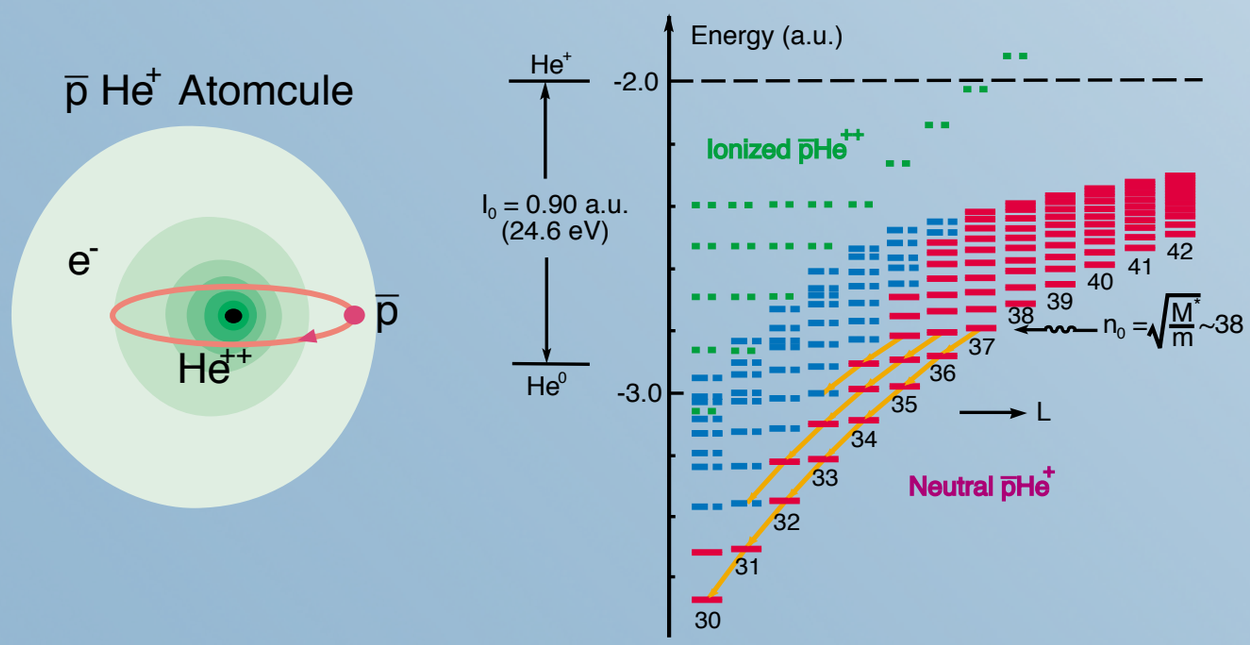
Physics of ASACUSA

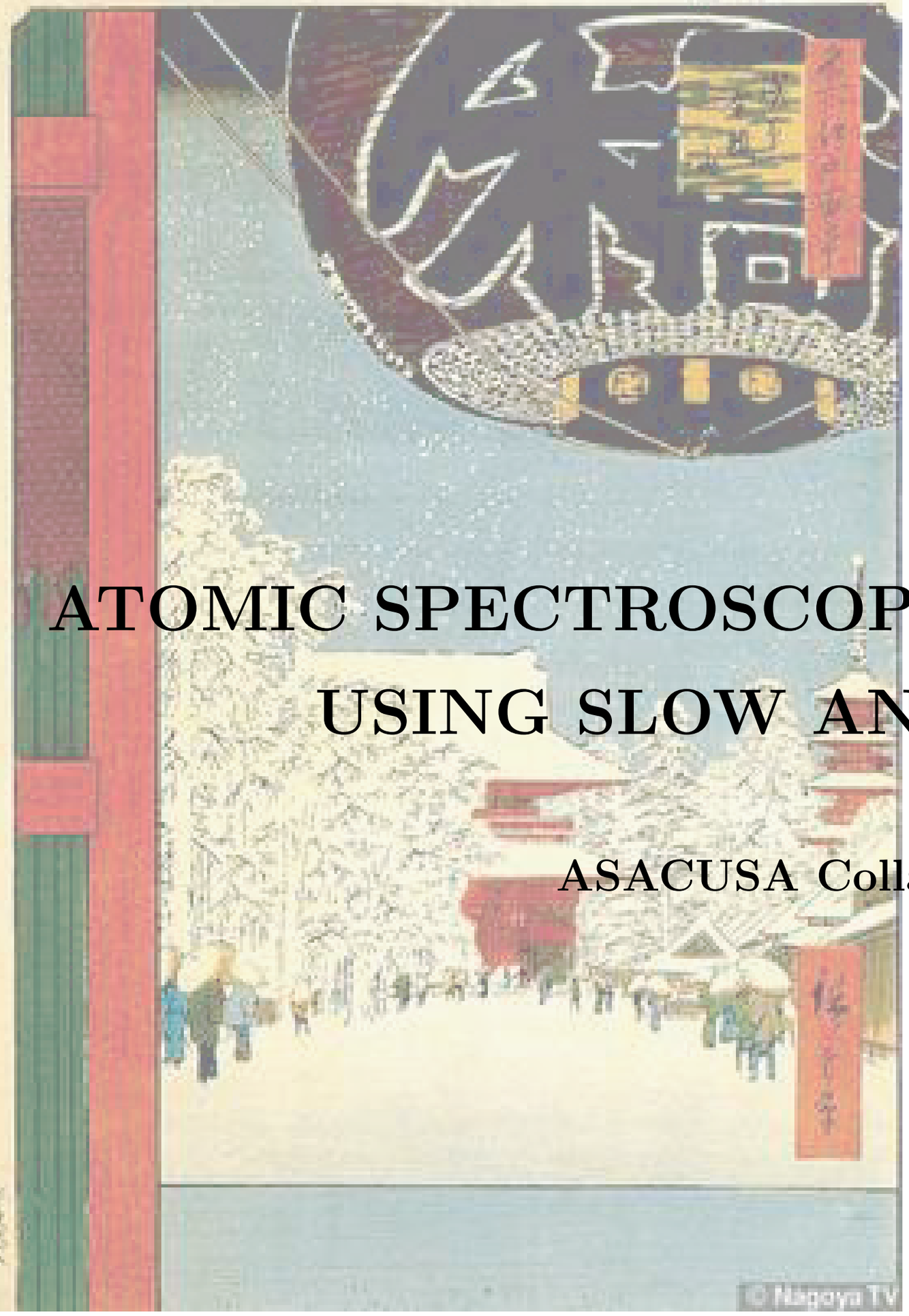
the spectroscopy of antiprotonic helium



Ryugo Hayano

THE UNIVERSITY OF TOKYO

June 9, 2017, 2nd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics



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

ATOMIC SPECTROSCOPY AND COLLISIONS USING SLOW ANTIPROTONS

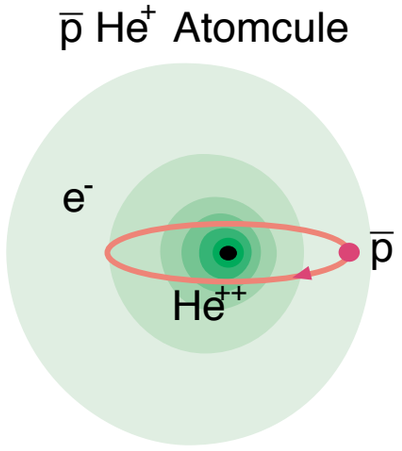
ASACUSA Collaboration

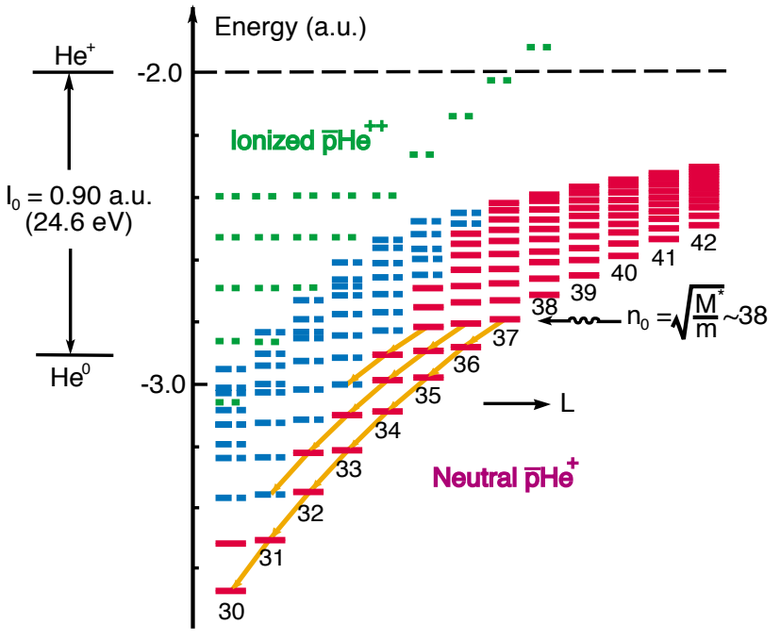
$\bar{p}$He spectroscopy: outline

What is it?

What is it good for?

Laser spectroscopy principles





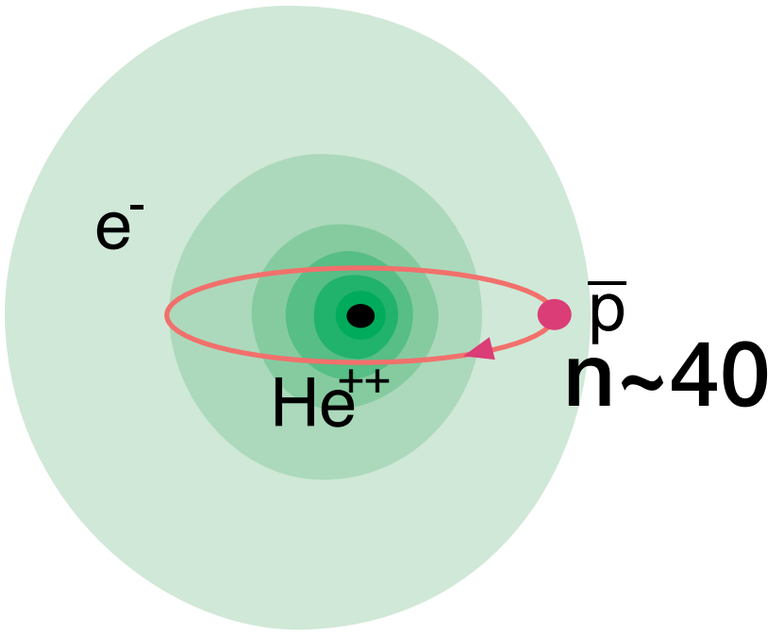
Theory

How to reach high precision?

Present status

What to expect with ELENA?

p̄He spectroscopy → $m_{\bar{p}}/m_e$



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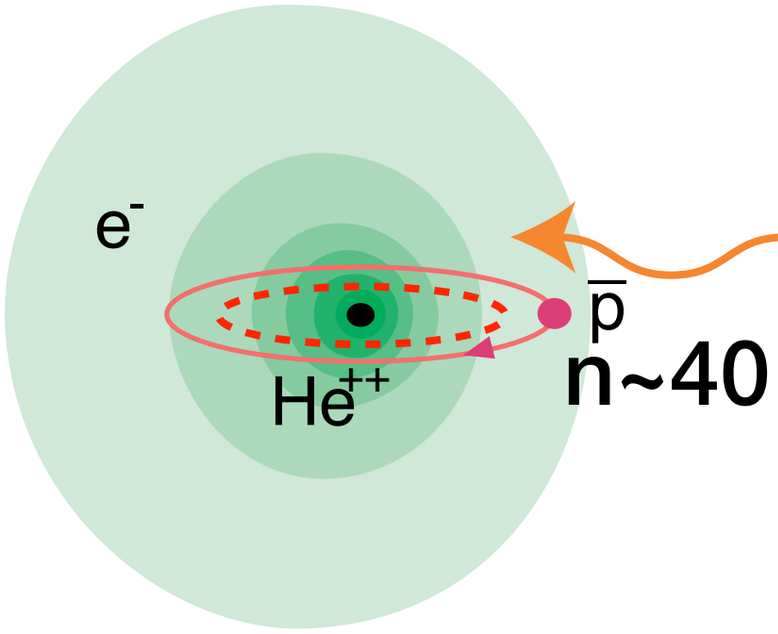
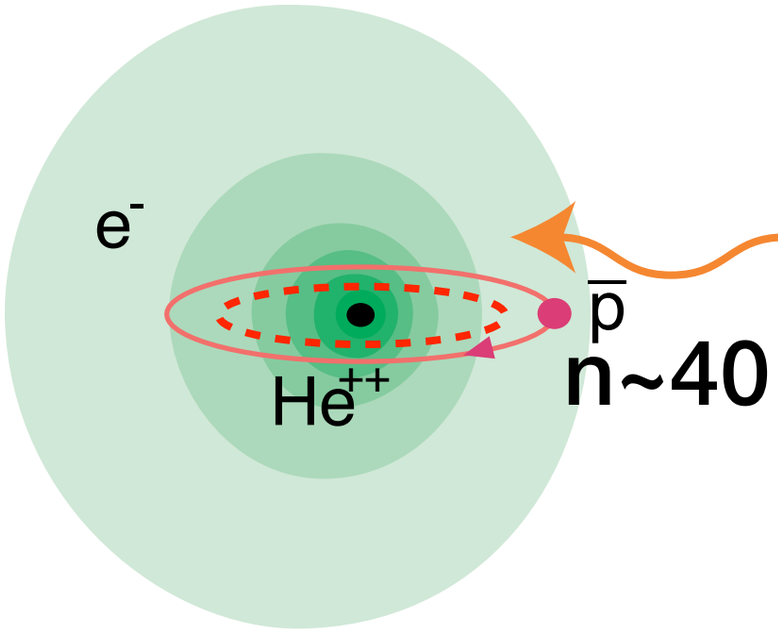


laser pulse changes the $\bar{p}$ orbit

resonance detection via $\bar{p}$ annihilation

p̄He spectroscopy → $m_{\bar{p}}/m_e$



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

resonance detection via $\bar{p}$ annihilation

Frequency

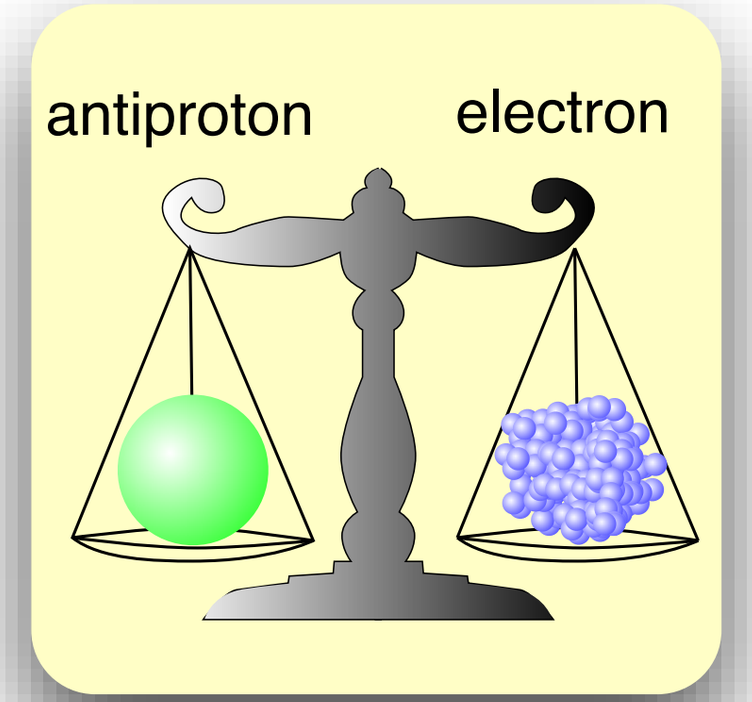
$$\nu_{n,\ell\to n',\ell'} = Rc\frac{m^*_{\bar{p}}}{m_e}Z^2_{\rm eff}\left(\frac{1}{n'^2}-\frac{1}{n^2}\right)+QED$$

