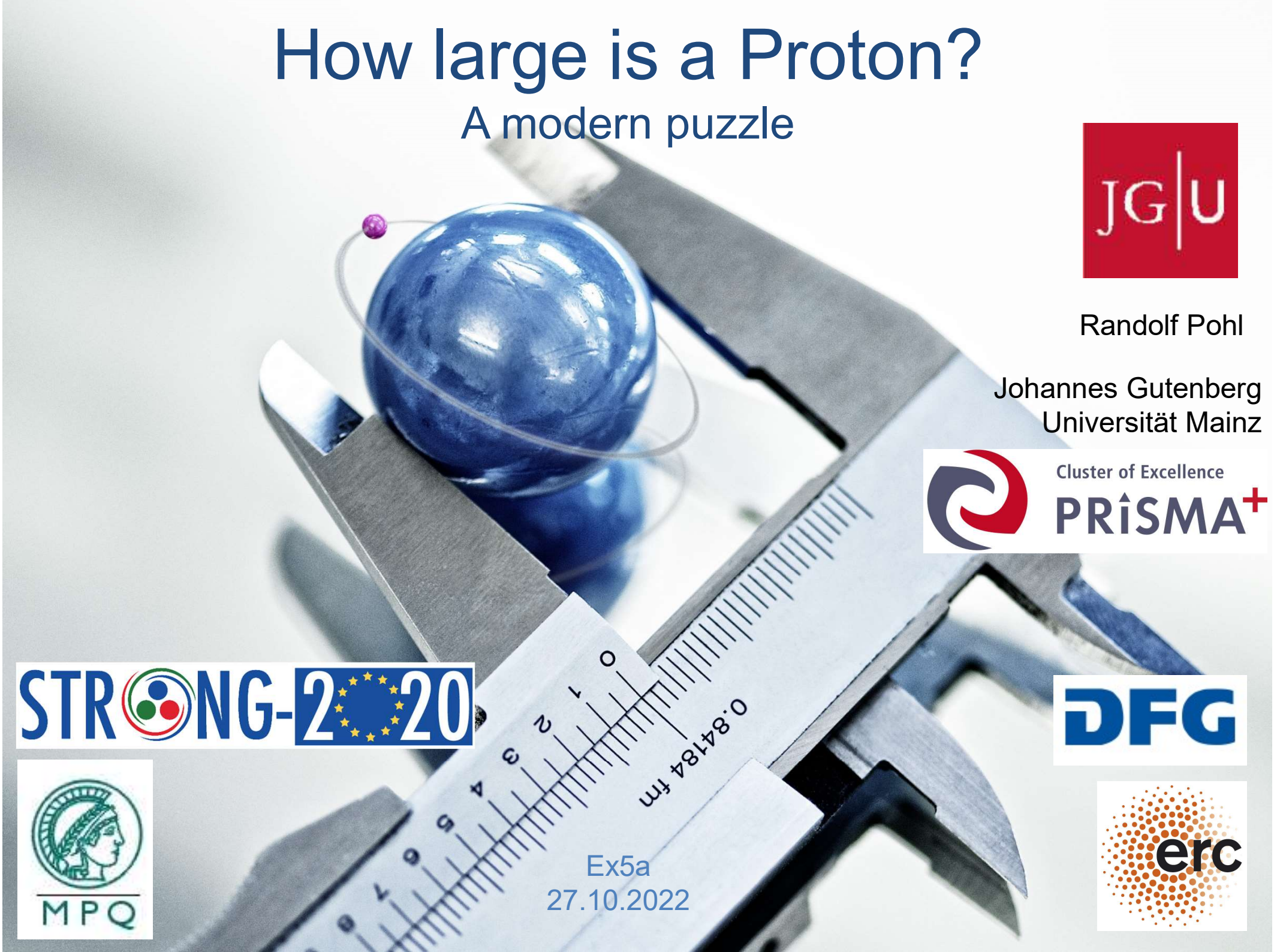
How large is a Proton?

A modern puzzle



Randolf Pohl

Johannes Gutenberg
Universität Mainz

Cluster of Excellence PRISMA+

STRONG-2020

DFG

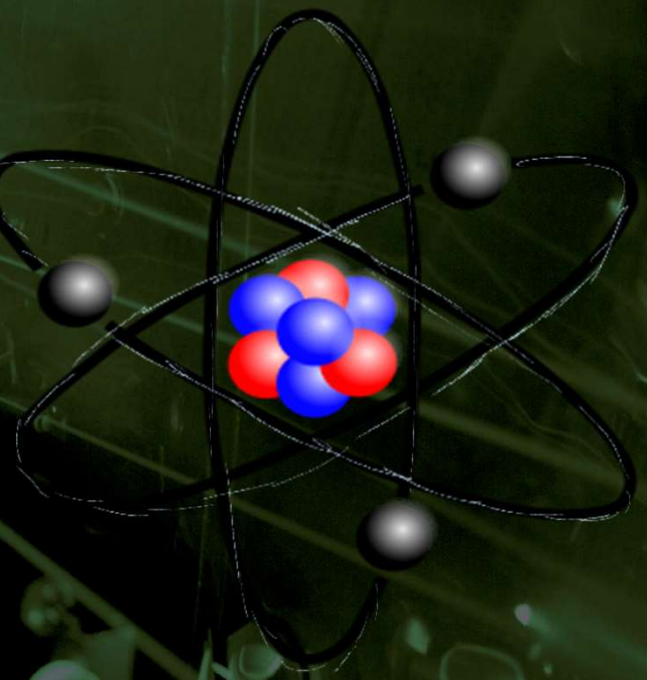
MPQ

erc

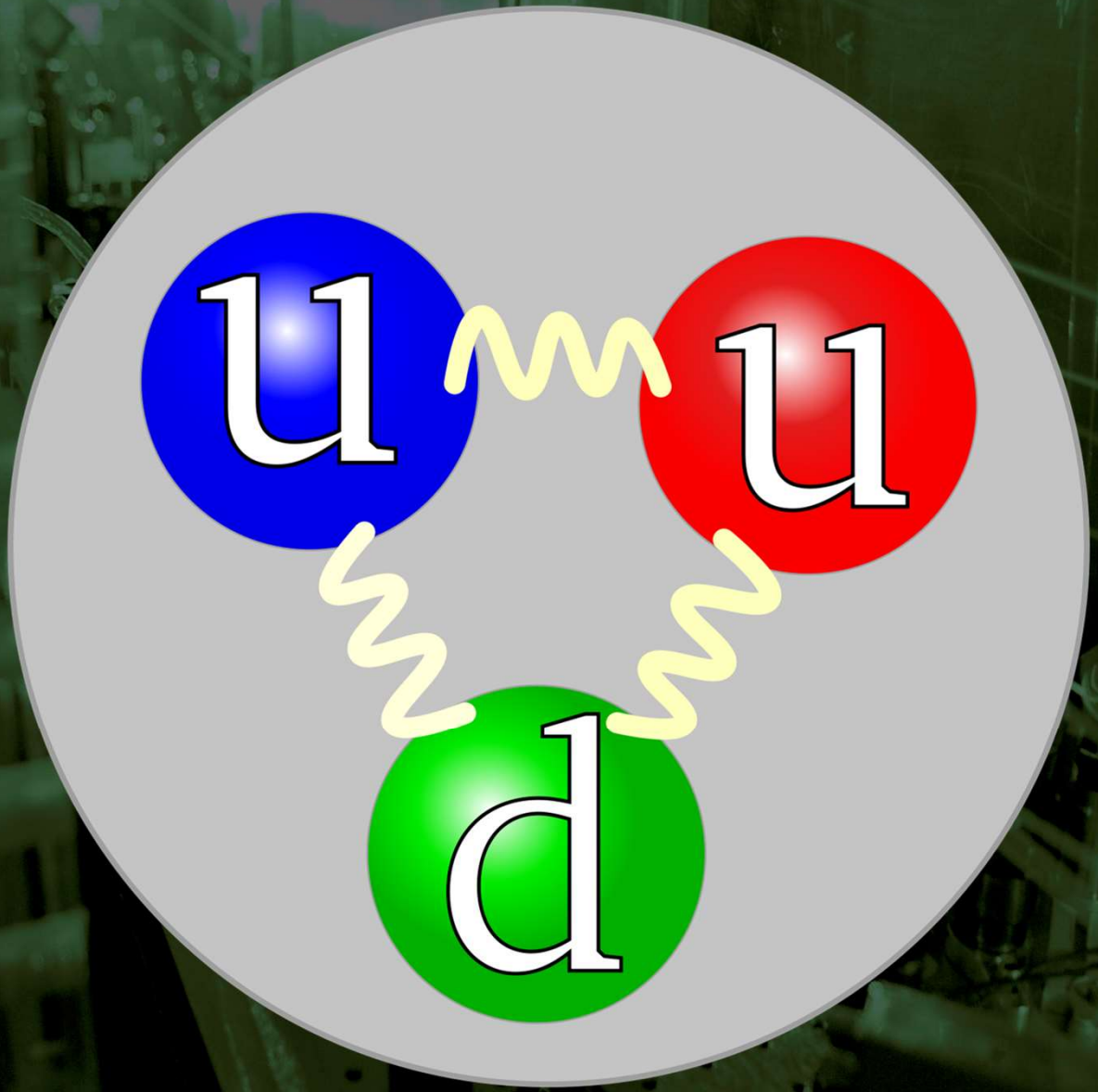
Ex5a
27.10.2022

Atoms!

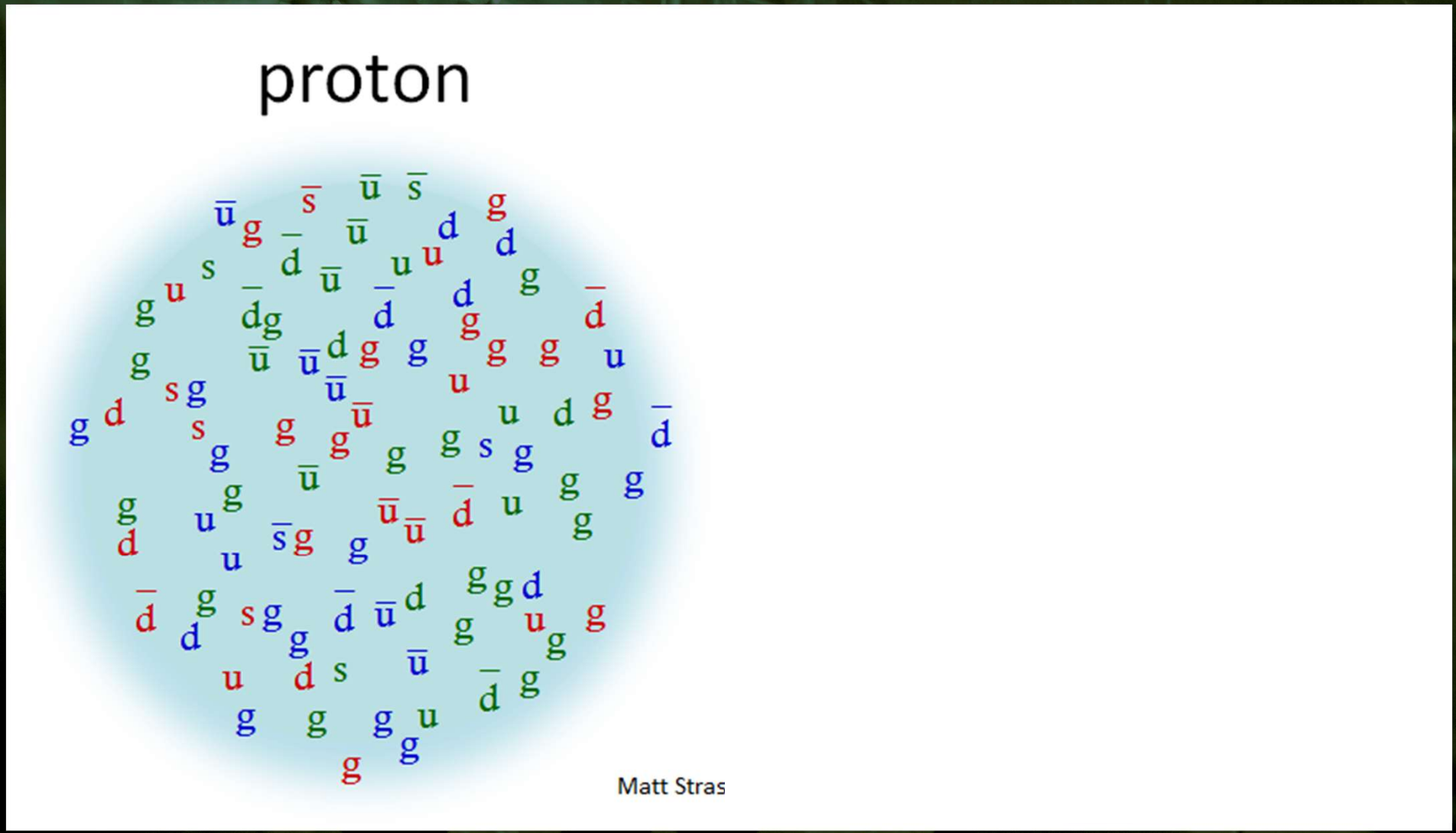
- **Atoms** have a **Nucleus**, which is orbited by Electrons.
- The **Nucleus** consists of Protons and Neutrons.
- Hydrogen is the simplest of all atoms:
  - one (extended) proton, and
  - one (point-like) electron



Proton: 3 Quarks

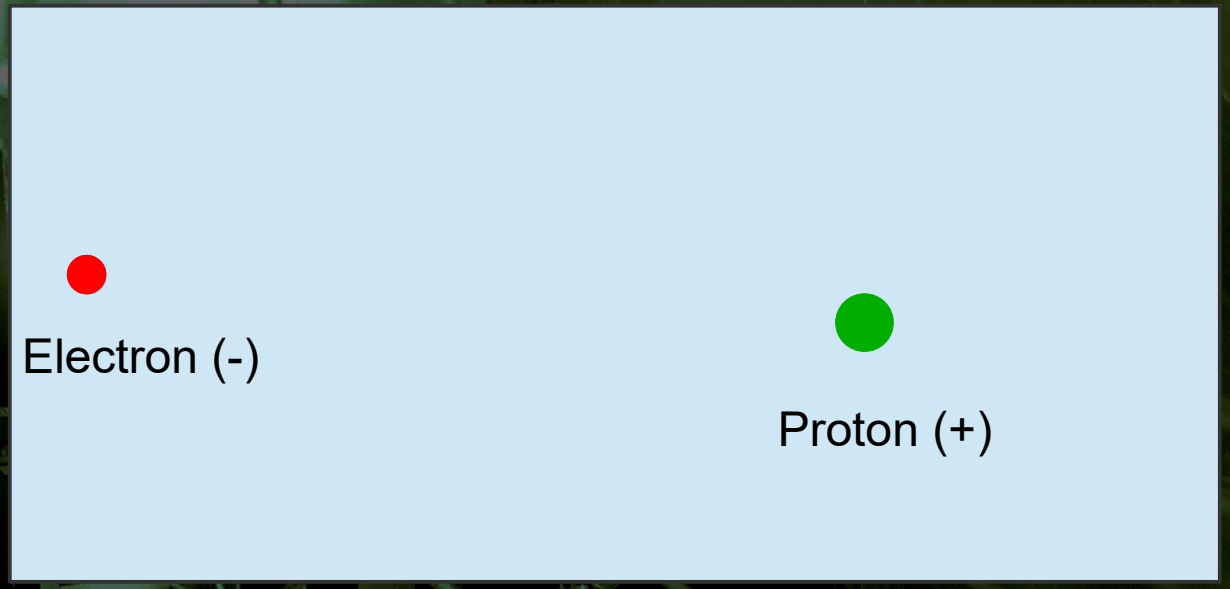


Proton: >>3 Quarks



Robert Hofstadter – 1955

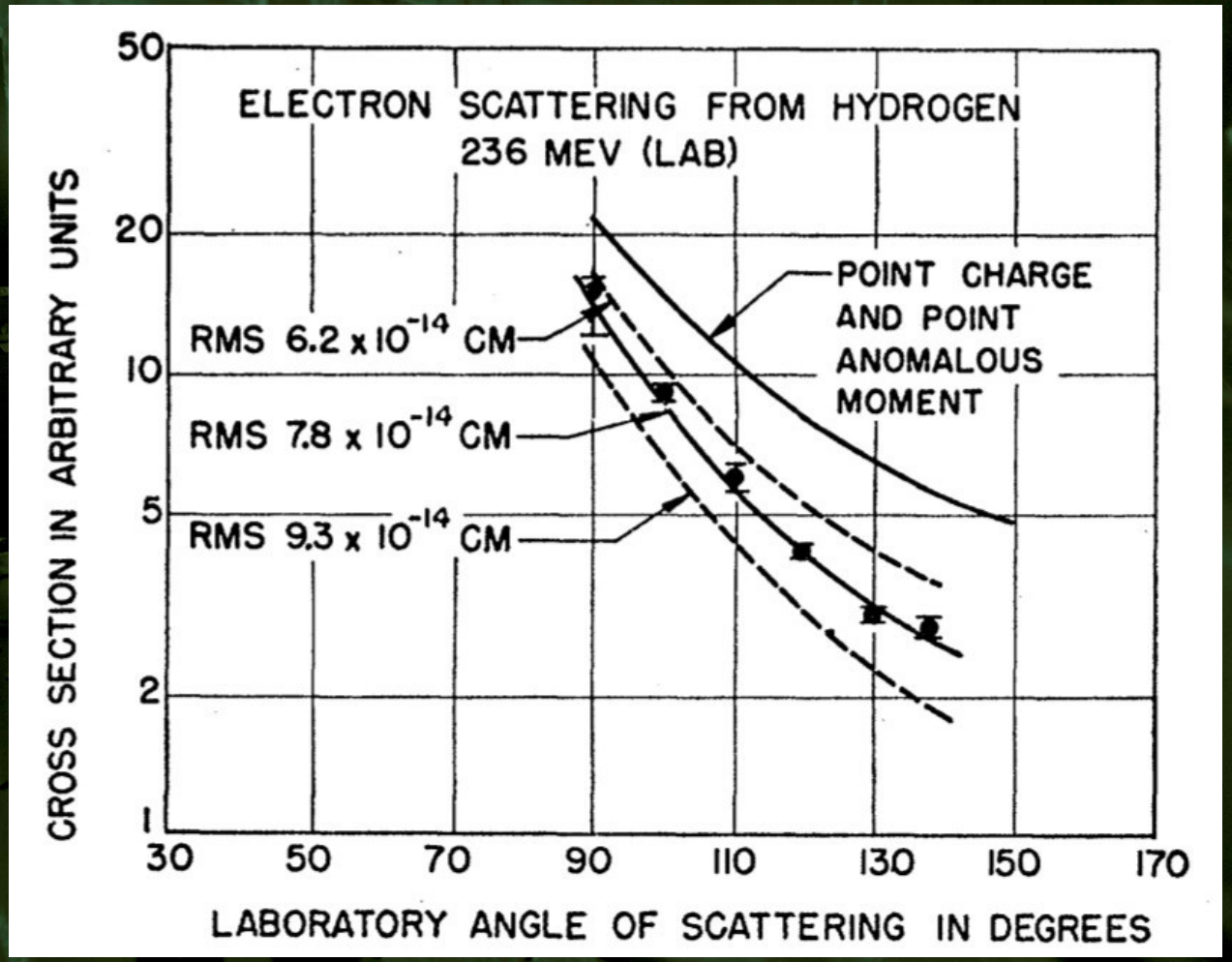
1915 – 1990
Nobel prize 1961



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

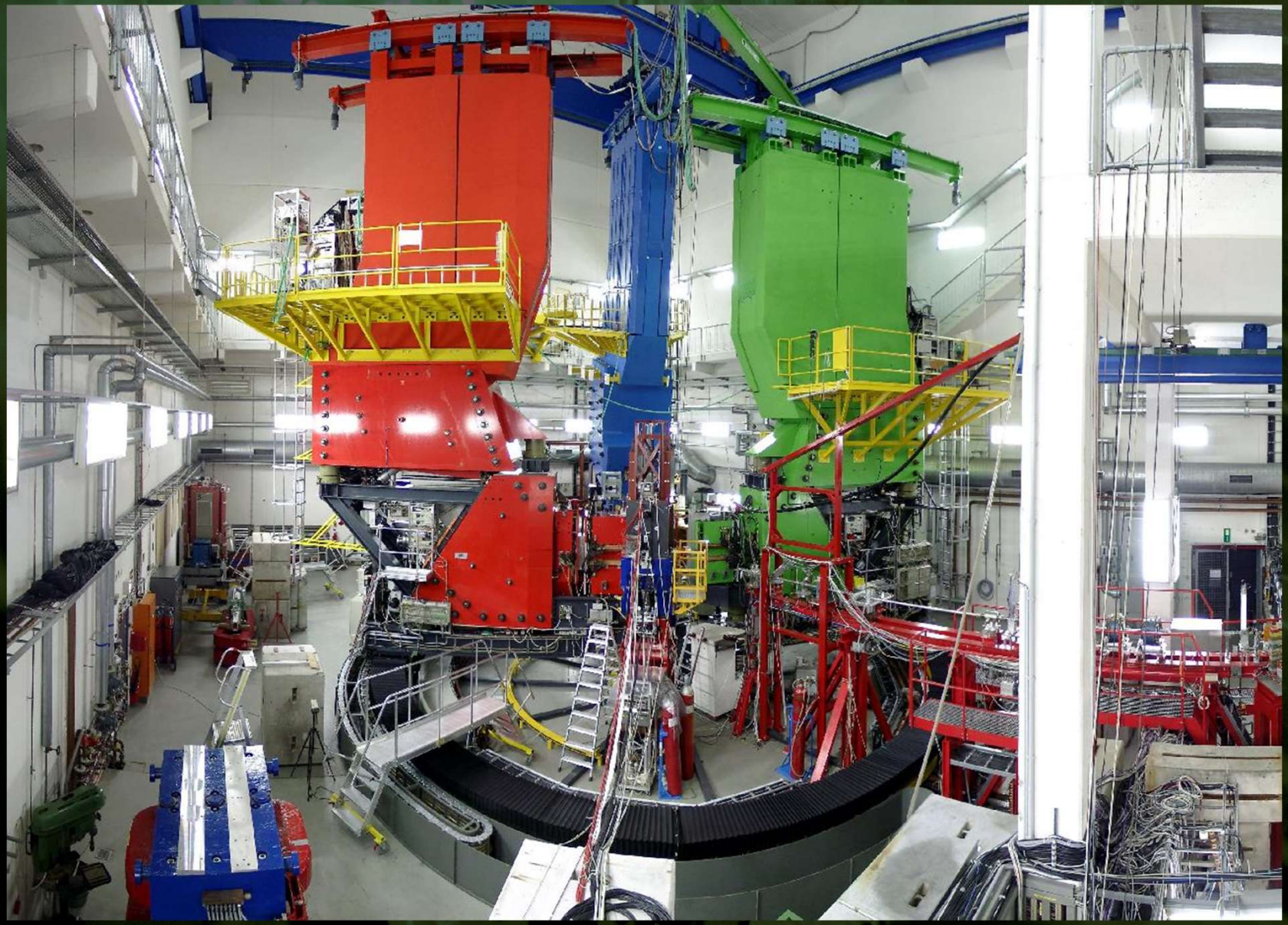
Robert Hofstadter – 1955

1915 – 1990
Nobel prize 1961



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

Mainzer Microtron MAMI

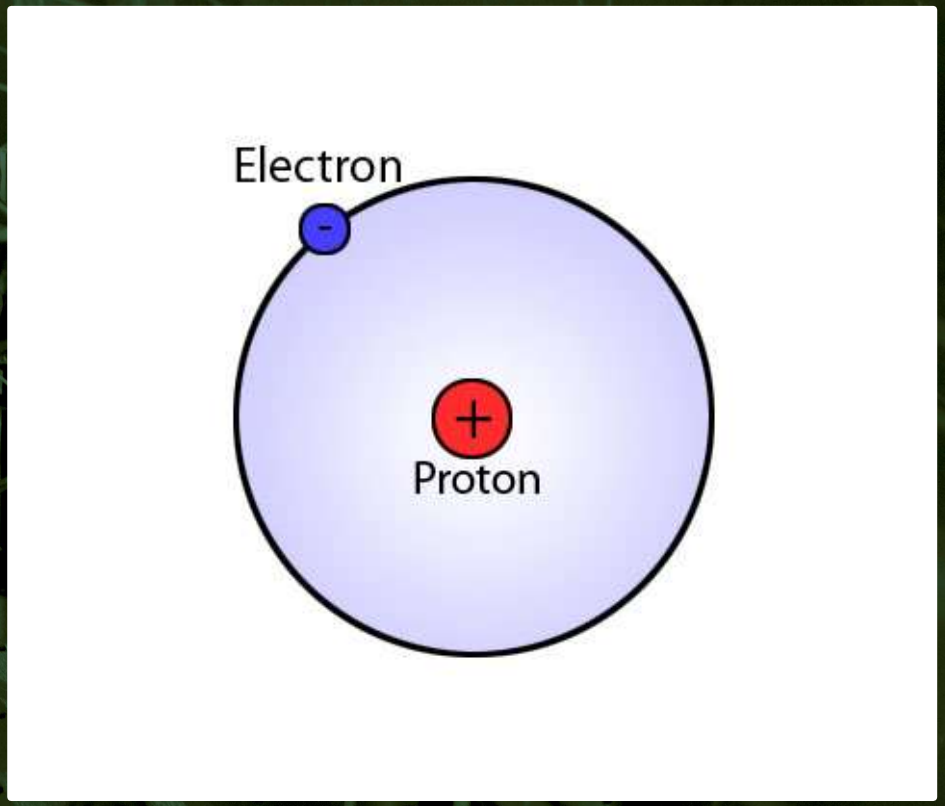


The Hydrogen Atom

Nils Bohr

1885 – 1962
Nobel prize
1922

One Proton, orbited by *one* Electron.



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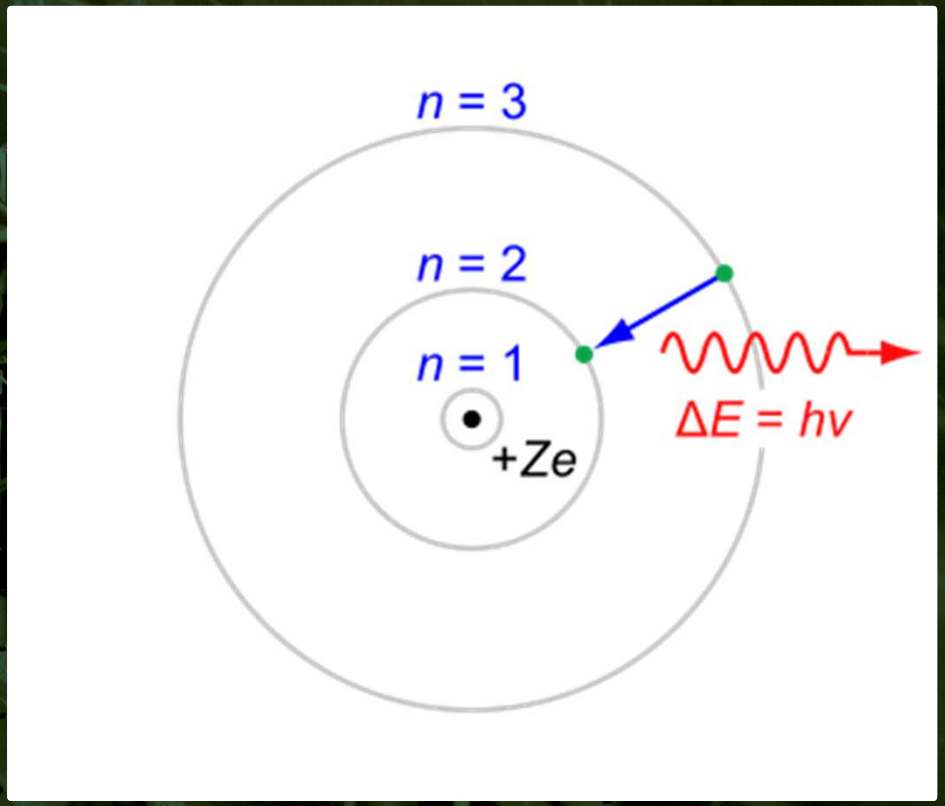

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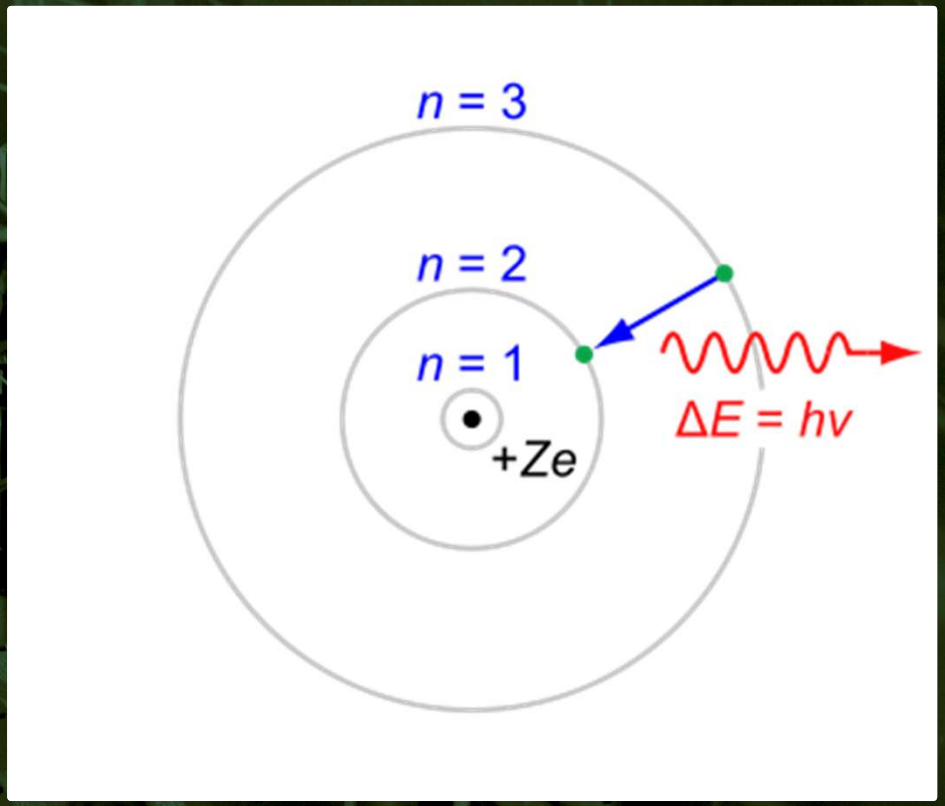
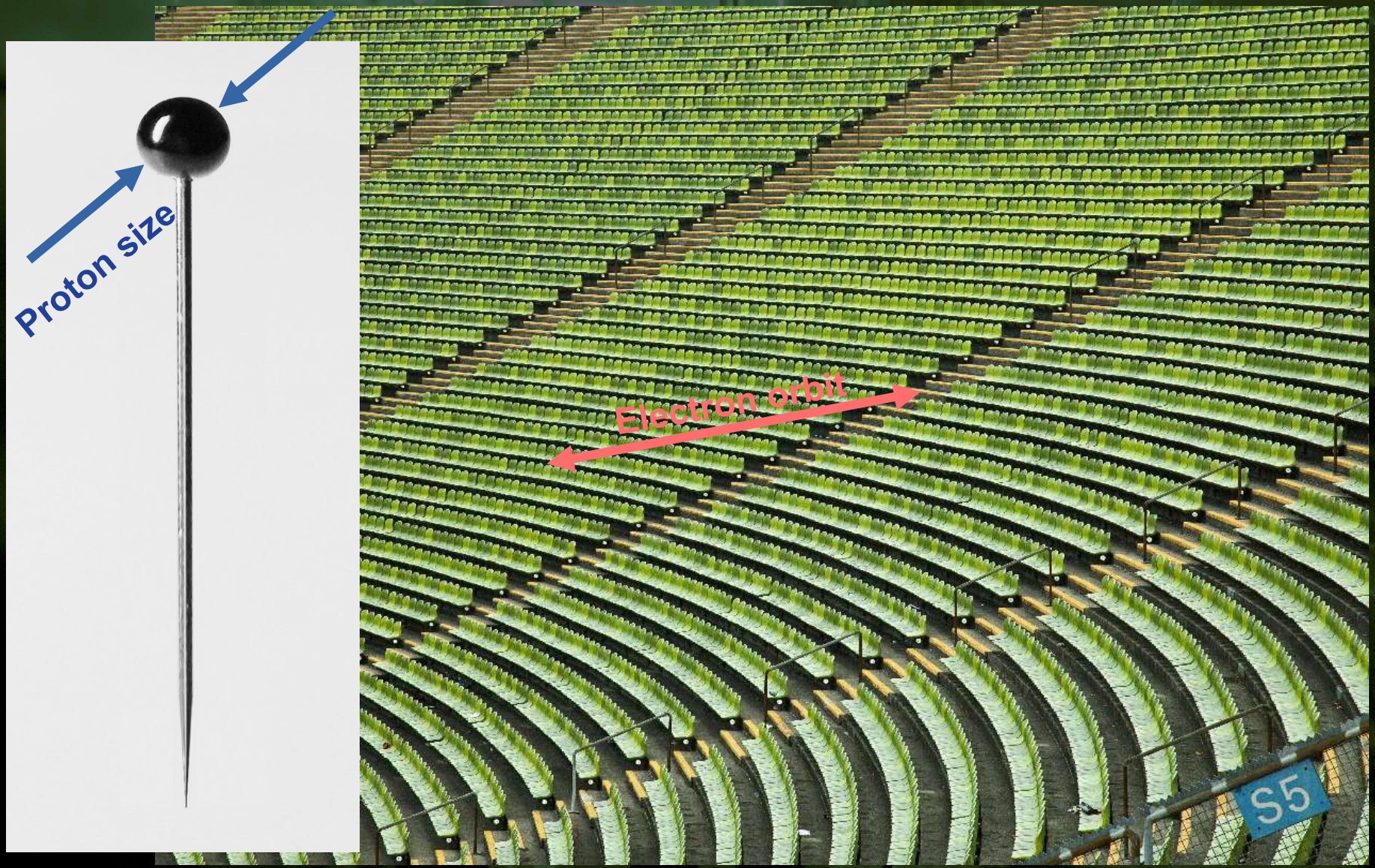


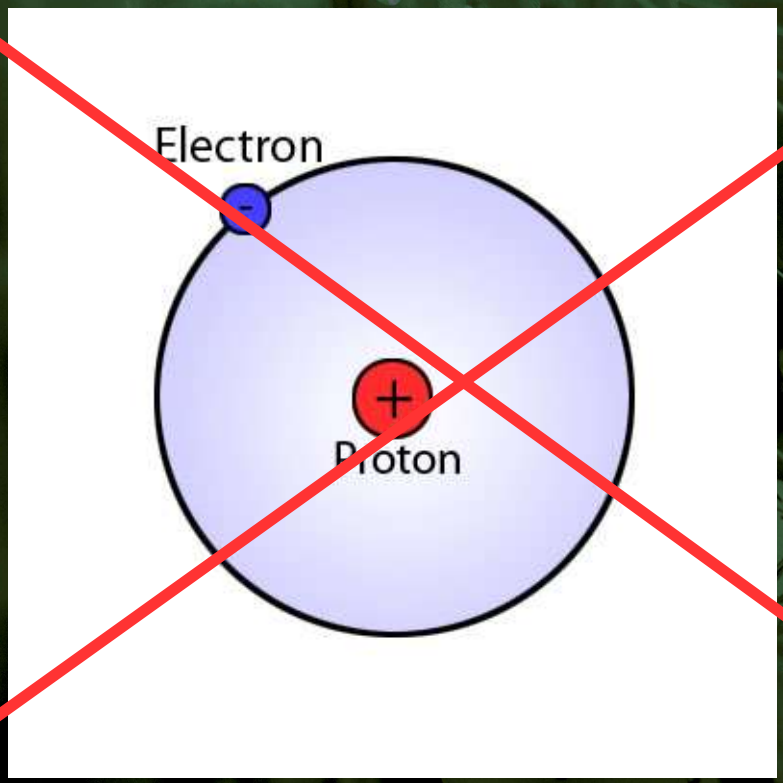
- Discrete orbits
- “Quantum leaps”

The Hydrogen Atom



The Hydrogen Atom

One Proton, orbited by *one* Electron.



