Precision Physics and Antimatter

Part 5 – Antiproton(ic) CPT invariance tests

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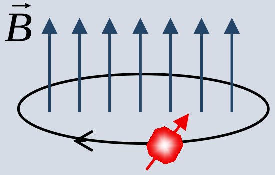
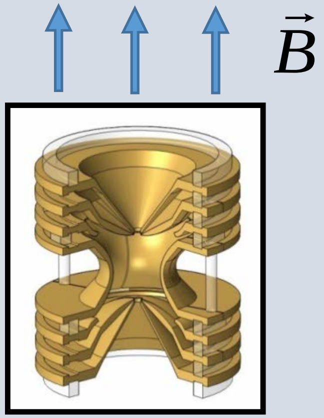
39th Graduate Days
Ruprecht-Karls-Universität Heidelberg

Summary on
precision magnetic moment measurements

High-precision measurements in Penning traps

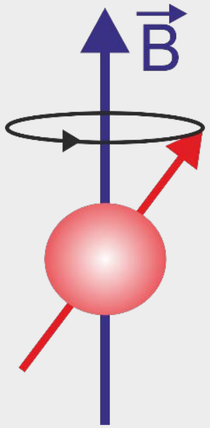
Cyclotron Frequency

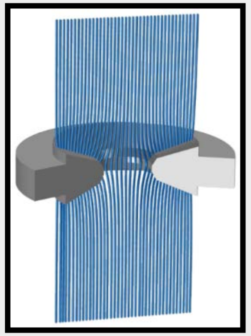




$$\omega_c = \frac{q}{m} B$$

Larmor Frequency



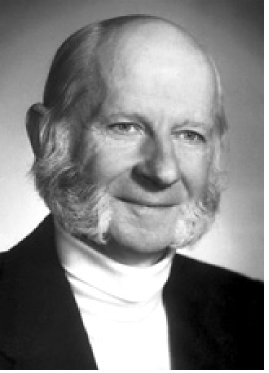


$$\omega_L = g \frac{e}{2m_p} B$$

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

$$\frac{\omega_L}{\omega_c} = \frac{g}{2} = \frac{\mu}{\mu_N}$$

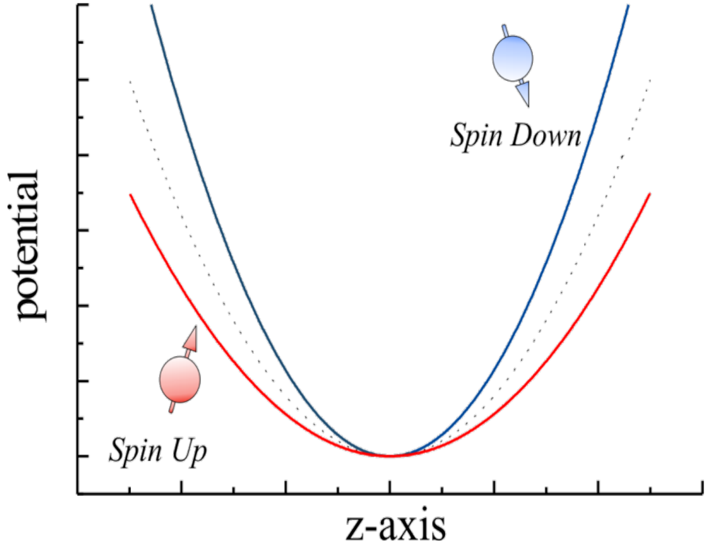
H. G. Dehmelt and P. Ekström, Bull. Am. Phys. Soc. 18, 72 (1973).
D. J. Wineland and H. G. Dehmelt, J. Appl. Phys. 46, 919 (1975).



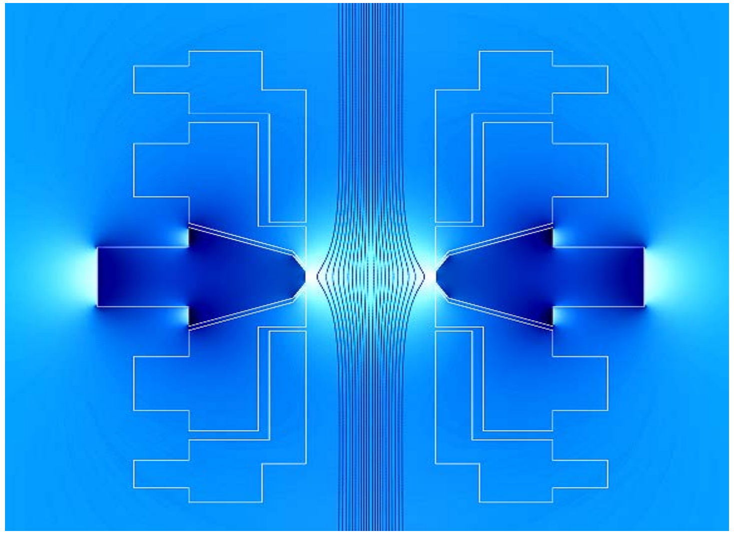
How to mesure the Larmor frequency?
The continuous Stern-Gerlach effect

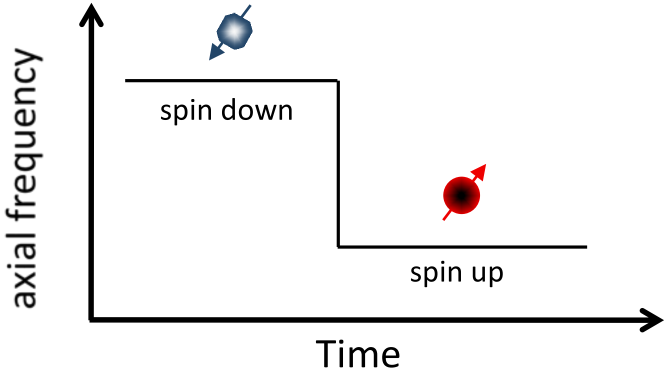
Introduce magnetic inhomogeneity, the magnetic bottle

$$B_z = B_0 + B_2\left(z^2 - \frac{\rho^2}{2}\right)$$



$$\Phi_z = \pm \mu_p B_z$$





Spin flip results in shift of the axial frequency

$$\nu_z \propto \frac{\mu_p}{m} B_2$$

Electron g-Faktor and QED

- Effects described by Schwinger series

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + \ldots$$
$$+ a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}},$$

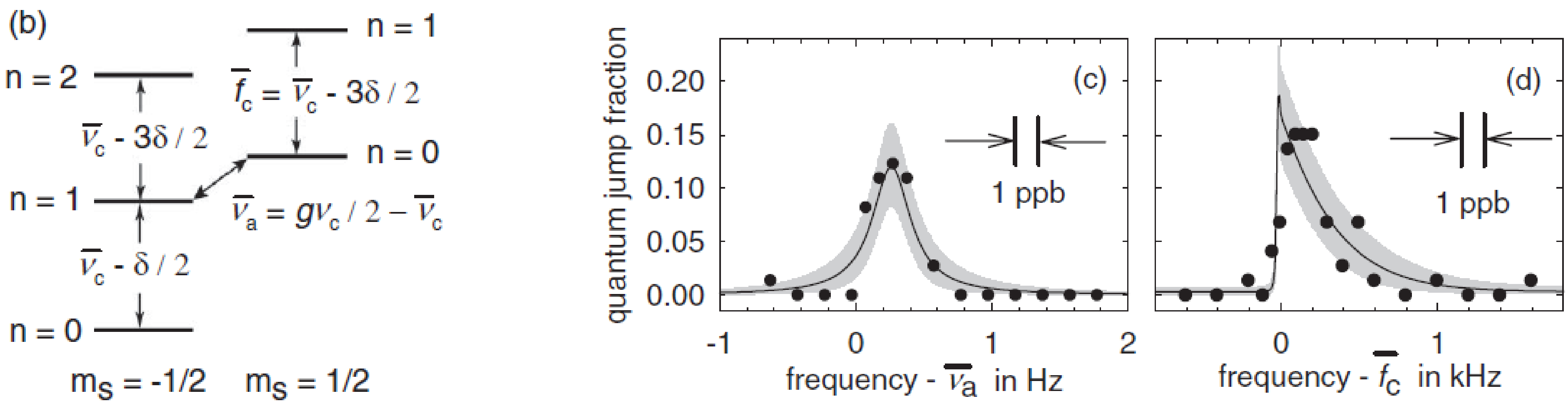
C_2	0,5
C4	-0,328478965579
C6	1,181241456587
C8	-1,9144(35)
$a_{\mu,\tau}$	2,720919(3) 10^{-12}
$a_{hadronic}$	1,682(20) 10^{-12}
a_{weak}	0,0297(5) 10^{-12}

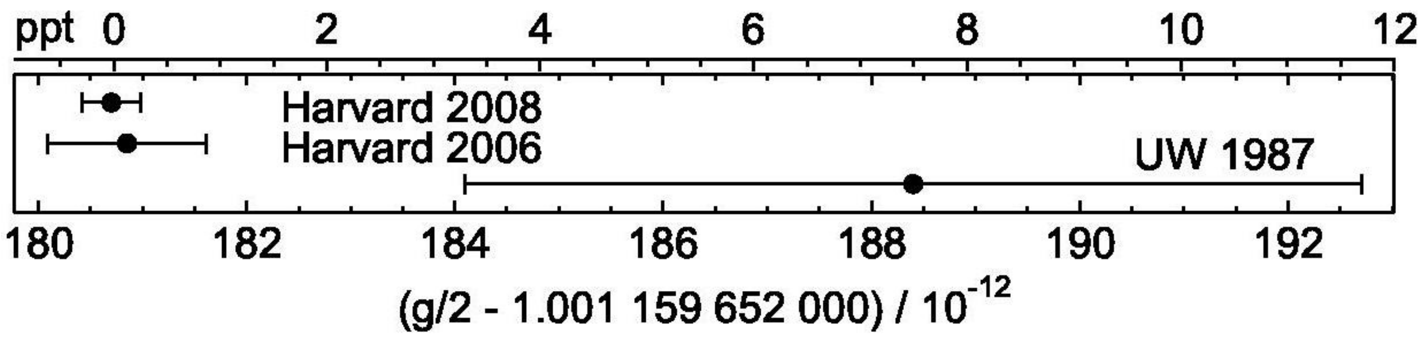
$$a_e(theo) = \frac{g-2}{2} = 0{,}00115965218113\ (84)$$

10th order 12 672 diagrams calculated

D. Hanneke et al., Phys. Rev. Lett. 100, 120801 (2008).
T. Aoyama et al., Phys. Rev. Lett. 99, 110406 (2007).

Single electron quantum jump spectroscopy





No signature for new physics yet - Independent measurement of the fine structure constant is necessary
CPT invariance test (g-2) measurement of the positron by Dehmelt - Best SME-limits for electrons

D. Hanneke et al., Phys. Rev. Lett. 100, 120801 (2008).

SME in a Penning trap I

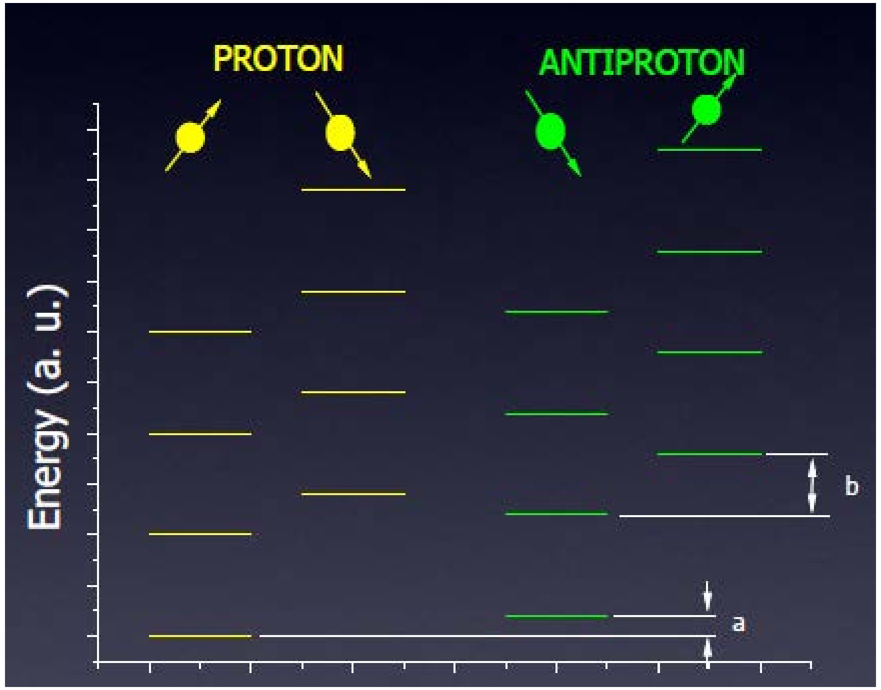
SME reduces to

$$\left(i\gamma^{\mu}D_{\mu}-m-a_{\mu}\gamma^{\mu}-b_{\mu}\gamma^{5}\gamma^{\mu}\right)\psi=0$$

a – shifts levels, no measurable effect in Penning trap
b – modification of anomaly frequency

$$r_g=\frac{E_p-E_{\bar{p}}}{E_p}=\frac{\delta\omega_a}{m}$$

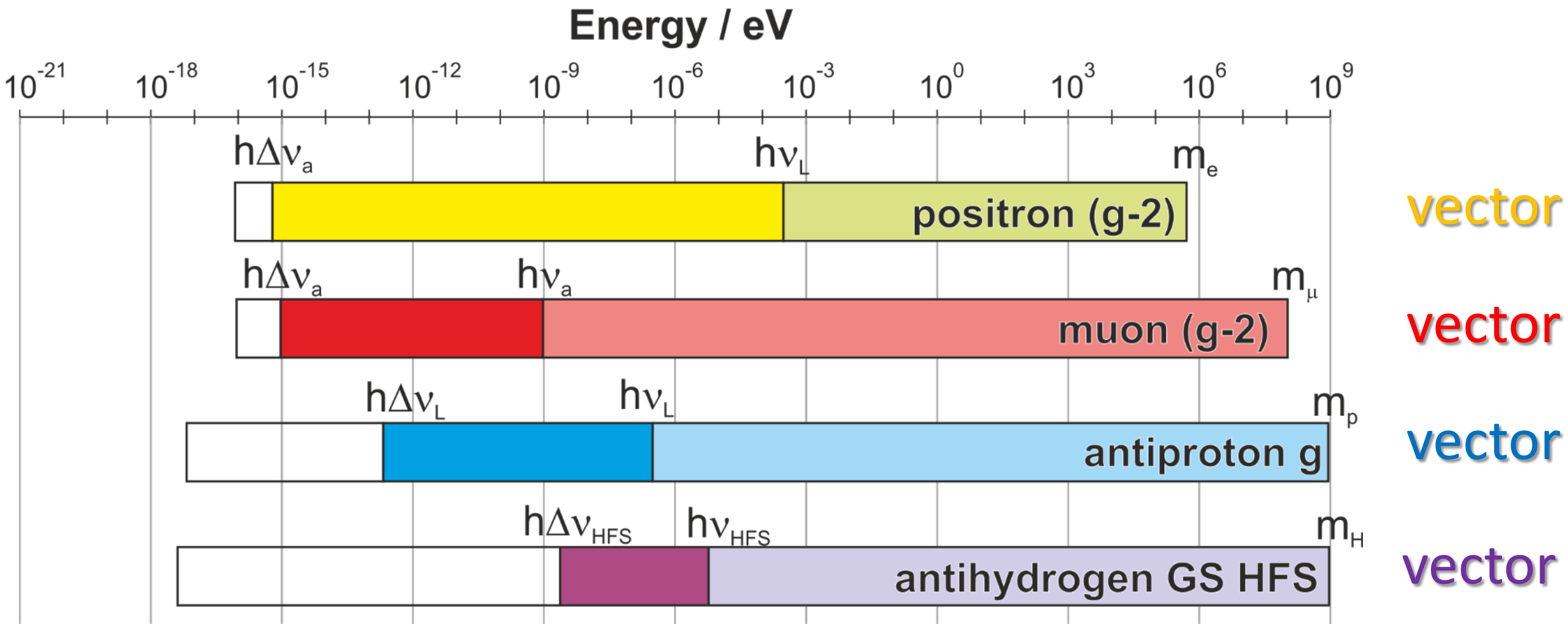
Electron Positron



R. Bluhm et al., Phys. Rev. D 57, 3932 (1998).

Energy resolution of g-factor measurements

$$\frac{\delta E}{E} = \frac{h\,\Delta\upsilon}{m\,c^2}$$



4 very important tests for CPT-odd interactions

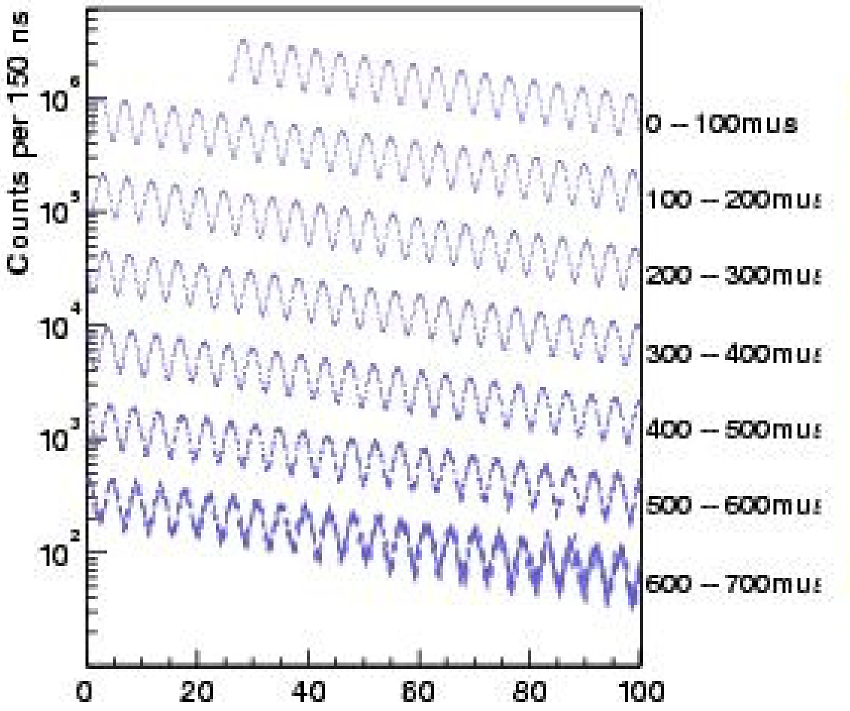
Think of CP-violation which exists only for a few mesons/exotic baryons

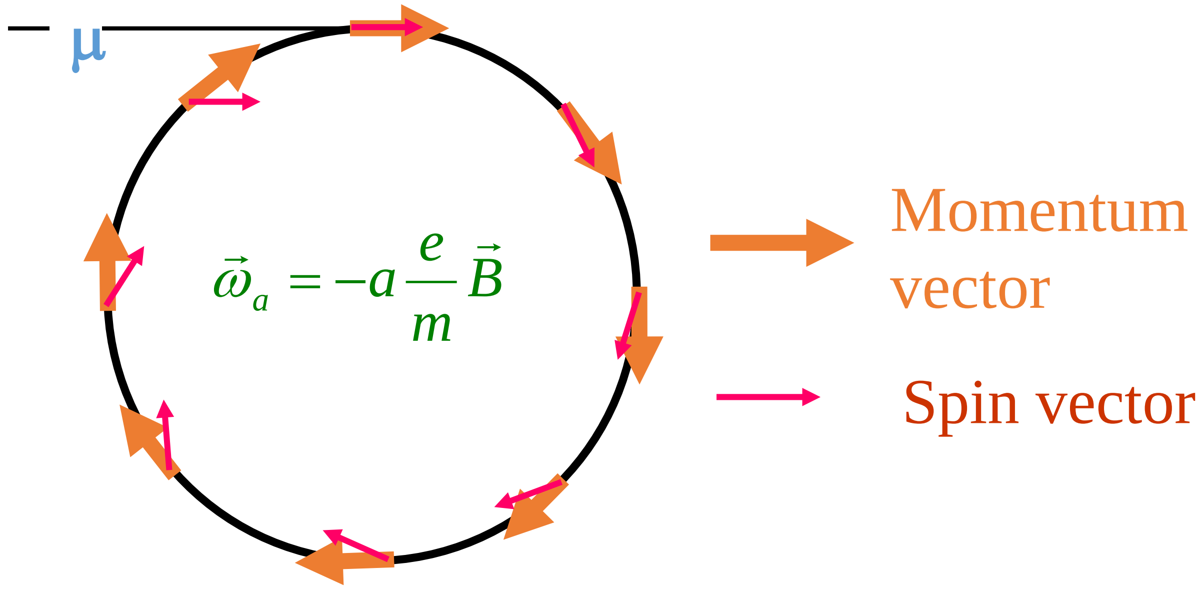
Need to search in all available systems

V. A. Kostelecky, N. Russell, 0801.0287v10 (2017).

Measurement of the muon magnetic moment

$$N(t) = N_0 e^{-\frac{t}{\gamma\tau}} \left[1 + A\cos(\omega_a t + \phi)\right]$$



