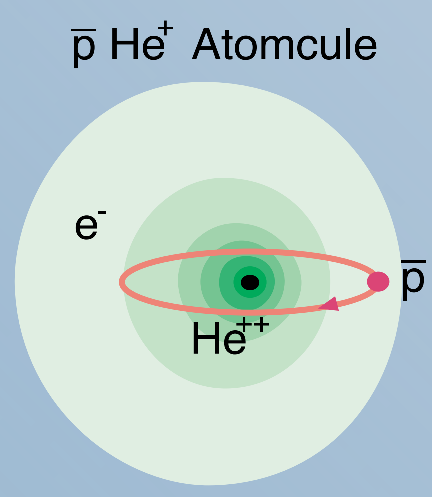
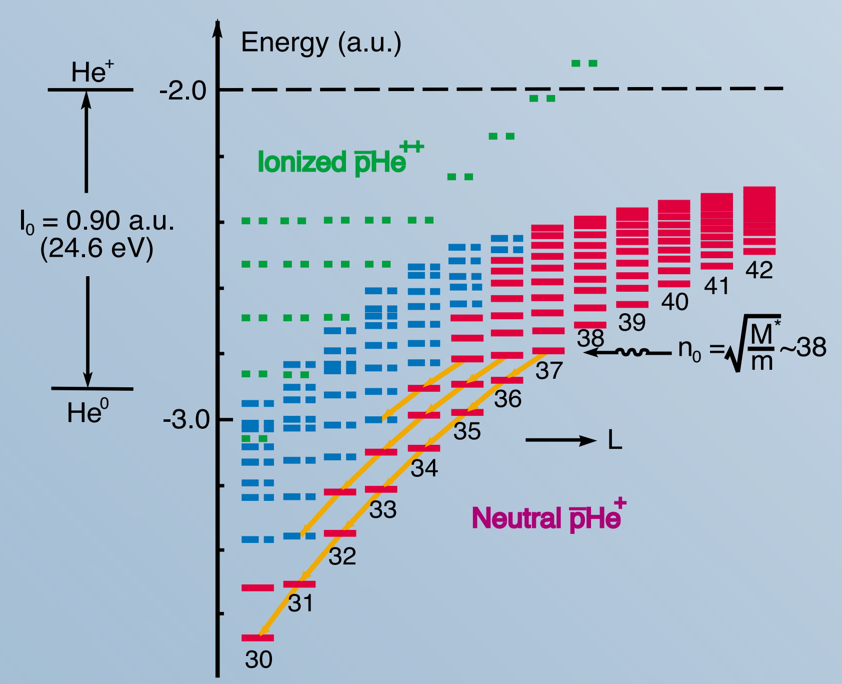
# 20 Years of Antiprotonic Helium

## - Overview and History -




## Ryugo S. Hayano

THE UNIVERSITY OF TOKYO

EXA 2011

# 発見

# Discovery

September 2, 1991

20 years + 3 days ago...

# KEK E215 (hayano et al.)

## Study of metastable states of $\bar{p}$ atom in liquid helium

VOLUME 67, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 1991

### Discovery of Antiproton Trapping by Long-Lived Metastable States in Liquid Helium

M. Iwasaki, S. N. Nakamura, K. Shigaki, Y. Shimizu, H. Tamura, T. Ishikawa, and R. S. Hayano
*Department of Physics and Meson Science Laboratory, Faculty of Science, University of Tokyo, Tokyo 113, Japan*

E. Takada
*National Institute of Radiological Sciences, Chiba 260, Japan*

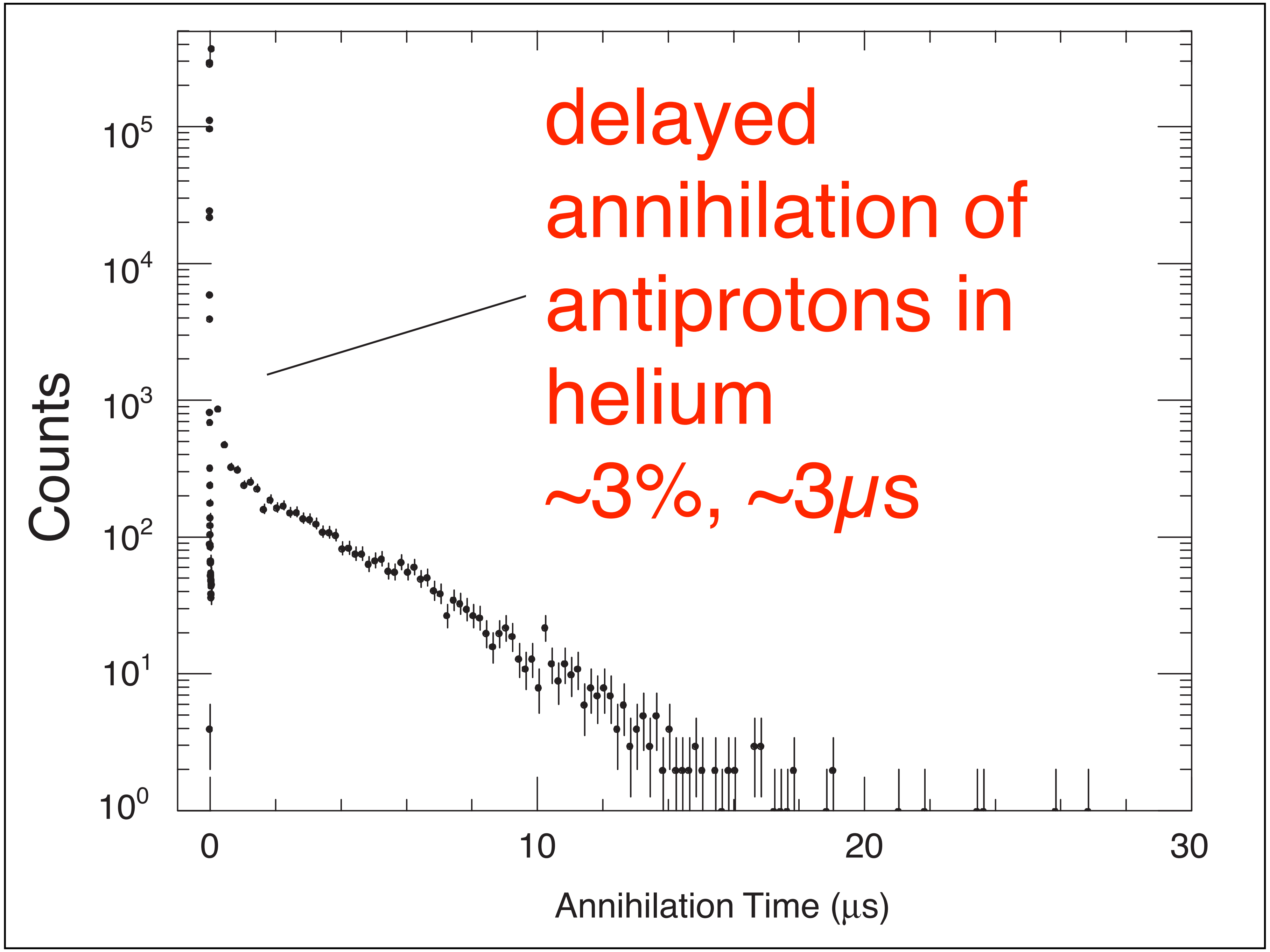
E. Widmann, H. Outa, M. Aoki, P. Kitching,[a] and T. Yamazaki
*Institute for Nuclear Study, University of Tokyo, Tokyo 188, Japan*
(Received 20 May 1991)

Delayed annihilation of antiprotons stopped in liquid helium has been observed, revealing that about 3.6% of stopped antiprotons are trapped in long-lived metastable states. No delayed component was found either in liquid nitrogen or in liquid argon. The observed time distribution of delayed annihilation shows fast-decaying components followed by a major part with a decay time constant of 3 $\mu$sec.

PACS numbers: 36.10.−k

# $\bar{p}$ annihilation time in liq. helium

## Naturally-occurring $\bar{p}$ trap




Iwasaki et al., PRL 67 (1991) 1246

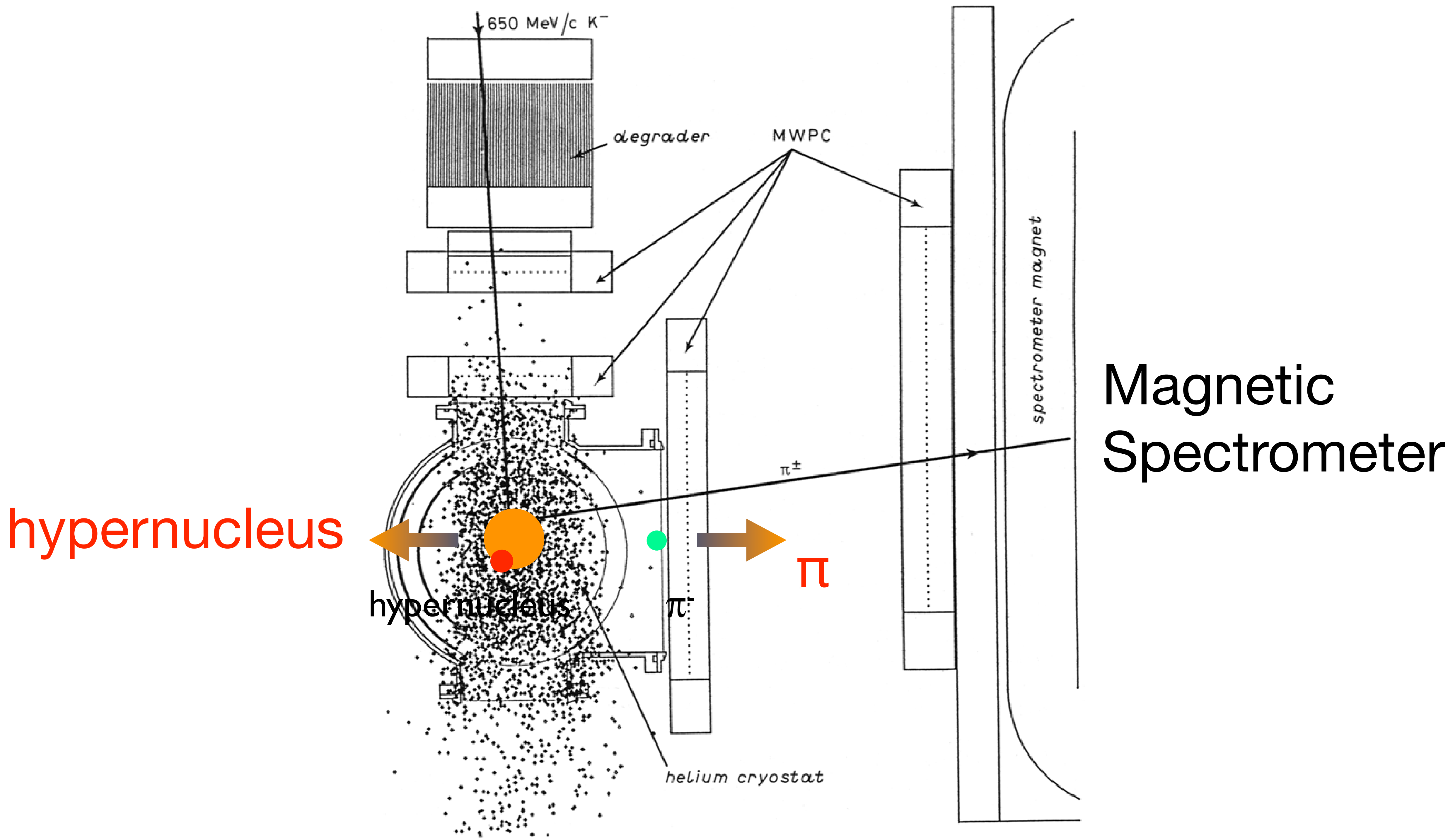
# 前史

## Before $\bar{p}$

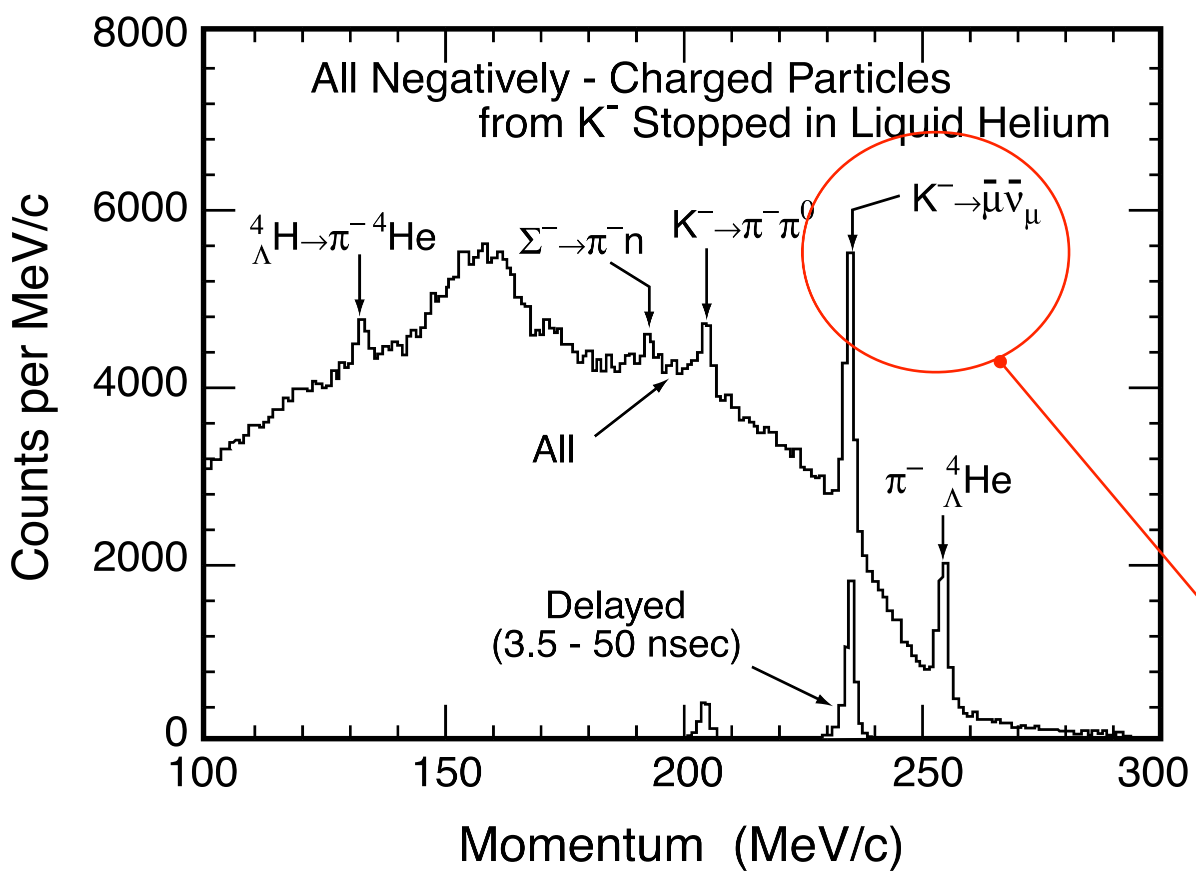
# KEK E167 (hayano et al.)

Search for Σ hypernuclear ground state by kaon absorption on $^4$He

prediction: Harada & Akaishi



# A **BIG** surprise

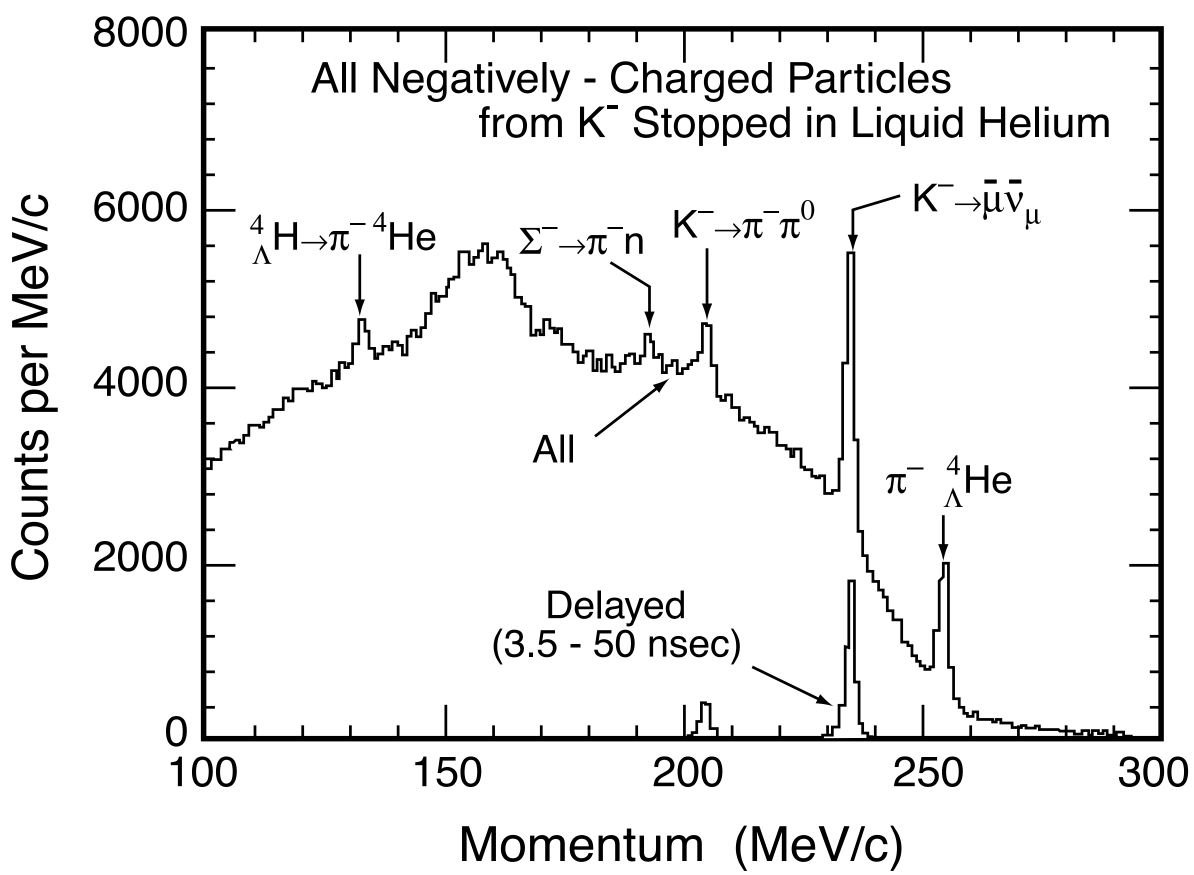


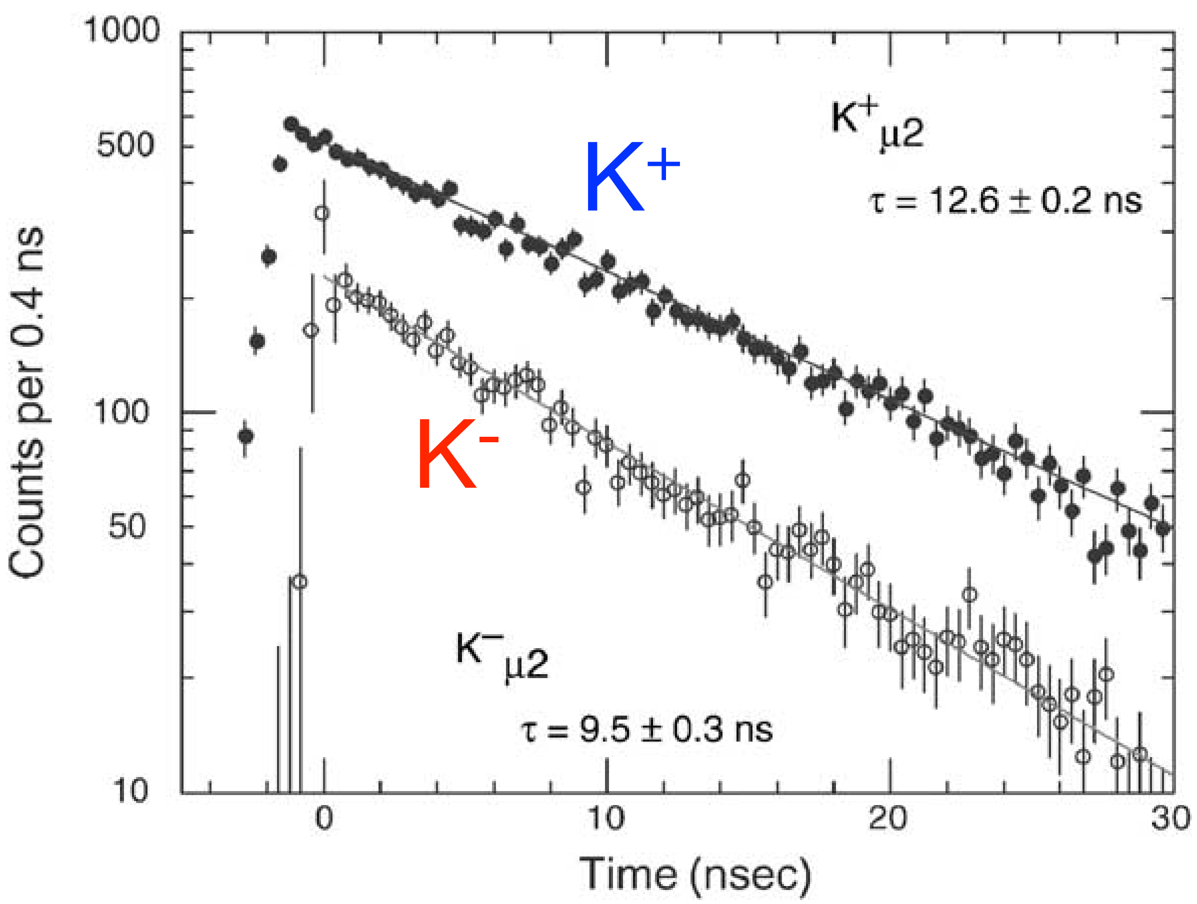

K- “cascade” time usually << ns

K lifetime (in vacuum) 12ns

Why K→μν peak so strong?

# “cascade trapping” of K⁻



# $\pi^-$ also trapped

PHYSICAL REVIEW A VOLUME 45, NUMBER 9 1 MAY 1992

## Negative-pion trapping by a metastable state in liquid helium

S. N. Nakamura, M. Iwasaki, H. Outa,* and R. S. Hayano
*Department of Physics and Meson Science Laboratory, Faculty of Science, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan*

Y. Watanabe,† T. Nagae, and T. Yamazaki
*Institute for Nuclear Study, University of Tokyo, Tanashi, Tokyo 188, Japan*

H. Tada
*Department of Natural Science, College of General Education, University of Tokyo, Komaba, Meguro-ku, Tokyo 153, Japan*

T. Numao, Y. Kuno, and R. Kadono†
*TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
(Received 6 November 1991)

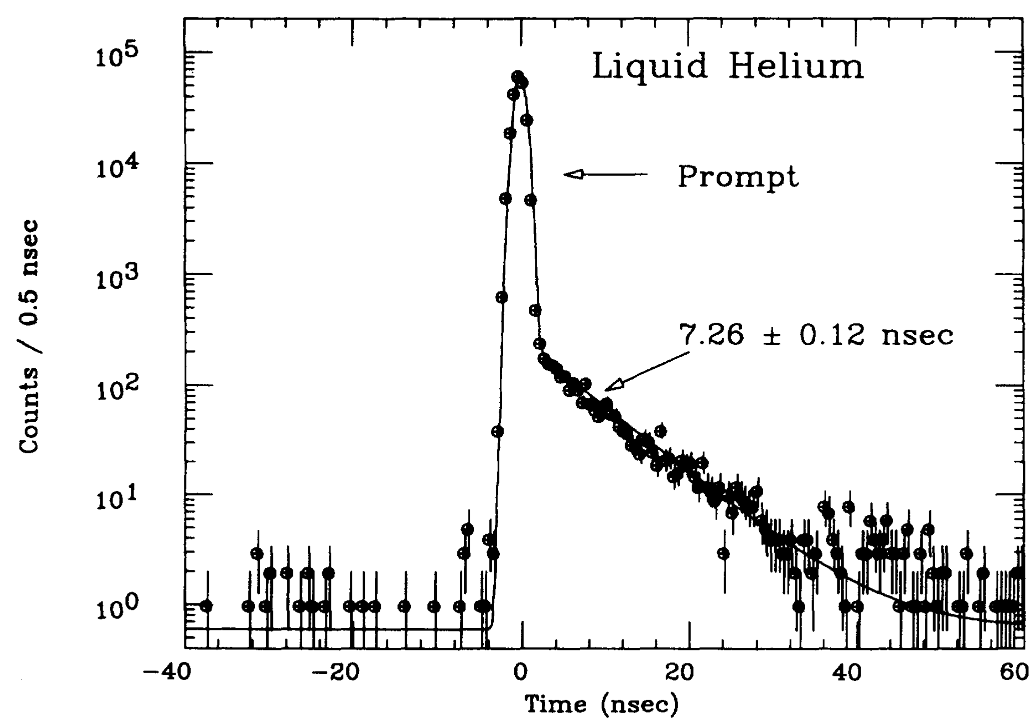



FIG. 4. A time spectrum of protons from stopped $\pi^-$ in liquid helium.

