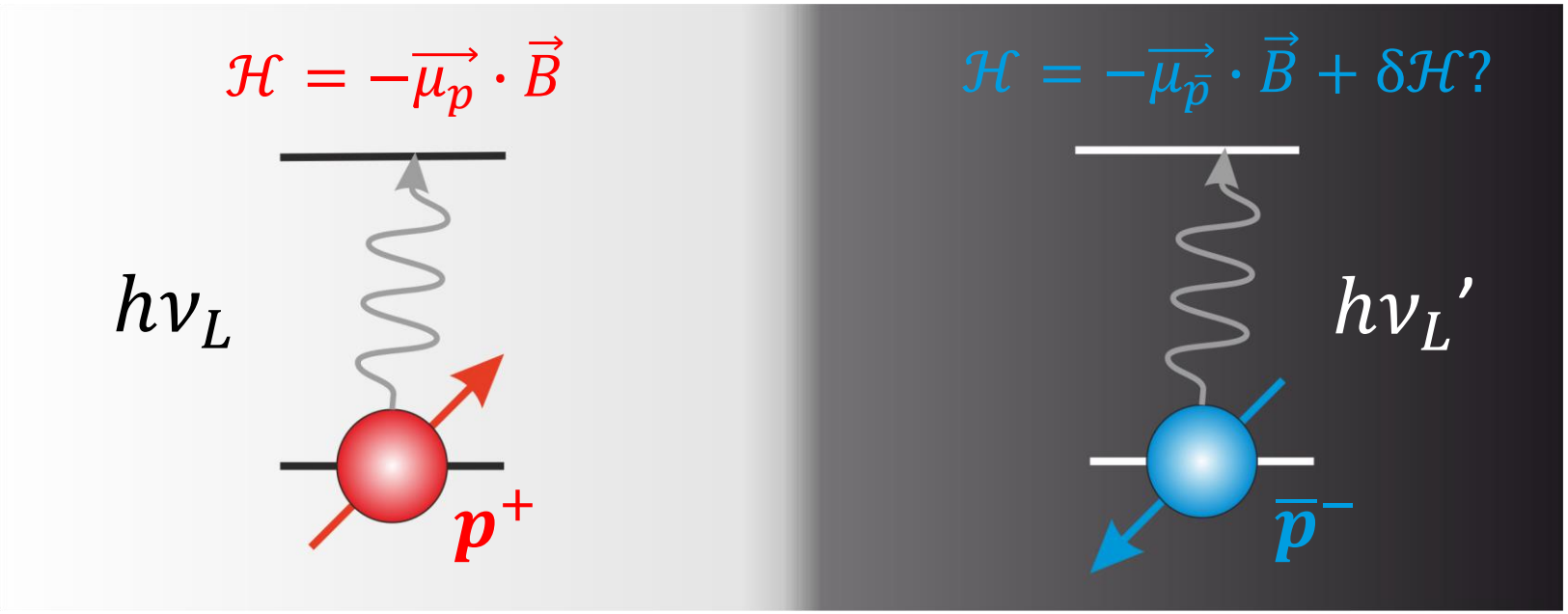
AVA School for Precision Studies

Searching for new physics in high-precision measurements with antiprotons

Christian Smorra
RIKEN – Fundamental Symmetries Laboratory
Johannes Gutenberg University Mainz

Why precision measurements with antiprotons?

Test the Standard Model with atomic physics methods



- We rely mostly on symmetry and assume that physics in antimatter systems is identical
- Low energy searches for new physics are (mostly) preformed in matter-based experiments

Antimatter precision experiments provide:

- **Tests of CPT invariance** as one of the fundamental symmetries
- **Complementary searches for new physics** compared to matter-based experiments

Contents

Paul Dirac

Carl David Anderson

Andrei Sakharov

1. Particles, Antiparticles, and the Baryon asymmetry

Dirac equation

Quantum mechanics

$$i\hbar \frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2\,m}\Delta\psi$$

Theory of relativity

$$E^2 = p^2c^2 + m^2c^4$$

Lorentz invariance

Dirac equation

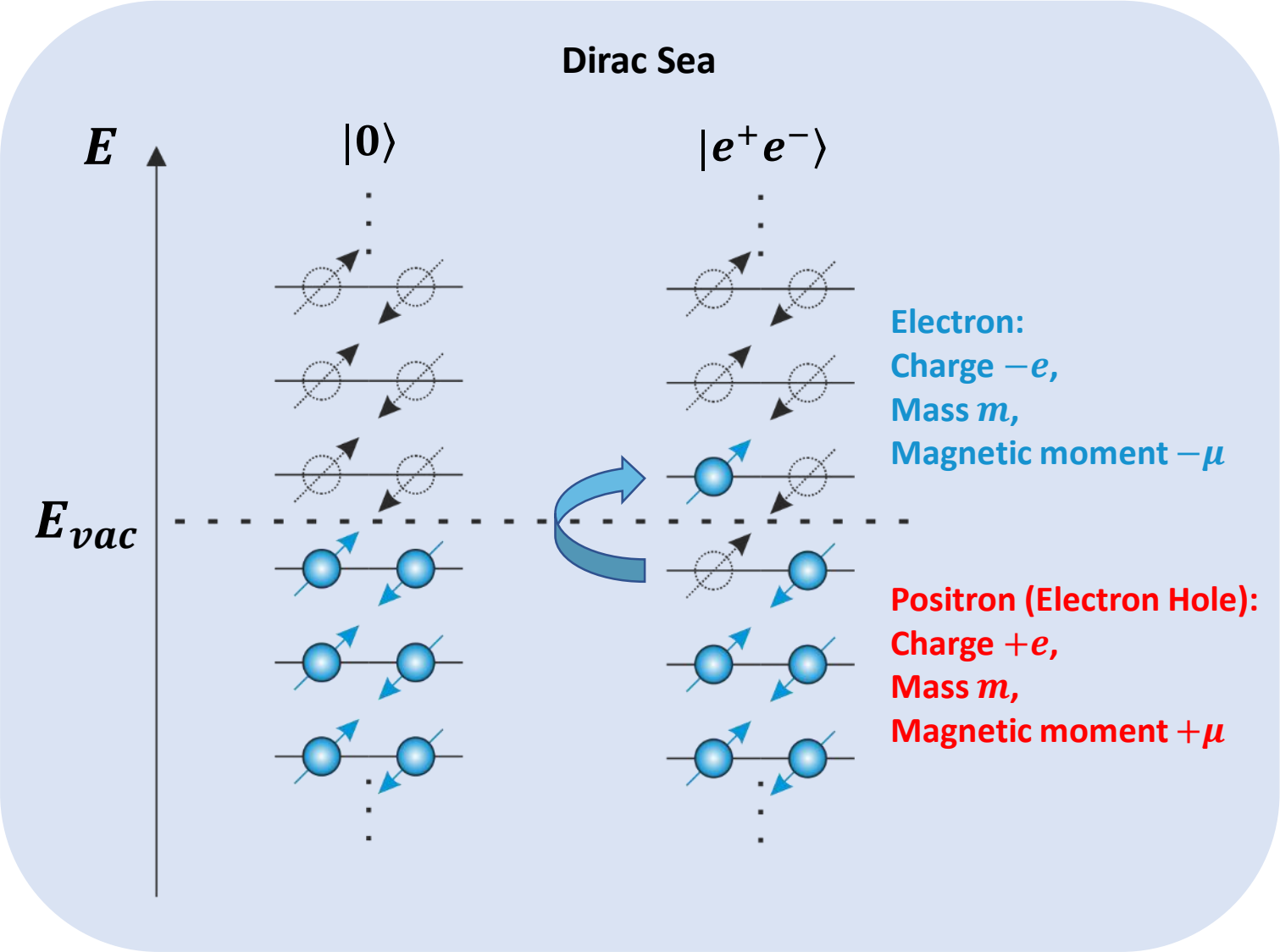
$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

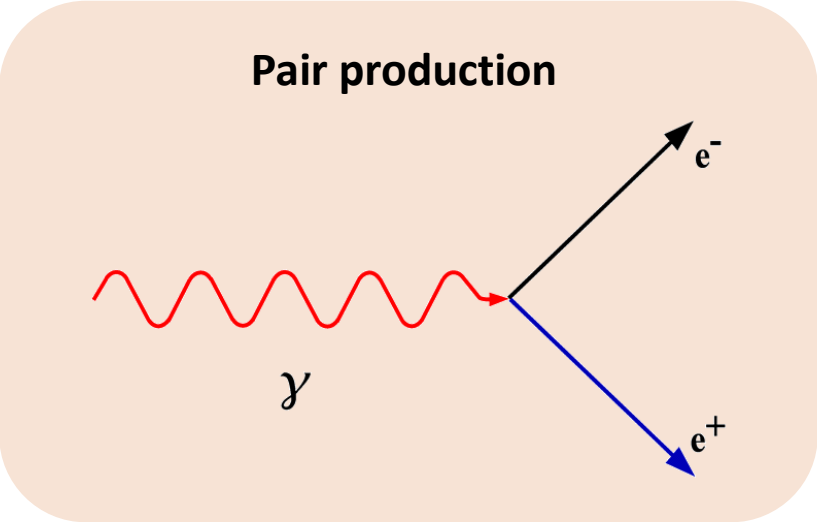
Quantum field theory

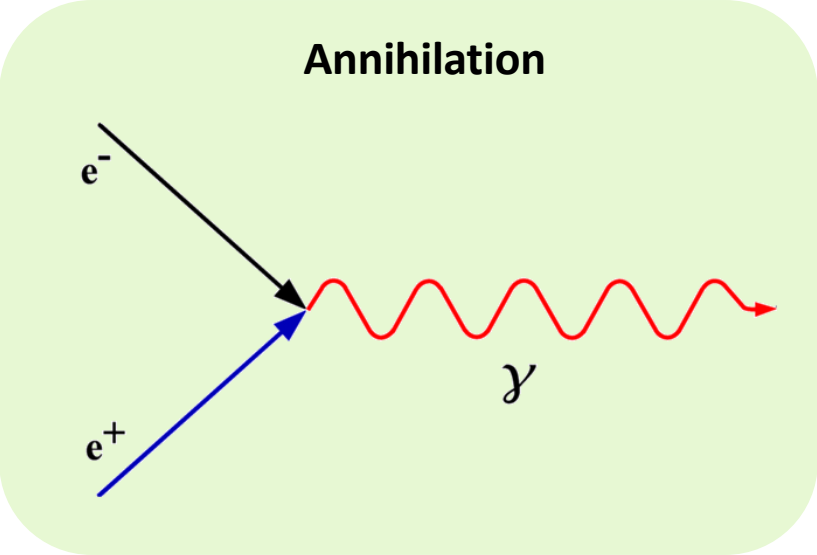
Dirac equation has four component solutions (Dirac, 1928 - 1931)
two for particles, two for antiparticles

Discovery of the positron – (Anderson, 1932)

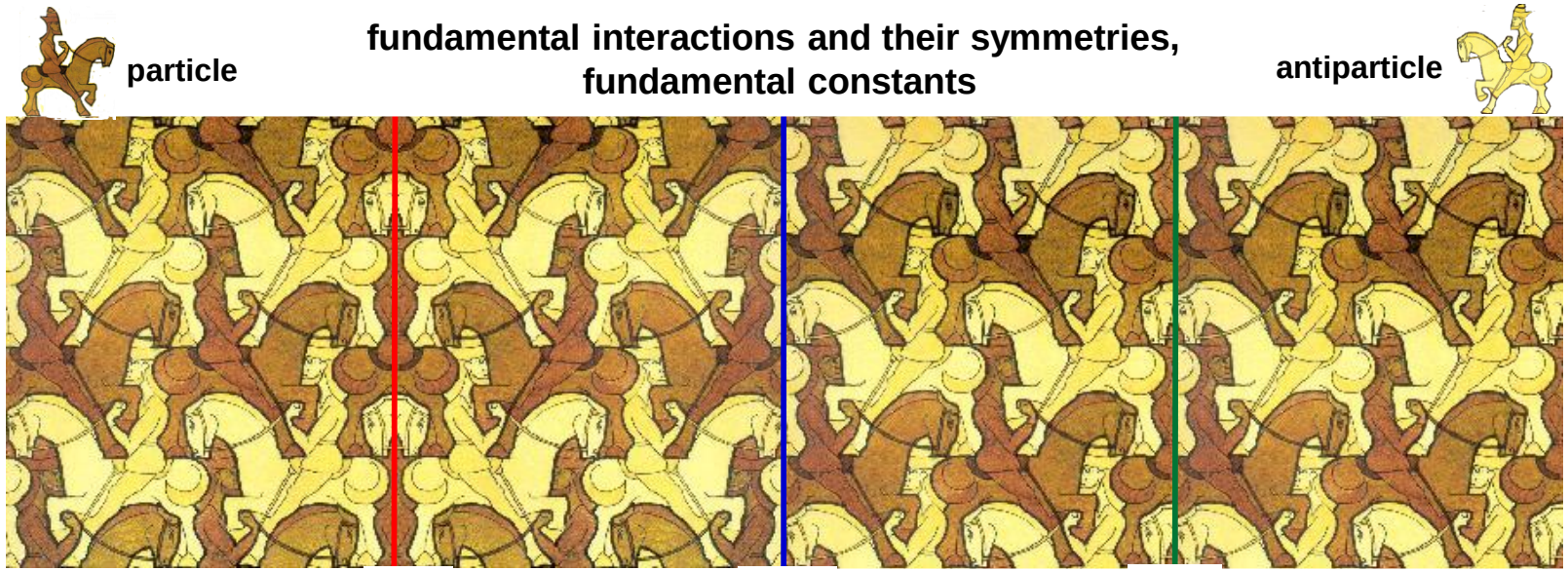
Fundamental concepts in Dirac's theory







Quantum field theory & the CPT Theorem



P C T

Adapted from H. Wilschut

CPT Theorem: Local, Lorentz invariant quantum-field theories are CPT invariant

Interactions in the CPT transformed state are identical

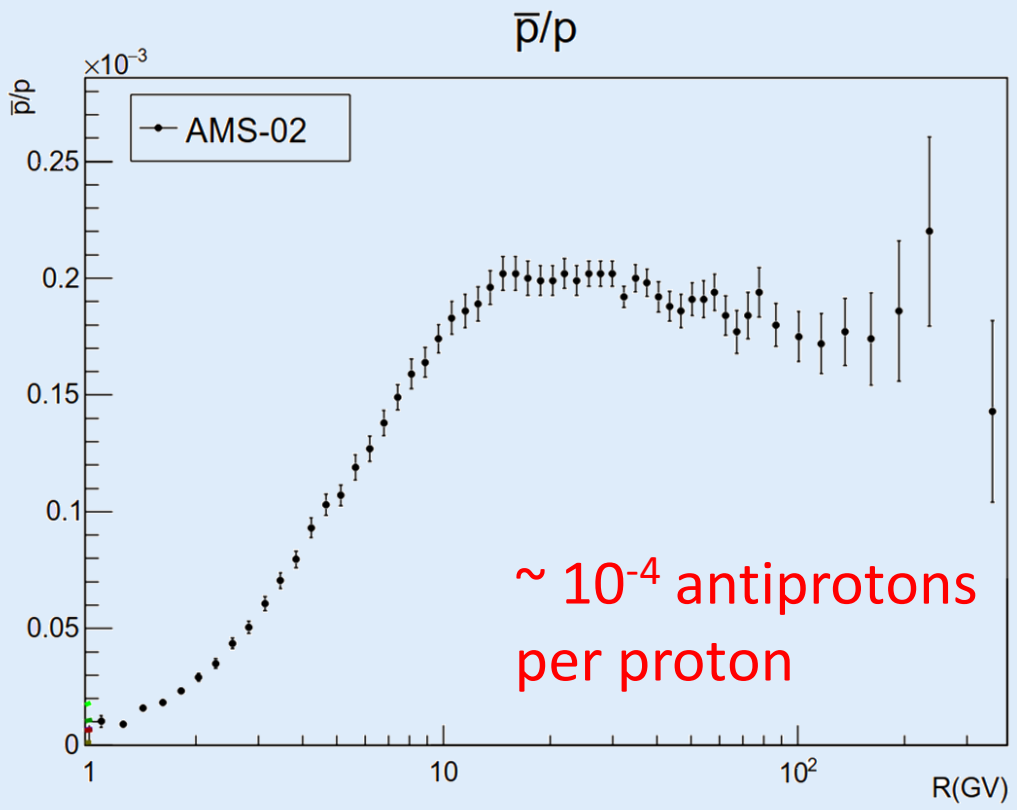
Requires fundamental properties of particle/antiparticle conjugates to be identical

Stringent tests of CPT invariance by high-precision comparison of these quantities

Test a fundamental symmetry of the Standard Model

Antimatter in the universe

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



R. Kappl et al., JCAP09, 051 (2014).
S.J. Lin et al., arXiV 1612.0400, (2016).

Baryon asymmetry:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \times 10^{-10}$$

≈ 0

No annihilation radiation/ No primordial antinuclei

How was this matter-antimatter asymmetry created?

1.) Asymmetric universe,
B > 0 , since the Big Bang (t = 0)

2.) Symmetric universe,
B = 0, separated "matter/antimatter bubbles"
In this scenario: $\eta \approx 10^{-18}$

3.) **Baryogenesis**
B = 0 at the big bang and now B > 0

M. Dine and A. Kusenko, Rev. Mod. Phys. **76**, 1 (2003).
D. V. Perepelitsa, Sakharov Conditions for Baryogenesis, Columbia University

The Sakharov Conditions

The "classic" ingredients for the Baryon asymmetry:

A baryon number violating process

$$B_L \to X_L \qquad B_R \to X_R$$

Breaking of C and CP symmetry:

$$\bar{B}_L \to \bar{X}_L \qquad \bar{B}_R \to \bar{X}_R$$

A thermal non-equilibrium:

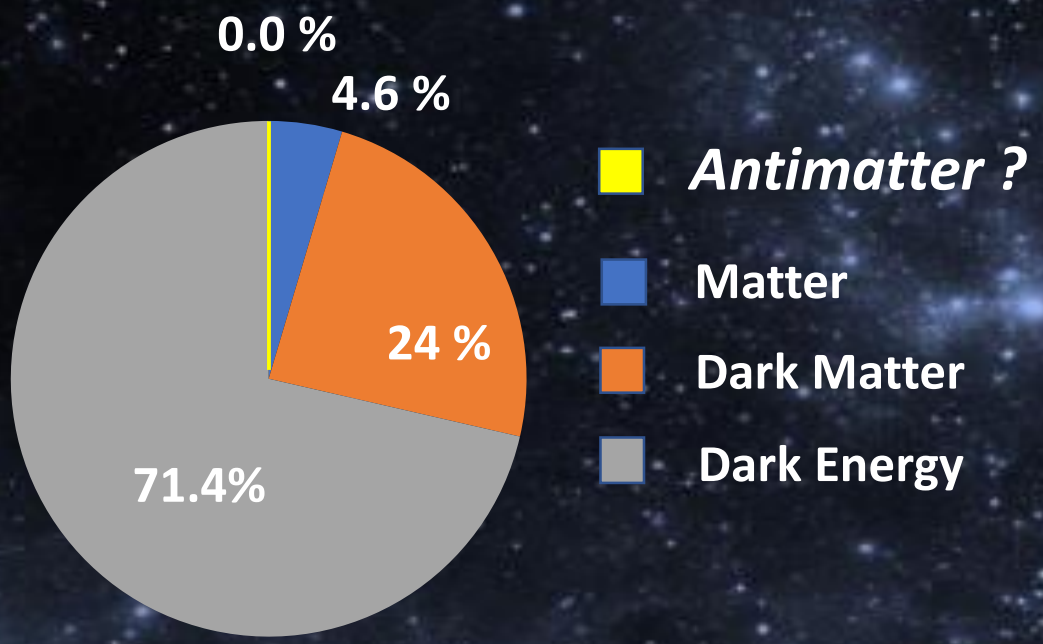
$$\Gamma(B_L \to X_L) + \Gamma(B_R \to X_R) = \Gamma(\bar{B}_L \to \bar{X}_L) + \Gamma(\bar{B}_R \to \bar{X}_R)$$

Breaking of CPT invariance

Different decay rates in thermal equilibrium

O. Bertolami et al., Phys. Lett. B 395, 178-83 (1997).

What happened to the antimatter?



https://wmap.gsfc.nasa.gov/universe/uni_matter.html

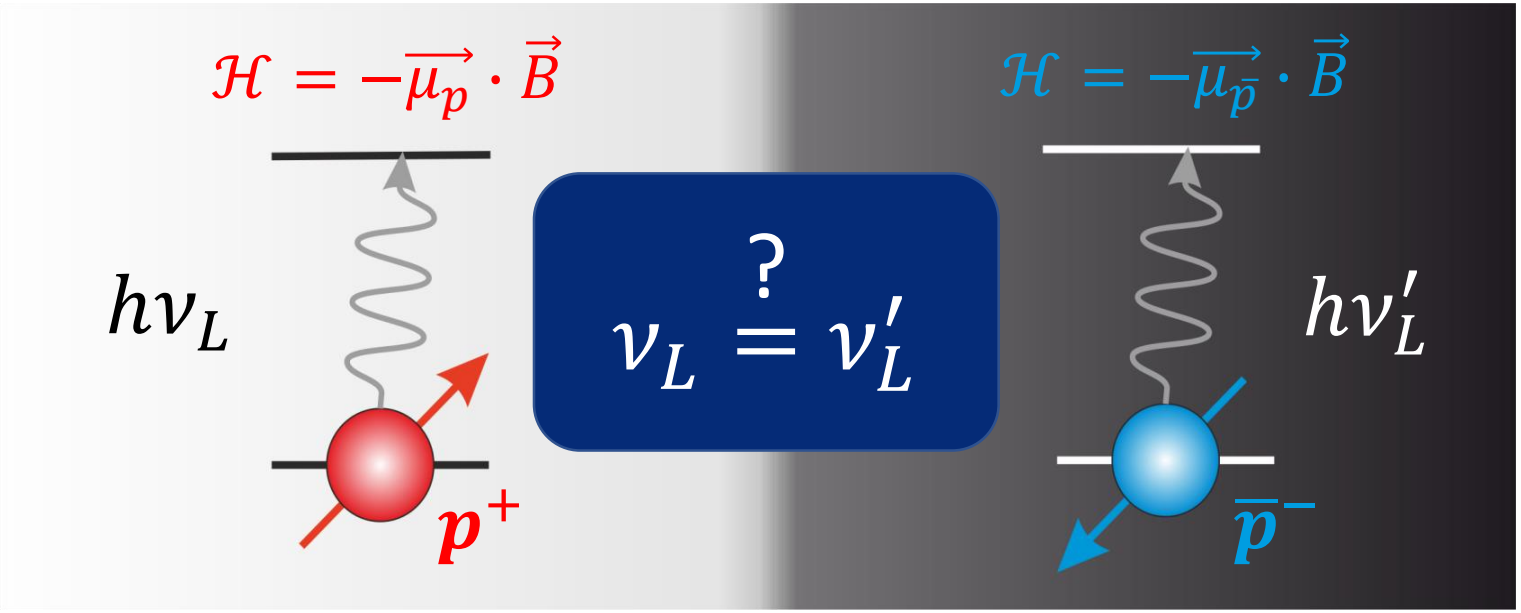
Why do we live in a matter-dominated universe?

Are the constituents of matter and antimatter exact mirror images?

Is dark matter interacting with antiparticles?

Does antimatter exhibit a modified gravitation?

Antiproton precision measurements can provide answers to these questions!



2. Tests of CPT invariance

Comparing fundamental properties of conjugate fields

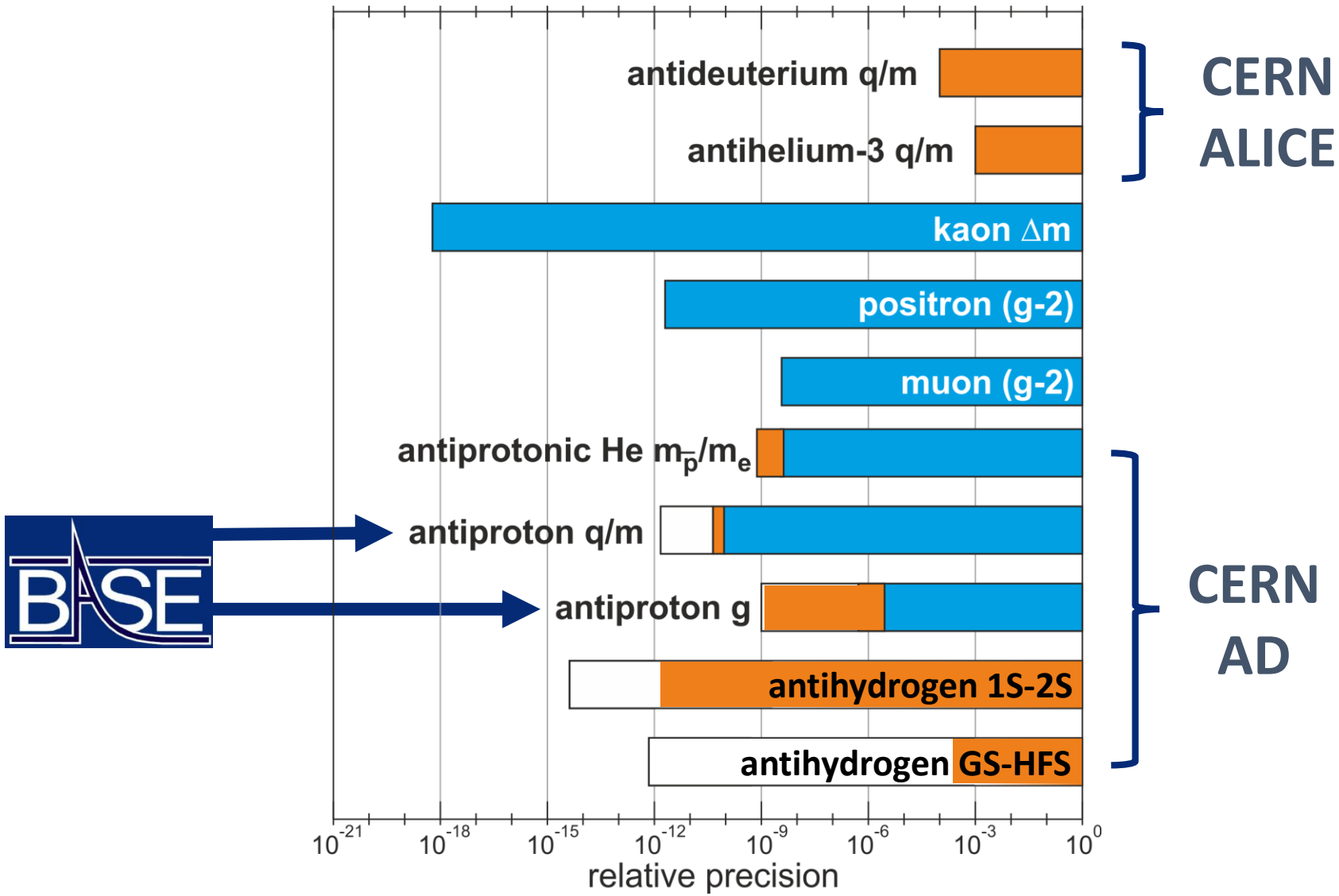
Fundamental properties:

Charge q
Mass m
Magnetic moment $\mu, g, (g-2)$
Lifetime τ
Transition frequencies

Antiparticle systems:

Positron e^+	Mesons $K_0/\bar{K}_0$	Antihydrogen $\bar{H}$
Muon μ^+	Antiproton $\bar{p}$	$\bar{H}^+$
e^+e^-	$\bar{p}He$	$\bar{H}_2^-$
μ^+e^-	$p\bar{p}$	Antinuclei $\bar{d}, {}^3\overline{He}$

CPT tests based on particle/antiparticle comparisons



Status: 12/2014

Status: 03/2020

R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwingenheuer, et al., Phys. Rev. Lett. 74, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabriesle et al., PRL **82**, 3199(1999).
J. DiSciacca et al., PRL **110**, 130801 (2013).
S. Ulmer, C. Smorra, et al., Nature **524**, 196-200 (2015).
ALICE Collaboration, Nature Physics **11**, 811–814 (2015).
M. Hori et al., Science **354**, 610 (2016).
H. Nagahama, C. Smorra, et al., Nat. Comm. **8**, 14084 (2017).
M. Ahmadi et al., Nature **548**, 66-69 (2017).
M. Ahmadi et al., Nature **557**, 71-75 (2018).

The work on CPT invariance tests in general has been summarized in:

V. A. Kostelecky, N. Russell, 0801.0287v13 (2020).

CPT violation in theory

CPT Theorem: A local, Lorentz-invariant quantum field theory is CPT invariant

⇒ Break Lorentz-invariance to violate CPT invariance

M. Charlton, S. Erikssen, and G. M. Shore, arXiv:2002:09348v1 (2020).

Standard Model Extension (SME):

A local effective quantum field theory, which includes Lorentz- and CPT-violation

Photon coefficients

$$\mathcal{L}_{LV} = \mathcal{L}_{QED} - \frac{1}{4}(k_F)_{\mu\rho\nu\sigma}F^{\mu\rho}F^{\nu\sigma} + \frac{1}{2}(k_{AF})^{\rho}\epsilon_{\rho\mu\nu\sigma}A^{\mu}F^{\nu\sigma}$$

$$-a_{\mu}\bar{\psi}\gamma^{\mu}\psi - b_{\mu}\bar{\psi}\gamma^{5}\gamma^{\mu}\psi - \frac{1}{2}H_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi + c^{\mu\nu}i\bar{\psi}\gamma_{\mu}D_{\nu}\psi + d^{\mu\nu}i\bar{\psi}\gamma_{5}\gamma_{\mu}D_{\nu}\psi.$$

Matter coefficients

70 possible parameters in the minimal version

Experiments constrain coefficients in terms of **energy resolution**

D. Colladay and V. A. Kostelecky, Phys. Rev. D 55, 6760 (1997).
D. Colladay and V. A. Kostelecky, Phys. Rev. D 58, 116002 (1998).

