ASACUSA: Measuring the Antiproton Mass and Magnetic Moment

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on behalf of the ASACUSA Collaboration

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Outline

- CPT Invariance and its Tests
- The Antiproton Decelerator at CERN
- The Charge and Mass of the Antiproton
- The Magnetic Moment of the Antiproton
- Outlook: ELENA

R.S. Hayano et al.: *Antiprotonic helium and CPT invariance*, **Reports on Progress in Physics**, 70 (2007) 1995-2065.

M. Hori et al.: *Two-photon laser spectroscopy of pbar-He$^+$ and the antiproton-to-electron mass ratio*, **Nature** 475 (2011) 484-488; **Few Body Systems** 54 (2013) 917-922

S. Friedreich et al.: *Microwave spectroscopic study of the hyperfine structure of antiprotonic helium-3*, **arXive:1303.2831**, 2013.

CPT Invariance

Charge conjugation: $C|\mathrm{p}(r,t)\rangle = |\bar{\mathrm{p}}(r,t)\rangle$

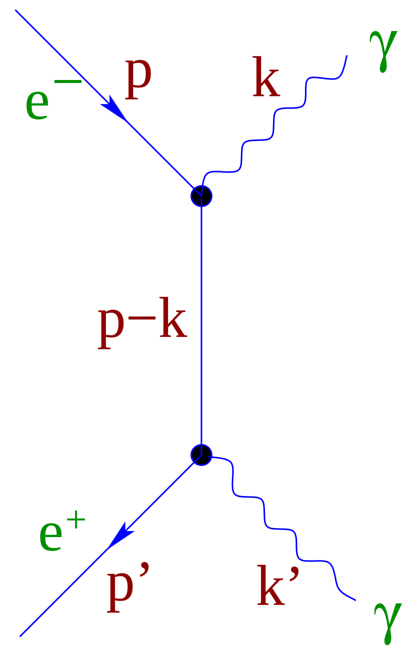
Space reflection: $P|\mathrm{p}(r,t)\rangle = |\mathrm{p}(-r,t)\rangle$

Time reversal: $T|\mathrm{p}(r,t)\rangle = |\mathrm{p}(r,-t)\rangle$

Basic assumption of field theory:

$CPT|\mathrm{p}(r,t)\rangle = |\bar{\mathrm{p}}(-r,-t)\rangle \sim |\mathrm{p}(r,t)\rangle$

meaning free antiparticle $\sim$ particle going backwards in space and time.



Giving up CPT one has to give up:

- locality of interactions ⇒ causality, or
- unitarity ⇒ conservation of matter, information, ... or
- Lorentz invariance

CPT Invariance: violation?

Field theorists in general: CPT cannot be violated!

CPT-violating theories:
(Alan Kostelecký, F.R. Klinkhamer, N.E. Mavromatos et al)

- Standard Model valid up to Planck scale ($\sim 10^{19}$ GeV).
  Above Planck scale new physics $\Rightarrow$
  Lorentz violation possible
- Quantum gravity: fluctuations $\Rightarrow$ Lorentz violation
  Loss of information in black holes $\Rightarrow$ unitarity violation

Motivation for testing CPT at low energy

- Quantitative expression of Lorentz and CPT invariance
  needs violating theory
- Low-energy tests can limit possible high energy violation

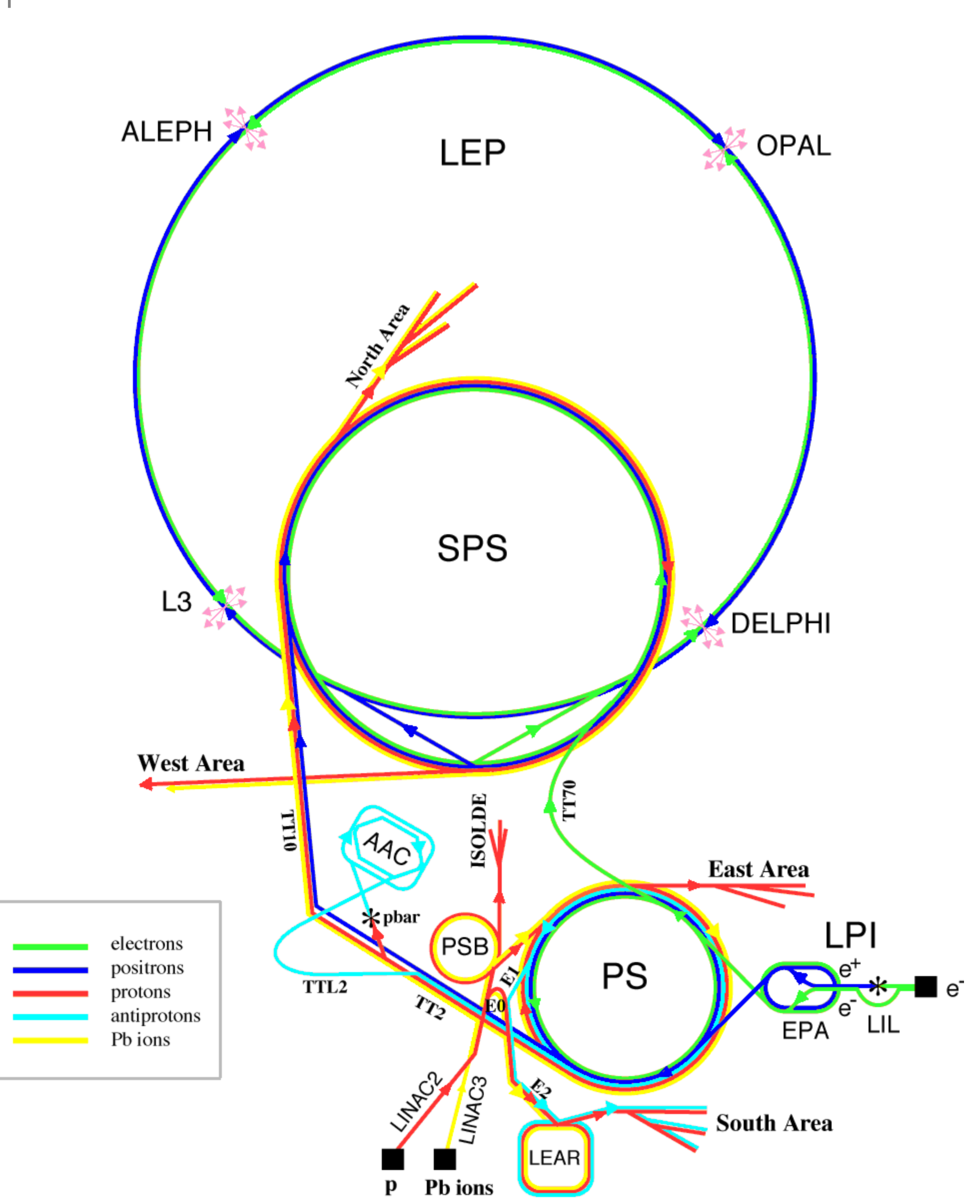
How to test CPT?

Particle = – antiparticle ?

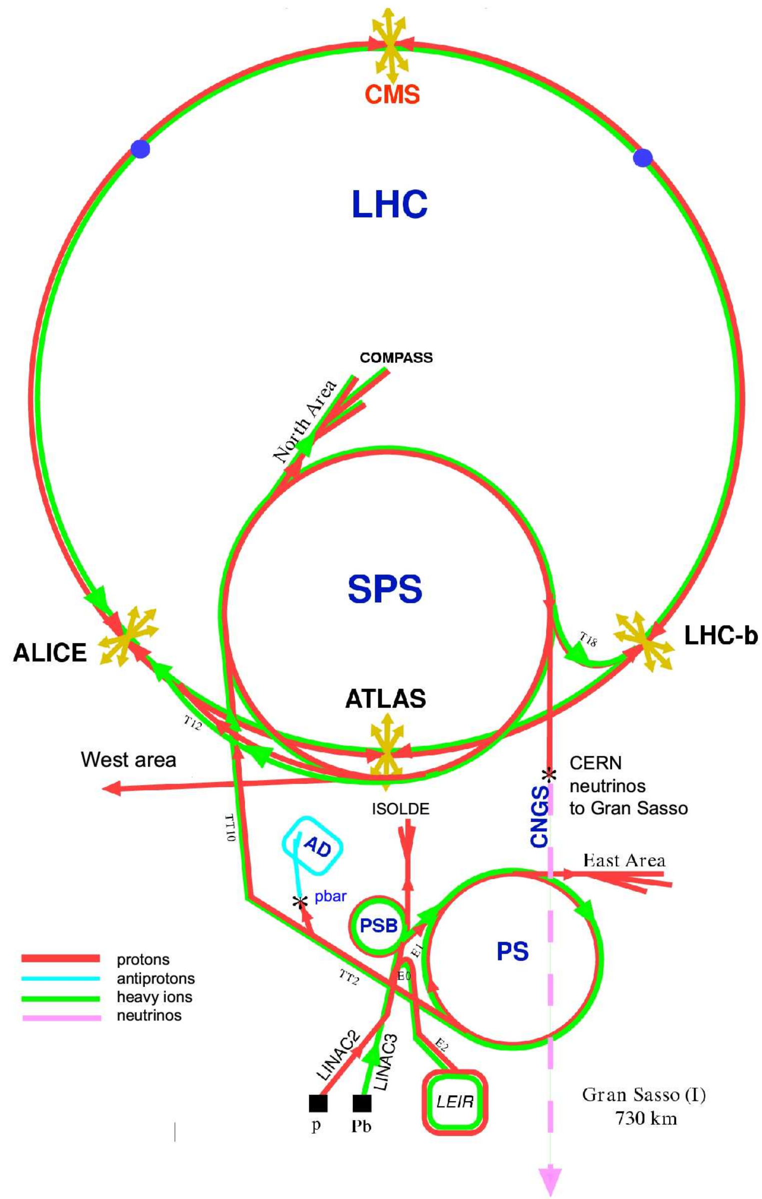
- $[m(\mathrm{K}^0) - m(\overline{\mathrm{K}}^0)]/m(\text{average}) < 10^{-18}$
- proton $\sim$ antiproton? (compare m, q, $\vec{\mu}$)
- hydrogen $\sim$ antihydrogen? ($2S - 1S$, HFS)

Accelerators at CERN

1989–2000



2009–2025??



The Antiproton Decelerator at CERN

has been built to test *CPT* invariance

Three experiments test CPT:

ATRAP: $q(\overline{\mathrm{p}})/m(\overline{\mathrm{p}}) \leftrightarrow q(\mathrm{p})/m(\mathrm{p})$

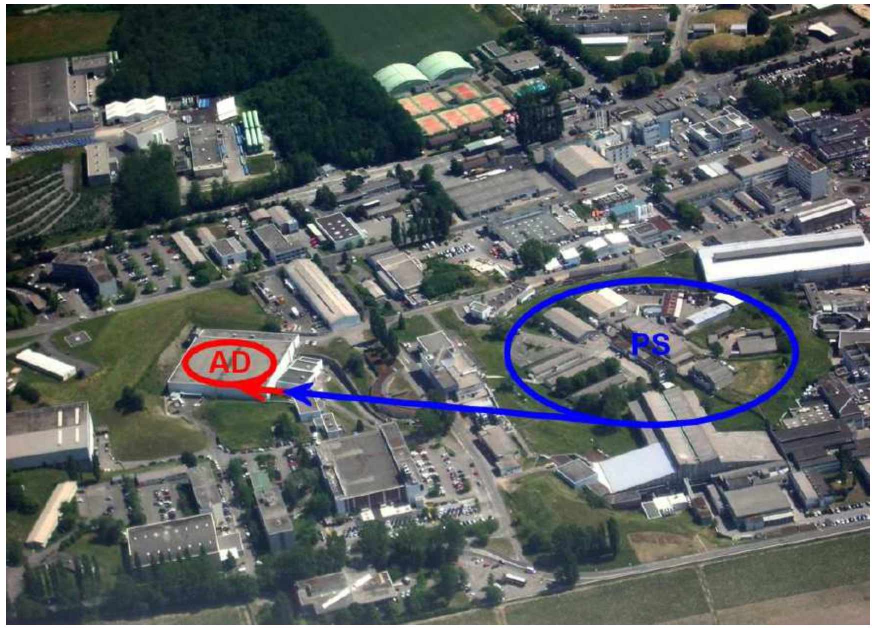
$\overline{\mathrm{H}}(2S-1S) \leftrightarrow \mathrm{H}(2S-1S)$

ALPHA: $\overline{\mathrm{H}}(2S-1S) \leftrightarrow \mathrm{H}(2S-1S)$

ASACUSA: $q(\overline{\mathrm{p}})^2 m(\overline{\mathrm{p}}) \leftrightarrow q(\mathrm{p})^2 m(\mathrm{p})$

$\mu_\ell(\overline{\mathrm{p}}) \leftrightarrow \mu_\ell(\mathrm{p})$

$\overline{\mathrm{H}} \leftrightarrow \mathrm{H}$ HF structure



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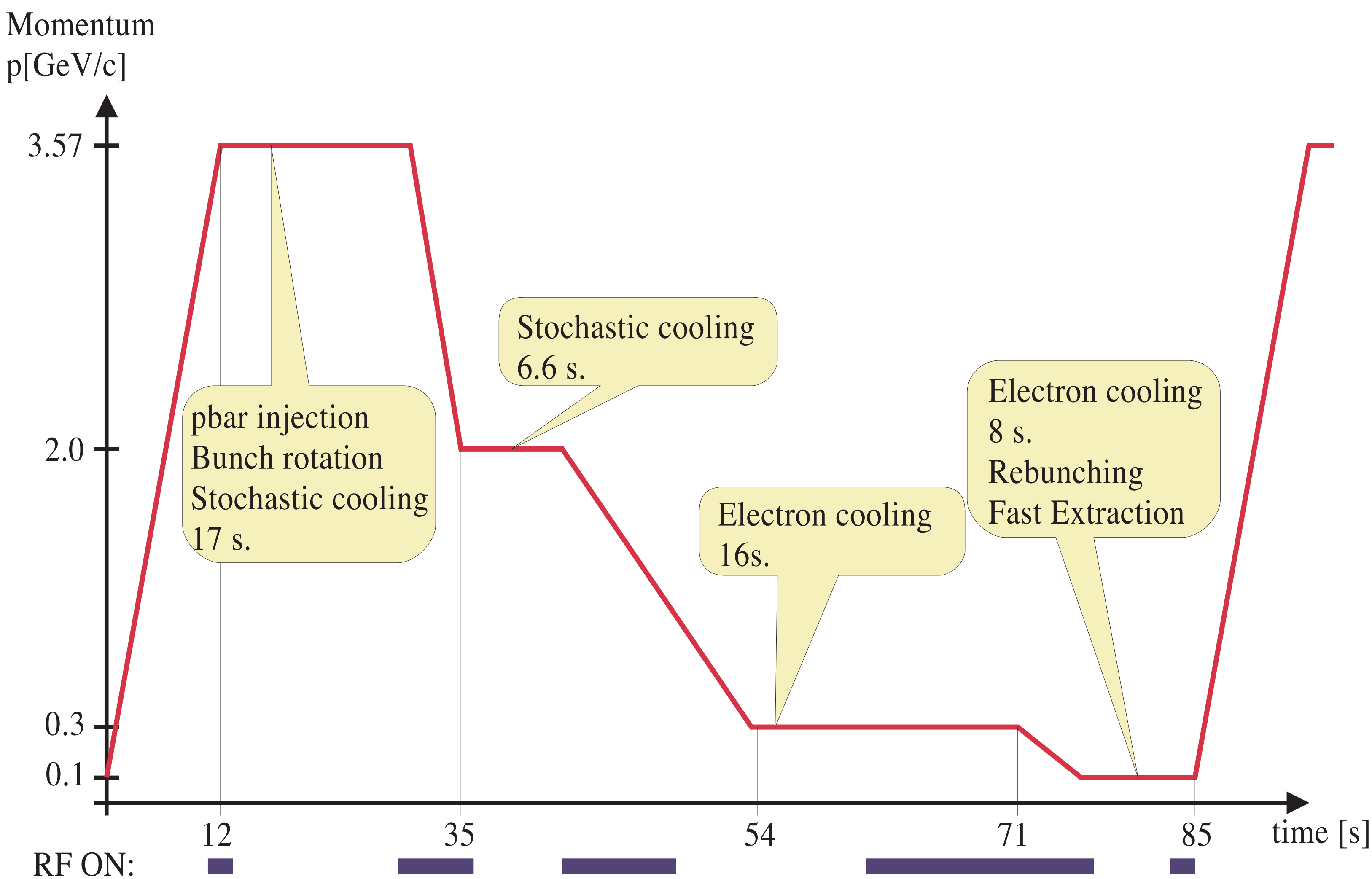
RED: done, GREEN: planned

