16th (Virtual) Marcel Grossmann Meeting

Studies of Exotic Physics with Antiprotons and Protons in Penning-traps

Stefan Ulmer

RIKEN

2021 / 07 / 06

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies. (RIKEN/MPG)

- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio. (RIKEN)

- **Hannover/PTB:** QLEDS-laser cooling project, new technologies. (RIKEN/PTB/UH)

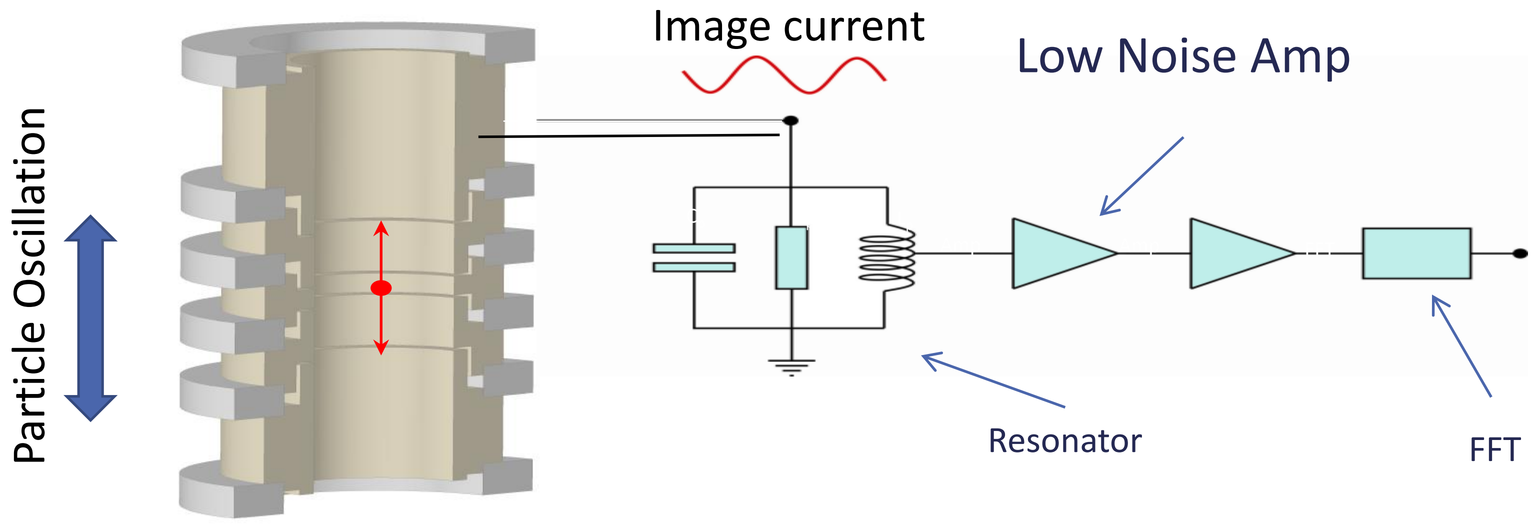
C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)

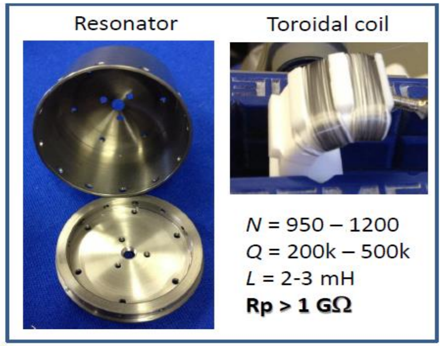
Institutes: RIKEN, MPIK, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig

Team at CERN

The Sound of Antimatter

- Concept of image current detection

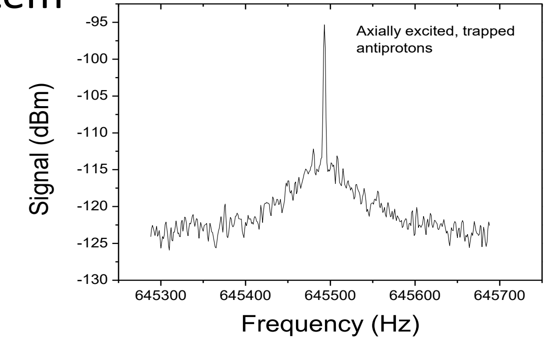




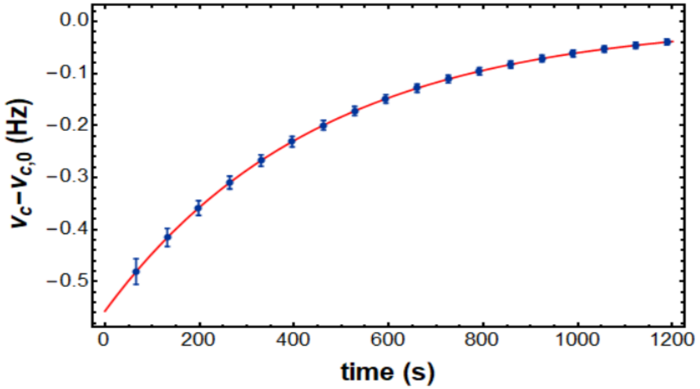
Inductor compensates system capacitance

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

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



- Special Relativity
  - Resistive cooling changes oscillation frequency

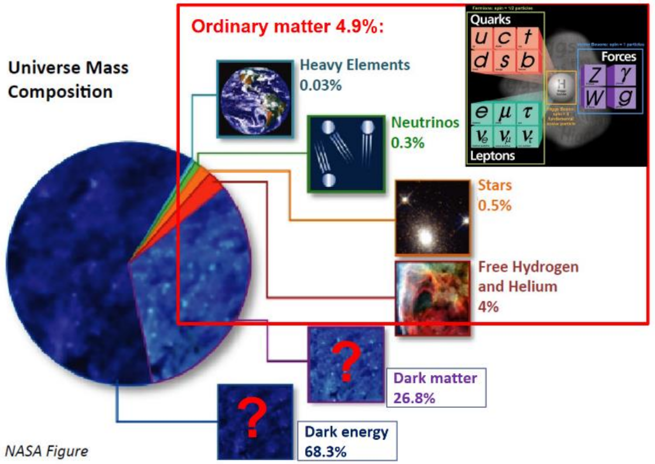


$$\nu_c = \frac{1}{2\pi} \left(\frac{q}{m} \sqrt{1 - \left(\frac{v}{c}\right)^2} B_0 \right)$$

  - Special relativity changes pitch

In BASE we are «listening» to the sound of **extremely simple**, well understandable antimatter systems to detect exotic physics , **which appears as changes in pitch / frequency beating**

Matter / Antimatter Asymmetry



Combining the Λ-CDM model and the SM, our predictions of the baryon to photon ratio are **inconsistent by about 9 orders of magnitude**

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

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

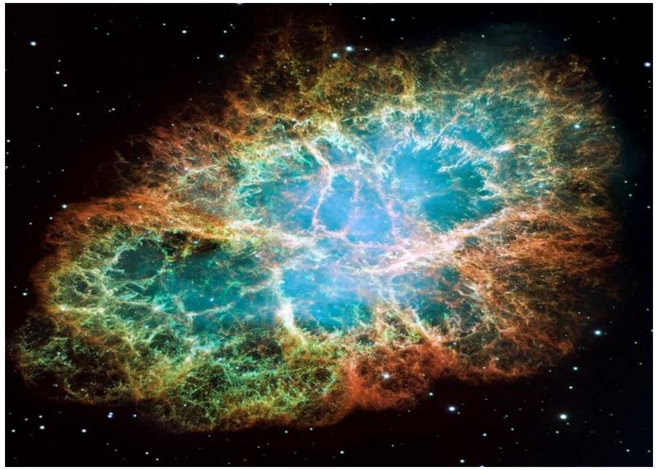
Sakharov conditions

1.) B-violation (plausible)

2.) CP-violation (observed / too small)

3.) Arrow of time (less motivated)

Alternative Source: CPT violation – adjusts matter/antimatter asymmetry by natural inversion given the effective chemical potential.



Experimental signatures sensitive to CPT violation can be derived from precise comparisons of the fundamental properties of simple matter / antimatter conjugate systems

Fundamentality of CPT Invariance

- **A relativistic theory which conserves CPT requires only five basic ingredients (Axioms):**

Lorentz and translation invariance

Energy Positivity

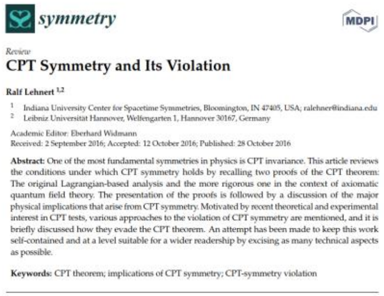
Micro Causality (Locality)

A stable vacuum ground state without momentum nor angular momentum

Unitary Field Operators Interpretation

→ **CPT**

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


symmetry MDPI

Review

CPT Symmetry and Its Violation

Ralf Lehnert [1,2]

[1] Indiana University Center for Spacetime Symmetries, Bloomington, IN 47405, USA; ralehner@indiana.edu
[2] Leibniz Universität Hannover, Welfengarten 1, Hannover 30167, Germany

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Received: 2 September 2016; Accepted: 12 October 2016; Published: 28 October 2016

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

Parameterized in the Standard Model Extension

	$\bar{\psi}\psi$	$i\bar{\psi}\gamma^5\psi$	$\bar{\psi}\gamma^\mu\psi$	$\bar{\psi}\gamma^5\gamma^\mu\psi$	$\bar{\psi}\sigma^{\mu\nu}\psi$	∂_μ
C	$+1$	$+1$	-1	$+1$	-1	$+1$
P	$+1$	-1	$(-1)^\mu$	$-(-1)^\mu$	$(-1)^\mu(-1)^\nu$	$(-1)^\mu$
T	$+1$	-1	$(-1)^\mu$	$(-1)^\mu$	$-(-1)^\mu(-1)^\nu$	$-(-1)^\mu$
CPT	$+1$	$+1$	-1	-1	$+1$	-1

The Standard Model Extension

Motivation

- String theories
- Loop-Quantum Gravity
- Non-commutative FT
- Brane scenarios
- Random dynamics models

→ **CPT-V**

- Which type of **measureable** signatures of these «BSM» theories would be imprinted onto the structure of the vacuum-box of relativistic quantum field theories.

$$\mathcal{L} = ?$$

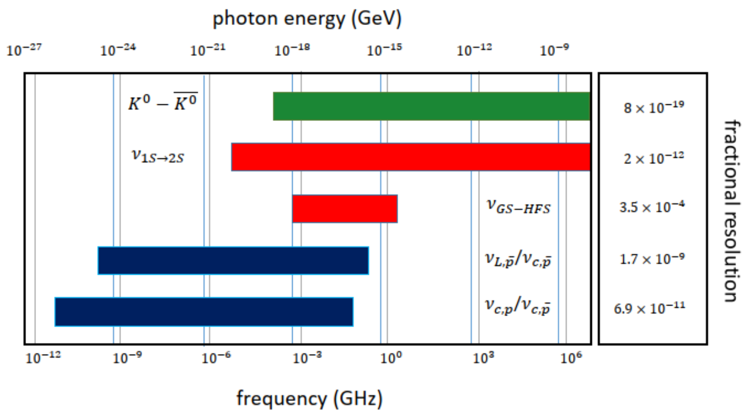
- Construct effective field theory which features:
  - Poincare invariance
  - microcausality
  - positivity of energy
  - energy and momentum conservation
  - standard quantization methods

- SME contains the Standard Model and General Relativity, but adds CPT violation

Expectation value / Mass Scale / Coupling strength

$$\mathcal{L}' \supset \frac{\lambda}{M^k}\langle T\rangle \cdot \overline{\psi}\Gamma(i\partial)^k\psi + \mathrm{h.c.}$$

