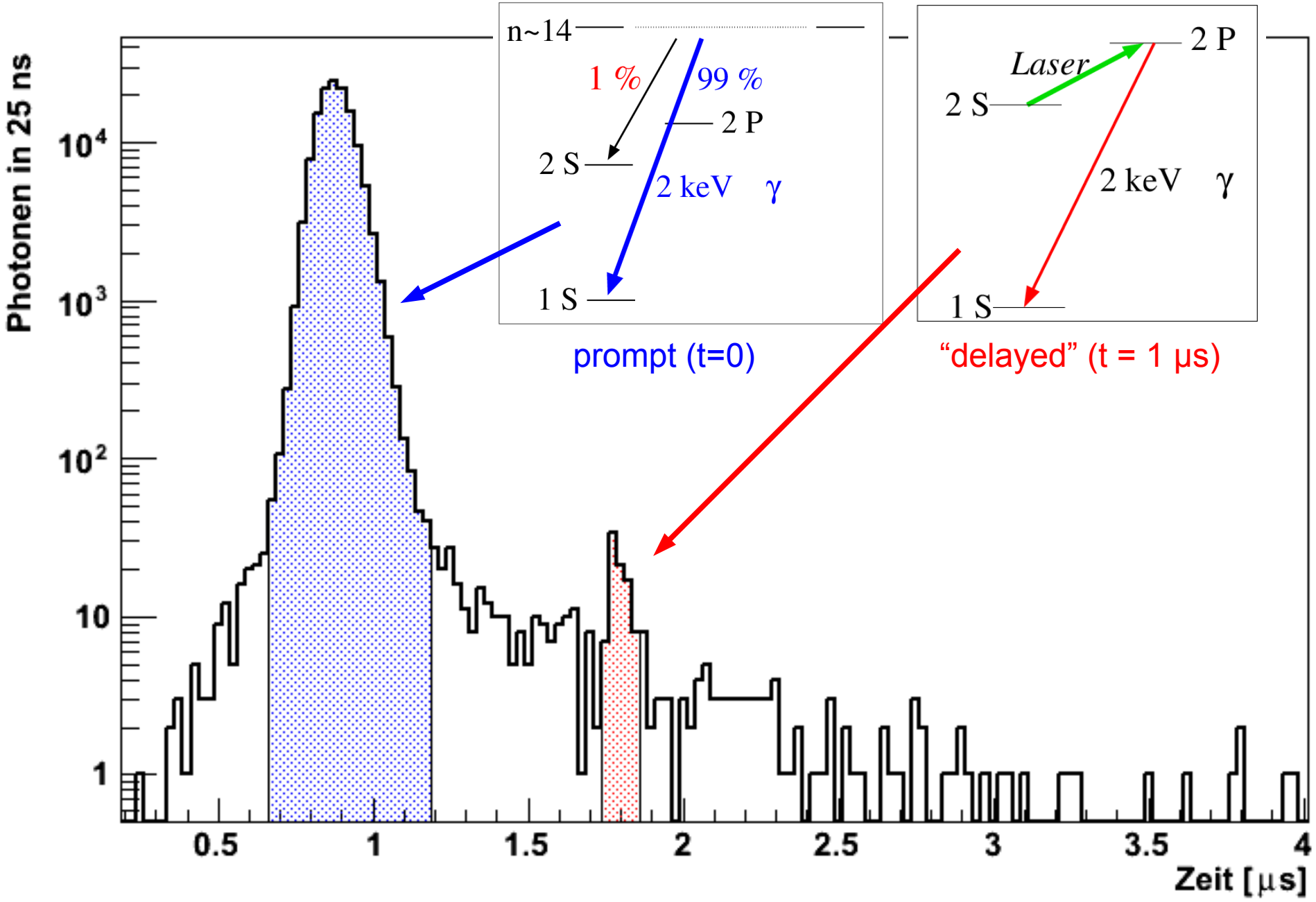
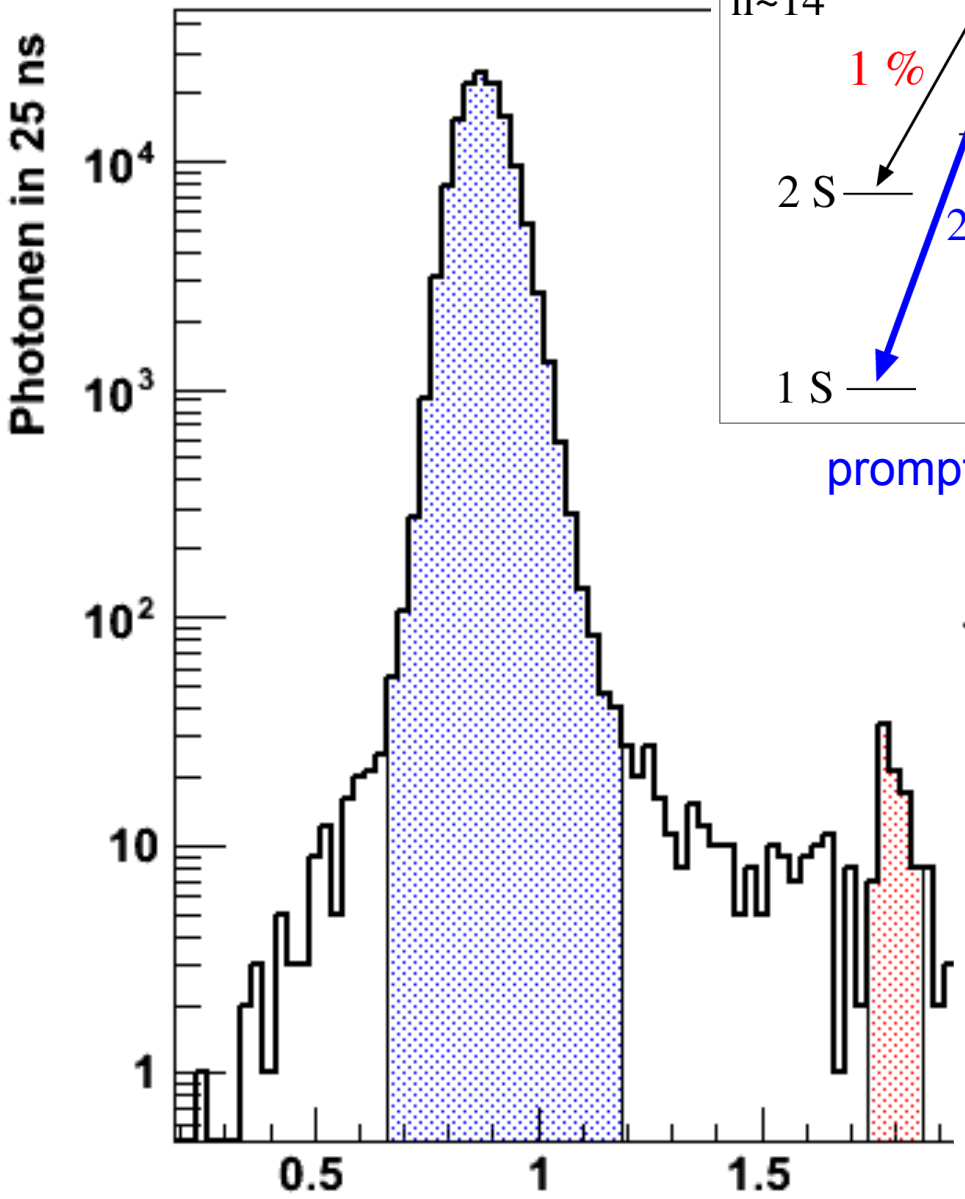
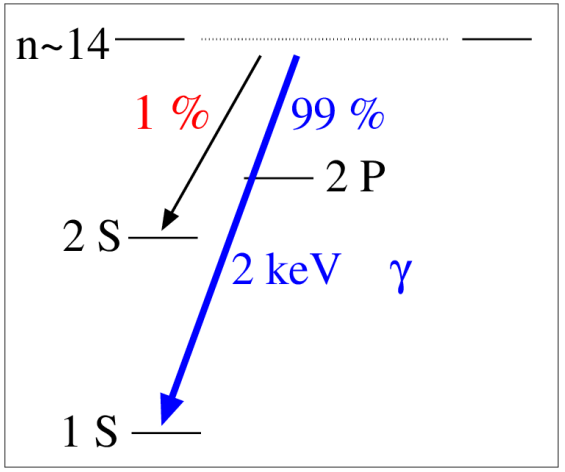


Time Spectra

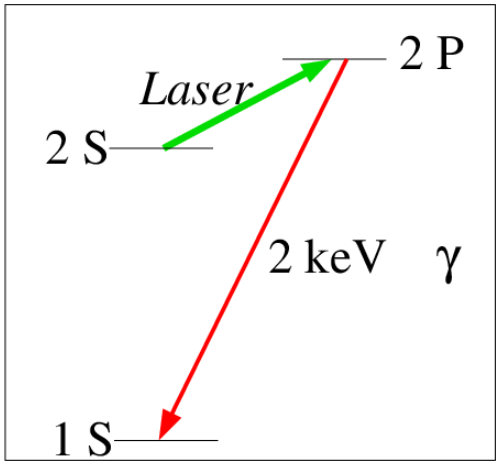


Time Spectra



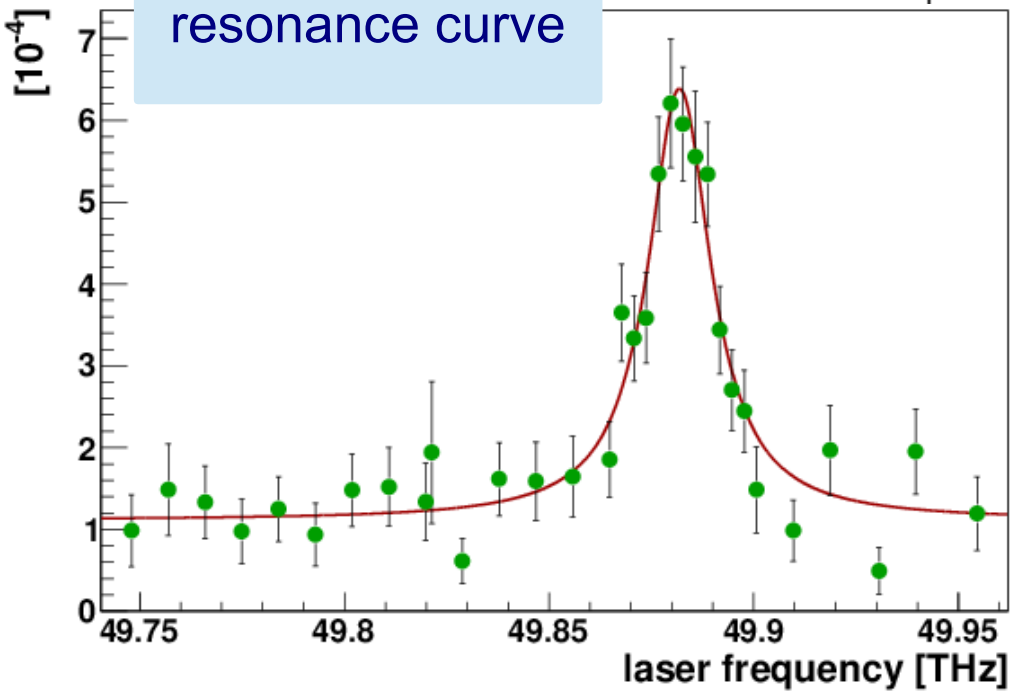


prompt (t=0)



“delayed” (t = 1 μs)

resonance curve



A long story….

- 1947 Lamb shift
- 1969 Muonic hydrogen
- 1970/80s No atoms in 2S state!
- 1997 Muonic hydrogen atoms in 2S!!!
- 1997 “Letter of Intent” at PSI
- 1998 Proposal at PSI
- 1999 Experiment approved
- 2002 0. Run → Tests
- 2003 1. Run → no resonance
- 2007 2. Run → again nothing
- 2009 3. Run → Results!!!

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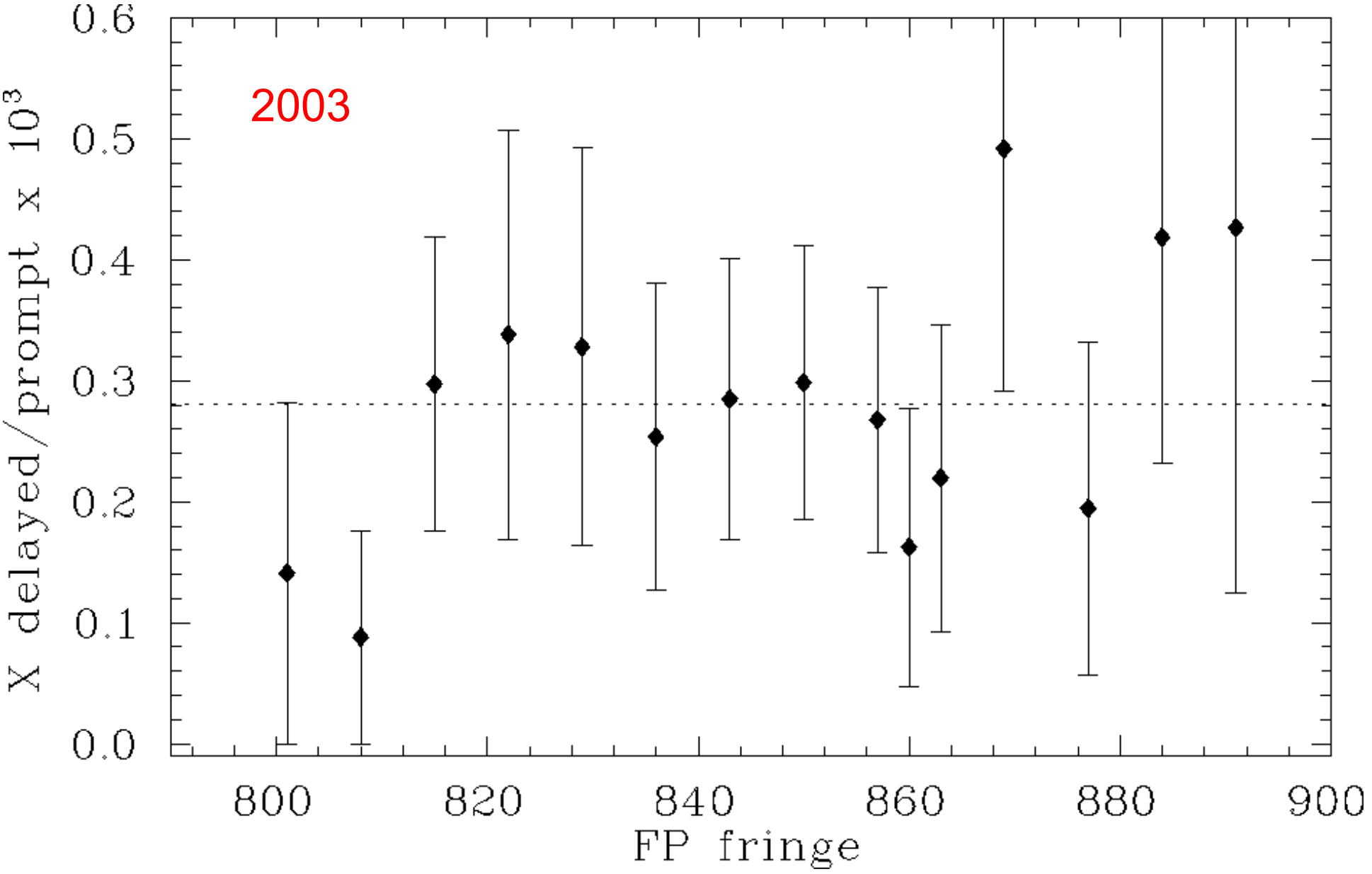
2003
X delayed/prompt x 10^3
0.0
0.1
0.2
0.3
0.4
0.5
0.6
800
820
840
860
880
900
FP fringe

A long story….