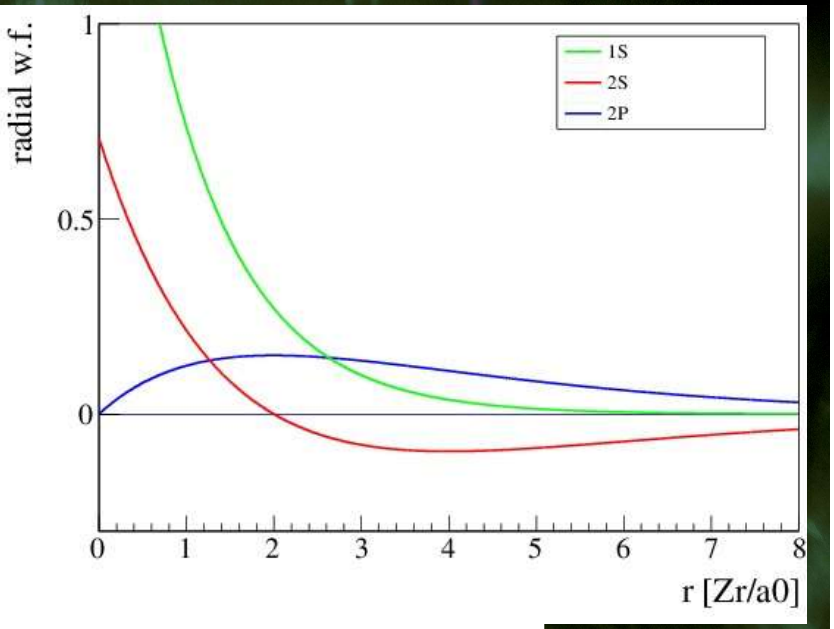
Atom is NO Planetary System.

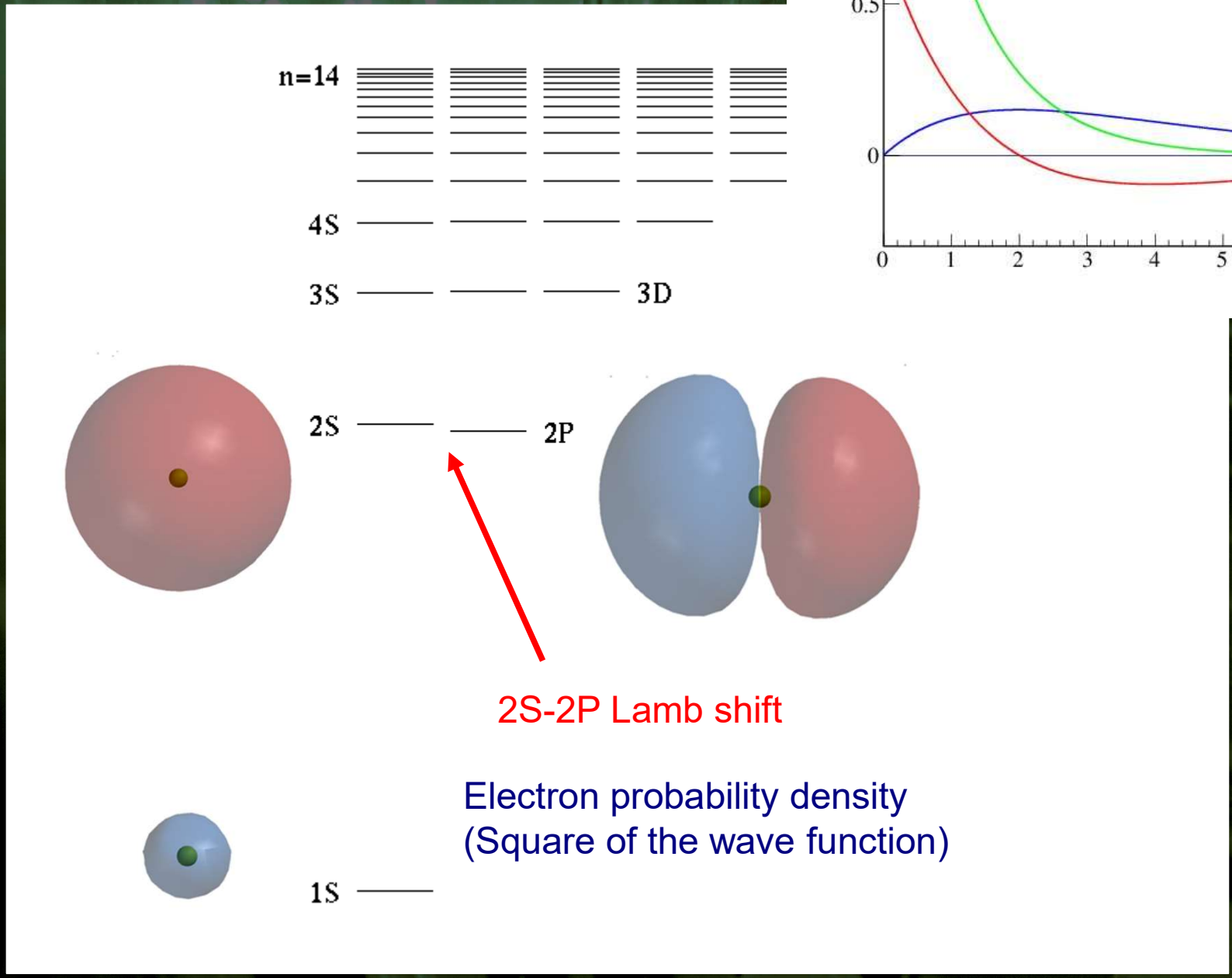
→ **Quantum mechanics**

→ **Wave functions**

→ **Probabilities**

Energy levels of

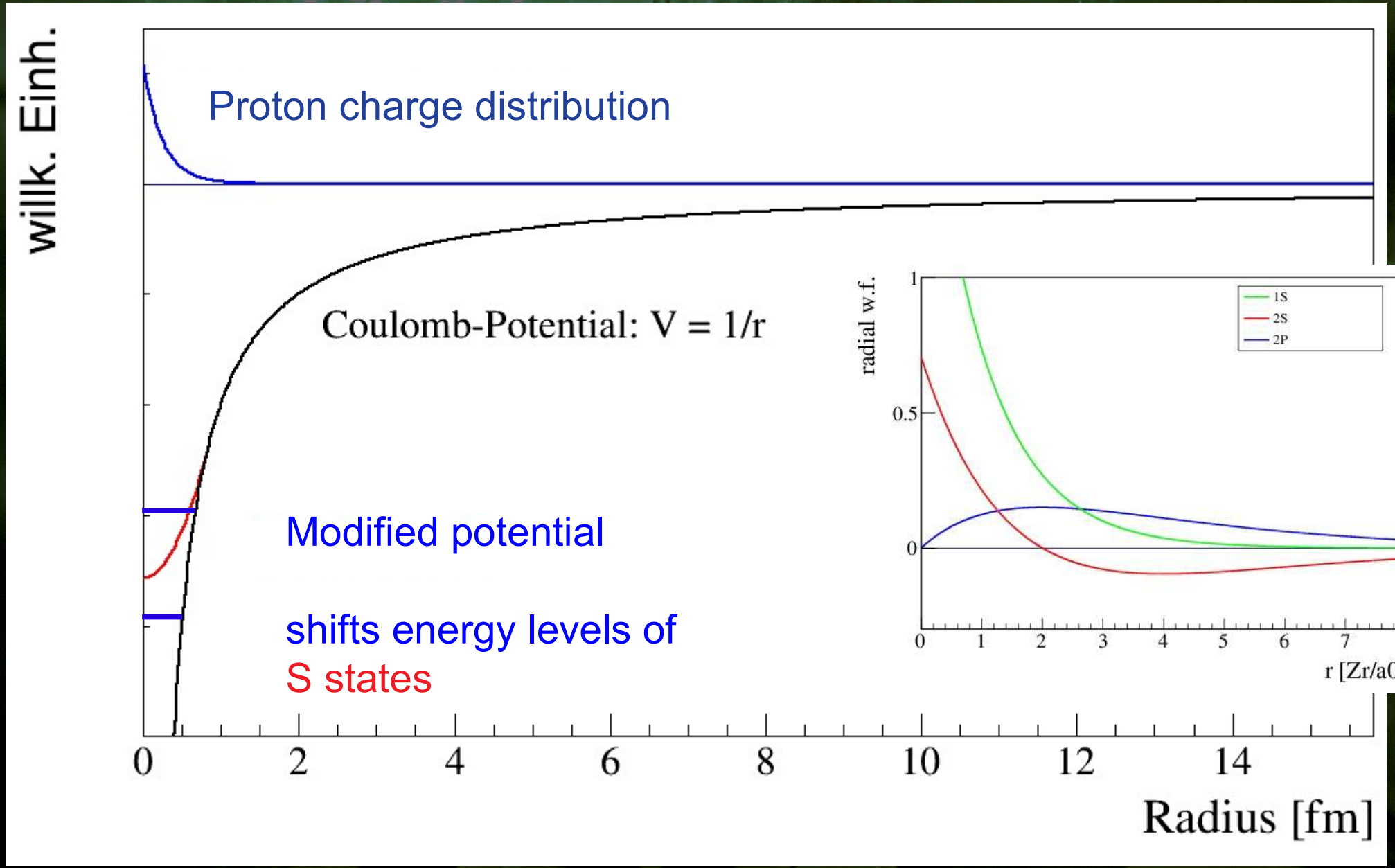




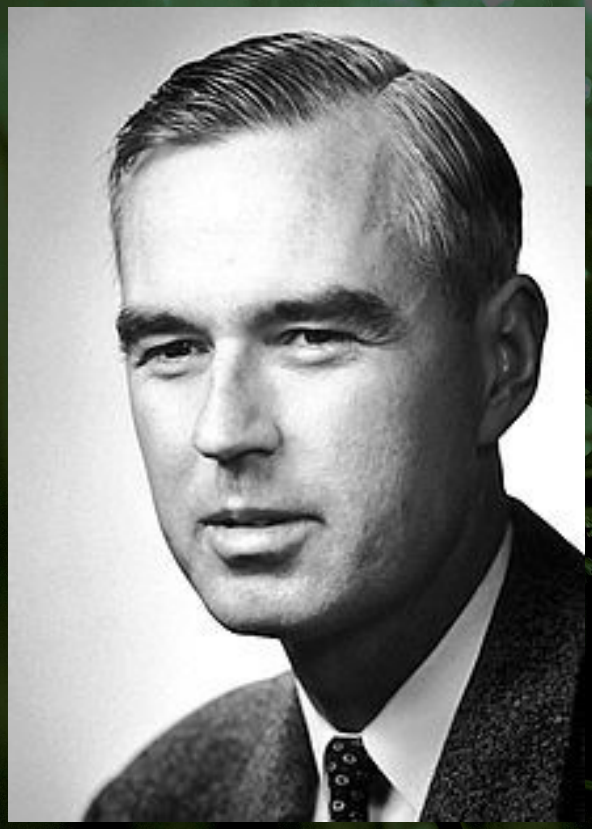
2S-2P Lamb shift

Electron probability density
(Square of the wave function)

Proton Radius and Hydrogen



The Lamb shift



Discovered 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

Willis E. Lamb, Jr.

1913 – 2008
Nobel prize 1955

→ Development of

Quantum electrodynamics(QED)

Energy levels of atomic hydrogen

Bohr & Schrödinger & Dirac & recoil & relativistic recoil

$$E = \left(-\frac{1}{n^2} - \frac{4n-3}{4n^3}\alpha^2 - \frac{2n^3+6n^2-12n+5}{8n^6}\alpha^4 \dots\right)\frac{1}{1+m_e/m_p}$$

$$+\left(\frac{1}{n^4}\alpha^2 - \frac{4n-3}{8n^6}\alpha^4 + \frac{8n^3+40n^2-72n+29}{64n^6}\alpha^6 \dots\right)\frac{m_e}{m_p}\frac{1}{(1+m_e/m_p)^3}$$

$$+\frac{2\alpha^3 m_e}{\pi n^3 m_p (1+m_e/m_p)^3}\left(-\frac{2}{3}\ln(\alpha) - \frac{8}{3}\ln k_0(n) - \frac{1}{9} + \frac{14}{3}\left(\ln(\frac{2}{n}) + \sum_{m=1}^{n}\frac{1}{m}\right.\right.$$

$$\left.\left.+1-\frac{1}{2n}\right) - \frac{2}{1-(m_e/m_p)^2}\ln(\frac{m_e}{m_p}+1) + \frac{2}{1-(m_p/m_e)^2}\ln(\frac{m_p}{m_e}+1)\right)$$

$$+\frac{2\alpha^4 m_e}{m_p n^3}\left(4\ln(2) - \frac{7}{2} - \frac{44\alpha}{60\pi}\ln(\alpha)^2\right)$$

$$N = \sqrt{n^2 - 2(n-k)(k-\gamma)}$$

$$k = j + 1/2$$

$$\gamma = \sqrt{k^2 - \alpha^2}$$

from Th. Udem

Energy levels of atomic hydrogen

Bohr & Schrödinger & Dirac & recoil & relativistic recoil & self energy & vacuum polarization & two-

$$E = \left(-\frac{1}{n^2} - \frac{4n-3}{4n^2}\alpha^2 - \frac{2n^3+6n^2-12n+5}{8n^6}\alpha^4 \ldots\right)\frac{1}{1+m_e/m_p}$$

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from Th. Udem

Fundamental constants and hydrogen spectroscopy

Hydrogen energy levels **in SI units** including relativistic, recoil, QED and finite nuclear size corrections:

$$E_{nlj} = R_\infty \left(-\frac{1}{n^2} + f_{nlj}\left(\alpha, \frac{m_e}{m_p}, \dots\right) + \delta_{\ell 0} \frac{C_{\mathrm{NS}}}{n^3} r_{\mathrm{p}}^2 \right)$$

Rydberg constant

Determined from H spectroscopy

Fine structure constant

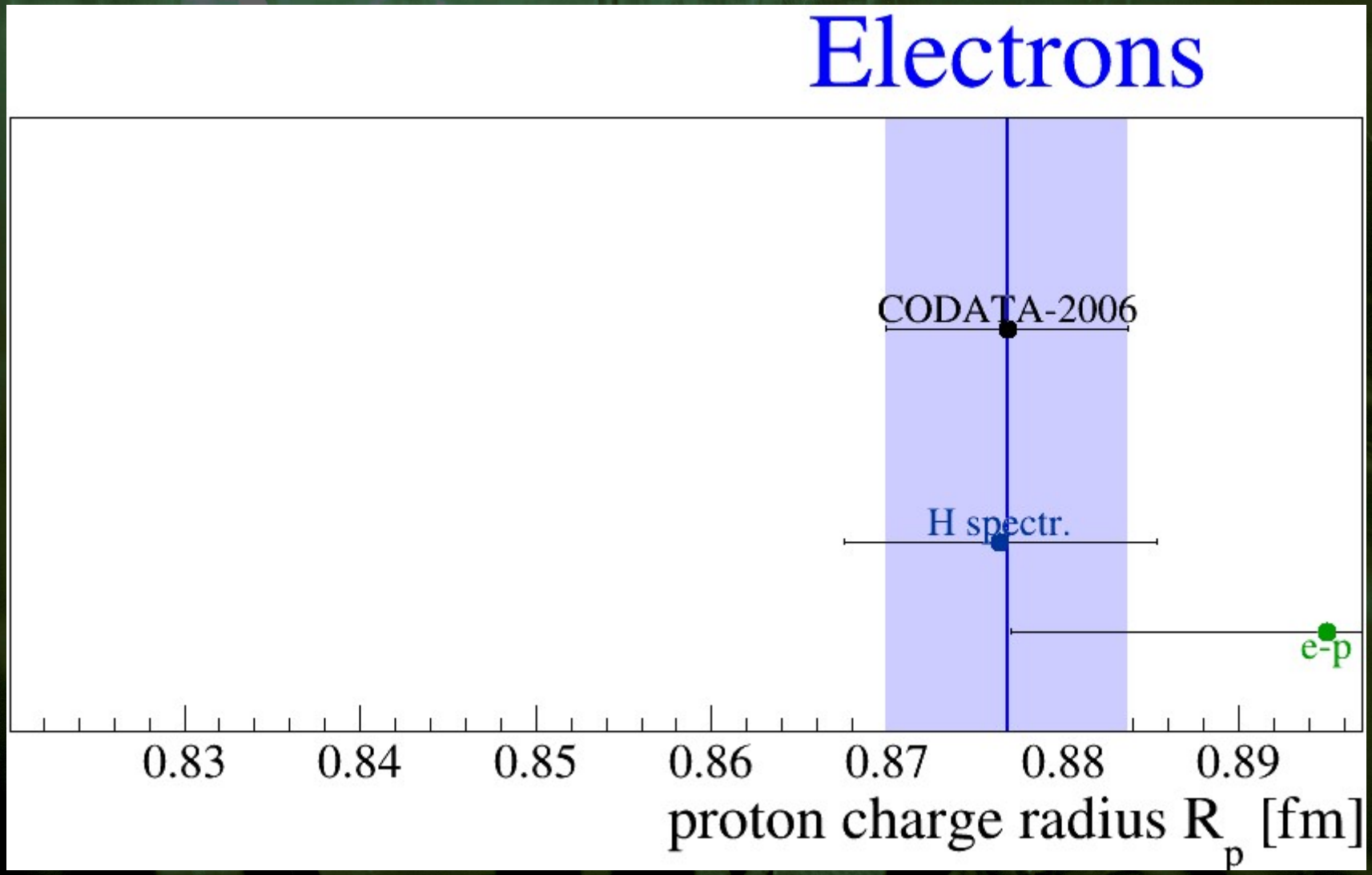
electron – proton mass ratio

Measured with high precision in Penning trap and atom interferometry experiments

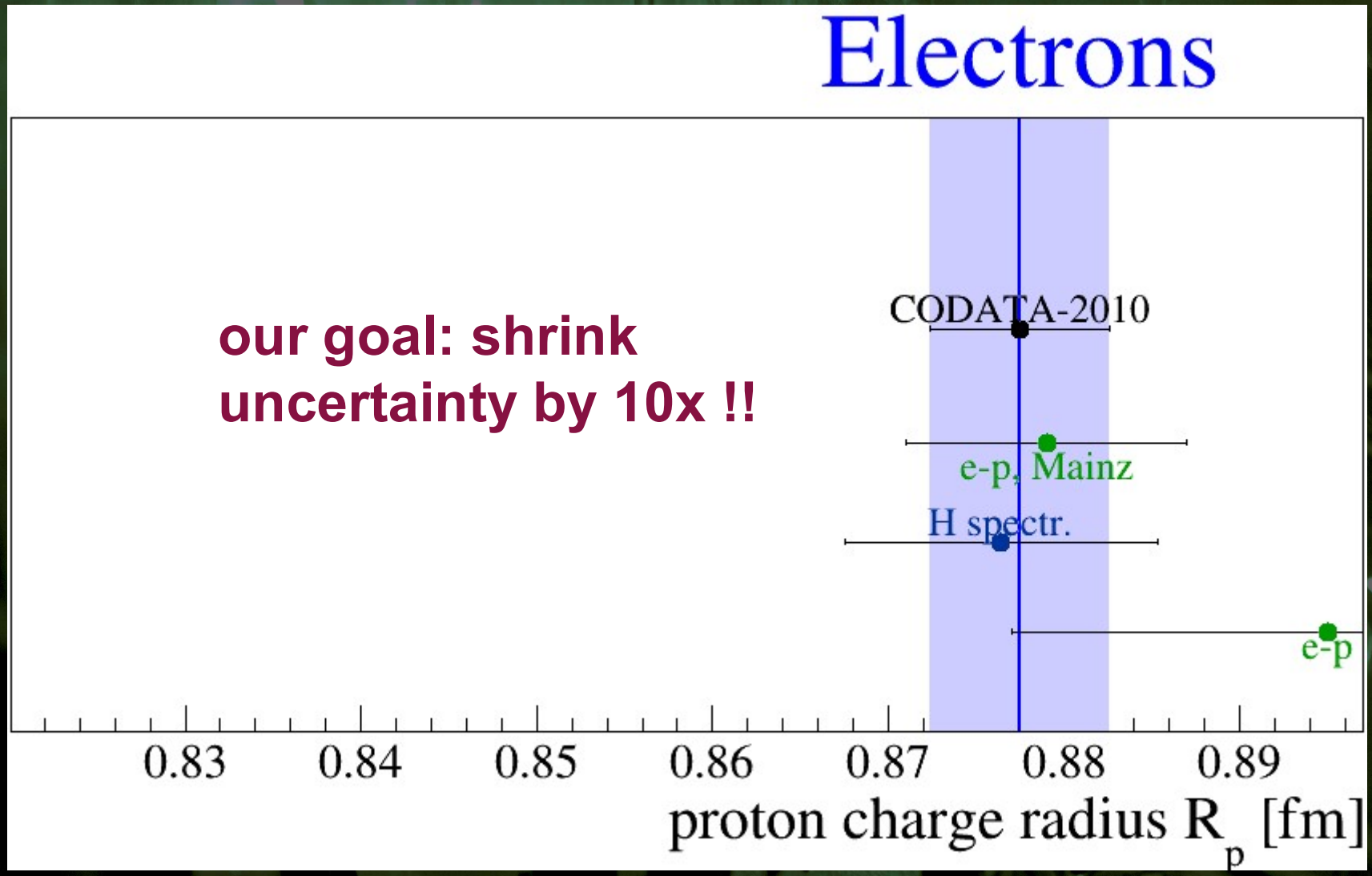
RMS proton charge radius

Determined from H spectroscopy

Proton radii

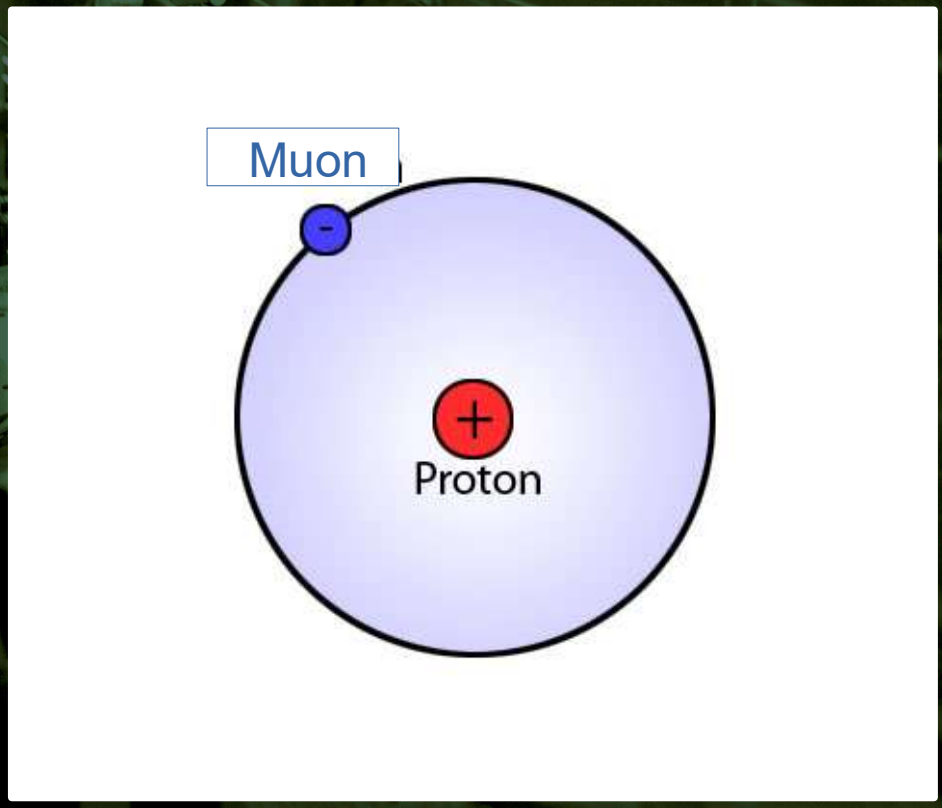


Proton radii



Muonic Hydrogen

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

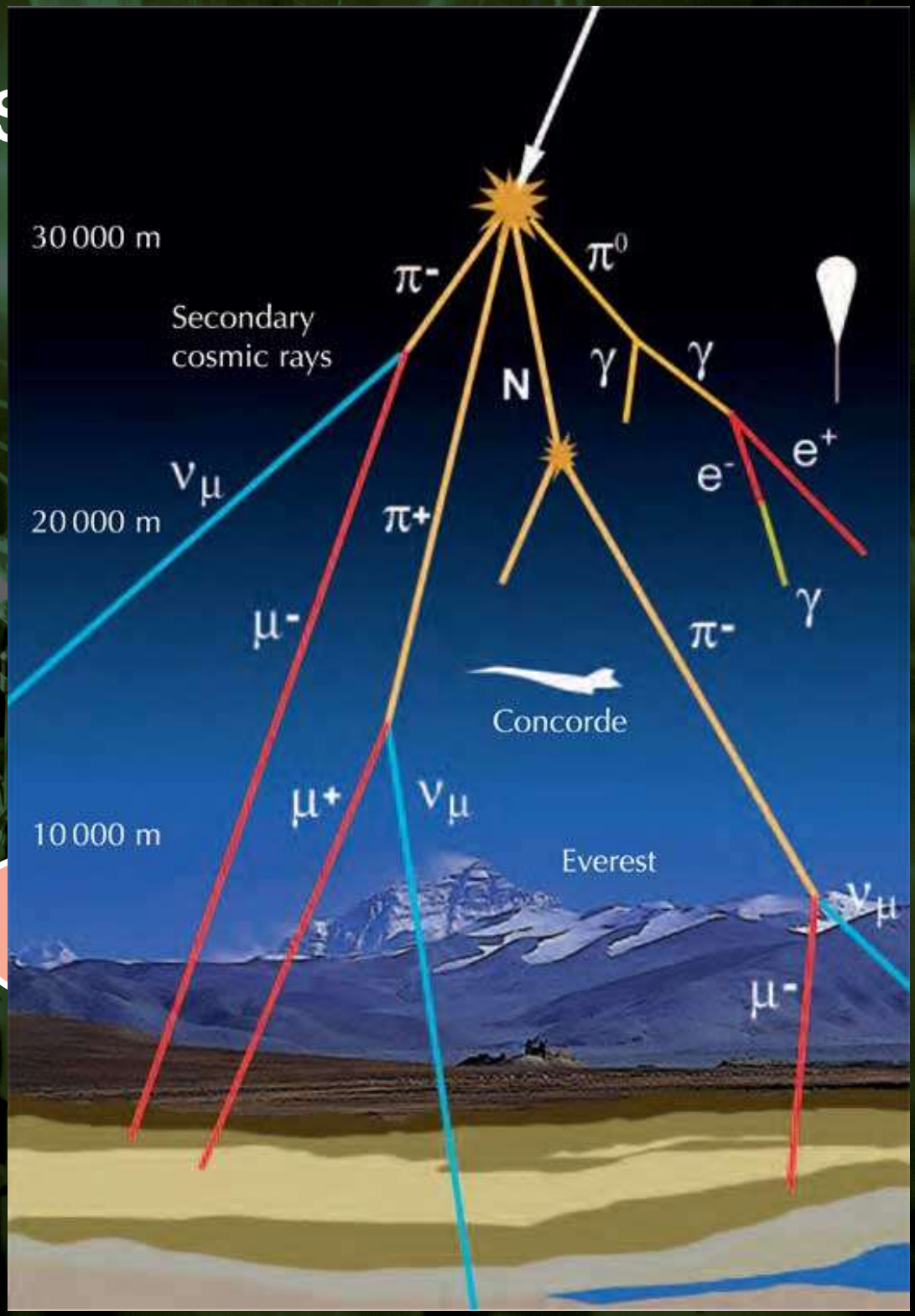


What is

Carl David Anderson

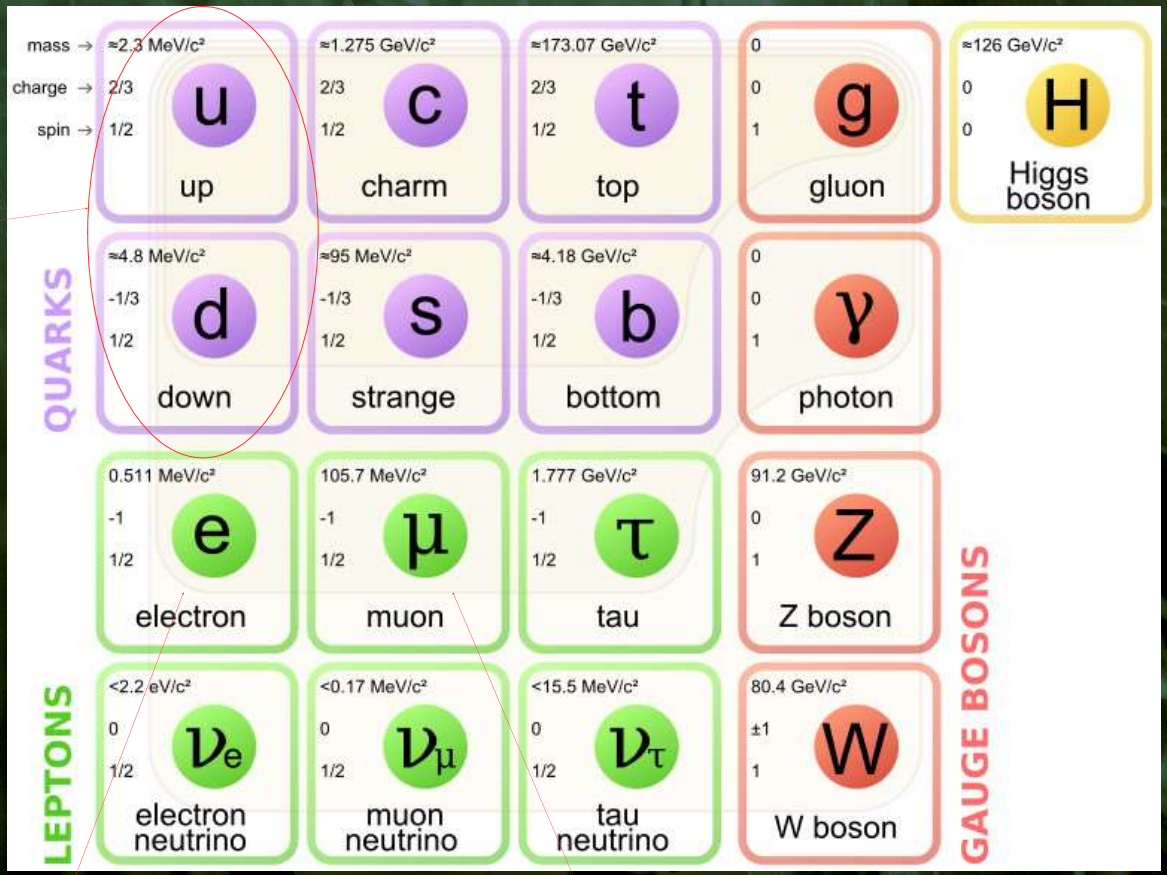
Seth Neddermeyer

Nobel prize 1936
(for the Positron!)



