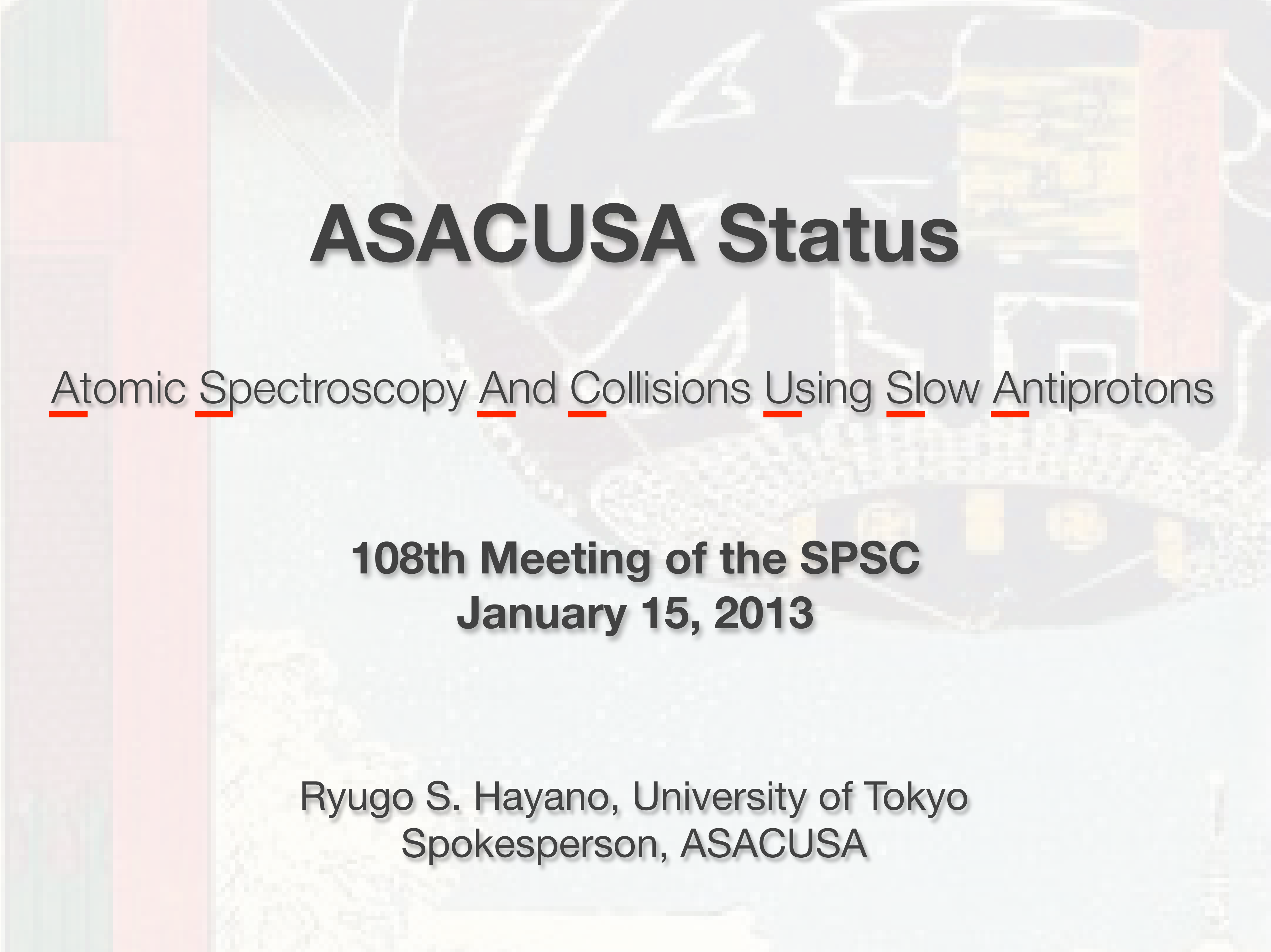


ASACUSA Status

Atomic Spectroscopy And Collisions Using Slow Antiprotons

108th Meeting of the SPSC
January 15, 2013

Ryugo S. Hayano, University of Tokyo
Spokesperson, ASACUSA

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

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

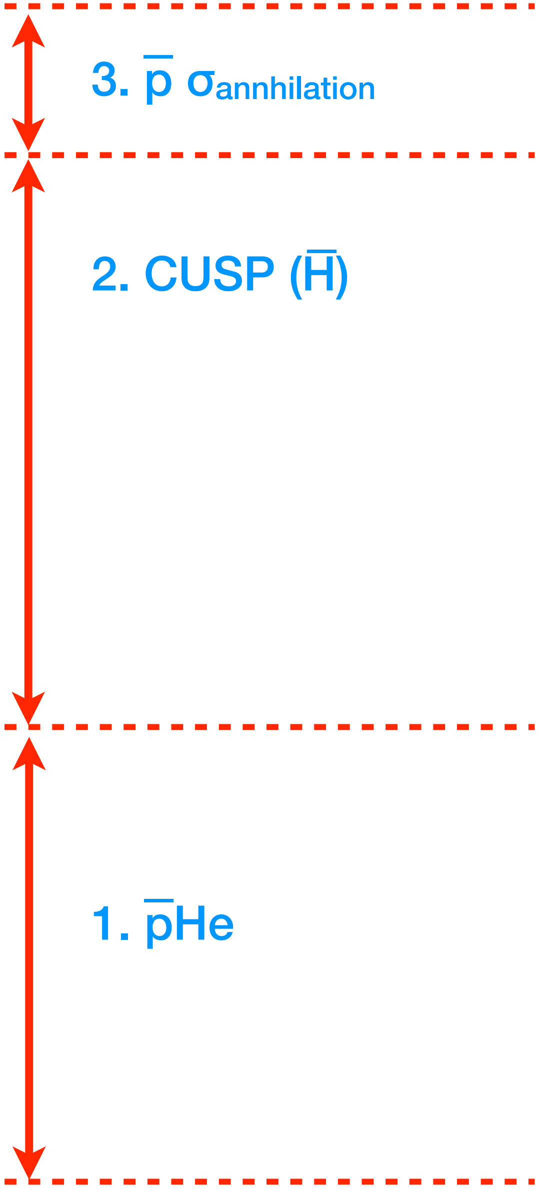
ASACUSA

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)*

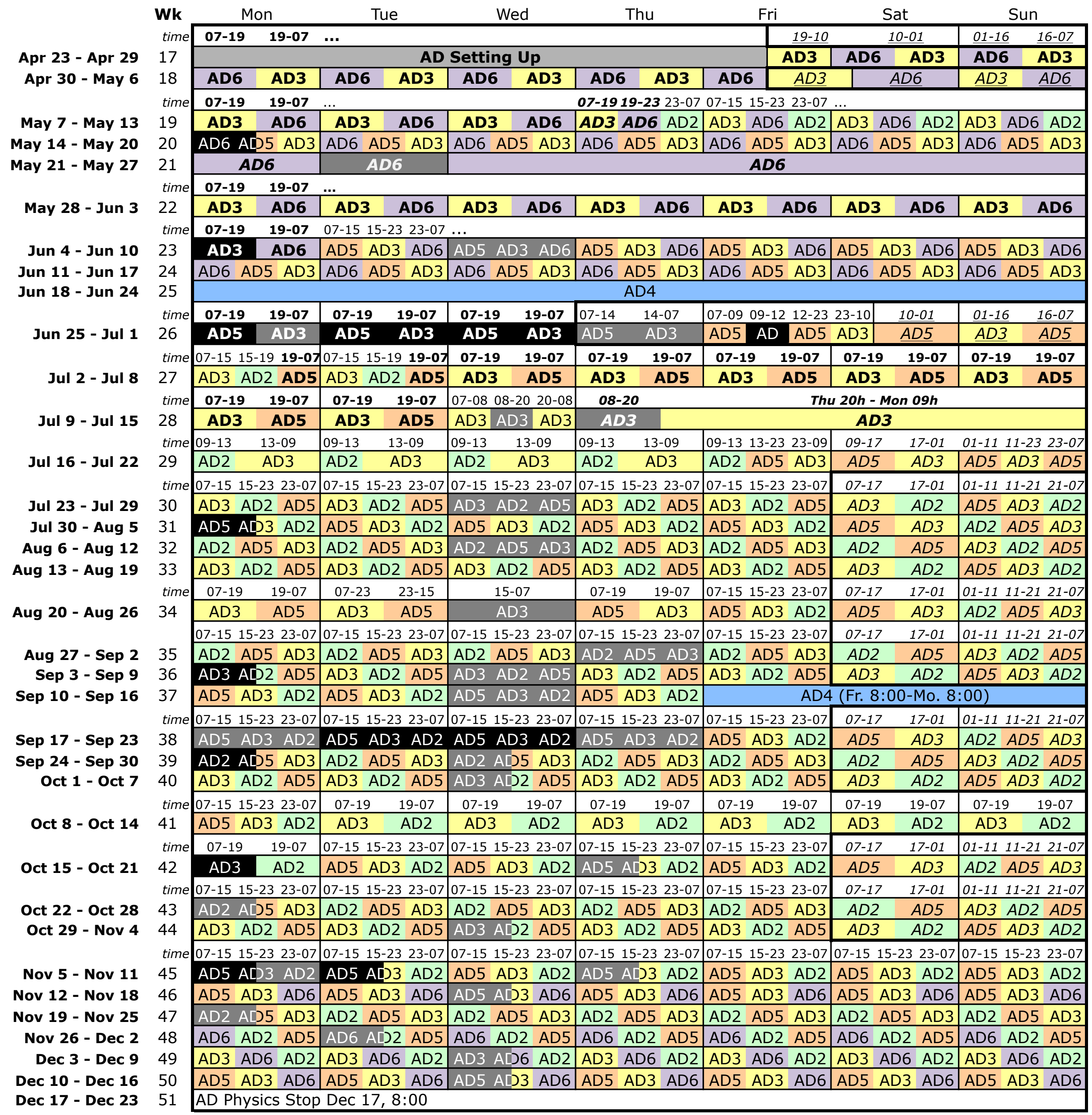
2012 Beam Usage



3. $\bar{p}$ $\sigma_{\text{annihilation}}$

2. CUSP ($\bar{H}$)

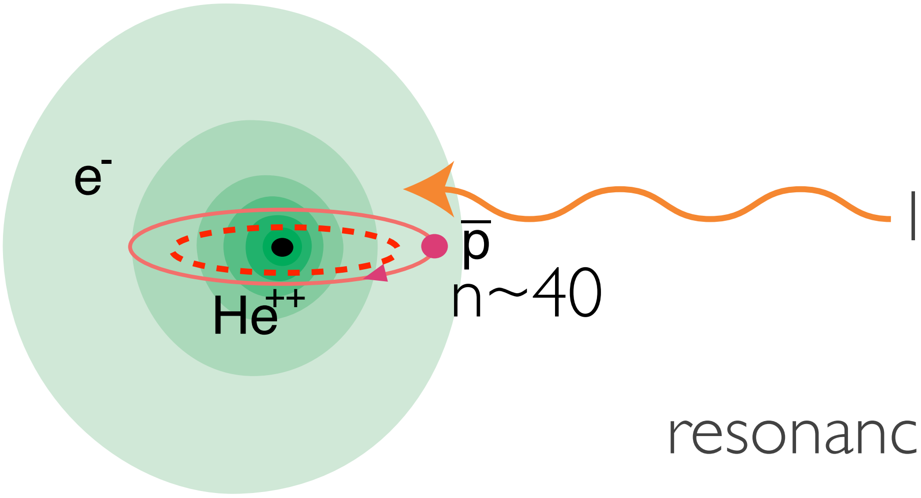
1. $\bar{p}$He



	Wk	Mon	Tue	Wed	Thu	Fri	Sat	Sun
	time	07-19 19-07	...			19-10	10-01	01-16 16-07
Apr 23 - Apr 29	17	AD Setting Up				AD3	AD6 AD3	AD6 AD3
Apr 30 - May 6	18	AD6 AD3	AD6 AD3	AD6 AD3	AD6 AD3	AD6 AD3	AD6	AD3 AD6
	time	07-19 19-07	...		07-19 19-23 23-07	07-15 15-23 23-07	...	
May 7 - May 13	19	AD3 AD6	AD3 AD6	AD3 AD6	AD3 AD6 AD2	AD3 AD6 AD2	AD3 AD6 AD2	AD3 AD6 AD2
May 14 - May 20	20	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3
May 21 - May 27	21	AD6	AD6	AD6				
	time	07-19 19-07	...					
May 28 - Jun 3	22	AD3 AD6	AD3 AD6	AD3 AD6	AD3 AD6	AD3 AD6	AD3 AD6	AD3 AD6
	time	07-19 19-07	07-15 15-23 23-07	...				
Jun 4 - Jun 10	23	AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6
Jun 11 - Jun 17	24	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3	AD6 AD5 AD3
Jun 18 - Jun 24	25	AD4						
	time	07-19 19-07	07-19 19-07	07-19 19-07	07-14 14-07	07-09 09-12 12-23 23-10	10-01	01-16 16-07
Jun 25 - Jul 1	26	AD5 AD3	AD5 AD3	AD5 AD3	AD5 AD3	AD5 AD AD5 AD3	AD5	AD3 AD5
	time	07-15 15-19 19-07	07-15 15-19 19-07	07-19 19-07	07-19 19-07	07-19 19-07	07-19 19-07	07-19 19-07
Jul 2 - Jul 8	27	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD5	AD3 AD5	AD3 AD5	AD3 AD5	AD3 AD5
	time	07-19 19-07	07-19 19-07	07-08 08-20 20-08	08-20		Thu 20h - Mon 09h	
Jul 9 - Jul 15	28	AD3 AD5	AD3 AD5	AD3 AD3 AD3	AD3		AD3	
	time	09-13 13-09	09-13 13-09	09-13 13-09	09-13 13-09	09-13 13-23 23-09	09-17 17-01	01-11 11-23 23-07
Jul 16 - Jul 22	29	AD2 AD3	AD2 AD3	AD2 AD3	AD2 AD3	AD2 AD5 AD3	AD5 AD3	AD5 AD3 AD5
	time	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-17 17-01	01-11 11-21 21-07
Jul 23 - Jul 29	30	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2	AD5 AD3 AD2
Jul 30 - Aug 5	31	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3	AD2 AD5 AD3
Aug 6 - Aug 12	32	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5	AD3 AD2 AD5
Aug 13 - Aug 19	33	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2	AD5 AD3 AD2
	time	07-19 19-07	07-23 23-15	15-07	07-19 19-07	07-15 15-23 23-07	07-17 17-01	01-11 11-21 21-07
Aug 20 - Aug 26	34	AD3 AD5	AD3 AD5	AD3	AD5 AD3	AD5 AD3 AD2	AD5 AD3	AD2 AD5 AD3
		07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-17 17-01	01-11 11-21 21-07
Aug 27 - Sep 2	35	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5	AD3 AD2 AD5
Sep 3 - Sep 9	36	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2	AD5 AD3 AD2
Sep 10 - Sep 16	37	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD4 (Fr. 8:00-Mo. 8:00)		
	time	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-17 17-01	01-11 11-21 21-07
Sep 17 - Sep 23	38	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3	AD2 AD5 AD3
Sep 24 - Sep 30	39	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5	AD3 AD2 AD5
Oct 1 - Oct 7	40	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2	AD5 AD3 AD2
	time	07-15 15-23 23-07	07-19 19-07	07-19 19-07	07-19 19-07	07-19 19-07	07-19 19-07	07-19 19-07
Oct 8 - Oct 14	41	AD5 AD3 AD2	AD3 AD2	AD3 AD2	AD3 AD2	AD3 AD2	AD3 AD2	AD3 AD2
	time	07-19 19-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-17 17-01	01-11 11-21 21-07
Oct 15 - Oct 21	42	AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3	AD2 AD5 AD3
	time	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-17 17-01	01-11 11-21 21-07
Oct 22 - Oct 28	43	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5	AD3 AD2 AD5
Oct 29 - Nov 4	44	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2 AD5	AD3 AD2	AD5 AD3 AD2
	time	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07	07-15 15-23 23-07
Nov 5 - Nov 11	45	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2	AD5 AD3 AD2
Nov 12 - Nov 18	46	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6
Nov 19 - Nov 25	47	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3	AD2 AD5 AD3
Nov 26 - Dec 2	48	AD6 AD2 AD5	AD6 AD2 AD5	AD6 AD2 AD5	AD6 AD2 AD5	AD6 AD2 AD5	AD6 AD2 AD5	AD6 AD2 AD5
Dec 3 - Dec 9	49	AD3 AD6 AD2	AD3 AD6 AD2	AD3 AD6 AD2	AD3 AD6 AD2	AD3 AD6 AD2	AD3 AD6 AD2	AD3 AD6 AD2
Dec 10 - Dec 16	50	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6	AD5 AD3 AD6
Dec 17 - Dec 23	51	AD Physics Stop Dec 17, 8:00						

1. $\bar{p}$He laser spectroscopy

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



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

resonance detection via $\bar{p}$ annihilation

Frequency

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

$\bar{p}$ (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.

