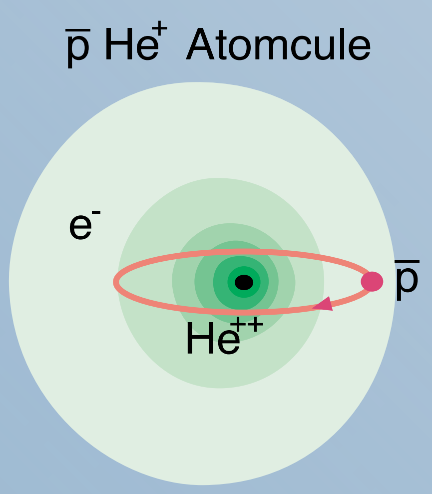
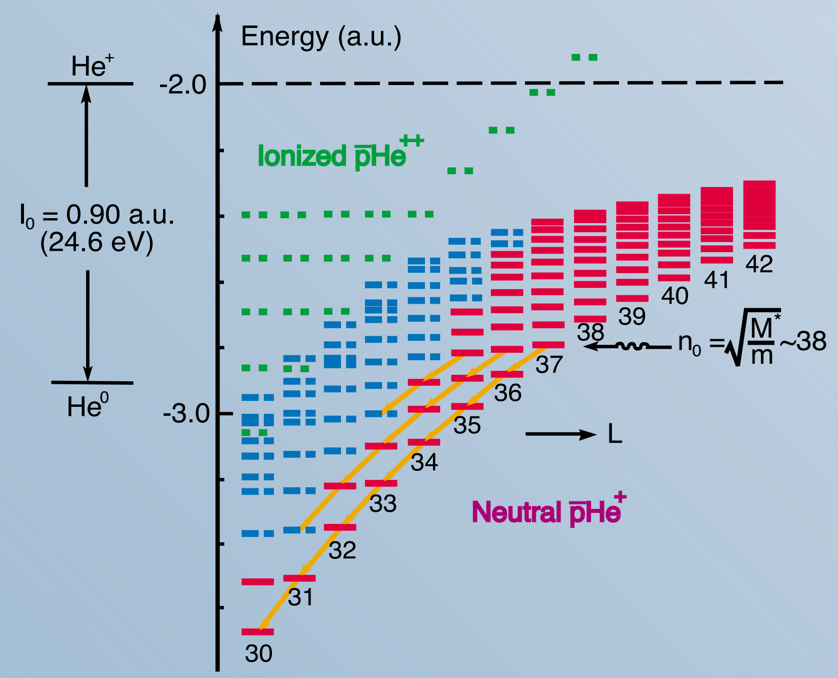
Weighing the antiproton: precision laser spectroscopy of antiprotonic helium atoms





Ryugo S. Hayano

R.S. Hayano, et al., Reports on Progress in Physics 70, 1995-2065 (2007)

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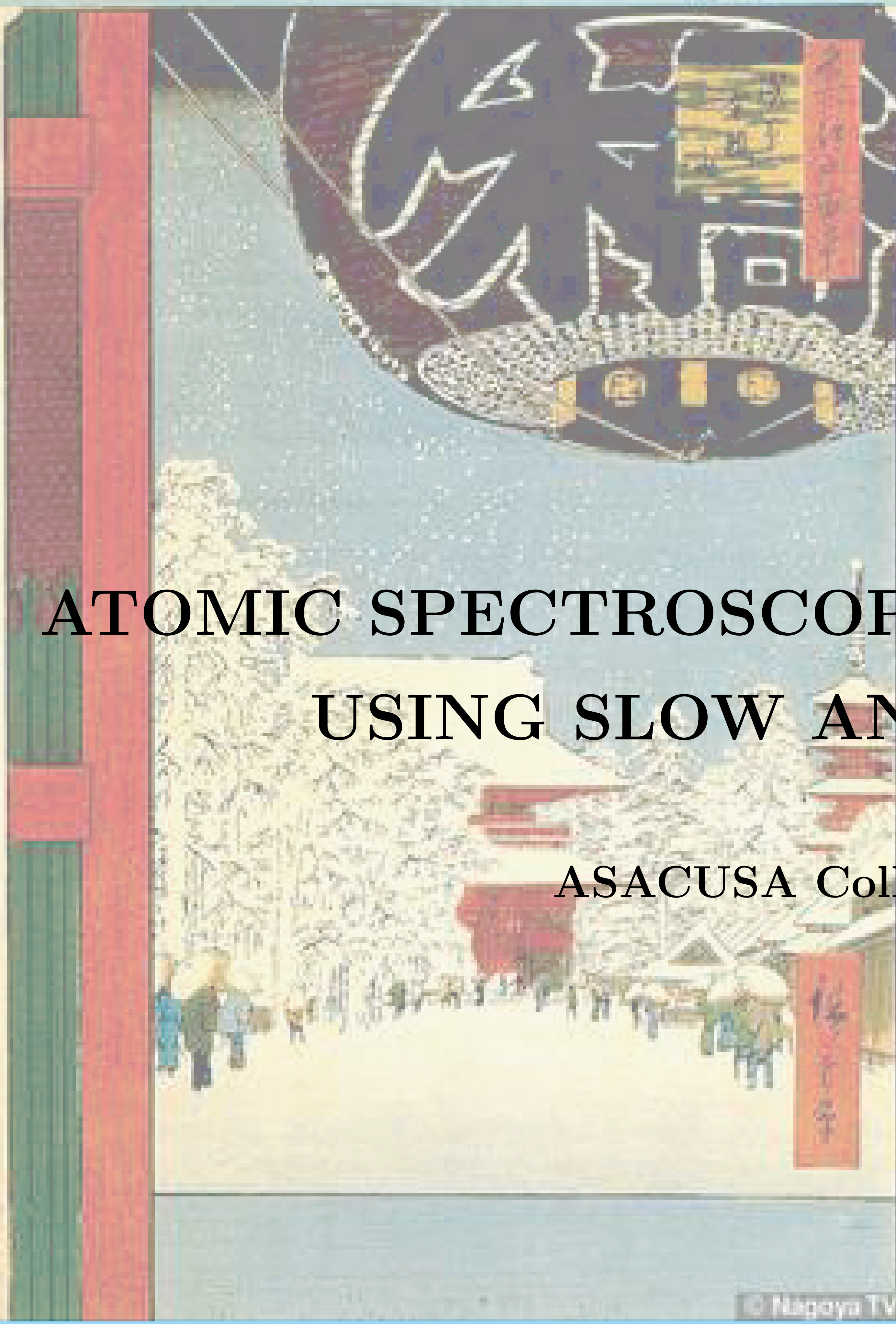
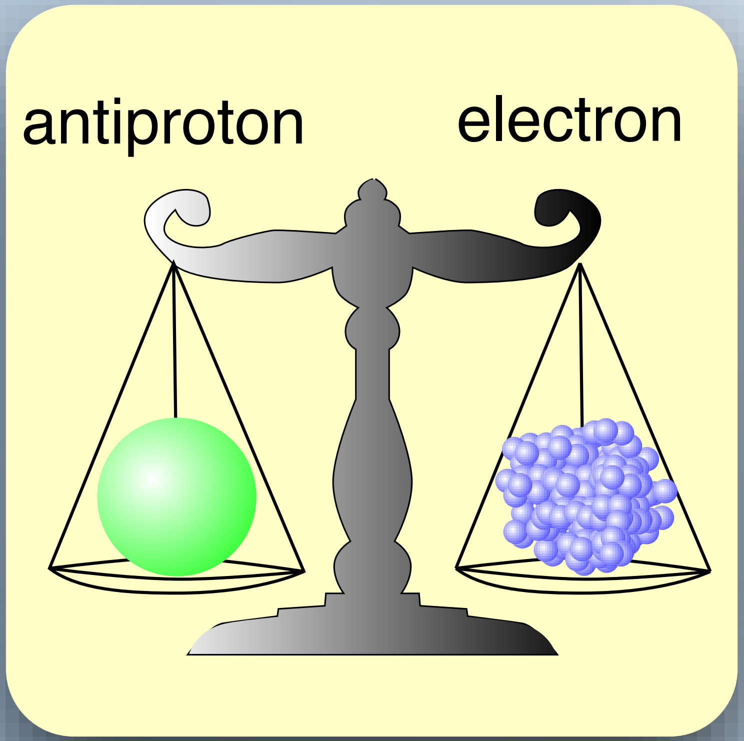


7-Oct-97
CERN/SPSC 97-19
CERN/SPSC P-307

ATOMIC SPECTROSCOPY AND COLLISIONS USING SLOW ANTIPROTONS

ASACUSA Collaboration

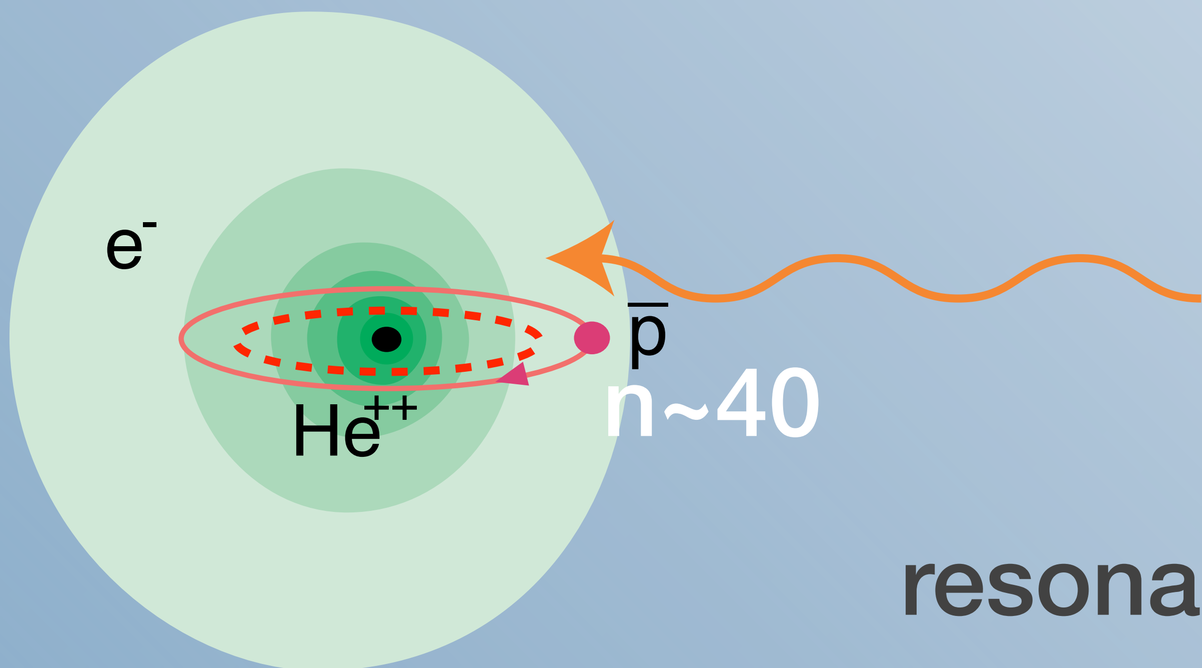


↓ CPT test

↓ CPT theorem

↓ proton-electron mass ratio

$\bar{p}$He laser spectroscopy



laser pulse changes the $\bar{p}$ orbit

resonance detection via $\bar{p}$ annihilation

Frequency

$$\nu_{n,\ell\to n',\ell'} = Rc\frac{m^*_{\bar{p}}}{m_e} Z^2_{\mathrm{eff}}\left(\frac{1}{n'^2}-\frac{1}{n^2}\right) + QED$$

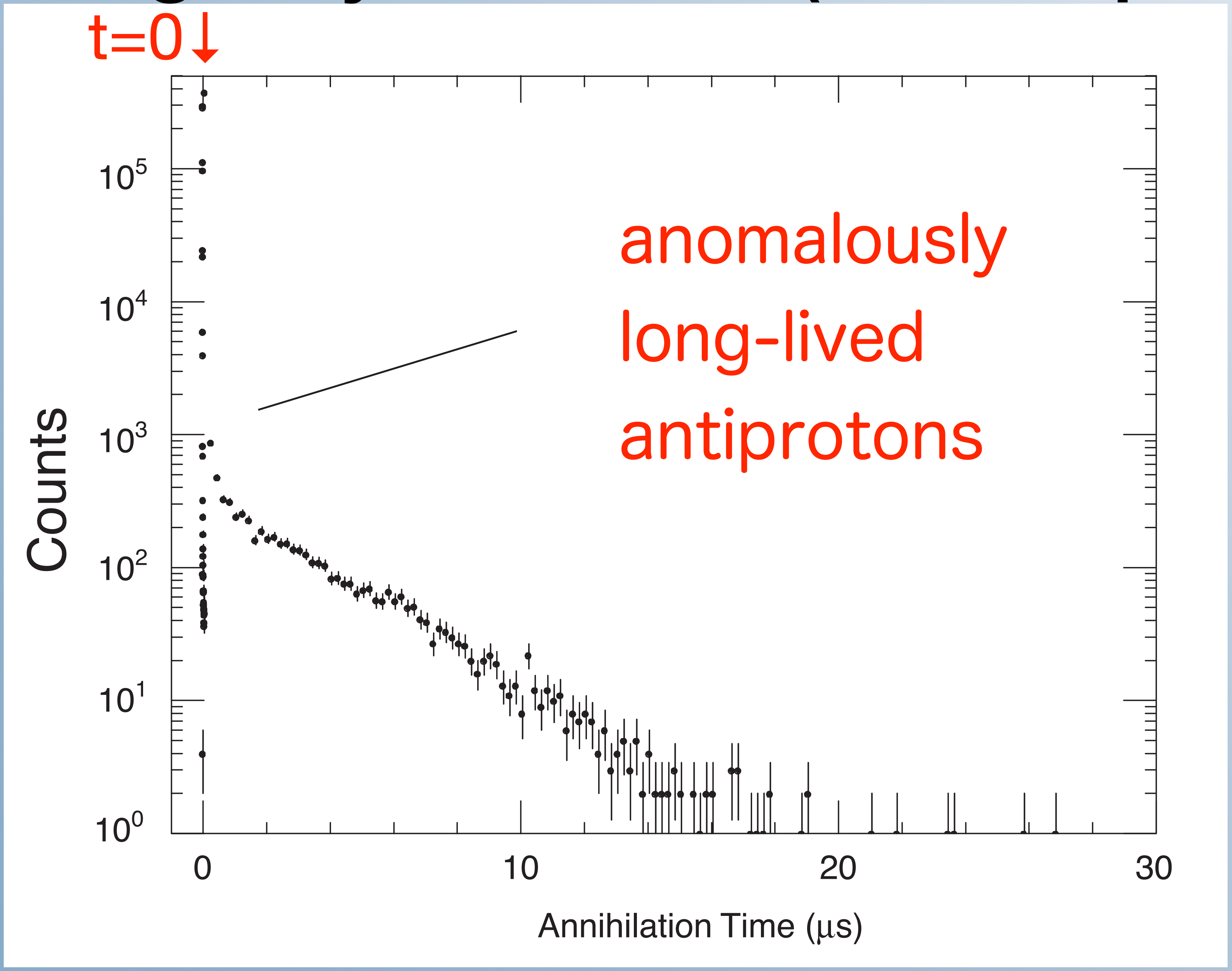
$\bar{p}$ - e mass ratio

Theory

Korobov
Kino et al.

1991

Serendipitous discovery of $\bar{p}$ longevity in helium (KEK Japan)



Iwasaki et al., PRL 67 (1991) 1246

消滅時間分布

“DATS”