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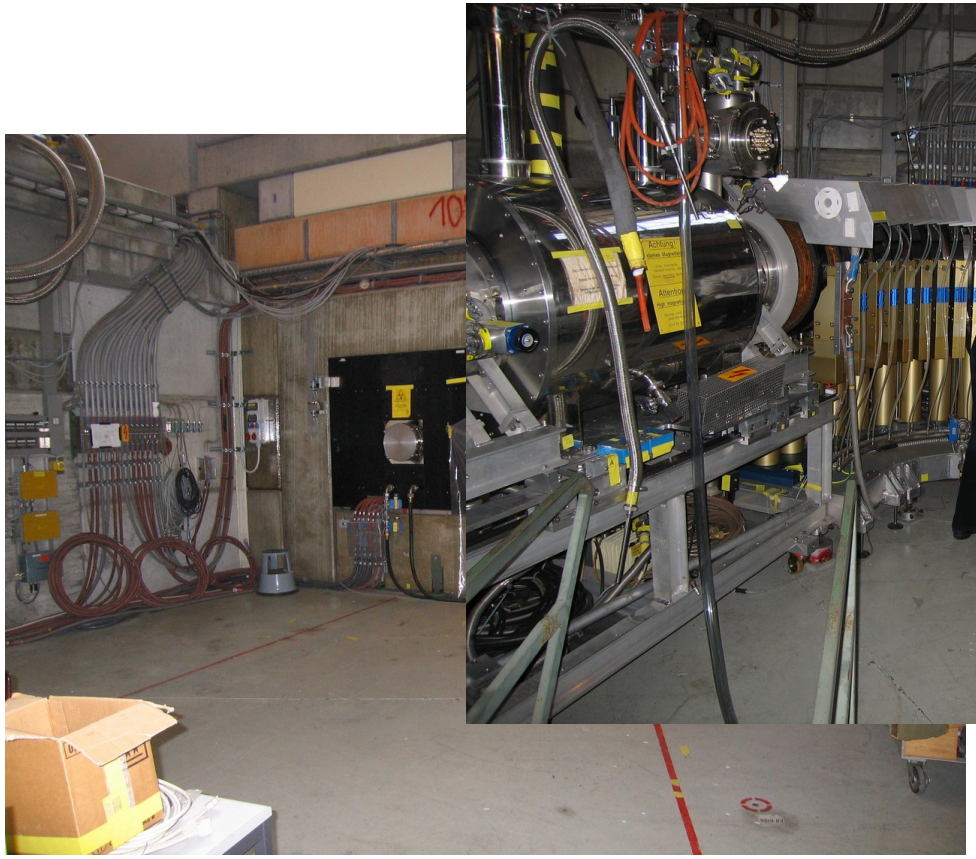
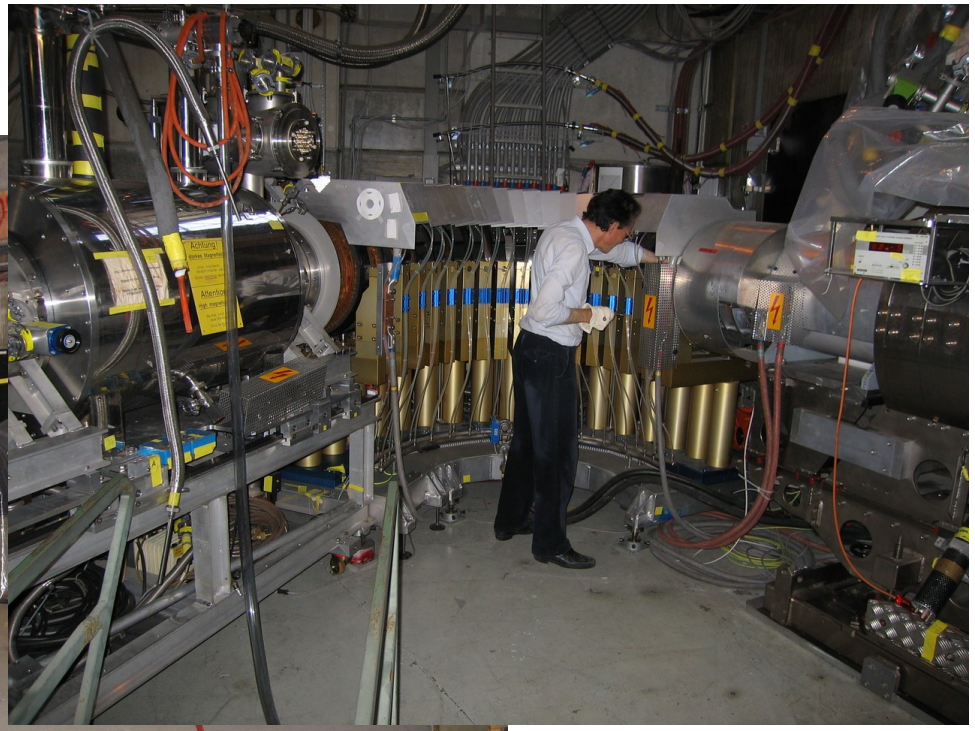
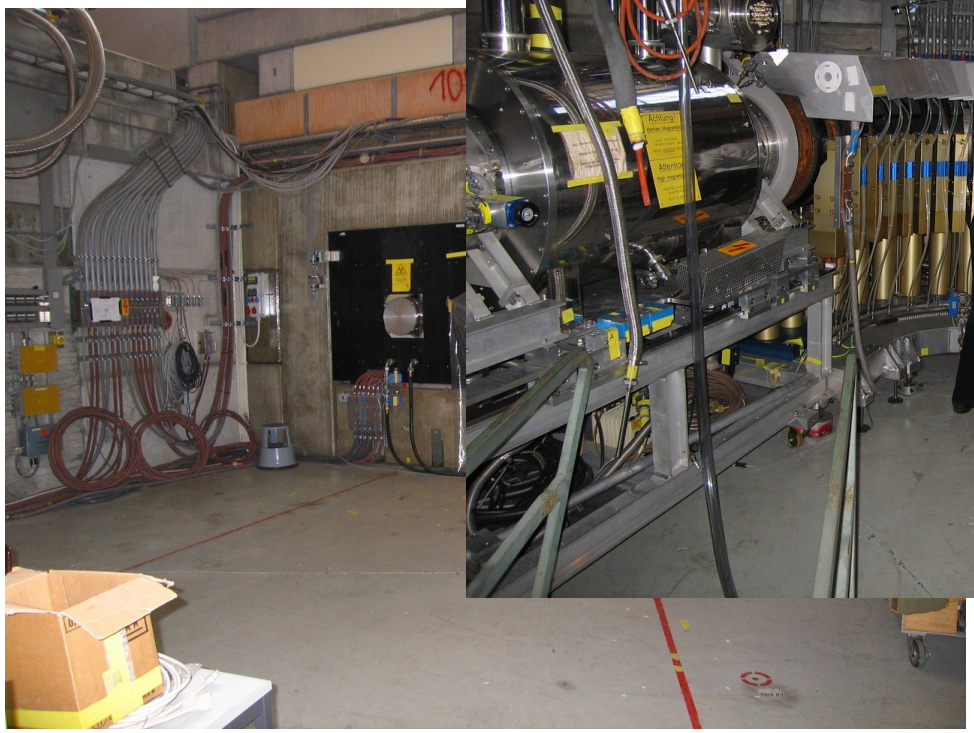
Run 2009

