Proton radius puzzle and large extra dimensions

Wei-Tou Ni (倪維斗)
National Tsing Hua University

Based on
(i) arXiv:1303.4885, Proton radius puzzle and large extra dimension, Li-Bang Wang, W-T Ni
(ii) Atomic transition frequencies and extra dimensions
Talk given by Li-Bang Wang (王立邦) in
Workshop on the Microscopic Origin of Gravity & related topics,
NCTS, Hsinchu, 1/26-27/2013

Atomic transitions frequencies and extra dimensions, talk given by Li-Bang Wang

小型研討會：重力微觀起源及相關論題探索 --實驗與理論之相互影響

Workshop on Interactions between Experimental and Theoretical Efforts for Probing the Microscopic Origin of Gravity and related Topics

– Celebrating the 30th Anniversary of the International School and Symposium on Precision Measurement and Gravity Experiment

January 26-27, 2013

Lecture Room 4A, NCTS, General 3rd Building, NTHU, Hsinchu

Registration: 9:30- 10:00

January 26 (Saturday), 2013 SCHEDULE C means Chair

Time	Speaker	Title
10:00-10:10 (C: W-T Ni)	Ci-Lin Pan (NTHU) Jow-Tseng Shy (NTHU)	Opening
10:10-11:40 (C: J-T Shy)	Wei-Tou Ni (NTHU)	Colloquium: No far place not probed無遠弗屆: from laser ranging to GW (gravitational wave) detection in space
11:40-12:10 (C: J-T Shy)	An-Ming Wu (NSPO)	Deployment of the ASTROD-GW and other gravitational wave mission formations
12:10-13:30	*Lunch*	
13:30-14:30 (S-s Pan)	Hsien-Hao Mei (NTHU)	Q & A experiment and the Parametrized Post-Maxwellian (PPM) framework
14:30-15:15 (S-s Pan)	Li-Bang Wang (NTHU)	Atomic transition frequencies and extra dimensions
15:15-15:45	*Break*	
15:45-16:30 (C: J Nester)	Dah-Wei Chiou (NTU)	Spin and rotation in gravity: meaning and significance
16:30-17:00 (C: J Nester)	Dah-Wei Chiou (NTU)	Precession of a Dirac-Pauli spinor and the Bargmann-Michel-Telegdi equation
17:00-18:00 (C: J Nester)	Kang-Kuen Ni (JILA/NIST)	eEDM search with molecular ions (eEDM: electron Electric Dipole Moment)
18:00-18:50	*Free discussions and dinner (box)*	

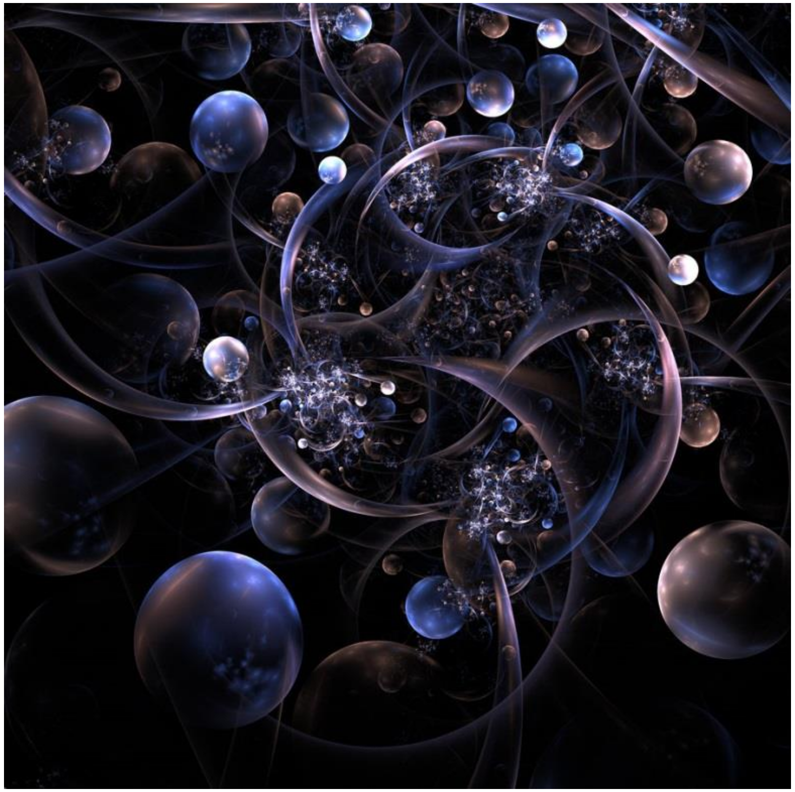
小型研討會：重力微觀起源及相關論題探索 --實驗與理論之相互影響

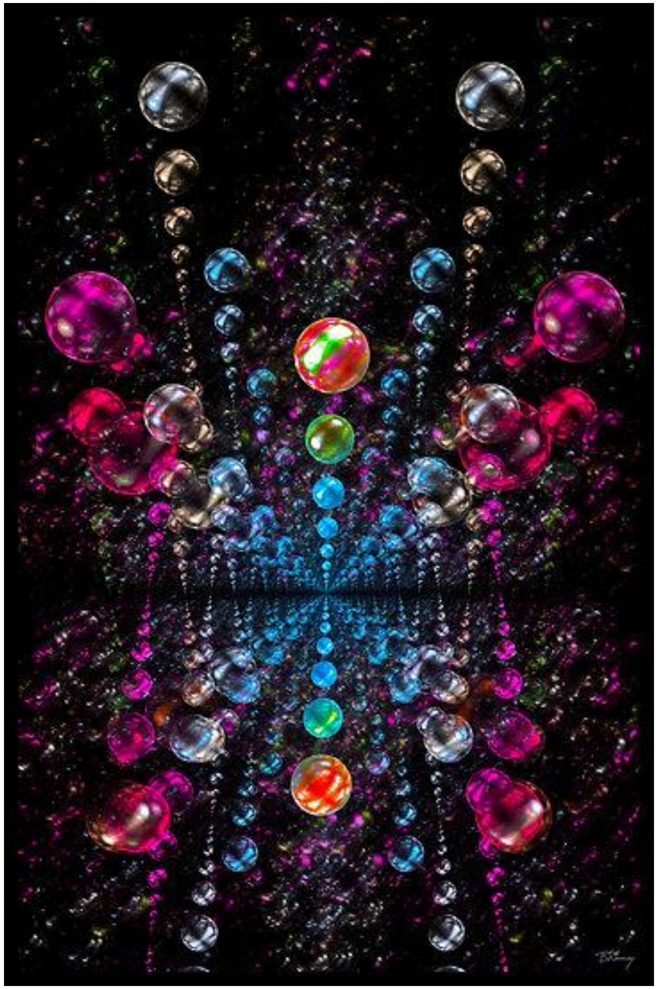
Probing the Microscopic Origin of Gravity and related Topics

January 27 (Sunday), 2013

Time	Speaker	Title
09:30-10:30 (C:H-T Cho)	Kin-Wang Ng (Academia Sinica)	Probing the birefringence of dark energy by CMB polarization
10:30-11:00 (C:H-T Cho)	Chih-Hung Wang (NCU)	Torsion effects in the early Universe
11:00-12:00 (C:H-T Cho)	Sheau-shi Pan (CMS, ITRI)	Experimental search for anomalous spin-spin interaction and theories of gravity
12:00-13:30	*Lunch*	
13:30-14:00 (C: S-Y Lin)	Wei-Tou Ni (NTHU)	Anomalous spin-spin interactions, Lense-Thiring effect and some thoughts on the gyro-gravitational ratio of particles
(C: S-Y Lin)	Bei-Lok Hu (U. Maryland)	Colloquium: Microscopic Origin of Gravity-- Quantum or Emergent?
15:00-15:30	*Break*	
15:30-16:00 (C: W-T Ni)	Presentation practice for *Asia Pacific School/Workshop on Gravitation and Cosmology 2013 (APCTP-NCTS-YITP Joint Program) February 19-22, 2013, Jeju Island, Korea* Fei-hung Ho (NCKU)	Testing the modification of BSSN to Improve Binary Evolution
16:00-17:30 (C: W-T Ni)	Panel Discussion on "Probing the microscopic origin of gravity" Panelist: H-H Mei, L-B Wang, D-W Chiou, K-W Ng, C-H Wang, B-L Hu	
17:30-18:30	*Free discussions and dinner (box)*	

Cosmic Bubbles, Spacetime Foams Primordial Black Holes, Worm Holes, White Holes, Primordial Soup & Transmutation of Dimensions in the Planckian World



