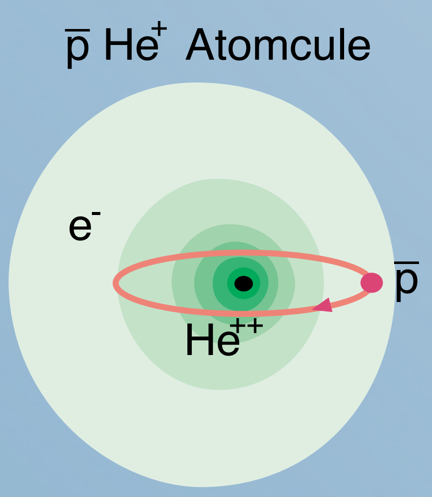
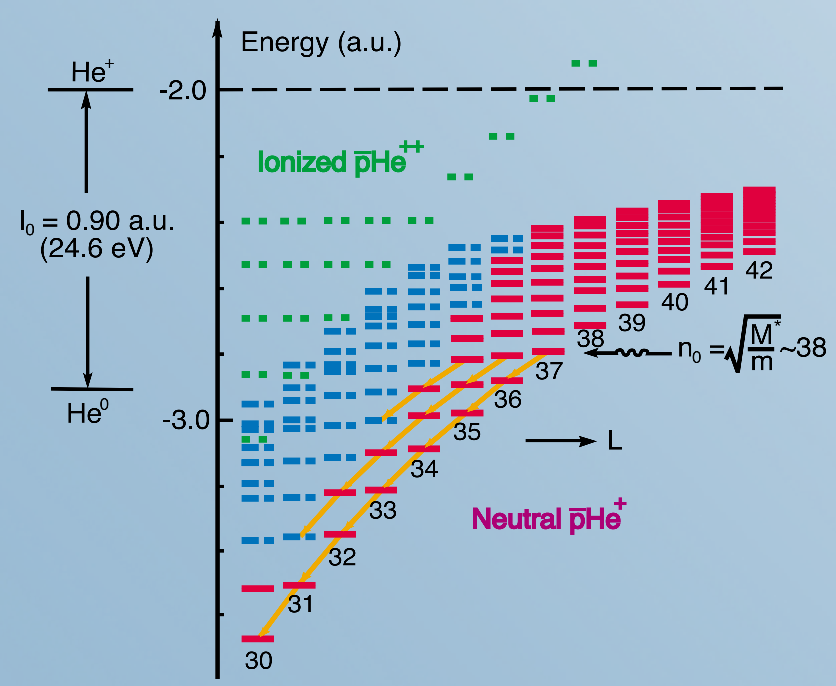
Physics of ASACUSA

the spectroscopy of antiprotonic helium

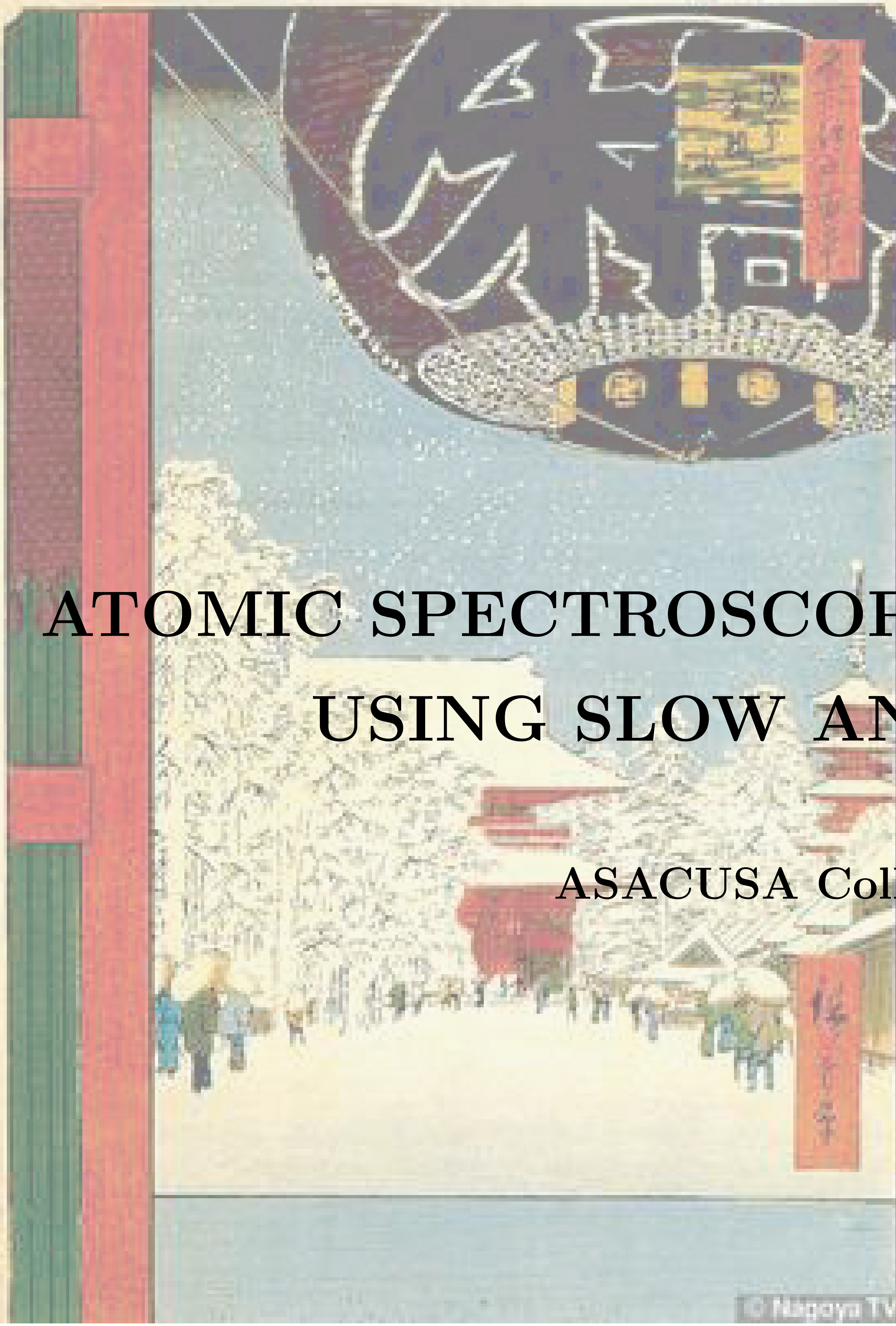




Ryugo S. Hayano

THE UNIVERSITY OF TOKYO

May 8, 2014, QFPP2014

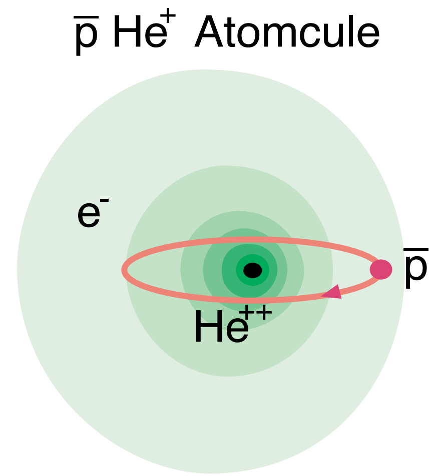


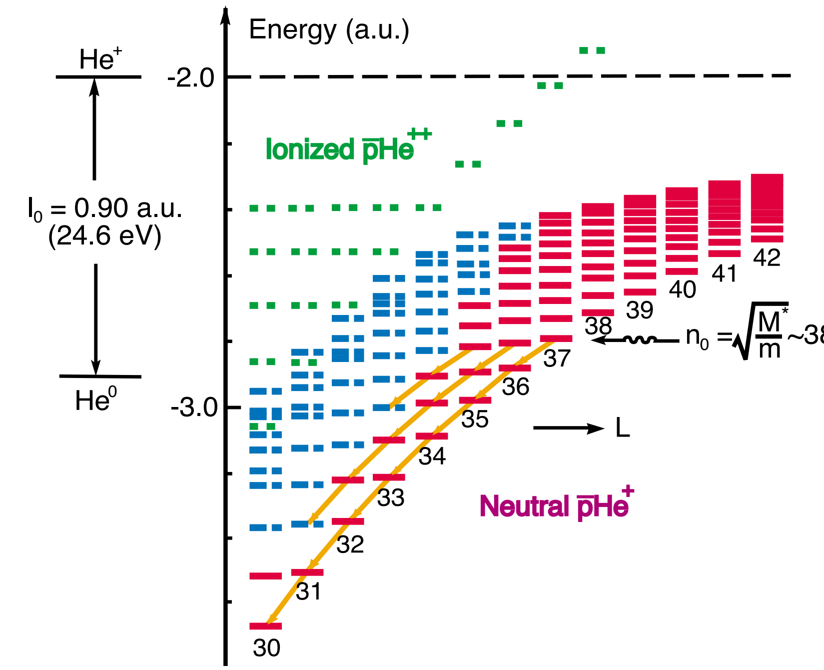
7-Oct-97
CERN/SPSC 97-19
CERN/SPSC P-307

ATOMIC SPECTROSCOPY AND COLLISIONS USING SLOW ANTIPROTONS

ASACUSA Collaboration

$\bar{p}$He spectroscopy: outline





What is it?

What is it good for?

Laser spectroscopy principles

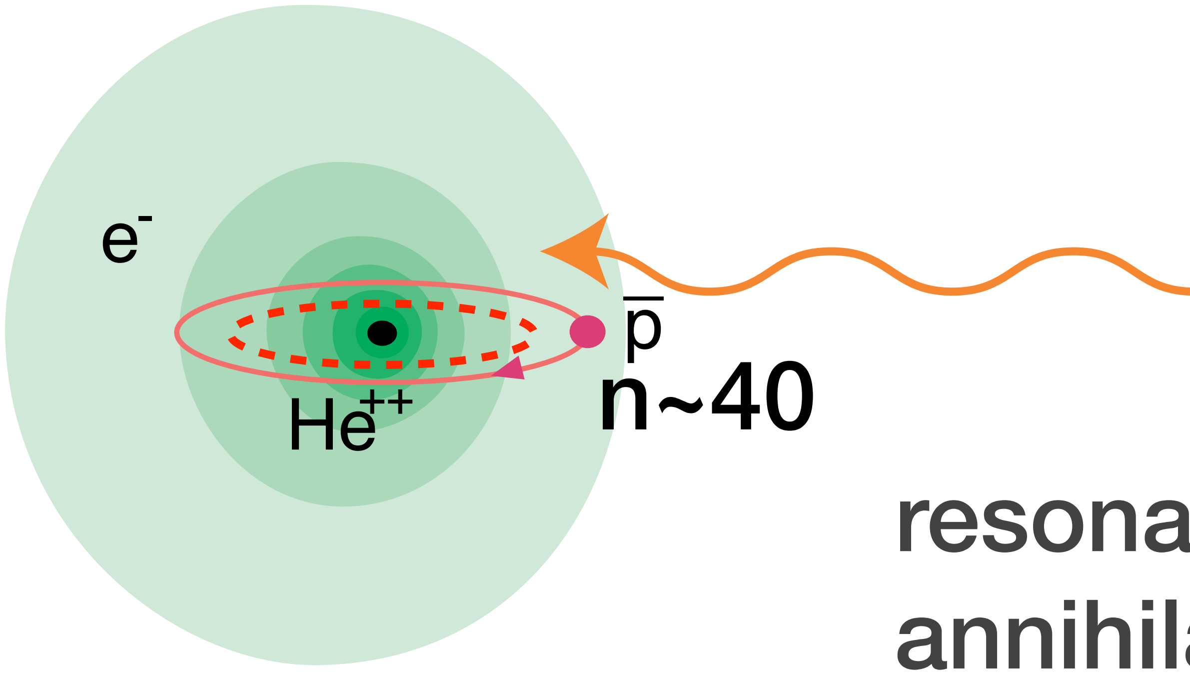
Theory

How to reach high precision?

Present status

What to expect with ELENA?

$\bar{p}$He spectroscopy → $m_{\bar{p}}/m_e$



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

resonance detection via $\bar{p}$ annihilation

Frequency

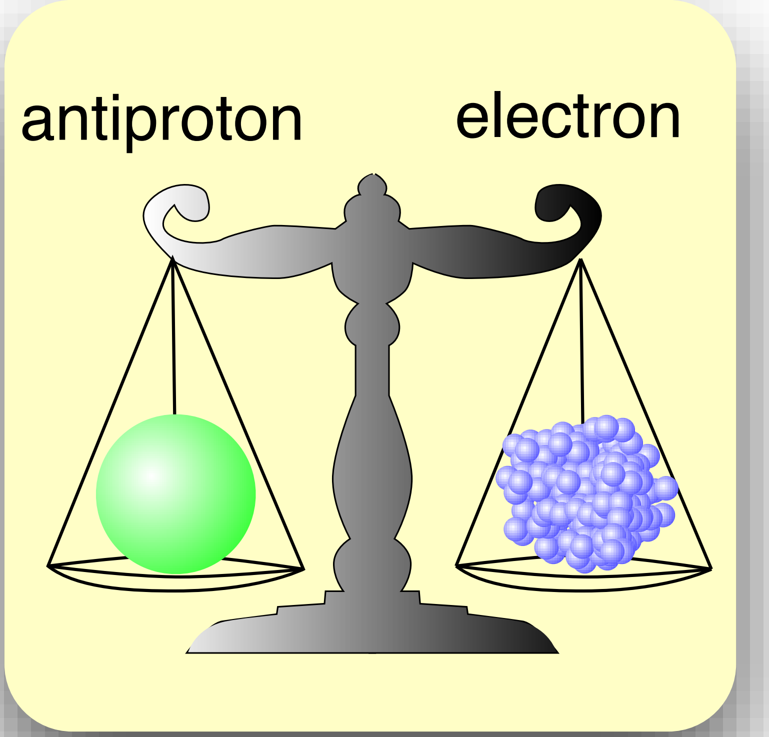
$$\nu_{n,\ell \to n',\ell'} = Rc \frac{m^*_{\bar{p}}}{m_e} Z^2_{\text{eff}} \left(\frac{1}{n'^2} - \frac{1}{n^2} \right) + QED$$

$\bar{p}$ - e mass ratio

Theory

Korobov

p̄He can contribute to



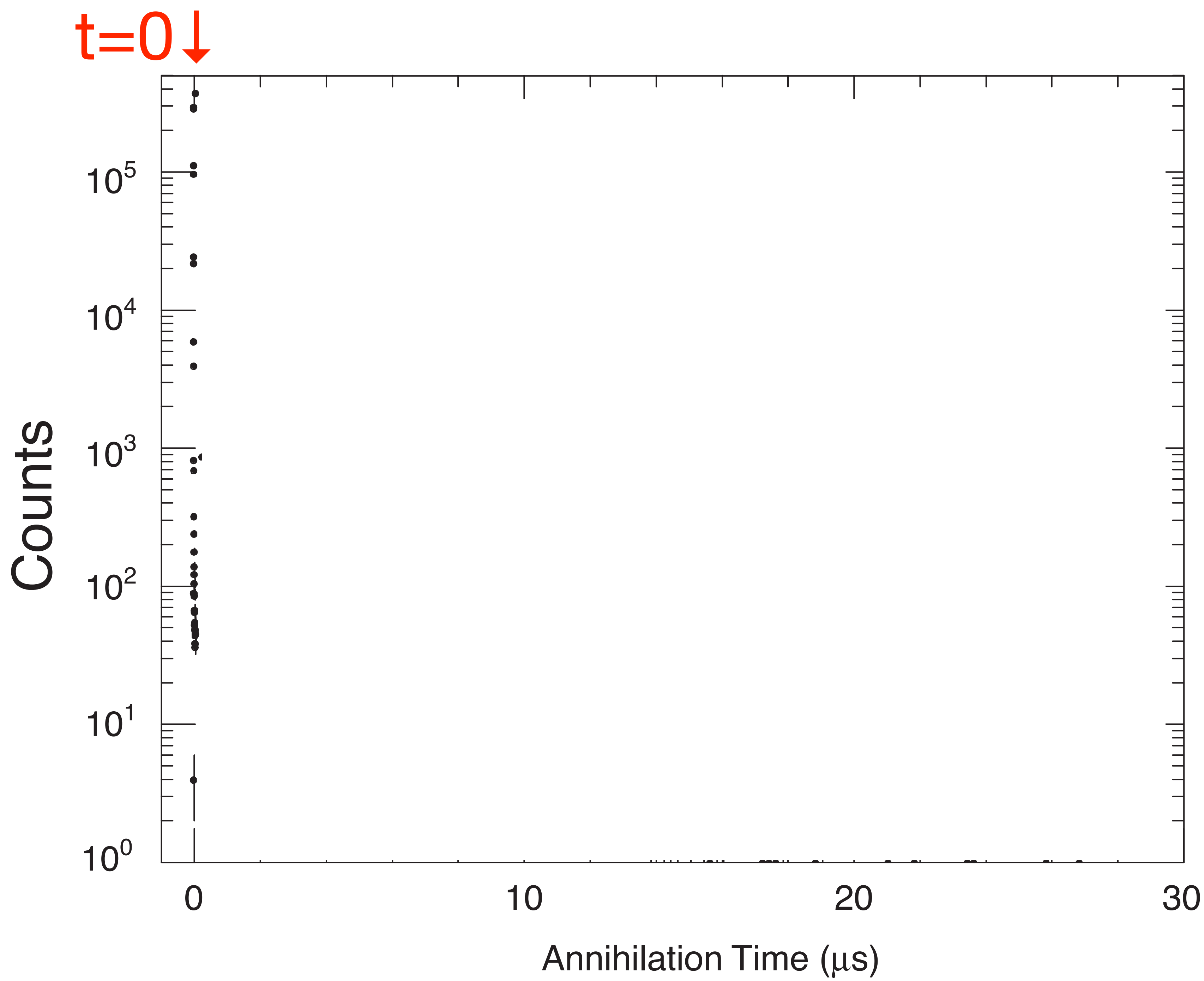
↓ CPT test

↓ CPT theorem

↓

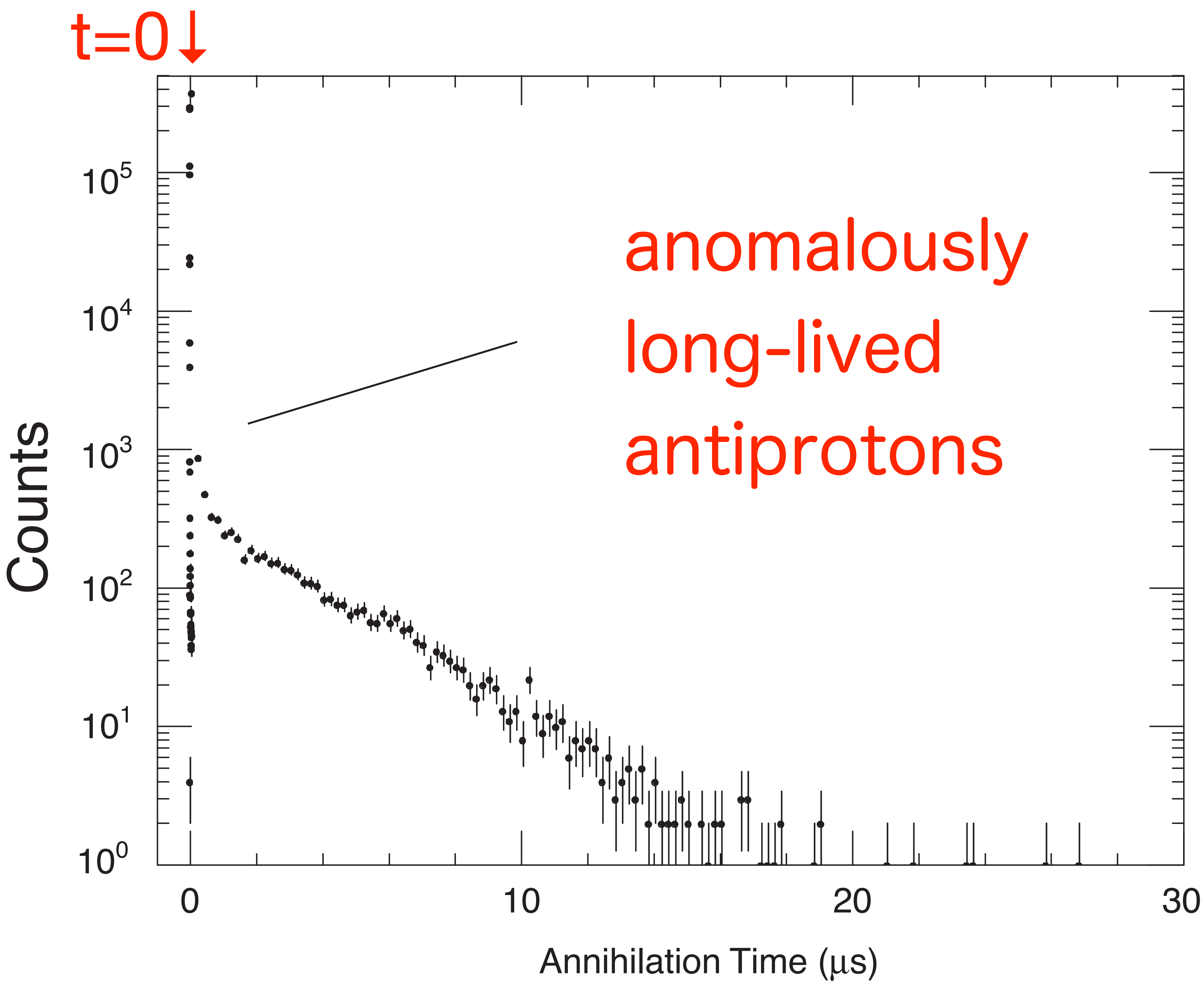
proton-electron mass ratio
(CODATA)

discovery of p̄ longevity in helium (at KEK)



Iwasaki et al., PRL 67 (1991) 1246

discovery of p̄ longevity in helium (at KEK)