CPT-odd interactions modifying spin-precession

- Minimal Standard Model Extension
  - Dirac's Equation with lowest order CPT-odd contributions:

$$(i\gamma^\mu\partial_\mu - a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu - m)\psi = 0$$

- Non-minimal Standard Model Extension
  - Contains higher dimensional operators and explicit antiparticle coefficients

Y. Ding, Symmetry, 11, 1220 (2019).
Y. Ding et al., Phys. Rev. D 94, 056008 (2016).

- Interactions by CPT-odd dimension-five operators:

$$\hat{H}^A_{\text{int}} = f^0 \boldsymbol{B} \cdot \Sigma,$$

Y. V. Stadnik et al., Phys. Rev. D 90, 045035 (2014).

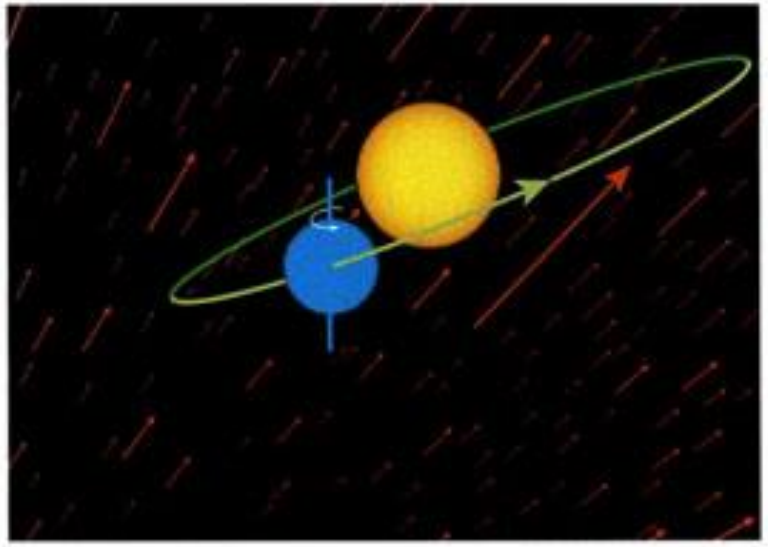
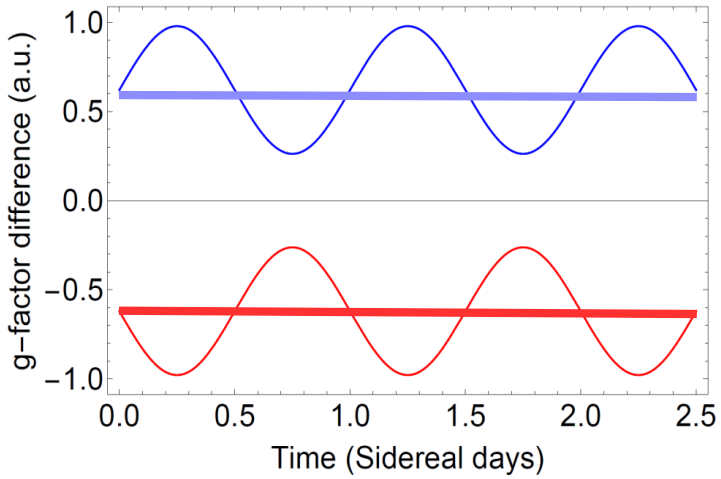
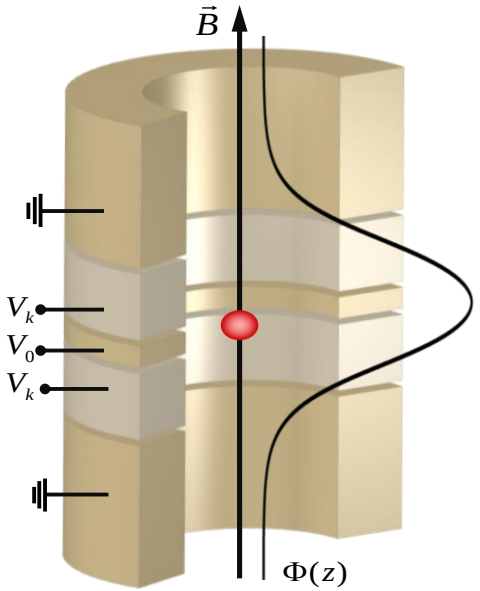
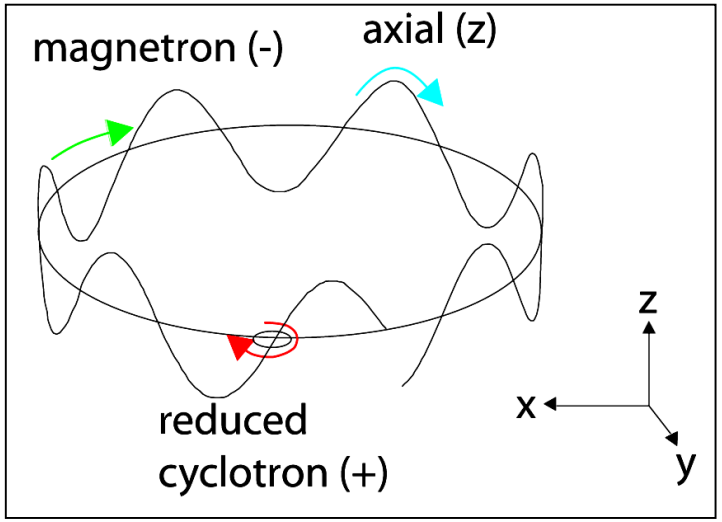


Figure from V.A. Kostelecky



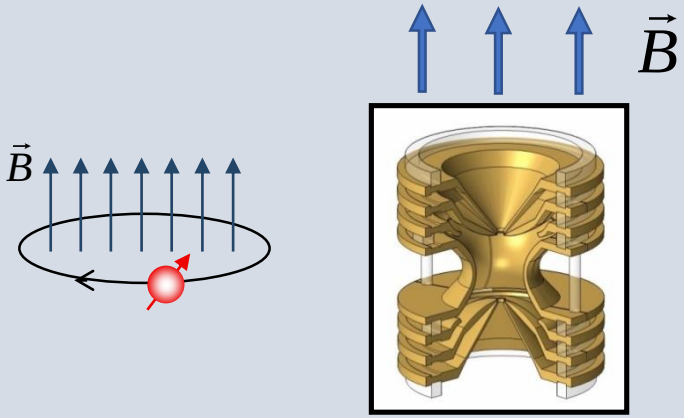




3. Precision measurement methods for antiprotons

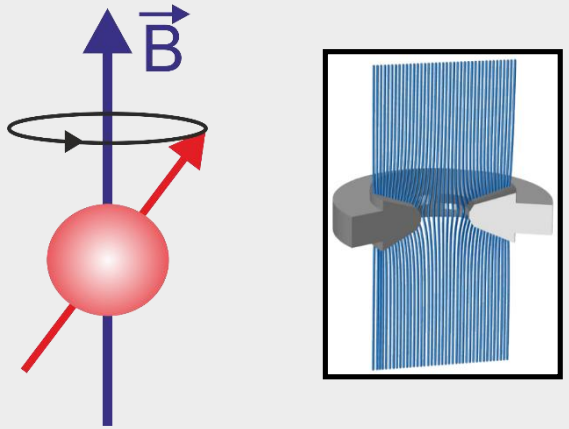
High-precision measurements in Penning traps

Cyclotron Frequency



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

Larmor Frequency



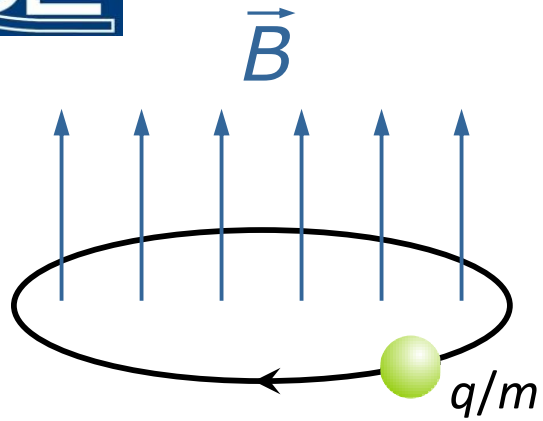
$$\omega_L = g \frac{e}{2m_p} B$$

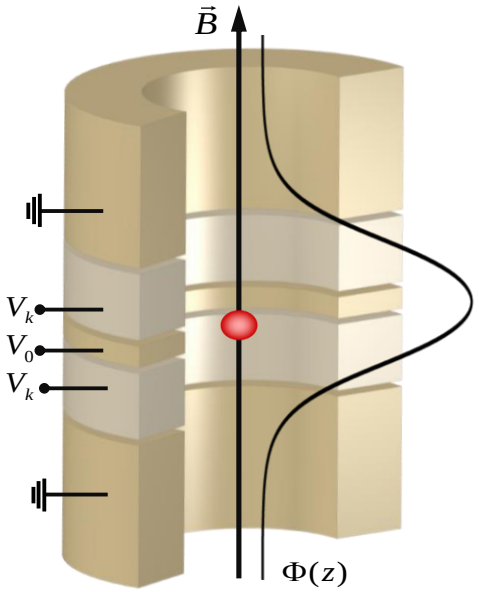
$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$

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

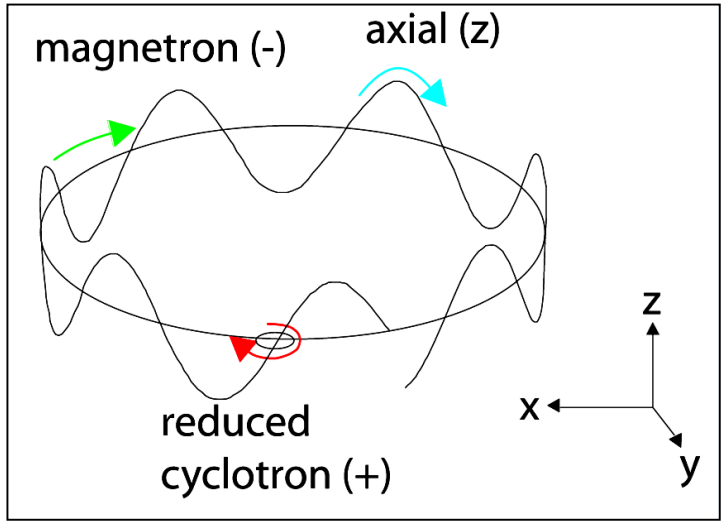
H. G. Dehmelt and P. Ekström, Bull. Am. Phys. Soc. 18, 72 (1973).
D. J. Wineland and H. G. Dehmelt, J. Appl. Phys. 46, 919 (1975).

The Penning trap





Motion of the confined particle:



Cyclotron frequency:

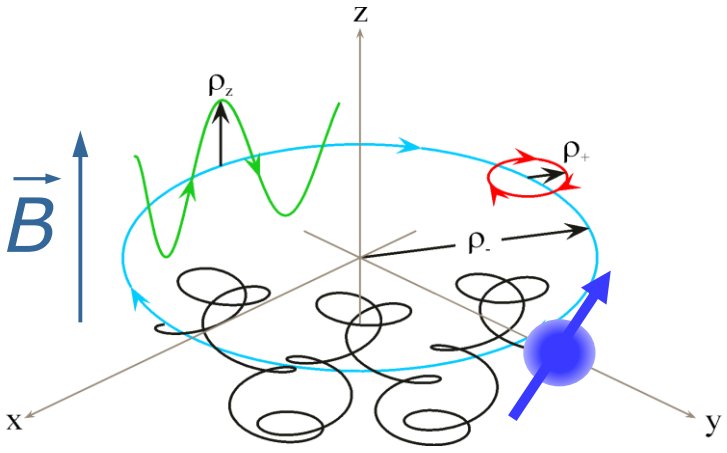
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}\cdot B$$

Invariance Theorem:

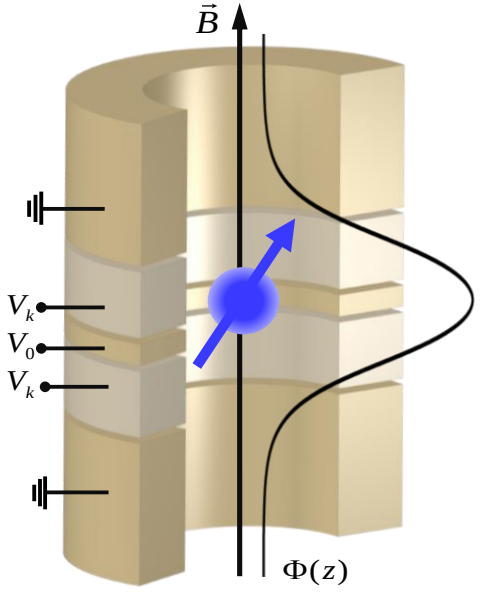
$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$

The cyclotron frequency can be determined by measuring the three particle eigenfrequencies

A quantum picture of a single trapped antiproton



$$\langle H_0 \rangle = -\vec{\mu} \cdot \vec{B} + h\nu_+(n_+ + {}^1/_2) + h\nu_z(n_z + {}^1/_2) - h\nu_-(n_- + {}^1/_2)$$



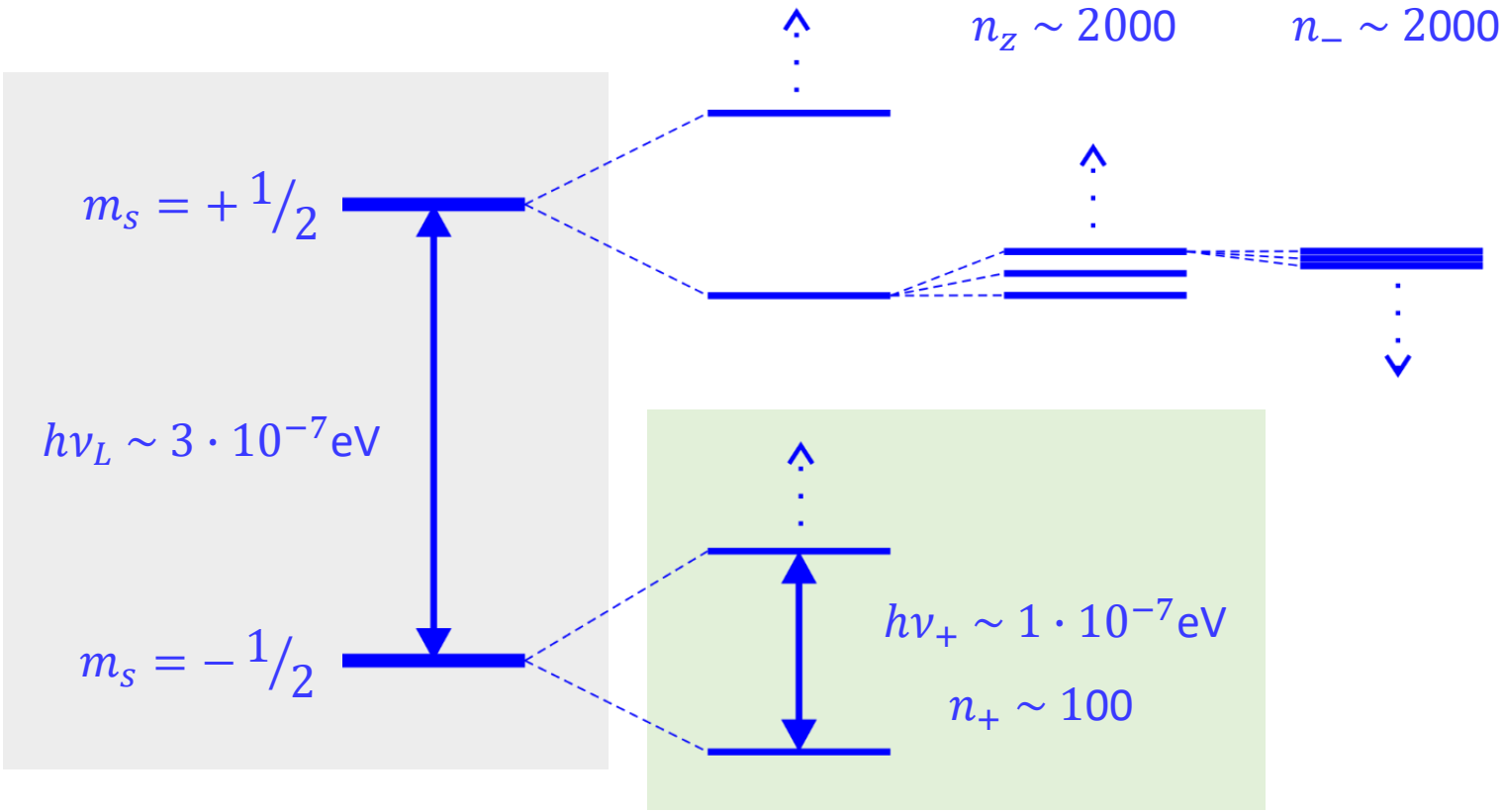


Image-current detection

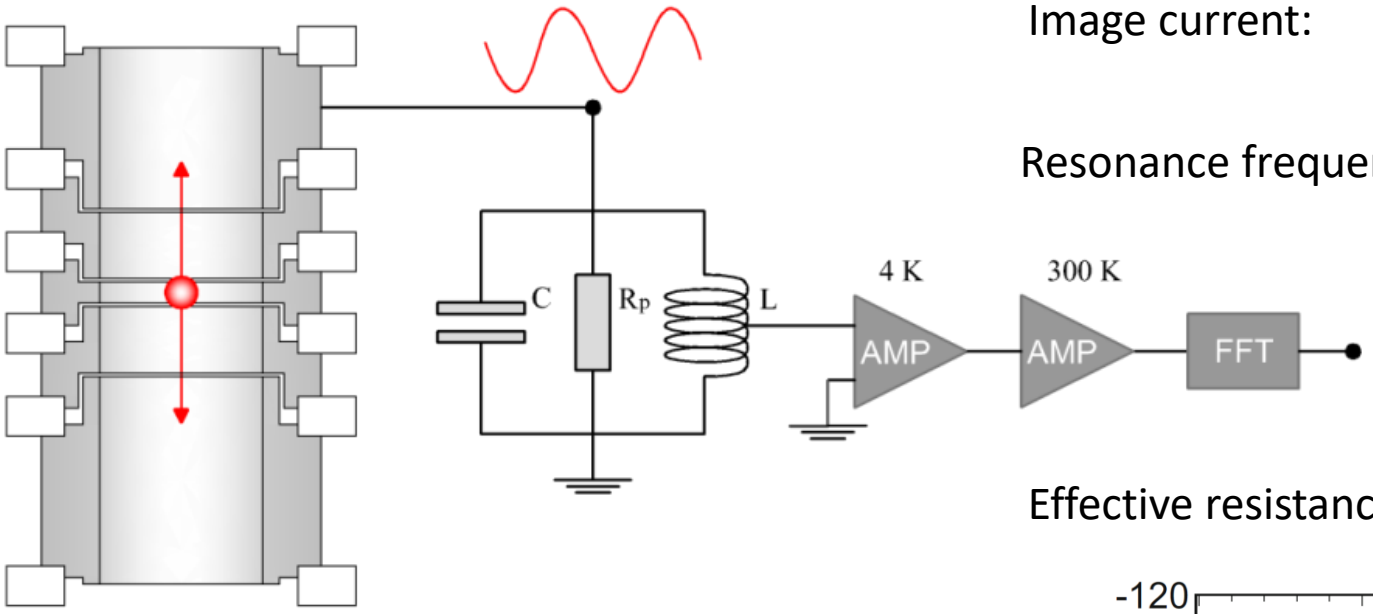
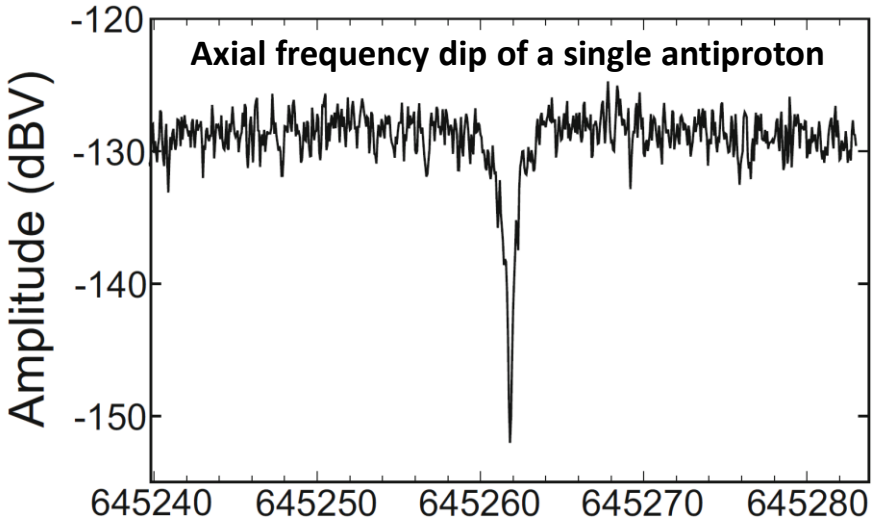


Image current: $I_p = \omega\, q\, \frac{r}{D} \approx 1$ to 10 fA

Resonance frequency: $\omega_{res} = \frac{1}{\sqrt{L\,C}} \approx 2\pi\ 670$ kHz

Effective resistance: $R_p = \omega\, L\, Q \approx 800\ \mathrm{M\Omega}$



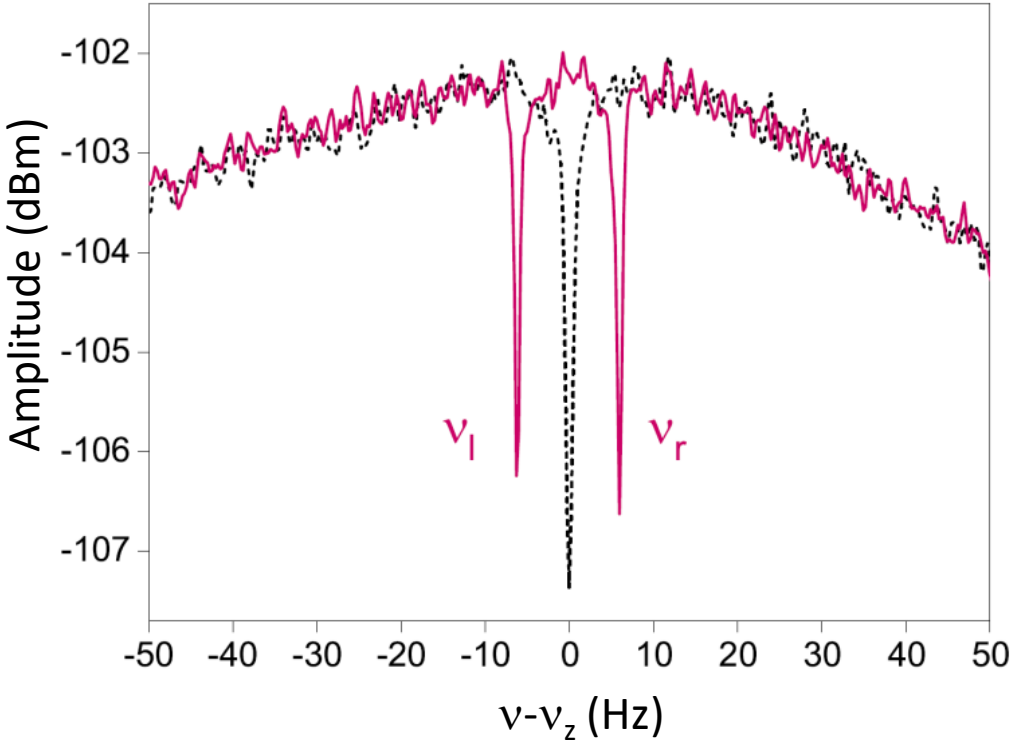
Consequences:

- **A signal at the eigenfrequency of the particle can be detected**
- **The particle dissipates energy and is resitively cooled**

D.J. Wineland, H.G Dehmelt, J. Appl. Phys. 46, 919 (1975).
C. Smorra et al., Eur. Phys. J. ST 224, 3055 (2015).

Detection of the radial frequencies

Sideband method:
A radiofrequency drive at $\nu_+ - \nu_z$ or $\nu_z + \nu_-$ couples two eigenmotions.
The amplitudes of the two states are periodically exchanged.



The magnetron frequency and the reduced cyclotron frequency can be measured by detecting ν_l, ν_r and ν_z

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

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

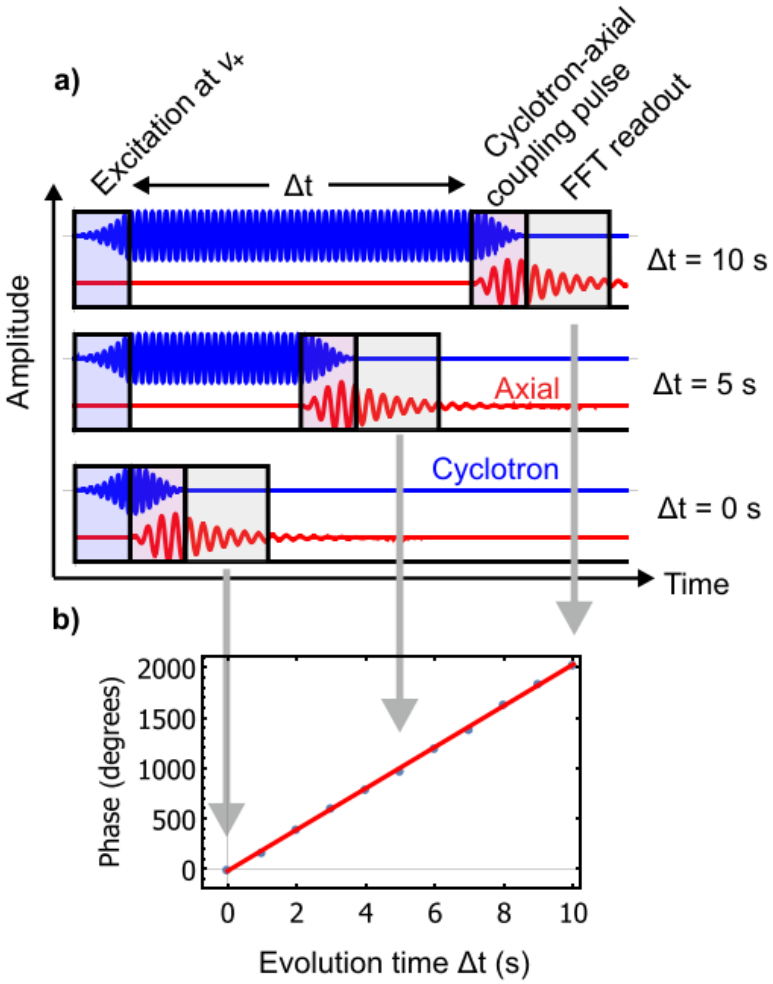
Using the invariance theorem

$$\boxed{\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2}$$

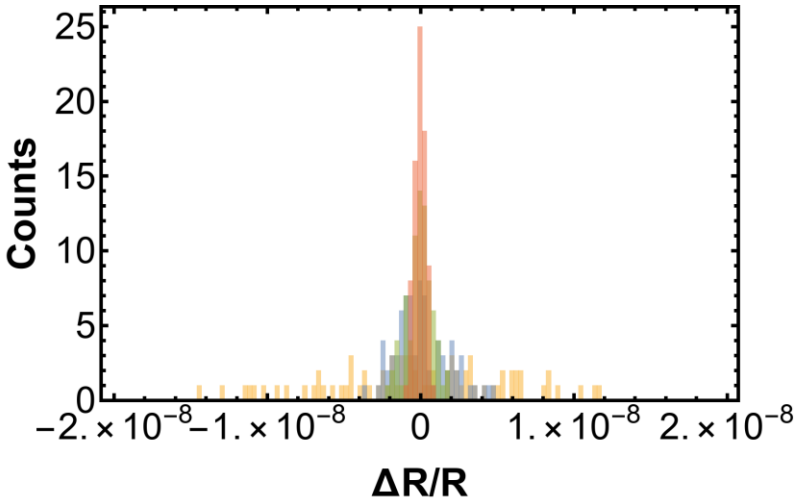
the free cyclotron frequency is derived.

Uncertainty limit: $\delta\nu_+ > \sqrt{3}\,\delta\nu_z$ → $\frac{\delta\nu_+}{\nu_+} \approx \frac{\sqrt{3}\ 30\ \text{mHz}}{30\ \text{MHz}} \approx 1.7\ 10^{-9}$

Implementation of Phase Sensitive Detection

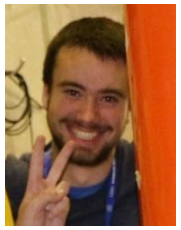


- Compared to dip method: Not limited by power supply noise
- Compared to peak method: Reduced systematics, reduced noise, faster measurement cycles.



