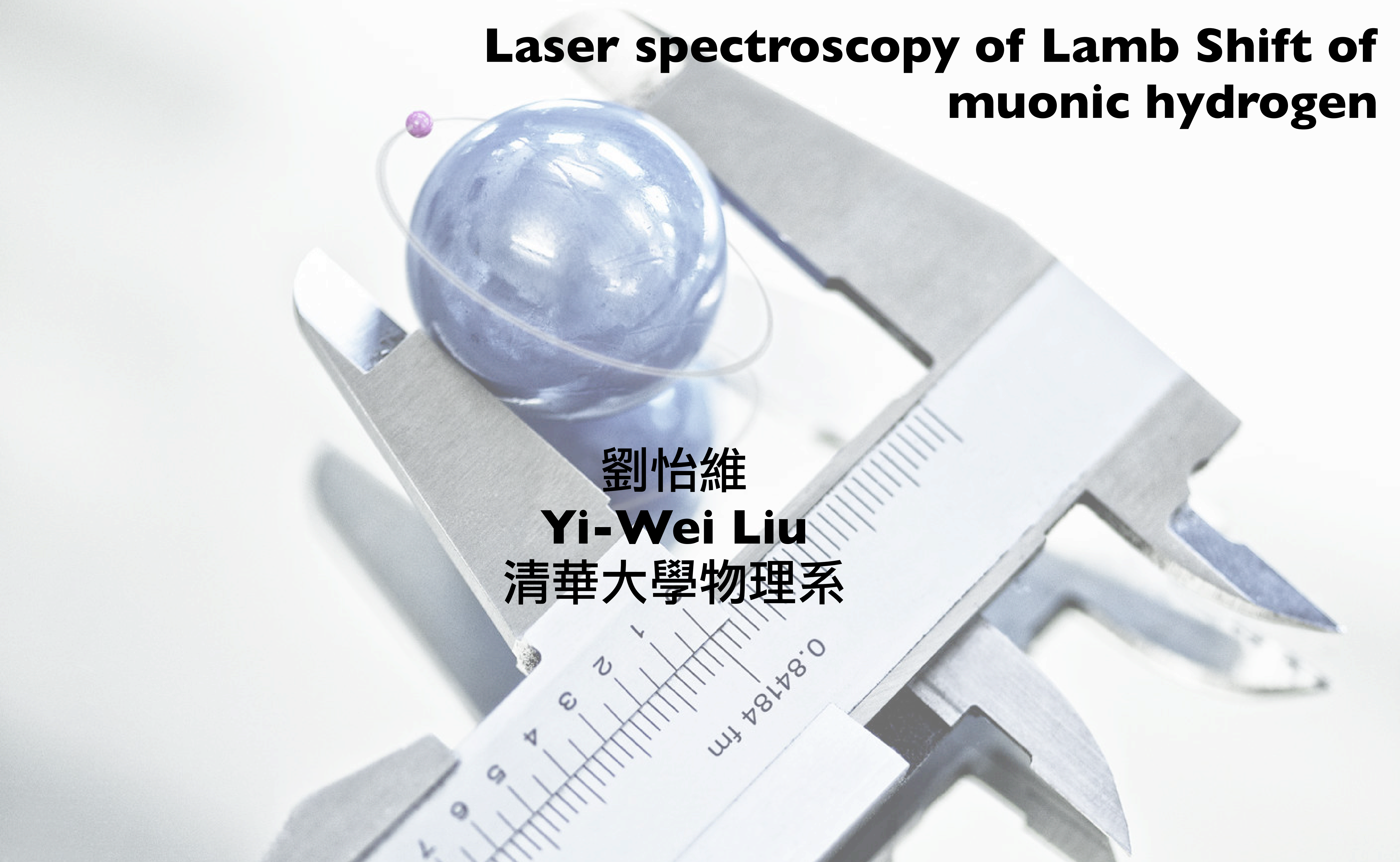
The size of the Proton

Laser spectroscopy of Lamb Shift of muonic hydrogen



劉怡維
Yi-Wei Liu
清華大學物理系

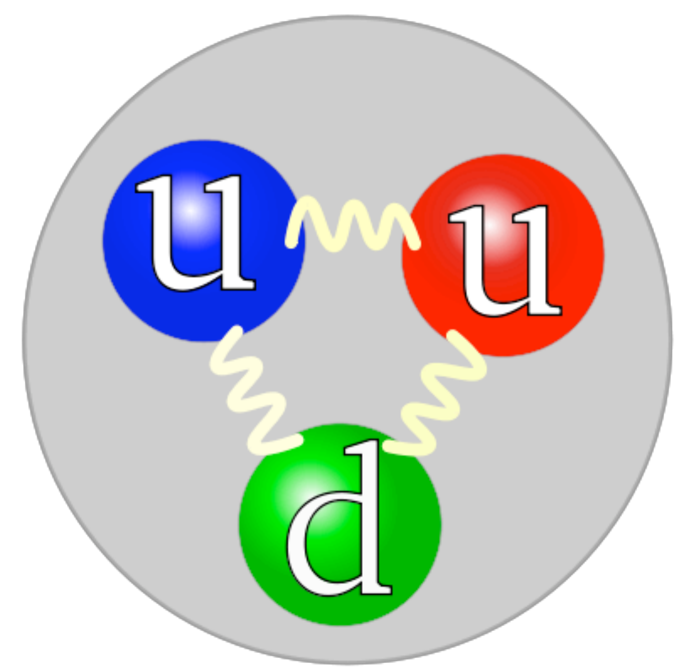
質子 Proton

所有物質的主要組成p, n, e。
但我們真的了解質子嗎？

Classification: Baryon
Composition: 2 up quarks, 1 down quark
Particle statistics: Fermionic
Symbol(s): p, p+, N+
*Theorized: **William Prout** (1815)*
*Discovered: **Ernest Rutherford** (1919)*

Mass: 1.672621637(83)×10^{-27} kg
Mean lifetime: >2.1×10^{29} yr (stabl
Electric charge: 1.602176487(
Charge radius: 0.877 (7) fm
Magnetic moment: 2.792847351(
Magnetic polarizability: 1.9(5)×10^{-4} fm^3
Spin: 1⁄2 Isospin: 1⁄2 Parity: +1
Electric dipole moment: <5.4×10^{-24} e·cm
Electric polarizability: 1.20(6)×10^{-3} fm^3

其實....對它的大小
不是很清楚



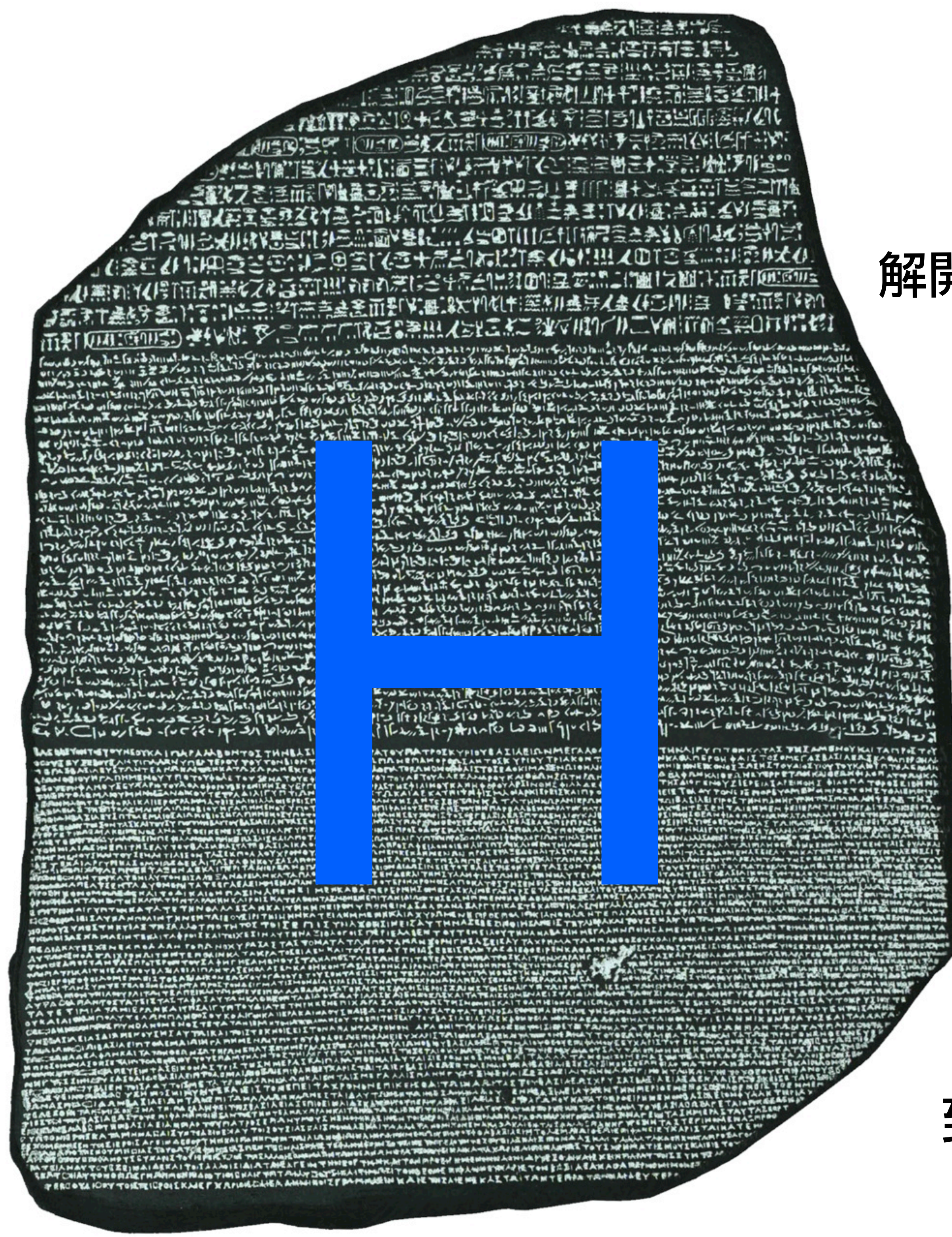
回到最簡單與最基本
-----現代物理的起點

H ....氫

一個電子+一個質子

Rosetta stone

氫原子



The **key** to decode the *secret* of ancient Egypt.

Idiomatic as something that is a critical *key* to the process of **decryption** or **transl**ation of a difficult **ENCODING** of INFORMATION.