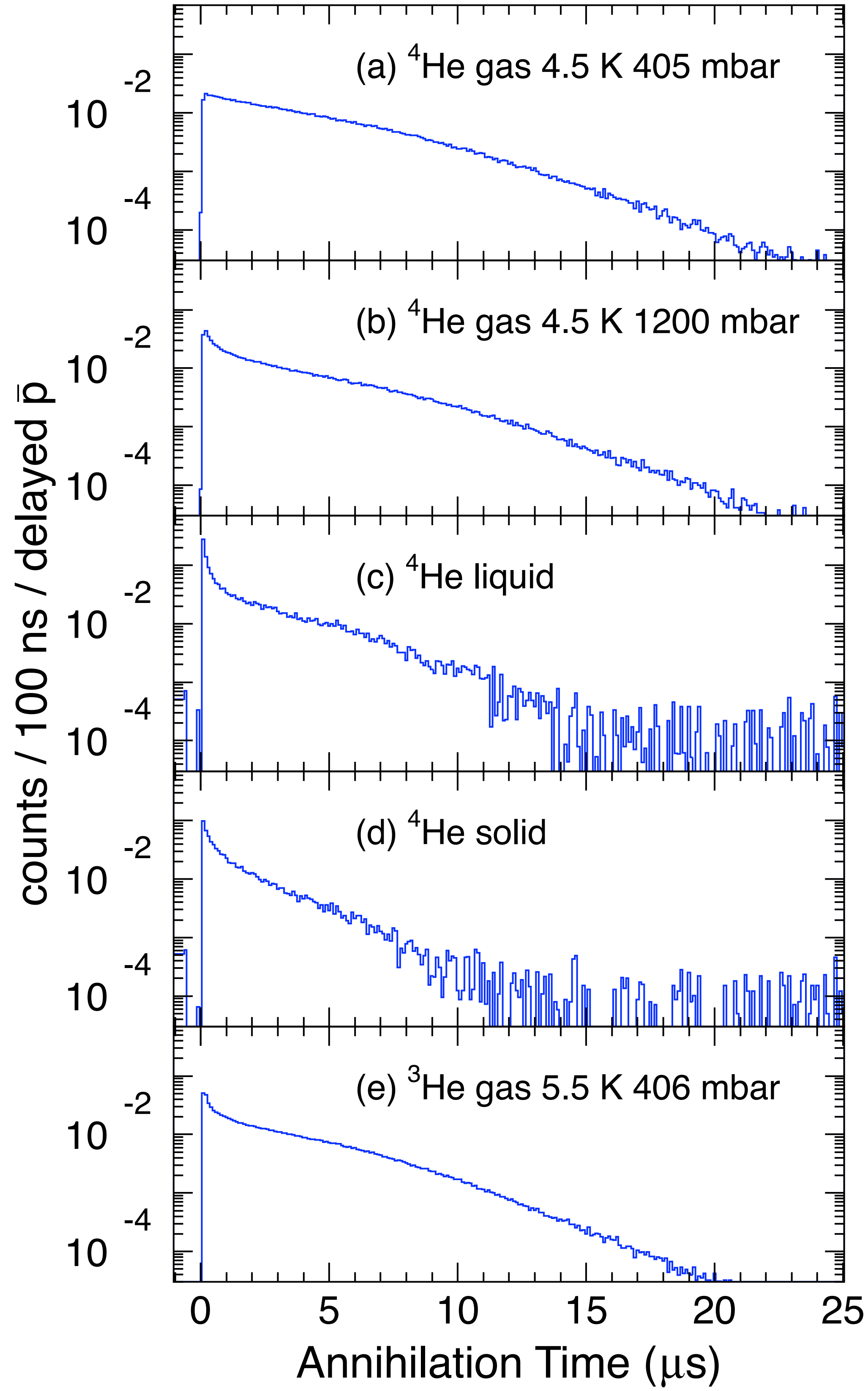
Iwasaki et al., PRL 67 (1991) 1246

p̄He formation probability & lifetime

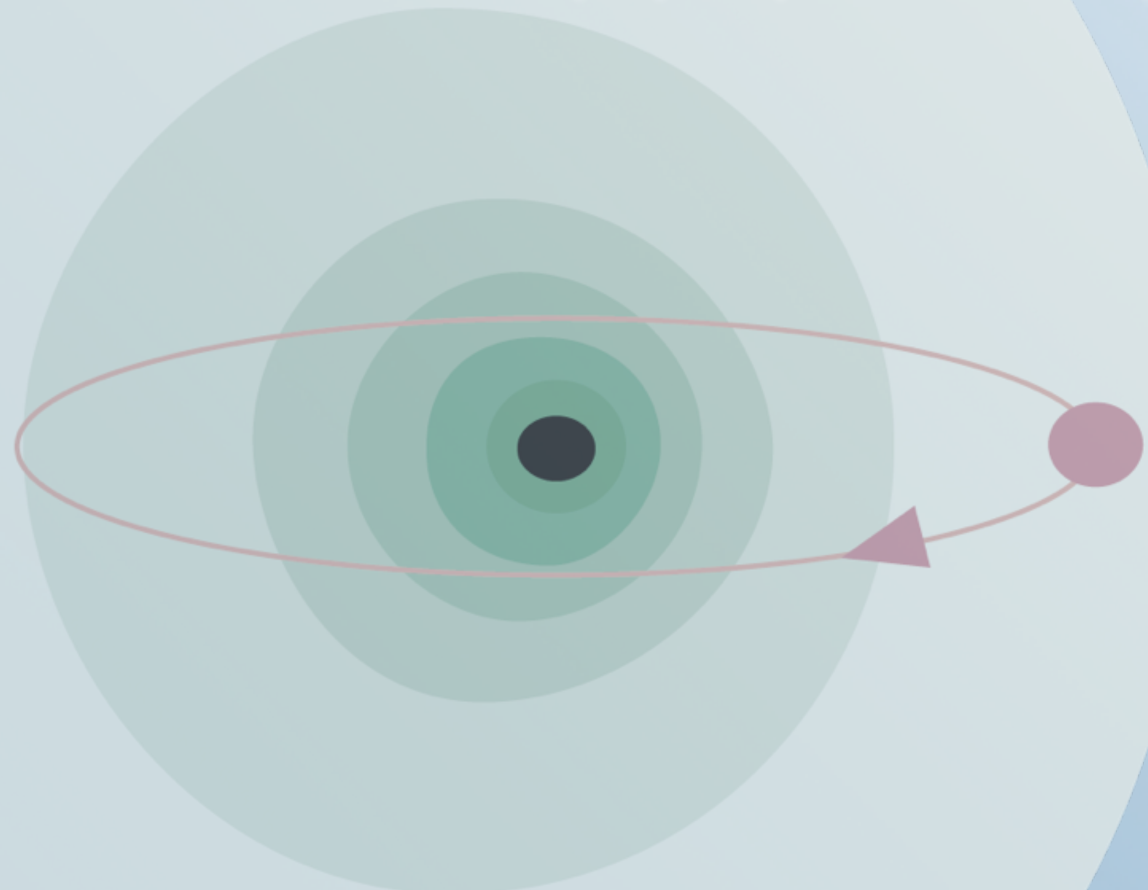
At LEAR -

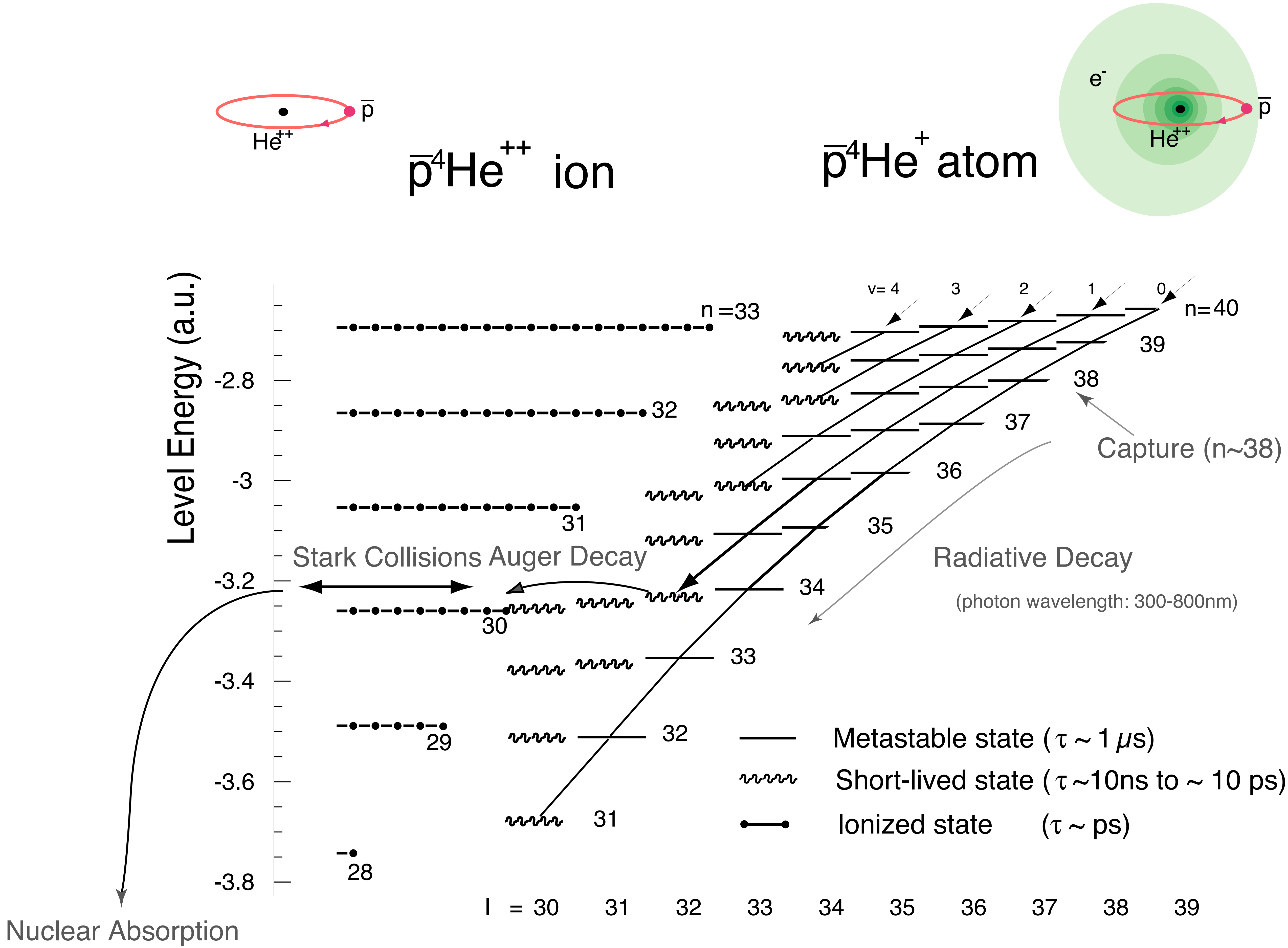
Established p̄ longevity in gas, liquid, solid helium-3 & helium-4

