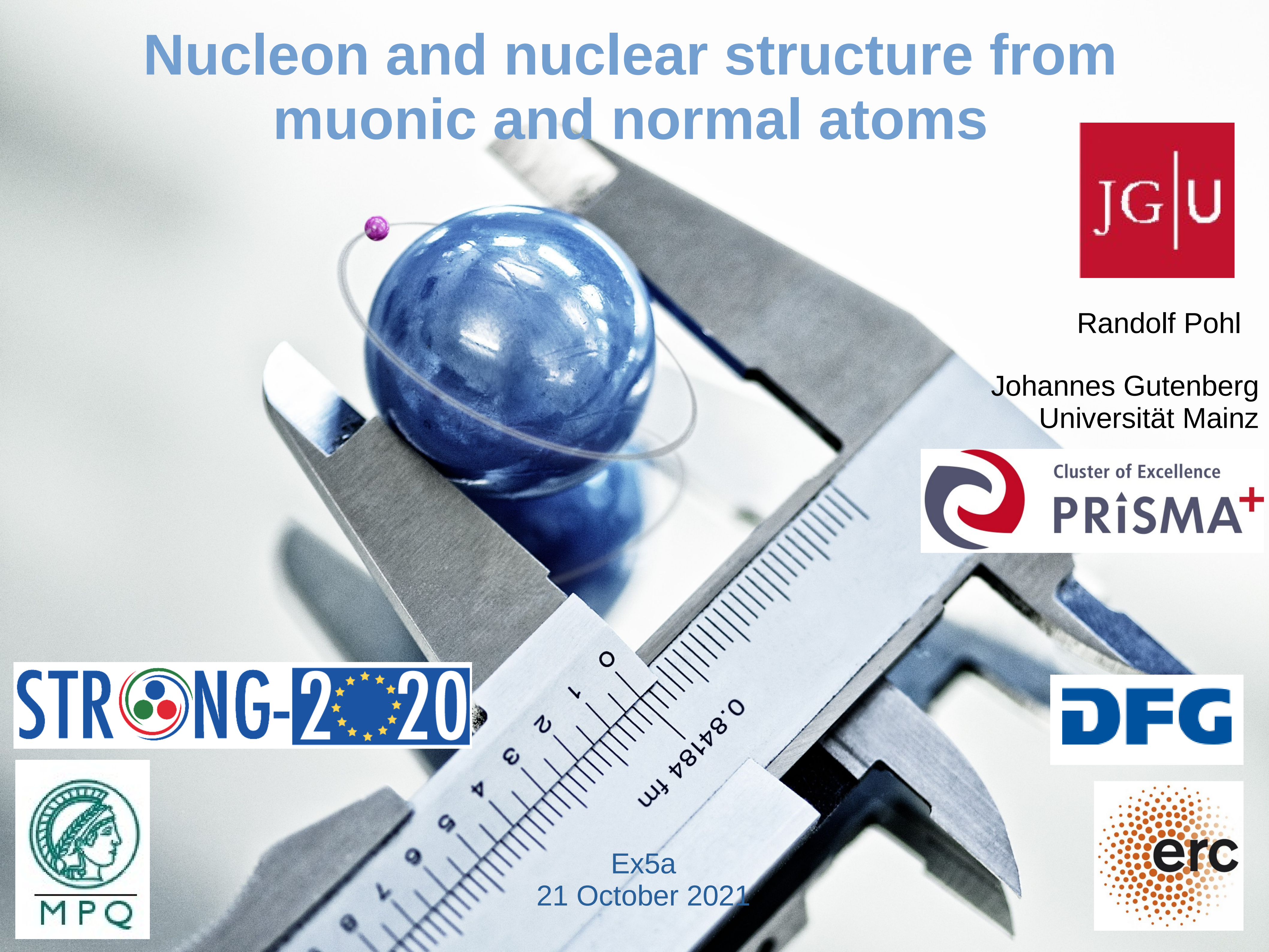
Nucleon and nuclear structure from muonic and normal atoms



Randolf Pohl

Johannes Gutenberg
Universität Mainz

Cluster of Excellence PRISMA+

STRONG-2020

MPQ

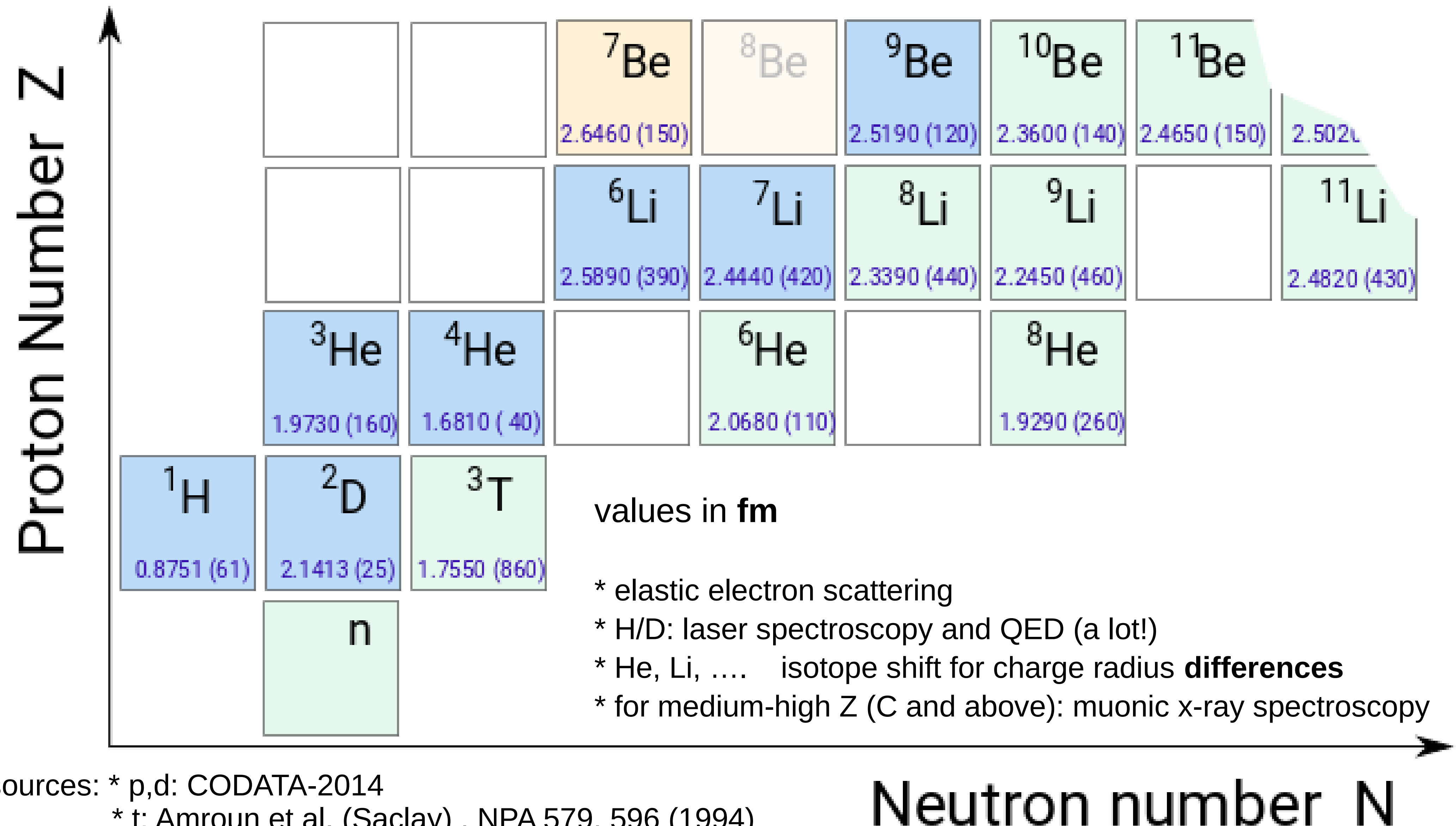
DFG

erc

Ex5a
21 October 2021

Nuclear rms charge radii

from measurements with **electrons**

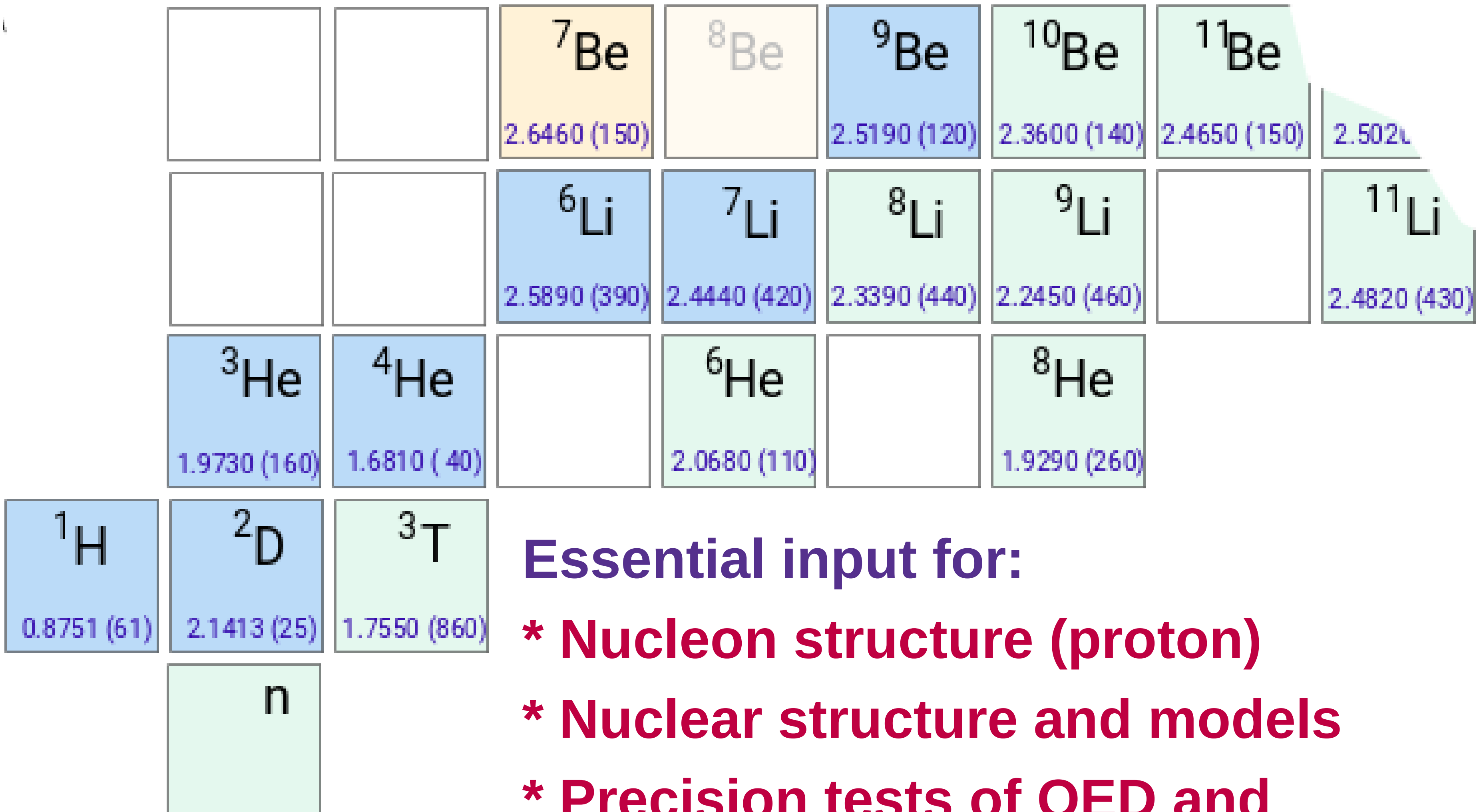


values in **fm**

* elastic electron scattering
* H/D: laser spectroscopy and QED (a lot!)
* He, Li, …. isotope shift for charge radius **differences**
* for medium-high Z (C and above): muonic x-ray spectroscopy

sources: * p,d: CODATA-2014
* t: Amroun et al. (Saclay) , NPA 579, 596 (1994)
* ^{3,4}He: Sick, J.Phys.Chem.Ref Data 44, 031213 (2015)
* Angeli, At. Data Nucl. Data Tab. 99, 69 (2013)

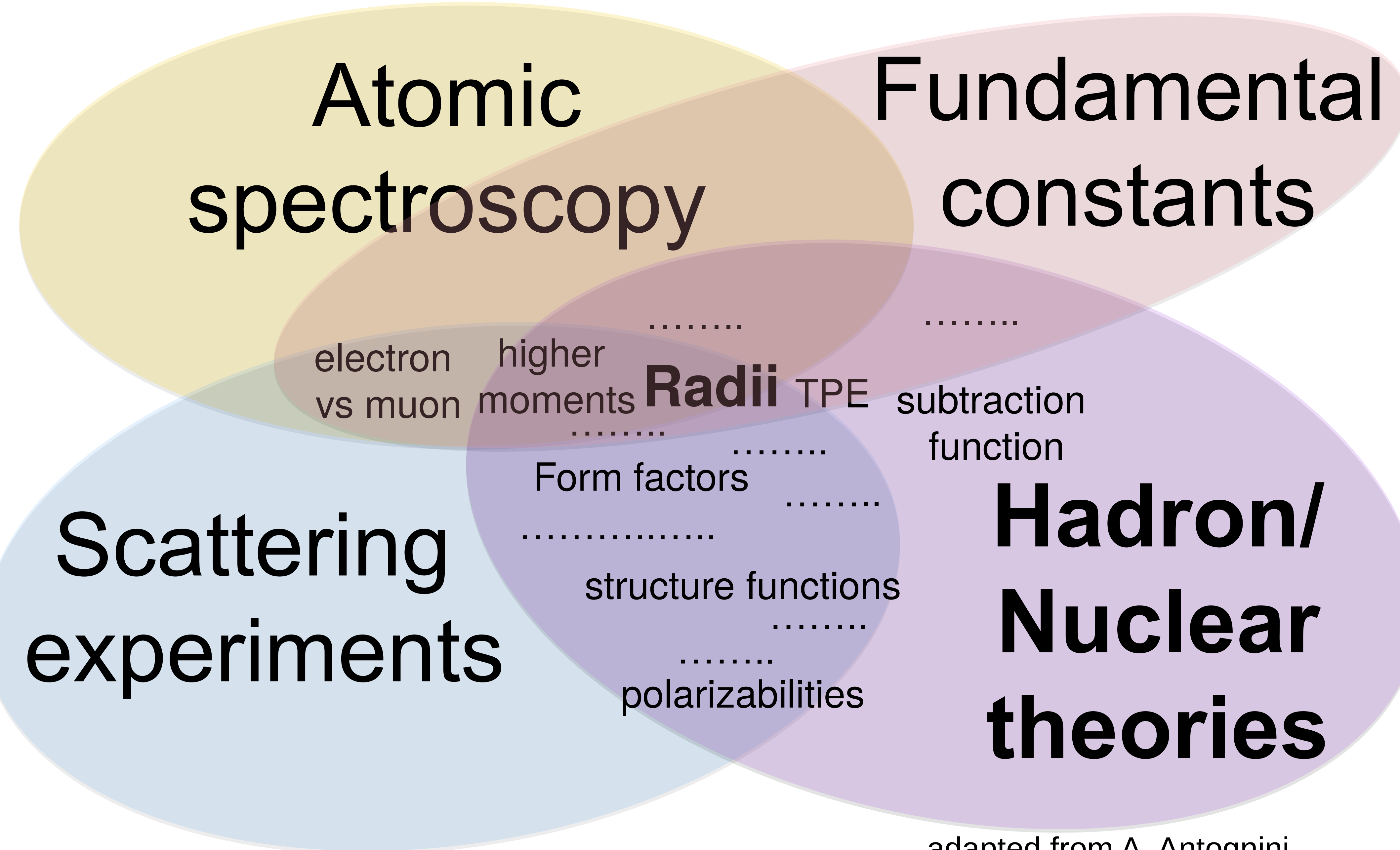
Nuclear radii



Essential input for:

- **Nucleon structure (proton)**
- **Nuclear structure and models**
- **Precision tests of QED and the Standard Model**
- **Fundamental constants (CODATA)**

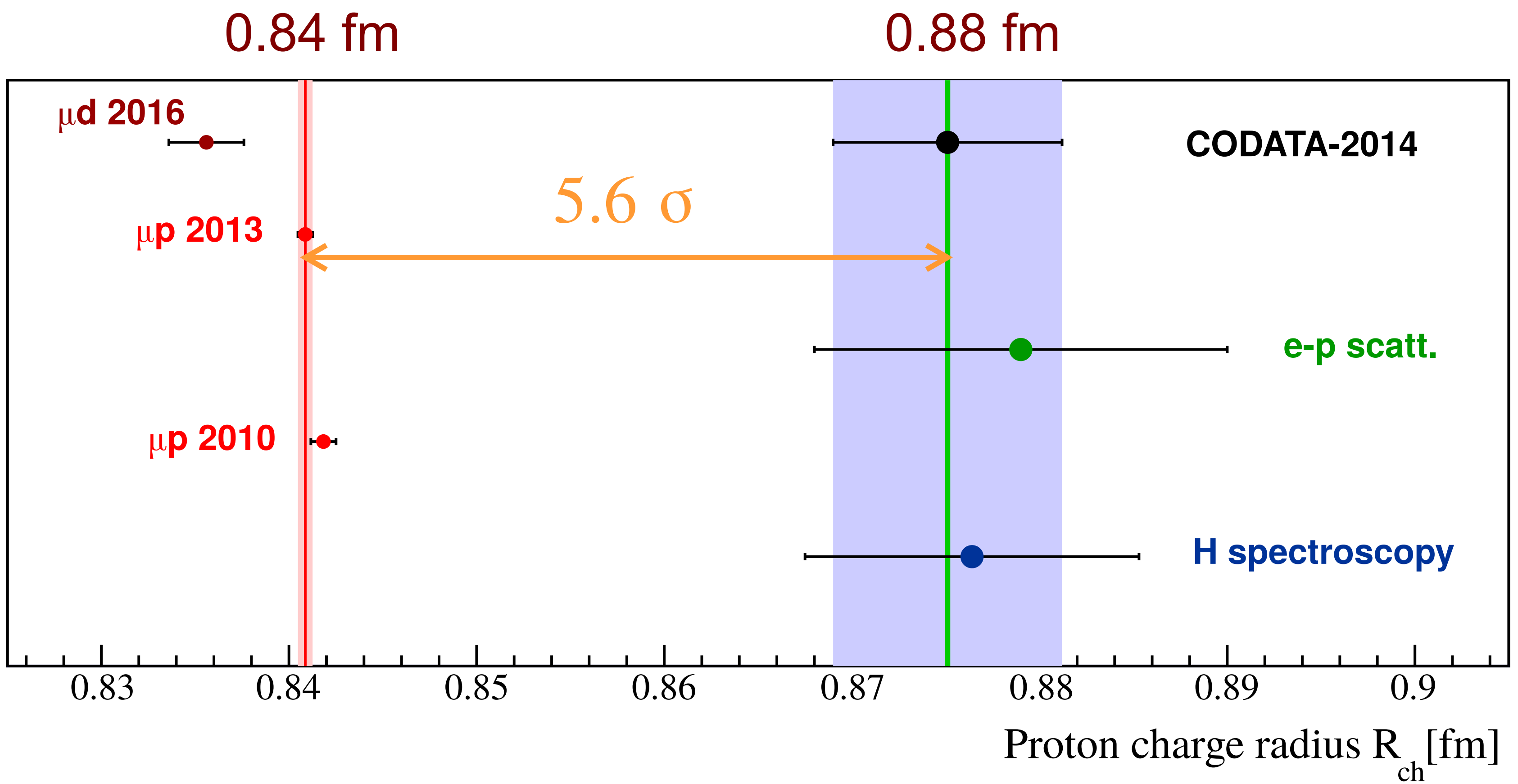
Nuclear radii



adapted from A. Antognini

The “Proton Radius Puzzle”

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



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

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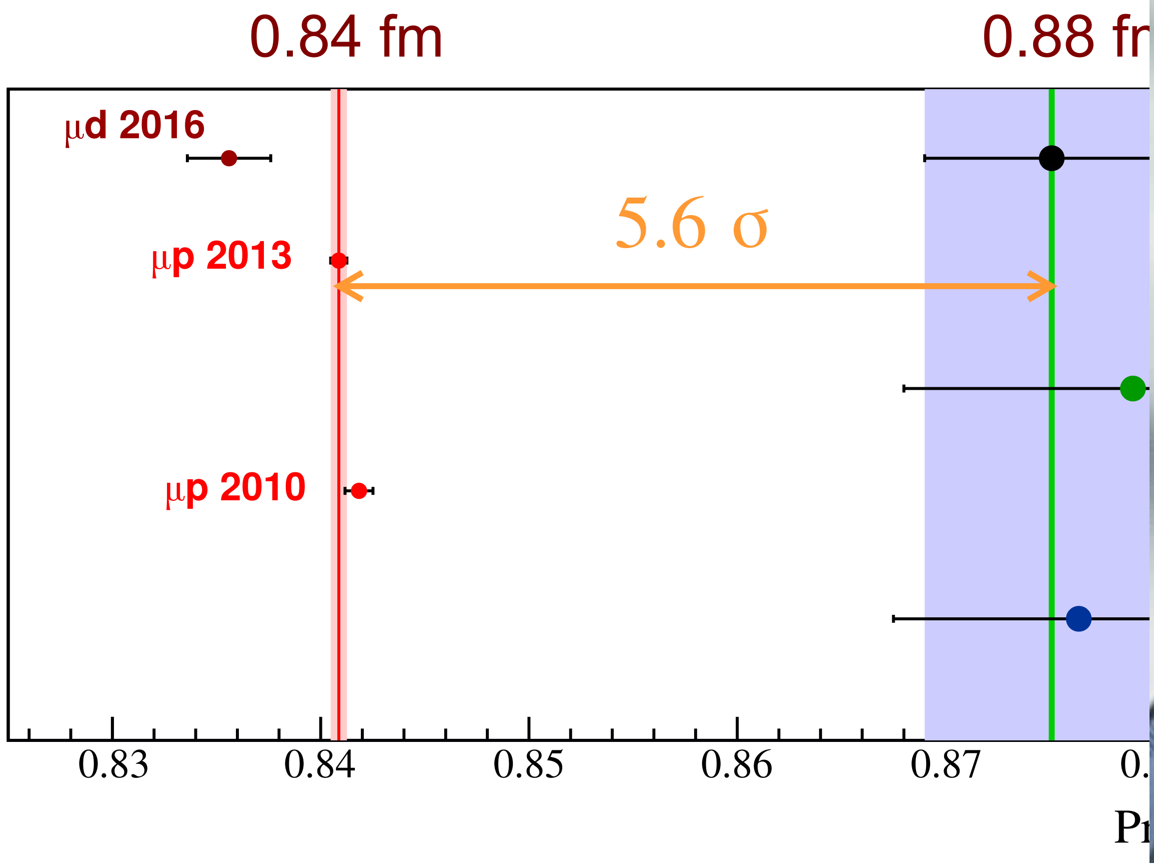

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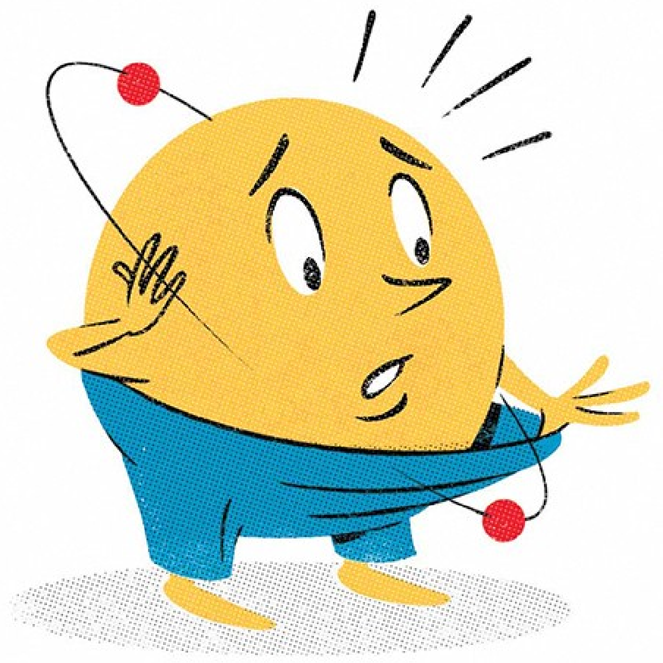
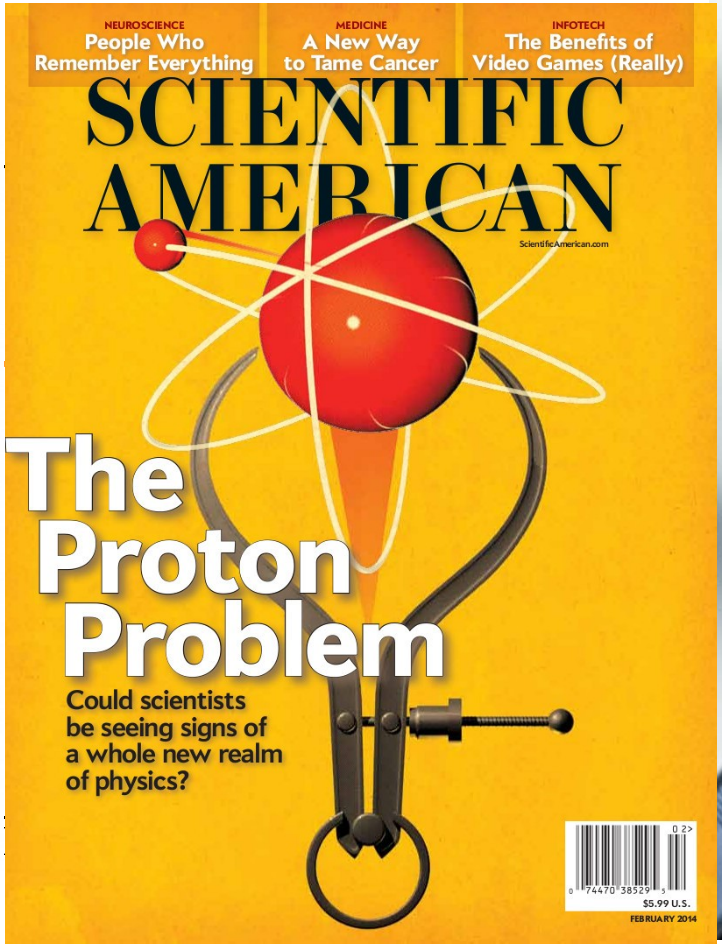
0.84 fm



The New York Times



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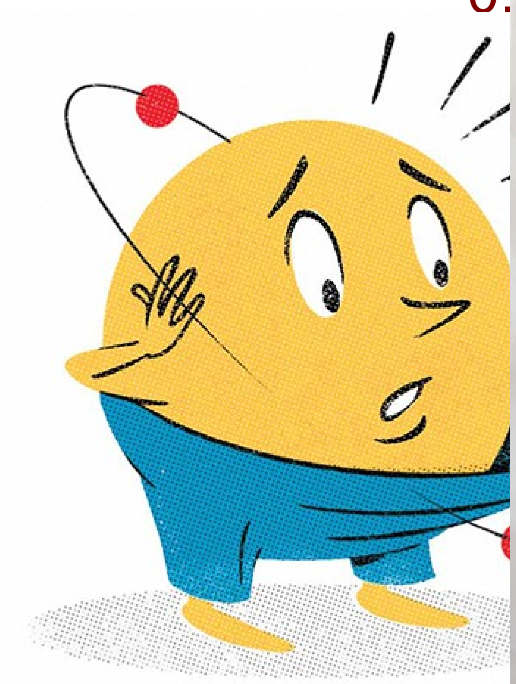
The “Proton Radius Puzzle”

Measuring ... ’%)

5%)

0.

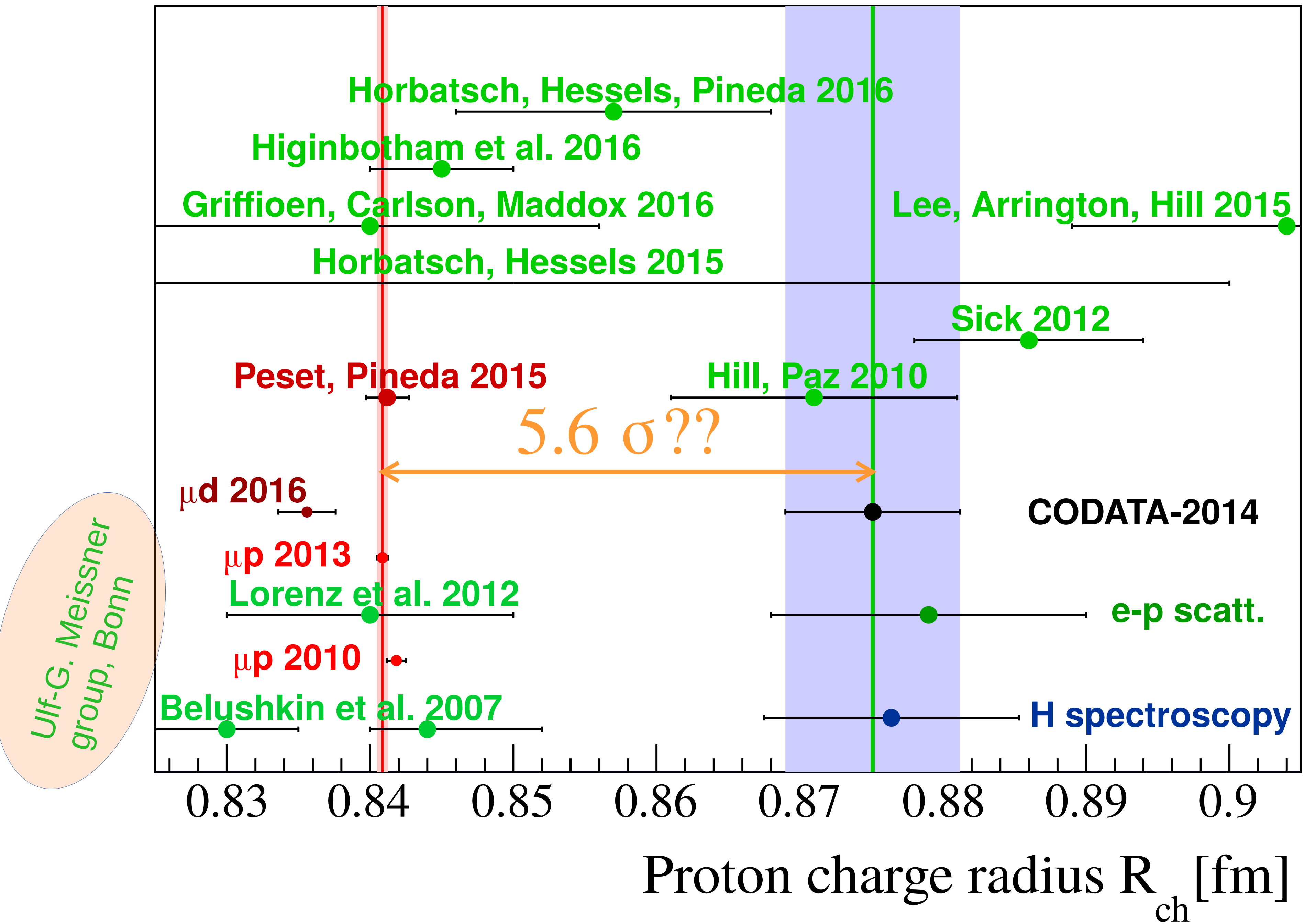


The New York Tim

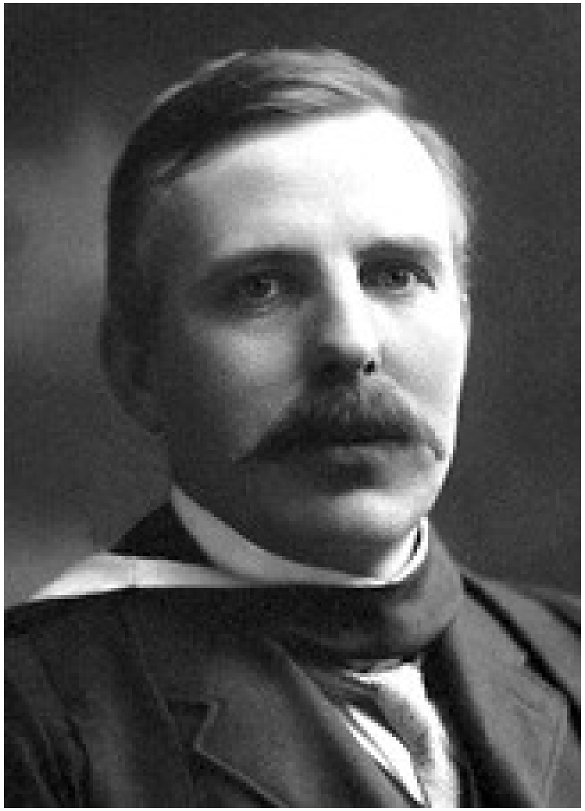
µd 2016: RP et al (CF

µp 2013: A. Antognini

A “Proton Radius **Puzzle**” ??



Ernest Rutherford – 1911



1871 – 1937
Nobel prize 1908

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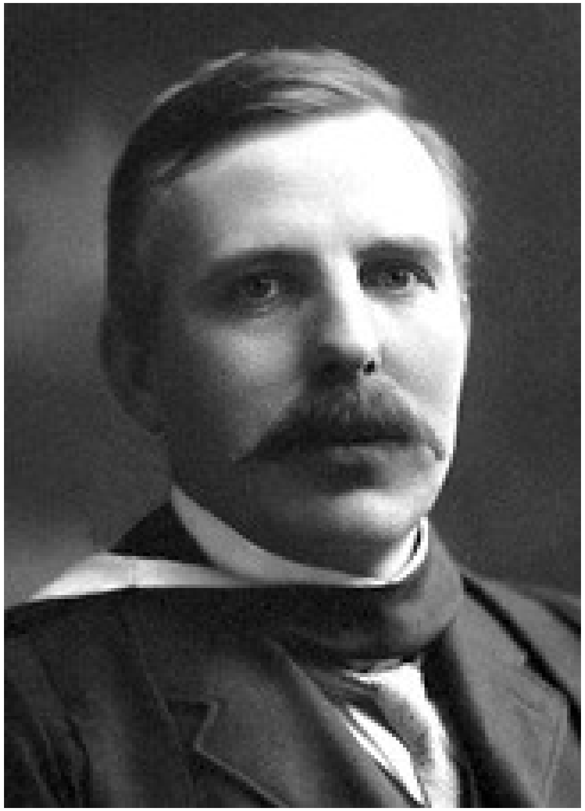

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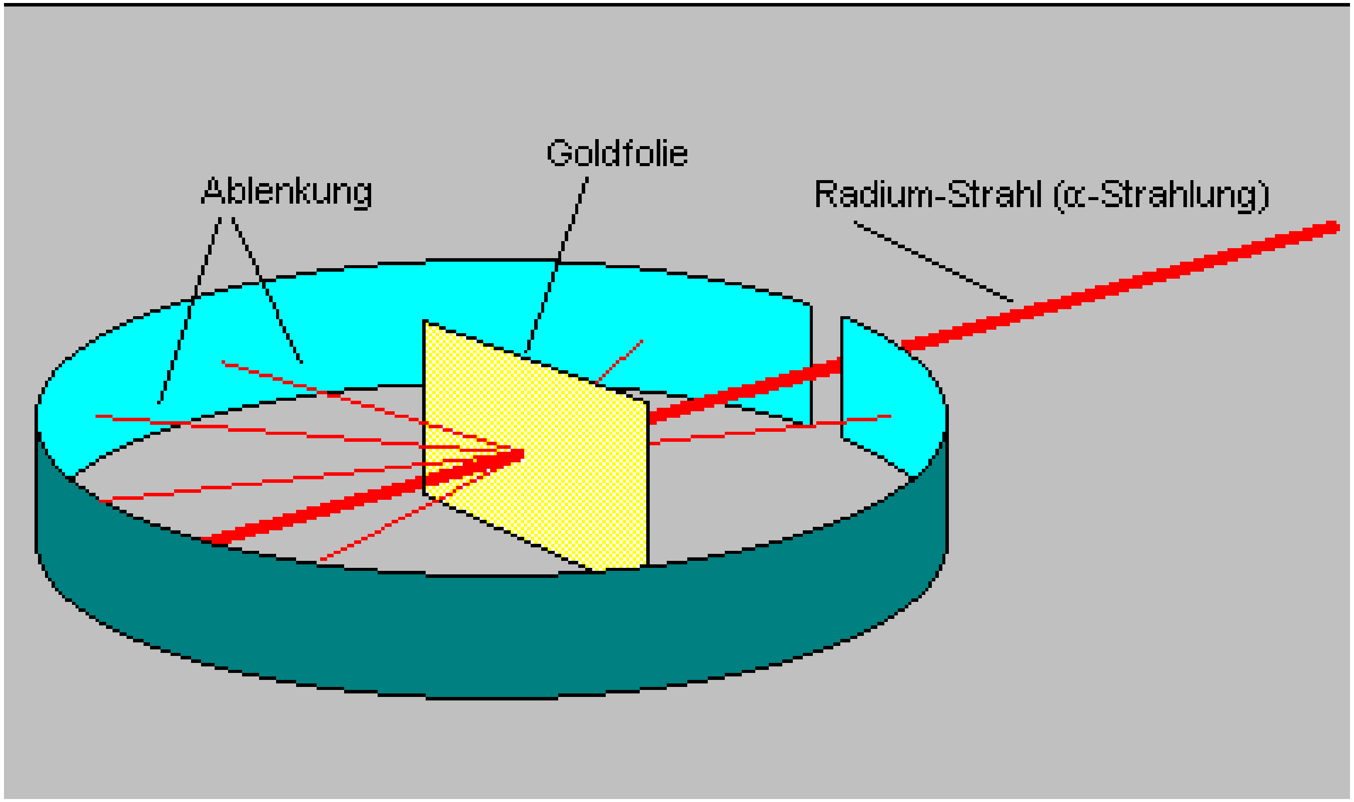
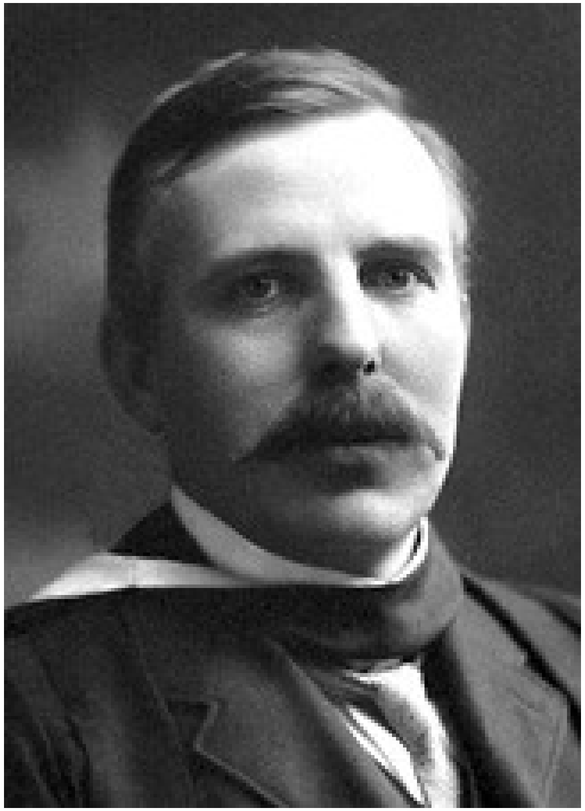
Rutherford shoots alpha particles onto a thin gold foil



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

Ernest Rutherford – 1911



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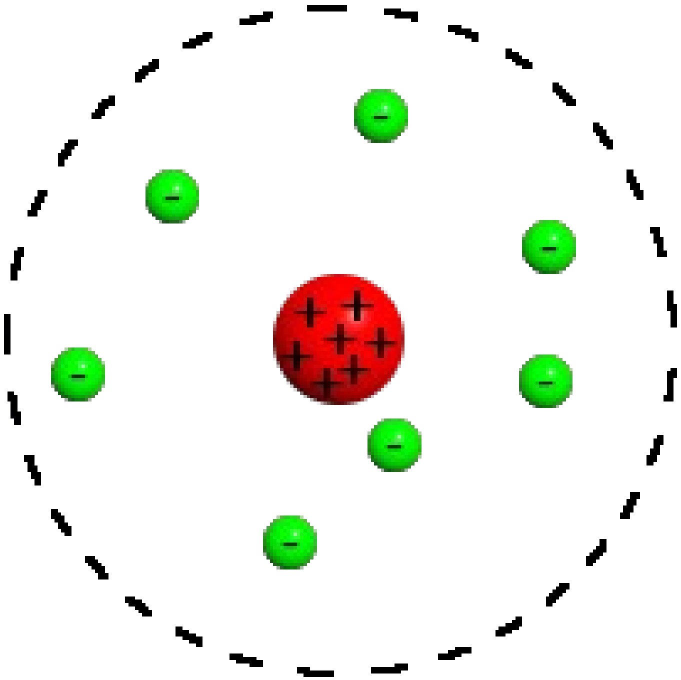
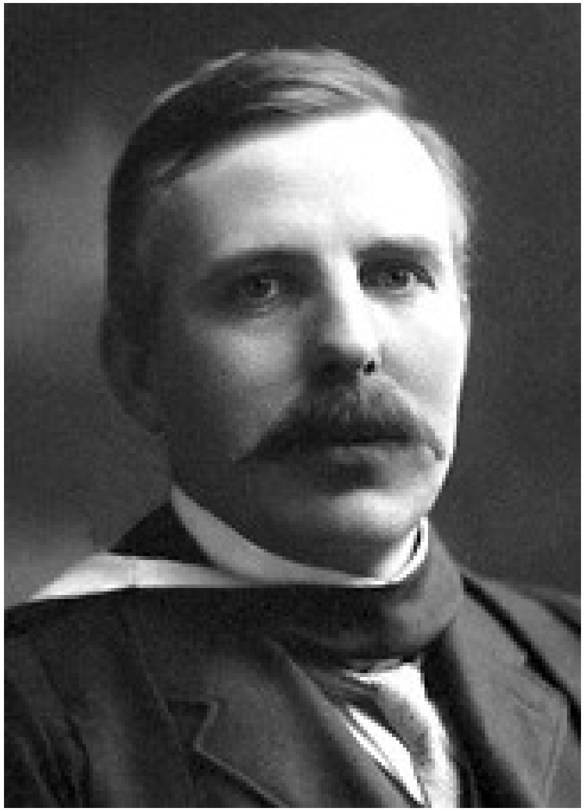


The Atom is a

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

orbited by negatively charged **Electrons**

Ernest Rutherford – 1917

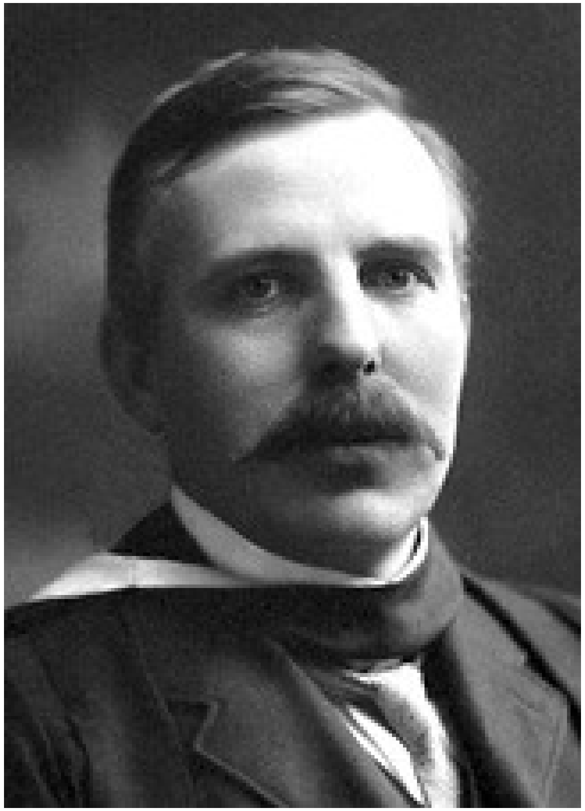


$^{14}N + \alpha \rightarrow {}^{17}O + p$

Rutherford achieves first man-made nuclear reaction.

Thereby he discovers the **Proton**.

Ernest Rutherford – 1917



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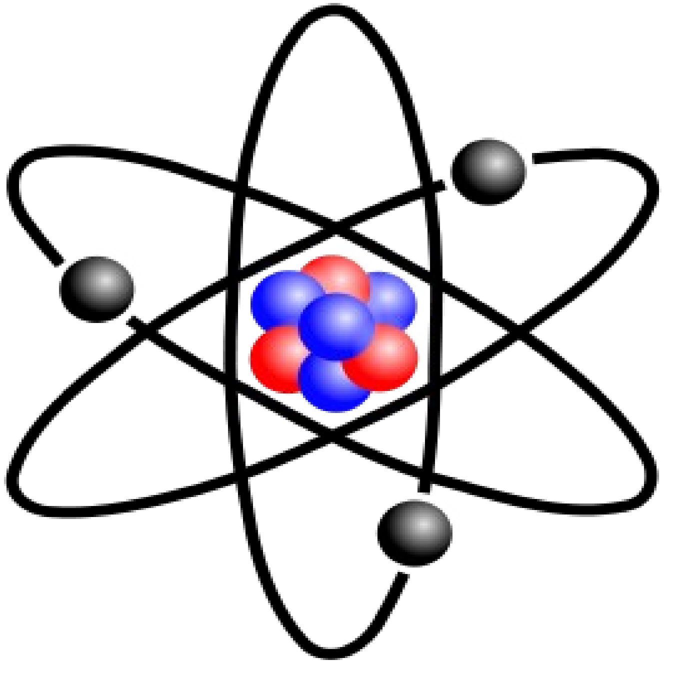
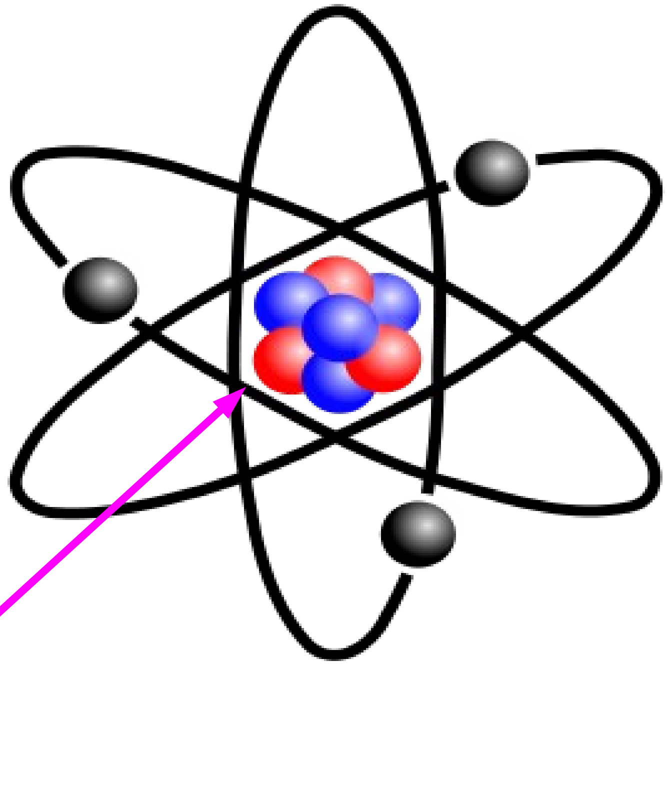
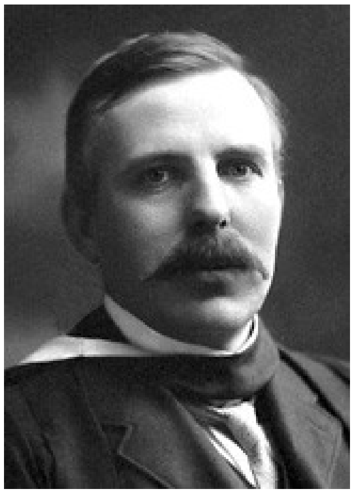
104 years of the proton !!!