The muon and its place in the world

Standard Modell of Particle Physics



Proton

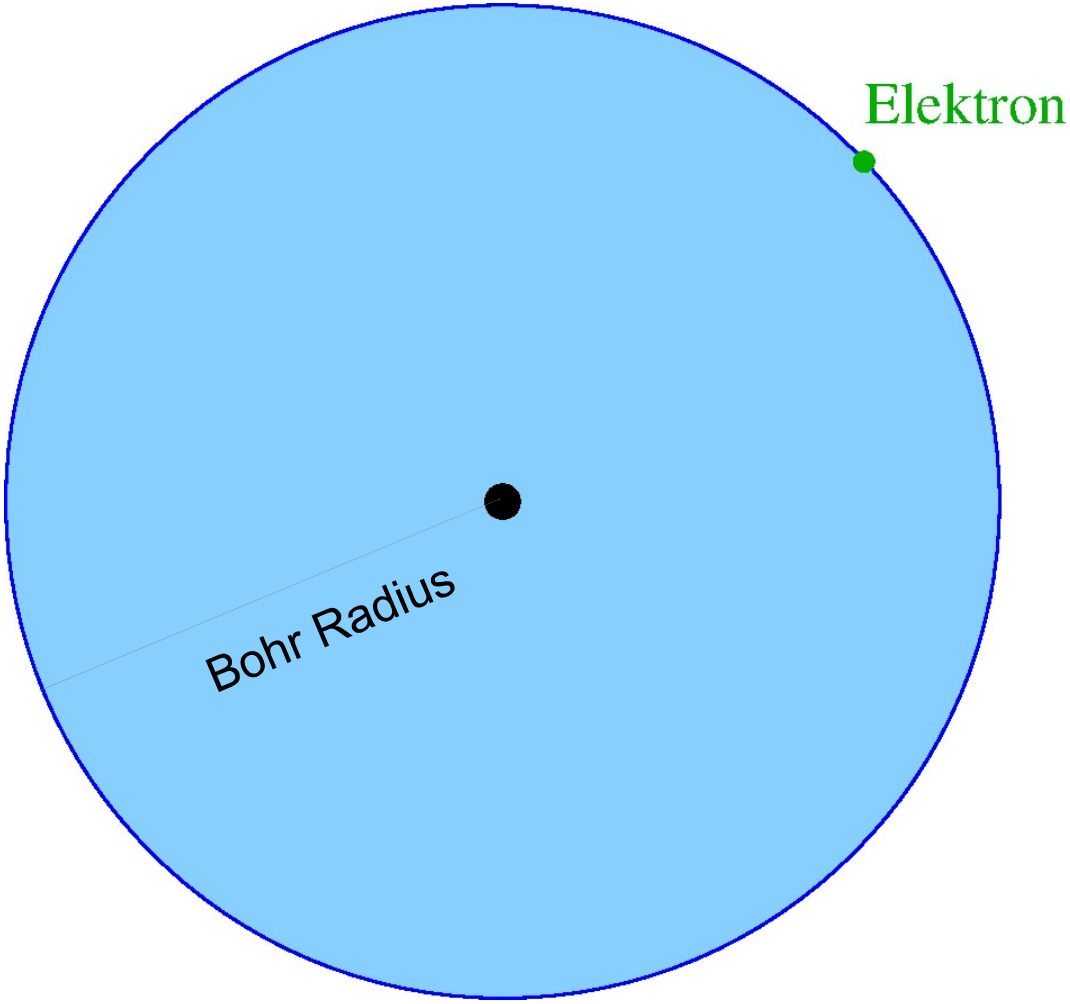
Electron

Muon

Normal and muonic hydrogen

normal hydrogen:

Proton + Electron



muonic hydrogen:

Proton + Muon

Mass = **200** * Electron mass

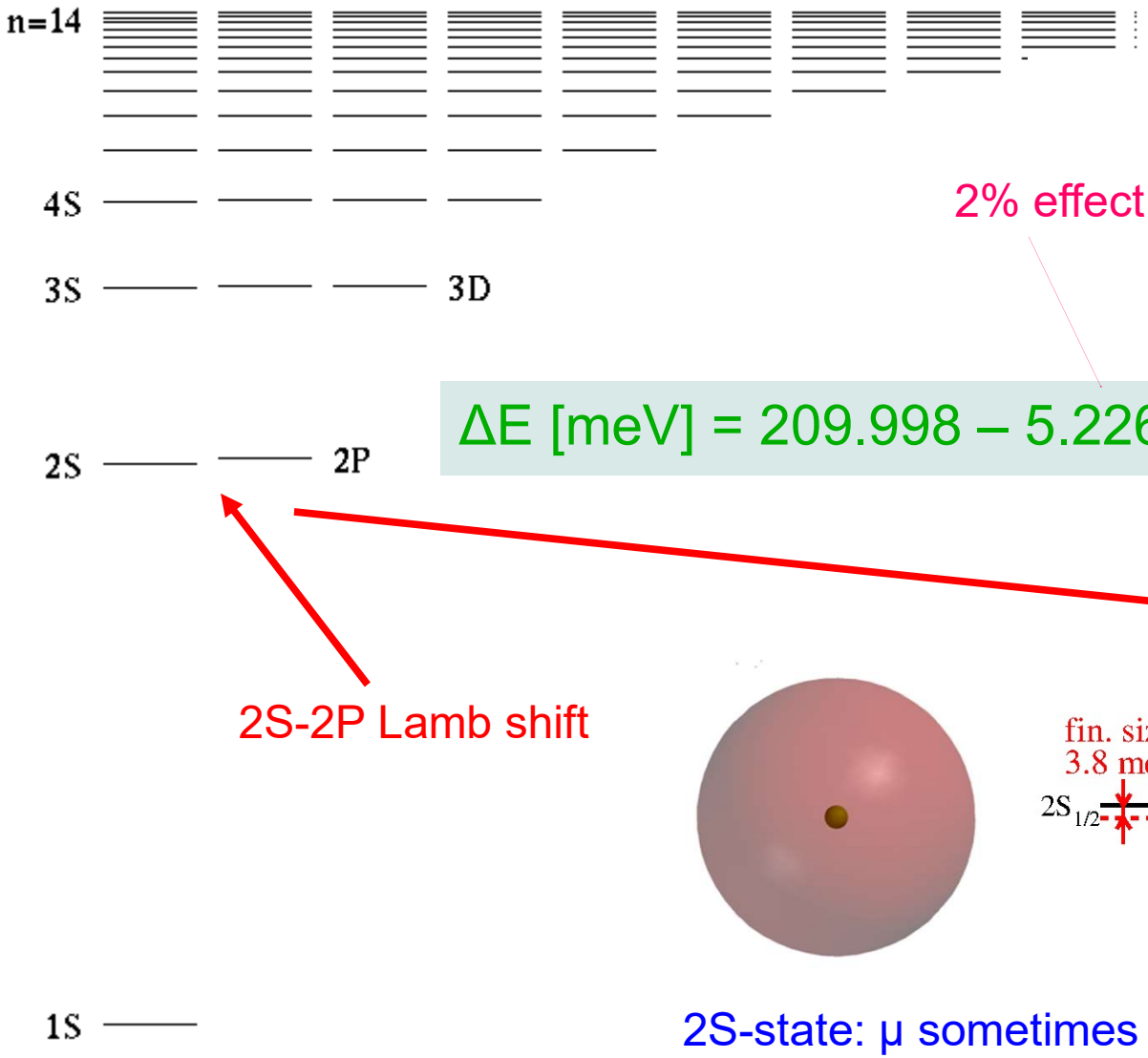
Bohr **Radius** = **1/200** of hydrogen

200^3 = 10 Million

times more sensitive

To the size of the proton

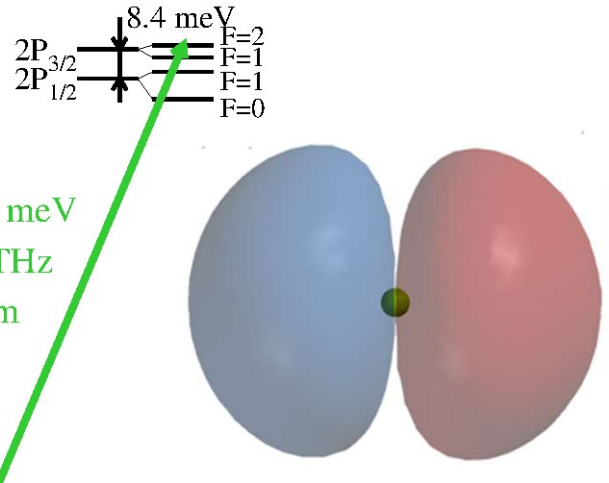
Muonic Hydrogen



2% effect!

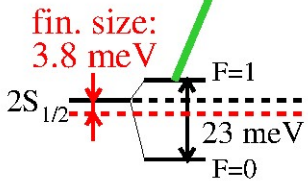
$\Delta E\ [meV] = 209.998 - 5.226\ R_p^2$

206 meV
50 THz
6 µm



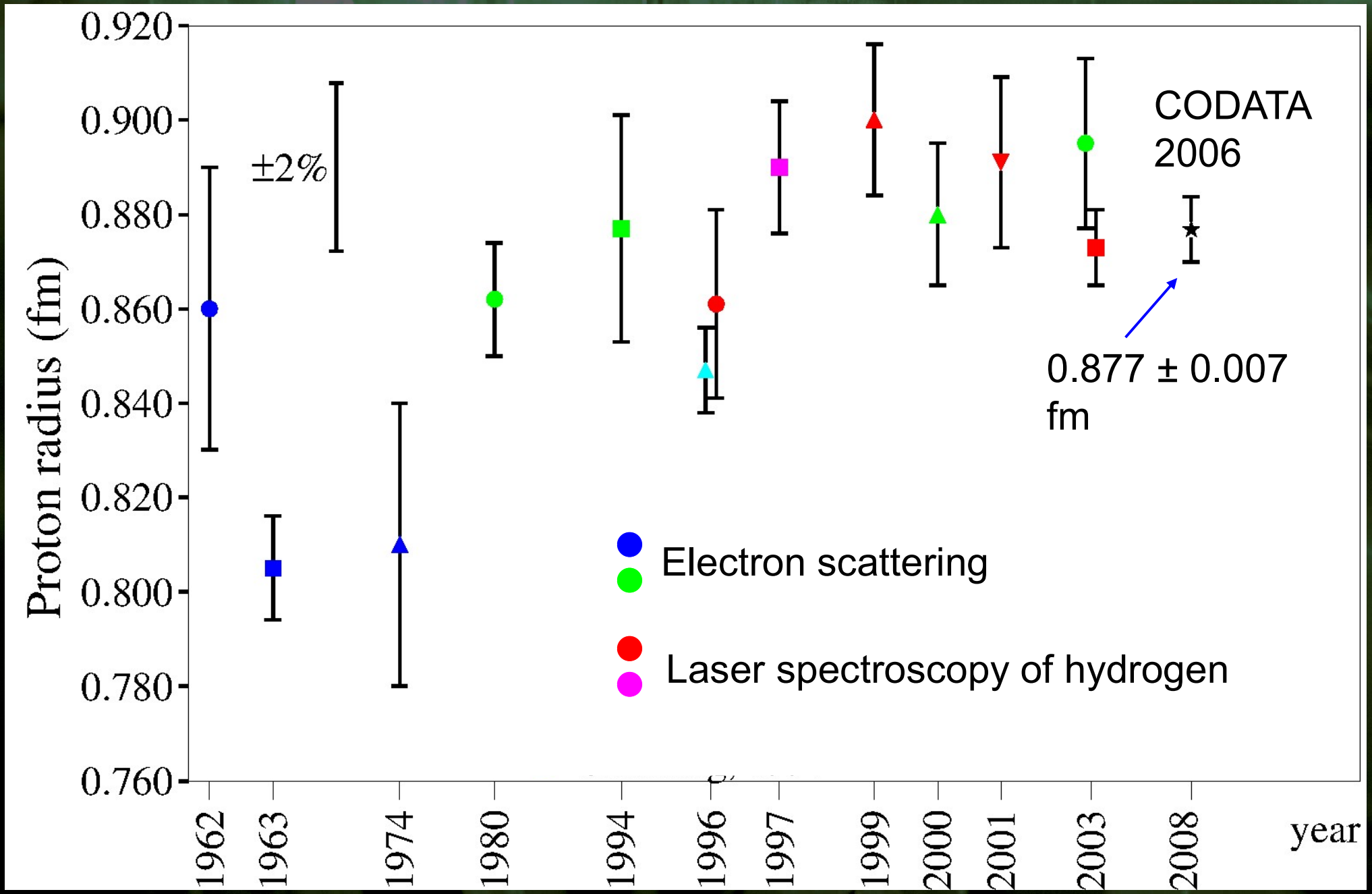
2P-state:
µ not inside proton
Level unaffected.

2S-2P Lamb shift

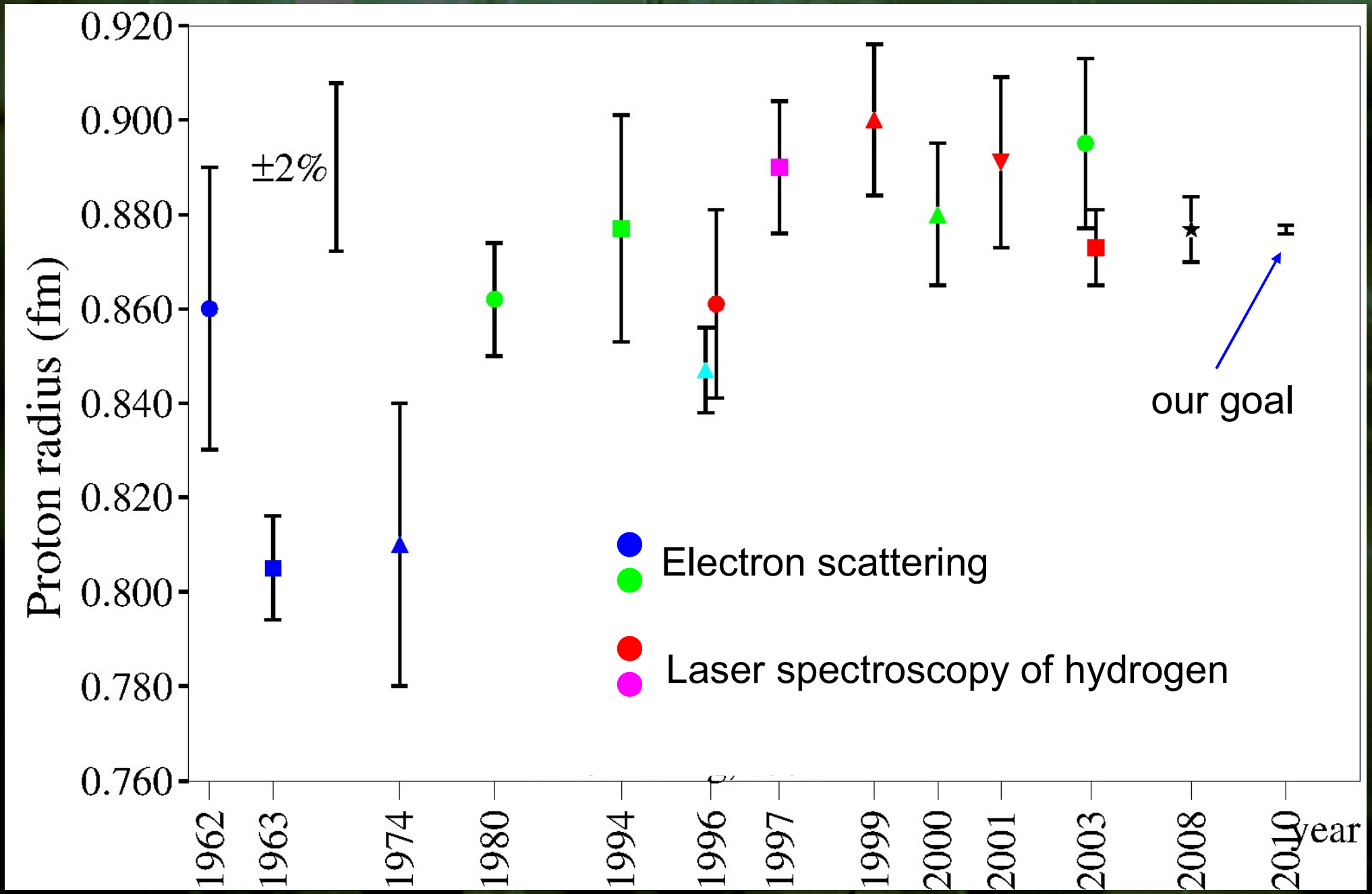


2S-state: µ sometimes inside the Proton!
Level sensitive to Proton Size

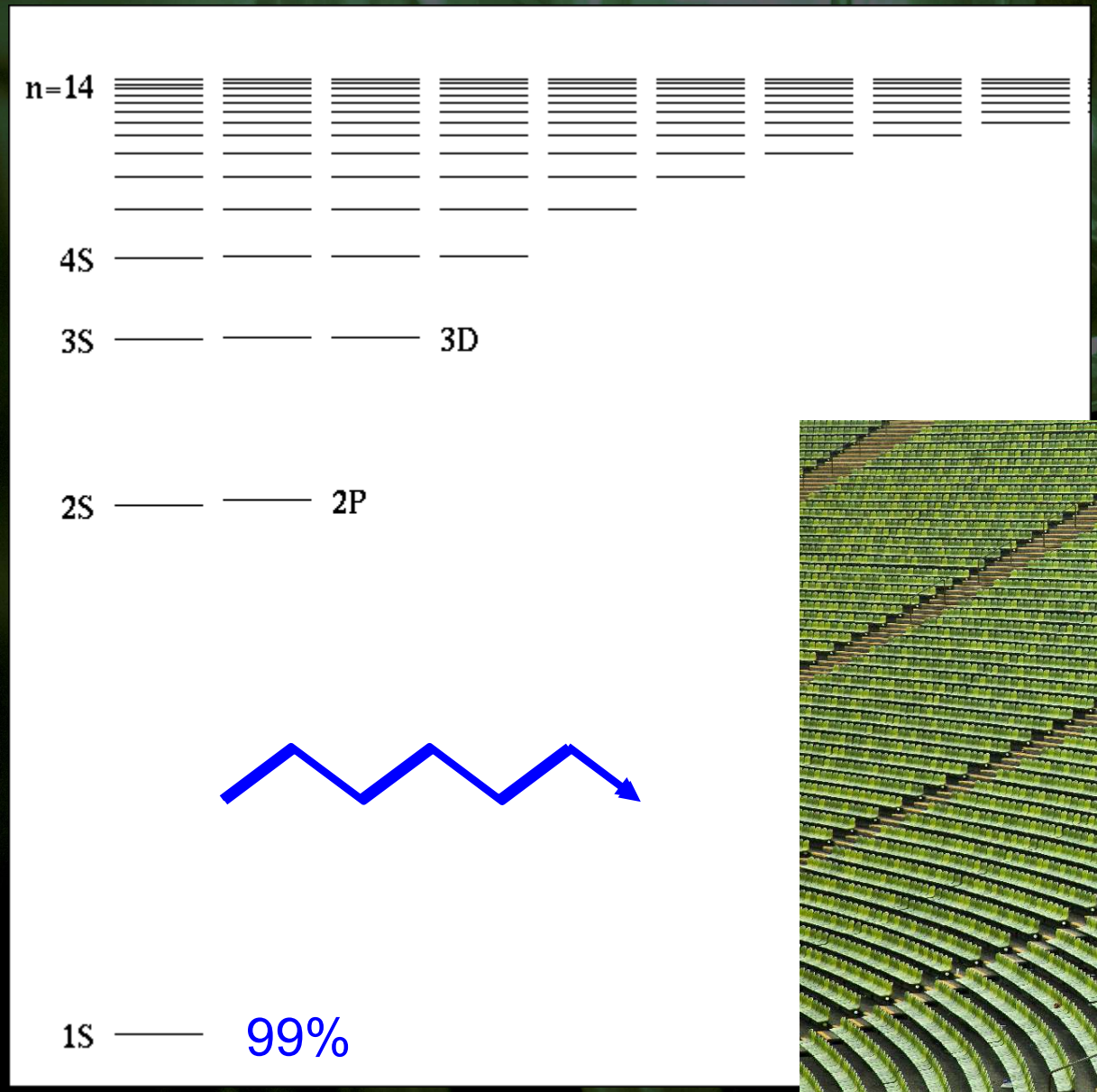
How large is a Proton?



How large is a Proton?

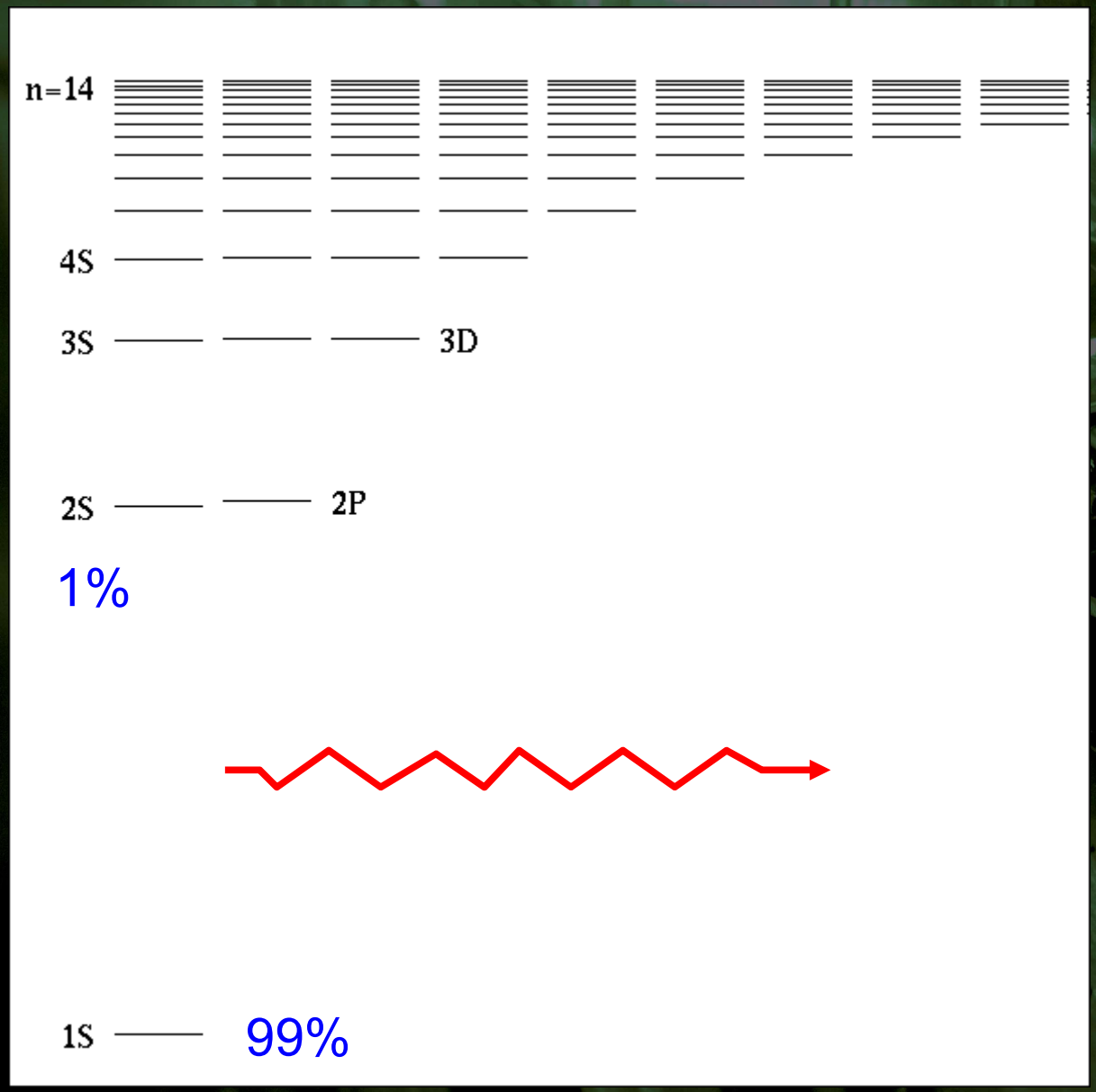


Measurement Principle



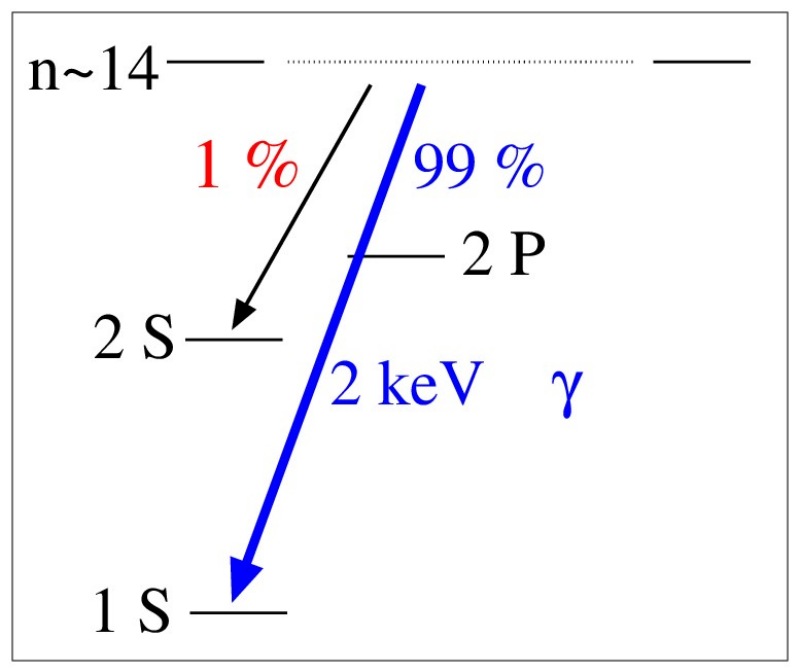
* Muons stop in H_2
* Capture into high states with n~14
* Cascade to lower n

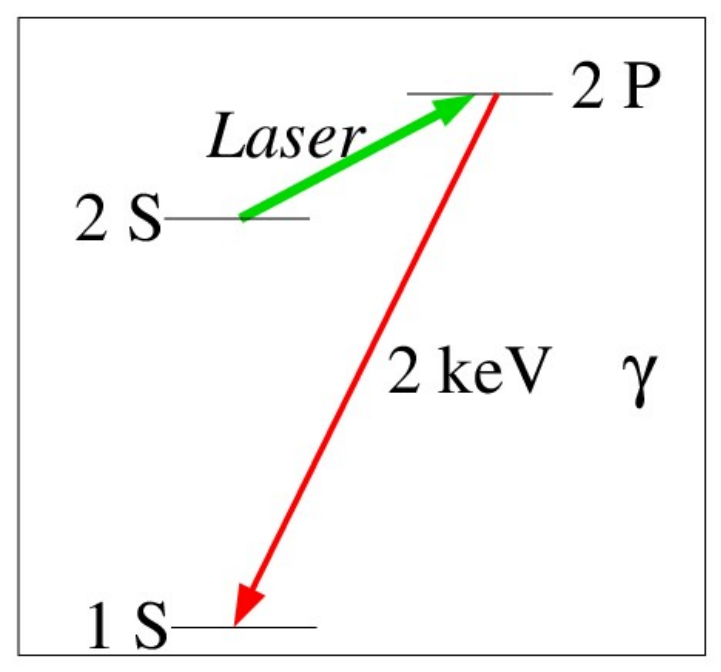
Measurement Principle



* Muons stop in H_2
* Capture into high states with n~14
* Cascade to lower n
* 1% end in long-lived 2S state
* Laser on resonance

Measurement Principle





"prompt" (t=0):

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

→ "prompt" X-ray photons

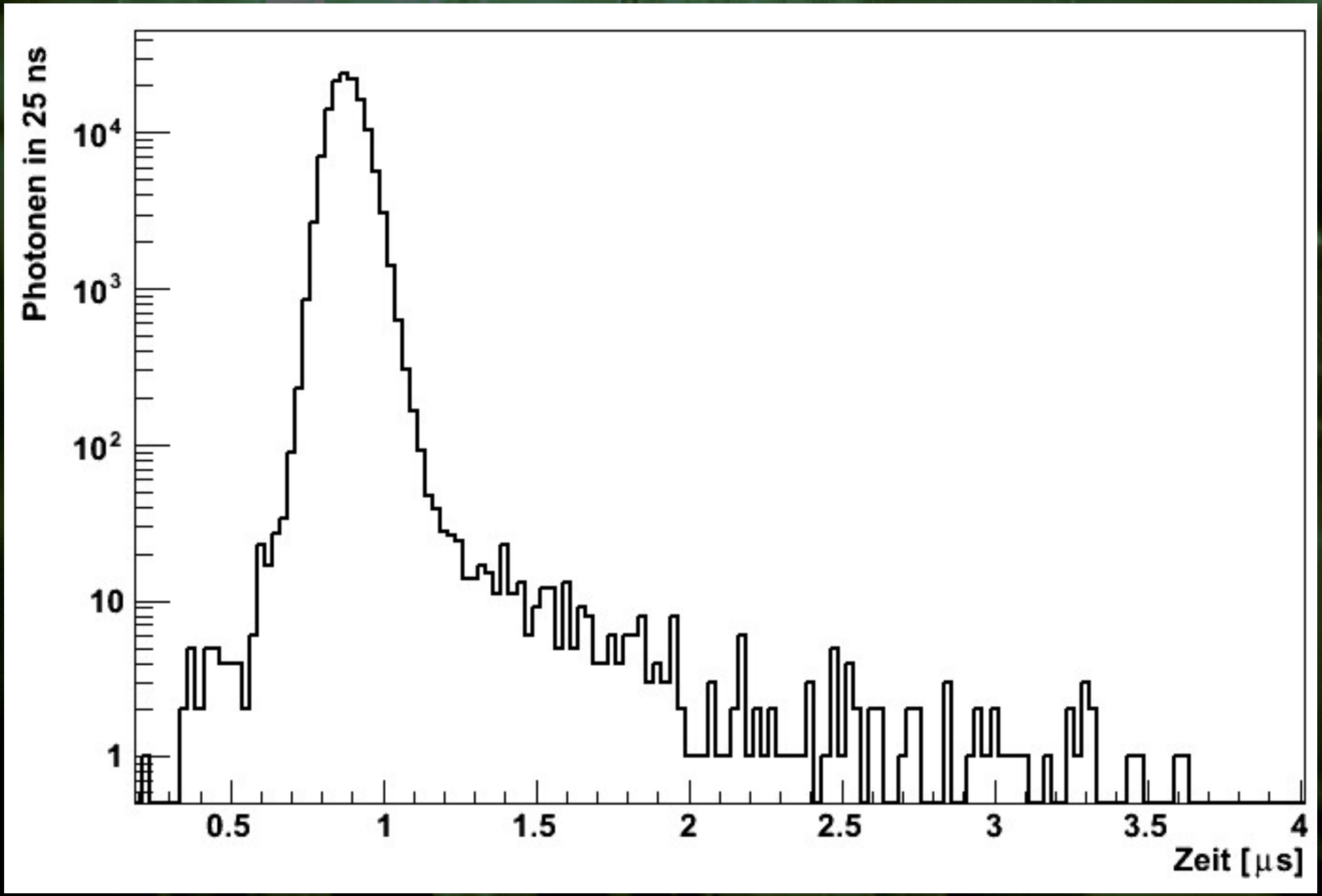
"delayed" (t ~ 1μs):