解開現代物理世界

祕密的羅賽塔石

氫原子光譜

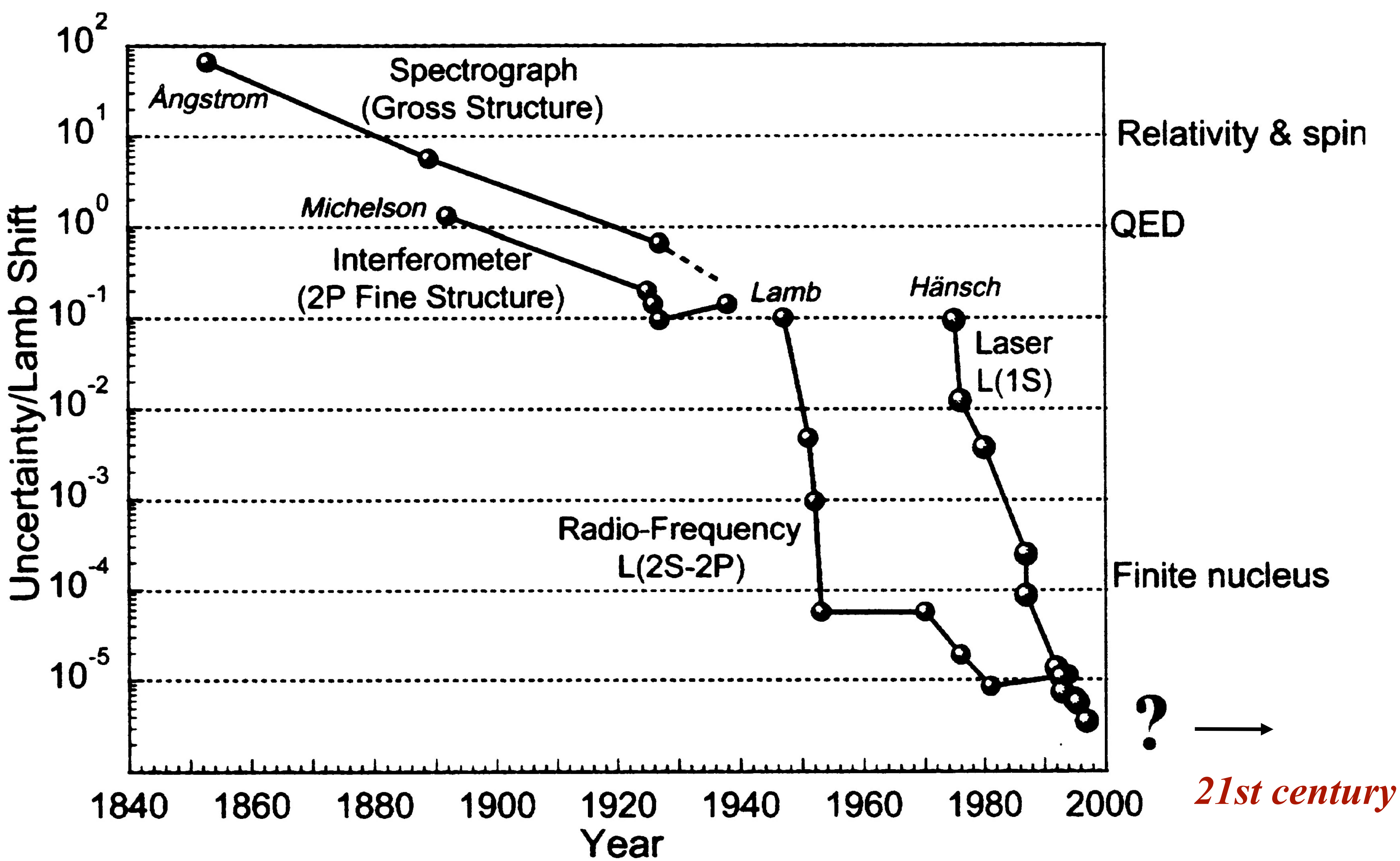
的解碼

是量子物理之鑰

從波爾的原子模型

到 量子電動力學

150年來的氫原子光譜量測



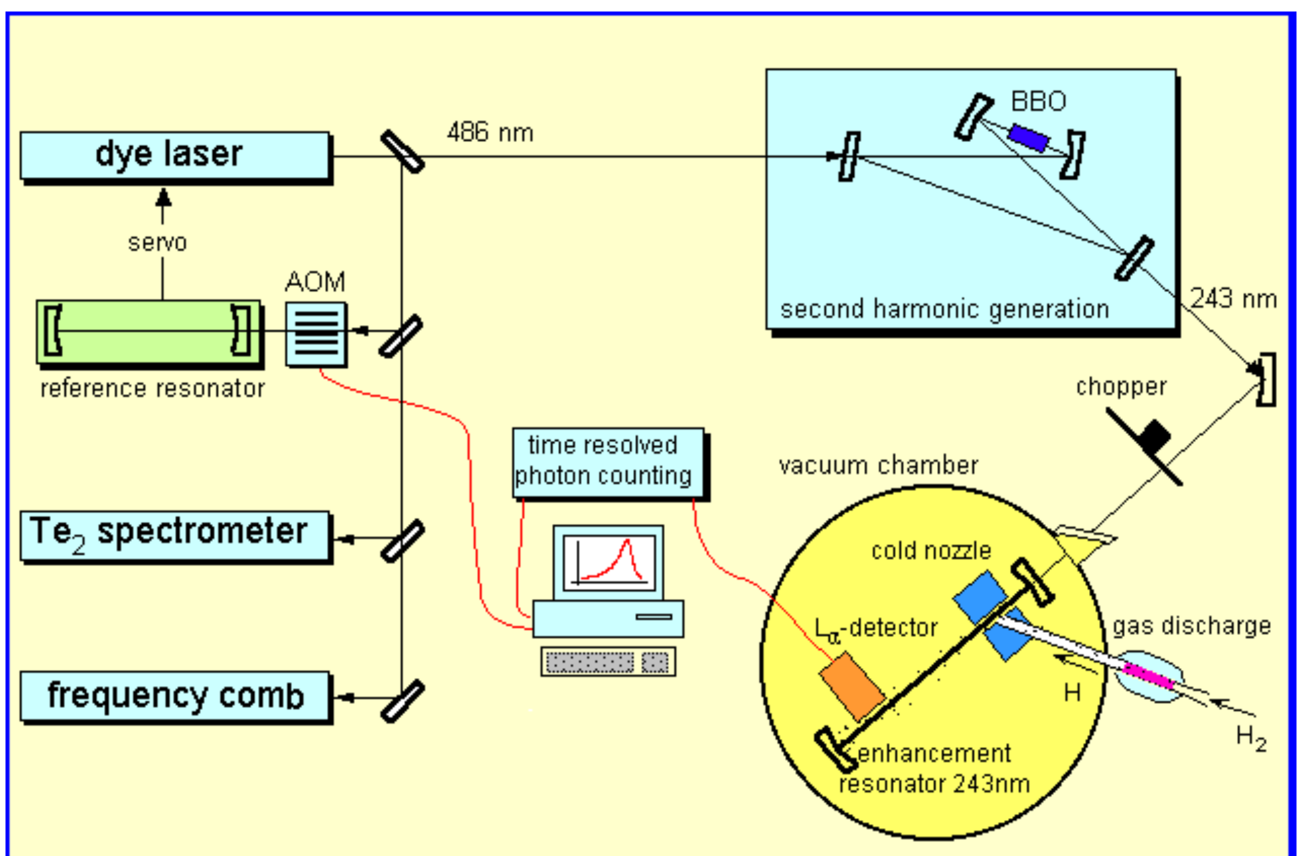
氫原子的超精確頻率量測

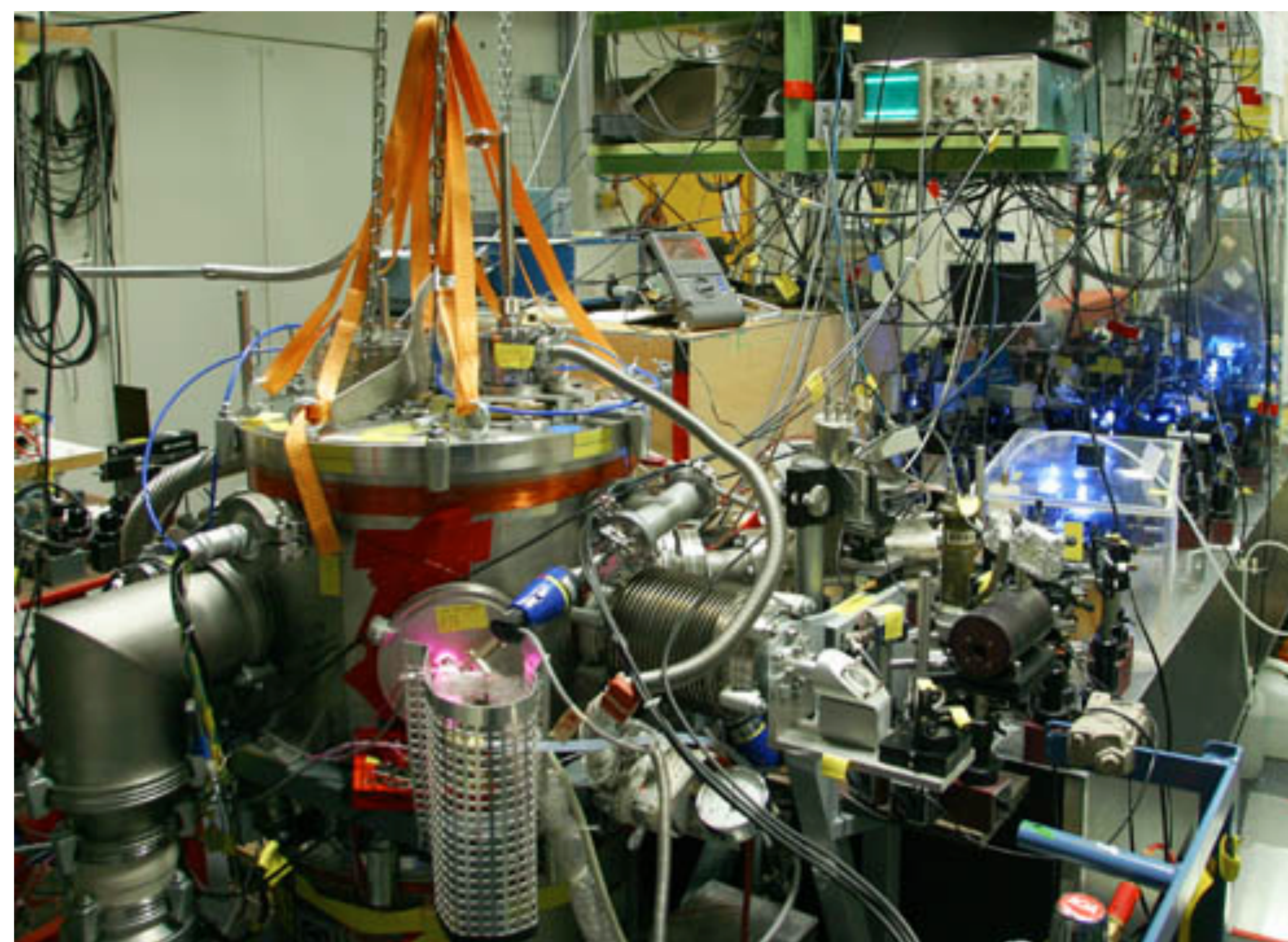
$$f(1S-2S) = 2\,466\,061\,413\,187\,074(34)\ \text{Hz}$$

1.4×10[14]

$$L(1S) = 8\,172\,840(22)\ \text{kHz}$$

By T. Hansch
(Max-Planck-Institut für Quantenoptik)