Building blocks of matter



Building blocks of matter

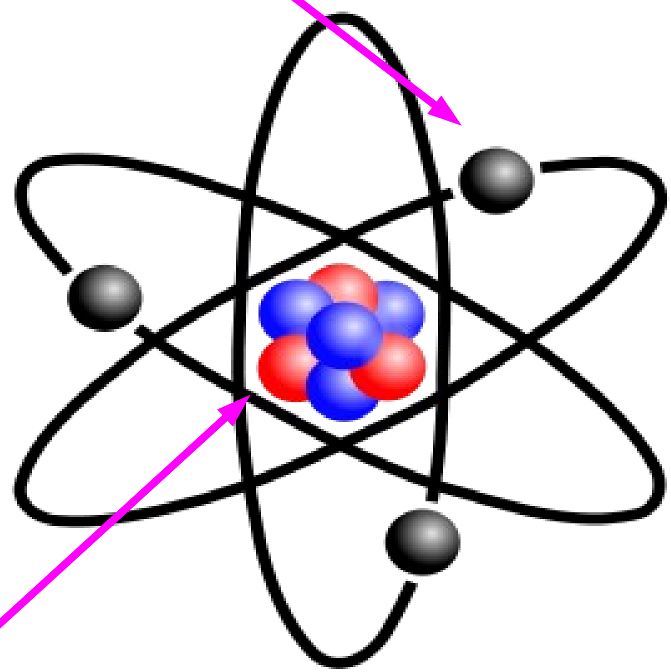


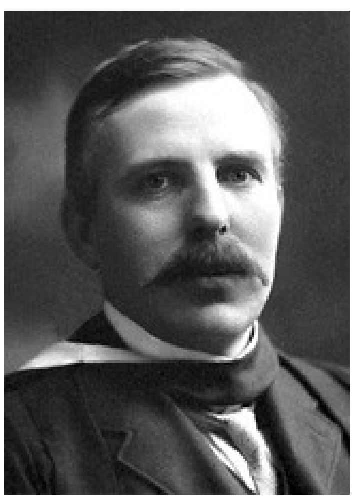


Proton: Ernest Rutherford
(1917)

Building blocks of matter

Electron: Joseph John Thomson
(1897)





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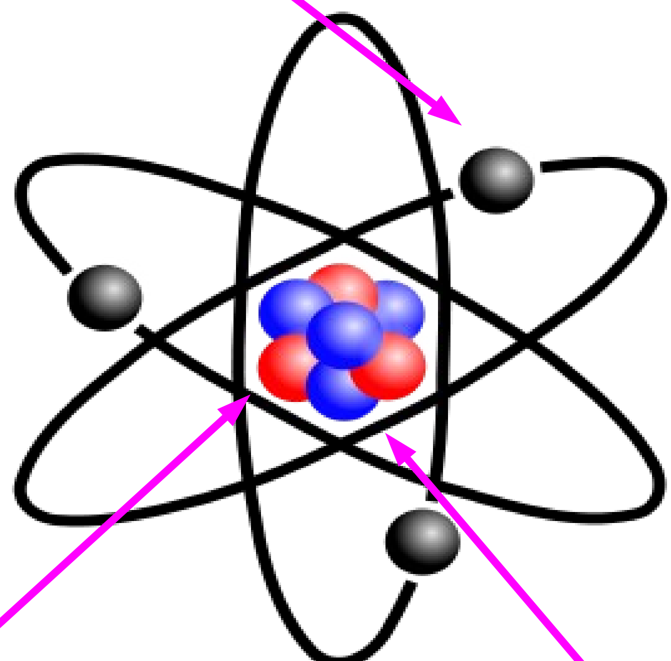
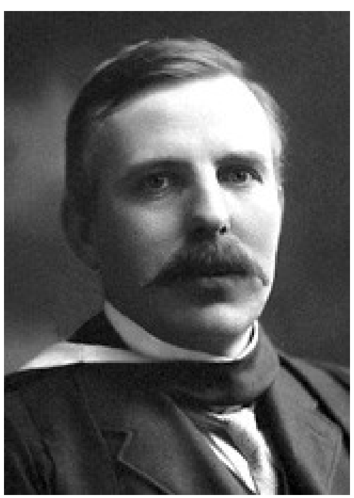
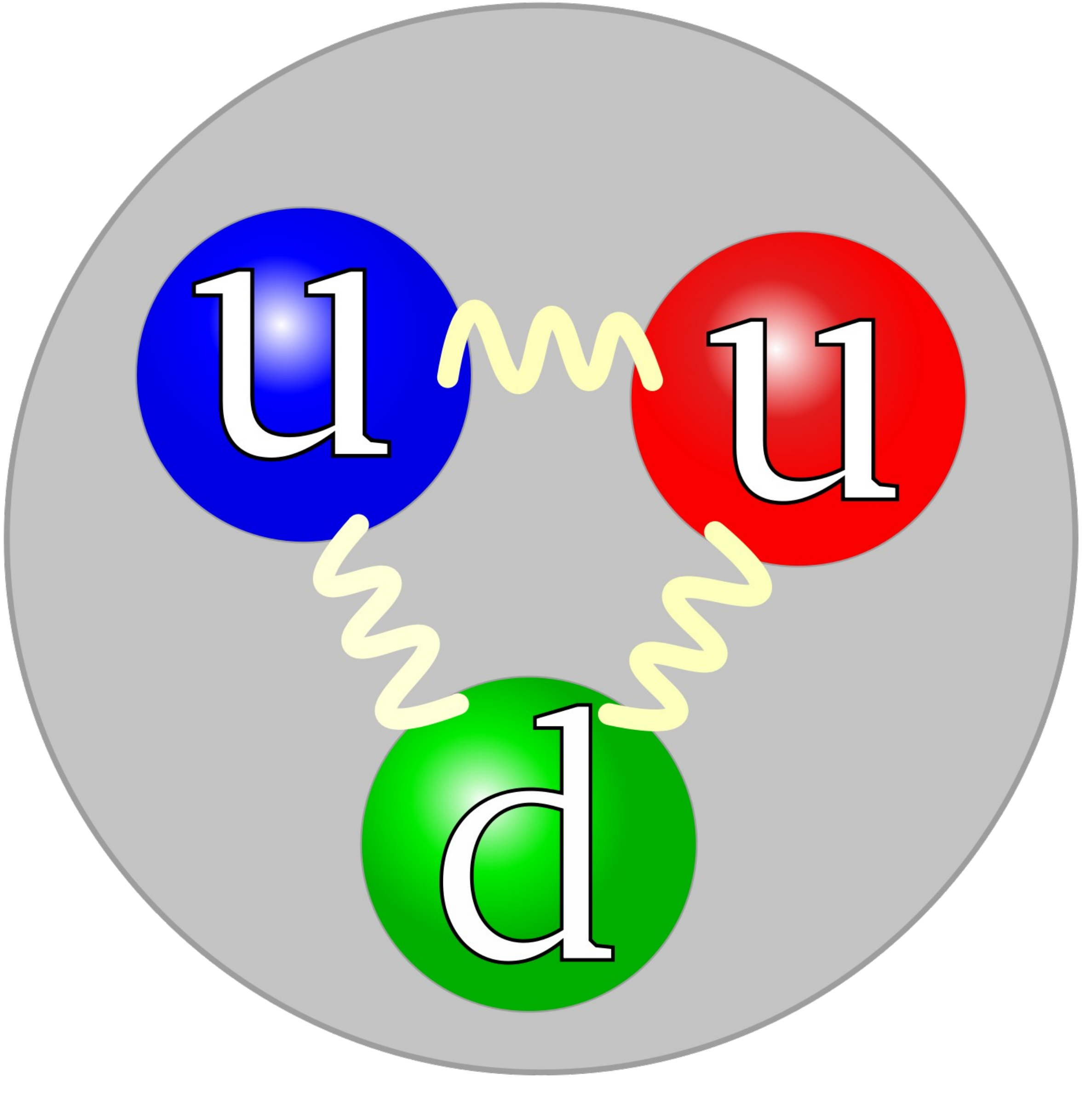




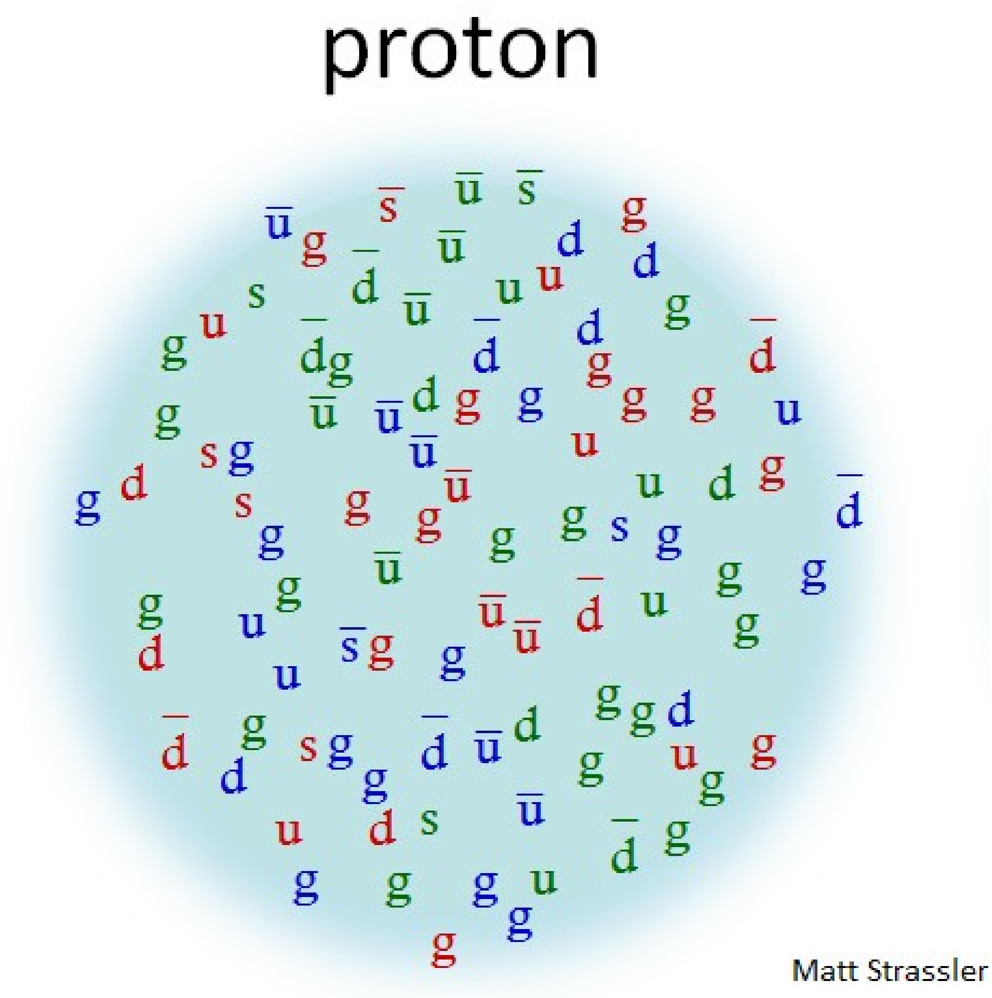
Proton: Ernest Rutherford
(1917)

Neutron: James Chadwick
(1932)
At the same time: **Deuterium!**
(Urey 1932)

Proton – 3 Quarks



Proton – >>3 Quarks



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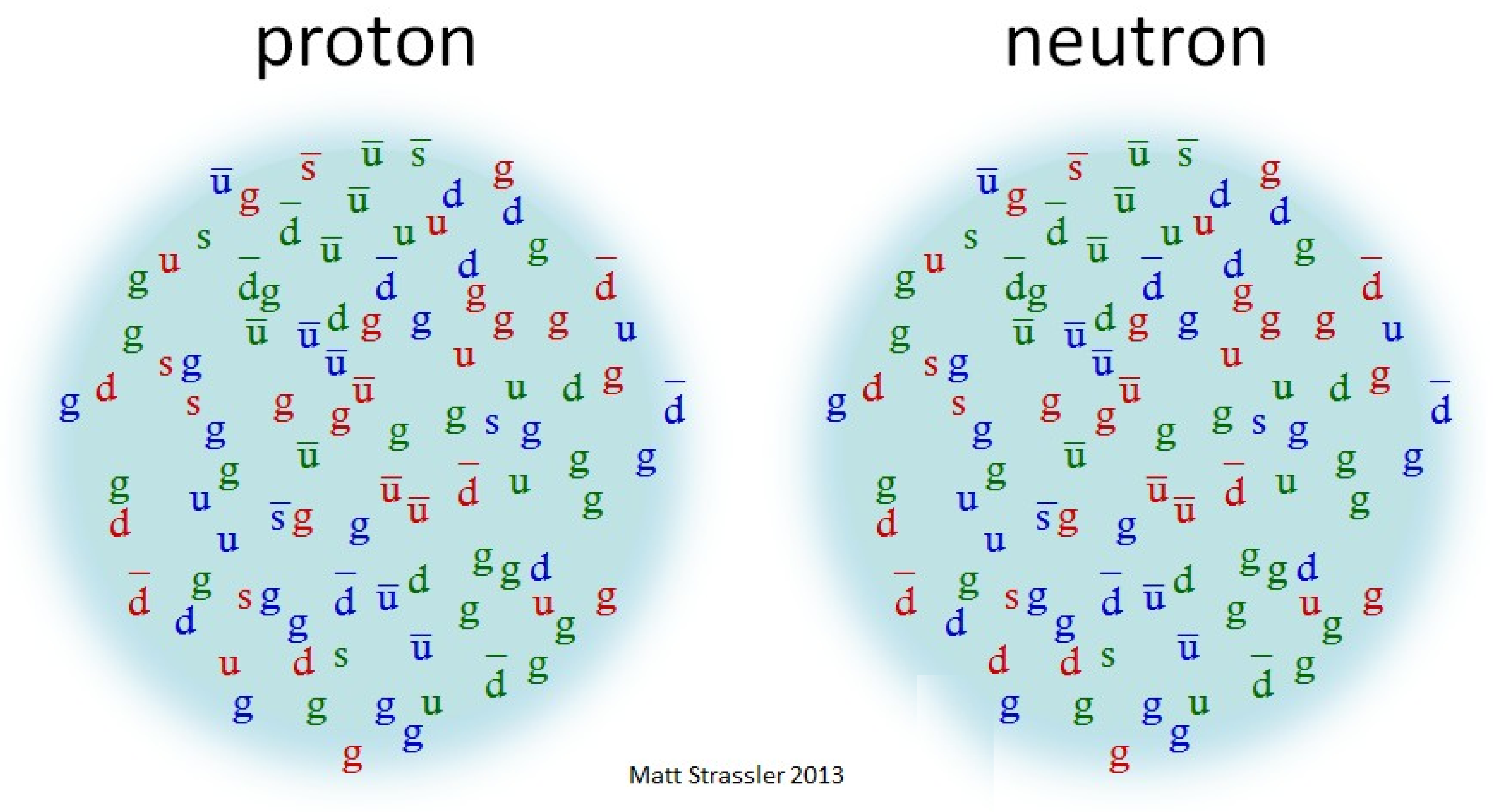
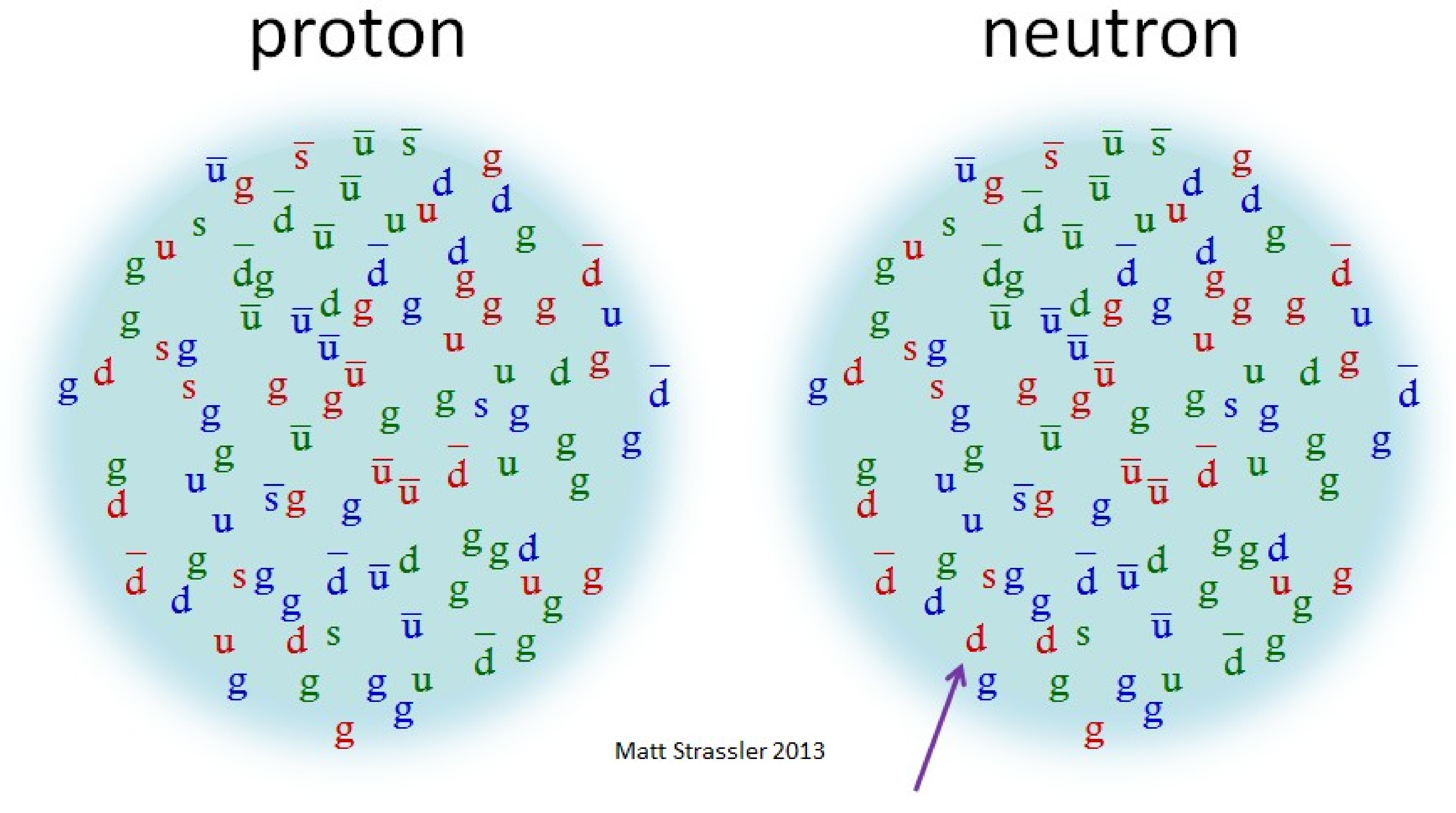


Proton –   >>3 Quarks



Robert Hofstadter – 1955

1915 – 1990
Nobel prize 1961

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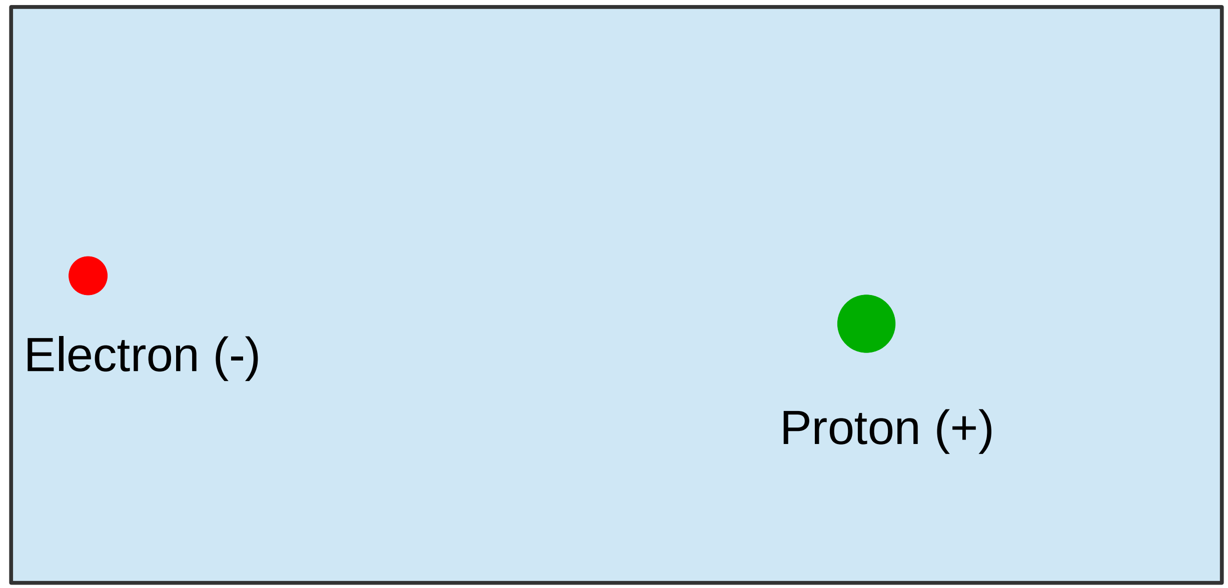
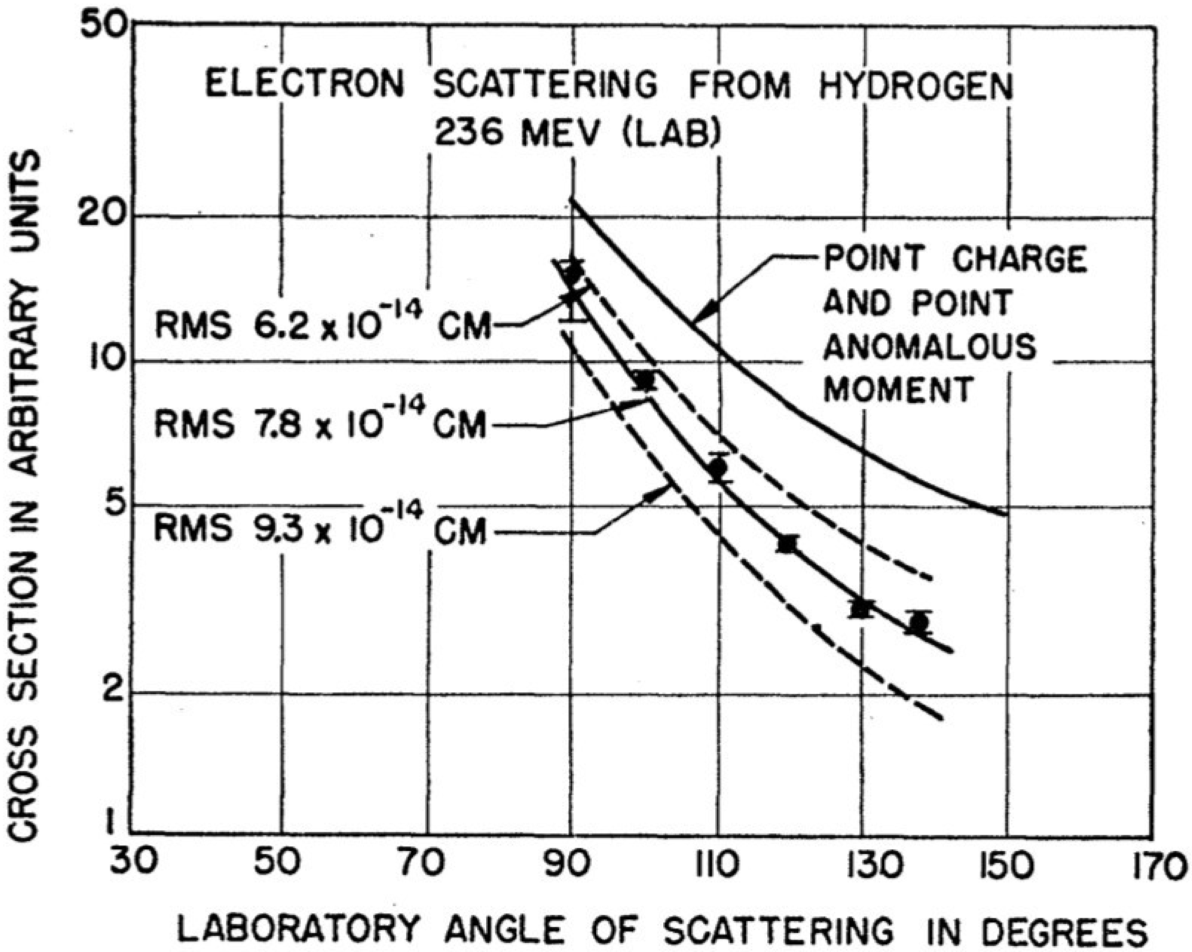


Scattering of (negatively charged) Electrons off (positively charged) Protons.

1915 – 1990
Nobel prize 1961

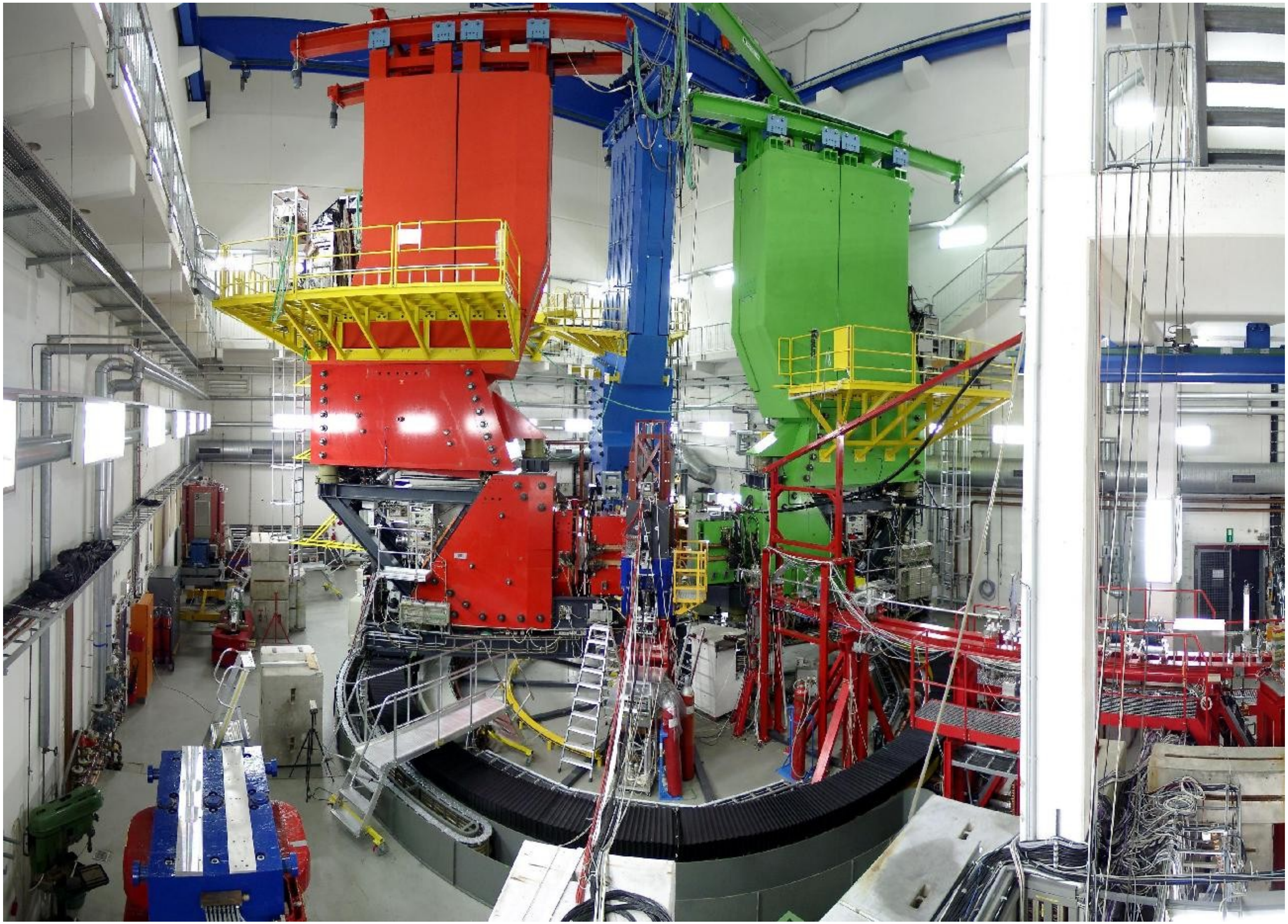
Robert Hofstadter – 1955

1915 – 1990
Nobel prize 1961



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

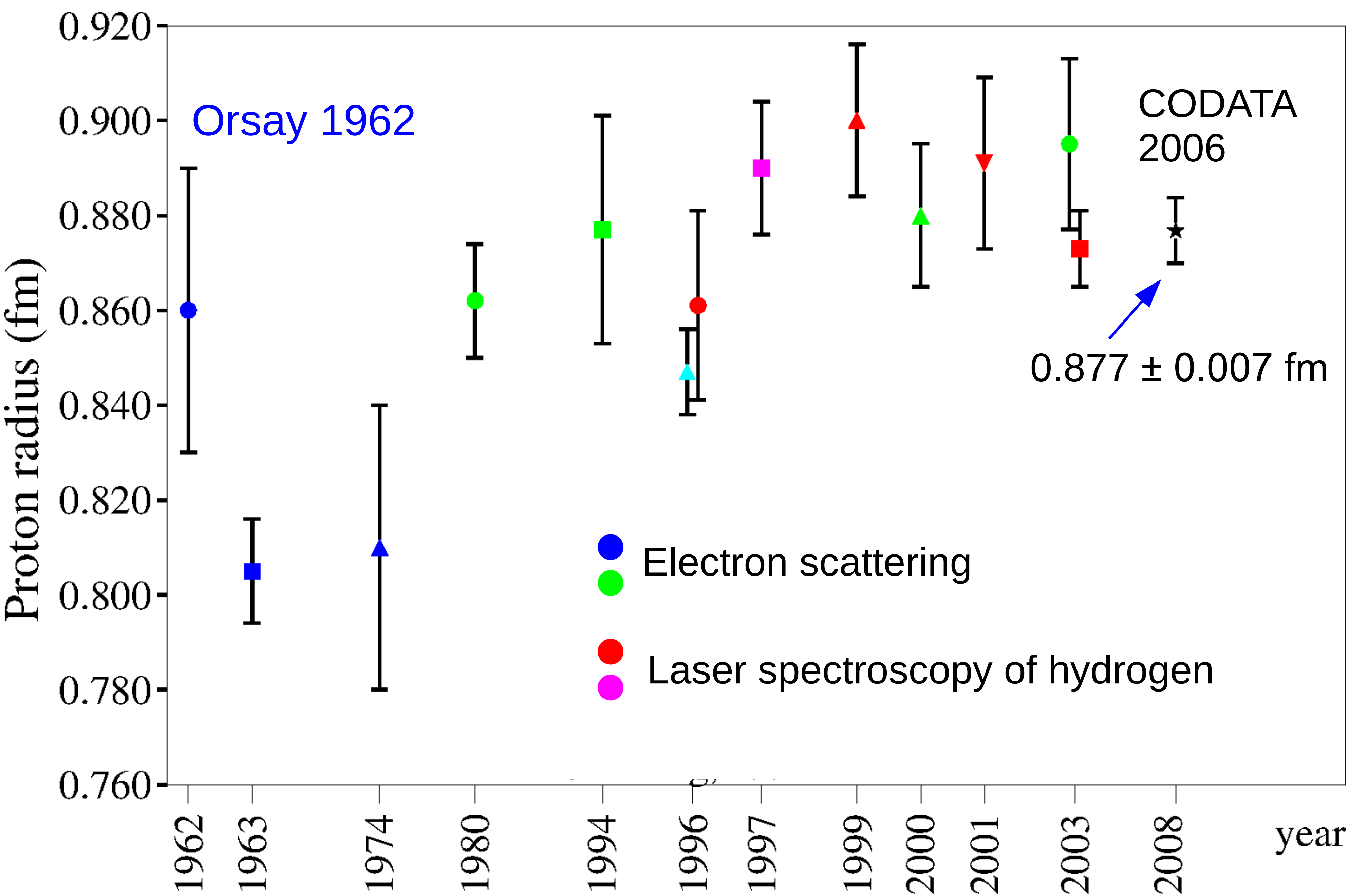
Mainzer Microtron MAMI



Mainzer Microtron
MAMI

Mainzer Microtron
MAMI

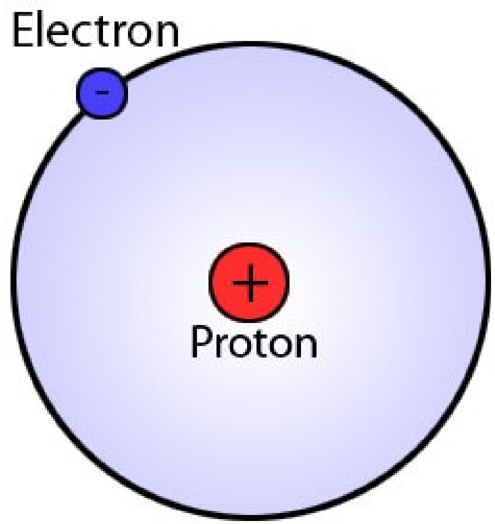
How large is a Proton?



Hydrogen

The Hydrogen Atom

One Proton, orbited by *one* Electron.



The Hydrogen Atom

Nils Bohr

1885 – 1962
Nobel prize 1922

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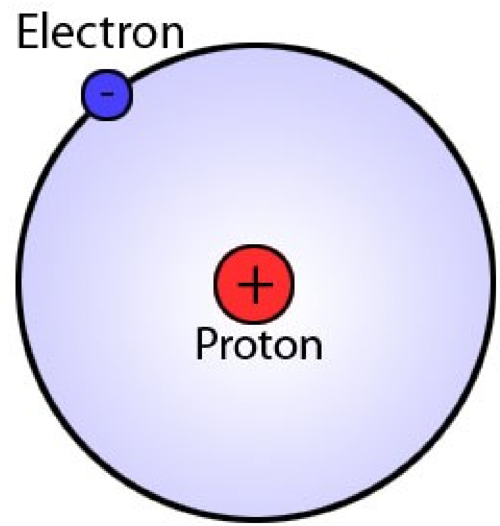

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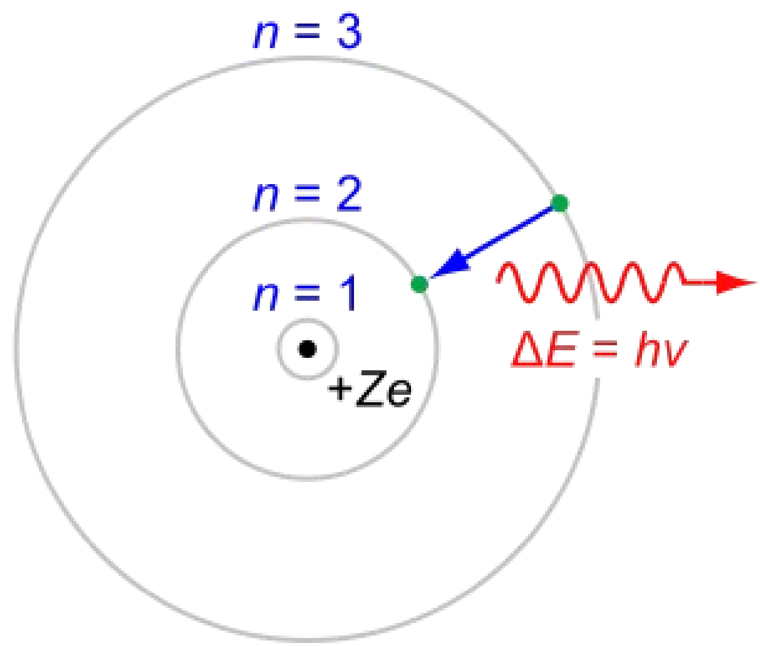

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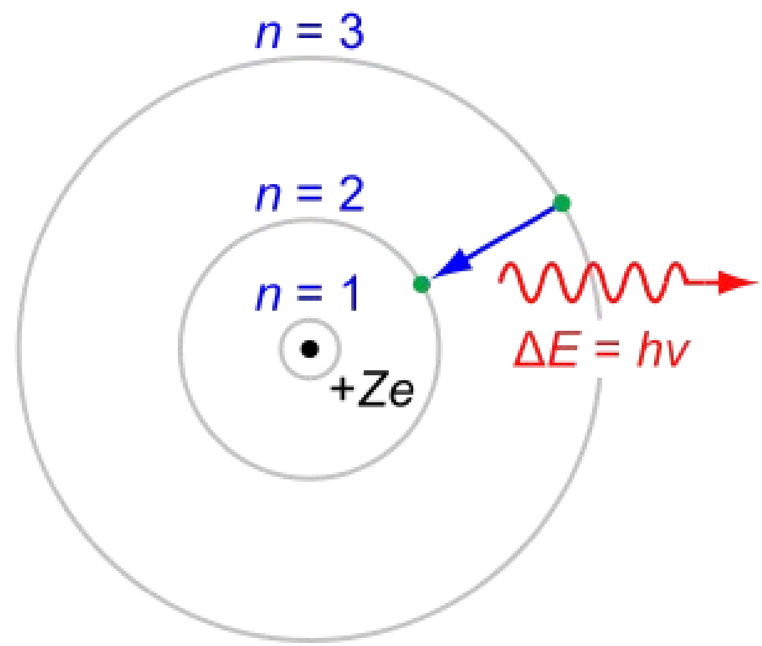


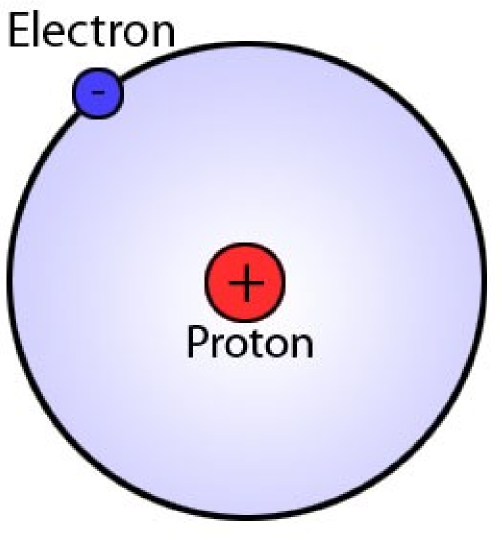
- Discrete orbits
- “Quantum leaps”

The Hydrogen Atom

The Hydrogen Atom

The Hydrogen Atom

One Proton, orbited by *one* Electron.



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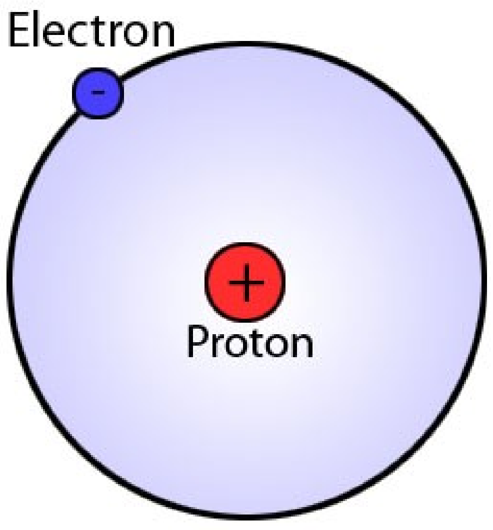

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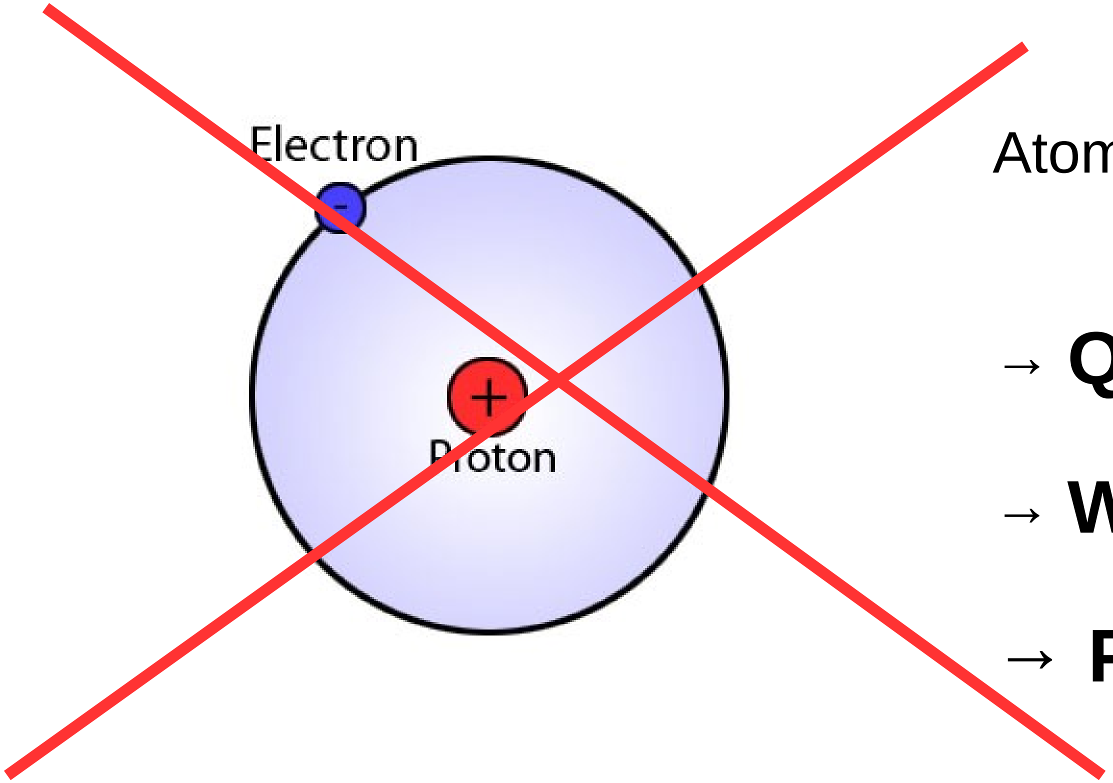


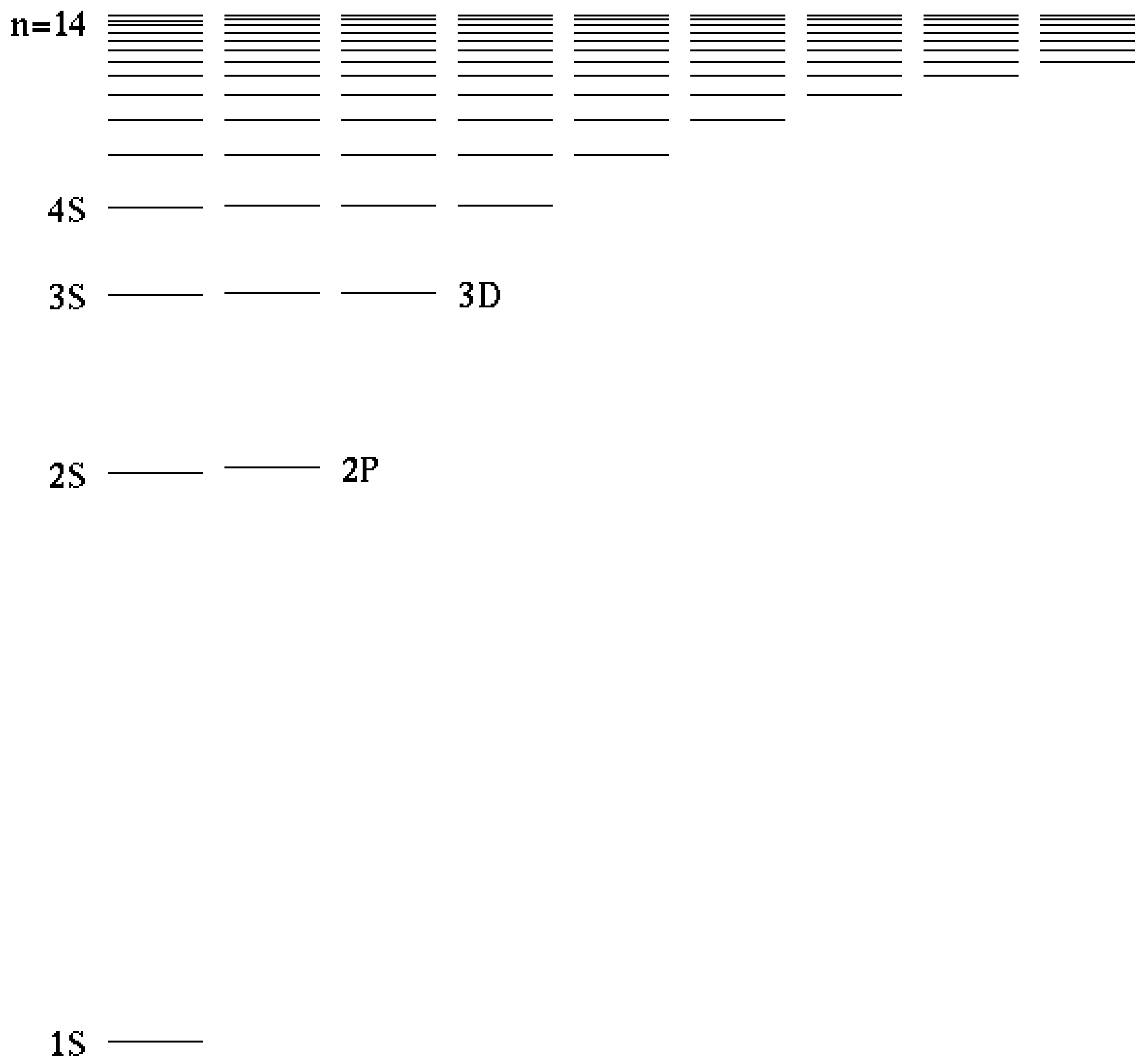
Atom is NO Planetary System.

→ **Quantum mechanics**

→ **Wave functions**

→ **Probabilities**

Energy levels of Hydrogen



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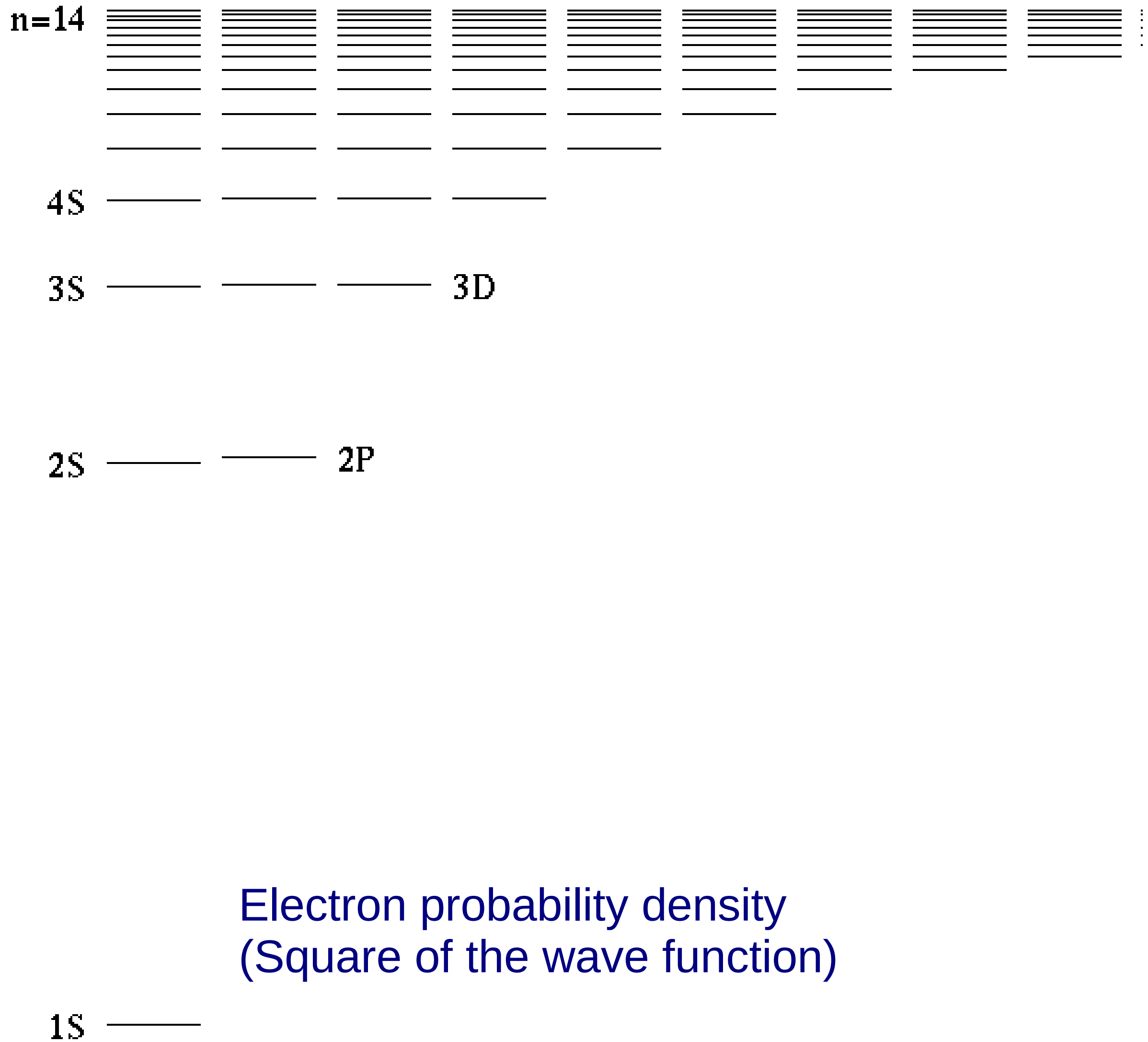
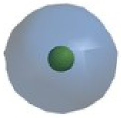
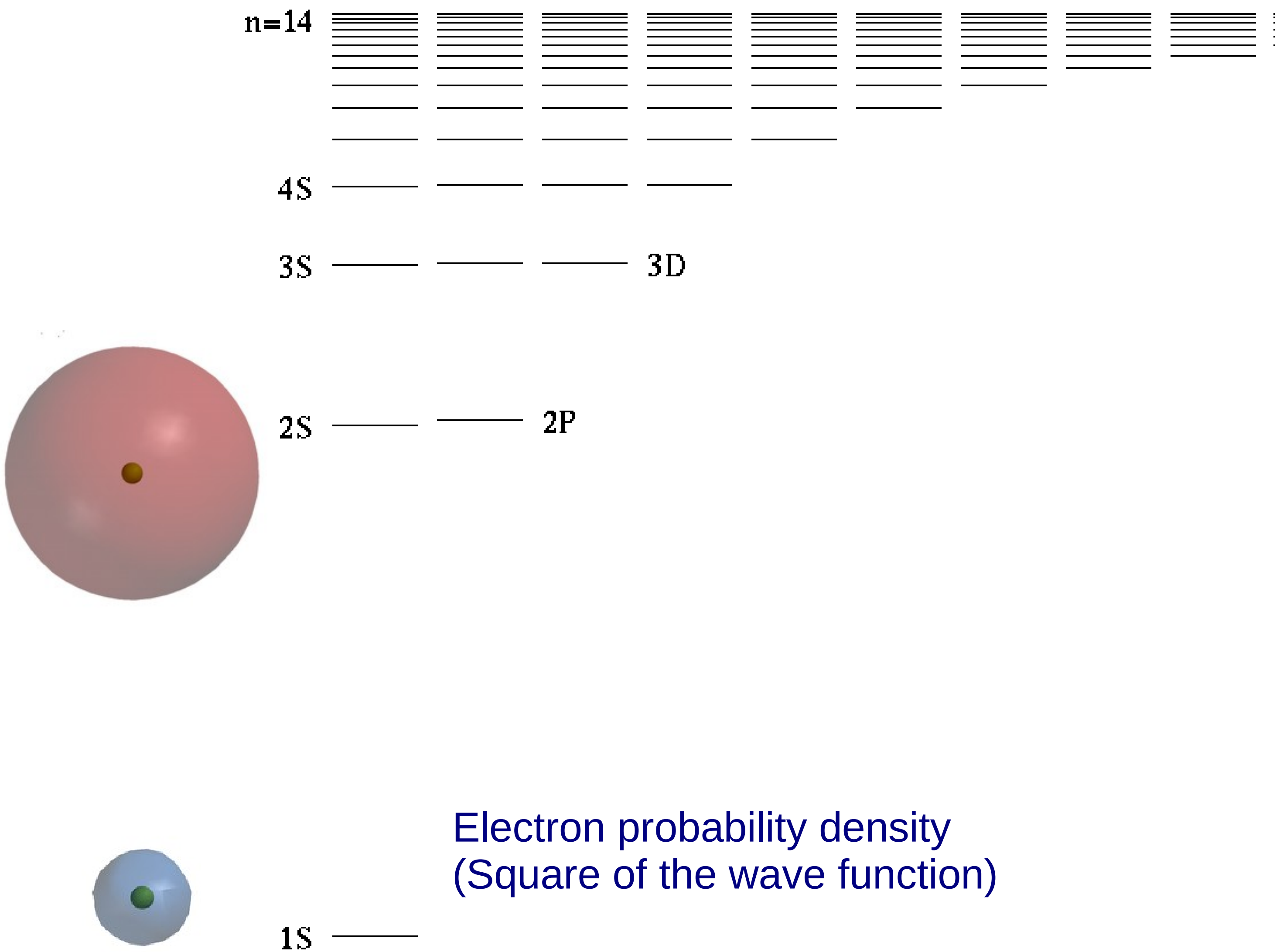




Electron probability density
(Square of the wave function)