# Predicted in '60s (we later realized)

ON THE ABSORPTION OF NEGATIVE PIONS BY LIQUID HELIUM

**G. T. CONDO**

*Department of Physics, The University of Tennessee,*
*and Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA*

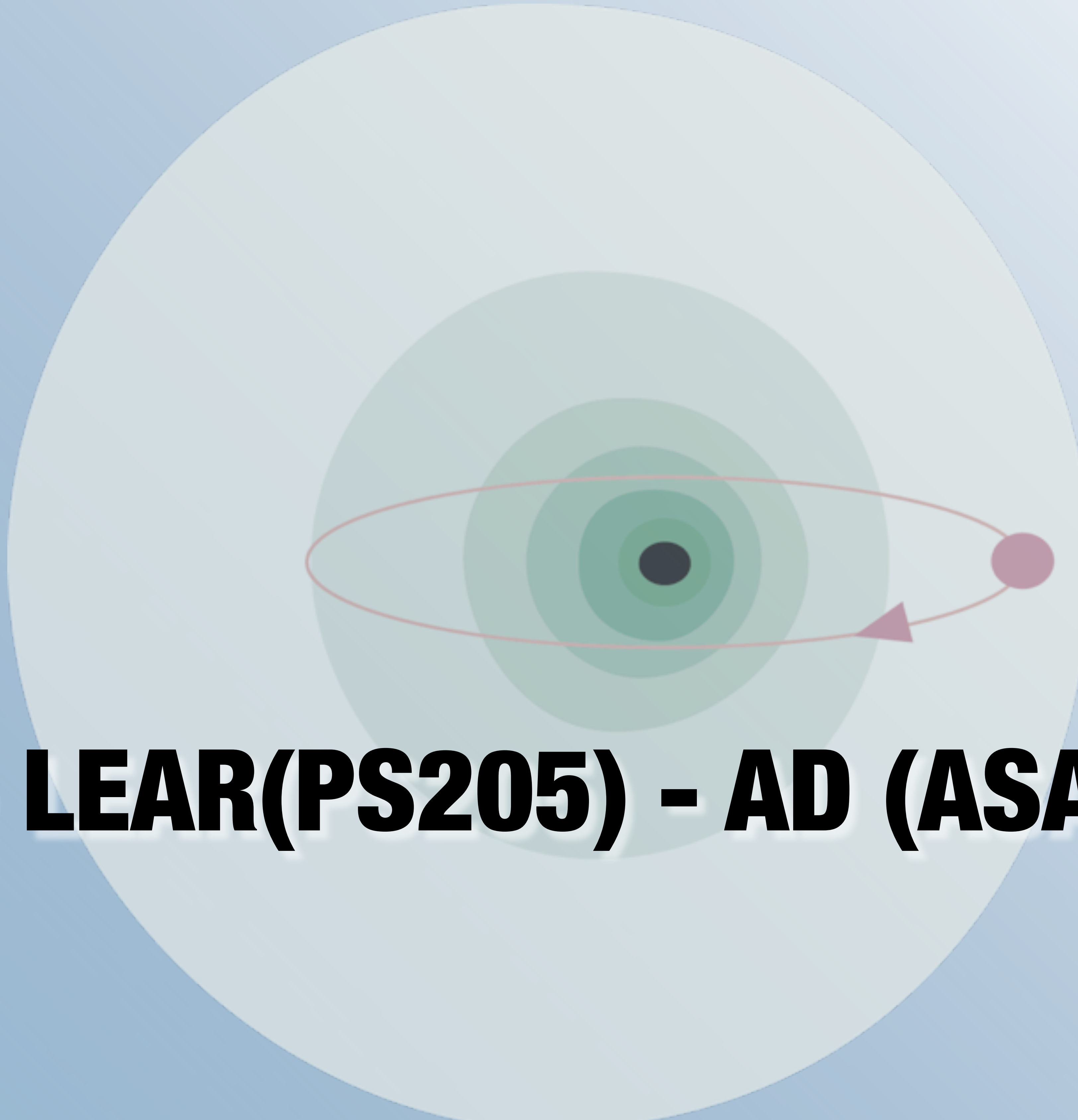
G.T. Condo, Phys. Lett. 9 (1964) 65

METASTABLE STATES OF $\alpha\pi^- e^-$, $\alpha K^- e^-$, AND $\alpha\bar{p}e^-$ ATOMS

**J. E. Russell**

Department of Physics, University of Cincinnati, Cincinnati, Ohio 45221
(Received 15 May 1969; revised manuscript received 16 June 1969)

J.E. Russell, Phys. Rev. Lett. 23 (1969) 63.



# KEK - LEAR(PS205) - AD (ASACUSA)

# 消滅時間分布

“DATS”

Delayed Annihilation Time Spectra

T.Yamazaki et al., PS205

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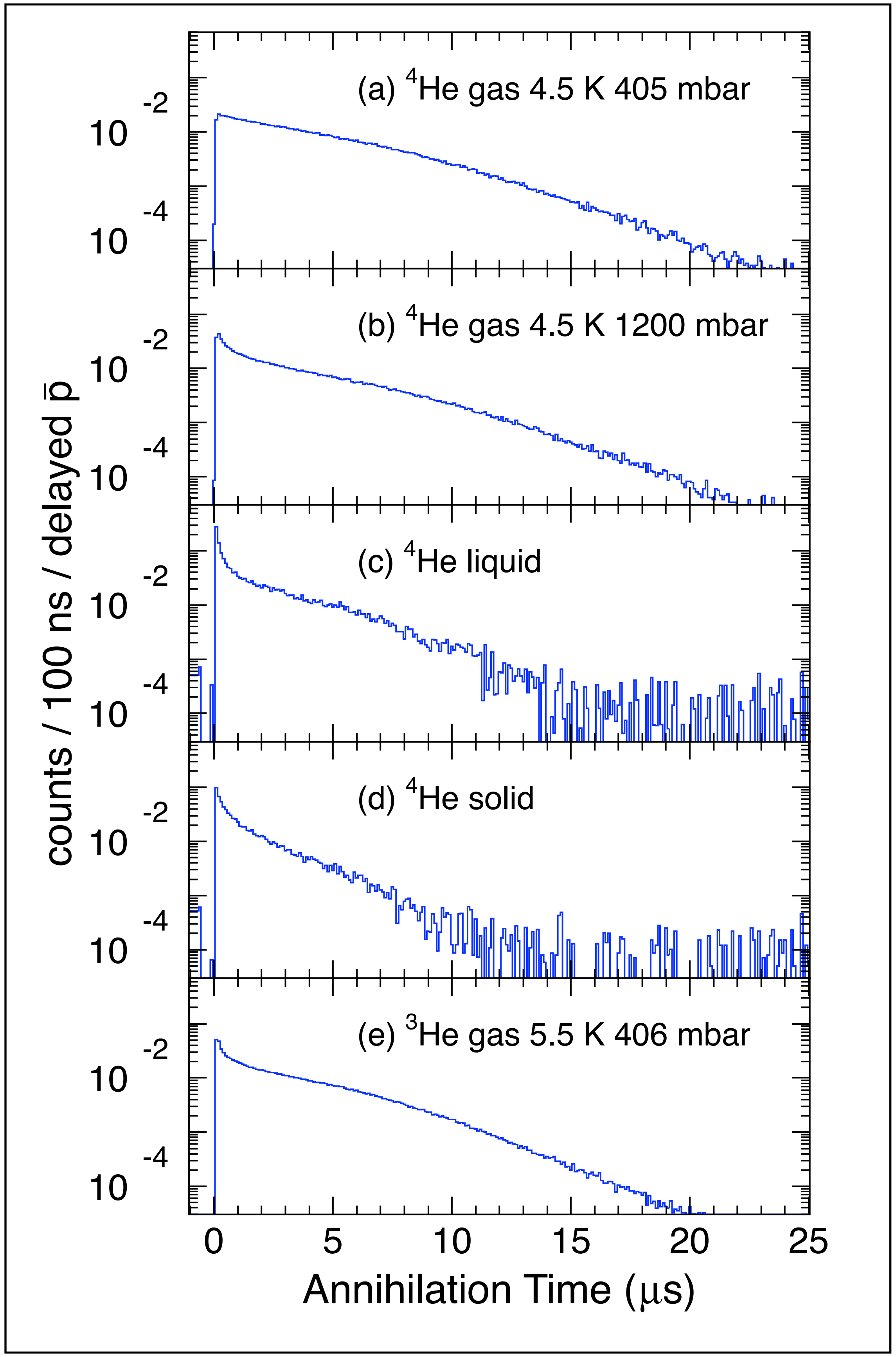
# "DATS" measured at LEAR

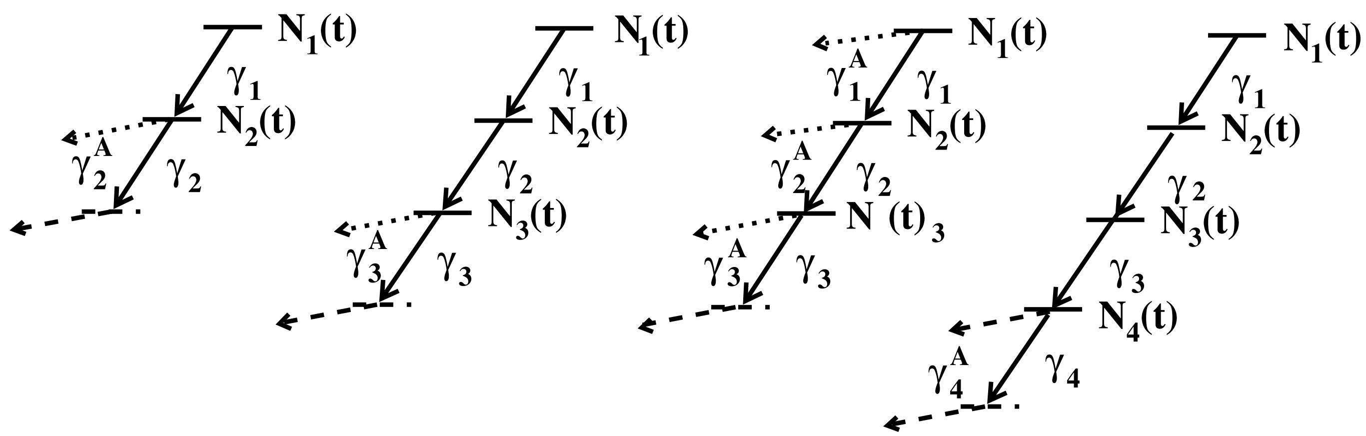
Early days of LEAR PS205

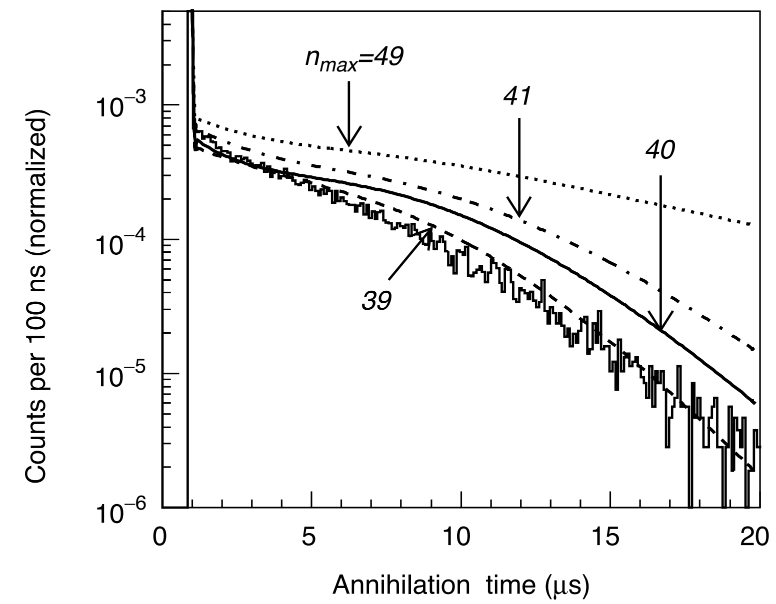
Established $\bar{p}$ longevity in gas, liquid, solid helium-3 & helium-4

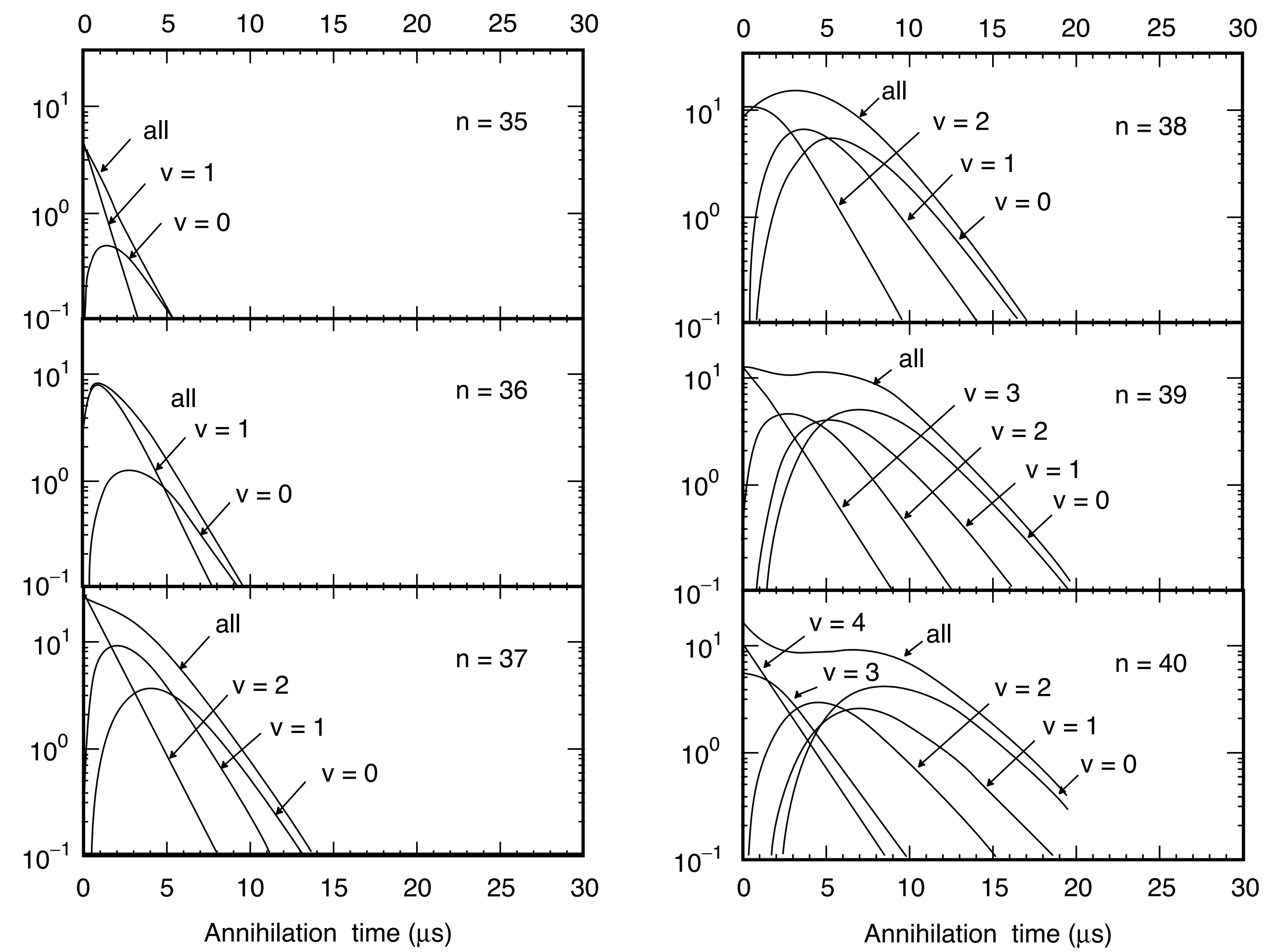
Lifetime 3~4μs, formation probability ~3%



# “DATS” understood by cascade

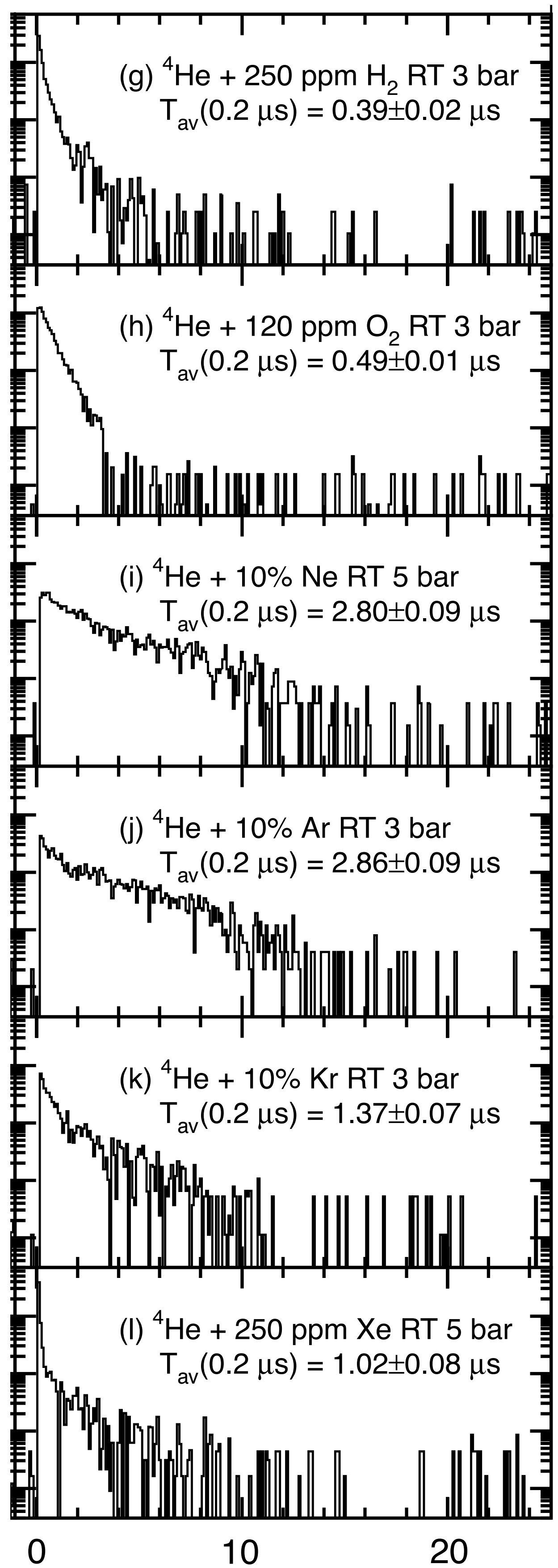



K. Ohtsuki and M. Hori

# Also found strong impurity effects




$H_2$ → "HAIR" method

$O_2$

Ne

Ar

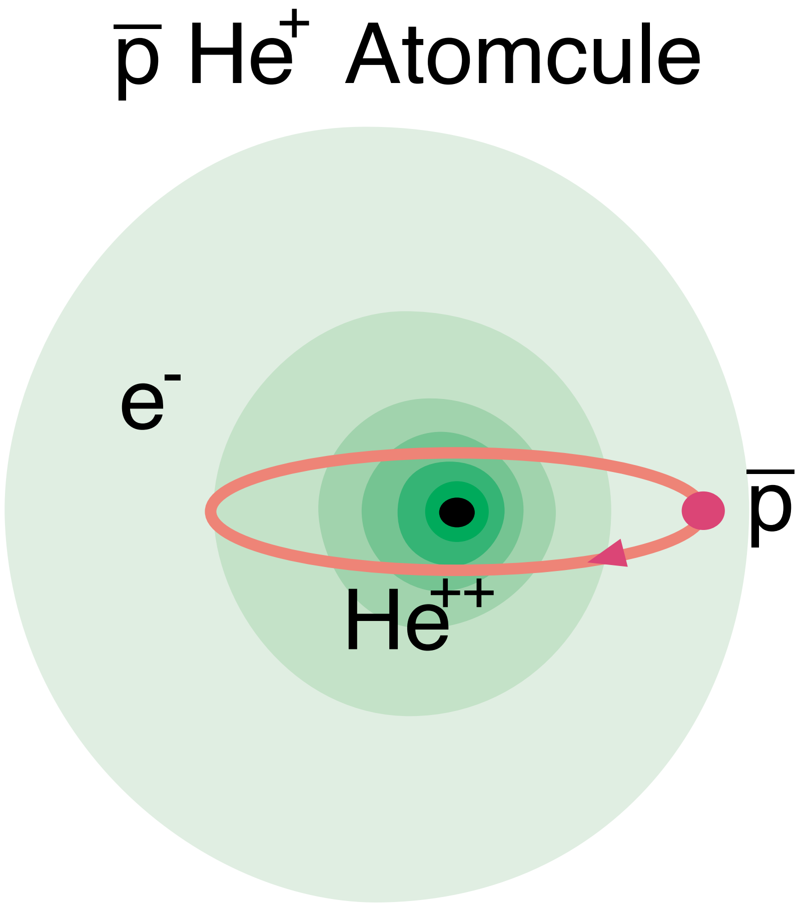
Kr

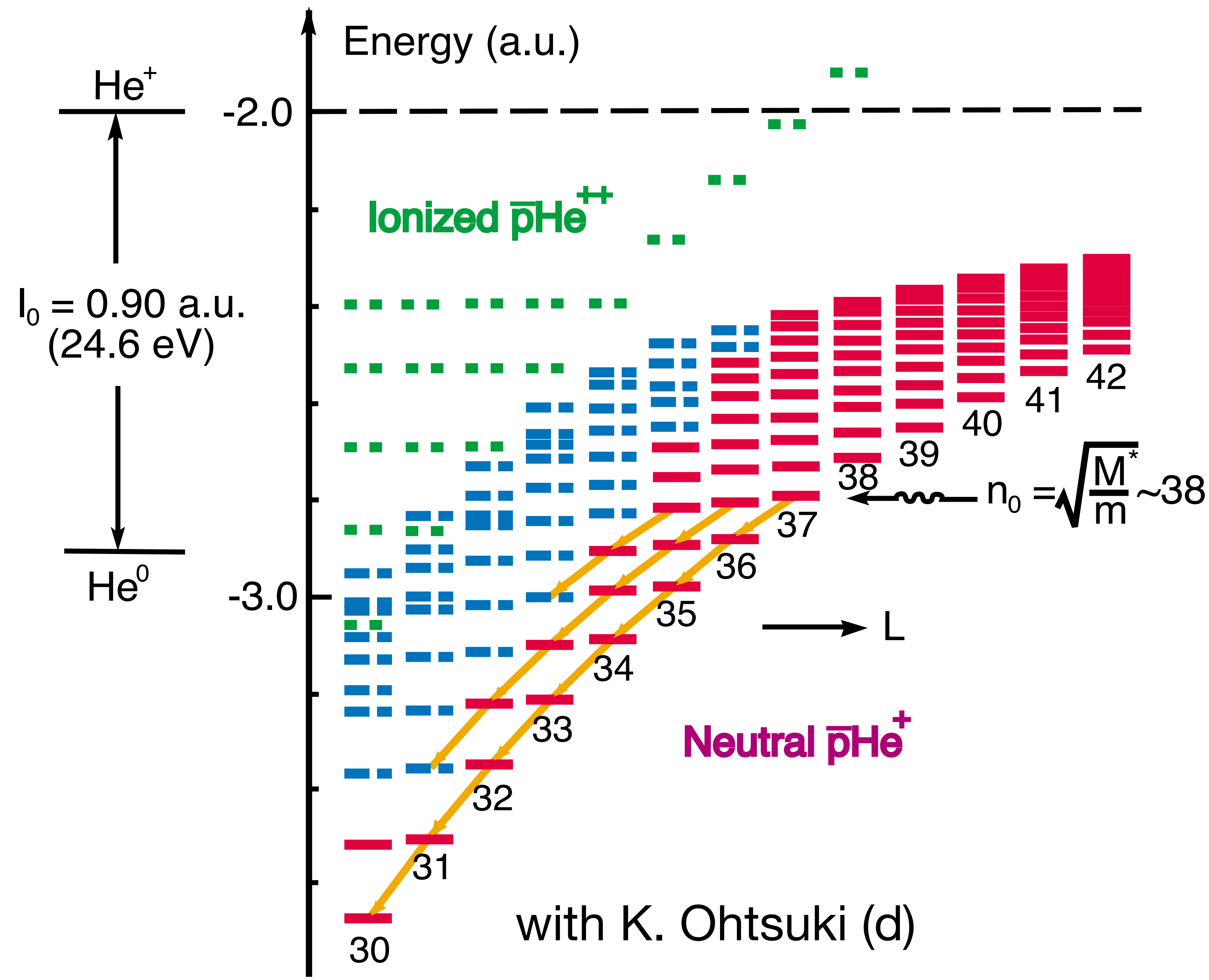
Xe

# 原子分子

Three-body "Atomcule"