Delayed Annihilation Time Spectra

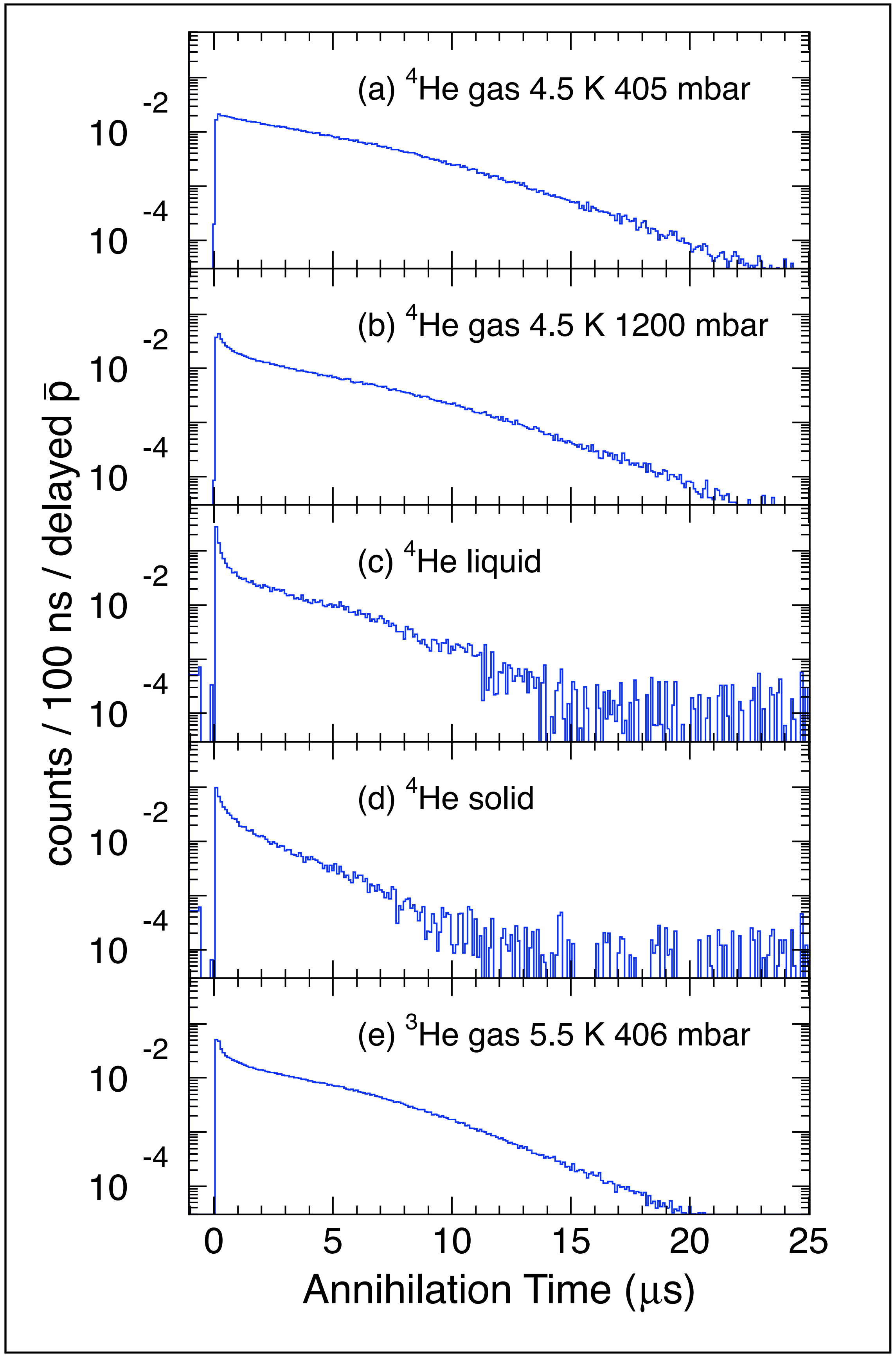
T. Yamazaki et al., PS205

"DATS" measured at LEAR

Early days of LEAR PS205

Established $\bar{p}$ longevity in gas, liquid, solid helium-3 & helium-4

Lifetime 3~4μs, formation probability ~3%



分光

Early days of laser spectroscopy
PS205

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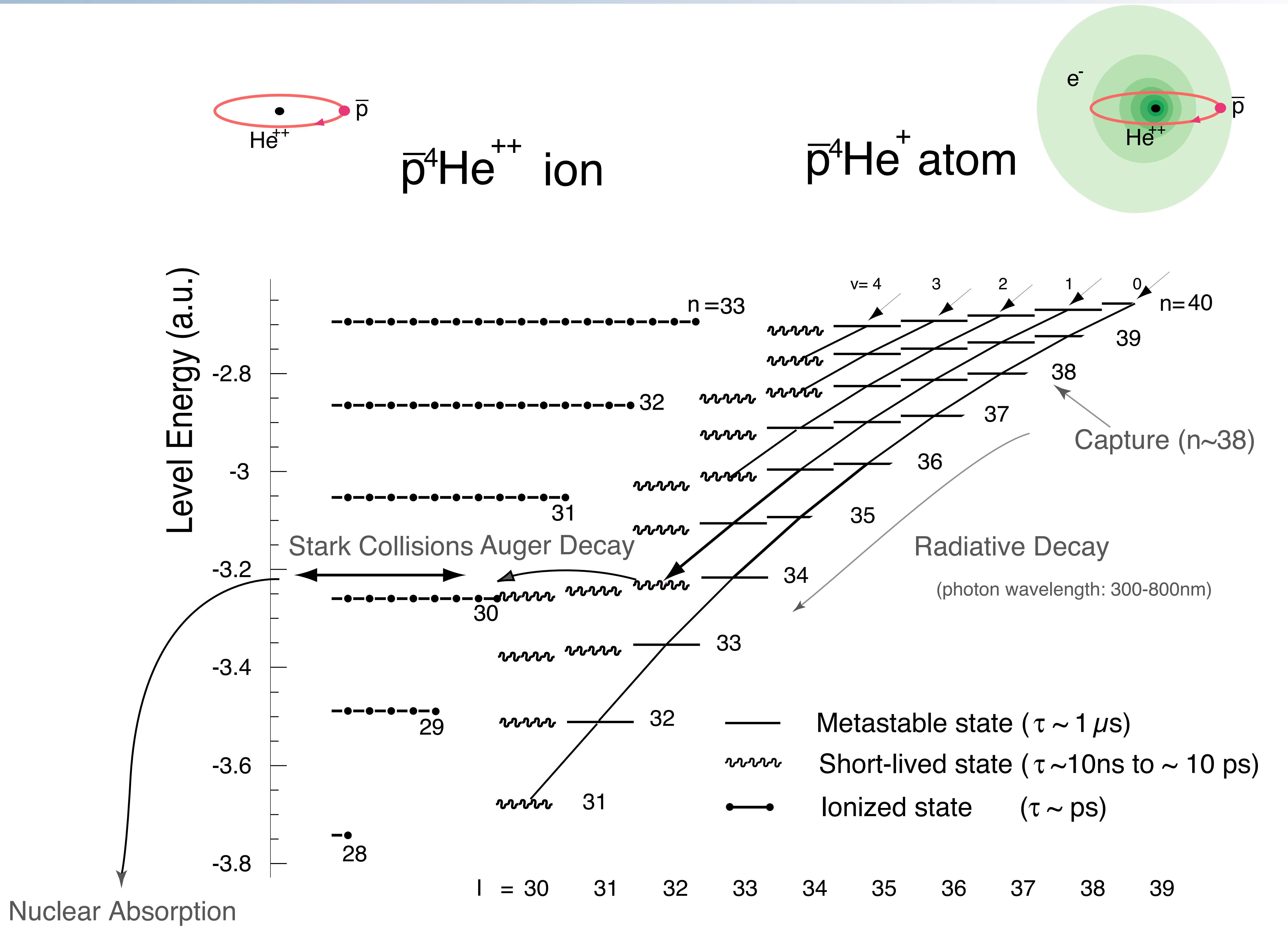
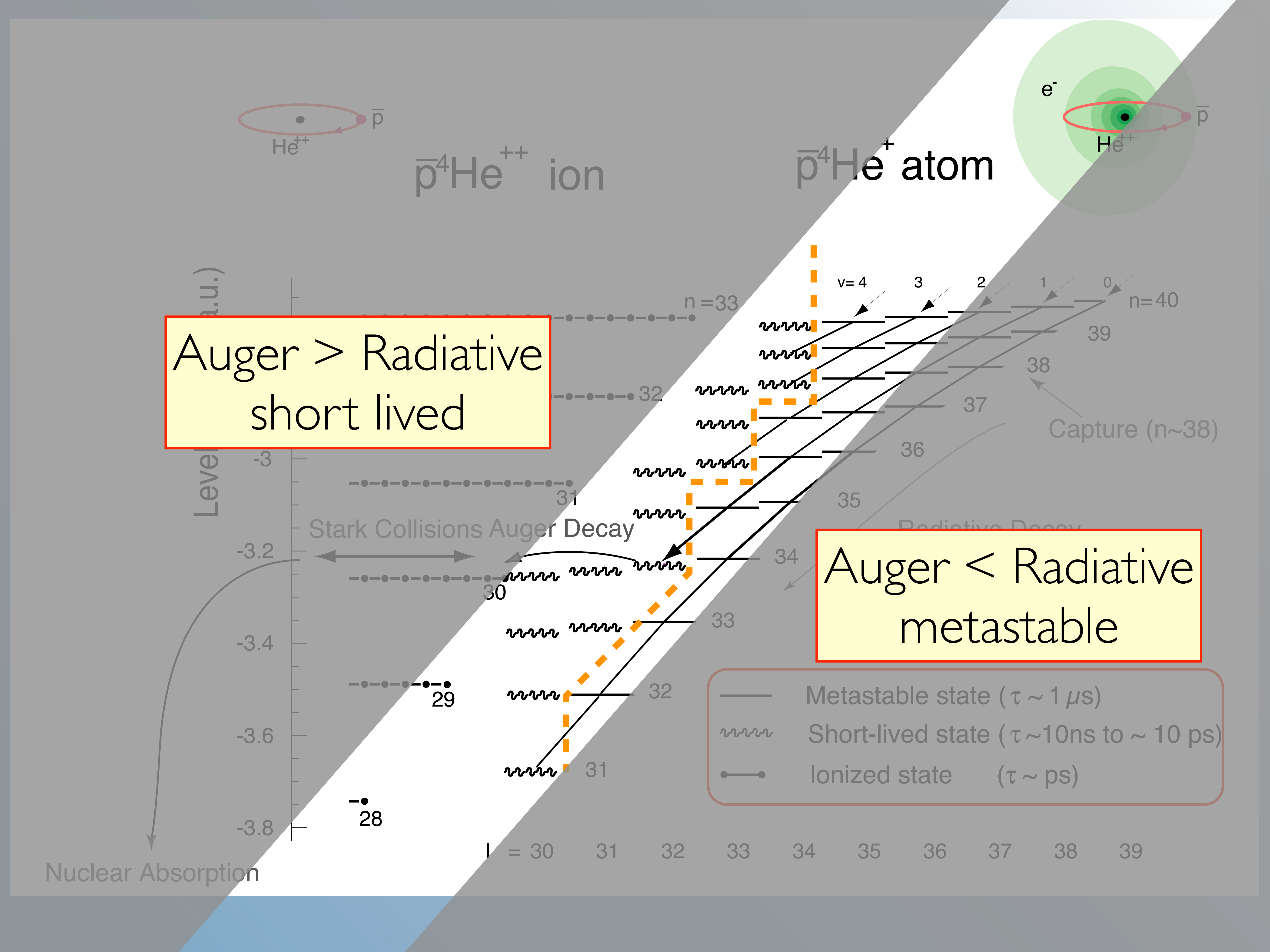
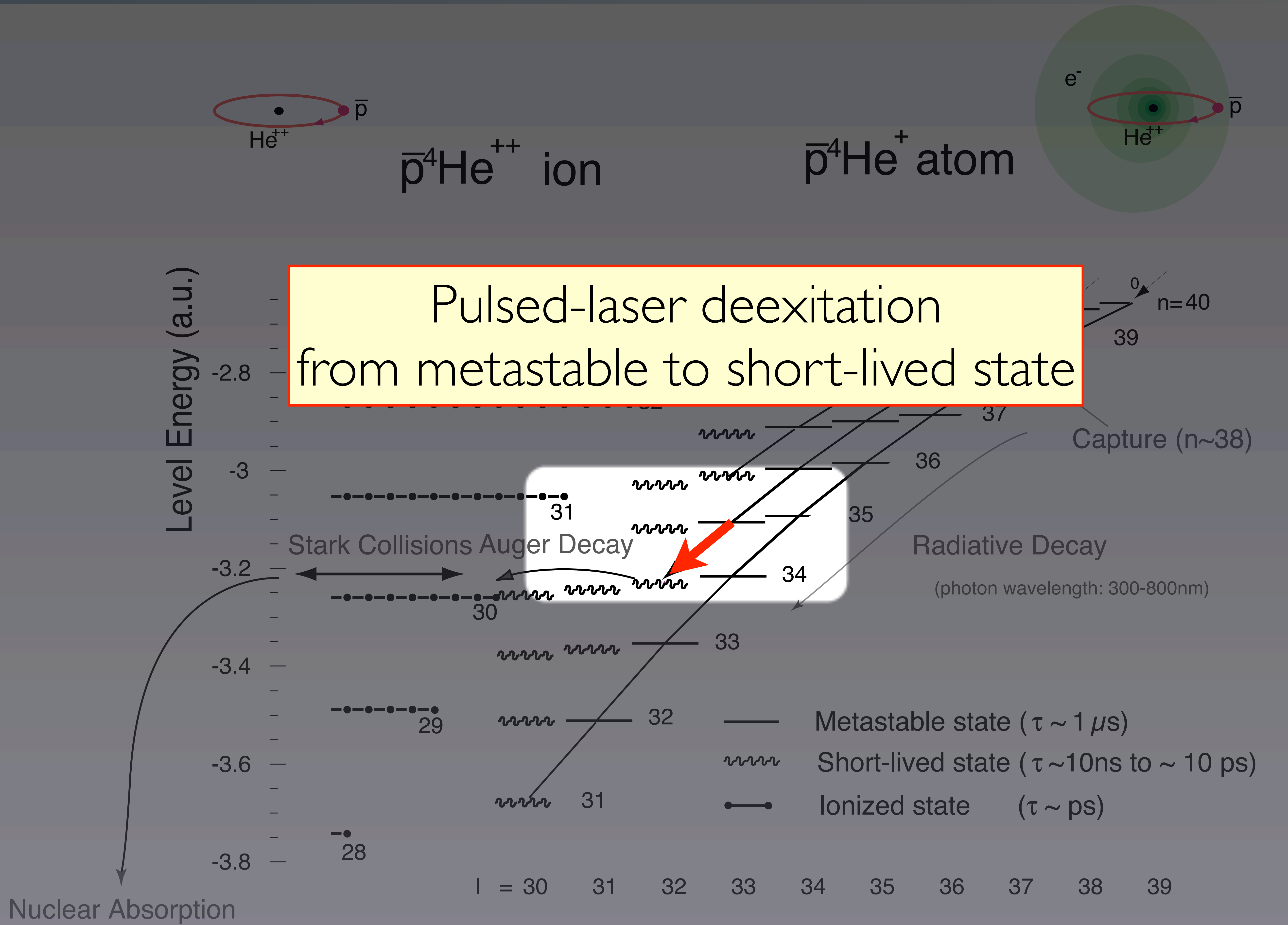


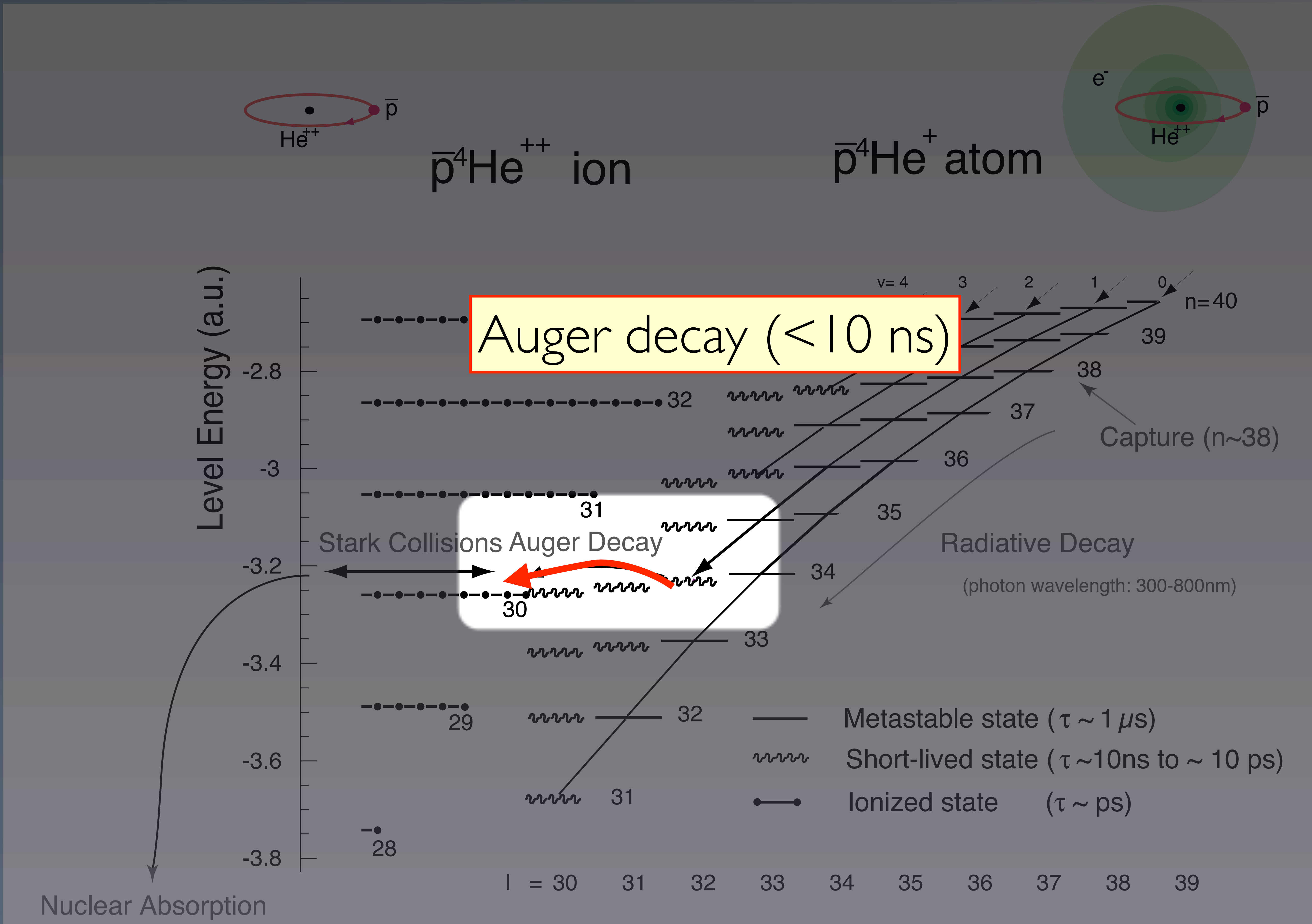
p̄
He++
p̄4He++ ion
p̄4He+ atom
e-
p̄
He++
Level Energy (a.u.)
-2.8
-3
-3.2
-3.4
-3.6
-3.8
n =33
32
31
30
29
28
v= 4
3
2
1
0
n= 40
39
38
37
36
35
34
33
32
31
Capture (n~38)
Radiative Decay
(photon wavelength: 300-800nm)
Stark Collisions Auger Decay
Nuclear Absorption
Metastable state (τ ~ 1 μs)
Short-lived state (τ ~10ns to ~ 10 ps)
Ionized state (τ ~ ps)
l = 30 31 32 33 34 35 36 37 38 39



Auger > Radiative
short lived
Auger < Radiative
metastable
p̄⁴He⁺⁺ ion
p̄⁴He⁺ atom
He⁺⁺
p̄
e⁻
v= 4
3
2
1
0
n=33
n=40
39
38
37
36
35
34
33
32
31
30
29
28
Capture (n~38)
Stark Collisions Auger Decay
Radiative Decay
Nuclear Absorption
Level (a.u.)
-3
-3.2
-3.4
-3.6
-3.8
l = 30
31
32
33
34
35
36
37
38
39
Metastable state (τ ~ 1 μs)
Short-lived state (τ ~10ns to ~ 10 ps)
Ionized state (τ ~ ps)

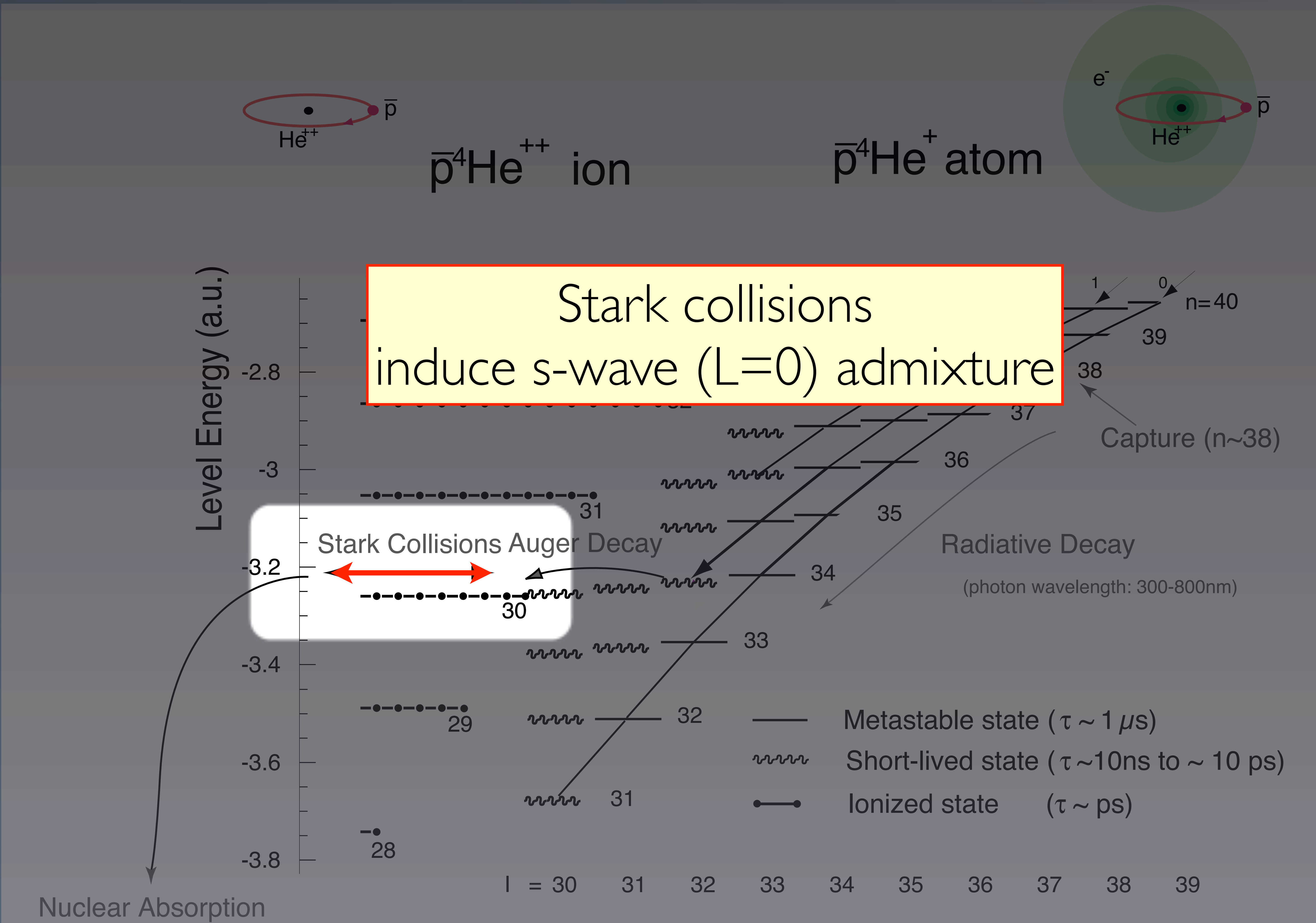
Pulsed-laser deexitation from metastable to short-lived state

