# Antimatter Experiments

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早野 龍五

THE UNIVERSITY OF TOKYO

金茶会，Oct 1, 2009

1. Antiprotonic Helium
2. Antihydrogen

# 反陽子減速器

## Experiments at CERN's Antiproton Decelerator (AD)


ダン・ブラウン
越前敏弥訳
上
天使と悪魔
ANGELS&DEMONS DAN BROWN
角川文庫

最近まで、反物質はほんの少量（一度に原子数個）しか生成できなかった。だがセルンは、新型の反陽子減速器の開発に着手した。この高度な製造施設が完成すれば、はるかに大量の反物質の生成が可能になる。

1 February 1996

1996

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 368 (1996) 251–258

# Production of antihydrogen

G. Baur[a], G. Boero[b], S. Brauksiepe[a], A. Buzzo[b], W. Eyrich[c], R. Geyer[a], D. Grzonka[a], J. Hauffe[c], K. Kilian[a], M. LoVetere[b], M. Macri[b], M. Moosburger[c], R. Nellen[a], W. Oelert[a], S. Passaggio[b], A. Pozzo[b], K. Röhrich[a], K. Sachs[a], G. Schepers[e], T. Sefzick[a], R.S. Simon[d], R. Stratmann[d], F. Stinzing[c], M. Wolke[a]

[a] *IKP, Forschungszentrum Jülich GmbH, Germany*
[b] *Genoa University and INFN, Italy*
[c] *PI, Universität Erlangen–Nürnberg, Germany*
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[e] *IKP, Universität Münster, Germany*

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Editor: L. Montanet

**Abstract**

Results are presented for a measurement for the production of the antihydrogen atom $\overline{\mathrm{H}}^0 \equiv \bar{\mathrm{p}}\mathrm{e}^+$, the simplest atomic bound state of antimatter.

A method has been used by the PS210 collaboration at LEAR which assumes that the production of $\overline{\mathrm{H}}^0$ is predominantly mediated by the $\mathrm{e}^+\mathrm{e}^-$-pair creation via the two-photon mechanism in the antiproton–nucleus interaction. Neutral $\overline{\mathrm{H}}^0$ atoms are identified by a unique sequence of characteristics. In principle $\overline{\mathrm{H}}^0$ is well suited for investigations of fundamental CPT violation studies under different forces, however, in our investigations we concentrate on the production of this antimatter object, since so far it has never been observed before.

The production of 11 antihydrogen atoms is reported including possibly $2\pm1$ background signals, the observed yield agrees with theoretical predictions.

## Abstract

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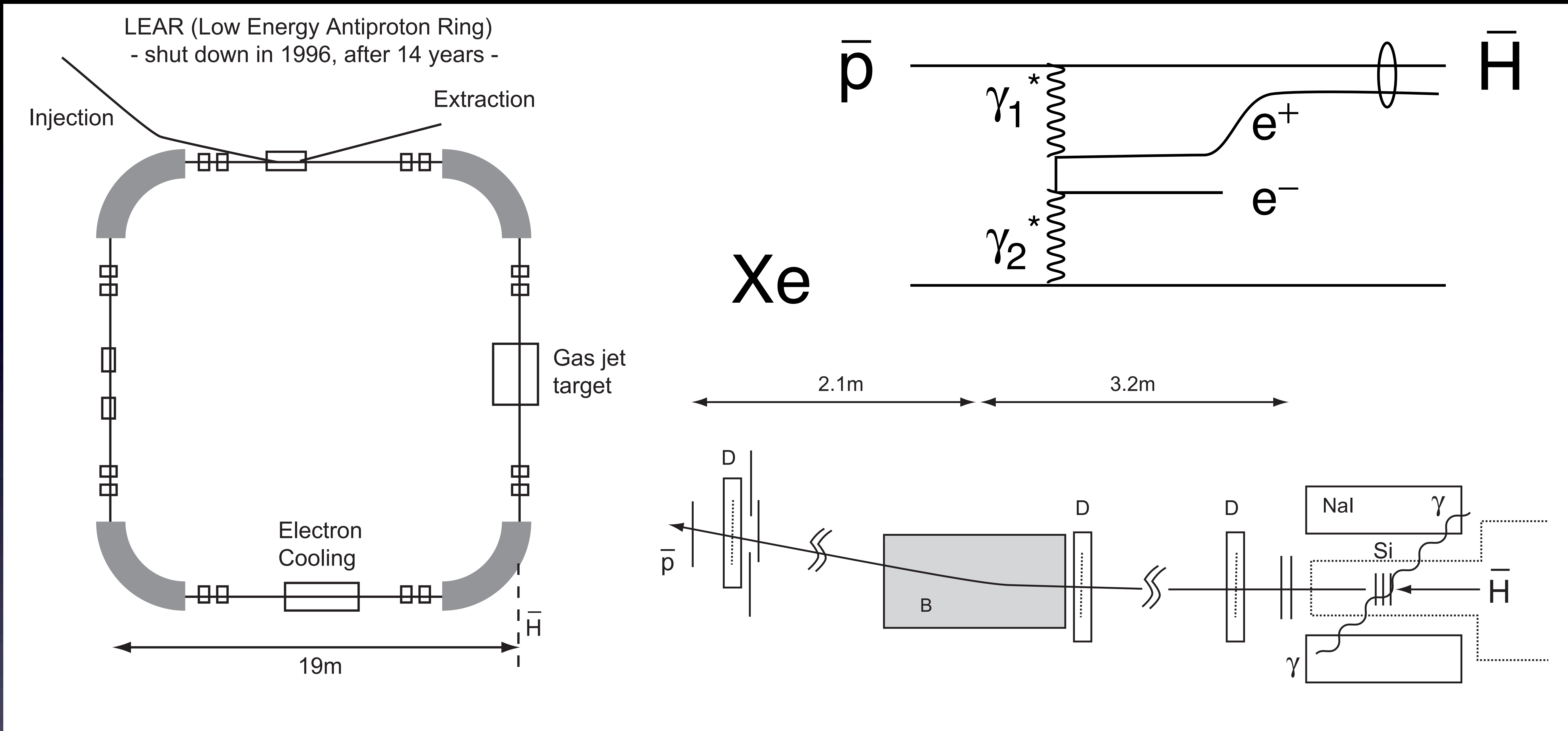
*PACS:* 25.43.+t
*Keywords:* Antihydrogen


反水素原子１１個の生成

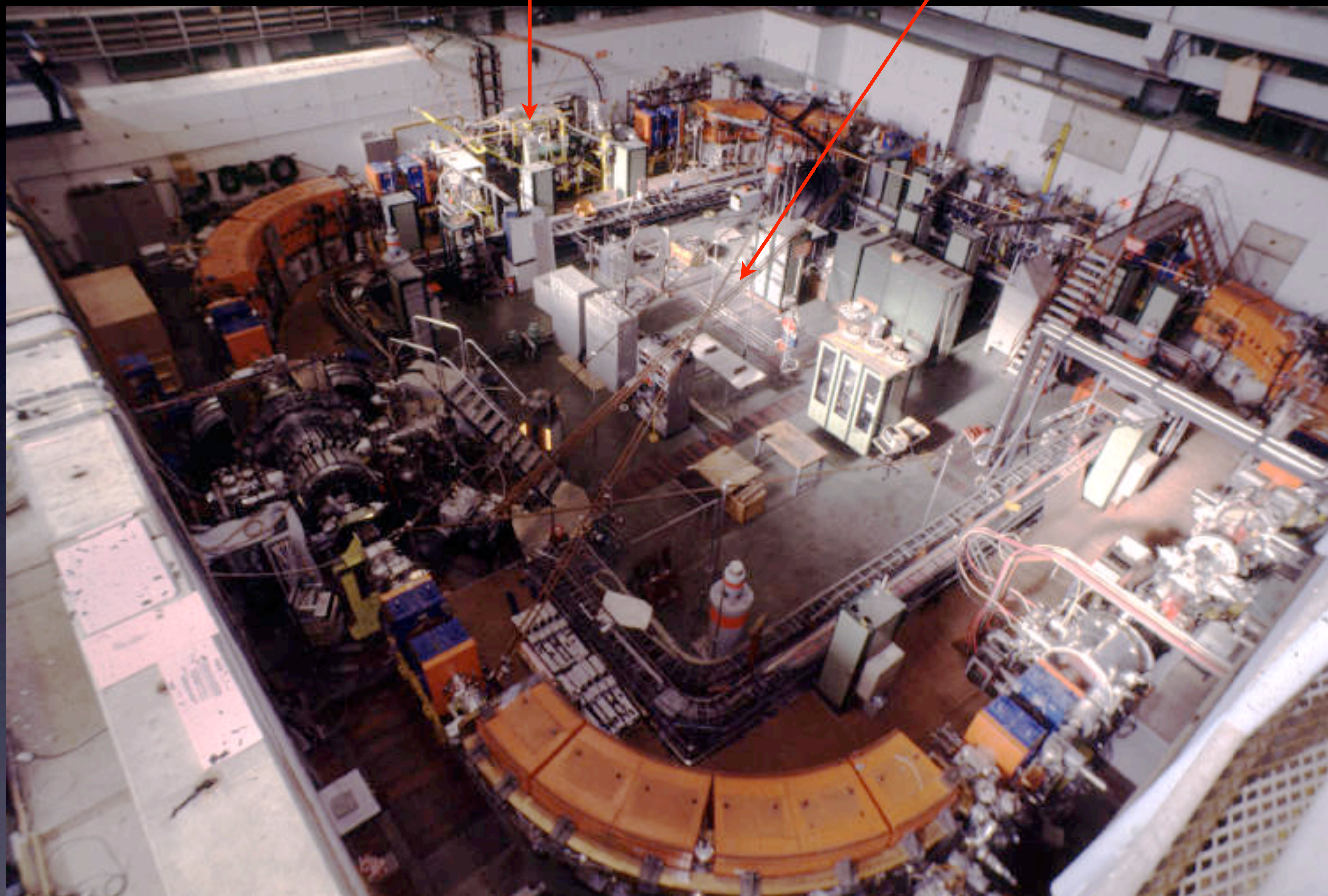
# Antihydrogen @ LEAR **PLB 368 (1996) 251**



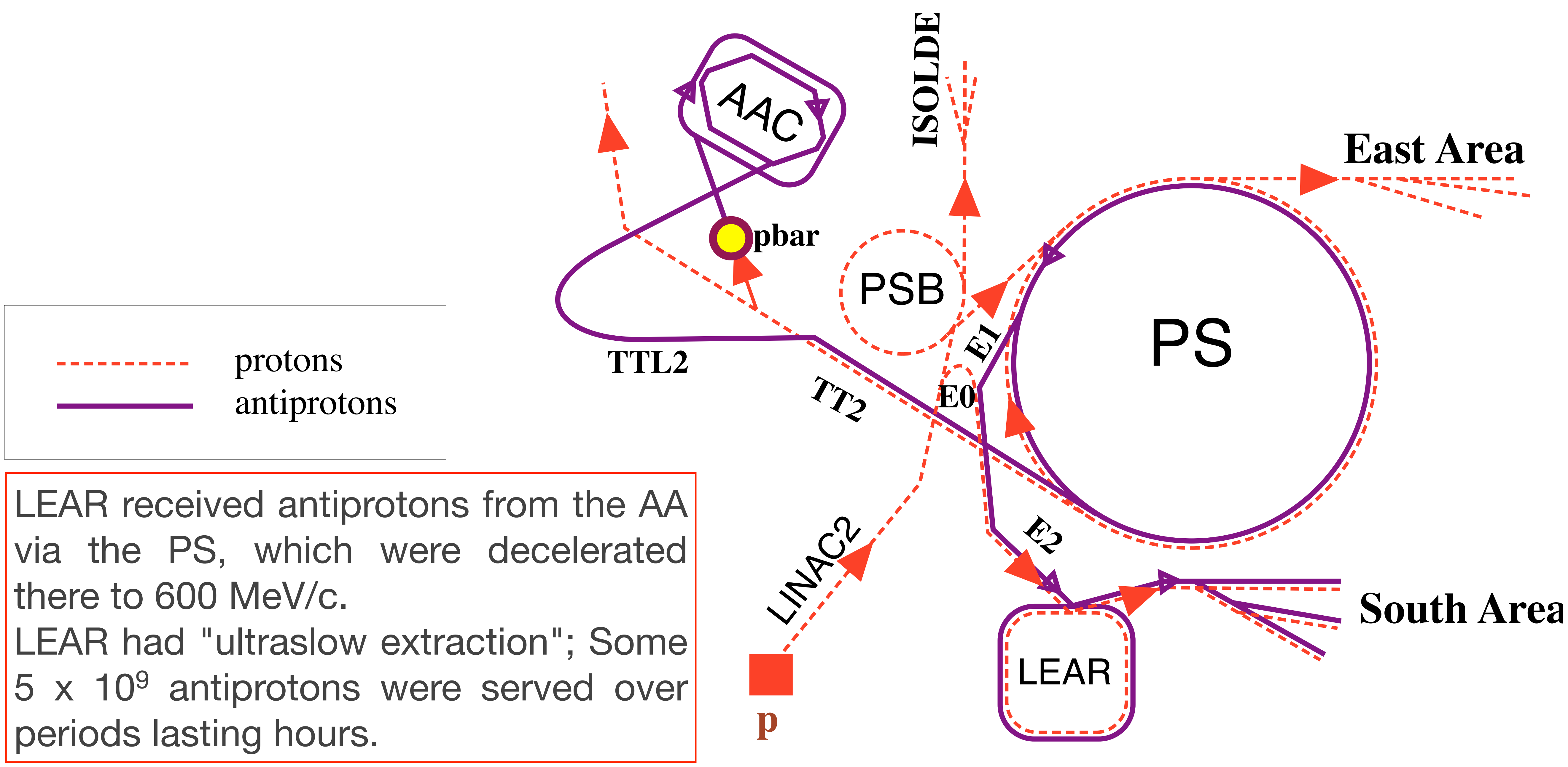

- 2 GeV antiprotons stored in the LEAR ring on Xe gas jet target
- Small quantity(11 ±2) of relativistic antihydrogen produced
- Not useful for high-precision spectroscopy but was essential for the AD approval

**electron cooling**
was optional
in the design report

**stochastic cooling**

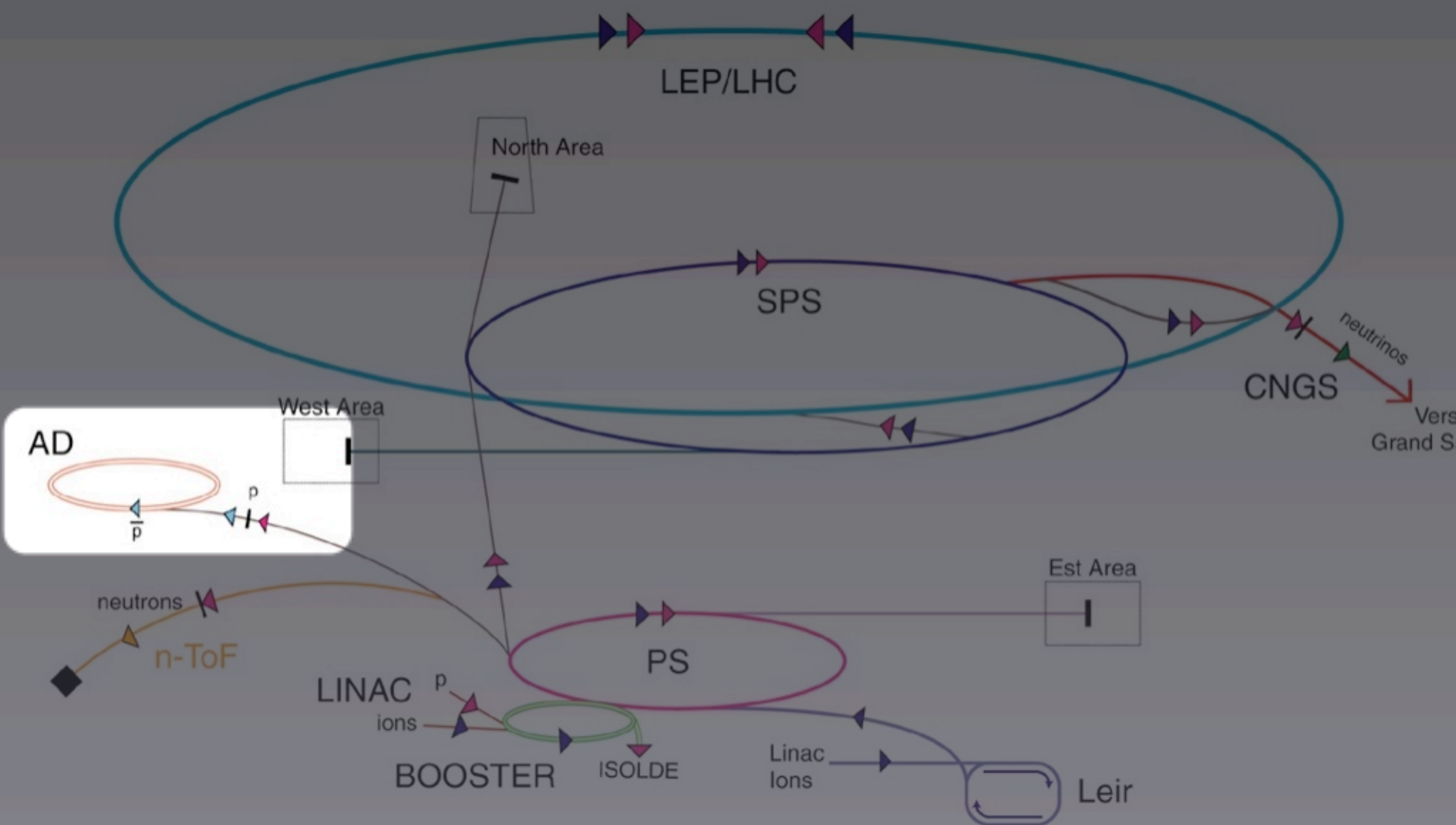


# LEAR Scheme



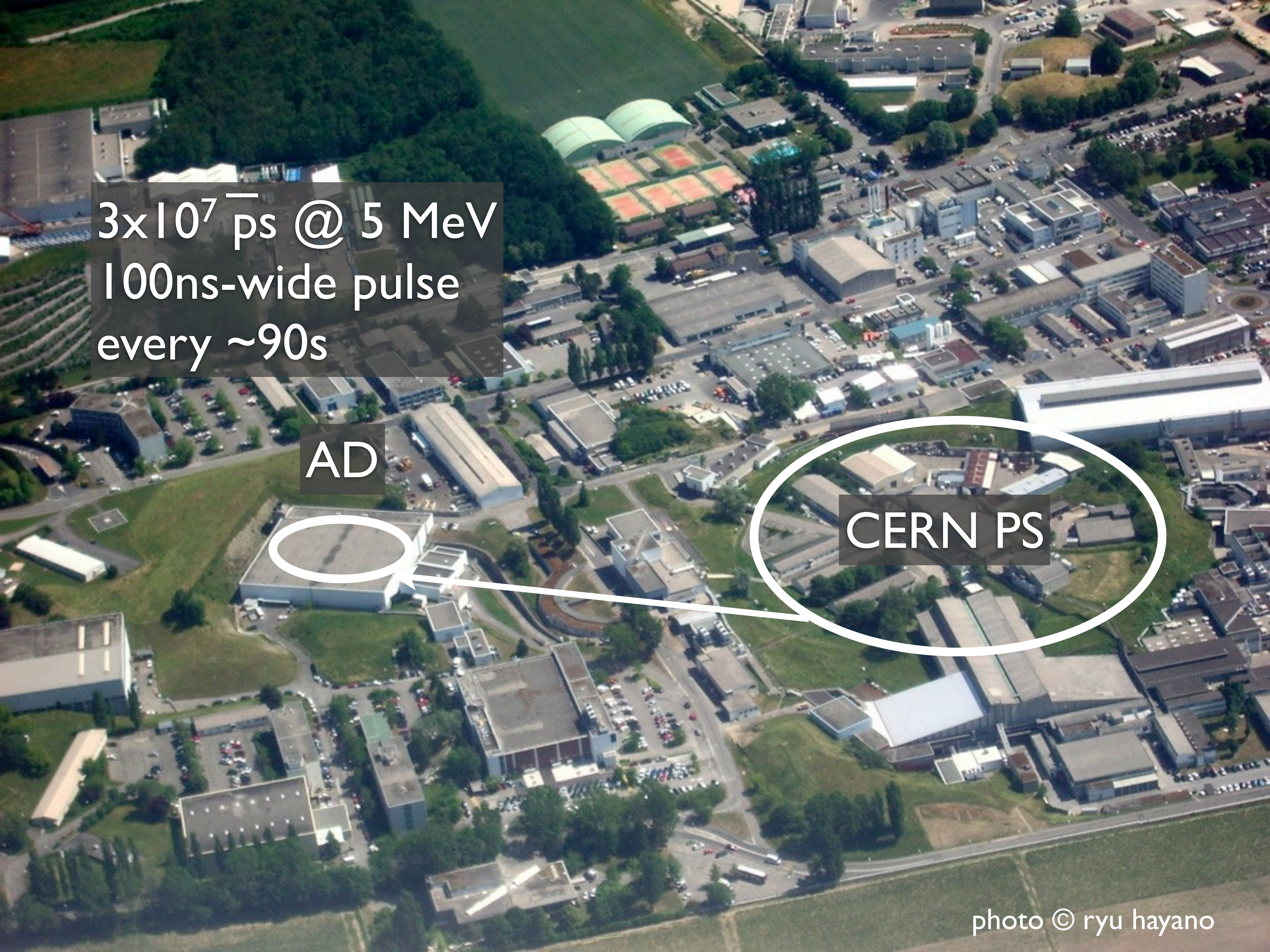

LEAR received antiprotons from the AA via the PS, which were decelerated there to 600 MeV/c.
LEAR had "ultraslow extraction"; Some 5 x $10^9$ antiprotons were served over periods lasting hours.

# Accelerator chain of CERN (operating or approved projects)

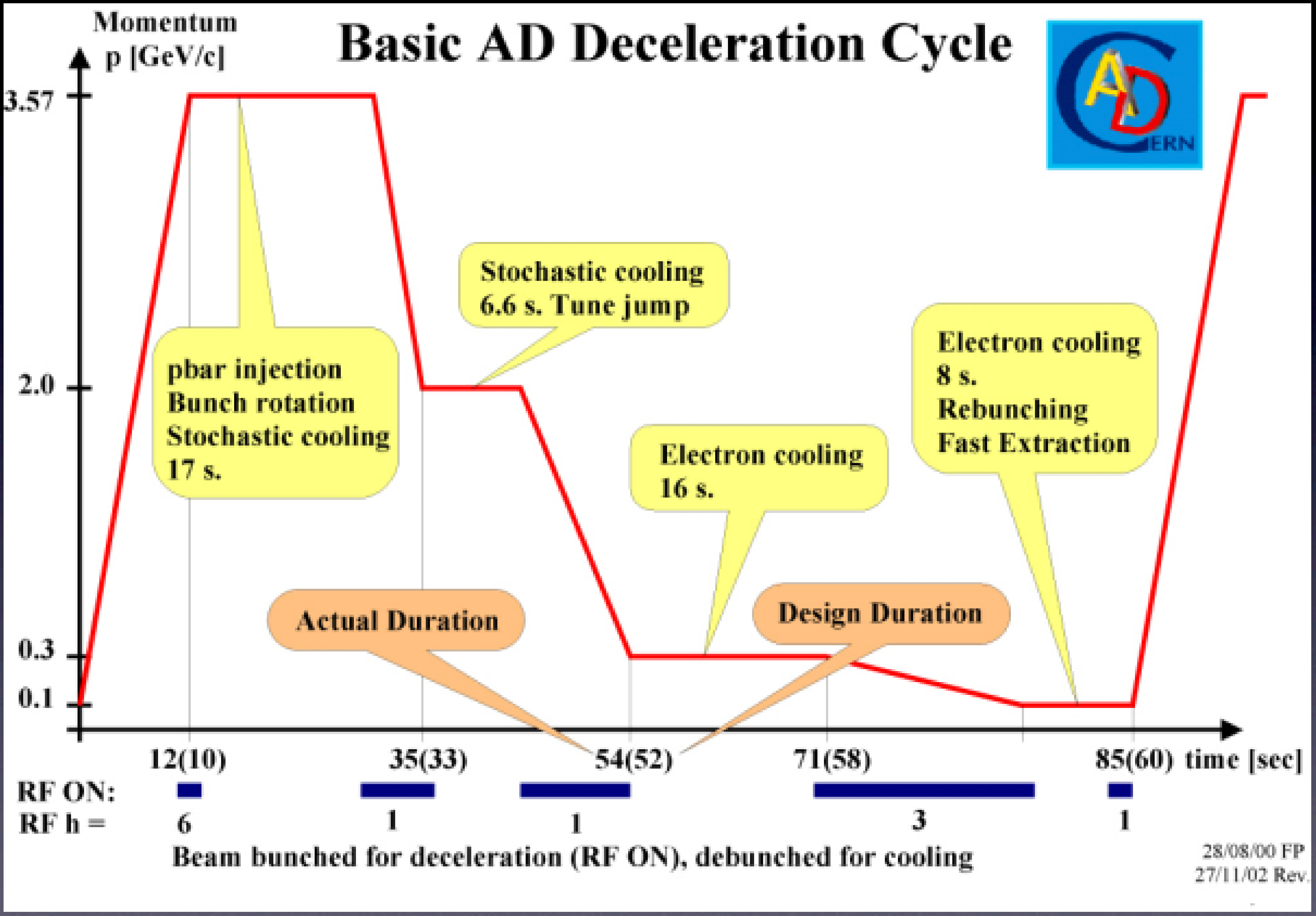



p (proton) | $\bar{p}$ (antiproton) | AD Antiproton Decelerator | LHC Large Hadron Collider
ion | proton/antiproton conversion | PS Proton Synchrotron | n-ToF Neutrons Time of Flight
neutrons | neutrinos | SPS Super Proton Synchrotron | CNGS Cern Neutrinos Grand Sasso