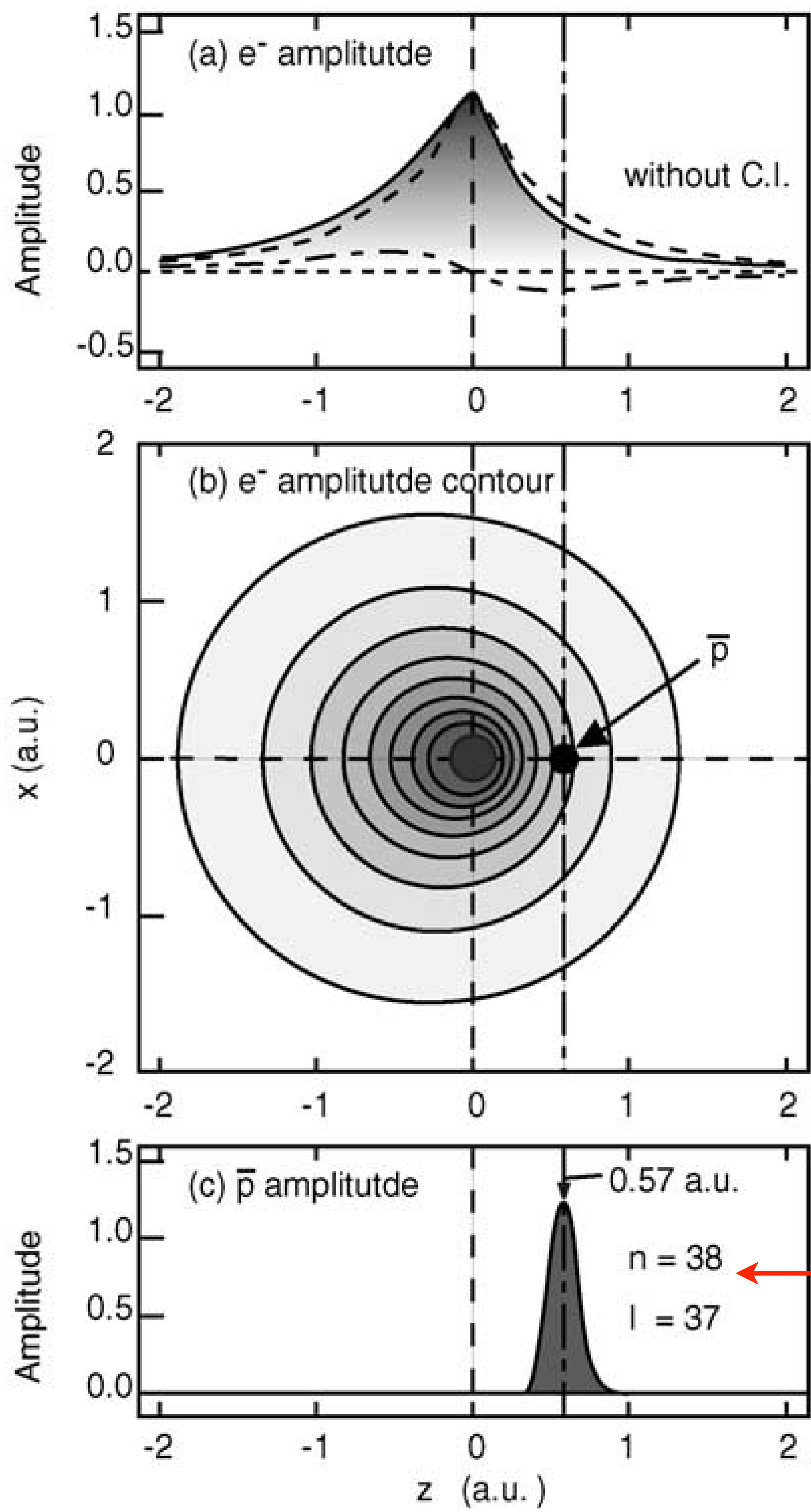
# Theoretical understanding




T. Yamazaki, et al., Nature 361 (1993) 238.

# $\bar{p} + e^- + \alpha$



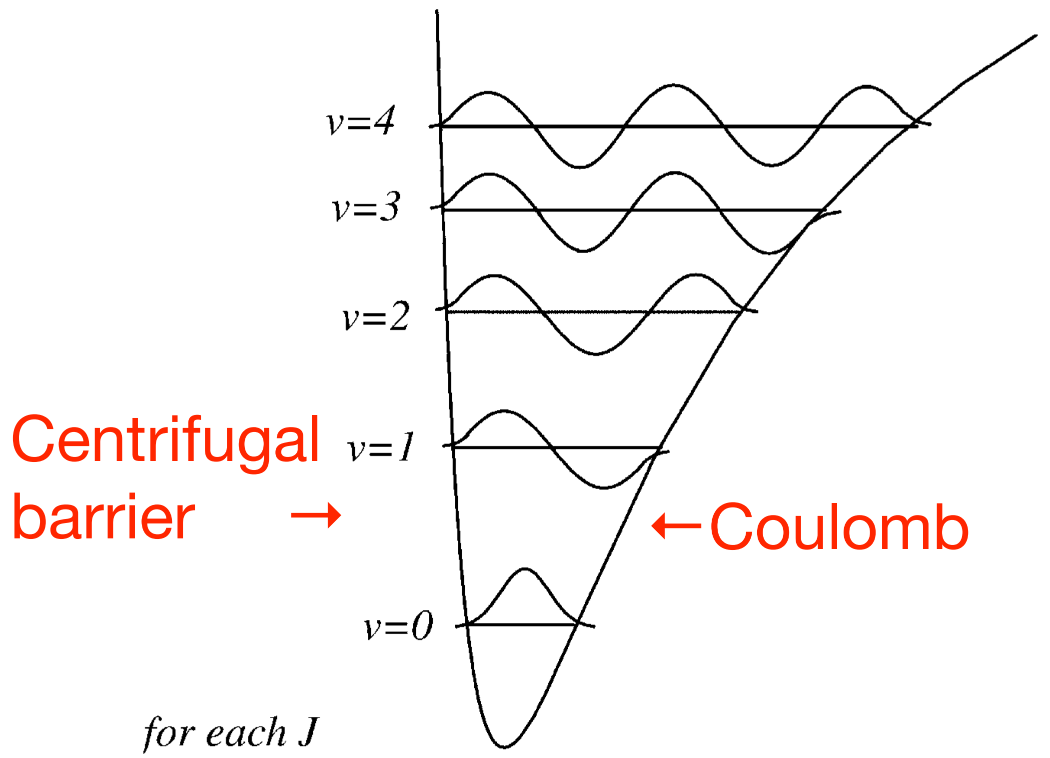

1. Atom: one of the two e- of He replaced by $\bar{p}$
2. Molecule: 2 heavy, 1 light

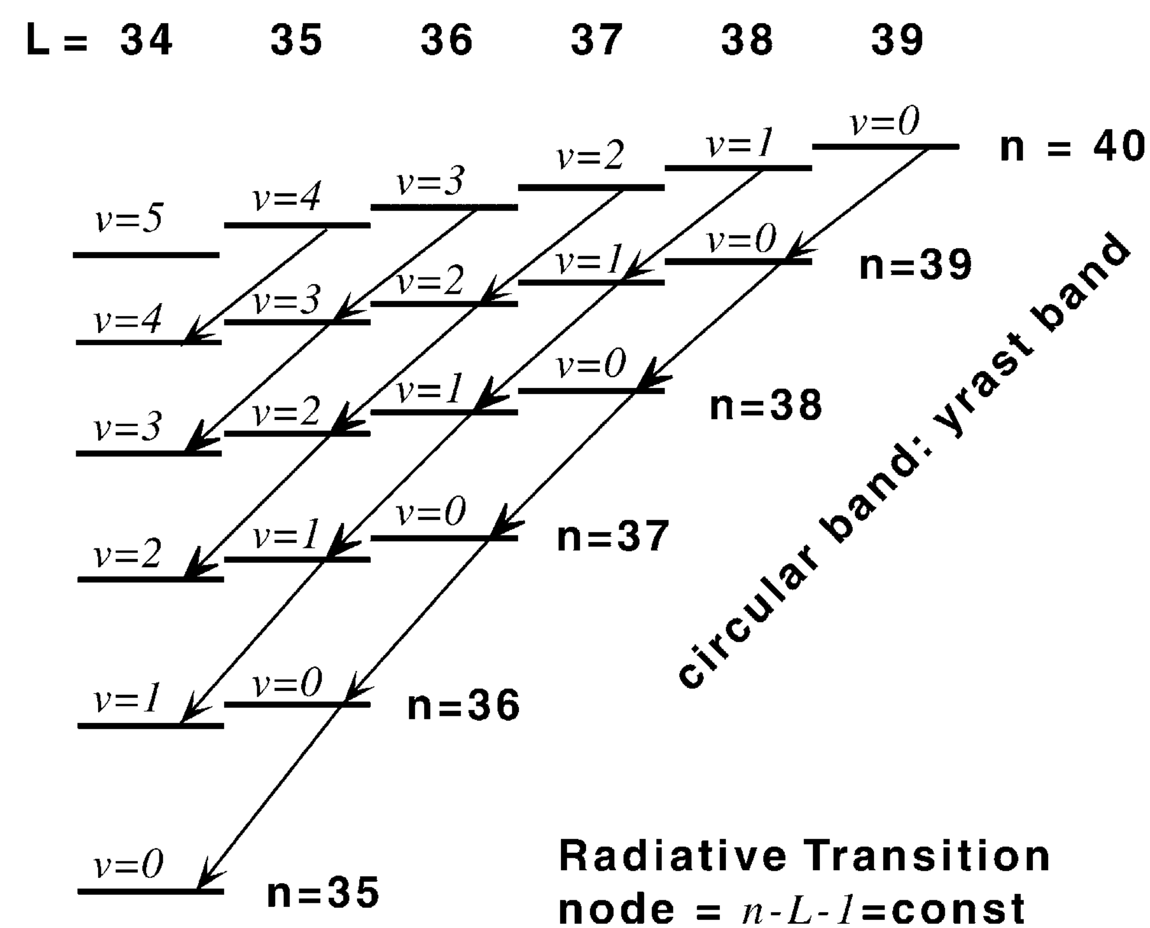
Large n & L
near-circular states

# "Atomcule"

## ATOMCULE: MOLECULAR ASPECT OF YRAST ATOMS

$$V_J(R) = -\frac{Z}{R} + \frac{J(J+1)}{2MR^2} + e_J(R)$$




**MOLECULAR** $(J, v)$ ⇄ **ATOMIC** $(n, L)$

unharmonic
rotation ~ vibration

**DUAL**

$J = L$

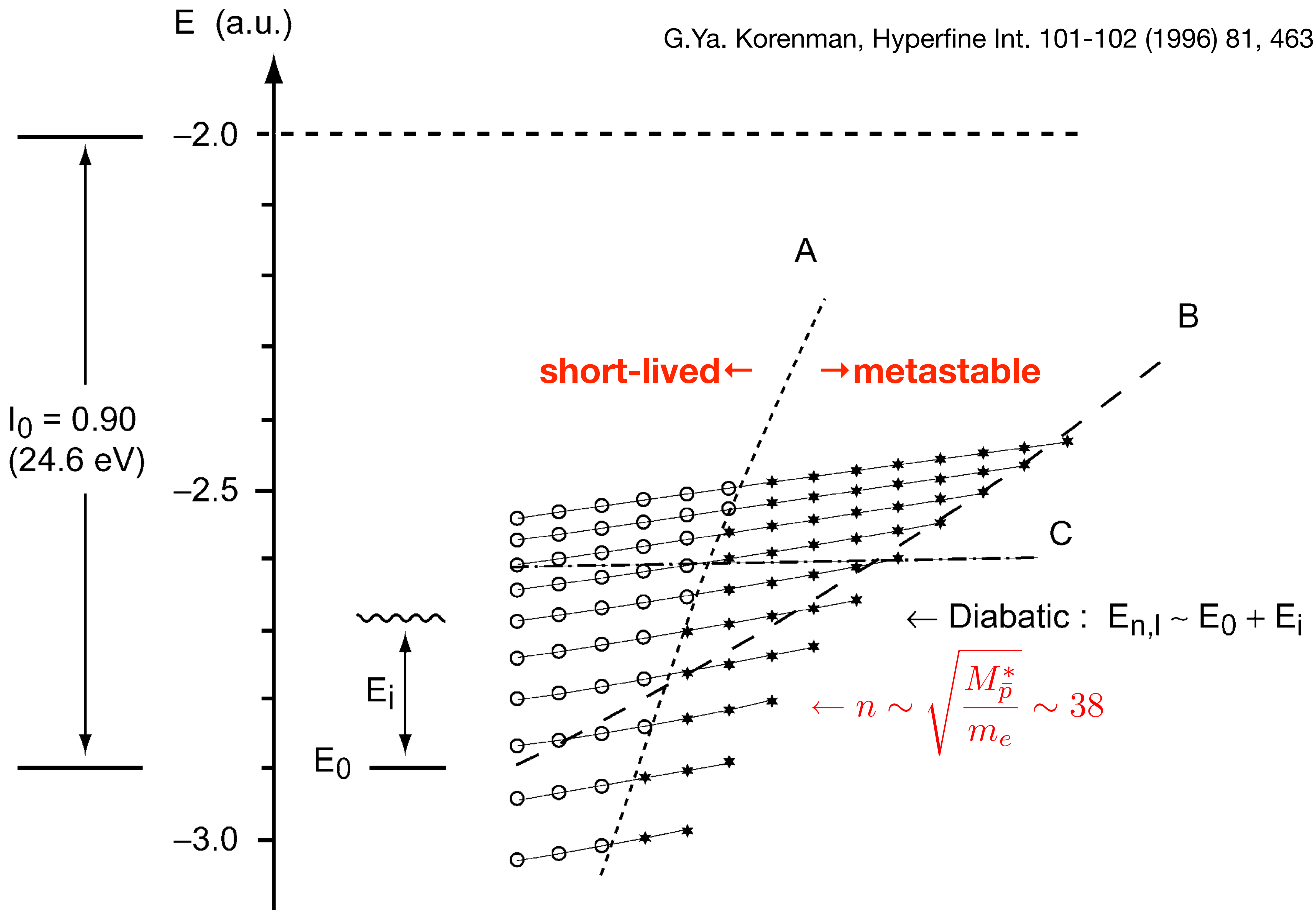
$v = n - L - 1$

# 生成と崩壊

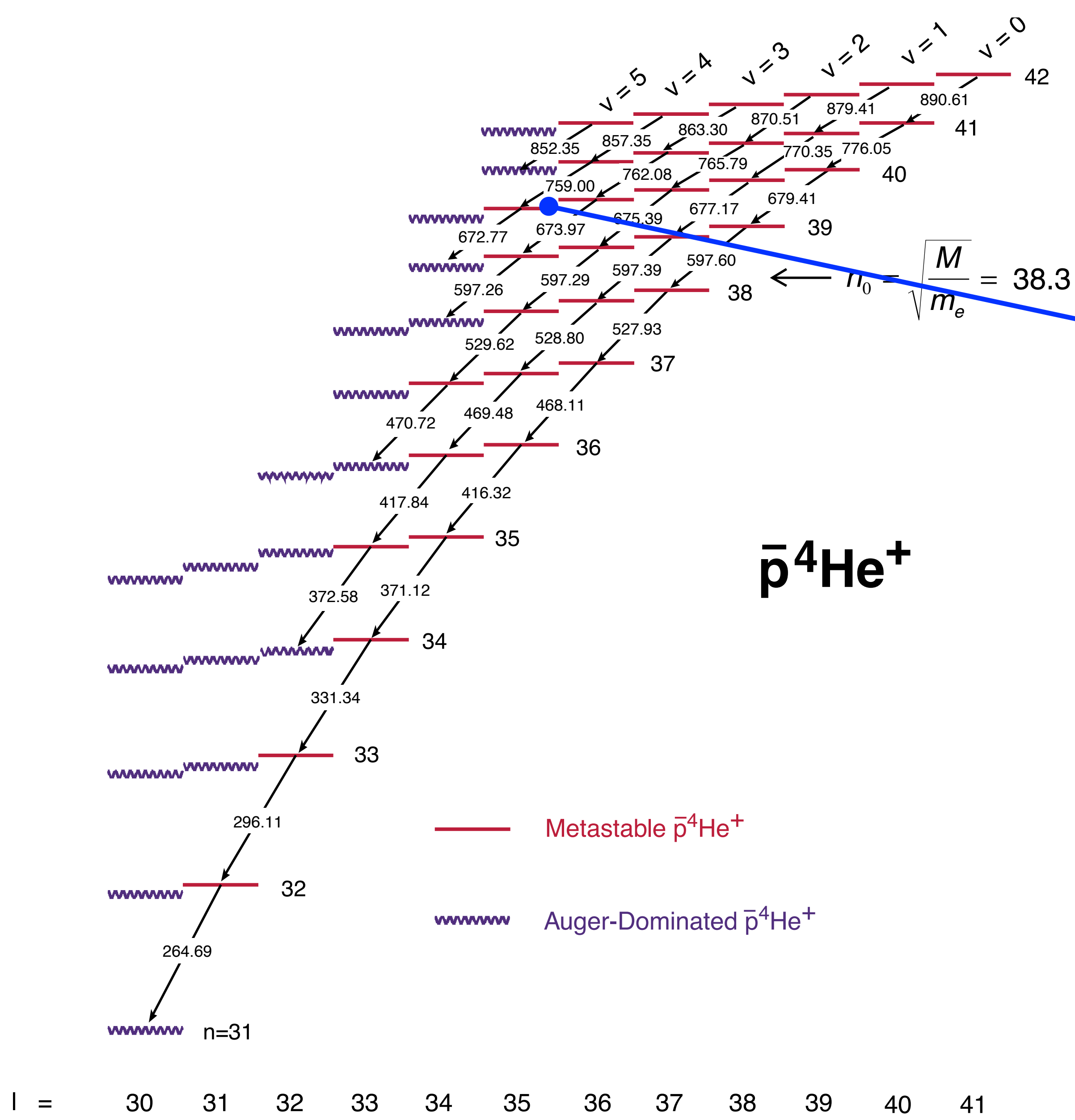
# Formation & Decay

# where is the $\bar{p}$ captured?

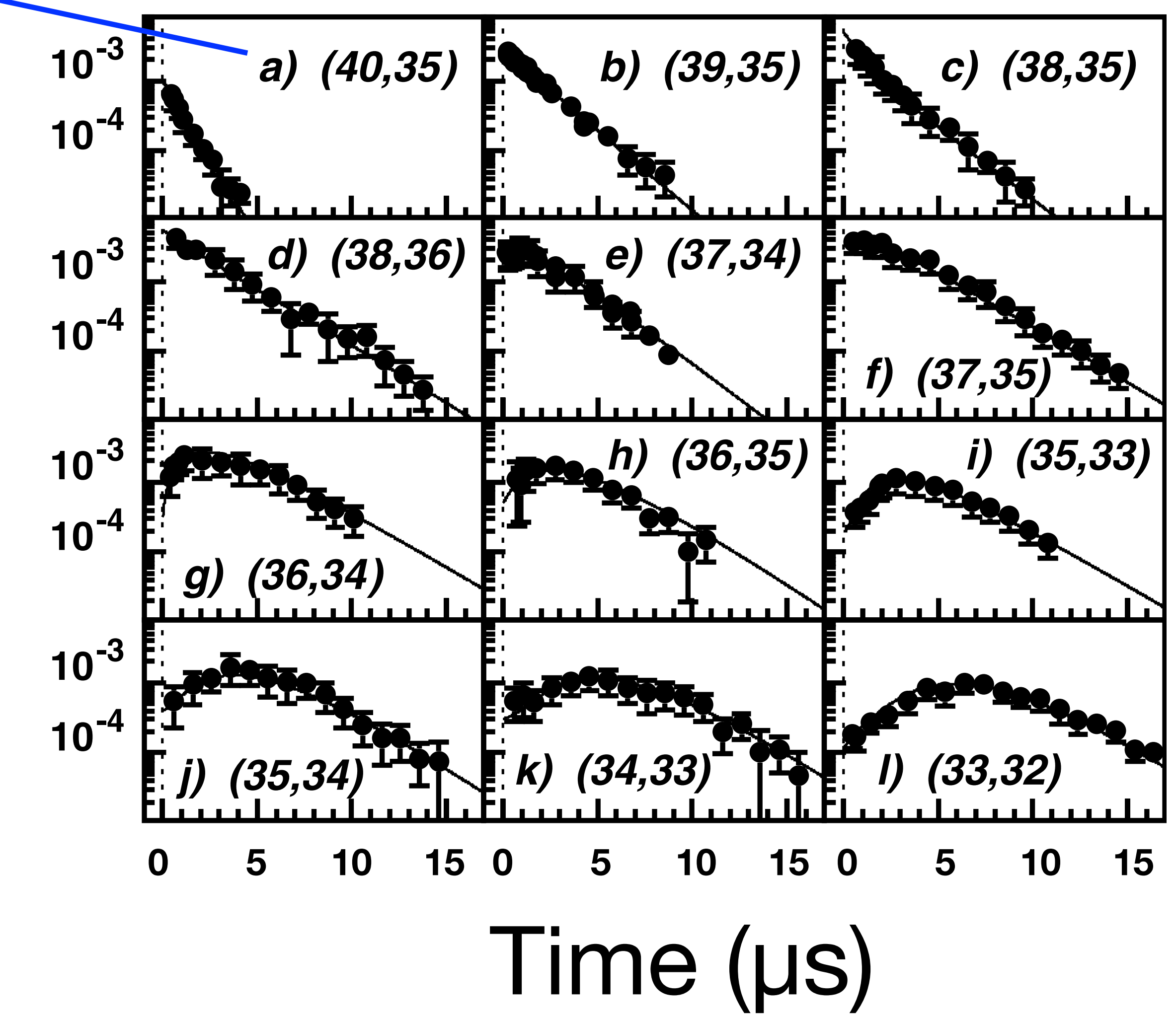
G.Ya. Korenman, Hyperfine Int. 101-102 (1996) 81, 463.