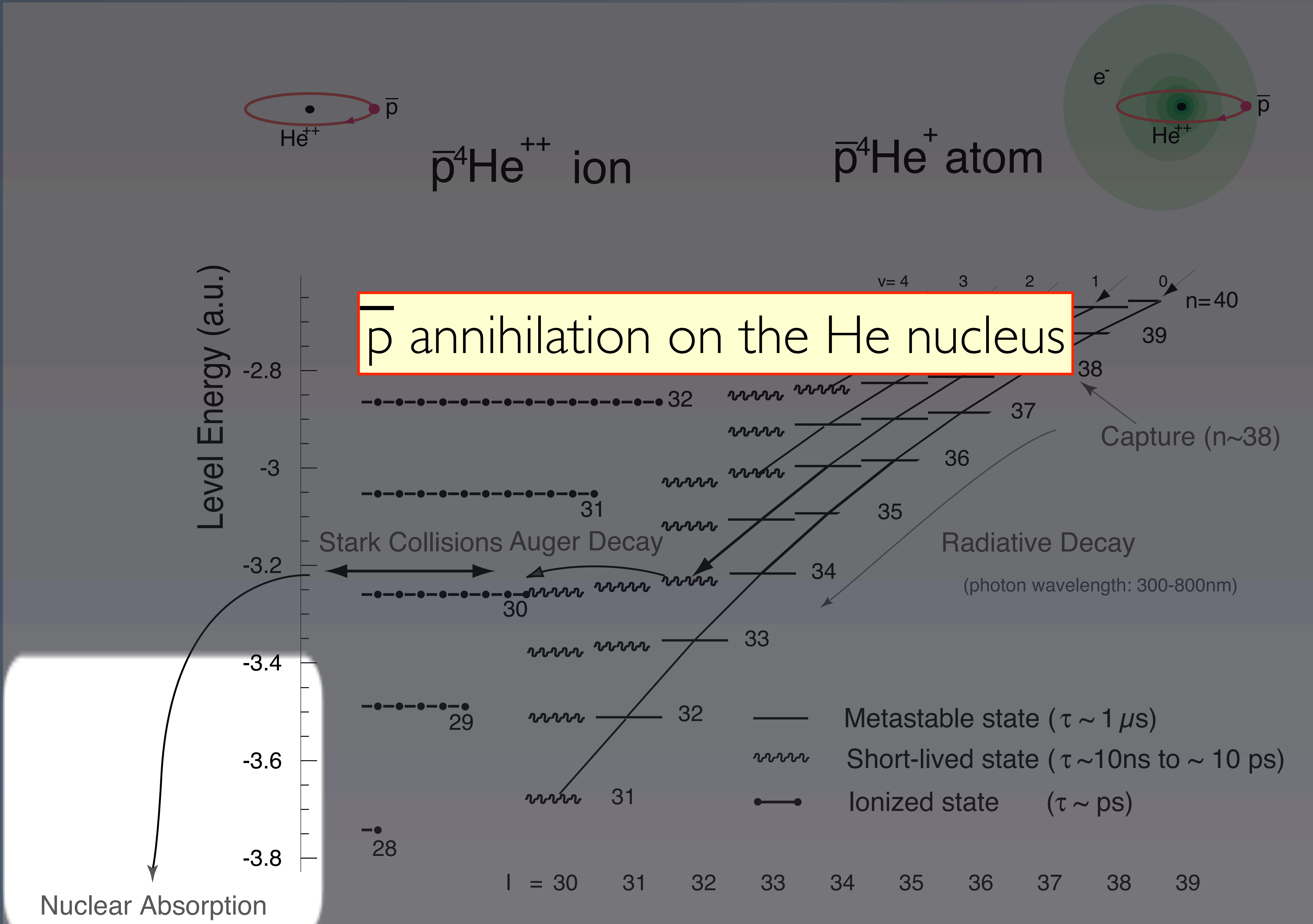




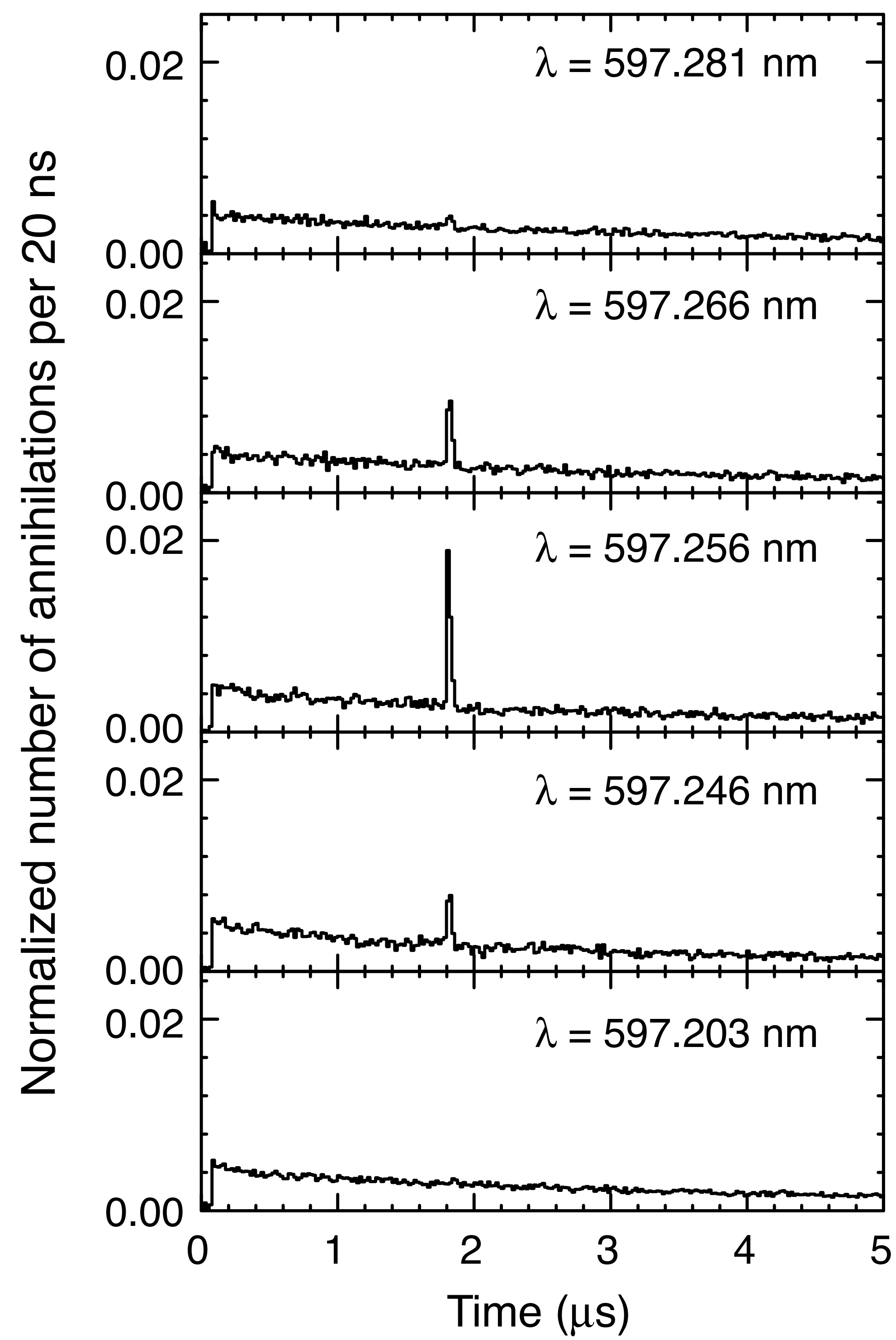
He++
p̄
p̄4He++ ion
p̄4He+ atom
e-
Auger decay (<10 ns)
Level Energy (a.u.)
-2.8
-3
-3.2
-3.4
-3.6
-3.8
v= 4
3
2
1
0
n=40
39
38
37
36
35
34
33
32
31
30
29
28
Capture (n~38)
Stark Collisions Auger Decay
Radiative Decay
(photon wavelength: 300-800nm)
Metastable state (τ ~ 1 μs)
Short-lived state (τ ~10ns to ~ 10 ps)
Ionized state (τ ~ ps)
l = 30 31 32 33 34 35 36 37 38 39
Nuclear Absorption

Stark collisions induce s-wave (L=0) admixture




p̄ annihilation on the He nucleus
p̄
He++
p̄4He++ ion
p̄4He+ atom
e-
Level Energy (a.u.)
-2.8
-3
-3.2
-3.4
-3.6
-3.8
v= 4
3
2
1
0
n=40
39
38
37
36
35
34
33
32
31
30
29
28
Capture (n~38)
Radiative Decay
(photon wavelength: 300-800nm)
Stark Collisions Auger Decay
Nuclear Absorption
Metastable state (τ ~ 1 μs)
Short-lived state (τ ~10ns to ~ 10 ps)
Ionized state (τ ~ ps)
l = 30 31 32 33 34 35 36 37 38 39

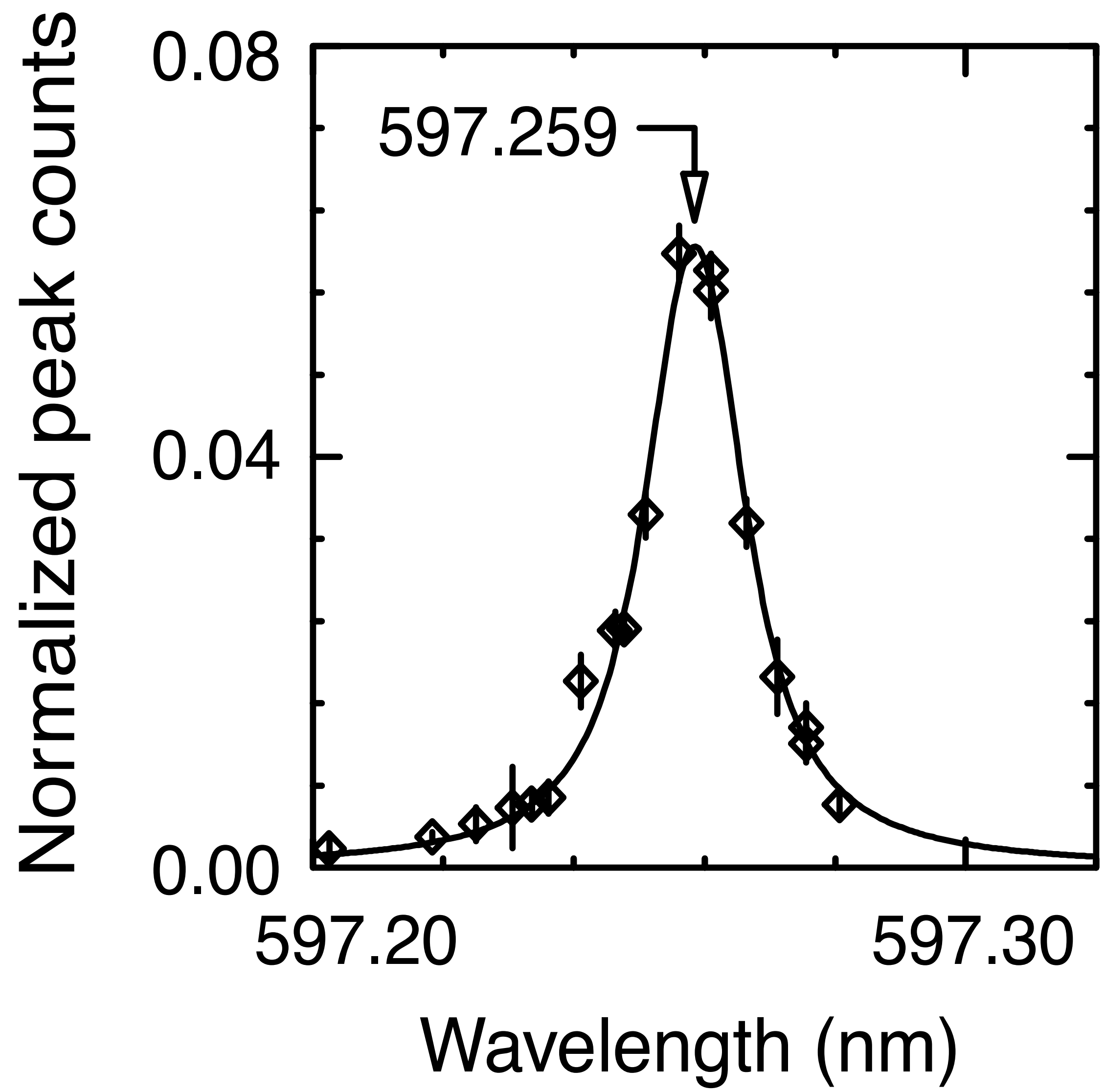
An example, (n,l)=(39,35)→(38,34)



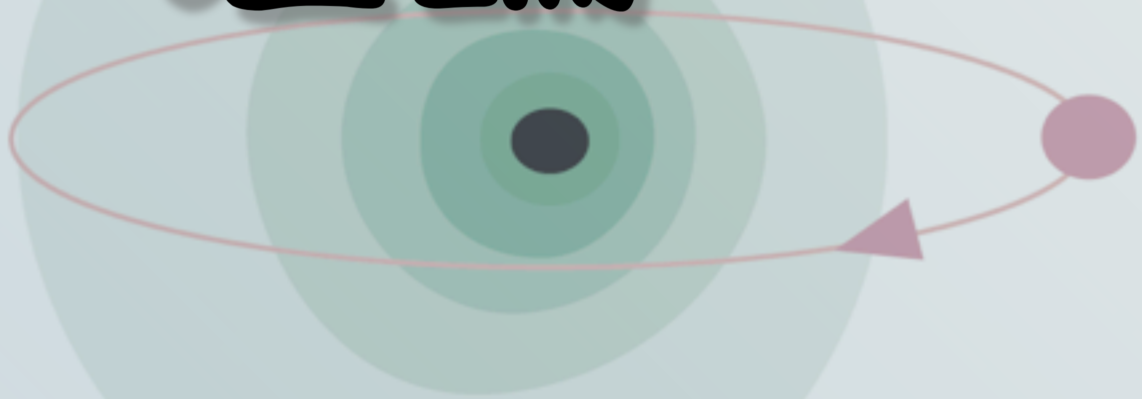
N. Morita et al, Phys. Rev. Lett. 72 (1994) 1180.

An example, (n,l)=(39,35)→(38,34)

N. Morita, et al., Phys. Rev. Lett. 72 (1994) 1180.

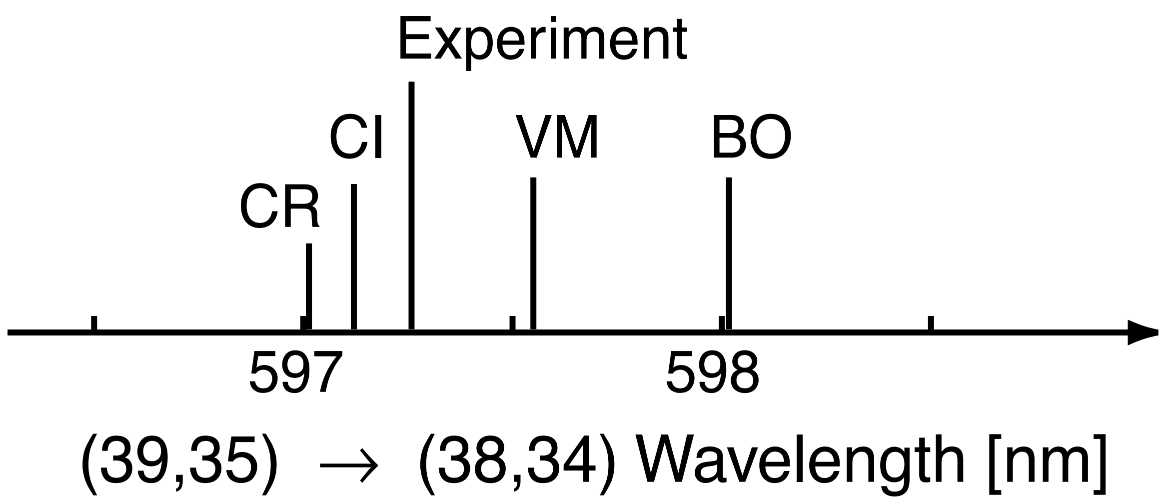


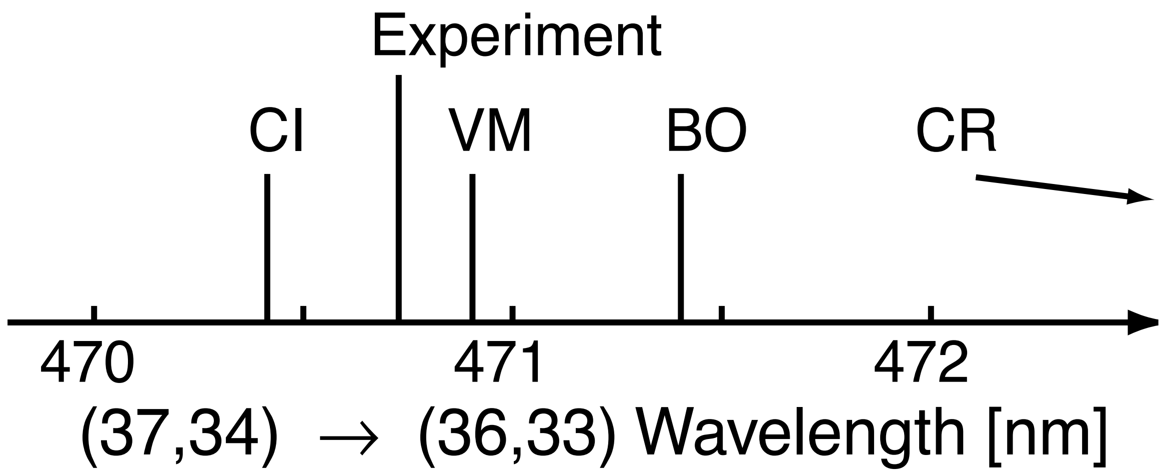
理論



Theory

Early days of PS205





Theory precision ~ 1000 ppm

~300 larger than the laser bandwidth of ~3GHz

Took weeks to hit the resonance

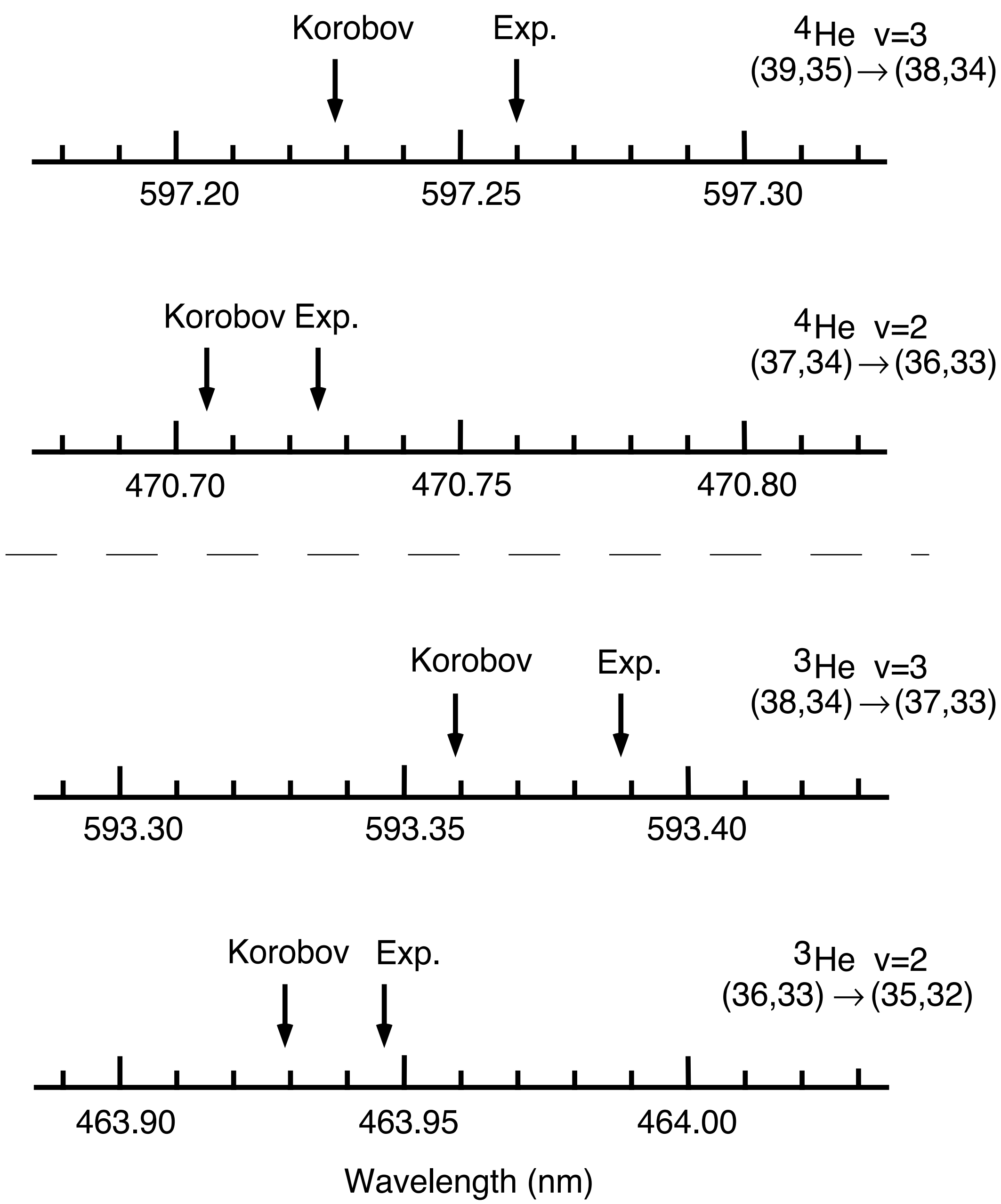
F.E. Maas et al., Phys. Rev. A 52 (1995) 4266.

Korobov revolution

PHYSICAL REVIEW A VOLUME 54, NUMBER 3 SEPTEMBER 1996

Variational calculation of energy levels in $\bar{p}$ He$^+$ molecular systems

V. I. Korobov
Joint Institute for Nuclear Research, Dubna, Russia
(Received 29 April 1996)



Theory precision ~ 50 ppm

Shifted in a systematic way

< hour to find a new resonance

Theory - non-relativistic H

antiproton

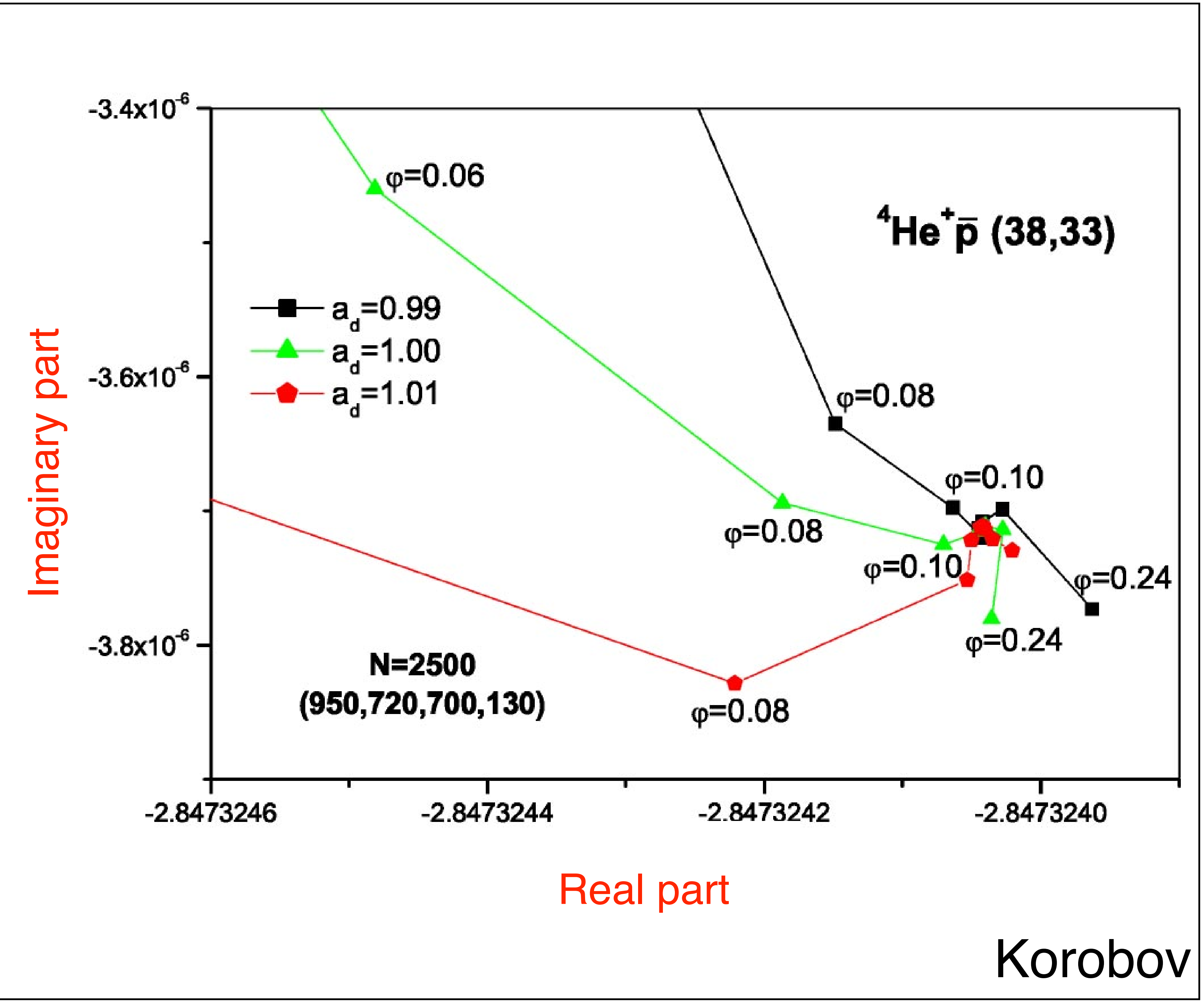
electron

$$H = T + V$$

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

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

Complex coordinate rotation (CCR) method



Careful treatment of Auger decay is needed

CCR calculates complex eigen values

add relativistic correction (~100 ppm)