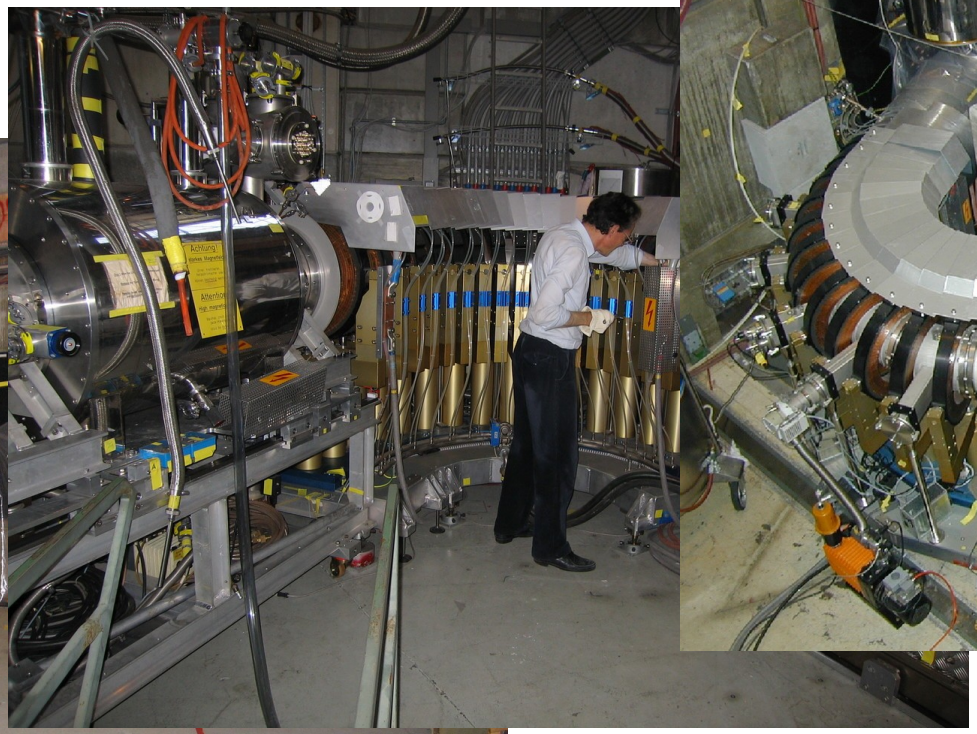
Run 2009

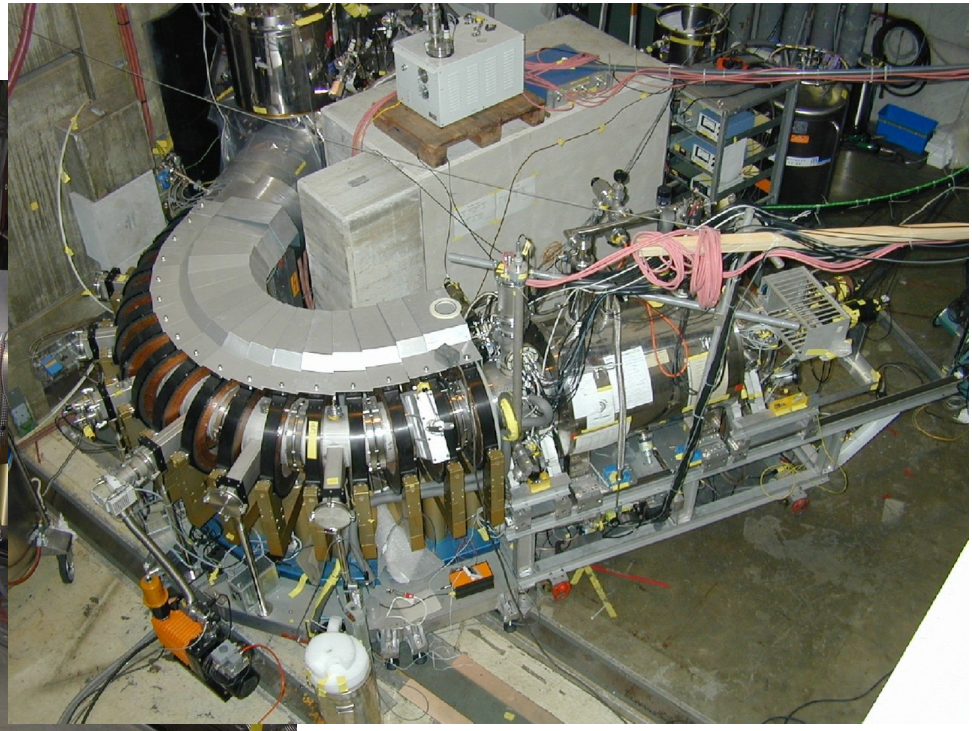




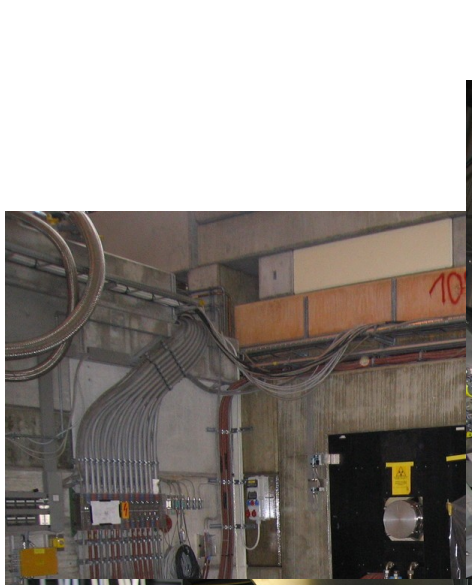
Run 2009

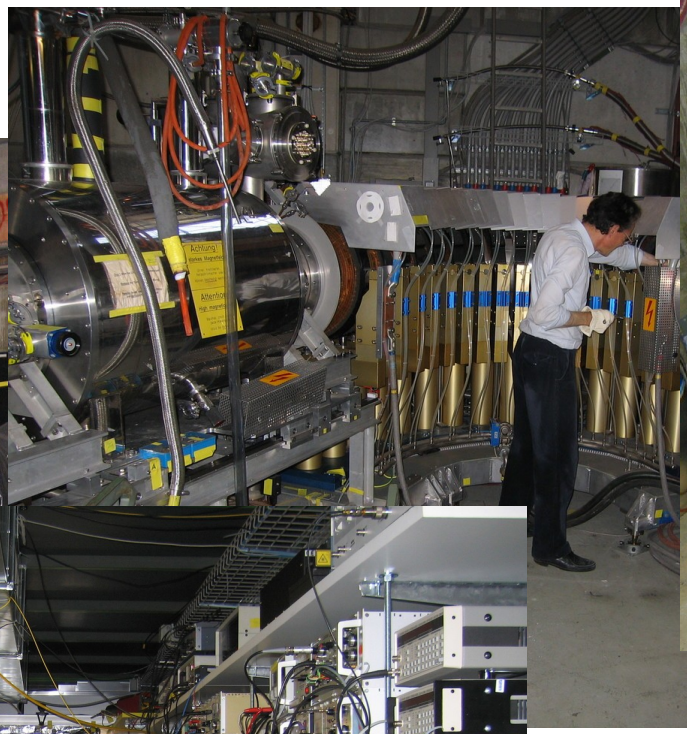


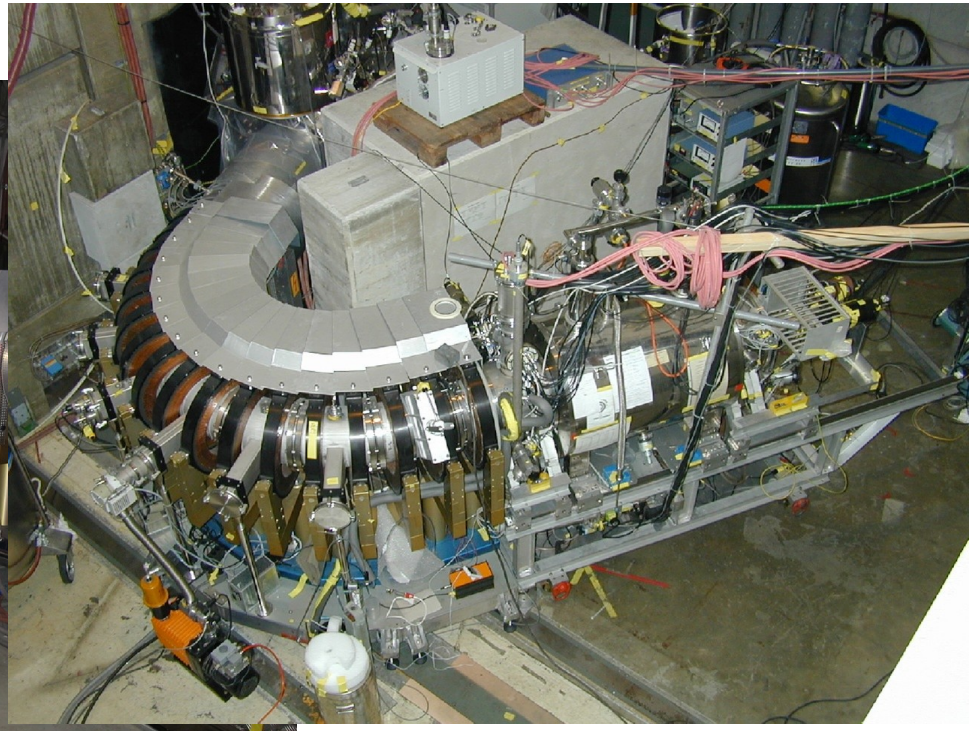


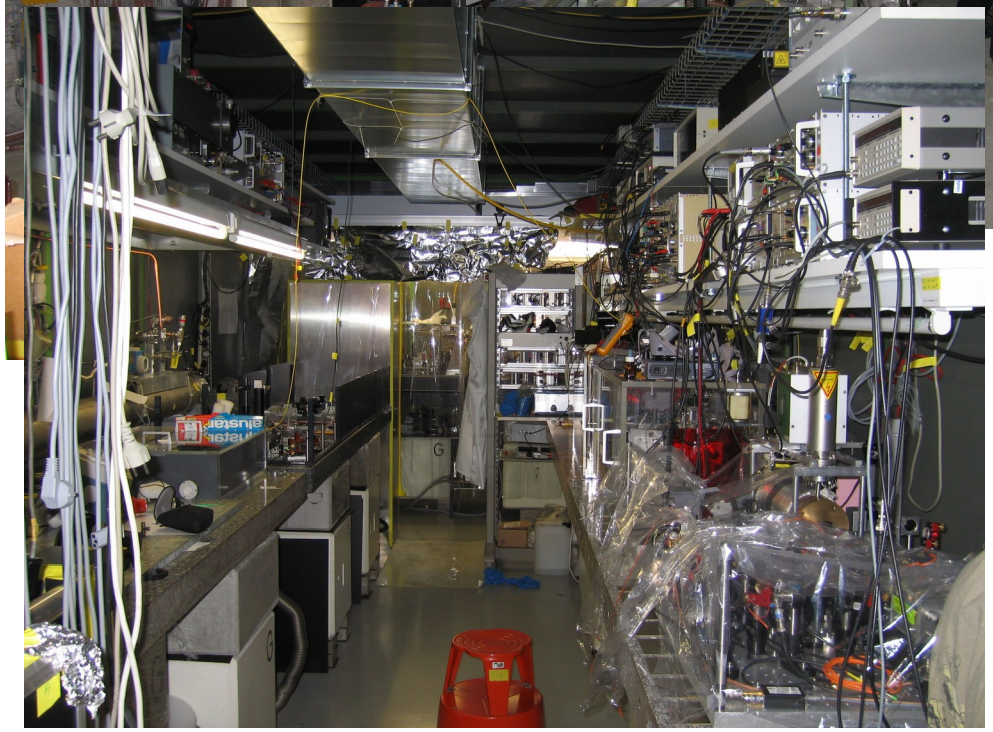


Run 2009

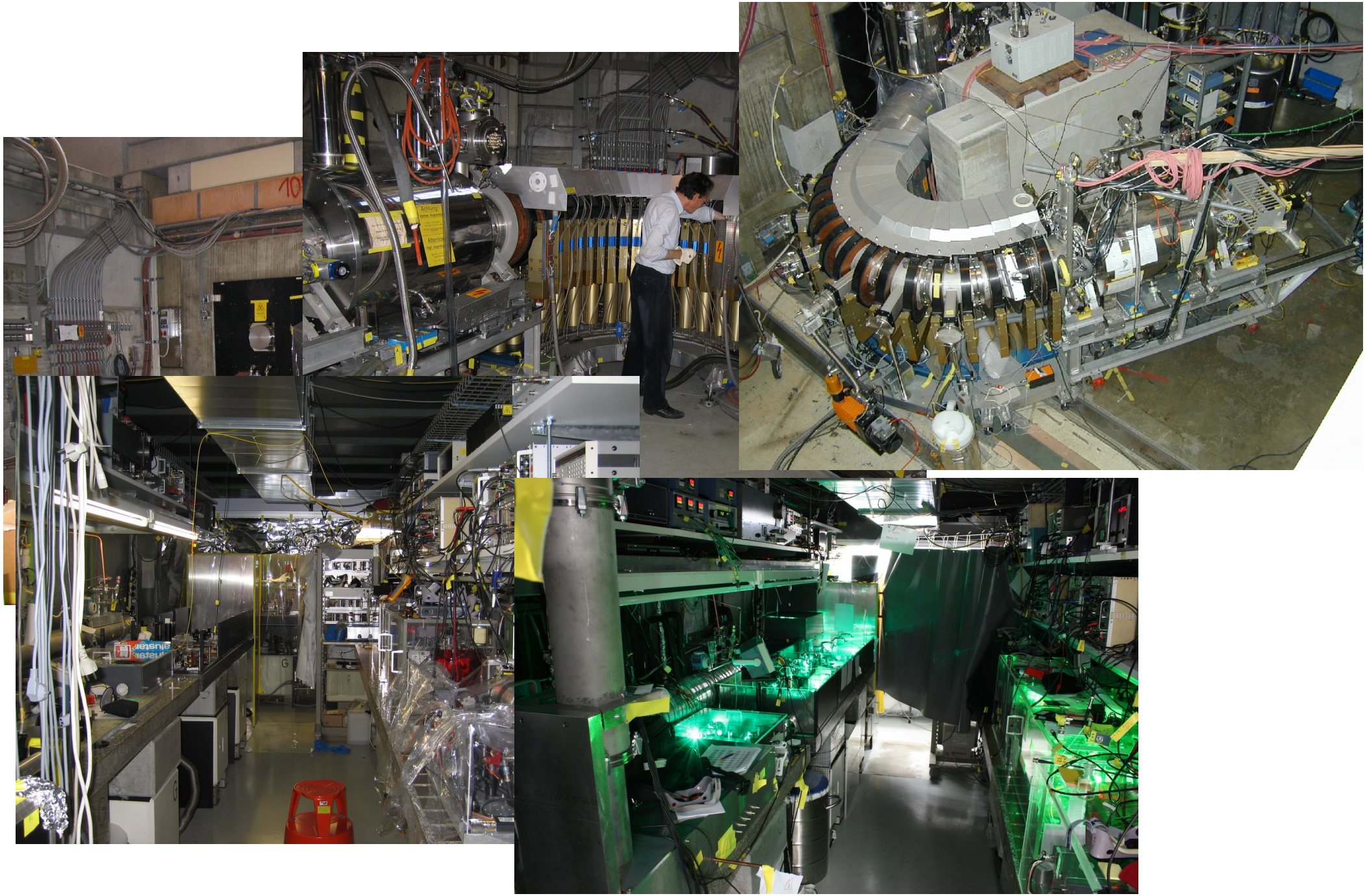




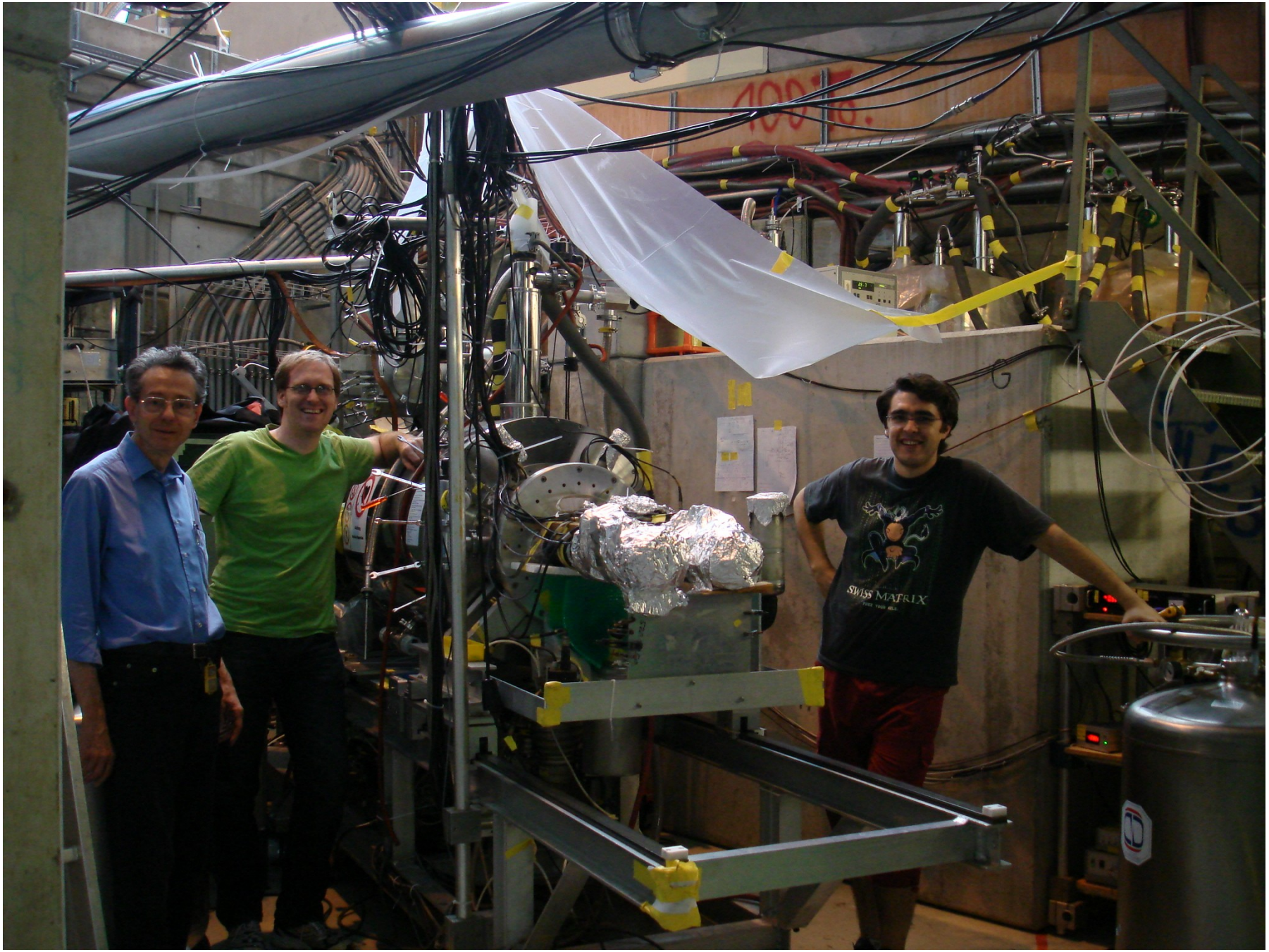




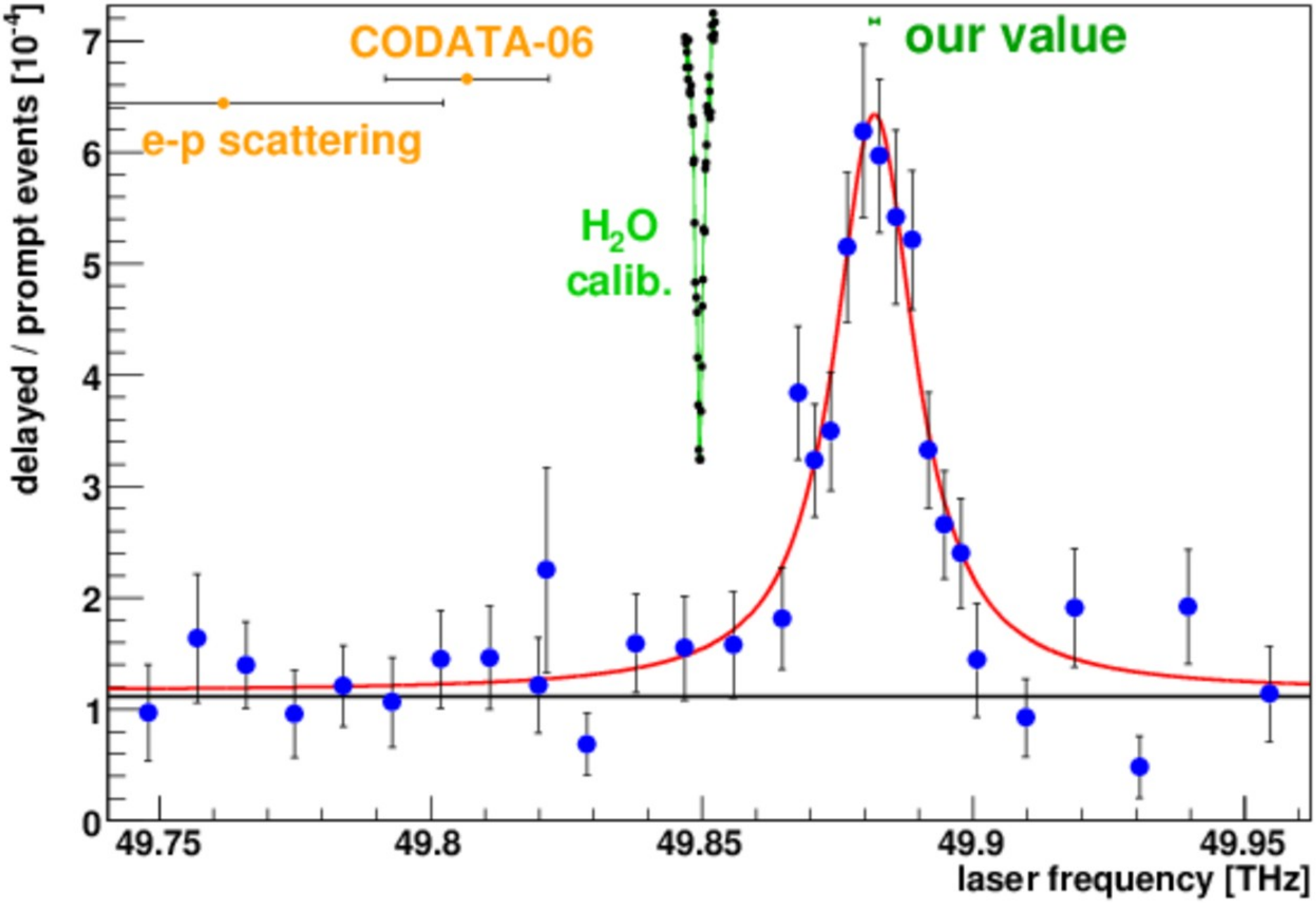
Run 2009



Ready to Rumble



The Resonance



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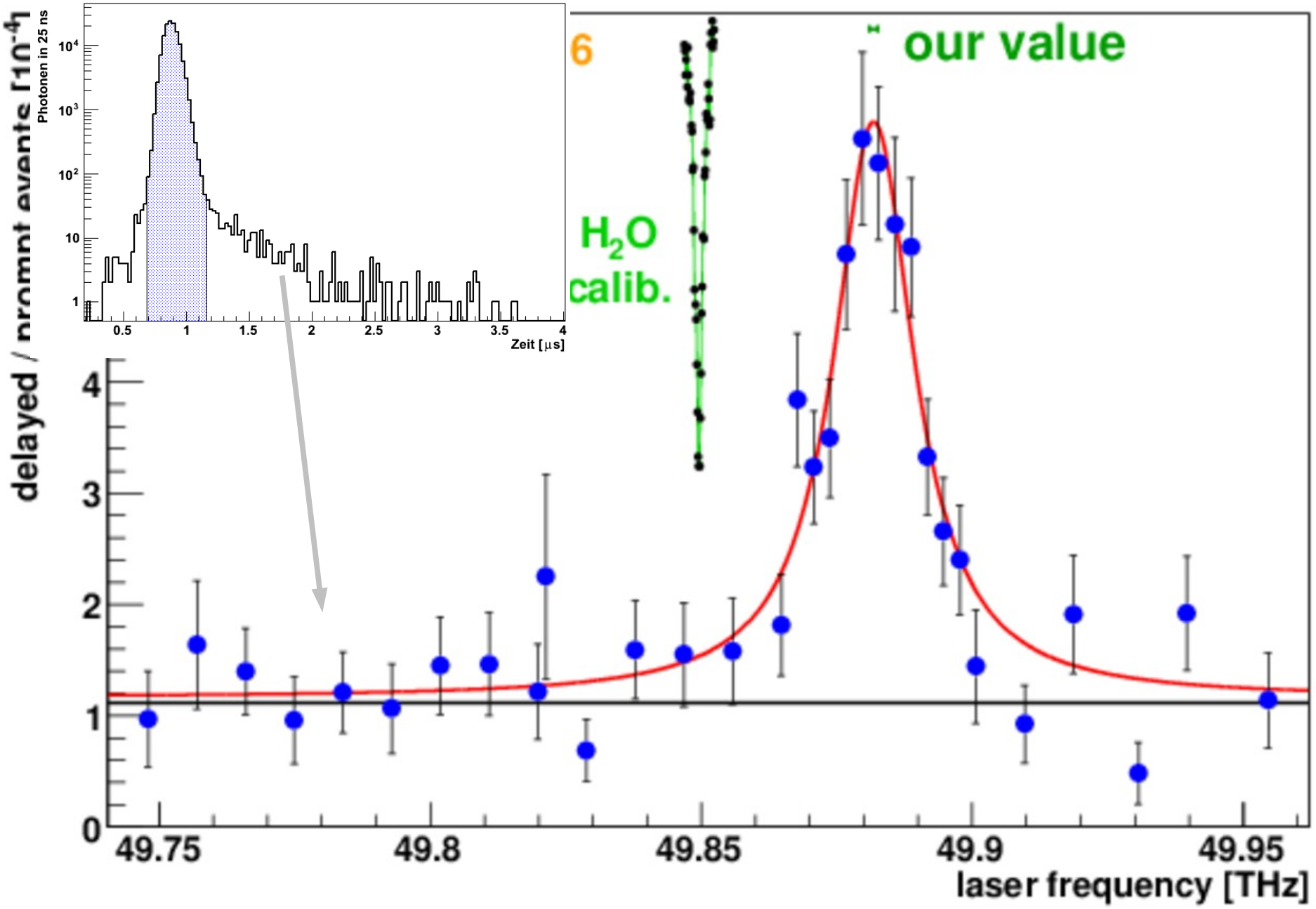