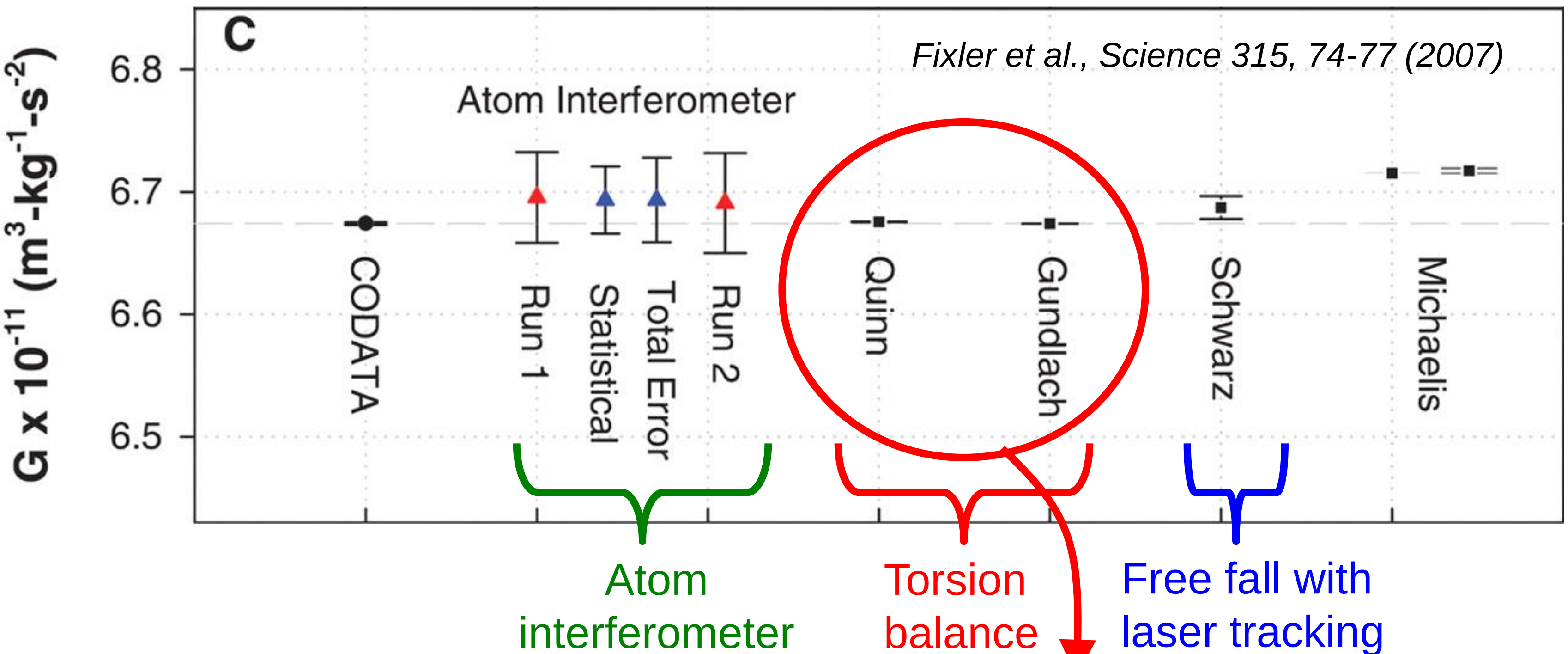


Introduction

- "Frequency": the physics quantity that can be measured very precisely
  - Magnetic moment of electron, g_e (exp) = 2.0023193043617(15)
  - Rydberg constant = 109,737.31568639(91)
  - EDM of electron $|d_e| < 1.05 \times 10^{-27}$ e·cm
  - The best atomic clock $\delta f/f = 8 \times 10^{-18}$

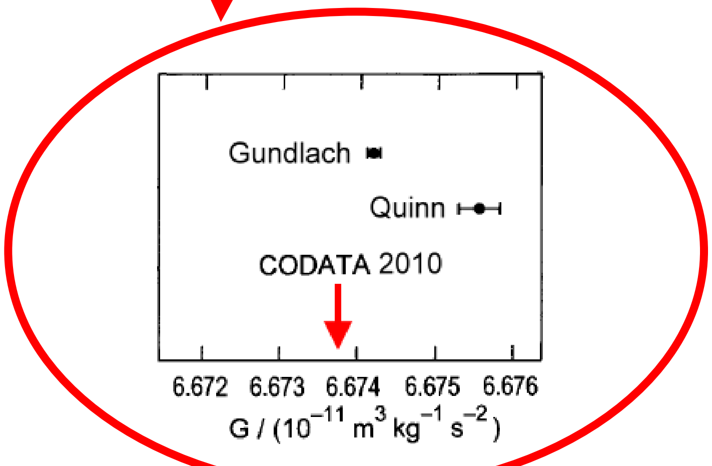
[1] G. Gabrielse et al., *Phys. Rev Lett.* **97**, 30802 (2006)
[2] Th. Udem et al., *Phys. Rev. Lett*. **79**, 2646 (1997)
[3] JJ Hudson et al., *Nature* **473**, 493 (2011)
[4] CW Chou et al., *Phys. Rev. Lett.* **104**, 070802 (2010)

G measurements



$$G = 6.673\ 84(80) \times 10^{-11}$$

$$\delta G/G \sim 100 \text{ ppm}$$



Outline

- Gravity problem
- Extra dimension and ADD model
- Precision atomic measurement
- Recent examples
- Proton Radius Puzzle
- Other possible tests
- Conclusion

What's wrong with Gravity?

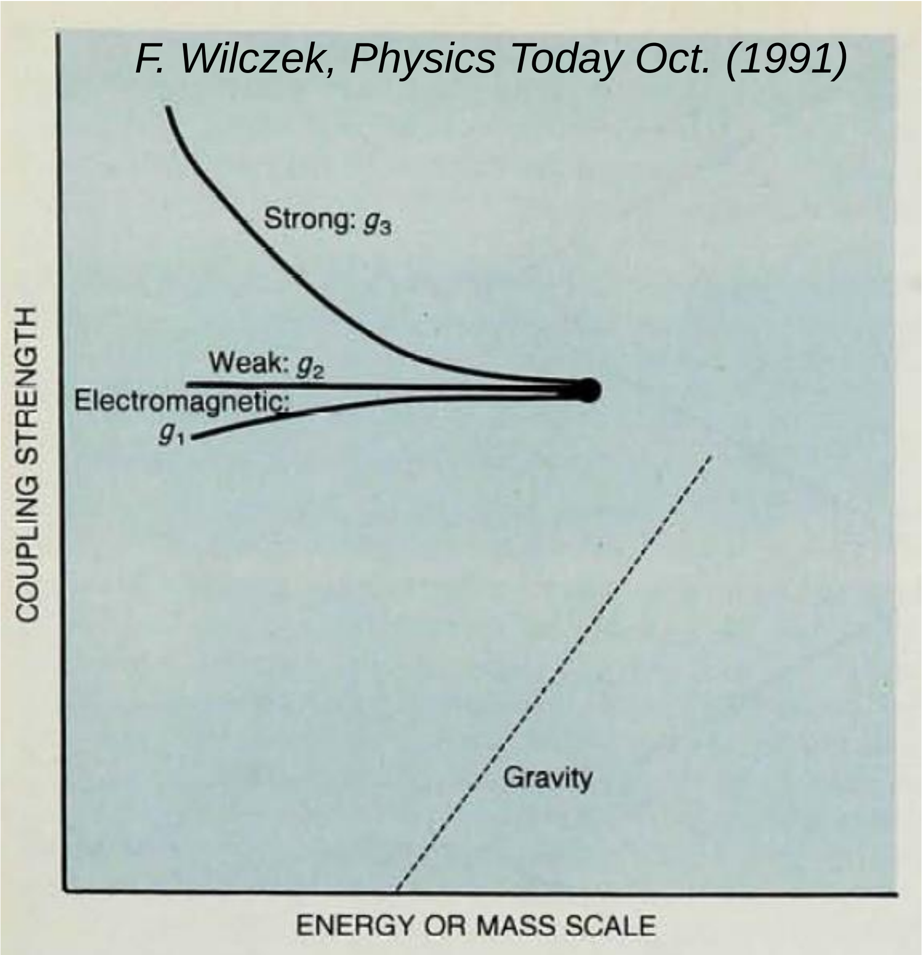
- In Planck scale:

$$M_{pl} = \sqrt{\frac{\hbar c}{G}} = \sqrt{\frac{1}{G}} = 10^{19} GeV$$

$$F_{Gravity} = \frac{G m_1 m_2}{r^2} = \frac{m_1 m_2}{M_{pl}^2 r^2}$$

Explanations?
Not force at all!

E. P. Verlinde, JHEP 1104, 029 (2011)



Modified Gravity or MOND

- Modify Newton's Law
- Gravity only tested ~100 μm, (U. W.)
- Rotation curve in galaxies
- Cosmology argument
- Dark matter vs Modified gravity
- Numerical Coincidence or not??? $a_0 \approx cH_0/2\pi$
- MOND phenomenology This acceleration scale appears in various seemingly unrelated galactic scaling relations, mostly unpredicted by the ΛCDM model The value of this scale is $a_0 \simeq 10^{-10}$ m s^{-2}, which yields in natural units, $a_0 \sim H_0$ (or $a_0 \approx cH_0/2\pi$). It is perhaps even more meaningful to note that: $a_0^2 \sim \Lambda$

MOND: Observational Phenomenology and Relativistic Extensions Famaey & McGaugh lrr 2012