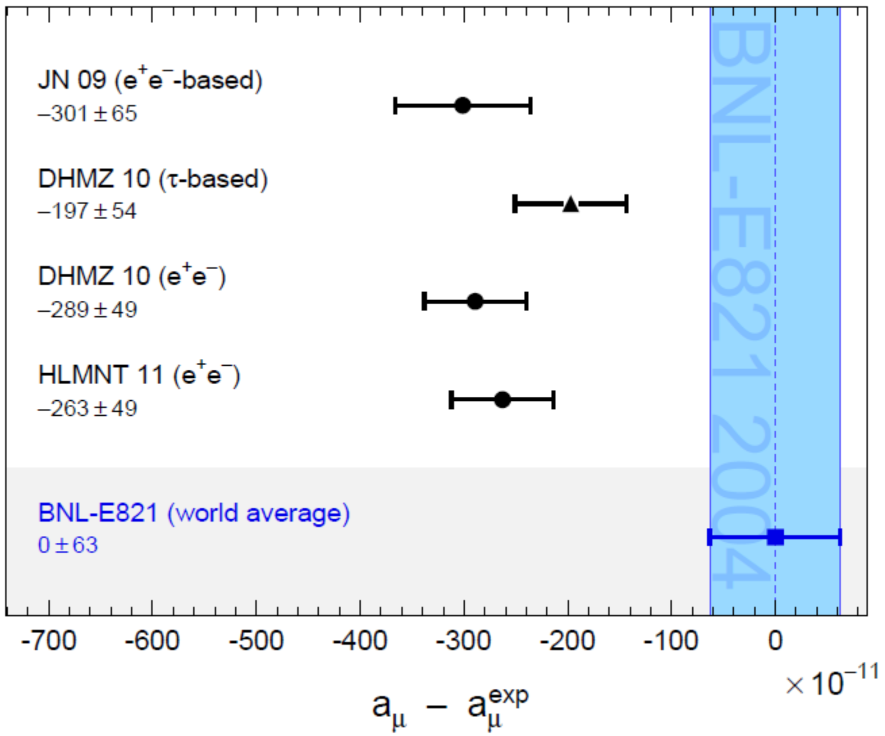


G. W. Bennett et al., Phys. Rev. Lett. 100, 091602 (2008).

Muon magnetic anomaly and Helium-3

Muon and Antimuon are found to agree

But 3.6 Sigma discrepancy observed to theory



New measurement at Fermilab

$$a_\mu = \frac{g-2}{2} = \frac{\omega_a/\omega_p}{\omega_L/\omega_p - \omega_a/\omega_p}$$

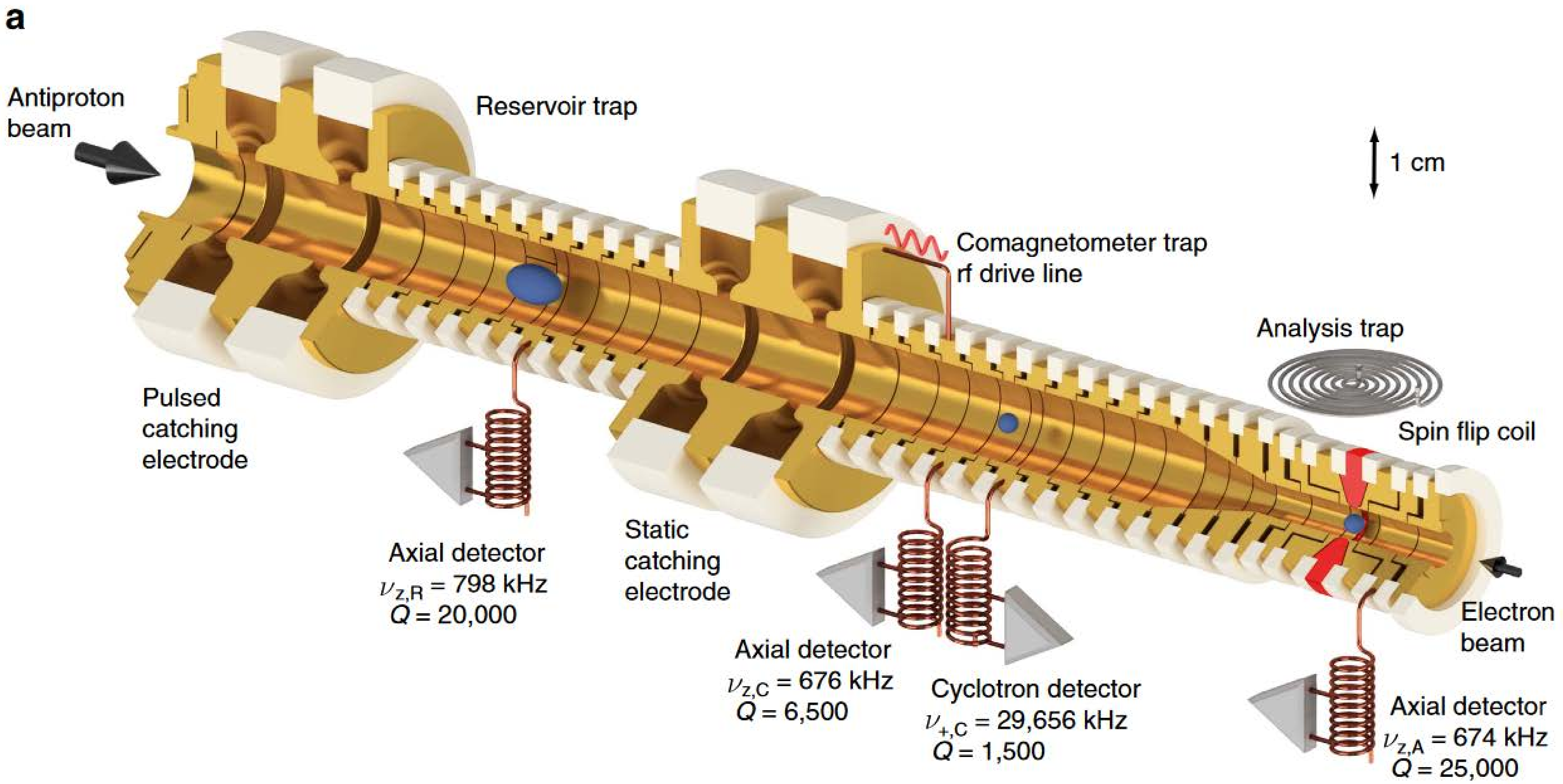
Muonium Hyperfine Splitting

Museum Experiment @ J-PARC (Japan)

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a}{\widetilde{\omega_p}}\frac{\widetilde{\omega_p}}{\omega_p} \Longleftrightarrow \frac{\omega_a}{\omega_p} = \frac{\omega_a}{\omega_{He-3}}\frac{\omega_{He-3}}{\omega_p}$$

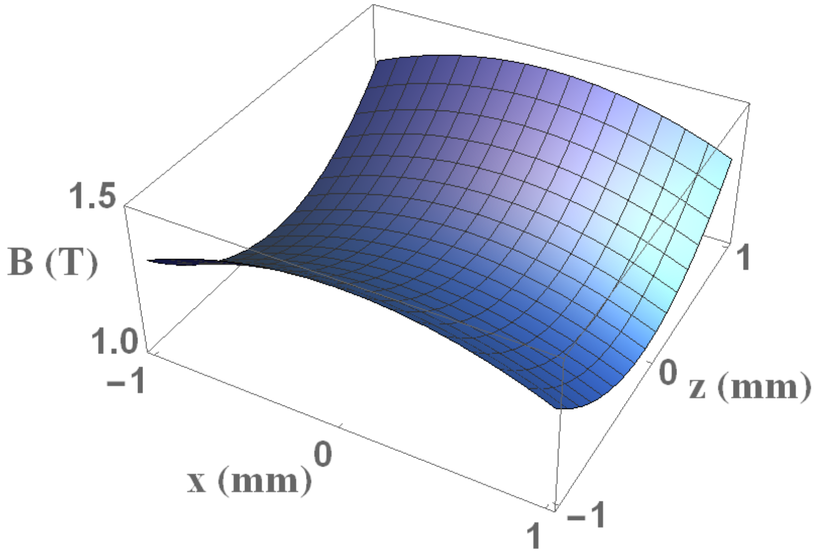
G. W. Bennett et al., Phys. Rev. Lett. 100, 091602 (2008).

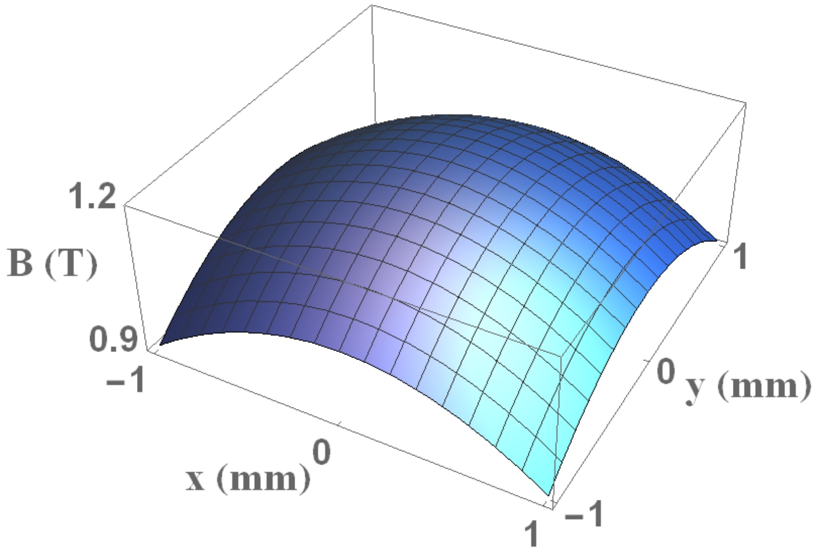
Antiproton magnetic moment measurement



H. Nagahama et al., Nat. Comm. 8, 14084 (2017).

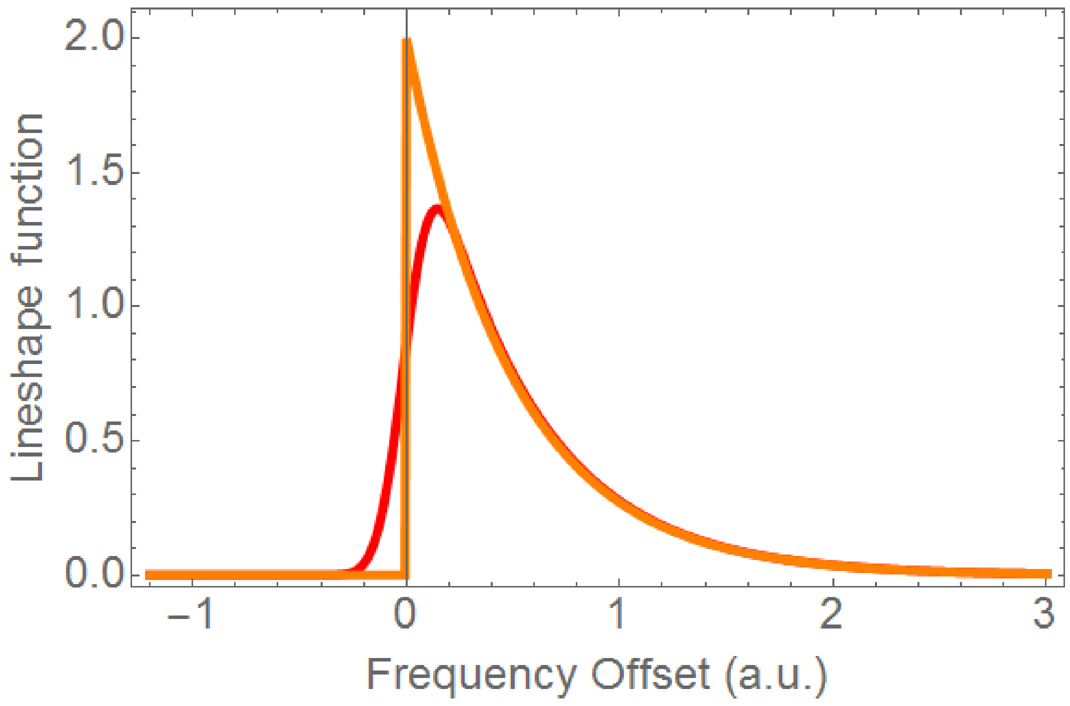
Measurements in the magnetic bottle





$$\omega_c = \frac{q}{m} B$$

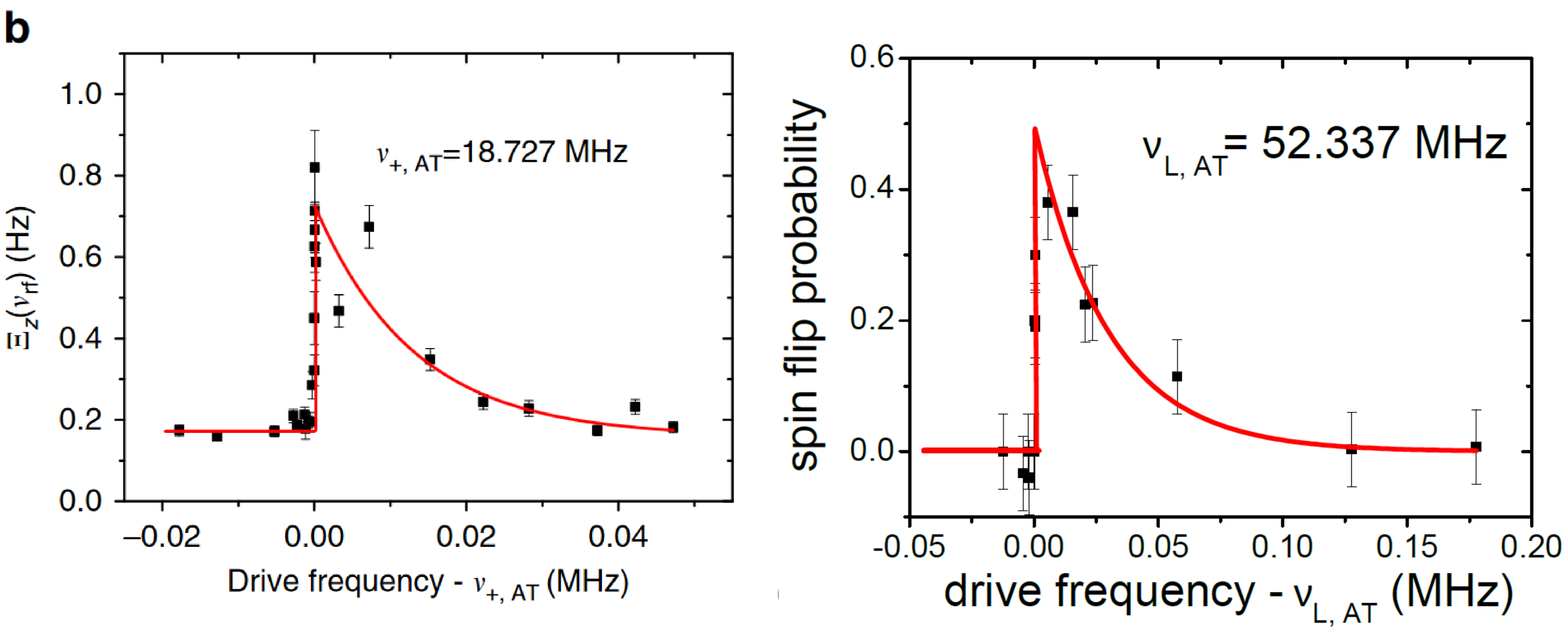
$$\omega_L = g \frac{e}{2m_p} B$$



$$\frac{\omega_L}{\omega_c} = \frac{g}{2} = \frac{\mu}{\mu_N}$$

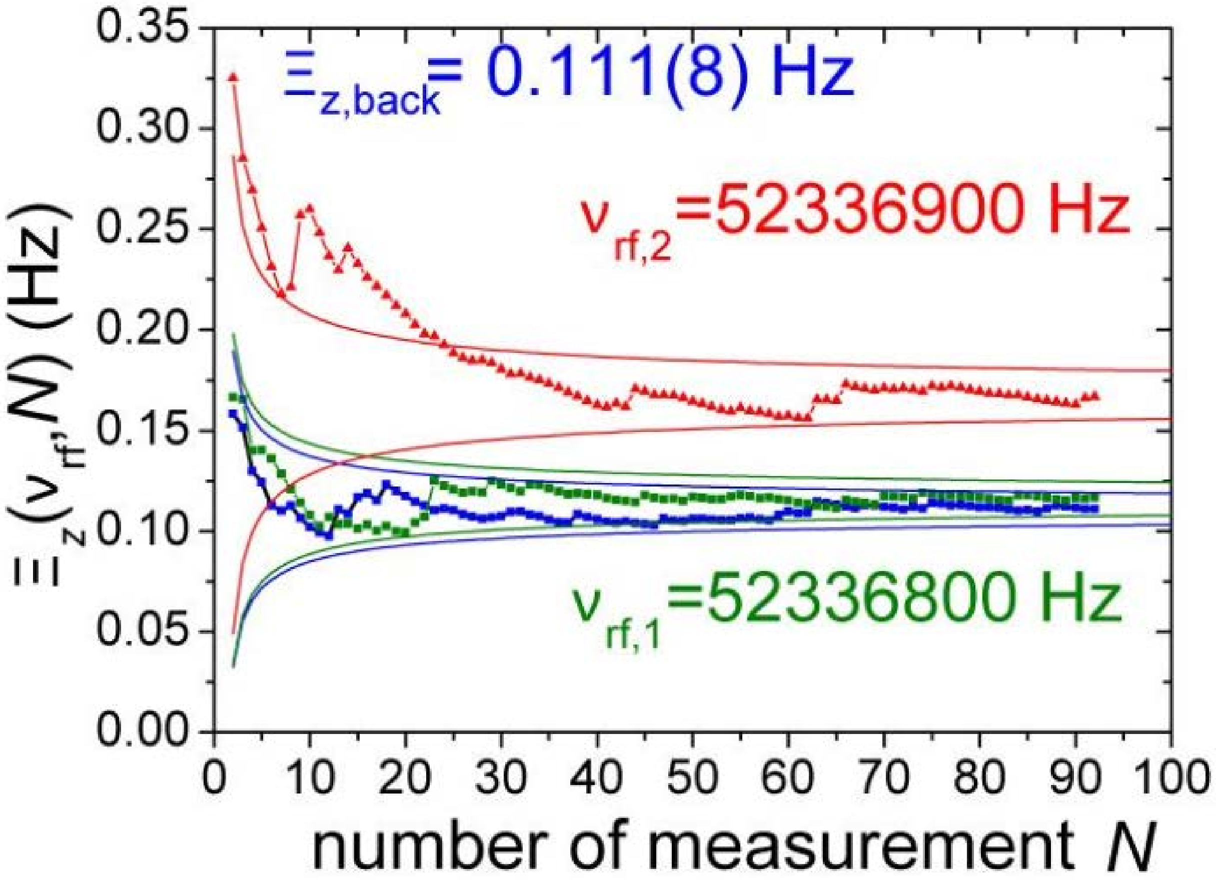
H. Nagahama et al., Nat. Comm. 8, 14084 (2017).