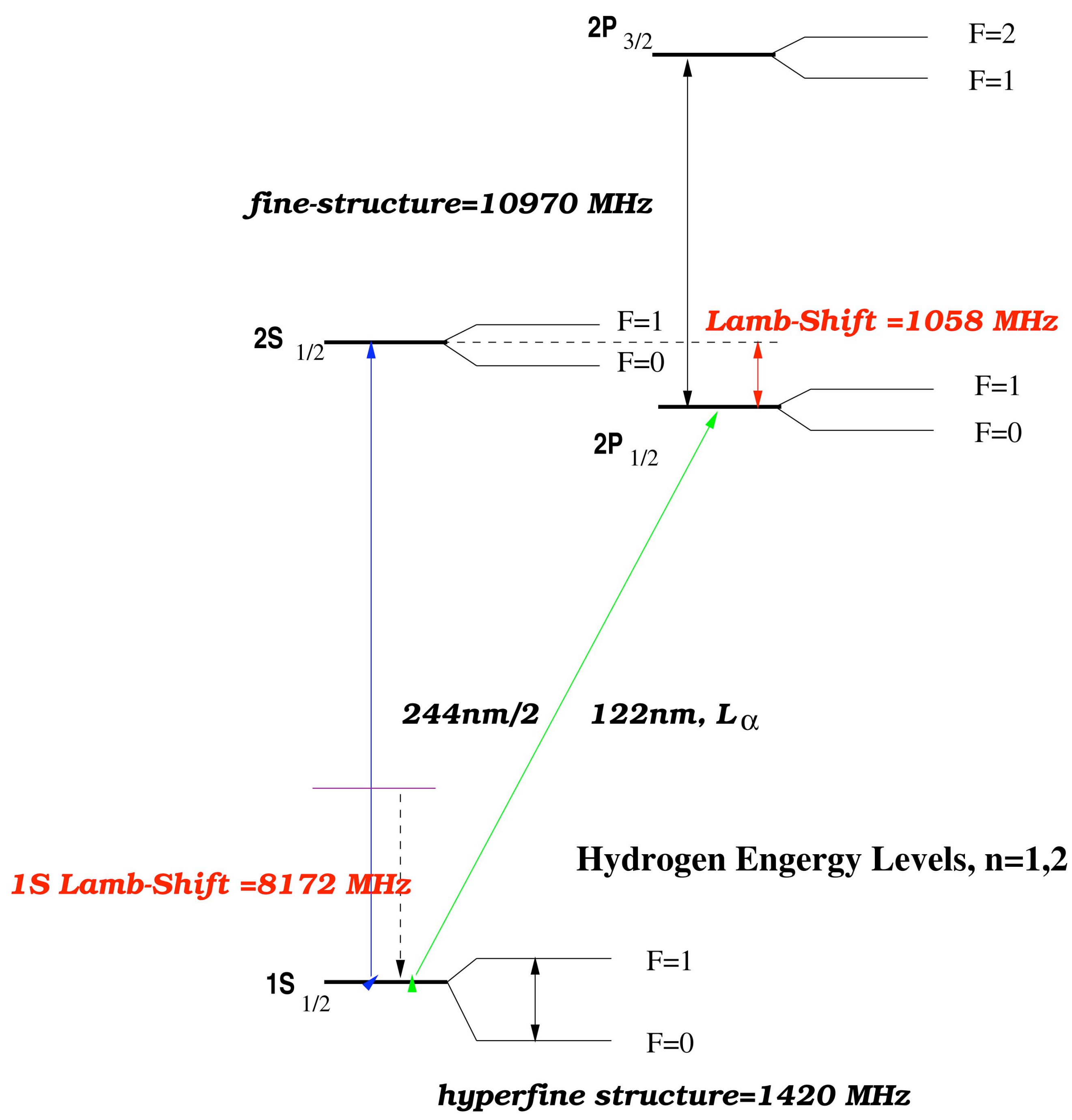
Bound QED的理論限制

以最簡單的原子系統為檢驗

氫原子**(ep)** 1S-2S躍遷中的

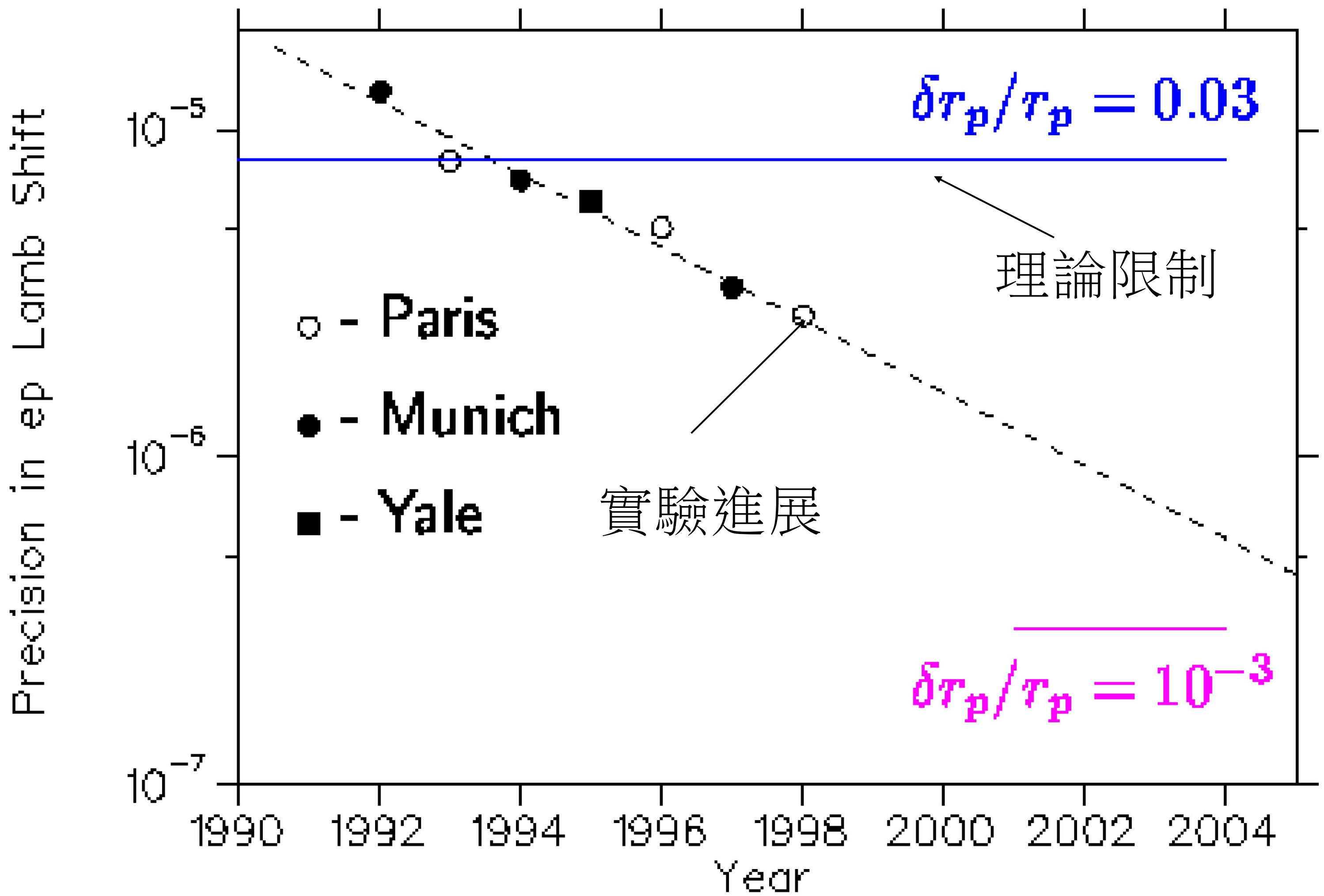
1S Lamb Shift (所有能階中最大):

$$\Delta E(nS) = \frac{\alpha(Z\alpha)^4 m}{\pi n^3} F_n(Z\alpha) + \frac{\alpha(Z\alpha)^4 m}{\pi n^3} G_n(Z\alpha) + \Delta E_{recoil} + \Delta E_{rad\ recoil}$$



目前理論與實驗精確度的比較

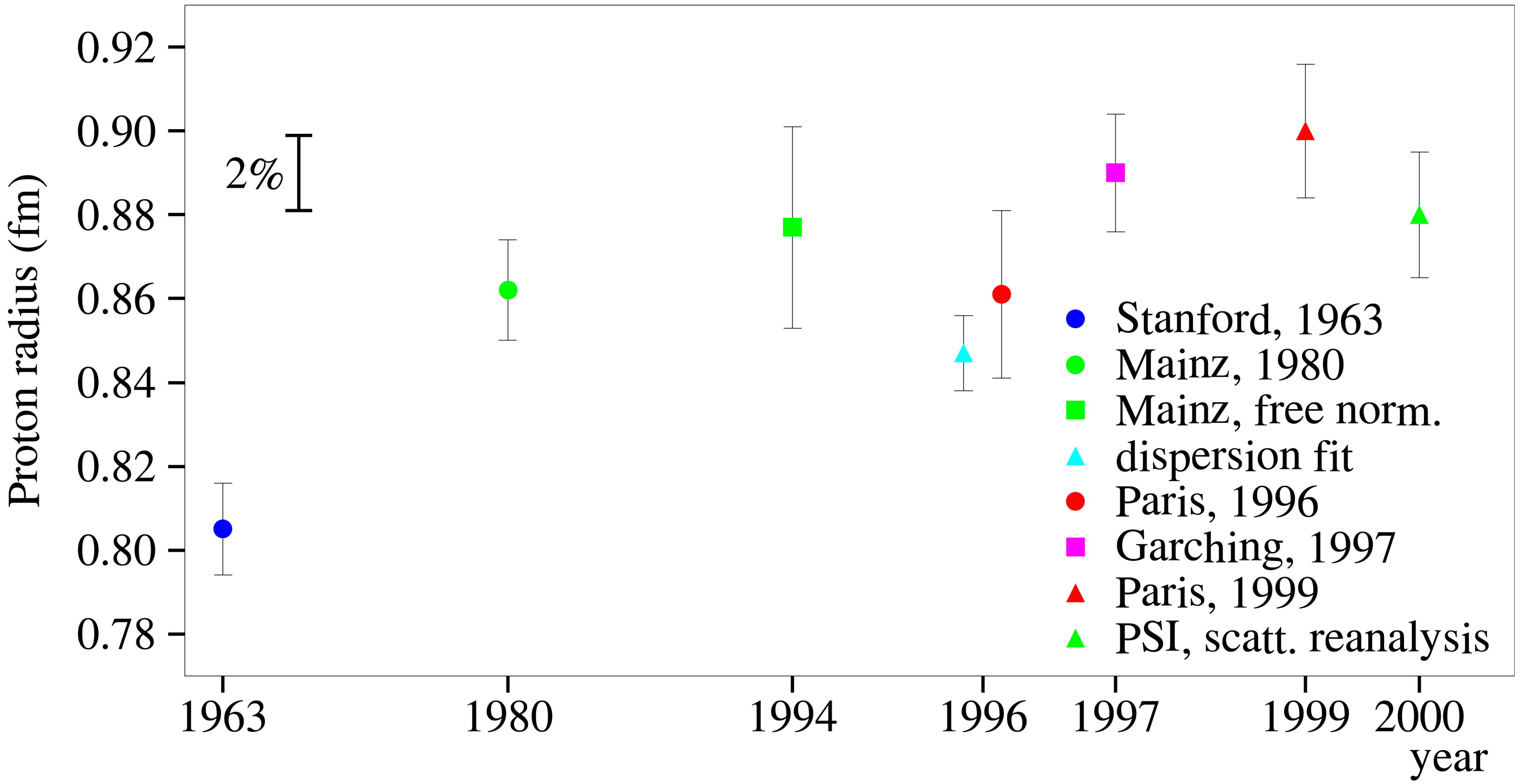
由於理論的精確度受制於$<r^2>$，使得無法進行真正的
Bound QED test



QED test and RMS of the proton charge radius

目前各質子<r²>的實驗結果

實驗誤差在**2-4%**間



transition energy=theory + proton size

→ proton size=transition energy - theory

氫原子無法再繼續檢驗QED
反而成為質子大小的量測

Few possible strategies to go around the finite size effect

- Purely leptonic system ：me、 e+e-

  muonium 1s-2s : muon mass problem (2000, PRL)

  positronium 1s-2s ：Second order Doppler effect (1993, S. Chu)

- Measuring the proton size

  muonic hydrogen spectroscopy

Recognized value of proton charge radius

The Committee on Data for Science and Technoloy

- H-spectroscopy (CODATA): 0.8768±0.0069 fm
- Electron-proton scattering : 0.897 ± 0.018 fm

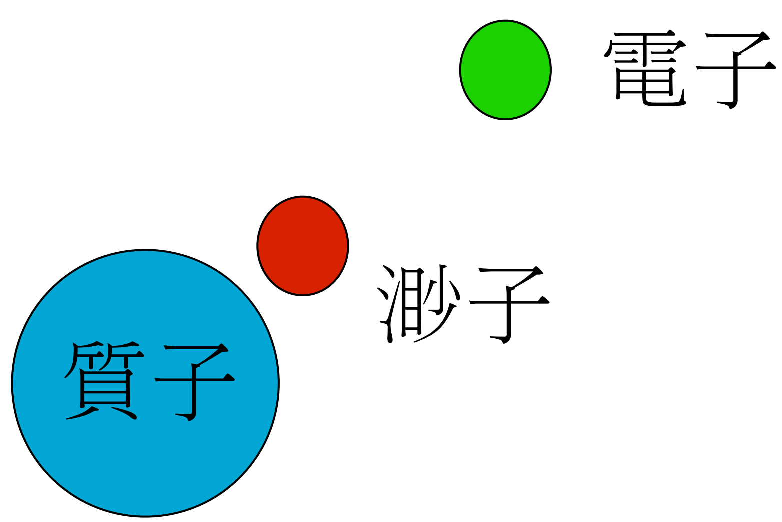
- 0.8% accuracy

奇異原子 = Exotic atom

- 字典說: Exotic=外國來的, 異國情調的, 奇特的, 脫衣舞孃的
- 含有電子、質子、中子等長半衰期以外的粒子(如 μ、π)所組成的原子系統,稱為奇異原子

渺子氫原子：Muonic Hydrogen: $\mu^- P^+$

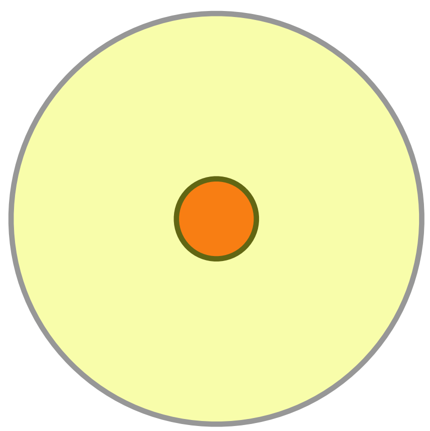
(μ 比電子重200倍的短命電子,生命期只有0.000002秒)



渺子氫原子

Lamb shift and r_P

S state



Electron
Muon

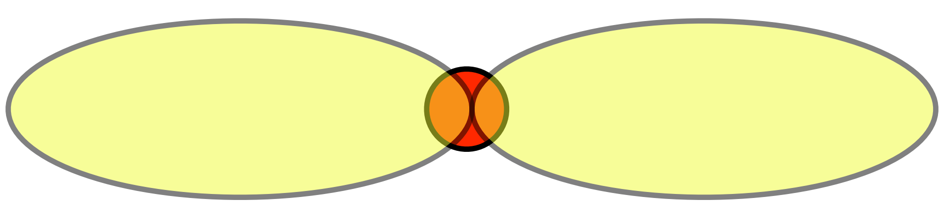
$r_{ep} \sim 5 \cdot 10^{-11}$ m $\quad r_{\mu p} \sim 3 \cdot 10^{-13}$ m