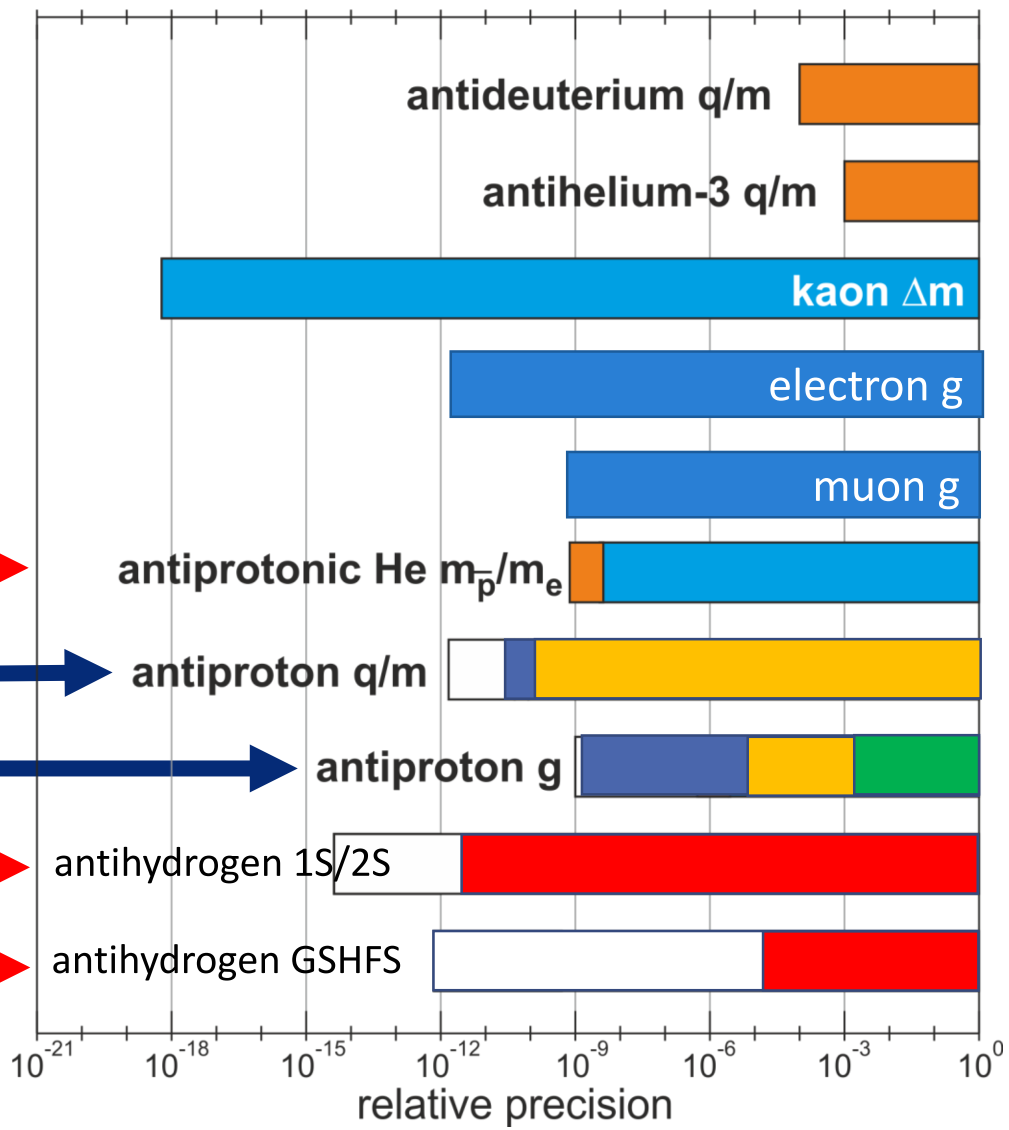
Lorentz bilinear



Kostelecký, V. Alan; Samuel, Stuart (1989-01-15). "Spontaneous breaking of Lorentz symmetry in string theory". Physical Review D. ***39*** *(2): 683–685.*

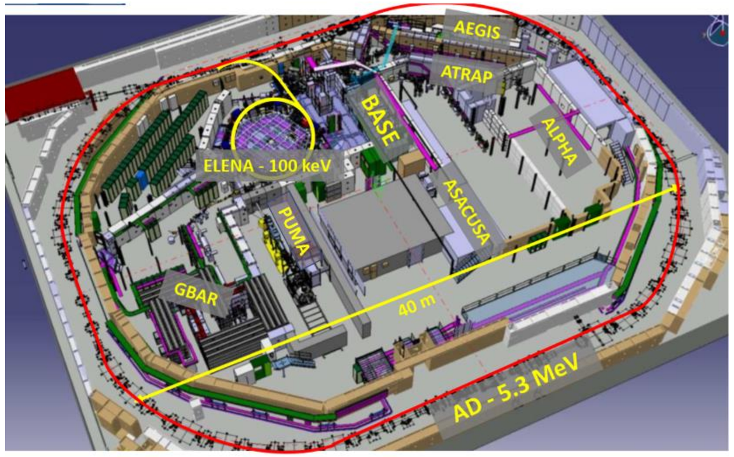
CPT tests based on particle/antiparticle comparisons

Recent
Past
Planned



CERN ALICE

CERN AD



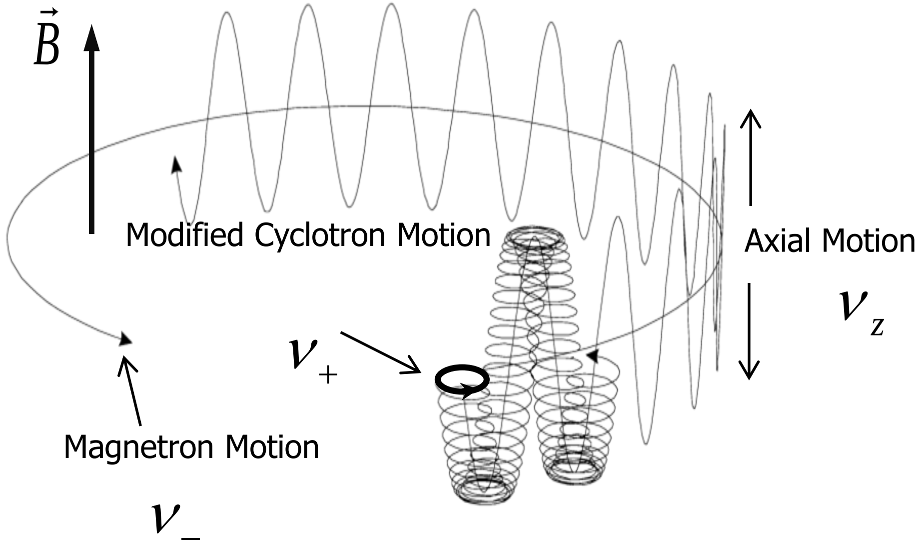
R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwingenheuer, et al., Phys. Rev. Lett. 74, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabrielse et al., PRL **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).

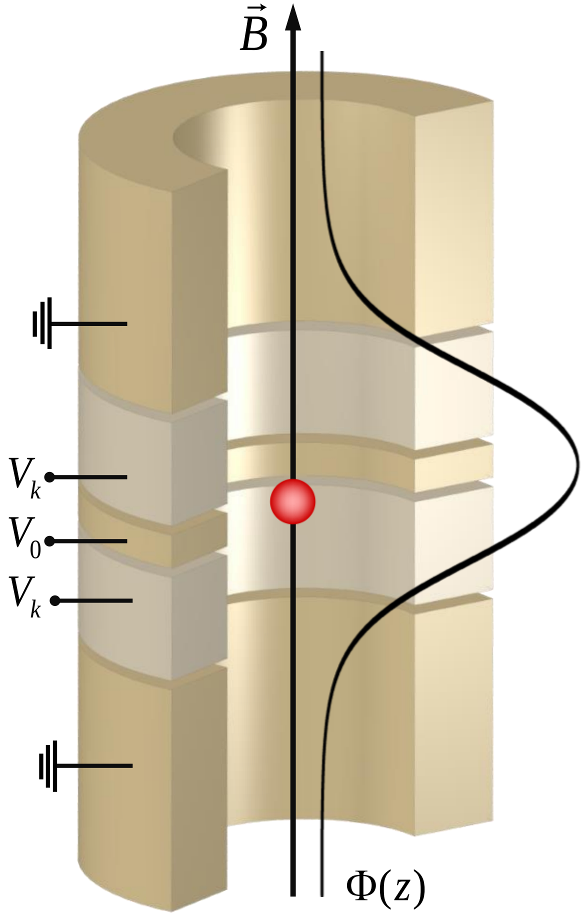
comparisons of the fundamental properties of simple matter / antimatter conjugate systems

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	$\nu_+ = 28{,}9\,\mathrm{MHz}$

Invariance Theorem

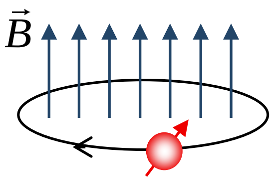
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

Gives undisturbed access to cyclotron frequencies

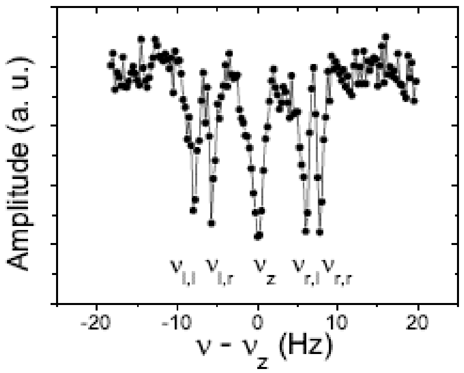
$$\nu_c = \frac{1}{2\pi}\frac{q_{ion}}{m_{ion}} B$$

Measurements in Precision Penning traps

Cyclotron Motion



simple



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

g: mag. Moment in units of nuclear magneton

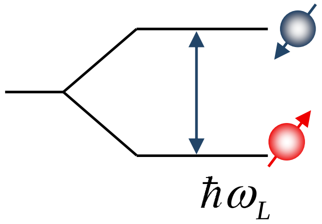
$$\omega_c = \frac{e}{m_p} B$$

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

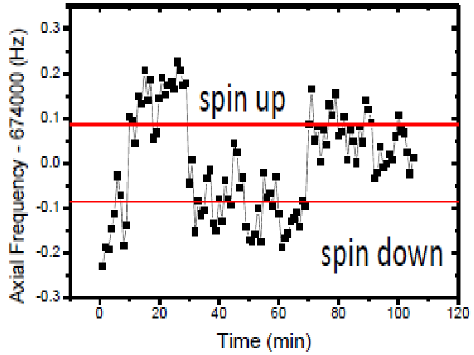
$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

