BASE

Virtual Seminar on Precision Physics and Fundamental Symmetries

Tests of Fundamental Symmetries with Antiprotons in Penning traps

RIKEN

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RIKEN

2020 / 04 / 21

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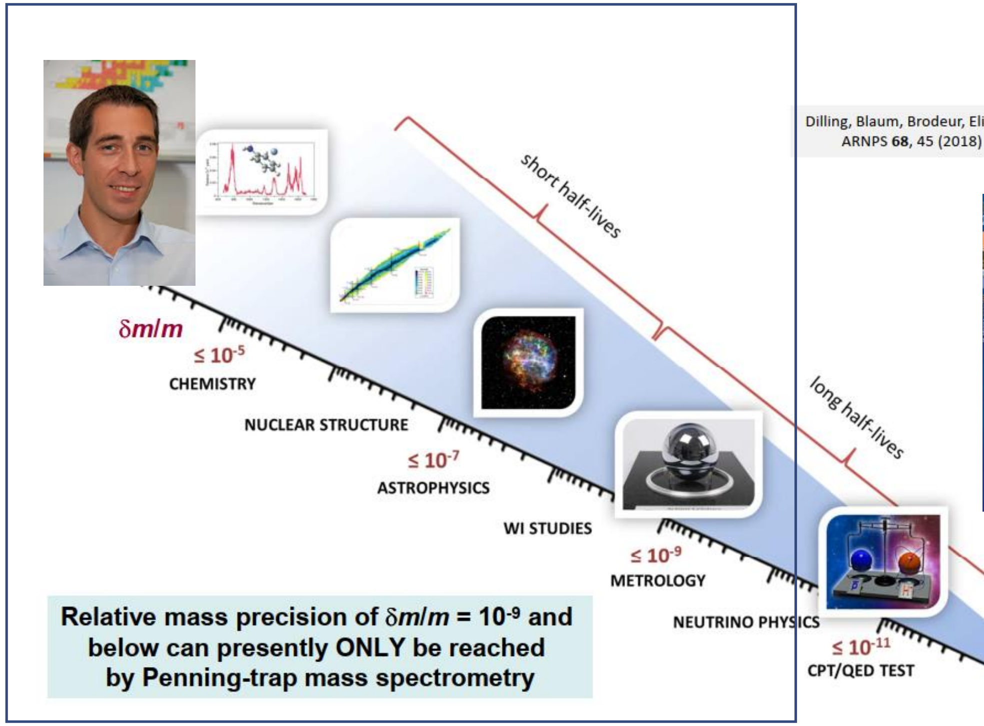
PTB

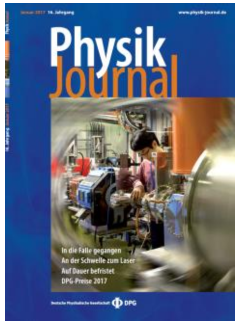
Outline of Talk

- Motivation to these Experiments
- Detailed Introduction to Precision Measurements in Penning Traps
- Discussion of Recent Results
- Outlook on Future



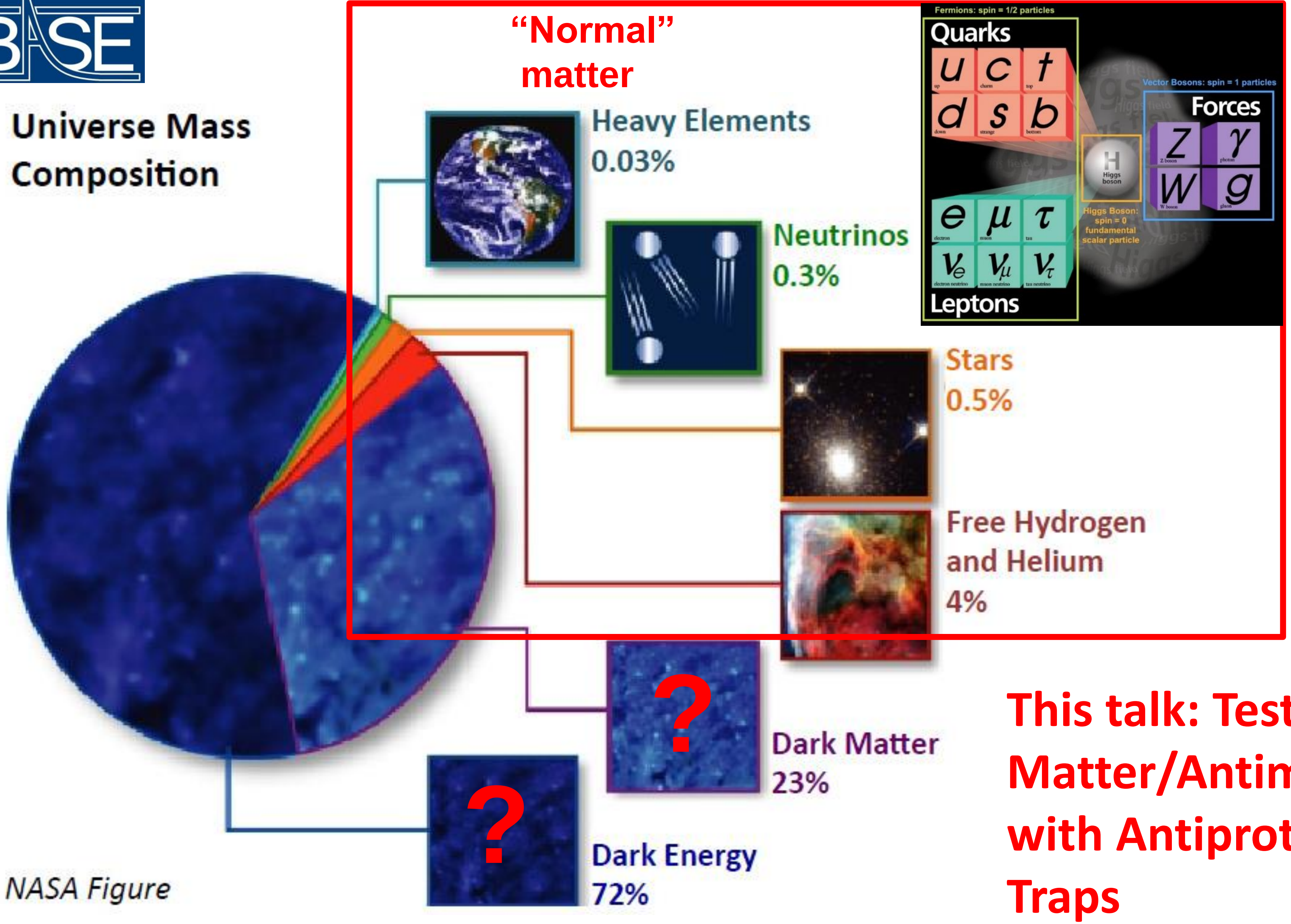
Relative mass precision of $\delta m/m = 10^{-9}$ and below can presently ONLY be reached by Penning-trap mass spectrometry

Dilling, Blaum, Brodeur, Eliseev, ARNPS **68**, 45 (2018)



Other groups which operate Penning traps at that precision level:

Pritchard, Myers, Sturm, Eliseev, Blaum, Mooser, Gabrielse

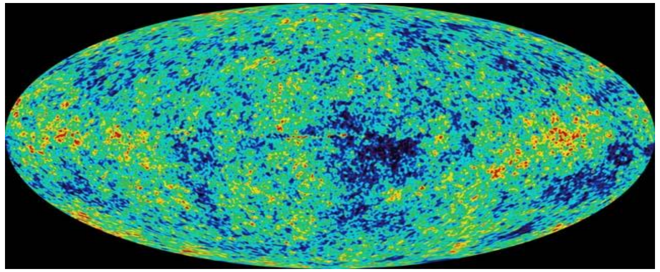


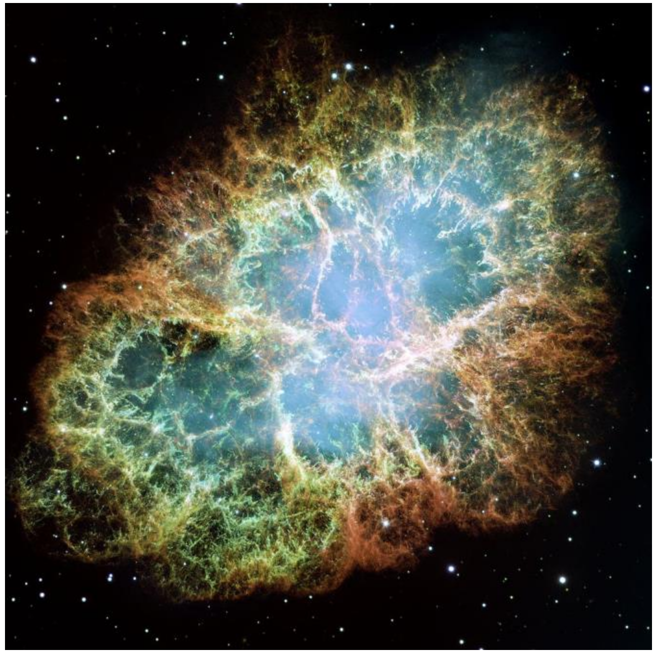
Elephants in modern physics

- Energy content of Universe has yet to be understood.
- Dark Matter (Budker)
- Strong CP problem and CP violation (Kirch)
- Element abundance in the universe (Blaum)
- Matter/Antimatter Symmetry (several)

This talk: Testing Matter/Antimatter Symmetry with Antiprotons in Penning Traps

Matter / Antimatter Asymmetry





1. Hubbles law and the big bang scenario
2. A cosmic microwave background should exist as a fire-ball remnant of the Big Bang
    1. 1965 Penzias and Wilson **observed CMWB with a black body spectrum of 2.73(1)K, by far too intense to be of stellar origin**.
3. Understandable Big Bang nucleosynthesis scenario **describes exactly the observed light element abundances as found in «cold» stellar nebulae**.
4. Looks consistent, BUT - **using the models which describe 1. and 2.:**

Naive Expectation	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

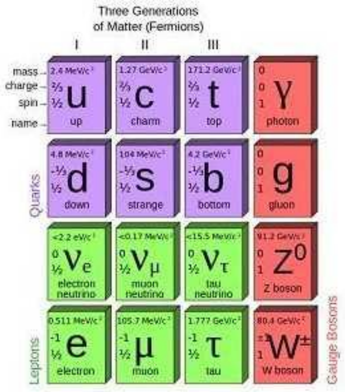
Observation	
Baryon/Photon Ratio	$0.6 * 10^{-9}$
Baryon/Antibaryon Ratio	10 000

Following the current Standard Model of the Universe our predictions of baryon to photon ratio are **wrong by about 9 orders of magnitude**

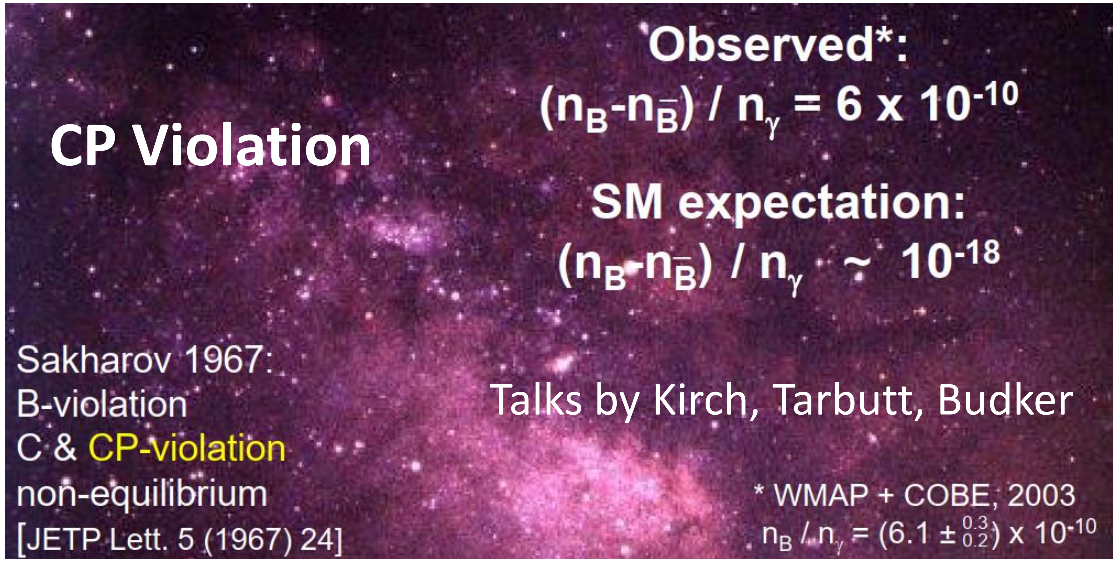
Summary

Standard models of particle physics and cosmology predict equal amounts of matter and antimatter (CPT symmetry).

The visible part of the Universe is entirely made out of matter.



Origin of matter/antimatter symmetry has yet to be understood.



CP Violation

Observed*:
$(n_B - n_{\bar{B}}) / n_\gamma = 6 \times 10^{-10}$

SM expectation:
$(n_B - n_{\bar{B}}) / n_\gamma \sim 10^{-18}$

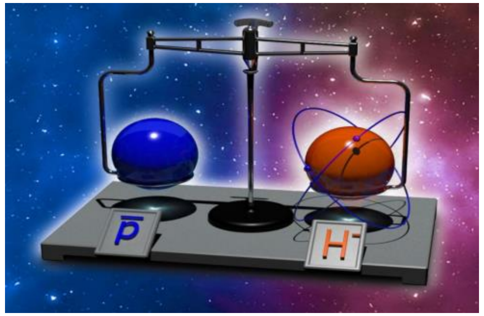
Sakharov 1967:
B-violation
C & CP-violation
non-equilibrium
[JETP Lett. 5 (1967) 24]

Talks by Kirch, Tarbutt, Budker

* WMAP + COBE, 2003
$n_B / n_\gamma = (6.1 \pm^{0.3}_{0.2}) \times 10^{-10}$

Alternative Source: CPT violation

Compare the fundamental properties of matter / antimatter conjugates with ultra high precision



Fundamentality of CPT Invariance

- According to an axiomatic proof of by Jost, based on Wightman functions, **a theory which conserves CPT requires only five basic assumptions (Axioms):**

Lorentz and translation invariance

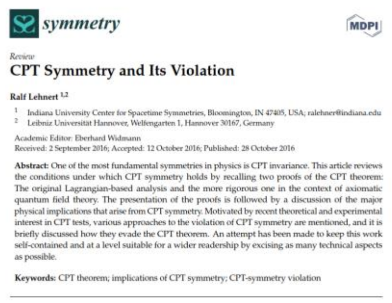
Energy Positivity

Micro Causality

A vacuum ground state which has neither momentum nor angular momentum

Field Operators which allow a particle interpretation

→ **CPT**



symmetry MDPI

Review

CPT Symmetry and Its Violation

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Academic Editor: Eberhard Widmann
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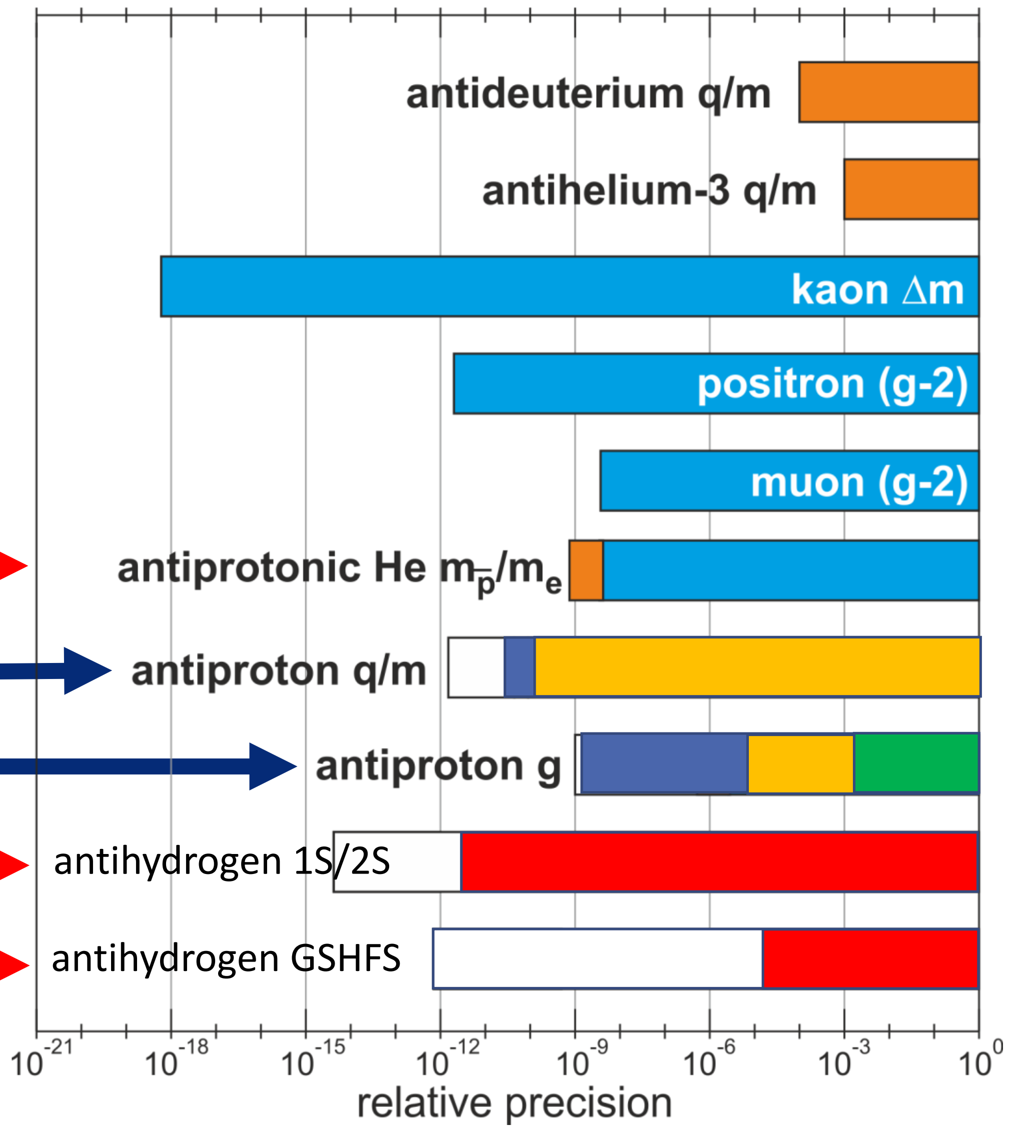
Abstract: One of the most fundamental symmetries in physics is CPT invariance. This article reviews the conditions under which CPT symmetry holds by recalling two proofs of the CPT theorem: The original Lagrangian-based analysis and the more rigorous one in the context of axiomatic quantum field theory. The presentation of the proofs is followed by a discussion of the major physical implications that arise from CPT symmetry. Motivated by recent theoretical and experimental interest in CPT tests, various approaches to the violation of CPT symmetry are mentioned, and it is briefly discussed how they evade the CPT theorem. An attempt has been made to keep this work self-contained and at a level suitable for a wider readership by excising as many technical aspects as possible.

Keywords: CPT theorem; implications of CPT symmetry; CPT-symmetry violation

READ: R. Lehnert, CPT Symmetry and its violation, *Symmetry* 8 (2016) 11, 114

CPT tests based on particle/antiparticle comparisons

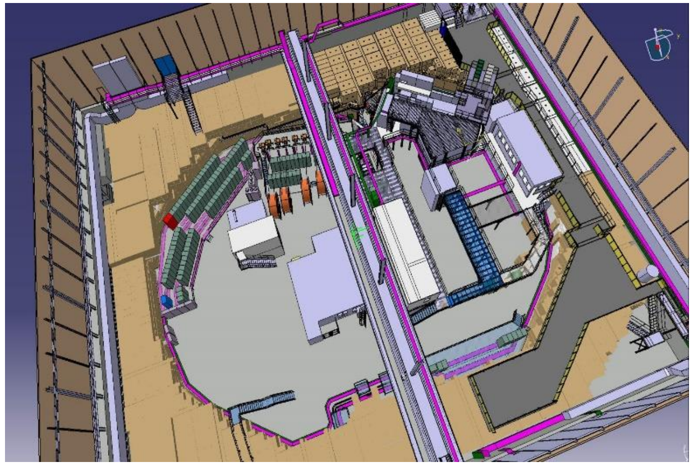
Recent
Past
Planned



CERN ALICE

CERN AD

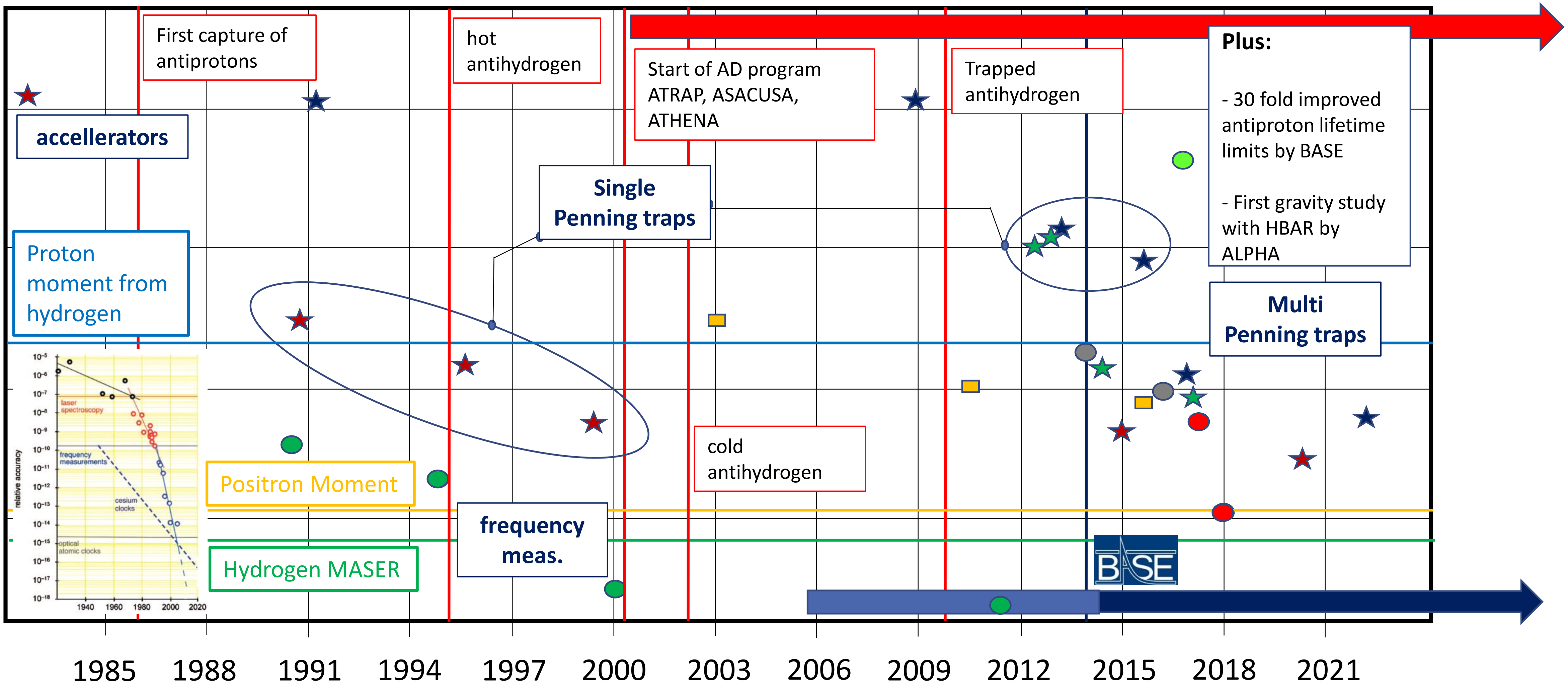
R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwingenheuer, et al., Phys. Rev. Lett. 74, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabrielse et al., PRL **82**, 3199(1999).
J. DiSciacca et al., PRL **110**, 130801 (2013).
S. Ulmer 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 et al., Nat. Comm. **8**, 14084 (2017).
M. Ahmadi et al., Nature **541**, 506 (2017).
M. Ahmadi et al., Nature **586**, doi:10.1038/s41586-018-0017 (2018).



CPT test with fractional precision of 10^{-18} available… why continue measuring?

Historical Milestones

● Hydrogen 1S2S
● HBAR 1S2S
★ Proton moment
★ PBAR moment
★ Proton/PBAR mass



First capture of antiprotons

hot antihydrogen

Start of AD program ATRAP, ASACUSA, ATHENA

Trapped antihydrogen

Plus:

- 30 fold improved antiproton lifetime limits by BASE
- First gravity study with HBAR by ALPHA

accellerators

Single Penning traps

Proton moment from hydrogen

Multi Penning traps

Positron Moment

cold antihydrogen

frequency meas.

Hydrogen MASER

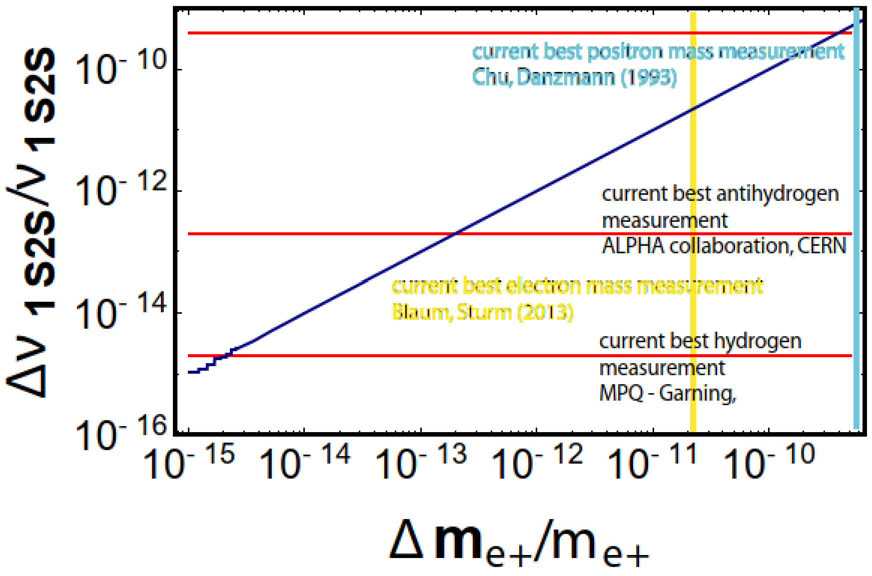
● HBAR GSHFS
● HBAR GSHFS
■ PBAR/He

CPT Tests at CERN – Masses and Spectra

- Antihydrogen

*ALPHA Collaboration, Nature, **557**, 71, (2018)*)

$$\nu_{n,k} = \frac{1}{2} m_e \left(\frac{1}{1 + m_e/m_p} \right) c^2 \alpha^2 \left(\frac{1}{n^2} - \frac{1}{k^2} \right)$$

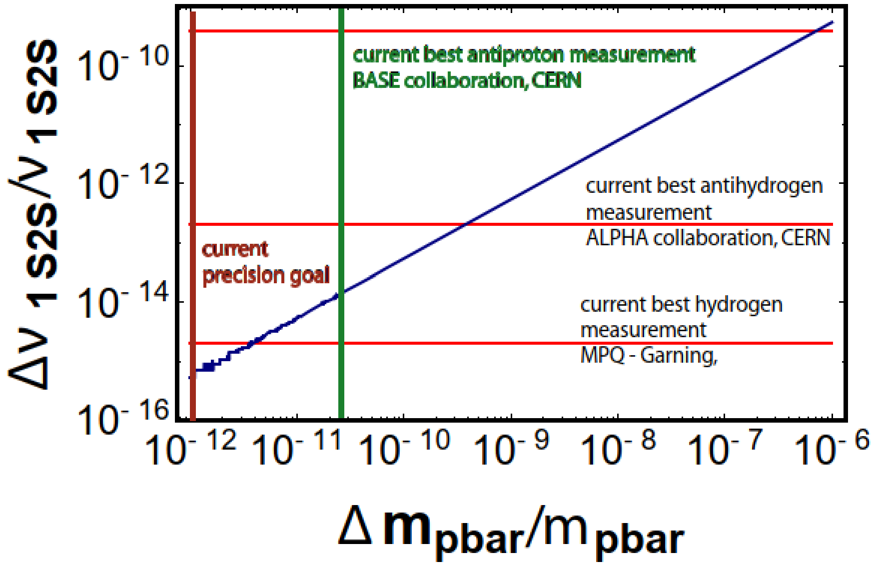


- HBAR -> sensitive to positron properties

See talks by J. Hangst and S. Eriksson

- Antiprotons

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$



- pbar -> sensitive to antiproton properties

See here and talk by M. Hori

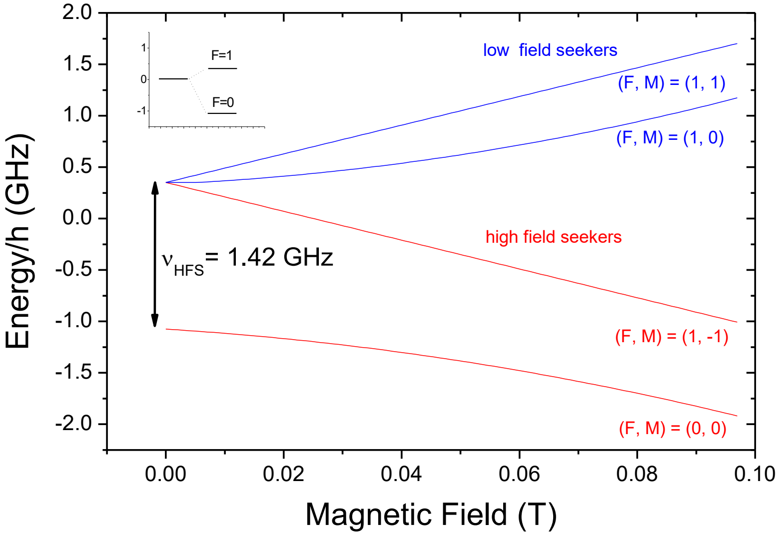
Ground State Hyperfine Splitting

Transition Frequency

1ppb

$$\nu_{\mathrm{HF}} = \boxed{\frac{16}{3}\cdot \mathrm{Ry}\cdot\alpha^2 c\cdot\left(\frac{1}{1+\frac{m_e}{m_p}}\right)^3\cdot\frac{m_e}{m_p}\cdot\frac{\mu_e}{\mu_B}}\cdot\boxed{\frac{\mu_p}{\mu_N}}\cdot(1+\delta_{str}+\delta_{QED})$$

<1ppb



	experiment (Hz)	Δνexp /ν	|νtheory-νexp |/ν
ν_{HFS}	1,420,405,751.768(1)	6.3 x 10^{-13}	(3.5+0.9) x 10^{-5}

Combination of antihydrogen GS-HFS (ASACUSA / ALPHA) and antiproton magnetic moment (BASE / ATRAP)

-> ppm measurements of GS-HFS will enable comparison of proton and antiproton substructure

ASACUSA CUSP group (Y. Yamazaki, E. Widmann)

Antihydrogen production in a CUSP trap
Y. Enomoto et. al., Phys. Rev. Lett. (2010).