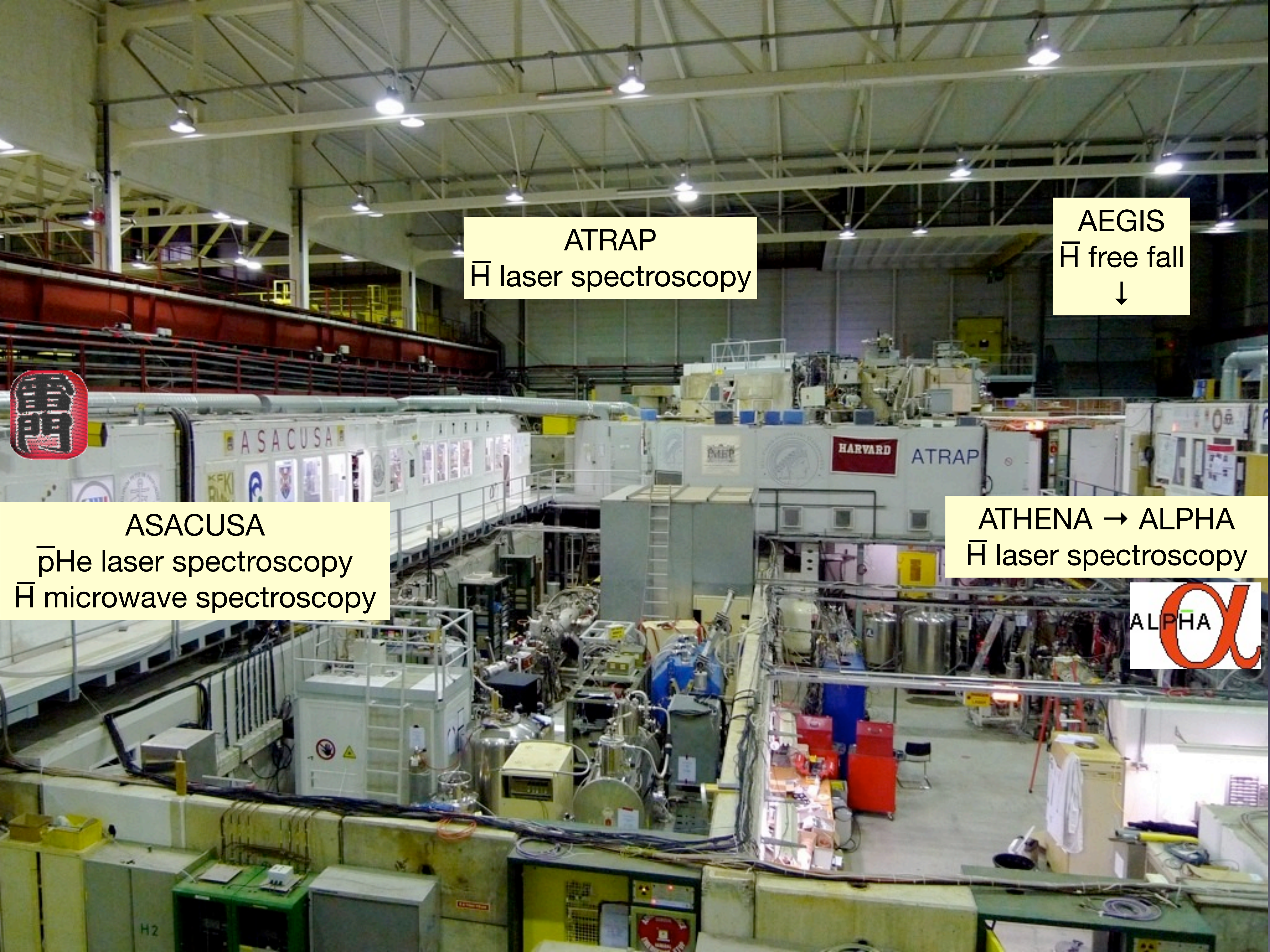
| | | |
|---|---|---|
| AD-1 (ATHENA) completed | Antihydrogen Production and Precision Experiments | $\bar{H}$ production |
| AD-2 (ATRAP) | Cold Antihydrogen for Precise Laser Spectroscopy | $\bar{H}$ 1s-2s laser spectroscopy |
| AD-3 (ASACUSA) | Atomic Spectroscopy and Collisions Using Slow Antiprotons | $\bar{p}$He spectroscopy<br>$\bar{H}$ hyperfine spectroscopy |
| AD-4 (ACE) | Relative Biological Effectiveness and Peripheral Damage of Antiproton Annihilation | |
| AD-5 (ALPHA) | Antihydrogen Laser PHysics Apparatus | $\bar{H}$ 1s-2s laser spectroscopy |
| AD-6 (AEGIS) | Antimatter Experiment: Gravity, Interferometry, Spectroscopy | $\bar{H}$ equivalence principle |


3x10$^7$ $\bar{p}$s @ 5 MeV
100ns-wide pulse
every ~90s
AD
CERN PS
photo © ryu hayano

# AD cycle



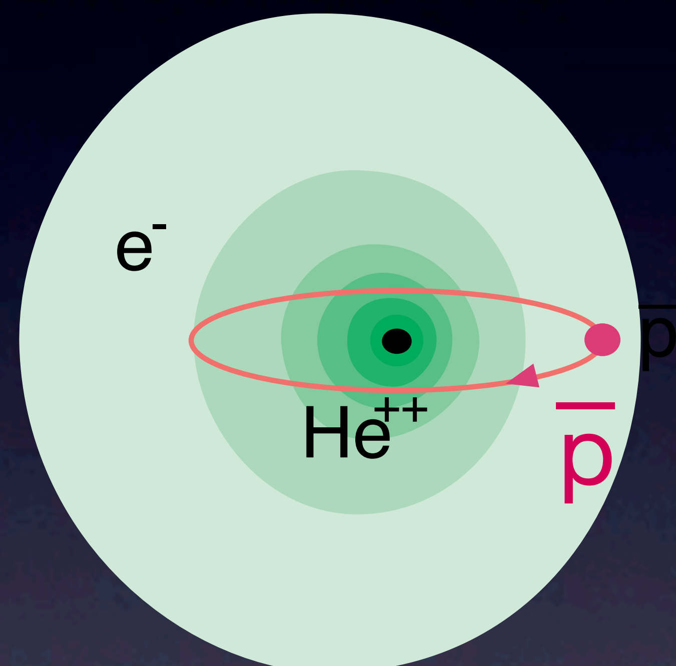
Momentum
p [GeV/c]
Basic AD Deceleration Cycle
CERN
3.57
2.0
0.3
0.1
pbar injection
Bunch rotation
Stochastic cooling
17 s.
Stochastic cooling
6.6 s. Tune jump
Electron cooling
16 s.
Electron cooling
8 s.
Rebunching
Fast Extraction
Actual Duration
Design Duration
12(10)
35(33)
54(52)
71(58)
85(60)
time [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.


ATRAP
H̄ laser spectroscopy
AEGIS
H̄ free fall
↓
ASACUSA
p̄He laser spectroscopy
H̄ microwave spectroscopy
ATHENA → ALPHA
H̄ laser spectroscopy
ASACUSA
HARVARD
ATRAP
ALPHA

# ①反陽子ヘリウム

antiprotonic helium

反陽子ヘリウム原子：
ヘリウム原子の２個の電子のうち１つを
反陽子で置換したもの




自然界には存在しない
CERNの反陽子源で作る
世界中で我々しか実験していない

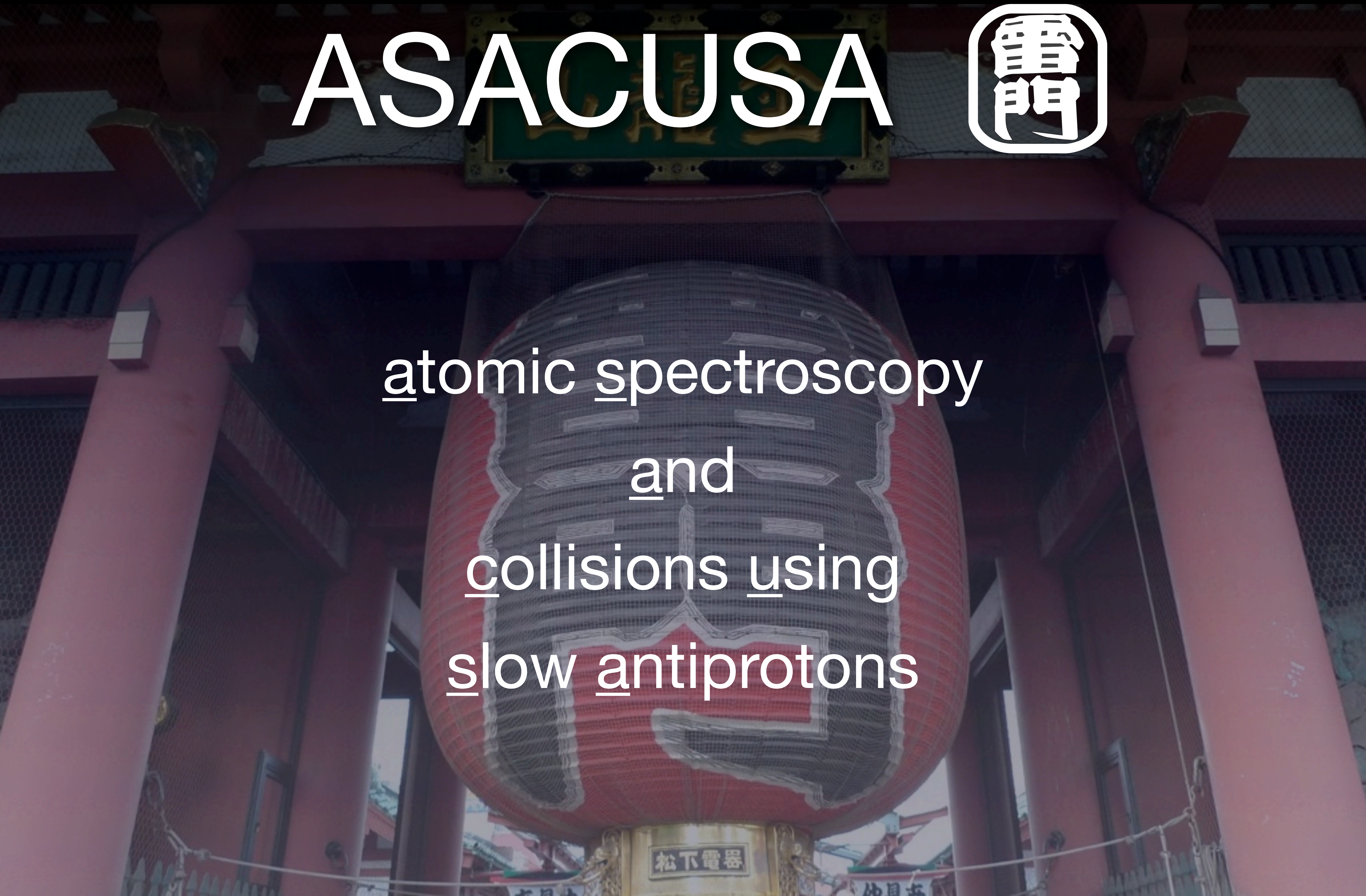
# ASACUSA

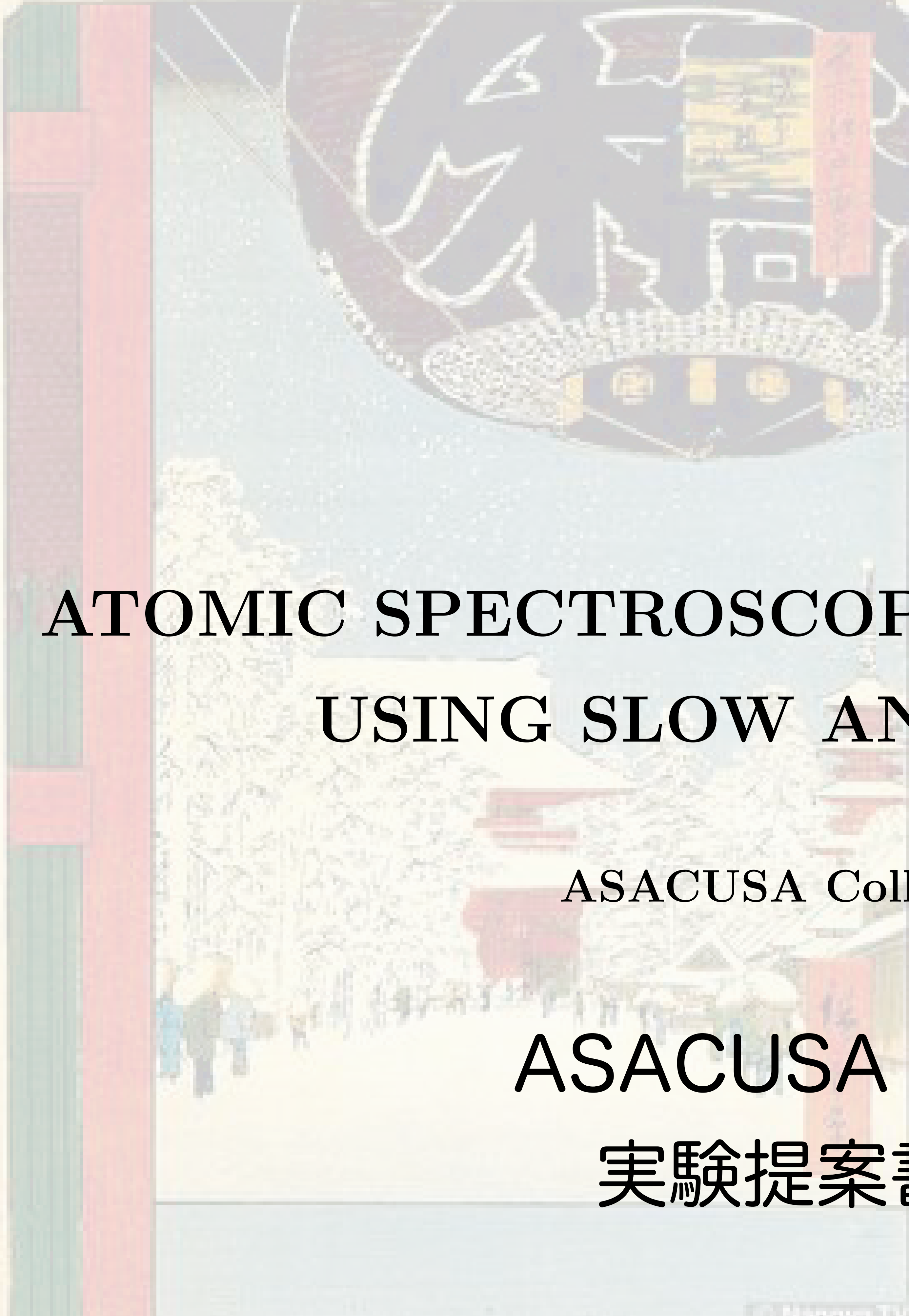
atomic spectroscopy

and

collisions using

slow antiprotons






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

# ATOMIC SPECTROSCOPY AND COLLISIONS USING SLOW ANTIPROTONS

**ASACUSA Collaboration**

ASACUSA (アサクサ)
実験提案書 1997

# 始

# The introduction

(&conclusion)

# 電子との質量比

1 2 3 4 5 6 7 8 9 10

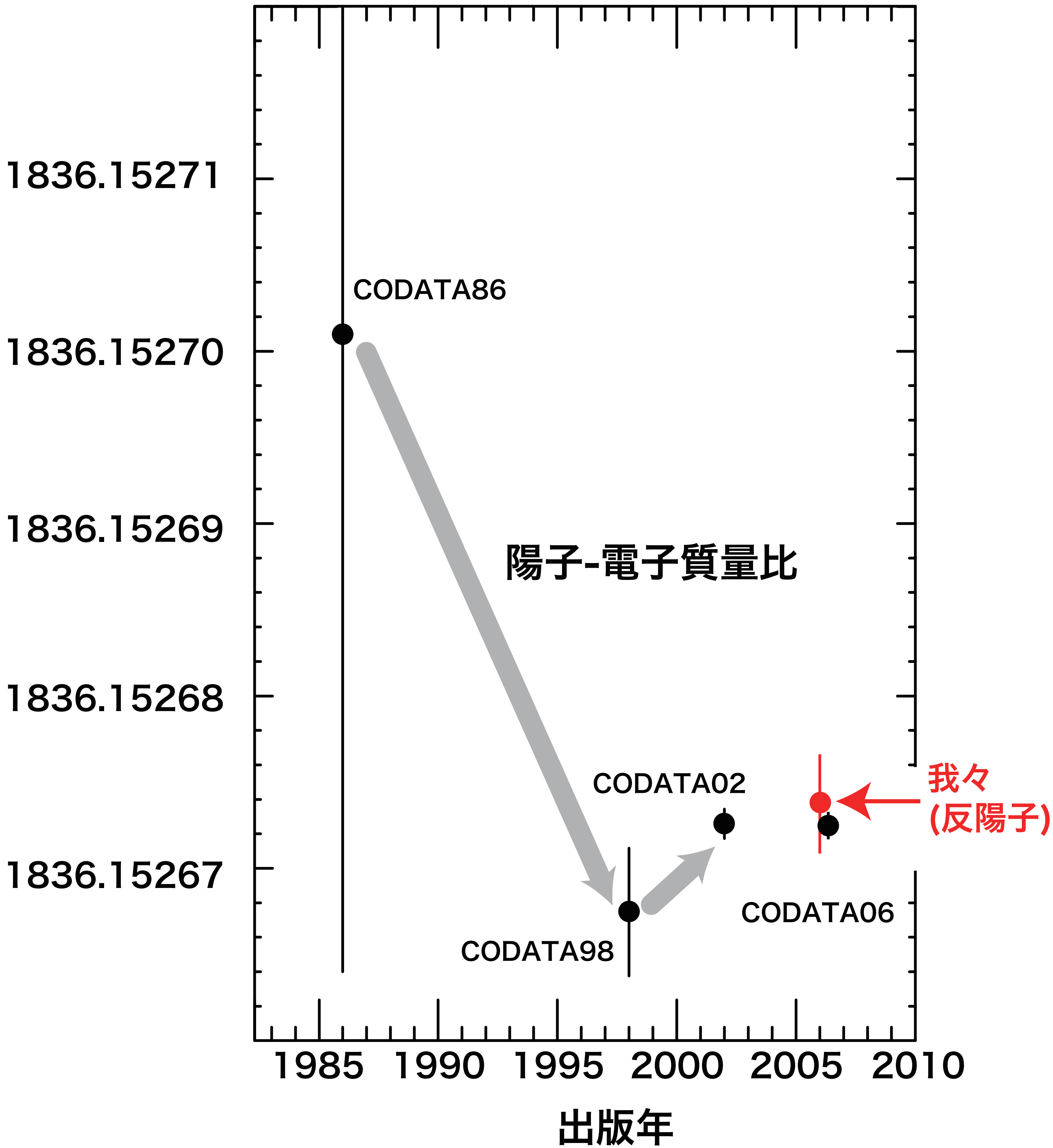
陽子 1836.1526725

我々2006→ 反陽子 1836.152674

±０．０００００５

9桁目までは完全に一致

10桁目も誤差の範囲で一致




1. CPTは破れていない

2. <u>基礎物理定数への貢献</u>

# 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-

基礎物理定数の例

CODATA 2006より

（単位系に深く関係している）

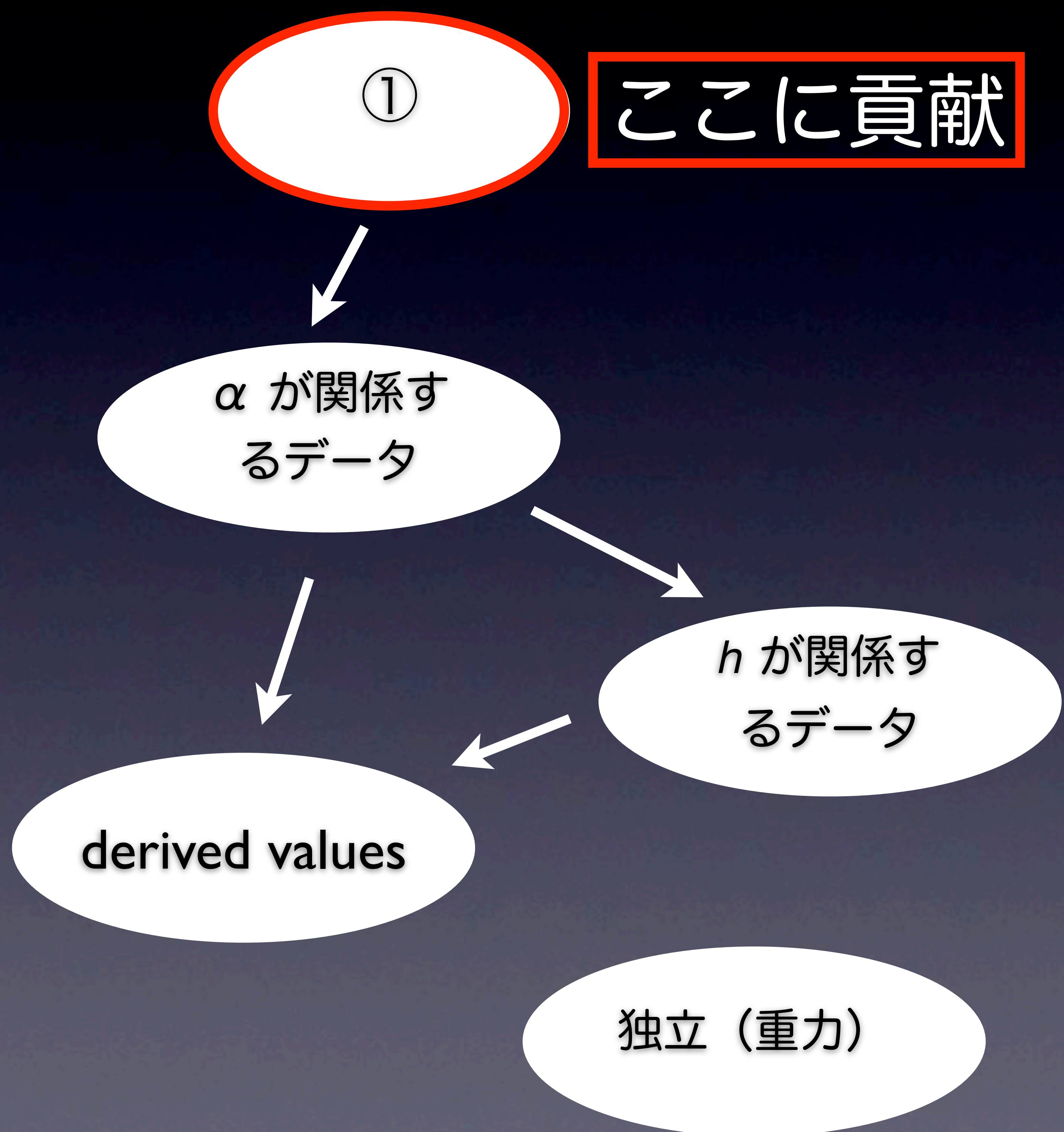
ppb=10億分の1

| 物理定数 | 数値 (下線の桁に不確定性がある) | 単位 | 精度 |
|---|---|---|---|
| 光速 | 299 792 458 | m $s^{-1}$ | 定義値 |
| 万有引力定数 | 6.674 3 | x $10^{-11}$ $m^3$ $kg^{-1}$ $s^{-2}$ | 100000 ppb |
| アボガドロ数 | 6.022 141 8 | x $10^{23}$ $mol^{-1}$ | 50 ppb |
| プランク定数 | 6.626 068 9 | x $10^{-34}$ J s | 50 ppb |
| 陽子の質量 | 1.672 621 64 | x $10^{-27}$ kg | 50 ppb |
| 電子の電荷 | 1.602 176 49 | x $10^{-19}$ C | 25 ppb |
| 微細構造定数$^{-1}$ | 137.035 999 68 | | 0.68 ppb |
| 陽子・電子質量比 | 1836.152 672 5 | | 0.43 ppb |
| リュードベリ定数 | 10 973 731.568 52 | $m^{-1}$ | 0.0066 ppb |

注目！

# CODATAフローチャート

from S.G. Karshenboim



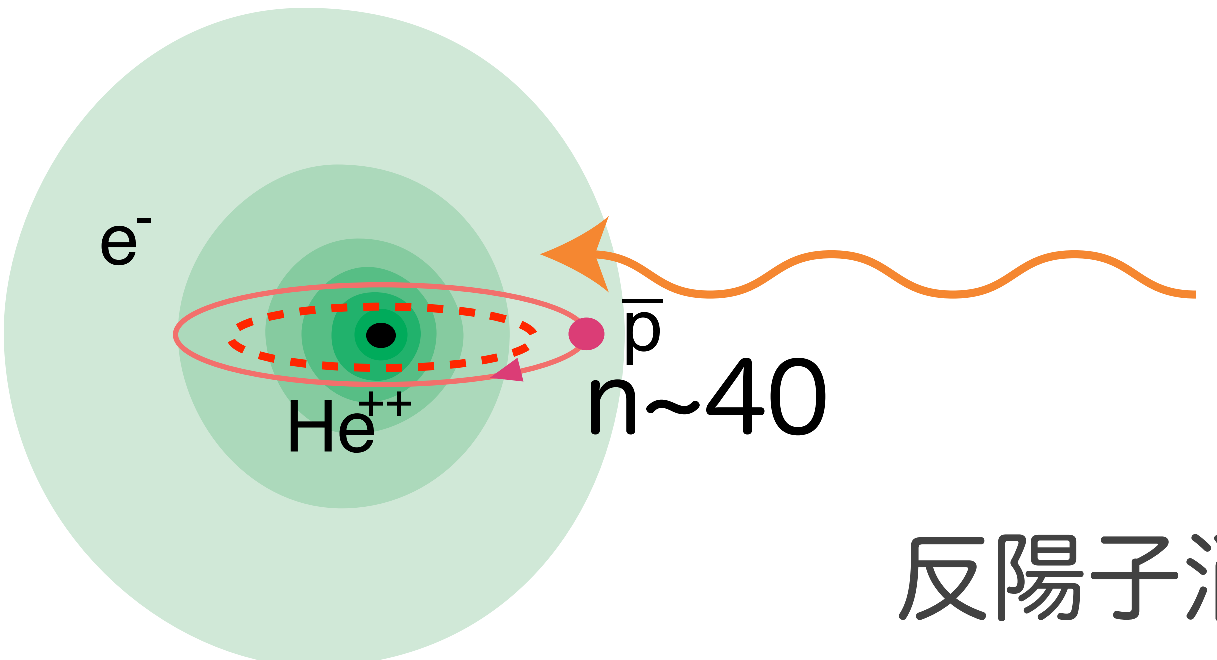

①= 最初に決定される高精度な値, $R_\infty$ と $\underline{m_e/m_p}$, ...