Lifetime 3~4μs, formation probability ~3%

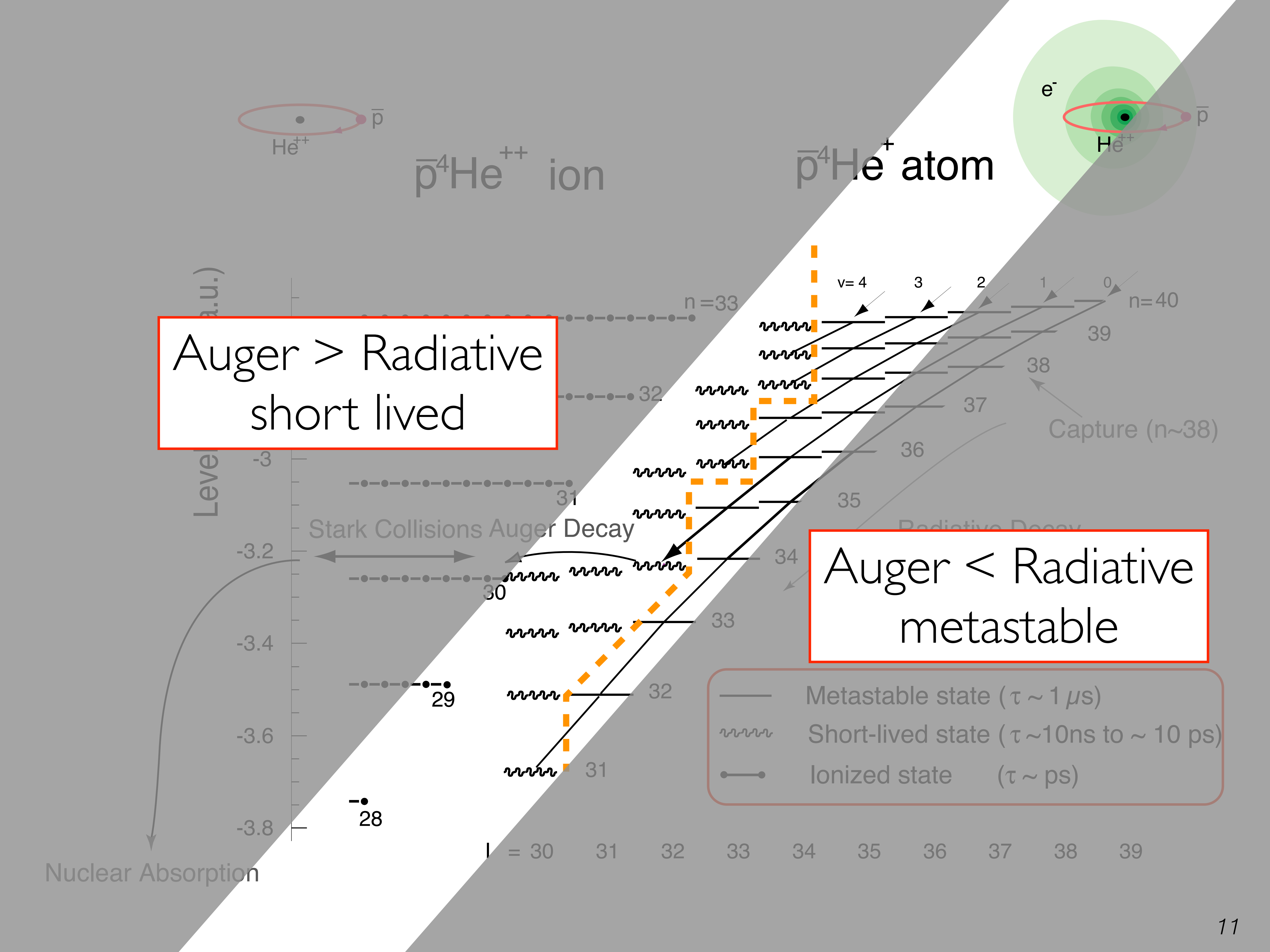


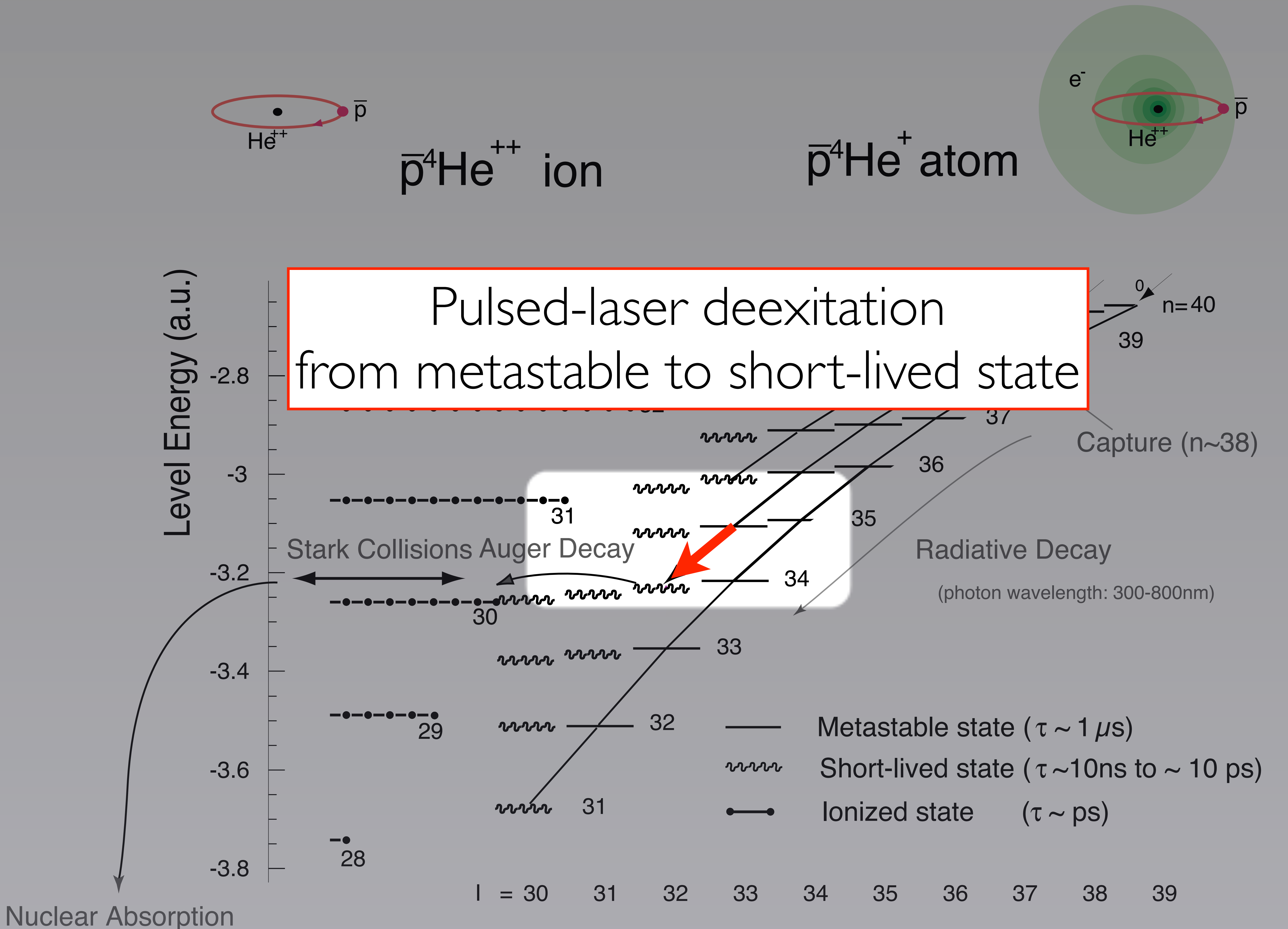
Laser spectroscopy principles



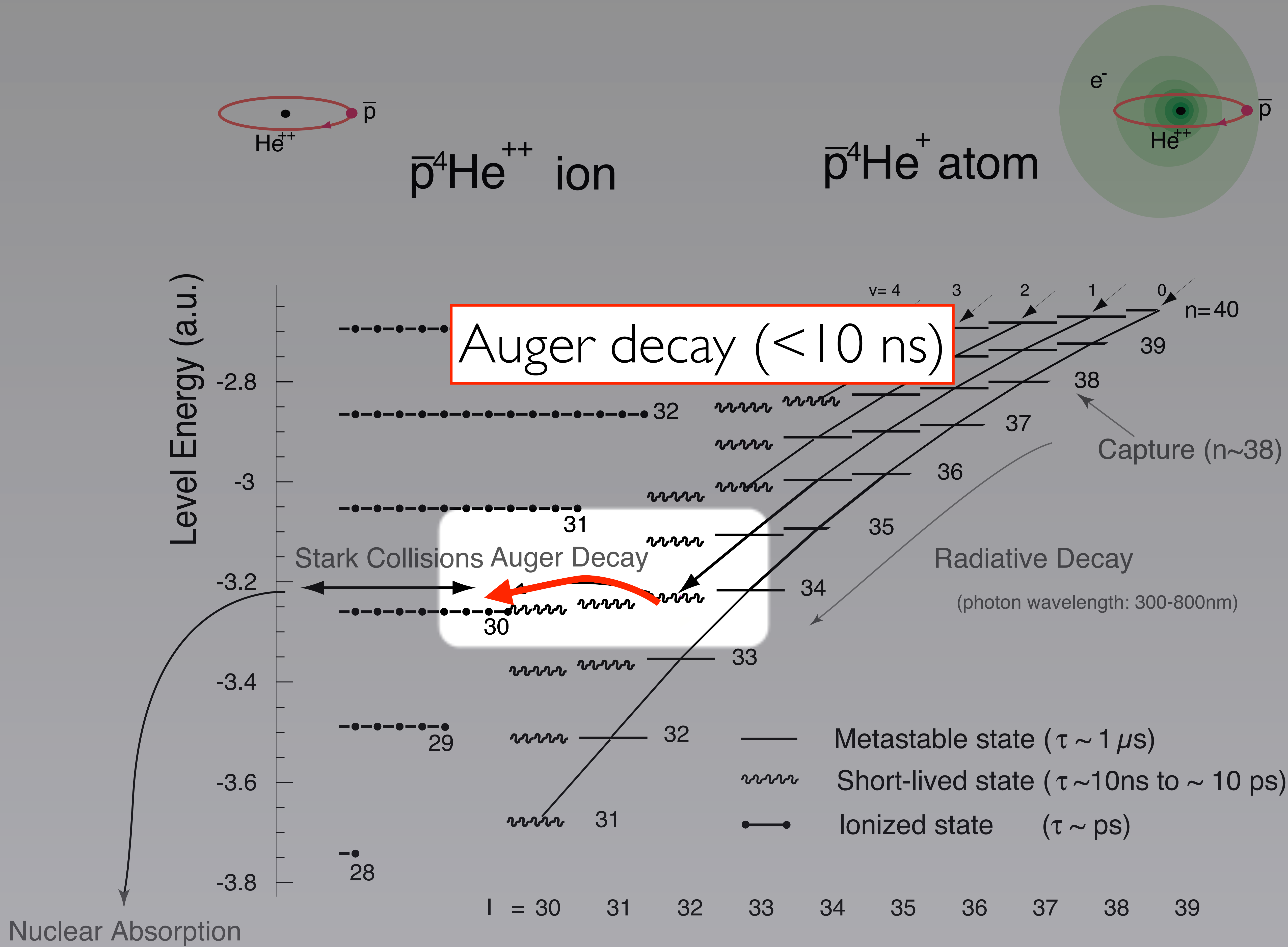


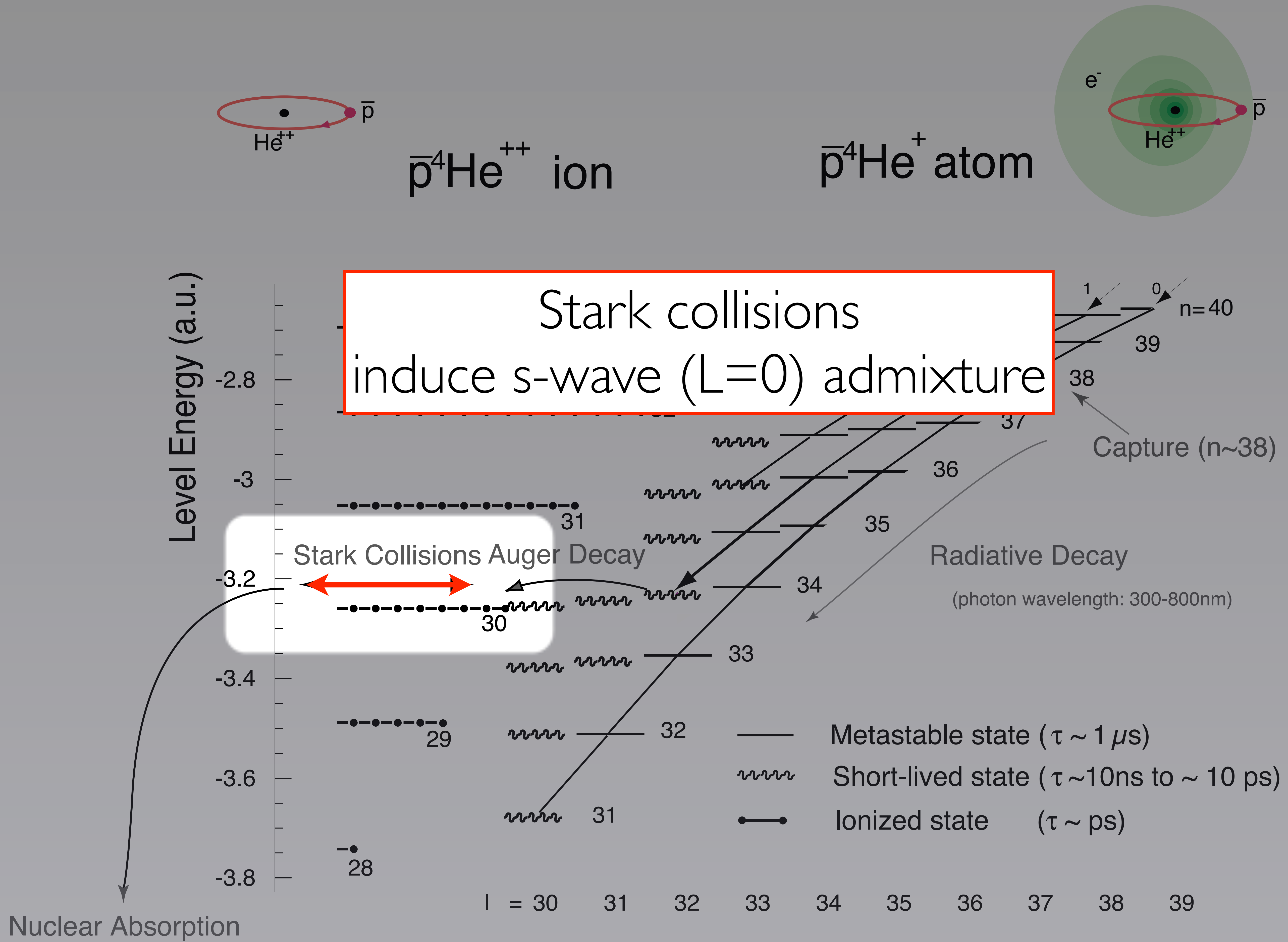
He++
p̄
$\bar{p}^4He^{++}$ ion
$\bar{p}^4He^{+}$ atom
e-
He++
p̄
Level Energy (a.u.)
-2.8
-3
-3.2
-3.4
-3.6
-3.8
n =33
32
31
30
29
28
v= 4
3
2
1
0
n= 40
39
38
37
36
35
34
33
32
31
Capture (n~38)
Stark Collisions Auger Decay
Radiative Decay
(photon wavelength: 300-800nm)
Nuclear Absorption
Metastable 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


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

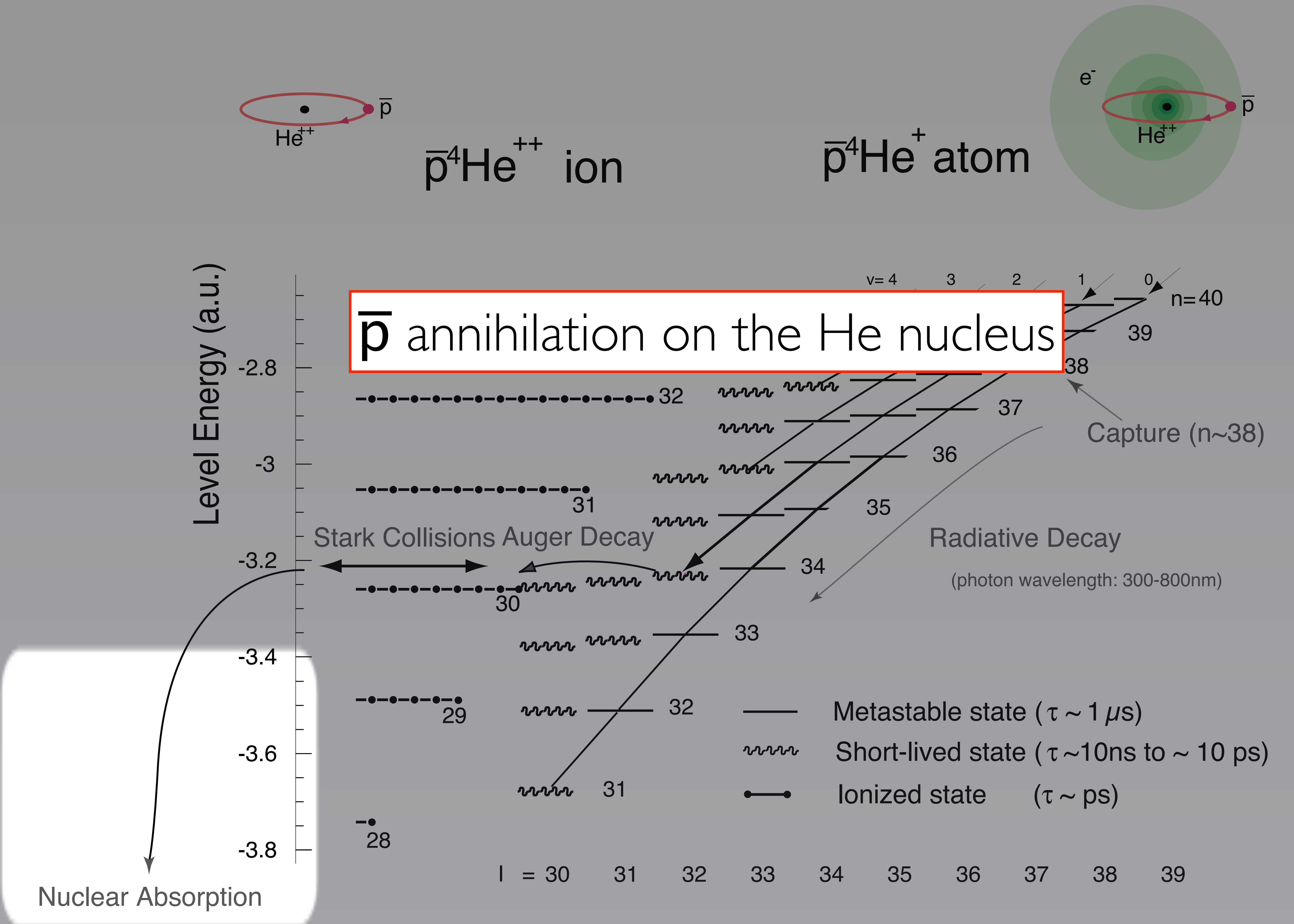


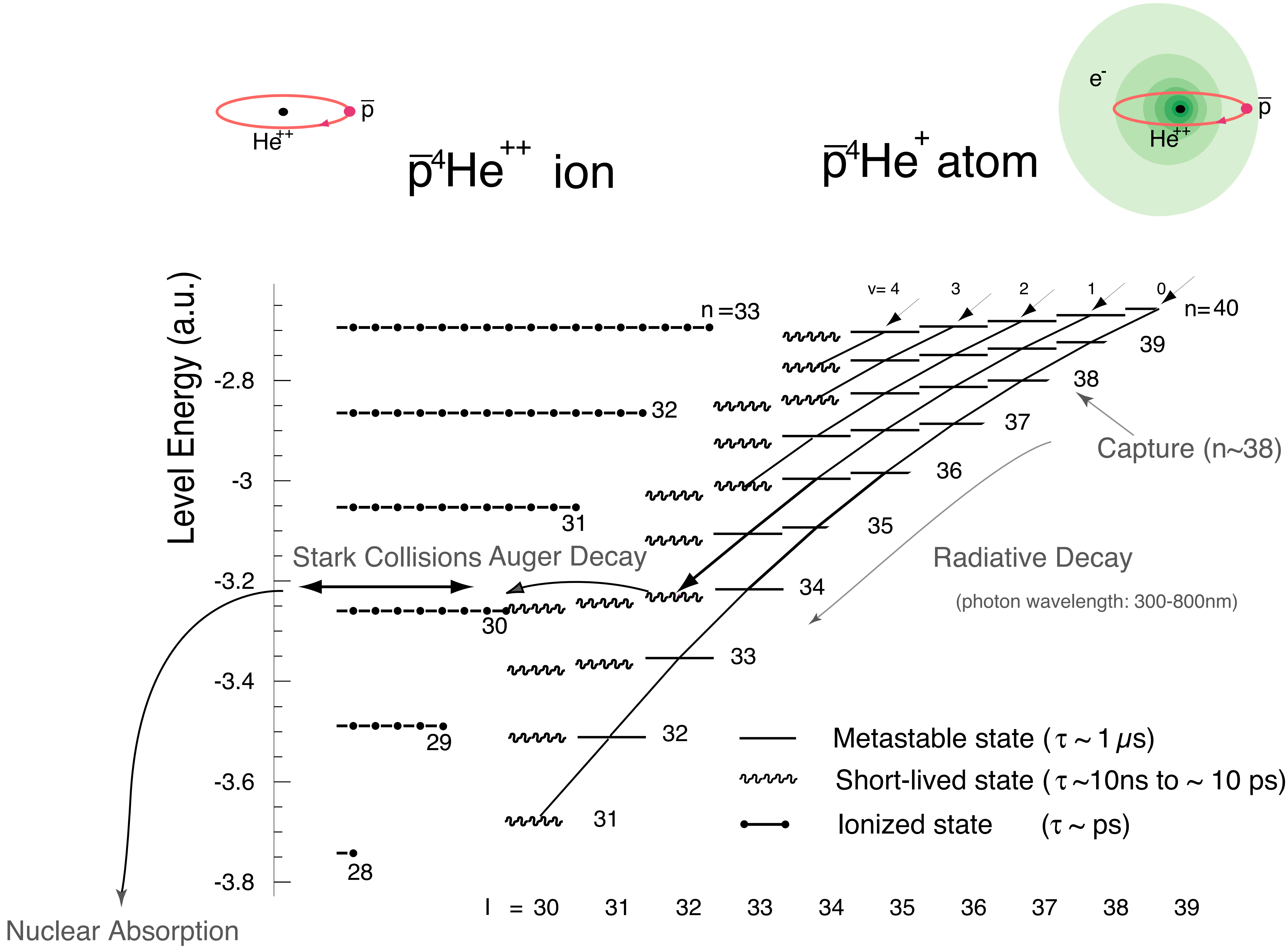
p̄
He++
p̄4He++ ion
p̄4He+ atom
e-
p̄
He++
Pulsed-laser deexitation
from metastable to short-lived state
Level Energy (a.u.)
-2.8
-3
-3.2
-3.4
-3.6
-3.8
n=40
39
37
36
35
34
33
32
31
31
30
29
28
Capture (n~38)
Stark Collisions Auger Decay
Radiative Decay
(photon wavelength: 300-800nm)
Nuclear Absorption
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


p̄⁴He⁺⁺ ion
p̄⁴He⁺ atom
He⁺⁺
p̄
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
Auger decay (<10 ns)
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


p̄
He++
p̄4He++ ion
p̄4He+ atom
e-
p̄
He++
Stark collisions
induce s-wave (L=0) admixture
Level Energy (a.u.)
-2.8
-3
-3.2
-3.4
-3.6
-3.8
1
0
n=40
39
38
37
36
35
34
33
32
31
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

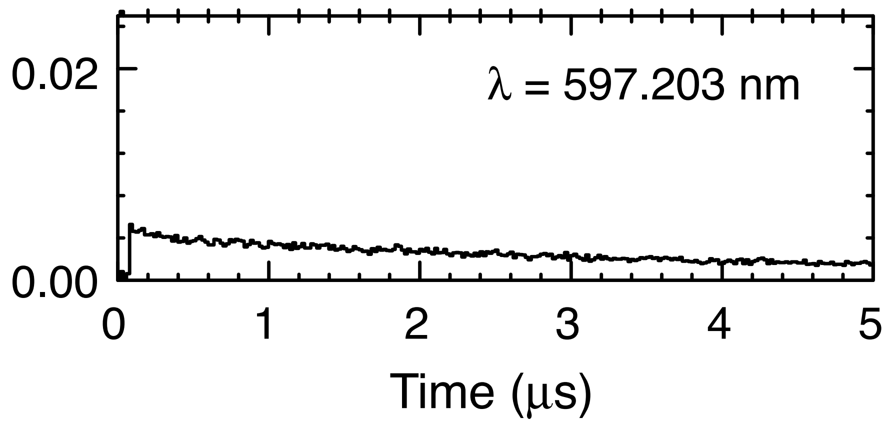
$\bar{p}$ annihilation on the He nucleus



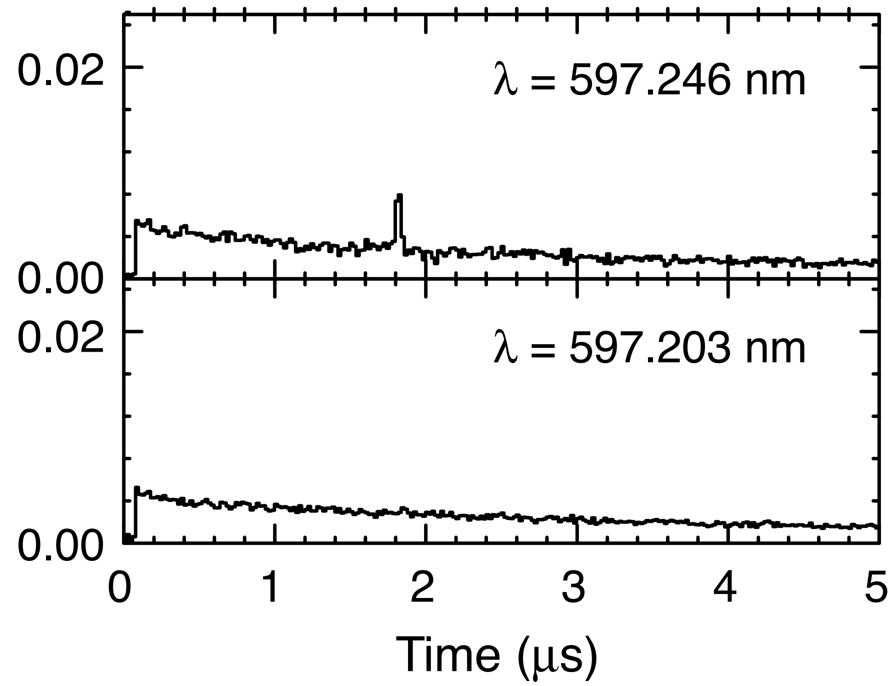


p̄
He++
p̄4He++ ion
p̄4He+ atom
e-
p̄
He++
Level Energy (a.u.)
-2.8
-3
-3.2
-3.4
-3.6
-3.8
v= 4
3
2
1
0
n=40
n =33
32
31
30
29
28
39
38
37
36
35
34
33
32
31
Capture (n~38)
Stark Collisions Auger Decay
Radiative Decay
(photon wavelength: 300-800nm)
Metastable state (τ ~ 1 μs)
Short-lived state (τ ~10ns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

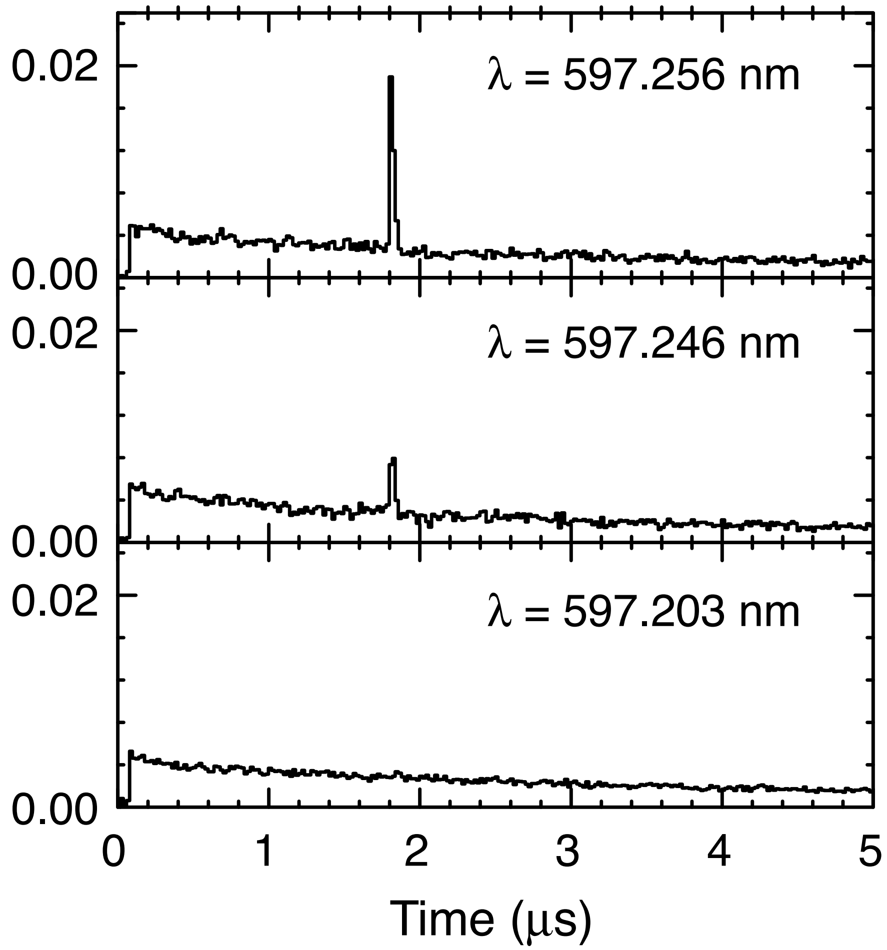
An example, (n,l)=(39,35)→(38,34)



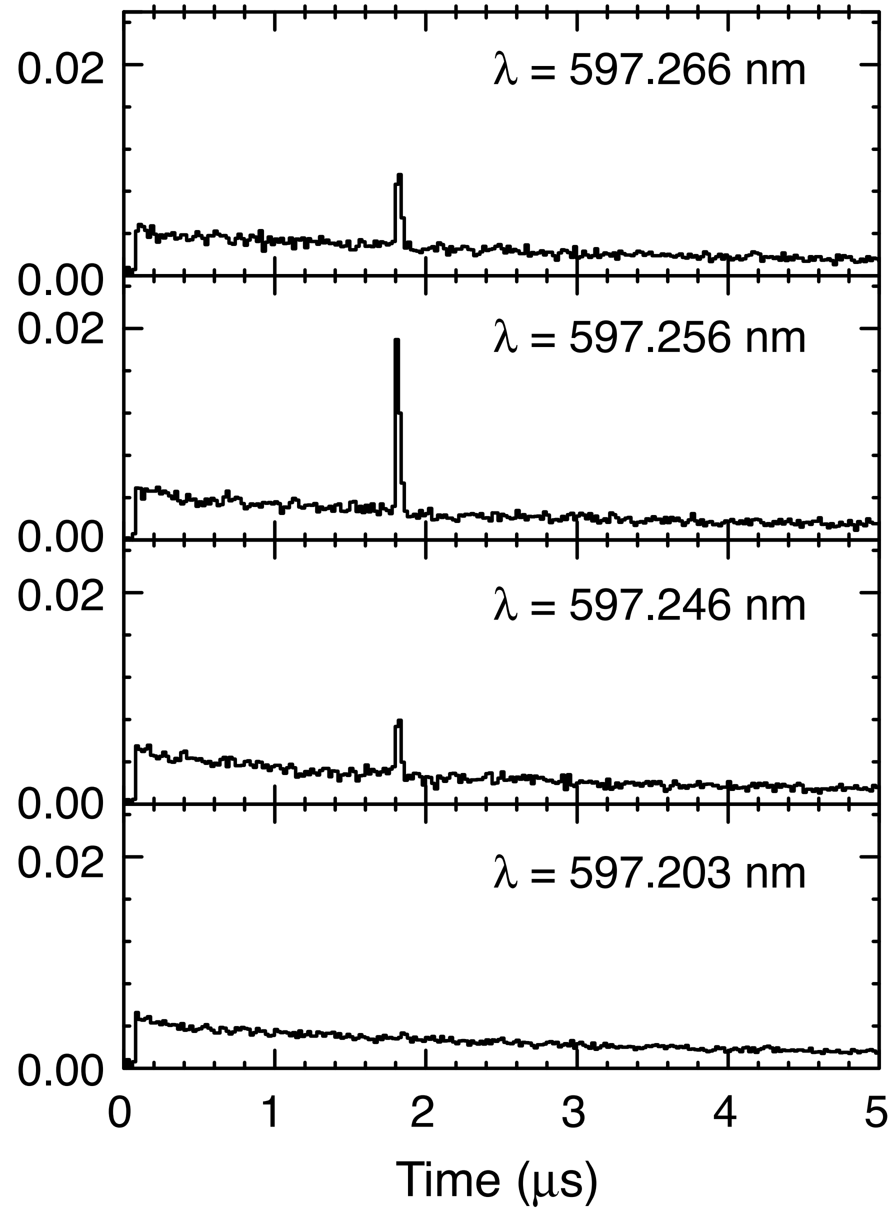
An example, (n,l)=(39,35)→(38,34)



An example, (n,l)=(39,35)→(38,34)