Larmor Precession



difficult



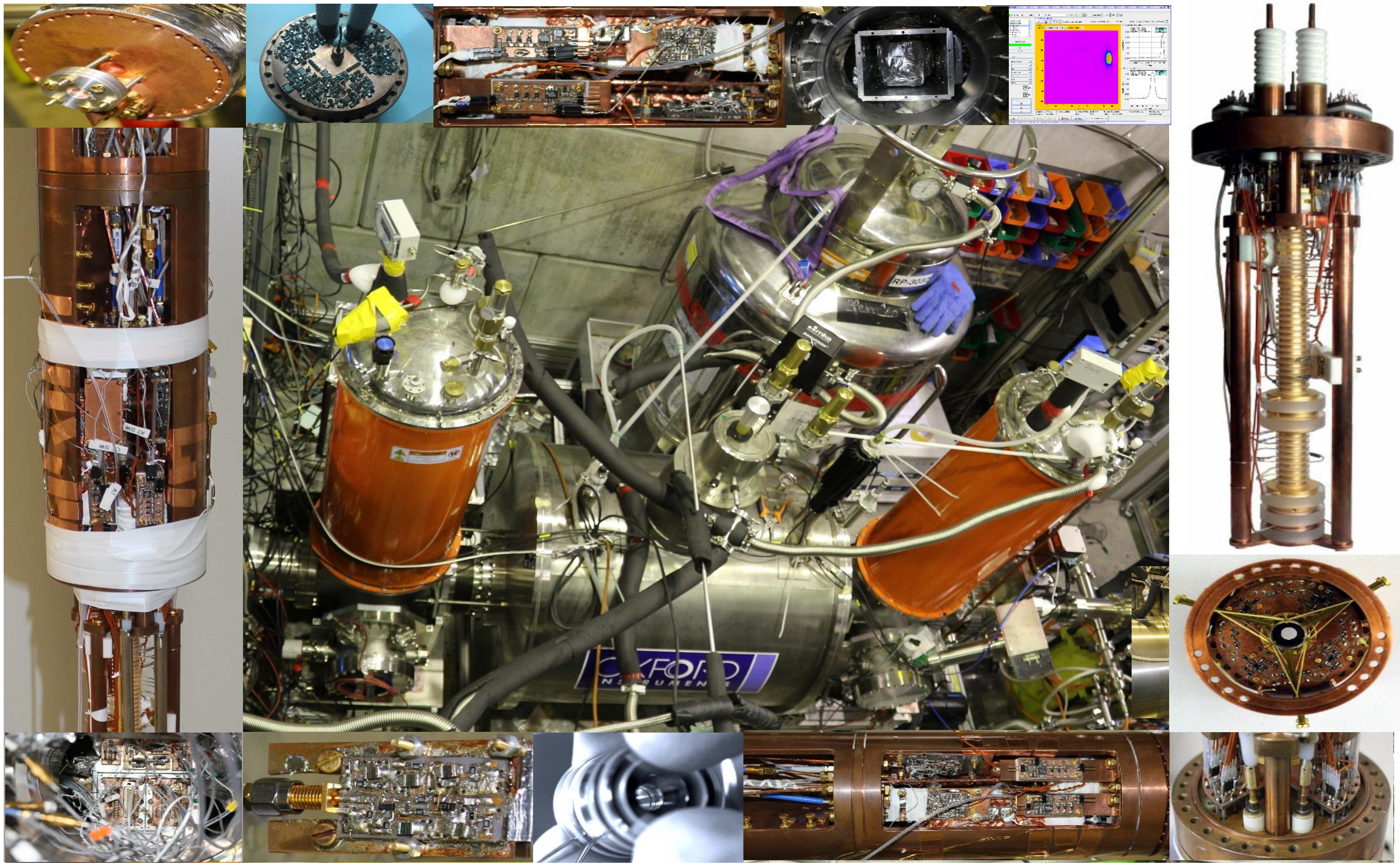
S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

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.**

High Precision Mass Spectrometry

High Precision Magnetic Moment Measurements

Experiment



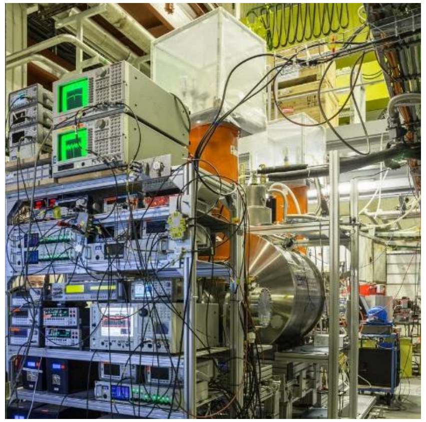
Common to all these experiments:

Superconducting magnets

Ultra sensitive superconducting partice detectors

Cryogenic operation of experiments

Use of «complex» multi-trap systems

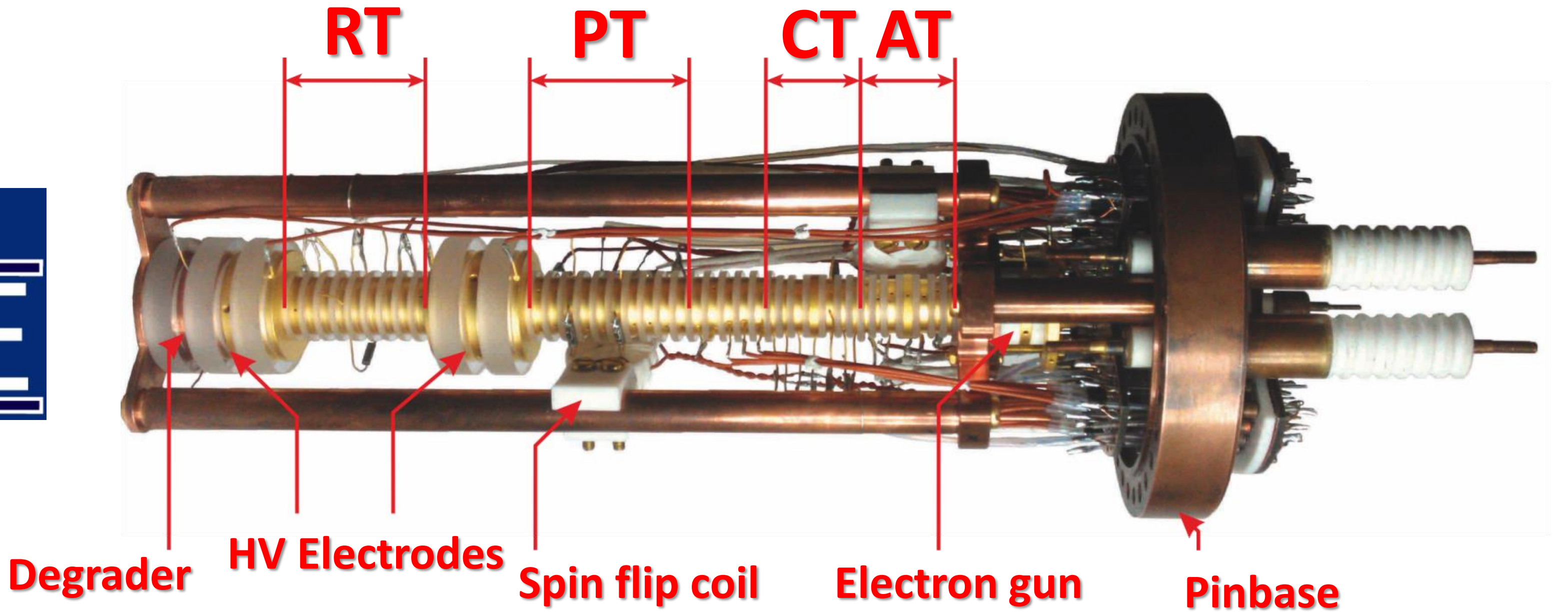


BASE Trap System

Access to beamline

Particles not continuously available

Trap for efficient cyclotron cooling



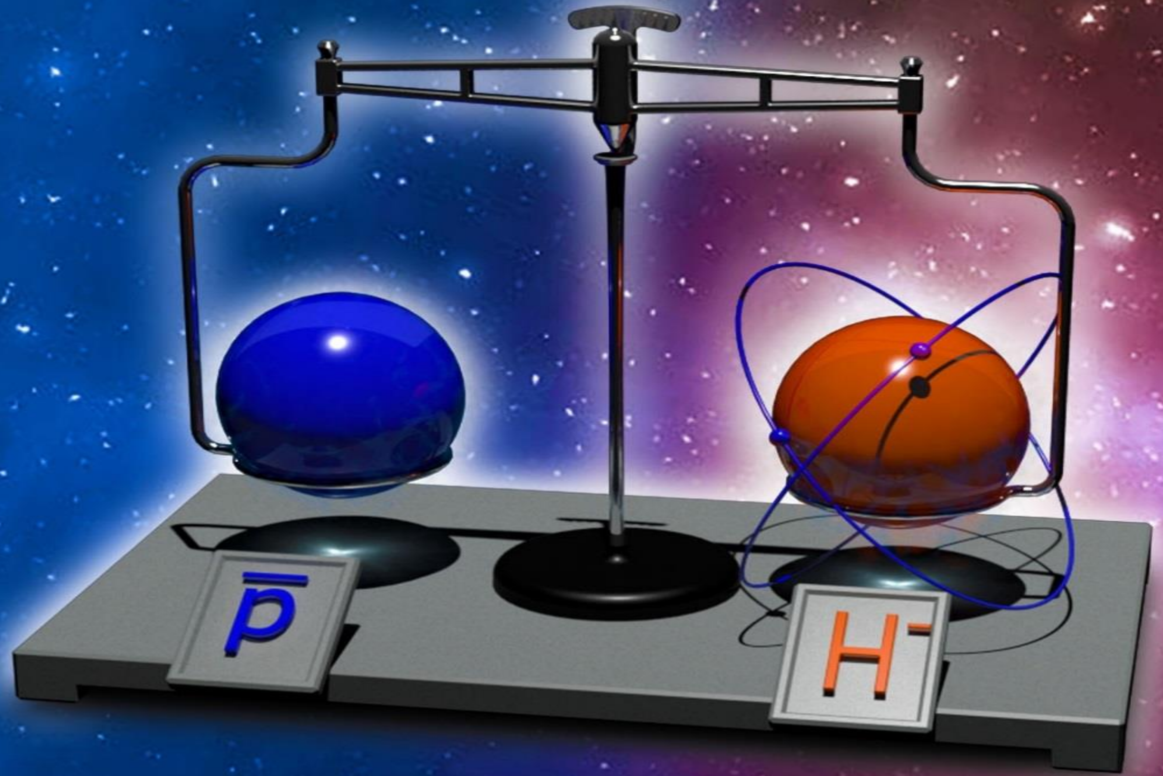
Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements. Trap is “power failure save”.

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, $B_2 = 300\ mT / mm^2$

High-Precision Comparison of the

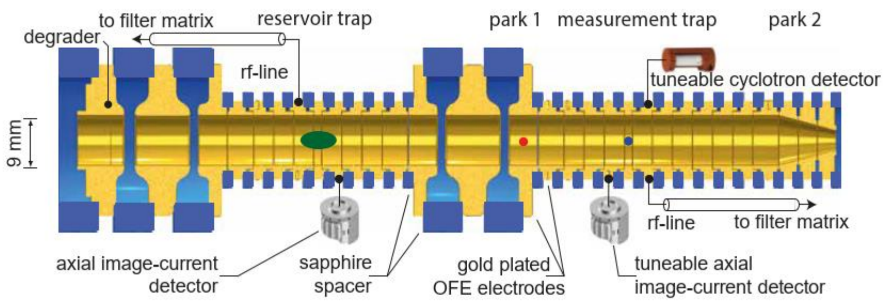


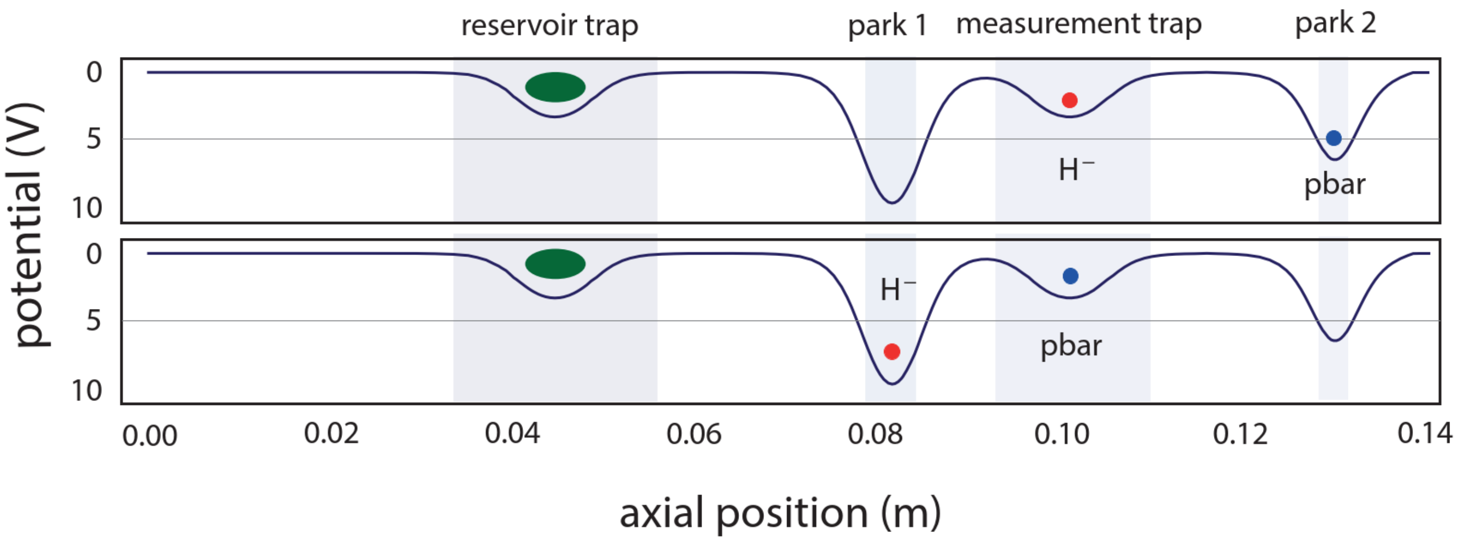
Antiproton-to-Proton Charge-to-Mass Ratio

Charge-to-Mass Ratio Measurement

- In BASE one frequency ratio measurement takes 240 s, 50 times faster than in 1999 measurement

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





- H^- ion is a perfect proxy for the proton at negative charge. Inversion of trapping potential can be avoided, which suppresses certain systematic effects by factor of 300.