The Antiproton Decelerator: cooling



$\sim 4 \times 10^7$ 100 MeV/c antiprotons every 85 s

Pavel Belochitskii: AIP Conf. Proc. 821 (2006) 48

Mass and Charge of Antiproton

Proton's well (?) known:

$m(\mathrm{p})/m(\mathrm{e}) = 1836.15267245(75)$

$q(\mathrm{e}) = 1.602176565(35) \times 10^{-19}$ C

Precision: $4 \cdot 10^{-10}$ and $2 \cdot 10^{-8}$

Relative measurements: proton vs. antiproton

Cyclotron frequency in trap $\rightarrow q/m$

TRAP $\Rightarrow$ ATRAP collaboration

Harvard, Bonn, München, Seoul

$\overline{\mathrm{p}}$ and H^- together $\Rightarrow 10^{-10}$ precision

Atomic transitions:

$E_n \approx -m_{\mathrm{red}} c^2 (Z\alpha)^2/(2n) \rightarrow m \cdot q^2$

PS-205 $\Rightarrow$ ASACUSA collaboration

Tokyo, Brescia, Budapest, Debrecen, Munich, Vienna

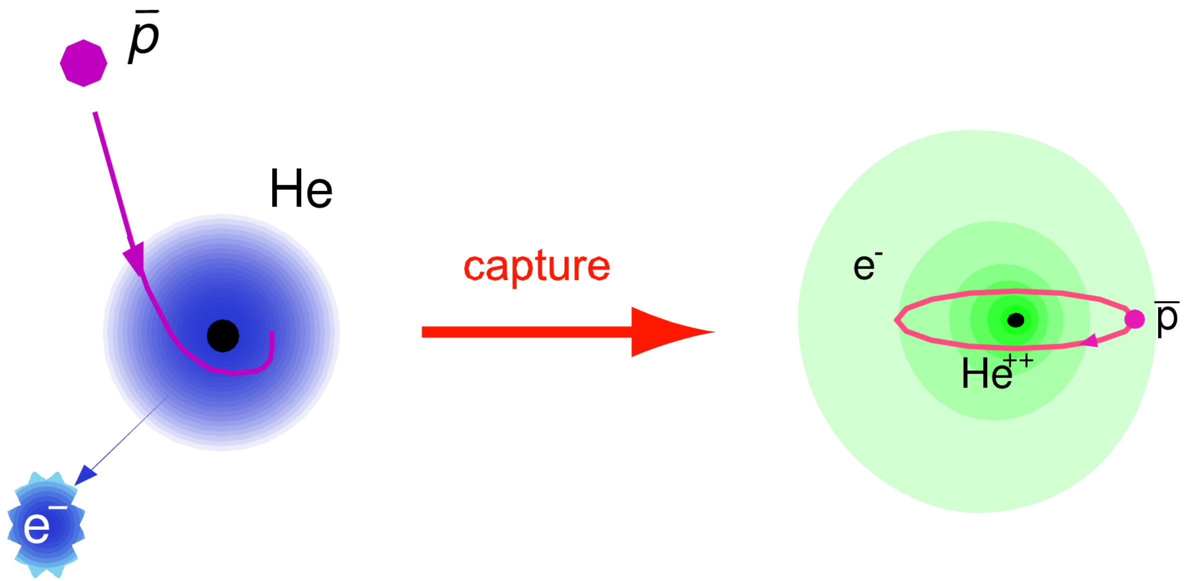
Atomic
Spectroscopy
And
Collisions
Using
Slow
Antiprotons

Asakusa, Tokyo

Metastable hadronic atoms

In matter (gas, liquid, solid) τ(hadron) $\tau \sim$ 1 ps

except $\sim 3\%$ of X^-He: K^-, π^-: decay lifetime; $\overline{\mathrm{p}}$: 3–4 μs



Metastable 3-body system

Auger suppressed, slow radiative transitions only

Electron *cloud* protects $\overline{\mathrm{p}}$ against collisions

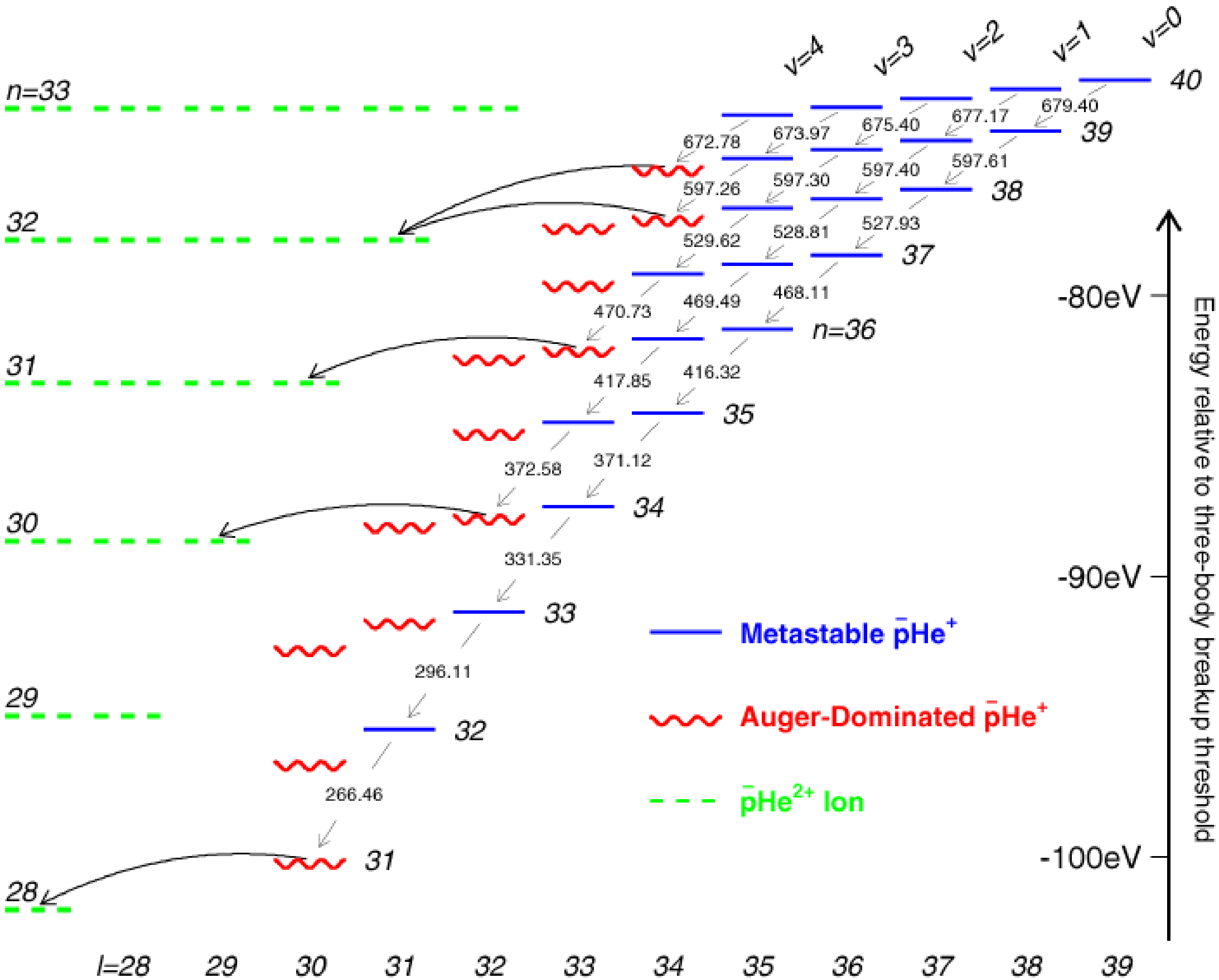
Electron tightly bound: $1S$

$\overline{\mathrm{p}}$He: $n \sim 40$, $l \sim n - 1$, Rydberg state

$\overline{\mathrm{p}}$-He$^+$: spectroscopy motivation

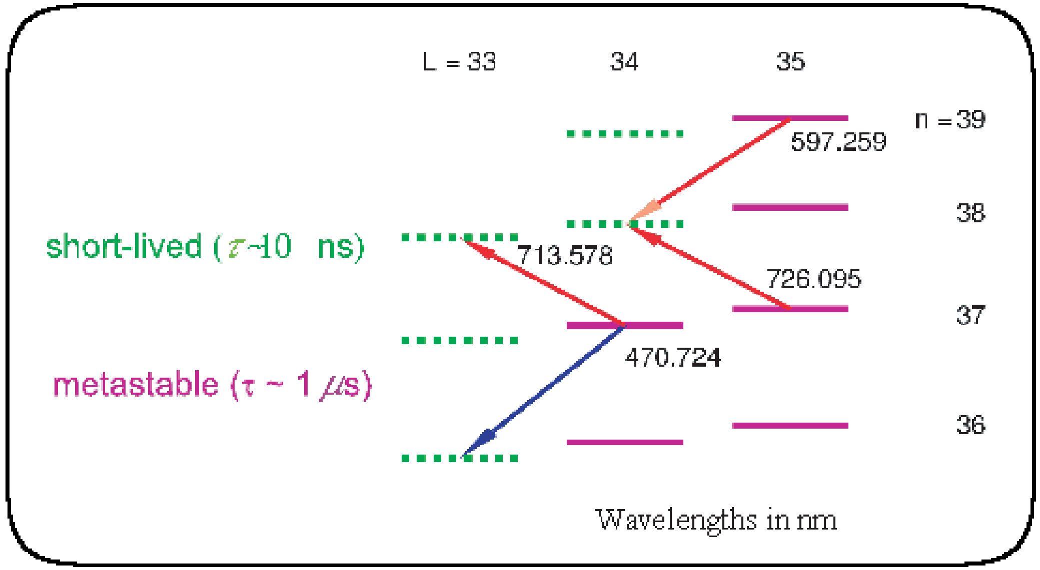
- Vladimir Korobov calculates $\overline{\mathrm{p}}$ transition frequencies in $\overline{\mathrm{p}}$-He$^+$ with the precision of $\sim 10^{-9}$
- Determination of antiproton-to-electron mass ratio to 1.3×10^{-9}.
  $\longrightarrow$ Dimensionless fundamental constant of nature.
- Determination of electron mass in a.u. to 1.3×10^{-9}
  $\longrightarrow$ One of the data points for CODATA2010 average.
- When combined with cyclotron frequency of antiprotons in a Penning trap measured by the TRAP collaboration, comparison of antiproton and proton mass and charge to 7×10^{-10}
  $\longrightarrow$ CPT consistency test in PDG2012.

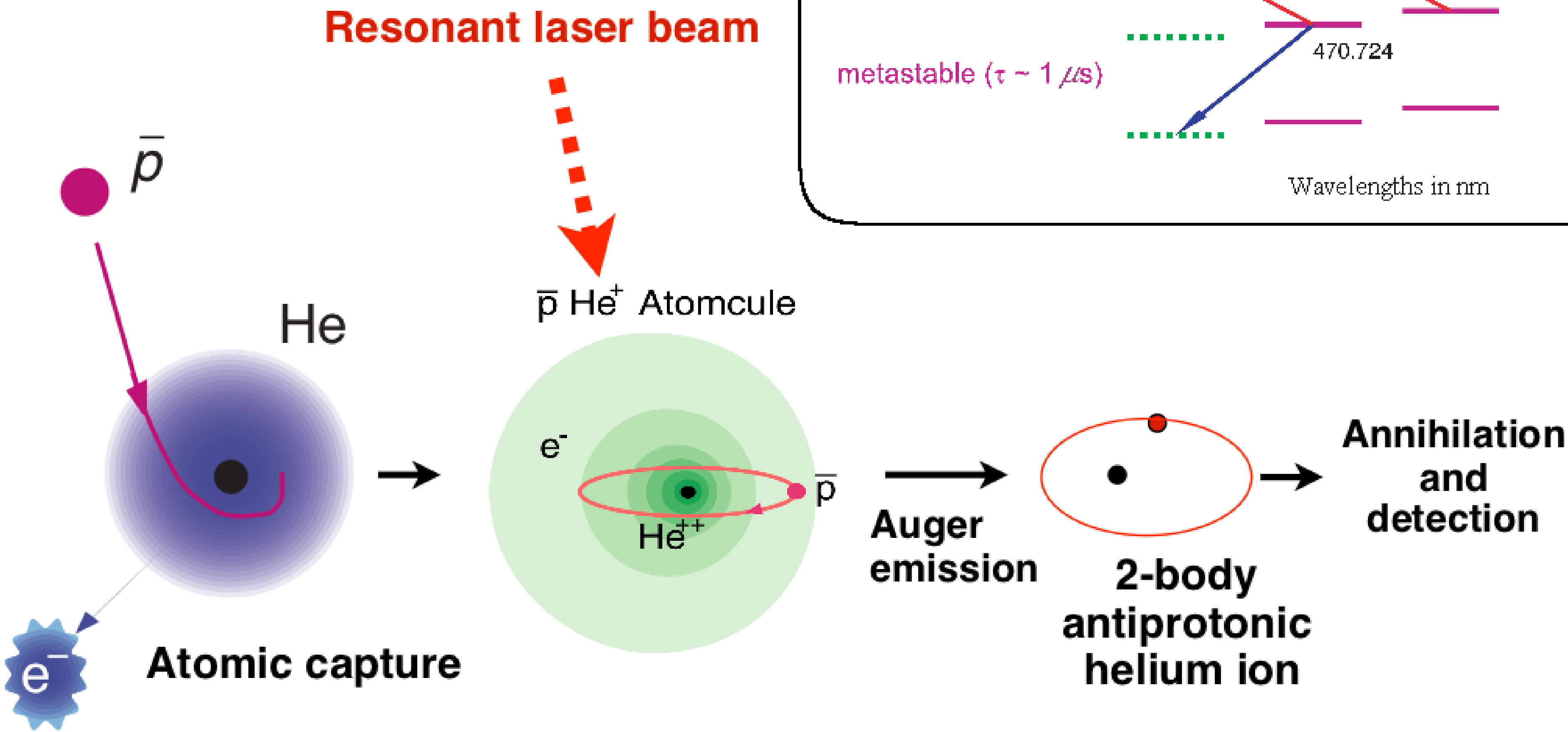
Energy levels of $\overline{\mathrm{p}}\mathrm{He}^4$