矢印は式

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

$m_{\bar{p}}/m_e$の量り方は

# $\bar{\mathrm{p}}$He レーザー分光




レーザーで反陽子軌道を変える

反陽子消滅を利用した共鳴検出

共鳴周波数

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

反陽子-電子質量比

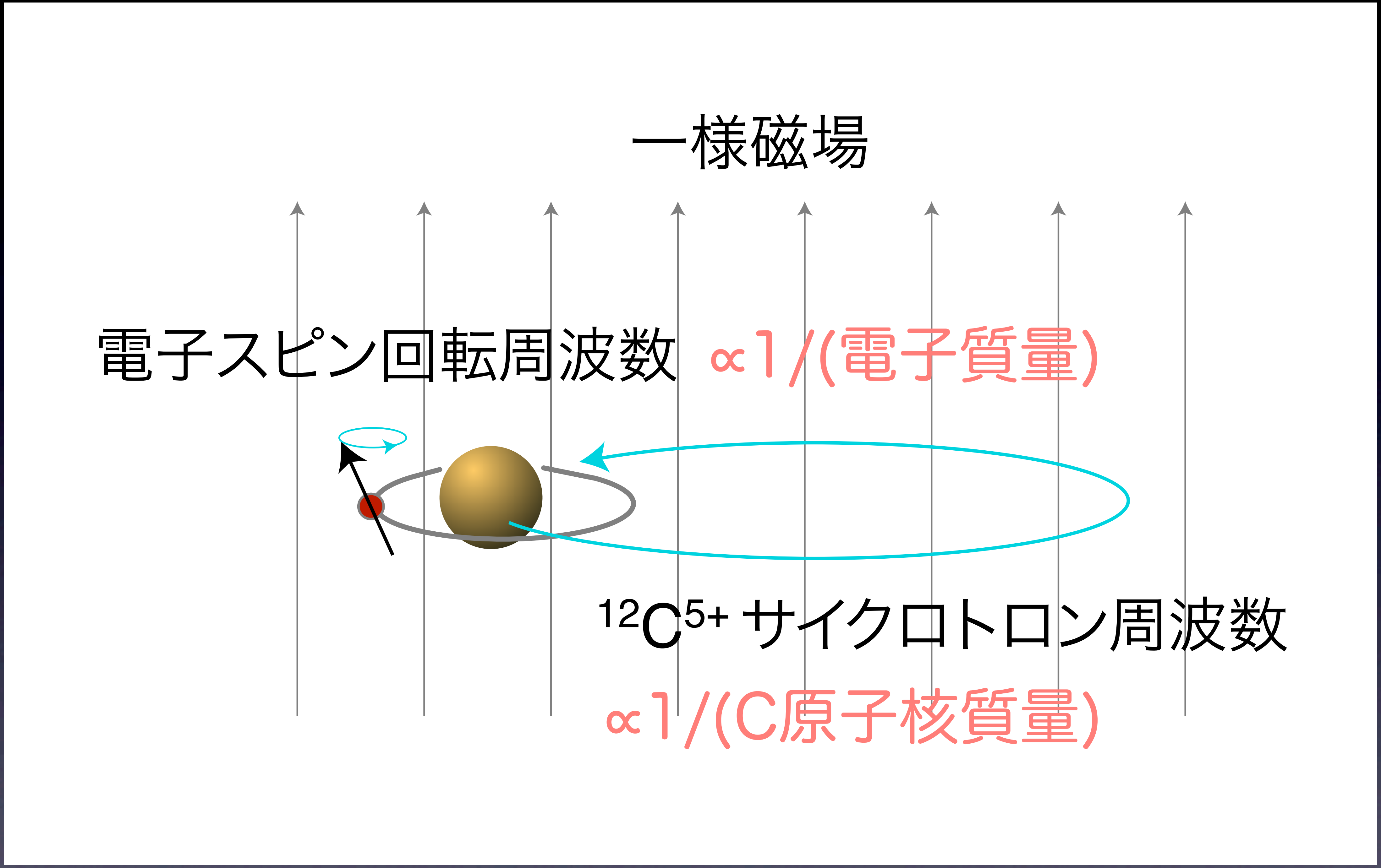
理論計算

Korobov
Kino et al.

ちなみに

$m_p/m_e$はどうやって量っているか

Beier et al, PRL 88 (2002) 011603



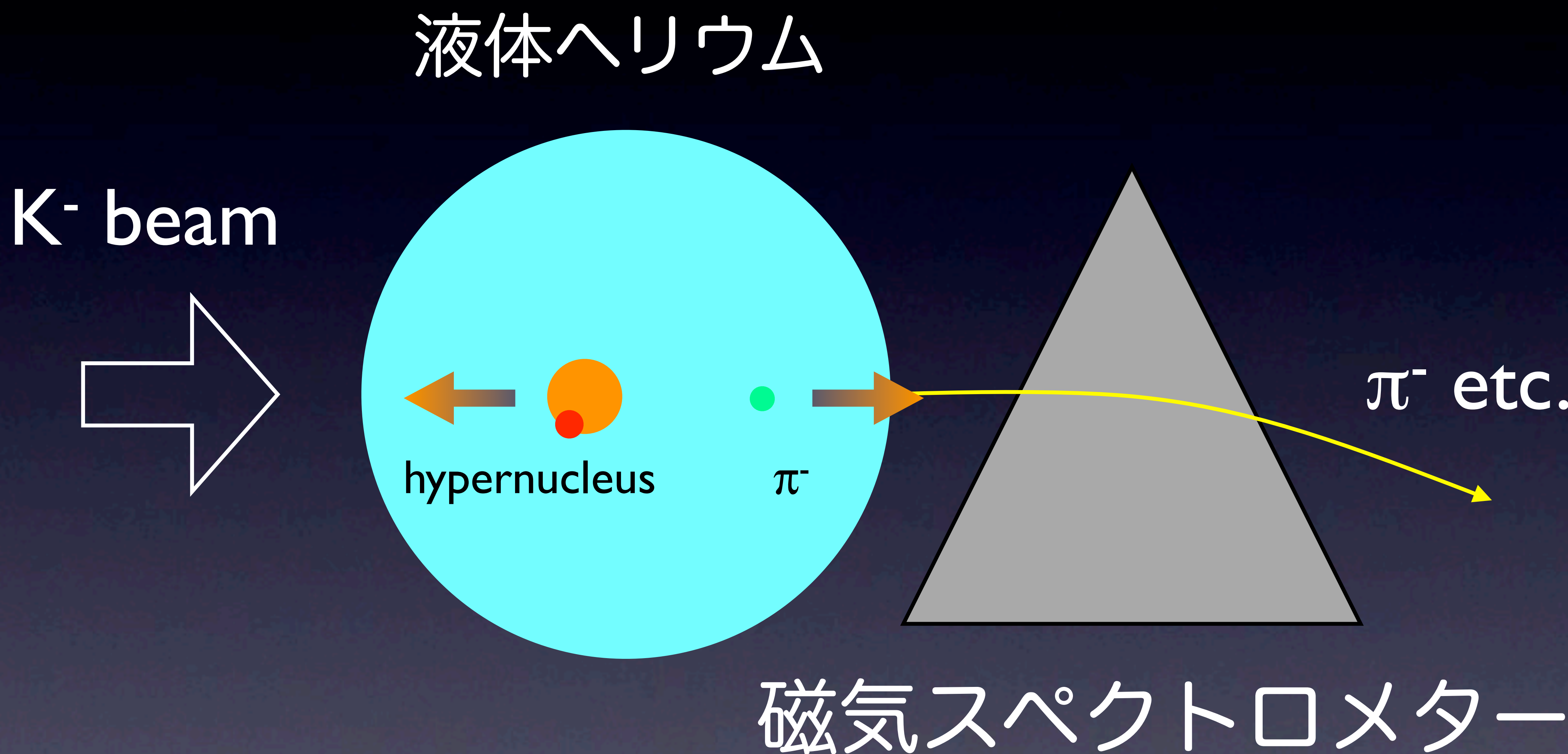

二つの周波数の比→量子電磁力学補正→
C原子核と電子の質量比→陽子・電子質量比

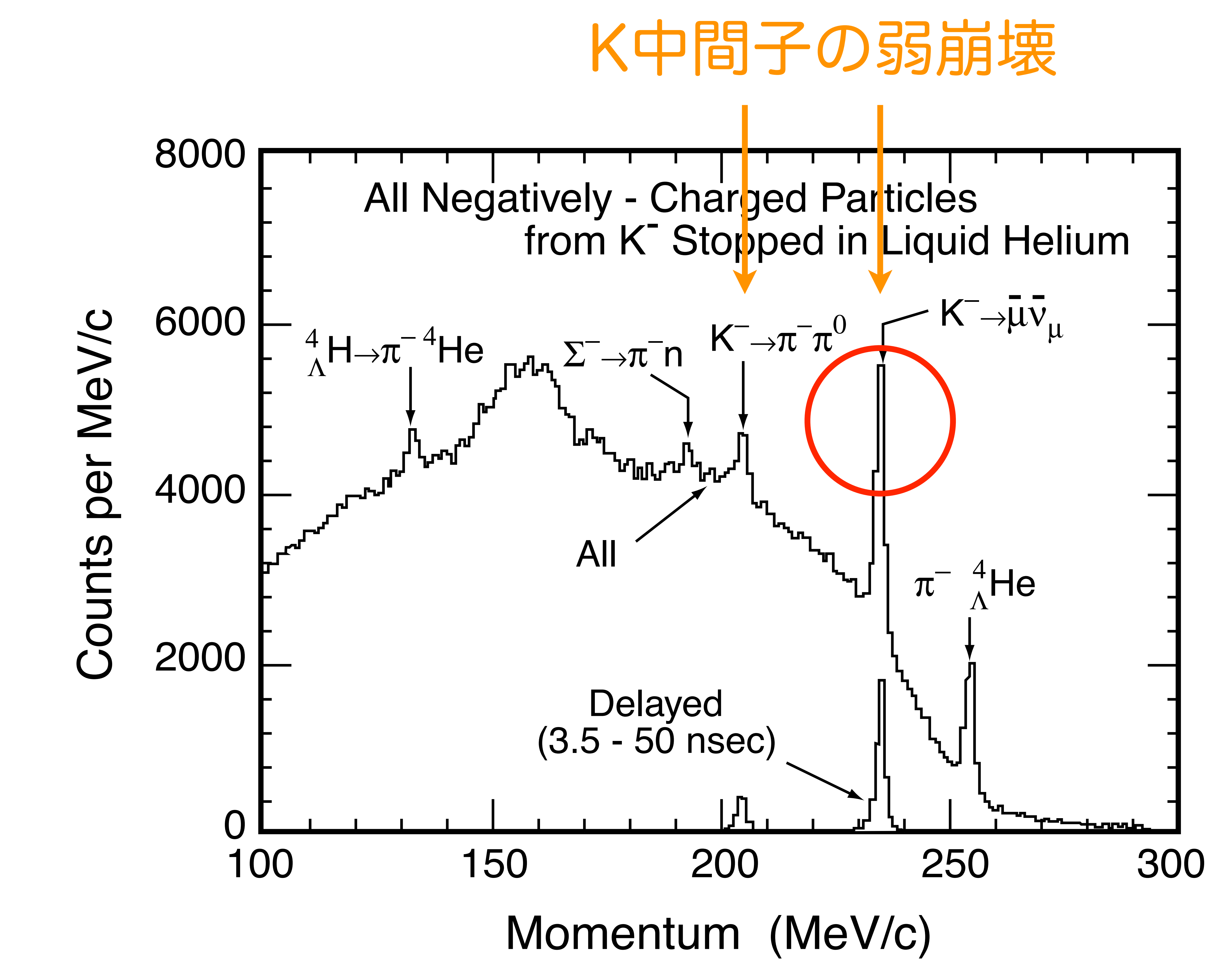
# 1989 ハイパー核研究
# 液体ヘリウムに止めた$K^-$

KEK実験 E167A (責任者 早野)

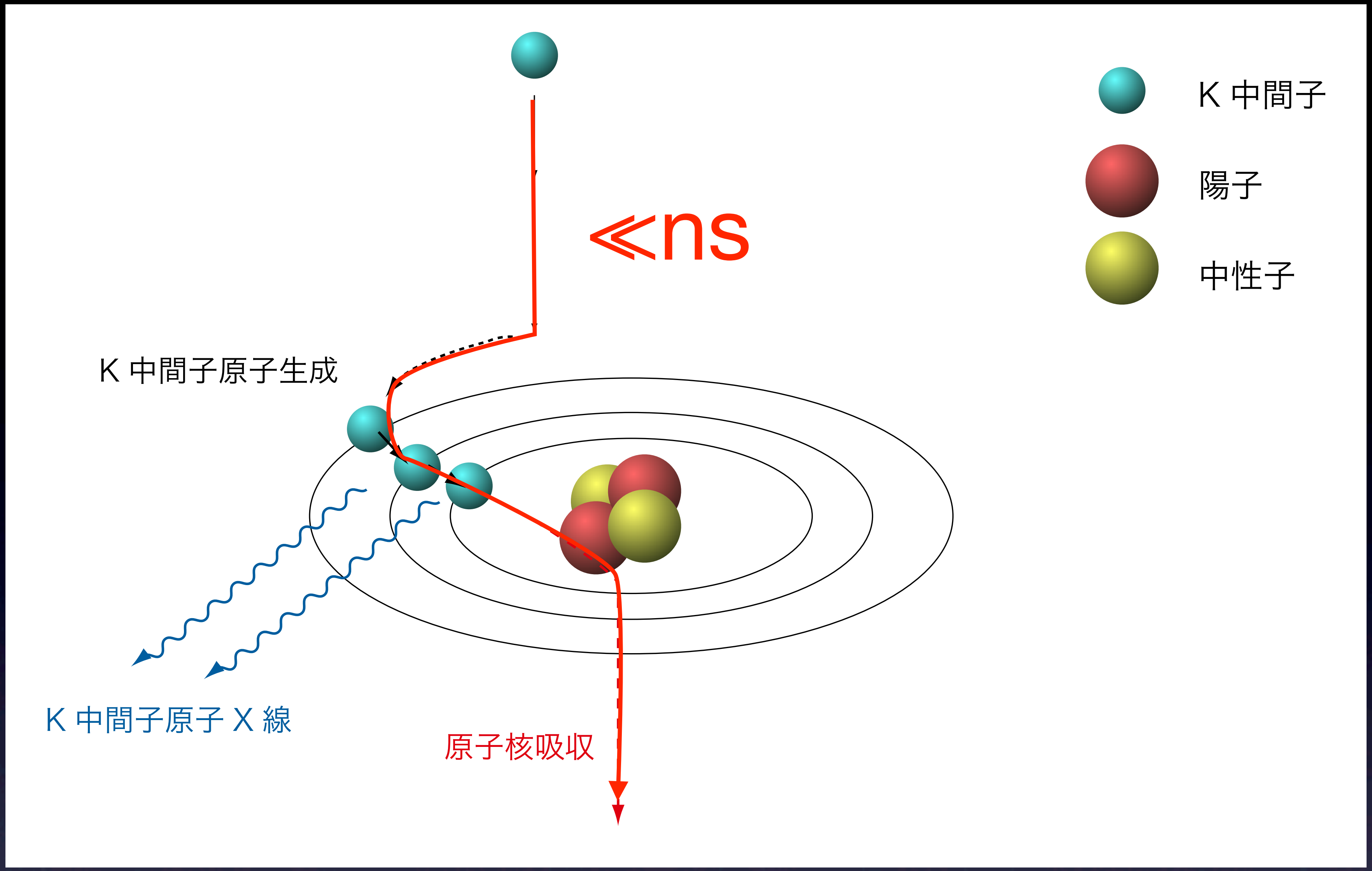
Search for Σ hypernuclear ground state by kaon absorption on $^4He$

Harada & Akaishi
の予言

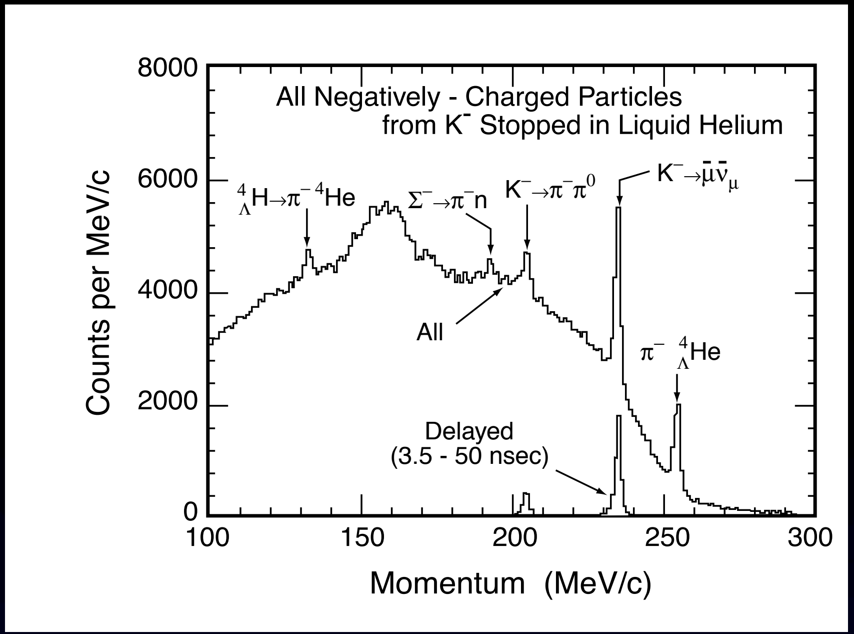

液体ヘリウム
K- beam
hypernucleus
π-
π- etc.
磁気スペクトロメーター




R. S. Hayano et al, Phys. Lett. B 231 (1989) 355




Kの弱崩壊（12ns）が、
脱励起→核吸収の間（≪ns）に
起きるはずがない（常識）

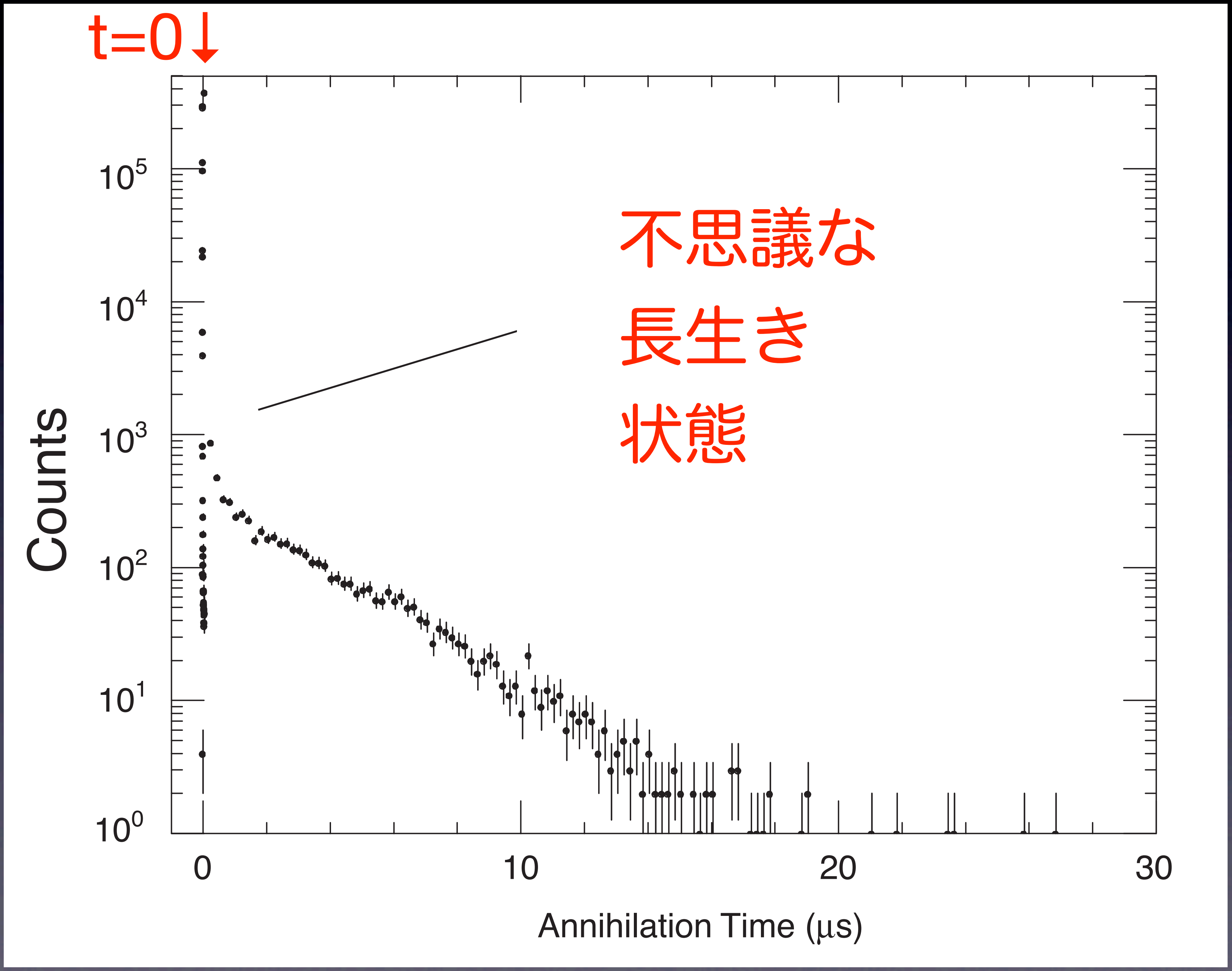



これは異常だ

反陽子でも異常が見えるか？

KEK実験E215 (実験責任者 早野)
Study of metastable states of
$\bar{p}$ atom in liquid helium