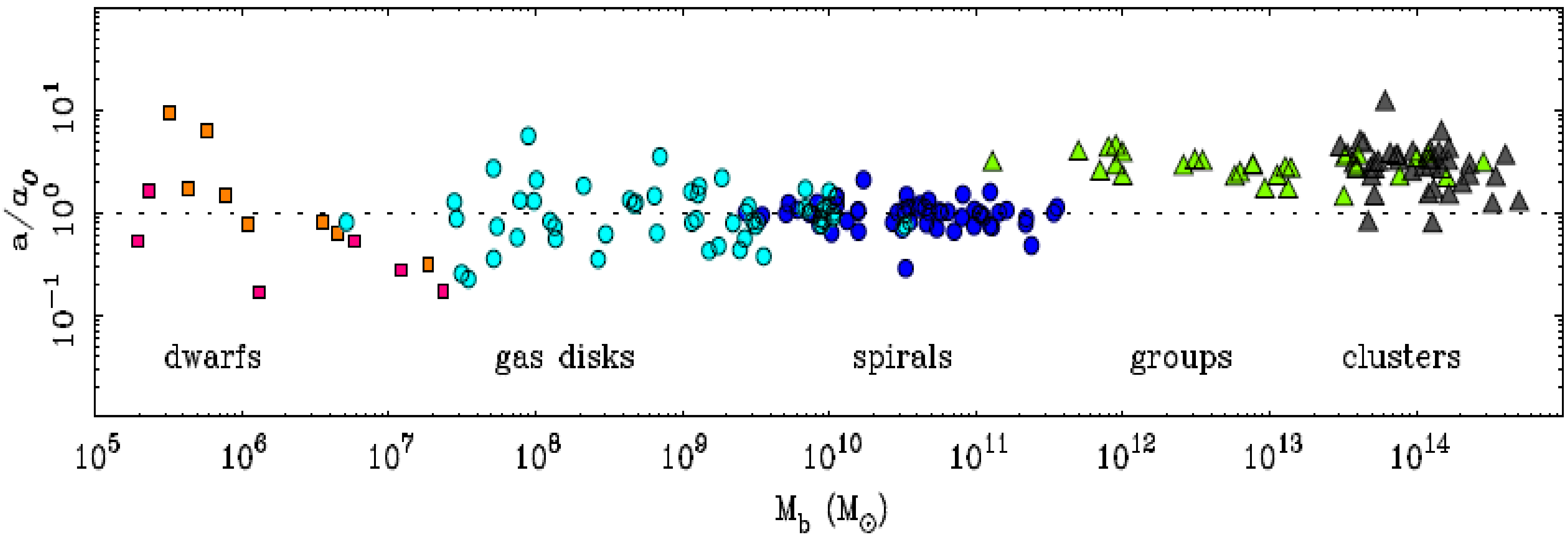
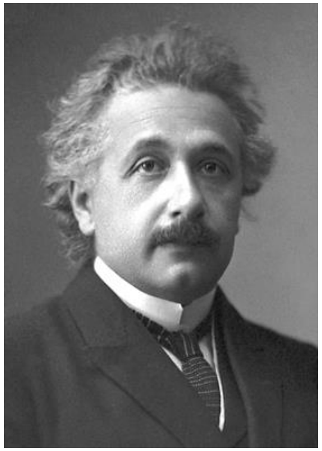


Figure 48: The acceleration parameter $\sim V_f^4/(GM_b)$ of extragalactic systems, spanning ten decades in baryonic mass M_b. X-ray emitting galaxy groups and clusters are visibly offset from smaller systems, but by a remarkably modest amount over such a long baseline. The characteristic acceleration scale $a_0 \sim \sqrt{\Lambda}$ is in the data, irrespective of the interpretation. And it actually plays various other independent roles in observed galaxy phenomenology. This is natural in MOND (see Section 5.2), but not in ΛCDM (see Section 4.3).

Modified Gravity

- Modify Newton's Law
- Gravity only tested ~100 μm, (U. W.)
- Rotation curve in galaxies
- Cosmology argument

Dark matter vs Modified gravity



General relativity 1915

MOND

- Modified Newtonian Dynamics

  M Milgrom, ApJ ***270,*** *365 (1983)*

- When a << a_0

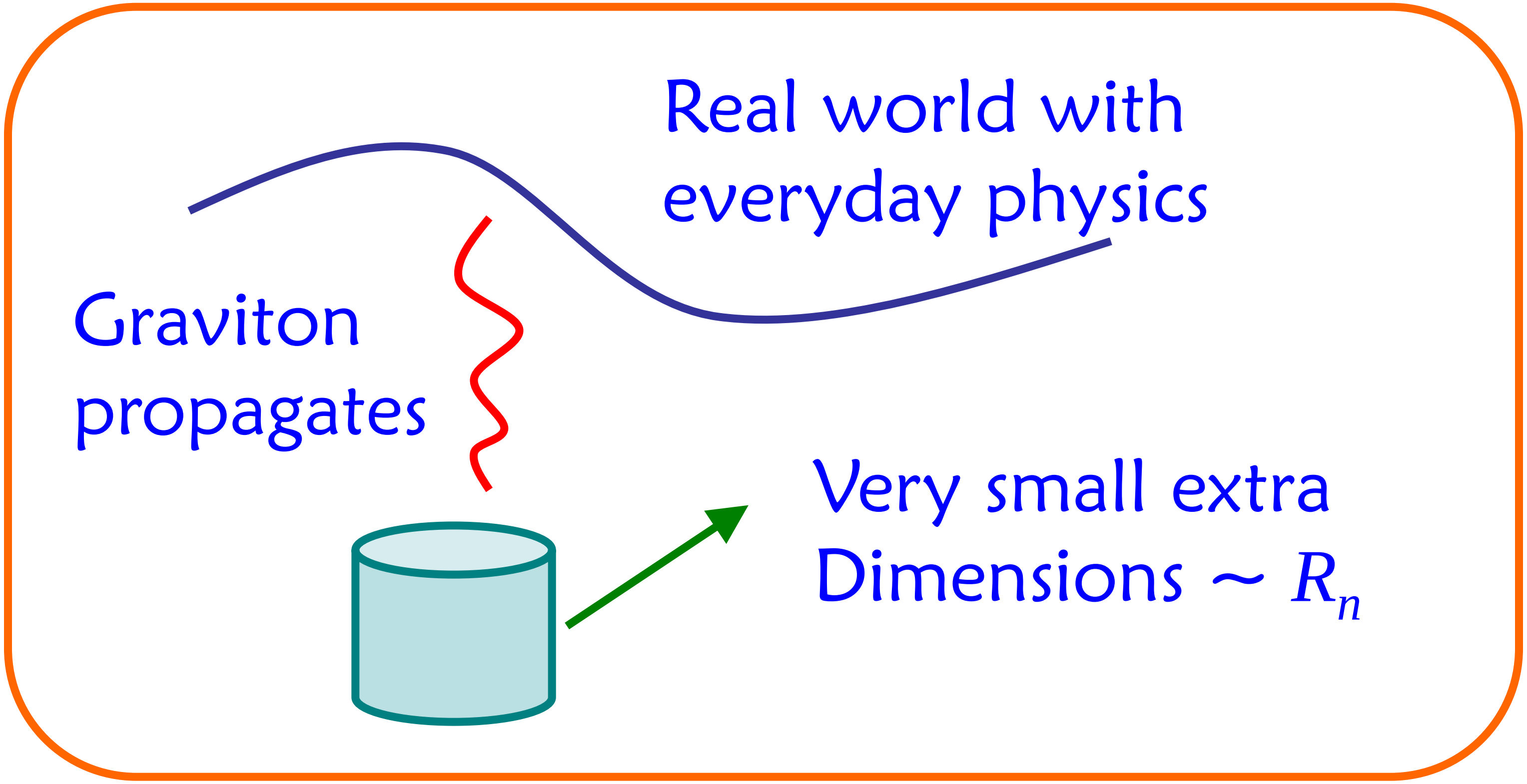
$$a = \sqrt{(a_0 a_N)}, \quad \text{where} \quad a_N = \frac{GM}{r^2}$$

- No dark matter needed
- Of minor interests as compared with dark matter in the physics community

ADD Model with LED

- Larger extra dimensions (LED)
- Arkani-Hamed, Dimopoulos, Dvali (ADD model)

Phys. Lett B ***429****, 263 (1998)*



ADD Model

- (4 + n) dimensions within R_n
- R_n too small to be observed directly

$$V(r) = \frac{m_1 m_2}{M_{pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, \quad (r < R_n)$$

$$V(r) = \frac{m_1 m_2}{M_{pl(4+n)}^{n+2}} \frac{1}{R_n^n r}, \quad (r > R_n)$$

$$M_{pl}^2 = M_{pl(4+n)}^{n+2} \cdot R_n^n$$

$$M_{pl(4+n)} \sim M_{EW} \sim TeV, \quad \underbrace{R_1 = 3\times10^{12} m, \quad R_2 = 0.3mm}_{\text{ruled out}}$$

Atomic probe

- Atomic scale ~ 10^{-10} m
- Nuclear scale ~ 10^{-15} m
- LED effect small → precise comparison
- Best testing ground → transition frequencies
- Requirement:
  - Atomic theory for electronic structures
  - Nuclear effect: nuclear size, nuclear moments, form factors, polarizibility, meson exchange current, weak interaction, etc…
  - QED effect, Lamb shift

Extra dimensions and atomic transition frequencies*

Li Zhi-Gang(李志刚)†, Ni Wei-Tou(倪维斗), and Antonio Pulido Patón

Table 1. Upper limits on the compactification radius R_n obtained from our argument and others.

	transition	R_3	R_4	R_5	R_6
hydrogen	1s–2s	13 μm	37 nm	1.0 nm	0.1 nm
	2s–2p	90 μm	200 nm	3.3 nm	0.3 nm
muonium	1s–2s	10 μm	8.2 nm	0.1 nm	6.7×10^{-3} nm
	2s–2p	30 μm	17 nm	0.2 nm	0.01 nm
inverse square law test[15]		36.6 μm	62 μm		
SN1987A[16]		1.14 nm	0.038 nm	0.0048 nm	1.2×10^{-3} nm