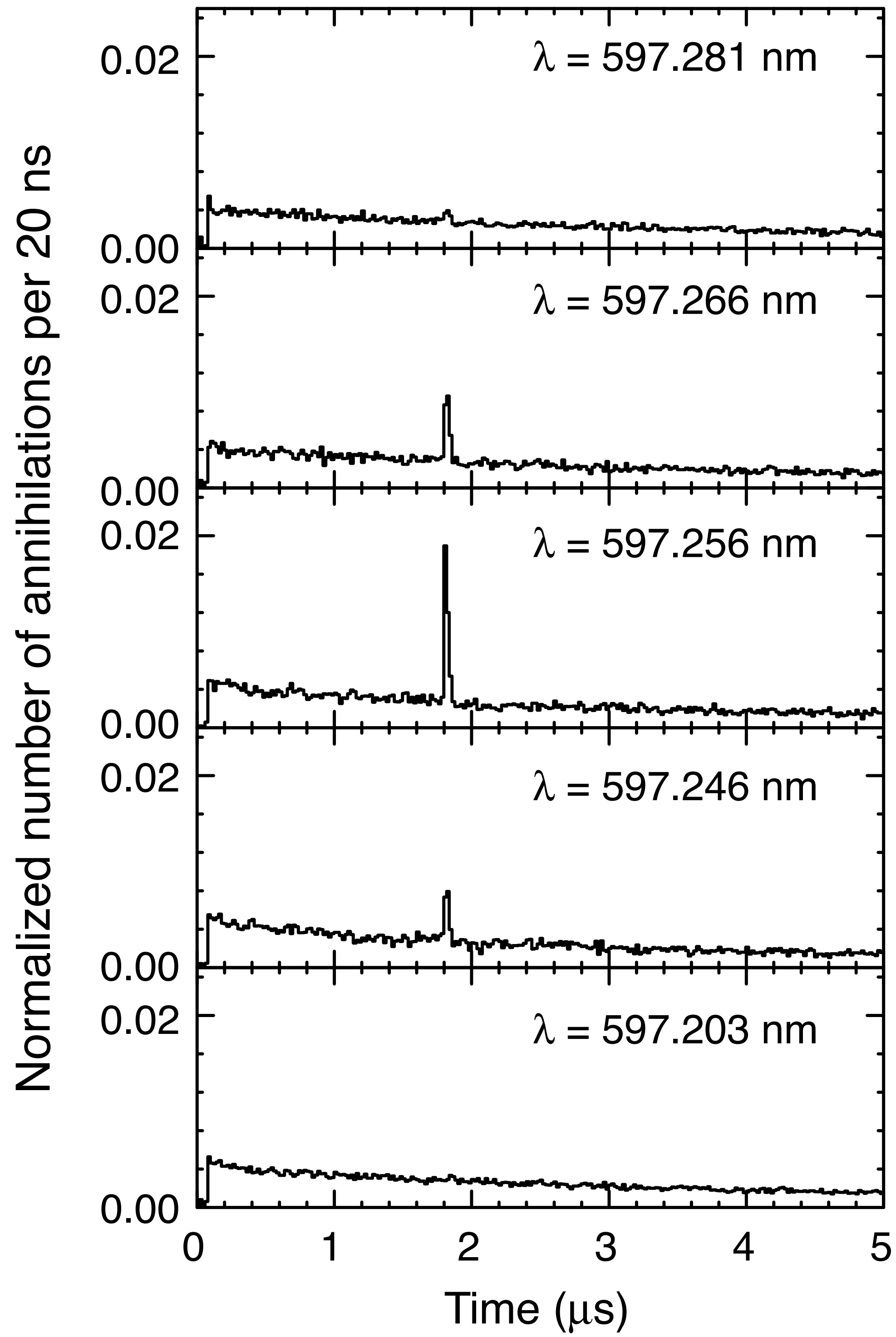


An example, (n,l)=(39,35)→(38,34)



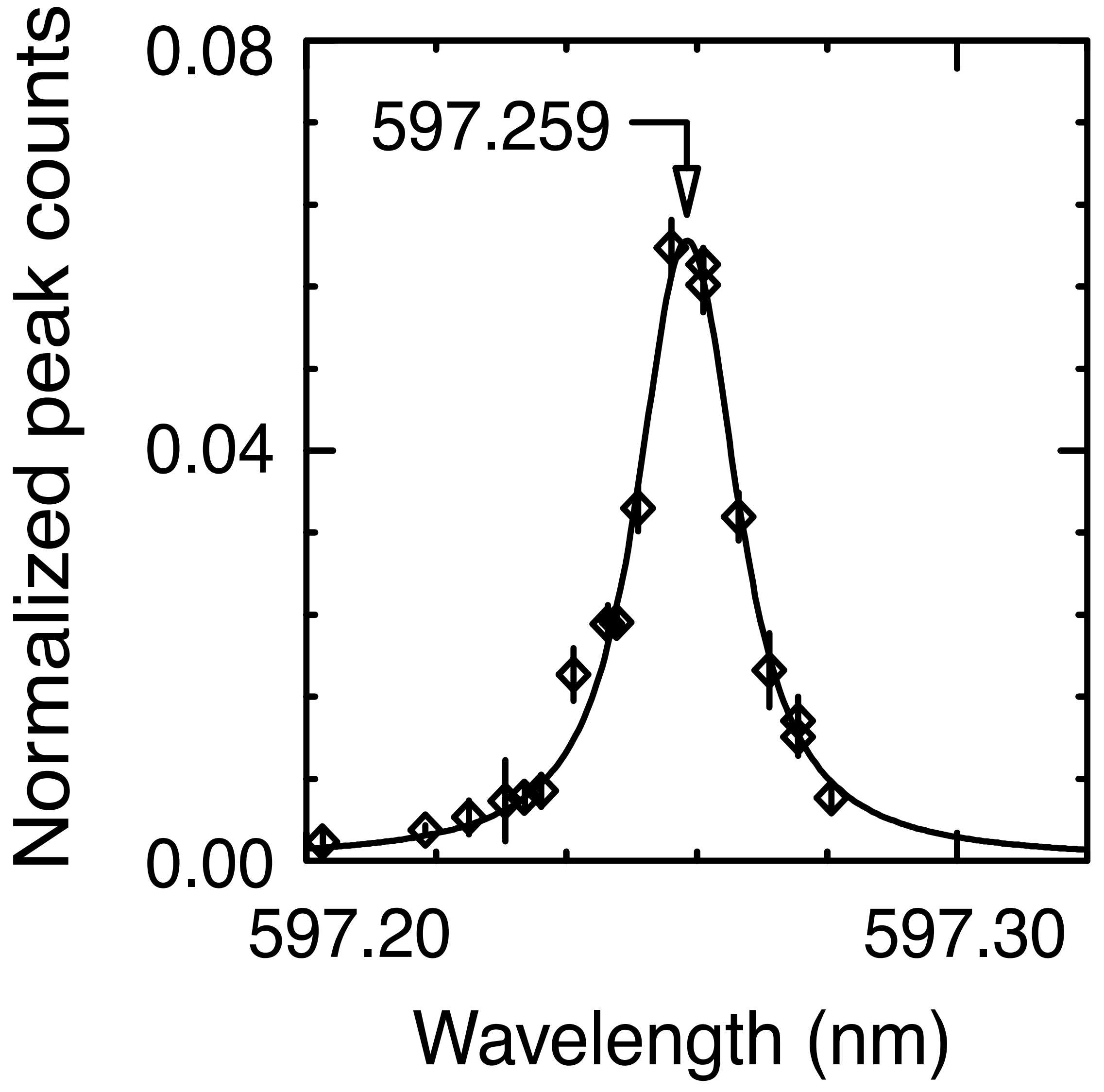
An example, (n,l)=(39,35)→(38,34)

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

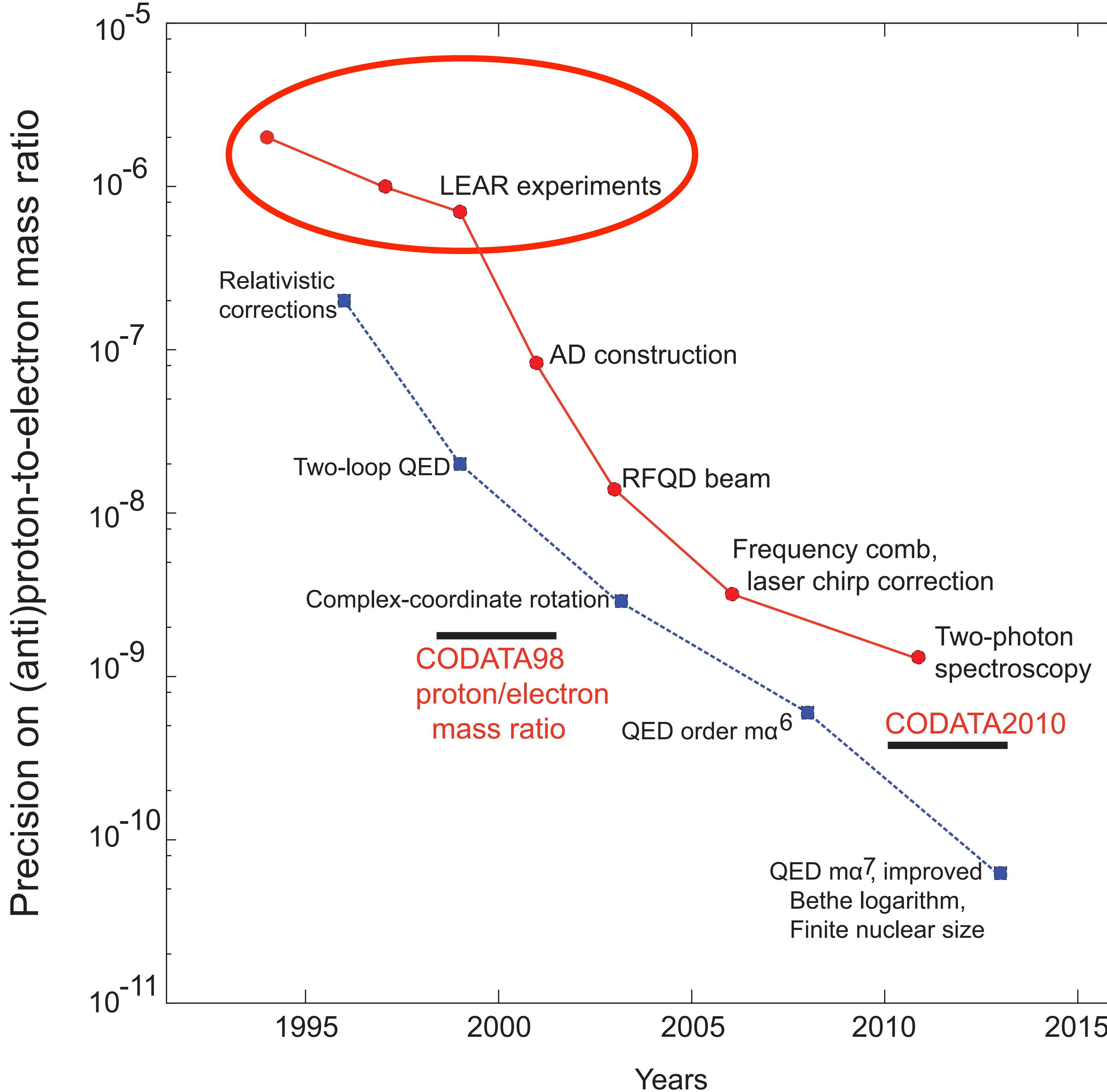


Laser Resonance Curve

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

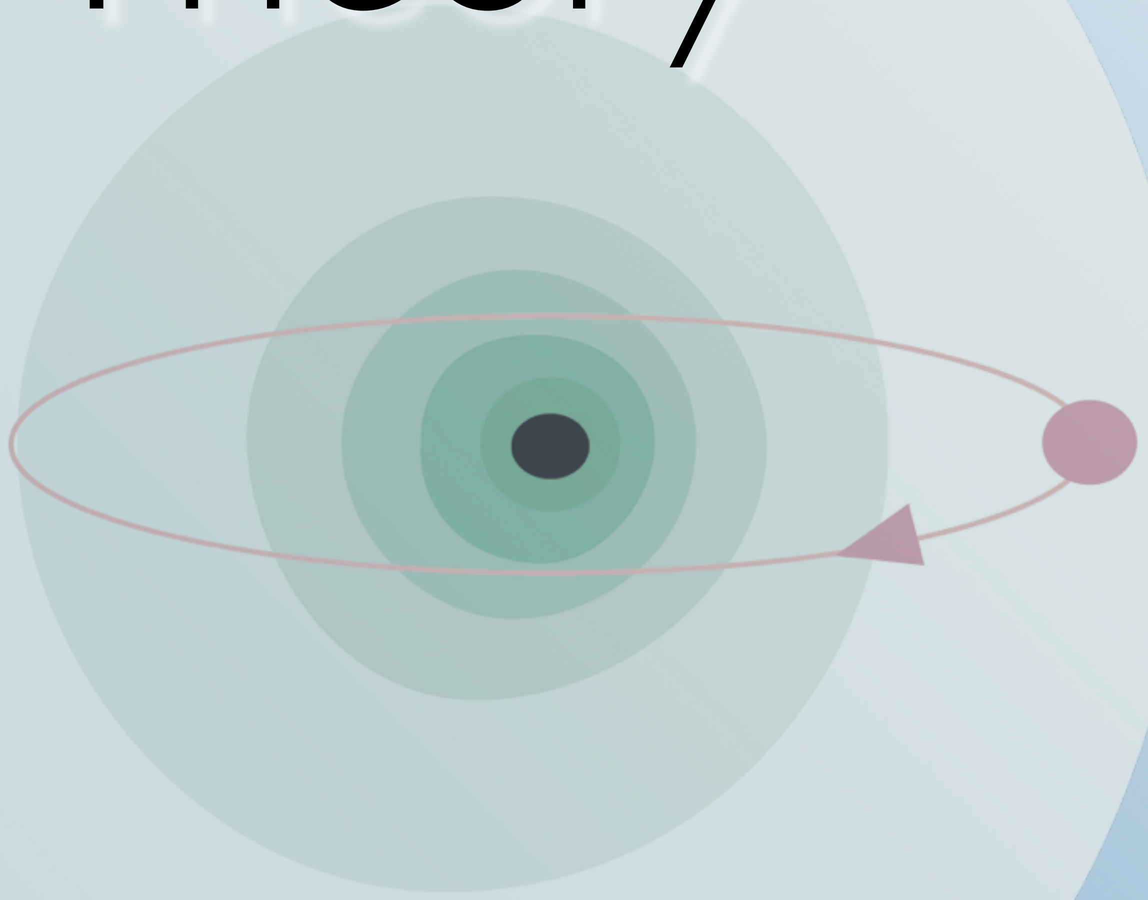


22

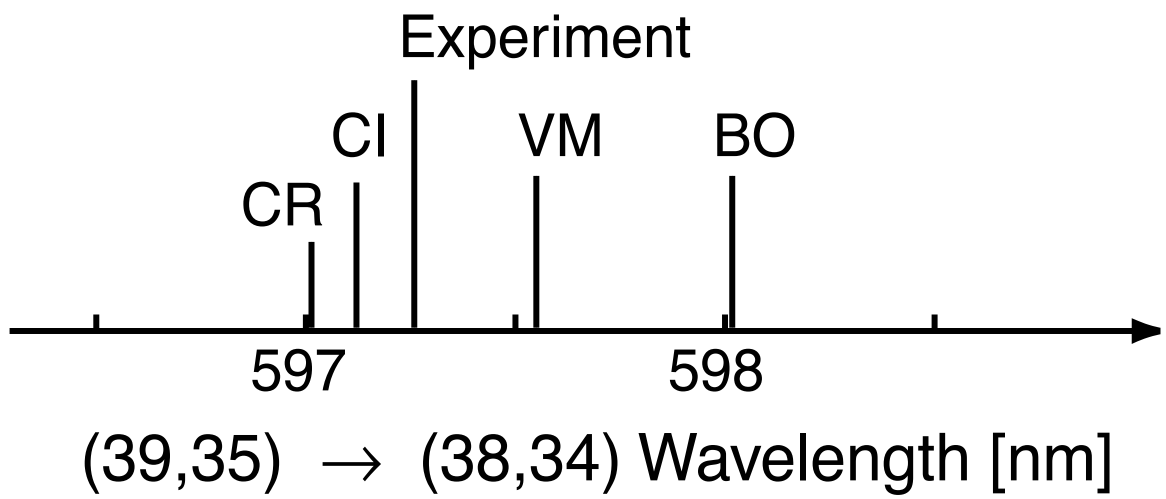


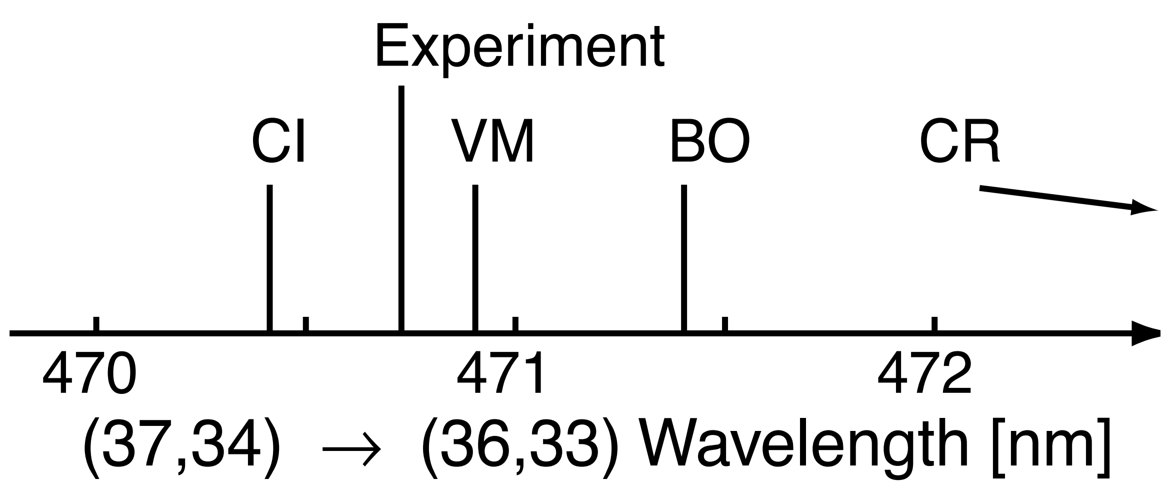
Precision on (anti)proton-to-electron mass ratio
Years
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
1995
2000
2005
2010
2015
LEAR experiments
Relativistic corrections
AD construction
Two-loop QED
RFQD beam
Frequency comb, laser chirp correction
Complex-coordinate rotation
Two-photon spectroscopy
CODATA98 proton/electron mass ratio
QED order mα6
CODATA2010
QED mα7, improved Bethe logarithm, Finite nuclear size

