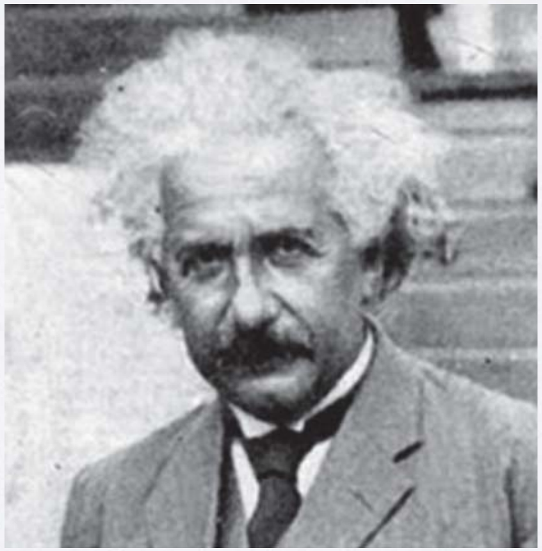
PRECISION MEASUREMENT AND FUNDAMENTAL PHYSICS

一句話惹毛物理學家大賽

什麼話?

這有什麼應用?



2012年七月四日
瑞士日內瓦的大型重子對撞機LHC
找到了可能的上帝粒子-希格子

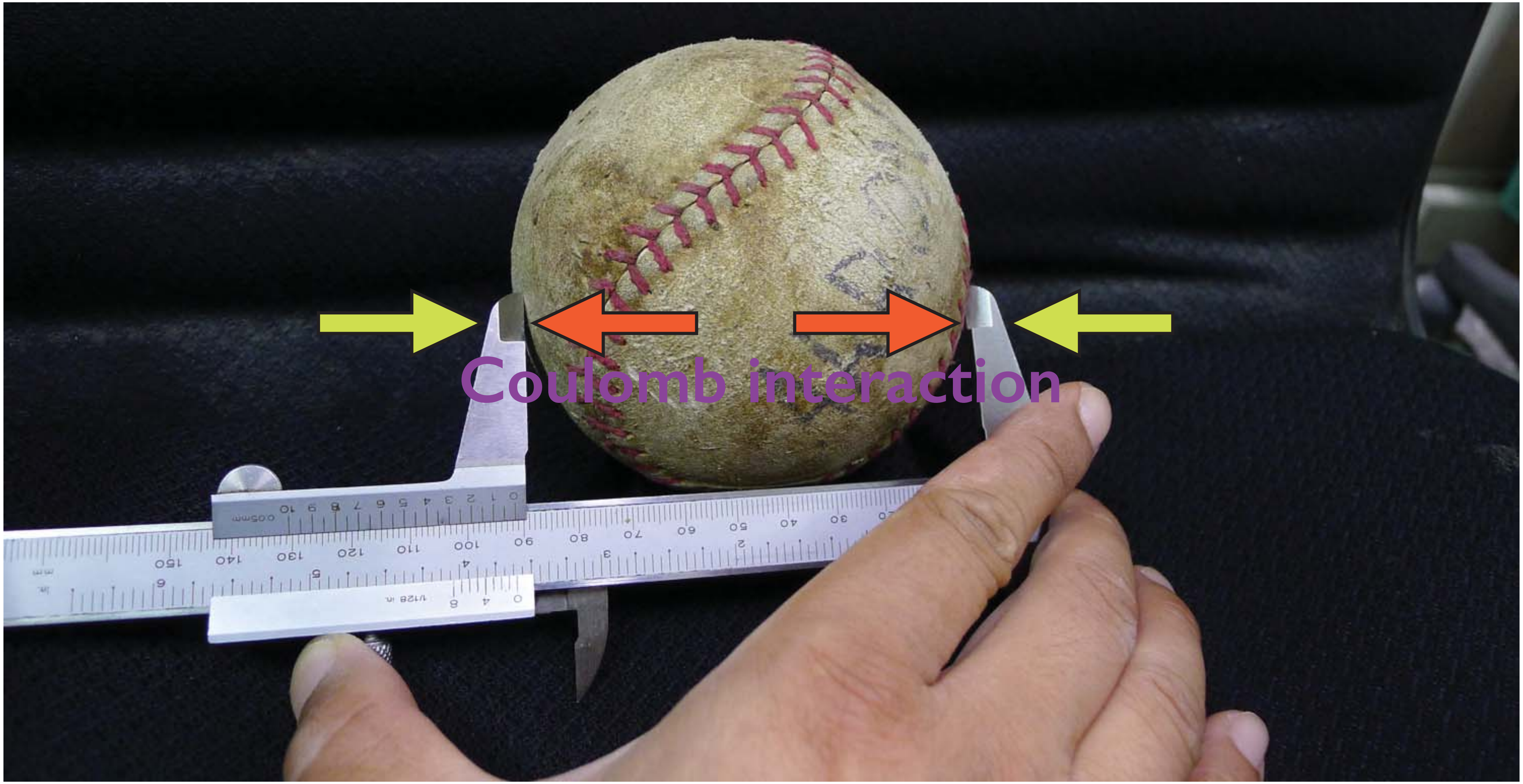
現今主宰物理學的“標準模型”
獲得了極重要驗證

物理學已經到了它完成的時候嗎?
任何的“新物理”已經不再可能嗎?

也許...，也許不...

What is “SIZE”

Distribution of charge density $r_E^2 = \int d^3r\, r^2 \rho(\boldsymbol{r})$



2S-3S two-photon transitions of atomic lithium

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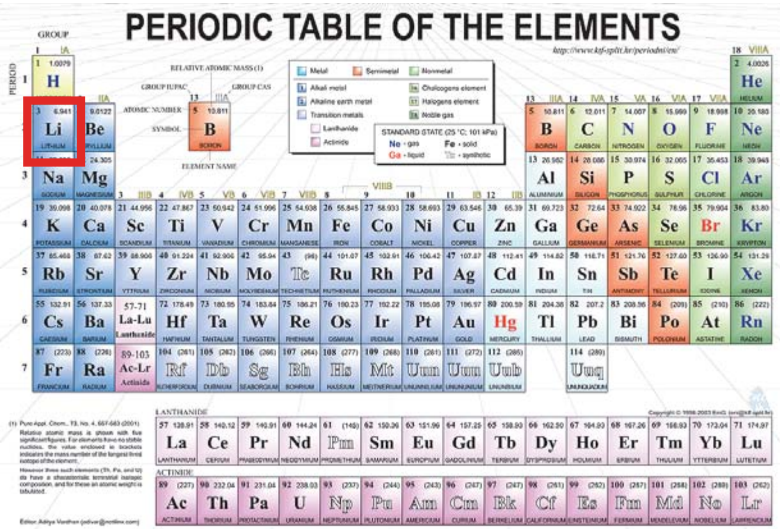
Electron as a probe to nuclear structure

- Two approaches to detect of nuclear structure (size: charge distribution)
- Scattering: model-dependent
- spectroscopy: high precision transition energy measurement.

Why lithium?

Only 3 elements (H, He, Li) that we, physicists, fully understand



- The "simplest" "complicated" atomic system
- Many isotopes, various nuclei with the same electronic structure (^{6,7,8,9,11}Li)

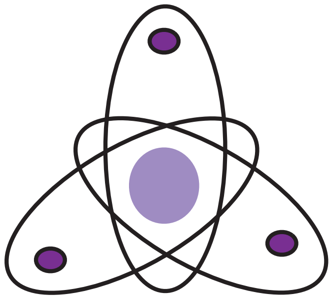
3 electrons + 1 nuclear= 4 body system

It can be calculated, but not trivial

Recently, the electronic wave function has been constructed using "Hylleraas coordinates" (Yan & Puchalski)

Isotope shift (stable ^{6,7}Li) can be utilized to study nuclear structure

Theoretical background



Lithium

$$E = [\mathcal{E}_{NR}^{(0)} + \lambda\mathcal{E}_{NR}^{(1)} + \lambda^2\mathcal{E}_{NR}^{(2)}] + [\alpha^2(\mathcal{E}_{R}^{(0)} + \lambda\mathcal{E}_{R}^{(1)})]$$
$$+ [\alpha^3(\mathcal{E}_{QED}^{(0)} + \lambda\mathcal{E}_{QED}^{(1)}) + \alpha^4(\mathcal{E}_{HO}^{(0)} + \lambda\mathcal{E}_{HO}^{(1)})]$$
$$+ [\bar{r}_c^2(\mathcal{E}_{NU}^{(0)} + \lambda\mathcal{E}_{NU}^{(1)})]$$

λ : mass factor

High order QED term

charge radius term

Transition energy = QED + Nuclear Structure

Isotope Shift

$$\Delta E(B-A) = \lambda_-[\mathcal{E}_{\rm NR}^{(1)} - \mathcal{E}_{\rm NR}^{(0)} + \lambda_+(\mathcal{E}_{\rm NR}^{(2)} - \mathcal{E}_{\rm NR}^{(1)}) + \alpha^2(\mathcal{E}_{\rm rel}^{(1)} - \mathcal{E}_{\rm rel}^{(0)}) + \alpha^3(\mathcal{E}_{\rm QED}^{(1)} - \mathcal{E}_{\rm QED}^{(0)}) + \alpha^4(\mathcal{E}_{\rm ho}^{(1)} - \mathcal{E}_{\rm ho}^{(0)})] + (\bar{r}_{c,B}^2 - \bar{r}_{c,A}^2)\mathcal{E}_{\rm nuc}^{(0)},$$

nuclear-related Energy shift

Mass effect

Size effect

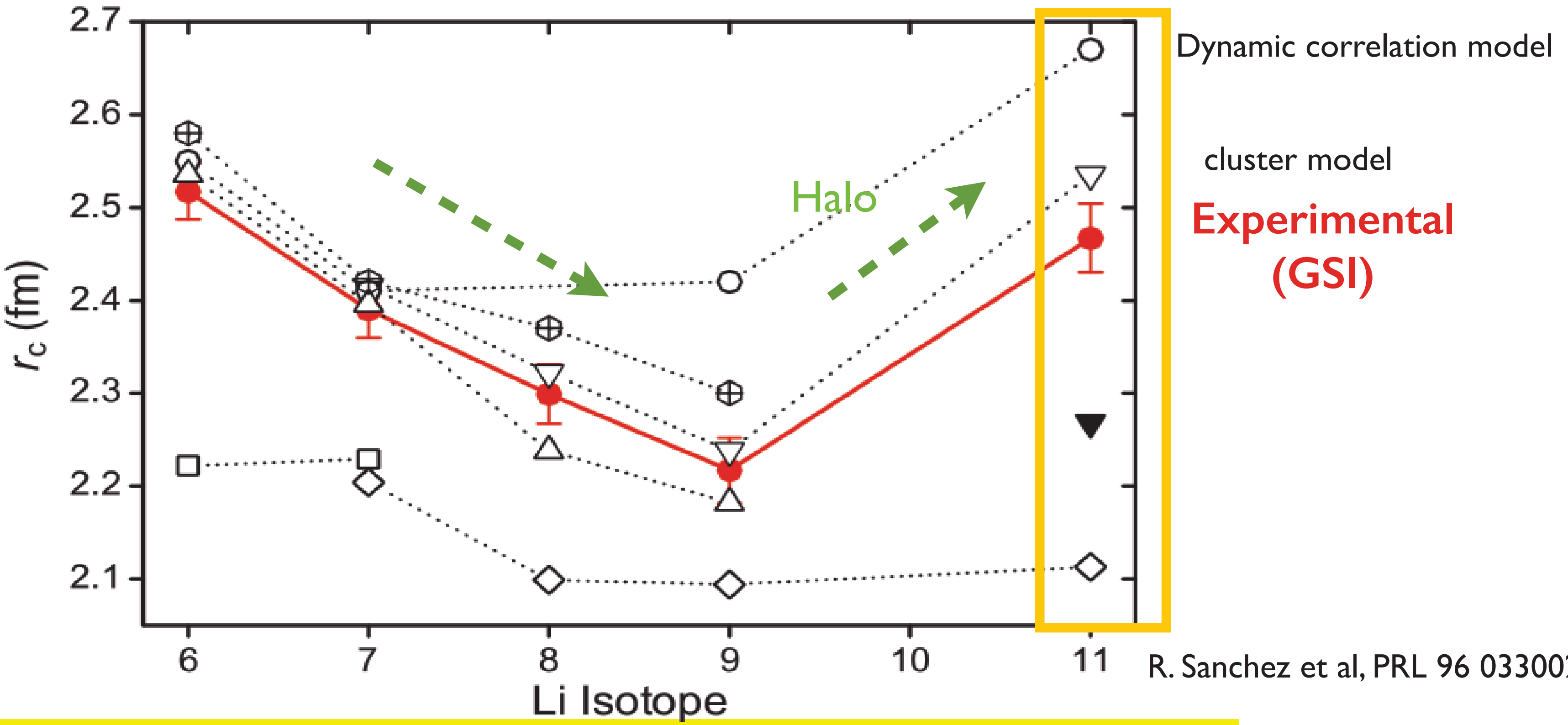
Few kHz contribution

Absolute transition energy → Higher order bound QED test(ε_{HO})

Isotope shift (relative) → charge radius difference

$$\delta\langle r_c^2\rangle = \langle r_c^2(^6\mathrm{Li})\rangle - \langle r_c^2(^7\mathrm{Li})\rangle = \frac{\Delta\nu_{exp} - \Delta\nu_{theo}}{C_{2S-3S}}$$