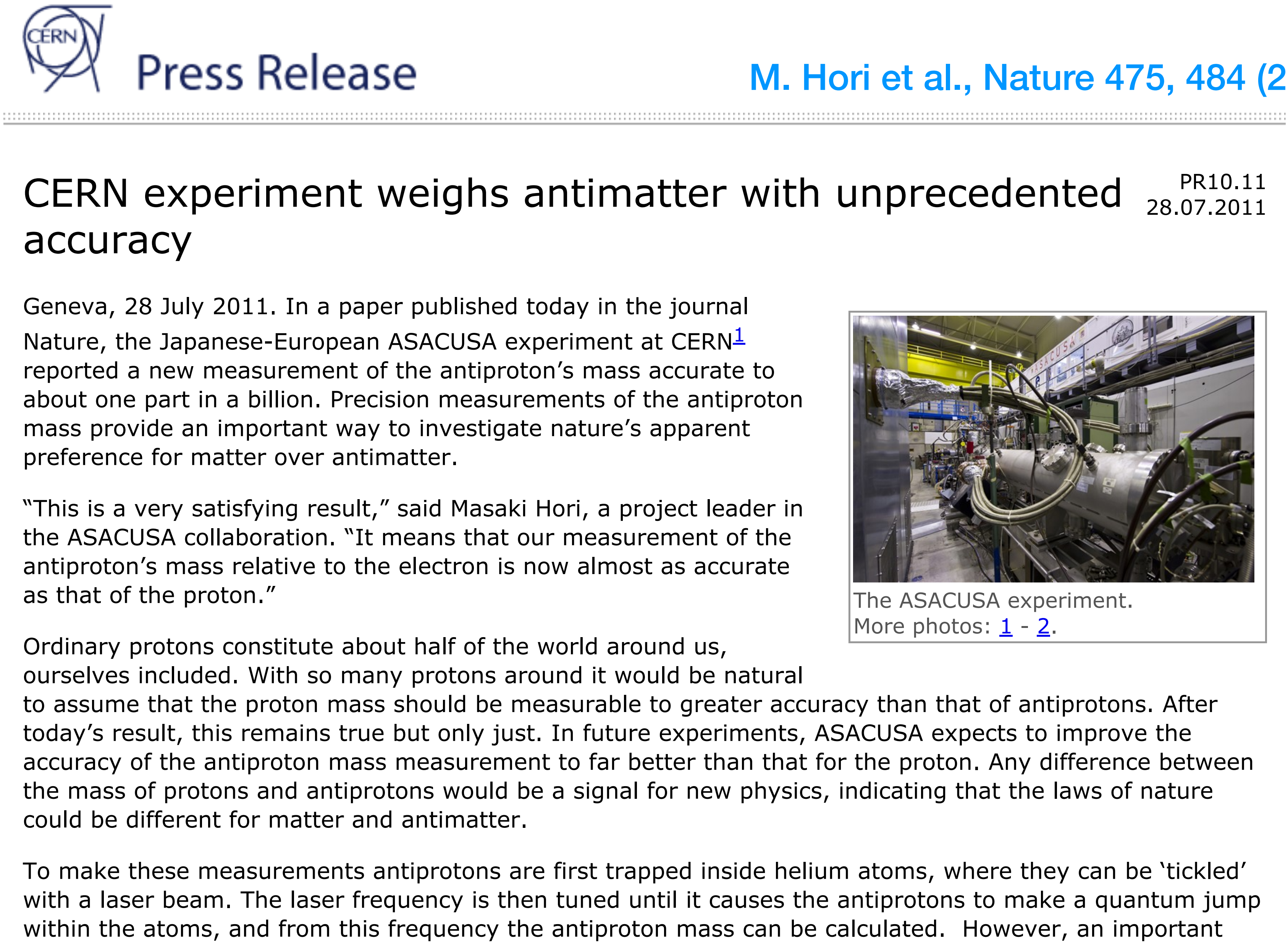
DOI: 10.1103/RevModPhys.84.1527 PACS numbers: 06.20.Jr, 12.20.−m

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

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



Press Release

PR10.11
28.07.2011

CERN experiment weighs antimatter with unprecedented accuracy

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.

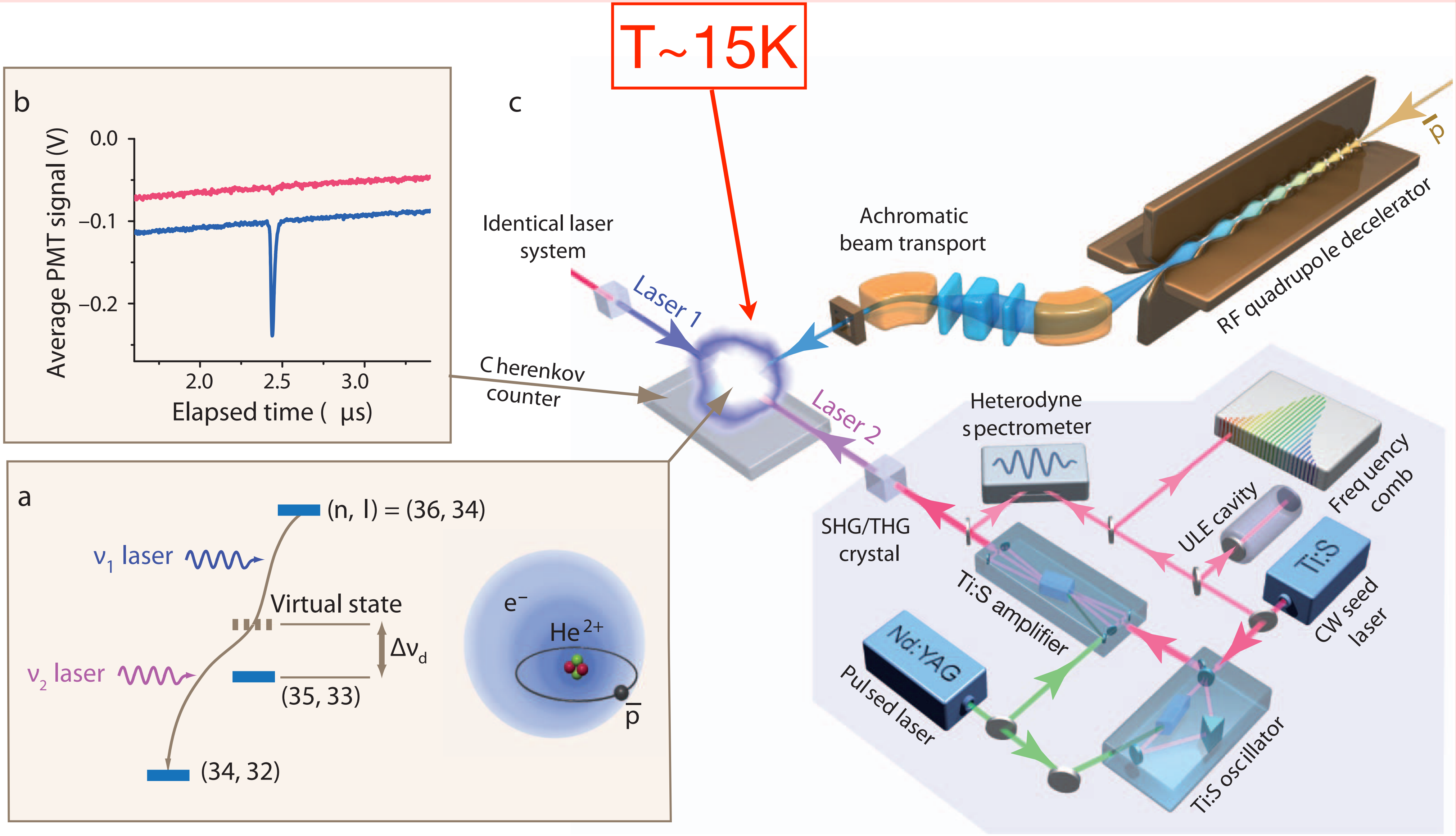
"This is a very satisfying result," said Masaki Hori, a project leader in the ASACUSA collaboration. "It means that our measurement of the antiproton's mass relative to the electron is now almost as accurate as that of the proton."

The ASACUSA experiment.
More photos: 1 - 2.

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

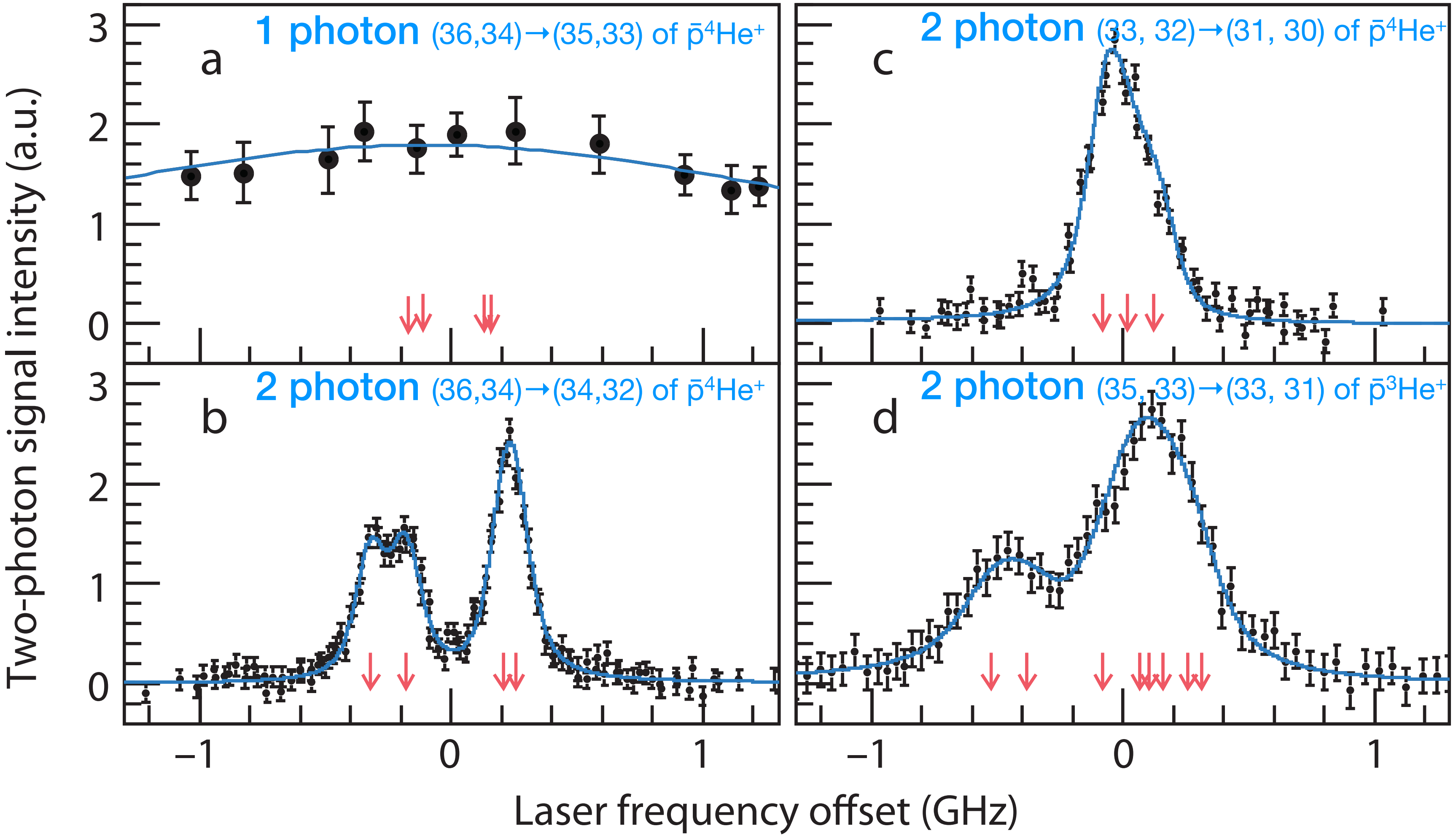
$\bar{p}$He sub-Doppler 2-photon spectroscopy



T~15K

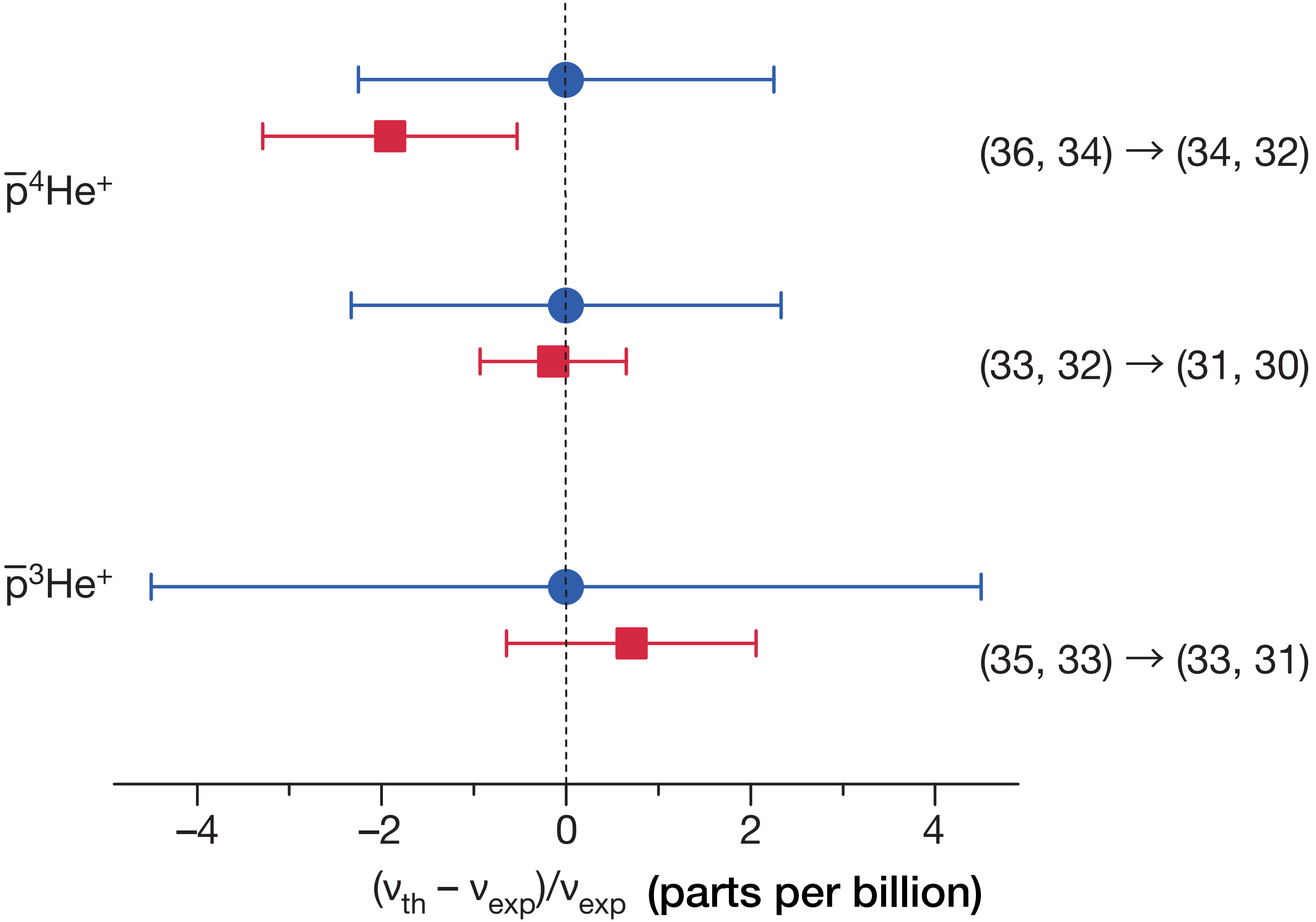
M. Hori et al., Nature 475, 484 (2011).