2014 BASE Sideband
2019 BASE Sideband
2019 BASE Phase

J. Devlin
CERN/RIKEN

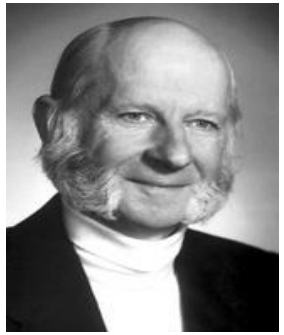


M. Borchert
Hannover/RIKEN

S. Ulmer
RIKEN

Reached in the best cases frequency scatters on the order of 330 p.p.t. per shot

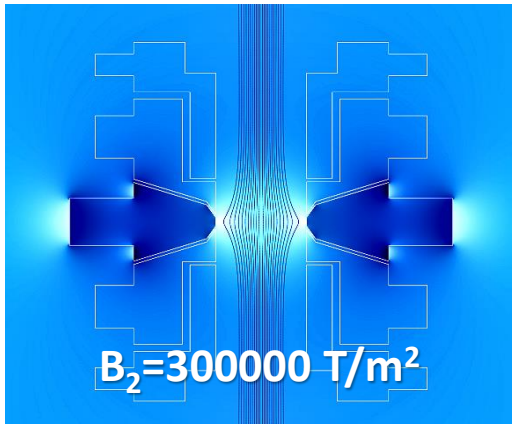
Larmor Frequency measurement



Measurement based on continuous Stern Gerlach effect.

Magnetic potential: $\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$

Harmonic force generated by a magnetic bottle: $B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$



Axial frequency becomes function of spin state

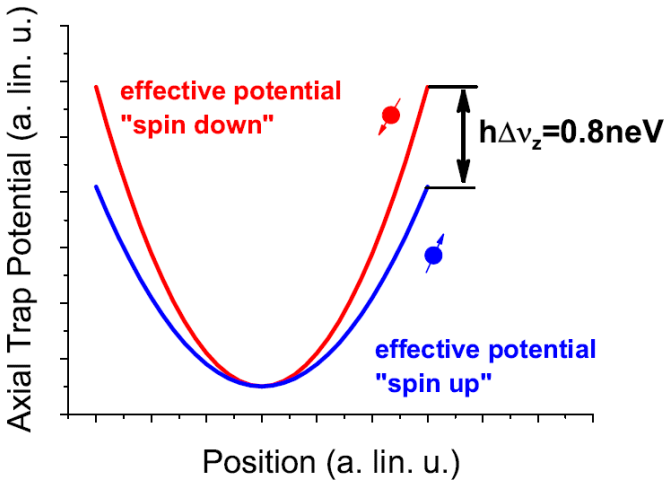
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

$$B_2 \sim 300000\ T/m^2$$

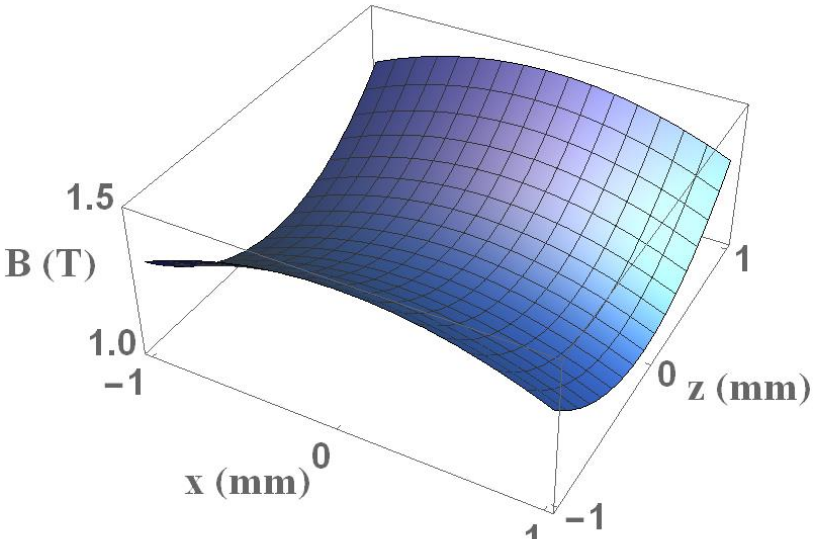
- Most extreme magnetic conditions ever applied to single particle.

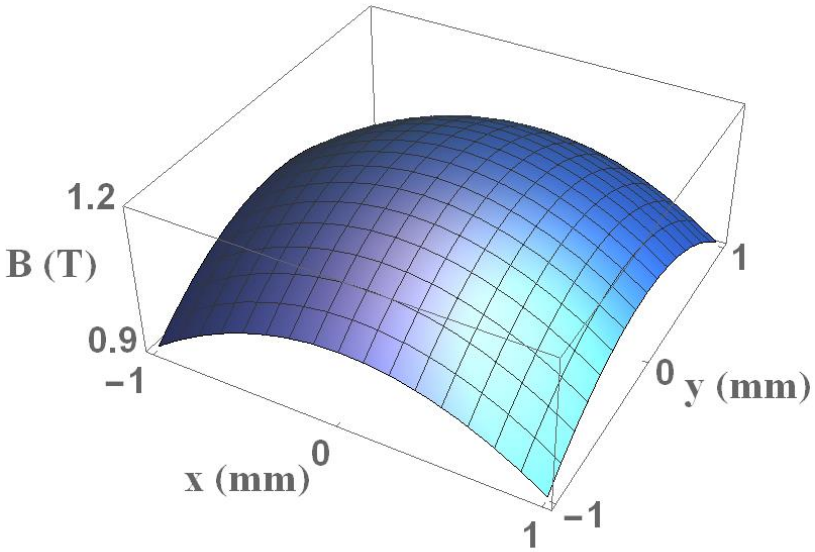
$$\Delta\nu_z \sim 170\ mHz$$



Observe driven spin transitions -> Measurement of Larmor resonance

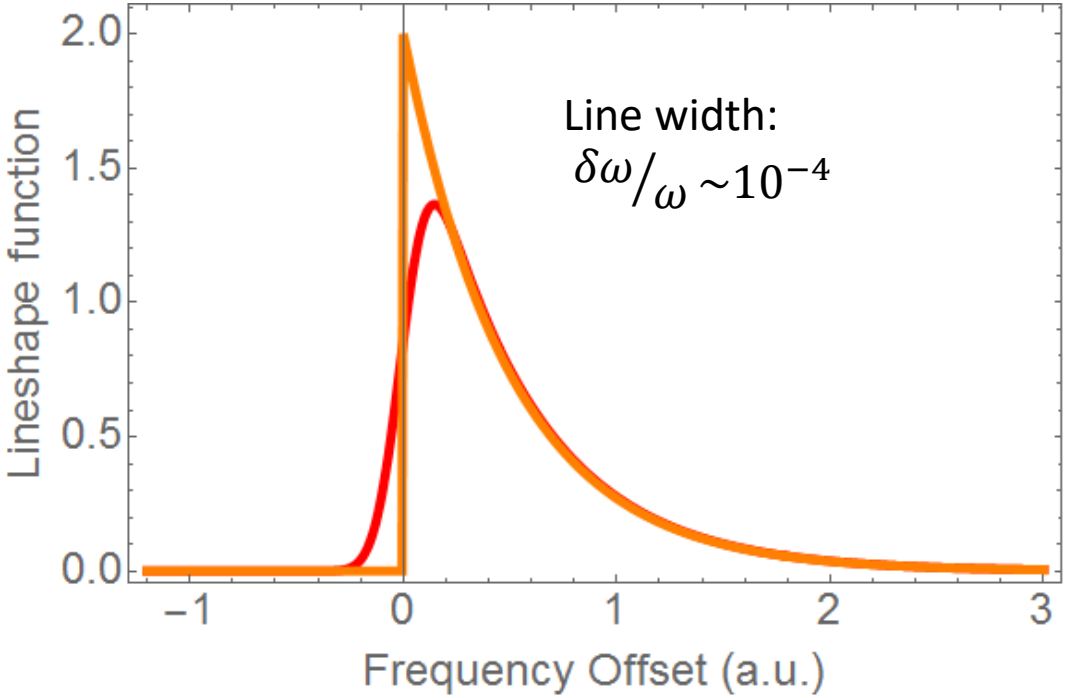
Measurements in the magnetic bottle





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

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



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

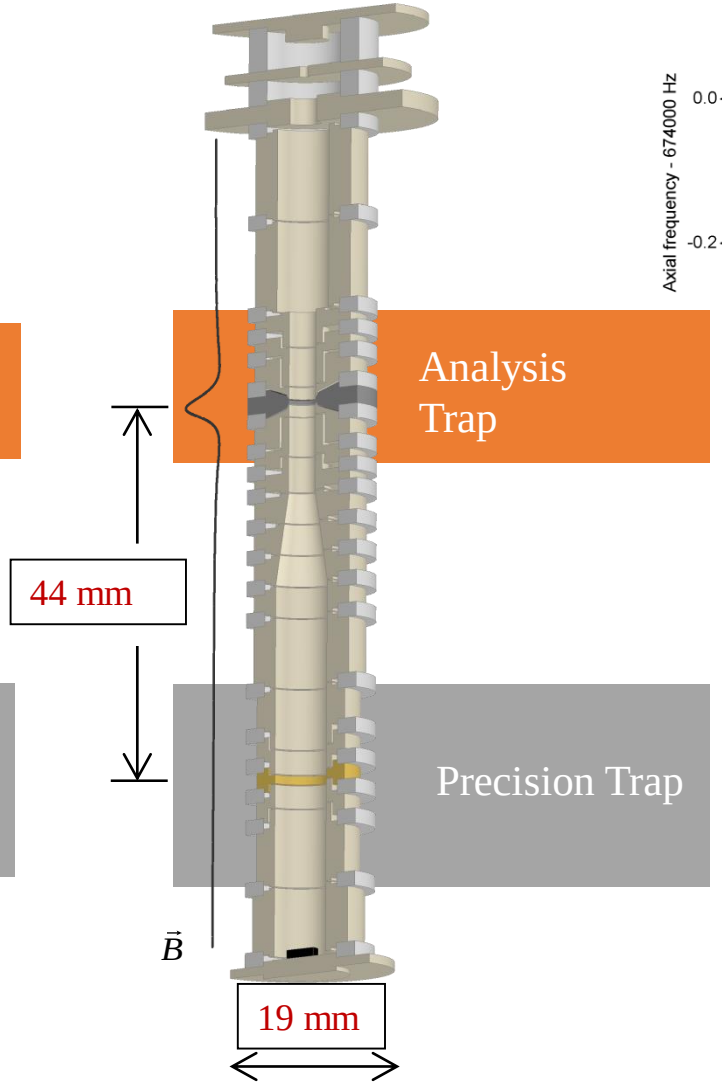
In the magnetic bottle:
Measurement limits at the 10^{-6} level

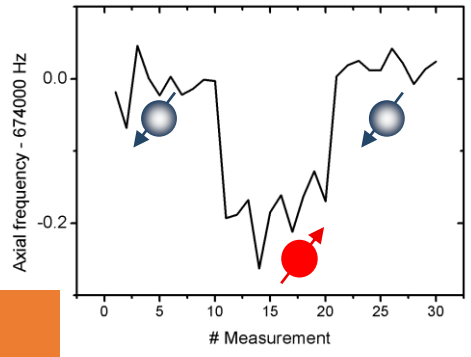
Divide and Conquer - Double Trap Method

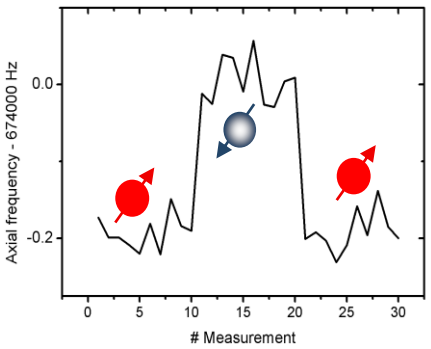
Idea: Separate spin state analysis and precision frequency measurements.

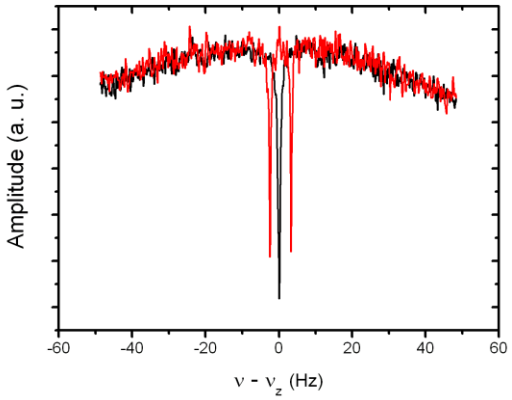
B_2 = 300000 T/m^2
T_+ < 0.2 K

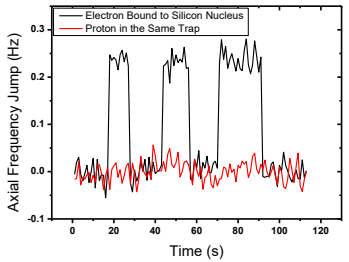
B_2 = 3.5 T/m^2
T_+ = 300 K
$\Delta\nu_z/\nu_c = 5 \times 10^{-9}$











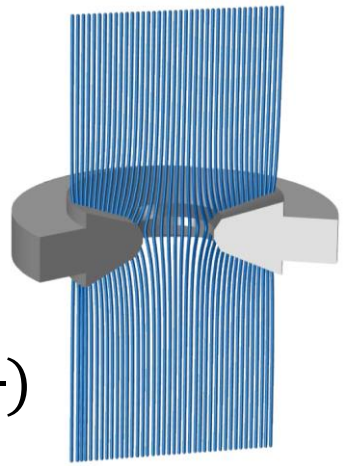
Requires clear identification of the spin state

H. Häffner et al., Phys. Rev. Lett. 85, 5308 (2000).
A. Mooser et al., Phys. Lett. B 723, 78–81 (2013).

Spin-state readout in a magnetic bottle

$$\Phi_M = -(\vec{\mu_p} \cdot \vec{B})$$

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



The magnetic bottle couples also the magnetic moment to the radial motion to the axial frequency!

$$\frac{\Delta\nu_z}{\nu_z} = \frac{1}{4\pi\, m_p\, \nu_z^2}\frac{B_2}{B_0}\left[\underbrace{h\nu_+\left(n_+ + \frac{1}{2}\right) + h\nu_-\left(n_- + \frac{1}{2}\right)}_{\text{orbital angular momentum}} + \underbrace{\frac{g}{2}h\nu_c n_S}_{\text{spin angular momentum}}\right]$$

Measurement needs to be done at constant n_+, n_-!

$$\frac{dn_{+,-}}{dt} \sim \frac{q^2}{2\, m_p\, h\, \nu_{+,-}}\, n_{+,-}\, \Lambda^2 \langle e_n(t), e_n(t-\tau)\rangle$$

Energy in the mode

Electric field noise density

Single antiproton spin-transitions

Physics Letters B 769 (2017) 1–6

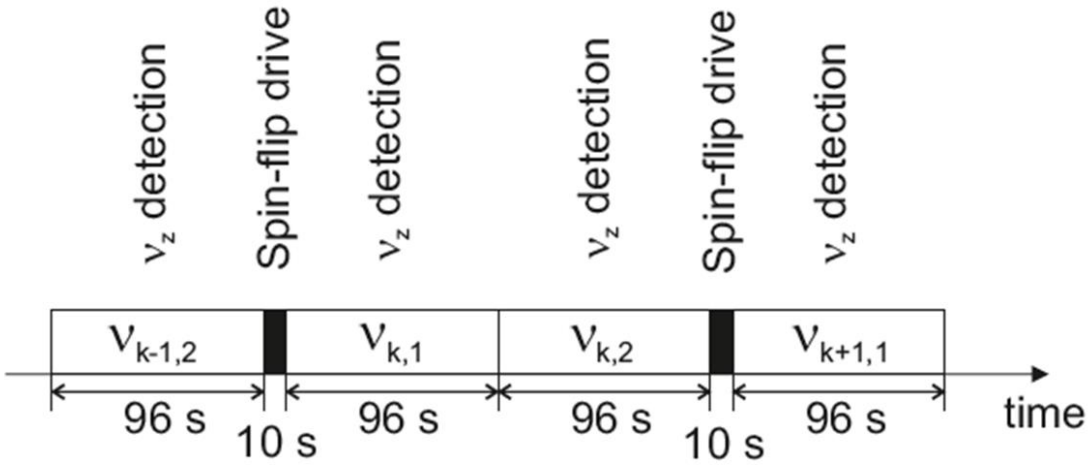
Contents lists available at ScienceDirect

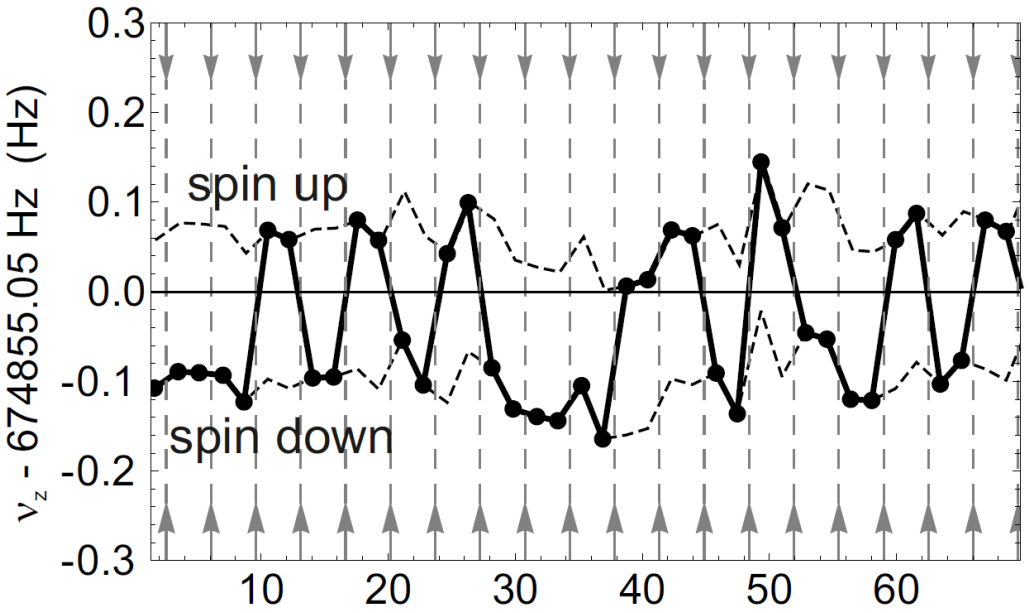
Physics Letters B

www.elsevier.com/locate/physletb

Observation of individual spin quantum transitions of a single antiproton

- **Single spin transitions can be identified with a high fidelity > 92 %**
- **Enables high-precision measurements of the antiproton g-factor with multi-trap methods**
  - **Larmor resonance spectroscopy in a homogeneous magnetic field**
  - **Spin-state identification in an inhomogeneous magnetic field**

