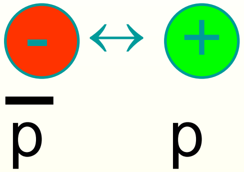
Low Energy Antiproton Experiments - A Review

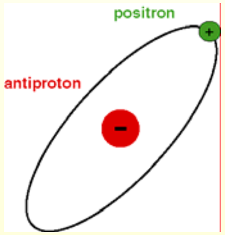
Physics with Ultraslow Antiproton Beams

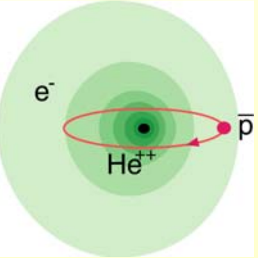
Riken Wako Japan, 14-16 March 2005

Klaus Jungmann, Kernfysisch Versneller Instituut,Groningen

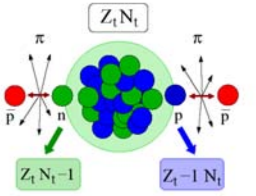


- **Atomic-, Nuclear-, Particle-Physics**
- **Forces and Symmetries**
- **Discrete Symmetries**
- **Properties of Known Basic Interactions**
- **Particles and Anti-Particles**
- **Hydrogen and Hydrogen-like Atoms**
- **Fundamental Constants**

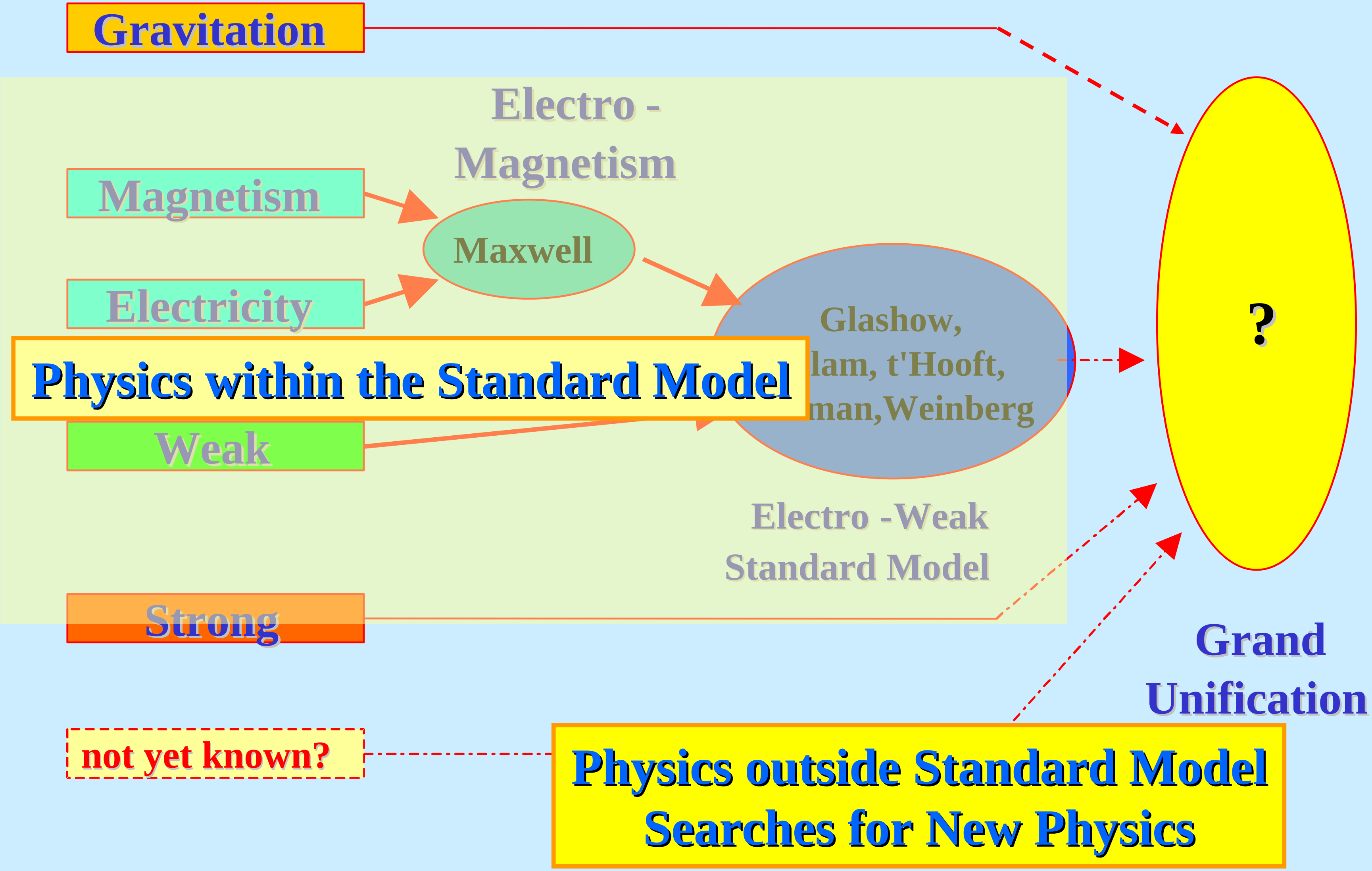




⇒ **only touching a few examples**



Fundamental Interactions – Standard Model



Gravitation

Electro - Magnetism

Magnetism

Maxwell

Electricity

Glashow,
lam, t'Hooft,
man,Weinberg

Physics within the Standard Model

Weak

Electro -Weak
Standard Model

Strong

?

Grand Unification

not yet known?

Physics outside Standard Model
Searches for New Physics

What are we concerned with ?

fundamental := “ forming a foundation or basis a principle, law etc. serving as a basis”

Standard Model

- 3 Fundamental Forces
  - Electromagnetic Weak Strong
- 12 Fundamental Fermions
  - Quarks, Leptons
- 13 Gauge Bosons
  - γ,W^+, W^-, Z^0, H, 8 Gluons

However

- many open questions
  - Why 3 generations ?
  - Why some 30 Parameters?
  - Why CP violation ?
  - Why us?
  - …..
- Gravity not included
- No Combind Theory of Gravity and Quantum Mechanics

What are we concerned with ?

fundamental := “ forming a foundation or basis a principle, law etc. serving as a basis”

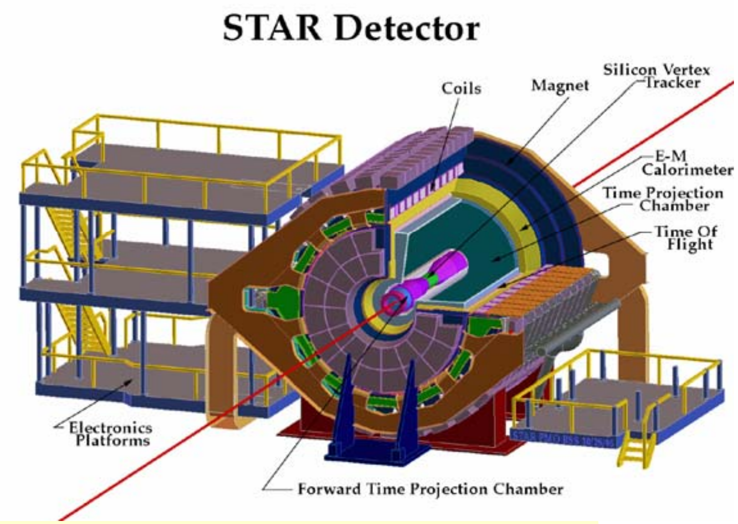
Forces and Symmetries

Local Symmetries ⇔ Forces
- fundamental interactions

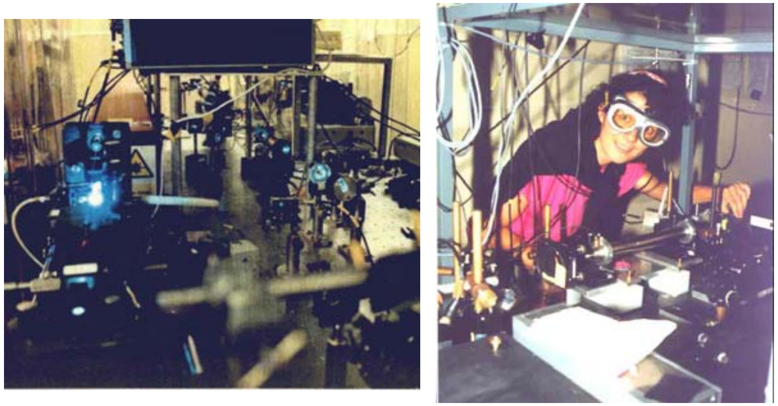
Global Symmetries ⇔ Conservation Laws
- energy
- momentum
- electric charge
- …..
- lepton number
- charged lepton family number
- baryon number
- …..

TRIμP

Possibilities to Test New Models



⇔



High Energies
& direct observations

Low Energies
& Precision Measurements

Discovery of Deuterium

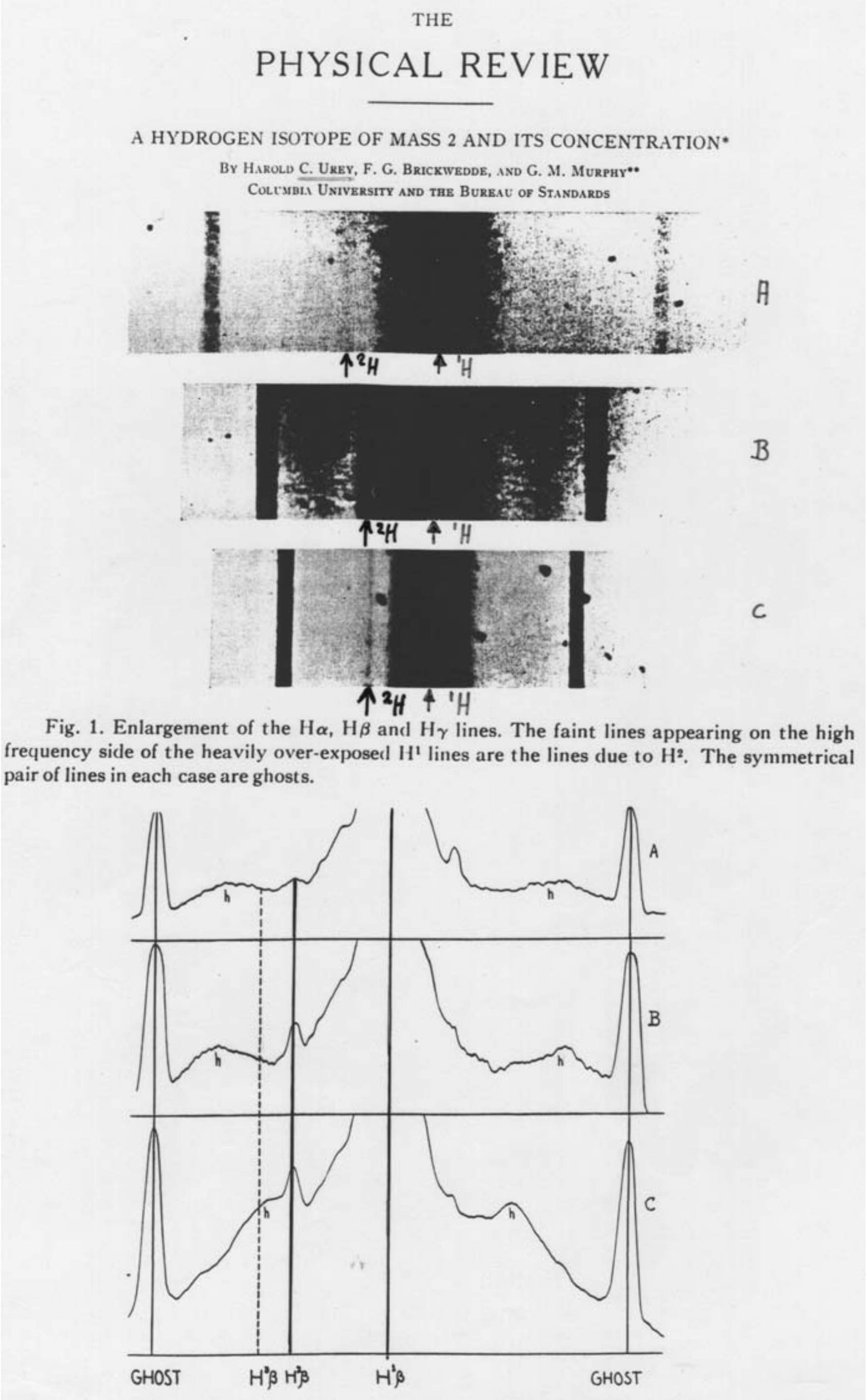
- A barely visible shadow in hydrogen spectral lines
- Reduced mass

$$\mu_{red} = \frac{m_{nucleus} * m_{electron}}{m_{nucleus} + m_{electron}}$$

used for identification

- $\mu_{red}(H) - \mu_{red}(D) = 2{,}7 \cdot 10^{-4}$

- Significant impact



THE

PHYSICAL REVIEW

A HYDROGEN ISOTOPE OF MASS 2 AND ITS CONCENTRATION*

By Harold C. Urey, F. G. Brickwedde, and G. M. Murphy**

Columbia University and the Bureau of Standards

Fig. 1. Enlargement of the Hα, Hβ and Hγ lines. The faint lines appearing on the high frequency side of the heavily over-exposed H¹ lines are the lines due to H². The symmetrical pair of lines in each case are ghosts.

Urey, Columbia University, New York(1932)

Some Fundamental Systems in Atomic Physics

(With Precision Experiments)

* Single particles

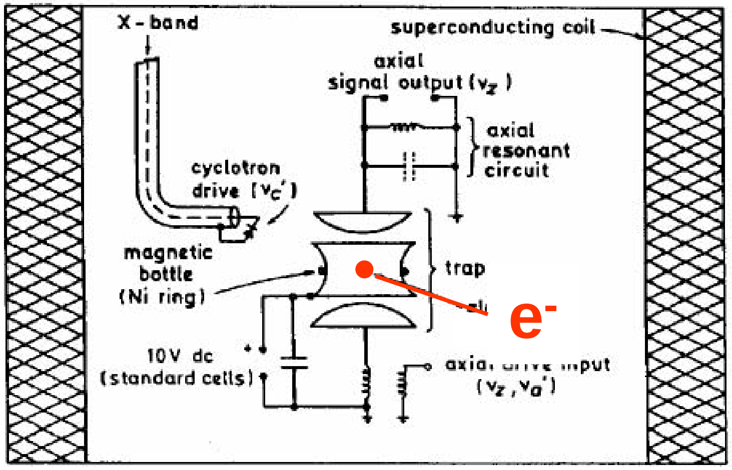
e^+, e^-	magnetic anomaly	*Dehmelt et al.*	*('87)*
	⇒ fine structure constant α	*Kinoshita et al.*	*('98)*
$p, \bar{p}$	charge - mass ratio	*Gabrielse et al.*	*('99)*
	⇒ Test of CPT symmetry		
n	search for edm	*Ramsey,*	
	⇒ Test of CP / T symmetry	*Pendlebury et al.*	*('99)*
μ^+, μ^-	magnetic anomaly	*Hughes,Roberts,Morse*	
	⇒ Conf. St. Mod./New Physics ?	*et.al.*	*('04)*

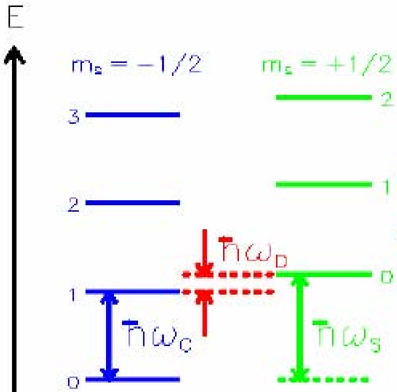
* Bound States

$H=(pe^-)$	hyperfine structure	*Essen, Hellwig et al.*	
	⇒ clock		*('71)*
	1s - 2s	*Hänsch, Biraben,*	*('99)*
	⇒ Rydberg constant R_{∞}	*Boshier et al.*	*('95)*
Cs	P violation experiments	*Wieman et al.*	*('99)*
	⇒ Test of Standard Model		
$Ps=(e^+e^-)$	(hyper)fine structure	*Hughes et al.*	*('84)*
	⇒ Test of QED	*Mills et al.*	*('83)*
	1s - 2s	*Chu et al.*	*('93)*
	⇒ m_{e-}/m_{e+}		
$M=(\mu^+e^-)$	hyperfine splitting,		
	1s - 2s	*Hughes, Jungmann* *et al. ('99,'00,'01)*	
	⇒ fundamental constants, CPT & search for new physics		

Electron Magnetic Anomaly

$$a_e = \frac{g_e - 2}{2}$$





$$a_e = \frac{\omega_D}{\omega_C}$$

Experiment : $a_{e+} = 1\,159\,652\,187.9\,(4.3) \bullet 10^{-12}$

(Dehmelt et al. 1987) $a_{e-} = 1\,159\,652\,188.4\,(4.3) \bullet 10^{-12}$

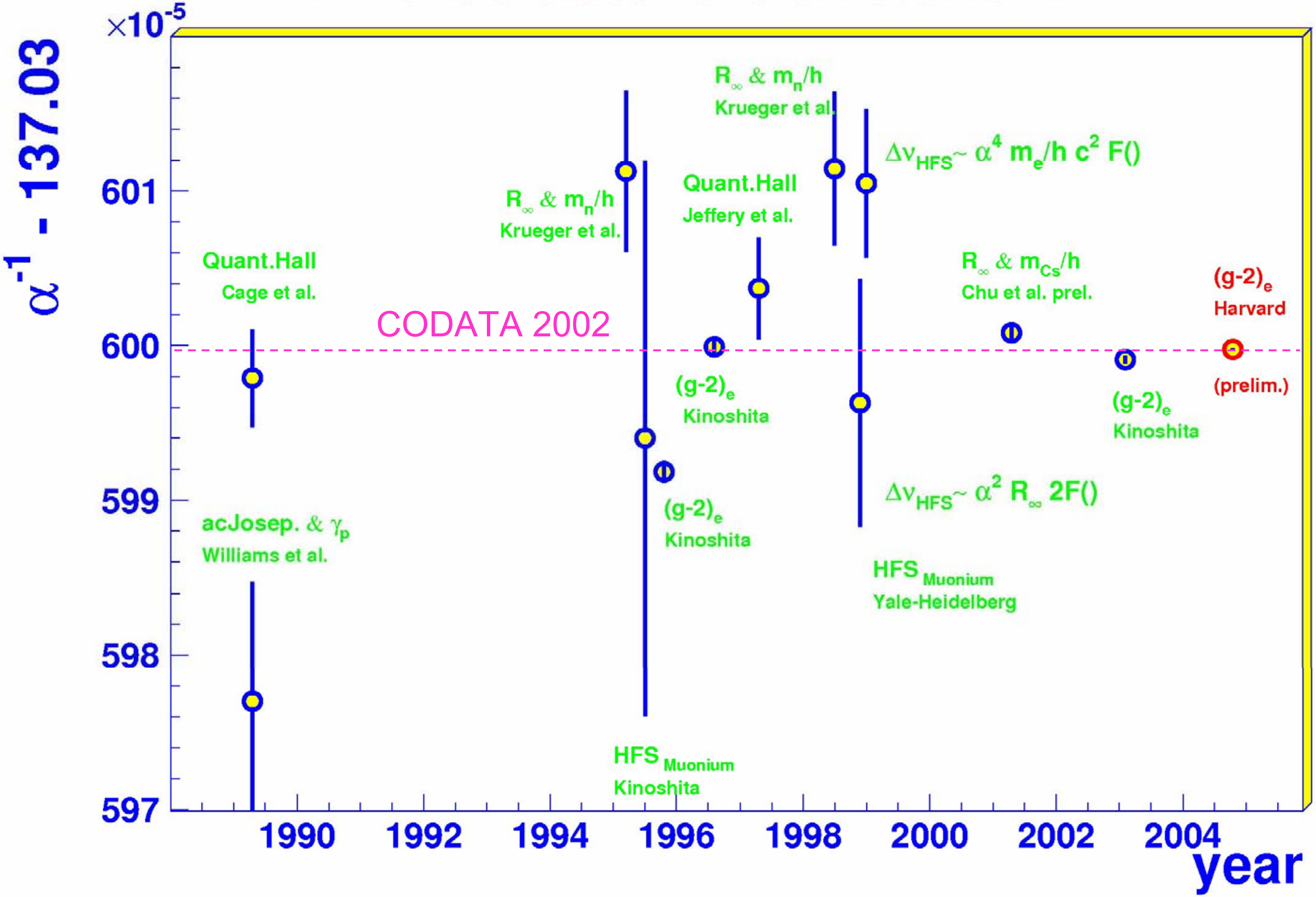
Theory: $a_{e\pm} = 1\,159\,652\,176.4\,(0.3)(8.5) \bullet 10^{-12}$ ← *with* $\boldsymbol{\alpha}$ *from Cs photon recoil,* R_∞ *&* m_{Cs}

(Kinoshita 2004) $$=0.5\left(\frac{\alpha}{\pi}\right) - 0.328\,478\,965...\left(\frac{\alpha}{\pi}\right)^2 + 1.181\,241\,456...\left(\frac{\alpha}{\pi}\right)^3 - 1.709(38)\left(\frac{\alpha}{\pi}\right)^4 + ... + \boxed{4.4*10^{-12}}$$

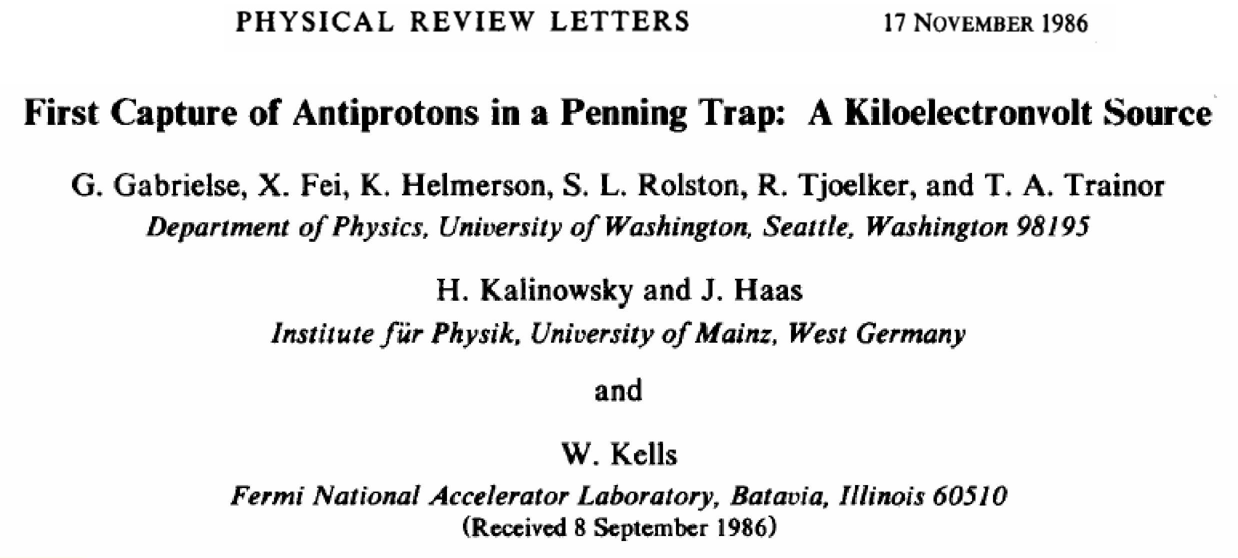
μ,τ, hadrons, W, Z

alternatively: $\Rightarrow \alpha^{-1} = 137.\,035\,998\,90\,(50)$

Fine Structure Constant α



K. Jungmann, 03-2005



PHYSICAL REVIEW LETTERS 17 NOVEMBER 1986

First Capture of Antiprotons in a Penning Trap: A Kiloelectronvolt Source

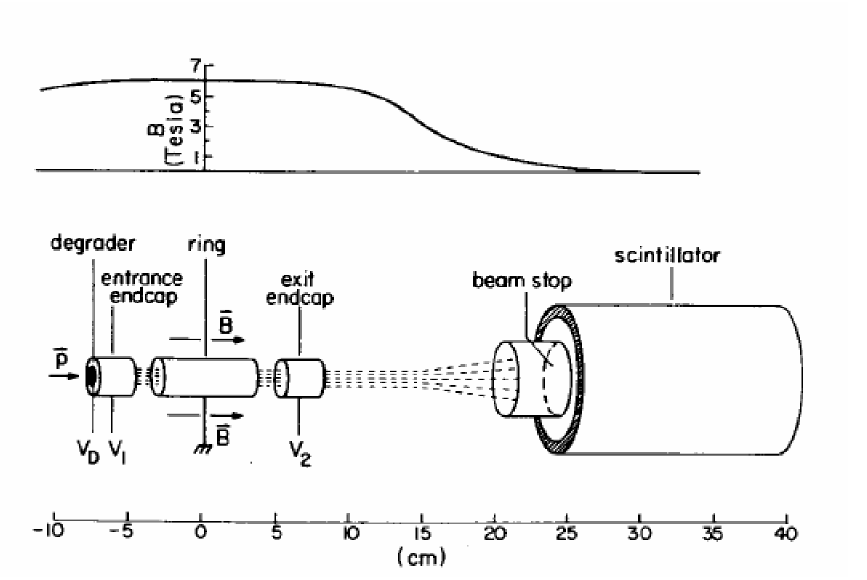
G. Gabrielse, X. Fei, K. Helmerson, S. L. Rolston, R. Tjoelker, and T. A. Trainor
Department of Physics, University of Washington, Seattle, Washington 98195

H. Kalinowsky and J. Haas
Institute für Physik, University of Mainz, West Germany

and

W. Kells
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

(Received 8 September 1986)



VOLUME 74, NUMBER 18 PHYSICAL REVIEW LETTERS 1 MAY 1995

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Special Relativity and the Single Antiproton: Fortyfold Improved Comparison of $\bar{p}$ and p Charge-to-Mass Ratios

G. Gabrielse, D. Phillips, and W. Quint*
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

H. Kalinowsky and G. Rouleau†
Institut für Physik, Universität Mainz, 55099 Mainz, Germany

W. Jhe
Department of Physics, Seoul National University, Seoul 151-742, Korea

(Received 17 October 1994; revised manuscript received 3 April 1995)

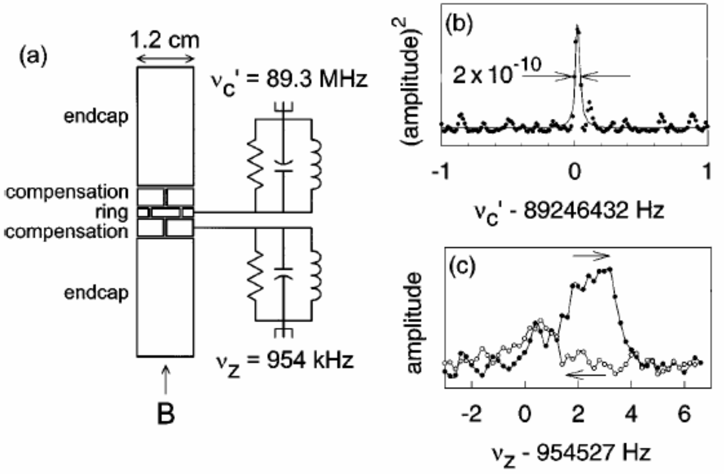


FIG. 2. Open access Penning trap electrodes and detection circuits in (a), with the cyclotron (b), and axial (c) signals from one trapped $\bar{p}$.

