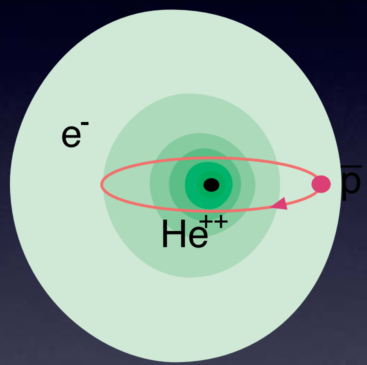
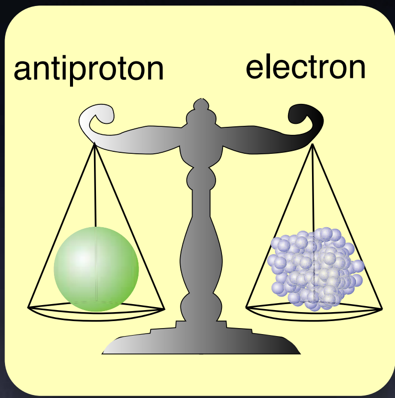
precision spectroscopy of antiprotonic helium - weighing the antiproton -

Ryugo S. Hayano
The University of Tokyo

THE UNIVERSITY OF TOKYO

μcf 2007





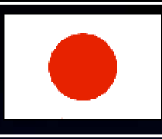
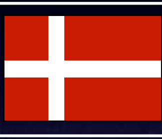
ASACUSA

atomic spectroscopy
and
collisions using
slow antiprotons

浅草

1998

ASACUSA collaboration @ CERN AD

	Tokyo RIKEN
	Aarhus
	RMKI Debrecen
CERN	CERN
	STEFAN MEYER INSTITUTE
	Brescia

PRL **96,** 243401 (2006) PHYSICAL REVIEW LETTERS week ending 23 JUNE 2006

Determination of the Antiproton-to-Electron Mass Ratio by Precision Laser Spectroscopy of $\bar{p}\mathrm{He}^+$

M. Hori,[1,2] A. Dax,[2] J. Eades,[2] K. Gomikawa,[2] R. S. Hayano,[2] N. Ono,[2] W. Pirkl,[2] E. Widmann,[3] H. A. Torii,[4] B. Juhász,[5,3] D. Barna,[6,2] and D. Horváth[6]

[1]*CERN, CH-1211 Geneva 23, Switzerland*
[2]*Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[3]*Stefan Meyer Institut für Subatomare Physik, Boltzmanngasse 3, Vienna 1090, Austria*
[4]*Institute of Physics, University of Tokyo, Komaba, Meguro-ku, Tokyo 153-8902, Japan*
[5]*Institute of Nuclear Research of the Hungarian Academy of Sciences, H-4001 Debrecen, Hungary*
[6]*KFKI Research Institute for Particle and Nuclear Physics, H-1525 Budapest, Hungary*

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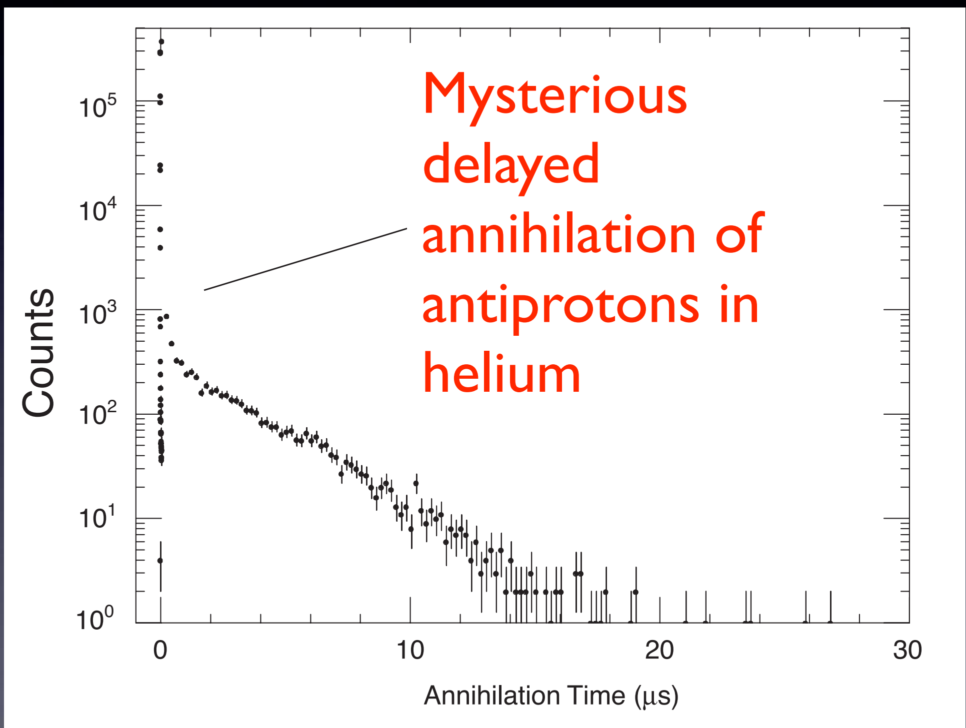
Photo CERN