$\bar{p}$ - e mass ratio

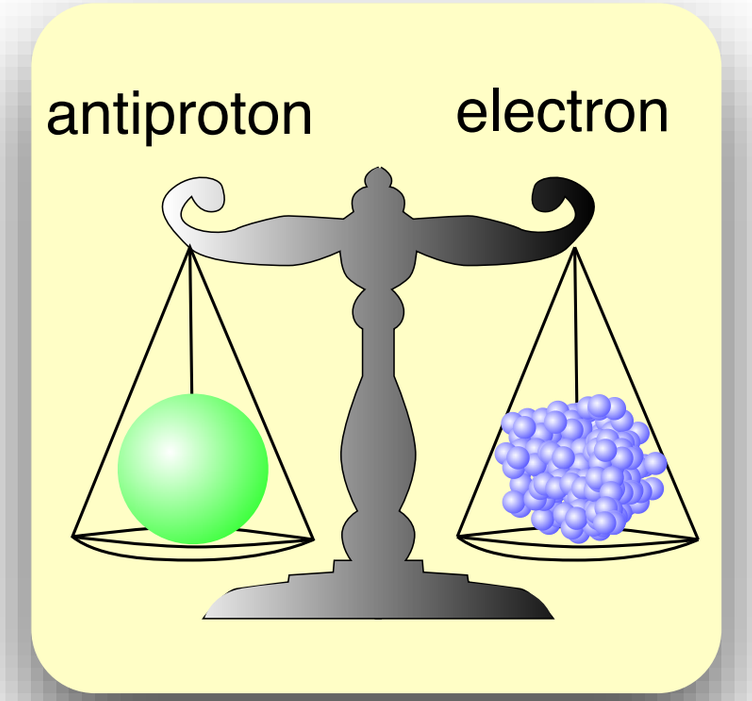
Theory

Korobov

p̄He can contribute to



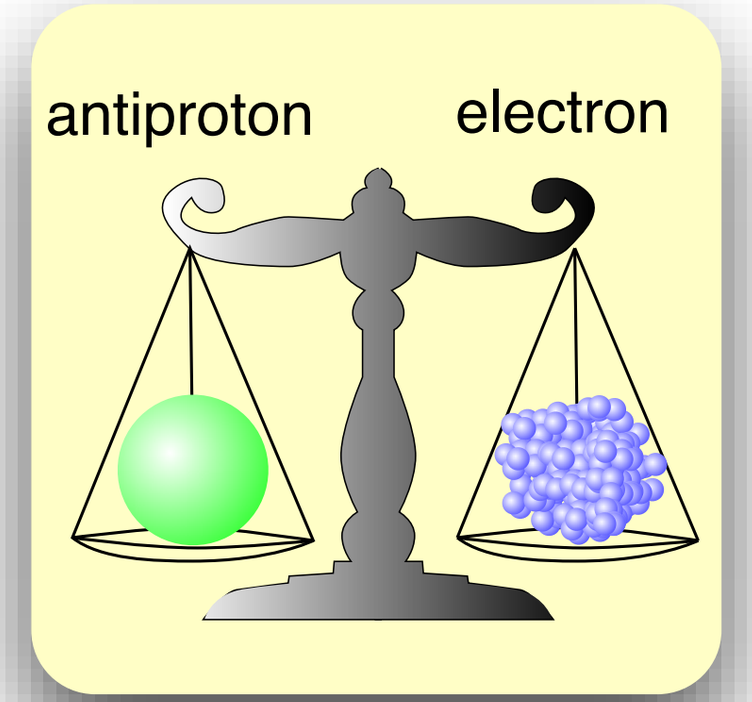
p̄He can contribute to



↓

CPT test

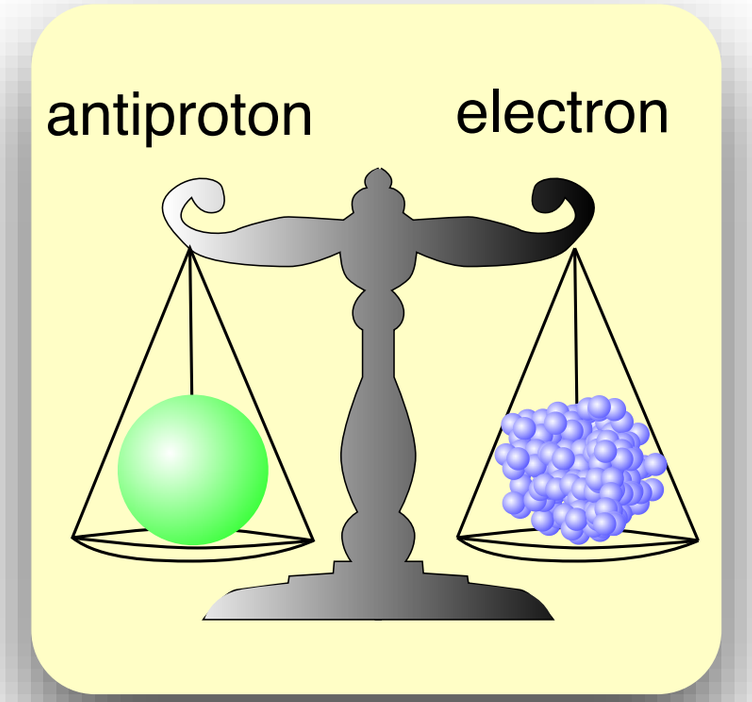
p̄He can contribute to



↓ CPT test

↓ CPT theorem

p̄He can contribute to

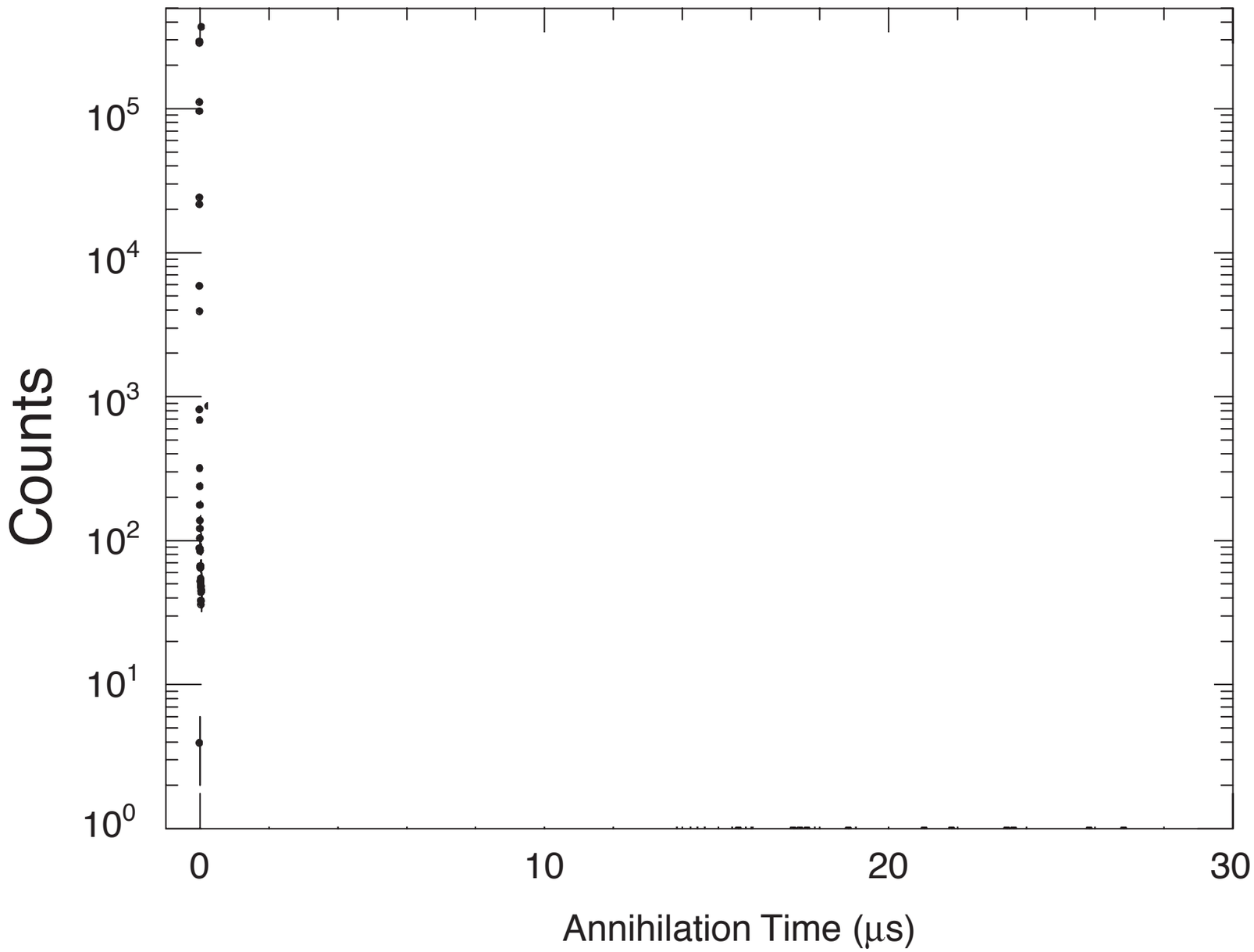


↓ CPT test

↓ CPT theorem

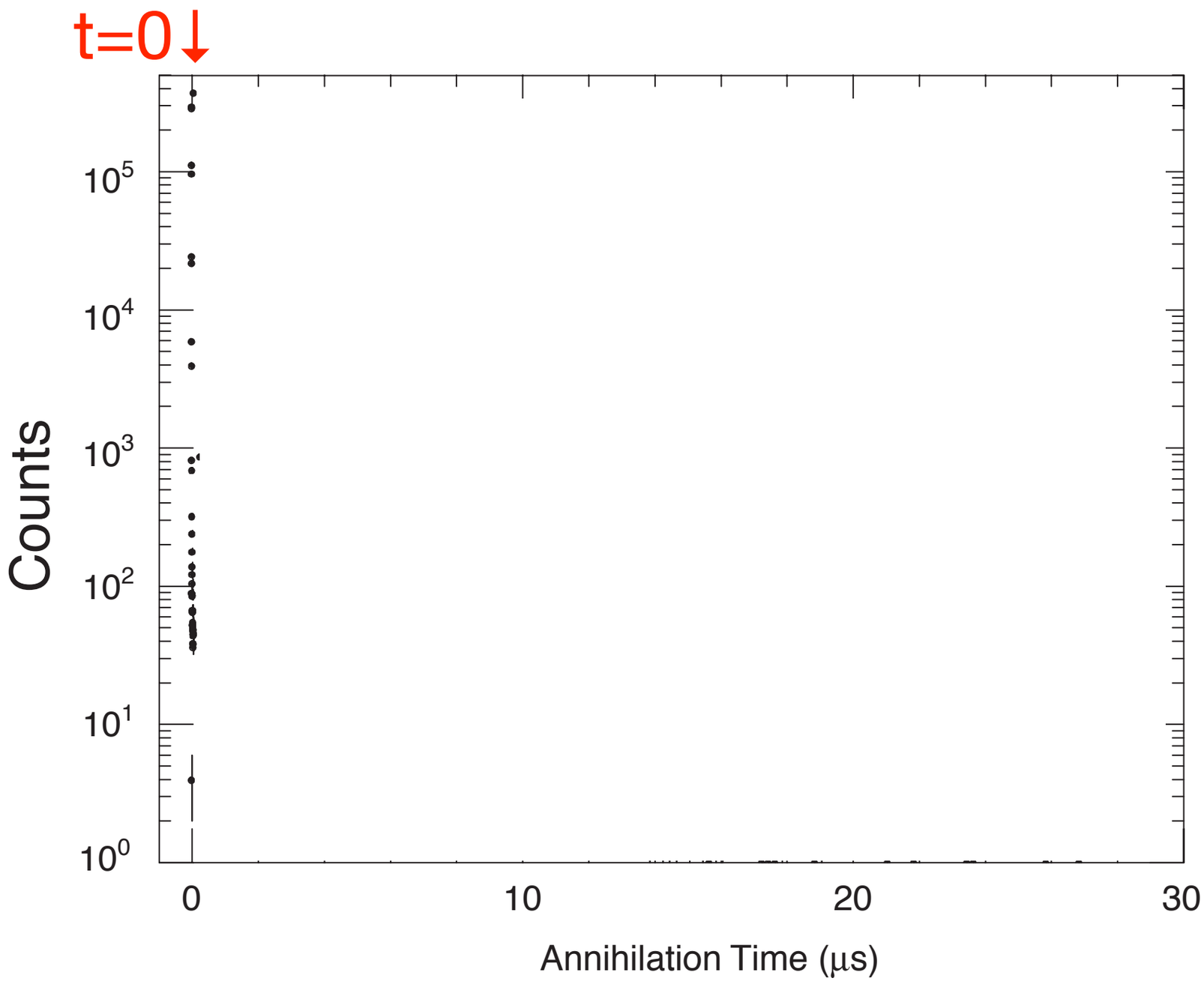
↓ proton-electron mass ratio (CODATA)

discovery of p̄ longevity in helium (at KEK)



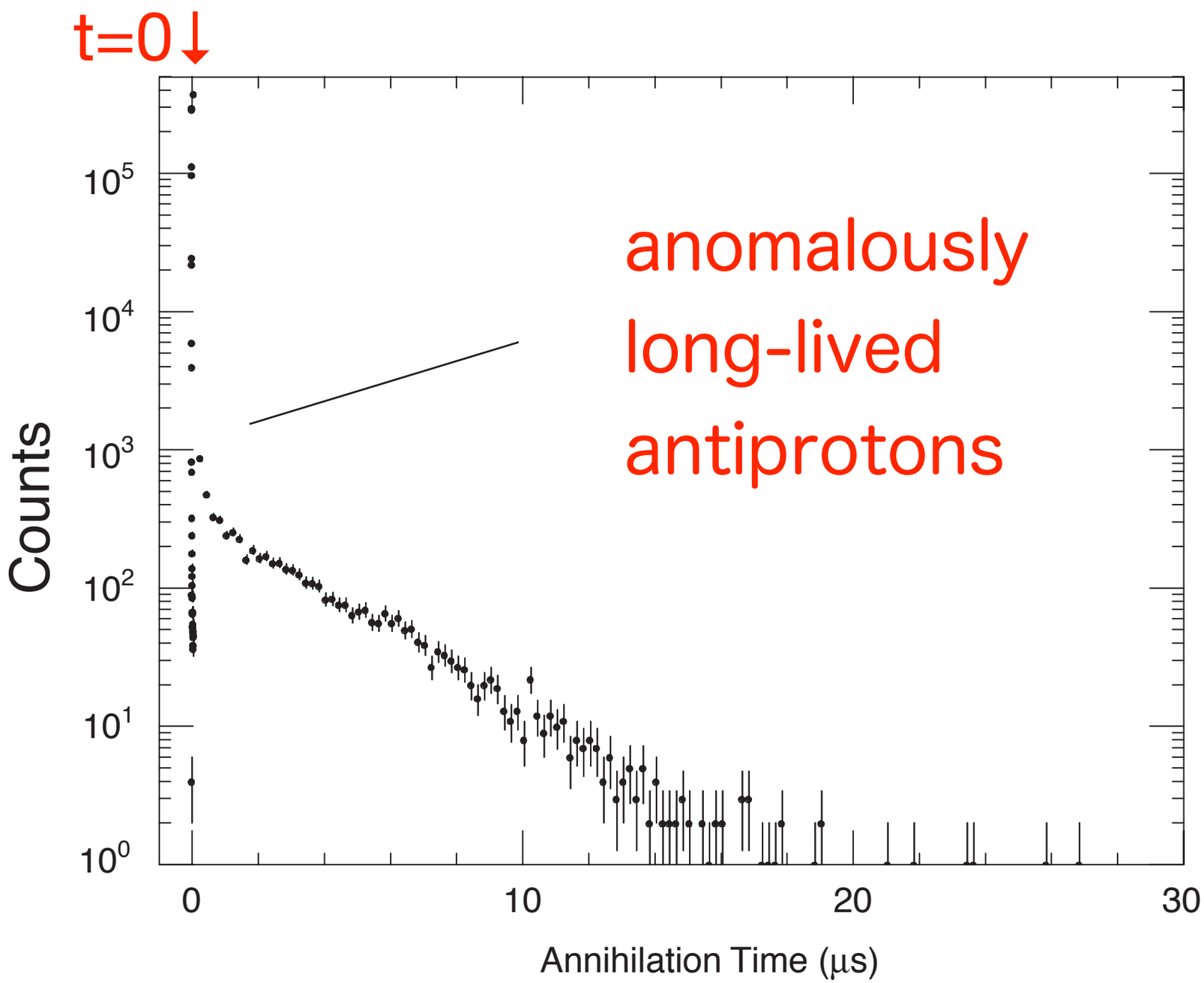
Iwasaki et al., PRL 67 (1991) 1246

discovery of p̄ longevity in helium (at KEK)