# Time evolution of level population

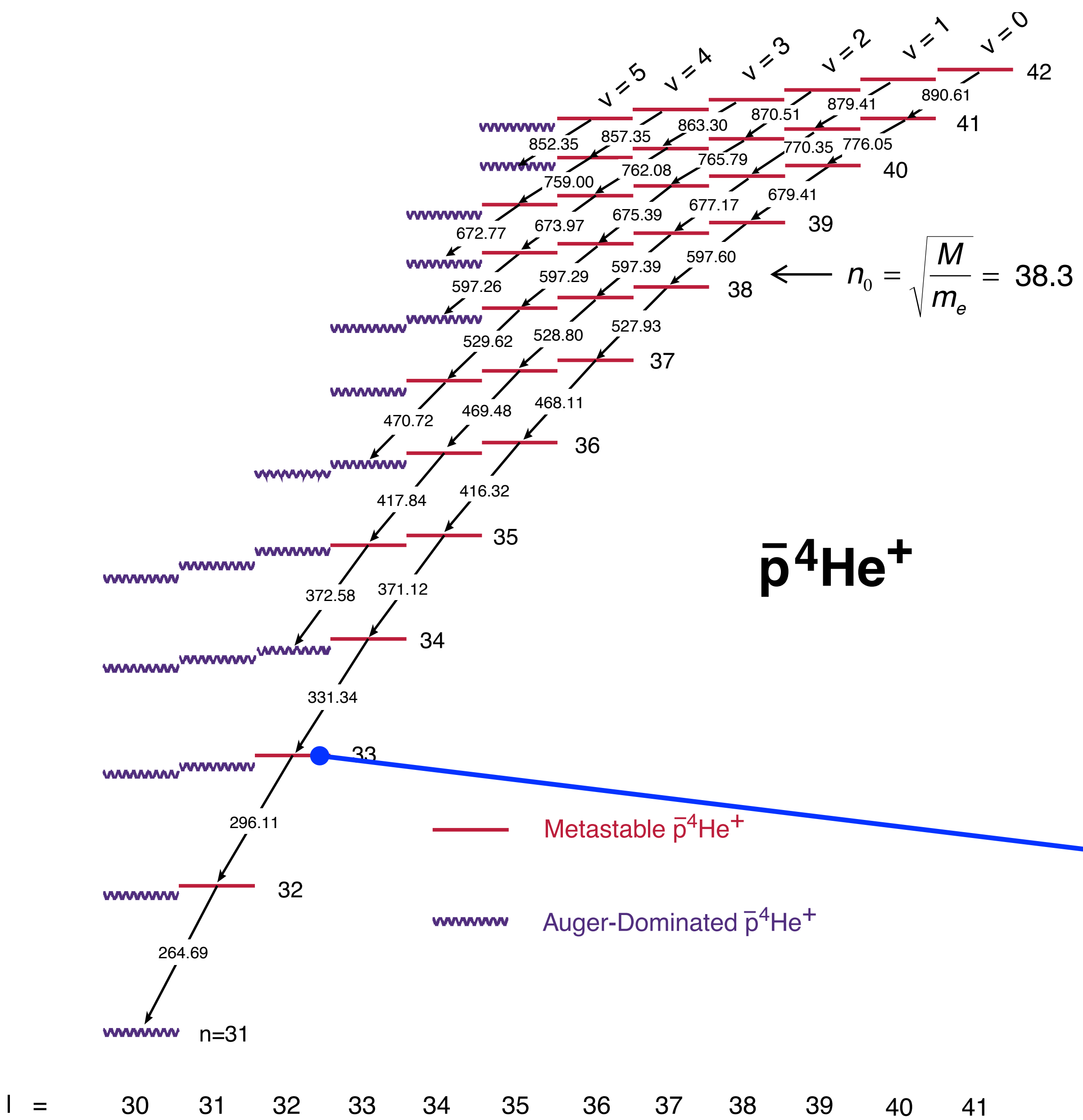



Level population
(probed by laser)

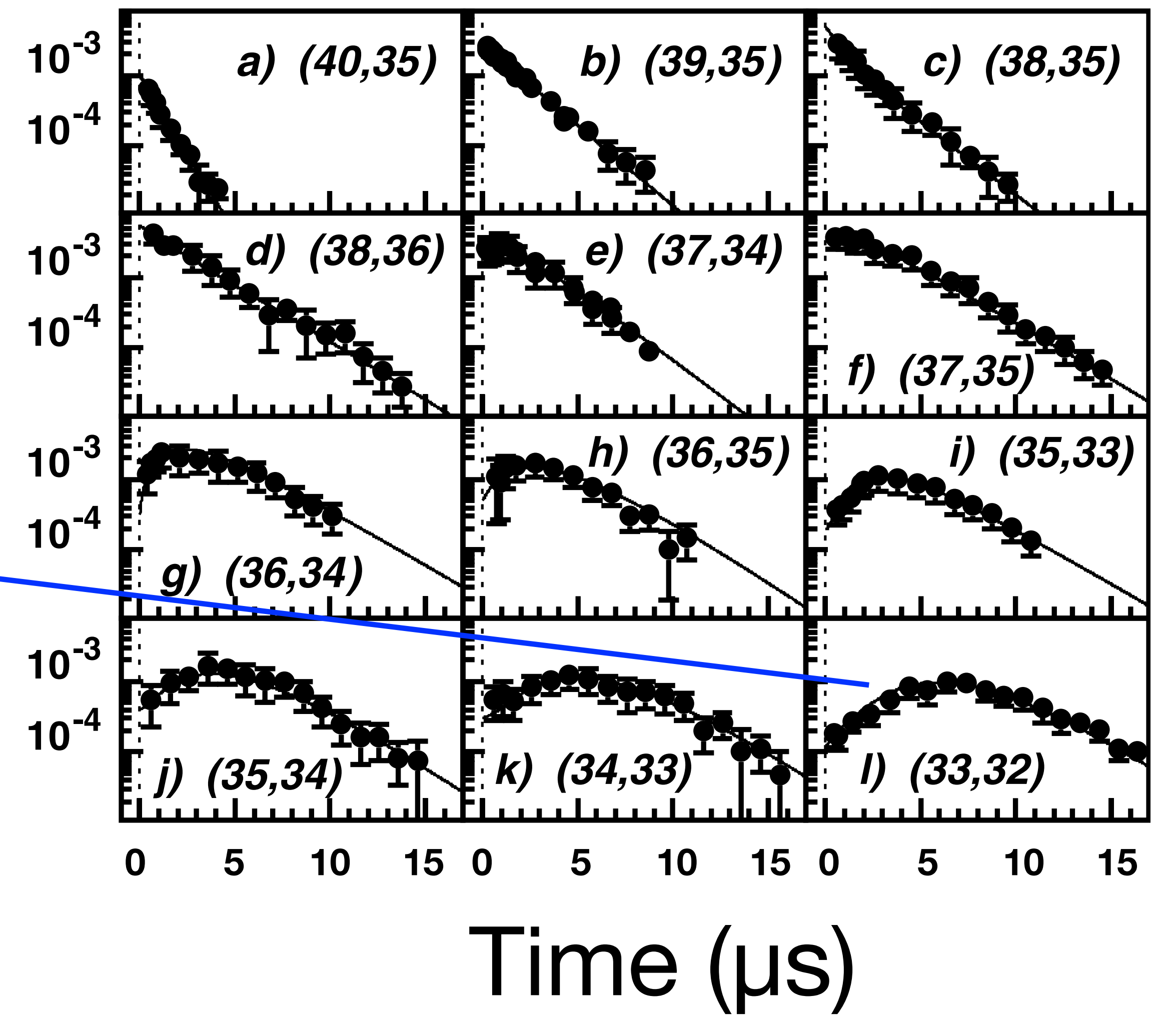



M. Hori et al., Phys. Rev. Lett. 89, 093401 (2002)

# Time evolution of level population



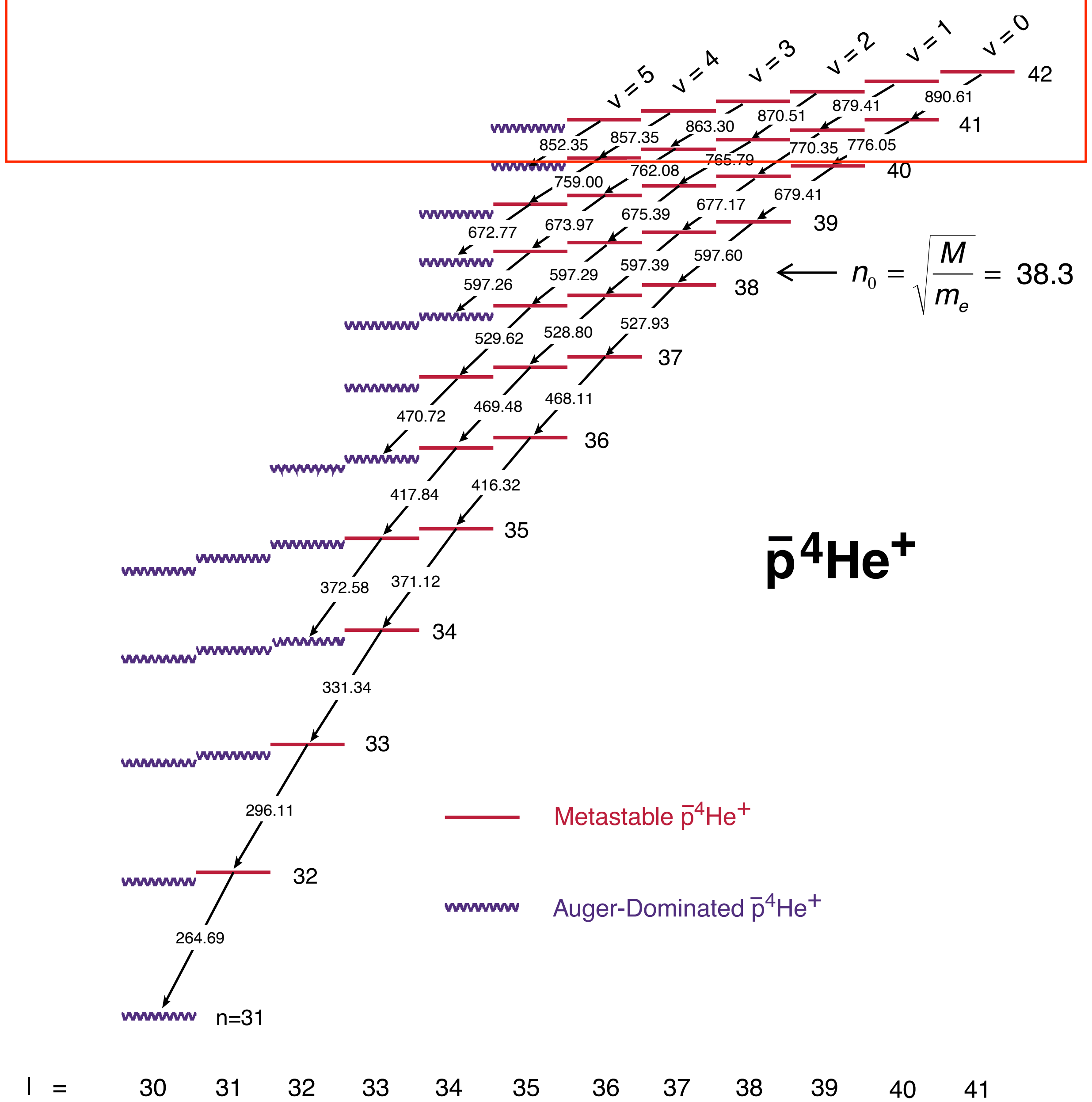

## Level population (probed by laser)



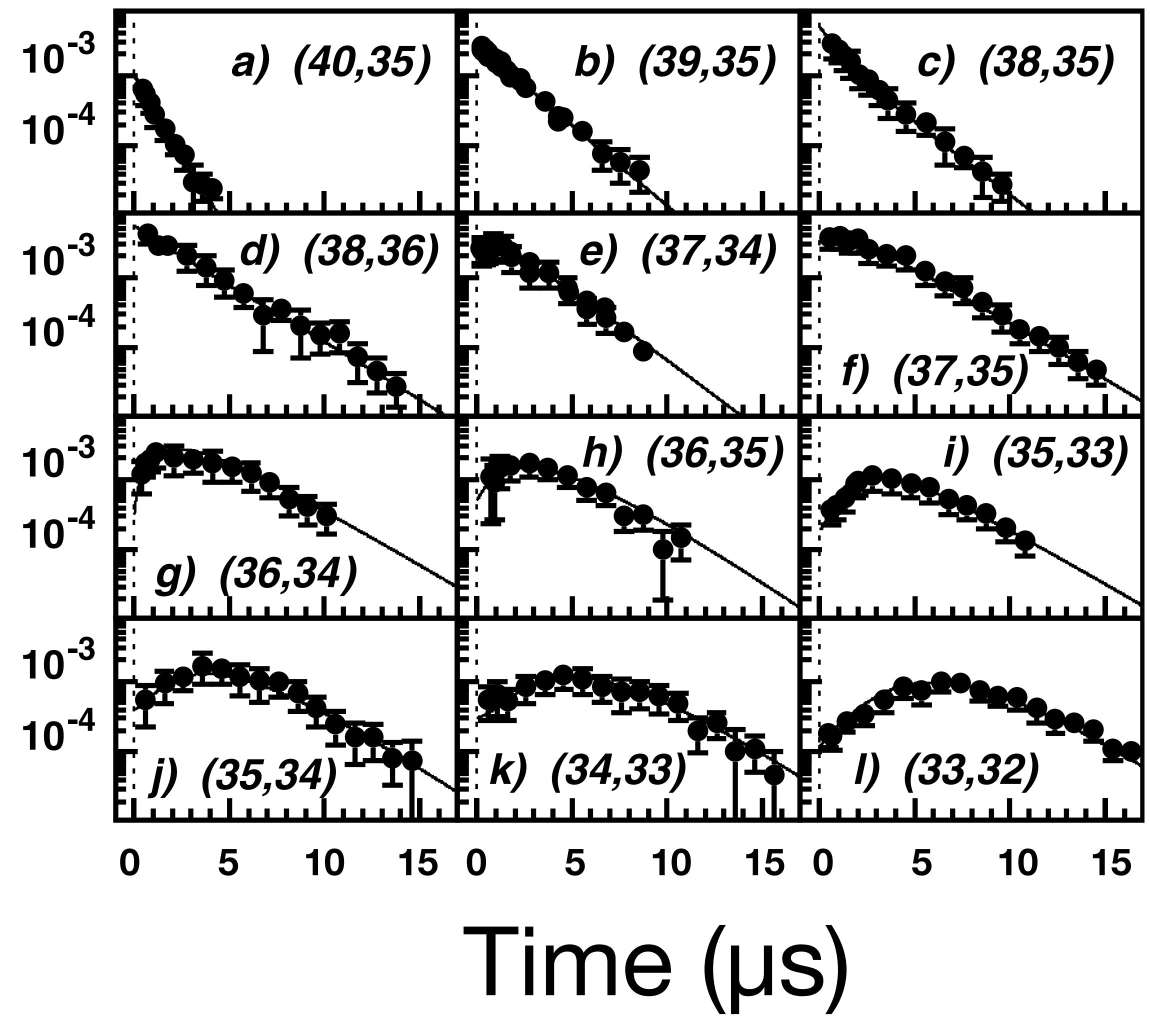

M. Hori et al., Phys. Rev. Lett. 89, 093401 (2002)

# Time evolution of level population

n>41 not populated
(destroyed during thermalization)




## Level population
## (probed by laser)

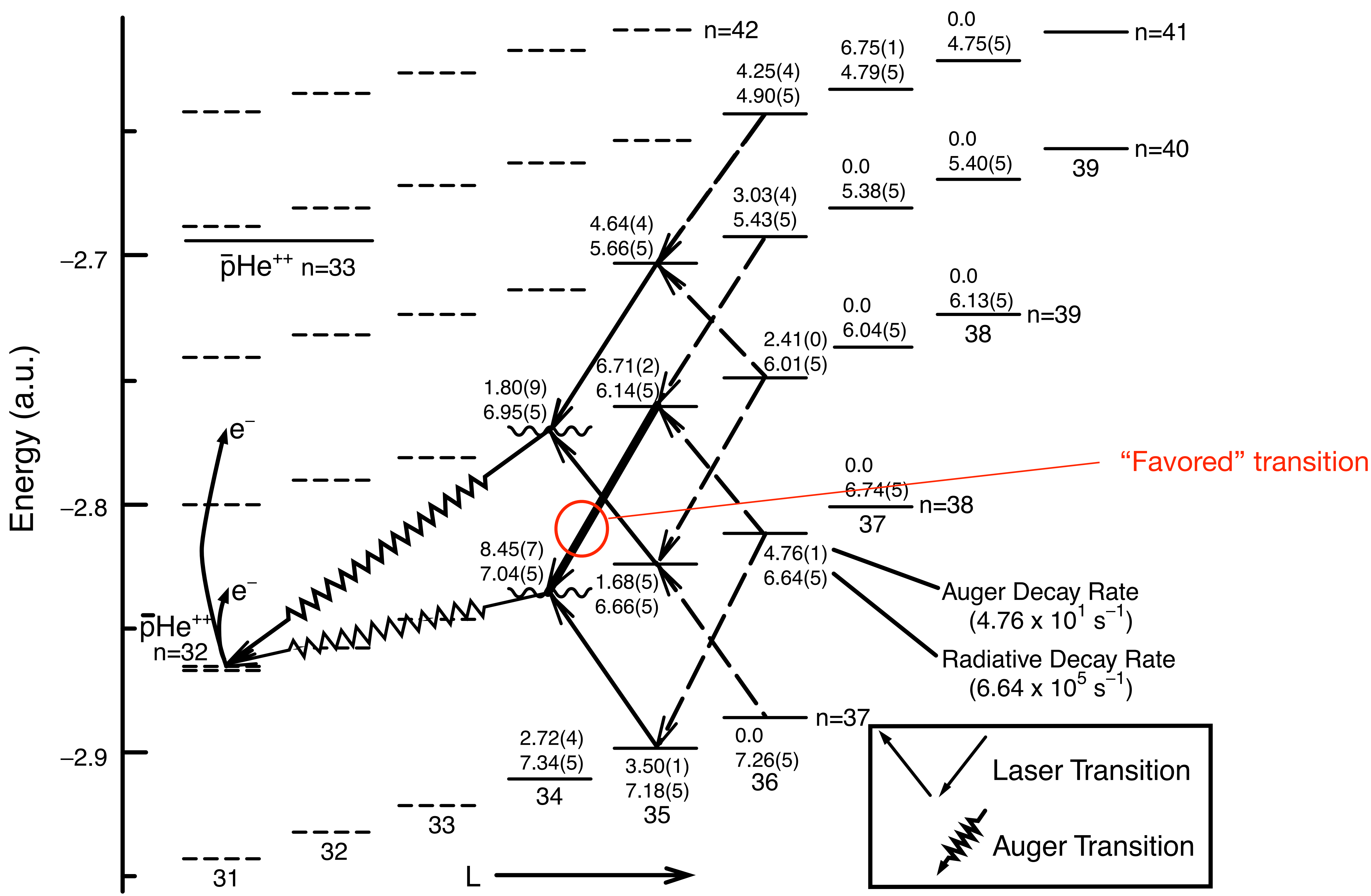



M. Hori et al., Phys. Rev. Lett. 89, 093401 (2002)

# 分光

## Early days of laser spectroscopy
## PS205

# Proposed method

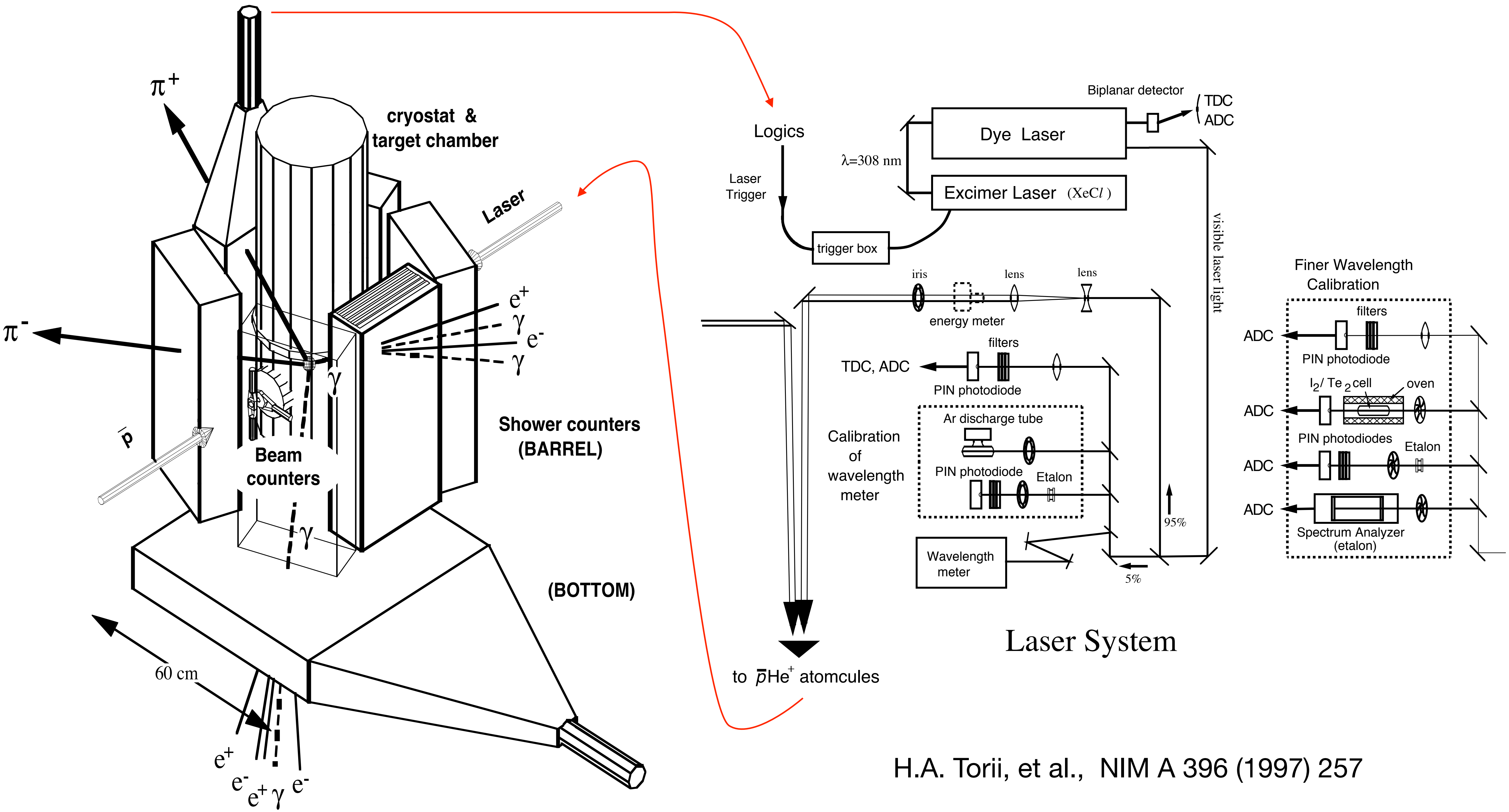



N. Morita et al., NIM A 330 (1993) 439.

# PS205 setup

LEAR ultra-slow extracted $\bar{p}$.