Level energies in eV, transition wavelengths in nm

Laser spectroscopy of antiprotonic helium



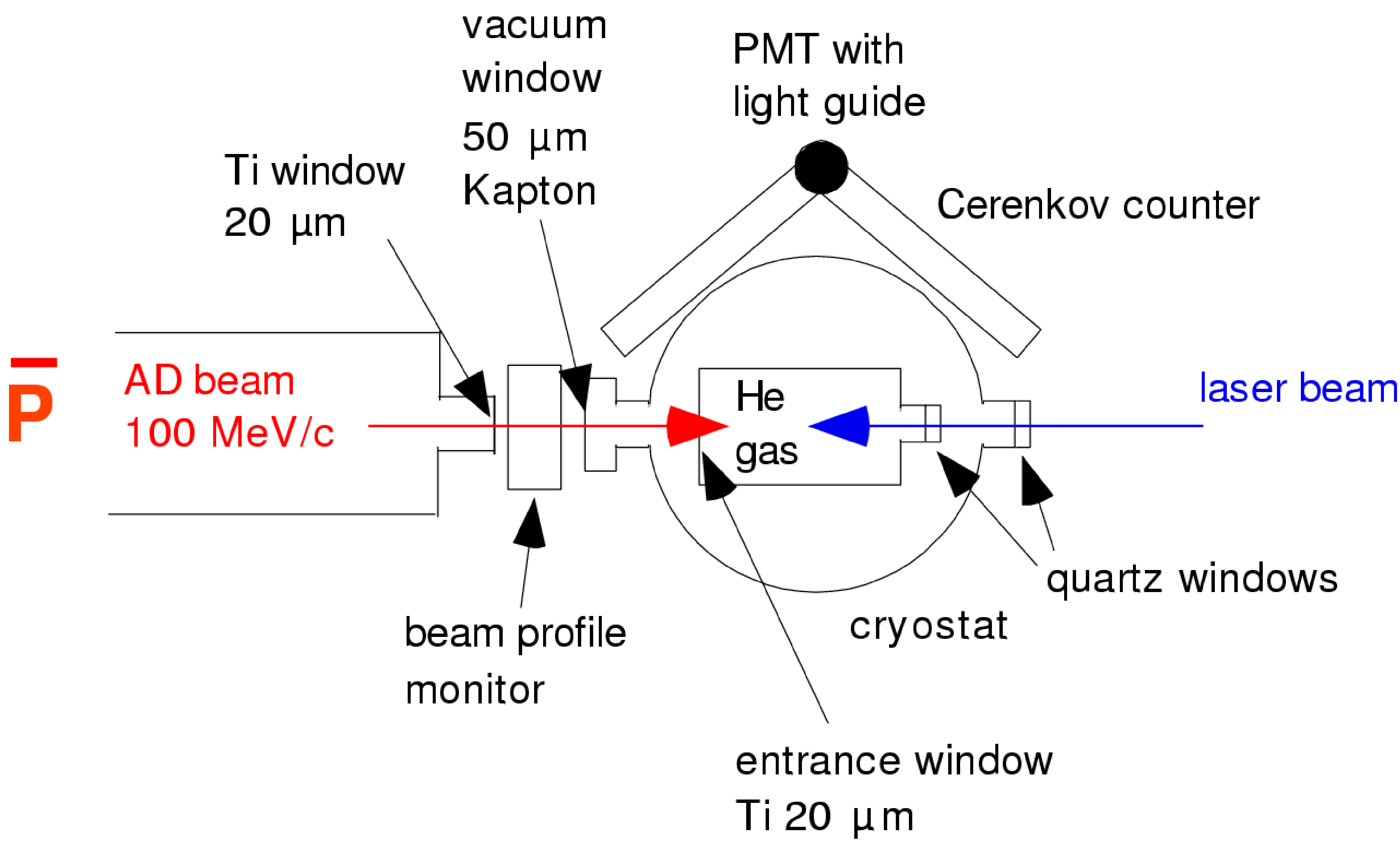


Induce transition between long-lived and short-lived states

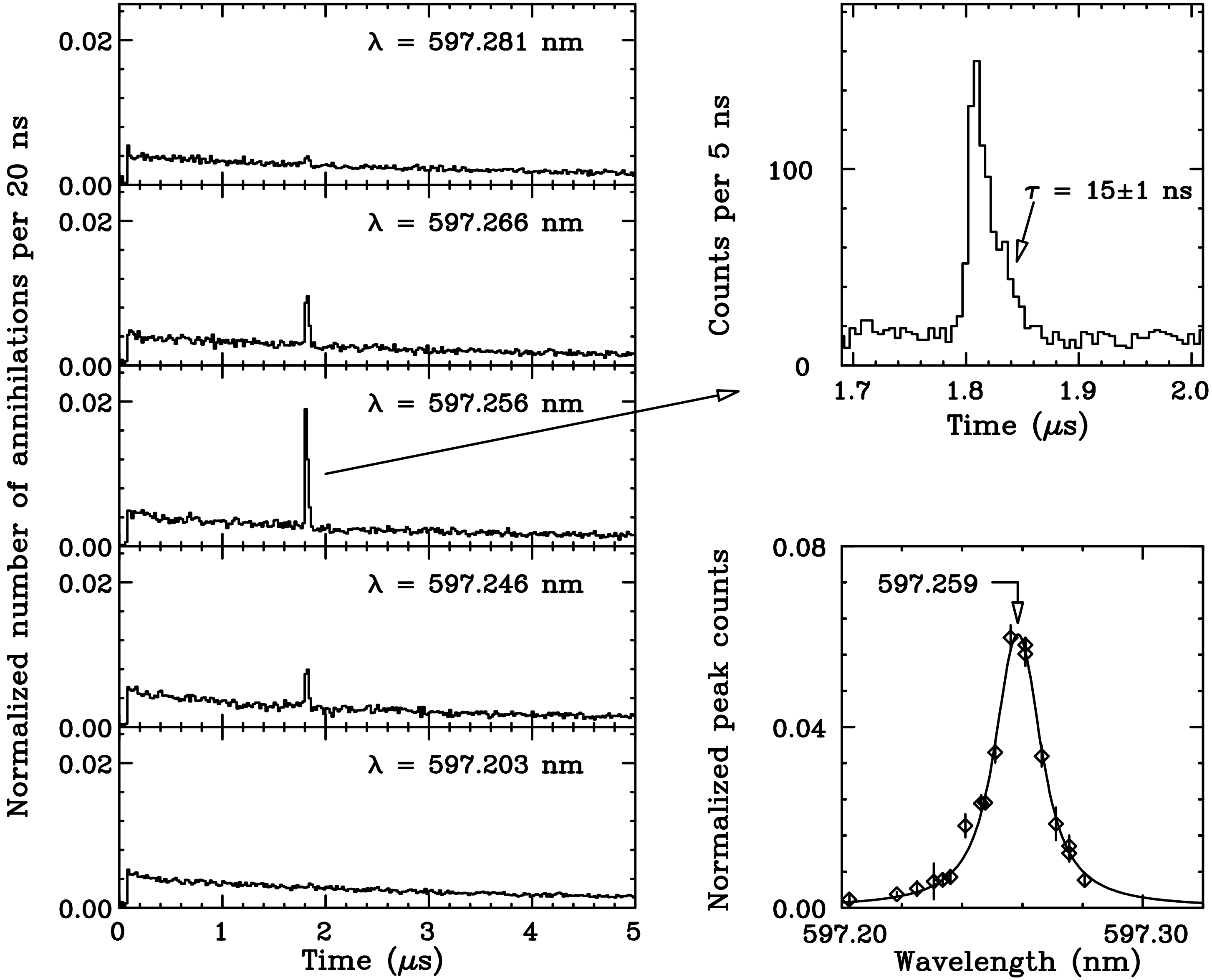
⇓

Force prompt annihilation

ASACUSA: Spectroscopy setup

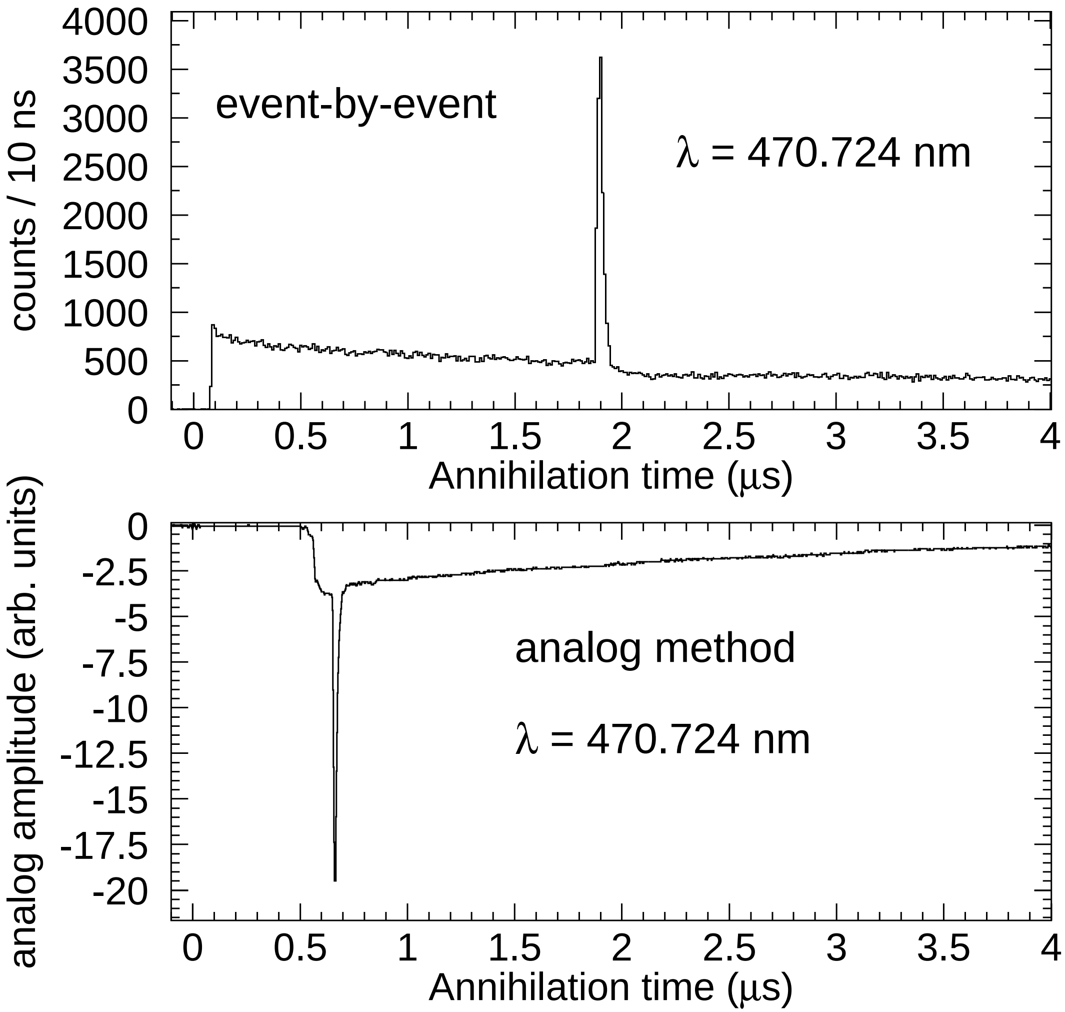


Laser spectroscopy of antiprotonic helium



N. Morita et al, **Phys. Rev. Lett.** *72* (1994) 1180–1183.

Laser spectroscopy: LEAR vs AD

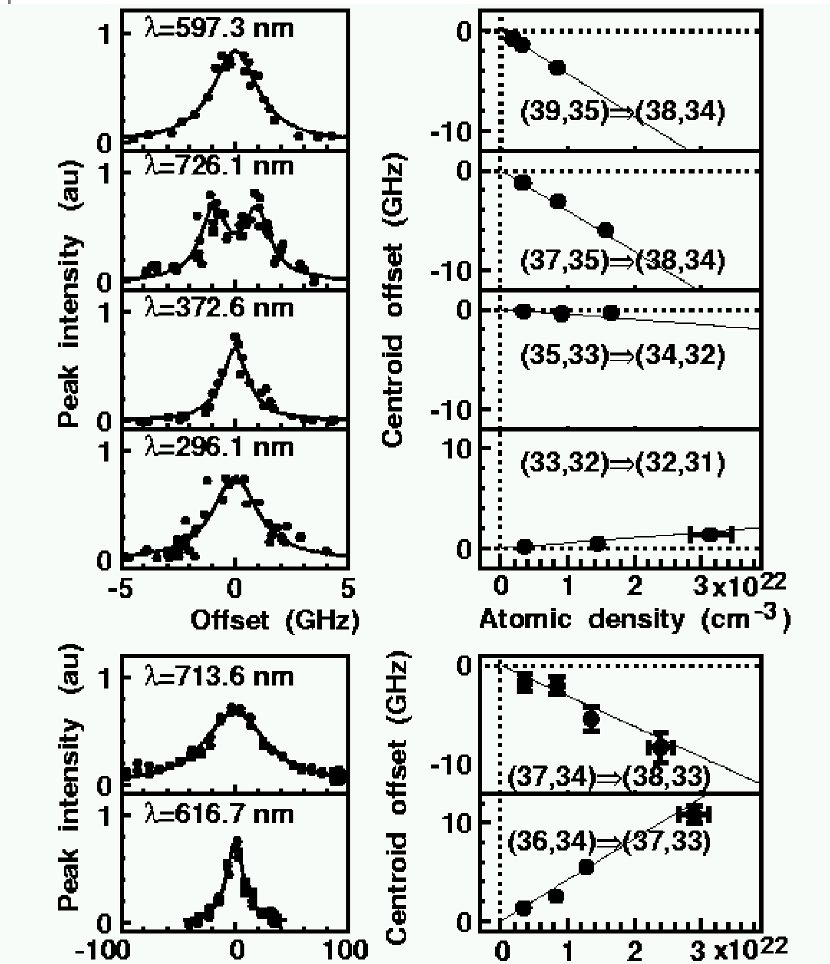


LEAR: slow extraction
10^6 laser shots, 50 min

AD: fast extraction
1 laser shot, 2 min

Gated phototube: prompt annihilation ($97\%\ \overline{\mathrm{p}}$) off (Hamamatsu)

Transition frequencies in isolated $\overline{\text{p}}\text{He}^+$ atoms



M. Hori et al.,

Phys. Rev. Lett. *87* (2001) 093401.