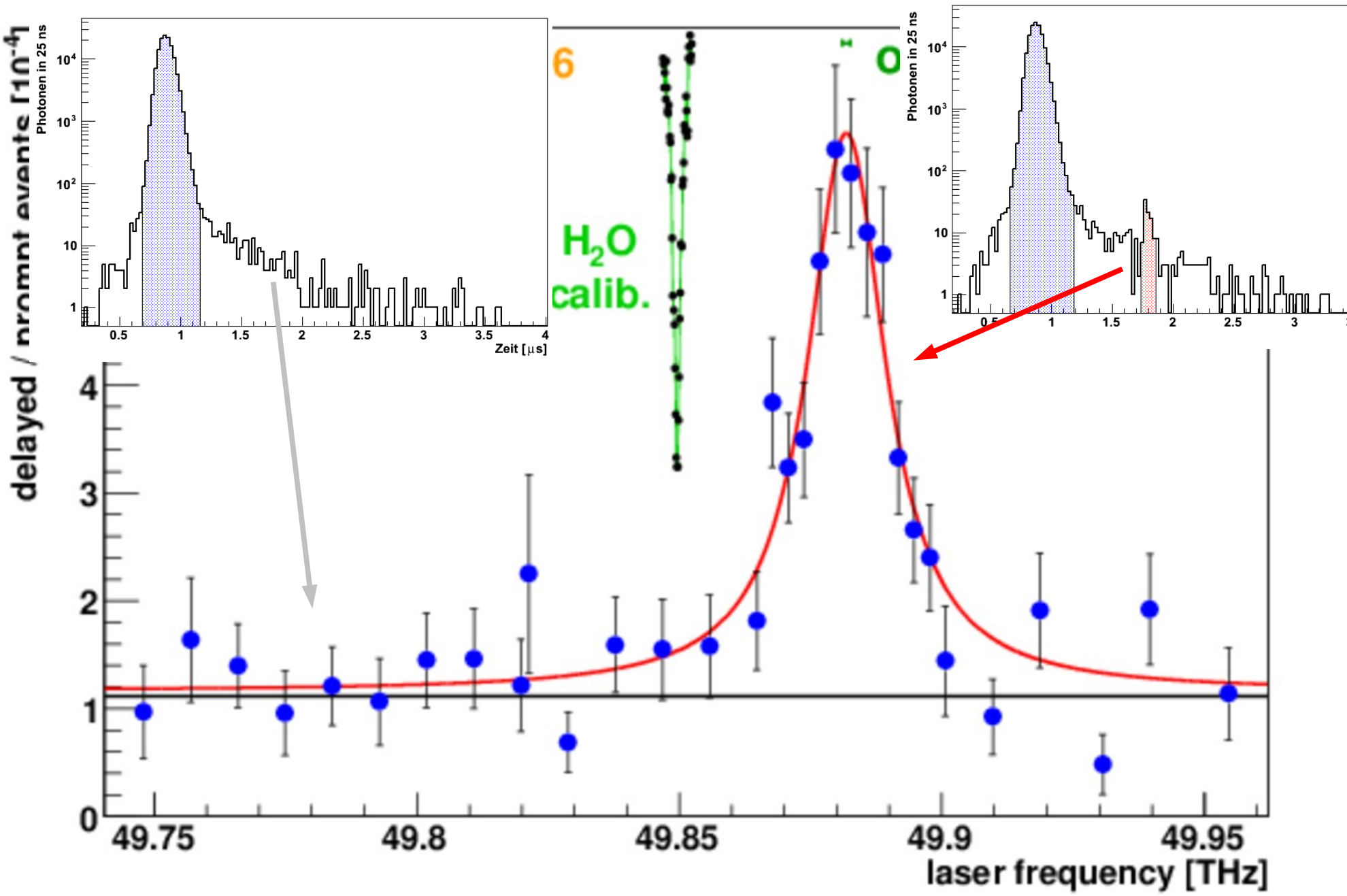


The Resonance



Yeah!

To the Resonance!

Resonance to our Resonance

Proton is 4% smaller!!!

0.84184 ± 0.00067 fm instead of

0.8768 ± 0.0069 fm

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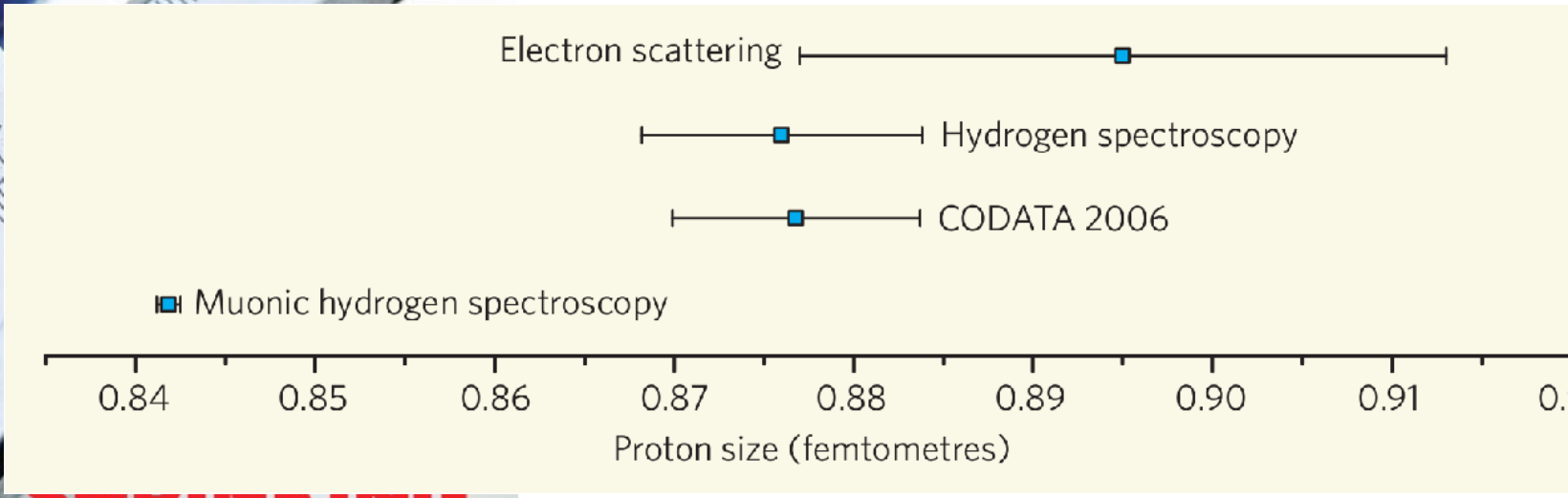


Resonance to our Resonance

Proton is 4% smaller!!!

0.84184 ± 0.00067 fm instead of

0.8768 ± 0.0069 fm

Our value from laser spectroscopy
Of muonic hydrogen is

10 times more precise!