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

→ "delayed" X-ray photons

Time Spectra

13 hours of data



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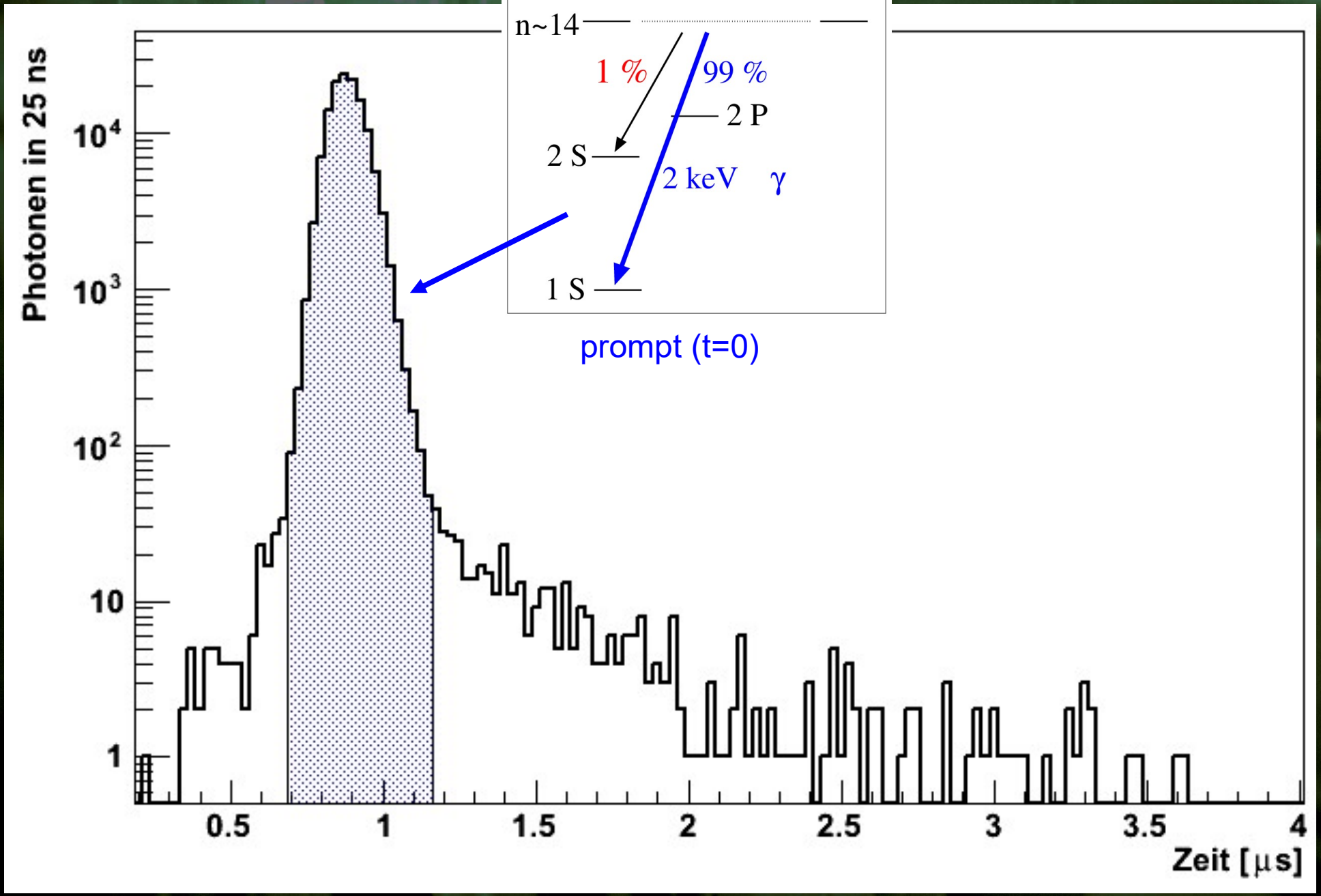

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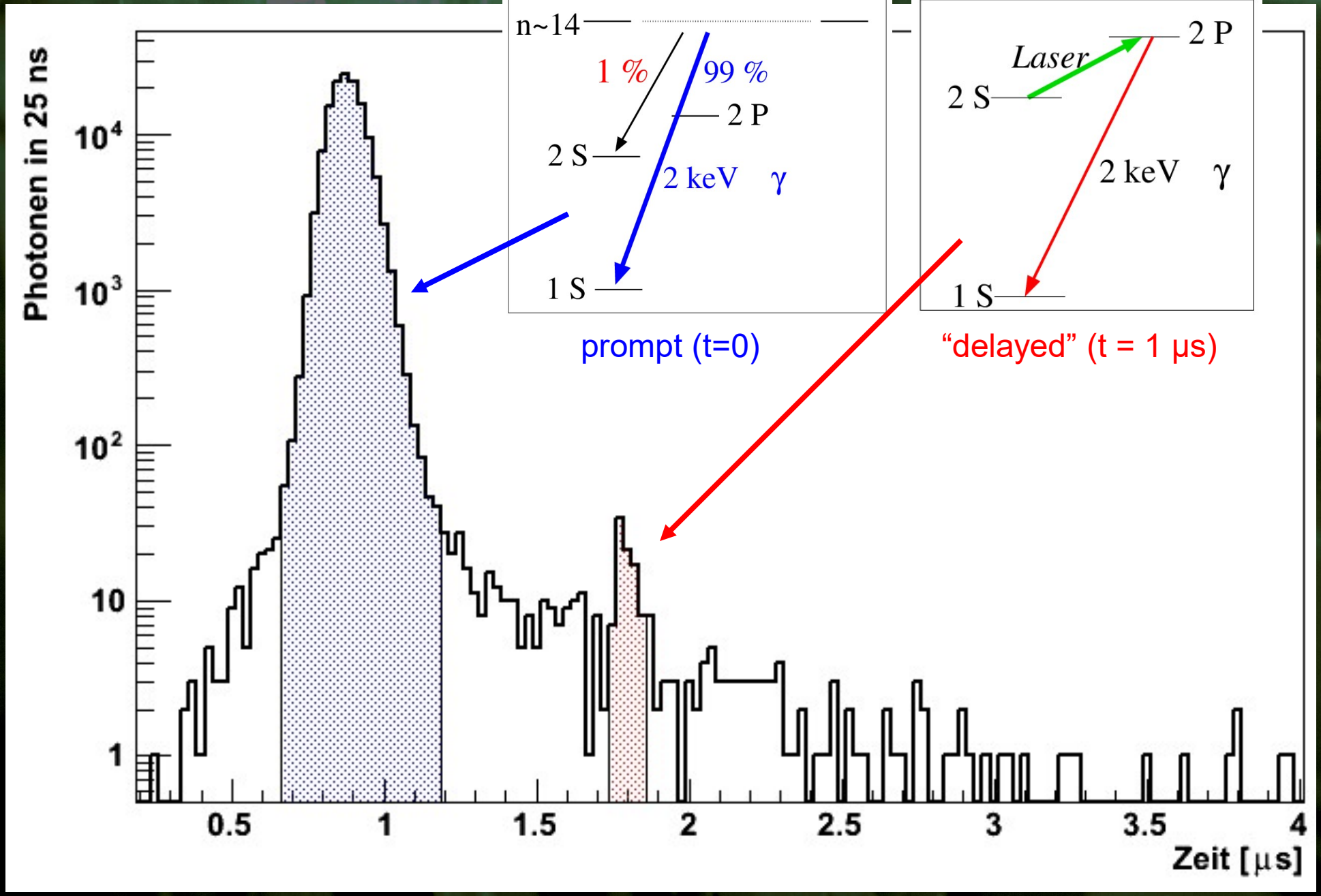
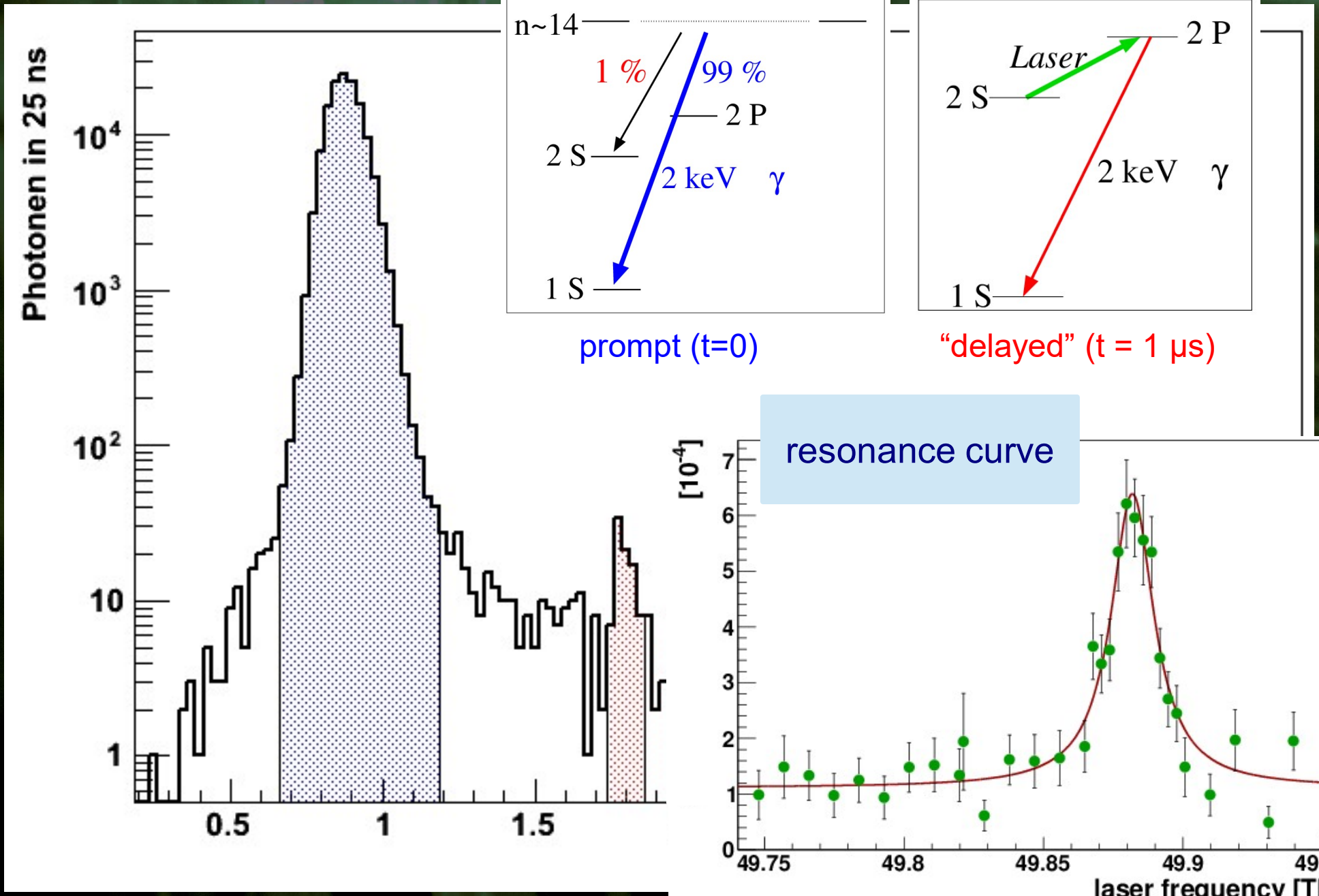
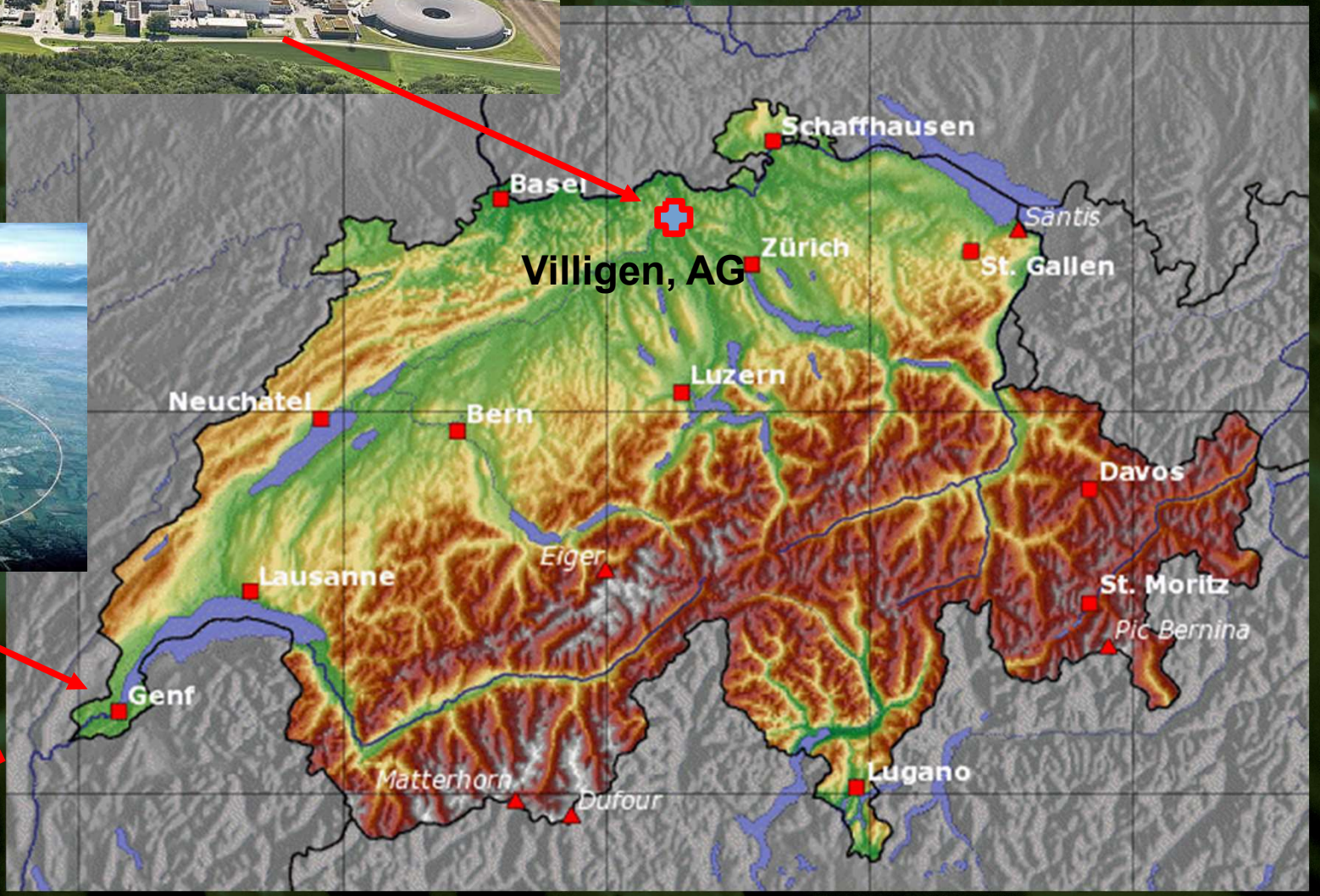


Time Spectra



The accelerator at PSI

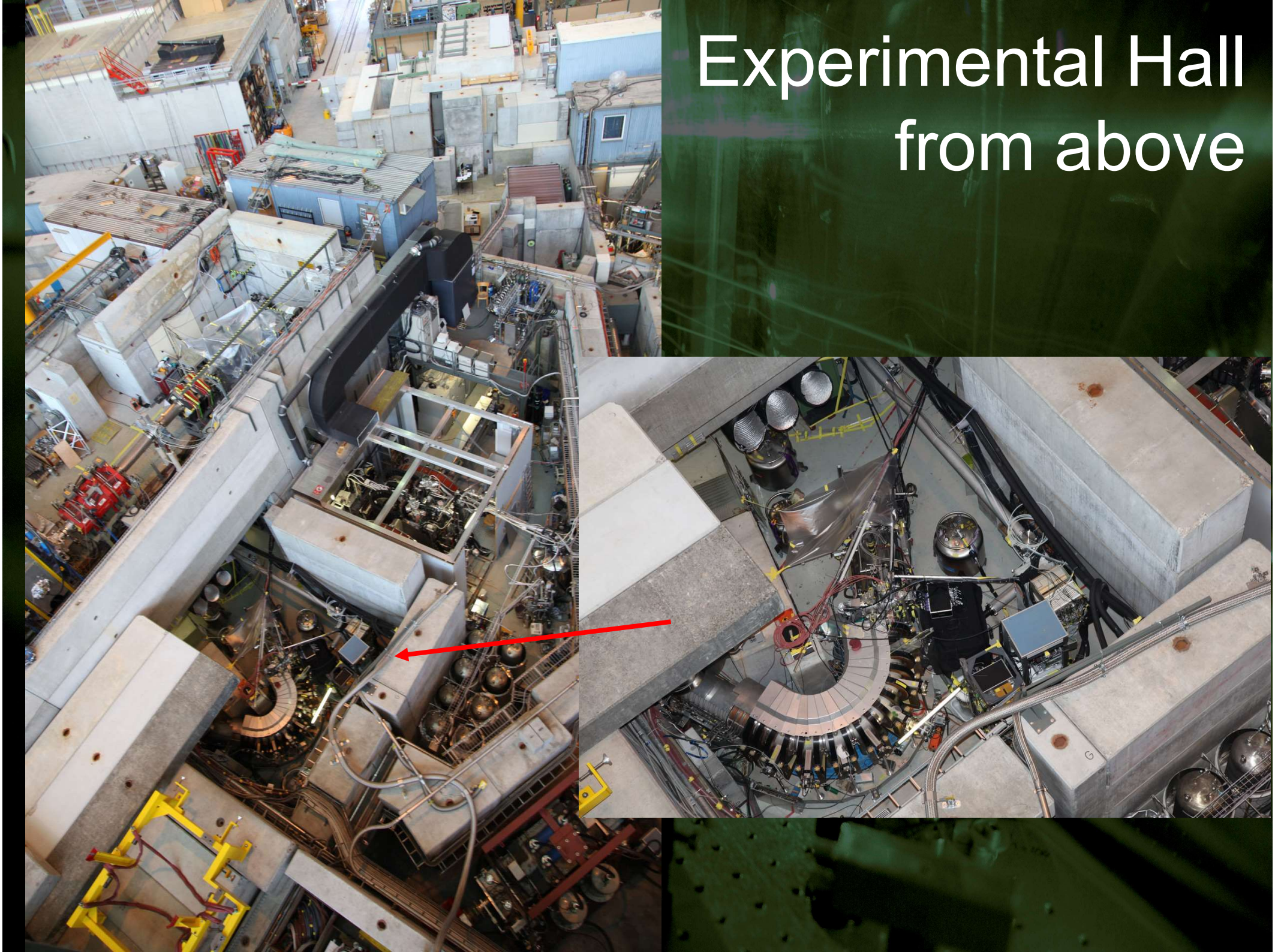
PAUL SCHERRER INSTITUT
PSI



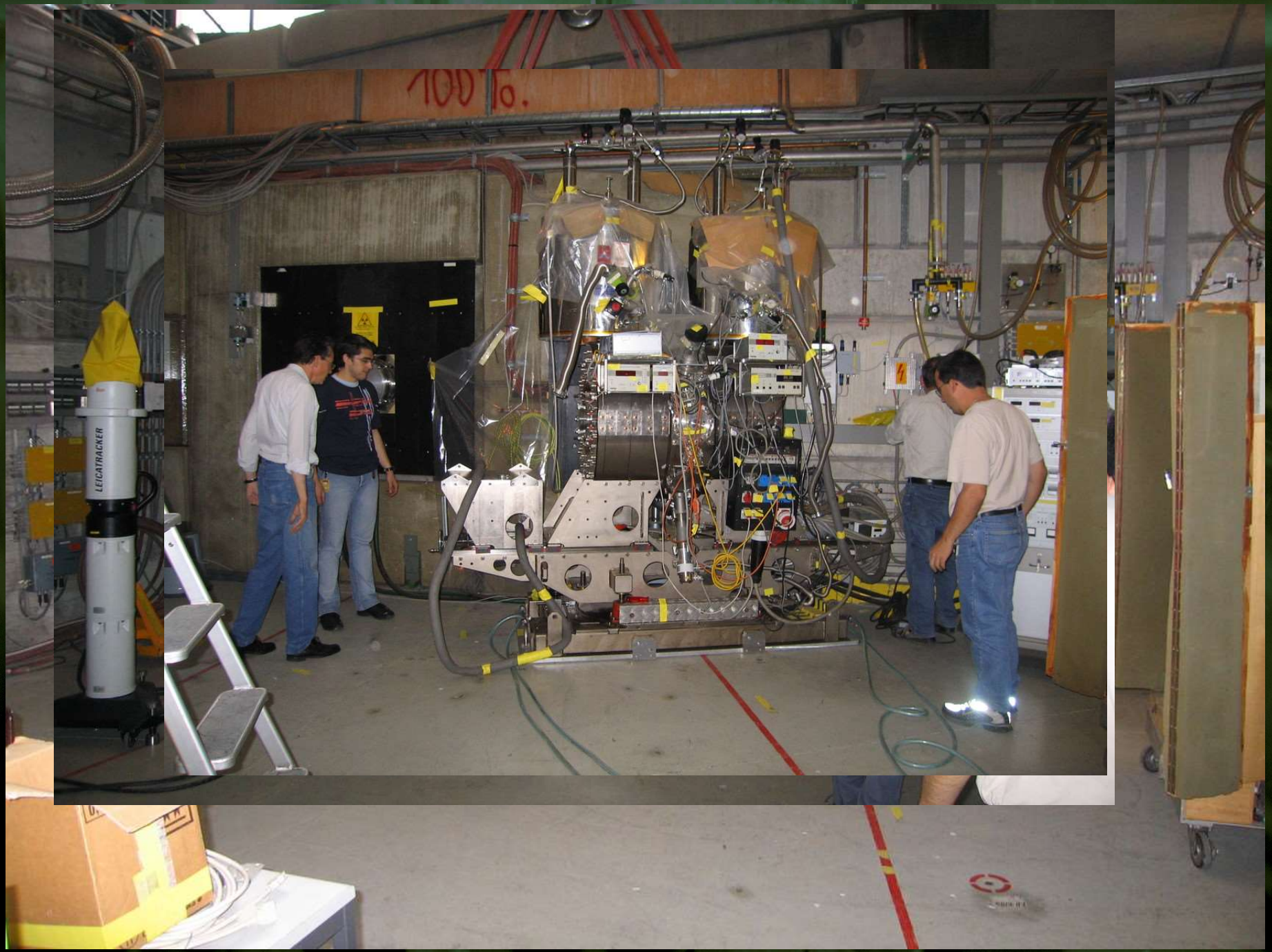
Paul Scherrer Institute

Experimental Hall

Experimental Hall from above

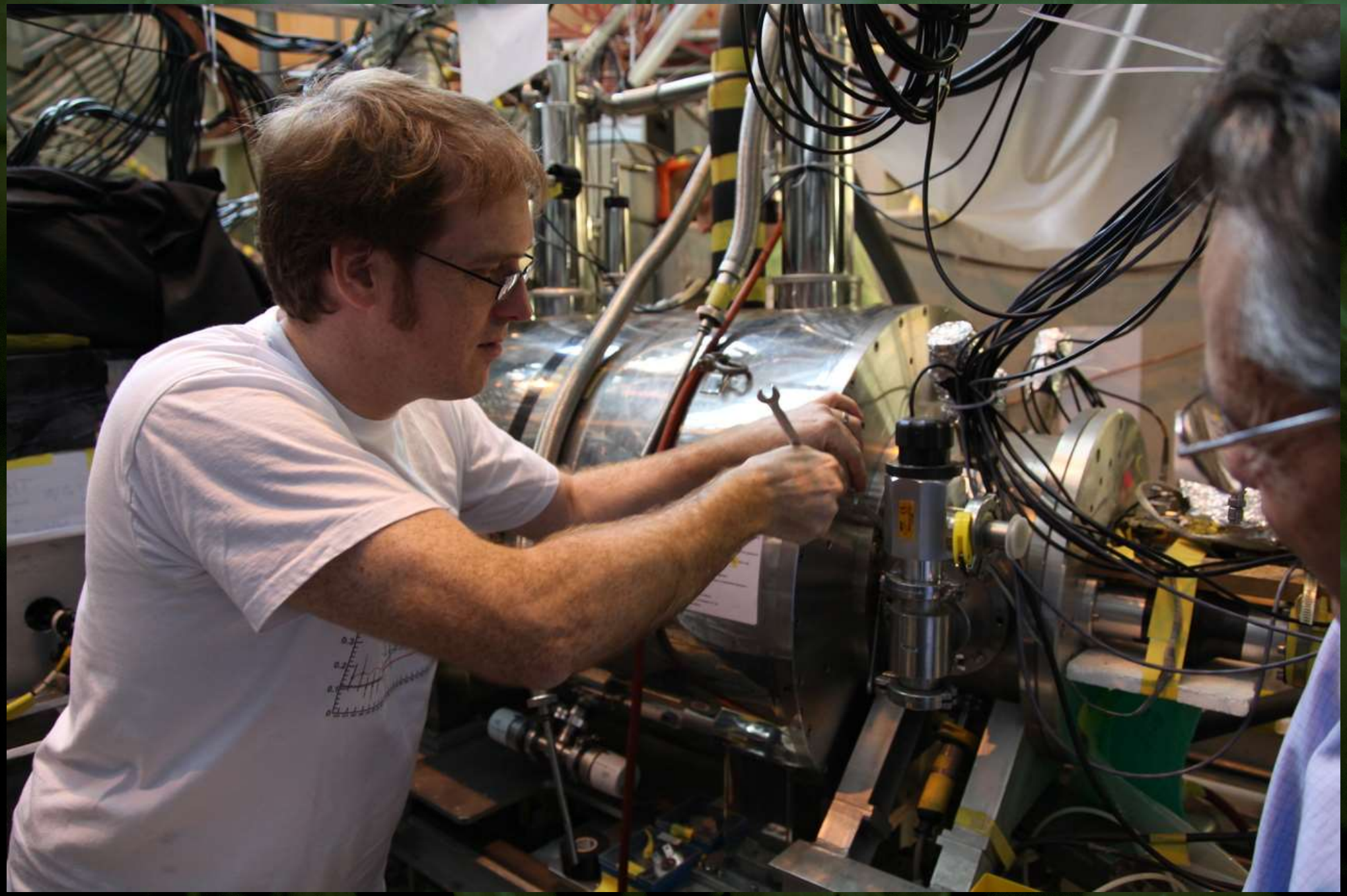


Muon Beam Line πE5

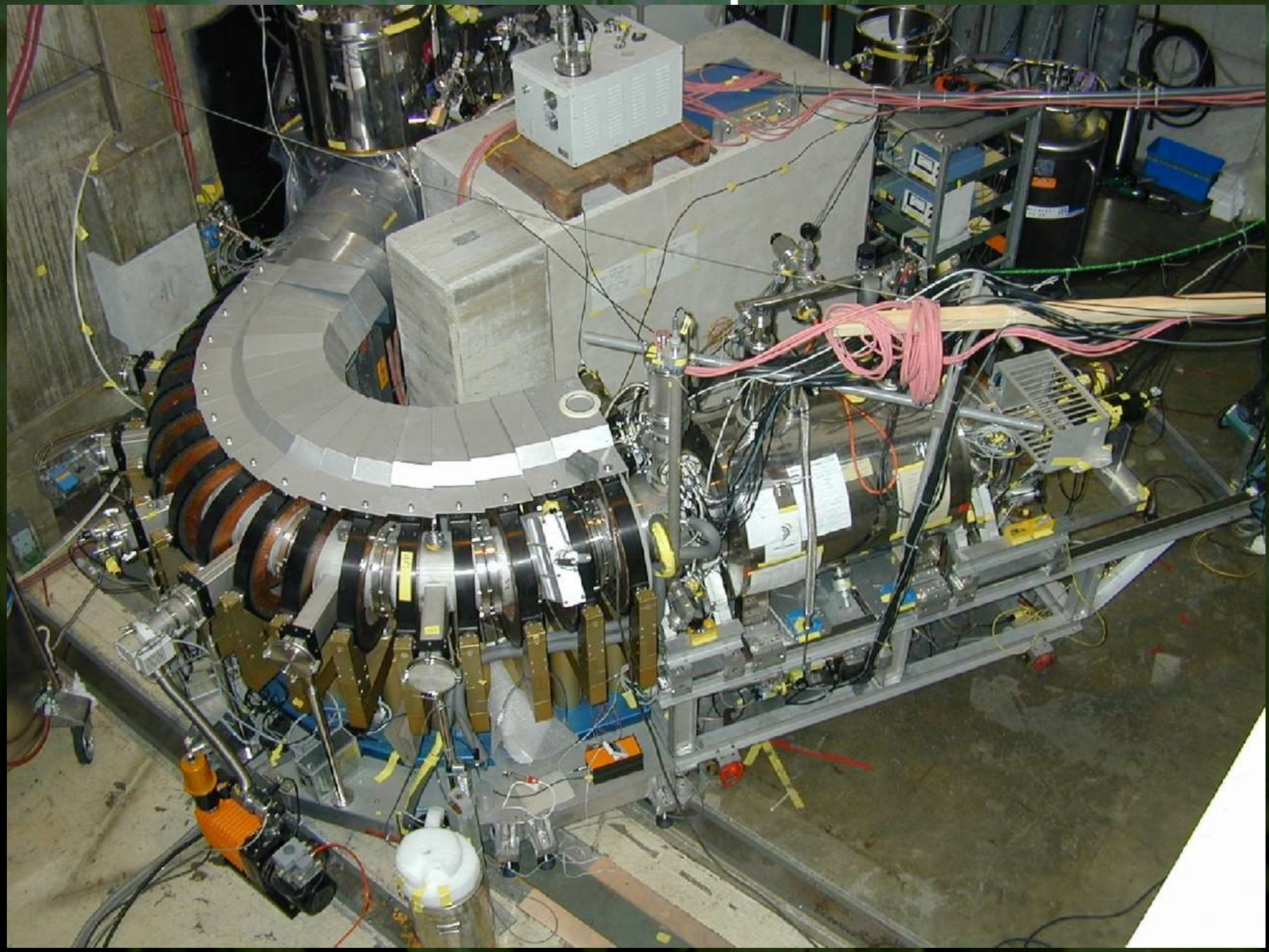


MEK in πE5

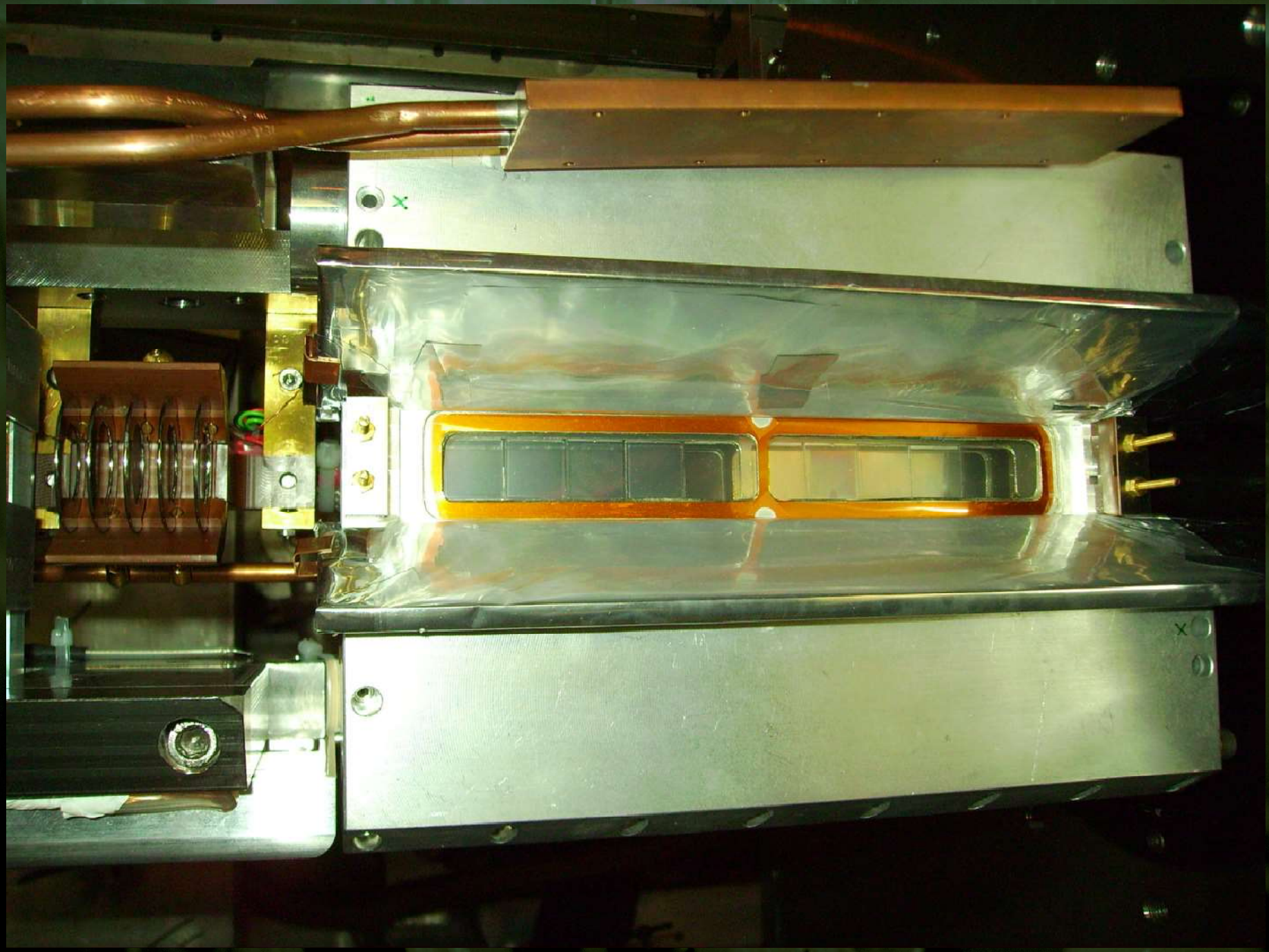
Getting ready….



