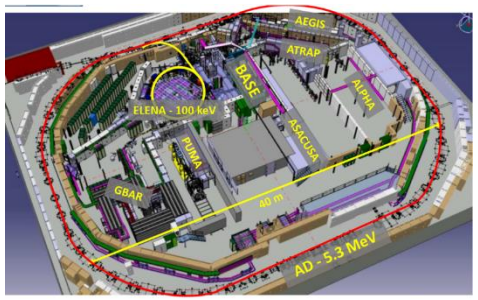
PSI2022

Testing Fundamental Symmetries by High Precision Comparisons of Matter Antimatter Conjugates, Precision Measurements in Penning Traps, and Superconducting Radio Frequency Resonators



Stefan Ulmer

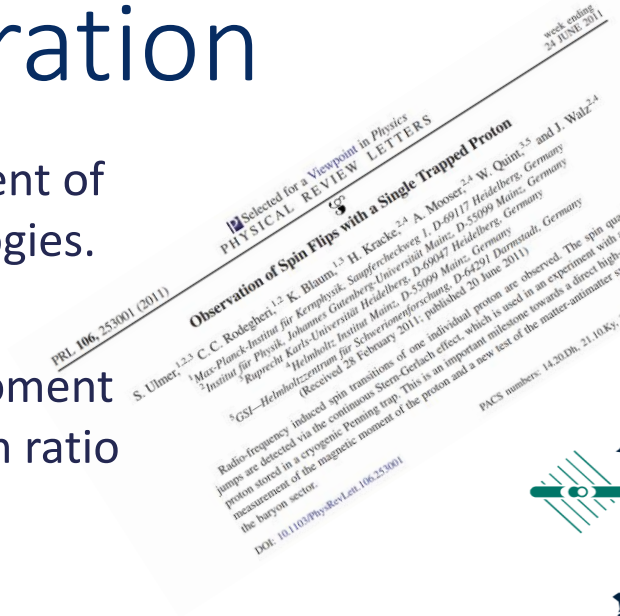
RIKEN

2022 / 10 / 21

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies.

- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio
- **BASE-STEP:** Development of transportable antiproton traps
- **Hannover/PTB:** QLEDS-laser cooling project, new technologies



week ending 24 JUNE 2011

Selected for a Viewpoint in Physics

PHYSICAL REVIEW LETTERS

PRL 106, 253001 (2011)

Observation of Spin Flips with a Single Trapped Proton

S. Ulmer,[1,2,3] C. C. Rodegheri,[1,2] K. Blaum,[1,3] H. Kracke,[2,4] A. Mooser,[2,4] W. Quint,[2,5] and J. Walz[2,4]

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[2]Institut für Physik, Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
[3]Ruprecht-Karls-Universität Heidelberg, D-69047 Heidelberg, Germany
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[5]GSI–Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany

(Received 28 February 2011; published 20 June 2011)

Radio-frequency induced spin transitions of one individual proton are observed. The spin quantum jumps are detected via the continuous Stern-Gerlach effect, which is used in an experiment with a single proton stored in a cryogenic Penning trap. This is an important milestone towards a direct high-precision measurement of the magnetic moment of the proton and a new test of the matter-antimatter symmetry in the baryon sector.

DOI: 10.1103/PhysRevLett.106.253001

PACS numbers: 14.20.Dh, 21.10.Ky, 37.10.Rs, 37.10.Ty

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

Team at CERN, running 24/7 since 2013

Three experiments, 9 institutes, about 30 collaborators, 10 at CERN

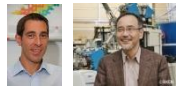
C. Smorra et al., EPJ-Special Topics, The BASE Experiment, (2015)

Scientific Activities and Highlights - Overview

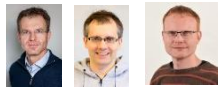
BASE-CERN | Exotics

BASE-Mainz | He moment

BASE-Logic



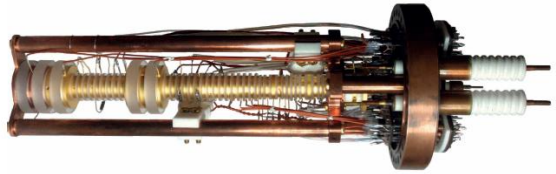
BASE-STEP

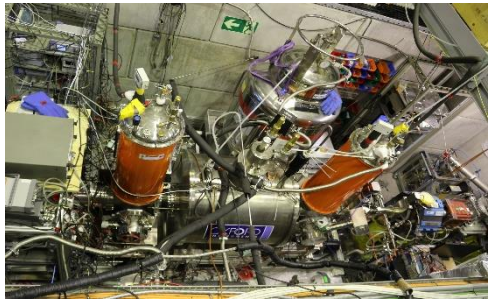


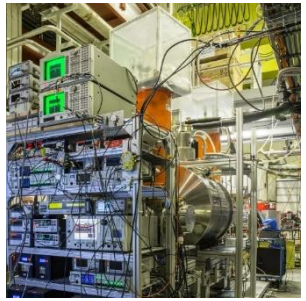
BASE-CDM

BASE-Lepton

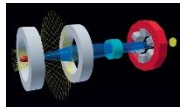
- **General:** Use ultra-high precision methods to measure fundamental constants and study fundamental symmetries with highest fractional accuracy
- **Main tools:** advanced Penning trap systems

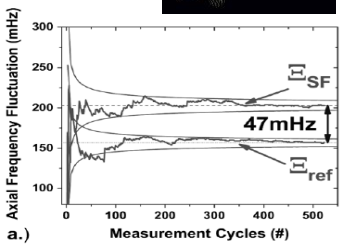






2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2019 | 2021 | 2022

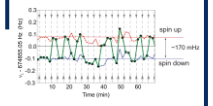




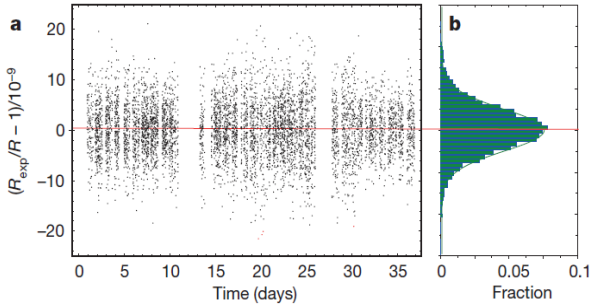
S. Ulmer, et al., **PRL 106, 253001 (2011)**

3ppb proton moment

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

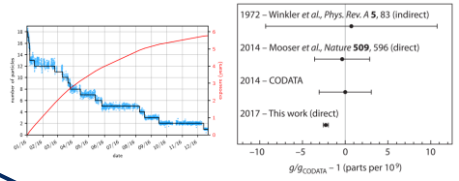


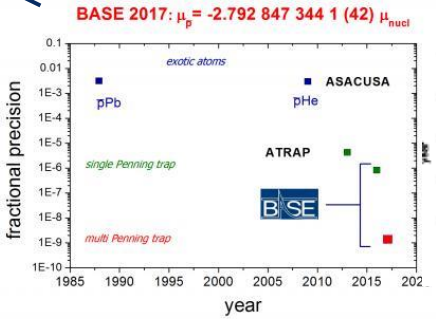
$$1 + \frac{(q/m)_{\bar{p}}}{(q/m)_{p}} = 1(69) \times 10^{-12}$$



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

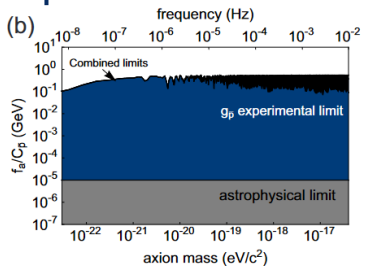
pbar moment, proton moment, pbar lifetime, proton mass



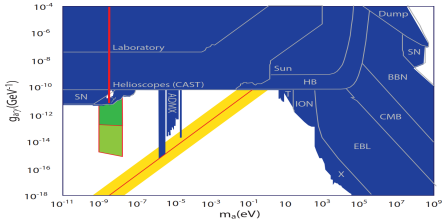


G. Schneider et al., Science **358**, 1081 (2017).

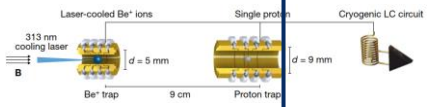
C. Smorra *et al.*, Nature **550**, 371 (2017)



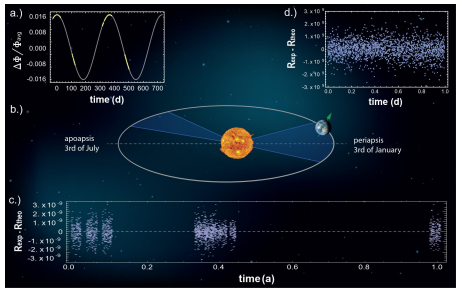
BASE, Nature **575**, 310 (2019)



J. A. Devlin, et al., **PRL, accepted (2021)**

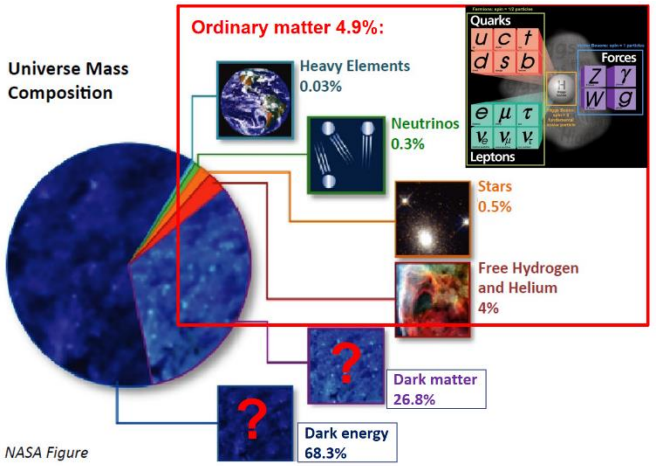


M. A. Bohman, et al., **Nature 596, 514 (2021)**



S. Ulmer, et al., **Nature, accepted (2021)**

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

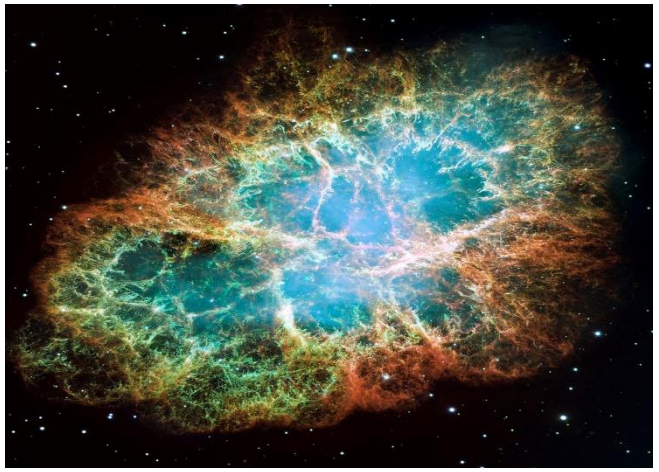
Sakharov conditions

1.) B-violation (plausible)