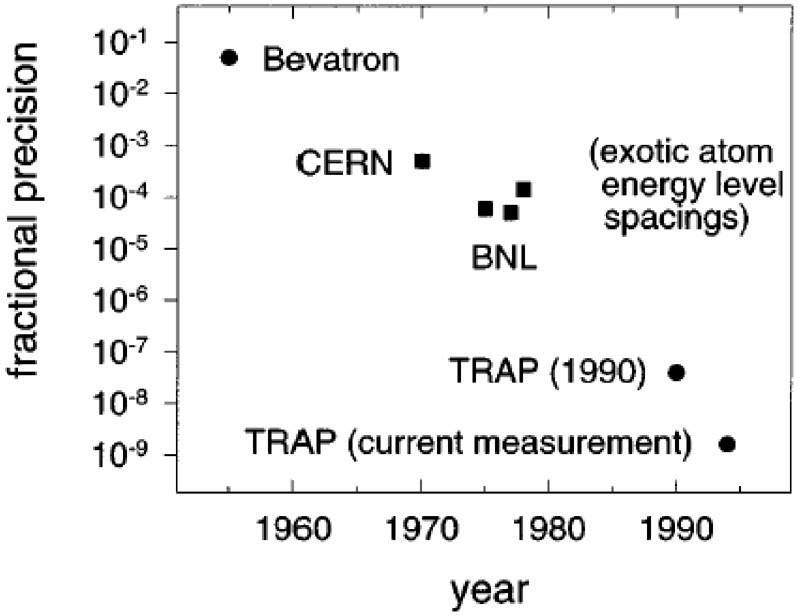


FIG. 1. Comparisons of charge-to-mass ratios (circles) and inertial masses (squares) for $\bar{p}$ and p.

$\Rightarrow$

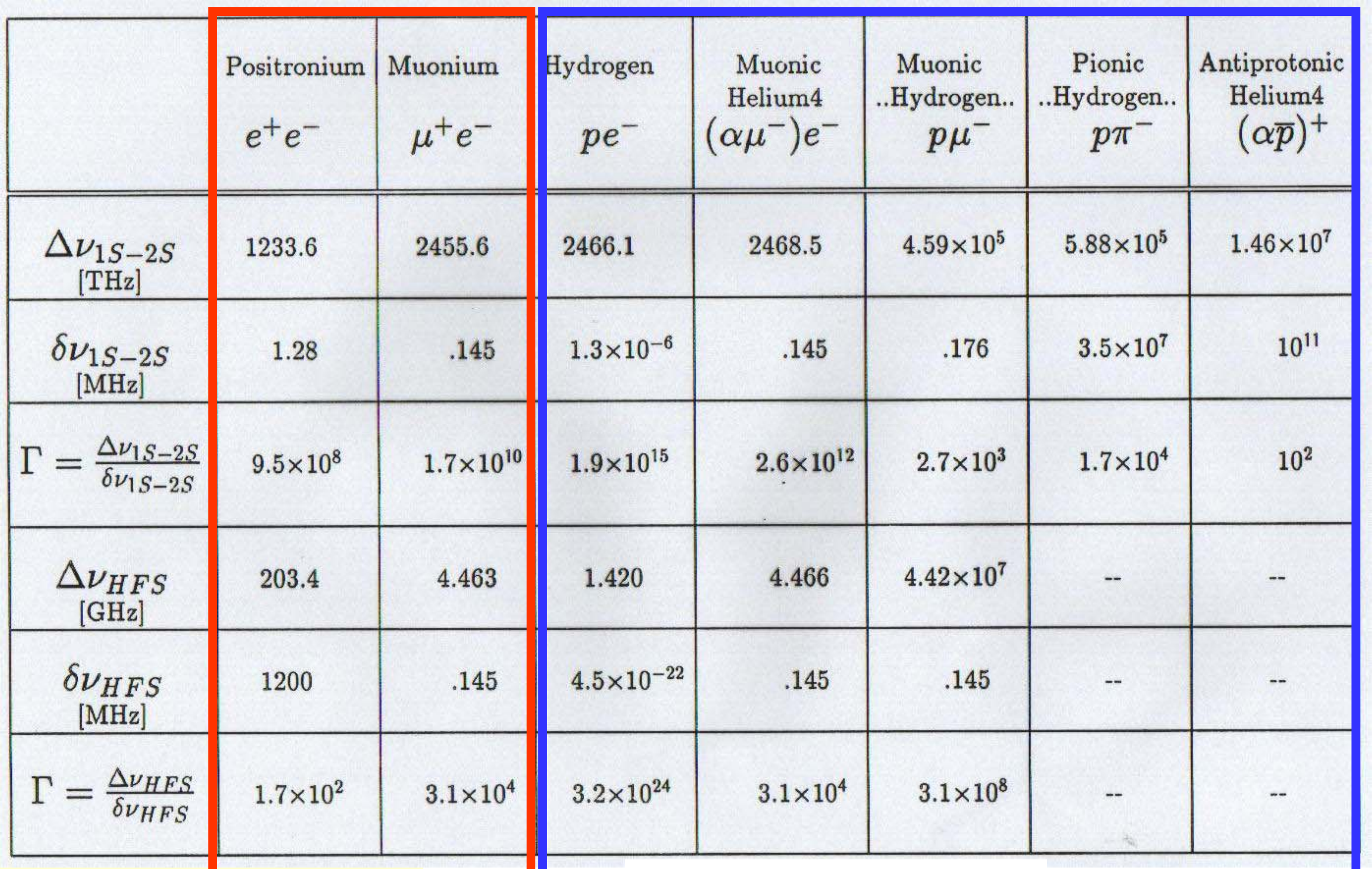
Proton and Antiproton q/m compare to 0.1 ppb

Clock Comparisons

$\Rightarrow$

Proton and Antiproton gravitational accceleration equal to 1 ppm

Hydrogen-like Atoms



	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen pe^-	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\bar{p})^+$
$\Delta\nu_{1S-2S}$ [THz]	1233.6	2455.6	2466.1	2468.5	4.59×10^5	5.88×10^5	1.46×10^7
$\delta\nu_{1S-2S}$ [MHz]	1.28	.145	1.3×10^{-6}	.145	.176	3.5×10^7	10^{11}
$\Gamma = \frac{\Delta\nu_{1S-2S}}{\delta\nu_{1S-2S}}$	9.5×10^8	1.7×10^{10}	1.9×10^{15}	2.6×10^{12}	2.7×10^3	1.7×10^4	10^2
$\Delta\nu_{HFS}$ [GHz]	203.4	4.463	1.420	4.466	4.42×10^7	--	--
$\delta\nu_{HFS}$ [MHz]	1200	.145	4.5×10^{-22}	.145	.145	--	--
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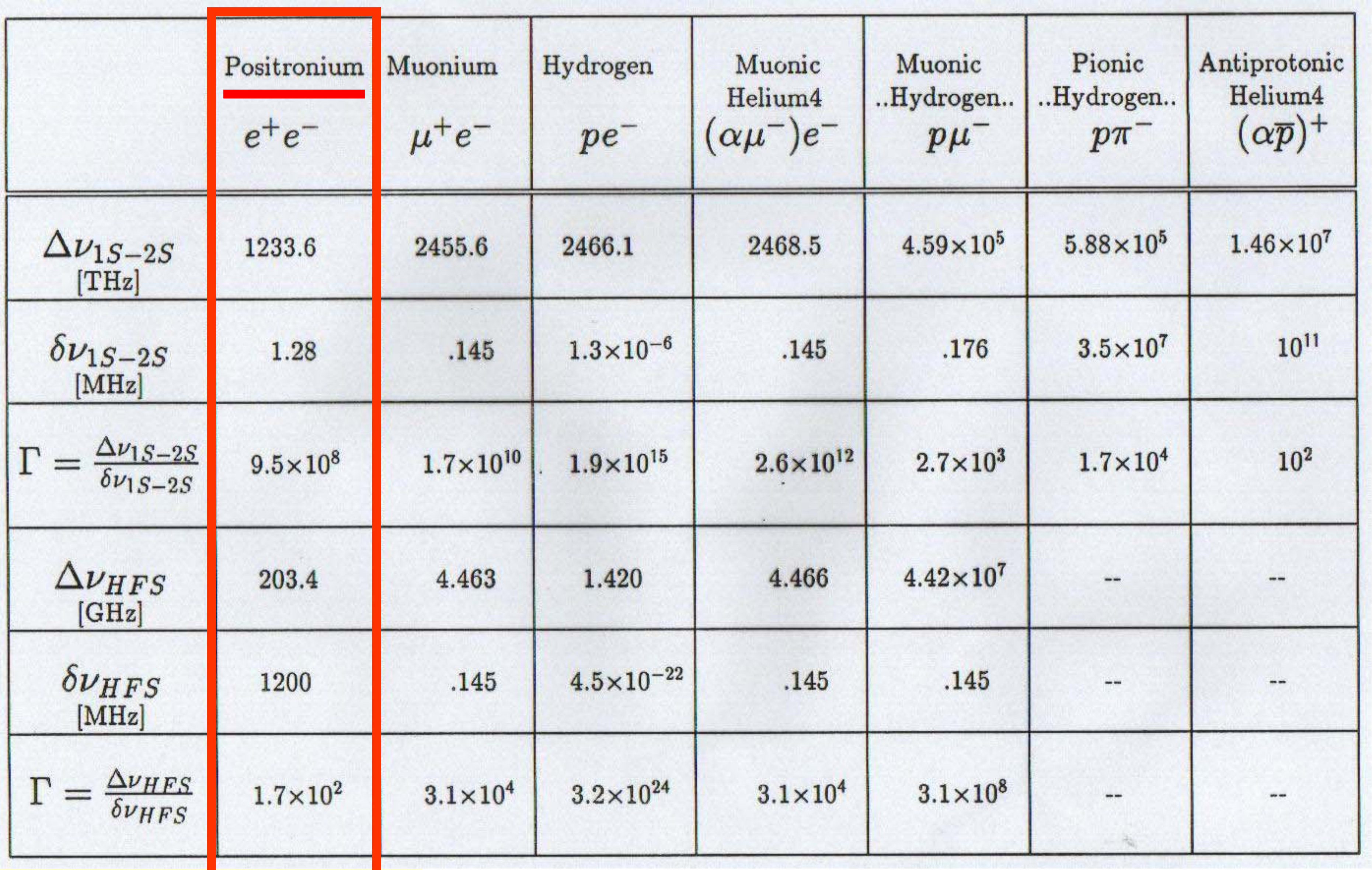
leptonic

hadronic

Hydrogen-like Atoms



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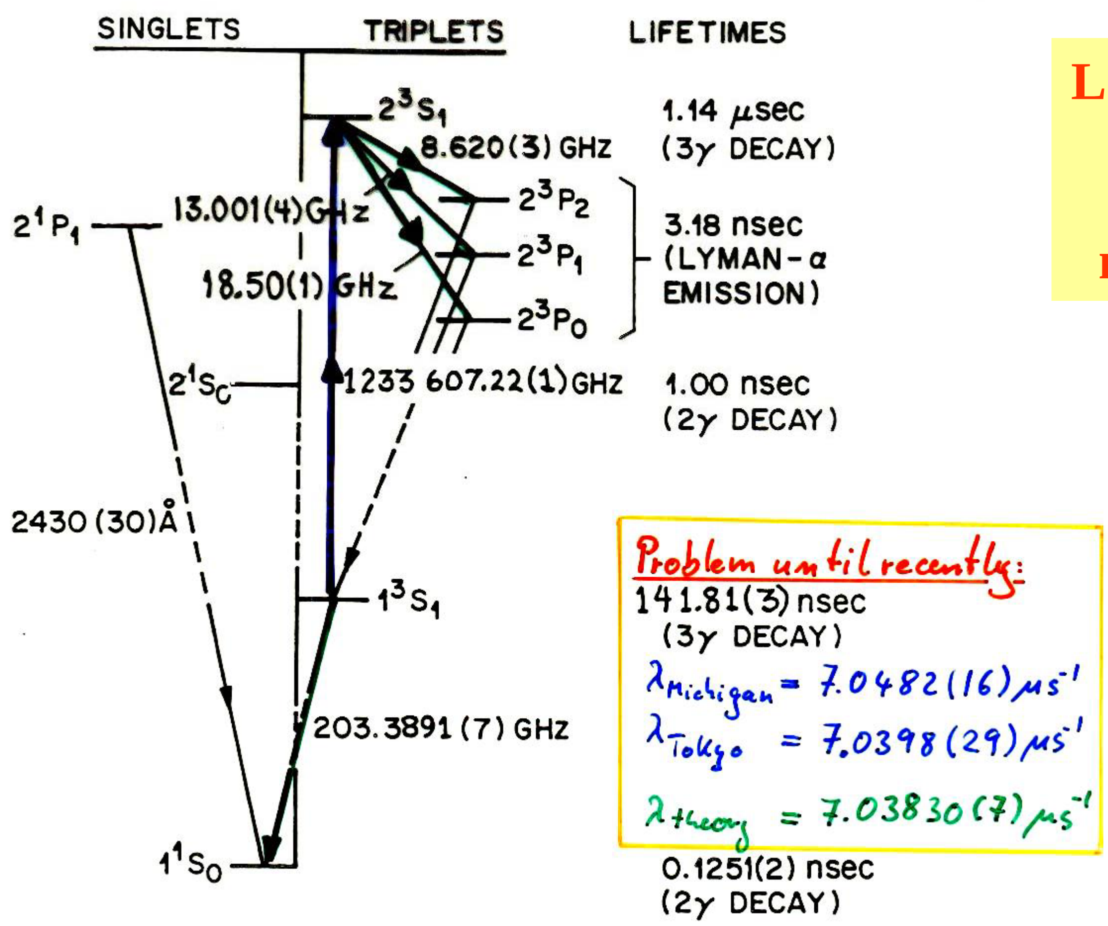
POSITRONIUM SPECTROSCOPY



Problem until recently:

141.81(3) nsec
(3γ DECAY)

$\lambda_{Michigan} = 7.0482(16)\,\mu s^{-1}$

$\lambda_{Tokyo} = 7.0398(29)\,\mu s^{-1}$

$\lambda_{theory} = 7.03830(7)\,\mu s^{-1}$

Fig. 1 Energy levels of the n=1 and n=2 states of positronium. The quantities with error estimates in parentheses are measured values. [A.P. Mills & S. Chu, 1990]

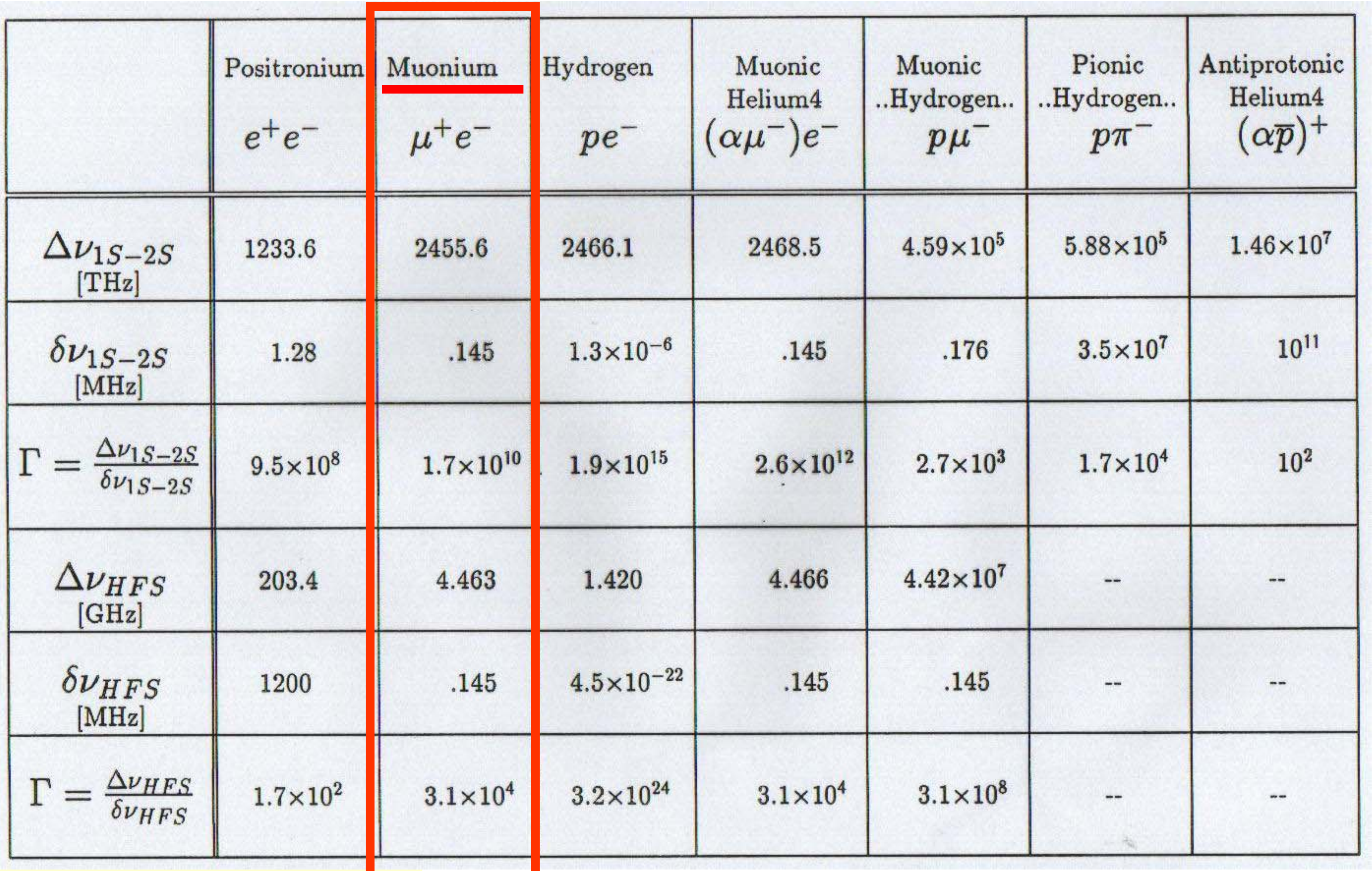
All measurements in agreement with theory (now)!

Laser spectroscopy 1s-2s

(Chu,Mills et al.)

$m_{e^-} = m_{e^+}$ ***at 10^{-8} level***

Hydrogen-like Atoms



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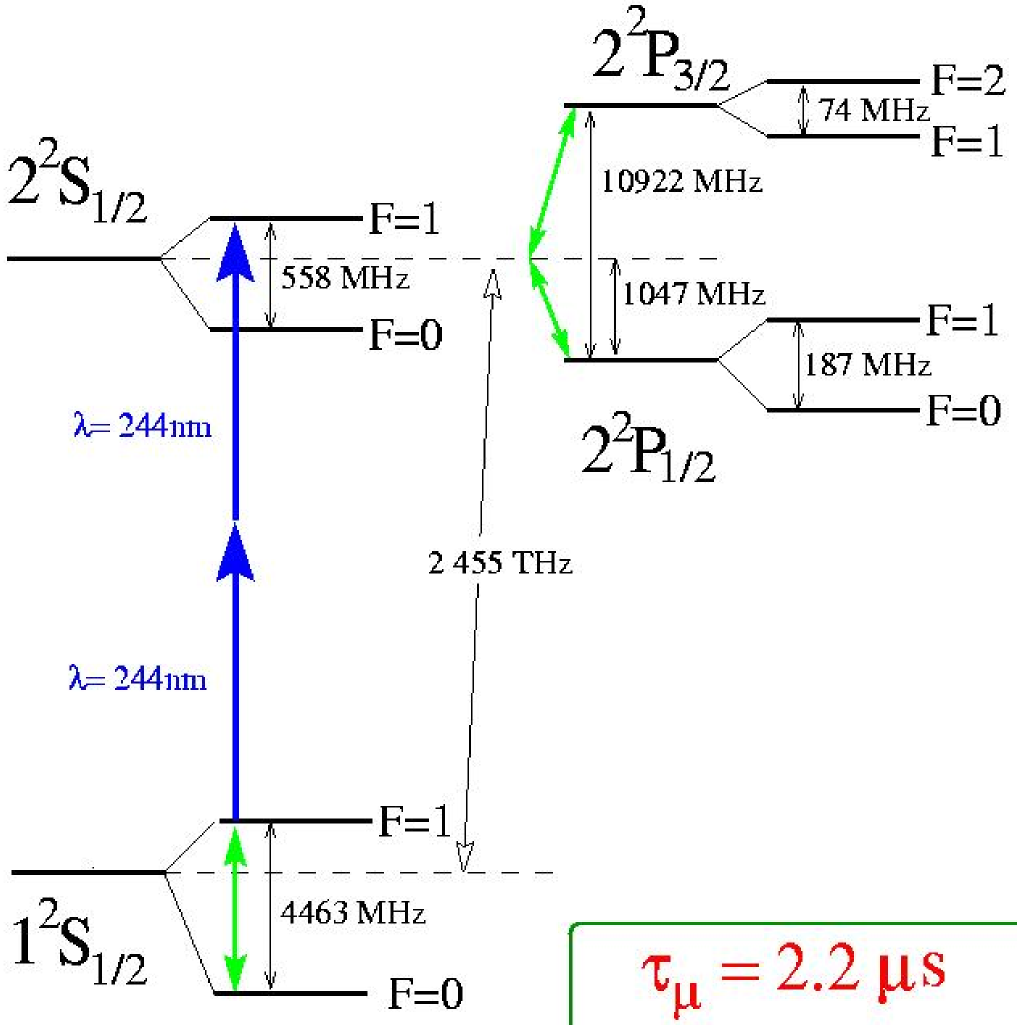
Muonium ($M=\mu^+e^-$) Energy Levels
n=1 and n=2



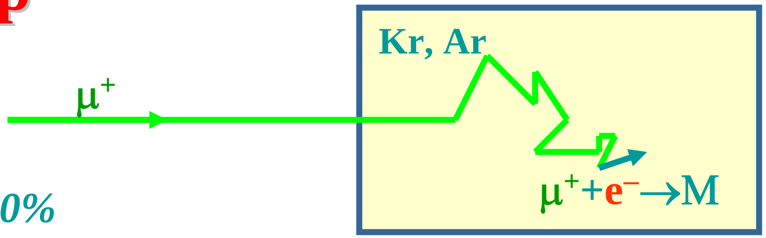
$\tau_\mu = 2.2\ \mu s$

min $\Delta\nu_{nat} = 145\ kHz$

(not to scale)

Methods of Muonium Production

- **Gas Stop**

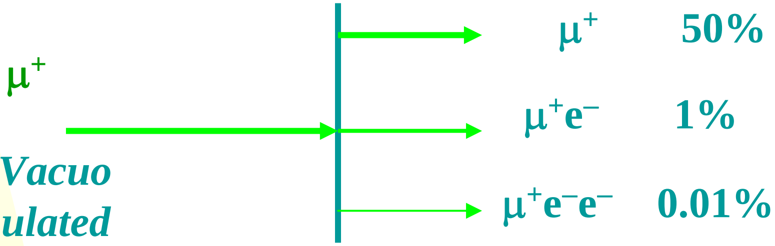


foreign gas effects

Yields up to 100%
Polarization up to 50% (B=0)
100% (B>>1T)

1960: Discovery of the atom
(V. Hughes et al.)