# ヘリウム中で異常に長生きする反陽子の発見



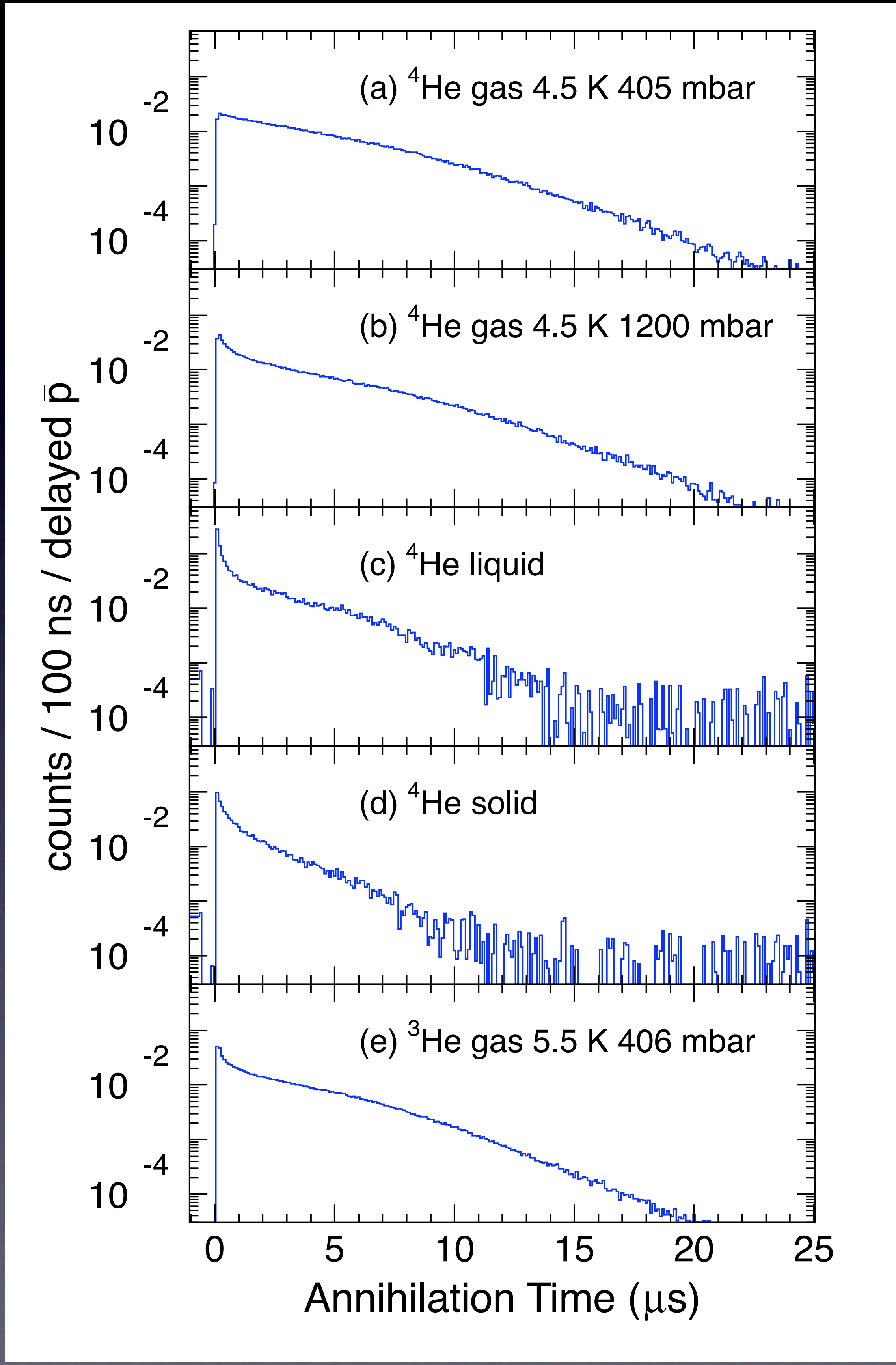

Iwasaki et al., PRL 67 (1991) 1246

# 博物学の時代

CERN LEARでの測定

ガス,液体,固体

helium-3 & helium-4



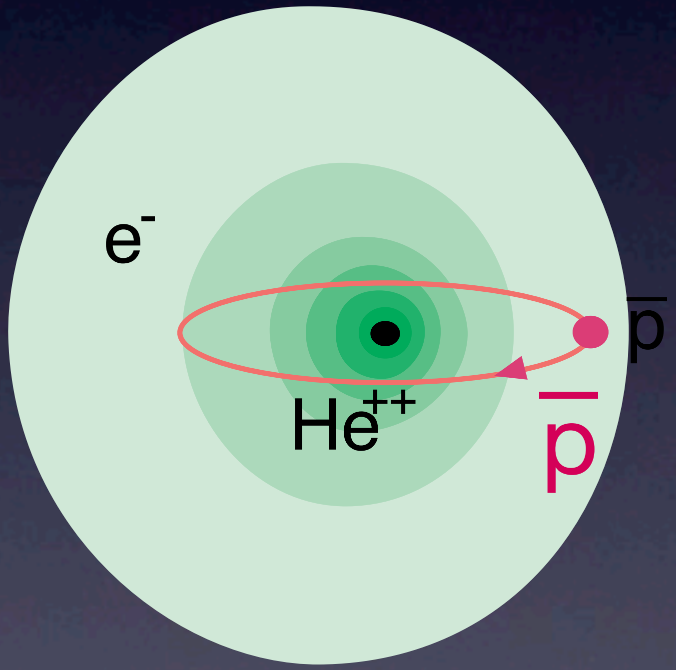

T. Yamazaki et al, とともに 特別推進研究

@LEAR 1992-1996

# 反陽子ヘリウム原子

## 量子的な反陽子トラップ装置

電子は ~ 1s

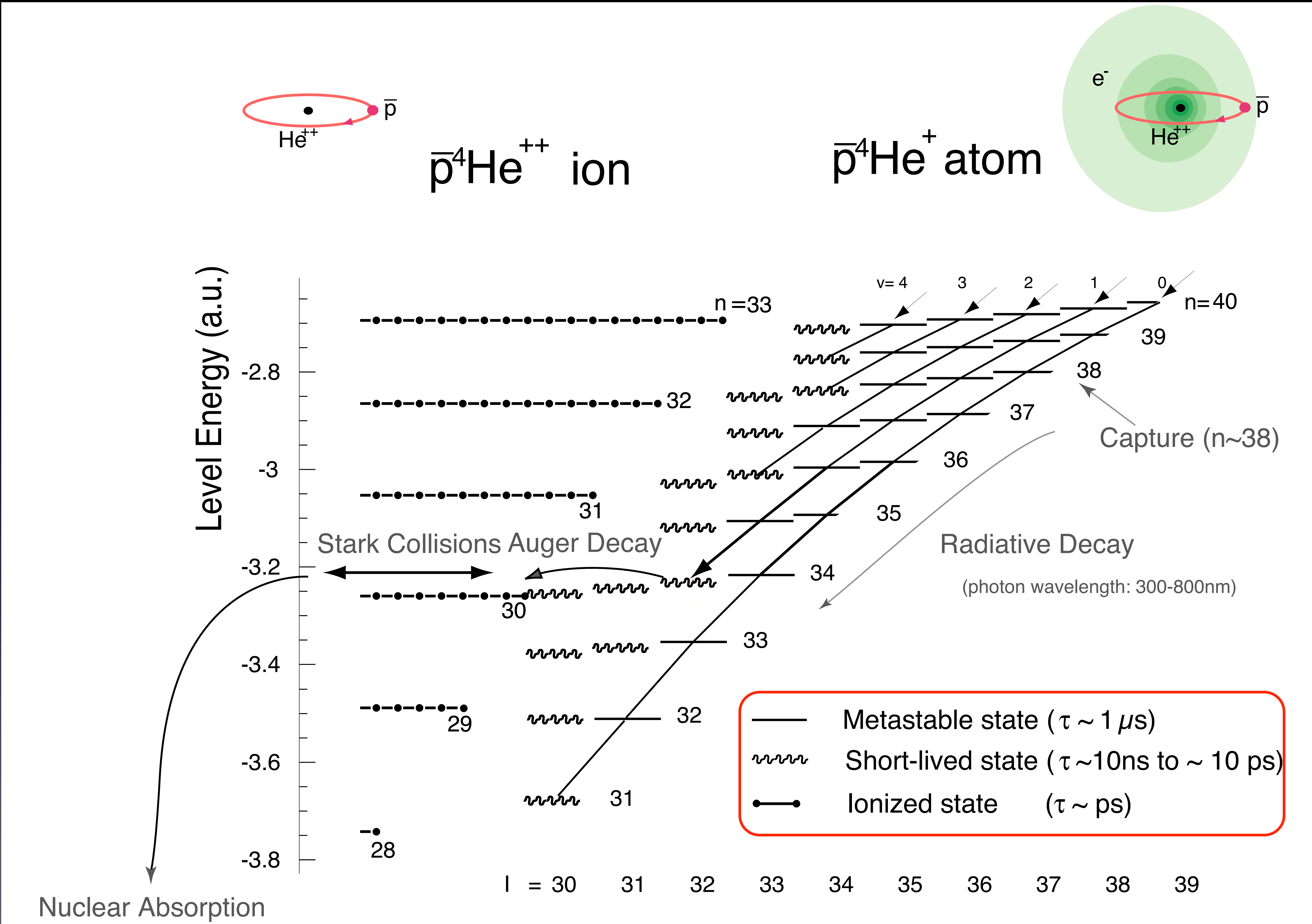



反陽子は n~40
L~n

容易な生成(~3%) 長い寿命(3μs)

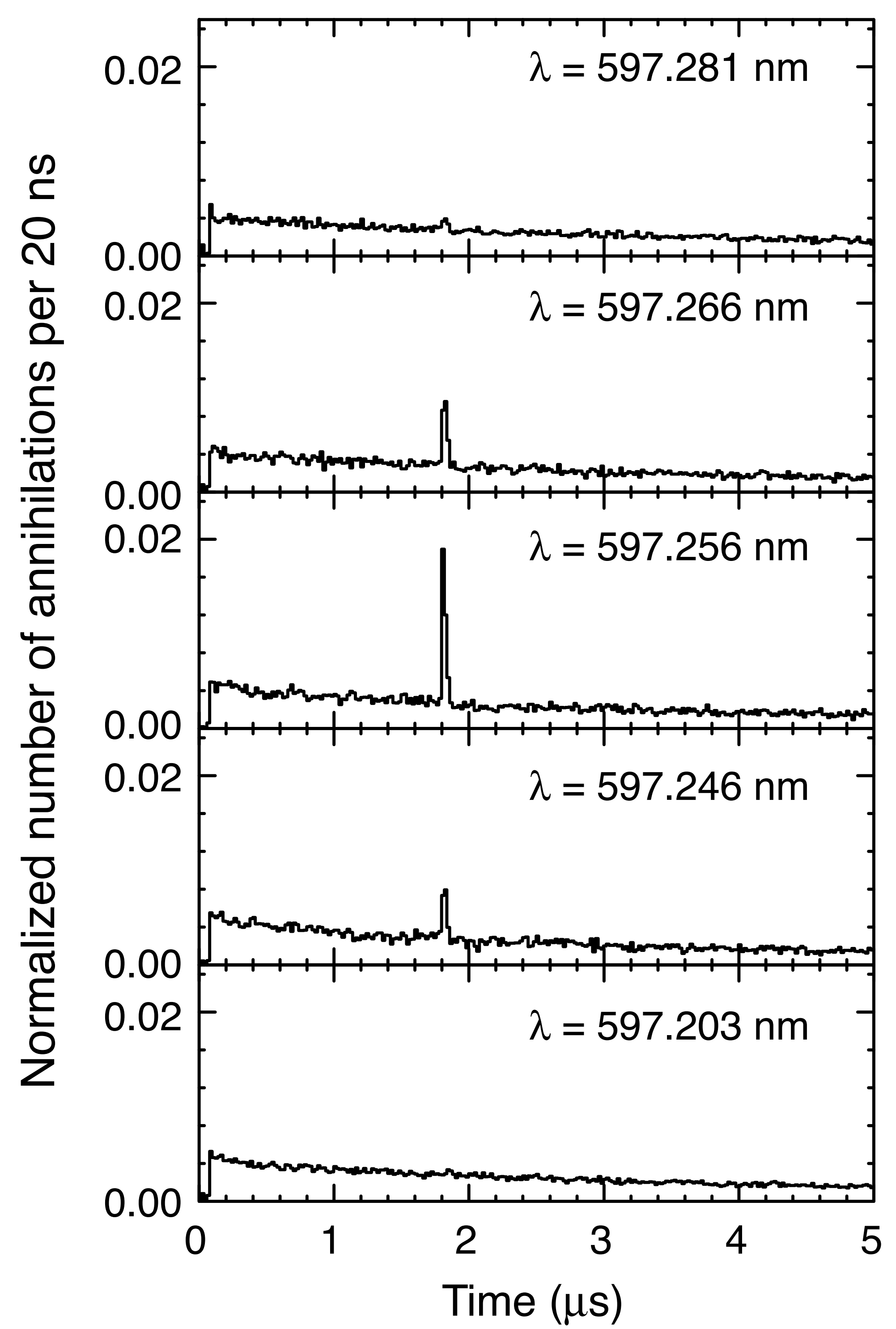
# 分光原理

laser-induced
annihilation



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)
Stark Collisions Auger Decay
Radiative Decay
(photon wavelength: 300-800nm)
Nuclear Absorption
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)

# An example, (n,l)=(39,35)→(38,34)




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

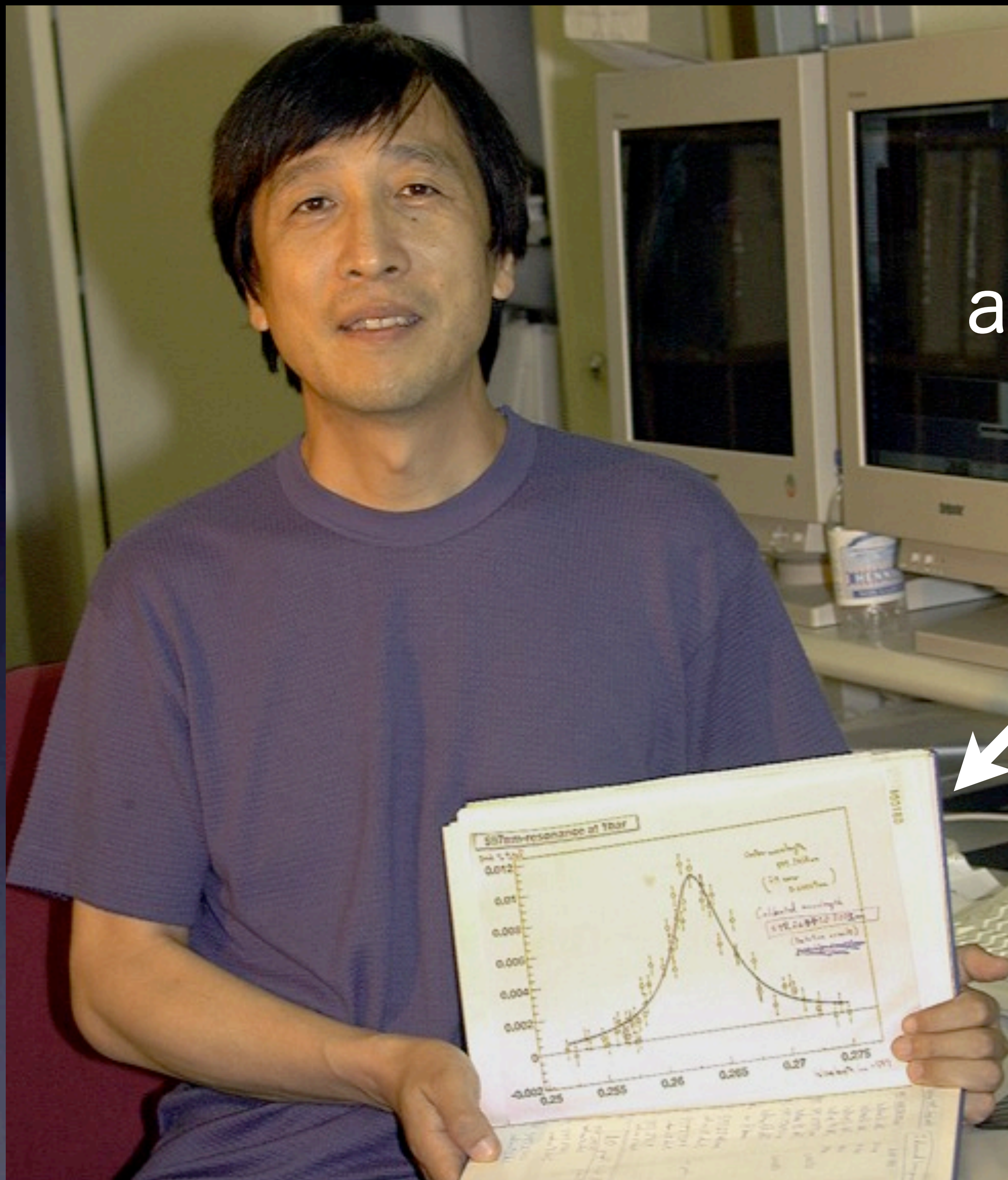


Photo CERN

annihilation peak intensity

vs

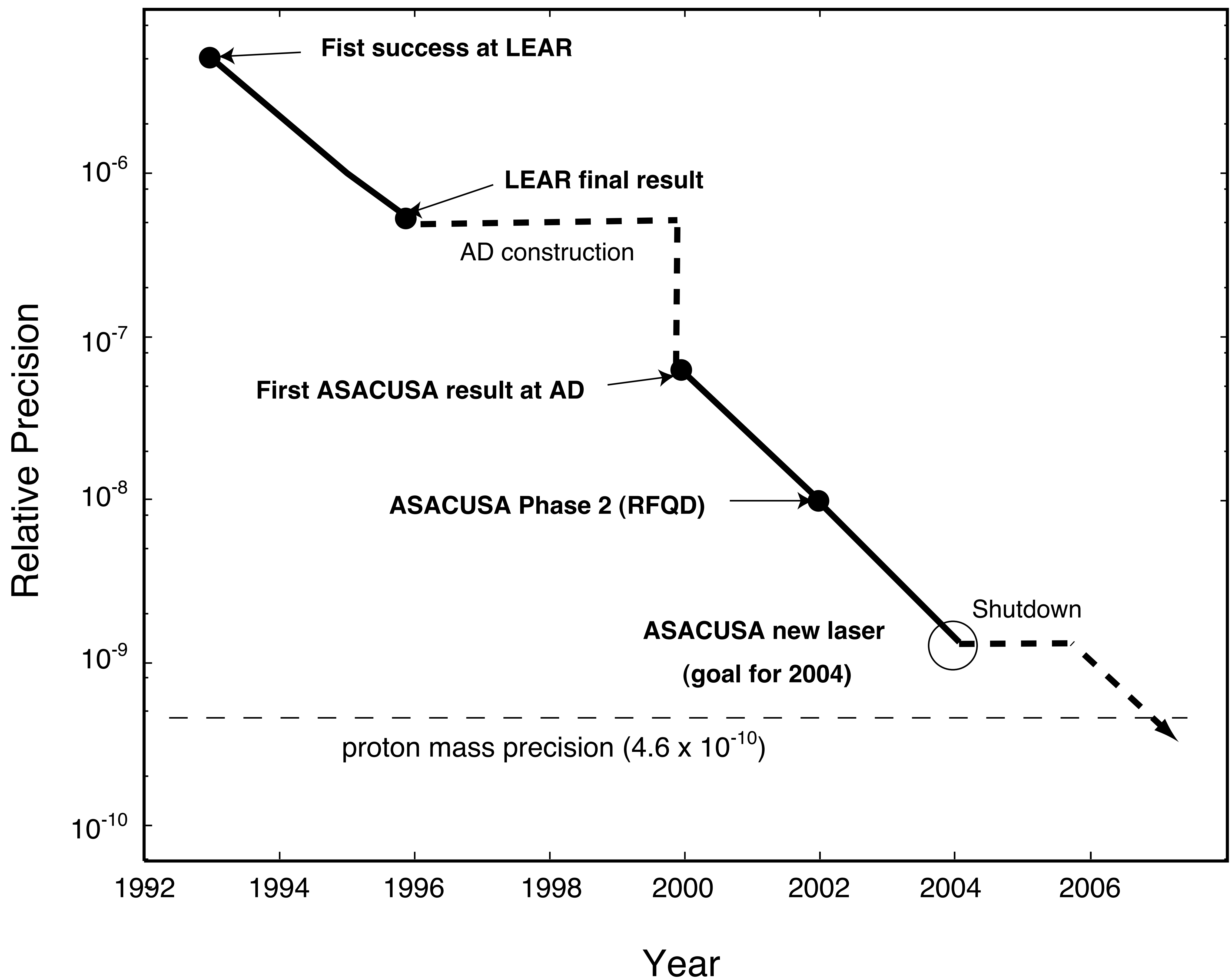
frequency

# 精度

improving precision

# 精度はどうやれば上がるか

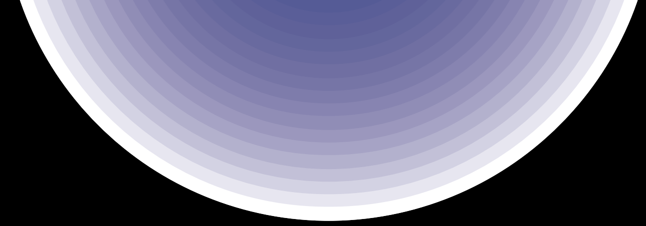
<table>
<tr><td>統計</td><td rowspan="2">ideally<br>$\sigma = \frac{\text{line width}}{\sqrt{N}}$</td></tr>
<tr><td><u>線幅</u></td></tr>
<tr><td colspan="2">系統誤差</td></tr>
<tr><td colspan="2">系統誤差</td></tr>
<tr><td colspan="2">系統誤差</td></tr>
<tr><td colspan="2">…</td></tr>
</table>



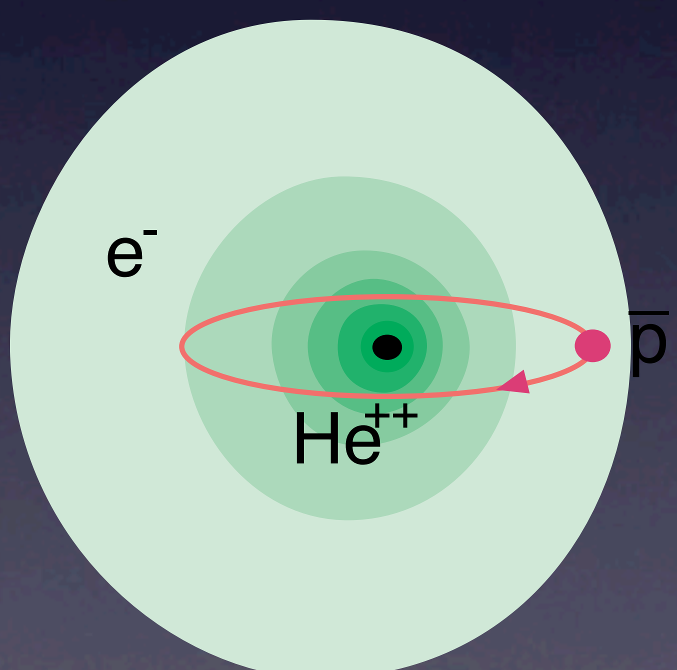
Fist success at LEAR
LEAR final result
AD construction
First ASACUSA result at AD
ASACUSA Phase 2 (RFQD)
Shutdown
ASACUSA new laser
(goal for 2004)
proton mass precision (4.6 x 10^-10)
Relative Precision
10^-6
10^-7
10^-8
10^-9
10^-10
1992
1994
1996
1998
2000
2002
2004
2006
Year

