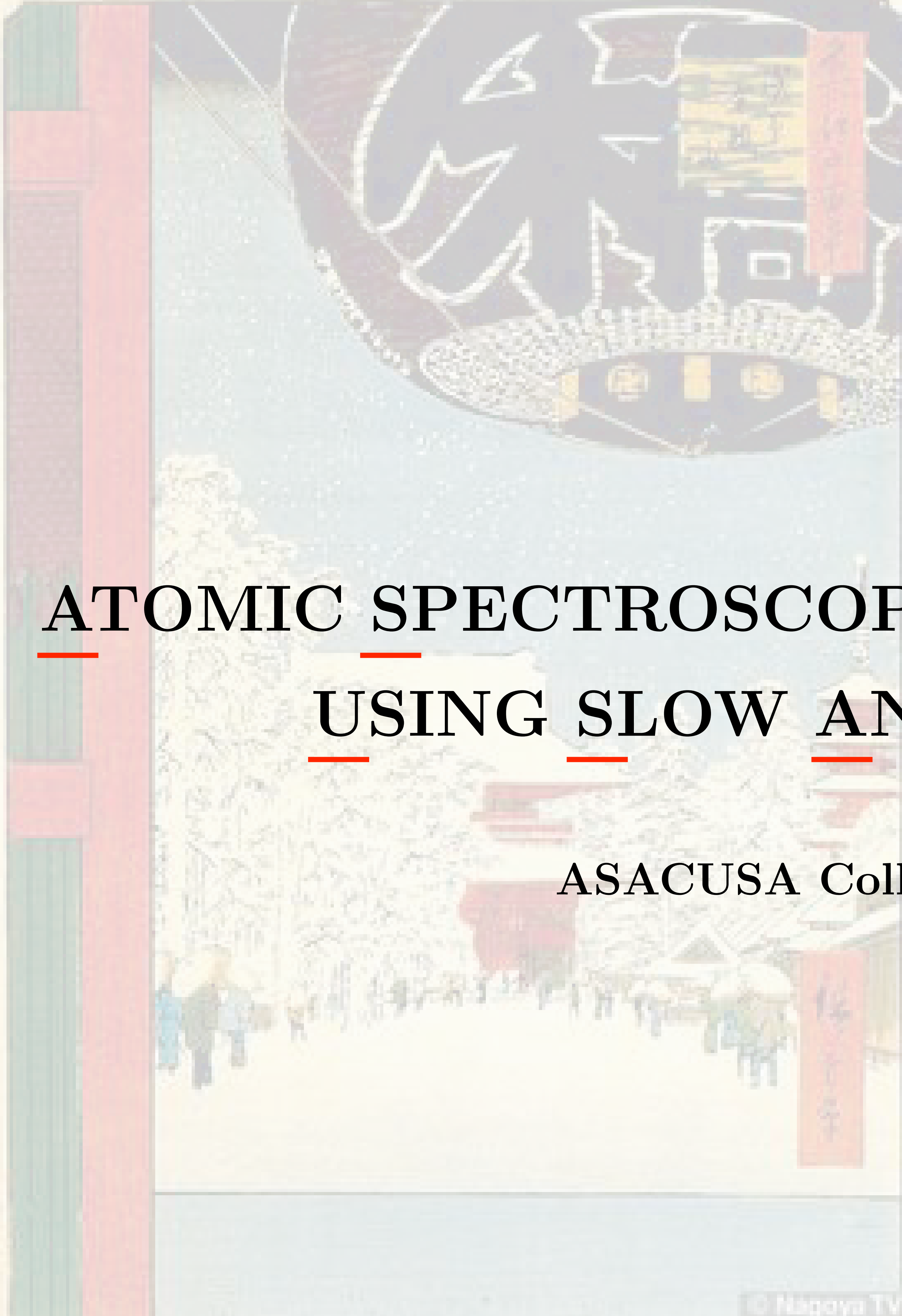
ASACUSA Overview

Ryugo S. Hayano (UTokyo)

ASACUSA Spokesperson

LEAP 2013: June 11, 2013

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



ATOMIC SPECTROSCOPY AND COLLISIONS USING SLOW ANTIPROTONS

ASACUSA Collaboration

100 keV $\bar{p}$s (RFQD)
100 eV $\bar{p}$s ("MUSASHI" trap)

ASACUSA

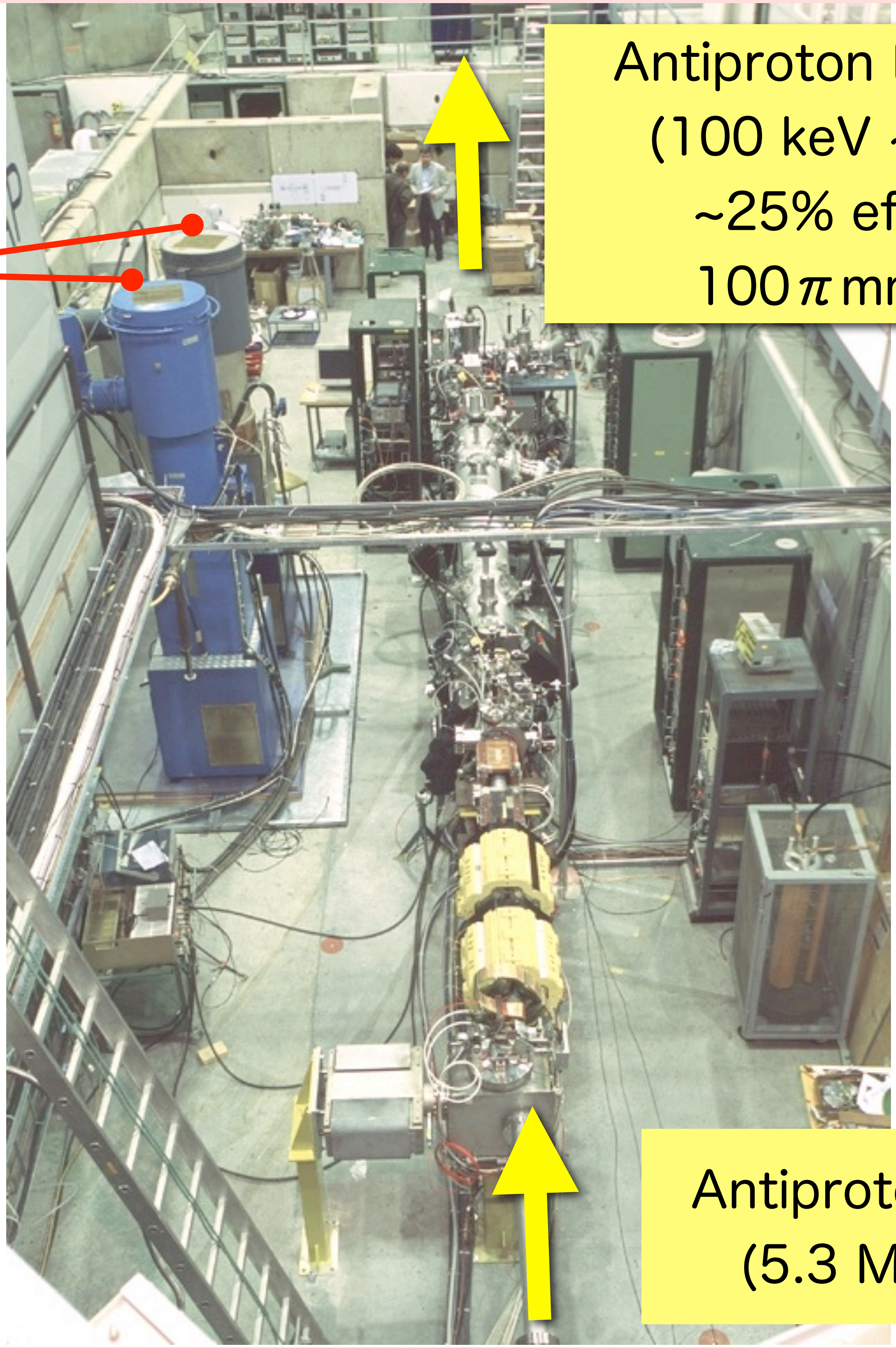
Atomic Spectroscopy And Collisions Using Slow Antiprotons

Aghai Khozani, H.[1], Barna, D.[2,6], Caradonna, P.[3], Corradini, M.[4], Dax, A.[2], Diermaier, M.[3], Federmann, S.[3], Friedreich, S.[3], Hayano, RS.[2], Higaki, H.[5], Hori, M.[1], Horvath, D.[6], Kanai, Y.[5], Knudsen, H.[7], Kobayashi, T.[2], Kuroda, N.[5], Leali, M.[4], Lodi-Rizzini, E.[4], Malbrunot, C.[3], Mascagna, V.[4], Massiczek, O.[3], Matsuda, Y.[5], Michishio, K.[5], Mizutani, T.[5], Murakami, Y.[2], Murtagh, D.[5], Nagahama, H.[5], Nagata, Y.[5], Otsuka, M.[5], Sauerzopf, C.[3], Soter, A.[1], Suzuki, K.[3], Tajima, M.[5], Todoroki, K.[2], Torii, H.[5], Uggerhoj, U.[7], Ulmer, S.[5], Van Gorp, S.[5], Venturelli, L.[4], Widmann, E.[3], Wunscheck, B.[3], Yamada, H.[2], Yamazaki, Y.[5], Zmeskal, J.[3], Zurlo, N.[4]

1. Max-Planck-Institut für Quantenoptik (DE), 2. The University of Tokyo (JP), 3. Stefan Meyer Institute (AT), 4. Universita' di Brescia, and INFN, Gruppo Collegato di Brescia, (IT), 5. RIKEN, and The University of Tokyo, Komaba (JP), 6. KFKI (HU), 7. University of Aarhus (DK)

RFQD - inverse linac

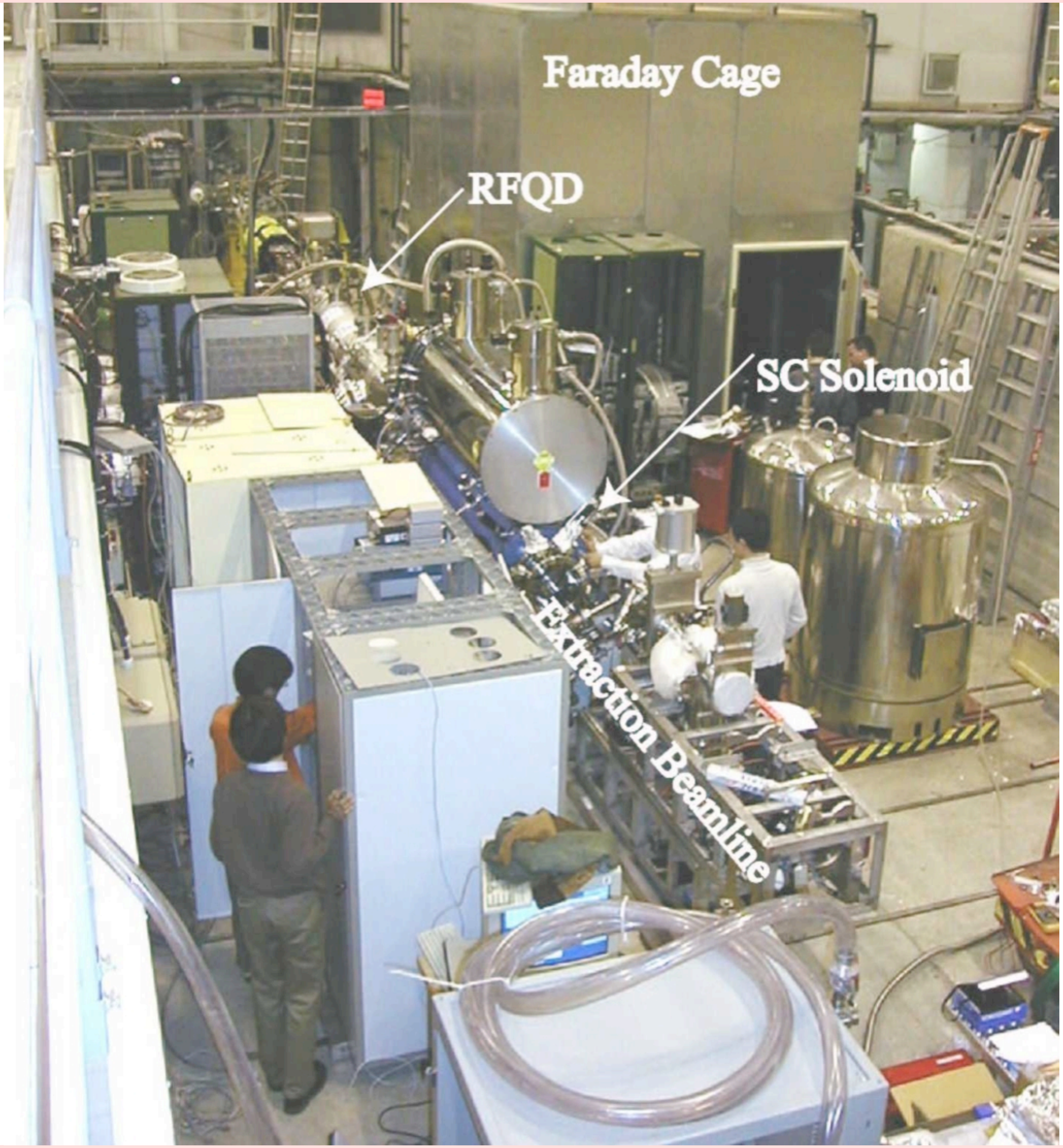
2 x 1 MW
200 MHz
amplifiers



Antiproton Decelerator
(100 keV ~ 1% of c,
~25% efficiency,
100 π mm·mrad)

Antiproton pulse from AD
(5.3 MeV ~ 10% of c)

Cooling and extraction



$\bar{p}He$ & $\bar{H}$ spectroscopy
→CPT, fundamental const.

ASACUSA

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Aghai Khozani, H.[1], Barna, D.[2,6], Caradonna, P.[3], Corradini, M.[4], Dax, A.[2], Diermaier, M.[3], Federmann, S.[3], Friedreich, S.[3], Hayano, RS.[2], Higaki, H.[5], Hori, M.[1], Horvath, D.[6], Kanai, Y.[5], Knudsen, H.[7], Kobayashi, T.[2], Kuroda, N.[5], Leali, M.[4], Lodi-Rizzini, E.[4], Malbrunot, C.[3], Mascagna, V.[4], Massiczek, O.[3], Matsuda, Y.[5], Michishio, K.[5], Mizutani, T.[5], Murakami, Y.[2], Murtagh, D.[5], Nagahama, H.[5], Nagata, Y.[5], Otsuka, M.[5], Sauerzopf, C.[3], Soter, A.[1], Suzuki, K.[3], Tajima, M.[5], Todoroki, K.[2], Torii, H.[5], Uggerhoj, U.[7], Ulmer, S.[5], Van Gorp, S.[5], Venturelli, L.[4], Widmann, E.[3], Wunscheck, B.[3], Yamada, H.[2], Yamazaki, Y.[5], Zmeskal, J.[3], Zurlo, N.[4]

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Related talks

N. Zurlo,	Tue	10:05	$\sigma(\bar{p}A)$
D. Barna,	Tue	11:25	$\bar{p}He$ expt.
V. Korobov,	Tue	12:00	$\bar{p}He$ theory
C. Malbrunot,	Thu	09:35	$\bar{H}$
N. Kuroda,	Thu	10:00	$\bar{H}$

Continuation of the original ASACUSA programme	Spectroscopy (CPT & fundamental constant)	Antiprotonic helium atoms	antiproton mass << 10^{-9} magnetic moment < 10^{-3}
	Collision	atomic collision cross section	Use ultra-slow antiprotons extracted from the trap
Extending ASACUSA programme approved 2005	Spectroscopy (CPT)	Antihydrogen ground-state hyperfine splitting	Sensitivity to CPTV higher than the K^0 system
	Collision	antiproton-nucleus cross section	Extend the LEAR measurements to much lower energies

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Continuation of the original ASACUSA programme	Spectroscopy (CPT & fundamental constant)	Antiprotonic helium atoms & ions ①	antiproton mass << 10^{-9} magnetic moment < 10^{-3}
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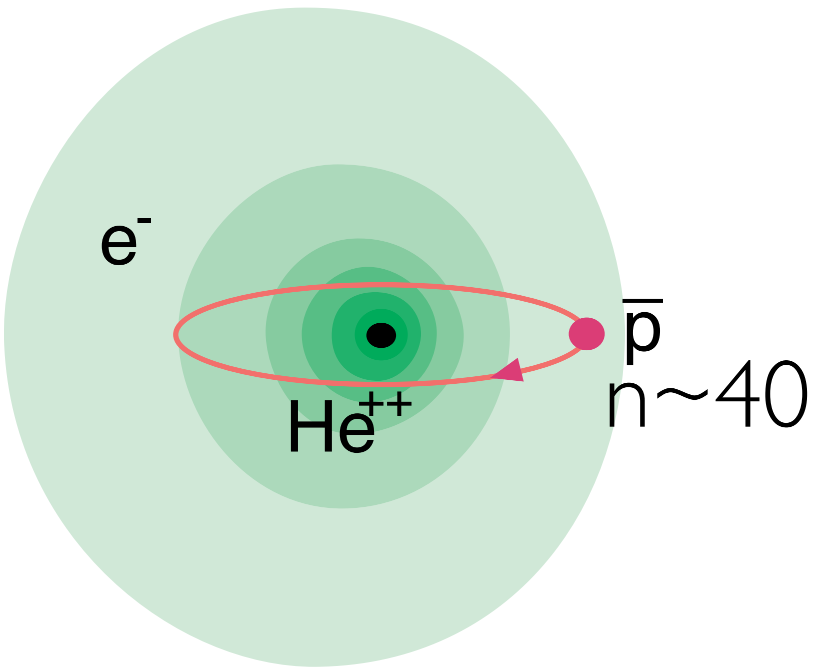
1. $\bar{p}$He laser spectroscopy

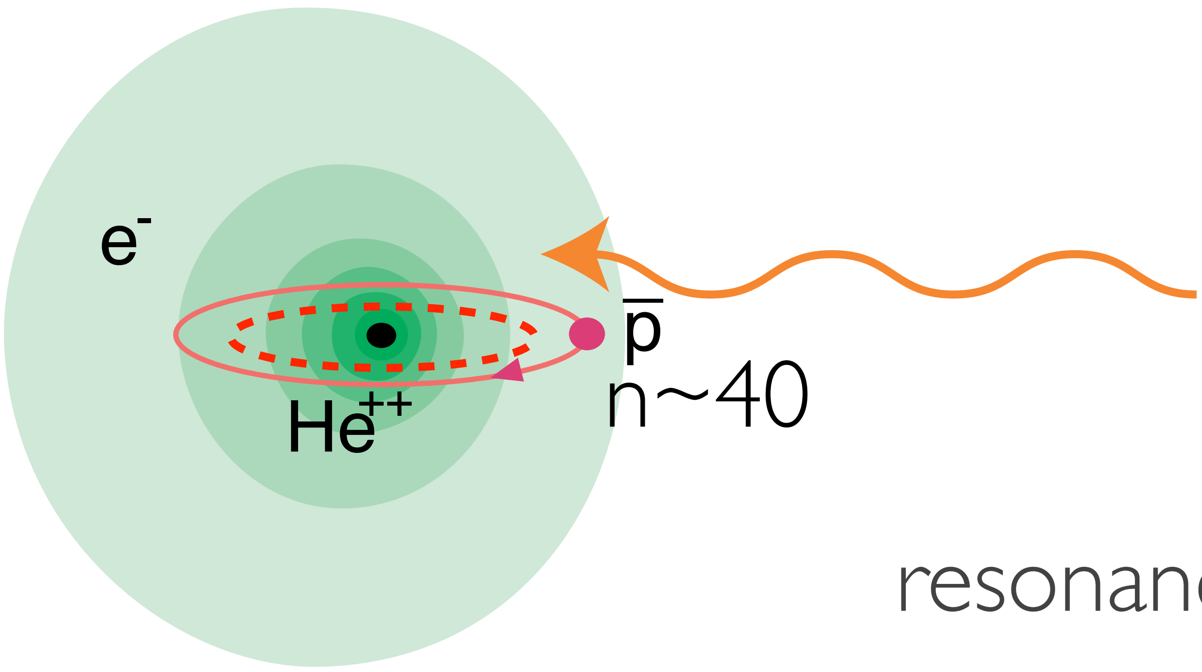
CPT & fundamental const.