- **Beam Foil**



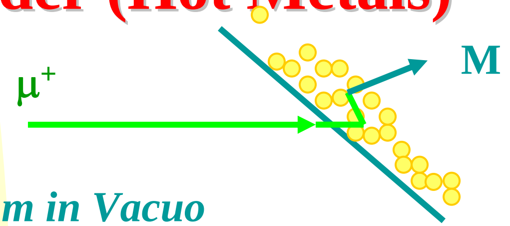
μ^+ 50%
μ^+e^- 1%
$\mu^+e^-e^-$ 0.01%

keV energy

Muonium in Vacuo
n=2 state populated
fast muonium

1980: Enable excited state spectroscopy
(LAMPF, TRIUMF)

- **SiO_2 Powder (Hot Metals)**



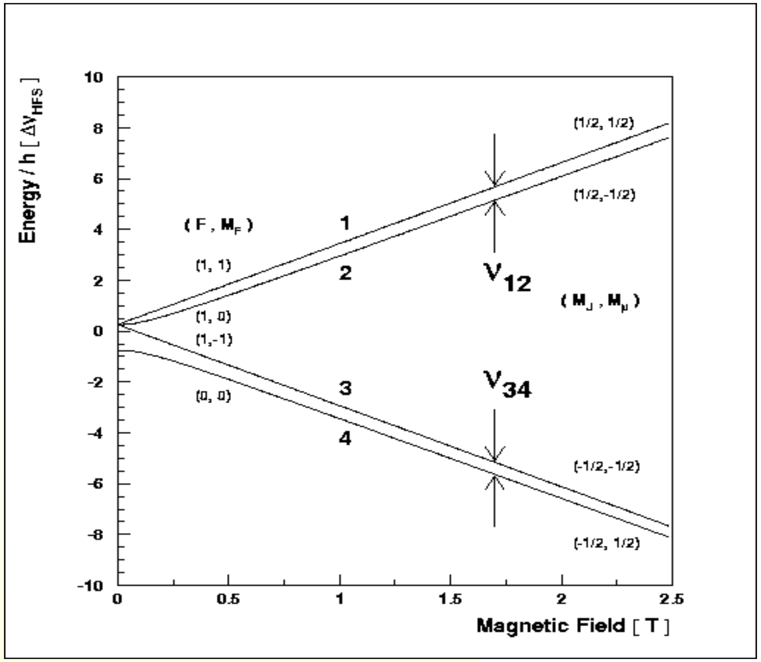
$M(2s)/M(1s) < 10^{-4}$
velocity 1.5 cm/ τ_μ

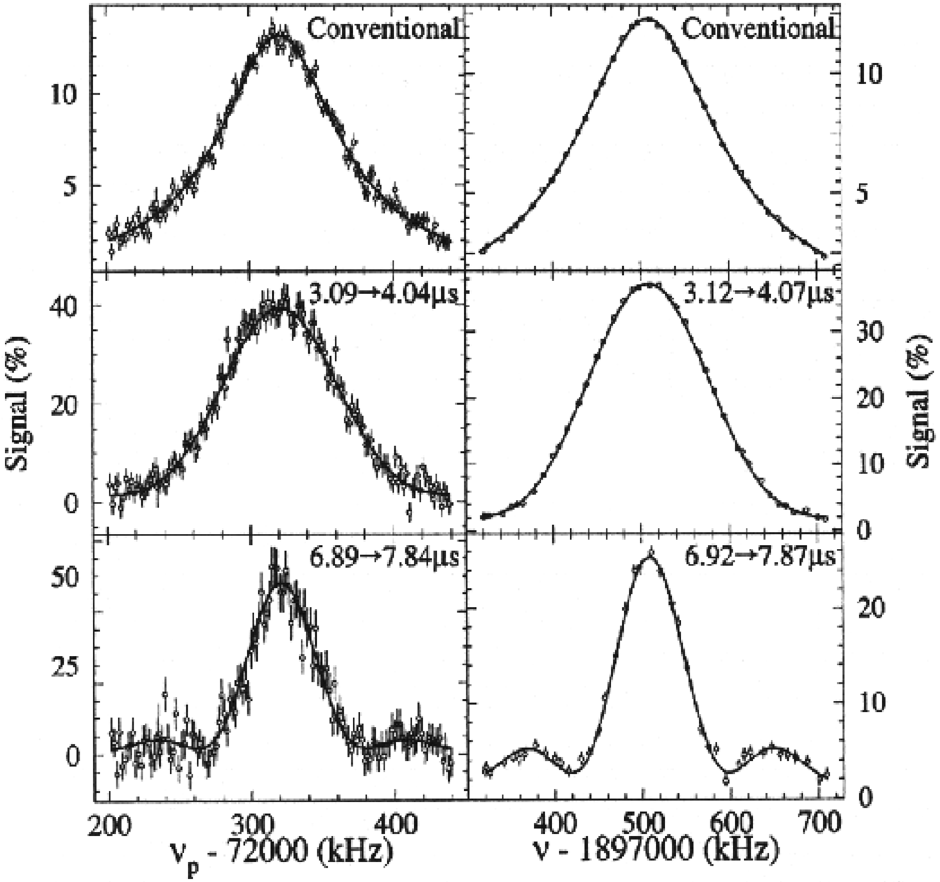
•thermal Muonium in Vacuo
Yields up to 12% (SiO_2)
Polarization 39(9)%

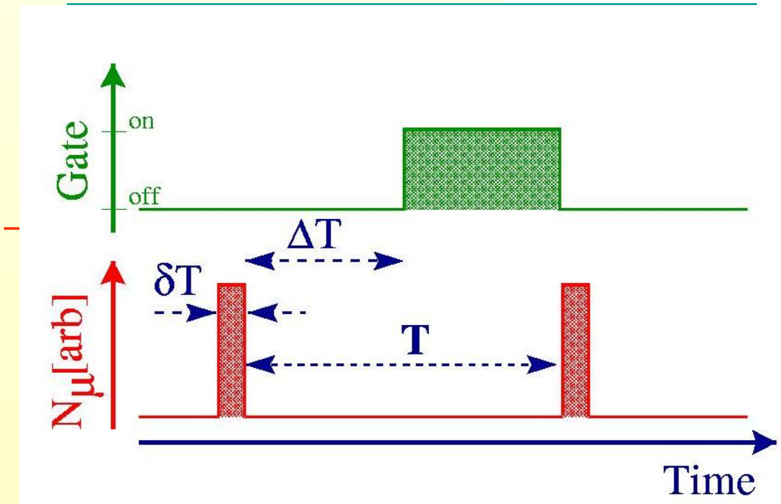
1986: Enable vacuum spectroscopy
(TRIUMF,KEK, PSI, LAMPF)

Muonium Hyperfine Structure

Yale - Heidelberg - Los Alamos







$\Delta\nu_{exp}$ = 4 463 302 765(53) Hz (12 ppb)

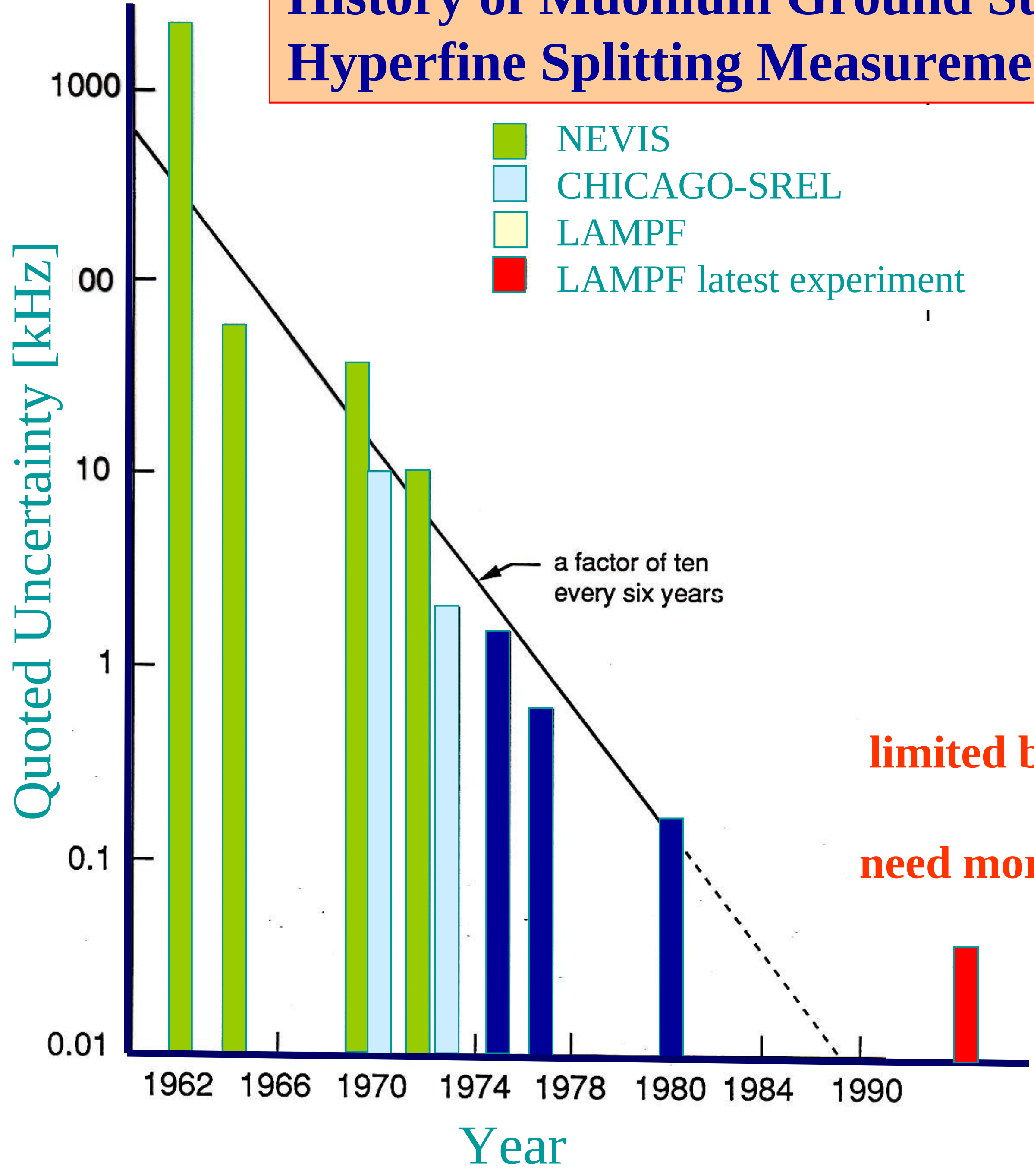
$\Delta\nu_{theo}$ = 4 463 302 649(520)(34)(<100) Hz(<120 ppb)

μ_μ/μ_p = 3.183 345 13(39) (120 ppb)

m_μ/m_e = 206.768 273(24) (120 ppb)

α^{-1} = 137.036 010 8(5 2) (39 ppb)

History of Muonium Ground State Hyperfine Splitting Measurements



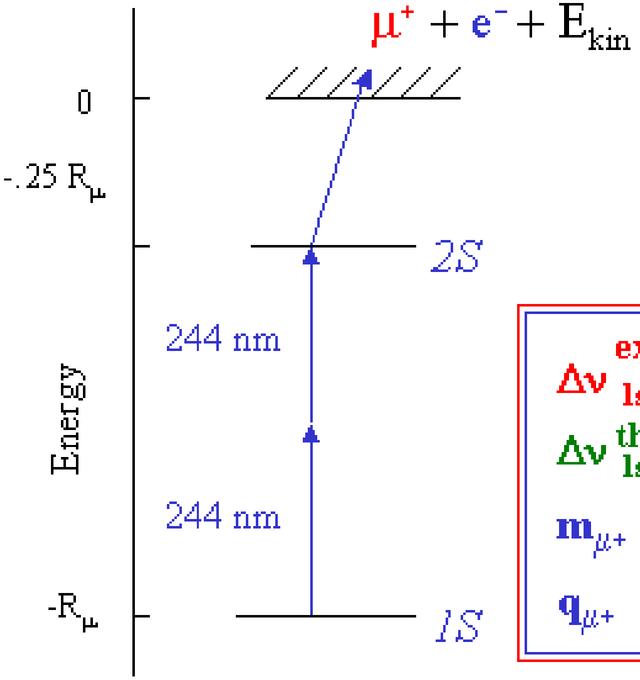
limited by statistics

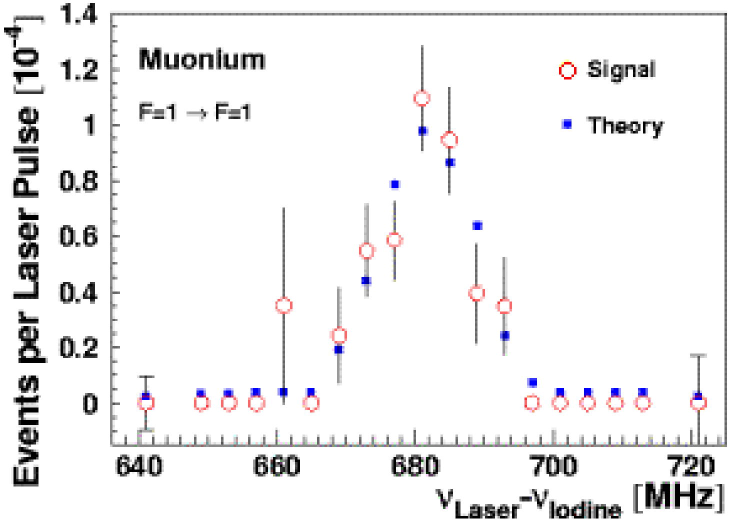
⇒

need more particles

Muonium 1S-2S Experiment

Heidelberg - Oxford - Rutherford - Sussex - Siberia - Yale



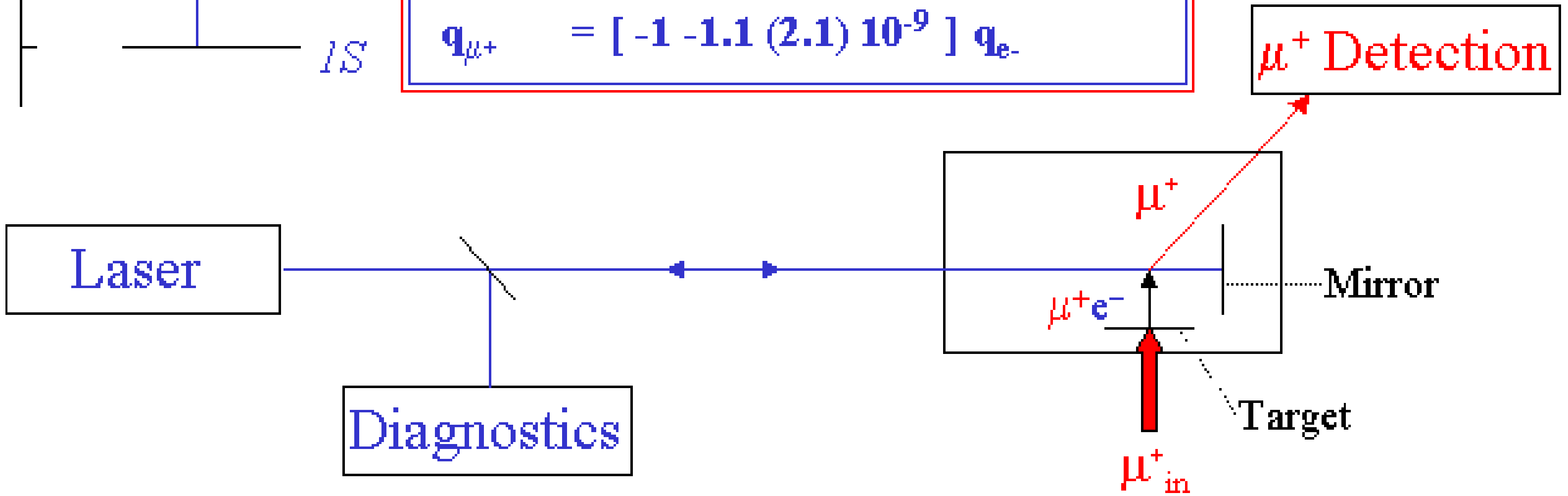


$\Delta\nu^{exp}_{1s-2s}$ = 2455 528 941.0(9.1)(3.7) MHz

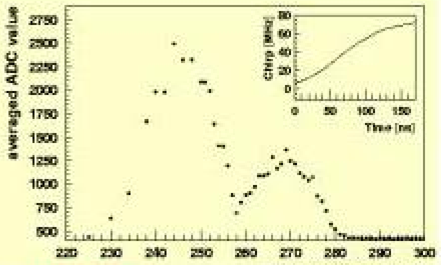
$\Delta\nu^{theo}_{1s-2s}$ = 2455 528 935.4(1.4) MHz

$m_{\mu+}$ = 206.768 38 (17) m_e

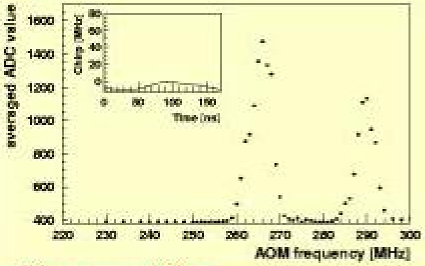
$q_{\mu+}$ = [-1 -1.1 (2.1) 10^{-9}] q_{e-}



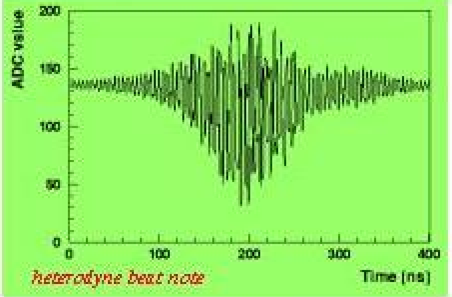
Deuterium Signals



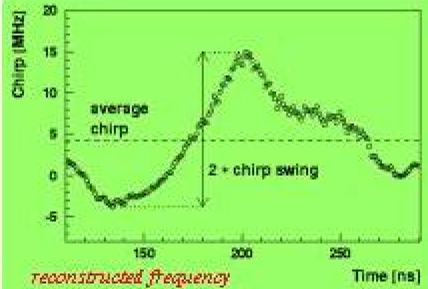
chirping laser



chirp compensated laser

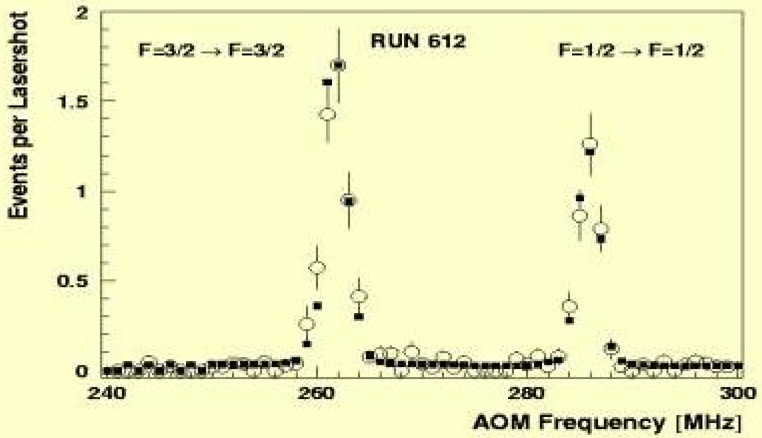


heterodyne beat note



reconstructed frequency chirp

deuterium 1s -2s - ionization signal

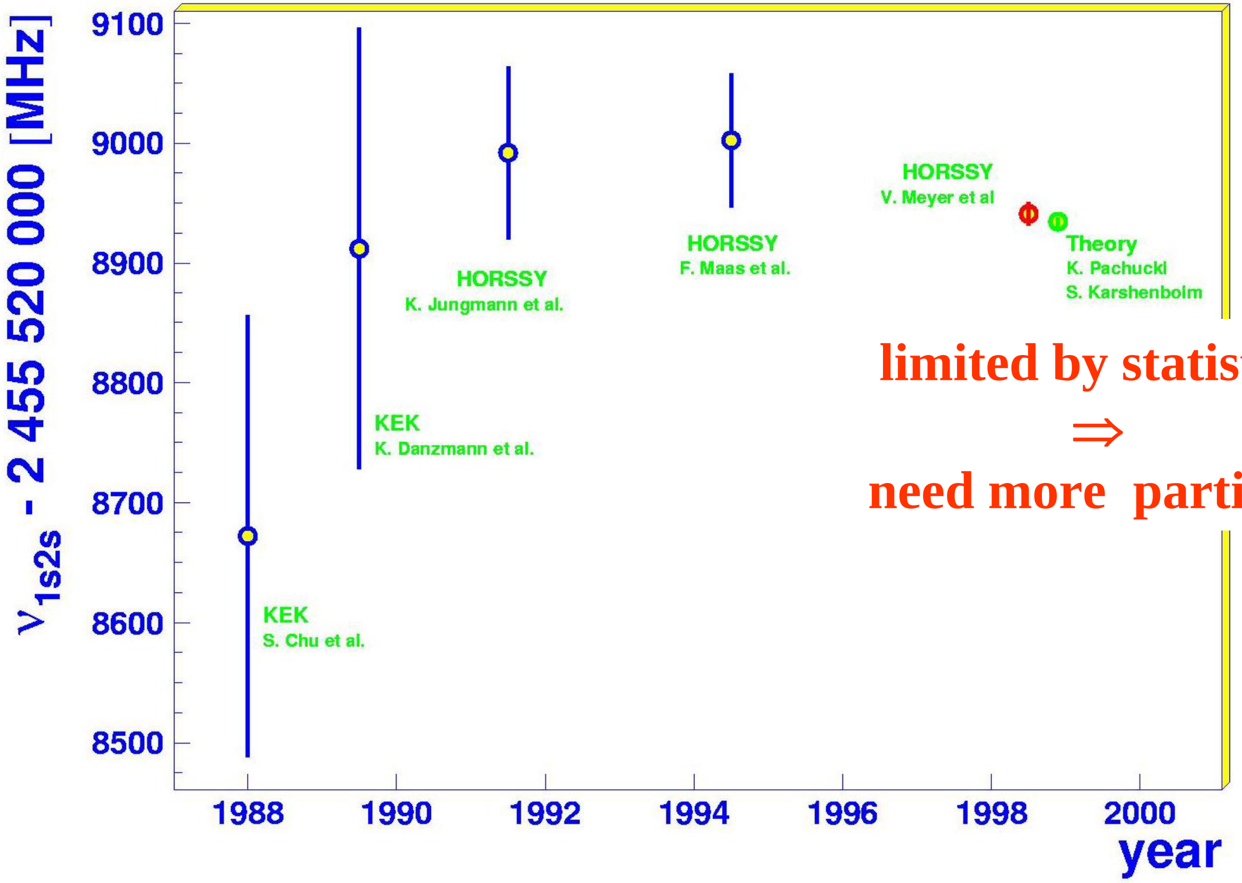


$\Delta\nu_{1s2s}$(exp) = 2 466 732 397.1(8.5) MHz

$\Delta\nu_{1s2s}$(theo) = 2 466 732 397.14(8) MHz

K Jungmann 11-98

Muonium 1s-2s Interval



limited by statistics

⇒

need more particles

Results:

$$\Delta\nu^{\text{exp}}_{\text{1s-2s}} = 2455\ 528\ 941.0(9.1)(3.7)\ \text{MHz}$$

$$\Delta\nu^{\text{theo}}_{\text{1s-2s}} = 2455\ 528\ 935.4(1.4)\ \text{MHz}$$

$$m_{\mu+} = 206.768\ 38\ (17)\ m_e \quad (0.8\text{ppm})$$

$$q_{\mu+} = [\ -1\ -1.1\ (2.1)\ 10^{-9}\ ]\ q_{e-} \quad (2.2\ \text{ppb})$$

onium–Antimuonium Conversio

$$M \overset{?}{\Leftrightarrow} \overline{M}$$

$$\mu^{+} e^{-} \overset{G_{M\overline{M}}}{\longleftrightarrow} \mu^{-} e^{+}$$

L_{μ}: -1 +1

L_{e}: +1 -1

$$\Delta L_{e/\mu} = \pm 2$$

vour oscillations well established in quark secto

$$K^0 \Leftrightarrow \overline{K^0}$$

$$(d\bar{s}) \qquad (\bar{d}s)$$

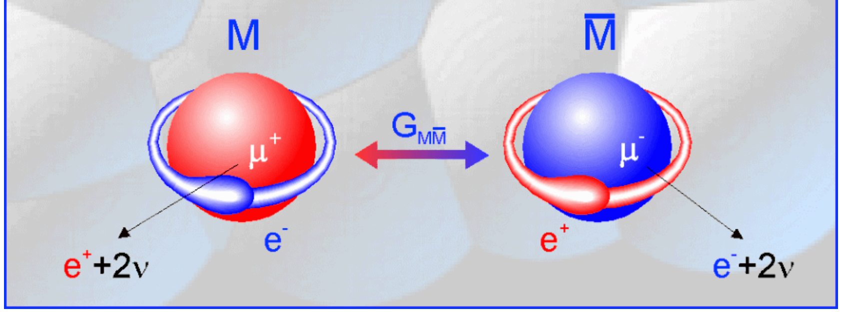
$$B^0 \Leftrightarrow \overline{B^0}$$

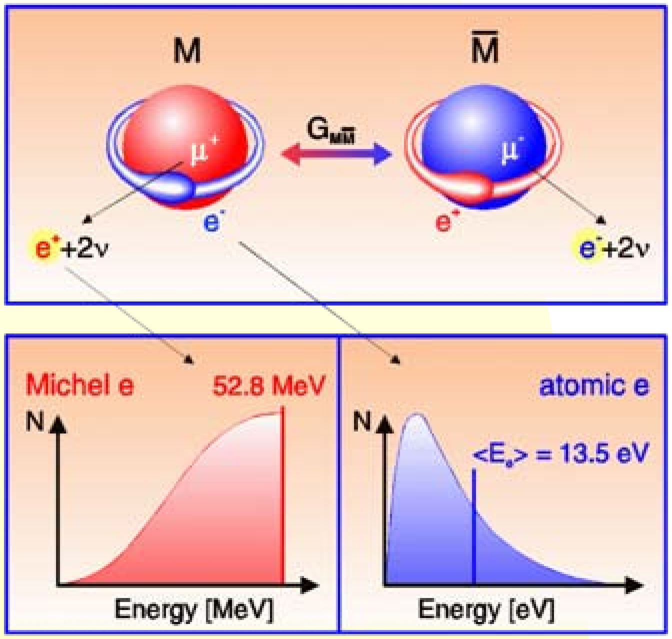
$$(d\bar{b}) \qquad (\bar{d}b)$$

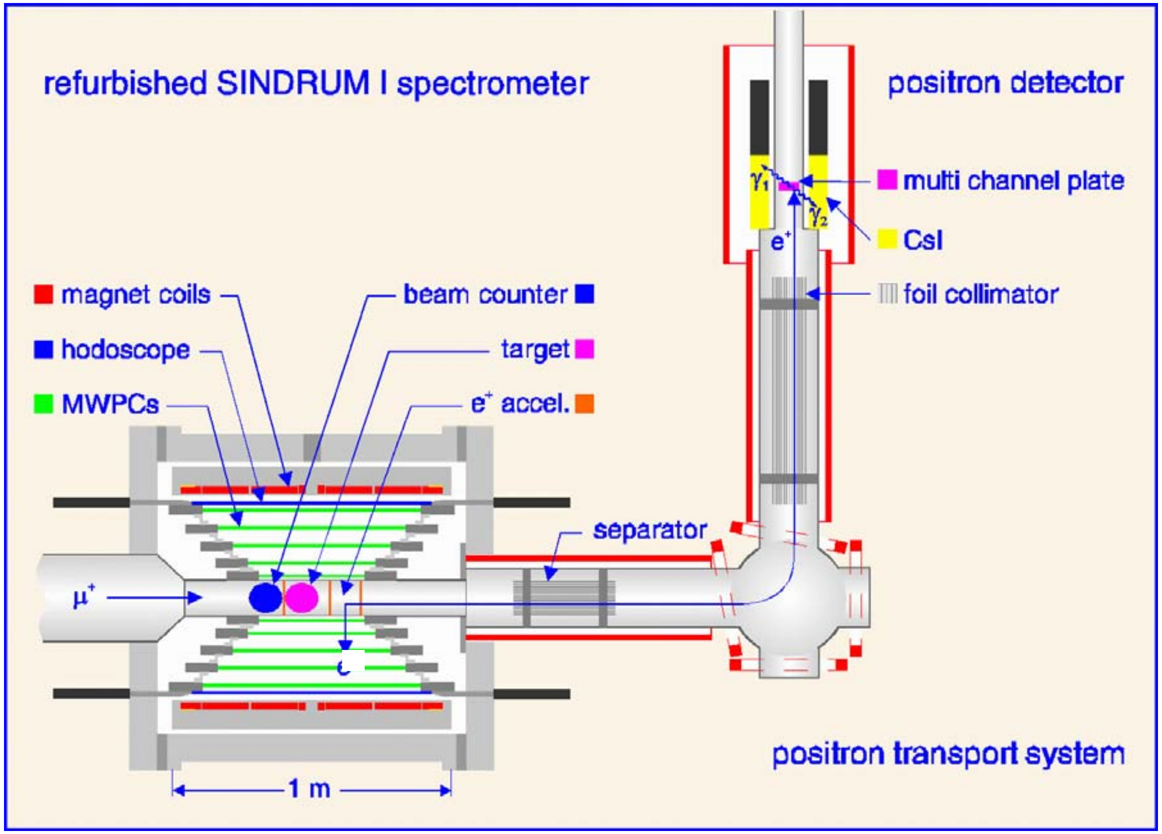
$$(s\bar{b}) \qquad (\bar{s}b)$$

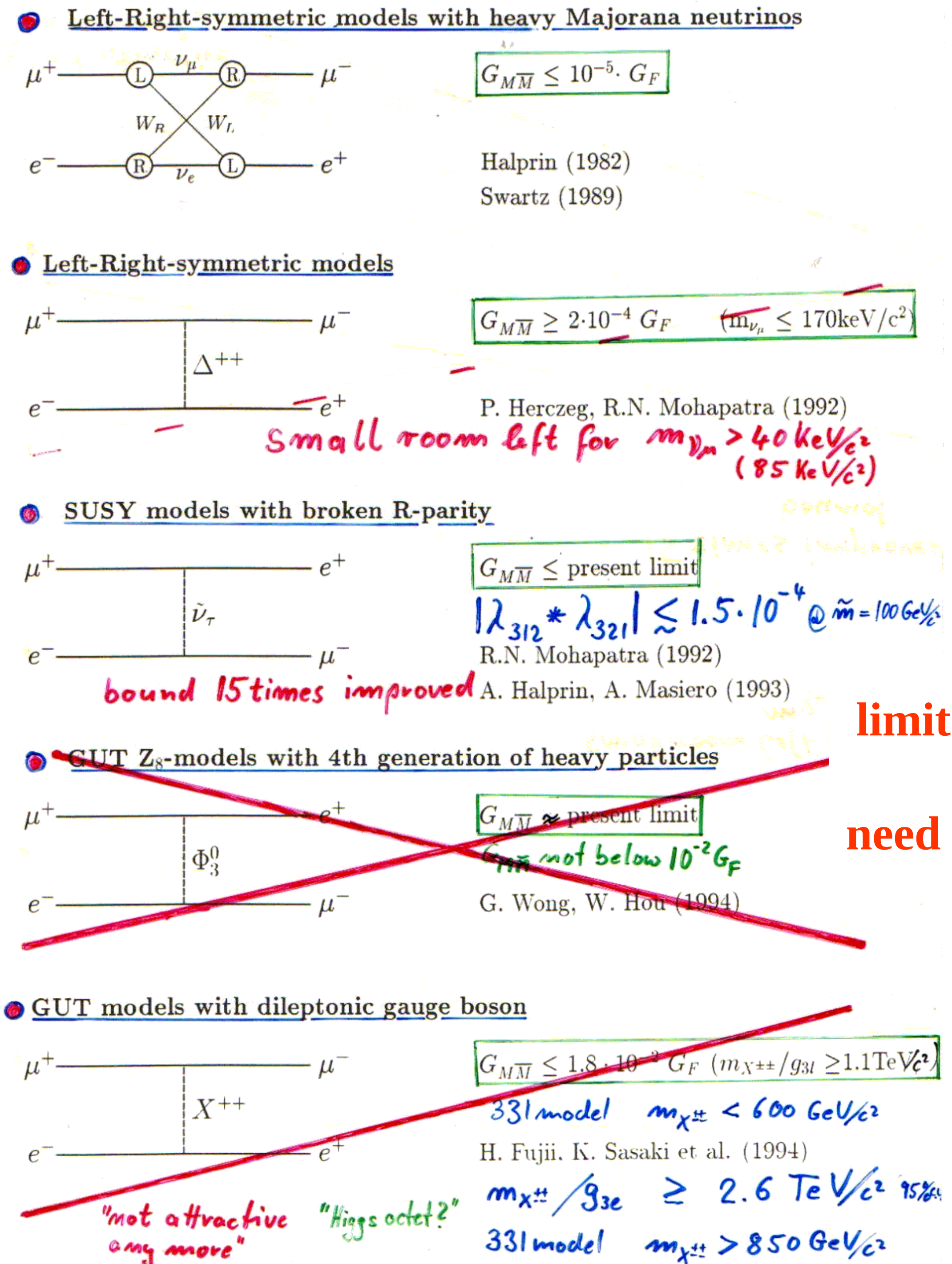
The MACS - M$\overline{\text{M}}$ collaboration