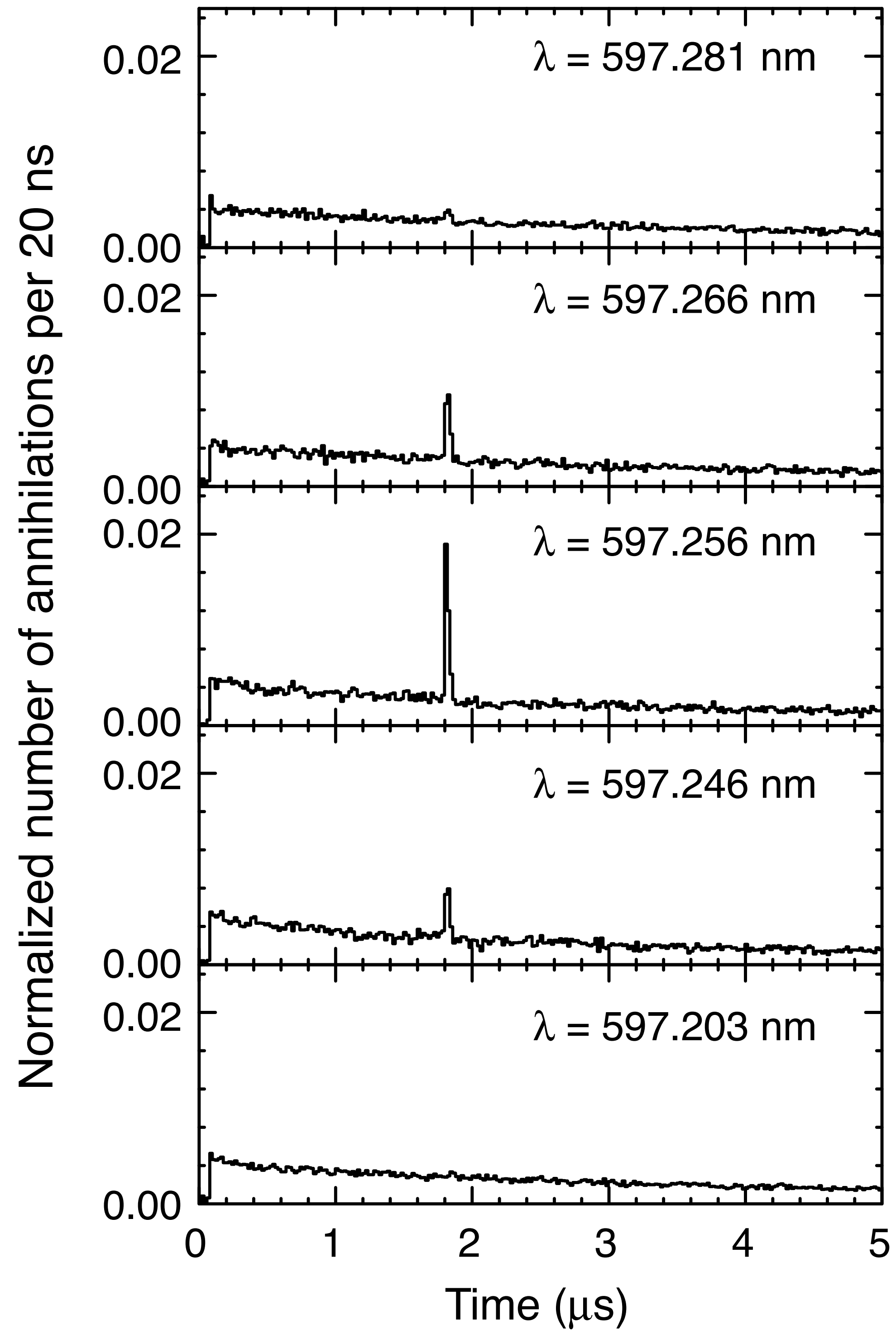
Laser randomly triggered for each $\bar{p}$He candidate




H.A. Torii, et al., NIM A 396 (1997) 257

# An example, (n,l)=(39,35)→(38,34)

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



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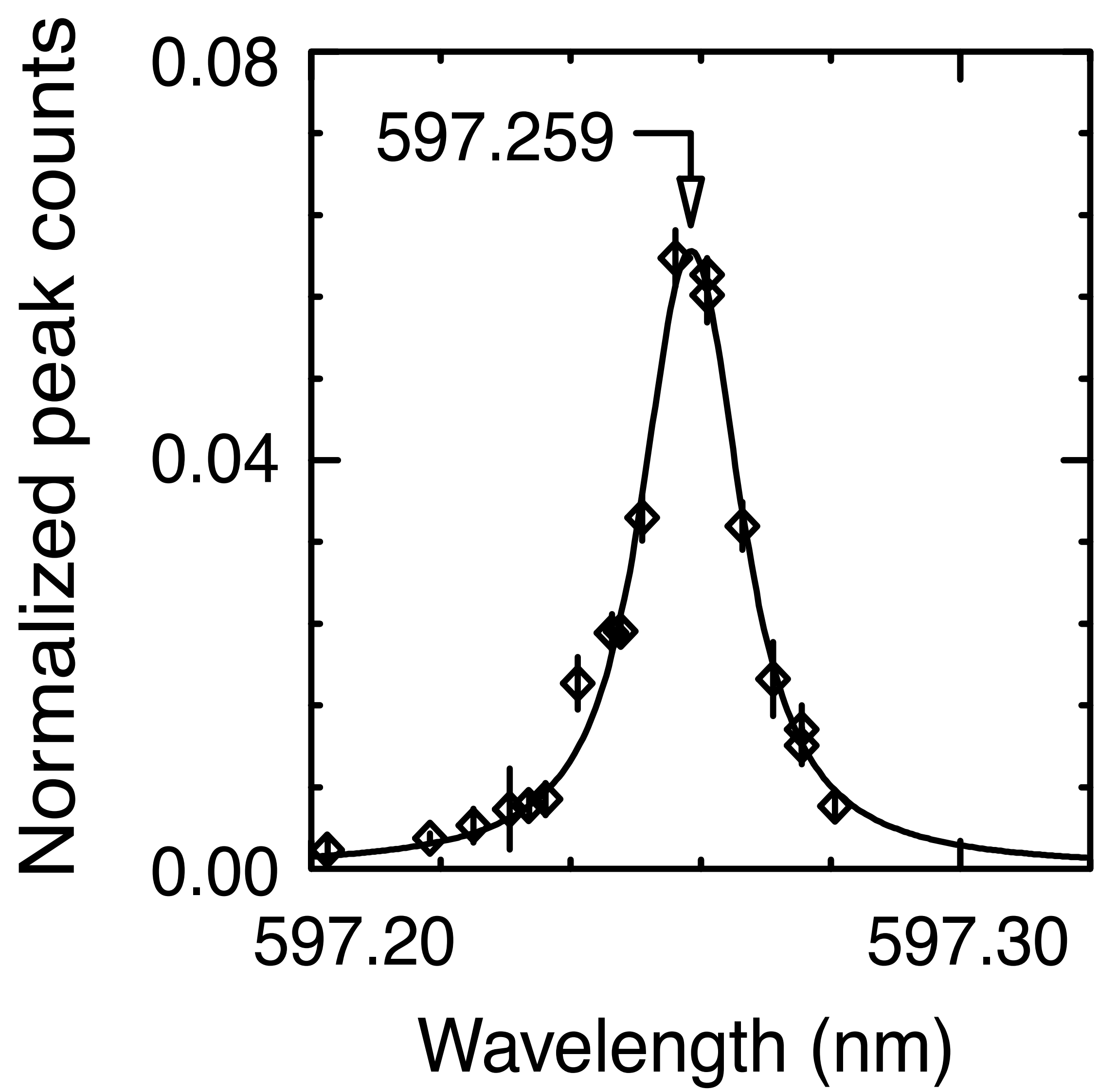
N. Morita, et al., Phys. Rev. Lett. 72 (1994) 1180.

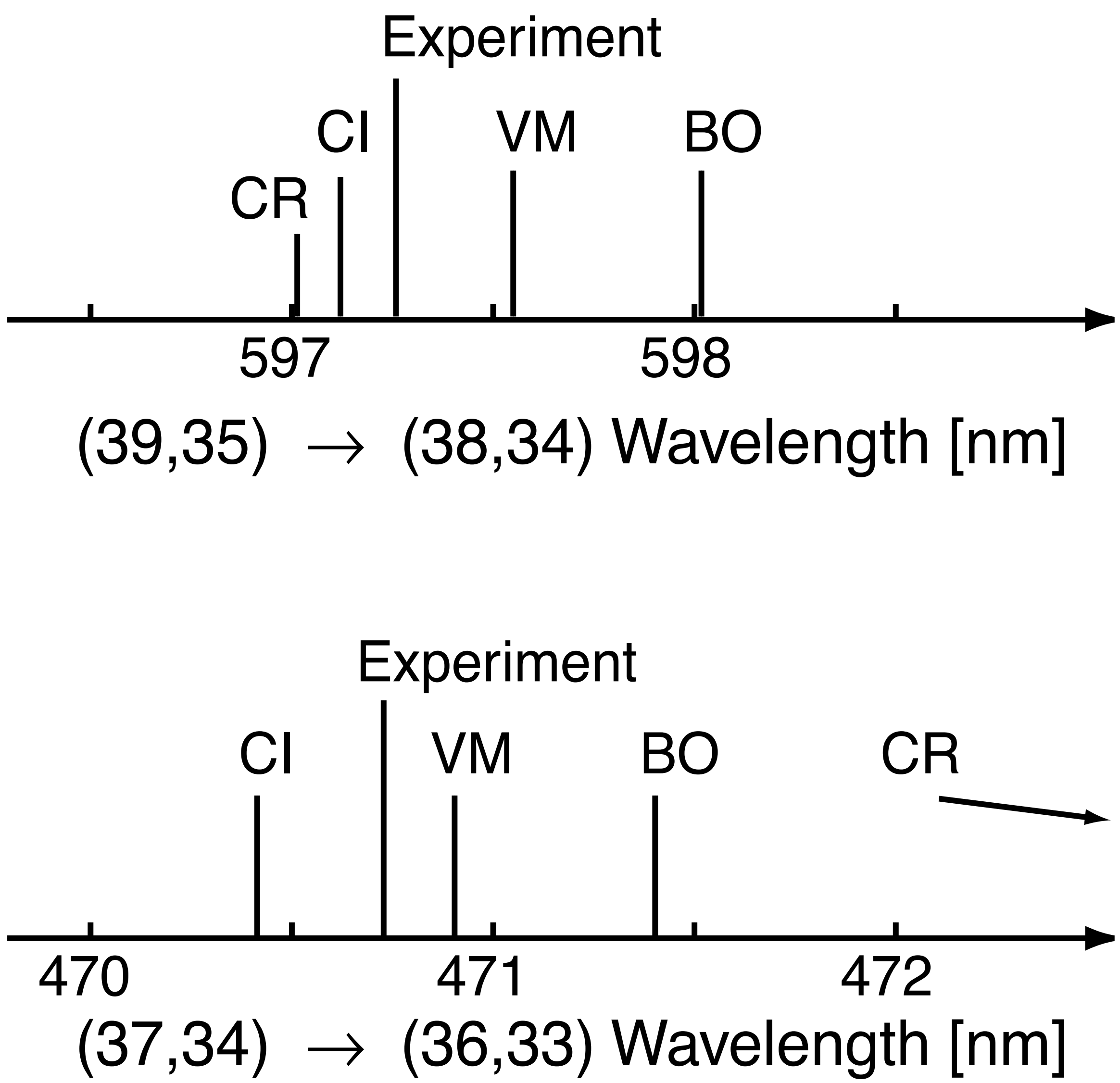


# 理論

Theory

(more on theory by V.I. Korobov)

# Early days of PS205




Theory precision ~ 1000 ppm

~300 larger than the laser bandwidth of ~3GHz

Took weeks to hit the resonance

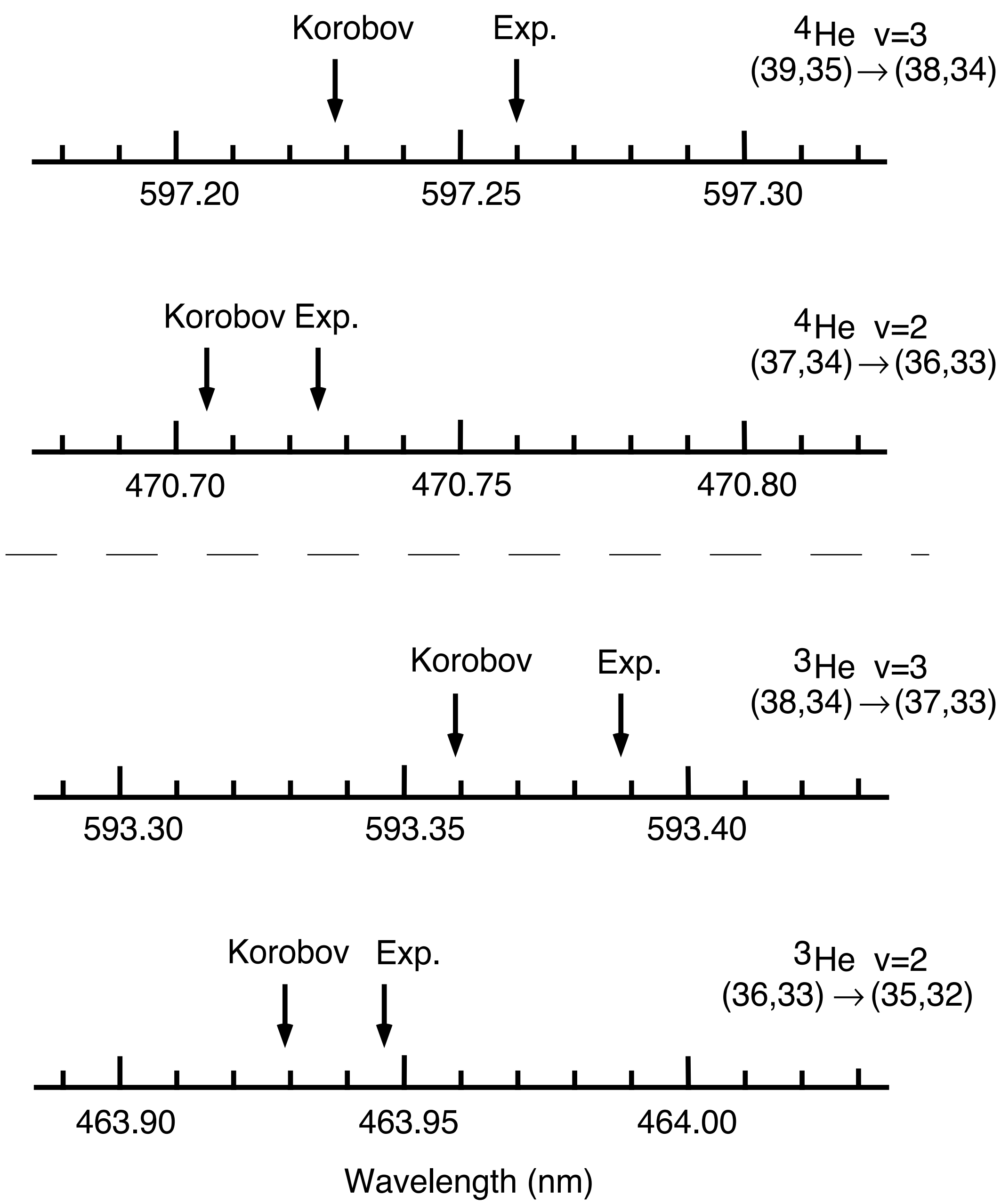
F.E. Maas et al., Phys. Rev. A 52 (1995) 4266.

# Korobov revolution

PHYSICAL REVIEW A VOLUME 54, NUMBER 3 SEPTEMBER 1996

**Variational calculation of energy levels in $p$ 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

$$H = T + V$$

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

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

# 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)

$$H = T + V$$

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

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

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

Bethe logarithm

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

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

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

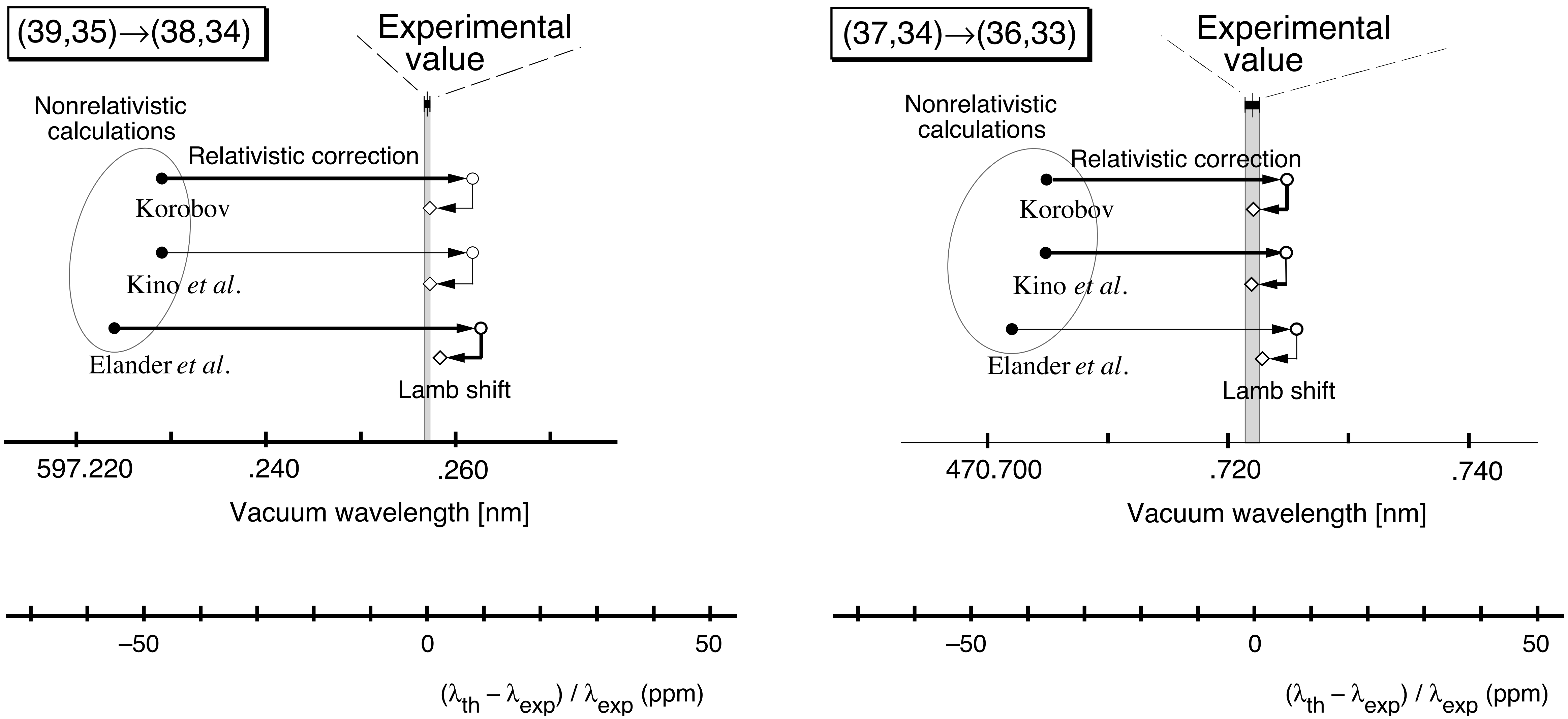
$$+ Z_{\bar{p}}^3\ln^2(Z_{\bar{p}}\alpha)^{-2}\delta(\mathbf{r}_{\bar{p}})\rangle,$$

# Relativistic & QED corrections

$\bar{p}$He first appeared in PDG
everyone was ecstatic

**end of LEAR PS205**

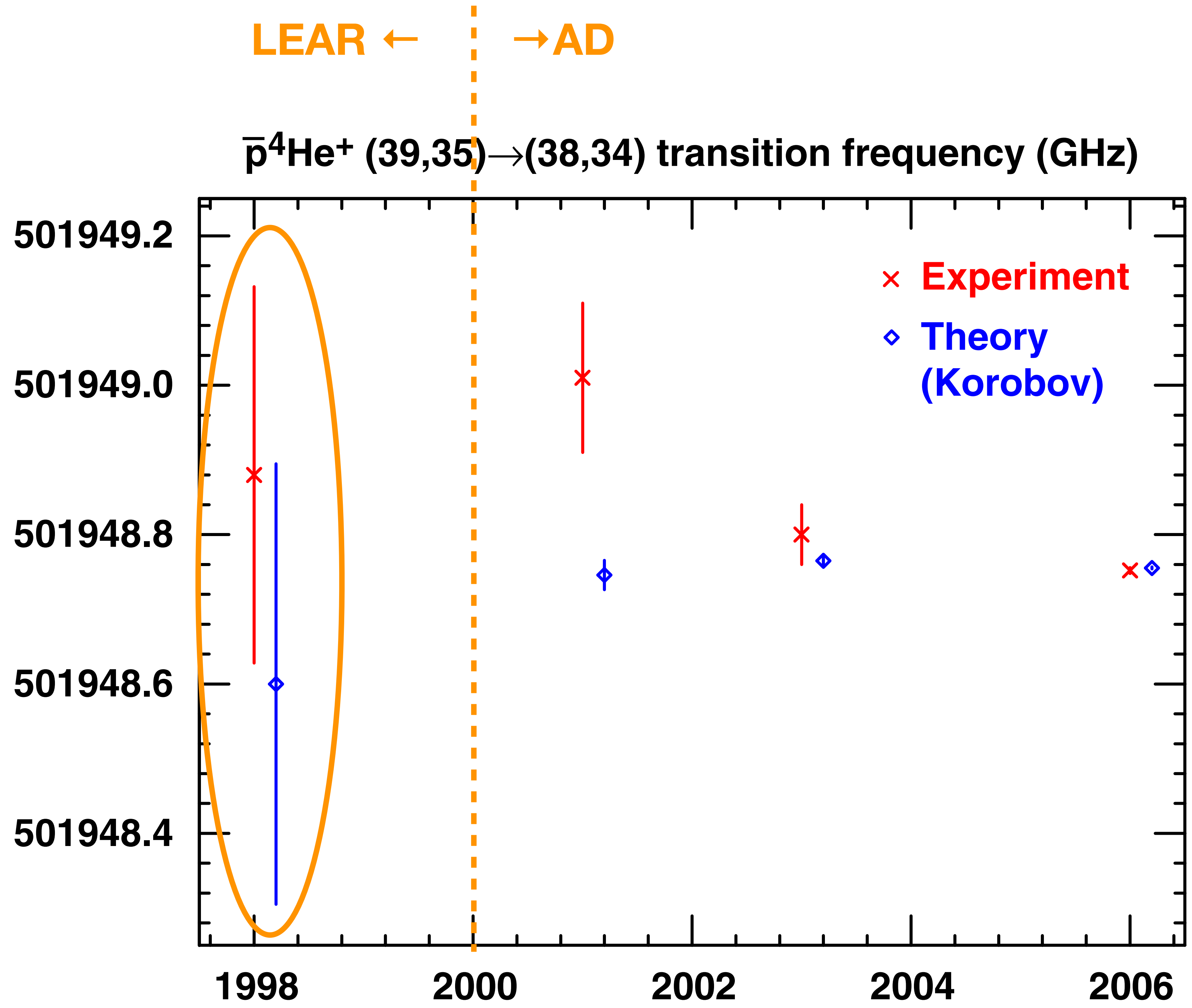
relative precision ~0.5ppm




note: wavelength comparison

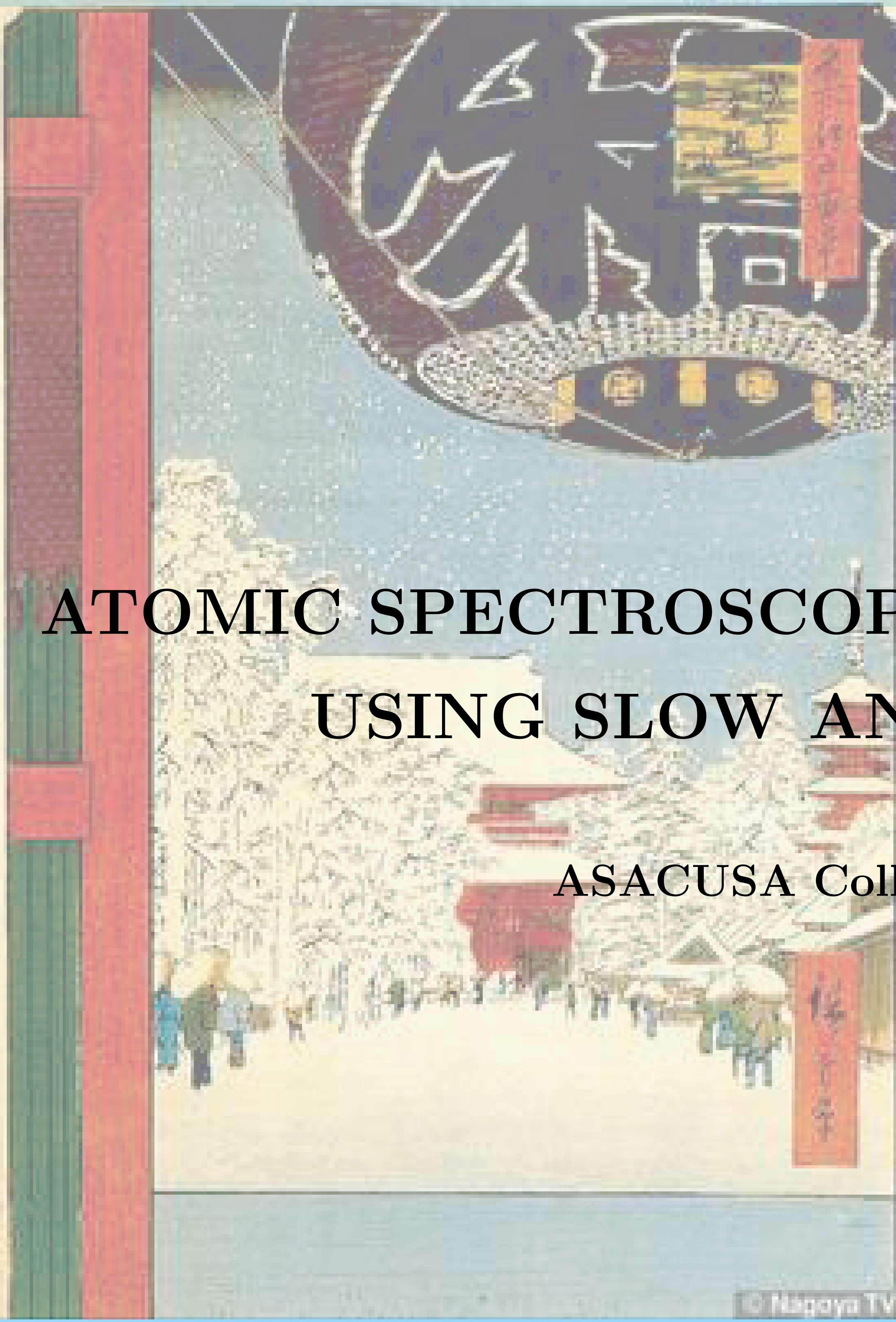
H.A. Torii et al., Phys. Rev. A 59 (1999) 223.