Alternating measurements of the cyclotron and Larmor cut frequencies



H. Nagahama et al., Nat. Comm. 8, 14084 (2017).

Larmor frequency cut measurement



~ 1 ppm measurement of the Larmor frequency

H. Nagahama et al., Nat. Comm. 8, 14084 (2017).

Antiproton g-factor results

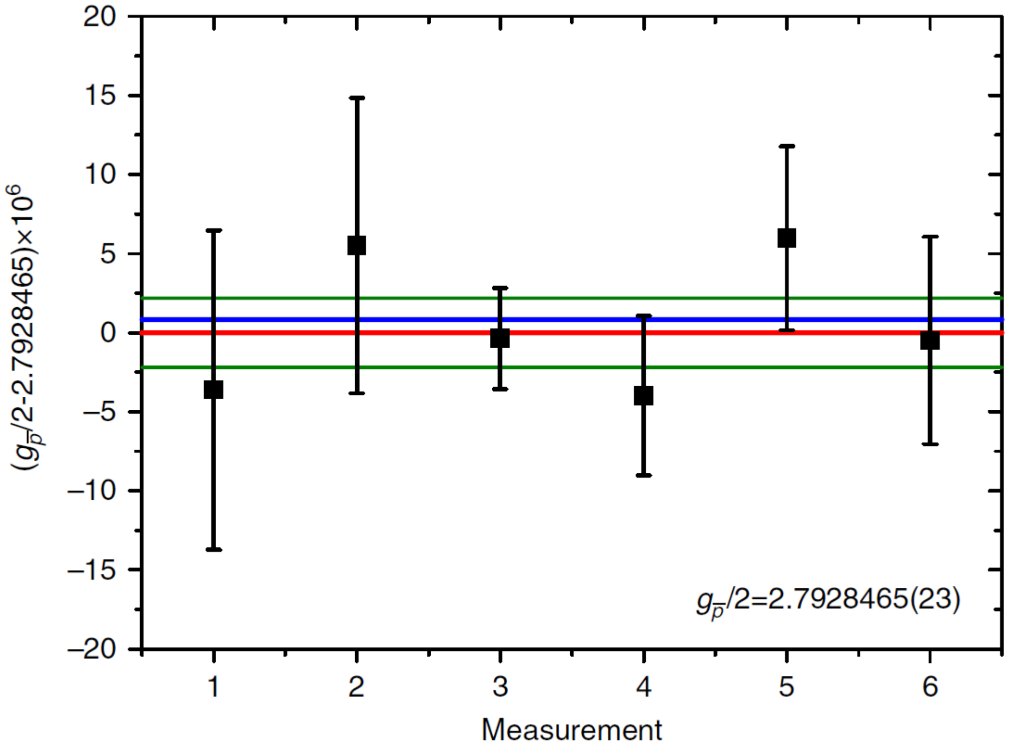


Table 1 | List of all SME-coefficients constrained by this measurement.

Coefficient	Constraint
$\left\|\tilde{b}_{\mathrm{p}}^{Z}\right\|$	$< 2.1 \times 10^{-22}$ GeV
$\left\|\tilde{b}_{\mathrm{p}}^{*Z}\right\|$	$< 2.6 \times 10^{-22}$ GeV
$\left\|\tilde{b}_{\mathrm{F,p}}^{XX} + \tilde{b}_{\mathrm{F,p}}^{YY}\right\|$	$< 1.2 \times 10^{-6}$ GeV^{-1}
$\left\|\tilde{b}_{\mathrm{F,p}}^{ZZ}\right\|$	$< 8.8 \times 10^{-7}$ GeV^{-1}
$\left\|\tilde{b}_{\mathrm{F,p}}^{*XX} + \tilde{b}_{\mathrm{F,p}}^{*YY}\right\|$	$< 8.3 \times 10^{-7}$ GeV^{-1}
$\left\|\tilde{b}_{\mathrm{F,p}}^{*ZZ}\right\|$	$< 3.0 \times 10^{-6}$ GeV^{-1}

Six fold improved uncertainty of the antiproton magnetic moment

$$g_{\bar{p}}/2 = 2.7928465(23)$$

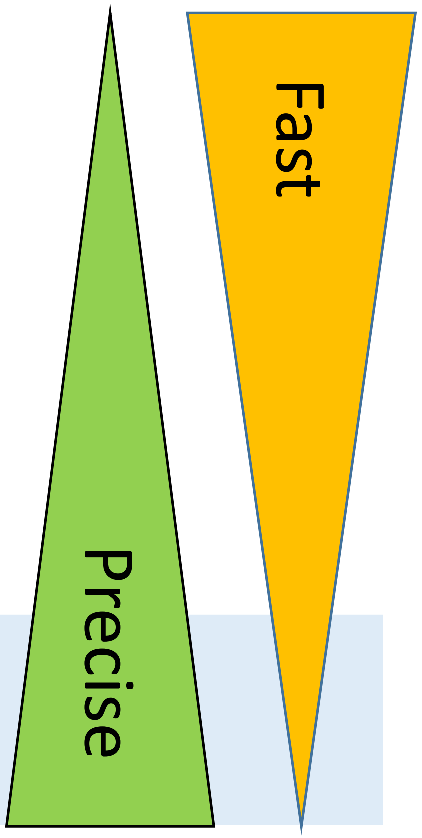
Respective limits on SME coefficients for CPT violation improved up to a factor 20

H. Nagahama et al., Nat. Comm. 8, 14084 (2017).

Mass or charge-to-mass ratio measurements of fundamental particles

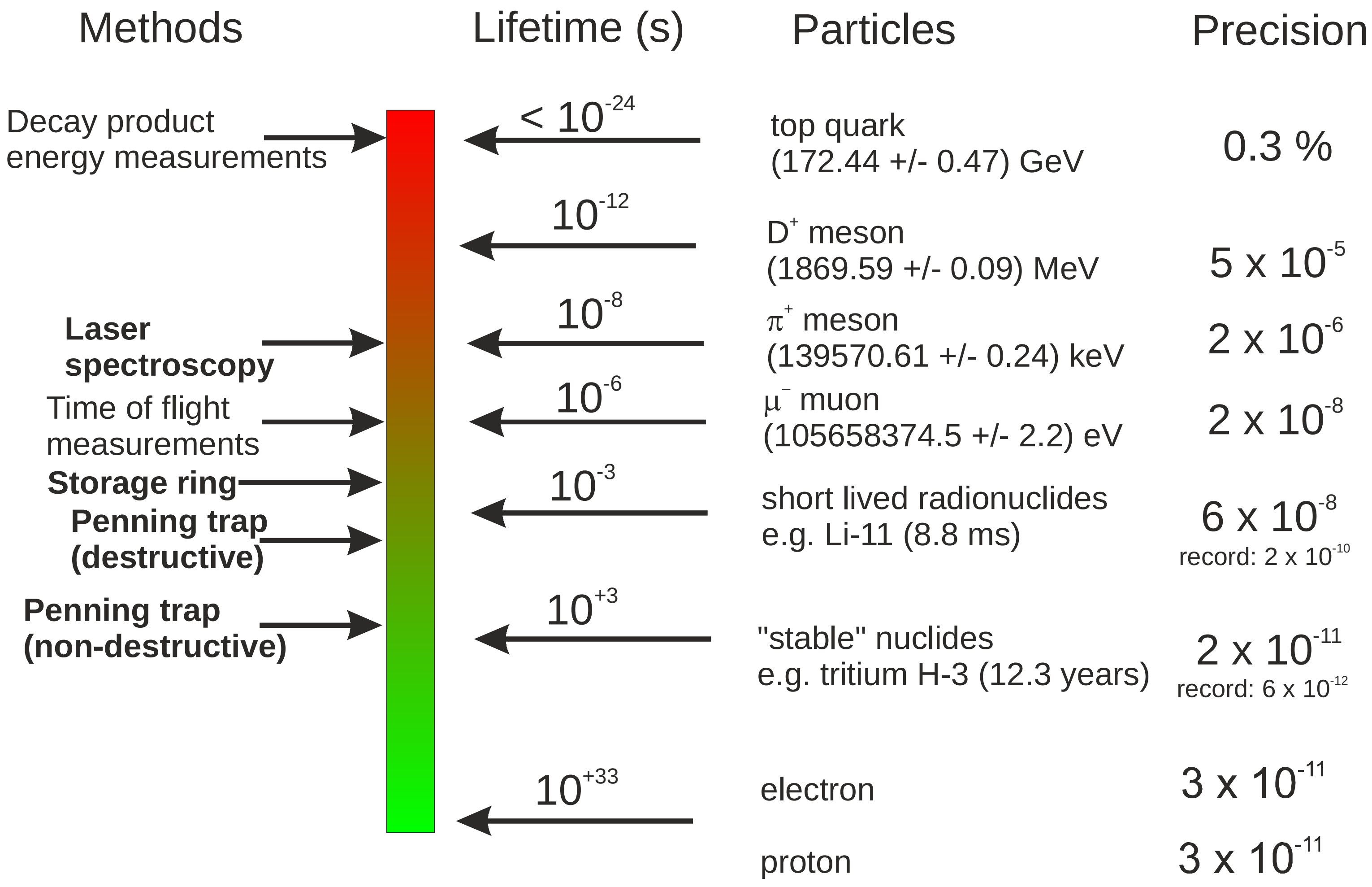
Applications of Mass Spectrometry

Field	Required relative precision $\delta m/m$
Applied Physics/Chemistry: Identification of atoms/molecules, sample analysis	$10^{-5} - 10^{-6}$
Nuclear Physics/Nuclear Structure	$10^{-6} - 10^{-7}$
Astrophysics: Nucleosynthesis	10^{-7}
Weak interaction tests: CVC hypothesis, CKM unitarity	10^{-8}
Atomic physics: Binding energies, Neutrino physics: Beta decay Q-values	$10^{-9} - 10^{-11}$
Fundamental Constants, Tests of Quantum Electrodynamics and CPT Symmetries	As high as possible, $< 10^{-10}$



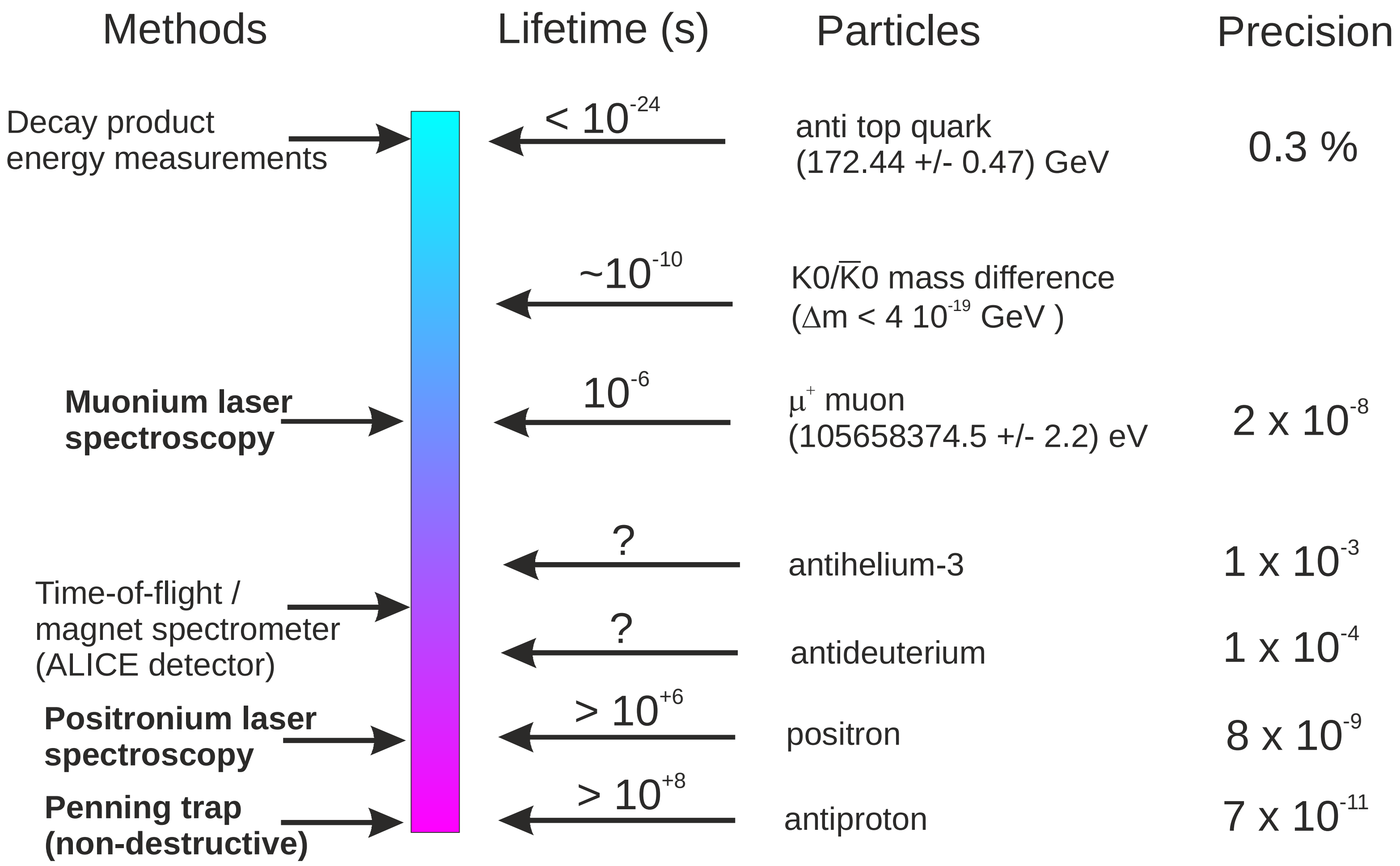
K. Blaum, Phys. Rep. 425, 1-78 (2006).

Lifetime, Methods, and Measurement Precision



C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).
M. Wang et al. (Atomic Mass Evaluation), Chin. Phys. C, 36, 1603 (2012) .

Anti-Lifetime, Anti-Methods, and Anti-Measurement Precision

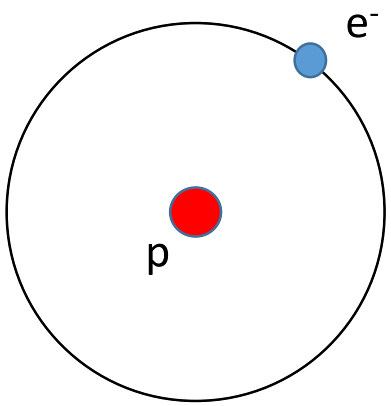


C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

What is an exotic atom?

NOT AN EXOTIC ATOM

Hydrogen

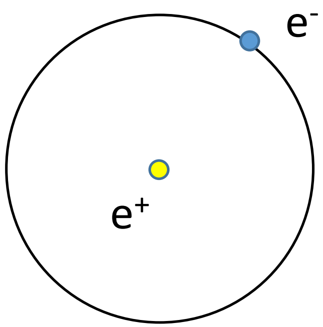


Bohr Atomic Model:

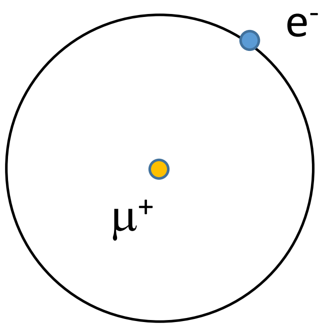
$$E = -Ry\, h\, c\, \frac{Z^2}{n^2} \qquad Ry = \frac{e^4}{8\,\varepsilon_0^2 h^3 c} \frac{m_e m_p}{(m_e + m_p)}$$

SOME EXAMPLES FOR EXOTIC ATOMS

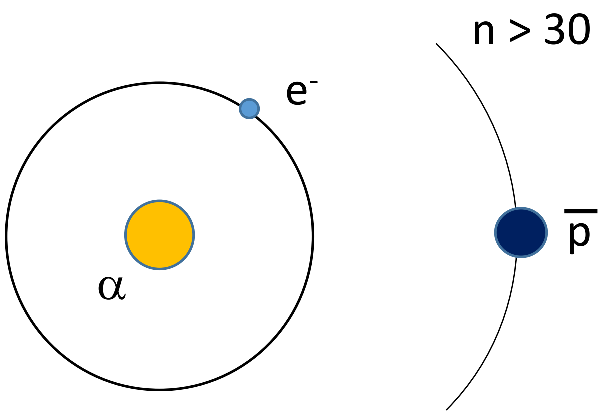
Positronium



Muonium



Antiprotonic Helium



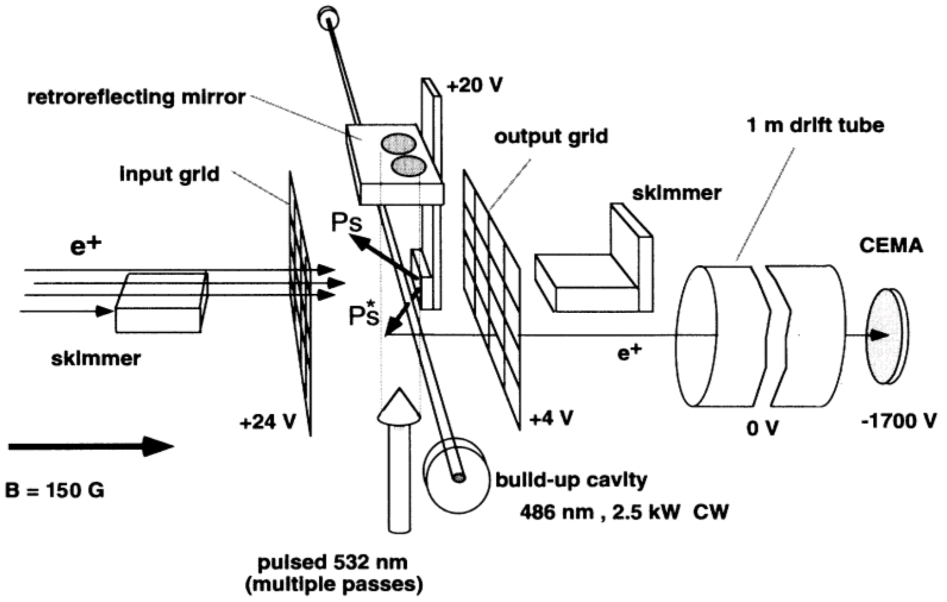
(Anti)particle masses from transition frequencies

- Spectroscopy of transition frequencies in exotic atoms can constrain the mass ratio of the constituents
- The reduced mass in the Rydberg constant allows to extract the mass ratio of the constituents.
- Ry_∞ known from hydrogen spectroscopy to 10^{-12}

$$Ry = Ry_\infty \frac{\mu}{m_e} = Ry_\infty \frac{m_1}{m_e} \frac{1}{\left(\frac{m_1}{m_2} + 1\right)}$$

- Transition frequencies: $\nu = \frac{E=5eV}{h} \approx 10^{15}$ Hz
- Linewidth due to lifetime of the ground-state: $\Delta\nu = \frac{1}{2\pi\ \tau=100\ ns} \approx 10^{6}$ Hz
- Promises high precision despite short half-life!
- Transition frequencies include QED corrections (the Lamb shift), which need to be known to the mass-ratio measurement accuracy

Example: 1S-2S Positronium spectroscopy

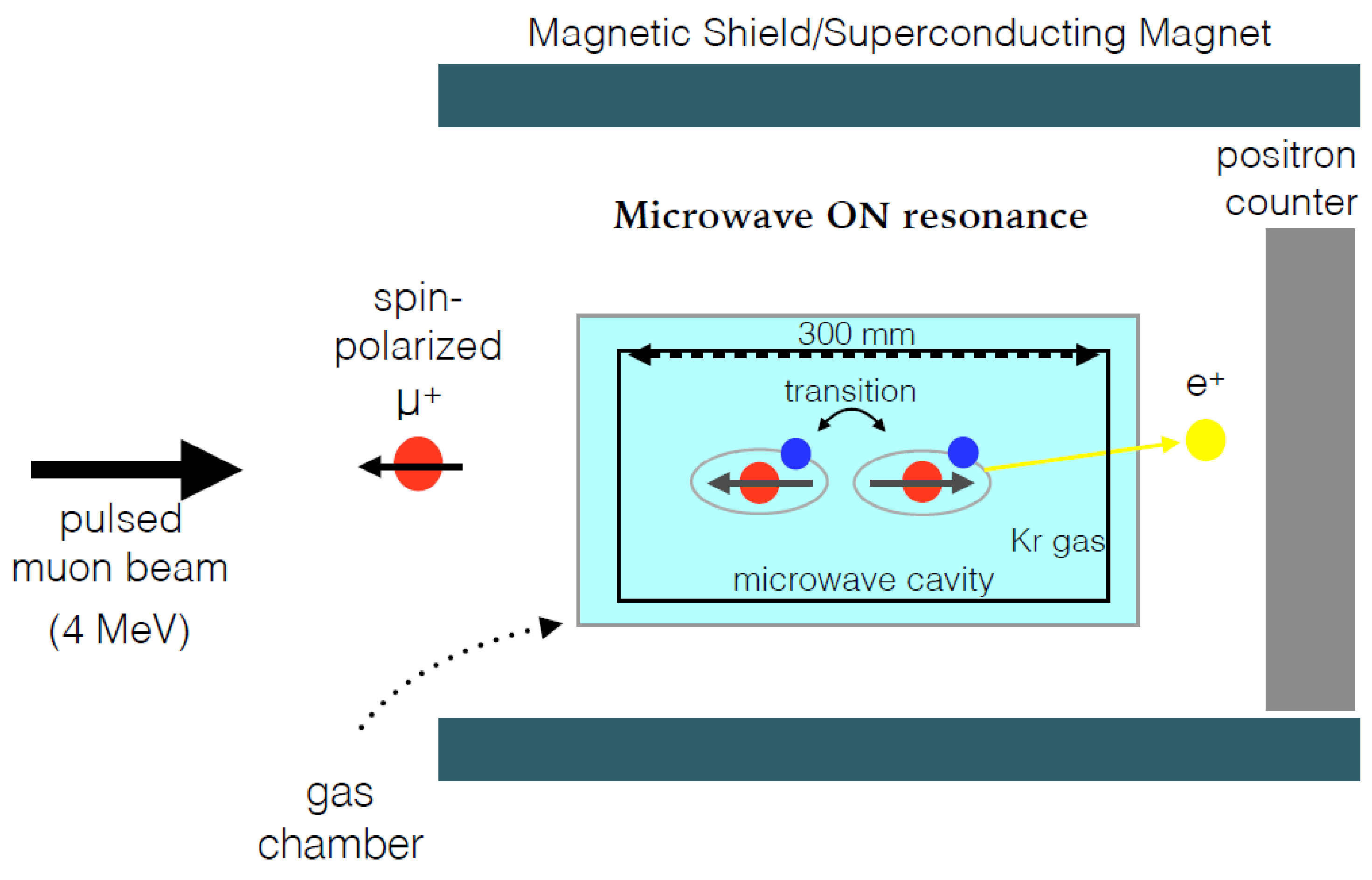


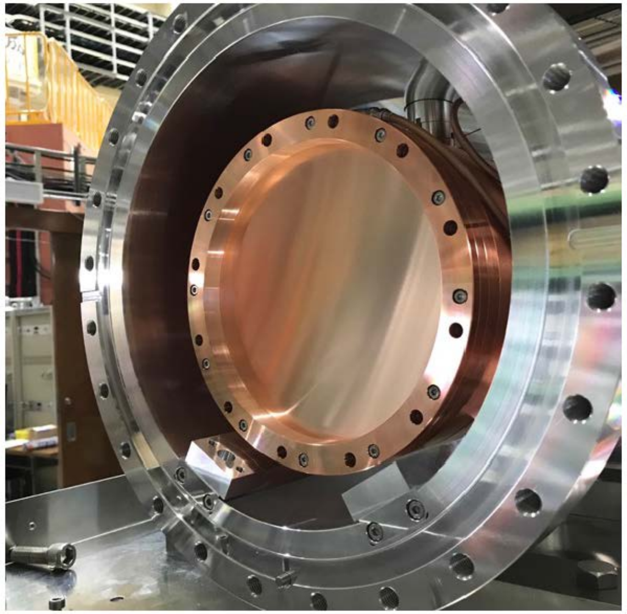
1*S*-2*S* transition frequency	616 803 608.2±1.6 MHz
1*S*-2*S* interval	1 233 607 216.4±3.2
Theory	
Fell [14]	1 233 607 221.7±O(10)

$$\frac{|m_{e+} - m_{e-}|}{m_{e-}} < 8\ 10^{-9}$$

M.S. Fee, S. Chu et al., Phys. Rev. A 48, 192 (1993).