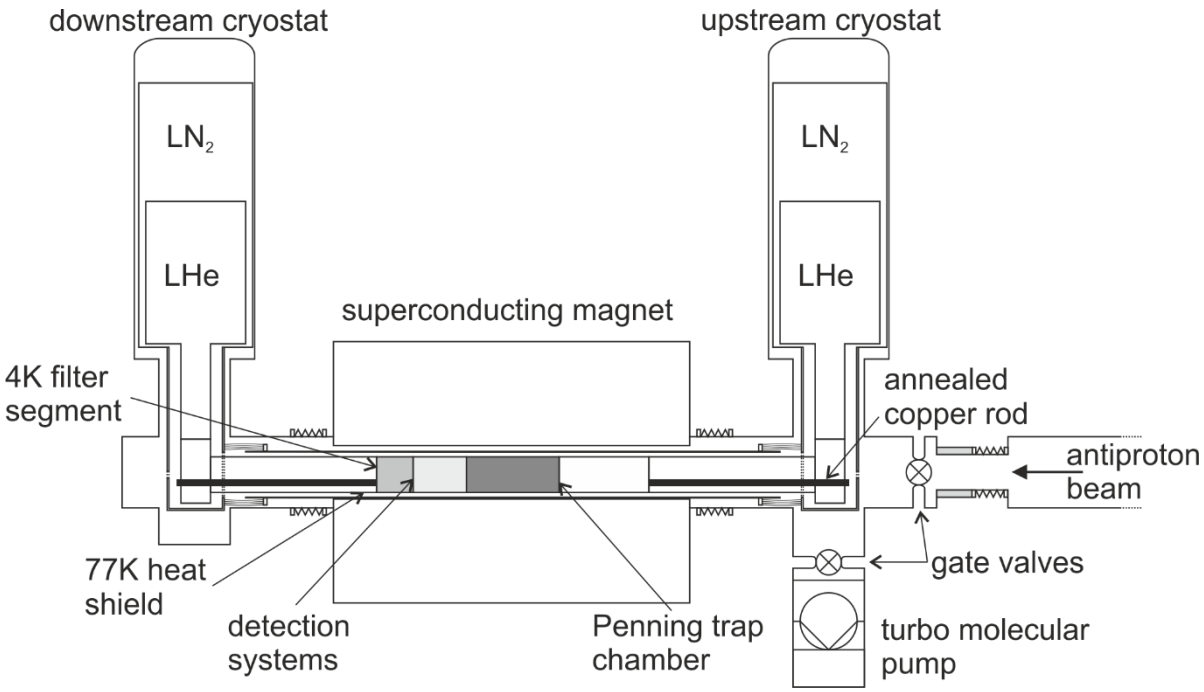


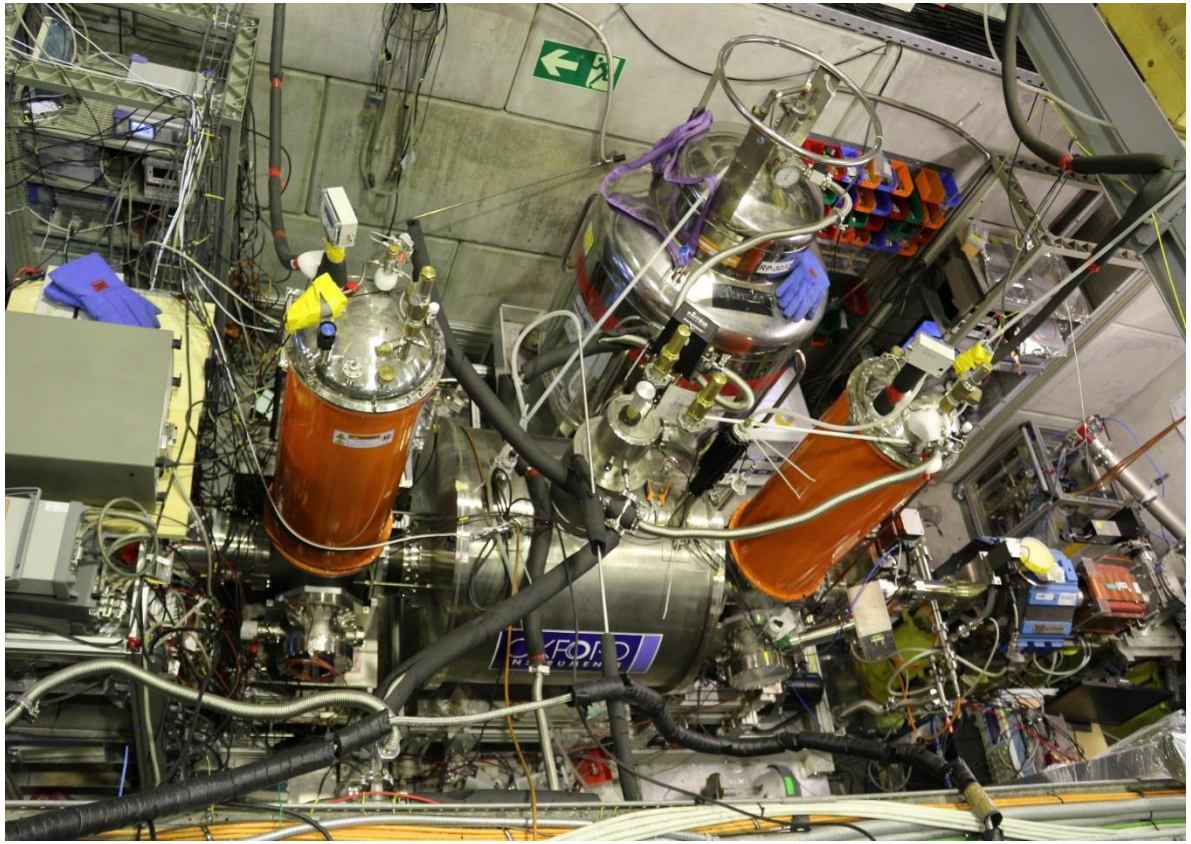


C. Smorra et al., Phys. Lett. B **769**, 1-6 (2017).

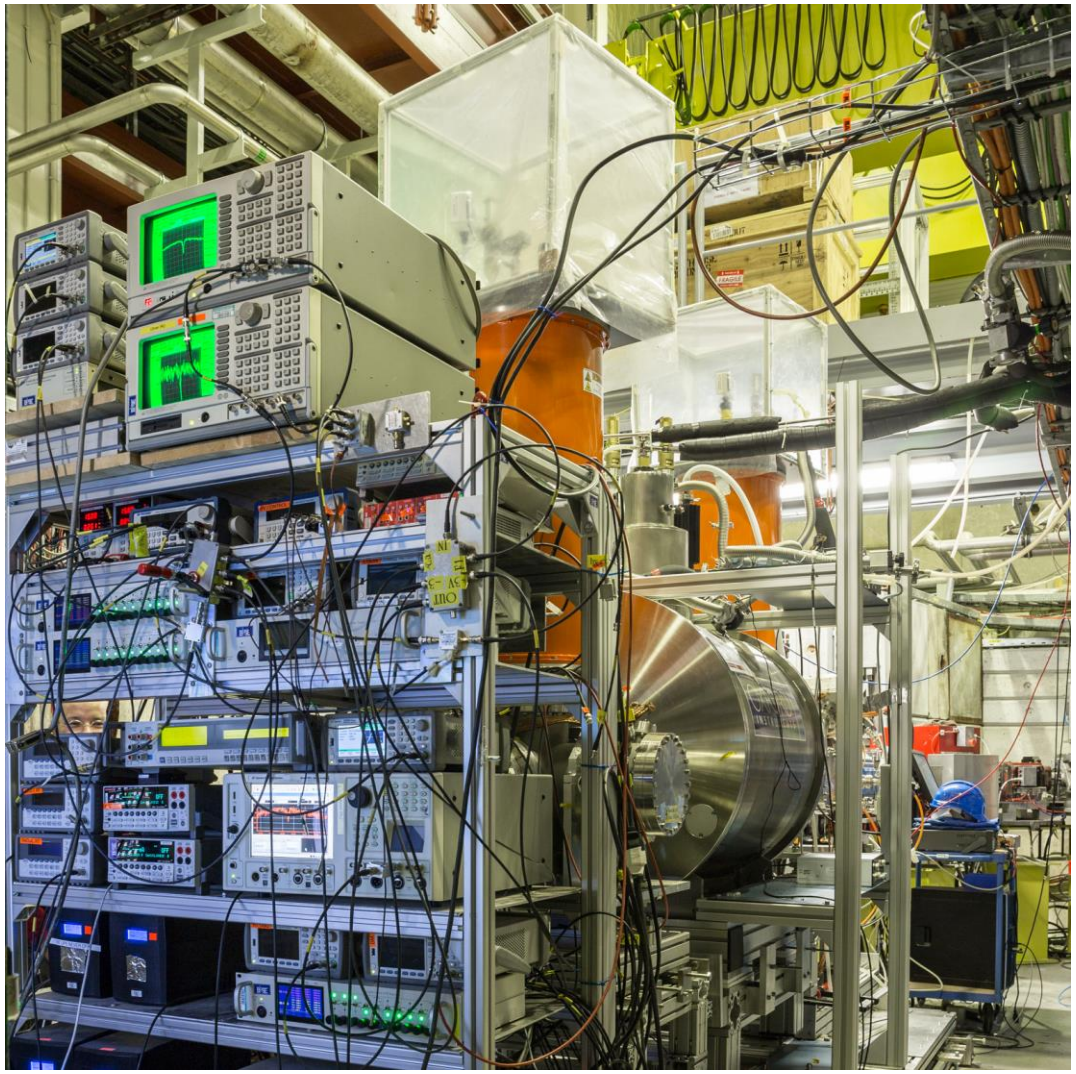
4. The BASE Experiment

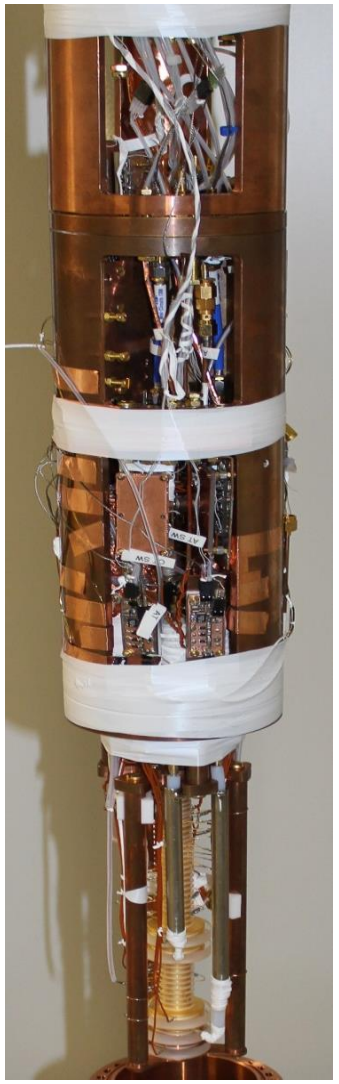
The BASE Apparatus at CERN

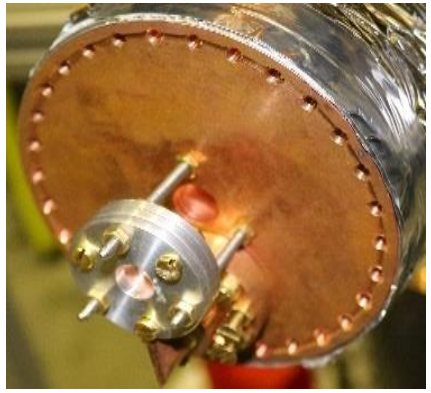


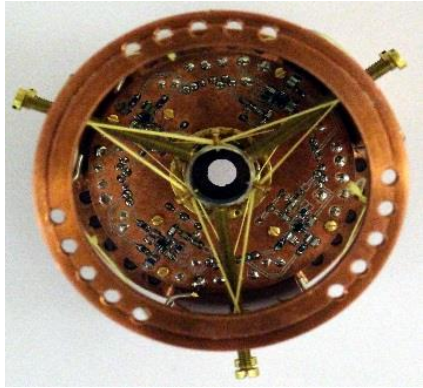


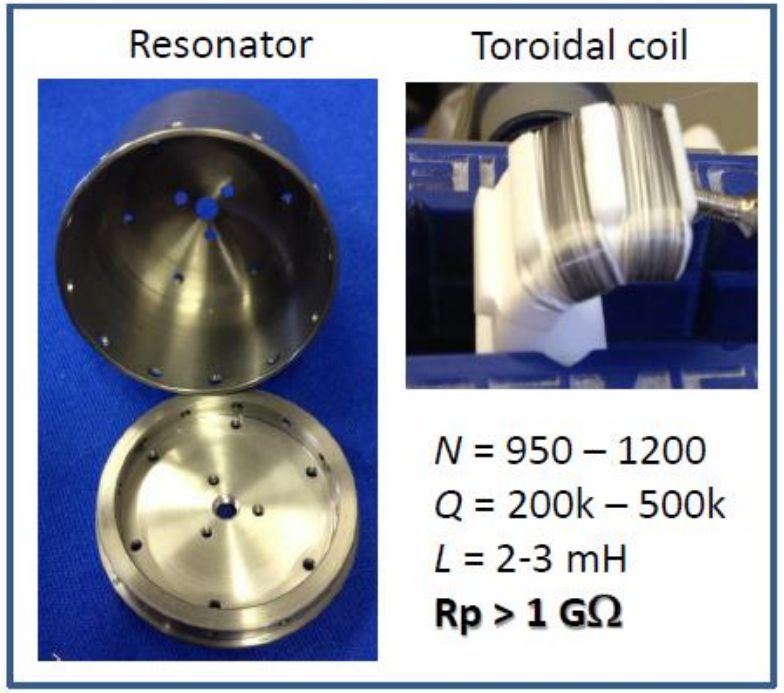
The BASE experiment





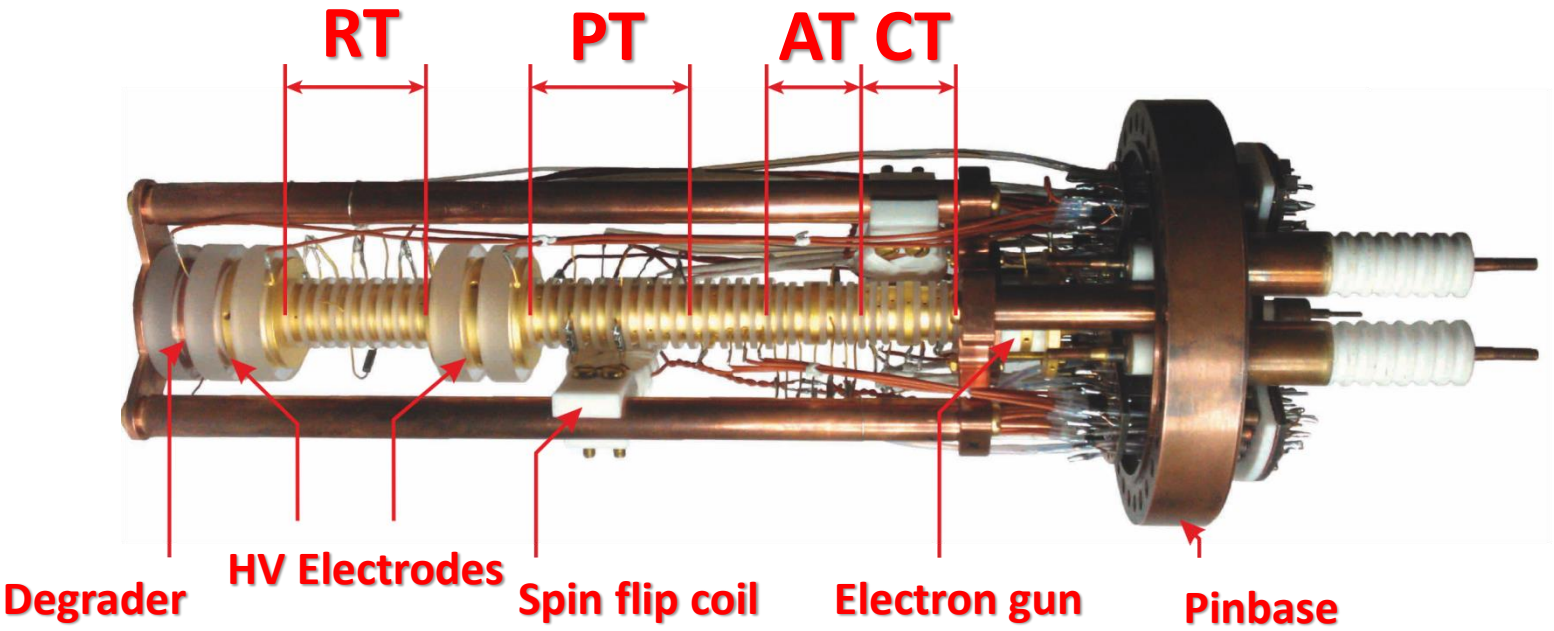






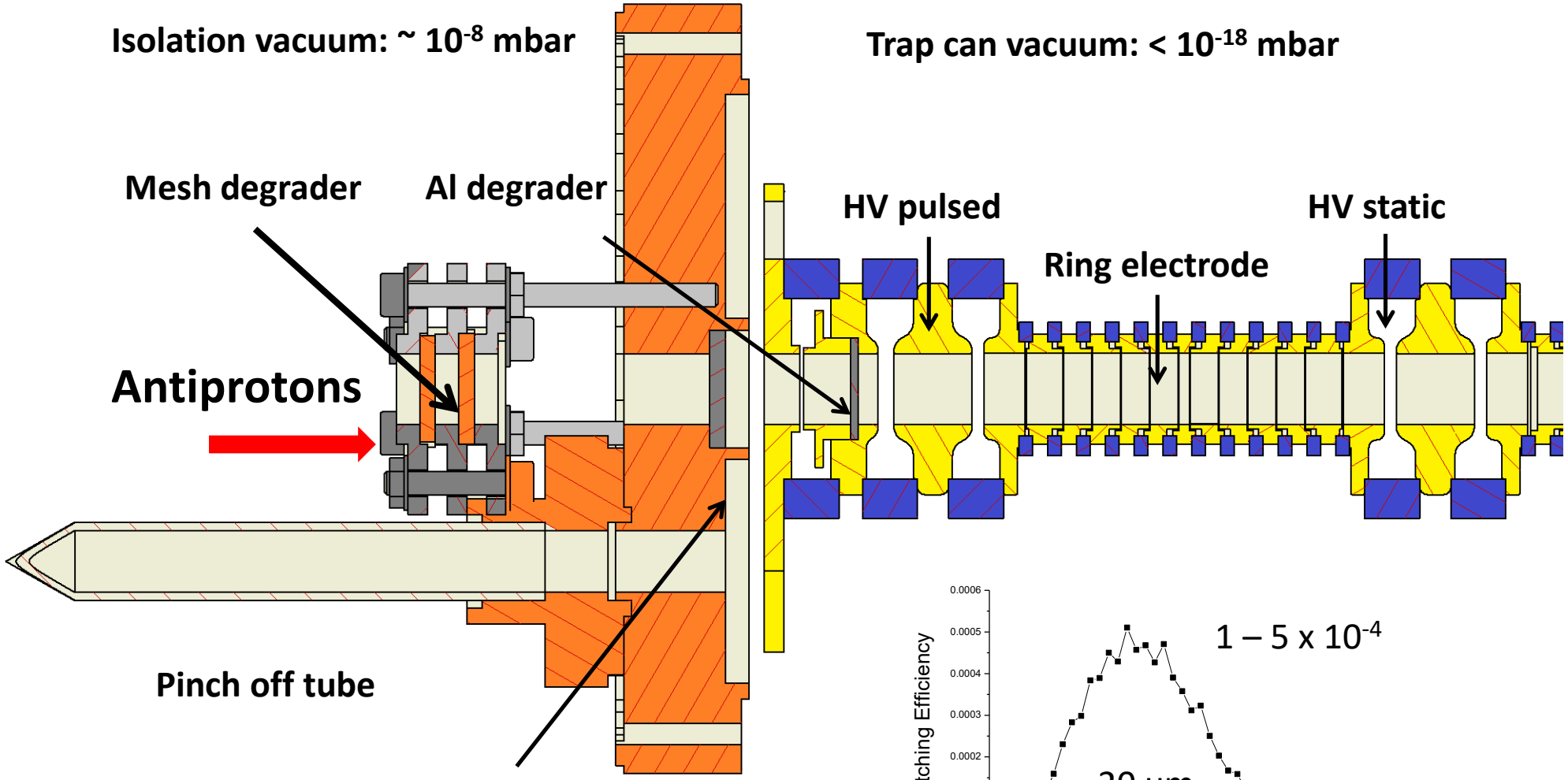
H. Nagahama et al., Rev. Sci. Instr. 87, 113305, (2016).

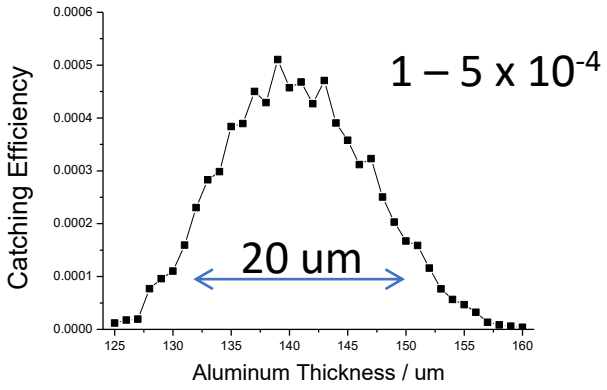
The BASE four Penning-trap system



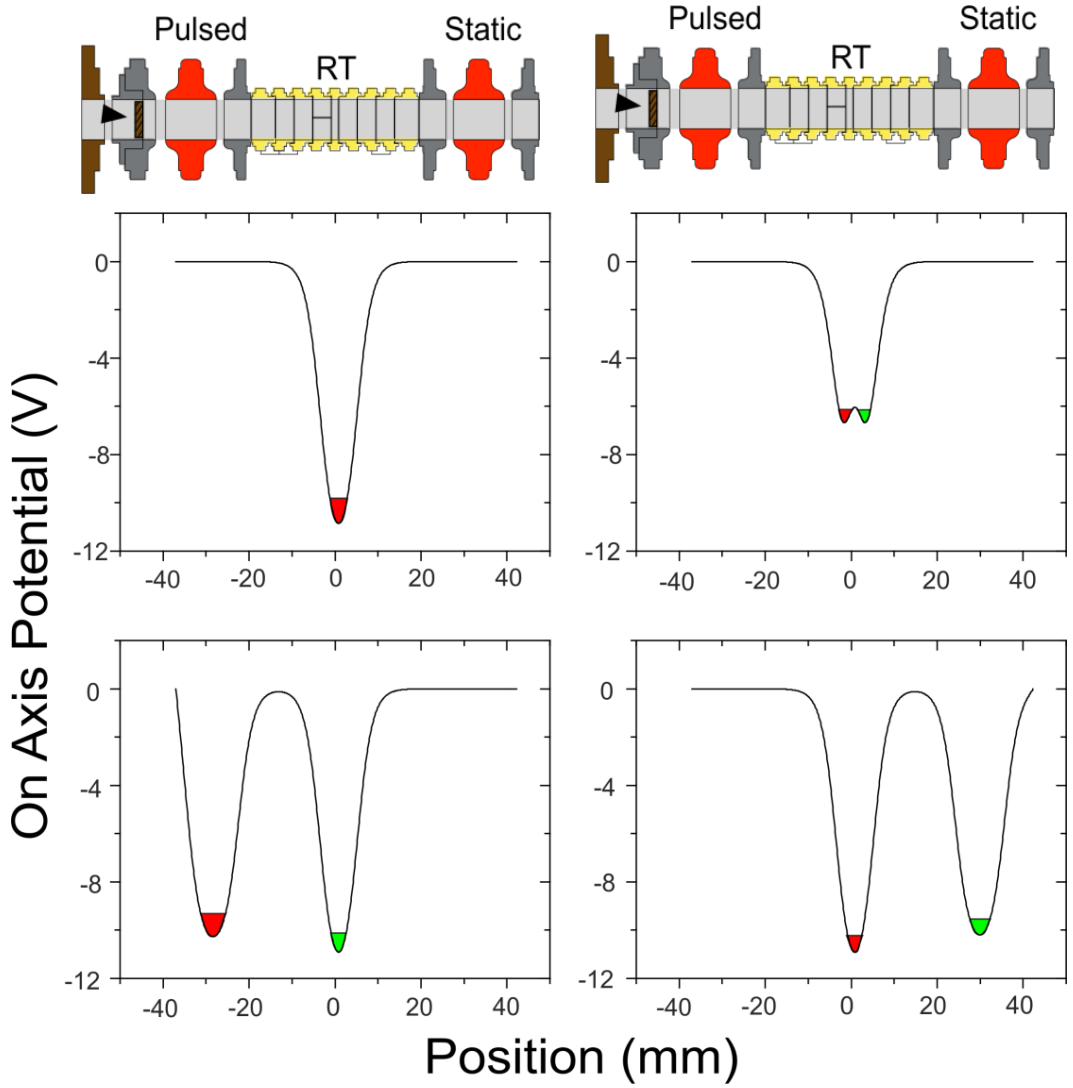
Catching / Reservoir Trap: Catching, cooling and storing of antiprotons
Precision Trap: Homogeneous field for frequency measurements
Cooling Trap: Fast cooling of the cyclotron motion
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, B_2 = 30 T / cm^2

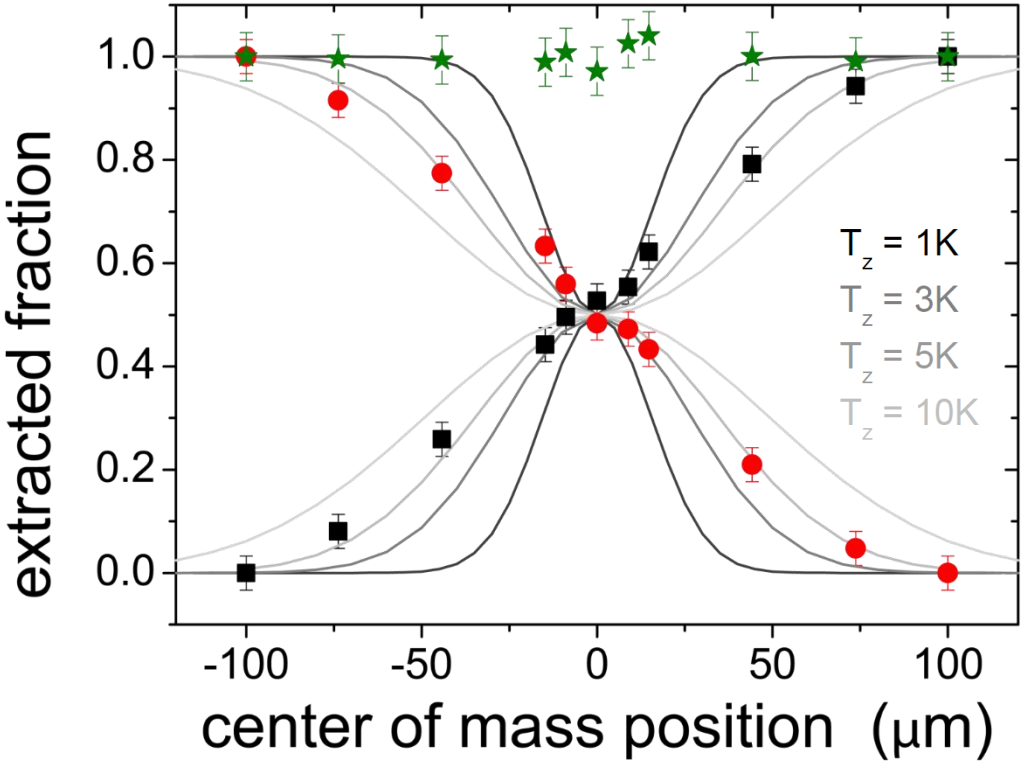
Deceleration from 5.3 MeV to 0.5 meV





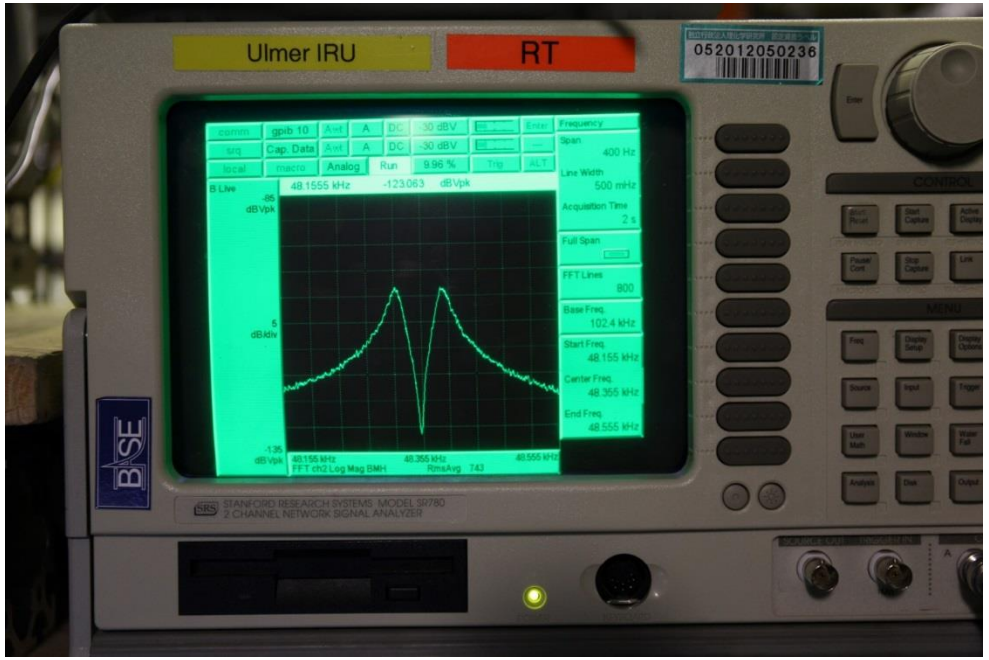
Non-destructive extraction: Separate and Merge

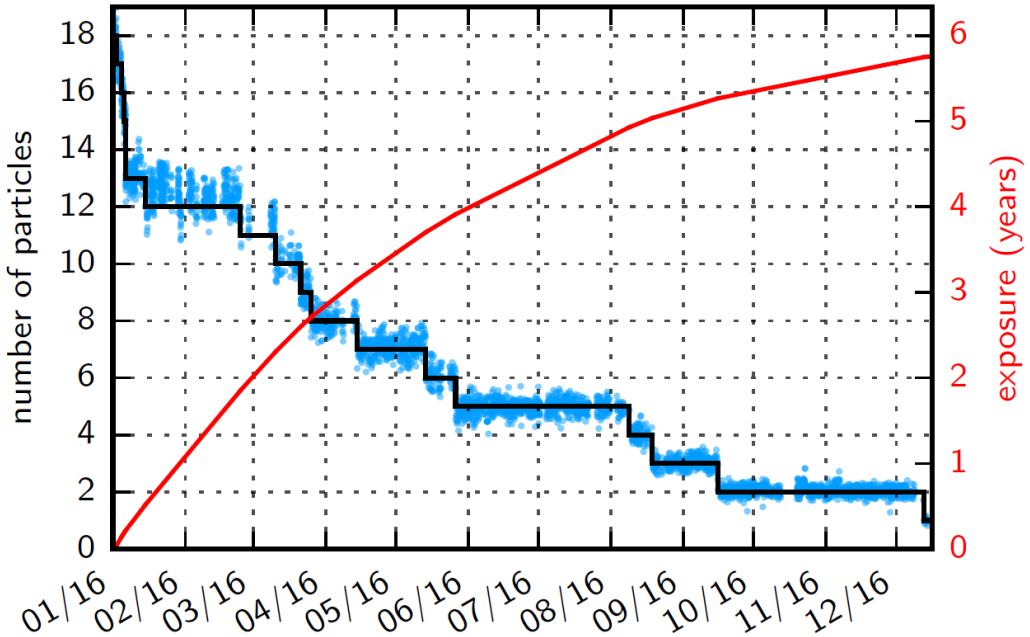




Reservoir trap performance in 2016

Antiprotons stored from 03.11.2015 – 22.12.2016



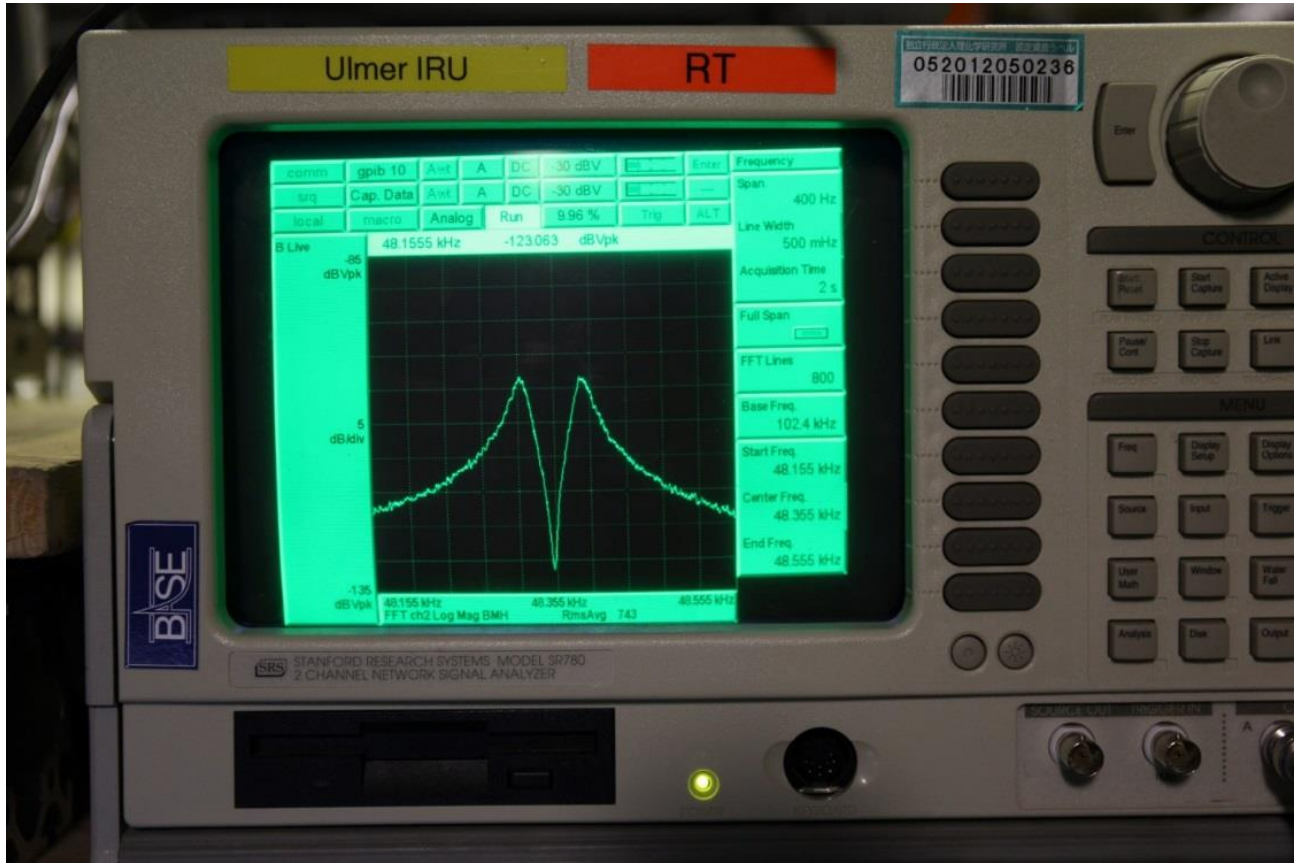


- Storage of antiprotons for more than one year: **405.5 days**
- Extraction of single particles by a potential tweezer scheme

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

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

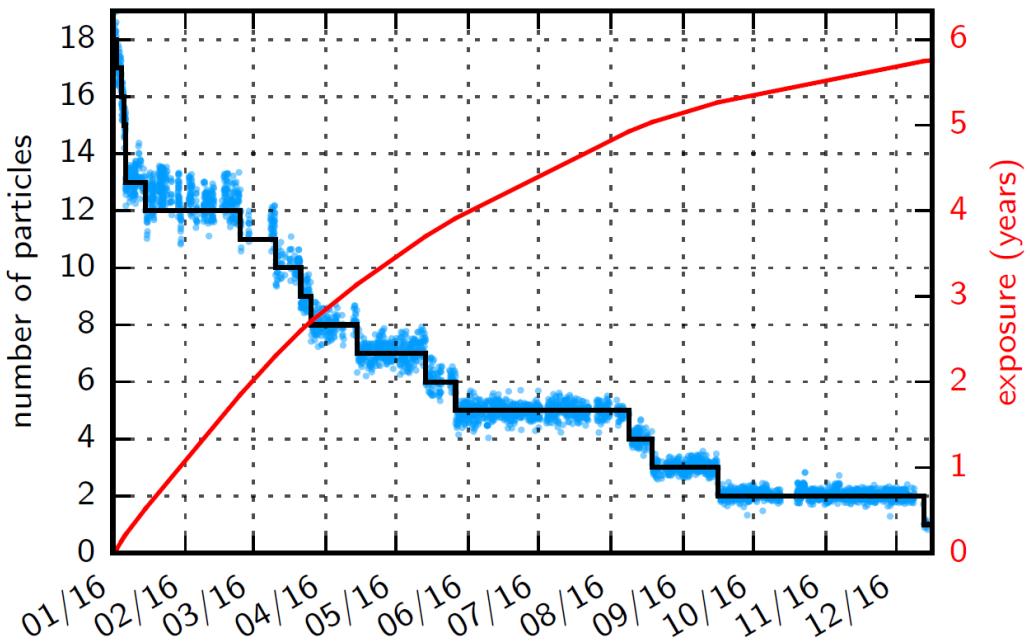


4.1. Antiproton lifetime limits

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).

Proton/Antiproton lifetime limits

- Proton lifetime limits:

Disappearance signals in ^{16}O: $\tau > 2.1\ 10^{29}$ years

Decay channels: $\tau/B(p \to e^+\pi^0) > 1.6\ 10^{34}$ years

S. N. Ahmed et al. (SNO collaboration), Phys. Rev. Lett. 92 (2004).
K. Abe et al. (Super-Kamiokande collaboration), Phys. Rev. D 95, 012004 (2017).