Iwasaki et al., PRL 67 (1991) 1246

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



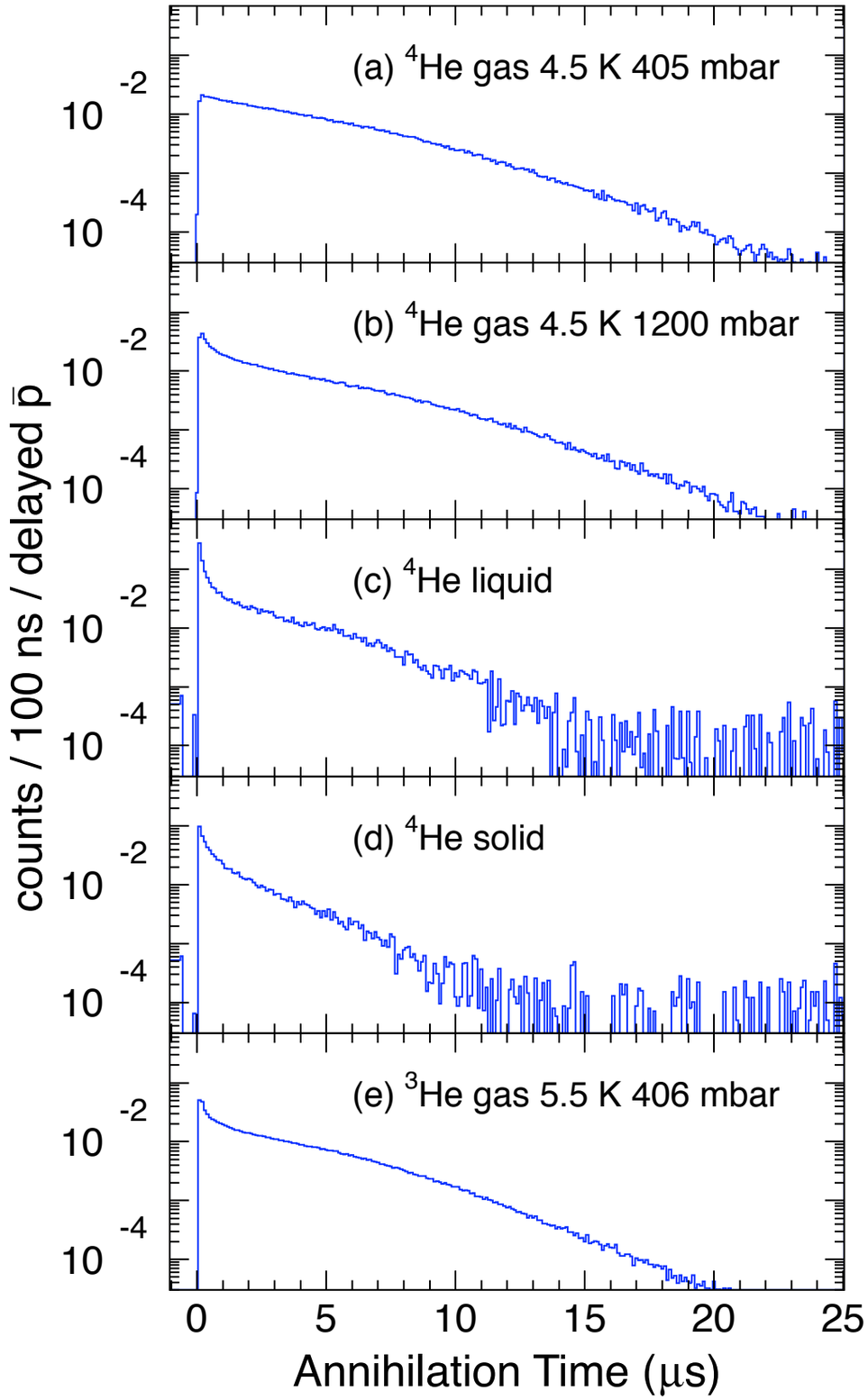
Iwasaki et al., PRL 67 (1991) 1246

p̄He formation probability & lifetime

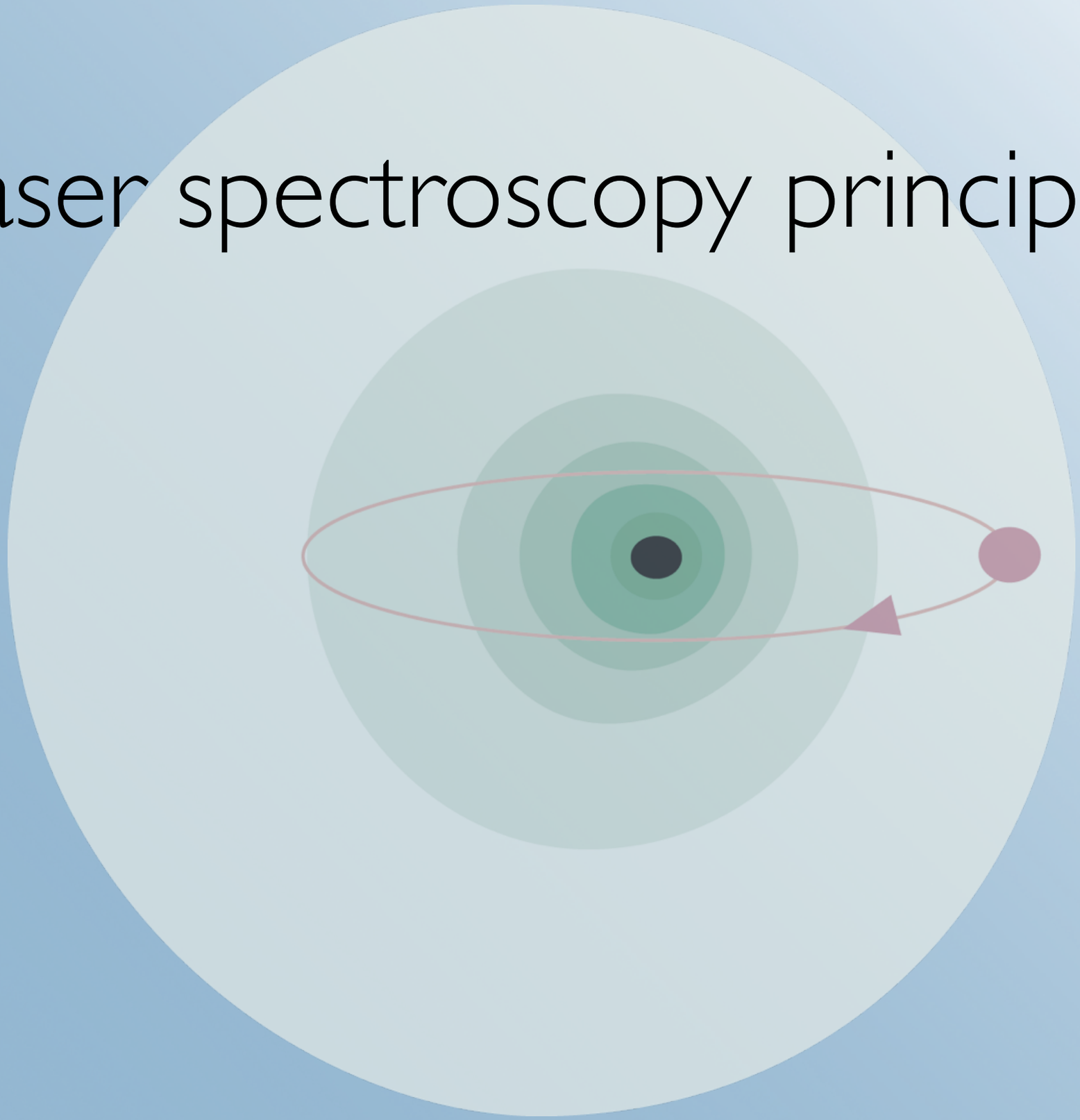
At LEAR -

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

Lifetime 3~4μs, formation probability ~3%

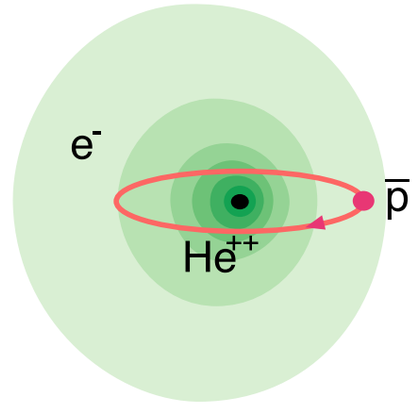


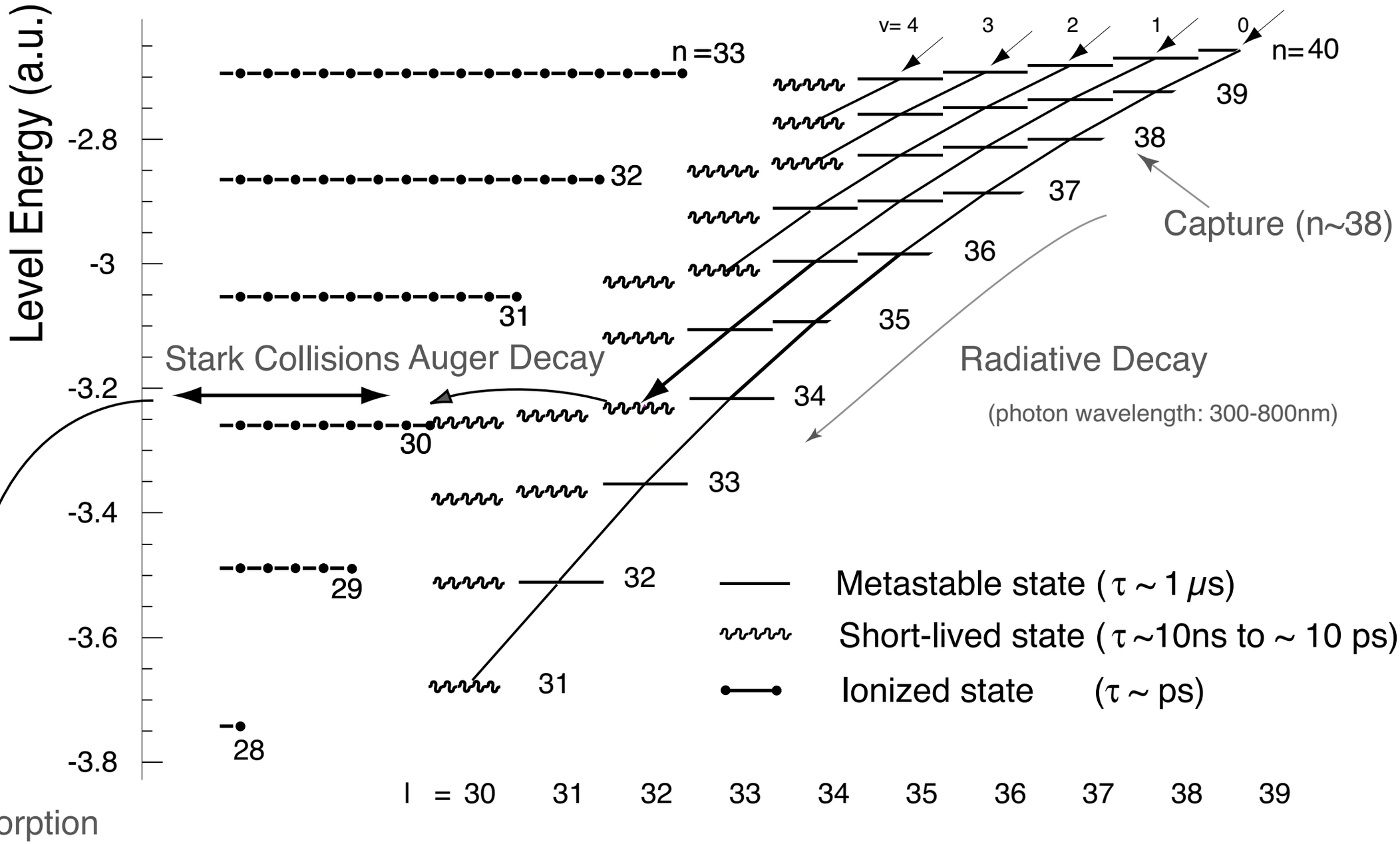
Laser spectroscopy principles

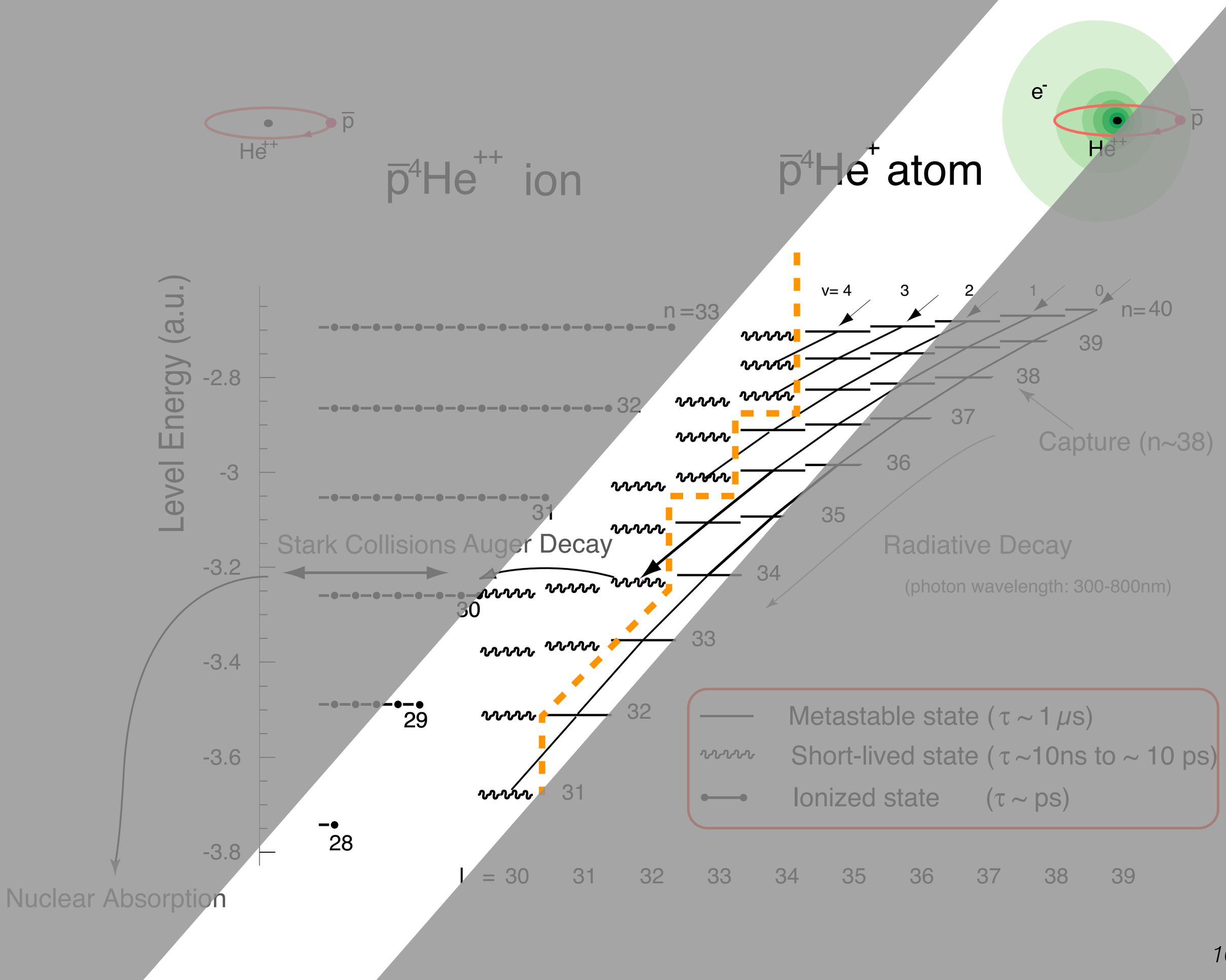


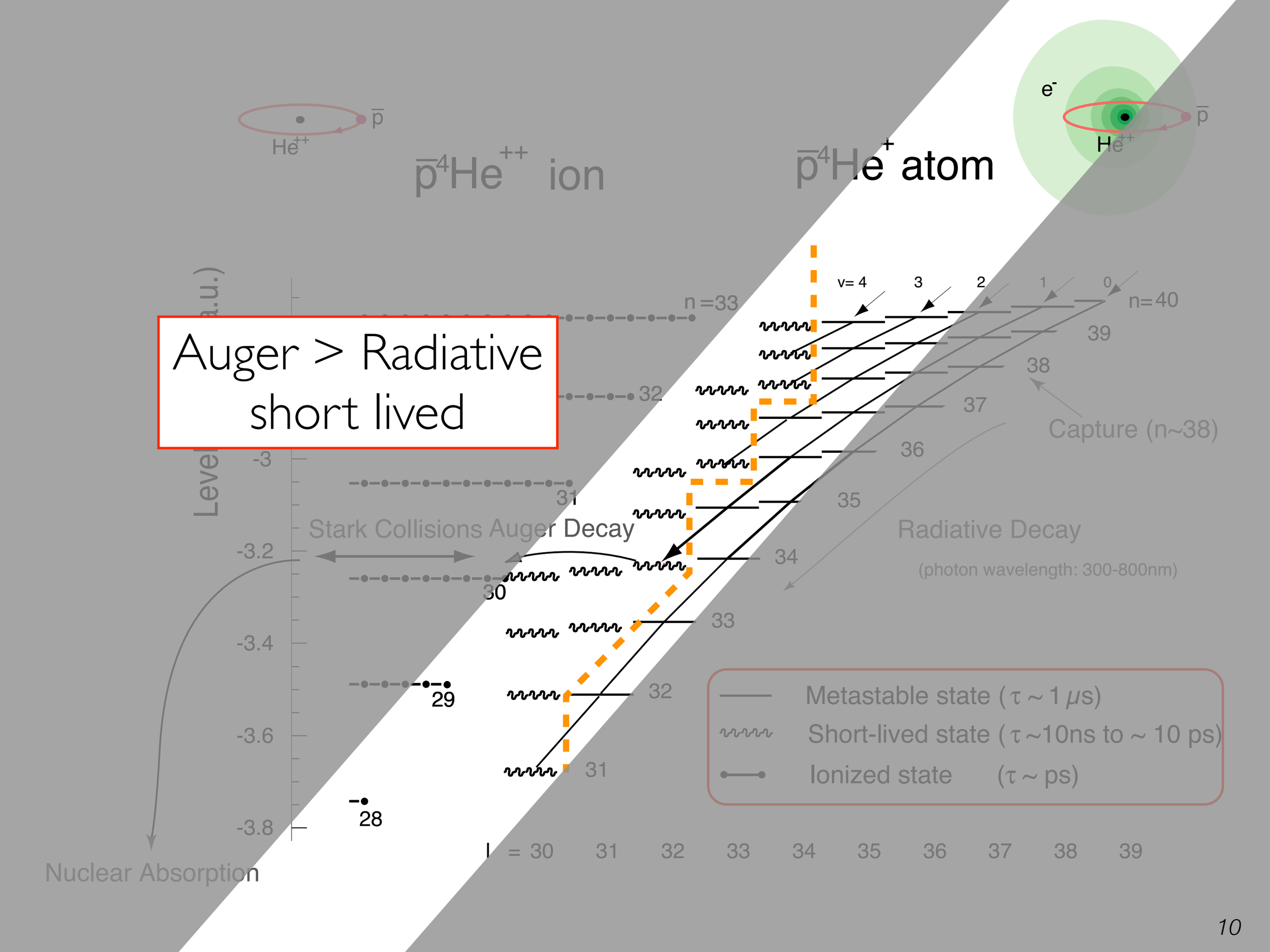
$\bar{p}^4He^{++}$ ion

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






$\bar{p}^4He^{++}$ ion
$\bar{p}^4He^{+}$ atom
He^{++}
$\bar{p}$
e^-
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
Stark Collisions Auger Decay
Capture (n~38)
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


p̄
He++
p̄4He++ ion
p̄4He+ atom
e-
p̄
He++
Auger > Radiative
short lived
v= 4
3
2
1
0
n =33
n=40
39
38
37
36
35
34
33
32
31
30
29
28
-3
-3.2
-3.4
-3.6
-3.8
Stark Collisions Auger Decay
Capture (n~38)
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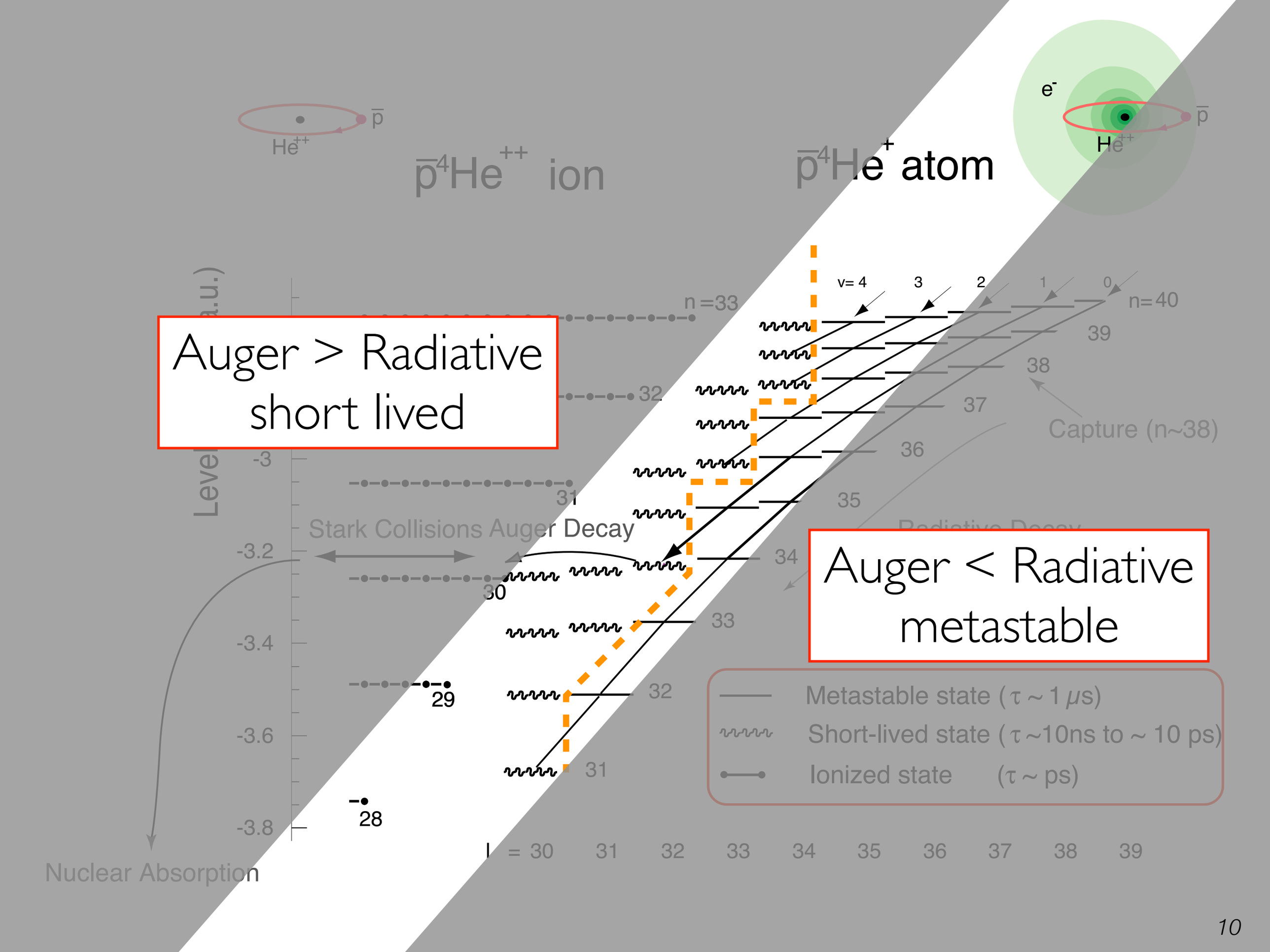
Nuclear Absorption


$\bar{p}^4He^{++}$ ion
$\bar{p}^4He^{+}$ atom
He^{++}
$\bar{p}$
e^-
Auger > Radiative
short lived
Auger < Radiative
metastable
Stark Collisions Auger Decay
Nuclear Absorption
Capture (n~38)
Radiative Decay
v= 4
3
2
1
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36
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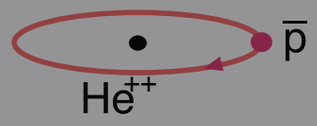
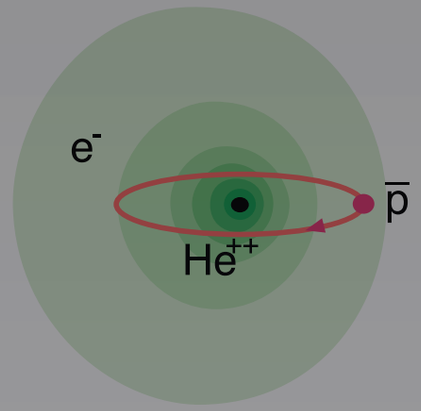
34
33
32
31
30
29
28
-3
-3.2
-3.4
-3.6
-3.8
l = 30 31 32 33 34 35 36 37 38 39
Metastable state ($\tau \sim 1\,\mu s$)
Short-lived state ($\tau \sim$10ns to $\sim$ 10 ps)
Ionized state ($\tau \sim$ ps)



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

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



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
30
29
28

Capture (n~38)

Stark Collisions Auger Decay

Radiative Decay

(photon wavelength: 300-800nm)

Nuclear Absorption

Metastable state ($\tau \sim 1\,\mu s$)

Short-lived state ($\tau \sim$10ns to $\sim$ 10 ps)

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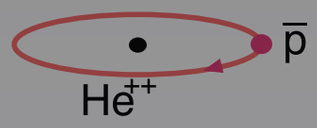

$\bar{p}^4He^{++}$ ion

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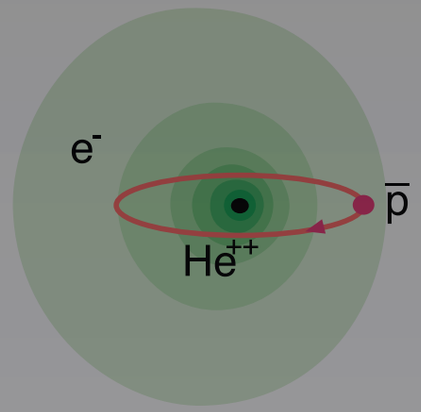


Auger decay (<10 ns)

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)

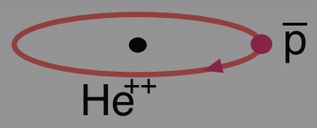
Nuclear Absorption

Metastable state ($\tau \sim 1\,\mu s$)

Short-lived state (τ ~10ns to ~ 10 ps)

Ionized state ($\tau \sim$ ps)

l = 30 31 32 33 34 35 36 37 38 39



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

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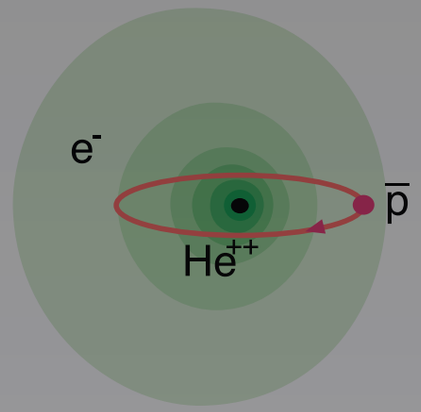

Stark collisions
induce s-wave (L=0) admixture

Level Energy (a.u.)

-2.8

-3

-3.2

-3.4

-3.6

-3.8

Stark Collisions Auger Decay

Nuclear Absorption

Capture (n~38)

Radiative Decay

(photon wavelength: 300-800nm)

n=40

39

38

37

36

35

34

33

32

31

30

29

28

Metastable state ($\tau \sim 1\,\mu s$)

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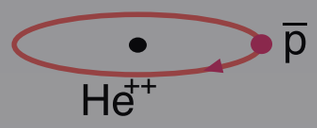
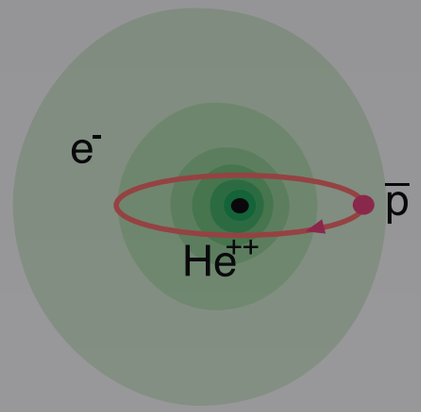
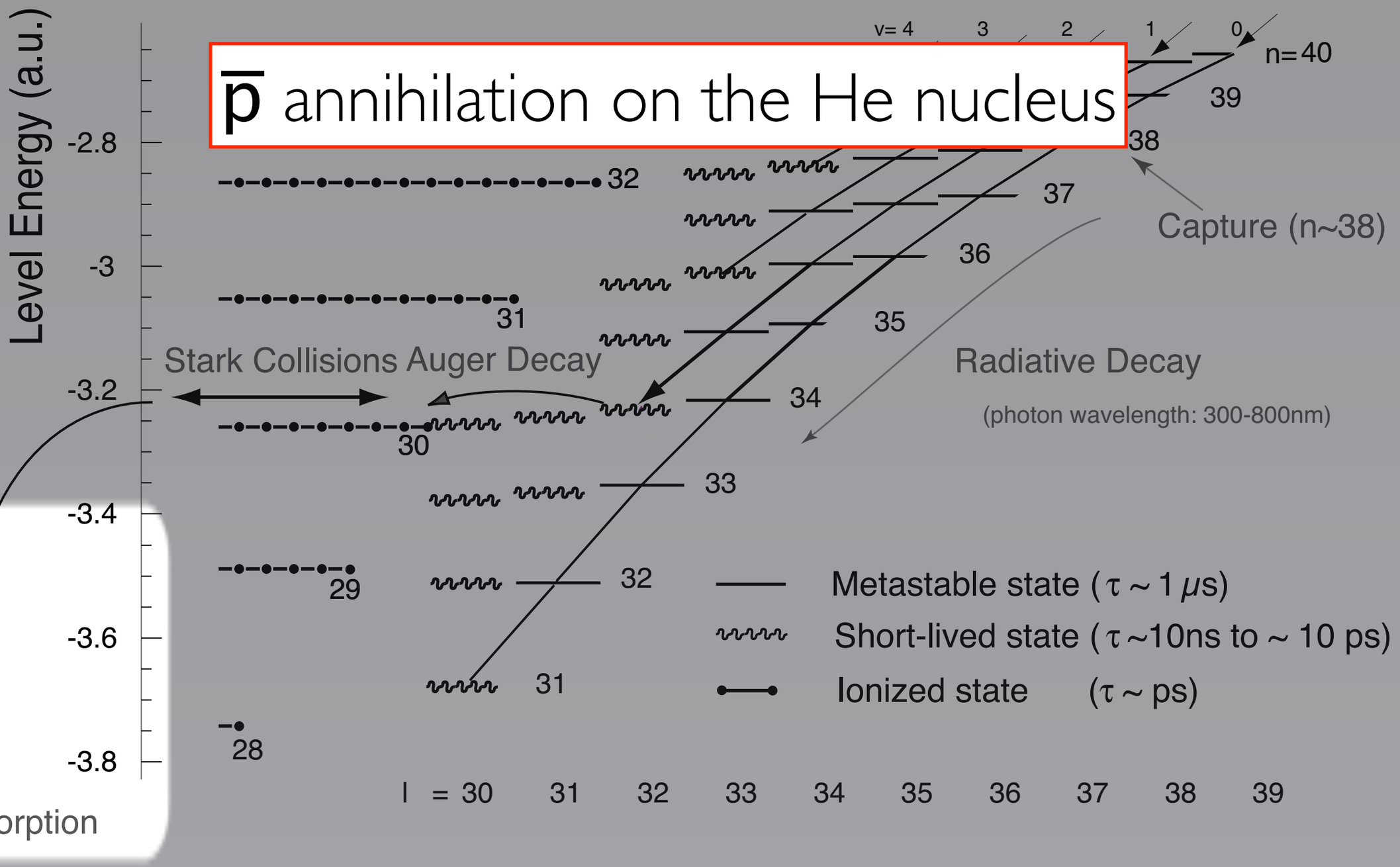


$\bar{p}^4He^{++}$ ion

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



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



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

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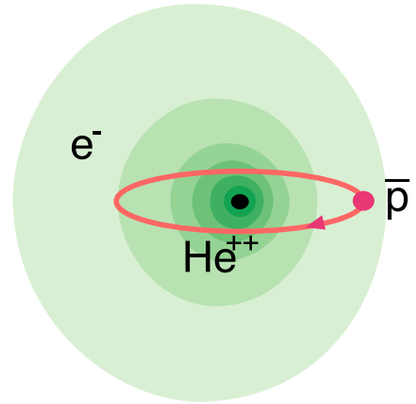
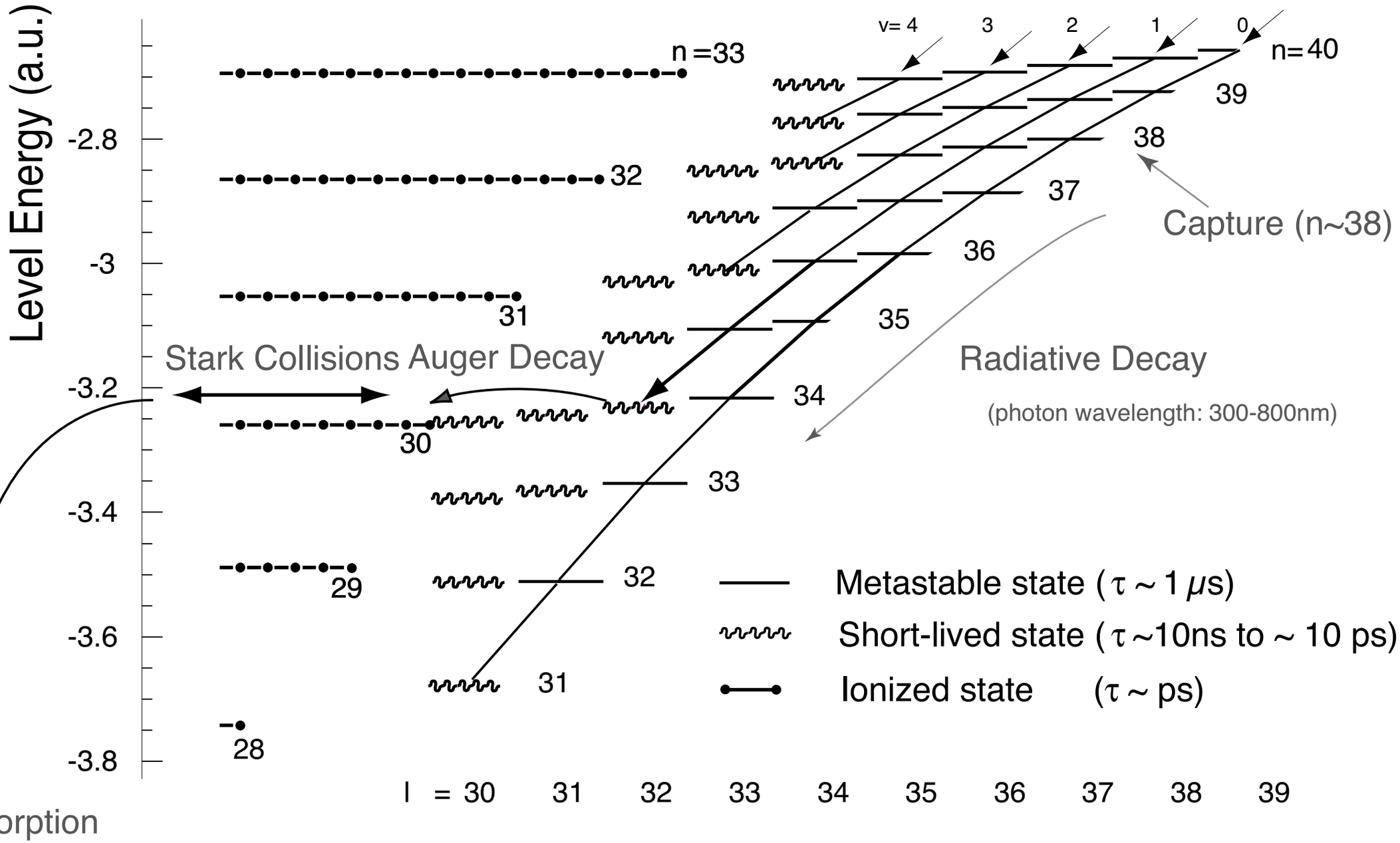
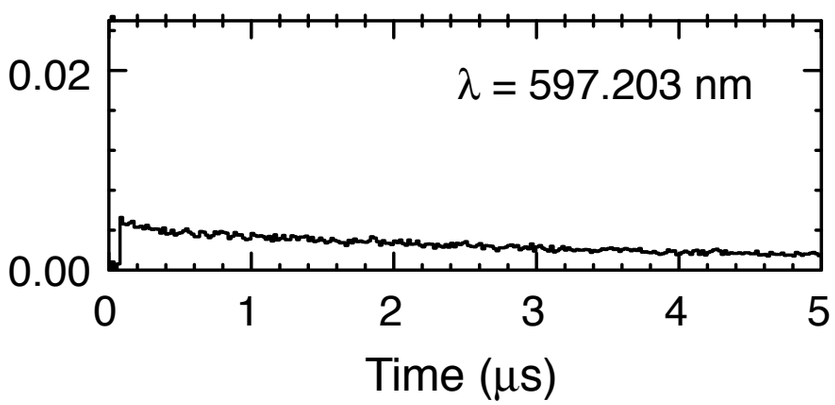




An example, (n,l)=(39,35)→(38,34)