# 初

the first results @ AD
2000-2001



He



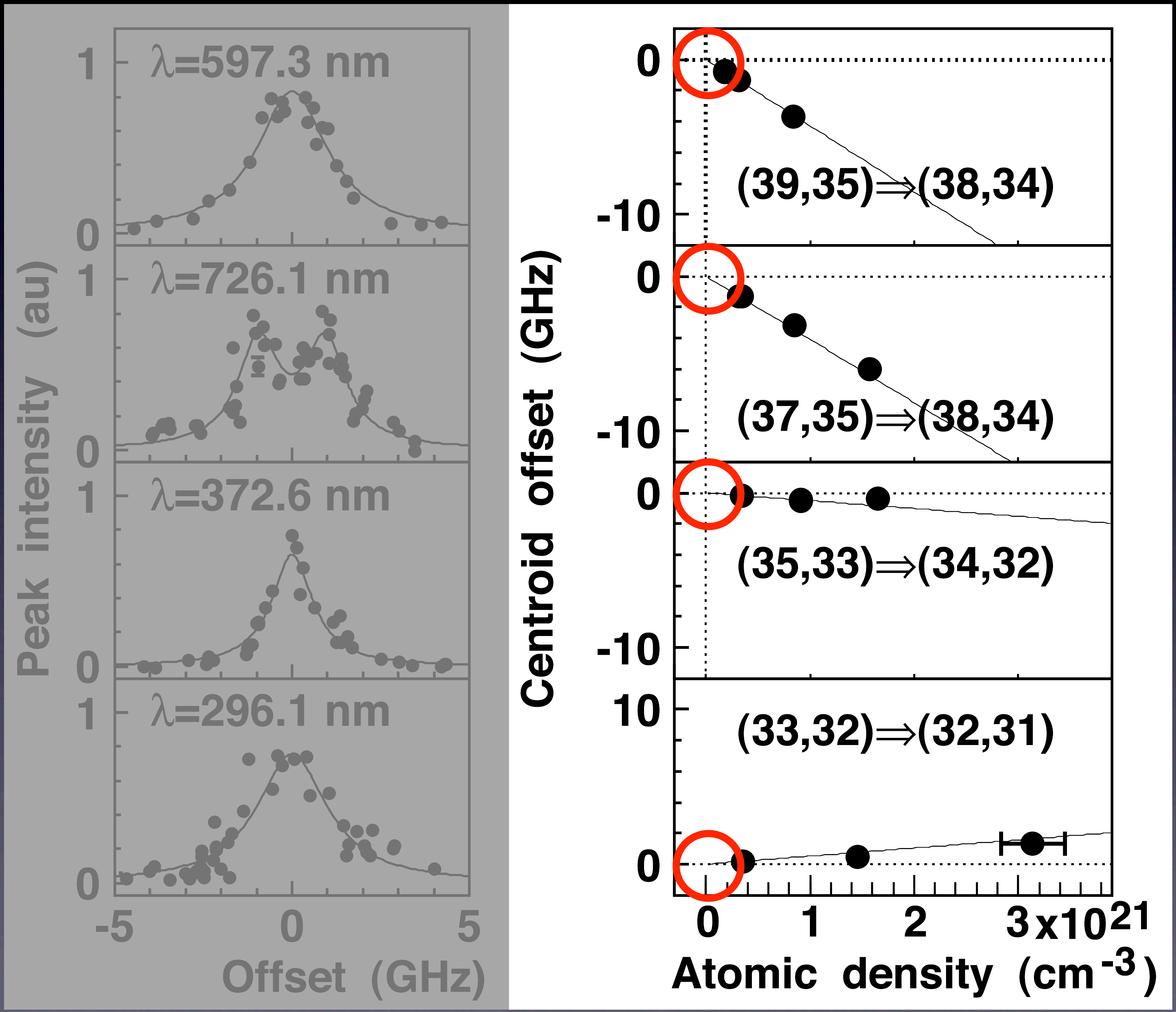

$\bar{p}$ He

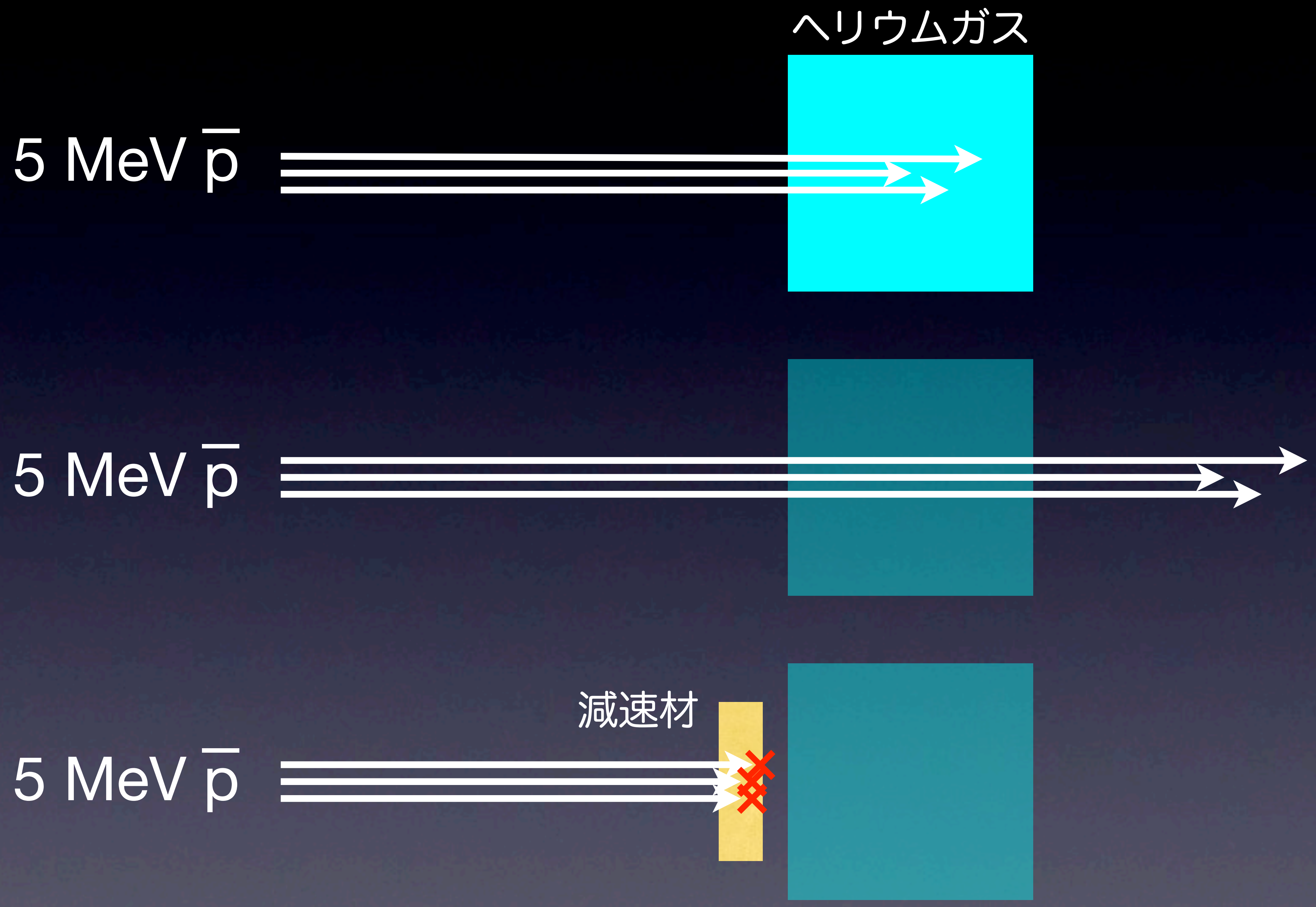
$\bar{p}$ HeはHeと衝突しても容易には壊れない

しかし影響は受ける

# 衝突効果

共鳴周波数がヘリウム標的密度に依存してしまう

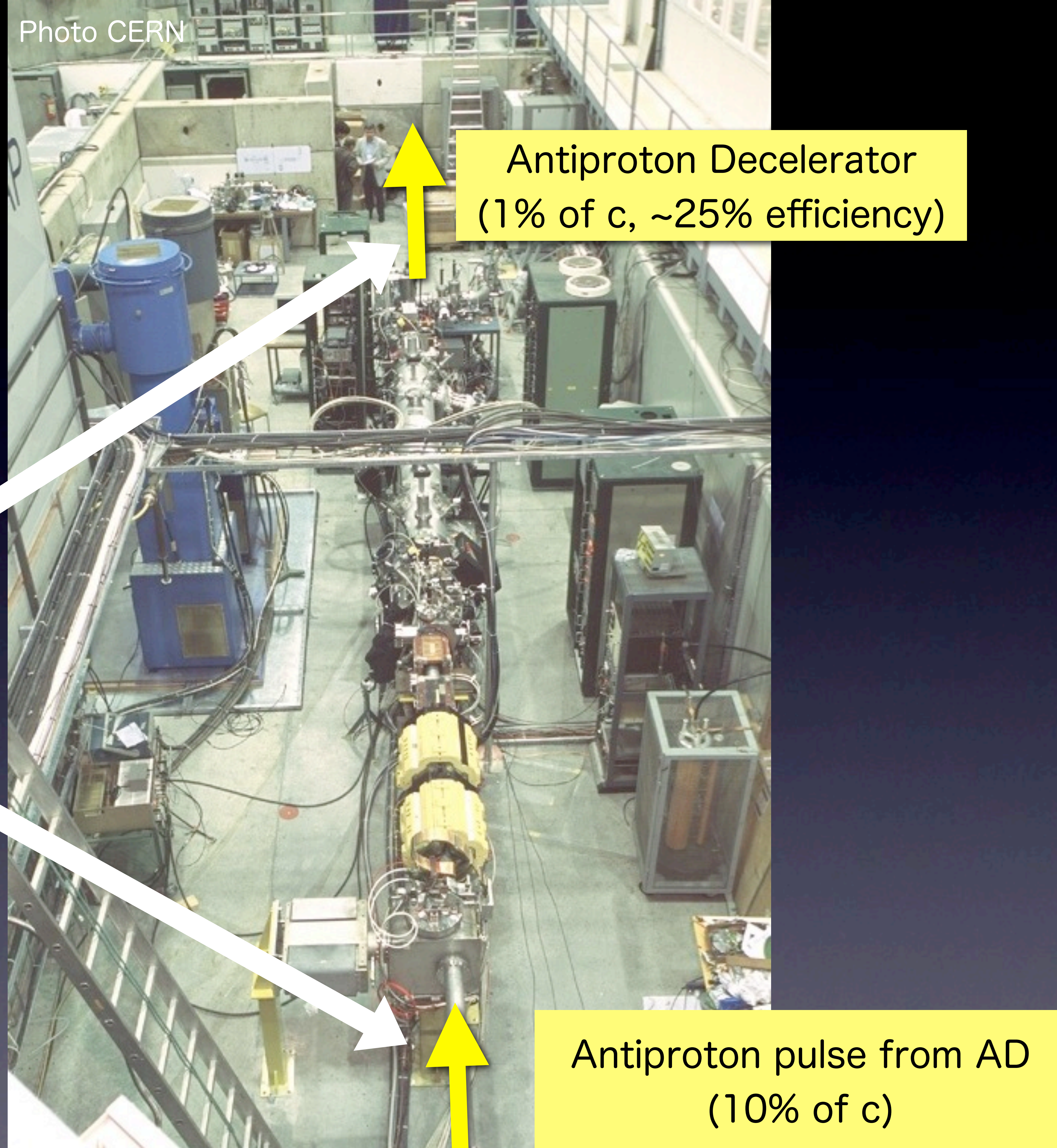




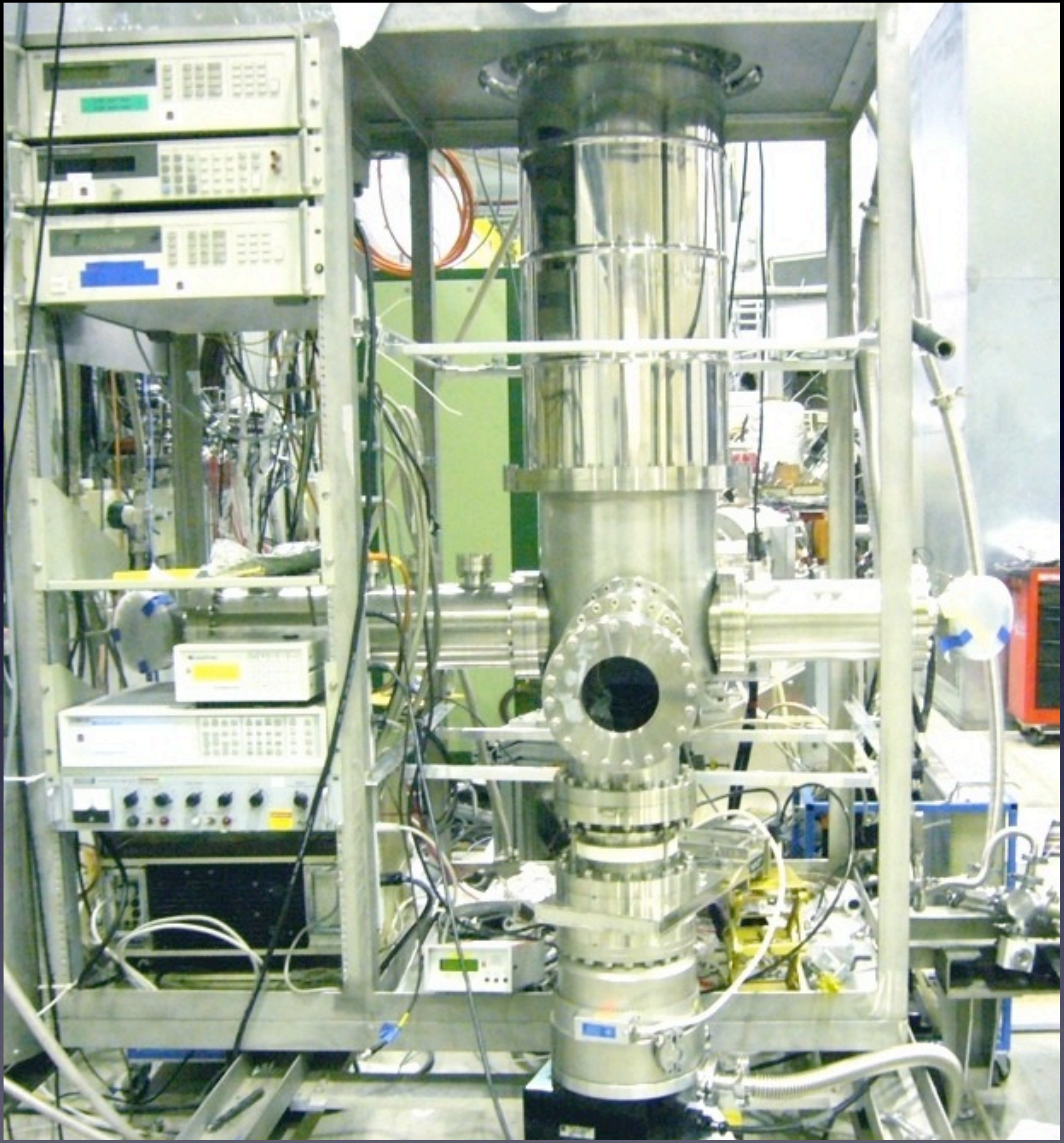
ヘリウムガス
5 MeV $\bar{p}$
5 MeV $\bar{p}$
減速材
5 MeV $\bar{p}$

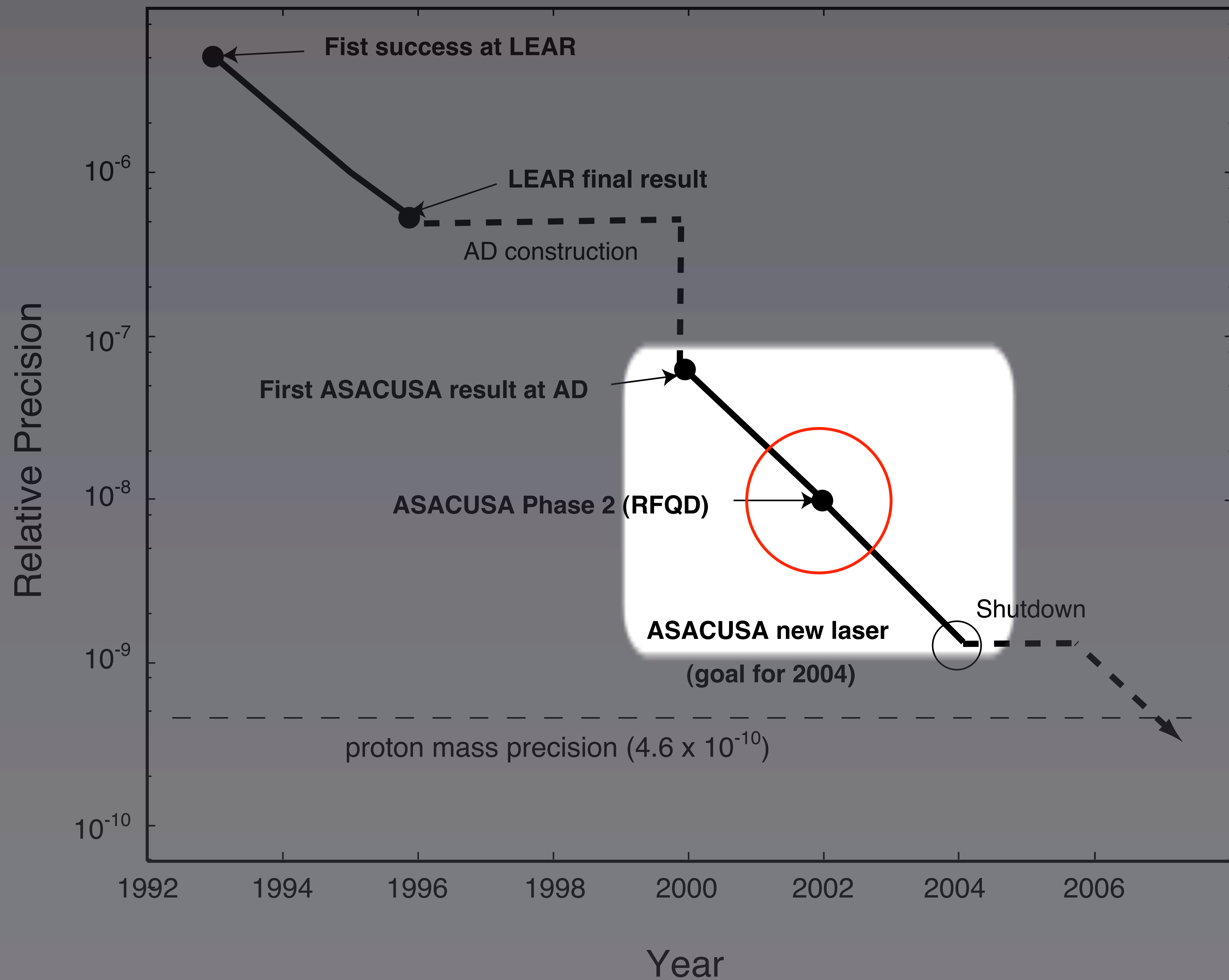
# 世界初の
# 減速型Linacの建設

| 標的密度 |
| --- |
| $10^{16}$-$10^{18}$cm$^{-3}$ |
| $10^{21}$cm$^{-3}$ |



# 低温ヘリウムガス(5 K)





Fist success at LEAR
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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