Theory



20 years ago - Theory precision ~ 1000 ppm





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

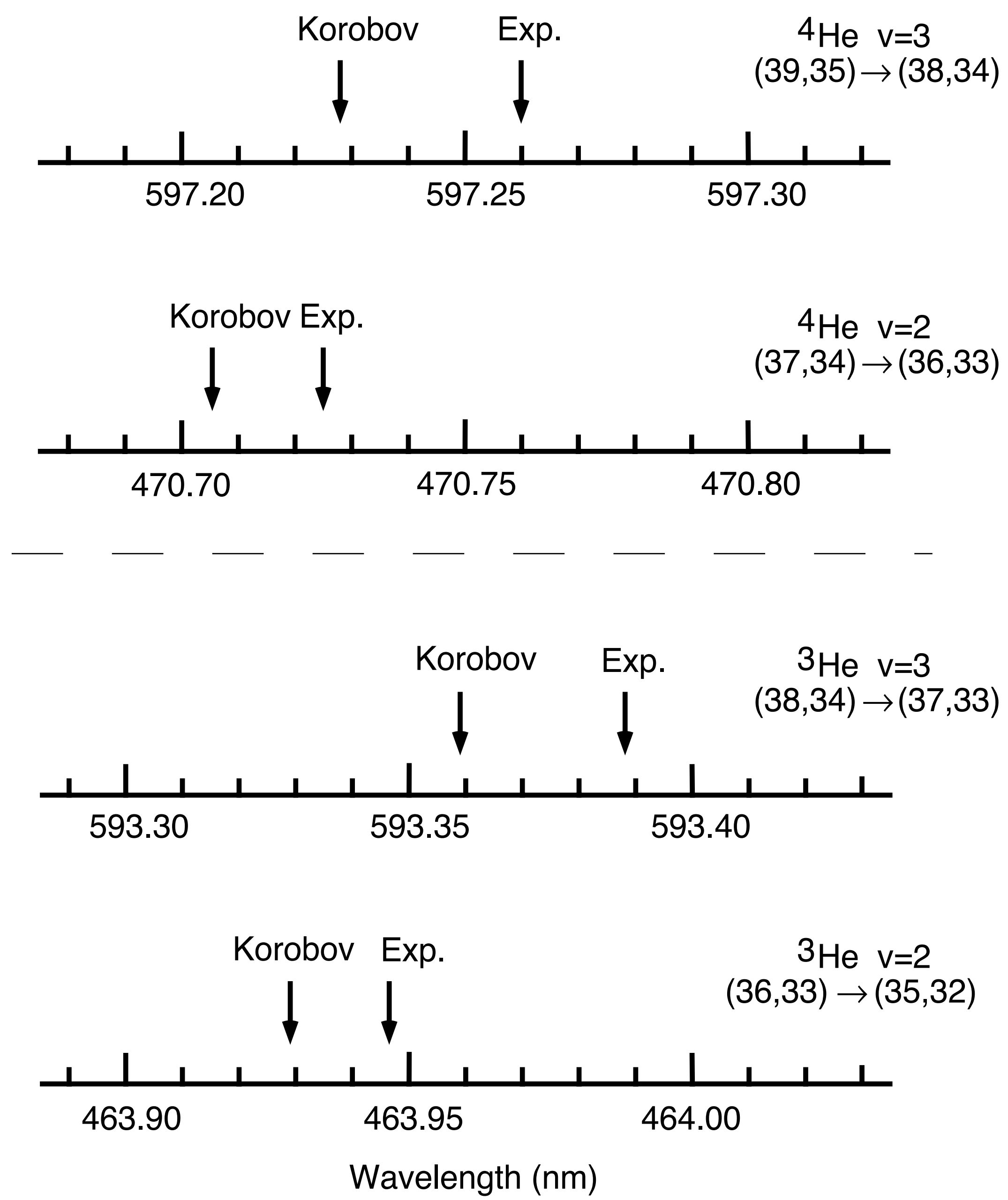
50 ppm in 1996

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 - non-relativistic H

antiproton

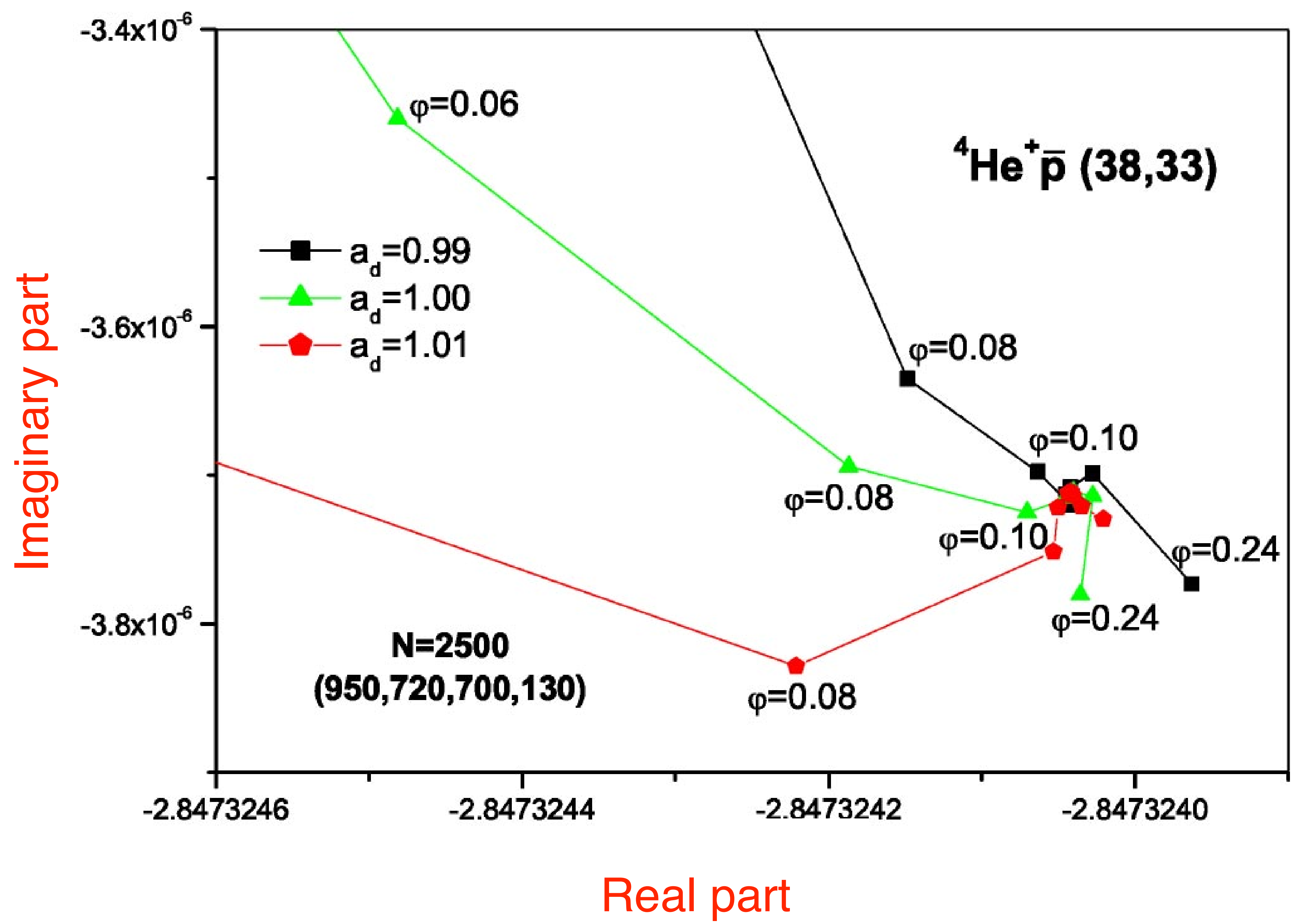
electron

$$H = T + V$$

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

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

Complex coordinate rotation (CCR) method



Korobov

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

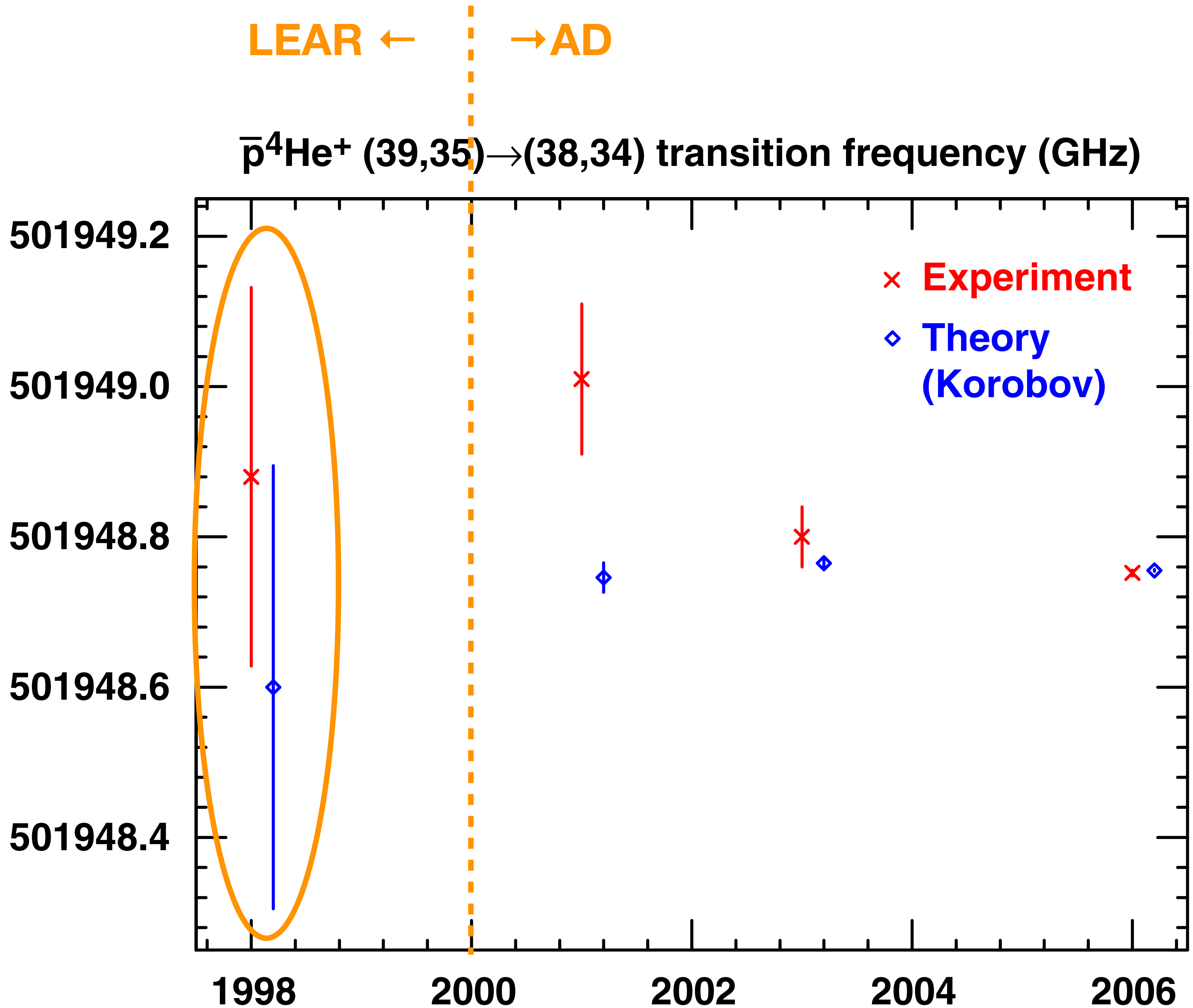
$$E_{se} = \frac{4\alpha^3}{3m_e^2}\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0}{R_\infty} + \frac{5}{6} - \frac{3}{8}\right]\langle Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\rangle$$

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

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

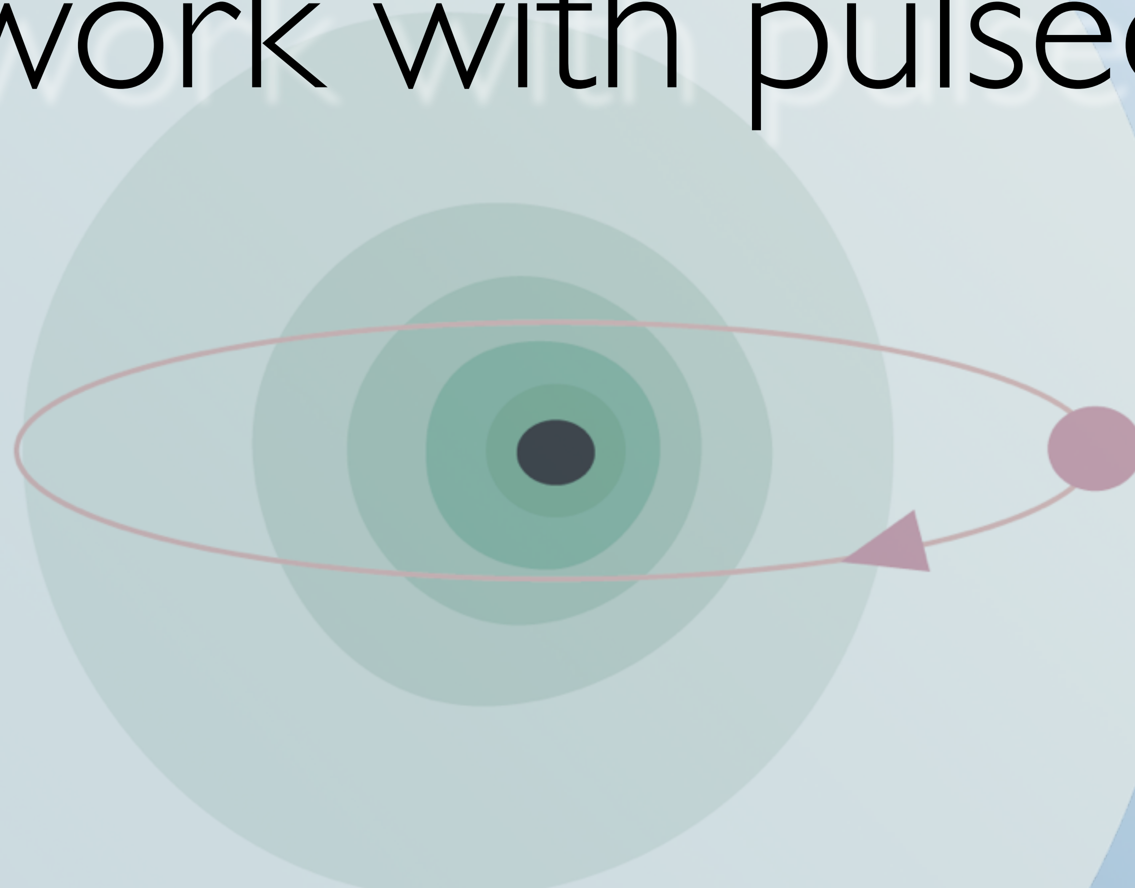
$$+ Z_{\bar{p}}^3\ln^2(Z_{\bar{p}}\alpha)^{-2}\delta(\mathbf{r}_{\bar{p}})\rangle,$$