- Antiproton lifetime limits:

Astrophysical limits: $\tau > \sim 10^6$ years

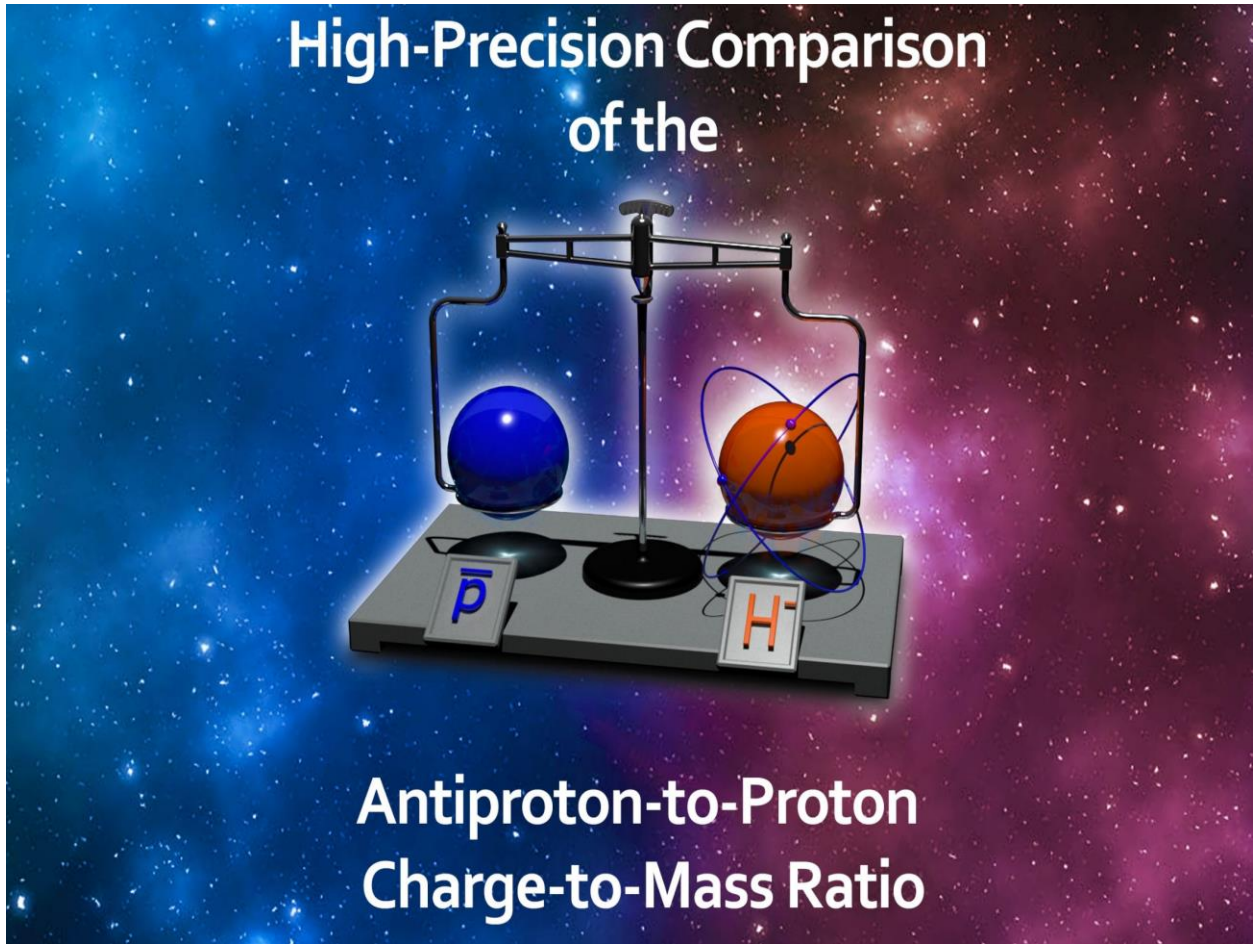
APEX collaboration (Fermilab): $\tau/B(p \to e^- + X) \sim 2{\cdot}10^2 - 7{\cdot}10^5$ years

$\tau/B(p \to \mu^- + X) \sim 7{\cdot}10^3 - 5{\cdot}10^4$ years

Storage rings / TRAP collaboration: $\tau > 0.28$ years

Penning trap / BASE collaboration: $\tau_{\bar{p}} > 10.2$ y (68% C.L.)

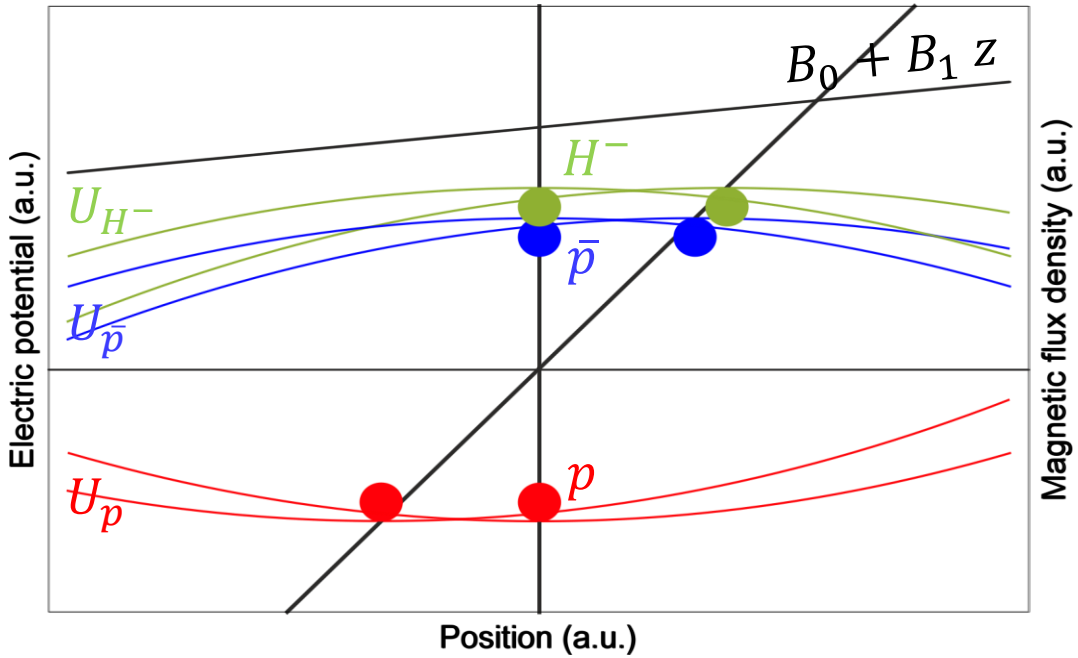
S. H. Geer and D. C. Kennedy, Astrophys. J. 532, 648-652 (2000).
S. H. Geer et al. (APEX collaboration), Phys. Rev. Lett. 84, 590 (2000).
G. Gabrielse et al. (TRAP collaboration), Phys. Rev. Lett. 65, 1317 (1990).

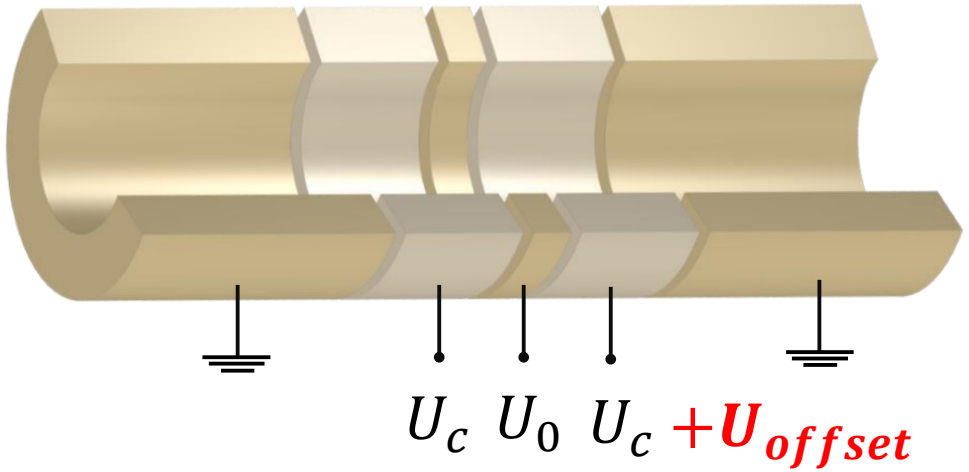


S. Ulmer, C. Smorra, A. Mooser et al., Nature 524, 196-200 (2015).

4.2 Charge-to-mass ratio comparison

Why not to use protons?





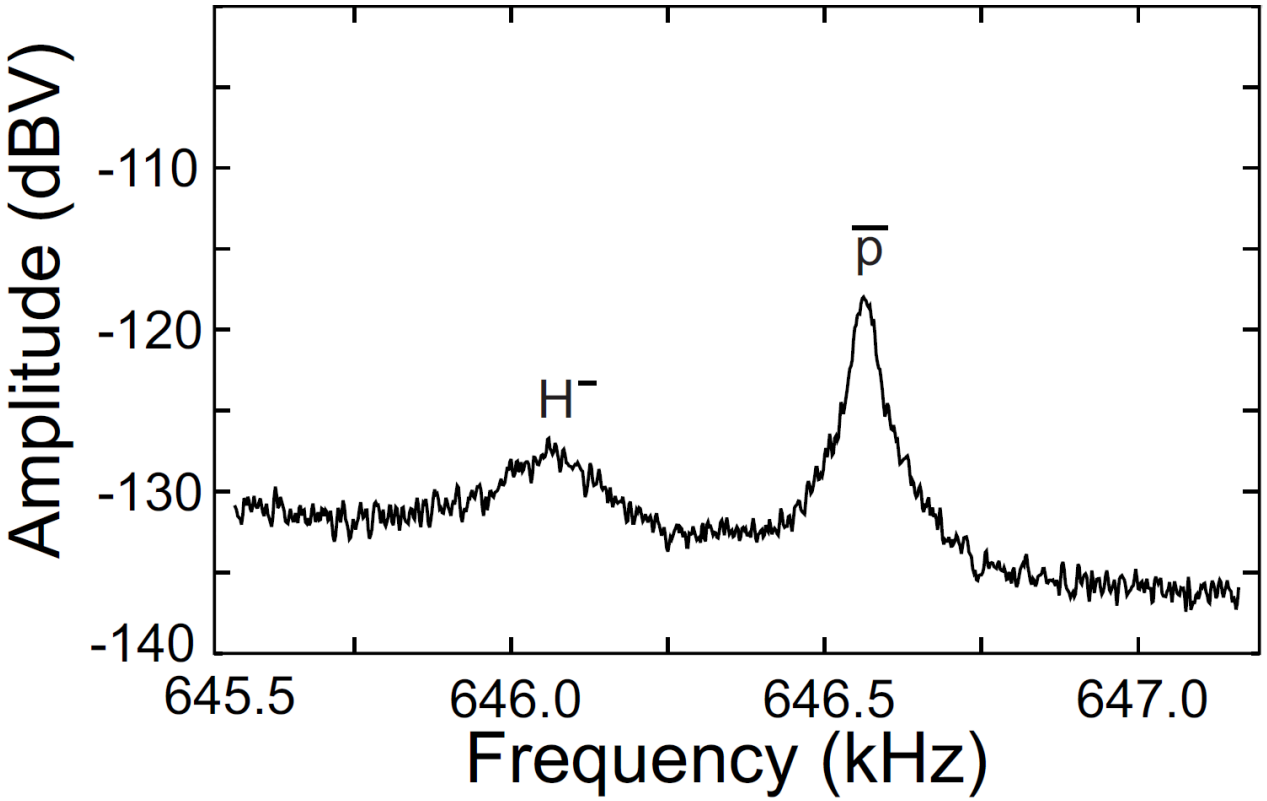
- Systematic uncertainties due to the particle position are large (~10^{-9})
- No significant uncertainties in converting the mass ratio

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

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

- Measure free cyclotron frequencies of antiproton and H^- ion.

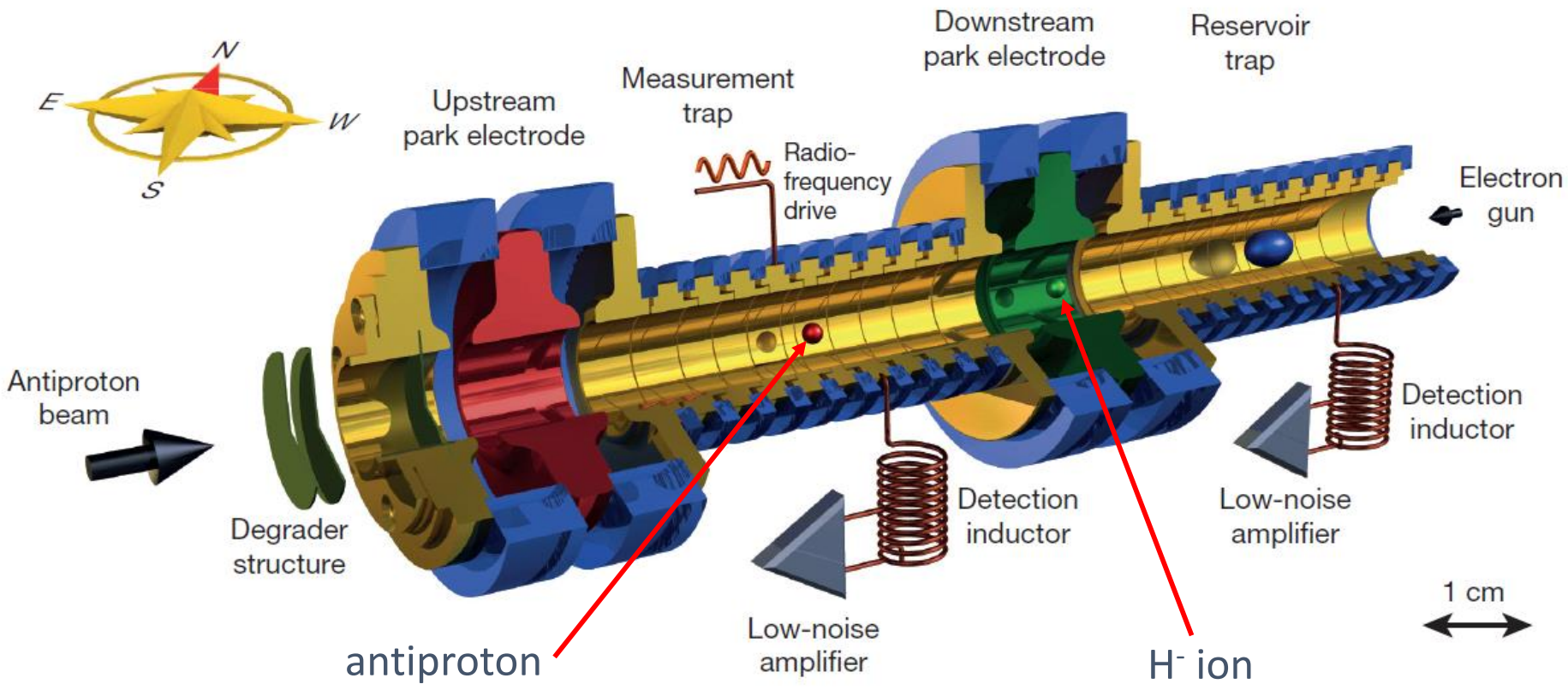
Loading antiprotons and H^- ions



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

Measurement configuration

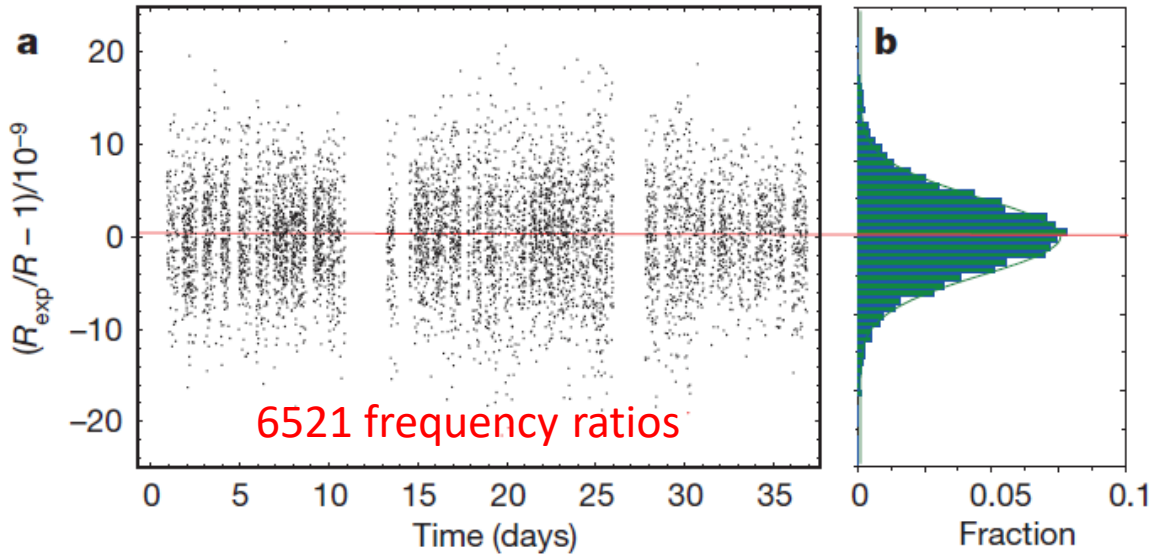
Based on reservoir extraction technique and developed methods to prepare negative hydrogen ions we prepared an interesting set of initial conditions



Comparison of H-/antiproton cyclotron frequencies:

One frequency ratio per 4 minutes with ~ 5 ppb uncertainty

Data analysis and result



Line-width limitation:
Random-walk noise
of the magnetic field: **5.5 ppb**

Major systematic limitation:
A displacement of 29 nm in the gradient of B_1 = 7.6 mT / m requires a correction of : **114(26) p.p.t.**

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

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

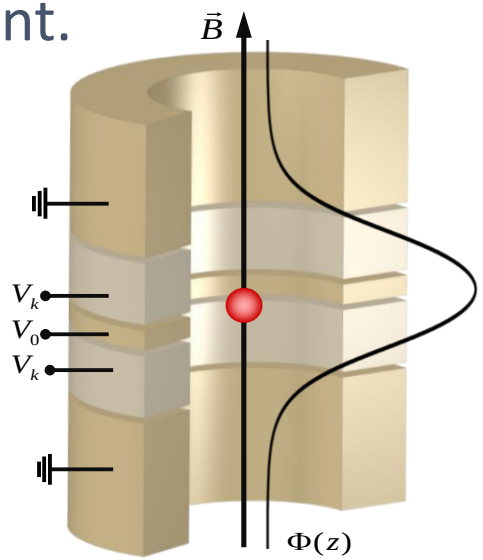
- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4.

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.



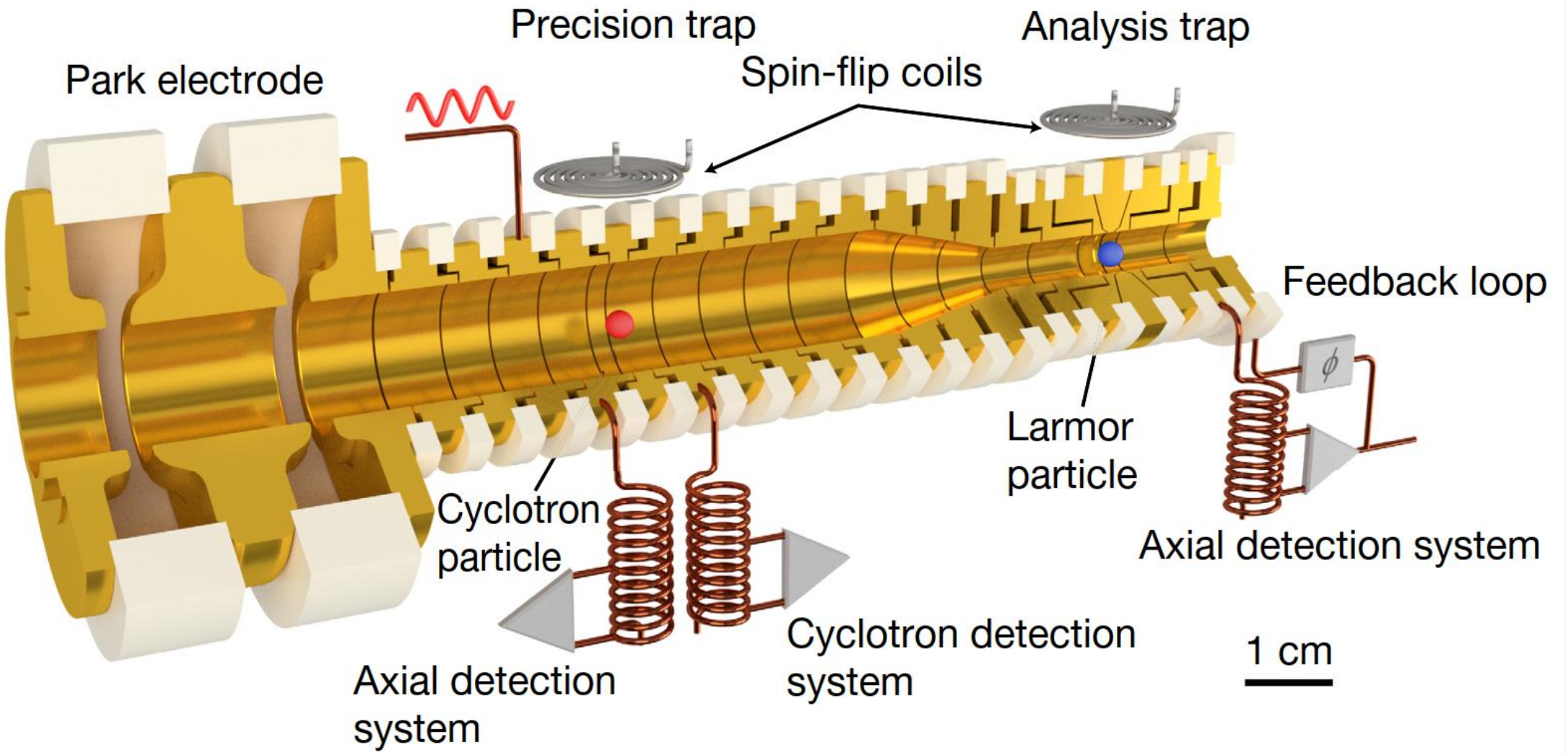
Final experimental result: **$R_{exp,c}$ = 1.001 089 218 755 (64) (26)**

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

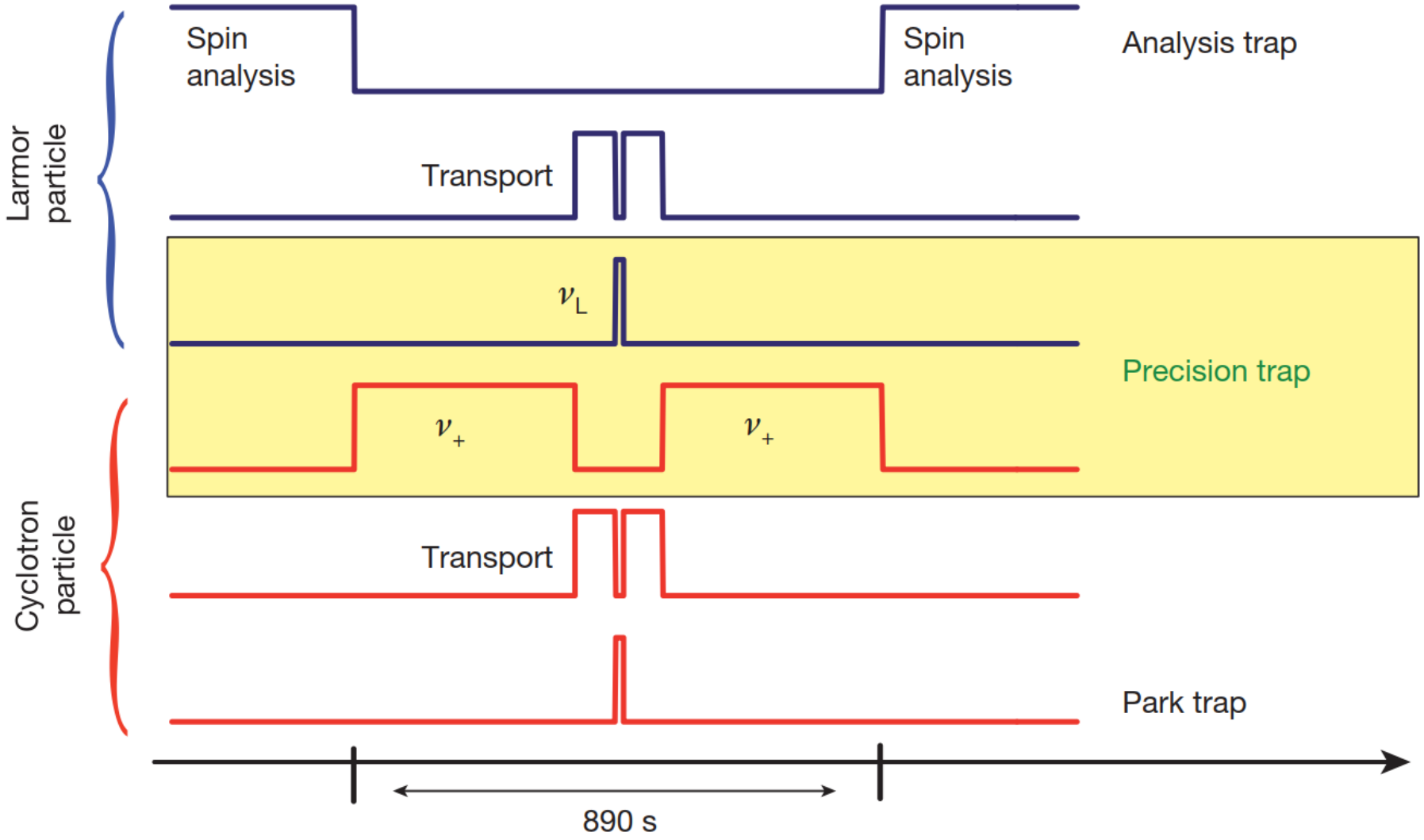
- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4.

4.3 Measuring the antiproton magnetic moment

Multi-trap measurement scheme



The measurement cycle



Why two particles?

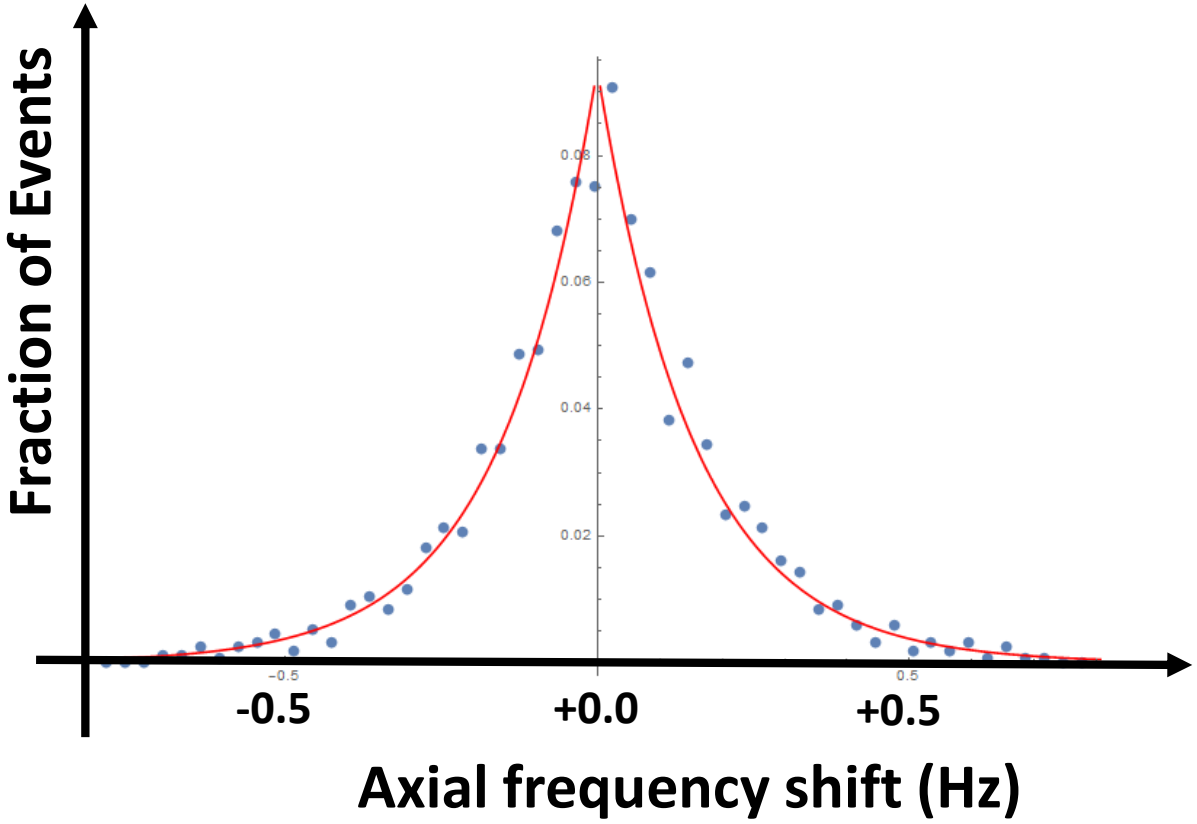
- Cyclotron frequency measurements heat the radial modes

- "Cooling limit" of the sideband method:

$$T_+ = \frac{\nu_+}{\nu_z} T_z$$

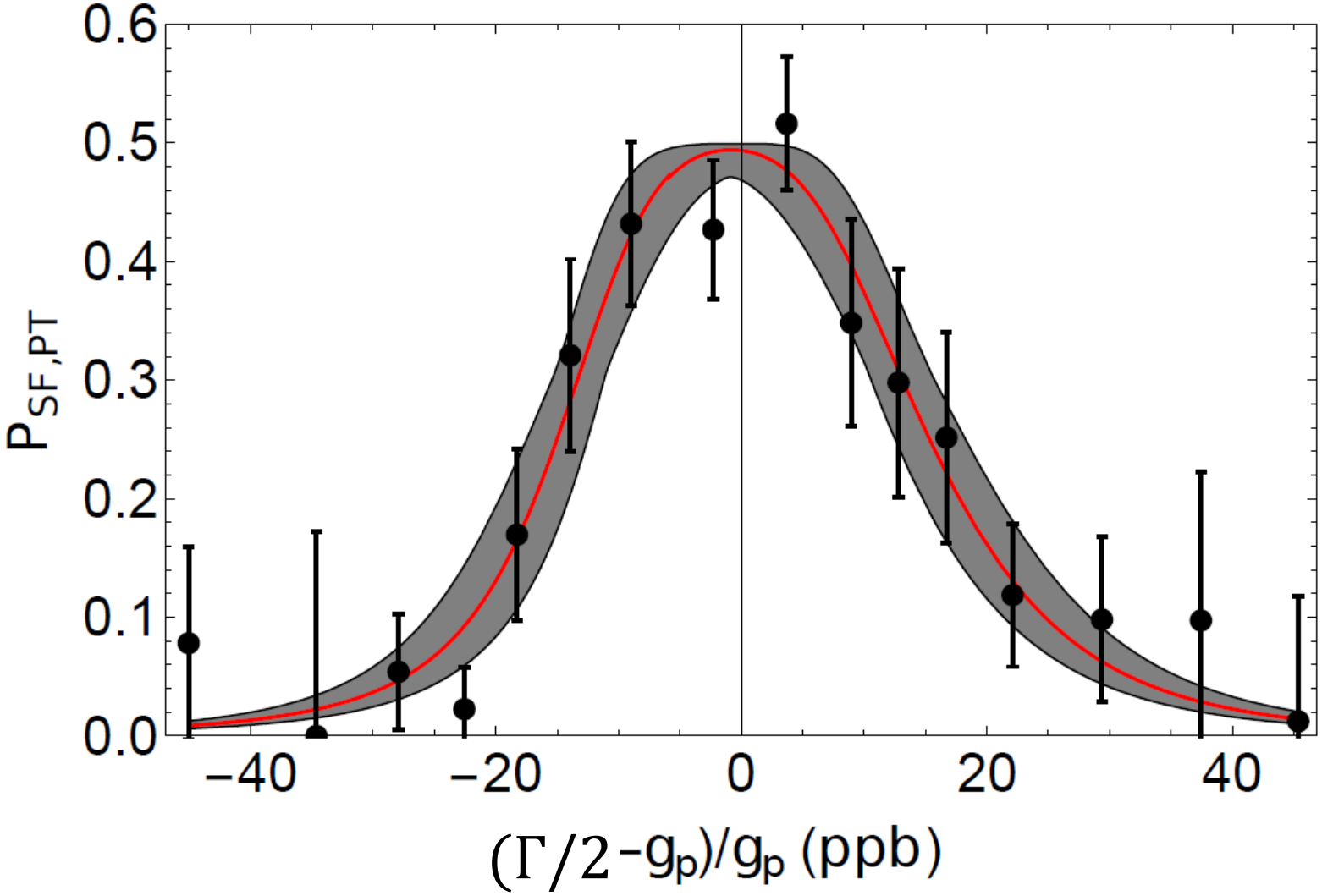
- From the observed shift distribution:
  $B_2 T_+ = 976(23)$T K m^{-2}

  $\Rightarrow T_+ \sim 356$ K, $B_{2,PT} \sim 2.7$ T m^{-2}



- Radial temperature is too hot to identify the spin state!
- A cooling cycle requires ~ 12 h to get a particle below 100 mK!