Heidelberg - Aachen - UNIZ - PSI - Dubna - Tbilisi - Yale









- **Left-Right-symmetric models with heavy Majorana neutrinos**

$\boxed{G_{M\overline{M}} \le 10^{-5} \cdot G_F}$

Halprin (1982)
Swartz (1989)

- **Left-Right-symmetric models**

$\boxed{G_{M\overline{M}} \ge 2\cdot 10^{-4}\, G_F \qquad (m_{\nu_\mu} \le 170 \mathrm{keV}/c^2)}$

P. Herczeg, R.N. Mohapatra (1992)

Small room left for $m_{\nu_\mu} > 40\ \mathrm{keV}/c^2$
$(85\ \mathrm{keV}/c^2)$

- **SUSY models with broken R-parity**

$\boxed{G_{M\overline{M}} \le \text{present limit}}$

$|\lambda_{312} * \lambda_{321}| \lesssim 1.5 \cdot 10^{-4}$ @ $\tilde{m} = 100\ \mathrm{GeV}/c^2$

R.N. Mohapatra (1992)
A. Halprin, A. Masiero (1993)

bound 15 times improved

- ~~**GUT Z_8-models with 4th generation of heavy particles**~~

~~$G_{M\overline{M}} \approx$ present limit~~

~~$G_{M\overline{M}}$ not below $10^{-2} G_F$~~

~~G. Wong, W. Hou (1994)~~

- ~~**GUT models with dileptonic gauge boson**~~

~~$G_{M\overline{M}} \le 1.8 \cdot 10^{-2}\, G_F \ (m_{X^{\pm\pm}}/g_{3l} \ge 1.1 \mathrm{TeV}/c^2)$~~

331 model $m_{X^{\pm\pm}} < 600\ \mathrm{GeV}/c^2$

H. Fujii, K. Sasaki et al. (1994)

$m_{X^{\pm\pm}} / g_{3e} \ge 2.6\ \mathrm{TeV}/c^2$ 95% CL

331 model $m_{X^{\pm\pm}} > 850\ \mathrm{GeV}/c^2$

"not attractive any more"

"Higgs octet?"

limited by statistics

⇒

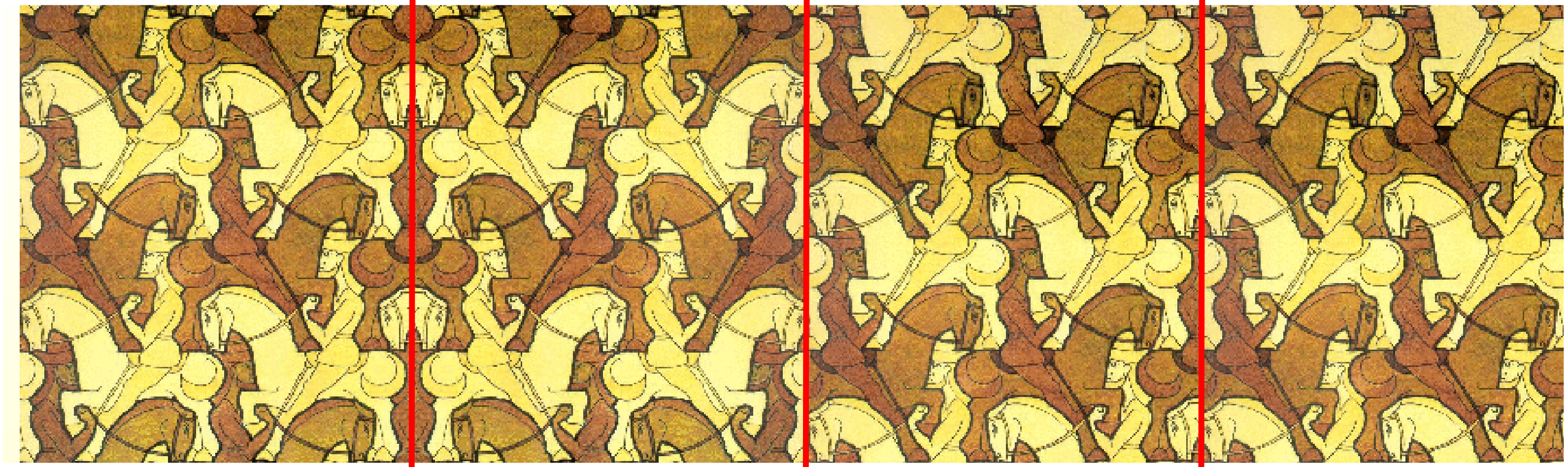
need more particles

The World according to Escher

start

P matter **C** anti-matter **T**

identical
to start



mirror image

time →

← time

anti-particle
e^+

particle
e^-

from H.W. Wilschut

CPT – Violation
Lorentz Invariance Violation

What is best CPT test ?

often quoted:

- **K^0- $\bar{K}^0$ mass difference (10^{-18})**
- **e^- - e^+ g- factors ($2^* 10^{-12}$)**

- **We need an interaction with a finite strength !**

New Ansatz (Kostelecky)

- **K** ≈ 10^{-21} **GeV**
- **n** ≈ 10^{-30} **GeV**
- **p** ≈ 10^{-24} **GeV**
- **e** ≈ 10^{-27} **GeV**
- **μ** ≈ 10^{-23} **GeV**
- **Future:**
  Anti hydrogen ≈ $10^{-??}$ GeV

CPT tests

$$r_K = \frac{|m_{K^0} - m_{\bar{K}^0}|}{m_{K^0}} \leq 10^{-18}$$

$$r_e = \frac{|g_{e^-} - g_{e^+}|}{g_{avg}} = 1.2\times10^{-3} \times \frac{|a_{e^-} - a_{e^+}|}{a_{avg}} \leq 2\times10^{-12}$$

? Are they comparable- Which one is appropriate ?

⇒ **Use common ground, e.g. energies**

generic CPT and Lorentz violating DIRAC equation

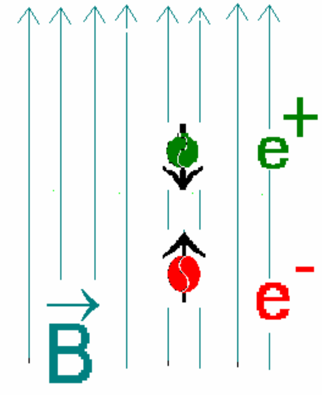
$$(i\gamma^\mu D_\mu - m - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu - \frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

$$iD_\mu \equiv i\partial_\mu - qA_\mu$$

a_μ, b_μ break CPT

$a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}, H_{\mu\nu}$ break Lorentz Invarianc

Leptons in External Magnetic Field



$$\Delta\omega_a = \omega_a^{l^-} - \omega_a^{l^+} \approx -4b_3^l$$

$$r_l = \frac{|E_{spin\ up}^{l^-} - E_{spin\ down}^{l^+}|}{E_{spin\ up}^{l^-}} \approx \frac{\hbar\Delta\omega_a}{m_l c^2}$$

Bluhm , Kostelecky, Russell, Phys.Rev. D **57**,3932 (1998)

For g-2 Experiments :

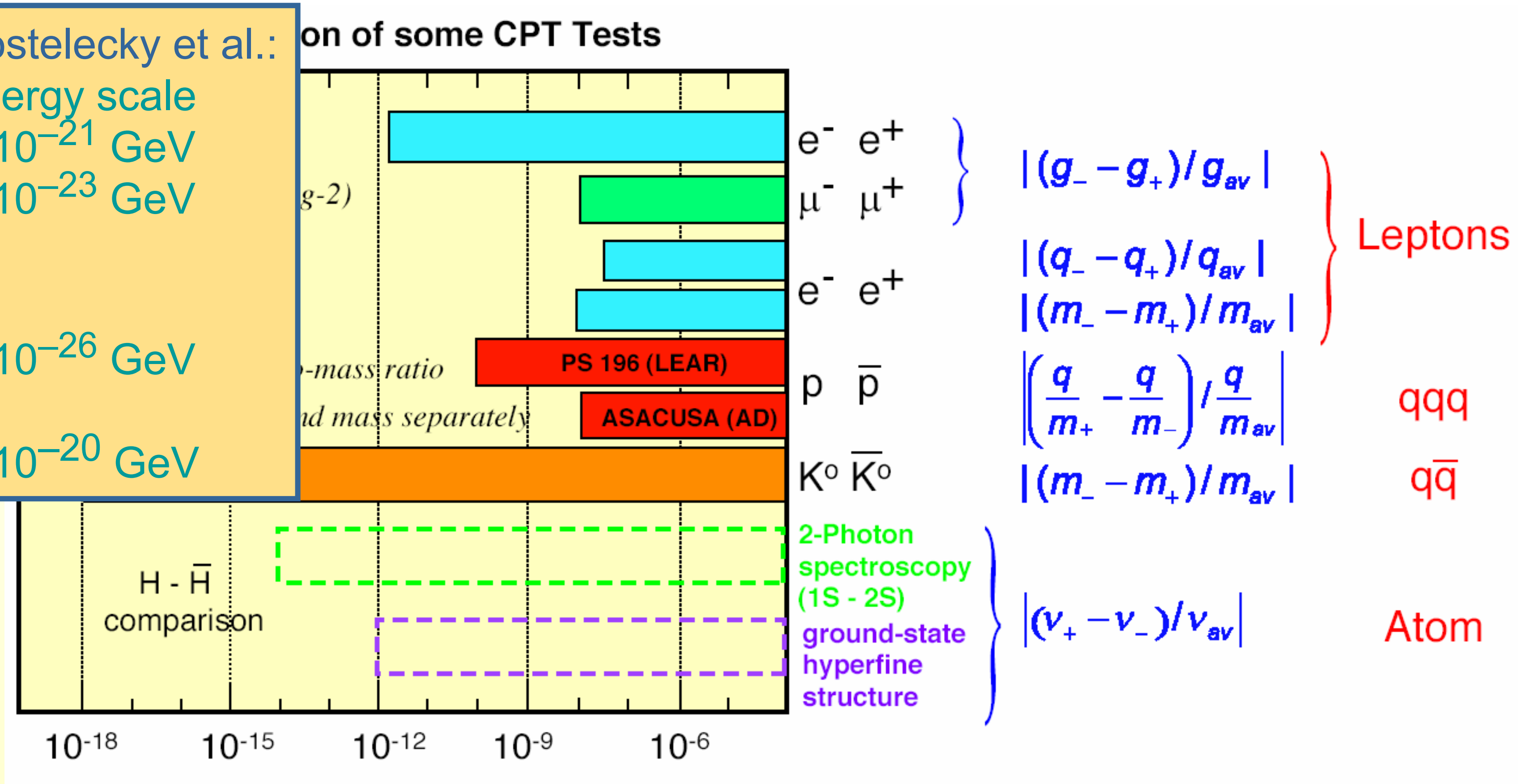
$$r_l = \frac{\hbar\omega_c}{m_l c^2} \times \frac{|a_{l^-} - a_{l^+}|}{a_{avg}}$$

Dehmelt, Mittleman,Van Dyck, Schwinberg, hep-ph/9906262

⇒ *electron* $r_e \leq 1.2\times10^{-21}$ *muon* $r_\mu \leq 3.5\times10^{-24}$

Verifications of CPT symmetry

- Tests of particle/antiparticle symmetry (PDG)



Kostelecky et al.:
energy scale
$< 10^{-21}$ GeV
$< 10^{-23}$ GeV

$< 10^{-26}$ GeV

$< 10^{-20}$ GeV

- Inconsistent definition of figure of merit: comparison difficult
- Pattern of CPT violation unknown (P: weak interaction, CP: mesons)

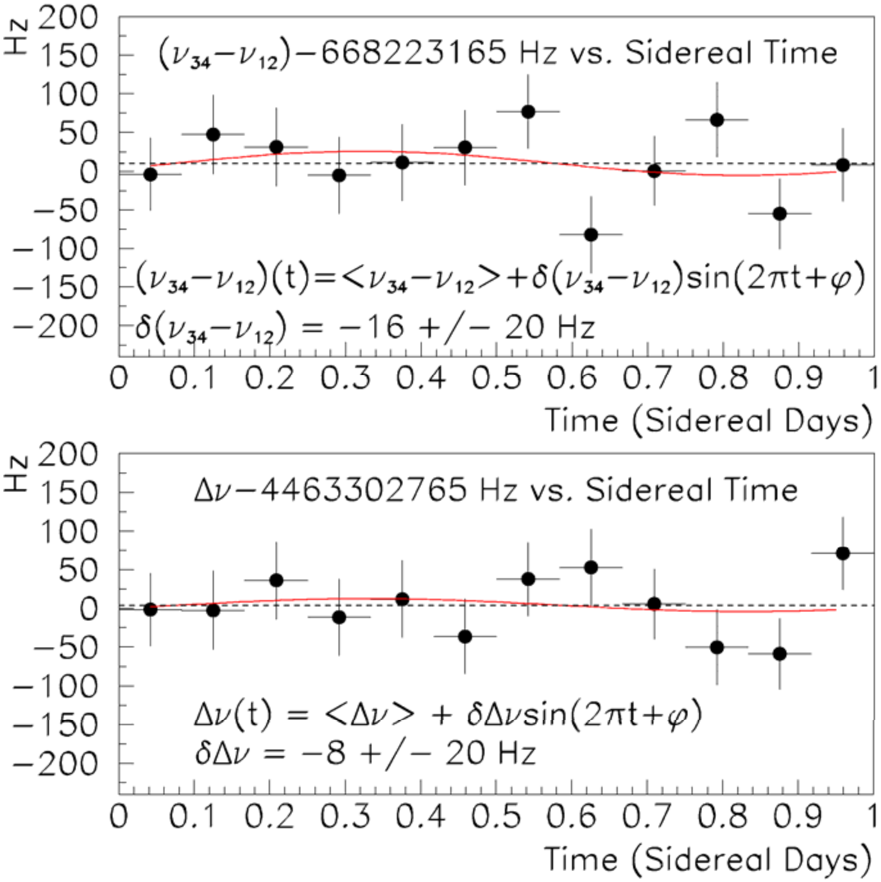
from E. Widmann

CPT

relates to various phenomena among which

- **Lorentz Invariance, perferred reference frame**
- **Particle – Antiparticle properties**
- **Spin**
- **Fermions and Bosons only**
- **….**

CPT and Lorentz Invariance from Muon Experiments



V.W. Hughes et al., Phys.Rev. Lett. 87, 111804 (2001)

Muonium:

new interaction below

$2 * 10^{-23}$ GeV

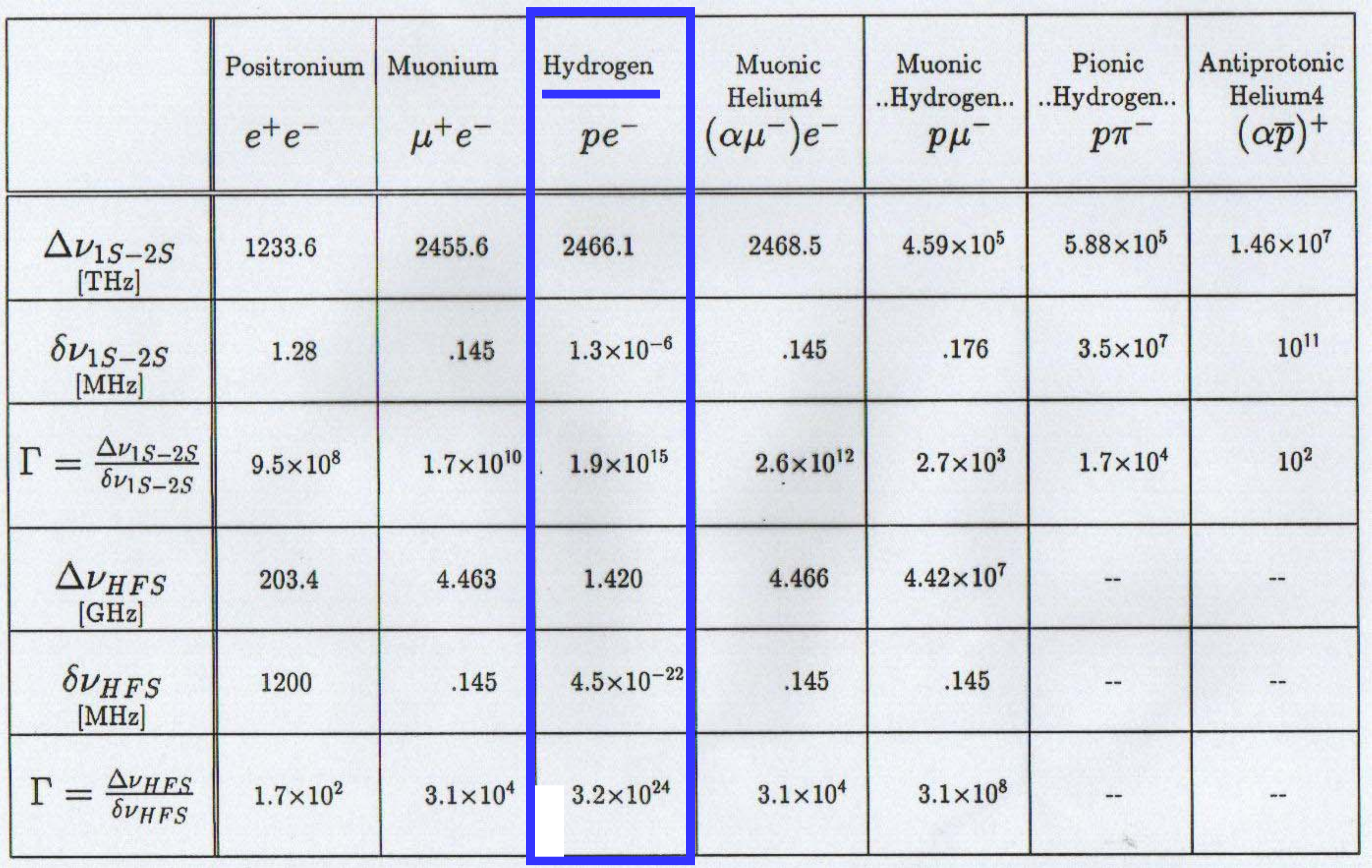
Muon g-2:

new interaction below

$4 * 10^{-22}$ GeV (CERN)

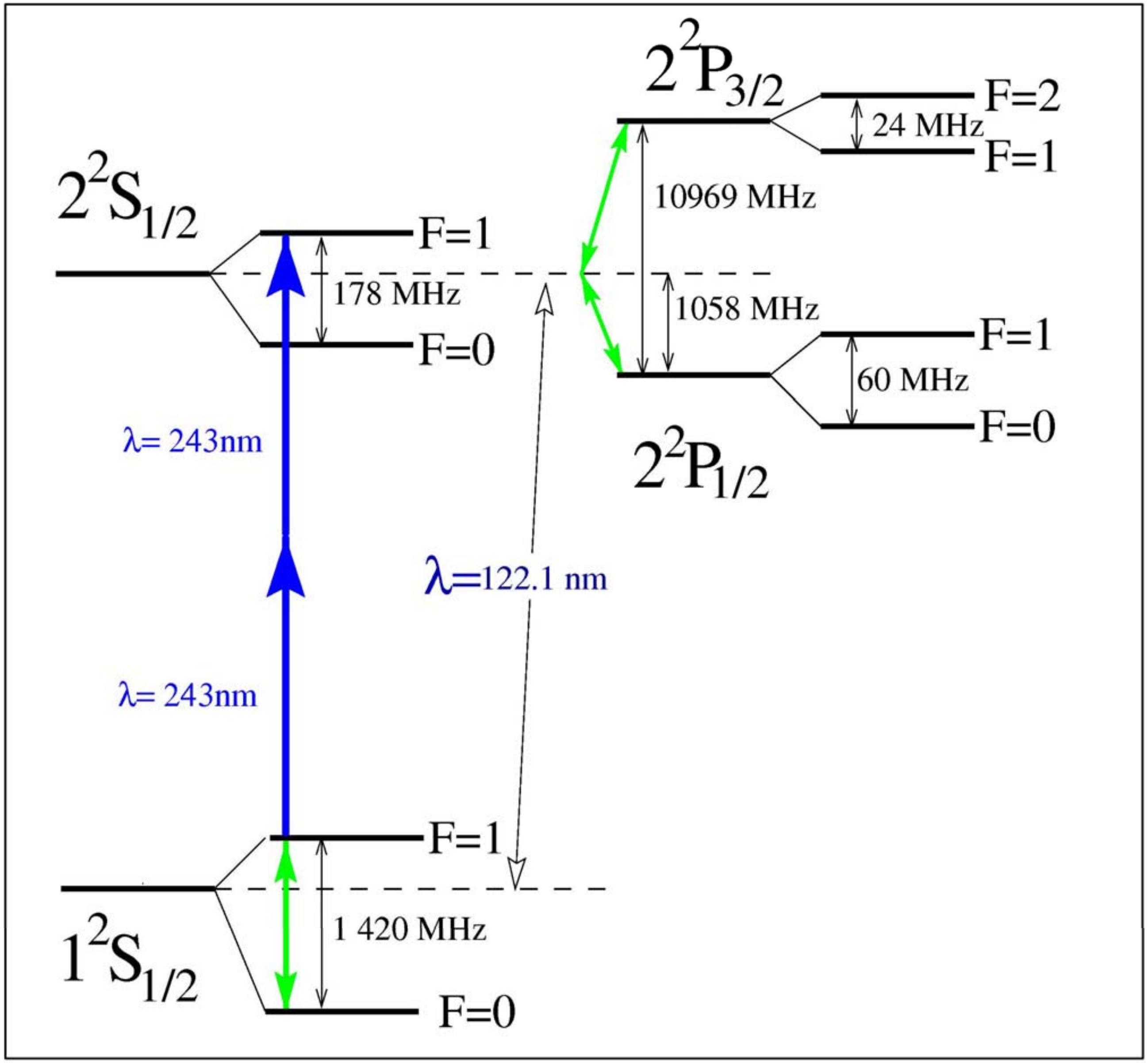
15 times better expected from BNL when analysis will be completed

Hydrogen-like Atoms



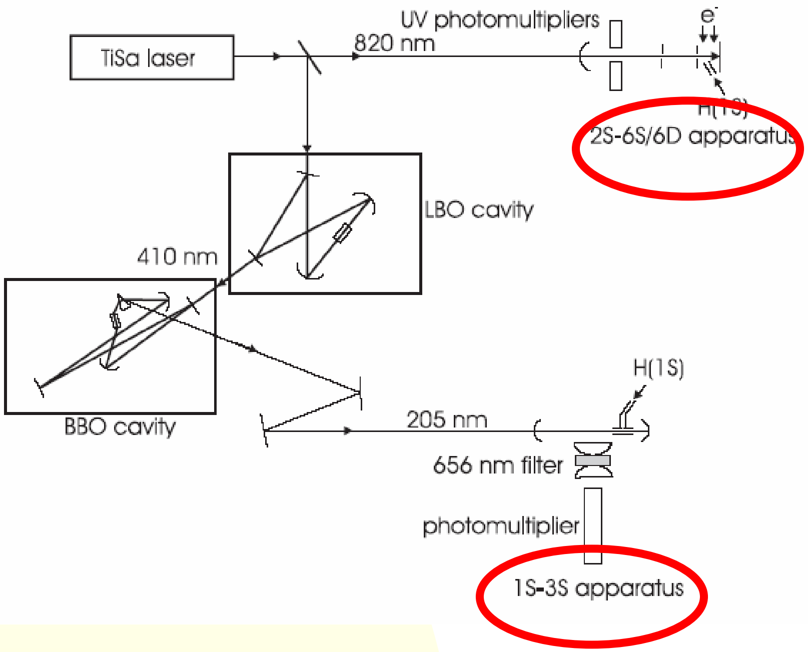
	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen pe^-	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\overline{p})^+$
$\Delta\nu_{1S-2S}$ [THz]	1233.6	2455.6	2466.1	2468.5	4.59×10^5	5.88×10^5	1.46×10^7
$\delta\nu_{1S-2S}$ [MHz]	1.28	.145	1.3×10^{-6}	.145	.176	3.5×10^7	10^{11}
$\Gamma = \frac{\Delta\nu_{1S-2S}}{\delta\nu_{1S-2S}}$	9.5×10^8	1.7×10^{10}	1.9×10^{15}	2.6×10^{12}	2.7×10^3	1.7×10^4	10^2
$\Delta\nu_{HFS}$ [GHz]	203.4	4.463	1.420	4.466	4.42×10^7	--	--
$\delta\nu_{HFS}$ [MHz]	1200	.145	4.5×10^{-22}	.145	.145	--	--
$\Gamma = \frac{\Delta\nu_{HFS}}{\delta\nu_{HFS}}$	1.7×10^2	3.1×10^4	3.2×10^{24}	3.1×10^4	3.1×10^8	--	--

Atomic Hydrogen



Hydrogen Laser spectroscopy

Haensch, Biraben et al.