Exp. precision limited by: collisions, Doppler broadening, laser bandwidth

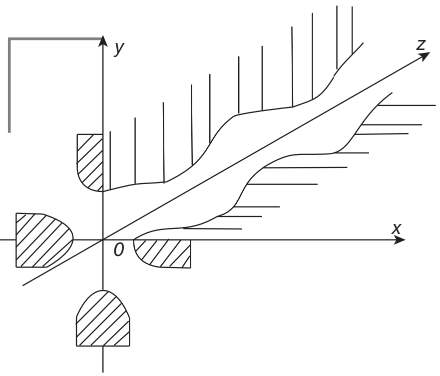
- 1996-2002: measured density dependence, extrapolated to zero
- 2003-2004: reduced collisional effects by stopping slow $\overline{\text{p}}$ from RFQ post-decelerator in low-pressure (< 1 mbar), cryogenic target
- 2005-2007: reduce laser bandwidth using frequency comb
- 2008: start 2-photon spectroscopy

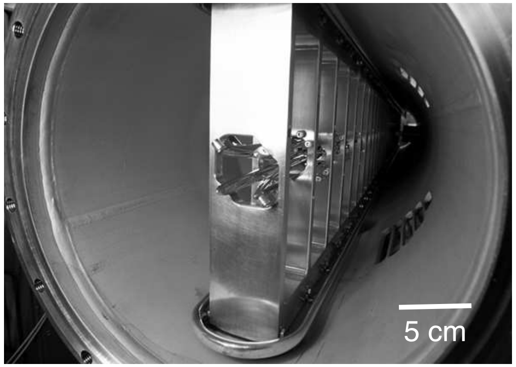
Last published CPT-violation limit by 1-photon spectroscopy:

2 ppb (2×10^{-9}) at CL 90%.

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

Radiofrequency quadrupole decelerator

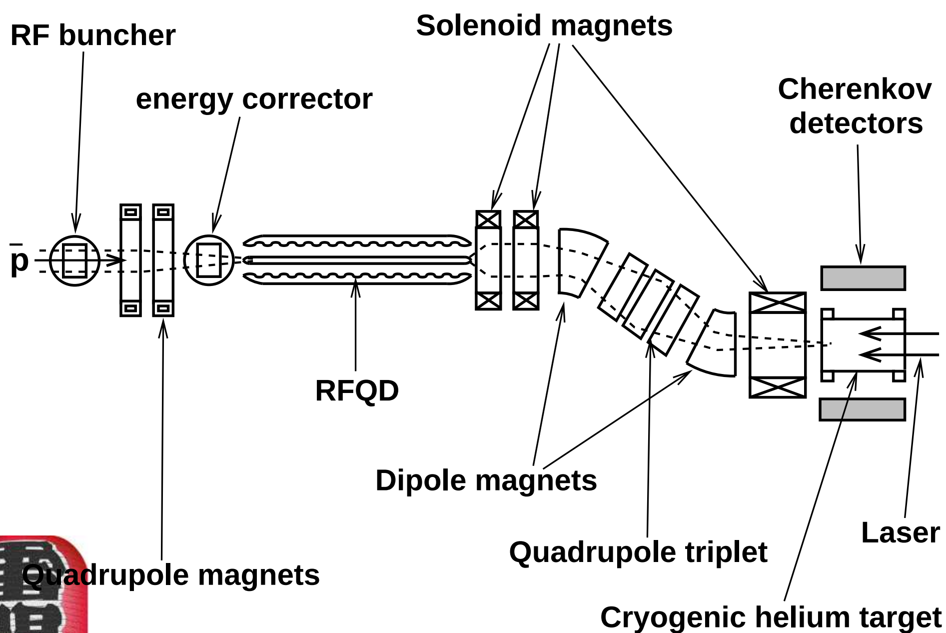




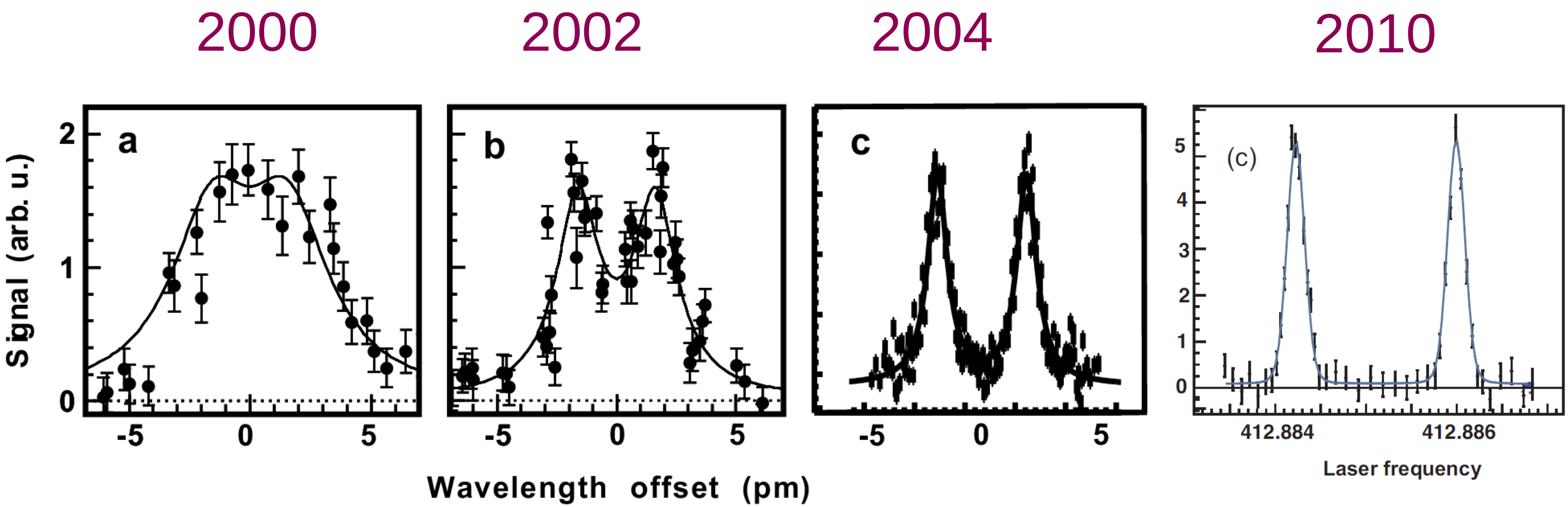
Focussing-defocussing in alternate planes

$V \sim 170$ kV; $f \sim 202$ MHz; bias $\sim \pm 55$ kV

5,3 MeV $\rightarrow$ 65 keV: efficiency $\sim 30\%$



Resolution and stability

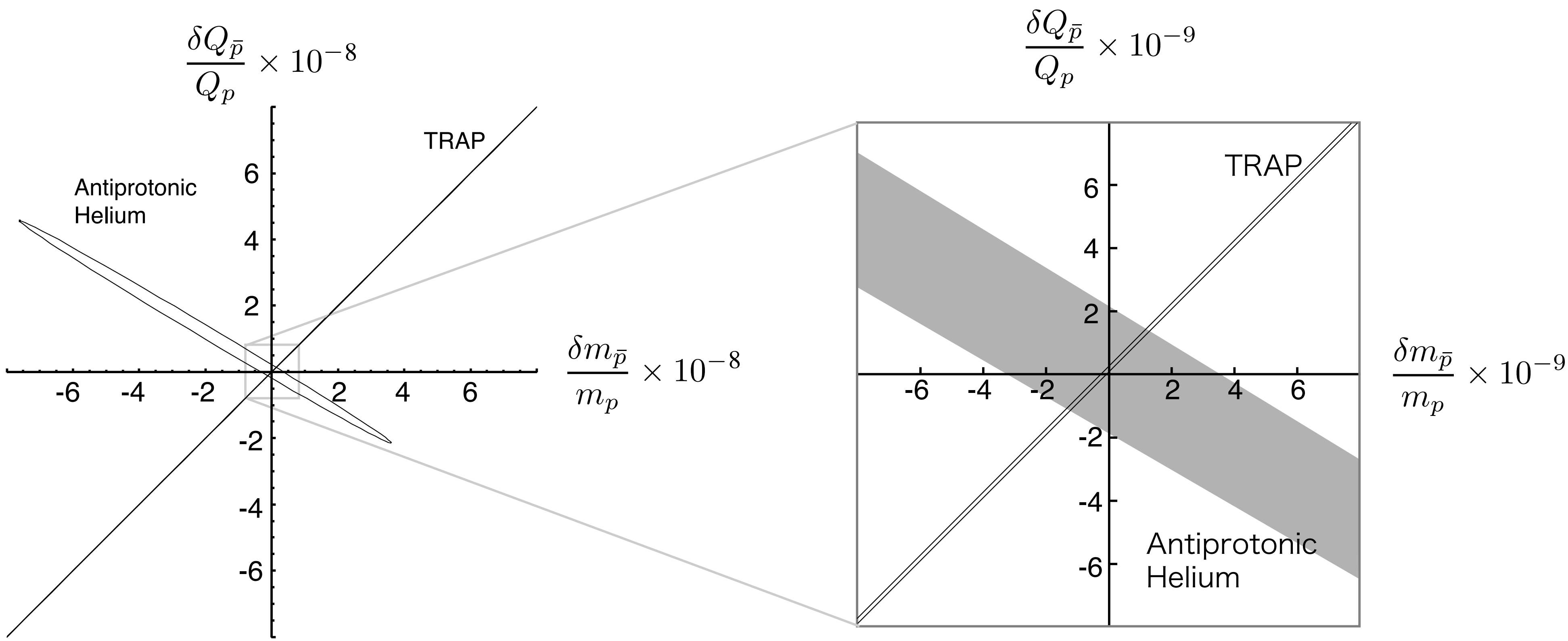


Dramatic improvement of resolution and stability

Resonance profile of the $(n, \ell) = (37, 35) \rightarrow (38, 34)$ transition at $\lambda = 726.1$ nm

2010: He at $T = 1.5K$, Ti:Sapphire pulsed laser

Determination of $m(\bar{\mathrm{p}}), q(\bar{\mathrm{p}})$



Determination of antiproton mass and charge:

possible deviation from those of the proton

TRAP: m/Q; ASACUSA: $m \cdot Q^2$

Two-photon spectroscopy

In low density gas main precision limitation:
thermal Doppler broadening even at $T < 10$ K

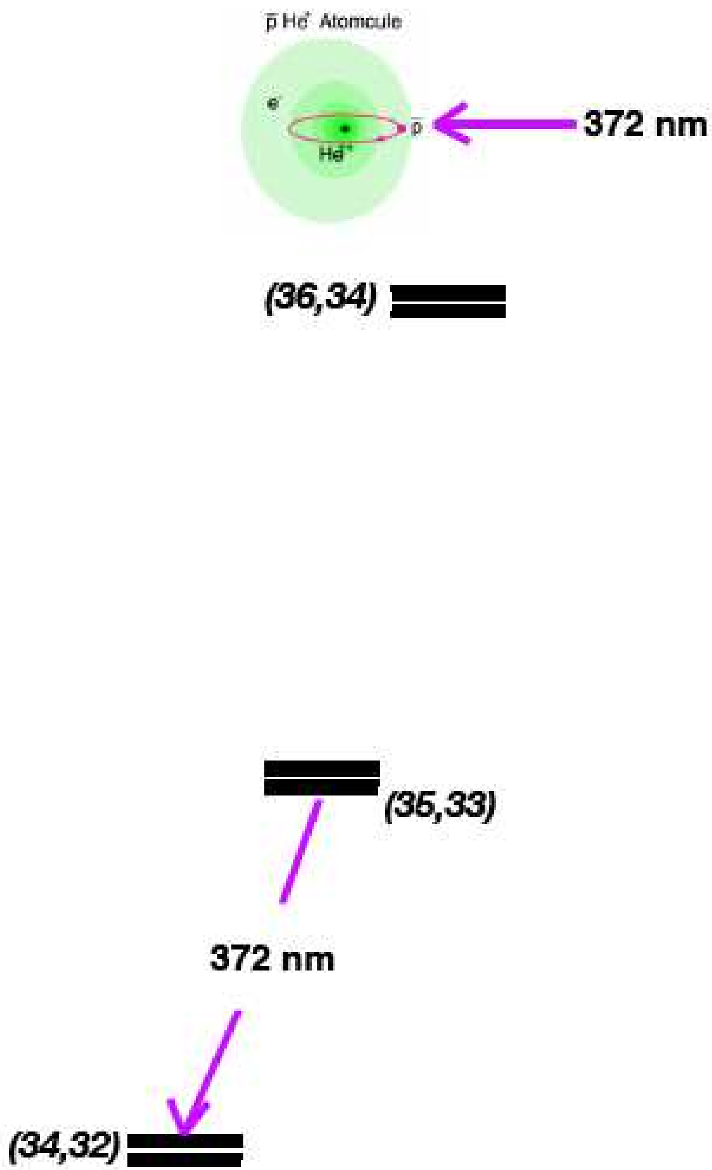
Excite $\Delta\ell = 2$ transition with 2 photons