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

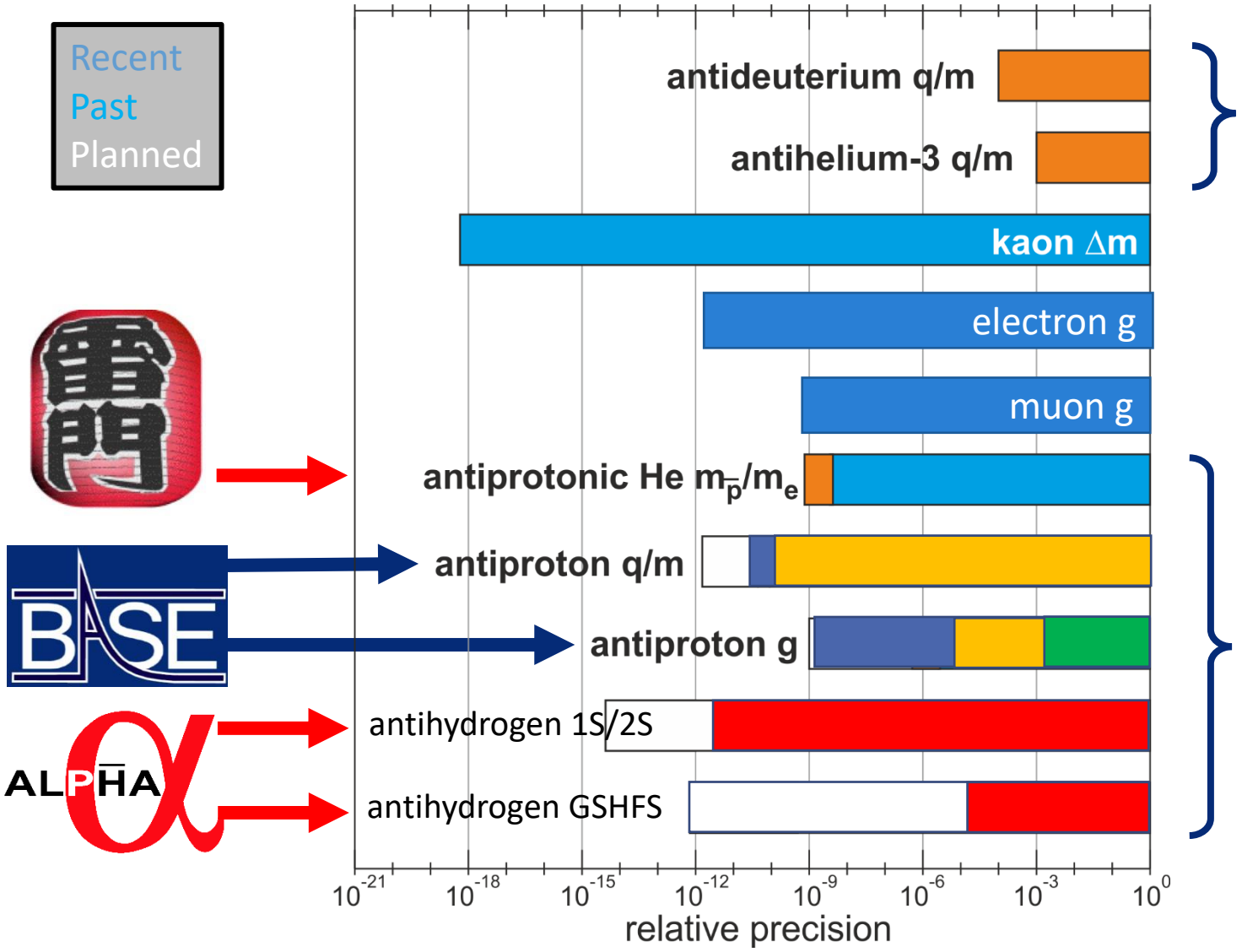
3.) Arrow of time (less motivated)

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

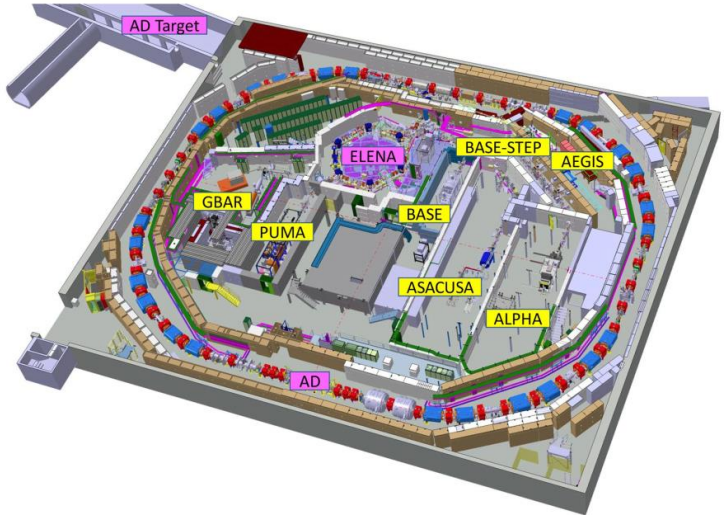
CPT tests based on particle/antiparticle comparisons



CERN ALICE

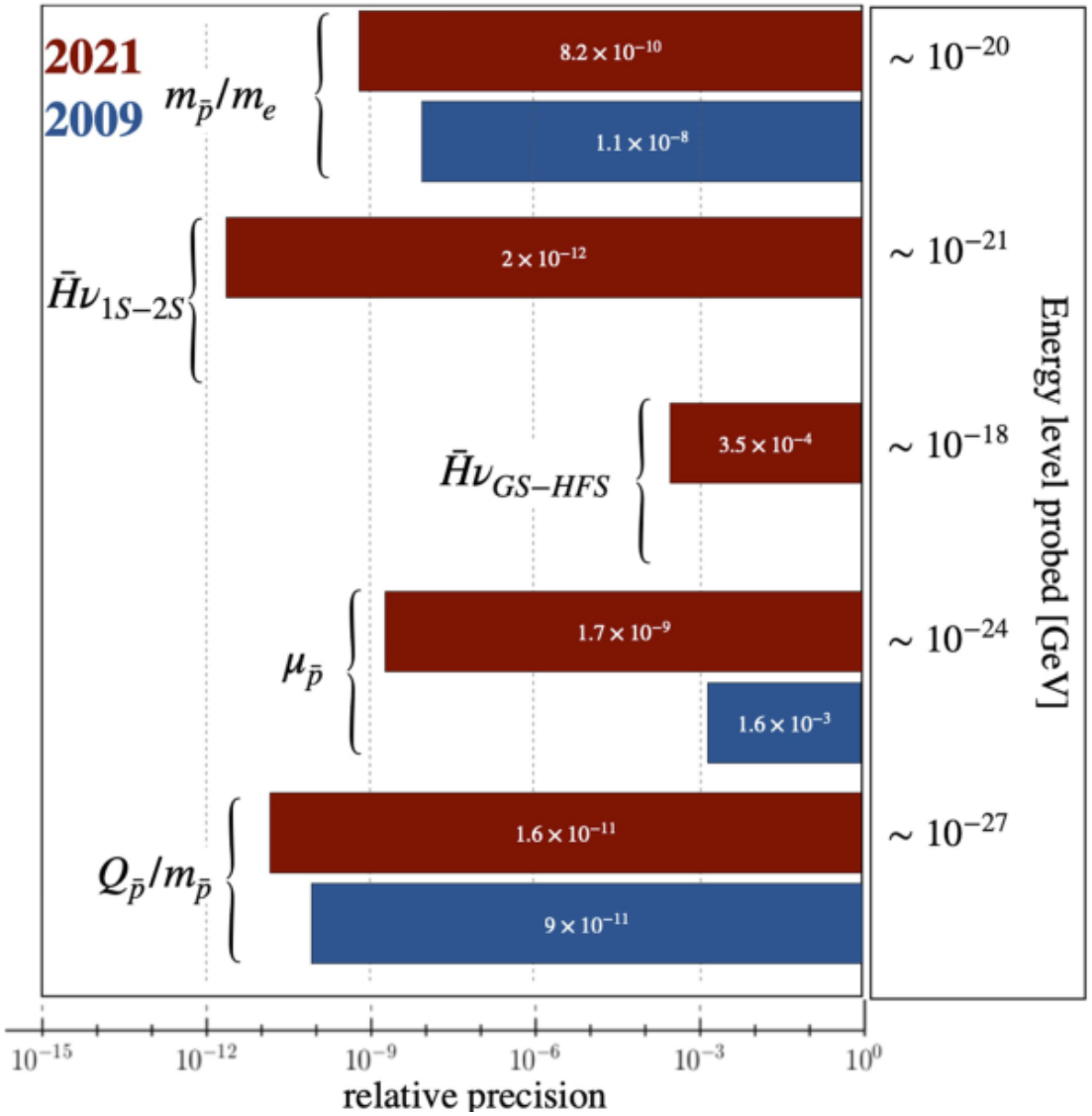
CERN AD

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. Gabriesle 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