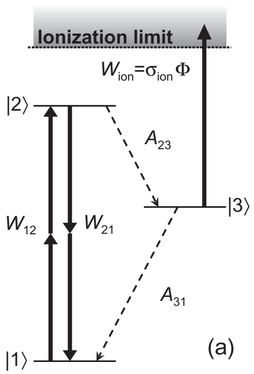
Halo nuclear of ^{11}Li



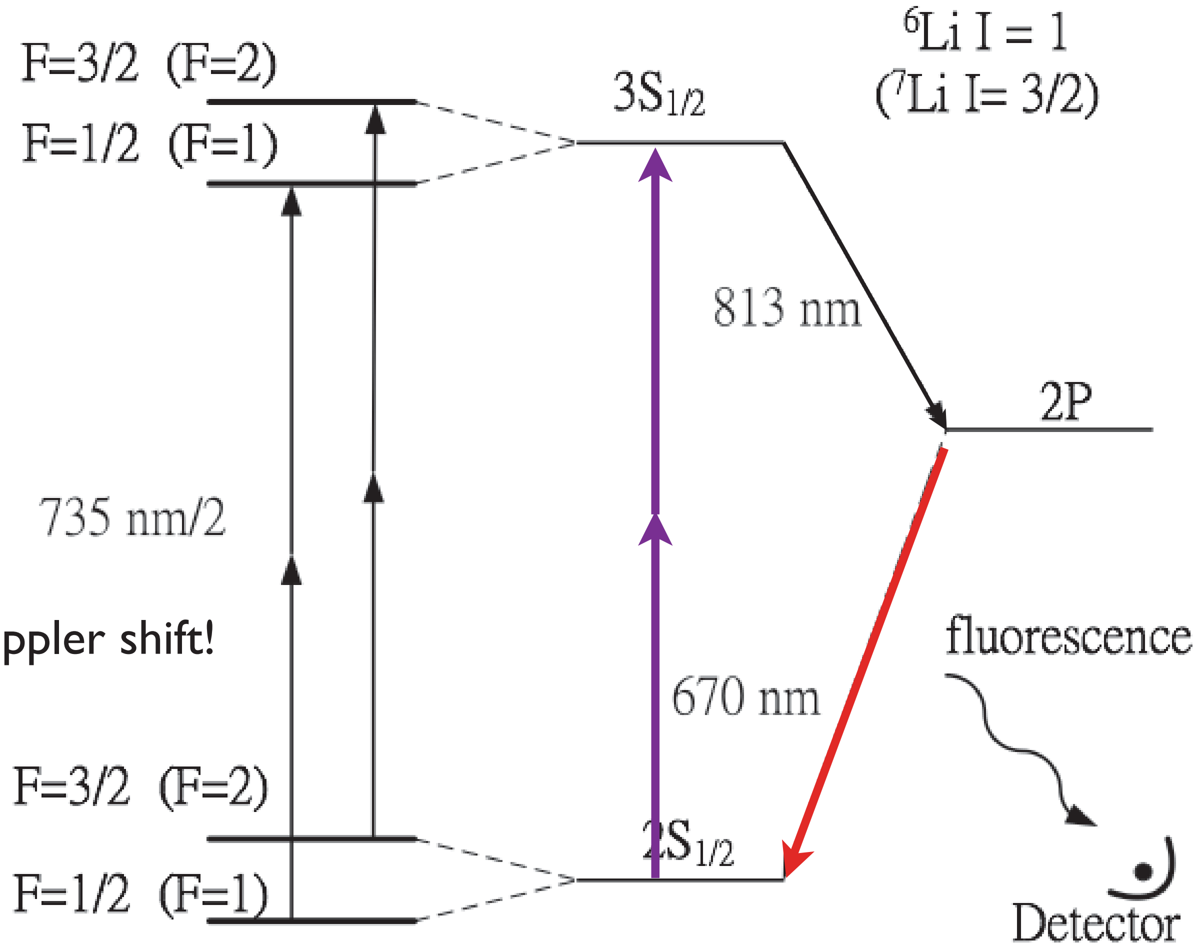
R. Sanchez et al, PRL 96 033002

- Theory or experiment?
- Naturally occurred ^{6,7}Li can be used for a test with a high precision

Partial Energy level of lithium



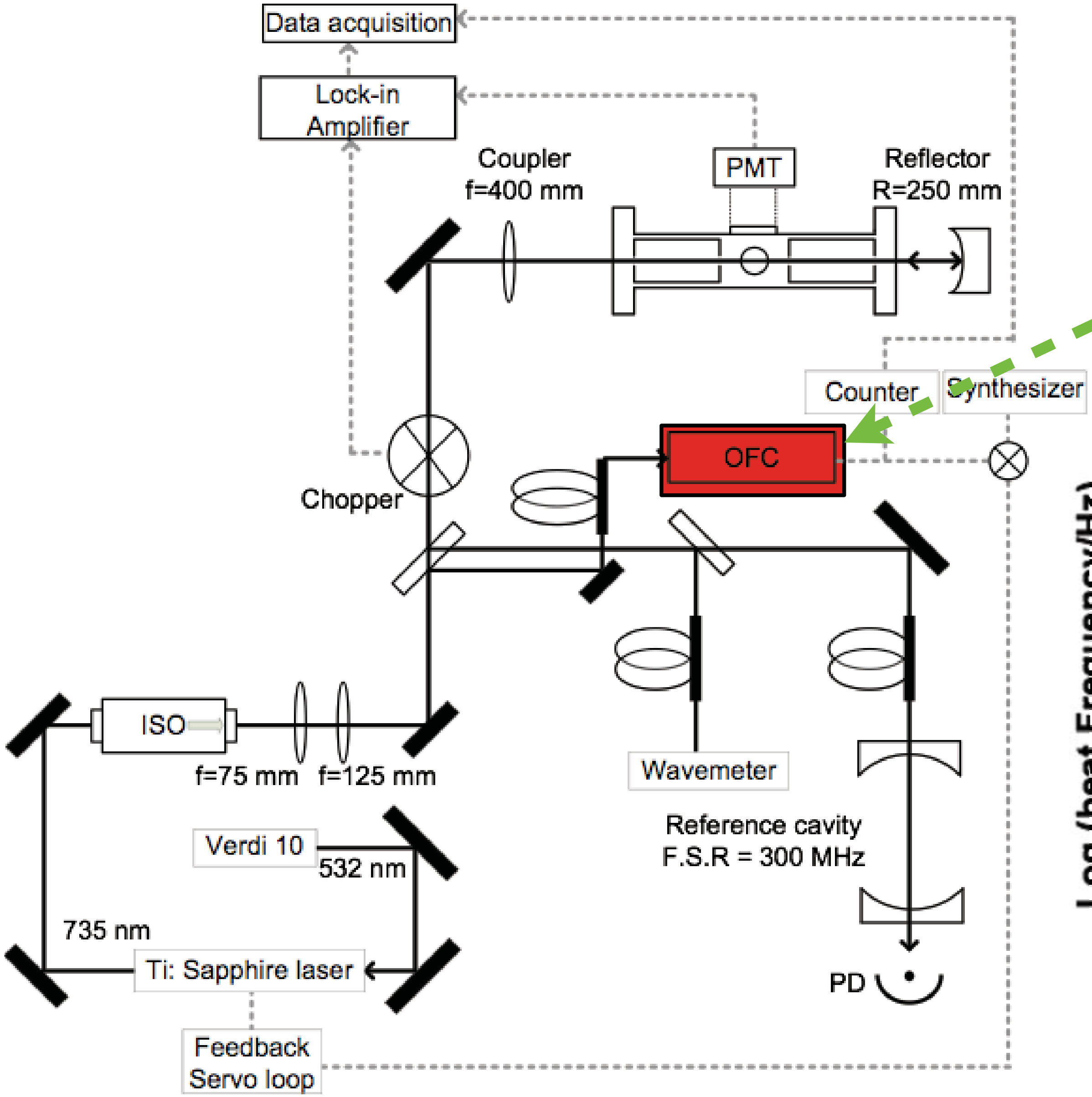
GSI experiment
(laser ionization)



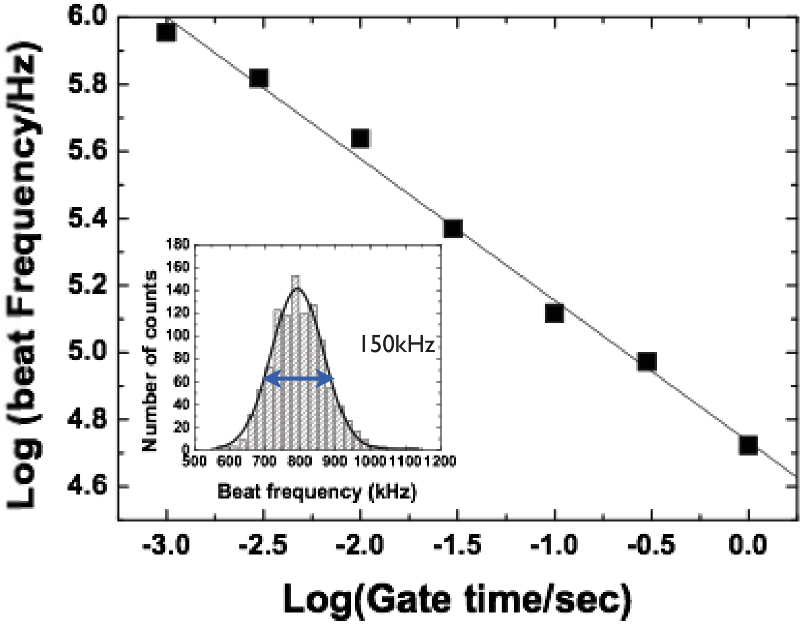
Two-photon transition

Free from the first order Doppler shift!

Spectroscopy with Optical Frequency Comb



Link to Cs clock (primary standard) on satellite

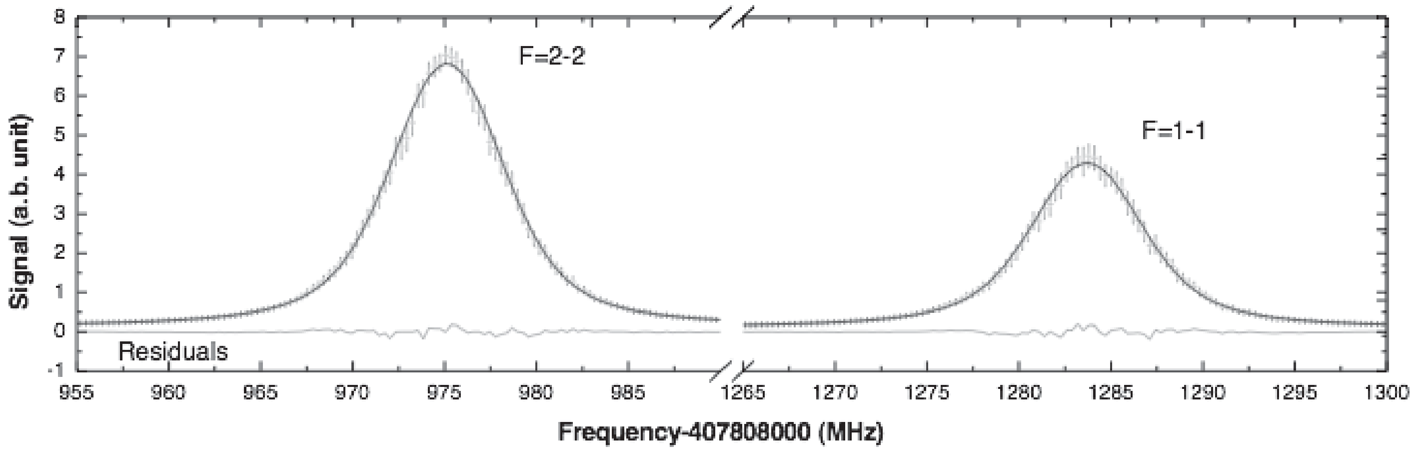


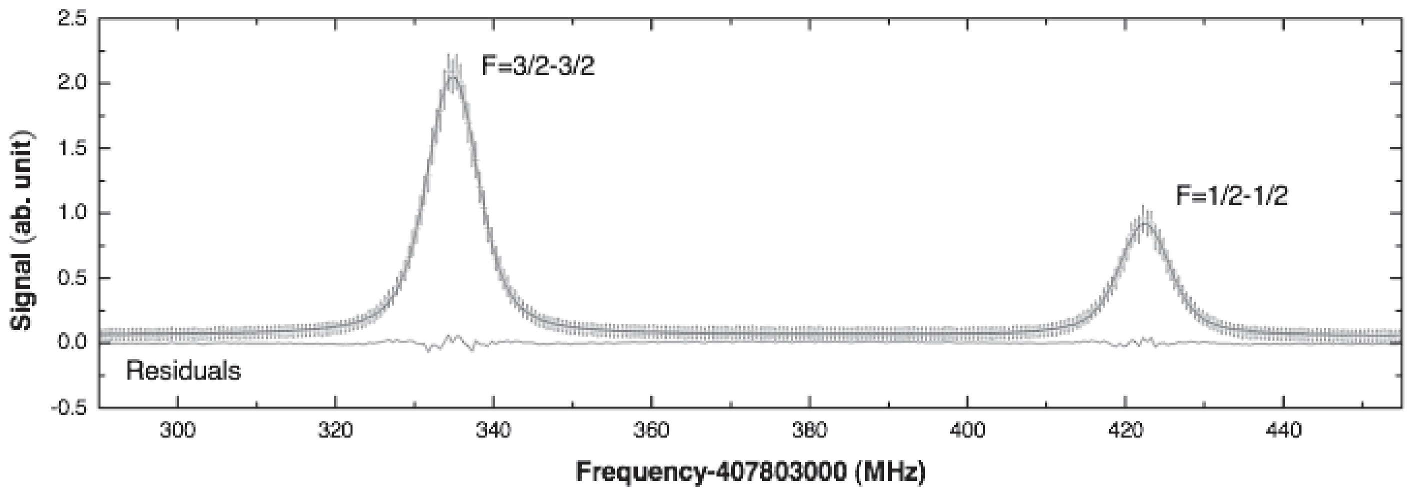
This set the ultimate limitation of our accuracy ,σ=75 kHz.