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

First measurement: Gabrielse et al., Phys. Rev. Lett. 82, 3198 (1999)

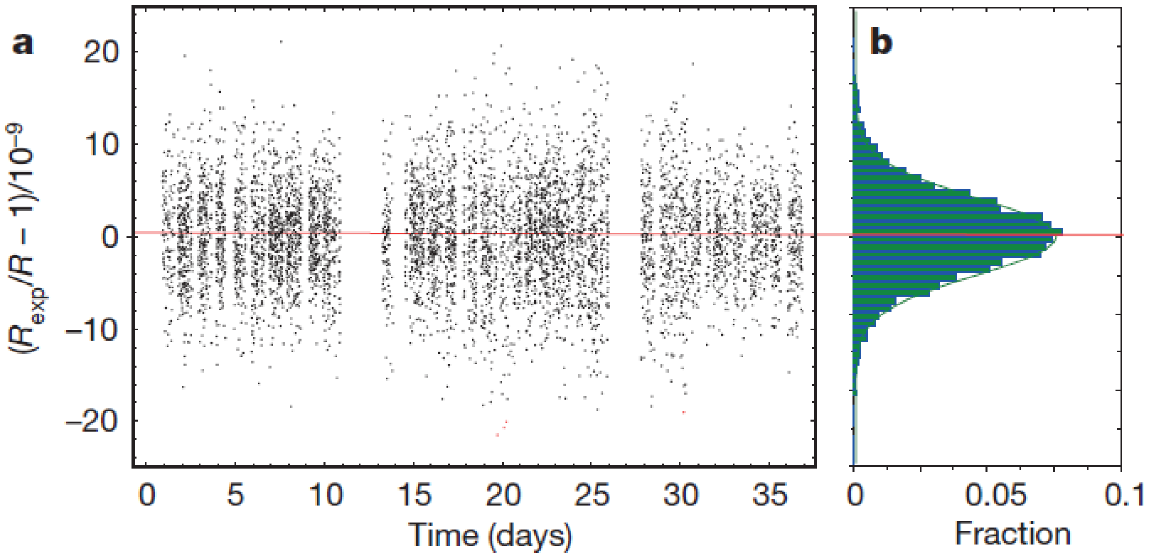
Effect	Magnitude	
m_e/m_p	0.001 089 234 042 95 (5)	MPIK
$-E_b/m_p$	0.000 000 014 493 061 …	MPQ
$-E_a/m_p$	0.000 000 000 803 81 (2)	Lykke

$2\,m_e/m_p = 0.001\,089\,234\,042\,95(5)$
m_p: $\nu_c(\mathrm{HD}^+)$ vs $\nu_c(^{12}C^{6+})$ (Rau et al., Nature585, 2020)
m_e: $g(^{12}C^{5+})$ & QED (Sturm et al., Nature506, 2014)

$-E_a/m_p = -0.000\,000\,000\,803\,81(2)$
Photodetachment spectroscopy
Lykke et al., PRA43 (1991)

$-E_b/m_p = -0.000\,000\,014\,493\,061$
1S-2S in hydrogen & bound state QED
Parthey et al., PRL107 (2011),
Jentschura et al., PRL95 (2005)

BASE Measurements – Proton to Antiproton Q/M



Result of 6500 proton/antiproton Q/M comparisons:

$R_{exp,c}$ = 1.001 089 218 755 (69)

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

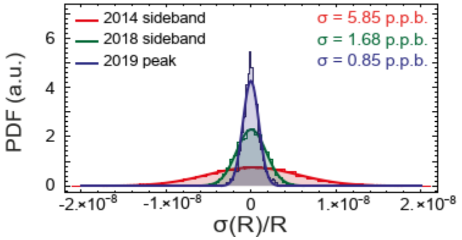
Stringent test of CPT invariance with Baryons.

Consistent with CPT invariance

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

New measurement:

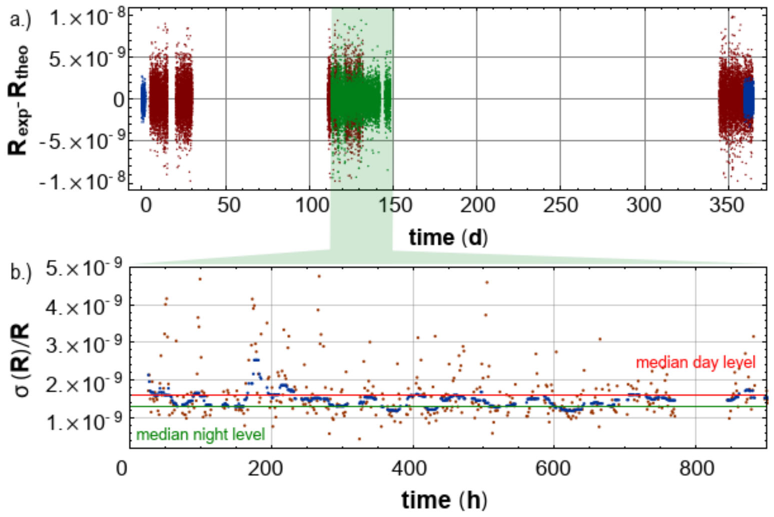
- Acquired 35000 frequency ratio measurements over 1.5 years, distributed over the sidereal year.
- Used two measurement methods, tunable axial detector to suppress systematics, and a rebuilt apparatus



$R_{exp,c,1}$ = 1.001 089 218 763 (23)

$R_{exp,c,2}$ = 1.001 089 218 7XX (2X)

Final data analysis is work in progress



BASE, *in preparation* (2021)

BASE Measurements – Proton to Antiproton Q/M

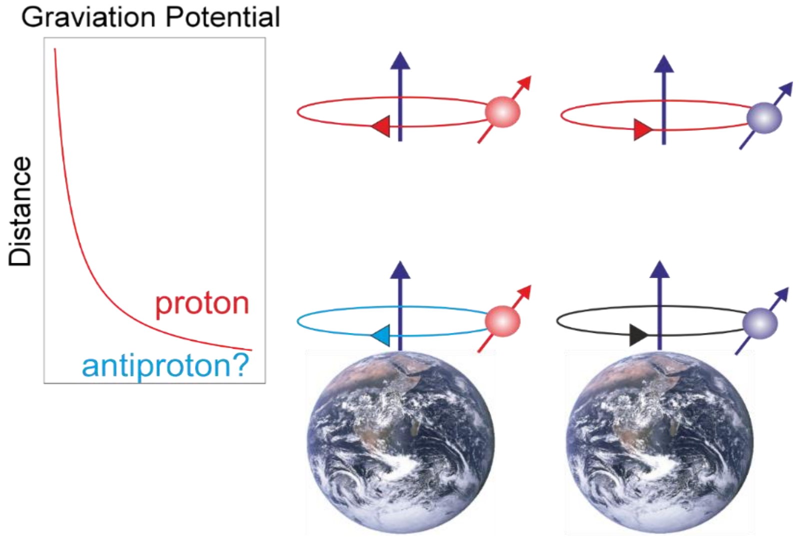
- Constrain of the gravitational anomaly for antiprotons:

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

Our recent result sets an upper limit of

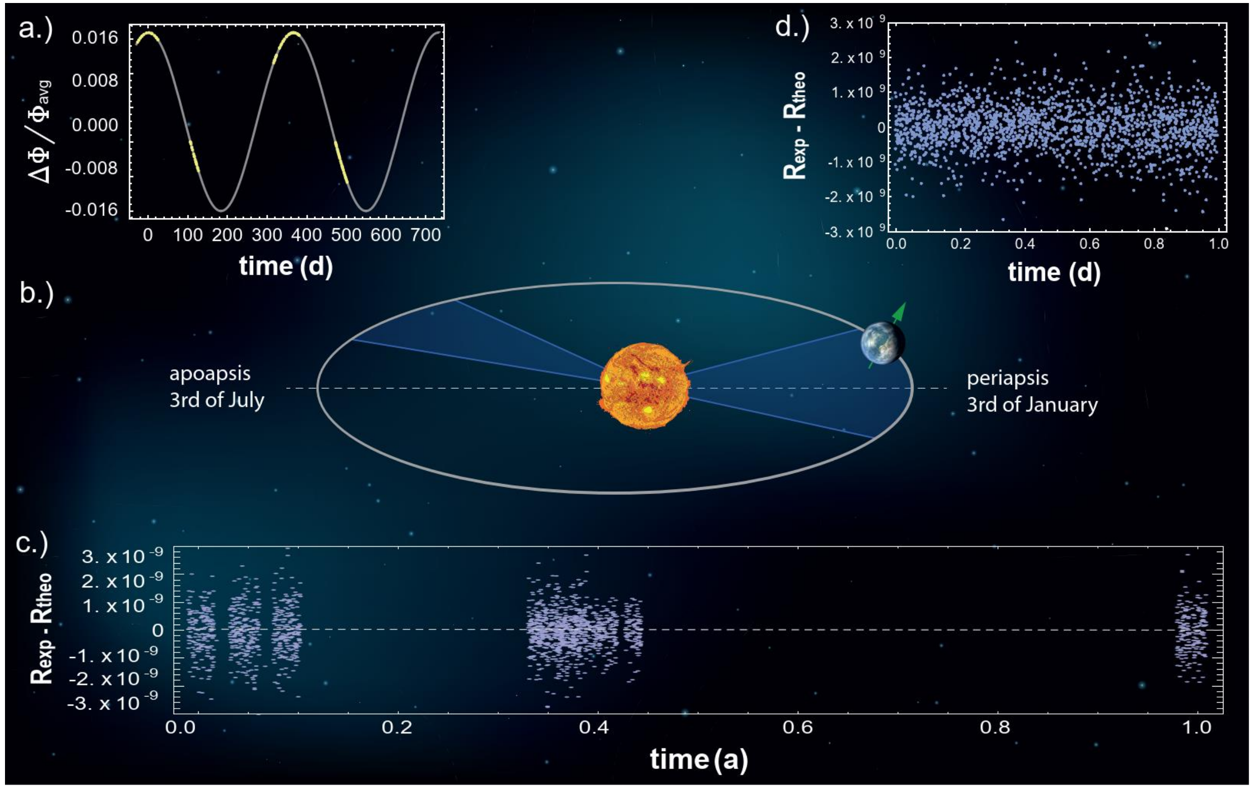
$$|\alpha_g - 1| < 1.9 \times 10^{-7}$$

tests WEPc, in aspects (vectors) different to WEPff



- Direct experiments planned by Aegis, GBAR, ALPHA

- Planned Longer Term Measurements



- Set differential constraints on the weak equivalence principle by measuring charge-to-mass ratio as a function of gravitational potential at surface of earth.
- Final data analysis is work in progress.

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

Physics Constraints

- Minimal SME limits (CL 0.95)

$$R_{H^-} < 4.2 * 10^{-27}\,\text{GeV}$$

- Non-minimal SME

$$\frac{|(q/m)_{pbar}|}{|(q/m)_p|} - 1 = \frac{\delta\nu_c^{pbar} - \delta\nu_c^{p}}{\nu_c}$$

$$\Delta(\delta\nu_c^p) = \frac{1}{m_{pbar}}\left(b'^3_{pbar} - b'^3_p\right) + f\left(c^{\mu\nu}_{pbar}, c^{\mu\nu}_p, b^{(>(+5))}\right)$$

- Other induced oscialltory signatures:

$$M(\vec{r},t) = M_0\left[1 + \frac{g_\text{n}}{M_0}\phi(\vec{r},t)\right]$$

Sidereal frequency analysis is work in progess.