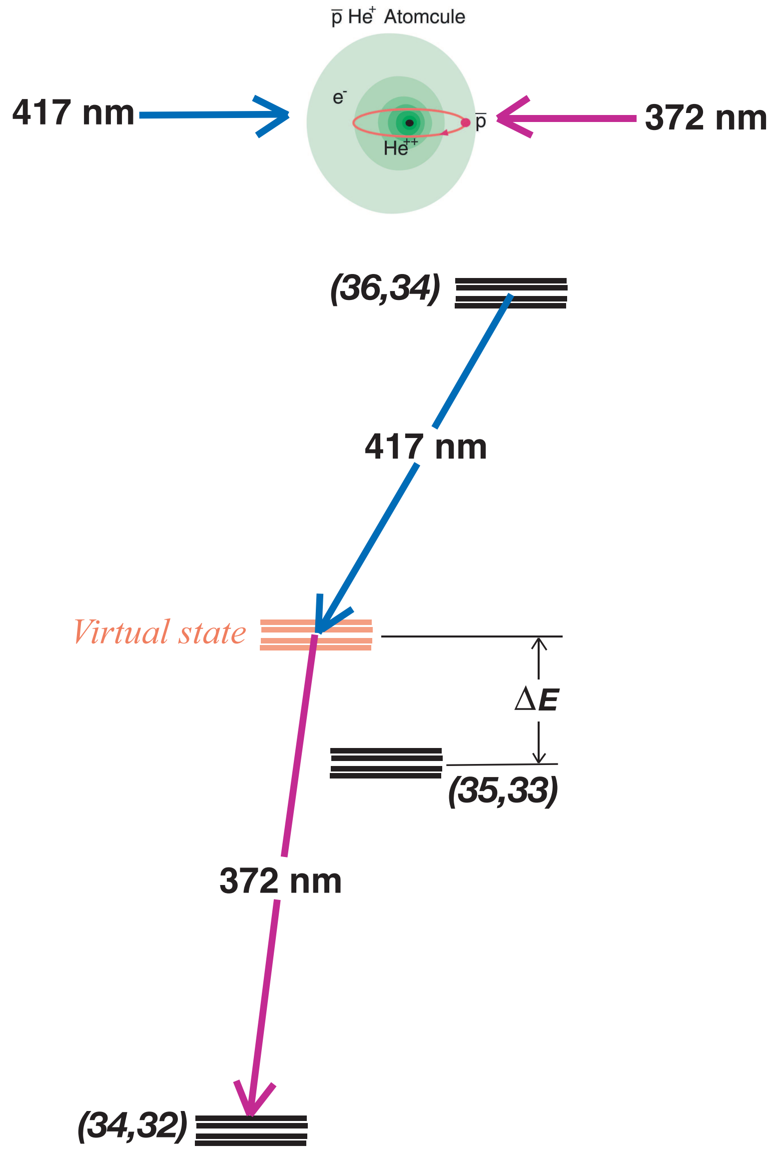
Two counterpropagating photons with $\nu_1 \sim \nu_2$
eliminate 1st order Doppler effect

Laser linewidth should not overlap with resonance

M. Hori, A. Sótér, D. Barna, A. Dax, R.S. Hayano, S. Friedreich, B. Juhász, T. Pask, E. Widmann, D. Horváth, L. Venturelli, N. Zurlo: *Two-photon laser spectroscopy of pbar-He$^+$ and the antiproton-to-electron mass ratio*,
Nature 475 (2011) 484-488,
Few Body Syst. *54* (2013) 917-922.

1-photon vs 2-photon spectroscopy





Near-resonant two-photon spectroscopy

$$(n,\ell) = (36,34)\rightarrow(34,32)$$

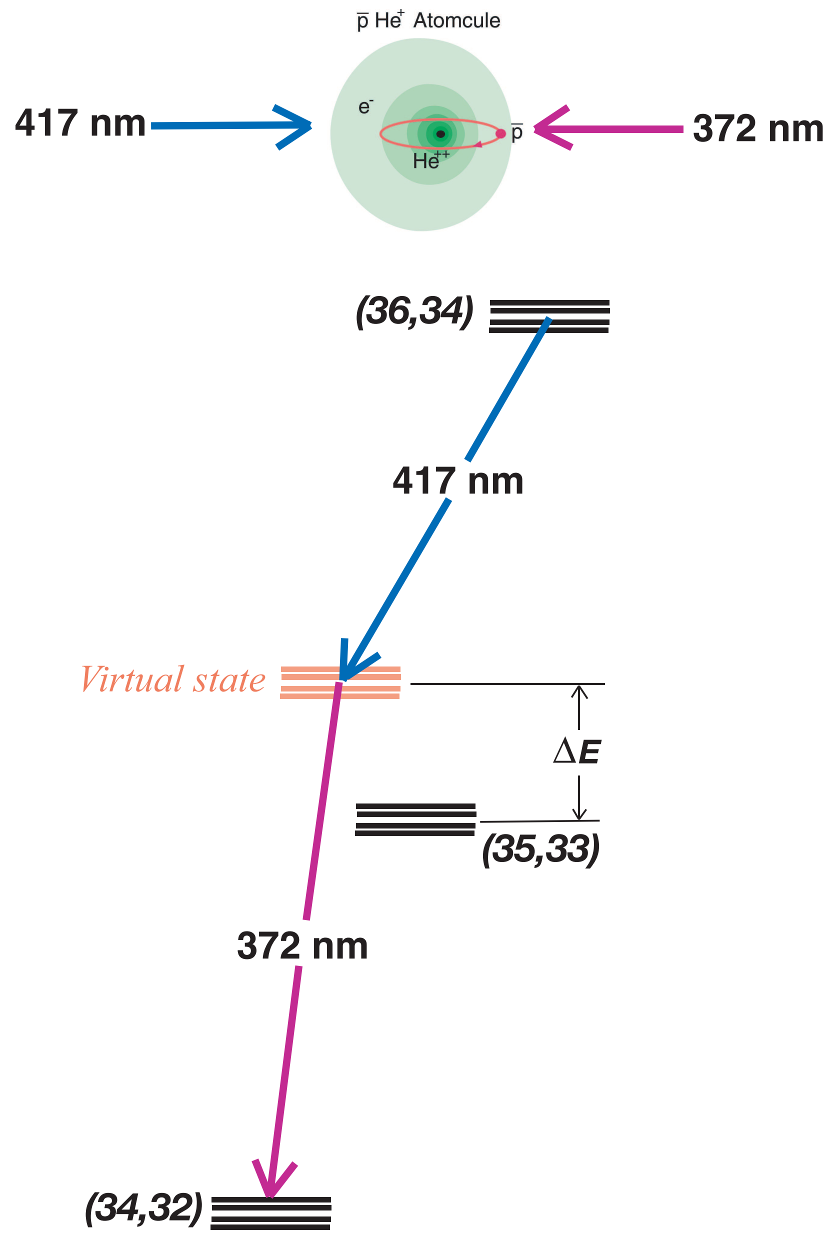
Doppler suppression:

$$\Delta\nu_{\gamma_1\gamma_2} = \left|\frac{\nu_1-\nu_2}{\nu_1+\nu_2}\right|\Delta\nu_{\mathrm{Doppler}}$$

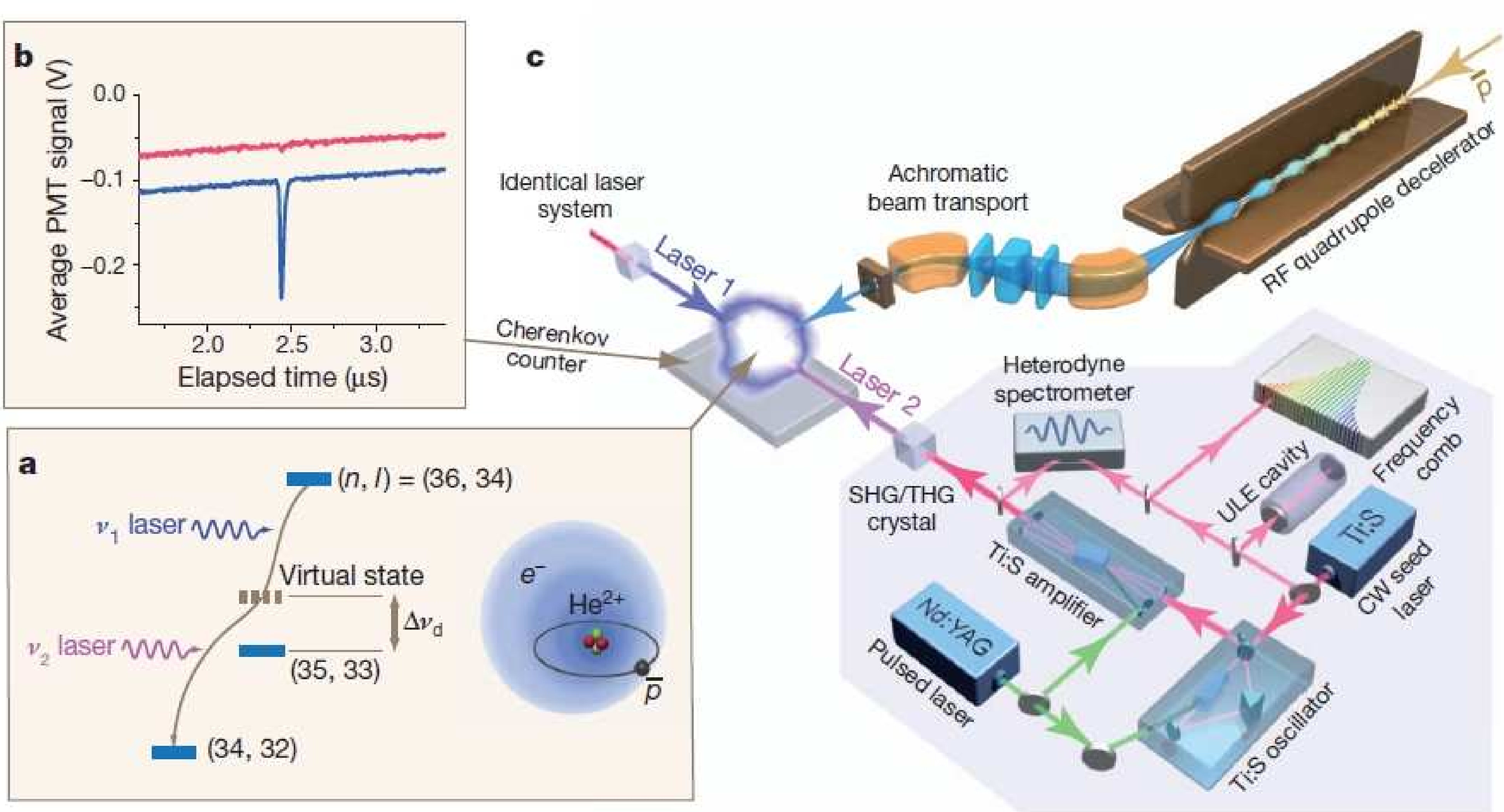
Gain: $\sim 20\times$

Limitation: residual Doppler, frequency chirp systematics

Expected $\Delta f \sim$ few MhZ



Two-photon spectroscopy: setup



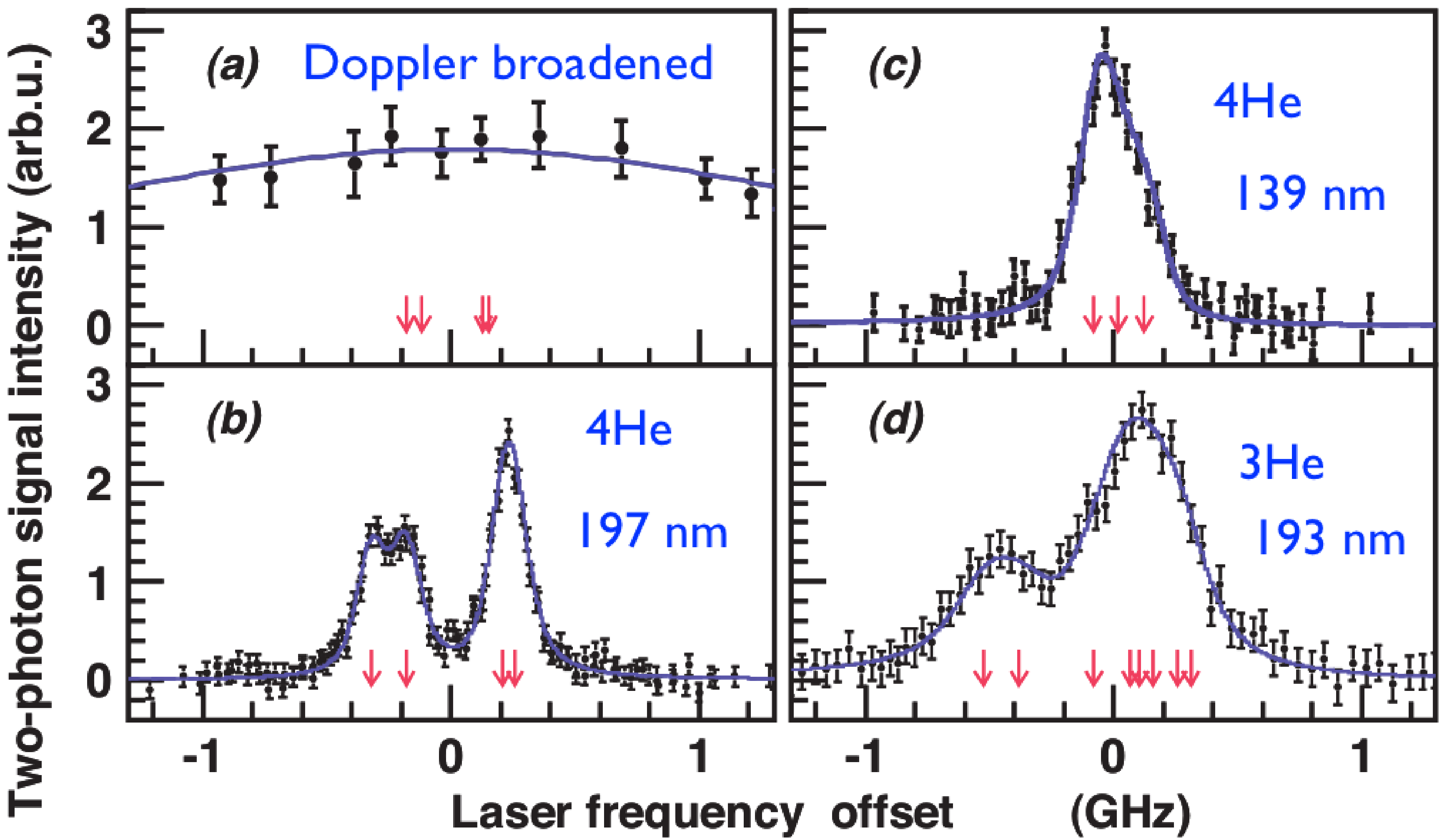
M. Hori et al., **Nature** 475 (2011) 484-488

Two-photon spectroscopy: parameters

- Precision of lasers: $< 1.4 \times 10^{-9}$.
- 7×10^6 $\overline{\mathrm{p}}$/pulse, $E \approx 70$ keV, 200 ns long, Ø20 mm.
- Target: He gas, $T \approx 15$ K, $p = 0.8 - 3$ mbar
- Laser beams: $\lambda_1 = 417$ nm, $\lambda_2 = 372$ nm, $P \approx 1$ mJ/cm^2
- Transition: (n=36, l=34) $\rightarrow$ (n=34, l=32); $\Delta\nu = 6$ GHz
- Measured linewidth: ≈ 200 MHz
- Width: Residual Doppler broadening, hyperfine structure, Auger lifetime, power broadening.