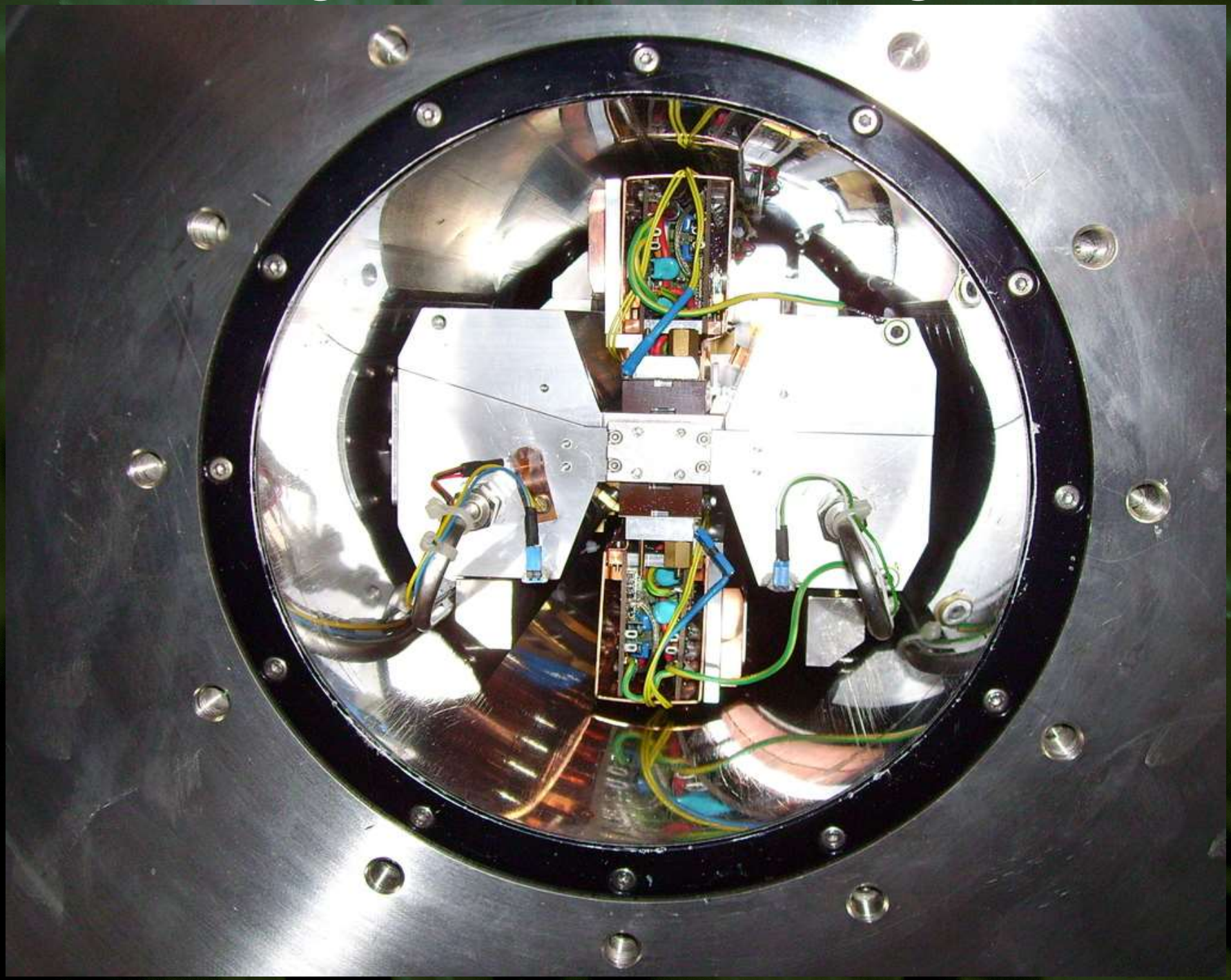
Muon Beam Setup inside πE5

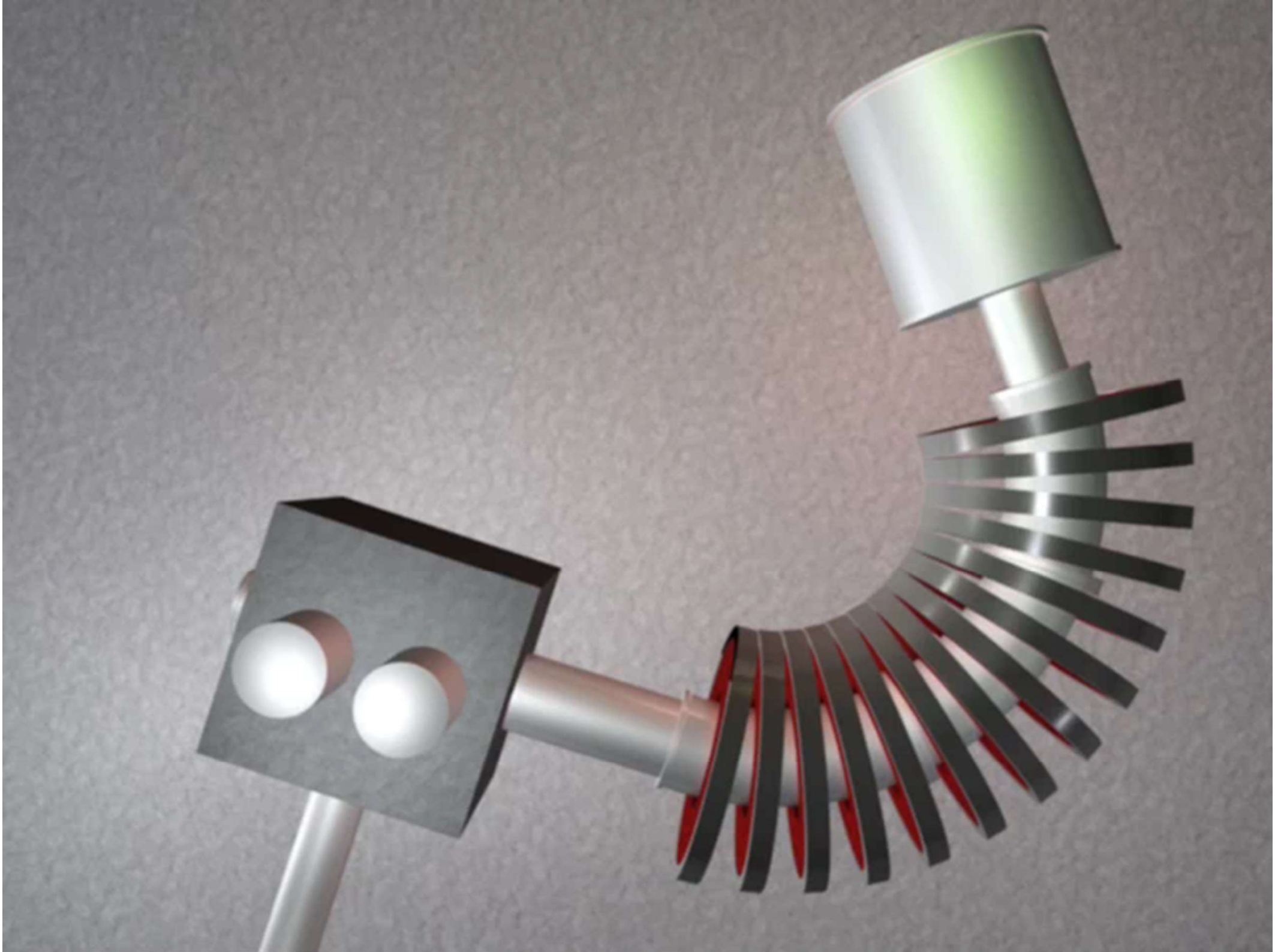


The Hydrogen Target

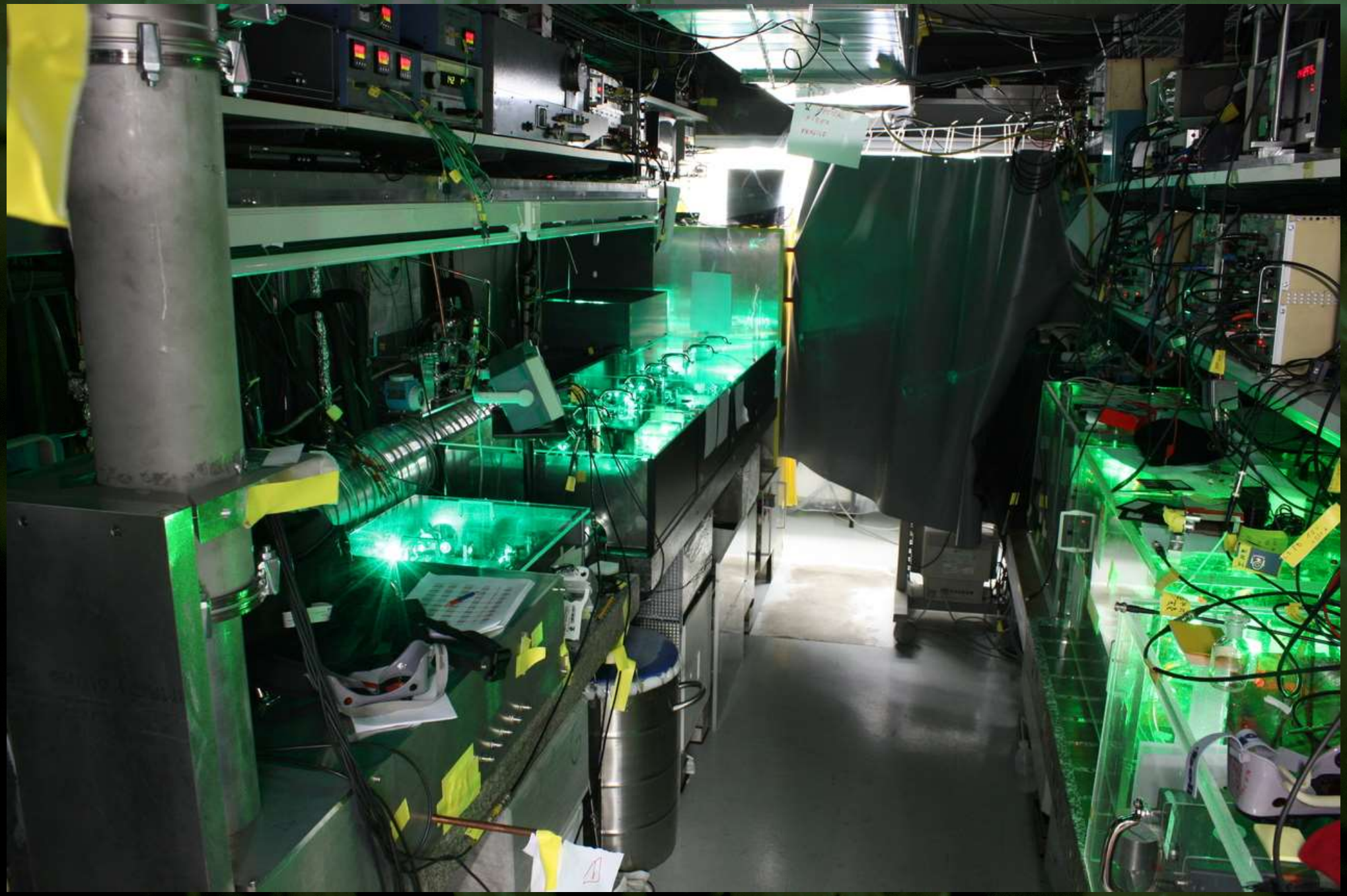


Target inside 5T magnet

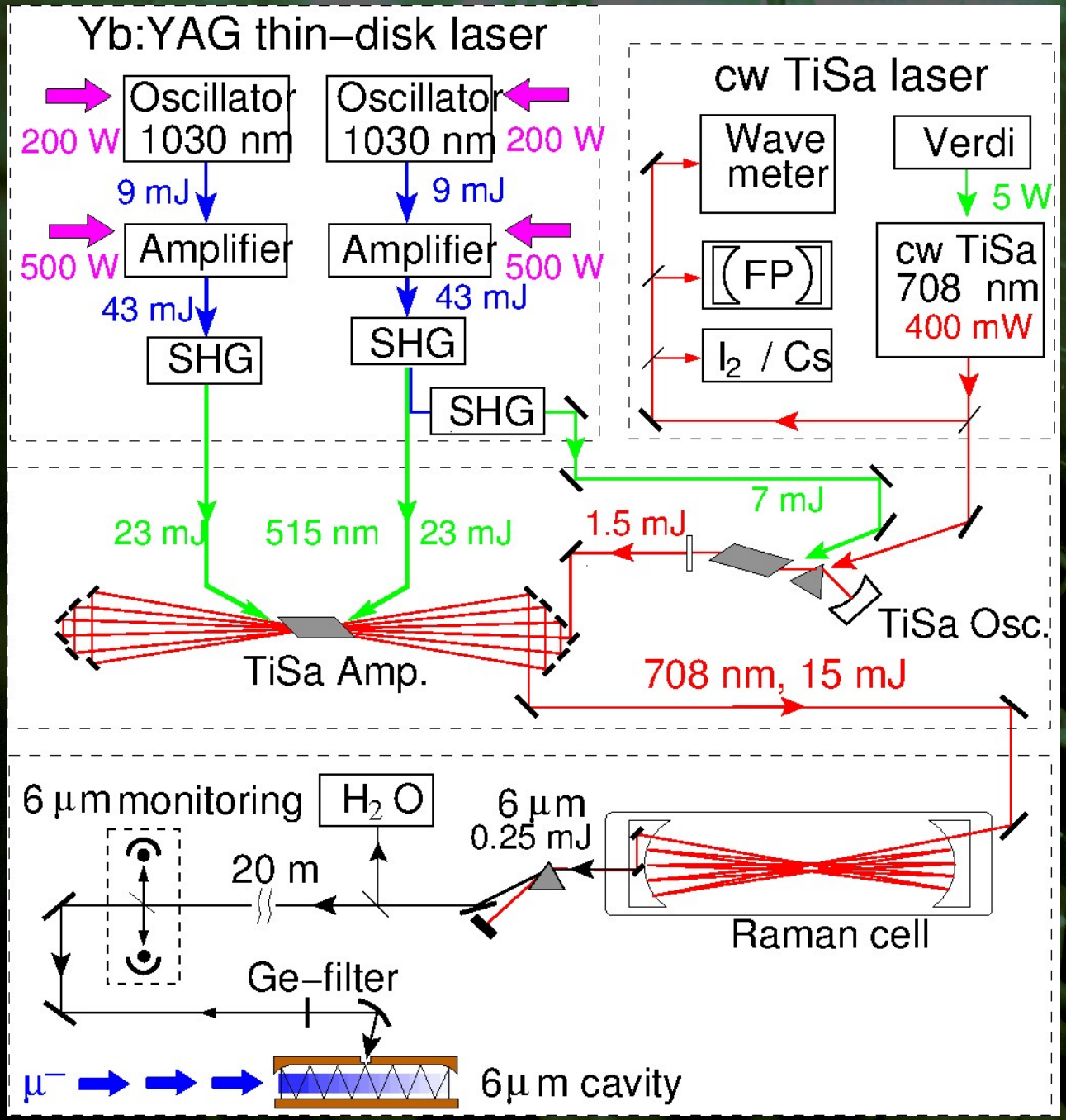




Laser Hut



The Laser System



Yb:YAG Disk Laser
→ fast reaction on µ

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

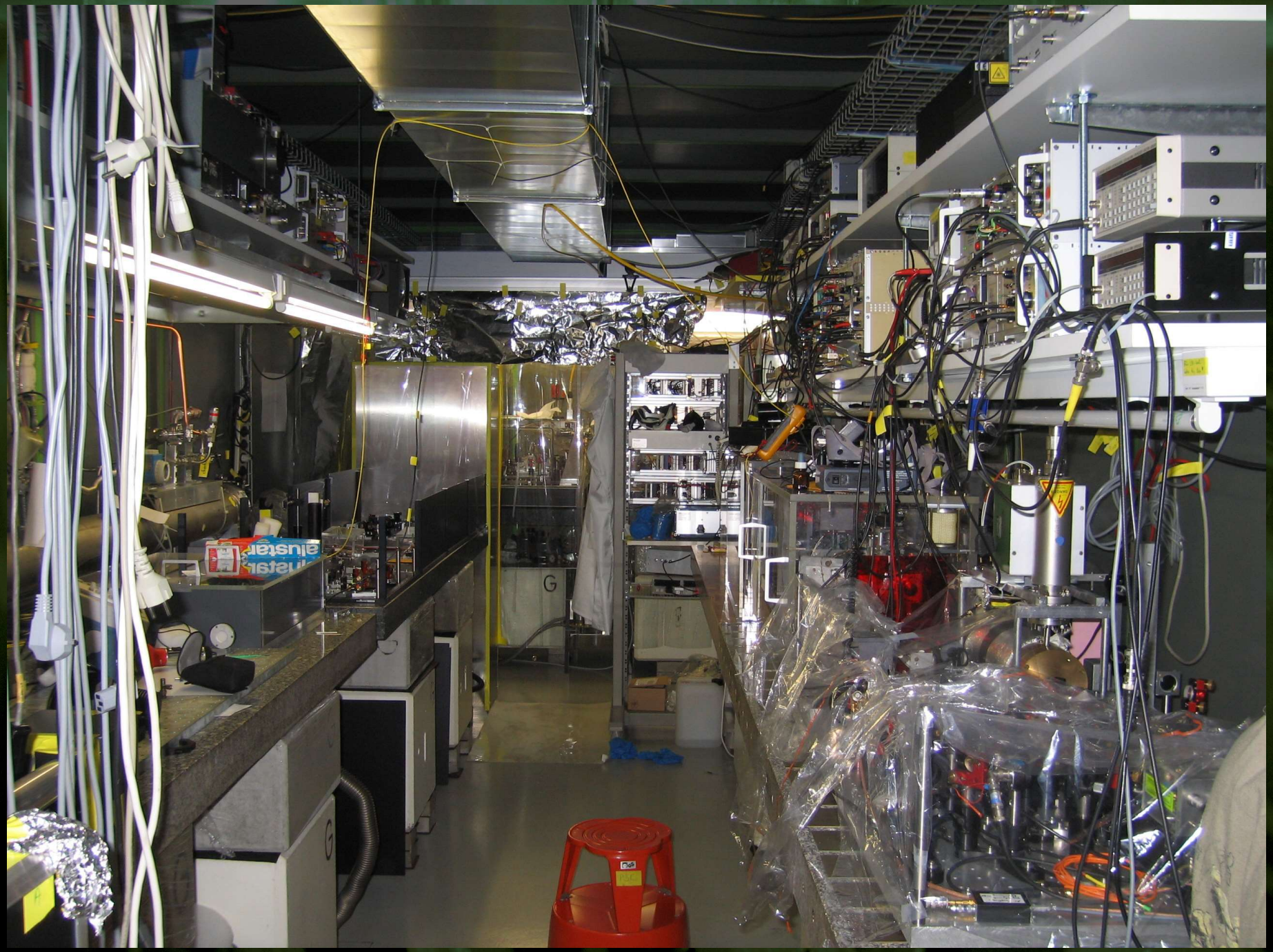
Ti:Sapphire cw Laser
→ determines laser wavelength (frequency)

Ti:Sapphire Oscillator/Amplifier
→ large pulse energy (15 mJ)

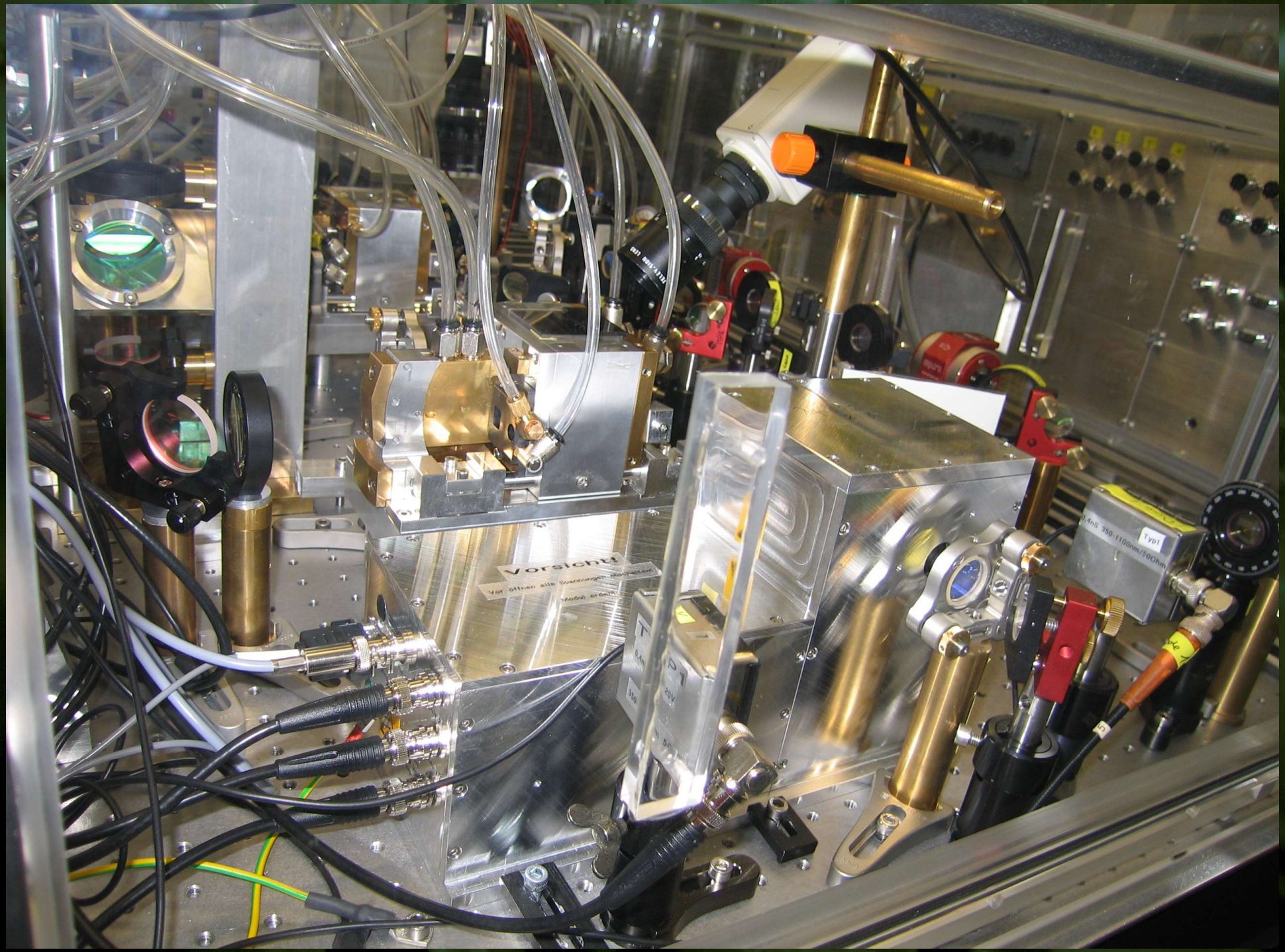
Raman cell
→ 3 Raman shifts change laser wavelength → 6 µm