T~15K

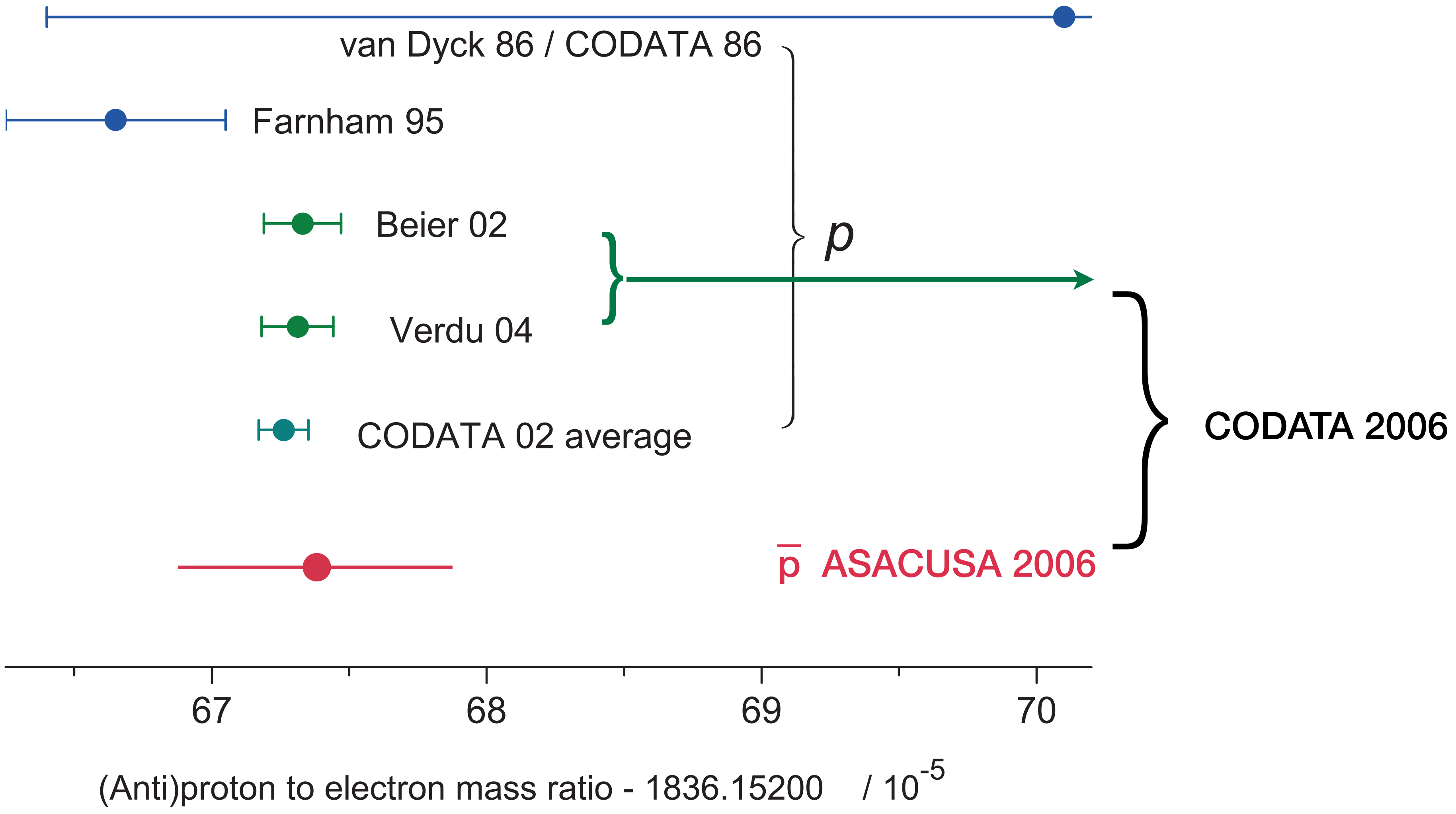


M. Hori et al., Nature 475, 484 (2011).

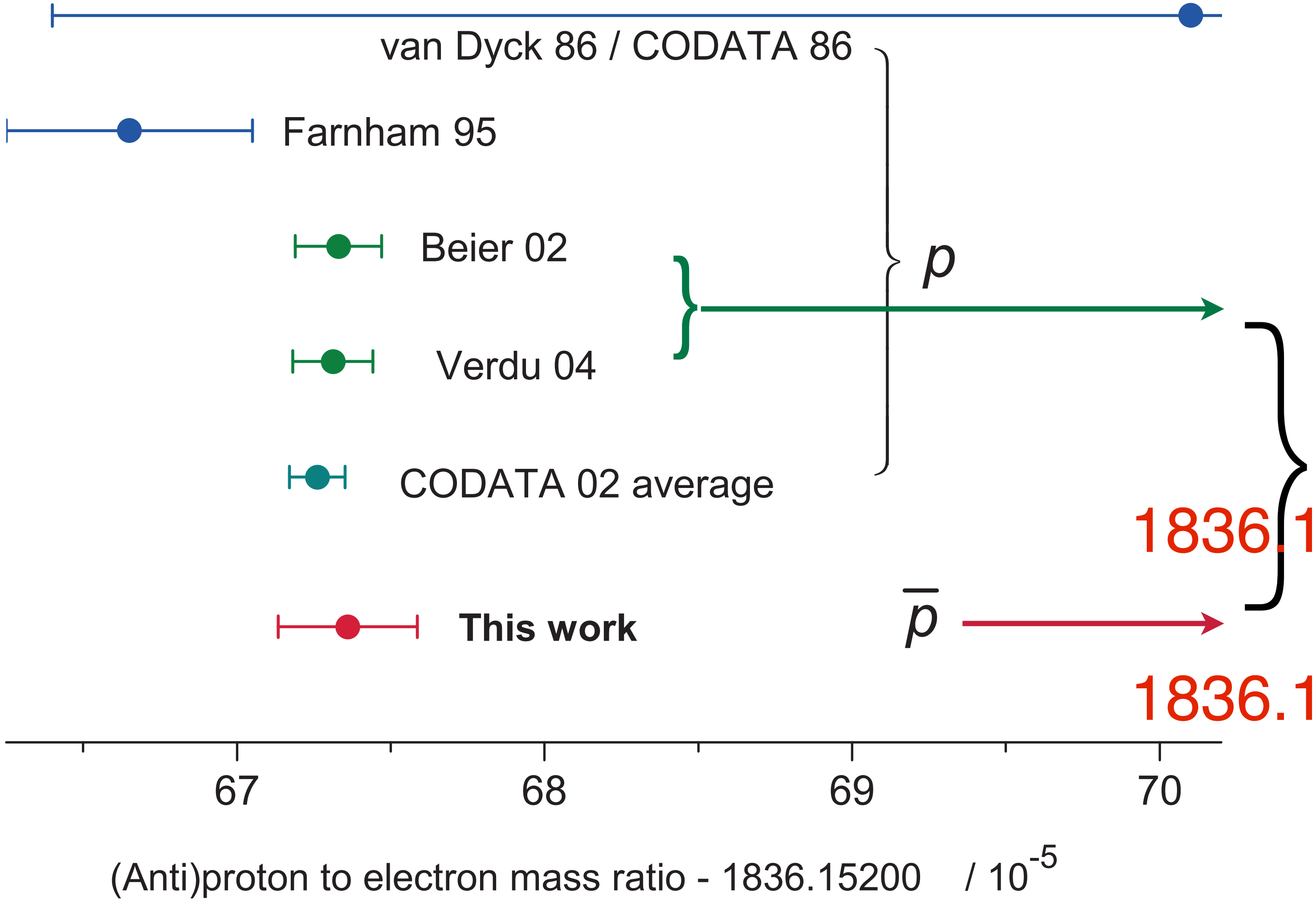
Vtheory VS Vexperiment



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


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

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



CODATA 2010

1836.15267245(75)

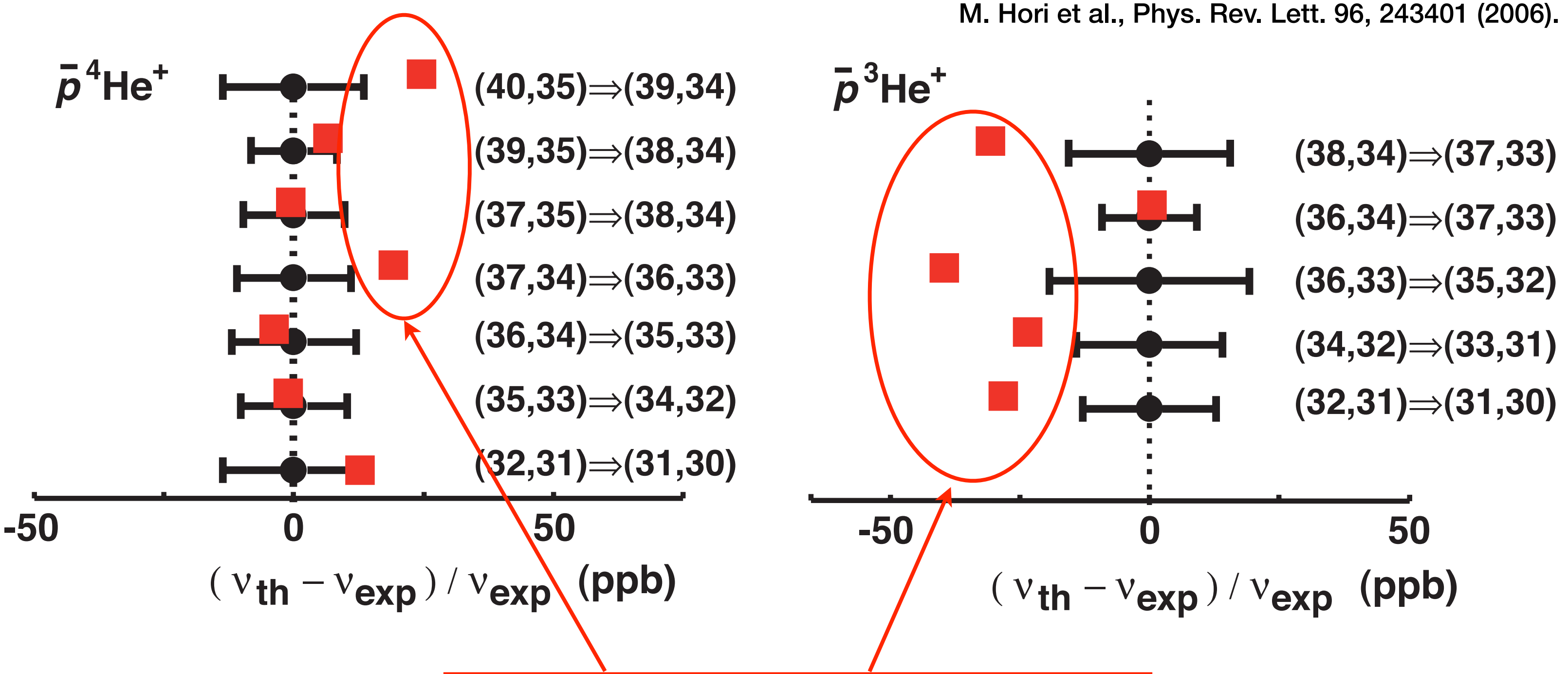
1836.1526736(23)

Nature 475, 484

1-photon spectroscopy of “cold” $\bar{p}$He in 2011-2012

↓ this was the problem in 2006

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



10-30 ppb differences

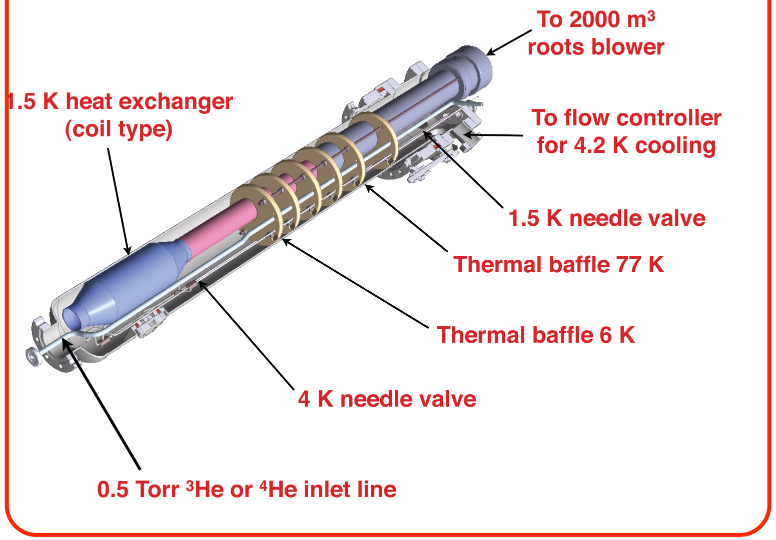
T~15K→T=1.5K

- “cold” $\bar{p}$He :
  (1) less Doppler
  (2) improve S/N
  (3) less collisional broadening

- Improvements
  - (1) laser
  - (2) $\bar{p}$ beam (electrostatic quad)
  - (3) detector (Cherenkov)
  - (4) collisional shift corrections ←
  - (5) AC stark shift corrections ←

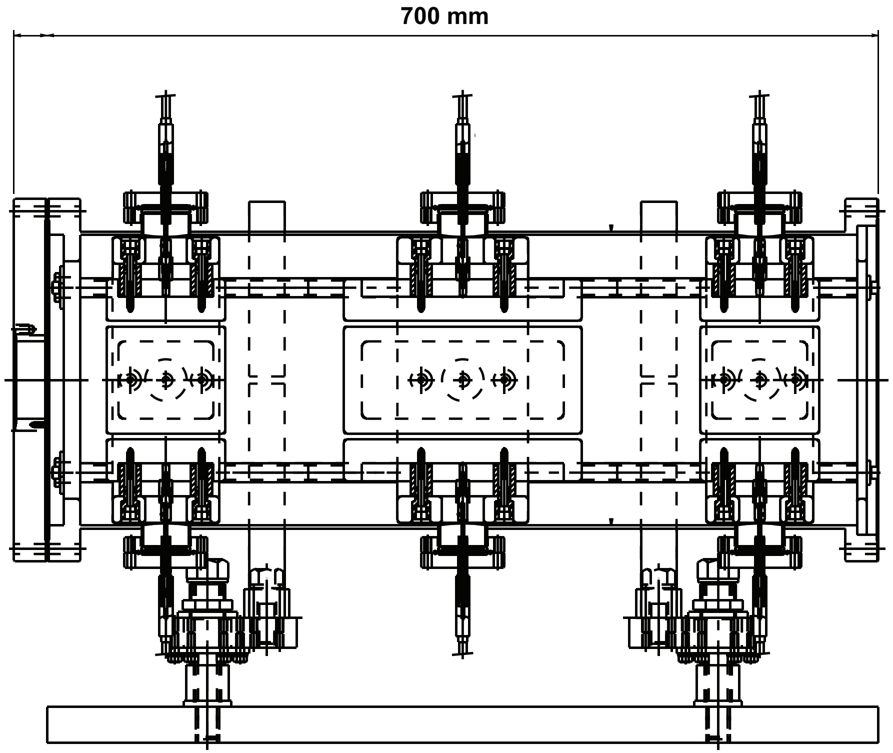
measurements at different target densities, and with various laser powers (time consuming)

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

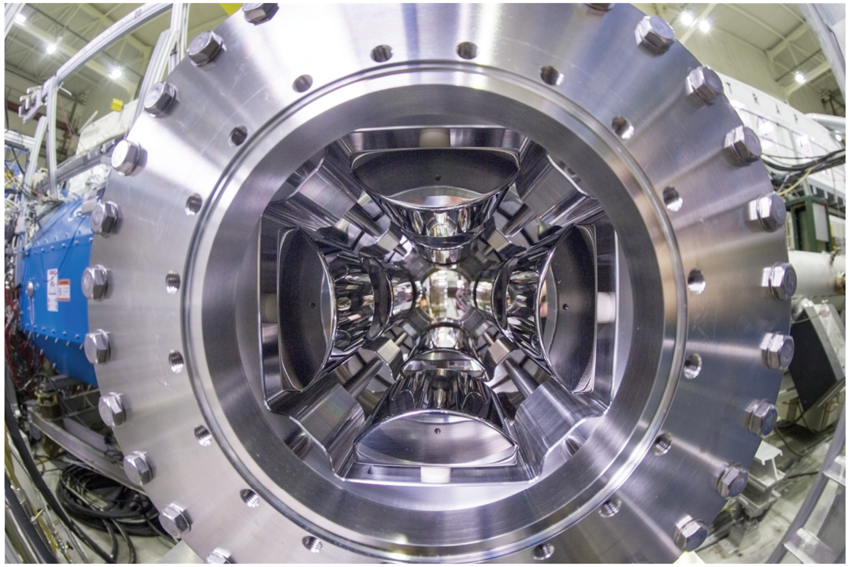


electrostatic quadrupole triplet lenses

a):



b):