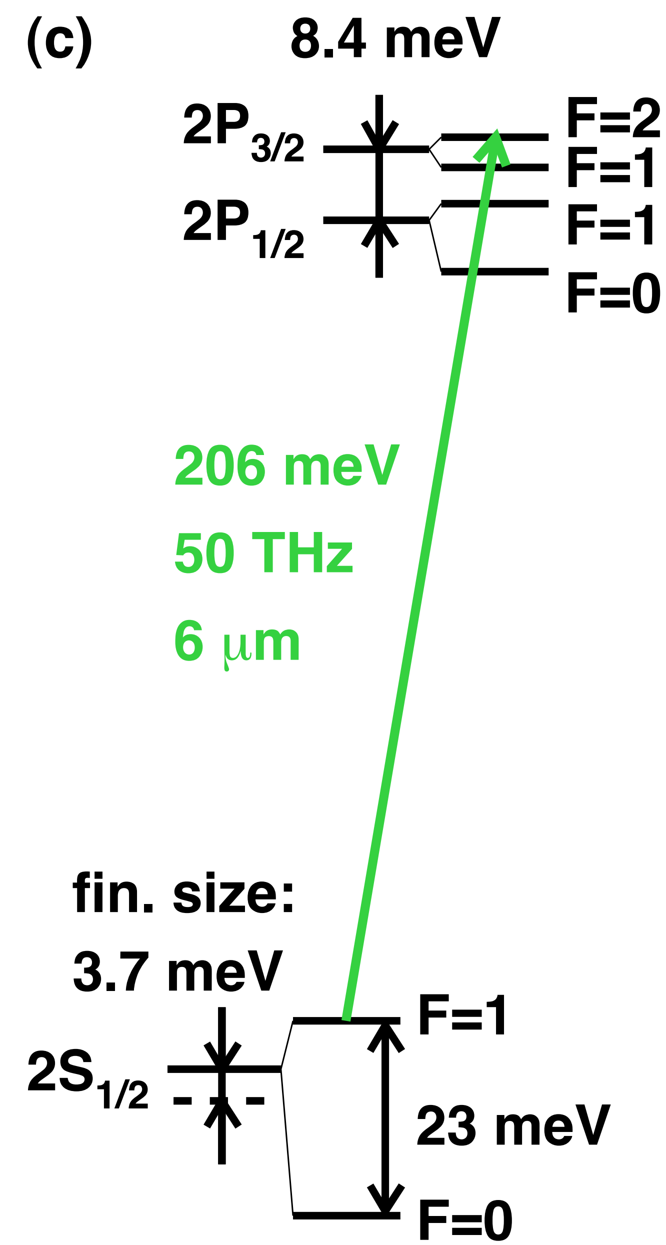
$r_p \sim 10^{-15}$ m

$$m_\mu \cong 200 \cdot m_e \implies r_{\mu p} \cong \frac{r_{ep}}{200}$$

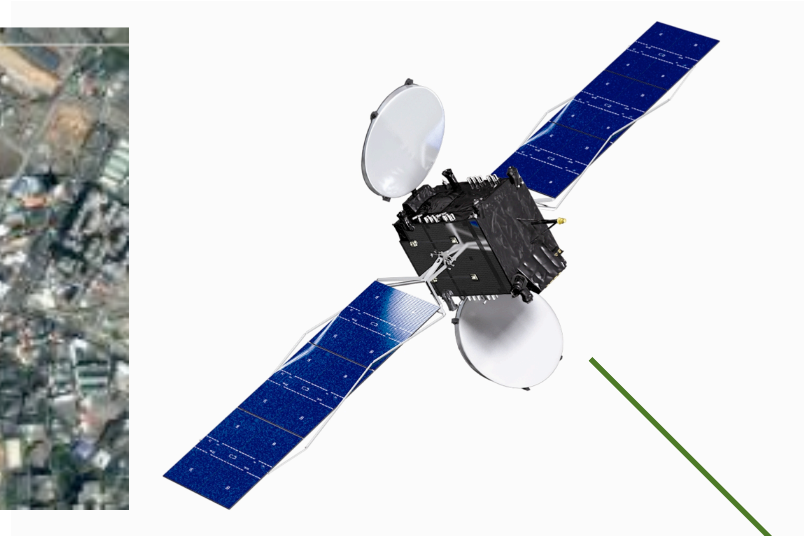
More sensitive to the structure of proton !!!!