# 櫛

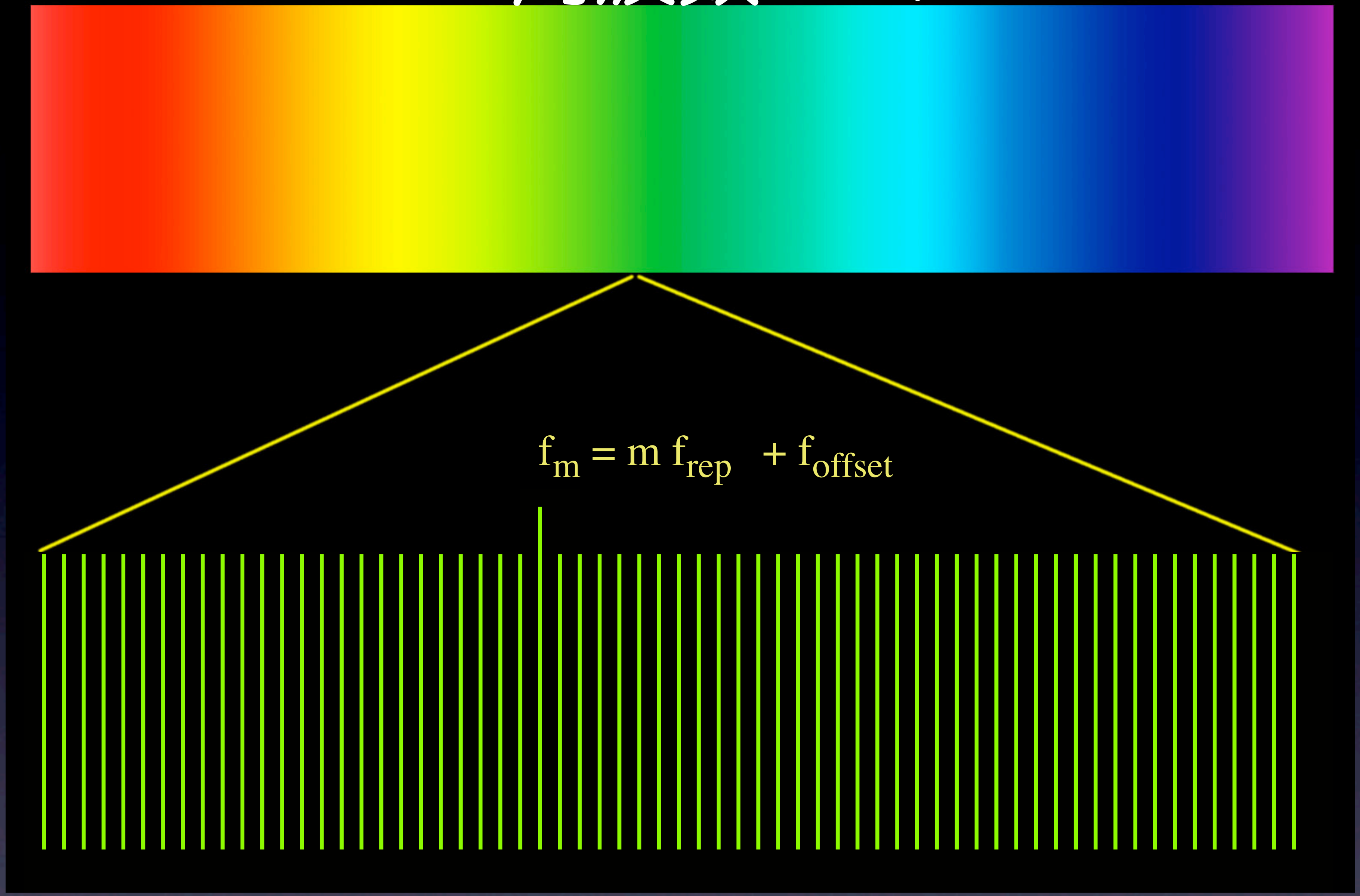
# Frequency Comb

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

2005年ノーベル賞 T.W. ヘンシュ,

周波数コム（櫛）の発明

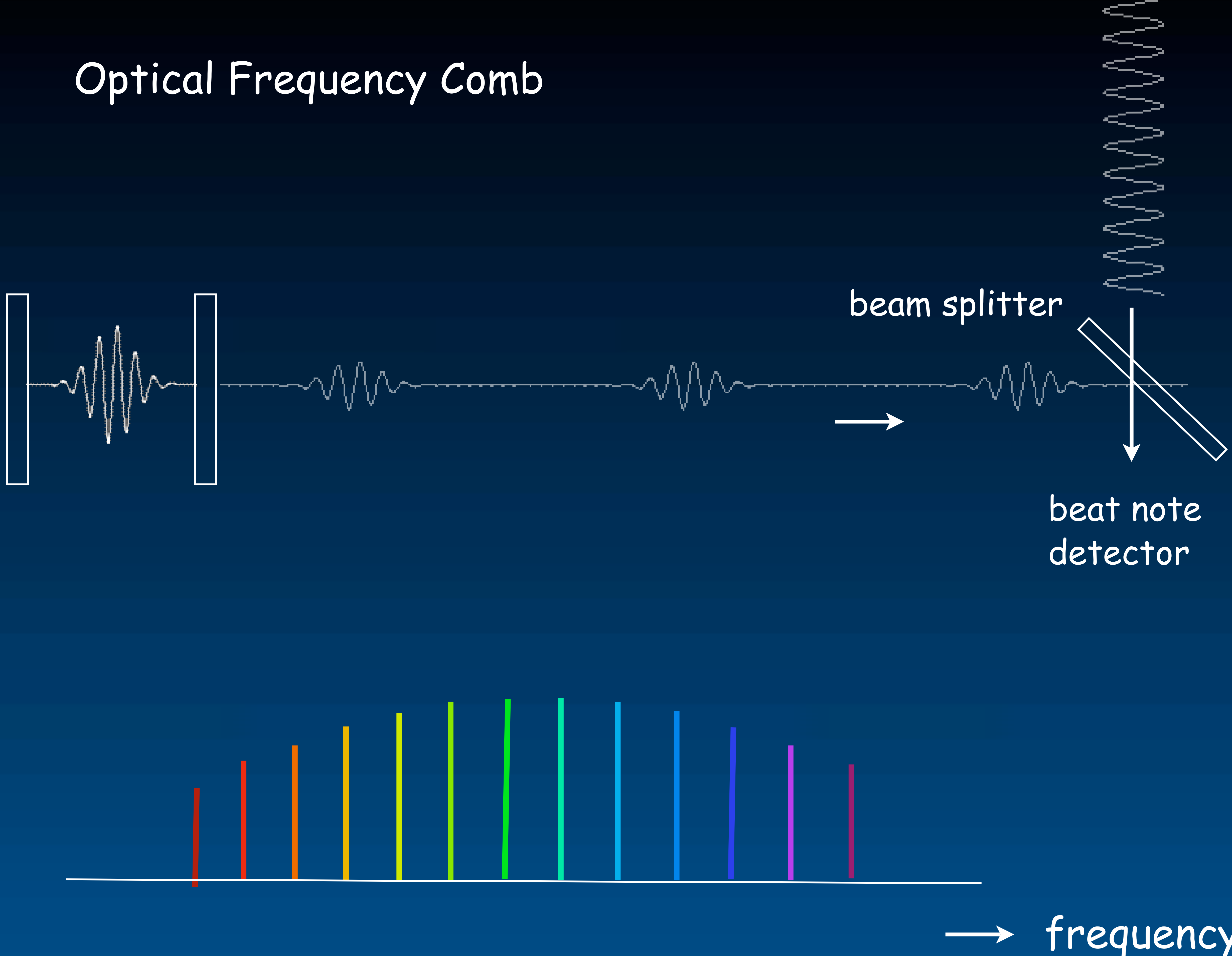
# 周波数コム



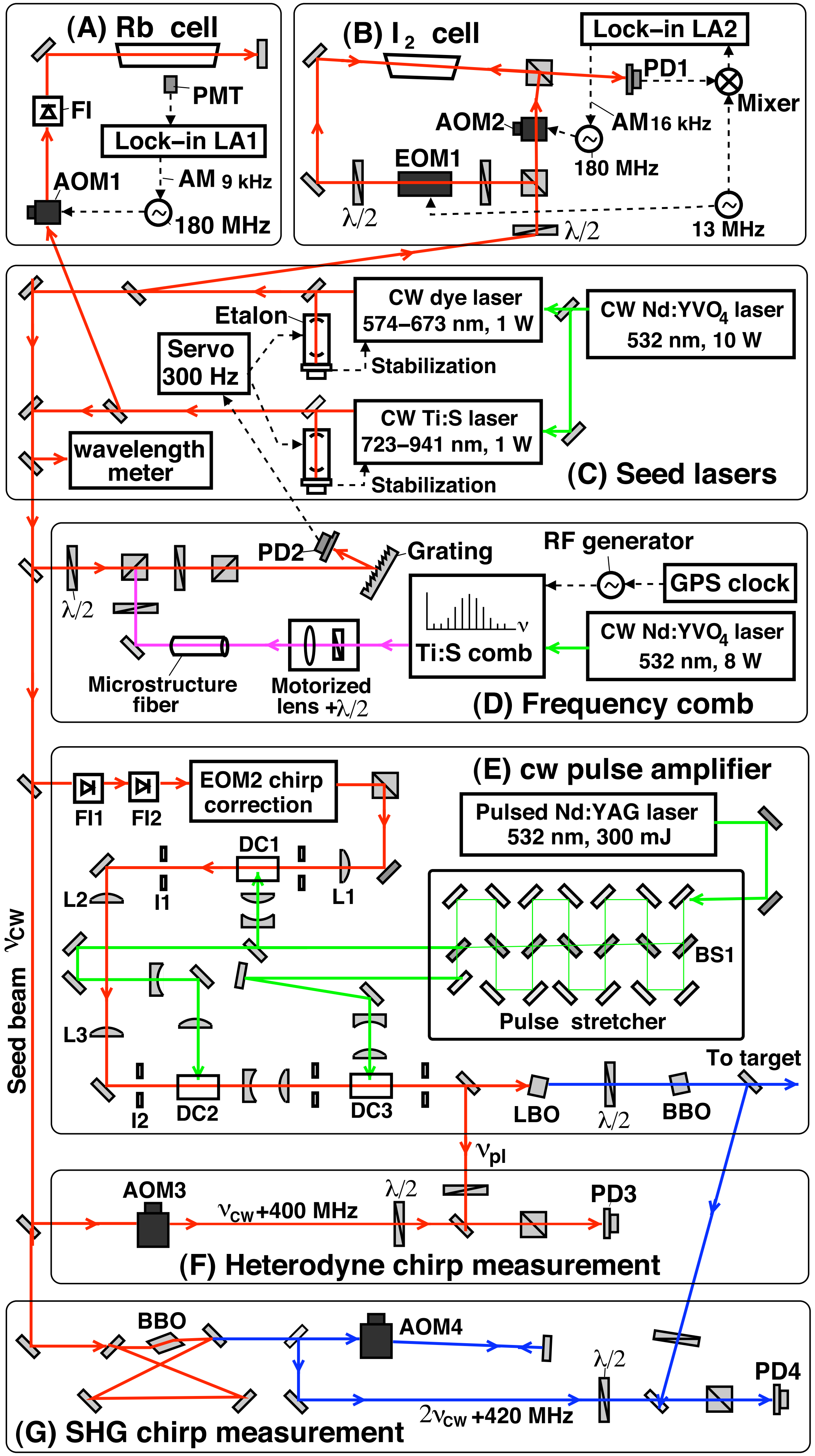

T.W. Hänsch, Nobel lecture

可視光領域に「原子時計の精度」のマーカー（目盛）を入れる

# Optical Frequency Comb




T.W. Hänsch, Nobel lecture



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

# 理論

and the results were compared with

(spinless) 3-body QED theoretical calculations

# 理論 - 非相対論的変分計算

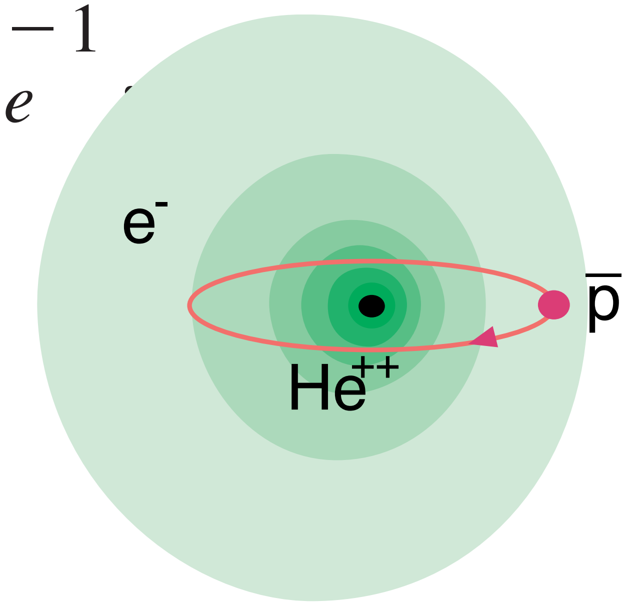
antiproton

electron

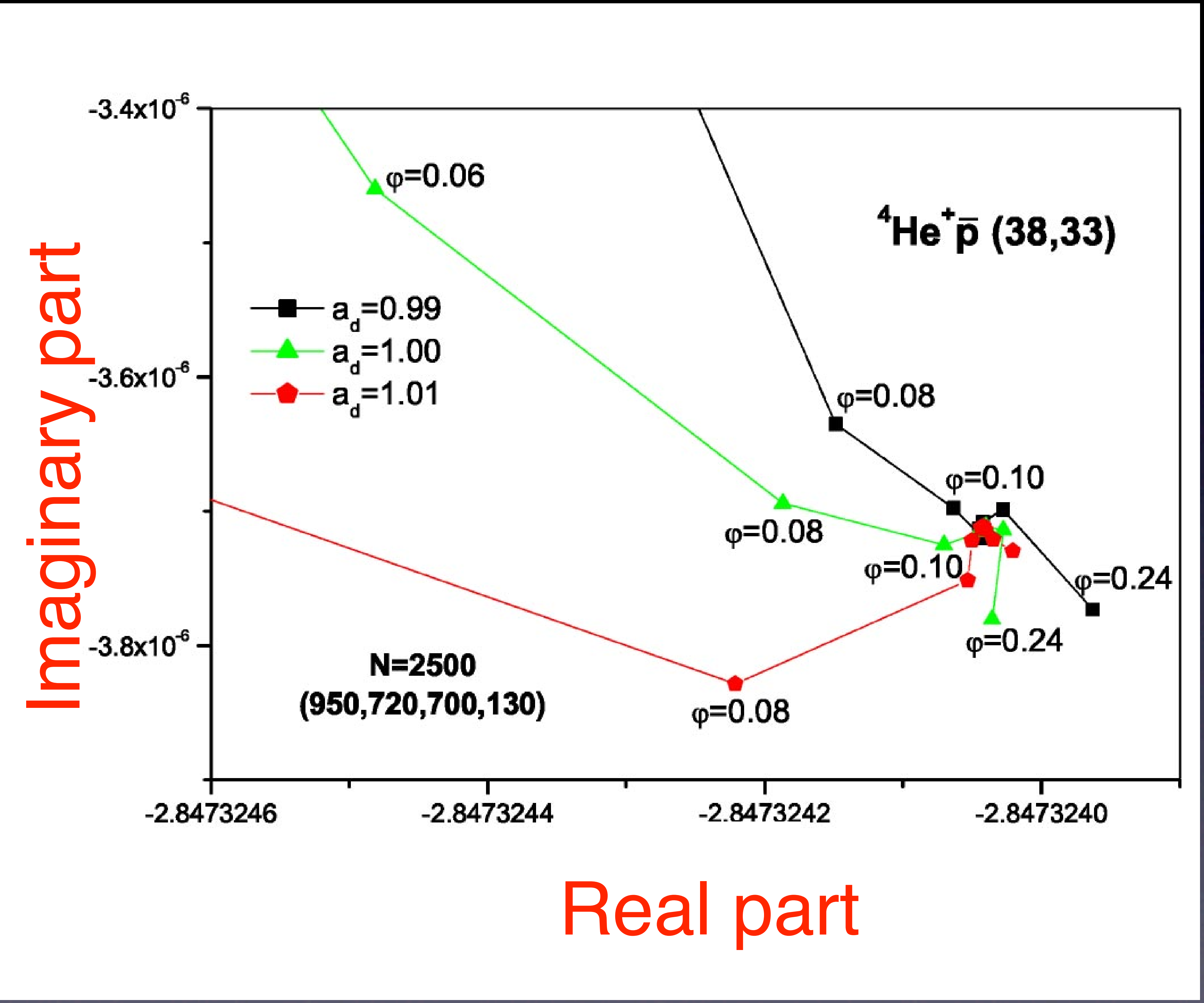
$$H = T + V$$

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

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



# Complex coordinate rotation (CCR) method




Not true bound states

Careful treatment of Auger decay is needed

CCR calculates complex eigen values

Korobov

# add relativistic correction (~100 ppm)

$$H = T + V$$

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

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

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

# 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

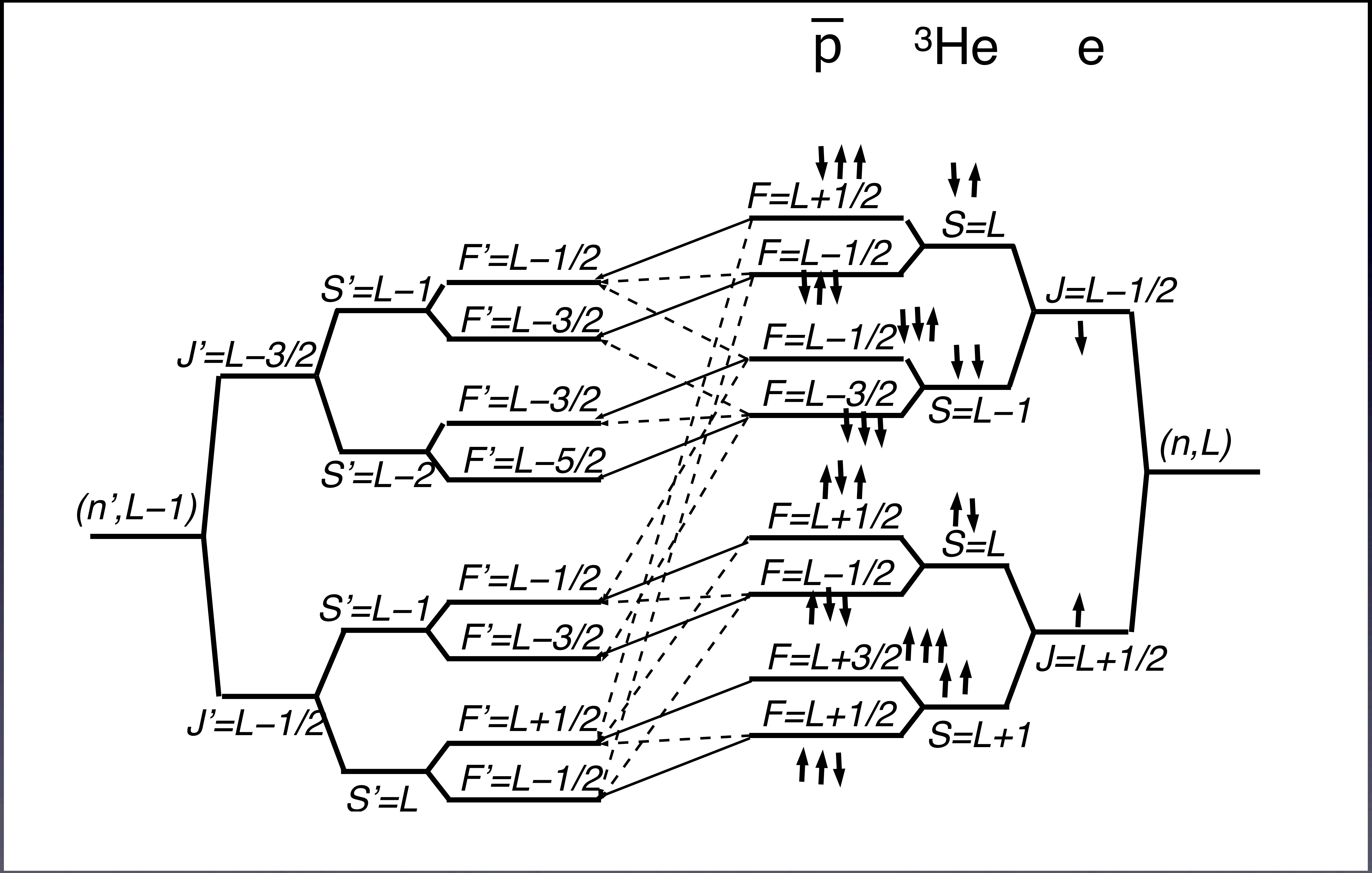
$$E_{se} = \frac{4\alpha^3}{3m_e^2}\left[\ln\frac{1}{\alpha^2} - \ln\frac{k_0}{R_\infty} + \frac{5}{6} - \frac{3}{8}\right]\langle Z_{\mathrm{He}}\delta(\mathbf{r}_{\mathrm{He}}) + Z_{\bar{p}}\delta(\mathbf{r}_{\bar{p}})\rangle$$
$$+ \frac{4\alpha^4}{3m_e^2}\left[3\pi\left(\frac{139}{128} - \frac{1}{2}\ln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

# 実験値と理論値の比較の例 (39,35) → (38,34) 遷移

| | | | |
|---|---|---|---|
| $E_{nr}$ | = | 501 972 347.9 | 非相対論三体計算 |
| $E_{rc}$ | = | −27 525.3 | 以下、相対論的量子電磁力学補正 |
| $E_{rc-qed}$ | = | 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 | $\Delta E_{\rm exch} = -\alpha^2\frac{z_i}{2m_im_3}\left\langle\frac{\boldsymbol{\nabla}_i\boldsymbol{\nabla}_3}{r_i}+\frac{\boldsymbol{r}_i(\boldsymbol{r}_i\boldsymbol{\nabla}_i)\boldsymbol{\nabla}_3}{r_i^3}\right\rangle,$ |
| $E_{\alpha^3-rec}$ | = | 0.8 | $\Delta E_{\rm recoil}^{(3)} = \frac{z_i\alpha^3}{m_im_3}\left\{\frac{2}{3}\left(-\ln\alpha-4\beta+\frac{31}{3}\right)\langle\delta(\boldsymbol{r}_i)\rangle-\frac{14}{3}\langle Q(r_i)\rangle\right\},$ |
| $E_{two-loop}$ | = | 0.9 | $\Delta E_{\text{two-loop}} = \alpha^4\frac{z_i}{m_3^2\pi}\left[-\frac{6131}{1296}-\frac{49\pi^2}{108}+2\pi^2\ln 2-3\zeta(3)\right]\langle\delta(\boldsymbol{r}_i)\rangle$ |
| $E_{nuc}$ | = | 2.4 | $\Delta E_{\rm nuc} = \frac{2\pi z_i(R_i/a_0)^2}{3}\langle\delta(\boldsymbol{r}_i)\rangle,$ |
| $E_{\alpha^4}$ | = | −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 | CODATA2002の陽子質量を仮定した 理論値(Korobov) |
| | | 501 948 752.0(4.0) MHz (誤差) | 実験値 |

全部で12の遷移を測定
CODATA 2006の
入力値を算出

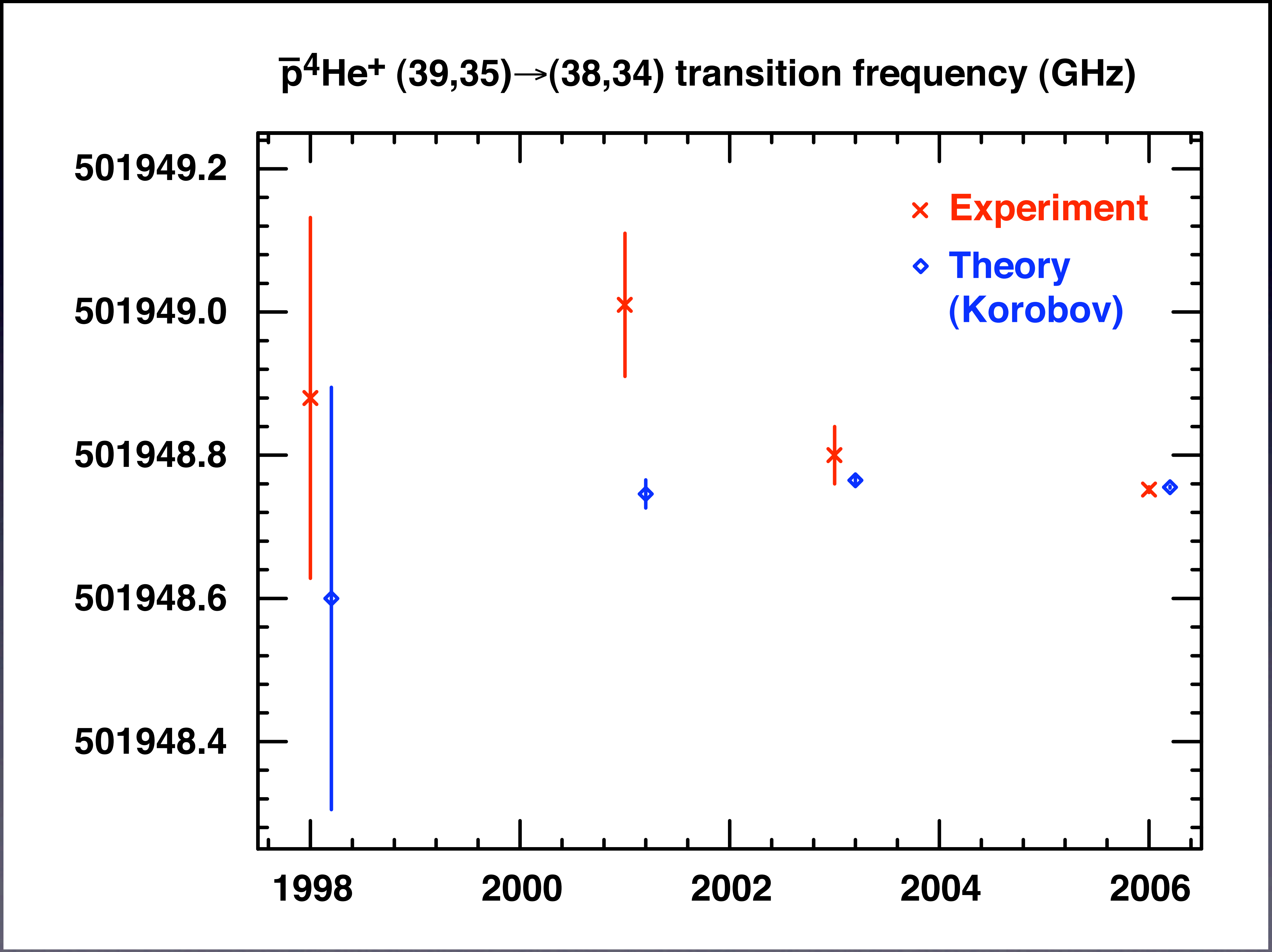
# $\overline{p}^3$He Hyperfine structure



# 結果

Results & Implications

# Experimental & theoretical precisions improved



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

$$\pm 0.000005$$

ASACUSA2006

PRL 96, 243401 (2006)