Muonium hyperfine splitting (MuSEUM@J-PARC)





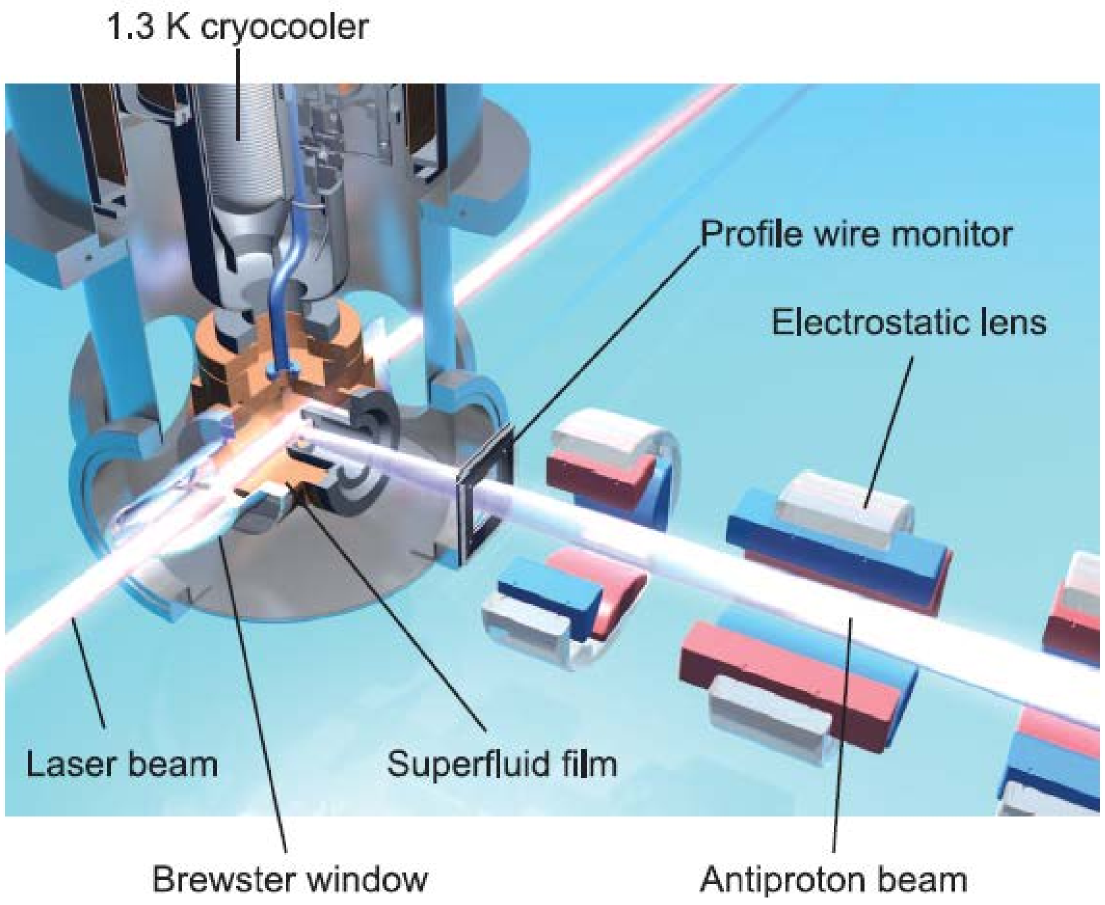
$$\Delta\nu_{HFS} \propto \mu_\mu$$

$$\frac{\mu_e}{\mu_\mu} = \frac{g_e}{g_\mu}\frac{m_\mu}{m_e}$$

$$\nu_{QED} = 4\ 463\ 302\ 720\ (253)(98)(3)\ \text{Hz}\ (m_\mu/m_e)(\text{QED})(\alpha)$$

MuSEUM collaboration, Y. Ueno, Y. Matsuda et al., EXA2017 conference slides

Antiprotonic helium experiment (ASACUSA)



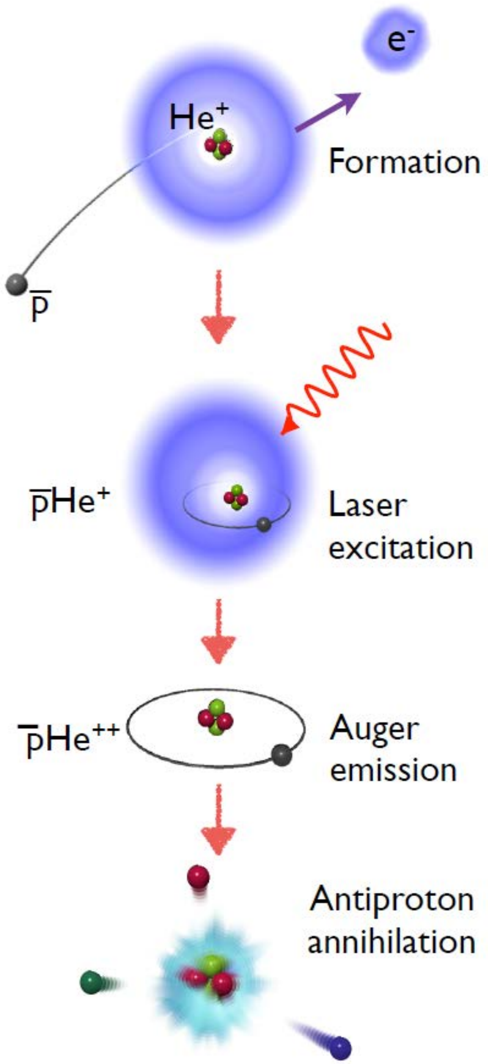
Antiprotons are stopped in thin cold helium gas.

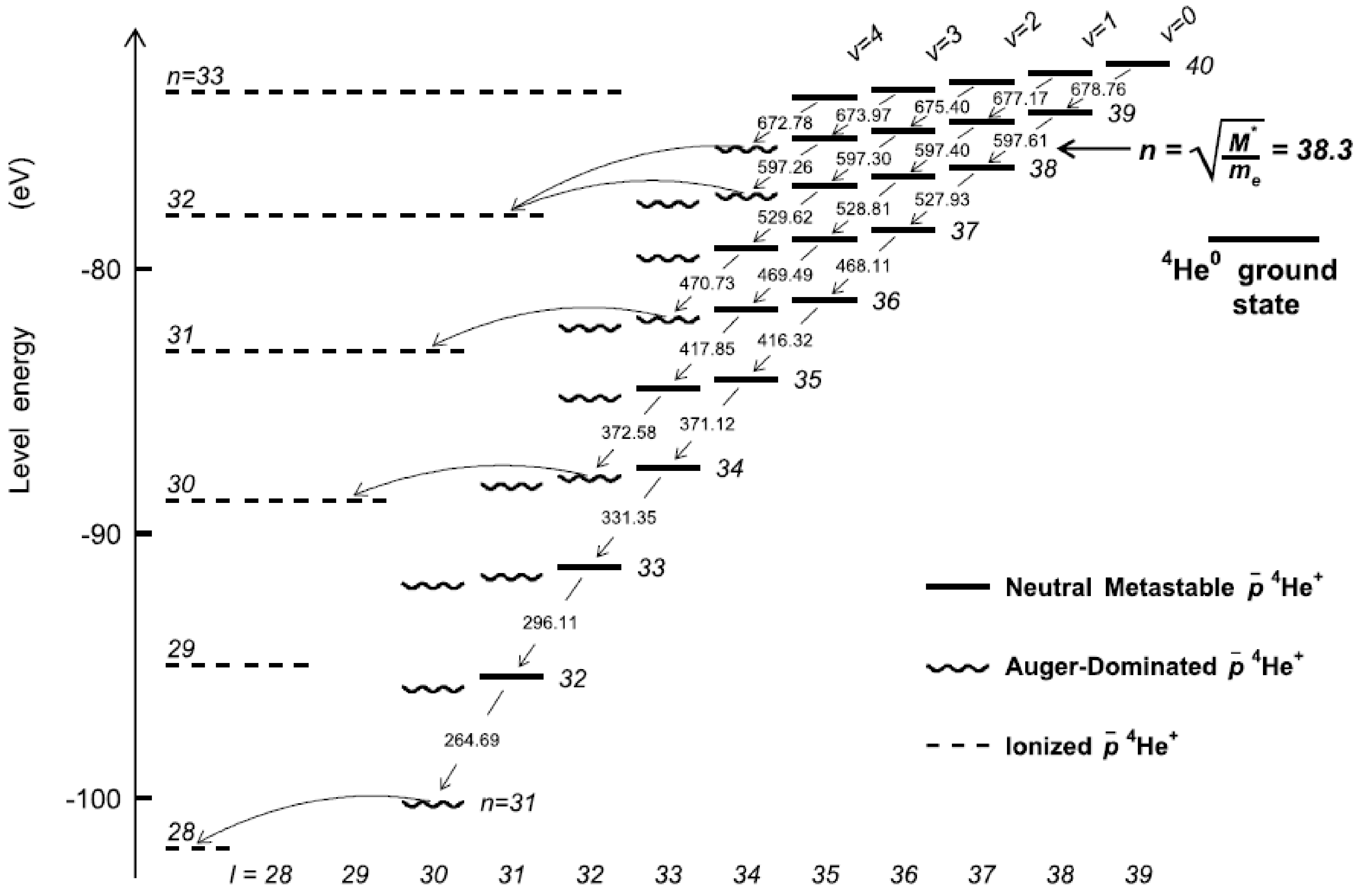
Antiprotonic helium is formed by replacing one of the electrons in the helium atom

Buffer-gas cooling cools the antiprotonic helium atom to low temperatures (T ~ 1.6 K)

M. Hori et al., Science 354, 610 (2016).

Antiprotonic Helium

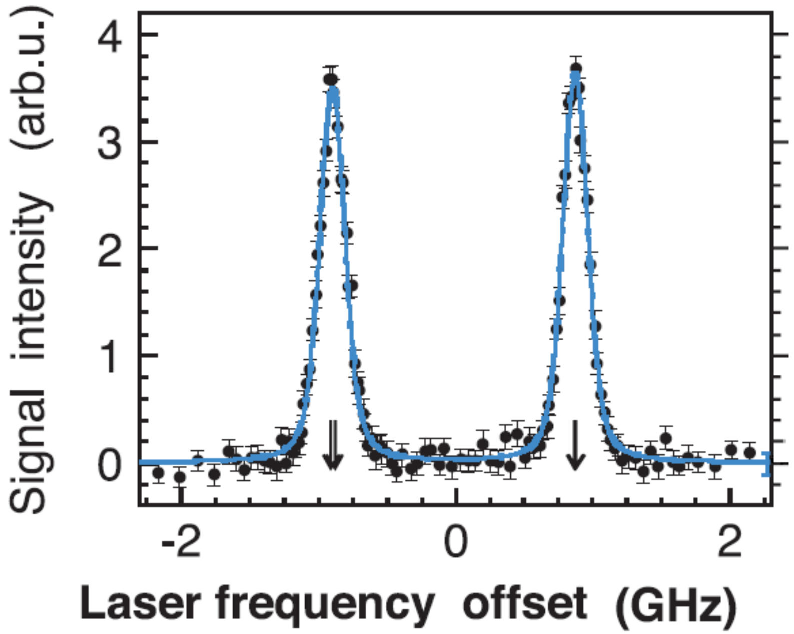




M. Hori et al., Science 354, 610 (2016).

Antiproton-to-electron mass ratio

Example signal



Single photon spectroscopy of antiprotonic helium at 1.6 (0.1) K

Comparison of experiment and QED calculations allows to extract the antiproton-to-electron mass ratio

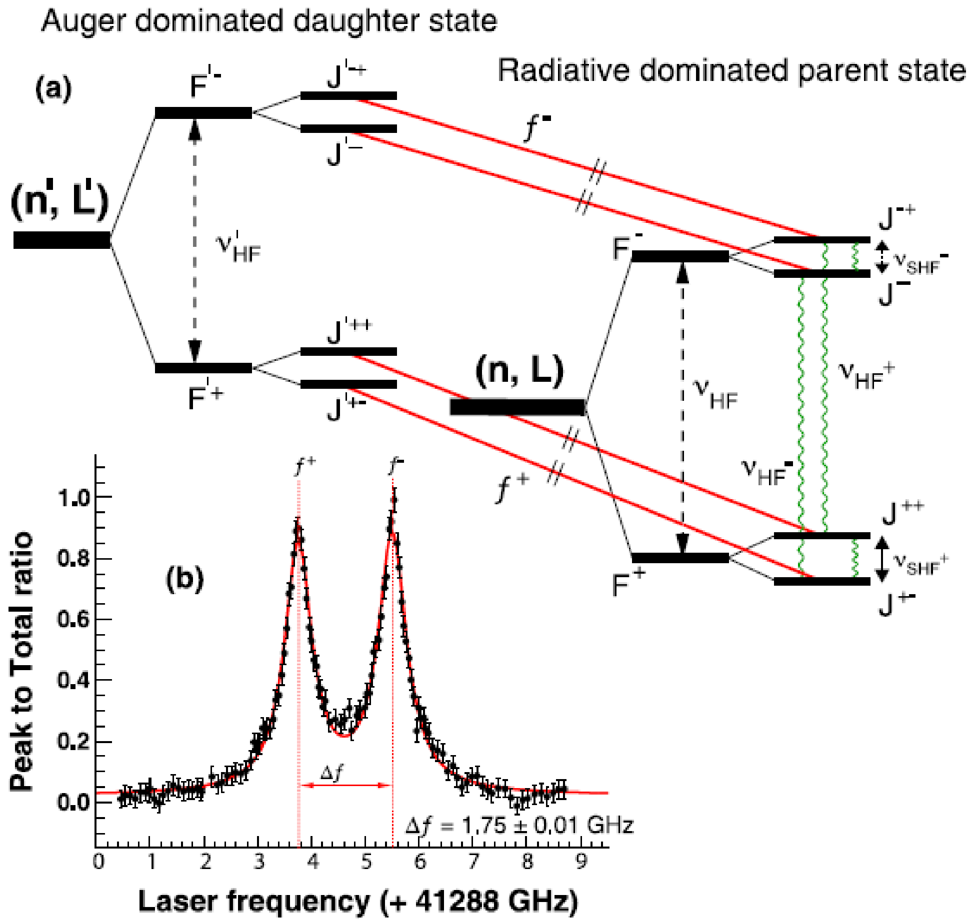
$$h\nu_{th} \approx \frac{m_{\bar{p}}}{m_e} Z_{eff}^2 R_y \left(\frac{1}{n'^2} - \frac{1}{n^2}\right)$$

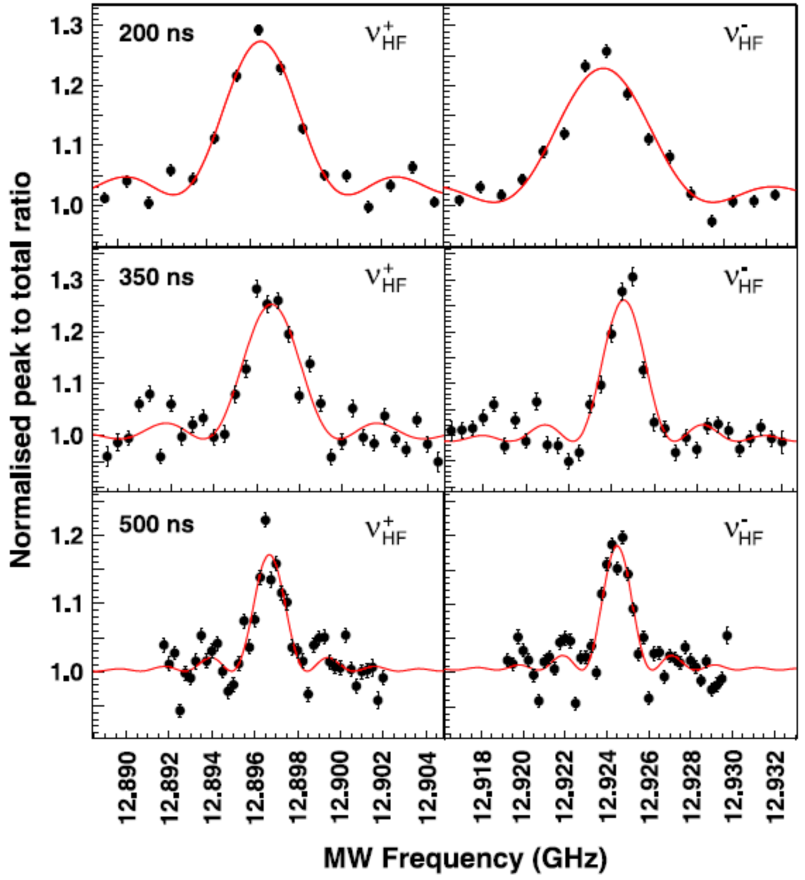
Recent measurements improve this value to 8 10^{-10} relative uncertainty

Result is in agreement with CPT invariance

M. Hori et al., Science 354, 610 (2016).

Antiproton magnetic moment from the "super fine structure"





$$\mu_s^{\bar{p}} = -2.7862(83)\mu_N$$

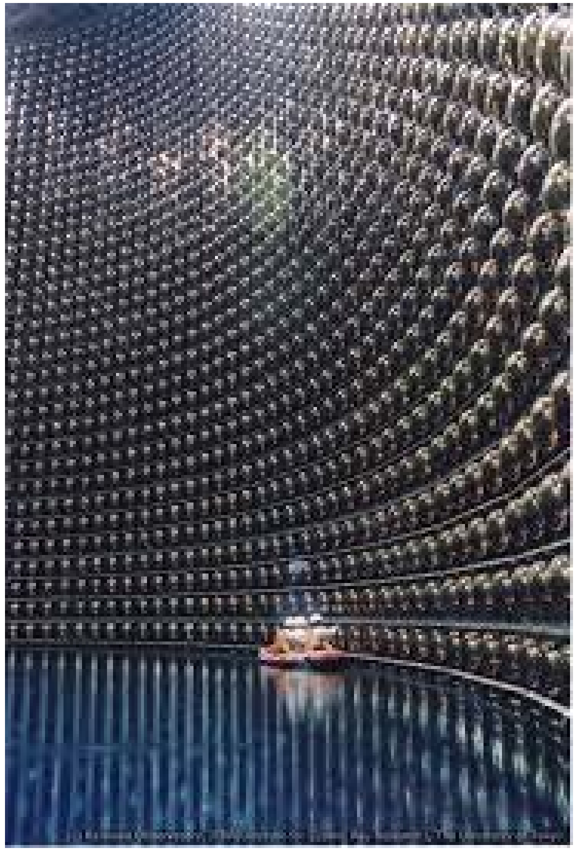
T. Pask et al., Phys. Lett. B 678, 55 (2009).