V.I. Korobov, D.D. Bakalov, Phys. Rev. Lett. 79 (1997) 3379.

$$H = T + V$$

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

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

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

add self energy (~15 ppm)

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

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

Bethe logarithm

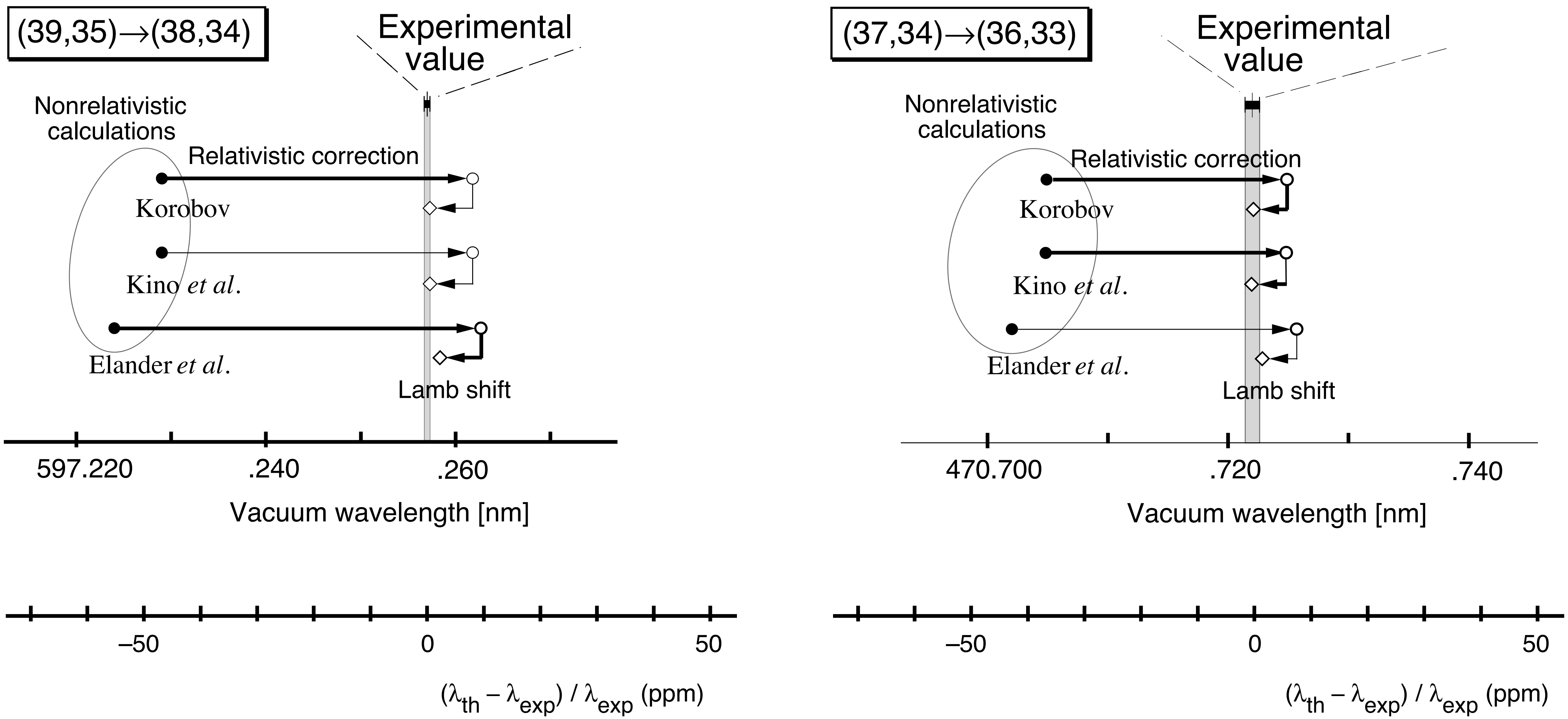
$$E_{se} = \frac{4\alpha^3}{3m_e^2}\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0}{R_\infty} + \frac{5}{6} - \frac{3}{8}\right]\langle Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\rangle$$
$$+ \frac{4\alpha^4}{3m_e^2}\left[3\pi\left(\frac{139}{128} - \frac{1}{2}\ln 2\right)\right]\langle Z_{\mathrm{He}}^2\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}^2\delta(\mathbf{r}_{\bar{p}})\rangle$$
$$- \frac{4\alpha^5}{3m_e^2}\left[\frac{3}{4}\right]\langle Z_{\mathrm{He}}^3 \ln^2(Z_{\mathrm{He}}\alpha)^{-2}\delta(\mathbf{r}_{\mathrm{He}})$$
$$+ Z_{\bar{p}}^3 \ln^2(Z_{\bar{p}}\alpha)^{-2}\delta(\mathbf{r}_{\bar{p}})\rangle,$$

Relativistic & QED corrections

p̅He first appeared in PDG
everyone was ecstatic

end of LEAR PS205

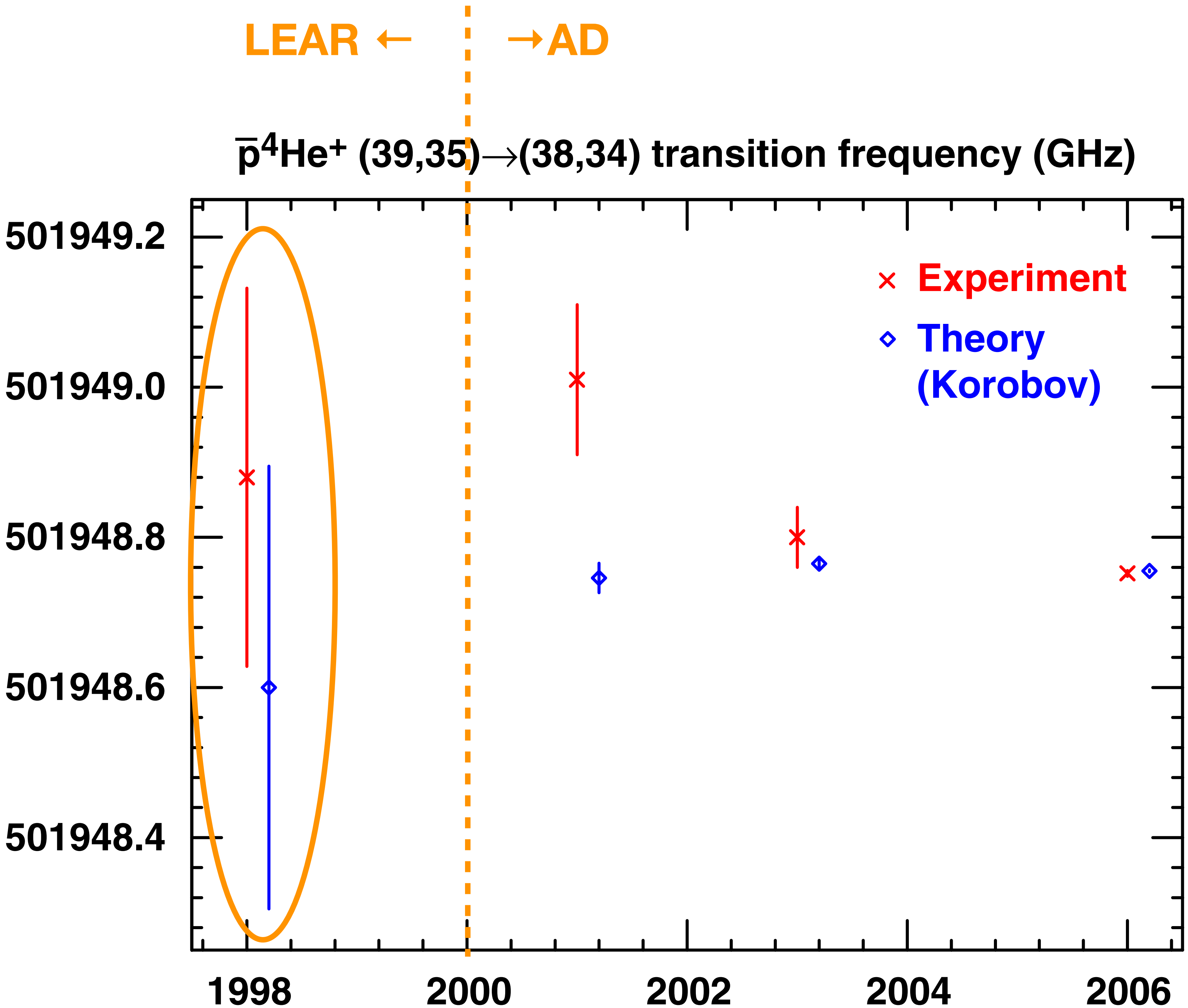
relative precision ~0.5ppm



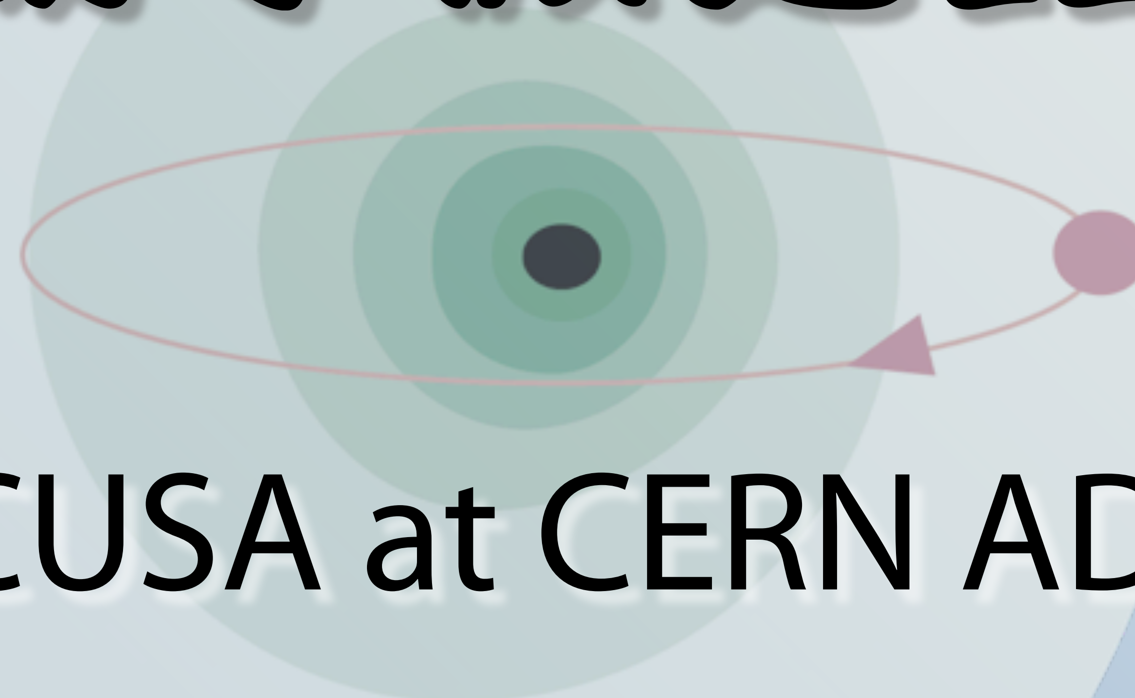
note: wavelength comparison

H.A. Torii et al., Phys. Rev. A 59 (1999) 223.