Energy levels of Hydrogen



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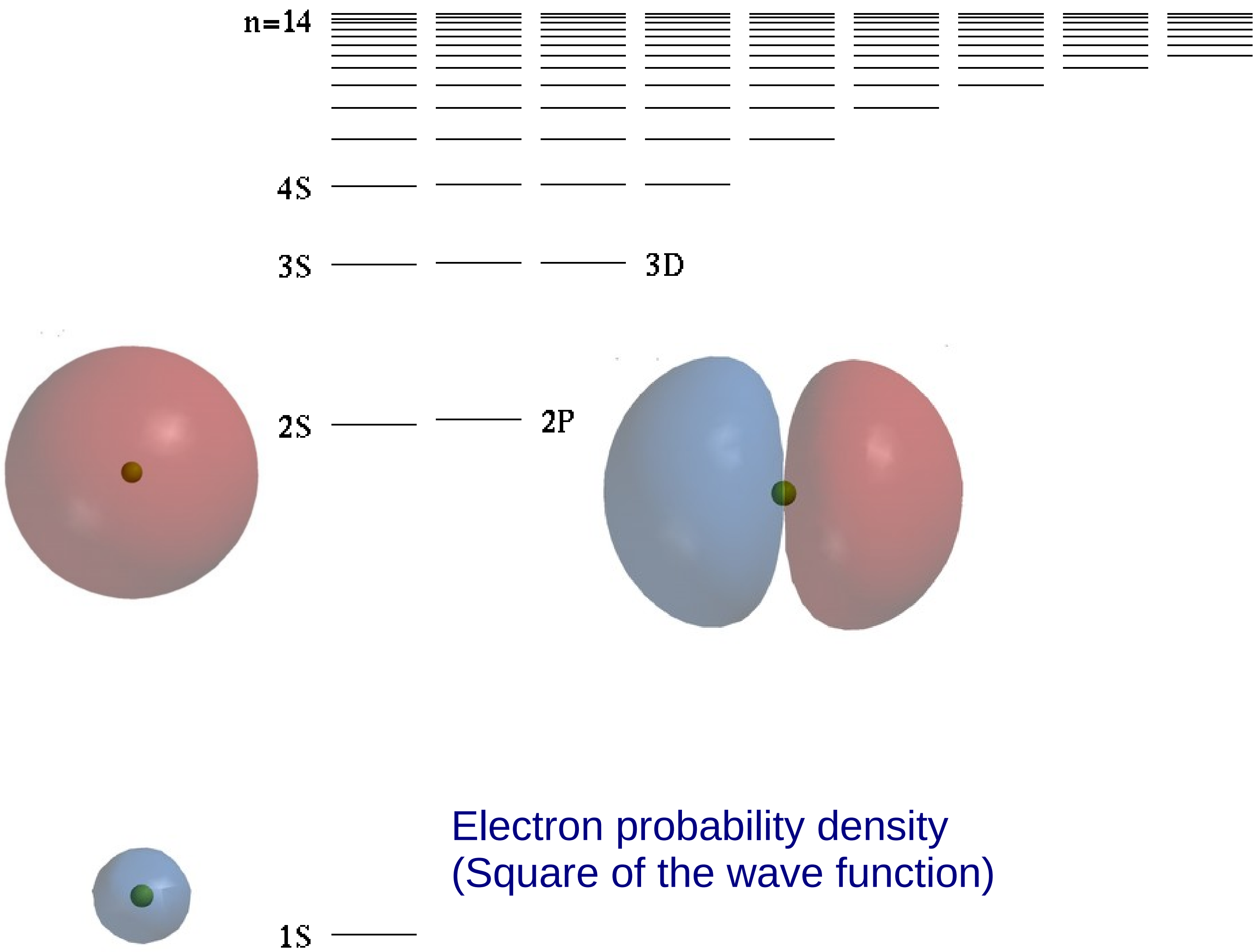
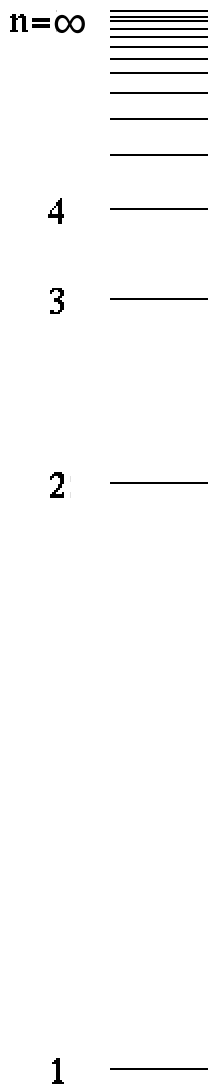
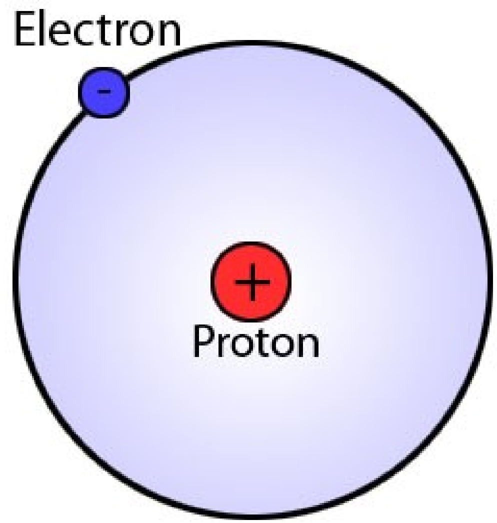


Energy levels of hydrogen

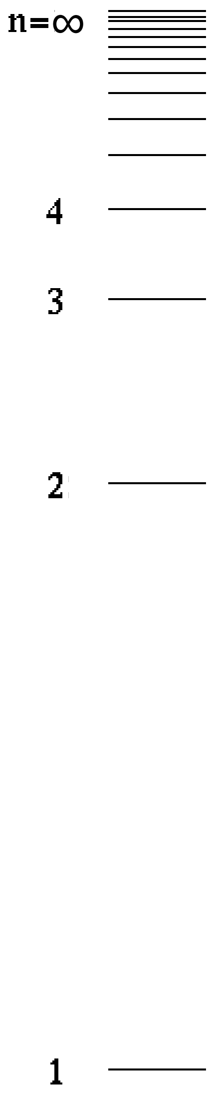




$$E_n \approx -\frac{R_\infty}{n^2}$$

Bohr formula

Energy levels of hydrogen

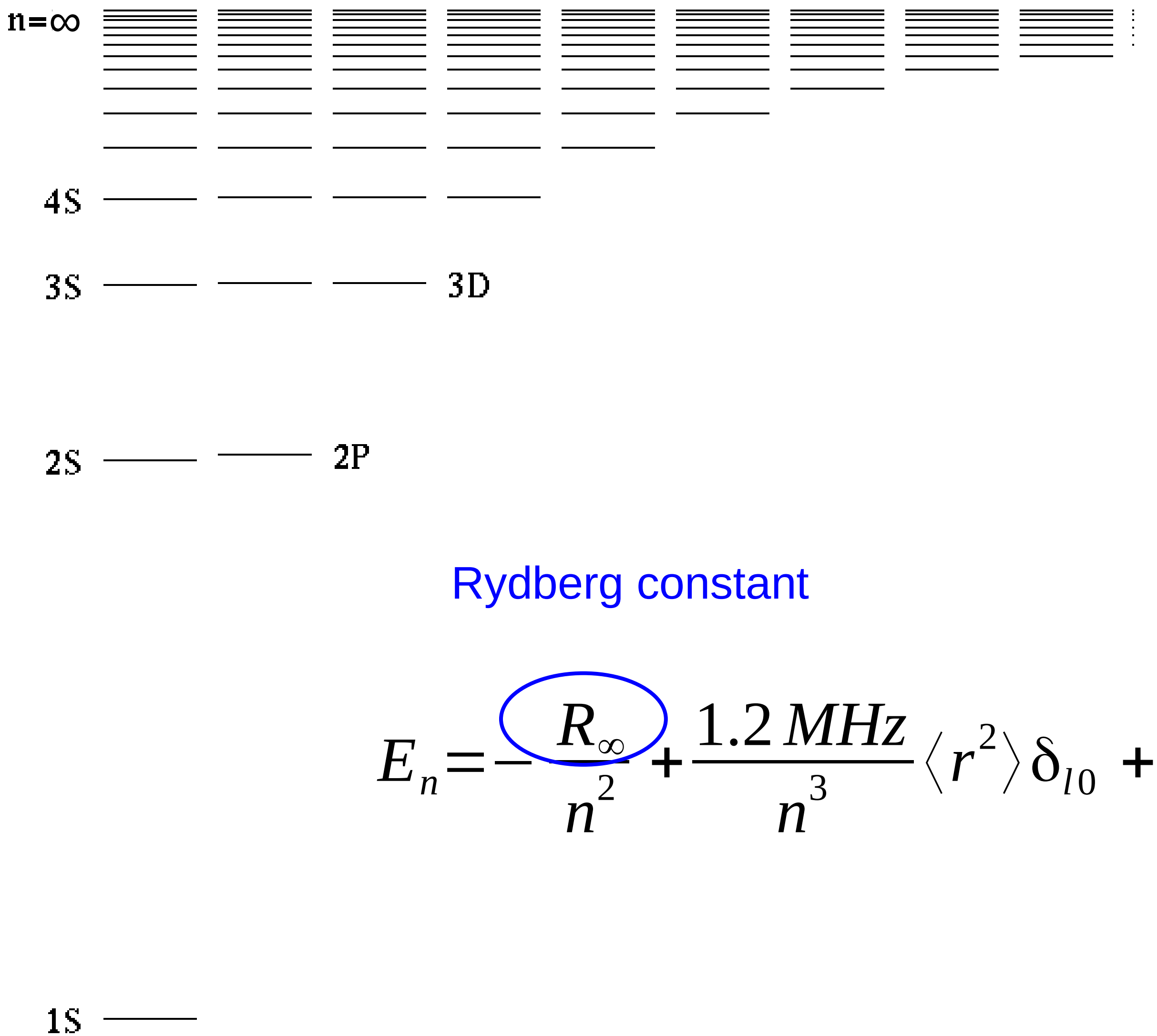


Rydberg constant

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

Bohr formula

Energy levels of hydrogen

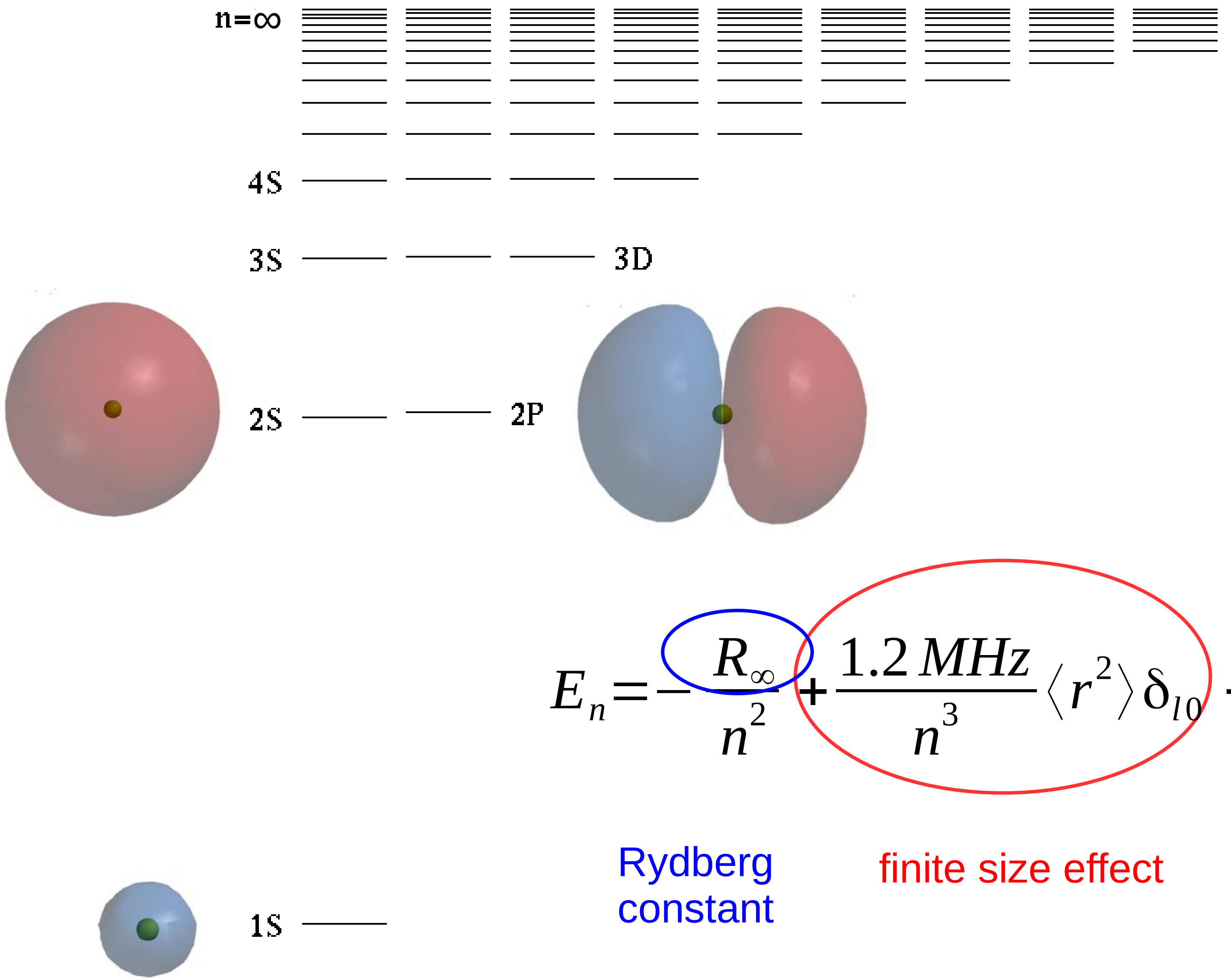


Rydberg constant

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

RP et al., Metrologia 54, L1 (2017)

Energy levels of hydrogen



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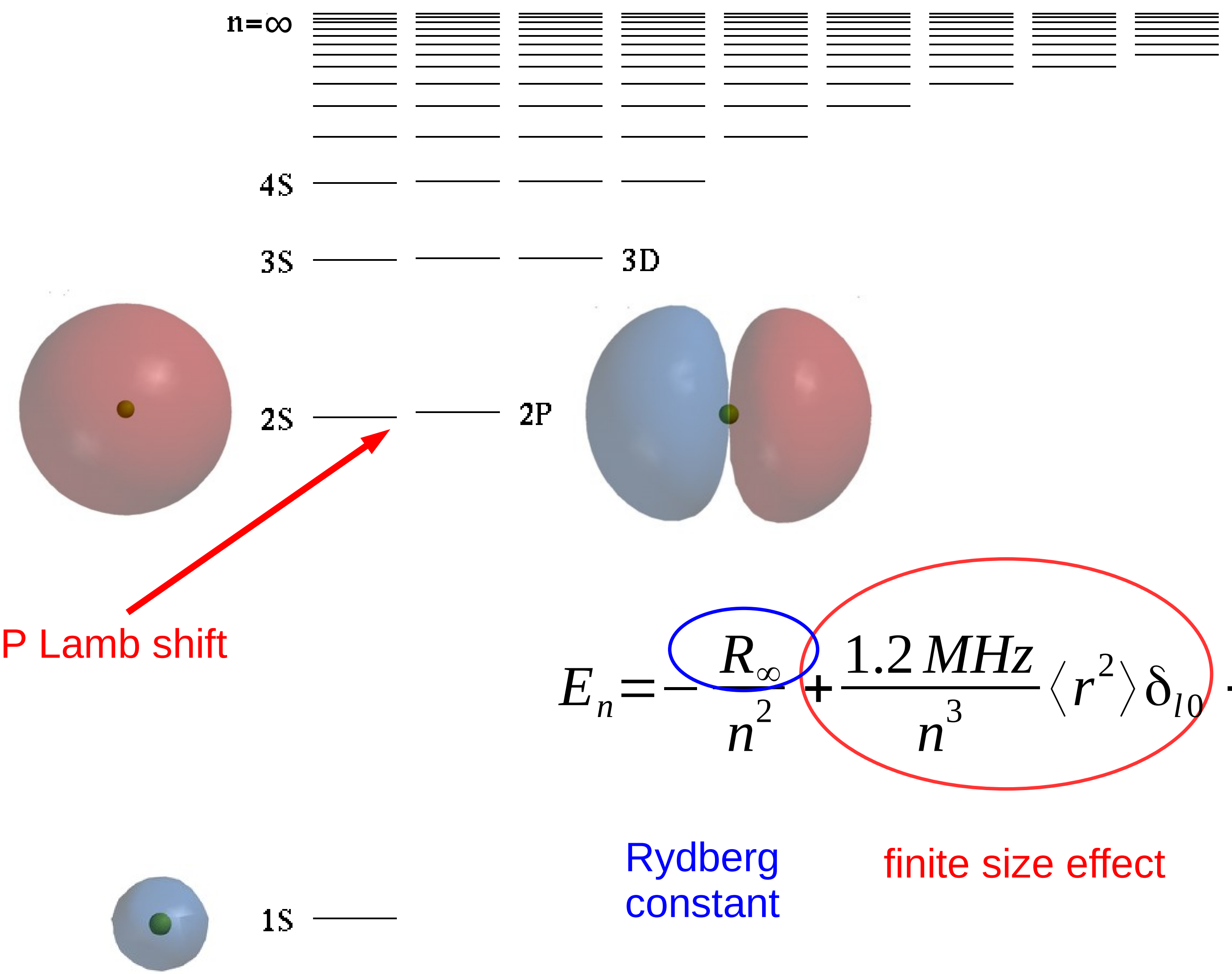
Rydberg constant

finite size effect

RP et al., Metrologia 54, L1 (2017)

Energy levels of hydrogen



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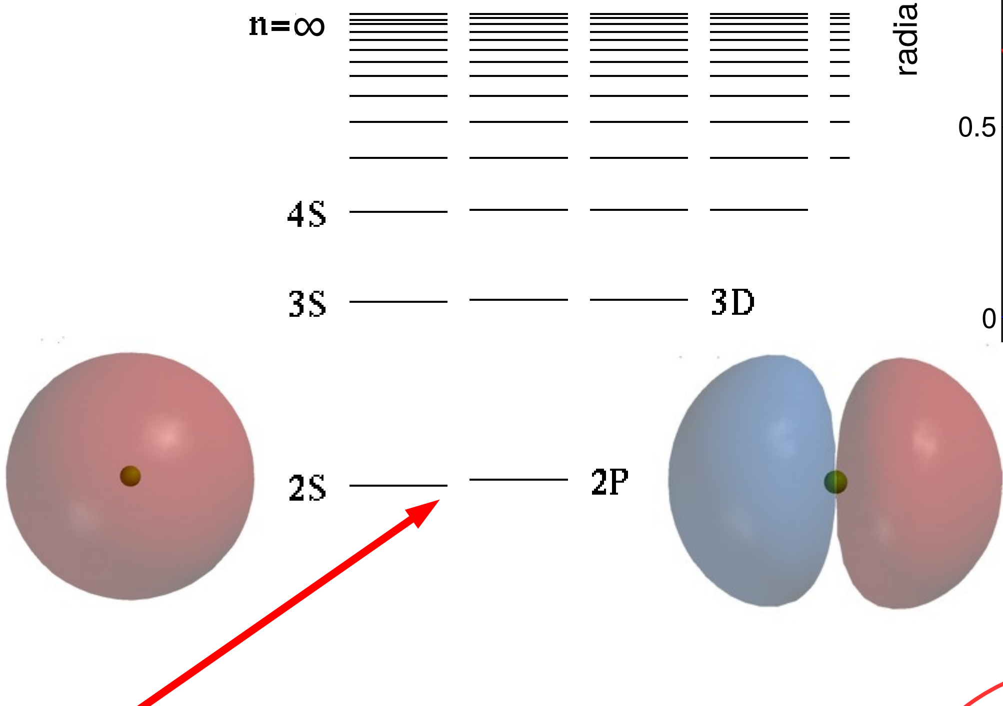
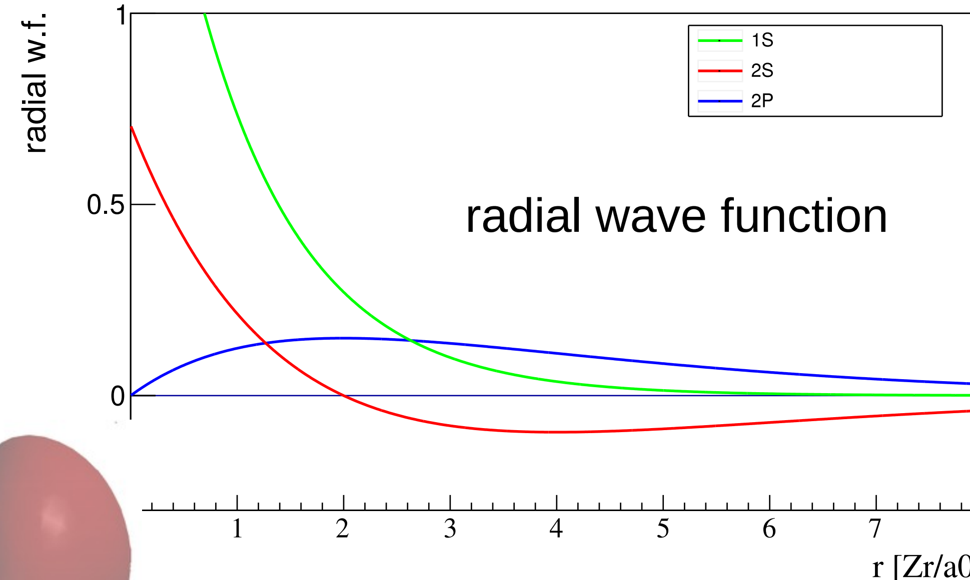




2S-2P Lamb shift

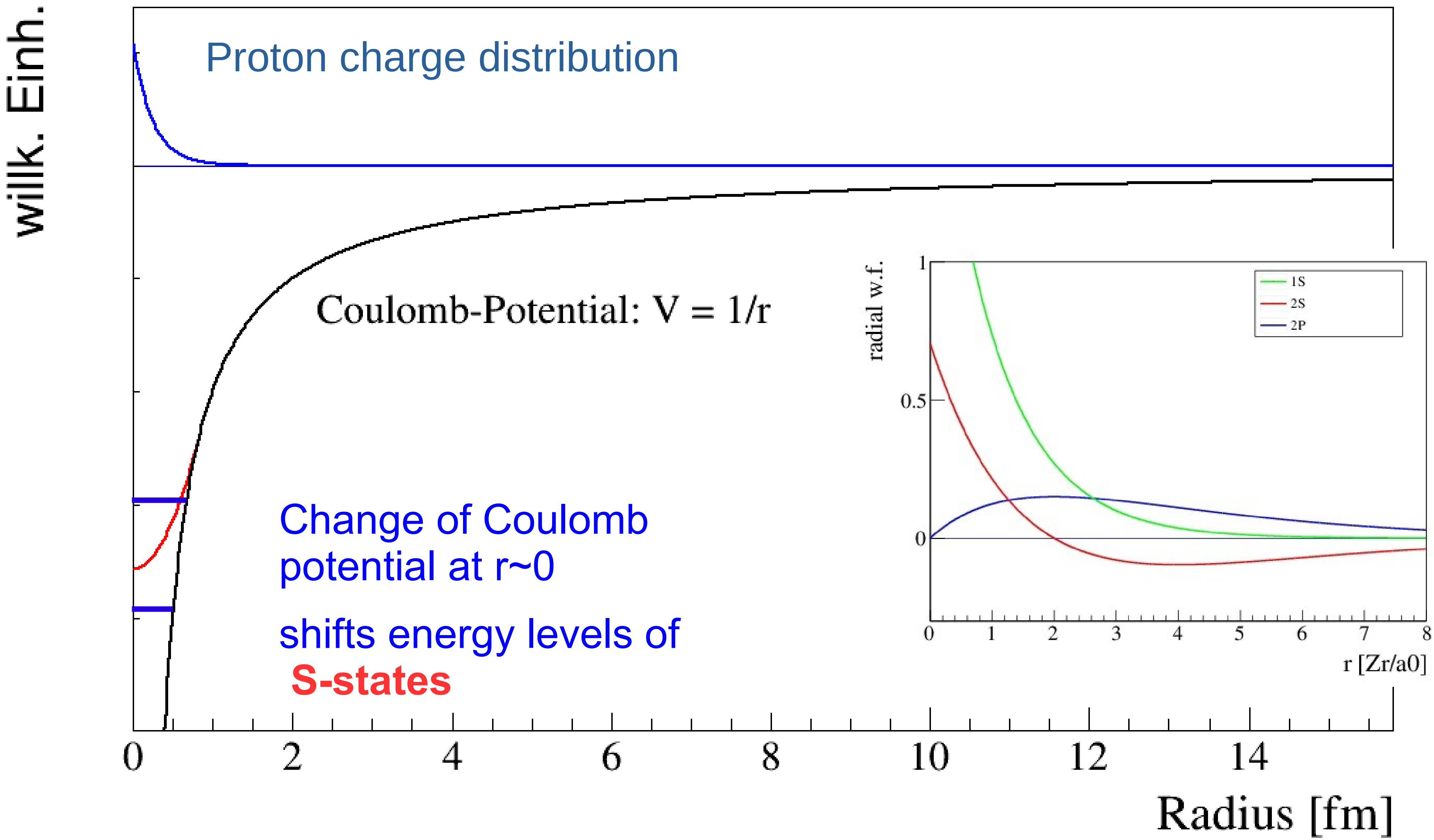
$$E_n = -\frac{R_\infty}{n^2} + \frac{1.2\,MHz}{n^3}\langle r^2 \rangle \delta_{l0} + \Delta(n, l, j)$$

Rydberg constant

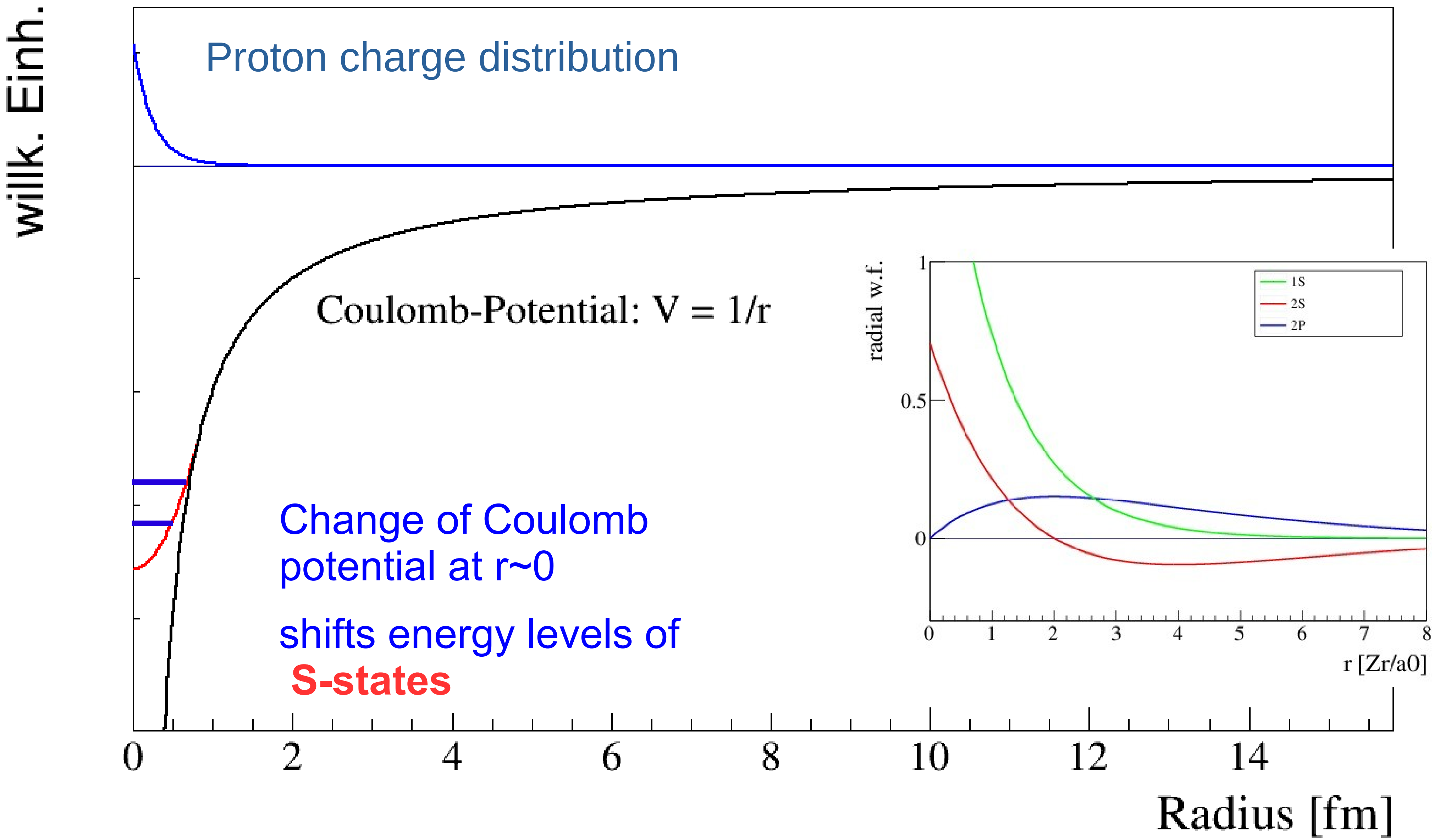
finite size effect

RP et al., Metrologia 54, L1 (2017)

Nuclear charge radius from atoms



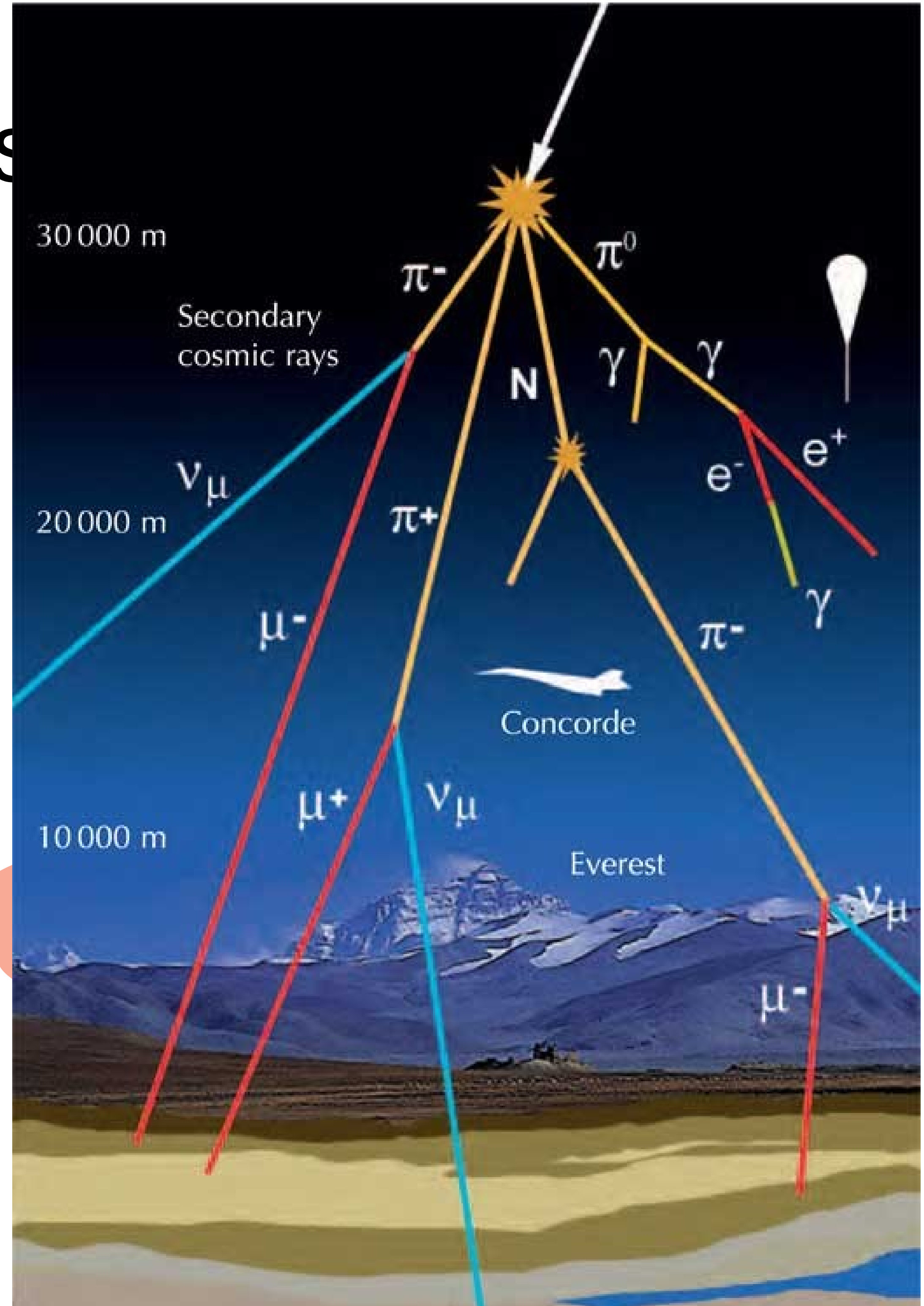
Nuclear charge radius from atoms



Muonic Hydrogen

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

What is

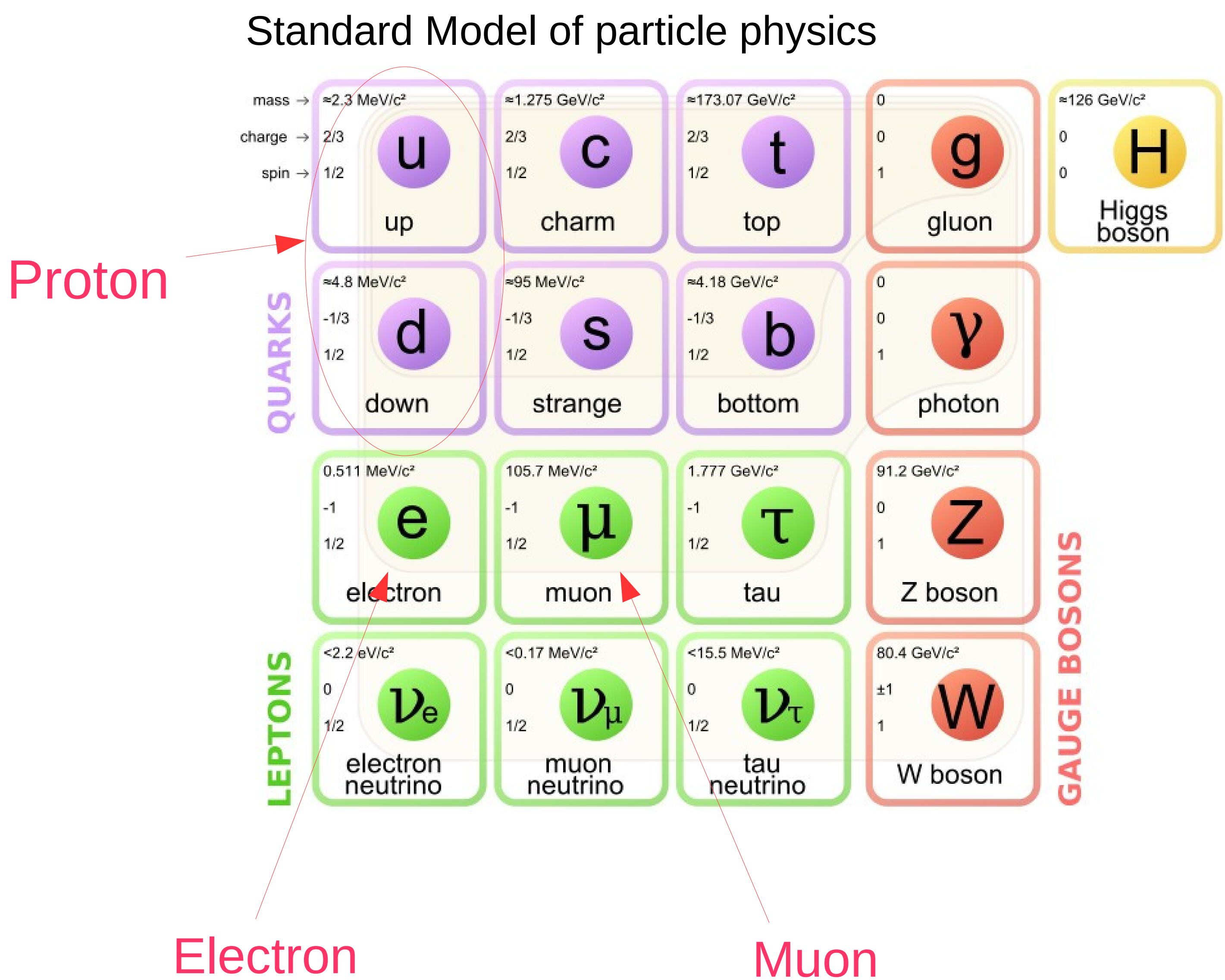


Carl David Anderson

Seth Neddermeyer

Nobel prize 1936
(for the Positron!)

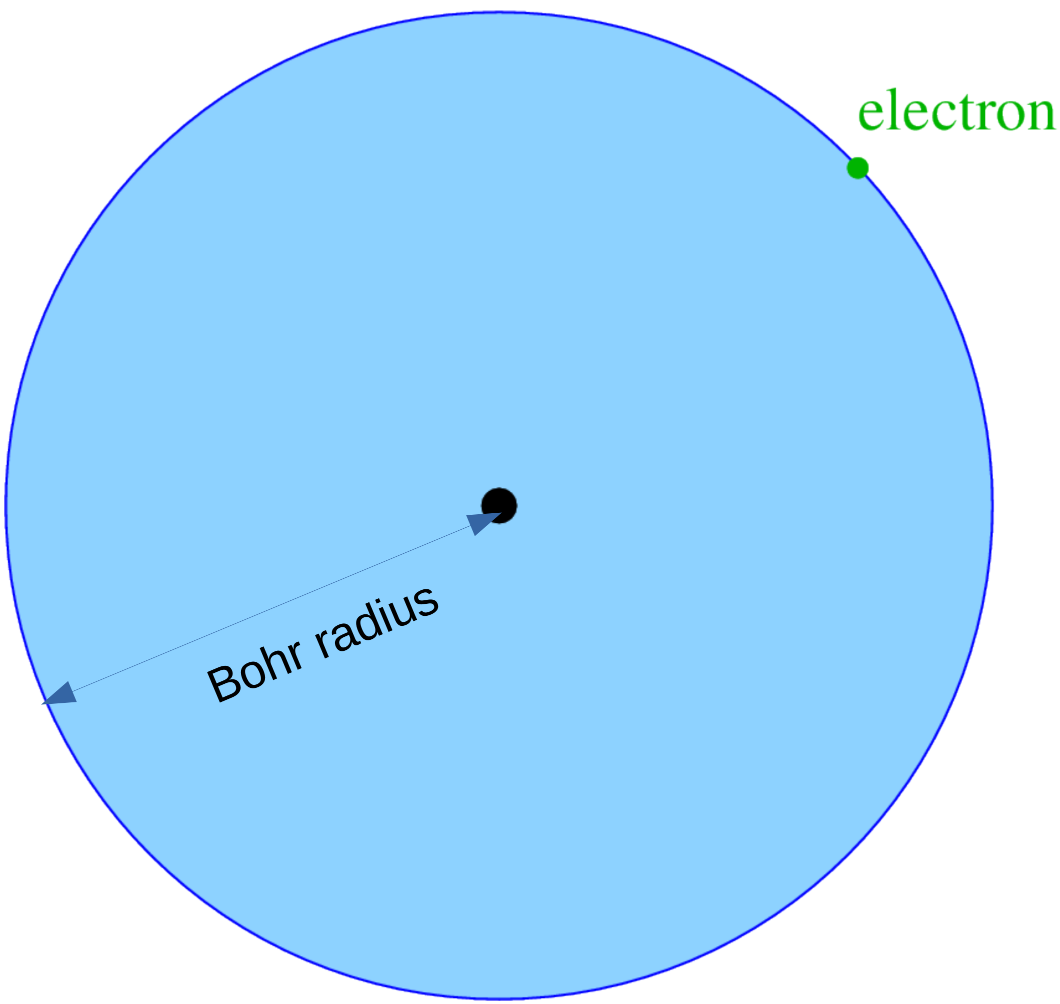
The Muon and its place in the Universe



Electronic and muonic atoms

Regular hydrogen:

Proton + Electron



Muonic hydrogen:

Proton + Muon

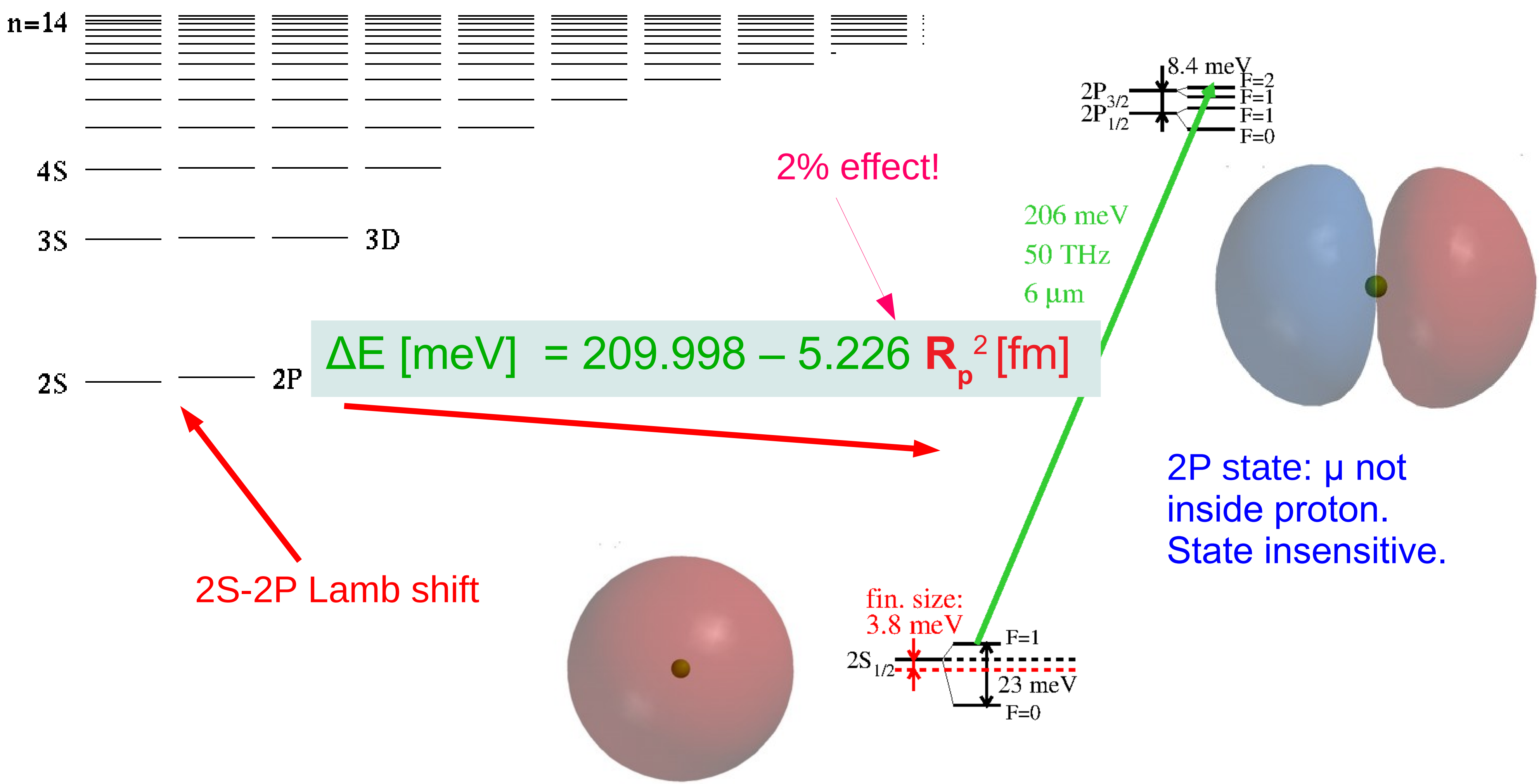
Muon **mass** = **200** * electron mass

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

200^3 = a **few million times** more sensitive to proton size

Vastly not to scale!!

Muonic Hydrogen

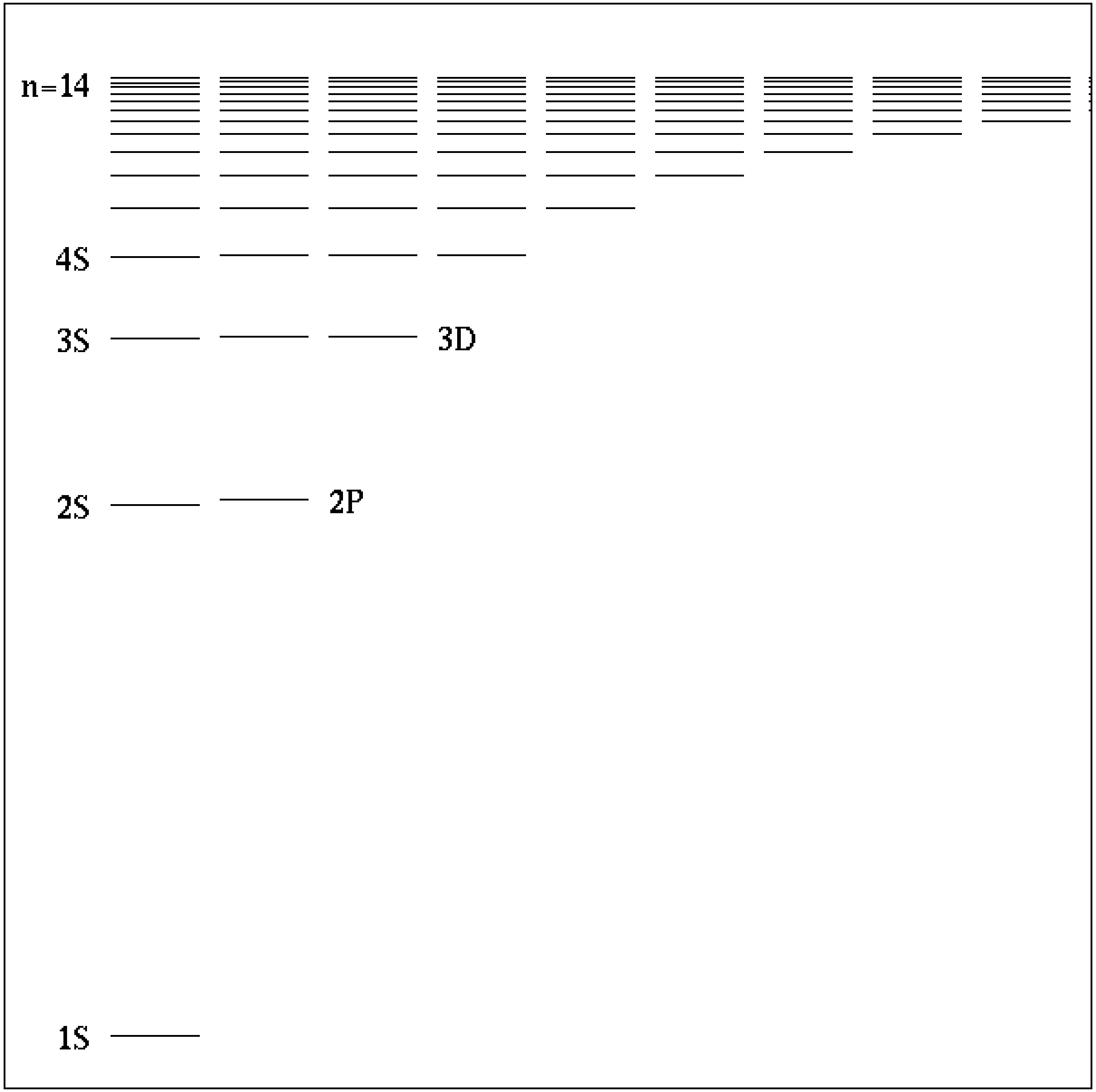


ΔE [meV] = 209.998 – 5.226 $\mathbf{R_p}^2$ [fm]

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

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

Measurement Principle

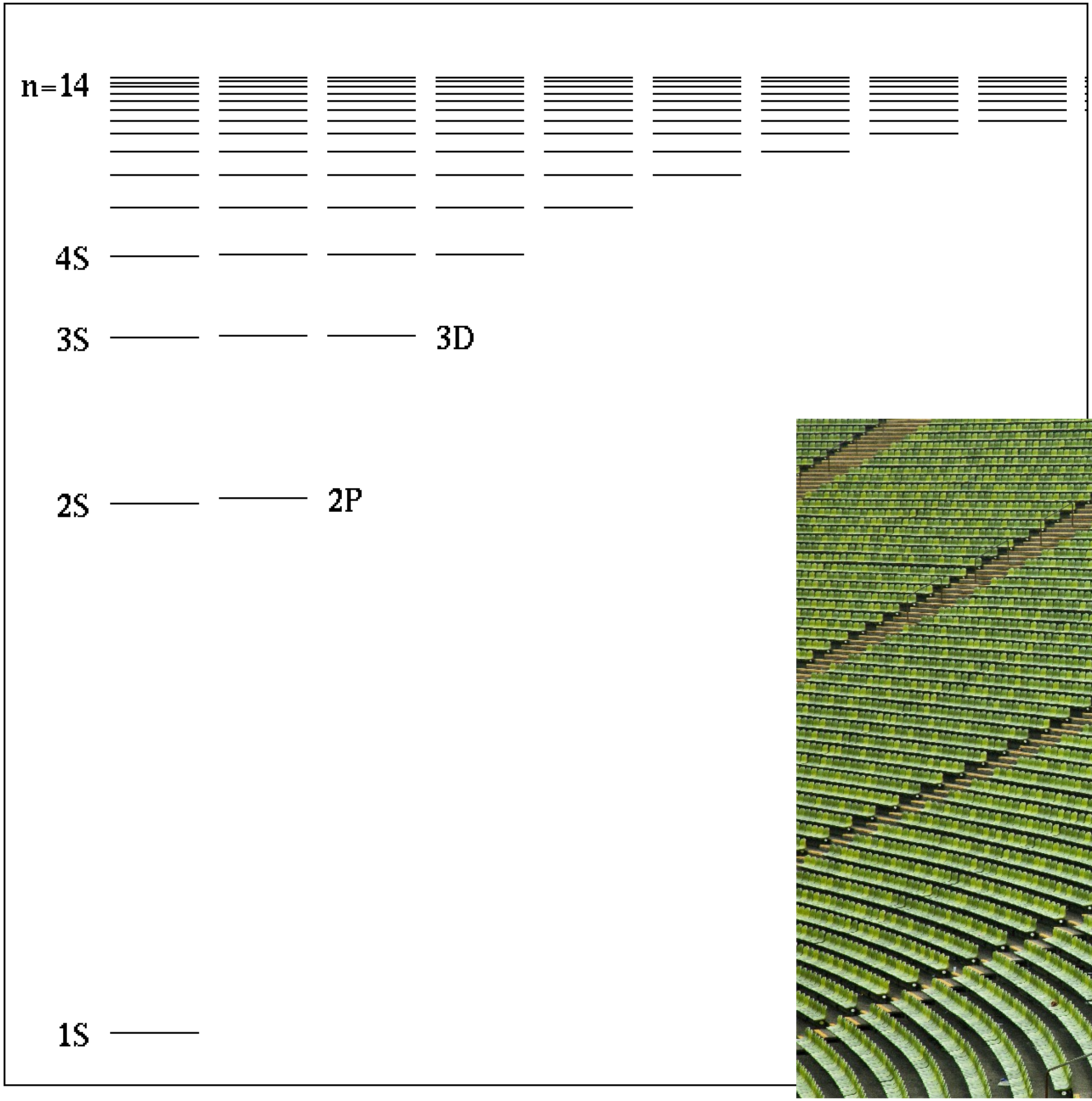


* Muons stop in H_2

* Capture into high states with n~14

* Cascade to lower n

Measurement Principle



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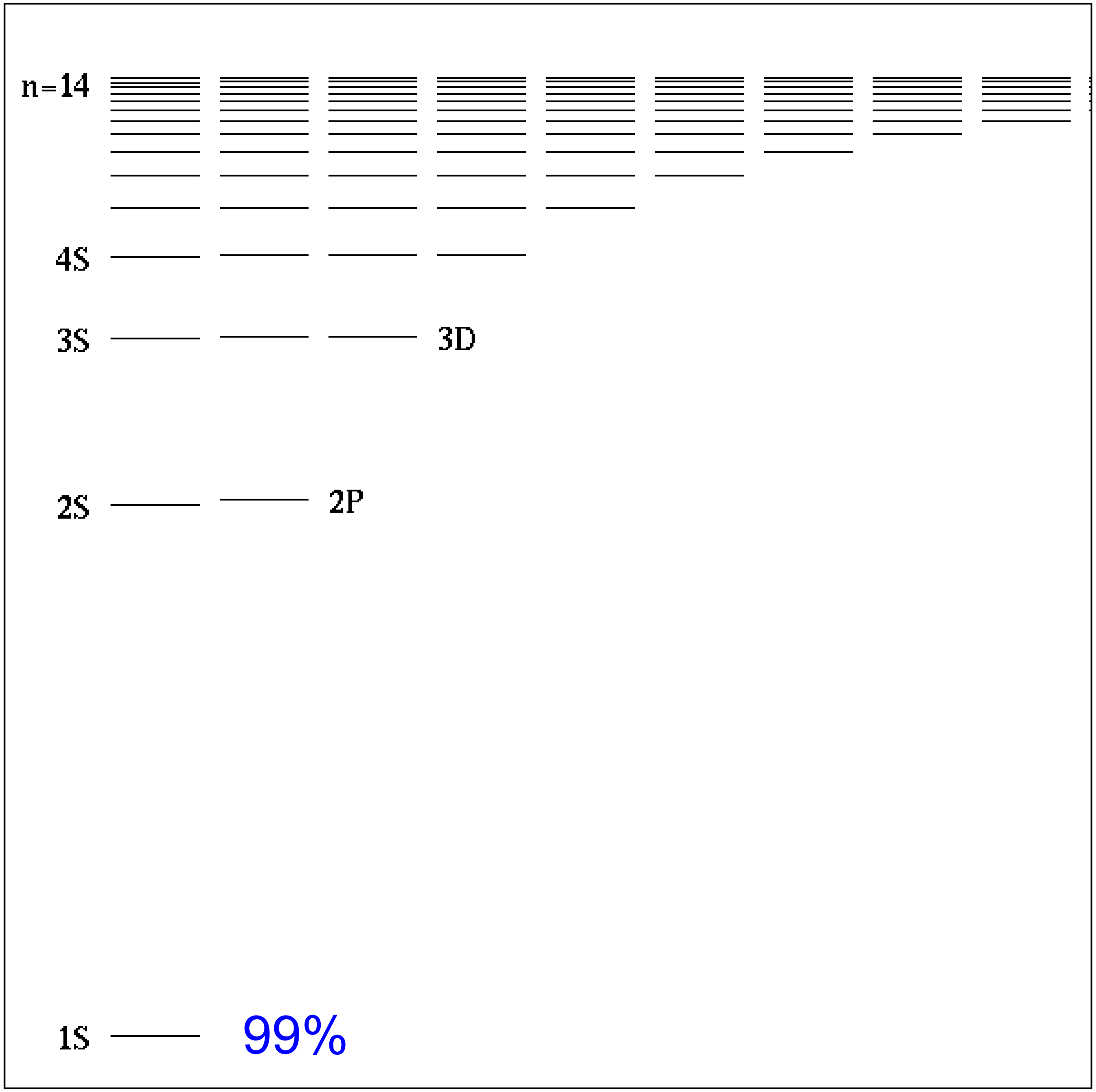
Measurement Principle