Resonance to our Resonance

DRS 1

Neue Zürcher Zeitung

SPIEGEL ONLINE

Süddeutsche Zeitung

DIE ZEIT

la Repubblica

Libération

NATIONAL GEOGRAPHIC

Los Angeles Times

Resonance to our Resonance

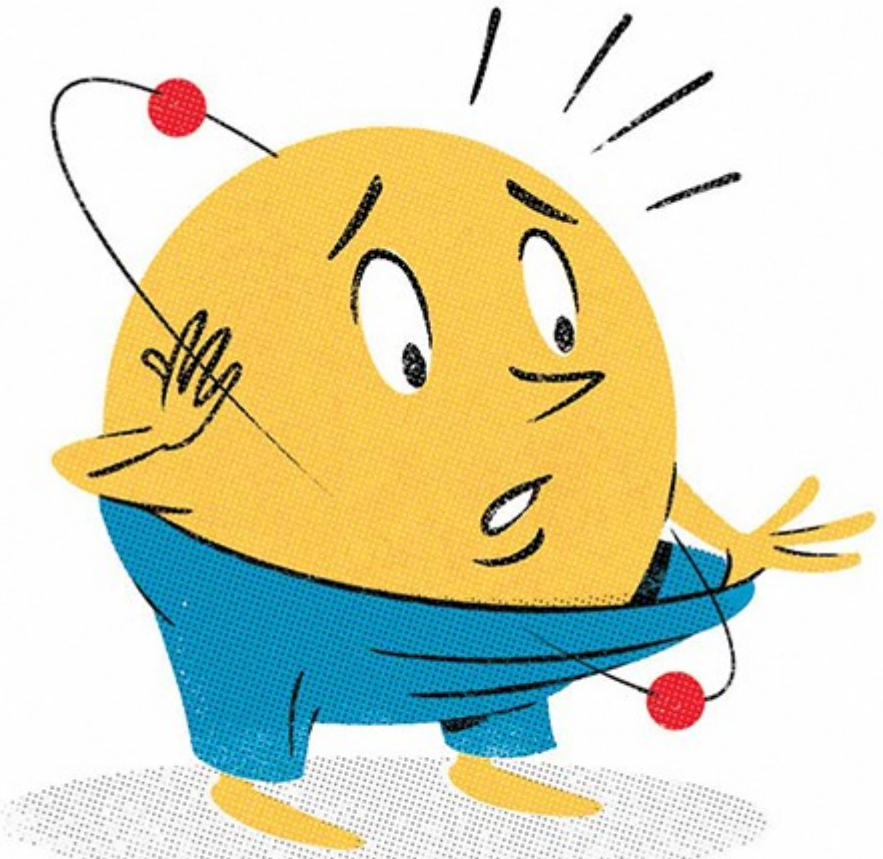
DRS 1

SPIEGEL

DIE

la Repubblica

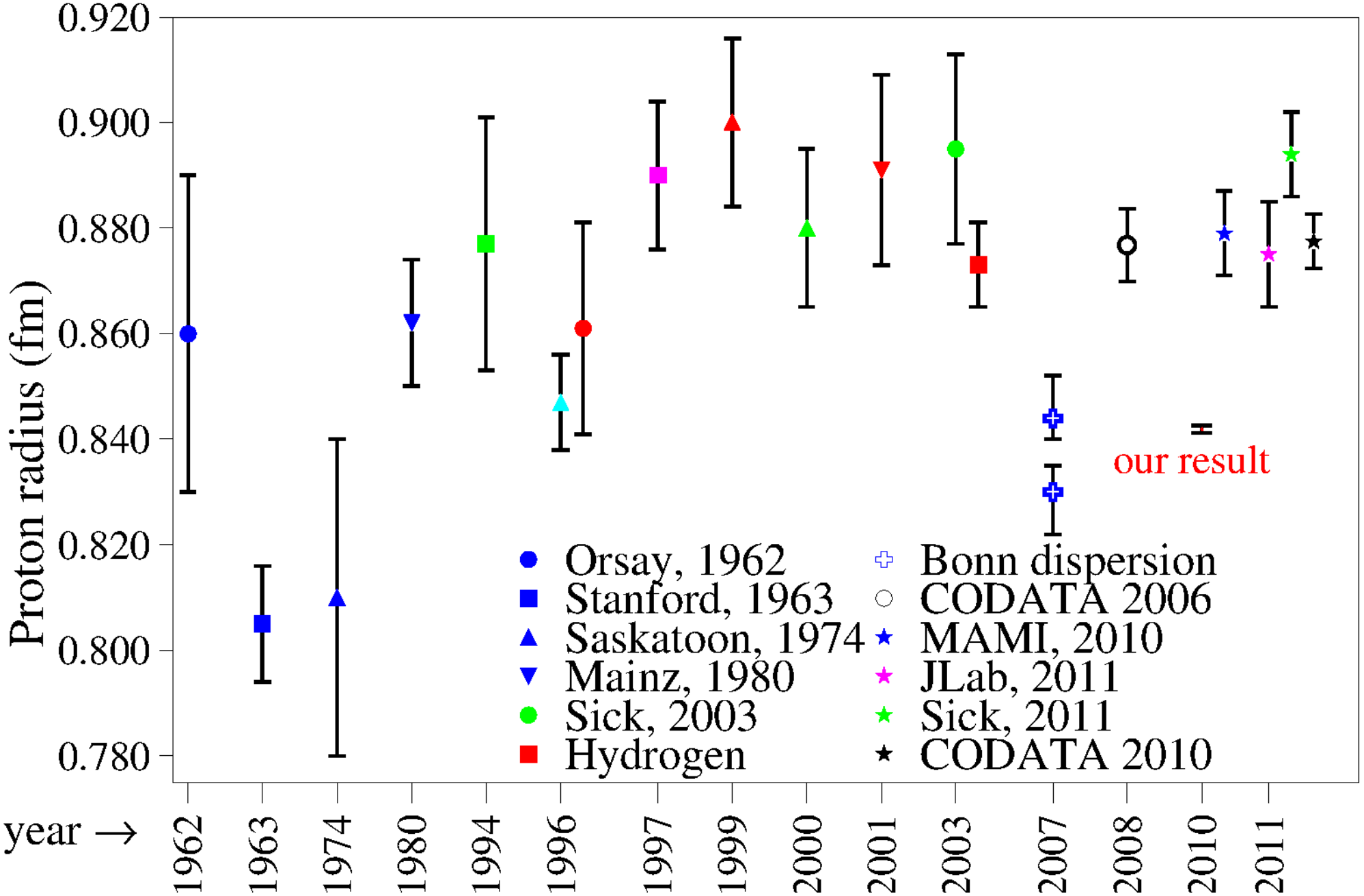
NATIONAL GEOGRAPHIC



The New York Times

Los Angeles Times

The “Proton Radius Puzzle”



The “Proton Radius Puzzle”

muonic hydrogen: 0.84 fm

electronic hydrogen: 0.88 fm

electron scattering: 0.88 fm

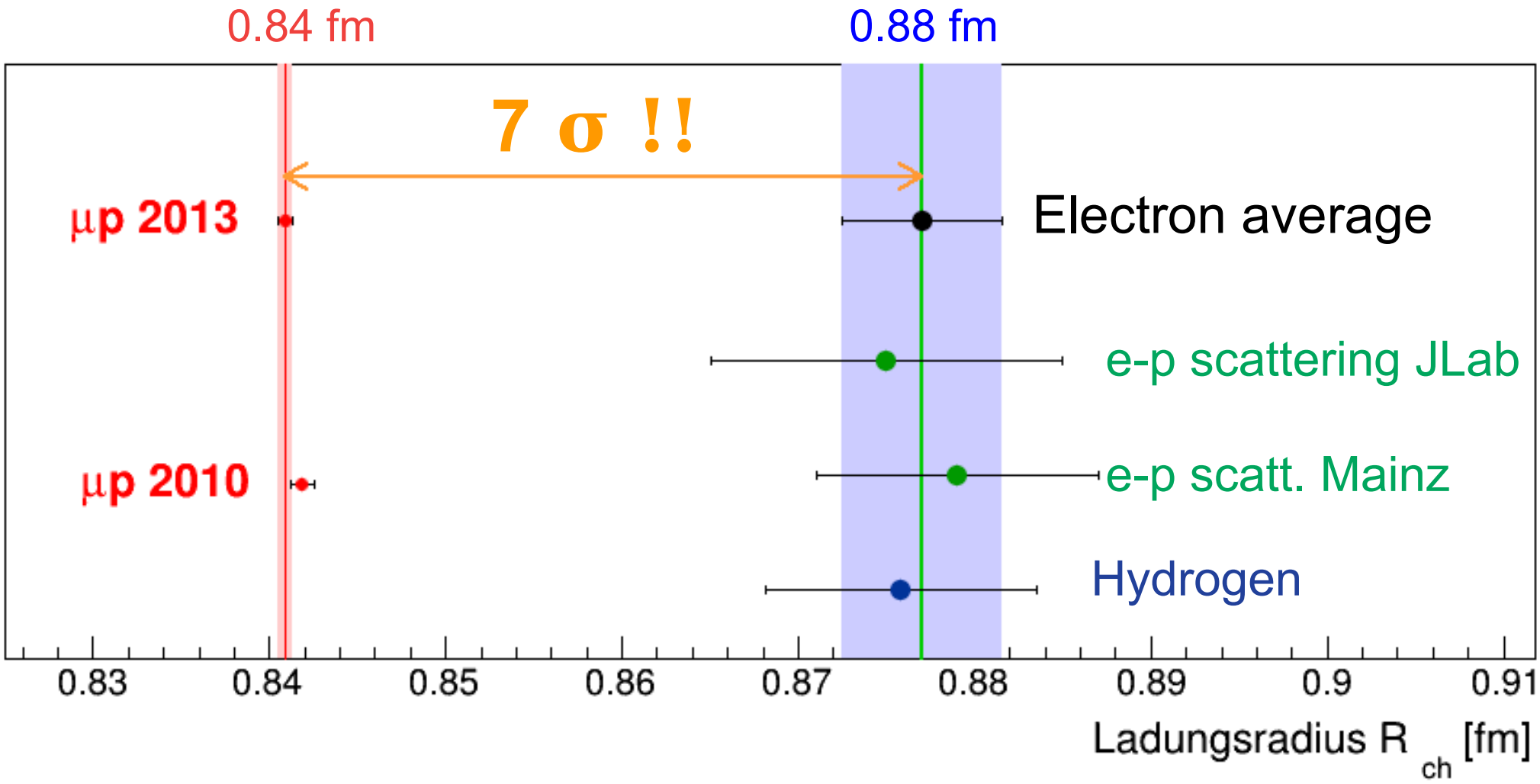
4% difference!

Measurement error? ← but who is wrong?

Theory error?

New Physics?

Das “Proton Radius Puzzle”



muonic hydrogen:	0.8409 ± 0.0004	fm	20x more precise!
electronic hydrogen:	0.876 ± 0.008	fm	
electron scattering:	0.879 ± 0.008	fm	

Workshop: The “Proton Radius Puzzle”

ECT* Trento, Italy, Oct. 2012

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

38 Talks
3 “Fighting Sessions”

Finally: **Vote (!)**

→ Measurement problem

We need **more data**.

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

Attempts to Explain

Measurement problem

Muonic hydrogen

or

Hydrogen AND Electron scattering

Theory Errorr

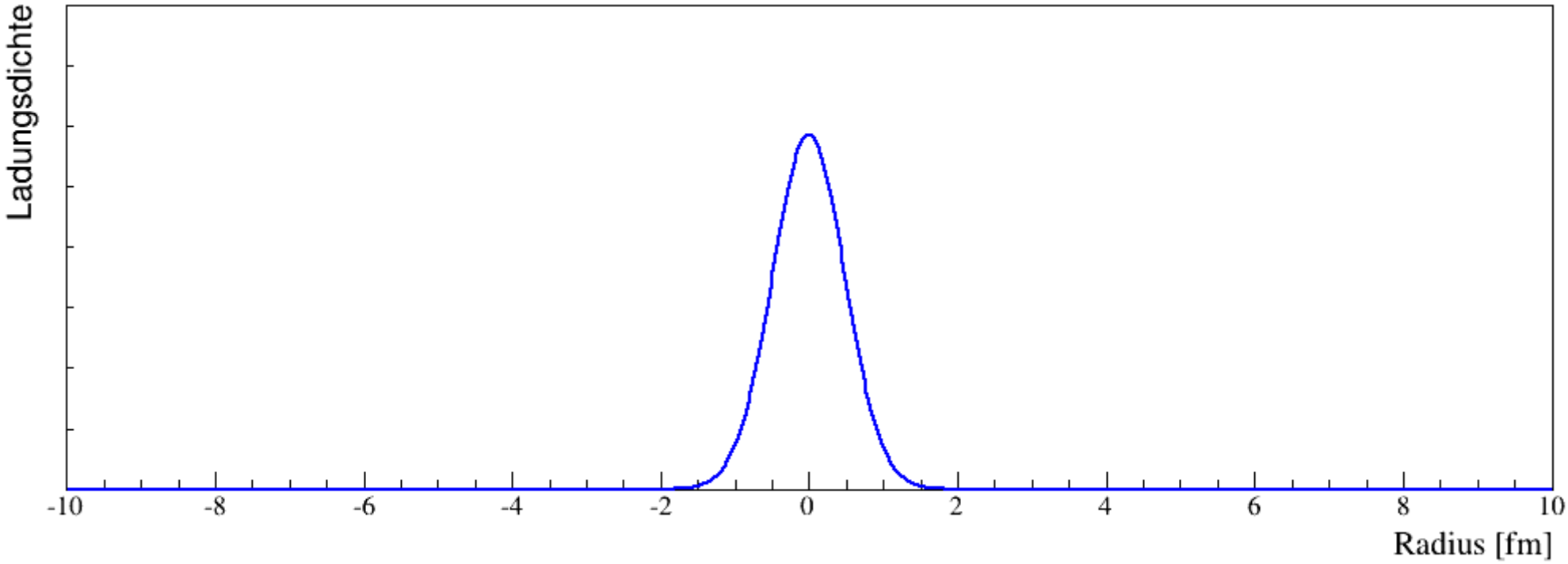
$$\Delta E = 209.998 - 5.226\ \mathbf{R}_p^2$$

Error in Standard Model of Particle Physics

The Proton looks different!

Proton is not a solid ball

The (radial) charge distribution is different!



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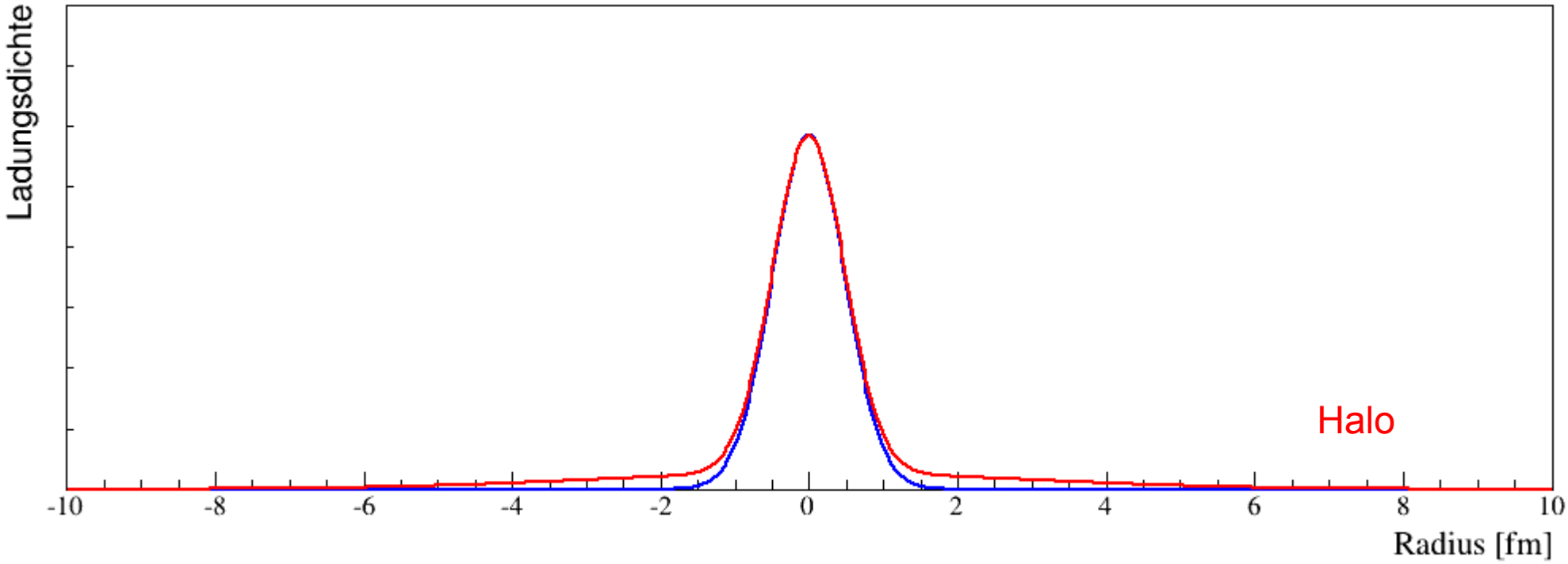
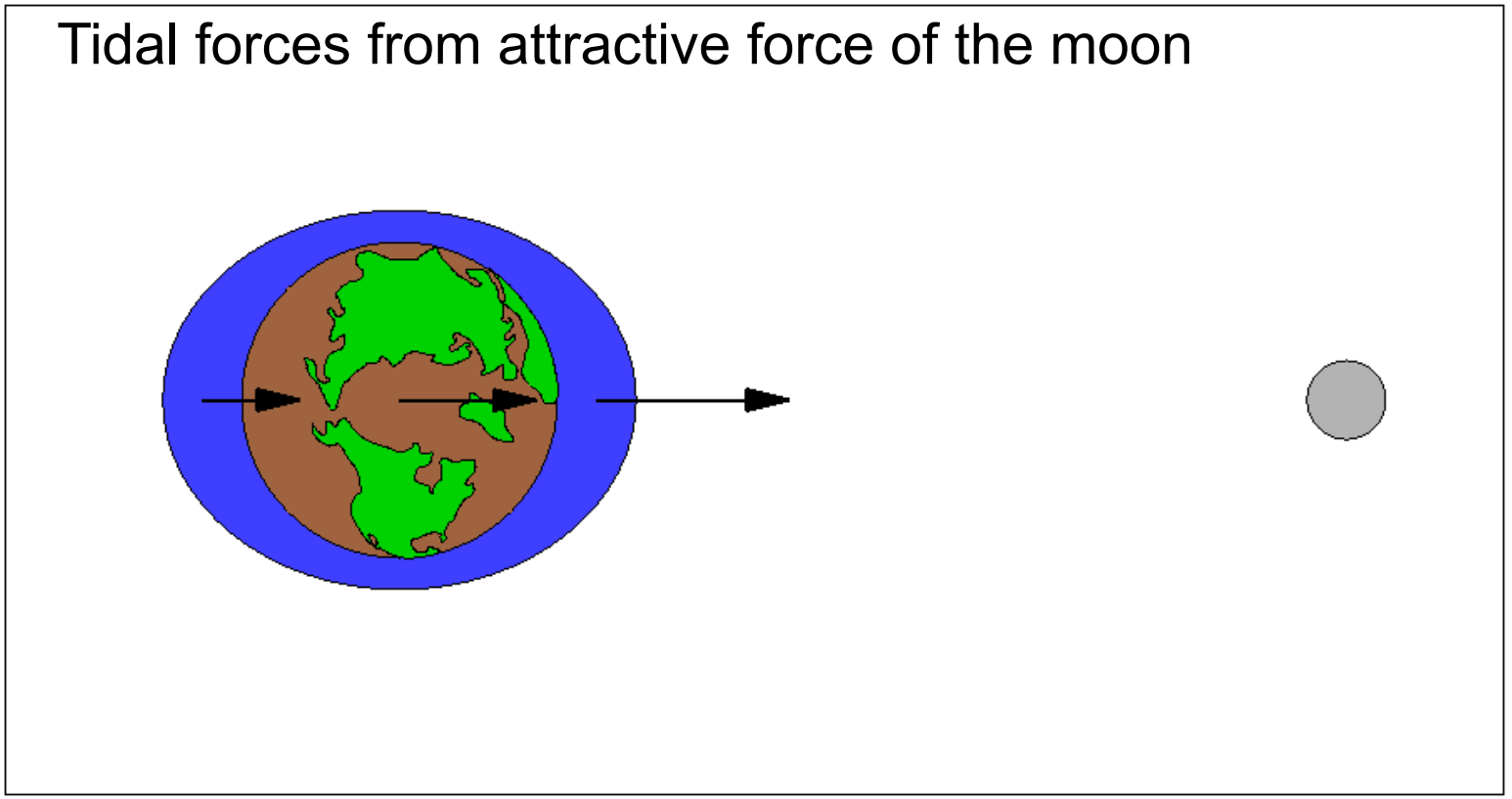