Theory vs experiment

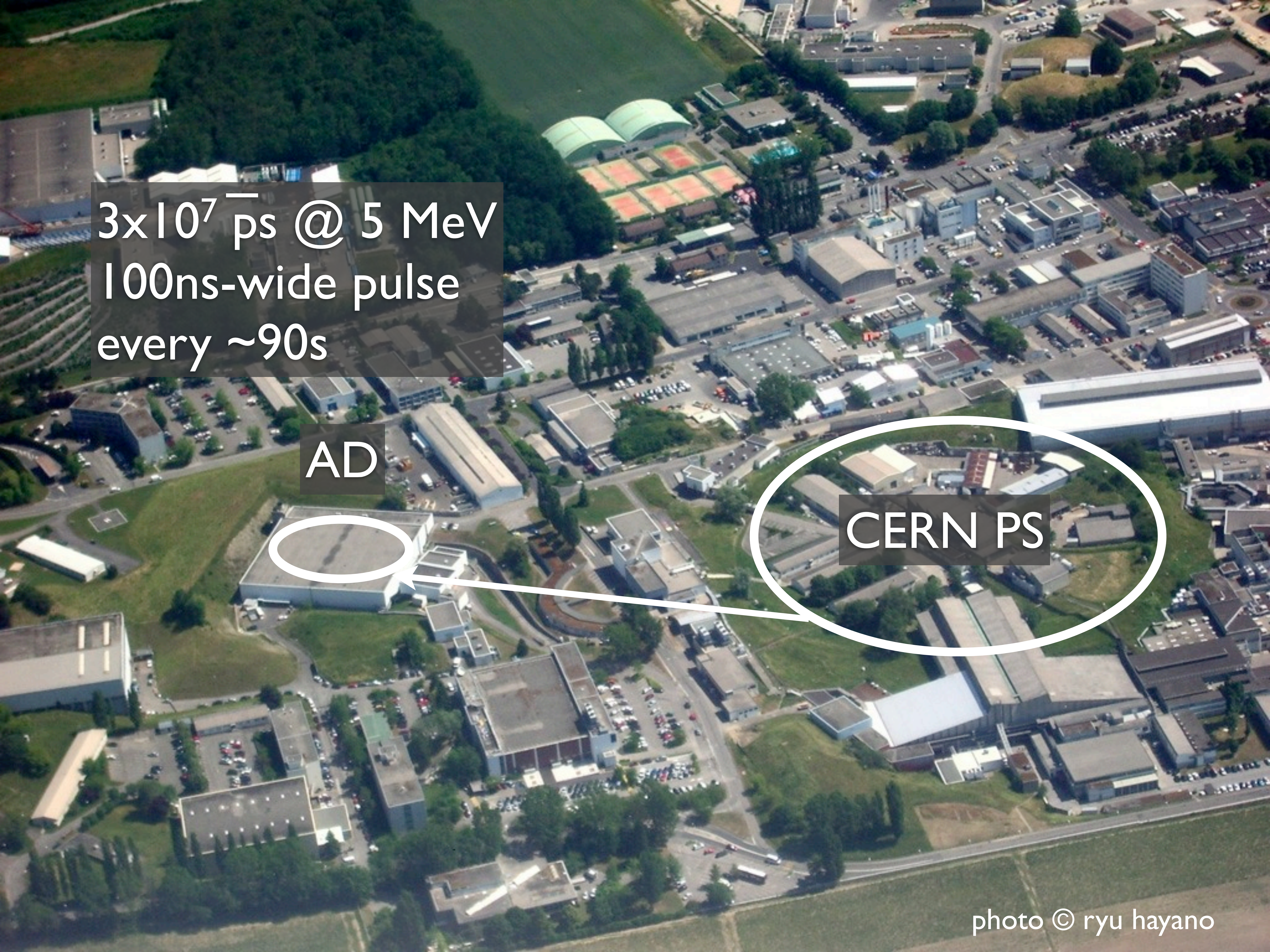


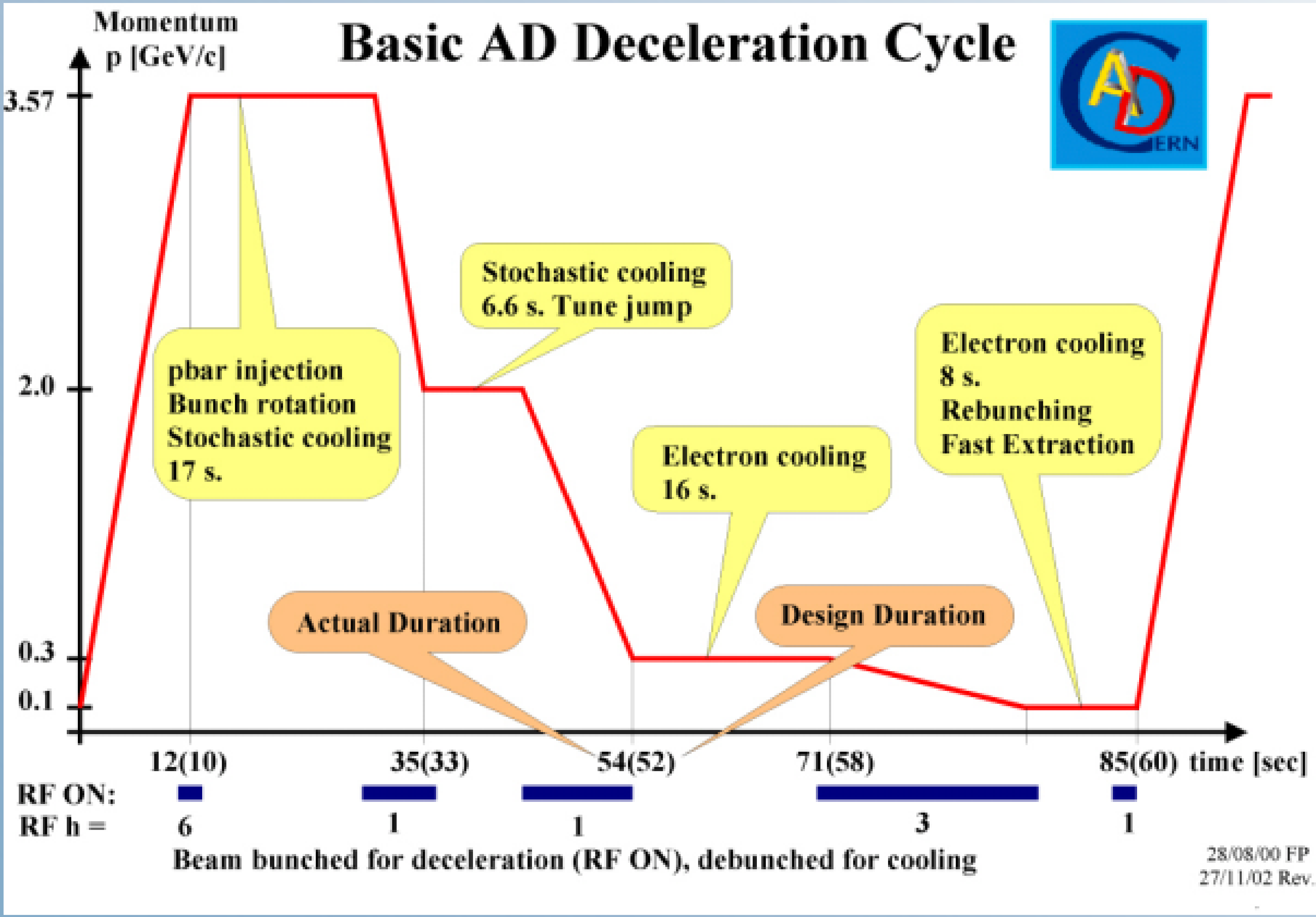
反陽子減速器

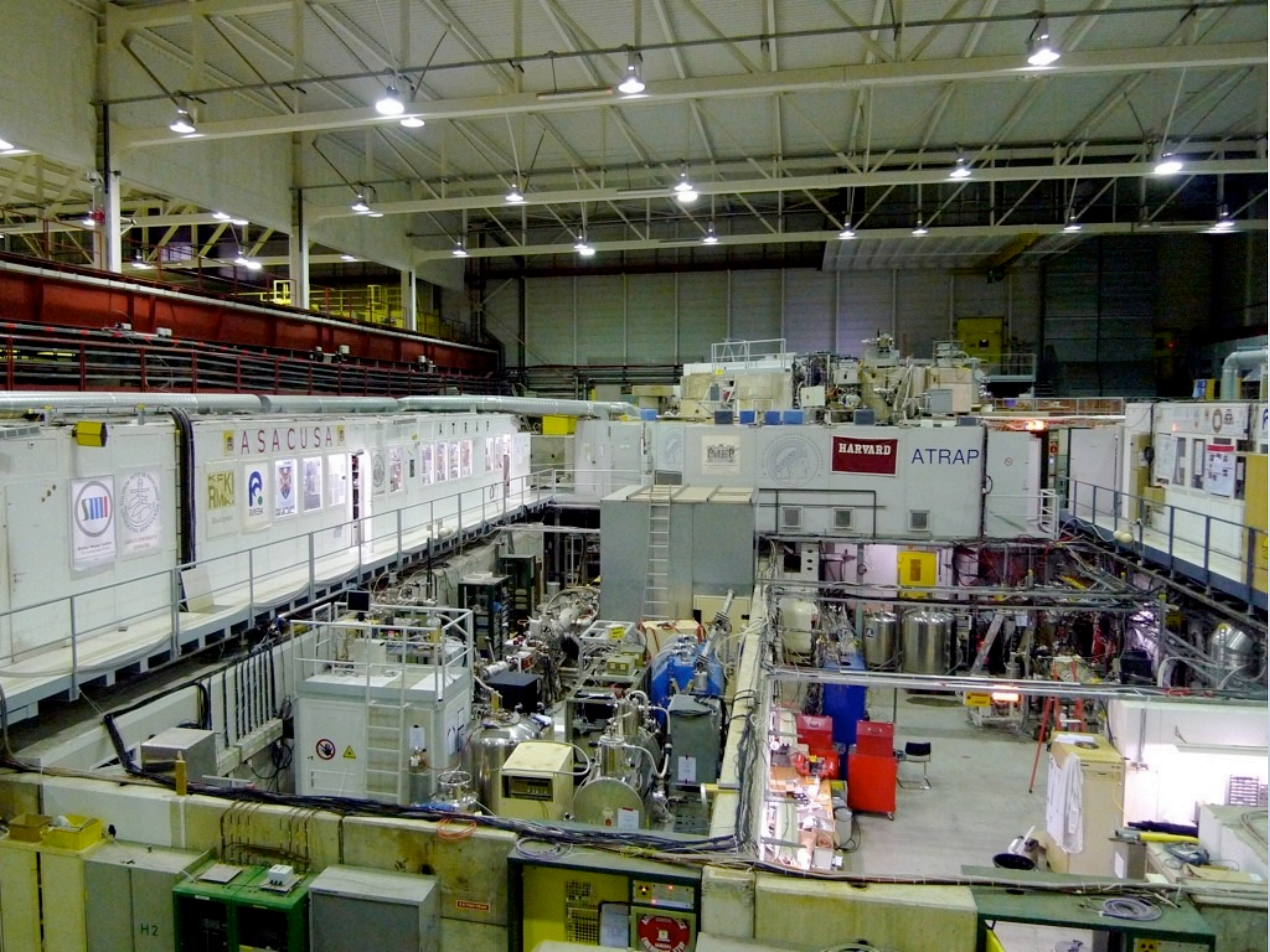


ASACUSA at CERN AD

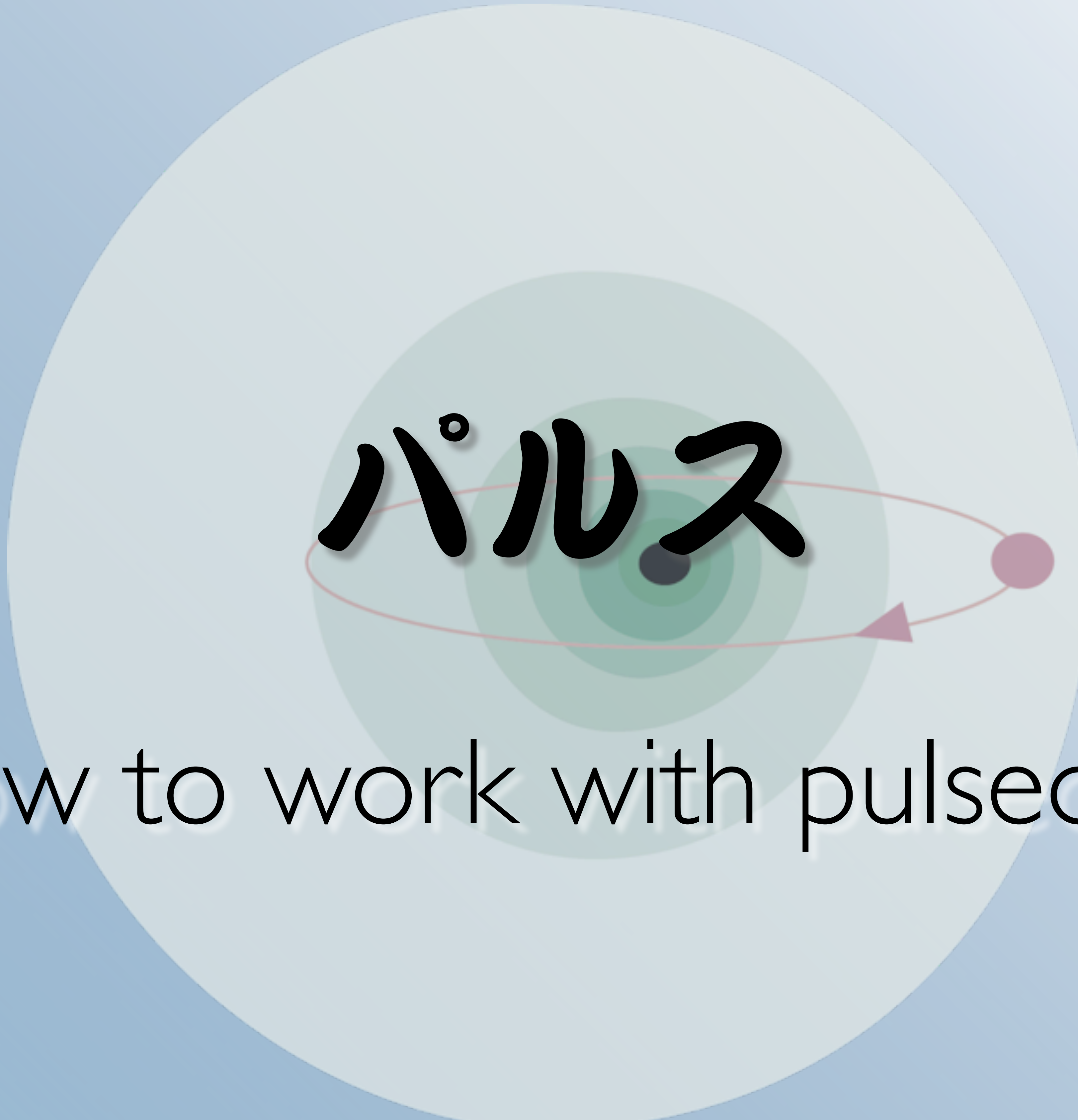
THE UNIVERSITY OF TOKYO


3x10^7 p̄s @ 5 MeV
100ns-wide pulse
every ~90s
AD
CERN PS
photo © ryu hayano


Momentum
p [GeV/c]
Basic AD Deceleration Cycle
3.57
2.0
0.3
0.1
pbar injection
Bunch rotation
Stochastic cooling
17 s.
Stochastic cooling
6.6 s. Tune jump
Electron cooling
16 s.
Electron cooling
8 s.
Rebunching
Fast Extraction
Actual Duration
Design Duration
12(10)
35(33)
54(52)
71(58)
85(60)
time [sec]
RF ON:
RF h =
6
1
1
3
1
Beam bunched for deceleration (RF ON), debunched for cooling
28/08/00 FP
27/11/02 Rev.

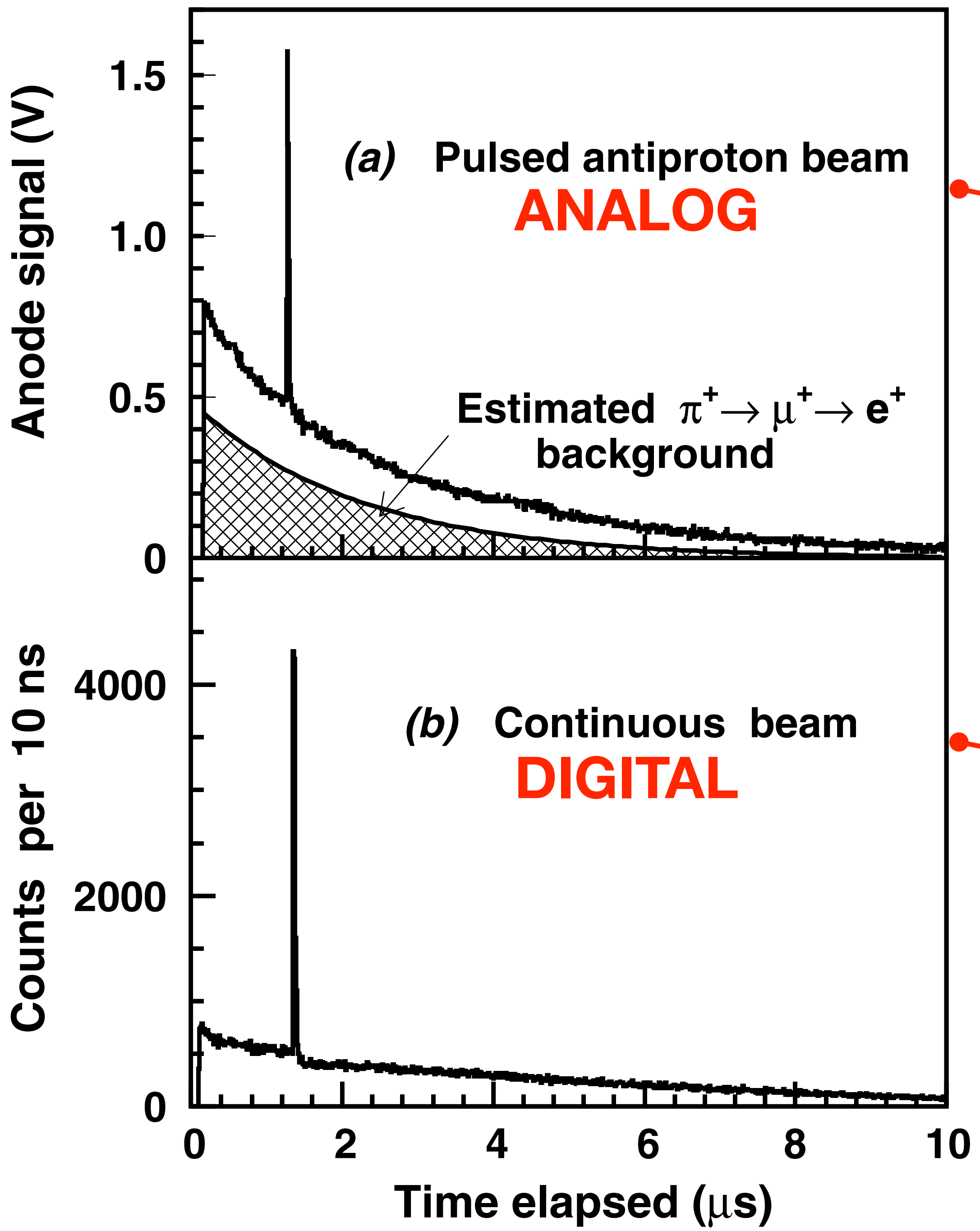

ASACUSA
ATRAP
HARVARD
ATRAP
H2

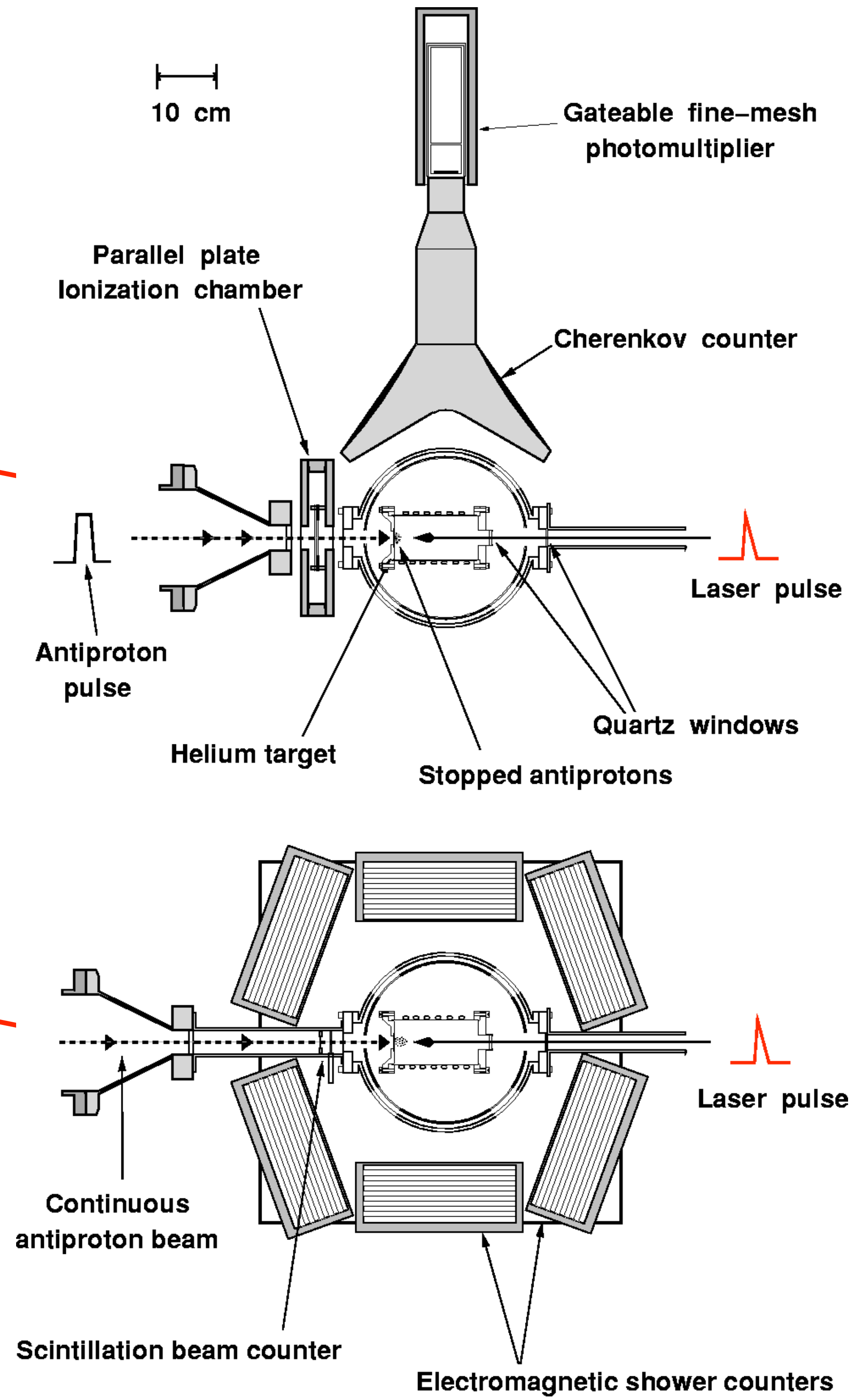
パルス



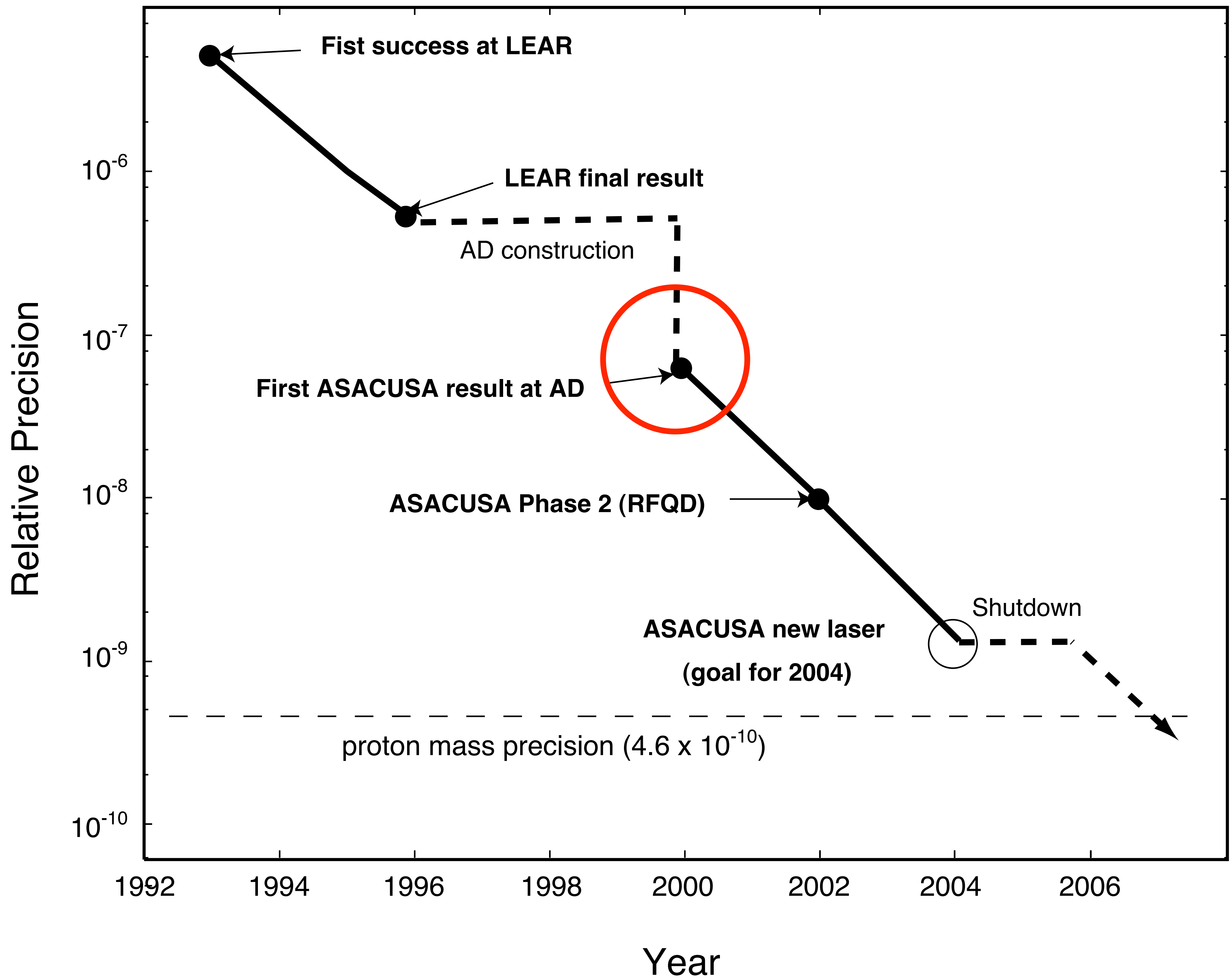
How to work with pulsed $\bar{p}$?

Can't use event-by-event counting





M. Hori et al., PHYSICAL REVIEW A 70, 012504 (2004).

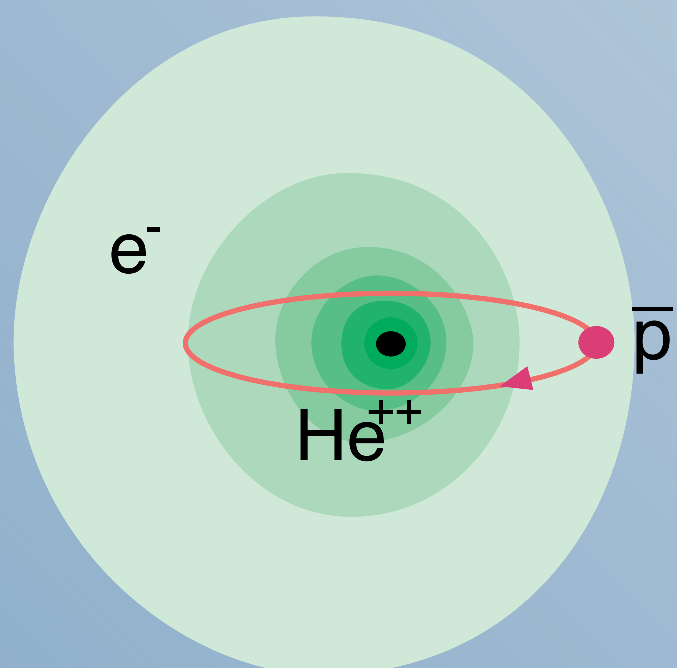


Fist success at LEAR
LEAR final result
AD construction
First ASACUSA result at AD
ASACUSA Phase 2 (RFQD)
Shutdown
ASACUSA new laser
(goal for 2004)
proton mass precision (4.6 x 10^-10)
Relative Precision
10^-6
10^-7
10^-8
10^-9
10^-10
1992
1994
1996
1998
2000
2002
2004
2006
Year