10 years of Community Progress

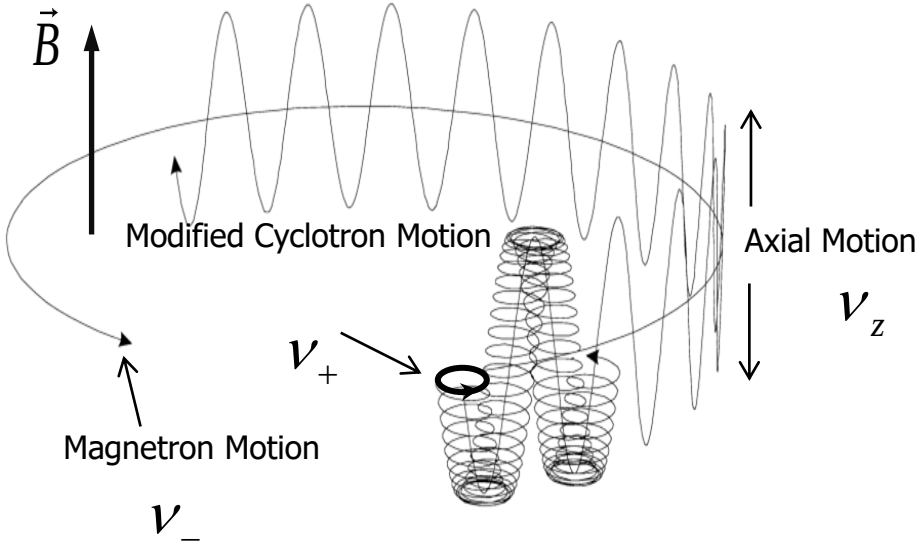


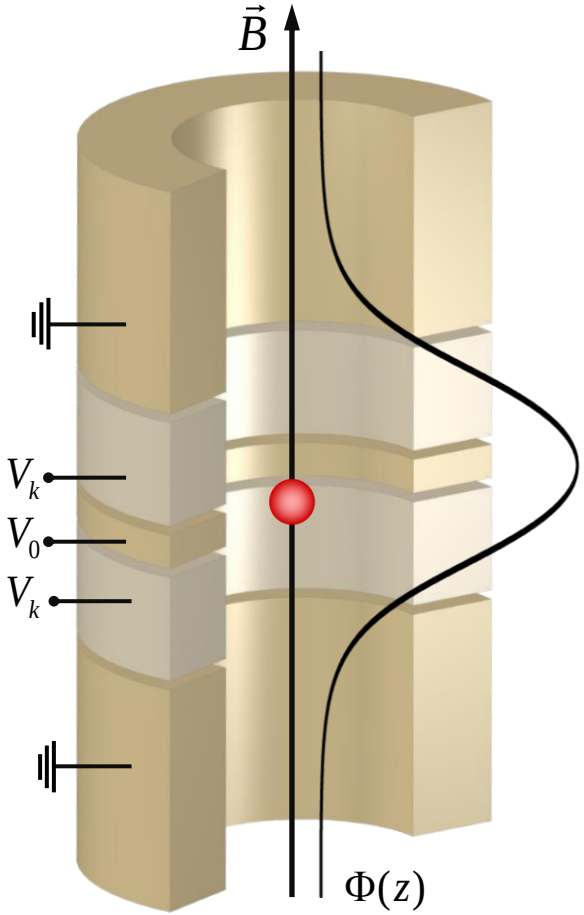
Coming soon: studies of the ballistsic properties of antihydrogen by ALPHA-g, GBAR, AEgIS.

Main Tool: Penning Trap

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

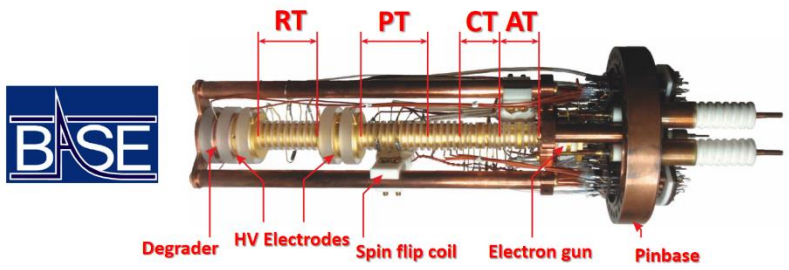
axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$





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

BASE – Multi-Trap-System



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

Invariance Theorem

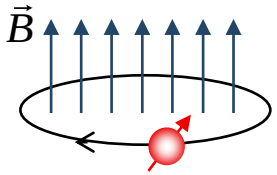
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

Gives undisturbed access to cyclotron frequencies

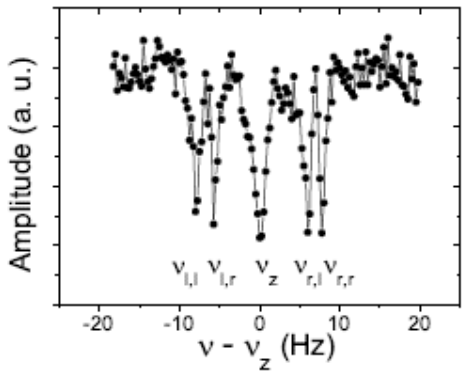
$$\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

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

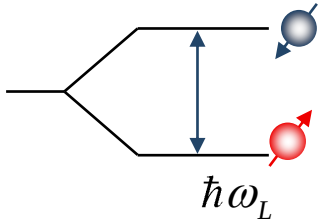
$$\omega_c = \frac{e}{m_p} B$$

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

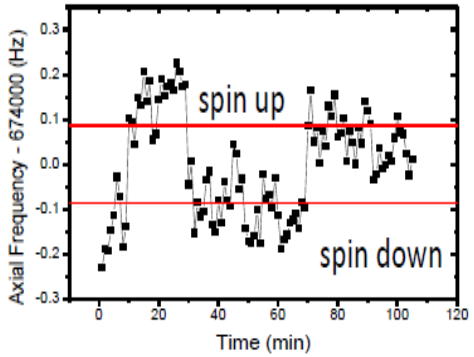
$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

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

Larmor Precession



difficult



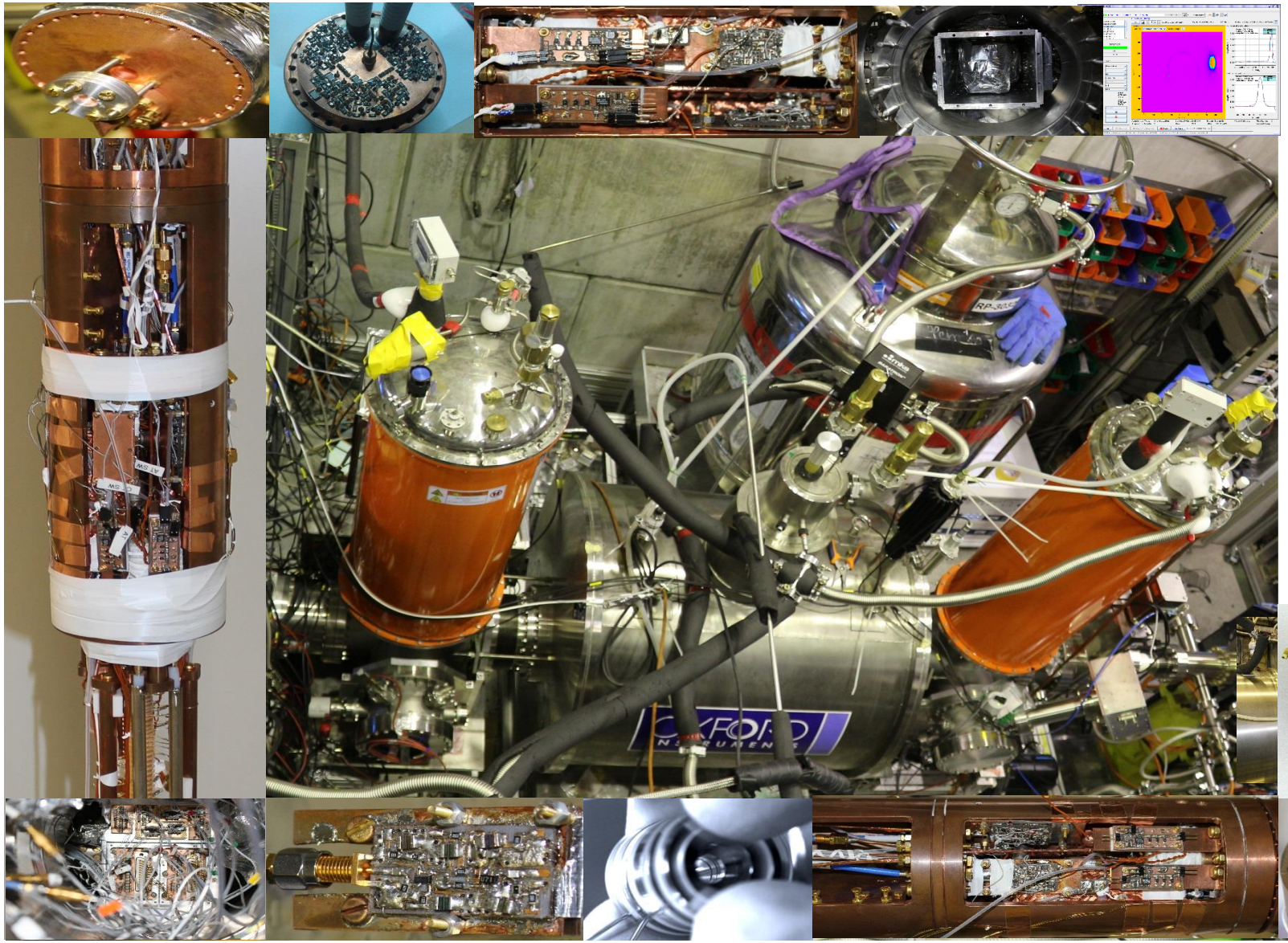
A. Mooser, S. Ulmer, *et al.* PRL 106, 253001 (2011)