Li 2s-3s spectrum

High signal rate, low laser intensity, more symmetrical

(No complicated model is needed, **less systematic error**)





Systematic effects and uncertainty

Correction for the AC Stark shift

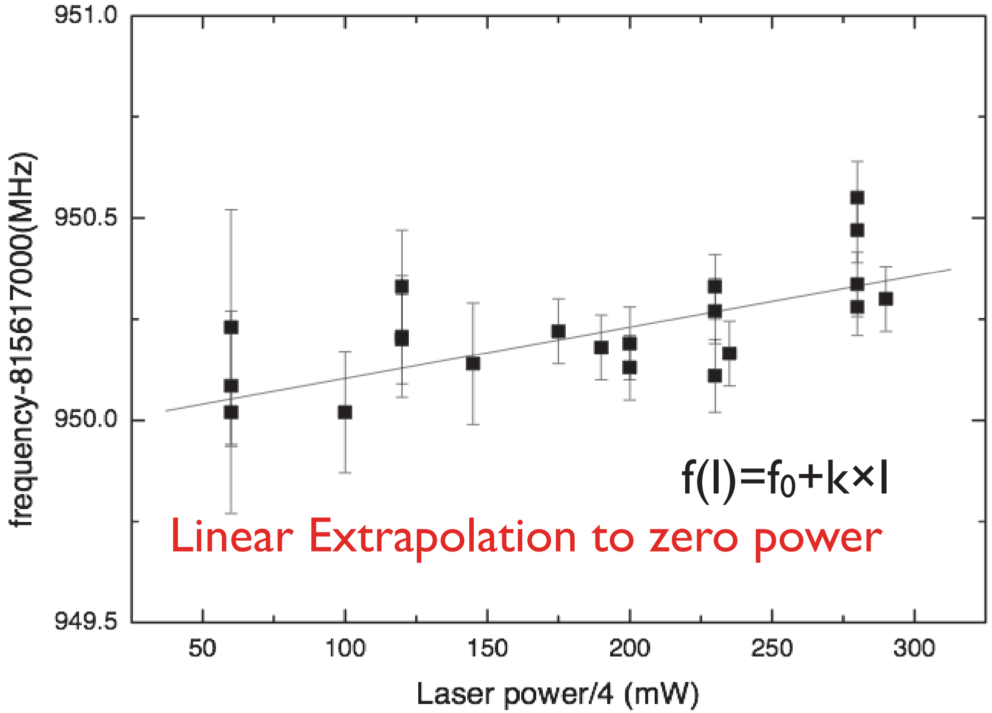


TABLE I. The uncertainty budget of the absolute frequency measurement

Effect (source)	(MHz)
Statistic	$0.08 \sim 0.32$
AC Stark shift (intensity fluctuation)	< 0.02
First order Doppler (beam collinearity)	0.088
Frequency comb	< 0.005
Second order Doppler (velocity of atom)	negligible
Total	$0.1 \sim 0.33$

Final accuracy is limited by the laser linewidth (σ=75 kHz)

Results

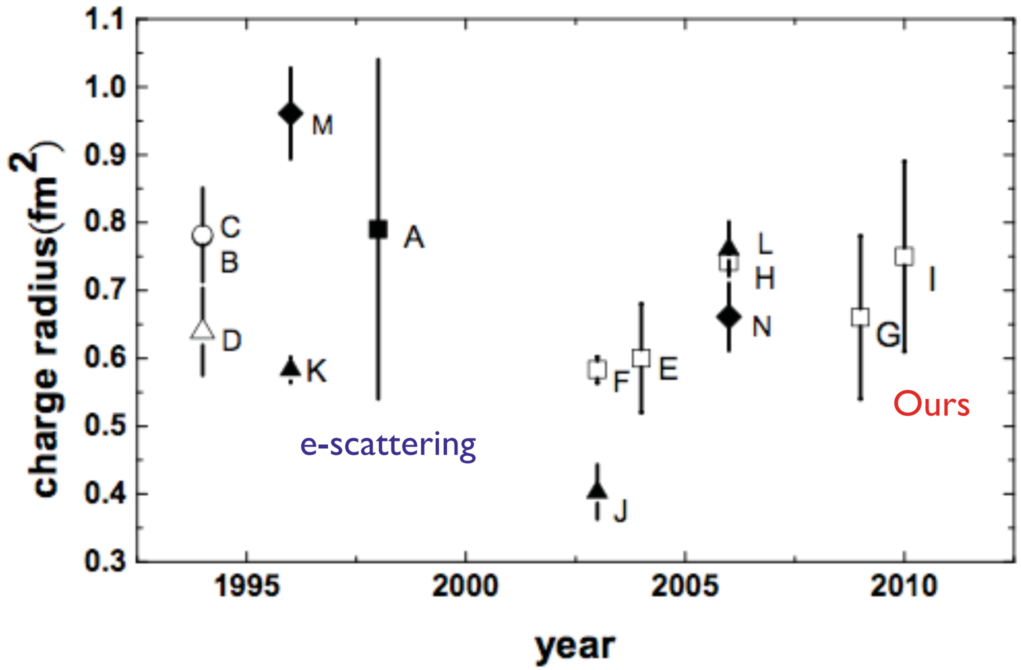
Isotope		Frequency (MHz)	Ref.
^{7}Li	F = 2–2	815 617 949.98(10)	this work
	F = 1–1	815 618 567.23(14)	this work
	C. G.	815 618 181.45(8)	this work
		815 618 181.57(18)	[13]
		815 618 185.2(30)	[12]
	theory	815 618 149.0(300)	[3]
		815 618 170.0(180)	[4]
^{6}Li	F = 3/2–3/2	815 606 668.99(22)	this work
	F = 1/2–1/2	815 606 844.40(33)	this work
	C. G.	815 606 727.46(18)	this work
		815 606 727.71(24)	[13]
		815 606 731.4(30)	[12]
	Isotope Shift	−11 453.99(19)	this work
		−11 453.85(19)	[13]
		−11 453.734(30)	[12]
		−11 453.983(20)	[2]
		−11 453.95(13)	[15]

suspicious!?

1. improved by a factor of 2.5
2. The accuracy is much better than theory, whose higher order QED calculation should be improved
3. Isotope shift in agreement with previous measurement

Charge radius difference (^{7}Li-^{6}Li)

The comparison of the measurements with various transitions



Method	$\Delta\gamma_c^2$(fm^2)	Reference
Electron scattering	-0.79(25)	[13]
$Li^+(2^3s_1 - 2^3p_0)$	-0.779(57)	[14]
$Li^+(2^3s_1 - 2^3p_1)$	-0.782(69)	[14]
$Li^+(2^3s_1 - 2^3p_2)$	-0.639(64)	[14]
$Li(2^2s_{1/2} - 3^2s_{1/2})$	-0.60(8)	[8]
	-0.583(19)	[3]
	-0.66(12)	[1]
	-0.742(12)	[12]
	-0.75(14)	This work
$Li(2^2s_{1/2} - 2^2p_{1/2})$	-0.403(40)	[3]
	-0.583(19)	[15]
	-0.761(40)	[16]
$Li(2^2s_{1/2} - 2^2p_{3/2})$	-0.961(67)	[15]
	-0.661(50)	[16]

It is hard to say that the measurements are converged

- The accuracy of the absolute transition energy of atomic lithium 2s-3s has been improved.
- Higher order theoretical calculation is required for testing QED with the experimental results.
- The resulted charge radius difference is consistent with most of previous measurements. Certain suspicious measurement should be ruled out.

Prospect on Charge radius measurement of atomic lithium

$$\delta\langle r_c^2\rangle = \langle r_c^2(^6\text{Li})\rangle - \langle r_c^2(^7\text{Li})\rangle = \frac{\Delta\nu_{exp} - \Delta\nu_{theo}}{C_{2S-3S}}$$

Transition	$\delta\nu_{jk}$ (MHz)	δE_{jk} (MHz)	C_{jk}
$Li^+(2\,^3S_1$-$2\,^3P_0)$	34747.73±0.55	34740.17±0.03	9.705
$Li^+(2\,^3S_1$-$2\,^3P_1)$	34747.46±0.67	34739.87±0.03	
$Li^+(2\,^3S_1$-$2\,^3P_2)$	34748.91±0.62	34742.71±0.03	
$Li(2\,^2S_{1/2}$-$3\,^2S_{1/2})$	11453.95±0.13	11453.01±0.06	1.566
	11453.734±0.030		
$Li(2\,^2S_{1/2}$-$2\,^2P_{1/2})$	10533.160±0.068	10532.17±0.07	2.457
	10533.13±0.15		
	10534.039±0.070		
$Li(2\,^2S_{1/2}$-$2\,^2P_{3/2})$	10534.93±0.15	10532.57±0.07	2.457
	10534.194±0.104		

Method	$\Delta\gamma_c^2(\text{fm}^2)$	Reference	
Electron scattering	-0.79(25)	[13]	
$Li^+(2^3s_1 - 2^3p_0)$	-0.779(57)	[14]	
$Li^+(2^3s_1 - 2^3p_1)$	-0.782(69)	[14]	?????
$Li^+(2^3s_1 - 2^3p_2)$	-0.639(64)	[14]	
$Li(2^2s_{1/2} - 3^2s_{1/2})$	-0.60(8)	[8]	
	-0.583(19)	[3]	
	-0.66(12)	[1]	
	-0.742(12)	[12]	
	-0.75(14)	This work	YW
$Li(2^2s_{1/2} - 2^2p_{1/2})$	-0.403(40)	[3]	
	-0.583(19)	[15]	
	-0.761(40)	[16]	LB
$Li(2^2s_{1/2} - 2^2p_{3/2})$	-0.961(67)	[15]	
	-0.661(50)	[16]	

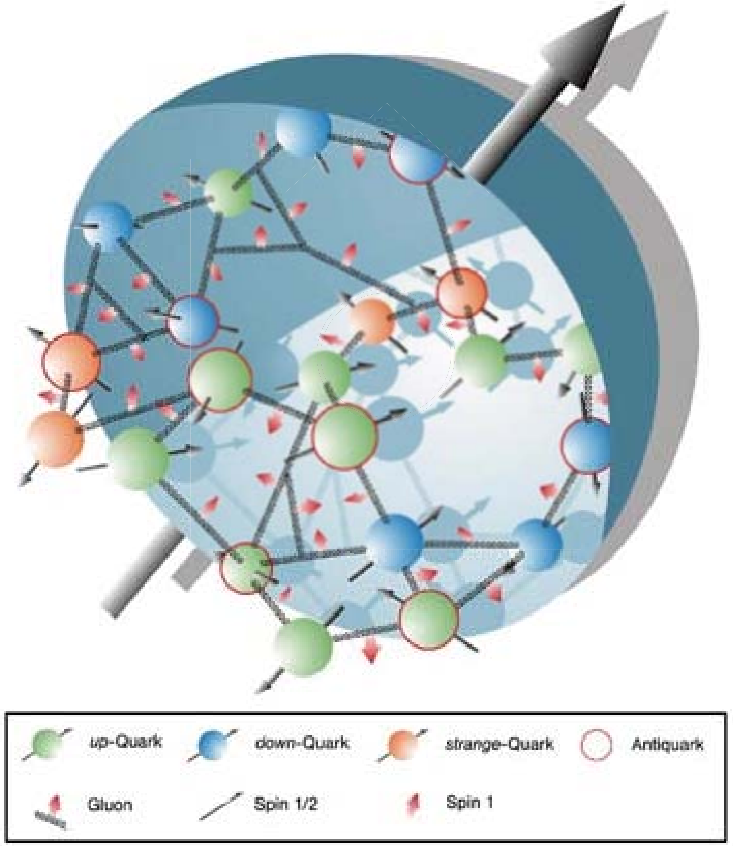
Precision Laser Spectroscopy of muonic atom

質子 Proton
Size does matter!

所有物質的主要組成p, n, e。
但我們真的了解質子嗎?

Charge radius: 0.877 (7) fm
Magnetic radius: 0.867(28) fm

對它的大小的了解是探知其
內部結構的第一步



量測質子大小的兩種傳統方法

- H-spectroscopy: 一般氫原子光譜。量測電子能量，就可以得到質子的相關特性。
  r_E=0.8775(51) fm(飛米)

- e-p scattering: 電子散射：電子轟擊質子，以其散射分布狀況推算質子大小。 r_E=0.879 (9) fm(飛米)