More by Barna & Korobov

$\bar{p}$He laser spectroscopy contributes to m_p/m_e



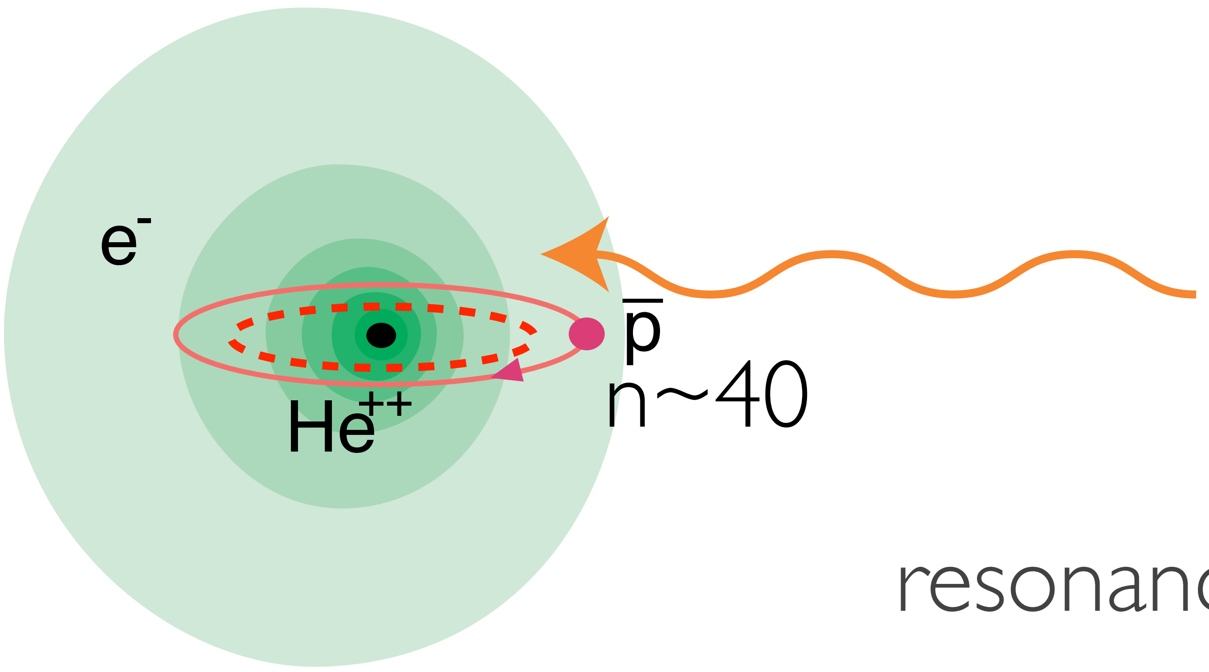
$\bar{p}$He laser spectroscopy contributes to m_p/m_e



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

resonance detection via $\bar{p}$ annihilation

$\bar{p}$He laser spectroscopy contributes to m_p/m_e



resonance detection via $\bar{p}$ annihilation

Frequency

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

$\bar{p}$ (p) - e mass ratio

Theory

Korobov

REVIEWS OF MODERN PHYSICS, VOLUME 84, OCTOBER–DECEMBER 2012

CODATA recommended values of the fundamental physical constants: 2010*

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

National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8420, USA

(published 13 November 2012)

This paper gives the 2010 self-consistent set of values of the basic constants and conversion factors of physics and chemistry recommended by the Committee on Data for Science and Technology (CODATA) for international use. The 2010 adjustment takes into account the data considered in the 2006 adjustment as well as the data that became available from 1 January 2007, after the closing date of that adjustment, until 31 December 2010, the closing date of the new adjustment. Further, it describes in detail the adjustment of the values of the constants, including the selection of the final set of input data based on the results of least-squares analyses. The 2010 set replaces the previously recommended 2006 CODATA set and may also be found on the World Wide Web at physics.nist.gov/constants.

DOI: 10.1103/RevModPhys.84.1527 PACS numbers: 06.20.Jr, 12.20.−m

IV. ATOMIC TRANSITION FREQUENCIES

Measurements and theory of transition frequencies in hydrogen, deuterium, antiprotonic helium, and muonic hydrogen provide information on the Rydberg constant, the proton and deuteron charge radii, and the relative atomic mass of the electron.

This ↓ contributed to CODATA

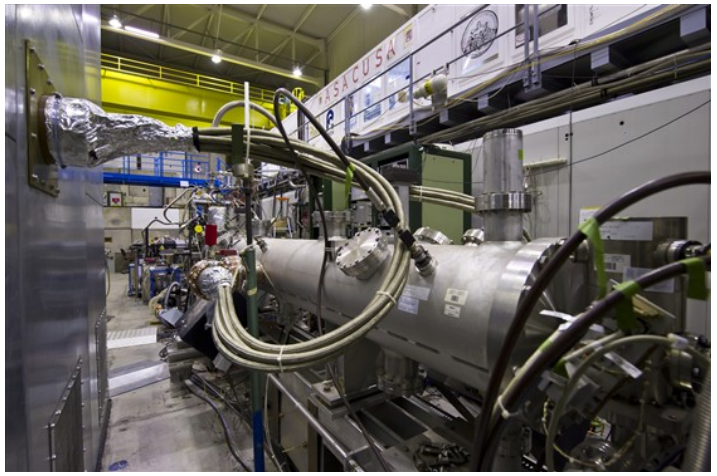
CERN Press Release

M. Hori et al., Nature 475, 484 (2011).

CERN experiment weighs antimatter with unprecedented accuracy

PR10.11
28.07.2011

Geneva, 28 July 2011. In a paper published today in the journal Nature, the Japanese-European ASACUSA experiment at CERN[1] reported a new measurement of the antiproton's mass accurate to about one part in a billion. Precision measurements of the antiproton mass provide an important way to investigate nature's apparent preference for matter over antimatter.



The ASACUSA experiment.
More photos: 1 - 2.

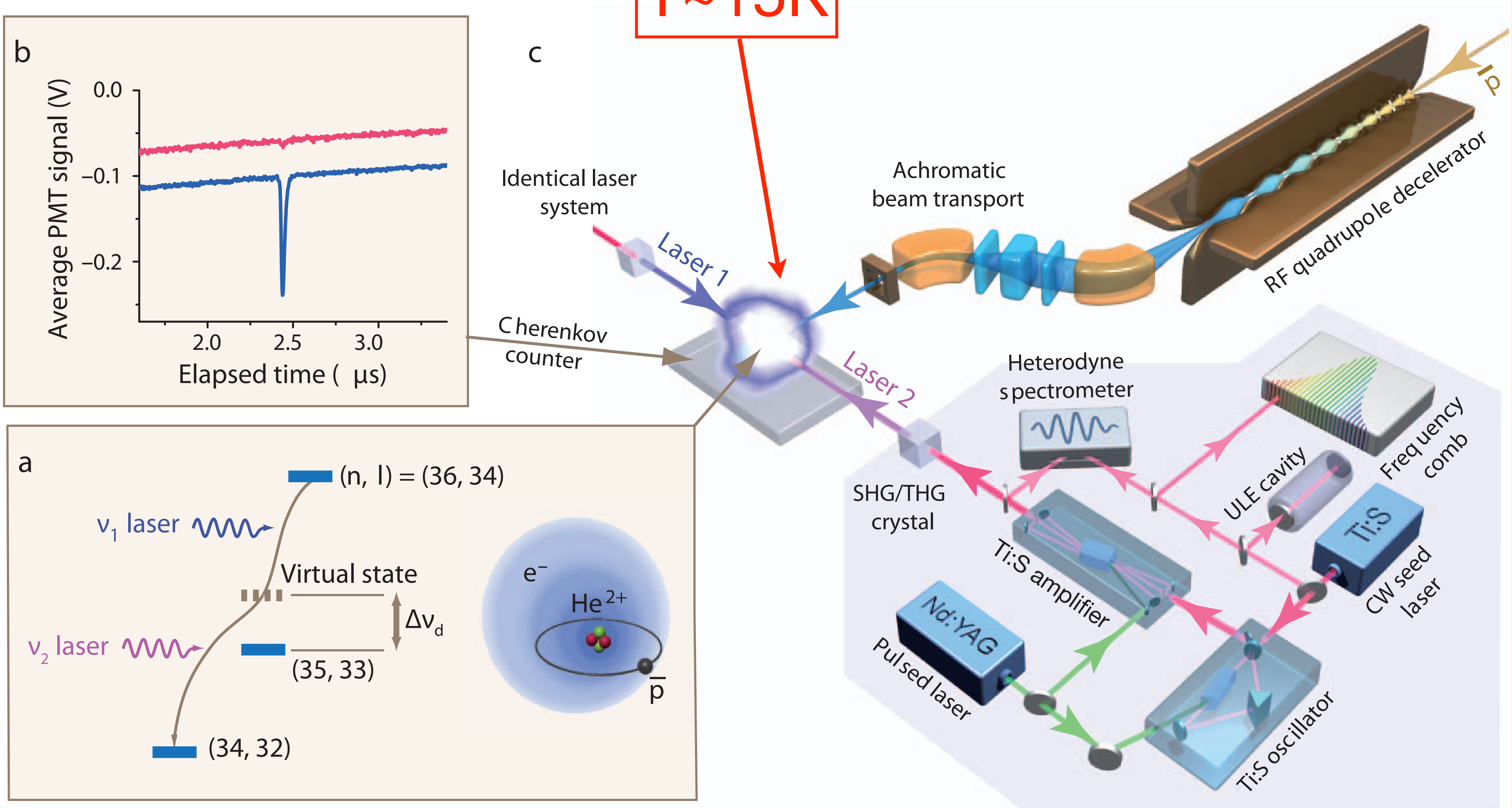
"This is a very satisfying result," said Masaki Hori, a project leader in the ASACUSA collaboration. "It means that our measurement of the antiproton's mass relative to the electron is now almost as accurate as that of the proton."

Ordinary protons constitute about half of the world around us, ourselves included. With so many protons around it would be natural to assume that the proton mass should be measurable to greater accuracy than that of antiprotons. After today's result, this remains true but only just. In future experiments, ASACUSA expects to improve the accuracy of the antiproton mass measurement to far better than that for the proton. Any difference between the mass of protons and antiprotons would be a signal for new physics, indicating that the laws of nature could be different for matter and antimatter.

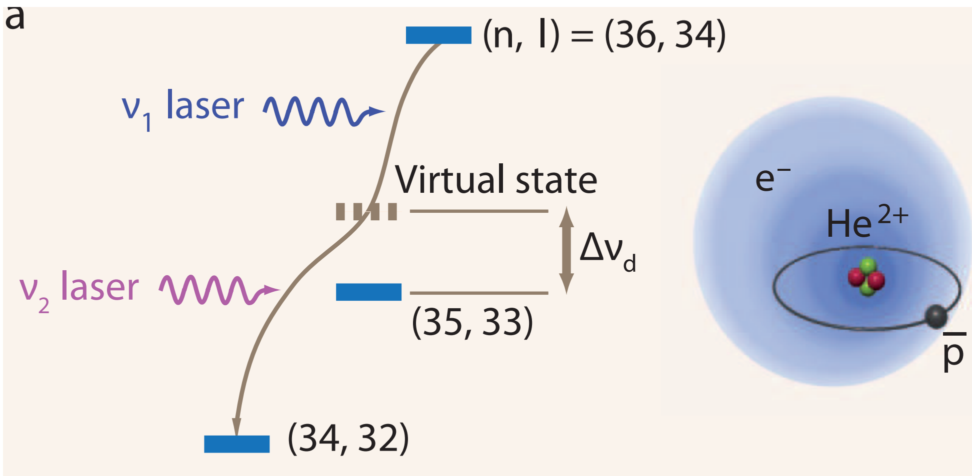
To make these measurements antiprotons are first trapped inside helium atoms, where they can be 'tickled' with a laser beam. The laser frequency is then tuned until it causes the antiprotons to make a quantum jump within the atoms, and from this frequency the antiproton mass can be calculated. However, an important