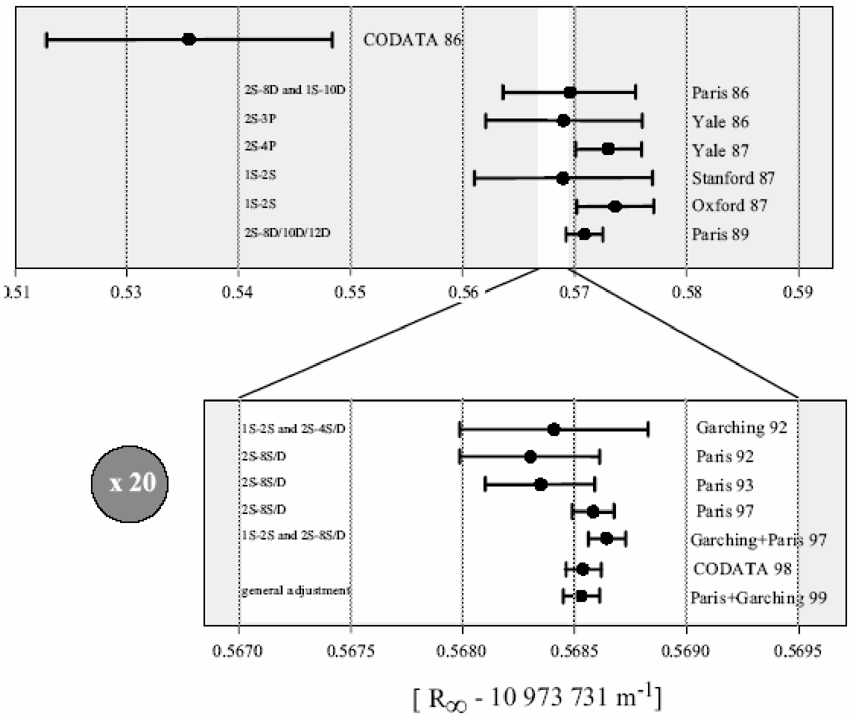
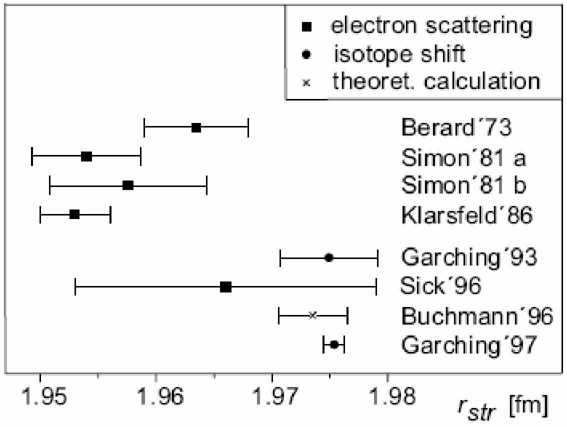


Fig. 14. A history of measurements of the Rydberg constant

“Deuteron Radius”



Hydrogen Laser Spectroscopy Accuracy

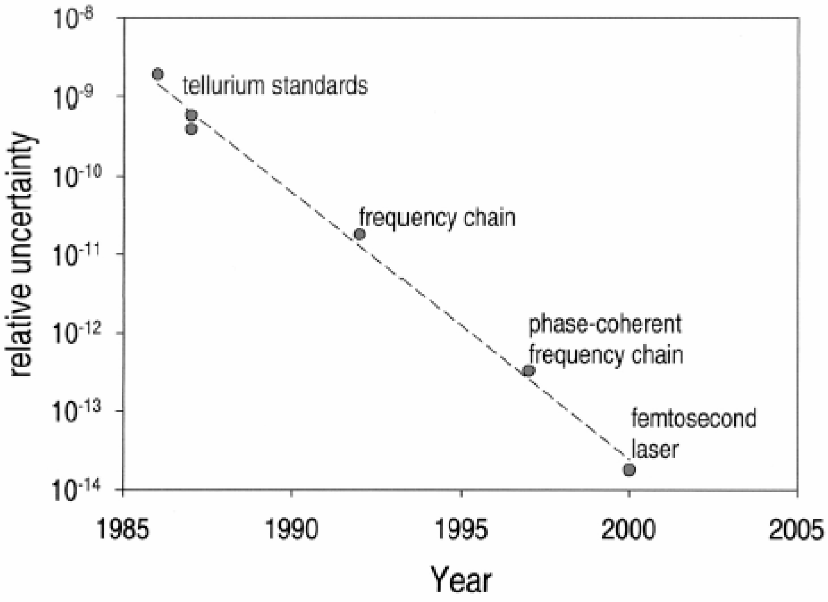


Figure 7. Improvements in 1S–2S measurement accuracy, showing the method of frequency metrology used at each stage.

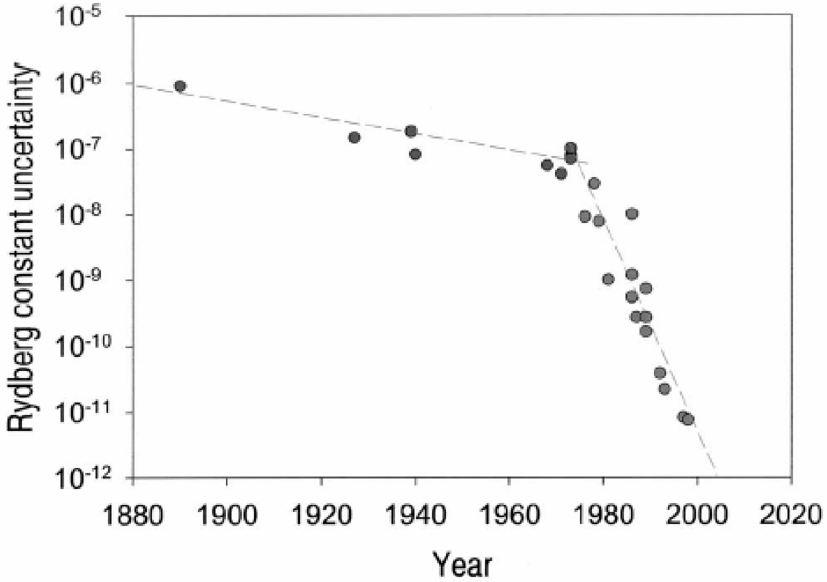
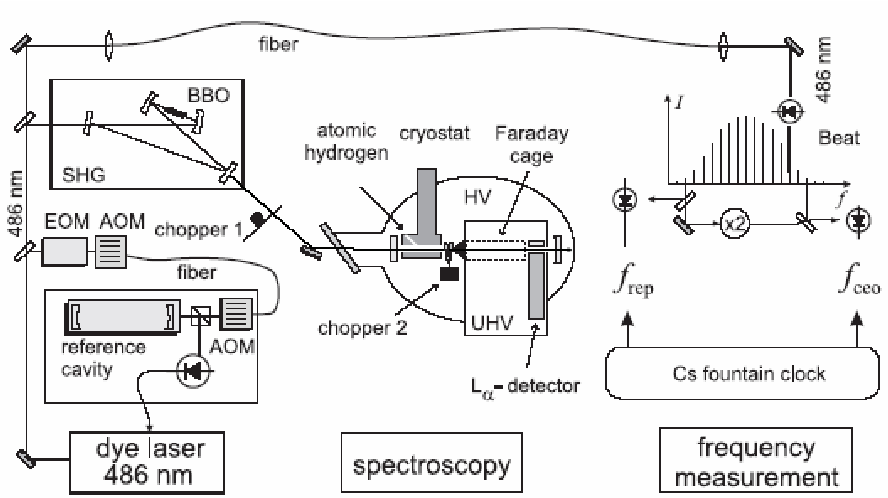
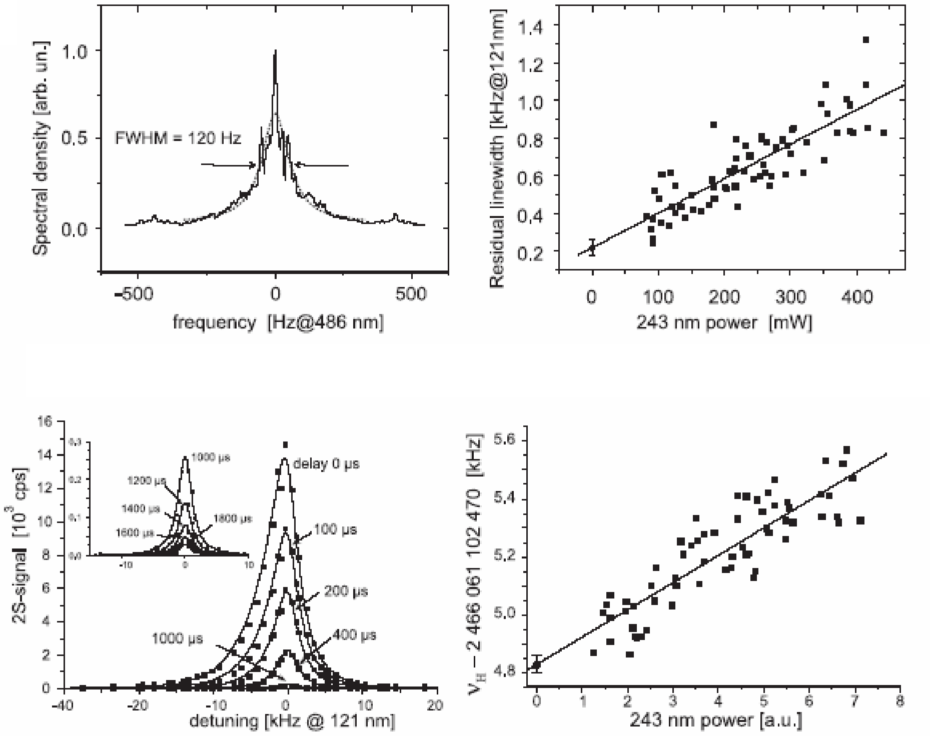


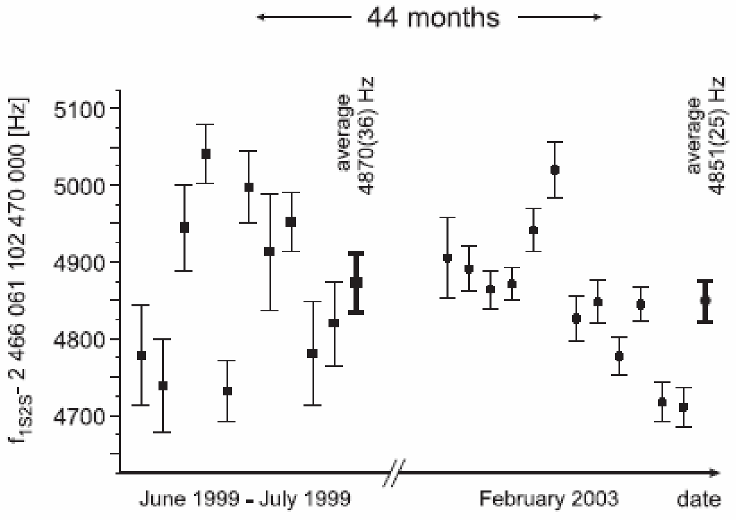
Figure 9. Improvement in the uncertainty of Rydberg constant measurements. The dashed lines are guides to the eye showing the change brought about by laser spectroscopy.

Hydrogen Laser spectroscopy

Haensch et al.







χ^2/df ≈4.2 χ^2/df ≈9

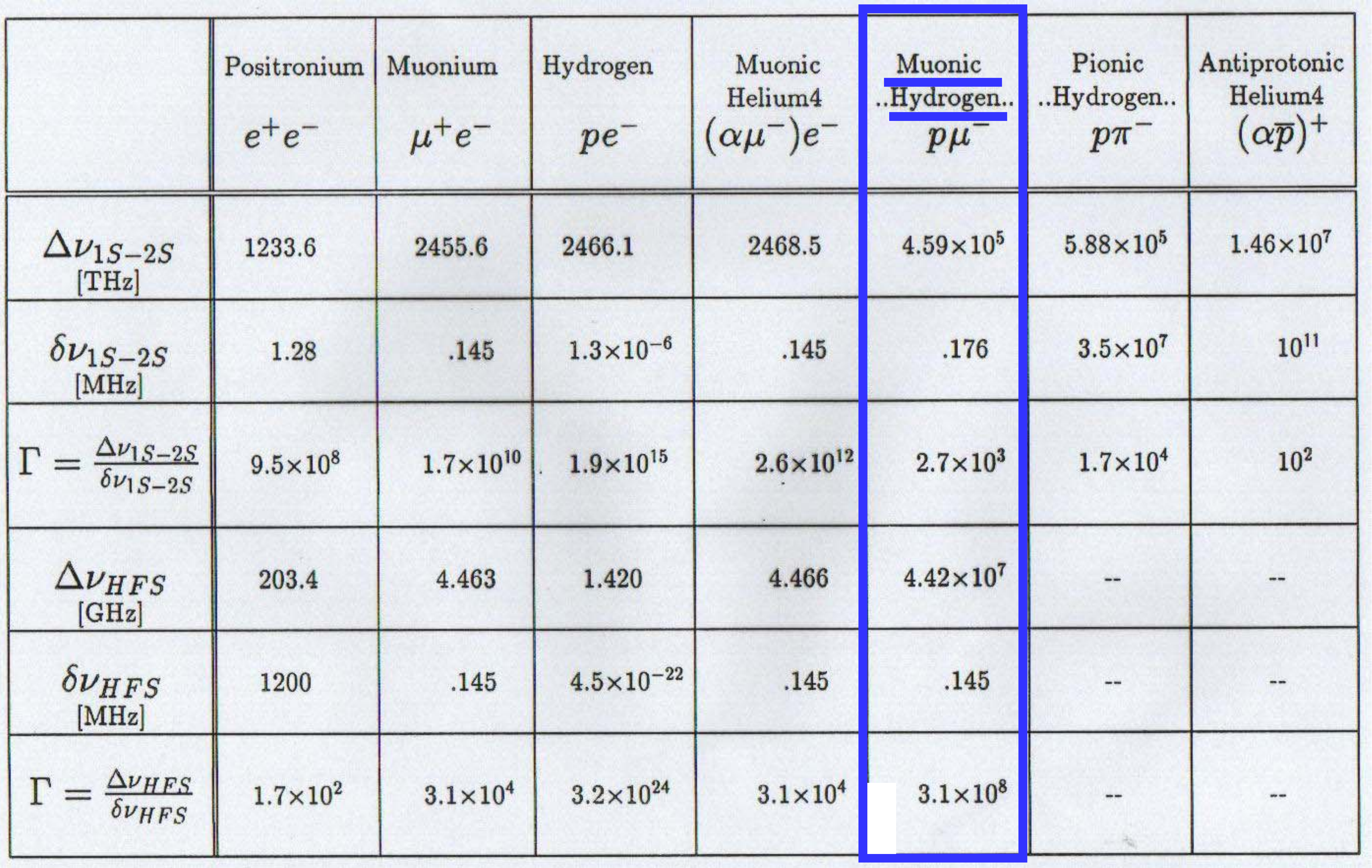
$$f_{1S-2S} = 2\,466\,061\,413\,187.29(37)\ \mathrm{kHz}.$$

$$\boxed{1.8 \times 10^{-14}}$$

$$\dot{\alpha}/\alpha = \partial/\partial t(\ln\alpha) = (-0.9 \pm 2.9) \times 10^{-15}\ \mathrm{yr}^{-1}$$

M. Fischer et al., Precision Spectroscopy of Atomic Hydrogen and Variations of Fundamental Constants, Lect. Notes Phys. 648, 209–227 (2004)

Hydrogen-like Atoms



	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen pe^-	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\overline{p})^+$
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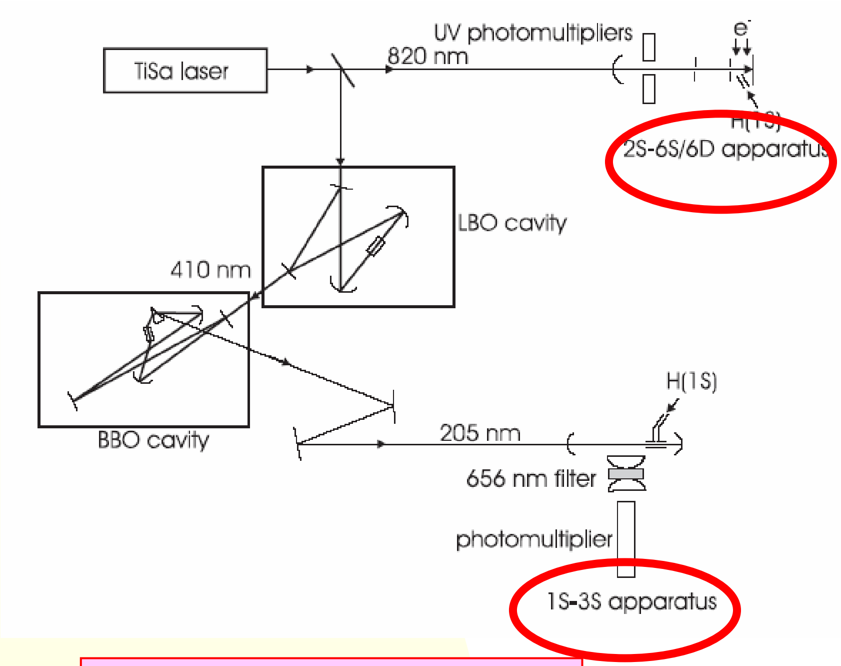
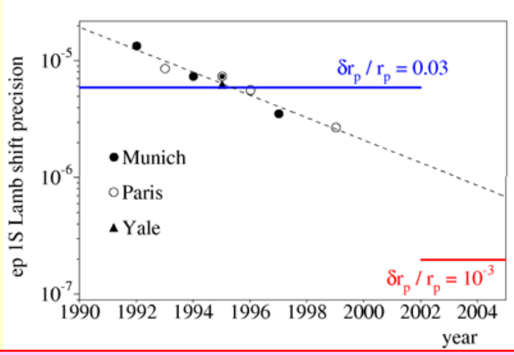
Hydrogen Laser spectroscopy

Haensch, Biraben et al.



"Proton Radius"



Muonic Hydrogen Lamb Shift

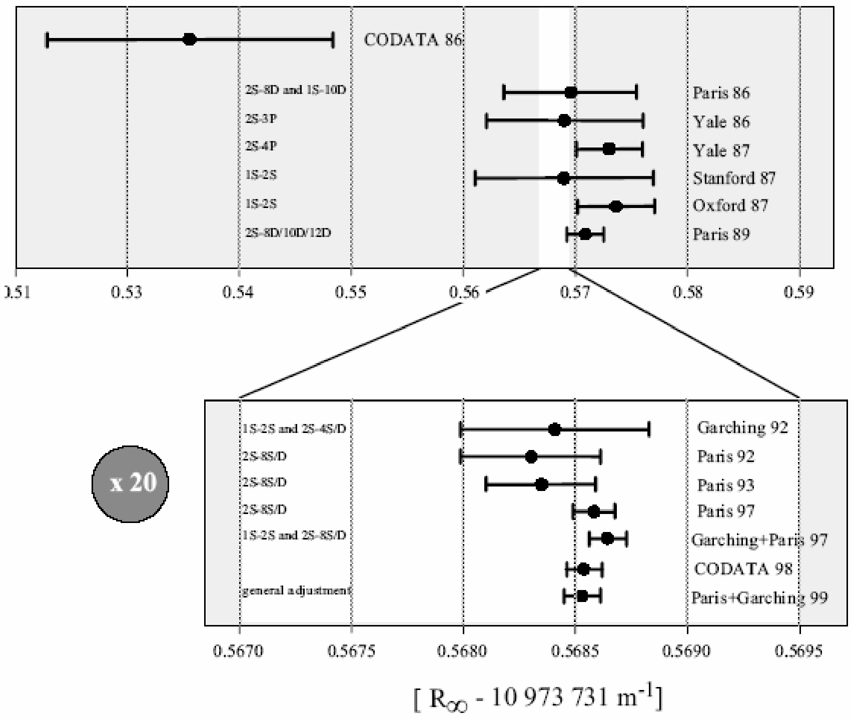
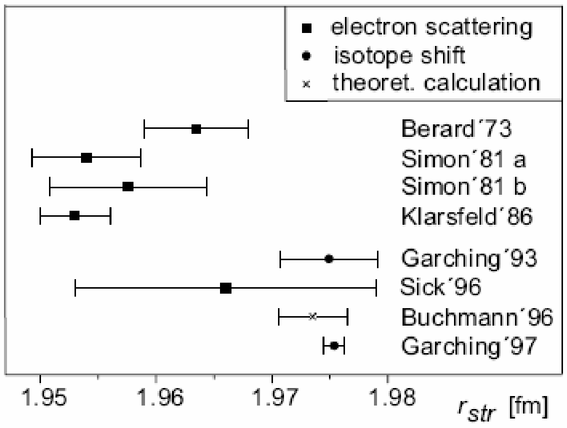


Fig. 14. A history of measurements of the Rydberg constant

"Deuteron Radius"



(Anti-)Hydrogen Spectroscopy*

Hydrogen 1s-2s Saturation Intensity I_s = 0.9 W/cm2
Excitation Rate $R_e = 4\pi * 84 * (I/W/s*cm^2)^2/\Delta\nu/Hz$
Photo Ionization Rate $R_p = 9 * I/W/s*cm^2$
Zeeman shift $\delta\nu_Z = 9.3 * B$ Hz/T
ac Stark shift $\delta\nu_{ac} = 1.7 * I$ Hz /W*cm^2

Velocity at 1mK V_{1K} = 4 m/s
Time-of-flight broadening $\Delta\nu_{TOF}$ = 3 kHz *(1 mK, 600 μm beam diam.)*

Lyman a detection efficiency $10^{-6} = \Omega * eff_{MCP} (= 10^{-4} * 10^{-2})$

10^{11} H-atoms ***(MIT Bose condens.)*** $\delta\nu/\nu_{1s2s} = 10^{-13}$ *(1s integration time)*

Just one Problem: Lyman-α detection via field quenching => atoms can be used once only

(all 1s, m_F states get equally populated)

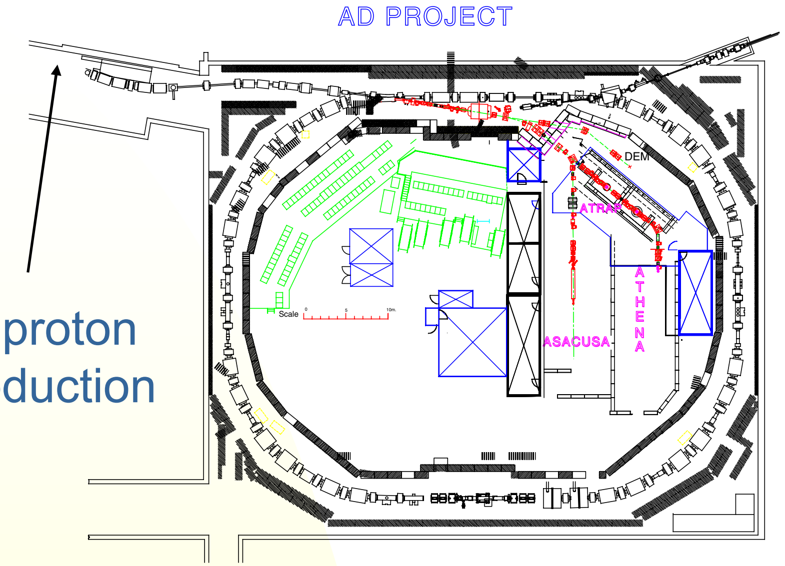
How to scale line center accuracy in absence of systematic errors?

$$\delta\nu = \Delta\nu_{exp.} / (Sign./Noise) \approx \Delta\nu_{exp.} / \sqrt{N_{particles}}$$

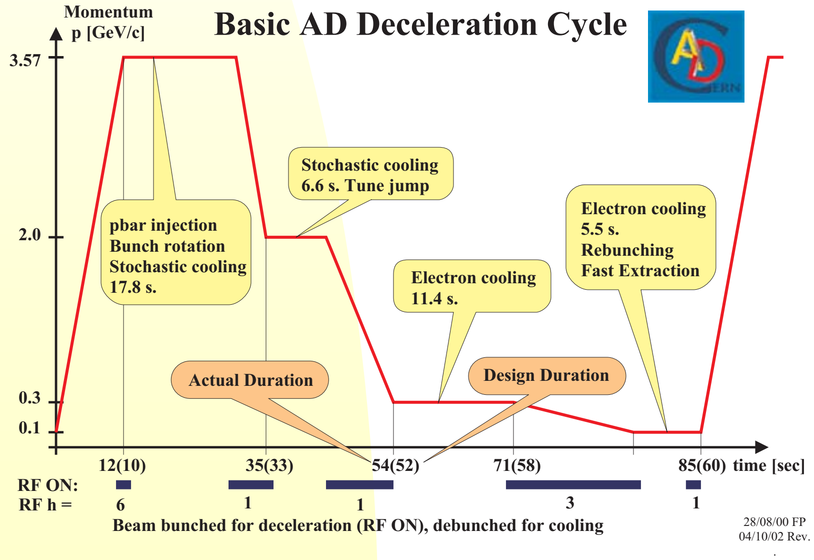
---

* numbers verified with L. Willmann

Antiproton Decelerator (AD) at CERN



Antiproton production



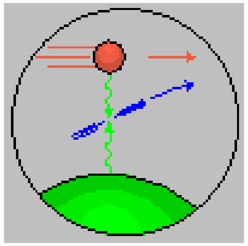
- Antiproton capture, deceleration, cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85 seconds
- Antihydrogen formation and 1S–2S spectroscopy (ATHENA, ATRAP)

  Antiprotonic atom spectroscopy, atomic collisions, Antihydrogen GS-HFS (ASACUSA)

First experimental observations (at CERN) attributed to hot, fast antihydrogen.

"Production of Antihydrogen"

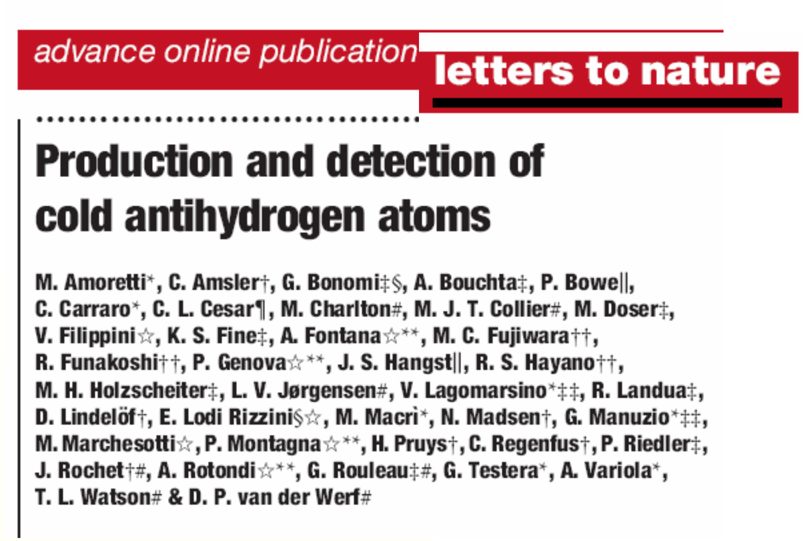
G.Baur et al. (includes D. Grzonka, W. Oelert, G. Schepers, and T. Sefzick, now part of ATRAP)
Phys.Lett. B 368 (1996) 251-258.



Second observations (at Fermilab, with improved setup and luminosity monitors) attributed to hot, fast antihydrogen atoms.

"Observation of Antihydrogen"
G. Blanford, et al.
Phys. Rev. Lett. **80,** 3037 (1998).