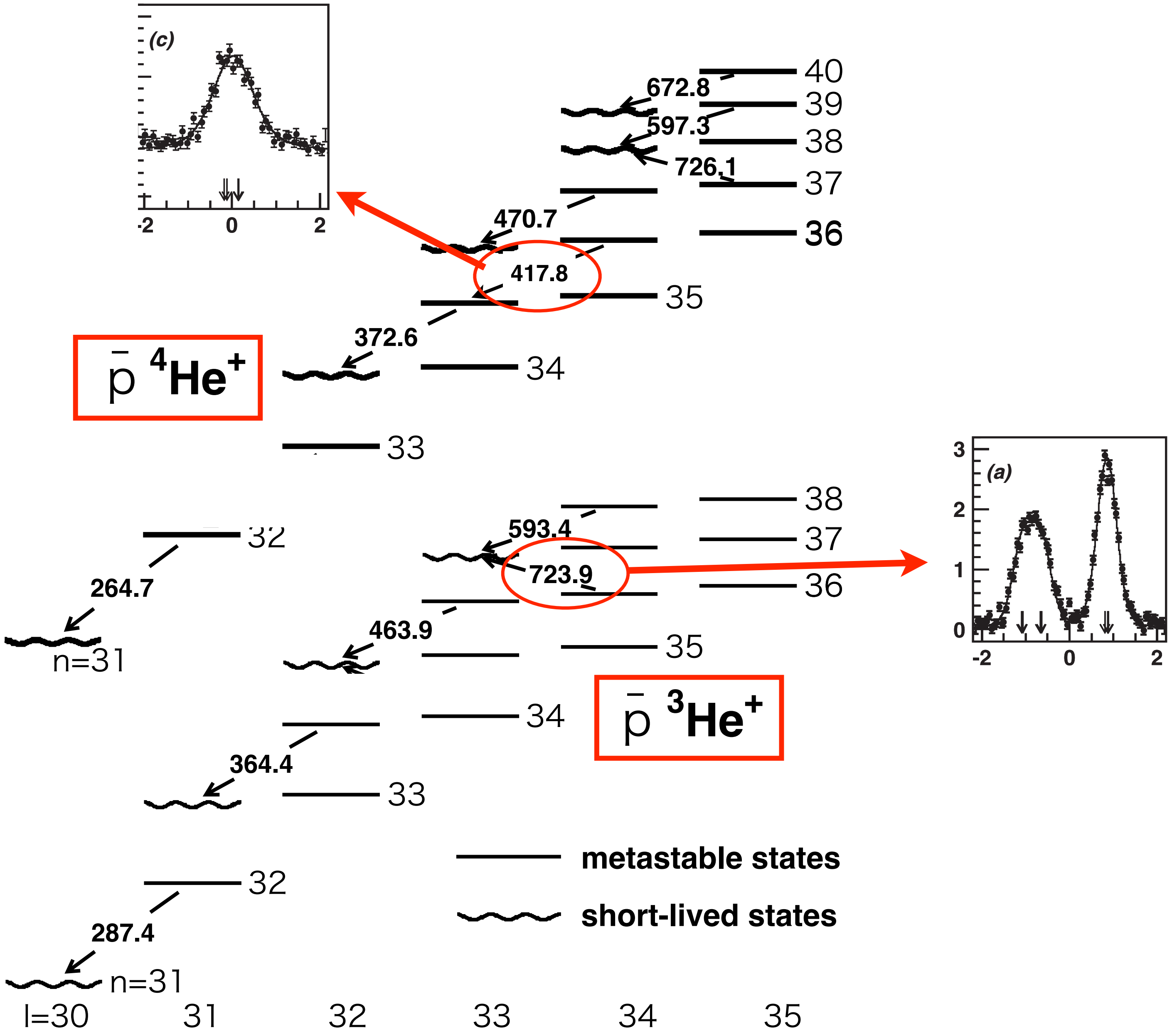


between the RFQD and the “cold” helium target

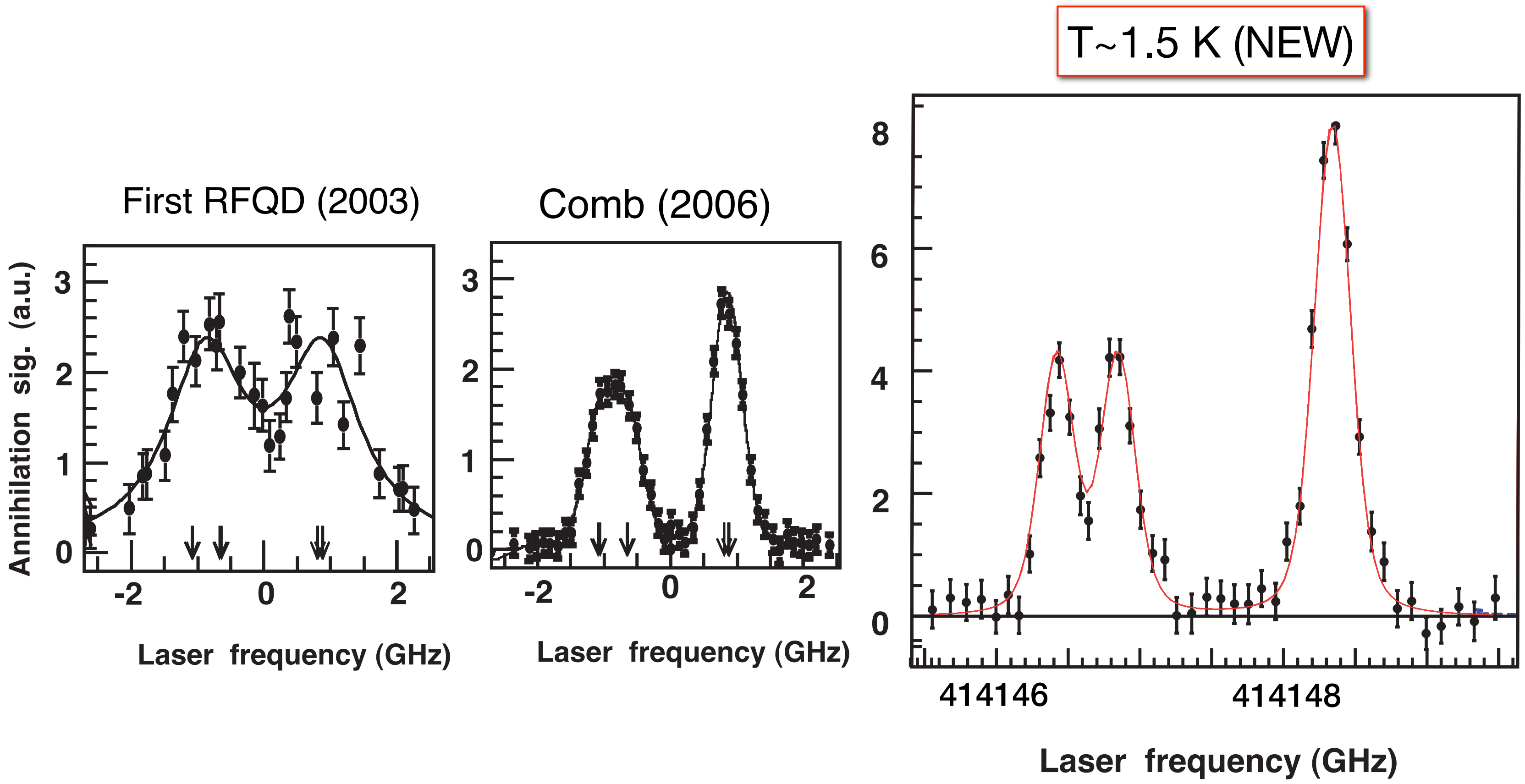
reduce p̄ beam halo, improve focus

part of an R&D for ELENA

Accessible 1-photon transitions (spectra from 2006)



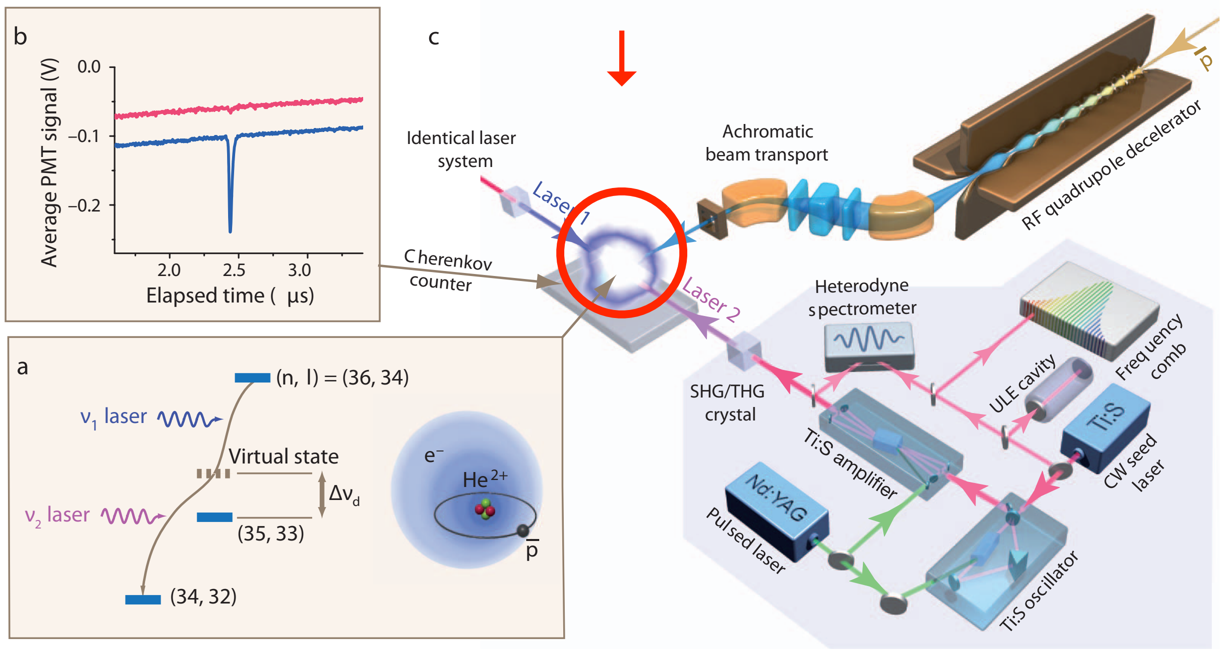
example (36,34)→(37,33) in $\bar{p}^{3}\mathrm{He}^{+}$ (wavelength ~ 723 nm)



$\nu_{th}-\nu_{exp}$ difference 10-30 ppb → <3~6 ppb

2-photon spectroscopy of “cold” $\bar{p}$He in 2012

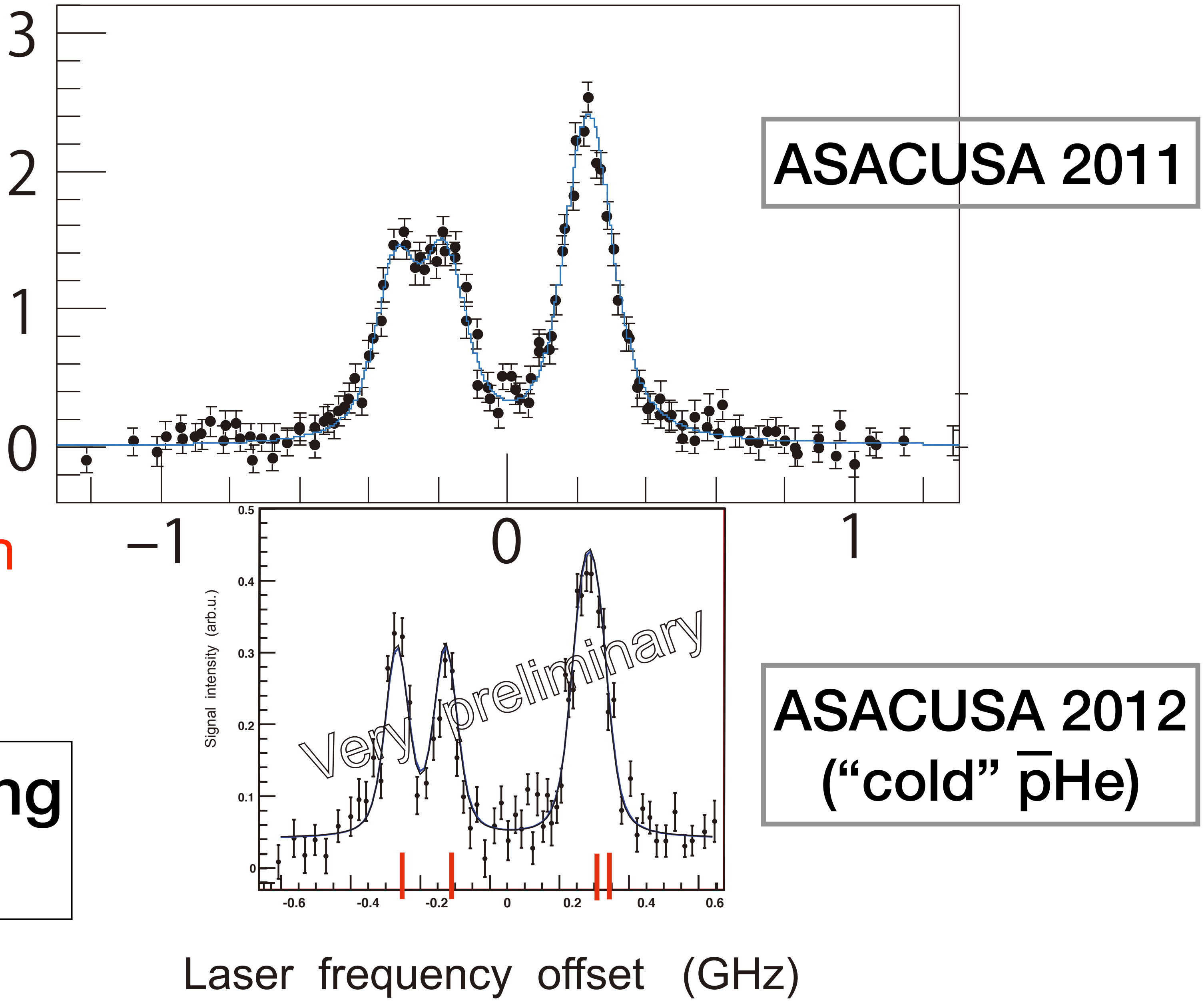
T~15K



“Cold (T=1.5)”
$\bar{p}$He$^+$
in 2012

2011 (Nature 475, 484)

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



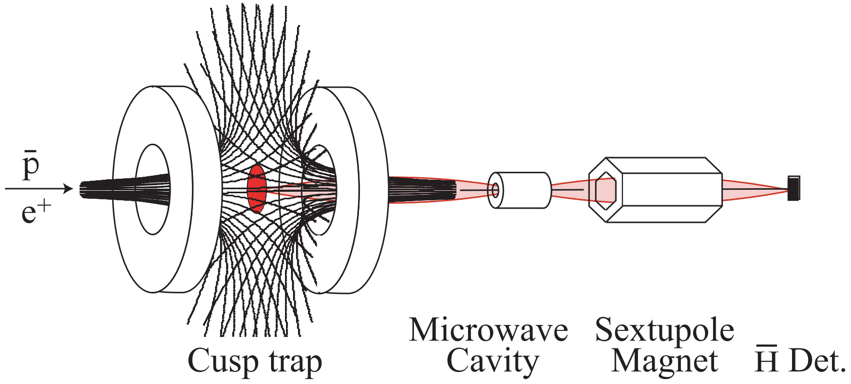
↓

spectral resolution x 3

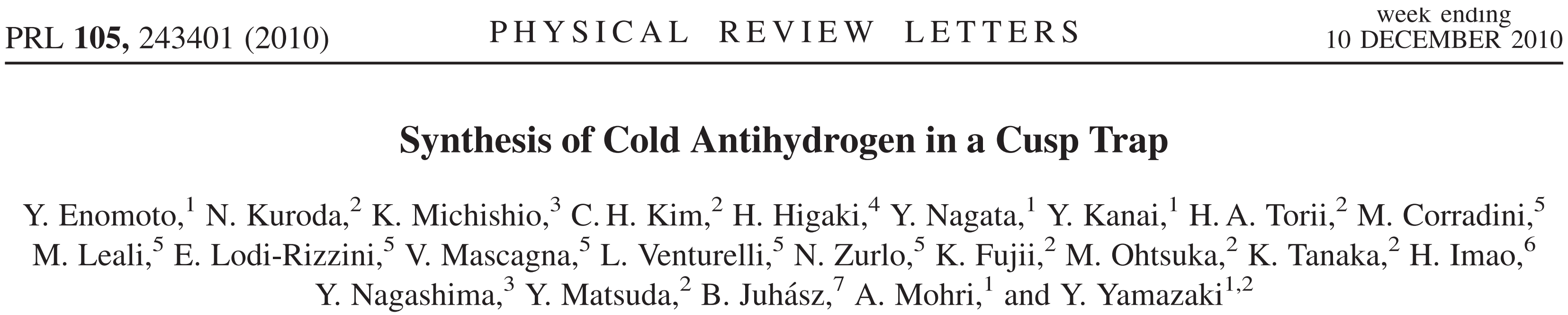
↓

data taking in 2014

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



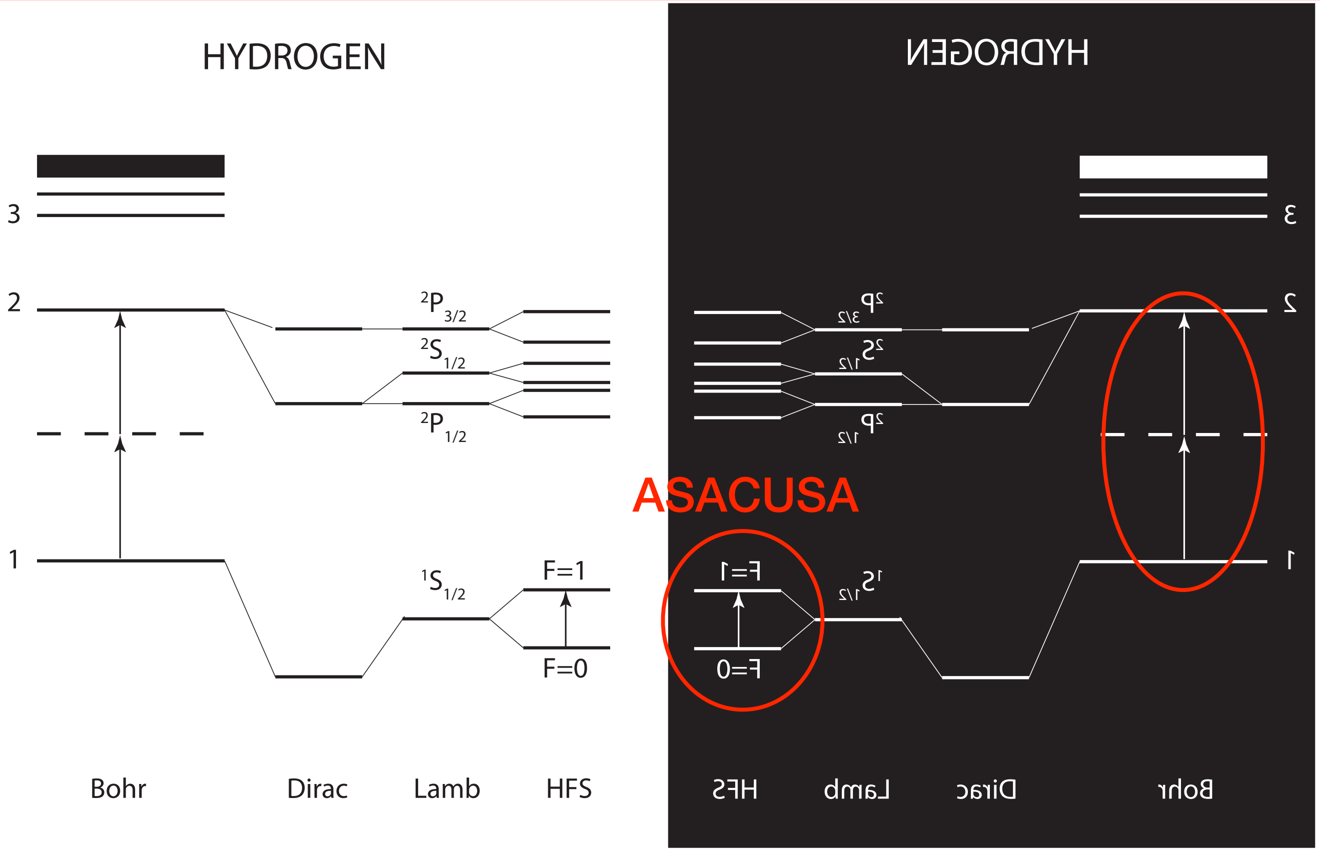
$\bar{\mathrm{H}}$ production demonstrated in 2010
$\bar{\mathrm{H}}$ beam development started in 2011
$\bar{\mathrm{H}}$ production rate optimization
& full setup development in 2012