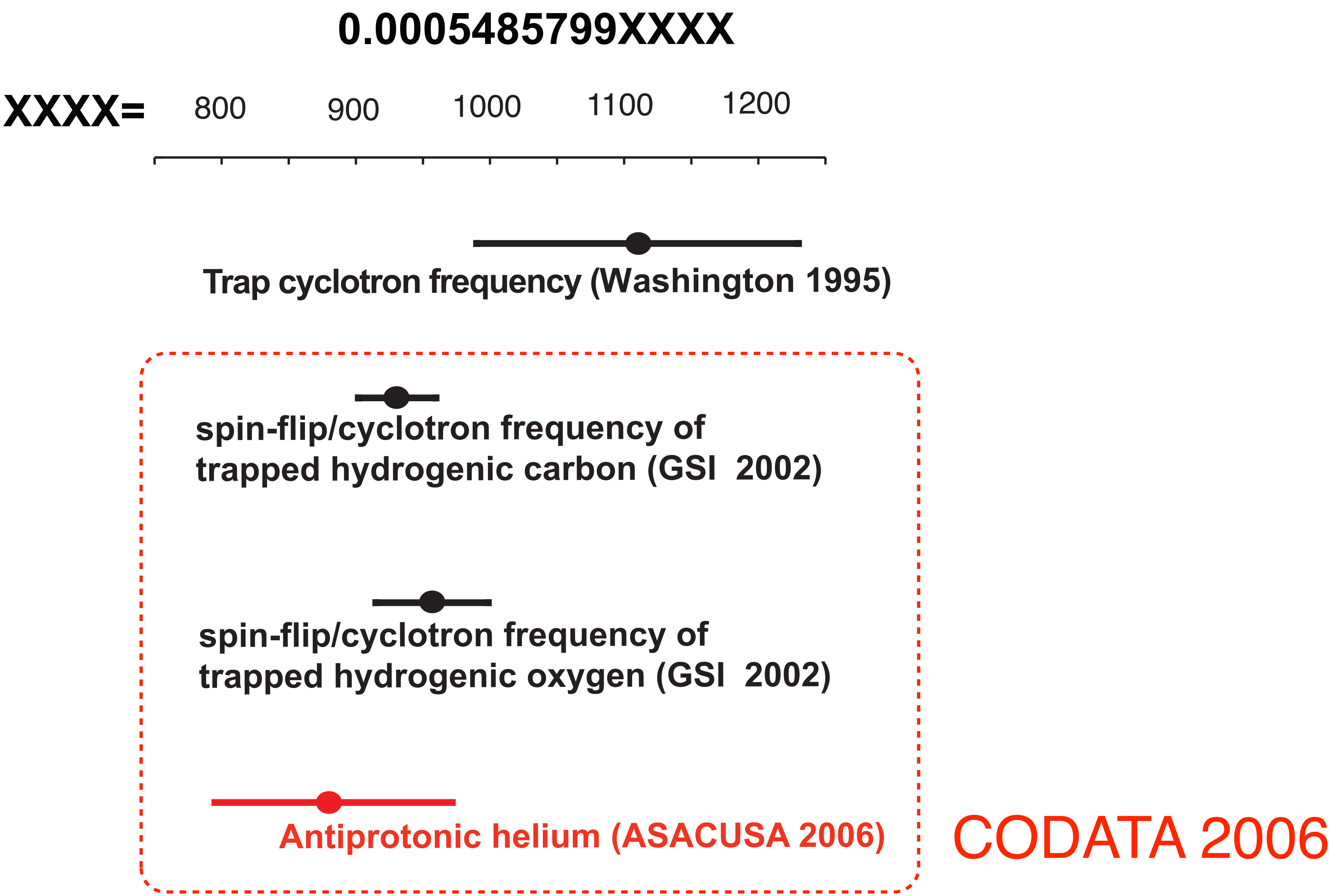
$$m_p/m_e = 1836.15267261$$

$$\pm 0.00000085$$

codata2002

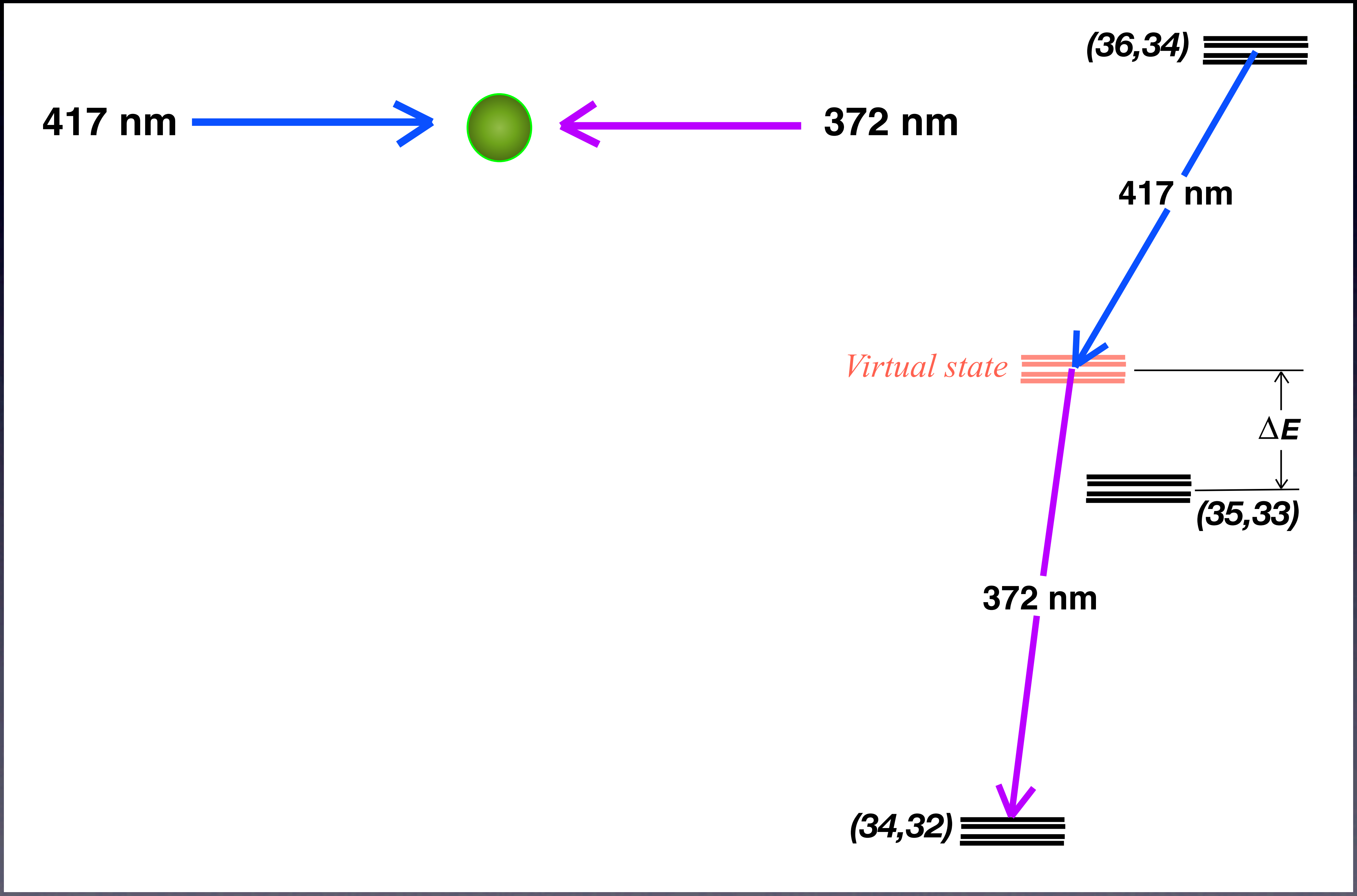
# $\bar{p}$He contribution to CODATA

## Electron mass in atomic mass unit A(e)

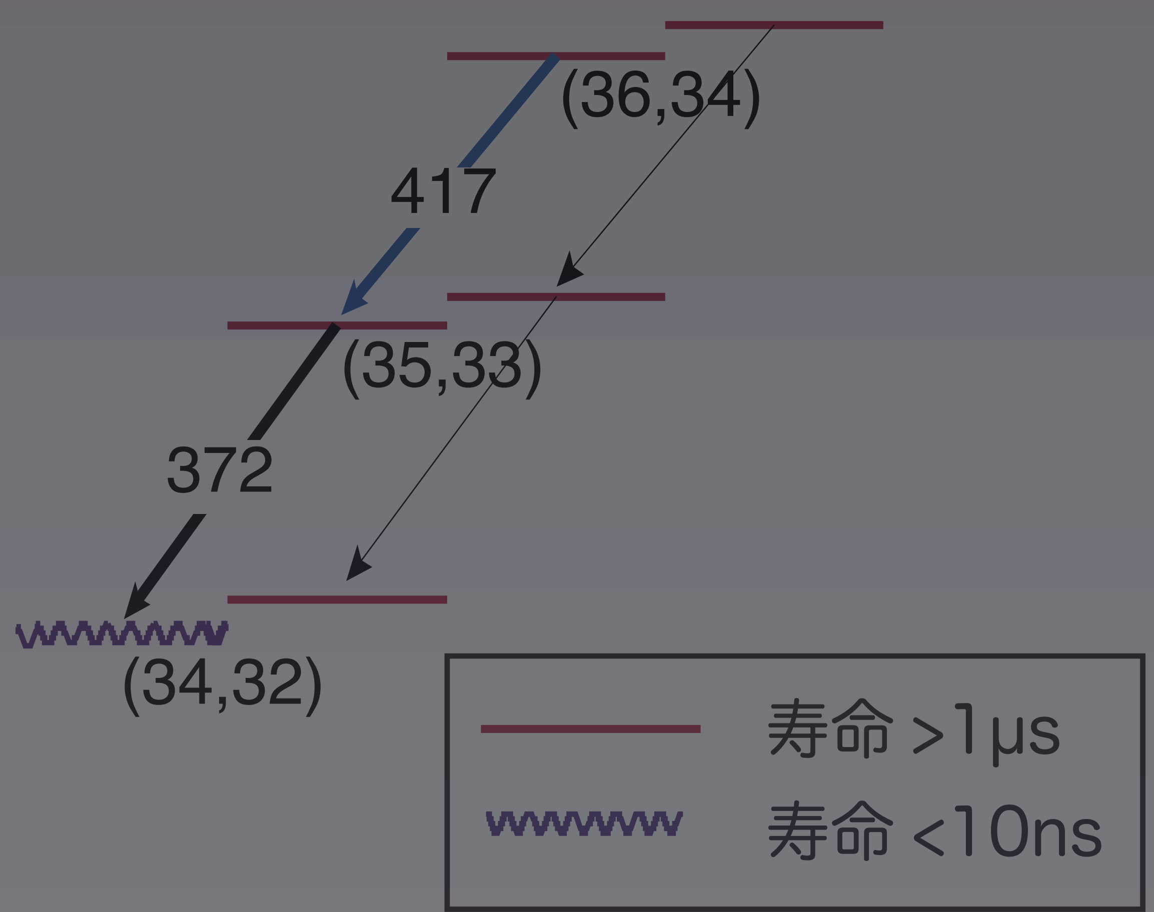


# まだまだやるぞ

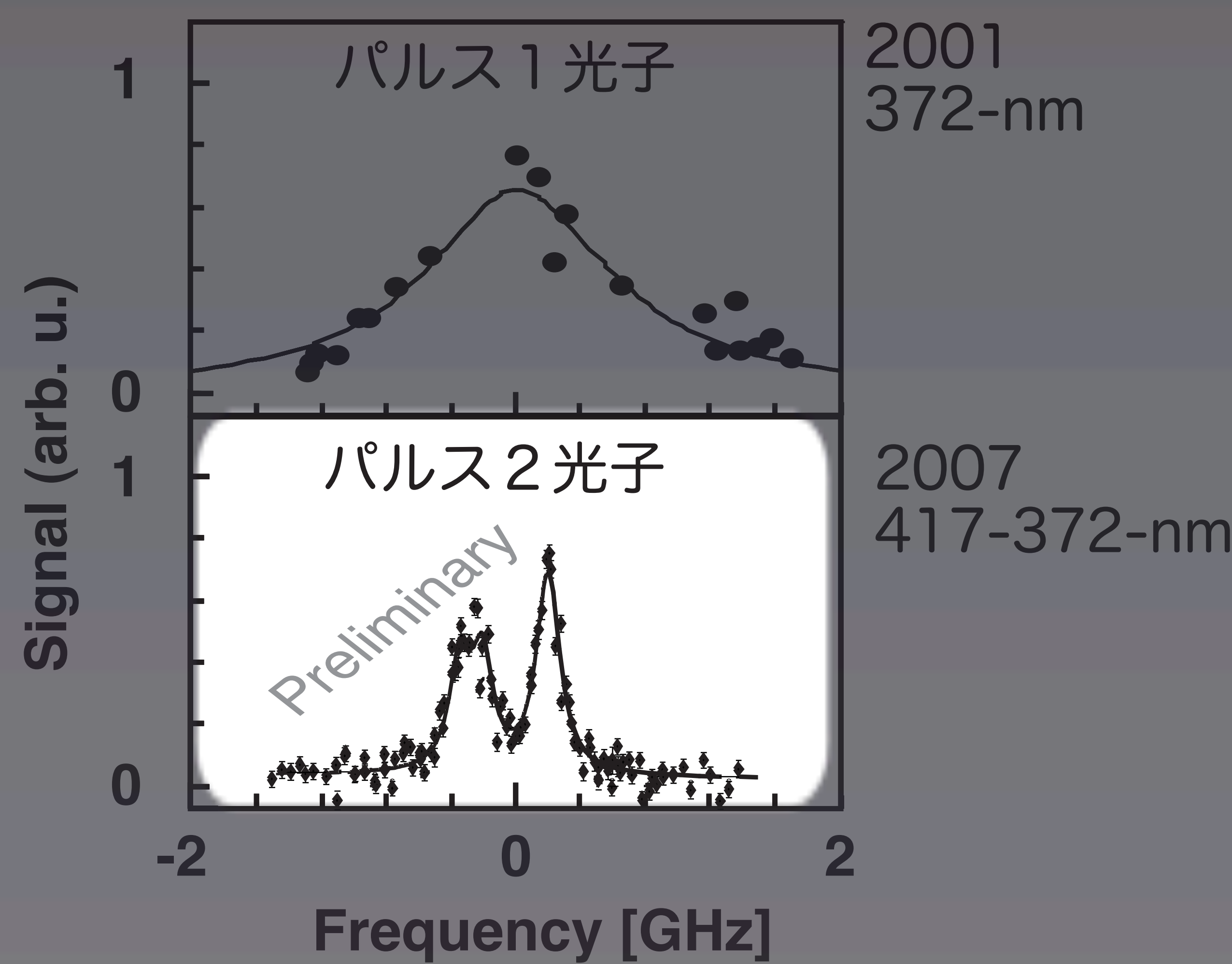
# 二光子分光でドップラー巾を消す



# 線幅大幅に減少

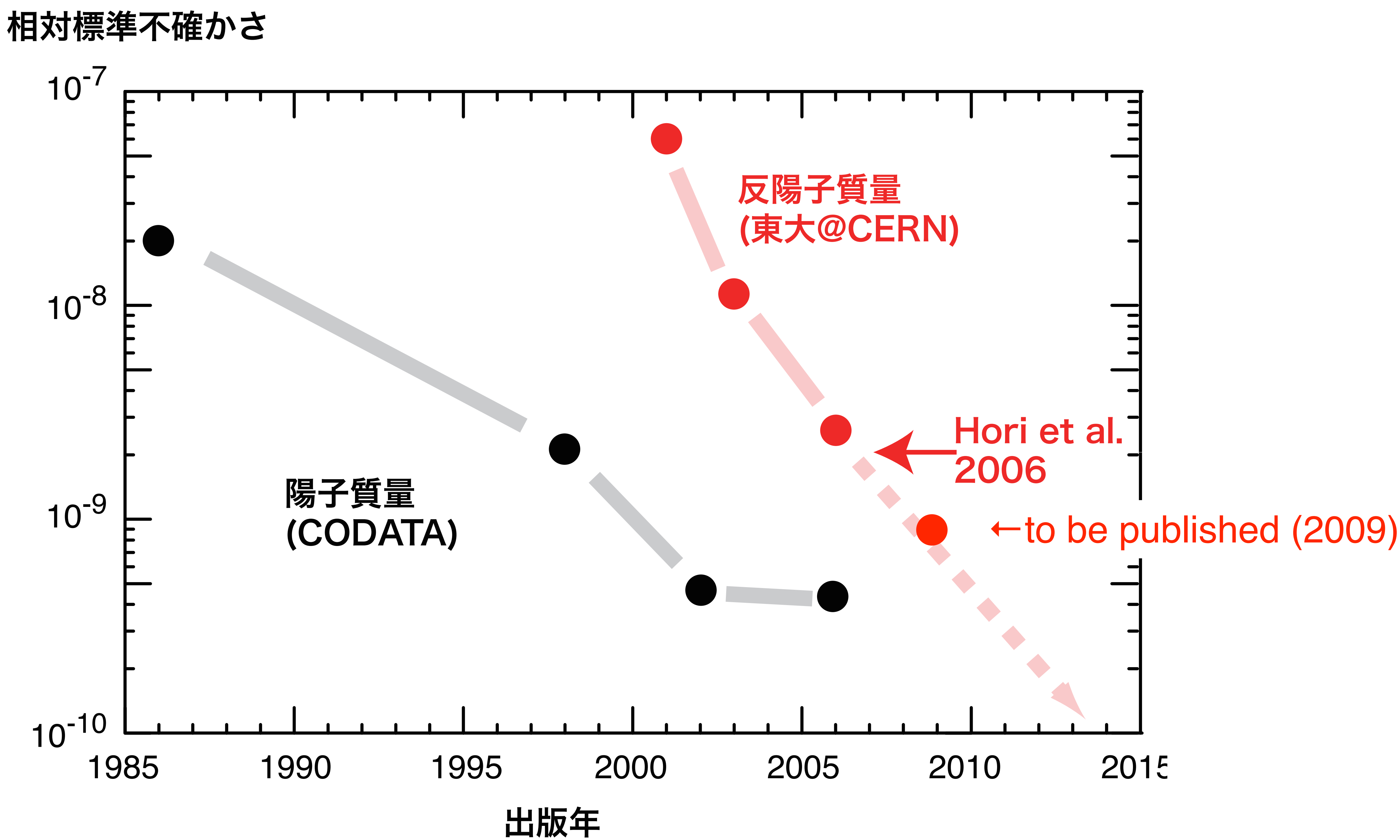


(36,34)
417
(35,33)
372
(34,32)
寿命 >1μs
寿命 <10ns

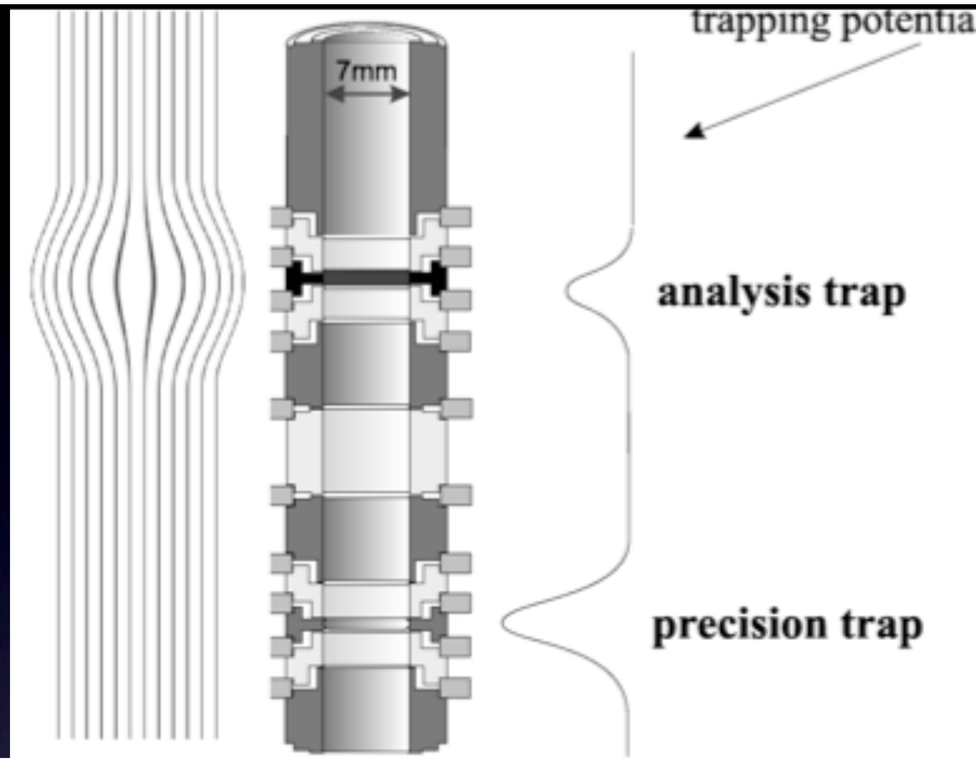



パルス１光子
2001
372-nm
パルス２光子
Preliminary
2007
417-372-nm
Signal (arb. u.)
1
0
1
0
-2
0
2
Frequency [GHz]

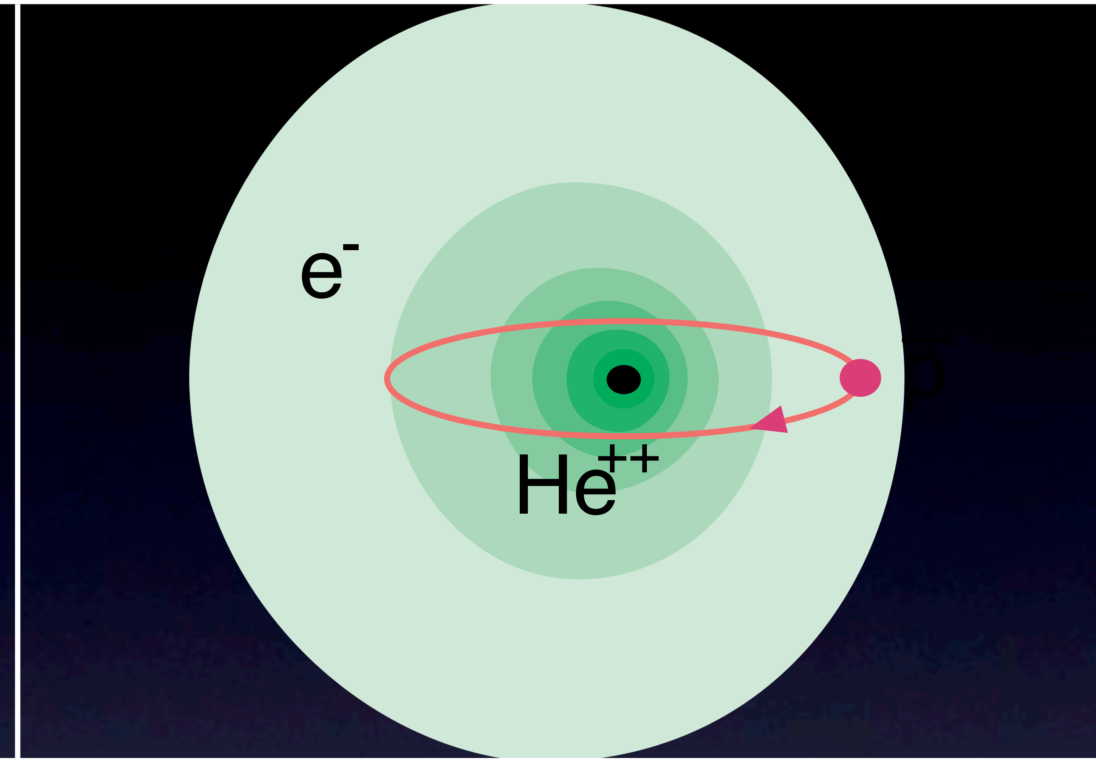
# 更に努力中



相対標準不確かさ
10-7
10-8
10-9
10-10
反陽子質量
(東大@CERN)
Hori et al.
2006
←to be published (2009)
陽子質量
(CODATA)
1985
1990
1995
2000
2005
2010
2015
出版年




Penning trap:
人工装置

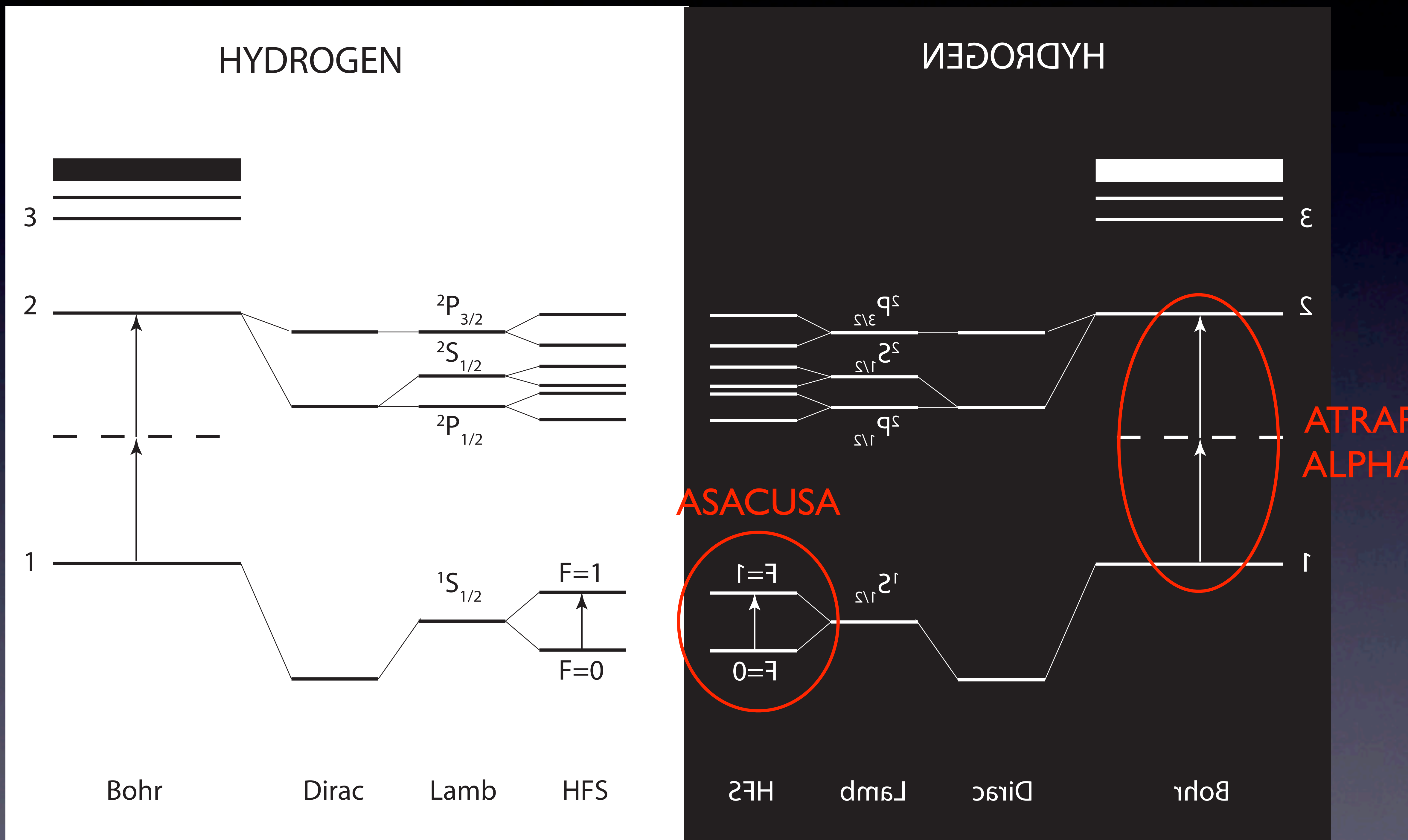



Antiprotonic helium:
量子系

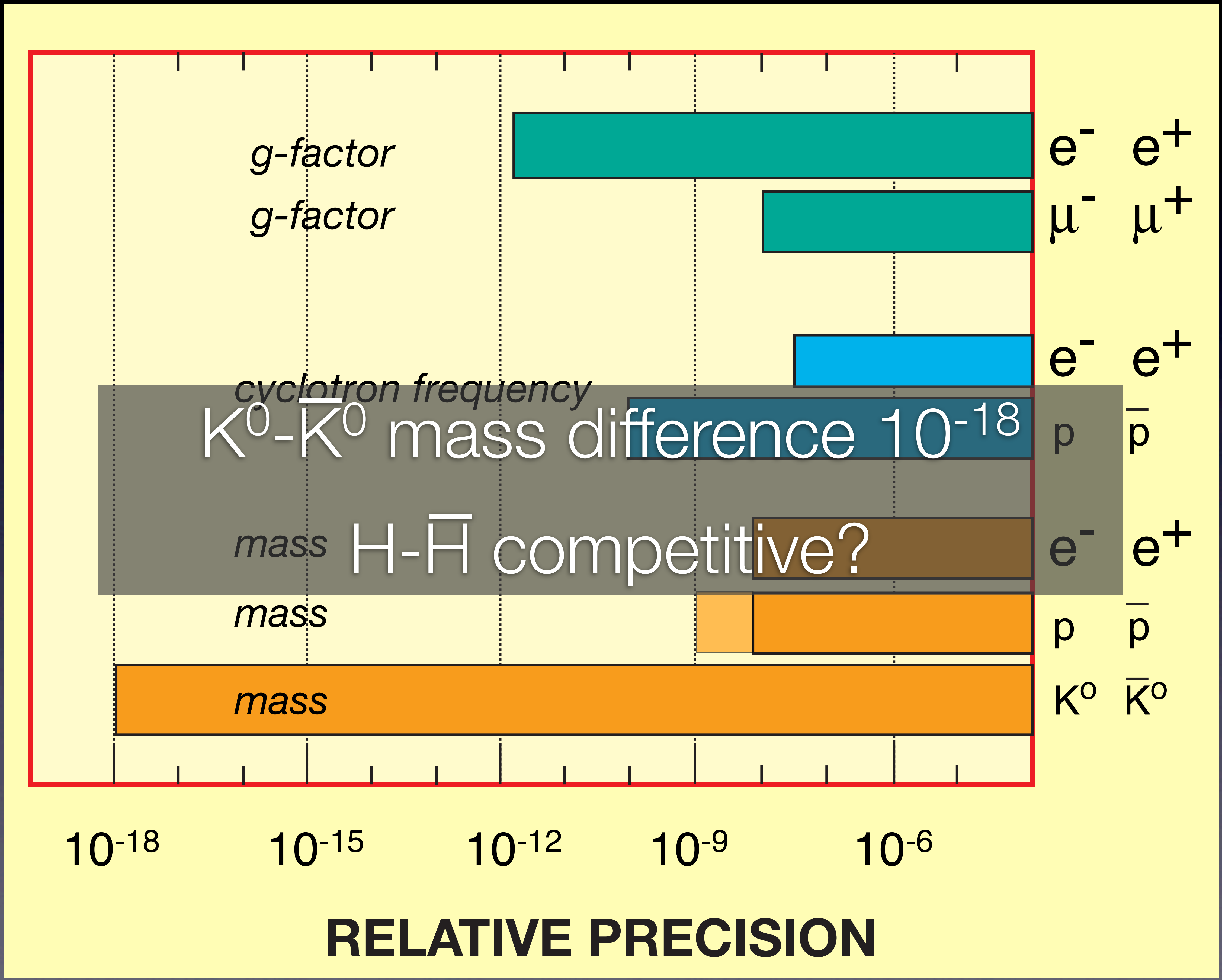
$m_p/m_e$を凌駕し
歴史に残る測定になる（と信じている）

# ②反水素

Antihydrogen


HYDROGEN
3
2
1
$^2P_{3/2}$
$^2S_{1/2}$
$^2P_{1/2}$
$^1S_{1/2}$
F=1
F=0
Bohr
Dirac
Lamb
HFS
ASACUSA
ATRAP
ALPHA

# CPT tests




$K^0$-$\bar{K}^0$ mass difference $10^{-18}$

H-$\bar{H}$ competitive?

# The Standard Model Extension

Indiana group, Kostelecký et al. (since 1997)

$$(i\gamma^\mu D_\mu - m - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu$$
$$-\frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^\mu D^\nu + id_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0$$

LIV and CPTV terms

extended Dirac eq.