$\bar{p}$He is 3-body: we owe a lot to the μCF community

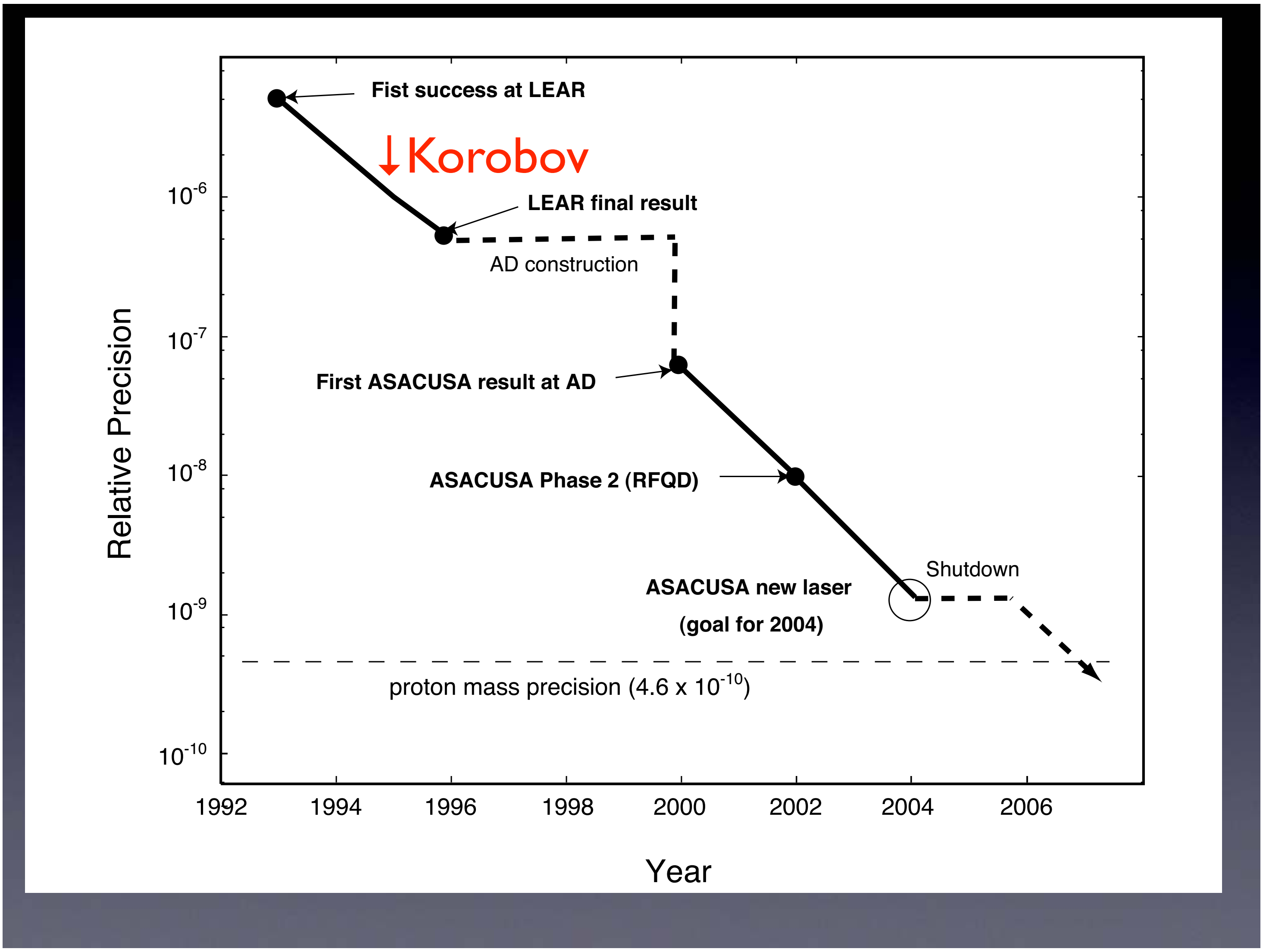
歴史

Historical

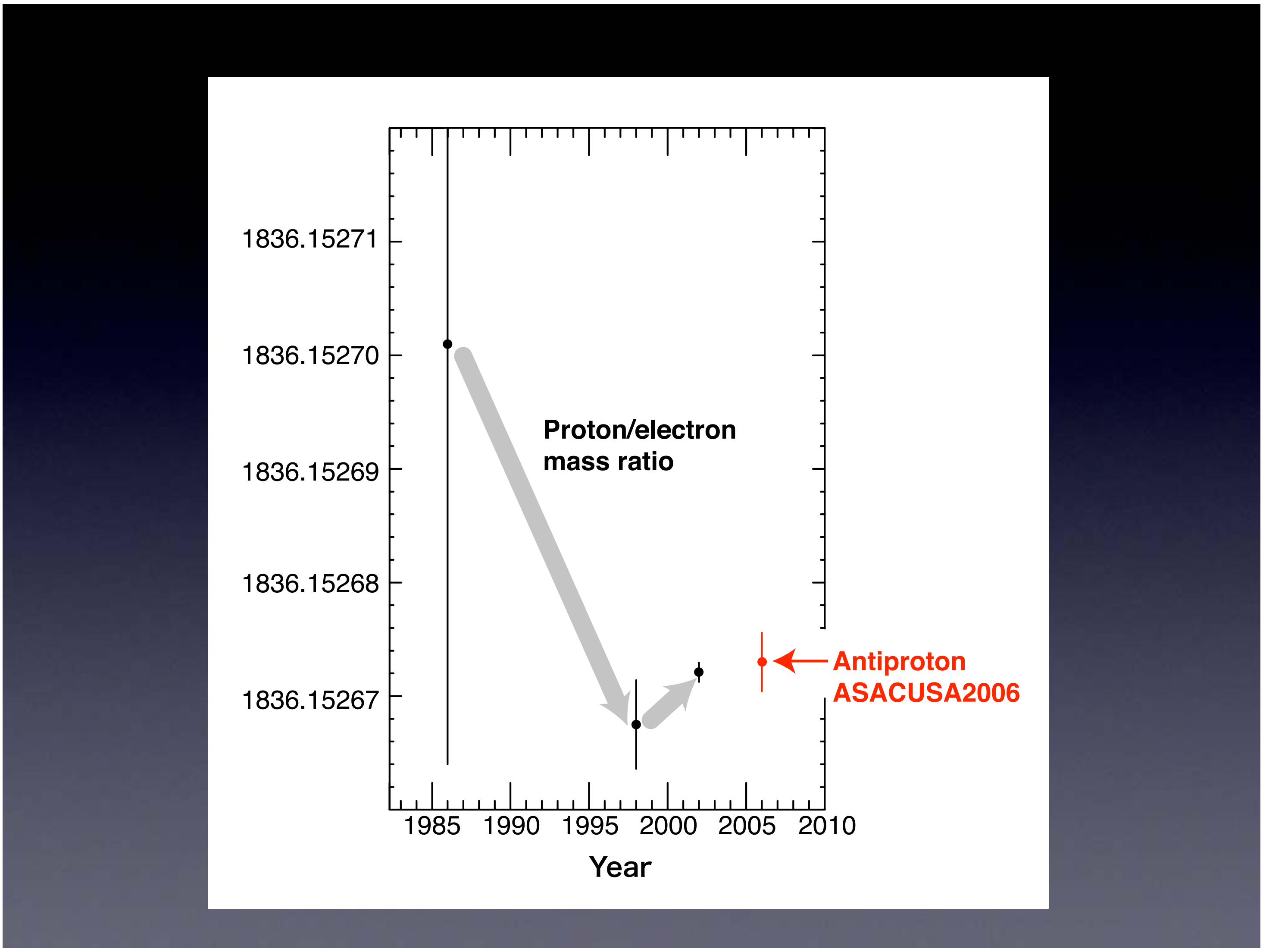
Serendipitous discovery of naturally-occurring $\bar{p}$ trap



Iwasaki et al., PRL 67 (1991) 1246



Fist success at LEAR
↓Korobov
LEAR final result
AD construction
First ASACUSA result at AD
ASACUSA Phase 2 (RFQD)
Shutdown
ASACUSA new laser
(goal for 2004)
proton mass precision (4.6 x 10-10)
Relative Precision
10-6
10-7
10-8
10-9
10-10
1992
1994
1996
1998
2000
2002
2004
2006
Year



1836.15271
1836.15270
1836.15269
1836.15268
1836.15267
Proton/electron
mass ratio
Antiproton
ASACUSA2006
1985
1990
1995
2000
2005
2010
Year

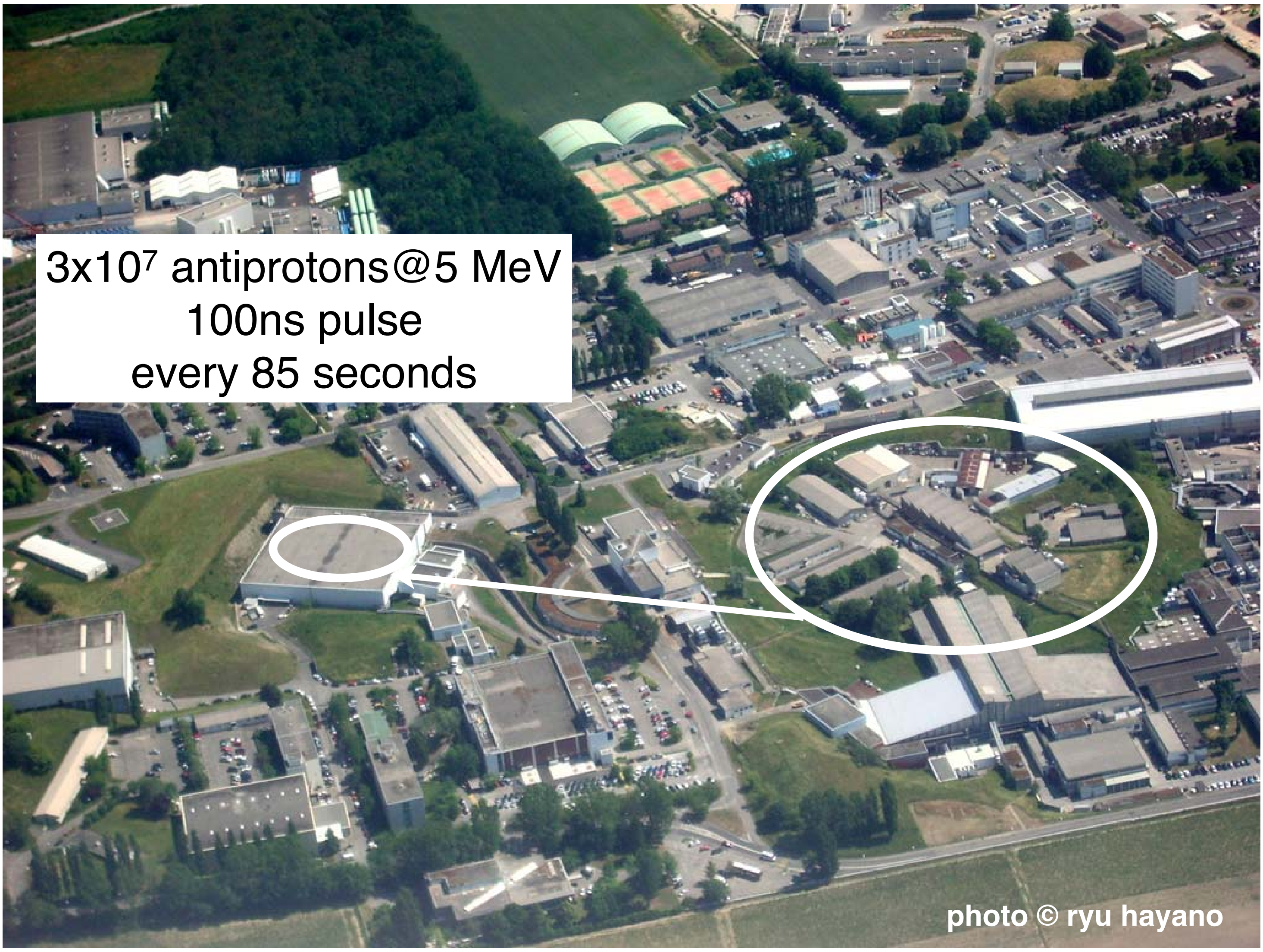
反陽子減速器

CERN AD

(Antiproton Decelerator)

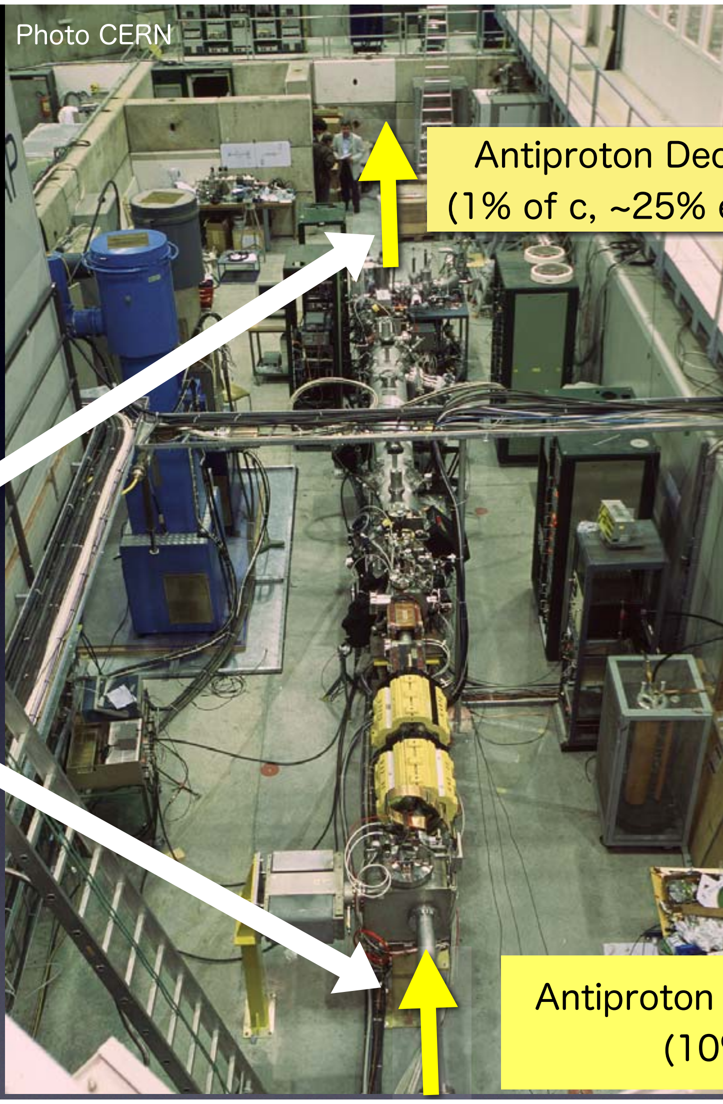
and ASACUSA RFQD

(radio-frequency quadrupole decelerator)



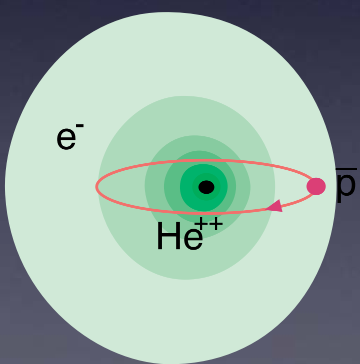
small (a few MHz)
collisional shift and width
(which we correct)