Hydrogen

Department of Physics
National Tsing Hua University

- non-relativistic $$En = -\alpha^2 mc^2\left(\frac{1}{2n^2}\right) = \frac{-13.6eV}{n^2}$$
- relativistic correction $$-\alpha^4 mc^2 \frac{1}{4n^2}\left[\frac{2n}{(l+1/2)} - \frac{3}{2}\right]$$
- spin-orbit interaction (L·S, fine structure) $$-\alpha^4 mc^2 \frac{1}{4n^2}\left[\frac{2n}{(j+1/2)} - \frac{3}{2}\right]$$
- QED effect (Lamb shift) $$\alpha^5 mc^2 \frac{1}{4n^3}\left\{k(n,l) \pm \frac{1}{\pi(j+1/2)(l+1/2)}\right\}$$
- nuclear magnetic moment (hyperfine structure) $$\left(\frac{m}{m_p}\right)\alpha^4 mc^2 \frac{4\gamma_p}{3n^2}[f(f+1)-3/2]$$
- nuclear size effect $$\frac{2\pi}{3} Ze^2 |\psi(0)|^2 \langle r^2 \rangle_{proton}$$
- $E = E_{Bohr} + E_{rel} + E_{LS} + E_{Darwin} + E_{HF} + E_{QED} + E_{nuclear}$

The Lamb Shift

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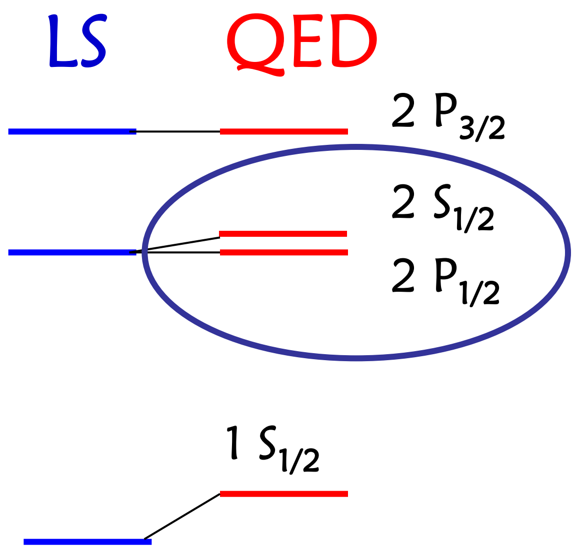
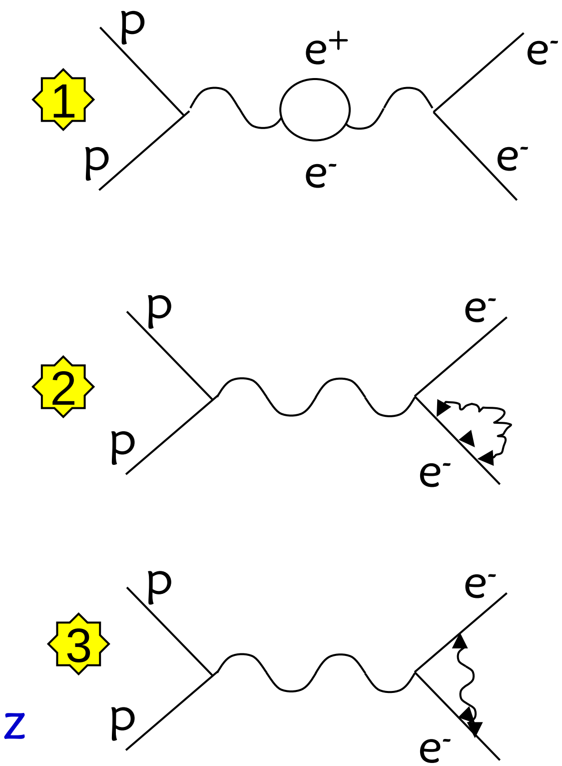
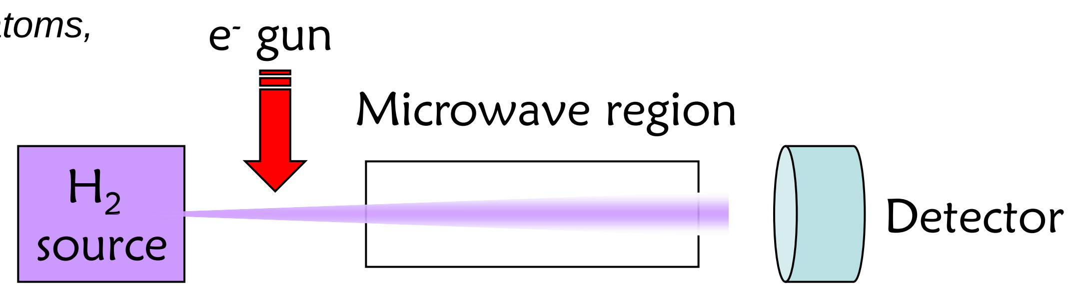




Willis Eugene Lamb
Nobel Prize in Physics 1955
"for his discoveries concerning the fine structure of the hydrogen spectrum"

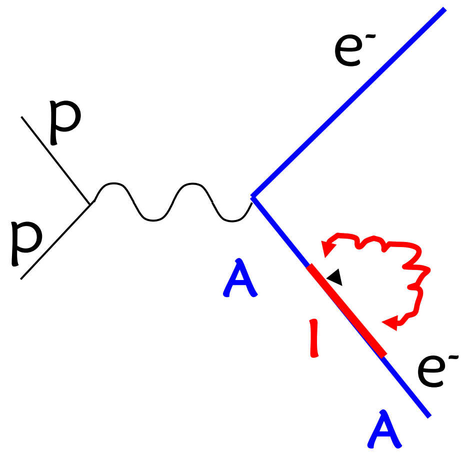
1947 by Lamb ~1060 MHz
Now exp: 1057.845(3) MHz
Now th: 1057.833(4) MHz

Eides et al.,Theory of light hydrogenlike atoms, Physics Reports, 342, 63-261 (2001).



Energy shift due to LED

- Electron mass renormalization
- Energy shift for bound electron



$$\Delta E_A = -\frac{e^2\hbar}{12\pi^2\varepsilon_0 m_e^2 c^3}\ln\frac{E_\gamma^{\max}}{\langle E_I - E_A\rangle_{AVG}}\times\int_{r_{cut-off}}^{\infty} d^3x\cdot|\psi_A|^2\nabla^2 V(x)$$

- *H.A. Bethe, The electromagnetic shift of energy levels, Phys. Rev. 72, 339 (1947).*
- *J.J. Sakurai, Advanced quantum mechanics, p70.*

Next step → put V(x) = V(gravity with ADD)
Integration outside proton, $r_{\text{cut-off}}$ ~ 0.88 fm

Numerical results

- Energy shift due to modified gravity (in eV)

	state	n = 3	n = 4	n = 5	n = 6
Hydrogen	1s	$1.3\times10^{-29}B_3$	$1.0\times10^{-24}B_4$	$7.4\times10^{-20}B_5$	$5.1\times10^{-15}B_6$
	2s	$1.7\times10^{-30}B_3$	$1.3\times10^{-25}B_4$	$9.3\times10^{-21}B_5$	$6.4\times10^{-16}B_6$
Muonium	1s	$6.8\times10^{-24}B_3$	$8.0\times10^{-17}B_4$	$1.0\times10^{-9}B_5$	$1.1\times10^{-2}B_6$
	2s	$0.9\times10^{-24}B_3$	$1.0\times10^{-17}B_4$	$1.3\times10^{-10}B_5$	$1.4\times10^{-3}B_6$

Z.-G. Li, W.-T. Ni and A. Pulido-Paton, Chin. Phys. B ***17****, 70 (2008)*

$B_n = (R_n/0.529\ \text{Å})^n$, R_n : size of LED

Comparison

- $E_{exp} - E_{th}$(no gravity) $= \Delta E$(LED)

$E_{th} = E_{Bohr} + E_{rel} + E_{LS} + E_{Darwin} + E_{HF} + E_{QED} + E_{nuclear}$

For hydrogen atom

E_{QED} = Lamb shift

$= 8171.657 + 1.56 \times r_p^2$ MHz for H 1s state

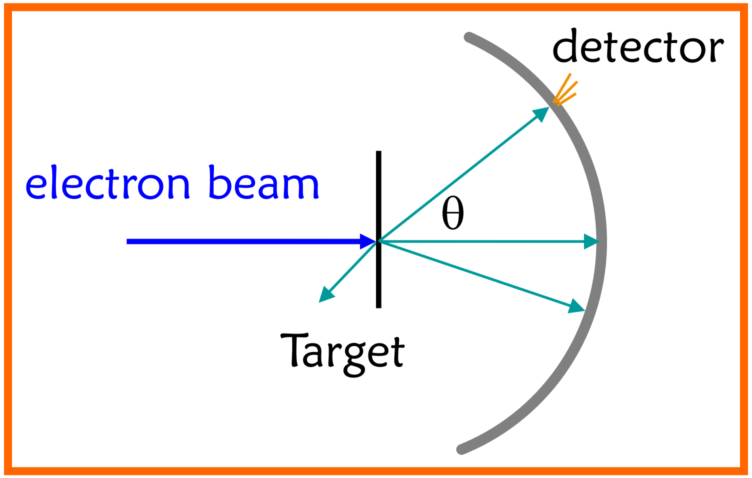
$= 1057.685 + 0.199 \times r_p^2$ MHz for H 2s state

$E_{nuclear} = \underbrace{E_{size}}_{\text{desired}} + \underbrace{E_{polarizibility} + E_{Zemach} + E_{weak}}_{\text{small, th + exp}}$

Electron scattering

- Electron beam on nucleus

$$\left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} = \frac{Z^2\alpha^2(\hbar c)^2}{4E^2\sin^4\frac{\theta}{2}}$$