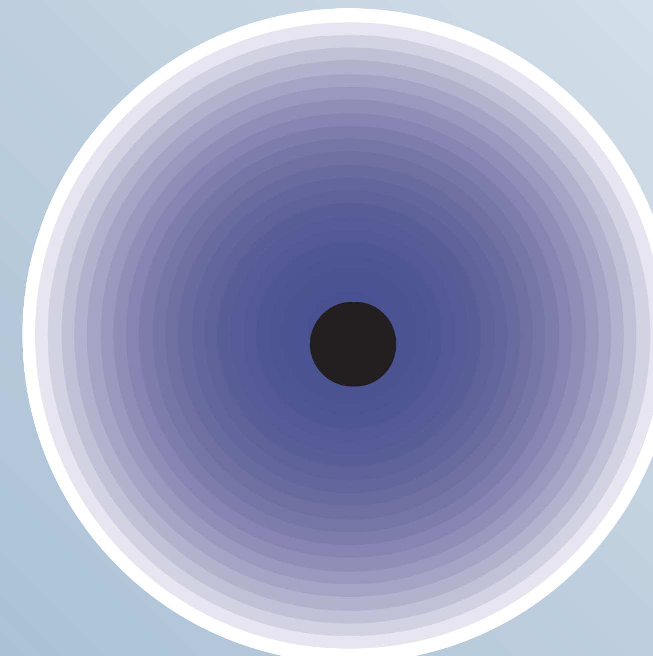
衝突

reducing collision

more on collisions by Grigory Korenman



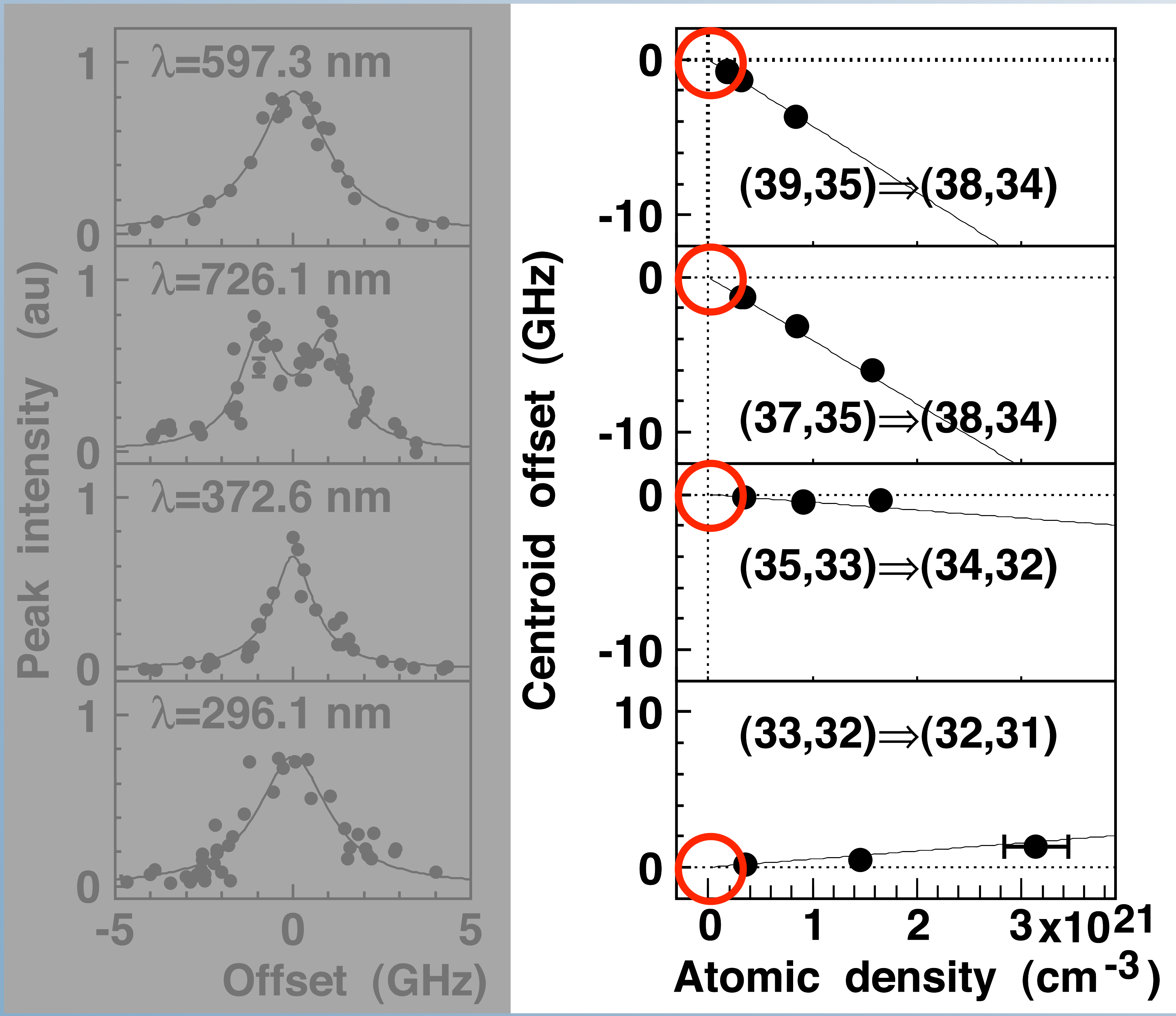
$\bar{p}$ He



He

$\bar{p}$He - He collisions do not destroy $\bar{p}$He but have consequences

Density-dependent shift

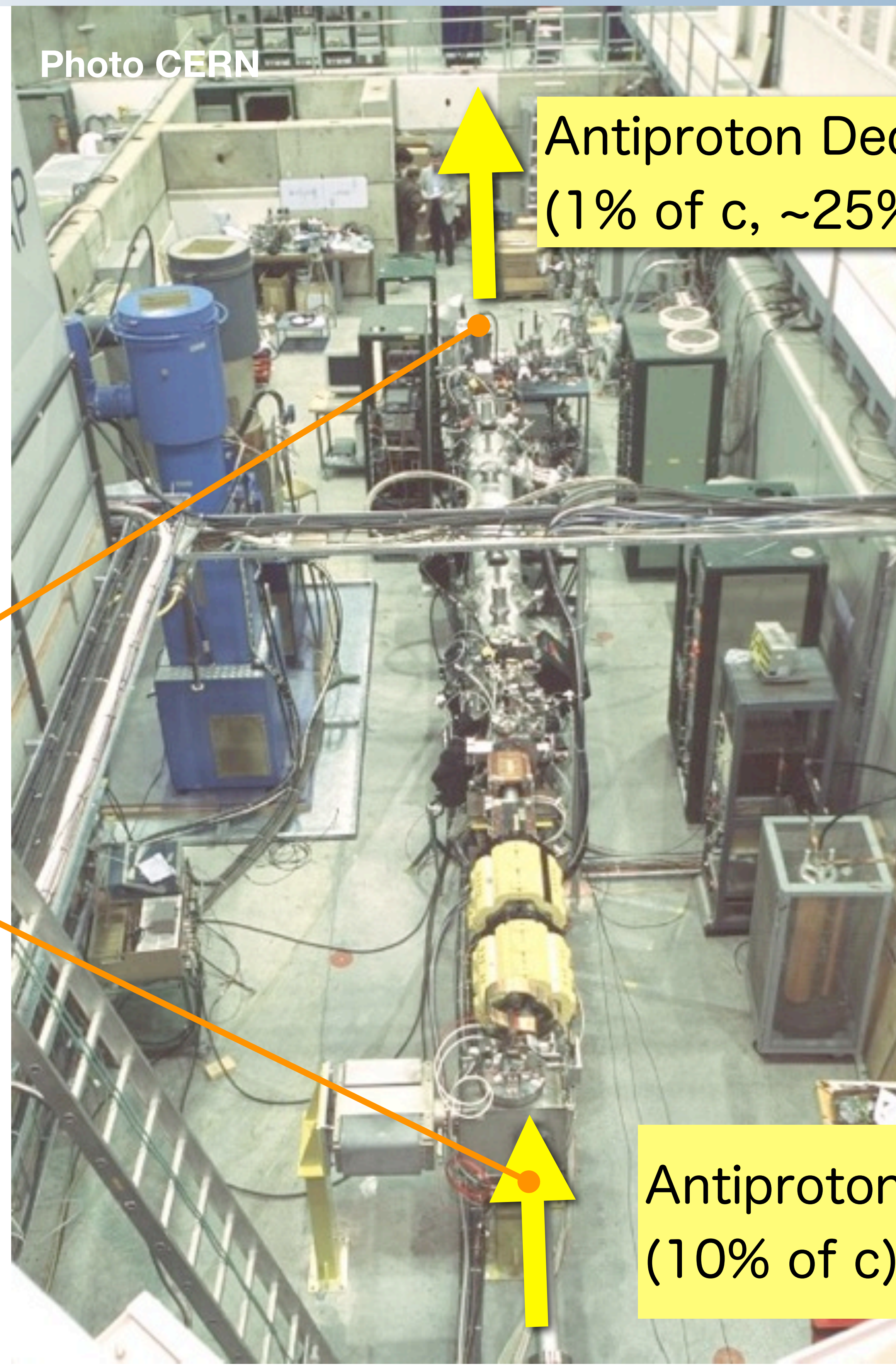


2002

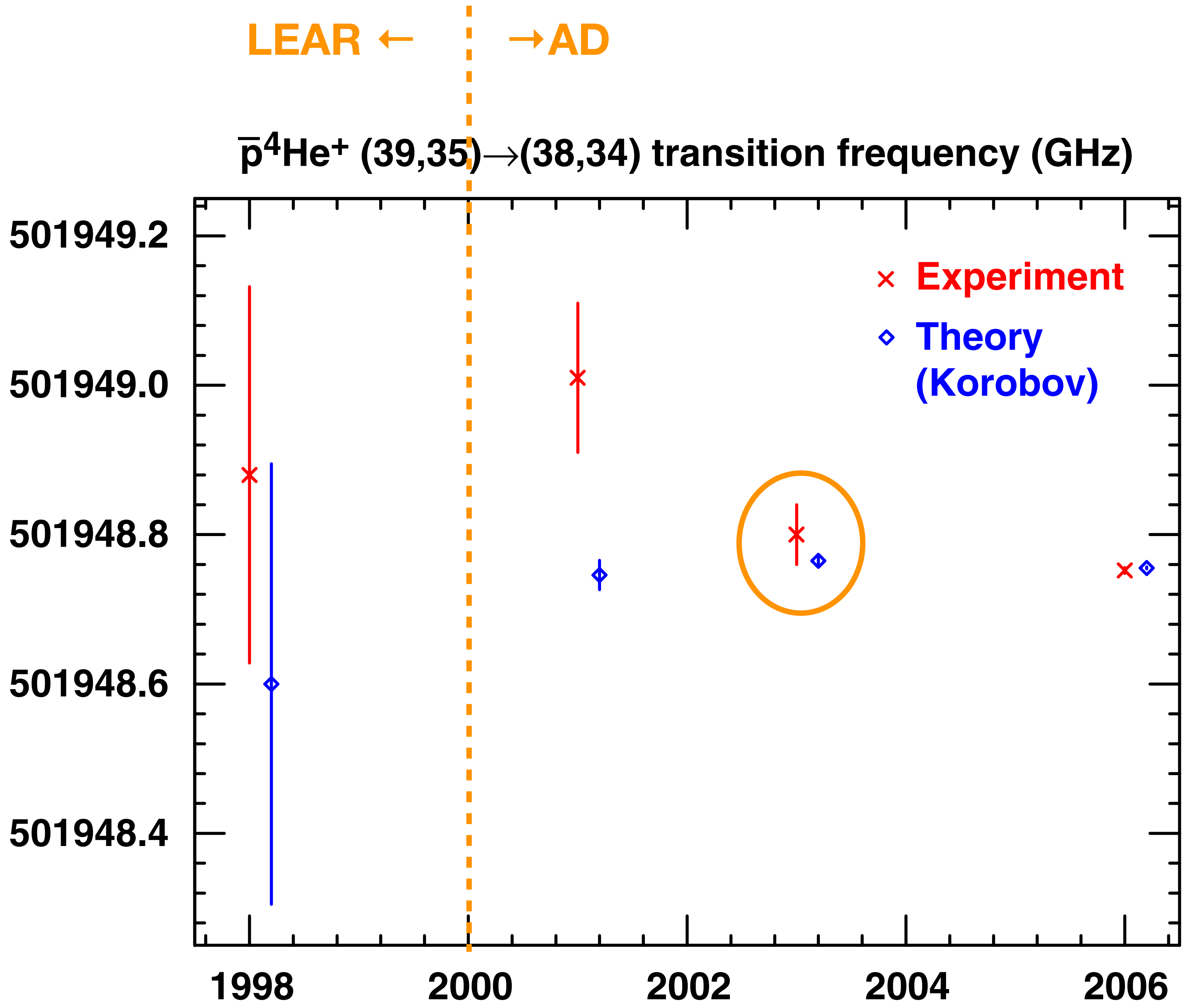
RFQD
a decelerating linac

RFQD

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

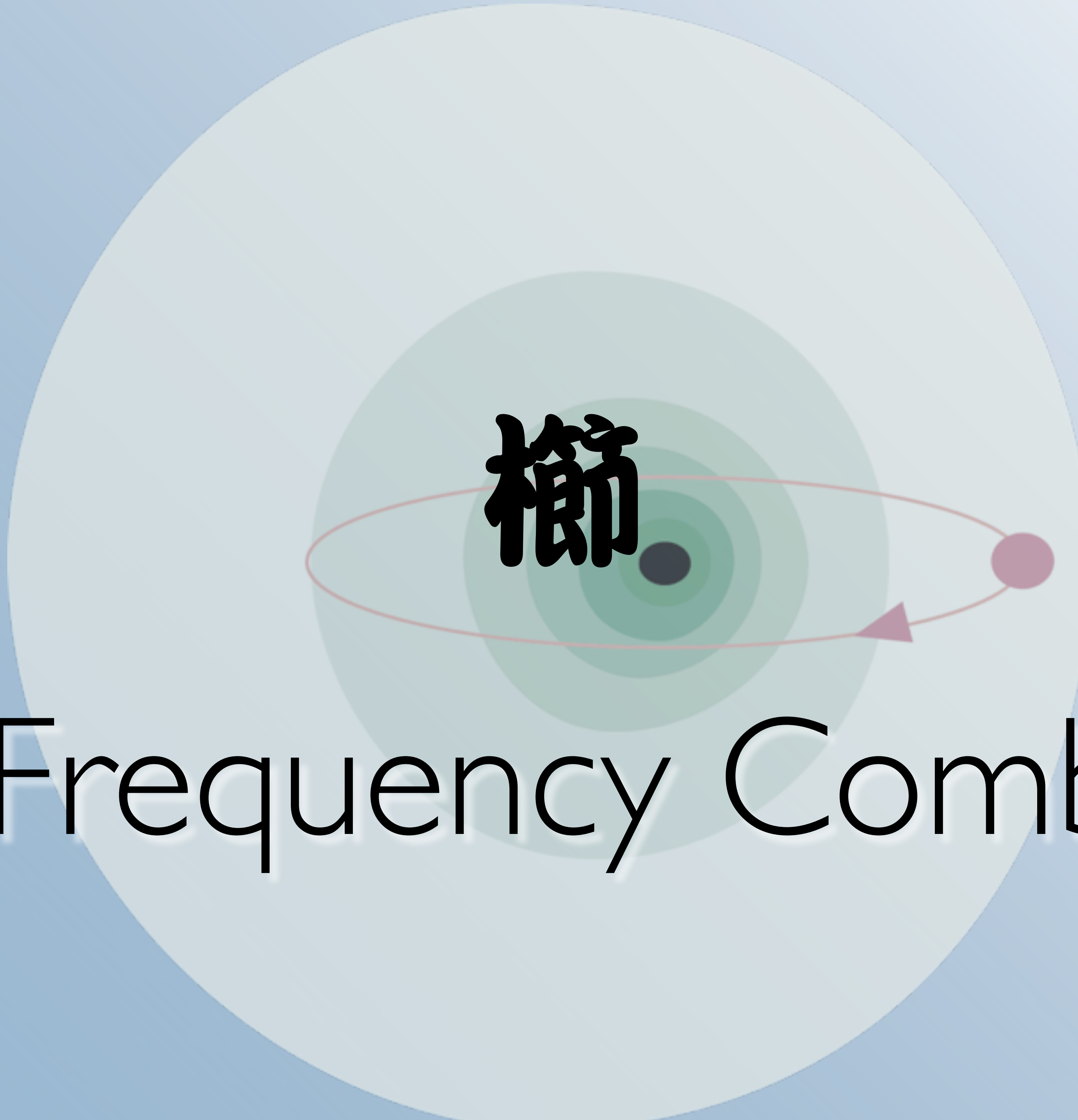


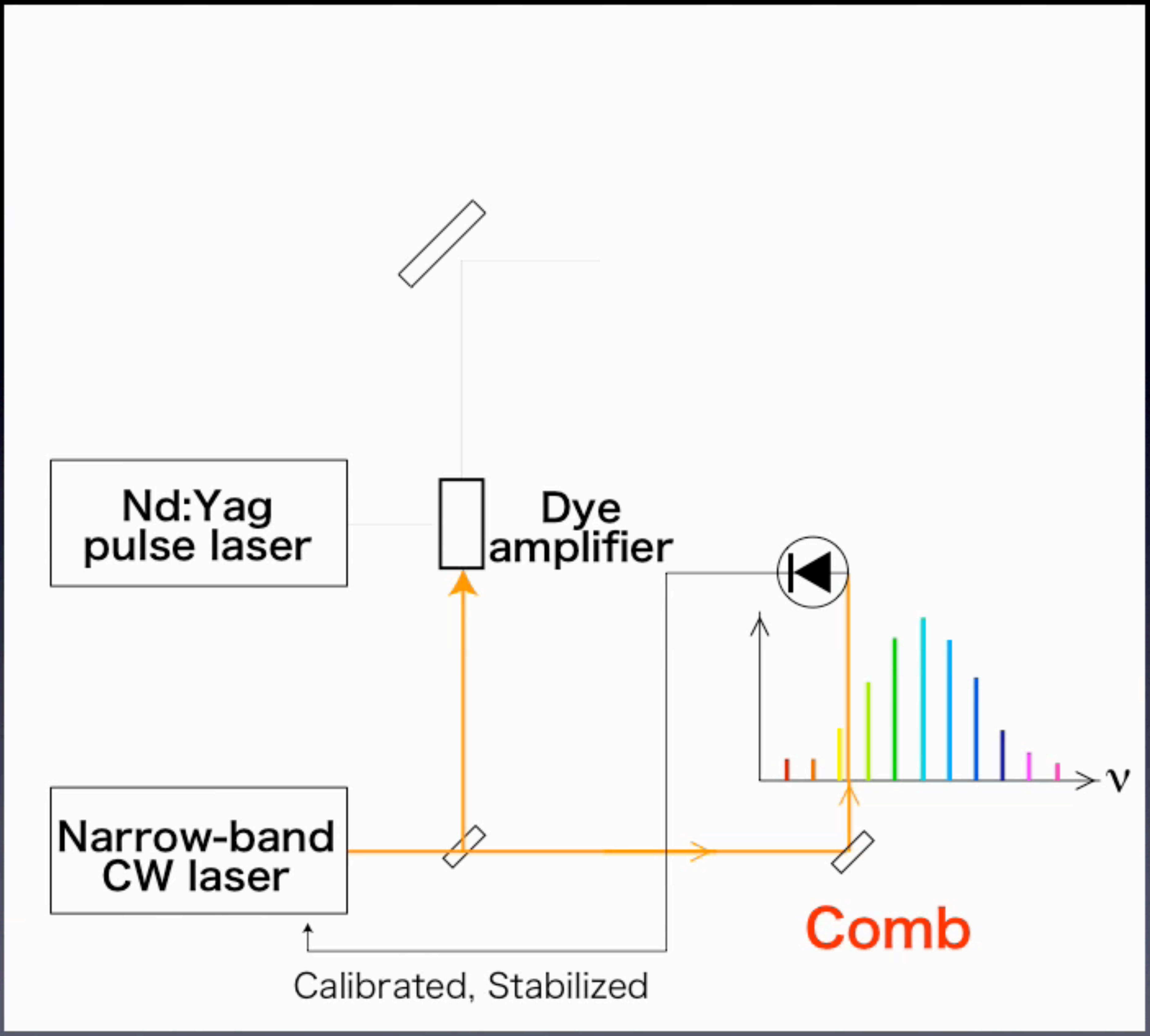
"Direct" measurement w RFQD



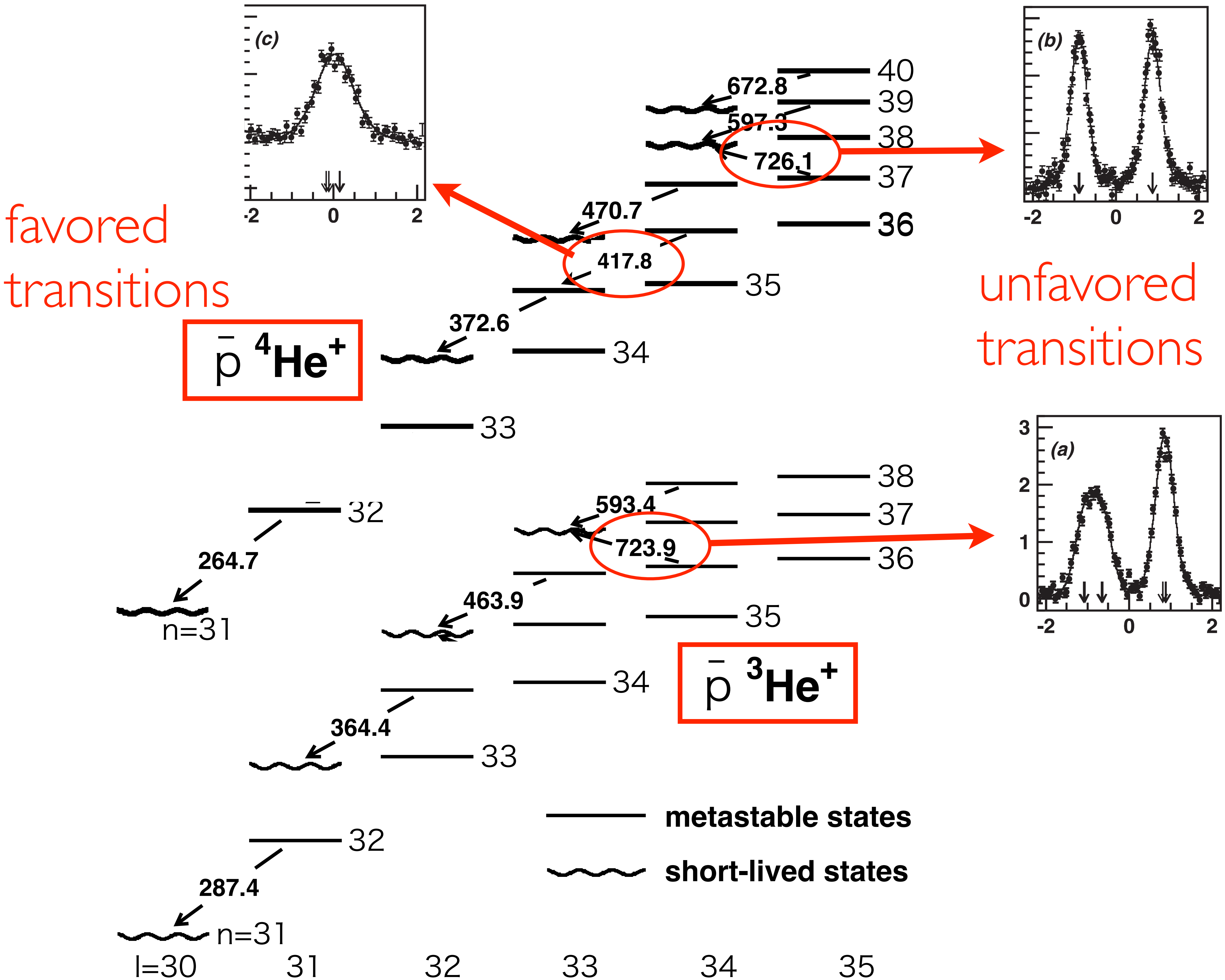
櫛

Frequency Comb

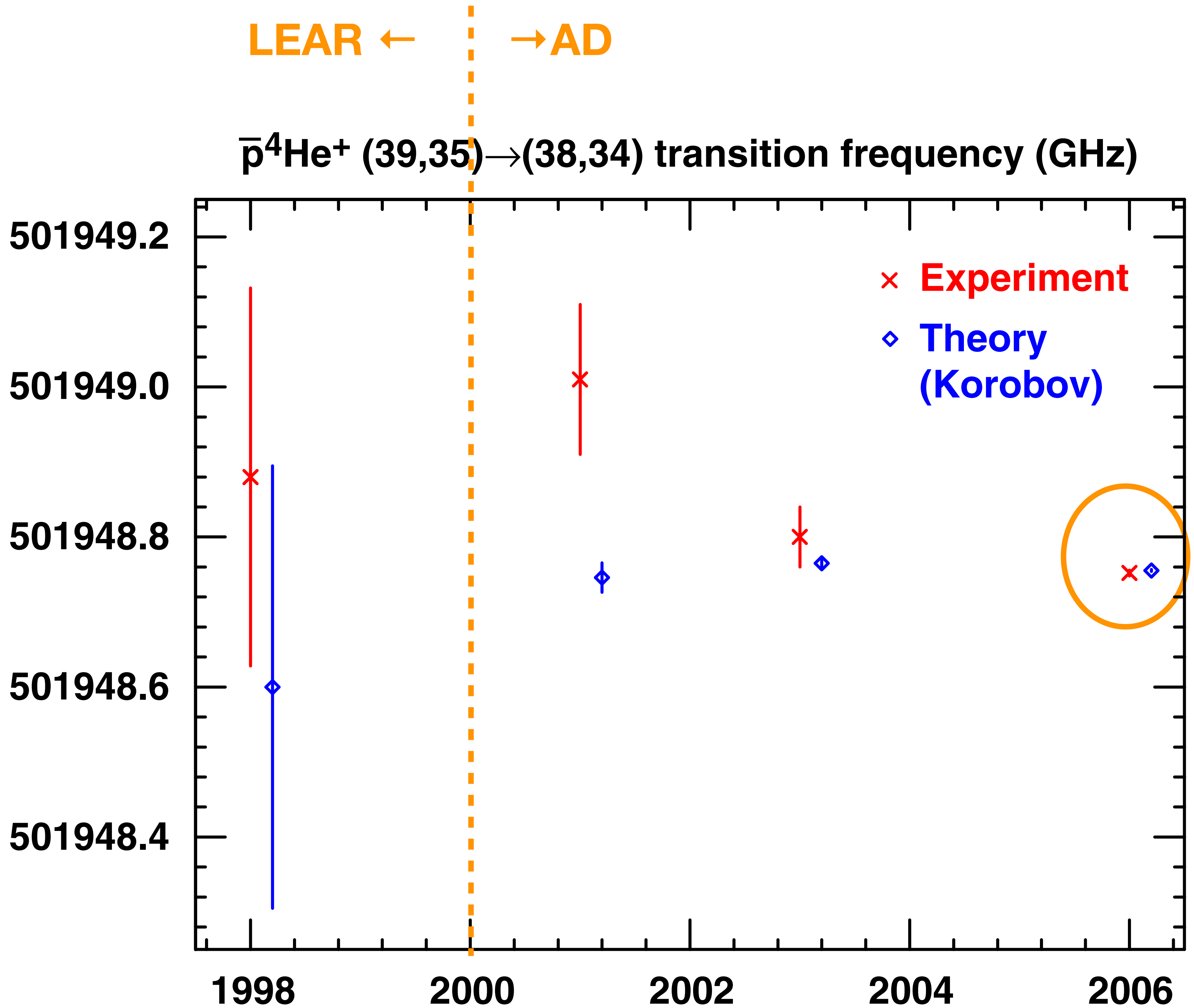



Nd:Yag pulse laser
Dye amplifier
Narrow-band CW laser
ν
Comb
Calibrated, Stabilized

12 transitions were measured



with RFQD+Comb



An example (39,35) → (38,34)

E_{nr}	$=$	501 972 347.9	Non relativistic
E_{rc}	$=$	$-27\,525.3$	+ Relativistic & QED corrections
E_{rc-qed}	$=$	233.3	
E_{se}	$=$	3 818.0	
E_{vp}	$=$	-122.5	$\Delta E_{\rm vp} = \frac{4z_i\alpha^3}{3m_3^2}\left[-\frac{1}{5}+(z_i\alpha)\pi\frac{5}{64}\right]\langle\delta(\boldsymbol{r}_i)\rangle,$
E_{kin}	$=$	37.3	$\Delta E_{\rm kin} = \alpha^2\left\langle -\frac{\boldsymbol{\nabla}_1^4}{8m_1^3}-\frac{\boldsymbol{\nabla}_2^4}{8m_2^3}+\frac{(1+2a_2)z_2}{8m_2^2}4\pi\delta(\boldsymbol{r}_2)\right\rangle,$
E_{exch}	$=$	-34.7	$\Delta E_{\rm exch} = -\alpha^2\frac{z_i}{2m_im_3}\left\langle\frac{\boldsymbol{\nabla}_i\boldsymbol{\nabla}_3}{r_i}+\frac{\boldsymbol{r}_i(\boldsymbol{r}_i\boldsymbol{\nabla}_i)\boldsymbol{\nabla}_3}{r_i^3}\right\rangle,$
E_{α^3-rec}	$=$	0.8	$\Delta E^{(3)}_{\rm recoil} = \frac{z_i\alpha^3}{m_im_3}\left\{\frac{2}{3}\left(-\ln\alpha-4\beta+\frac{31}{3}\right)\langle\delta(\boldsymbol{r}_i)\rangle-\frac{14}{3}\langle Q(r_i)\rangle\right\},$
$E_{two-loop}$	$=$	0.9	$\Delta E_{\rm two\text{-}loop} = \alpha^4\frac{z_i}{m_3^2\pi}\left[-\frac{6131}{1296}-\frac{49\pi^2}{108}+2\pi^2\ln 2-3\zeta(3)\right]\langle\delta(\boldsymbol{r}_i)\rangle$
E_{nuc}	$=$	2.4	$\Delta E_{\rm nuc} = \frac{2\pi z_i(R_i/a_0)^2}{3}\langle\delta(\boldsymbol{r}_i)\rangle,$
E_{α^4}	$=$	-2.6	$\Delta E_{\alpha^4} \approx -\alpha^4\frac{\pi}{2}\delta(\boldsymbol{r}_1).$
E_{total}	$=$	501 948 755.6(1.3) MHz	Theory (Korobov)
		501 948 752.0(4.0) MHz (error)	Exp.

12 such transitions
CODATA 2006

contribution to CODATA

REVIEWS OF MODERN PHYSICS, VOLUME 80, APRIL–JUNE 2008

CODATA recommended values of the fundamental physical constants: 2006*

Peter J. Mohr,† Barry N. Taylor,‡ and David B. Newell§

IV. ATOMIC TRANSITION FREQUENCIES