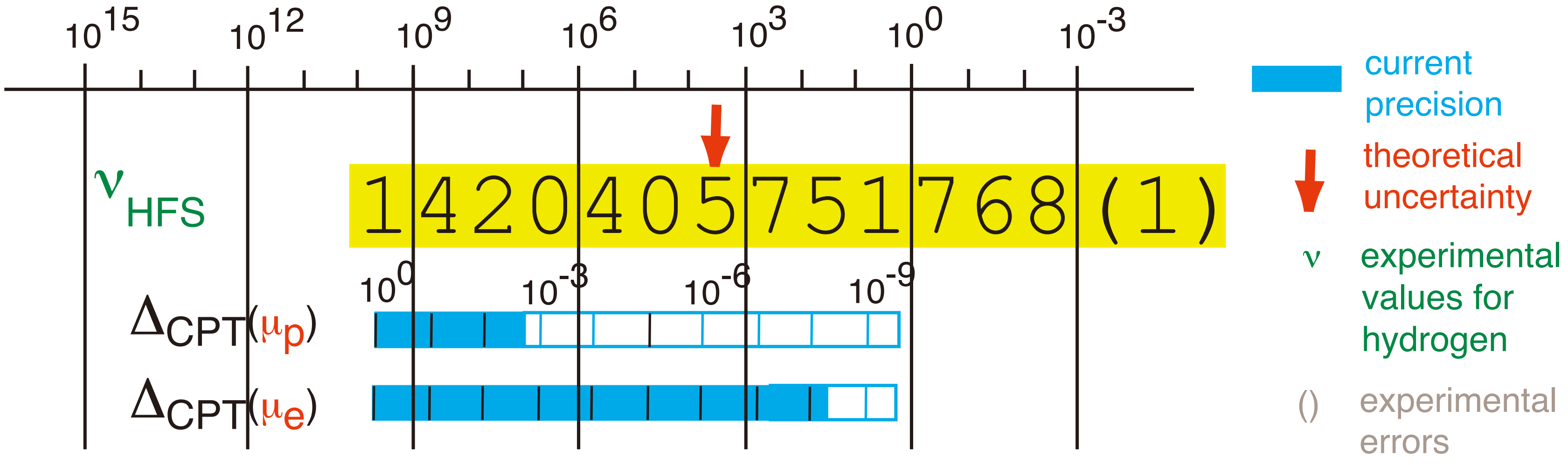
PRL **105,** 243401 (2010) PHYSICAL REVIEW LETTERS week ending 10 DECEMBER 2010

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]

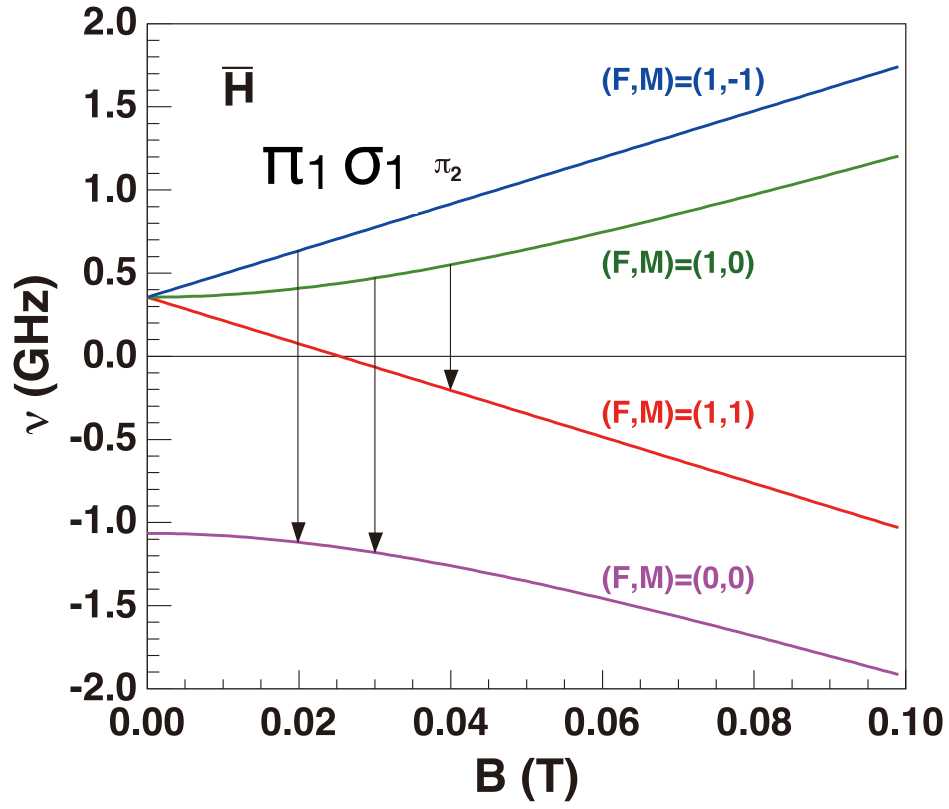


TRANSITION FREQUENCY (Hz)



Method

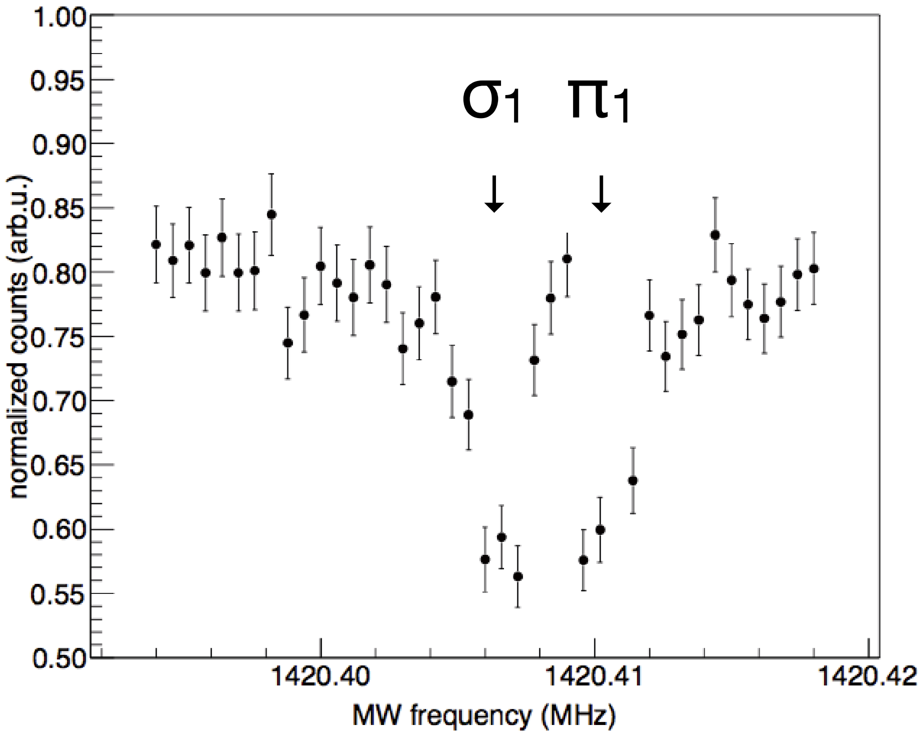
- (anti)atomic beam
- measure σ_1 at several B's, extrapolate to $B = 0$
- achievable precision $\lesssim 10^{-6}$ for $T \leq 100$ K
- $> 100\ \bar{H}$/s in 1S state needed



Method

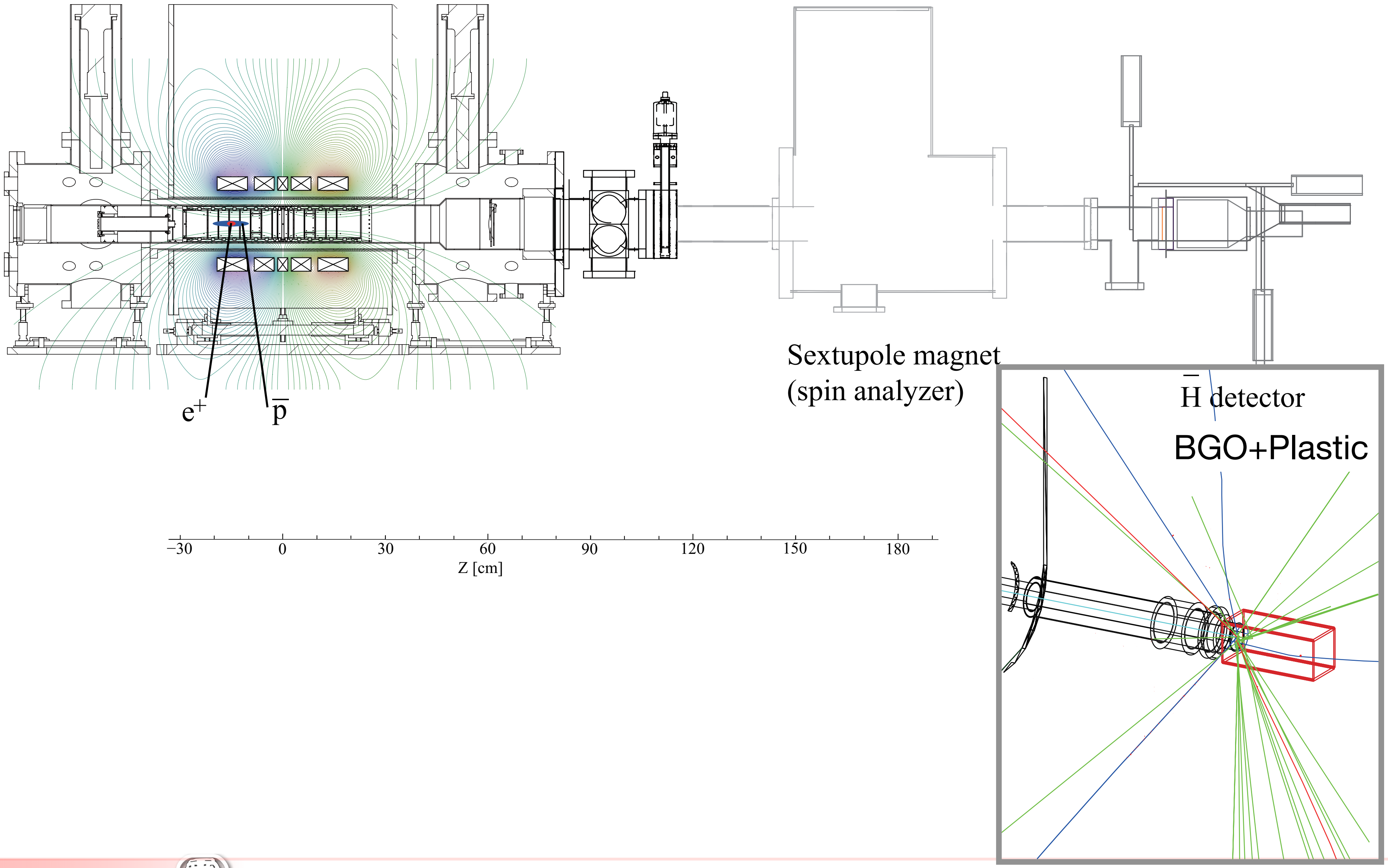
- (anti)atomic beam
- measure σ_1 at several B's, extrapolate to B = 0
- achievable precision $\lesssim 10^{-6}$ for T ≤ 100 K

Simulated T=5K, B=1G



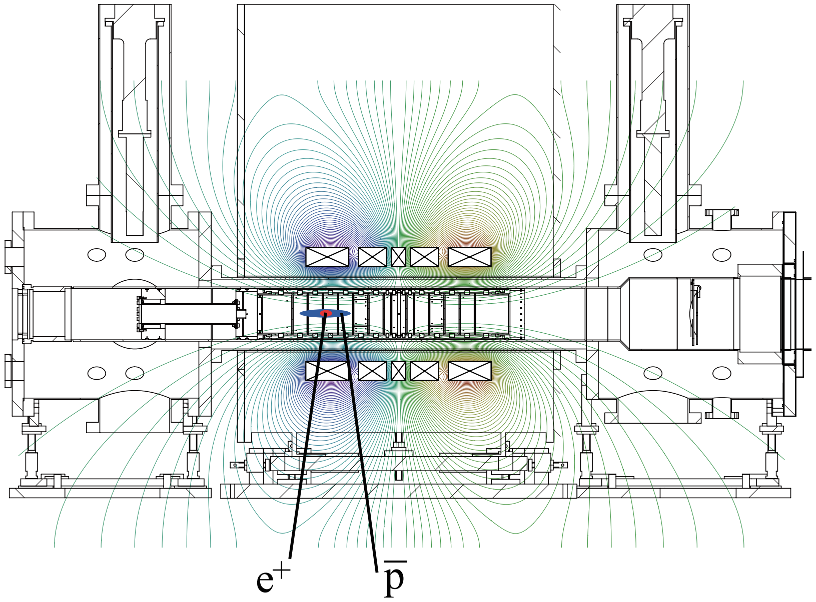
σ_1 transition, $\Delta B/B = 1\%$

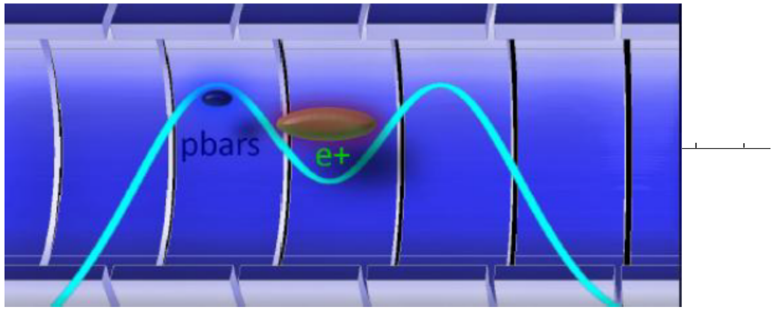
$\bar{H}$ setup in 2012

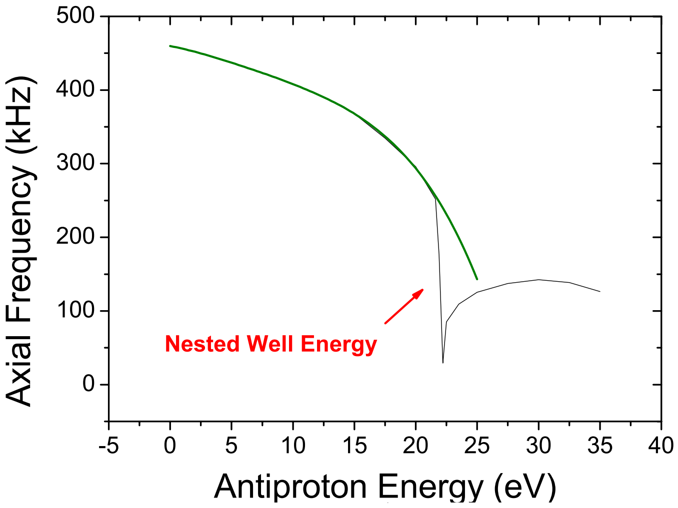


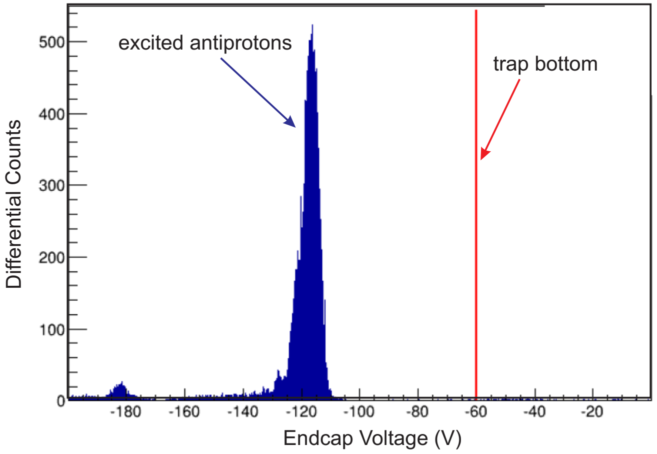
Autoresonance scheme developed

(à la ALPHA)