- Nonminimal SME limits

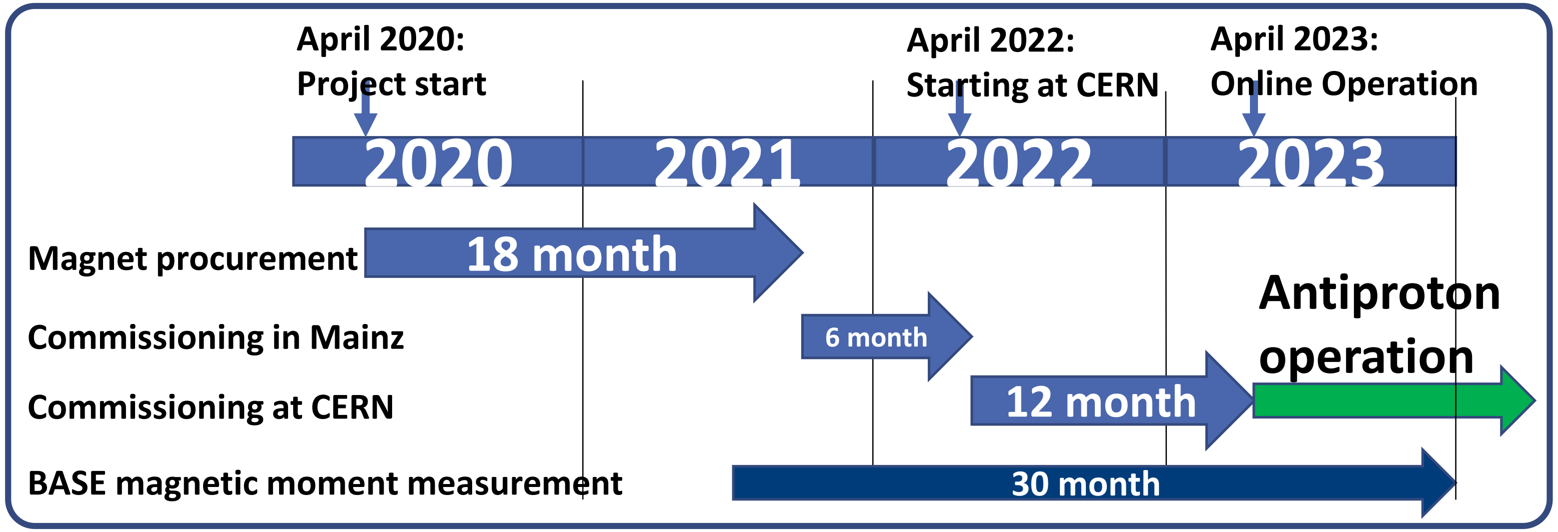
Coefficient	Unit	Previous Limit	Improved Limit	Factor
$\lvert\tilde{b}'^{Z}_e\rvert$	GeV	$< 1.74\cdot10^{-17}$	$< 6.37\cdot10^{-18}$	2.73
$\lvert\tilde{c}^{XX}_e\rvert$		$< 3.23\cdot10^{-14}$	$< 7.79\cdot10^{-15}$	4.14
$\lvert\tilde{c}^{YY}_e\rvert$		$< 3.23\cdot10^{-14}$	$< 7.79\cdot10^{-15}$	4.14
$\lvert\tilde{c}^{ZZ}_e\rvert$		$< 2.14\cdot10^{-14}$	$< 4.96\cdot10^{-15}$	4.31
$\lvert\tilde{b}^{X(XZ)}_e\rvert$	$(\text{GeV})^{-1}$	$< 1.21\cdot10^{-10}$	$< 2.81\cdot10^{-11}$	4.31
$\lvert\tilde{b}^{Y(YZ)}_e\rvert$	$(\text{GeV})^{-1}$	$< 1.21\cdot10^{-10}$	$< 2.81\cdot10^{-11}$	4.31
$\lvert\tilde{b}^{ZZZ}_e\rvert$	$(\text{GeV})^{-1}$	$< 1.21\cdot10^{-10}$	$< 2.81\cdot10^{-11}$	4.31
$\lvert\tilde{b}^{ZXX}_e\rvert$	$(\text{GeV})^{-1}$	$< 8.75\cdot10^{-11}$	$< 4.50\cdot10^{-11}$	1.94
$\lvert\tilde{b}^{ZYY}_e\rvert$	$(\text{GeV})^{-1}$	$< 8.75\cdot10^{-11}$	$< 4.50\cdot10^{-11}$	1.94
$\lvert\tilde{b}'^{Z}_p\rvert, \lvert\tilde{b}'^{*Z}_p\rvert$	GeV	$< 1.17\cdot10^{-10}$	$< 4.29\cdot10^{-11}$	2.73
$\lvert\tilde{c}^{XX}_p\rvert, \lvert\tilde{c}^{*XX}_p\rvert$		$< 1.19\cdot10^{-10}$	$< 2.86\cdot10^{-11}$	4.14
$\lvert\tilde{c}^{YY}_p\rvert, \lvert\tilde{c}^{*YY}_p\rvert$		$< 1.19\cdot10^{-10}$	$< 2.86\cdot10^{-11}$	4.14
$\lvert\tilde{c}^{ZZ}_p\rvert, \lvert\tilde{c}^{*ZZ}_p\rvert$		$< 7.85\cdot10^{-11}$	$< 1.82\cdot10^{-11}$	4.31
$\lvert\tilde{b}^{X(XZ)}_p\rvert, \lvert\tilde{b}^{*X(XZ)}_p\rvert$	$(\text{GeV})^{-1}$	$< 2.42\cdot10^{-10}$	$< 5.62\cdot10^{-11}$	4.31
$\lvert\tilde{b}^{Y(YZ)}_p\rvert, \lvert\tilde{b}^{*Y(YZ)}_p\rvert$	$(\text{GeV})^{-1}$	$< 2.42\cdot10^{-10}$	$< 5.62\cdot10^{-11}$	4.31
$\lvert\tilde{b}^{ZZZ}_p\rvert, \lvert\tilde{b}^{*ZZZ}_p\rvert$	$(\text{GeV})^{-1}$	$< 2.42\cdot10^{-10}$	$< 5.62\cdot10^{-11}$	4.31
$\lvert\tilde{b}^{ZXX}_p\rvert, \lvert\tilde{b}^{*ZXX}_p\rvert$	$(\text{GeV})^{-1}$	$< 1.76\cdot10^{-10}$	$< 8.99\cdot10^{-11}$	1.94
$\lvert\tilde{b}^{ZYY}_p\rvert, \lvert\tilde{b}^{*ZYY}_p\rvert$	$(\text{GeV})^{-1}$	$< 1.76\cdot10^{-10}$	$< 8.99\cdot10^{-11}$	1.94

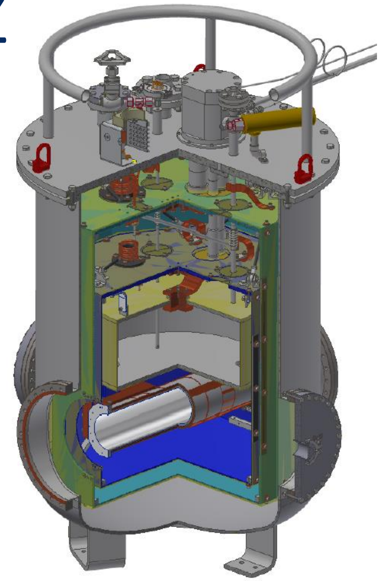
D. Antypas et al., ArXiV 2012.01519 (2020) (relaxion dark matter)

Y. Ding, A. Kostelecky et al., PRD 102, 056009 (2021)

BASE-STEP – C. Smorra – ERC Univ. Mainz

Under development at University of Mainz



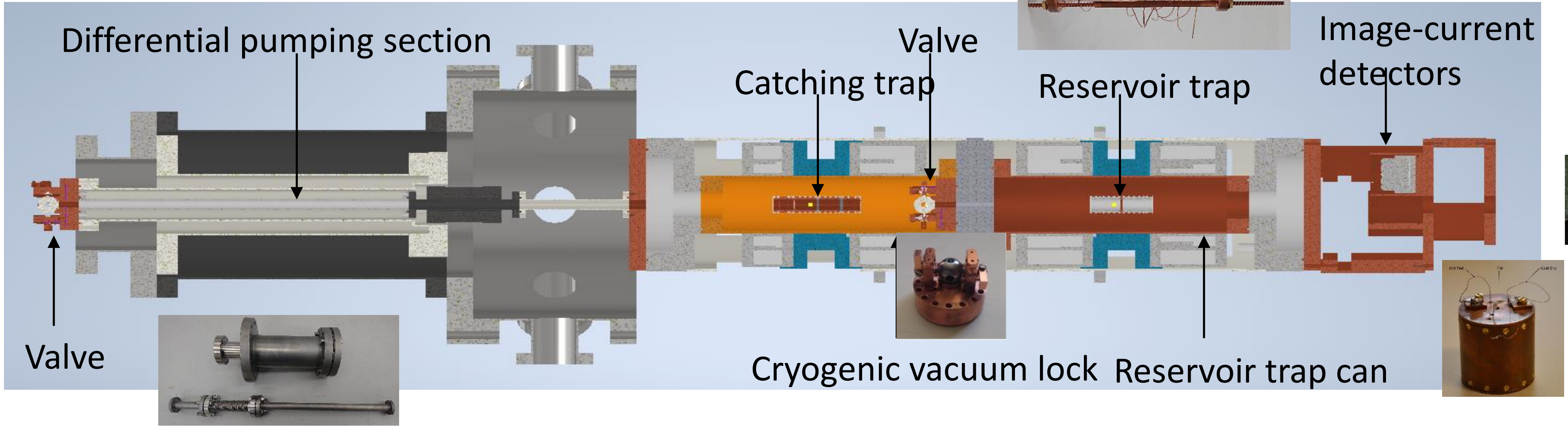


Magnet is ordered

Expected delivery window 12/21 to 03/22

- Apparatus has been developed, currently in the workshop, likely operational late 2021 / early 2022.

Recommended for Approval



Developed by Smorra group

C. Smorra

The Antiproton Magnetic Moment

A milestone measurement in antimatter physics


LETTER

OPEN

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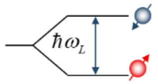
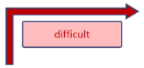
A parts-per-billion measurement of the antiproton magnetic moment

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]

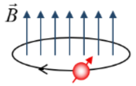




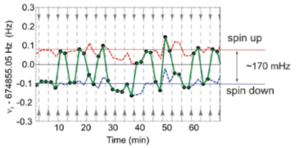
Continuous Stern Gerlach Effect

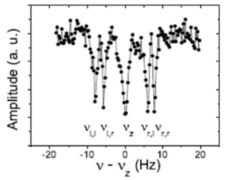
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

Image Current Measurements

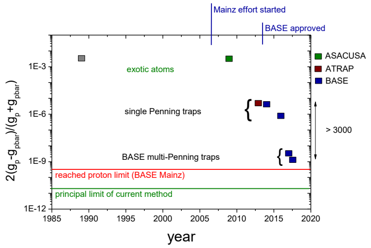


C. Smorra *et al.*, Phys. Lett. B 769, 1 (2017)





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



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

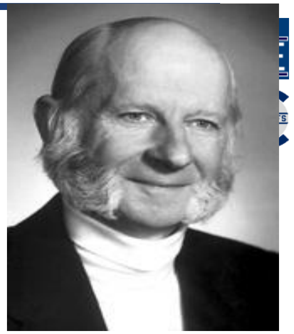
The BASE result relies on a quantum measurement scheme to observe spin transitions of a single antiproton in a non-destructive manner. In experimental physics, non-destructive observations of quantum effects are usually accompanied by a tremendous increase in measurement precision. For example, the non-destructive 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

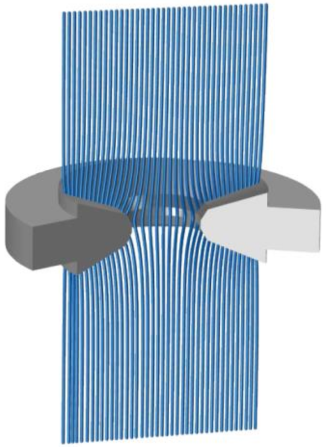
The multi-Penning-trap system used by BASE to detect the spin-flips of single trapped protons and antiprotons.