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

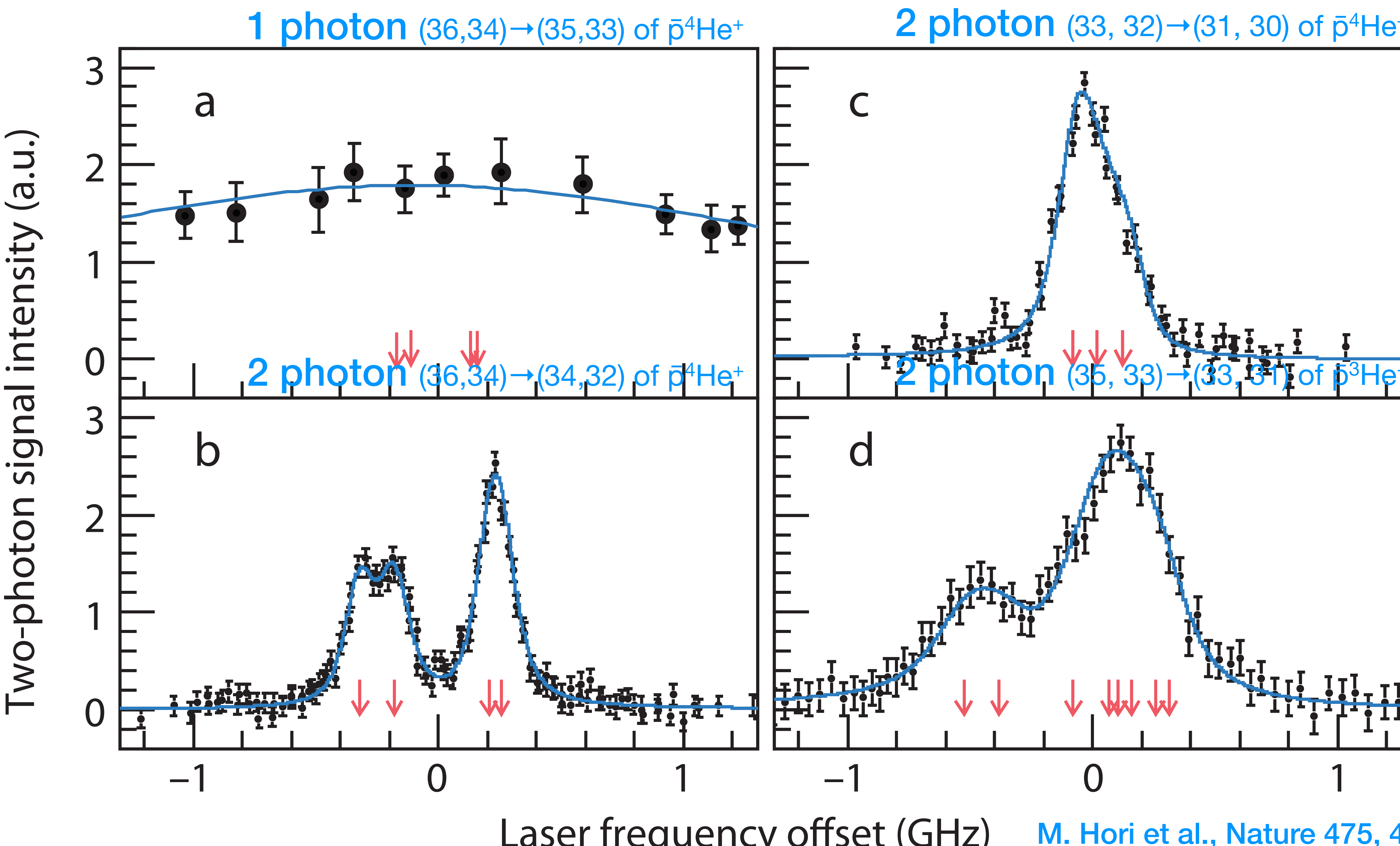
T~15K



M. Hori et al., Nature 475, 484 (2011).

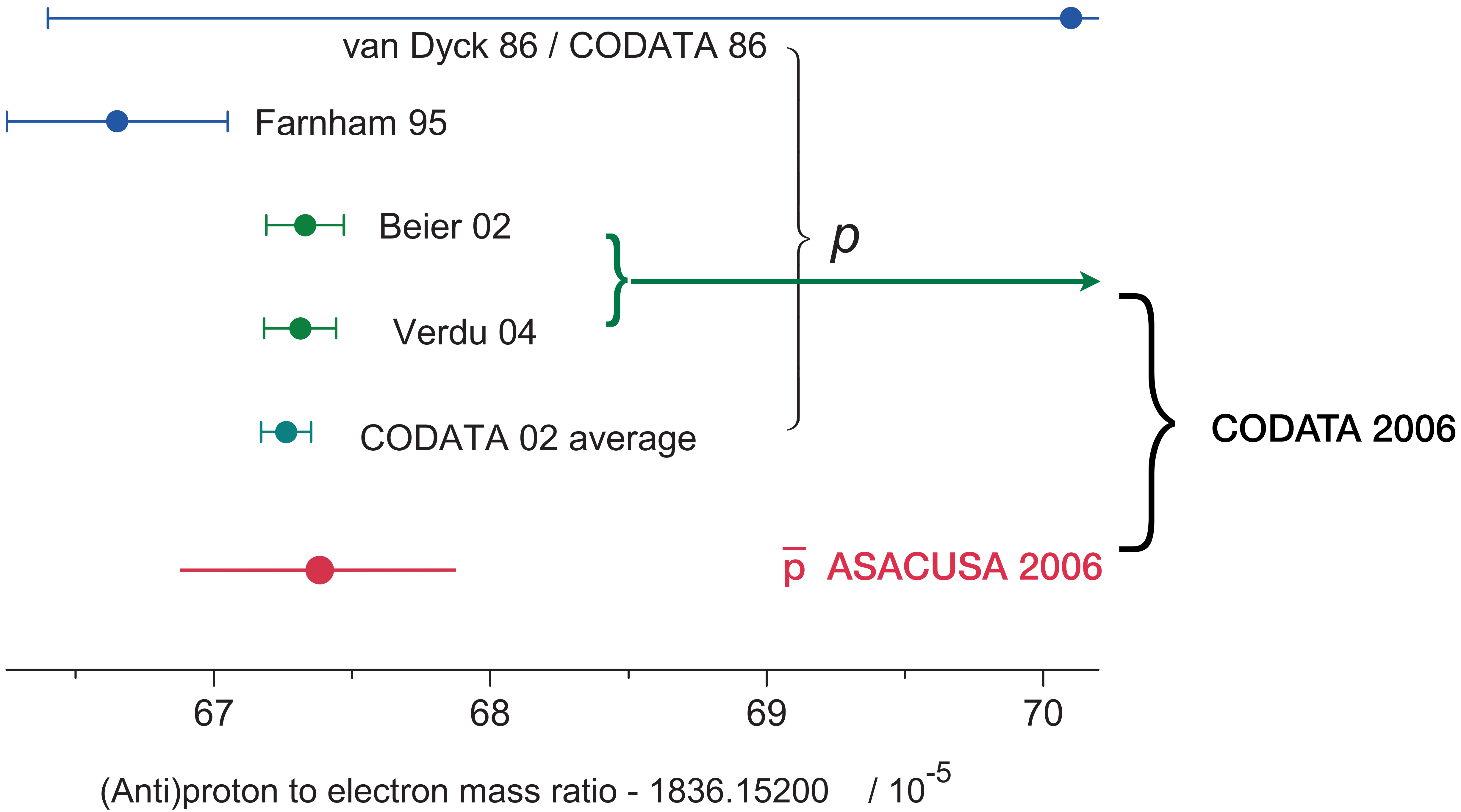


T~15K

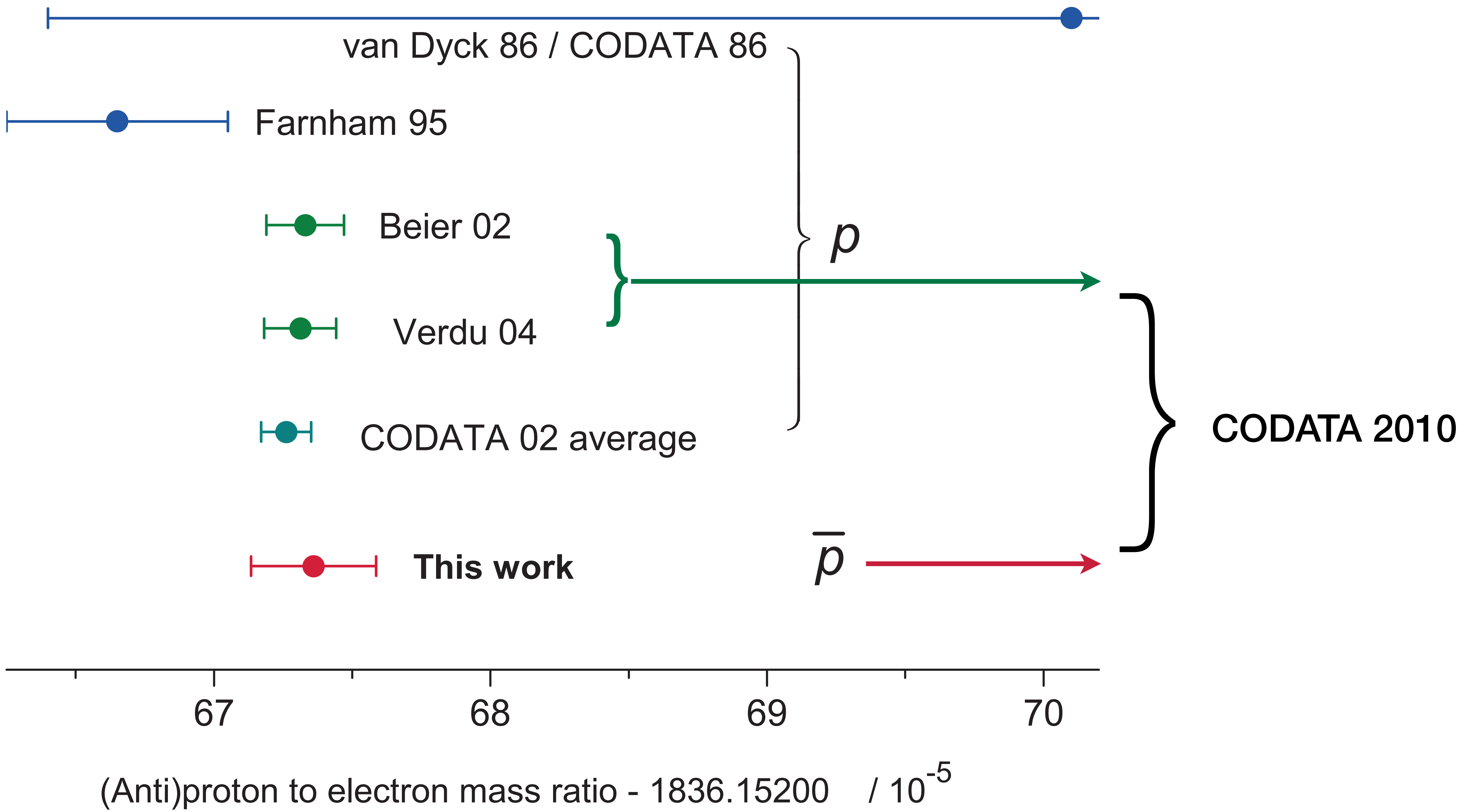


M. Hori et al., Nature 475, 484 (2011).

m_p ($m_{\bar{p}}$) / m_e


van Dyck 86 / CODATA 86
Farnham 95
Beier 02
Verdu 04
CODATA 02 average
p
CODATA 2006
p̄ ASACUSA 2006
67
68
69
70
(Anti)proton to electron mass ratio - 1836.15200 / 10-5

m_p ($m_{\bar{p}}$) / m_e



van Dyck 86 / CODATA 86
Farnham 95
Beier 02
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This work
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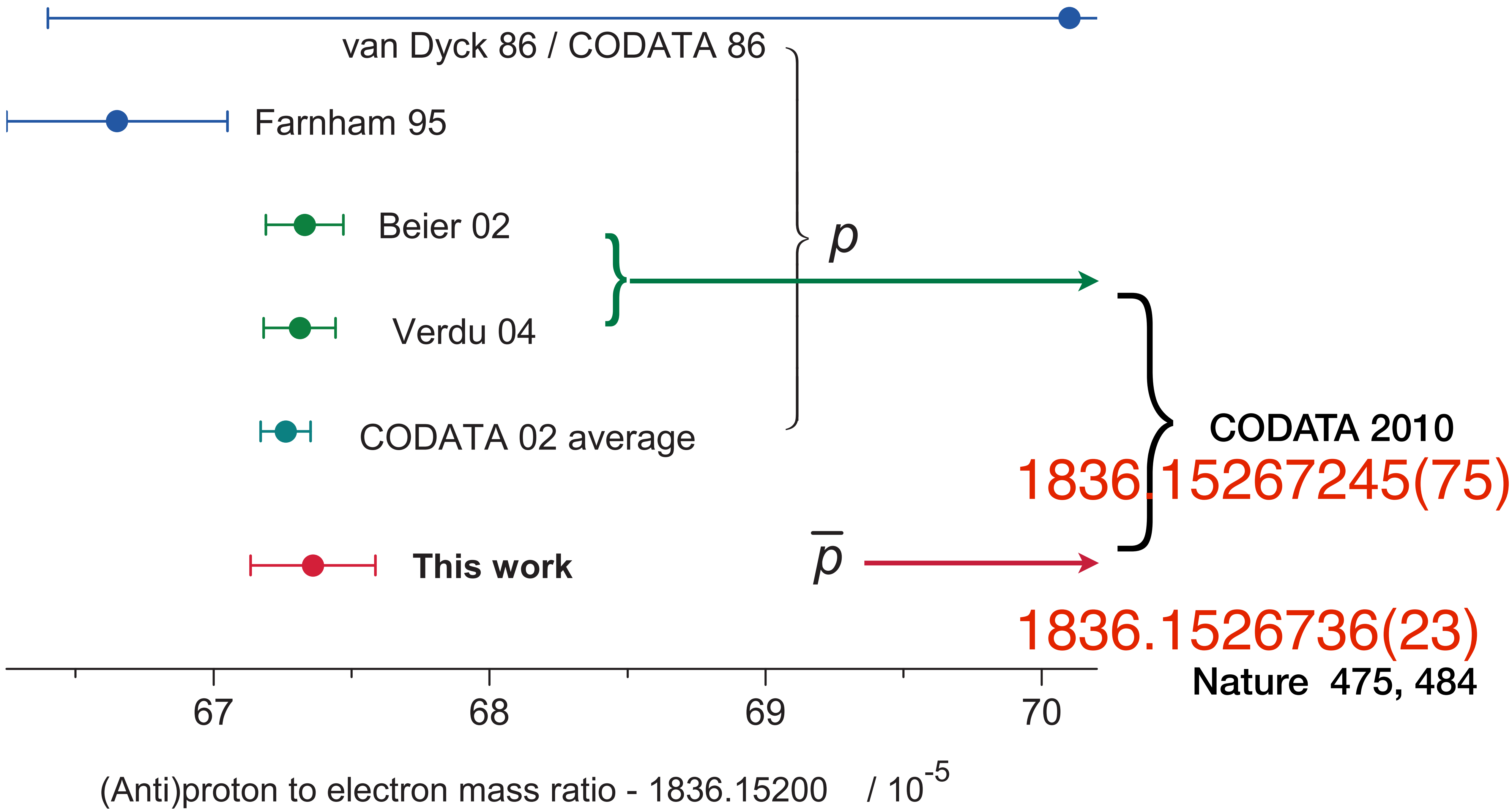

van Dyck 86 / CODATA 86
Farnham 95
Beier 02
Verdu 04
CODATA 02 average
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p
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CODATA 2010
1836.15267245(75)
1836.1526736(23)
Nature 475, 484
67
68
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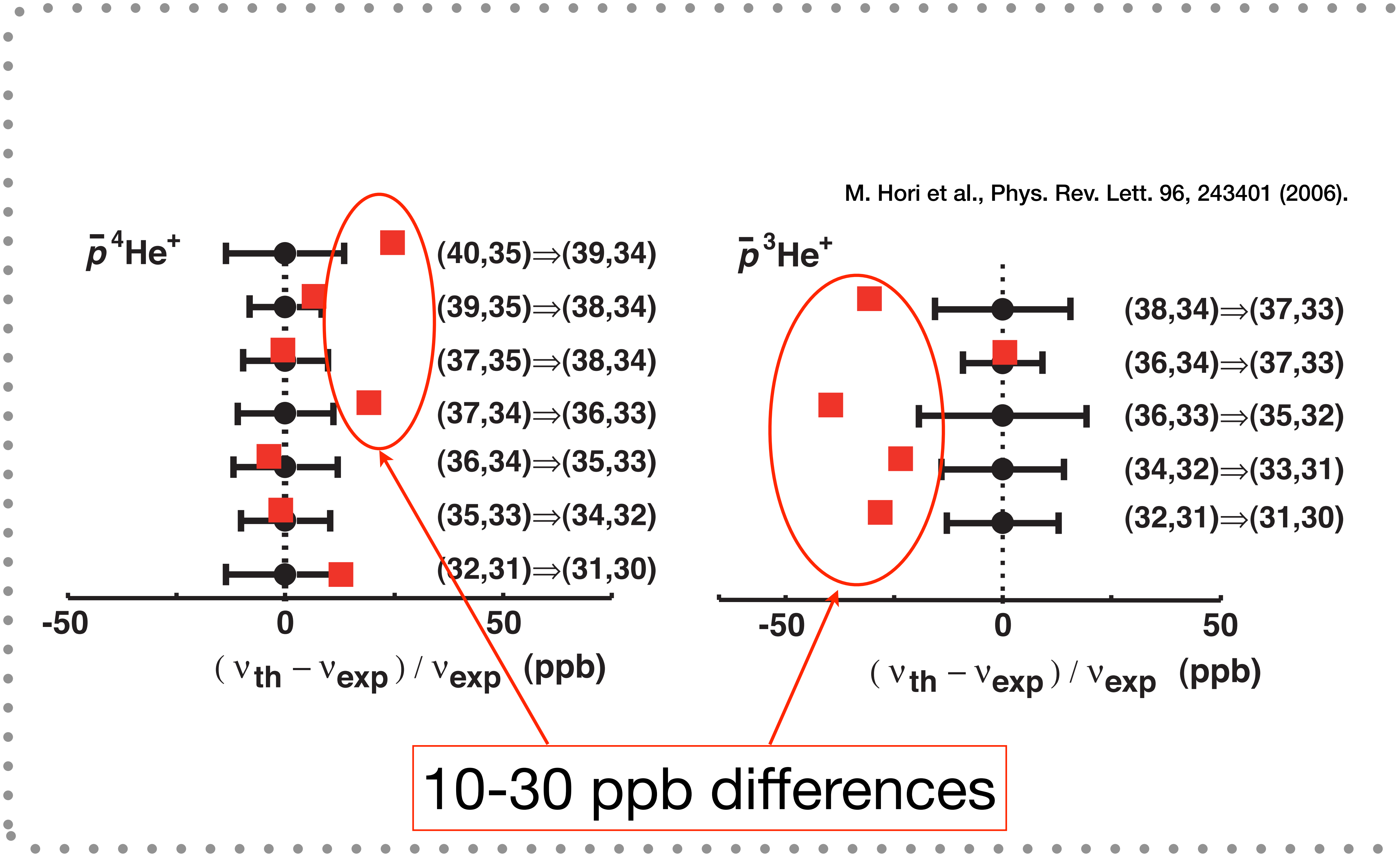
(Anti)proton to electron mass ratio - 1836.15200 / 10^-5

↓ this was the problem in 2006

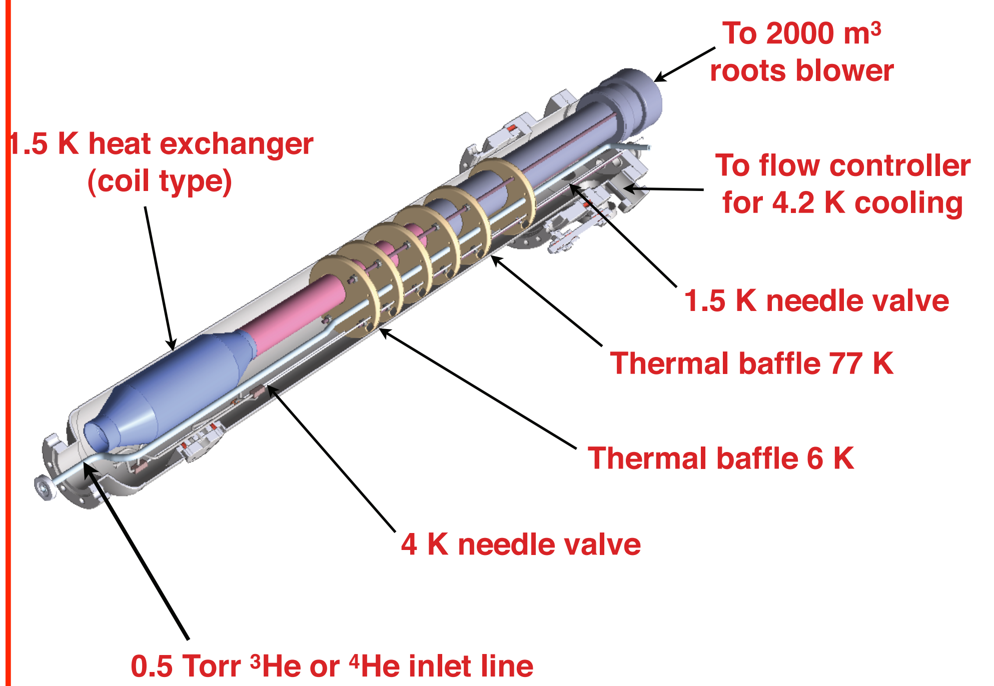


T~15K→T=1.5K

- “cold” p̄He :
  (1) less Doppler
  (2) improve S/N
  (3) less collisional broadening

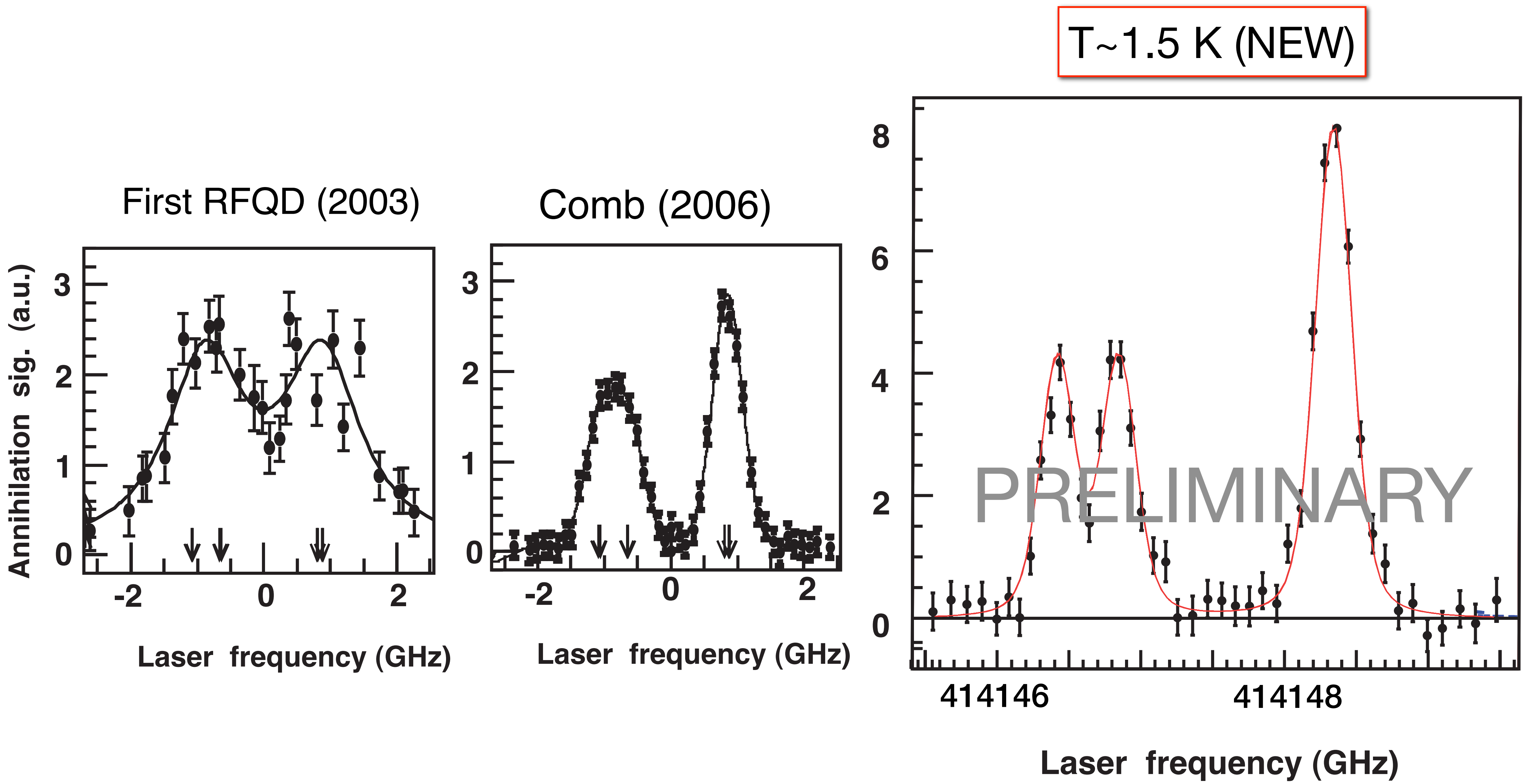
- Improvements
  (1) laser
  (2) p̄ beam (electrostatic quad)
  (3) detector (Cherenkov)
  (4) collisional shift corrections
  (5) AC stark shift corrections

cool $\bar{p}He^{+}$ to T = 1.5 K



measurements at different target densities, and with various laser powers (time consuming)

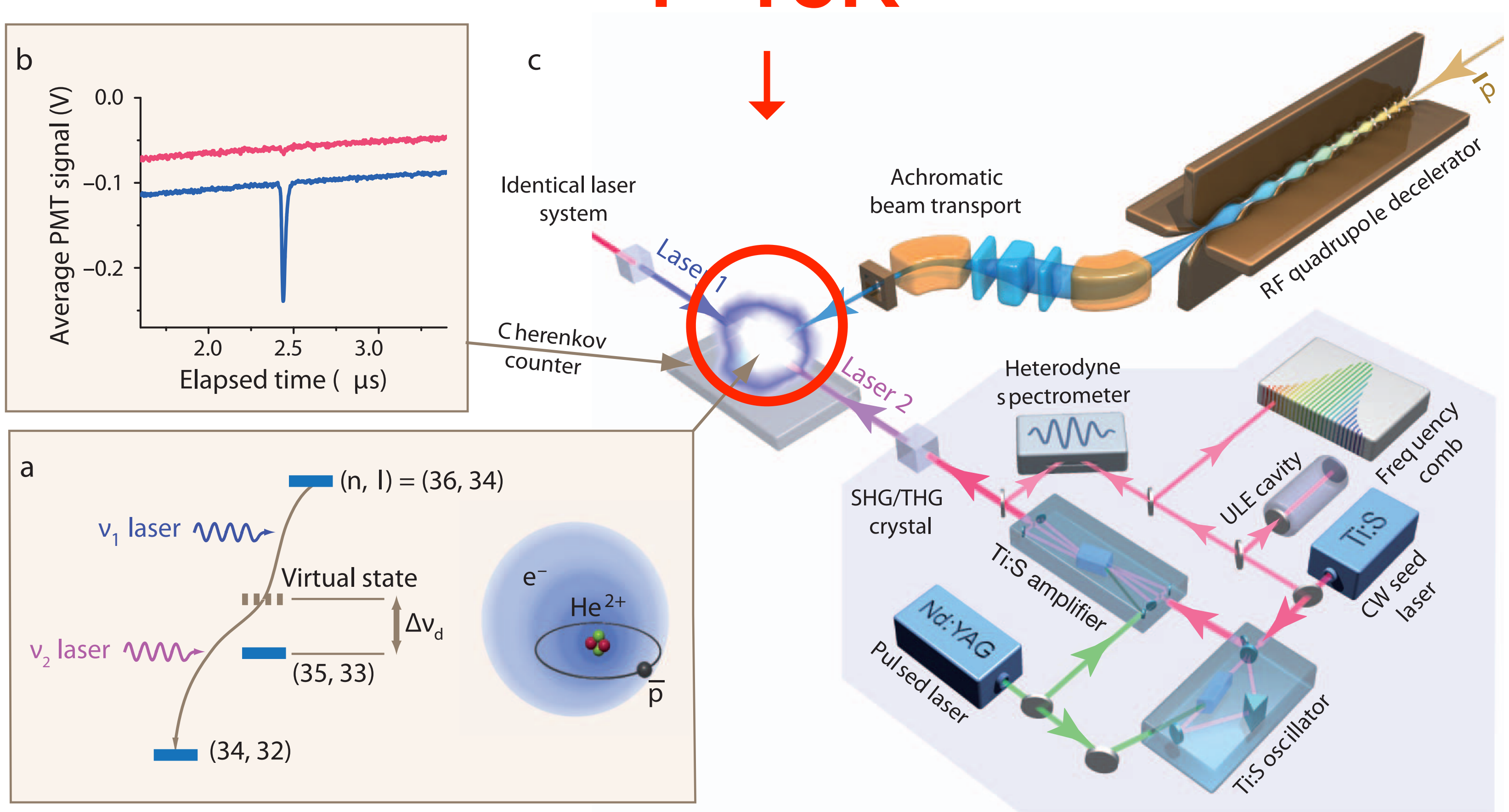
example (36,34)→(37,33) in $\bar{p}^3He^+$ (wavelength ~ 723 nm)