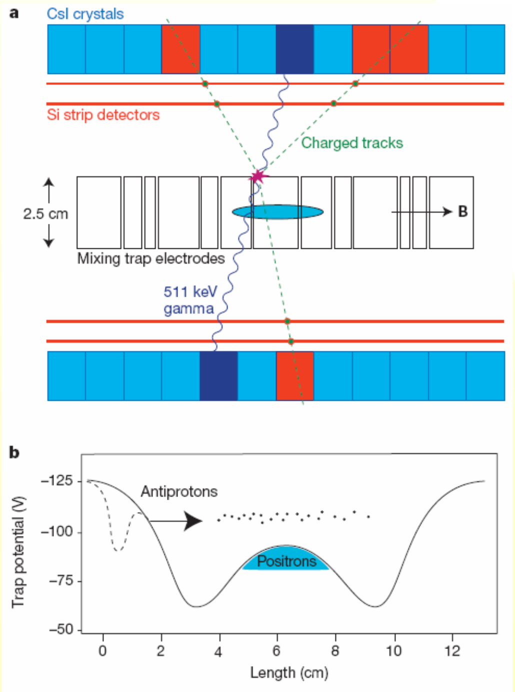
ATHENA

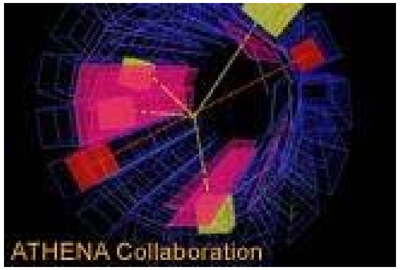


advance online publication **letters to nature**

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe||, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst||, R. S. Hayano††, M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macri*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#**



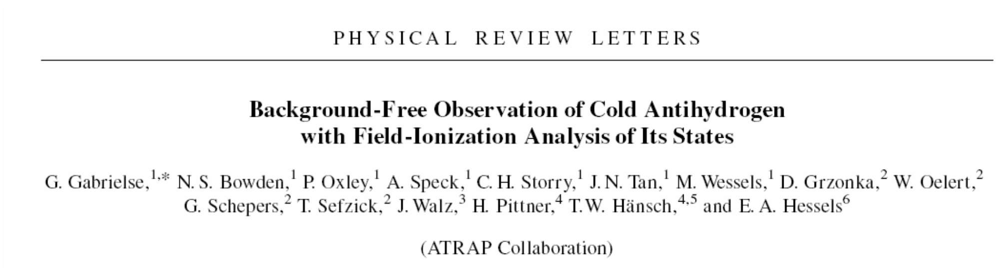


Scientists Create 'Star Trek' Antihydrogen in Quantity

By Alex Dominguez
Associated Press
posted: 02:59 pm ET
18 September 2002

NATURE | 18 SEPTEMBER 2002 | doi:10.1038/nature01096 | www.nature.com/nature

ATRAP

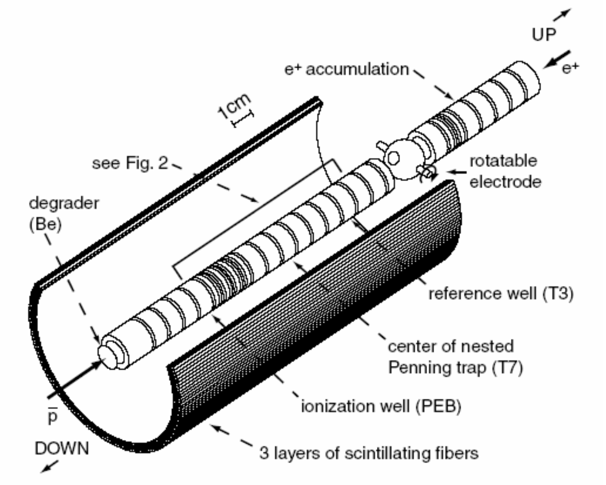


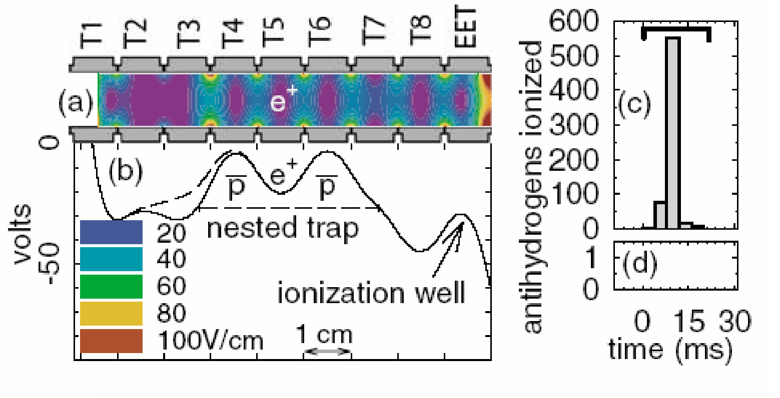
PHYSICAL REVIEW LETTERS

Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T. W. Hänsch,[4,5] and E. A. Hessels[6]

(ATRAP Collaboration)





Physical Review Letters 89, 213401 online (2002)

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Physics Letters B 578 (2004) 23–32
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High rate production of antihydrogen

ATHENA Collaboration

M. Amoretti[a], C. Amsler[b], G. Bazzano[c,d], G. Bonomi[e], A. Bouchta[e], P. Bowe[f], C. Carraro[a,g], C.L. Cesar[h], M. Charlton[i], M. Doser[e], V. Filippini[c,d], A. Fontana[c,d], M.C. Fujiwara[j,k], R. Funakoshi[k], P. Genova[c,d], J.S. Hangst[f], R.S. Hayano[k], L.V. Jørgensen[i], V. Lagomarsino[a,g], R. Landua[e], D. Lindelöf[b], E. Lodi Rizzini[c,l], M. Macri[a], N. Madsen[f], G. Manuzio[a,g], M. Marchesotti[e], P. Montagna[c,d], H. Pruys[b], C. Regenfus[b], P. Riedler[e], A. Rotondi[c,d], G. Rouleau[e], G. Testera[a], A. Variola[a], D.P. van der Werf[i]

[a] *Istituto Nazionale di Fisica Nucleare, Sezione di Genova, 16146 Genova, Italy*
[b] *Physik-Institut, Zurich University, CH-8057 Zurich, Switzerland*
[c] *Istituto Nazionale di Fisica Nucleare, Universita di Pavia, 27100 Pavia, Italy*
[d] *Dipartimento di Fisica Nucleare e Teorica, Universita di Pavia, 27100 Pavia, Italy*
[e] *EP Division, CERN, CH-1211 Geneva 23, Switzerland*
[f] *Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark*
[g] *Dipartimento di Fisica, Universita di Genova, 16146 Genova, Italy*
[h] *Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21945-970, Brazil*
[i] *Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK*
[j] *Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan*
[k] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[l] *Dipartimento di Chimica e Fisica per l'Ingegnieria e per i Materiali, Universita di Brescia, 25123 Brescia, Italy*

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Abstract

We show that antihydrogen production is the dominant process when mixing antiprotons and positrons in the ATHENA apparatus, and that the initial production rate exceeds 300 Hz, decaying to 30 Hz within 10 s. A fraction of 65% of all observed annihilations is due to antihydrogen.

VOLUME 92, NUMBER 6 PHYSICAL REVIEW LETTERS week ending 13 FEBRUARY 2004

Three-Dimensional Annihilation Imaging of Trapped Antiprotons

M. C. Fujiwara,[1,2,*] M. Amoretti,[3] G. Bonomi,[4] A. Bouchta,[4] P. D. Bowe,[5] C. Carraro,[3,6] C. L. Cesar,[7] M. Charlton,[5]
M. Doser,[4] V. Filippini,[8] A. Fontana,[8,9] R. Funakoshi,[1] P. Genova,[8,9] J. S. Hangst,[10] R. S. Hayano,[1] L. V. Jørgensen,[5]
V. Lagomarsino,[3,6] R. Landua,[4] E. Lodi-Rizzini,[8,11] M. Marchesotti,[8] M. Macri,[3] N. Madsen,[10] G. Manuzio,[3,6]
P. Montagna,[8,9] P. Riedler,[4] A. Rotondi,[8,9] G. Rouleau,[4,5] G. Testera,[3] A. Variola,[3] D. P. van der Werf,[5] and Y. Yamazaki[2]

(ATHENA Collaboration)

[1]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[2]*Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan*
[3]*Istituto Nazionale di Fisica Nucleare, Sezione di Genova, I-16146 Genova, Italy*
[4]*EP Division, CERN, Geneva, Switzerland*
[5]*Department of Physics, University of Wales Swansea, Swansea SA2 8PP, United Kingdom*
[6]*Dipartimento di Fisica di Genova, I-16146 Genova, Italy*
[7]*Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21945-970, Brazil*
[8]*Istituto Nazionale di Fisica Nucleare Sezione di Pavia, I-27100 Pavia, Italy*
[9]*Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, I-27100 Pavia, Italy*
[10]*Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark*
[11]*Dipartimento di Chimica e Fisica per l'Ingegneria e per i Materiali, I-25123 Brescia, Italy*

(Received 31 July 2003; published 13 February 2004)

We demonstrate three-dimensional imaging of antiprotons in a Penning trap, by reconstructing annihilation vertices from the trajectories of the charged annihilation products. The unique capability of antiparticle imaging has allowed, for the first time, the observation of the spatial distribution of the particle loss in a Penning trap. The radial loss of antiprotons on the trap wall is localized to small spots, strongly breaking the azimuthal symmetry expected for an ideal trap. Our observations have important implications for detection of antihydrogen annihilations.

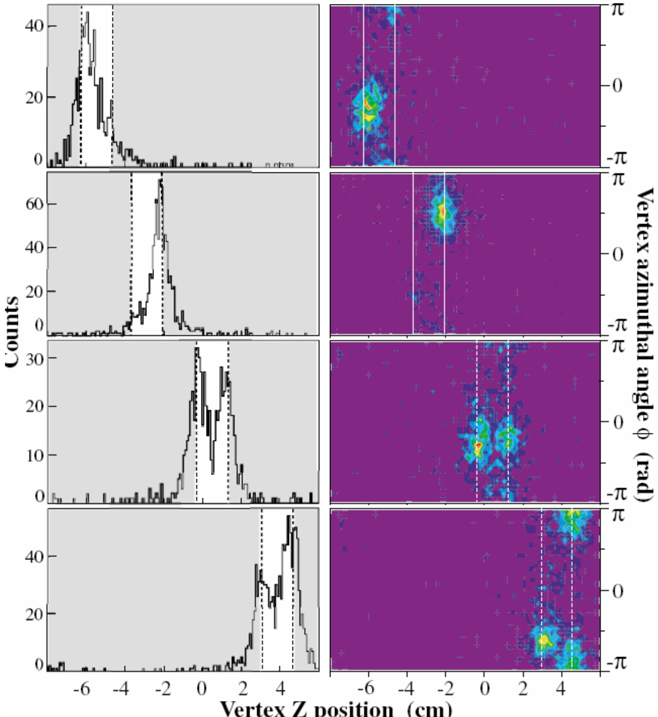


FIG. 4 (color). The projection of the annihilation distribution on the z axis (left column) and on the $z-\phi$ plane (right column) for four different confinement setups. The trap well positions are indicated by the unshaded regions, and the dimensions of the electrodes are depicted with dashed lines.

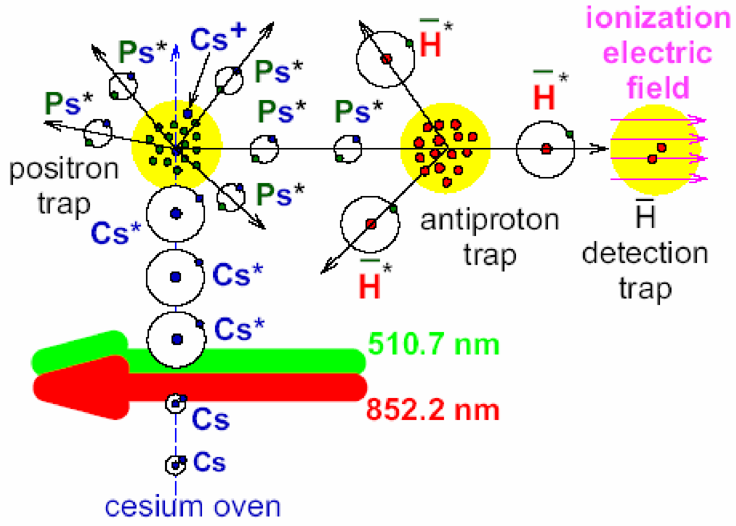
First Laser-Controlled Antihydrogen Production

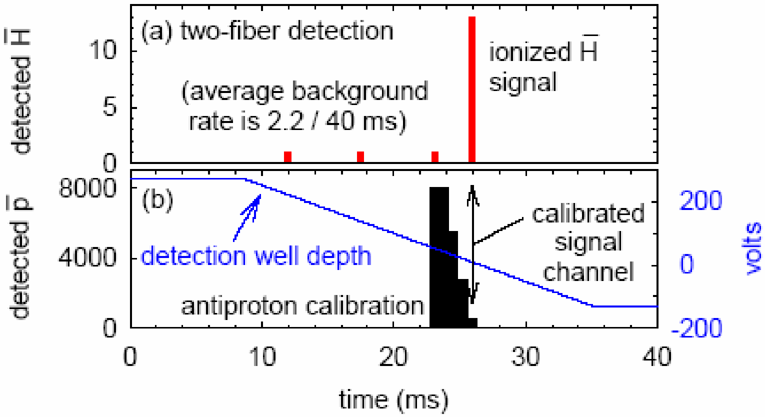
C.H. Storry,[1] A. Speck,[1] D. Le Sage,[1] N. Guise,[1] G. Gabrielse*,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2]
T. Sefzick,[2] H. Pittner,[3] M. Herrmann,[3] J. Walz,[3] T.W. Hänsch,[3,4] D. Comeau,[5] and E.A. Hessels[5]
(ATRAP Collaboration)

[1]*Department of Physics, Harvard University, Cambridge, MA 02138*
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany*
[4]*Ludwig-Maximilians-Universität München, Schellingstrasse 4/III, 80799 München, Germany*
[5]*York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*

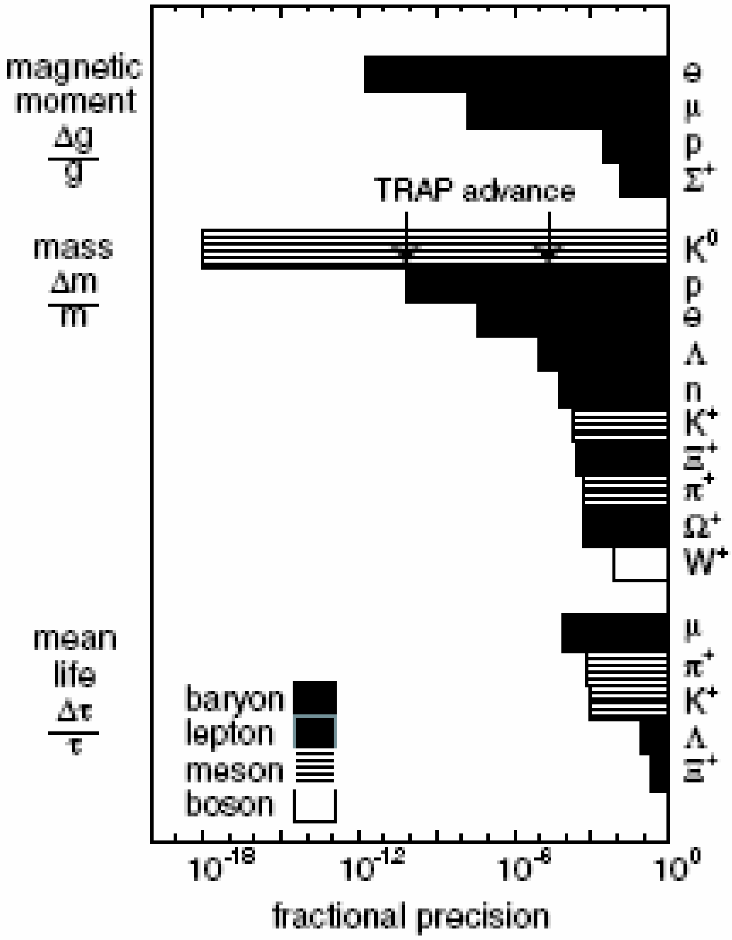
(Dated: Submitted to PRL: 17 August 2004)

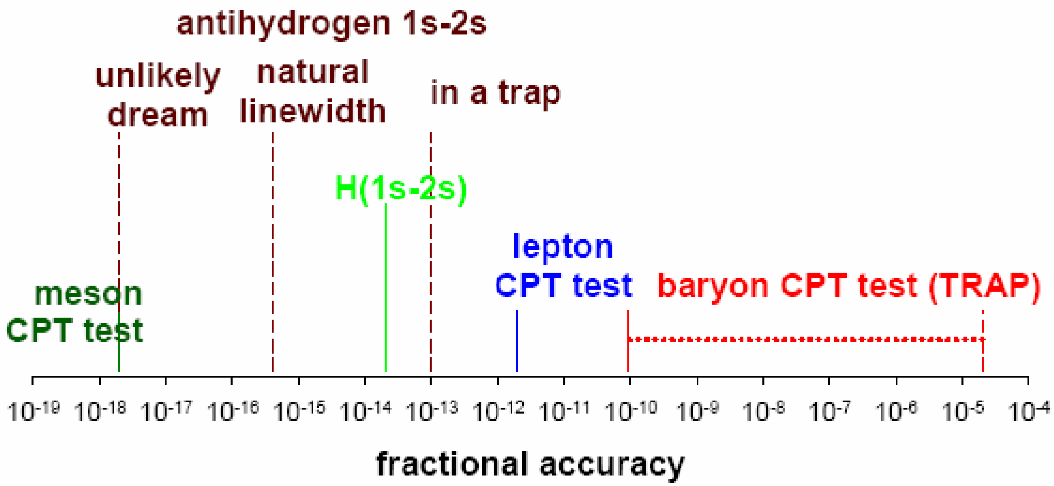
Lasers are used for the first time to control the production of antihydrogen ($\overline{\mathrm{H}}$). Sequential, resonant charge exchange collisions are involved in a method that is very different than the only other method used so far – producing slow $\overline{\mathrm{H}}$ during positron cooling of antiprotons in a nested Penning trap. Two attractive features are that the laser frequencies determine the $\overline{\mathrm{H}}$ binding energy, and that the production of extremely cold $\overline{\mathrm{H}}$ should be possible in principle – likely close to what is needed for confinement in a trap, as needed for precise laser spectroscopy.



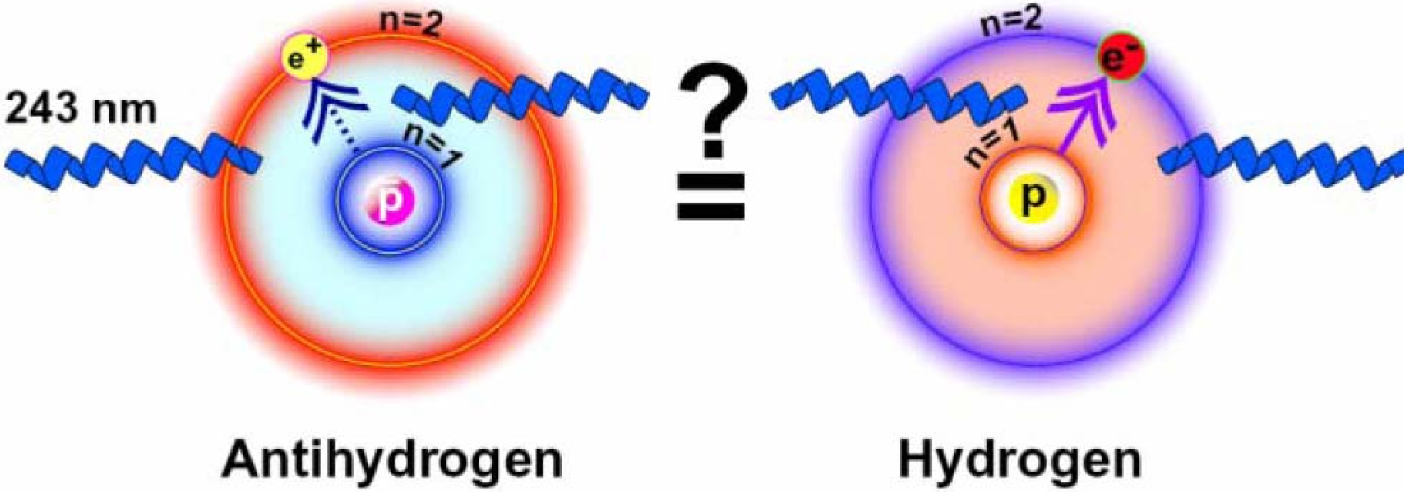


Antihydrogen CPT Tests





(Anti-)Hydrogen CPT tests



Laser spectroscopy 1s-2s -------- Microwave spectroscopy
1s Hyperfine Structure

$\Delta\nu_{1s2s} = \frac{3}{4} * R_\infty + \varepsilon_{QED} + \varepsilon_{nucl} + \varepsilon_{weak} + \varepsilon_{CPT}$

$\Delta\nu_{HFS} = \text{cons.} * \alpha^2 R_\infty + \varepsilon'_{QED} + \varepsilon'_{nucl} + \varepsilon'_{weak} + \varepsilon'_{CPT}$

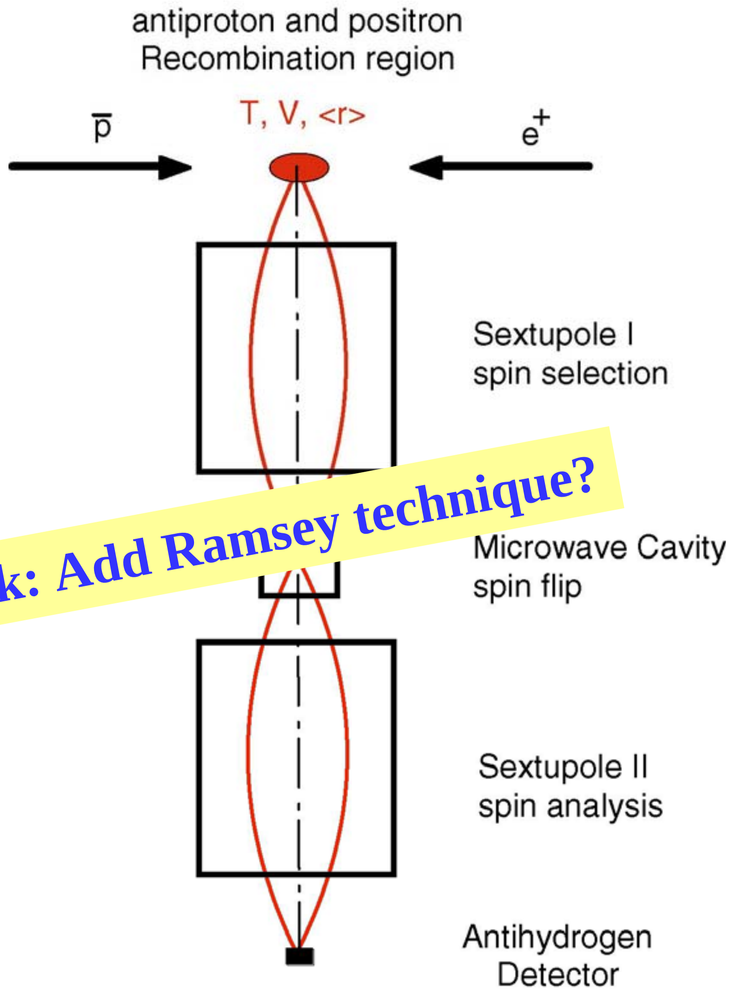
"Long distance" Interaction

"Contact" interaction

$R_\infty = m_e c^2 * \alpha^2 / 2 h$

$\bar{H}$ Ground-state Hyperfine Structure

- atoms "evaporate"
  - No trapping needed !!
- atomic beam for focussing and spin selection
- spin-flip by microwave radiation
- low-background high-efficiency detection of antihydrogen through annihilation
- achievable resolution
  - better 10^{-6} for $T \leq 100$ K
  - > 100 H/s in 1S state needed
- ultimate precision:
  - atomic fountain of H ->_
    FLAIR

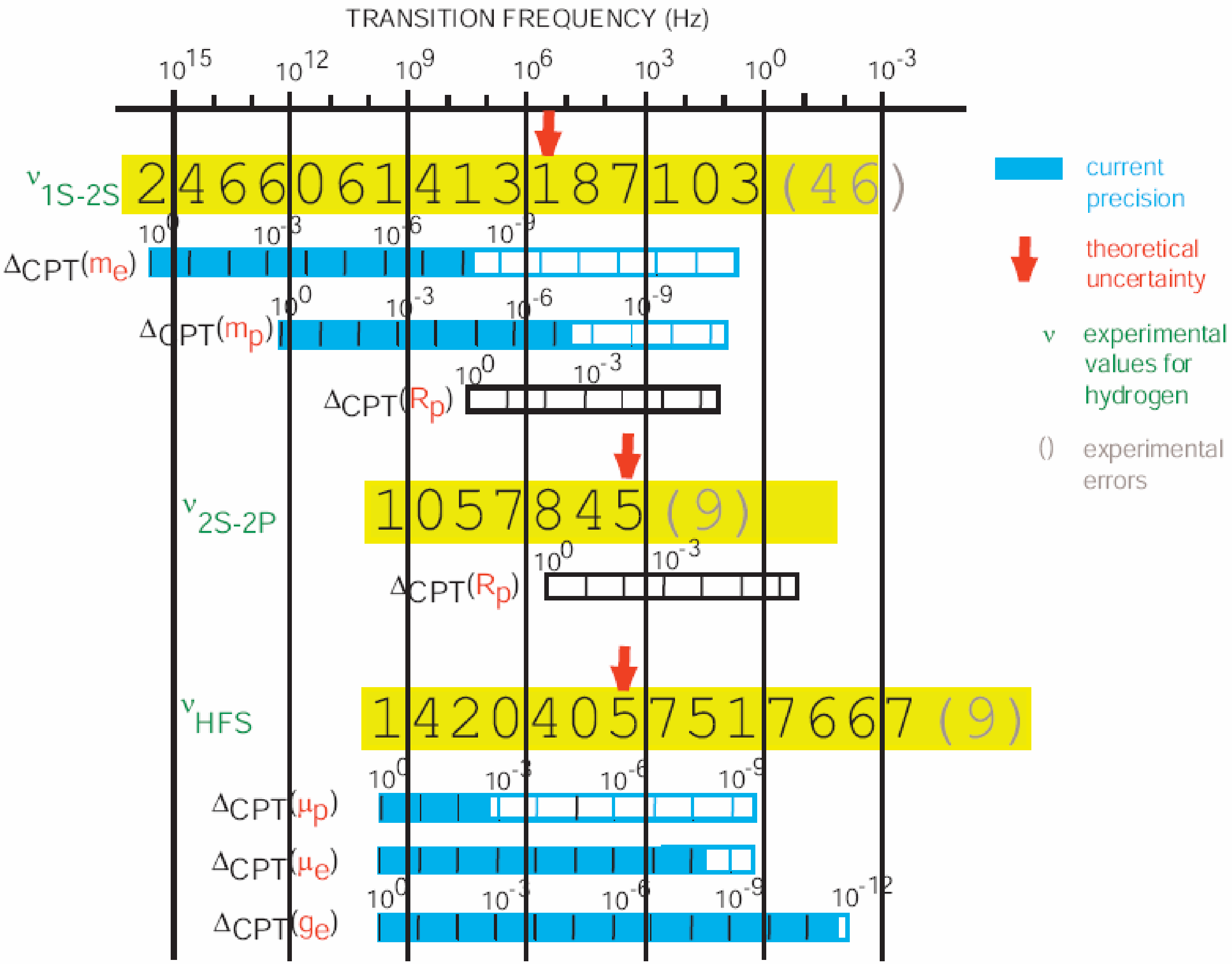


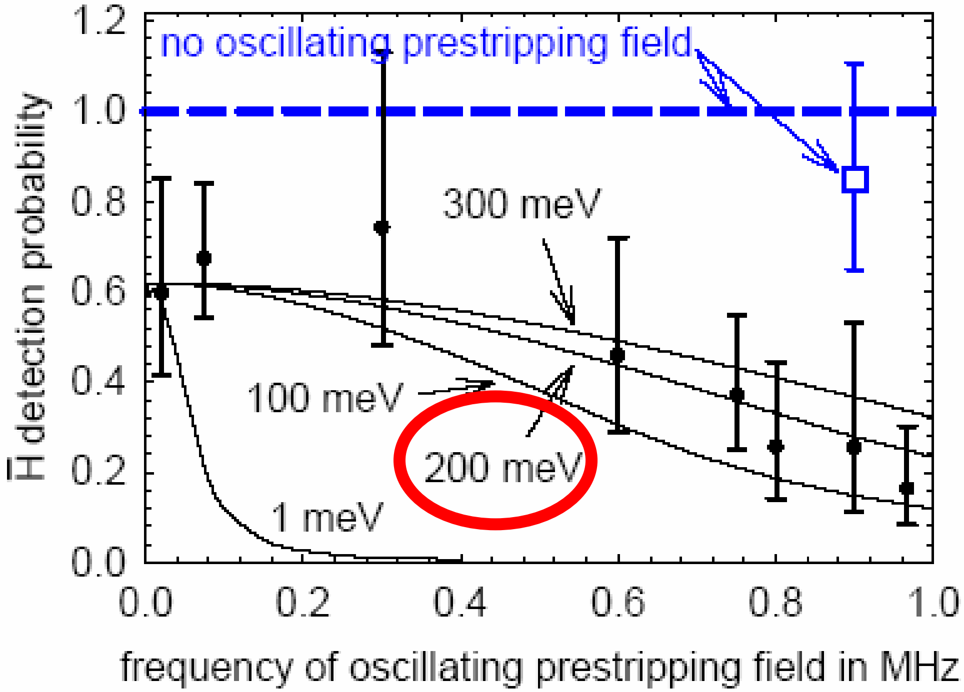
Remark: Add Ramsey technique?