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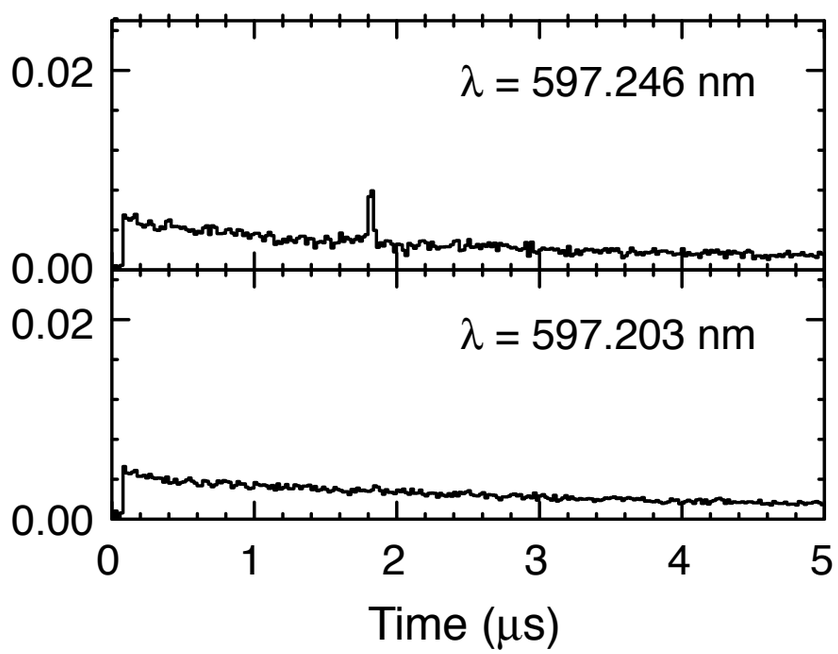

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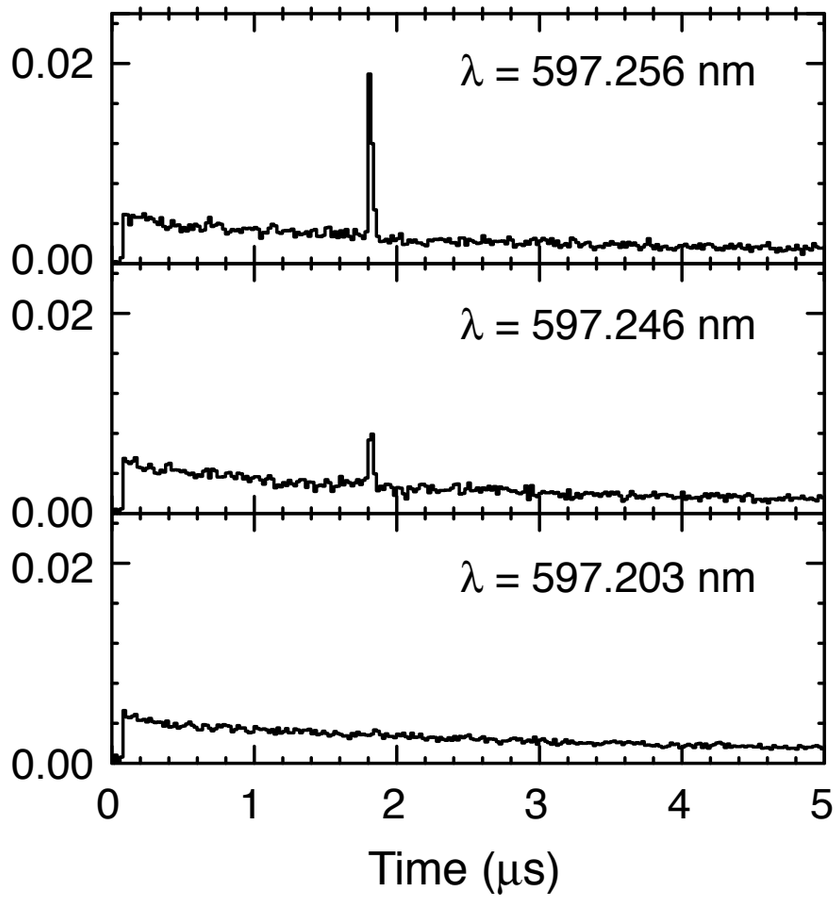

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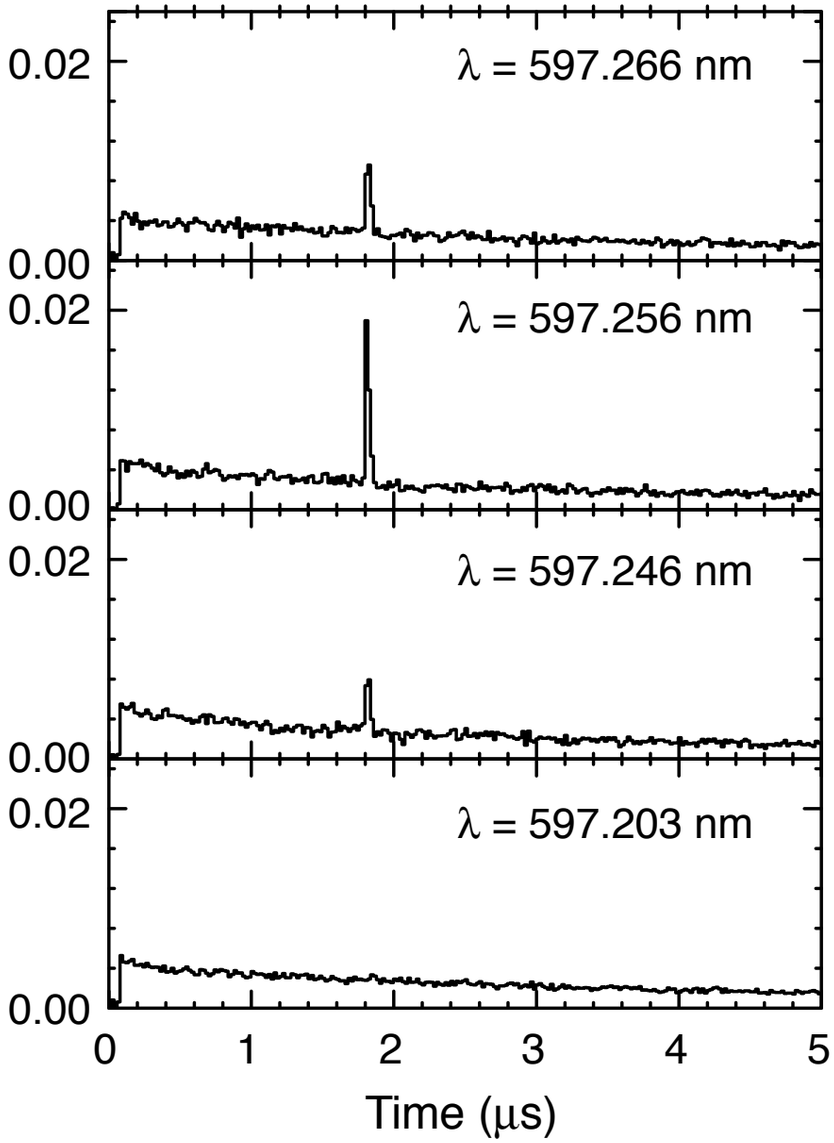

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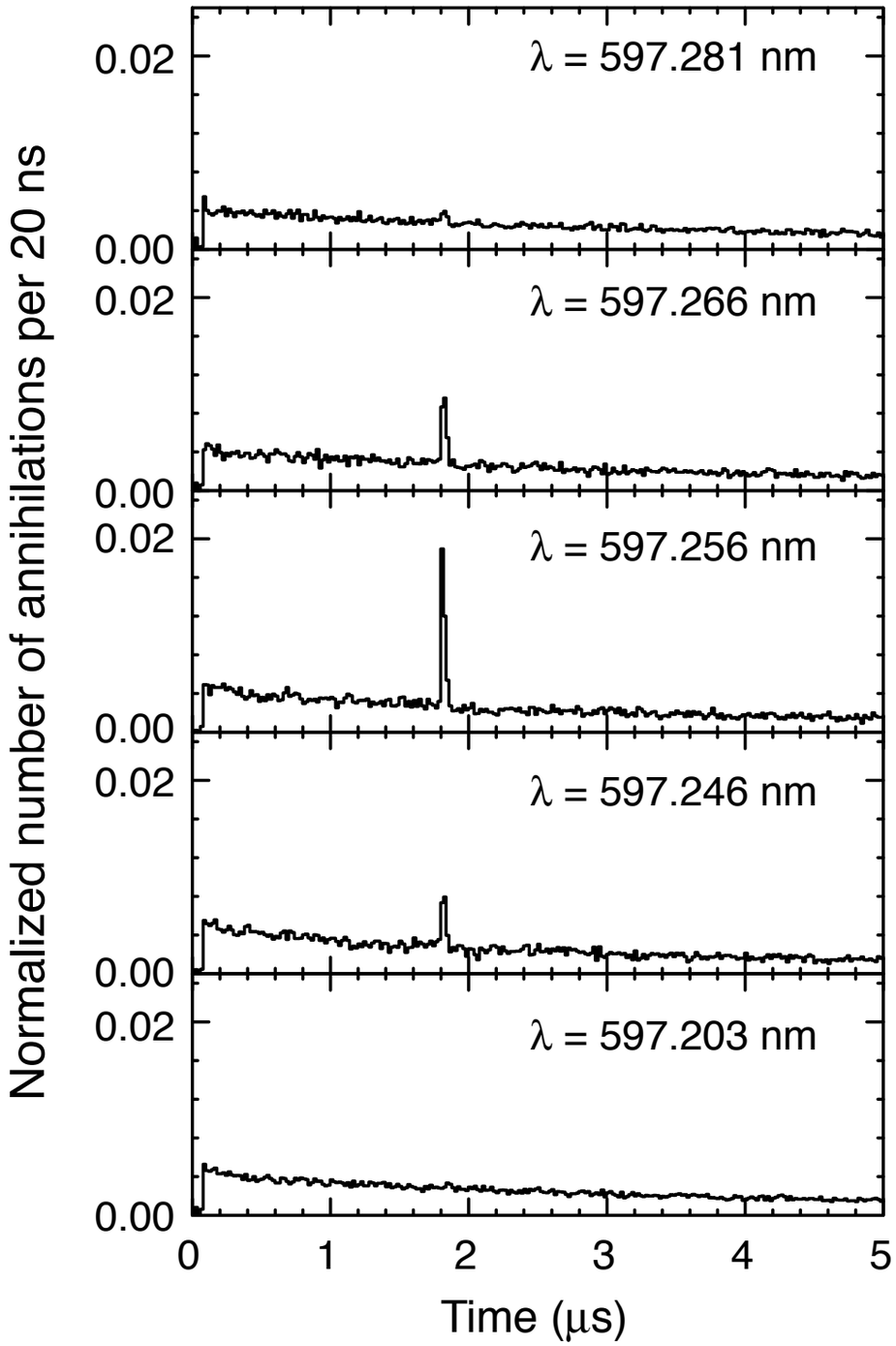
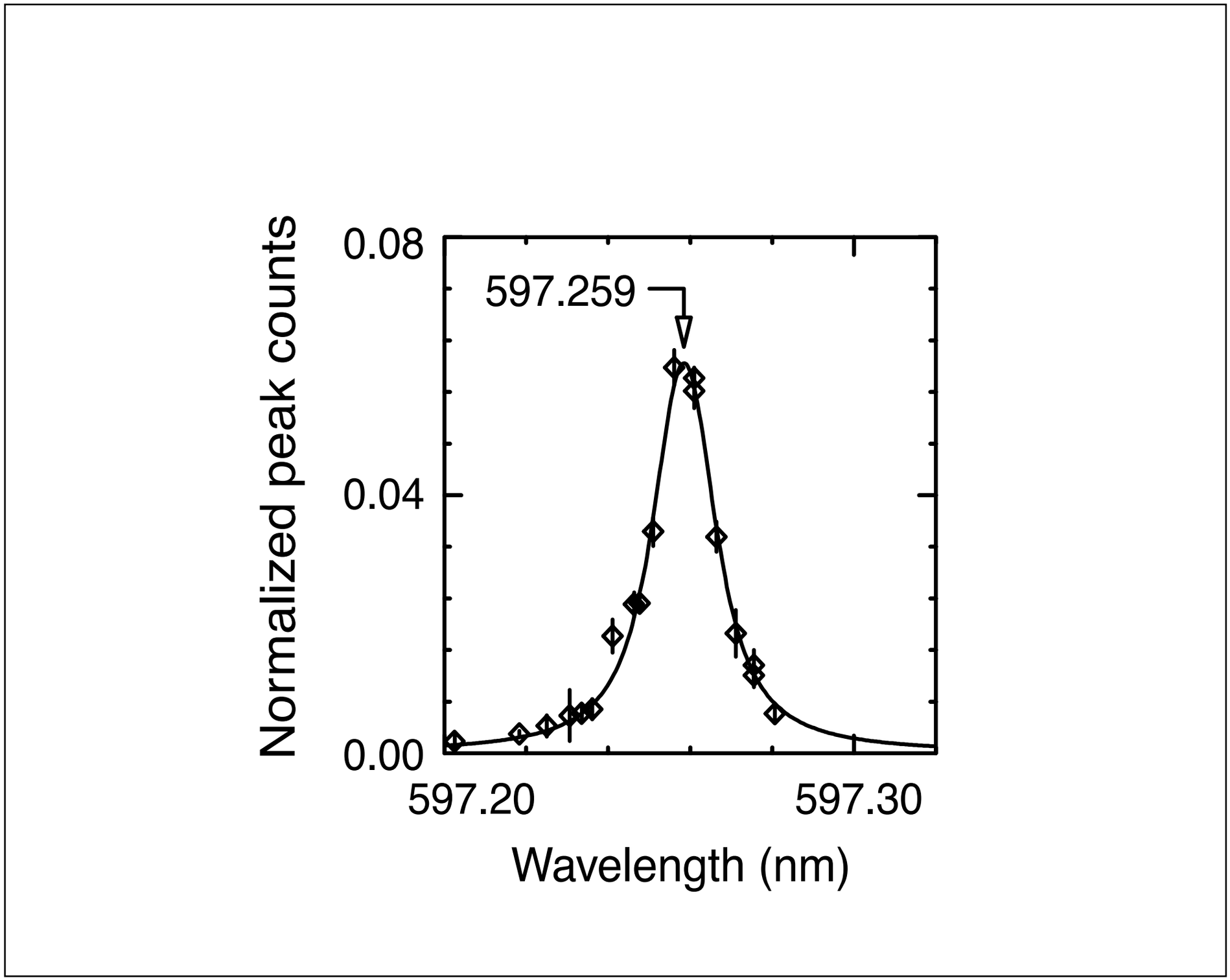
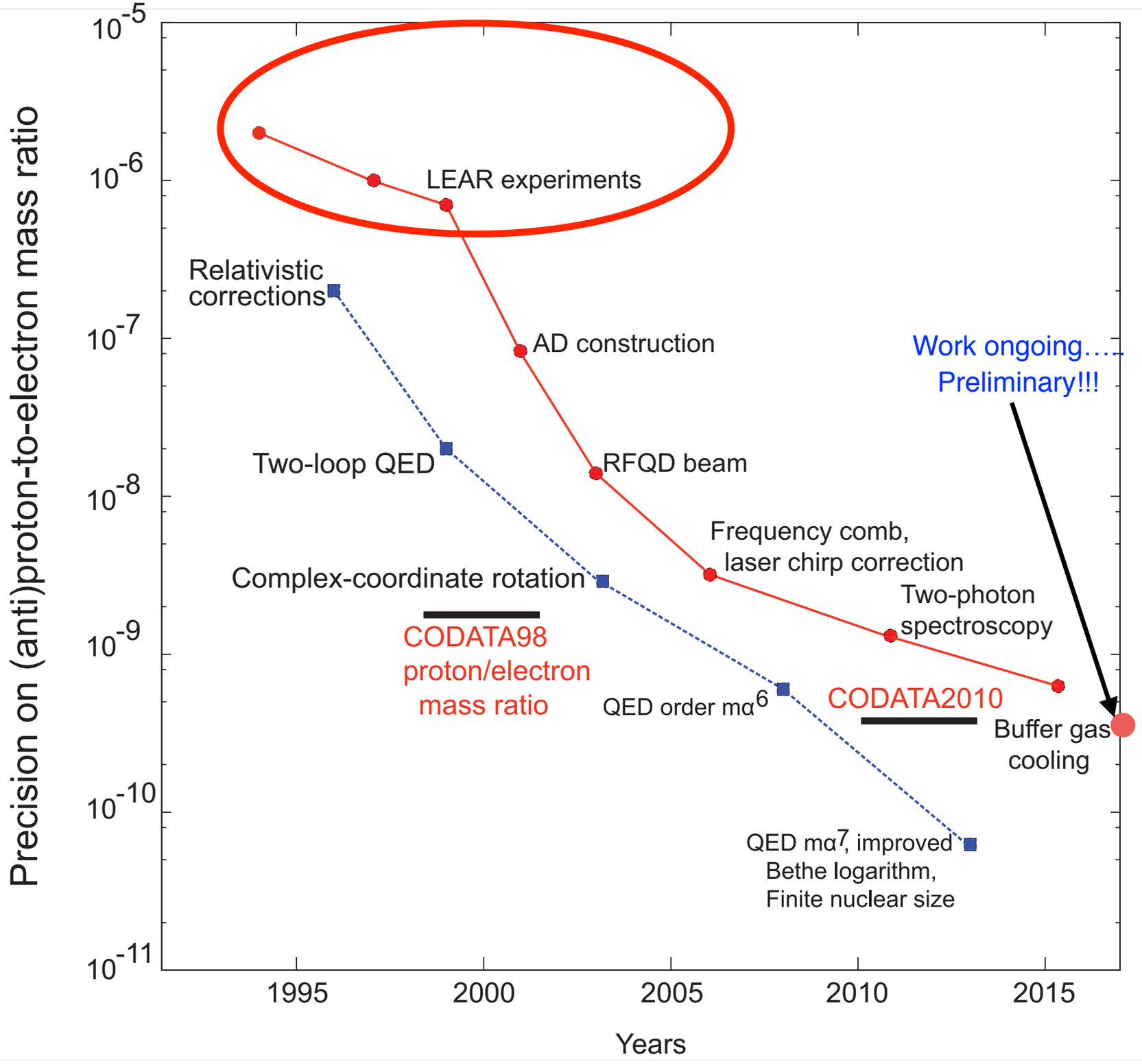
N. Morita et al, Phys. Rev. Lett. 72 (1994) 1180.



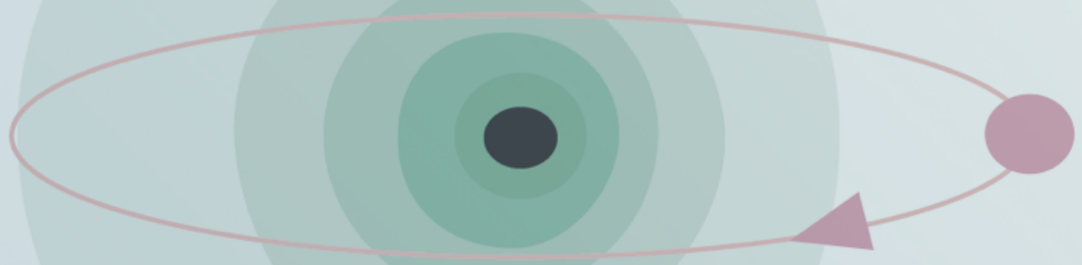
Laser Resonance Curve

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

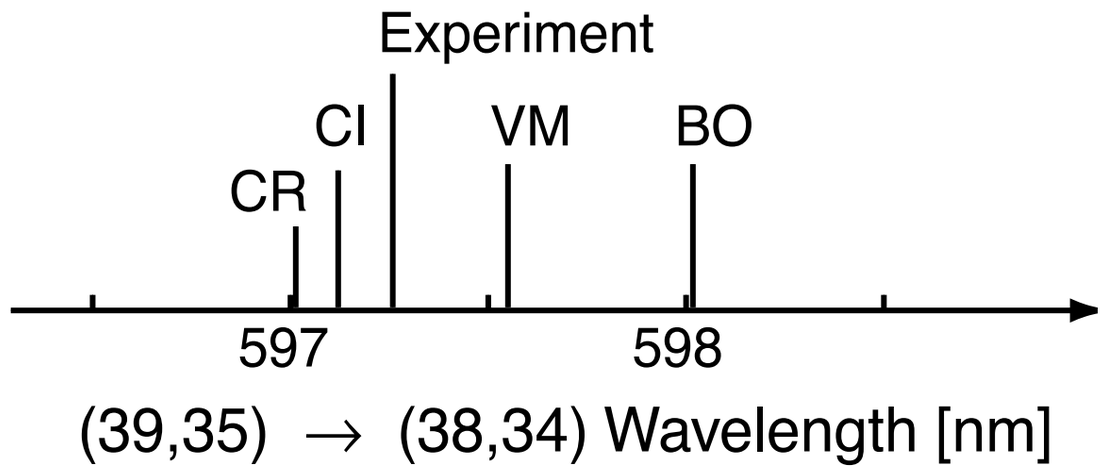


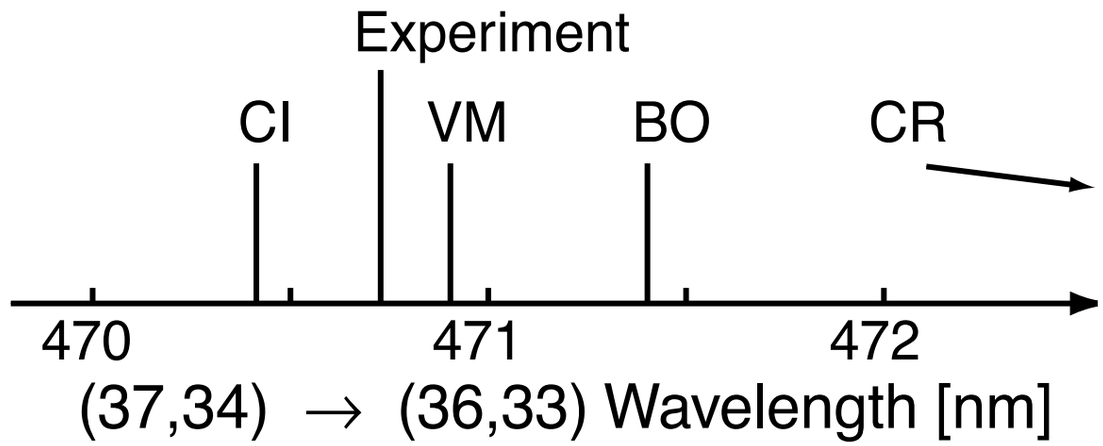

Precision on (anti)proton-to-electron mass ratio
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
1995
2000
2005
2010
2015
Years
LEAR experiments
AD construction
RFQD beam
Frequency comb,
laser chirp correction
Two-photon
spectroscopy
Buffer gas
cooling
Work ongoing…..
Preliminary!!!
Relativistic
corrections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

Theory



20 years ago - Theory precision ~ 1000 ppm





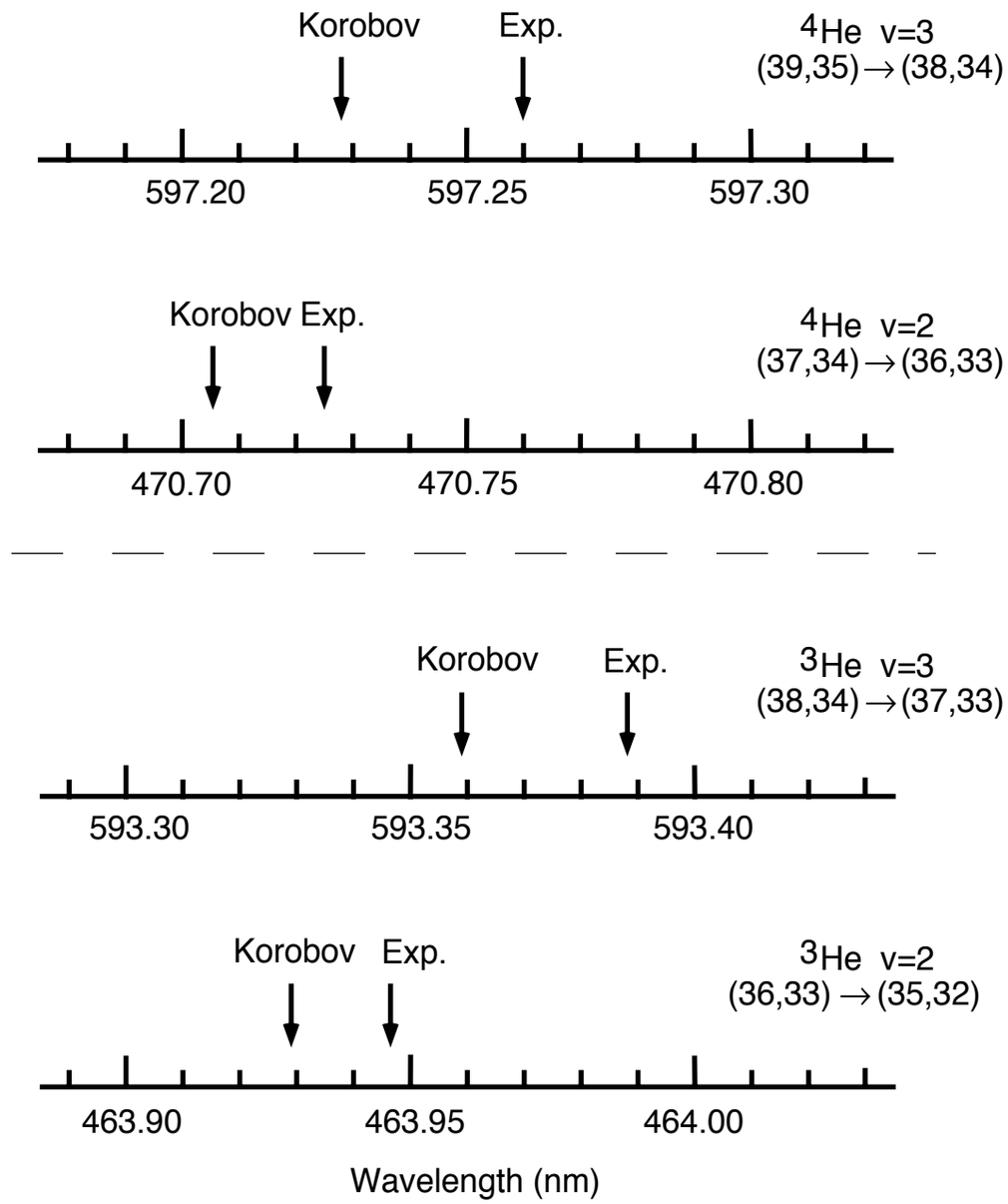
F.E. Maas et al., Phys. Rev. A 52 (1995) 4266.