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



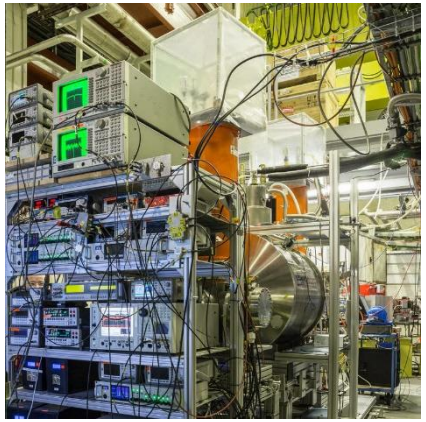
Common to all these experiments:

Superconducting magnets

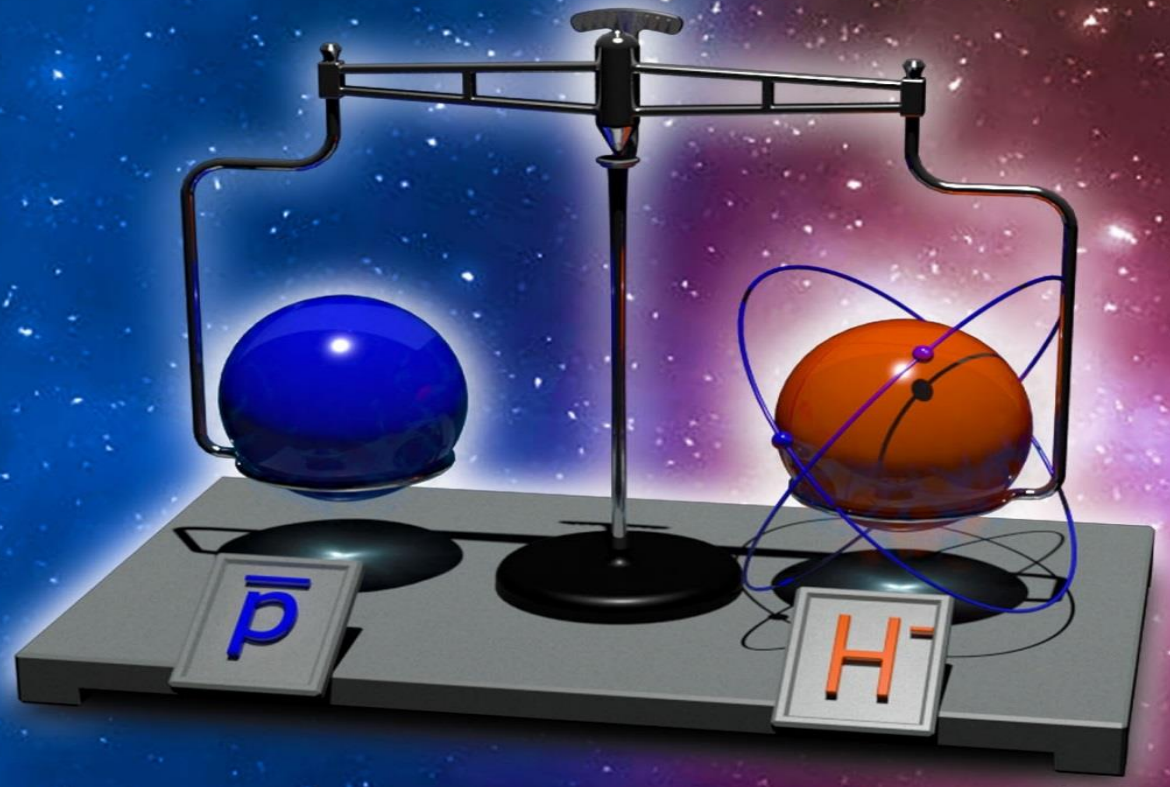
Ultra sensitive superconducting partice detectors

Cryogenic operation of experiments

Use of «complex» multi-trap systems



High-Precision Comparison of the

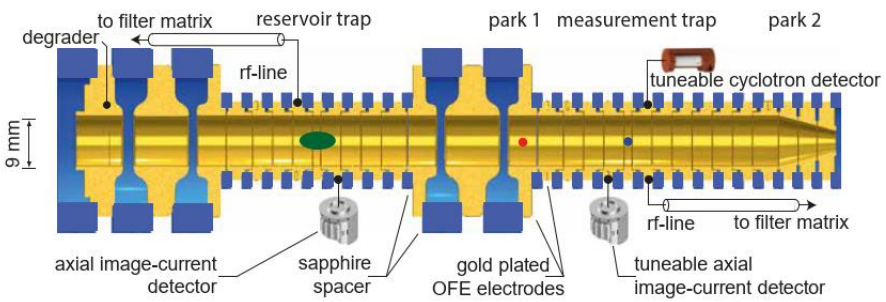


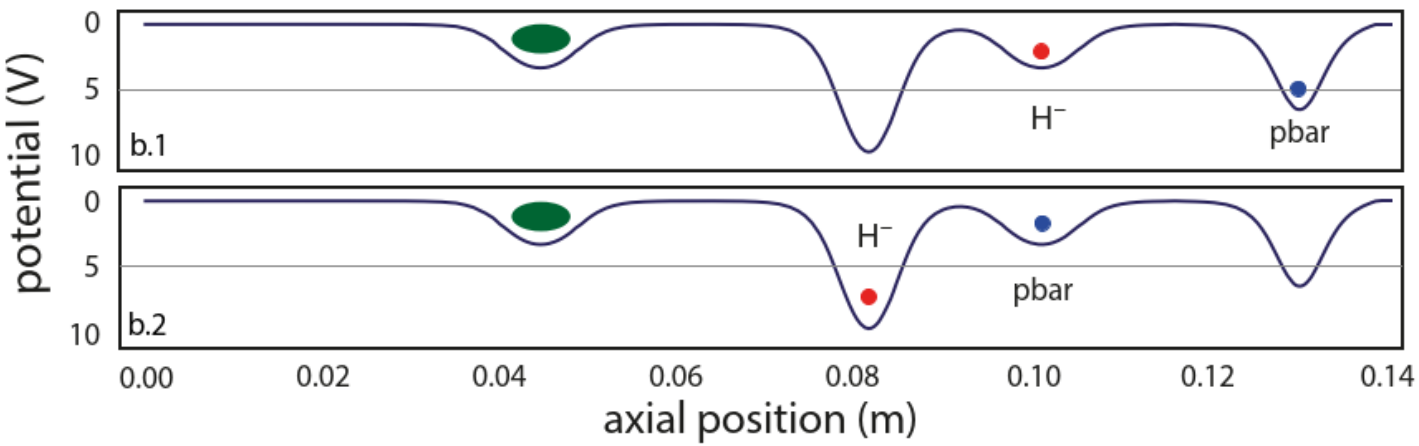
Antiproton-to-Proton Charge-to-Mass Ratio

Charge-to-Mass Ratio Measurement

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

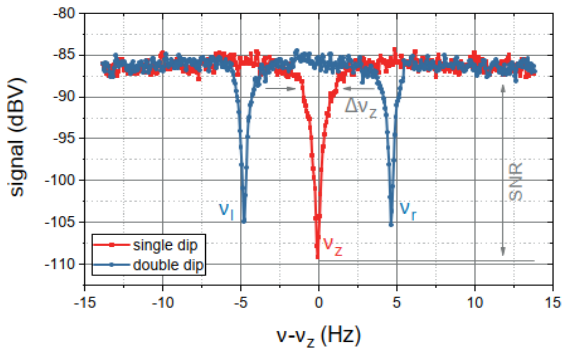
First Measurement: S. Ulmer, et al., **Nature 524, 196 (2015)**





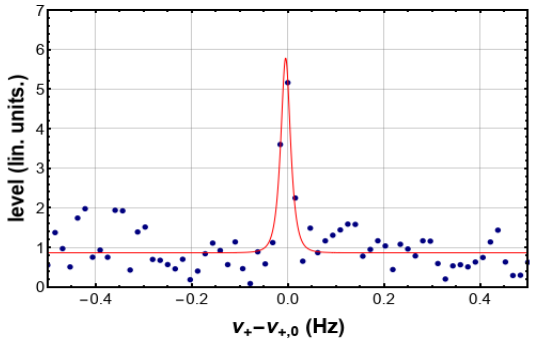
BASE is the first experiment which has implemented this method, now also used by many others

- Sideband Method



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

- Peak Method



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

A. Mooser, et al., **Nature 509, 596 (2014) /** Cornell et al., **PRA (1991)**

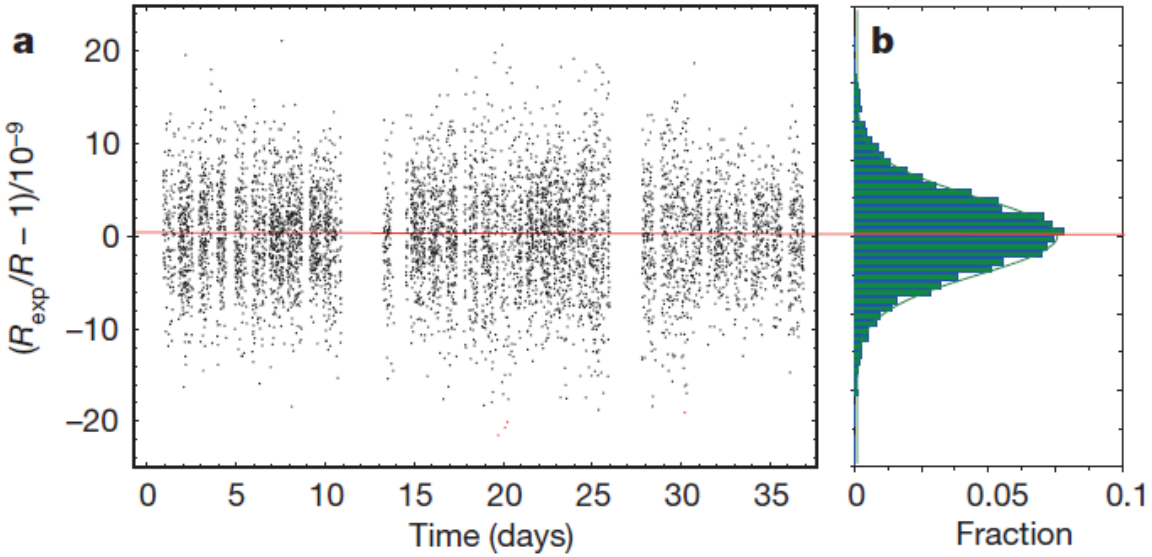
In aspects similar to G. Gabrielse, et al.,**Phys. Rev. Lett. 82, 3198 (1999)**