1飛米=0.000000000000001公尺

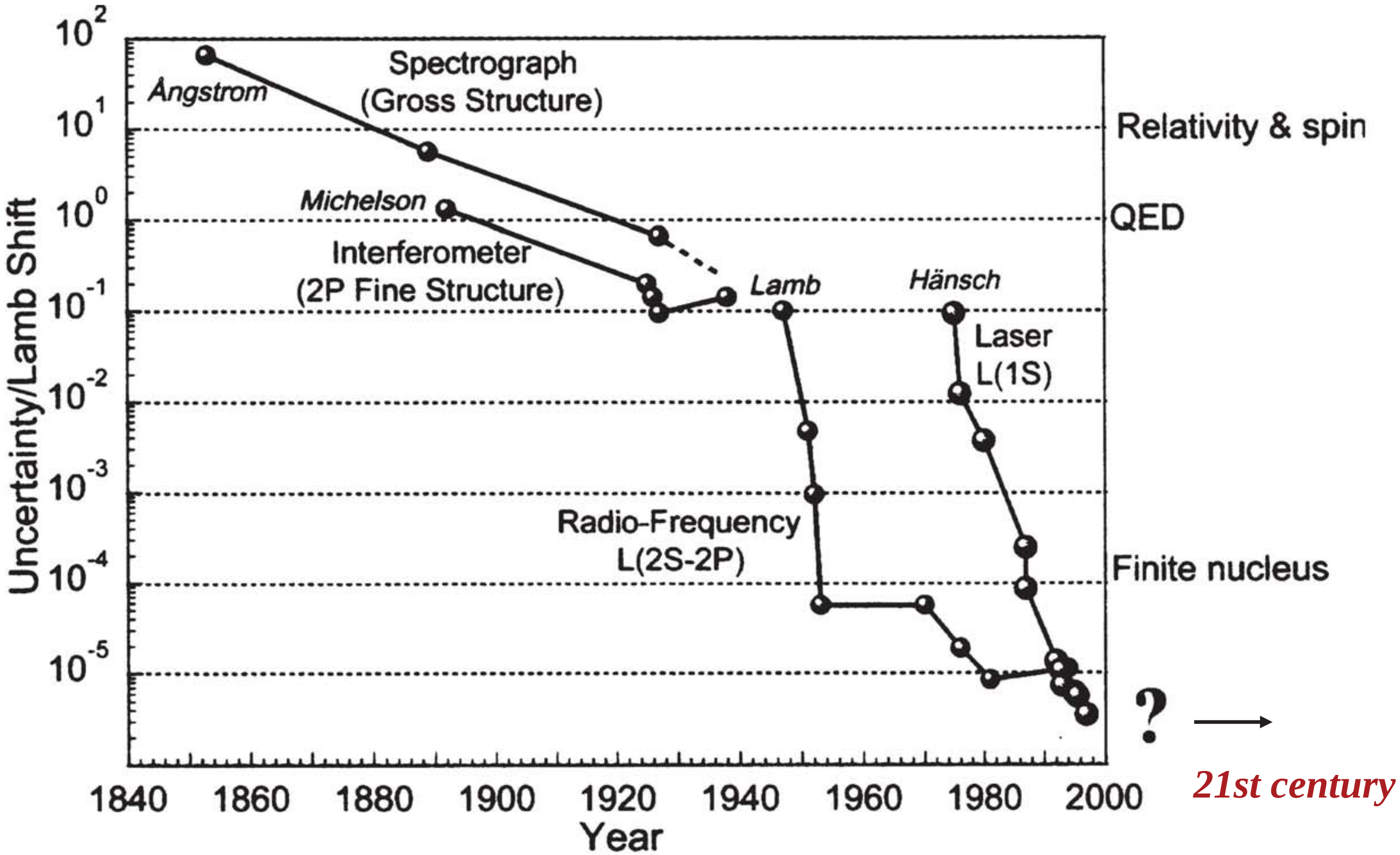
質子相對於氫原子
只是在巨蛋裡飛翔的小瓢蟲

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

150年來的氫原子光譜量測



氫原子的超精確頻率量測

The flagship of the precision measurement

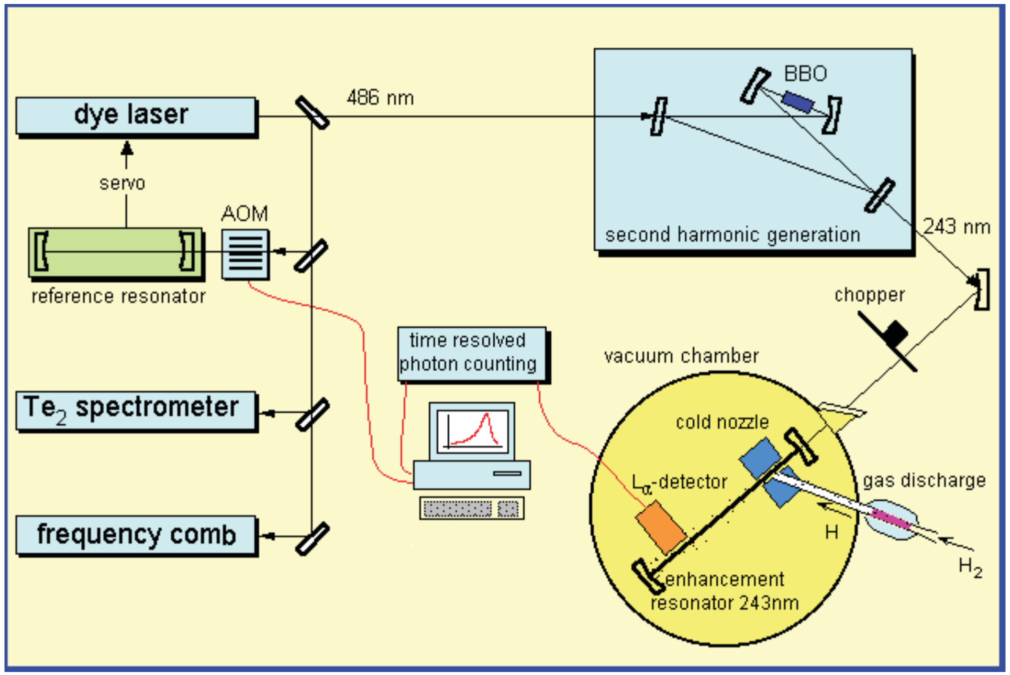
$$f(1S-2S) = 2\,466\,061\,413\,187\,074(34)\ \mathrm{Hz}$$

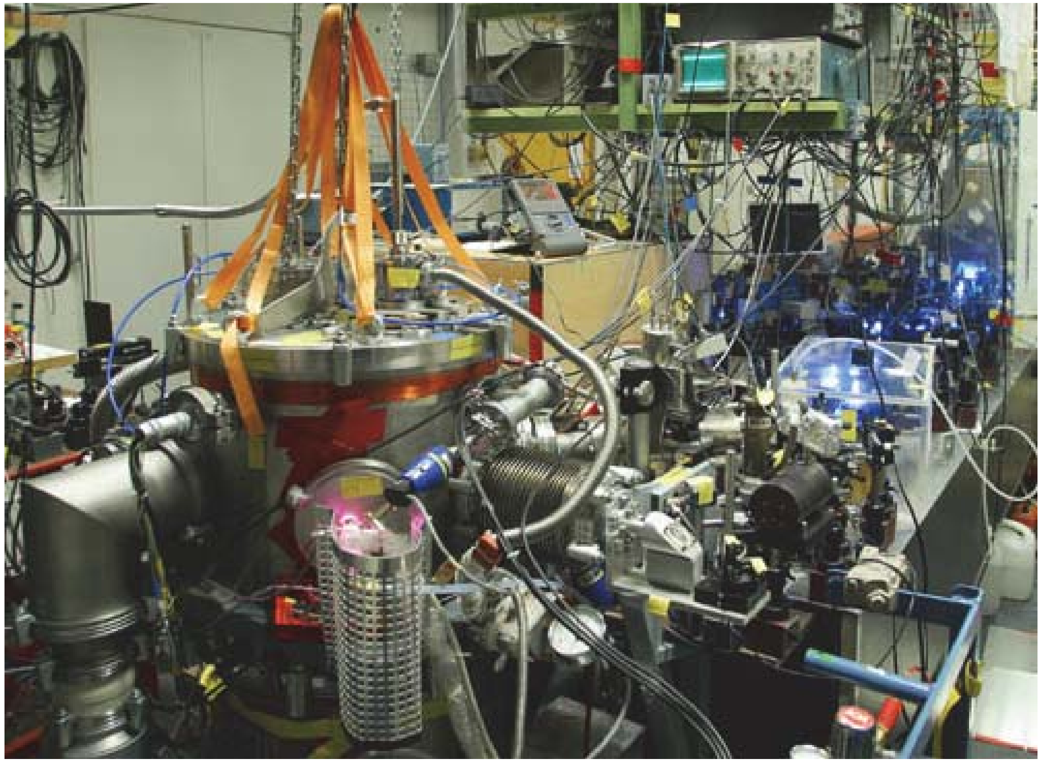
1.4×10^{14}

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

By T. Hansch

(Max-Planck-Institut für Quantenoptik)





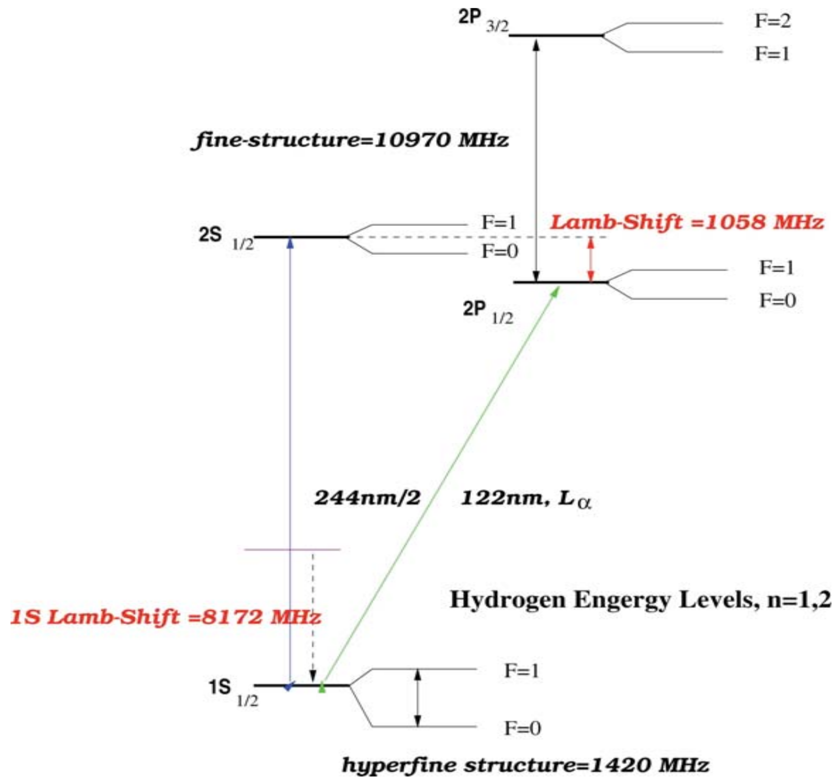
Test Bound QED

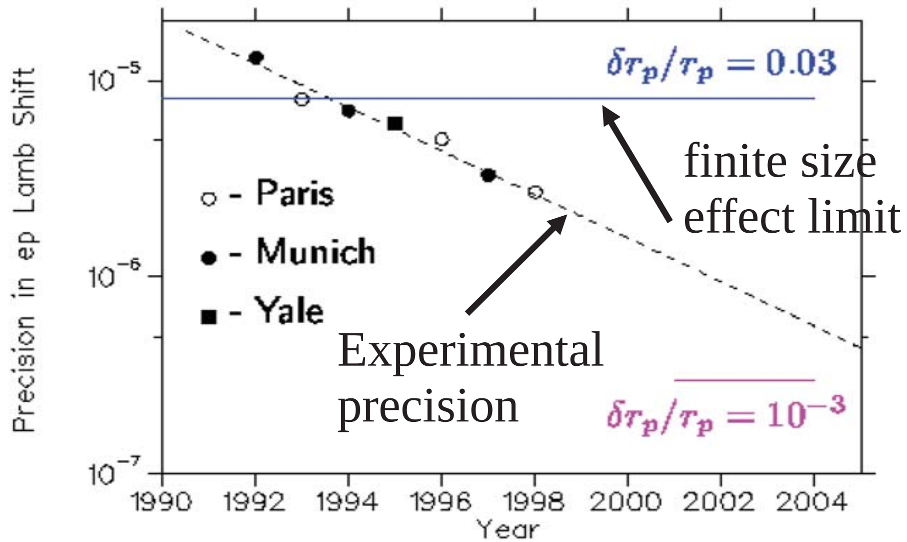
using the simplest atomic system

氫原子(ep) 1S-2S躍遷中的

1S Lamb Shift (所有能階中最大):

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





QED test and RMS of the proton charge radius

H spectroscopy become a precision measurement of proton size

Recognized value of proton charge radius

The Committee on Data for Science and Technology

- H-spectroscopy (CODATA): 0.8775±0.0051 fm
- Electron-proton scattering : 0.897 ± 0.018 fm

- 0.8% accuracy *Can we do it better?*

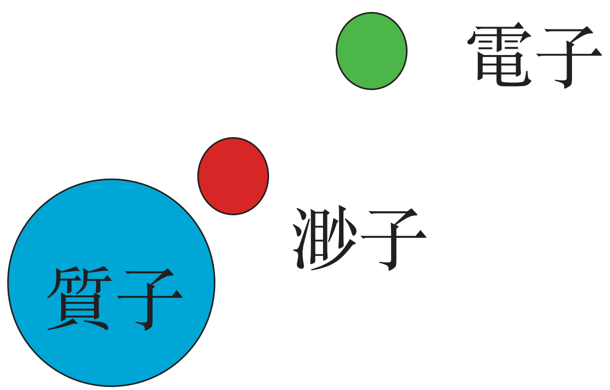
What is muonic hydrogen?

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 **atoms beyond periodic table**

渺子氫原子： Muonic Hydrogen: $\mu^- P^+$

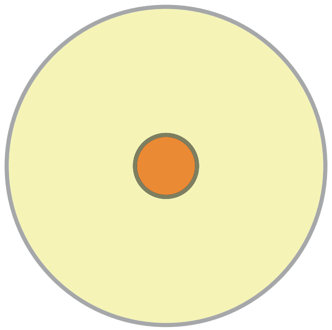
$M_\mu=200M_e$
$\tau_\mu=2.2\mu s$



渺子氫原子

Lamb shift and r_P

S state



Electron

Muon

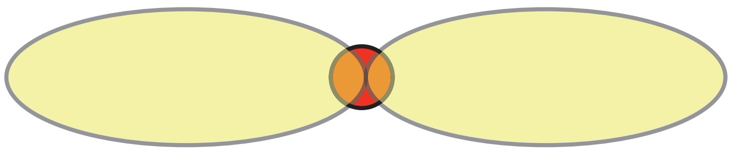
$r_{ep} \sim 5{\cdot}10^{-11}$ m $\qquad r_{\mu p} \sim 3{\cdot}10^{-13}$ m

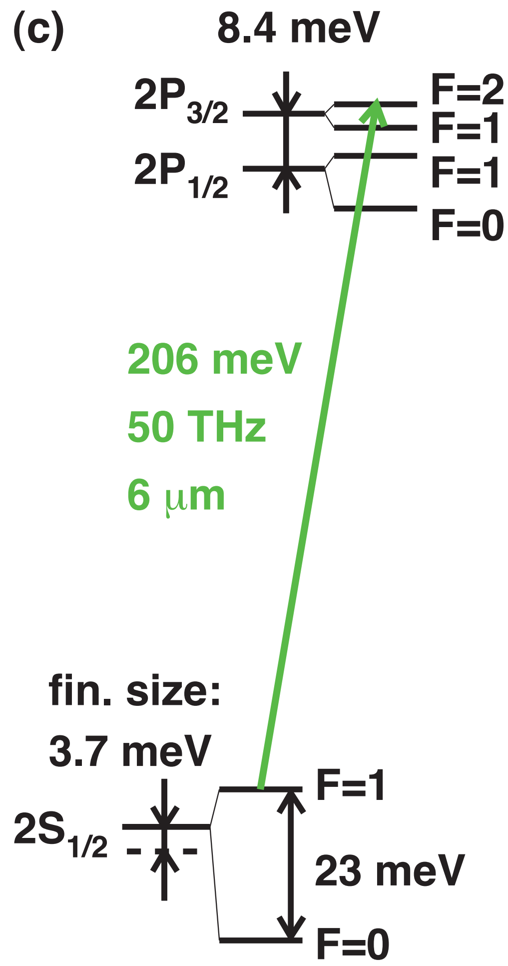
$r_p \sim 10^{-15}$ m

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

More sensitive to the structure of proton !!!!