50 ppm in 1996

PHYSICAL REVIEW A VOLUME 54, NUMBER 3 SEPTEMBER 1996

Variational calculation of energy levels in p He^+ molecular systems

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



Theory - non-relativistic H

antiproton

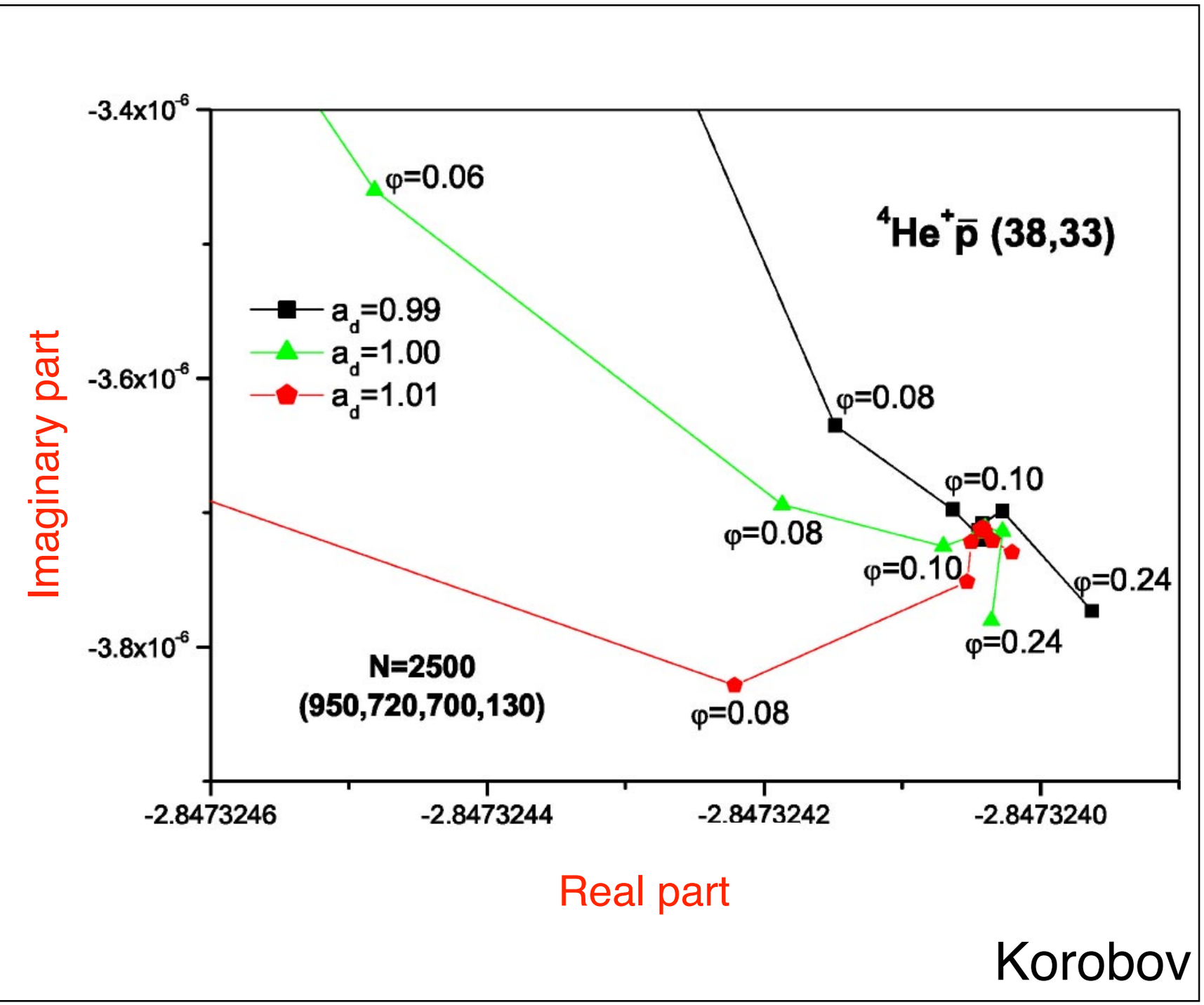
electron

$$H = T + V$$

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

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

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.

$$H = T + V$$

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

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

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

add self energy (~15 ppm)

$$H = T + V$$

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

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

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

Bethe logarithm

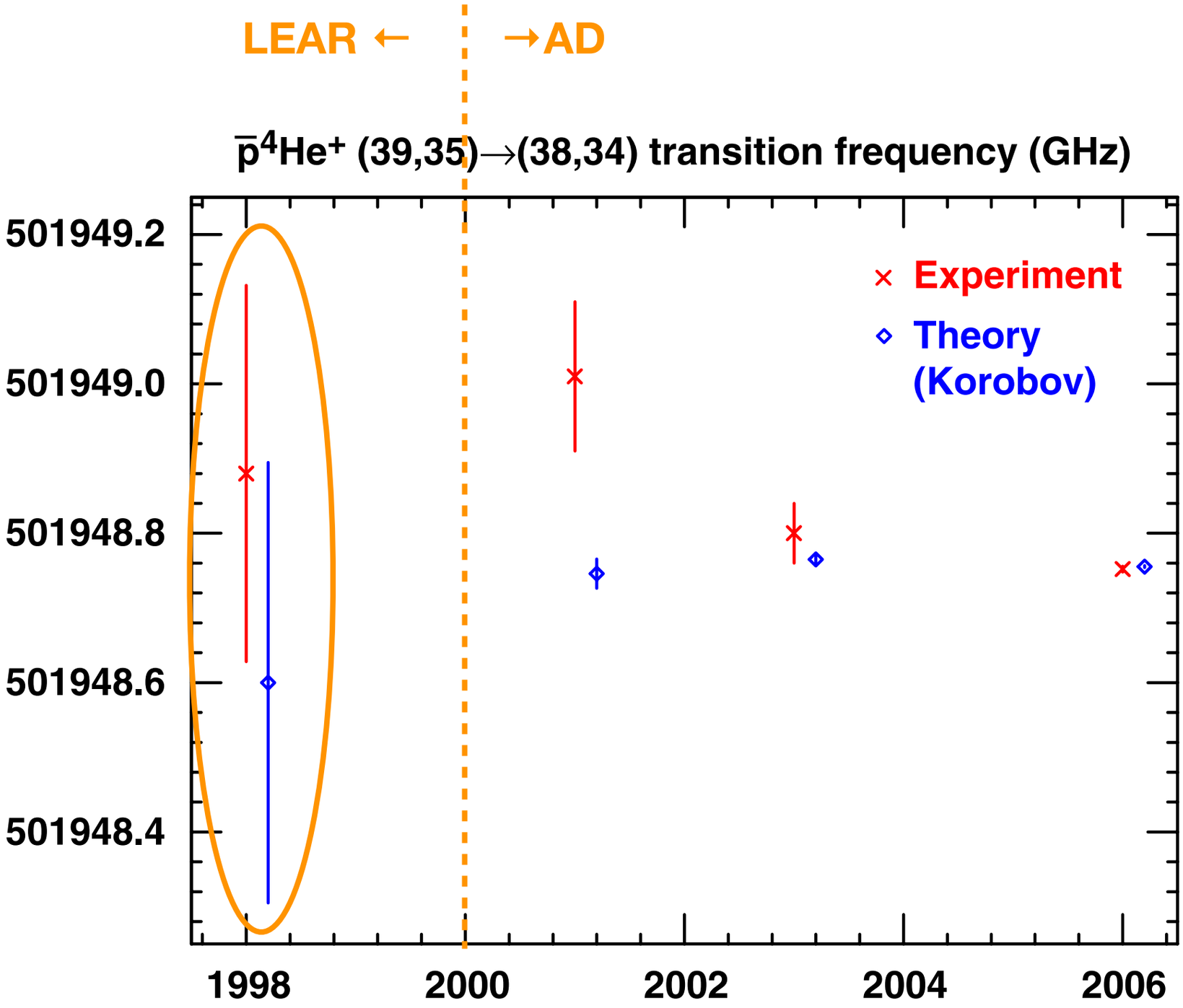
$$E_{se} = \frac{4\alpha^3}{3m_e^2}\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0}{R_\infty} + \frac{5}{6} - \frac{3}{8}\right]\langle Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\rangle$$

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

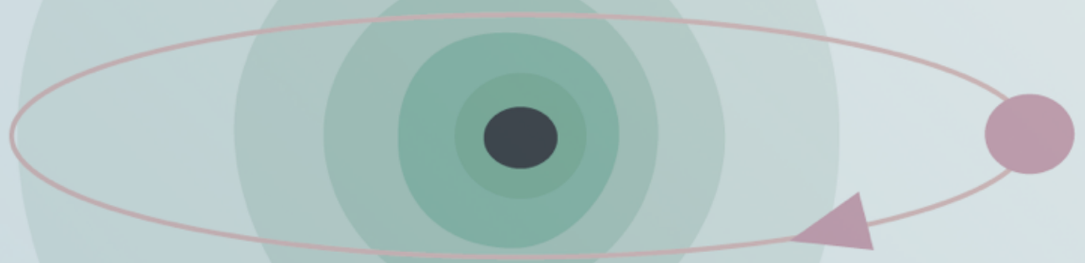
$$- \frac{4\alpha^5}{3m_e^2}\left[\frac{3}{4}\right]\langle Z_{\mathrm{He}}^3\ln^2(Z_{\mathrm{He}}\alpha)^{-2}\delta(\mathbf{r}_{\mathrm{He}})$$

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

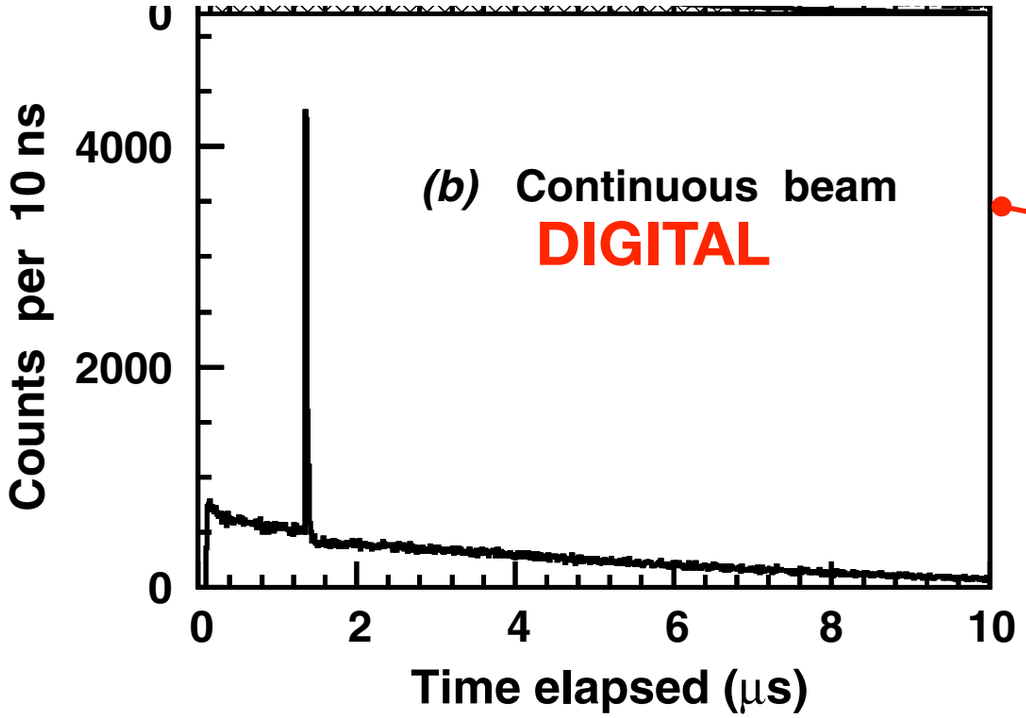
Theory vs experiment

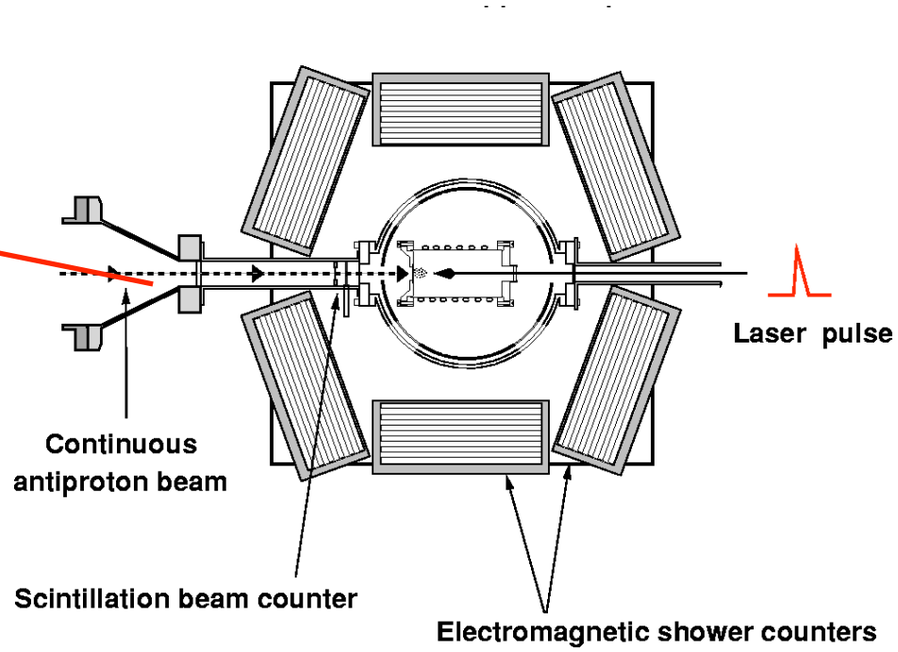


ASACUSA @ CERN AD
How to work with pulsed $\bar{p}$?