* Muons stop in H_2

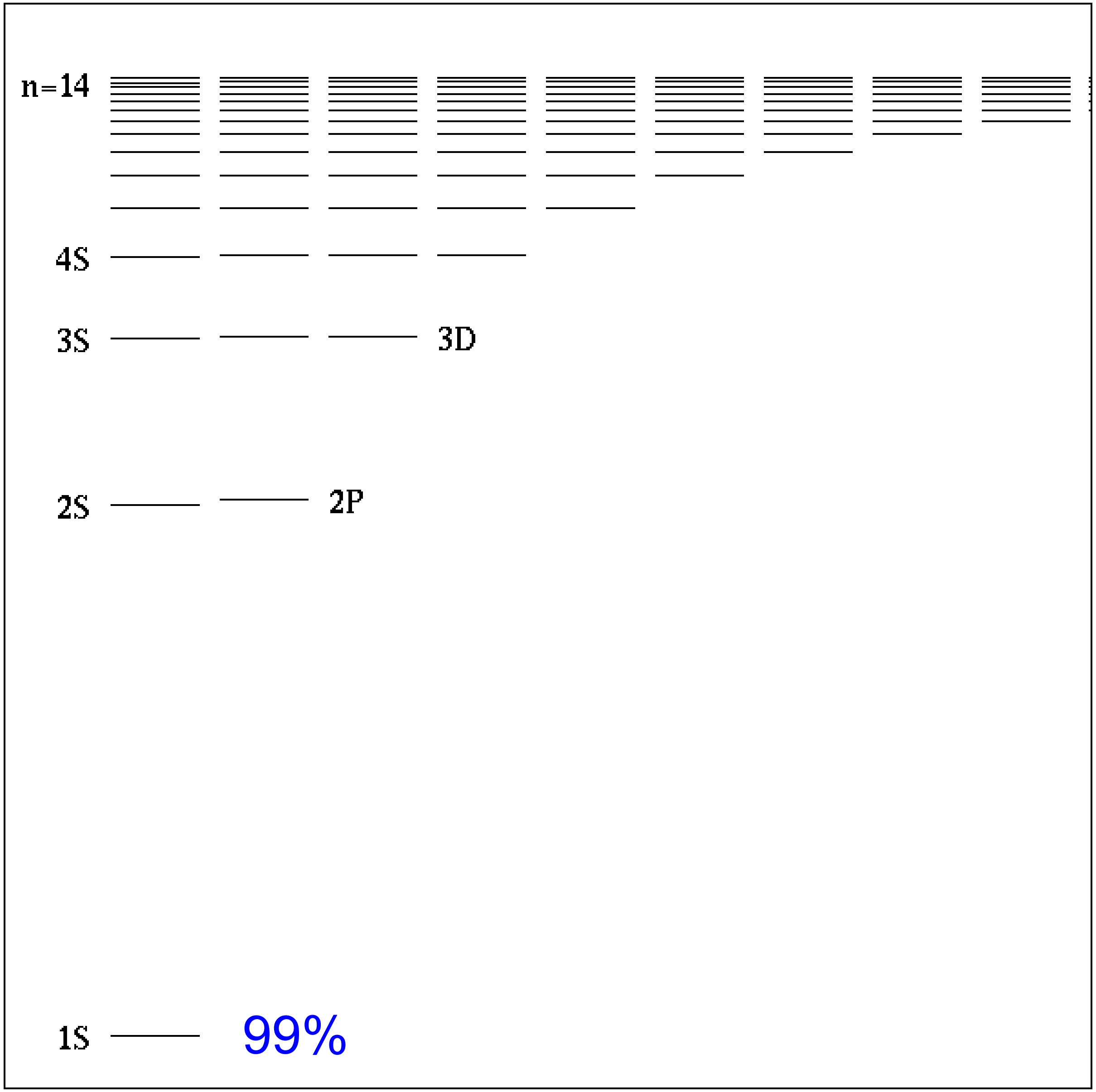
* Capture into high states with n~14

* Cascade to lower n

* 99% end in 1S ground-state

* X-ray photons

Measurement Principle



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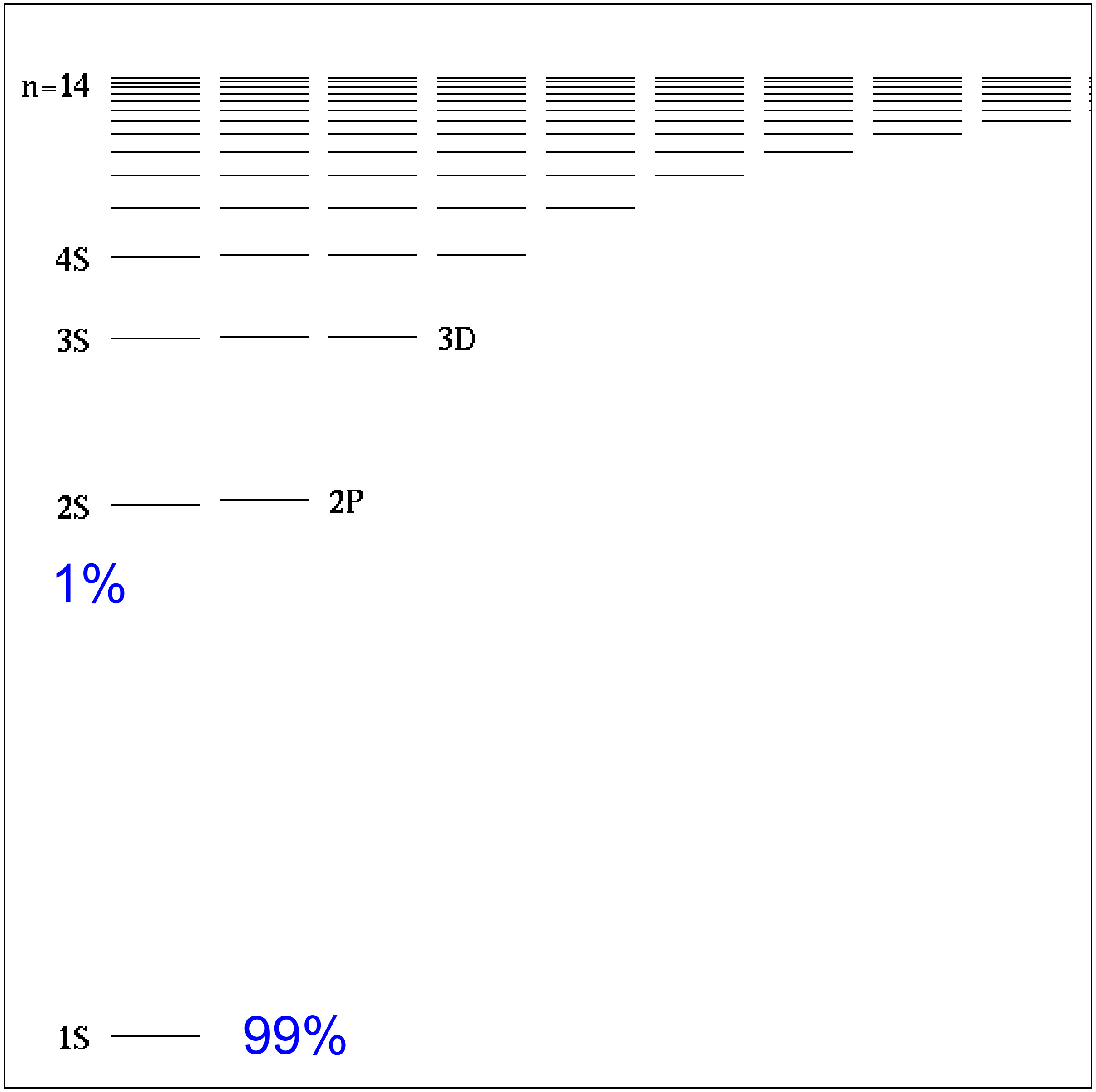
Measurement Principle



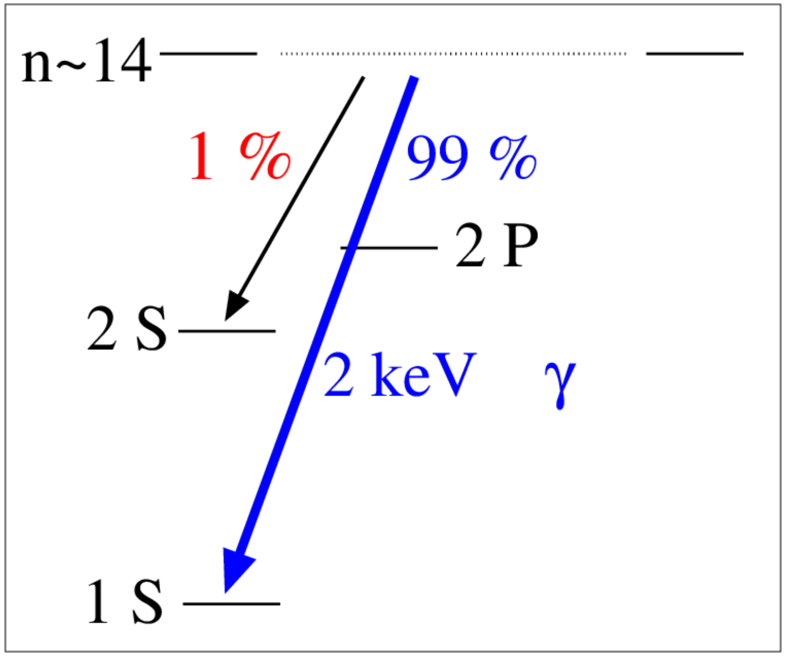
* Muons stop in H_2

* Capture into high states with n~14

* Cascade to lower n

* 1% end in long-lived 2S state

Measurement Principle

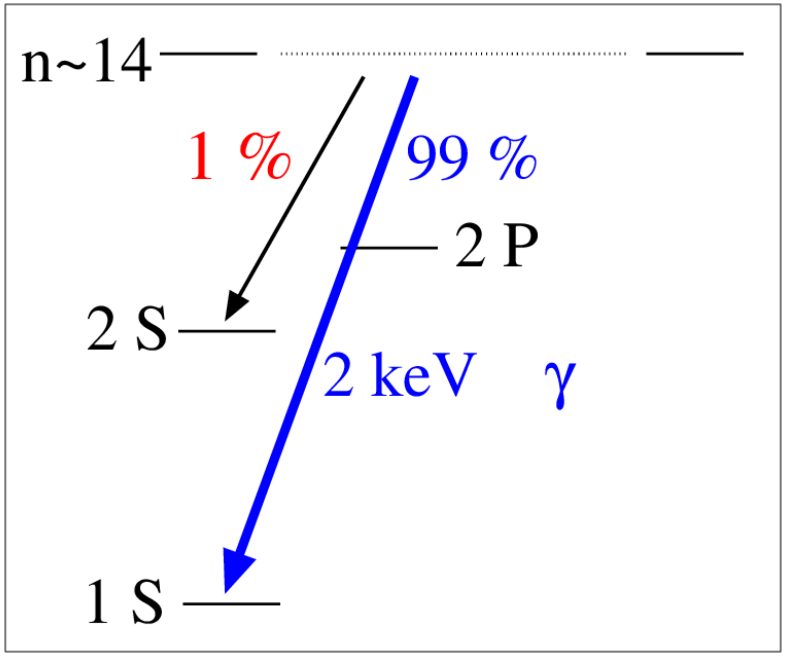


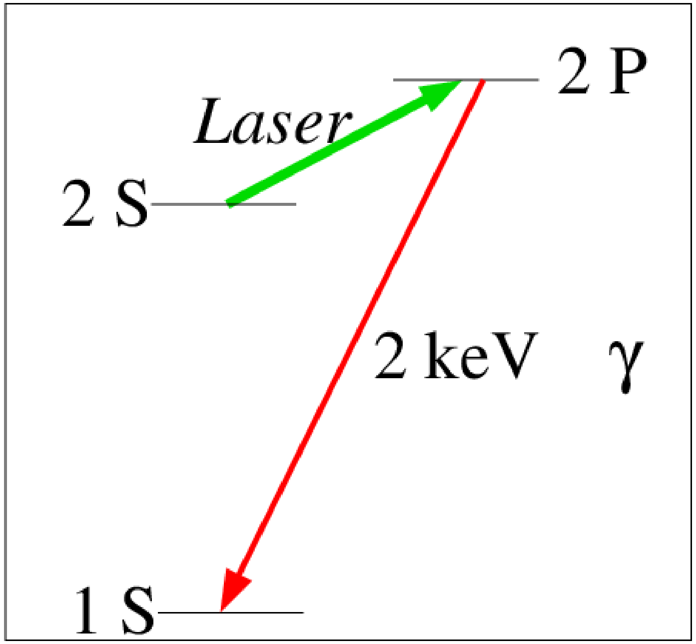
“prompt” (t=0):

* 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

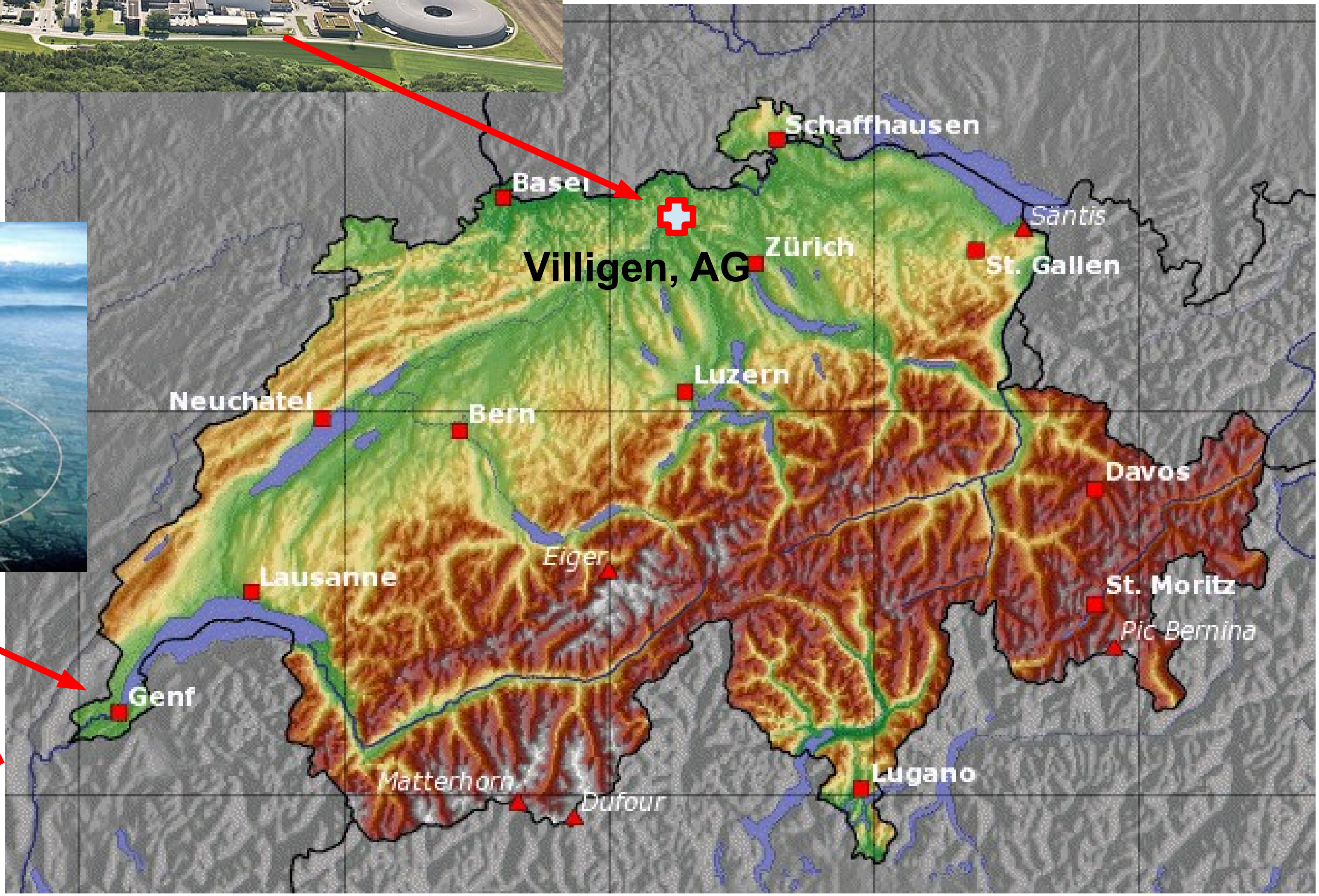
“delayed” (t ~ 1μs):

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

→ “delayed” X-ray photons

The accelerator at PSI

PAUL SCHERRER INSTITUT PSI

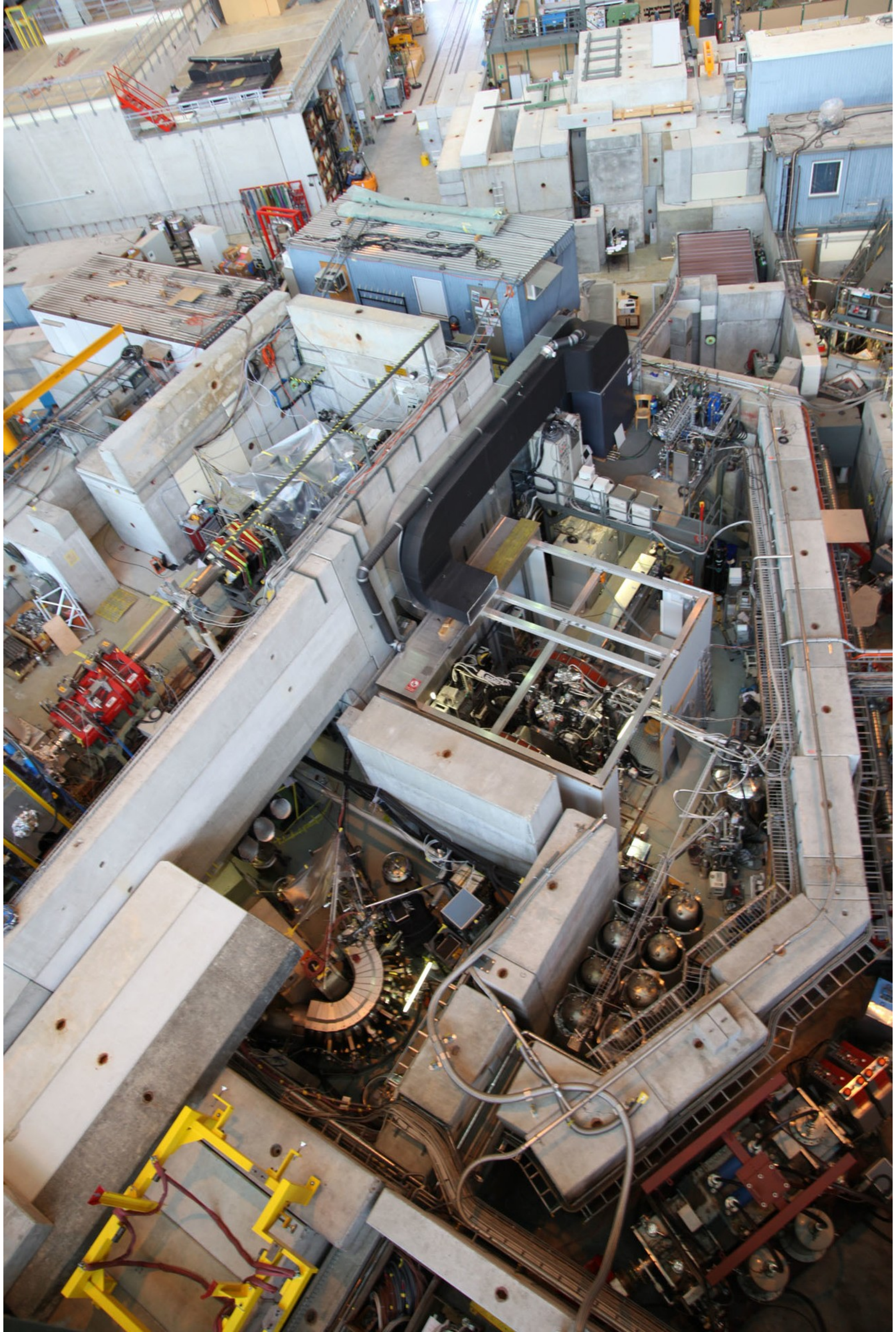


Paul Scherrer Institute

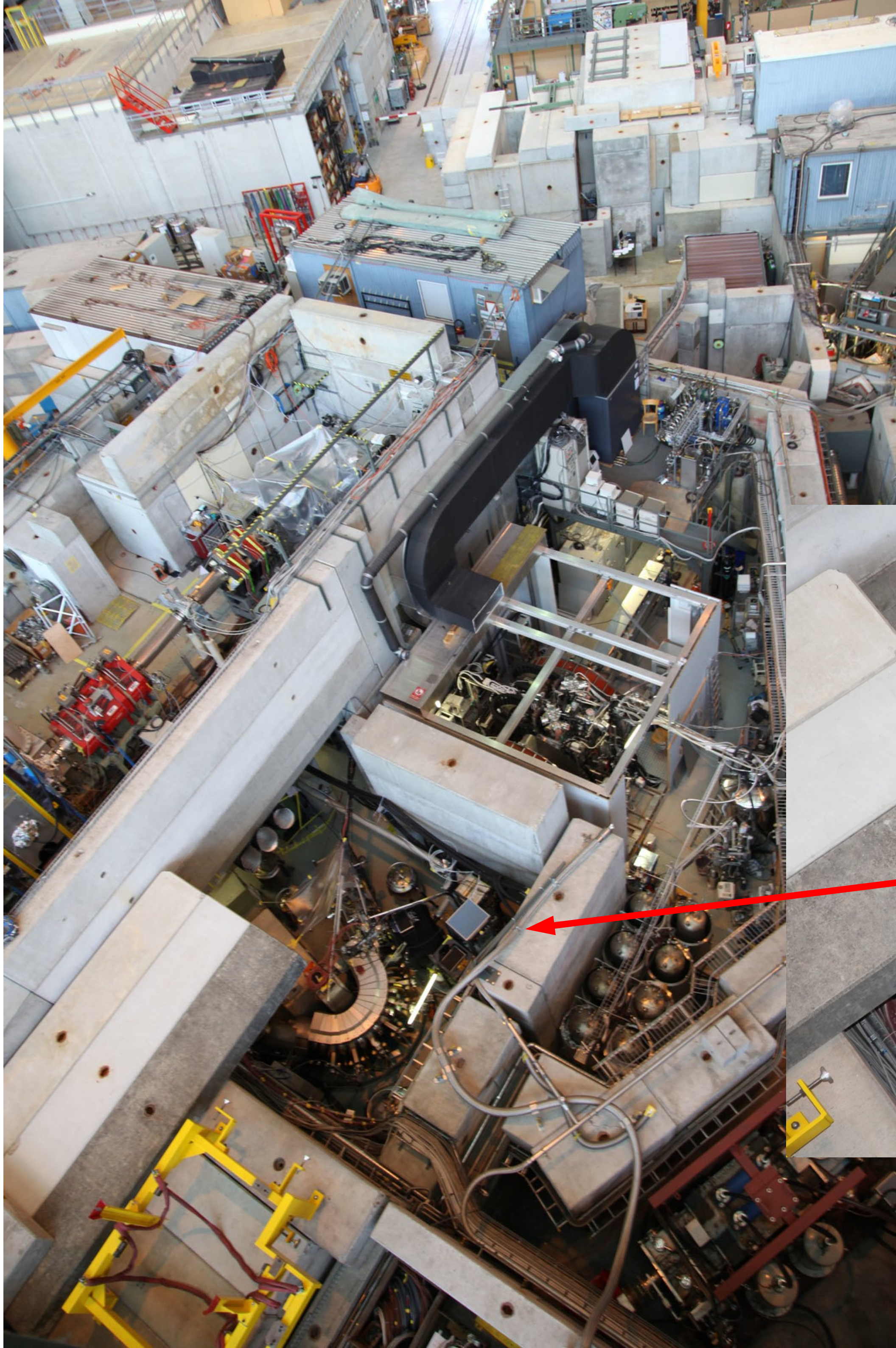
Paul Scherrer Institute

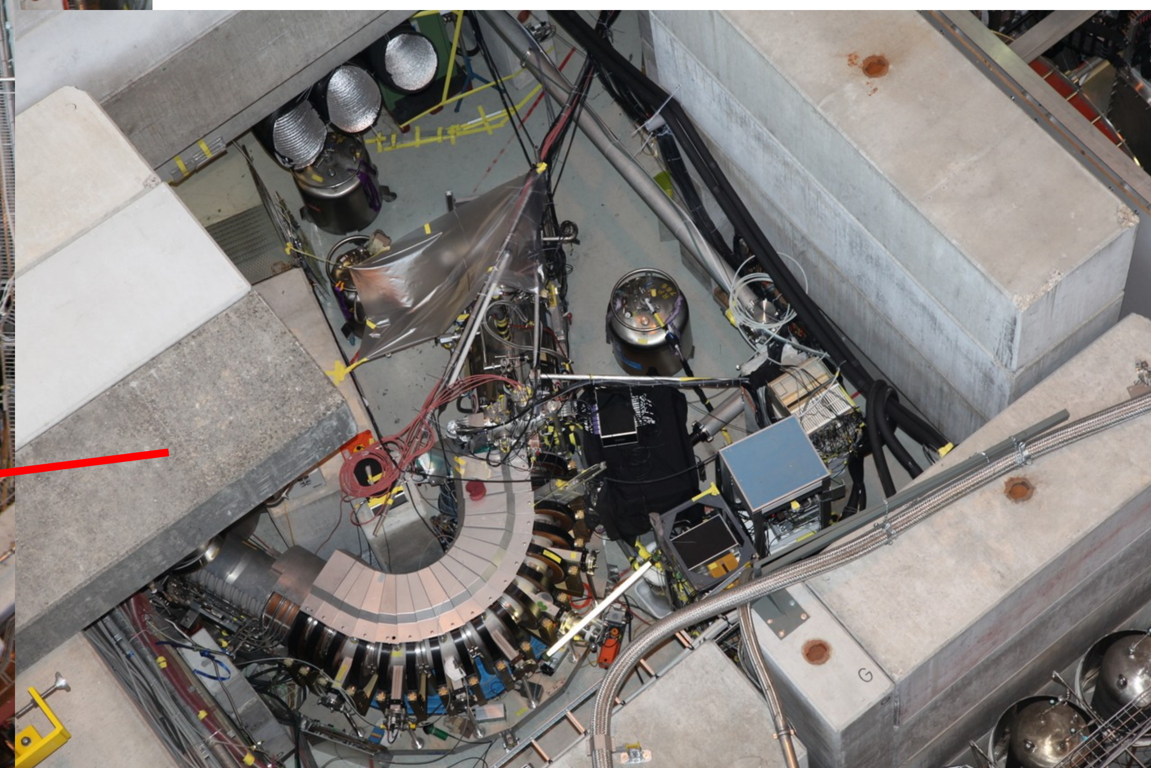
Experimental Hall

Experimental Hall from above



Experimental Hall from above



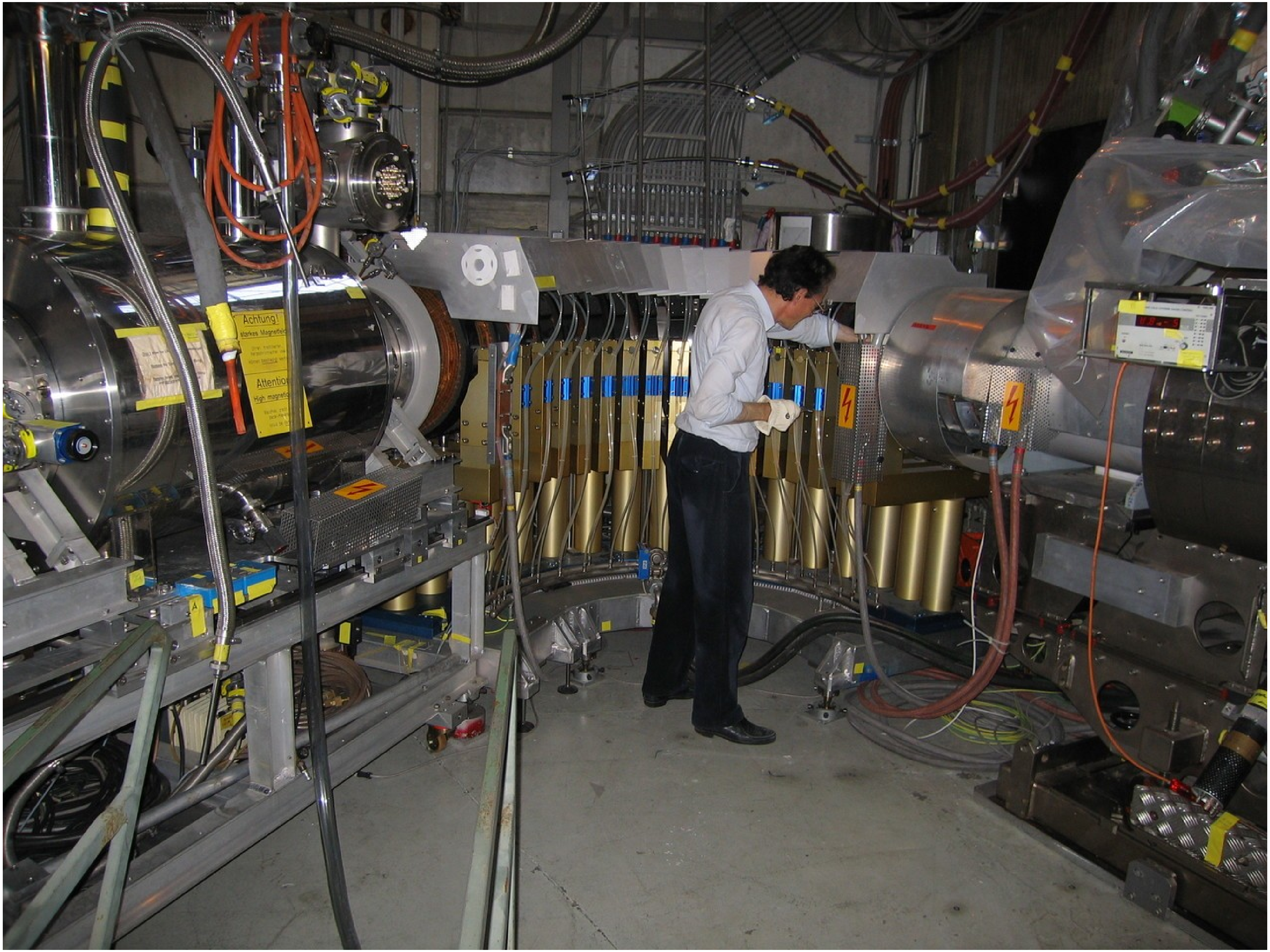


Beam Area πE5

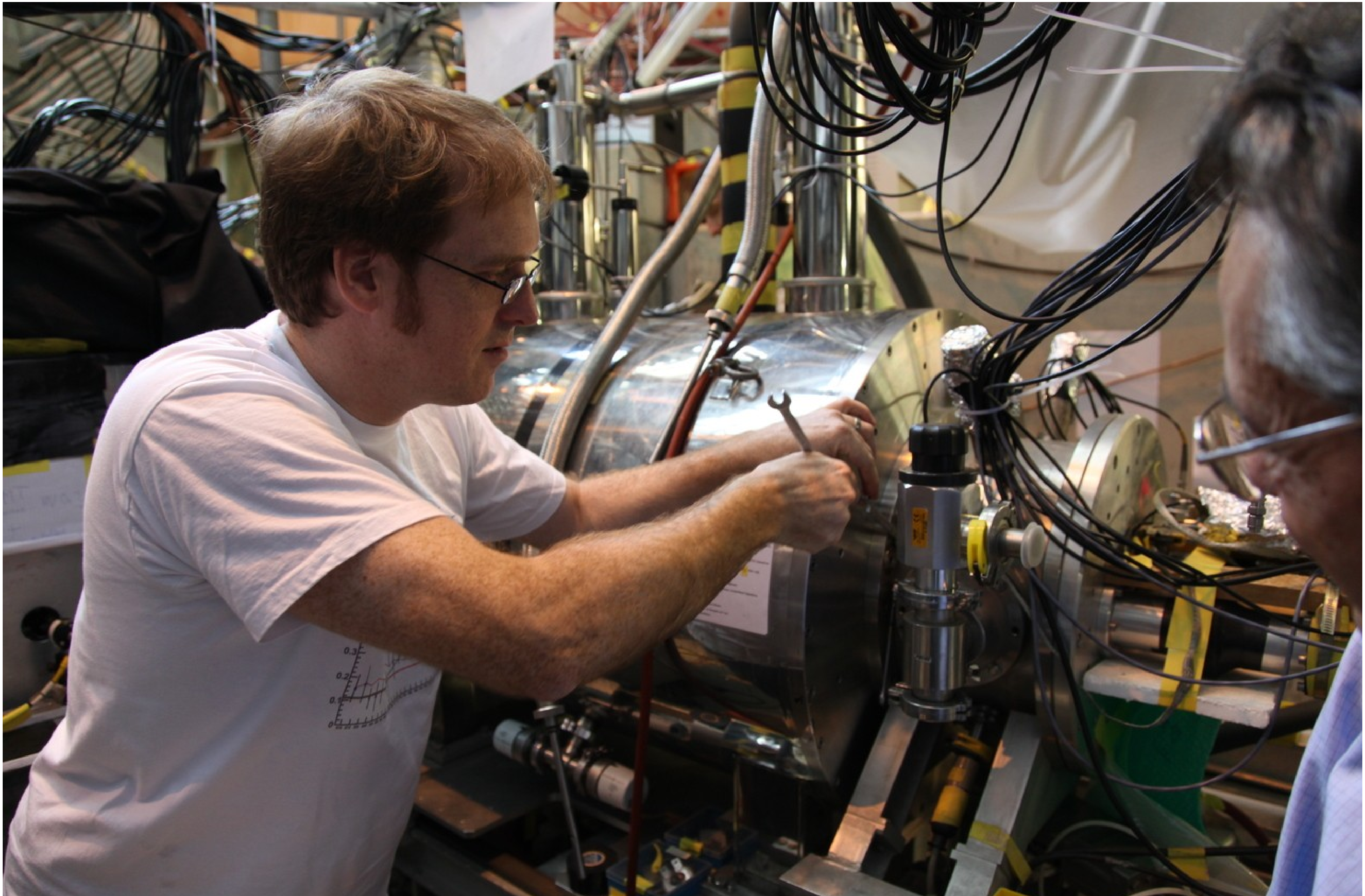
Beam Area πE5

Beam Area πE5

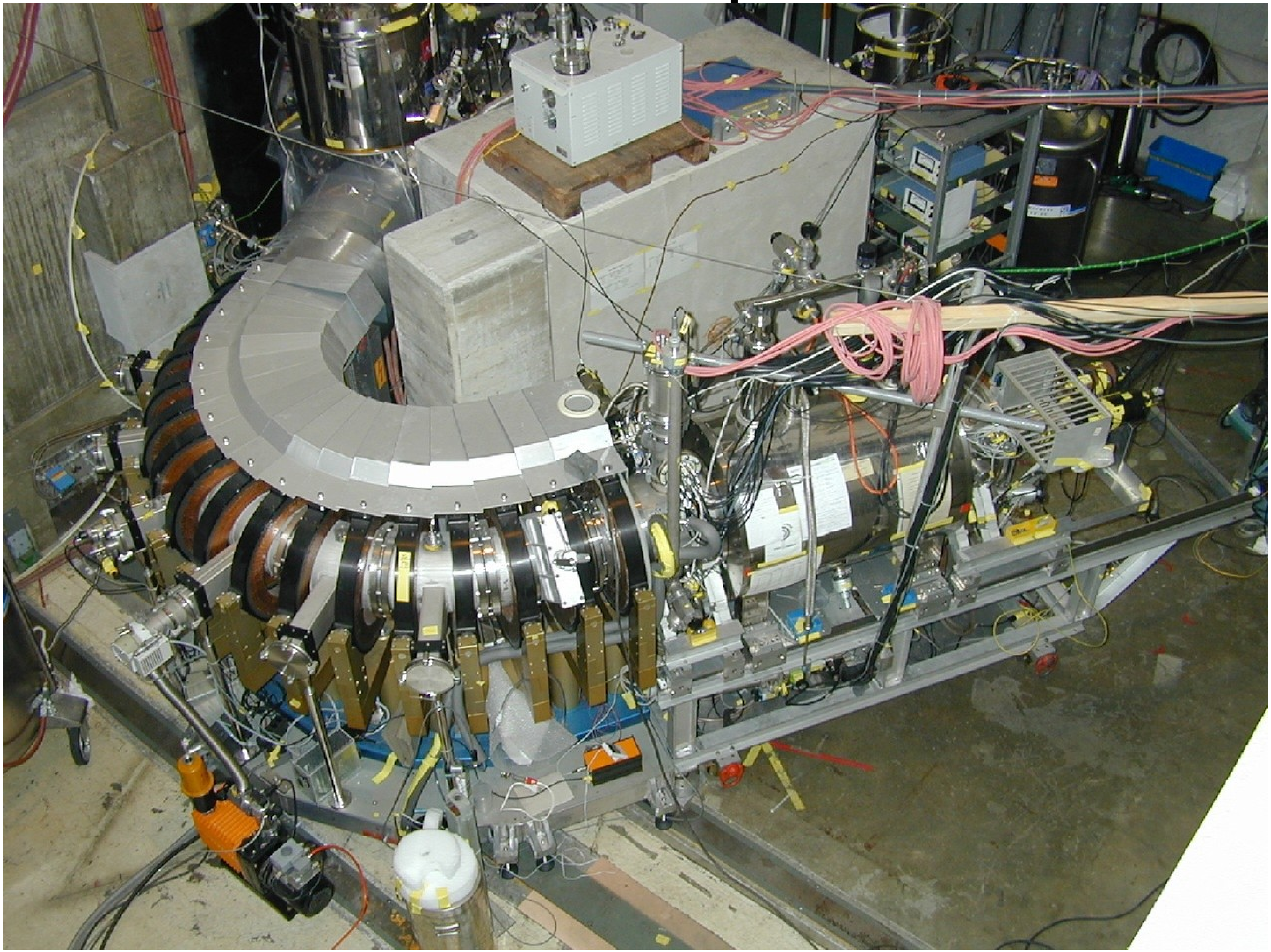
Our Muon Beam inside πE5



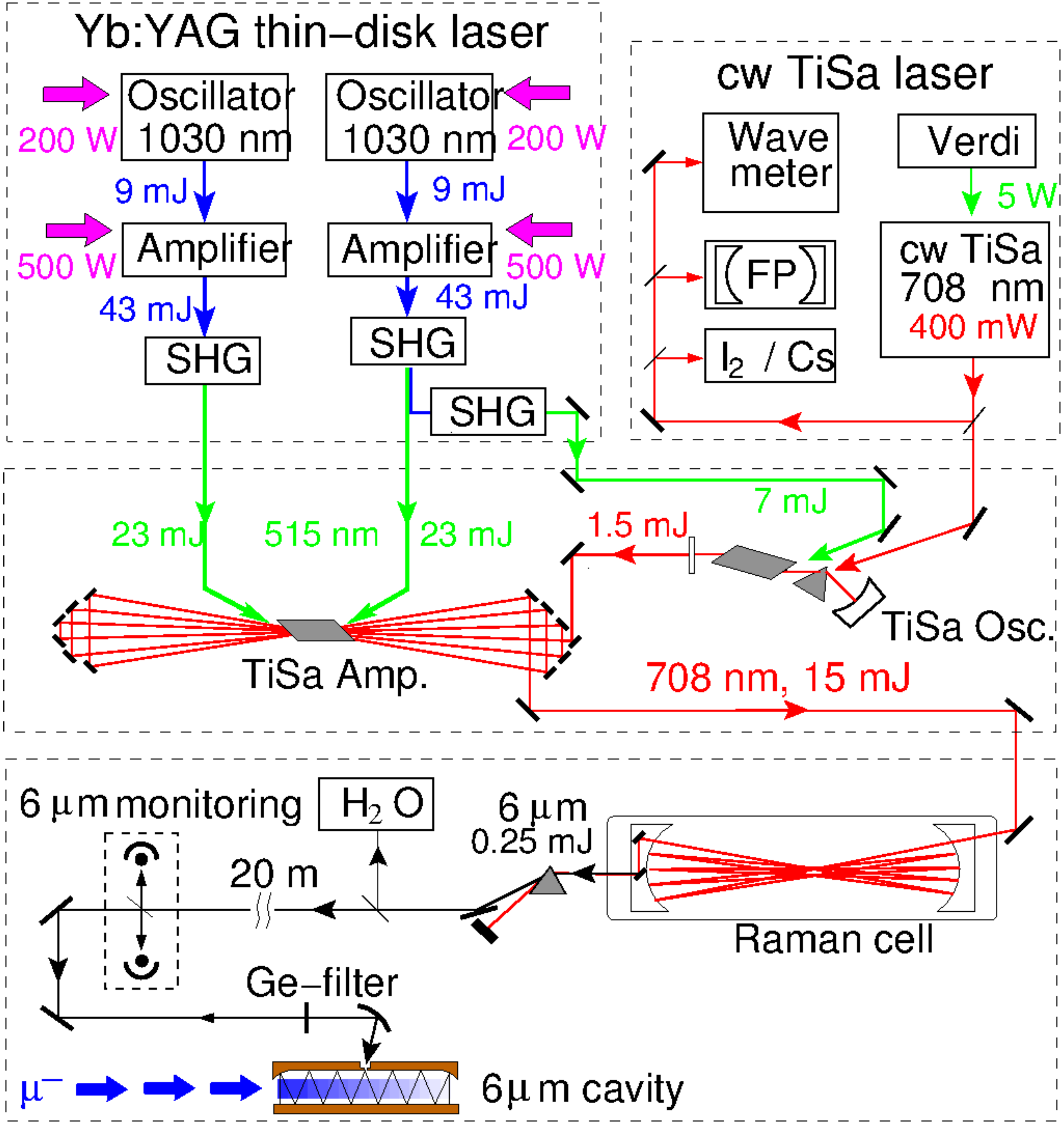
Getting ready….



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

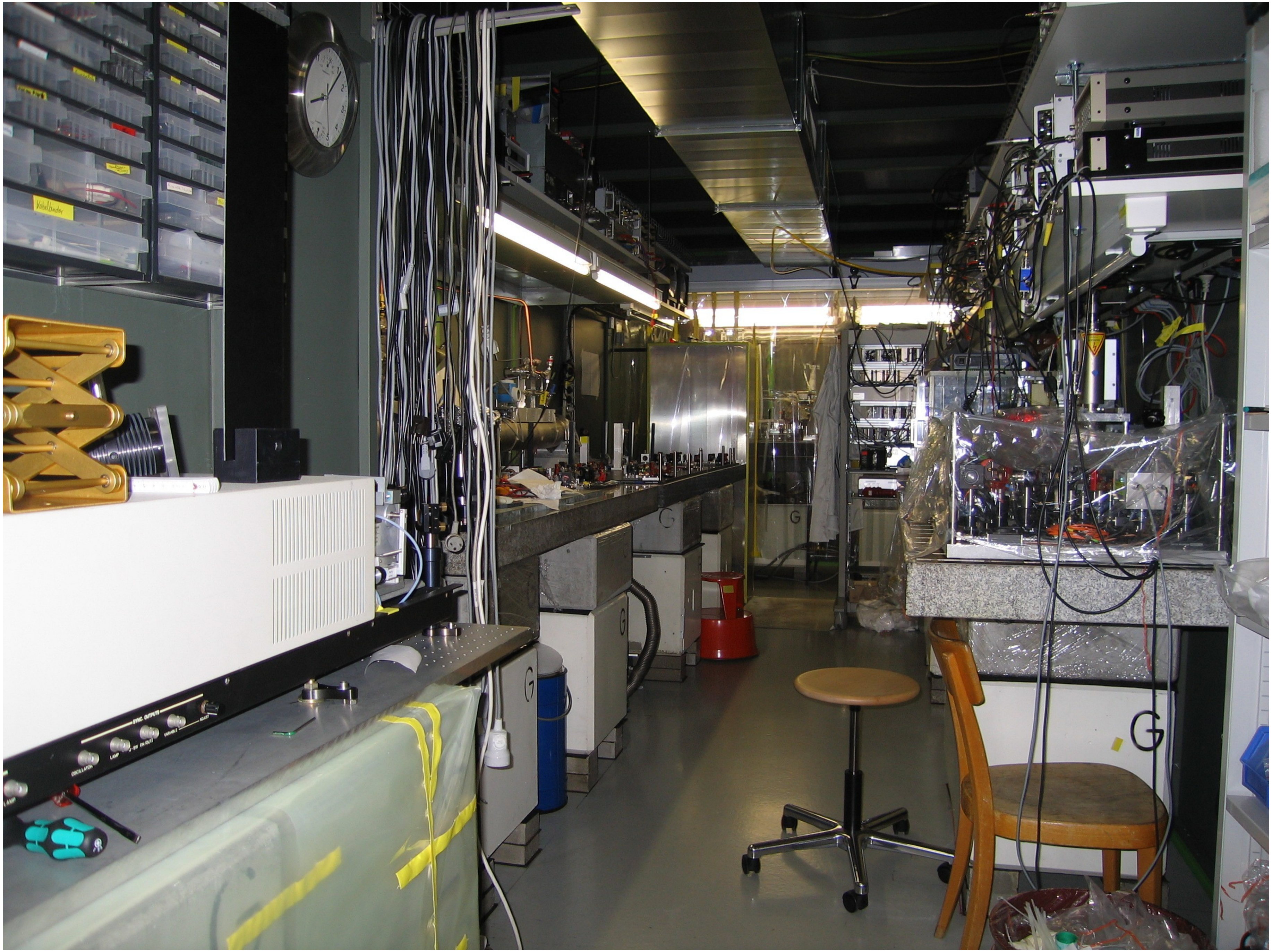
Ti:sapphire oscillator/amplifier
→ large pulse energy (15 mJ)

Raman cell
→ 3fold wavelength change
→ 6 µm

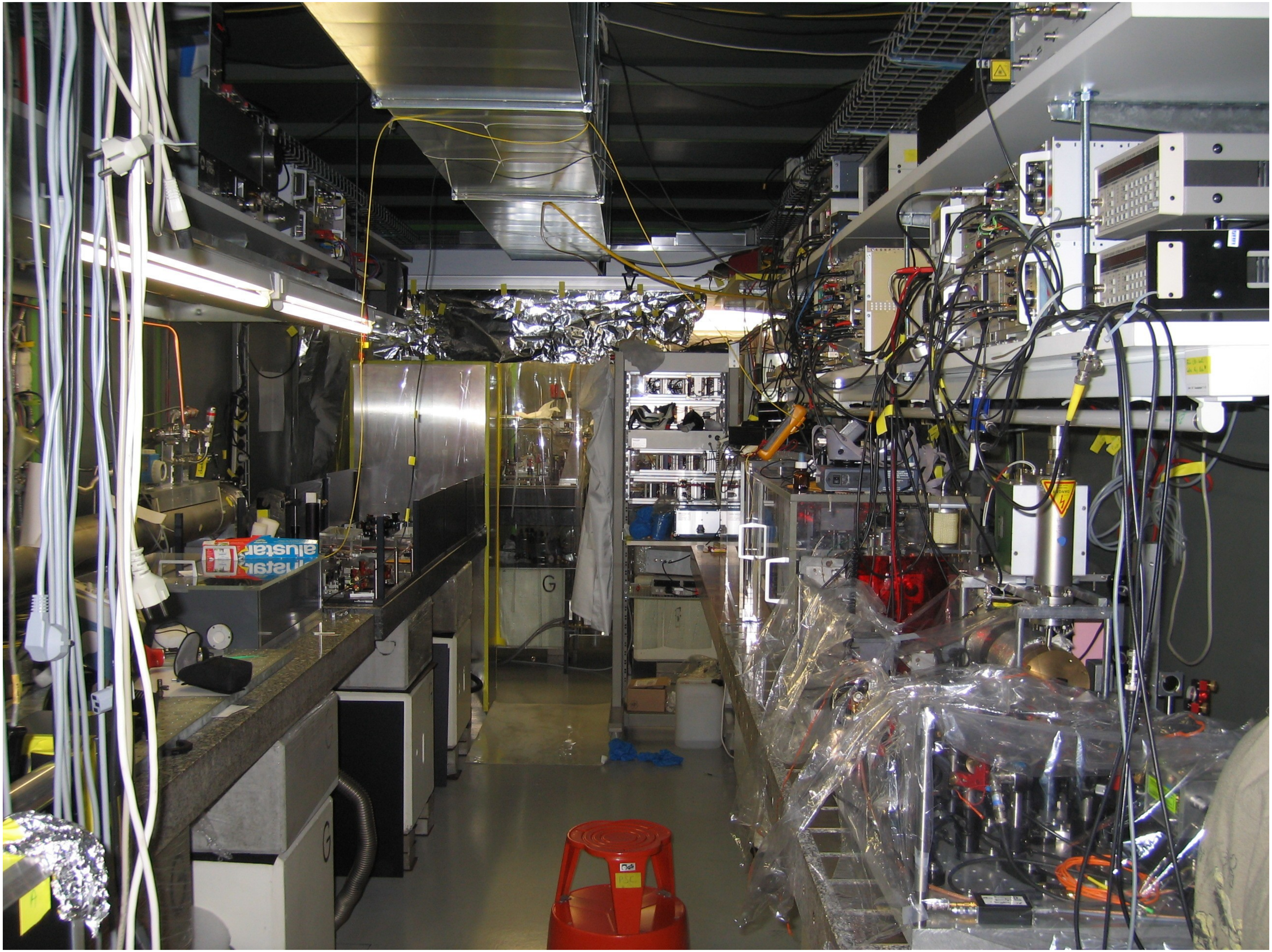
Target Cavity
→ Mirror system surrounds muon stop volume