Result



Lineshape:

Incoherent Rabi resonance

- Boltzmann distribution of axial energy
- Drive saturation
- Magnetic field fluctuations
- Cyclotron frequency shift
  due to the sideband temperature limit

Likelihood analysis results in:

$$\frac{g_{\bar{p},exp}}{2} = 2.7928473455(36)$$

Systematics

Table 1 | Error budget of the antiproton magnetic moment measurement

Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)	
Image-charge shift	0.05	0.001	
Relativistic shift	0.03	0.003	
Magnetic gradient	0.22	0.020	Difference in radial energy
Magnetic bottle	0.12	0.009	
Trap potential	−0.01	0.001	
Voltage drift	0.04	0.020	
Contaminants	0.00	0.280	
Drive temperature	0.00	0.970	Difference in axial temperature
Spin-state analysis	0.00	0.130	
Total systematic shift	0.44	1.020	

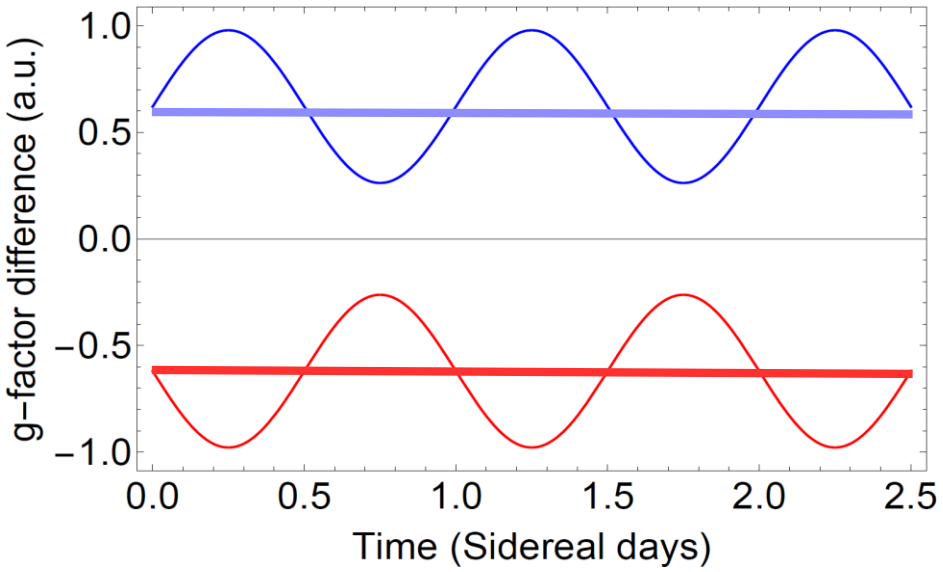
Placing the two antiprotons on similar trajectories during the frequency measurements is the limiting systematic effect

Solutions: More homogeneous magnetic field / improved axial temperature measurements

Limits on CPT-odd interactions from the g-factor difference

$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,3\,(46)$$

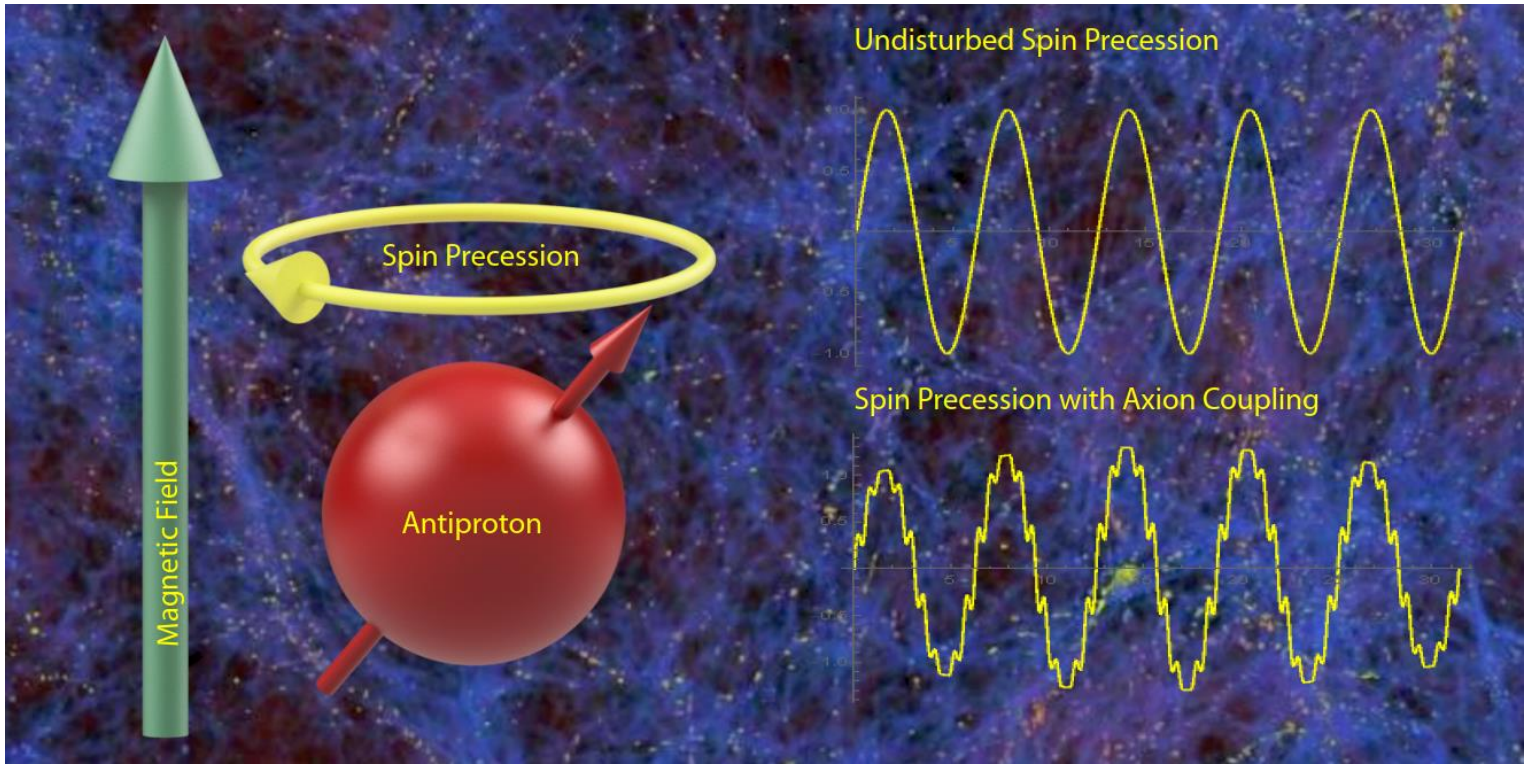
$$\frac{g_p}{2} = 2.792\,847\,344\,62\,(83)$$



$$\left|\frac{g_p}{2} - \frac{g_{\bar{p}}}{2}\right| < 0.3\,(8.3)\,10^{-9}$$

3000-fold improved limits on CPT-odd interactions in the baryon sector

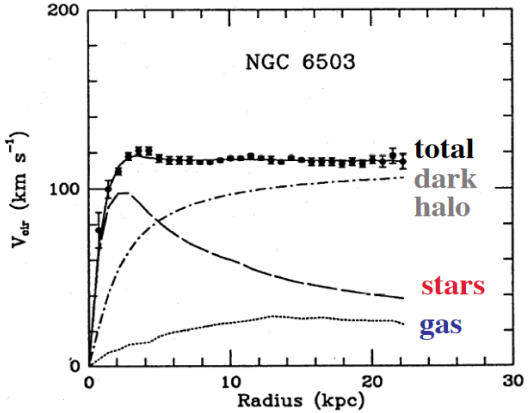
Coefficient	Limit
$\tilde{b}_p^Z$	$8.1 * 10^{-25}$GeV
$\tilde{b}_p^{ZZ}$	$3.3 * 10^{-9}$ GeV^{-1}
$\tilde{b}_{F,p}^{XX}+\tilde{b}_{F,p}^{YY}$	$4.6 * 10^{-9}$ GeV^{-1}
$\tilde{b}_{F,p}^{*Z}$	$1.5 * 10^{-24}$ GeV
$\tilde{b}_{F,p}^{*ZZ}$	$1.1 * 10^{-8}$ GeV^{-1}
$\tilde{b}_{F,p}^{*XX}+\tilde{b}_{F,p}^{*YY}$	$3.1 * 10^{-9}$ GeV^{-1}
f_p^0	4.5 10^{-12} μ_B



4.4 Searching for dark matter with antiprotons

Antiproton interaction with dark matter?

A typical observation



What is the dark matter made of?

How does dark-matter interact with Standard Model particles?

Is dark matter interaction with antiparticles?

The axion:

- introduced to solve the strong CP problem (Peccei/Quinn)
- candidate for dark matter (QCD-axion and axion-like particles)
- dark matter halo could be a classical wave of axions similar to diffuse light

$$\omega_a \approx \frac{m_a c^2}{\hbar}$$

The antiproton spin-precession frequency exhibits periodic changes due to a pseudo-magnetic field:

Interaction parameter

Experiment orientation

$$\Delta\omega_L^{\bar{p}} \approx \frac{C_{\bar{p}}}{f_a} m_a a_0 |\vec{v}_a| [A\cos(\Omega_{sid} t + \alpha) + B] \sin(\omega_a t)$$

Dark matter density & velocity

Y. V. Stadnik, D. Budker

Part 1: Detection

How consistent is the data with a zero signal?

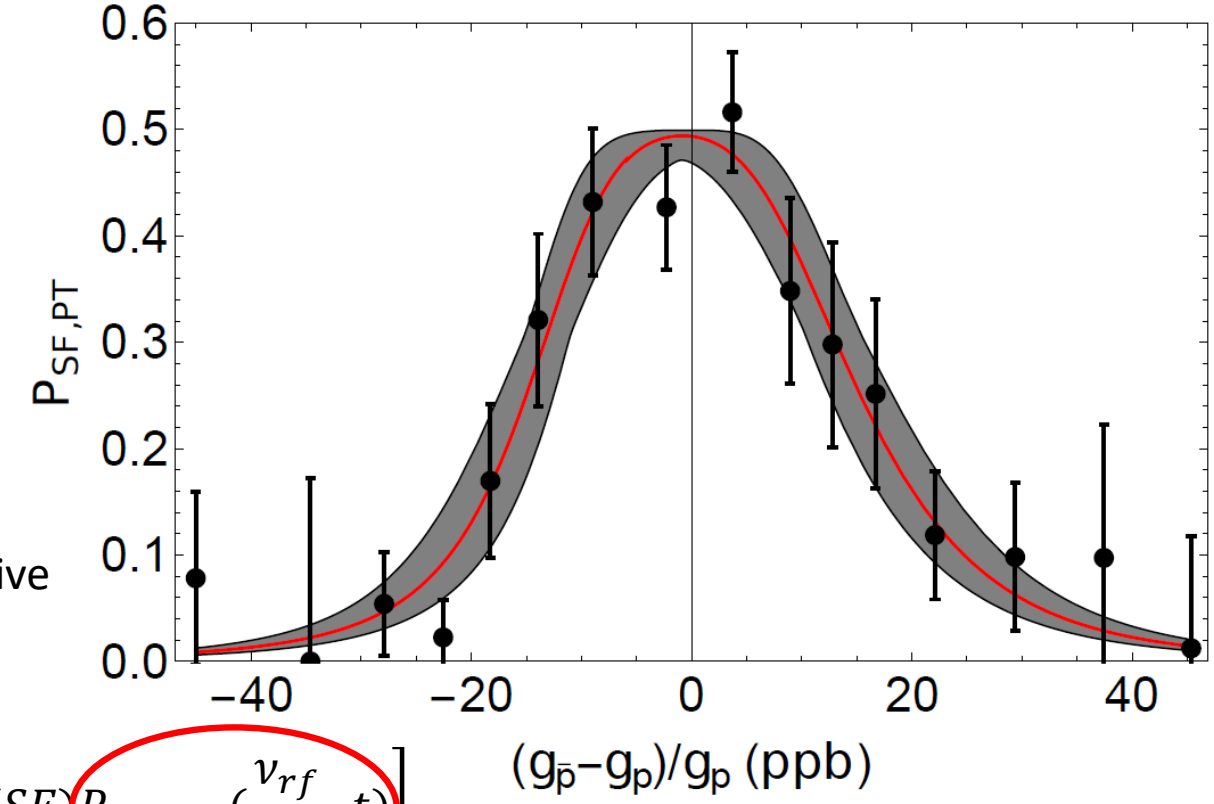
Indication for new physics: 3 σ inconsistency (0.3%)

Discovery of new physics: 5 σ inconsistency (5 10^{-7})

Hypothesis test:

$$q = -2\,\frac{L_0(b{=}0)}{L_\omega(b{>}0,\varphi)} > 0$$

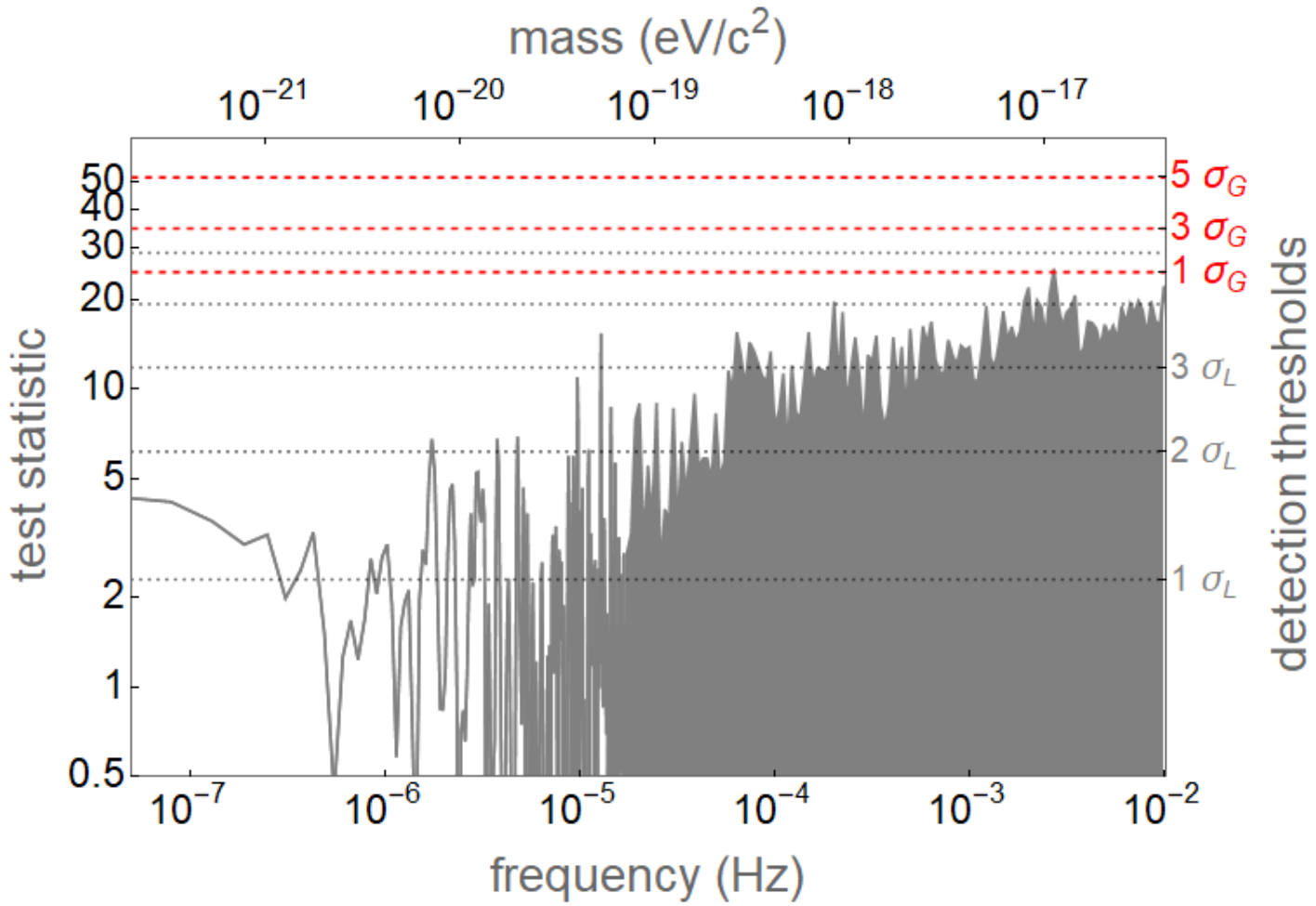
L_0 and L_ω are the maximum likelihood for the respective lineshape models.



$$L = \frac{1}{2^k}\prod_k\left[1 - P_k(SF) - P_{SF,PT,k}\left(\frac{\nu_{rf}}{\langle\nu_c\rangle},t\right) + 2\,P_k(SF)\,P_{SF,PT,k}\left(\frac{\nu_{rf}}{\langle\nu_c\rangle},t\right)\right]$$

Lineshape $g_{\bar{p}}, \Omega_R, \sigma_B$ with axion model ω_a, b, ϕ

Detection results

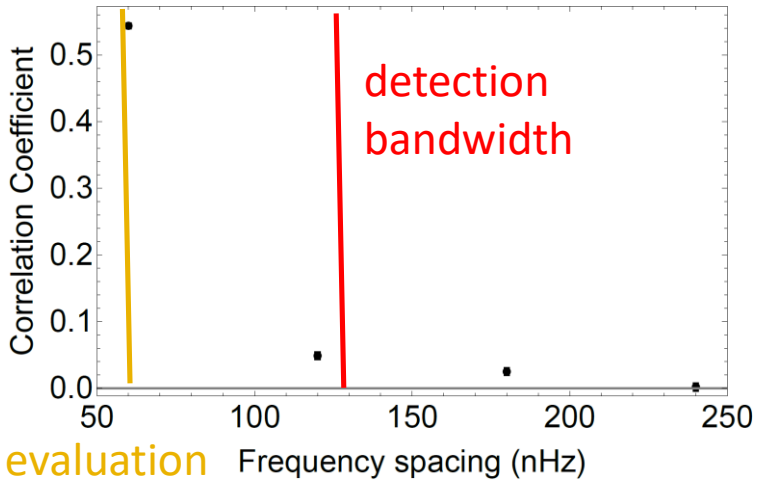


Look-elsewhere effect

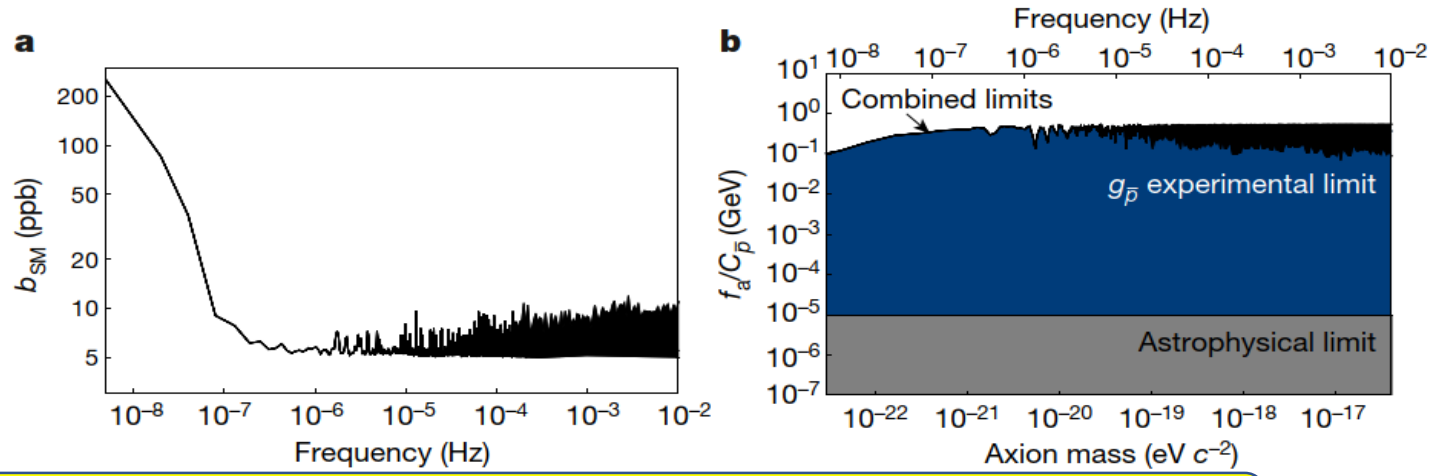
If you perform N zero hypothesis tests, where is the threshold to find the maximum test statistic only with 0.3% probability (3 σ significance)?

$$P_G = 1 - (1 - P_{L,max})^N$$

$$N = \eta\, N_0$$



Limits from experiment & SN-1987A



Addition: Limits on six previously unconstrained SME antimatter coefficients

Coefficient	Limit
$\tilde{b}_p^{*X}$	$9.7 * 10^{-25}$GeV
$\tilde{b}_p^{*Y}$	$9.7 * 10^{-25}$GeV
$\tilde{b}_{F,p}^{*XX}$-$\tilde{b}_{F,p}^{*YY}$	$5.4 * 10^{-9}$/GeV
$\tilde{b}_{F,p}^{*XZ}$	$3.7 * 10^{-9}$/GeV
$\tilde{b}_{F,p}^{*YZ}$	$3.7 * 10^{-9}$/GeV
$\tilde{b}_{F,p}^{*XY}$	$2.7 * 10^{-9}$/GeV

$$\Rightarrow \quad {f_a}/{C_{\bar{p}}} \gtrsim 10^{-1}\ \text{GeV} \ \text{ for } m_a \lesssim 4 \cdot 10^{-17}\ \text{eV}$$

- Bremsstrahlung type axion emission:
  - $\Gamma_{pp\to ppa} \sim n_p n_p \left({C_p^2}/{f_a^2}\right)$
  - $\Gamma_{p\bar{p}\to p\bar{p}a} \sim n_p n_{\bar{p}} \left({C_p C_{\bar{p}}}/{f_a^2}\right)$

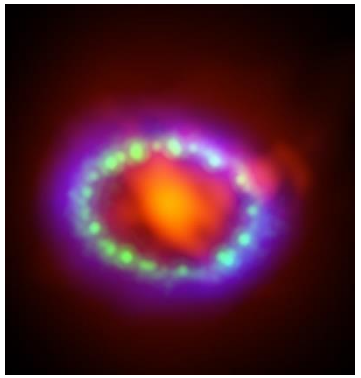

S. Ulmer


D. Budker


Y. Stadnik

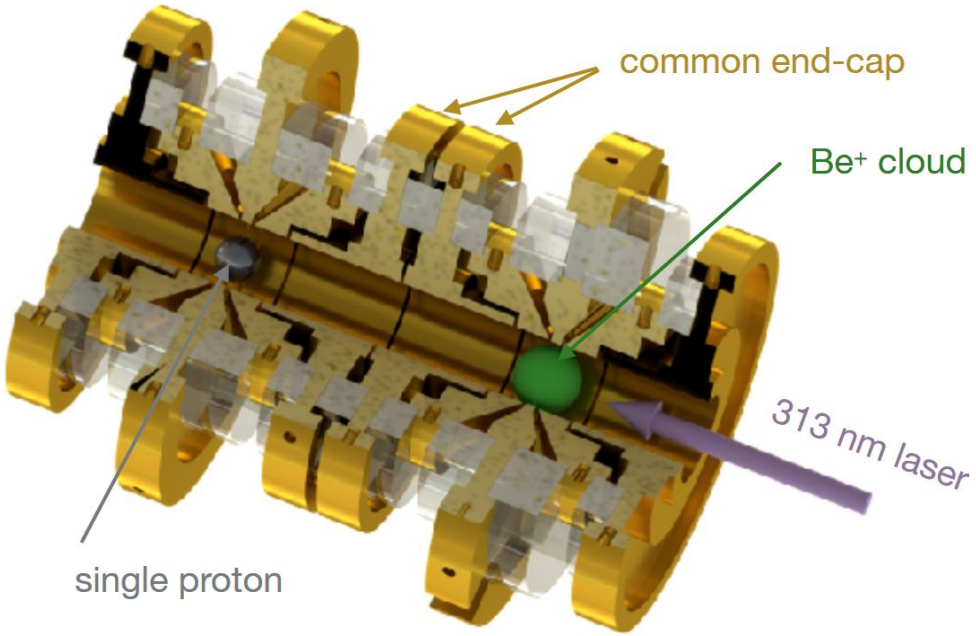
SN-1987A

SN-1987A-remnant



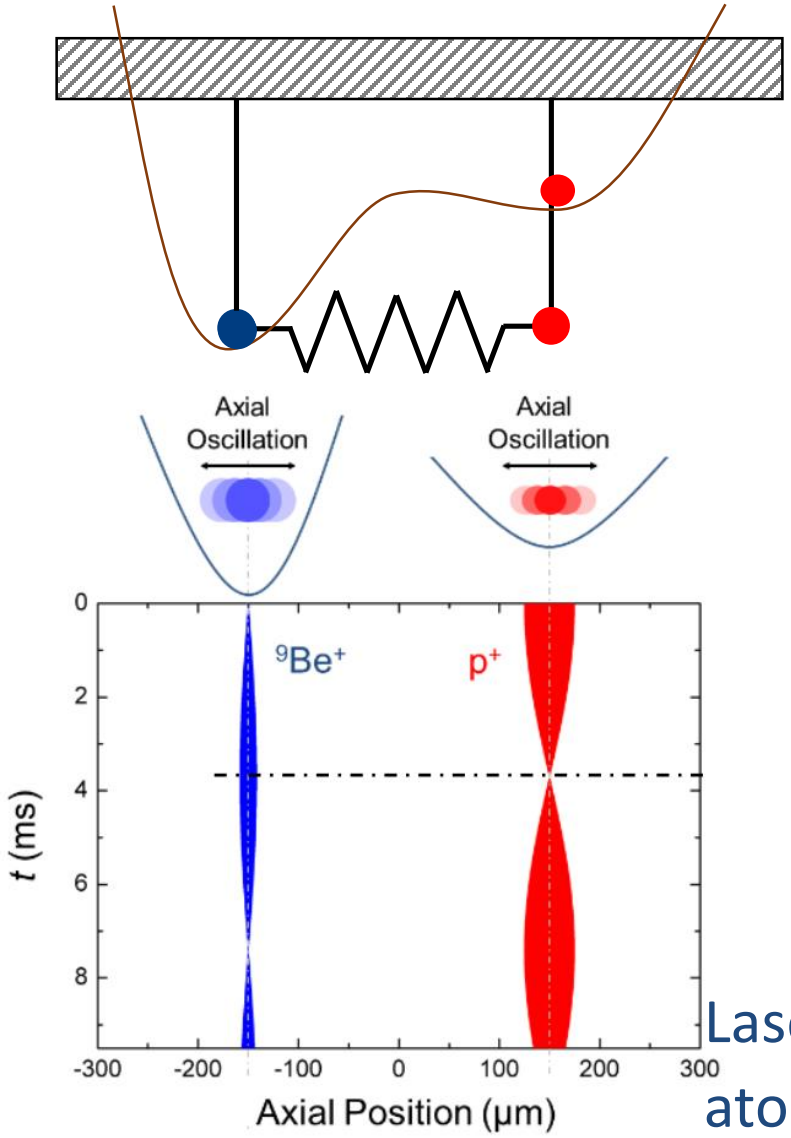
$$\Rightarrow \quad {f_a}/{C_{\bar{p}}} \gtrsim 10^{-5}\ \text{GeV} \ \text{ for } m_a \lesssim T_{core} \sim 30\ \text{MeV}$$

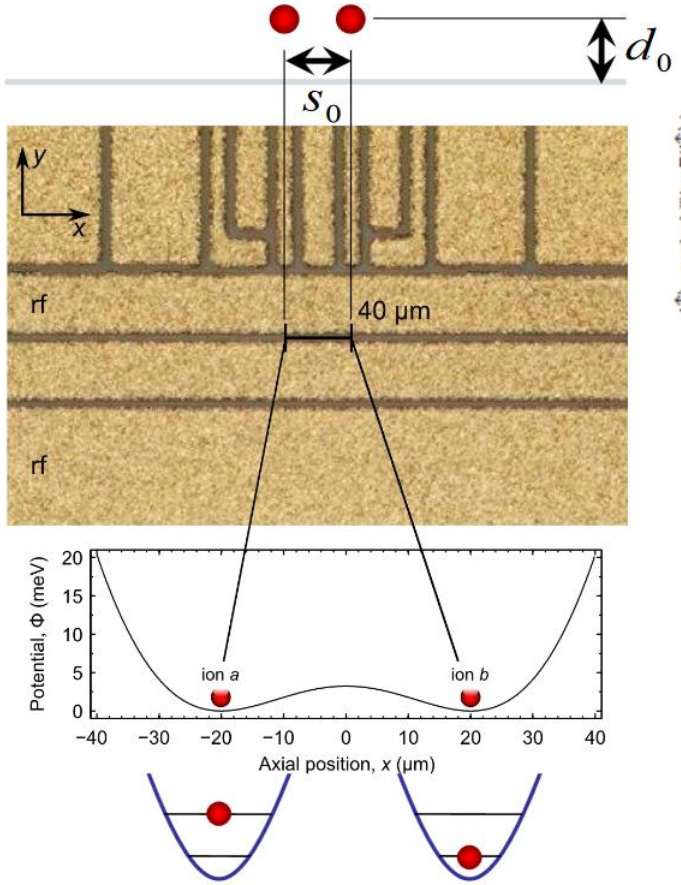
C. S. & Y. V. Stadnik et al., Nature 575, 310-314 (2019).