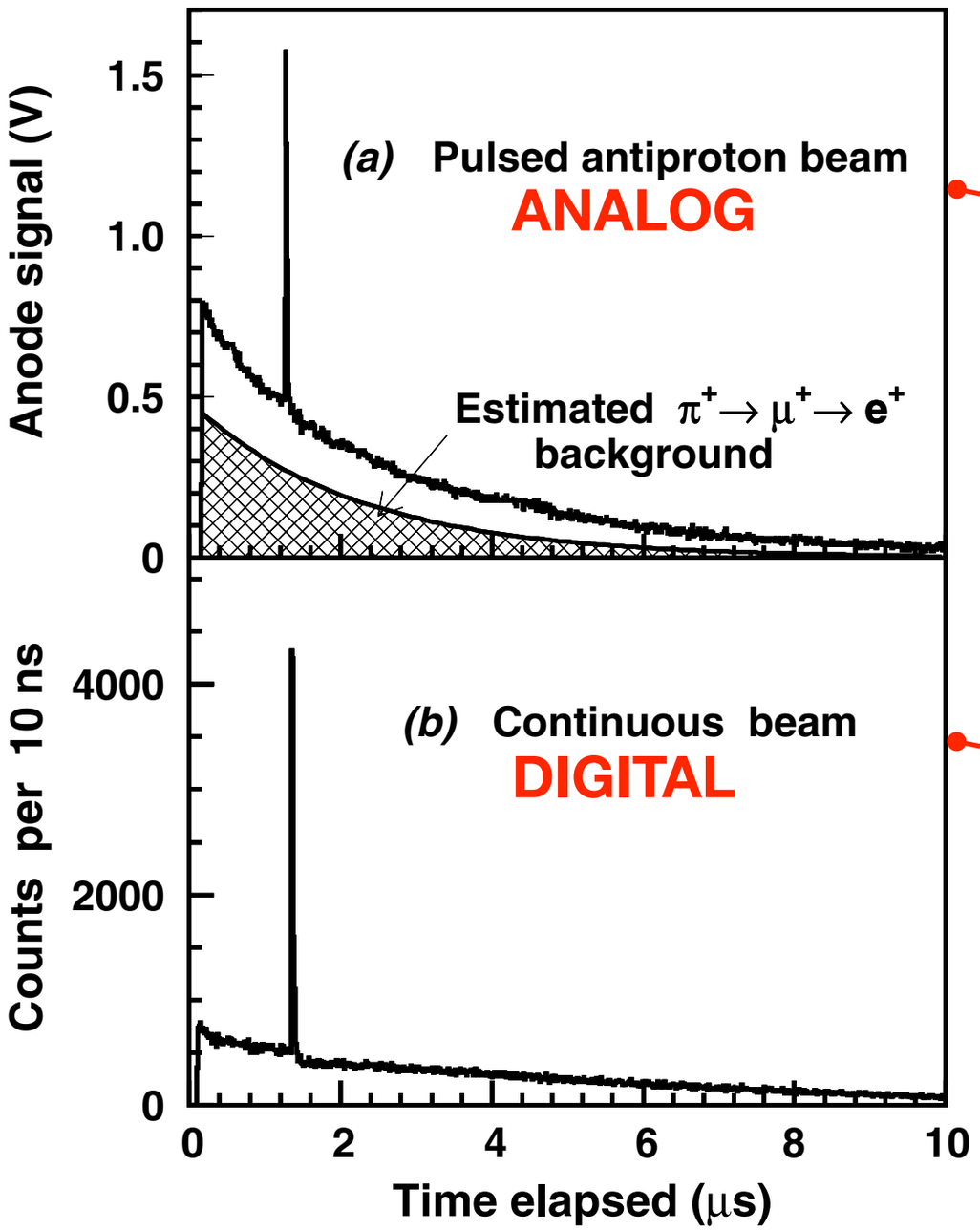
Conventional event-by-event counting

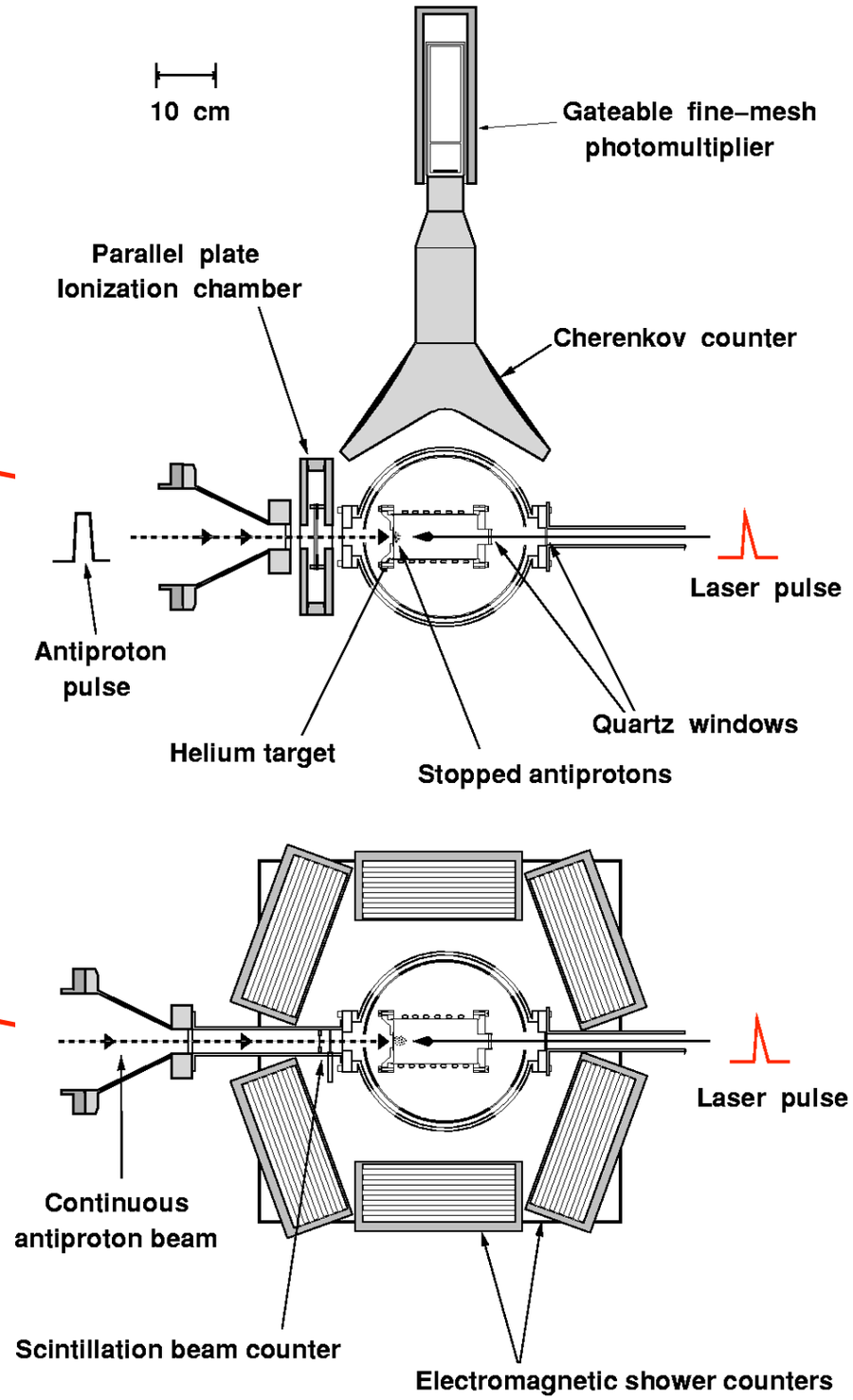




M. Hori et al., PHYSICAL REVIEW A 70, 012504 (2004).

Can’t use event-by-event counting





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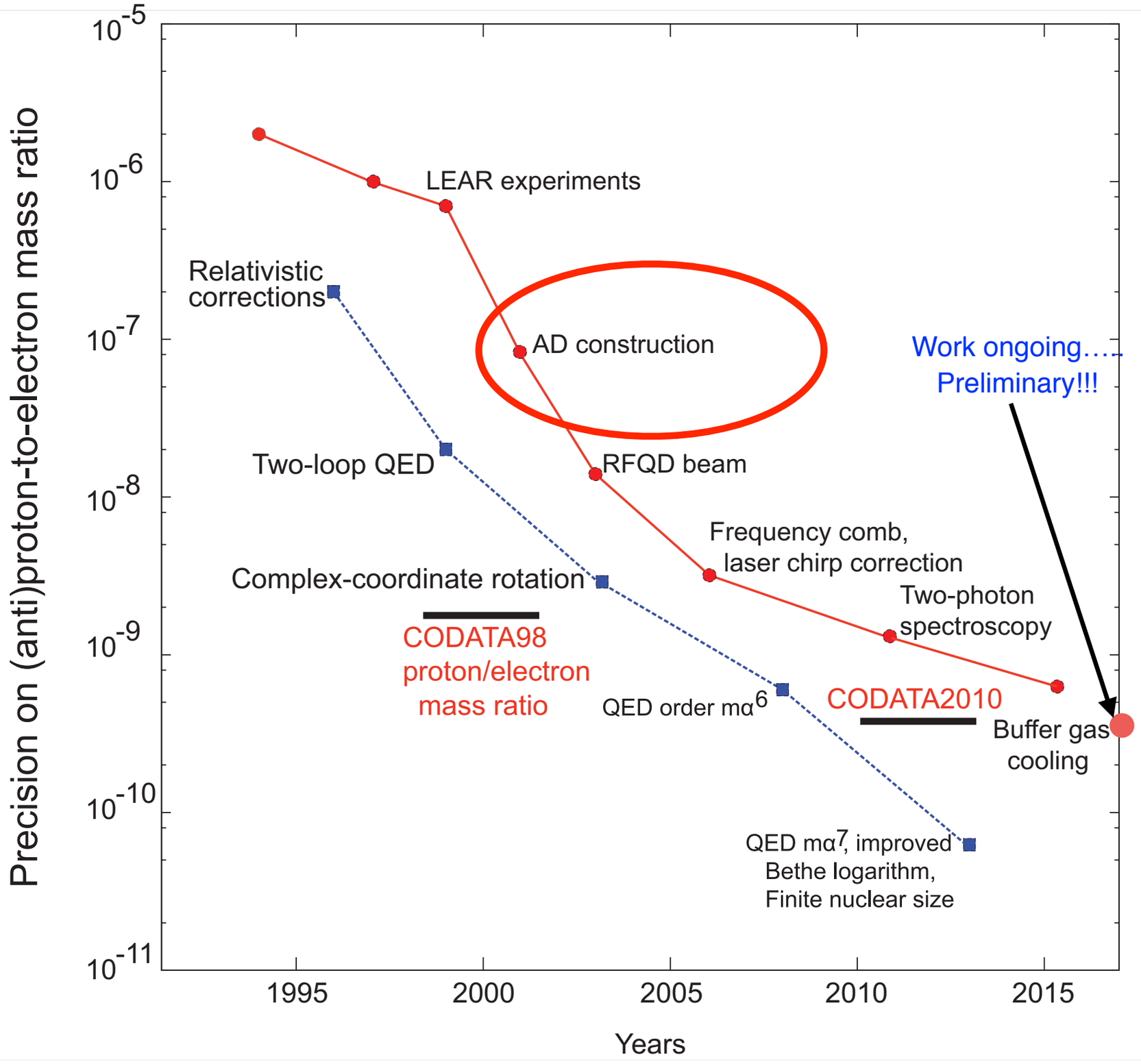
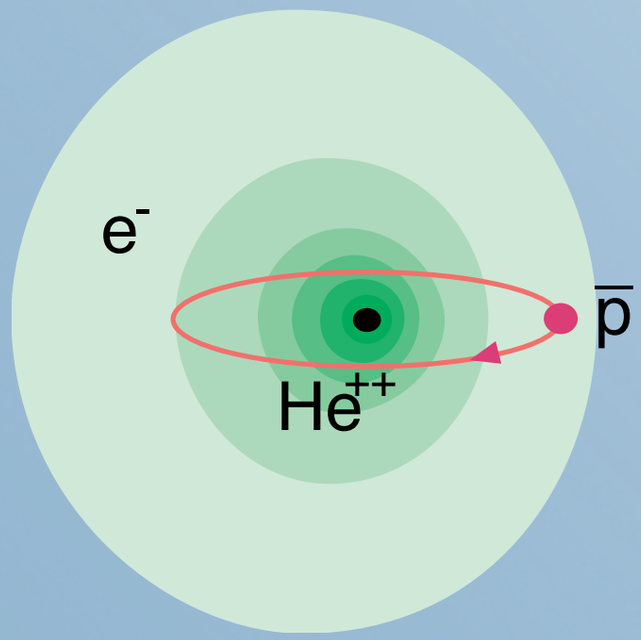
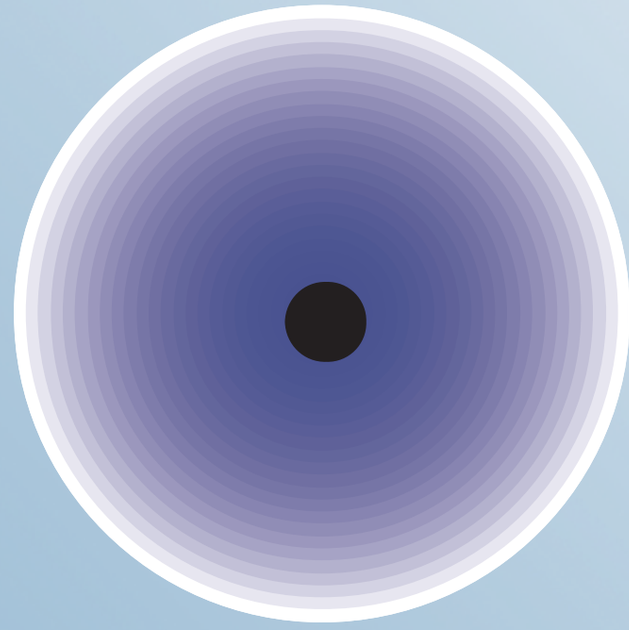

Precision on (anti)proton-to-electron mass ratio
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
1995
2000
2005
2010
2015
Years
LEAR experiments
Relativistic corrections
AD construction
Two-loop QED
RFQD beam
Frequency comb, laser chirp correction
Complex-coordinate rotation
Two-photon spectroscopy
CODATA98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