Typical target density
10^{16}-10^{18}cm^{-3}
10^{21}cm^{-3}



反陽子ヘリウム

electron is in ~ 1s
(slightly polarized to
the opposite side of $\bar{p}$)

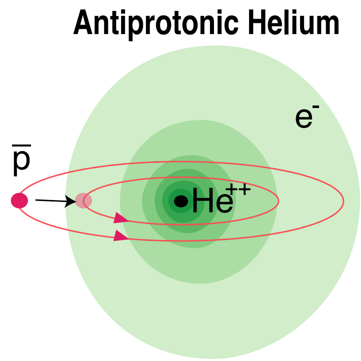


antiproton is in a
highly excited
(n~40) orbit

Laser resonance to change $\bar{\text{p}}$ orbit → $\bar{\text{p}}$ - e mass ratio

For antiprotonic helium $(\bar{p} + e^- + \alpha)$,

$$\nu(n, n') = Rc \frac{M^*_{\bar{p}}}{m_e} Z^2_{\text{eff}} \left(\frac{1}{n^2} - \frac{1}{n'^2} \right)$$

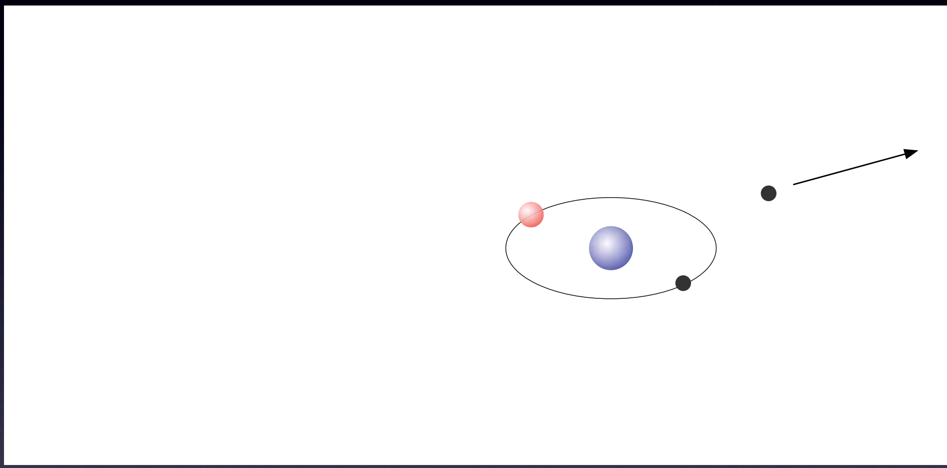


Would be exact for $\bar{\text{p}}$He ion
approximate for the 3-body system

Z^2_{eff}: helium charge, shielded by electron (calculated by theory)

Easy production
Large yield
Long lifetime

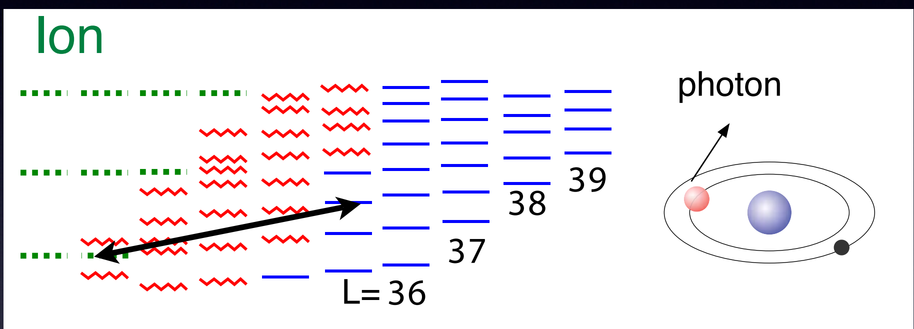
One of the two electrons of He, replaced by $\bar{p}$



3% of stopped antiprotons form $\bar{p}$He, lifetime > 3 μs

a few tens of thousands of $\bar{p}$He produced every 90s

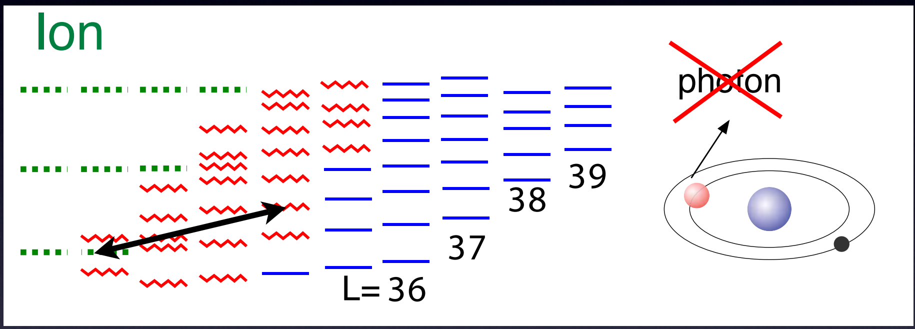
Mechanism of longevity



$\Delta L=4,\ \Gamma_{auger}<\Gamma_{radiative}$

If Auger is hindered (high multipolarity ΔL)
slow radiative deexcitation (~ μs / step)

Mechanism of longevity



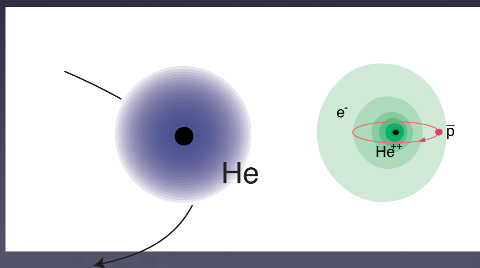
$\Delta L=3,\ \Gamma_{auger} > \Gamma_{radiative}$

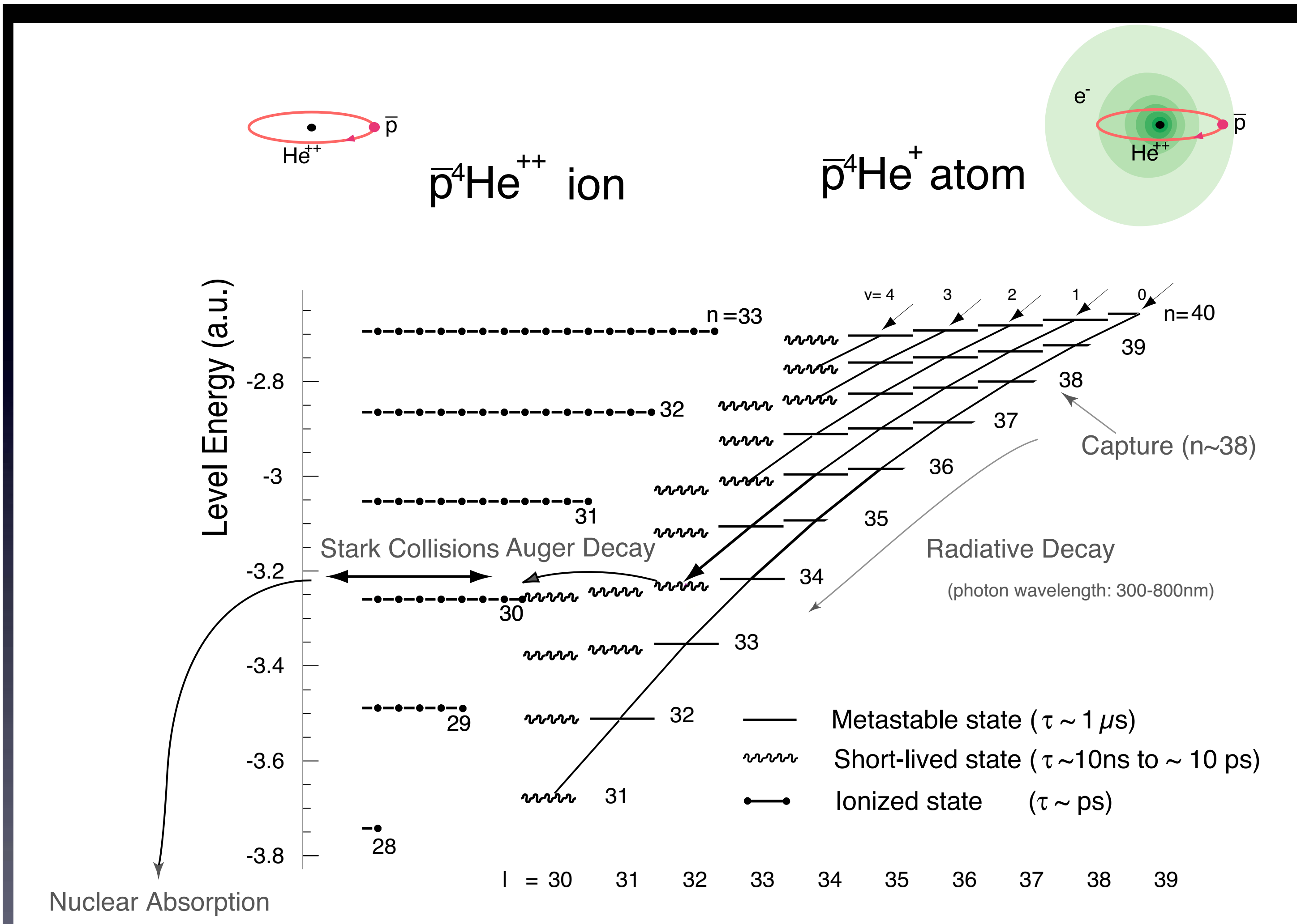
If Auger is fast, the system is short lived