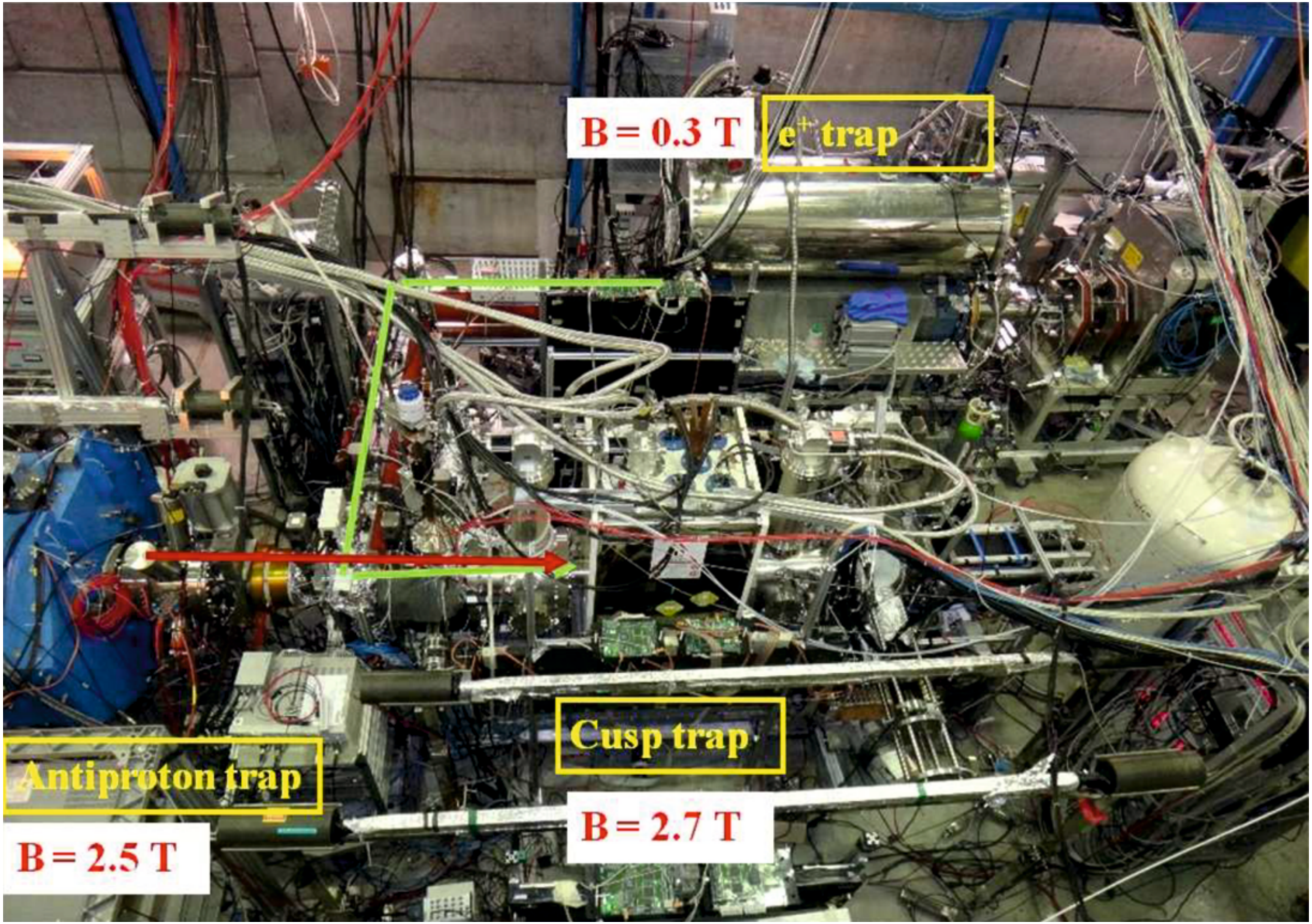




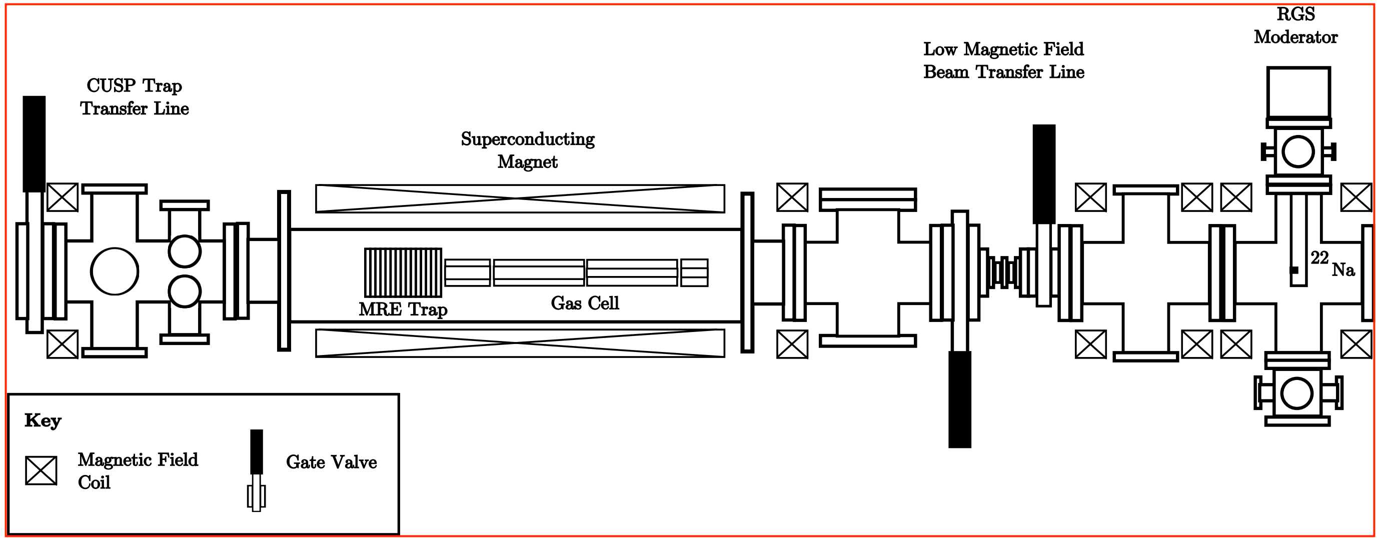


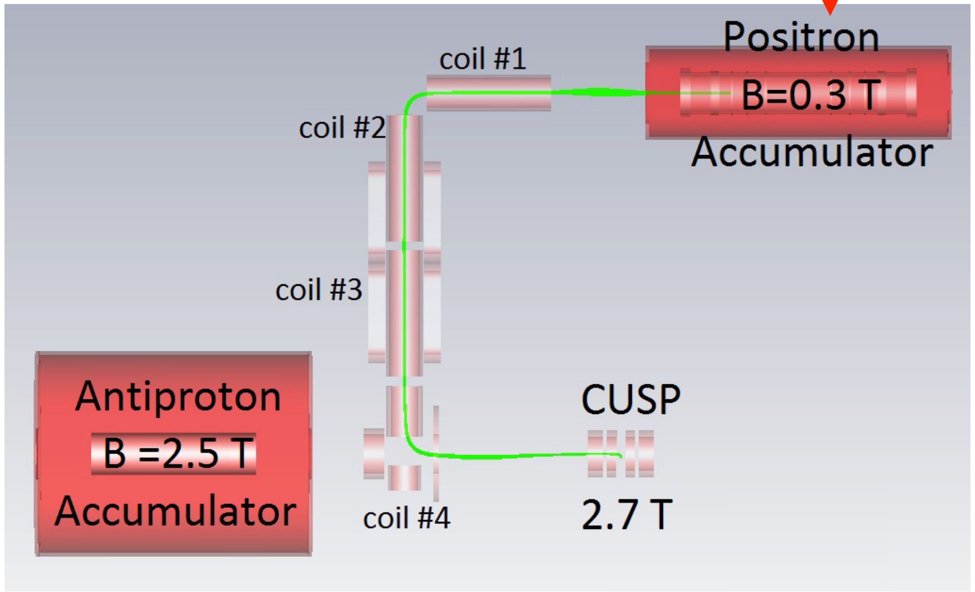


Sweep the axial-drive frequency,
change the $\bar{p}$ energy
optimize the $\bar{H}$ production rate


B = 0.3 T
e^+ trap
Cusp trap
Antiproton trap
B = 2.5 T
B = 2.7 T

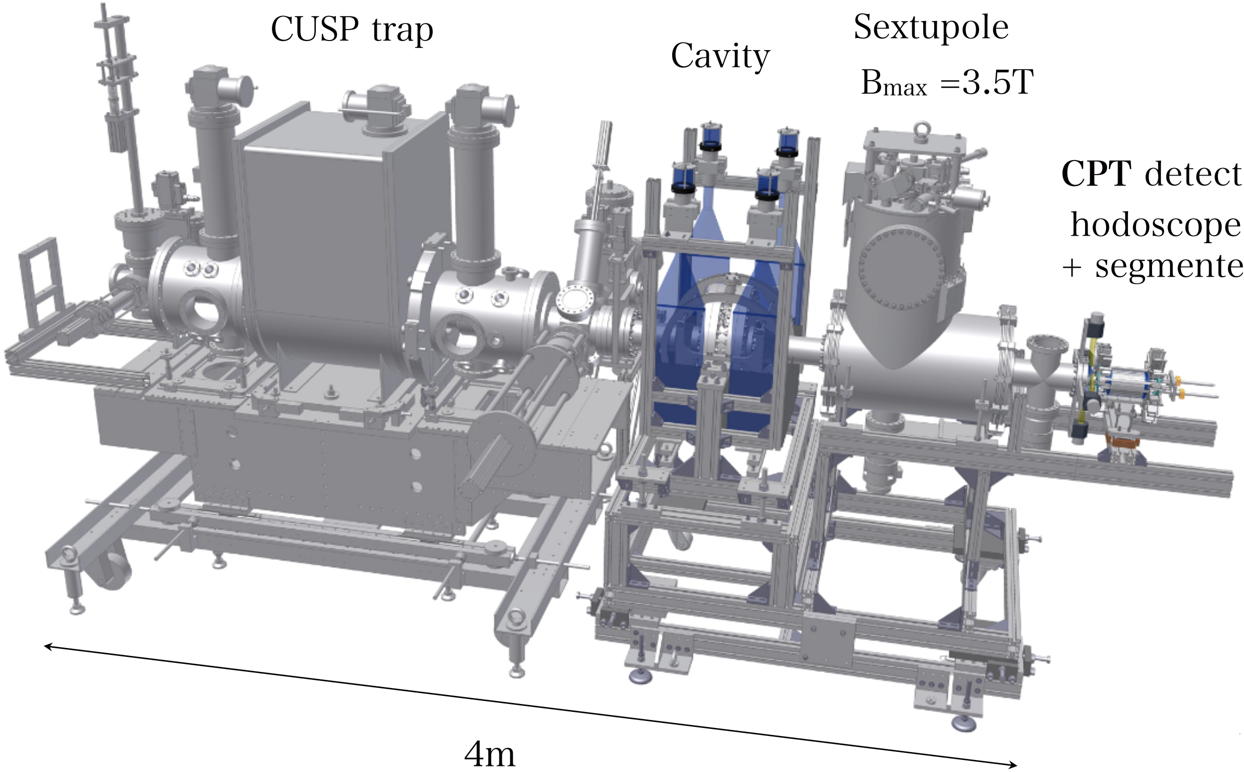
Positron trap (x 20 improvement)



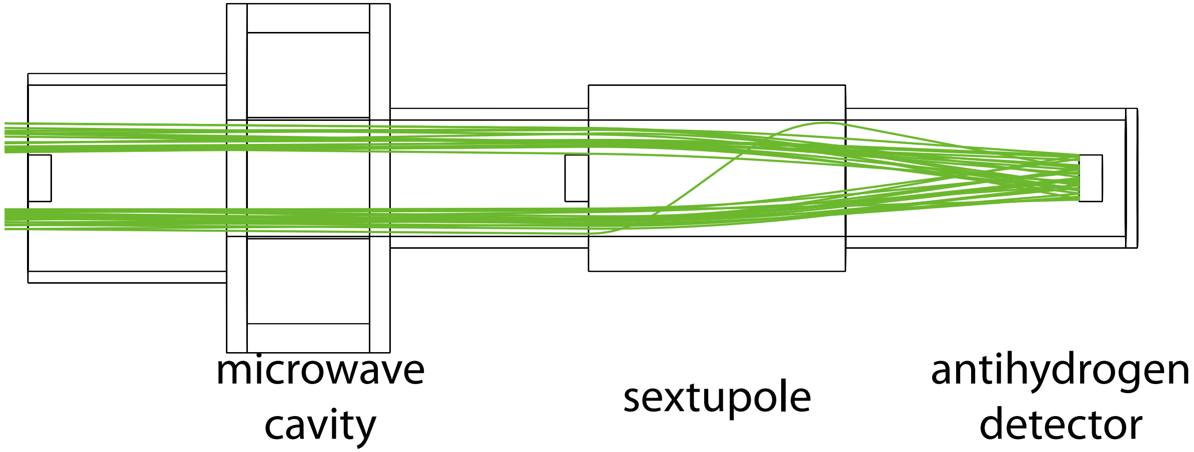


- Solid-neon moderator & longer N_2 gas cell
- ~3 × 10^7 e^+ in the CUSP in ~30 transfer cycles(15 s each)
- x 20 better than in 2011

Full setup (ready to be deployed in 2014)

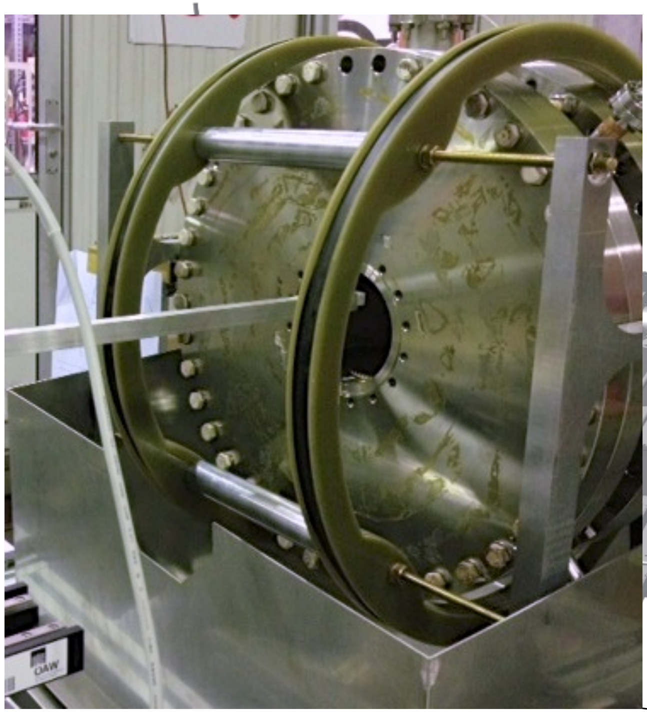


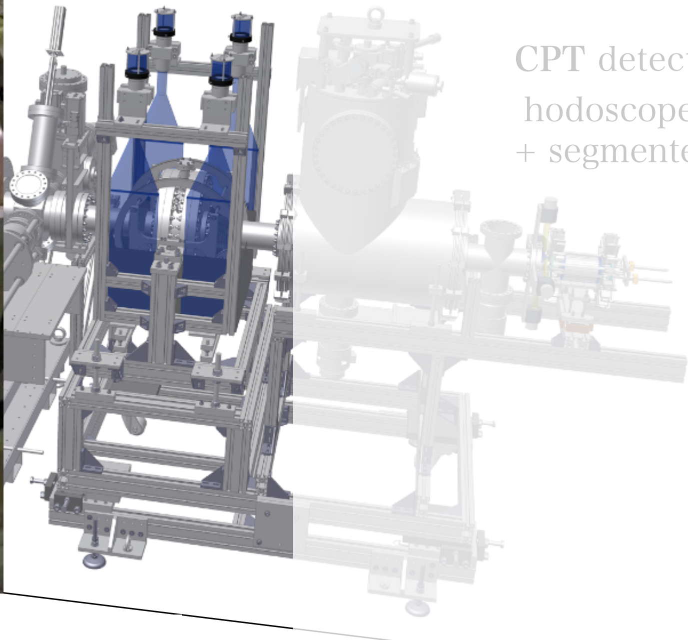
CPT detector:
hodoscope
+ segmented scintillator array