reducing collisions

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

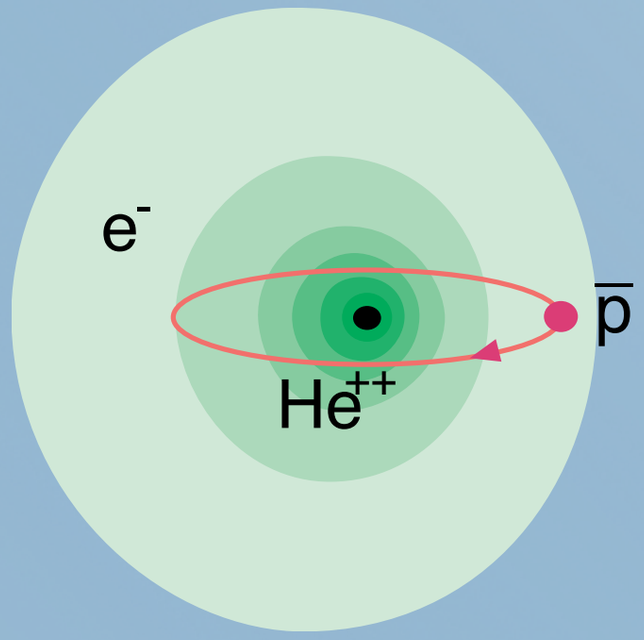


$\overline{p}$ He



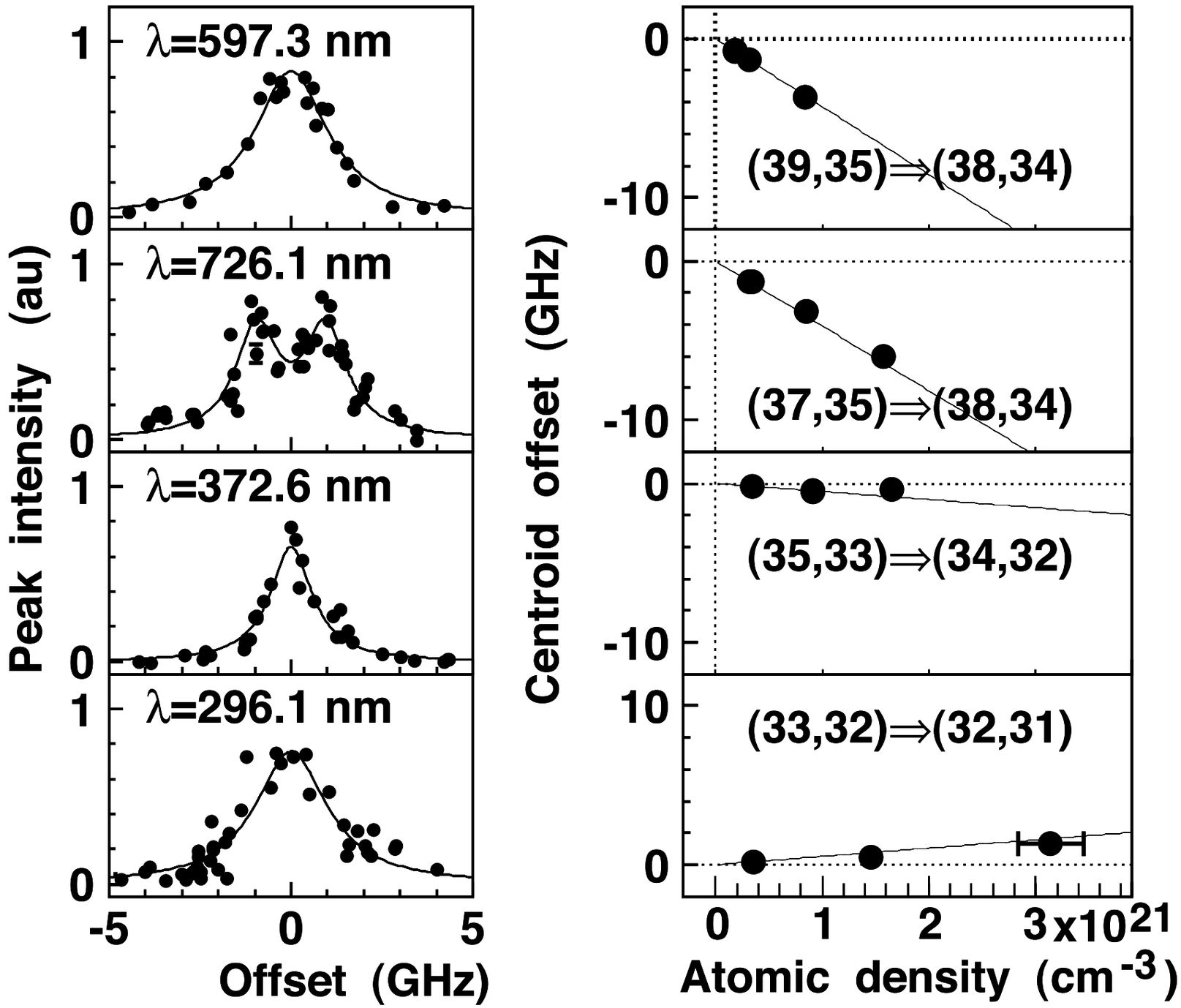
He

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

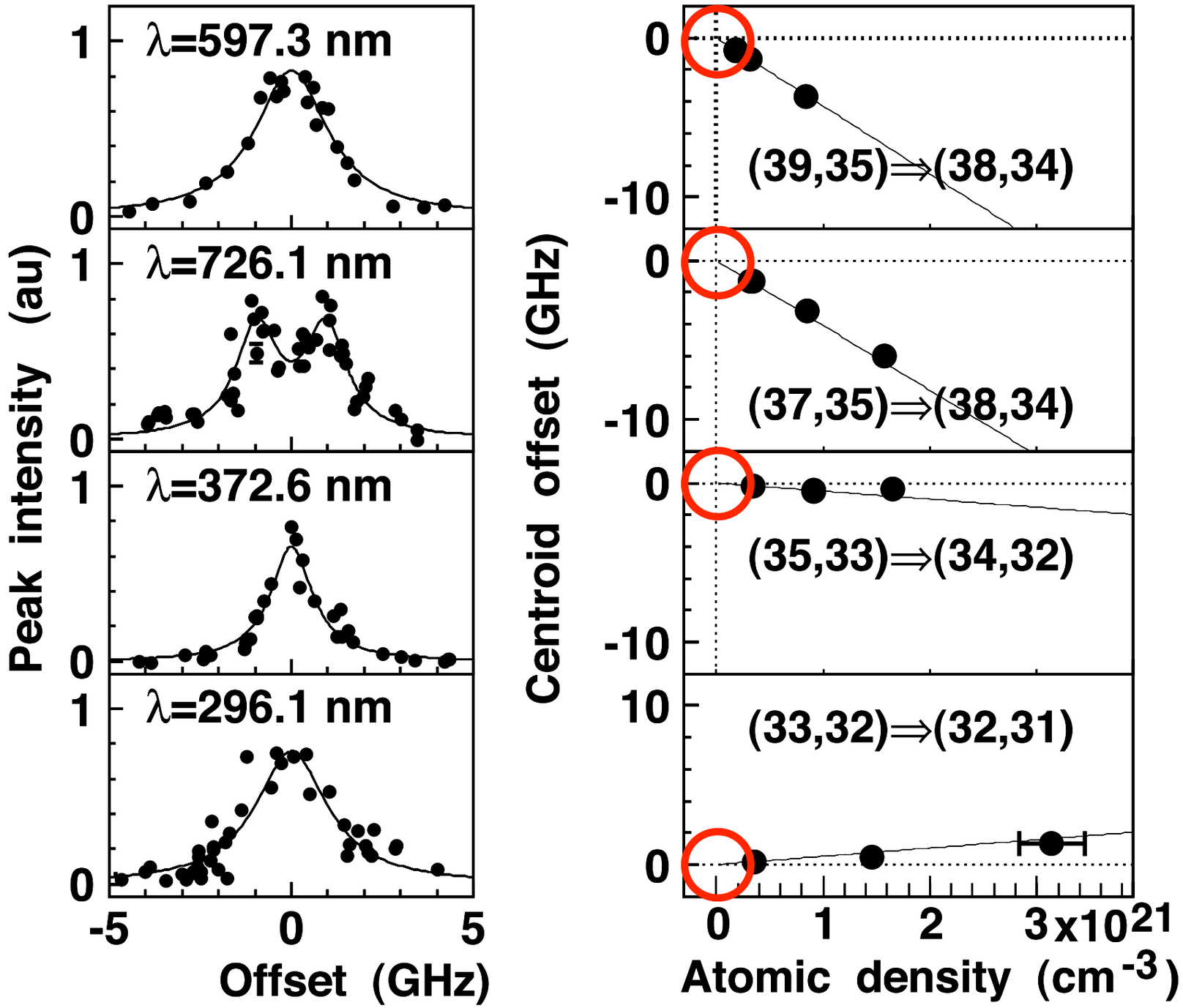


$\overline{p}$ He

Density-dependent shift



Density-dependent shift

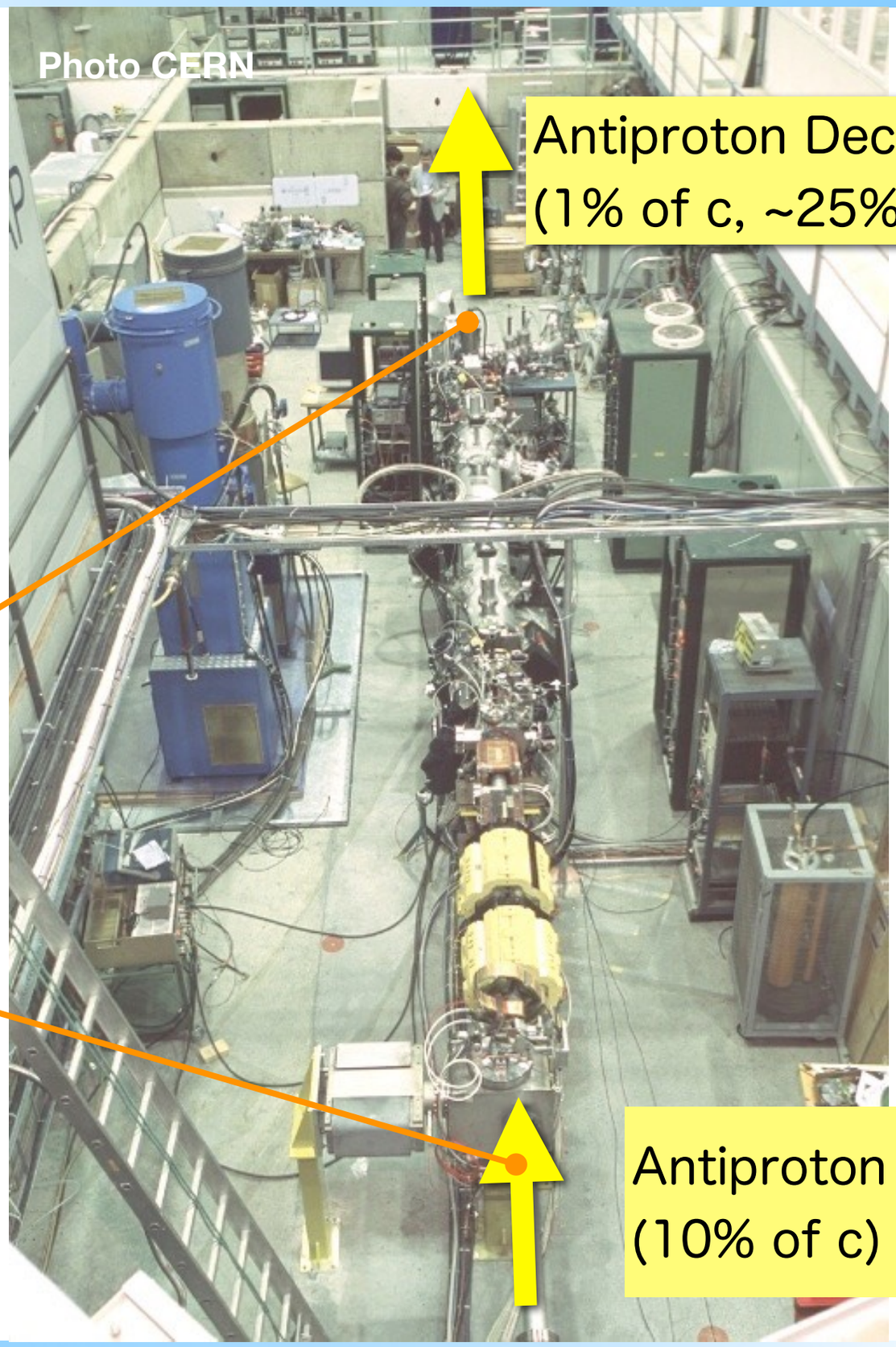


RFQD

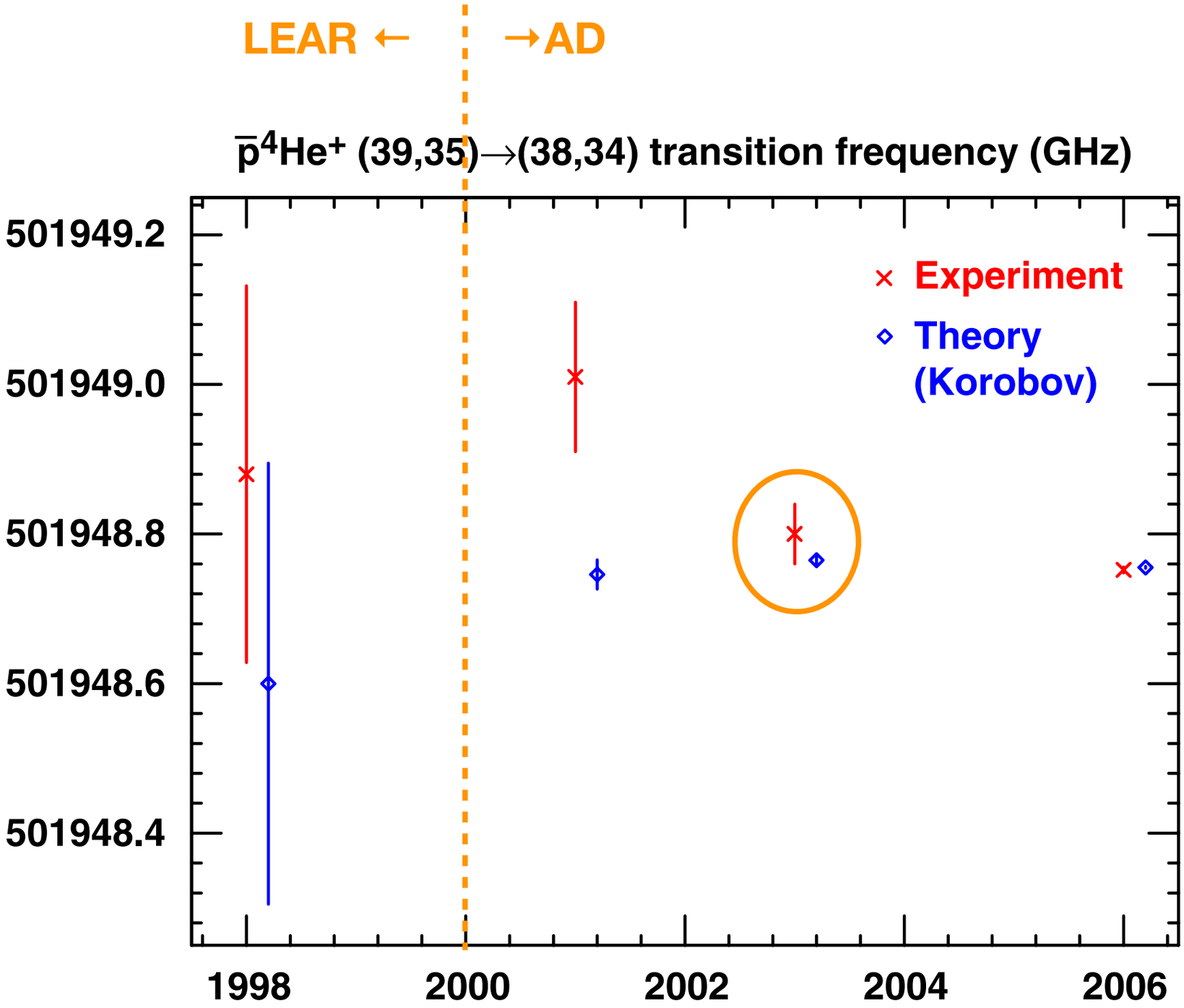
Typical target density

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

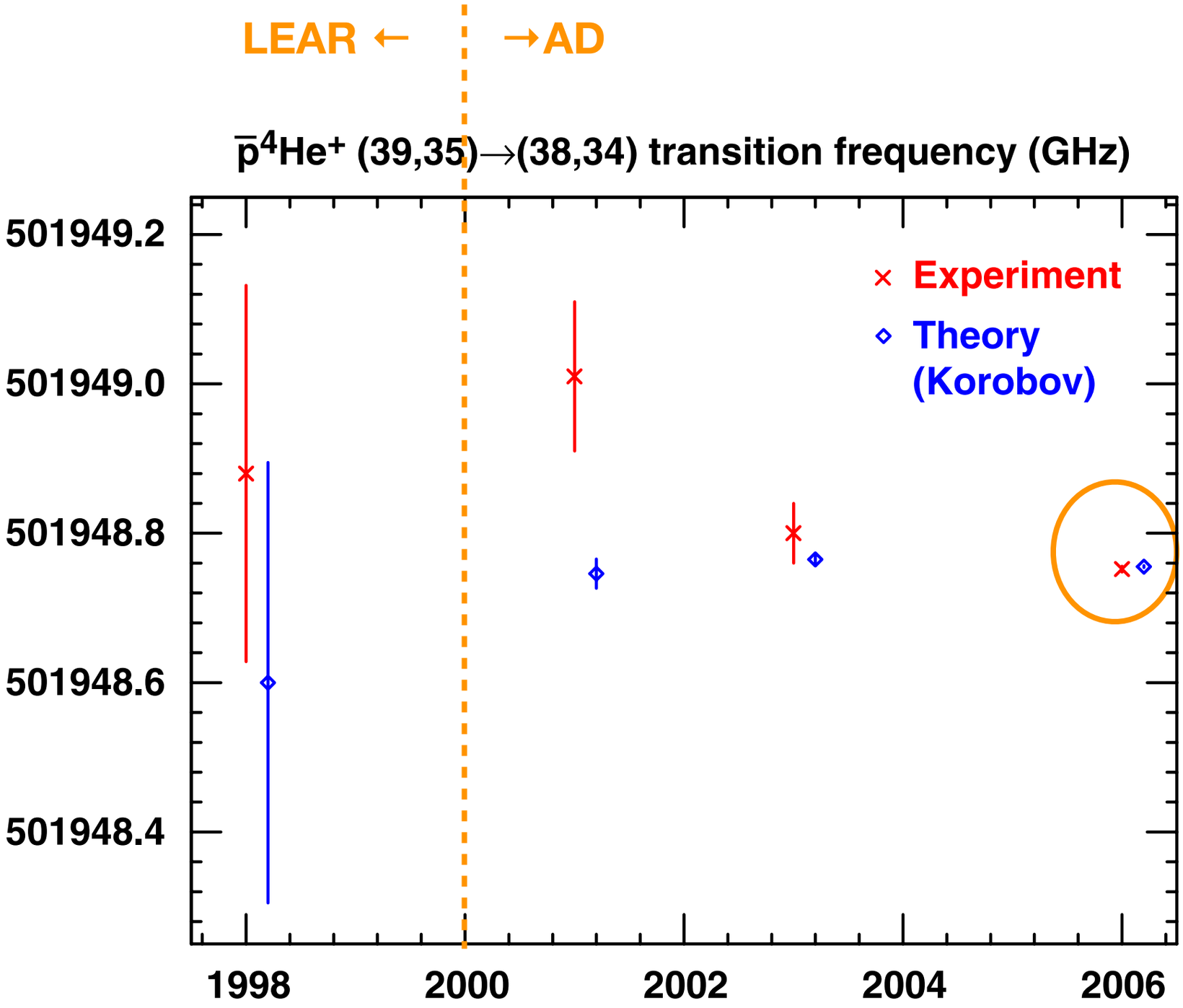
10^{21}cm^{-3}



“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	$\Delta E_{\rm vp} = \frac{4 z_i \alpha^3}{3 m_3^2}\left[-\frac{1}{5} + (z_i\alpha)\pi\frac{5}{64}\right]\langle\delta(\boldsymbol{r}_i)\rangle,$
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	$\Delta E_{\rm exch} = -\alpha^2\frac{z_i}{2m_i m_3}\left\langle\frac{\boldsymbol{\nabla}_i\boldsymbol{\nabla}_3}{r_i} + \frac{\boldsymbol{r}_i(\boldsymbol{r}_i\boldsymbol{\nabla}_i)\boldsymbol{\nabla}_3}{r_i^3}\right\rangle,$
E_{α^3-rec}	$=$	0.8	$\Delta E^{(3)}_{\rm recoil} = \frac{z_i\alpha^3}{m_i m_3}\left\{\frac{2}{3}\left(-\ln\alpha - 4\beta + \frac{31}{3}\right)\langle\delta(\boldsymbol{r}_i)\rangle - \frac{14}{3}\langle Q(r_i)\rangle\right\},$
$E_{two-loop}$	$=$	0.9	$\Delta E_{\text{two-loop}} = \alpha^4\frac{z_i}{m_3^2\pi}\left[-\frac{6131}{1296} - \frac{49\pi^2}{108} + 2\pi^2\ln 2 - 3\zeta(3)\right]\langle\delta(\boldsymbol{r}_i)\rangle$
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 Exp.
(error)

12 such transitions
CODATA 2006

contribution to CODATA, 2006 & 2010

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

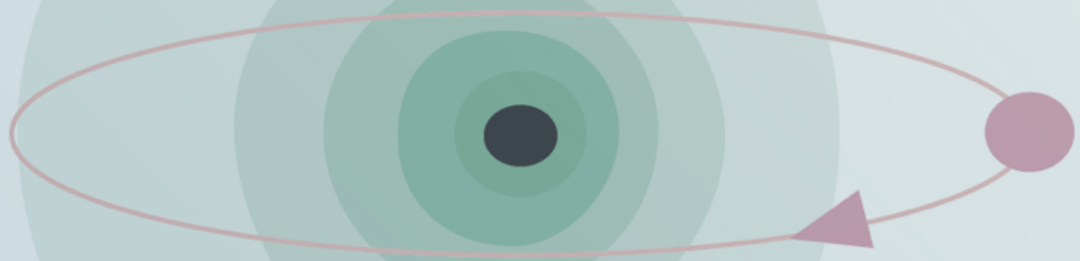
CODATA recommended values of the fundamental physical constants: 2006*

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

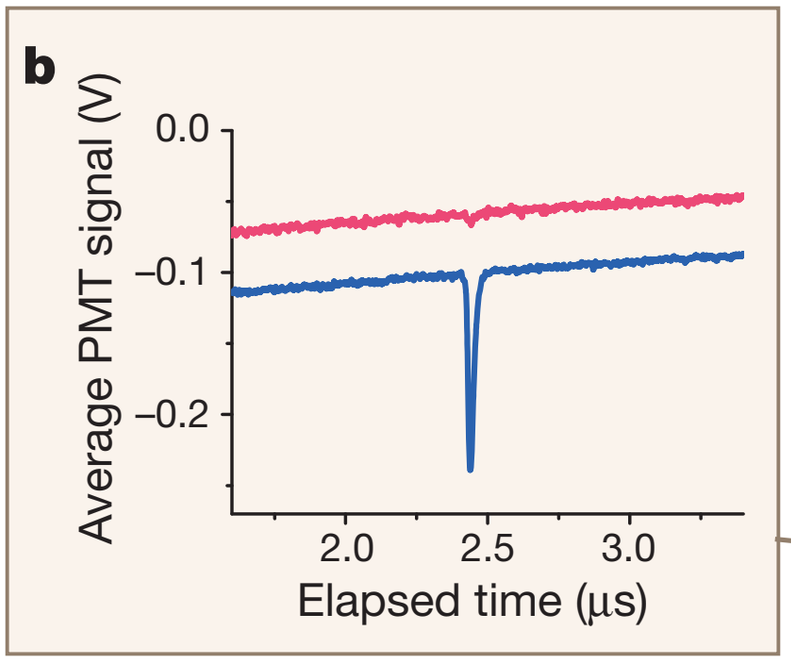
IV. ATOMIC TRANSITION FREQUENCIES

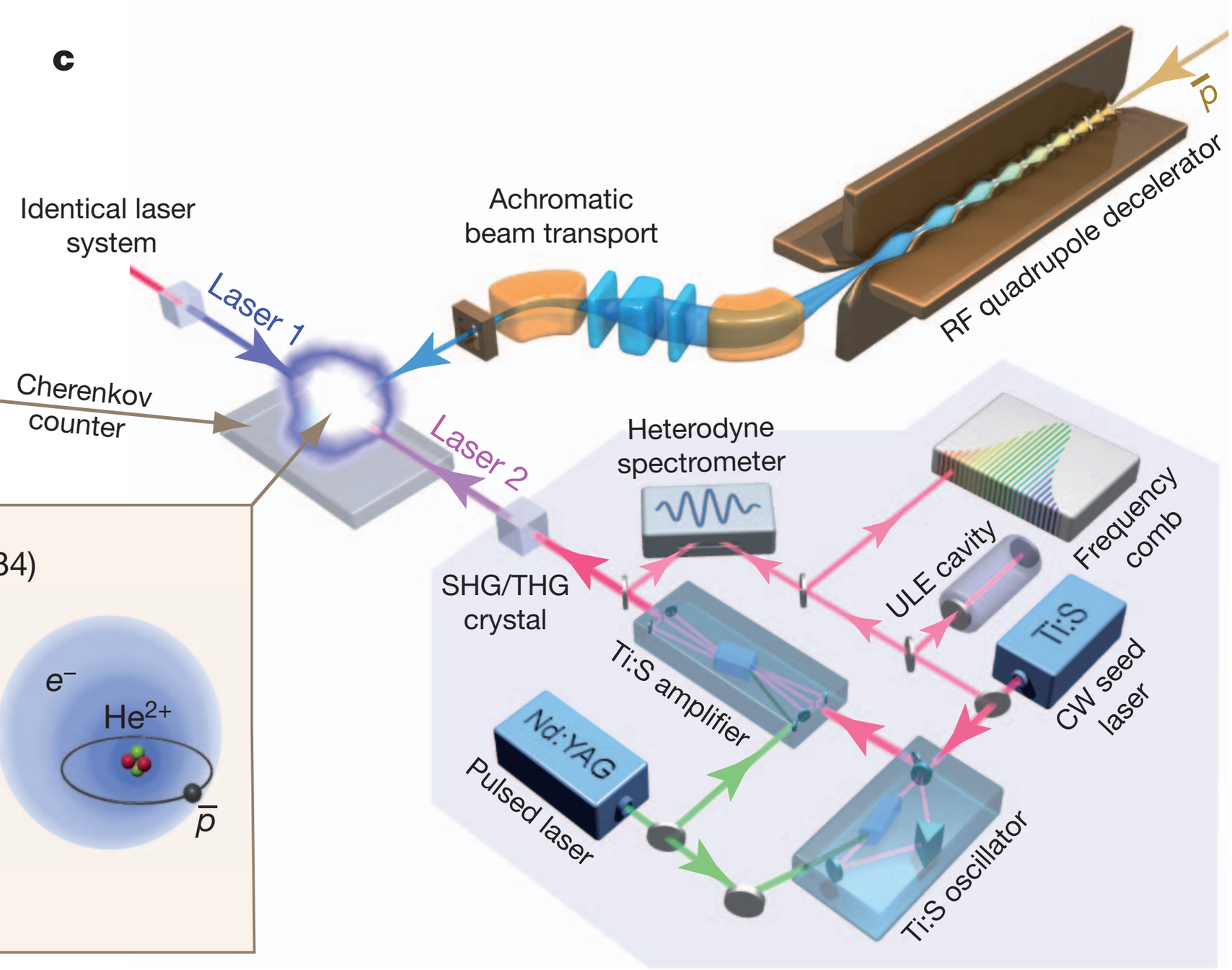
Atomic transition frequencies in hydrogen, deuterium, and antiprotonic helium yield information on the Rydberg constant, the proton and deuteron charge radii, and the relative atomic mass of the electron. The hyper-

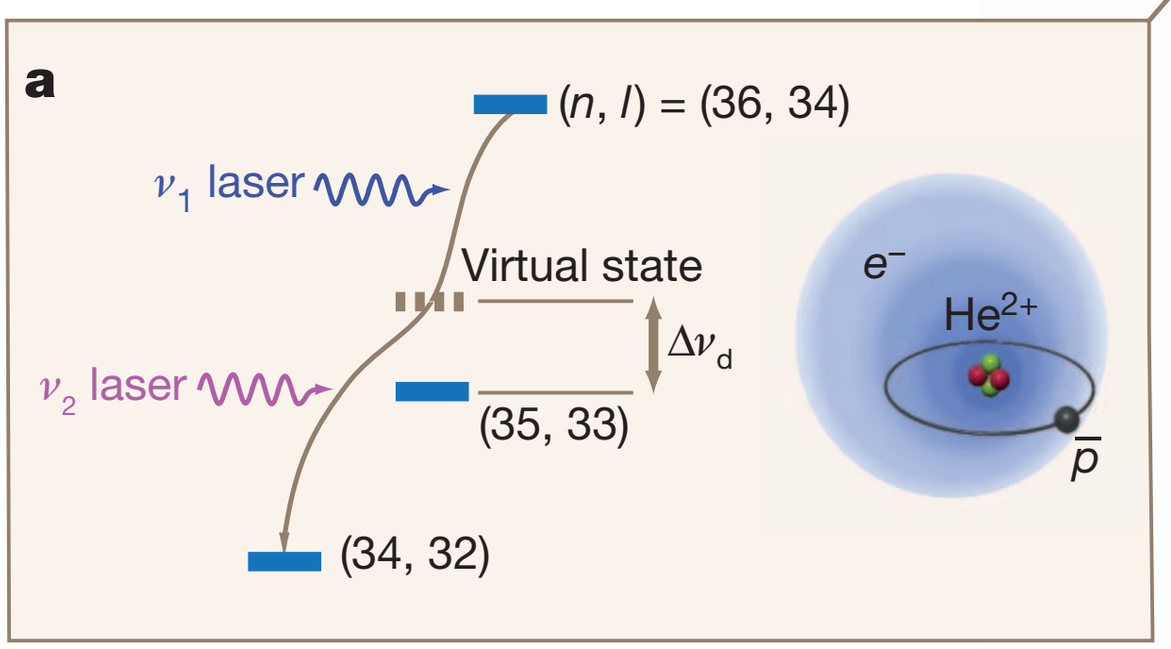
Reduce Doppler width 2-photon spectroscopy



p̄He 2-photon spectroscopy



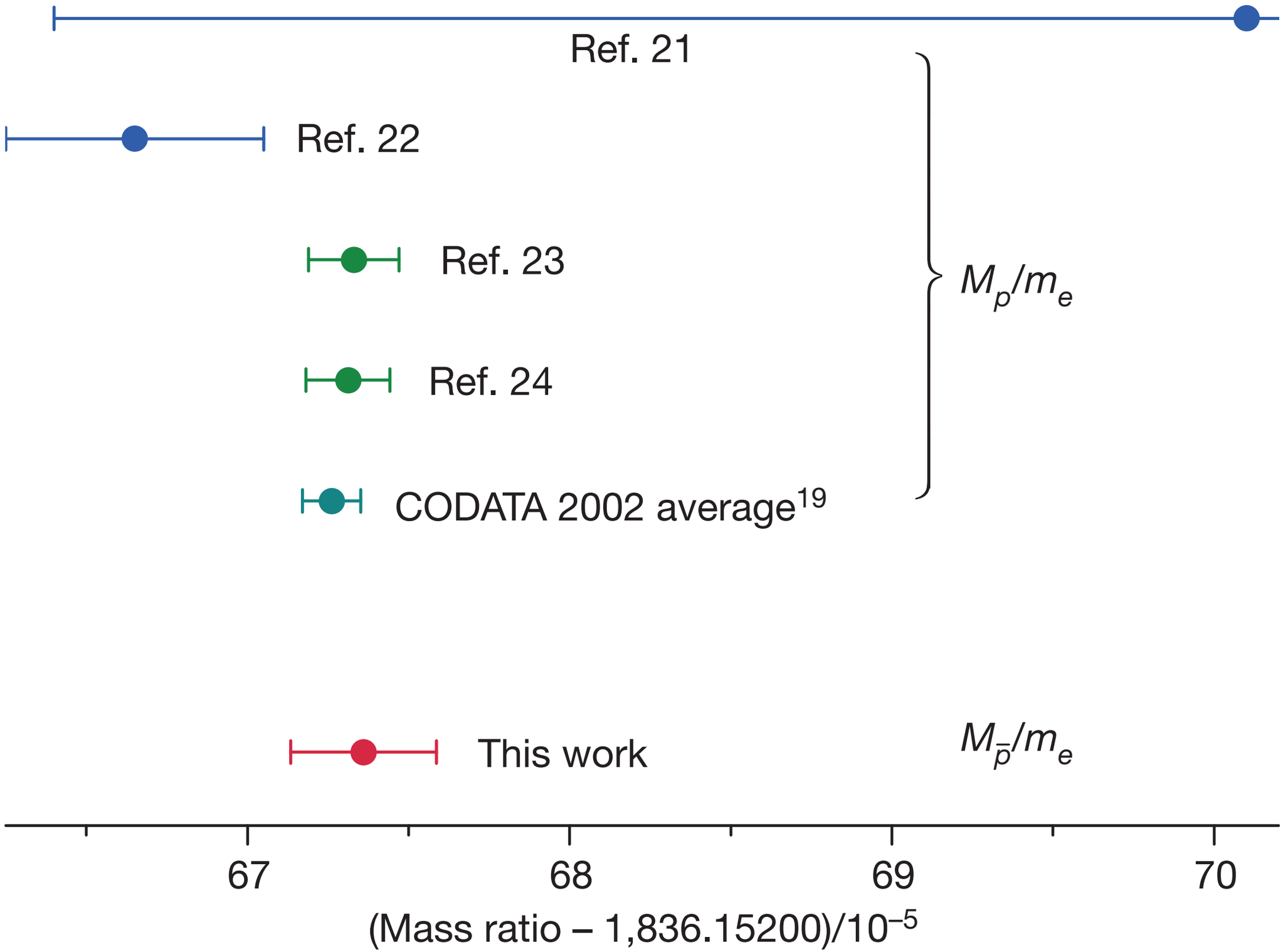




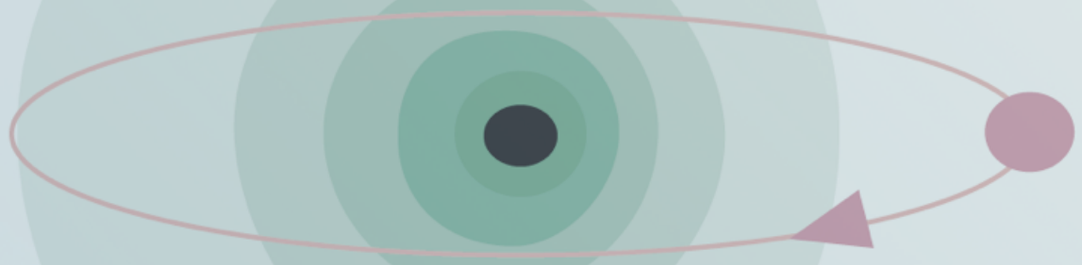
Hori et al., Nature 475 (2011) 484

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

Hori et al., Nature 475 (2011) 484



How to improve?
theory & exp



Theory progress

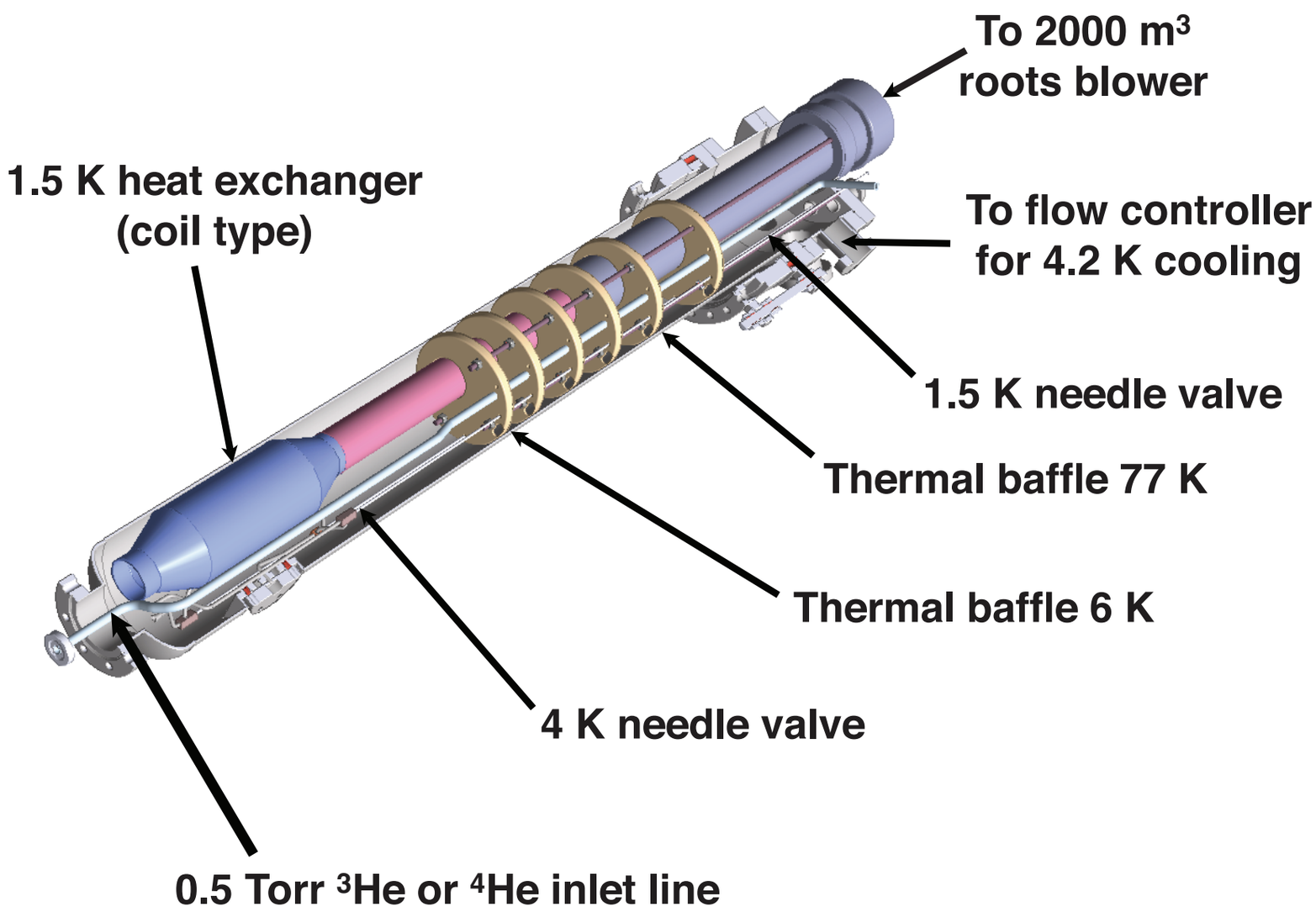
PHYSICAL REVIEW A **89**, 014501 (2014)