Atoms are relatively cold

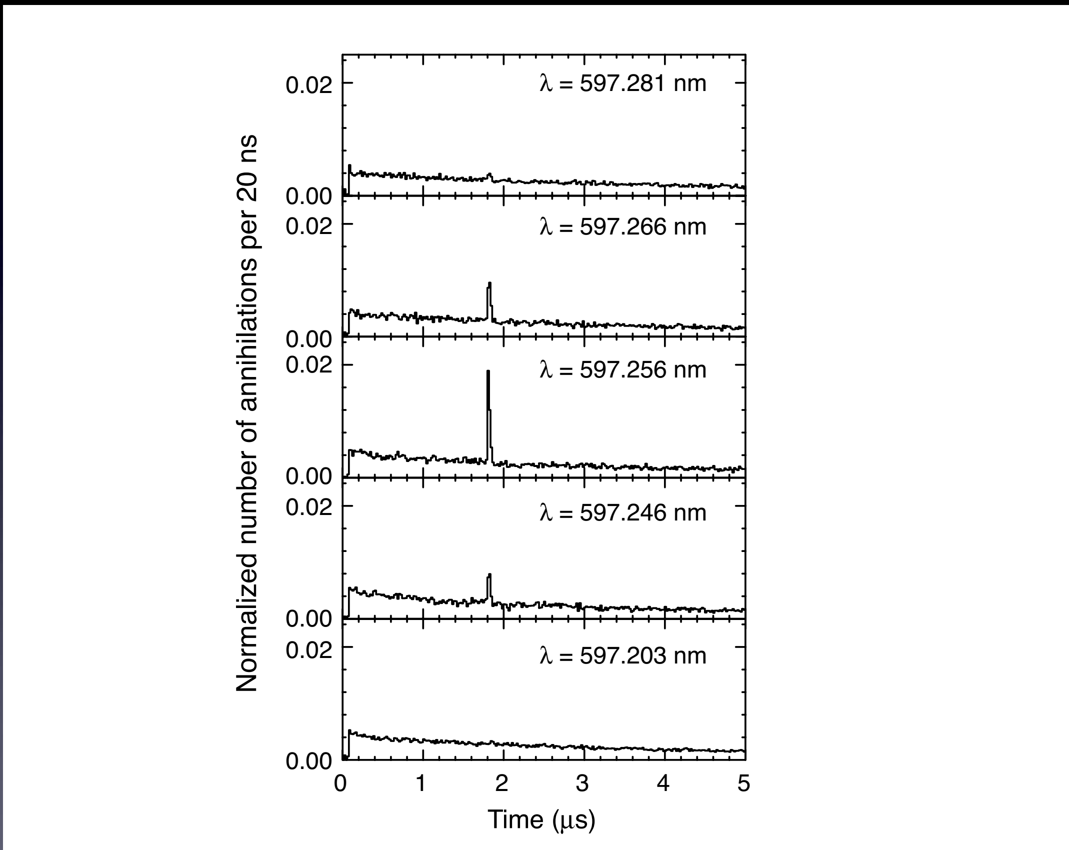
Our target is cryogenic (~10 K) helium gas

Antiprotonic helium atoms are quickly thermalized (small Doppler width)





An example, (n,l)=(39,35)→(38,34)



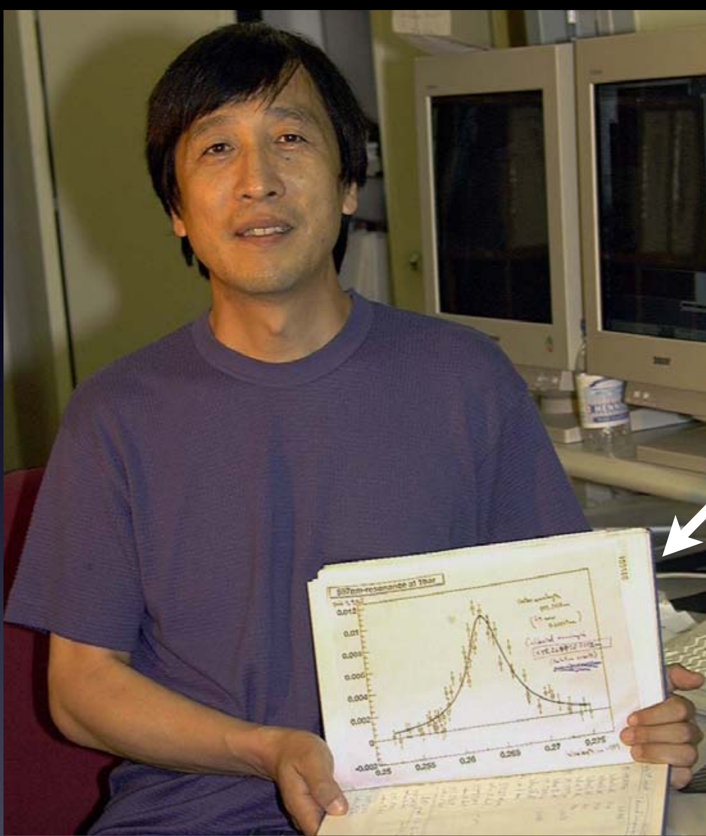


Photo CERN

a typical resonance profile

質量比

How to obtain

$m_{\bar{p}}/m_e$

3-body QED

input

antiprotn/electron mass ratio

result

Resonance Frequency

Comparison

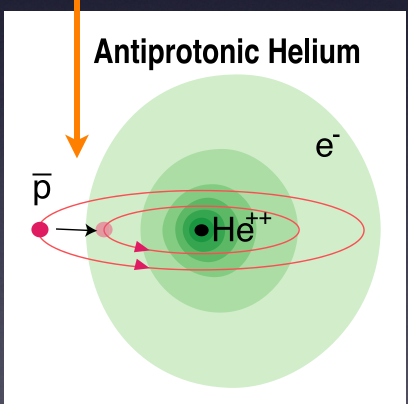
Adjustment

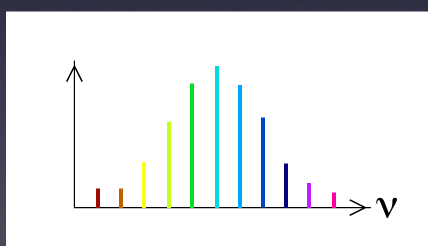
Laser

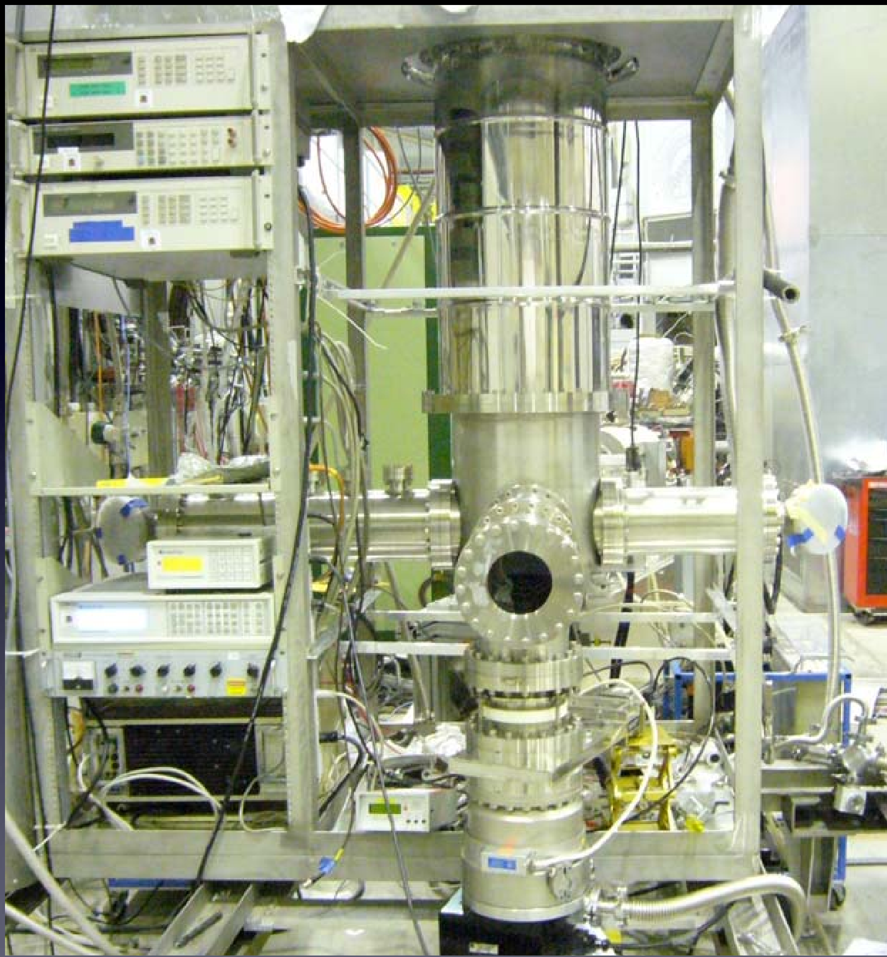
Experiment

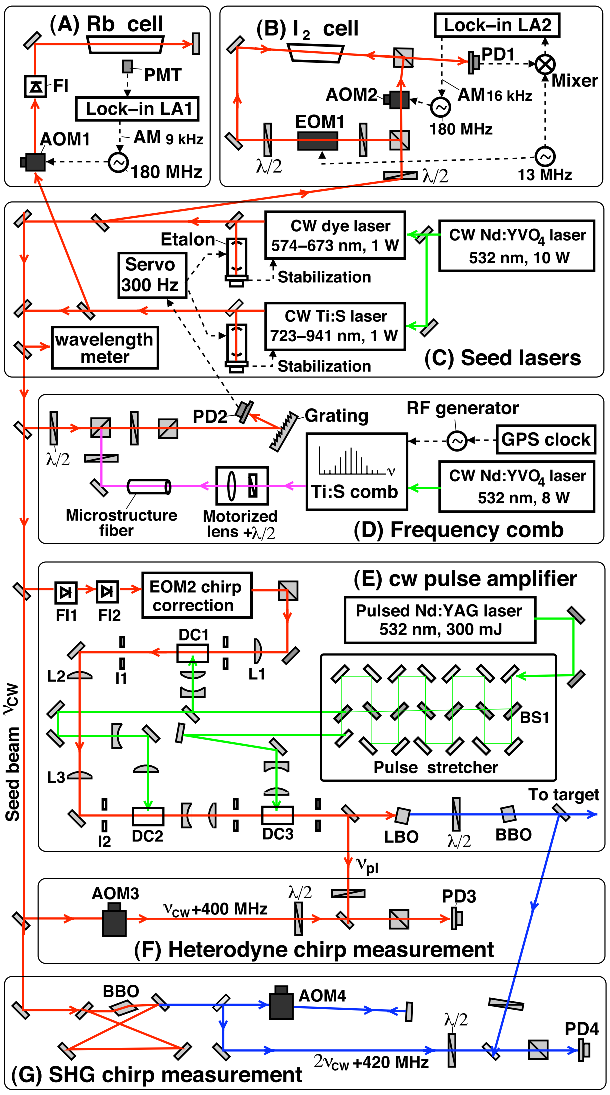
calibration

Comb (Menlo Systems)