Nuclei with finite size:

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} * \cos^2\frac{\theta}{2} * \left|G_E(q^2)\right|^2$$

$$< r^2 > = -6\hbar^2 \frac{dG_E(q^2)}{dq^2}\Big|_{q^2=0}$$

Note: not the shape to fit, but the slope at $q^2=0$

Discrepancy

0.862(12) fm, original electron scattering result

G.G. Simon et.al. Nucl. Phys. A **333**, 381 (1980)

0.895(18) fm, re-analysis of world data

I. Sick, Phys. Lett. **B 576**, 62-67 (2003)

0.879(8) fm, new experiment by GSI

J. C. Bernauer et al., Phys. Rev. Lett. **105**, 242001 (2010)

0.883(14) fm, hydrogen spectroscopy, ENS Paris

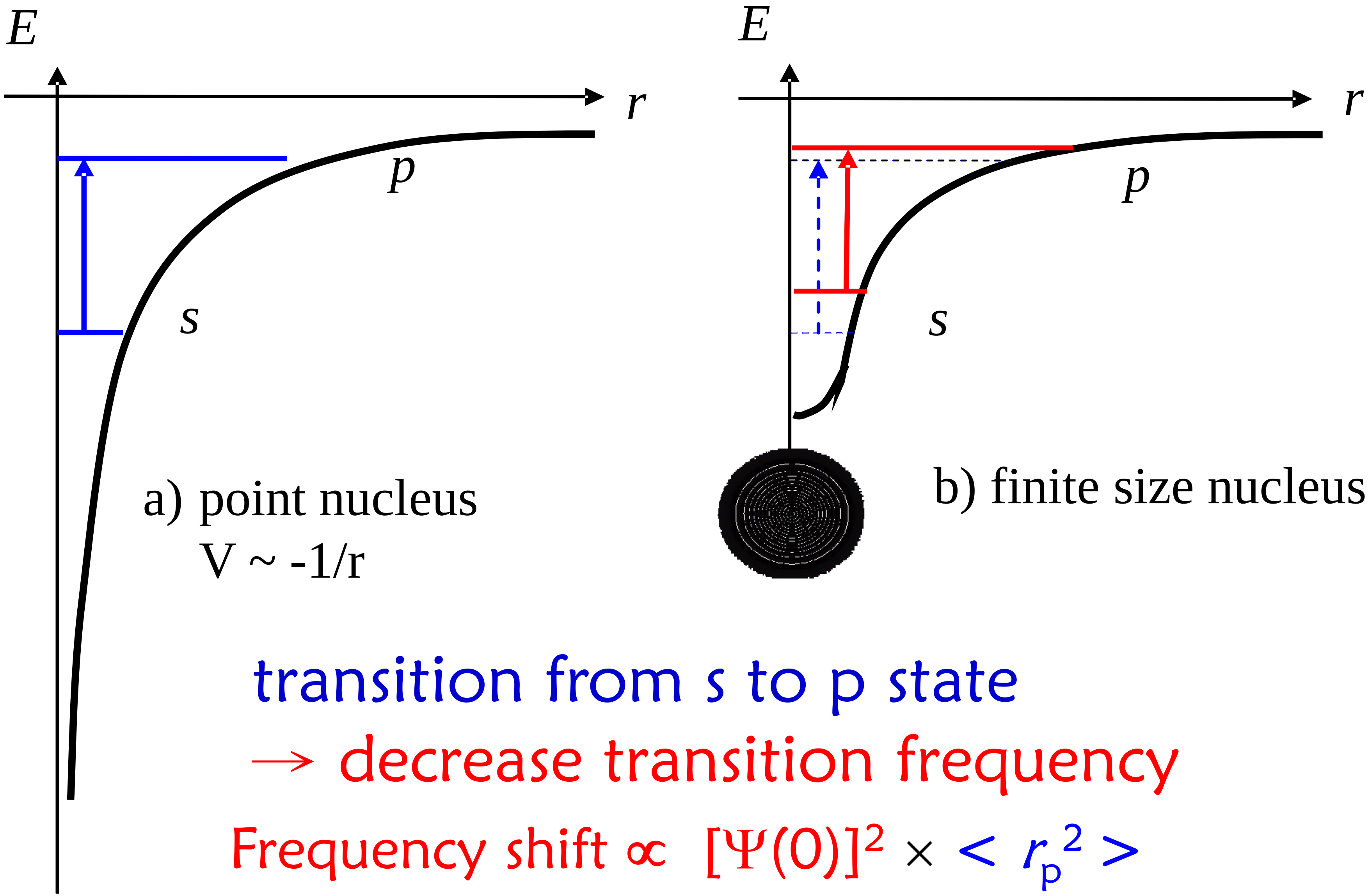
C. Schwob et al., Phys. Rev. Lett. **82**, 4960 (1999).
K. Melnikov and T. van Ritbergen, Phys. Rev. Lett. **84**, 1673(2000).

0.890(14) fm, hydrogen spectroscopy, MPI Garching

T. Udem et al. Phys. Rev. Lett. **79**, 2646, (1997).

0.8775(51) fm, CODATA

Nuclear size effect



transition from s to p state

→ decrease transition frequency

Frequency shift ∝ $[\Psi(0)]^2 \times < r_p^{\,2} >$

Optical frequency measurement

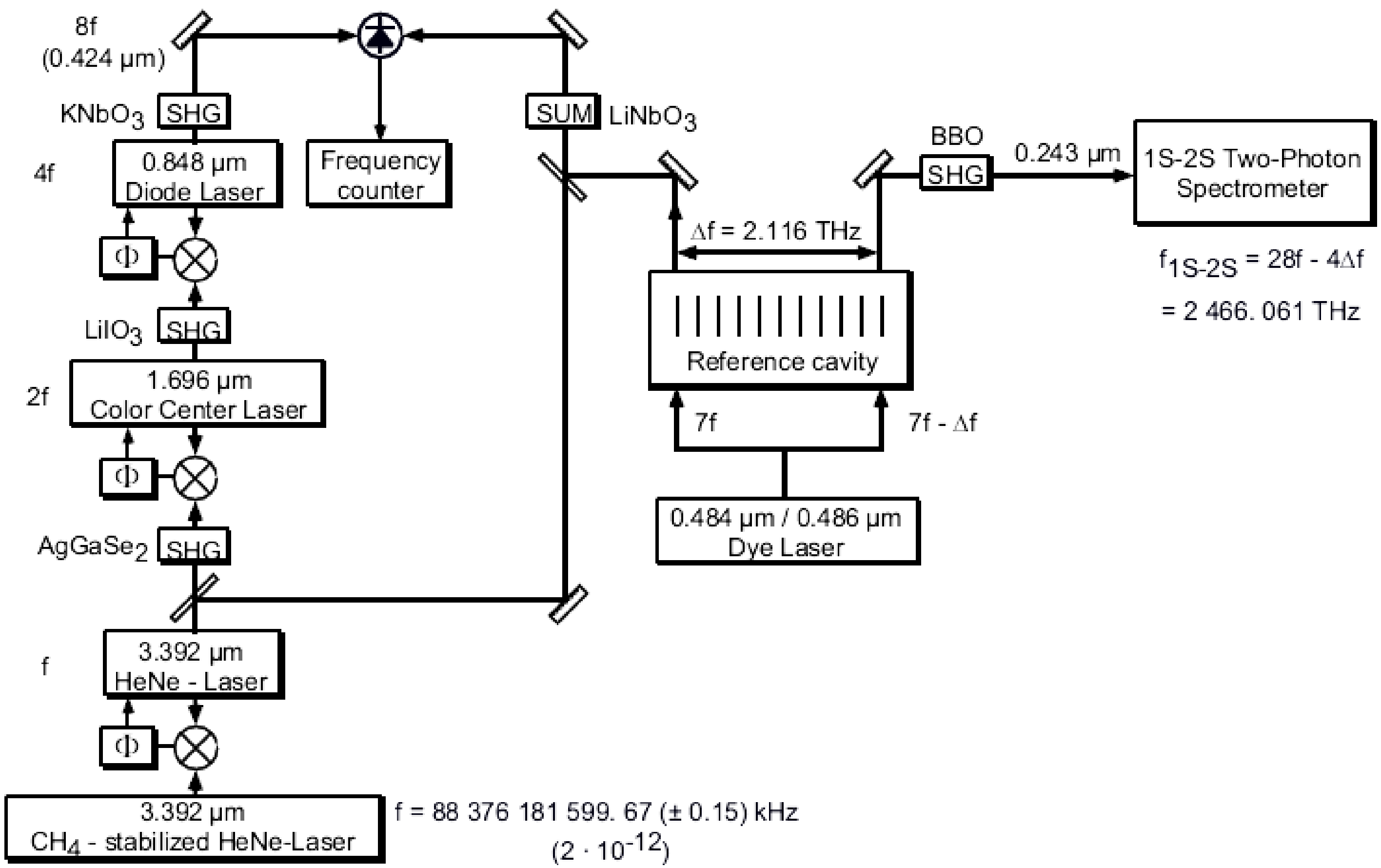


Fig. 4. The first 1992 Garching frequency chain for the measurement of the $1S-2S$ transition in atomic hydrogen (Φ: phase-locked loop, SHG: second harmonic generation)