A source of antihydrogen for in-flight hyperfine spectroscopy
N. Kuroda et. al., Nature Comms. (2014).

First GS-HFS measurement by the ALPHA collaboration with a fractional precision 350 ppm.

ALPHA collaborarion, Nature 548, 66 (2017).

Limits on Exotic Physics – ONE example

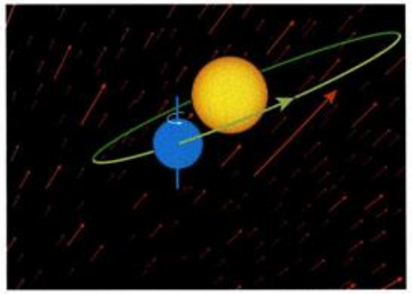
- Test the Standard Model (CPT invariance) by comparing the fundamental properties of protons and antiprotons with high precision

$$\left(\boxed{i\gamma^{\mu}D_{\mu} - m} - \boxed{a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_5\gamma^{\mu}}\right)\psi = 0$$

Dirac equation CPT-odd modifications

$$\boldsymbol{H\,\psi = (H_0 + V_{exotic})\,\psi}$$

$$\boldsymbol{\Delta E_{exotic} = \langle\psi|V_{exotic}|\psi\rangle}$$



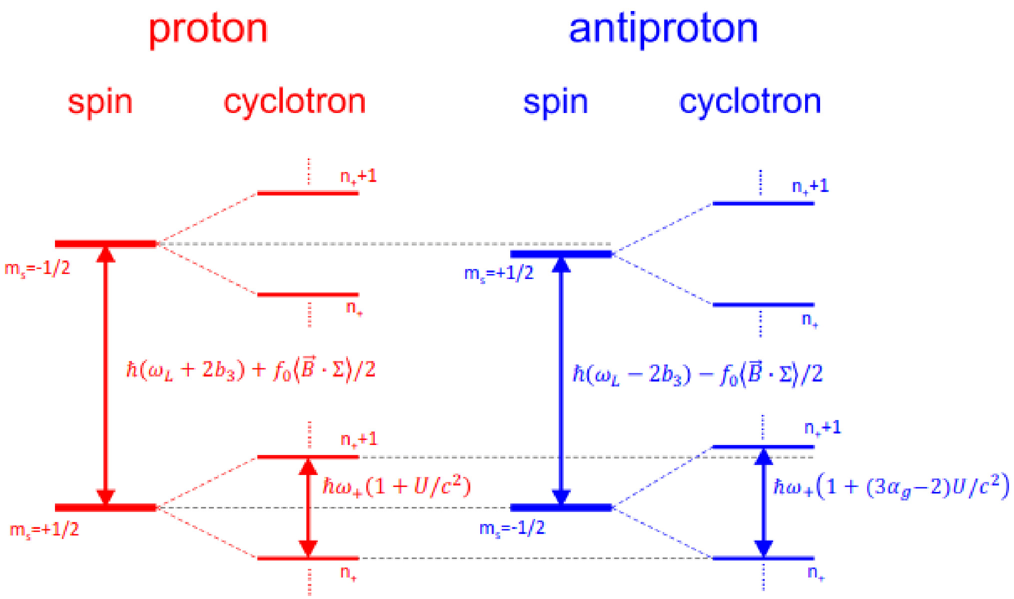
$$b_{\mu}\gamma_5\gamma^{\mu} \rightarrow b_x\begin{pmatrix} -\boldsymbol{\sigma_x} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\sigma_x} \end{pmatrix} + b_y\begin{pmatrix} -\boldsymbol{\sigma_y} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\sigma_y} \end{pmatrix} + b_z\begin{pmatrix} -\boldsymbol{\sigma_z} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\sigma_z} \end{pmatrix}$$

Pseudo-magnetic field, with different coupling to matter and antimatter, respectively

$$\Delta V_{int} = \widetilde{b_{z,D}}\begin{pmatrix} \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \pm\boldsymbol{\sigma_z} \end{pmatrix}$$

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

Would correspond to the discovery of a boson field which exclusively couples to antimatter.



sensitive: comparisons of particle/antiparticle magnetic moments in traps

These Measurements Explore the Unknown

- Summary: Almost all these experiments measure frequencies
- With these experiments we “listen” to the sound of what actually does not exist in our universe. Apart from predictions (which are mostly defined by our experience with matter), we may find some additional surprises.
- We test CPT, which is the last discrete fundamental symmetry operation of the Standard Model which holds.

$$\psi(r) = \frac{g_c}{r} e^{-r/R_0}$$

HEP: Direct production of exchange bosons

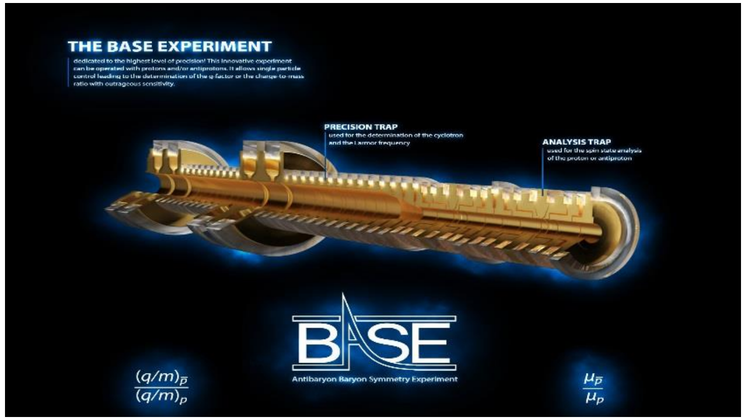
$$R_0 = \frac{h}{mc}$$

LEP: search for effects mediated by not yet directly discovered exchange bosons

A special place (in the universe?) – the BASE trap

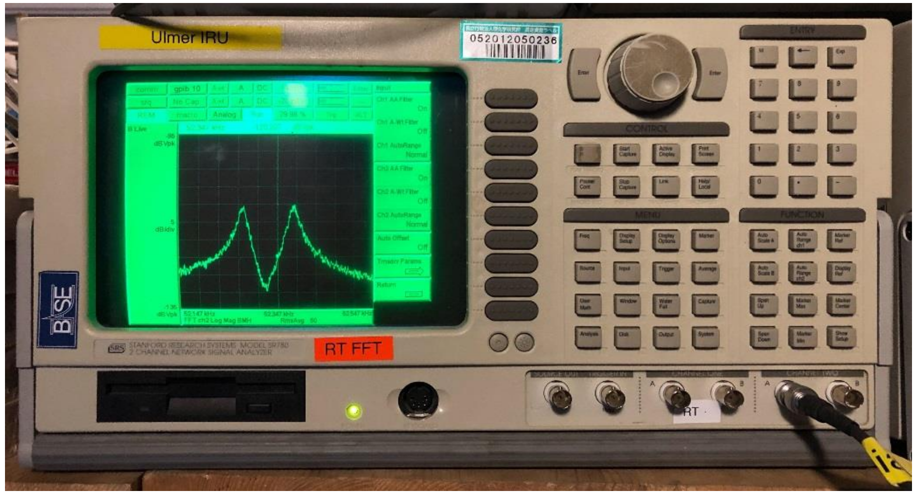
405 day of antiproton-cloud trapping demonstrated

- We have
  - A vacuum of 5e-19 mbars
    - best characterized vacuum on earth,
    - comparable to pressures in the interstellar medium
  - Antiproton storage times of several 10 years.
  - Not more than 3000 atoms in a vacuum volume of 0.5l
  - Order 100 to 1000 trapped antiprotons
  - A local inversion of the baryon asymmetry


THE BASE EXPERIMENT

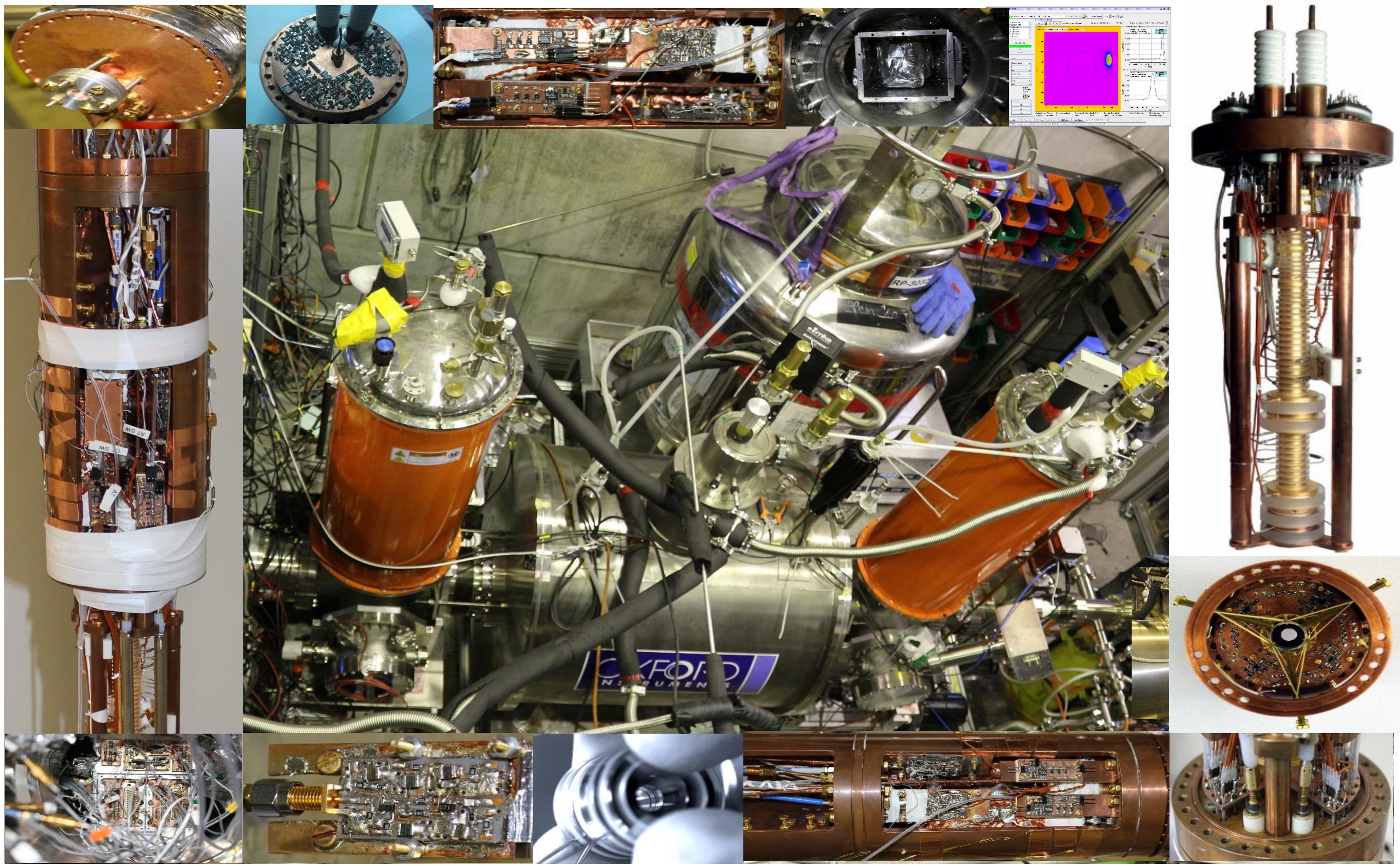
dedicated to the highest level of precision! This innovative experiment can be operated with protons and/or antiprotons. It allows single particle control leading to the determination of the g-factor or the charge-to-mass ratio with outrageous sensitivity.

BASE ANTIMATTER INVERSION	
local volume	0.0001^3 m^3
Baryons in local trap volume	$1.65*10^{-7}$
Antibaryon in local trap volume	100
Antibaryon/Baryon Ratio	**$5.9*10^8$**
Ratio Inversion	**$3.8*10^{12}$**



With this instrument: Investigate properties of antimatter very precisely

Experiment



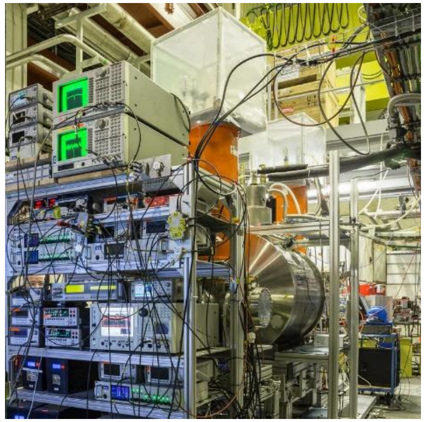
Common to all these experiments:

Superconducting magnets

Ultra sensitive superconducting partice detectors

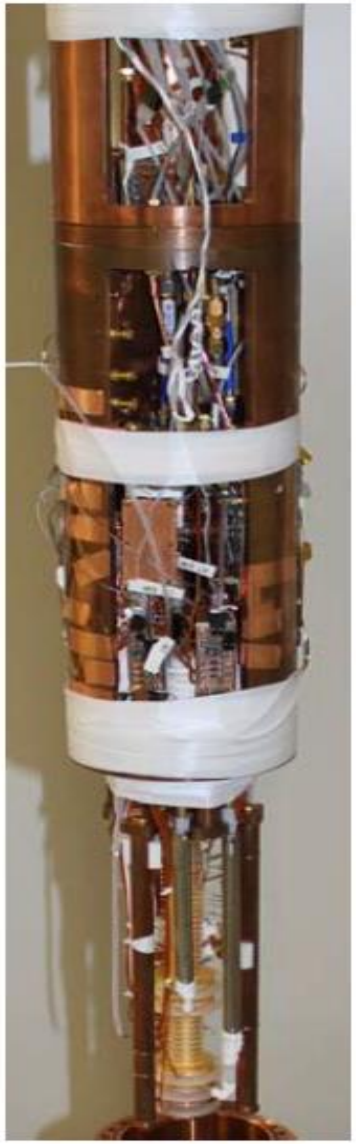
Cryogenic operation of experiments

Use of «complex» multi-trap systems



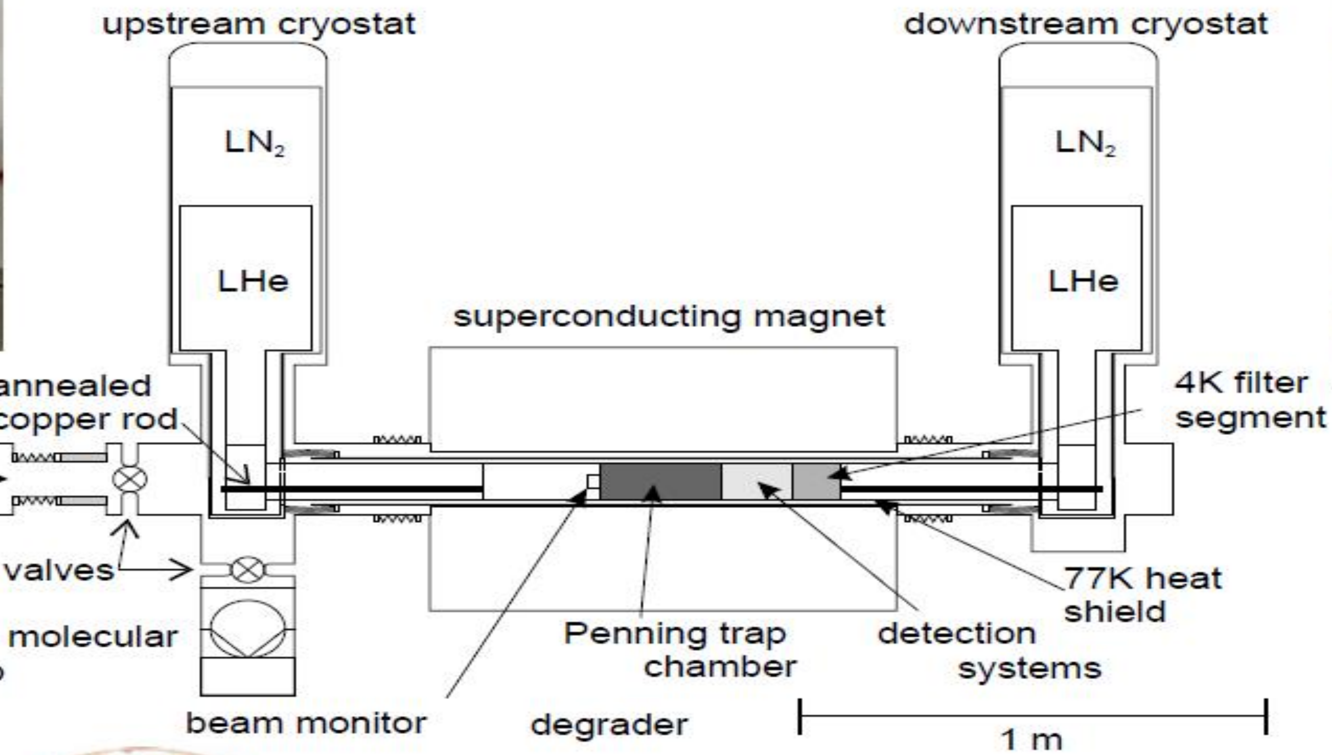
Penning trap stack

4K stage

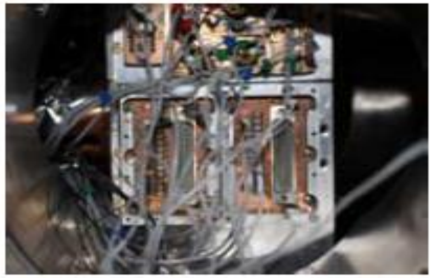


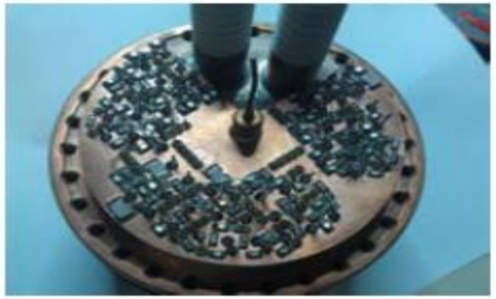
two detectors

DC/RF-interface



filter electronics



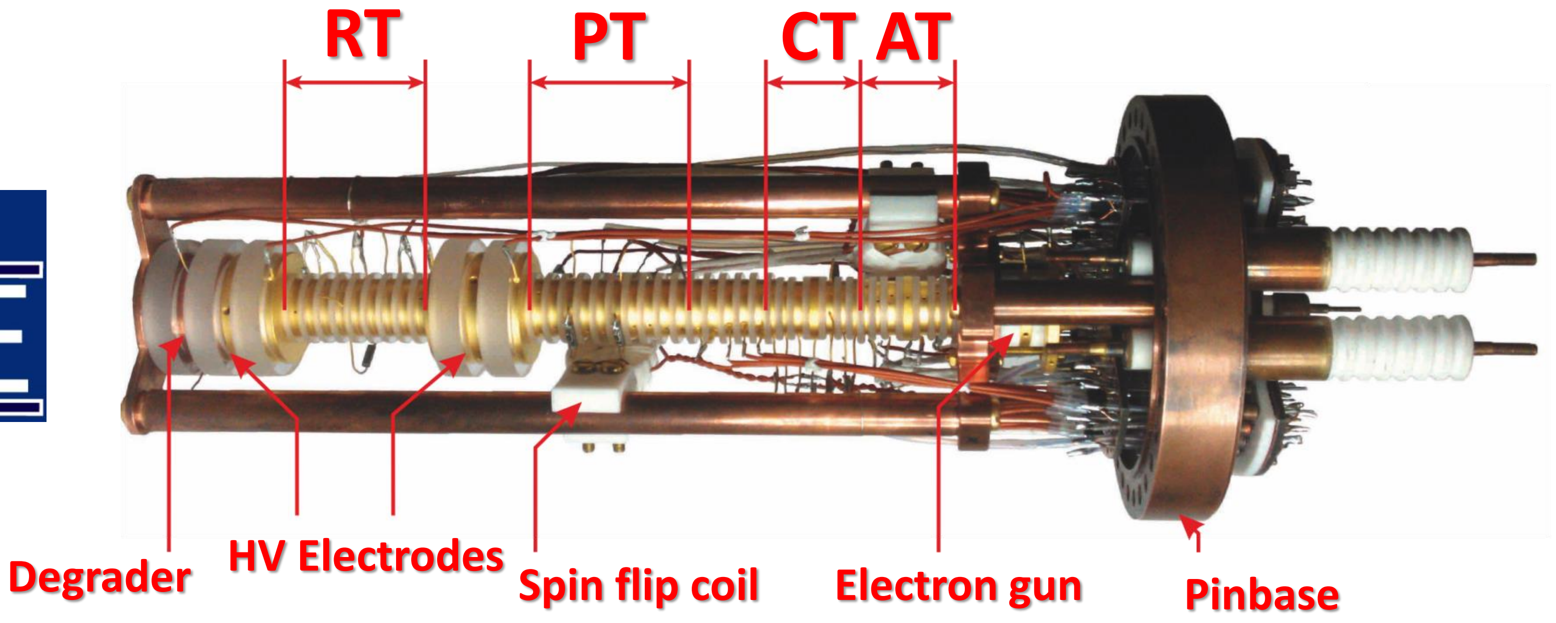


BASE Trap System

Access to beamline

Particles not continuously available

Trap for efficient cyclotron cooling



Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.
Trap is “power failure save”.

Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$ **(10 x improved)**

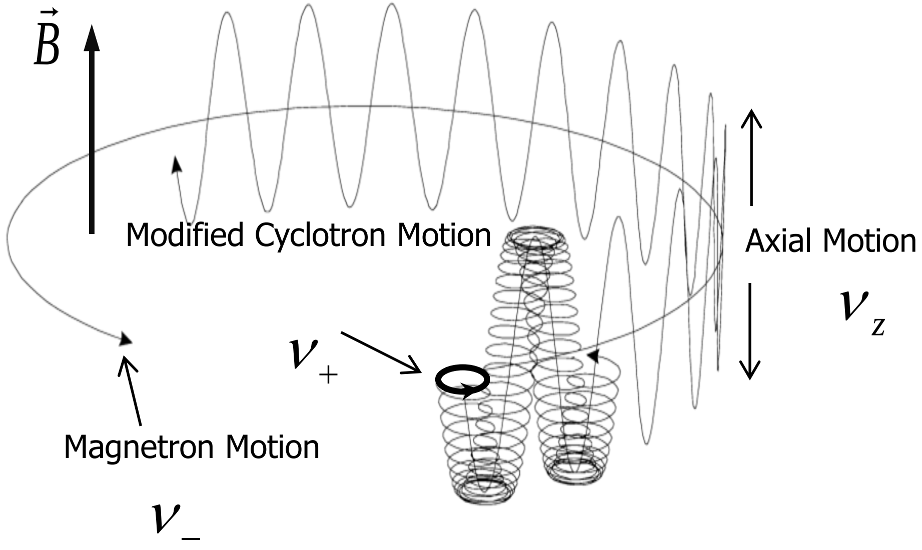
Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4$ s **(10 x improved)**

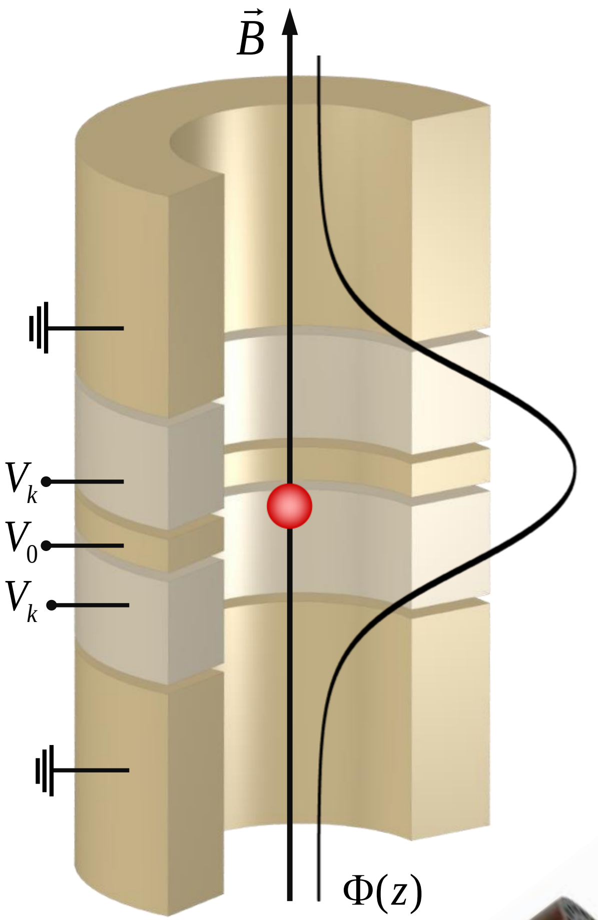
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300\ mT / mm^2$

Main Tool: Penning Trap

radial confinement: $\vec{B} = B_0 \hat{z}$

axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$

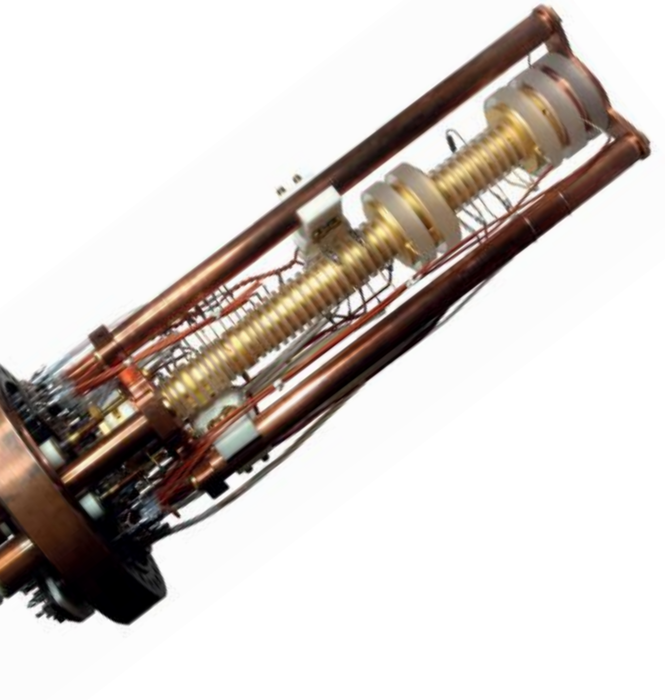




$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{2C_2 q V_0}{m}}$$

$$\nu_+ = \frac{1}{2}\left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$

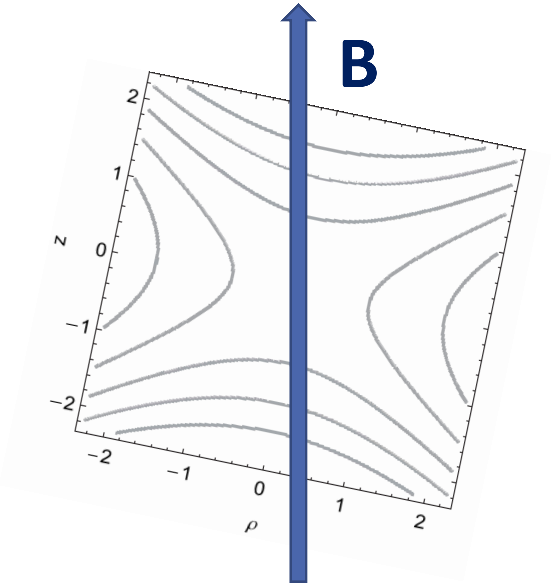
$$\nu_- = \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$



Axial	$\nu_z = 680\,\mathrm{kHz}$
Magnetron	$\nu_- = 8\,\mathrm{kHz}$
Modified Cyclotron	$\nu_+ = 28{,}9\,\mathrm{MHz}$

The Invariance Theorem

$$\left.\begin{aligned}\nu_z &= \frac{1}{2\pi}\sqrt{\frac{2C_2 q V_0}{m}}\\ \nu_+ &= \frac{1}{2}\left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)\\ \nu_- &= \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)\end{aligned}\right\}$$



In case of misalignment of B and V(z,r), and in case of elliptical modifications of the trapping potential (dominant first order shifts in traps) the individual frequency modifications compensate in the square sum of the frequencies exactly