Antiproton lifetime limits

Motivation

- A proton and antiproton lifetime comparison tests
  - CPT invariance
  - B-violation

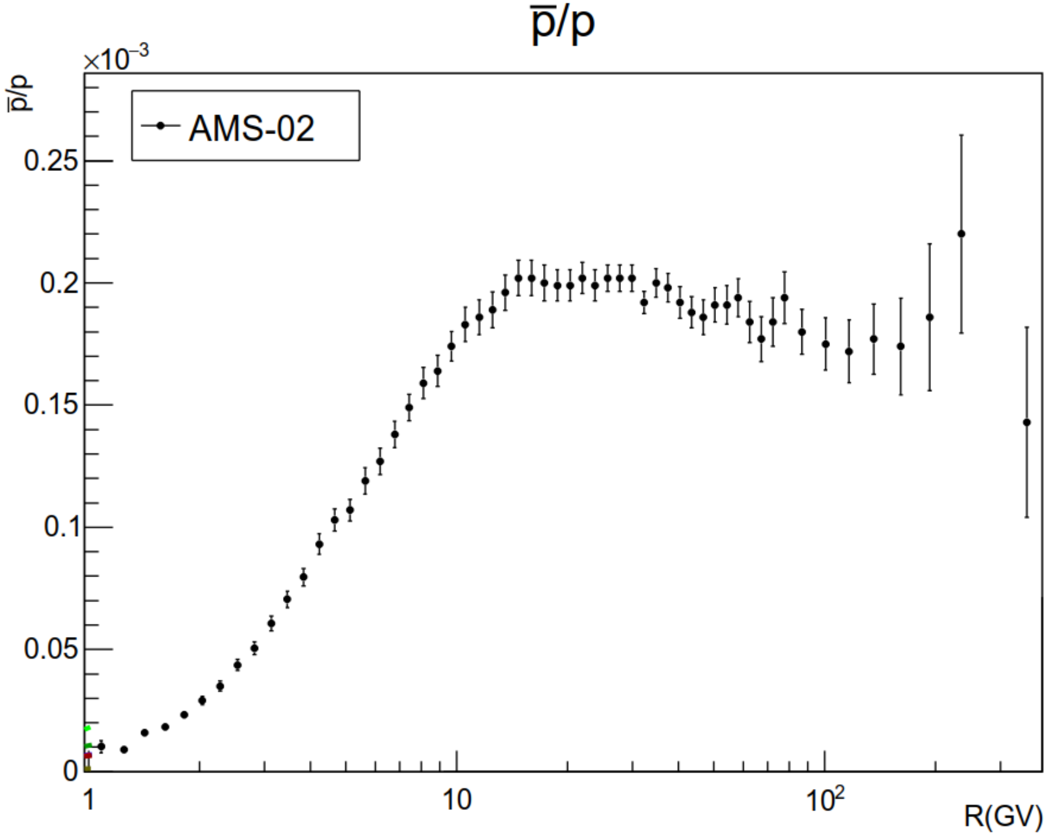
- Super-Kamiokande experiment
  - Proton lifetime: invisible modes $\tau > 10^{29}$ y
    specific channels $1/\Gamma_i > 10^{34}$ y
  - Sample: 50000 tons of purified water



Superkamiokande Experiment

Antiproton lifetime limits from cosmology

Cosmic ray flux analysed with the Alpha Magnetic Spectrometer (ISS)



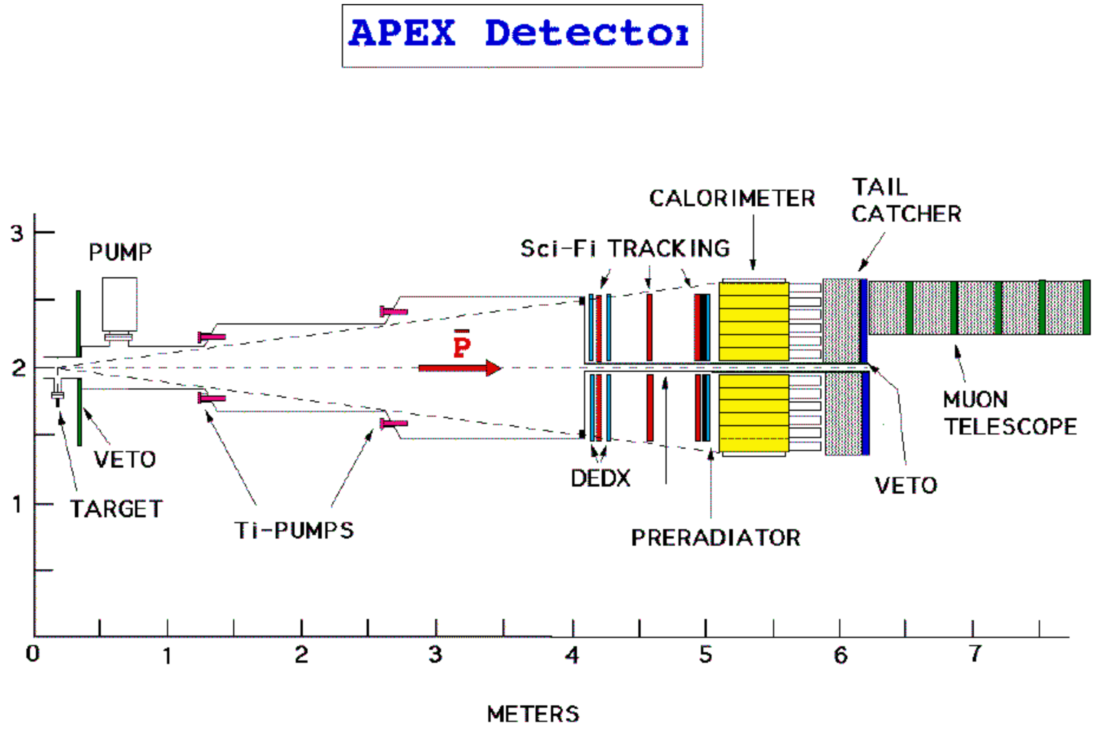
- How long do these antiprotons exist until they reach us?
- How many antiprotons do we expect to see?
- Limit depends on model dependent parameters on antiproton production, propagation and interaction in the interstellar medium

- $\tau_{\bar{p}} > 8\ 10^5$ y

arXiv: 1612.04001 (2016).

APEX Experiment at Fermilab (~1999)

Search for antiproton decay product from antiprotons cycling in a storage ring



S. Geer et al., Phys. Rev. Lett. 84, 590 (2000).

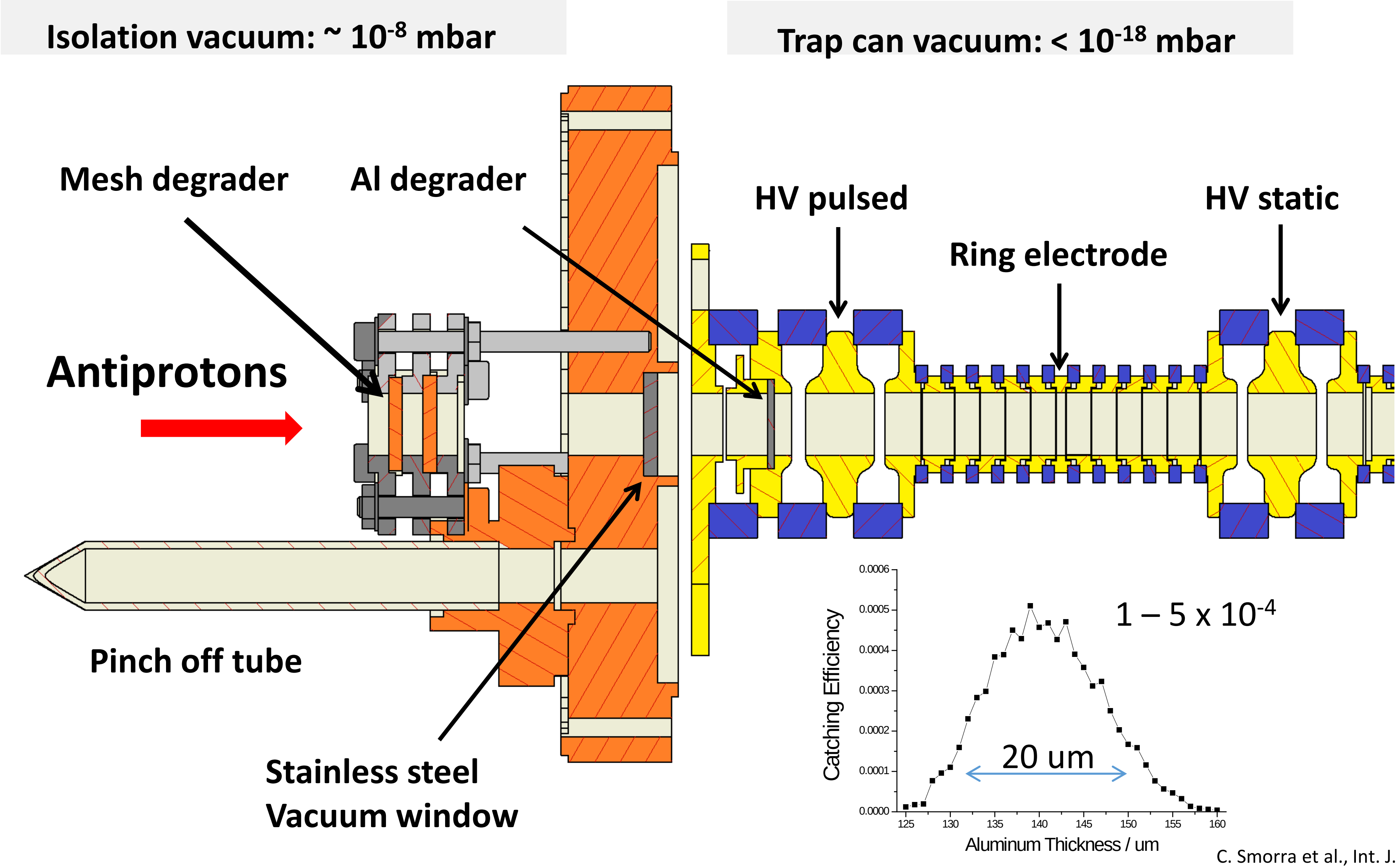
APEX results

TABLE I. Summary of results: 90% C.L. limits on τ/B for 15 antiproton decay modes.

Decay mode	τ/B Limit (years)	Decay mode	τ/B Limit (years)
$\mu^-\gamma$	5×10^4	$e^-\gamma$	7×10^5
$\mu^-\pi^0$	5×10^4	$e^-\pi^0$	4×10^5
$\mu^-\eta$	8×10^3	$e^-\eta$	2×10^4
$\mu^-\gamma\gamma$	2×10^4	$e^-\gamma\gamma$	2×10^4
$\mu^-K_L^0$	7×10^3	$e^-K_L^0$	9×10^3
$\mu^-K_S^0$	4×10^3	$e^-K_S^0$	9×10^2
		$e^-\rho$	2×10^2
		$e^-\omega$	2×10^2
		$e^-K^{0\star}$	1×10^3

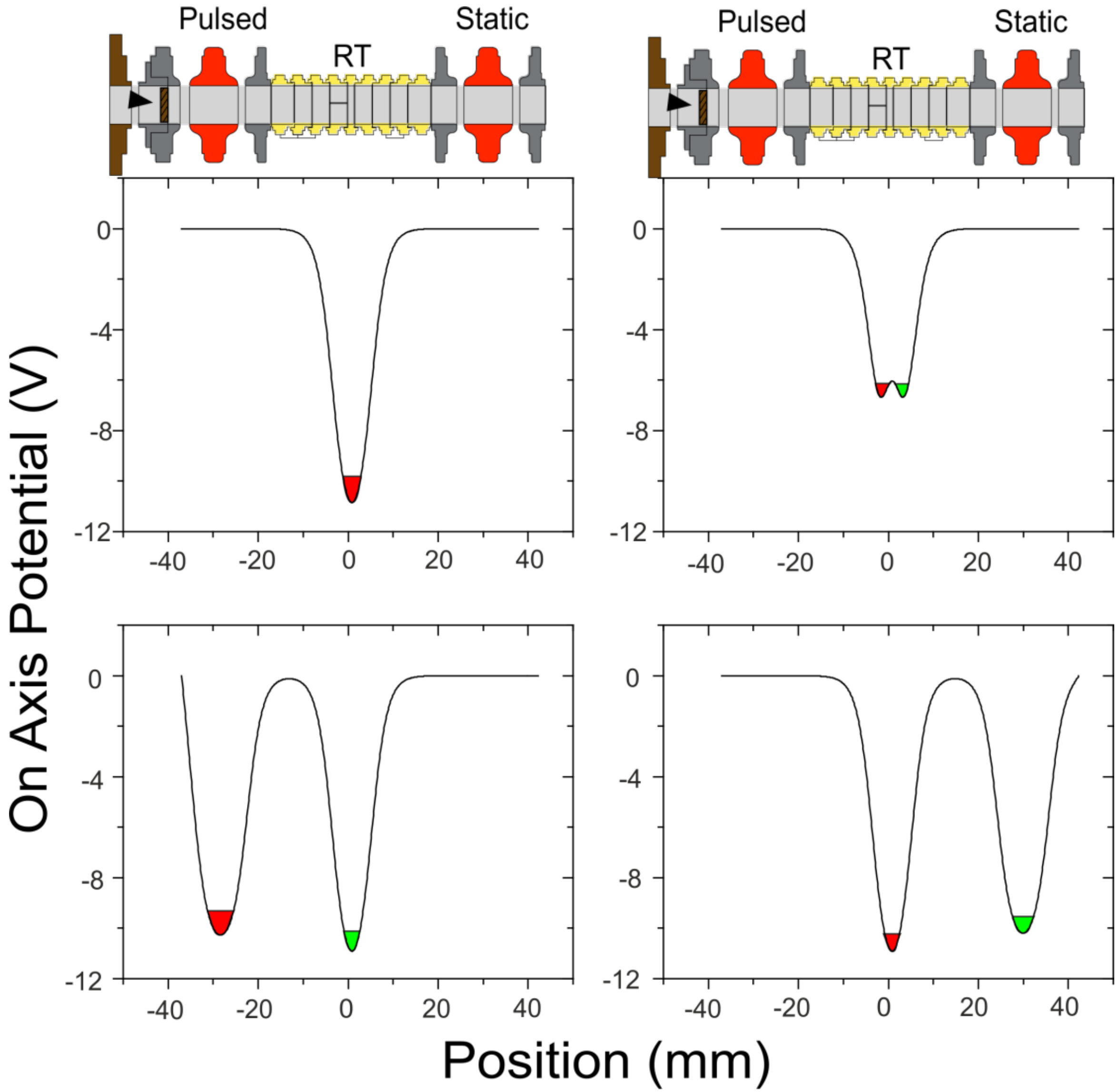
S. Geer et al., Phys. Rev. Lett. 84, 590 (2000).

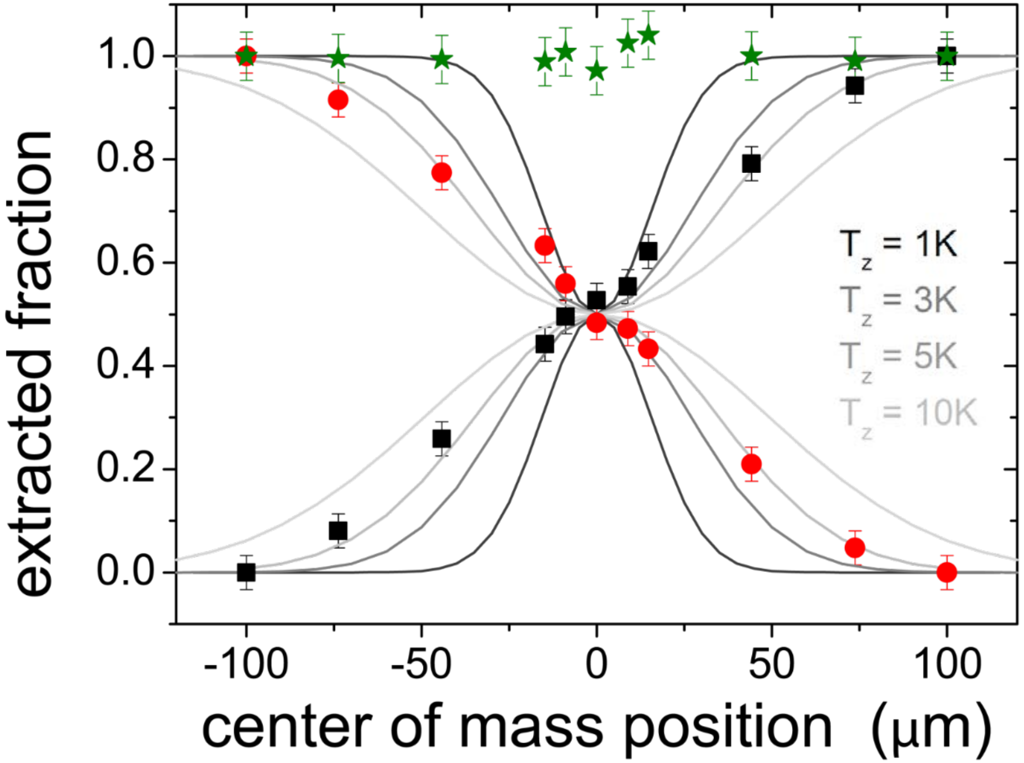
Deceleration from 5.3 MeV to 0.5 meV



C. Smorra et al., Int. J. Mass Spectr. **389**, 10 (2015).
S. Sellner et al., New J. Phys. 19, 083023 (2017).

Non-destructive extraction: Separate and Merge

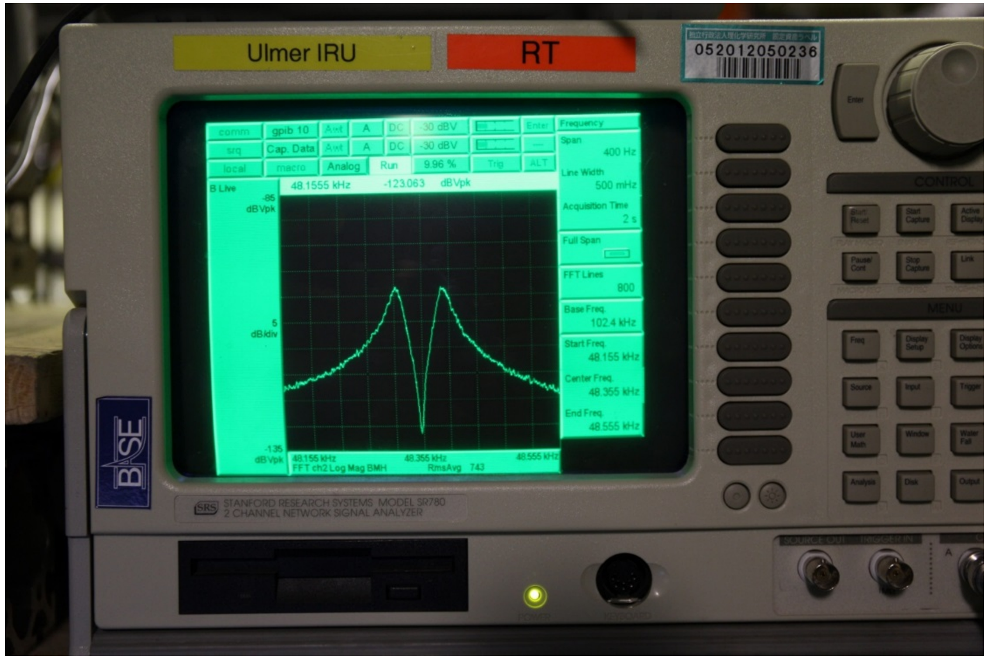


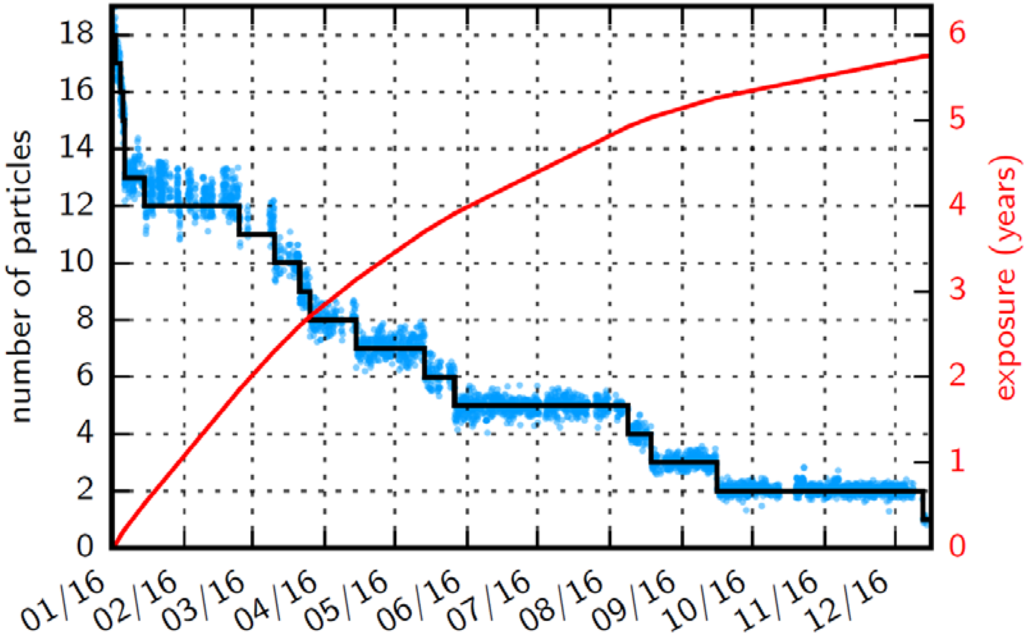


C. Smorra et al., Int. J. Mass Spectr. **389**, 10 (2015).
S. Sellner et al., New J. Phys. 19, 083023 (2017).

Reservoir trap

Antiprotons stored from 03.11.2015 – 22.12.2016





- Storage of antiprotons for more than one year: **405.5 days**
- Extraction of single particles by a potential tweezer scheme