CERN COURIER, 3 / 2018.

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

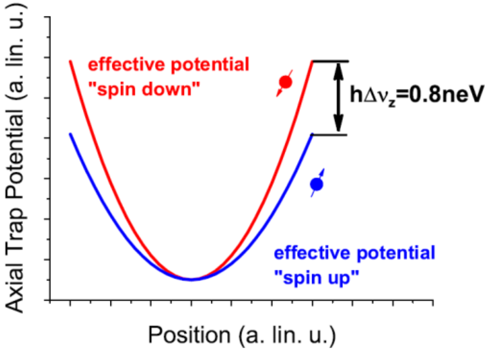
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

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

- Most extreme magnetic conditions ever applied to single particle.

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

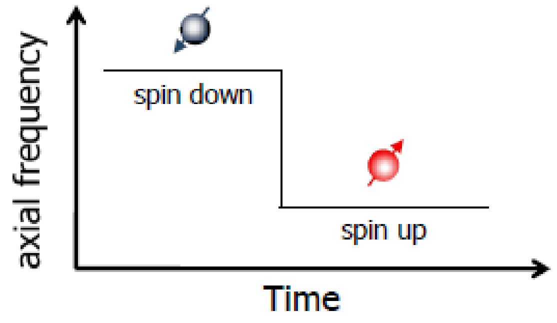


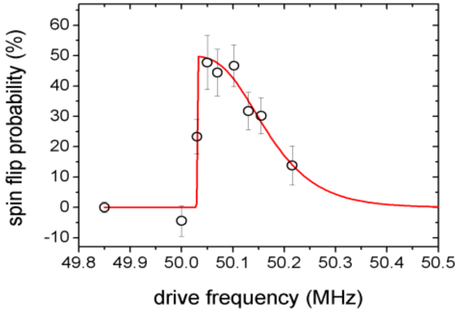
Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

Limited to p.p.m level

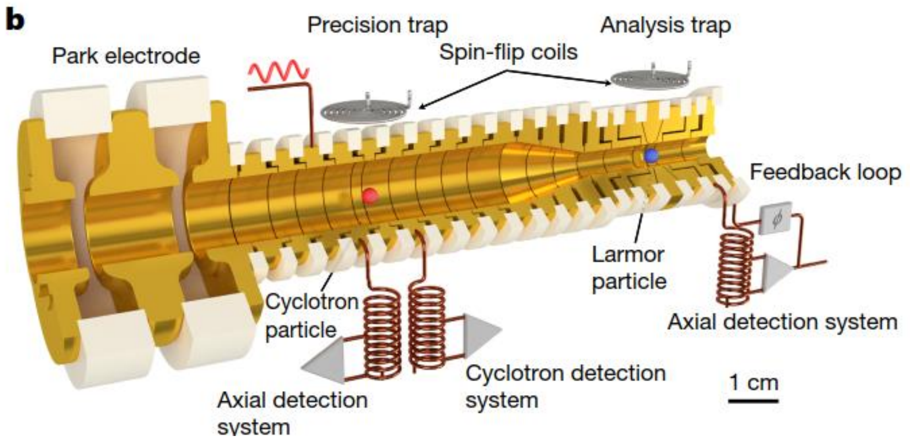


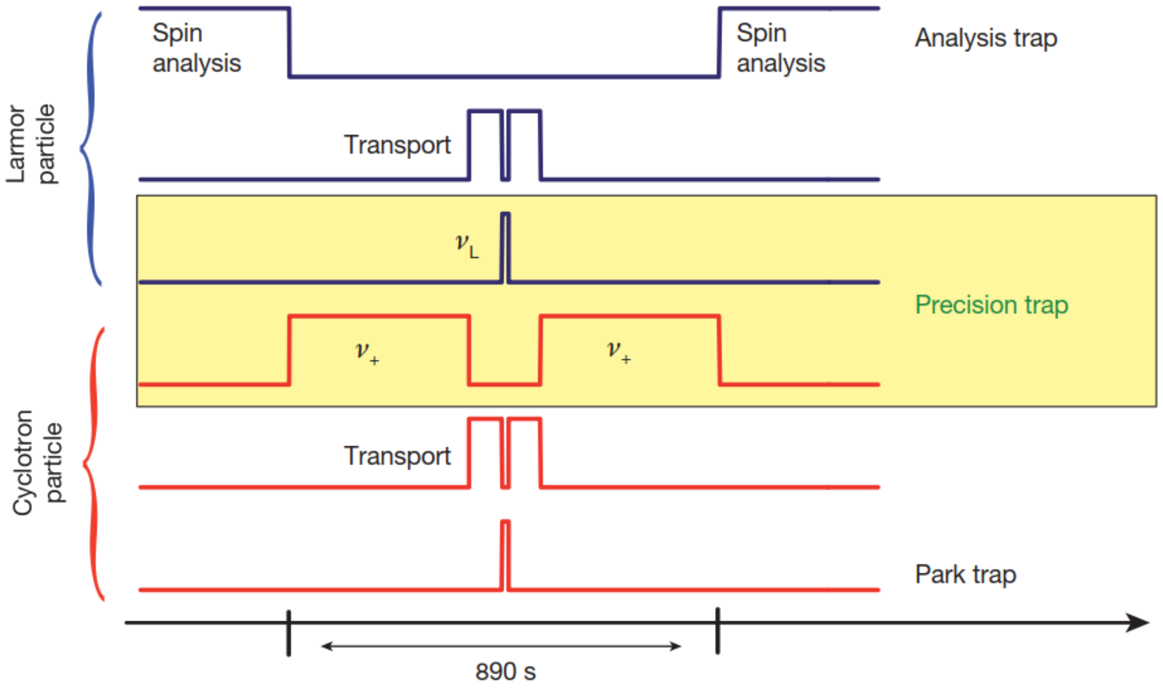


S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

BASE Two-Particle/Three Trap Method

Idea: divide measurement to two particles



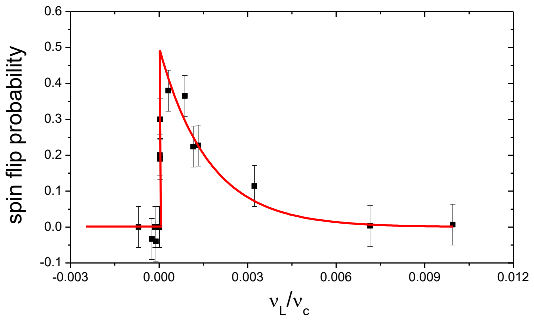


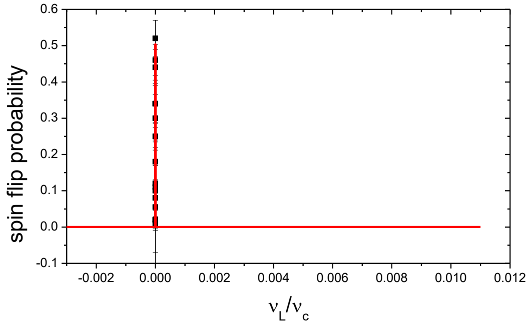
«hot» cyclotron particle which probes the magnetic field in the precision trap

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

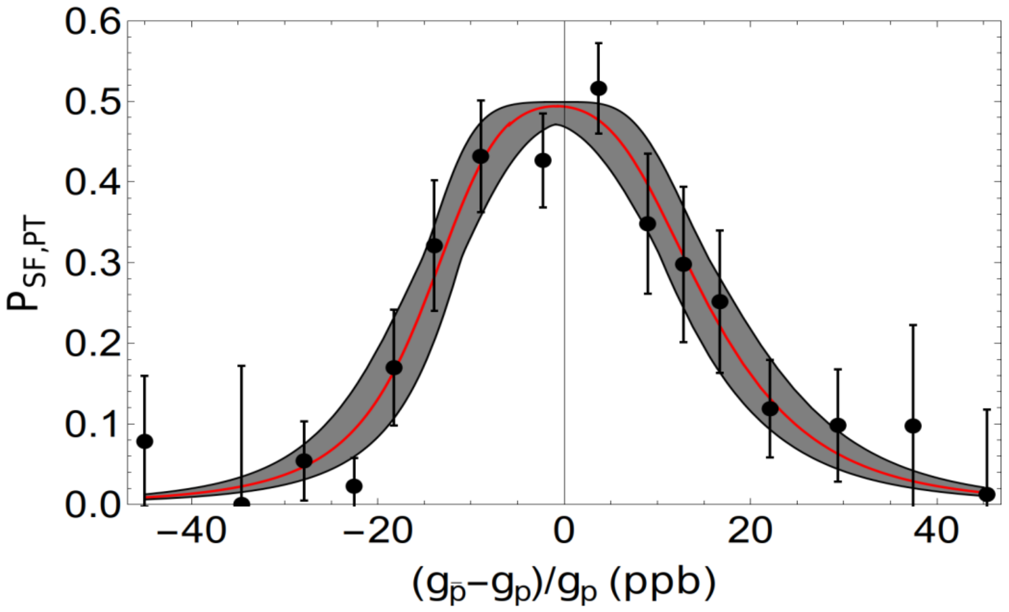
pay: measure with two particles at different mode energies

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

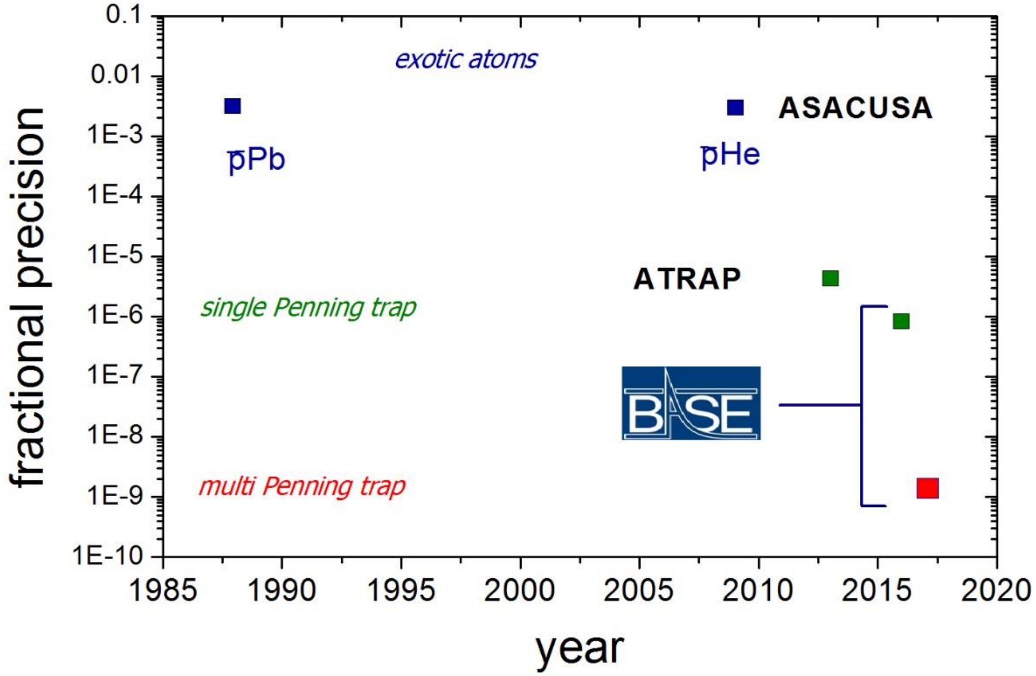




The Magnetic Moment of the Antiproton



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



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

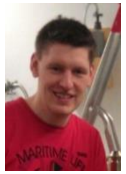
$$\frac{g_p}{2} = 2.792\,847\,350\,(9)$$