- Compare hydrogen ions to antiprotons

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

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

BASE Measurements – Proton to Antiproton Q/M



Result of 6500 proton/antiproton Q/M comparisons:

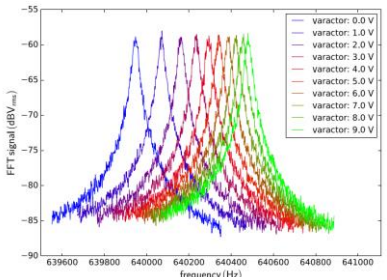
$R_{exp,c}$ = 1.001 089 218 755 (69)

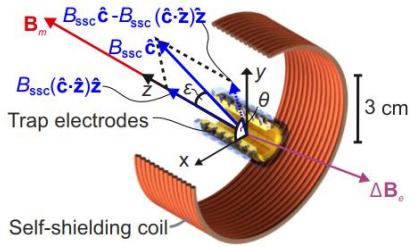
$$\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} + 1 = 1(69) \times 10^{-12}$$

Stringent test of CPT invariance with Baryons.

Consistent with CPT invariance

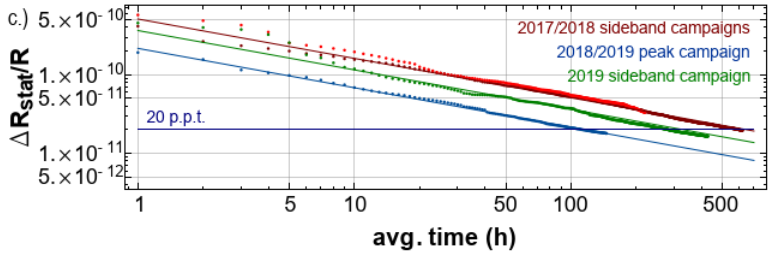
S. Ulmer et al., *Nature* **524** 196 (2015)

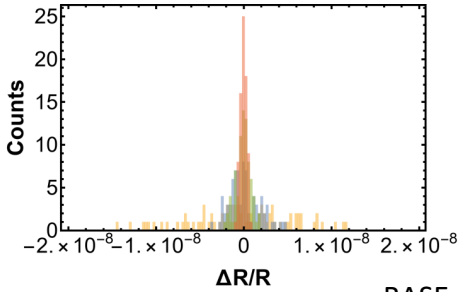


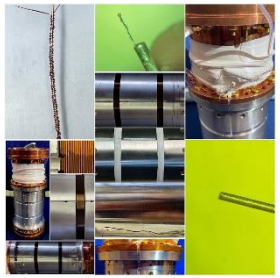


Previous Limitations:

- Systematics by resonant particle tuning.
- Accelerator imposed magnetic field fluctuations -> Multi layer shielding systems / reservoir trap
- Intrinsic magnetic field stability limitation -> redesign of parts of the apparatus
- Development of direct detection techniques for lower measurement fluctuation.

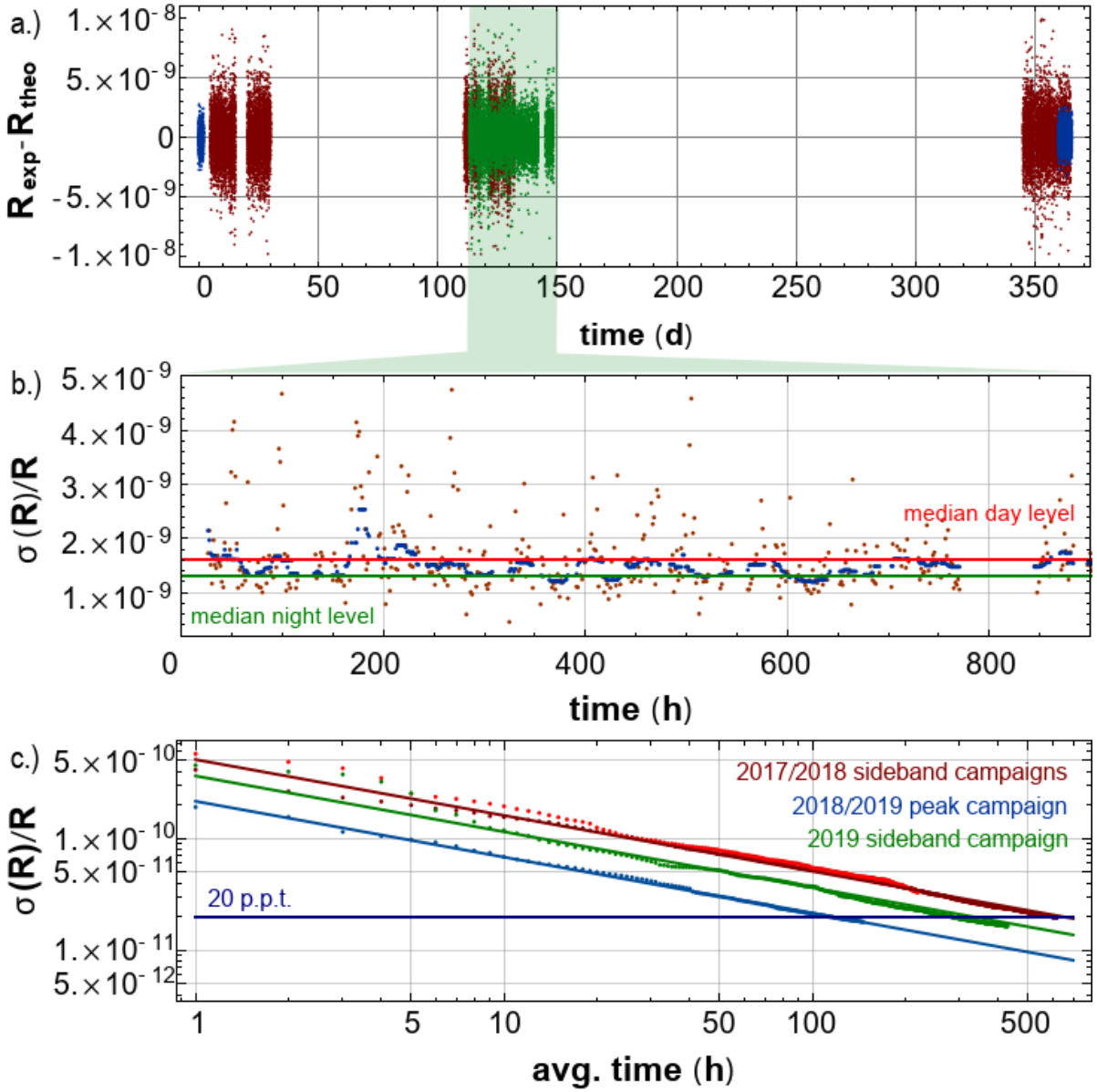


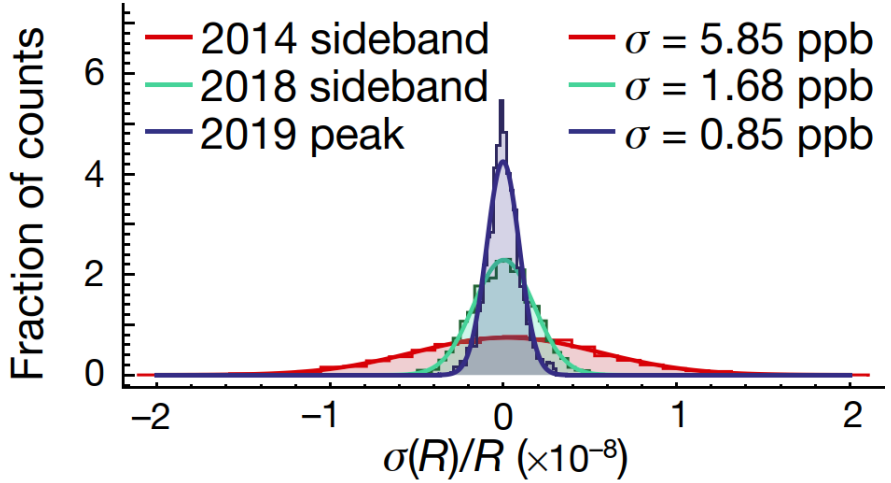




BASE, *accepted, Nature* (2021)