C. Smorra et al., Int. J. Mass Spectr. **389**, 10 (2015).
S. Sellner et al., New J. Phys. 19, 083023 (2017).

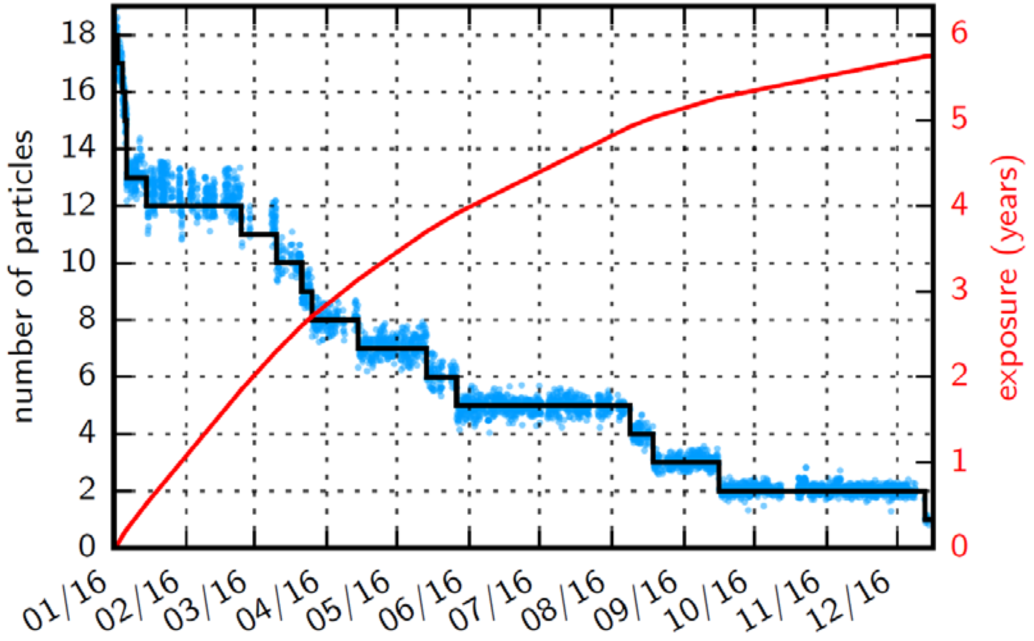
Inversion of the baryon asymmetry:

Antibaryon density: ~ $10^8/cm^3$
$V < (50\ \mu m)^3$
Baryon density: ~ $1 / cm^3$
$p < 10^{-16}$ Pa

Antiproton Lifetime Limits

Table 1. List of individual data sets which contribute to the derived antiproton lifetime limit.

Specific dataset	Exposure time (years)
RT	5.77
Precision traps	1.72
RT systematics	2.61
2014 run	1.56
Sum	11.66



Antiproton lifetime limits:

$\tau_{\bar{p}} > 10.2$ y (68% C.L.)

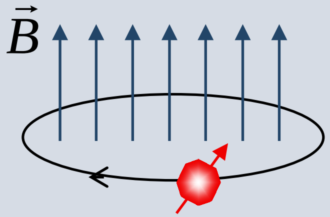
$\tau_{\bar{p}} > 5.0$ y (90% C.L.)

S. Sellner *et al.*, New J. Phys. **19**, 083023 (2017).

Penning trap mass spectrometers

Charge-to-mass ratio determination in Penning traps

Cyclotron Frequency Ratio

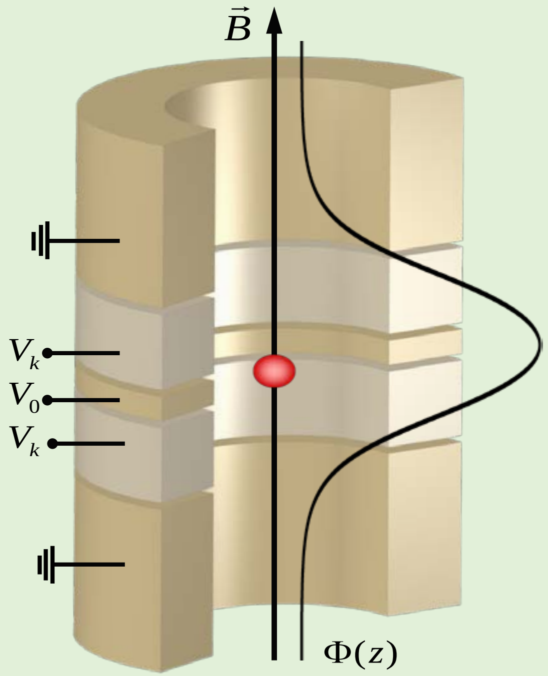


$$\omega_c = \frac{q}{m} B \qquad \frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

Stable magnetic field:
Superconducting magnet in persistent mode $\frac{\delta B}{B} < 10^{-8}$ / h

Long observation time for precise frequency measurements

Well-controlled contamination-free environment for single particles



H. G. Dehmelt and P. Ekström, Bull. Am. Phys. Soc. 18, 72 (1973).
D. J. Wineland and H. G. Dehmelt, J. Appl. Phys. 46, 919 (1975).

Basic principles of Penning traps

Radial confinement by a strong homogeneous magnetic field B (~ 7 T)

Axial confinement by a weak quadrupolar electric field U (~ 10 V) :

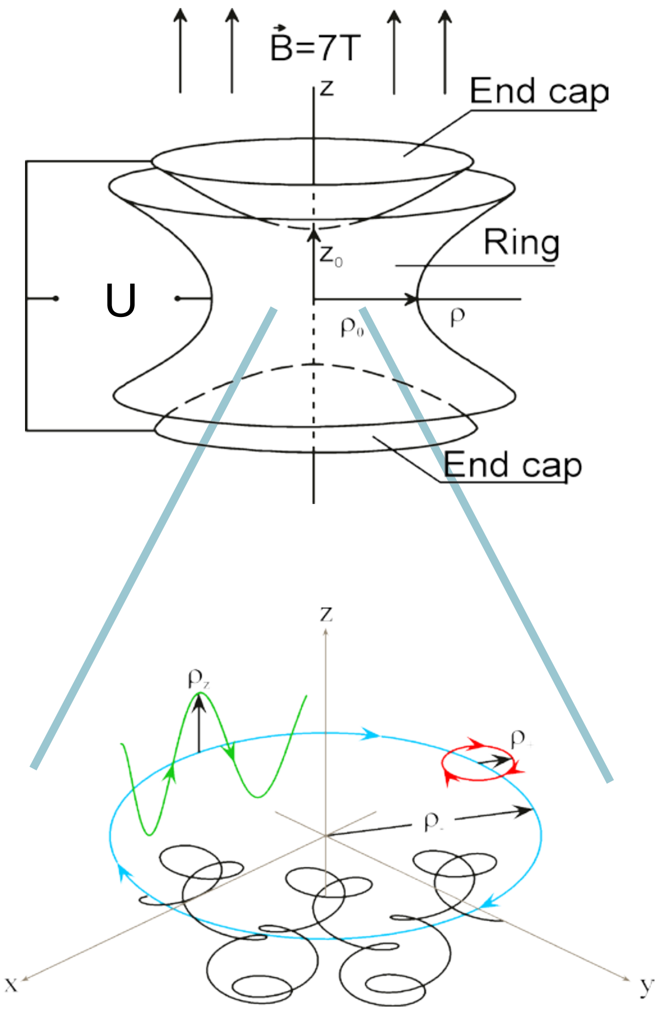
$$V(\rho, z) = \frac{U}{2d^2}\left(z^2 - \frac{\rho^2}{2}\right)$$

Motion in the trap:
Three independent harmonic oscillators

Axial motion: $$\omega_z = \sqrt{\frac{q \cdot U}{m \cdot d^2}}$$

Reduced cyclotron and magnetron motion:

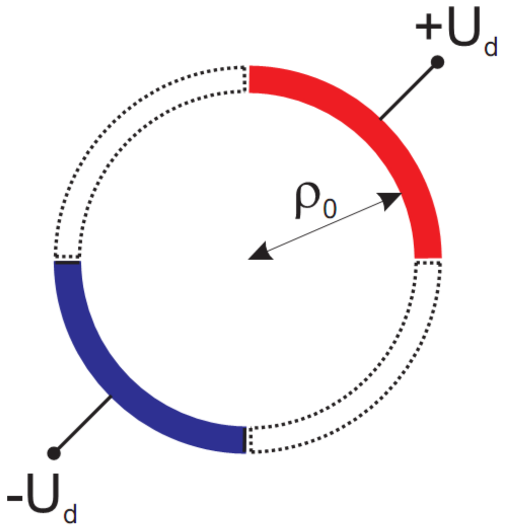
$$\omega_\pm = \frac{1}{2}\left(\omega_c \pm \sqrt{\omega_c^2 - 2\omega_z^2}\right)$$

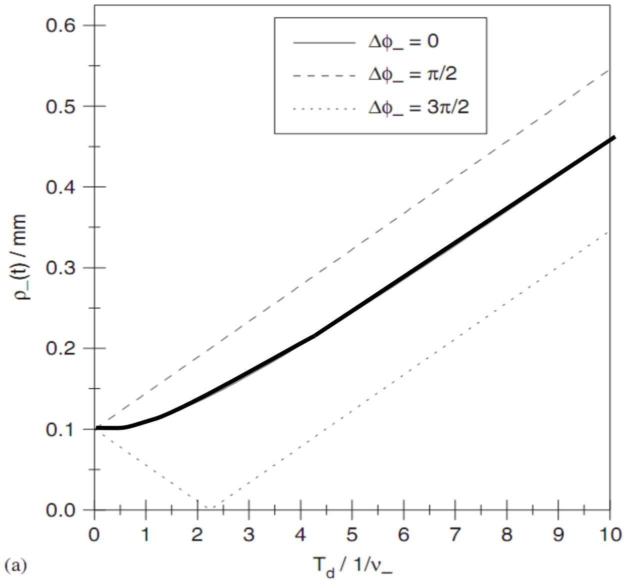


L.S. Brown and G. Gabrielse, *Rev. Mod. Phys.* **58**, 233-311, (1986)

Ion manipulation in a Penning trap

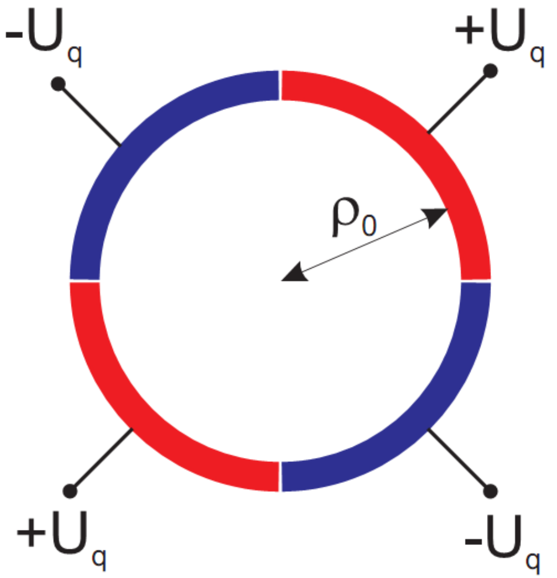
Dipolar excitation:

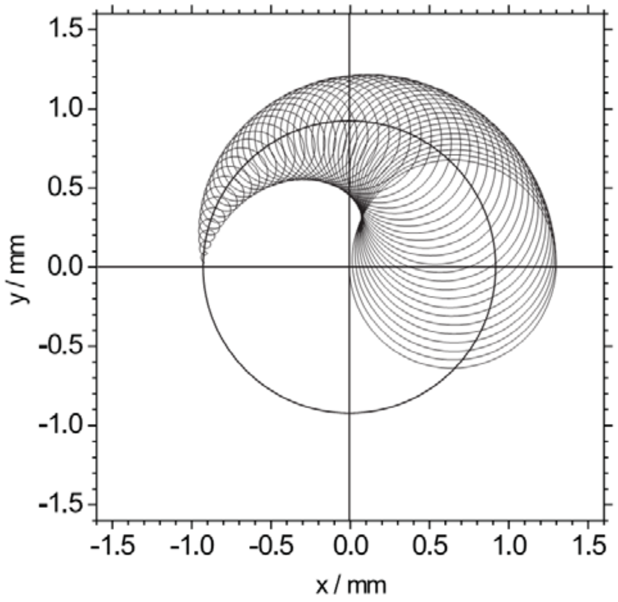


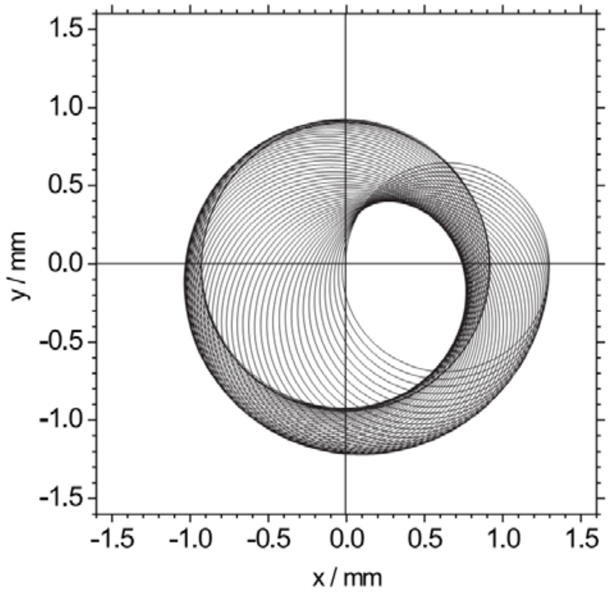


(a)

Mode coupling: Quadrupolar excitation



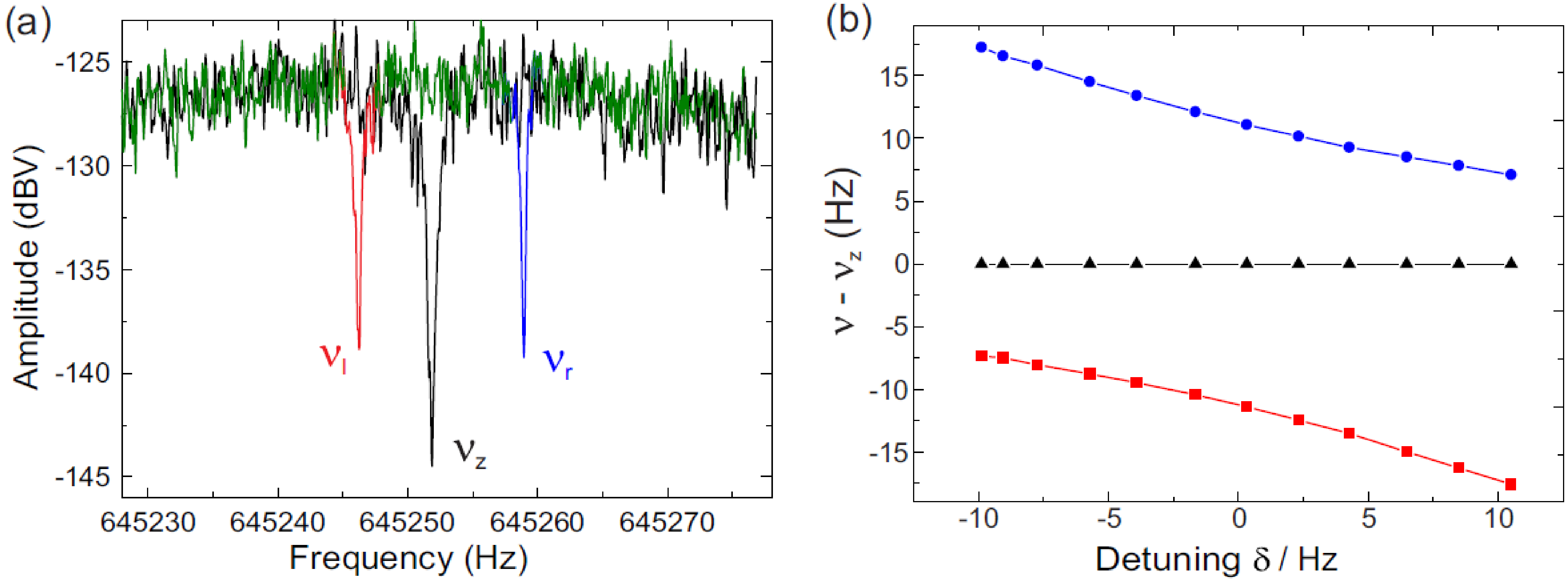




Conversion between two eigenmotions by excitation at the sum frequency: $\omega_{rf} = \omega_{+} + \omega_{-}$

Continuous excitation leads to an amplitude modulation in the two involved trap modes with exchange frequency $\Omega/2$.