P state

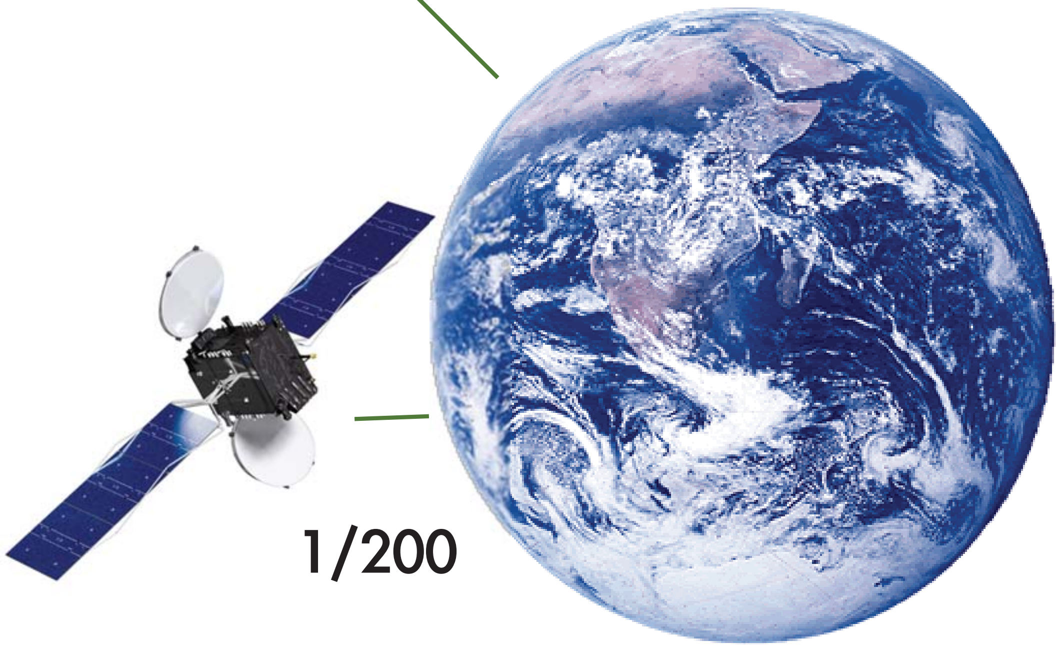




$$\Delta E = 209.9779(49) - 5.2262\, r_P^2 + 0.0347\, r_P^3 \text{ meV}$$

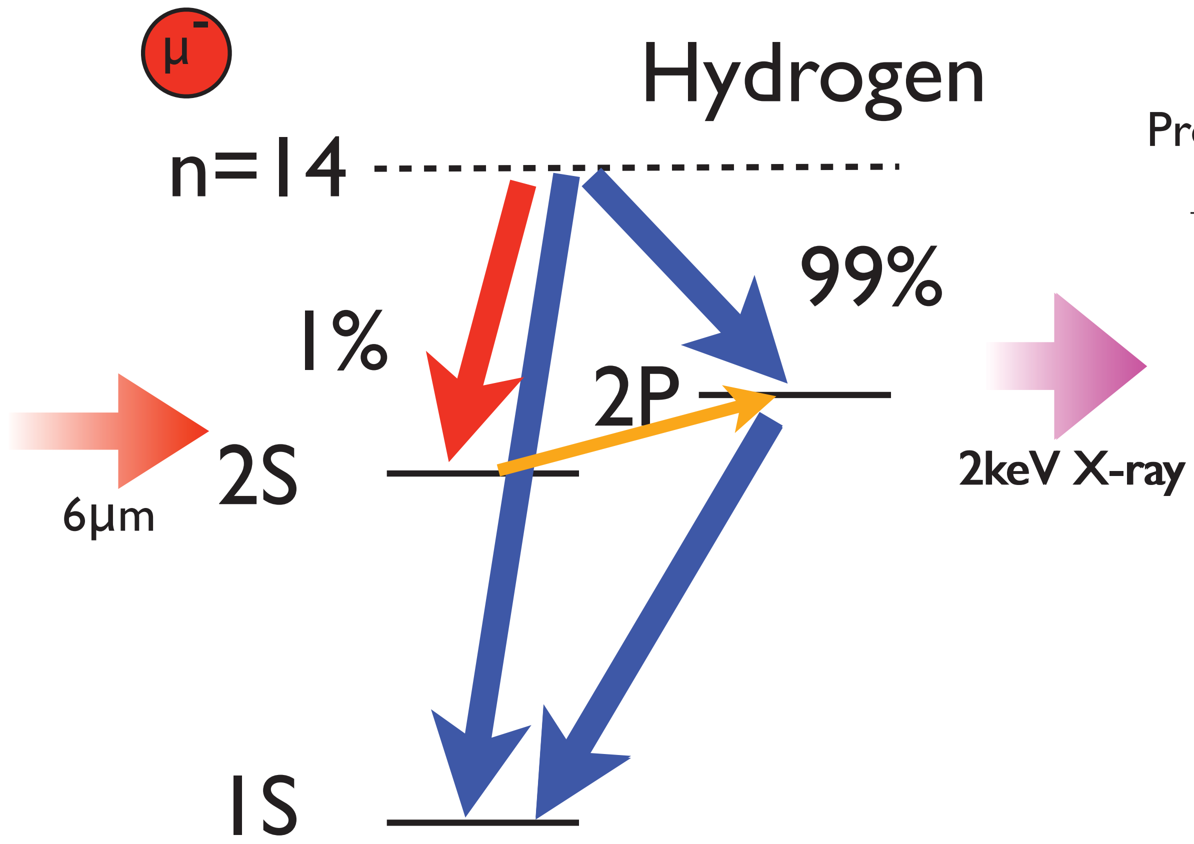
為甚麼是渺子氫原子？

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。

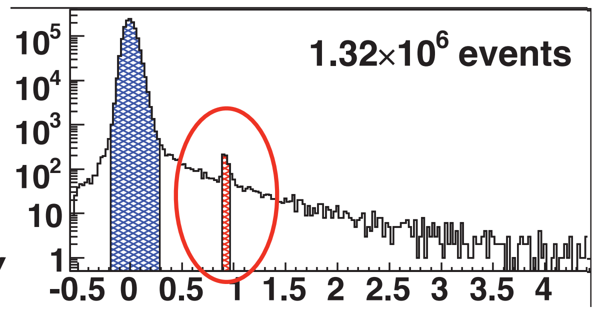


Principle

Cascade and detection mechanism



Prompt X-ray



Signal!!!

delay X-ray

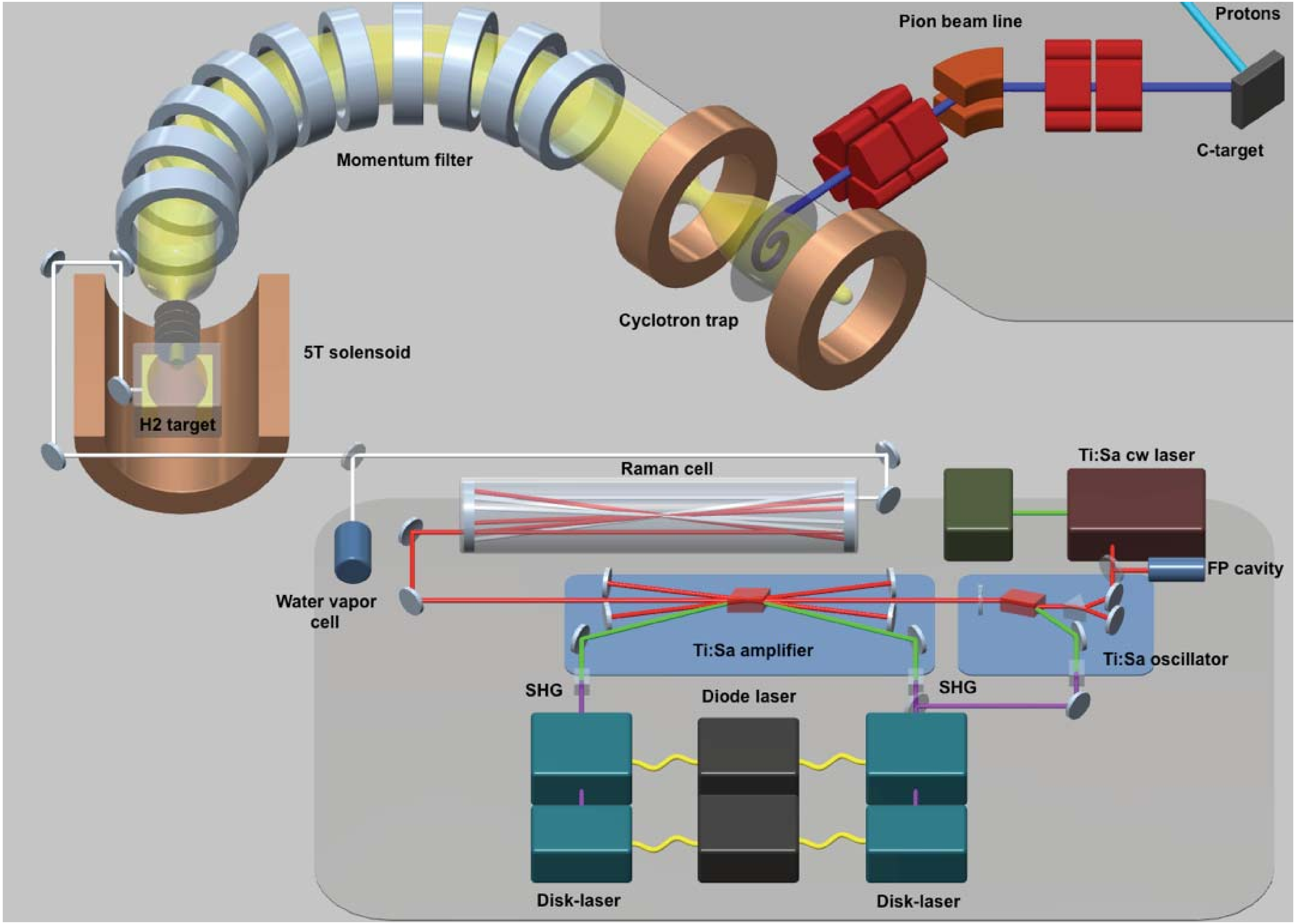
Two major technical challenges

<5keV

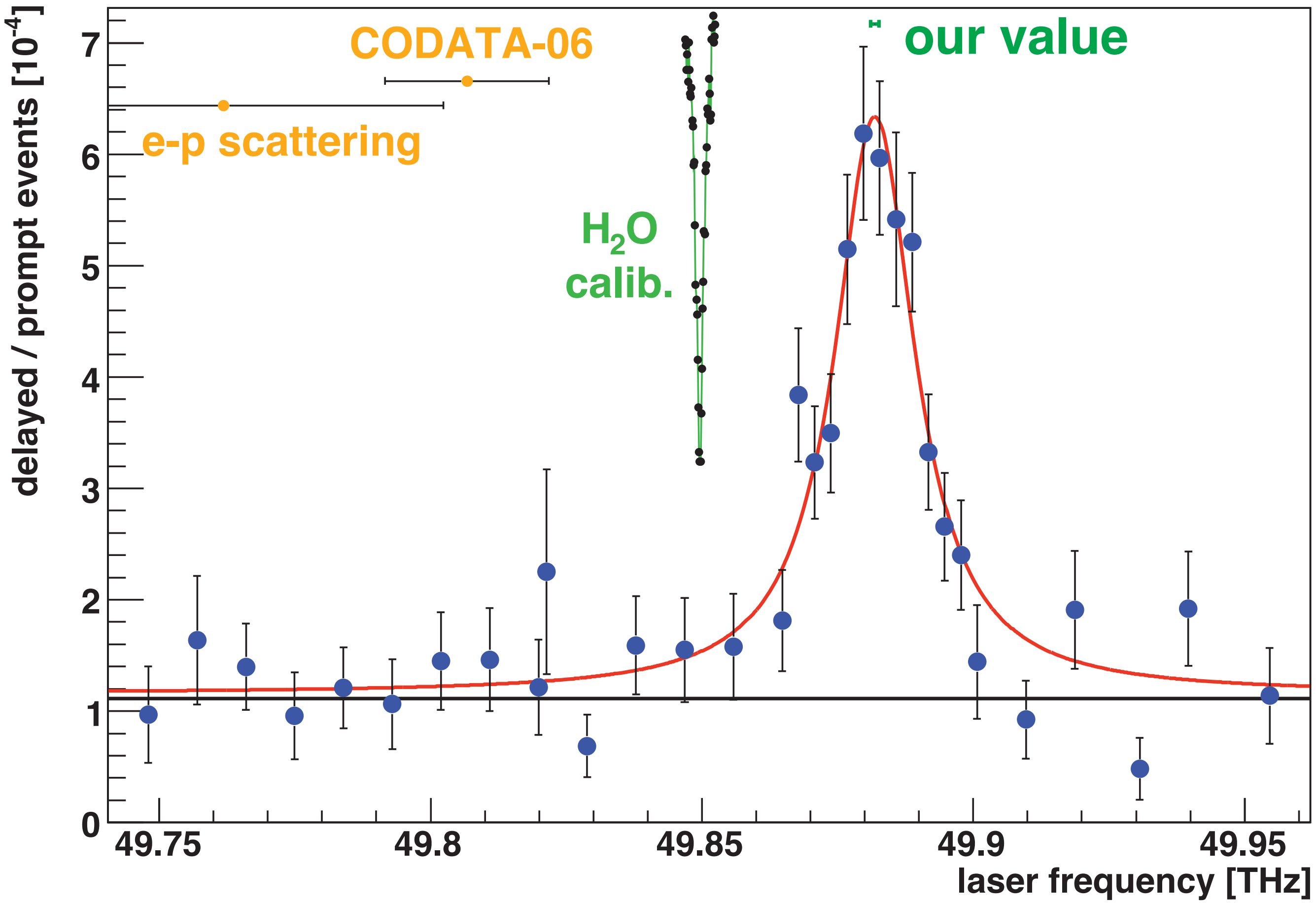
- Muonic hydrogen: Produce slow muon that can stop in low pressure hydrogen gas. 1 hPa
- Light source: 6μm laser source, powerful, well-controlled frequency, triggered on demand. 0.2 mJ