Theory vs experiment

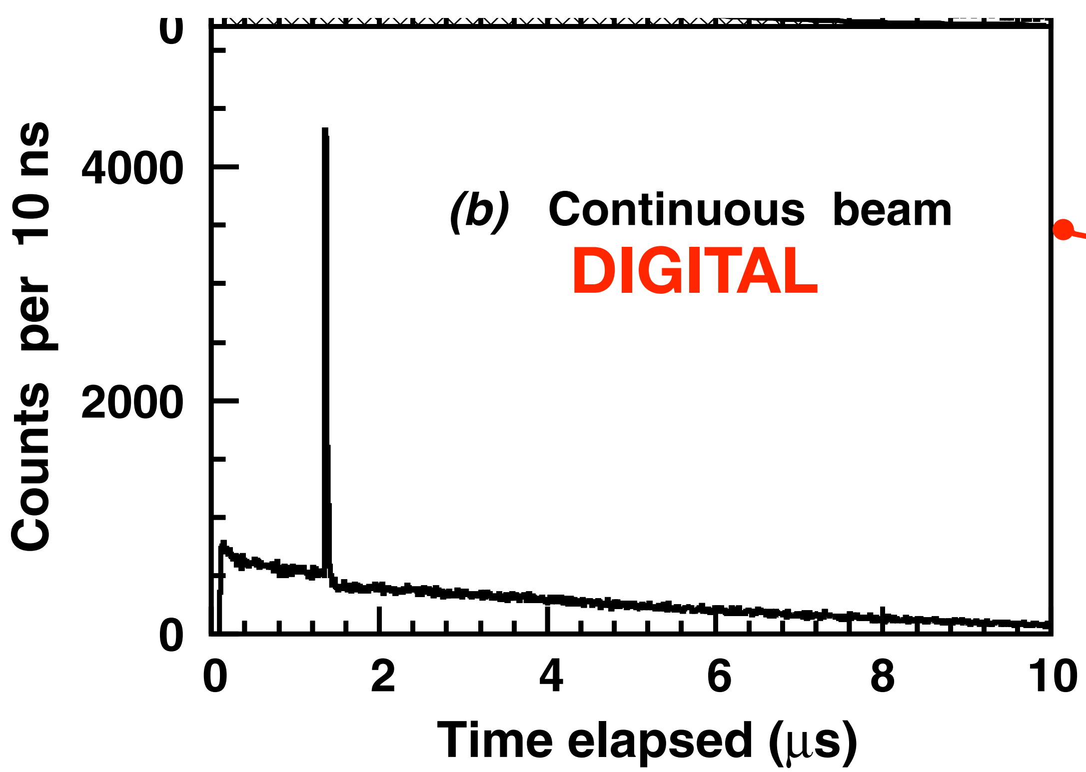


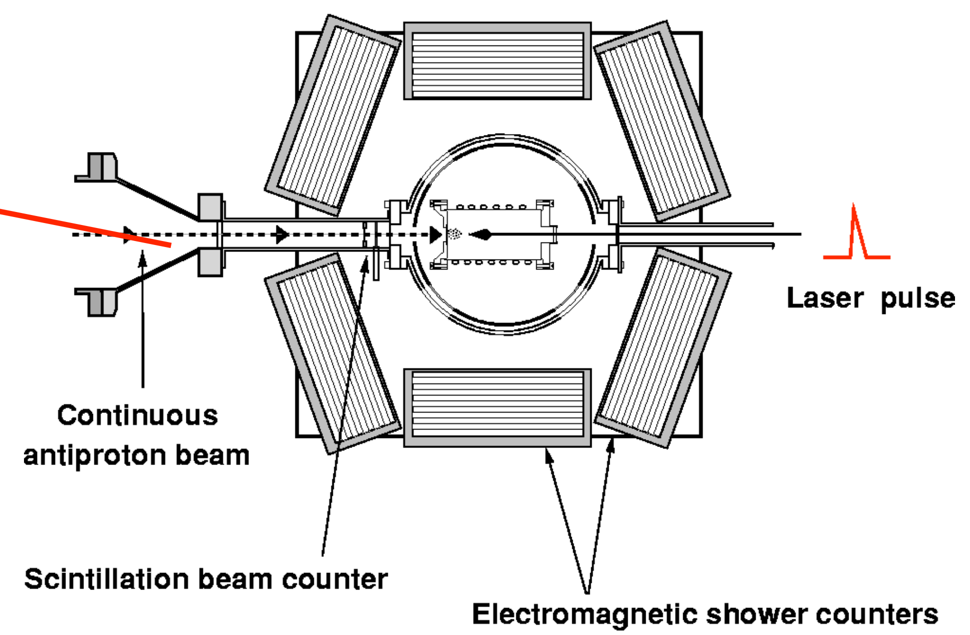
ASACUSA @ CERN AD

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



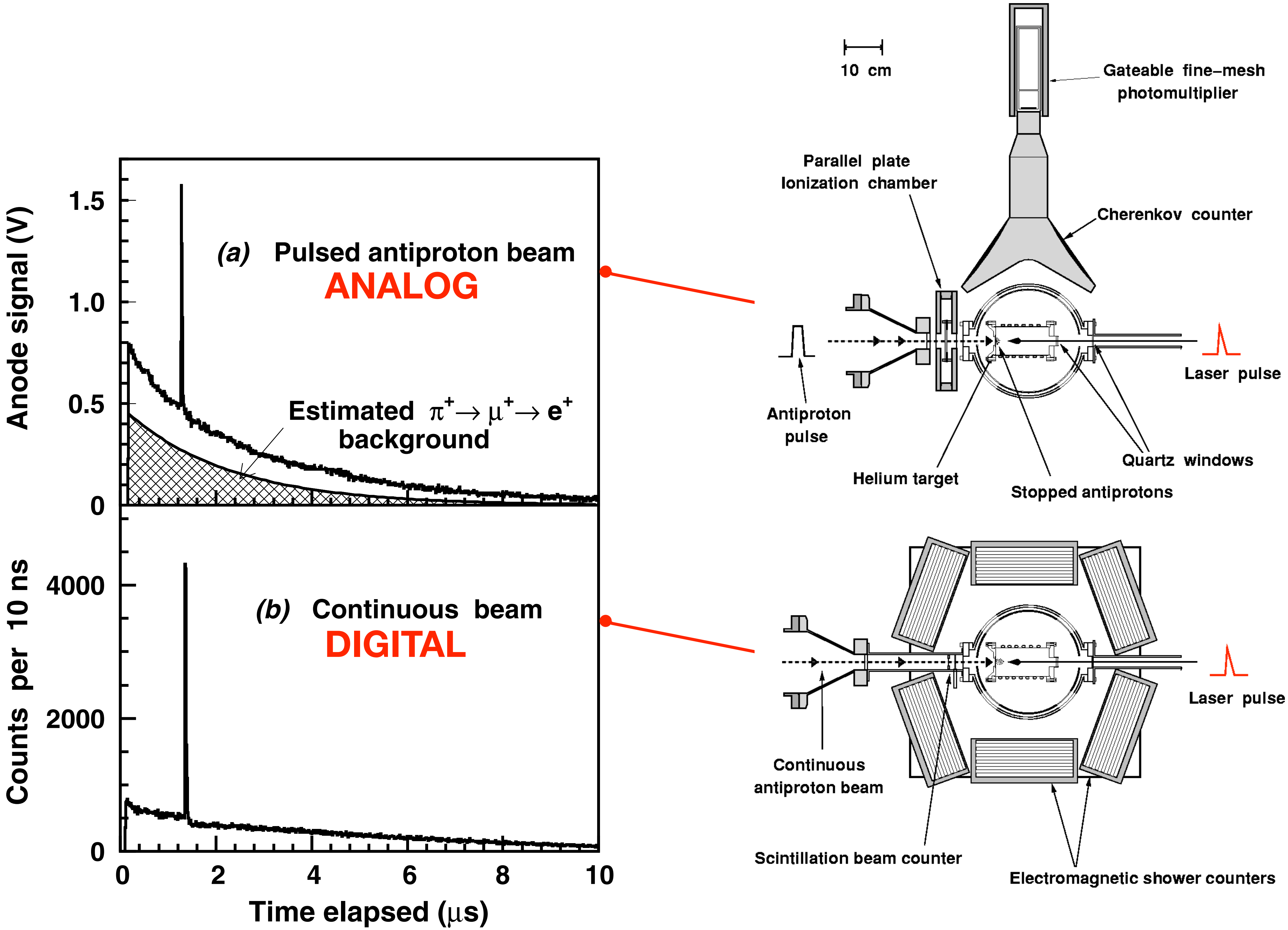
Conventional event-by-event counting



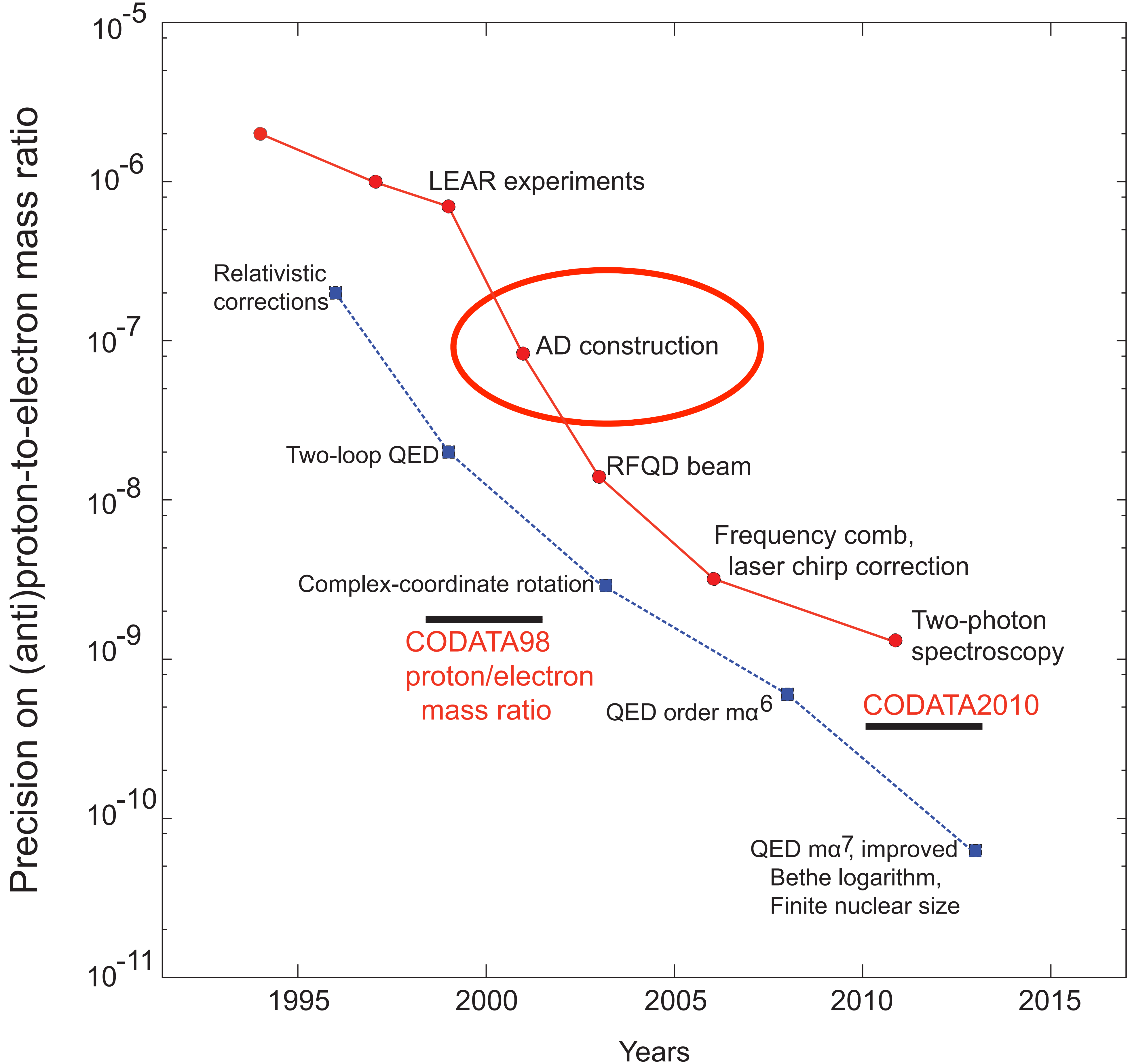


M. Hori et al., PHYSICAL REVIEW A 70, 012504 (2004).

Can’t use event-by-event counting

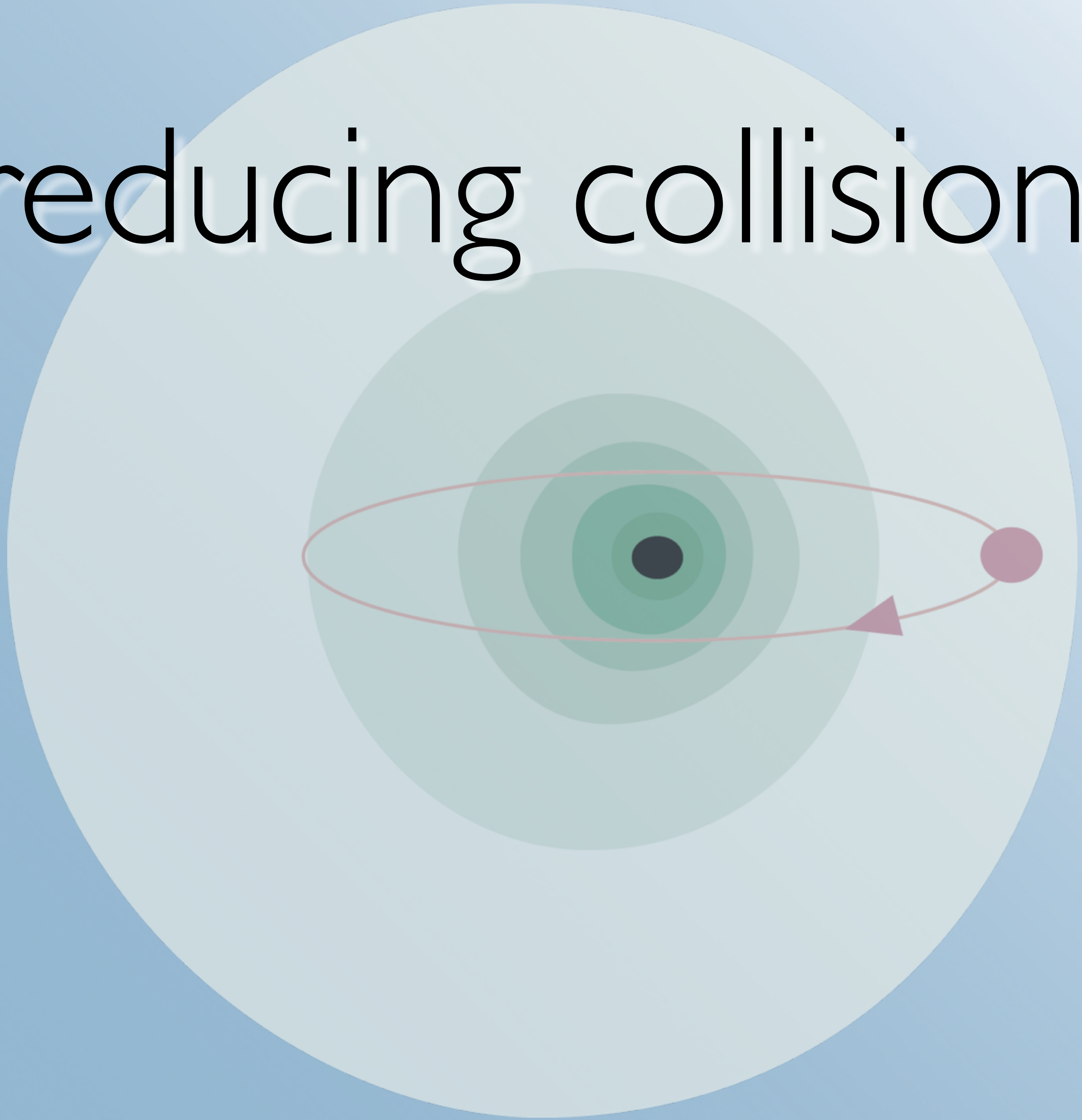


M. Hori et al., PHYSICAL REVIEW A 70, 012504 (2004).

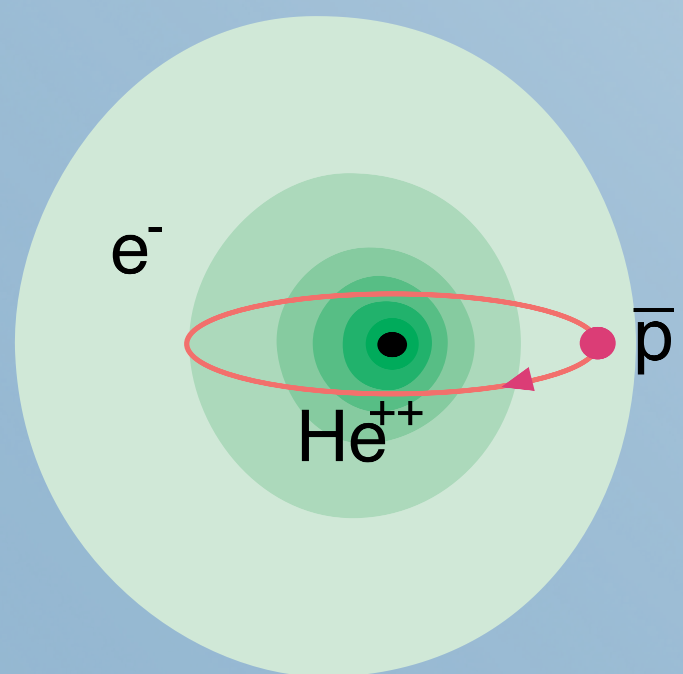


Precision on (anti)proton-to-electron mass ratio
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
1995
2000
2005
2010
2015
Years
LEAR experiments
Relativistic
corrections
AD construction
Two-loop QED
RFQD beam
Frequency comb,
laser chirp correction
Complex-coordinate rotation
Two-photon
spectroscopy
CODATA98
proton/electron
mass ratio
QED order mα6
CODATA2010
QED mα7, improved
Bethe logarithm,
Finite nuclear size

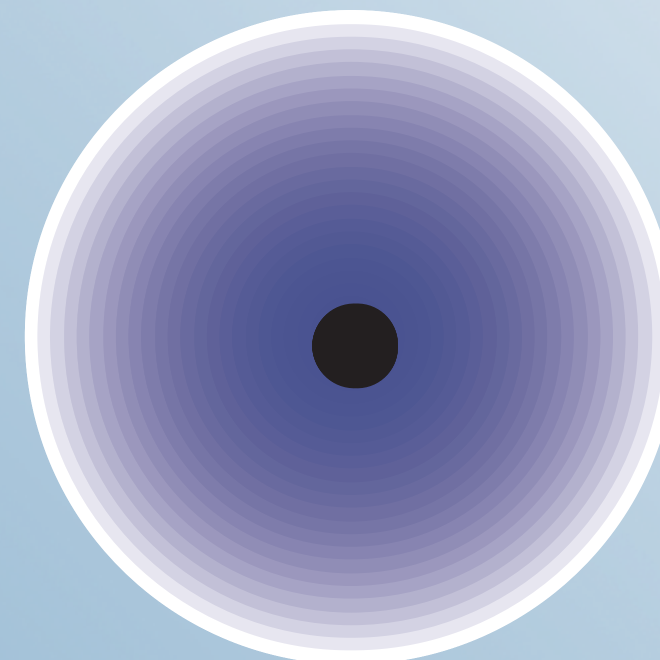
reducing collisions



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

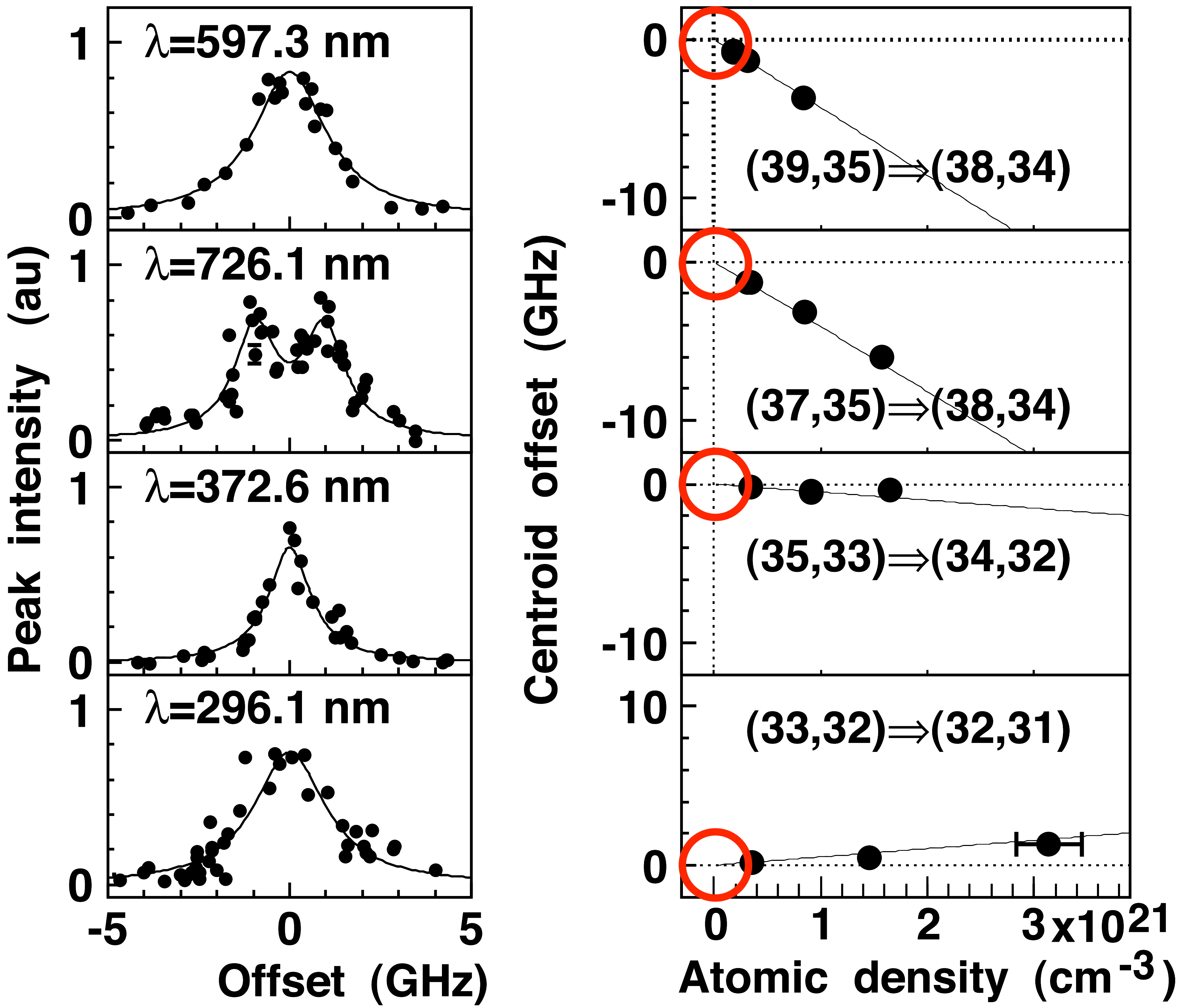


$\bar{p}$ He



He

Density-dependent shift

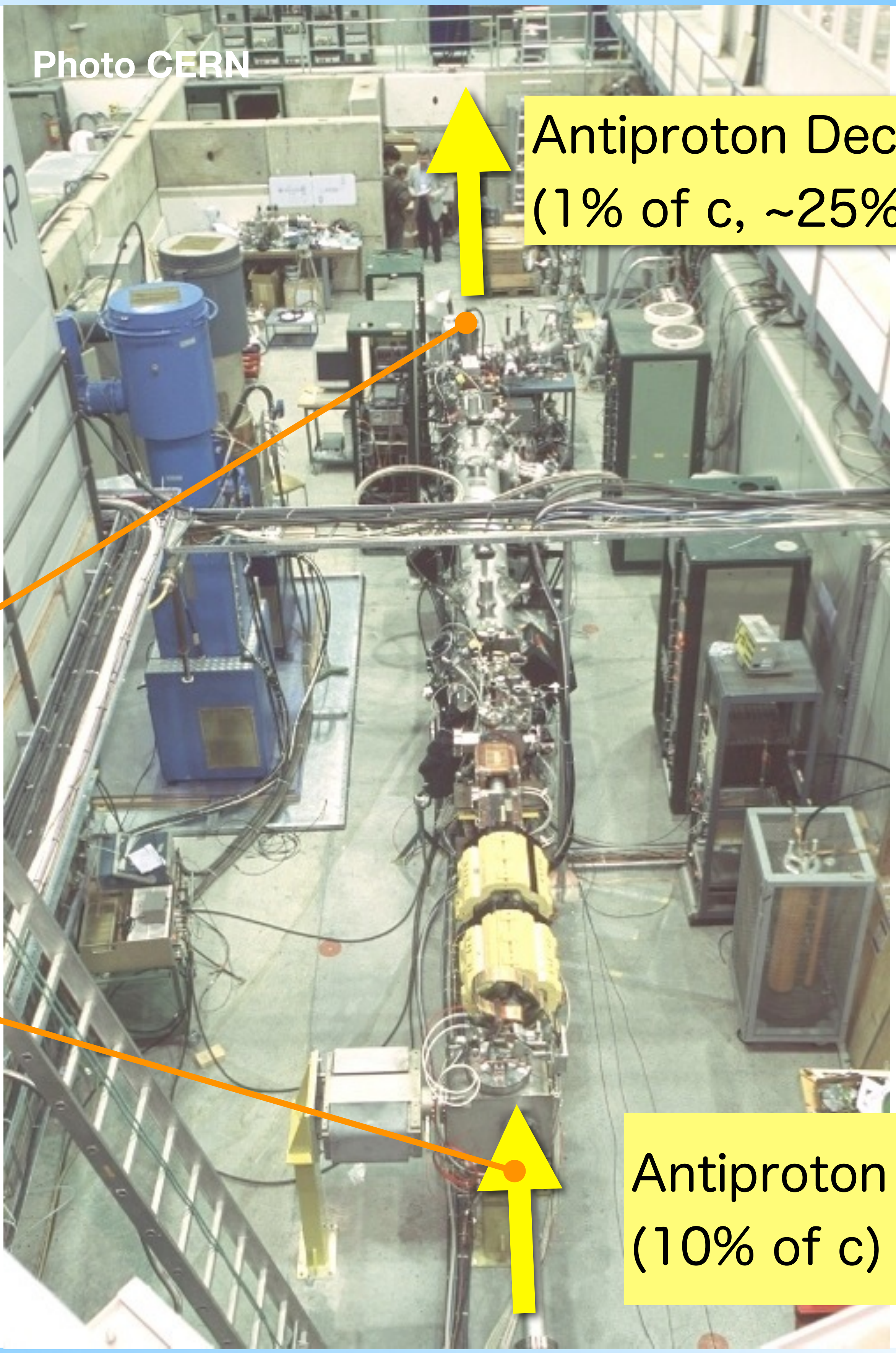


RFQD

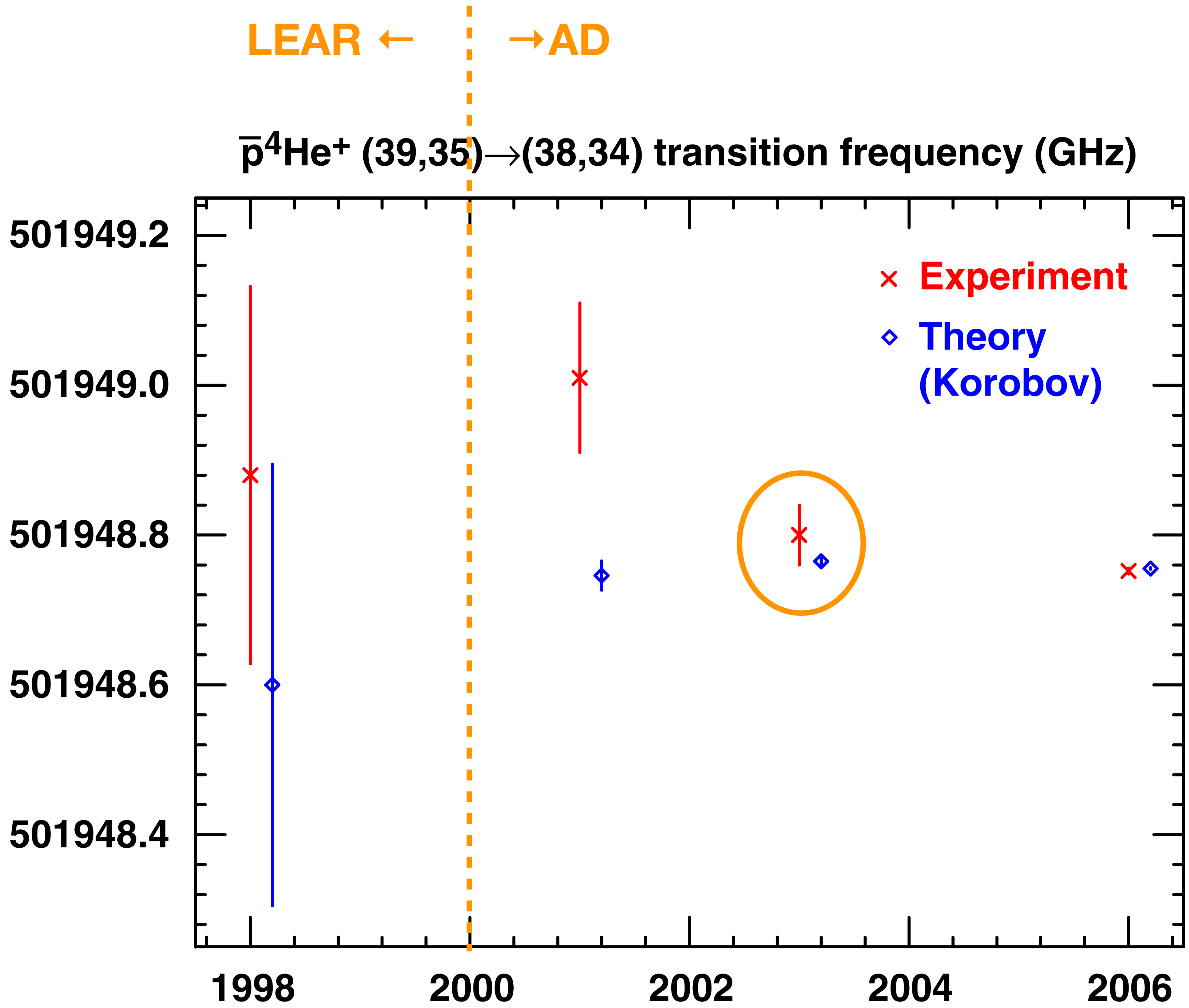
Typical target density

10^{16} - 10^{18} cm^{-3}

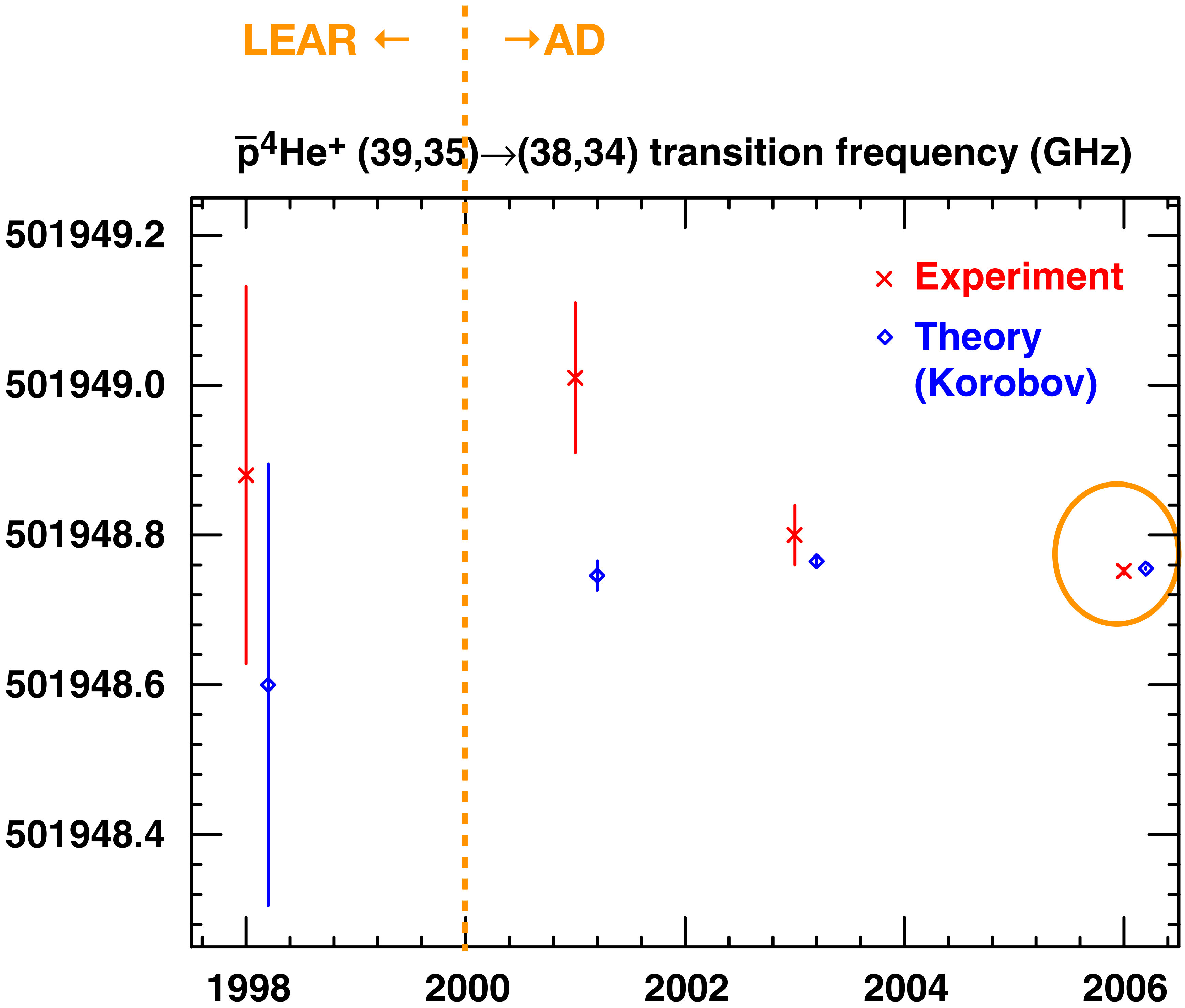
10^{21} cm^{-3}



“Direct” measurement w RFQD



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, 2006 & 2010

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

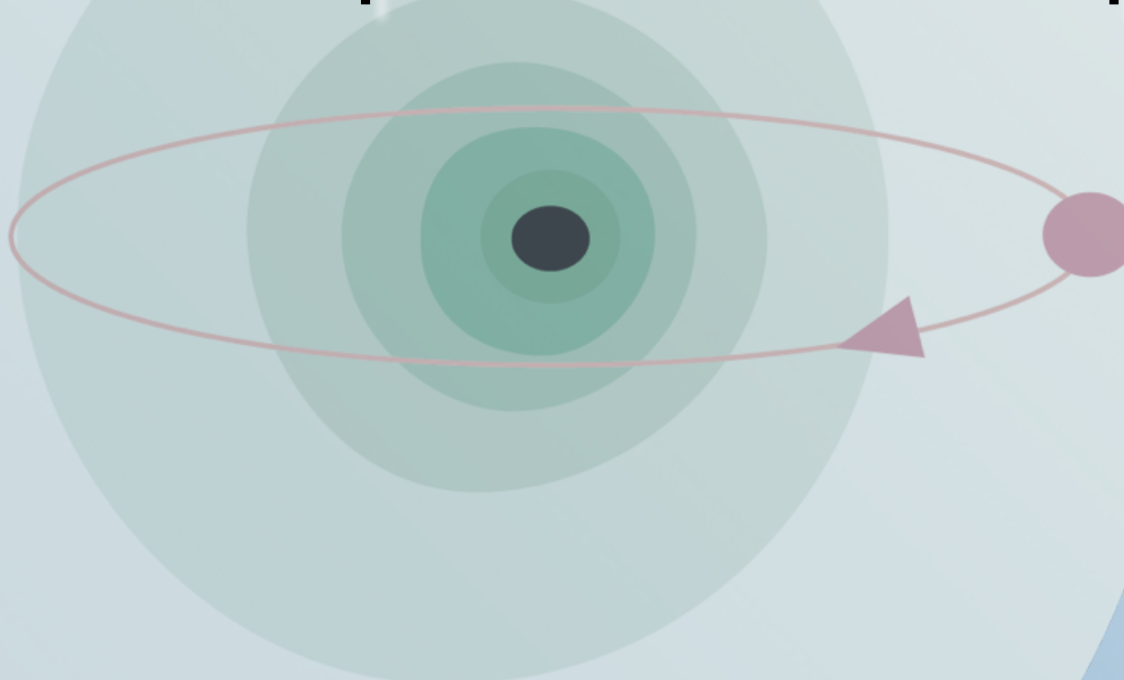
CODATA recommended values of the fundamental physical constants: 2006*