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

Gives undisturbed access to cyclotron frequencies

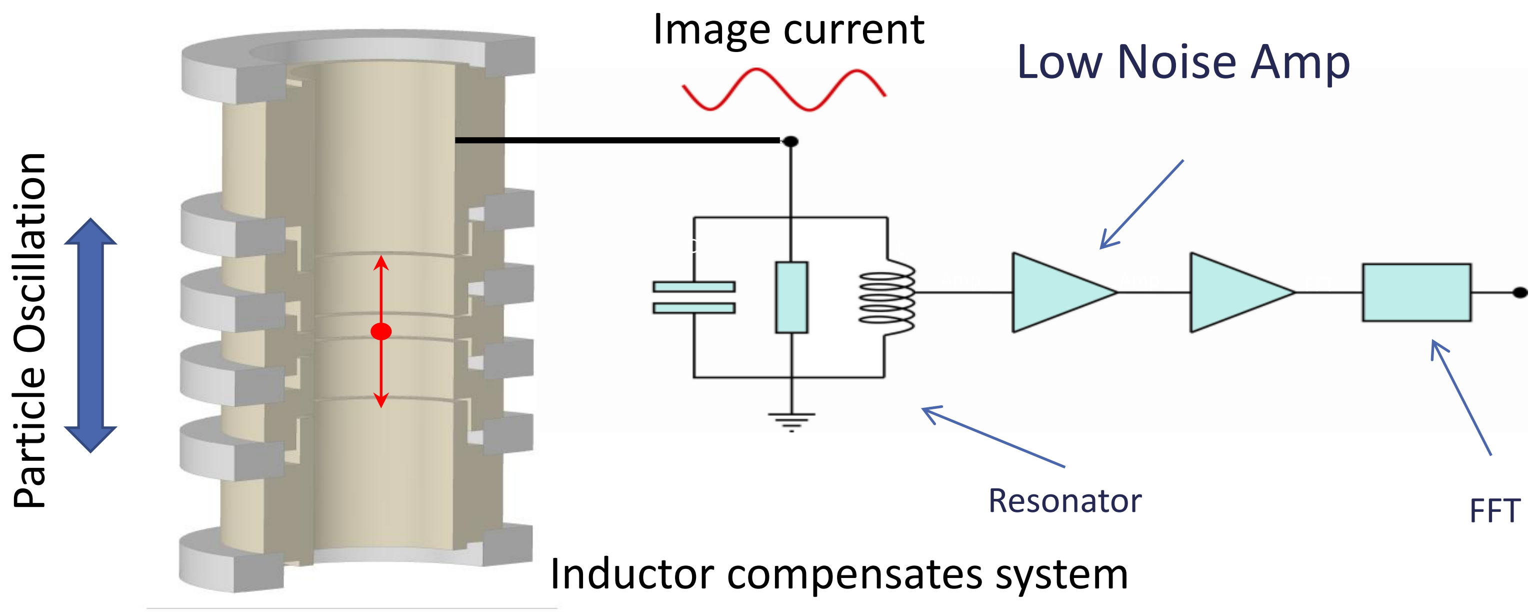
$$\boxed{\nu_c = \frac{1}{2\pi}\frac{q_{ion}}{m_{ion}}B}$$

- Note: all other systematic shifts need to be characterized out

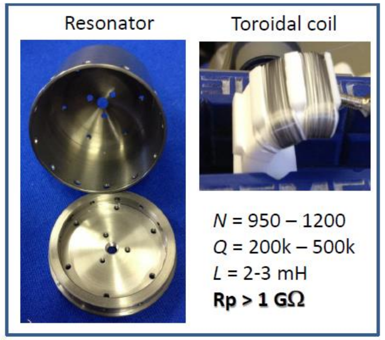
Effect	Magnitude
Magnetic Gradient	p.p.t. to 100 p.p.t.
Magnetic Bottle	50 p.p.t. /K
Trap Potential	usually negligible
Relativistic	p.p.b./eV
Image Charge	10 p.p.t. to 100 p.p.t.
Technical drifts (B/V)	p.p.b./h

Frequency Measurements in Penning Traps

- Concept of image current detection

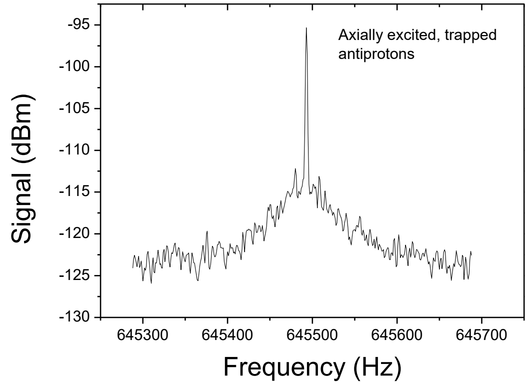


Inductor compensates system capacitance



$$I_{p,x} \sim \frac{q}{D_{eff}}(2\pi\nu_x)x$$

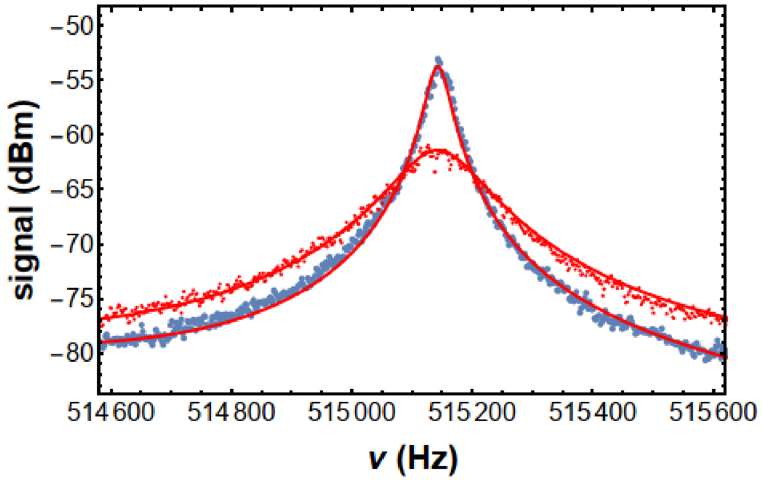
$$I_{p,x} \sim 0.1\ fA\ /(MHz\ \mu m)$$



- Resonant Detection

$$R_p = Q(2\pi\nu_x L)$$

$$R_p = 100\ M\Omega \text{ to } 500\ M\Omega$$



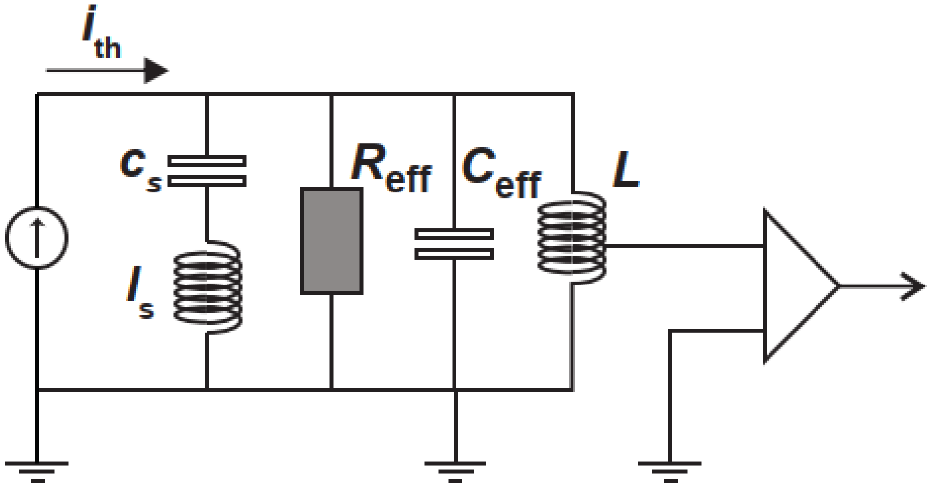
- Voltage drops of order

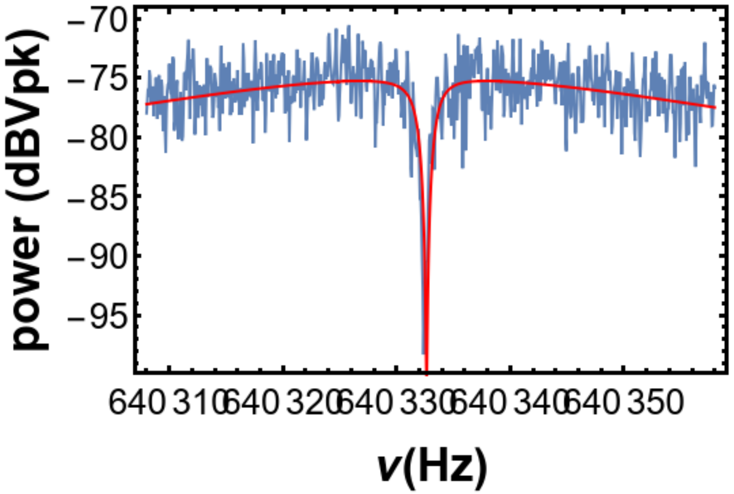
$$U_{p,x} \sim 10\ nV\ /(MHz\ \mu m)$$

H. Nagahama, Rev. Sci. Instum. 87, 113305 (2016)

Thermal Equilibrium Measurements

- Interesting and useful aspect of particle / detector interaction
  - An undisturbed particle in a Penning trap is a perfect conductor
  - Once particle is tuned to resonance with the detection system it will short the thermal noise in parallel



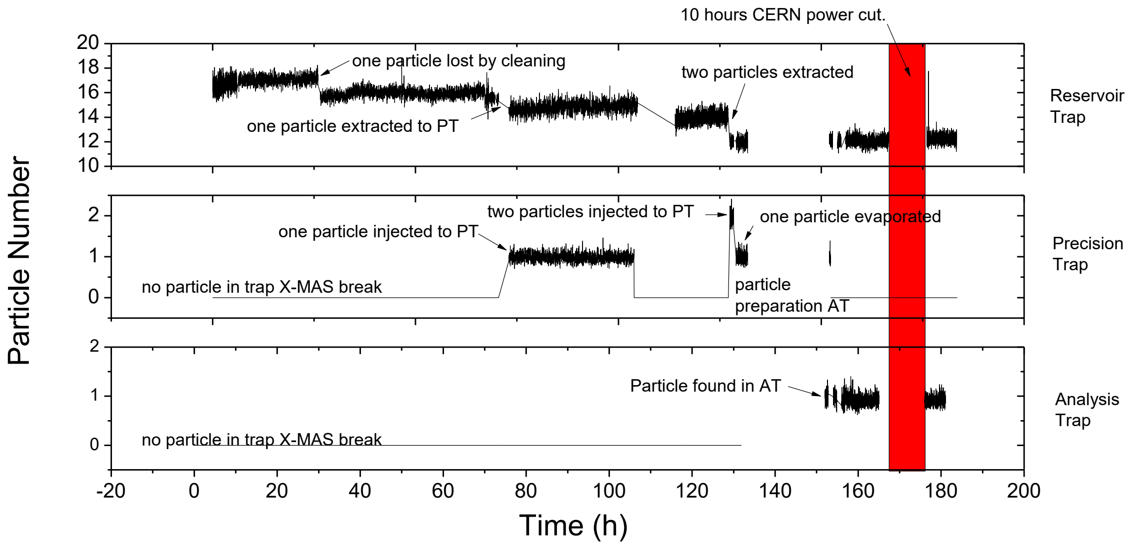


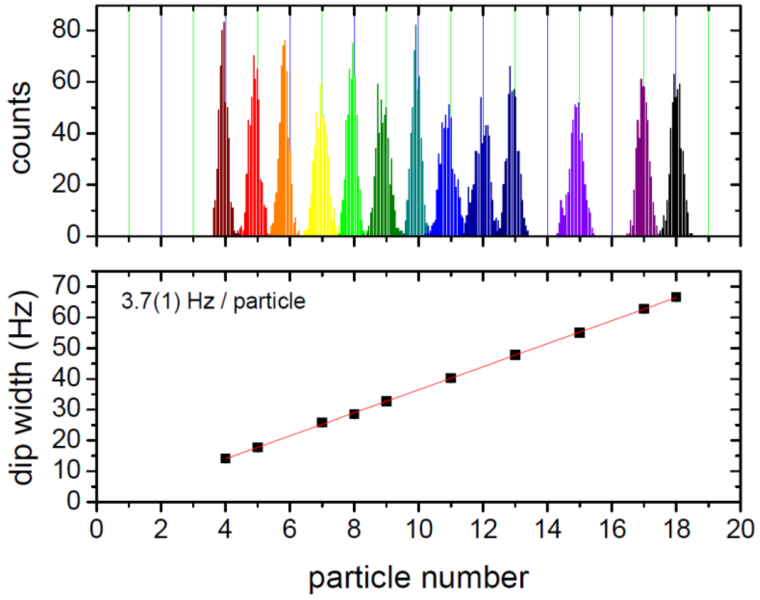
- Measures axial frequency of the particle in thermal equilibrium with detection system.

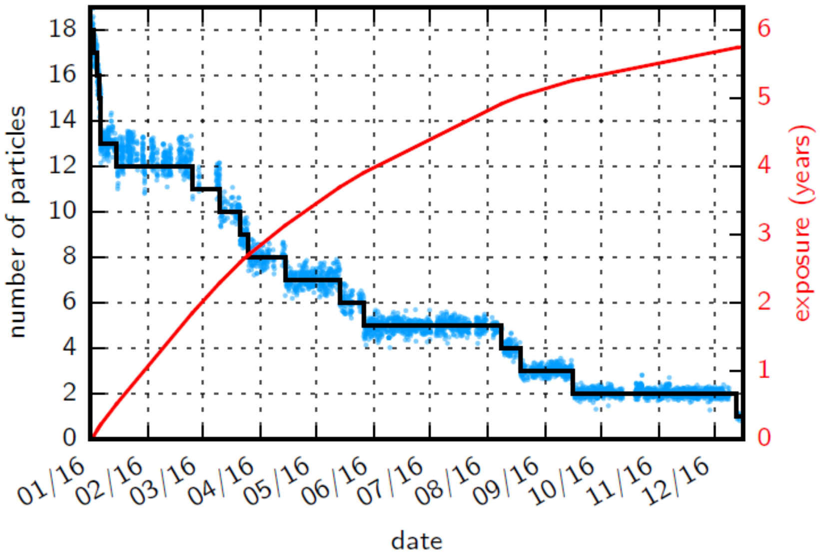
- Useful to count particles in traps and to characterize whether a trap is clean

$$\Delta \nu = \frac{1}{2\pi} \frac{R}{m} \left(\frac{q}{D} \right)^2 \cdot N$$

Application Antiproton Lifetime Constraints







Experiment has been operated with antiprotons trapped in October 2015 for more than 400 days.

Measurement provides most stringent direct limit on lifetime of the antiproton

Best pressure-limit ever characterized by measurement 5*10^{-19} mbar

S. Sellner et al., New Journ. Phys. 083023 (2017)

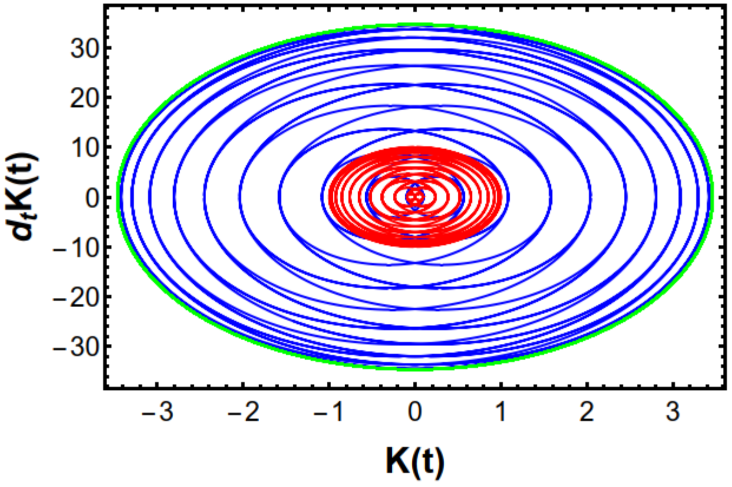
Sideband Measurements

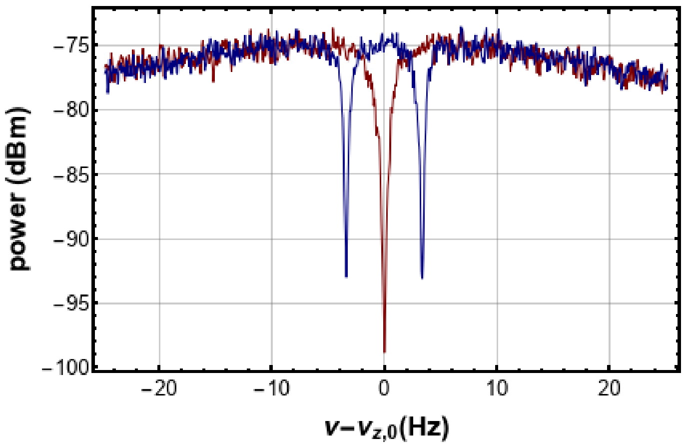
- Induce mode coupling by irradiating a drive which couples coordinates

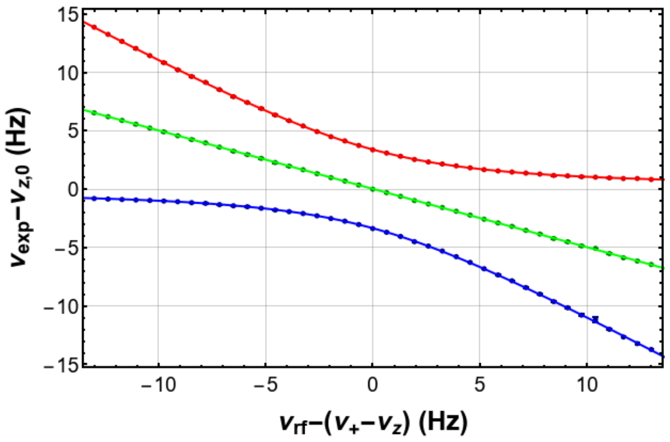
$$\frac{d^2}{dt^2}z+\omega_z^2 z=\frac{qE_0}{m}\cos\left(\omega_{\rm rf}t\right)r$$

$$\frac{d^2}{dt^2}r+\omega_+^2 r=\frac{qE_0}{m}\cos\left(\omega_{\rm rf}t\right)z$$

$$z(t)=\sqrt{\omega_z}\exp\left(-i\omega_z t\right)\left(\left(\cos\left(\frac{1}{2}\sqrt{\Omega^2+\delta^2 t}\right)-\frac{\delta}{\sqrt{\Omega^2+\delta^2}}\sin\left(\frac{1}{2}\sqrt{\Omega^2+\delta^2 t}\right)\right)\right)$$







- Induce mode coupling by irradiating a drive which couples coordinates

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

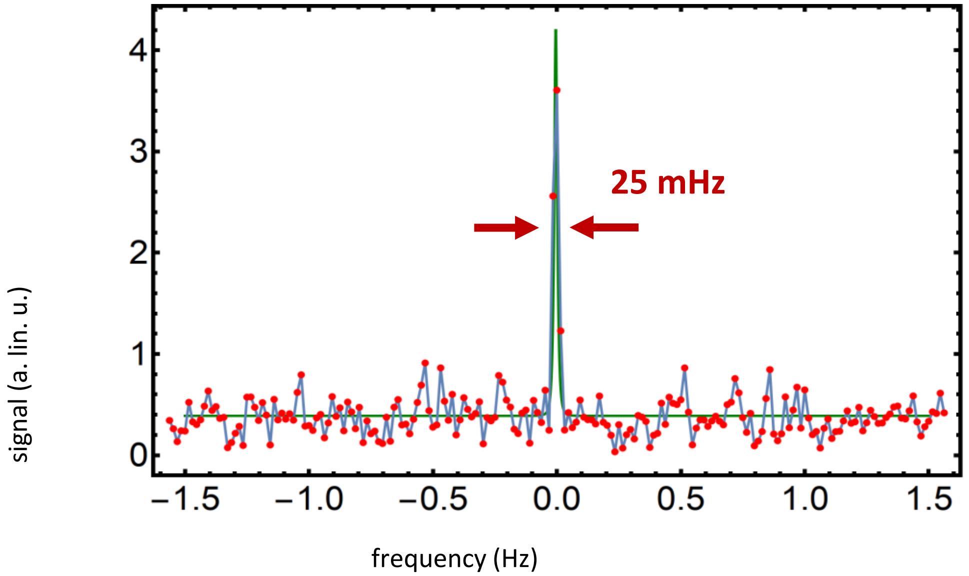
$$\boxed{\nu_c=\frac{1}{2\pi}\frac{q_{ion}}{m_{ion}}B}$$

E. A. Cornell et al., Phys. Rev. A 41, 312 (1990)

Other Frequency Measurement Methods

- Direct Peak Detection
  - direct measurement of modified cyclotron frequency using peak detection

Groups: Gabrielse (TRAP), BASE

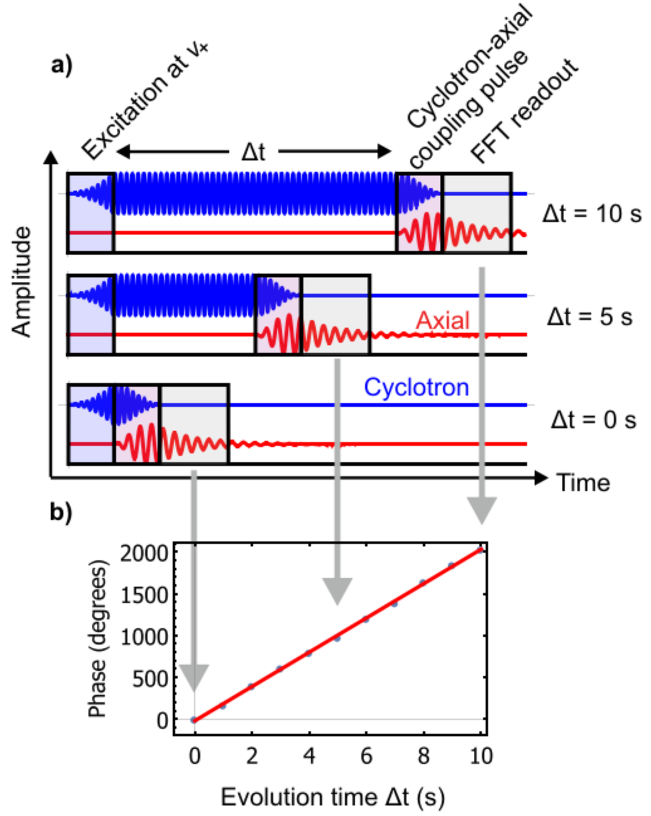


- Nice to track magnetic field but comes with considerable systematics which requires careful control

PhD Thesis J. A. Harrington

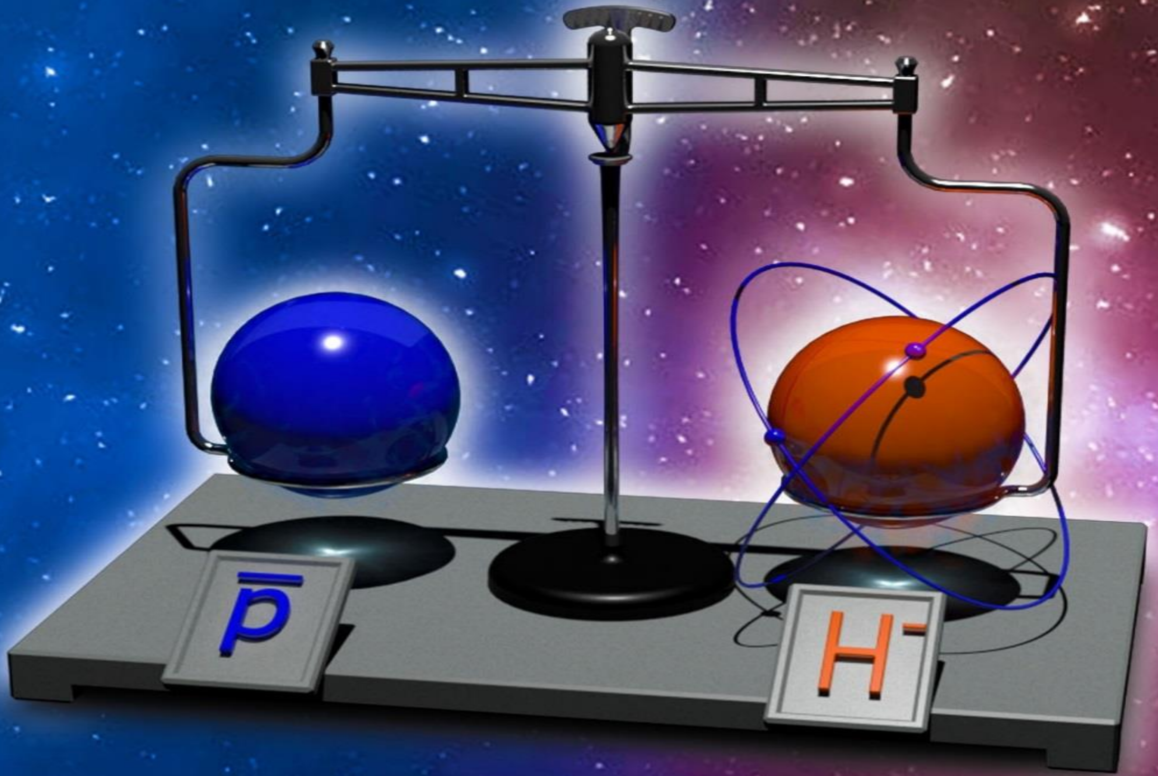
- Phase Methods

Groups: Pritchard, Myers, Sturm, Blaum, BASE



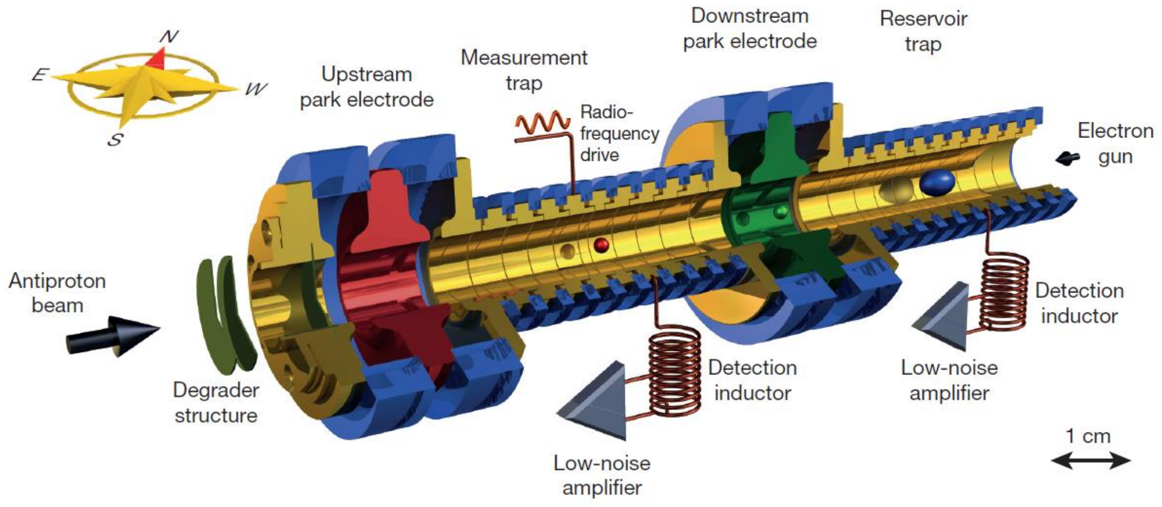
- Currently the method of choice in most precision trap experiments, requires however a basic background stability which is not necessarily given in an accelerator hall

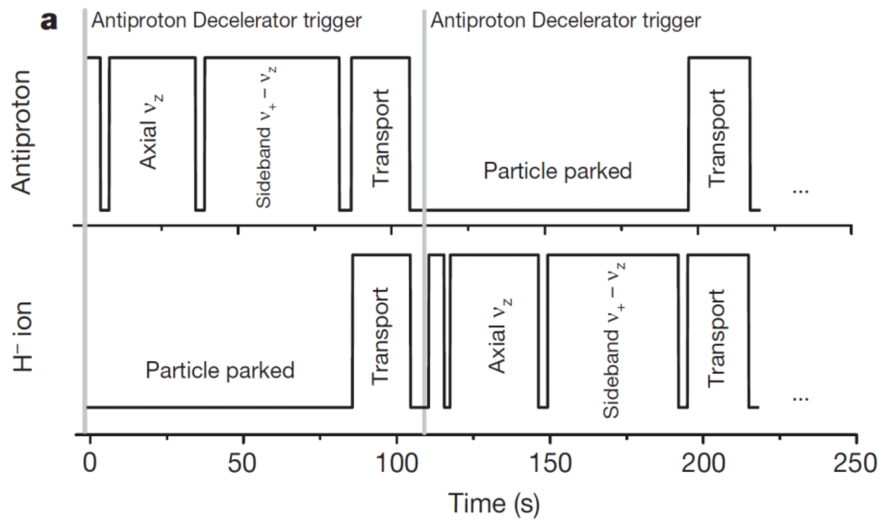
High-Precision Comparison of the



Antiproton-to-Proton Charge-to-Mass Ratio

BASE Specialties: Fast Shuttling Technique





Are able to prepare single particles upstream and downstream of a measurement trap and interchange the particles rapidly.

Invented: scheme to perform one cyclotron frequency ratio measurement within 4 minutes, which is 50 times faster than in any previous high-precision mass spectrometry experiment -> Higher statistics, improved precision.

Scheme can be applied to any arbitrary mass doublet and thus potential to improve arbitrary mass ratio measurements.

Interesting: proton in a.m.u. or 3He/Tritium.

Applied this scheme to measure proton/antiproton q/m ratio using antiprotons and **hydrogen ions.**

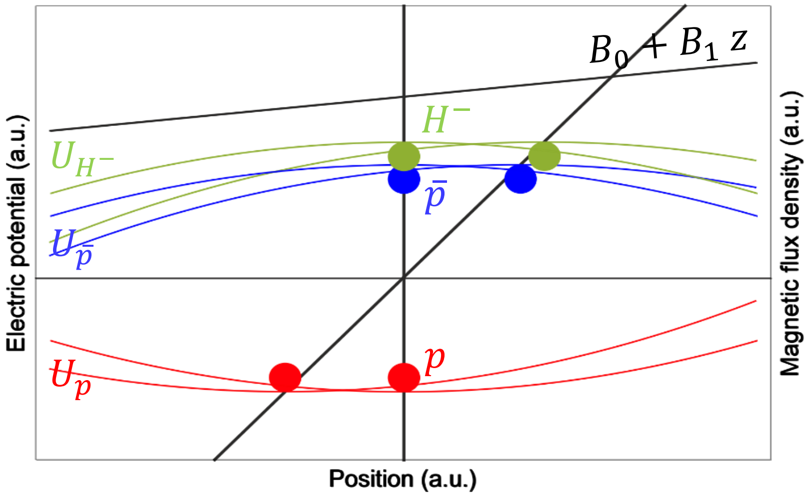
S. Ulmer et al., *Nature* **524** 196 (2015)

H$^-$ ions

- Slightly inhomogeneous magnetic field.
- Offset potentials on the electrodes of the cryogenic trap.

- Change of polarity leads to position shift of the particle.
- Systematic uncertainties due to the particle position are large (~10^{-9})

- For protons (polarity inversion (dV=10V)) much larger as for H- ions (dV=0.005V).