The Acquired Data Set

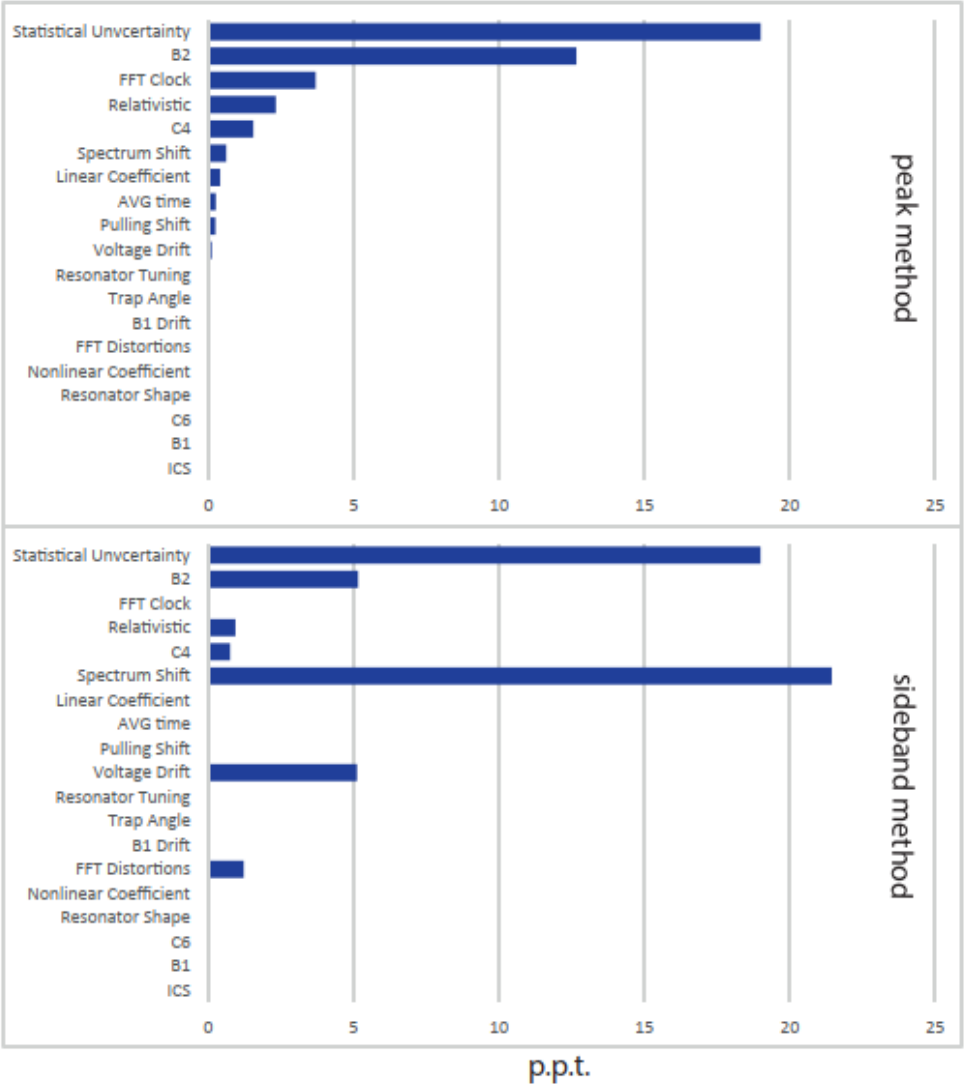




- 24000 data points acquired in four measurement campaigns and in a time range of 1.5 years.
- Temporal experiment stability fluctuation due to fluctuations imposed by other users and accelerators.
- Continuously improved stability over time.

Systematic Effects and Result

Effect	2018-1-SB	2018-2-SB	2018-3-PK	2019-1-SB
B_1-shift	0.03(2)	0.01(2)	< (0.01)	< (0.01)
B_2-shift	20.27(14.86)	8.38(14.86)	10.79(12.66)	3.75 (5.16)
C_4-shift	(1.12)	(1.13)	(1.54)	(0.76)
C_6-shift	< (0.01)	< (0.01)	< (0.01)	< (0.01)
Relativistic	1.20(92)	0.47(90)	1.90(2.32)	0.65(94)
Image charge shift	0.05(0)	0.05(0)	0.05(0)	0.05(0)
Trap misalignment	0.06(0)	0.06(0)	0.05(0)	0.05(0)
Voltage Drifts	−3.35(5.12)	−3.77(5.12)	−0.11(11)	−5.03(5.12)
Spectrum Shift	0.37(20.65)	16.89(46.49)	0.74(61)	−8.61(21.45)
FFT-Distortions	(1.57)	(3.48)	(0.03)	(1.23)
Resonator-Shape	0.02(3)	0.02(2)	< (0.01)	0.01(2)
B_1-drift offset	< (0.11)	< (0.11)	< (0.04)	< (0.04)
Resonator Tuning	< (0.16)	< (0.16)	< (0.06)	< (0.06)
Averaging Time	–	–	−2.87(25)	–
FFT Clock	–	–	(3.69)	–
Pulling Shift	–	–	2.86(24)	–
Linear Coefficient Shift	–	–	0.16(40)	–
Nonlinear Shift	–	–	0.03(2)	–
Systematic Shift	18.65(26.04)	22.11(49.22)	13.60(13.50)	−9.13(22.71)
$R_{exp} - R_{theo}$	13.02(27.12)	−5.04(46.57)	7.99(18.57)	18.34(18.89)
$R_{exp,c} - R_{theo}$	−5.63(37.60)	−27.15(67.76)	−5.61(22.66)	27.47(29.54)



The Result

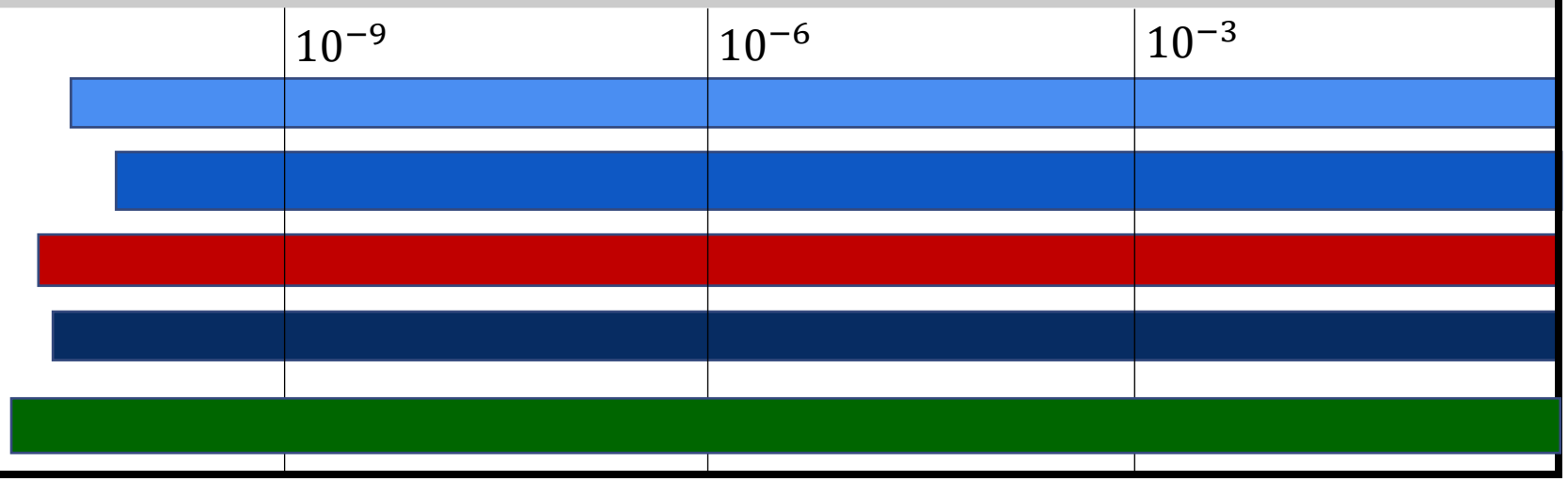
- Most precise test of CPT invariance in the baryon sector

Campaign	R_{exp}	$\sigma(R)_{stat}$	$\sigma(R)_{sys}$
2018-1-SB	1.001089218748	$27 * 10^{-12}$	$27 * 10^{-12}$
2018-2-SB	1.001089218727	$47 * 10^{-12}$	$49 * 10^{-12}$
2018-3-PK	1.001089218748	$19 * 10^{-12}$	$14 * 10^{-12}$
2018-1-SB	1.001089218781	$19 * 10^{-12}$	$23 * 10^{-12}$
Result	1.001 089 218 757 (16)		

SME Limits

$$|\delta\omega_c^{\bar{p}} - R_{\bar{p},p,\mathrm{exp}}\delta\omega_c^{p} - 2R_{\bar{p},p,\mathrm{exp}}\delta\omega_c^{e^-}| < 1.96 \times 10^{-27}\ \mathrm{GeV}$$

Coefficient	Previous Limit	Improved Limit	Factor
$\lvert\tilde{c}_e^{XX}\rvert$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\lvert\tilde{c}_e^{YY}\rvert$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\lvert\tilde{c}_e^{ZZ}\rvert$	$< 2.14 \cdot 10^{-14}$	$< 4.96 \cdot 10^{-15}$	4.31
$\lvert\tilde{c}_p^{XX}\rvert, \lvert\tilde{c}_p^{*XX}\rvert$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\lvert\tilde{c}_p^{YY}\rvert, \lvert\tilde{c}_p^{*YY}\rvert$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\lvert\tilde{c}_p^{ZZ}\rvert, \lvert\tilde{c}_p^{*ZZ}\rvert$	$< 7.85 \cdot 10^{-11}$	$< 1.82 \cdot 10^{-11}$	4.31