ν_{th}-ν_{exp} difference 10-30 ppb → <3~6 ppb

next: 2-photon of “cold” $\bar{p}$He

T~15K



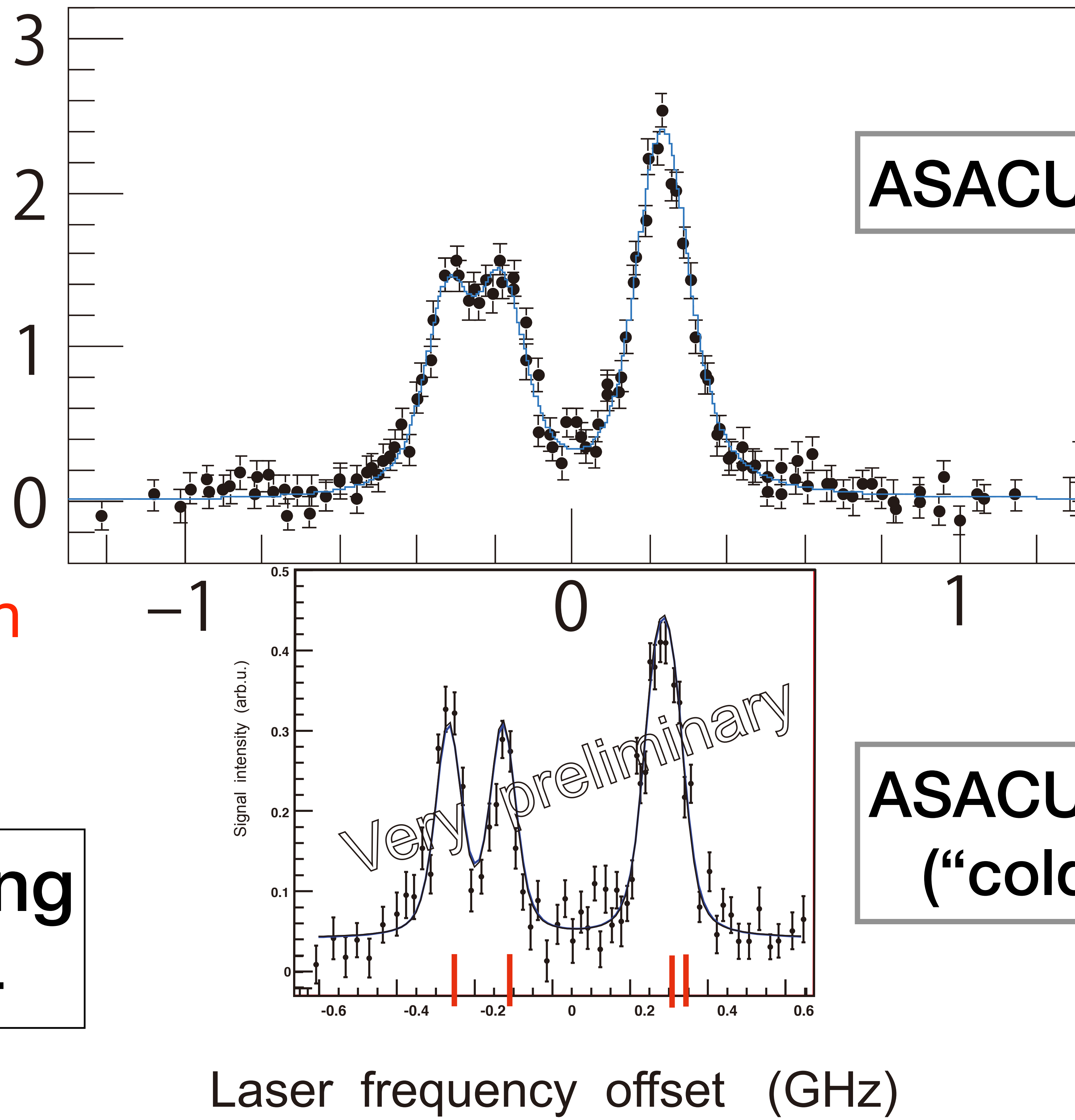
2011 (Nature 475, 484)

“Cold (T=1.5)”
$\bar{p}He^+$
in 2012

“warm” vs “cold” 2-photon $\bar{p}^4$He (36,34)→(34,32)

↓
spectral resolution x 3
↓

data taking in 2014



ASACUSA 2011

ASACUSA 2012 (“cold” $\bar{p}$He)

1.5 $\bar{p}$He microwave spectroscopy

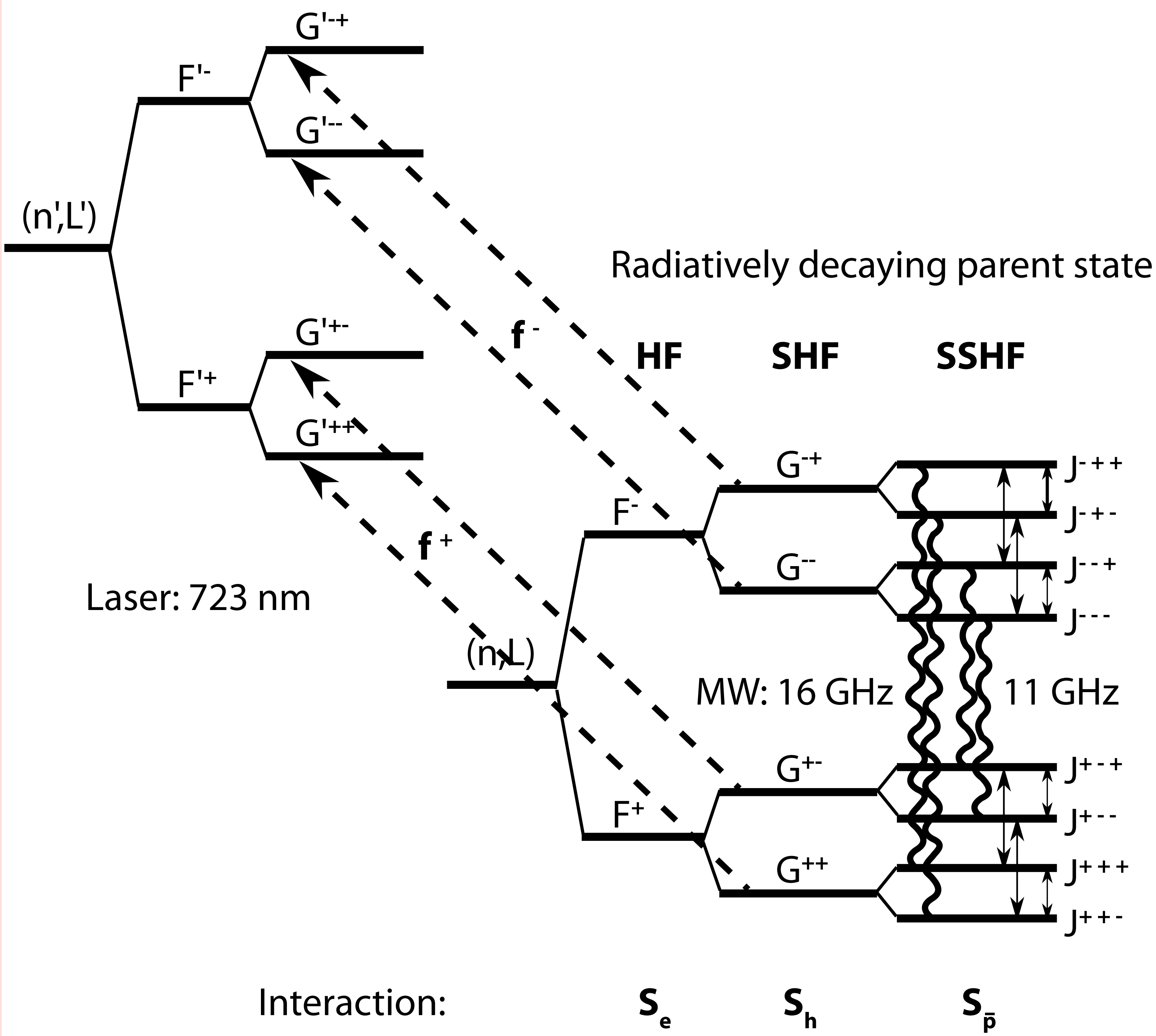
OPEN ACCESS
IOP PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

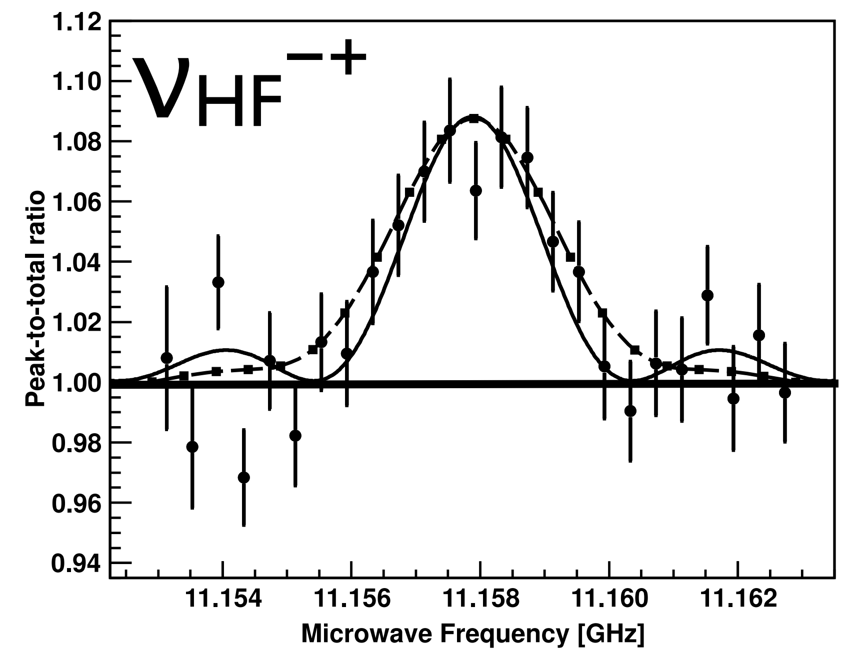
J. Phys. B: At. Mol. Opt. Phys. **46** (2013) 125003 (9pp) doi:10.1088/0953-4075/46/12/125003

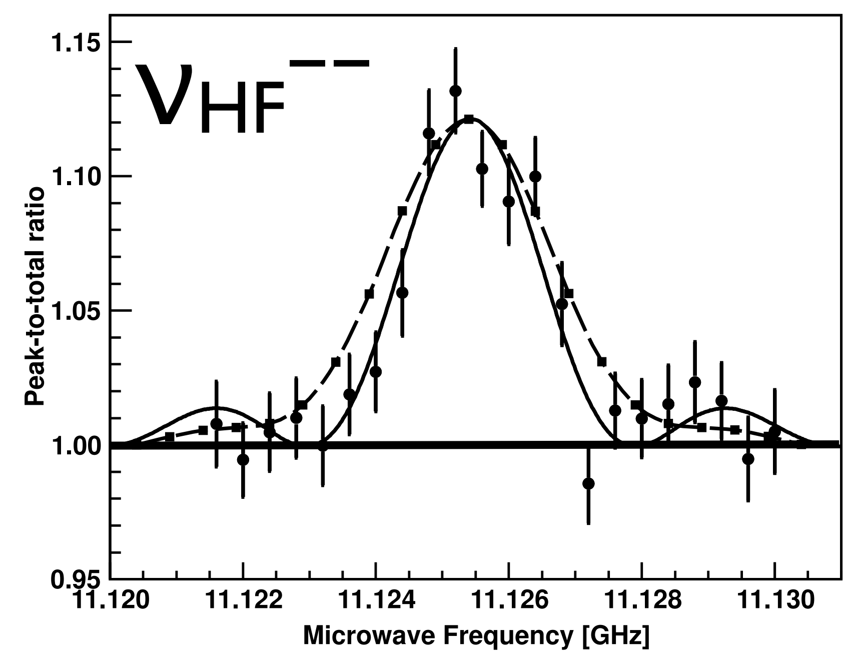
Microwave spectroscopic study of the hyperfine structure of antiprotonic ^{3}He

S Friedreich[1], D Barna[2,3], F Caspers[4], A Dax[2], R S Hayano[2], M Hori[2,5], D Horváth[3,6], B Juhász[1,7], T Kobayashi[2], O Massiczek[1], A Sótér[5], K Todoroki[2], E Widmann[1] and J Zmeskal[1]

hyperfine structure of $\overline{p}^3He$



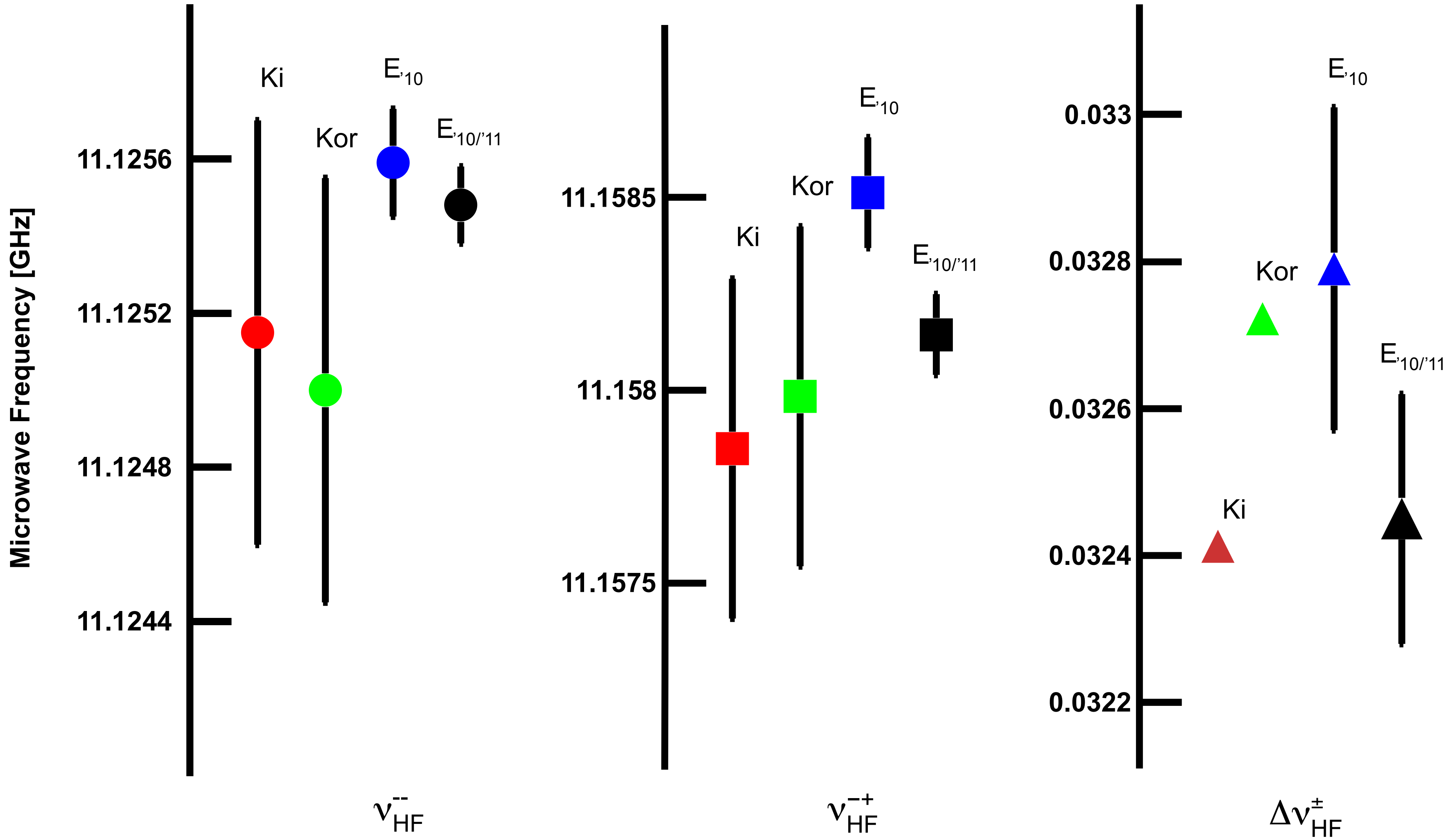




Agreement th-exp $<5\times10^{-5}$
(~theory error)

Comparison theory-experiment ^{3}He

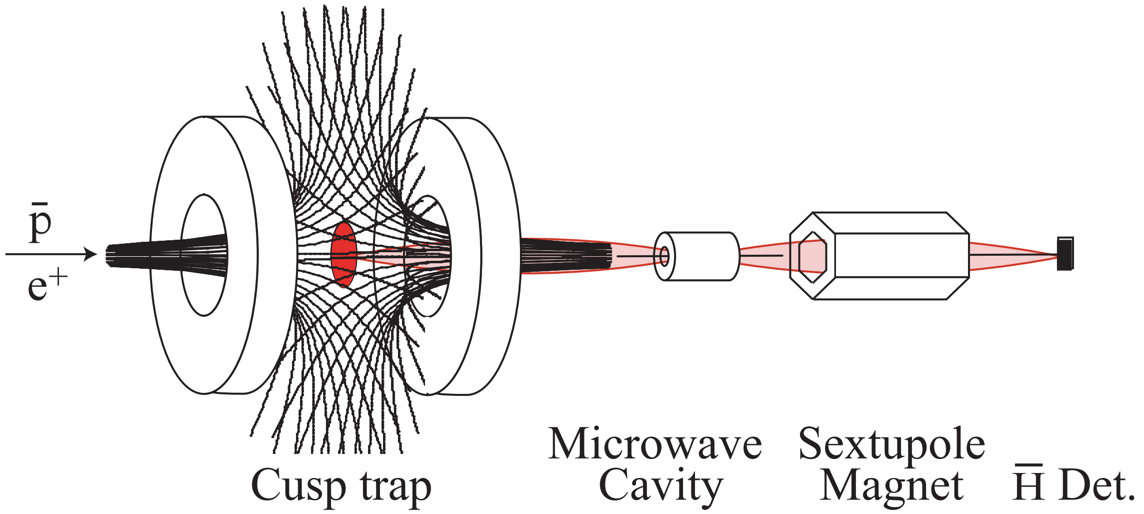
exp. error:	13 ppm	16 ppm	0.7%
theory error	50 ppm	50 ppm	50 ppm



Kor: V. Korobov, Phys. Rev. A 73 (2006) 022509.
Ki: Y. Kino, et al., Hyperfine Interactions 146–147 (2003) 331.
E_{10}: S. Friedreich et al., Physics Letters B 700 (2011) 1–6
$E_{10/11}$: S. Friedreich et al., J. Phys. B: At. Mol. Opt. Phys. 46 (2013) 125003.