P state



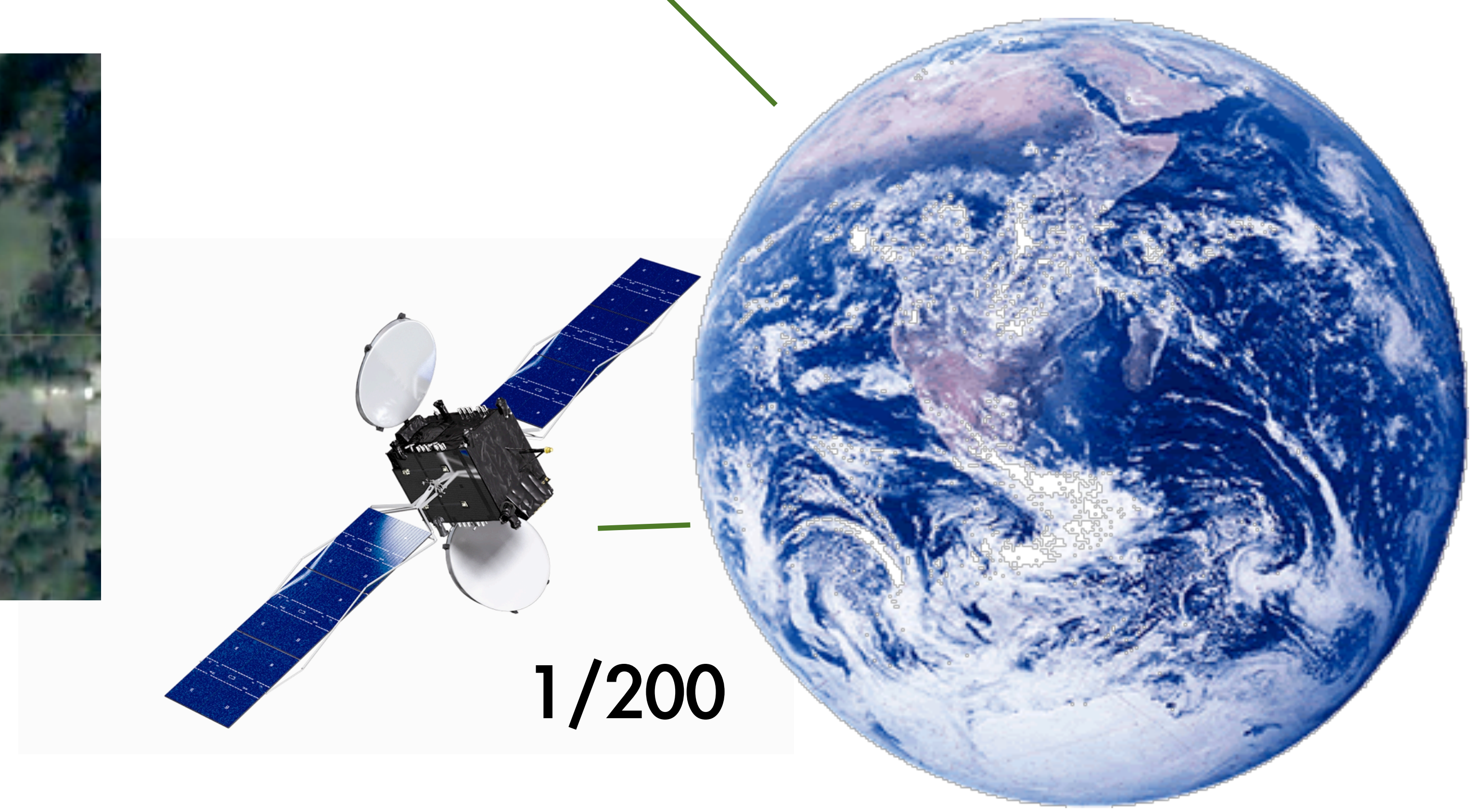


$$\Delta E = 209.9779(49) - 5.2262\, r_P^2 + 0.0347\, r_P^3 \text{ meV}$$



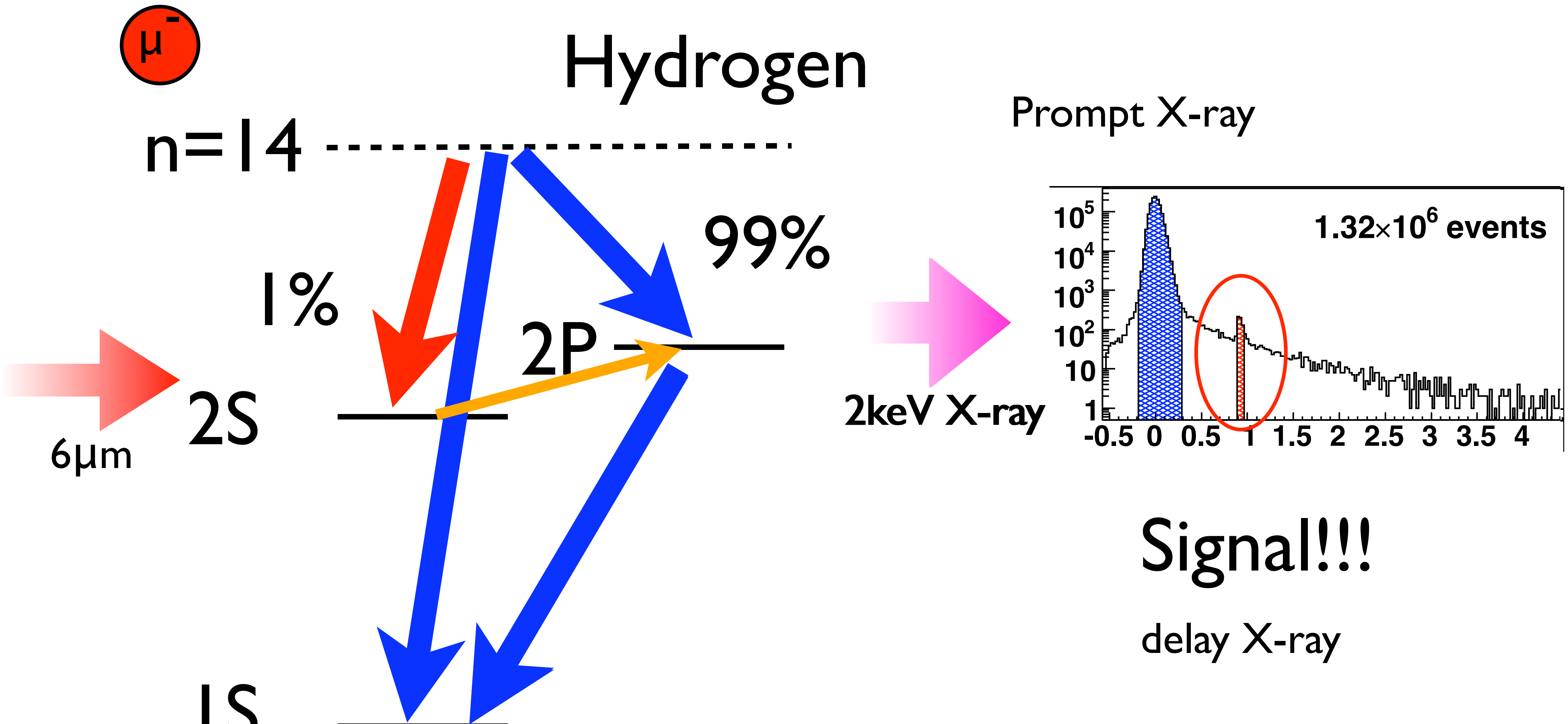
為甚麼是渺子氫原子？

渺子比電子重兩百倍，更靠近質子兩百倍，能更敏銳地偵測到質子的大小。



Principle

Cascade and detection mechanism

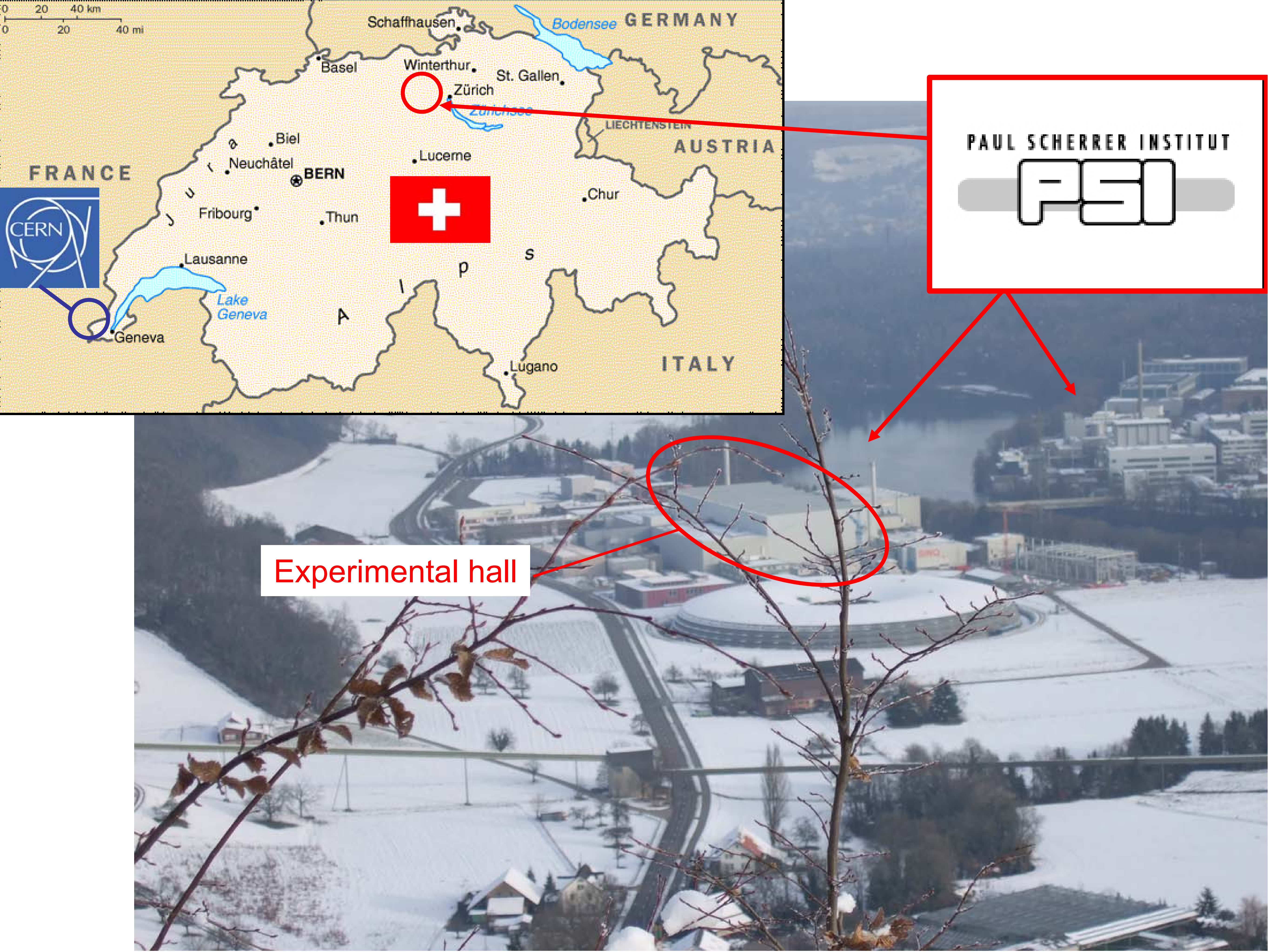


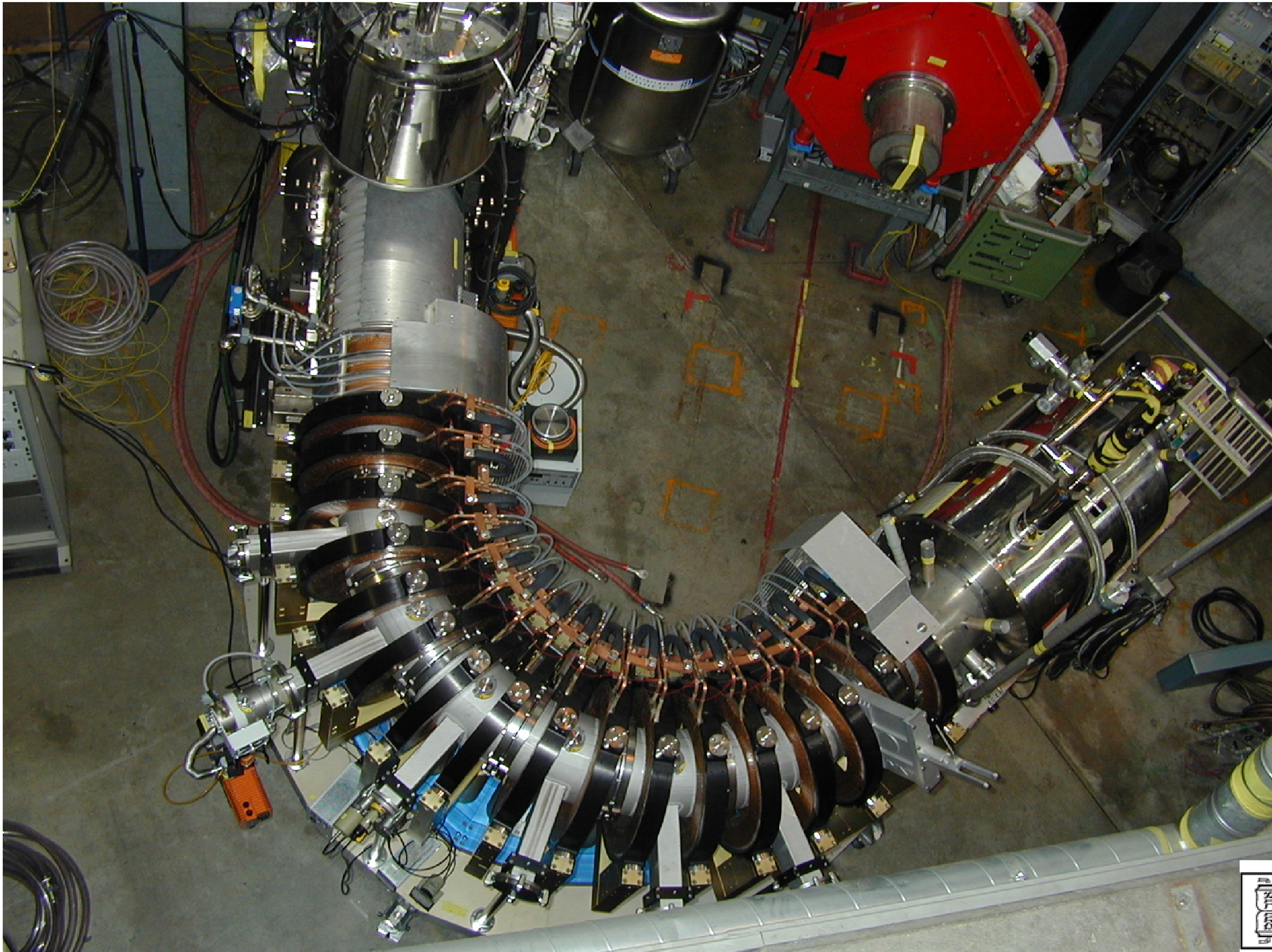
Two major technical challenges

<5keV

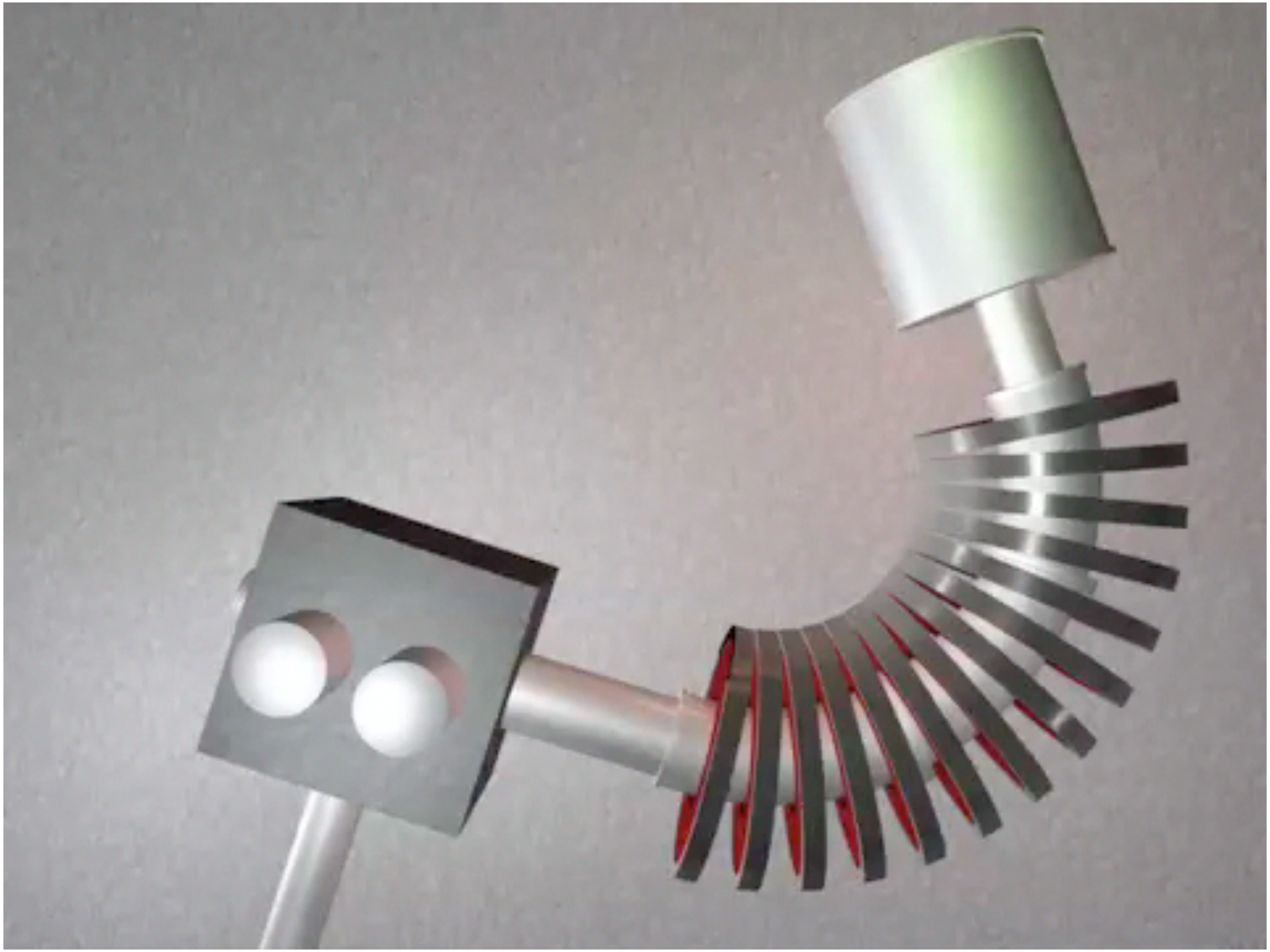
- Muonic hydrogen: Produce slow muon that can stop in low pressure hydrogen gas. 1 hPa
- Light source: 6μm laser source, powerful, well-controlled frequency, triggered on demand. 0.2 mJ

$\Delta t < 1\,\mu s$

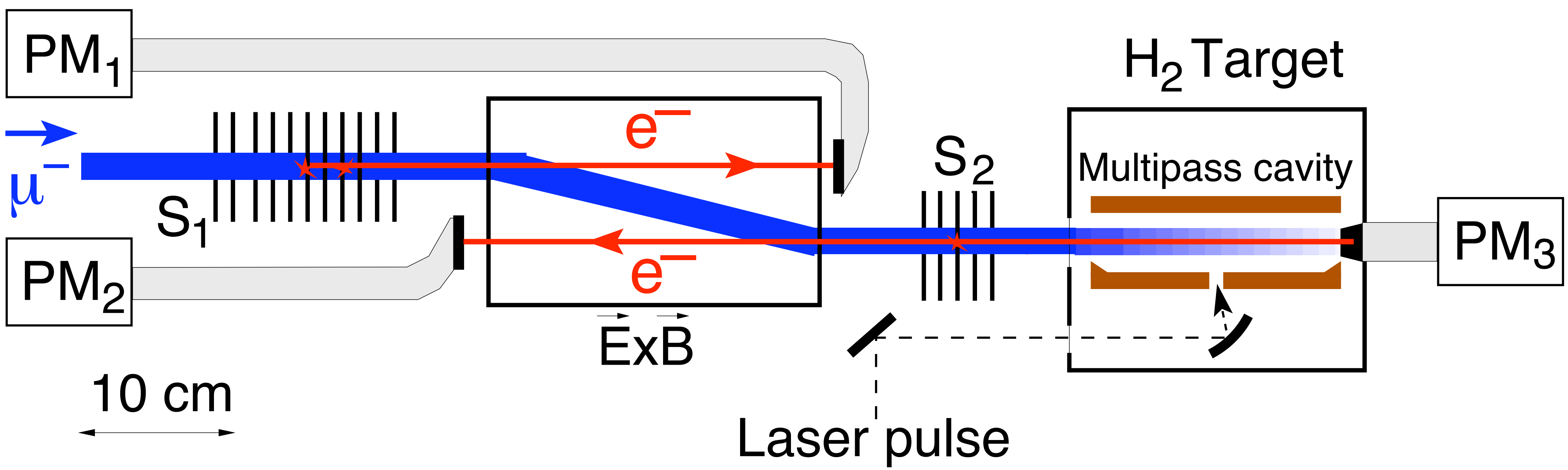

0 20 40 km
0 20 40 mi
Schaffhausen
Bodensee
GERMANY
Basel
Winterthur
St. Gallen
Zürich
Zürichsee
LIECHTENSTEIN
AUSTRIA
Biel
Neuchâtel
BERN
Lucerne
FRANCE
Jura
Chur
Fribourg
Thun
Lausanne
Alps
Lake Geneva
Geneva
Lugano
ITALY
CERN
PAUL SCHERRER INSTITUT
PSI
Experimental hall