Target Cavity
→ Mirror system surrounding muon stop volume

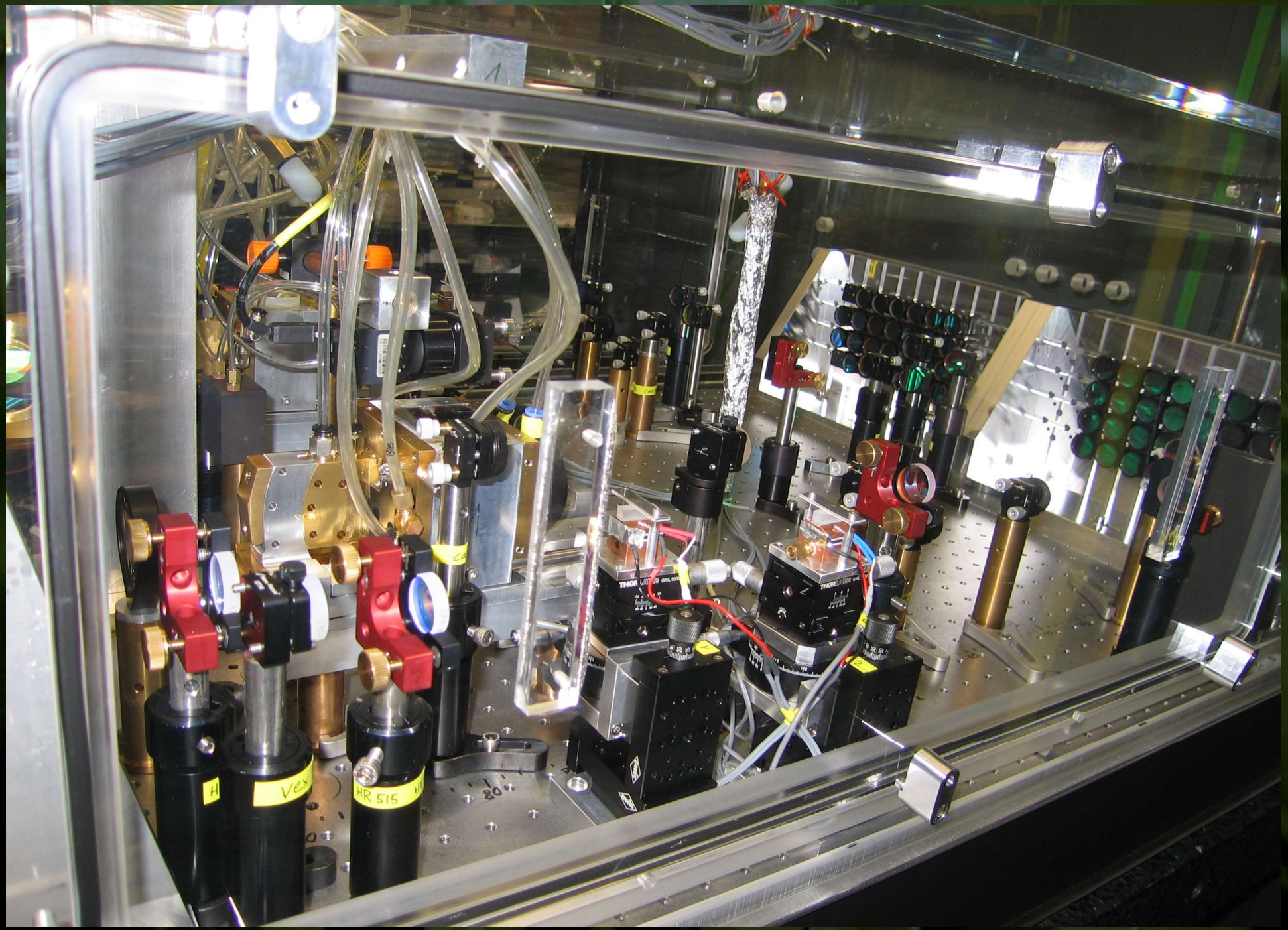
Inside the Laser Hut



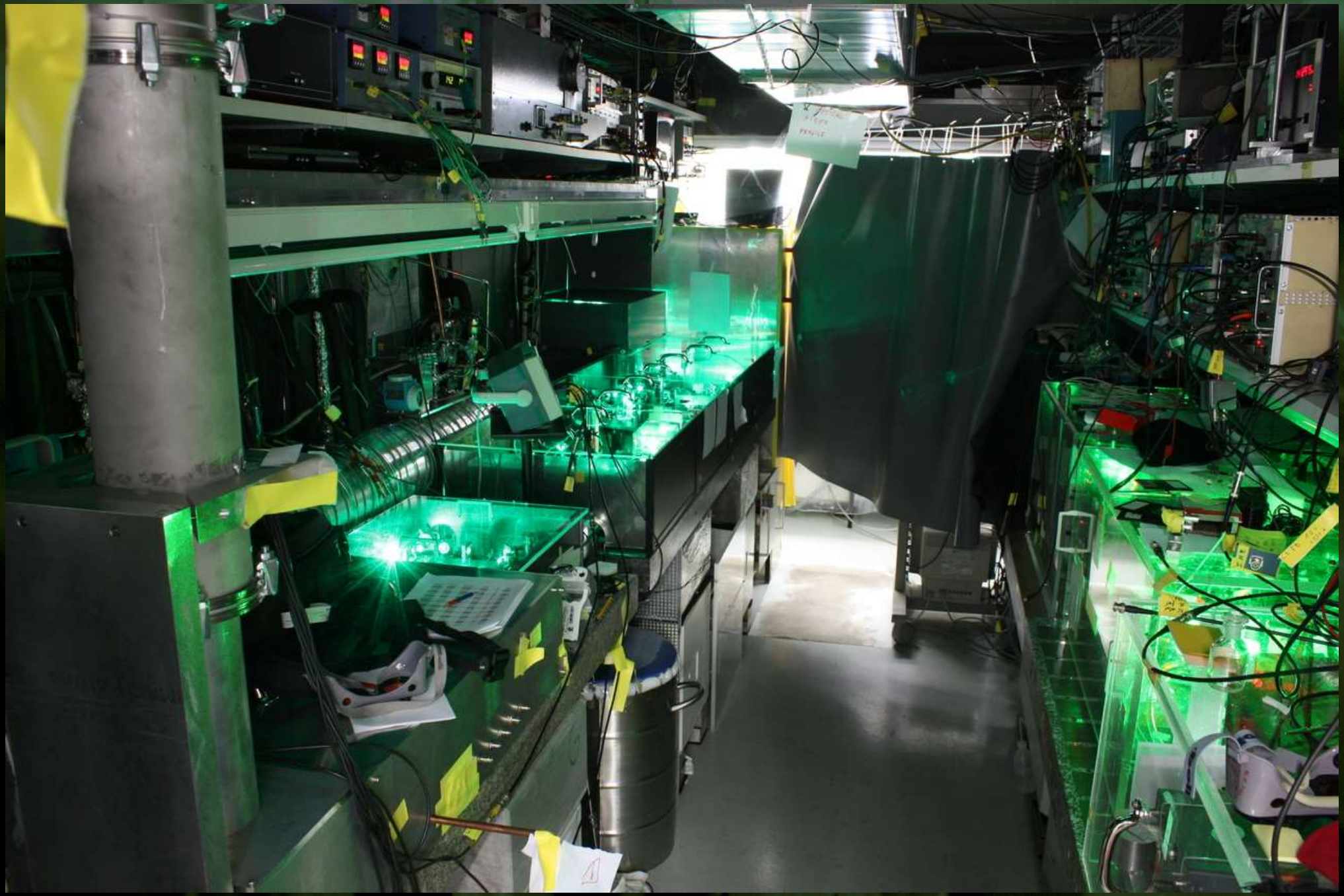
Yb:YAG Oscillator



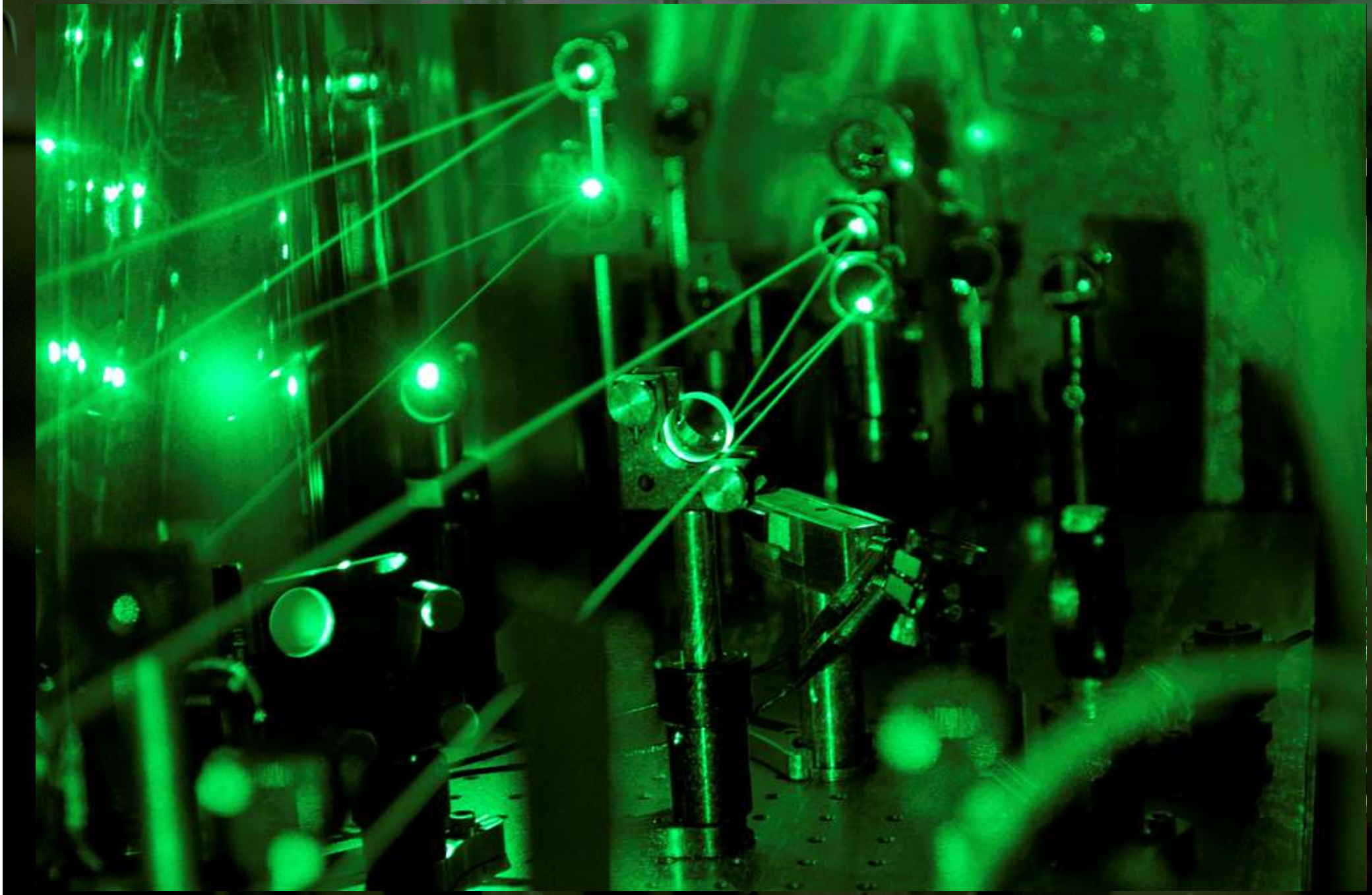
Yb:YAG Amplifier



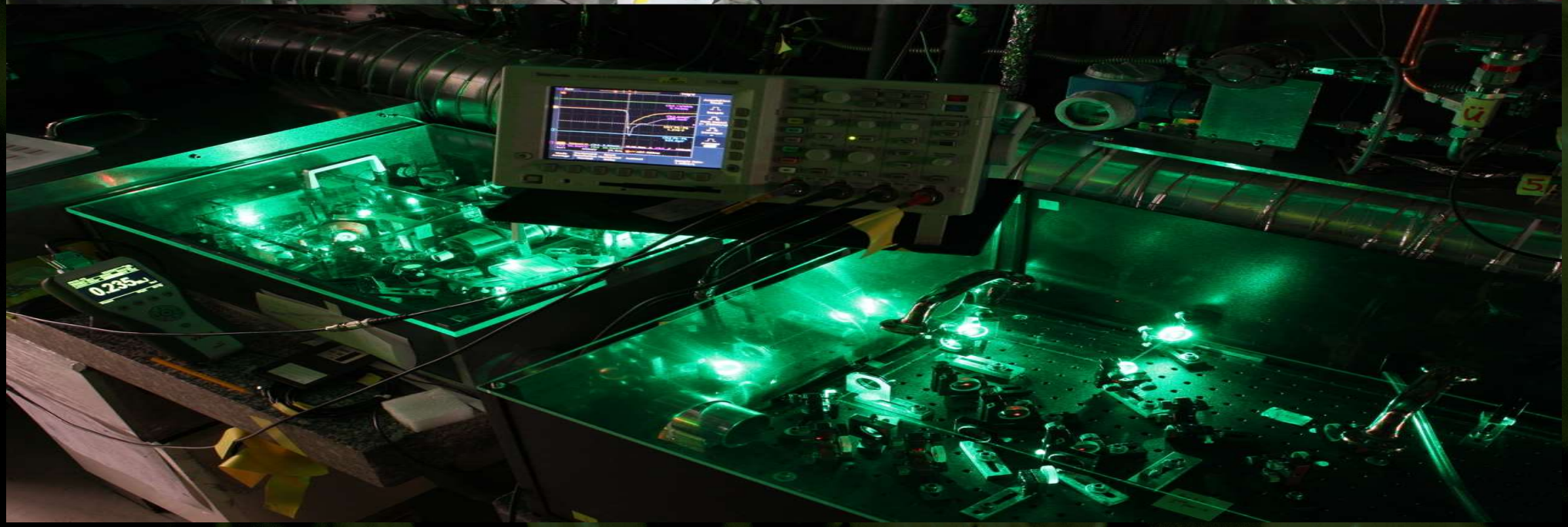
Laser Hut



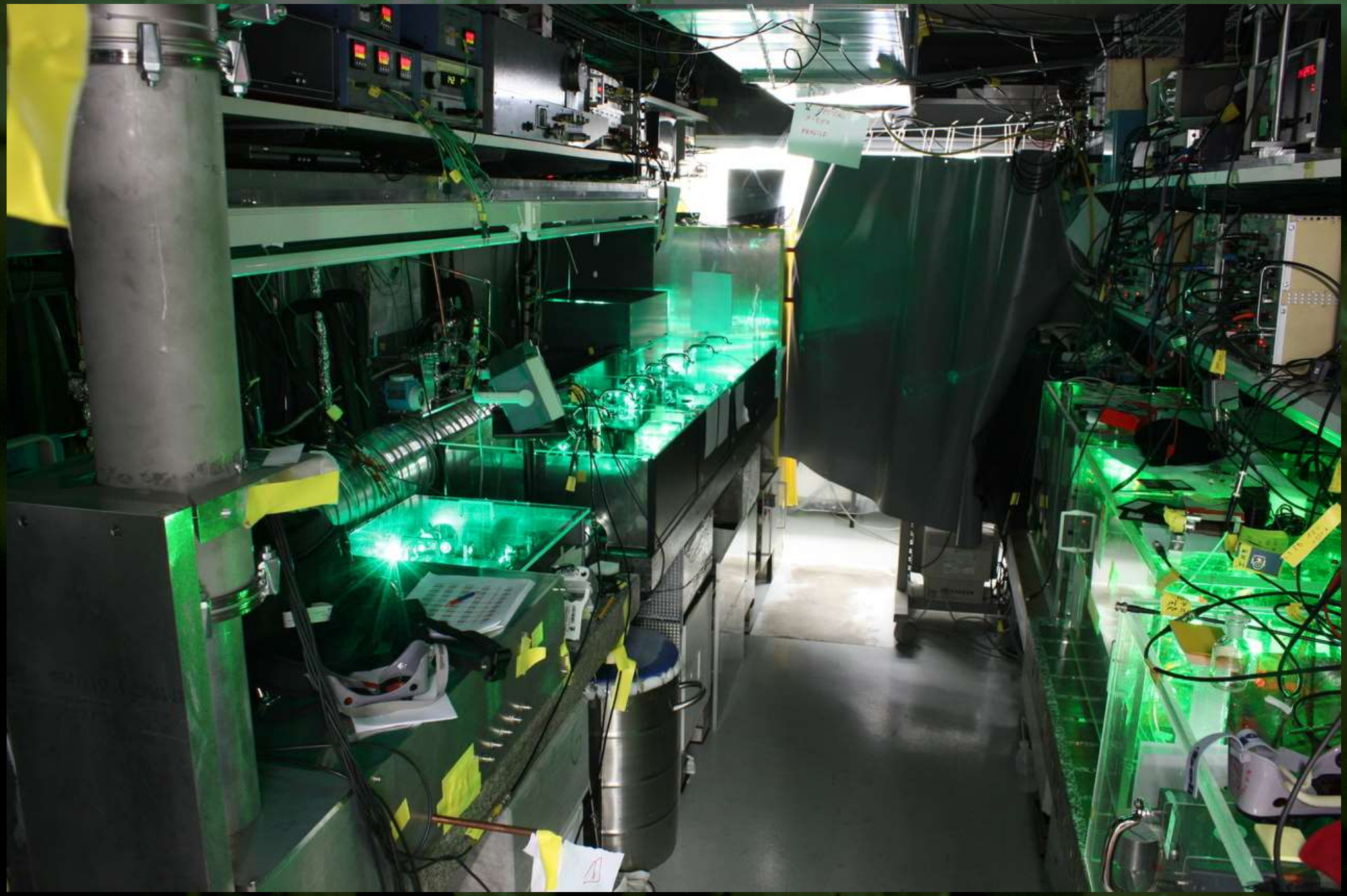
Rayleigh Scattering



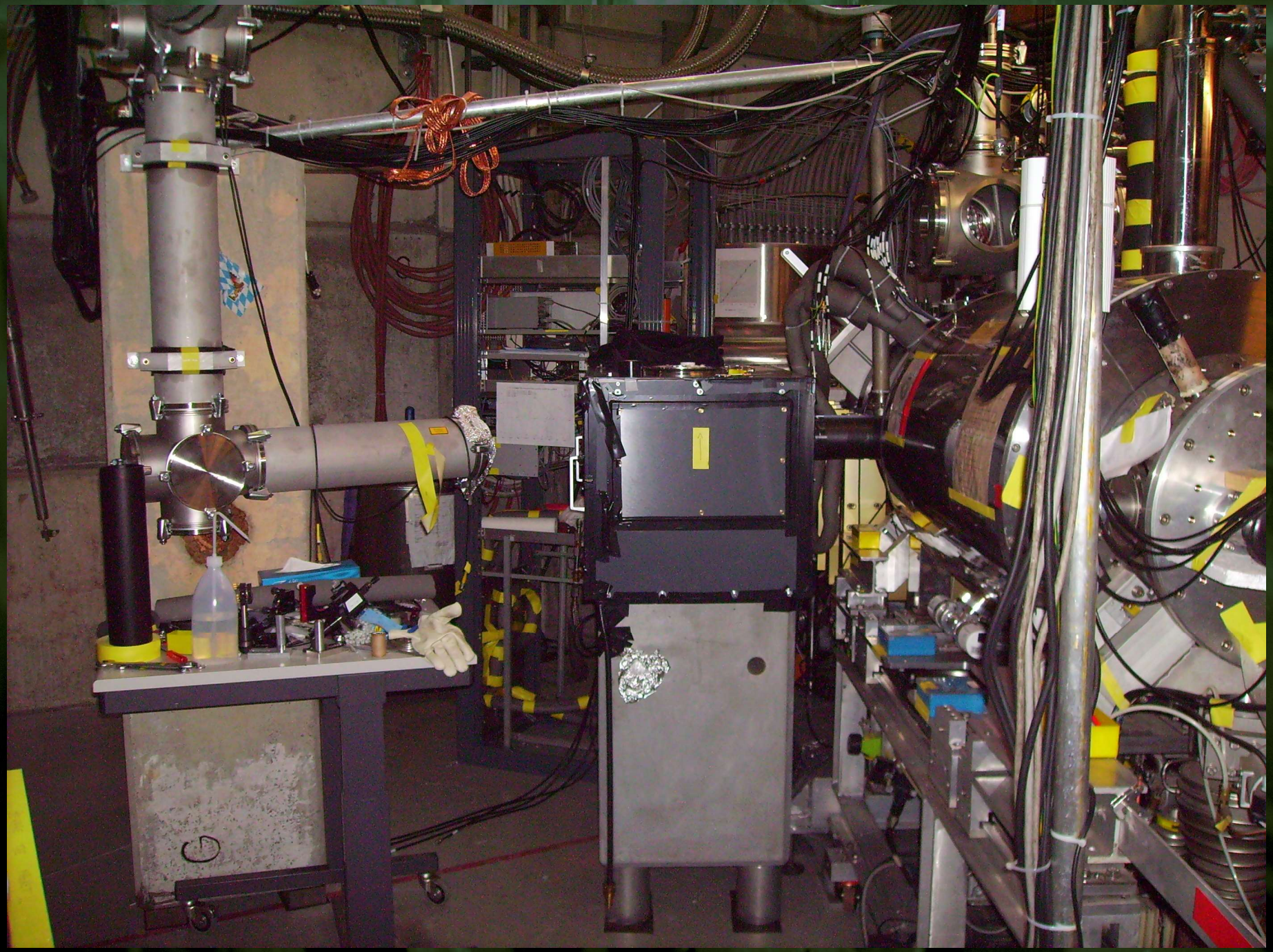
Ti:Sapphire laser



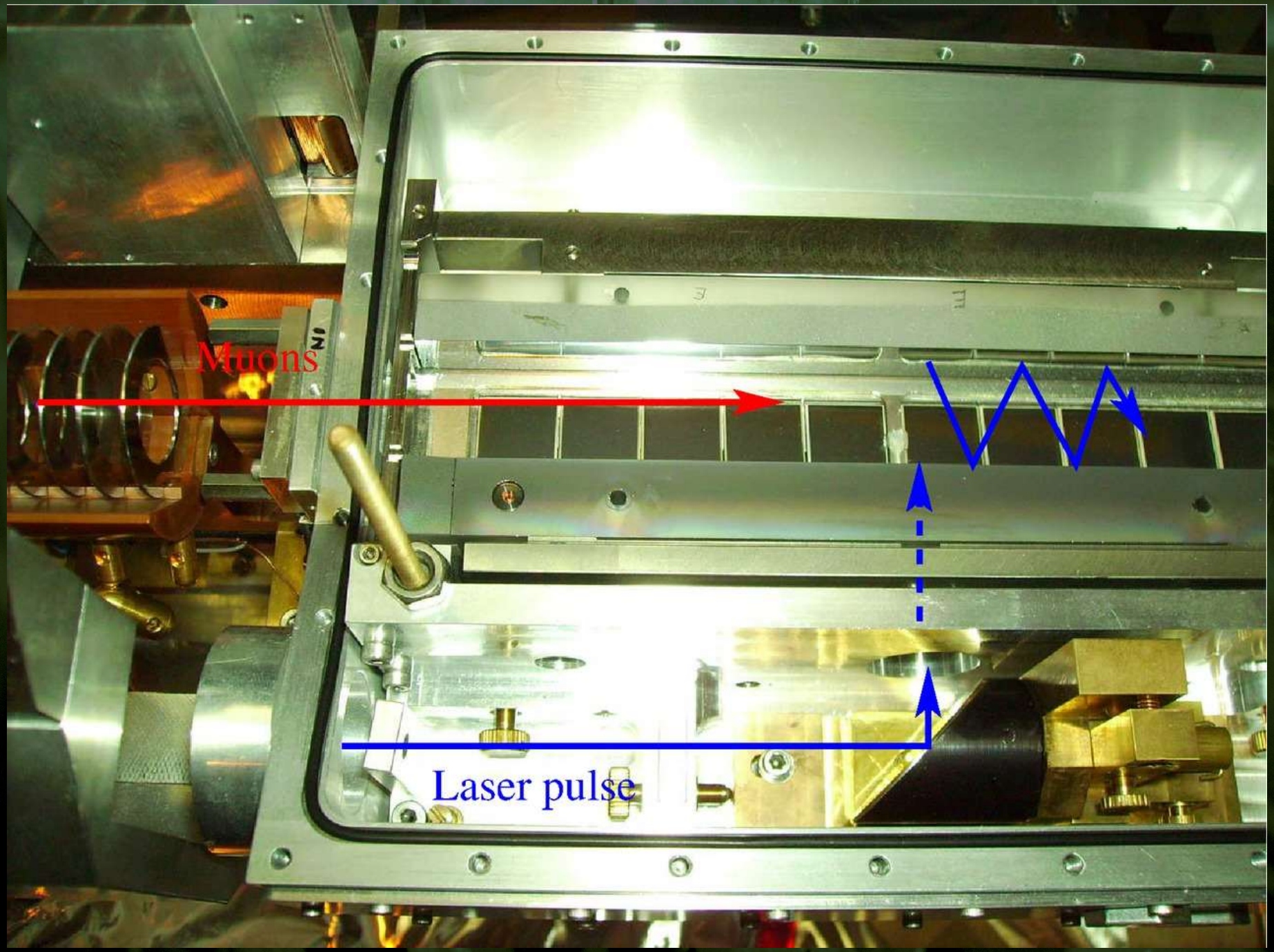
Raman cell



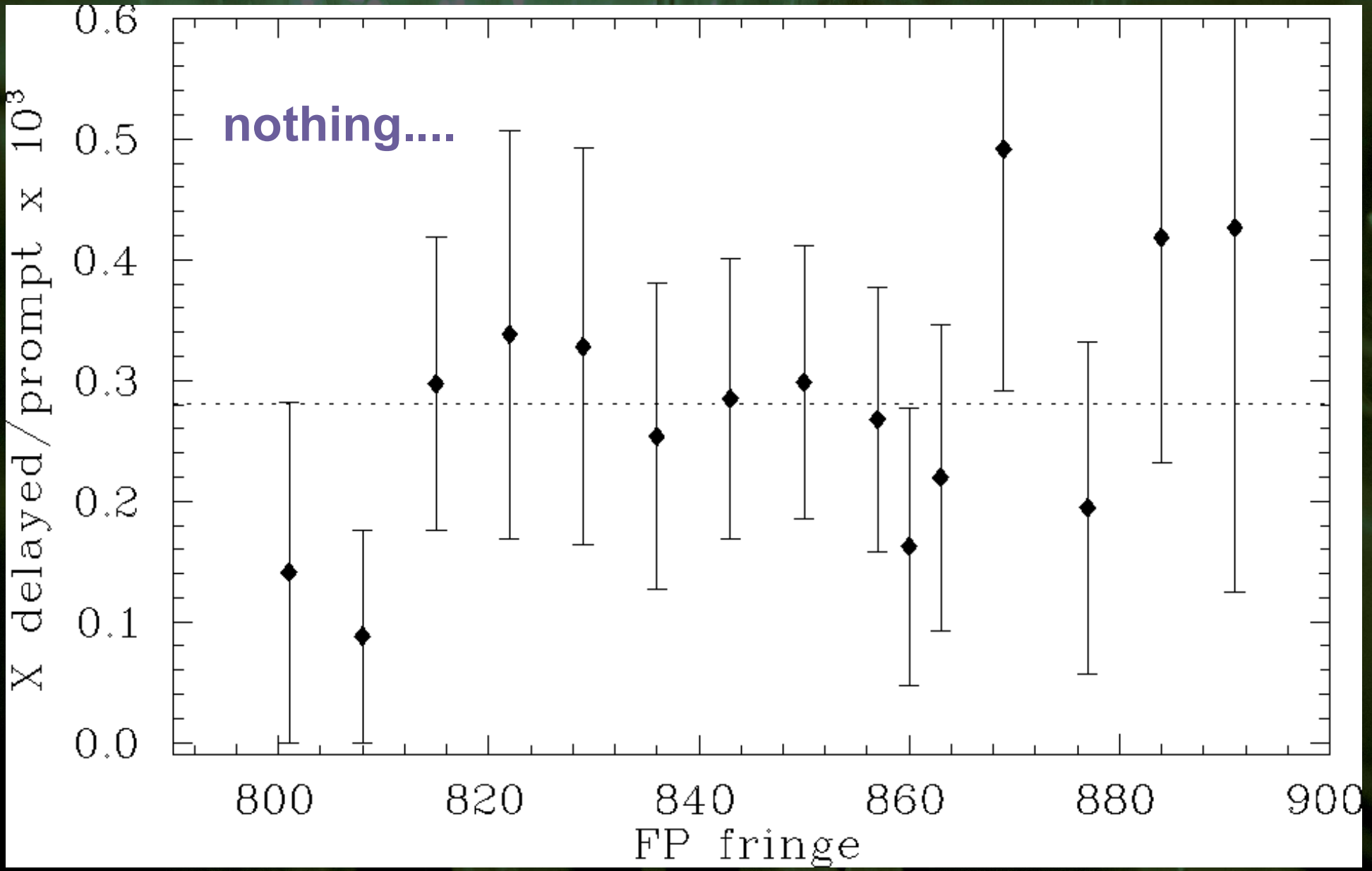
6um light to the muons



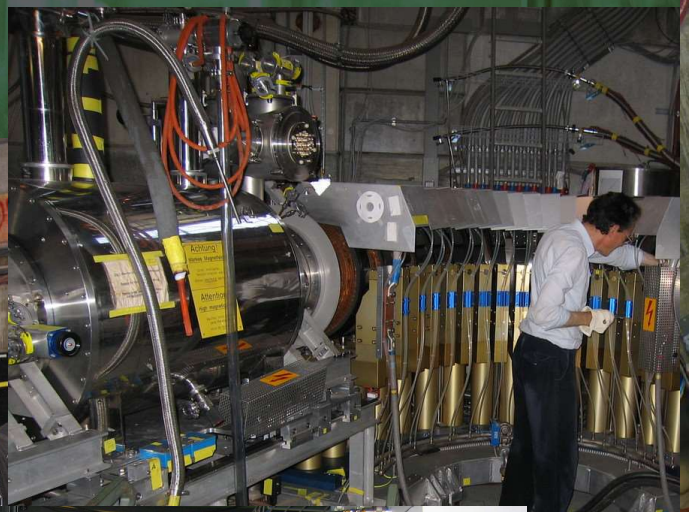
The Heart of the Setup -- Target

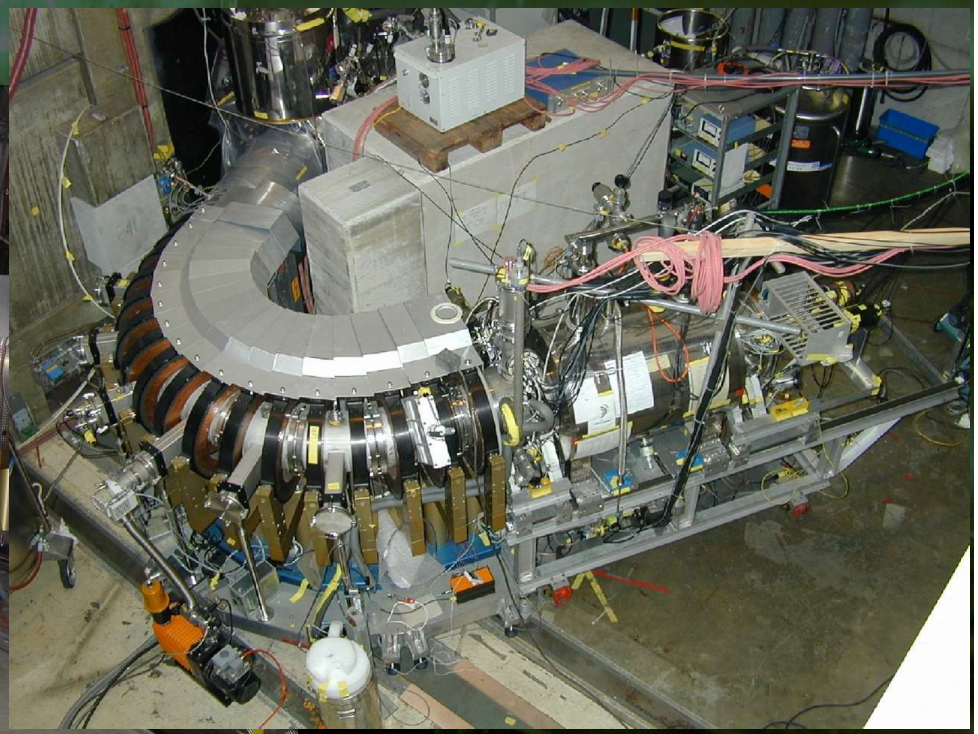


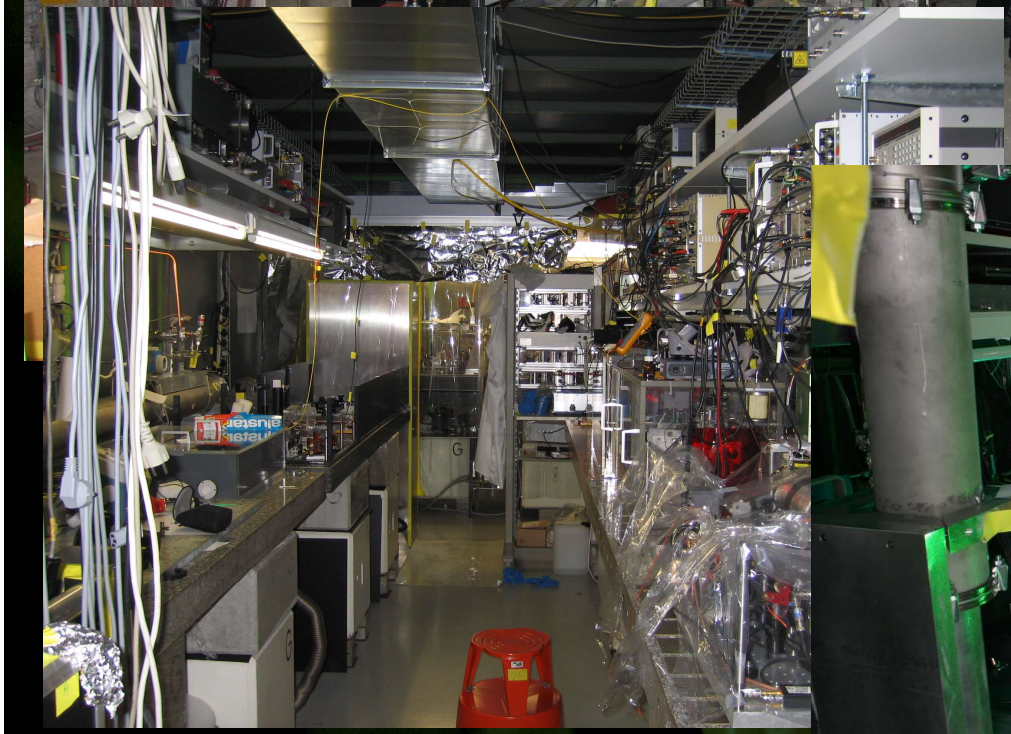
1997 - 2008

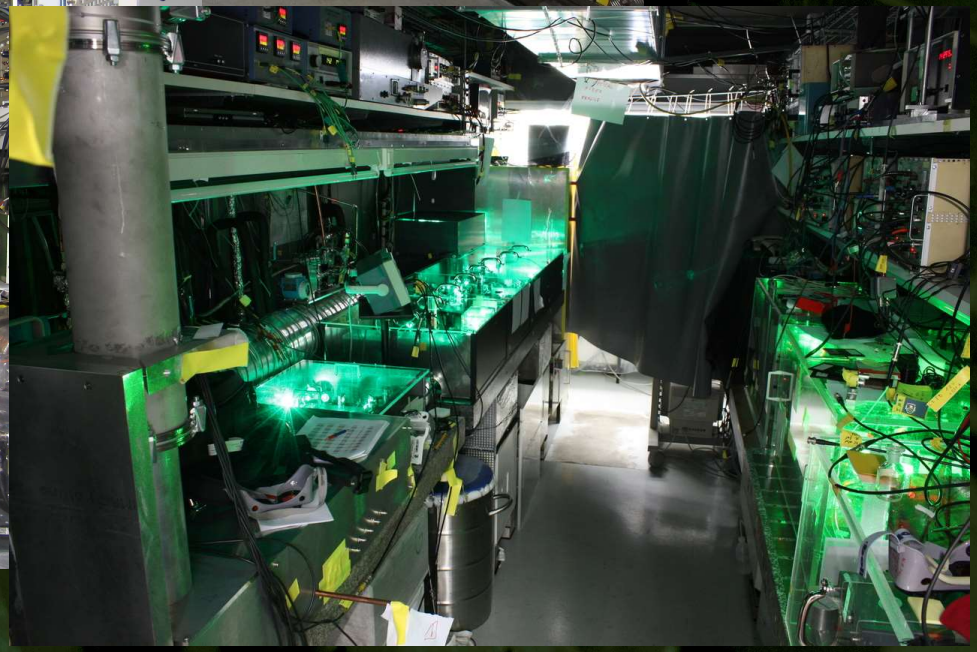

nothing....
X delayed/prompt x 10^3
0.0
0.1
0.2
0.3
0.4
0.5
0.6
800
820
840
860
880
900
FP fringe

Run 2009

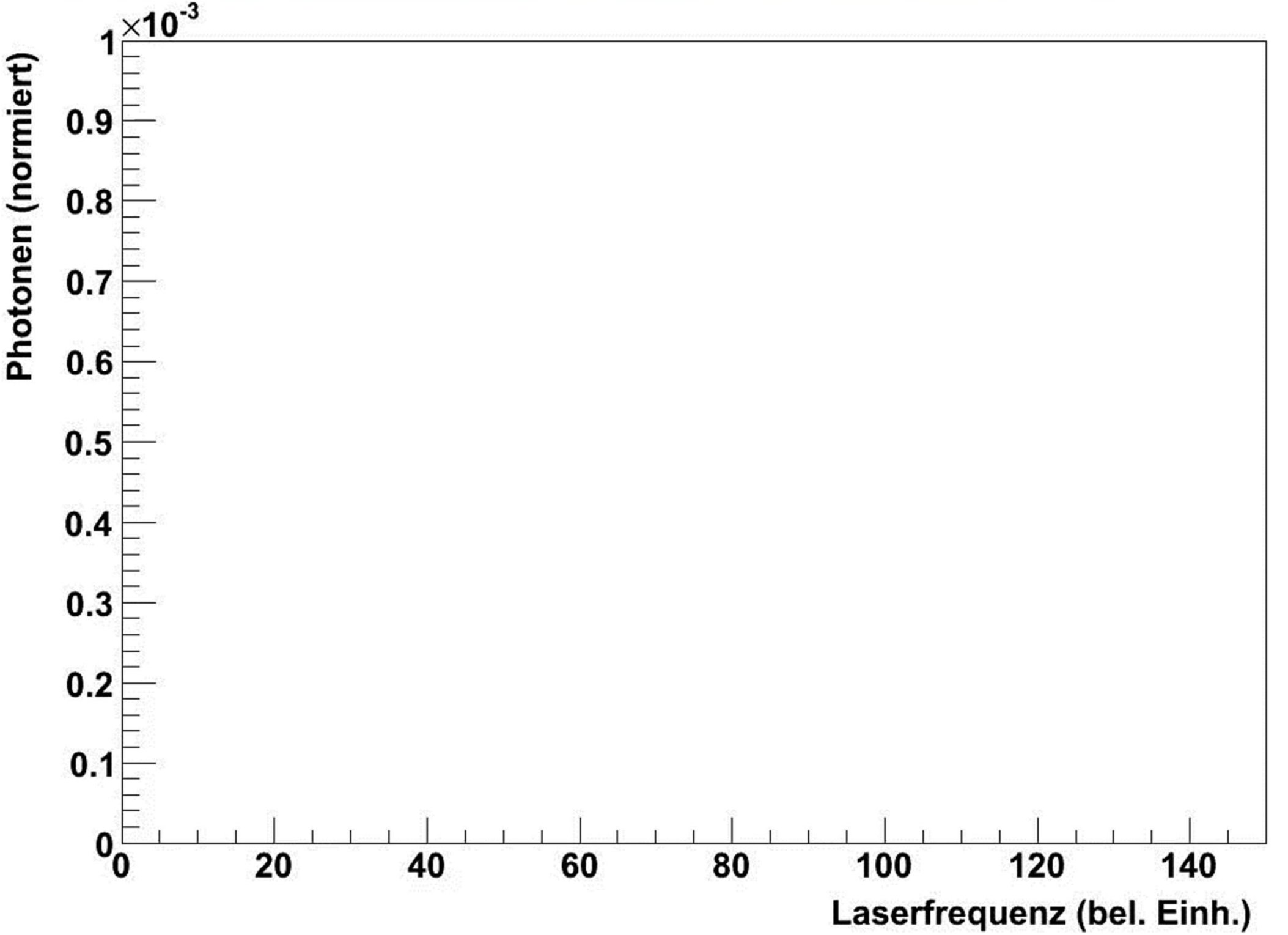




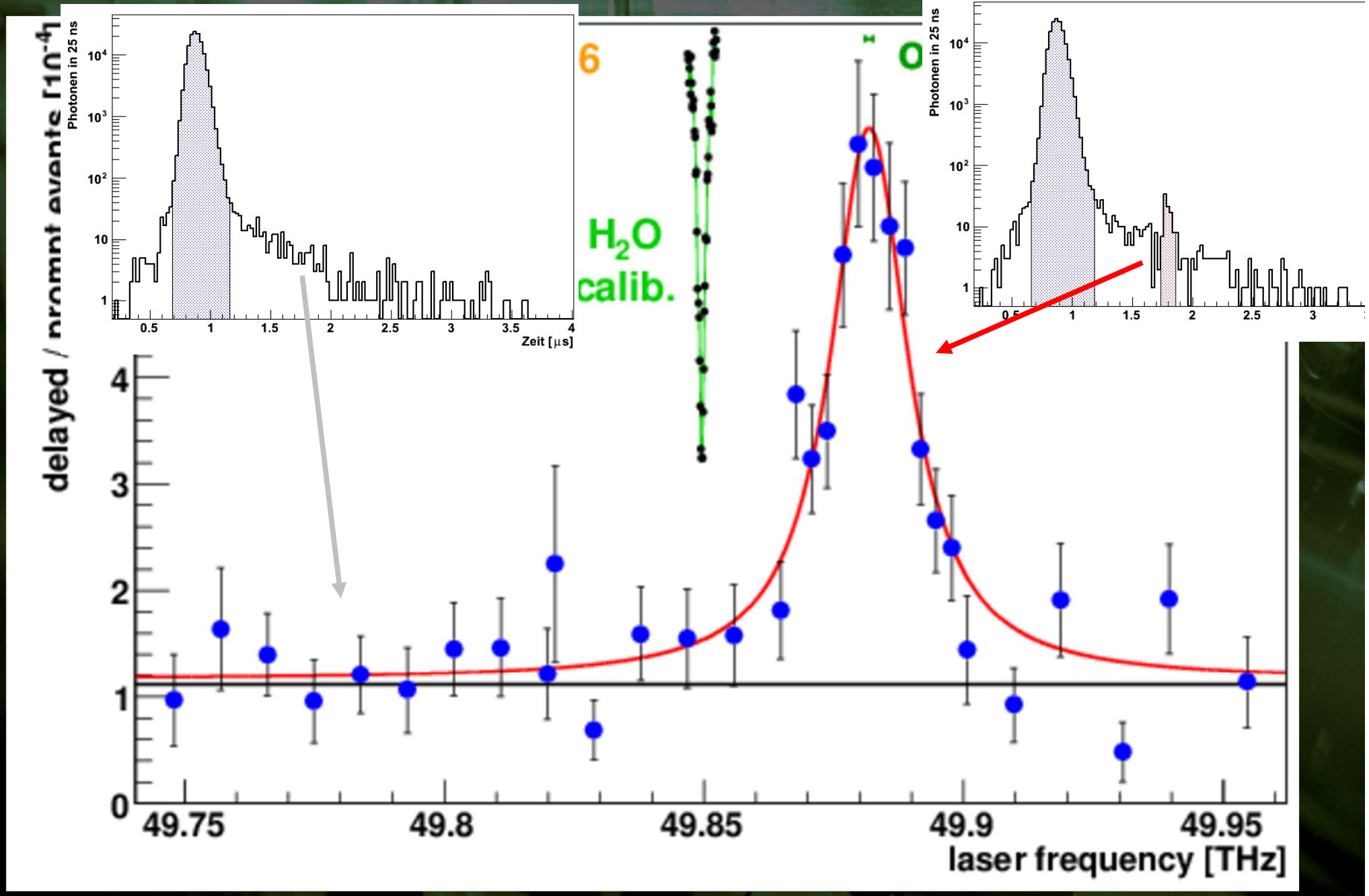




Movie: Search for the Resonance


×10^-3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Photonen (normiert)
0
20
40
60
80
100
120
140
Laserfrequenz (bel. Einh.)