M. Hori, A. Sótér, D. Barna, A. Dax, R.S. Hayano, S. Friedreich, B. Juhász, T. Pask, E. Widmann, D. Horváth, L. Venturelli, N. Zurlo: „Two-photon laser spectroscopy of pbar-He$^+$ and the antiproton-to-electron mass ratio"
Nature 475 (2011) 484-488

Two-photon spectroscopy: spectra



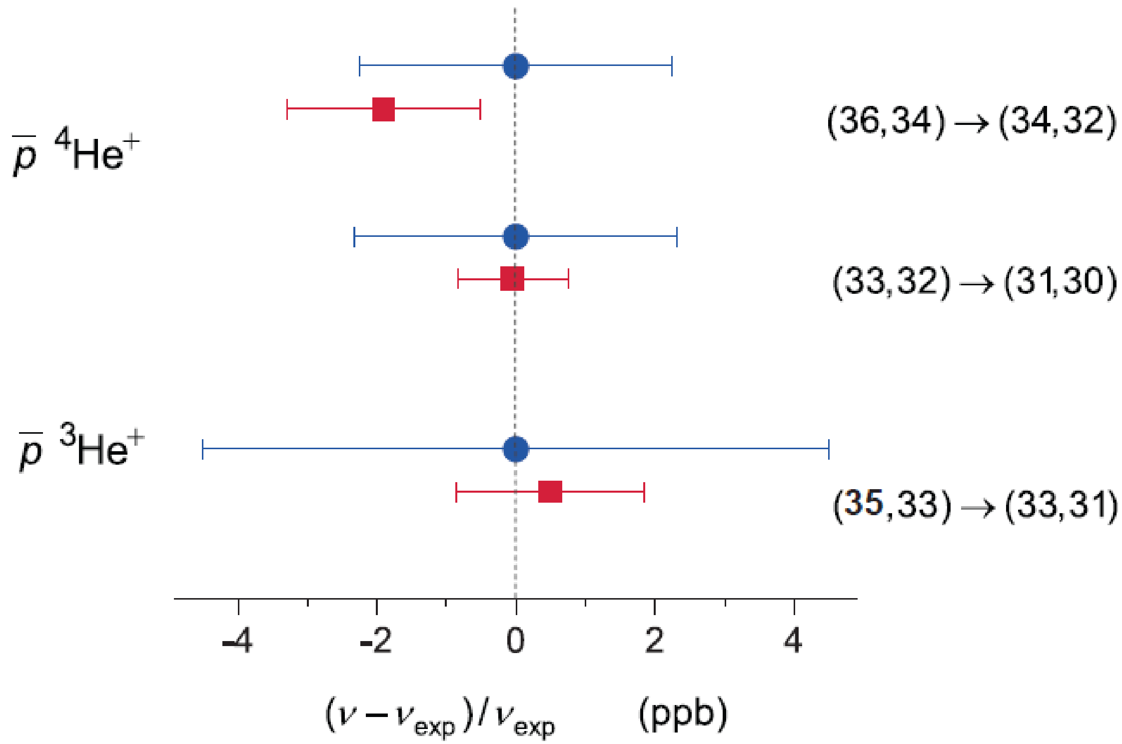
M. Hori et al., **Nature** 475 (2011) 484-488

Arrows: hyperfine transitions

Two-photon spectroscopy: uncertainties

Source	error (MHz)
Statistics	3
Collisional shift	1
A.c. Stark shift	0.5
Zeeman shift	<0.5
Frequency chirp	0.8
Laser freq. cal.	<0.1
Hyperfine structure	<0.5
Line profile sim.	1
Total systematic	1.8
Total experimental	3.5
Theory	2.1

Experiment-theory (Korobov) comparison of spin-averaged transition frequency



Two-photon spectroscopy: results

$$M_{\overline{p}}/m_{\mathrm{e}} = 1836.1526736(23)$$

Uncertainties:

$$1.8 \times 10^{-6}(\mathrm{stat}),\ 1.2 \times 10^{-6}(\mathrm{syst}),\ 1.0 \times 10^{-6}(\mathrm{theor})$$

Good agreement with proton results, similar (slightly higher) uncertainty.

Assuming CPT invariance our result can be included in the determination of M_{p} and m_{e}.

Using the TRAP limit for difference of Q/M for the proton and the antiproton and averaging our three values we can establish an upper limit for the charge and mass difference (i.e. possible CPT violation) at

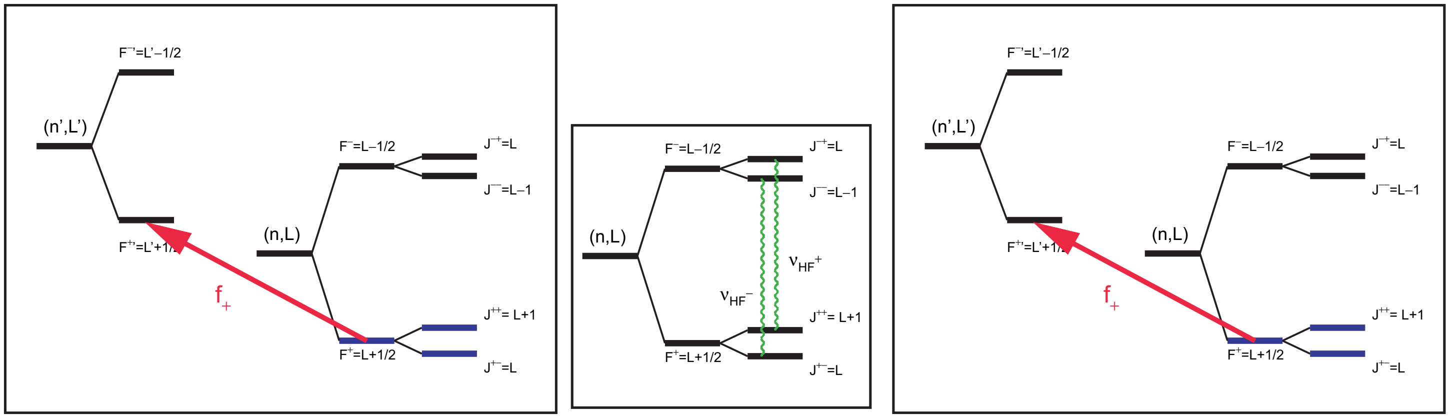
$$\boxed{7 \times 10^{-10}}$$

on a 90% confidence level.

M. Hori et al., **Nature** 475 (2011) 484-488

Measuring the magnetic moment of $\overline{\mathrm{p}}$

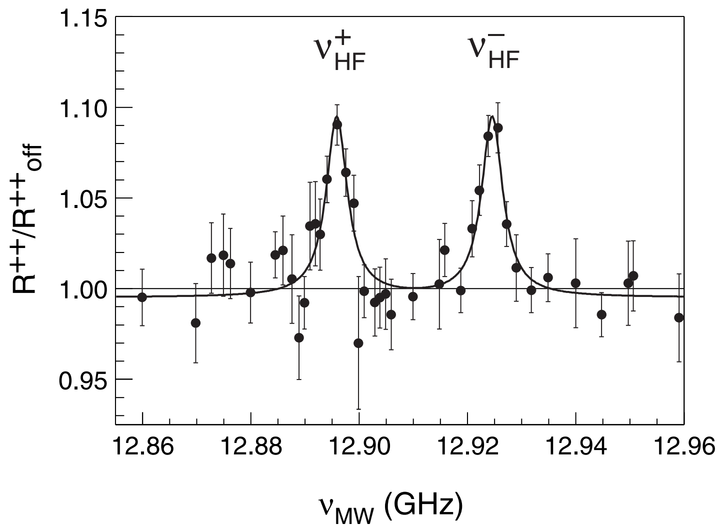
Level splitting in $\overline{\mathrm{p}}\mathrm{He}^{+}$ atoms



Step 1: depopulation of F^{+} doublet with f_{+} laser pulse

Step 2: equalization of populations of F^{+} and F^{-} by microwave

Step 3: probing of population of F^{+} doublet with 2nd f_{+} laser pulse



Microwave frequency scan

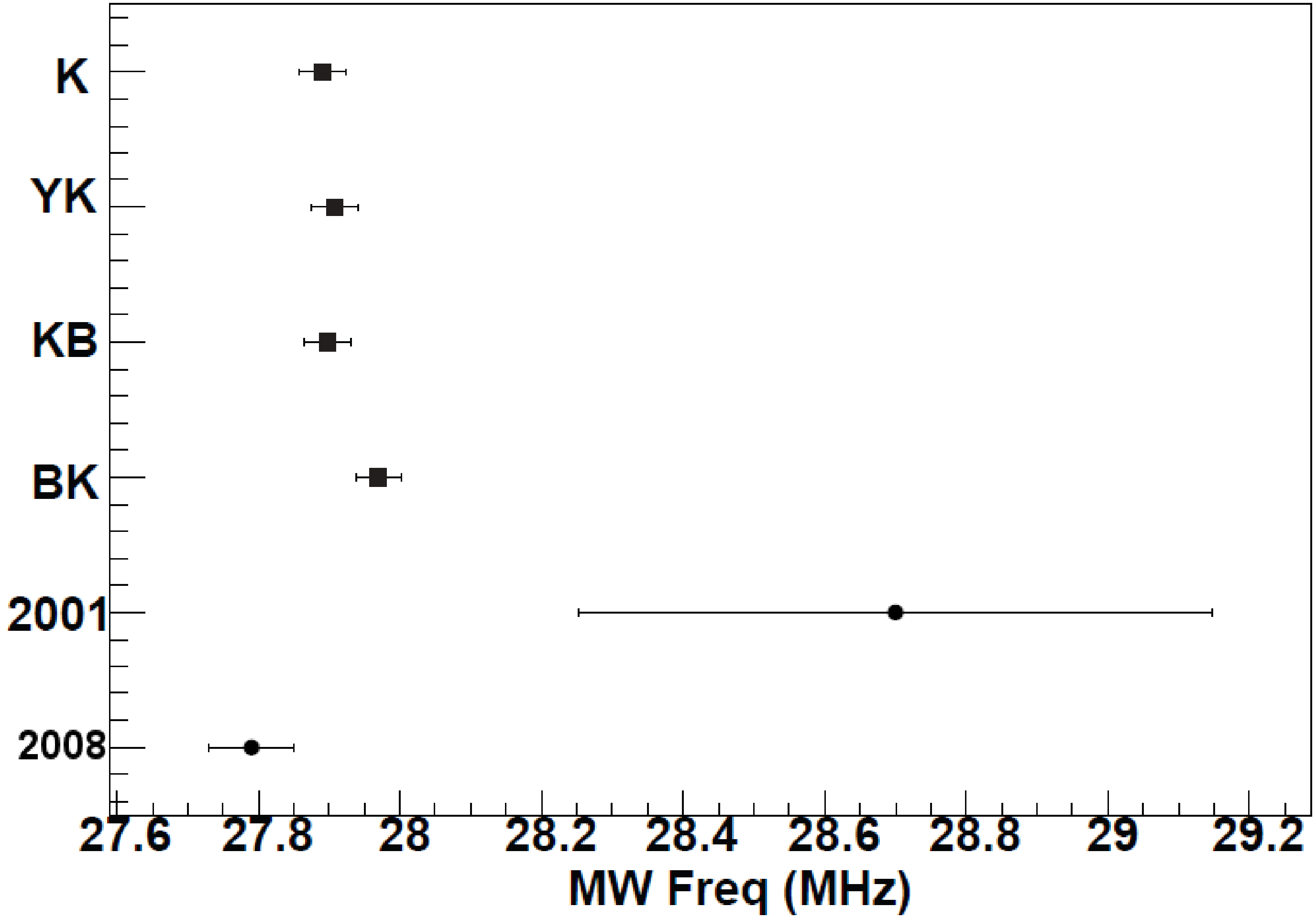
Magnetic moments

$\mu(\mathrm{p}) \sim \mu(\overline{\mathrm{p}}) \quad \Rightarrow$ *CPT* invariance OK

E. Widmann, R.S. Hayano, T. Ishikawa, J. Sakaguchi, H. Yamaguchi, J. Eades, M. Hori, H.A. Torii, B. Juhász, D. Horváth, T. Yamazaki:

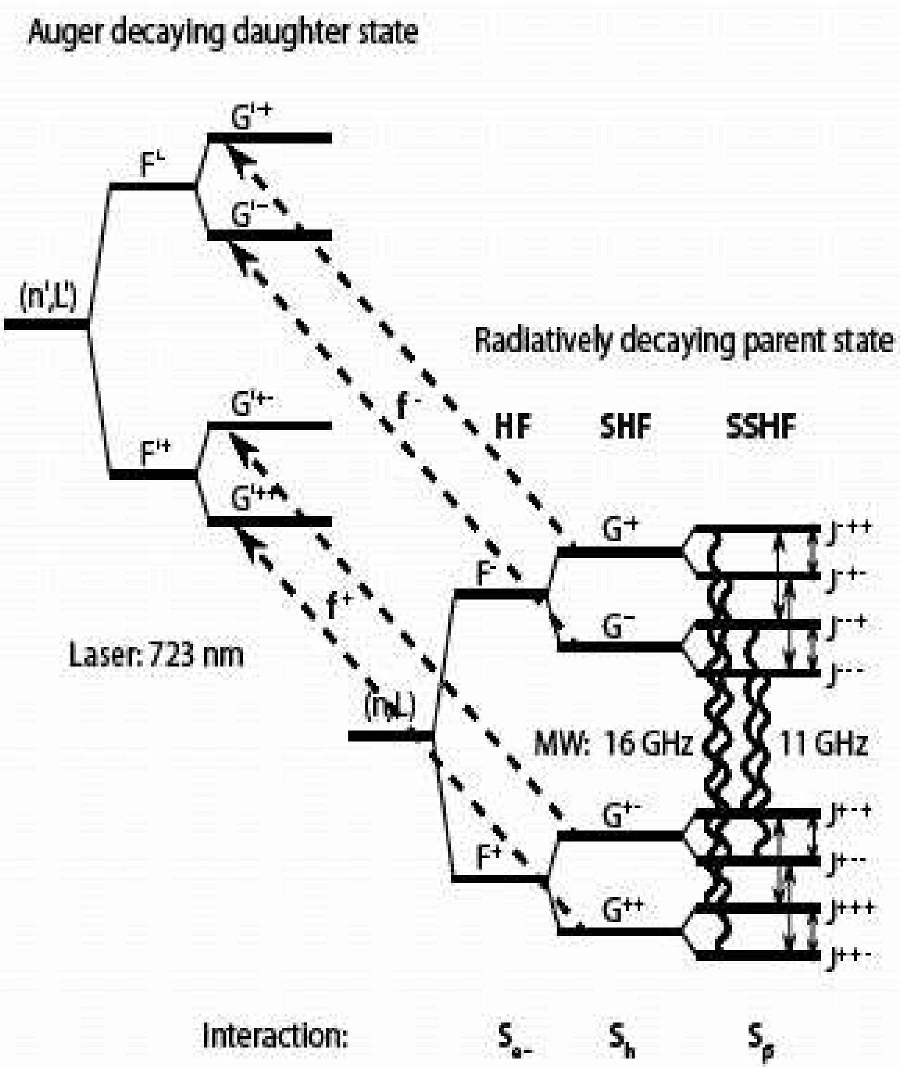
Phys. Rev. Lett. *89* (2002) 243402.