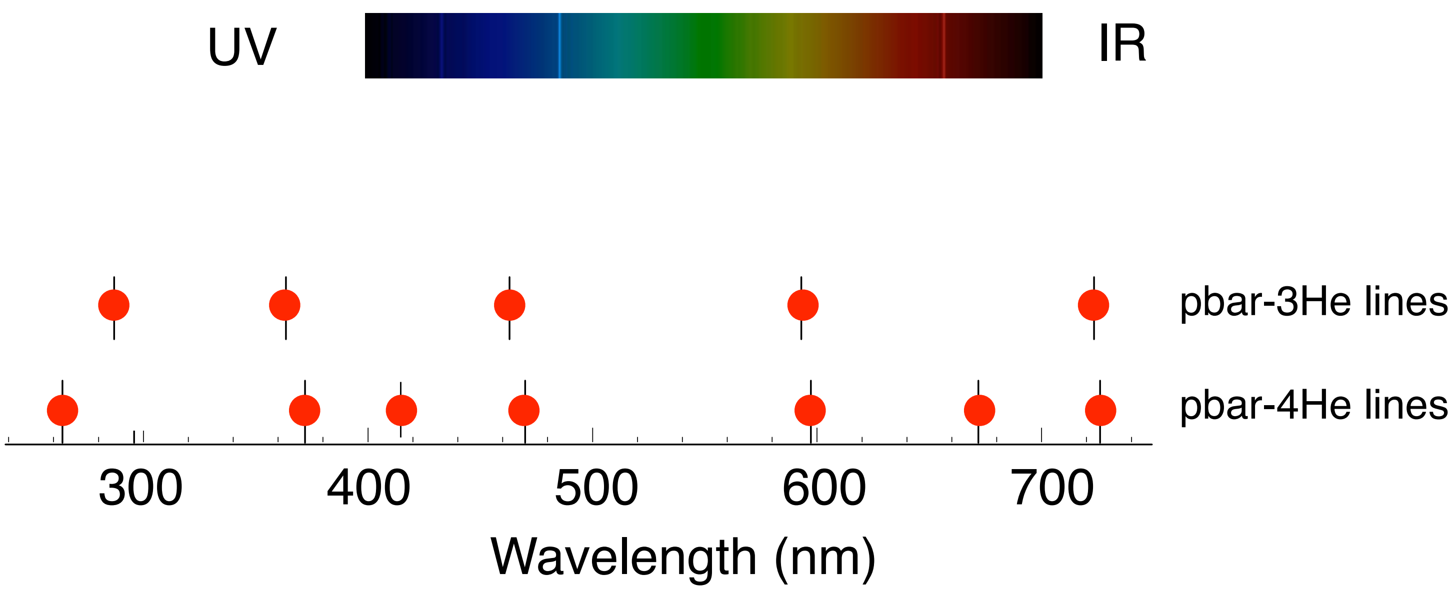




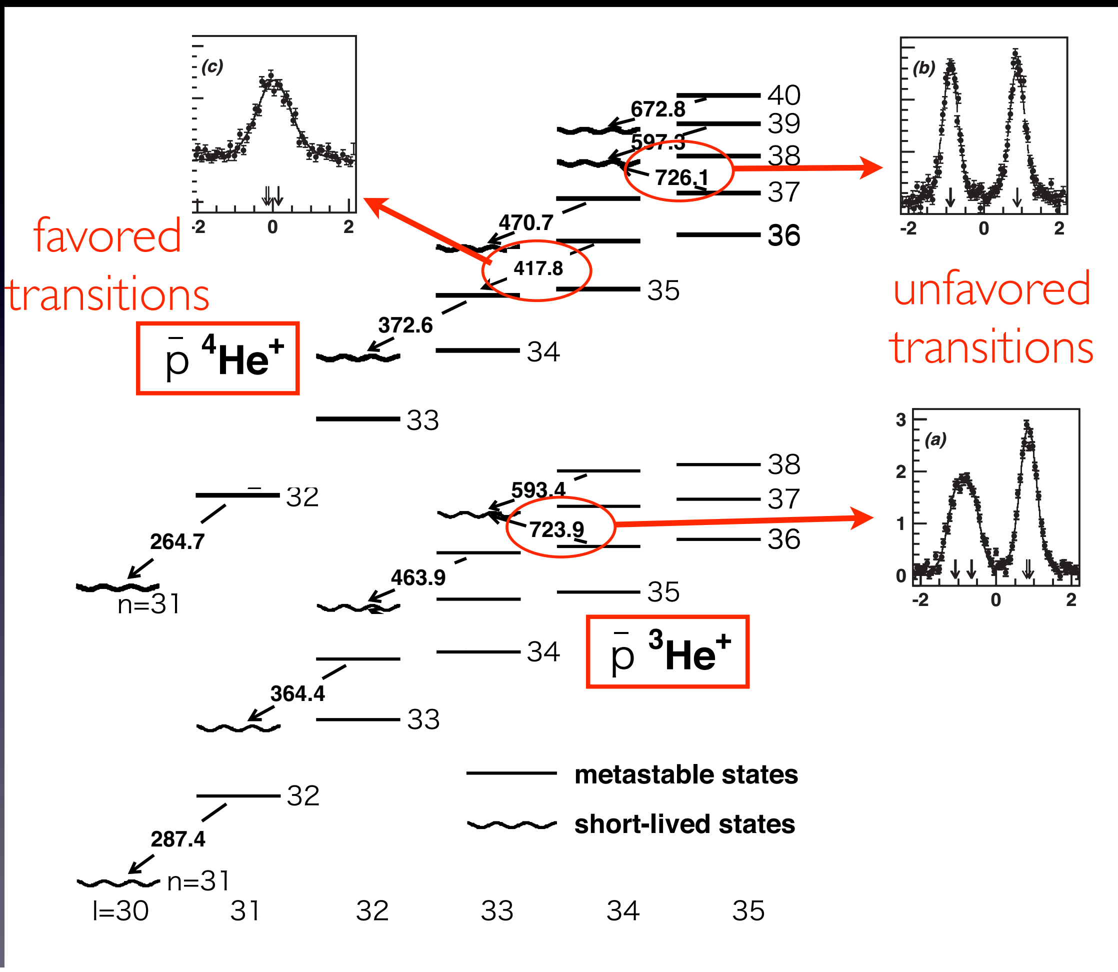


(A) Rb cell
FI
PMT
Lock–in LA1
AOM1
AM 9 kHz
180 MHz
(B) I2 cell
Lock–in LA2
PD1
Mixer
AOM2
AM 16 kHz
180 MHz
EOM1
λ/2
λ/2
13 MHz
Etalon
CW dye laser
574–673 nm, 1 W
CW Nd:YVO4 laser
532 nm, 10 W
Servo
300 Hz
Stabilization
CW Ti:S laser
723–941 nm, 1 W
wavelength
meter
Stabilization
(C) Seed lasers
PD2
Grating
RF generator
GPS clock
λ/2
Ti:S comb
CW Nd:YVO4 laser
532 nm, 8 W
Microstructure
fiber
Motorized
lens +λ/2
(D) Frequency comb
(E) cw pulse amplifier
FI1
FI2
EOM2 chirp
correction
Pulsed Nd:YAG laser
532 nm, 300 mJ
DC1
L2
I1
L1
BS1
Seed beam
νcw
L3
Pulse stretcher
To target
I2
DC2
DC3
LBO
λ/2
BBO
νpl
AOM3
νcw+400 MHz
λ/2
PD3
(F) Heterodyne chirp measurement
BBO
AOM4
λ/2
PD4
2νcw +420 MHz
(G) SHG chirp measurement