Take a ratio of measured cyclotron frequency of antiproton $\nu_{c\bar{p}}$ to H$^-$ ion ν_{cH^-} => reduces to antiproton to proton charge-to-mass ratio

Magnetic field cancels out!

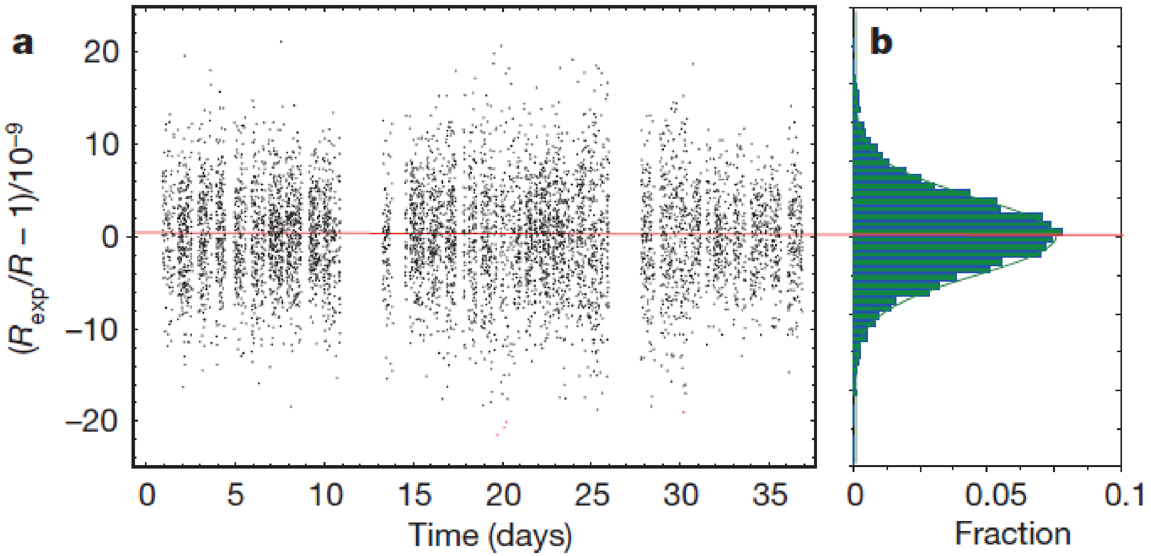
$$R = \frac{\nu_{c\bar{p}}}{\nu_{cH^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \text{x} \frac{\cancel{B/2\pi}}{\cancel{B/2\pi}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$

$$\boxed{m_{H^-} = m_p\left(1 + 2\frac{m_e}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p}\right)}$$

$$R_{theo} = 1.001\,089\,218\,754\,2(2)$$

G. Gabrielse, Phys. Rev. Lett 82, 3198 (1999)

BASE Measurements – Proton to Antiproton Q/M



Result of 6500 proton/antiproton Q/M comparisons:

$R_{\mathrm{exp,c}}$ = 1.001 089 218 755 (64) (26)

$$\boxed{\frac{(q/m)_{\bar{\mathrm{p}}}}{(q/m)_{\mathrm{p}}}+1=1(69)\times10^{-12}}$$

Stringent test of CPT invariance with Baryons.

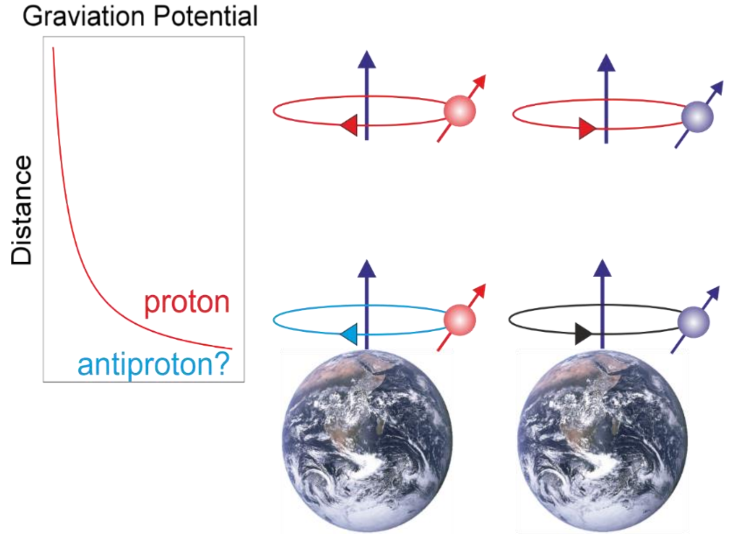
Consistent with CPT invariance

- Constrain of the gravitational anomaly for antiprotons:

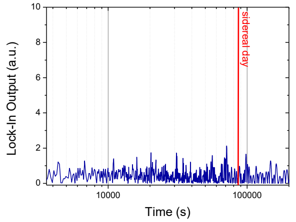
$$\frac{\omega_{c,p}-\omega_{c,\bar{p}}}{\omega_{c,p}}=-3(\alpha_g-1)\,U/c^2$$

Our 69ppt result sets a new upper limit of

$$|\alpha_g-1|<8.7\times10^{-7}$$



- Understanding: cosmological background field couples to particles -> Sidereal variations could be observed.

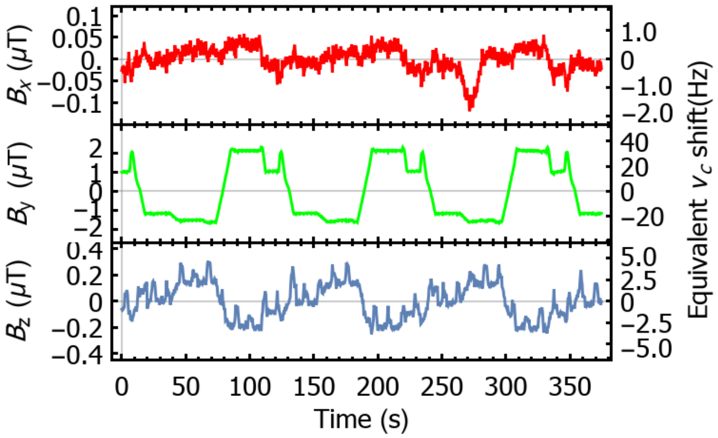


- Set limit of sidereal (diurnal) variations in proton/antiproton charge-to-mass ratios to < 0.72 ppb/day

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

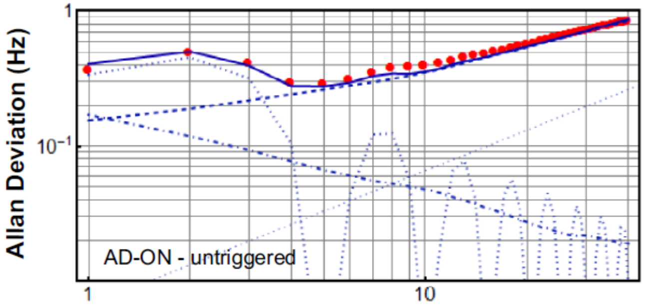
Systematics in an Accelerator Hall

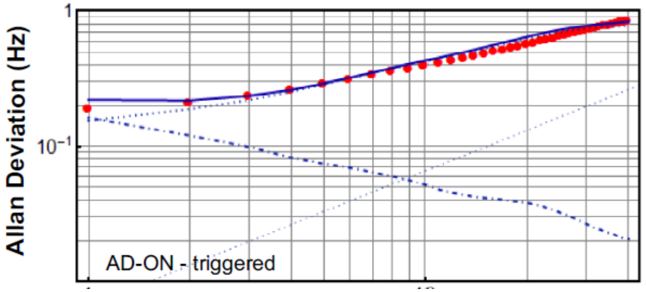
AD – Magnetic Noise

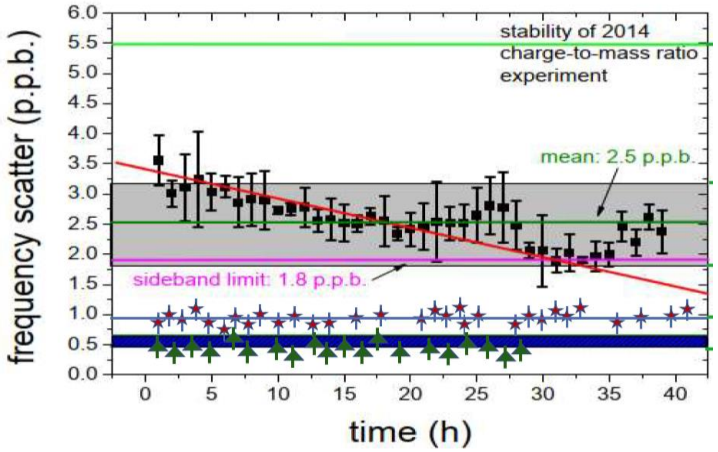


100 ppb fluctuation by the AD
Reduced by factor of 10 by SS-solenoid

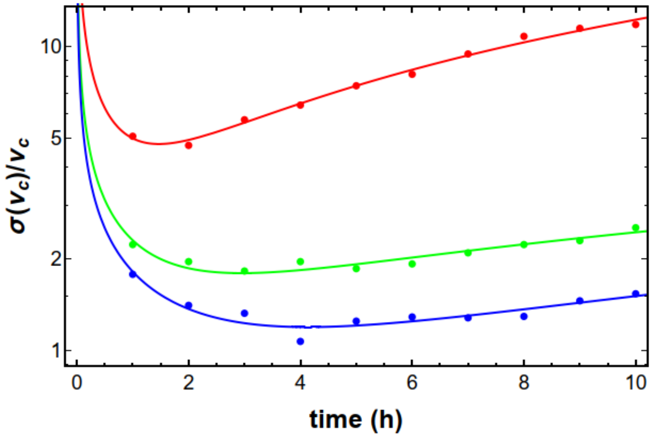
- High sampling rate enables us to perform detailed systematic studies
- Allan Deviations
  - AD on
  - AD on / triggered cycle
  - AD off







- Invented multi-layer self-shielding system
- Vibrational decoupling by rebuilding the apparatus
- More homogeneous magnetic field
- Improved detectors

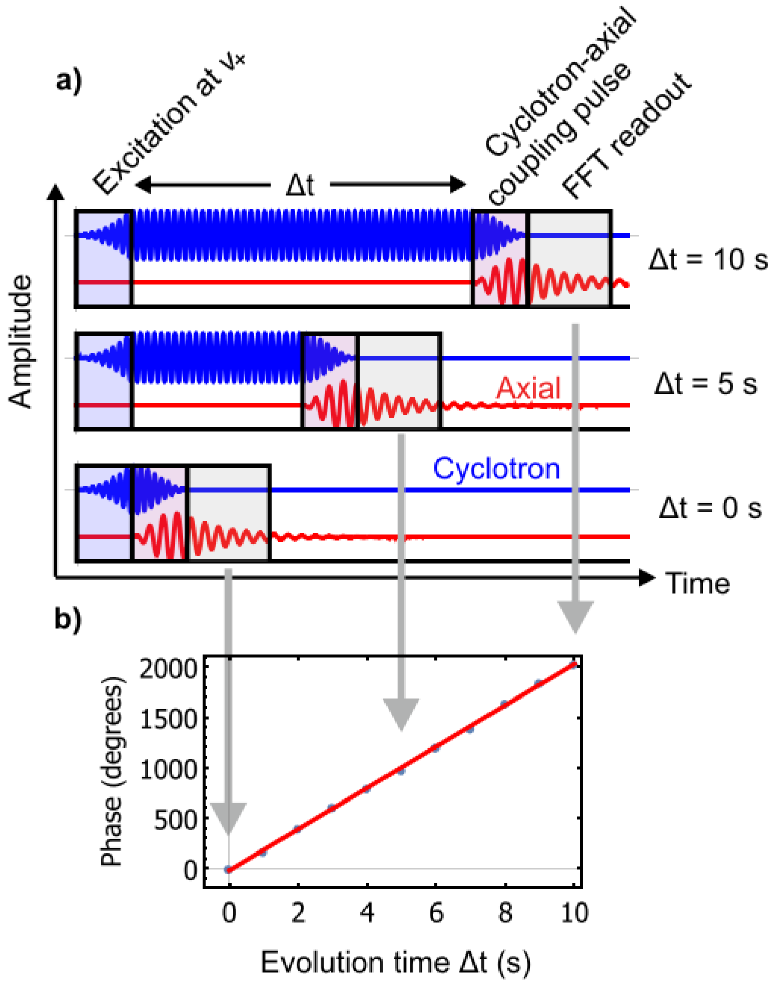


- Prepared to apply phase methods.

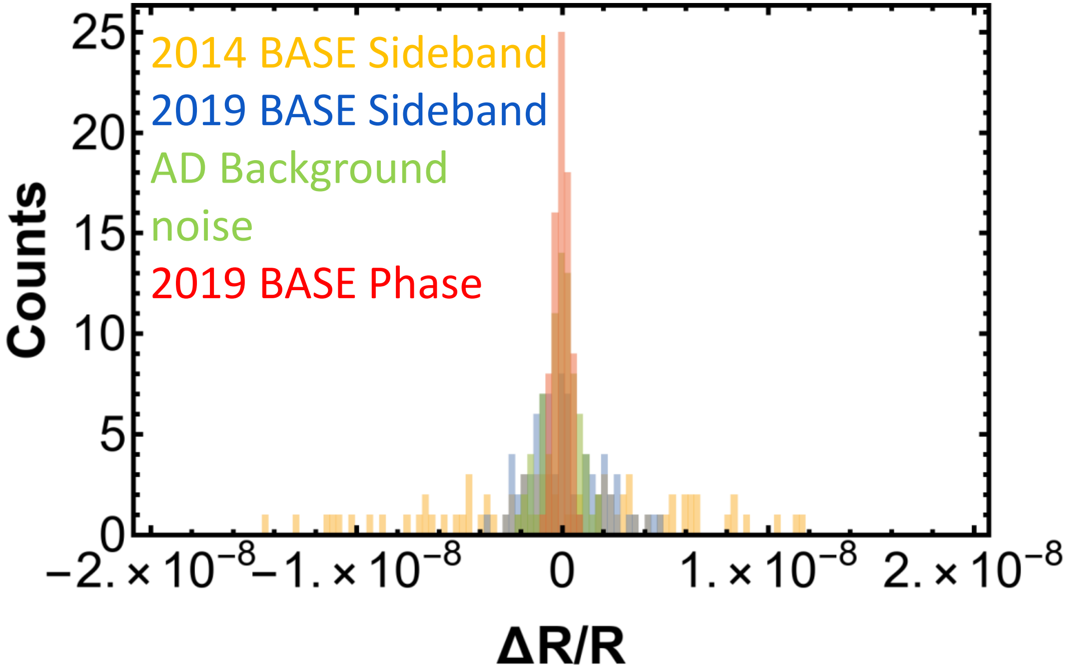
J. A. Devlin and E. Wursten, Phys. Rev. Appl. 12, 044012 (2019)

Partly content of PhD Thesis by M. J. Borchert

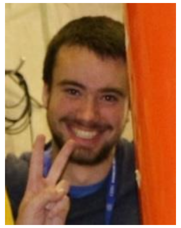
Implementation of Phase Sensitive Detection



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



J. Devlin
CERN/RIKEN

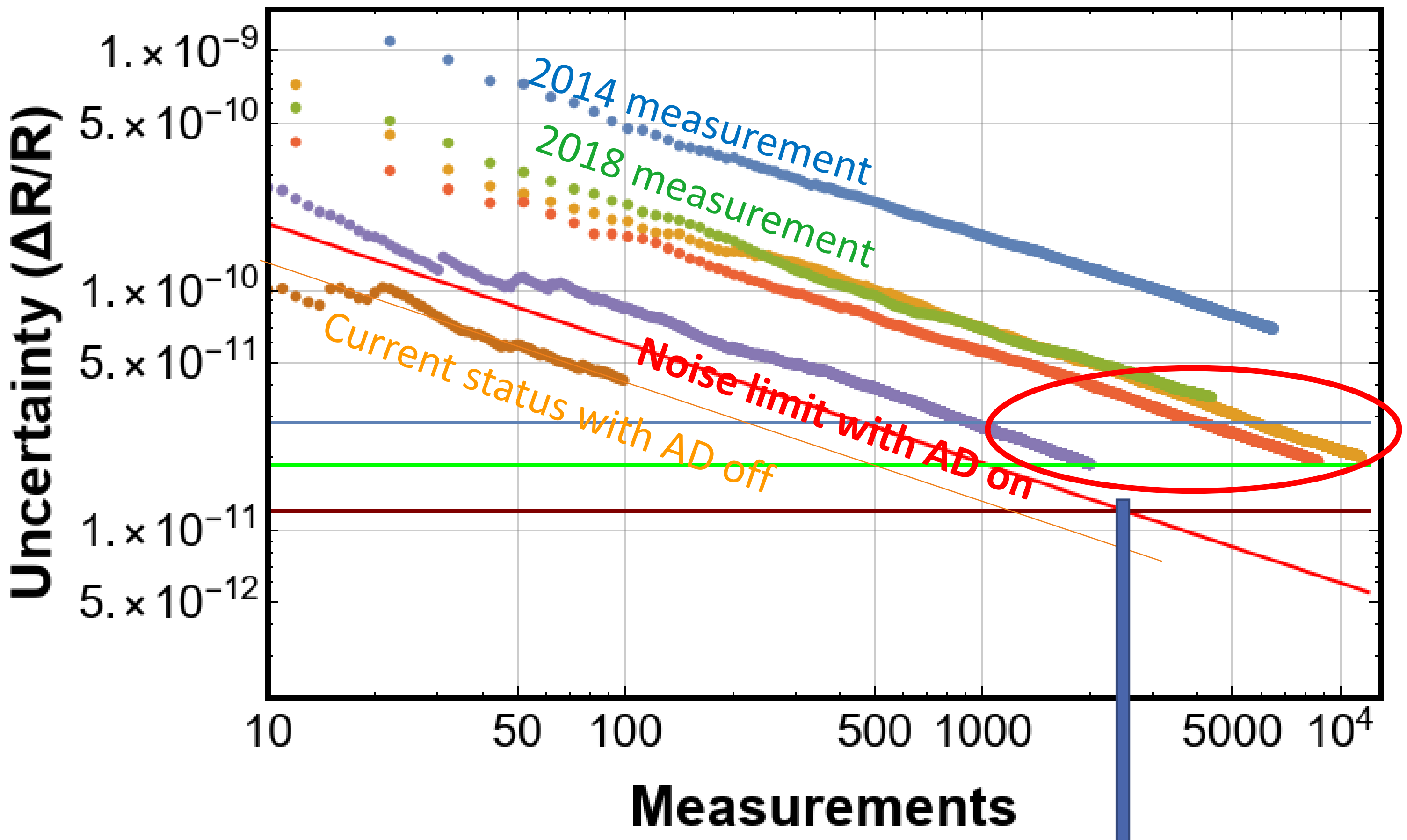


M. Borchert
Hannover/RIKEN

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

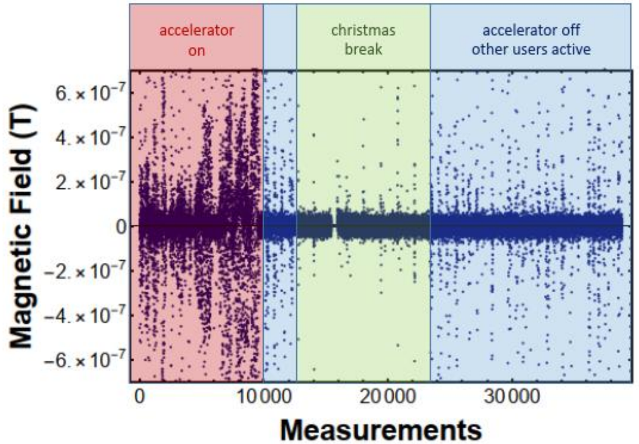
See Cornell, Thompson, Rainville, Myers, Sturm, Heisse, Blaum

Summary of Achievements



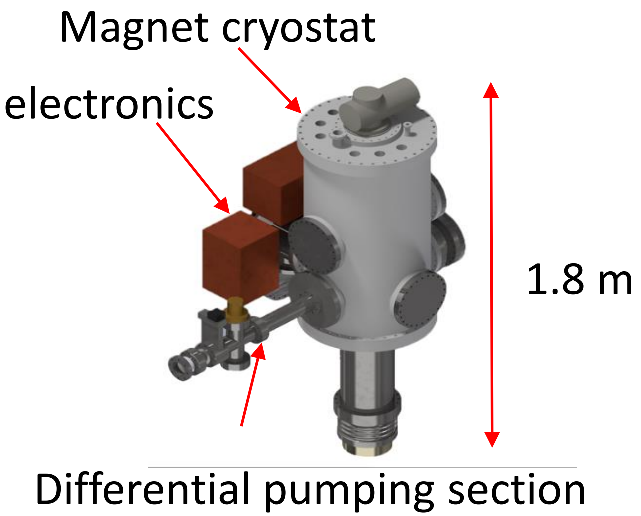
- Final resolution: 15 p.p.t. to 20 p.p.t.
- Goal of next measurement should be at the level of 1 p.p.t. to 5 p.p.t.
- Given the AD noise level of 600 p.p.t. this will require measurement time of years

Data currently under evaluation



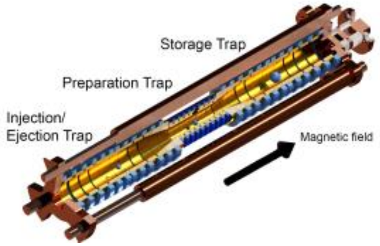
Partly content of PhD Thesis by J. A. Harrington

Transportable Trap – BASE STEP

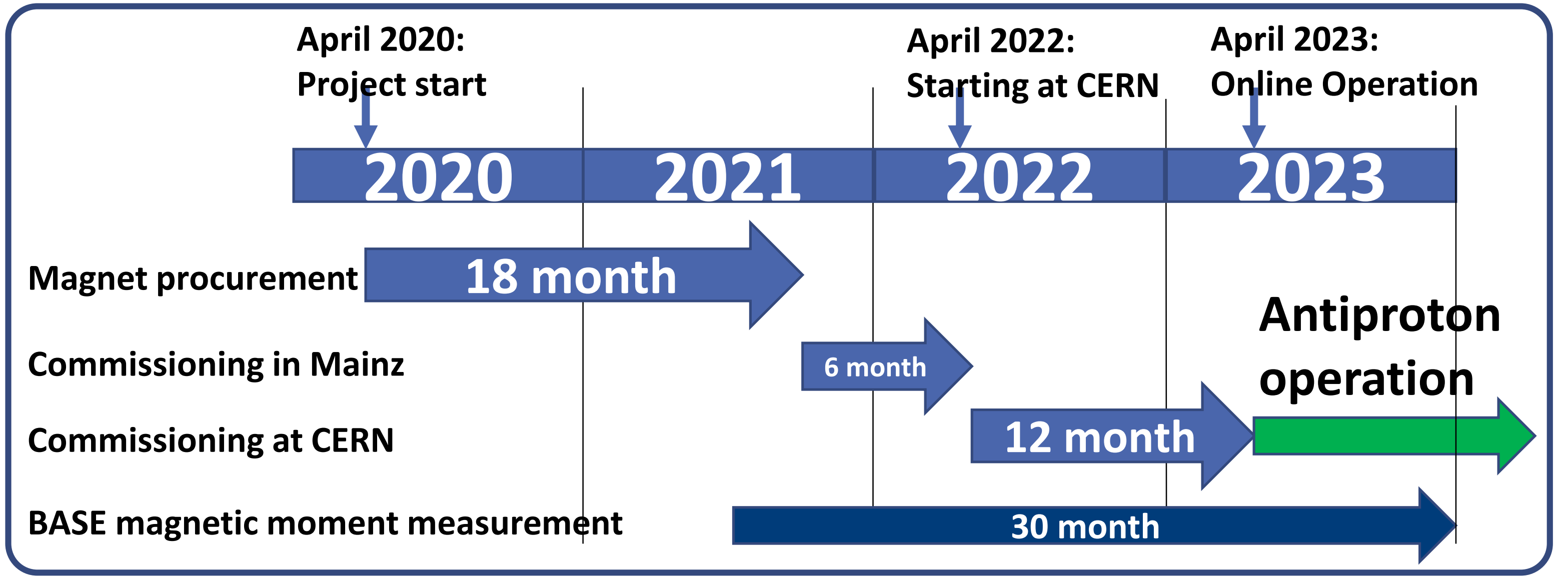


- Portable reservoir trap with 10000 antiprotons
- non-destructive extraction
- Emergency power connection desired
- „Compact“ design, weight below 1000 kg

All these methods have already been demonstrated by



Yet open: Extraction mechanism (under development at Mainz)



April 2020:
Project start

April 2022:
Starting at CERN

April 2023:
Online Operation

2020 **2021** **2022** **2023**

Magnet procurement — **18 month**

Commissioning in Mainz — **6 month**

Commissioning at CERN — **12 month**

Antiproton operation

BASE magnetic moment measurement — **30 month**

Christian Smorra

European Research Council
Established by the European Commission

The Antiproton Magnetic Moment

A milestone measurement in antimatter physics

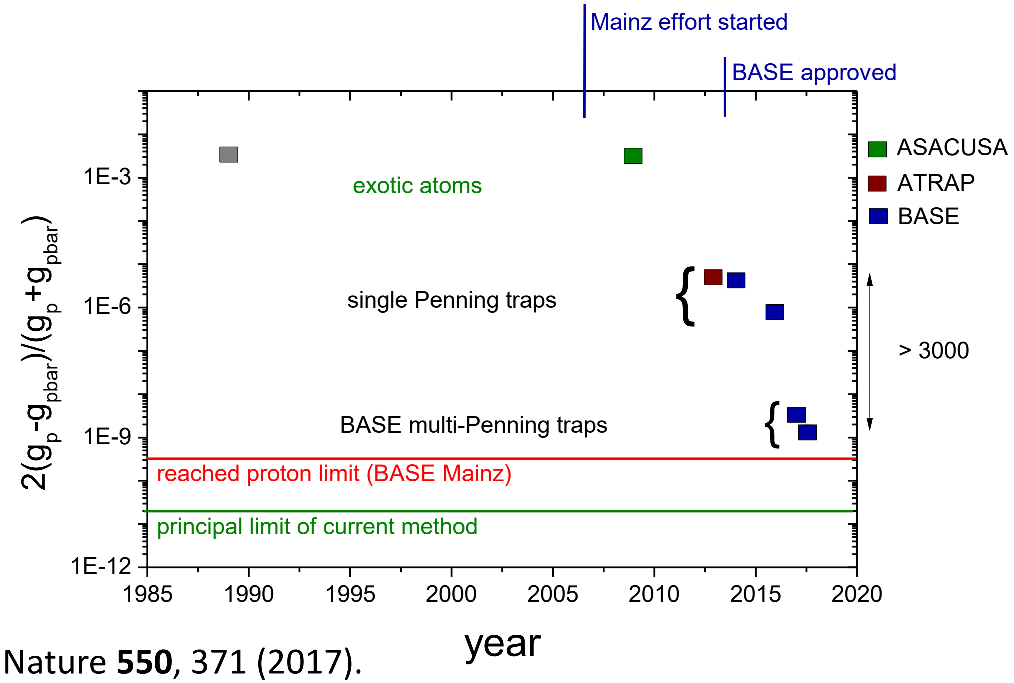

LETTER

OPEN

doi:10.1038/nature24048

A parts-per-billion measurement of the antiproton magnetic moment

C. Smorra[1,2], S. Sellner[1], M. J. Borchert[1,3], J. A. Harrington[4], T. Higuchi[1,5], H. Nagahama[1], T. Tanaka[1,5], A. Mooser[1], G. Schneider[1,6], M. Bohman[1,4], K. Blaum[4], Y. Matsuda[5], C. Ospelkaus[3,7], W. Quint[8], J. Walz[6,9], Y. Yamazaki[1] & S. Ulmer[1]



C. Smorra et al., Nature **550**, 371 (2017).


CERN Courier March 2018

BASE

Experiment of the moment

The BASE collaboration at CERN has measured the antiproton magnetic moment with extraordinary precision, offering more than 100-fold improved limits on certain tests of charge–parity–time symmetry.

The enigma of why the universe contains more matter than antimatter has been with us for more than half a century. While charge–parity (CP) violation can, in principle, account for the existence of such an imbalance, the observed matter excess is about nine orders of magnitude larger than what is expected from known CP-violating sources within the Standard Model (SM). This striking discrepancy inspires searches for additional mechanisms for the universe's baryon asymmetry, among which are experiments that test fundamental charge–parity–time (CPT) invariance by comparing matter and antimatter with great precision. Any measured difference between the two would constitute a dramatic sign of new physics. Moreover, experiments with antimatter systems provide unique tests of hypothetical processes beyond the SM that cannot be uncovered with ordinary matter systems.

The Baryon Antibaryon Symmetry Experiment (BASE) at CERN, in addition to several other collaborations at the Antiproton Decelerator (AD), probes the universe through exclusive antimatter "microscopes" with ever higher resolution. In 2017, following many years of effort at CERN and the University of Mainz in Germany, the BASE team measured the magnetic moment of the antiproton with a precision 350 times better than by any other experiment before, reaching a relative precision of 1.5 parts per billion (figure 1). The result followed the development of a multi-Penning-trap system and a novel two-particle measurement method and, for a short period, represented the first time that antimatter had been measured more precisely than matter.

The BASE setup at CERN's Antiproton Decelerator.

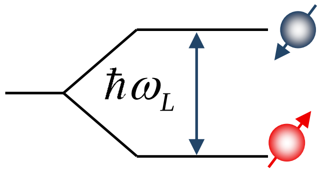
Non-destructive physics

The BASE result relies on a quantum measurement scheme to observe spin transitions of a single antiproton in a non-destructive manner. In experimental physics, non-destructive observations of quantum effects are usually accompanied by a tremendous increase in measurement precision. For example, the non-destructive observation of electronic transitions in atoms or ions led to the development of optical frequency standards that achieve fractional precisions on the 10^{-18} level. Another example, allowing one of the most precise tests of CPT invariance to date, is the comparison of the electron and positron g-factors. Based on quantum non-demolition detection of the spin state, such studies during the 1980s reached a fractional accuracy on the parts-per-trillion level.