Inside the Laser Hut

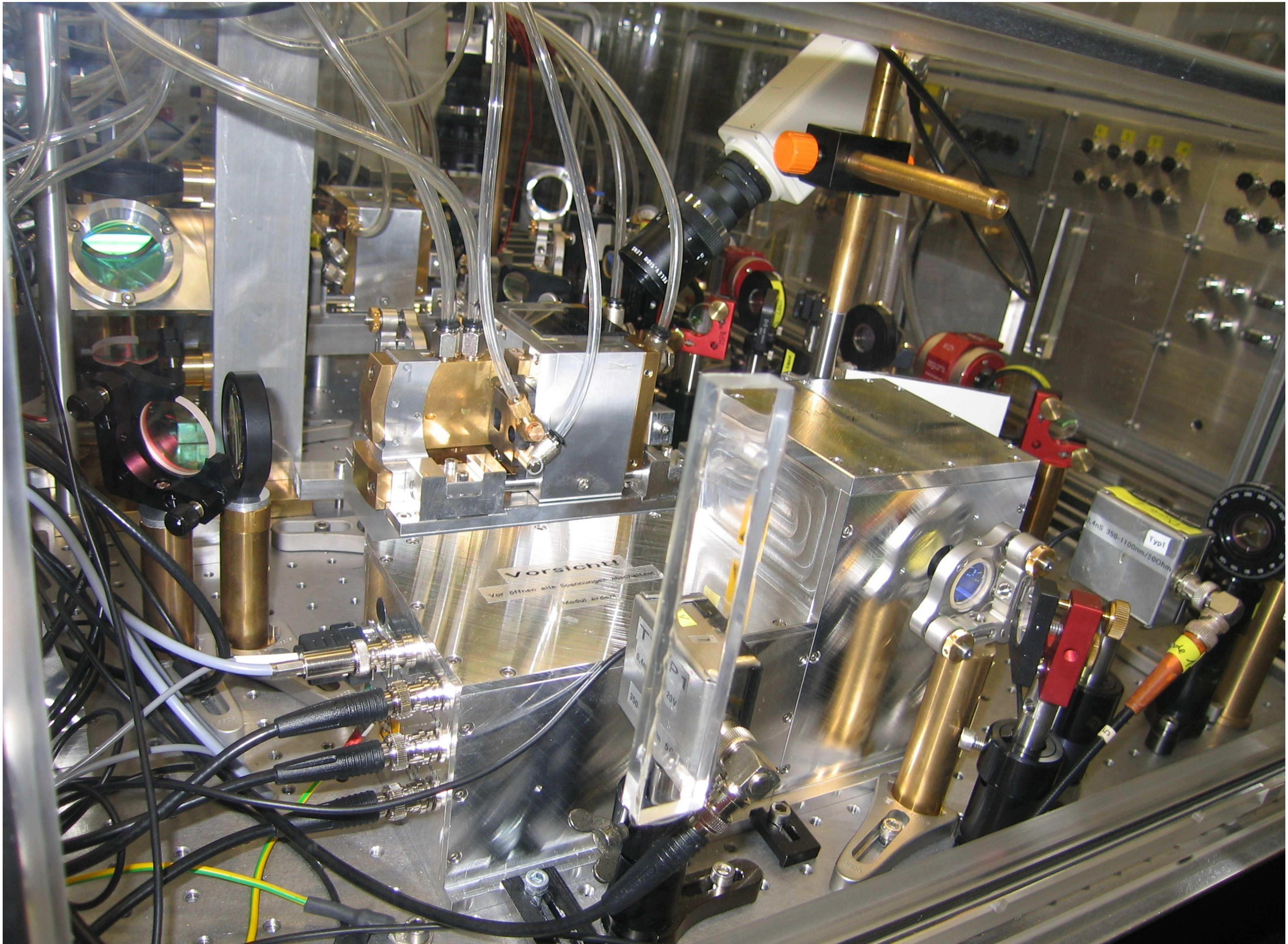
Inside the Laser Hut



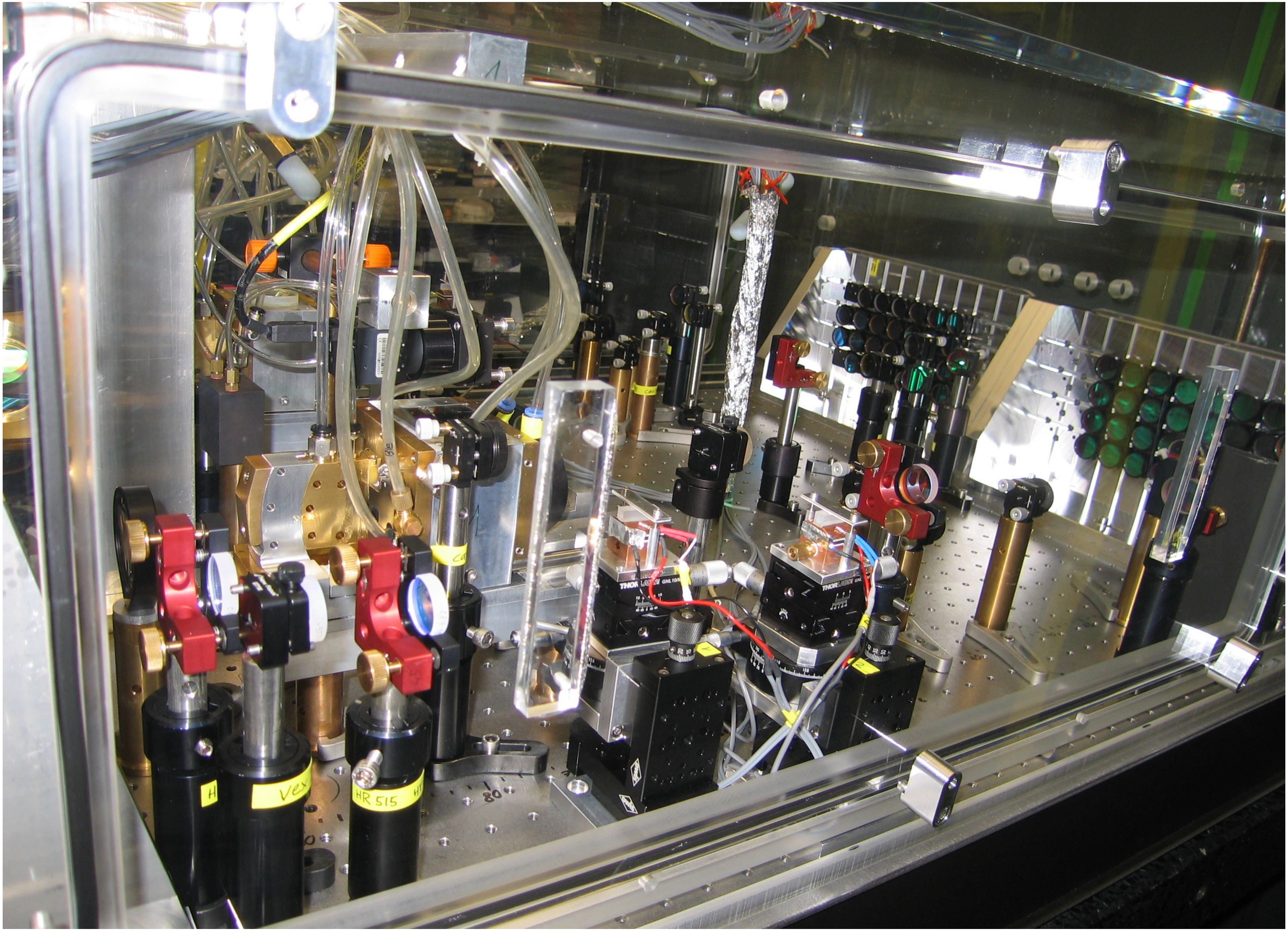
Inside the Laser Hut



Yb:YAG Oscillator



Yb:YAG Amplifier



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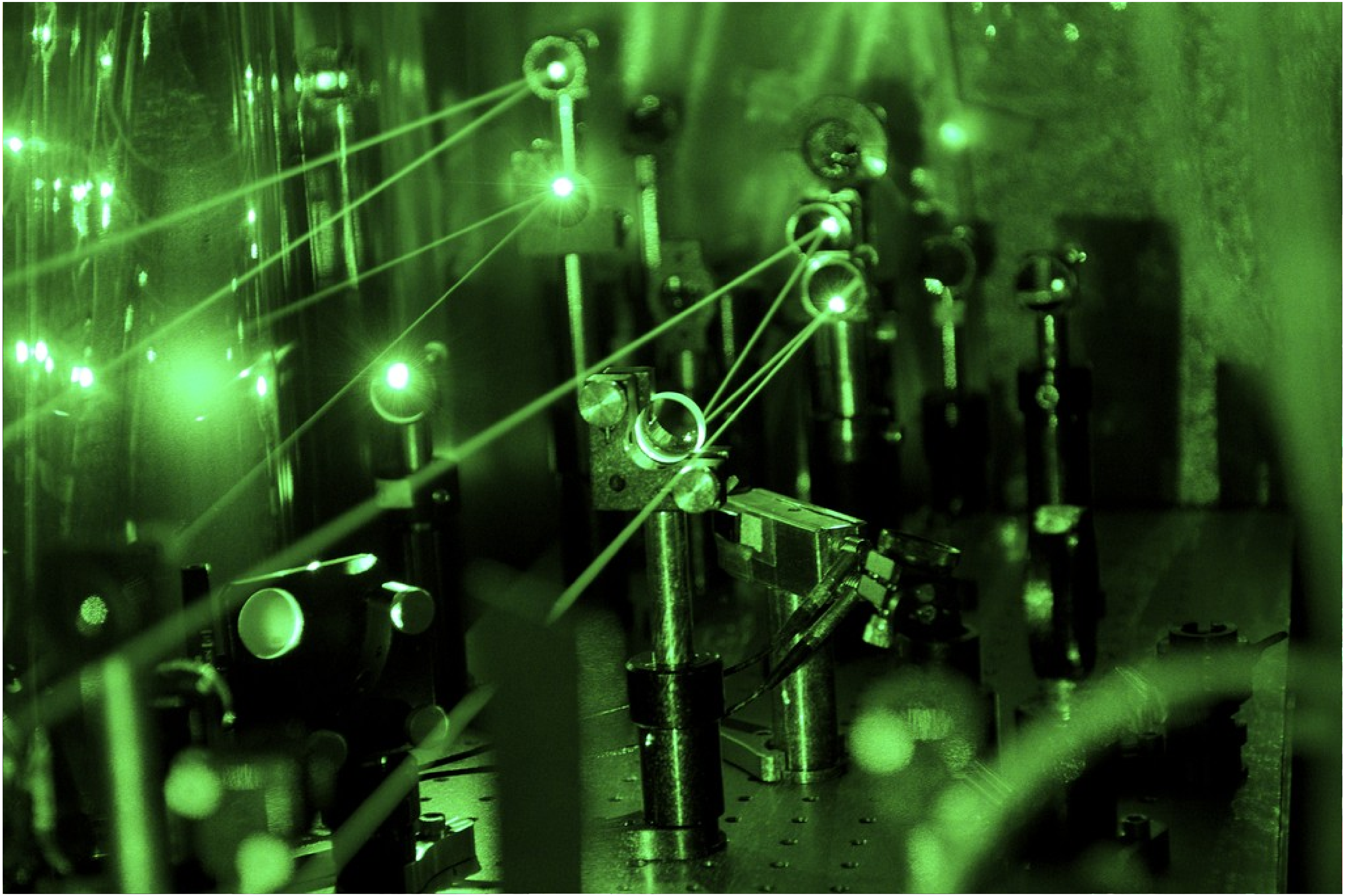

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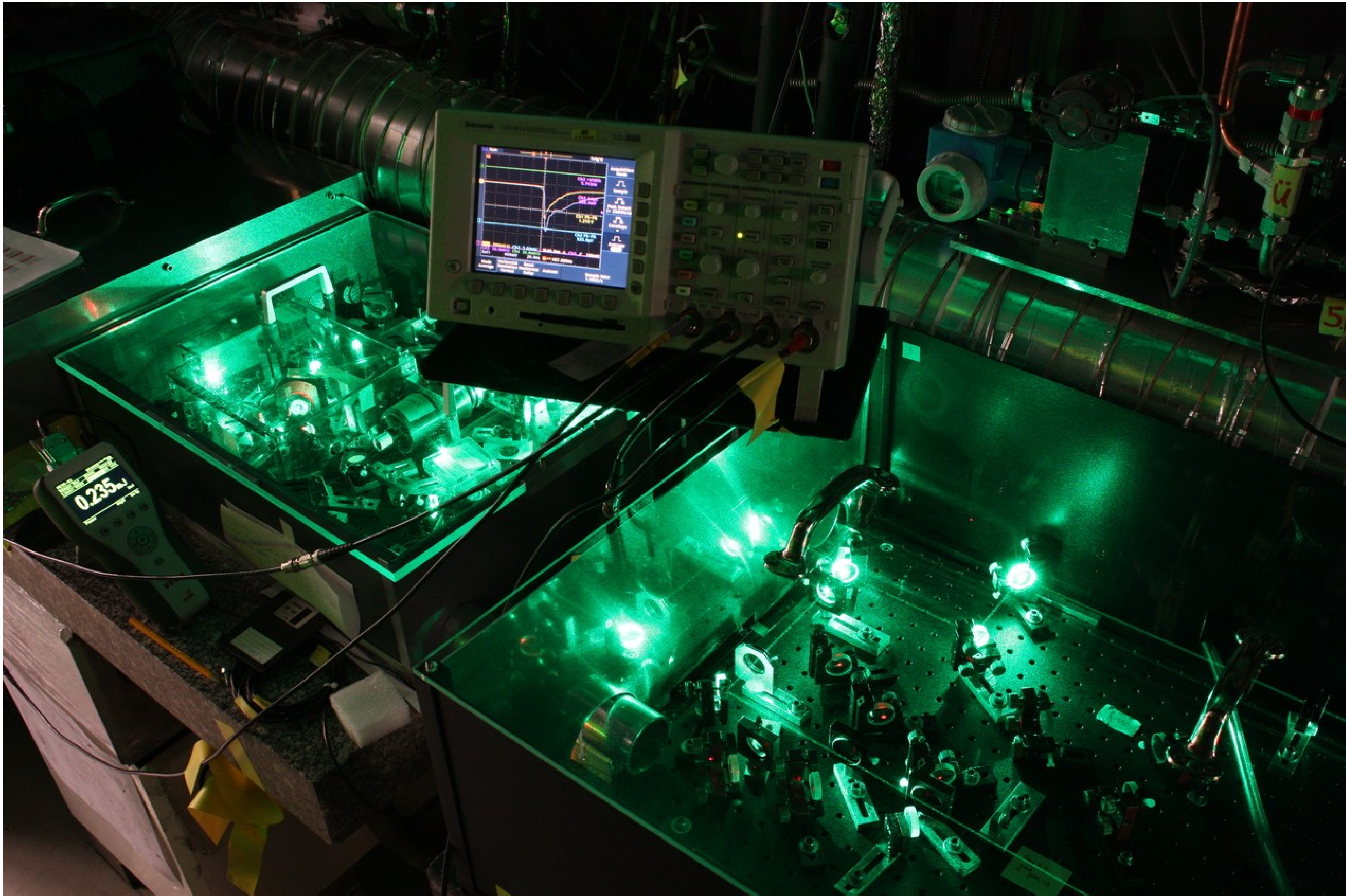
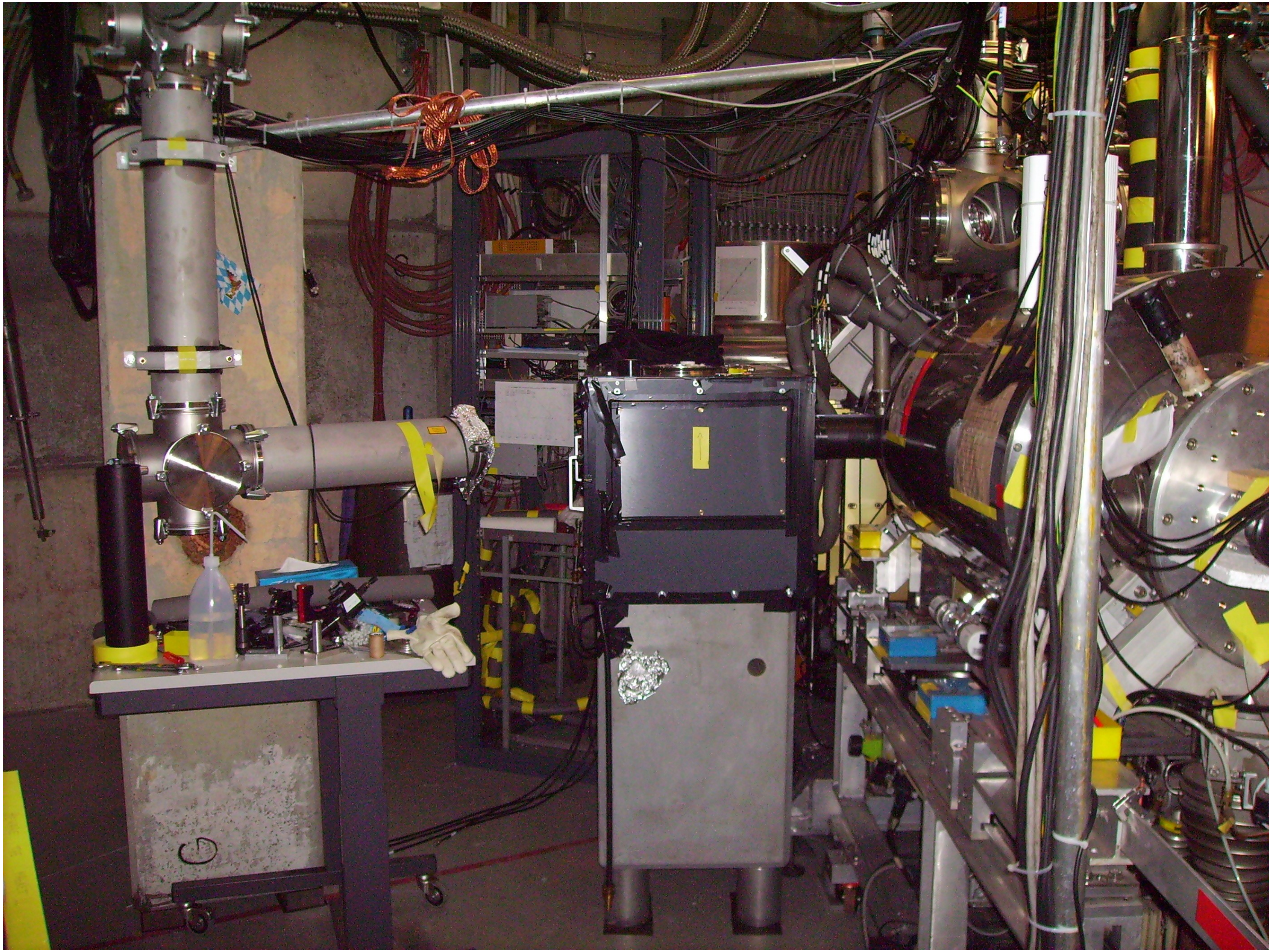
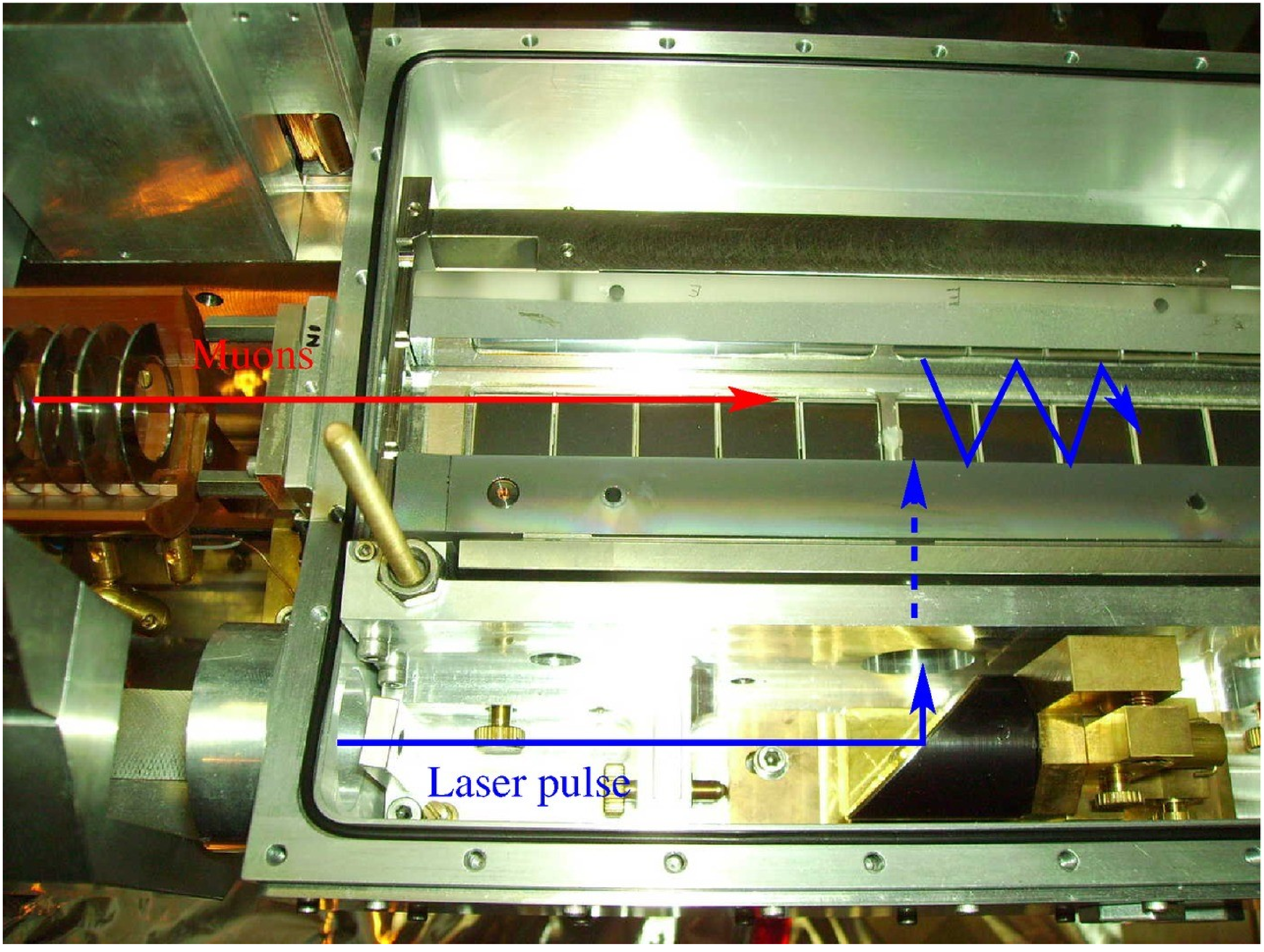


Light through the Tube



The Heart of the Setup -- Target



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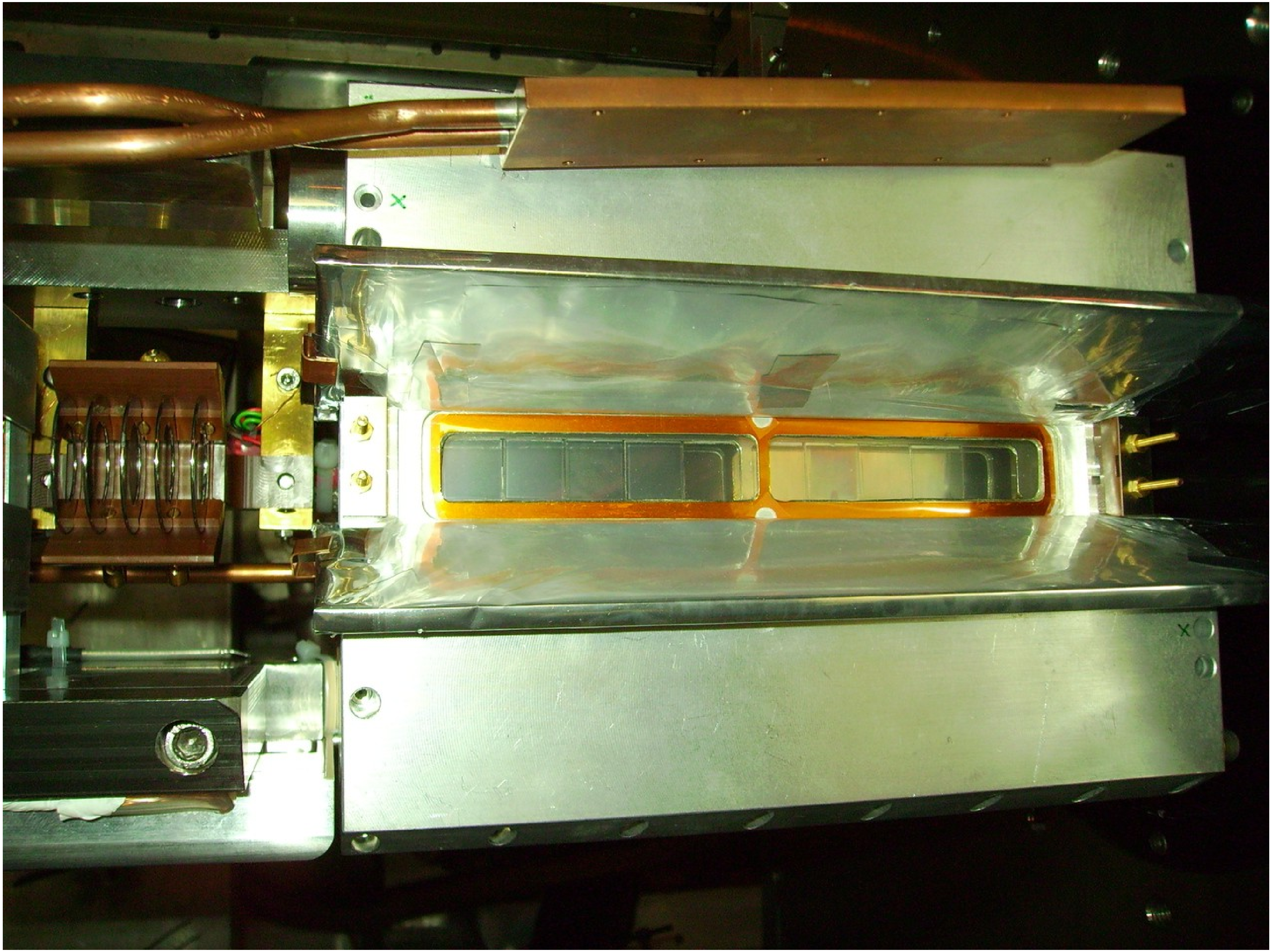

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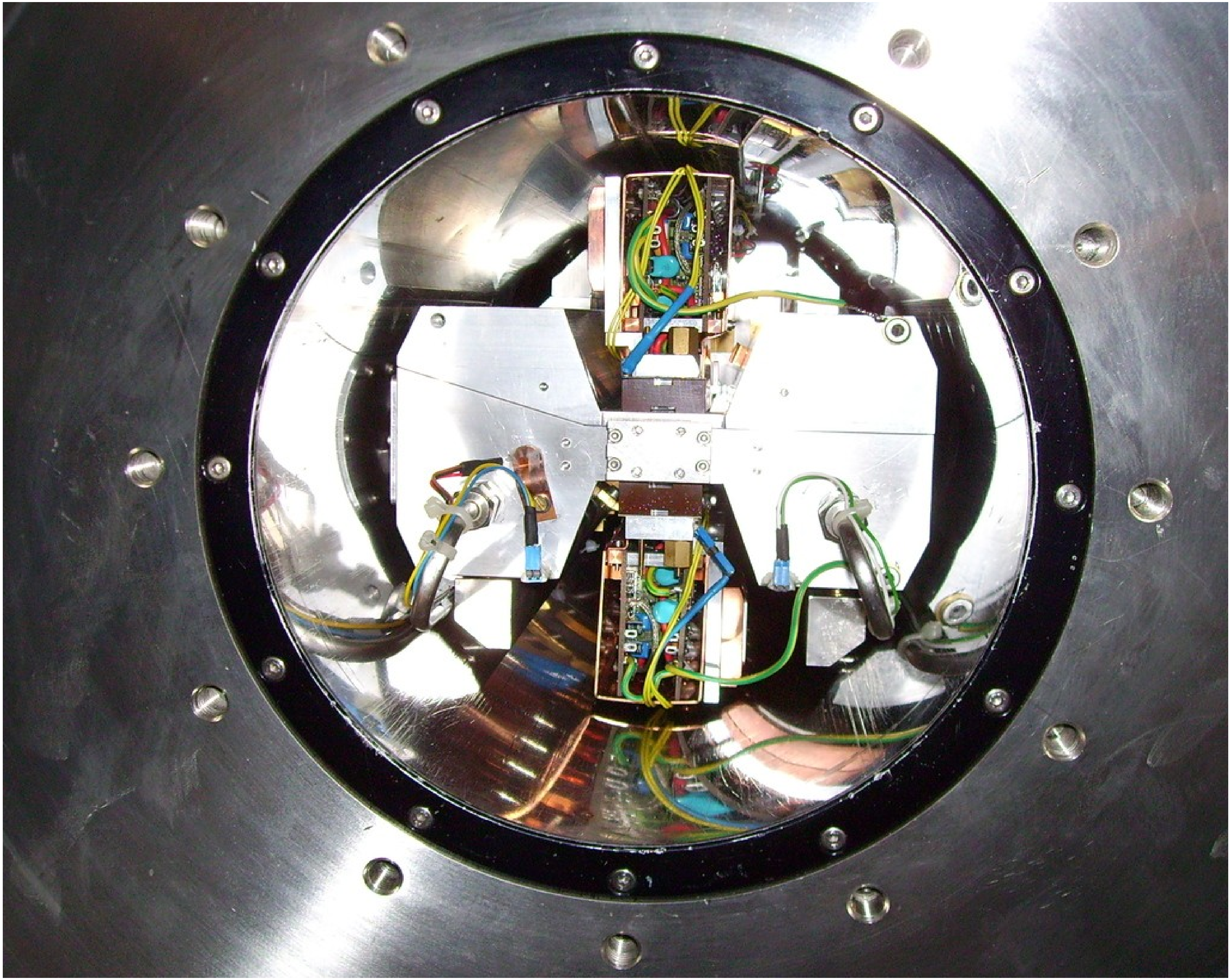
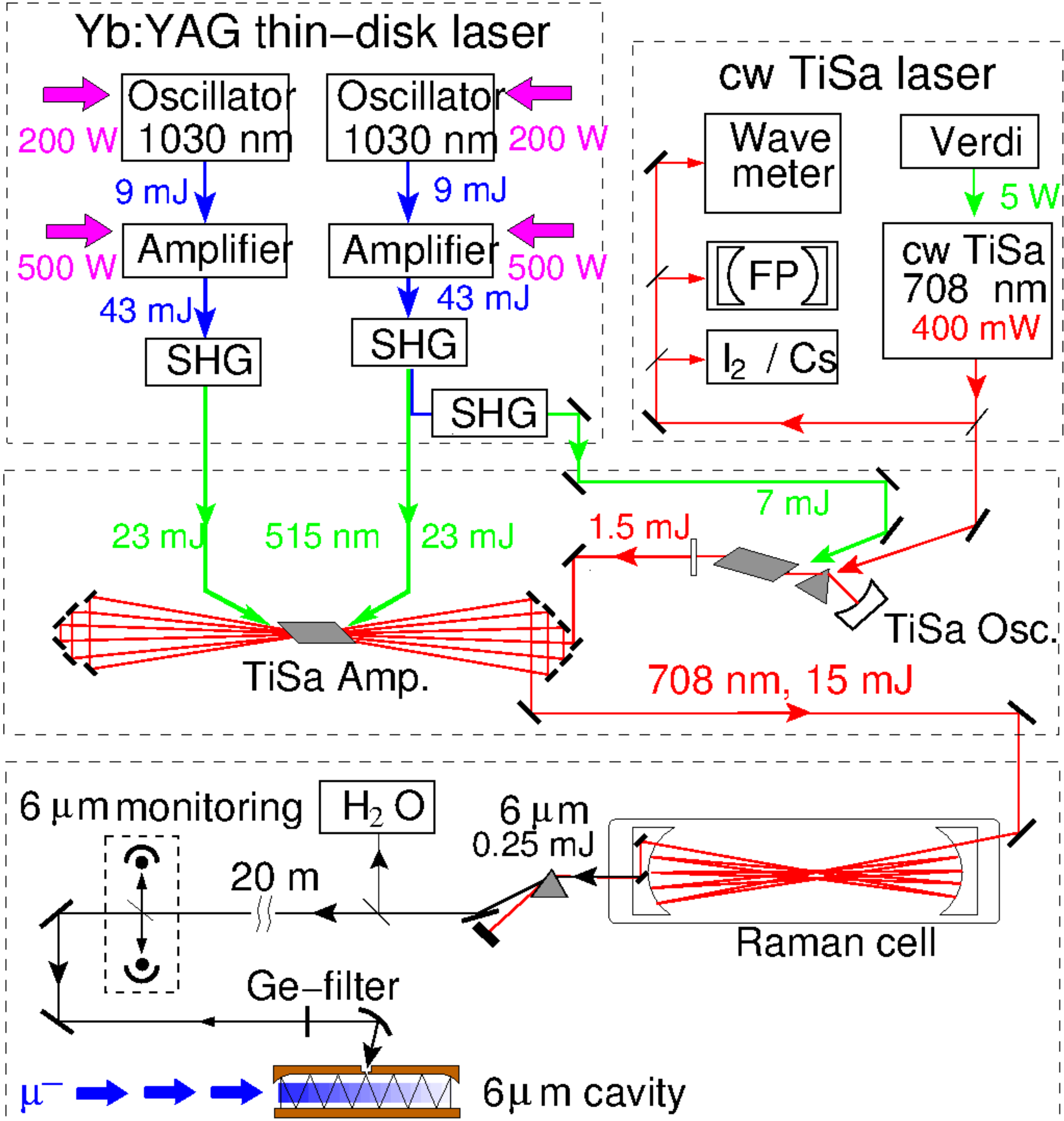


Muon beam movie

The Laser System



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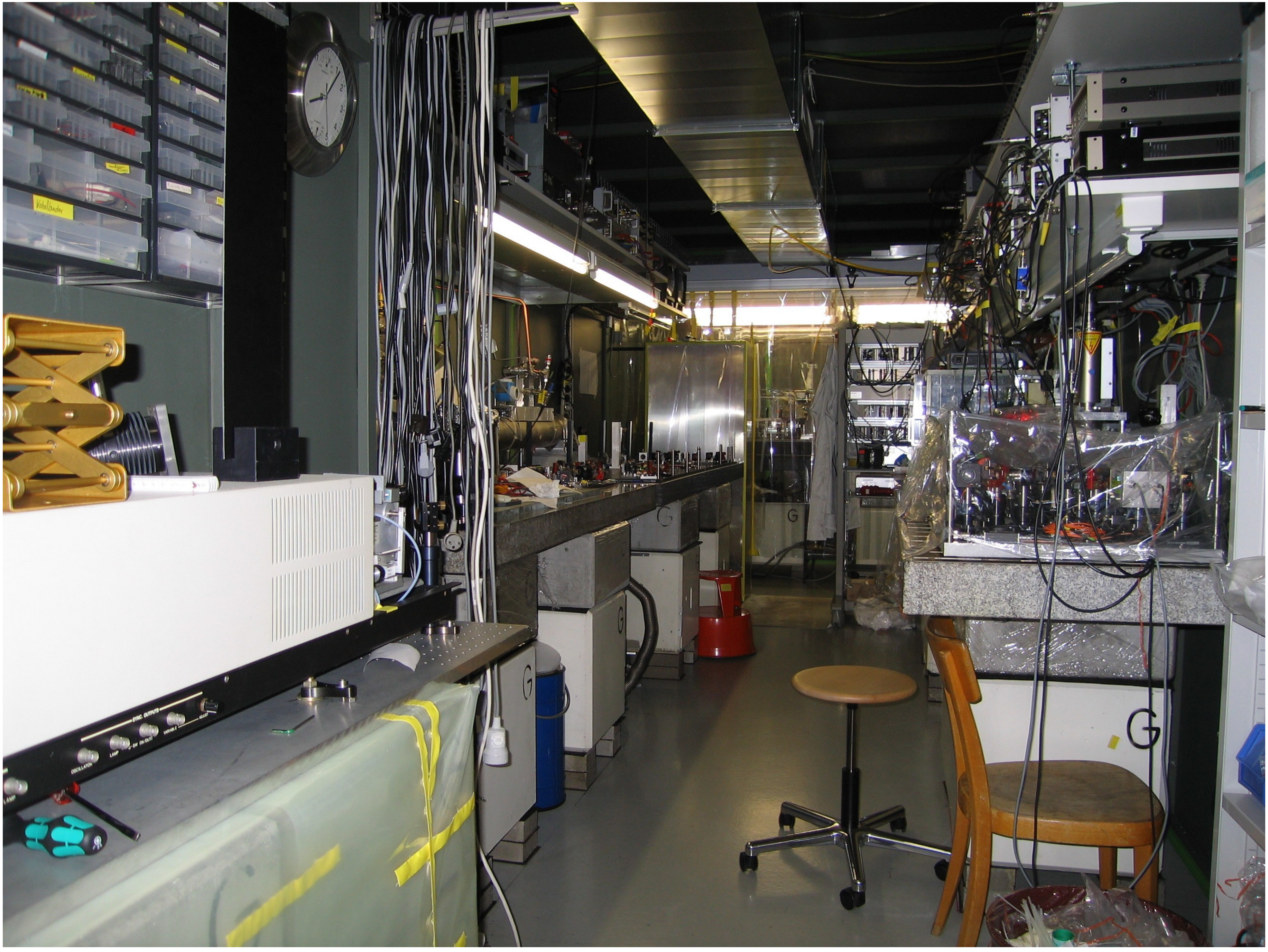
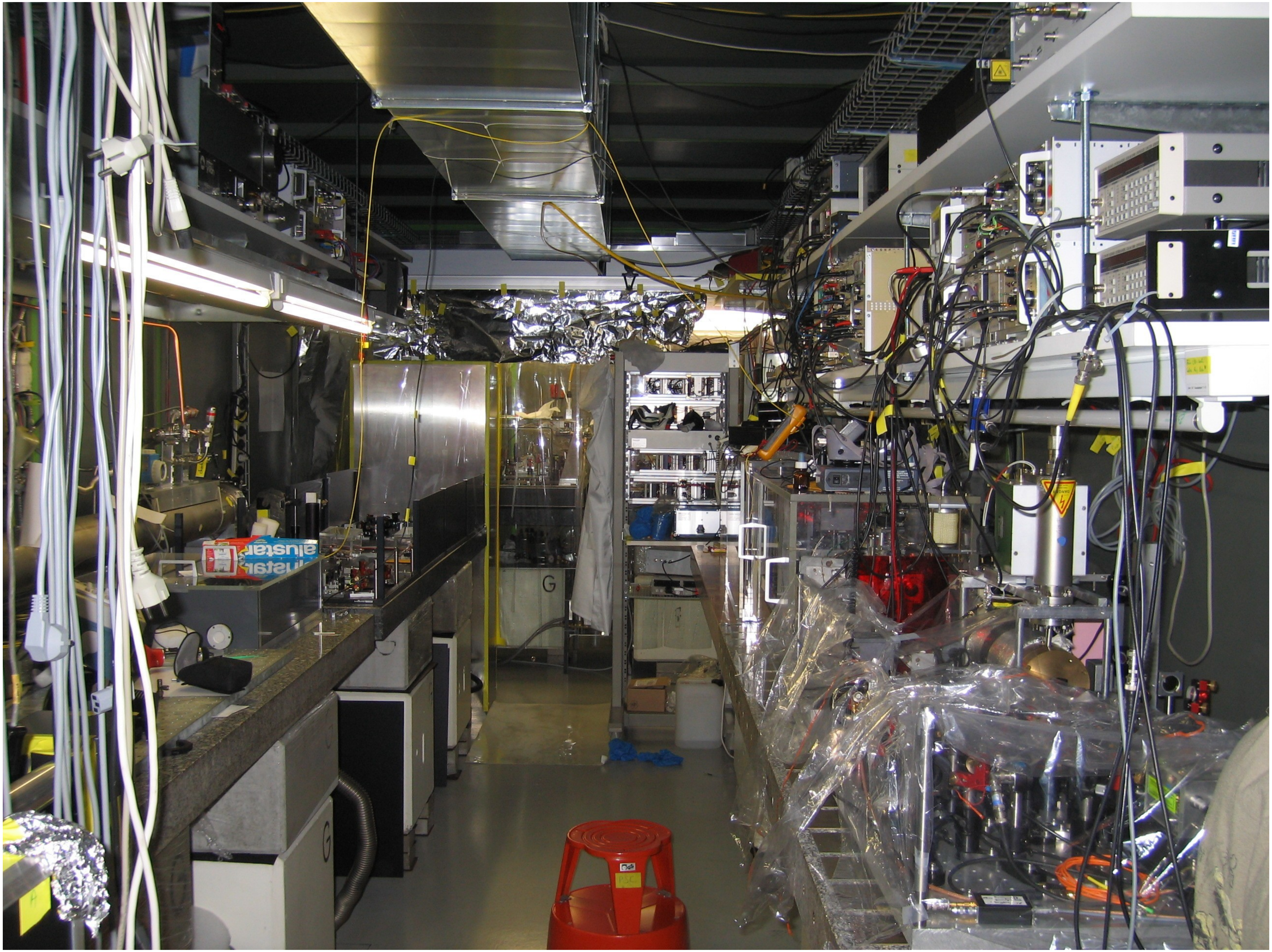
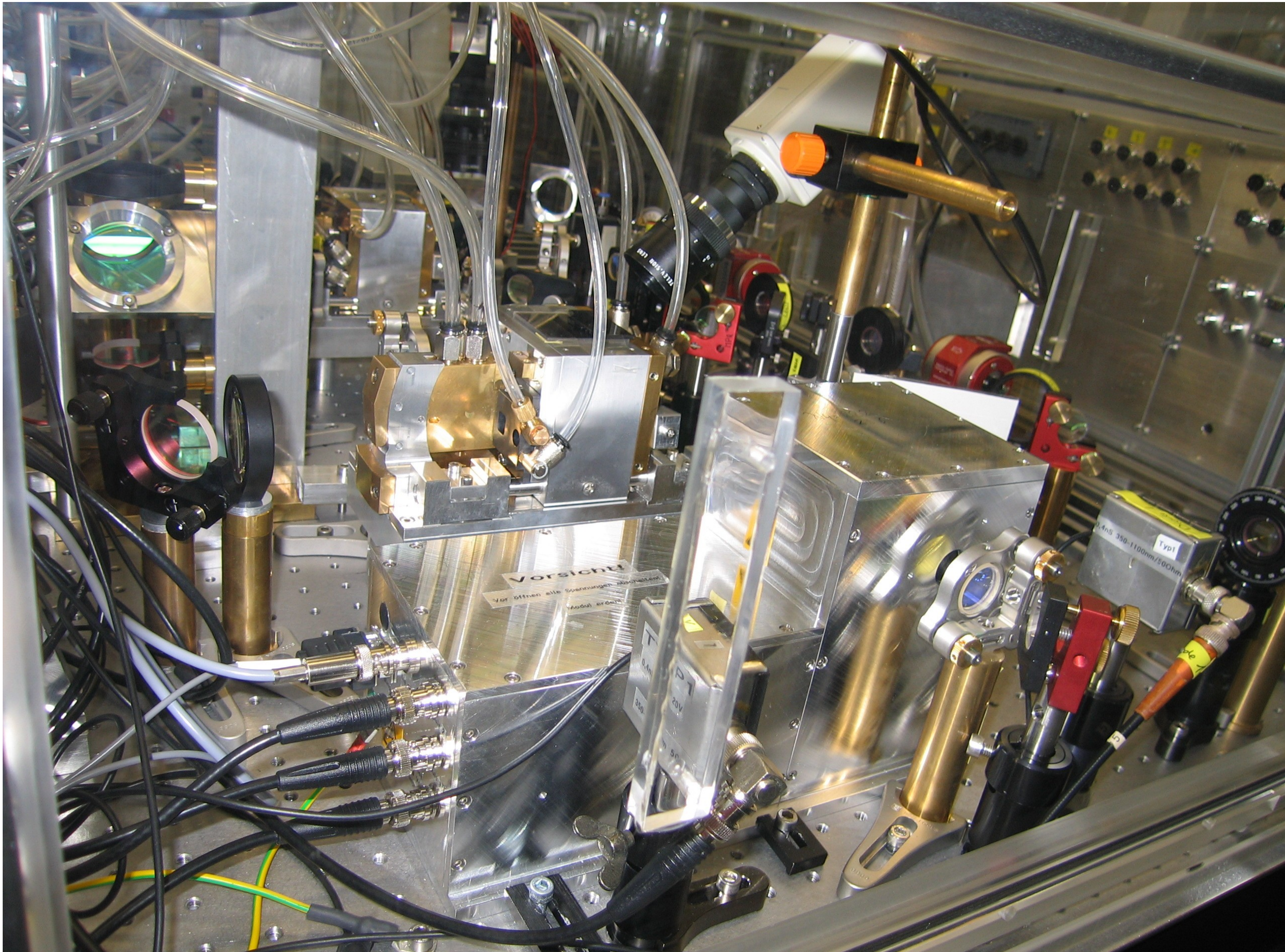


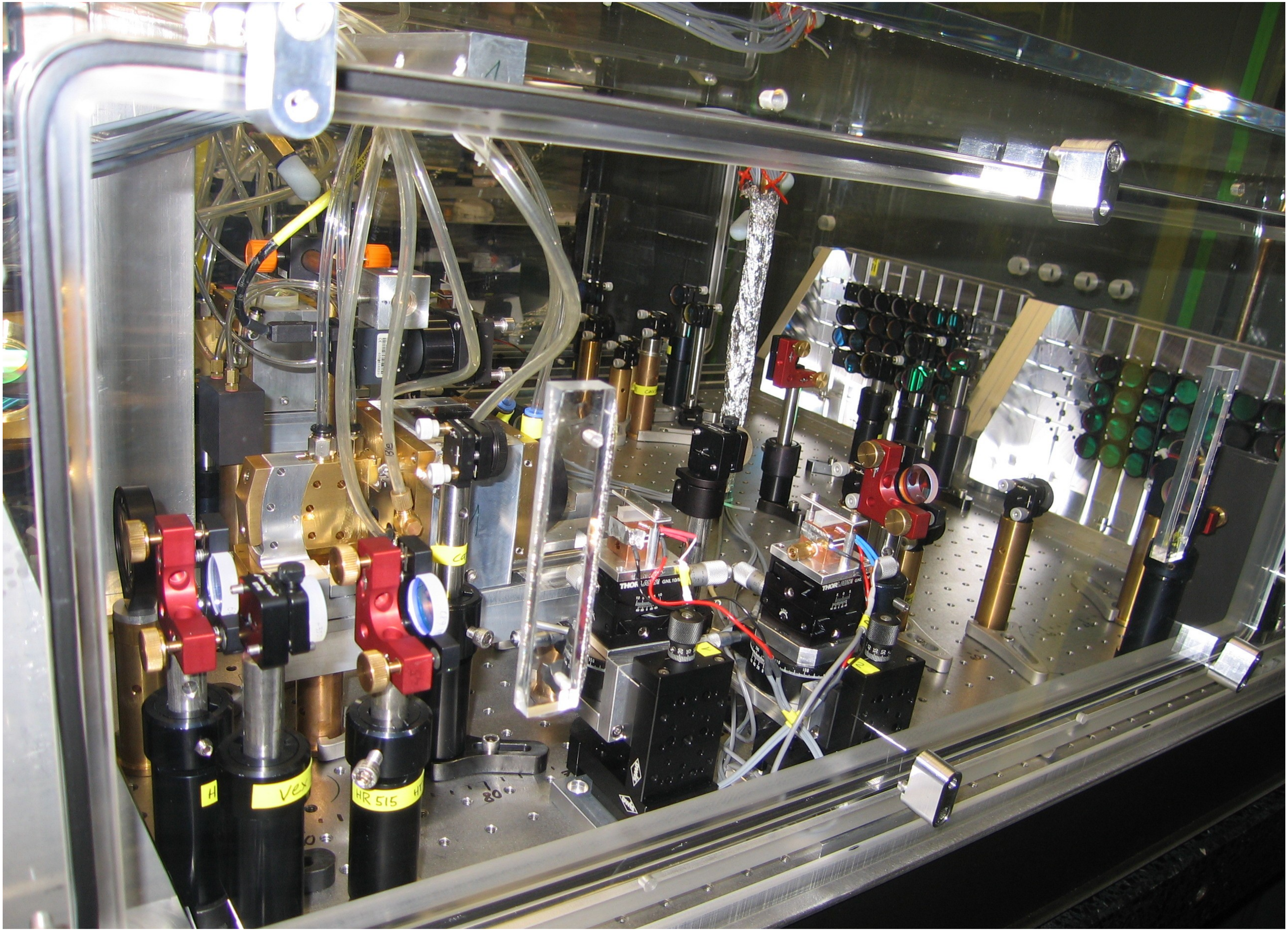
Inside the Laser Hut



Yb:YAG Oscillator

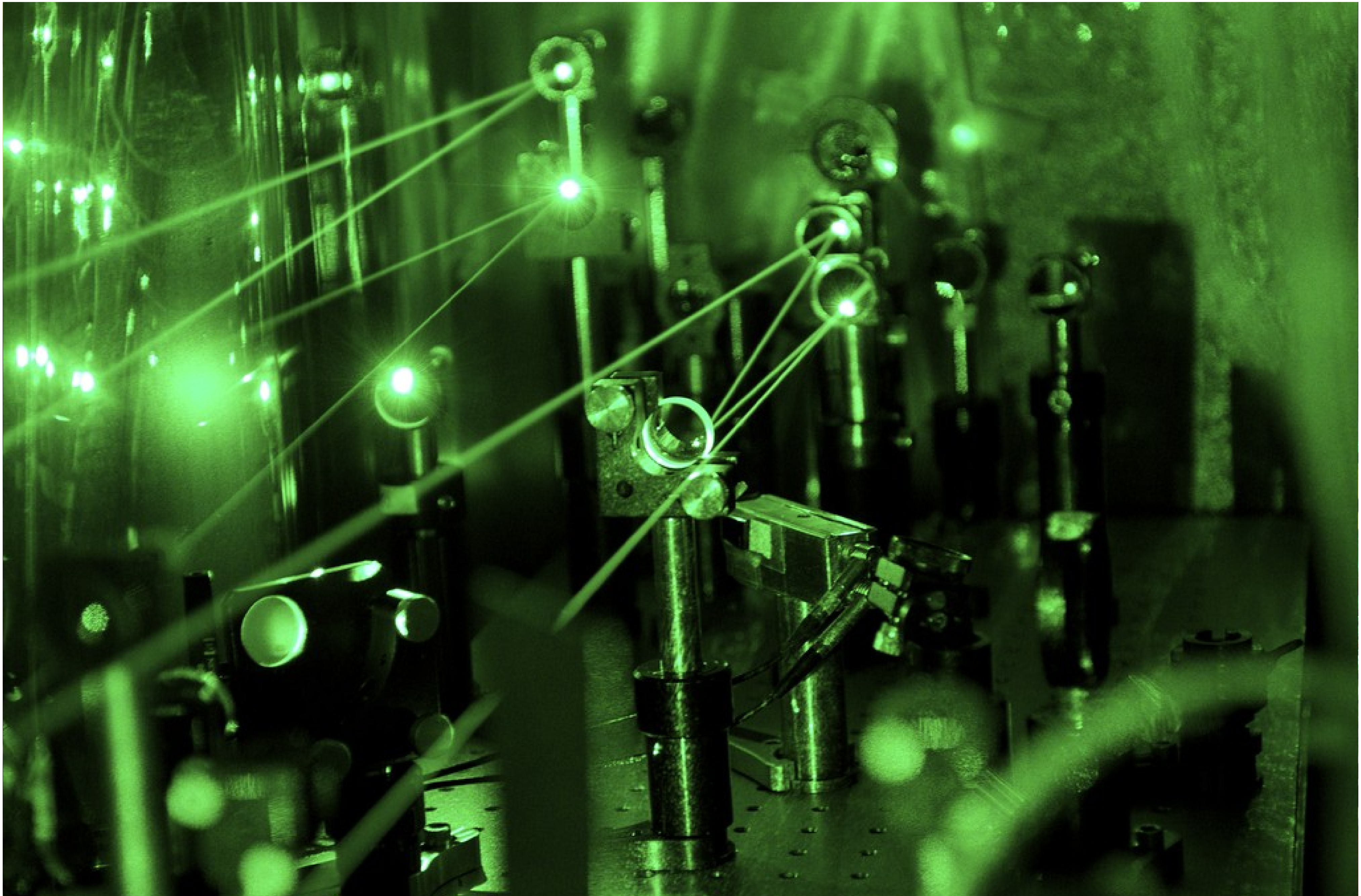


Yb:YAG Amplifier



Inside the Laser Hut

Inside the Laser Hut



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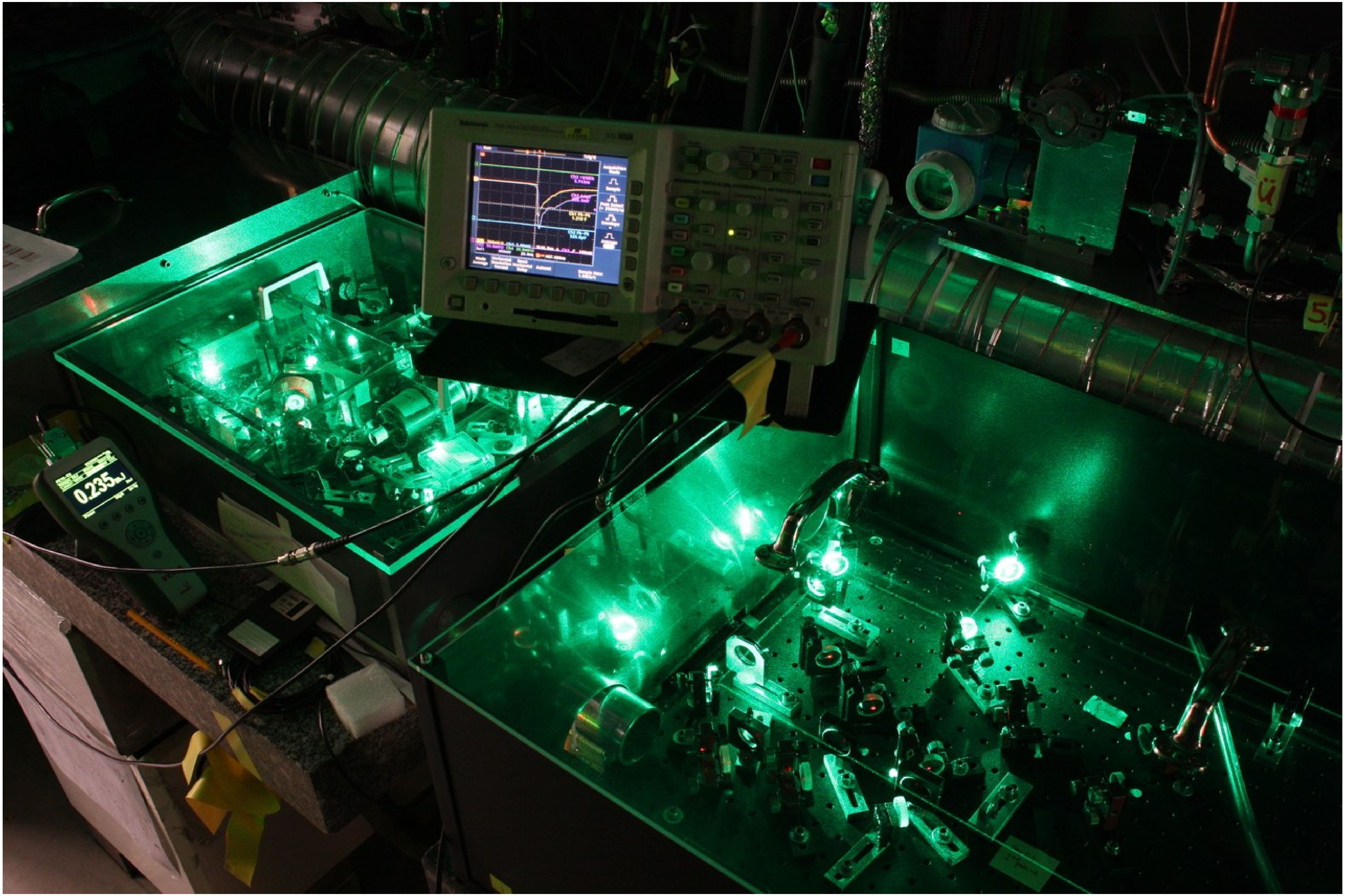