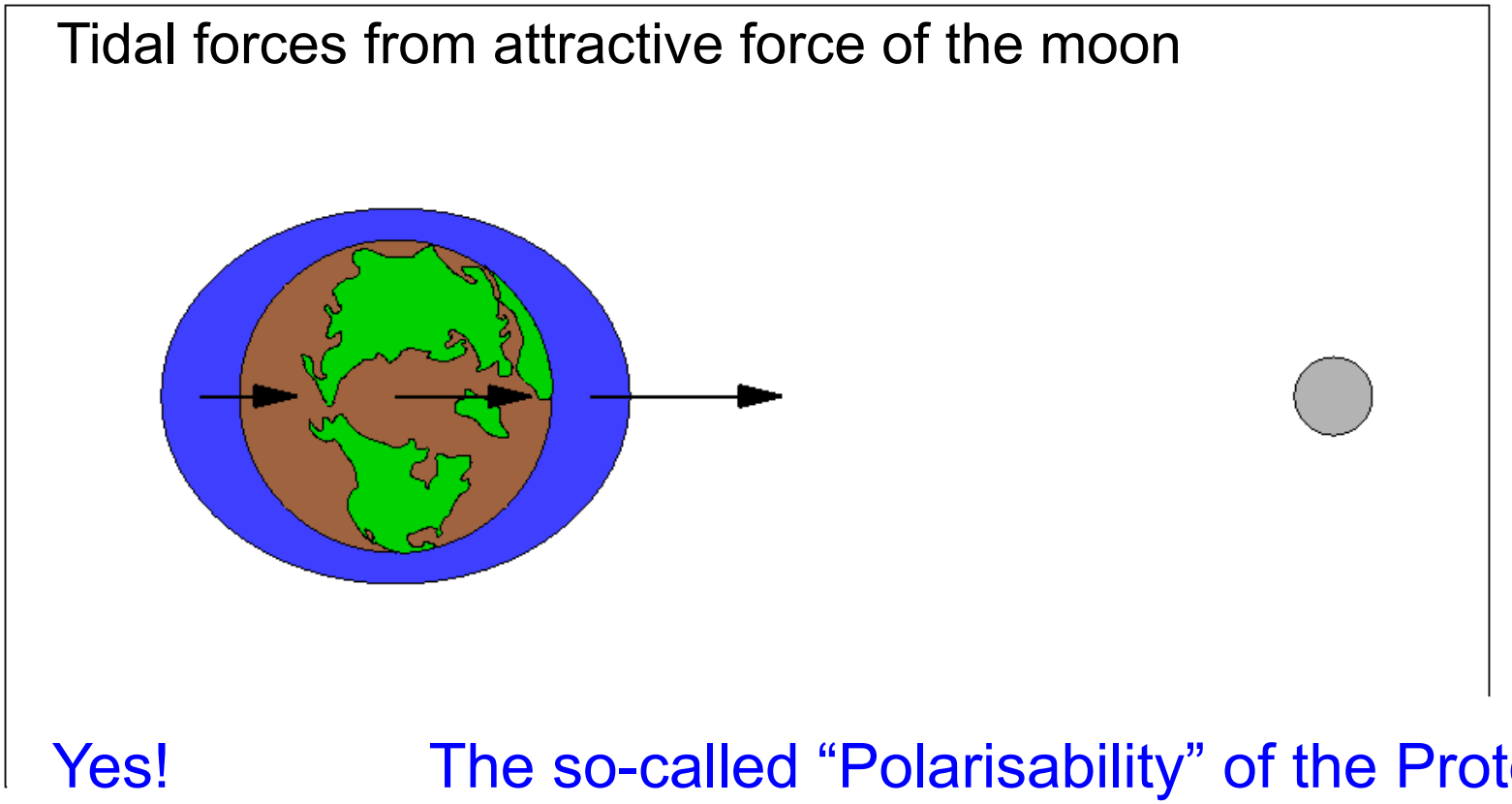
Such a long-range halo would explain the discrepancy!
Is however in disagreement with scattering measurements of halo.

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

Muon modifies the Proton



Muon modifies the Proton

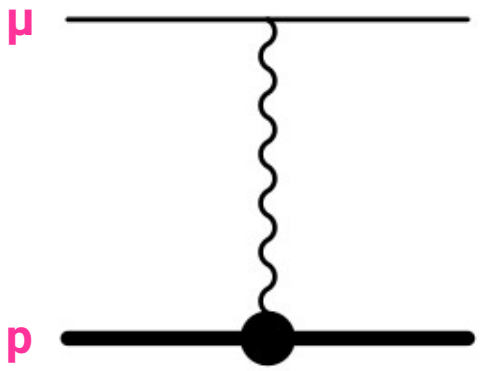


Yes! The so-called “Polarisability” of the Proton

But the effect is already considered (and much too small)

Diskrepancy: 0.31 meV
Polarisability: 0.0127 ± 0.0005 meV

Muon modifies the Proton



1-photon exchange

charge radius

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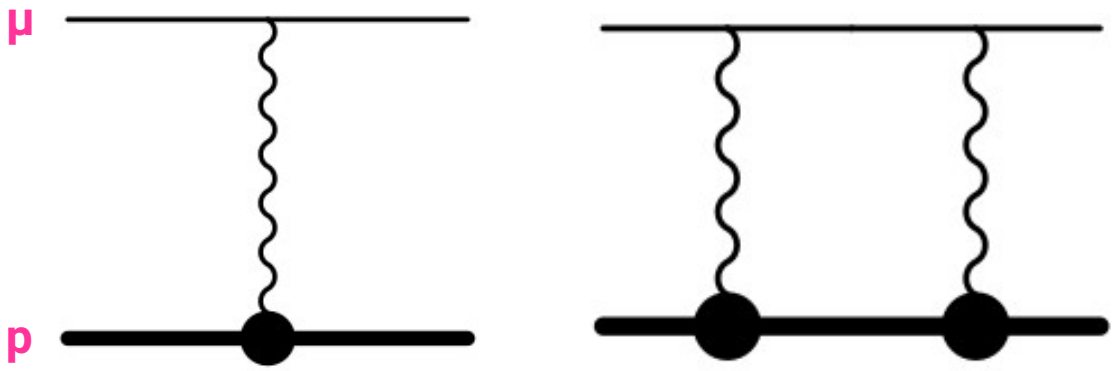

1-photon exchange

charge radius

2-photon exchange
(elastic)

Proton-"Halo"

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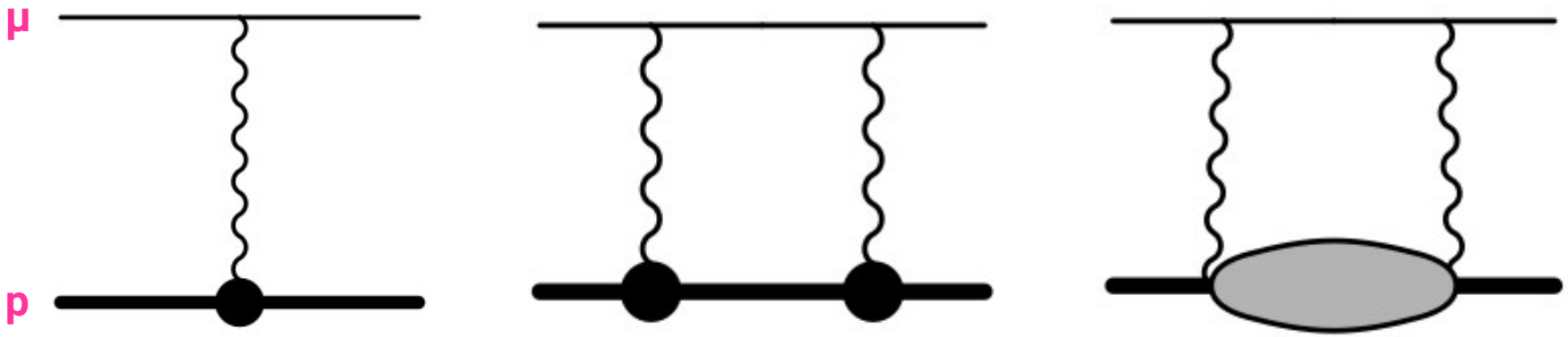

1-photon exchange

charge radius

2-photon exchange (elastic)

Proton-"Halo"

2-photon exchange (inelastic)

Proton polarisability

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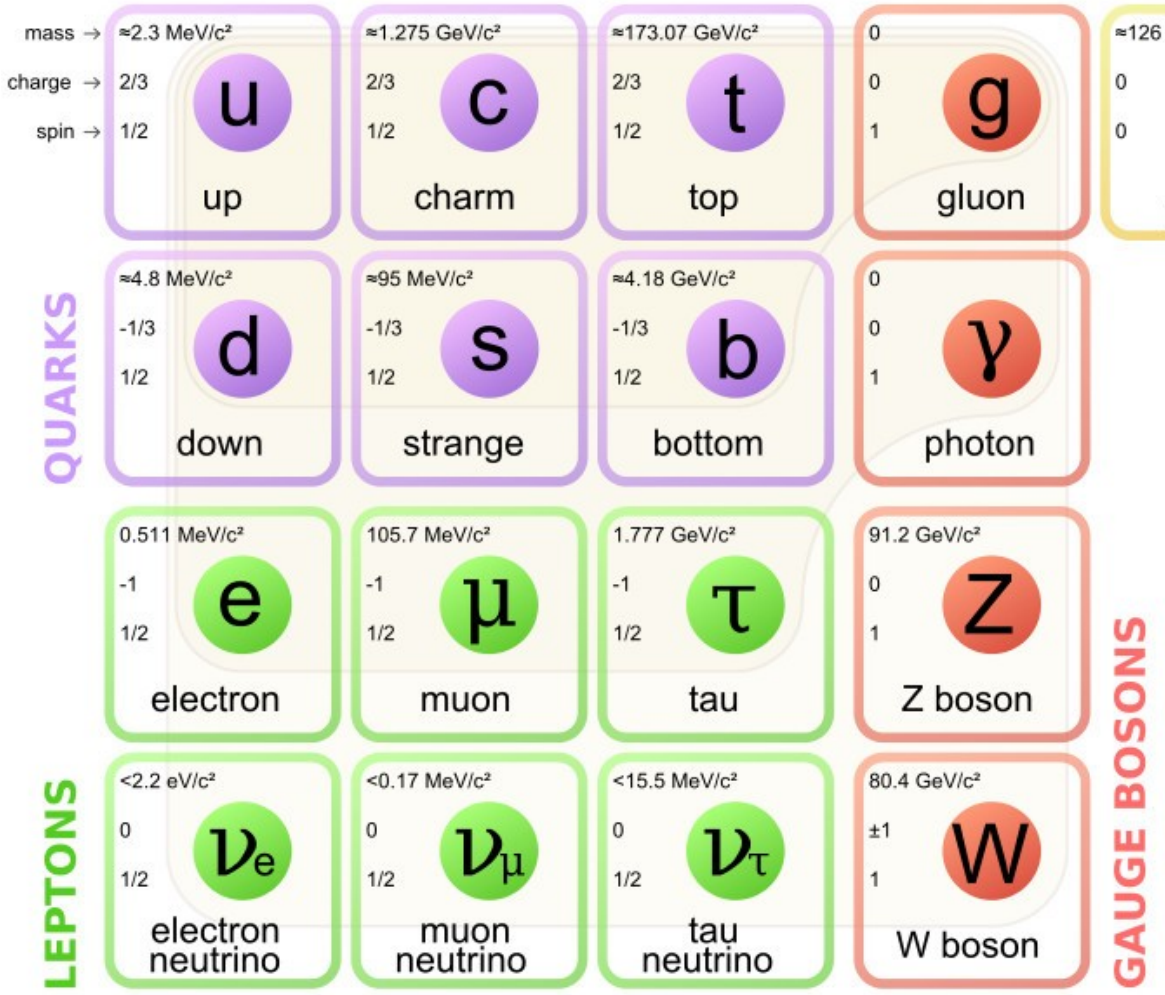
Polarisability: 0.0127 ± 0.0005 meV

A new particle!