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

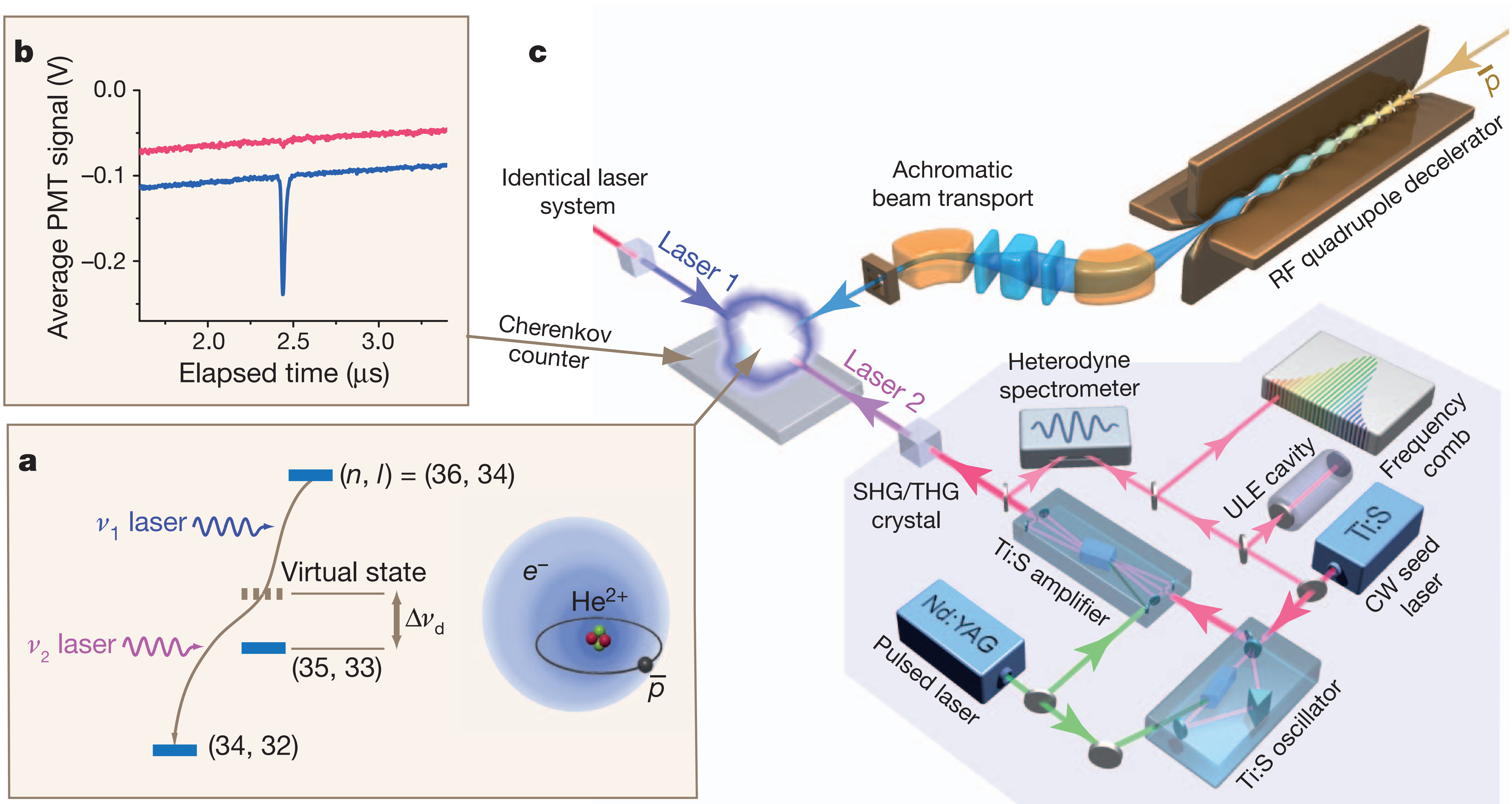
IV. ATOMIC TRANSITION FREQUENCIES

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-

Reduce Doppler width
2-photon spectroscopy

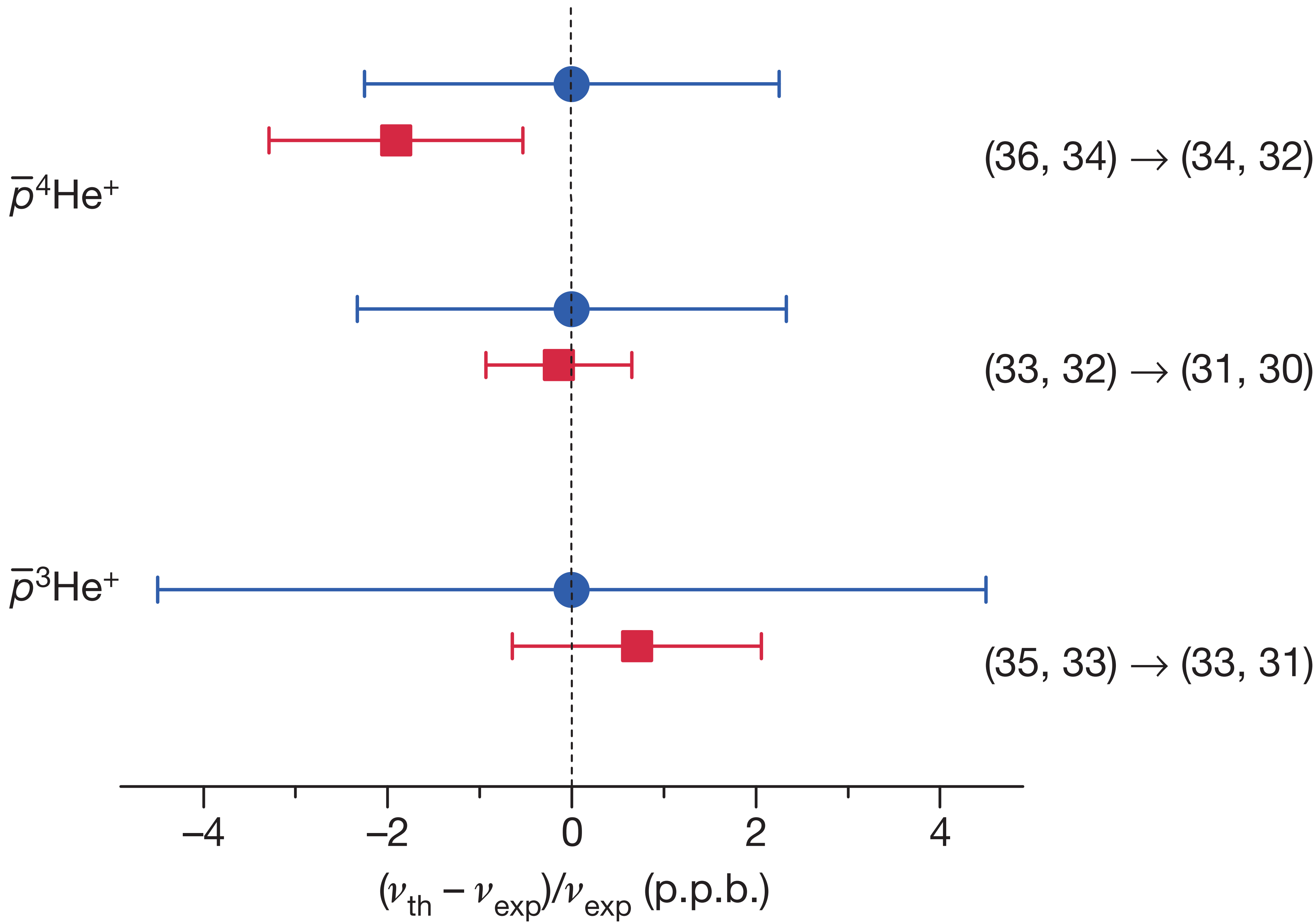


$\bar{p}$He 2-photon spectroscopy



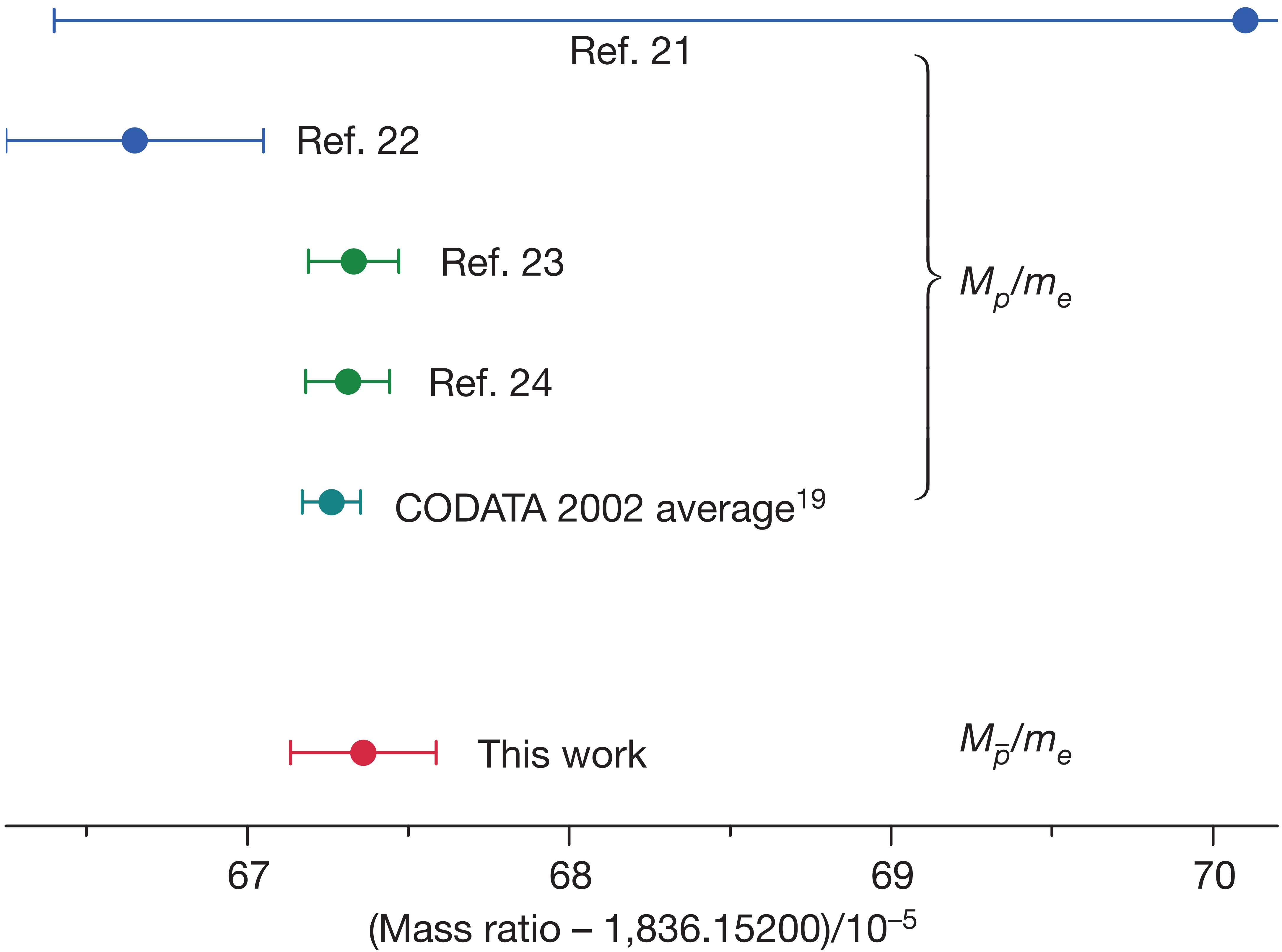
Hori et al., Nature 475 (2011) 484

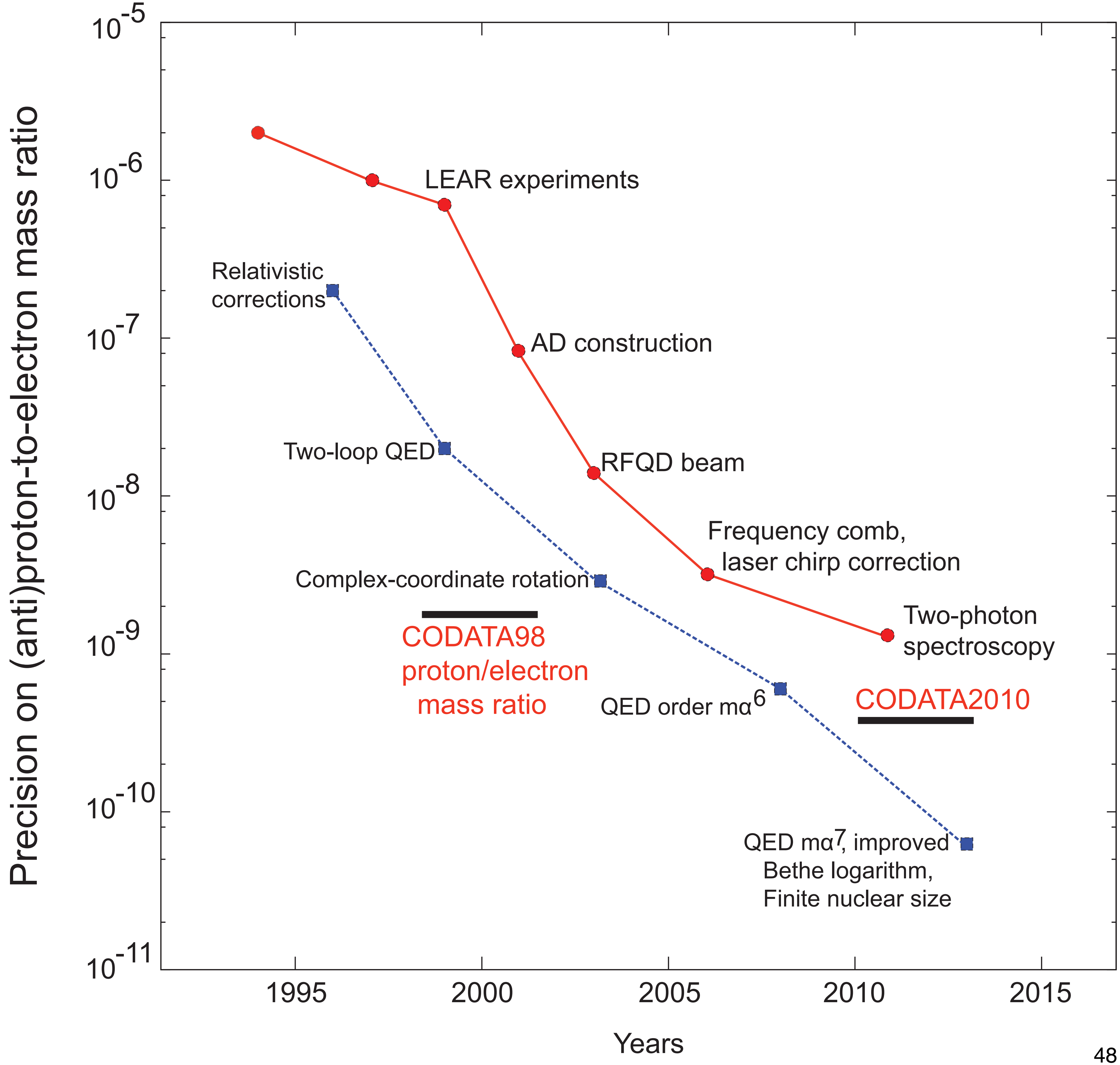
Theory vs Exp



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

Hori et al., Nature 475 (2011) 484



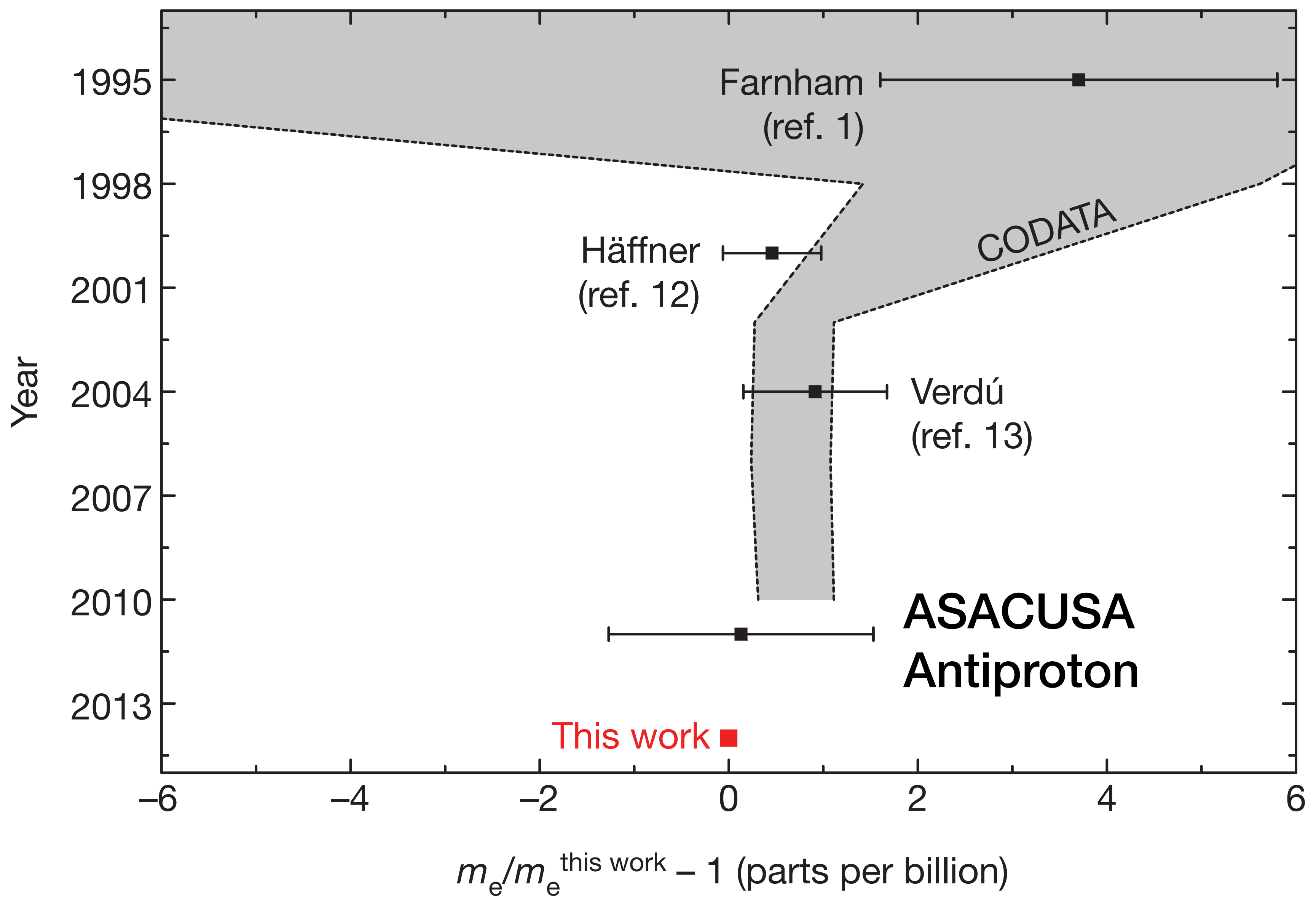

Precision on (anti)proton-to-electron mass ratio
Years
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
1995
2000
2005
2010
2015
LEAR experiments
AD construction
RFQD beam
Frequency comb, laser chirp correction
Two-photon spectroscopy
Relativistic corrections
Two-loop QED
Complex-coordinate rotation
QED order mα6
QED mα7, improved Bethe logarithm, Finite nuclear size
CODATA98 proton/electron mass ratio
CODATA2010