The Resonance



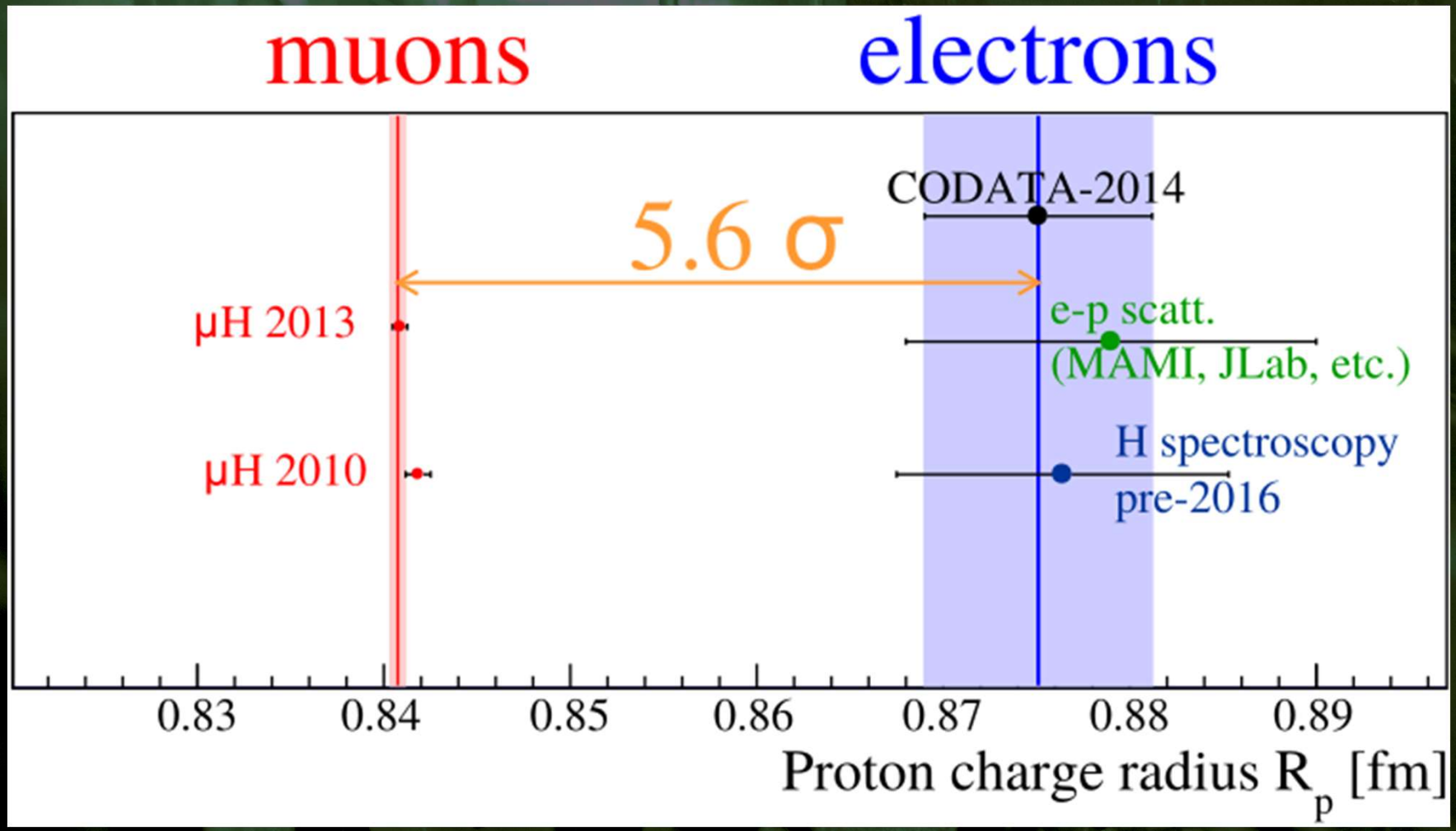
Yeah!

To the Resonance!

PSAS 2010 Conference

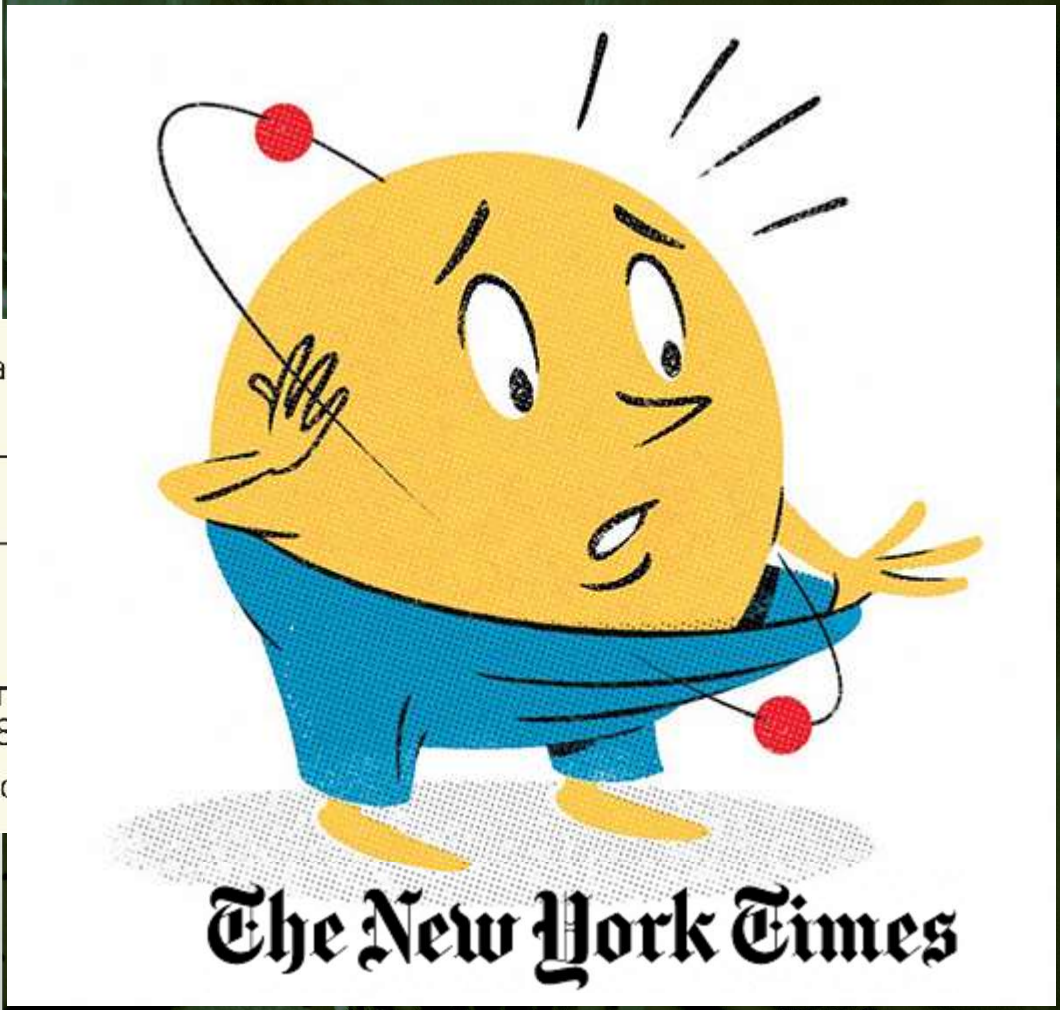
ÉCOLE DE PHYSIQUE DES HOUCHES

The “Proton Radius Puzzle”



Resonance to our Resonance

Proton is 4% smaller!!!



10 times more precise!


公視
20:36:50
EVENING NEWS
晚間新聞
質子重大發現 比原本所知小4%

Workshop: The “Proton Radius Puzzle”

ECT* Trento, Italy, Oct. 2012

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

38 Talks
3 “Fighting Sessions”

Finally: **Vote (!)**

→ Measurement problem

We need **more data**.

Follow-up conferences
*** Mainz 2014 * Losinj 2019**
*** Trento 2016 * Paris 2022**
*** Mainz 2018**

Attempts to Explain

Measurement problem

Muonic hydrogen

or

Hydrogen AND Electron scattering

Theory Error

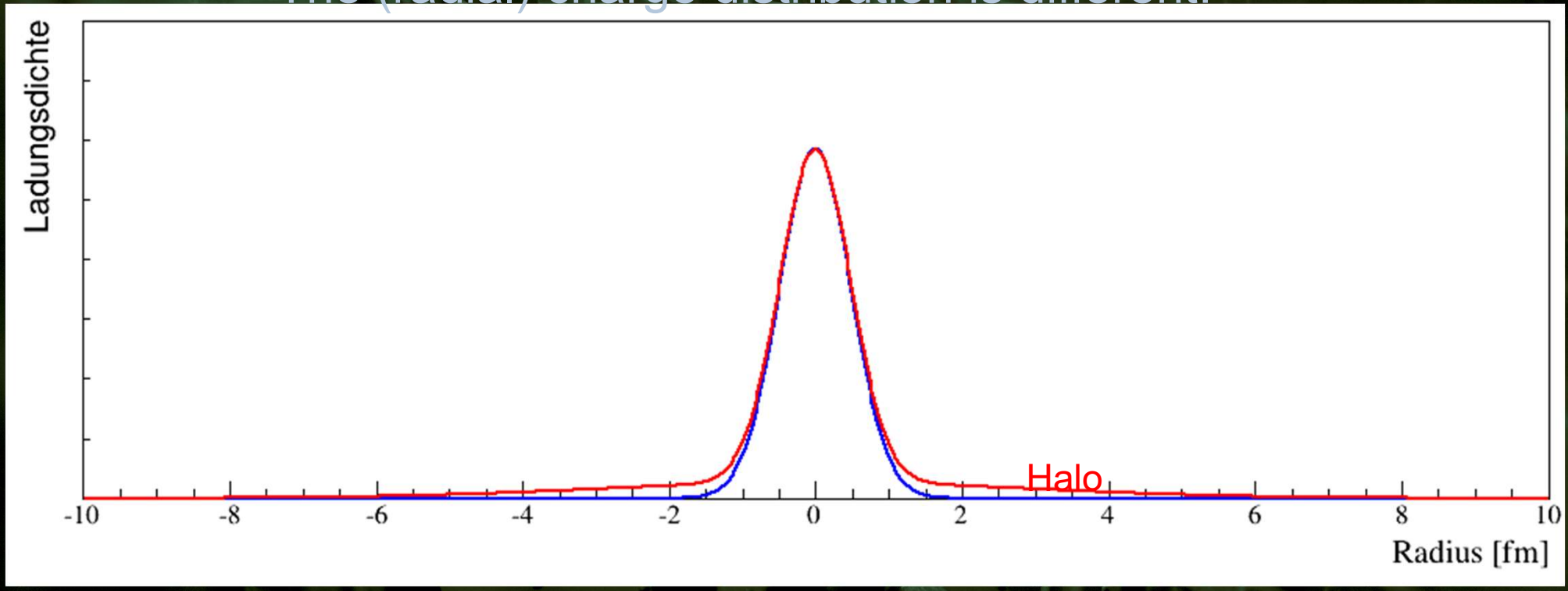
$$\Delta E = 209.998 - 5.226\ \mathbf{R}_p^{\,2}$$

Error in Standard Model of Particle Physics

The Proton looks different!

Proton is not a solid ball

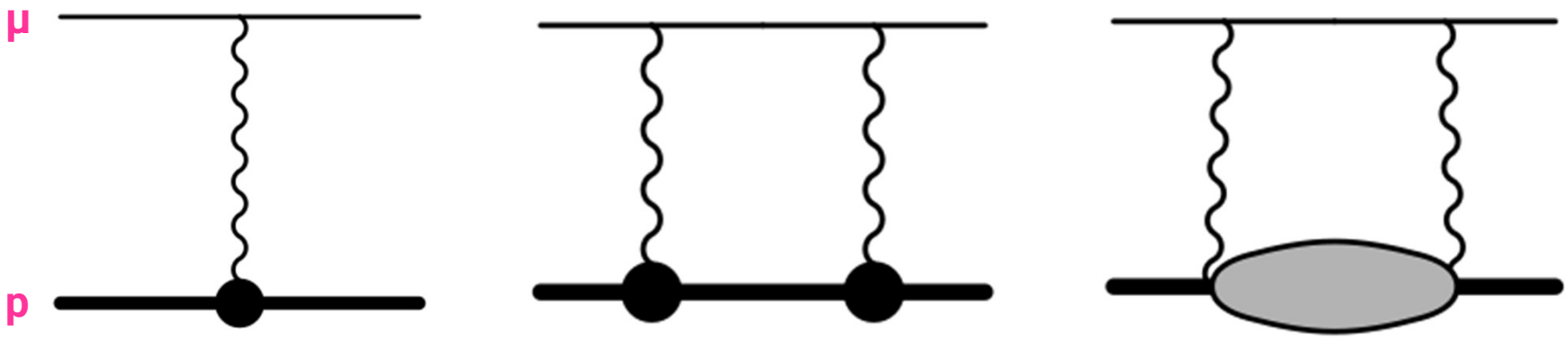
The (radial) charge distribution is different!



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

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

Muon modifies the Proton



1-photon exchange

2-photon exchange (elastic)

2-photon exchange (inelastic)

charge radius

Proton-"Halo"

Proton polarisability

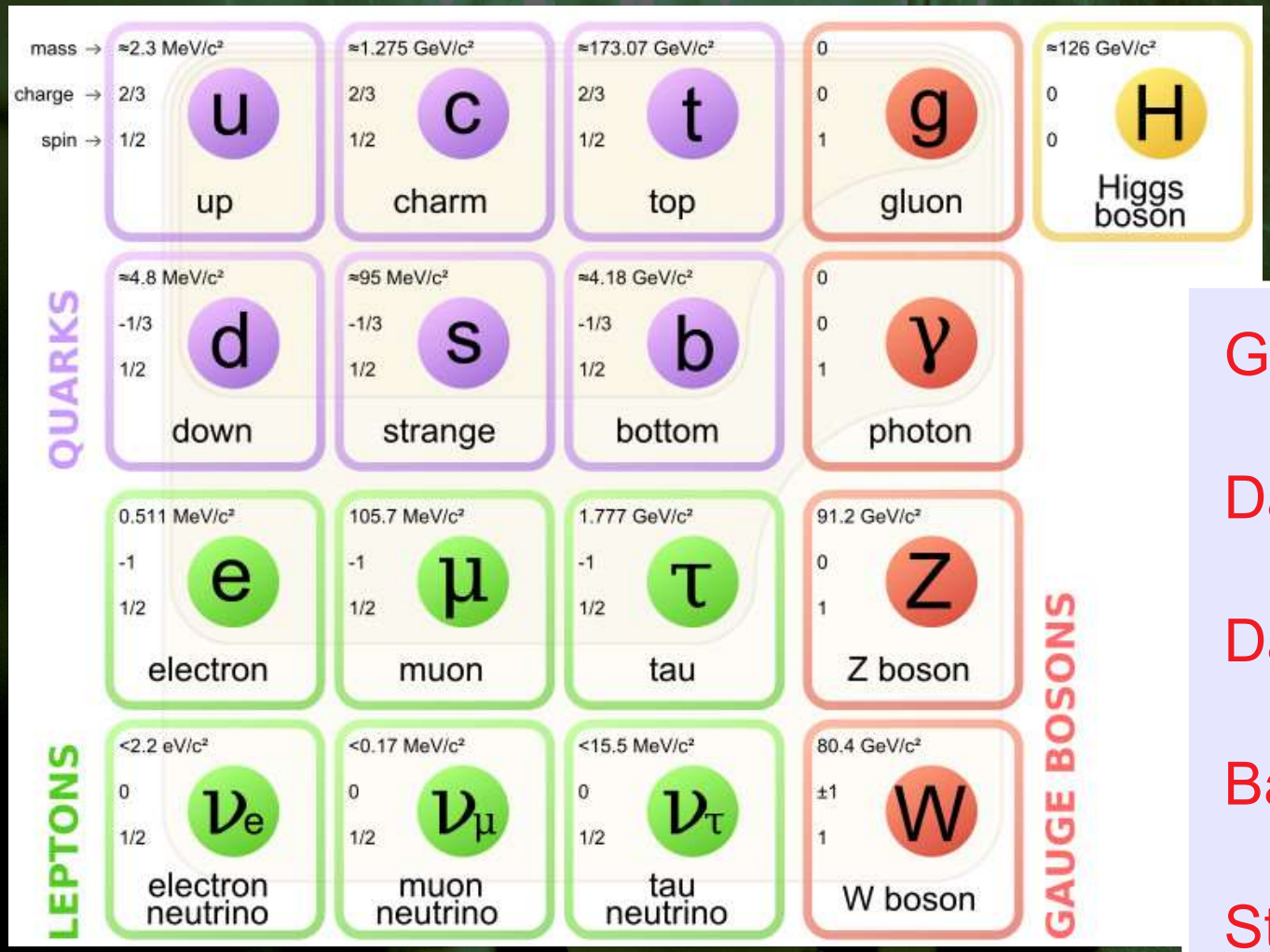
Yes! The so-called "Polarisability" of the Proton

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

Discrepancy: 0.31 meV

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 (BSM)

Could in principle be responsible for the discrepancy

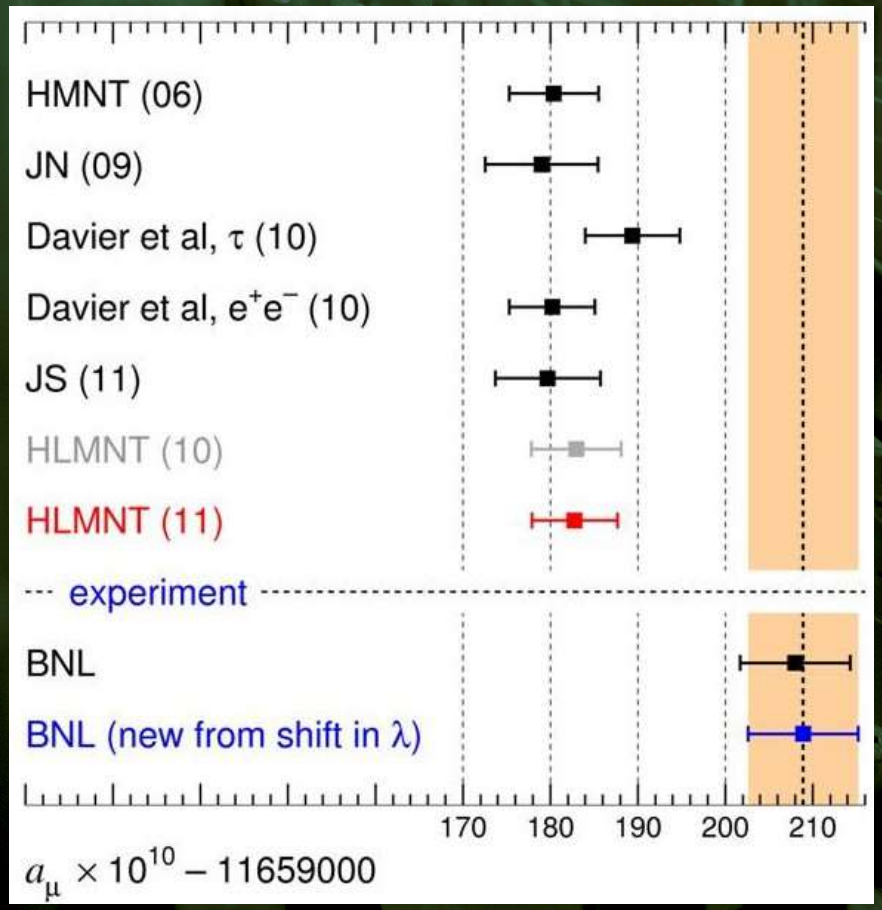
A new particle, responsible for a new force for muons

This particle however must fit into many existing measurements (which agree with the SM)!

Difficult.....

TWO Problems with Muons!

Anomalous magnetic moment of the muon (g-2)



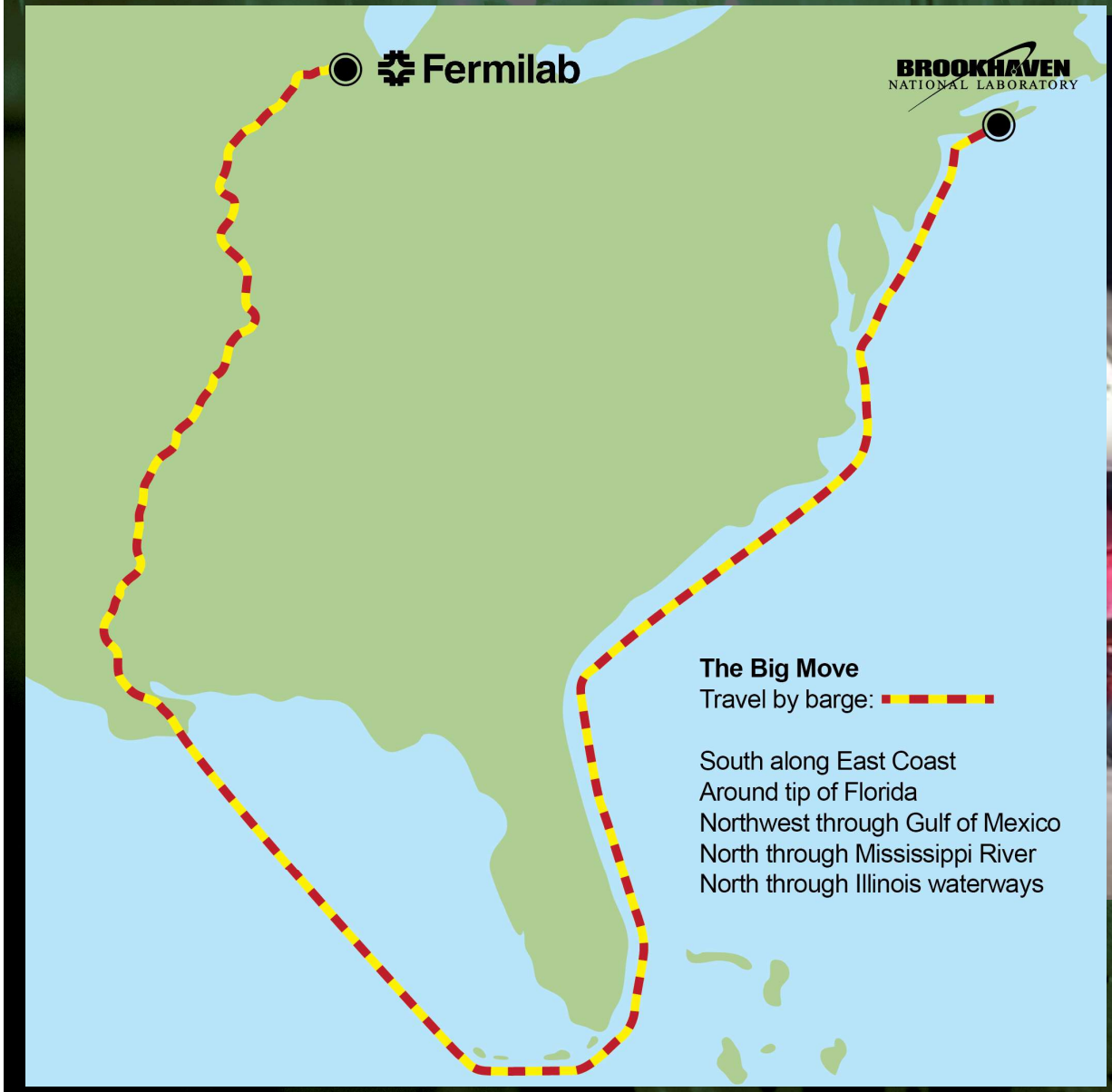
Thc

Exp men

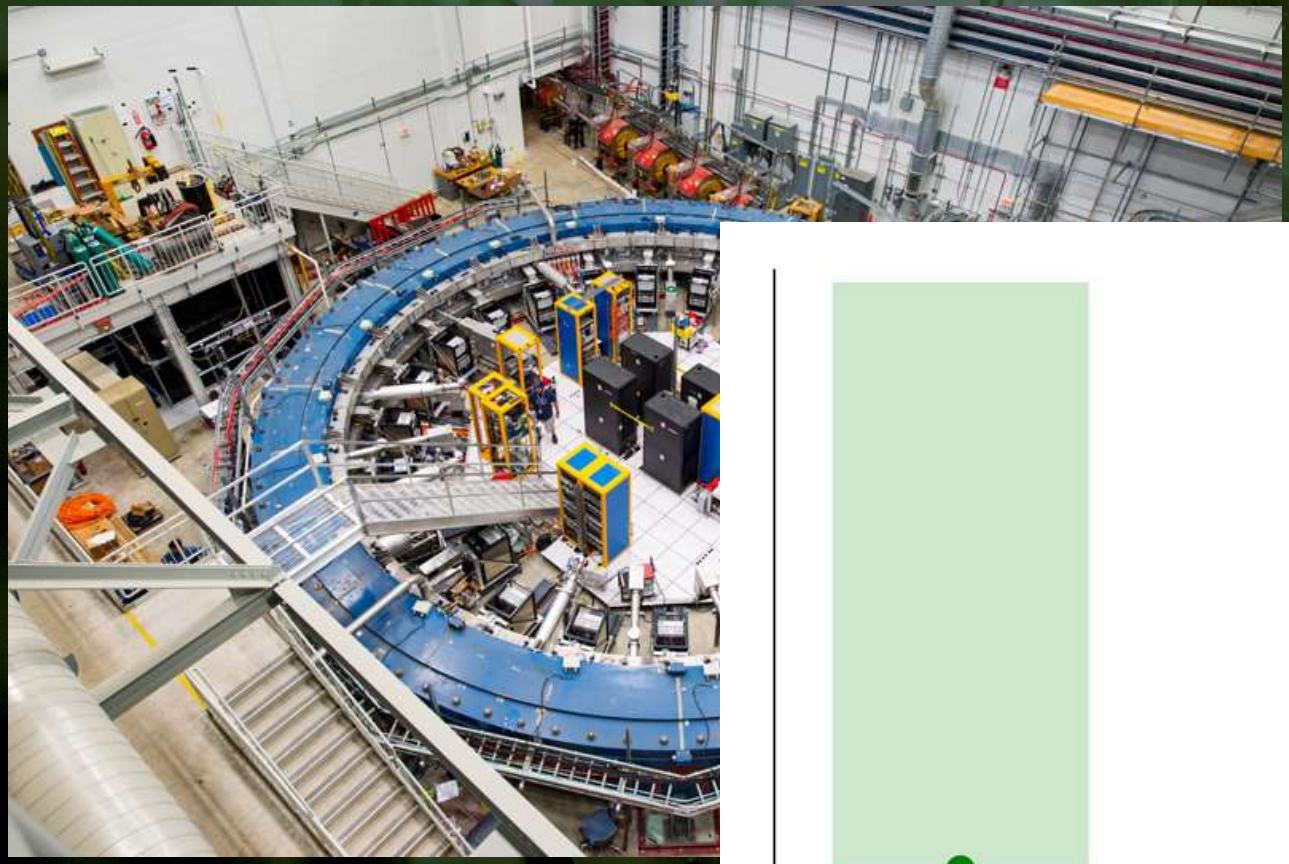
t

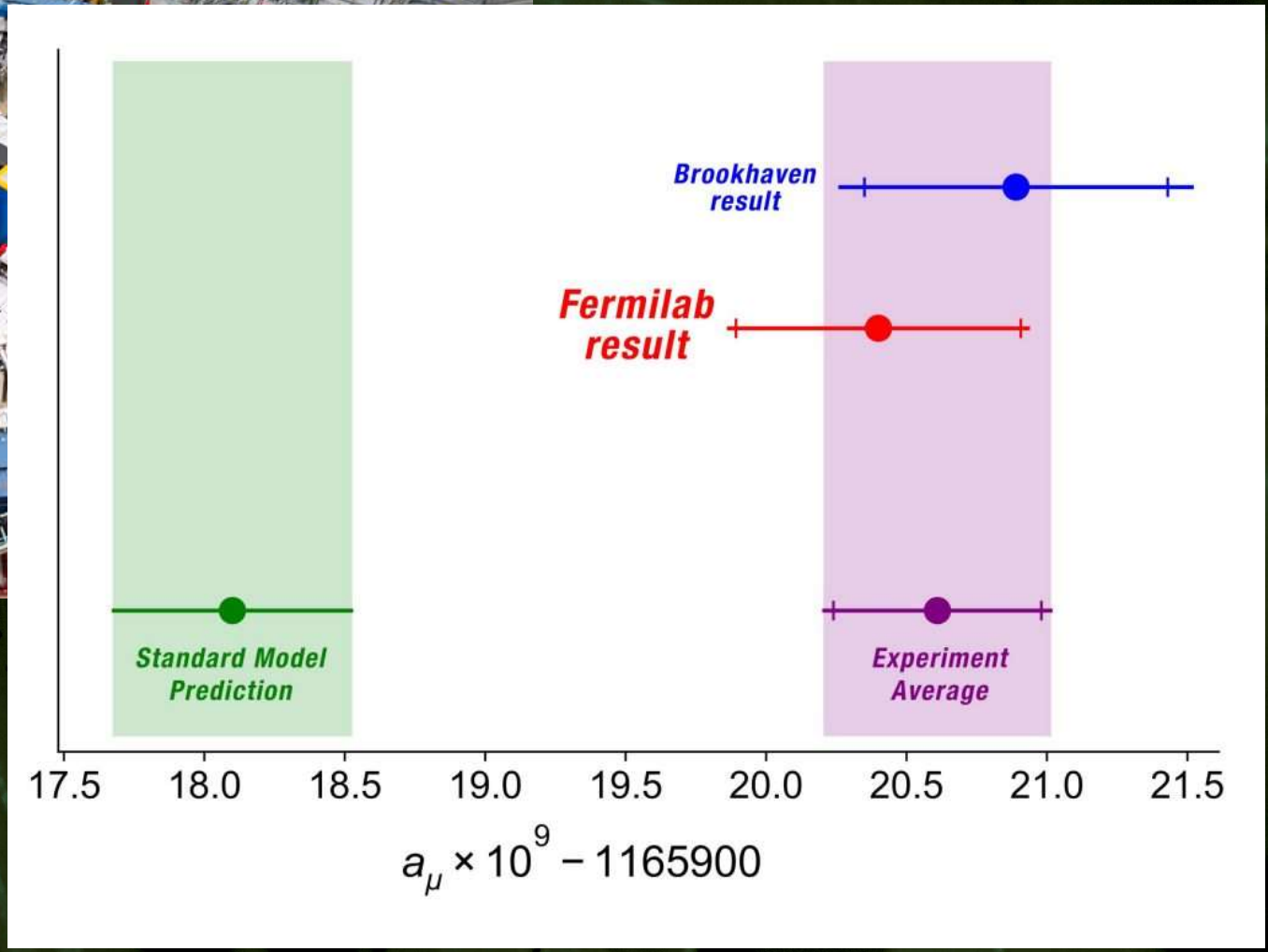
3.6 σ discrepancy to the SM since 2001 (20 years!)