2. “CUSP” experiment for $\bar{H}$ Spectroscopy

More by Malbrunot & Kuroda

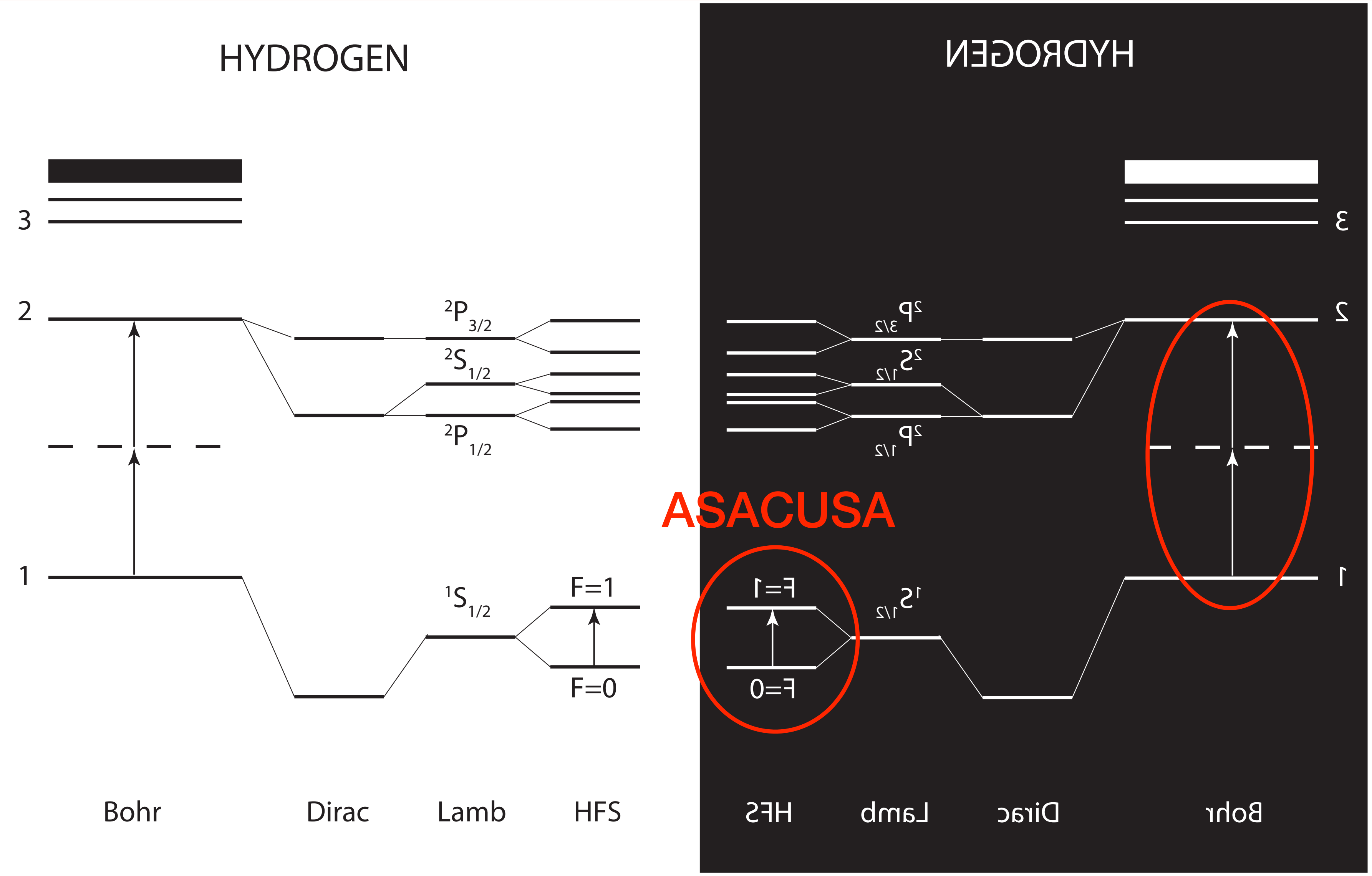


- $\bar{H}$ production demonstrated in 2010
- $\bar{H}$ beam development started in 2011
- $\bar{H}$ production rate optimization & full setup development in 2012

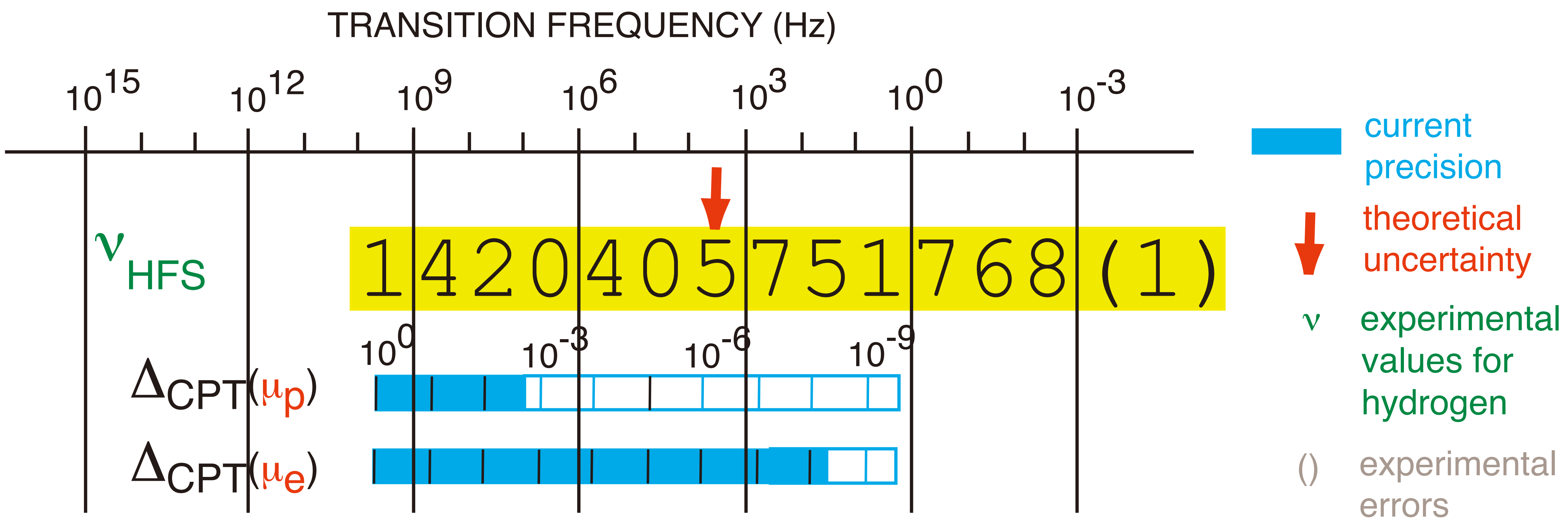
PRL **105,** 243401 (2010) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2010

Synthesis of Cold Antihydrogen in a Cusp Trap

Y. Enomoto,[1] N. Kuroda,[2] K. Michishio,[3] C. H. Kim,[2] H. Higaki,[4] Y. Nagata,[1] Y. Kanai,[1] H. A. Torii,[2] M. Corradini,[5] M. Leali,[5] E. Lodi-Rizzini,[5] V. Mascagna,[5] L. Venturelli,[5] N. Zurlo,[5] K. Fujii,[2] M. Ohtsuka,[2] K. Tanaka,[2] H. Imao,[6] Y. Nagashima,[3] Y. Matsuda,[2] B. Juhász,[7] A. Mohri,[1] and Y. Yamazaki[1,2]



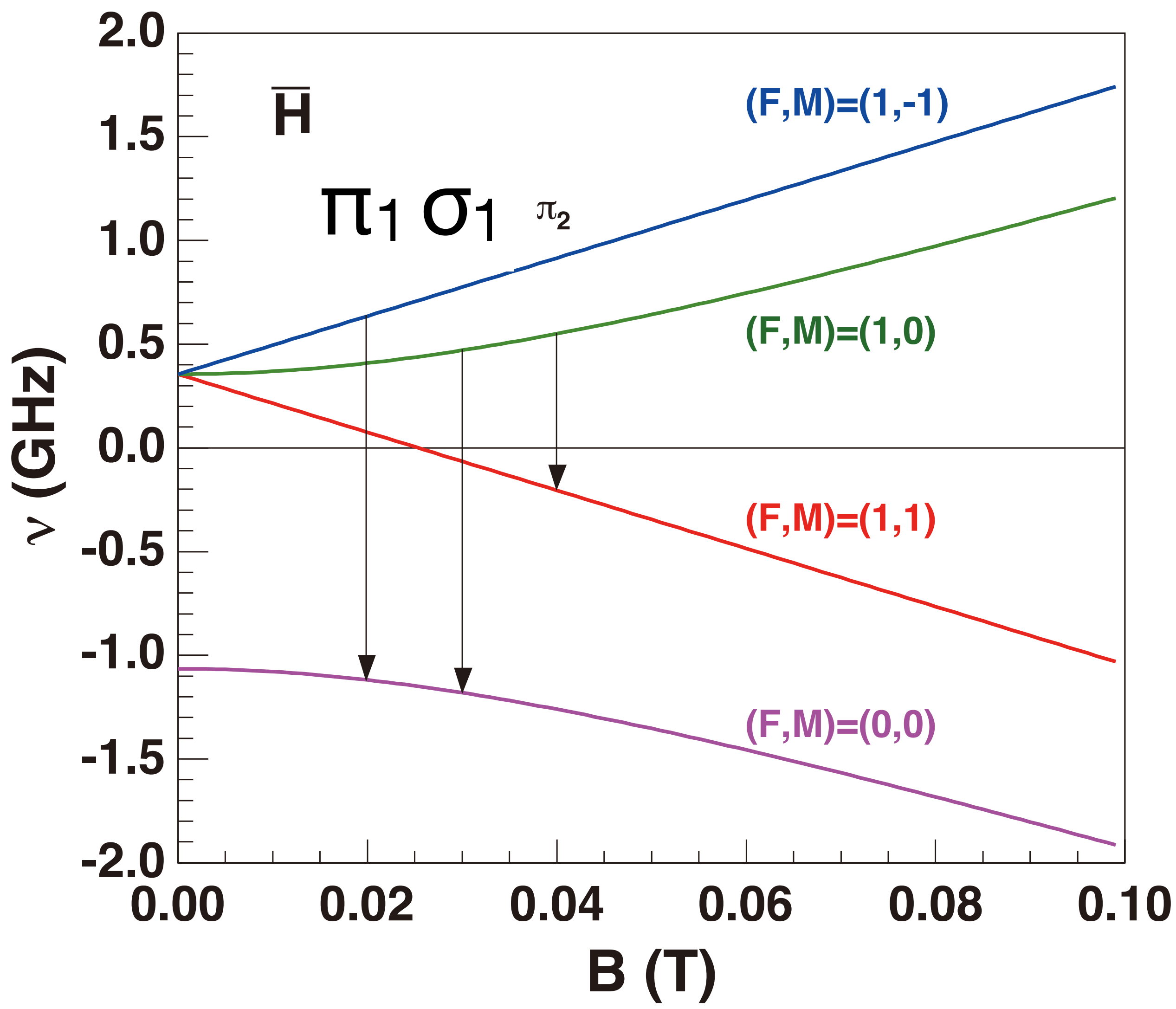
HYDROGEN
3
2
1
$^2P_{3/2}$
$^2S_{1/2}$
$^2P_{1/2}$
$^1S_{1/2}$
F=1
F=0
Bohr
Dirac
Lamb
HFS
ASACUSA



TRANSITION FREQUENCY (Hz)
10^{15} 10^{12} 10^{9} 10^{6} 10^{3} 10^{0} 10^{-3}
ν_{HFS}
1 4 2 0 4 0 5 7 5 1 7 6 8 (1)
10^{0} 10^{-3} 10^{-6} 10^{-9}
$\Delta_{CPT}(\mu_p)$
$\Delta_{CPT}(\mu_e)$
current precision
theoretical uncertainty
ν experimental values for hydrogen
() experimental errors

Method

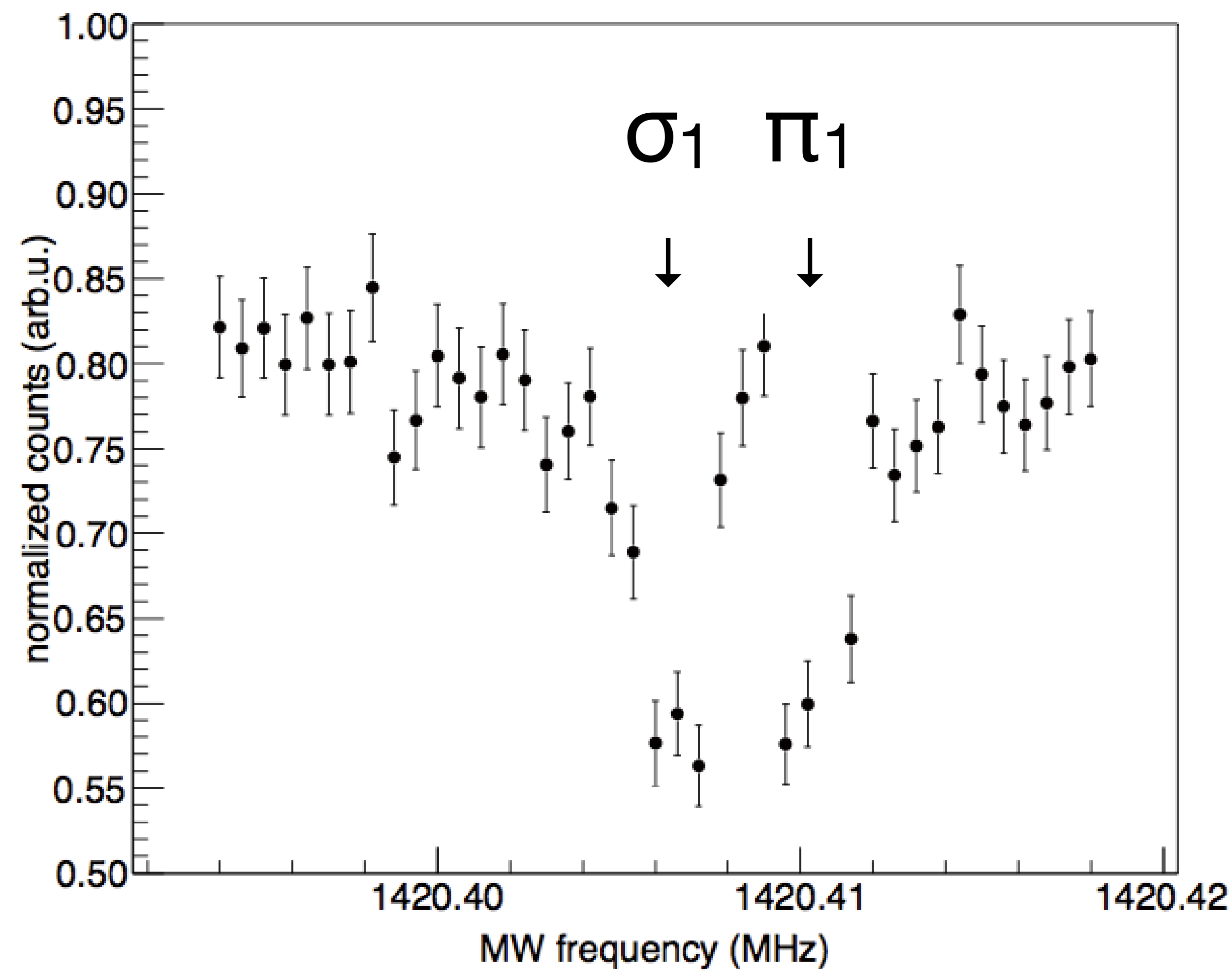
- (anti)atomic beam
- measure σ_1 at several B's, extrapolate to B = 0
- achievable precision $\lesssim 10^{-6}$ for T ≤ 100 K



Method

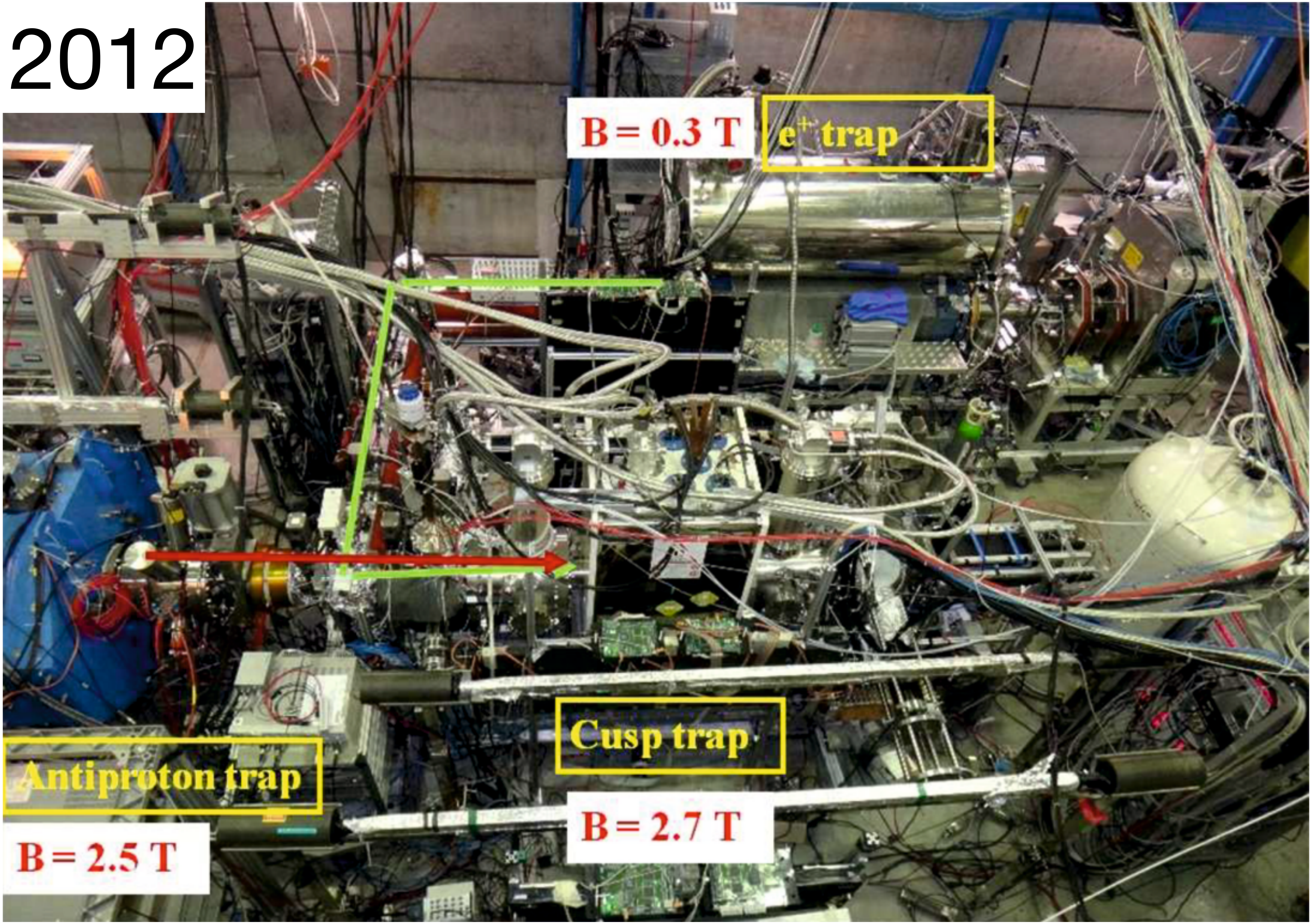
- (anti)atomic beam
- measure σ_1 at several B's, extrapolate to B = 0
- achievable precision ≲10^{-6} for T ≤ 100 K