# Theory vs experiment



# 反陽子減速器

ASACUSA at CERN AD

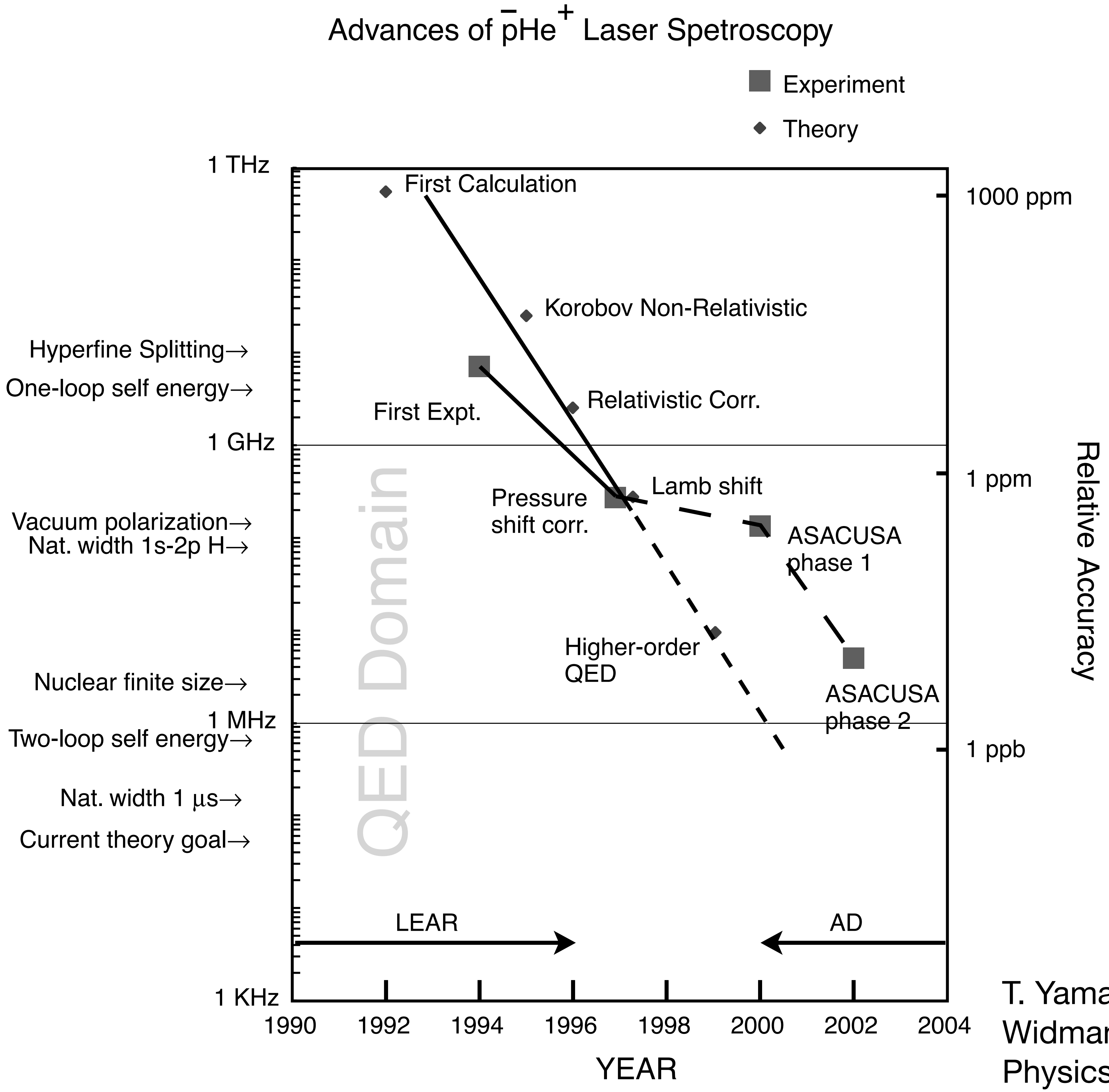



**7-Oct-97**
CERN/SPSC 97-19
CERN/SPSC P-307

# ATOMIC SPECTROSCOPY AND COLLISIONS USING SLOW ANTIPROTONS

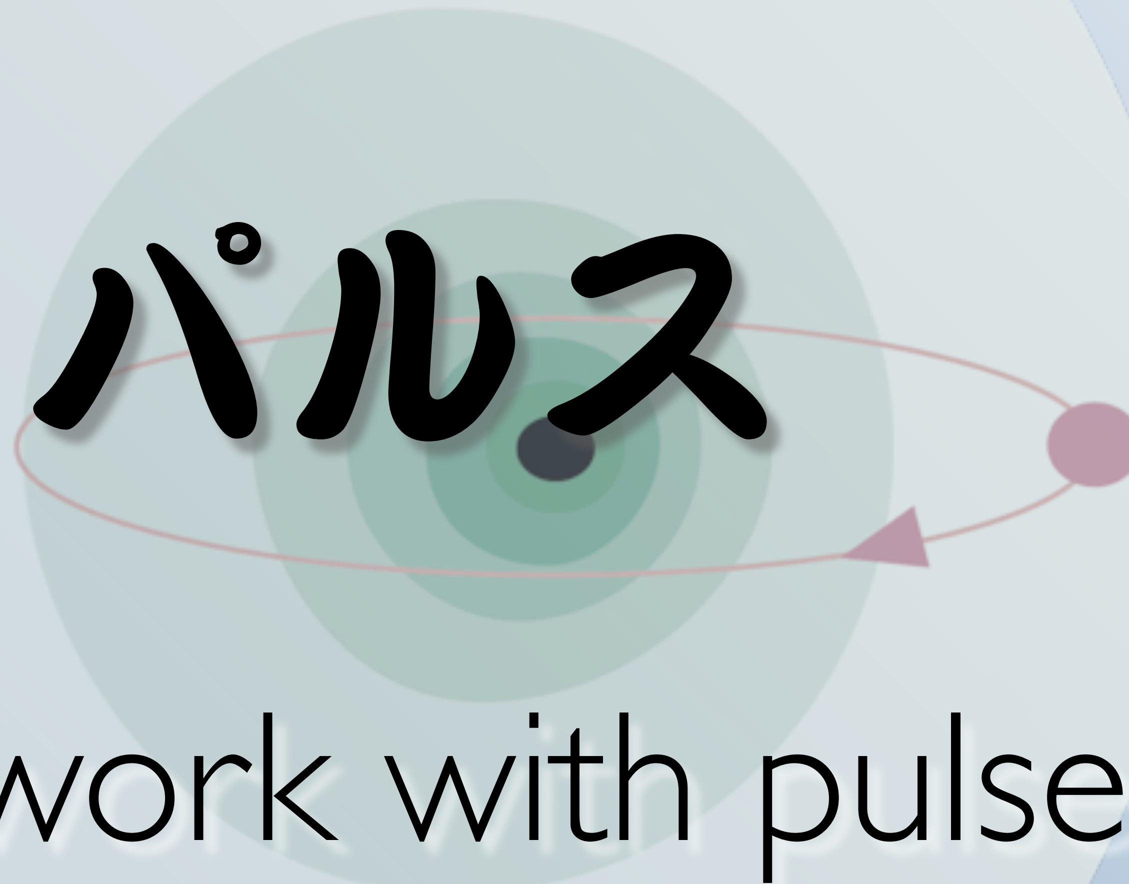
**ASACUSA Collaboration**

# LEAR - AD prospect as of 1997



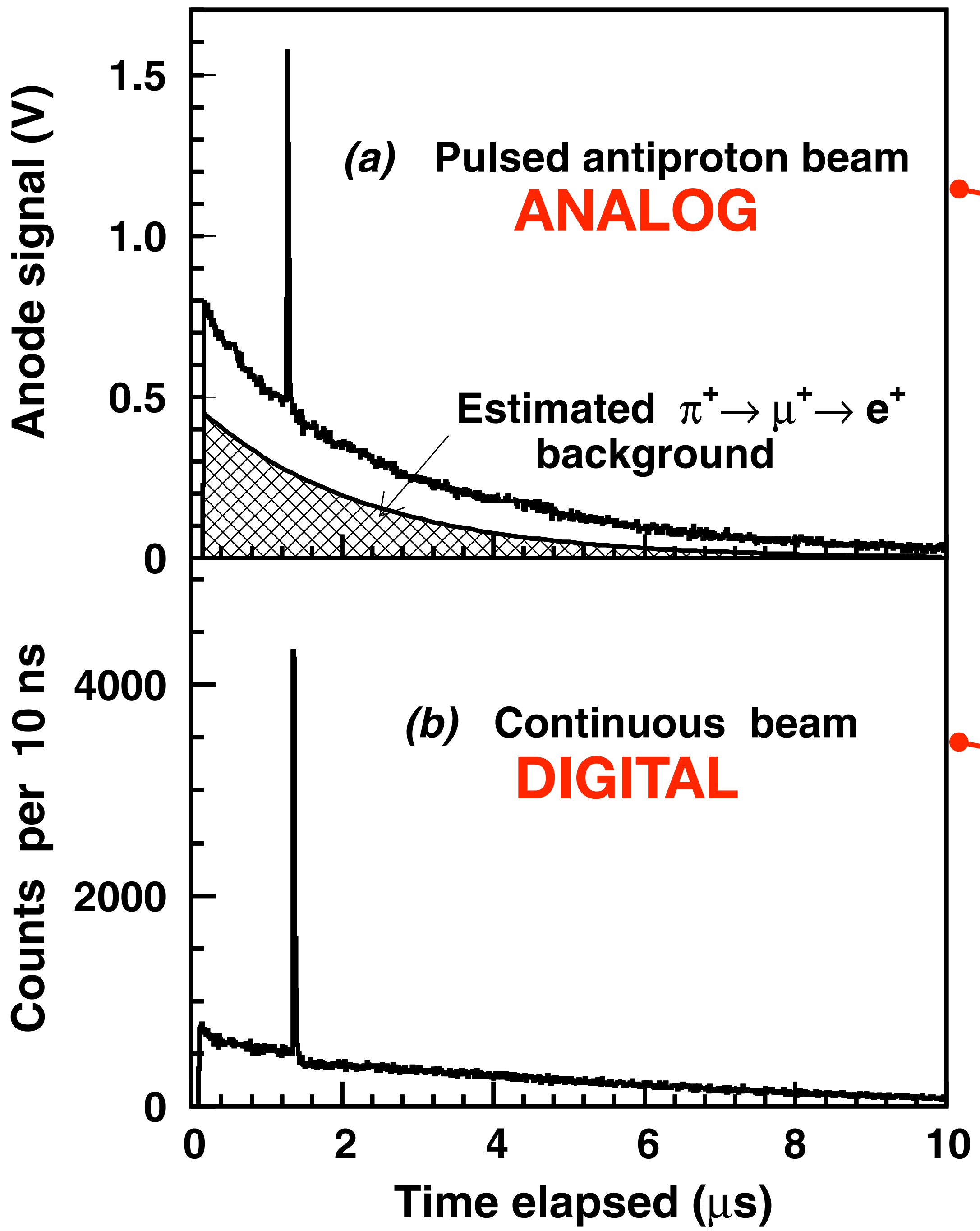

T. Yamazaki, N. Morita, RS. Hayano, E. Widmann, John Eades,
Physics Reports 366 (2002) 183–329

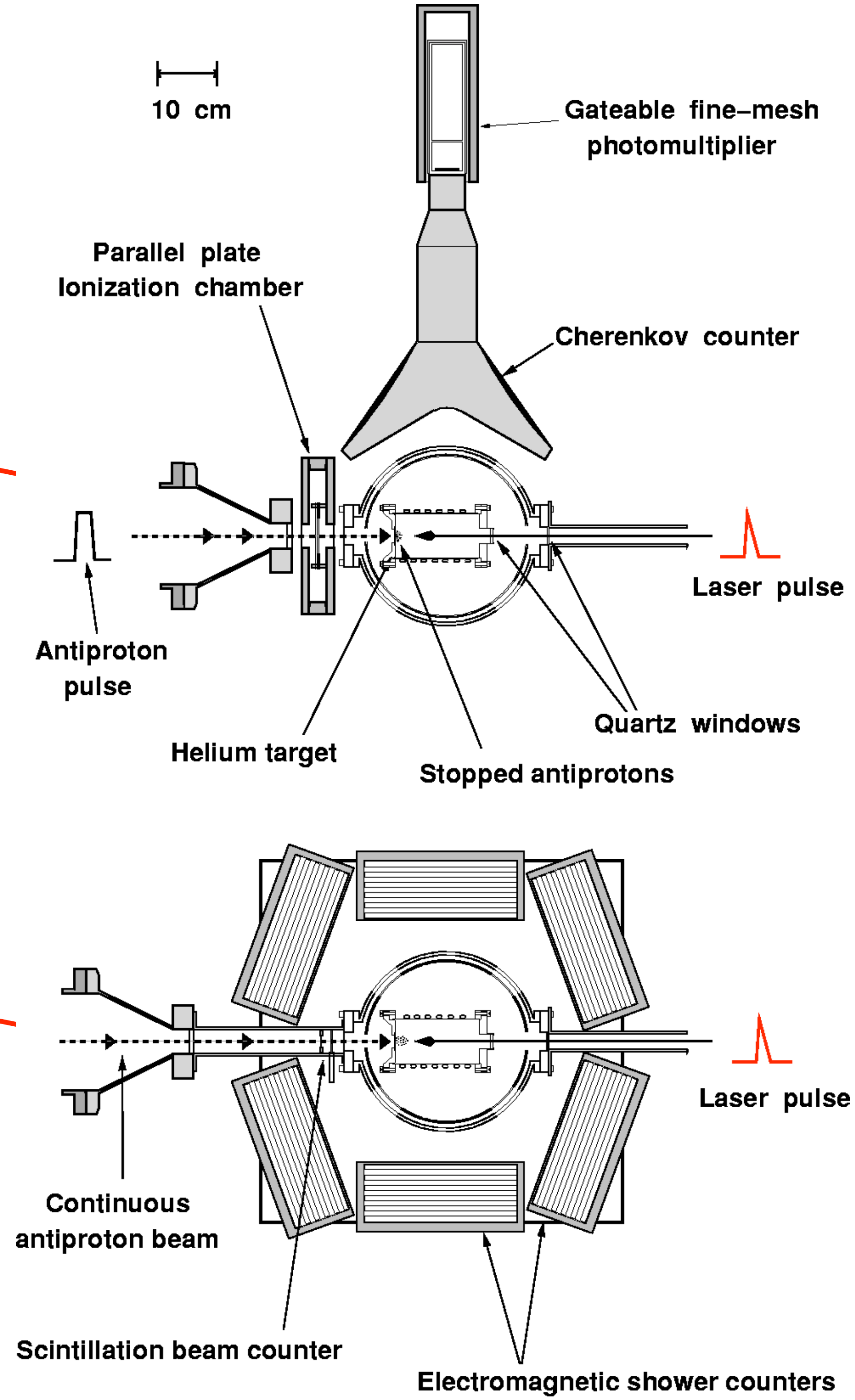
# パルス



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

# Can't use event-by-event counting

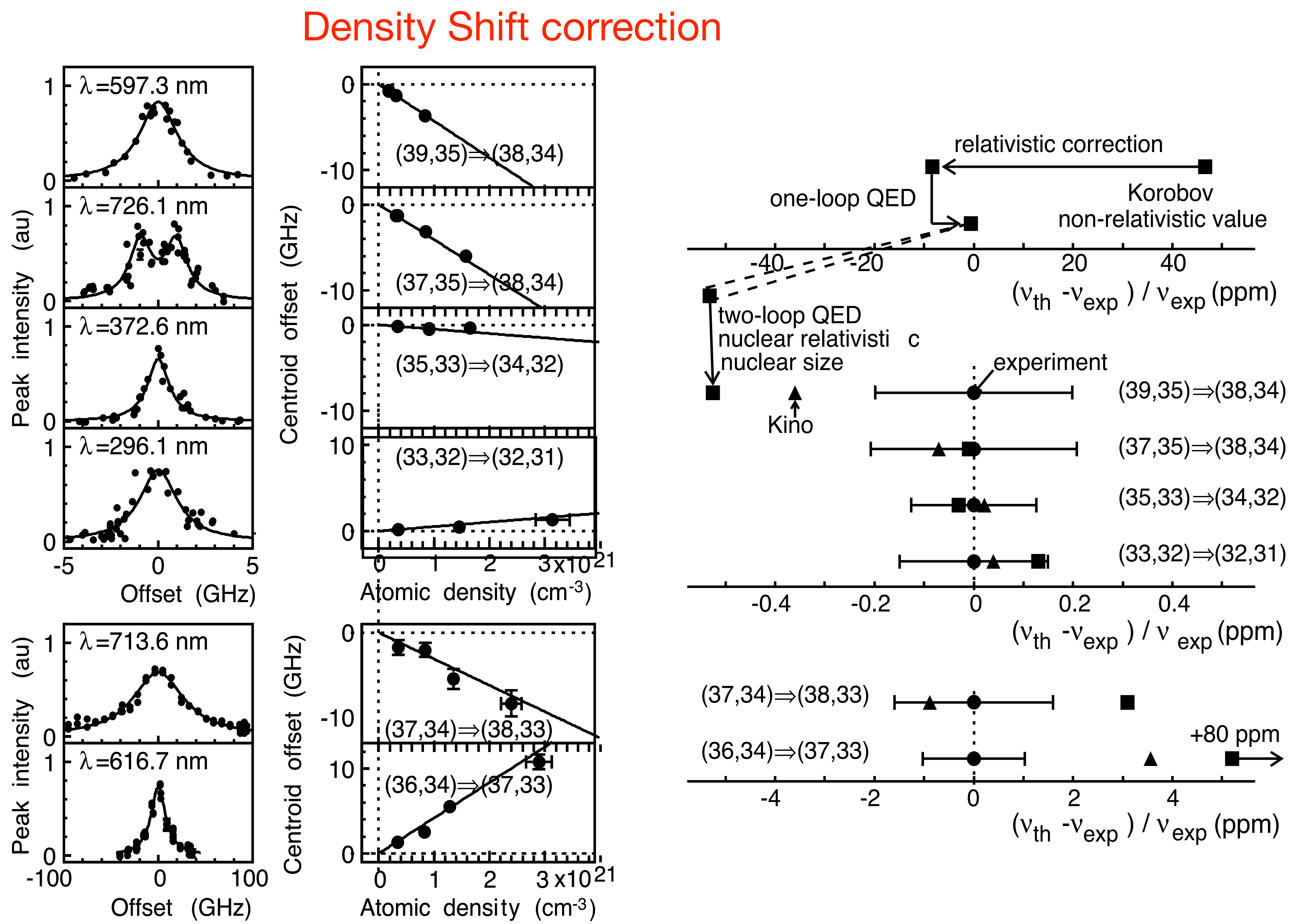



M. Hori et al., PHYSICAL REVIEW A 70, 012504 (2004).

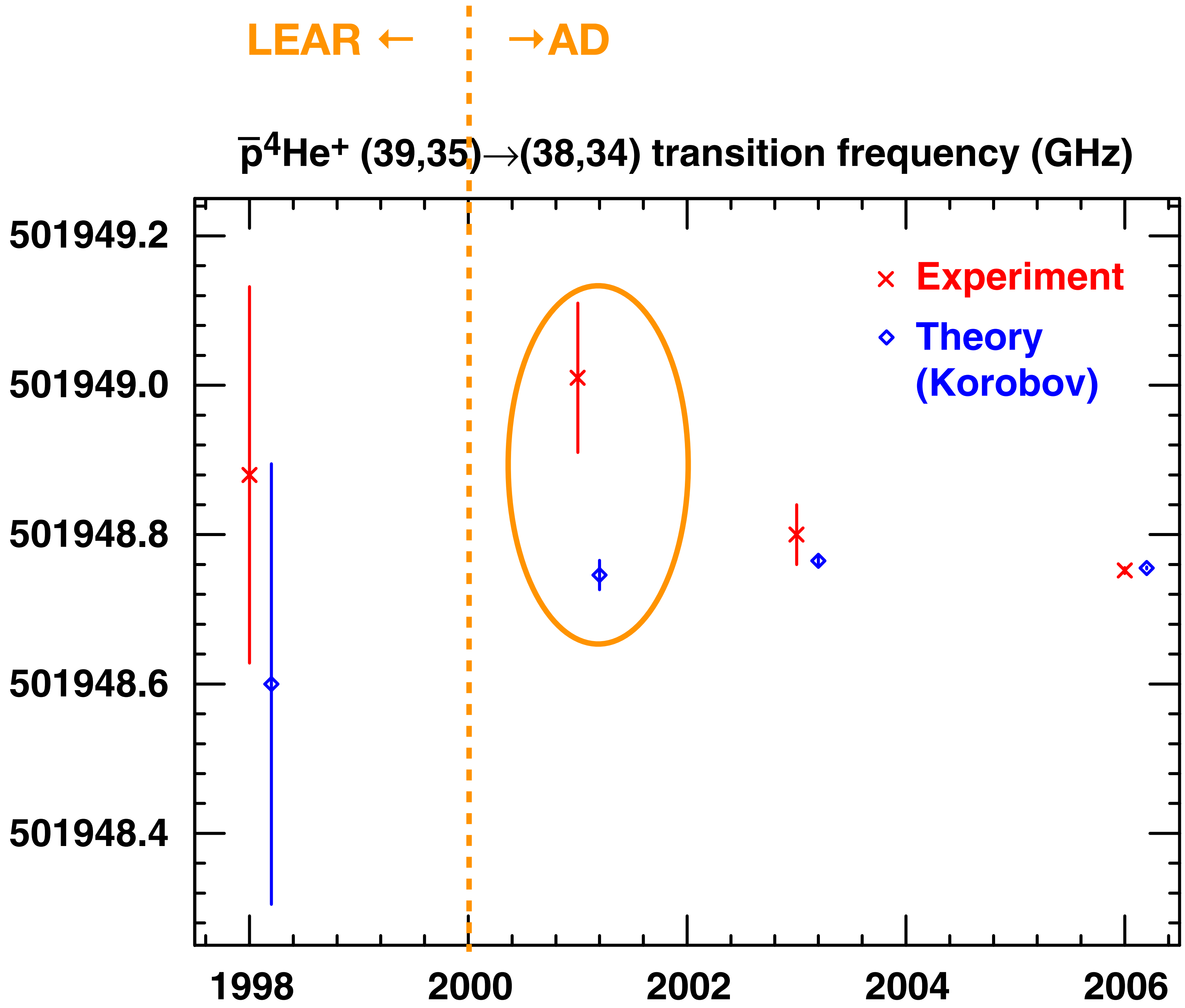
# The first ASACUSA result

Frequency measured to (1.3-16)×$10^{-7}$




M. Hori et al., Phys. Rev. Lett. 87 (2001) 093401

# Sub-ppm precision achieved

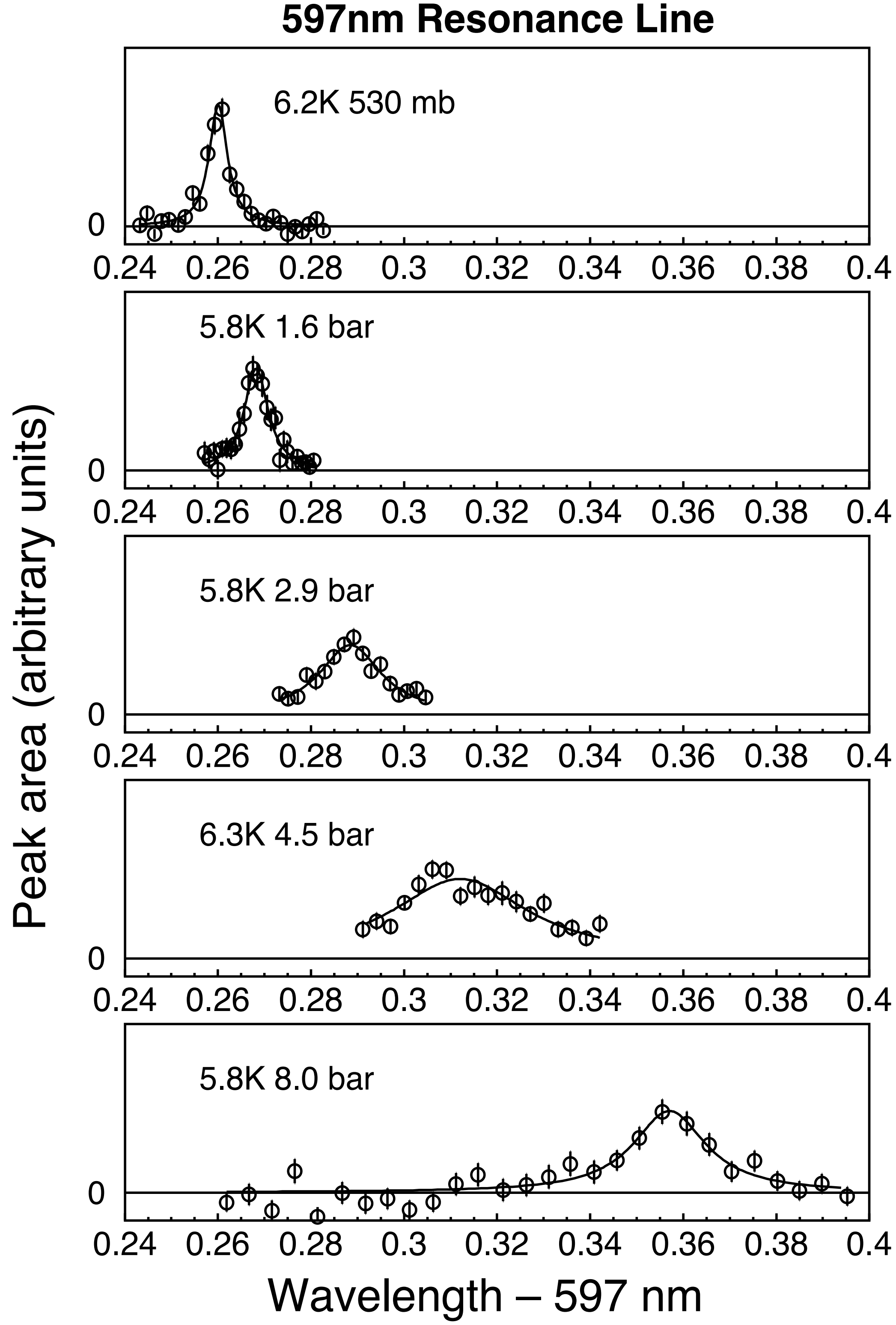


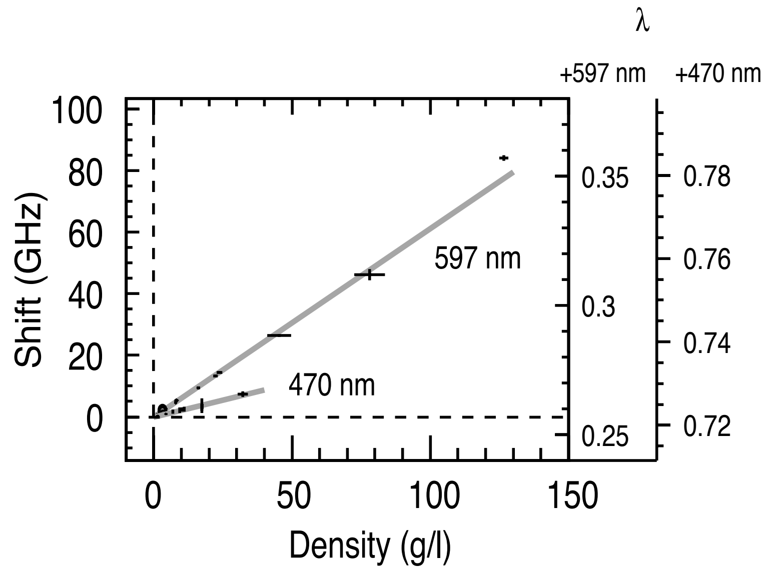
# 衝突

# reducing collision

more on collisions by Grigory Korenman

# PS205 saw this already

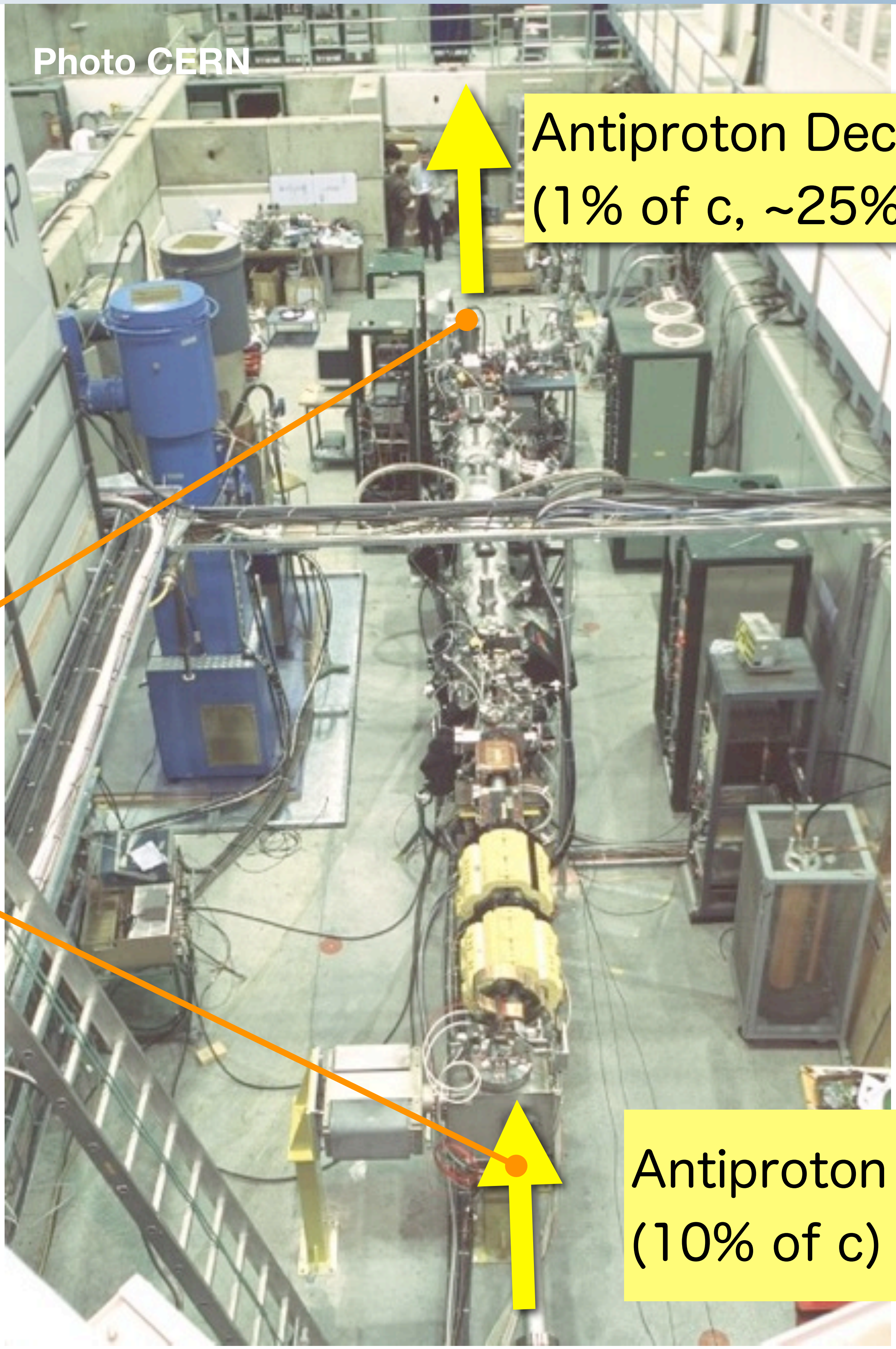



H.A. Torii et al, Phys. Rev. A 59 (1999) 223,
Theory D. Bakalov et al., Phys. Rev. Lett. 84 (2000) 2350.