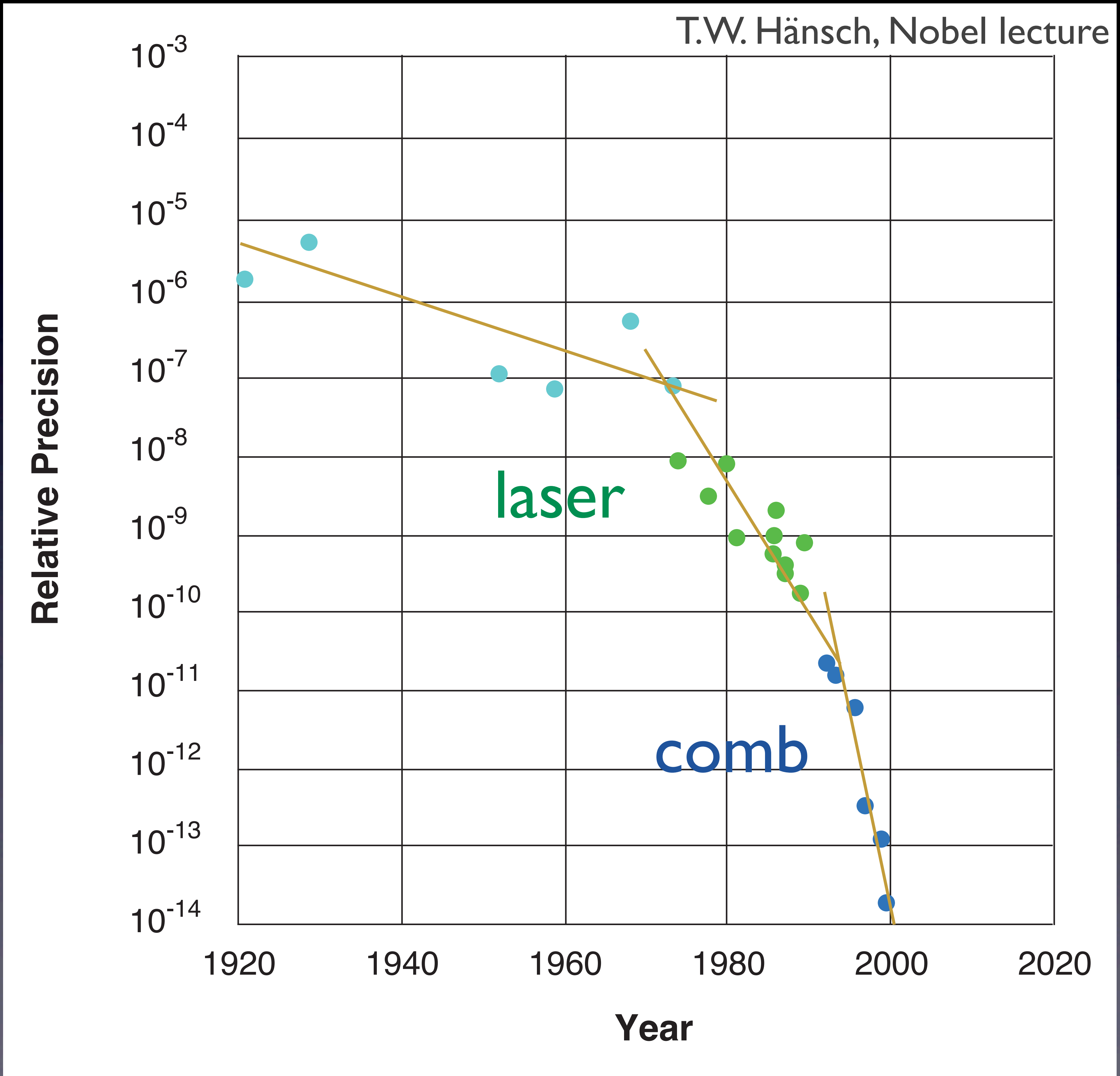
- The CPTV parameters (**a** & **b**) have energy dimensions (dimensionless comparison not meaningful)
- $\delta m/m \sim 10^{-18}$ of $K^0$ system ⇔ **$10^5$ Hz**;
- $\overline{H}$ spectroscopy better than $10^5$Hz precision competitive

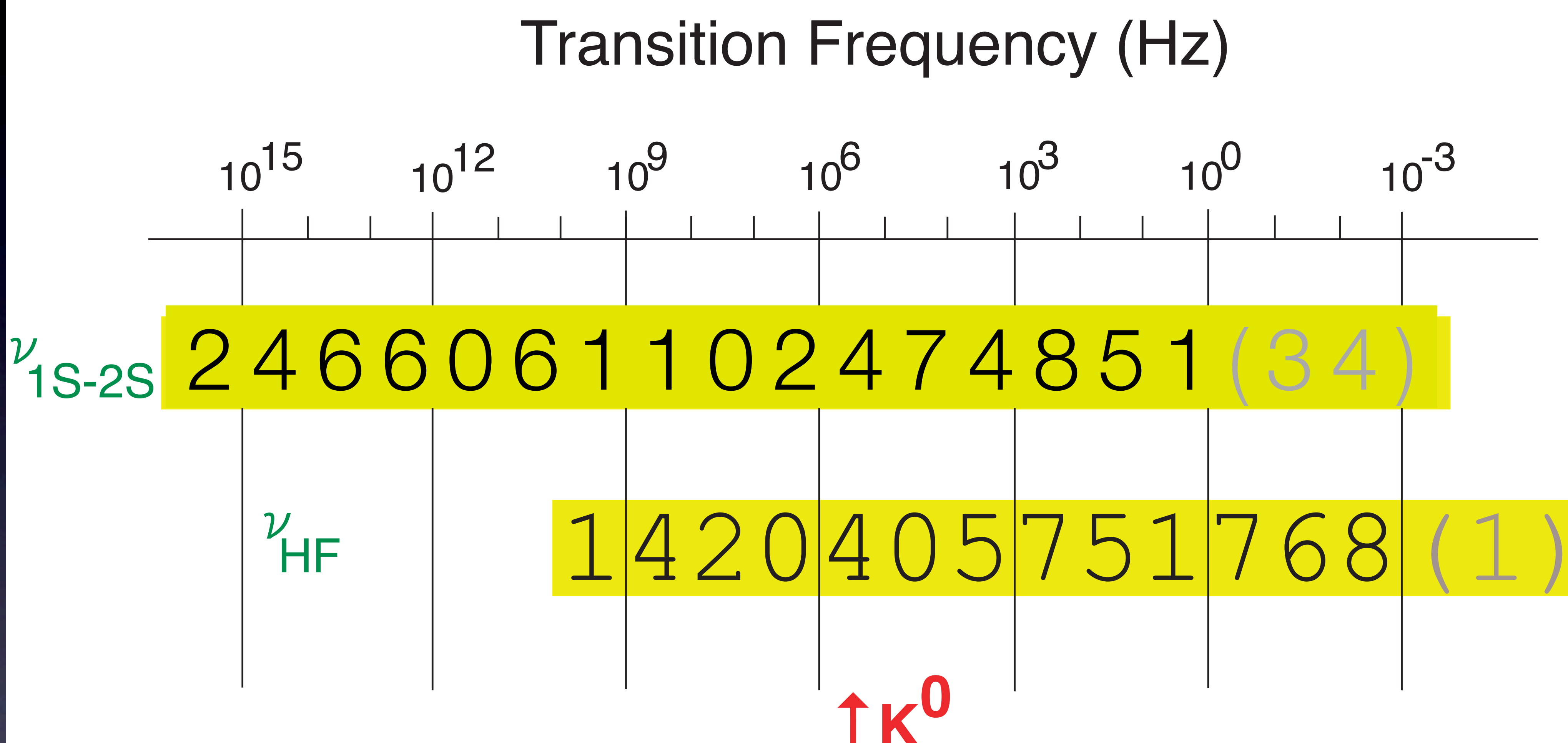
# Hänsch's Motto

never measure anything but hydrogen
水素しか測らない

never measure anything but frequency
周波数しか測らない

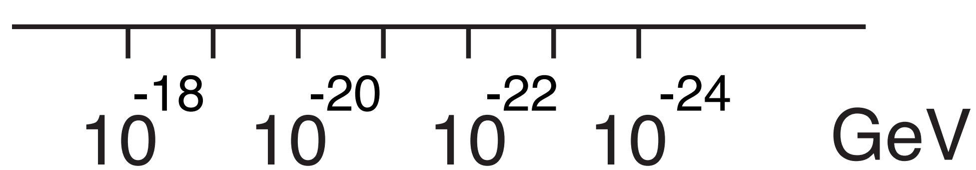
# 水素原子分光精度
# (Rydberg定数精度)の急激な向上






$\delta m/m \sim 10^{-18}$ of

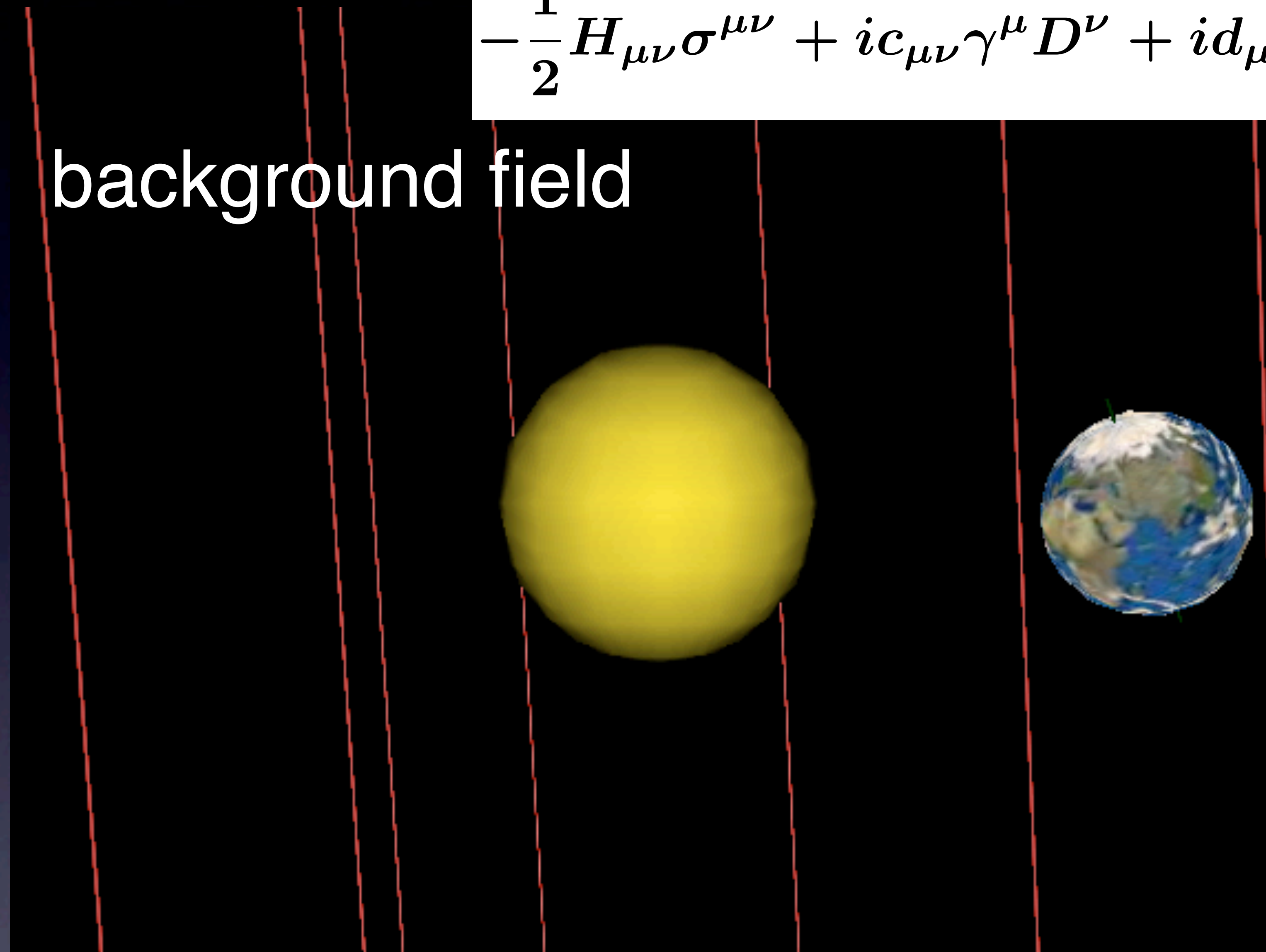
$K^0$ system ⇔ $10^5$ Hz




Approximate CPTV scale
"Planck-scale"

# Another possibility - sidereal variation

$$(i\gamma^{\mu}D_{\mu} - m - a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_5\gamma^{\mu}$$
$$-\frac{1}{2}H_{\mu\nu}\sigma^{\mu\nu} + ic_{\mu\nu}\gamma^{\mu}D^{\nu} + id_{\mu\nu}\gamma_5\gamma^{\mu}D^{\nu})\psi = 0$$




This can be tested using ordinary atoms

some CPTV parameters only accessible using $\overline{\mathrm{H}}$

Production of "cold" antihydrogen demonstrated in 2002

# Nature, September 18, 2002, ATHENA

advance online publication

letters to nature

## Production and detection of cold antihydrogen atoms

**M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe||, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst||, R. S. Hayano††, M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macrì*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#**

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*# Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK*
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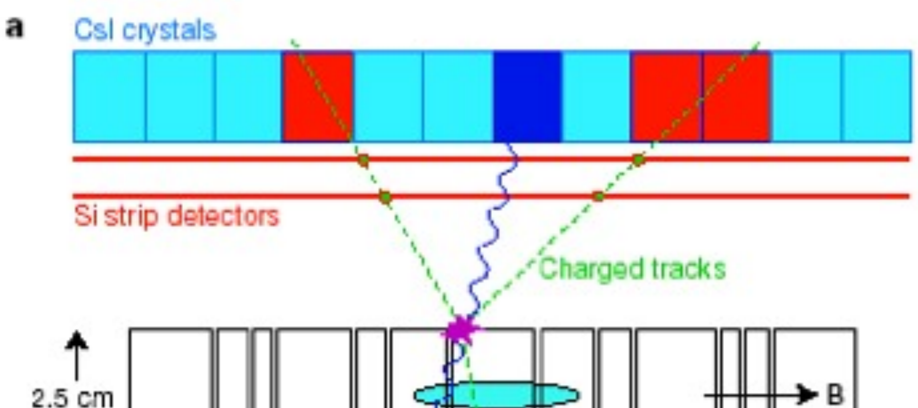
*†† Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*

**A theoretical underpinning of the standard model of fundamental particles and interactions is CPT invariance, which requires that the laws of physics be invariant under the combined discrete operations of charge conjugation, parity and time reversal. Antimatter, the existence of which was predicted by Dirac, can be used to test the CPT theorem—experimental investigations involving comparisons of particles with antiparticles are numer-**

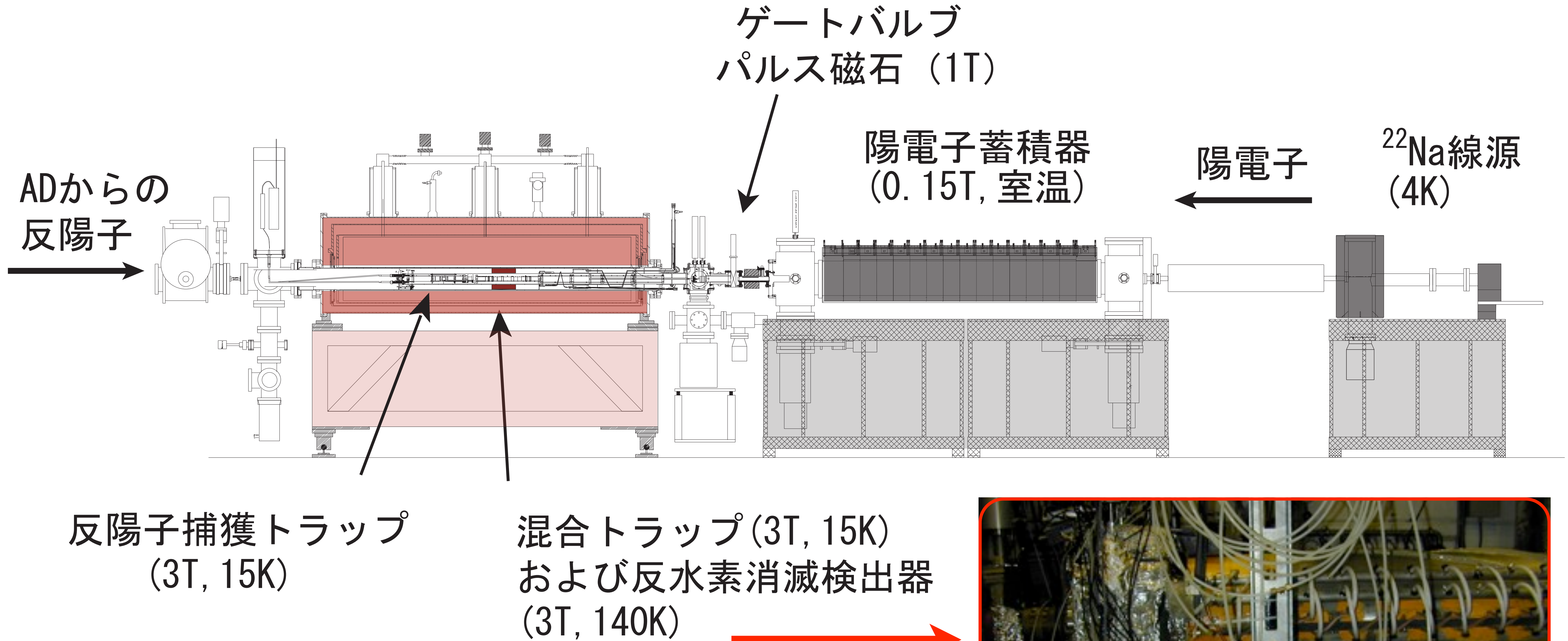
drogen annihilation detector. All traps in the experiment are variations on the Penning trap[6], which uses an axial magnetic field to transversely confine the charged particles, and a series of hollow cylindrical electrodes to trap them axially (Fig. 1a). The catching and mixing traps are adjacent to each other, and coaxial with a 3 T magnetic field from a superconducting solenoid. The positron accumulator has its own magnetic system, also a solenoid, of 0.14 T. A separate cryogenic heat exchanger in the bore of the superconducting magnet cools the catching and mixing traps to about 15 K. The ATHENA apparatus[7] features an open, modular design that allows great experimental flexibility, particularly in introducing large numbers of positrons into the apparatus—an essential factor in the current work.

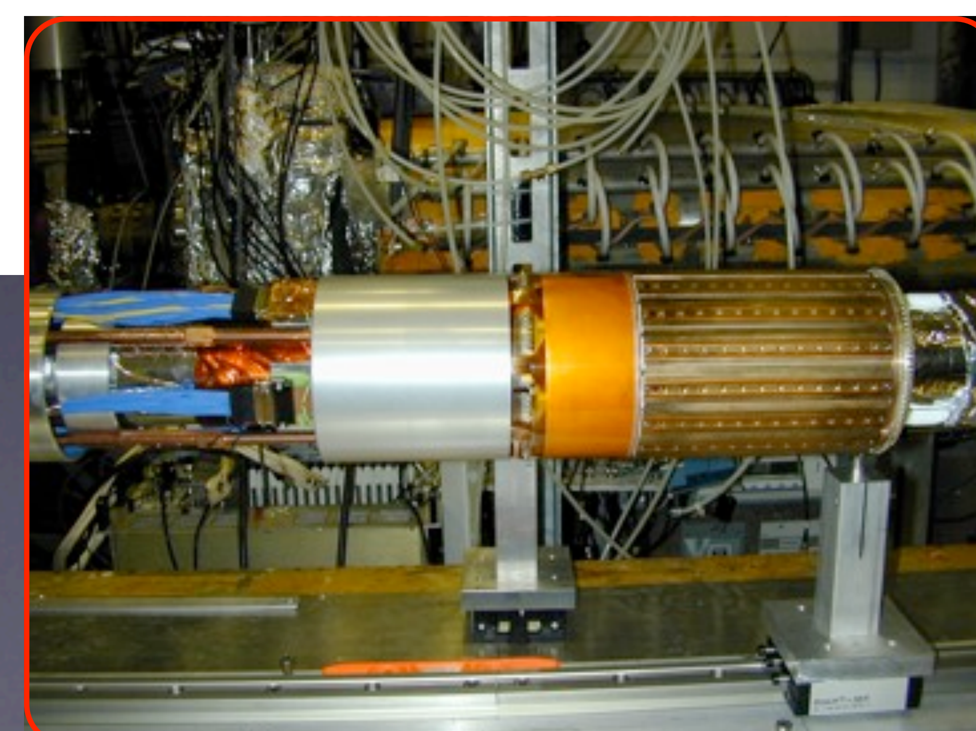
The catching trap[8] slows, traps, cools and accumulates antiprotons. To cool antiprotons, the catching trap is first loaded with $3 \times 10^8$ electrons, which cool by synchrotron radiation in the 3 T magnetic field. Typically, the AD delivers $2 \times 10^7$ antiprotons having kinetic energy 5.3 MeV and a pulse duration of 200 ns to the experiment at 100-s intervals. The antiprotons are slowed in a thin foil and trapped using a pulsed electric field. The antiprotons lose energy and equilibrate with the cold electrons by Coulomb interaction. The electrons are ejected before mixing the antiprotons with positrons. Each AD shot results in about $3 \times 10^3$ cold antiprotons for interaction experiments.

**a**



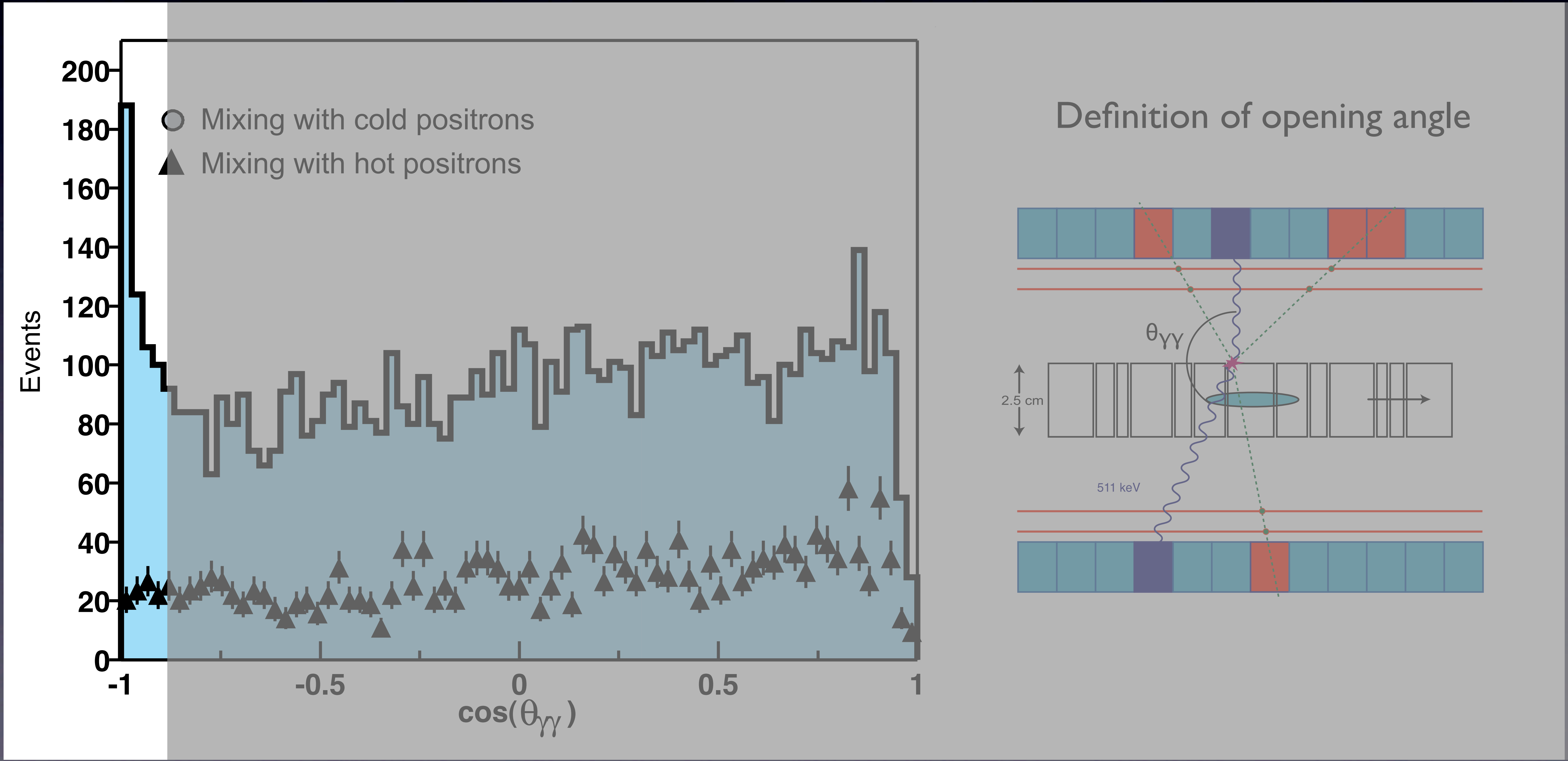
# 反水素生成装置


ゲートバルブ
パルス磁石（1T）
陽電子蓄積器
(0.15T,室温)
陽電子
$^{22}$Na線源
(4K)
ADからの
反陽子
反陽子捕獲トラップ
(3T,15K)
混合トラップ(3T,15K)
および反水素消滅検出器
(3T,140K)

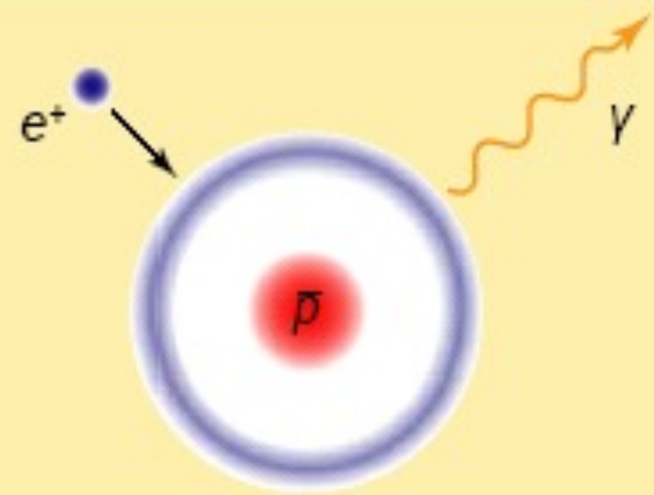
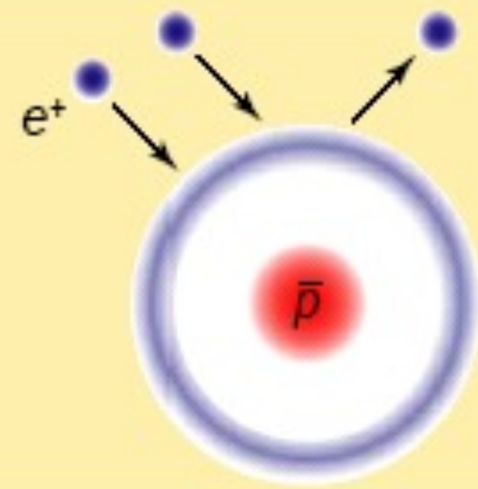


# Antihydrogen Signal

annihilation of $e^+$ and $\bar{p}$ on the wall,
simultaneously at the same point



# (Re)combination mechanisms

| | Two-Body Recombination | Three-Body Recombination |
|---|---|---|
| Principle |  |  |
| | $(e^+ + \overline{p} \rightarrow \overline{H} + \gamma)$ | $(e^+ + e^+ + \overline{p} \rightarrow \overline{H} + e^+)$ |
| $e^+$ density dependence | $\propto n_e$ | $\propto n_e{}^2$ |
| Final internal states | $n < 10$ | $n >> 10$ |
| Expected rates | few 10 Hz | high (at low T) |

[J. Stevefelt *et al.*, PRA **12** (1975) 1246] [M. E. Glinsky *et al.*, Phys. Fluids B **3** (1991) 1279]

Observed initial rate (ATHENA) 440 ±40 Hz
must be three body

It’s been 6.5 years since

the first cold $\bar{H}$ production

what’s new?

| | | |
|---|---|---|
| Rate | mix $10^8$ $e^+$ & $10^4$ $\bar{p}$,<br>$\bar{H}$ rate ~100 Hz | |
| Ground state? | No proof<br>ATRAP detected $\bar{H}$s with n~60 | |
| Cold? | both ATRAP & ATHENA found $T_{\bar{H}} \gg 500$ K | |
| Trapped? | not yet | ATRAP → ATRAP II<br>ATHENA → ALPHA |
| other than<br>1s-2s? | ASACUSA : $\bar{H}$ beam → HFS<br>AEGIS : free fall | |

lots of progress, but
many more hurdles to be cleared

# 結論

summary

## Antiprotonic Helium

the only $\bar{p}$-containing atom studied by the laser spectroscopy methods

started to contribute to the fundamental physical constants

the $\bar{p}$ mass may become better known than the $p$ mass

## Antihydrogen

future hopeful, but still many problems

abundantly produced, but not cold enough, not in the ground state

if CPT is violated at the level of $10^{-20-25}$ GeV, we will (eventually) see this