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

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

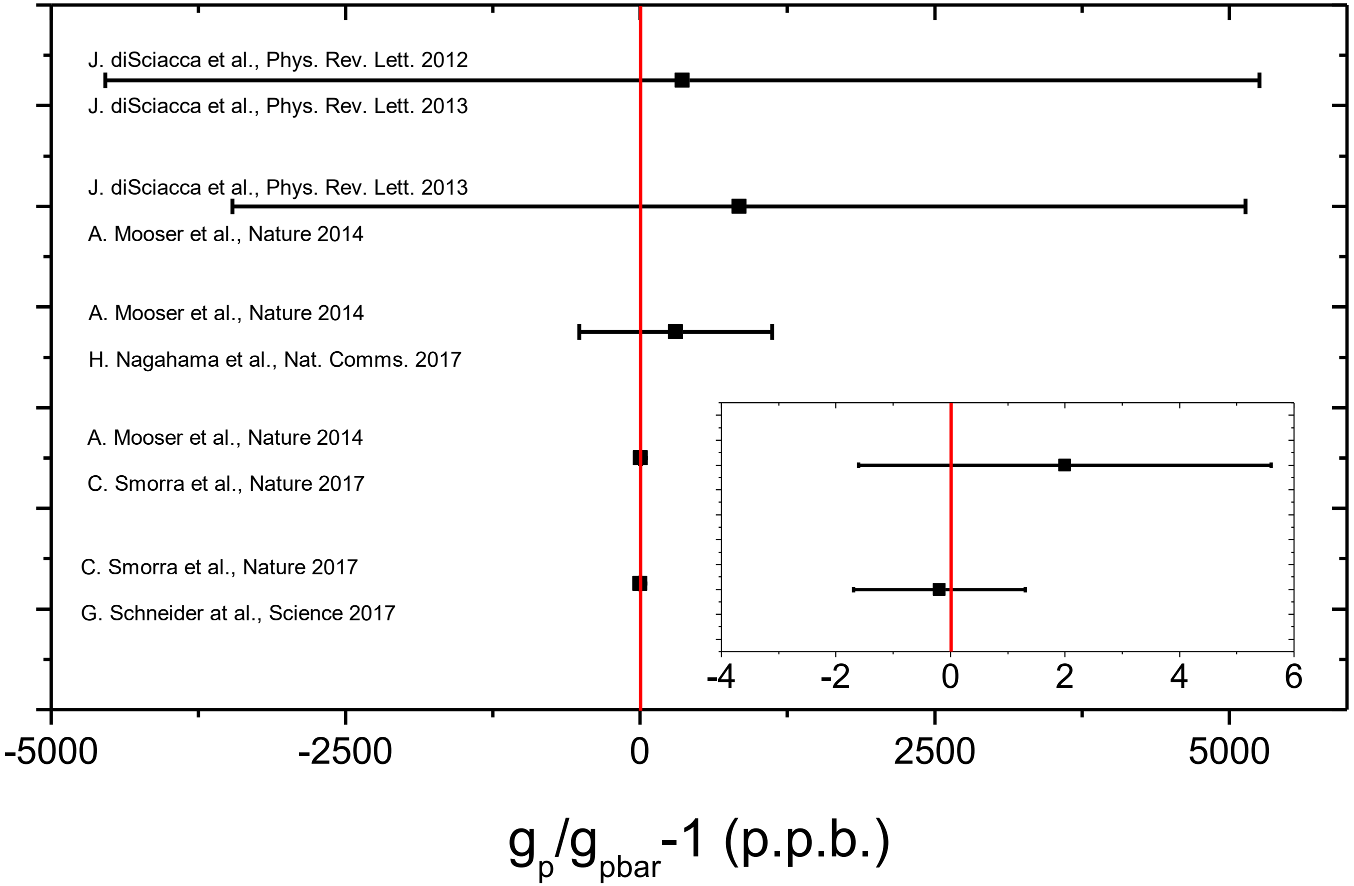
first measurement more precise for antimatter than for matter...

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



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

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

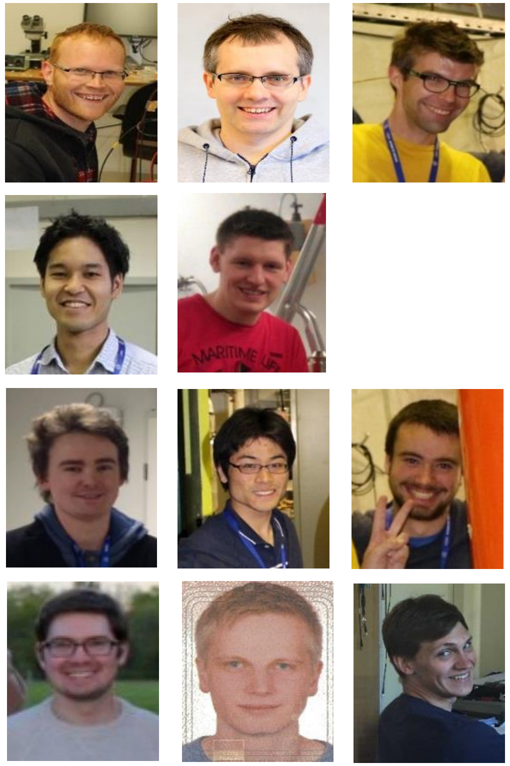
2014

2016

2017

2018

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



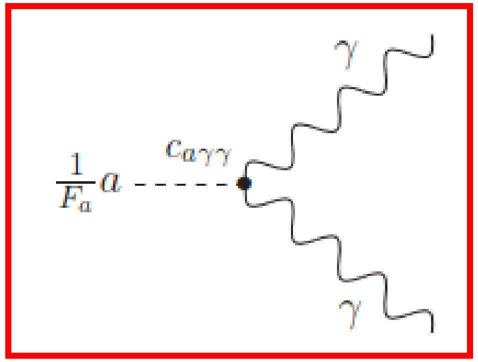
$$\frac{g_p}{g_{\bar{p}}} - 1 = -0.000\,000\,000\,2\,(15)$$

Time-base Analysis and Antiproton Axion Constraints

- Axion / fermion coupling:

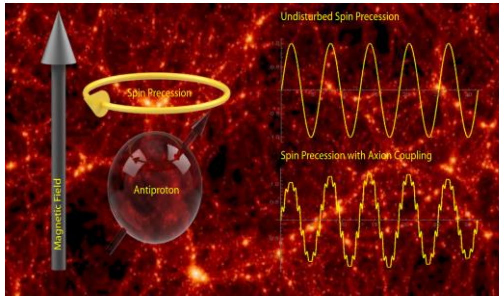
J. Kim, G. Carosi, https://arxiv.org/pdf/0807.3125.pdf

$$\begin{aligned}\mathcal{L}_\theta = &\frac{1}{2}f_S^2\partial^\mu\theta\partial_\mu\theta - \frac{1}{4g_c^2}G^a_{\mu\nu}G^{a\mu\nu} + (\bar{q}_L i\not{D} q_L + \bar{q}_R i\not{D} q_R)\\ &+ c_1(\partial_\mu\theta)\bar{q}\gamma^\mu\gamma_5 q - (\bar{q}_L\ m\ q_R e^{ic_2\theta} + \text{h.c.})\\ &+ c_3\frac{\theta}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\ (\text{or } \mathcal{L}_{\text{det}}) \qquad (19)\\ &+ c_{\theta\gamma\gamma}\frac{\theta}{32\pi^2}F^i_{\text{em},\mu\nu}\tilde{F}^{i\mu\nu}_{\text{em}} + \mathcal{L}_{\text{leptons},\theta}\end{aligned}$$



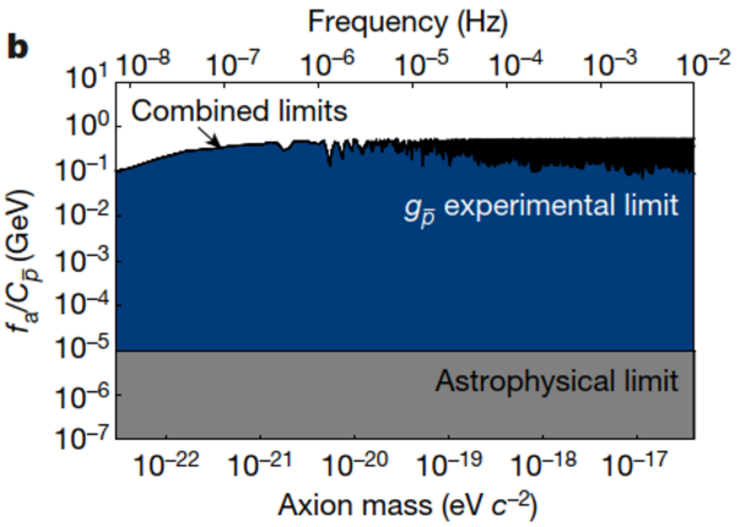
A very "simplistic" translation of this "derivative interaction": the axion dissociates to photons which interact with SM-particles.

- Cold dark matter is gravitationally bound to galaxies.
- They produce an "oscillating background field", comparable to diffuse light, which oscillates at the Compton frequency $\boldsymbol{\nu_a \sim m_a c^2/h}$



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

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

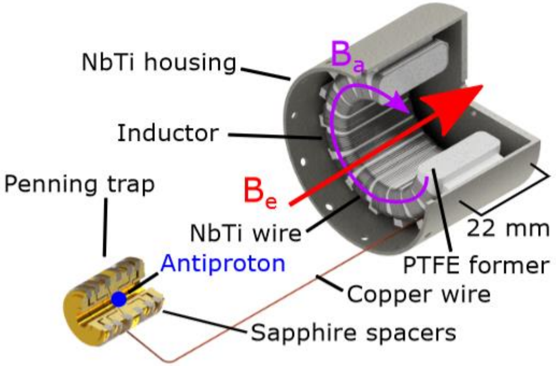


C. Smorra, Y. Stadnik, Nature **(575)**, 310 (2019)

Constraining Axion/Photon Coupling

J. Devlin et al., (BASE collaboration), Physical Review Letters. **126,** 041301 (2021).

- Axions at the right Compton frequency would source a radio-frequency signal that could be picked up by our single particle detection systems

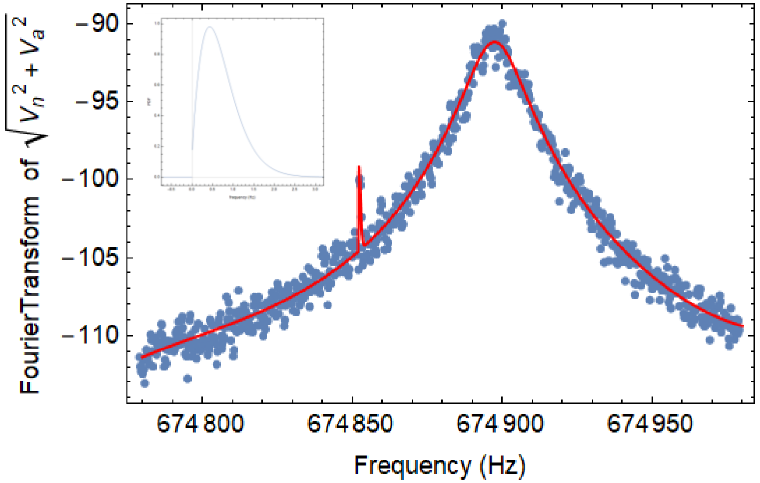


- Important feature: cold axions and axion like particles oscillate at their Compton frequencies

$$\nu_a = m_a c_0^2 / h$$

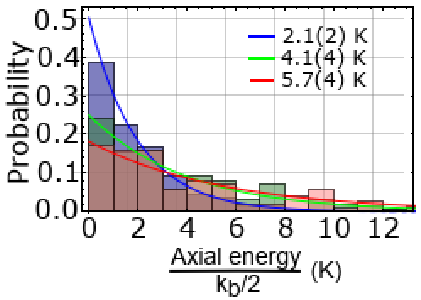
- In a strong external magnetic field **axions can convert into photons** via the inverse Primakoff effect.