The new muon g-2 experiment



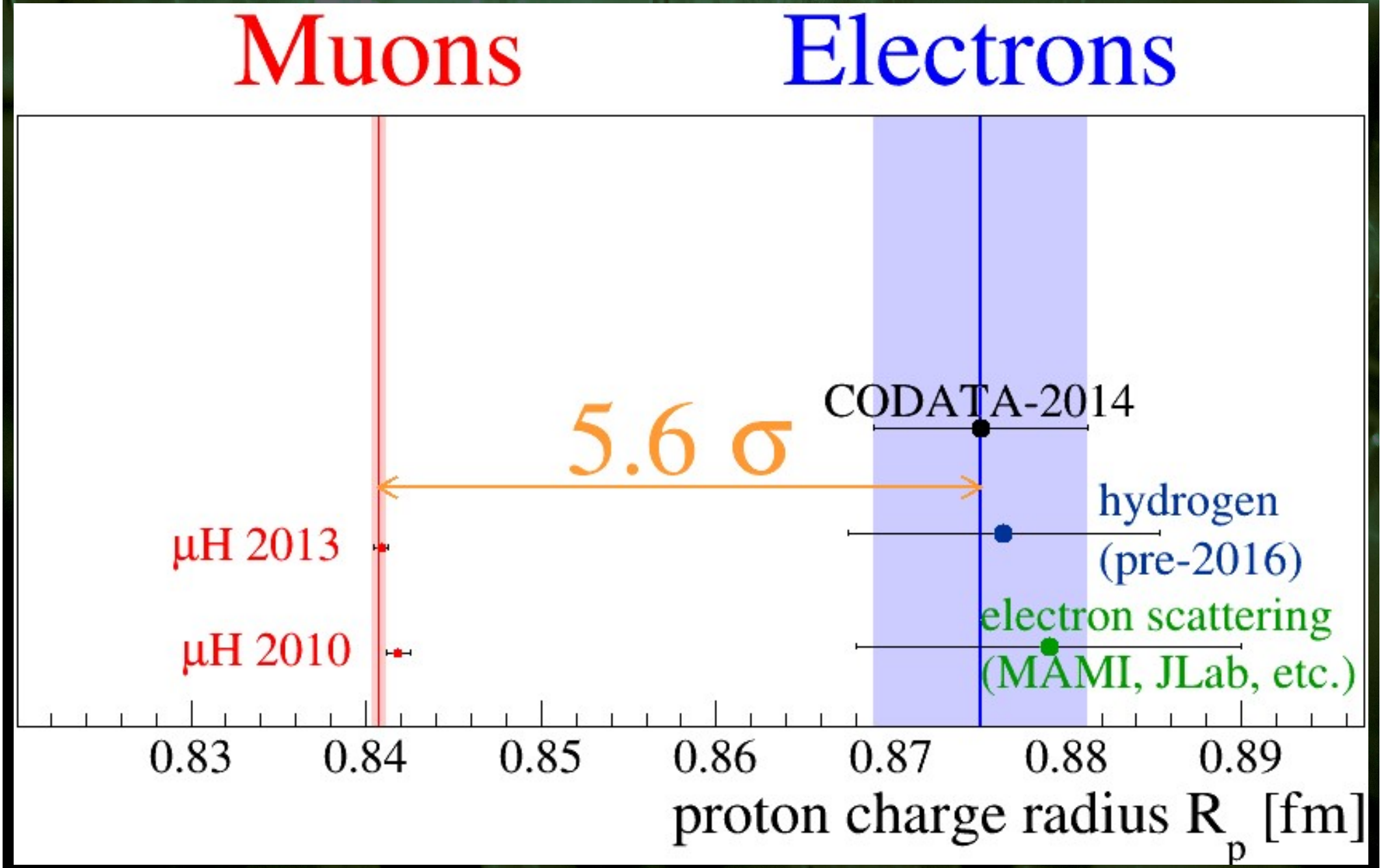
The new muon g-2 experiment



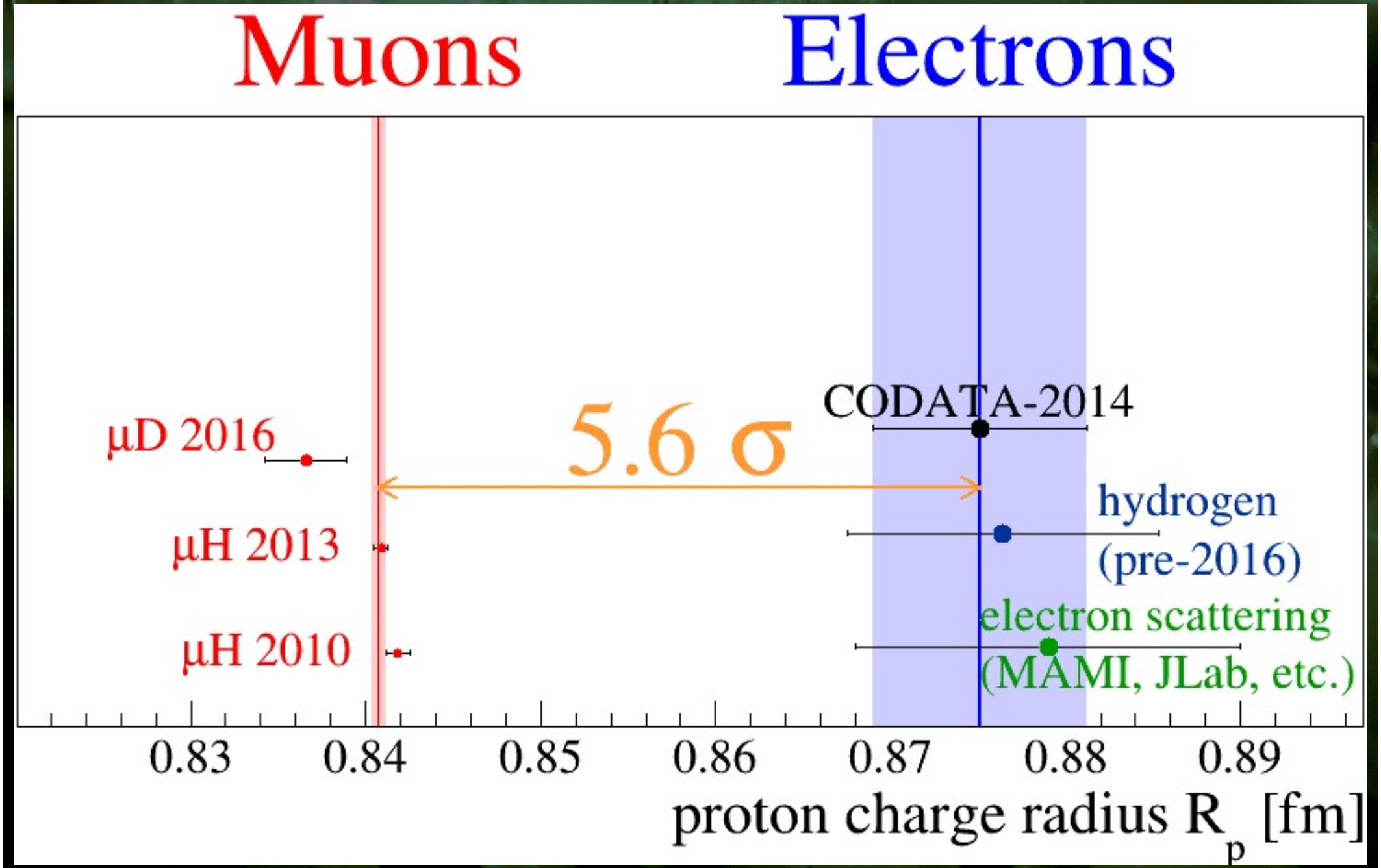



But first:
New DATA
check for errors....

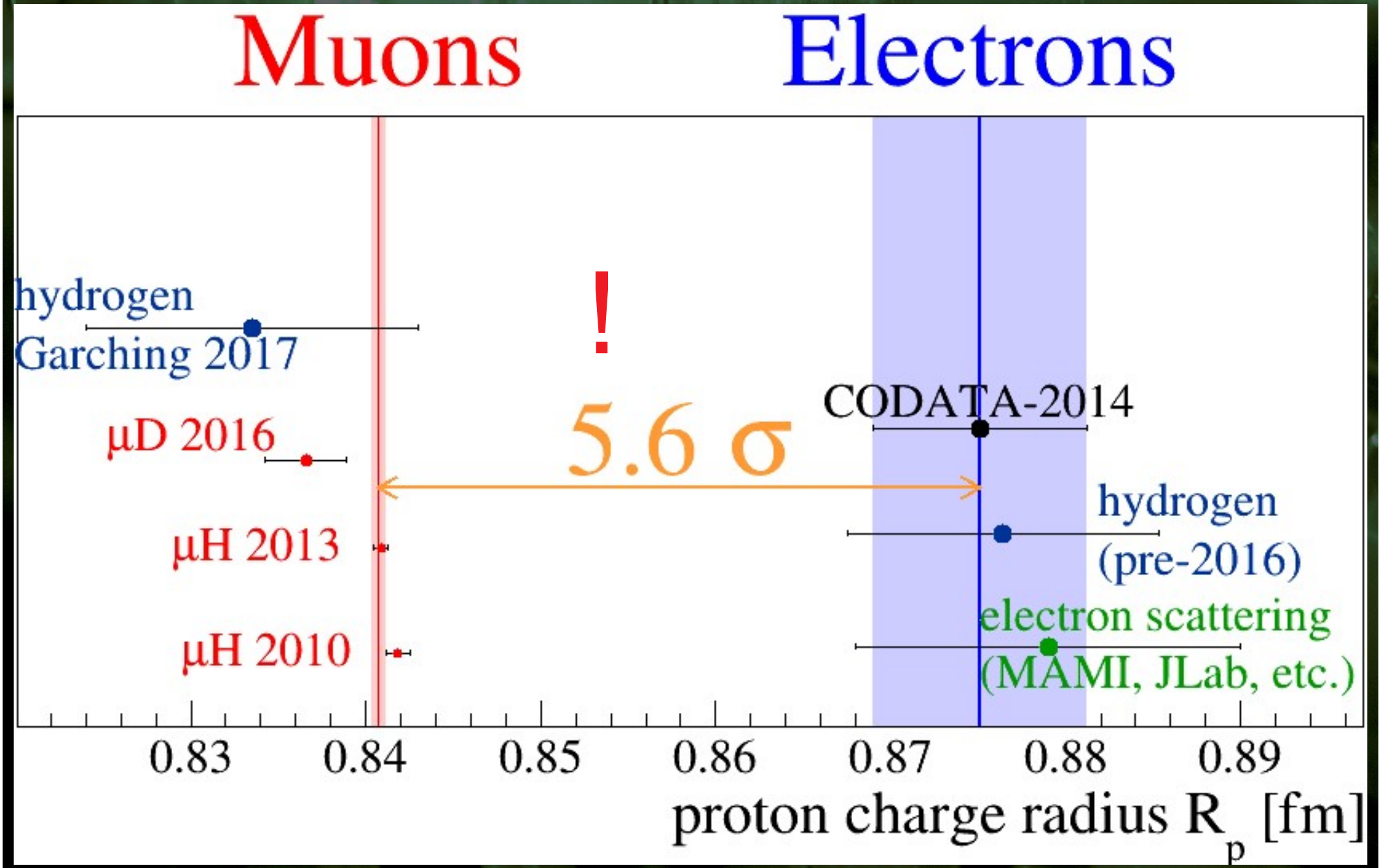
The “Proton Radius Puzzle”



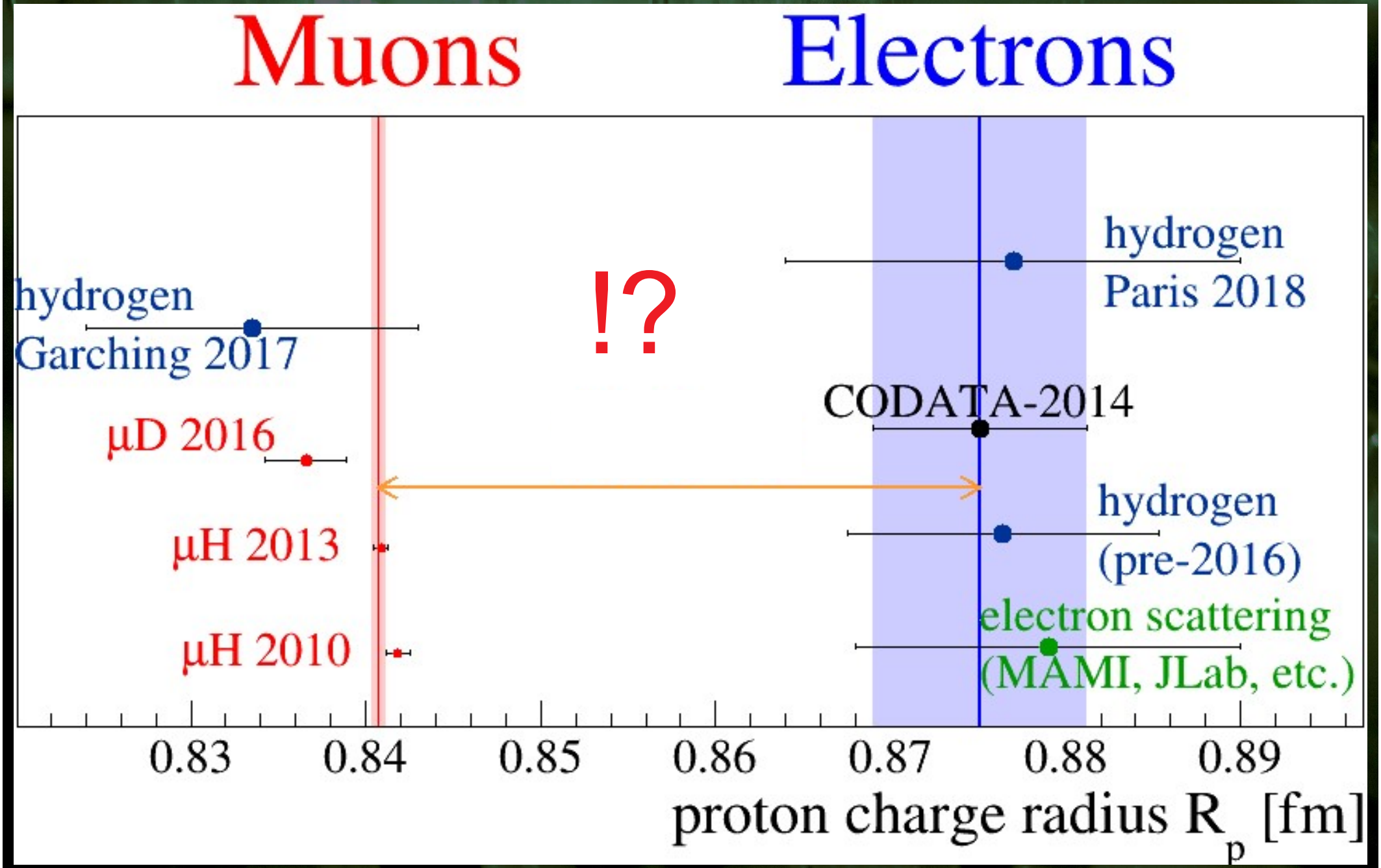
The “Proton Radius Puzzle”



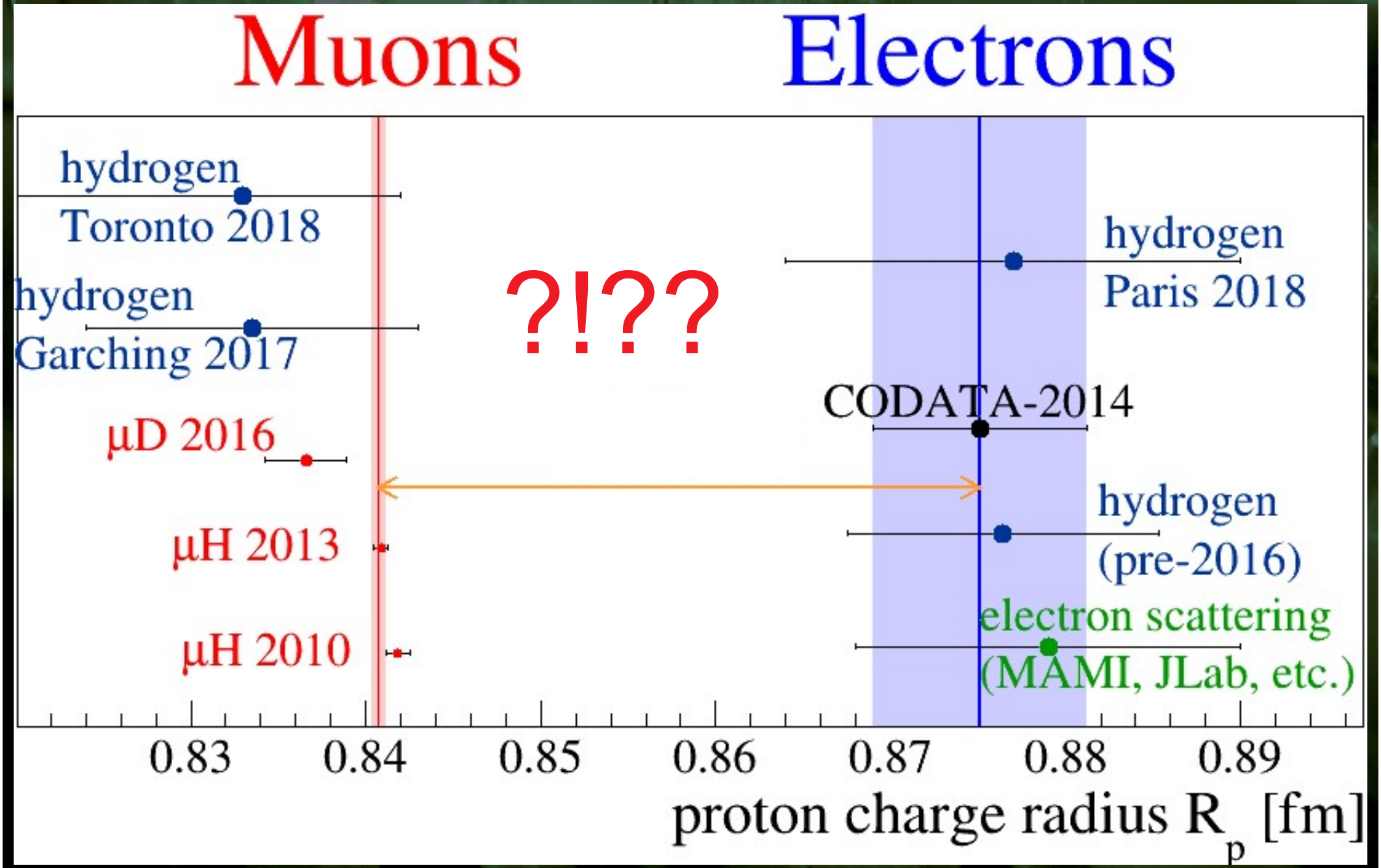
New Measurements



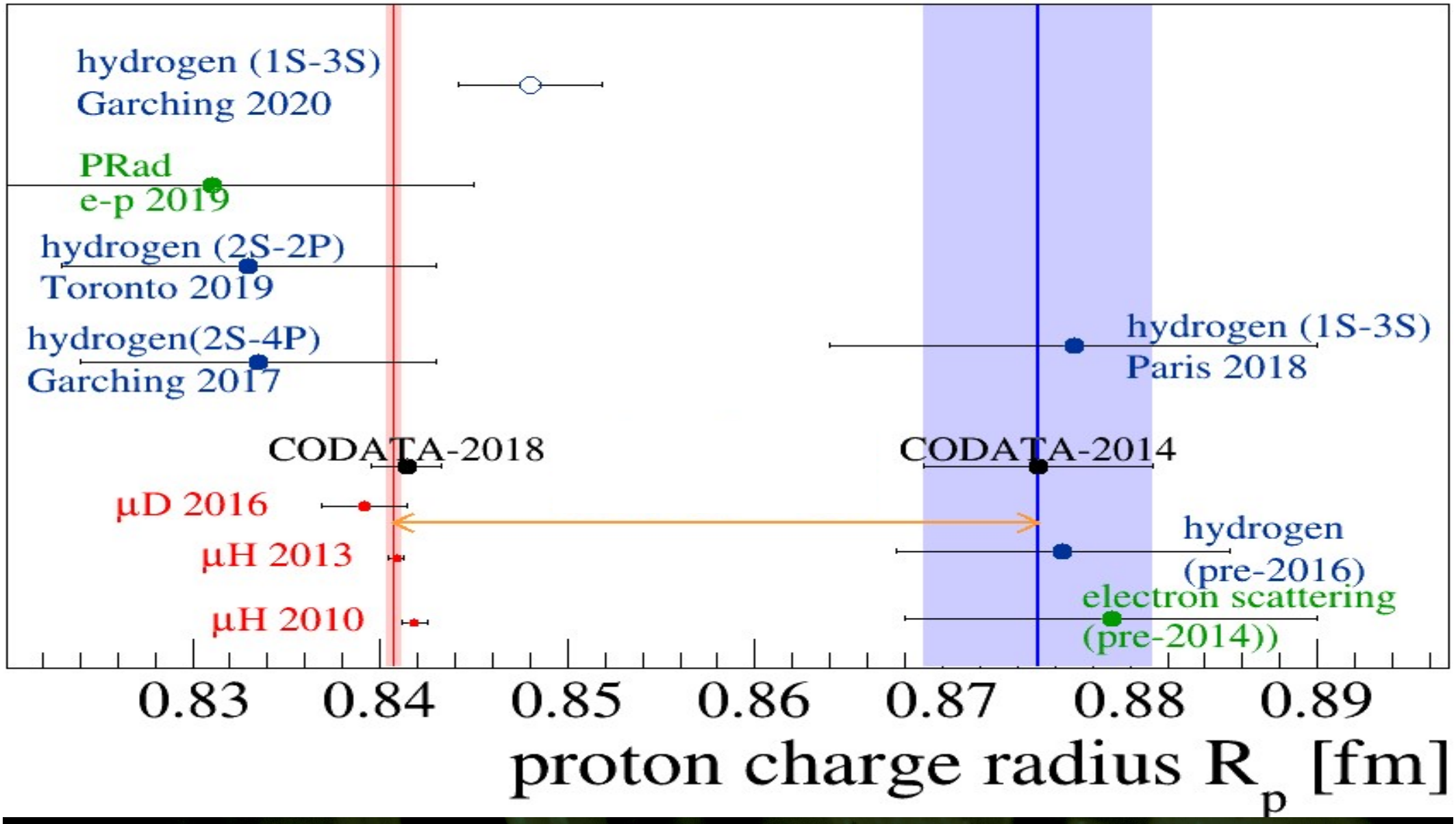
New Measurements



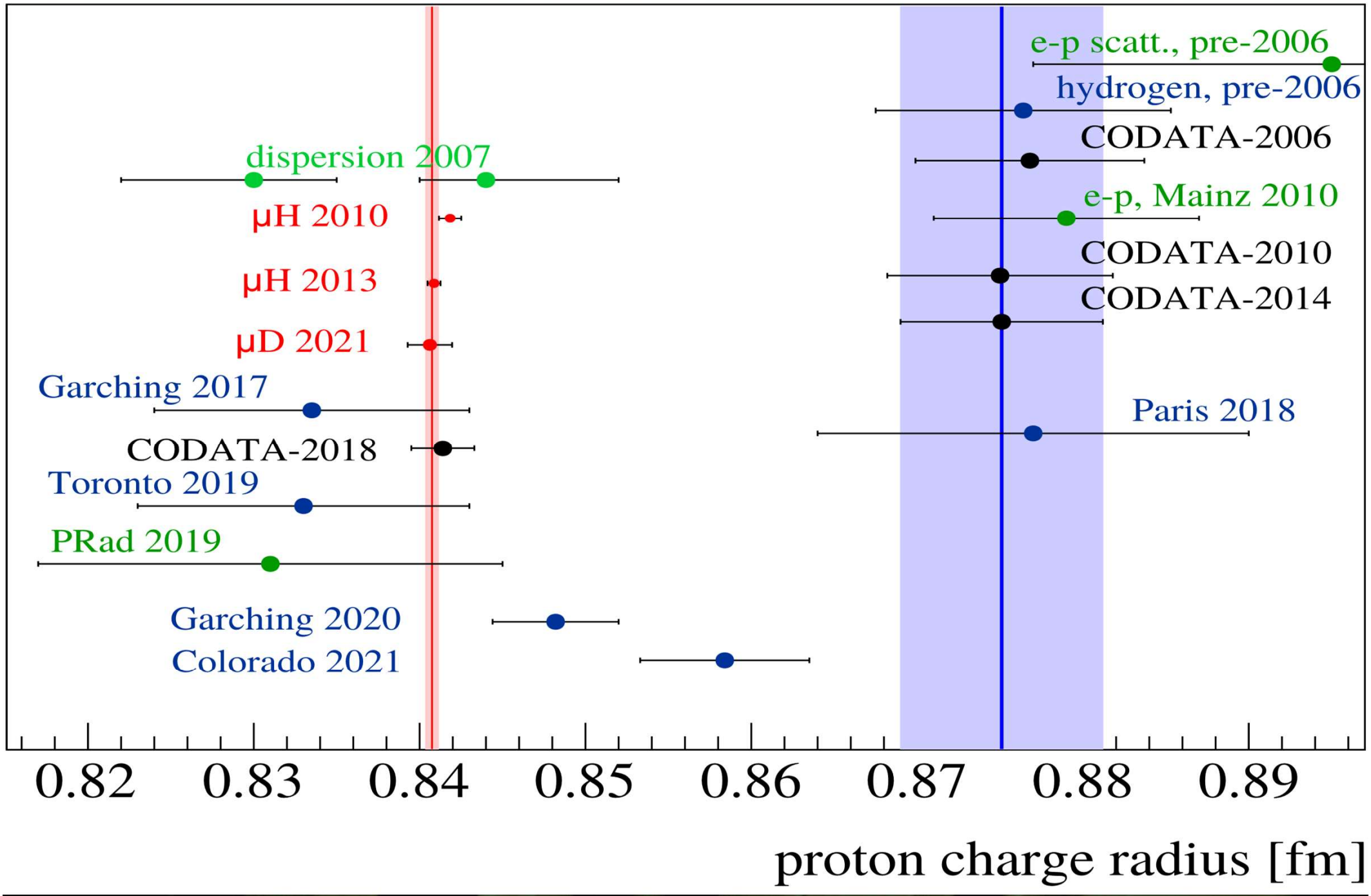
New Measurements



New Measurements



The situation in 2022



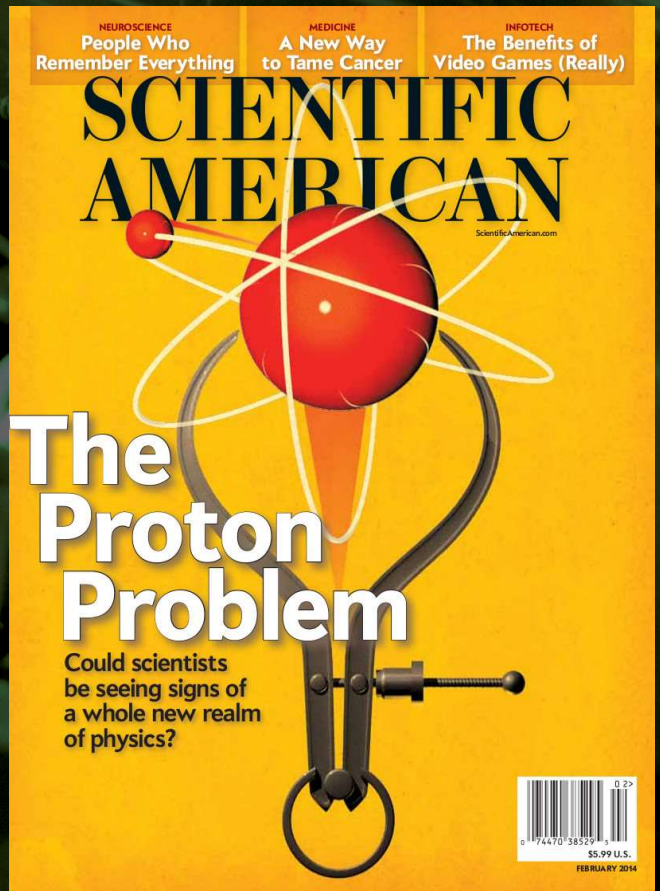
Summary

The “Proton Radius Puzzle” is still not really “solved” after 12 years

Maybe the muon wants to tell us something exciting?

Or a (freaky) measurement error?

A lot of new measurements are on the way.

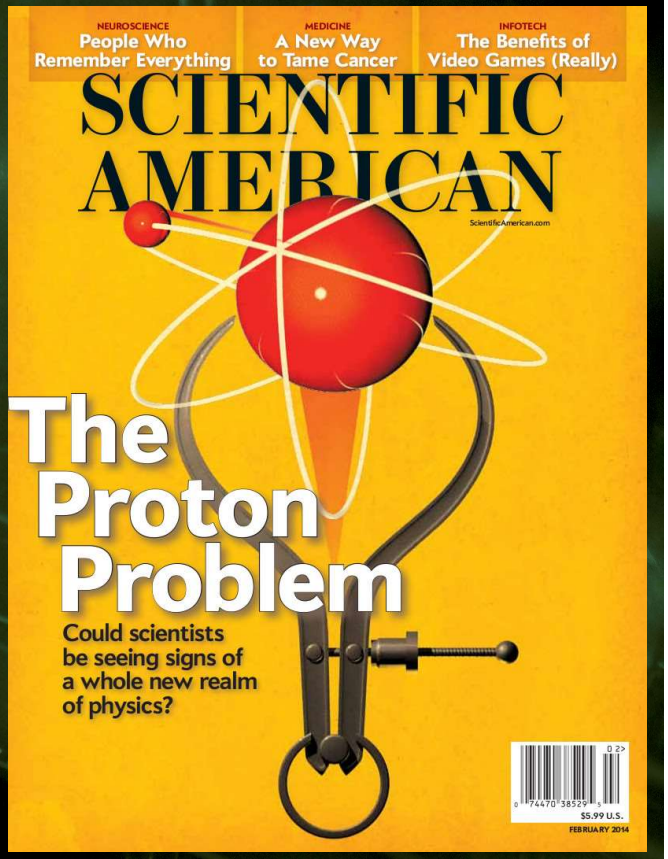


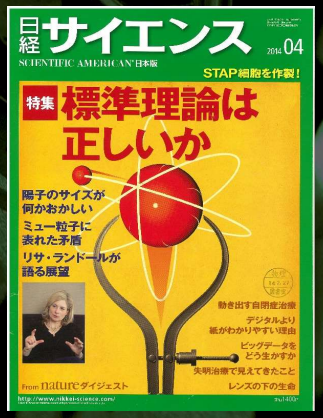
Jan Bernauer & RP, 2014

Proton Size Investigators thank you for your attention

Summary

The “Proton Radius Puzzle” is still exciting!





Jan Bernauer & Randolf Pohl, 2014

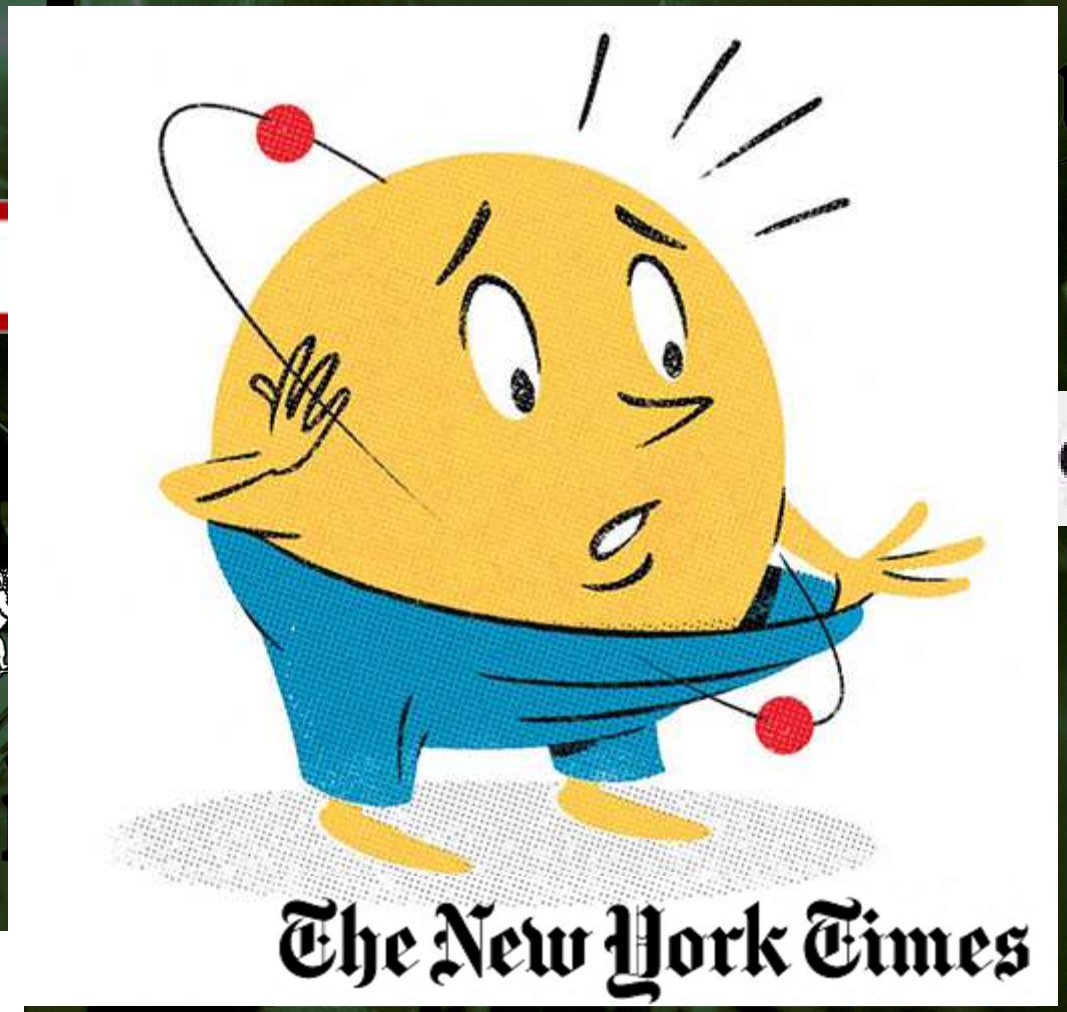

Backup

Resonance to our Resonance

DRS 1

SPIEGE

la Repubbl



NATIONAL GEOGRAPHIC

Los Angeles Times