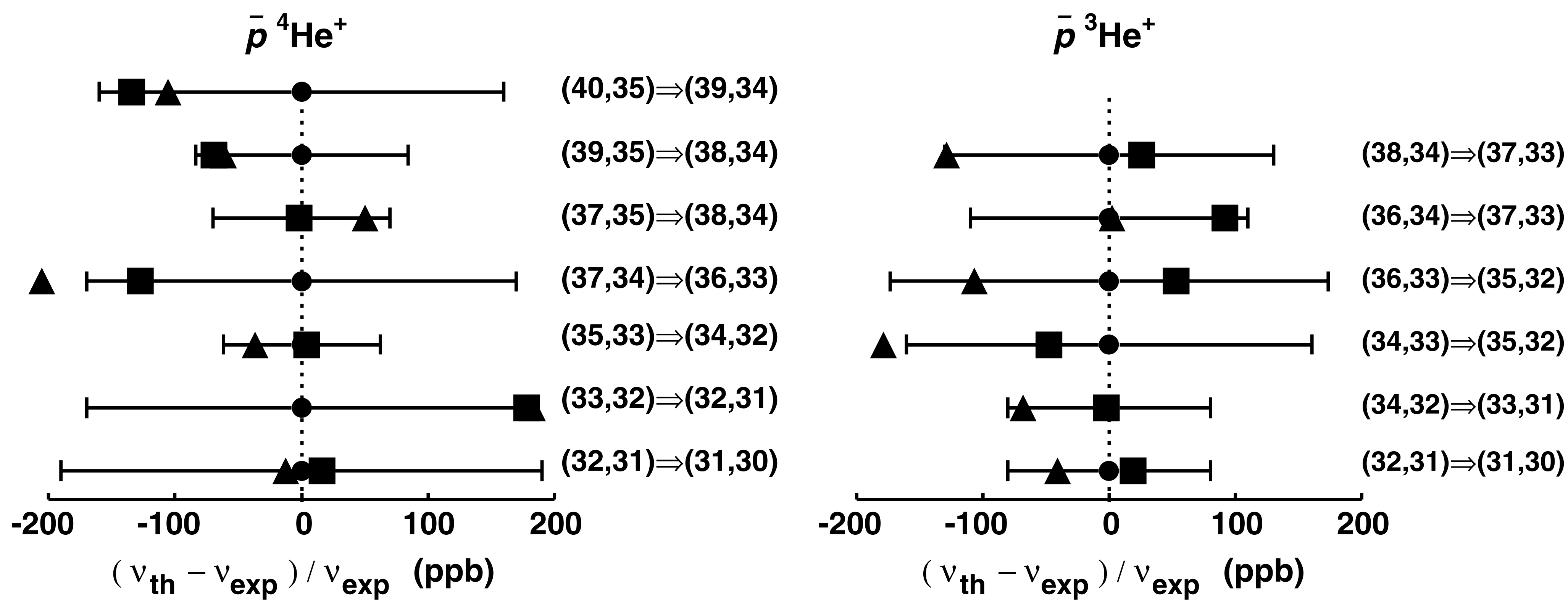
# RFQD

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



# With RFQD

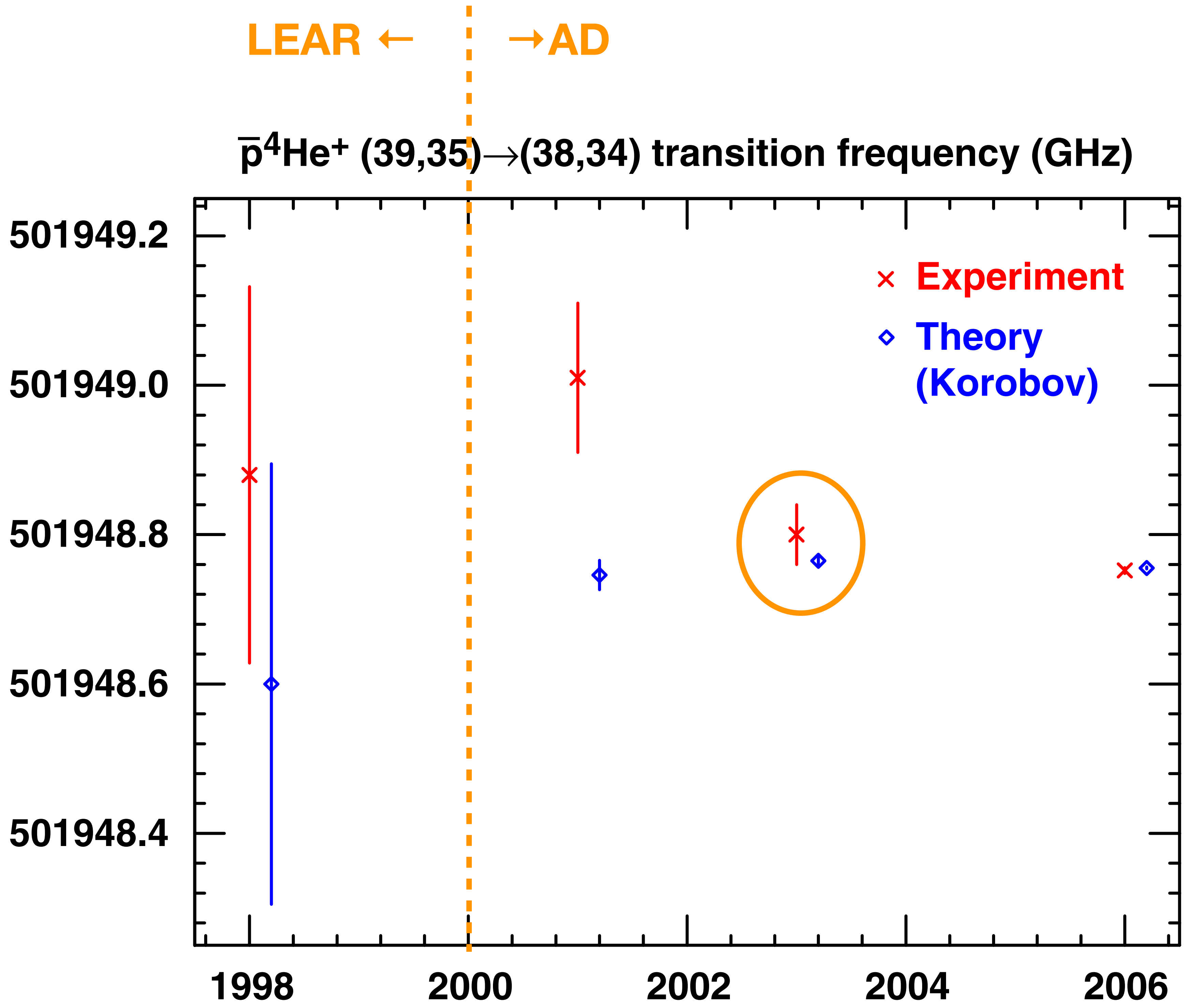
Frequency measured to (6-19)×$10^{-8}$



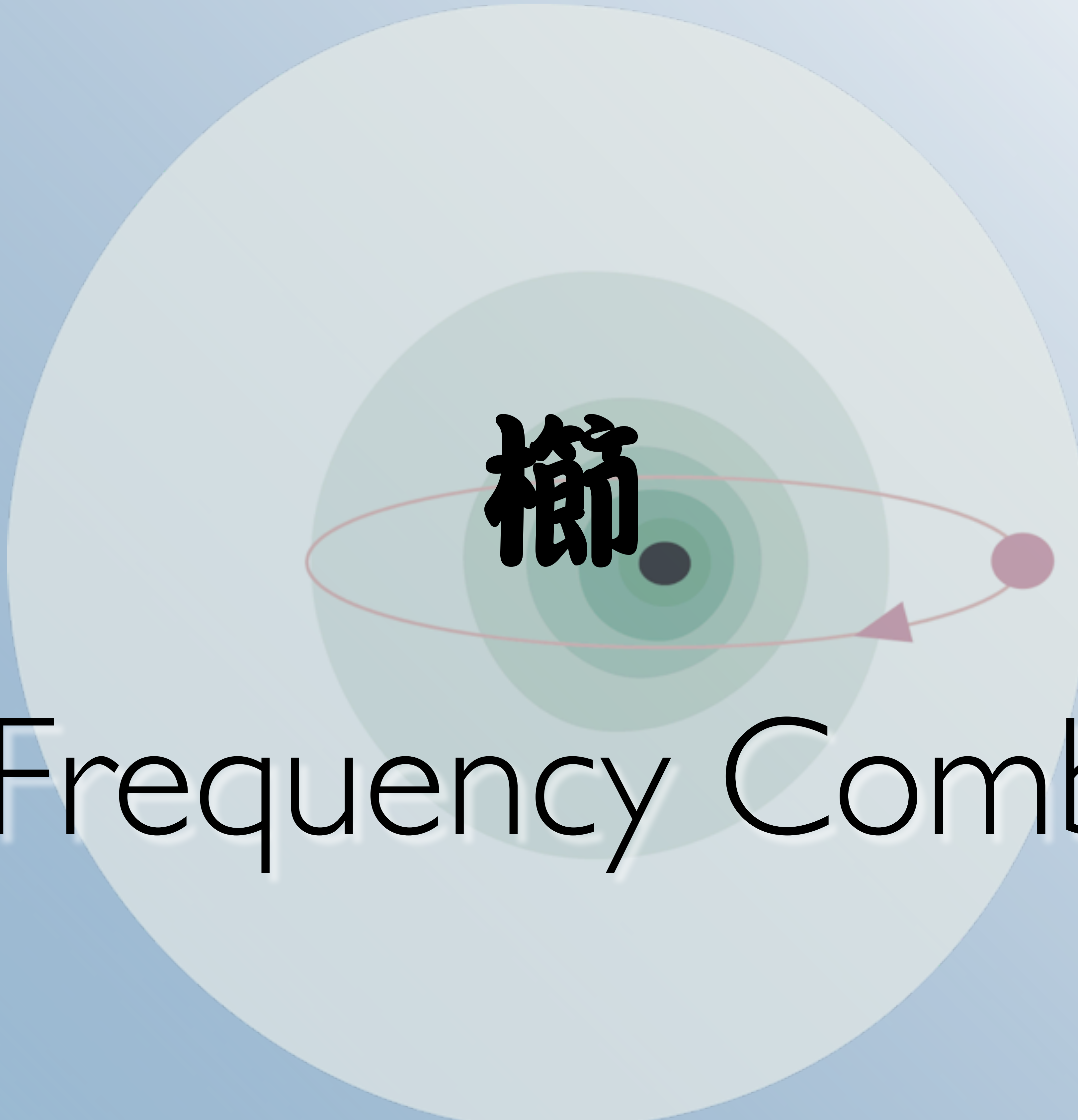

M. Hori, et al., PRL 91, 123401 (2003).

note: wavelength measurement

# "Direct" measurement w RFQD

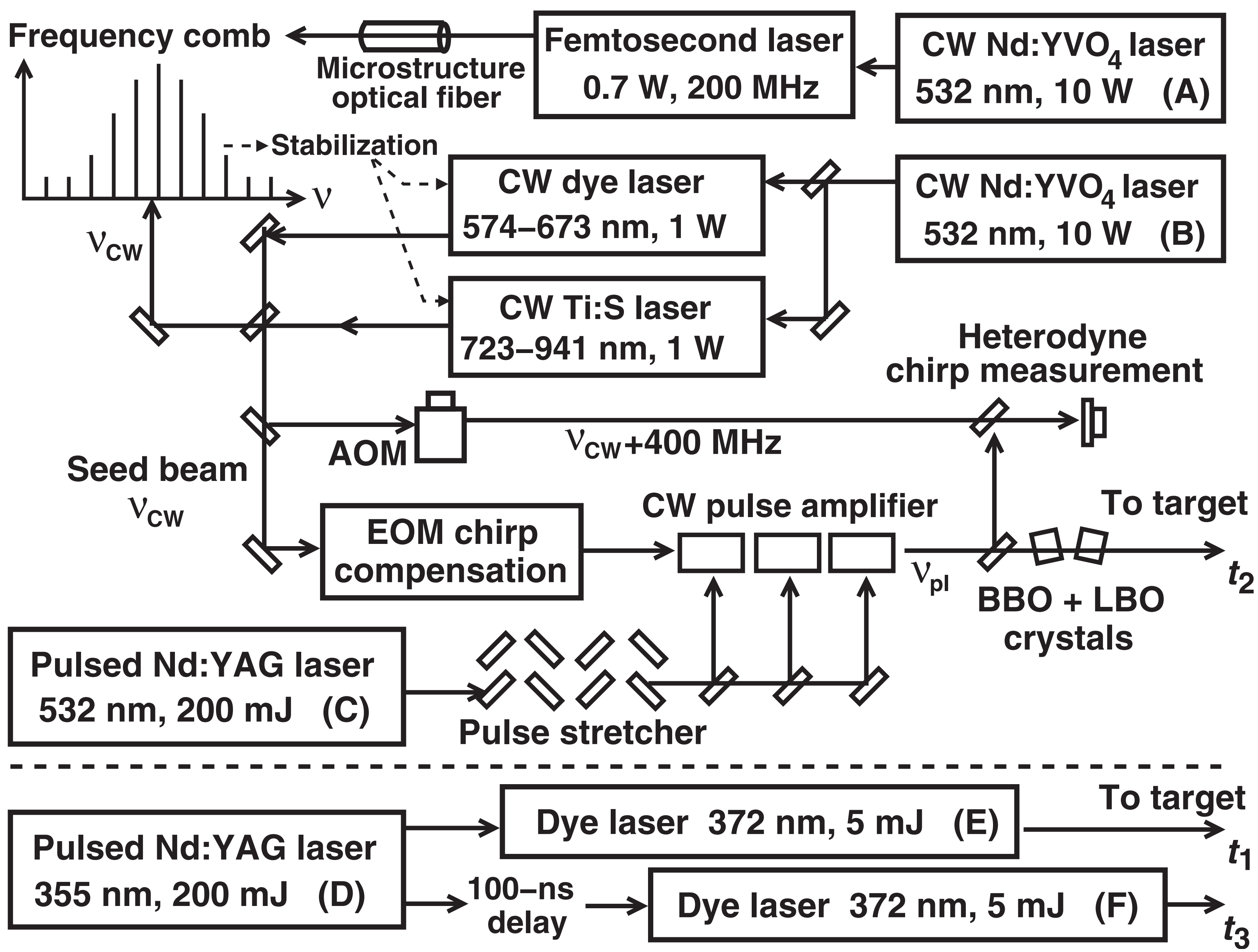


# 櫛



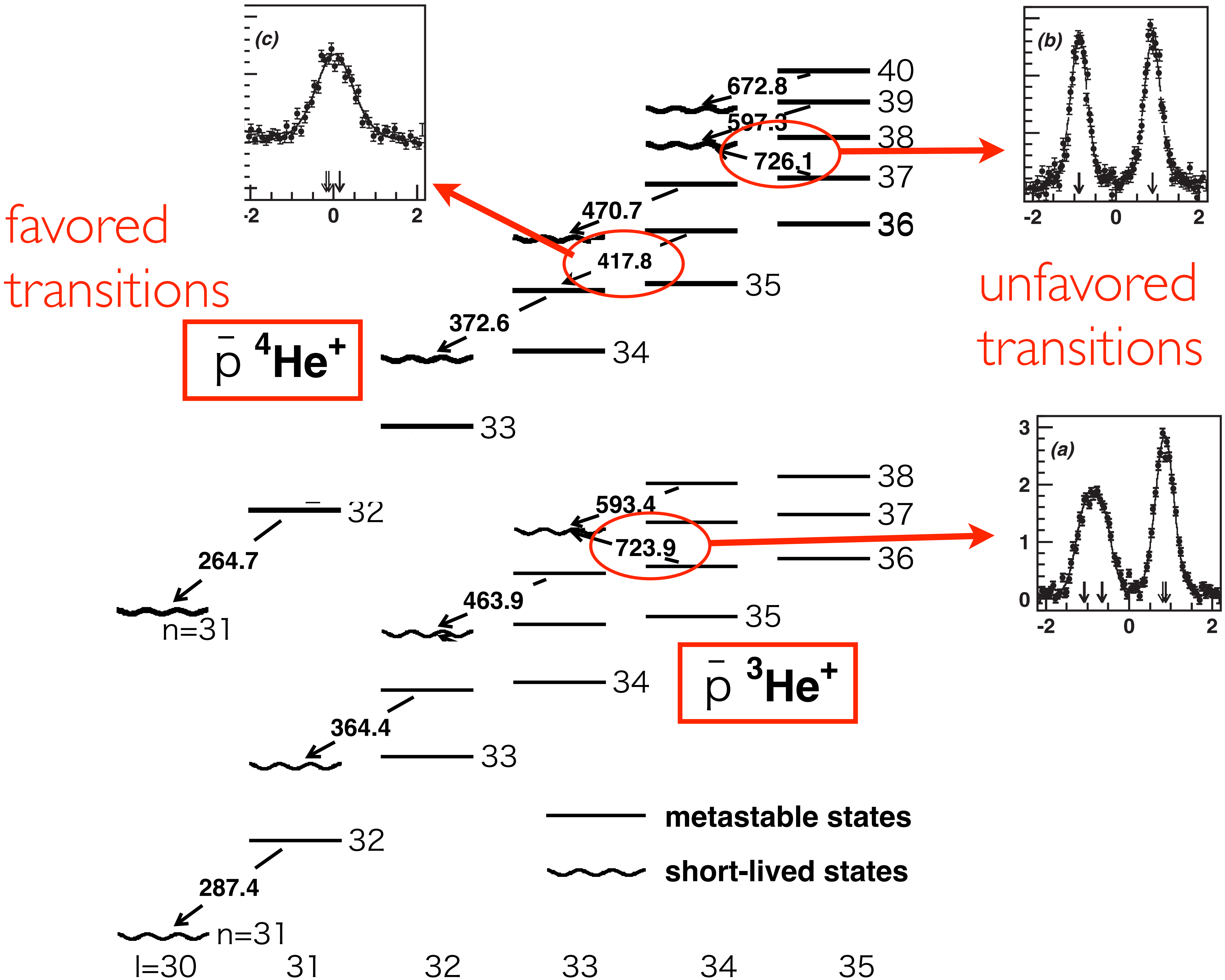
# Frequency Comb

# Wavelength→Frequency

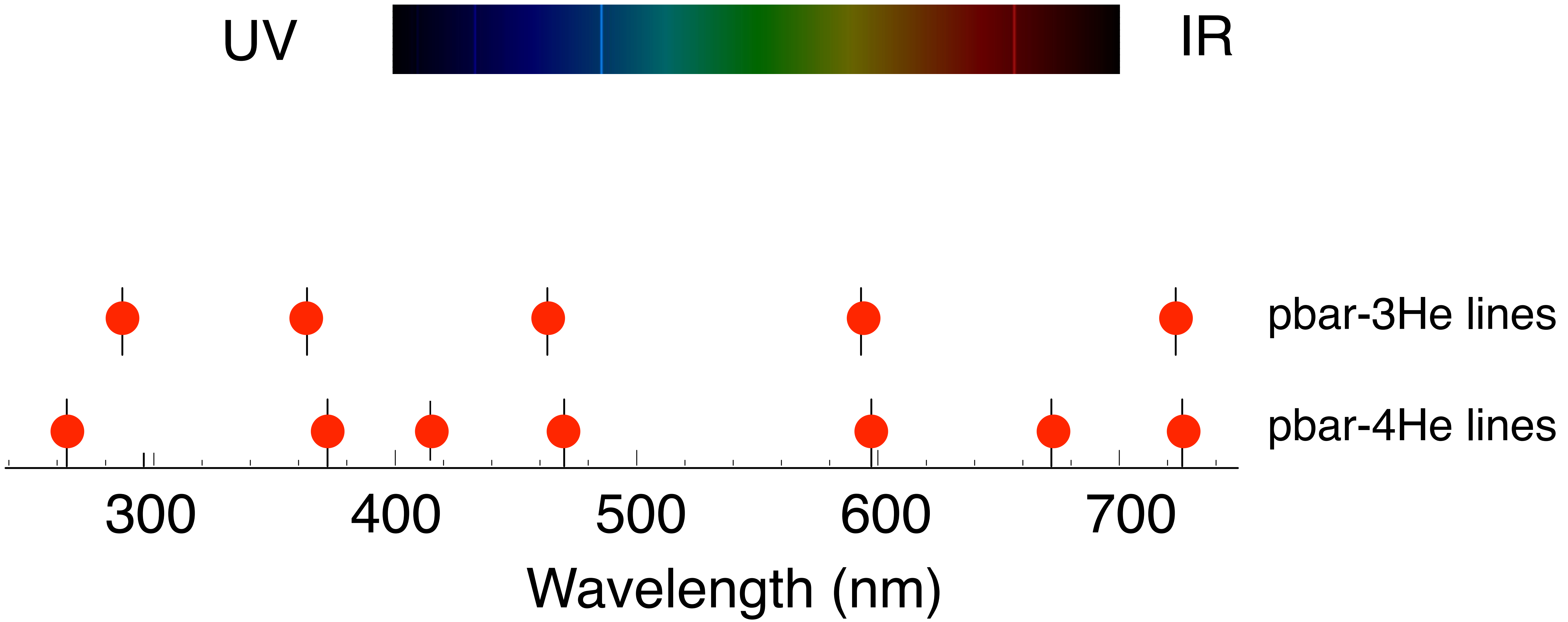



M. Hori et al., Phys. Rev. Lett. 96, 243401(2006)

# 12 transitions were measured

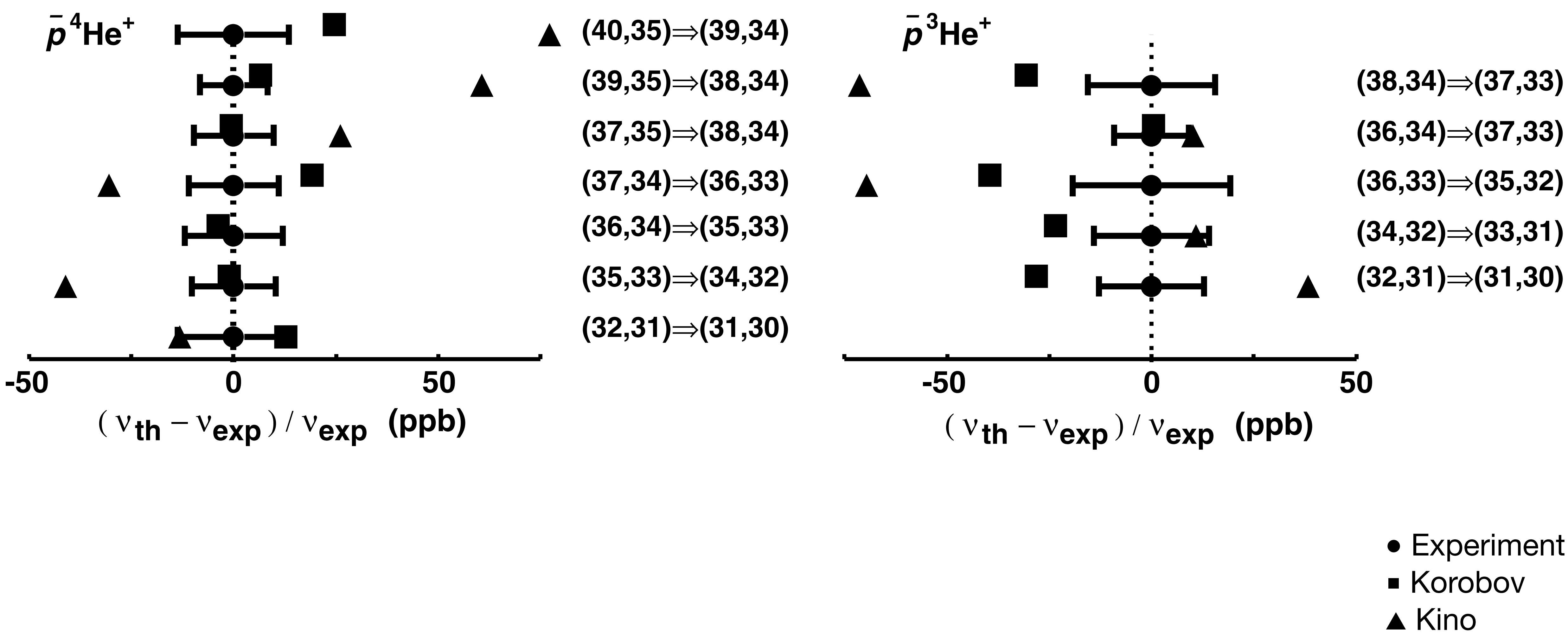


# Wavelengths of resonance lines



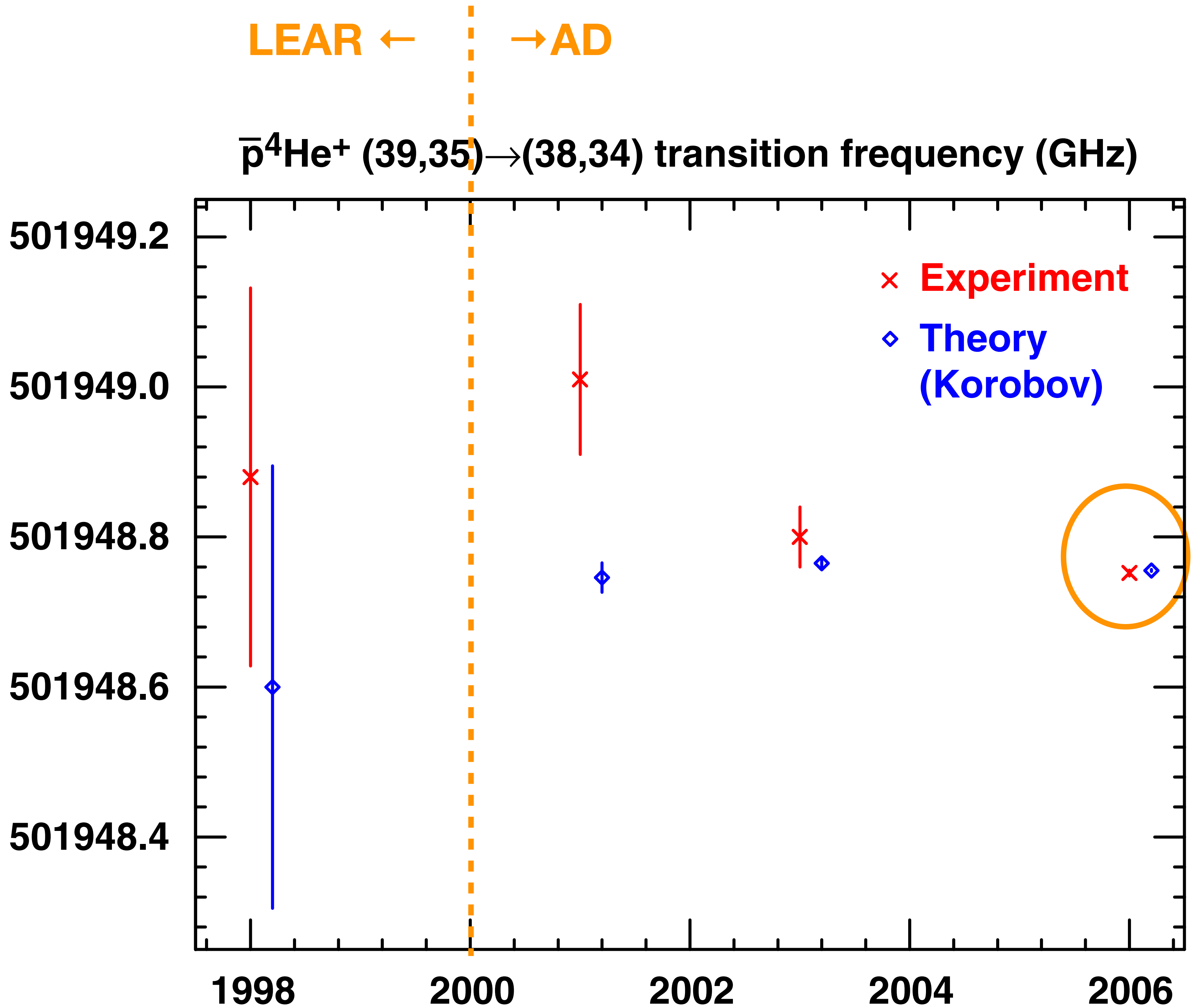
# RFQD+Comb

## Frequency measured to (9–16)x10$^{-9}$

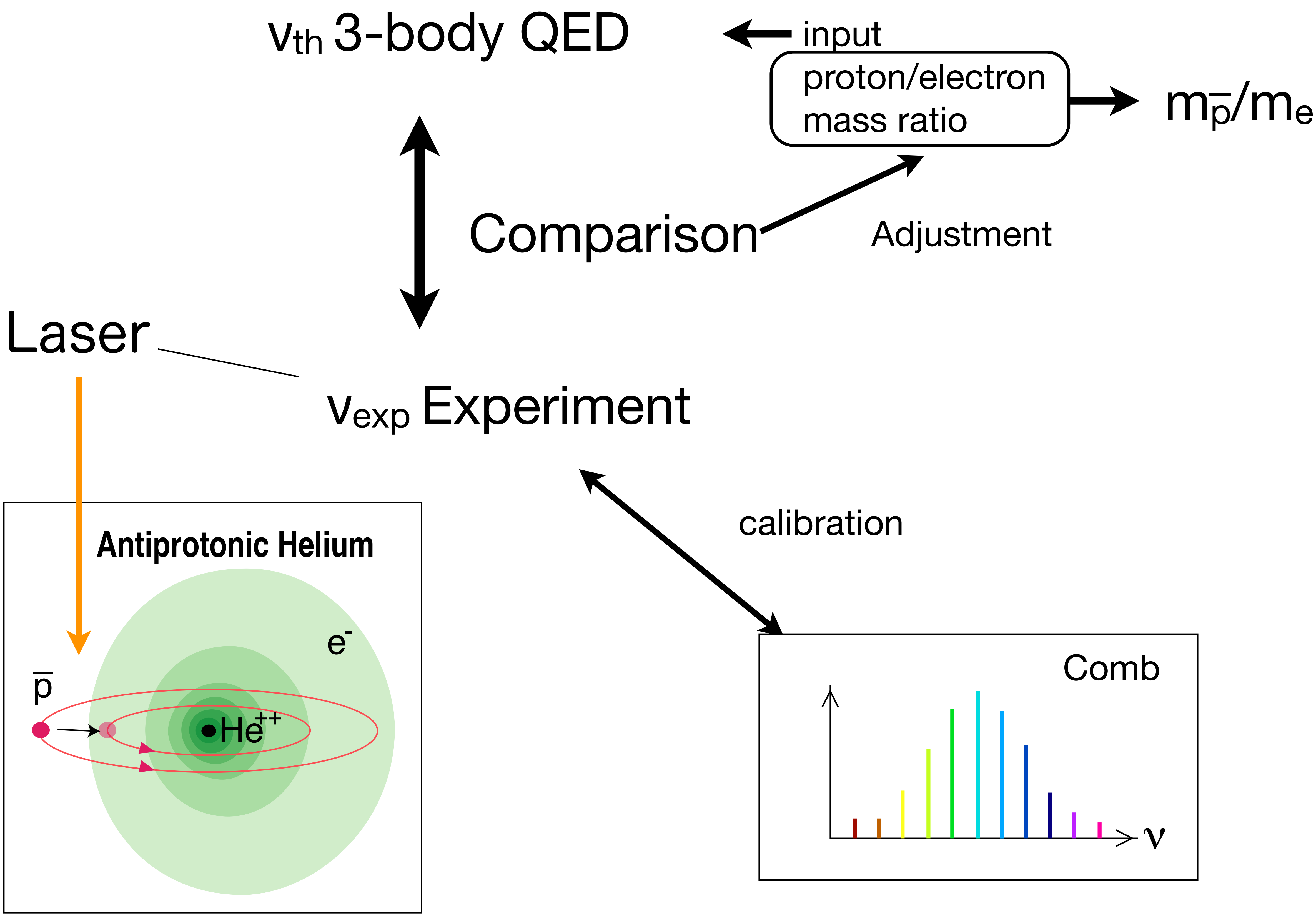



M. Hori et al., Phys. Rev. Lett. 96, 243401(2006)

# with RFQD+Comb



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