Result consistent with CPT invariance

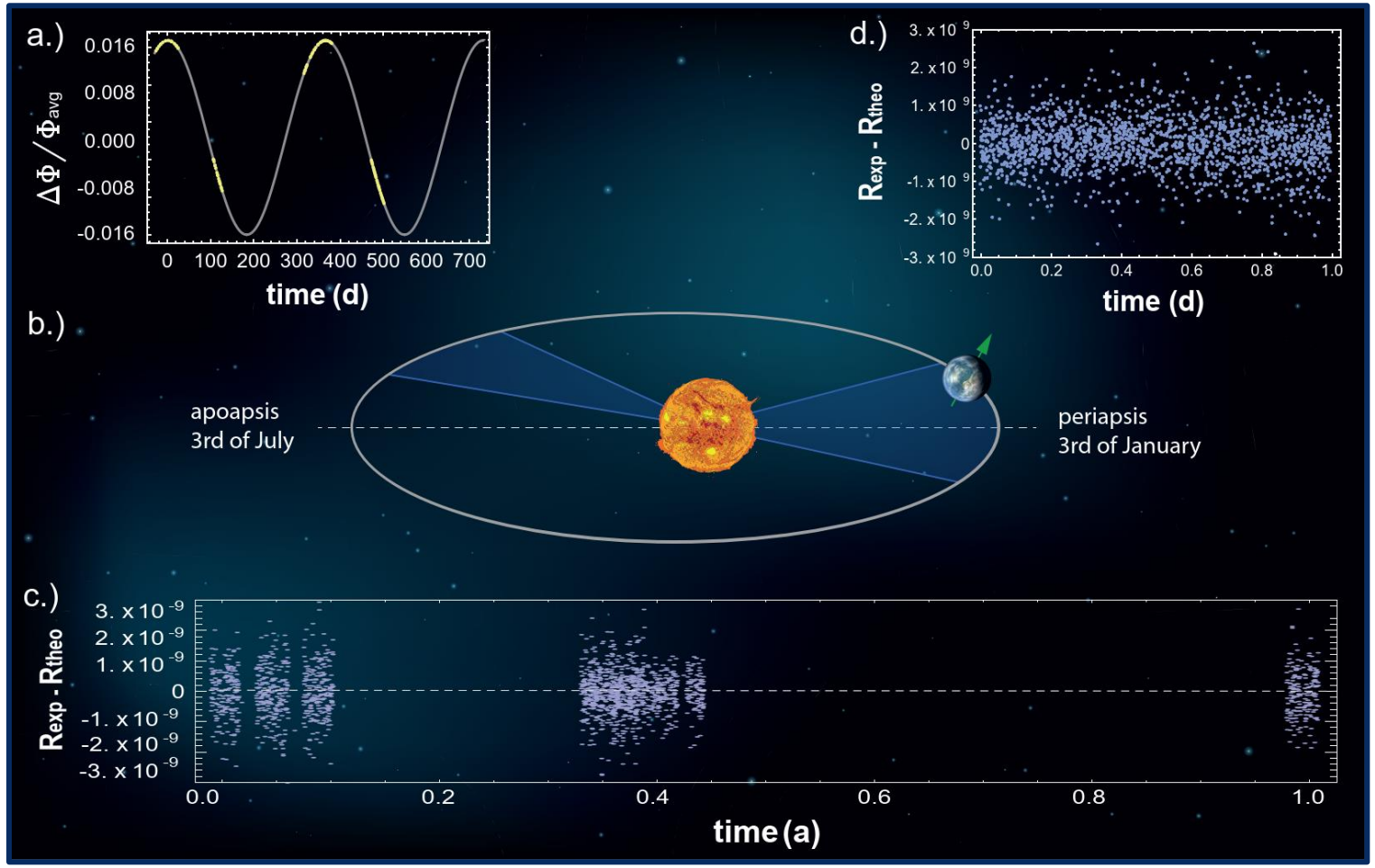
$$R_{\bar{p},p} = -1.000\ 000\ 000\ 003\ (16)$$

Ding et al., Phys. Rev. D 102, 056009 (2020)

Interpretation

- Differential test of the weak equivalence principle comparing a matter and an antimatter clock

$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3GM_{\mathrm{sun}}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)}-\frac{1}{O(t_0)}\right)$$



- Derived limits for global and differental considerations

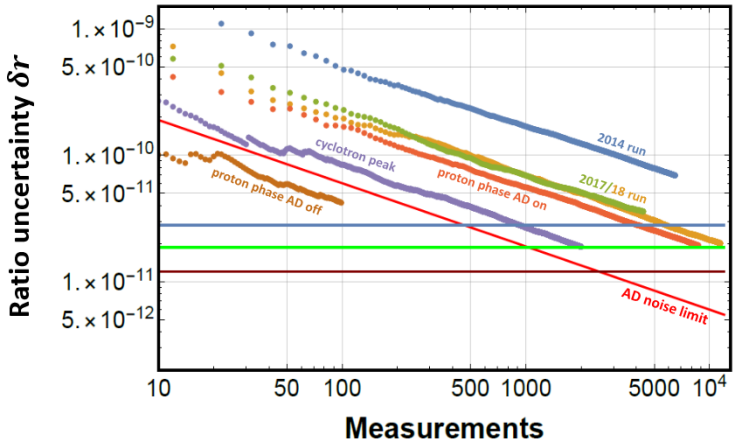
Property	Limit
$\alpha_g - 1$	$< 1.8 * 10^{-7}$
$\alpha_{g,D} - 1$	< 0.03

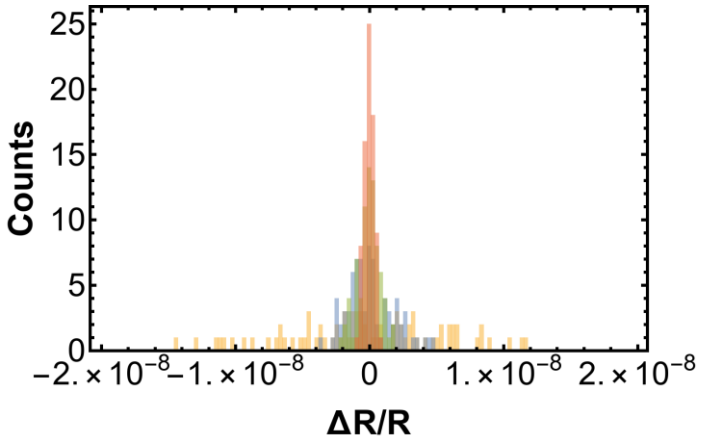
- Constraints set limits similar to goals of experiments that drop antihydrogen in the gravitational field of the earth.
- Looking forward to these results, rapid progress in ALPHA-g and GBAR, stay tuned for beamtime 2022 / 2023.

Broad band time base analysis is under evaluation -> time dependen coefficients

Outlook

- Using phase sensitive methods

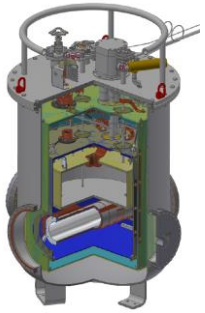




- Recent development: Two Particle Method (similar to recent MPIK-Results), moderately «simple» for Q/M ratios, difficult for nuclear moments

Antiproton: Two particles in one trap

- Current problem: Magnetic field fluctuations imposed by the accelerator hall.



Transportable antiproton traps coming soon (see also PUMA)

20 p.p.t. / 24h , but only possible during accelerator shutdown

The Antiproton Magnetic Moment

A milestone measurement in antimatter physics

LETTER

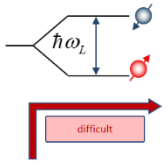
OPEN

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]

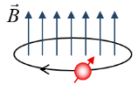
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$



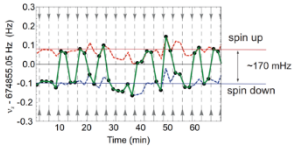
Continuous Stern Gerlach Effect

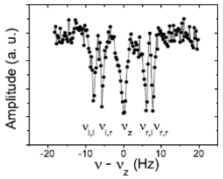
straight forward

Image Current Measurements

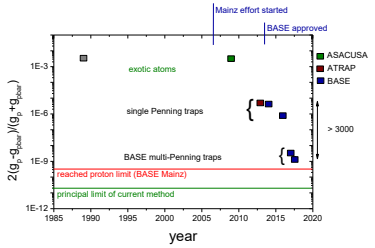


C. Smorra *et al.*, Phys. Lett. B 769, 1 (2017)





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

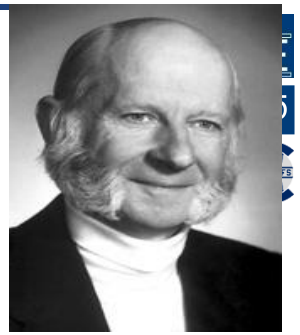
The BASE result relies on a quantum measurement scheme to observe spin transitions of a single antiproton in a non-destructive manner. In experimental physics, non-destructive observations of quantum effects are usually accompanied by a tremendous increase in measurement precision. For example, the non-destructive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

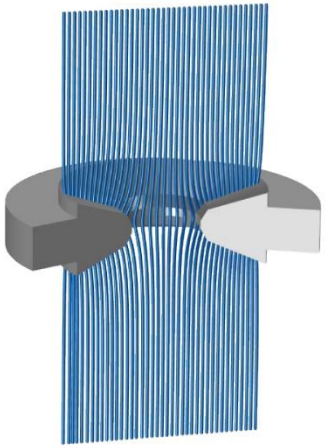
The multi-Penning-trap system used by BASE to detect the spin-flips of single trapped protons and antiprotons.

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

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

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

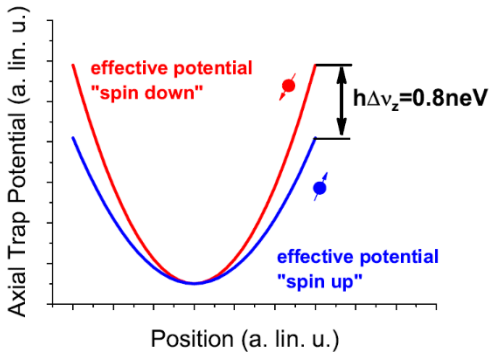
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

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

- Most extreme magnetic conditions ever applied to single particle.