Simulated T=5K, B=1G

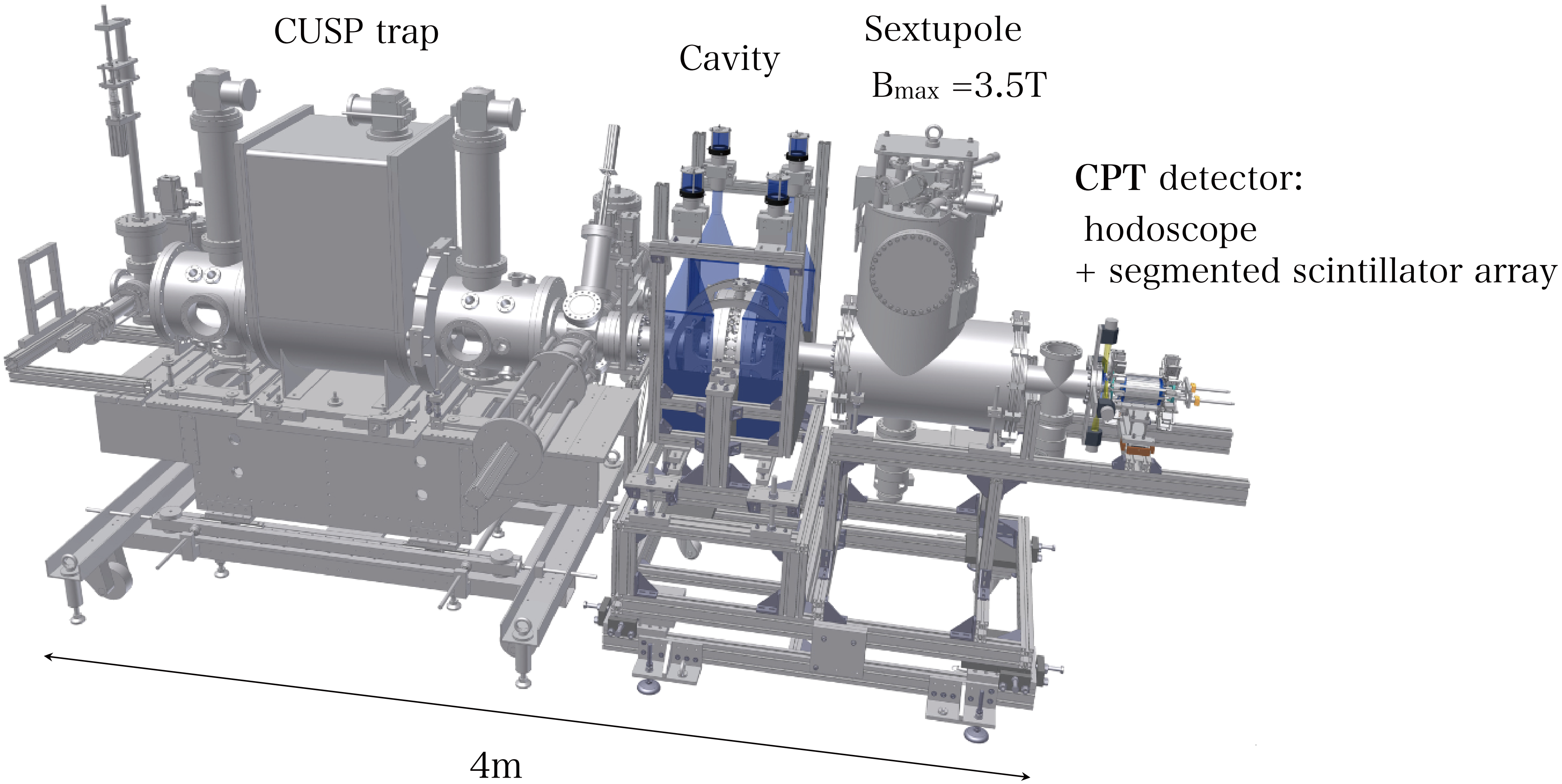


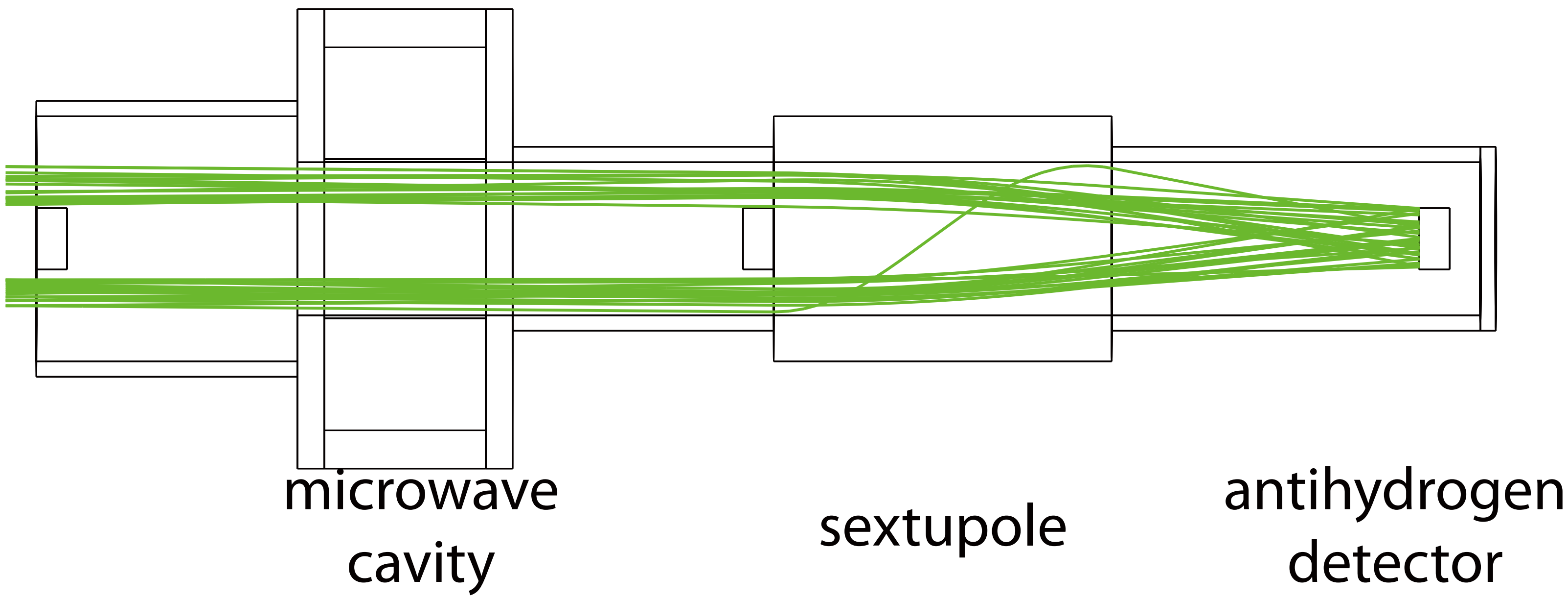
σ_1 transition, $\Delta B/B = 1\%$

2012



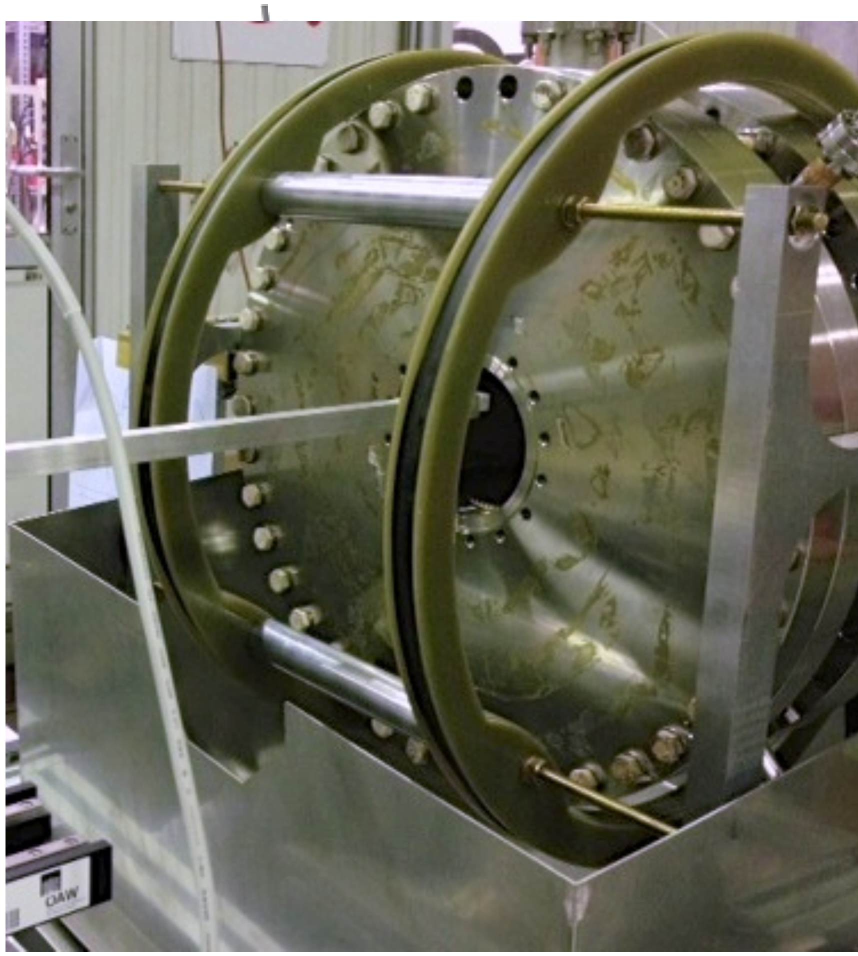
Full setup (ready to be deployed in 2014)

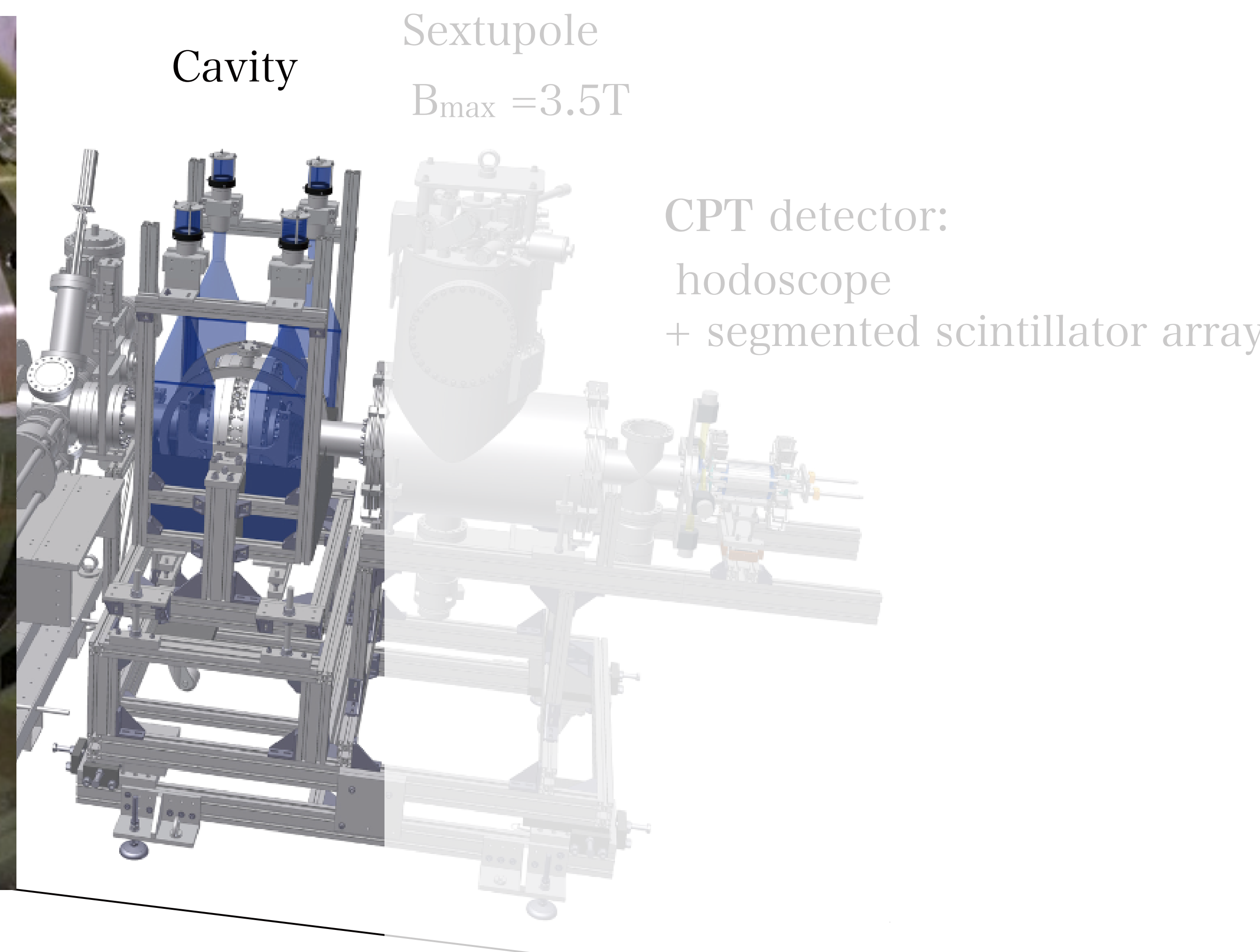


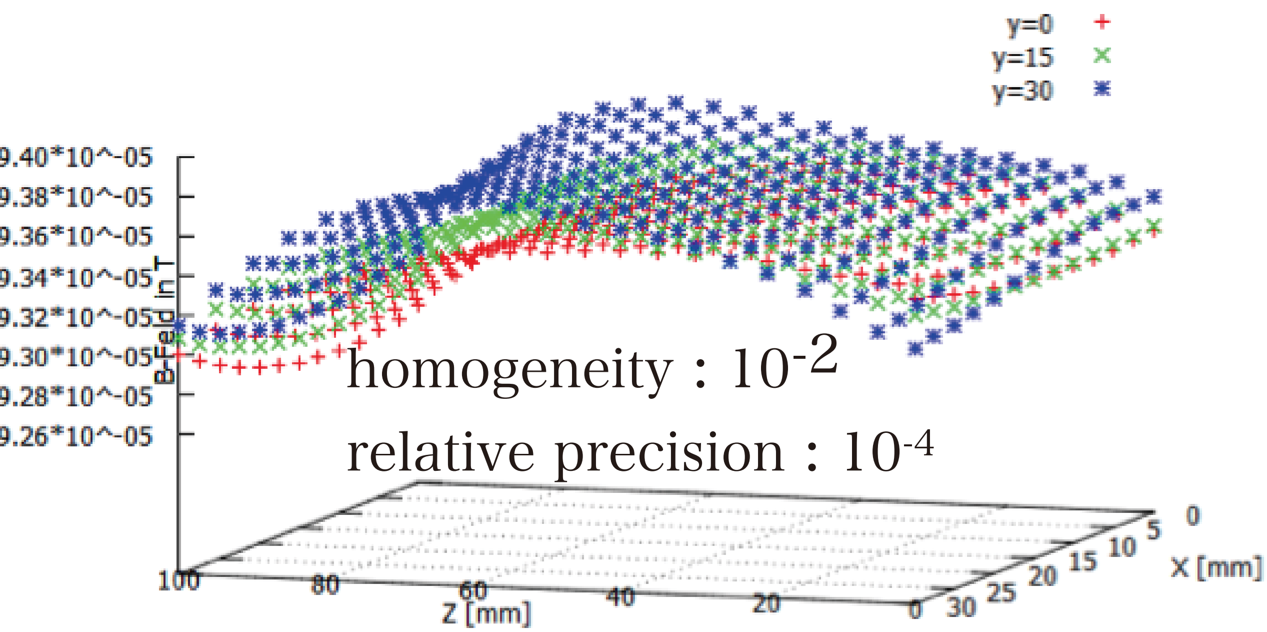


efficiency ~10^{-4}

Cavity

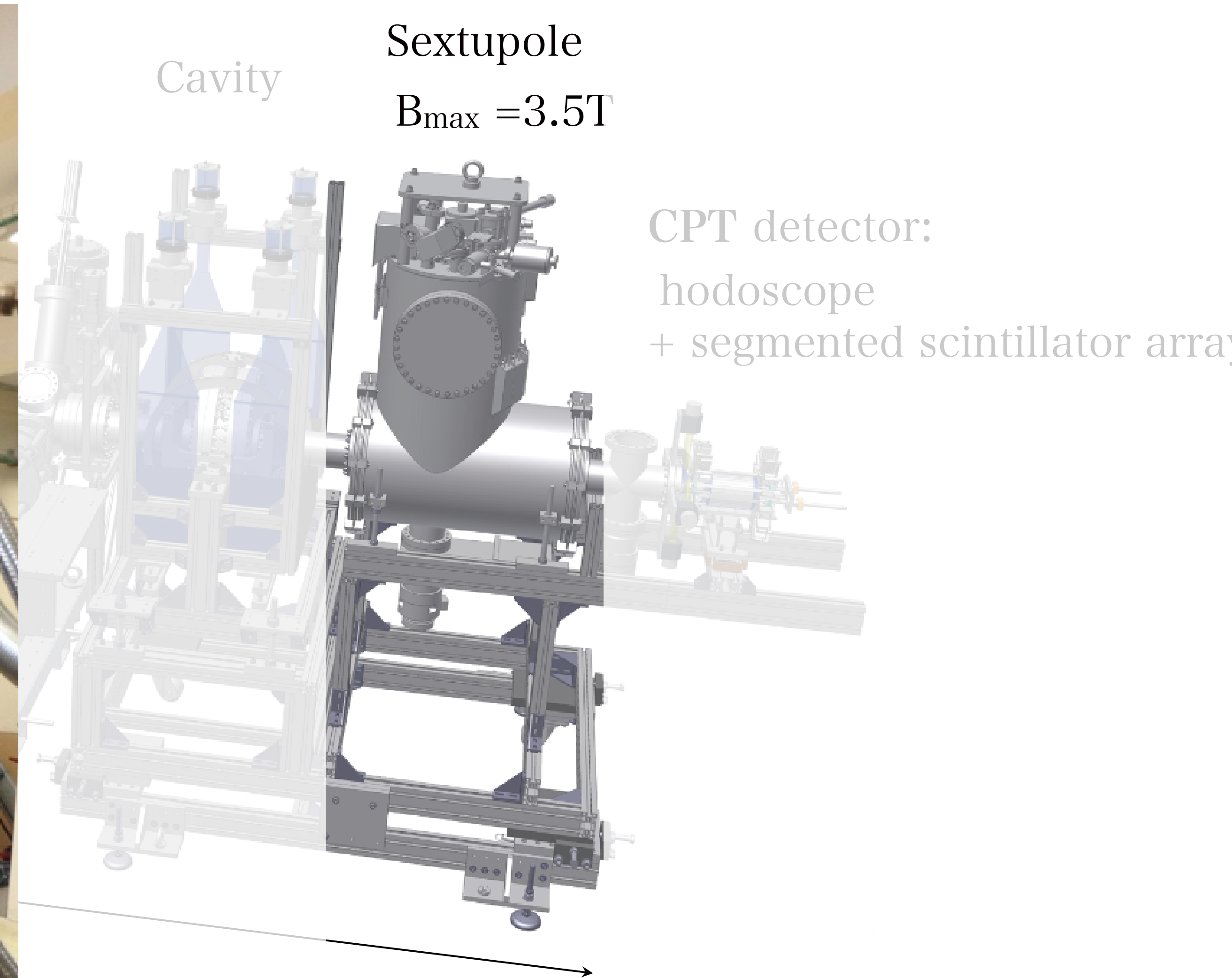






- 1.4 GHz cavity surrounded by Helmholtz coils
- 3 layers of mu-metal
- Highly sensitive flux gate sensors monitor field inside the cavity

Sextupole



superconduting magnet

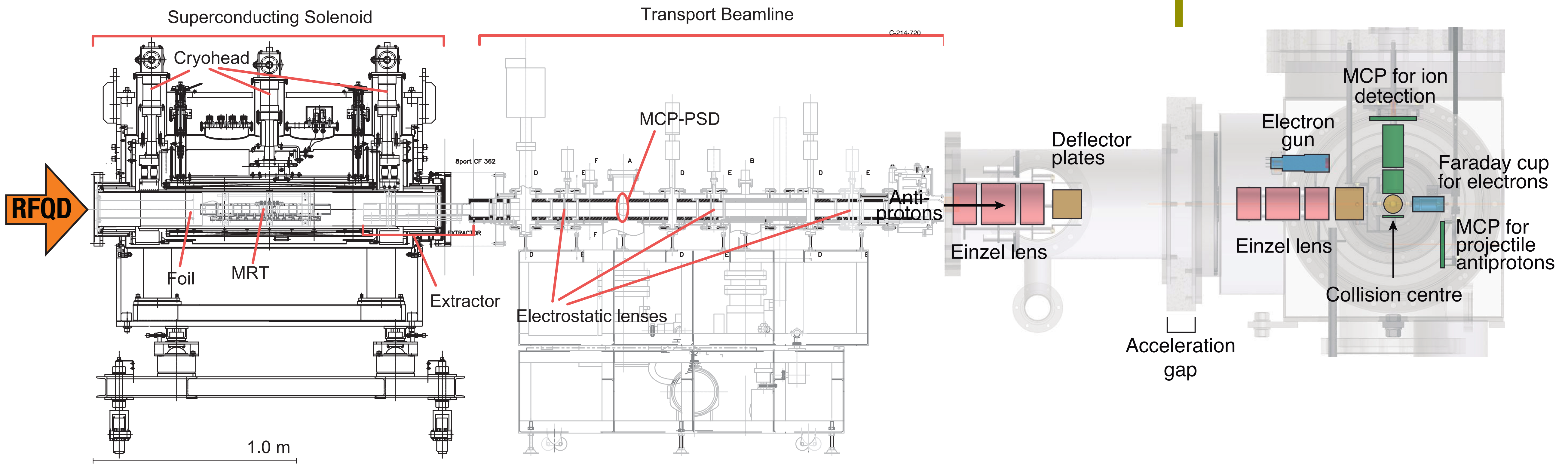
B_{max}=3.5T, I_{max}= 400A

effective length: 22 cm

3. Collision experiments

AIA - Aarhus Ionization Apparatus

slow-extracted (~30s) 250 eV $\bar{p}$ ➙
reaccelerated to ~10 keV (~7x10^5/AD shot)