efficiency ~10^{-4}

Cavity





Cavity

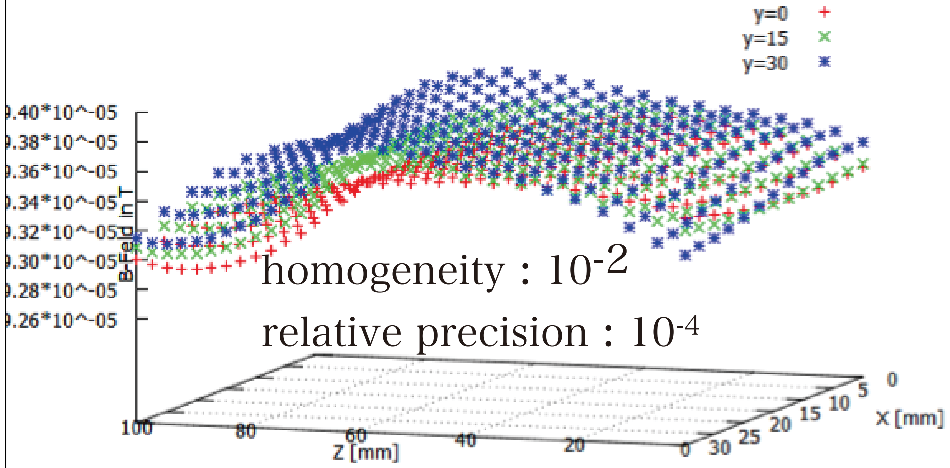
Sextupole

B_{max} =3.5T

CPT detector:

hodoscope

+ segmented scintillator array

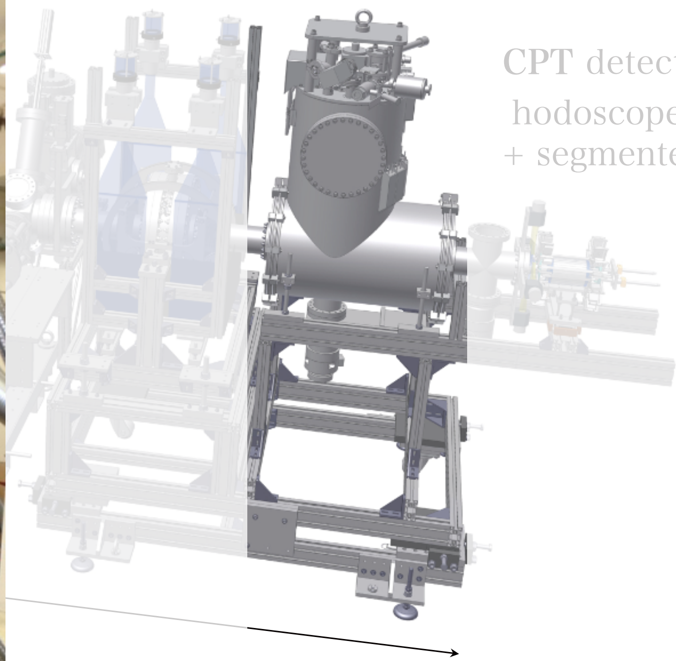


homogeneity : 10^{-2}

relative precision : 10^{-4}

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

Sextupole

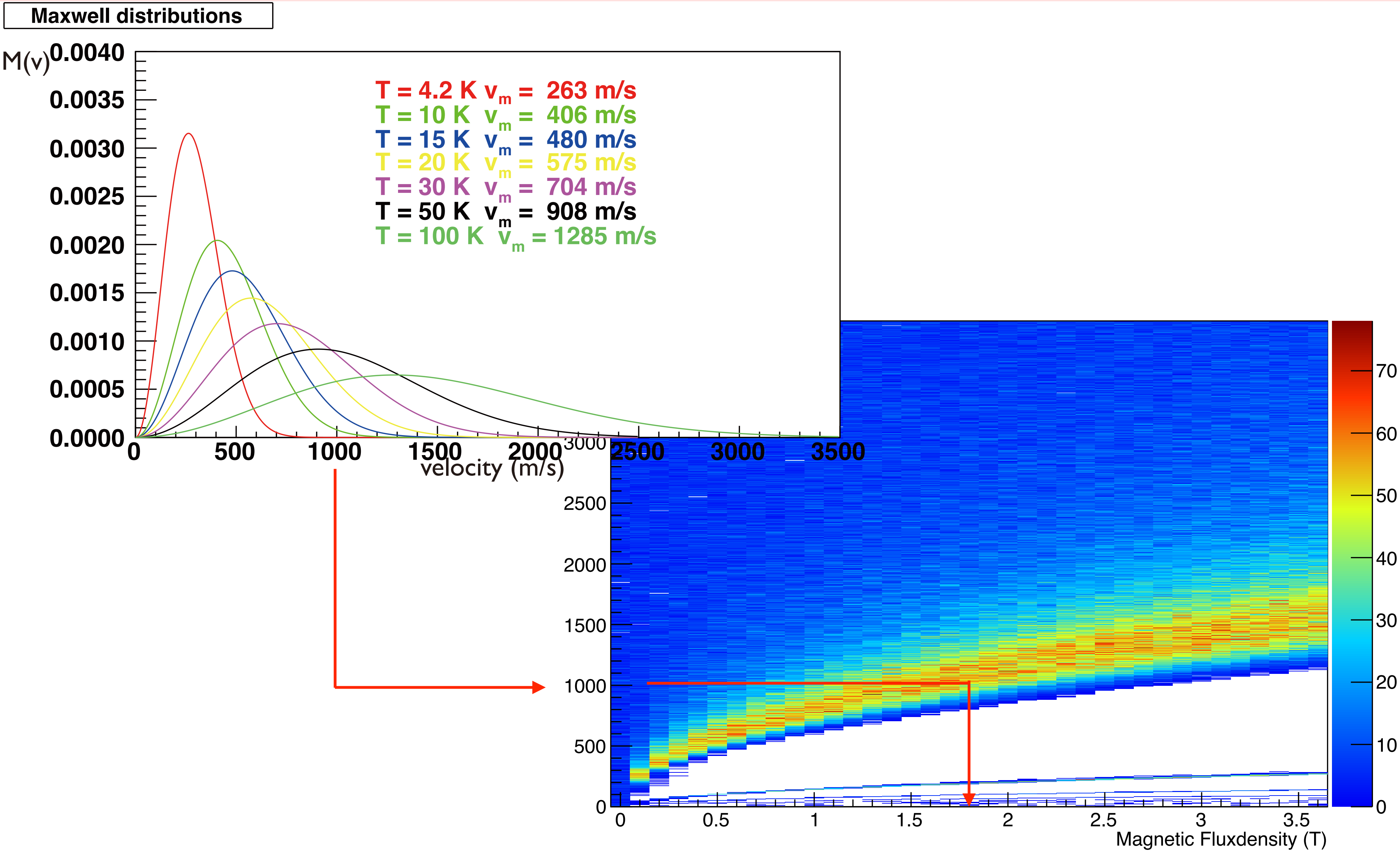


superconduting magnet

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

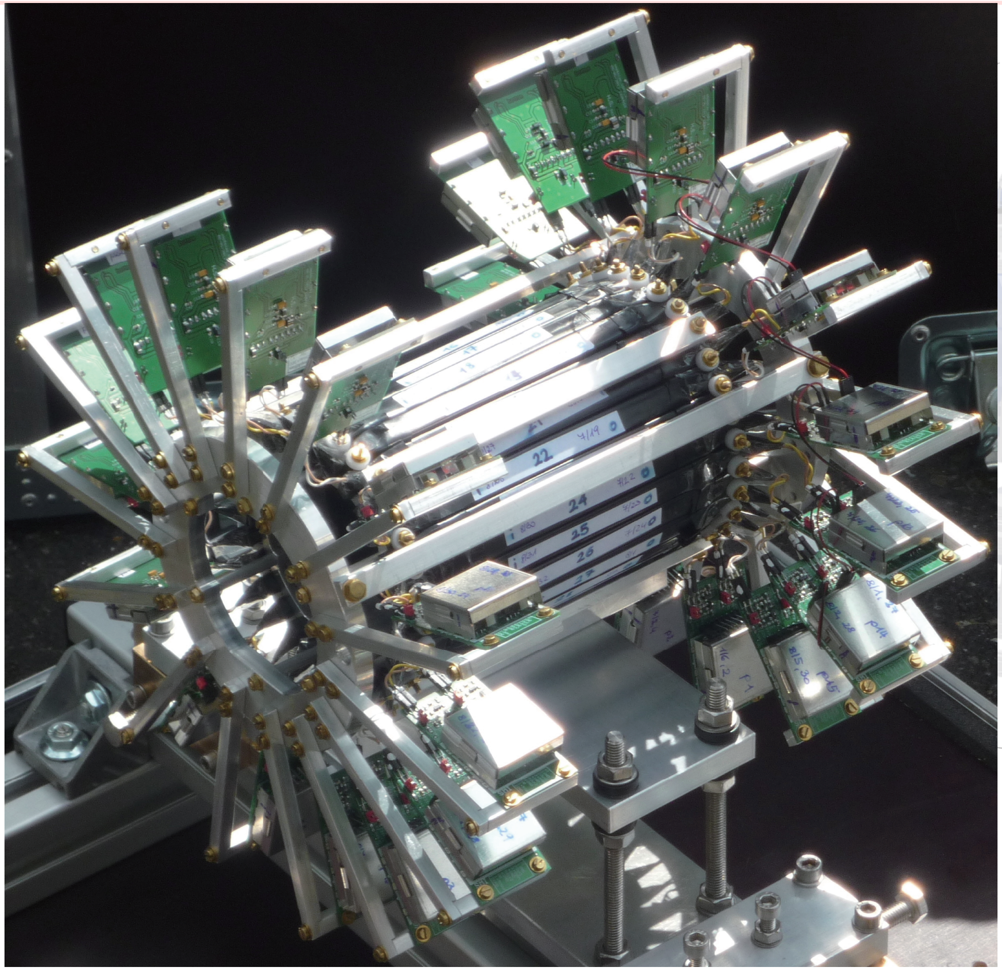
effective length: 22 cm

Sextuple acceptance vs $\bar{H}$ temperature

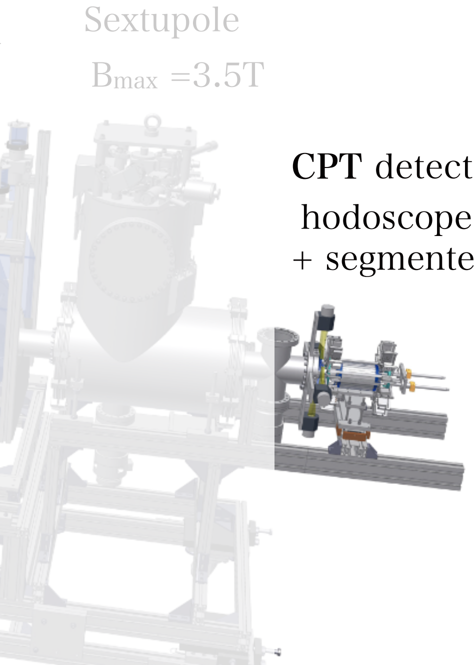


input: all low field seekers, flat velocity distribution

$\bar{H}$ detector

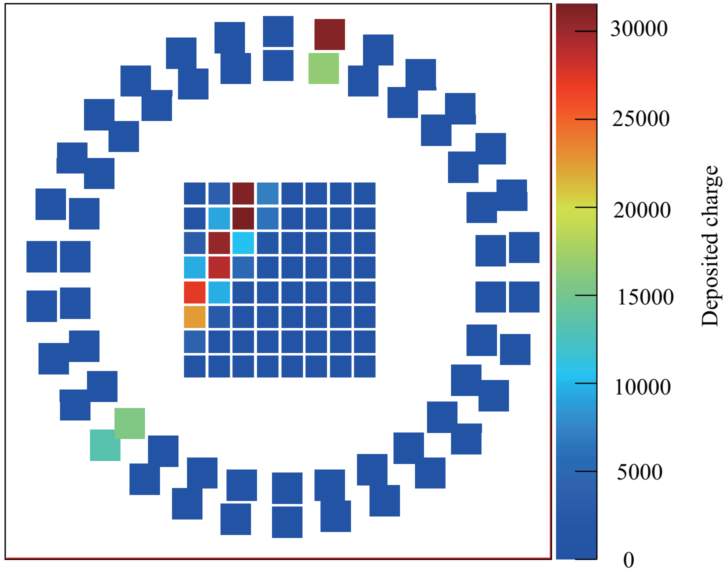


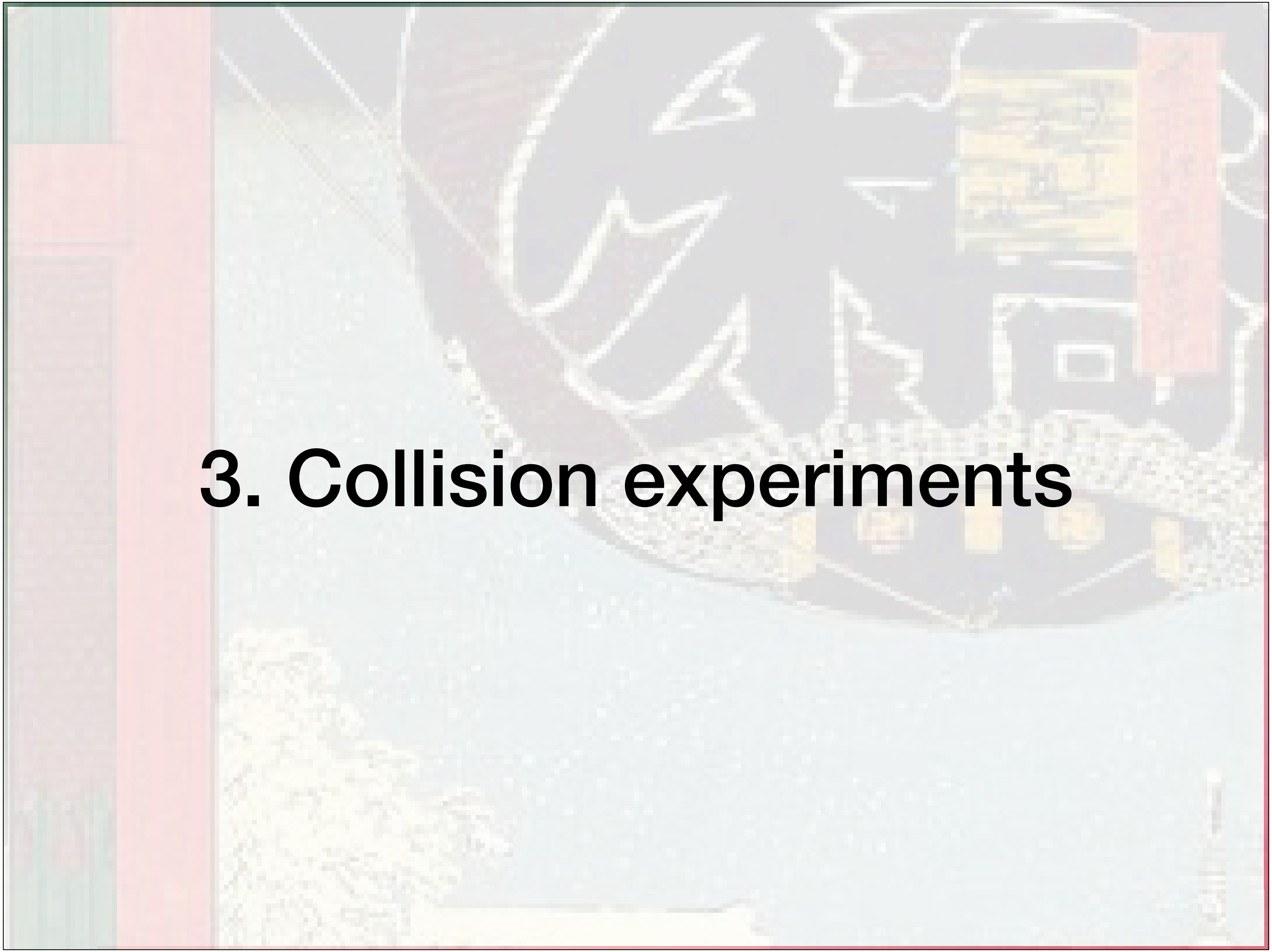
hodoscope read-out by SiPM



CPT detector:
hodoscope
+ segmented scintillator array

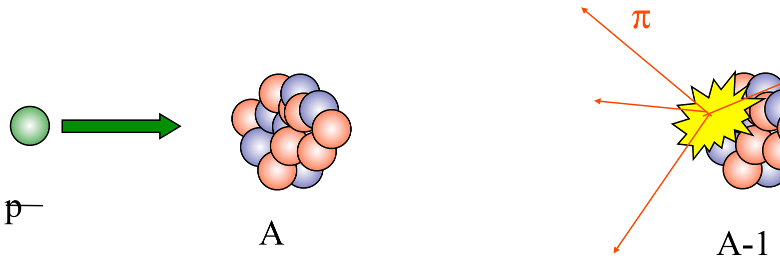
A cosmic event

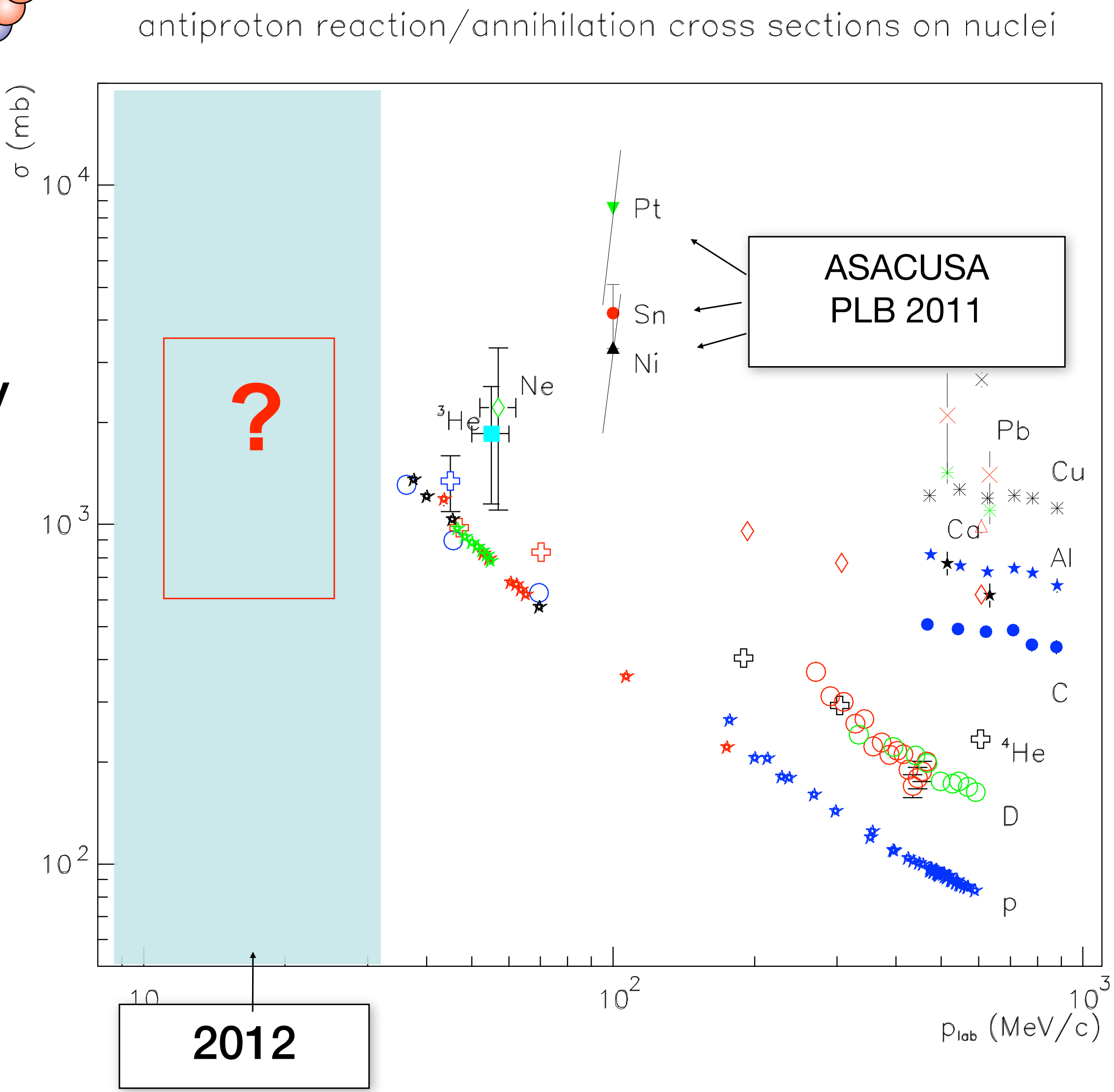




3. Collision experiments

Nuclear collisions with antiprotons





?

ASACUSA
PLB 2011

2012

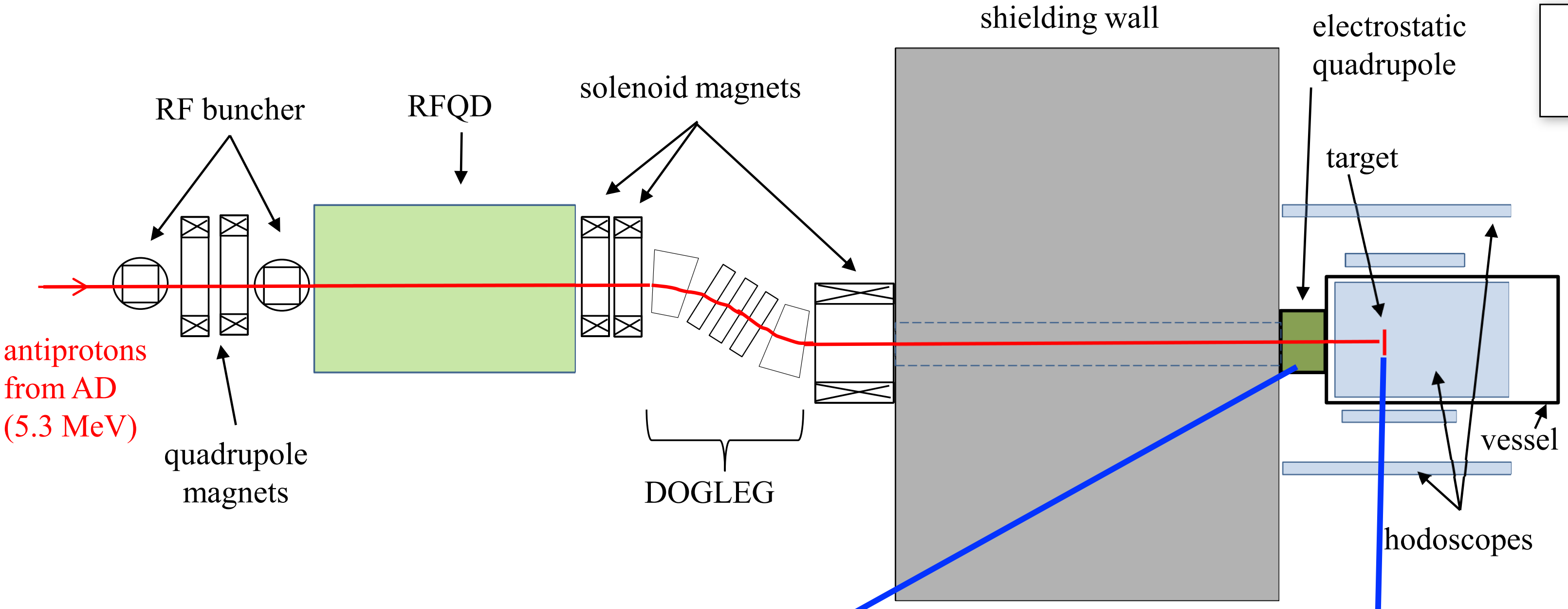
At 5.3 MeV
Medium-heavy and heavy nuclear targets

Results consistent with theoretical expectations

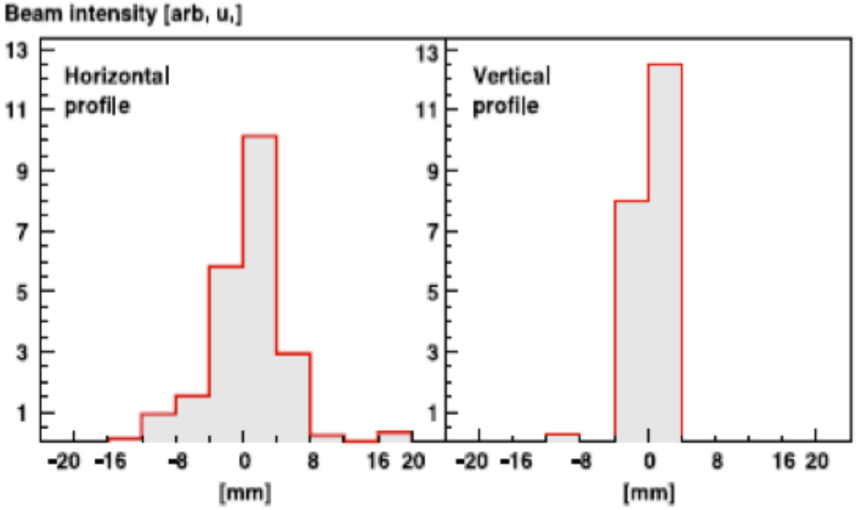
(Bianconi et al. Phys. Lett.B 2011)

2012: Annihilations cross-sections @ 130 keV

Aghai-Khozani et al.
Eur. Phys. J. Plus
2012

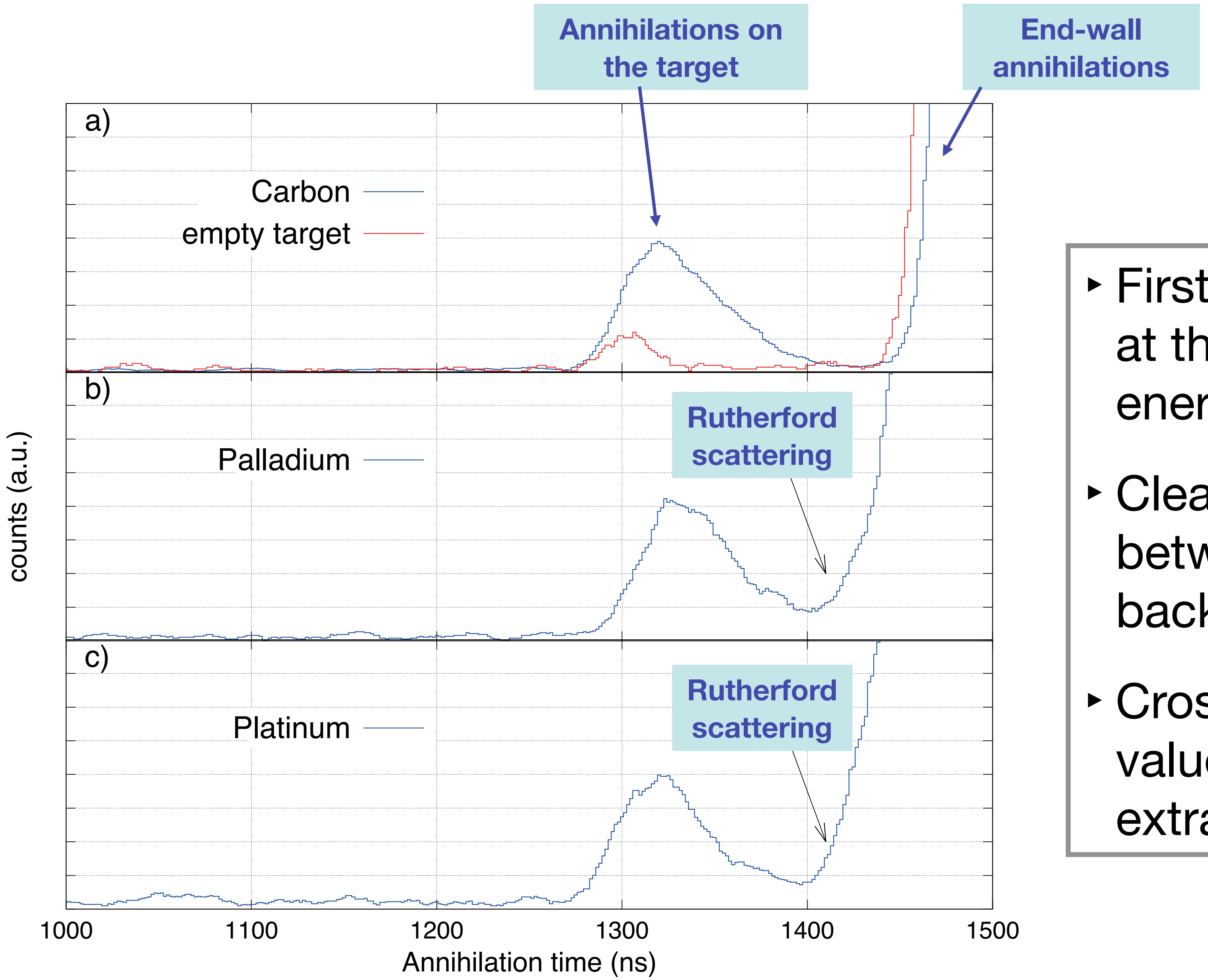


Beam monitor @ target position

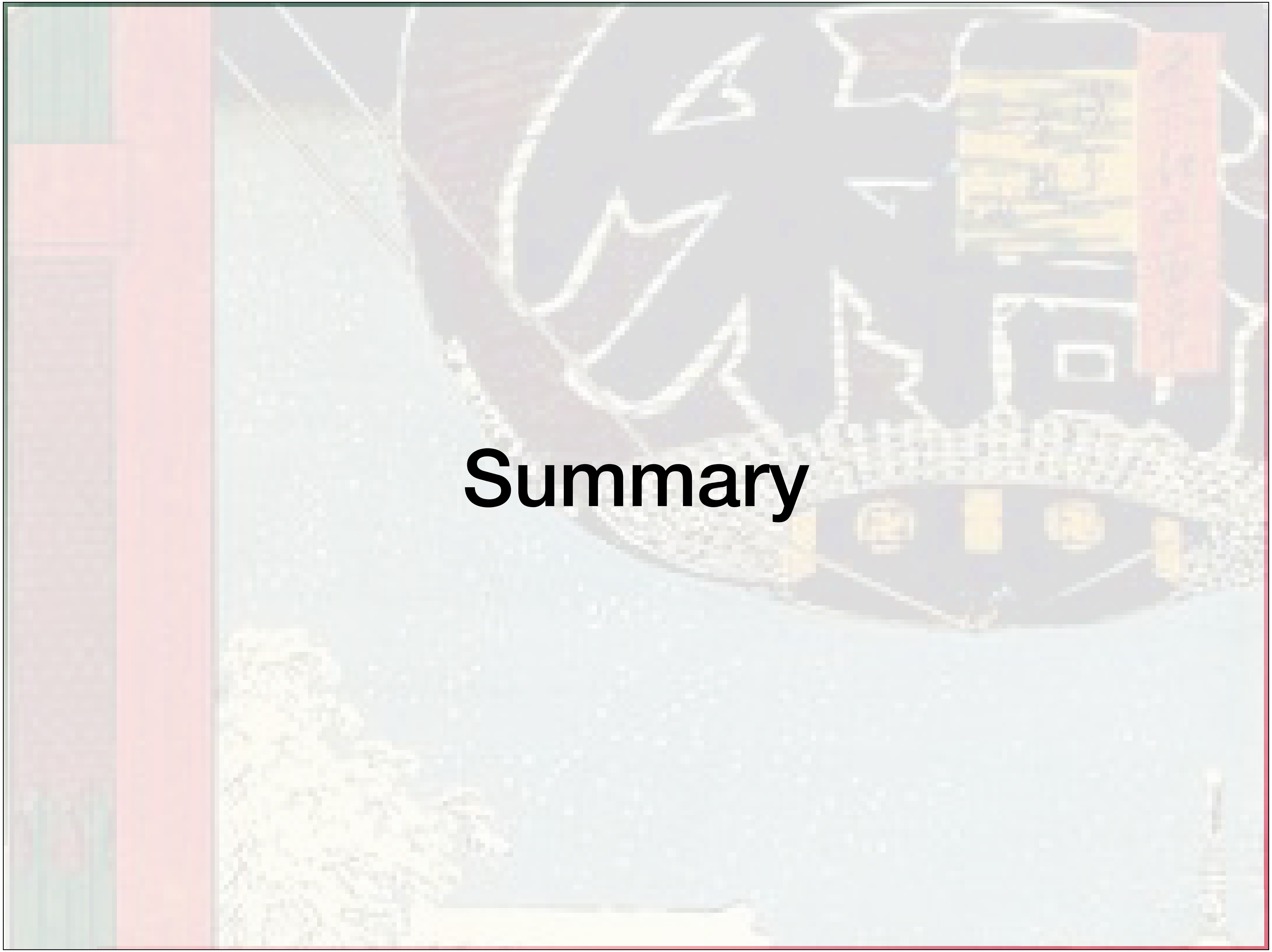


2012: Annihilations cross-sections @ 130 keV

Aghai-Khozani et al.
Eur. Phys. J. Plus
2012



- First measurement at these very low energies
- Clear separation between signal and background
- Cross-sections values to be extracted from data



Summary

2012 Accomplishments

$\bar{p}$He	‣ $m_{\bar{p}}/m_e$ in CODATA 2010 ‣ 1-photon spectroscopy of “cold” $\bar{p}He^+$ completed (x5-10 better than the 2006 results) ‣ First attempt at 2-photon spectroscopy of “cold” $\bar{p}$He - higher than ever precision
CUSP ($\bar{H}$)	‣ Autoresonance scheme for $\bar{p}$ injection into the e^+ cloud ‣ e^+ intensity x20 with a solid Ne moderator and longer N_2 gas cells. ‣ $\bar{H}$ beam production was tested elongating the $\bar{H}$ formation period. Data analysis is in progress. ‣ $\bar{H}$ beam detectors developed
$\bar{p}$ $\sigma_{annihilation}$	‣ observation of $\bar{p}$-A annihilation at 130 keV (published in EPJ+)

Funding

- ERC Advanced Grant to Eberhard Widmann, Vienna
- JSPS Grant-in-Aid for Specially Promoted Research to Yasunori Yamazaki, Japan,
- University of Tokyo funding for ELENA to Ryugo Hayano, Tokyo.
- All last for five years.