Frequency chain

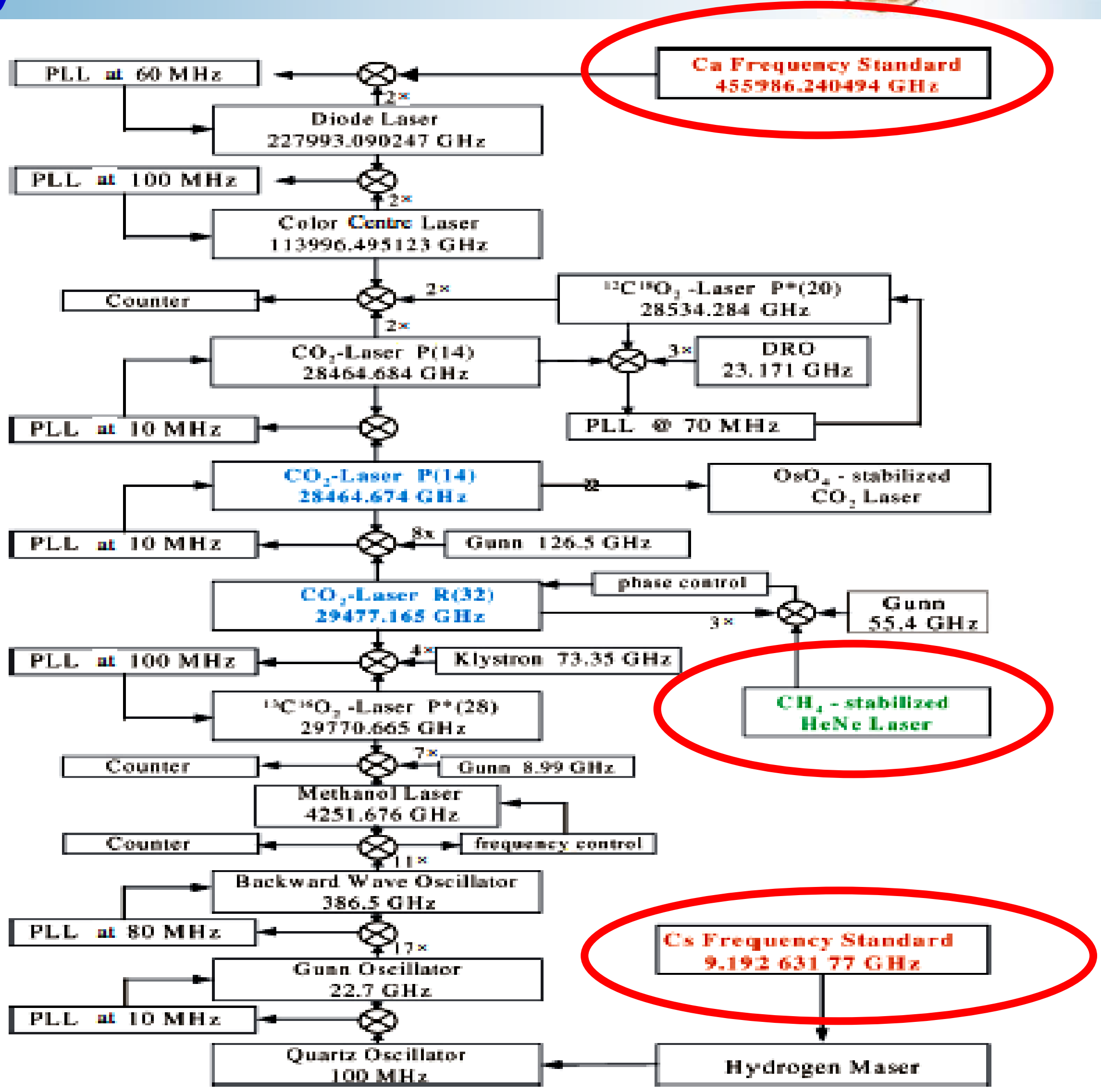
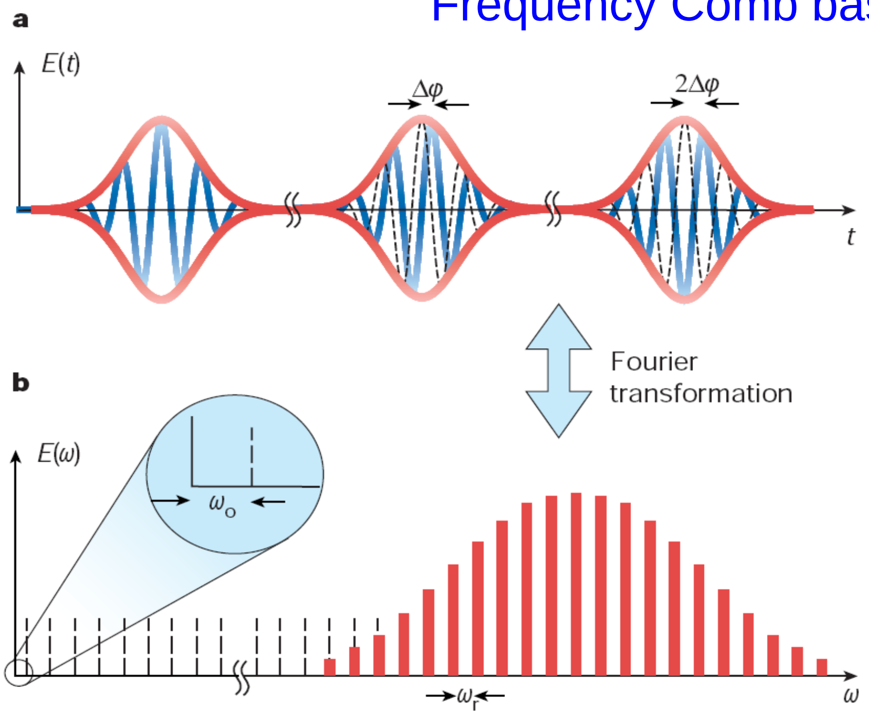


Figure 5. The PTB harmonic frequency chain was the first to achieve a phase-coherent connection between the caesium primary standard and an optical-frequency reference in the visible range. In this case, the target was the calcium optical frequency standard at 457 THz (657 nm). (Adapted with permission from [96].)

Optical atomic clock

- Frequency comb: pioneering work by T.W. Hänsch and J. Hall made frequency measurement possible

Frequency Comb basics



$\omega_n = n\, \omega_r + \omega_{offset}$

ω_r : 50MHz ~ 1GHz

ω_r:
Determined by cavity length

ω_{offset}:
measured by f-2f technique

Picture from Th. Udem, R. Holzwarth, T.W. Hänsch, Nature 416, 233, 2002

Discrepancy

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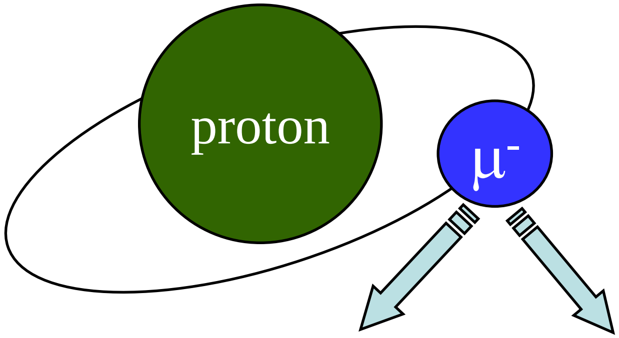
Muonic hydrogen



muon decay $\mu^- \rightarrow e^- \nu \bar{\nu}$

- $m_\mu / m_e \sim 200$
- Bohr radius $a_0 = \dfrac{4\pi\varepsilon_0 \hbar^2}{m_e e^2}$
- Energy level $E_n = -\dfrac{e^4}{2(4\pi\varepsilon_0 \hbar)^2} \dfrac{m_e}{n^2}$
- Wave function $\Psi(r) \sim a_0^{-3/2} e^{-r/a_0}$
- Energy shift due to nuclear size~

$$|\Psi(0)|^2 \langle r^2 \rangle$$

- Sensitivity ~ $(m_\mu / m_e)^2$

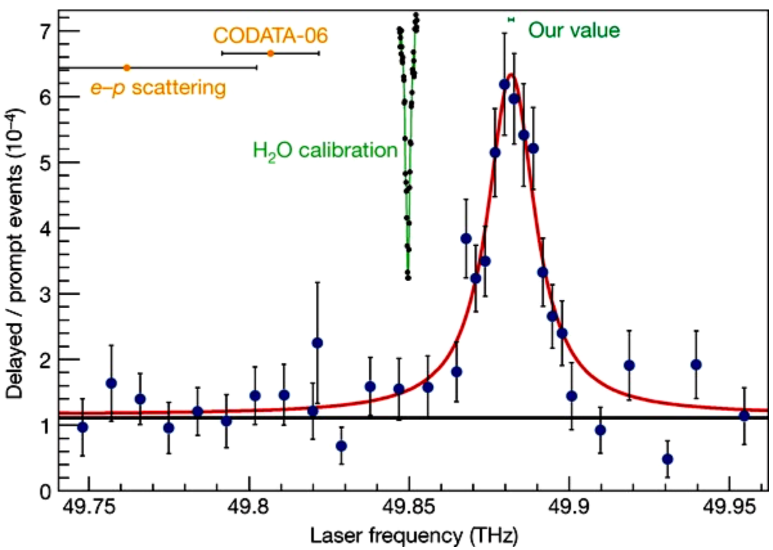
Proton size puzzle

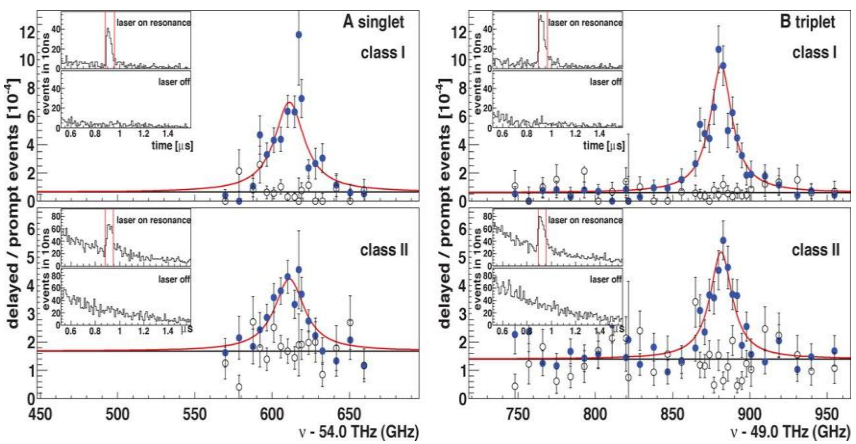
r_p = 0.84184(67) fm

R. Pohl et al, Nature **466**, 213–216, 2010

r_p = 0.84087(39) fm

A. Antognini et al, Science **339**, 417–420, 2013





Comparison

- $E_{exp} - E_{th}$(no gravity) $= \Delta E$(LED)

$$E_{th} = E_{Bohr} + E_{rel} + E_{LS} + E_{Darwin} + E_{HF} + E_{QED} + E_{nuclear}$$