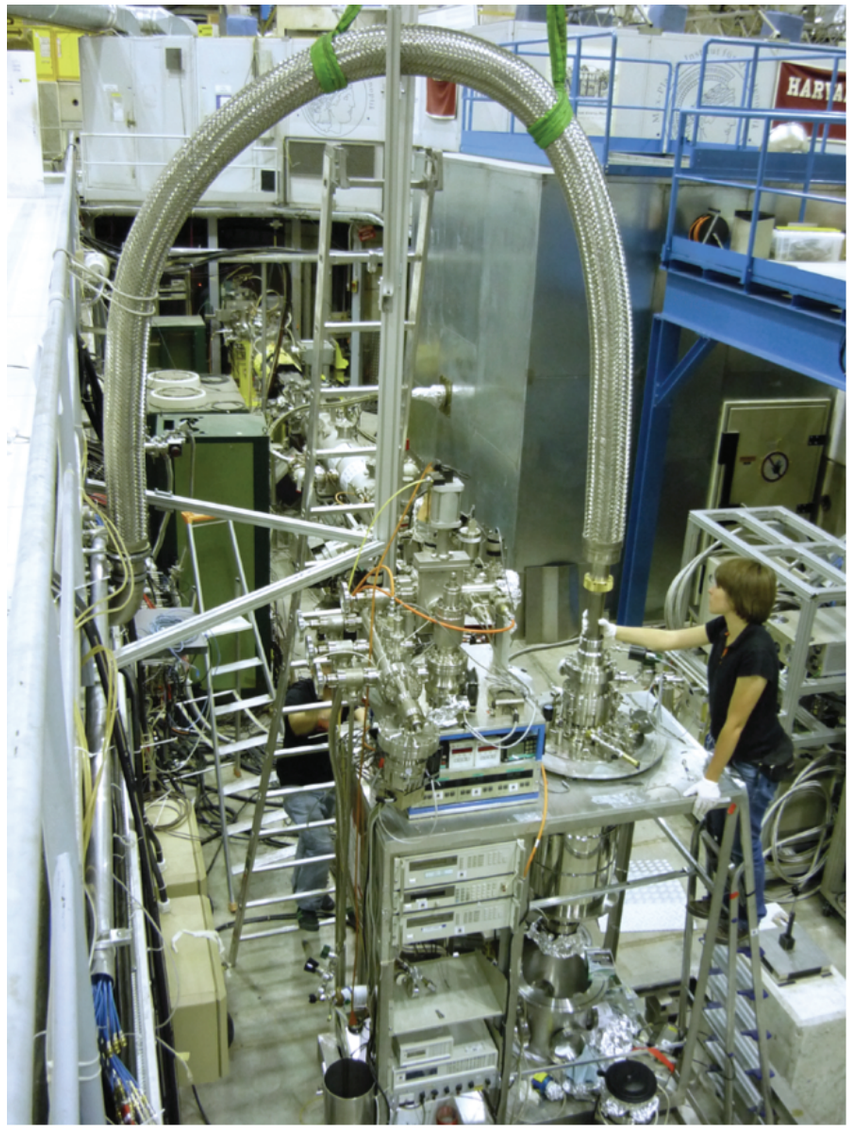
Bethe logarithm for resonant states: Antiprotonic helium

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

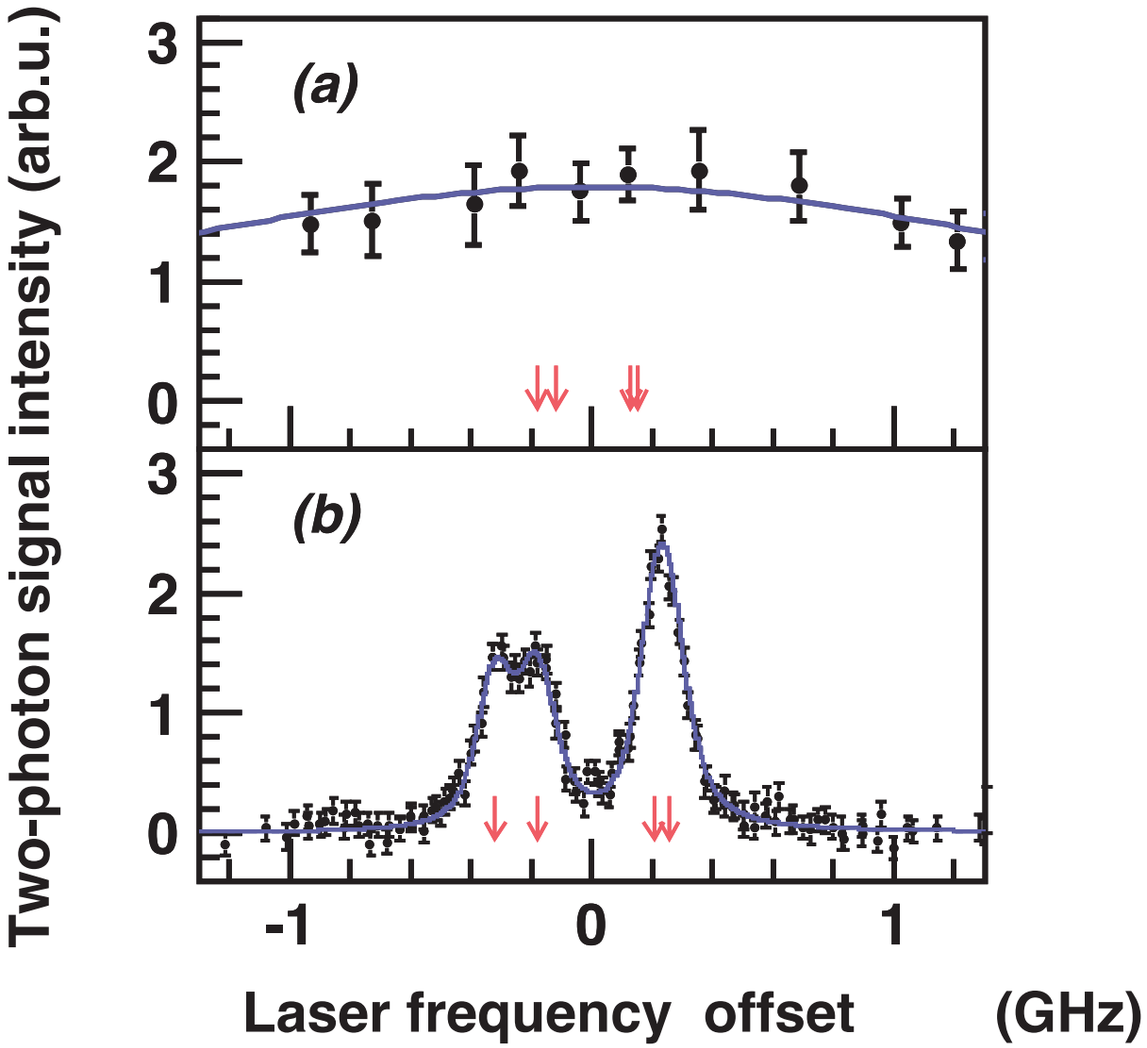
Experiment - go to 1.5K (and to ELENA)

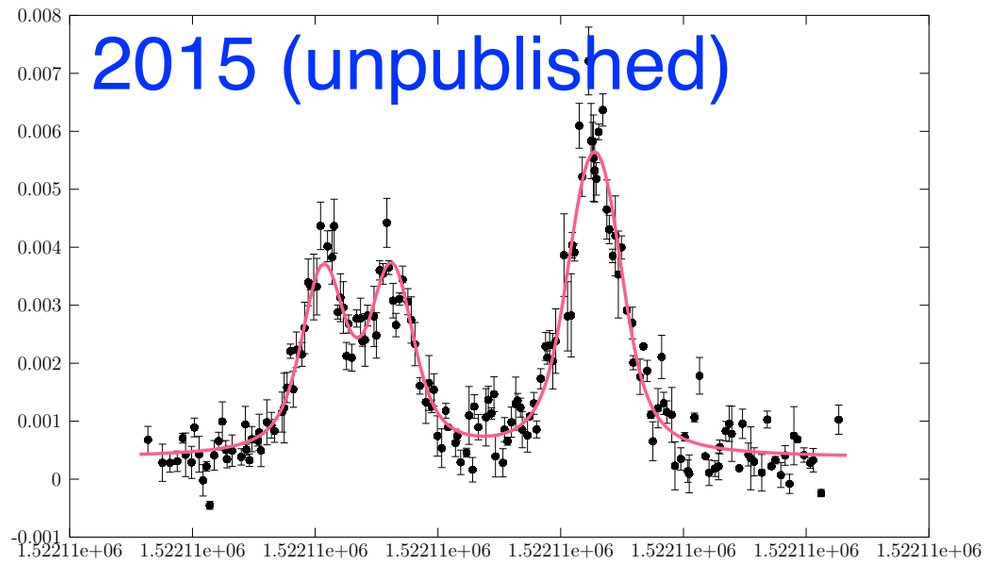


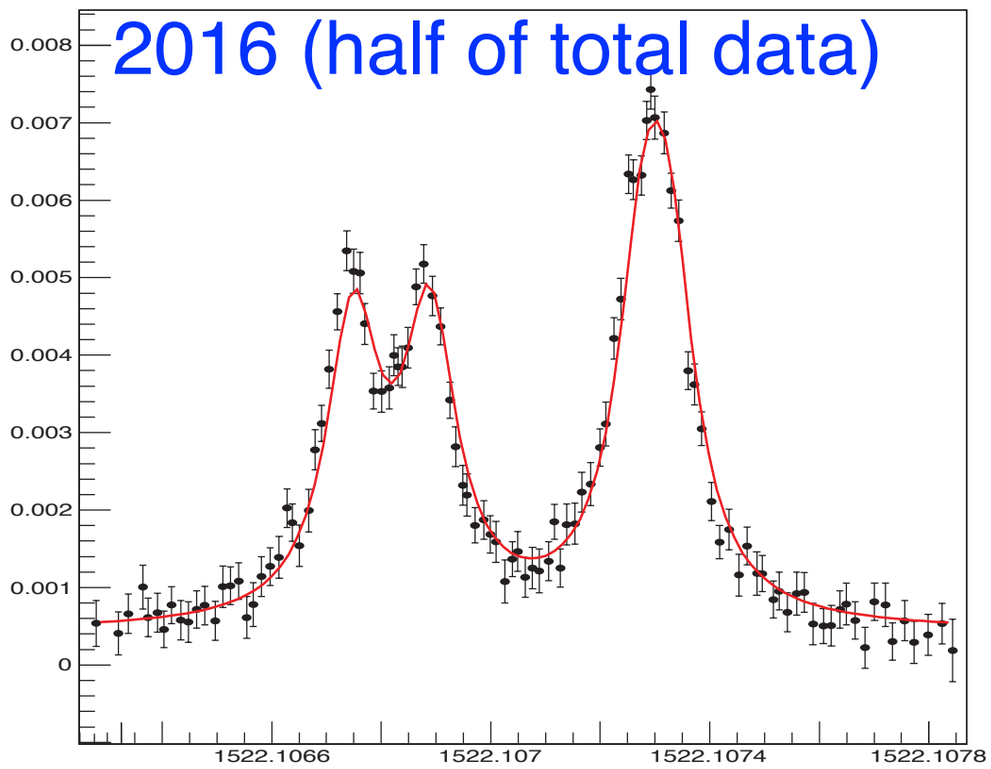


T=1.5K two-photon scan in progress

$\bar{p}^4He(36,34) \rightarrow (35,32)$

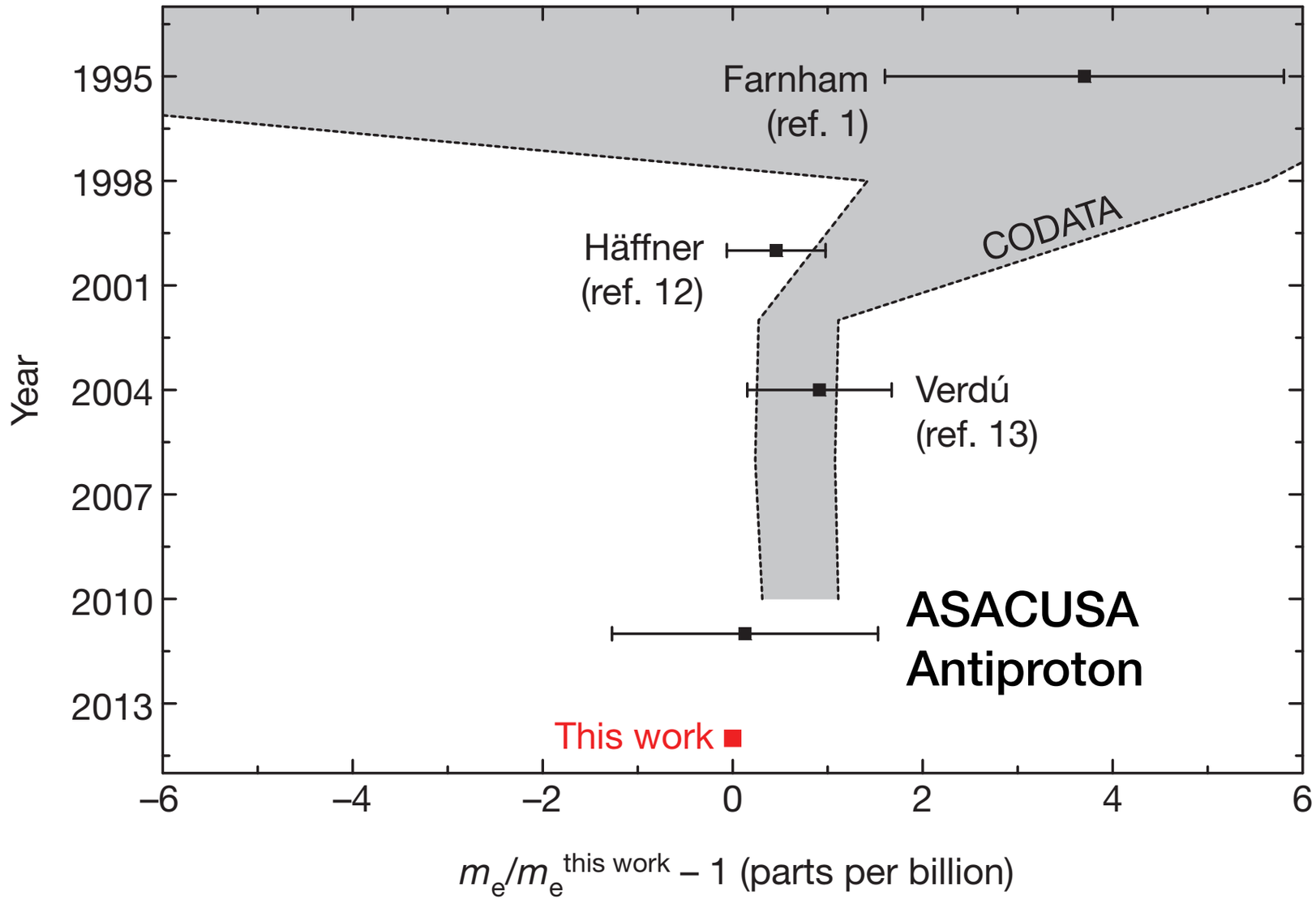




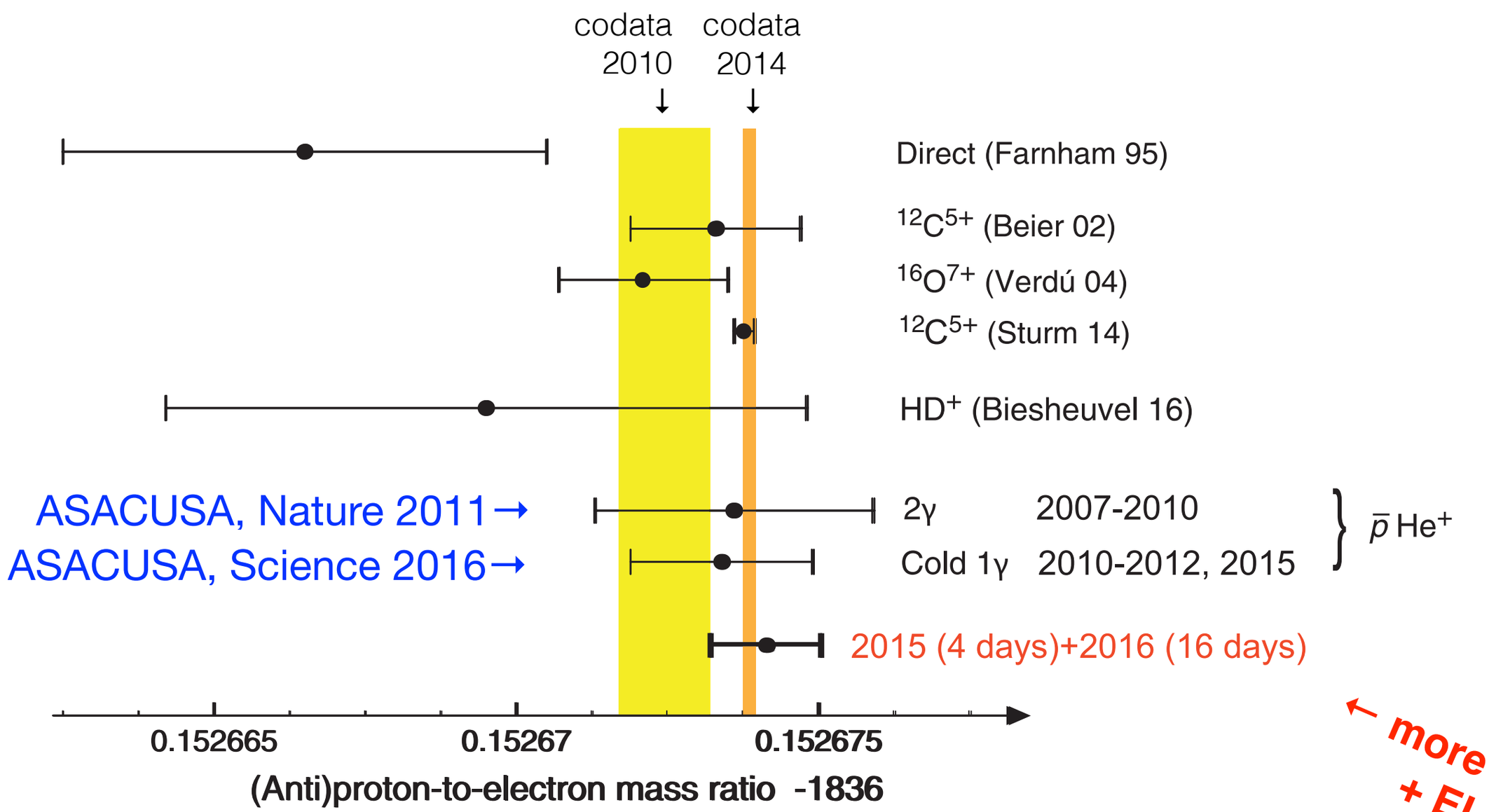


Recently, m_p/m_e much improved

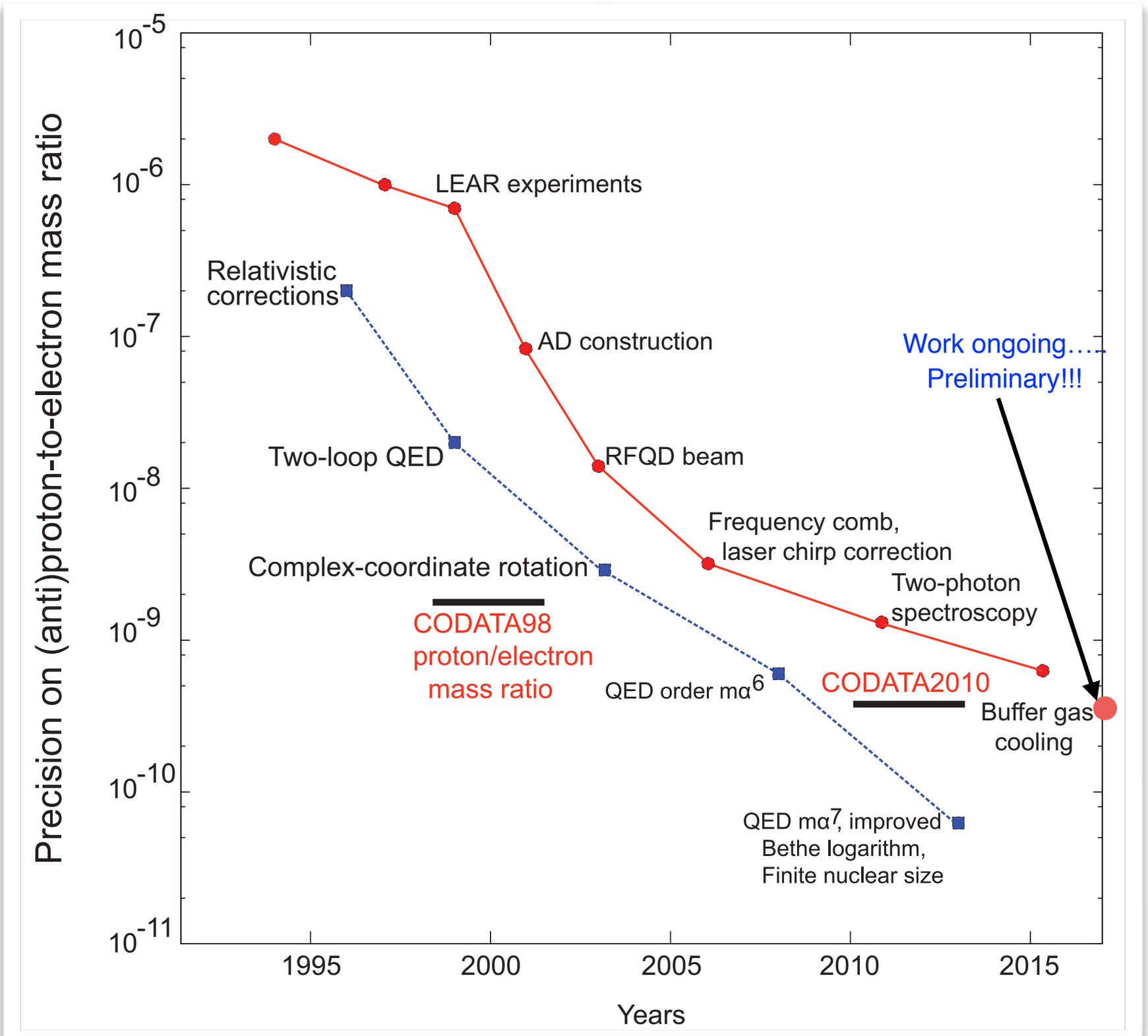
NATURE 506 (2014) 467



recent (preliminary) result



← more statistics + ELENA


Precision on (anti)proton-to-electron mass ratio
10^-5
10^-6
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1995
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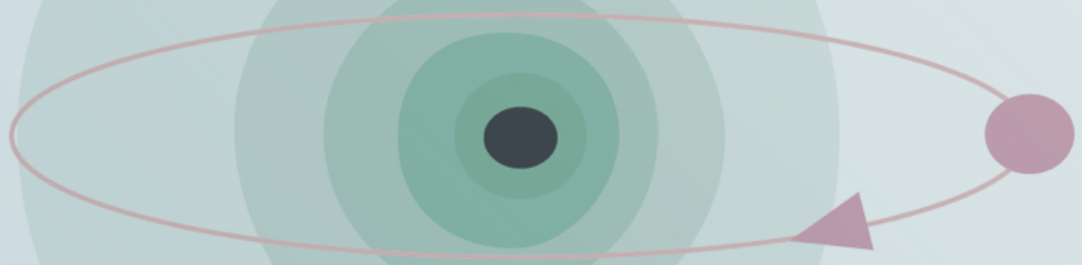
CODATA98 proton/electron mass ratio
QED order mα^6
CODATA2010
Buffer gas cooling
QED mα^7, improved Bethe logarithm, Finite nuclear size
Work ongoing…. Preliminary!!!
ELENA
←codata 2014

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