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

Generation of Cold muonic hydrogen


Protons
Pion beam line
C-target
Momentum filter
Cyclotron trap
5T solensoid
H2 target
Raman cell
Ti:Sa cw laser
FP cavity
Water vapor cell
Ti:Sa amplifier
Ti:Sa oscillator
SHG
Diode laser
SHG
Disk-laser
Disk-laser

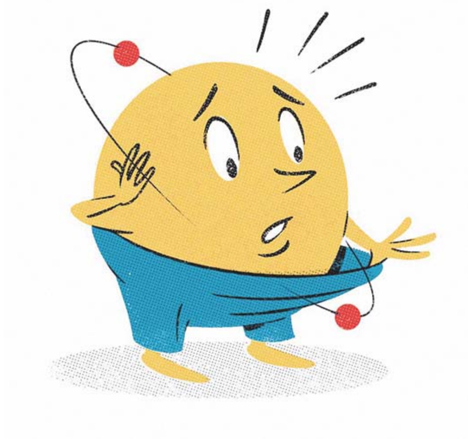
Results



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

r_p=0.84184(36)(56) fm

R. Pohl et al., Nature 466, 213 (2010)



變小的質子

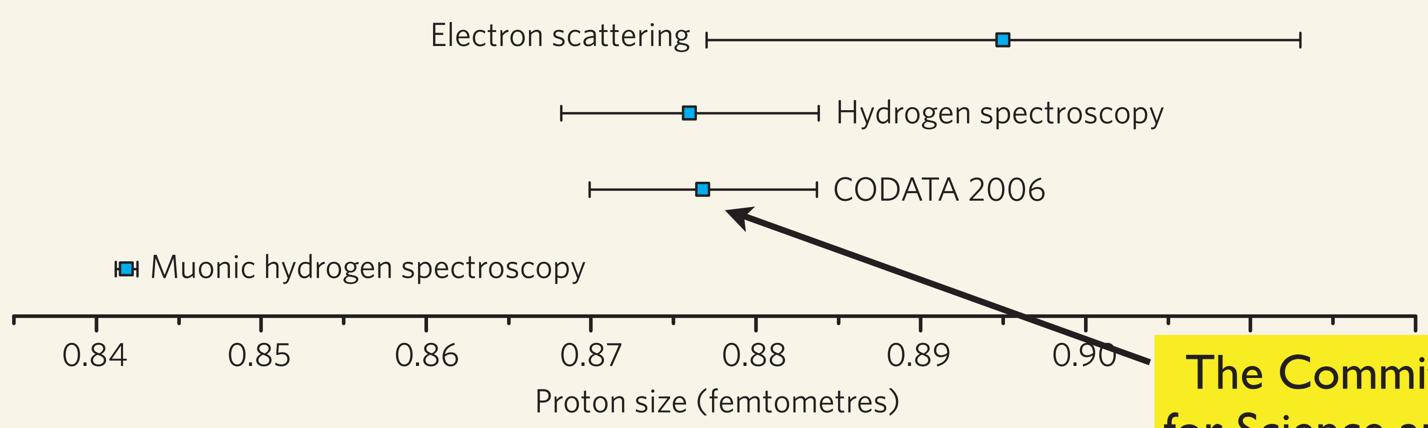
10^{-15}m

雖然不大, 確影響深遠

- 新數值 **0.84184** fm<0.8768 fm, 小了**4%**

0.000000000000000084184 公尺

精確度到達了, 尚未被研究過的極小世界



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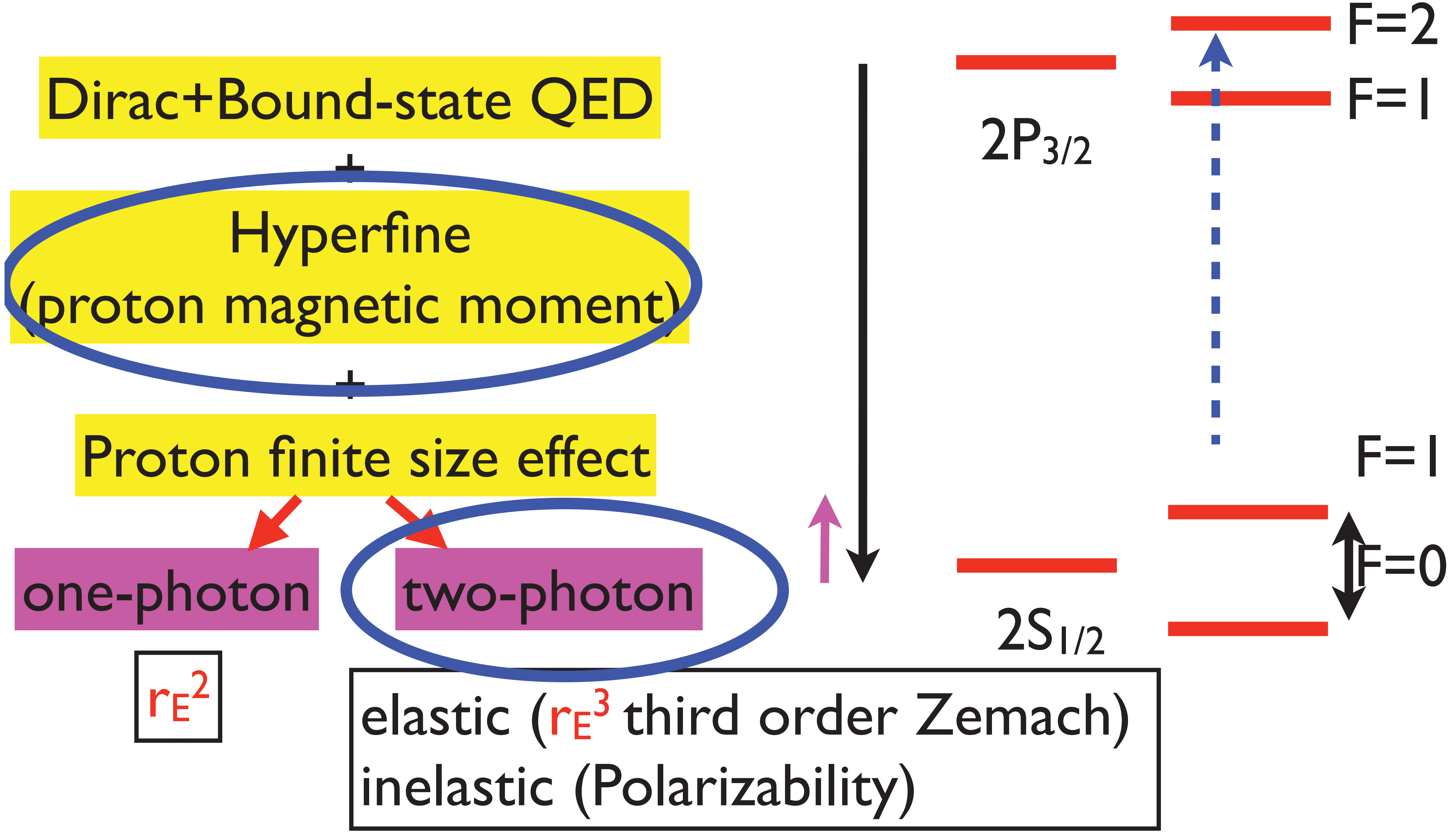
Contributions to transition energy

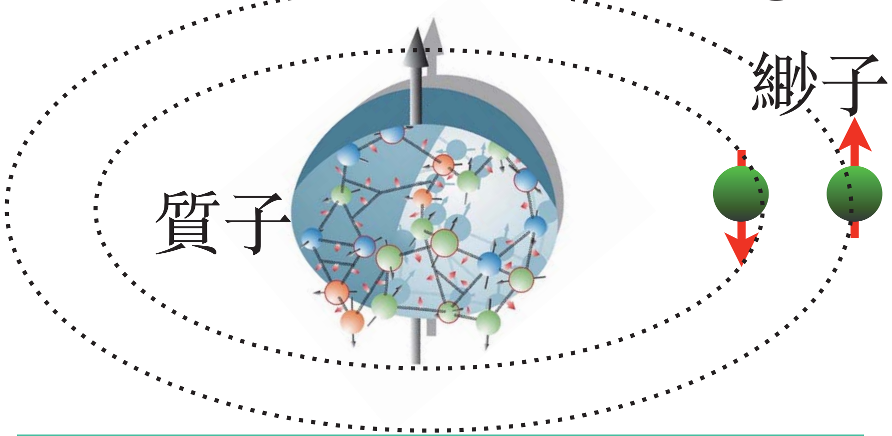


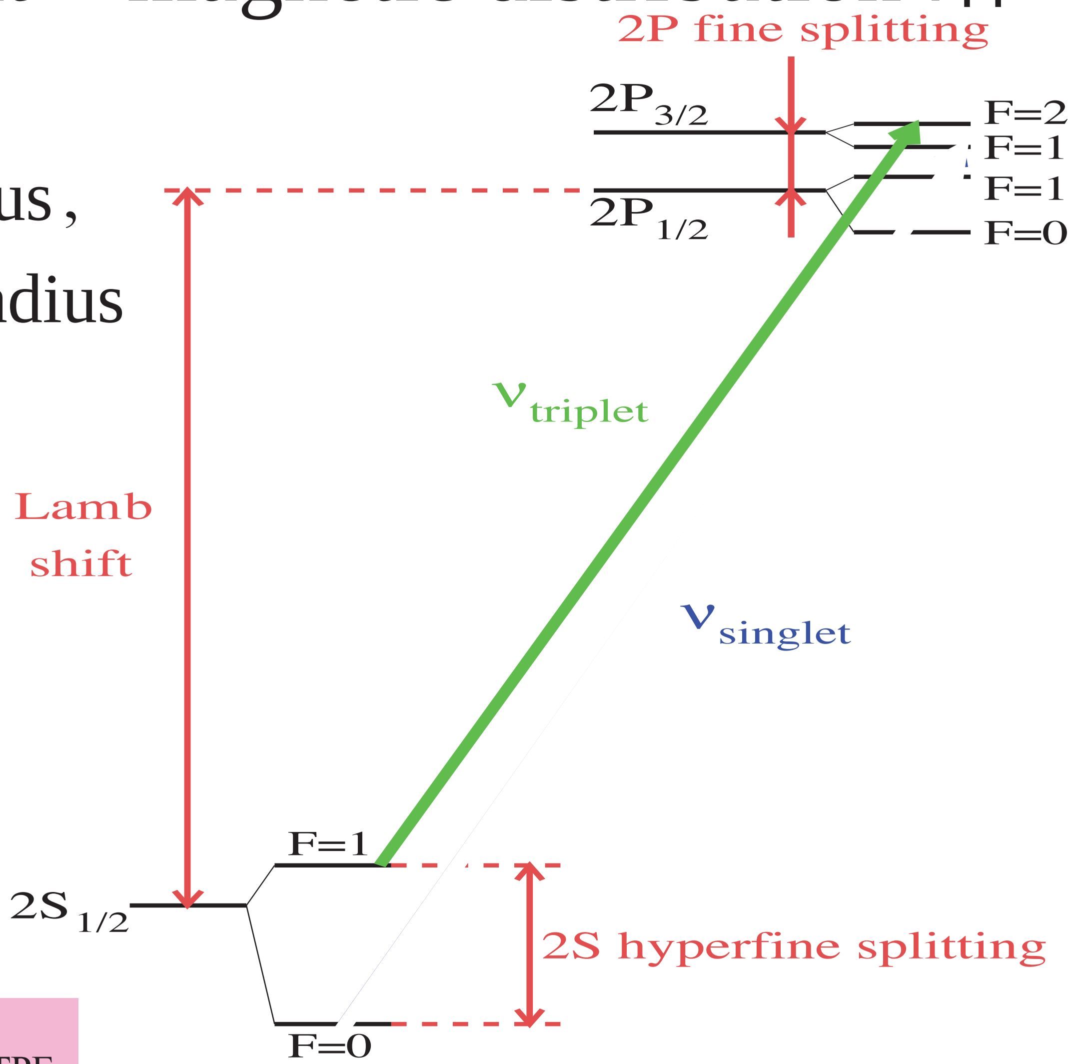
$$\Delta E = 209.9779(49) - 5.2262\, r_E^2 + 0.0347\, r_E^{\,3}\ \text{meV}$$