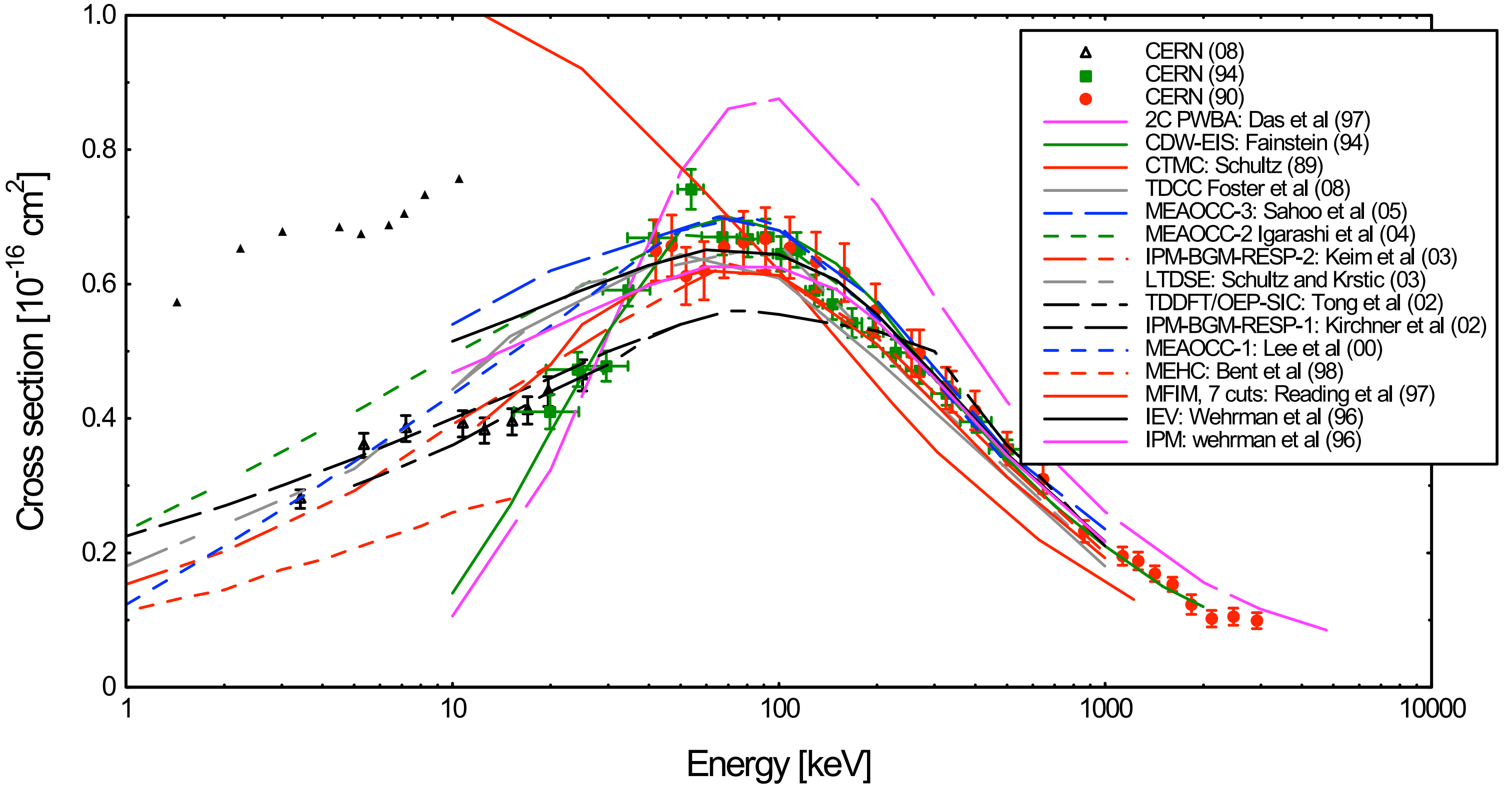


“MUSASHI” ultra slow beam

Ionization apparatus (not to scale)

p̄ - He single ionization

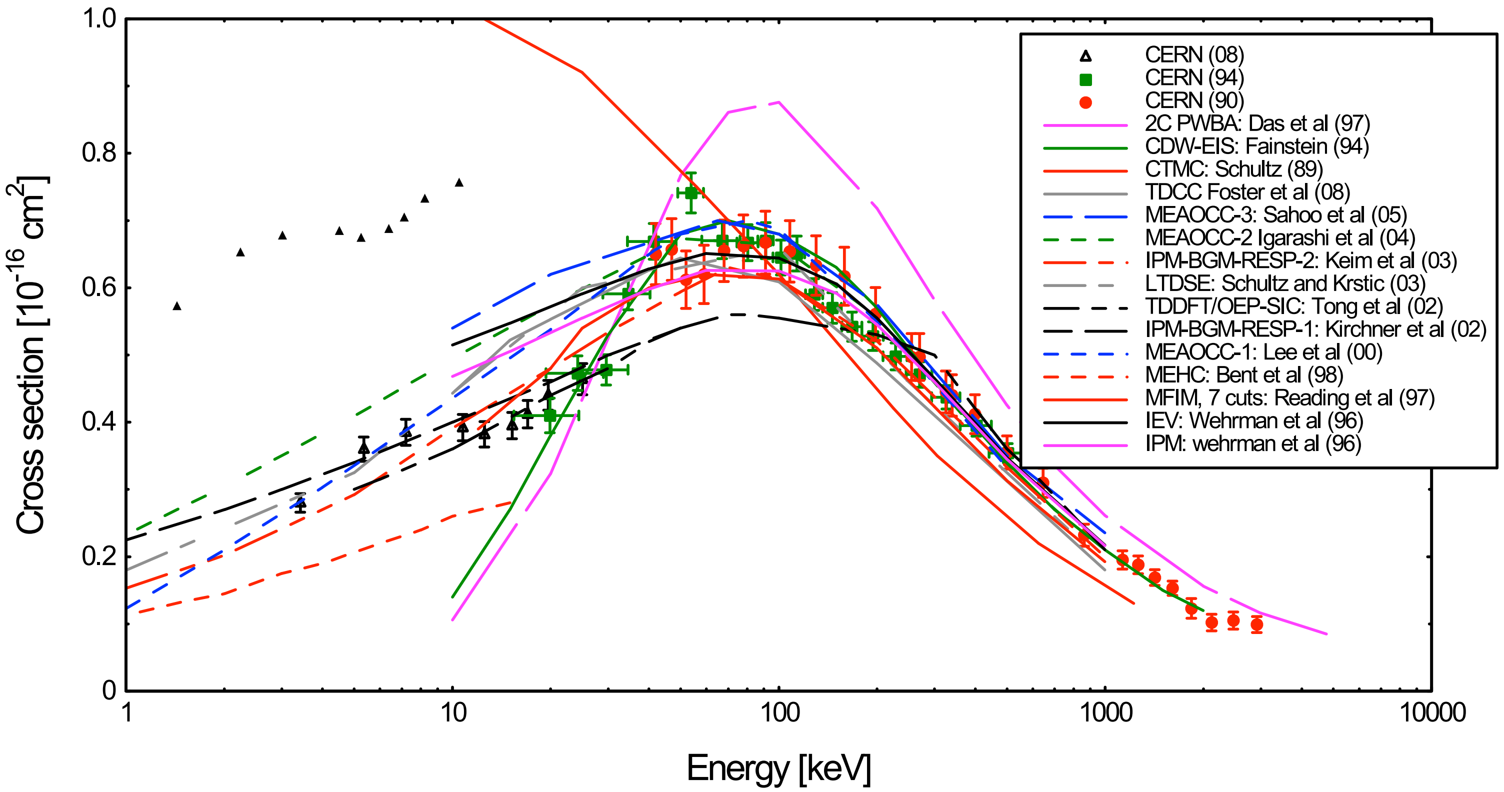
Knudsen et al PRL **101**, 043201 (08)



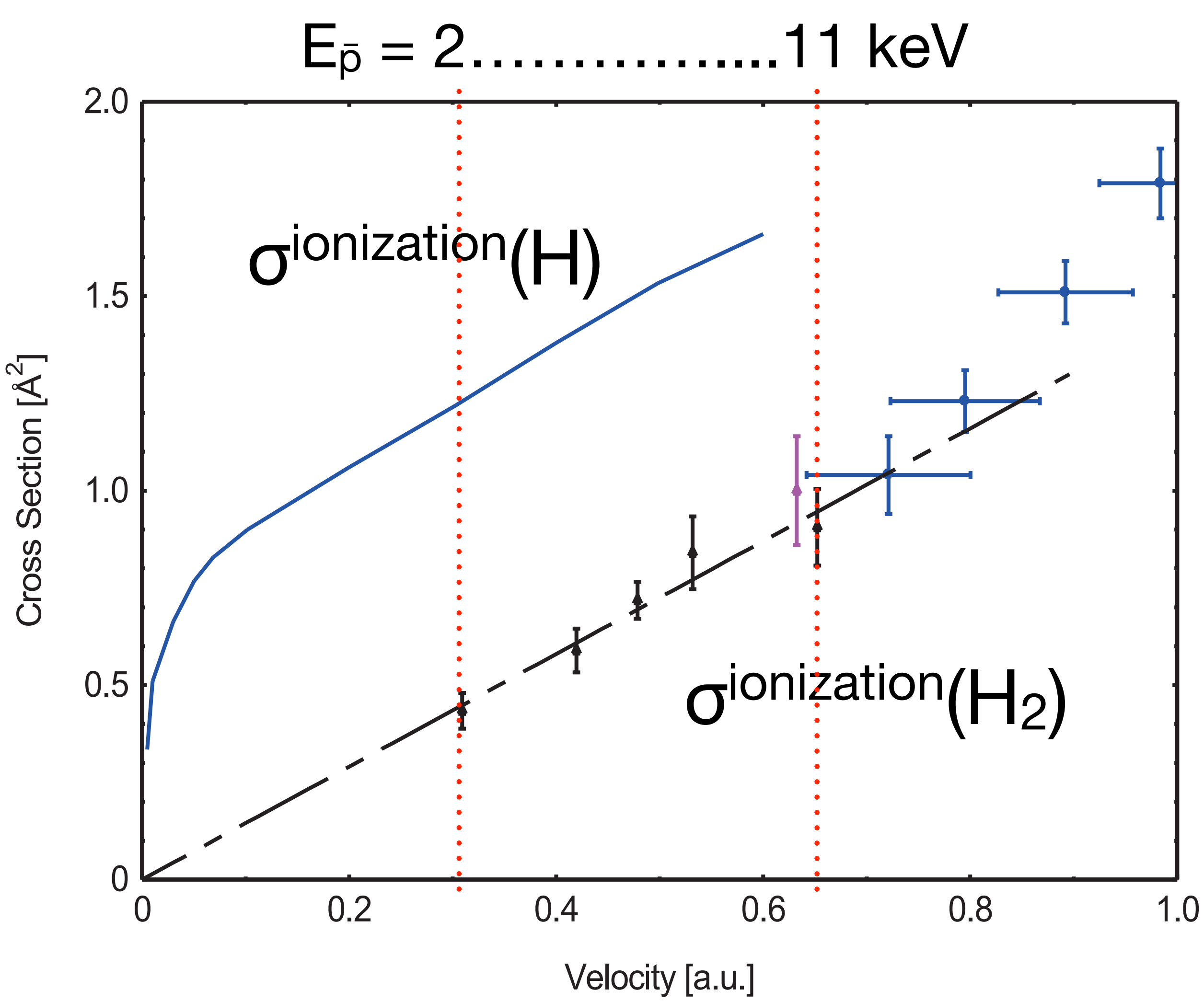
Knudsen et al PRL **105**, 213201 (2010)

$\bar{p}$ - He single ionization

Knudsen et al PRL **101**, 043201 (08)

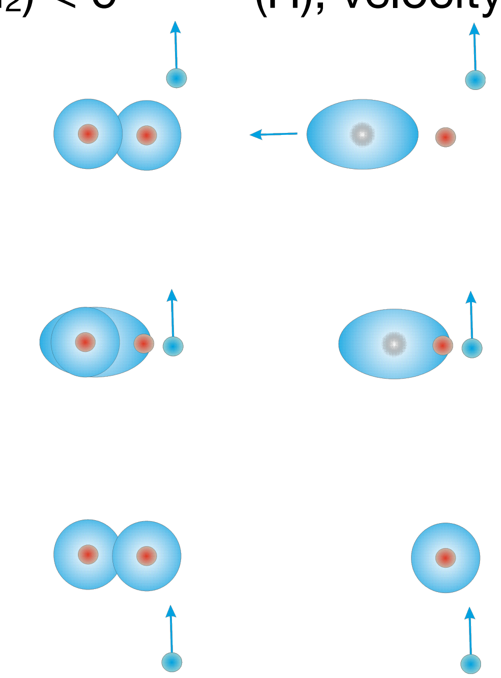


$\bar{p}$ - H_2 single ionization



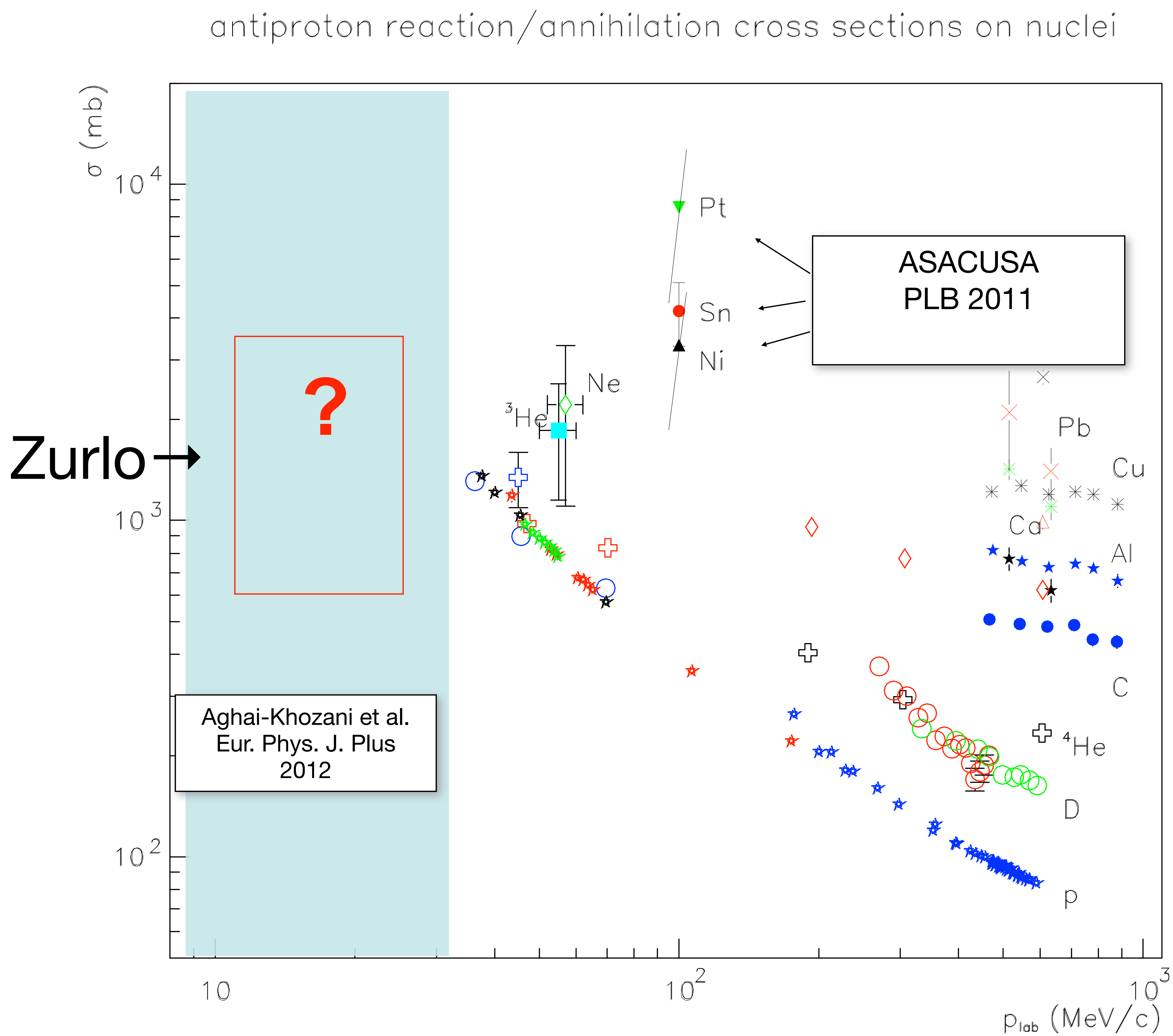
Naive expectation: $\sigma^{ionization}(H_2) \sim 2 \times \sigma^{ionization}(H)$, but

$\sigma^{ionization}(H_2) < \sigma^{ionization}(H)$, velocity linear behavior

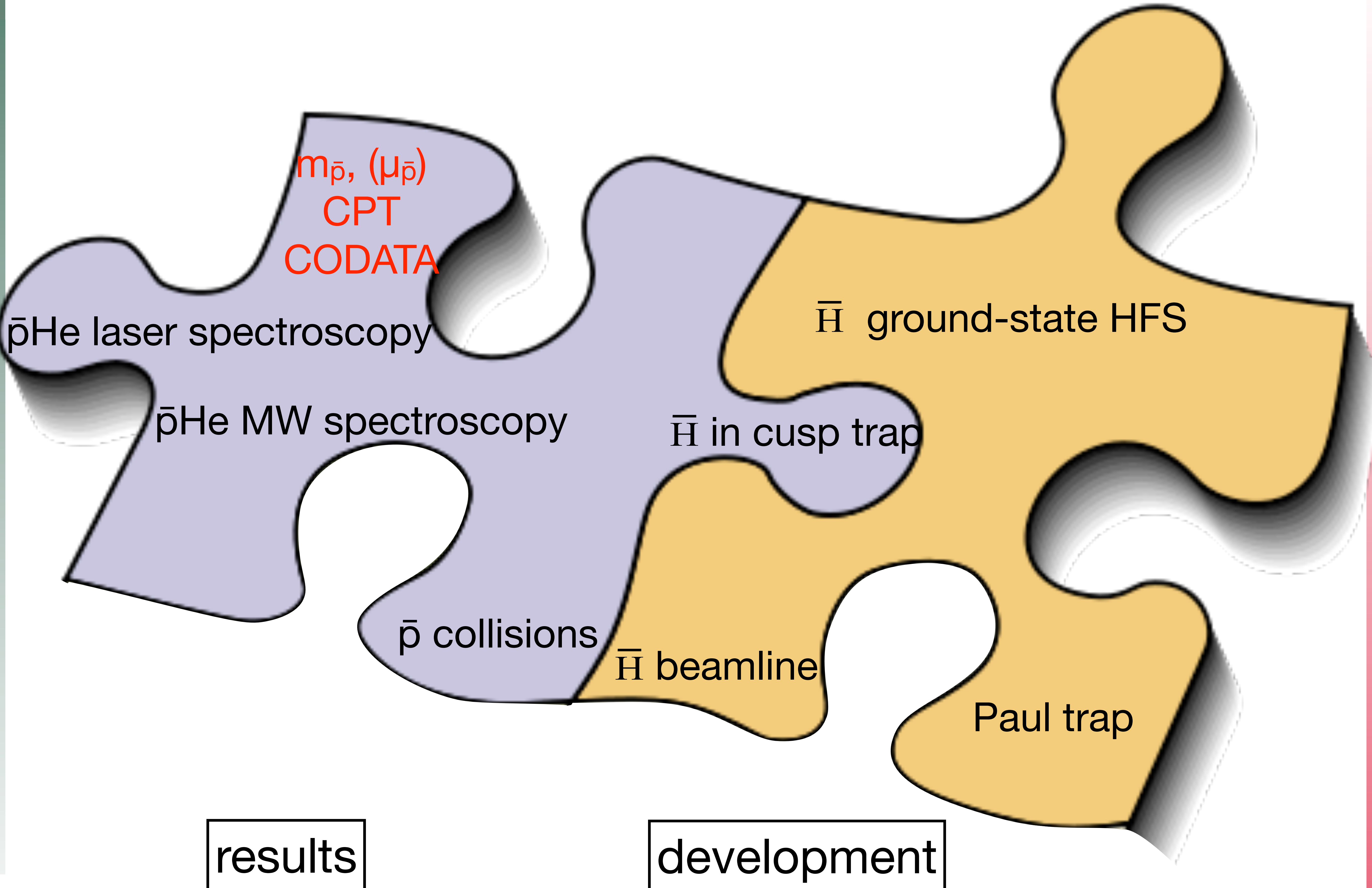


Knudsen et al PRL **105**, 213201 (2010)