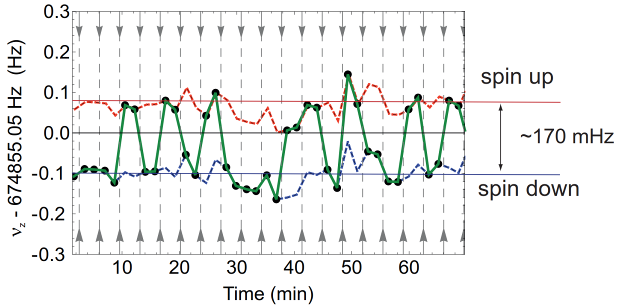
The latest BASE measurement follows the same scheme but targets the magnetic moment of protons and antiprotons instead of electrons and positrons. This opens tests of CPT in a totally different particle system, which could behave entirely differently. In practice, however, the transfer of quantum measurement methods from the electron/positron to the proton/antiproton system constitutes a considerable challenge owing to the

The multi-Penning-trap system used by BASE to detect the spin-flips of single trapped protons and antiprotons.

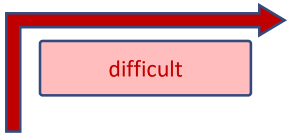
CERN COURIER, 3 / 2018.



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

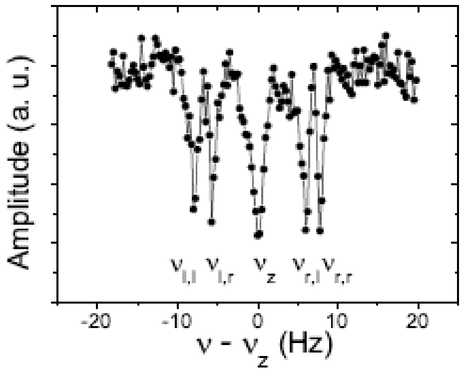


Continuous Stern Gerlach Effect

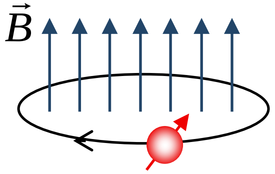


$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\,\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

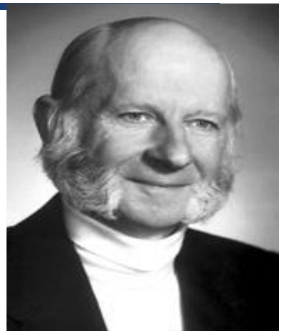
Image Current Measurements



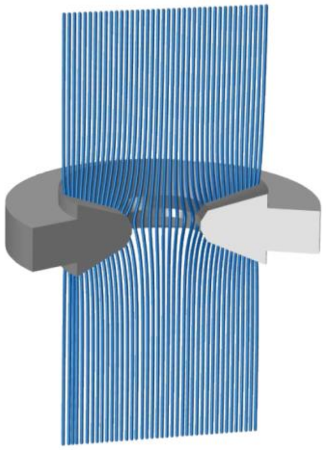
S. Ulmer *et al.*, PRL 107, 103002 (2011)



Larmor Frequency – extremely hard



Measurement based on continuous Stern Gerlach effect.



Energy of magnetic dipole in magnetic field

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

Leading order magnetic field correction

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

This term adds a spin dependent quadratic axial potential
-> Axial frequency becomes a function of the spin state

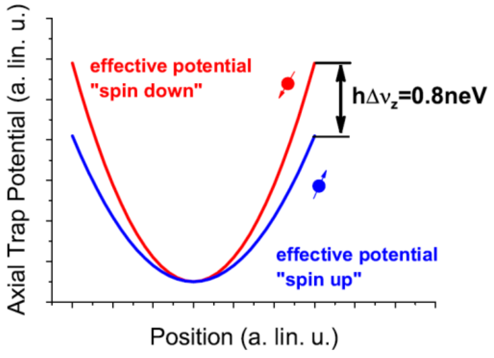
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

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

- Most extreme magnetic conditions ever applied to single particle.

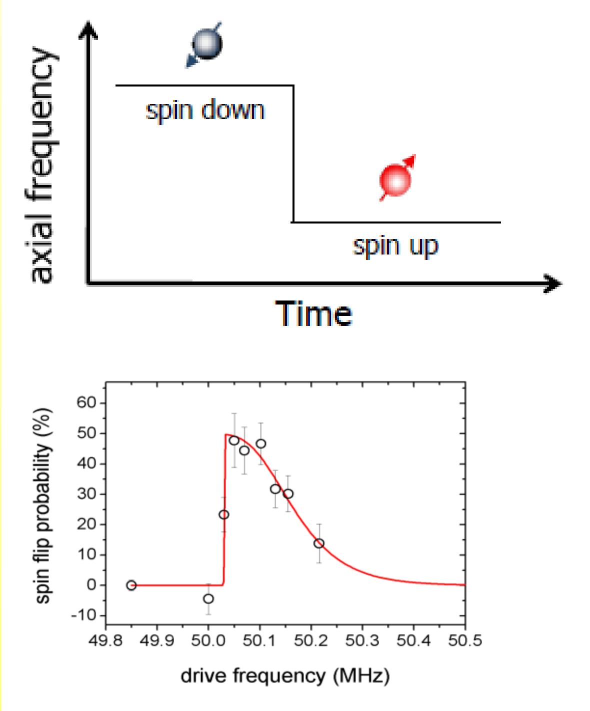
$$\Delta\nu_z \sim 170\ mHz$$



Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

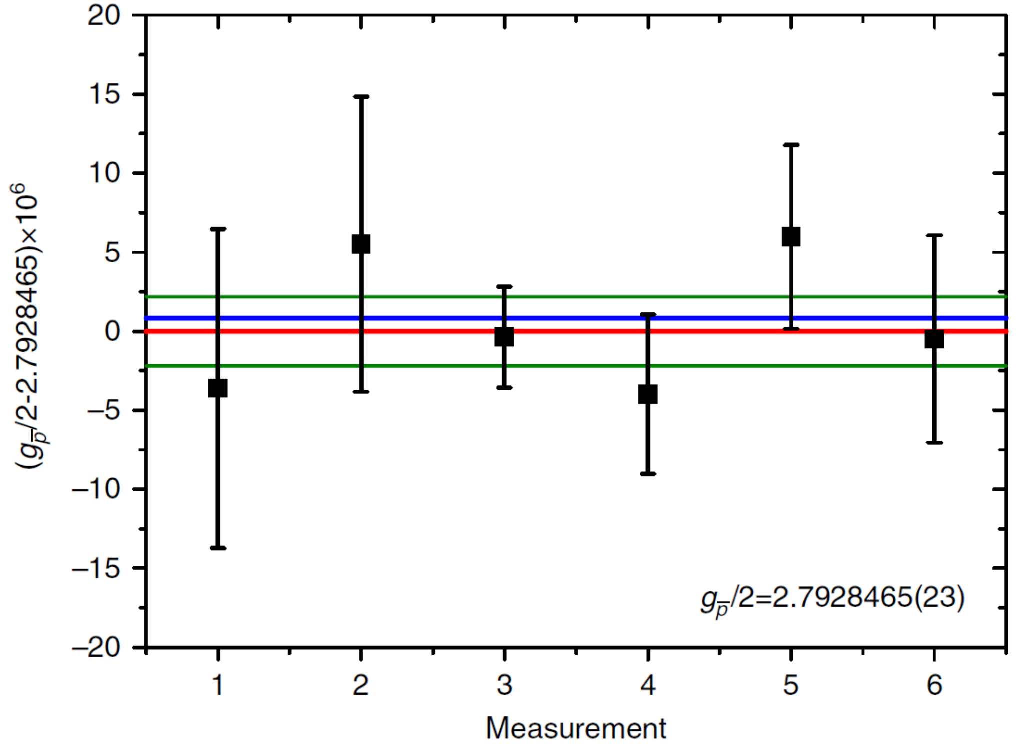
Spin is detected and analyzed via an axial frequency measurement



S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

Antiproton g-factor results – single trap

Performed 6 Larmor resonance and 12 cyclotron resonance scans



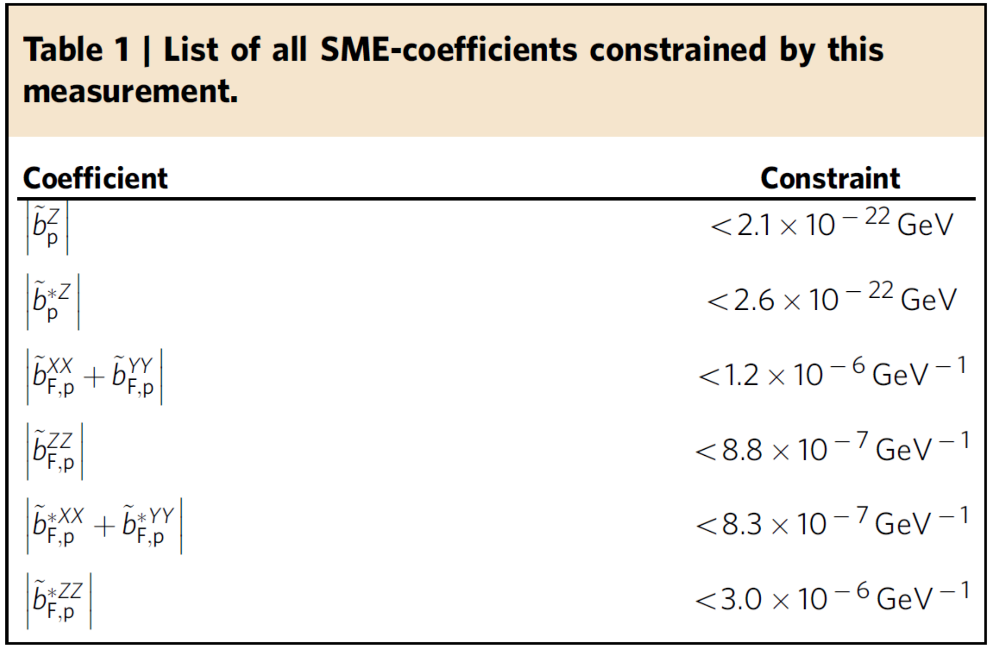


Table 1 | List of all SME-coefficients constrained by this measurement.

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

Based on Ding, Y. & Kostelecký, V. A. *Lorentz-violating spinor electrodynamics and Penning traps. Phys. Rev. D* **94**, 056008 (2016).

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

Six fold improved uncertainty of the antiproton magnetic moment

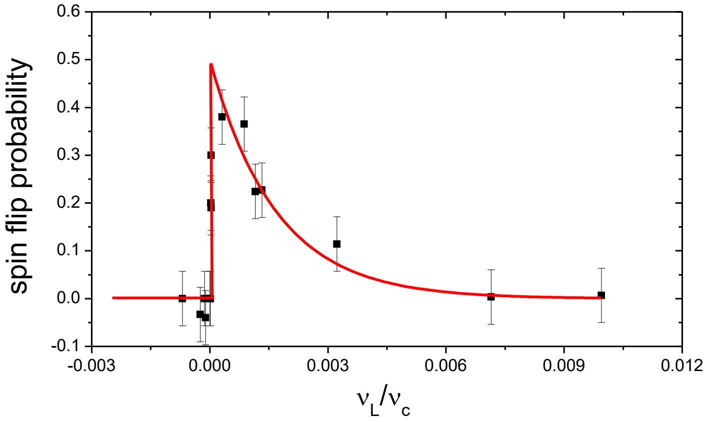
$$\frac{g_{\bar{\mathrm{p}}}}{g_{\mathrm{p}}}-1 = -0.31(82)\times 10^{-7}$$

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

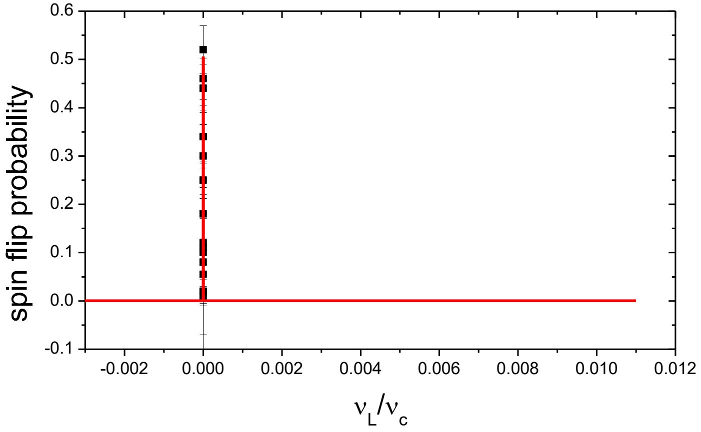
Earlier work: J. DiSciacca et al., PRL **110**, 130801 (2013).

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

??? Can we do better ???

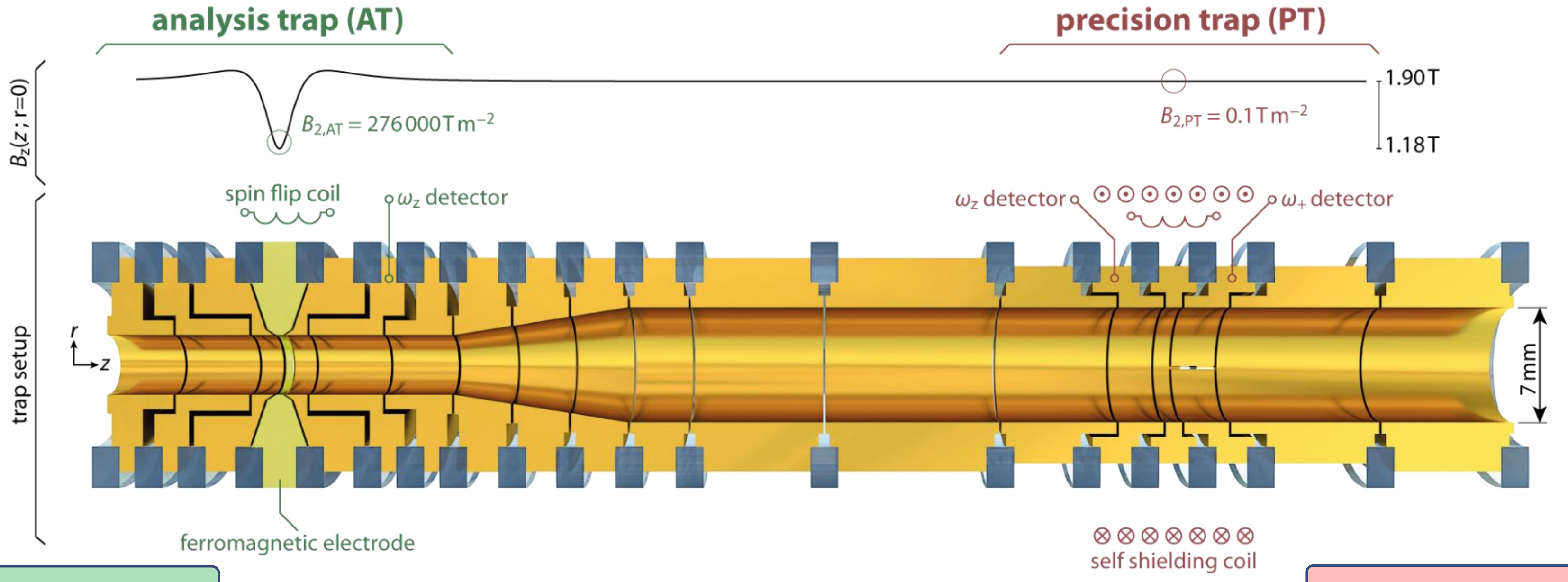


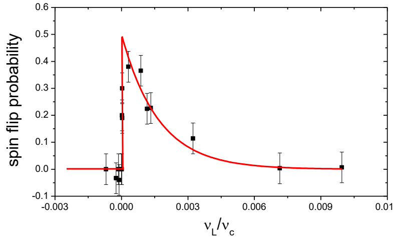
???

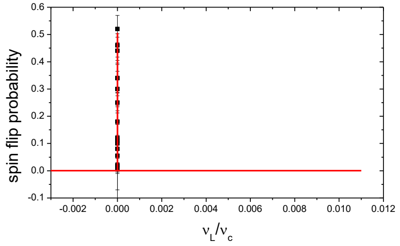


Next Step: The Double Penning-Trap Method

Invented at GSI Darmstadt and Univ. of Mainz by J. Kluge, G. Werth, W. Quint, H. Haeffner and collaborators





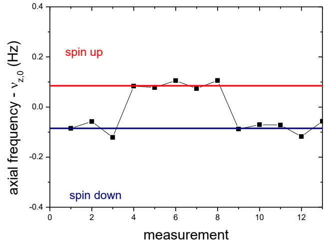


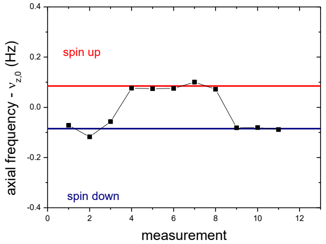
Initialize the spin state

particle transport

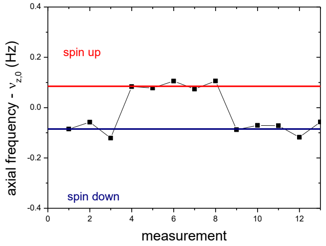
1.) measure cyclotron ν_c
2.) drive spin transition at ν_{rf}

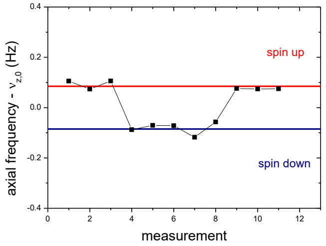
analyze the spin state





no spin-flip in PT

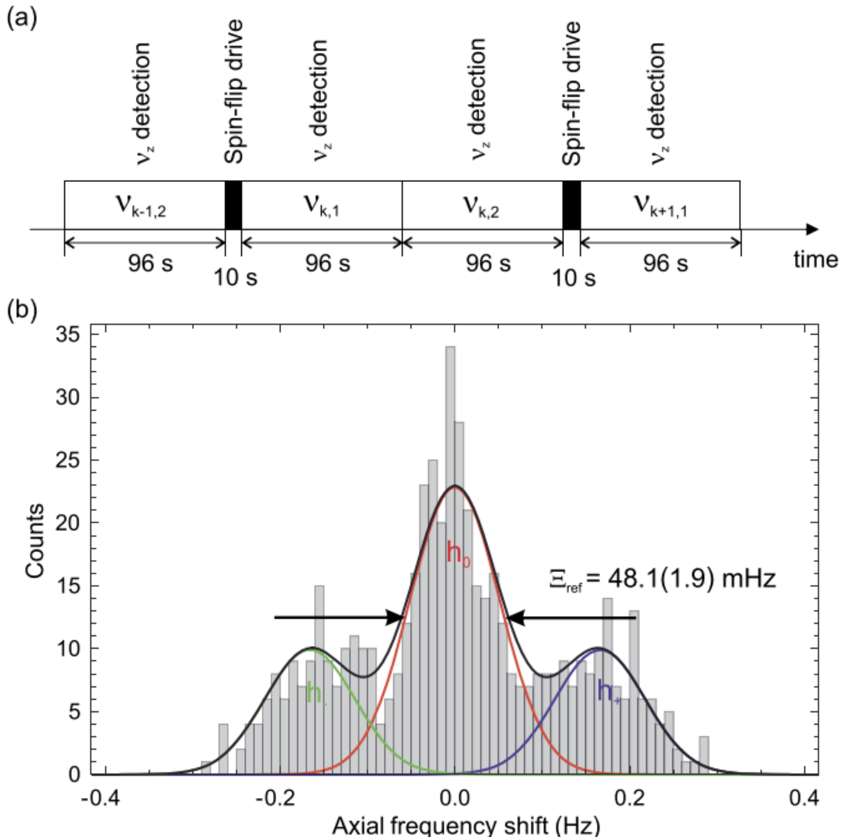


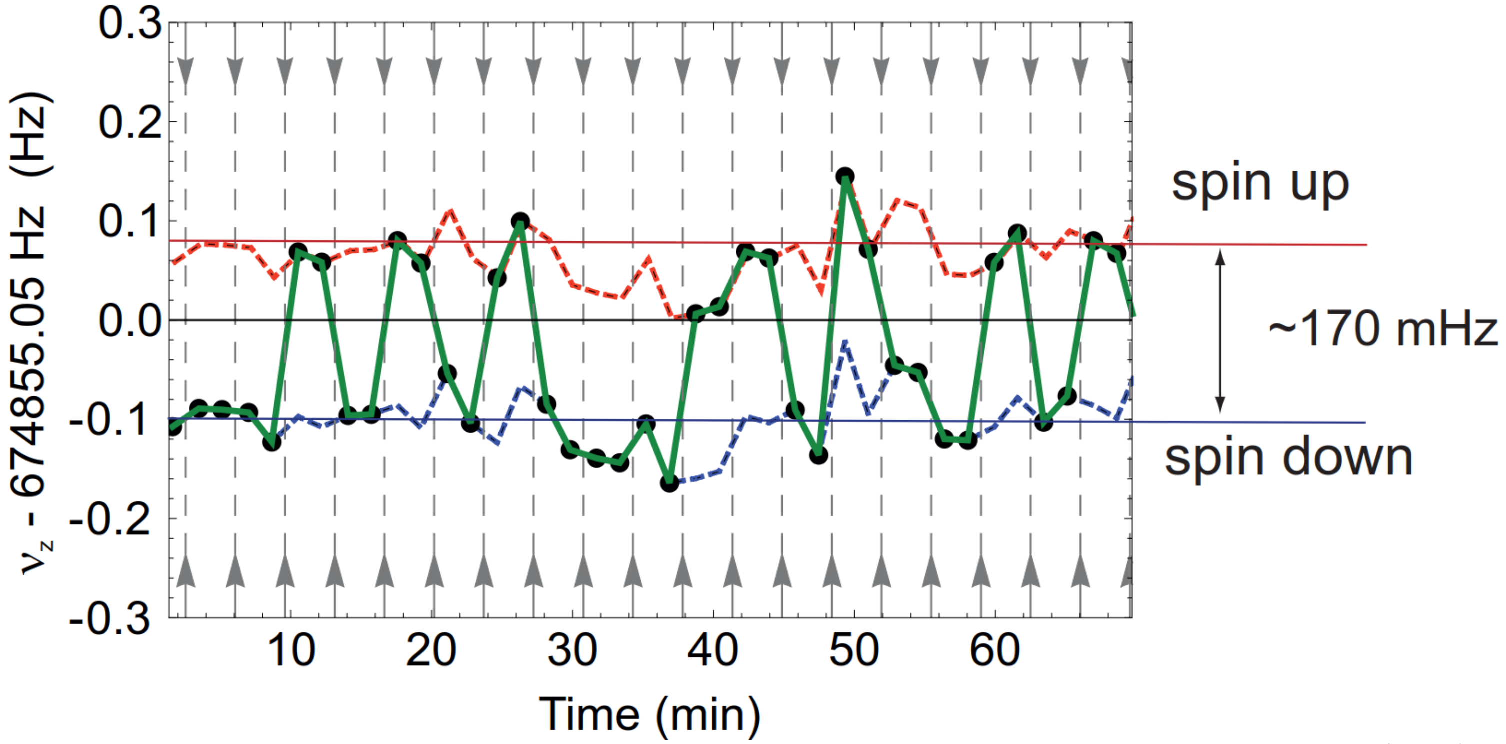


spin flipped in PT

measures spin flip probability as a function of the drive frequency in the homogeneous magnetic field of the precision trap

The holy-grail: single antiproton spin flips





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

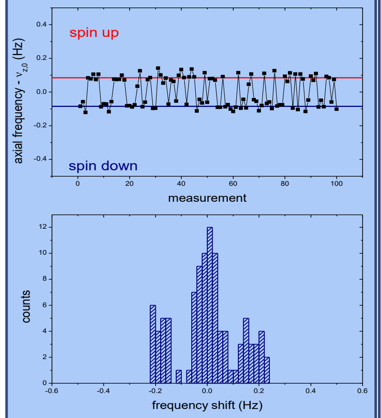
- First non-destructive observation of single antiproton spin quantum transitions.

Heating Rates

- Achieve single spin flip resolution only with cold particles.
- Reason: Heating rates scale with particle energy

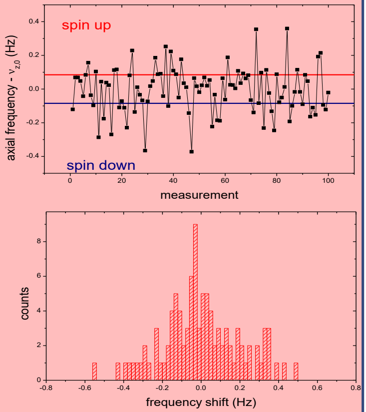
$$\frac{\mathrm{d}n_{+,-}}{\mathrm{d}t} \approx \frac{q^2}{2m_{\bar{p}}h\nu_{+,-}}\boxed{n_{+,-}}\Lambda^2\langle e_\mathrm{n}(t), e_\mathrm{n}(t-\tau)\rangle$$

cold particle (50mK)

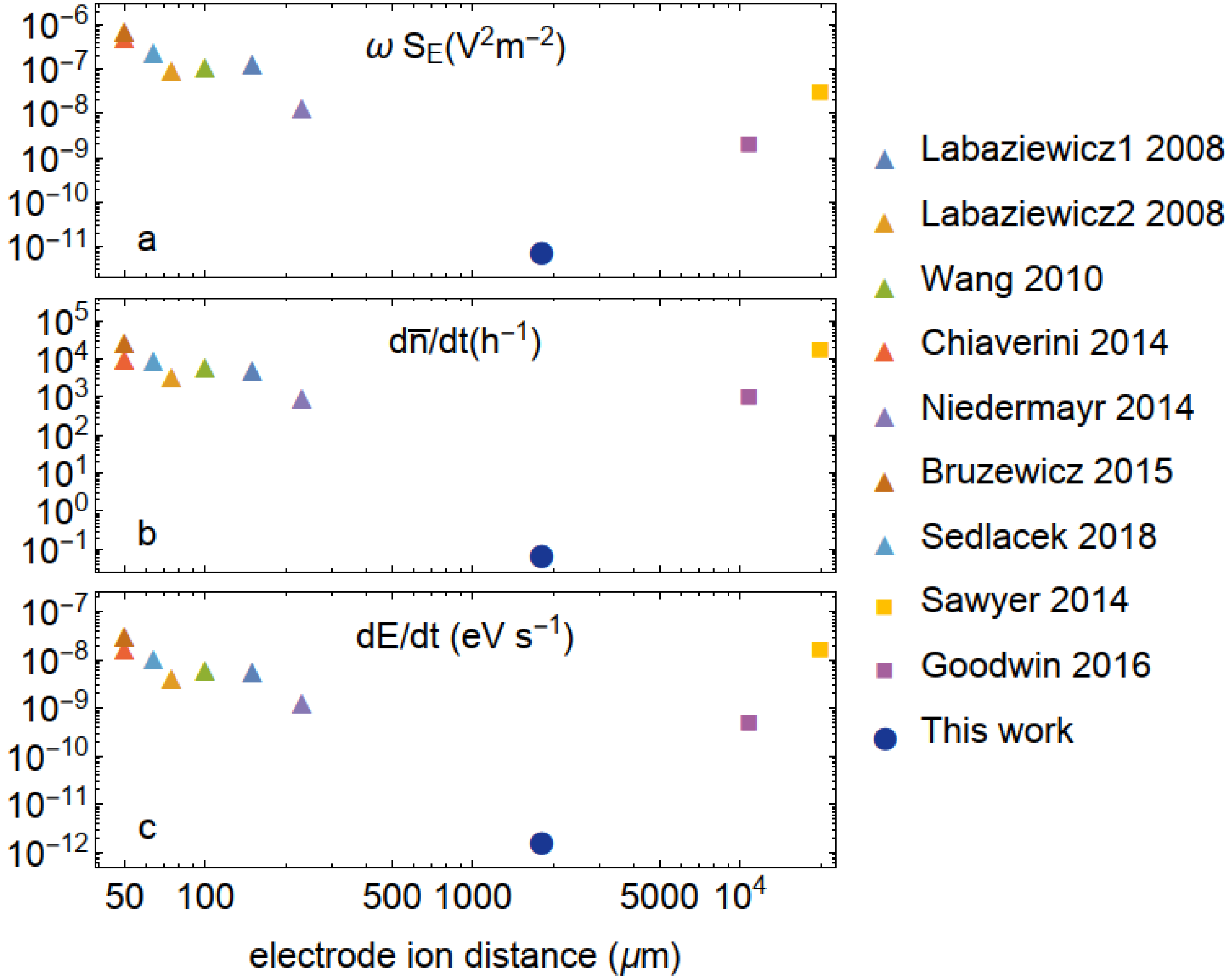


high-fidelity spin state resolution

hot particle (1K)



fidelity at 65%, not useful for measurements

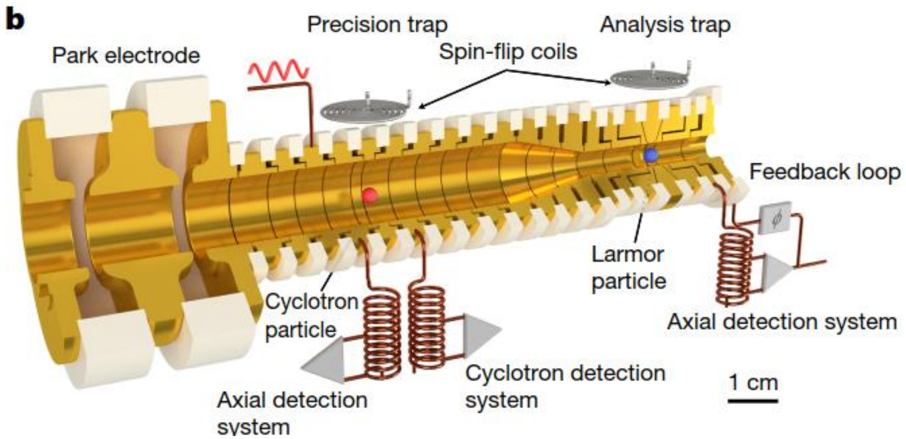


takes hours per preparation cycle

M. J. Borchert, Phys. Rev. Lett. **122**, 043001 (2019)

Invented: BASE Two-Particle Method

Idea: divide measurement to two particles

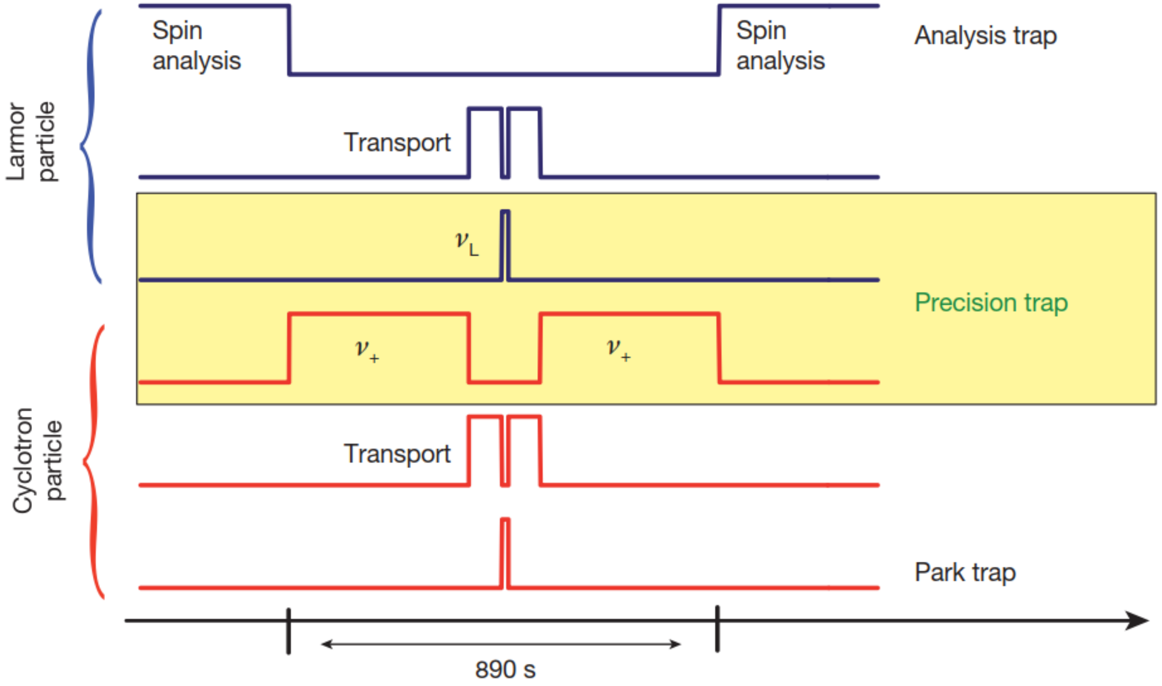


«hot» cyclotron particle which probes the magnetic field in the precision trap

«cold» cyclotron particle to flip and analyze the spin-eigenstate

pay: measure with two particles at different mode energies

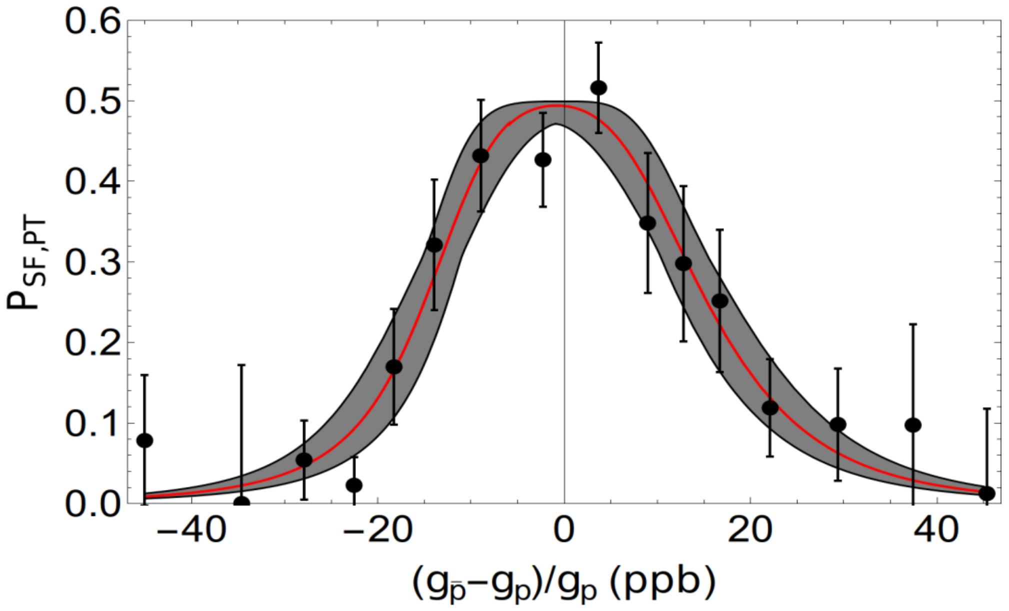
win: 60% of time usually used for sub-thermal cooling useable for measurements