Hyperfine structure

- Hyperfine splitting
- proton magnetic moment + magnetic distribution r_M

除了量測電核半徑 charge radius，
還可得到磁核半徑 magnetic radius





$$\frac{1}{4}h\nu_s + \frac{3}{4}h\nu_t = \Delta E_L + 8.8123(2)\mathrm{meV}$$

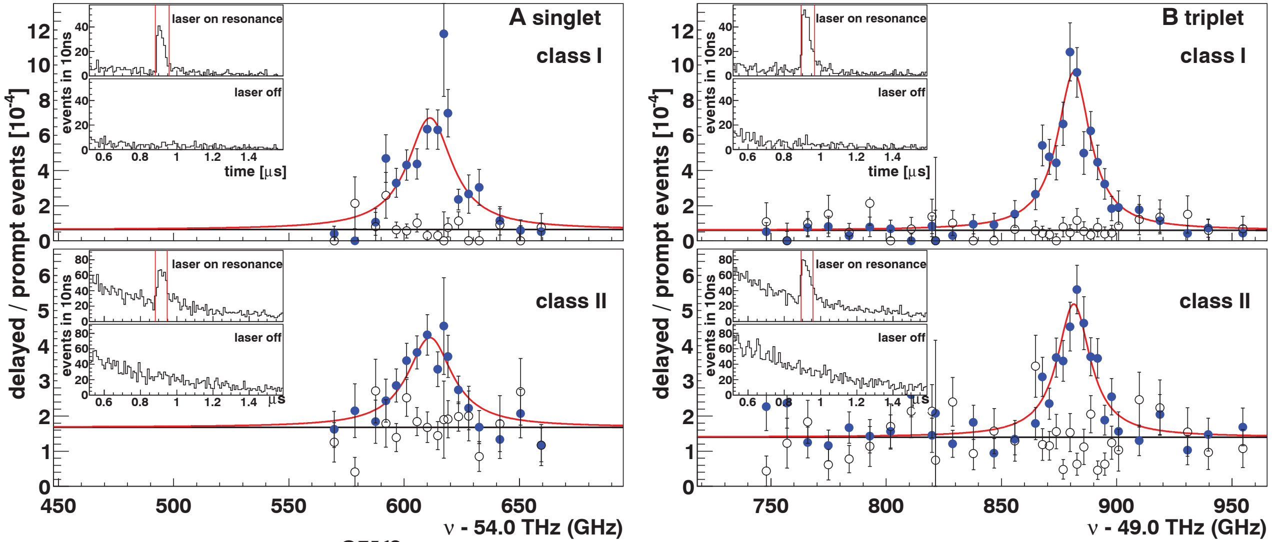
$$h\nu_s - h\nu_t = \Delta E_{HFS} - 3.2480(2)\mathrm{meV}$$

$$\Delta E_L^{th} = 206.0336(15) - 5.2275(10)r_E^2 + \Delta E_{TPE}$$

$$\Delta E_{HFS}^{th} = 22.9763(15) - 0.1621(10)r_Z + \Delta E_{HFS}^{pol}$$

$$r_Z = \int d^3r \int d^3r' r' \rho_E(\mathbf{r})\rho_M(\mathbf{r} - \mathbf{r}')$$ Zemach radii

實驗結果



$$\Delta E_{\rm L}^{\rm exp} = 202.3706(23)\ \rm meV$$

$$\Delta E_{\rm HFS}^{\rm exp} = 22.8089(51)\ \rm meV$$

$r_{\rm E} = 0.84087(39)$ fm

charge radius

$r_{\rm M} = 0.87(6)$ fm

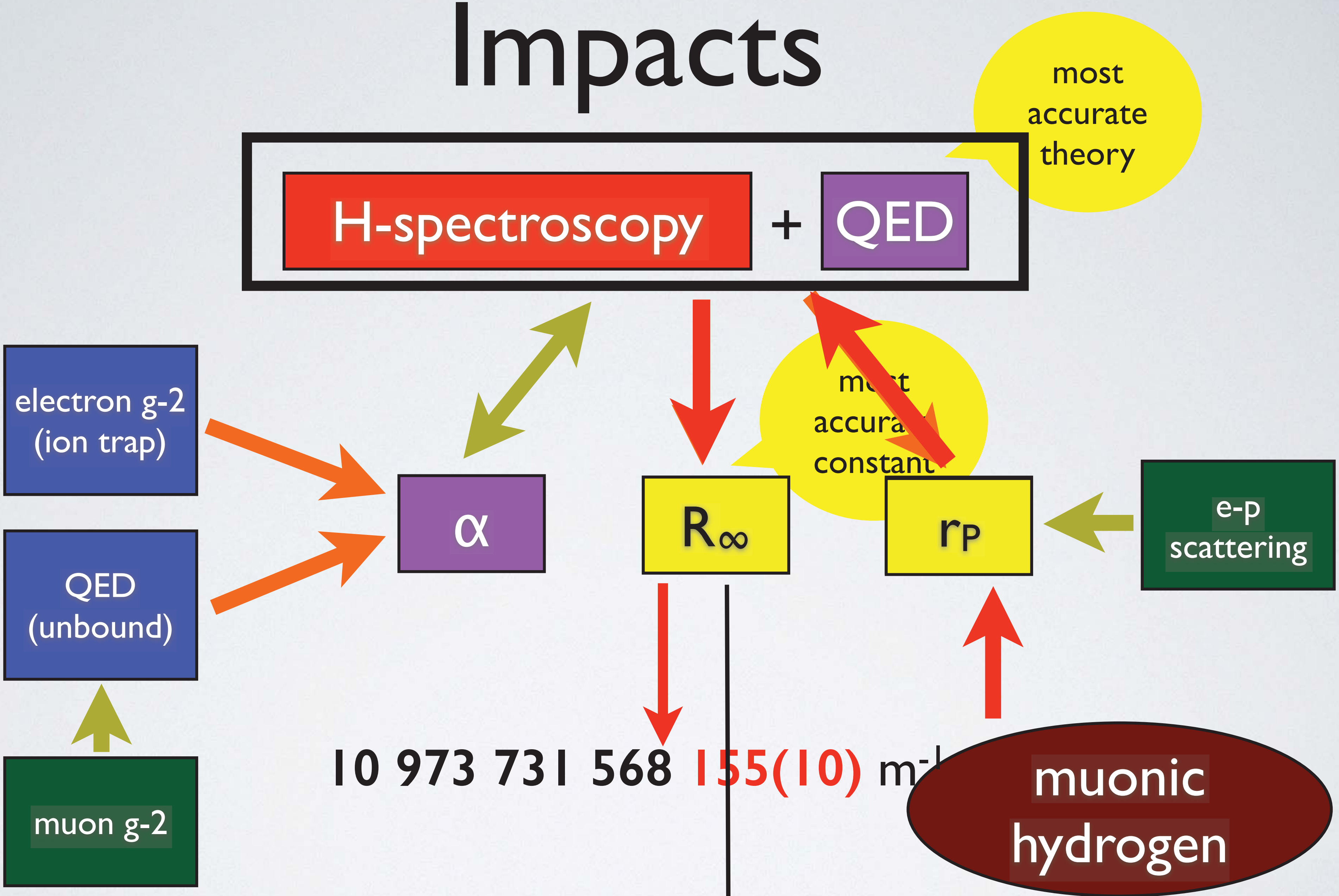
magnetic radius

A smaller proton size is confirmed. Accuracy is improved by 1.7 times. The hyperfine structure issue is settled

Science AAAS

Aldo Antognini *et al. Science* **339**, 417 (2013);

Impacts



$$R_\infty = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c} = 1.0973\,731\,568\,539(55) \times 10^7\ \mathrm{m}^{-1},$$

What is wrong?

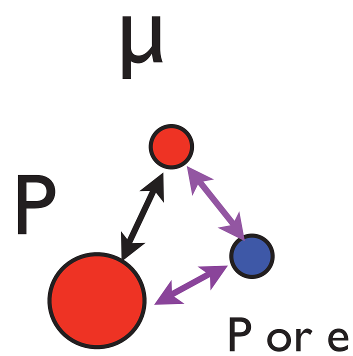
Before being radical, try to find a "patch" first
Just like a "normal" scientific research

- Experimental systematic effect?

molecular perturbation? ppμ or μpe?

Ruled out by three-body calculation

J.-P. Karr, L. Hilico, *Phys. Rev. Lett.* **109**, 103401 (2012).

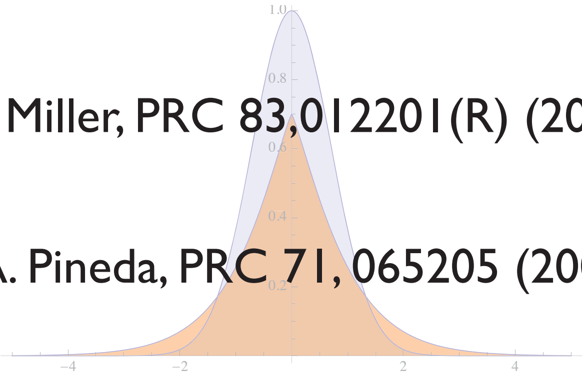


- Theocratical inaccurate calculation?

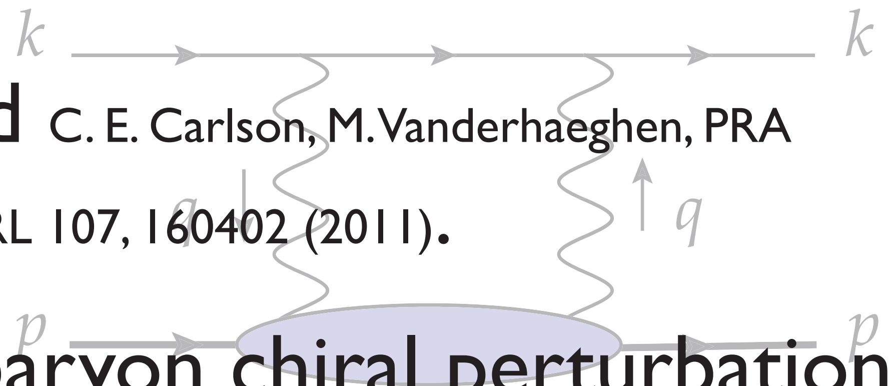
Shape? polarizability?Two-photon exchange?

Theories on high order radius

- A large tail distribution to enlarge r_E^3 term? X
  - e-p scattering data. C. Cloët, G.A. Miller, PRC 83,012201(R) (2011).
  - chiral perturbation theory A. Pineda, PRC 71, 065205 (2005)

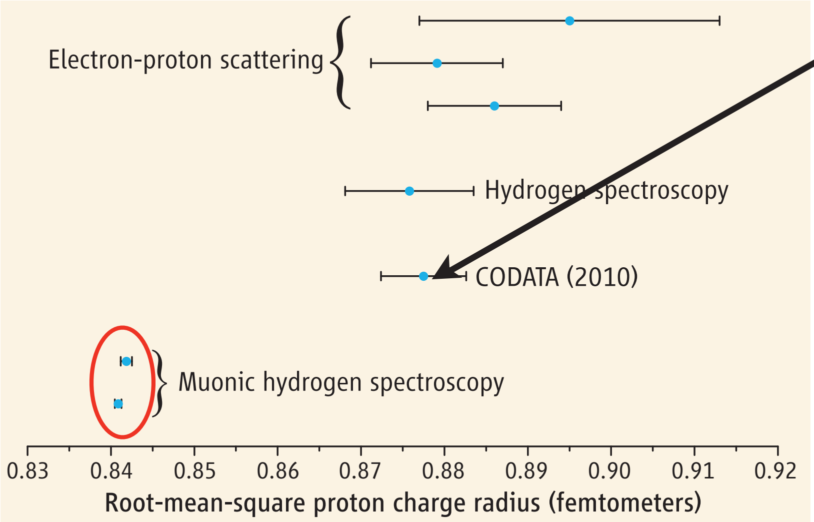


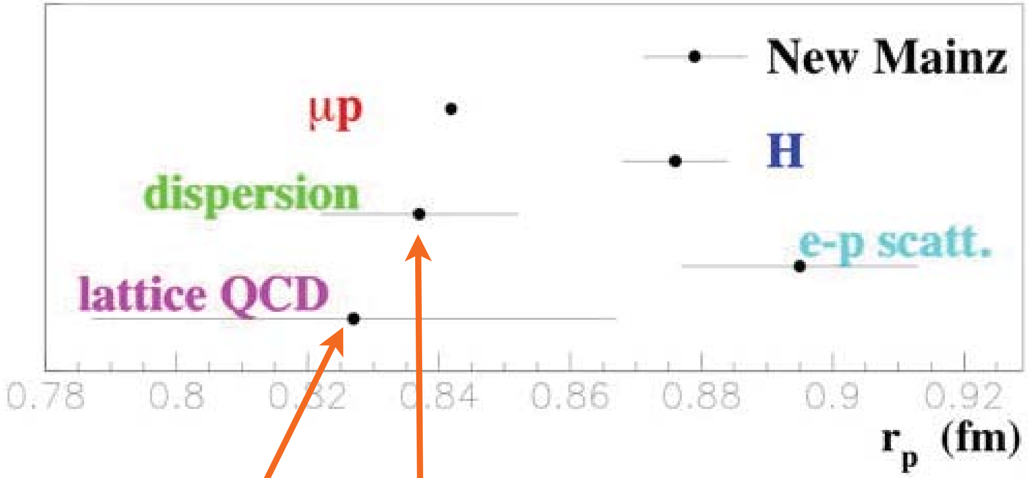
- Insufficient calculation on Two-photon exchange ΔE_{TPE} ? X
  - intensively re-examined C. E. Carlson, M. Vanderhaeghen, PRA 84,020102 (2011). & R. J. Hill, G. Paz, PRL 107, 160402 (2011).
  - constrained by heavy-baryon chiral perturbation theory(M. C. Birse, J.A. McGovern, Eur. Phys. J.A 48, 120 (2011)



質子大小之謎
Proton size puzzle is reinforced

7 σ away from 2010CODATA





Is this the only one small proton?

1. **0.84(1) fm**: "model dependent" dispersion fit for the e-p scattering data.