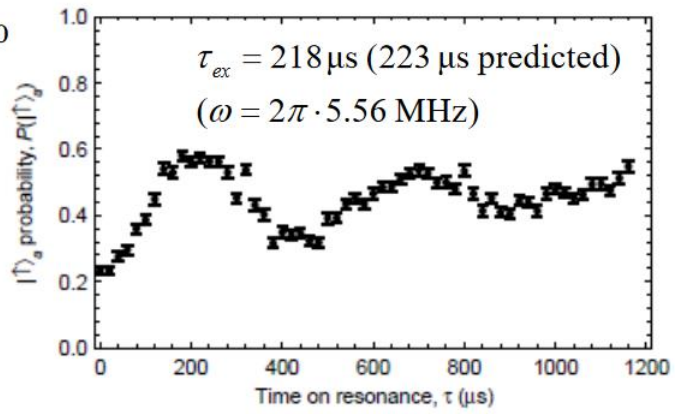


5. New antiproton cooling methods

Quantum logic detection of antiproton spin-flips







Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

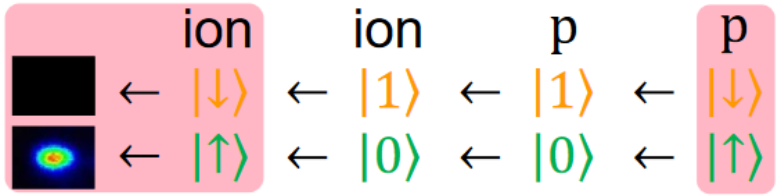
See also: M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel, Nature **471**, 200 (2011).

NIST

- Quantum logic readout

Laser cooled atomic ion

Proton



All figures courtesy of J. M. Cornejo & C. Ospelkaus

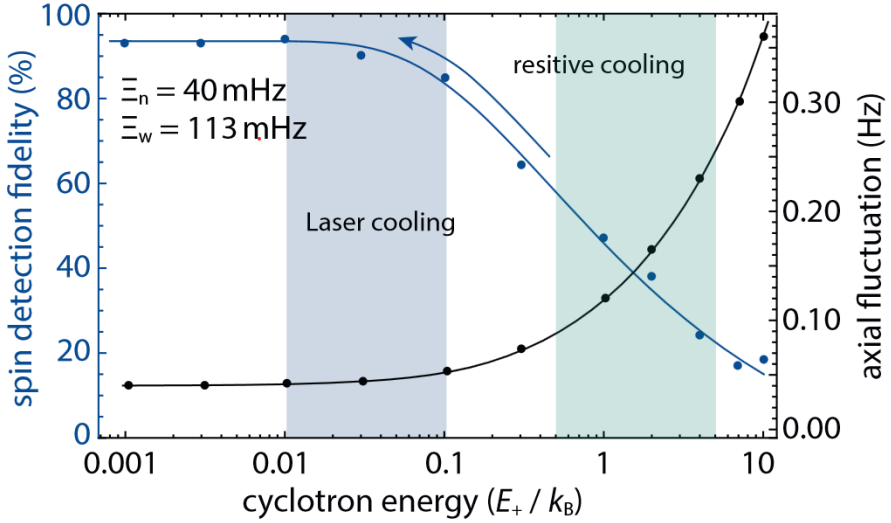
Proton/antiproton cooling below LHe temperature

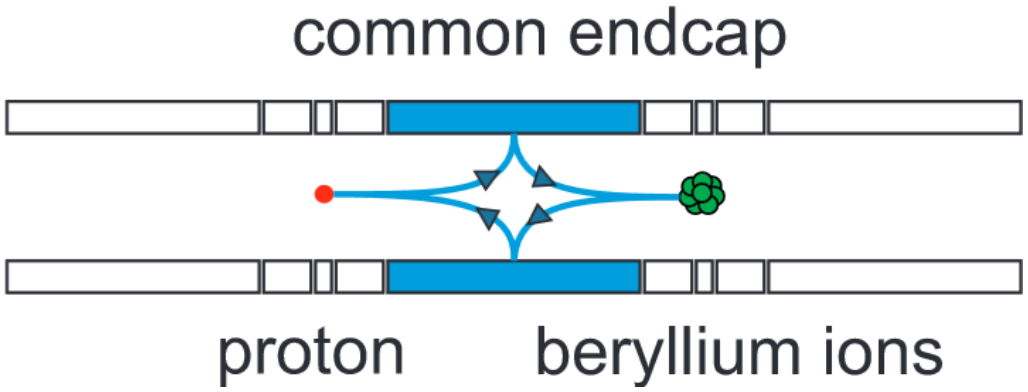
Slow cooling at a moderate temperature limit (4.2 K) is an obstacle for future antiproton high-precision measurements

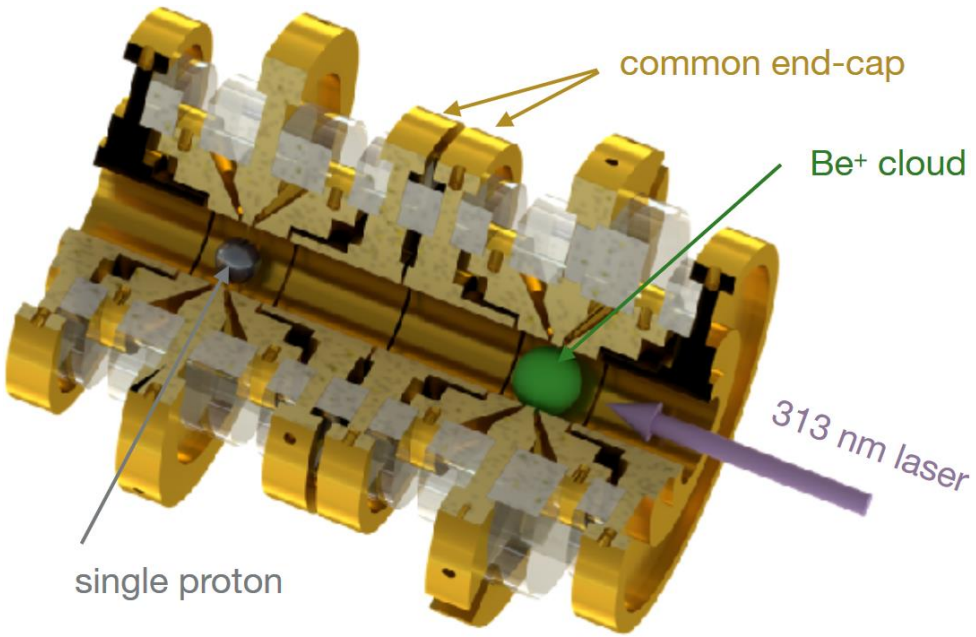
Form a **coupled oscillator of a single (anti-)proton and a cloud of laser-cooled beryllium ions** to reduce the temperature

Energy exchange: $\tau = \frac{\pi}{Z(\omega)} \frac{D^2}{q^2} \frac{\sqrt{m_p m_{Be}}}{\sqrt{N_{Be}}}$

Benefits: **Fast cooling** (few minutes vs. hours), **100% spin-state fidelity**

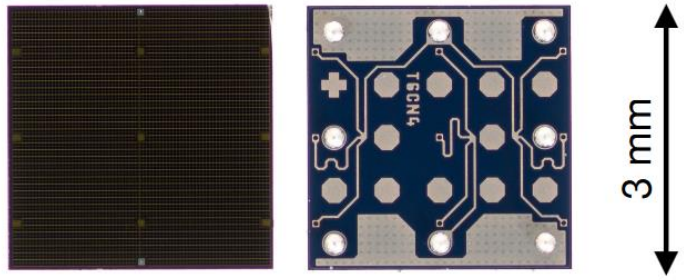




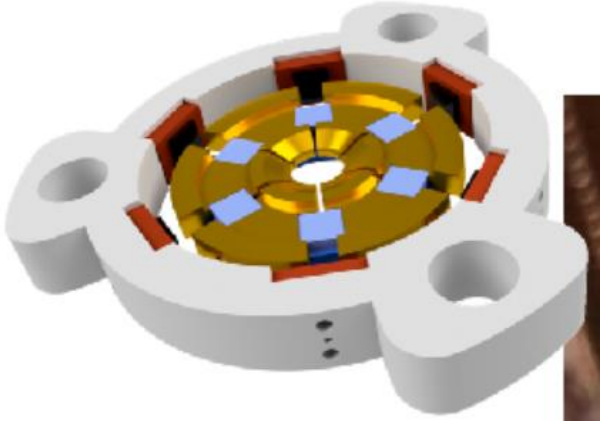


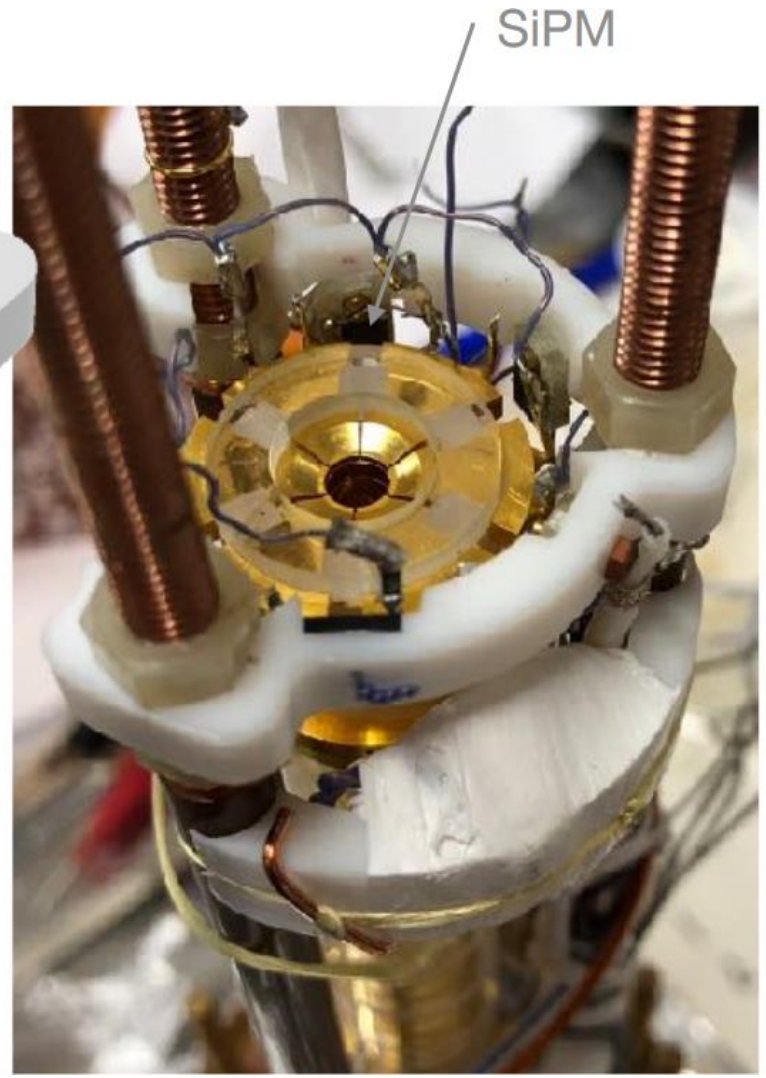
M. Bohman et al., J. Mod. Optics B **65**, 568-576 (2017).

Fluorescence Detection with a SiPM @ 4 K

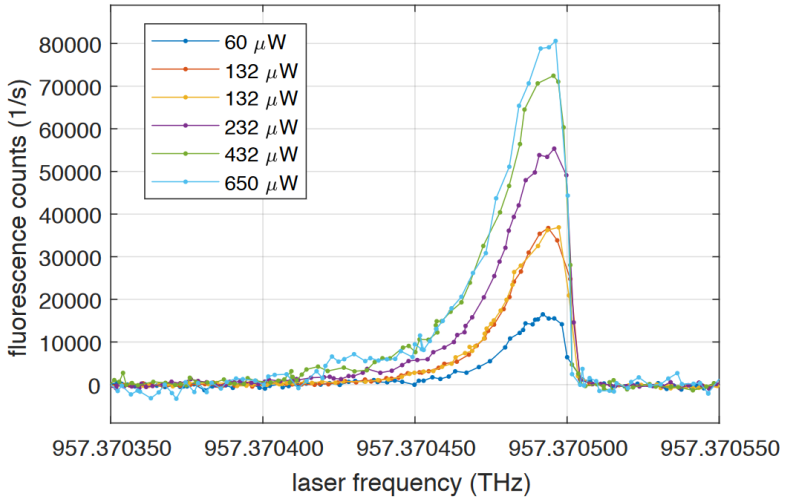


MicroFJ-30035-TSV from SensL
(now ON semiconductor)





Detection of fluorescence of 100 beryllium ions from the 313 nm cooling transition



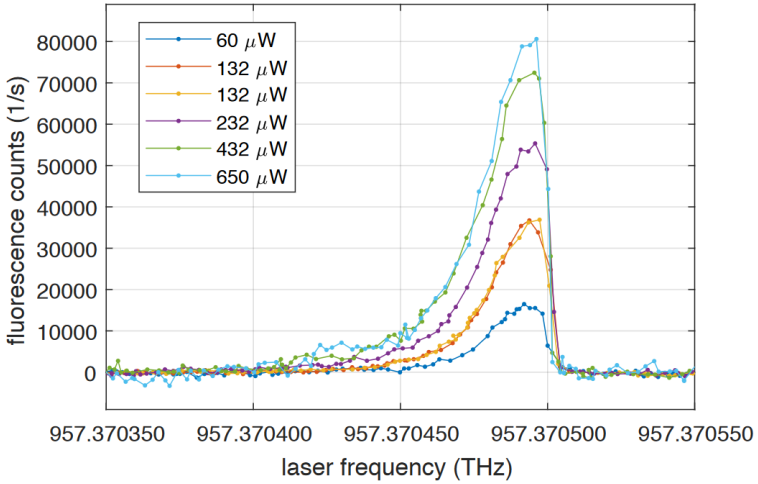
M. Wiesinger et al., to be published (2020).

Present status of the cooling @ BASE-Mainz

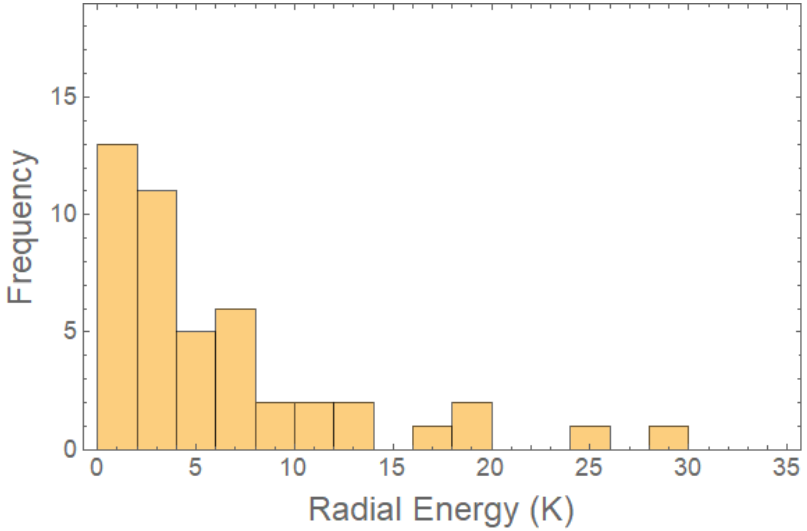
Measurements with **beryllium ions**:

- Cloud of 100 ions with **axial temperature of 25 (15) mK**
- Single beryllium ion cooled in the coupling trap with 6.5 K cyclotron temperature in the analysis trap
- Temperature limits:
  - **Transport heating** (**3 K for Be**, 33 mK for p)
  - **Off-resonant pumping into a dark state** (no re-pumping laser)
  - Laser pointing stability

Axial temperature: 25 (15) mK compared to 4.2 K



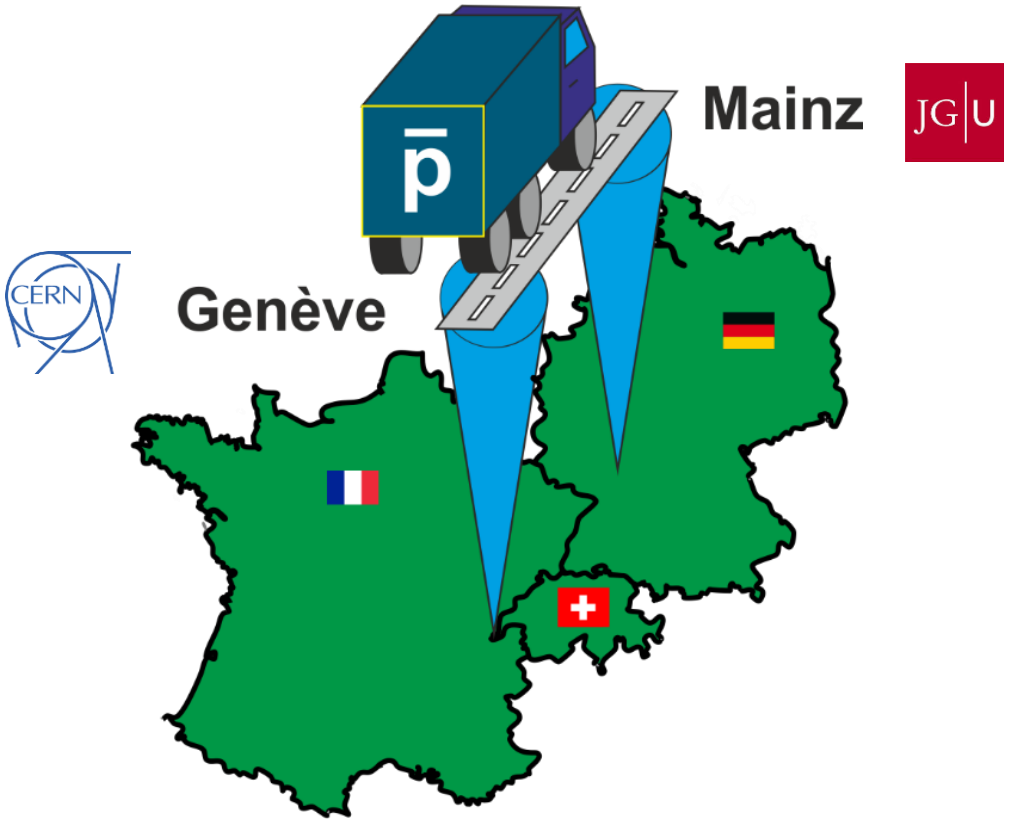
Cyclotron temperature: 6.5 (1.0) K compared to 45 K



Proton measurements:

- Expect to reach below 100 mK cyclotron energy
- Cooling time:
  - Capacitively: ~ 1 min with 100 beryllium ions
  - LC-Circuit: ~ 250 ms with 1 ion, but at higher temperature

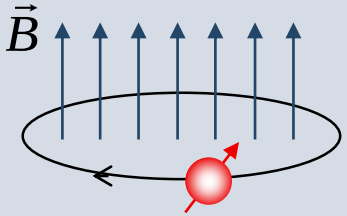
- Proton temperature measurements are ongoing…



6. Antiproton transportable traps

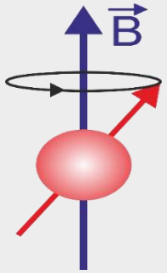
Developing transportable antiproton traps

Cyclotron Frequency



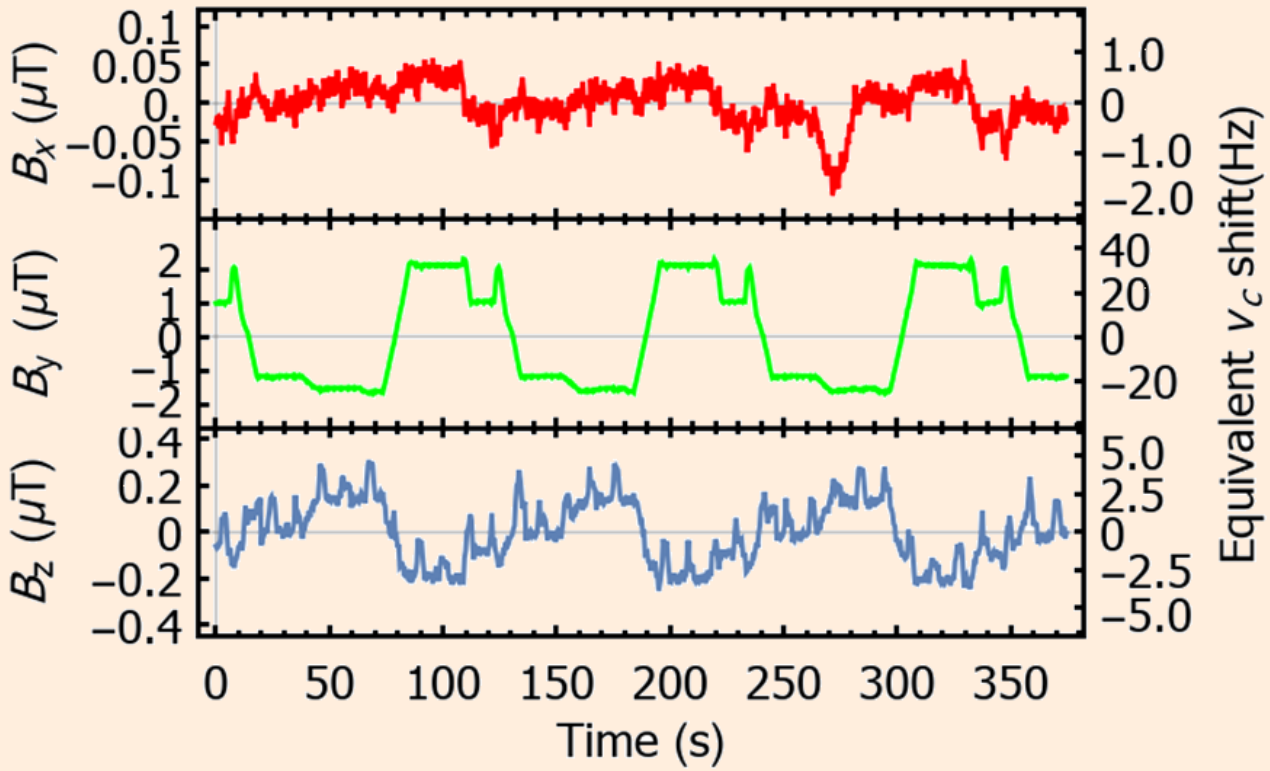
$$\omega_c = \frac{q}{m} B$$

Larmor Frequency



$$\omega_L = \frac{g}{2}\frac{q}{m} B$$

Magnetic field in the AD/ELENA facility

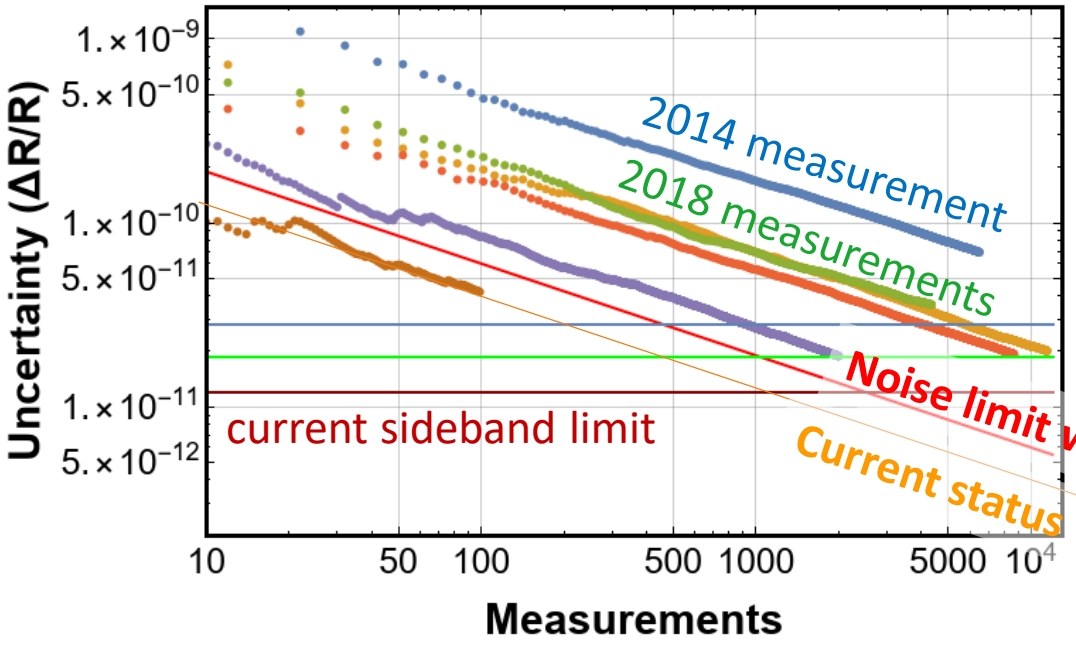


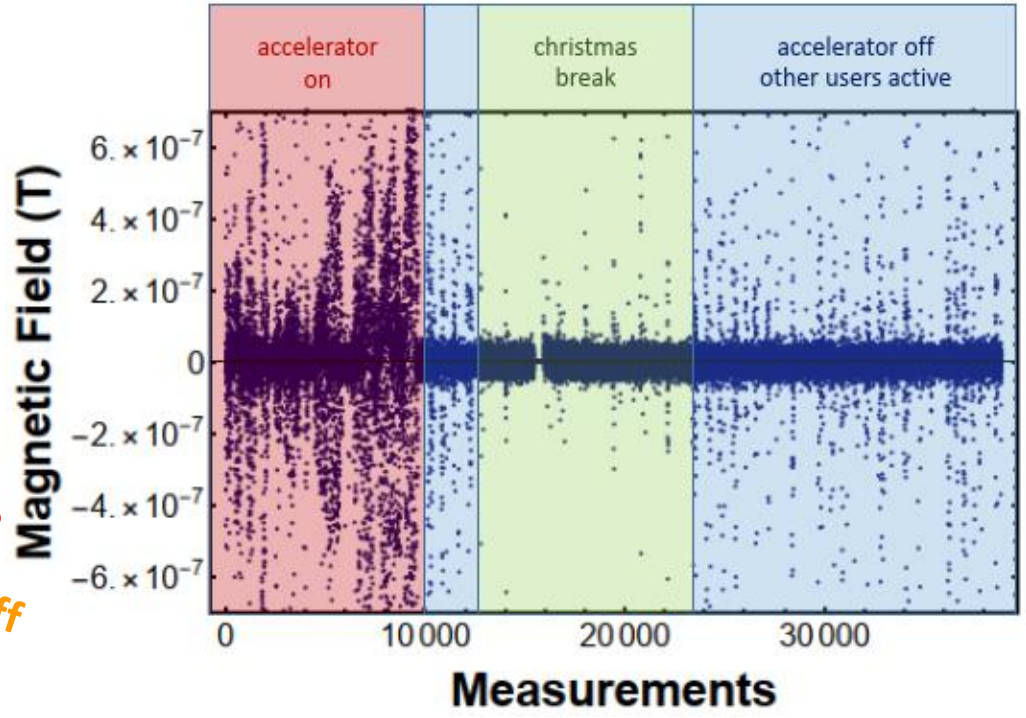
Future antiproton precision measurements need to average the magnetic field down to 2 pT!