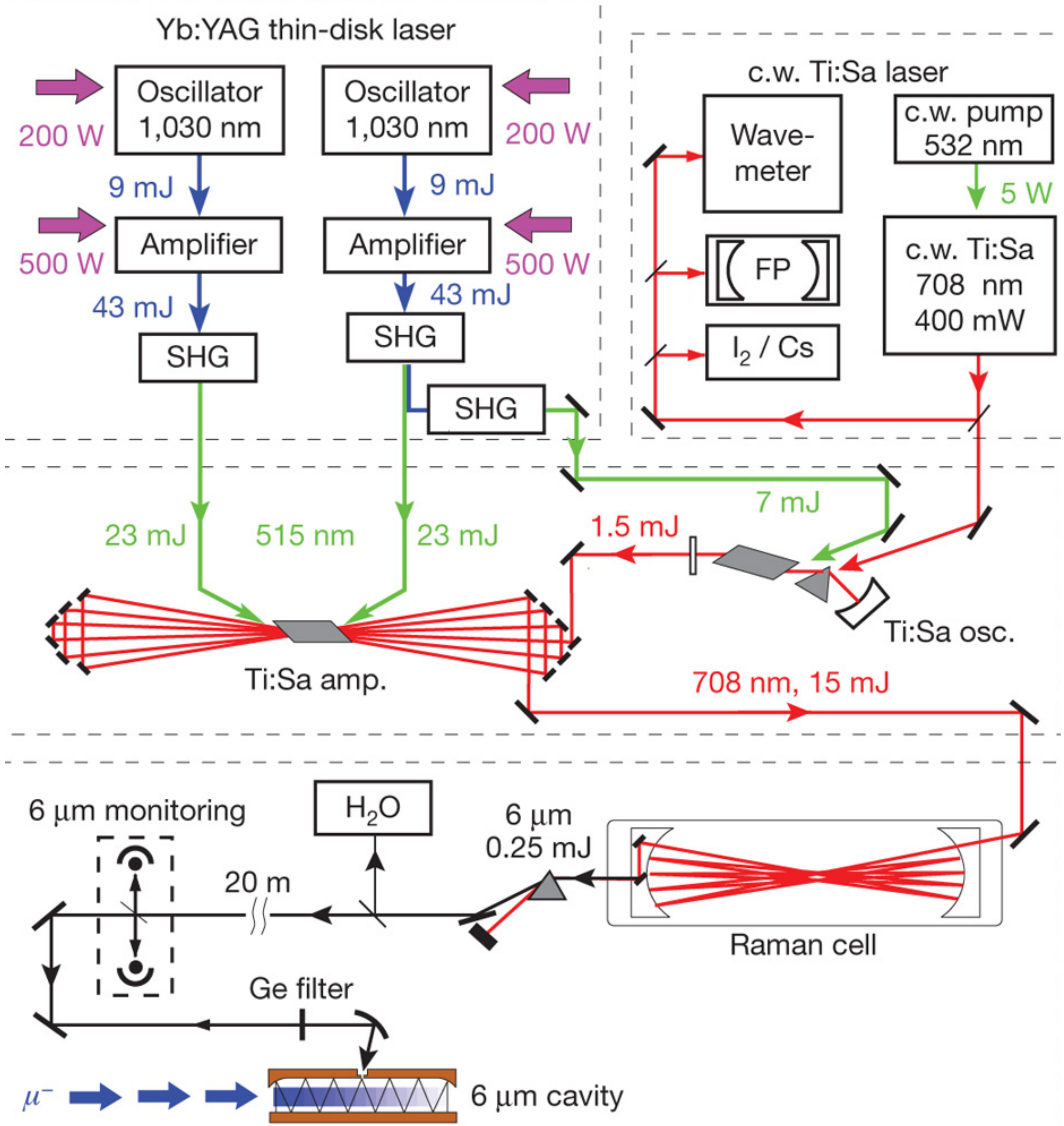
Generation of Cold muonic hydrogen



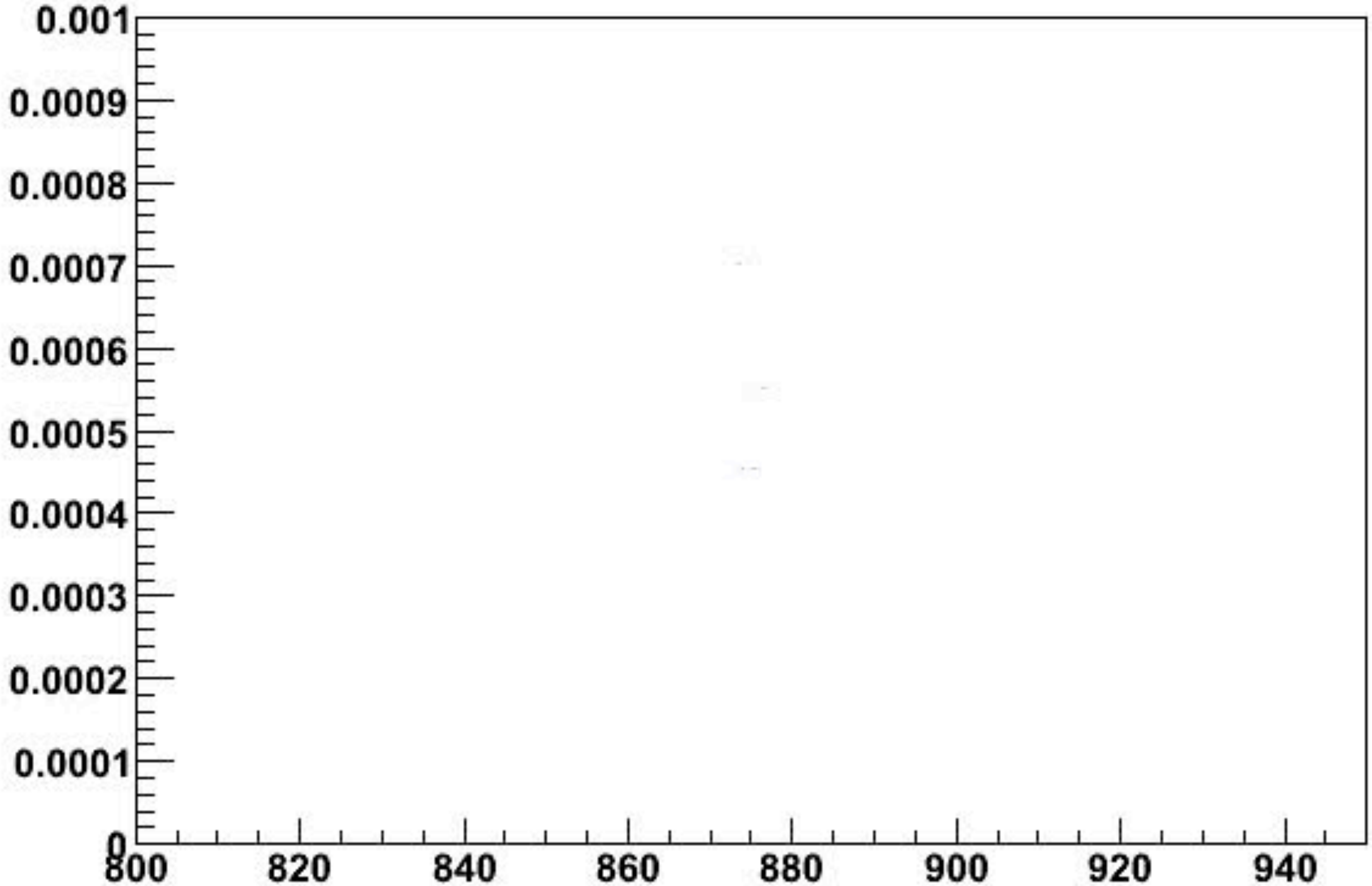
Interaction region



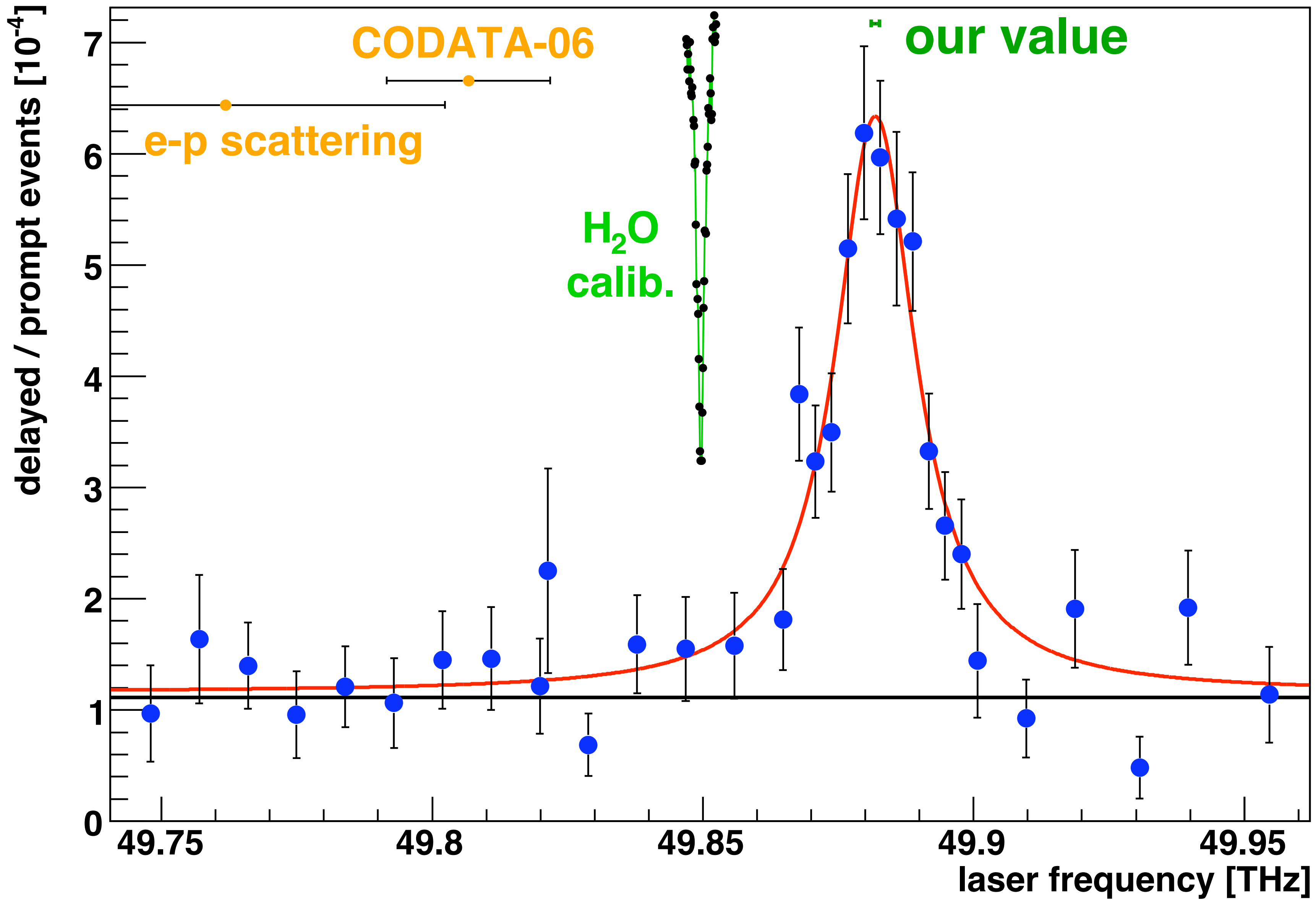
708nm→6μm Laser system



Replay the MOMENT...