I. T. Lorenz, H.-W. Hammer, U. Meißner, Eur. Phys. J. A 48, 151 (2012).

2. **0.83(3) fm**: Lattice QCD calculation.

P. Wang, D. B. Leinweber, A. W. Thomas, and R. D. Young, Phys. Rev. D 79, 094001 (2009)

Implications

Now, we have a big trouble in atomic physics and try to think something big...

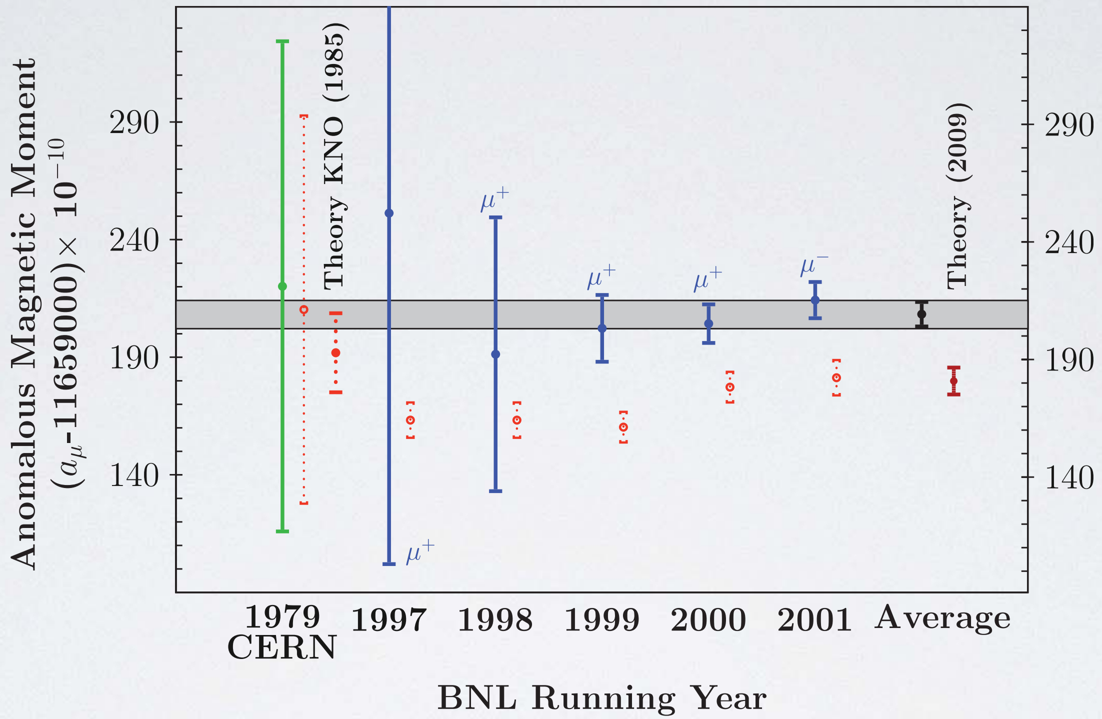
Some possible routes to the puzzle:

- Physics in very small scale (am 10^{-18}, zm 10^{-21})???
  - Spectroscopy as a test of Coulomb's law: A probe of the hidden sector, PRD 82, 125020 (2010)
  - Proton radius puzzle and large extra dimensions, LB Wang and WT Ni, arXiv: 1303.4885
- Unexplored μ-p or e-p interaction???
- Is bound state QED calculation wrong???

Is there any sign shown in the past ?

Hint A:

IS MUON A FISHY PARTICLE?

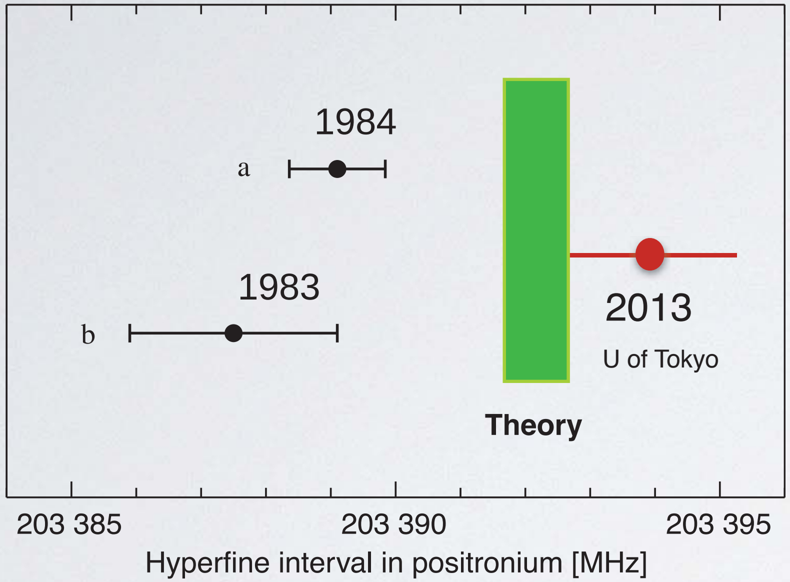


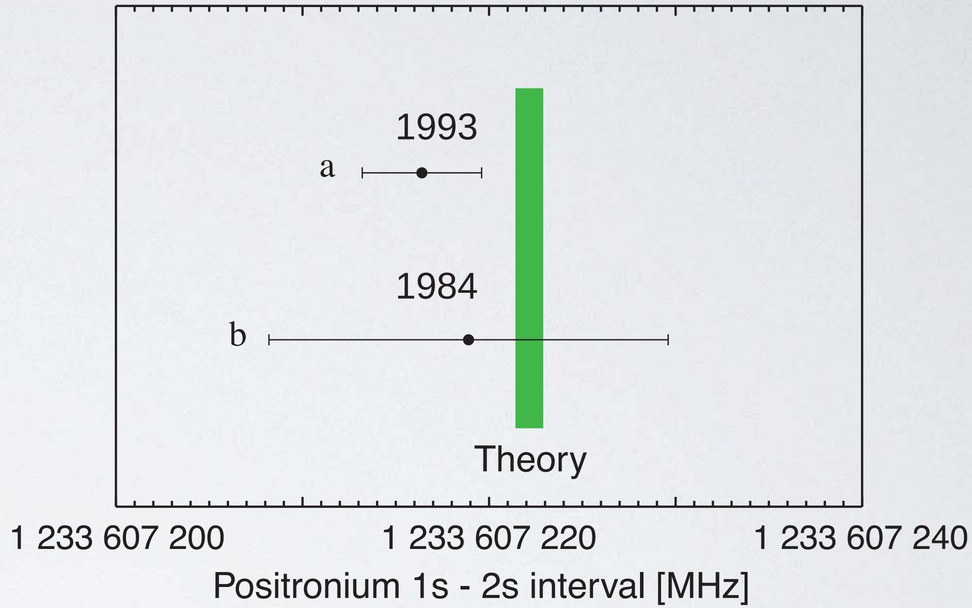
Muon g-2 experiment is 3.2σ away from theory
Is muon fishy particle?

"New Parity-Violating Muonic Forces and the Proton Charge Radius"
PRL 107, 011803 (2011)
"Constraint on Parity-Violating Muonic Forces"
PRL 108, 081802 (2012)

Hint B: Laser spectroscopy of positronium

A purely leptonic system, no finite size effect
A cleaner test for QED





1s

DISCREPANCIES IN THE POSITRONIUM SPECTROSCOPY

But, muonium (μ^+e^-) is in agreement with QED theory

V. Meyer and et al., Phys. Rev. Lett. 84, 1136 (2000)

I. Fan and et al., arXiv:1310.1660(2013)—frequency comb recalibration at NTHU

Hint C:

A HINT
HOW ABOUT THE
CHARGE RADIUS DIFFERENCE

Absolute size:

μP: r_p=0.84087 fm

H : r_p=0.8775 fm

7σ away........... **DISCREPANCY**

Proton-Deutron Size difference:

e-d scattering & μP→$r_d^2 - r_p^2 = (2.130)^2 - (0.84087)^2 = 3.830(35)$

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 ???

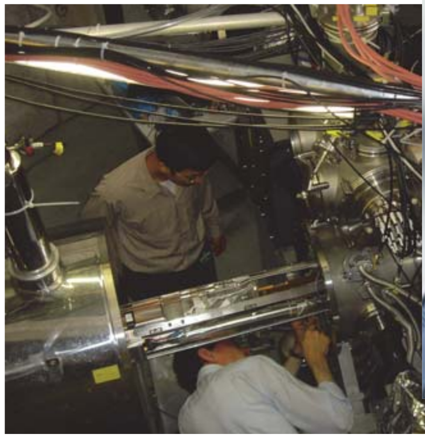
Let's wait for the muonic deuterium, coming soon!

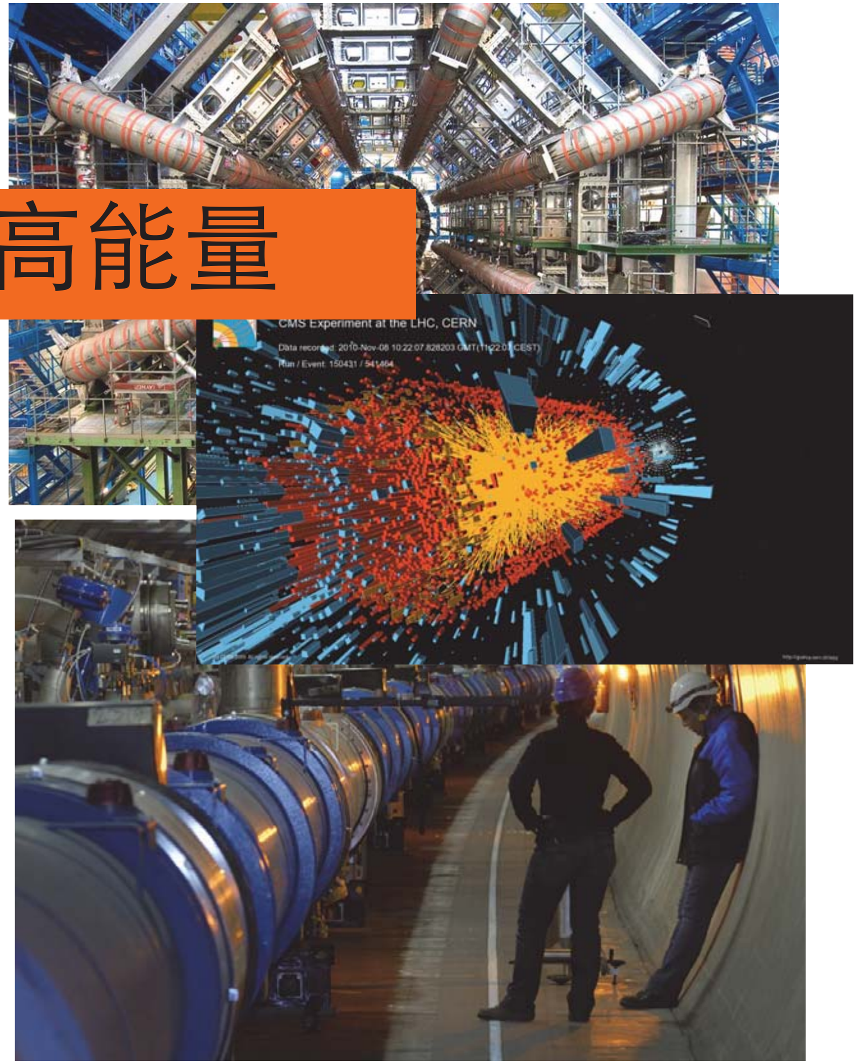
誰能發現新物理?

緲子原子光譜學 V.S. CERN的大型重子對撞機LHC

耗費: 1 : 10000

超高精密度: 超高能量



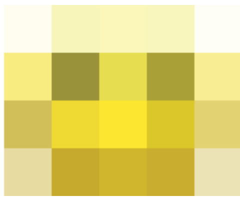


New experiments for the puzzle

- New electron scattering
  - experiments:Jefferson Lab E12-11-106
- Elastic muon-proton scattering
  - MUSE collaboration proposes at PSI
- Spectroscopy of exotic atoms
  - positronium(PRL**109**,073401), muonium(PRL, 108,143401)
- Spectroscopy of electronic atoms and ions
  - 2S-6S/D(NPL), 2S-4P(MPQ), 1S-3S(LKB), He^+(MPQ), H-like ion (NIST), 2S-2P(York)

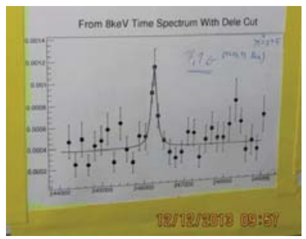
如何解開質子大小之謎
我們的未來計劃

- 原計劃中的核心成員組成一個新的研究團隊 CREMA (Charge Radius Experiment with Muonic Atom)，包括清華大學在內的九個國際團隊)
- 將於去年底開始進行渺子氦原子μHe^{+}的光譜實驗。
- 將可以得到更精確的氦原子核大小，與已知的數據比較，將可進一步釐清質子大小之謎。


2010 Nature


2012 Science


What’s next?



國際研究團隊 Collaboration

12 institutes, 6 countries, 36 physicists

清華團隊自(2001)本實驗構想階段即開始參與實驗，主要負責雷射系統，並參與實驗的整體設計，偵測器，頻率量測，數據截取等系統的建造。我們也與各頂尖實驗室與物理學家建立起緊密的合作與友誼

Laboratoire Kastler Brossel
Physique quantique et applications

cnrs

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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

MPQ

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Yale University

TGSW

UNIVERSITÉ DE FRIBOURG / UNIVERSITÄT FREIBURG

PRINCETON UNIVERSITY

DEPARTMENT OF PHYSICS
National Tsing Hua University

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

清華大學物理系
AMO研究群原子操控實驗室

sponsors: 國科會，教育部

Thanks: 清華大學 施宙聰 余怡德, 王立邦 成功大學蔡錦俊
中正大學 韓殿君, Durham(UK): Simon Cornish

我們邀請
博士後 博士生 碩士生 專題生 一起加入我們