European Research Council
Established by the European Commission

How precise can we measure in the AD hall?

Best season of the year for physics!





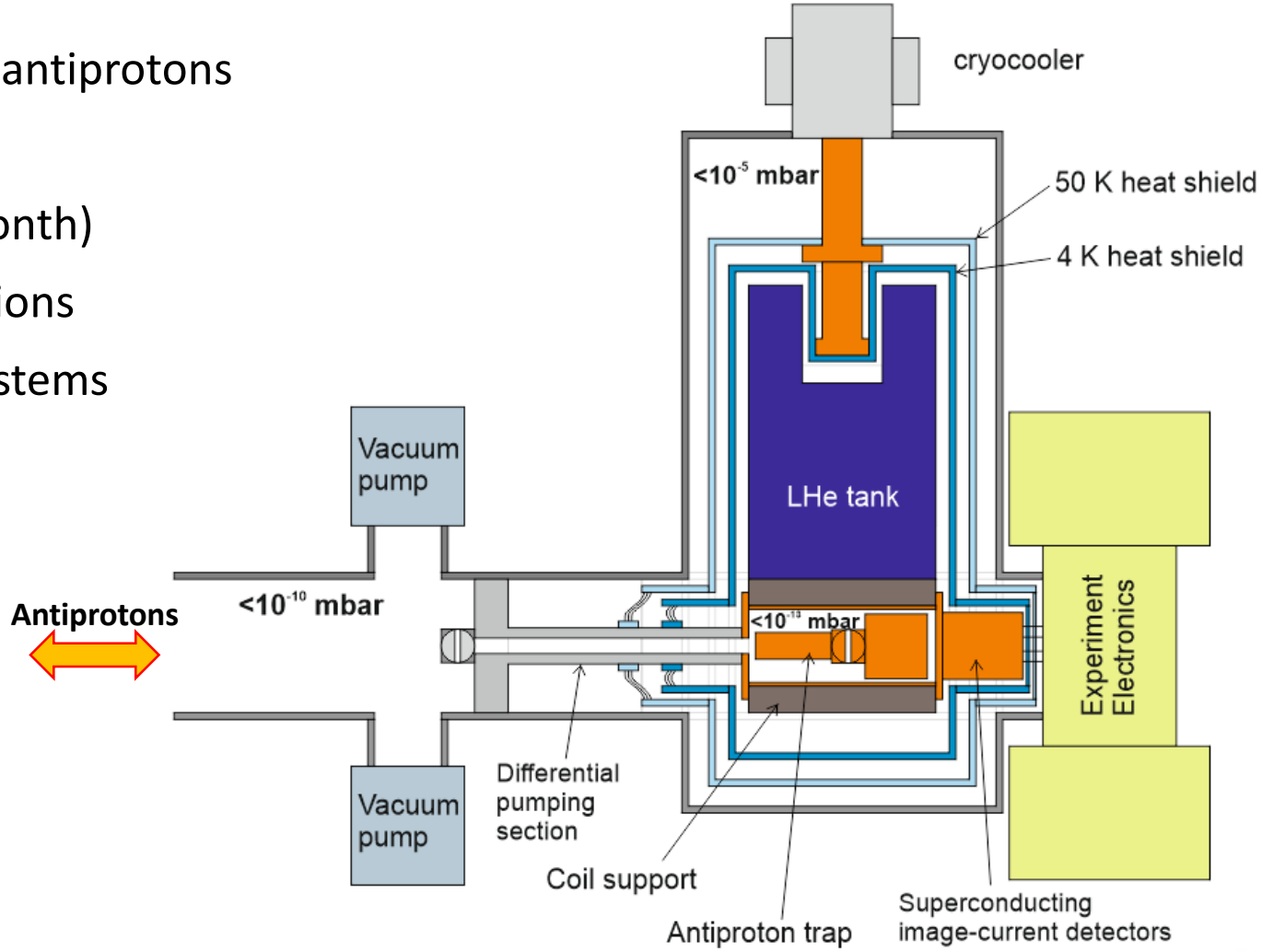
We need to relocate the antiprotons in to a calm magnetic environment!

Transportable antiproton trap – BASE-STEP

- Portable reservoir trap with up to 10000 antiprotons
- Catch and cool antiprotons in a 1 T field
- Long-term storage of antiprotons (> 3 month)
- Non-destructive extraction of small fractions
- Shuttle antiprotons between two trap systems

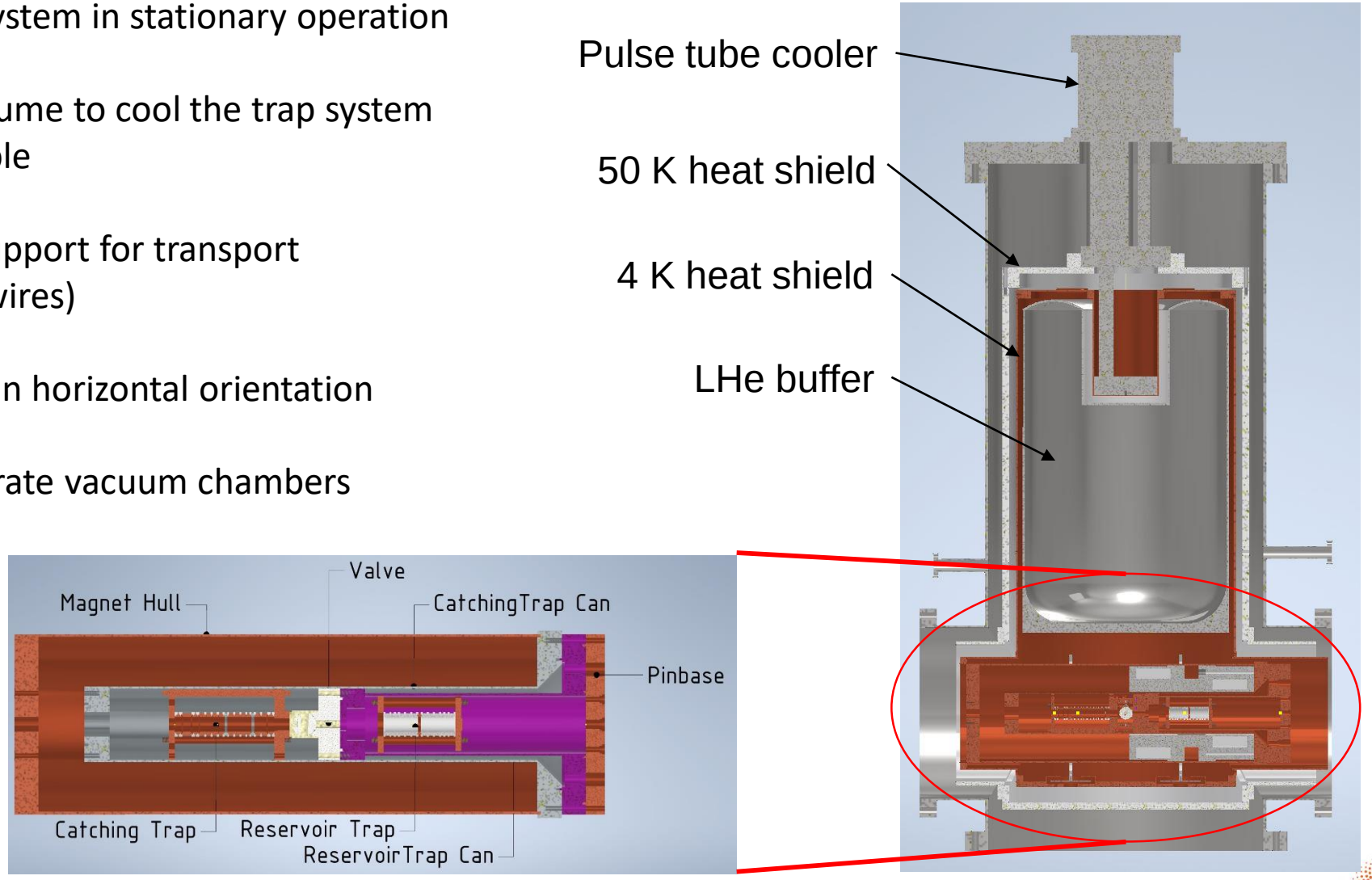
To be developed:

- A transportable magnet/trap system
- The vacuum interface
- The transfer between two trap systems



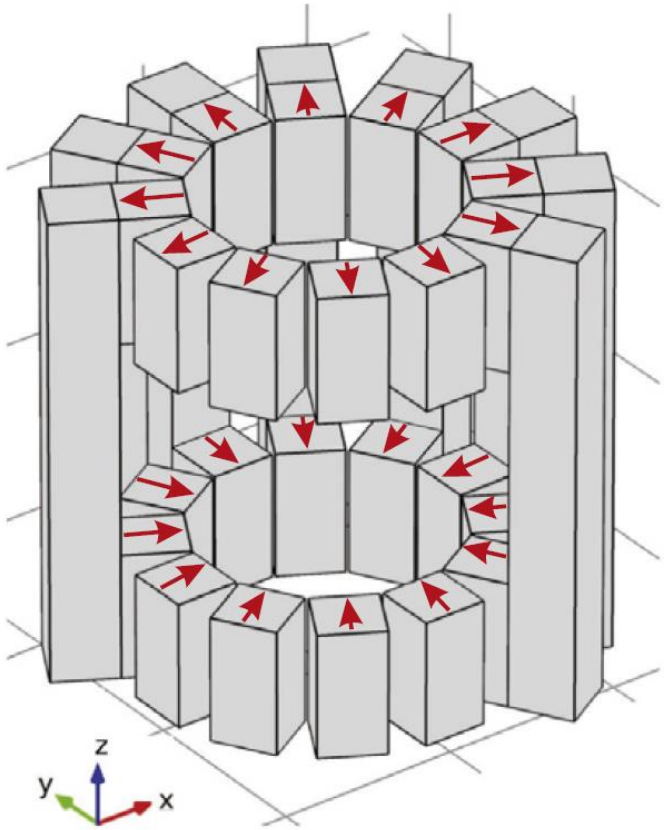
Transportable cryostat/trap system

- Cryocooler to cool the system in stationary operation
- Liquid Helium buffer volume to cool the trap system while power is unavailable
- Enhanced mechanical support for transport (titanium grade 5 rods/wires)
- Trap system installation in horizontal orientation
- Two trap system in separate vacuum chambers

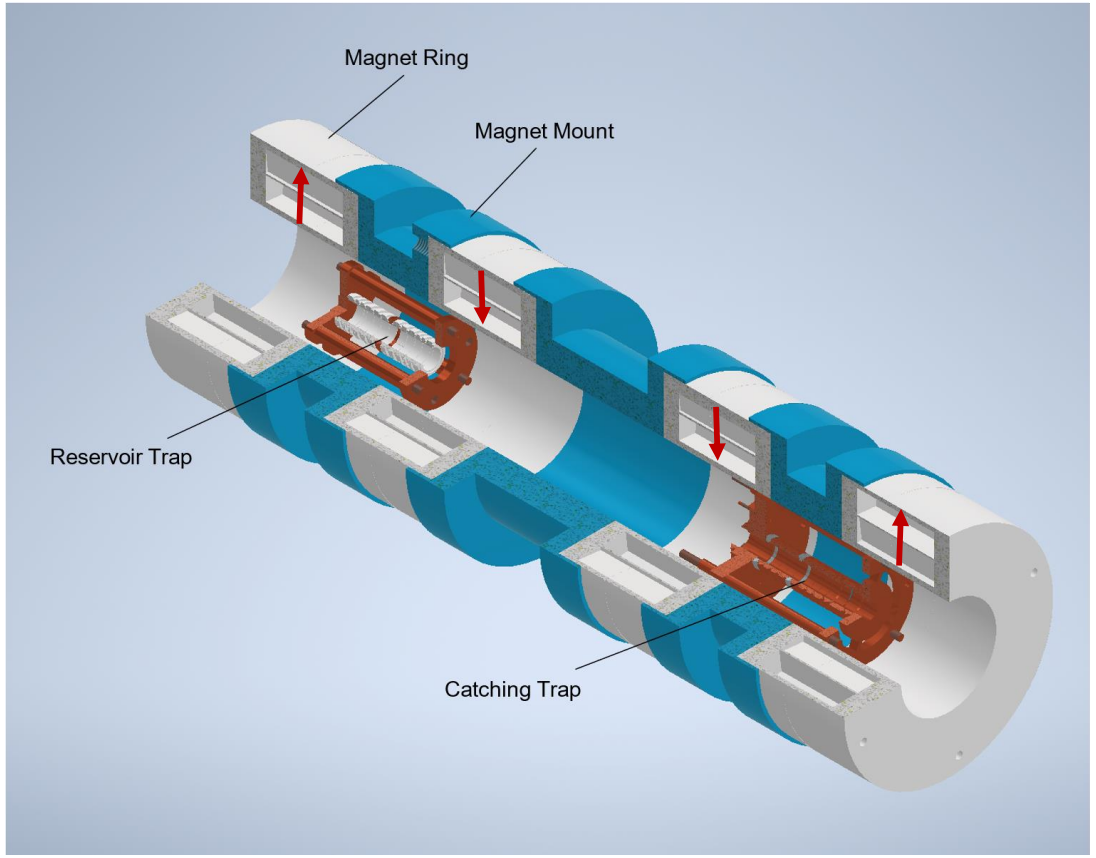


Permanent magnet Penning traps

Aubert configuration



250 mT to 500 mT field strength



See e.g.: K. Menzel et al., Sep. Pur. Techn. **134**, 220-231 (2014).

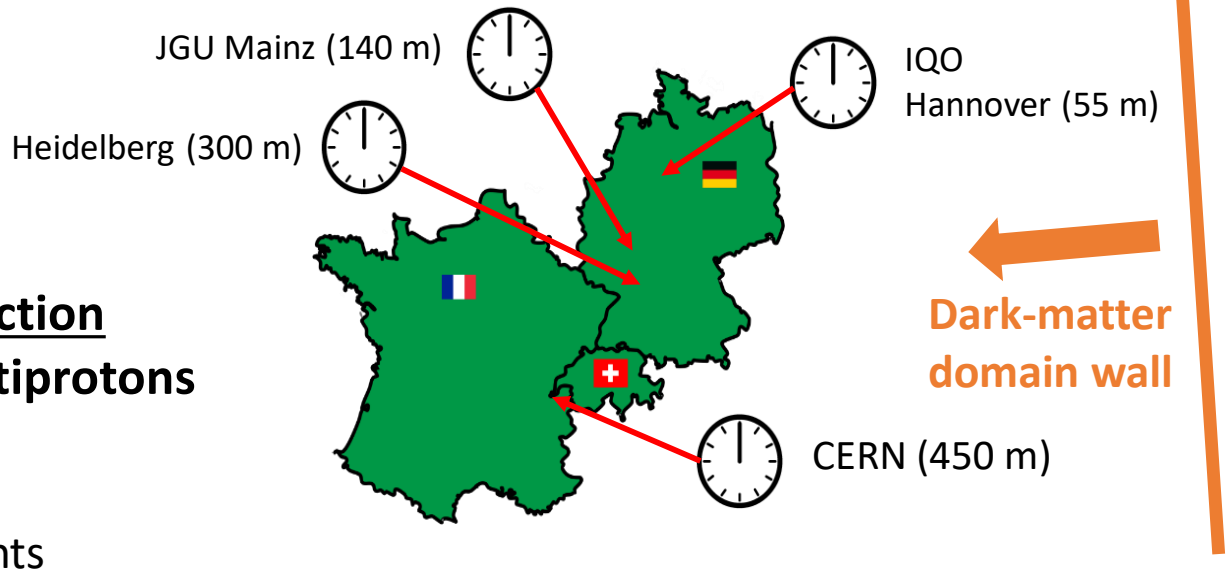
New high-precision tests with portable antiprotons

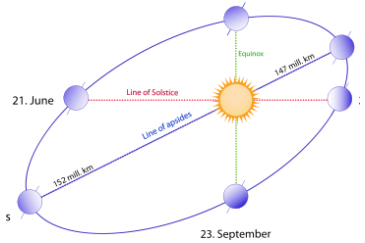
<u>Physics objective #1: Test CPT invariance</u>
Measure the antiproton charge-to-mass ratio with improved precision

<u>Physics objective #2: Dark-matter antimatter interaction</u>
Search for dark-matter topological defects using antiprotons

Correlated frequency shifts in a clock network with simultaneous antiproton cyclotron frequency measurements

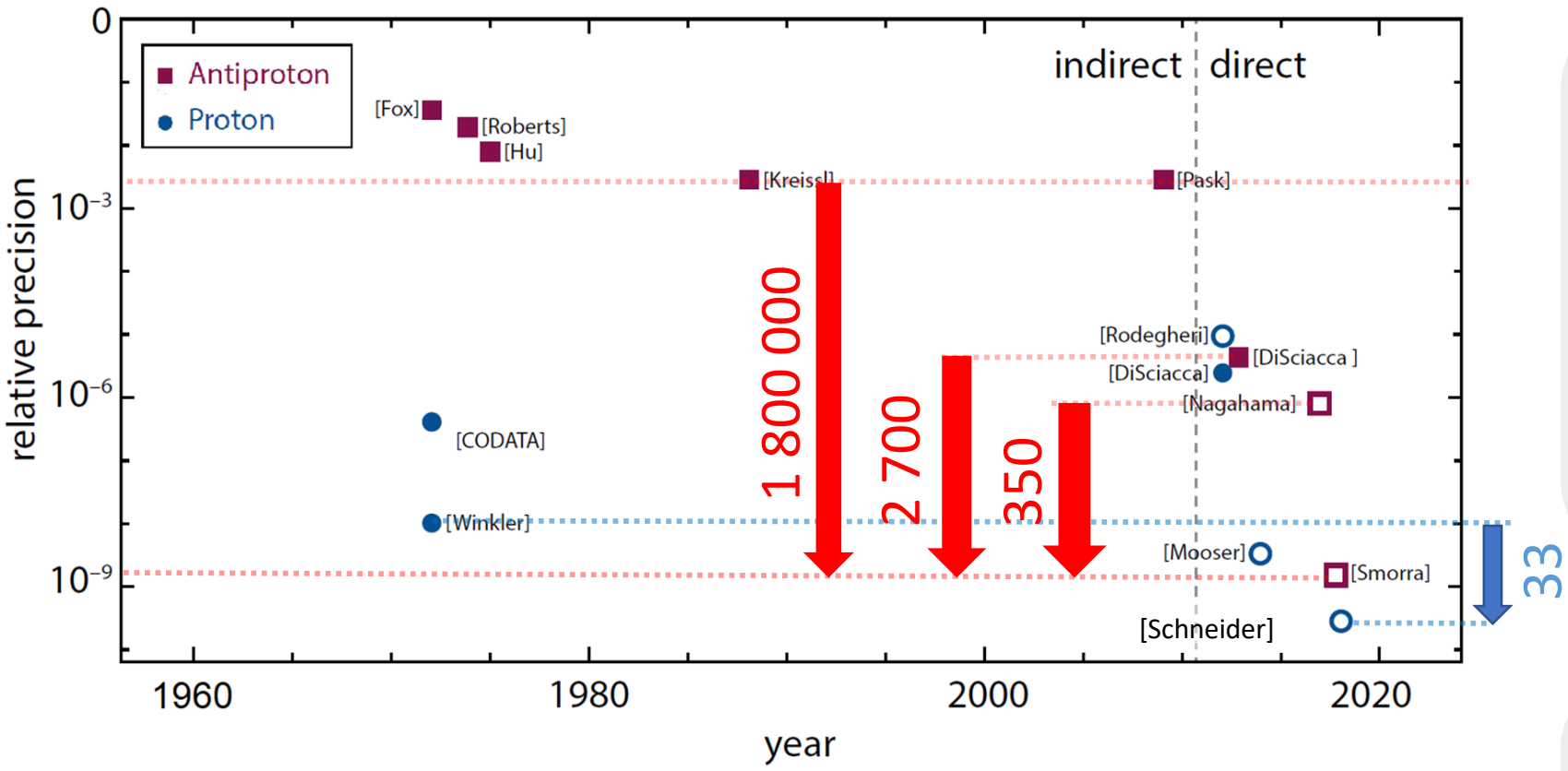
<u>Physics objective #3: Charged antimatter gravitation</u>
Test the weak equivalence principle with antiprotons





7. Summary and Conclusions

Summary



Comparing the proton/antiproton charge-to-mass ratio

$$\frac{(q_{\bar{p}}/m_{\bar{p}})}{(q_p/m_p)} + 1 = 1(69)\ 10^{-12}$$

Improved by ~25% and a factor of 4 in energy resolution

In total, improvement of the CPT invariance test by a factor 2700

Most precise measurement of a nuclear magnetic moment

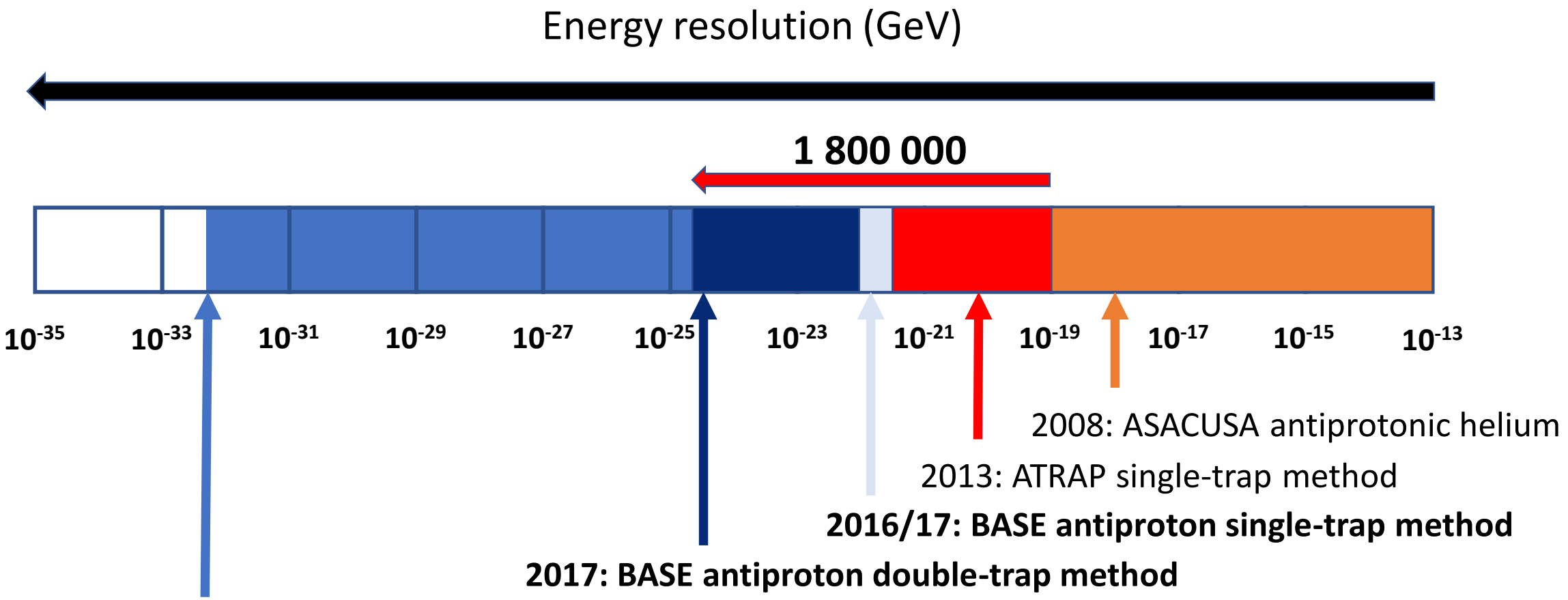
Antiproton lifetime limits

$\tau_{\bar{p}} > 10.2$ years

Improved by a factor of 30

CPT invariance tested in matter and antimatter systems

Example: Limits on the SME b-coefficient for protons and antiprotons



Finish!

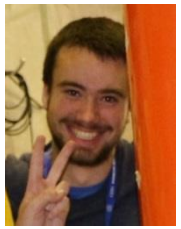
BASE – CERN:


S. Ulmer
RIKEN


J. A. Devlin
CERN/RIKEN


E. Wursten
CERN/RIKEN


B. Latacz
RIKEN


M. Borchert
U - Hannover


J. Harrington
RIKEN & MPIK


S. Erlewein
MPIK/RIKEN


M. Fleck
RIKEN/U. Tokyo

- Thanks to the BASE team
- BASE collaborators:
  K. Blaum, J. Walz, C. Ospelkaus,
  Y. Matsuda, W. Quint, Y. Yamazaki

- **Thank you for the funding:**

European Research Council
Established by the European Commission

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MAX-PLANCK-GESELLSCHAFT

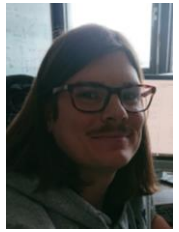
IPH - QUANTUM

BASE – Mainz:


M. A. Bohman
RIKEN/MPIK


M. Wiesinger
MPIK (AVA Fellow)


C. Will
MPIK


V. Grunhofer
Uni Mainz

STEP:


S. Gavranovic
Uni Mainz


D. Popper
Uni Mainz

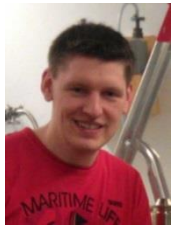
Former Collaborators:


A. Mooser
RIKEN

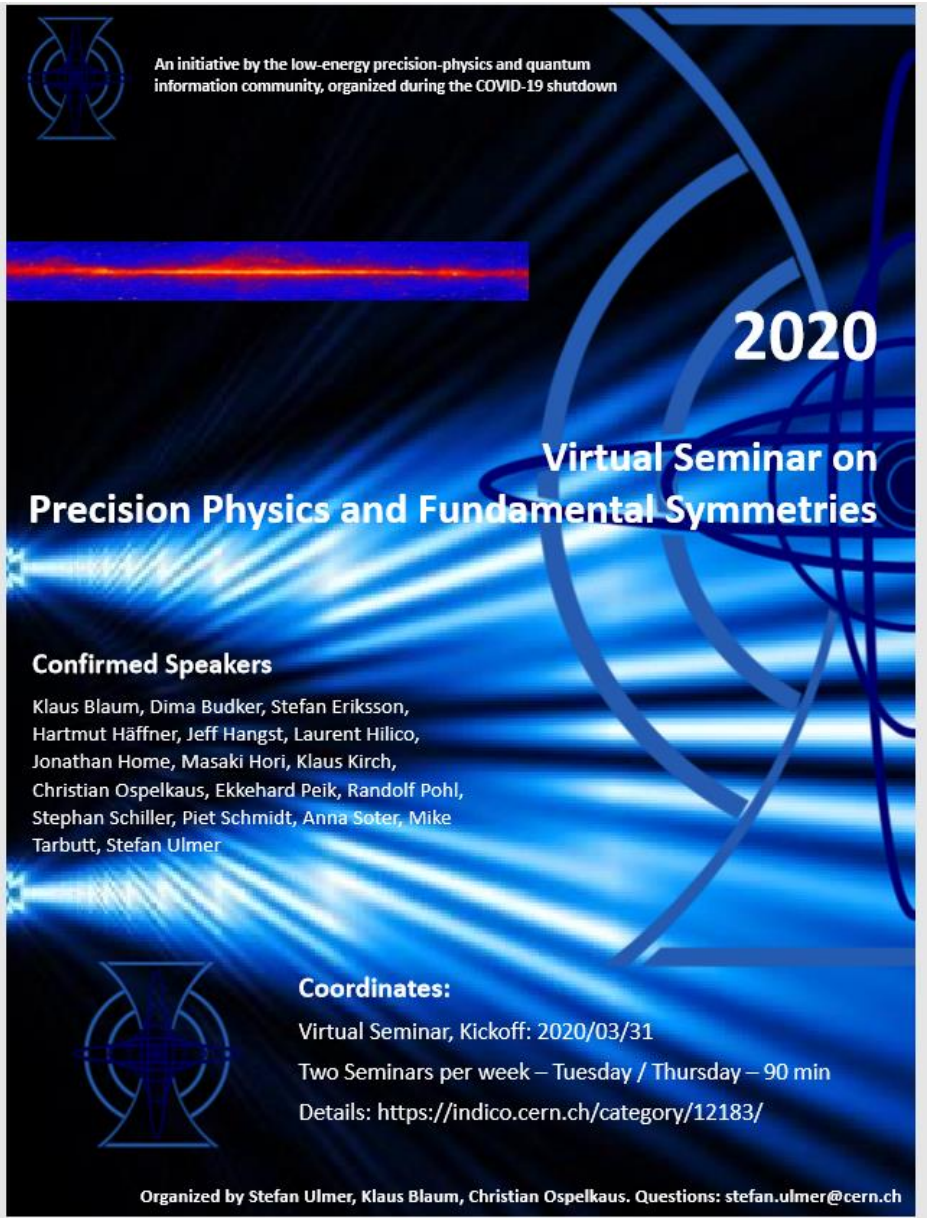

S. Sellner
RIKEN


H. Nagahma
RIKEN /
Tokyo


T. Higuchi
RIKEN /
Tokyo


G. Schneider
U - Mainz

If you like remote seminars: Join this event!



First event: Next Tuesday (31st March 2020)

Speaker: Christian Ospelkaus

Towards a Small-Scale Trapped-Ion Quantum Processor Based on Near-Field Microwave Quantum Logic Gates

LINK:
https://indico.cern.ch/category/12183/