ASACUSA LoI for AD CERN-SPSC-2003-009, proposal CERN-SPSC-2005-002

from E. Widmann

Measured quantities in hydrogen and relevance to CPT tests





Measurements indicate

T ≈ 2400 K

needed for trapping

0.5 K

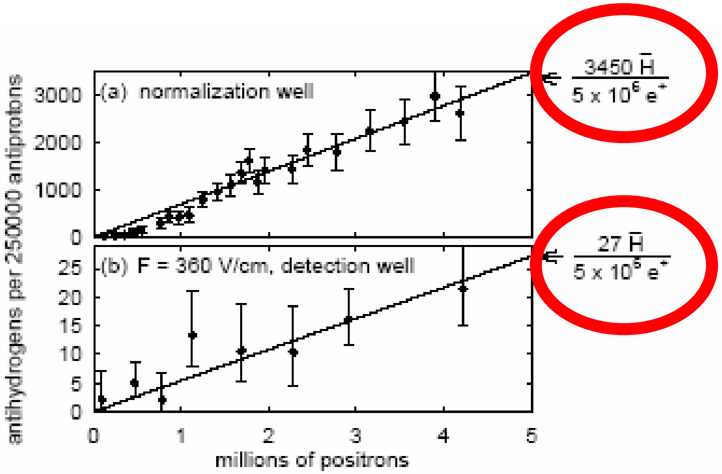


Fig. 20. $\overline{\mathrm{H}}$ produced from 2.5×10^5 $\overline{\mathrm{p}}$ and detected in the normalization (a) and detection wells (b), the latter having survived a 360 V/cm field without ionizing. From (Gabrielse et al., 2004a).

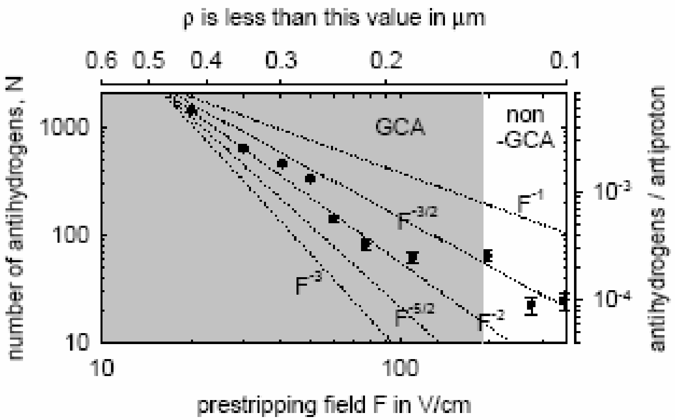


Fig. 21. Number N of $\overline{\mathrm{H}}$ that survive an ionization field $F = F_z$, for 2.5×10^5 $\overline{\mathrm{p}}$ and 5×10^6 e^+, taken from measurements such as shown in Fig. 20. From (Gabrielse et al., 2004a).

$$\rho \leq \frac{a}{\sqrt{F}} \sqrt{\frac{e}{4\pi\epsilon_o}},$$

ρ mostly above .1 µm

n > 15

(Anti-)Hydrogen Spectroscopy*

Hydrogen 1s-2s Saturation Intensity I_s $= 0.9$ W/cm2

Excitation Rate R_e $= 4\pi*84*(I/W/s*cm^2)^2/\Delta\nu/Hz$

Photo Ionization Rate R_p $= 9*I/W/s*cm^2$

Zeeman shift $\delta\nu_Z$ $= 9.3*B$ Hz/T

ac Stark shift $\delta\nu_{ac}$ $= 1.7\ I$ Hz /W*cm^2

Velocity at 1mK V_{1K} $= 4$ m/s

Time-of-flight broadening $\Delta\nu_{TOF}$ $= 3$ kHz *(1 mK, 600 μm beam diam.)*

Lyman a detection efficiency 10^{-6} $= \Omega * eff_{MCP}\ (= 10^{-4} * 10^{-2})$

10^{11} H-atoms ***(MIT Bose condens.)*** $\delta\nu/\nu_{1s2s}$ $= 10^{-13}$ *(1s integration time)*

Just one Problem: Lyman-α detection via field quenching => atoms can be used once only

(all 1s, m_F states get equally populated)

How to scale line center accuracy in absence of systematic errors?

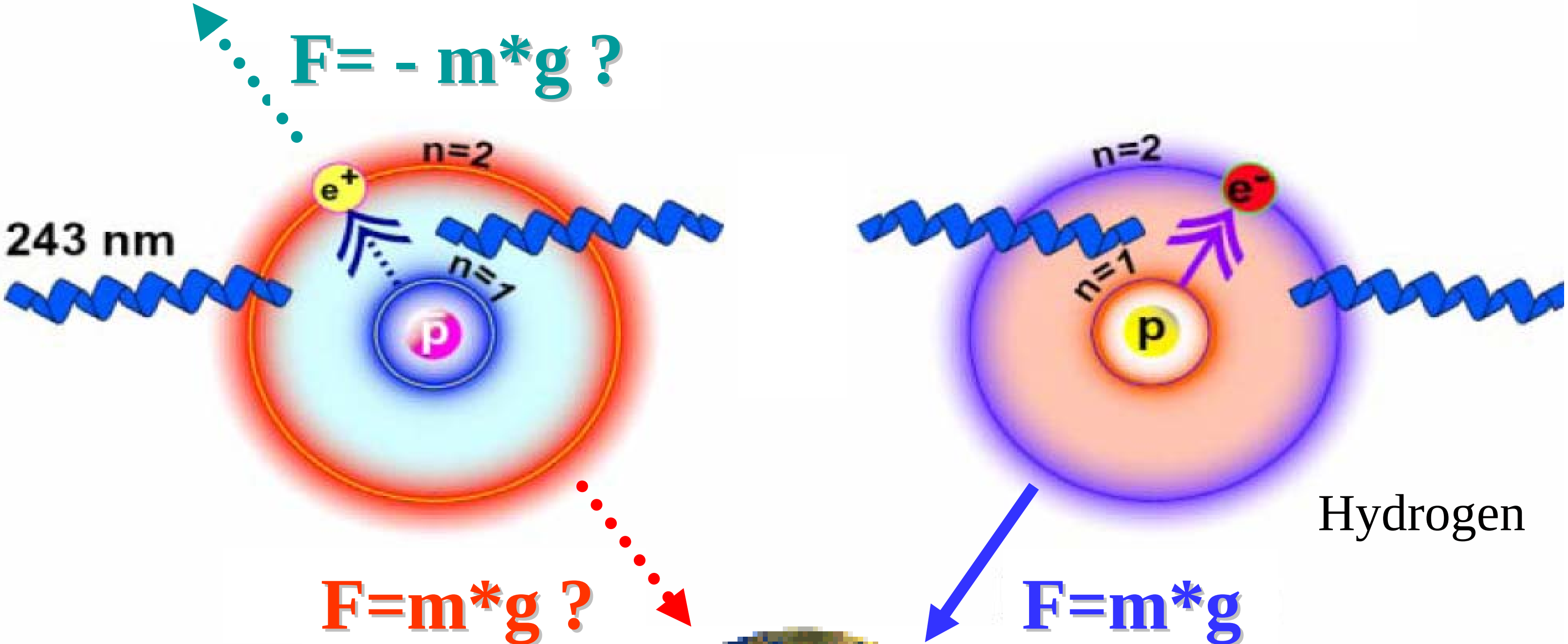
$$\delta\nu = \Delta\nu_{exp.} / (Sign./Noise) \approx \Delta\nu_{exp.} / \sqrt{N_{particles}}$$

---

* numbers verified with L. Willmann

(Anti-)Hydrogen Gravity Tests

F= - m*g ?



Hydrogen

F=m*g ?

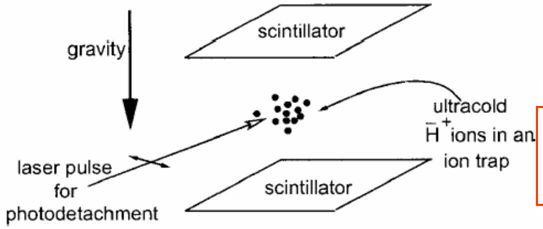
F=m*g

General Relativity and Gravitation, Vol. 36, No. 3, March 2004 (© 2004)

A Proposal to Measure Antimatter Gravity Using Ultracold Antihydrogen Atoms

Jochen Walz[1] and Theodor W. Hänsch[1,2]

Received September 19, 2003

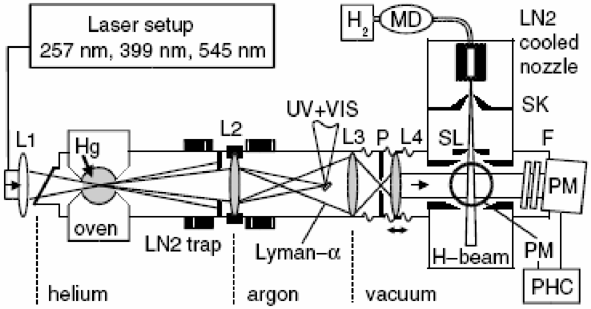


Lyman –α laser required

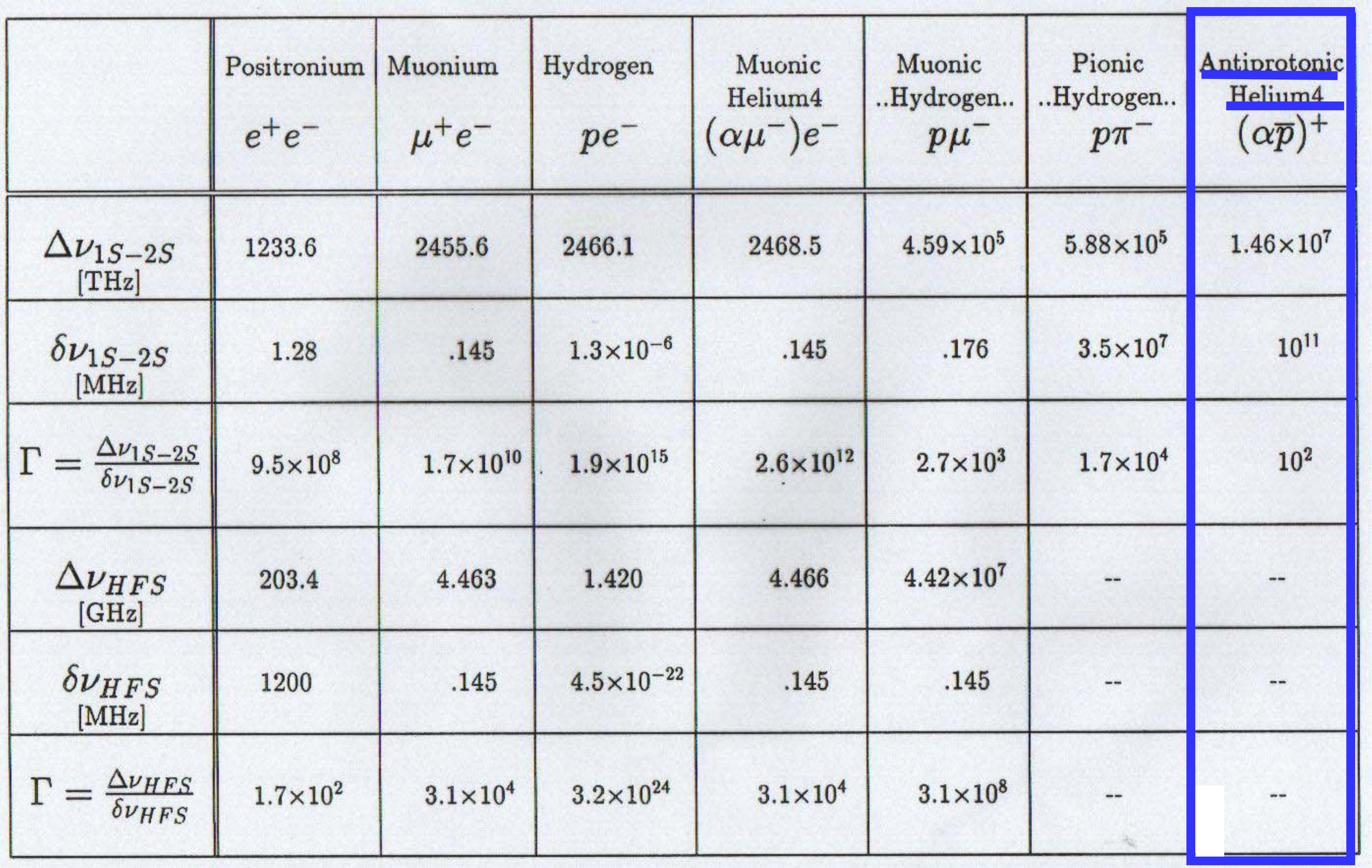
VOLUME 86, NUMBER 25 PHYSICAL REVIEW LETTERS

Continuous Coherent Lyman-α Excitation of Atomic Hydrogen

K. S. E. Eikema,* J. Walz,† and T. W. Hänsch

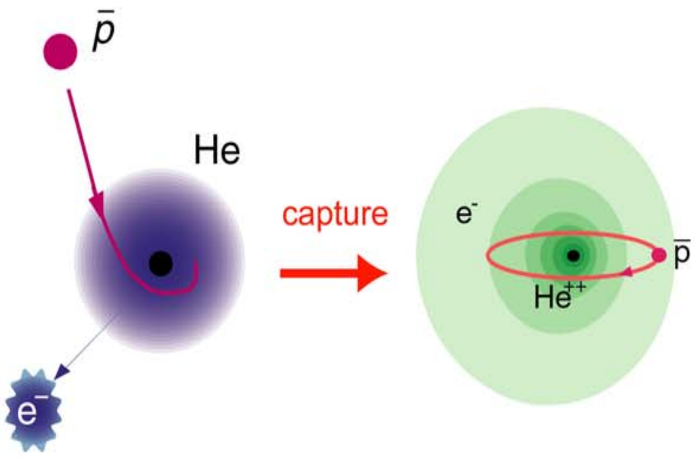


Hydrogen-like Atoms

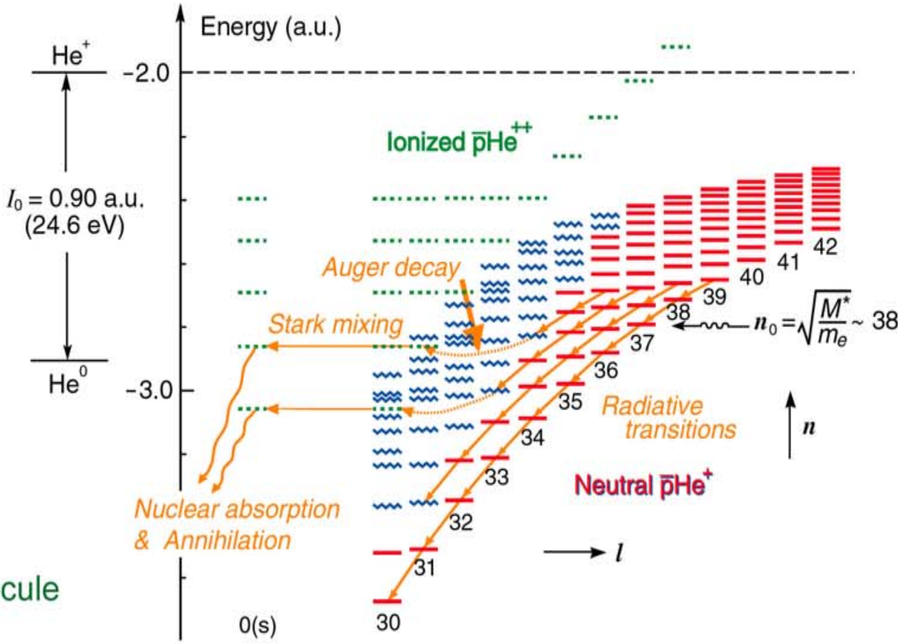


	Positronium e^+e^-	Muonium μ^+e^-	Hydrogen pe^-	Muonic Helium4 $(\alpha\mu^-)e^-$	Muonic ..Hydrogen.. $p\mu^-$	Pionic ..Hydrogen.. $p\pi^-$	Antiprotonic Helium4 $(\alpha\overline{p})^+$
$\Delta\nu_{1S-2S}$ [THz]	1233.6	2455.6	2466.1	2468.5	4.59×10^5	5.88×10^5	1.46×10^7
$\delta\nu_{1S-2S}$ [MHz]	1.28	.145	1.3×10^{-6}	.145	.176	3.5×10^7	10^{11}
$\Gamma = \frac{\Delta\nu_{1S-2S}}{\delta\nu_{1S-2S}}$	9.5×10^8	1.7×10^{10}	1.9×10^{15}	2.6×10^{12}	2.7×10^3	1.7×10^4	10^2
$\Delta\nu_{HFS}$ [GHz]	203.4	4.463	1.420	4.466	4.42×10^7	--	--
$\delta\nu_{HFS}$ [MHz]	1200	.145	4.5×10^{-22}	.145	.145	--	--
$\Gamma = \frac{\Delta\nu_{HFS}}{\delta\nu_{HFS}}$	1.7×10^2	3.1×10^4	3.2×10^{24}	3.1×10^4	3.1×10^8	--	--

pHe$^+$ Atom – a naturally occurring trap for antiprotons



characteristics of both atom and molecule



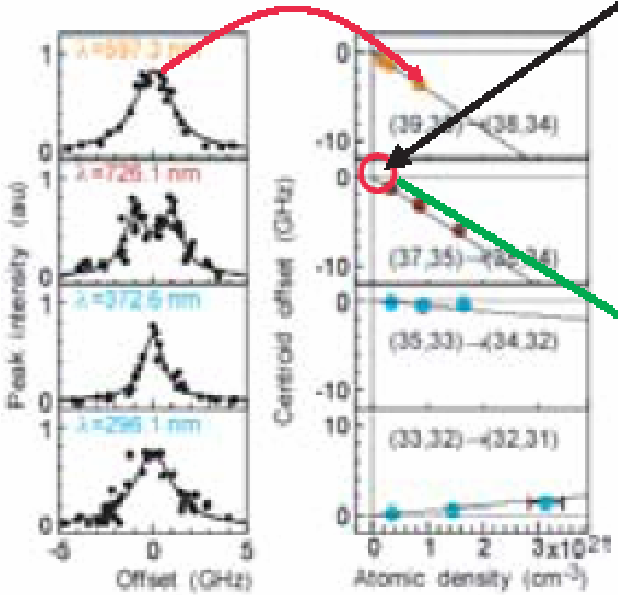
- Serendipitously discovered by Tokyo group at KEK
- 3-body system, Metastable
- ~ 3% of stopped antiprotons survive with average lifetime of ~ 3 μs
- Precision laser spectroscopy by ASACUSA:
  - best test of 3-body QED theories
  - proton-antiproton mass & charge comparison, 60 ppb (PDG 2002)

Hayano, Yamazaki et al.

CPT Test with Antiprotonic Helium

5 MeV 1 π mm mrad beam

- Zero-density values compared to state of-the-art three-body QED calculations
- $\bar{p}$ mass and charge CPT limit: 60 ppb



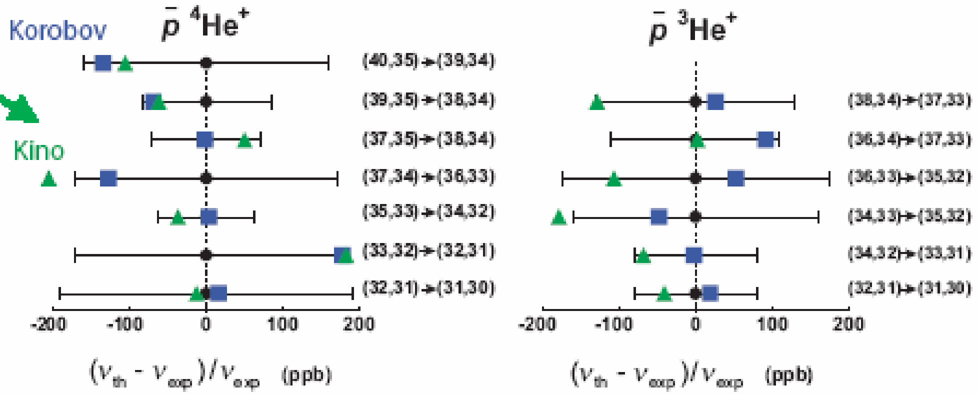
Resonance scans

Shift of center with density

Exp. Accuracy 1.3 x 10^{-7}

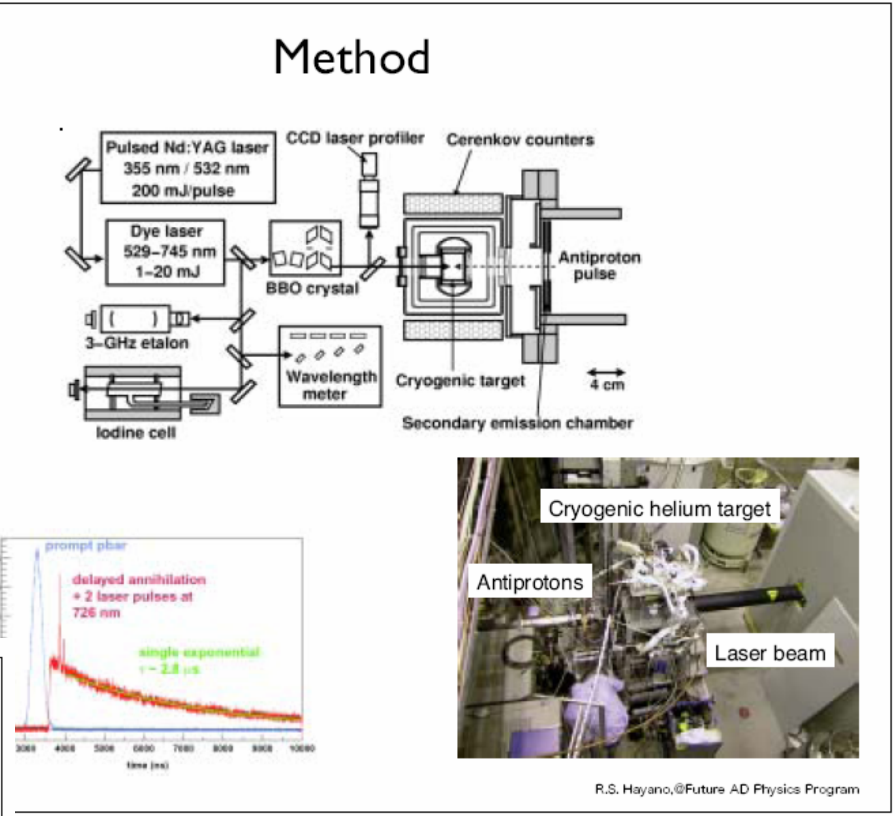
100 keV 100 π mm mrad beam

With RFQD: direct measurement at zero density (in "vacuum"): CPT limit 10 ppb



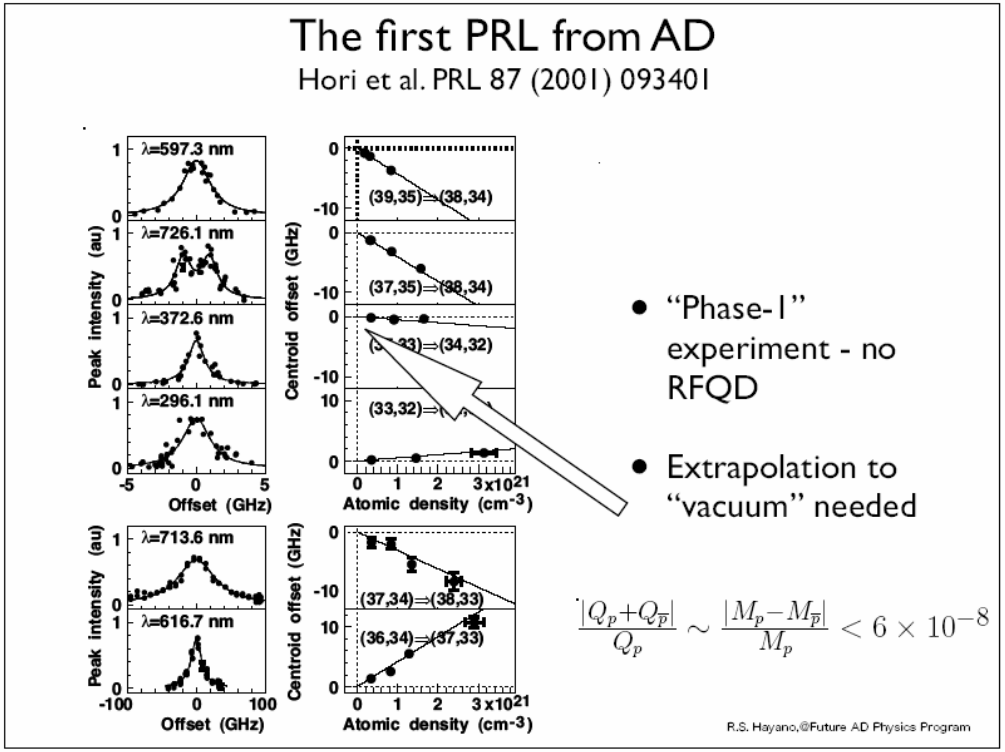
Exp. Accuracy 6 x 10^{-8}

CPT test in Antiprotonic Helium



Method

R.S. Hayano,@Future AD Physics Program



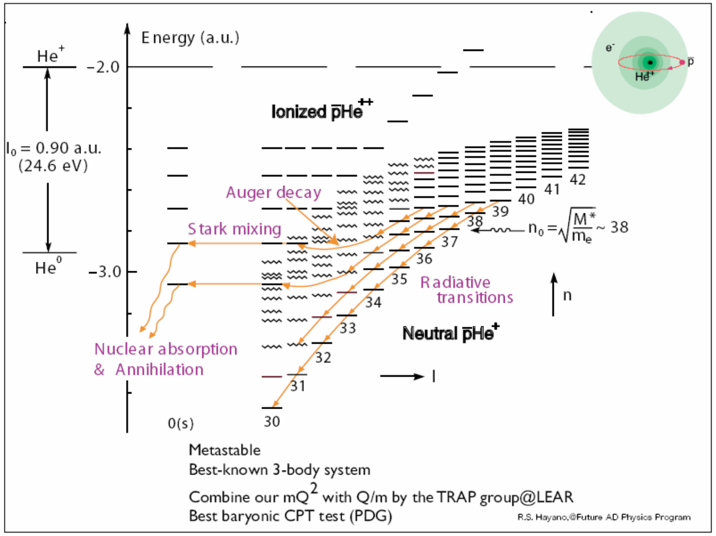
The first PRL from AD

Hori et al. PRL 87 (2001) 093401

- “Phase-I” experiment - no RFQD
- Extrapolation to “vacuum” needed

$$\frac{|Q_p+Q_{\bar{p}}|}{Q_p} \sim \frac{|M_p-M_{\bar{p}}|}{M_p} < 6\times10^{-8}$$