For hydrogen atom

E_{QED} = Lamb shift

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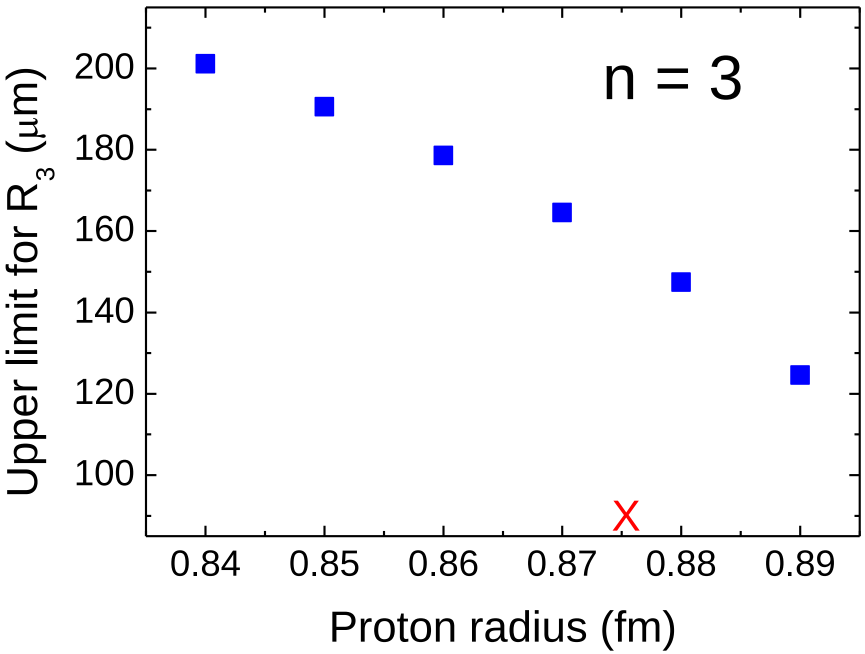
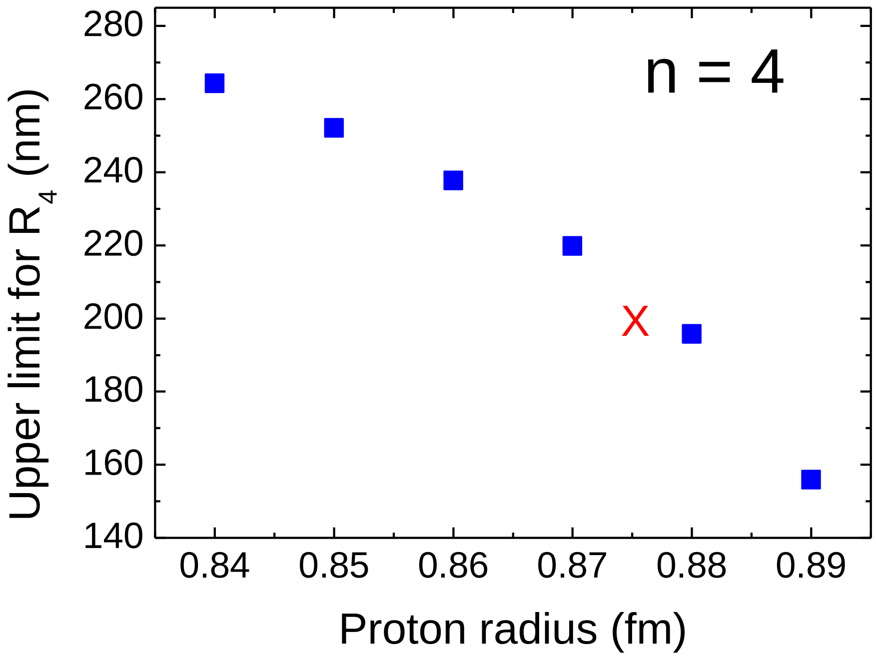
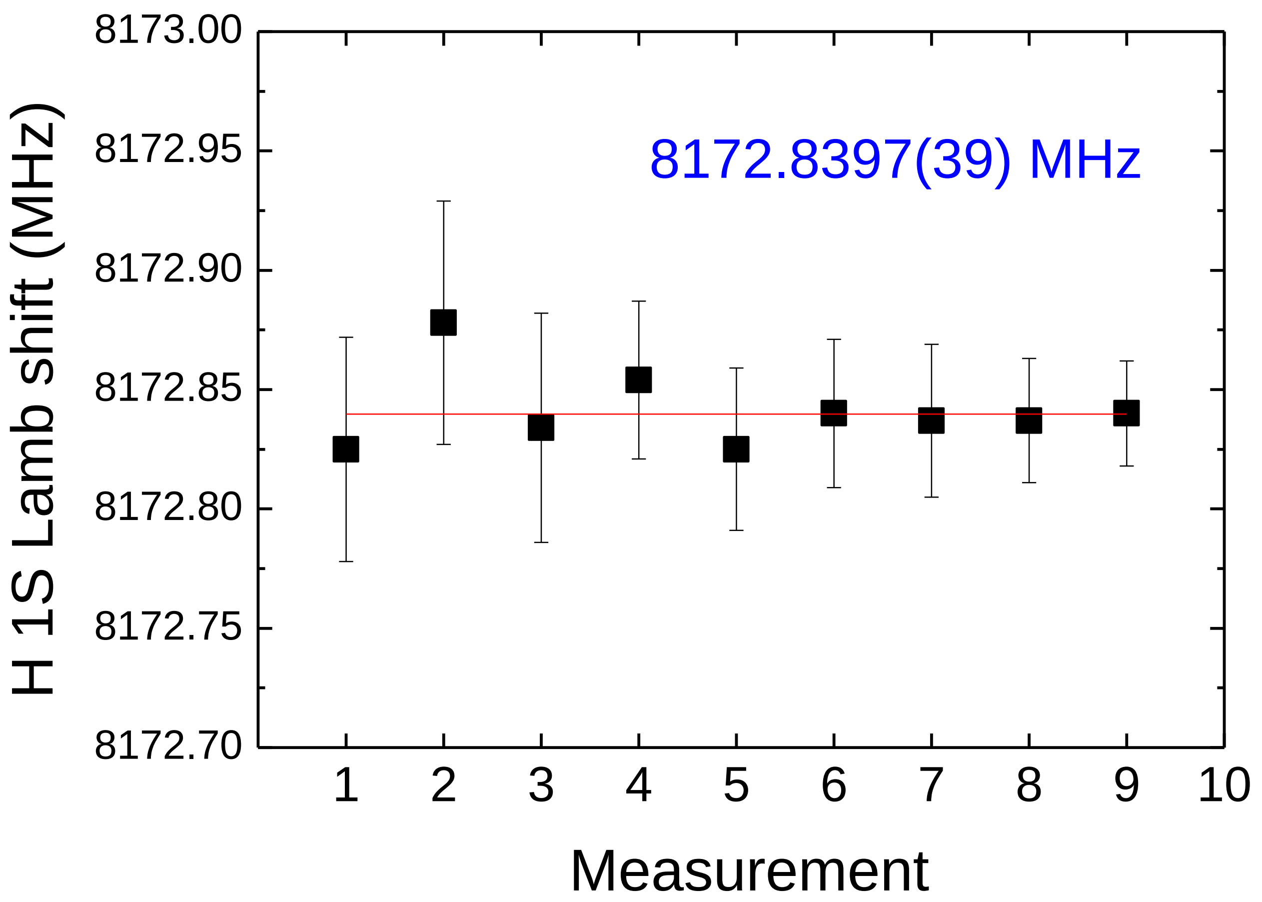
Hydrogen 2S-2P





X: result from Z.G. Li, Chin. Phys. B **17**, 70 (2008)
without including theoretical uncertainties

H 1S-2S



Data summarized in Biraben, et al.: Precision spectroscopy of atomic hydrogen. In: The Hydrogen Atom: Precision Physics of Simple Atomic Systems. Lecture Notes in Physics, vol. 570, p. 17. Berlin Springer Verlag (2001)