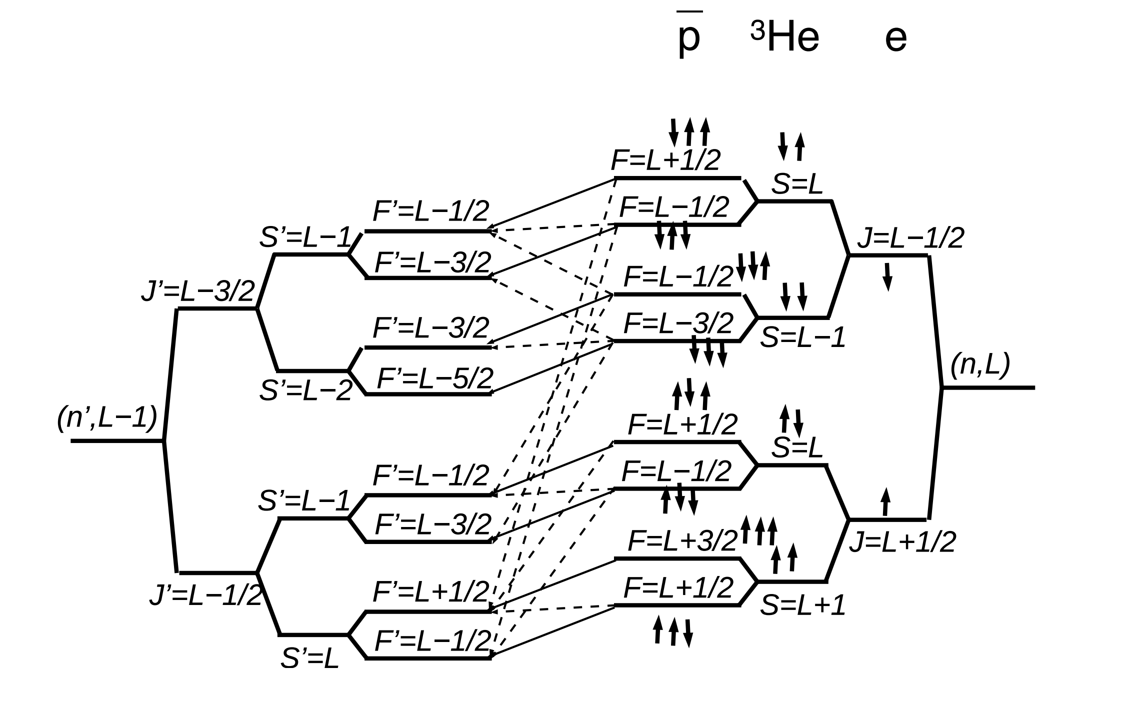
wavelengths of the resonance lines



12 transitions were measured



$\bar{p}^3He$ Hyperfine structure



理論

and the results were compared with

(spinless) 3-body QED theoretical calculations

Theory - non-relativistic H

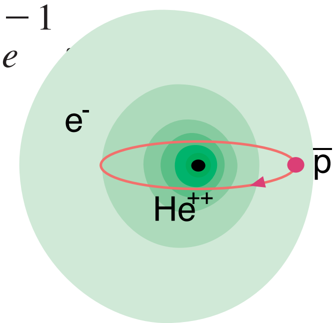
antiproton

electron

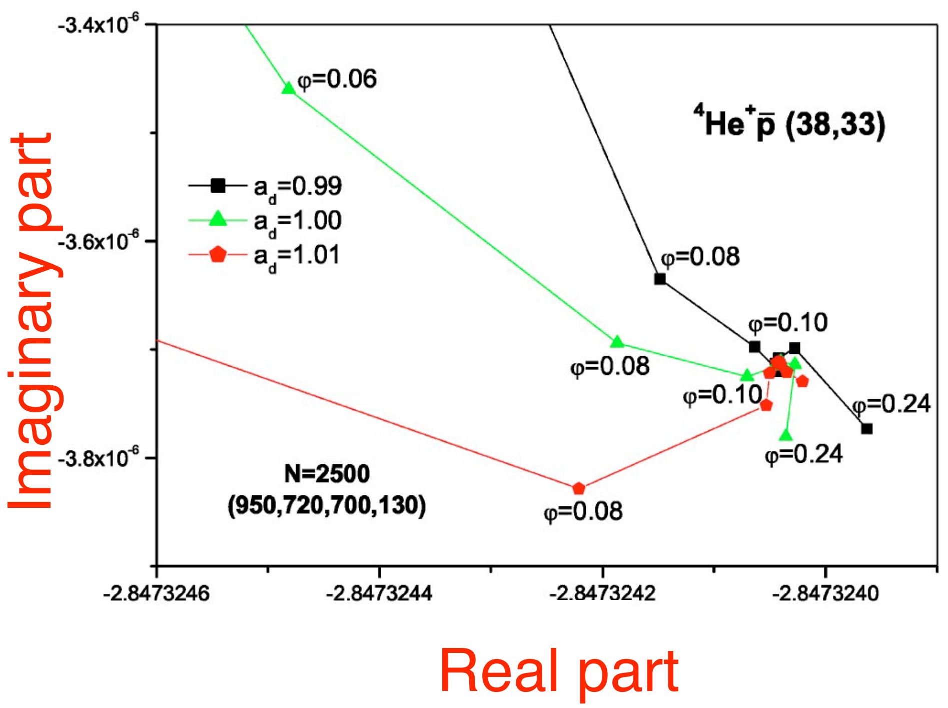
$$H = T + V$$

$$= -\frac{1}{2\mu_1}\nabla^2_{\mathbf{R}} - \frac{1}{2\mu_2}\nabla^2_{\mathbf{r}} - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}}\cdot\nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R}-\mathbf{r}|},$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \qquad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1},$$



Complex coordinate rotation (CCR) method



Not true bound states

Careful treatment of Auger decay is needed

CCR calculates complex eigen values

Korobov

add relativistic correction (~100 ppm)

$$H = T + V$$

$$= -\frac{1}{2\mu_1}\nabla_{\mathbf{R}}^2 - \frac{1}{2\mu_2}\nabla_{\mathbf{r}}^2 - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}}\cdot\nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R}-\mathbf{r}|},$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1},$$

$$E_{rc} = \alpha^2 \left\langle -\frac{\mathbf{p}_e^4}{8m_e^3} + \frac{4\pi}{8m_e^2}[Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})] \right\rangle.$$

add self energy (~15 ppm)

$$H = T + V$$

$$= -\frac{1}{2\mu_1}\nabla_{\mathbf{R}}^2 - \frac{1}{2\mu_2}\nabla_{\mathbf{r}}^2 - \frac{1}{M_{\mathrm{He}}}\nabla_{\mathbf{R}}\cdot\nabla_{\mathbf{r}} - \frac{2}{R} - \frac{2}{r} + \frac{1}{|\mathbf{R}-\mathbf{r}|},$$

$$\mu_1^{-1} = M_{\mathrm{He}}^{-1} + M_X^{-1}, \quad \mu_2^{-1} = M_{\mathrm{He}}^{-1} + m_e^{-1},$$

$$E_{rc} = \alpha^2 \left\langle -\frac{\mathbf{p}_e^4}{8m_e^3} + \frac{4\pi}{8m_e^2}[Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})] \right\rangle.$$

$$E_{se} = \frac{4\alpha^3}{3m_e^2}\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0}{R_\infty} + \frac{5}{6} - \frac{3}{8}\right]\langle Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\rangle$$

$$+ \frac{4\alpha^4}{3m_e^2}\left[3\pi\left(\frac{139}{128} - \frac{1}{2}\ln 2\right)\right]\langle Z_{\mathrm{He}}^2\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}^2\delta(\mathbf{r}_{\bar{p}})\rangle$$

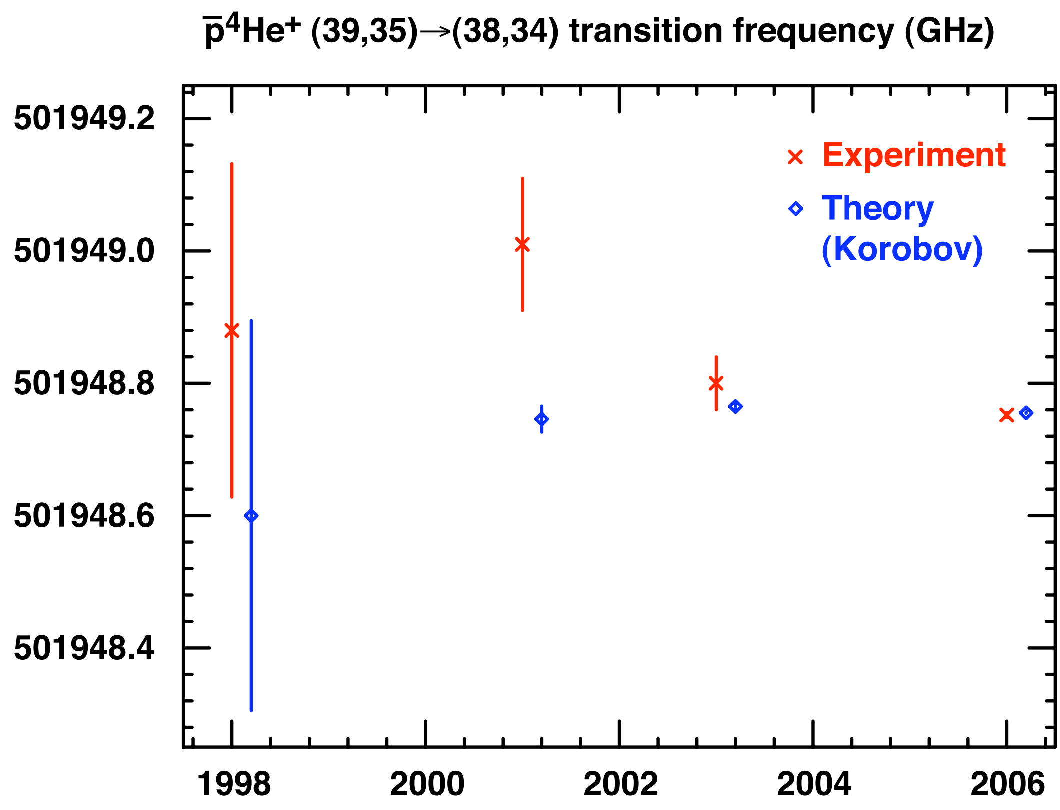
$$- \frac{4\alpha^5}{3m_e^2}\left[\frac{3}{4}\right]\langle Z_{\mathrm{He}}^3 \ln^2(Z_{\mathrm{He}}\alpha)^{-2}\delta(\mathbf{r}_{\mathrm{He}})$$

$$+ Z_{\bar{p}}^3 \ln^2(Z_{\bar{p}}\alpha)^{-2}\delta(\mathbf{r}_{\bar{p}})\rangle,$$

(39,35) → (38,34) example (Korobov)

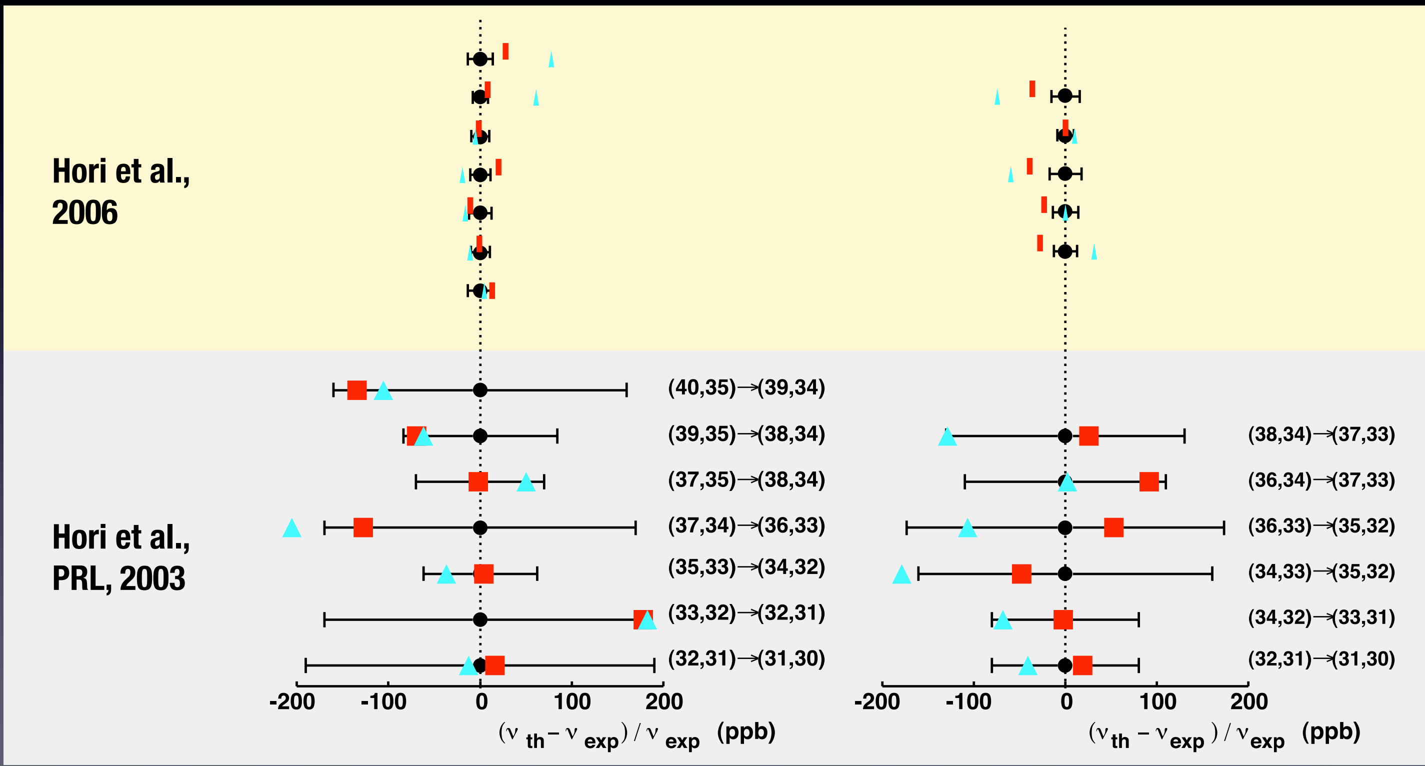
E_{nr}	=	501 972 347.9
E_{rc}	=	−27 525.3
E_{rc-qed}	=	233.3
E_{se}	=	3 818.0
E_{vp}	=	−122.5
E_{kin}	=	37.3
E_{exch}	=	−34.7
E_{α^3-rec}	=	0.8
$E_{two-loop}$	=	0.9
E_{nuc}	=	2.4
E_{α^4}	=	−2.6
E_{total}	=	501 948 755.6(1.3) MHz