Atomic transition frequencies in hydrogen, deuterium, and antiprotonic helium yield information on the Rydberg constant, the proton and deuteron charge radii, and the relative atomic mass of the electron. The hyper-

2012

$m_{\bar{p}} / m_e = 1836.1526736(23)$

NATURE | LETTER

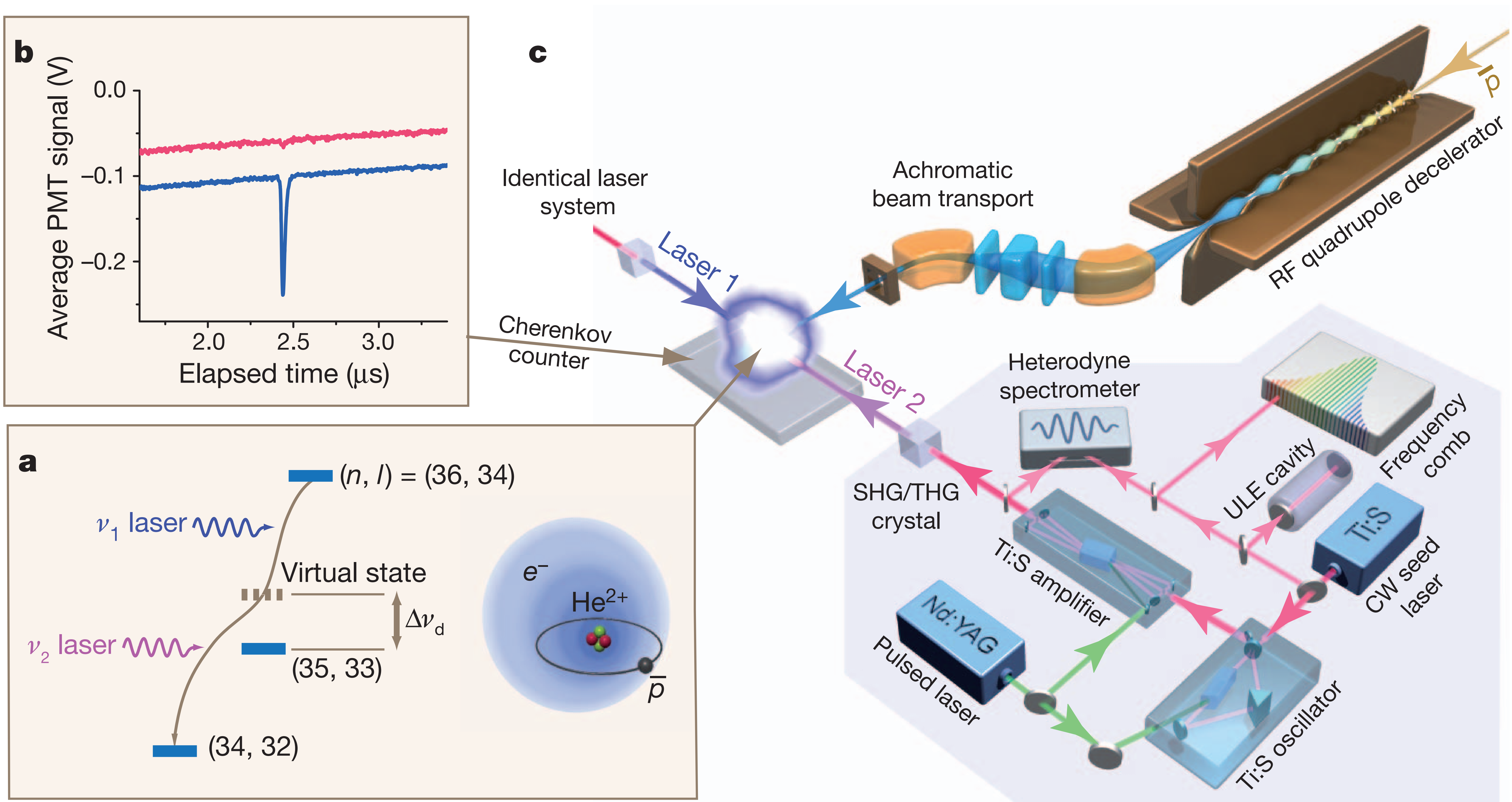
Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio

Masaki Hori, Anna Sótér, Daniel Barna, Andreas Dax, Ryugo Hayano, Susanne Friedreich, Bertalan Juhász, Thomas Pask, Eberhard Widmann, Dezső Horváth, Luca Venturelli & Nicola Zurlo

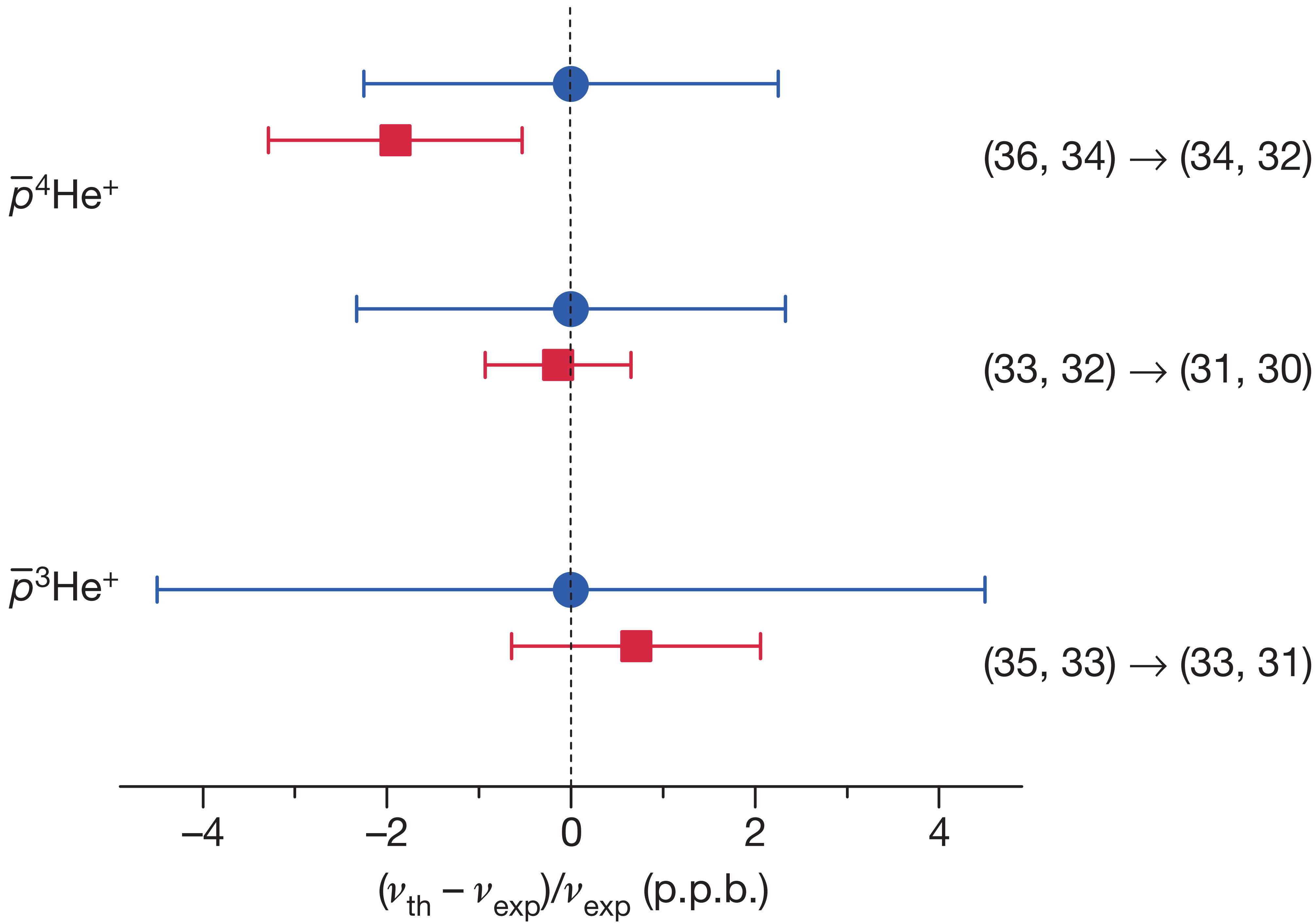
Nature **475**, 484–488 (28 July 2011) doi:10.1038/nature10260
Received 12 April 2011 Accepted 26 May 2011 Published online 27 July 2011

Physical laws are believed to be invariant under the combined transformations of charge, parity and time reversal (CPT symmetry[1]). This implies that an antimatter particle has exactly the same mass and absolute value of charge as its particle counterpart. Metastable antiprotonic helium ($\bar{p}He^+$) is a three-body atom[2] consisting of a normal helium nucleus, an electron in its ground state and an antiproton ($\bar{p}$) occupying a Rydberg state with high principal and angular momentum quantum numbers, respectively n and l, such that $n \approx l + 1 \approx 38$. These atoms are amenable to precision laser spectroscopy, the results of which can in principle be used to determine the antiproton-to-electron mass ratio and to constrain the equality between the antiproton and proton charges and masses. Here we report two-photon spectroscopy of antiprotonic helium, in which $\bar{p}{}^3He^+$ and $\bar{p}{}^4He^+$ isotopes are irradiated by two counter-propagating laser beams. This excites nonlinear, two-photon transitions of the antiproton of the type $(n, l) \rightarrow (n-2, l-2)$ at deep-ultraviolet wavelengths (λ = 139.8, 193.0 and 197.0 nm), which partly cancel the Doppler broadening of the laser resonance caused by the thermal motion of the atoms. The resulting narrow spectral lines allowed us to measure three transition frequencies with fractional precisions of 2.3–5 parts in 10^9. By comparing the results with three-body quantum electrodynamics calculations, we derived an antiproton-to-electron mass ratio of 1,836.1526736(23), where the parenthetical error represents one standard deviation. This agrees with the proton-to-electron value known to a similar precision.

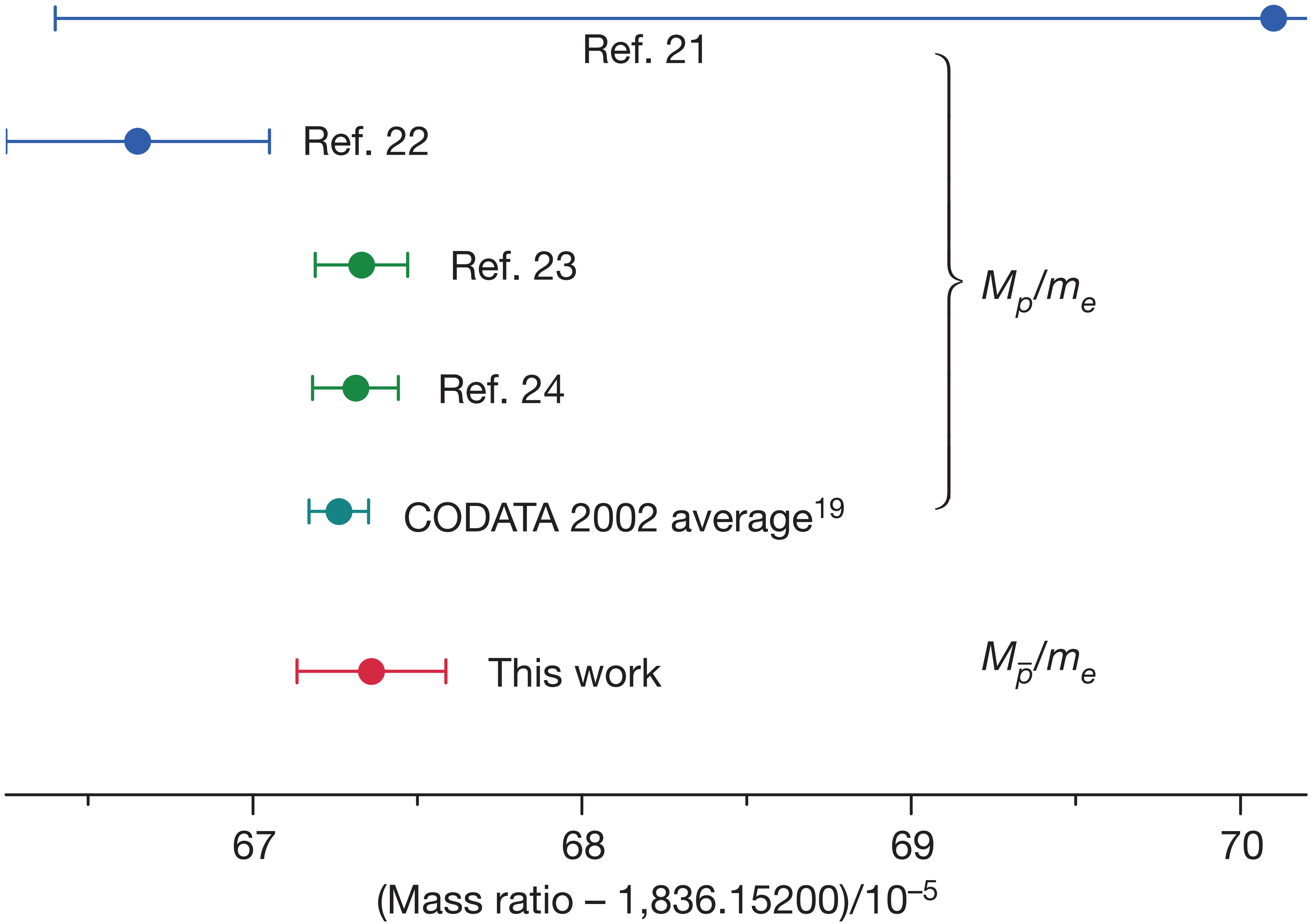
$\bar{p}$He 2-photon spectroscopy



Theory vs Exp



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

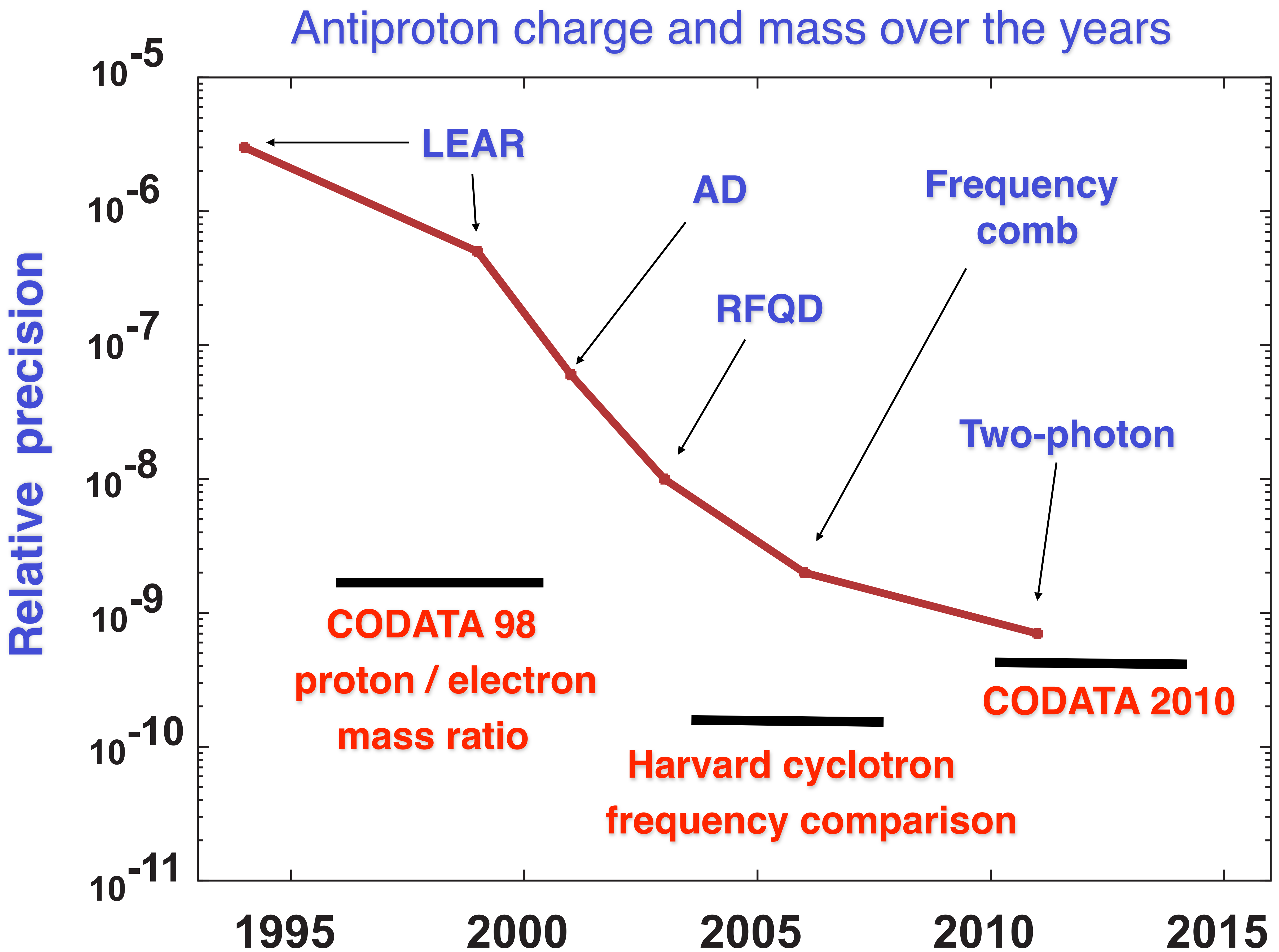


$\bar{p}$He spectroscopy: errors

Table 2 | Errors for transition (*n*, *l*) = (36, 34) → (34, 32) of $\bar{p}^4He^+$