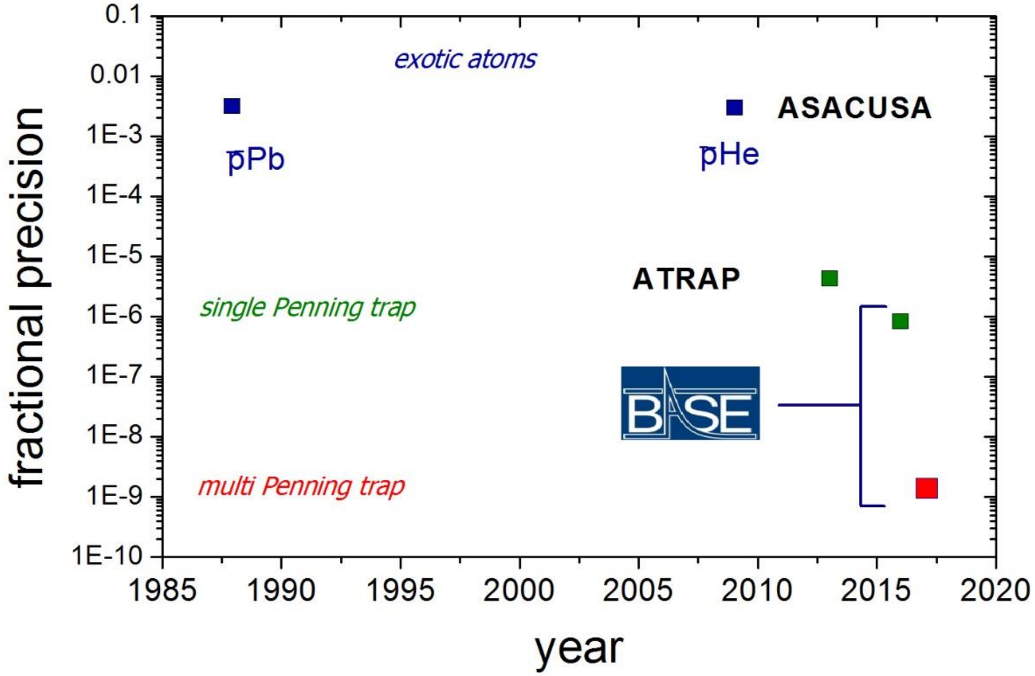
challenges:

- transport without heating
- more challenging systematics

The Magnetic Moment of the Antiproton



BASE 2017: $\mu_{\bar{p}}$ = -2.792 847 344 1 (42) μ_{nucl}



A. Mooser *et al.*, Nature **509**, 596 (2014)

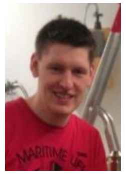
$$\frac{g_p}{2} = 2.792\,847\,350\,(9)$$

$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,1\,(42)$$

C. Smorra *et al.*, Nature **550**, 371 (2017)

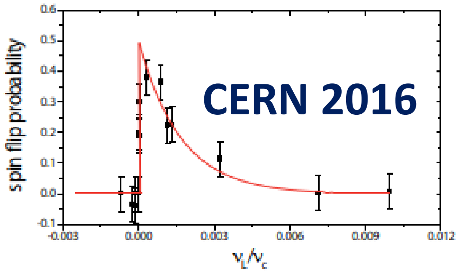
first measurement more precise for antimatter than for matter...

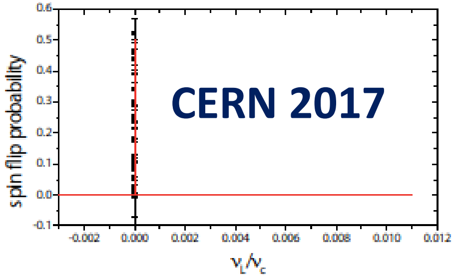
$$\frac{g_p}{2} = 2.792\,847\,344\,62\,(82)$$

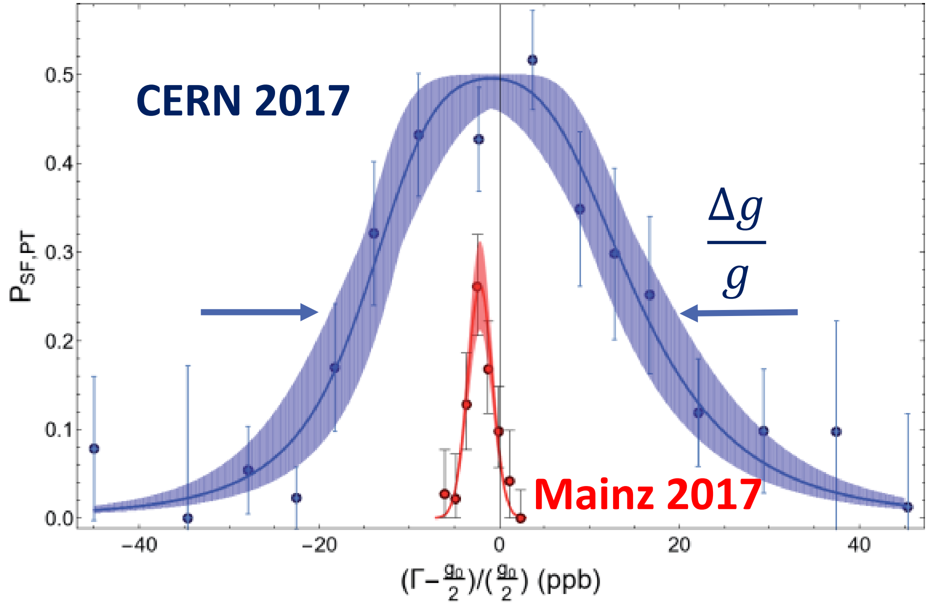


G. Schneider *et al.*, Science **358**, 1081 (2017)

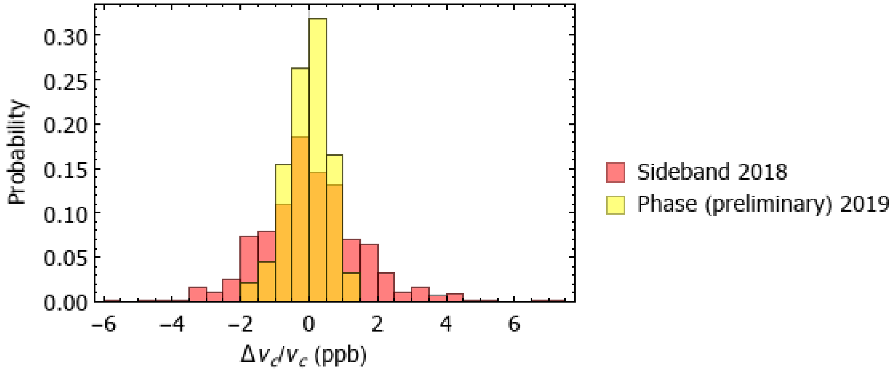
BASE – «Short Term» Goal – Magnetic Moment







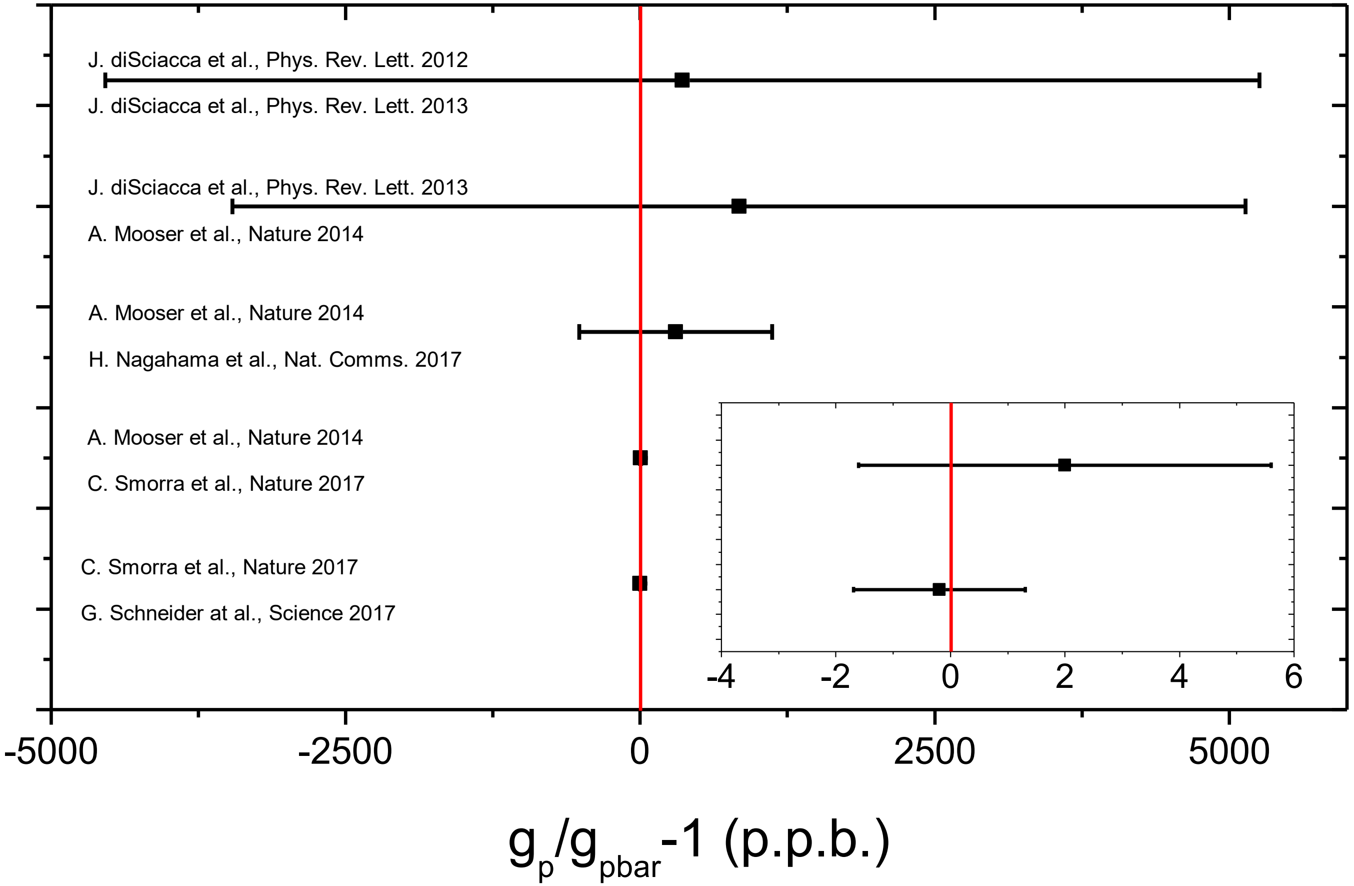
	CERN	Mainz
TOTAL:	$\frac{\Delta g}{g} = 14\ p.p.b.$	$\frac{\Delta g}{g} = 1.3(2)\ p.p.b.$
Drive:	$\left(\frac{\Delta g}{g}\right)_D = 13\ p.p.b.$	$\left(\frac{\Delta g}{g}\right)_D < 0.2\ p.p.b.$
B-field:	$\left(\frac{\Delta g}{g}\right)_B = 4\ p.p.b.$	$\left(\frac{\Delta g}{g}\right)_B = 1.41(2) p.p.b.$



Indicates a possible width of 650 p.p.t.

- With the current magnet at CERN and the implemented magnetic shielding system, regardless whether AD is on or off, we could reach Δg/g=0.8 p.p.b. or even better **-> Improved measurement 80 p.p.t. to 200 p.p.t.**

Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	CPT $\lvert g_p/g_{\bar{p}}\rvert - 1$	Collaboration
2011	2.792 847 353 (28)	2.786 2 (83)	0.002 4 (29)	Pask (ASACUSA)
2013	2.792 846 (7)	2.792 845 (12)	0.000 000 4 (49)	diSciacca (ATRAP)
2014	**2.792 847 349 8 (93)**	2.792 845 (12)	0.000 000 8 (43)	**Mooser(BASE)/**diSciacca (ATRAP)
2016	**2.792 847 349 8 (93)**	**2.792 846 5 (23)**	**0.000 000 30 (82)**	**Mooser/Nagahama (BASE)**
2017/1	**2.792 847 349 8 (93)**	**2.792 847 344 1 (42)**	**0.000 000 002 0 (36)**	**Mooser/Smorra (BASE)**
2017/2	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**-0.000 000 000 2 (15)**	**Schneider/Smorra (BASE)**



2013

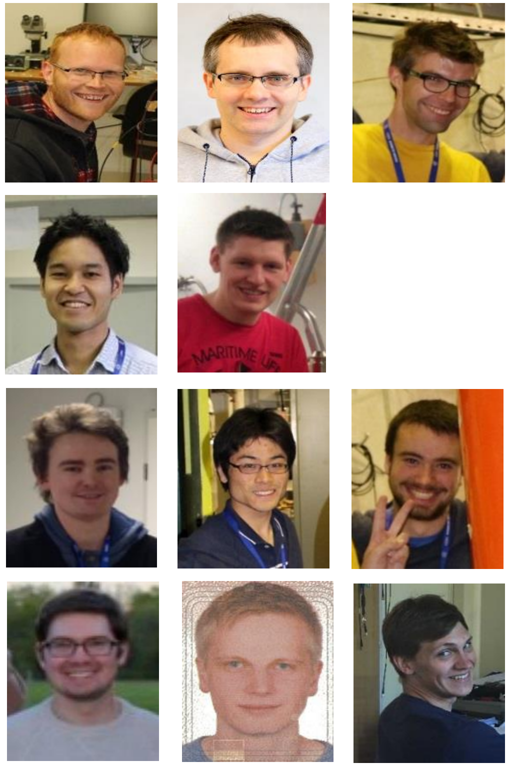
2014

2016

2017

2018

K. Blaum, Y. Yamazaki
J. Walz, W. Quint,
Y. Matsuda, C. Ospelkaus

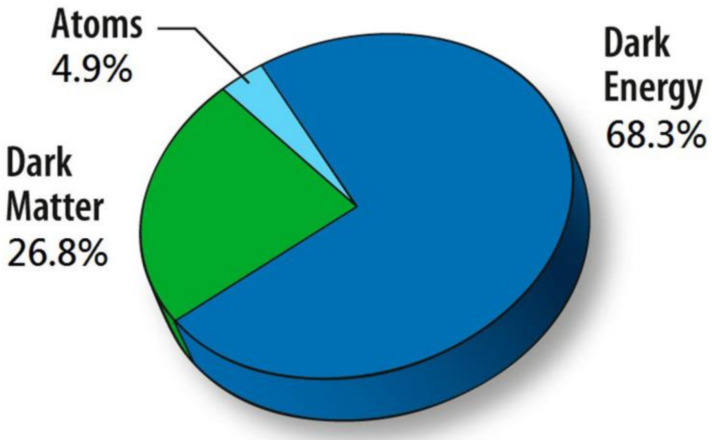


$$\frac{g_p}{g_{\bar{p}}} - 1 = -0.000\,000\,000\,2\,(15)$$

Limits on Antiproton/Dark Matter Coupling

Not understood why they survived

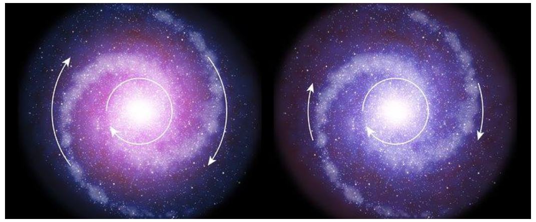
Know it exists ($\rho_{DM}^{local} = 0.4\ GeV/cm^3$), but microscopic properties have yet to be understood.



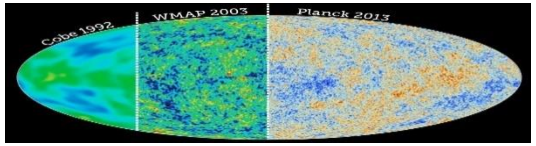
BASE study: Could the appearance of matter/disappearance of antimatter and dark matter be in any sense related?

Gravitational lensing

Galactic rotation



Structures in CMWB



Need a model which allows us to study this question

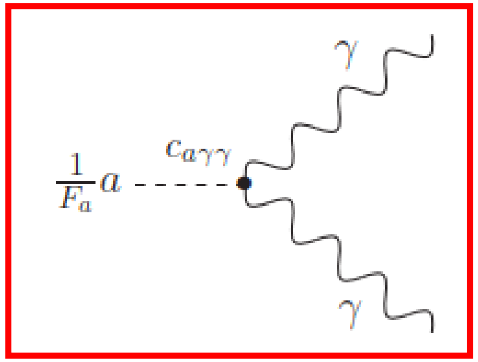
- the axion
  - introduced to solve the strong CP problem (Peccei/Quinn)
  - candidate for dark matter (axion like particles)

Axion Wind Model

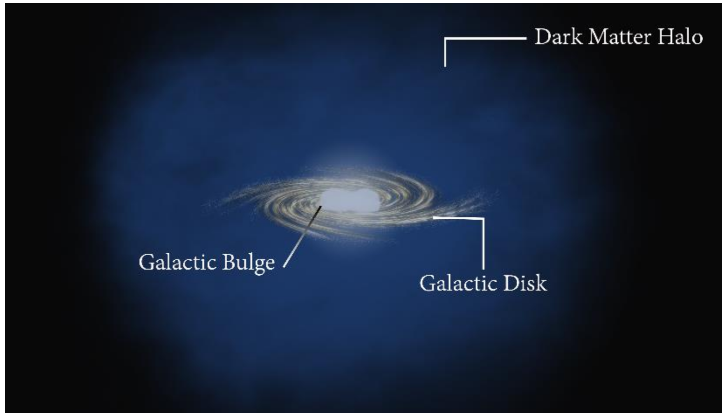
- Frist of all: a quick comment on axion fermion coupling

J. Kim, G. Carosi, https://arxiv.org/pdf/0807.3125.pdf

$$
\begin{aligned}
\mathcal{L}_\theta = {} & \frac{1}{2} f_S^2 \partial^\mu \theta \partial_\mu \theta - \frac{1}{4g_c^2} G^a_{\mu\nu} G^{a\,\mu\nu} + (\bar{q}_L i \not{D} q_L + \bar{q}_R i \not{D} q_R) \\
& + c_1 (\partial_\mu \theta) \bar{q} \gamma^\mu \gamma_5 q - \left(\bar{q}_L \; m \; q_R e^{i c_2 \theta} + \text{h.c.}\right) \\
& + c_3 \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu} \; (\text{or } \mathcal{L}_{\text{det}}) \qquad (19) \\
& \boxed{+ c_{\theta\gamma\gamma} \frac{\theta}{32\pi^2} F^i_{\text{em},\mu\nu} \tilde{F}^{i\,\mu\nu}_{\text{em}}} + \mathcal{L}_{\text{leptons},\theta}
\end{aligned}
$$



A very "simplistic" translation of this "derivative interaction": the axion dissociates to photons which interact with SM-particles.



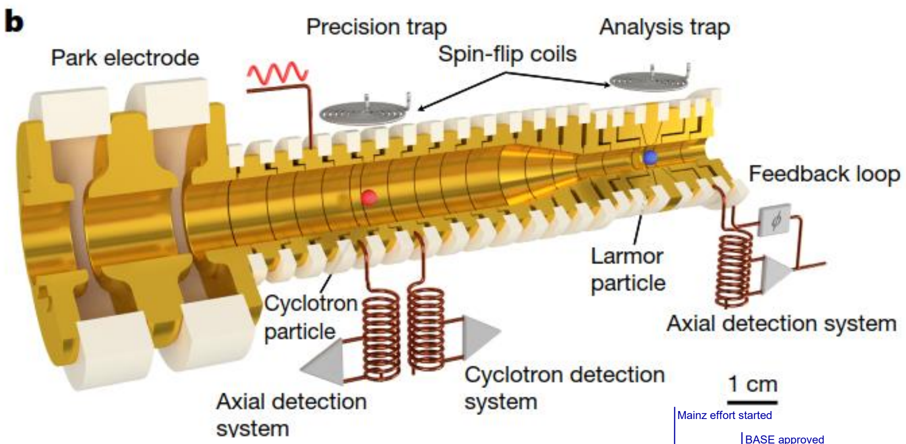
- Cold dark matter – axion like particles – are gravitationally bound to galaxies.
- They produce an "oscillating background", comparable to diffuse light, which oscillates at a frequency $\boldsymbol{v_a \sim m_a}$

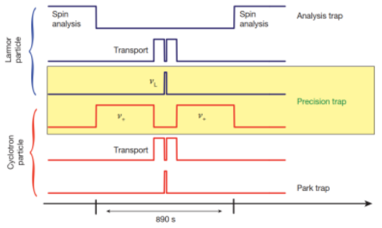
$$\boxed{\delta\omega_L^{\overline{p}}(t) \approx \frac{C_{\overline{p}} m_\mathrm{a} a_0 |\mathbf{v}_\mathrm{a}|}{f_\mathrm{a}} [A \cos(\Omega_\mathrm{sid} t + \alpha) + B] \sin(\omega_\mathrm{a} t)}$$

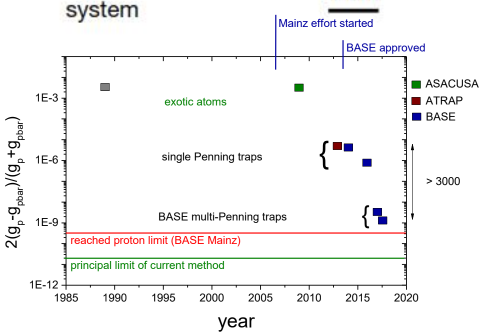
This type of interaction would look like a "pseudo"-magnetic field which leads to frequency modulations in the antiproton Larmor frequency.

Illustration of the concept:

- Most important is still that we have a measurement



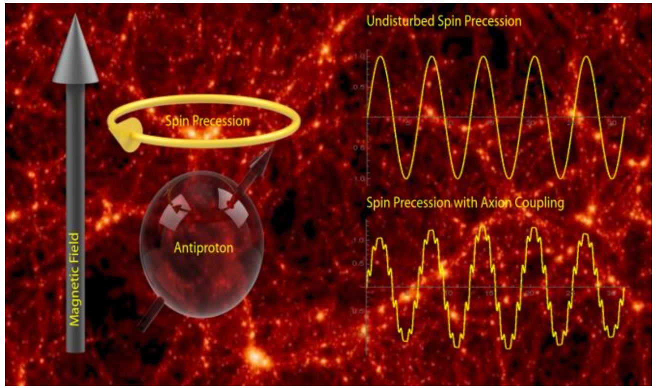


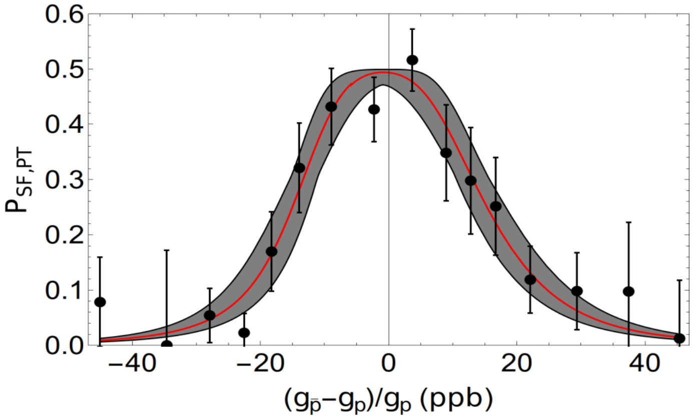


Antiproton/axion coupling would induce a frequency modulation

$$\nu_a = \frac{1}{2\pi}\frac{m_a c^2}{\hbar}$$

of the measured Larmor frequency.