Experimental & theoretical precisions improved



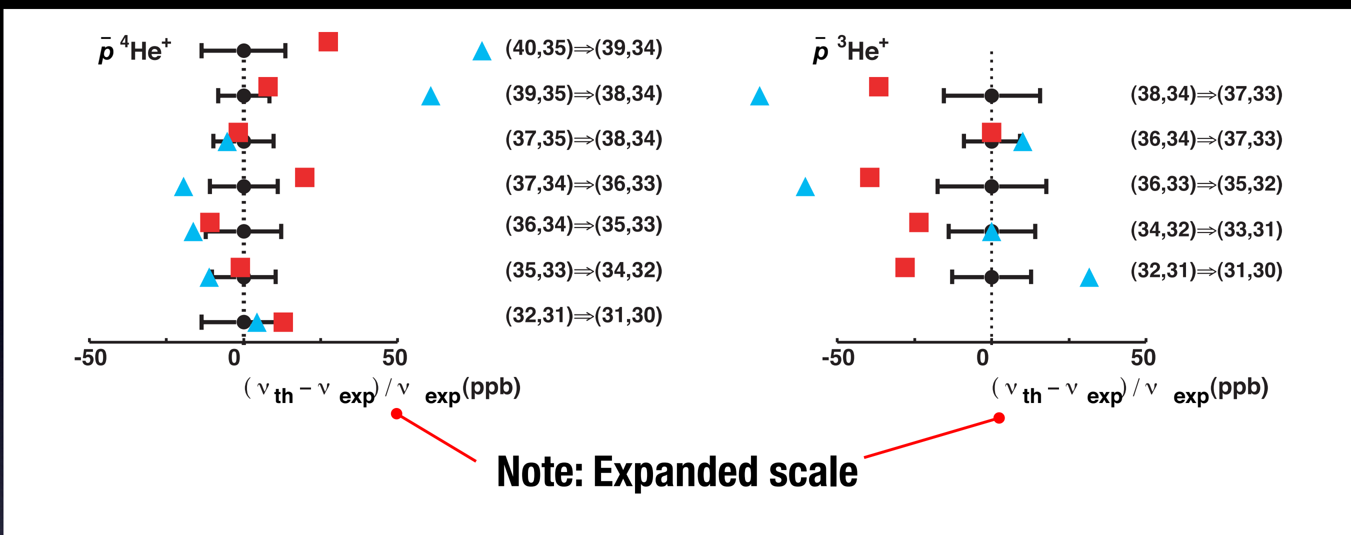
Results

Two theory calculations (▲and■) compared with experiment ●



Closer look

Two theory calculations (▲and■) compared with experiment ●



- Up to ~50 ppb differences between the two theoretical calculations (▲ and ■) ; we now take ■ in view of the claimed accuracy
- Systematic shift of some 20 ppb in $\bar{p}^3He$?
- antiproton mass value will be improved if the theories converge

Errors

σ_{exp} = 4-15 MHz

statistical 3-13 MHz,

systematic: chirp 2-4 MHz, collisional shifts 0.1-2 MHz, harmonic generation 1-2 MHz

(and negligible AC-Stark)

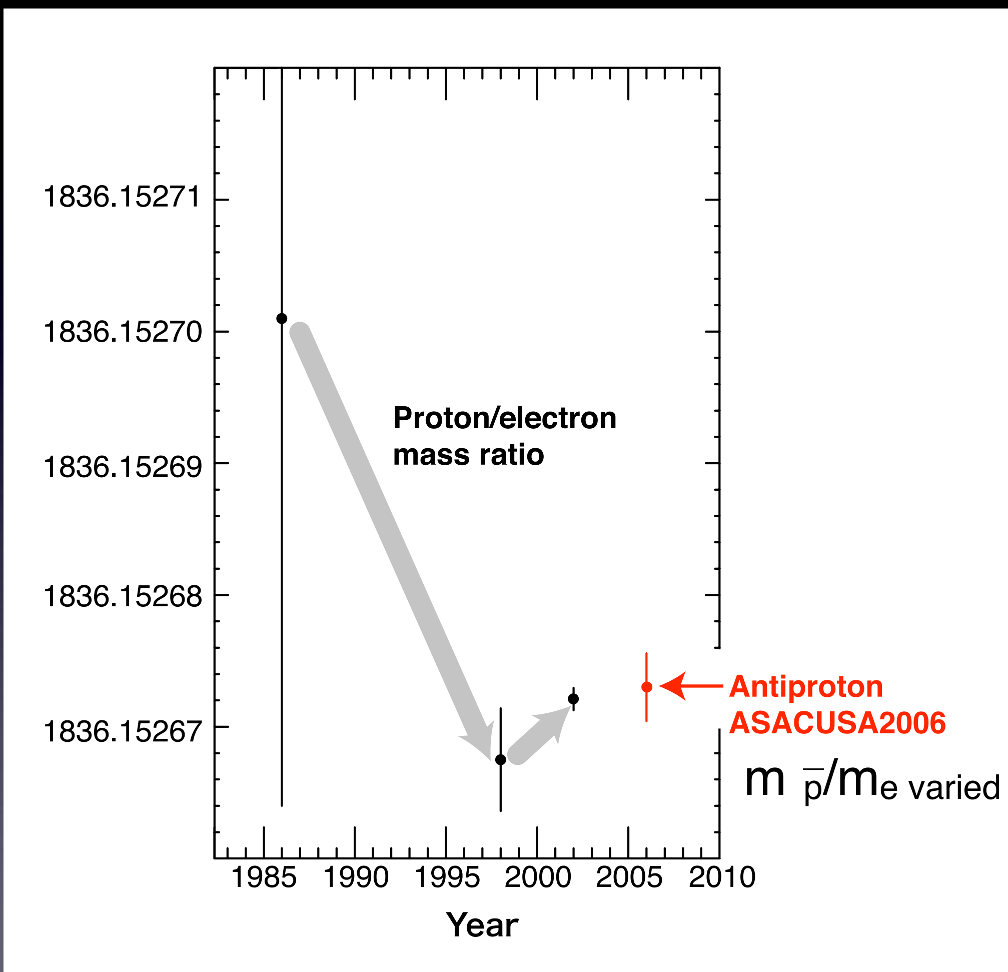
σ_{theory} = 1-2 MHz (Korobov)

結果

Results & Implications

Two views

Derive m_p/m_e (assume CPT)	$Q_{\bar{p}}=Q_e$	vary m_e relative to m_p and m_α
CPT test p - $\bar{p}$ mass & charge comparison	$Q_{\bar{p}} \neq Q_e$	Vary Q_p and M_p with TRAP constraint on Q/m 9×10^{-11}



$$m_{\bar{p}}/m_e = 1836.152674$$

± 0.000005

ASACUSA2006
PRL 96, 243401 (2006)

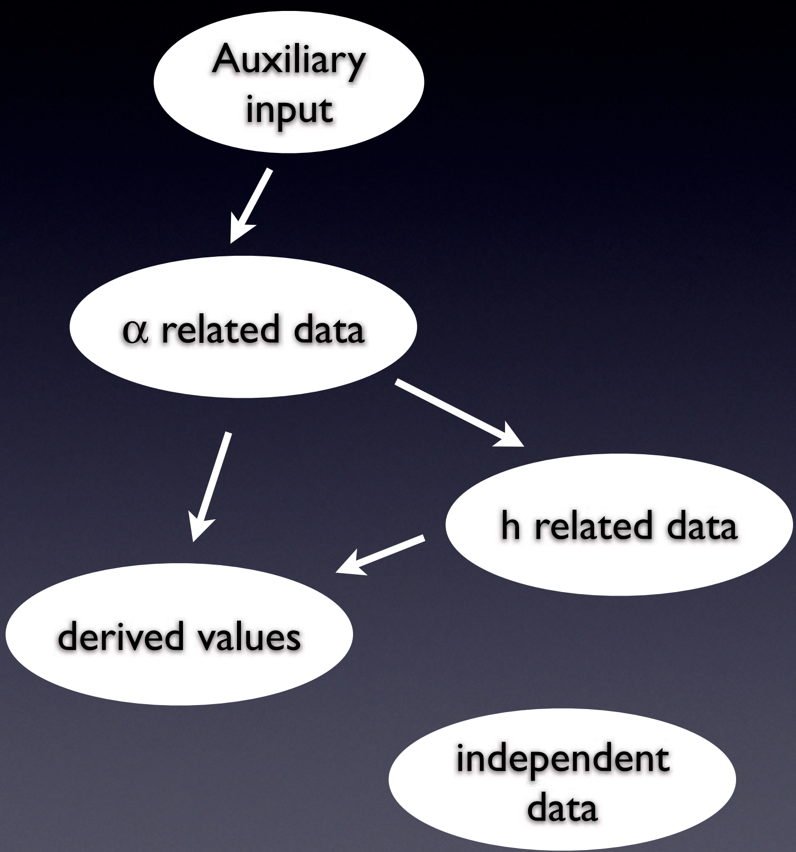
$$m_p/m_e = 1836.15267261$$

± 0.00000085

codata2002

CODATA adjustment flowchart

from S.G. Karshenboim



Auxiliary data = the most accurate data which are to be evaluated prior to the adjustment, R_∞, m_e/m_p, ...