$\nu_{th}$ 3-body QED
input
proton/electron mass ratio
$m_{\bar{p}}/m_e$
Comparison
Adjustment
Laser
$\nu_{exp}$ Experiment
calibration
Antiprotonic Helium
$e^-$
$\bar{p}$
$He^{++}$
Comb
$\nu$

# 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

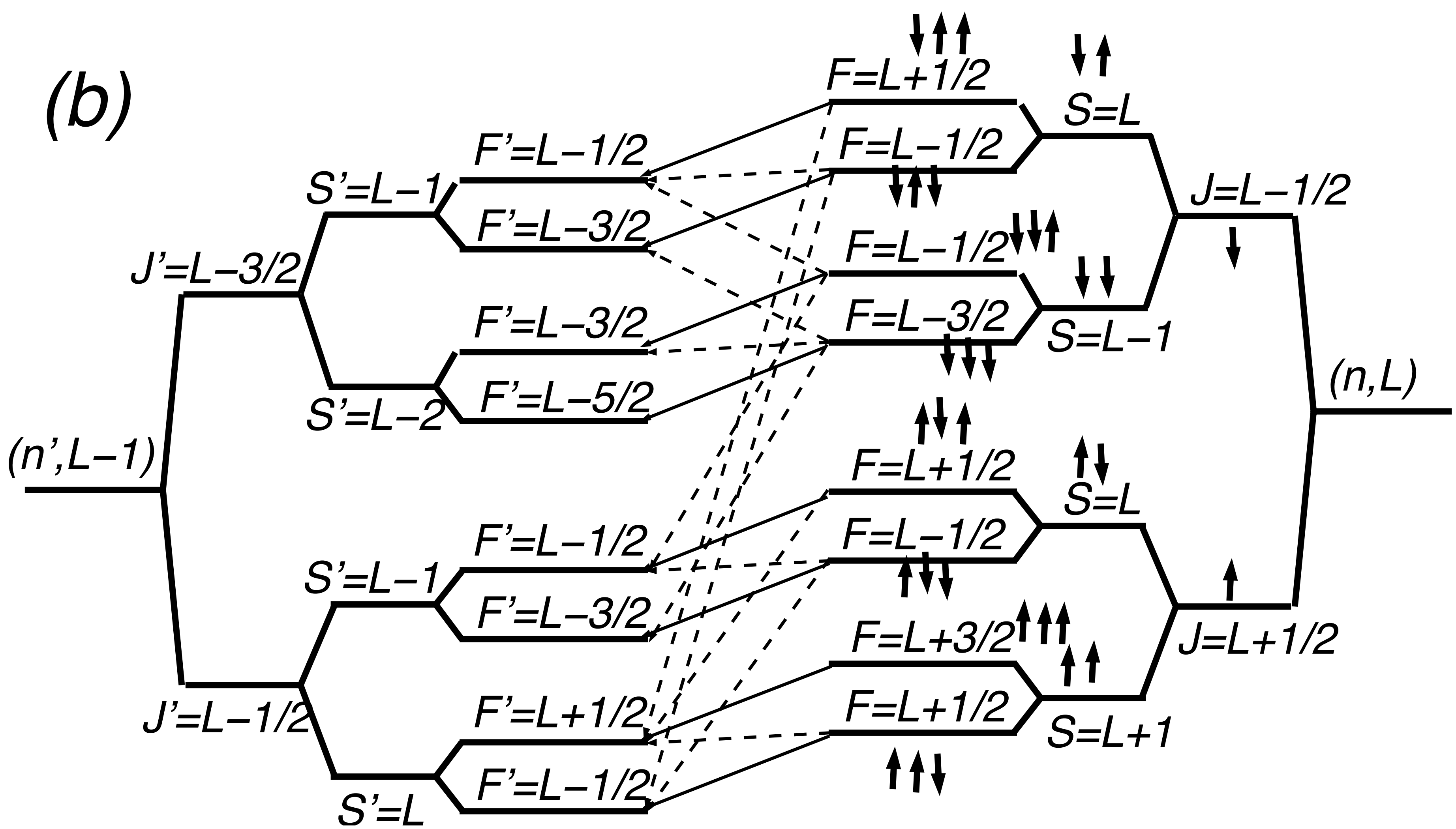
Atomic transition frequencies in hydrogen, deuterium, and antiprotonic helium yield information on the Rydberg constant, the proton and deuteron charge radii, and the relative atomic mass of the electron. The hyper-

# 超微細構造

## Hyperfine

# p̄He hyperfine

(more by S. Friedreich)



# 結

# summary

*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
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**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 ($\lambda$ = 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.**

# 20 years of $\bar{p}$He

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

Thanks: KEK/LEAR/AD and many theorists