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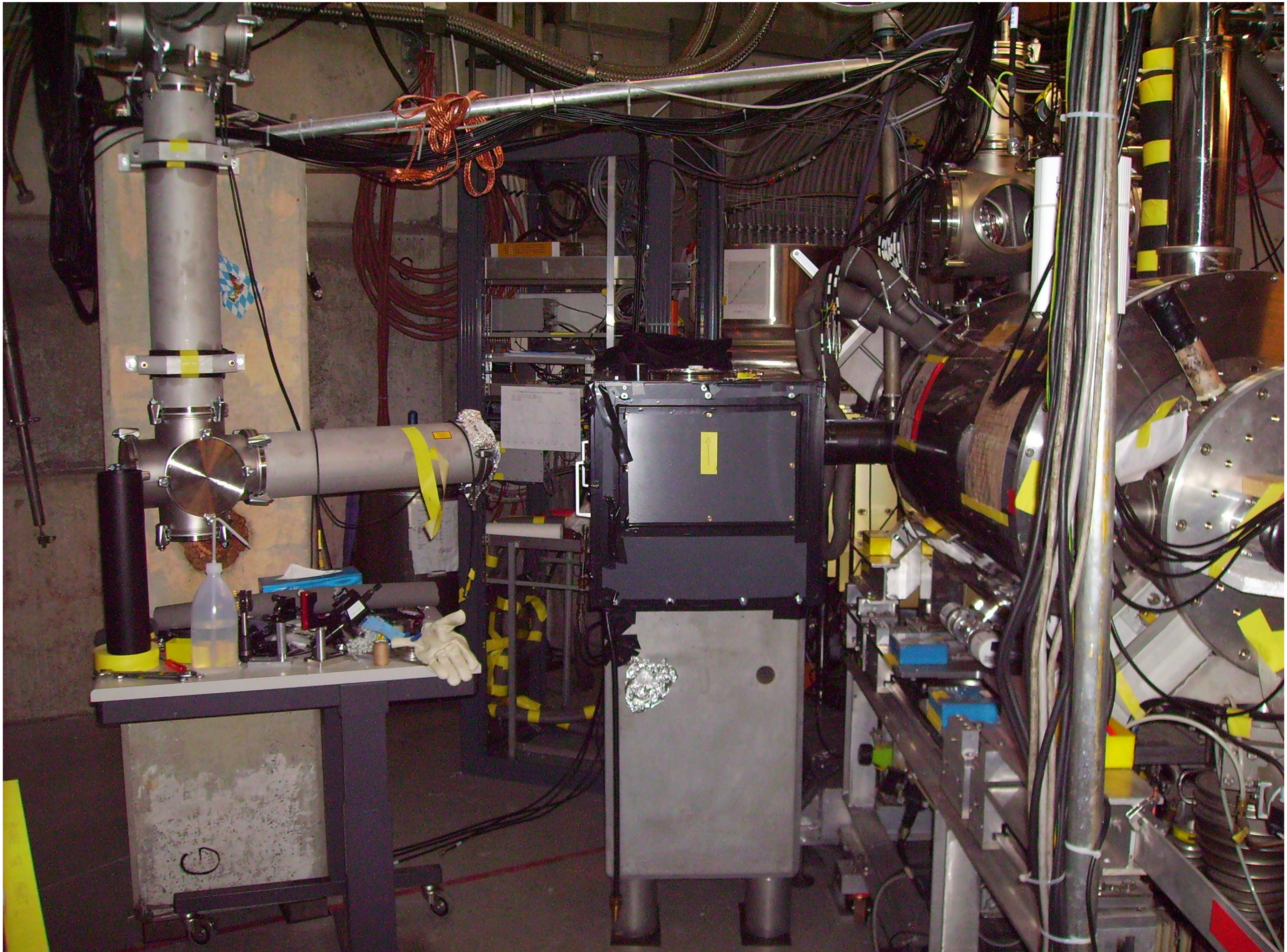
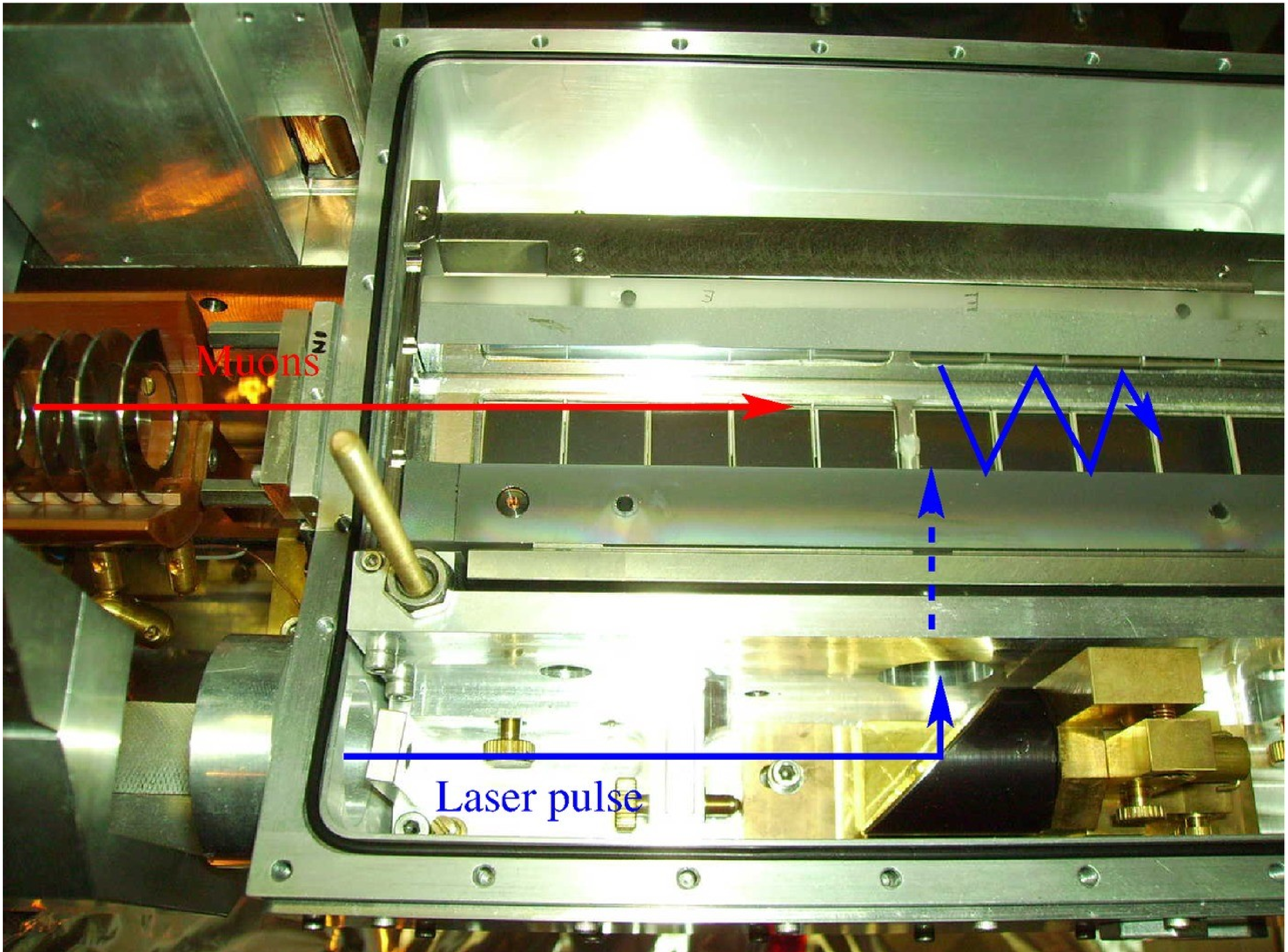


The Heart of the Setup -- Target



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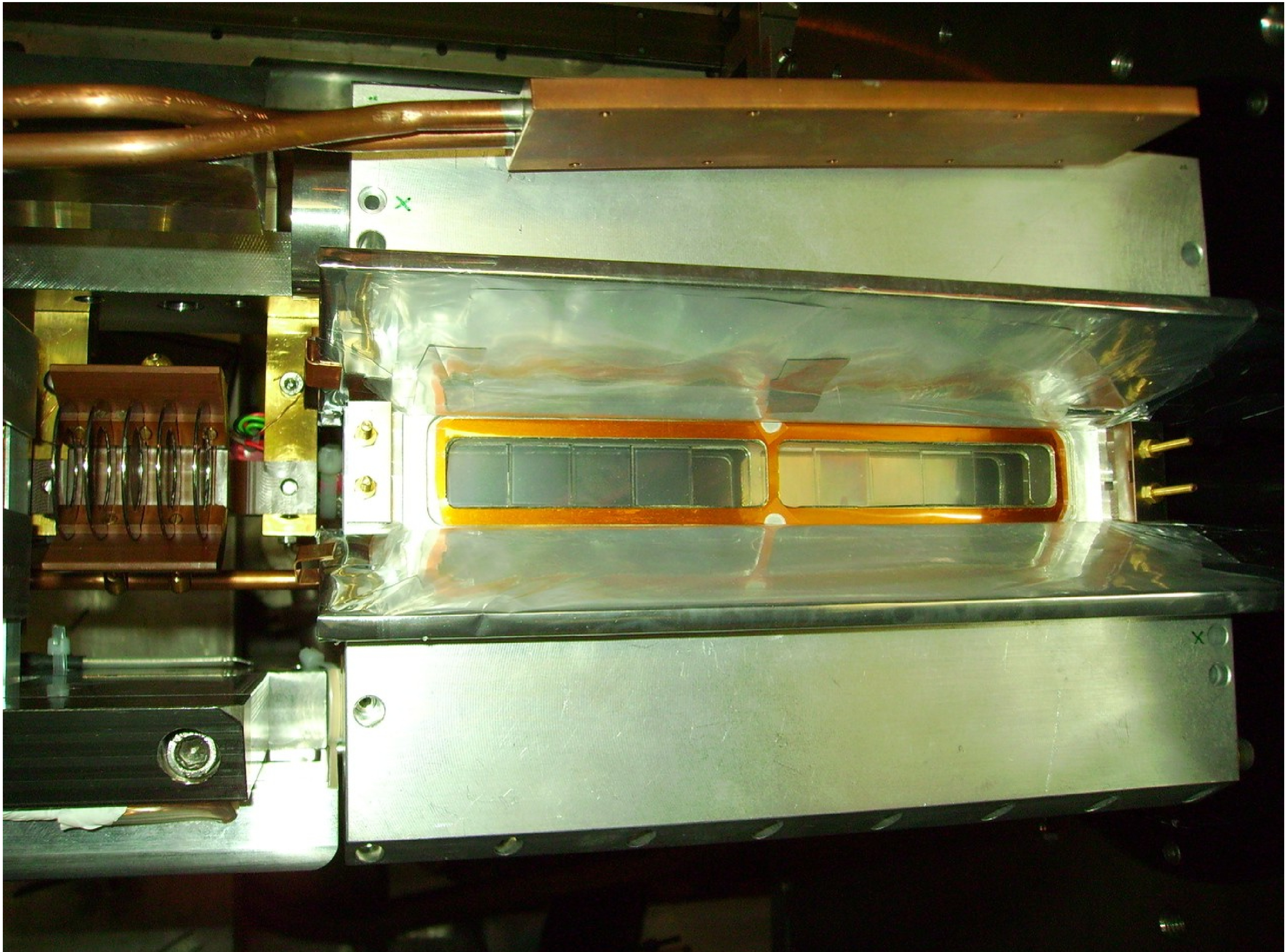
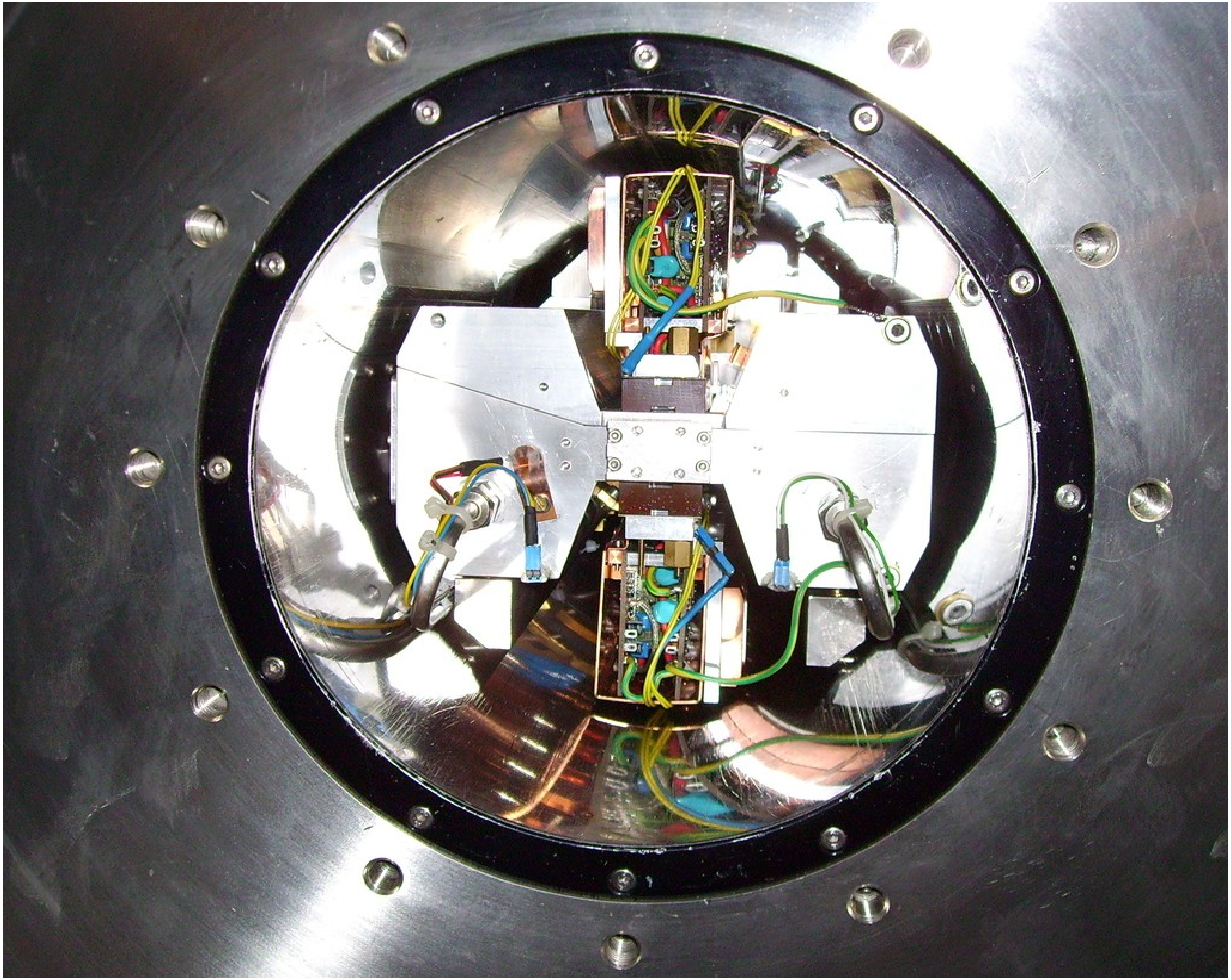
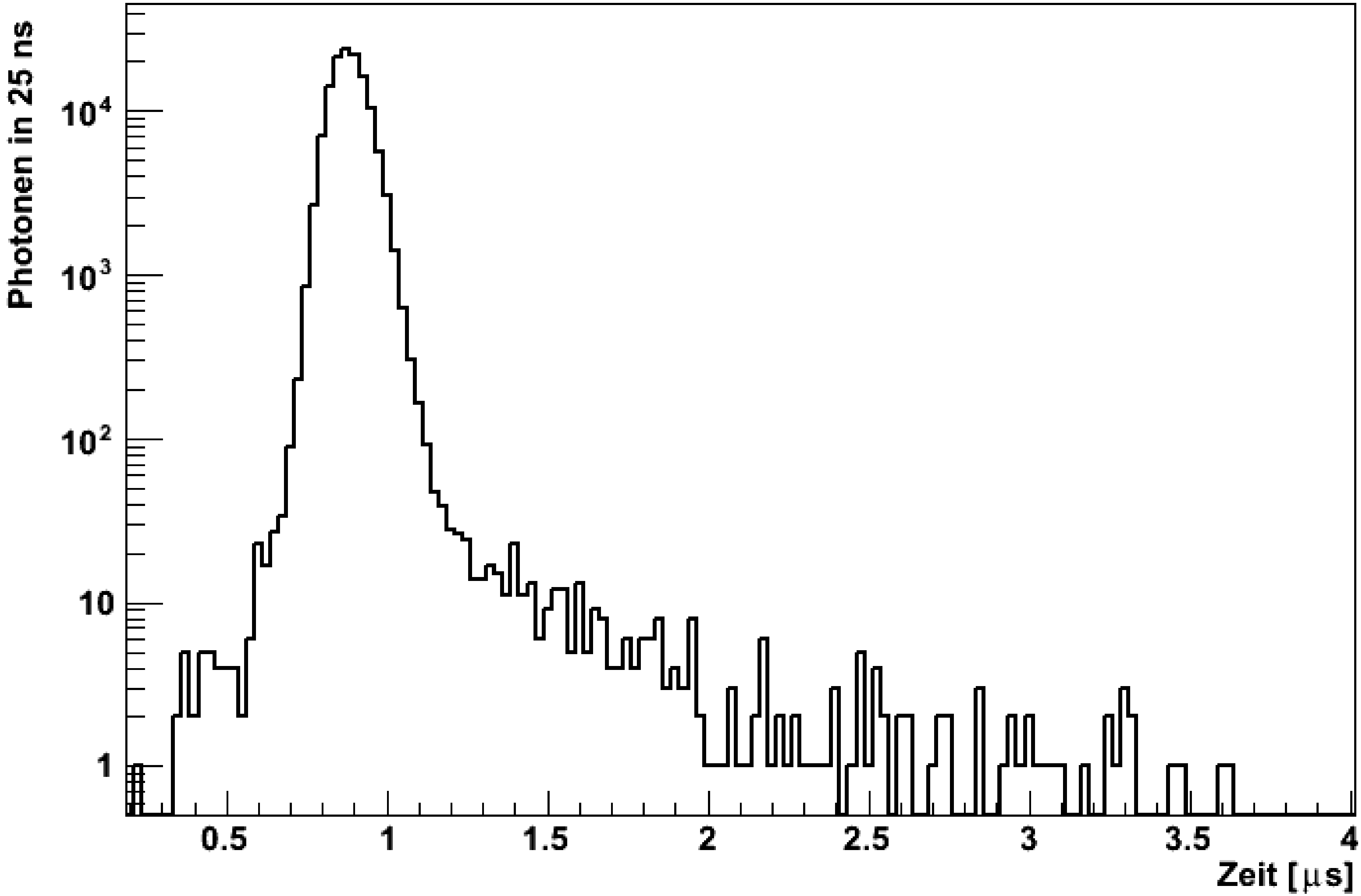


The Heart of the Setup -- Target



Time Spectra

13 hours of data



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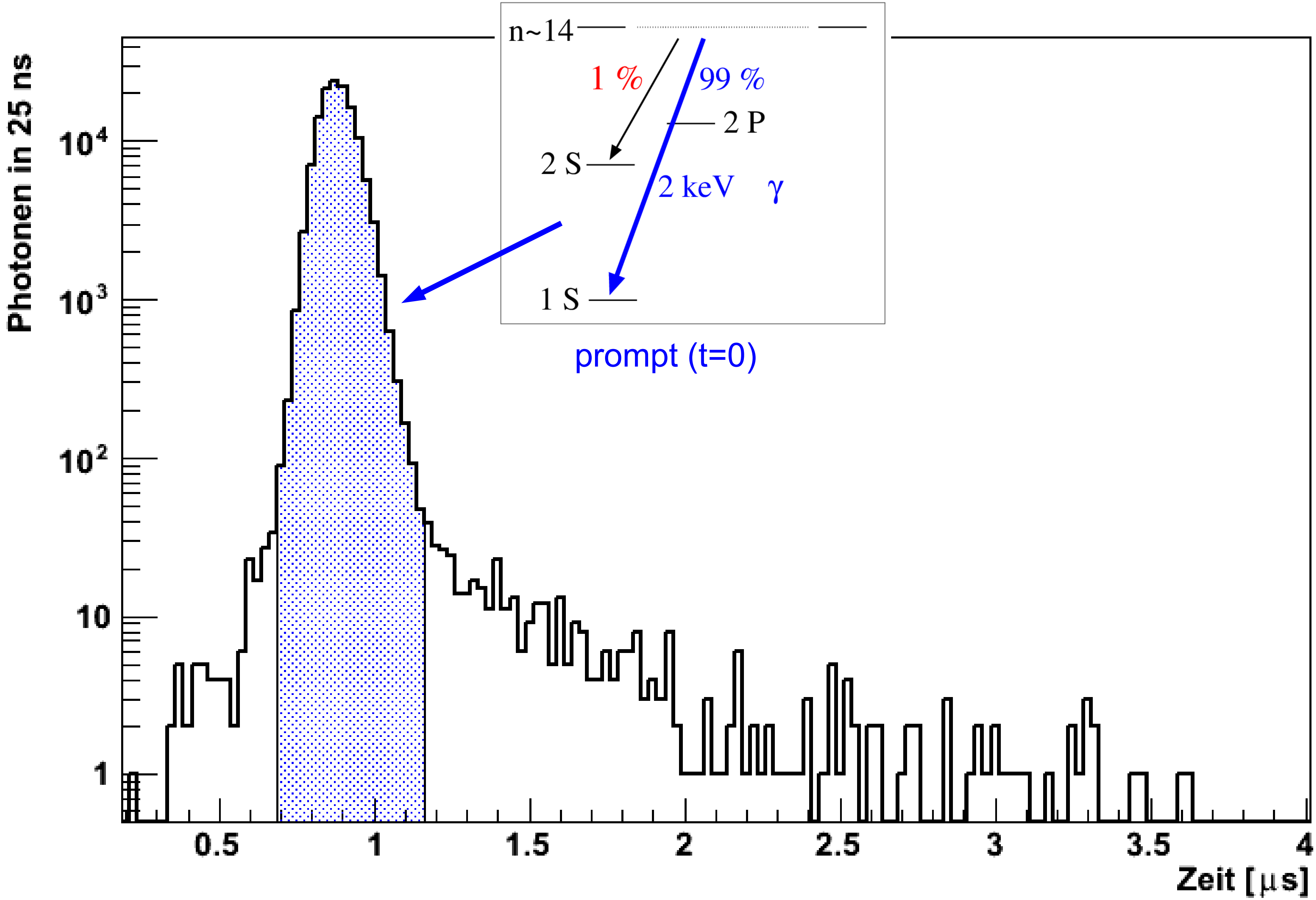
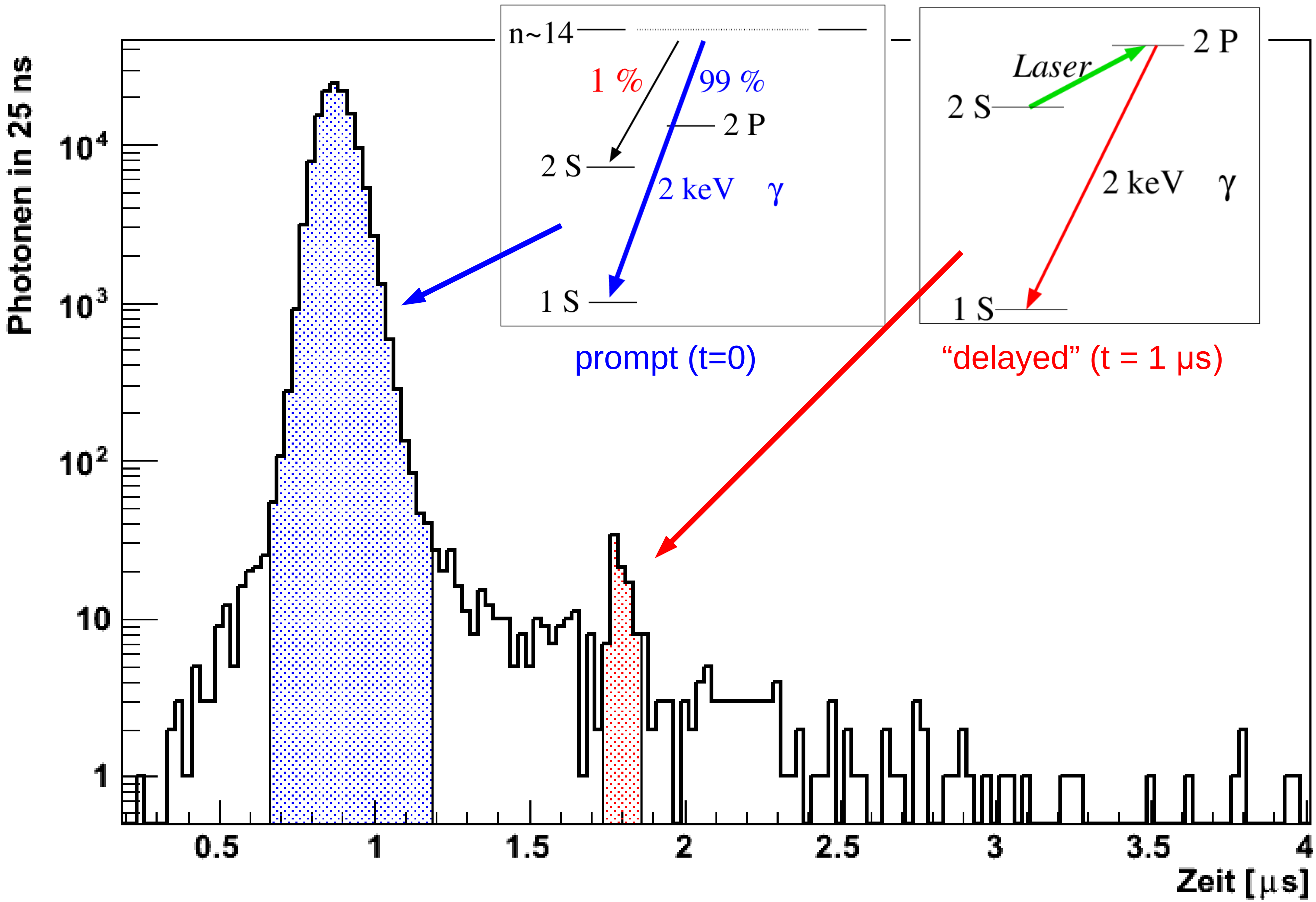
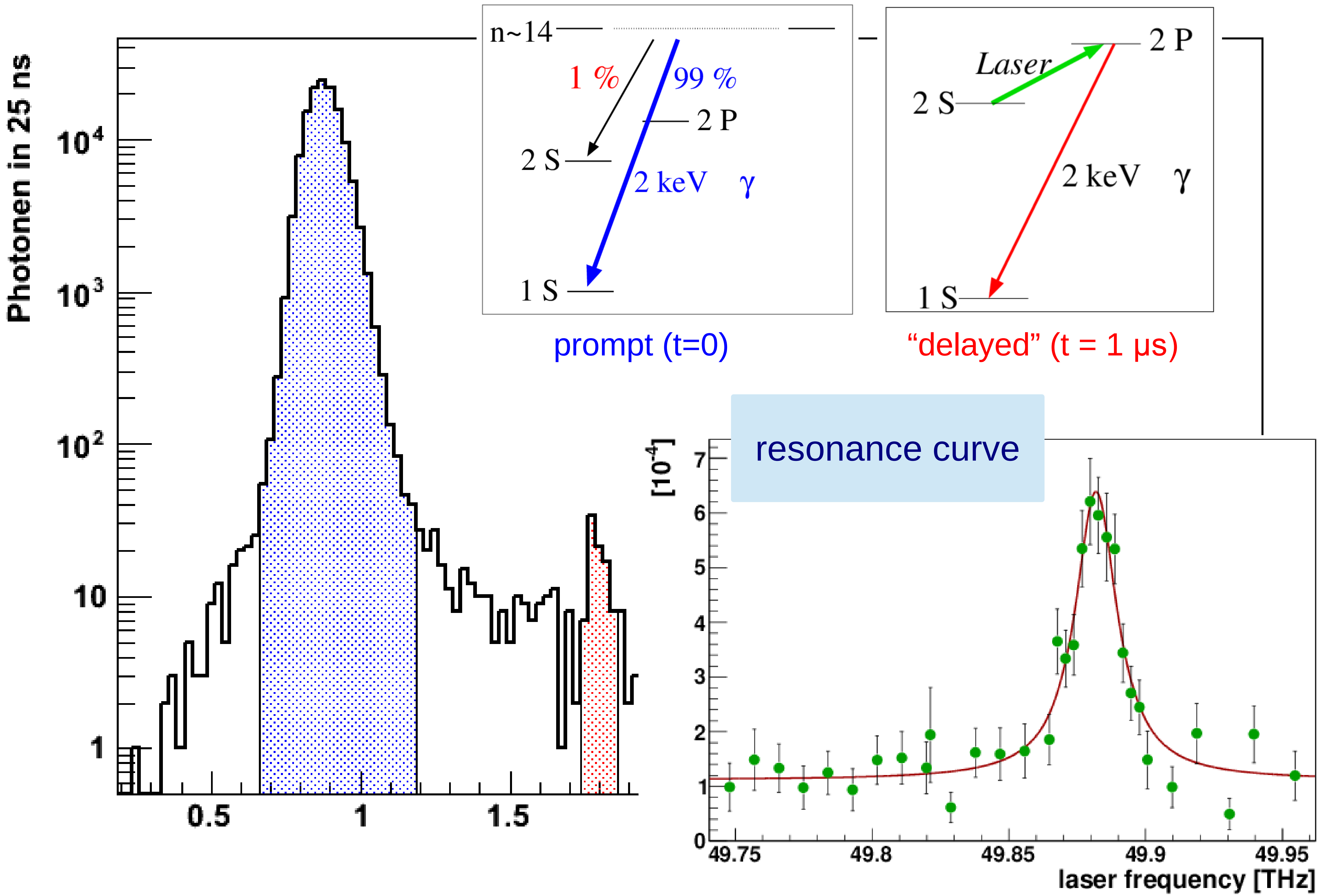


Time Spectra

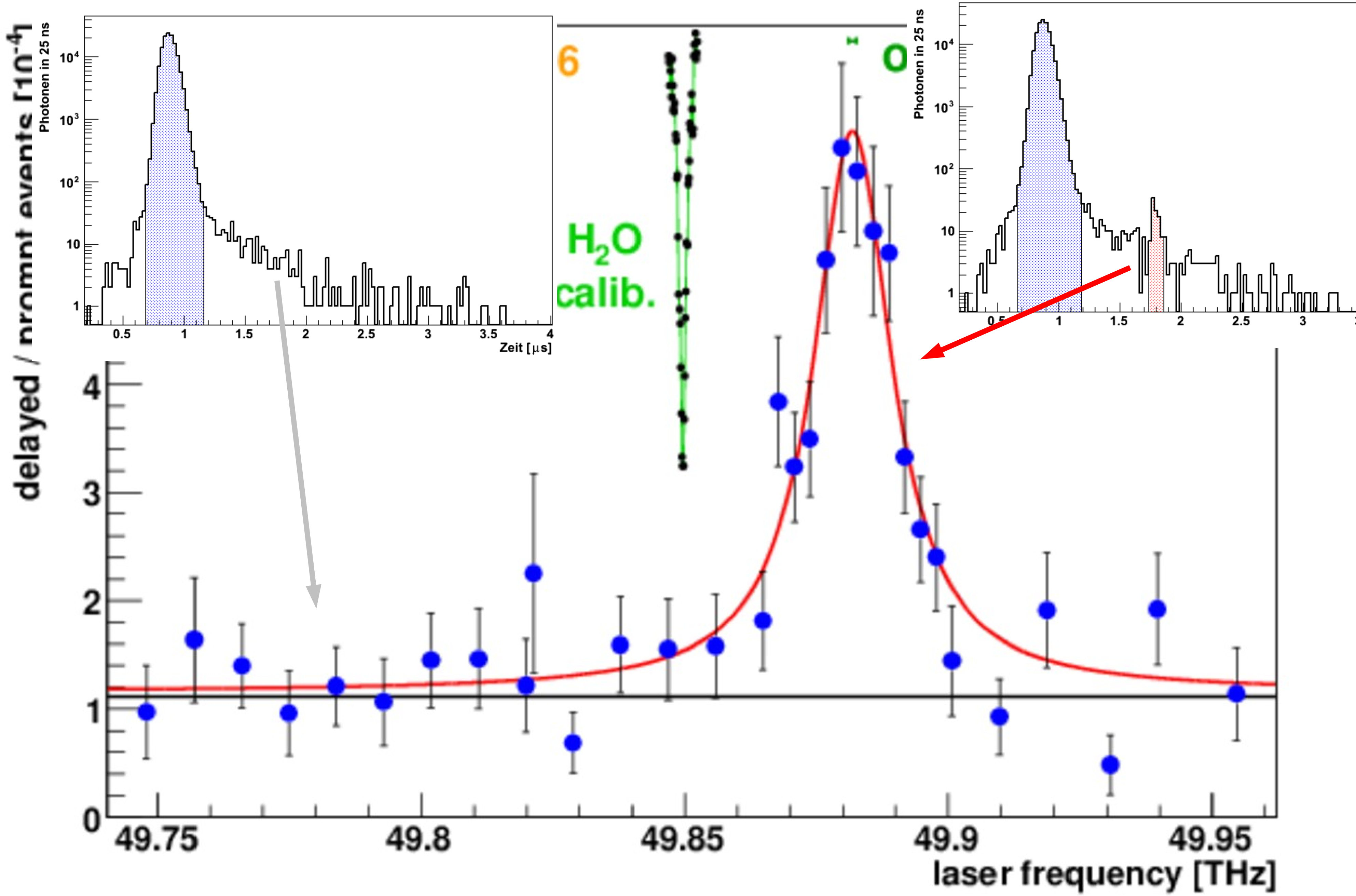


Time Spectra



Resonance search movie

The resonance line

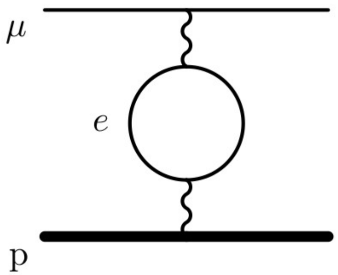


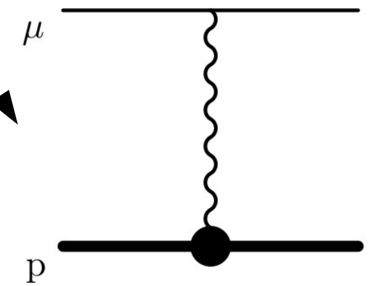
Yeah!

Theory in muonic H

$\Delta E_{Lamb} = 206.0336\ (15)\ \mathrm{meV}_{QED} + 0.0332\ (20)\ \mathrm{meV}_{TPE} - 5.2275\ (10)\ \mathrm{meV/fm}^2 * \mathbf{R_p}^{\mathbf{2}}$

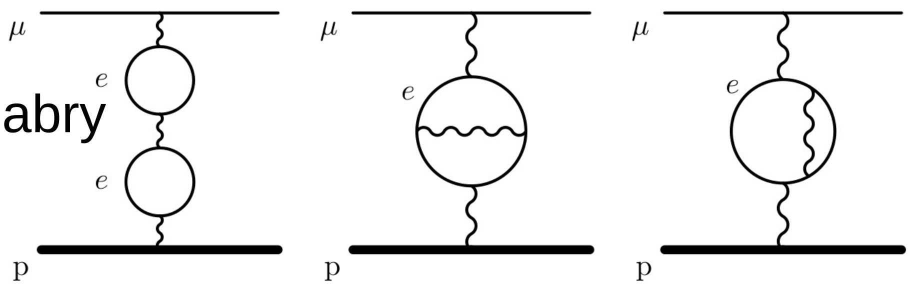
Uehling



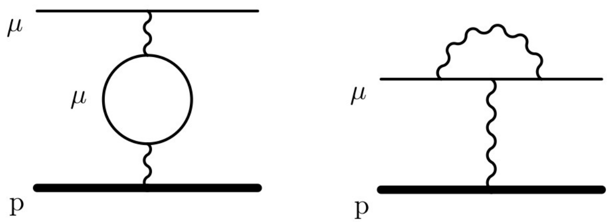


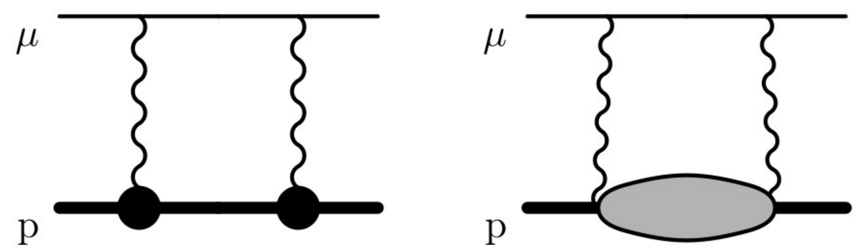
Proton form factor

Källen-Sabry



Muon SE+VP

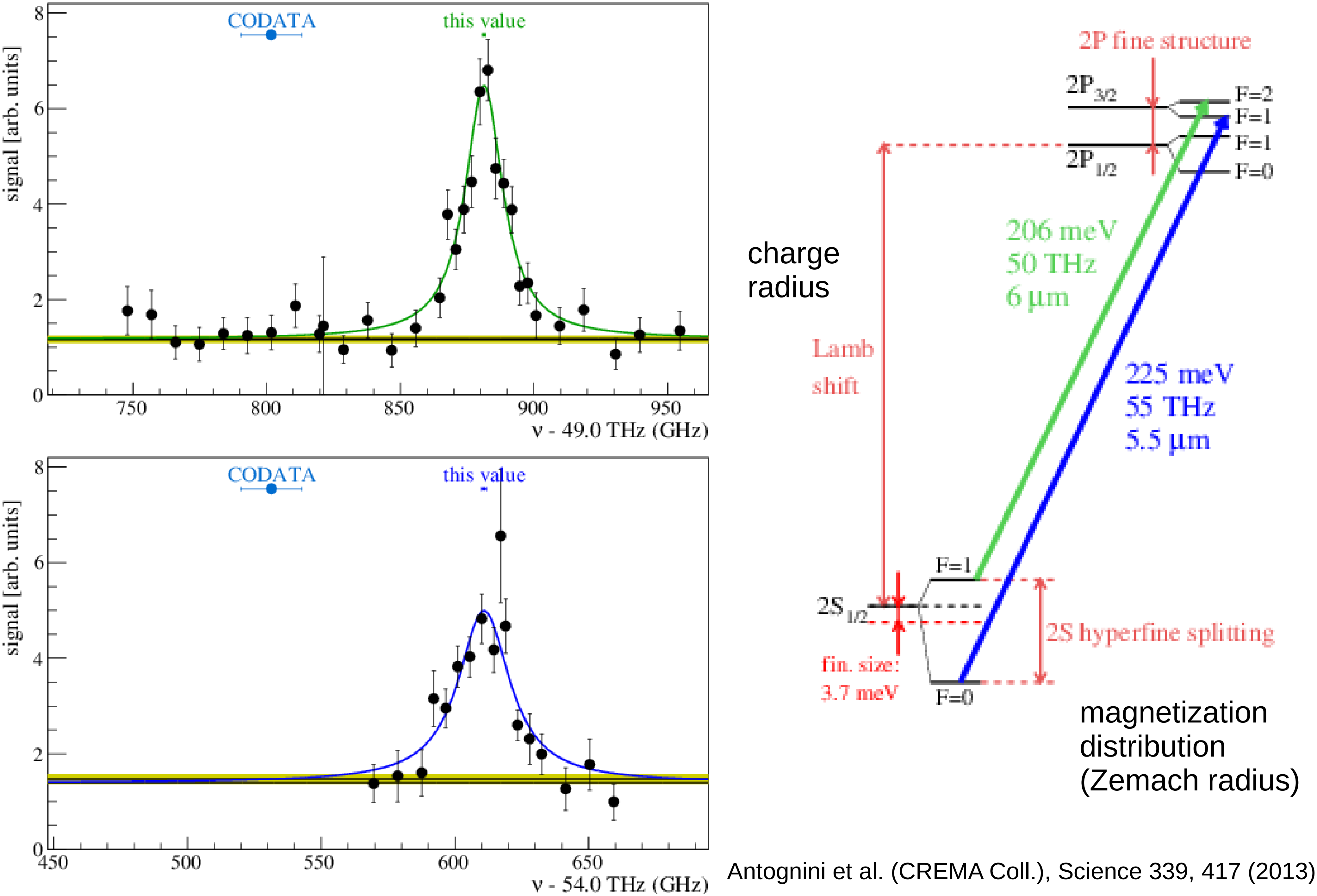




elastic and inelastic two-photon exchange
(Friar moment and polarizability)

and 20+ more….