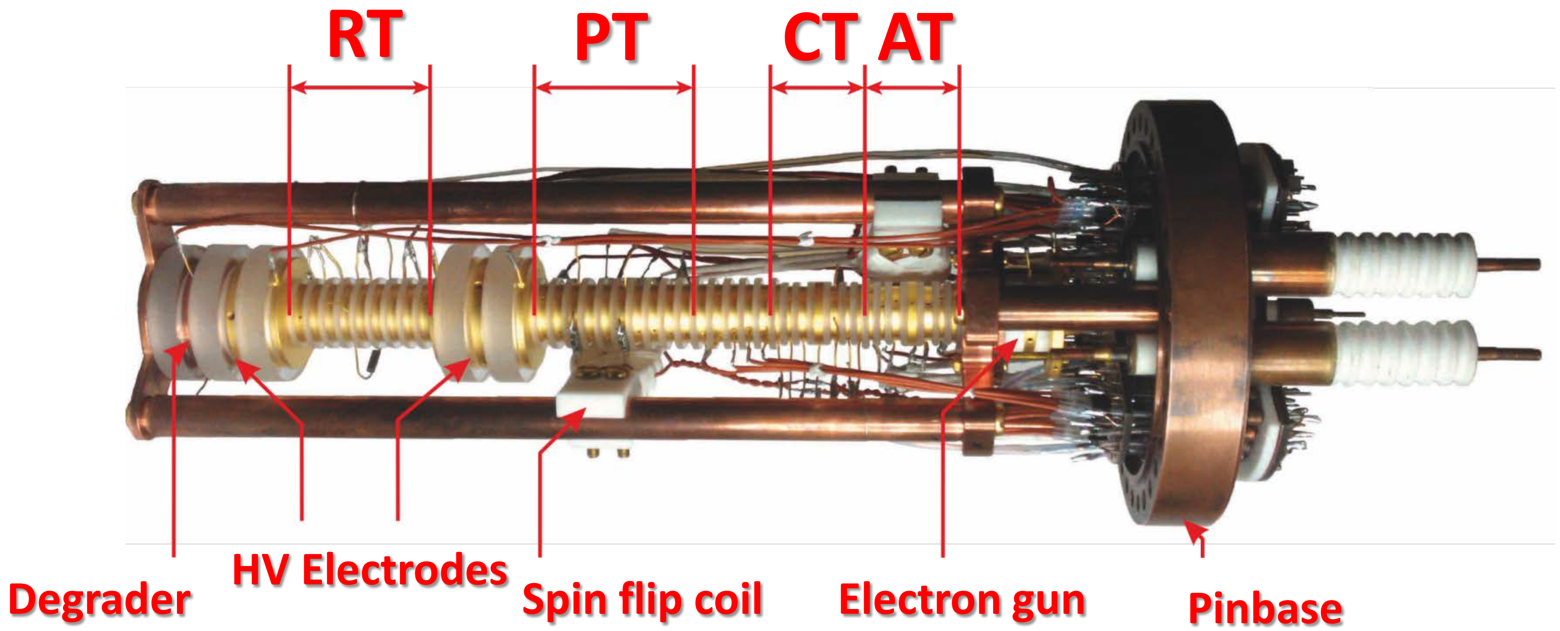
Axial-cyclotron sideband coupling



$$\nu_{l,r} = \nu_z - \frac{\delta}{2} \pm \sqrt{\frac{\Omega_0^2}{4\pi^2} + \delta^2}$$

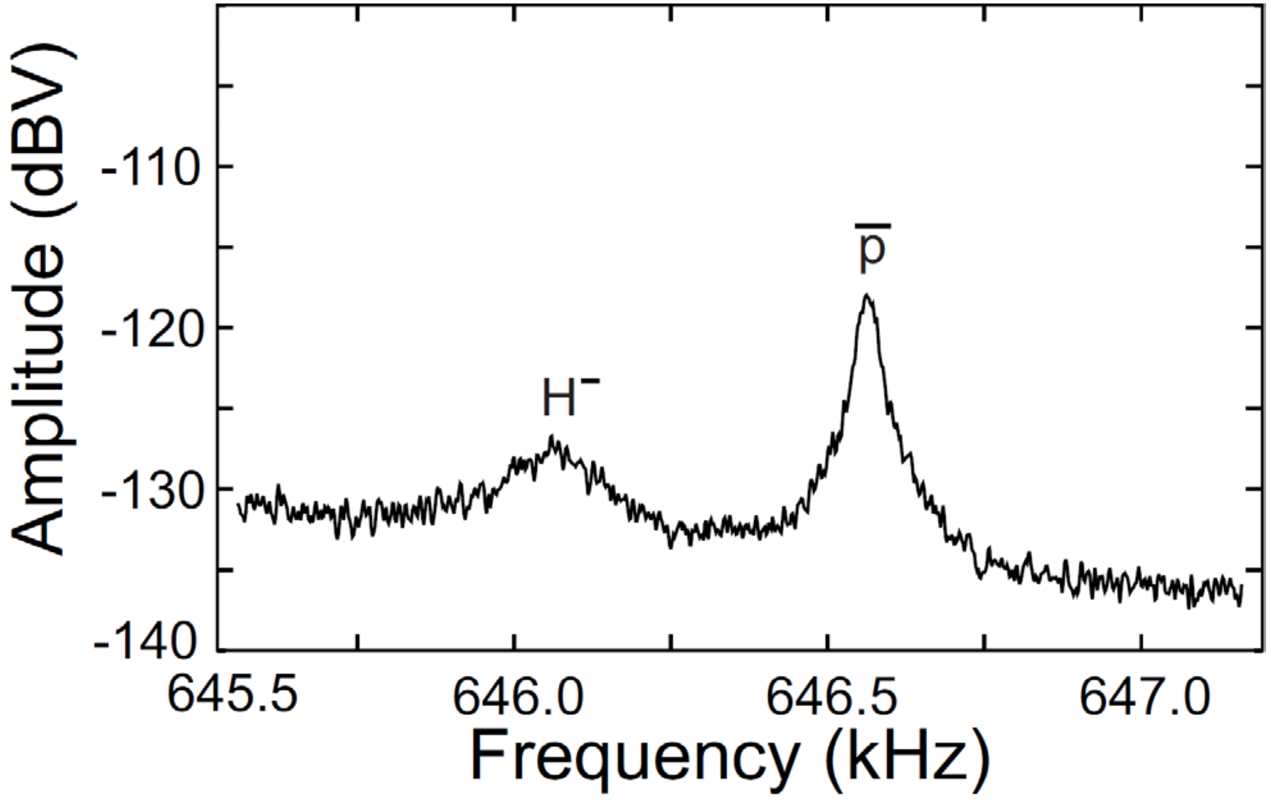
$$\nu_+ = \nu_{rf} + \nu_l + \nu_r - \nu_z$$

The BASE four Penning-trap system



RT: Catching / Reservoir Trap: Catching, cooling and storing of antiprotons
PT: Precision Trap: Homogeneous magnetic field for precision frequency measurements
CT: Cooling Trap: Fast cooling of the cyclotron motion
AT: Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, B_2 = 30 T / cm^2

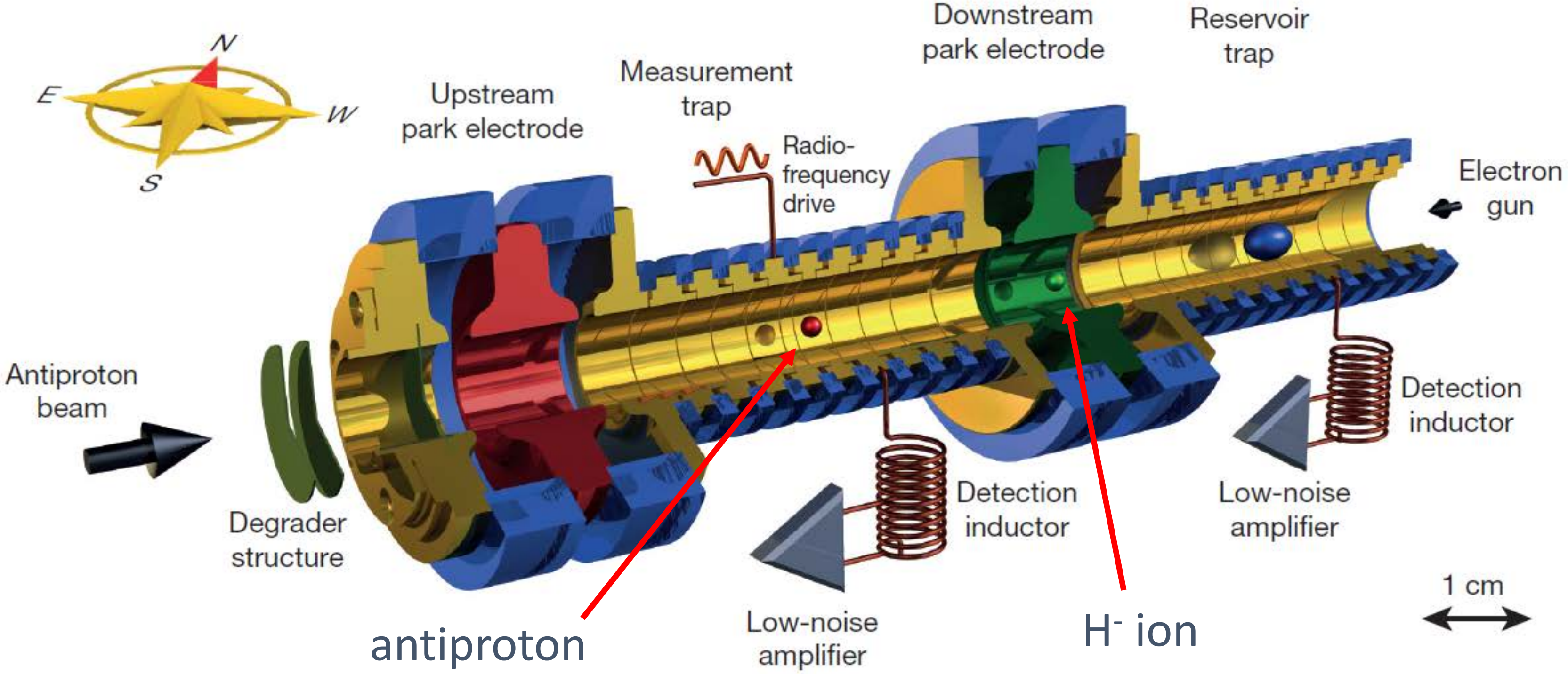
Loading antiprotons and H^- ions



- details of H^- trapping have yet to be understood.
- typical yield H^- /pbar = 1/3.
- managed to prepare a clean composite cloud of H^- and antiprotons.

Measurement configuration

Based on reservoir extraction technique and developed methods to prepare negative hydrogen ions we prepared an interesting set of initial conditions

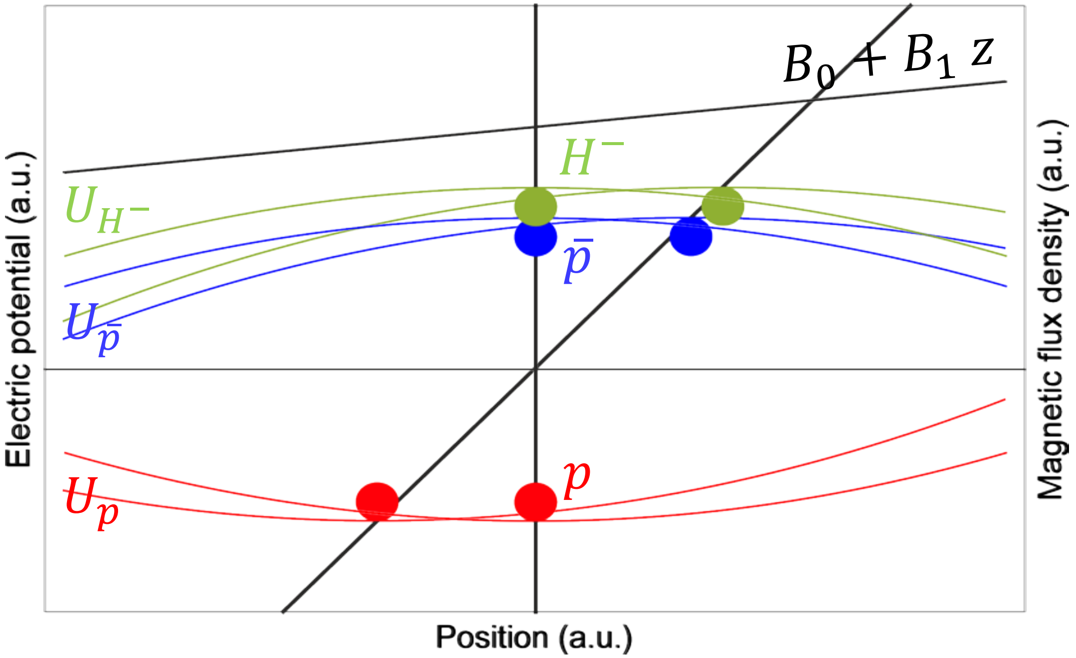


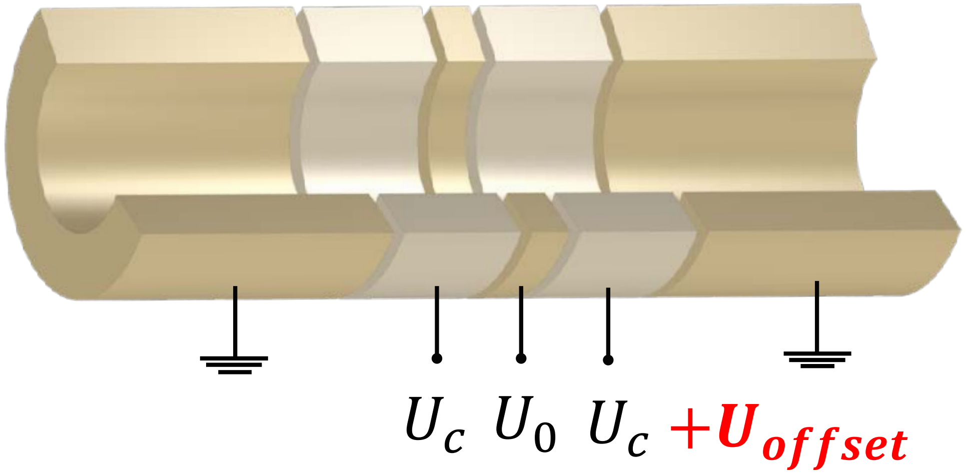
Comparison of H-/antiproton cyclotron frequencies:

One frequency ratio per 4 minutes with ~ 5 ppb uncertainty

S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196 (2015).

Why not to use protons





- Systematic uncertainties due to the particle position are large (~10^{-9})
- No significant uncertainties in converting the mass ratio

$$\frac{m_{\mathrm{H}^-}}{m_{\mathrm{p}}} = \left(1 + 2\frac{m_{\mathrm{e}}}{m_{\mathrm{p}}} - \frac{E_{\mathrm{b}}}{m_{\mathrm{p}}} - \frac{E_{\mathrm{a}}}{m_{\mathrm{p}}} + \frac{\alpha_{\mathrm{pol,H^-}} B_0^2}{m_{\mathrm{p}}}\right)$$

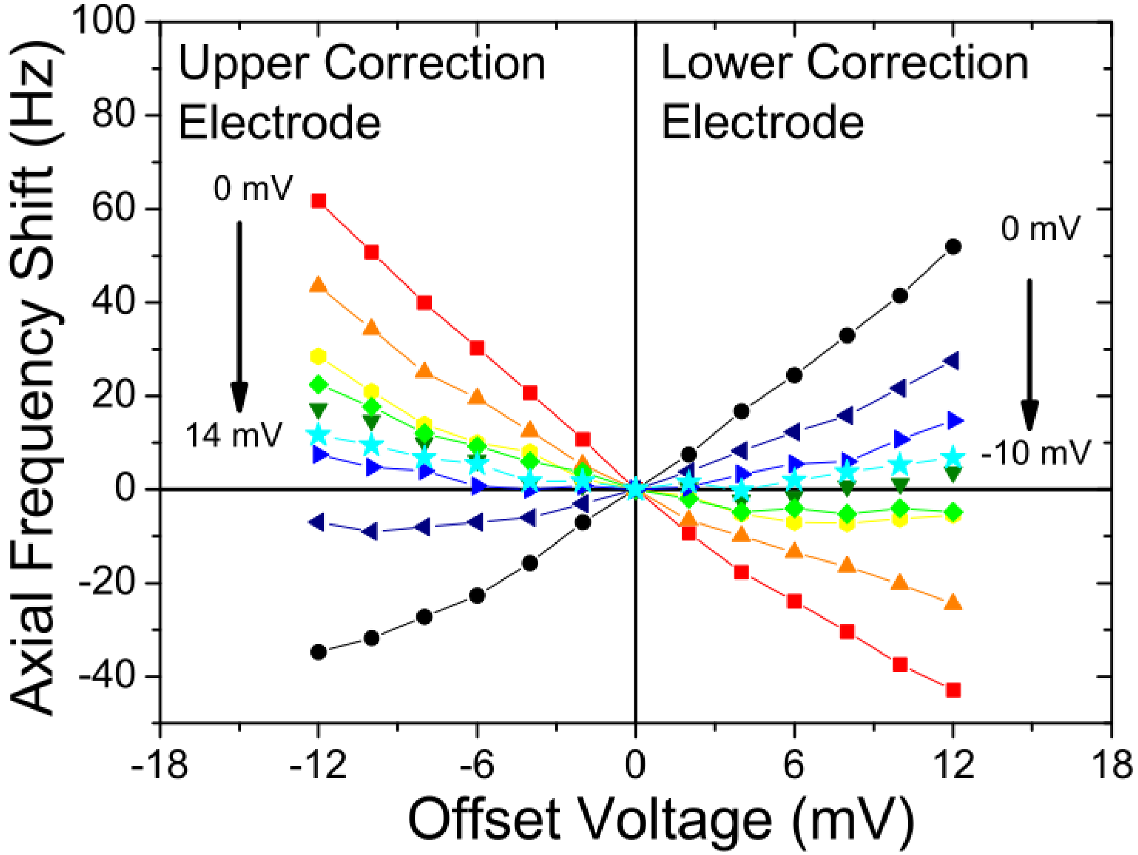
$R_{theo} = 1.0010892187542(2)$ (0.2 ppt)

- CPT test by a measurement of the cyclotron frequency ratio of antiproton and H^- ion

G. Gabriesle et al., PRL **82**, 3199(1999).
S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196-200 (2015).

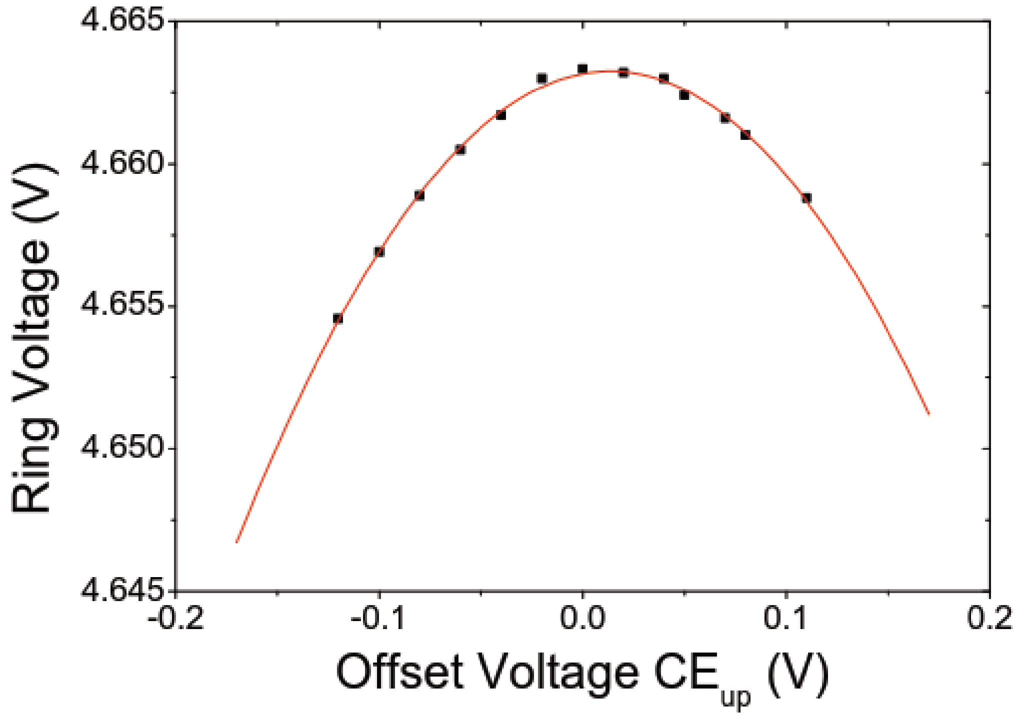
Asymmetry compensation

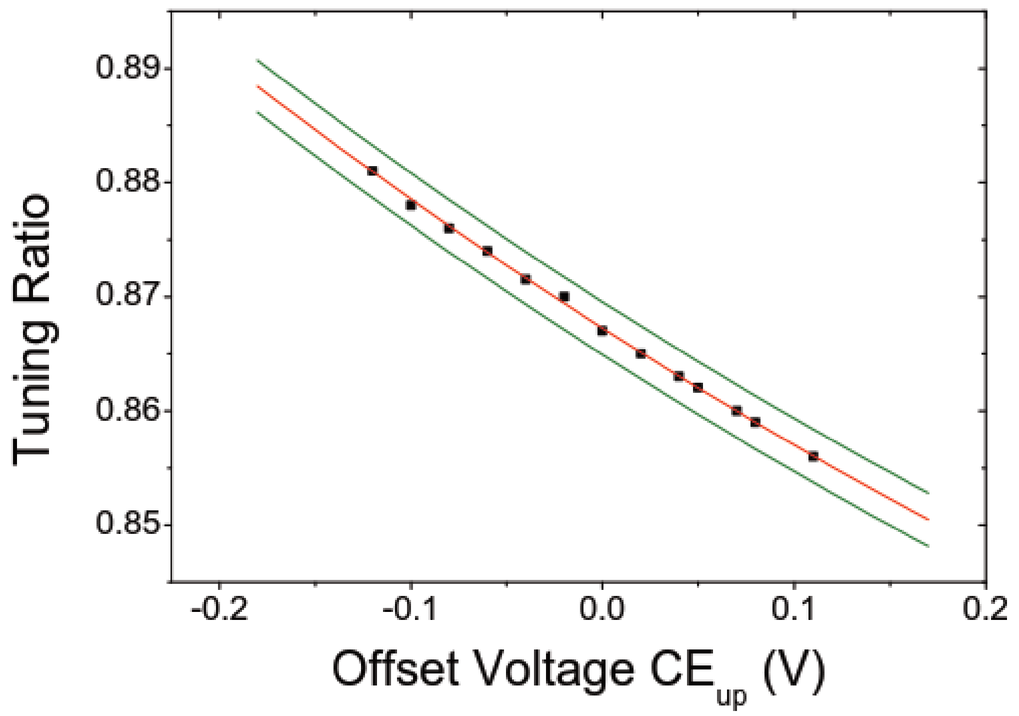
- The trap is symmetric if the potential on the correction electrodes (and endcaps) is identical
- The frequency shift induced by a voltage difference *ΔV* applied to one correction electrode should be the same for both correction electrodes
- This allows to determine the offset potentials and compensate the voltage asymmetry
- The particle position becomes (more) independent from the ring voltage