Gravity!

Dark Matter?

Dark Energy?

Baryon asymmetry!

Strong CP-Problem!

...

A new particle!

Physics beyond the Standard Model

could in principle be responsible for the discrepancy.

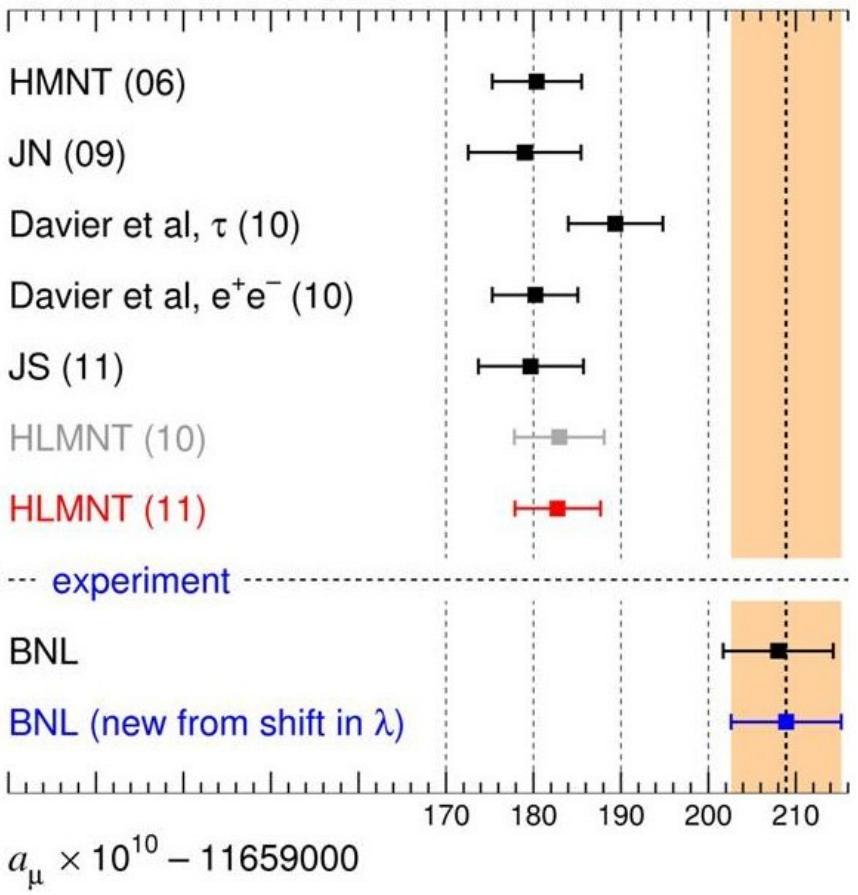
This would be a new particle, creating a new force!

New particle must fit into the constraints from many Precision measurements!

Difficult.....

Two problems with muons!

Anomalous magnetic moment of the muon (g-2)



Theory

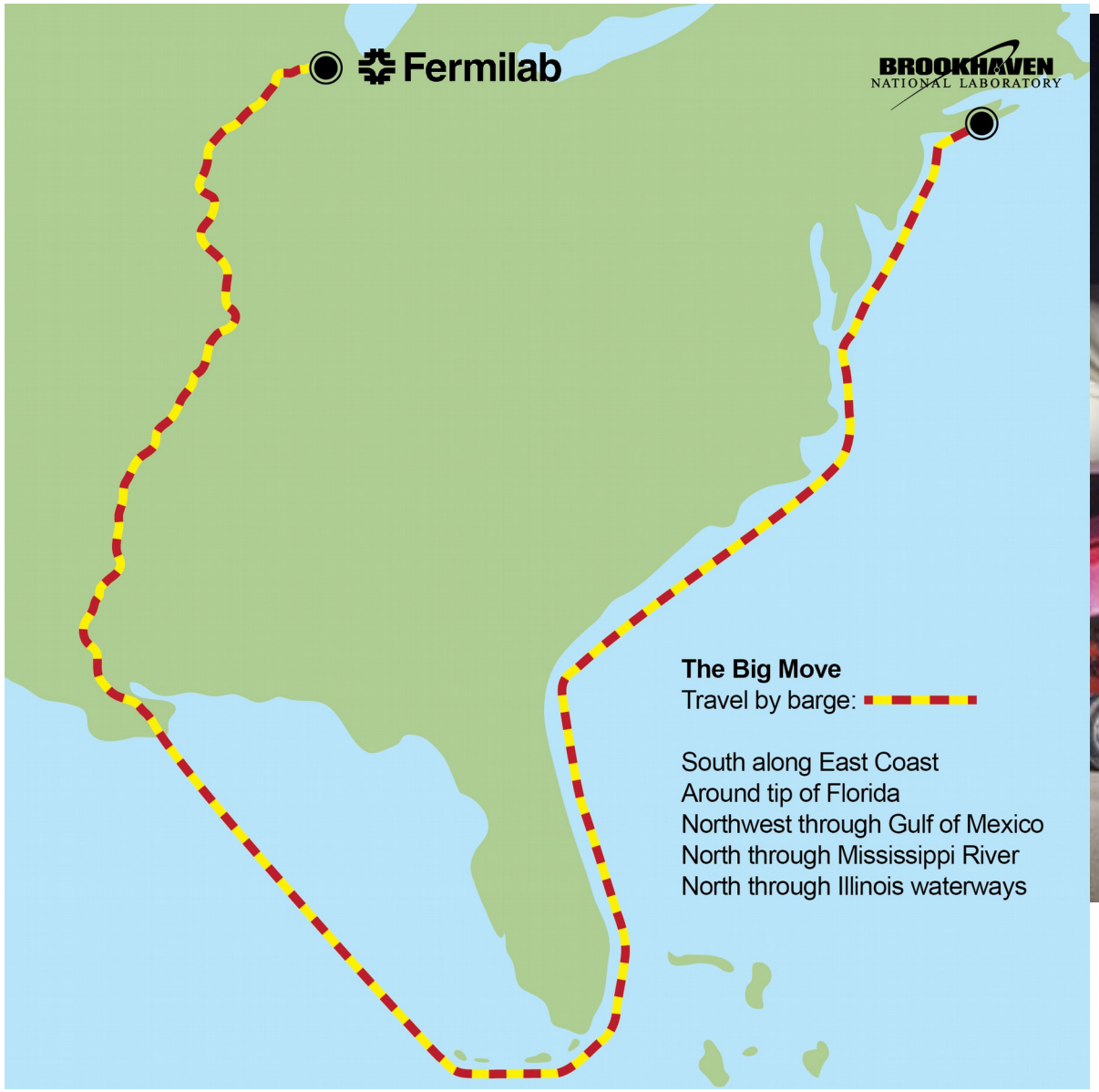
Experiment

For 10 years now: 3.6 σ diskrepancy to Standard Model

The new muon g-2 experiment

move: summer 2013
data taking: since 2017

The new muon g-2 experiment



move: summer 2013
data taking: since 2017

Summary

The “Proton Radius Puzzle” is still unsolved after 8 years

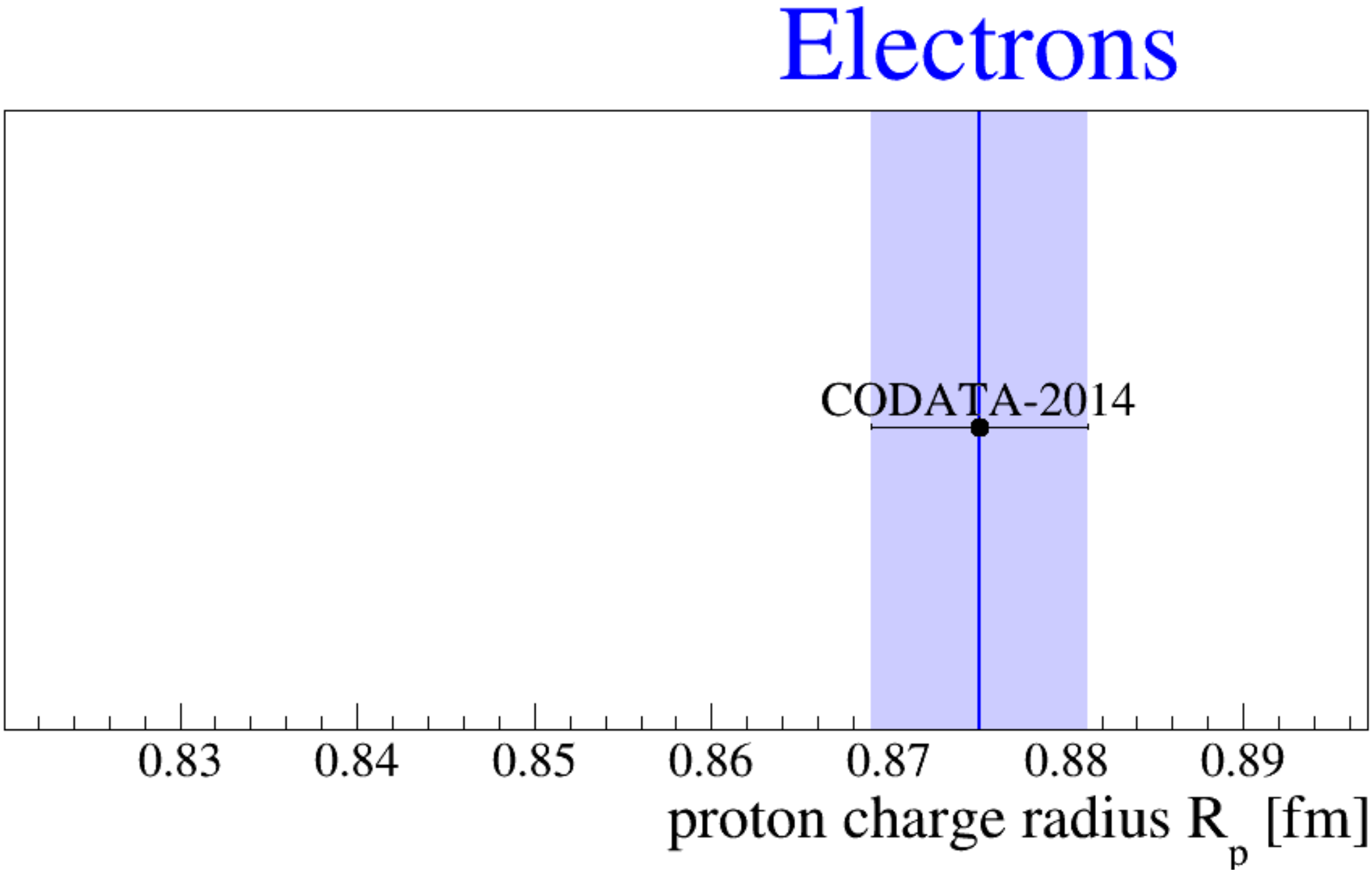
Maybe the muon wants to tell us something exciting?

Or a (freaky) measurement error?

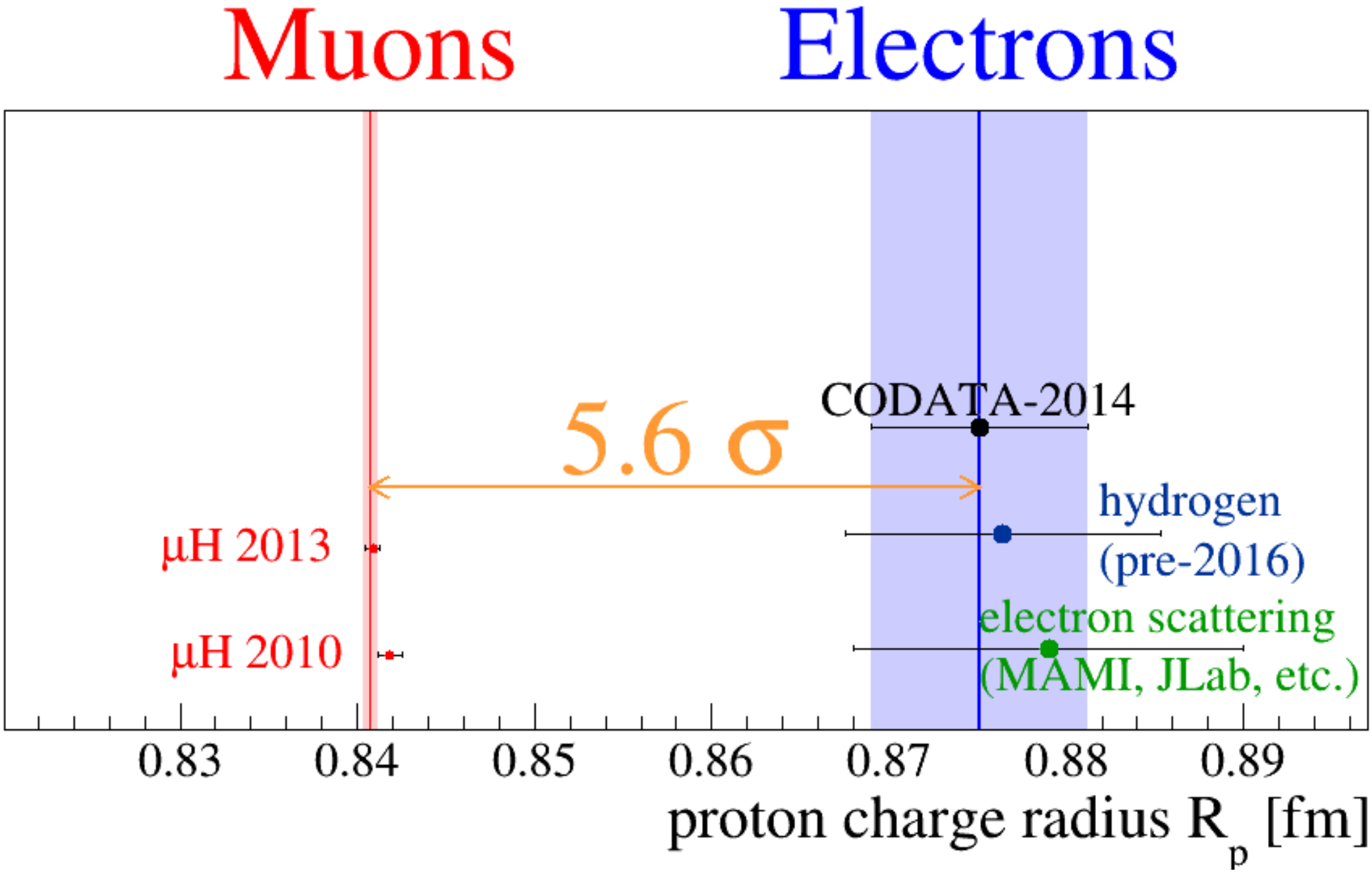
A lot of new measurements are on the way:

For example: **Muonic Deuterium, etc.**
Normal hydrogen
Electron scattering
Muon scattering

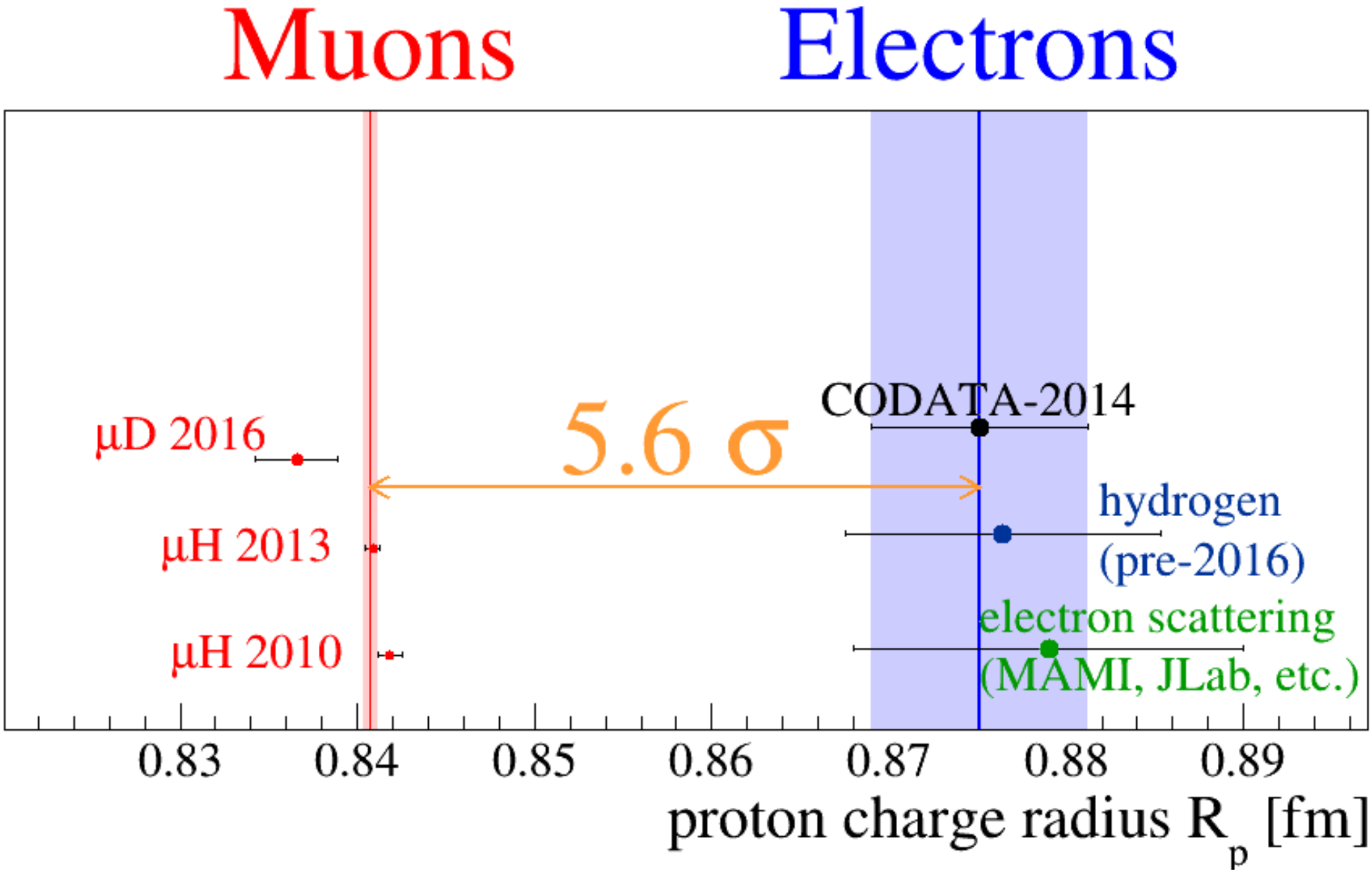
The “old” measurements



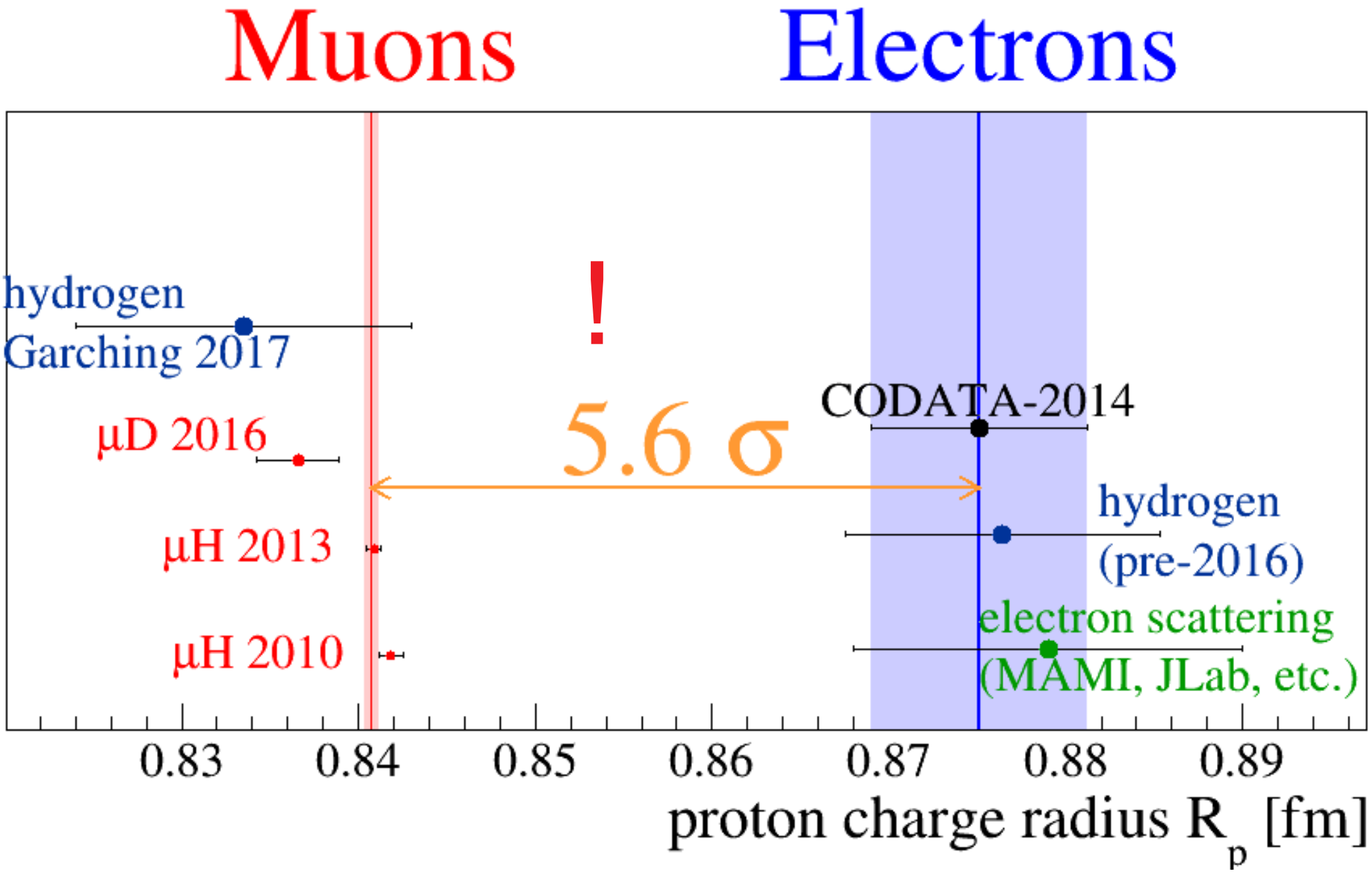
The “Proton Radius Puzzle”



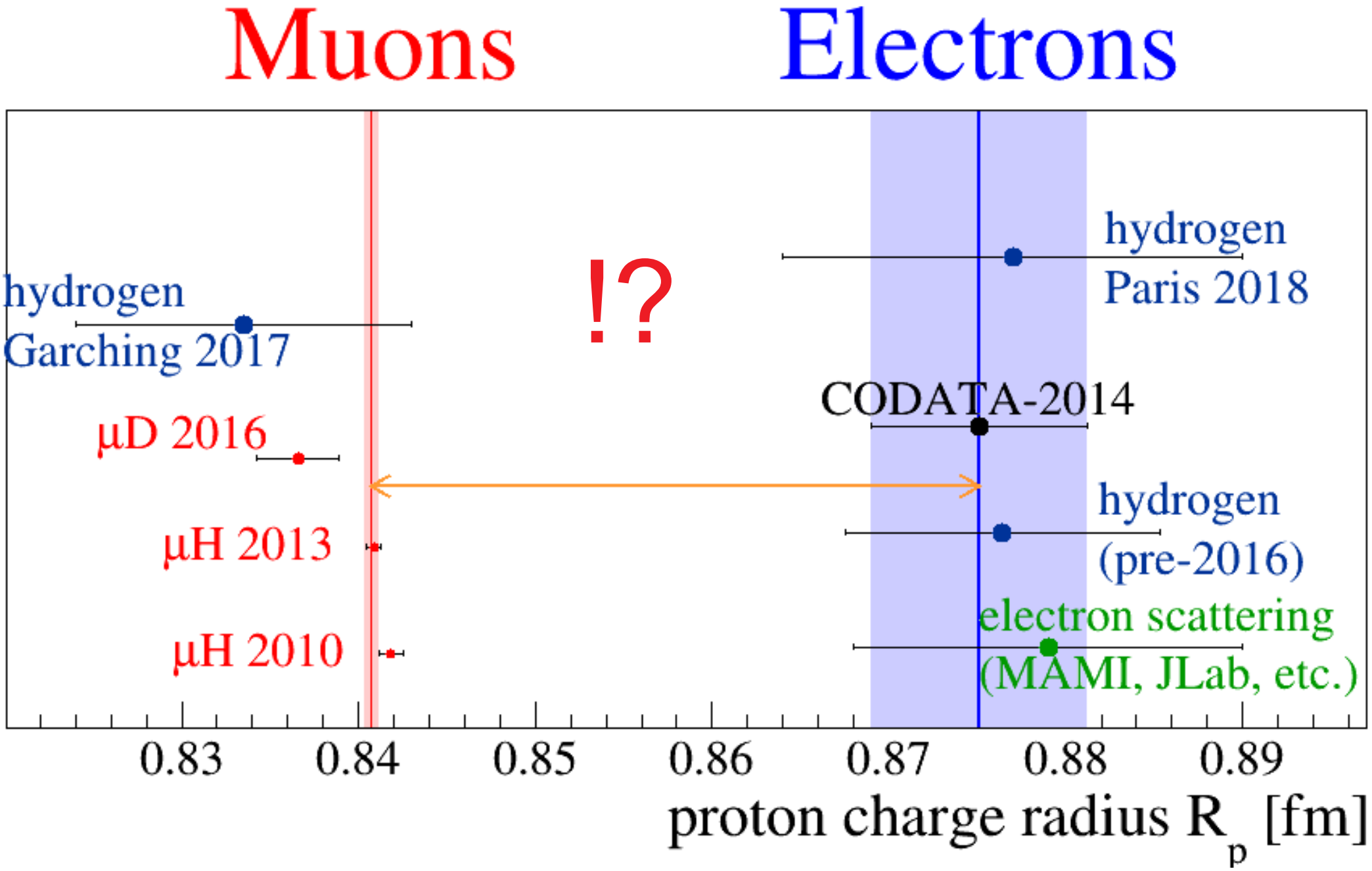
The “Proton Radius Puzzle”



New Measurements



New Measurements

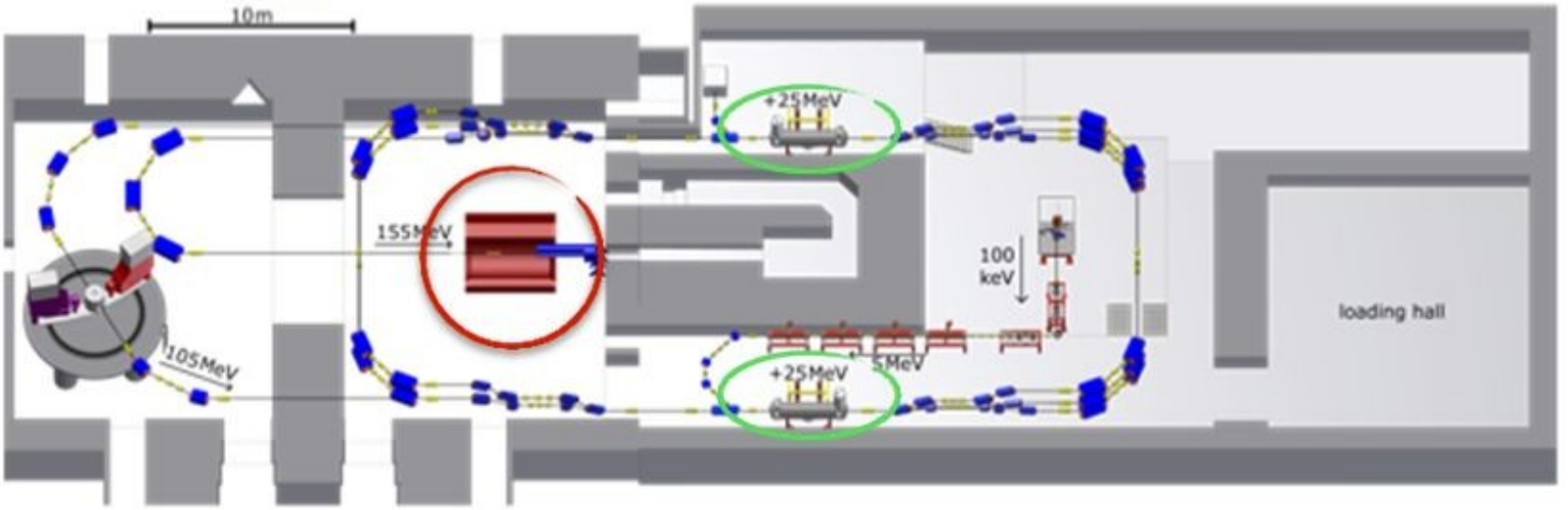


New Mainz electron accelerator **MESA**

Kurt Aulenbacher

MESA — "**M**ainz **E**nergy-Recovering **S**uperconducting **A**ccelerator

Beam energy: 105 MeV / 155 MeV Current: 1–2 mA



Being built on **Campus of JGU Mainz**

Cluster of Excellence **PRISMA**, since 27.9. also **PRISMA+ !!!**

(2x 7 years of funding)

Summary

The “Proton Radius Puzzle” is still unsolved after 8 years

Maybe the muon wants to tell us something exciting?

Or a (freaky) measurement error?

A lot of new measurements are on the way.

Jan Bernauer & RP, 2014

Proton Size Investigators thank you for your attention