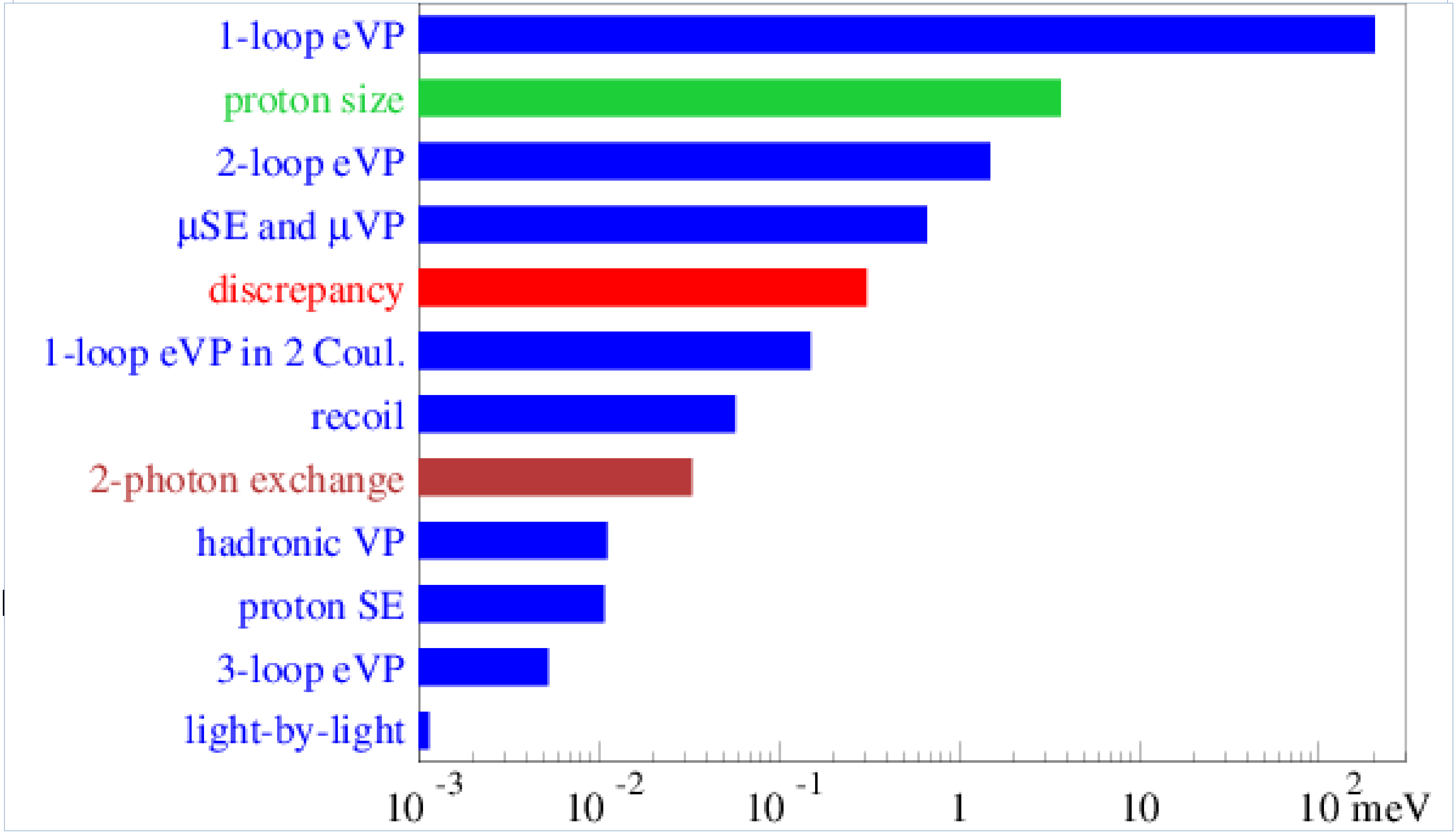
2 transitions in muonic H



Antognini et al. (CREMA Coll.), Science 339, 417 (2013)

Theory in muonic H

ΔE_{Lamb} = 206.0336 (15) meV_{QED} + 0.0332 (20) meV_{TPE} – 5.2275 (10) meV/fm² * R_p^2



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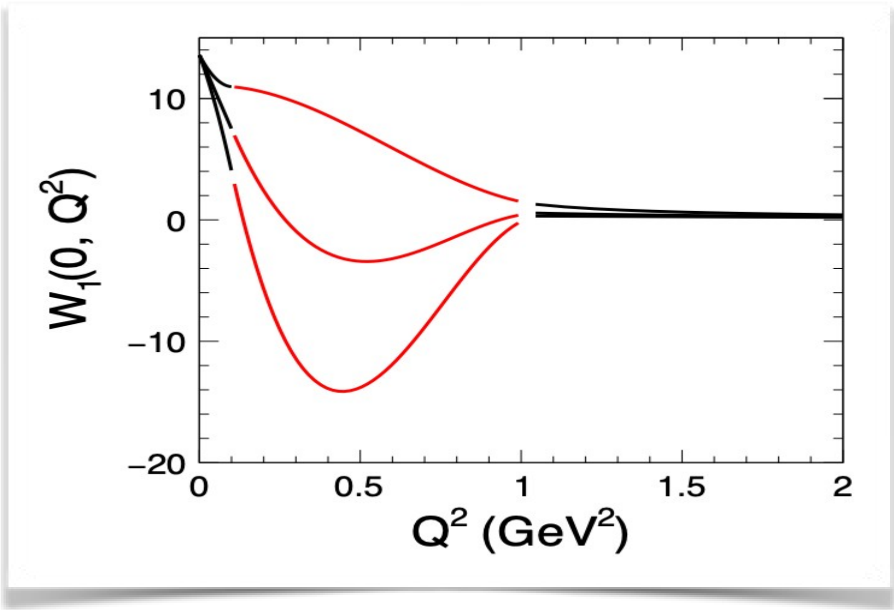
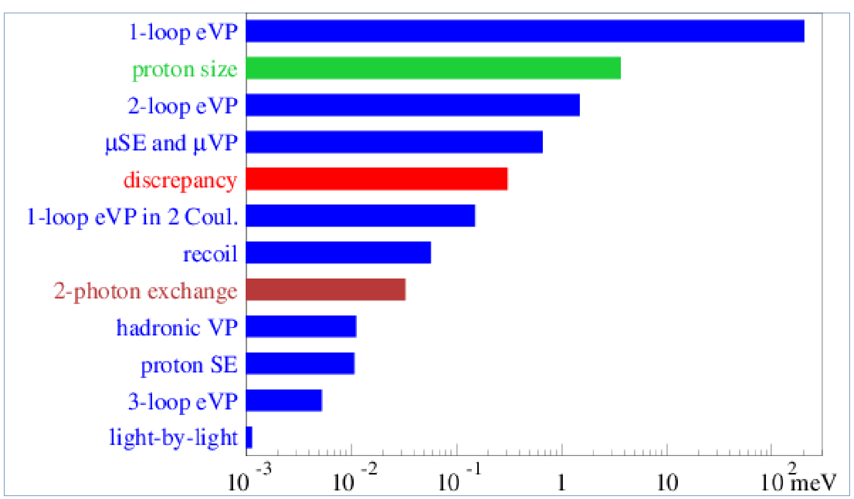
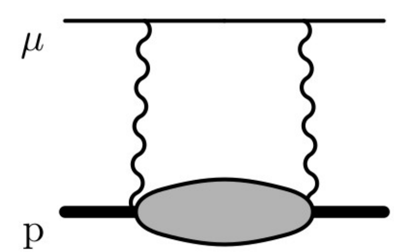


Pachucki, Carlson, Birse, McGovern, Pineda, Peset, Gorchtein, Pascalutsa, Vanderhaeghen, Tomalak, Martynenko, Alarcon, Miller, Paz, Hill, Hagelstein…

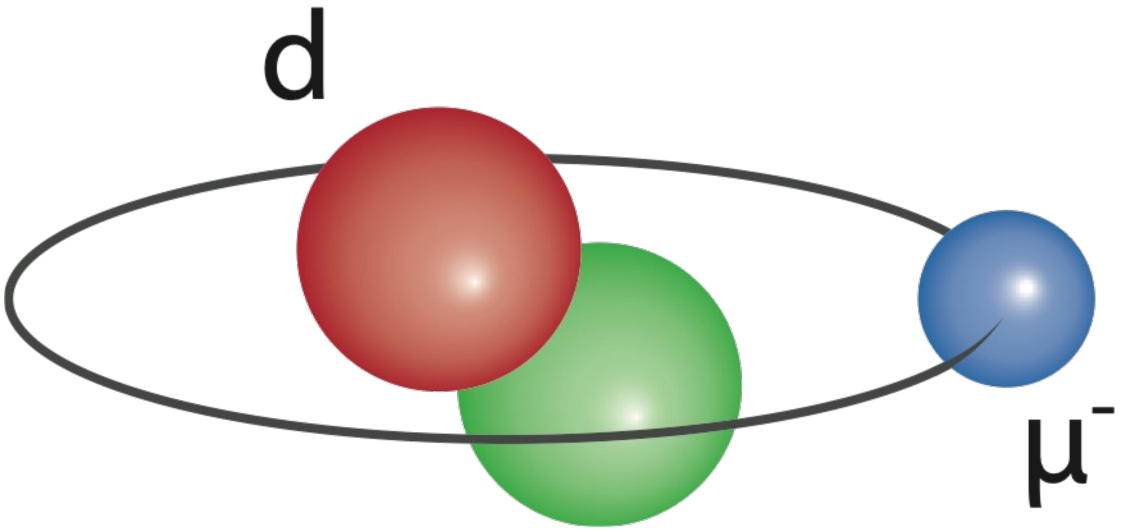
(25) Pascalutsa et al.
(100) Hill & Paz



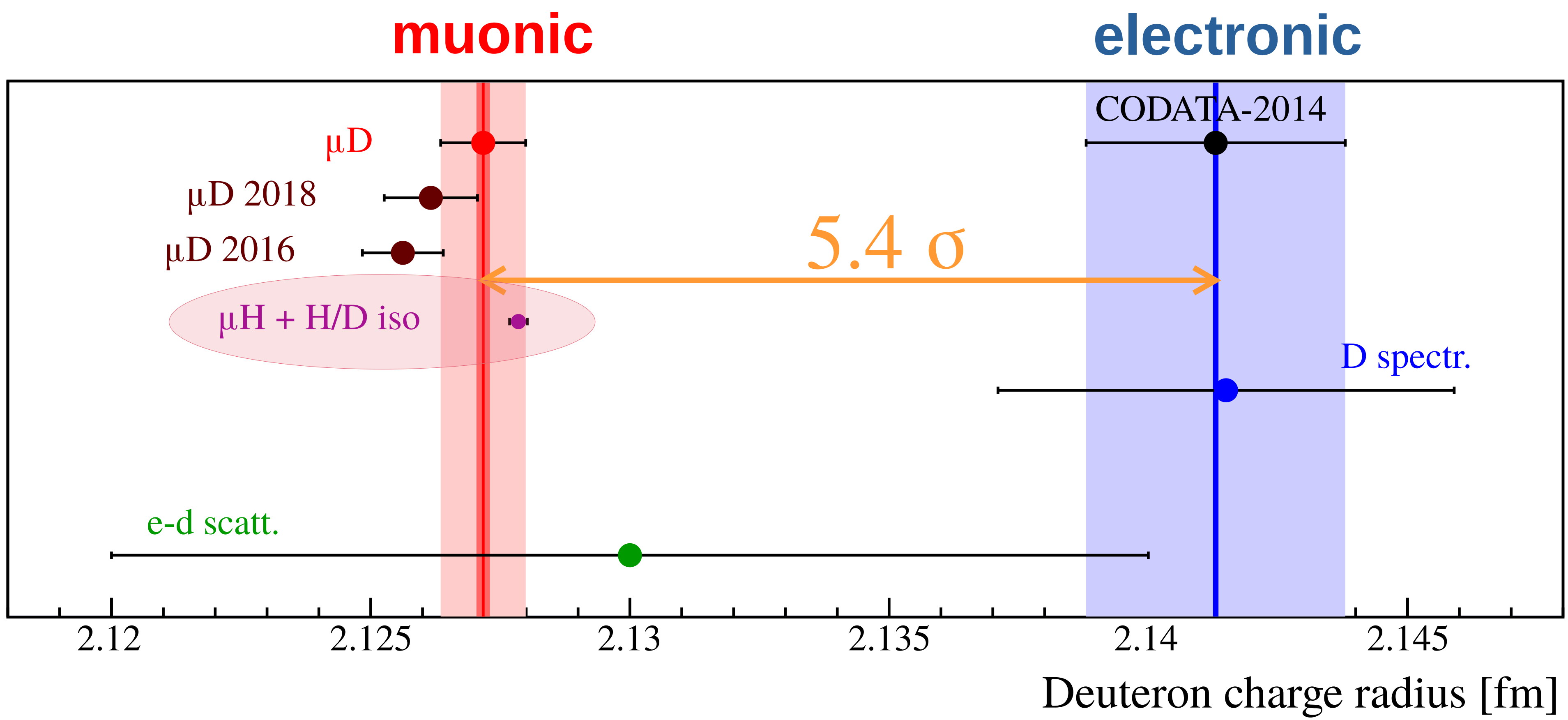


inelastic two-photon exchange
(polarizability)

Muonic Deuterium



Muonic Deuterium



μD: 2.12717 $(13)_{exp}$ $(82)_{theo}$ fm (theo = nucl. polarizability)

μH + H/D(1S-2S): 2.12785 (17) fm

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

H/D 1S-2S isotope shift:
$r_d^2 - r_p^2 = 3.82070(31)\ fm^2$

Pachucki et al., PRA 97, 062511 (2018)

μD: RP et al. (CREMA) Science 353, 669 (2016)

H/D 1S-2S. Parthey, RP et al., PRL 104, 233001 (2010), PRL 107, 203001 (2011)

Theory in muonic D

$$\Delta E^{\mu D}_{Lamb} = 228.7854\ (13)\ \text{meV}_{QED} + 1.7500\ (\mathbf{210})\ \text{meV}_{TPE} - 6.1103\ (3)\ \text{meV/fm}^2 * \mathbf{R_d}^{\mathbf{2}}$$

ΔE_{TPE} (theo) = 1.7500 +- 0.0210 meV (Kalinowski, 2018)

vs. +- 0.0034 meV experimental uncertainty

(1) **charge radius**, using **calculated TPE**

r_d (μD) = 2.12717 (13) $_{exp}$ (82) $_{theo}$ fm vs.

r_d (CODATA-14) = 2.1**4**130 (250) fm

(2) **polarizability**, using **charge radius from isotope shift**

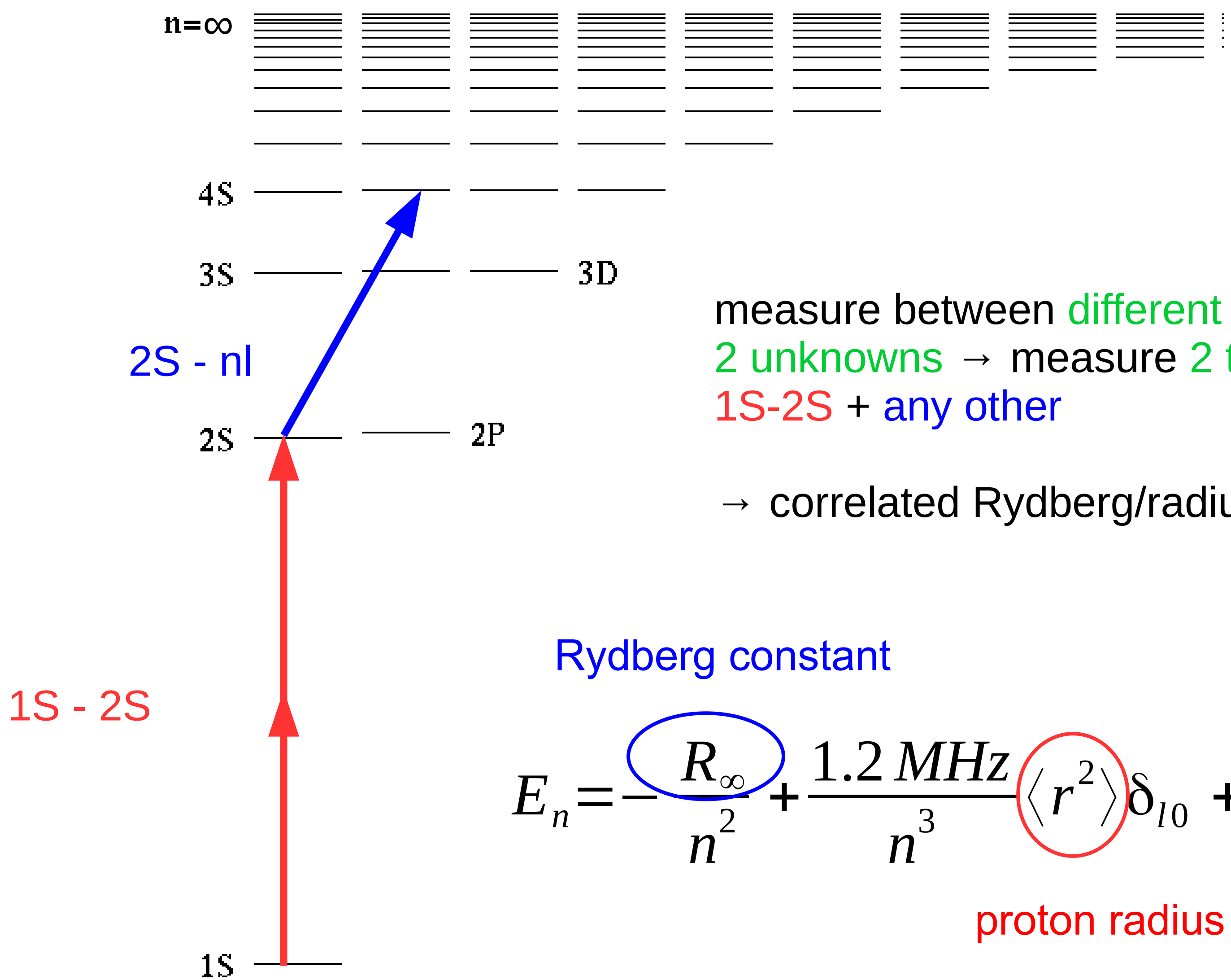
ΔE_{TPE} (theo) = 1.7500 (210) meV vs.

ΔE_{TPE} (exp) = 1.7591 (59) meV 3.5x more accurate

Krauth et al. (2016) + Pachucki et al. (2018) + Hernandez et al. (2018) + Kalinowski (2018)

Hydrogen

Energy levels of hydrogen



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

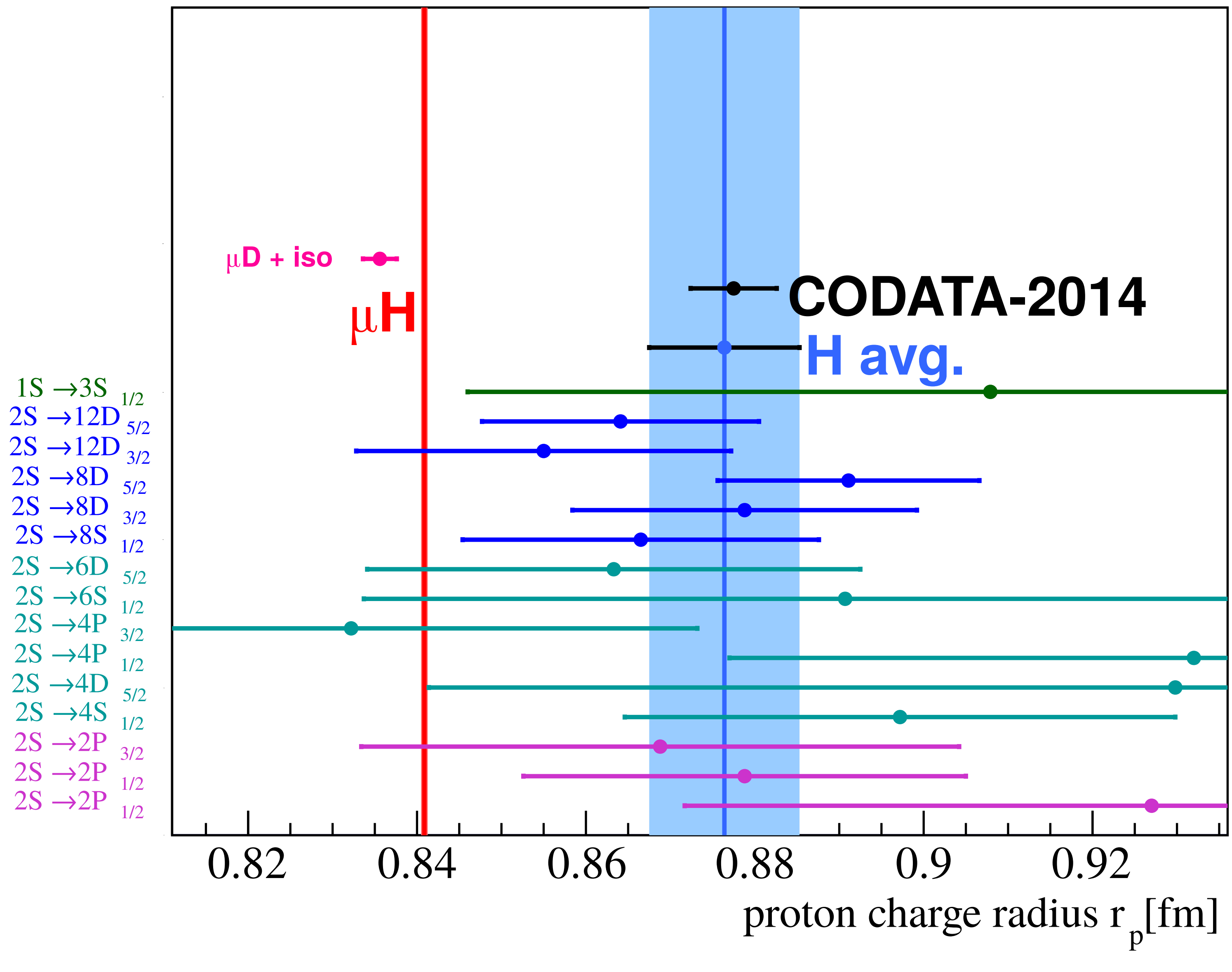
→ correlated Rydberg/radius pairs

Rydberg constant

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

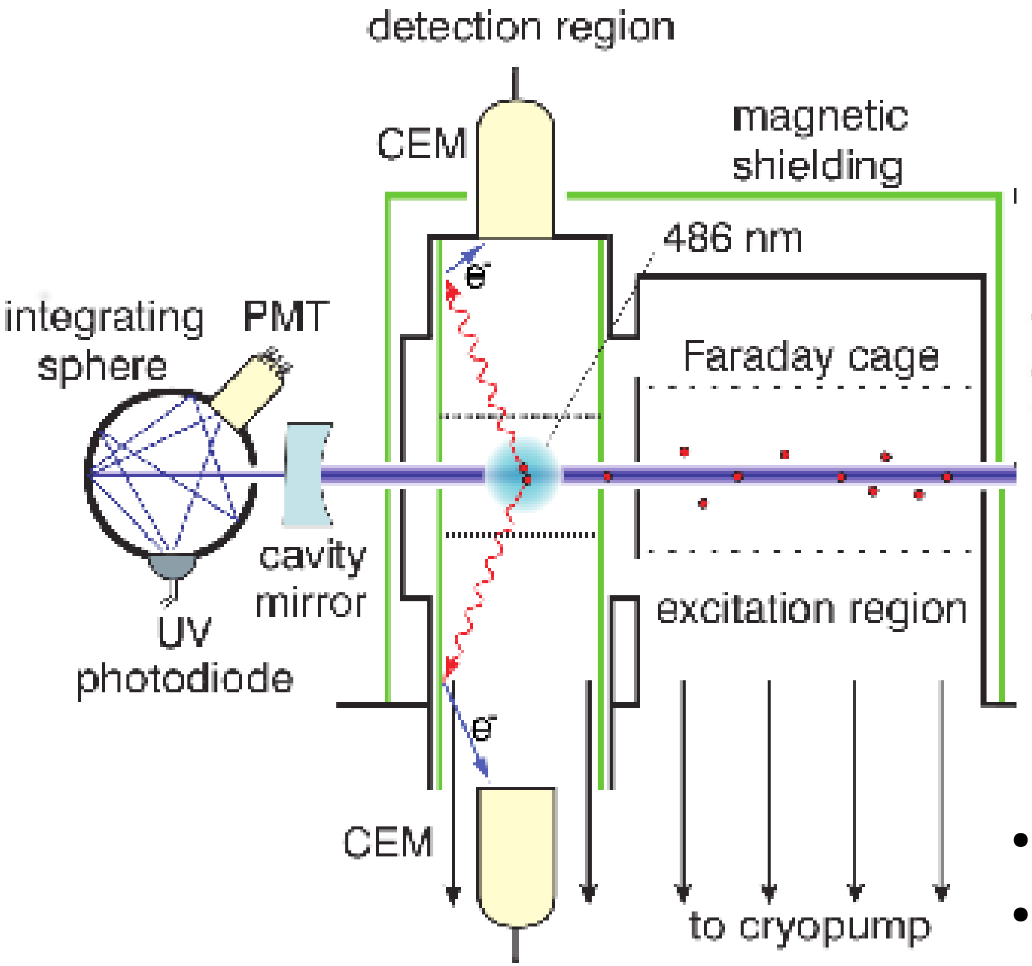
proton radius

Rp from H spectroscopy

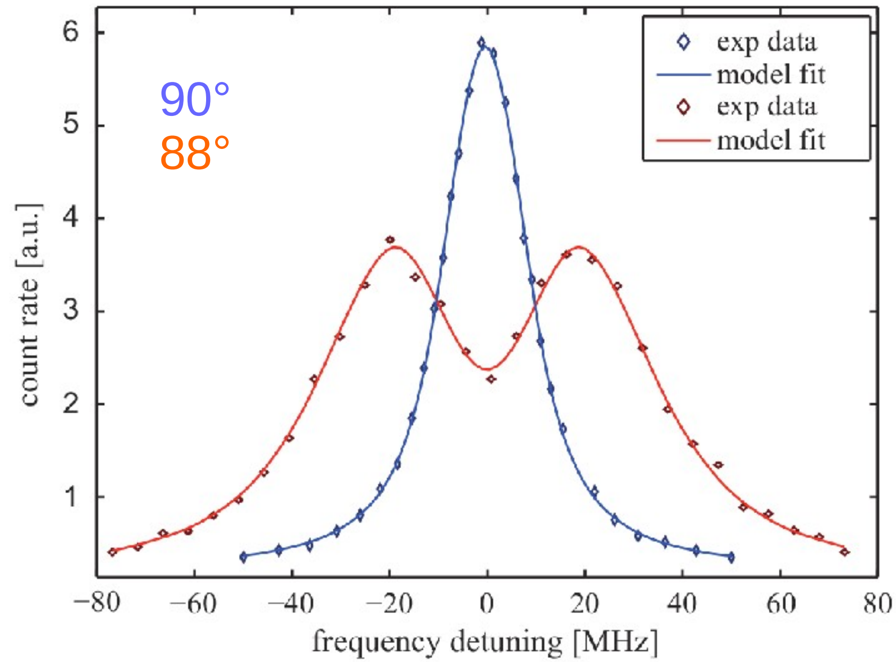


RP et al., Metrologia 54, L1 (2017)

Garching H(2S-4P)



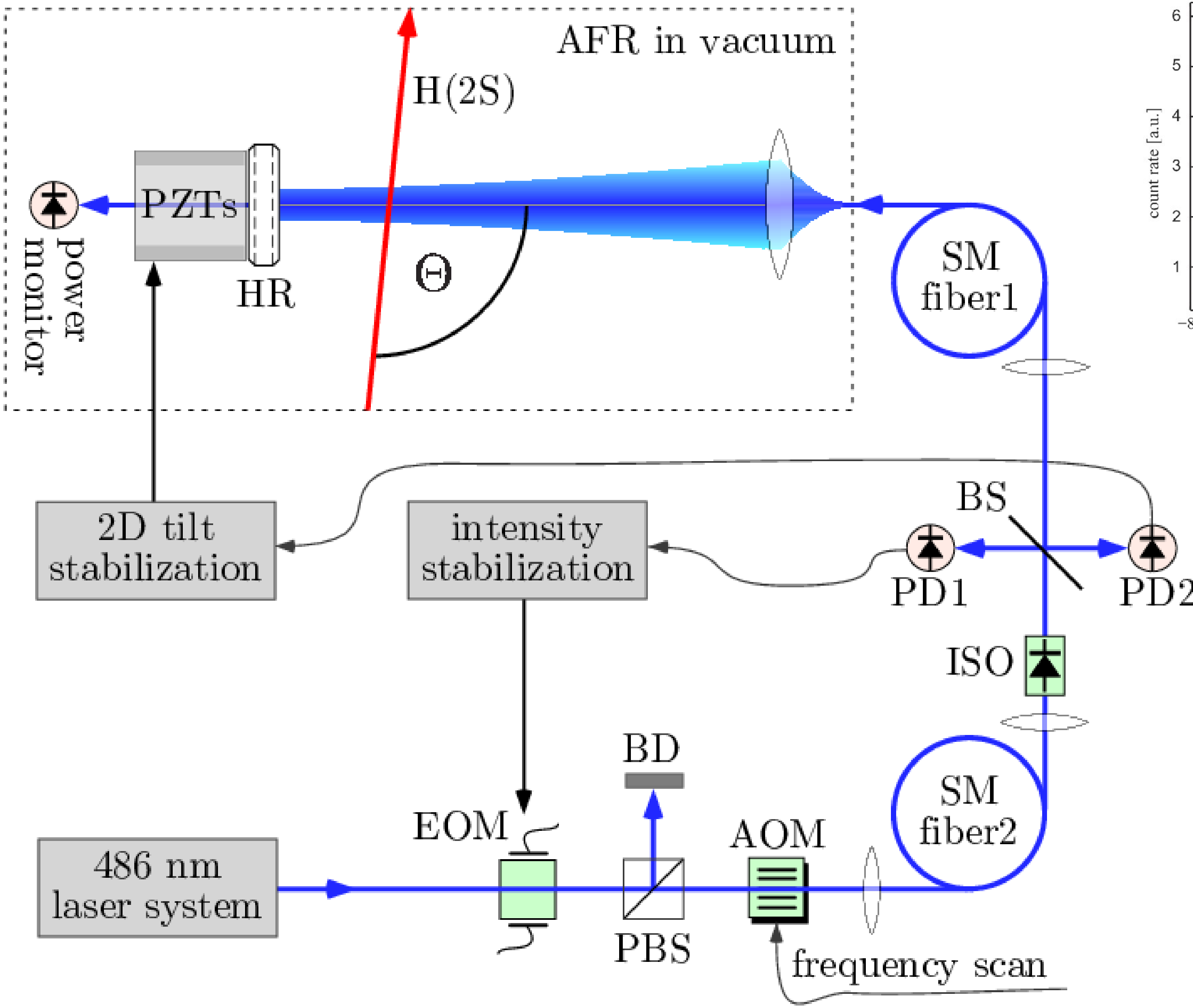
1st order Doppler cancellation

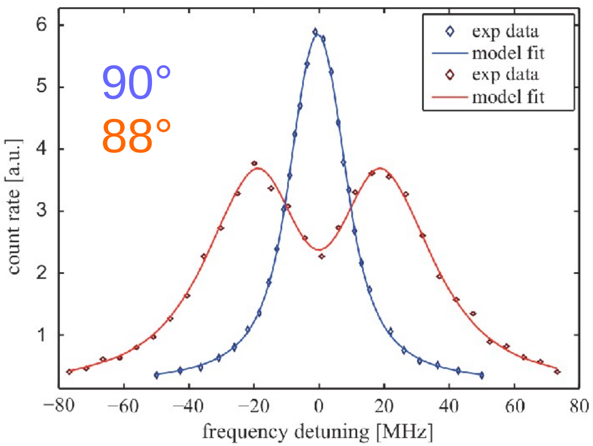


- cryogenic H beam (6 K)
- optical 1S-2S excitation (2S, F=0)
- 2S-4P transition is 1-photon: retroreflector
- split line to 10^{-4} !!!
- 2.3 kHz vs. 9 kHz PRP
- large systematics

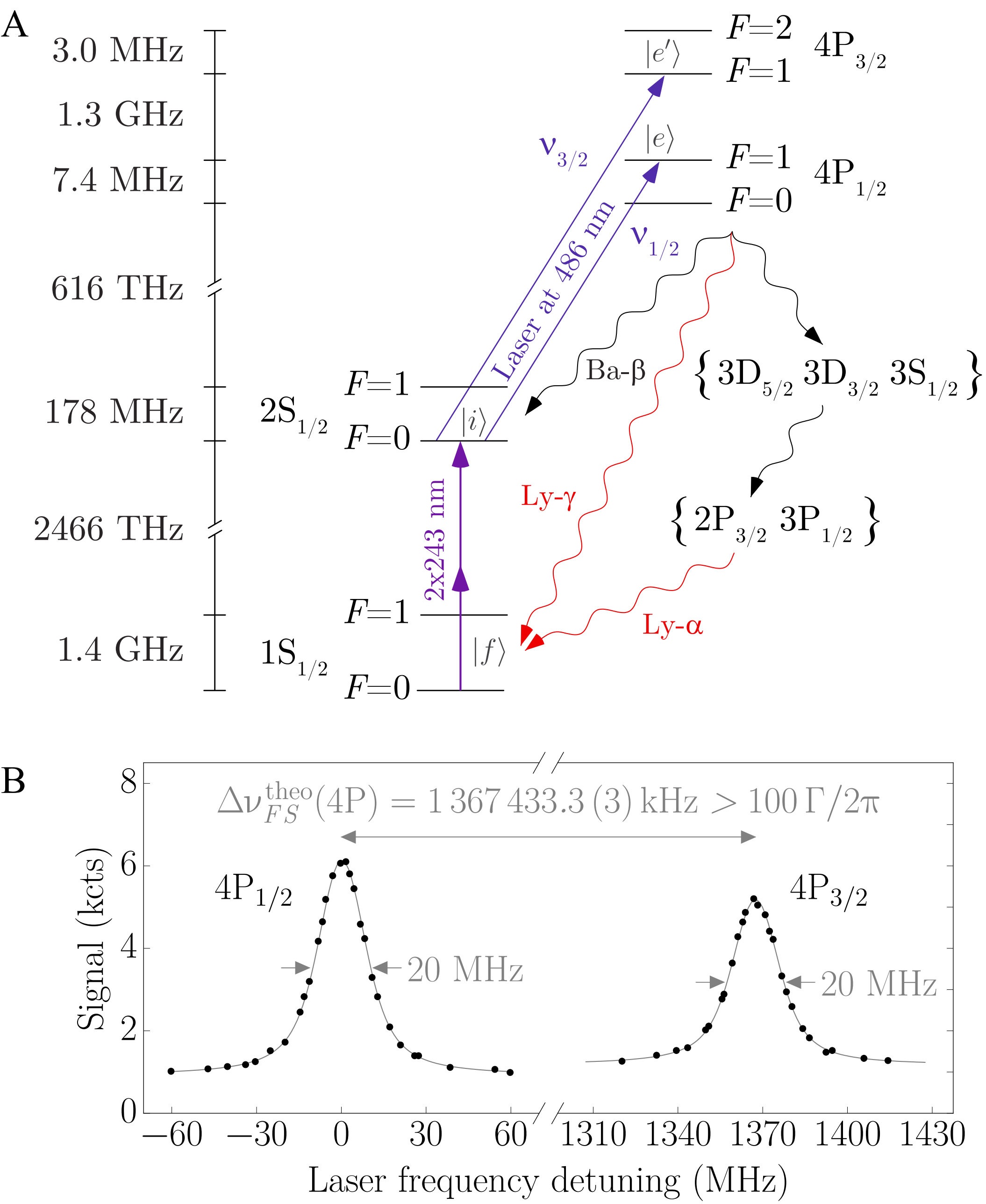
Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

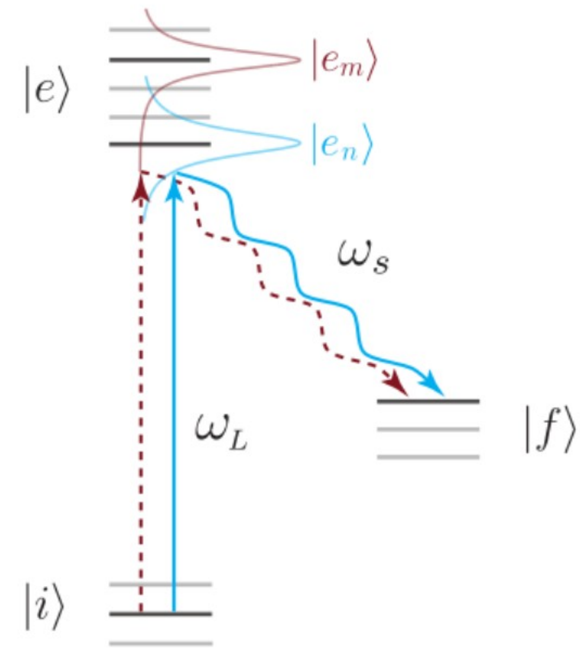
1st order Doppler shift





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)

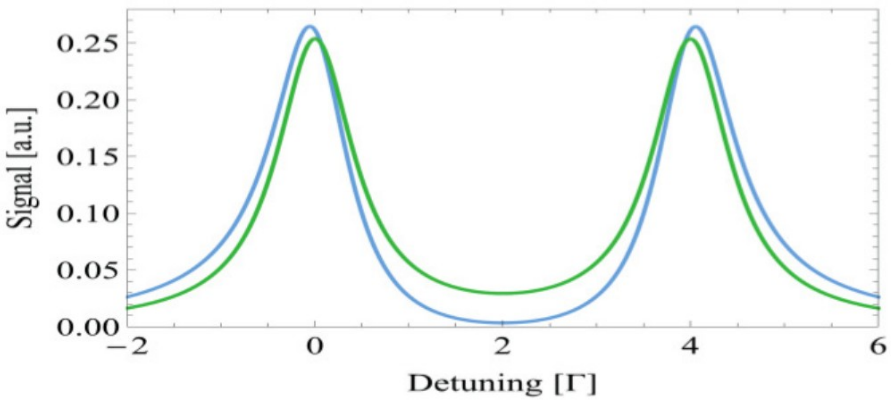
see

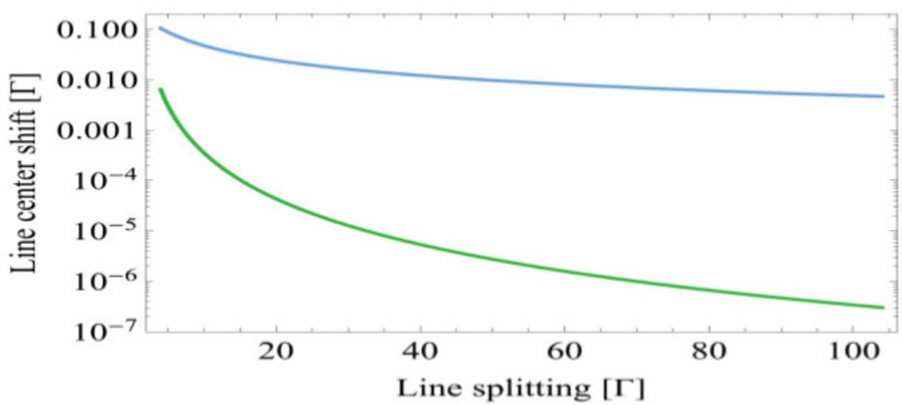
Horbatsch, Hessels, PRA 82, 052519 (2010); PRA 84, 032508 (2011); PRA 86 040501 (2012)

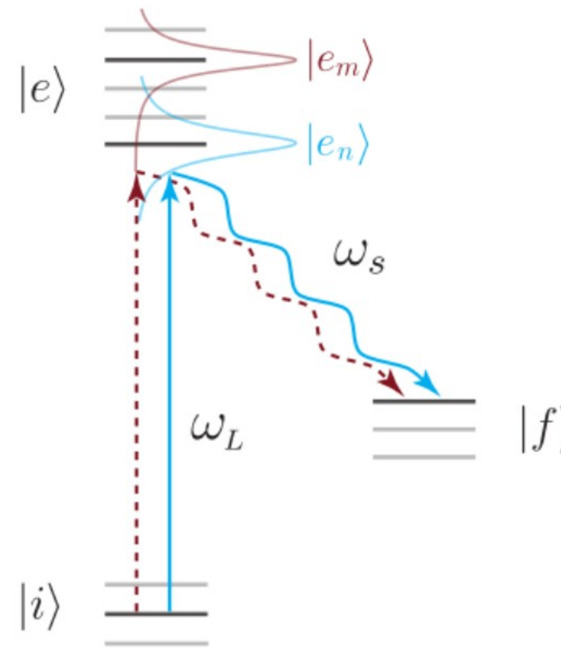
Sansonetti et al., PRL 107, 021001 (2011)

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

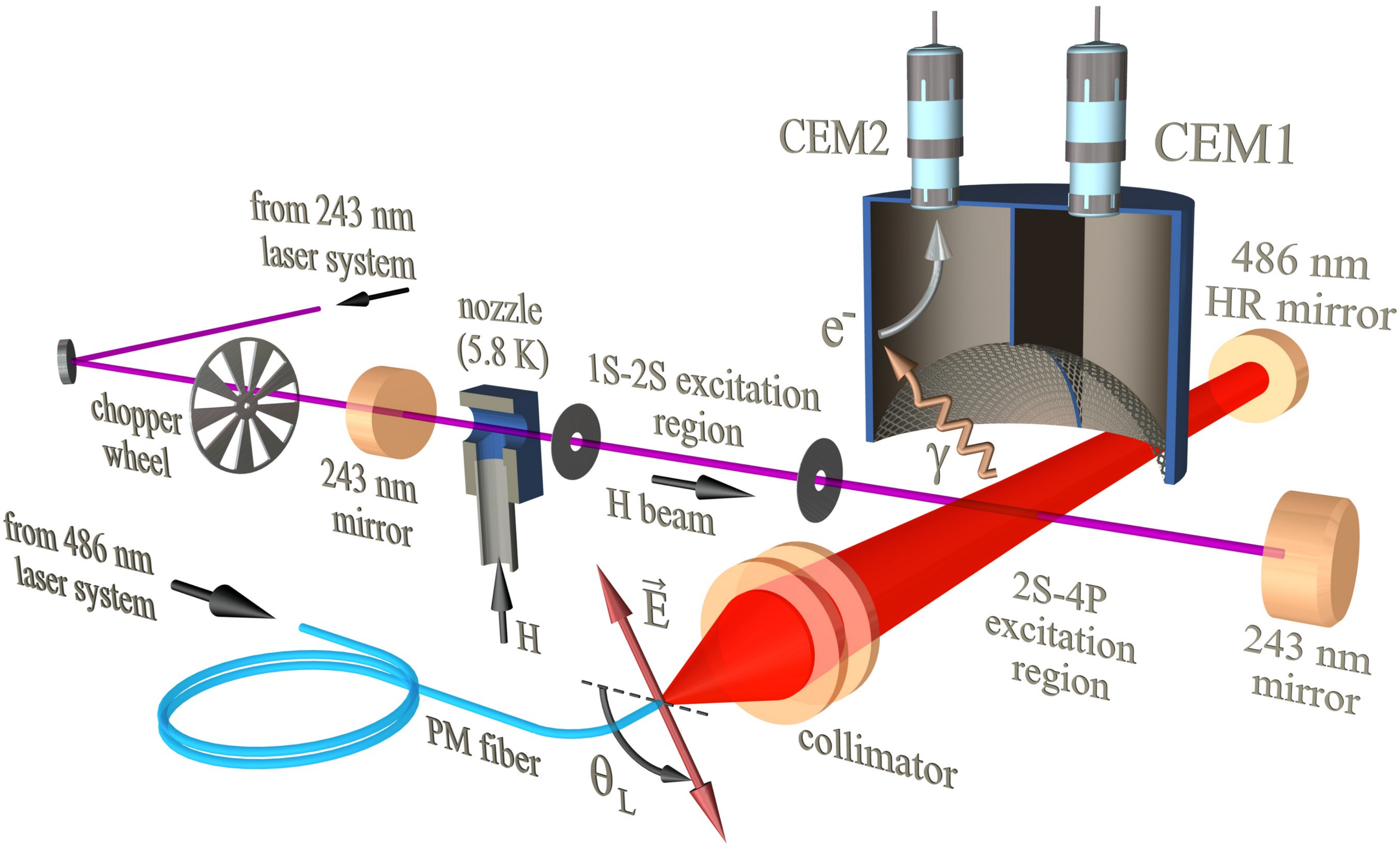
see

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

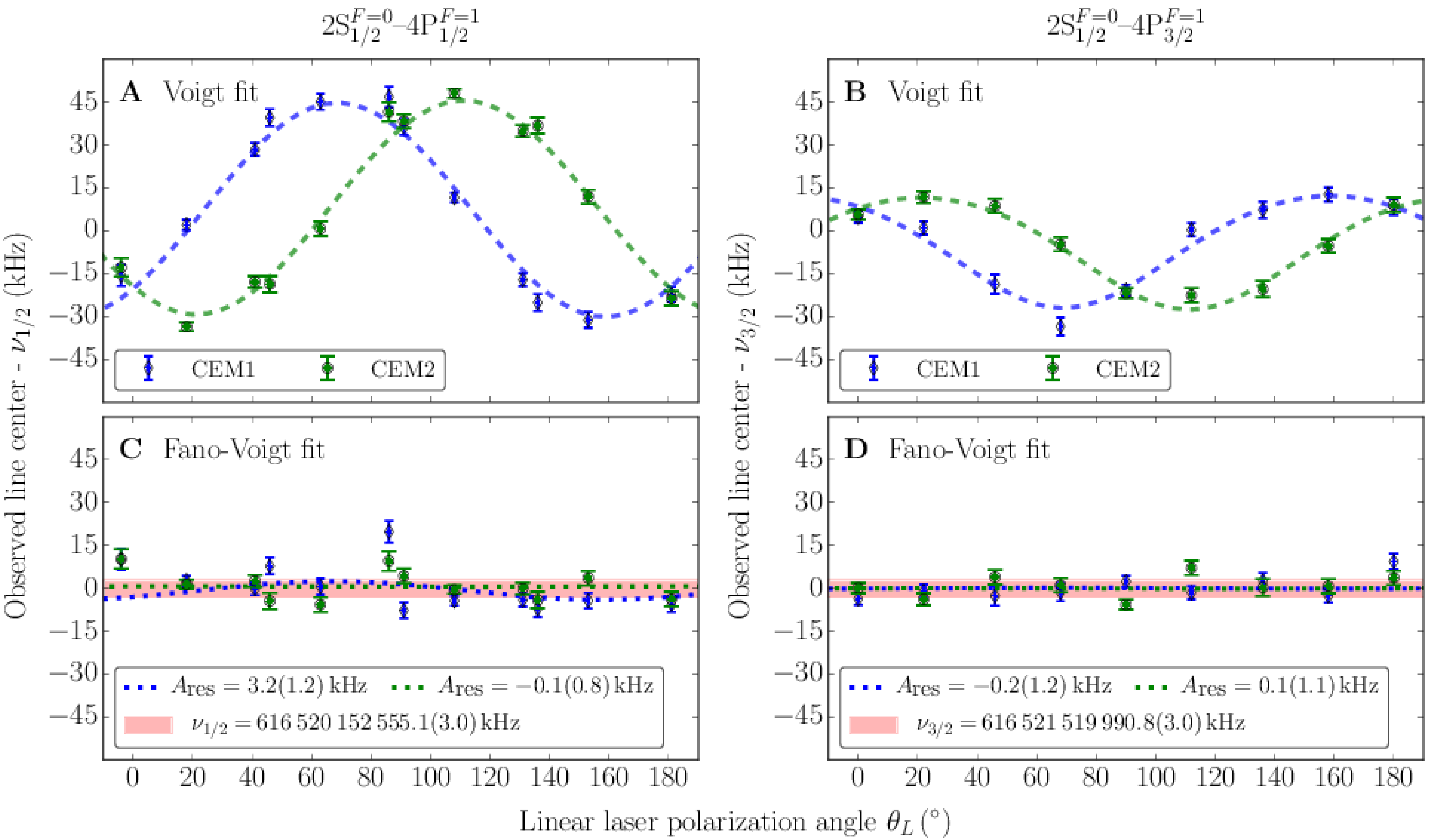
Sansonetti et al., PRL 107, 021001 (2011)

Brown et al., PRA 87, 032504 (2013)

Studying QI in 2S-4P



QI in hydrogen   (Δ = 100 Γ)

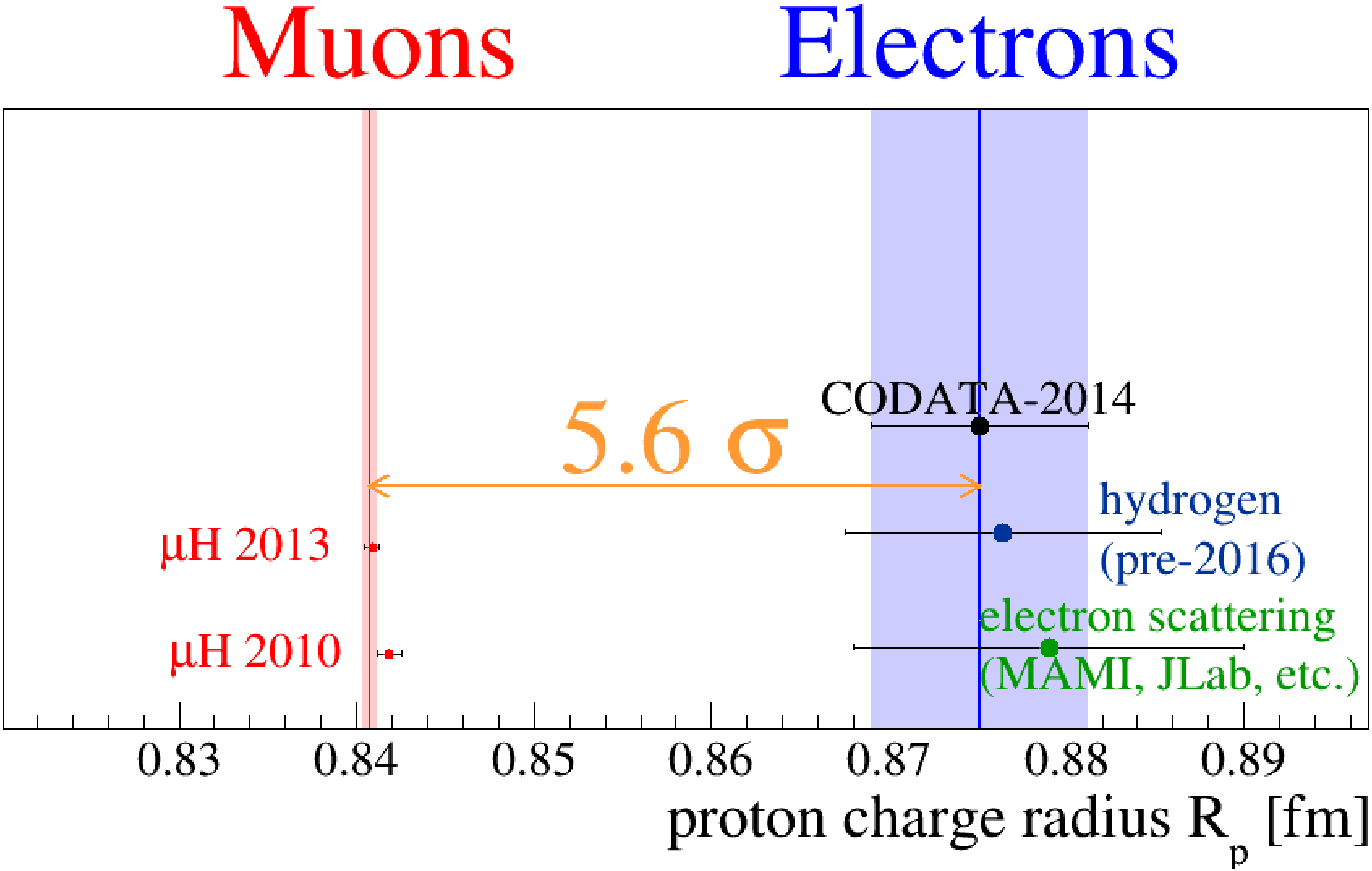


Beyer, Maisenbacher, RP et al, Science 358, 79 (2017)

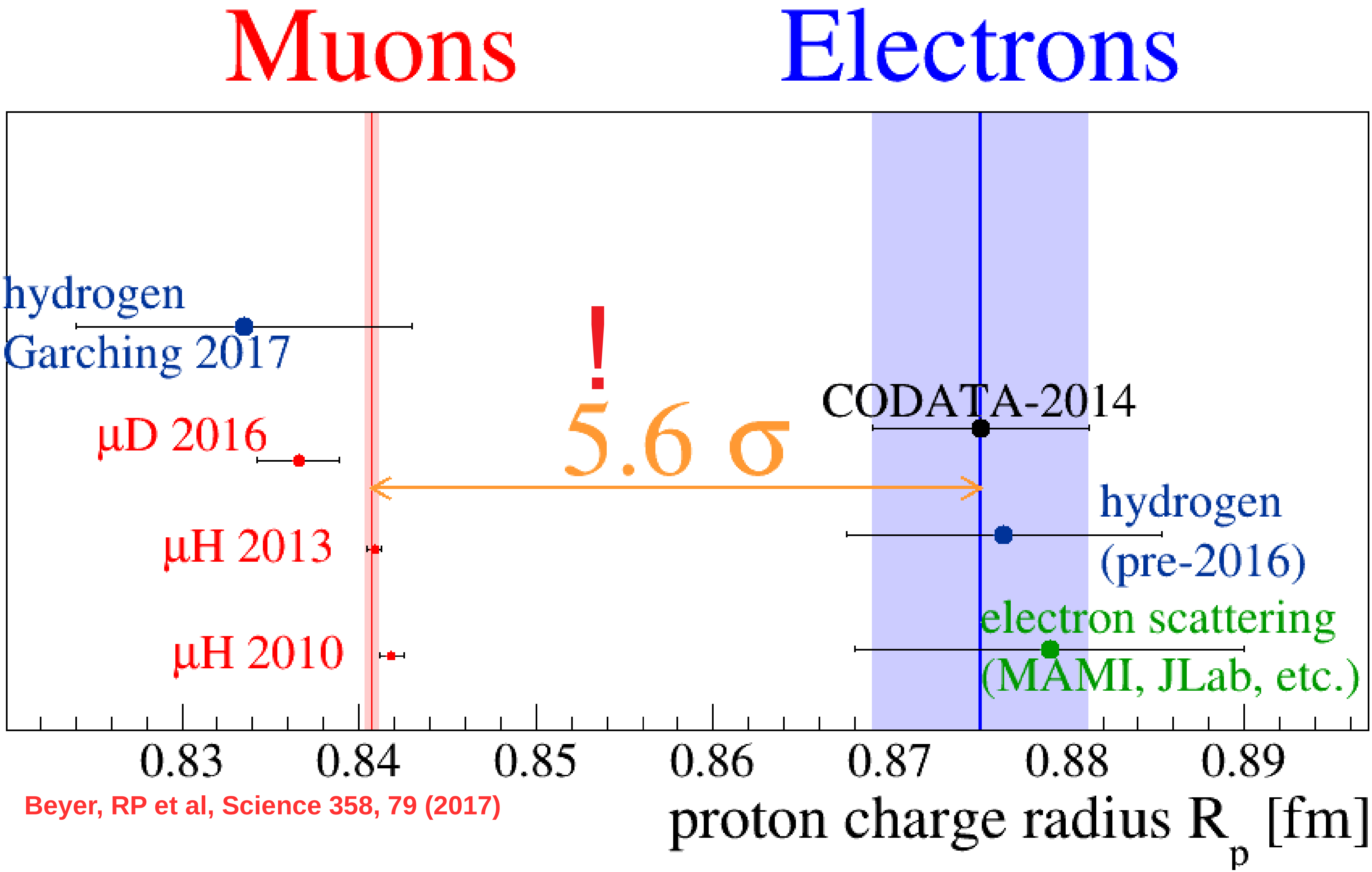
Systematics

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”