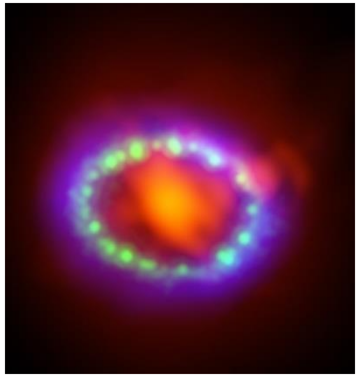
- Analysis: Compare hypotheses H0 – no oscillation / H1 – oscillation at certain g-amplitude
- Define test statistic based on Nyman/Pearson Lemma (likelihood ratio test)
- Derive constraints base on CLs method (p/power)

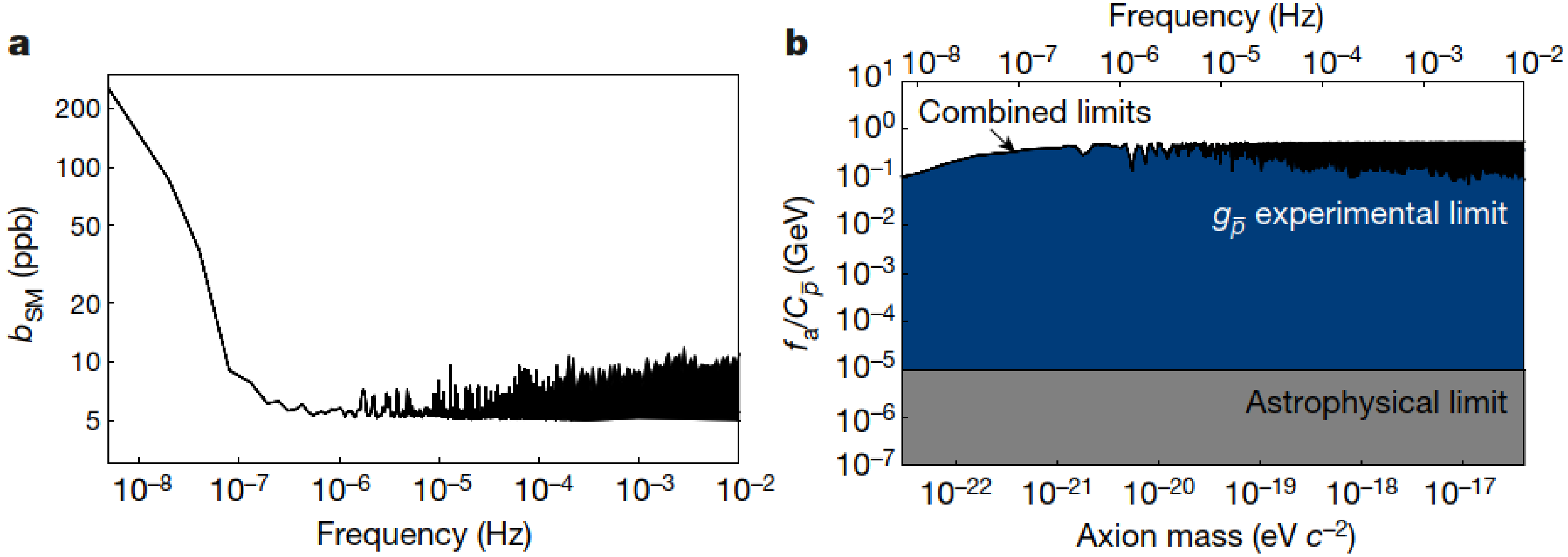
Limits from SN-1987A

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

SN-1987A

SN-1987A-remnant





- Addition: We set limits on six previously unconstrained coefficients of the Standard Model Extension

- Thanks to fruitful collaboration with D. Budker and Y. Stadnik

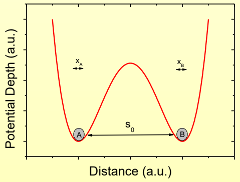
C. Smorra, Y. Stadnik, Nature **(575)**, 310 (2019)

Future – Sympathetic Cooling of Antiprotons

- Current antiproton magnetic moment measurements are limited by particle preparation time and particle mode temperature
- Expect: With traditional methods another 50-fold improvement is possible, **afterwards: limit of traditional methods will be reached!**

New Method

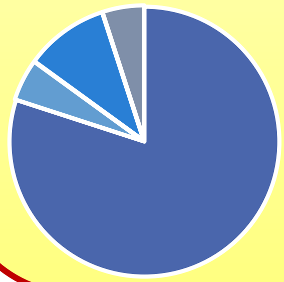
Couple protons/antiprotons sympathetically to laser cooled $^9Be^+$ ions and imprint Doppler temperatures to the antiproton



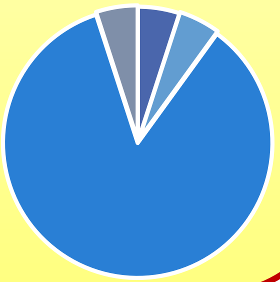
Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

Was demonstrated for $^9Be^+$ ions in Paul traps – implement same in Penning traps

Current Time Budget

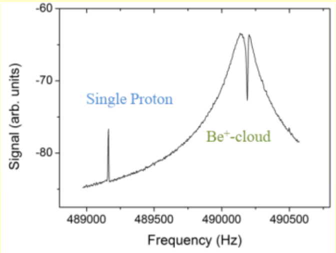


Laser Time Budget



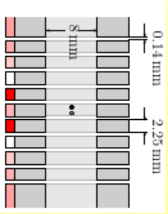
Effort at University of Mainz

5 trap design implemented and simultaneous detection of $^9Be^+$ ion and proton in common endcap trap was demonstrated.

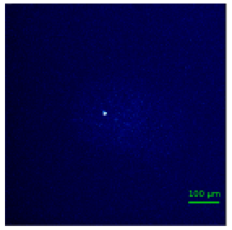


C. Smorra, M. Bohman, M. Wiesinger, C. Will, et al.

Effort at University of Hannover and PTB

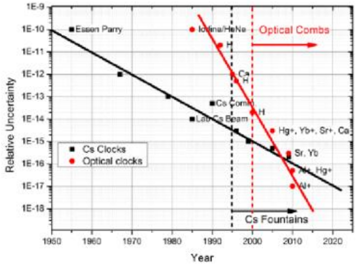


Recent dramatic progress:
Detection of a single laser cooled $^9Be^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN



J. M. Cornejo, M. Niemann, T. Meiners, J. Mielke **C. Ospelkaus** et al.

The Vision



>100-fold improved antiproton cooling time seems to be in reach

Implement hypefine clock for magnet stabilization

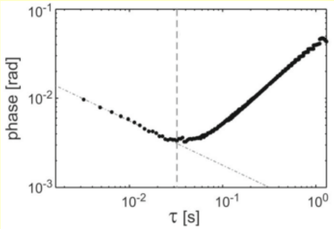
The $^3He^{2+}$ Magnetic Moment – TCFS Center Experiment

- Similar methods as in antiproton g-factor measurements
- Another 3 times more difficult
- **Goal: Establish ^3He as a new standard for magnetometry.**

Why meaningful ?

Polarizable, thus fast and accurate

$$\frac{\Delta B}{B} = 10^{-12}/s$$



Noble gas:
compared to water NMR, systematic shifts by pressure, temperature, chemical environment are >100-fold suppressed

Potential applications

Surface science

Sensor science

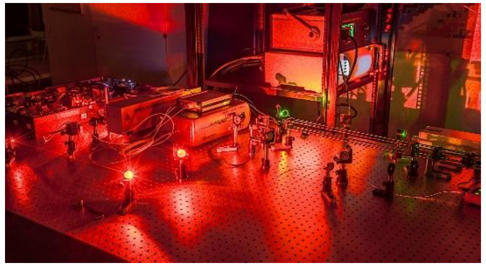
Fundamental magnetometry, fifth force experiments, SME coefficients

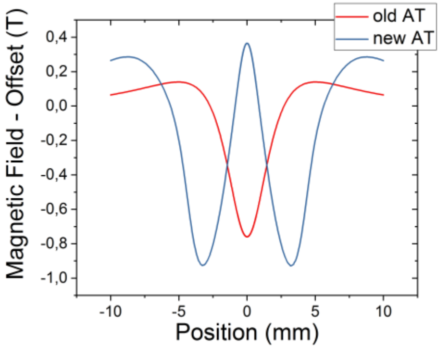
Penning traps

Future tests of CPT invariance

A. Mooser et al 2018 J. Phys.: Conf. Ser.1138 012004 (2018)

- Laboratory under commissioning
- New 5-trap system under development including high-fi double magnetic bottle
- ^3He source implemented
- First experimental results coming soon

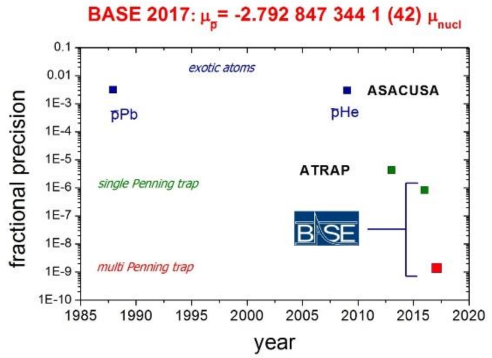


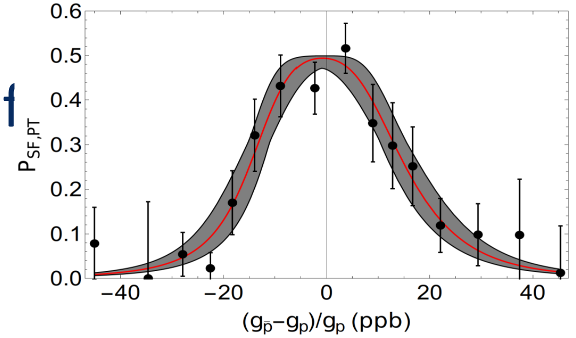


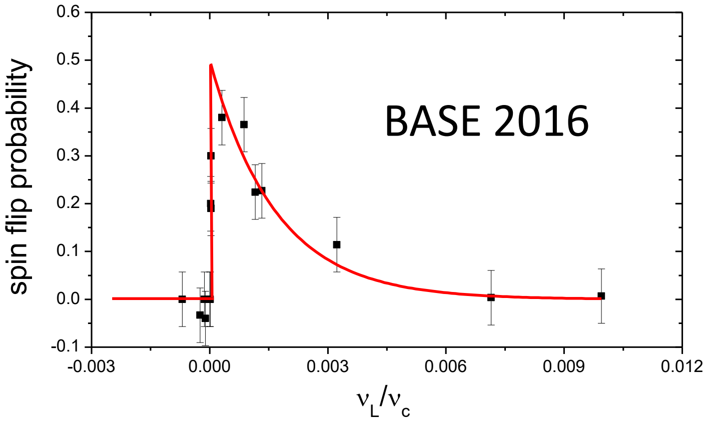
A. Mooser
A. Schneider
A. Rischka

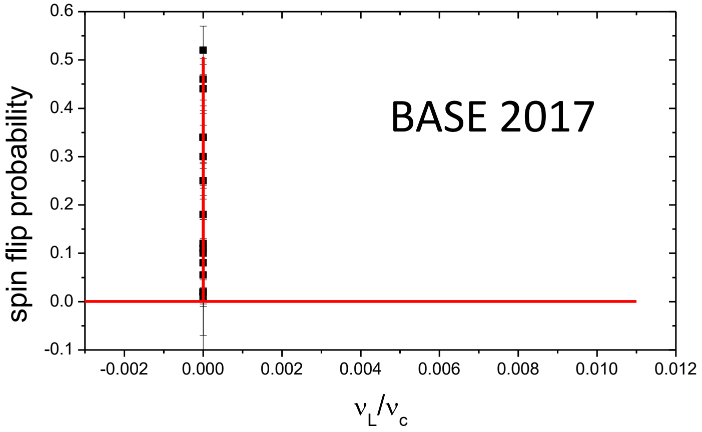
Summary and Outlook

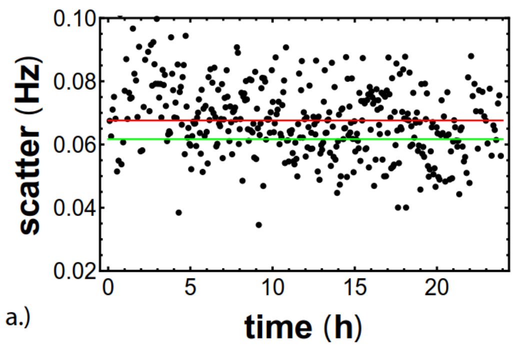
- Performed a 69 p.p.t. - test of CPT invariance with baryons by comparing proton/antiproton charge-to-mass ratios
- Improved the magnetic moment of the proton by a factor of 11 and measured the antiproton magnetic moment with 1.5 ppb precision, which improves the moment CPT test by a factor of >3000.
- Used antimatter as an antenna for dark matter searches.
- Strategies to improve the moment measurement by another factor of 10.
- Strategies to improve q/m ratio measurements to the sub-ppt level.

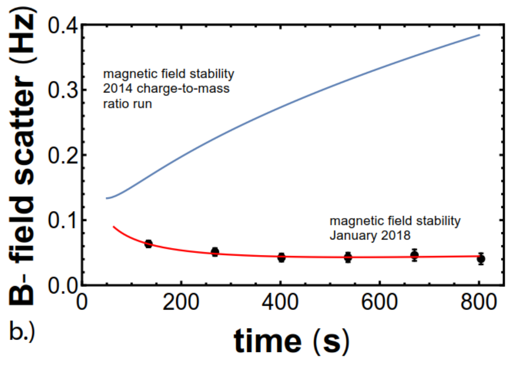












Open PhD Positions

- Two open PhD positions available at BASE-CERN
  - Temperature and pressure stabilization of the BASE superconducting magnet and measurement of the antiproton magnetic moment with sub-p.p.b. precision
  - Development of a 5-Penning-trap system and measurement of the proton-to-antiproton charge-to-mass ratio with a fractional precision on the sub 10 parts in a trillion level

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton (Smorra, Ulmer, Blaum, Walz, Quint).
- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio (Ulmer, Blaum, Ospelkaus, Matsuda, Yamazaki).
- **Hannover/PTB:** QLEDS-laser cooling project (Ospelkaus, Ulmer)


CERN Courier March 2018

BASE

Experiment of the moment

The BASE collaboration at CERN has measured the antiproton magnetic moment with extraordinary precision, offering more than 100-fold improved limits on certain tests of charge–parity–time symmetry.

The enigma of why the universe contains more matter than antimatter has been with us for more than half a century. While charge–parity (CP) violation can, in principle, account for the existence of such an imbalance, the observed matter excess is about nine orders of magnitude larger than what is expected from known CP-violating sources within the Standard Model (SM). This striking discrepancy inspires searches for additional mechanisms for the universe's baryon asymmetry, among which are experiments that test fundamental charge–parity–time (CPT) invariance by comparing matter and antimatter with great precision. Any measured difference between the two would constitute a dramatic sign of new physics. Moreover, experiments with antimatter systems provide unique tests of hypothetical processes beyond the SM that cannot be uncovered with ordinary matter systems.

The Baryon Antibaryon Symmetry Experiment (BASE) at CERN, in addition to several other collaborations at the Antiproton Decelerator (AD), probes the universe through exclusive antimatter "microscopes" with ever higher resolution. In 2017, following many years of effort at CERN and the University of Mainz in Germany, the BASE team measured the magnetic moment of the antiproton with a precision 350 times better than by any other experiment before, reaching a relative precision of 1.5 parts per billion (figure 1). The result followed the development of a multi-Penning-trap system and a novel two-particle measurement method and, for a short period, represented the first time that antimatter had been measured more precisely than matter.

The BASE setup at CERN's Antiproton Decelerator.

Non-destructive physics

The BASE result relies on a quantum measurement scheme to observe spin transitions of a single antiproton in a non-destructive manner. In experimental physics, non-destructive observations of quantum effects are usually accompanied by a tremendous increase in measurement precision. For example, the non-destructive observation of electronic transitions in atoms or ions led to the development of optical frequency standards that achieve fractional precisions on the 10^{-18} level. Another example, allowing one of the most precise tests of CPT invariance to date, is the comparison of the electron and positron g-factors. Based on quantum non-demolition detection of the spin state, such studies during the 1980s reached a fractional accuracy on the parts-per-trillion level.

The latest BASE measurement follows the same scheme but targets the magnetic moment of protons and antiprotons instead of electrons and positrons. This opens tests of CPT in a totally different particle system, which could behave entirely differently. In practice, however, the transfer of quantum measurement methods from the electron/positron to the proton/antiproton system constitutes a considerable challenge owing to the

The multi-Penning-trap system used by BASE to detect the spin-flips of single trapped protons and antiprotons.


The European Physical Journal volume 224 · number 1 · February 2015

EPJ ST

Recognized by European Physical Society

Special Topics

THE BASE EXPERIMENT

BASE

Baryon Antibaryon Symmetry Experiment

edp sciences Springer

Institutes: RIKEN Ulmer IRU, RIKEN APL, Max Planck Society, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig

Collaborators: 20

C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)

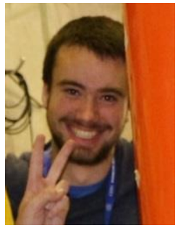
Thanks for your attention!


S. Ulmer
RIKEN


J. Devlin
CERN / RIKEN


E. Wursten
CERN / RIKEN


J. Harrington
MPIK/RIKEN


M. Borchert
Hannover/RIKEN


S. Erlewein
CERN/MPIK/RIKEN


M. Fleck
RIKEN/U. Tokyo

J. Warncke
Hannover / RIKEN


C. Smorra
RIKEN / Mainz


M. Bohman
RIKEN/MPIK


M. Wiesinger
MPIK/RIKEN


C. Will
MPIK


V. Grunhofer
Uni Mainz


S. Gavranovic
Uni Mainz

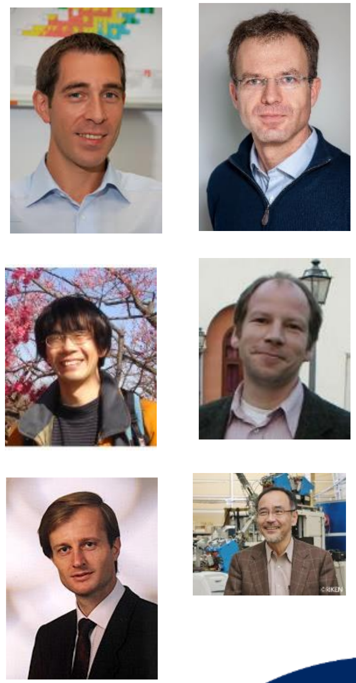

D. Popper
Uni Mainz

Programs for Junior Scientists

MAX-PLANCK-GESELLSCHAFT

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Leibniz Universität Hannover

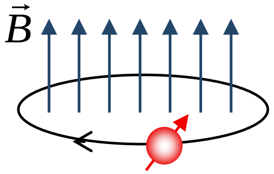


K. Blaum, Y. Matsuda,
C. Ospelkaus, W. Quint,
J. Walz, Y. Yamazaki

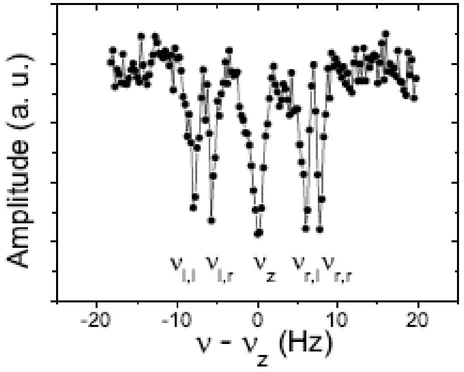
Measurements in Penning traps

A. Schawlow -> Ted Haensch: «Never measure anything but frequency»

Cyclotron Motion



simple



S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)

g: mag. Moment in units of nuclear magneton

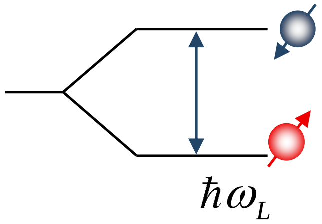
$$\omega_c = \frac{e}{m_p} B$$

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

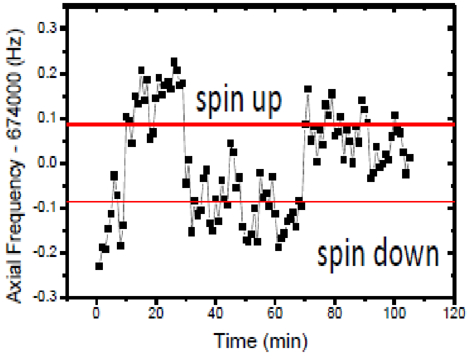
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Larmor Precession



difficult



S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

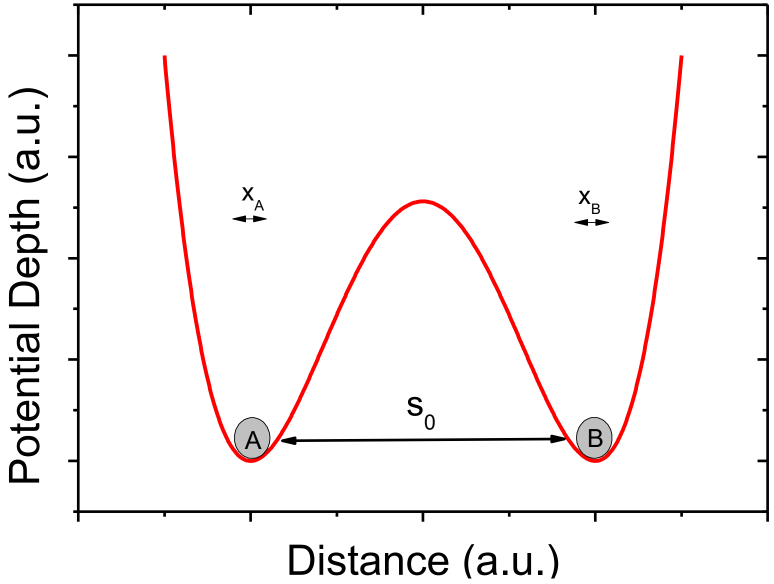
Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

Sympathetic Cooling of Antiprotons

Goal: Accelerate magnetic moment measurement cycles

Two charged particles trapped in direct vicinity coupled by coulomb interaction.

Of utmost importance for future BASE precision studies



$$U(x_a,x_b)=\frac{1}{4\pi\varepsilon_0}\frac{q_aq_b}{s_0-x_a+x_b}$$

$$\approx\frac{1}{4\pi\varepsilon_0}\frac{q_aq_b}{s_0}\left(\underbrace{1+\frac{x_a-x_b}{s_0}+\frac{x_a^2}{s_0^2}+\frac{x_b^2}{s_0^2}}_{\text{Static}}-\underbrace{\frac{2x_ax_b}{s_0^2}}_{\text{Dynamic}}\right)$$

$$\frac{-q_aq_b}{2\pi\varepsilon_0 s_0^3}(x'_a x'_b)=-\hbar\Omega_{\text{ex}}(a+a^\dagger)(b+b^\dagger)\approx-\hbar\Omega_{\text{ex}}(ab^\dagger+a^\dagger b)\longrightarrow\Omega_{\text{ex}}\equiv\frac{q_aq_b}{4\pi\varepsilon_0 s_0^3\sqrt{m_am_b}\sqrt{\omega_{0a}\omega_{0b}}}$$

Resonant Coupling:

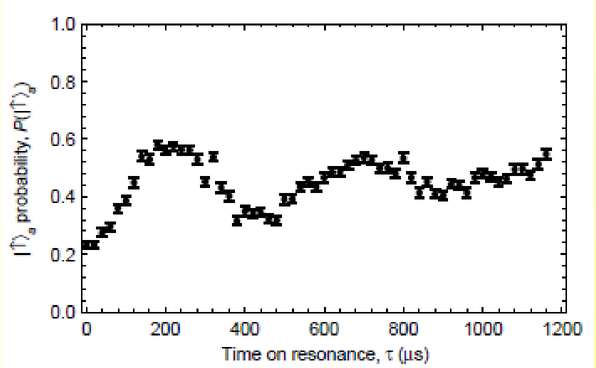
$$a^\dagger(t)=\exp(i\omega_0 t)(a^\dagger(0)\cos(\Omega_{\text{ex}}t)-ib^\dagger(0)\sin(\Omega_{\text{ex}}t))$$

$$b^\dagger(t)=\exp(i\omega_0 t)(b^\dagger(0)\cos(\Omega_{\text{ex}}t)-ia^\dagger(0)\sin(\Omega_{\text{ex}}t))$$

Effective Energy Exchange

Effective Energy Exchange

Successfully demonstrated in Paul trap with Be ions



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

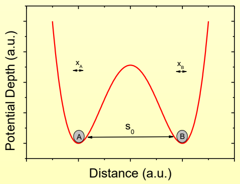
See also: M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel, Nature **471**, 200 (2011).

Planned Developments – Sympathetic Cooling of pbars

- Current antiproton magnetic moment measurements are limited by particle preparation time and particle mode temperature
- Expect: With traditional methods another 50-fold improvement is possible, **afterwards: limit of traditional methods will be reached!**

New Method

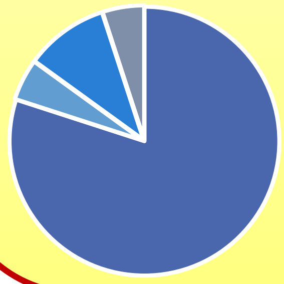
Couple protons/antiprotons sympathetically to laser cooled $^9Be^+$ ions and imprint Doppler temperatures to the antiproton



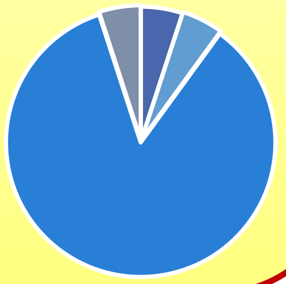
Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

Was demonstrated for $^9Be^+$ ions in Paul traps – implement same in Penning traps

Current Time Budget

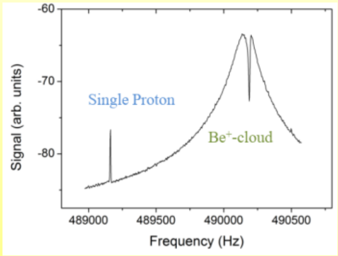


Laser Time Budget



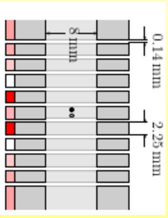
Effort at University of Mainz

5 trap design implemented and simultaneous detection of $^9Be^+$ ion and proton in common endcap trap was demonstrated.

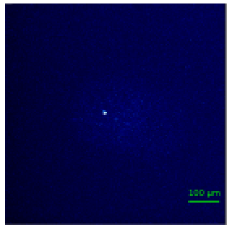


C. Smorra, A. Mooser, M. Bohman, M. Wiesinger et al.

Effort at University of Hannover and PTB

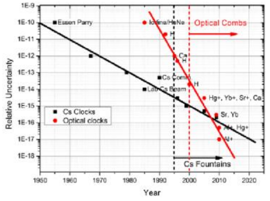


Recent dramatic progress:
Detection of a single laser cooled $^9Be^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN



J. M. Cornejo, M. Niemann, T. Meiners, J. Mielke **C. Ospelkaus** et al.

The Vision



>100-fold improved antiproton cooling time seems to be in reach

Next Step: Statistical Detection of Spin Flips

Measure axial frequency stability:

1.) reference measurement with detuned drive on,

2.) measurement with resonant drive on.

Spin flips add up

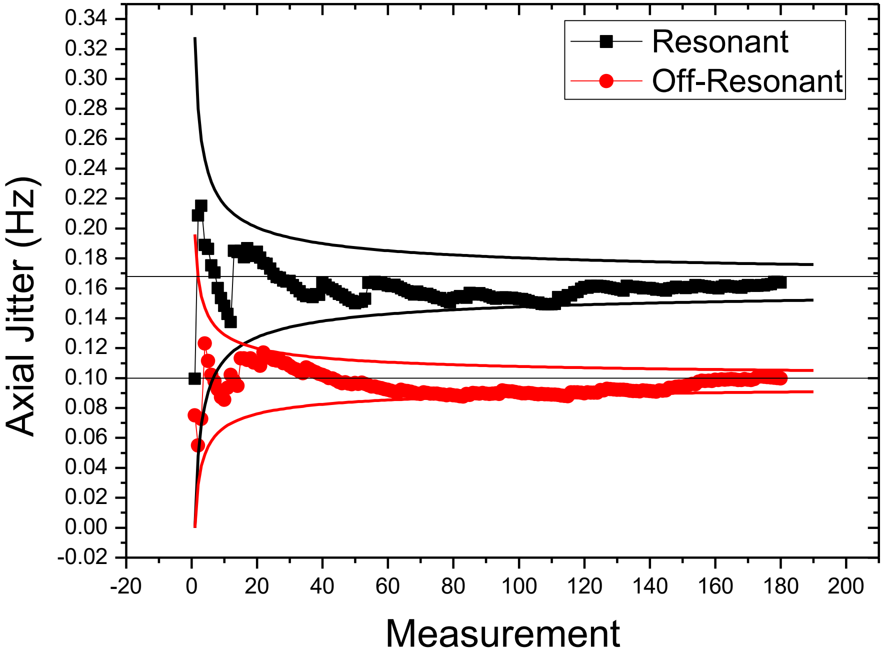
$$\Xi_{SF} = \sqrt{\Xi_{ref}^2 + P_{SF}\Delta\nu_{z,SF}^2}$$

S. Ulmer, C. C. Rodegheri, K. Blaum, H. Kracke, A. Mooser, W. Quint, J. Walz , Phys. Rev. Lett 106, 253001 (2011)

Cumulative measurement:

Black – frequency stability with superimposed spin flips.

Red – background stability

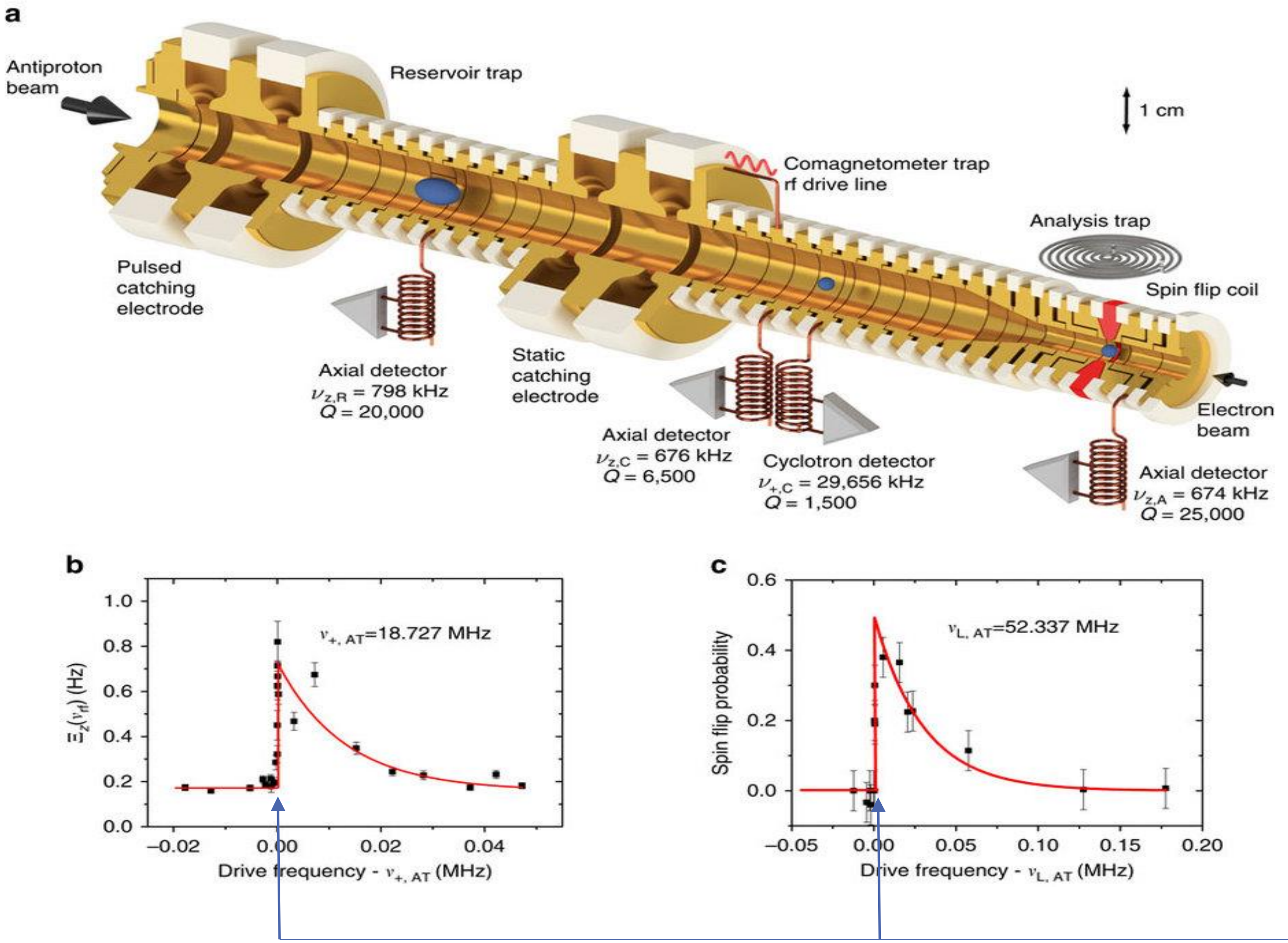


Tune drive frequency:

changes spin flip probability and thus moves resonant data-set.