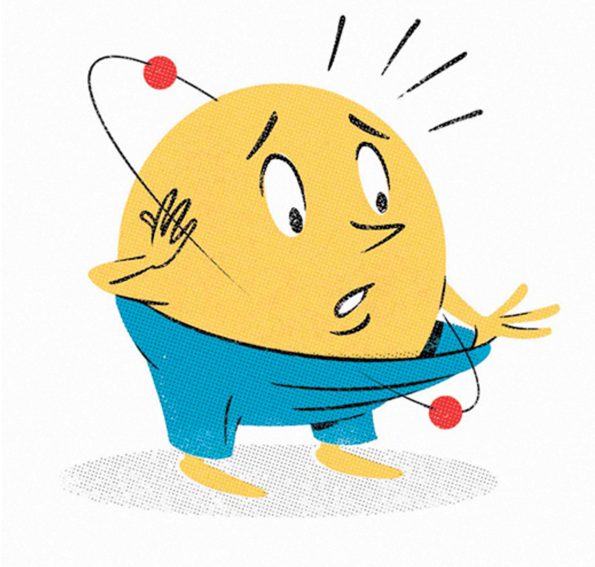


Results



$2S_{1/2}$ (F=1)→$2P_{3/2}$ (F=2): 49881.88±0.76GHz

r_p=0.84184(36)(56) fm



變小的質子

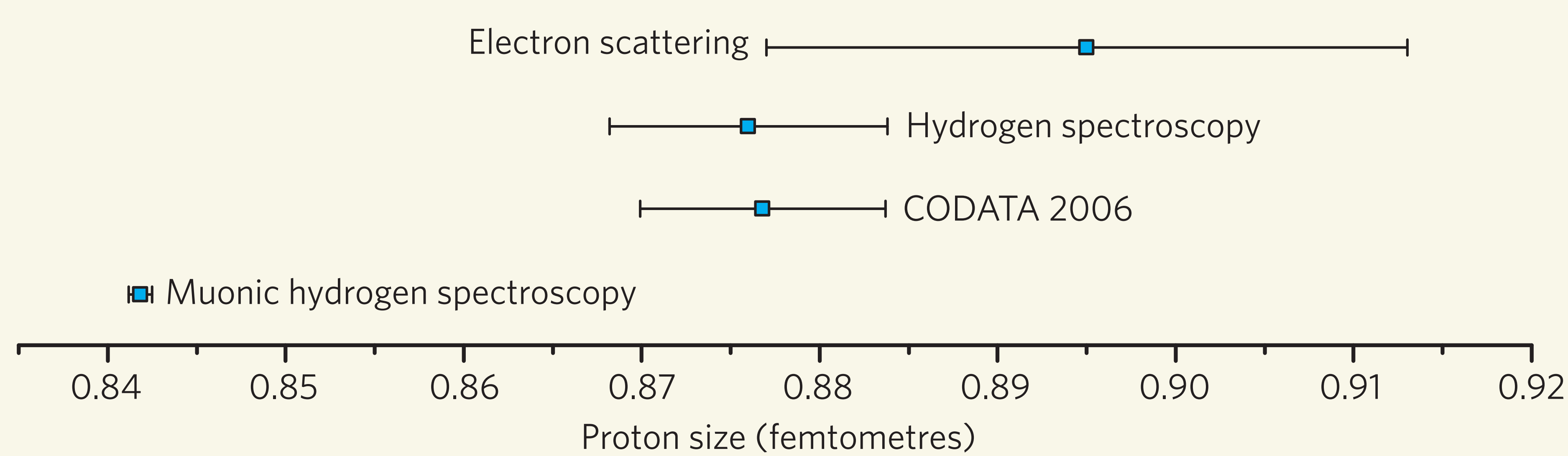
10^{-15}m

雖然不大, 確影響深遠

- 新數值 0.84184 fm<0.8768 fm, 小了4%

0.00000000000000084184 公尺

精確度到達了, 尚未被研究過的極小世界

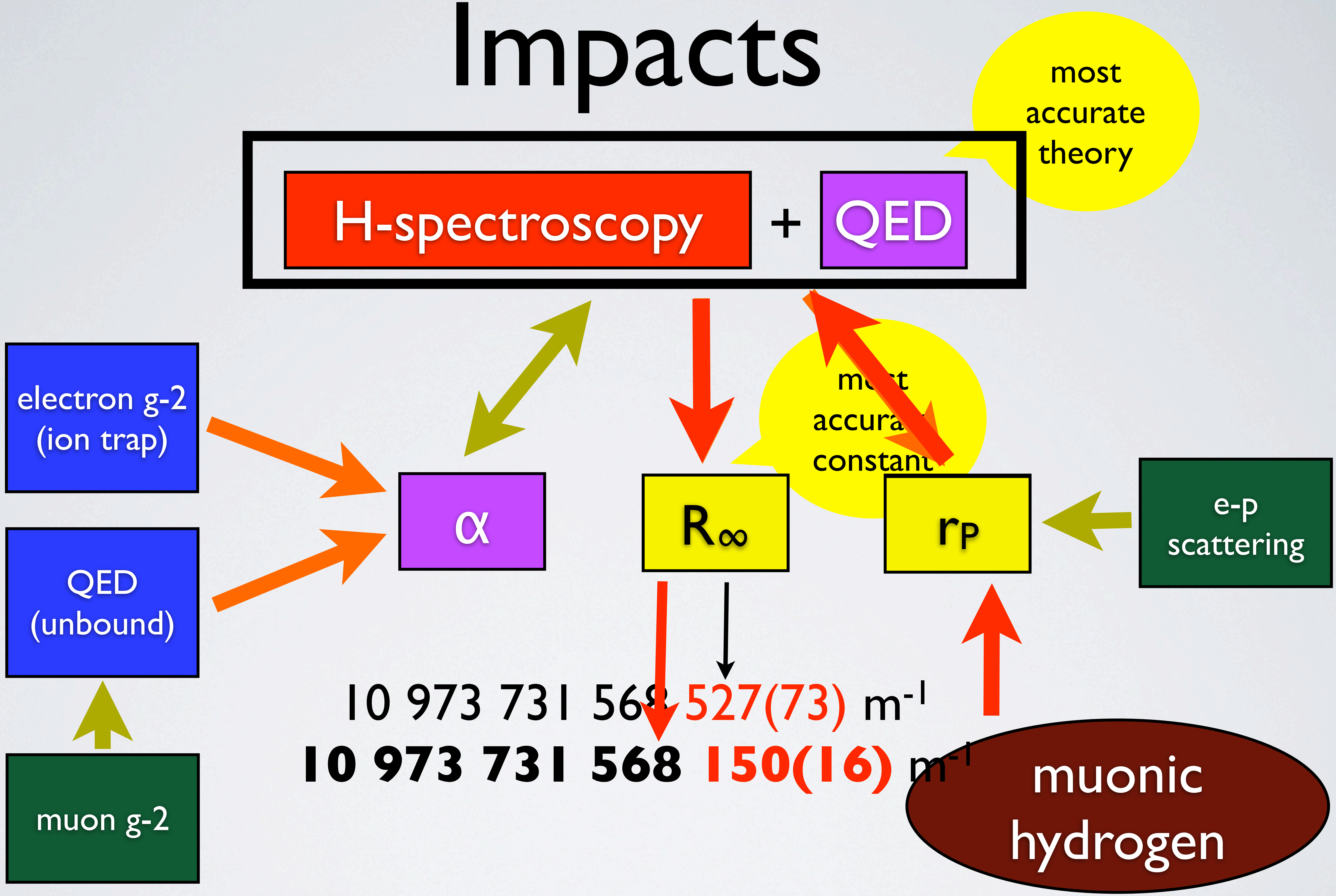


CODATA experimental inputs

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

Authors	Laboratory	Frequency interval(s)	Reported value (ν/kHz)	Rel. stand. uncert. u_r
Fischer *et al.*, 2004a, 2004b	MPQ	$\nu_H(1S_{1/2}-2S_{1/2})$	2 466 061 413 187.074(34)	1.4×10^{-14}
Weitz *et al.*, 1995	MPQ	$\nu_H(2S_{1/2}-4S_{1/2})-\frac{1}{4}\nu_H(1S_{1/2}-2S_{1/2})$	4 797 338(10)	2.1×10^{-6}
		$\nu_H(2S_{1/2}-4D_{5/2})-\frac{1}{4}\nu_H(1S_{1/2}-2S_{1/2})$	6 490 144(24)	3.7×10^{-6}
		$\nu_D(2S_{1/2}-4S_{1/2})-\frac{1}{4}\nu_D(1S_{1/2}-2S_{1/2})$	4 801 693(20)	4.2×10^{-6}
		$\nu_D(2S_{1/2}-4D_{5/2})-\frac{1}{4}\nu_D(1S_{1/2}-2S_{1/2})$	6 494 841(41)	6.3×10^{-6}
Huber *et al.*, 1998	MPQ	$\nu_D(1S_{1/2}-2S_{1/2})-\nu_H(1S_{1/2}-2S_{1/2})$	670 994 334.64(15)	2.2×10^{-10}
de Beauvoir *et al.*, 1997	LKB/SYRTE	$\nu_H(2S_{1/2}-8S_{1/2})$	770 649 350 012.0(8.6)	1.1×10^{-11}
		$\nu_H(2S_{1/2}-8D_{3/2})$	770 649 504 450.0(8.3)	1.1×10^{-11}
		$\nu_H(2S_{1/2}-8D_{5/2})$	770 649 561 584.2(6.4)	8.3×10^{-12}
		$\nu_D(2S_{1/2}-8S_{1/2})$	770 859 041 245.7(6.9)	8.9×10^{-12}
		$\nu_D(2S_{1/2}-8D_{3/2})$	770 859 195 701.8(6.3)	8.2×10^{-12}
		$\nu_D(2S_{1/2}-8D_{5/2})$	770 859 252 849.5(5.9)	7.7×10^{-12}
Schwob *et al.*, 1999, 2001	LKB/SYRTE	$\nu_H(2S_{1/2}-12D_{3/2})$	799 191 710 472.7(9.4)	1.2×10^{-11}
		$\nu_H(2S_{1/2}-12D_{5/2})$	799 191 727 403.7(7.0)	8.7×10^{-12}
		$\nu_D(2S_{1/2}-12D_{3/2})$	799 409 168 038.0(8.6)	1.1×10^{-11}
		$\nu_D(2S_{1/2}-12D_{5/2})$	799 409 184 966.8(6.8)	8.5×10^{-12}
Bourzeix *et al.*, 1996	LKB	$\nu_H(2S_{1/2}-6S_{1/2})-\frac{1}{4}\nu_H(1S_{1/2}-3S_{1/2})$	4 197 604(21)	4.9×10^{-6}
		$\nu_H(2S_{1/2}-6D_{5/2})-\frac{1}{4}\nu_H(1S_{1/2}-3S_{1/2})$	4 699 099(10)	2.2×10^{-6}
Berkeland *et al.*, 1995	Yale	$\nu_H(2S_{1/2}-4P_{1/2})-\frac{1}{4}\nu_H(1S_{1/2}-2S_{1/2})$	4 664 269(15)	3.2×10^{-6}
		$\nu_H(2S_{1/2}-4P_{3/2})-\frac{1}{4}\nu_H(1S_{1/2}-2S_{1/2})$	6 035 373(10)	1.7×10^{-6}
Hagley and Pipkin, 1994	Harvard	$\nu_H(2S_{1/2}-2P_{3/2})$	9 911 200(12)	1.2×10^{-6}
Lundeen and Pipkin, 1986	Harvard	$\nu_H(2P_{1/2}-2S_{1/2})$	1 057 845.0(9.0)	8.5×10^{-6}
Newton *et al.*, 1979	U. Sussex	$\nu_H(2P_{1/2}-2S_{1/2})$	1 057 862(20)	1.9×10^{-5}

Impacts


most accurate theory
H-spectroscopy
+
QED
electron g-2 (ion trap)
QED (unbound)
muon g-2
α
R∞
rP
e-p scattering
constant
10 973 731 568 527(73) m-1
10 973 731 568 150(16) m-1
muonic hydrogen

Implications

Now, we have a big trouble in atomic physics

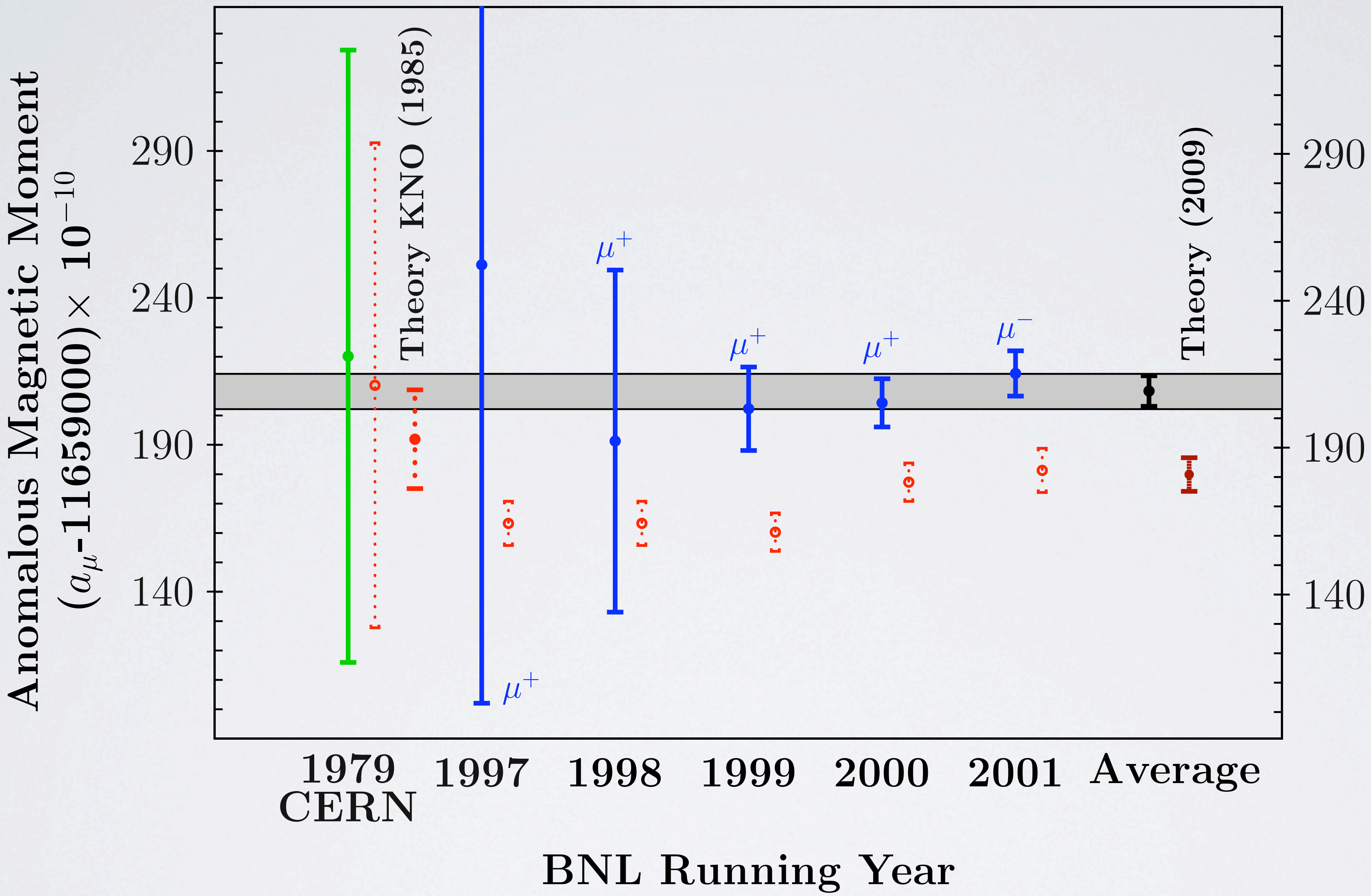
Some possible routes to the puzzle:

- Is QED wrong???
- Physics in very small scale (am 10^{-18}, zm 10^{-21})???
- Unexplored μ-p or e-p interaction???

Is there any sign shown in the past ?

Hint A:

IS MUON A FISHY PARTICLE?



Muon g-2 experiment is 3.2σ away from theory
Is muon fishy particle?

A POSSIBLE WAY TO SOLVE THE PUZZLE

If QED is the trouble maker, then we should find a system that tests QED only, without the nucleus size problem.