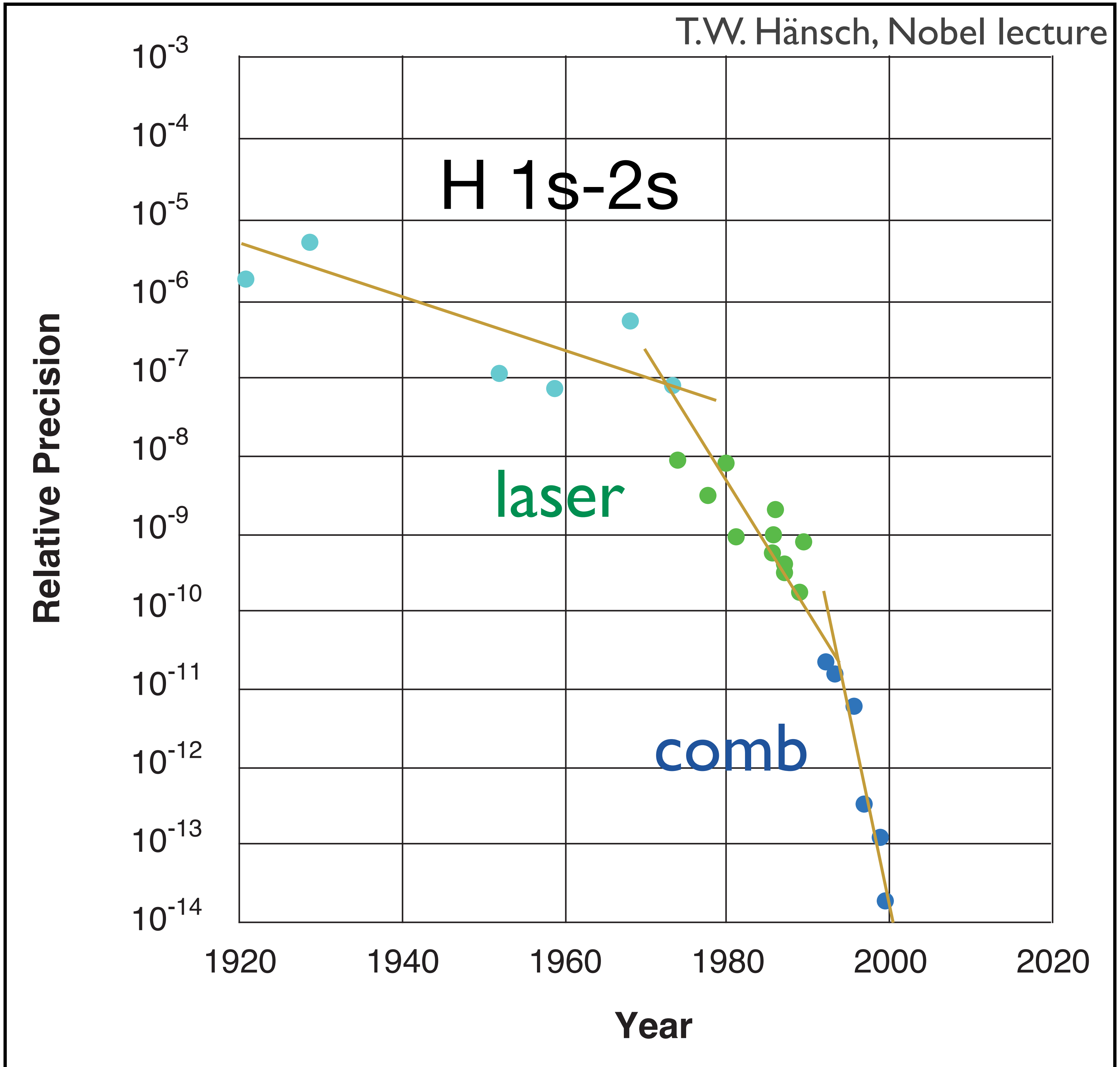
Nuclear collisions with antiprotons

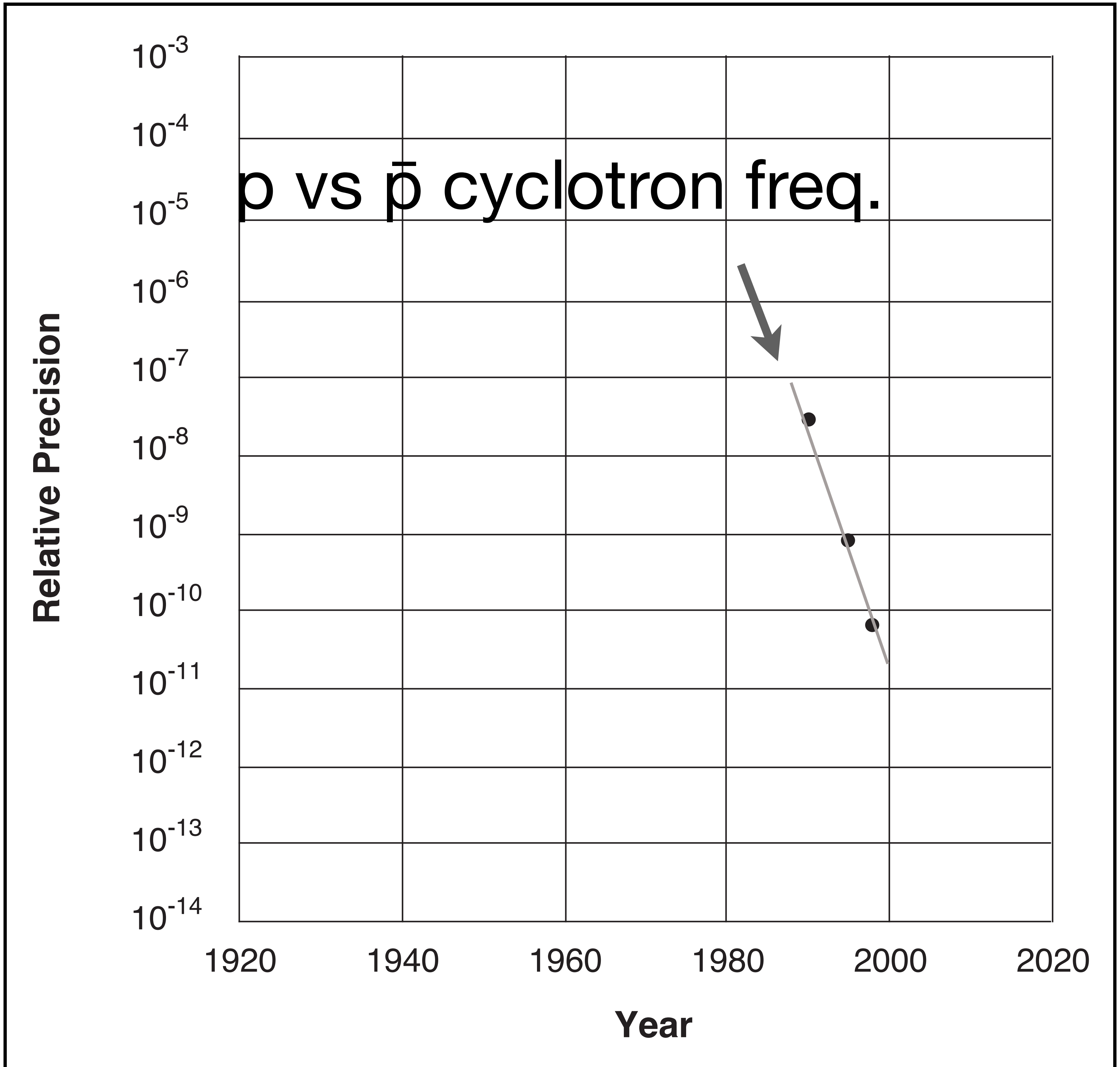


Summary

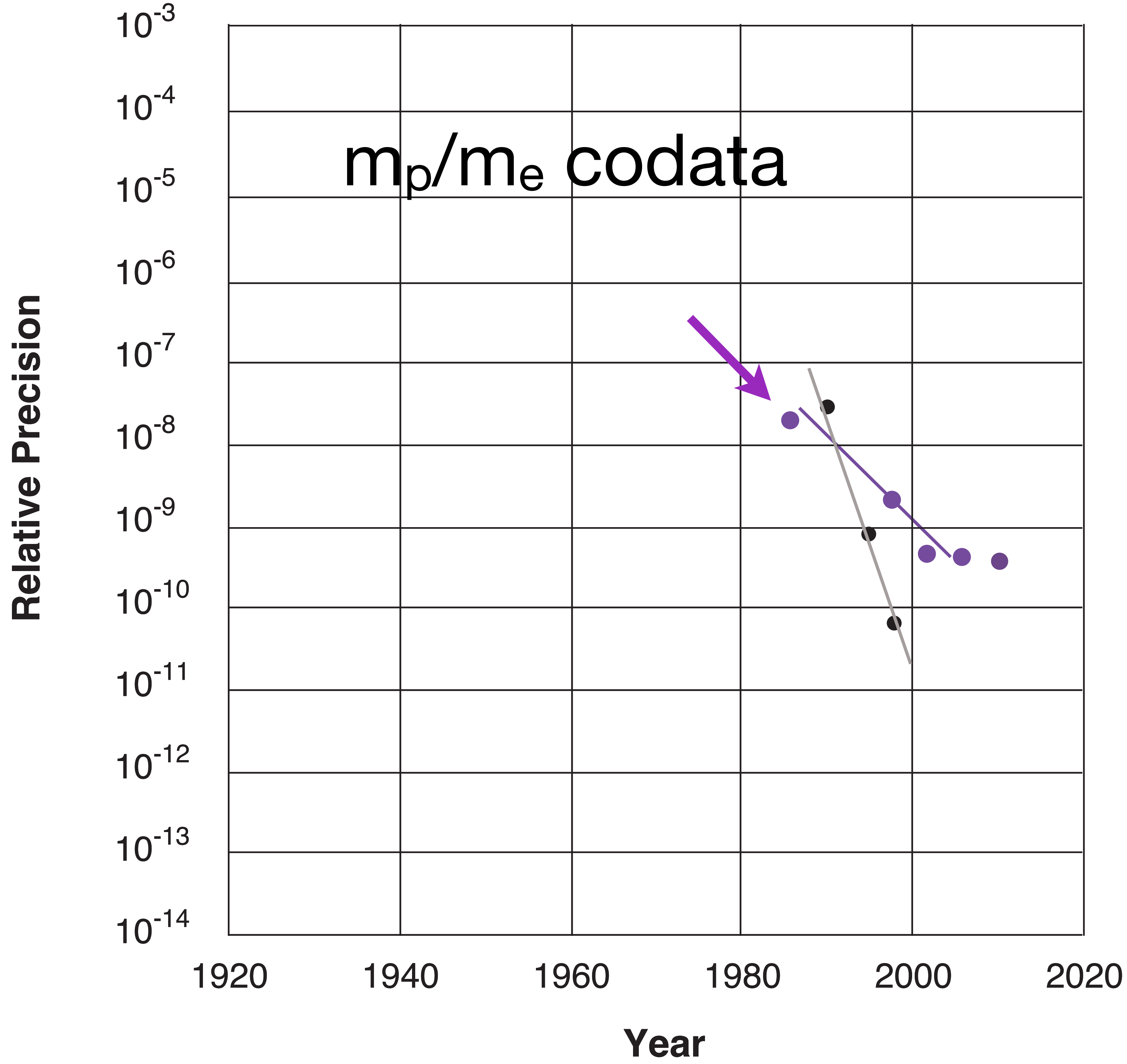


$m_{\bar{p}}$, ($\mu_{\bar{p}}$)
CPT
CODATA
p̄He laser spectroscopy
p̄He MW spectroscopy
p̄ collisions
$\bar{H}$ in cusp trap
$\bar{H}$ ground-state HFS
$\bar{H}$ beamline
Paul trap
results
development

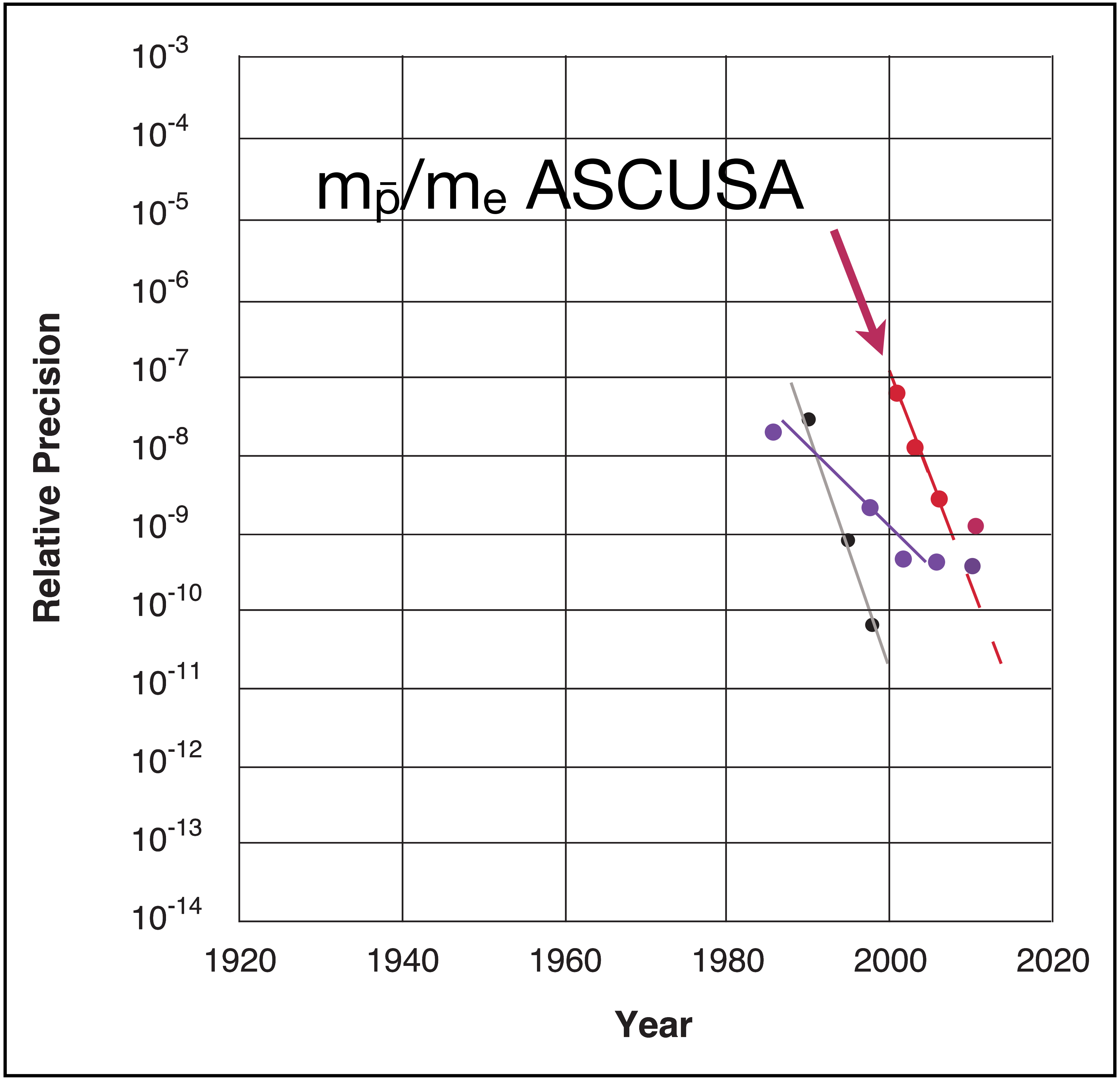

T.W. Hänsch, Nobel lecture
H 1s-2s
laser
comb
Relative Precision
Year
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
1920
1940
1960
1980
2000
2020



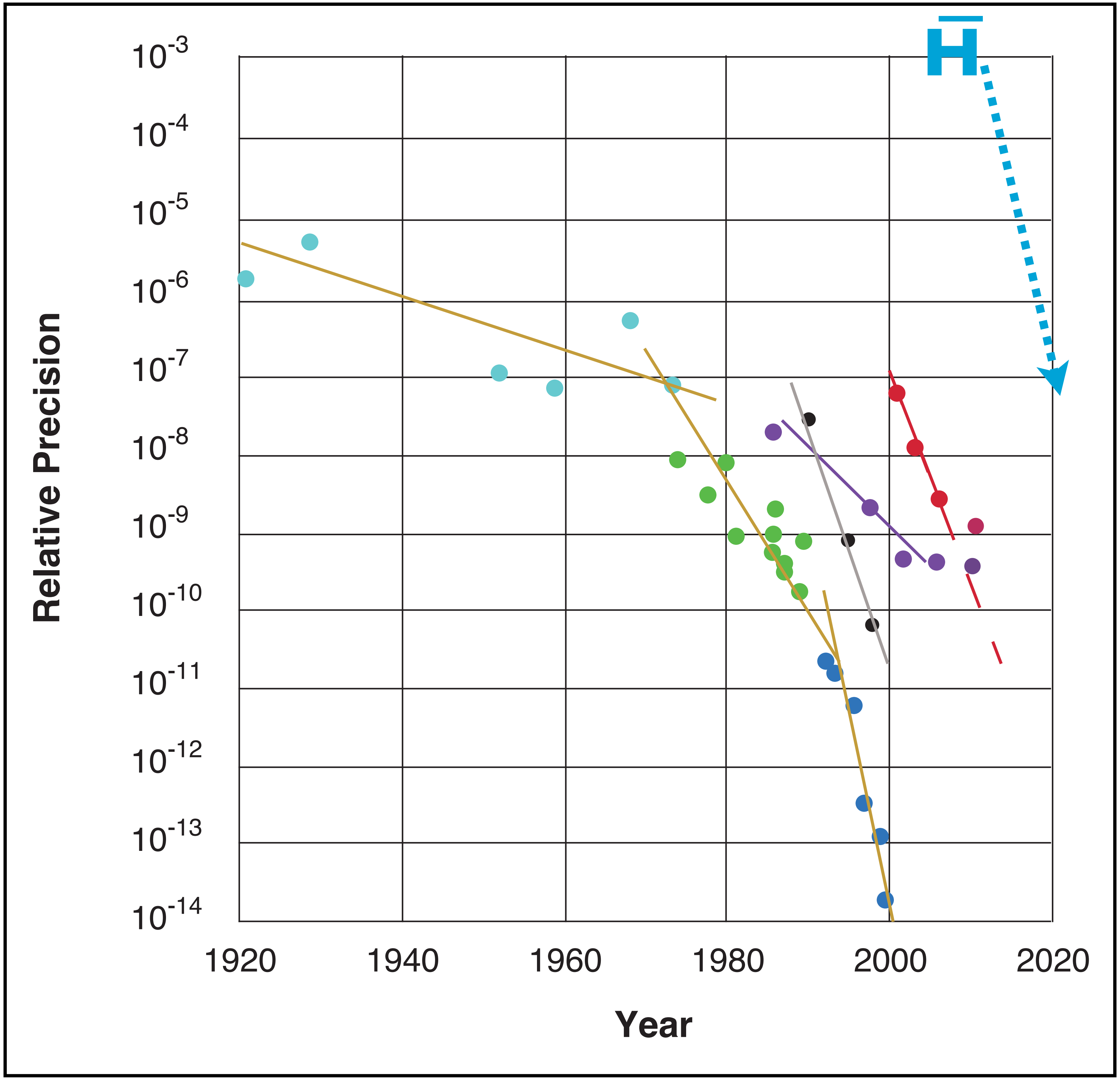
p vs p̄ cyclotron freq.
Relative Precision
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
1920
1940
1960
1980
2000
2020
Year



m_p/m_e codata
Relative Precision
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1920
1940
1960
1980
2000
2020
Year



$m_{\bar{p}}/m_e$ ASCUSA
Relative Precision
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1920
1940
1960
1980
2000
2020
Year



H̄
Relative Precision
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
1920
1940
1960
1980
2000
2020
Year