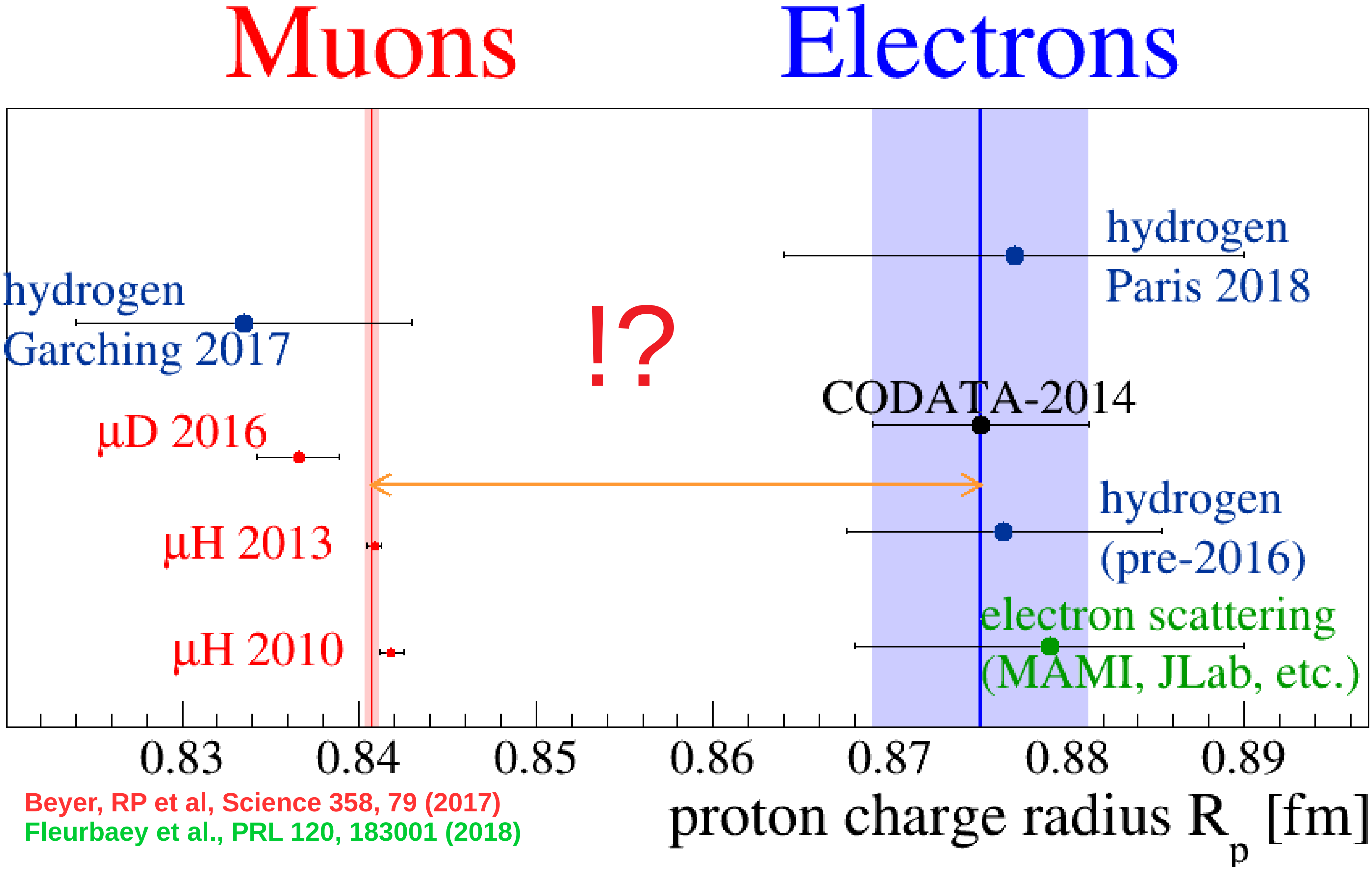


New Measurements: Garching 2S-4P



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

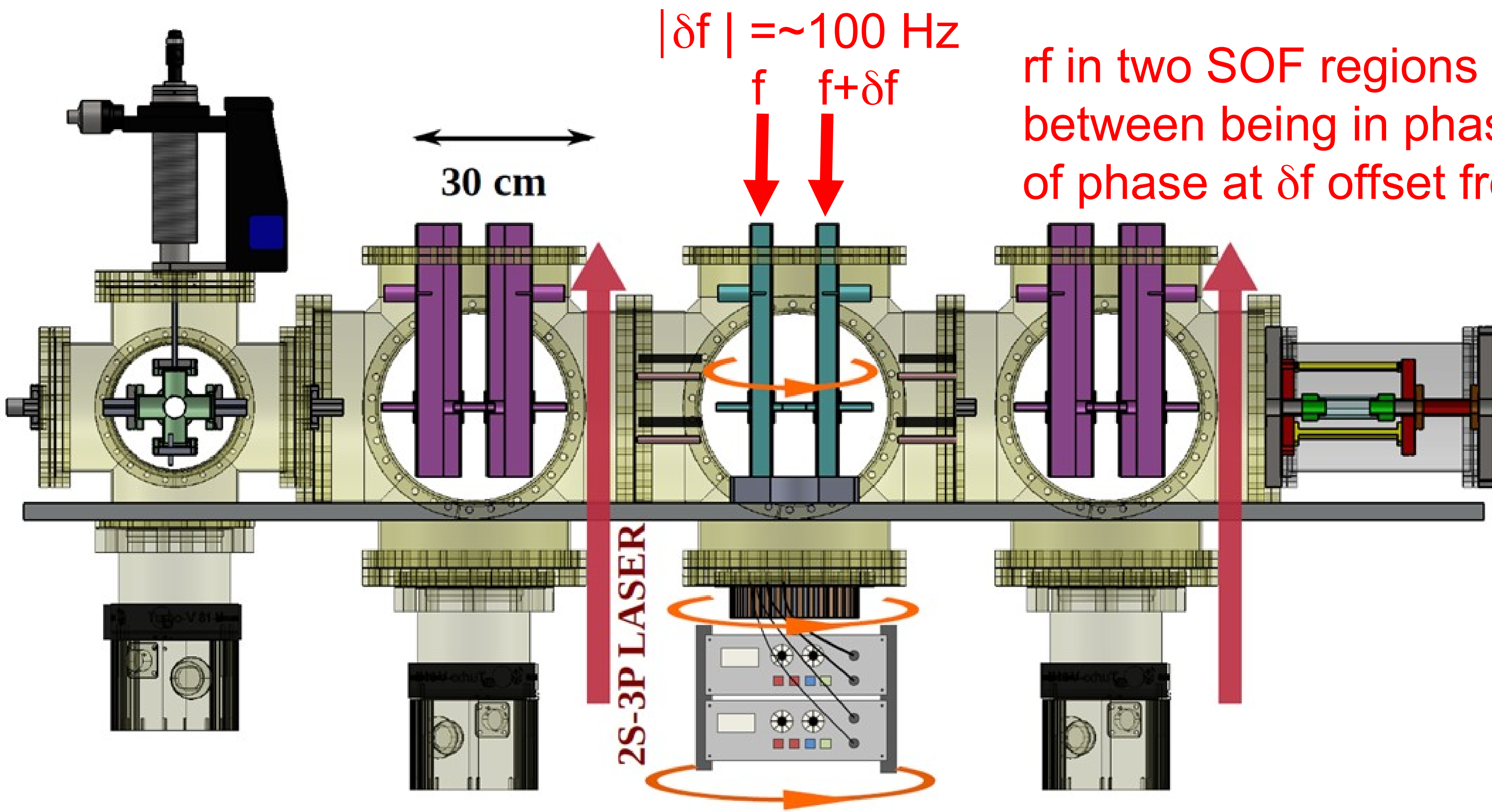
New Measurements: Paris 1S-3S



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

Lamb shift

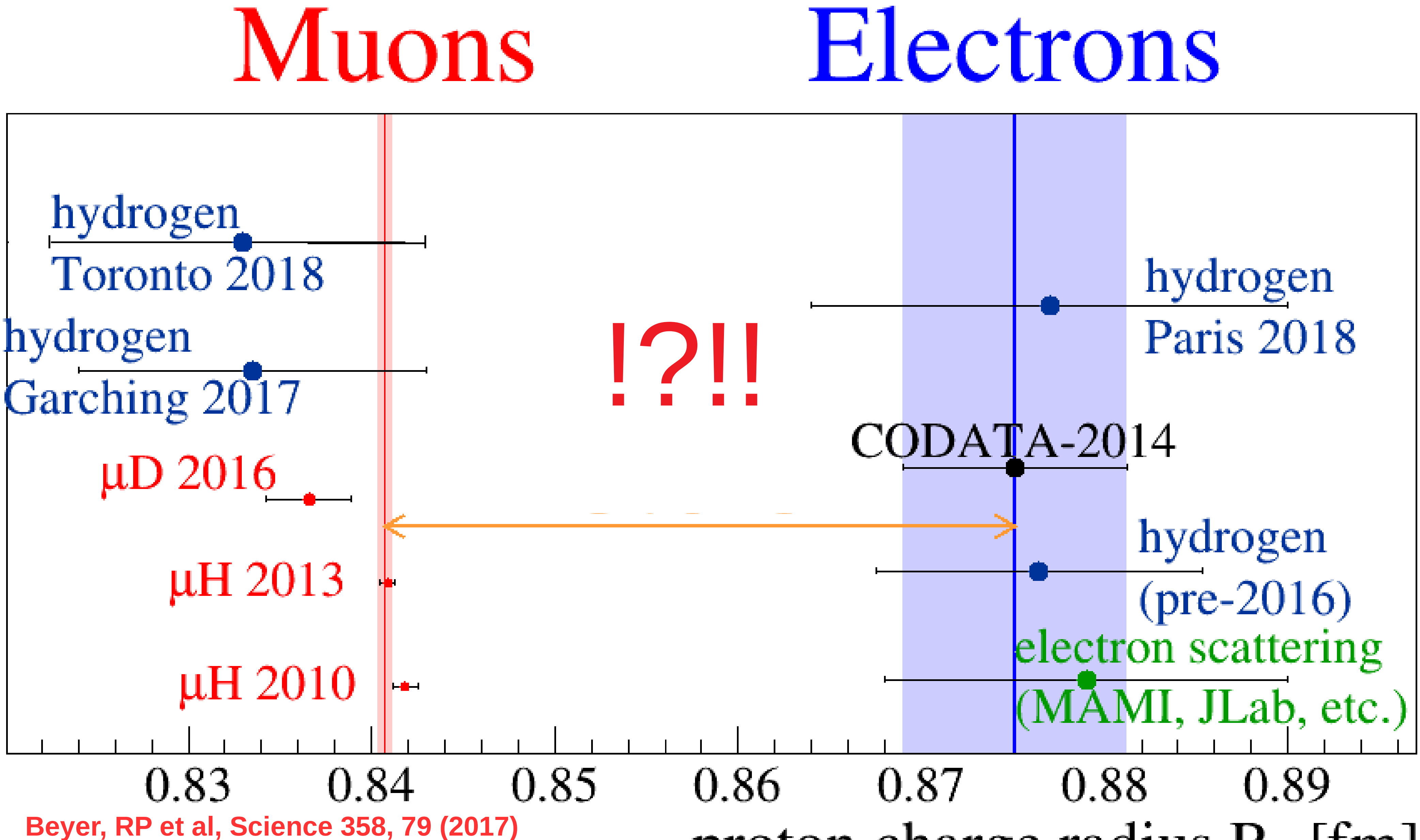
We are using a new Frequency-offset SOF technique (FOSOF)
(AC Vutha and EA Hessels Phys. Rev. A052504 (2015))



rf in two SOF regions oscillate between being in phase and out of phase at δf offset frequency

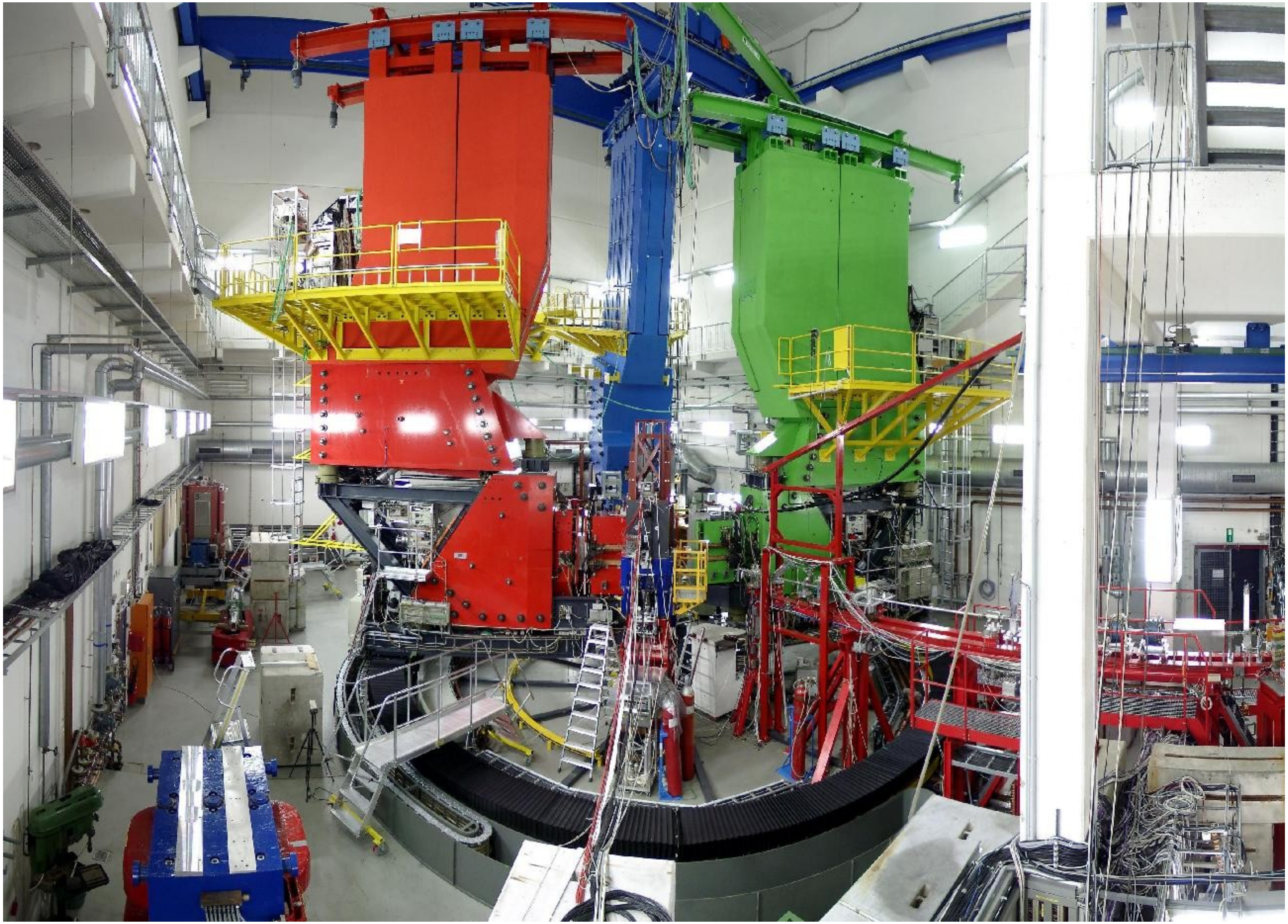
Bezginov et al., Science 365, 1007 (2019)
Hessels group (York U, Toronto)

New Measurements: Toronto 2S-2P

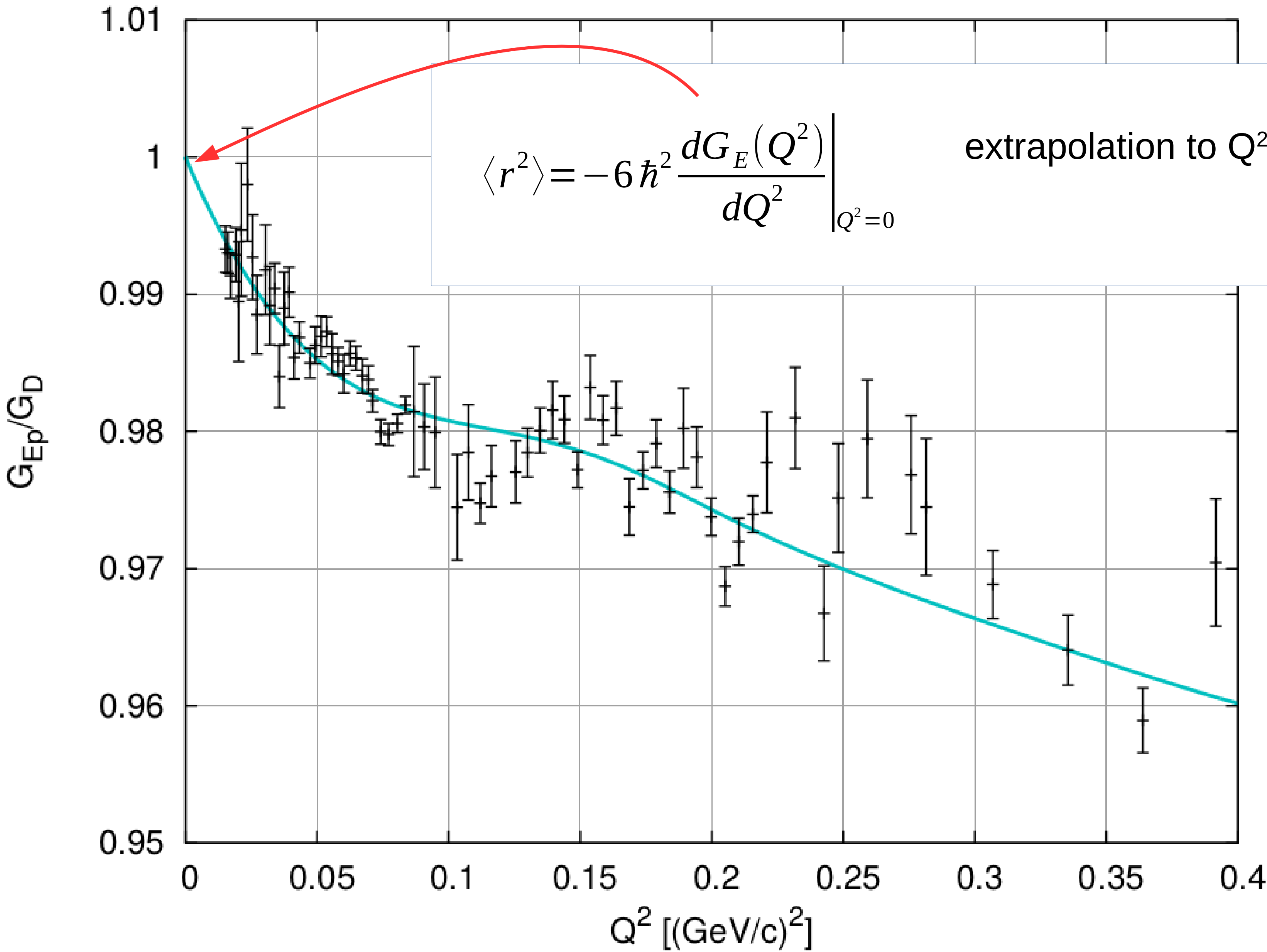


Beyer, RP et al, Science 358, 79 (2017)
Fleurbaey et al., PRL 120, 183001 (2018)
Bezginov et al., Science 365, 1007 (2019)

Mainzer Microtron MAMI



Electron scattering



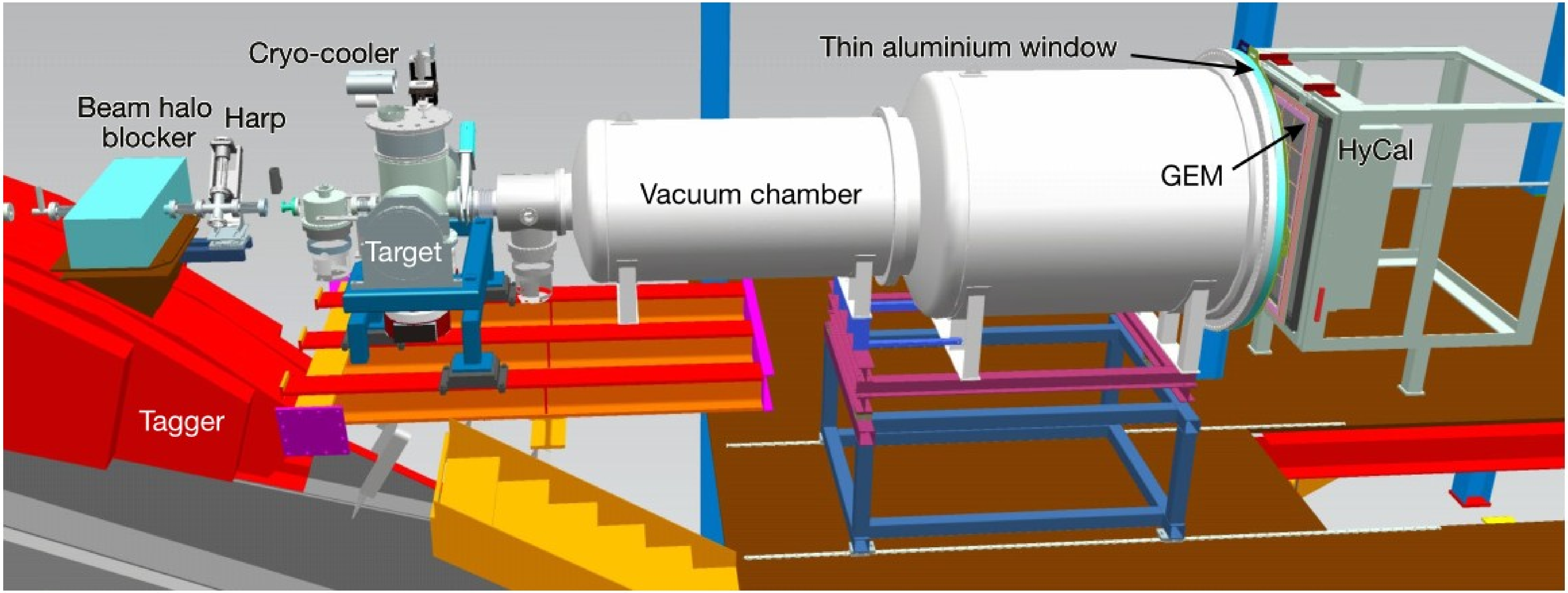
$$\langle r^2 \rangle = -6\hbar^2 \left. \frac{dG_E(Q^2)}{dQ^2} \right|_{Q^2=0}$$

extrapolation to $Q^2 = 0$ required

Mainz MAMI data 2010

Vanderhaeghen, Walcher: 1008.4225

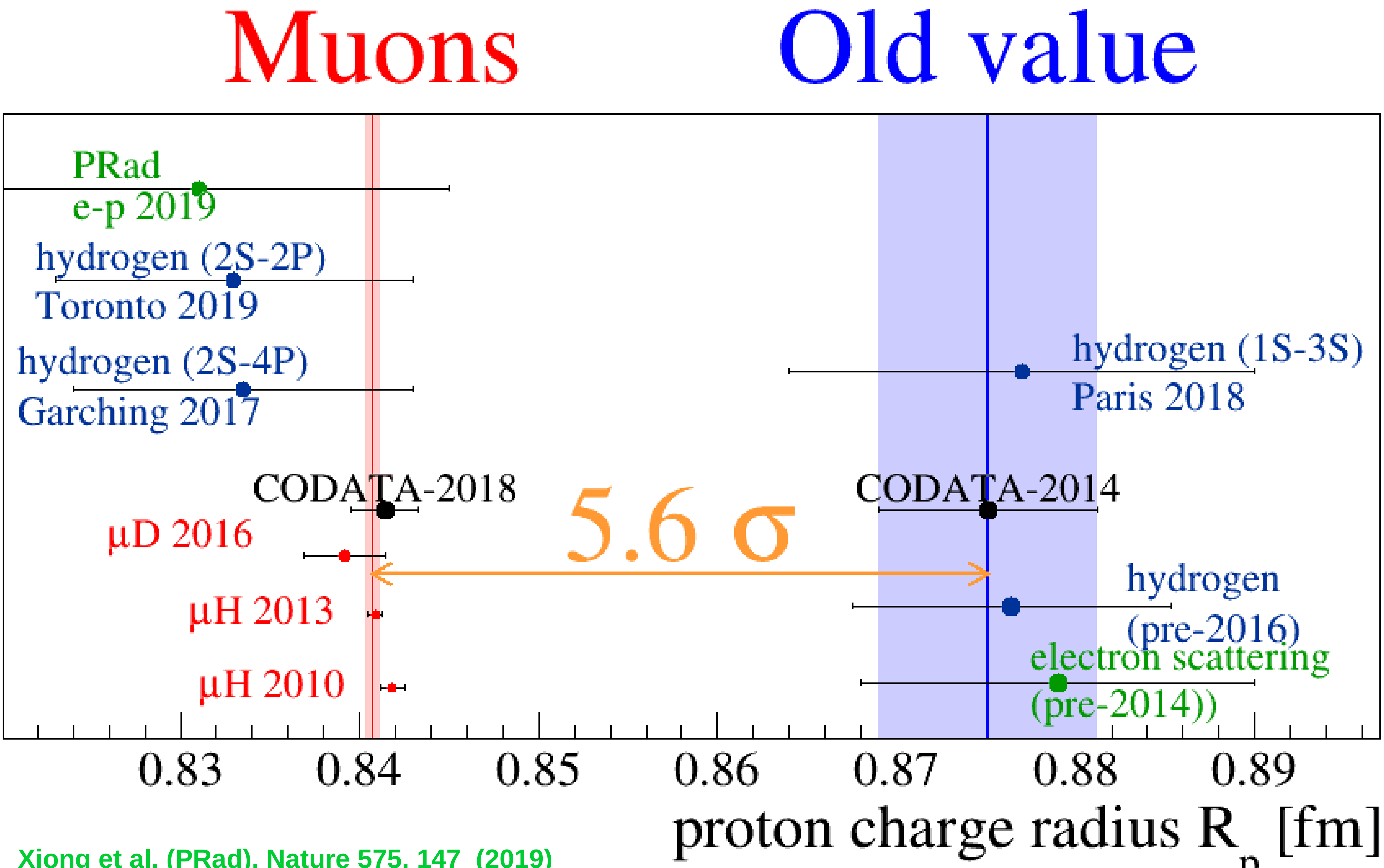
PRad @ Jefferson Lab



no magnetic spectrometer
angle 0.7-7° (0.002 -
large Q^2 range in one setting
windowless cryogenic gas target

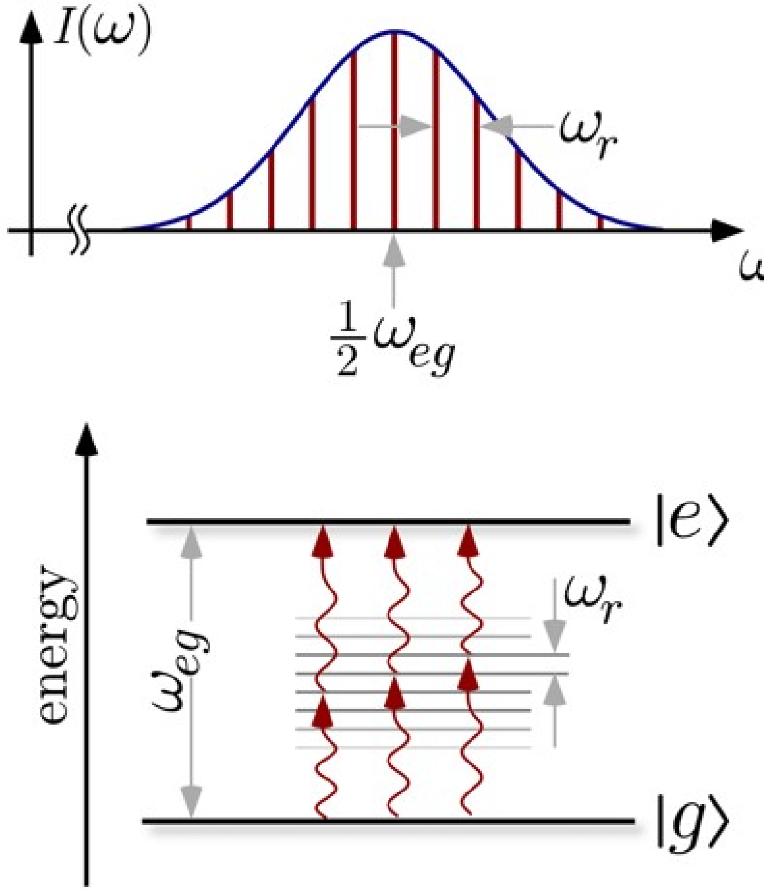
Xiong et al., Nature 575, 147 (2019)

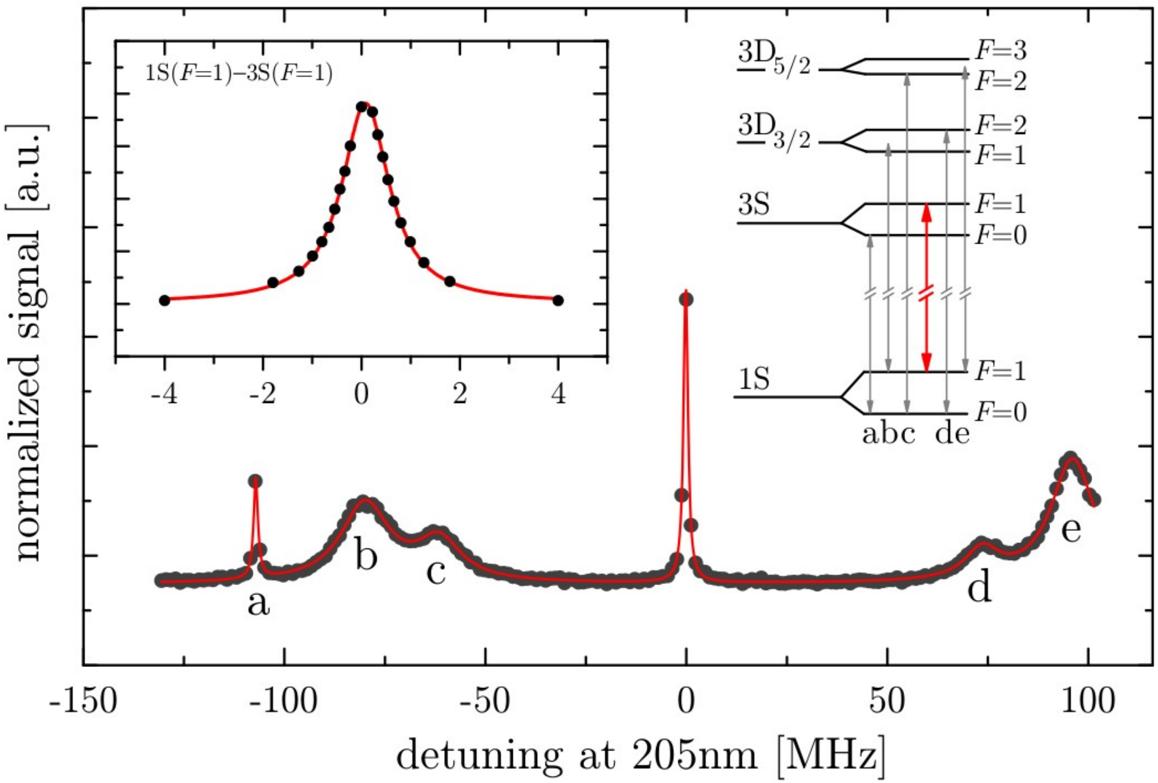
New Measurements: PRad



Xiong et al. (PRad), Nature 575, 147 (2019)

Garching H(1S-3S)

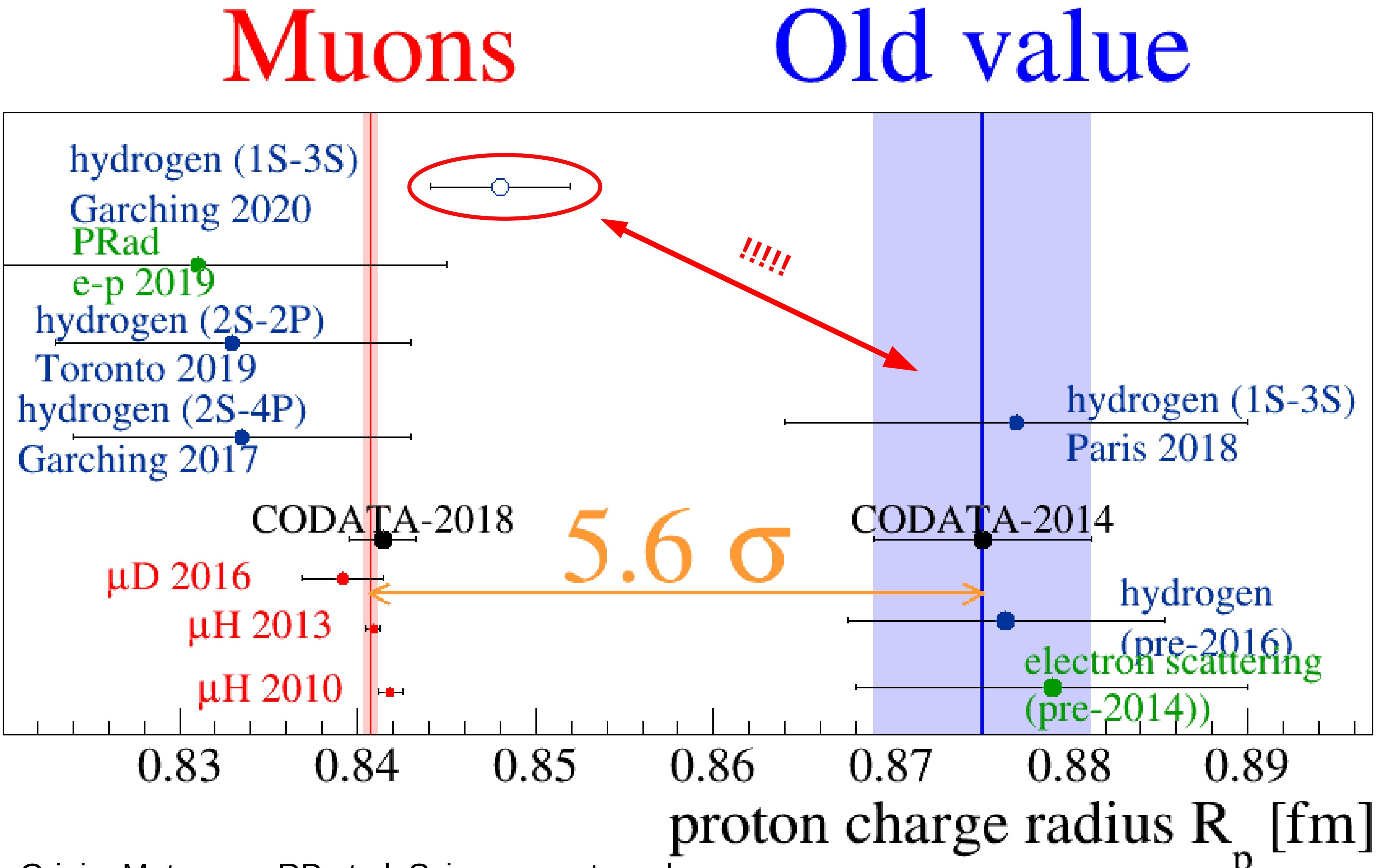




- Direct Frequency Comb Spectroscopy
- cryogenic H beam (6 K)

Grinin, Matveev,.. RP et al, Science, next week

H(1S-3S) Garching 2020



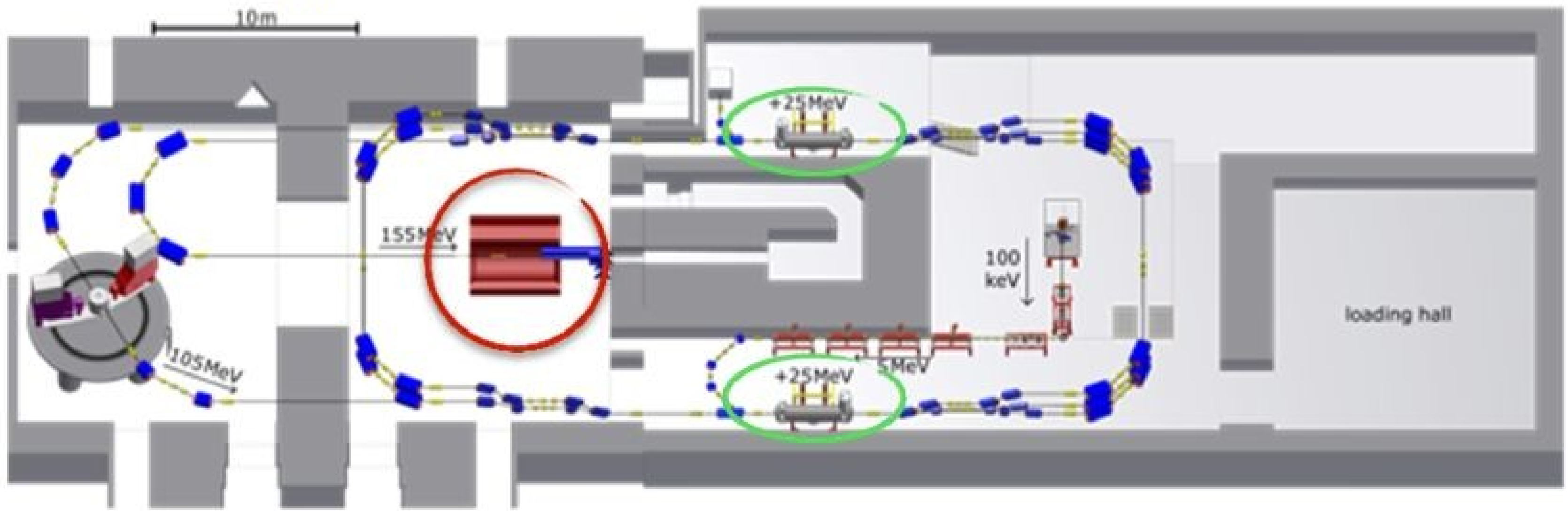
Grinin, Matveev,.. RP et al, Science, next week

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

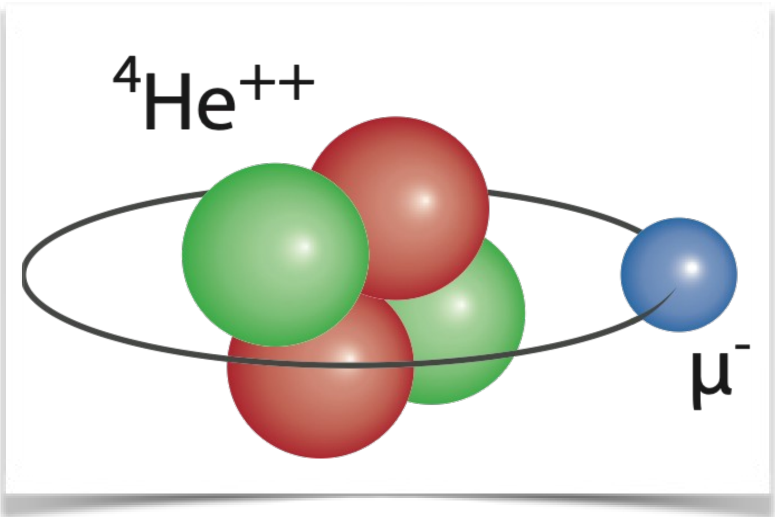


Being built on **Campus of JGU Mainz**

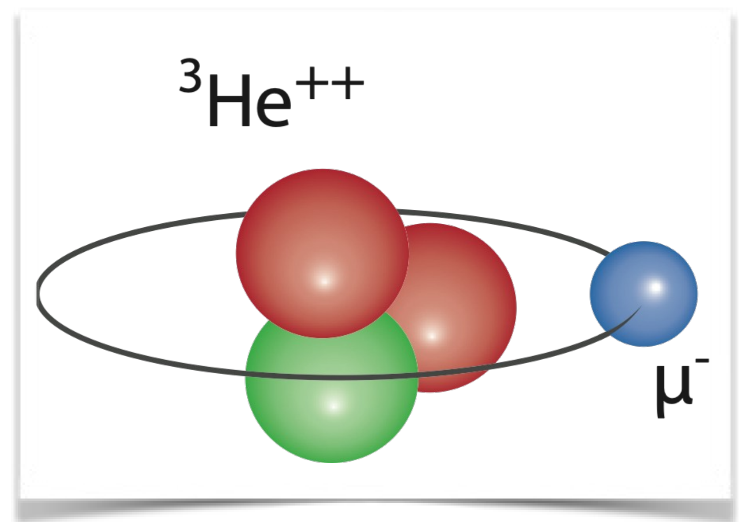
MAGIX: windowless (gas-jet) target, lowest Q^2

Cluster of Excellence
PRISMA+

Muonic Helium

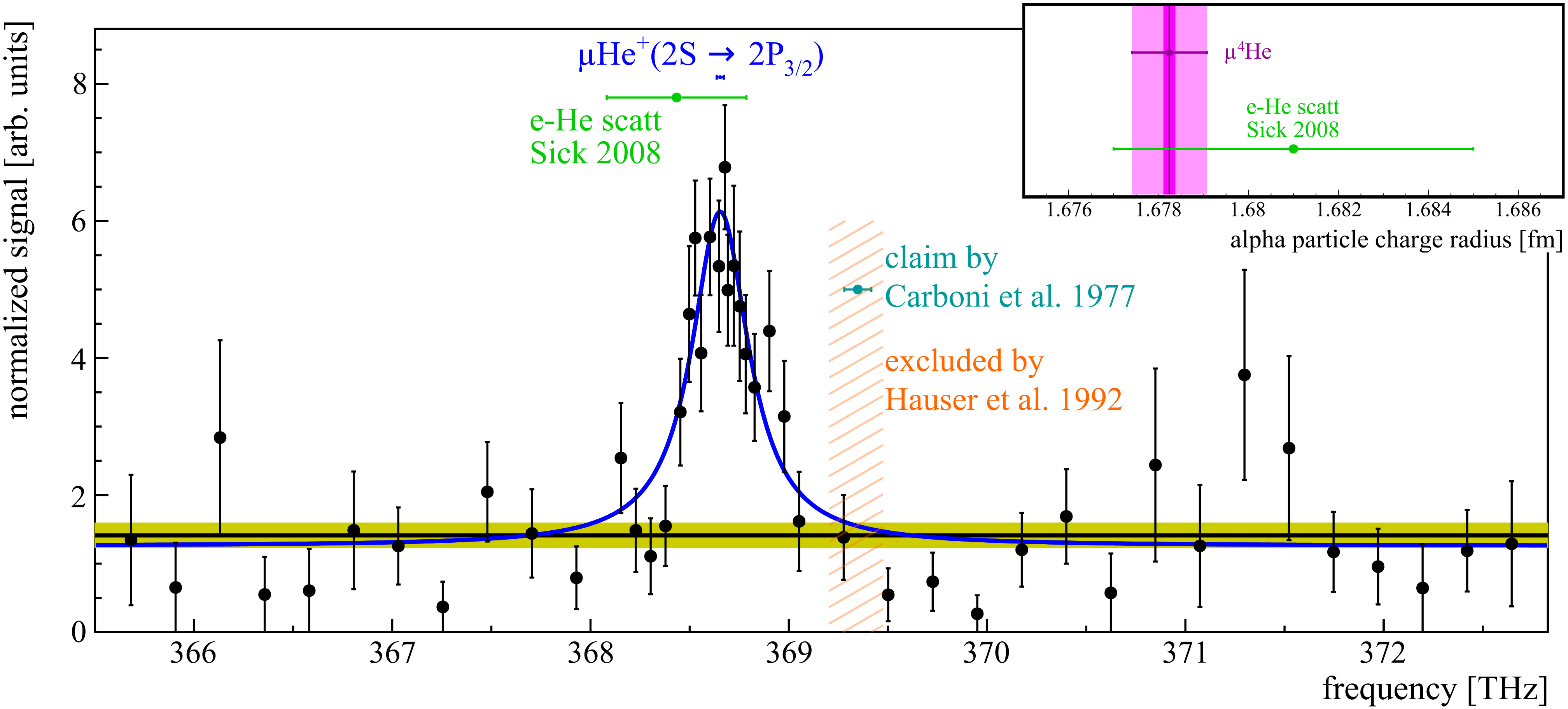


Krauth et al. (CREMA), Nature (2021)



Measured

muonic ^{4}He ions

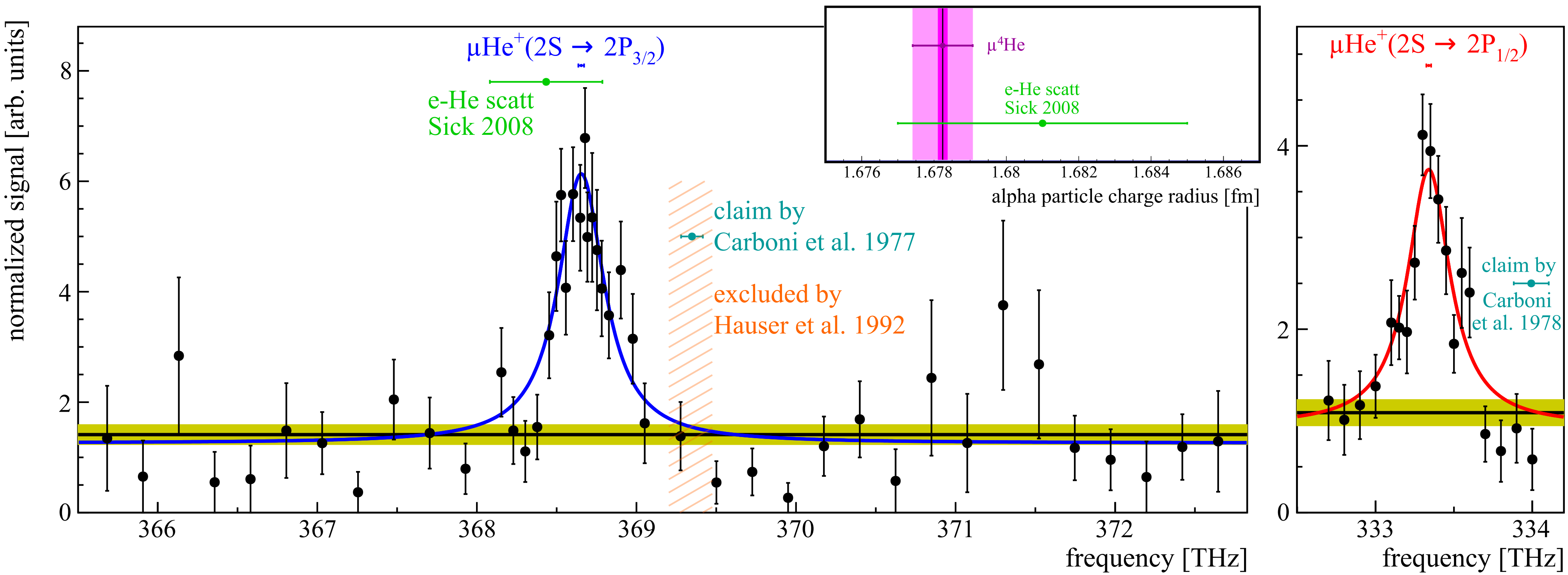


$R(^4\text{He}) = 1.67824\ (13)_{\text{exp}}\ (82)_{\text{theo}}$ fm

Krauth, RP et al. (CREMA Coll.)
Nature 589, 527 (2021)

Theory: Diepold et al., Ann. Phys. (2018)
incl. 3-photon nuclear polarizability (Pachucki, 2018)

muonic ^{4}He ions



$2P_{3/2}$: ±17 GHz **$2P_{3/2}$: ±15 GHz**

$$R(^4\mathrm{He}) = 1.67824\,(13)_{exp}\,(82)_{theo}\ \mathrm{fm}$$

Krauth, RP et al. (CREMA Coll.)
Nature 589, 527 (2021)

Theory: Diepold et al., Ann. Phys. (2018)
incl. 3-photon nuclear polarizability (Pachucki, 2018)

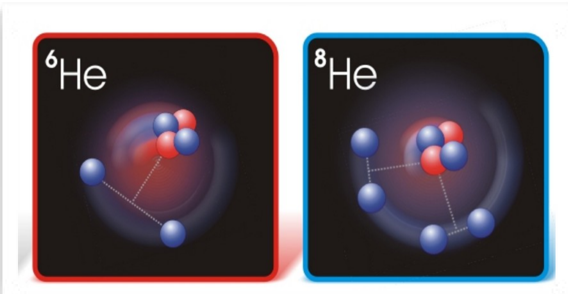
Impact of μ^{4}He$^+$ measurements

Few-nucleon theories

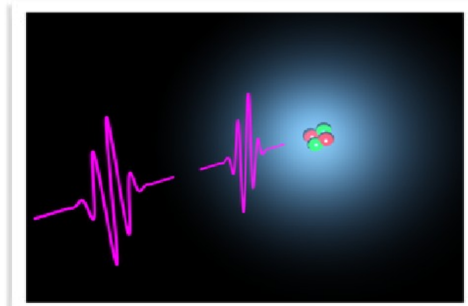
- r_α represents a benchmark for few-nucleon theories.
- r_α can be used also to fix a low-energy constant of nuclear potential.
- r_α improves ^{6}He and ^{8}He radii

BSM physics

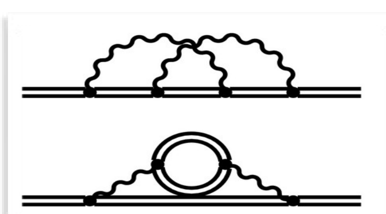
- Agreement constrains BSM models suggested to explain the R_p puzzle



Müller, Lu



Udem, MPQ
Eikema, LaserLab



Combined with upcoming He$^+$ (He) exp.

- bound-state QED test He$^+$(1S-2S): 60 kHz, $u_r = 6\text{x}10^{-12}$
- Rydberg constant: 24 kHz
- **2PE+3PE in μHe with 0.1 meV uncertainty**

from A. Antognini

Conclusions

Muonic atoms / ions provide:

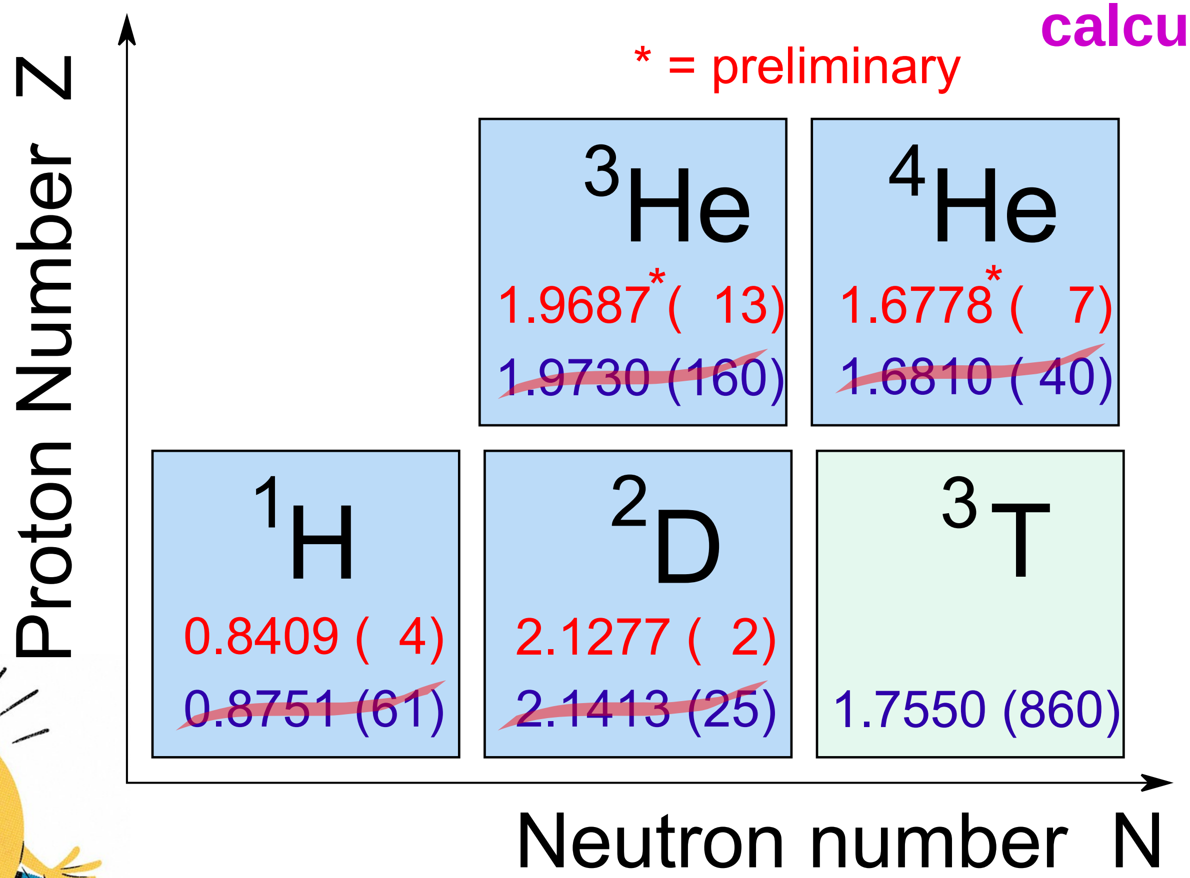
- **~10x more accurate charge radii**, when combined with

  calculated polarizability

Conclusions

Muonic atoms / ions provide:

- **~10x more accurate charge radii**, when combined with **calculated polarizability**



Intermediate conclusions

Muonic atoms / ions provide:

- **~10x more accurate charge radii**, when combined with **calculated polarizability**

- few times more accurate **nuclear polarizability**, when combined with **charge radius from regular atoms**

Muonic atoms are a novel tool for proton and new-nucleon properties!