BASE – Antiproton Magnetic Moment Measurement

Invented co-magnetometer assisted g-factor measurement.



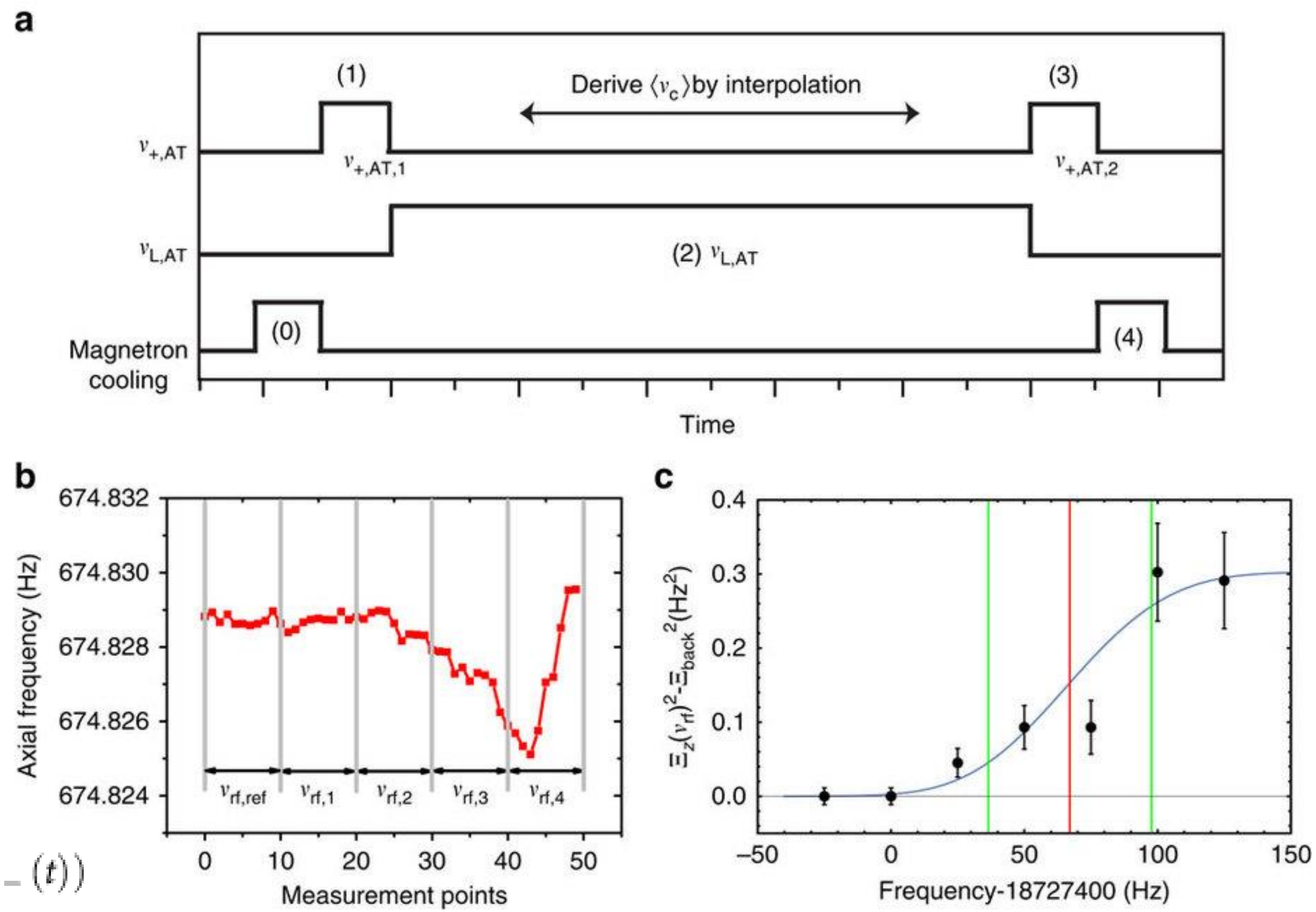
Co-magnetometer trap allows for in-situ monitoring of magnetic field fluctuations.

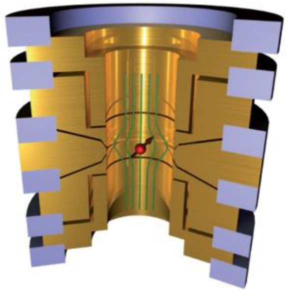
Of importance during the hours of statistical data accumulation in the noisy environment of an accelerator hall.

!!! CUT SCANS !!!

Measurement, Cut Scans and Limitations

Measurement scheme





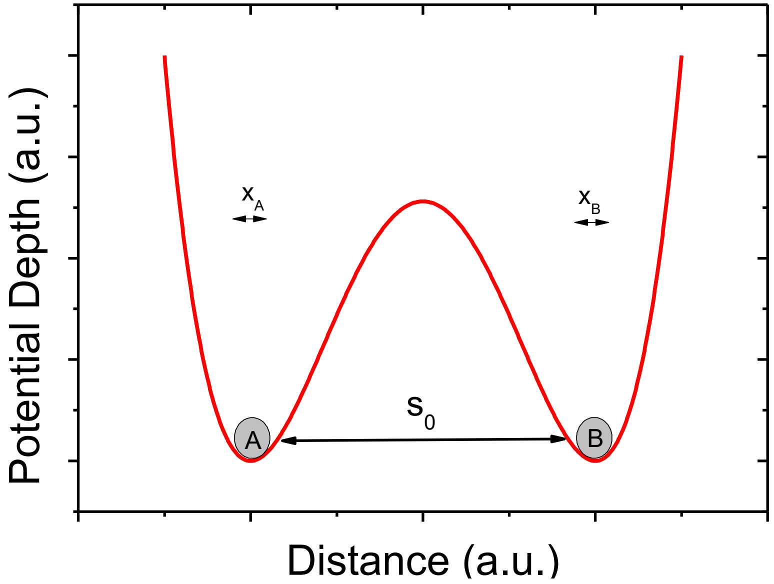
Limitations in frequency resolution

Magnetron random walk in the magnetic bottle:

$$\Xi_z(\nu_{\mathrm{rf},k}) = \Upsilon \int_0^{\nu_{\mathrm{rf},k}} \mathrm{d}\nu \int_0^{\tau_\mathrm{m}} \mathrm{d}t \cdot w_k(\nu, \nu_+(0) + \xi_-(t))$$
$$:= f\left(w_k(\nu_{\mathrm{rf},k}, \langle \nu_+(0) + \xi_-(\tau_\mathrm{m}) \rangle)\right), \qquad (4)$$

Sympathetic Cooling of Antiprotons

Two charged particles trapped in direct vicinity interact via coulomb interaction.



$$U(x_a,x_b) = \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{s_0 - x_a + x_b}$$

$$\approx \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{s_0}\left(\underbrace{1 + \frac{x_a - x_b}{s_0} + \frac{x_a^2}{s_0^2} + \frac{x_b^2}{s_0^2}}_{\text{Static}} - \underbrace{\frac{2x_a x_b}{s_0^2}}_{\text{Dynamic}}\right)$$

$$-\frac{q_a q_b}{2\pi\varepsilon_0 s_0^3}(x'_a x'_b) = -\hbar\Omega_{\mathrm{ex}}(a+a^\dagger)(b+b^\dagger) \approx -\hbar\Omega_{\mathrm{ex}}(ab^\dagger + a^\dagger b) \longrightarrow \Omega_{\mathrm{ex}} \equiv \frac{q_a q_b}{4\pi\varepsilon_0 s_0^3\sqrt{m_a m_b}\sqrt{\omega_{0a}\omega_{0b}}}$$

Resonant Coupling:

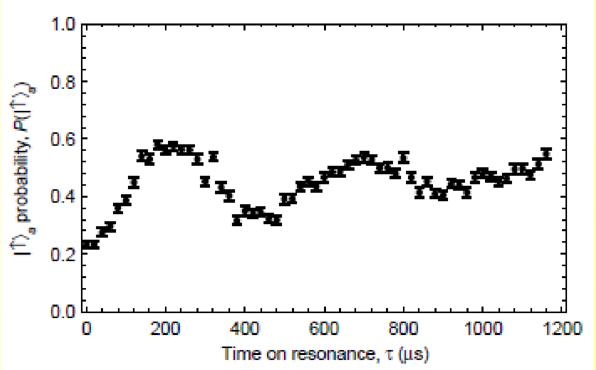
$$a^\dagger(t) = \exp(i\omega_0 t)(a^\dagger(0)\cos(\Omega_{\mathrm{ex}}t) - ib^\dagger(0)\sin(\Omega_{\mathrm{ex}}t))$$

$$b^\dagger(t) = \exp(i\omega_0 t)(b^\dagger(0)\cos(\Omega_{\mathrm{ex}}t) - ia^\dagger(0)\sin(\Omega_{\mathrm{ex}}t))$$

Effective Energy Exchange

Effective Energy Exchange

Successfully demonstrated in Paul trap with Be ions

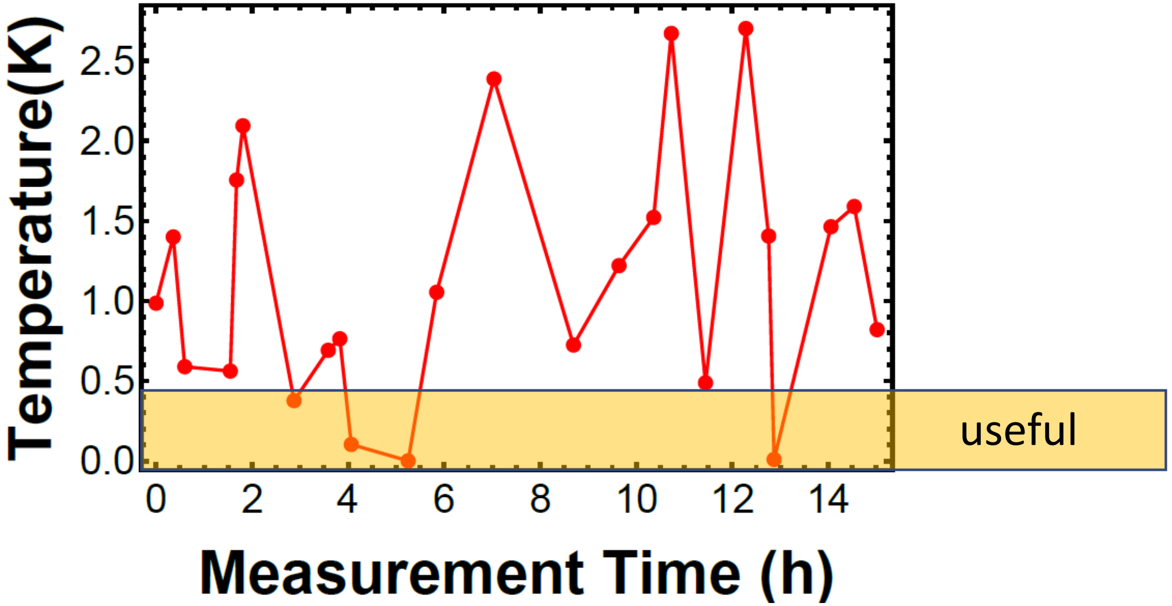


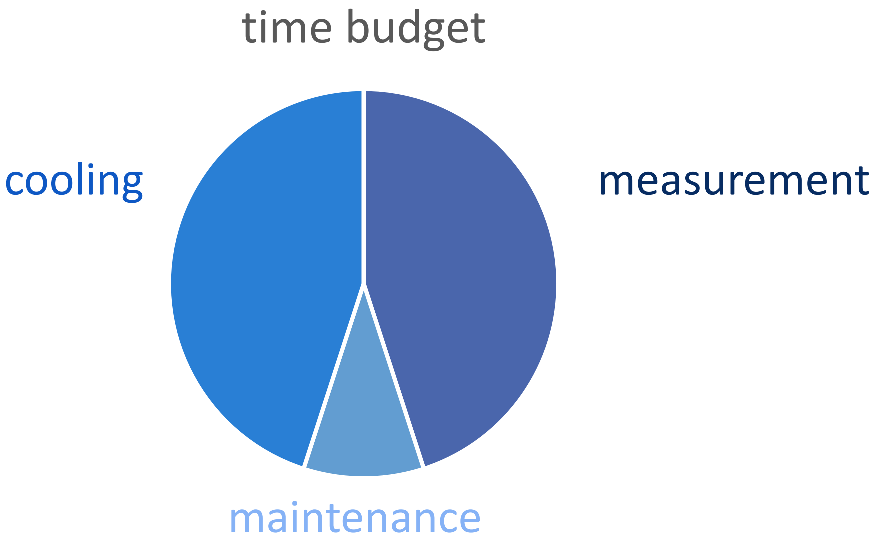
Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

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

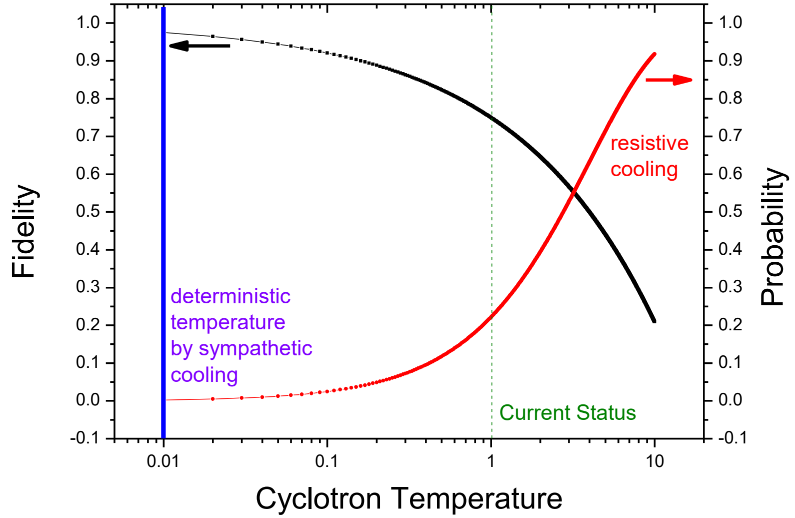
Benefits: Deterministic Cooling

Current in multi trap cycles: Sub thermal resistive cooling





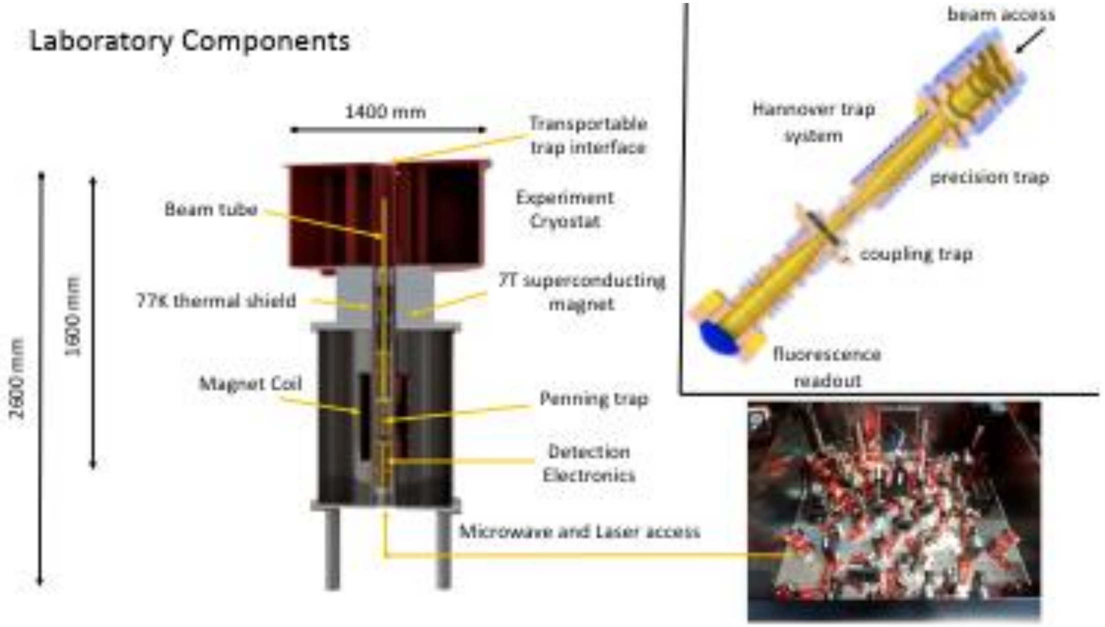
develop technique for efficient cooling



Solution: Deterministic preparation of ultra cold antiprotons.

- Future perspectives:
  - Use spectroscopy particle for active magnetic field stabilization.
  - Use spectroscopy particle as sensitive detection system

Laboratory Requirements



- Wish list – Magnetically Calm
  - Access to a bridge crane with a lifting capability of at least 2 T, better 5 T.
  - Access to liguid nitrogen delivery.
  - Access to liquid helium supplies.
  - Helium recovery line.
  - Power supplies comparable to those in the current BASE experiment zone.
  - The option to connect to CERN’s uninterruptable power supply.
  - A well defined, calm, isolated mains ground.
  - The laboratory should have at least the size of the current BASE experiment zone (≈ 40 m^2, better 60 m^2).

Systematics TTM Measurement

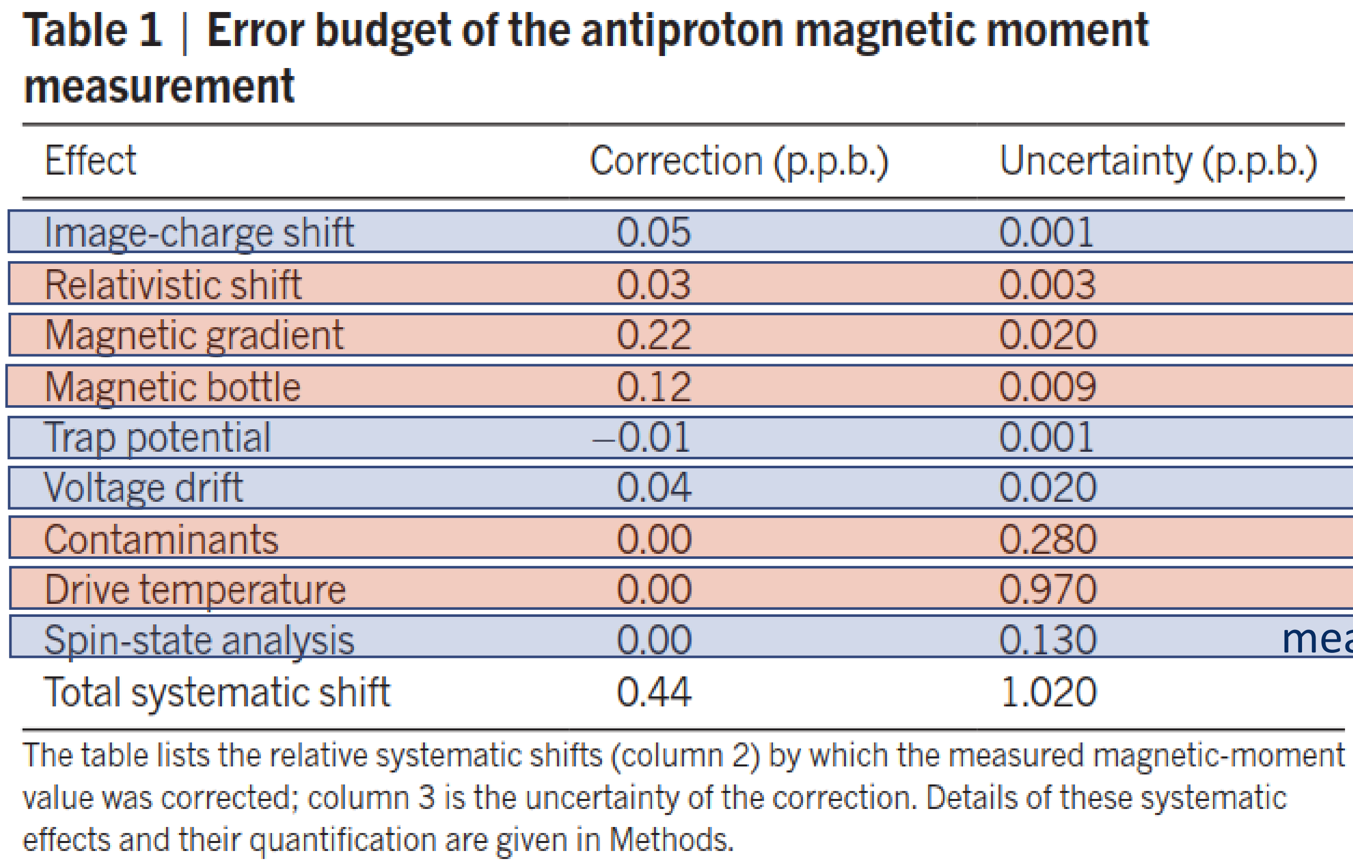


Table 1 | Error budget of the antiproton magnetic moment measurement

Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)	
Image-charge shift	0.05	0.001	calculate
Relativistic shift	0.03	0.003	measure T / calculate
Magnetic gradient	0.22	0.020	measure / calculate
Magnetic bottle	0.12	0.009	measure / calculate
Trap potential	–0.01	0.001	measure / calculate
Voltage drift	0.04	0.020	measure / calculate
Contaminants	0.00	0.280	measure / constrain
Drive temperature	0.00	0.970	measure / constrain
Spin-state analysis	0.00	0.130	measure / simulate / constrain
Total systematic shift	0.44	1.020	

The table lists the relative systematic shifts (column 2) by which the measured magnetic-moment value was corrected; column 3 is the uncertainty of the correction. Details of these systematic effects and their quantification are given in Methods.

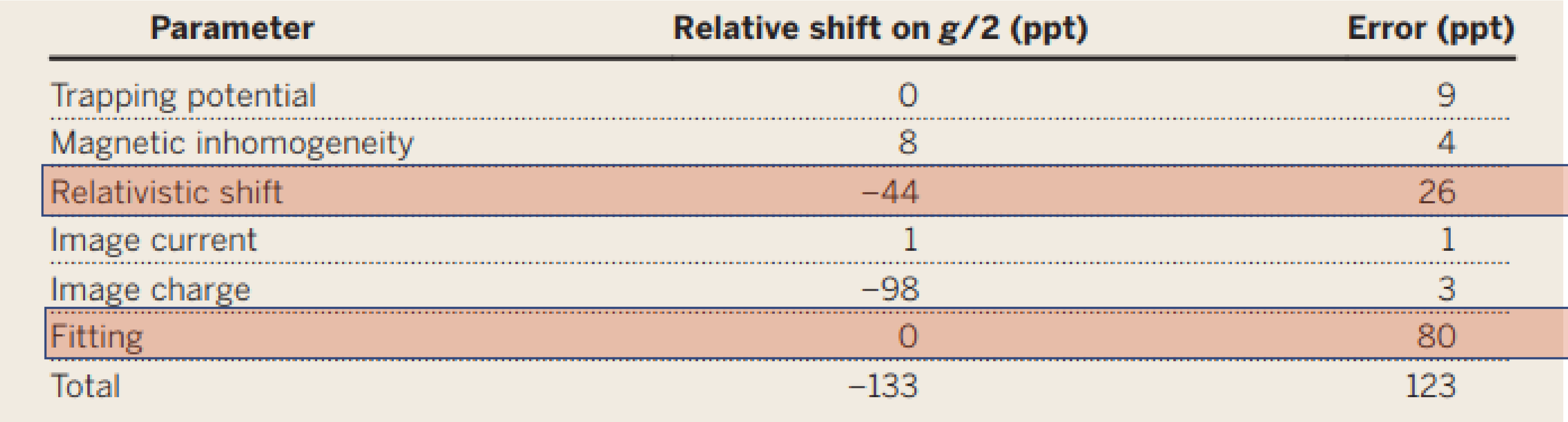
classical trap shifts

shifts induced by 2 particle approach

this dominant error is not present in double trap measurements.
Has been estimated with the conservative 95% C.L.

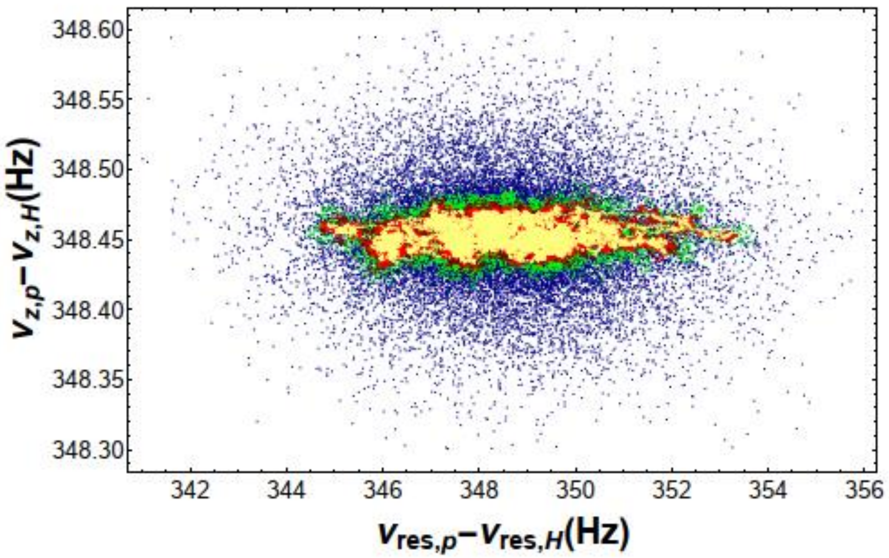
All systematics can be **reduced / eliminated** once a cyclotron detector and a tunable magnet will be implemented around the trap can

Error Budget Mainz



Parameter	Relative shift on *g*/2 (ppt)	Error (ppt)	
Trapping potential	0	9	
Magnetic inhomogeneity	8	4	
Relativistic shift	−44	26	better methods
Image current	1	1	
Image charge	−98	3	
Fitting	0	80	better methods
Total	−133	123	

- Estimate on the effect of fitting was too conservative, can be done much better (10 times)
- Direct methods will suppress this by factor of 50
- Much better methods available to determine axial temperature

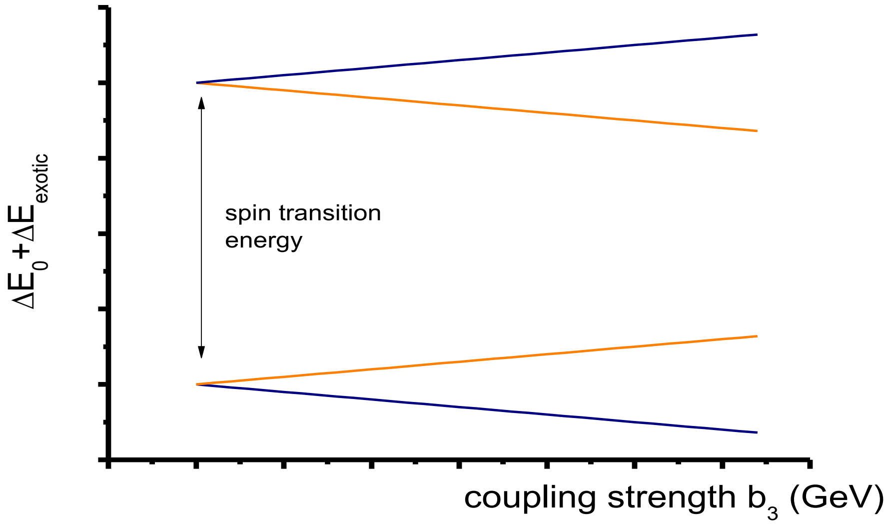


Moment CPT Tests

Year	Matter $g/2$	Antimatter $\bar{g}/2$	CPT $\lvert g/\bar{g}\rvert - 1$	System	SME $\lvert b_L\rvert$ (GeV)	$\lvert f_X^0\rvert\ (\mu_B)$
1987	1.001 159 652 188 9 (43)	1.001 159 652 187 9 (43)	0.000 000 000 000 5 (21)	electron/positron	$6 * 10^{-25}$	$2 * 10^{-12}$
2006	1.001 165 921 5 (11)	1.001 165 920 4 (12)	0.000 000 001 1 (12)	muon (μ^-,μ^+)	$1 * 10^{-23}$	$3 * 10^{-11}$
2017	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**-0.000 000 000 2 (15)**	**proton/antiproton**	$\mathbf{2 * 10^{-24}}$	$\mathbf{6 * 10^{-12}}$

SME: $\left(\boxed{i\gamma^\mu D_\mu - m} - \boxed{a_\mu\gamma^\mu - b_\mu\gamma_5\gamma^\mu}\right)\psi = 0$

$$b_\mu\gamma_5\gamma^\mu \rightarrow b_x\begin{pmatrix}-\boldsymbol{\sigma}_x & \mathbf{0}\\ \mathbf{0} & \boldsymbol{\sigma}_x\end{pmatrix}+b_y\begin{pmatrix}-\boldsymbol{\sigma}_y & \mathbf{0}\\ \mathbf{0} & \boldsymbol{\sigma}_y\end{pmatrix}+b_z\begin{pmatrix}-\boldsymbol{\sigma}_z & \mathbf{0}\\ \mathbf{0} & \boldsymbol{\sigma}_z\end{pmatrix}$$



Theoretical framework provided by A. Kostelecky (SME) and Y. Stadnik, V. Flambaum et al.