Datum	Error (MHz)
Experimental errors	
Statistical error, σ_{stat}	3
Collisional shift error	1
A.c. Stark shift error	0.5
Zeeman shift	<0.5
Frequency chirp error	0.8
Seed laser frequency calibration	<0.1
Hyperfine structure	<0.5
Line profile simulation	1
Total systematic error, σ_{sys}	1.8
Total experimental error, σ_{exp}	3.5
Theoretical uncertainties	
Uncertainties from uncalculated QED terms*	2.1
Numerical uncertainty in calculation*	0.3
Mass uncertainties*	<0.1
Charge radii uncertainties*	<0.1
Total theoretical uncertainty*, σ_{th}	2.1

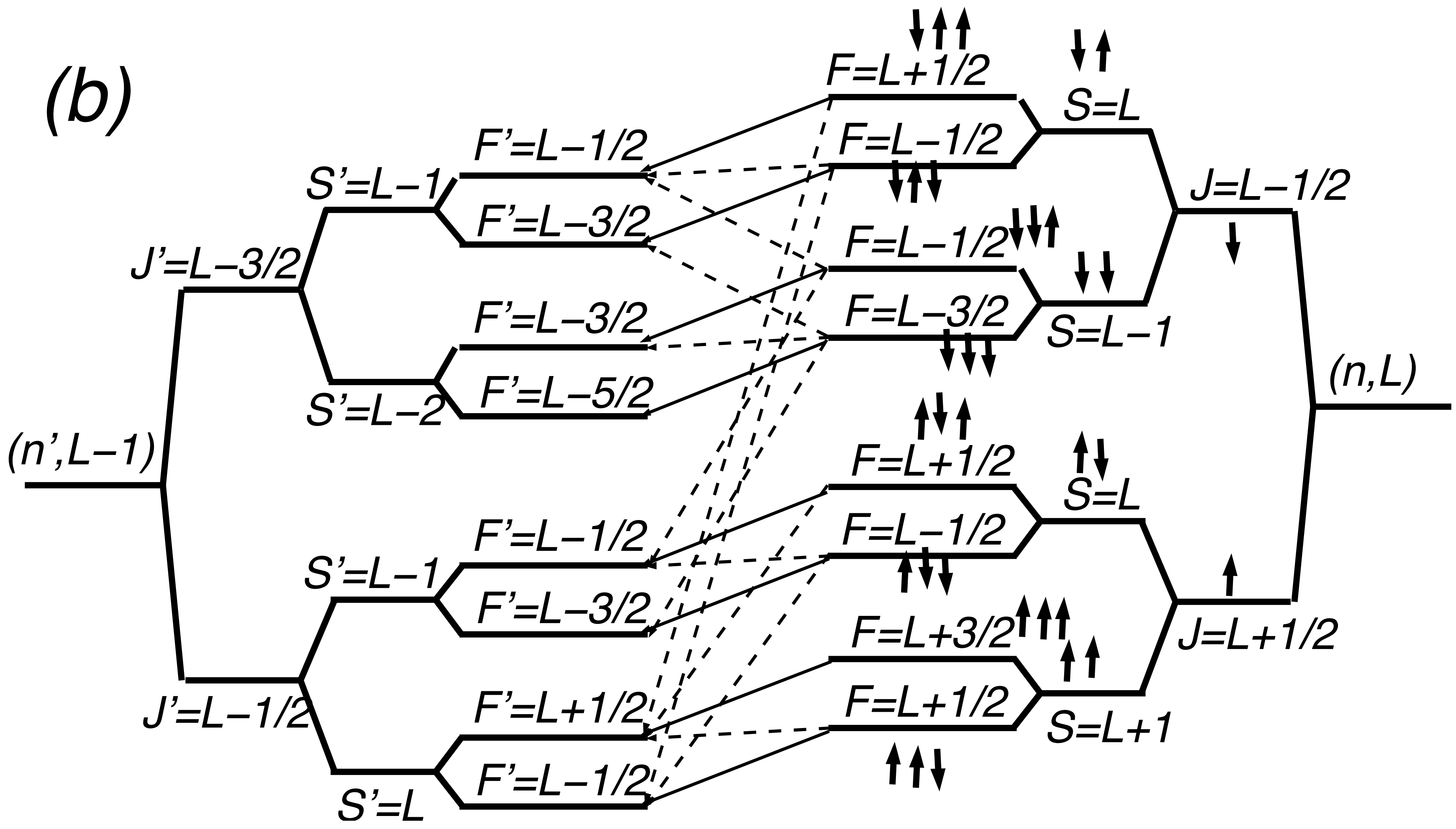
Experimental errors and theoretical uncertainties are 1 s.d.
* Ref. 3 and V. I. Korobov, personal communication.


Antiproton charge and mass over the years
Relative precision
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
1995
2000
2005
2010
2015
LEAR
AD
RFQD
Frequency comb
Two-photon
CODATA 98
proton / electron
mass ratio
Harvard cyclotron
frequency comparison
CODATA 2010

超微細構造

Hyperfine

$\bar{p}$He hyperfine



$\bar{p}\,{}^4He^+$

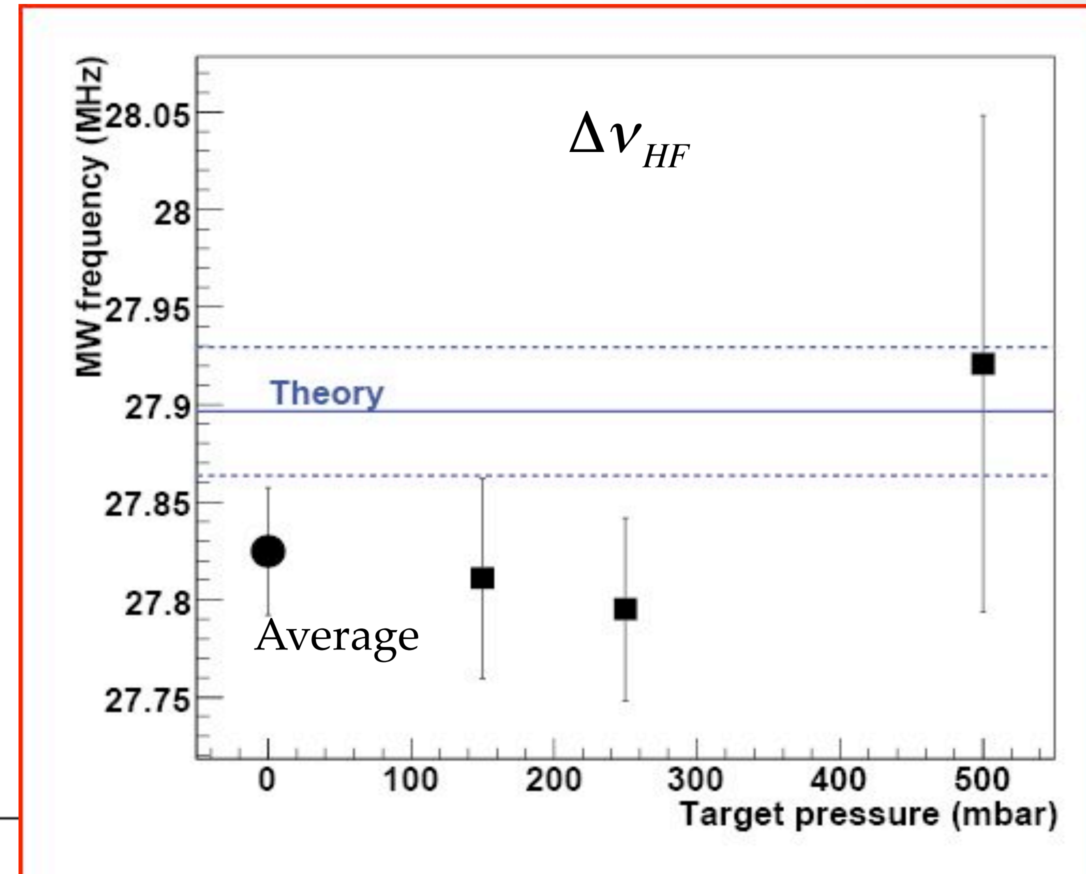
New Value for the $\bar{p}$ Magnetic Moment

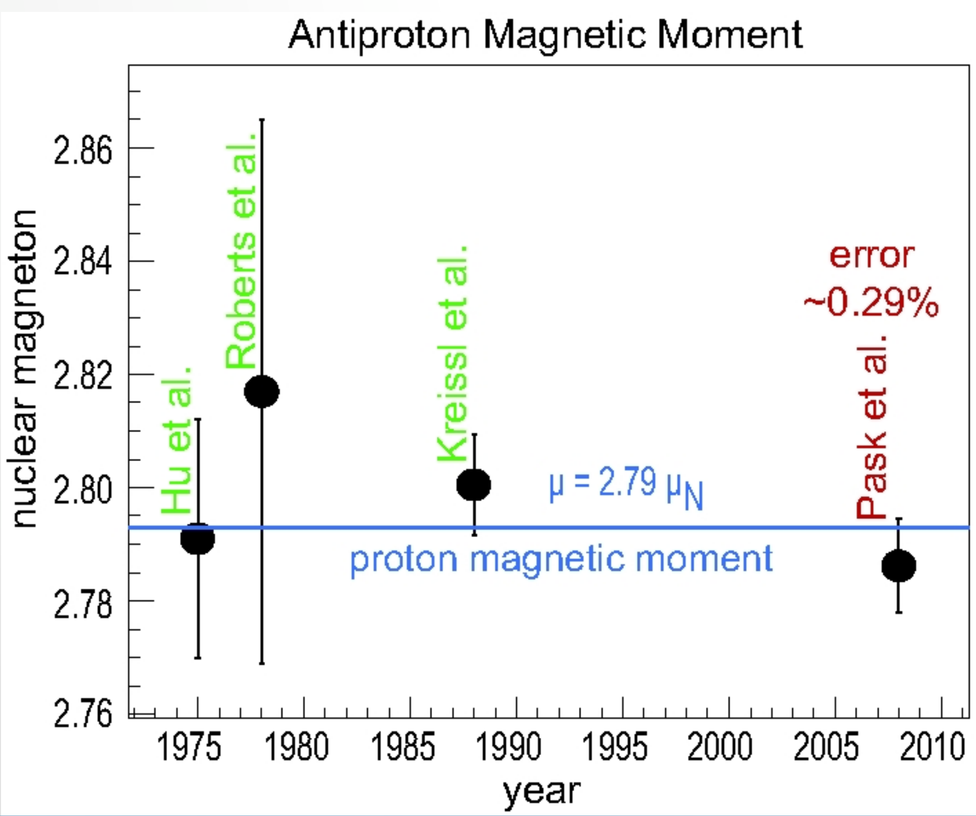
$\bar{p}$ MAGNETIC MOMENT References History since 1950

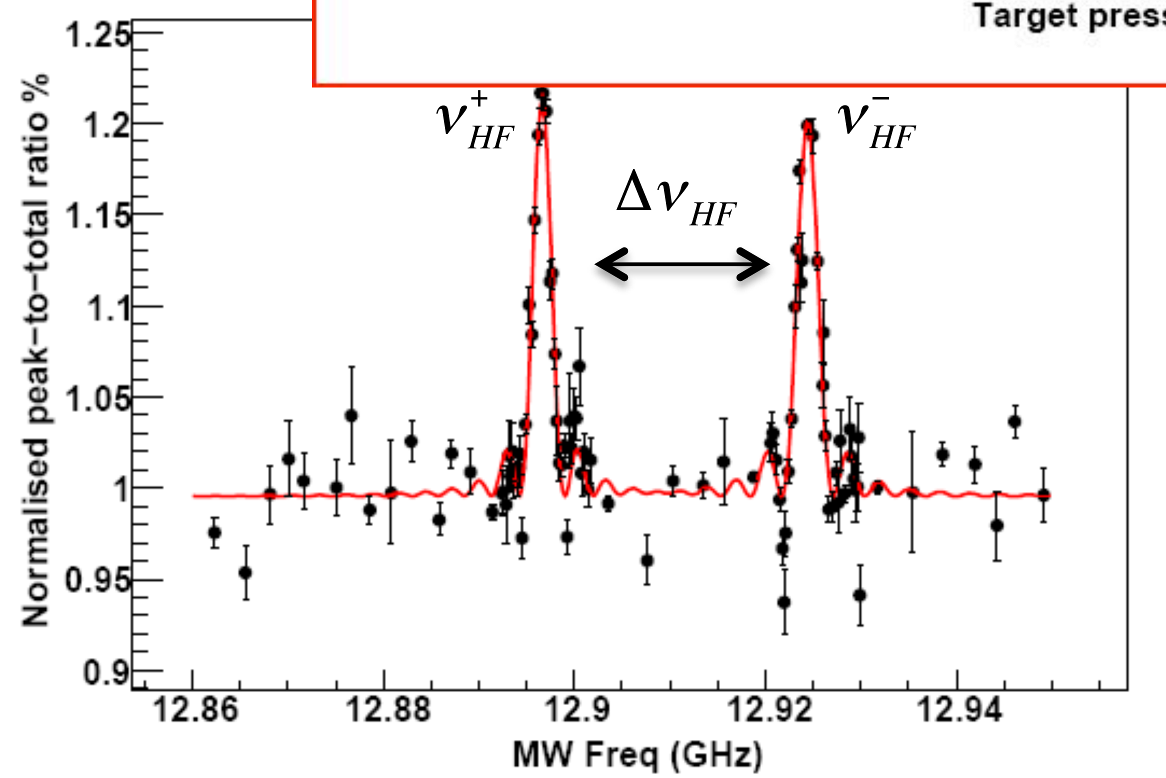
A few early results have been omitted.

VALUE (μ_N)	DOCUMENT ID		TECN	COMMENT
−2.793±0.006	OUR AVERAGE			
−2.7862±0.0083	PASK	09	CNTR	$\bar{p}\,He^+$ hyperfine structure
−2.8005±0.0090	KREISSL	88	CNTR	$\bar{p}\,{}^{208}Pb$ 11→10 X-ray
−2.817±0.048	ROBERTS	78	CNTR	
−2.791±0.021	HU	75	CNTR	Exotic atoms

<ins>**Published in Physics Letters B in 2009:**</ins>
T. Pask, D. Barna, A. Dax, R. S. Hayano, M. Hori, D. Horvath, S. Friedreich, B. Juhasz, O. Massiczek, N. Ono, A. Soter, E. Widmann, Antiproton magnetic moment determined from the HFS of $\bar{p}He^+$, Phys. Lett. B 678, Issue 1, 6, 2009







結

summary

20 years of $\bar{p}He$

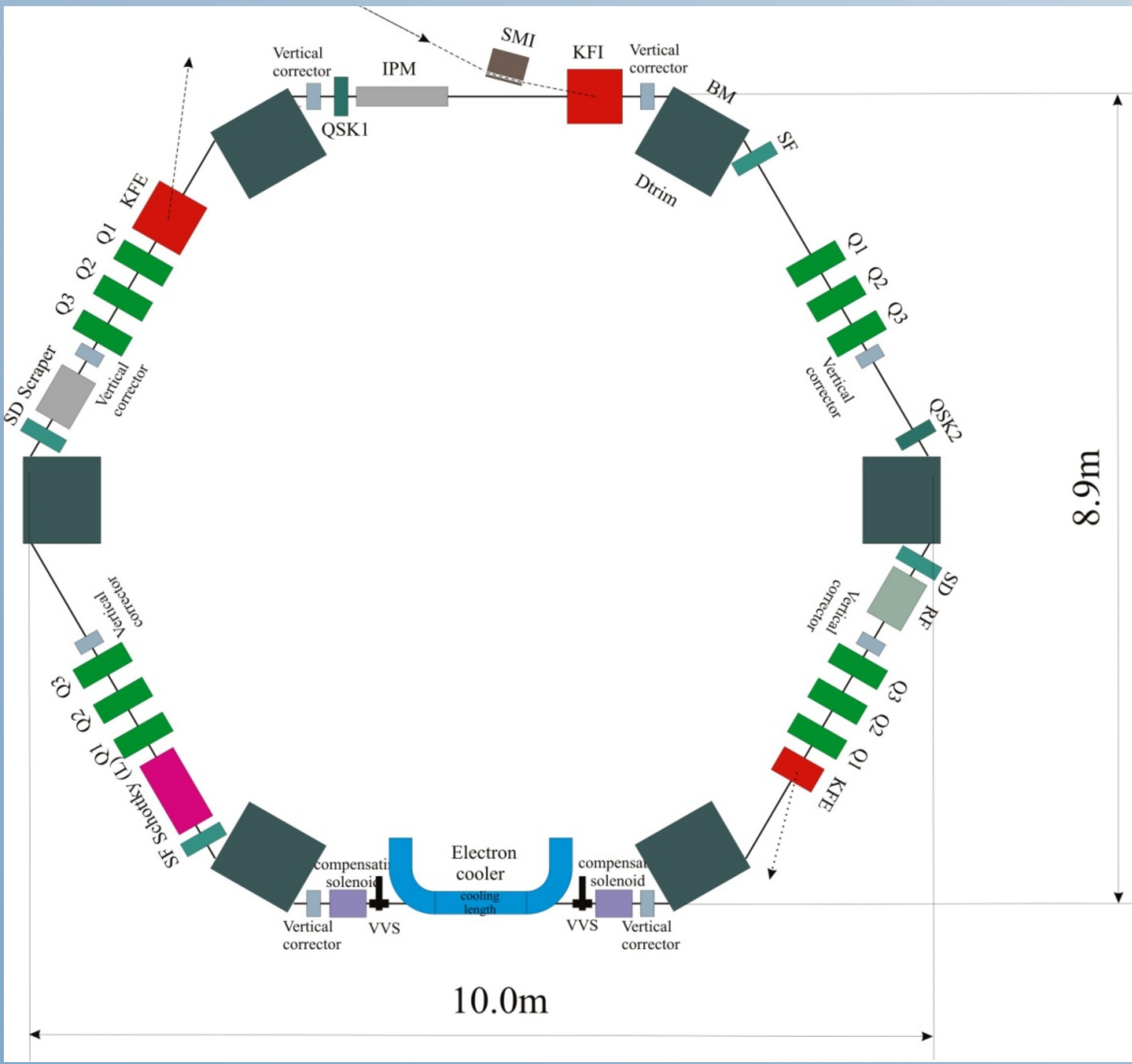
Serendipitous discovery

Precision now at $\sim 10^{-9}$ (RFQ, Comb, 2-photon, ...)

Contribute to fundamental constant (m_p/m_e)

Further improvements possible (takes exp/theory efforts), esp. with the ELENA

ELENA



Energy range, MeV	5.3 - 0.1
Circumference, m	30.4
Intensity of injected beam	3×10^7
Intensity of ejected beam	2.5×10^7
Number of extracted bunches	4
Emittance at 100 KeV, π.mm.mrad, [95%]	4
Δp/p after cooling, [95%]	10^{-4}
Bunch length at 100 keV, m / ns	1.3/300
Required vacuum, Torr	3×10^{-12}