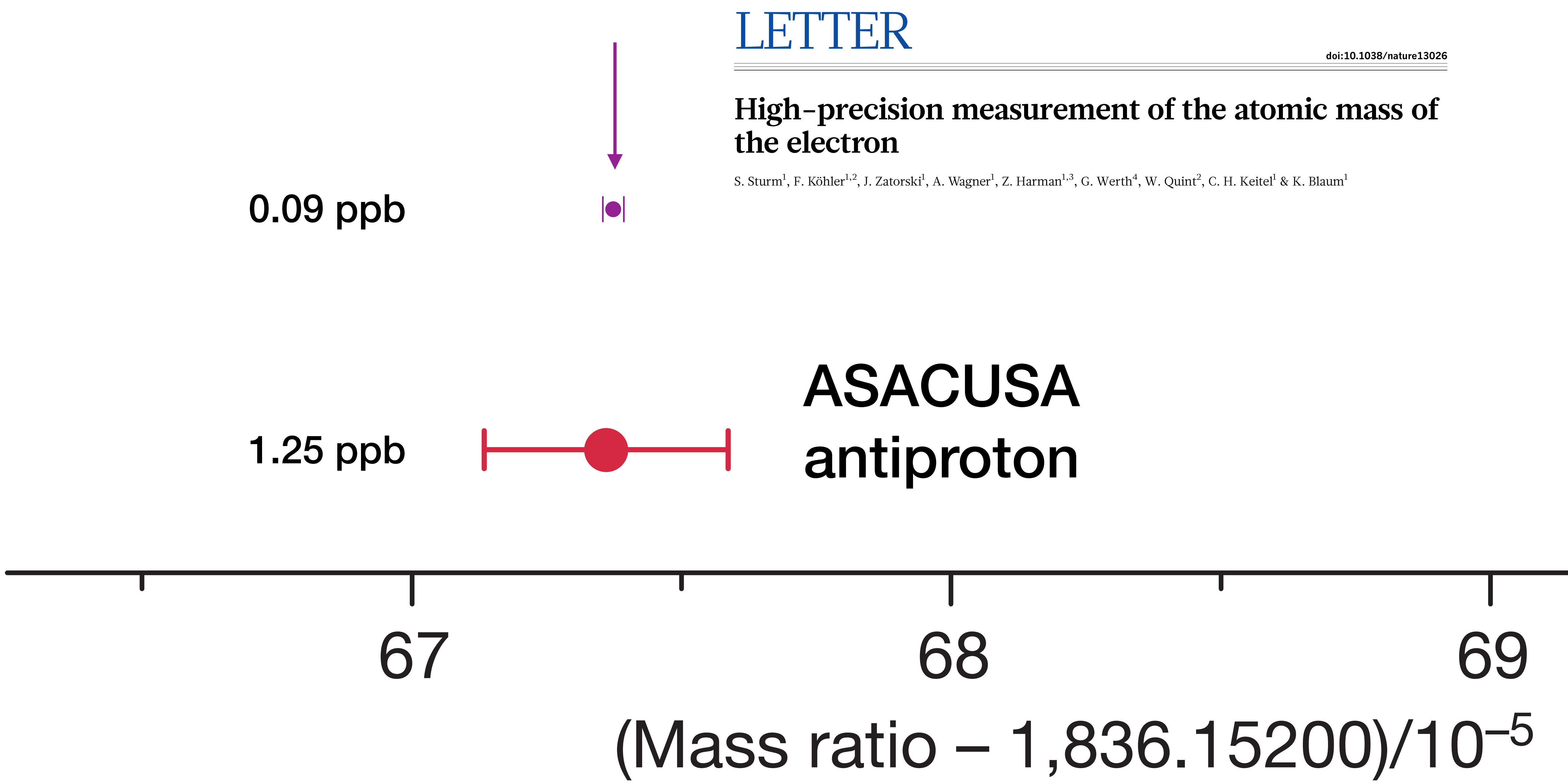
Recently, m_p/m_e much improved

NATURE 506 (2014) 467

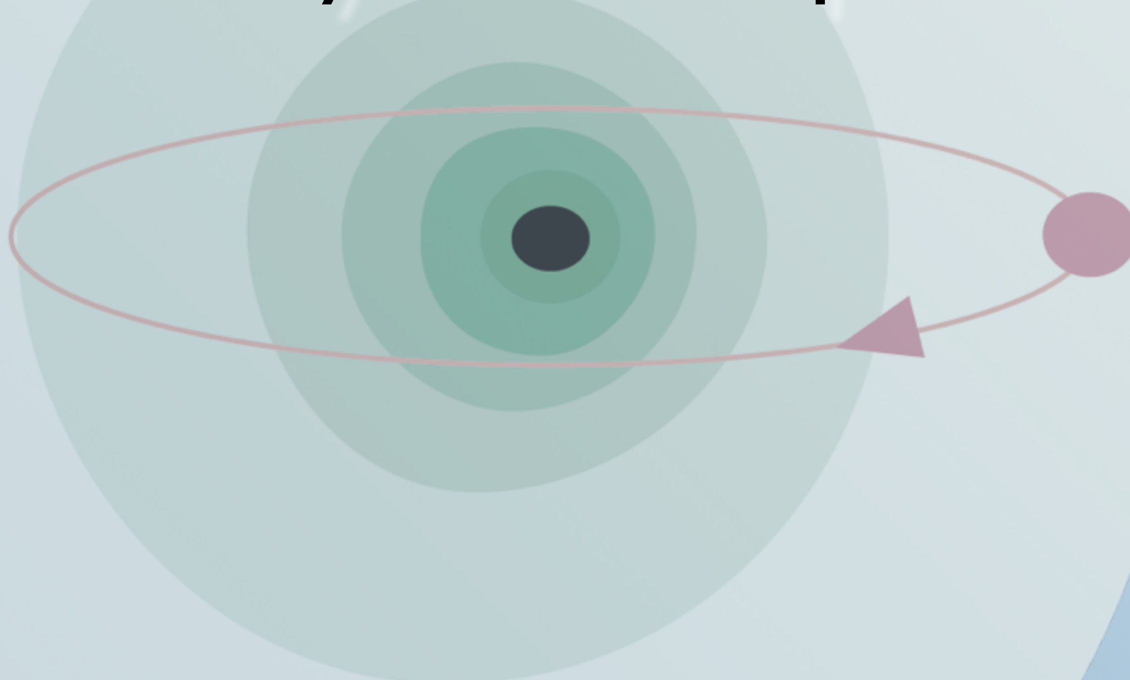
High-precision measurement of the atomic mass of the electron

S. Sturm[1], F. Köhler[1,2], J. Zatorski[1], A. Wagner[1], Z. Harman[1,3], G. Werth[4], W. Quint[2], C. H. Keitel[1] & K. Blaum[1]




LETTER
doi:10.1038/nature13026
High-precision measurement of the atomic mass of the electron
S. Sturm[1], F. Köhler[1,2], J. Zatorski[1], A. Wagner[1], Z. Harman[1,3], G. Werth[4], W. Quint[2], C. H. Keitel[1] & K. Blaum[1]
0.09 ppb
1.25 ppb
ASACUSA
antiproton
67
68
69
(Mass ratio – 1,836.15200)/10–5

How to improve?
theory & exp



Theory progress

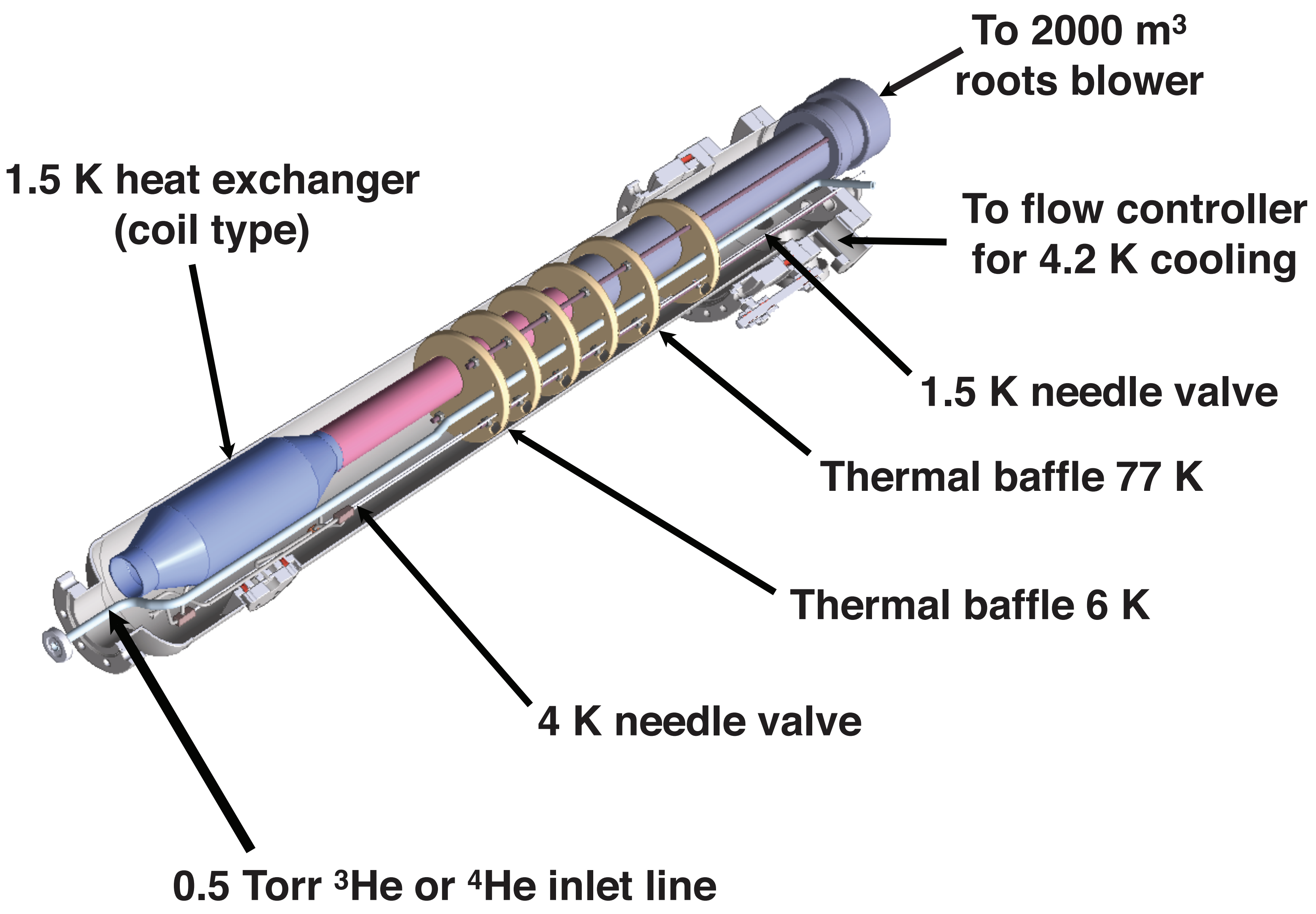
PHYSICAL REVIEW A **89**, 014501 (2014)

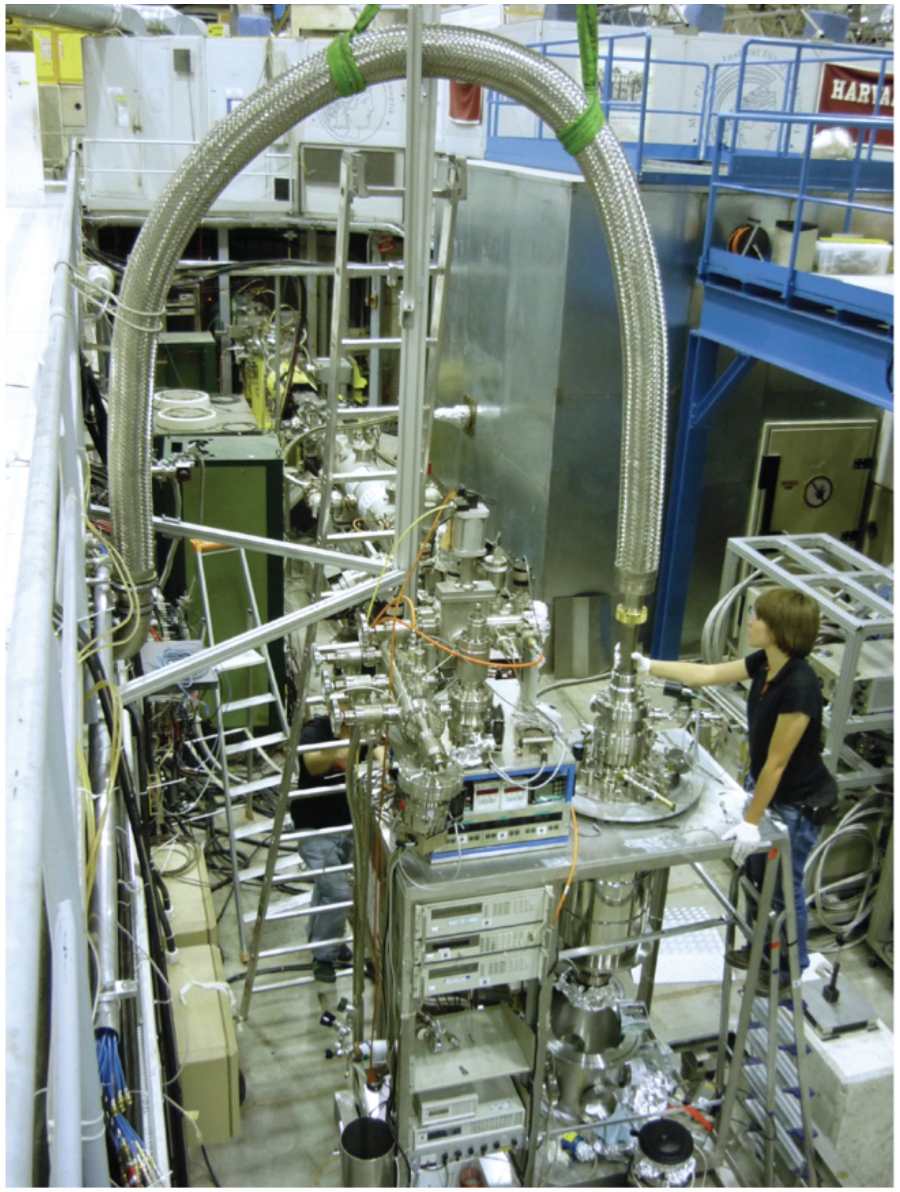
Bethe logarithm for resonant states: Antiprotonic helium

Vladimir I. Korobov
Joint Institute for Nuclear Research 141980, Dubna, Russia
(Received 16 December 2013; published 21 January 2014)

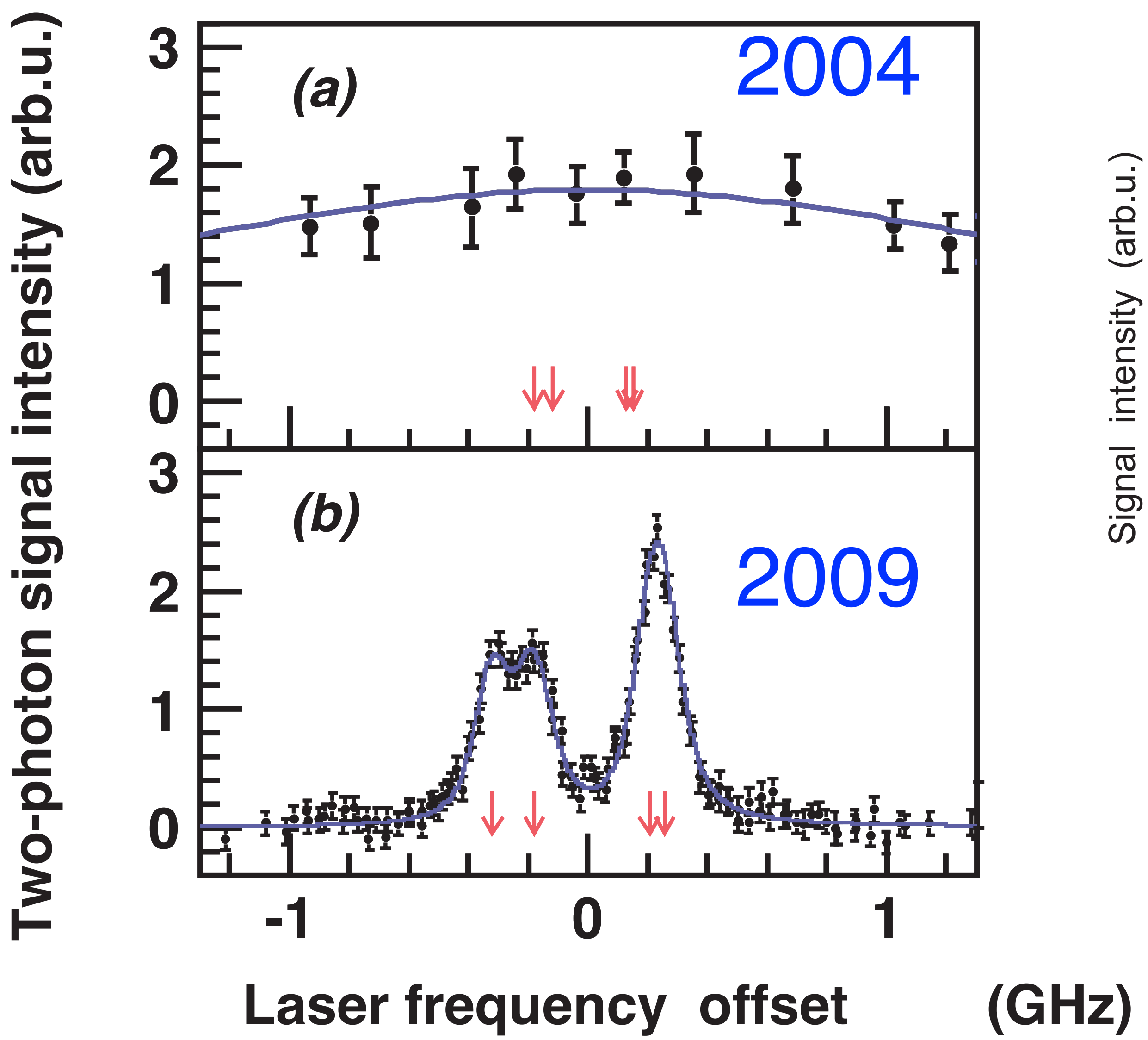
		MHz	
(33,32)→(31,30)	theory	2 145 054 869.9 (1.6)	0.8 ppb
		2 145 054 858.1 (2)	0.09 ppb
	experiment	2 145 054 858 (5)	2.3 ppb

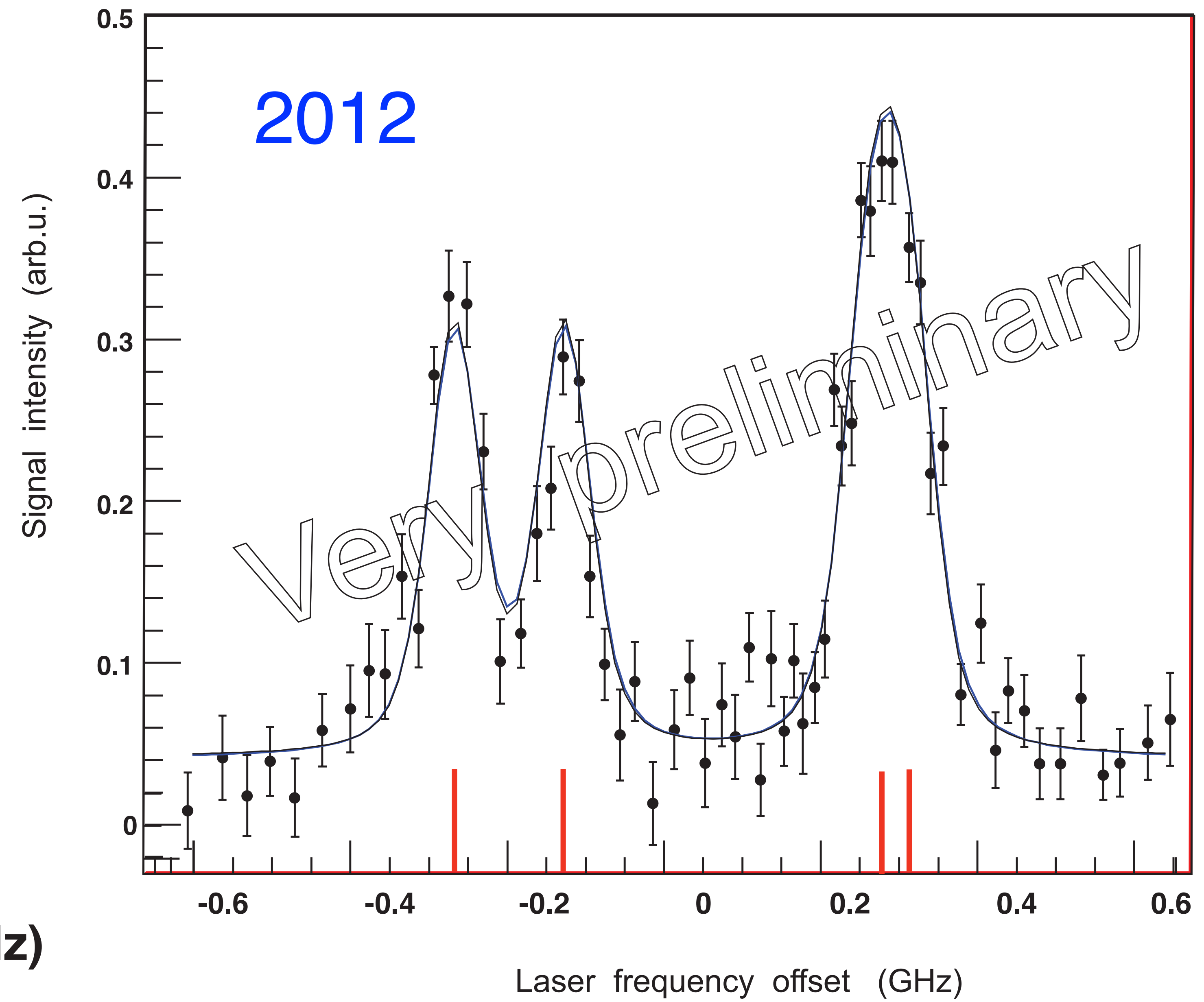
Experiment - go to 1.5K (and to ELENA)





T=1.5K scan looks promising





Reduction of residual Doppler broadening, by cooling atom to T=1.5 K via gas buffer cooling. Experimental precision should improve by >3x compared to before.

summary

p̄He contributes to CODATA & tests CPT

Serendipitous discovery

Precision now at ~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