$\overline{p}^4$He HF structure: expt vs. theory

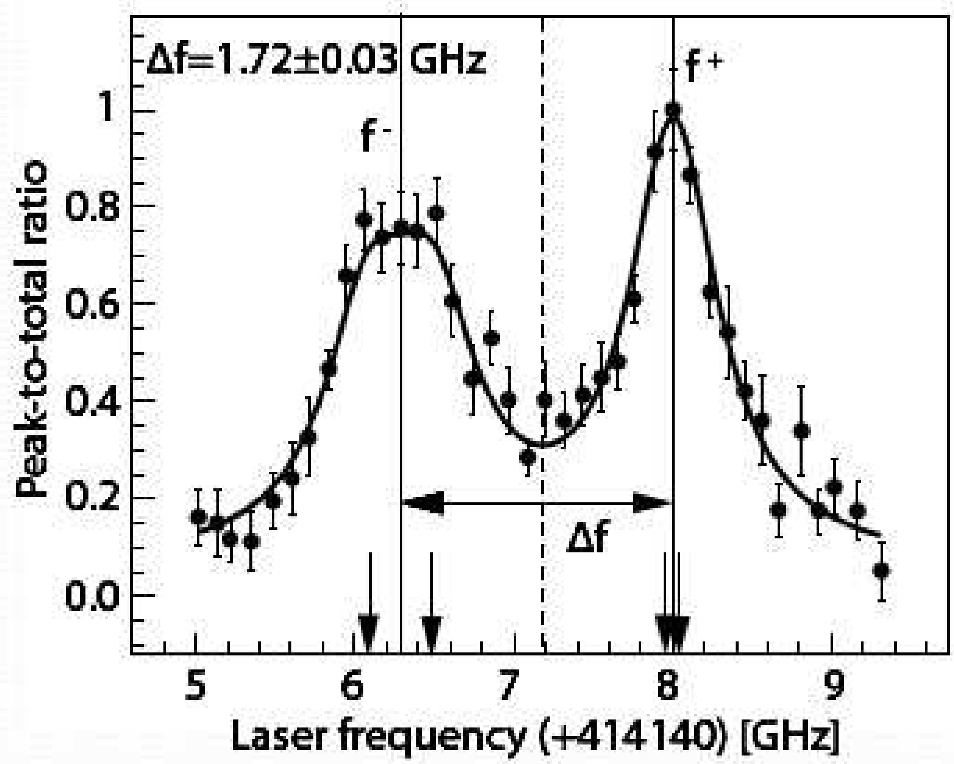


Th. Pask et al., Phys. Lett. B 678 (2009) 55.

$\overline{\mathrm{p}}^3$He HF structure: laser scan



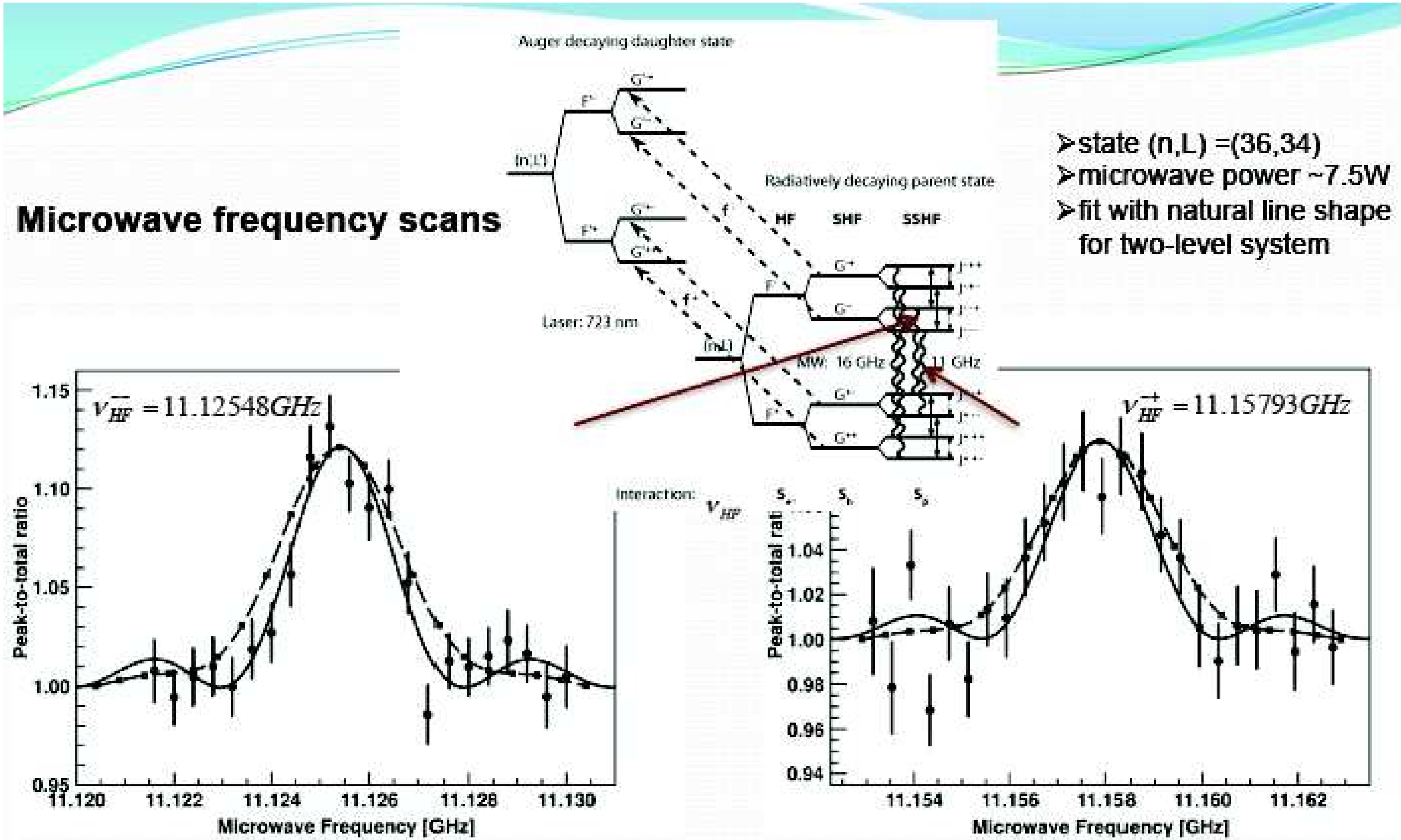
- ➢verify splitting of laser transition lines
- ➢determine laser resonance frequency



- ➢fit with 4 Voigt functions plus constant for signal background

S. Friedreich et al., Physics Letters B 700 (2011) 1.

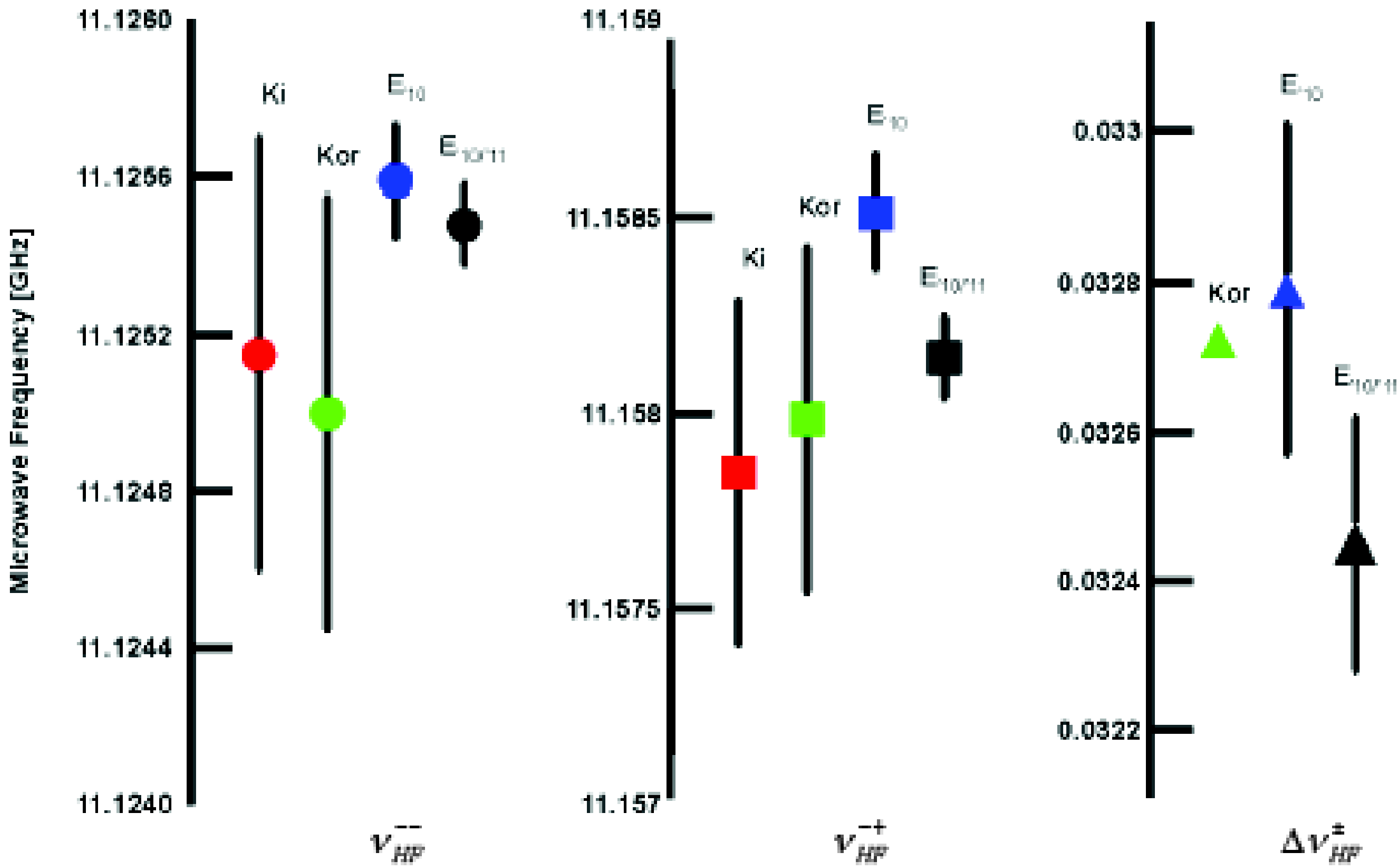
$\bar{p}^3$He HF structure: microwave scan



	ν_{exp} (GHz)	δ_{exp} (ppm)	Γ (MHz)	Korobov [37,70]	$\Delta\nu_{th\text{-}exp}$ (ppm)	Kino [41]	$\Delta\nu_{th\text{-}exp}$ (ppm)
ν_{HF}^{--} (GHz)	11.125 48(08)	7.2	1.69(0.11)	11.125 00(55)	43	11.125 15(55)	30
ν_{HF}^{-+} (GHz)	11.157 93(13)	11.7	2.20(0.15)	11.157 73(55)	18	11.157 56(55)	33
$\Delta\nu_{HF}^{\pm}$ (GHz)	0.03245(15)	523.9		0.0327219(16)	48.9		

S. Friedreich et al., Physics Letters B 700 (2011) 1.

Comparison of Theory & Experiment



Results published in Physics Letters B

First observation of two hyperfine transitions in antiprotonic ^{3}He, S. Friedreich, D. Barna, F. Caspers, A. Dax, R.S. Hayano, M. H Horváth, B. Juhász, T. Kobayashi, O. Massiczek, A. Sóter, K. Todoroki, E. Widmann, J. Zmeskal, *Phys. Lett B* 700(1) 1 (2011).

➔ **Publication on final results is in progress**

Theory

V. Korobov, *Phys. Rev. A* 73 022509 (2006).

Y. Kino et al., *Hyperfine Interactions* 146 331 (2003).

S. Friedreich et al.
arXive:1303.2831, 2013.

Plans, future prospects

- Colder atoms ($T = 1.6$ K), better lasers, better detectors (segmented scints)
- Use more transitions, collect more statistics
- ELENA (colder antiproton beams at 100 keV of higher luminosity)
- Spectroscopy on $\overline{\mathrm{H}}$beam

MUSASHI: slow $\overline{\mathrm{p}}$ and $\overline{\mathrm{H}}$ beam

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

Musashi Miyamoto self-portrait ~ 1640

5.8 MeV $\overline{\mathrm{p}}$ injected into RFQ

100 keV $\overline{\mathrm{p}}$ injected into trap

10^6 $\overline{\mathrm{p}}$ trapped and cooled (2002)

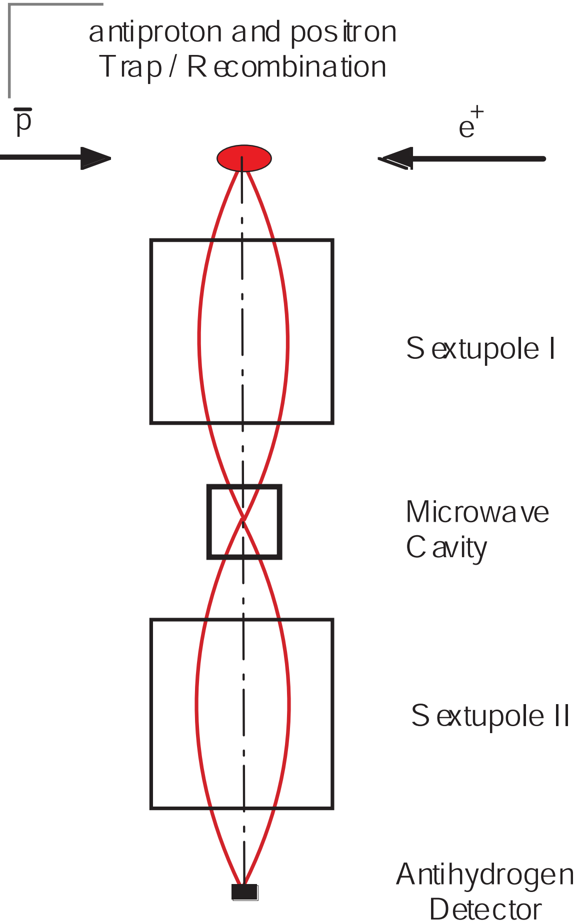
~ 350000 slow $\overline{\mathrm{p}}$ extracted (2004)