Results if no puzzles

- Upper limit for the radius R_n in ADD model

	transition	R_3	R_4	R_5	R_6
Hydrogen	1s-2s	80-160 μm	140-230 nm	3-5 nm	0.2-0.3 nm
	2s-2p	120-200 μm	190-270 nm	4-5 nm	0.3-0.4 nm
Muonium	1s-2s	10 μm	8.2 nm	0.1 nm	0.007 nm
	2s-2p	30 μm	17 nm	0.2 nm	0.01 nm
Inverse square Law		40 μm	62 μm		
Supernova		1 nm	0.04 nm	4.8 pm	1.2 pm

The non-zero nuclear size could affect the atomic transition frequencies due to distortions of the Coulomb potential when the electron has the probability inside the nucleus. This volume effect has been known as field shift in atomic transitions and formed the basis for spectroscopic determination of the nuclear charge radii. For atomic hydrogen, the field shift is (in SI unit):

Proton Radius Puzzle

*The measured rms charge radius r_p = 0.8418(7) fm from Muonic Hydrogen (Pohl et al 2010) is significantly smaller than the CODATA value of 0.8775(39) fm, which is a combined result from electron scattering experiments and atomic hydrogen spectroscopy.
*A recent measurement on the hyperfine transition in muonic hydrogen yields a result of r_p = 0.84087(39) fm and reinforces the proton radius puzzle.
*Numerous investigations have been attempted to explain this puzzle
*they include, for example, multi-photon exchange correction to the electron scattering results
*peculiar electromagnetic form factors that may mislead the interpretation of the scattering data
*and differences in interaction between muon and electron which directly imply physics beyond standard model.
*Pohl and coworkers have recently examined all experimental methods together with theoretical models and conclude the proton radius puzzle is real.

Contribution to Energy level

$$\Delta E = \frac{e^2}{6\varepsilon_0} |\psi(0)|^2 \cdot r_p{}^2$$

to be considered. The total predicted $^2S_{1/2,\,F=1}$ to $^2P_{3/2,\,F=2}$ energy difference is given in Ref. 1

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

where r_p is given in fm. The discrepancy arises when the measured result is different from the predicted value using Eq. (2) and with r_p = 0.8775(39) fm from CODATA.

Namely, 0.31 meV or 75 GHz higher in transition frequency is obtained. No other effects can be found so far to produce such large energy shift. Since the results from electron scattering experiments and hydrogen atomic spectroscopy are in reasonable agreement, the discrepancy has bothered physicists for years after the result was announced and is the so-called proton radius puzzle.

due to vanishing wave function at origin. If we assume V_{LED} acts as a small perturbation, the energy shift due to the new interaction can be estimated using perturbation theory and is set to be 0.31 meV to make up the higher measured transition energy.

$$\Delta E_{LED} = \int \psi_{2S}^{*} V_{LED} \psi_{2S} d\tau = 0.31 \text{ meV} \tag{3}$$

where $\psi_{2S} = (8\pi)^{-1/2}(a_0)^{-\frac{3}{2}} \cdot e^{-\frac{r}{2a_0}}(1 - r/2a_0)$, $a_0 = 2.85 \times 10^{-13}$ m is the Bohr radius of the

Results

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Table 1. The size R_n and mass scale $M_{pl(4+n)}$ of LED which gives correct energy contribution 0.31 meV to solve the proton radius puzzle in hard core models with core radius r_0 of 1 fm, 1 am, 0.1 am and 0.02 am. The last one corresponds to the smallest length scale LHC can probe.

n	Size (R_n) in m and mass scale $M_{pl(4+n)}$ in TeV/c^2 of the LED				
		$r_0 = 1$ fm	$r_0 = 1$ am	$r_0 = 0.1$ am	$r_0 = 0.02$ am
3	R_n	5.0×10^{-4}	4.8×10^{-5}	2.2×10^{-5}	1.3×10^{-5}
	$M_{pl(4+n)}$	4.8×10^{-4}	2.0×10^{-3}	3.1×10^{-3}	4.3×10^{-3}
4	R_n	6.8×10^{-7}	2.2×10^{-8}	6.8×10^{-9}	3.1×10^{-9}
	$M_{pl(4+n)}$	2.8×10^{-4}	2.8×10^{-3}	6.0×10^{-3}	1.0×10^{-2}
5	R_n	1.3×10^{-8}	2.0×10^{-10}	5.1×10^{-11}	1.9×10^{-11}
	$M_{pl(4+n)}$	1.9×10^{-4}	3.7×10^{-3}	9.9×10^{-3}	2.0×10^{-2}
6	R_n	9.0×10^{-10}	8.7×10^{-12}	1.9×10^{-12}	6.4×10^{-13}
	$M_{pl(4+n)}$	1.5×10^{-4}	4.7×10^{-3}	1.5×10^{-2}	3.3×10^{-2}
7	R_n	1.3×10^{-10}	9.2×10^{-13}	1.8×10^{-13}	5.6×10^{-14}
	$M_{pl(4+n)}$	1.2×10^{-4}	5.7×10^{-3}	2.0×10^{-2}	5.9×10^{-2}

ADD and LHC ATLAS

ADD mass scale below 2 TEV ix excluded

Search for Dark Matter Candidates and Large Extra Dimensions in Events with a Photon and Missing Transverse Momentum in pp Collision Data at $\sqrt{s} = 7$ TeV with the ATLAS Detector

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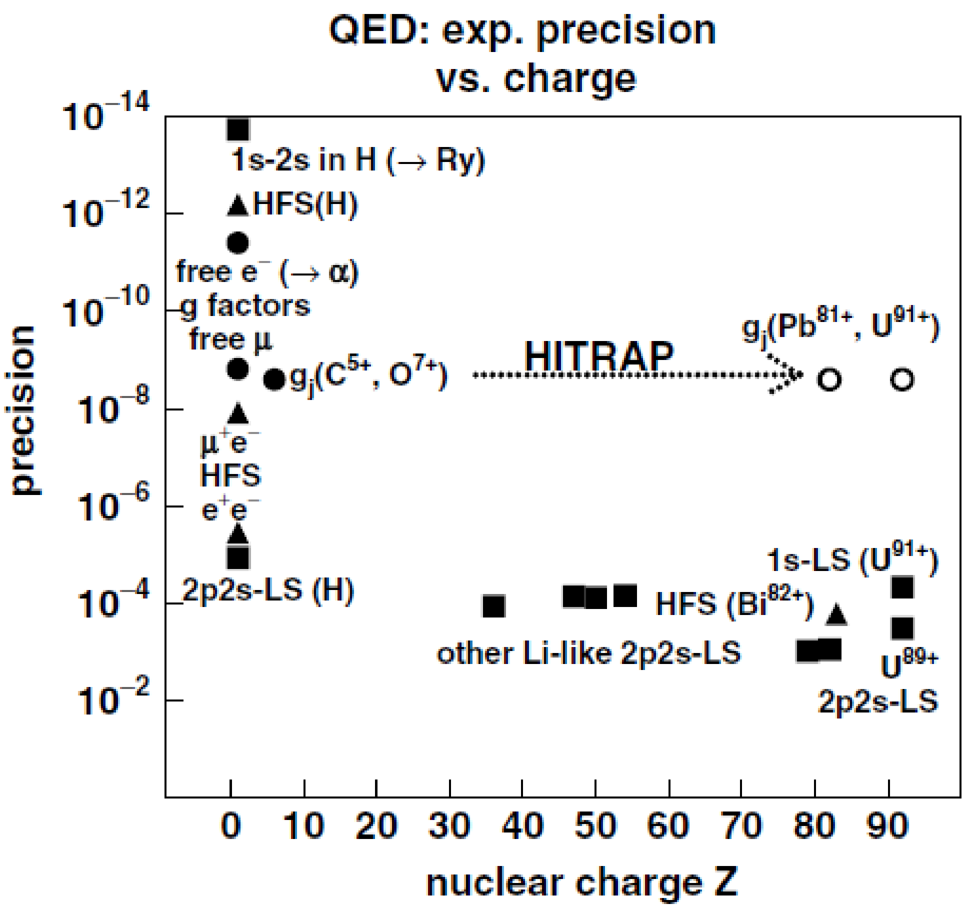
(Received 20 September 2012; published 3 January 2013)

Results of a search for new phenomena in events with an energetic photon and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7$ TeV are reported. Data collected by the ATLAS experiment at the LHC corresponding to an integrated luminosity of 4.6 fb^{-1} are used. Good agreement is observed between the data and the standard model predictions. The results are translated into exclusion limits on models with large extra spatial dimensions and on pair production of weakly interacting dark matter candidates.

Trapping ions of hydrogen-like uranium: The HITRAP project at GSI, Thomas Beier et al 2005

Current status of the experimental precision in leading QED-investigating experiments together with the expected improvement by HITRAP. Data have been taken from [8,9,2,10–13,5,6,14–23]. In the high-Z region, only selected systems of hydrogen-like up to lithium-like ions are shown. For the low-Z region, only a few systems can be displayed. Triangles mark hyperfine-structure splittings, squares indicate level shifts (Lamb shift) and circles denote g-factors



Conclusion

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- Sensitivity using atomic transitions better than torsion balance experiments
- Indication of new physics from extra dimensions from the proton radius puzzle???
- For muonic deuterium, the energy shift of the same transition is 0.73 meV (176 GHz), mainly due to the stronger gravitational force from the deuteron and also from slightly reduced Bohr radius in the muonic deuterium system.
- More spectroscopic experiments on muonic hydrogen, muonic deuterium and muonium are important to test this scenario.
- Once proton size puzzle resolved in other ways, more stringent constraint can obtained

THANK YOU!!