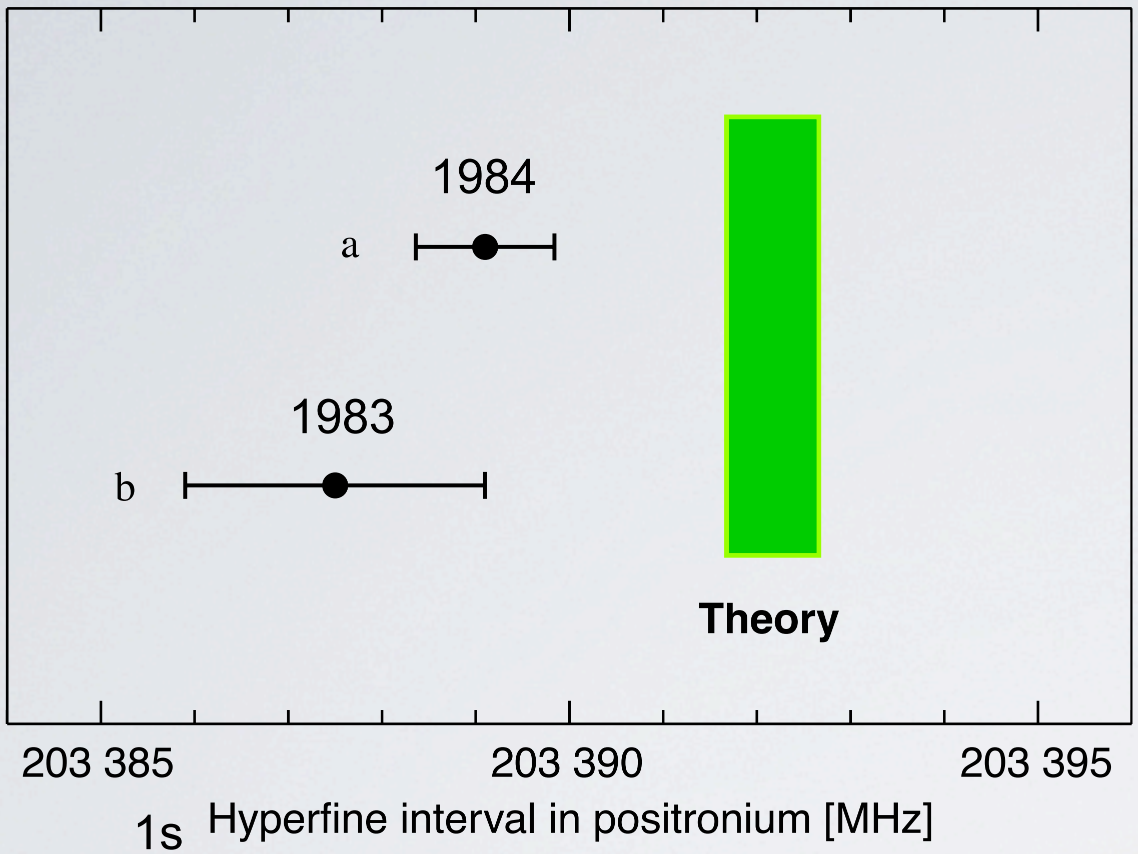
↓

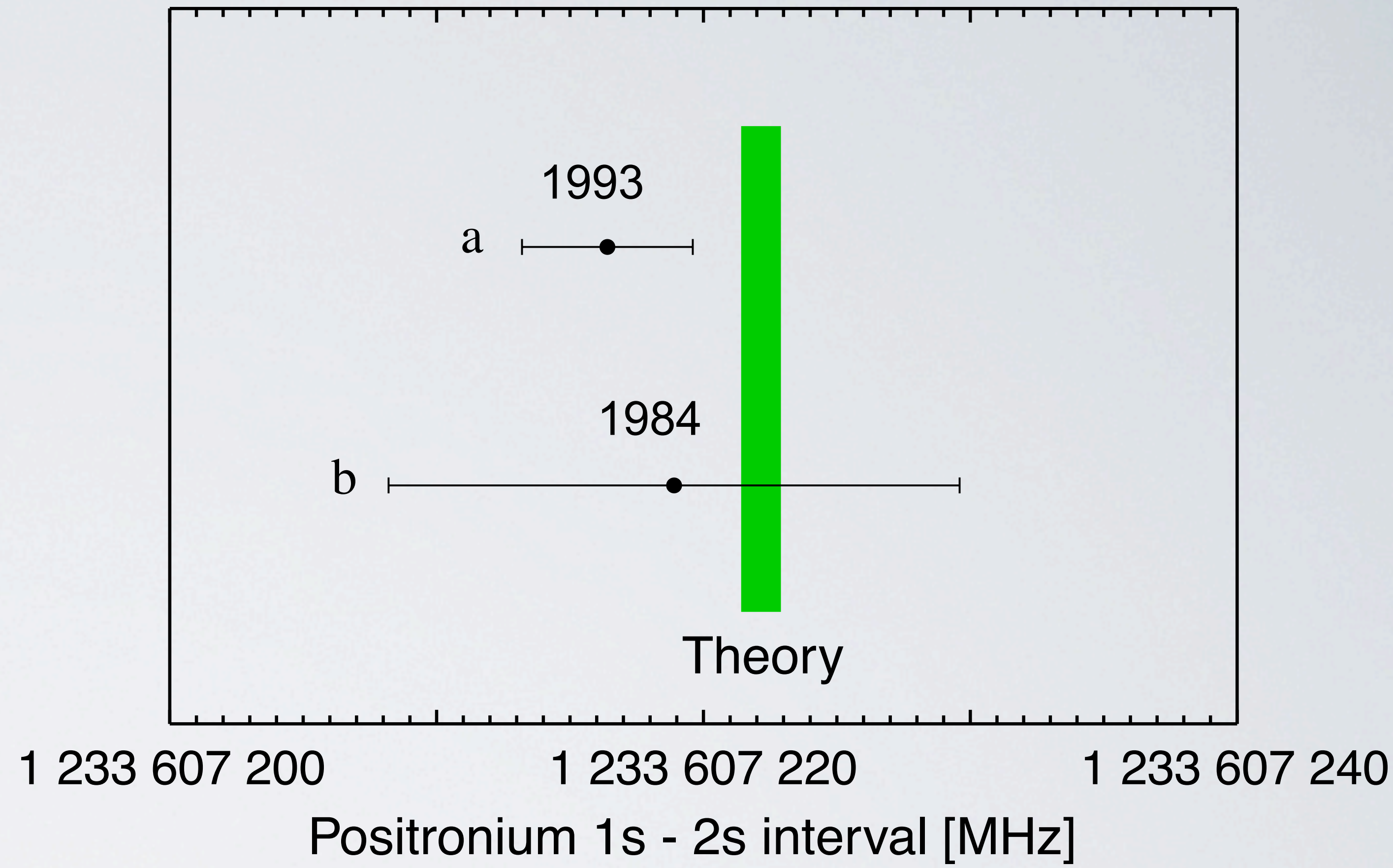
Purely leptonic system

↓

1. muonium → limited by the knowledge of muon mass m_μ/m_e
2. positronium → a forgotten one, no news for 15 years

Hint B: Laser spectroscopy of positronium





DISCREPANCIES IN THE POSITRONIUM SPECTROSCOPY

Do they tell us anything? Any clue to the puzzle from the anti-world?

Hint C:

A HINT
HOW ABOUT THE
CHARGE RADIUS DIFFERENCE

Absolute size:

μP: r_p=0.84184 fm

H : r_p=0.8768 fm

5σ away.......... **DISCREPANCY**

Proton-Deutron Size difference:

e-d scattering & μP→$r_d^2 - r_p^2 = (2.130)^2 - (0.84184)^2 = 3.828(24)$

H-D spectroscopy→$r_d^2 - r_p^2$ =3.82007(65)

0.3σ only! AMAZINGLY **AGREE**

Hint C:

ISOTOPE SHIFT & CHARGE DIFFERENCE

H-spectroscopy → ~~QED~~ + r_p

− D-spectroscopy → ~~QED~~ + r_d

Isotope shift → $r_d^2 - r_p^2$

The deduced radius difference is "almost" QED free
(QED plays no role here)

Absolute size, with QED → discrepancy
Size difference, without QED → agree

→ QED problematic ???

Future of the experiment

- Analysis other hyperfine transitions and muonic Deuterium.

- muonic helium (μHe^{+}) experiment (approved project, take data in 2013)

Few more thoughts after sometime

QED is not endangered by the proton 's size: A De Rújula - Physics Letters B, 2010

$$\Delta E_{ns} = -\frac{2\alpha Z}{3}\left(\frac{\alpha Z m_r}{n}\right)^3 \left[\langle r^2 \rangle - \frac{\alpha Z m_r}{2} \langle r^3 \rangle_{(2)} + (\alpha Z)^2 (F_{REL} + m_r^2 F_{NR}) \right],$$

$\Delta E = 209.9779(49) - 5.2262\, r_P^2 + 0.0347\, r_P^3$ meV

Zemach moment : Charge or Magnetic moment, form factor

Third Zemach moment of the proton: IC Cloet, GA Miller - Arxiv preprint arXiv:1008.4345, 2010

Re-analysis electron scattering world data to find more precise Zemach moment

Spectroscopy as a test of Coulomb's law - A probe of the hidden sector J Jaeckel, S Roy - Arxiv preprint arXiv:1008.3536v2, 2010

Is Coulomb's law valid in a very small scale?

"Soon it will be a flood wrong (theoretical)works."
--- a colleague

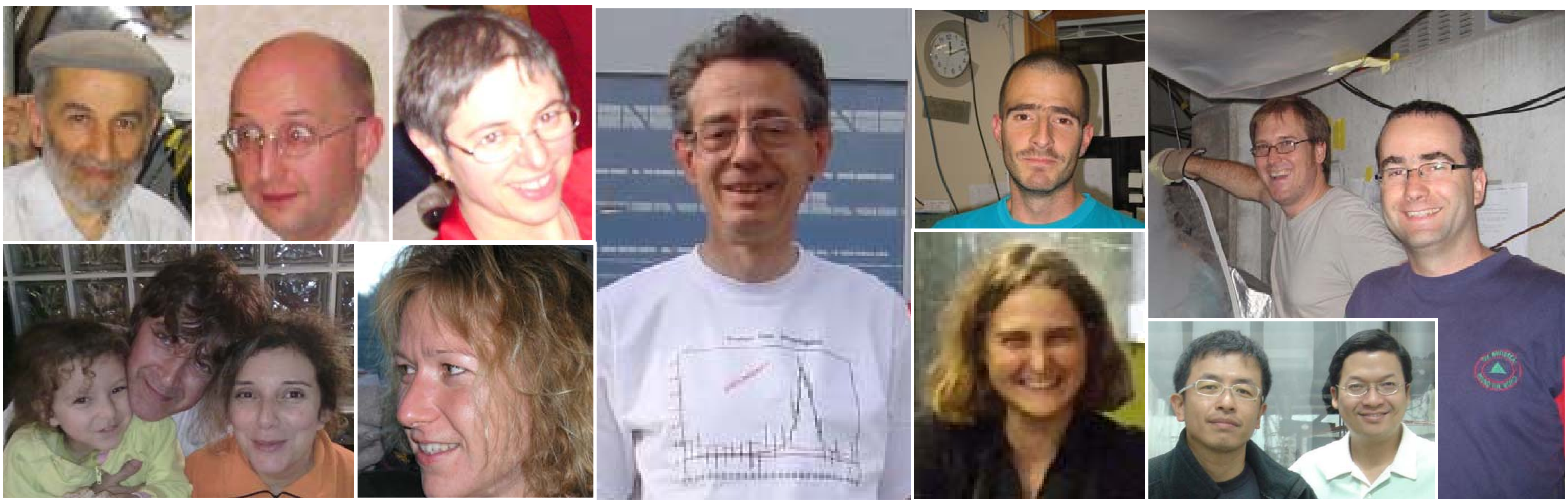
muonic hydrogen 2S Lamb shift Collaboration

----- 12 institutes from 6 countries

F.D Amaro, A. Antognini, F.Biraben, J.M.R. Cardoso, D.S. Covita, A. Dax, S. Dhawan, L.M.P. Fernandes, A. Giesen, T. Graf, T.W. Hänsch, P. Indelicato, L.Julien, C.-Y. Kao, P.E. Knowles, F. Kottmann, J.A.M. Lopes, E. Le Bigot, Y.-W. Liu, L. Ludhova, C.M.B. Monteiro, F. Mulhauser, T. Nebel, F. Nez, R. Pohl, P. Rabinowitz, J.M.F. dos Santos, L.A. Schaller, K. Schuhmann, C. Schwob, D. Taqqu, J.F.C.A. Veloso

http://muhy.web.psi.ch   http://www.lkb.ens.fr/-Metrologie-Quantique-

Proton Size Investigators thank you for your attention



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

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nature

OIL SPILLS
There's more to come

PLAGIARISM
It's worse than you think

CHIMPANZEES
The battle for survival

SHRINKING THE PROTON

New value from exotic atom trims radius by four per cent

$10.00US $12.99CAN

感謝

- 國家科學委員會的經費支持，特別是國際合作處的台瑞雙邊合作協議。

- 清華大學校方以及物理系的長期支持。