Arrows are equations

Derived: m_p [kg], m_e[MeV/c^2], etc...

1836.15267261(85) 0.46 ppb (CODATA2002)

to

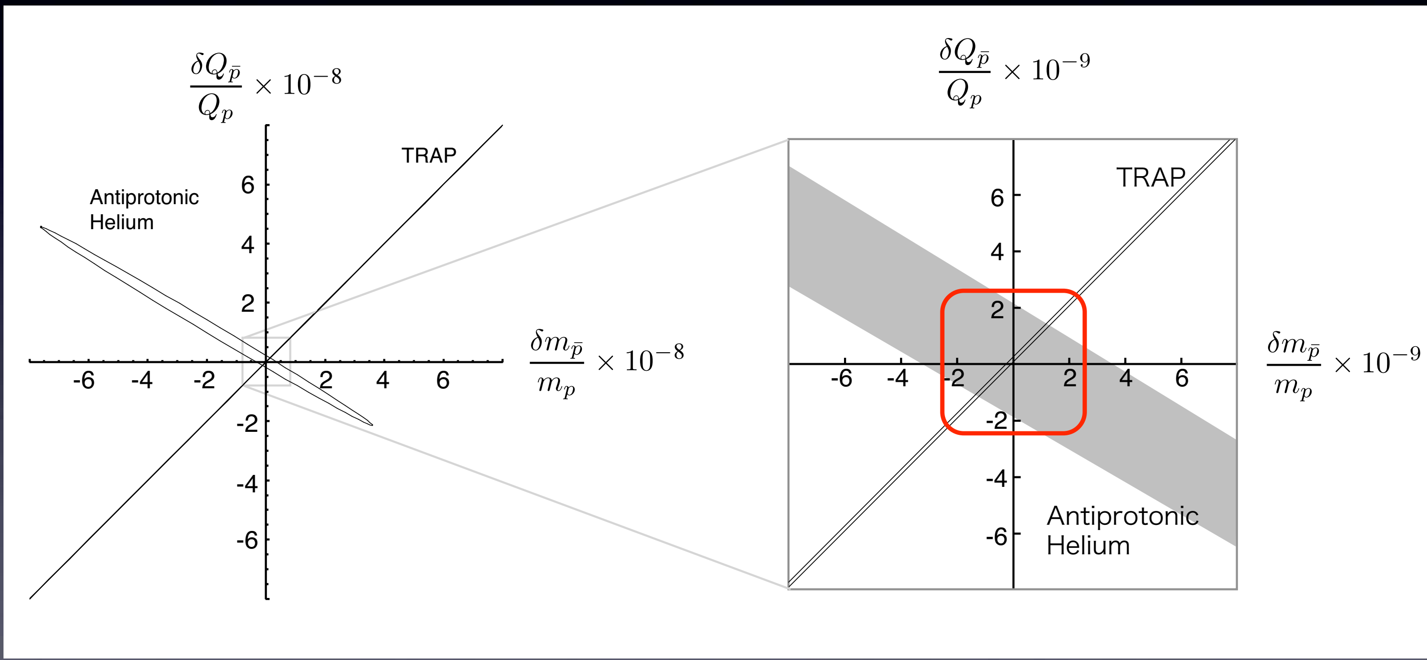
1836.15267247(80) 0.43 ppb (CODATA2006)

Two views

Derive m_p/m_e (assume CPT)	$Q_{\bar{p}}=Q_e$	vary m_e relative to m_p and m_α
CPT test p - $\bar{p}$ mass & charge comparison	$Q_{\bar{p}} \neq Q_e$	Vary Q_p and M_p with TRAP constraint on Q/m 9×10^{-11}

CPT limit

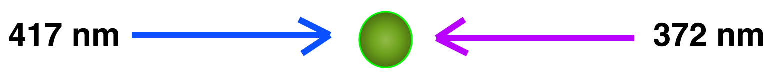
trap: Q/m, $\bar{p}$He : mQ^2



次

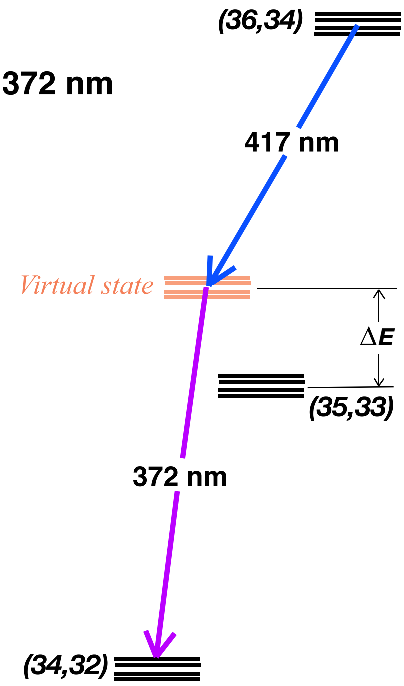
Next step

Sub-Doppler two-photon laser spectroscopy



Doppler width decreased
from 1300 MHz to 70 MHz

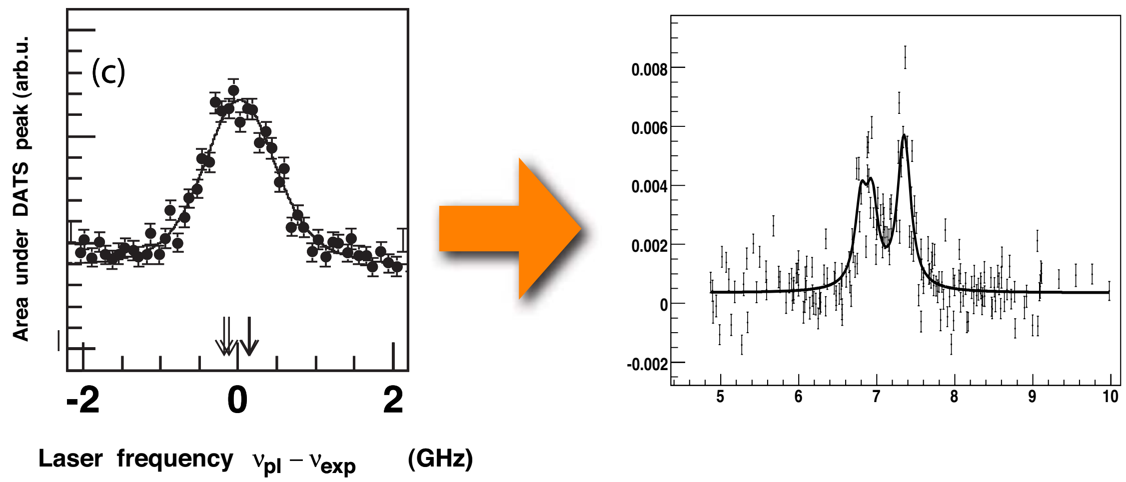
$$\Gamma = \frac{|\nu_1 - \nu_2|}{\nu_1 + \nu_2} \times 2.35(\nu_1 + \nu_2)\sqrt{\frac{kT}{M}}$$

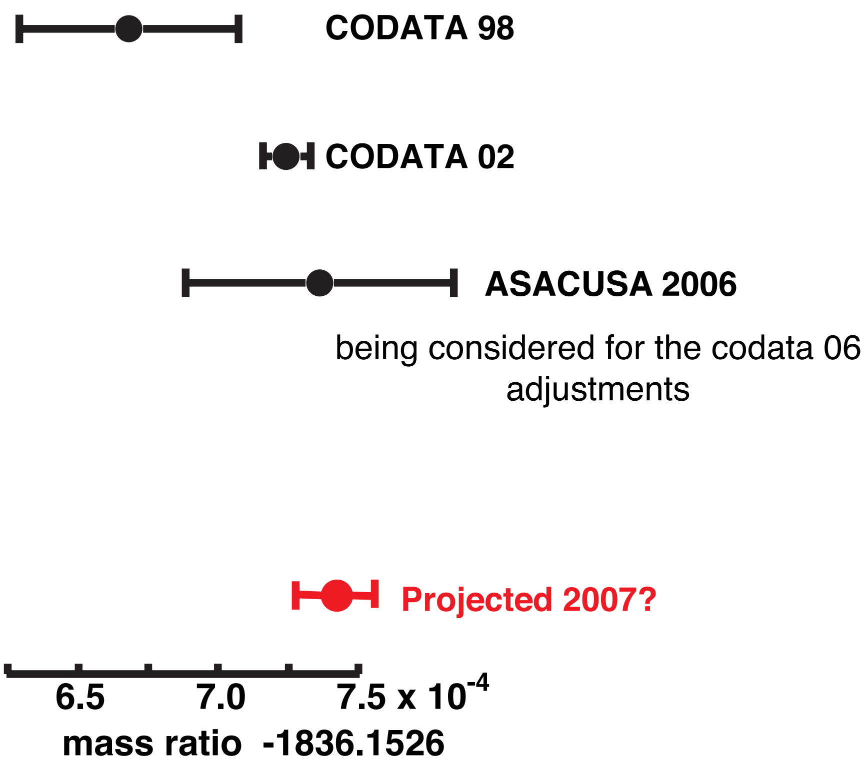


(36,34)→(35,33)

single photon

two photon




CODATA 98
CODATA 02
ASACUSA 2006
being considered for the codata 06 adjustments
Projected 2007?
6.5
7.0
7.5 x 10-4
mass ratio -1836.1526

結

summary

Serendipitous discovery

Precision of $\bar{p}$He spectroscopy has reached 10^{-9}
(RFQ, Comb, ..., took us a long time)

Fundamental constant (m_p/m_e)

x10 improvement possible (two-photon spectroscopy), but

Must better understand 3-body QED calculations

and thank again to the μCF community