R.S. Hayano,@Future AD Physics Program



Metastable

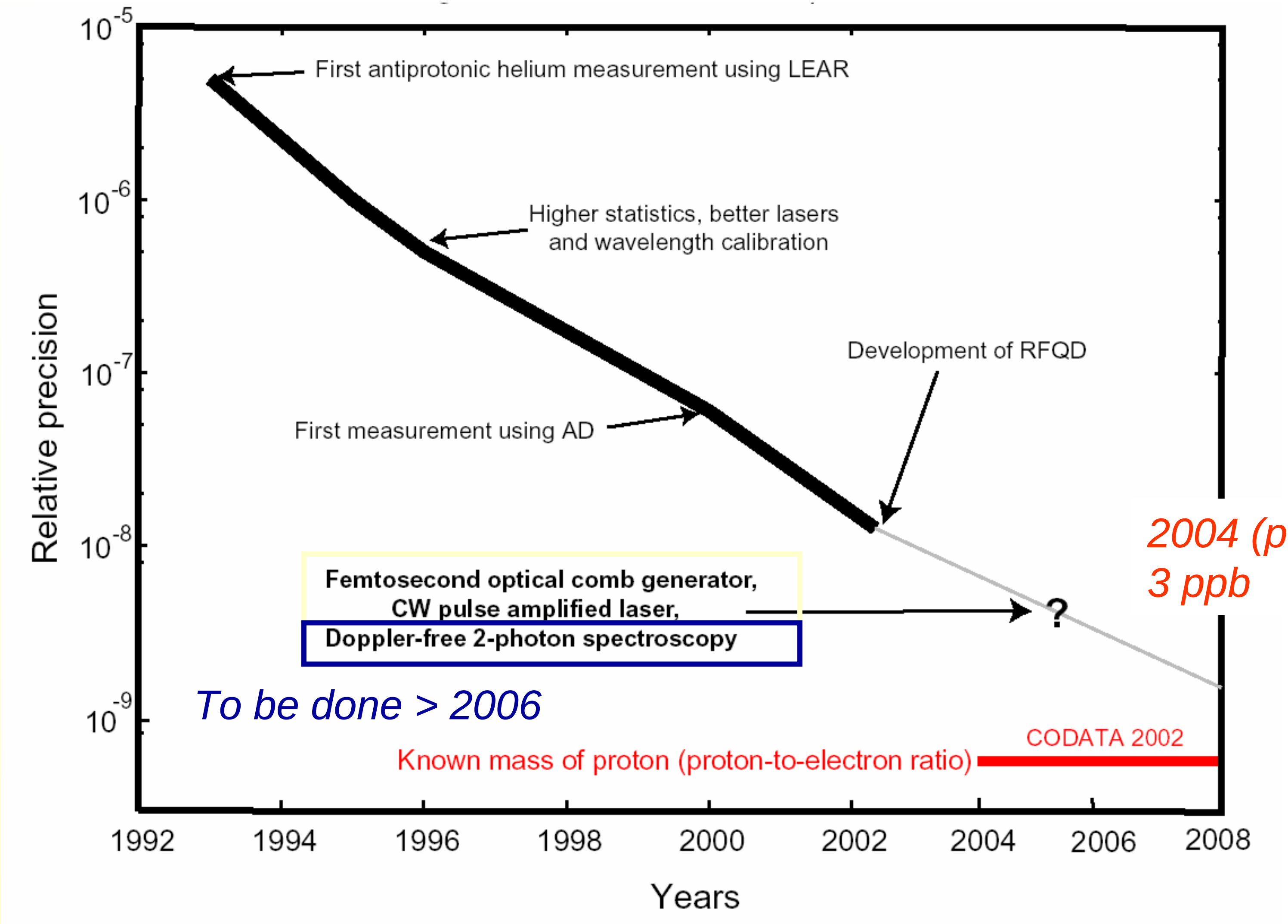
Best-known 3-body system

Combine our mQ^2 with Q/m by the TRAP group@LEAR

Best baryonic CPT test (PDG)

R.S. Hayano,@Future AD Physics Program

Progress in atomcule spectroscopy



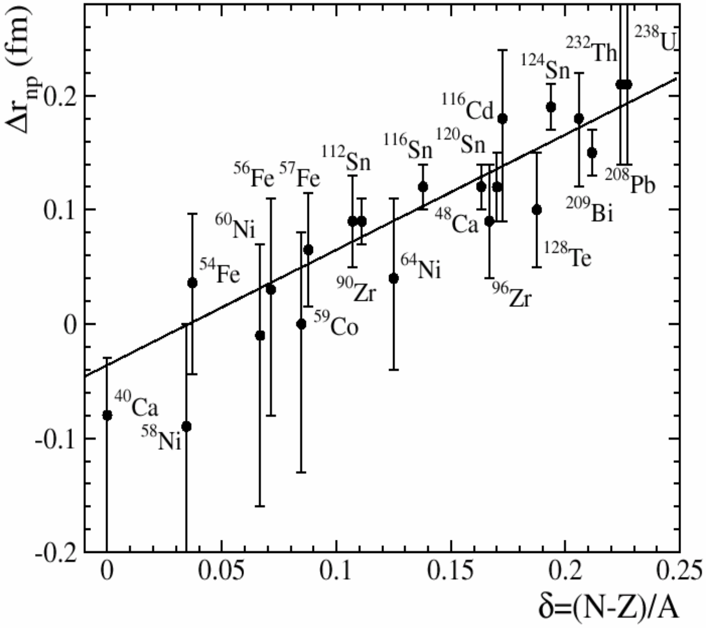
Femtosecond optical comb generator,
CW pulse amplified laser,
Doppler-free 2-photon spectroscopy

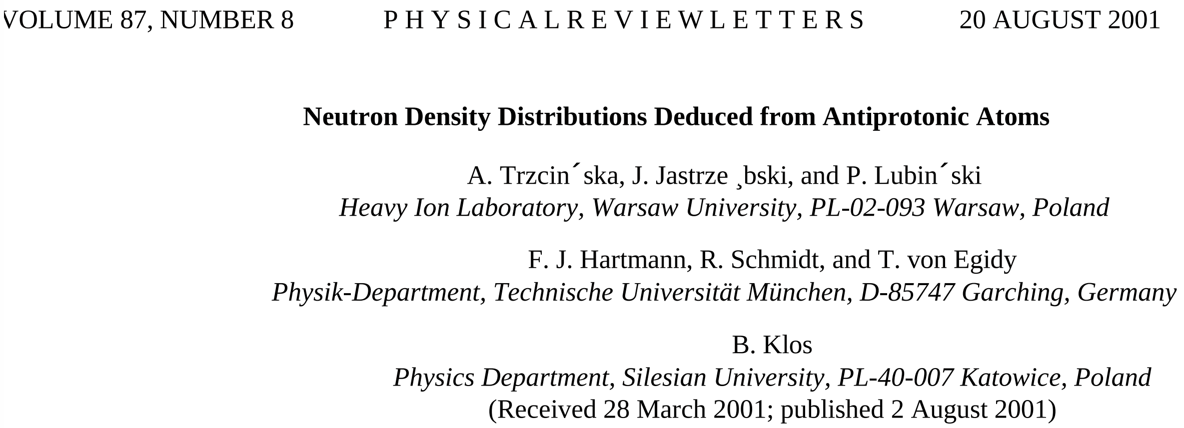
To be done > 2006

2004 (prelim.)
3 ppb

Antiprotonic Radioactive Atoms

Process	Observable	Deduced quantity	Physics
Capture in high orbit (atomic x-sections), cascade	Antiprotonic x-rays *O*(MeV)	Annihilation orbit, energy shifts	Matter distributions, neutron vs. protons on nuclear surface, …
Annihilation (n>7) on peripheral nucleon	De-excitation γ, particles, daughter activity	n vs. p annihilation	




VOLUME 87, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 2001

Neutron Density Distributions Deduced from Antiprotonic Atoms

A. Trzcińska, J. Jastrzębski, and P. Lubiński
Heavy Ion Laboratory, Warsaw University, PL-02-093 Warsaw, Poland

F. J. Hartmann, R. Schmidt, and T. von Egidy
Physik-Department, Technische Universität München, D-85747 Garching, Germany

B. Klos
Physics Department, Silesian University, PL-40-007 Katowice, Poland
(Received 28 March 2001; published 2 August 2001)

Highest Uncertainty Arising from Theory

Where is Slow Antiproton Physics in 2004 ?

- Driven by ambitious goals – CPT, Gravity,
  Nuclear Properties, Medical, ….

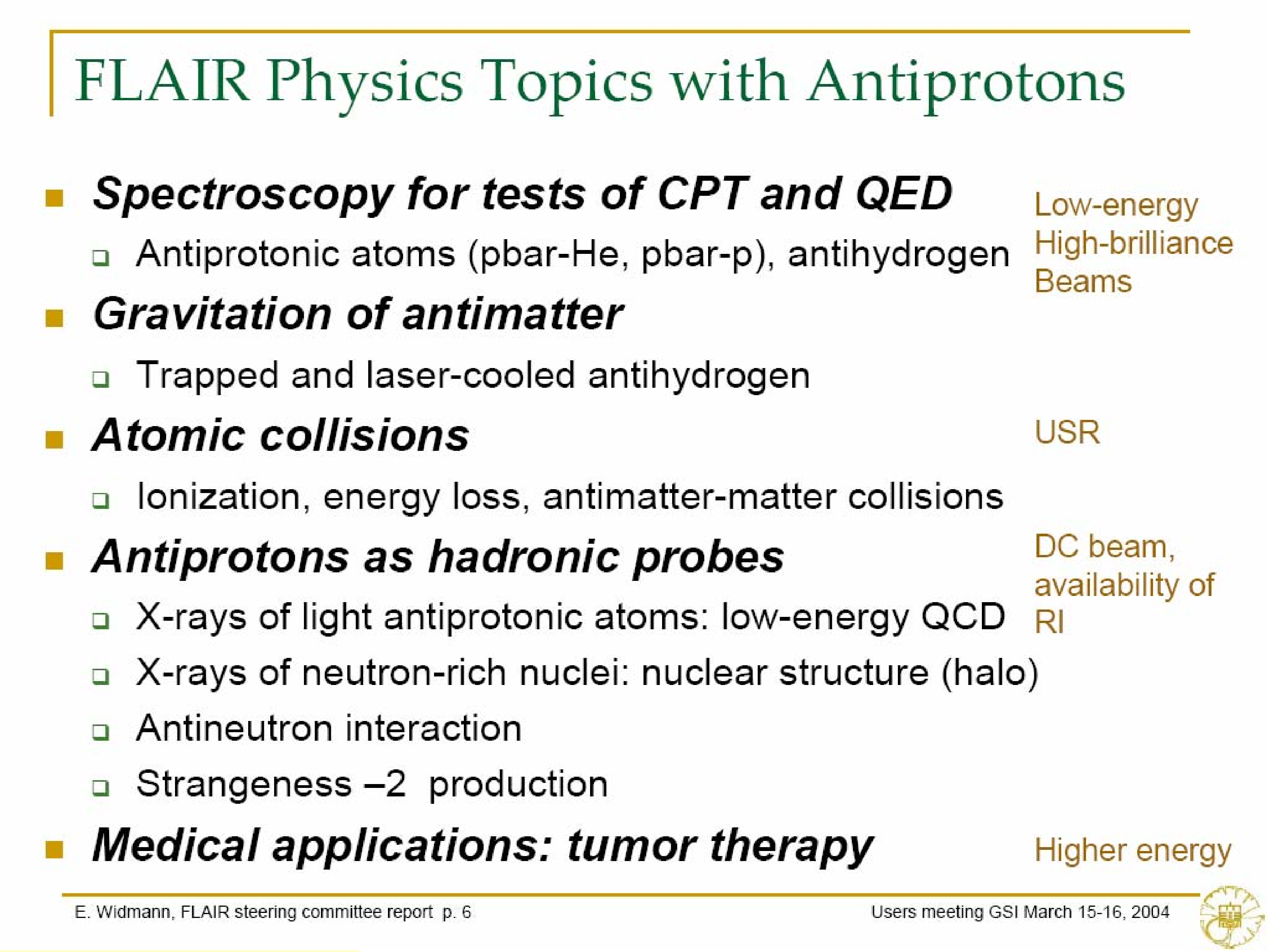
- Antiprotonic Helium and Antihydrogen somewhat central
  - Antiprotonic Helium at KEK, LEAR, AD
  - Antihydrogen at CERN, FERMILAB (fast) and CERN (slow)

- There is slow Antiproton Facility available: AD

- AD produced beautiful results
  - Antiprotonic Helium
  - Antihydrogen

- Central now:
  - Learn to produce Antihydrogen (still highly excited / high velocities)
  - Prepare spectroscopy
  - Plasma Physics, Collision Physics, basic Atomic and Molecular Physics
  - Antimatter-Matter Interactions
  - . . . . .

Future Dreams & Plans



FLAIR Physics Topics with Antiprotons

- ***Spectroscopy for tests of CPT and QED***
  - Antiprotonic atoms (pbar-He, pbar-p), antihydrogen
- ***Gravitation of antimatter***
  - Trapped and laser-cooled antihydrogen
- ***Atomic collisions***
  - Ionization, energy loss, antimatter-matter collisions
- ***Antiprotons as hadronic probes***
  - X-rays of light antiprotonic atoms: low-energy QCD
  - X-rays of neutron-rich nuclei: nuclear structure (halo)
  - Antineutron interaction
  - Strangeness –2 production
- ***Medical applications: tumor therapy***

Low-energy
High-brilliance
Beams

USR

DC beam,
availability of
RI

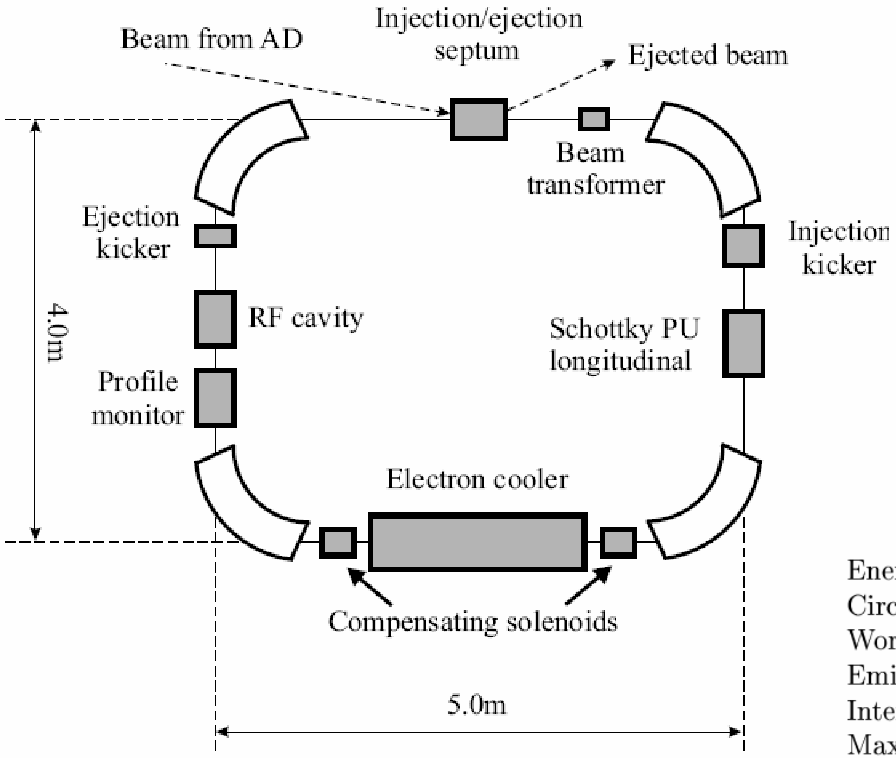
Higher energy

E. Widmann, FLAIR steering committee report p. 6

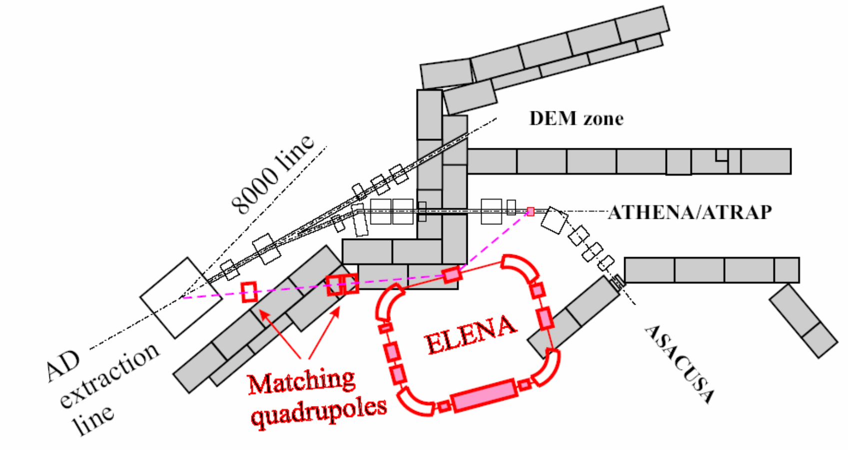
Users meeting GSI March 15-16, 2004

Future Dreams & Plans

ELENA@CERN

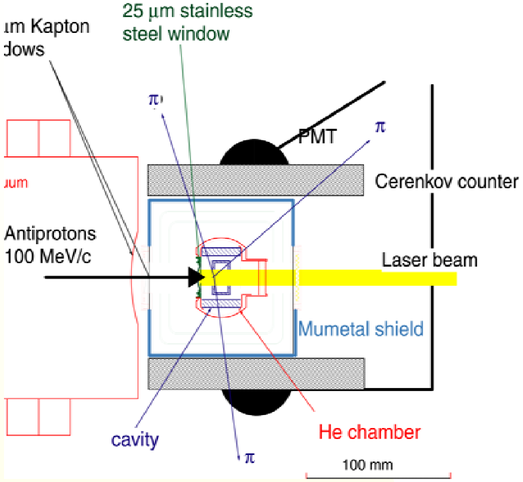


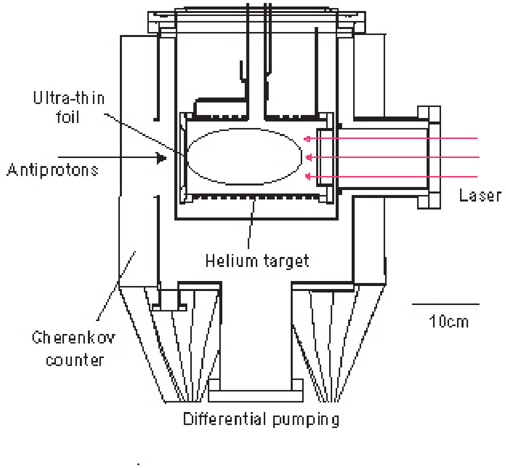
Layout of the ELENA ring.

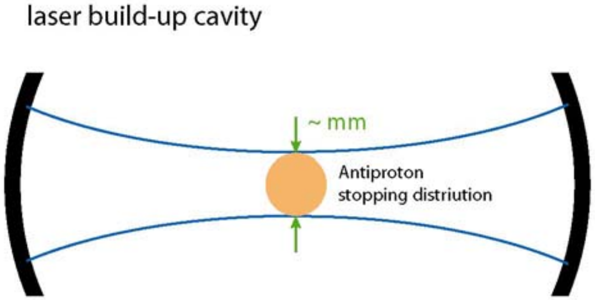


Energy range, MeV	5.3 - 0.1
Circumference, m	16.7
Working point	1.64 / 1.62
Emittances at 100 keV, π mm mrad	5 / 5
Intensity limitations due to space charge	1.7×10^{7}
Maximal incoherent tune shift	0.10
Bunch length at 100 keV, m / ns	1.3 / 300
Multiple scattering blow up rate for 3×10^{-12} Torr (N_2 equiv.), $\pi mm\ mrad/s$	0.5
IBS blow up times, s ($\Delta p/p = 2\ 10^{-3}$)	3.2 /-30.6 / 3.9

Precision Spectroscopy of p Atoms





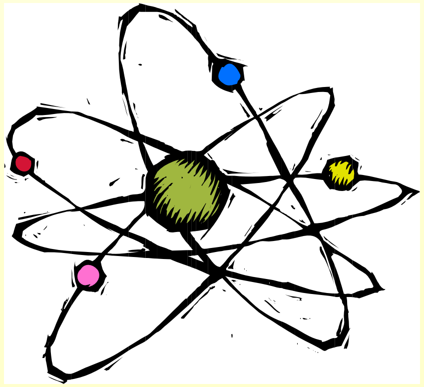


AD	AD + RFQD	FLAIR
5.3 MeV pbar	100 keV	20 keV
1 π mm mrad	100 π	1 π
ΔE/E~10^-4	5%	10^-4
Pbar cloud: 1 cm^3	1000 cm^3	1 mm^3
CPT test 60 ppb	10(3) ppb	<< 1 ppb

Atomic Physics Aspects of the Standard Model

***Atomic Physics** can be expected to continue to*

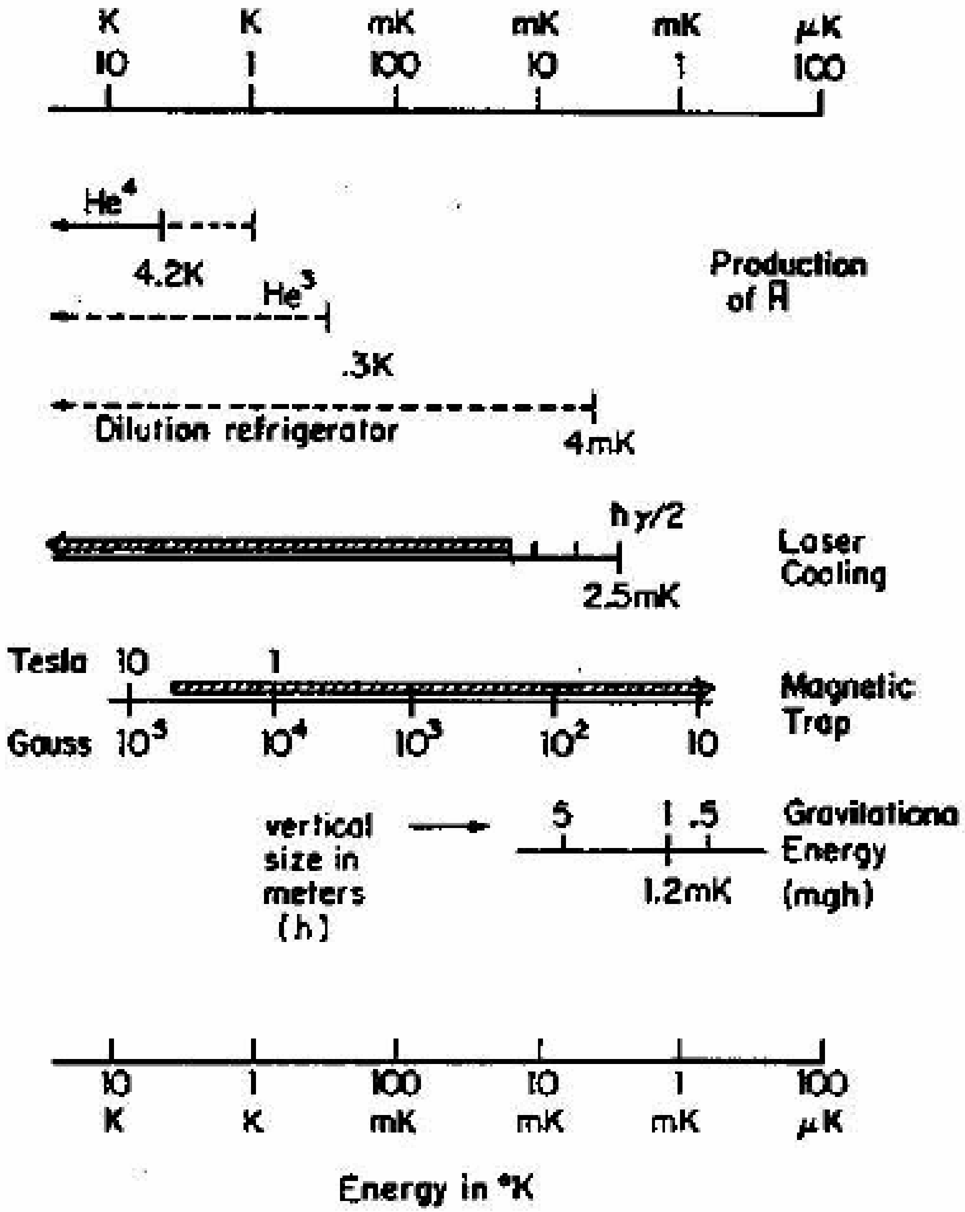
- ★ *provided sensitive tests of Standard Theory*
- ★ *contribute to the Development of Modern Fundamental Physical Concepts*
- ★ *search for new Phenomena*
- ★ *provide most accurate parameters*
- ★ *provide state of the art tools and techniques*
- ★ *show that every system has its own benefits*
- ★ *be good for surprises*



Antiproton contributions to this field just started –

Precison takes T ime C are and P articles

Thank YOU !


10 K
1 K
100 mK
10 mK
1 mK
100 μK
He^4
4.2K
He^3
.3K
Dilution refrigerator
4mK
Production of $\bar{H}$
hγ/2
2.5mK
Laser Cooling
Tesla 10 1
Gauss 10^5 10^4 10^3 10^2 10
Magnetic Trap
vertical size in meters (h)
5 1 .5
1.2mK
Gravitationa Energy (mgh)
Energy in °K