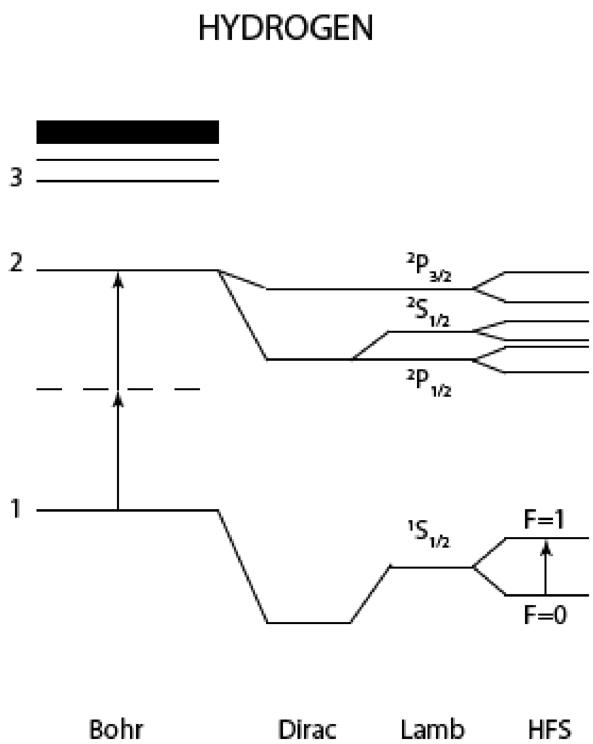
Cold $\overline{\mathrm{p}}$ compressed in trap (2008)

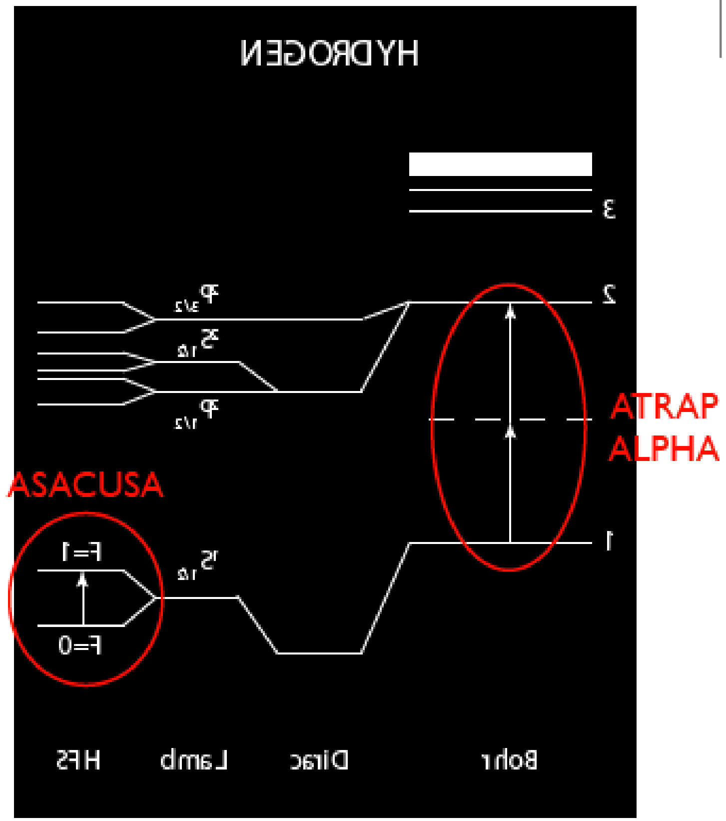
(5×10^5 $\overline{\mathrm{p}}$, $E = 0.3$ eV, $R = 0.25$ mm)

$\overline{\mathrm{H}}$-beam formed for in-flight spectroscopy: 2010-2012

Spectroscopy with $\overline{\mathrm{H}}$ beam







$\overline{\mathrm{H}}$ spectr in flight: polariser, resonator, analyser

Analogy: polarised light

R.S. Hayano et al., **Rep. Progr. Phys.** *70* (2007) 1995.

E. Widmann et al., progress reports in conf. papers

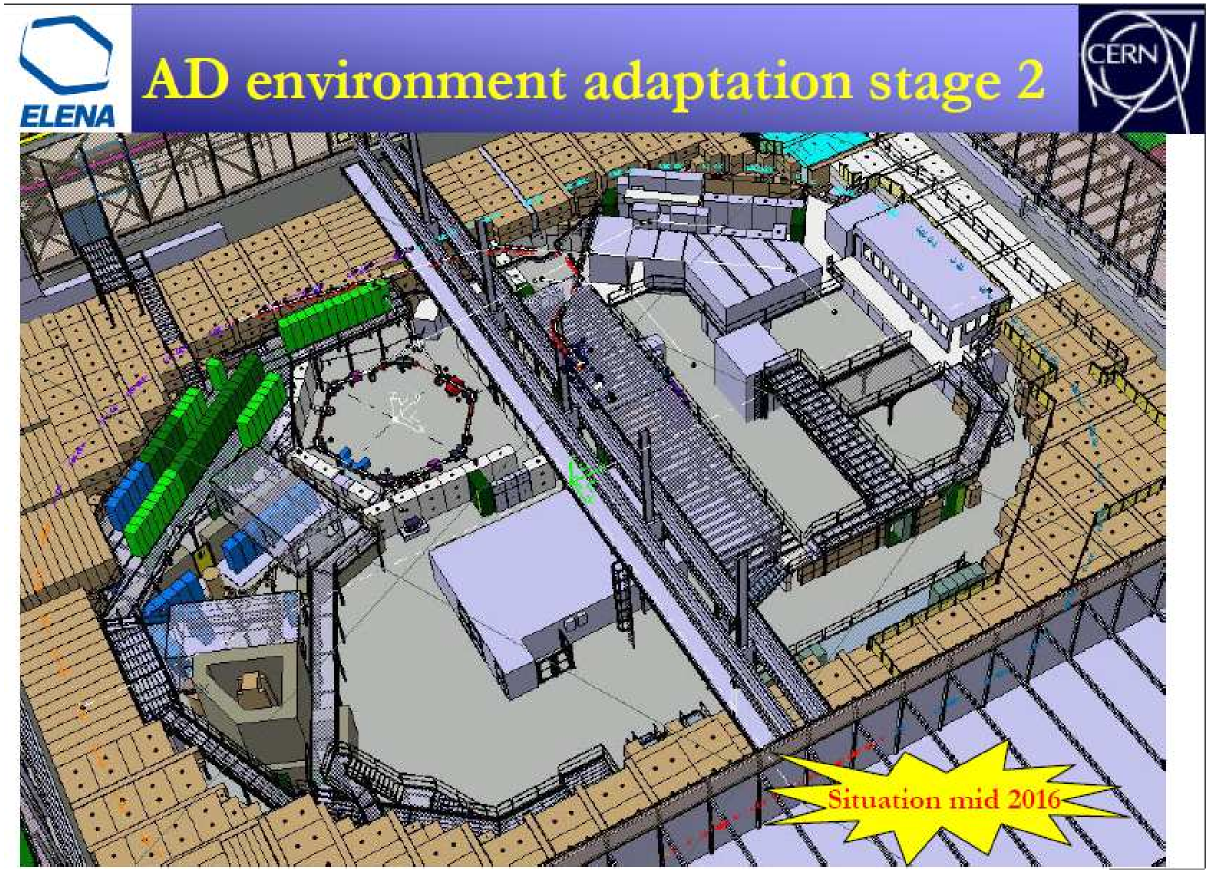
Extra Low ENergy Antiprotons

Success of RFQ post-decelerator of ASACUSA ⇒
CERN decided to build storage ring ELENA.

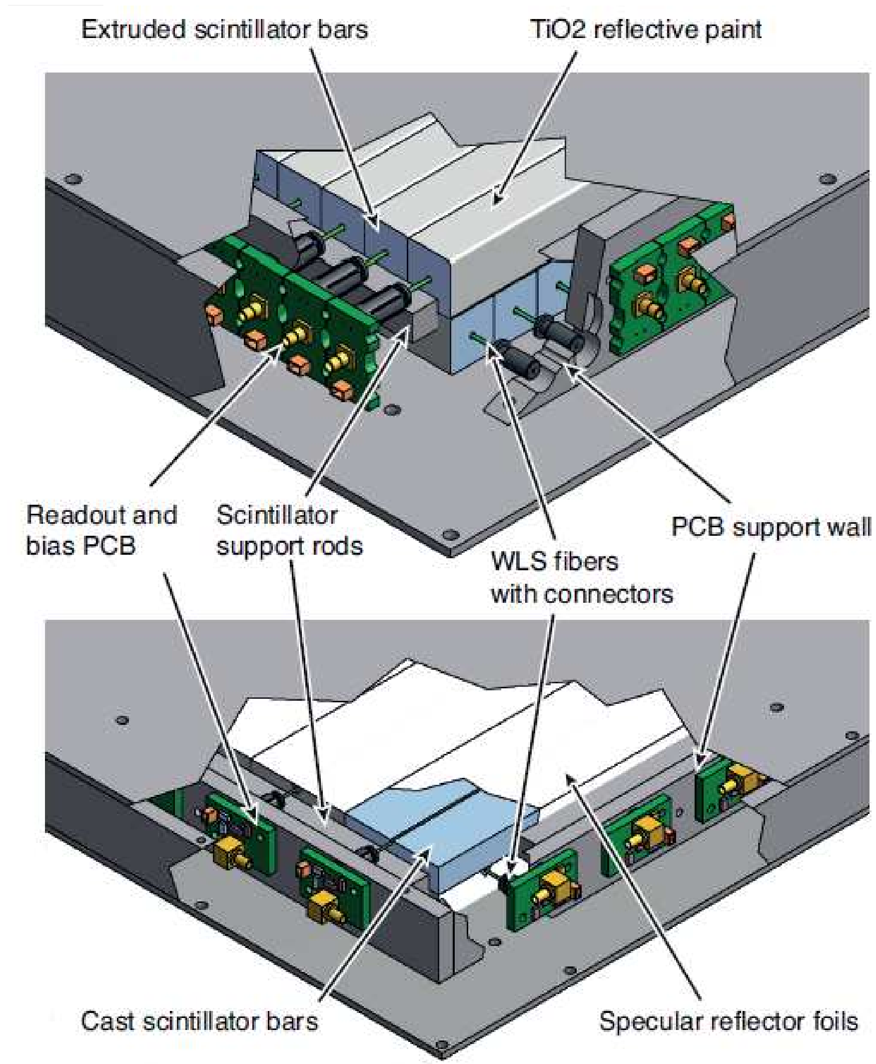
Plan: launch it in 2016.

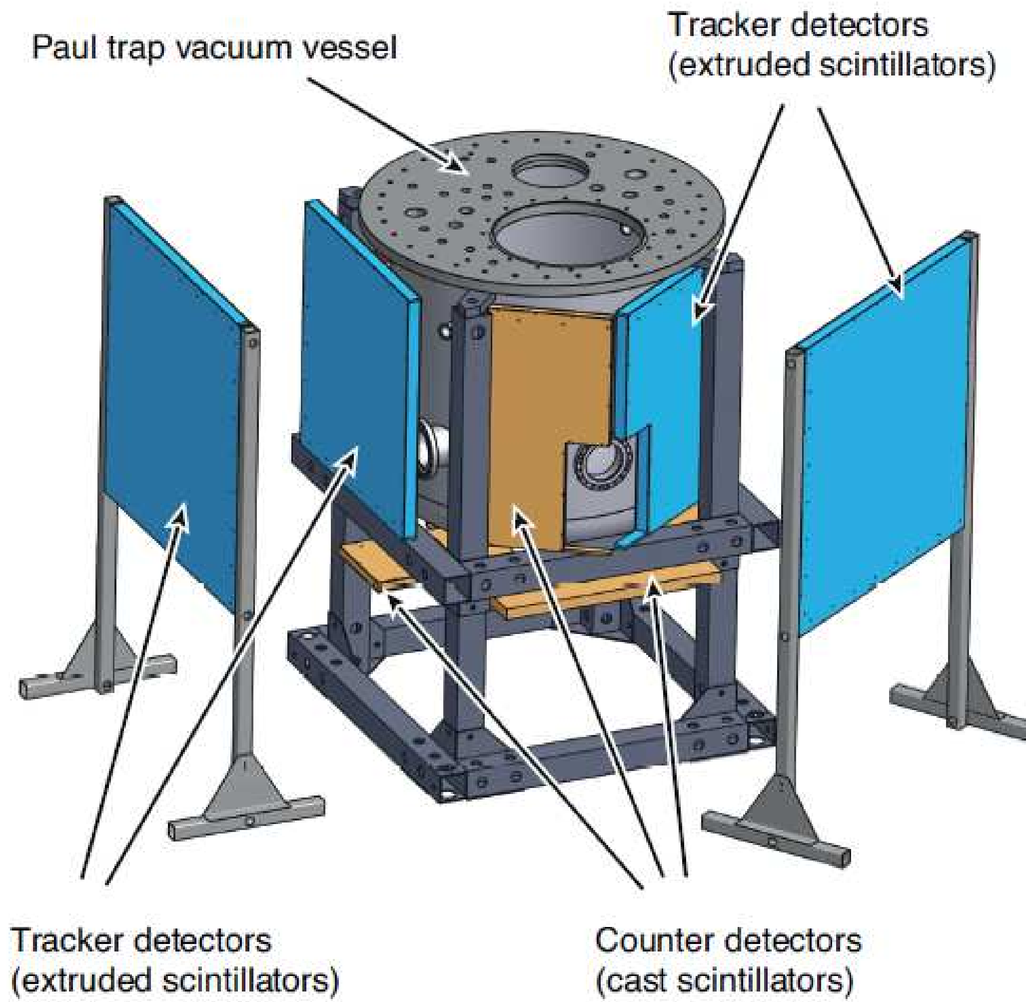
AD:
5.8 MeV $\overline{\mathrm{p}}$, 3×10^7/shot
ELENA:
100 keV $\overline{\mathrm{p}}$,
1.8×10^7/shot
4 bunches to 4 expts
every 120 sec

Dániel Barna:
Design of beam line



Segmented detectors for Paul trap





A. Sótér, K. Todoroki, T. Kobayashi, D. Barna, D. Horváth, M. Hori:
Submitted to Nucl. Instr. Meth

Trap design: D. Barna, M. Hori

Conclusion

- The first sub-Doppler two-photon spectroscopy of antiprotonic helium: two transitions in ^{4}He and one in ^{3}He. Results agree with 3-body QED calculations.
- Determined $M_{\overline{\mathrm{p}}}/m_{\mathrm{e}}$ ratio to 1.3 ppb. Result agrees with CODATA proton value (0.4 ppb).
- Further improvement partially hindered by theoretical uncertainty (QED terms $< \alpha^6$, radiative recoil corrections)
- Big improvement expected from ELENA in 2016.

Thanks for your attention