Trap geometry imperfections

Additional information on potential offsets and geometry imperfections can be learned from measuring the antiproton axial frequency for different voltage configurations:





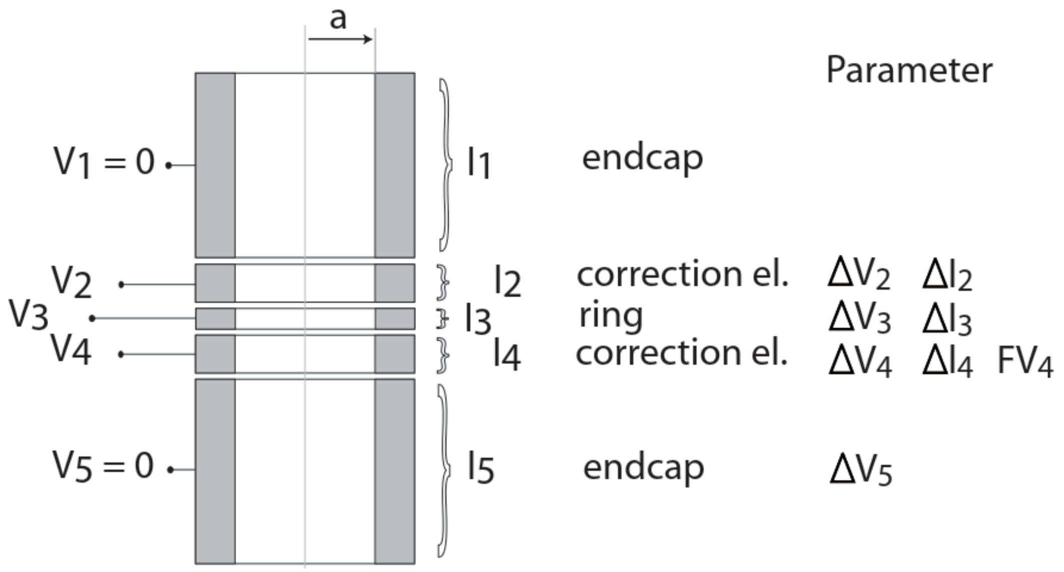
S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196 (2015).

Characterization of trap parameters

Comparing measurements and the trap coefficients from potential theory allows to determine the offset potentials and imperfections in the trap geometry:

$$C_j = \sum_{n=1}^{\infty}\left[\frac{V_1\cos(k_n z_0) - V_5\cos(k_n\Lambda)}{k_n} + \sum_{i=1}^{4}\frac{V_{i+1}-V_i}{k_n^2 d}\sin(k_n z_{2i}) - \sin(k_n z_{2i-1})\right]$$
$$\times\frac{2}{j!\Lambda V_3}\left(\frac{n\pi}{\Lambda}\right)^j\frac{1}{I_0(k_n a)}\sin\left(\frac{\pi}{2}(n+j)\right)\ .$$

This allows to determine the position offset and the accompanied systematic shift.



parameter	value	uncertainty	uncertainty in ratio shift in p.p.t.
ΔV_1	$0\,\mathrm{mV}$	$9\,\mathrm{mV}$	9.9
ΔV_2	$-2\,\mathrm{mV}$	$5\,\mathrm{mV}$	12.4
ΔV_3	$0\,\mathrm{mV}$	$7\,\mathrm{mV}$	0.2
ΔV_4	$119\,\mathrm{mV}$	$1\,\mathrm{mV}$	2.5
ΔV_5	$-10\,\mathrm{mV}$	$2\,\mathrm{mV}$	2.2
Δl_2	$18\,\mu\mathrm{m}$	$4\,\mu\mathrm{m}$	4.7
Δl_3	$29\,\mu\mathrm{m}$	$1\,\mu\mathrm{m}$	1.1
Δl_4	$0\,\mu\mathrm{m}$	$4\,\mu\mathrm{m}$	4.7
F_4	0.985	0.002	19.8

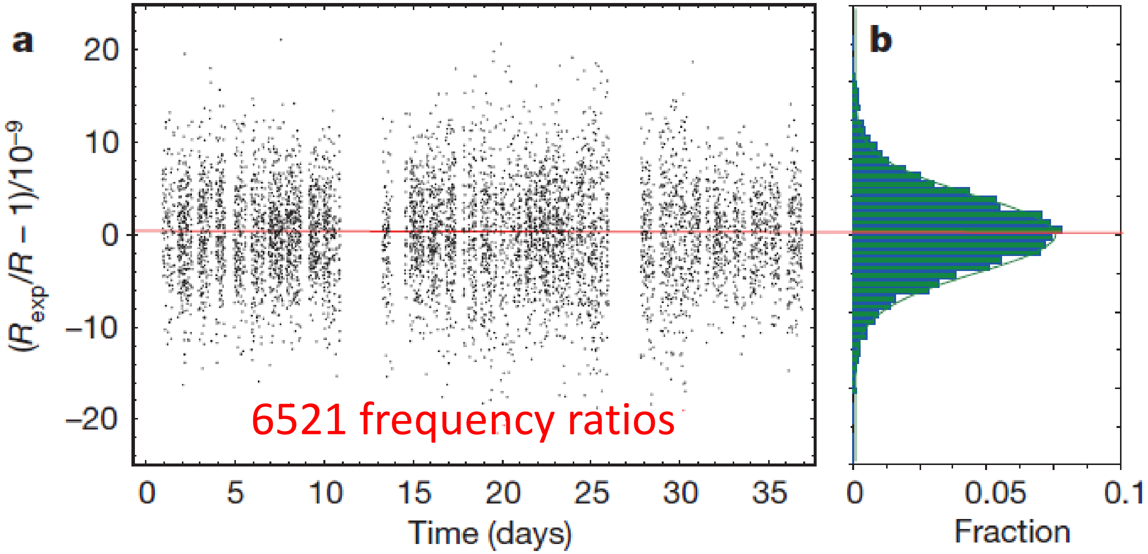
S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196 (2015).

Other systematic uncertainties

	Effect	Shift (p.p.t.)	Uncertainty (p.p.t.)
B_1	Magnetic gradient shift	-0.002	0.0002
B_2	Magnetic bottle shift	0.009	0.012
a	Image charge shift	0.047	0.004
	Image current shift	$<\lvert 0.001 \rvert$	$<\lvert 0.001 \rvert$
T_+	Relativistic shift	-0.024	0.002
	Voltage drift	0.015	0.003
θ	Tilt of apparatus	-0.027	0.007
	Rb-clock	–	3
C_4	Trap anharmonicity	3	1

S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196 (2015).

Data analysis and result



Width limited by random-walk noise of the magnetic field (~ 5.5 ppb)

- Experimental result:

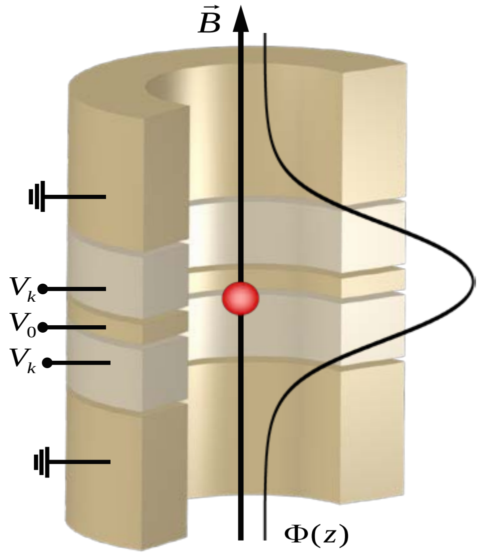
$$R_{exp} = 1.001\,089\,218\,872\,(64)$$

- Cyclotron frequency ratios for $\bar{\mathrm{p}}$-to-$\bar{\mathrm{p}}$ and H^--to-H^- R_{id} are also evaluated

$$R_{id} - 1 = -3(79) \times 10^{-12}$$ ← Consistent with 1

S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196 (2015).

Systematic Corrections



- Major systematic correction due to the residual magnetic B1 gradient.
  - A displacement of 29 nm in the gradient of B1 = 7.6 mT / m causes a correction of

    dR_{B1} = -114(26) p.p.t.

  - Slight re-adjustment of the trapping potential: dR_{C4} = -3(1) p.p.t.

Final experimental result: **$R_{exp,c}$ = 1.001 089 218 755 (64) (26)**

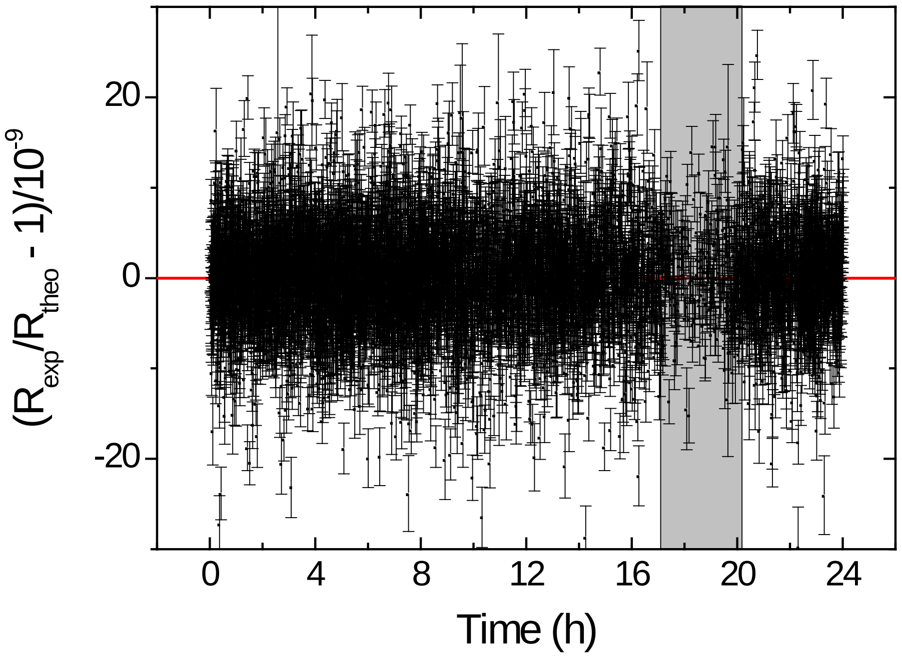
$$\frac{(q/m)_{\bar{\mathrm{p}}}}{(q/m)_{\mathrm{p}}} + 1 = 1(69) \times 10^{-12}$$

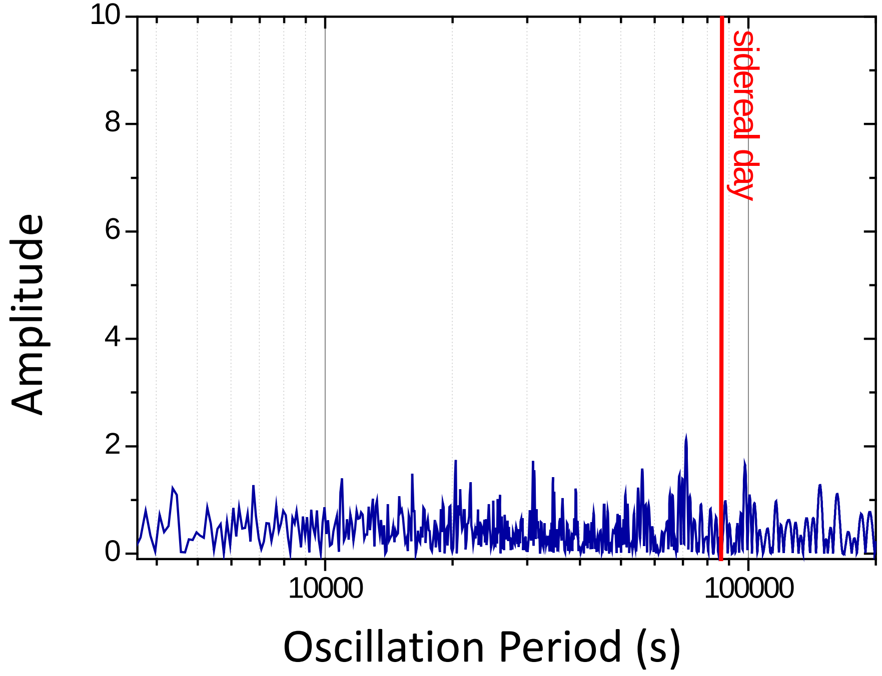
- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4.

S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196 (2015).

Sidereal Variations (Lorentz violation)

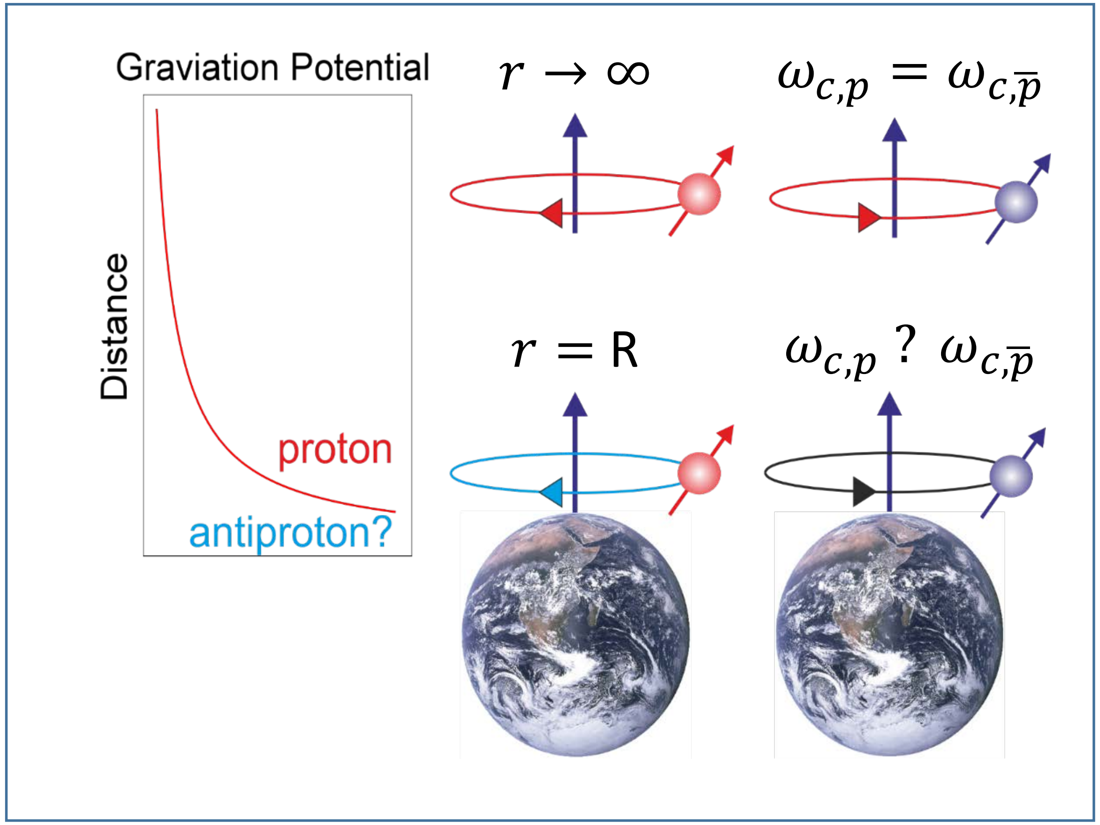
- Constrains in first order CPT-even parameters of the Standard Model Extension
- Limit of sidereal variations in proton/antiproton charge-to-mass ratios to < 0.72 ppb





S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196 (2015).

Antiproton gravitational redshift



- Cyclotron Frequency reflects the gravitational binding energy of the antiproton
- Gravitational anomaly can be constrained

$$\frac{\omega_{c,p} - \omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1)\, U/c^2$$

Our 69ppt result sets
a new upper limit of

$$|\alpha_g - 1| < 8.7\times 10^{-7}$$

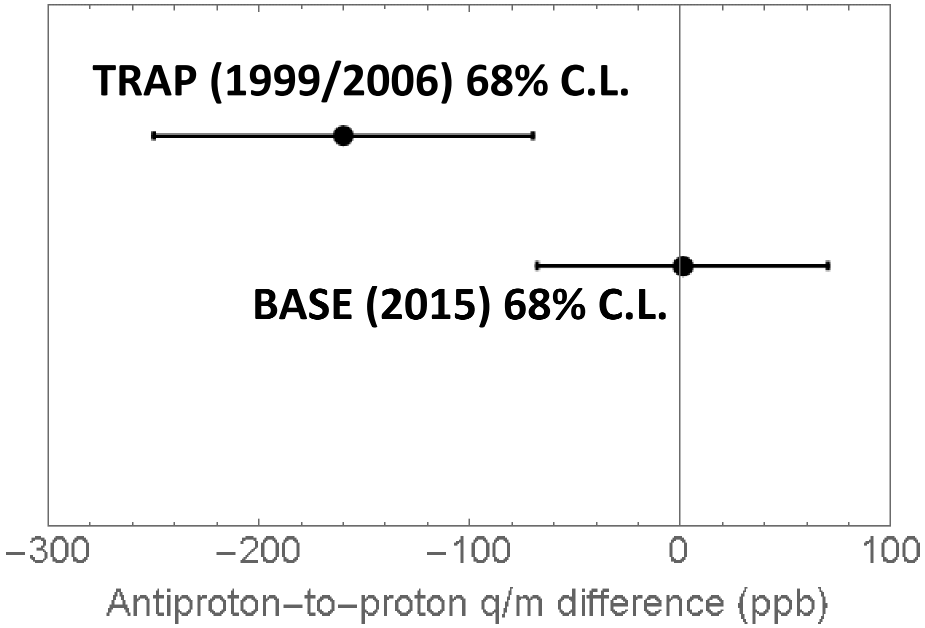
S. Ulmer et al., *Nature* **524** 196 (2015)

- Cyclotron frequency ratio depends on (q/m)-difference, SME-coefficients, and the gravitational anomaly
- Limits on the gravitational anomaly depend on assumptions on the gravitation potential U

S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196 (2015).

R. J. Hughes, & M. H. Holzscheiter, Phys. Rev. Lett. 66, 854-857 (1991).
R. J. Hughes, Contemporary Physics, 34:4, 177-191 (1993).

Conclusions to antiproton Q/M



Most precise comparison of a fundamental quantity of baryons and antibaryons.

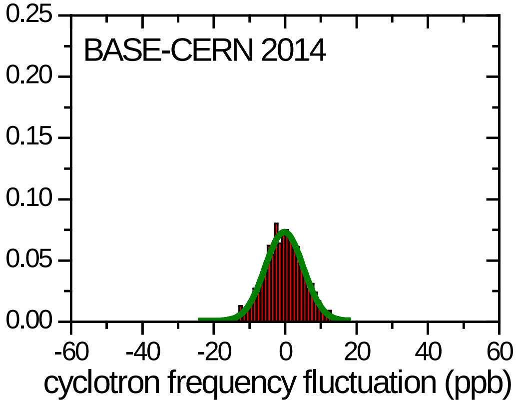
Test of the standard model with $h\Delta\upsilon_c = 8\ 10^{-18}$eV energy resolution.

Factor 4 improvement in energy resolution due to lower cyclotron frequency

Limitations due to the magnetic field fluctuations have been improved

A more precise measurement seems feasible

5.5 ppb



1.25 ppb