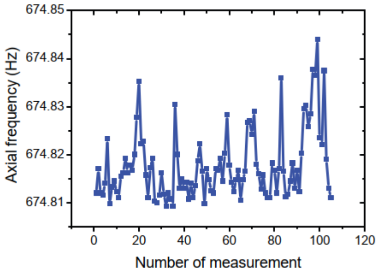
$$\boldsymbol{B_a} = -\frac{1}{2} g_{a\gamma} r \sqrt{\rho_a c_0 \hbar} B_e \boldsymbol{e_\phi}$$



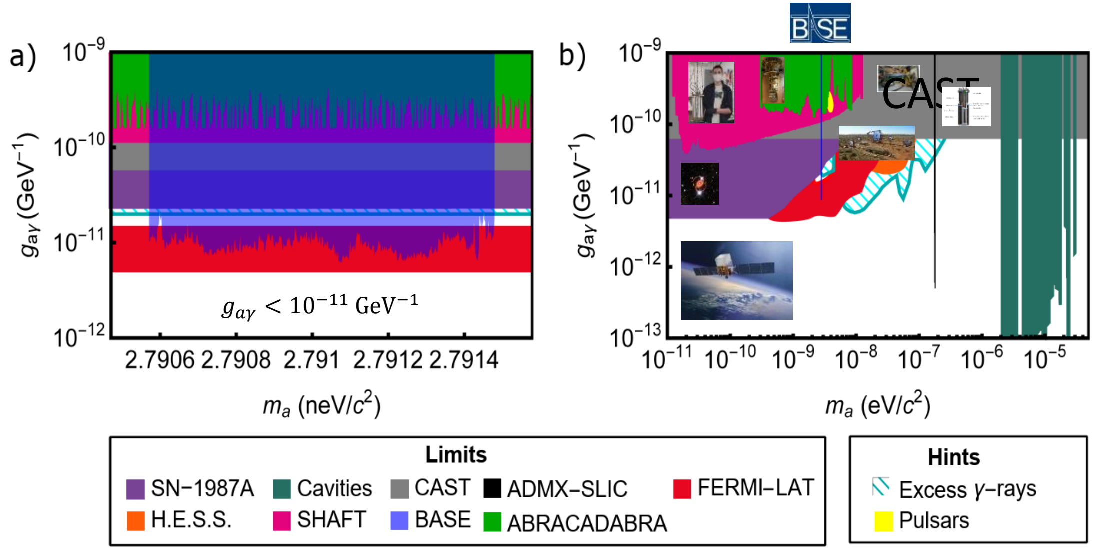
- Axion signal: $V_a = \frac{\pi}{2} g_{a\gamma} \nu_a \sqrt{\rho_a \hbar c_0} * Q\sqrt{\tau(\nu, Q, p)} \kappa N_T (r_2^2 - r_1^2) B_e$
- Noise-Floor: $V_n = \sqrt{e_n^2 \Delta\nu + 4 k_B T_z R_p \tau(\nu, Q, p) \kappa^2 \Delta\nu}$

The most important parameter to derive **appropriate limits** is the resonator temperature T_z





Penning trap: calibrated by single particle quantum thermometry



Possible factor of 1000 of improvement in the 1neV to 1ueV mass range

Future Projection

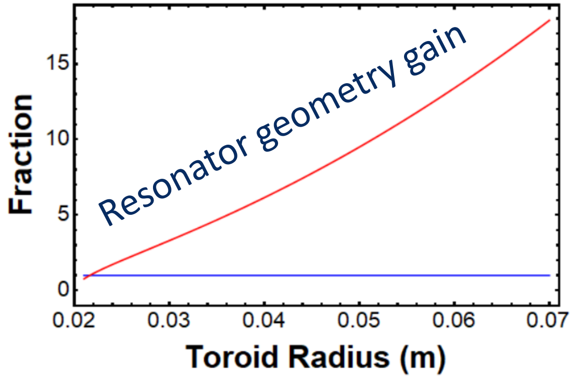
- With a purpose-built experiment we should be able to improve sensitivity considerably

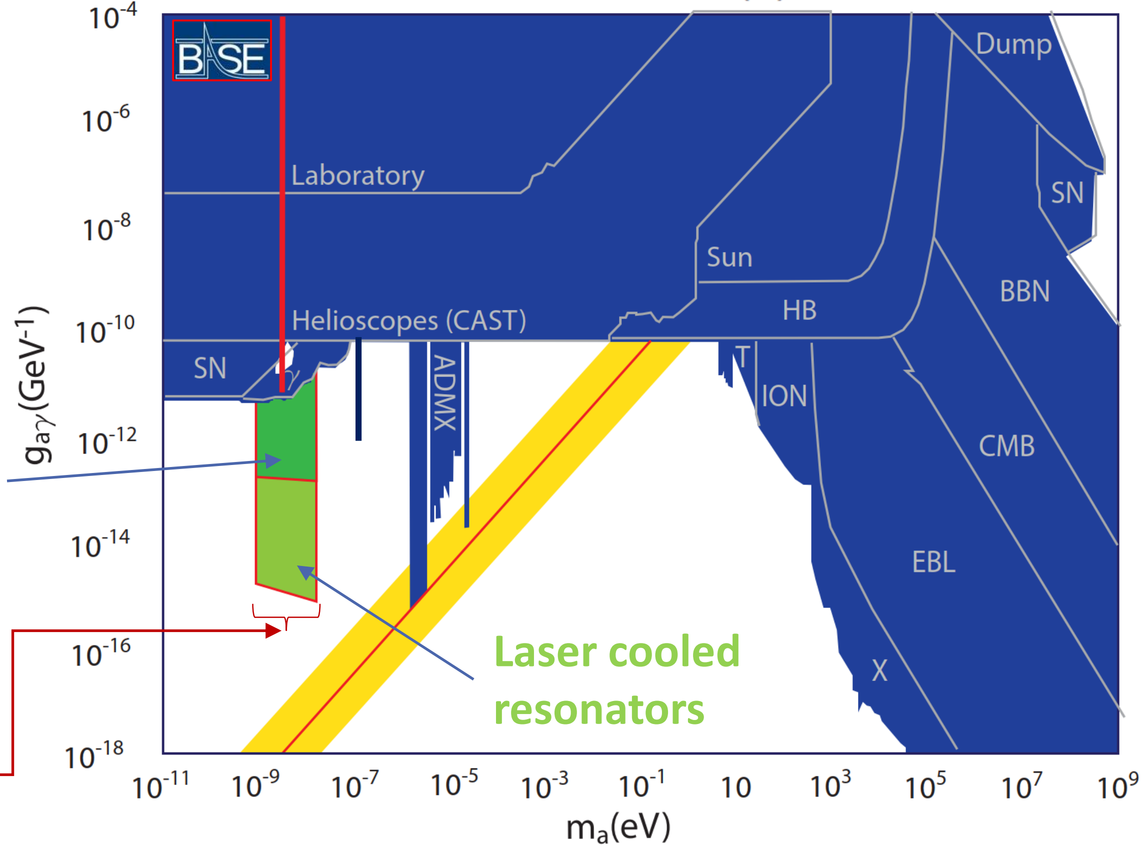
$$\frac{V_a}{V_n} \propto \frac{\pi}{2} g_{a\gamma}\sqrt{\nu_a \rho_a \hbar c_0} * \sqrt{\frac{f(Q)}{4k_B g(T_z)}} \sqrt{(r_2 - r_1)(r_2 + r_1)^{3/2} B_e}$$

Parameter	Current	New	Factor
Temperature	$5.5\ K$	$0.05K - 0.1K$	> 3
Q	$40\ k$	$160\ k$	> 1.4
e_n	$1\ nV/\sqrt{Hz}$	$0.1\ nV/\sqrt{Hz}$	> 3
B_0	$1.8\ T$	$7.0\ T$	3.9
Geometry	1	16	16
Peak Sens.	1		> 260

Bandwidth-gain currently under development (F. Voelksen)

Recent lab result: 600 kHz tunability achieved (x 3000)

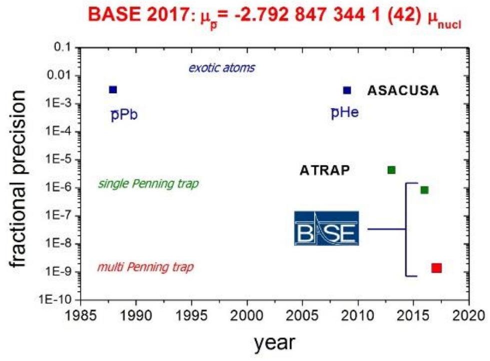


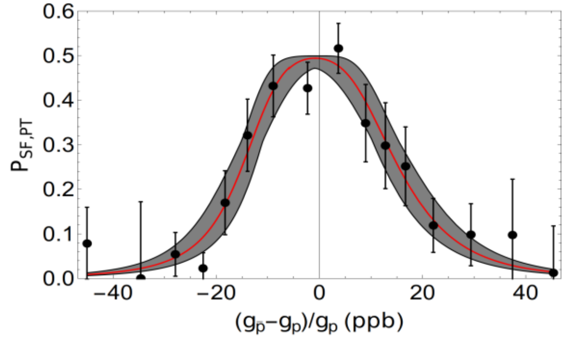


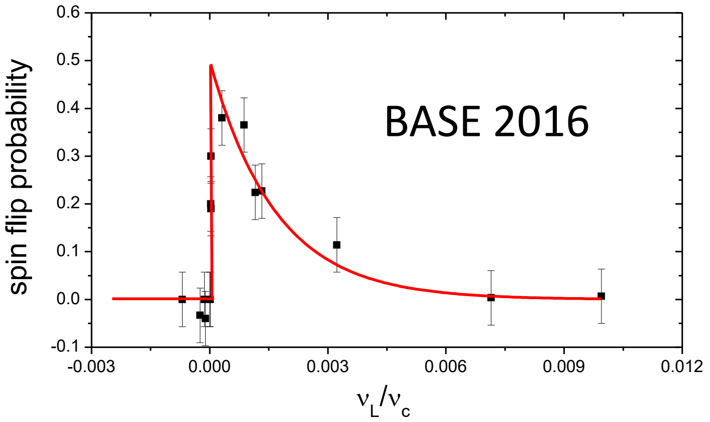
Technologies available to build such an experiment / discussion with IAXO started

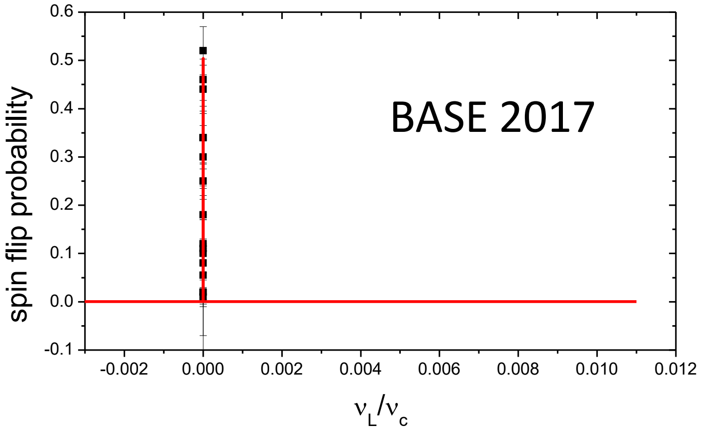
Summary and Outlook

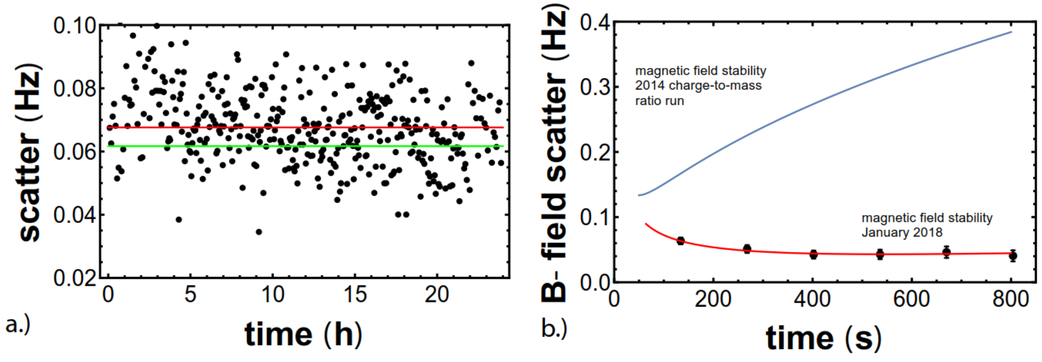
- Reported on status of improved proton/antiproton charge-to-mass ratio comparison.
- Improved the magnetic moment of the proton by a factor of 11 and measured the antiproton magnetic moment with 1.5 ppb precision, which improves the moment CPT test by a factor of >3000.
- Used antimatter as an antenna for dark matter searches.
- Summarized status of using single particle detectors as antennas for axions.
- Development of a transportable trap for antiprotons (BASE-STEP).











Thanks for your attention