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

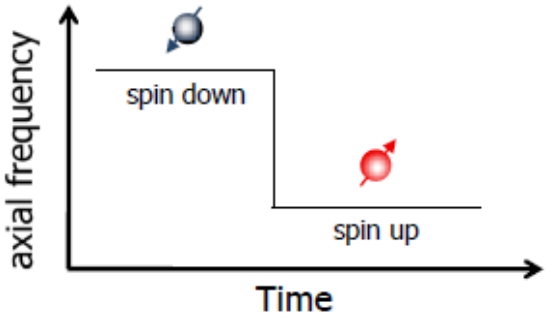


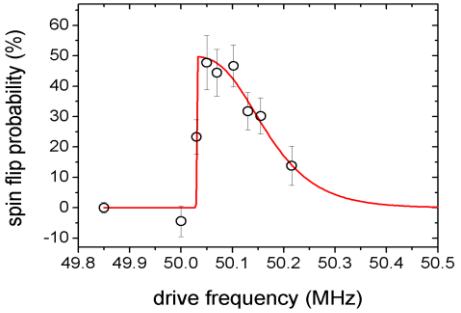
Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

Limited to p.p.m level

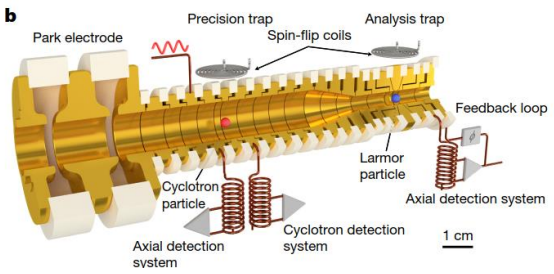


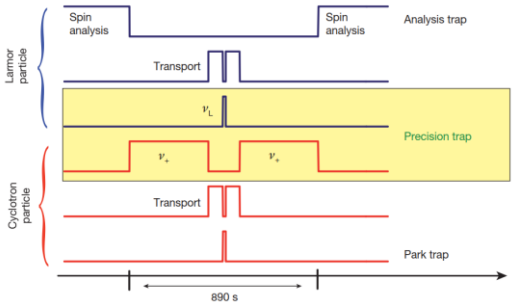


S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

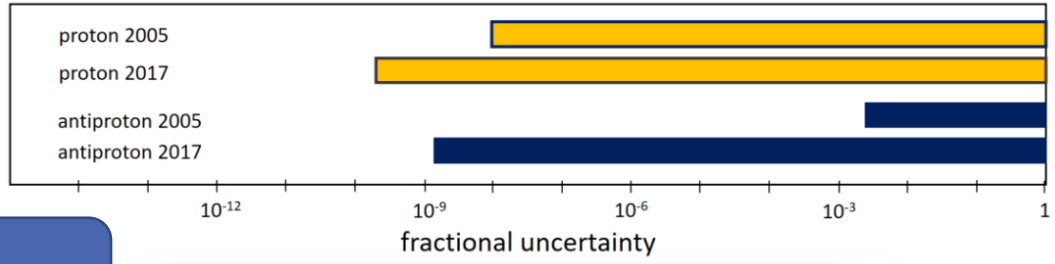
3000-fold Improved Antiproton Moment Measurement

New idea: divide measurement to two particles

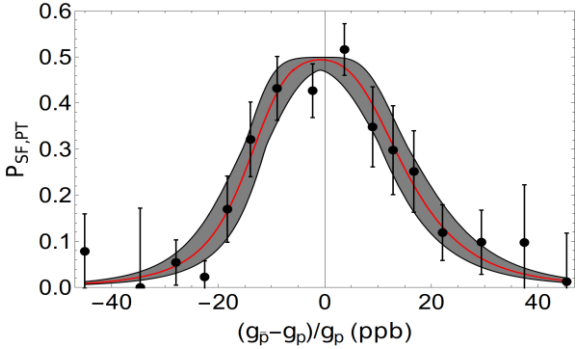


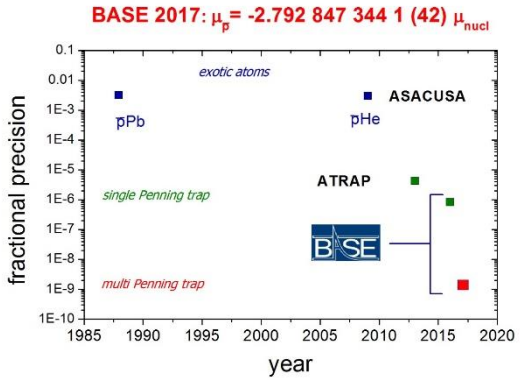


Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	Collaboration	Method
2011	2.792 847 353 (28)	2.786 2 (83)	Pask (ASACUSA)	MASER / Exotic Atoms
2012	2.792 846 (7)		diSciacca (ATRAP)	Single Penning-trap
2013		2.792 845 (12)	diSciacca (ATRAP)	Single Penning-trap
2014	**2.792 847 349 8 (93)**		Mooser (BASE)	Double Penning-trap
2015				
2016		**2.792 846 5 (23)**	Nagahama (BASE)	Single Penning-trap
2017	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	Schneider / Smorra (BASE)	Double Penning-trap / TTM



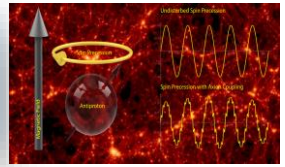
win: 60% of time usually used for sub-thermal cooling useable for measurements

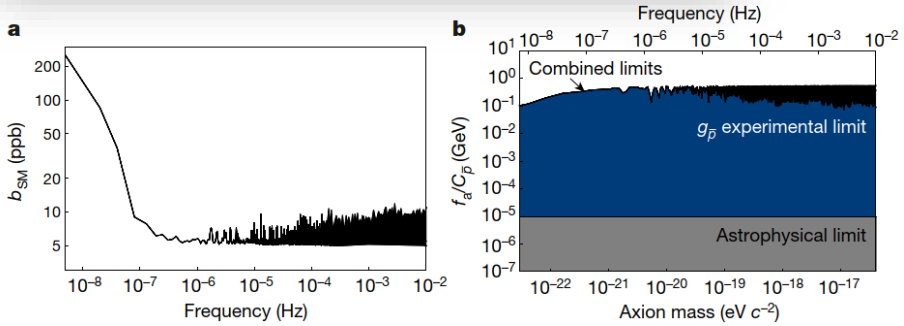




First constraints on antimatter/dark matter coupling

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





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

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

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

Smorra et al.(BASE), Nature **(575)**, 310 (2019)

Systematic Limitations of 2017 Measurement

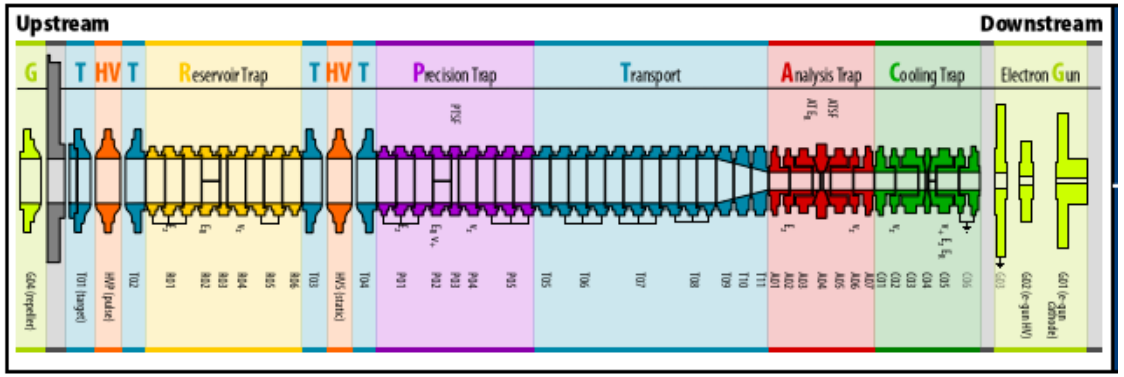
Error Budget

Table 1 | Error budget of the antiproton magnetic moment measurement

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

Limited by magnetic bottle strength of 2.7(3) T/m^2

New trap layout with increased distance between analysis trap and precision trap.



Recent magnetic field measurements:

Property	Value 2021	Value 2017
B_1	0.0270(7) T/m	0.0712(4) T/m
B_2	0.1298(8) T/m^2	2.7(3) T/m^2

B1 improved by factor of 3.

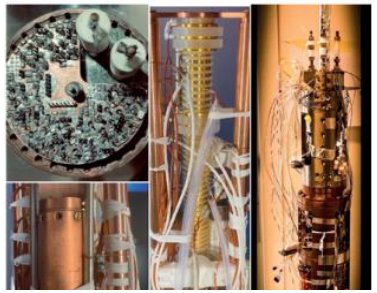
B2 improved by factor of 20.

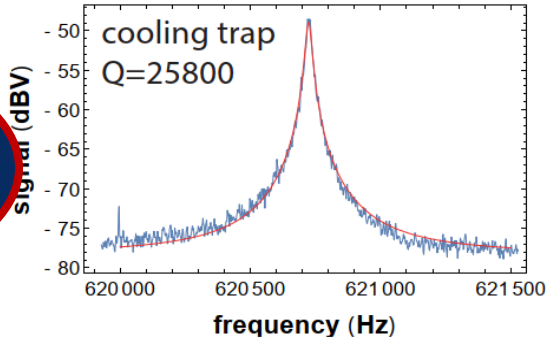
→ g-factor target precision of order 100 p.p.t. at much higher sampling rate in reach (so far no show stoppers identified).

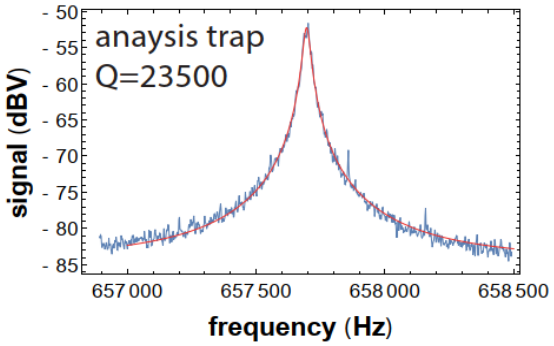
New Experiment, New Inventions

- Implement the best trap experiment we are able to build at the moment.

Property	Value 2021	Value 2019
Resonance Frequency	29.64 MHz	29.64 MHz
Tuning range	4.3 MHz	1.5 MHz
Inductance	1.52 μH	1.68 μH
Capacitance	2.72 pF	2.63 pF
Free Q @ 5 K	1250(150)	196(8)
Detection Resistance @ 5 K	376 kΩ	61 kΩ



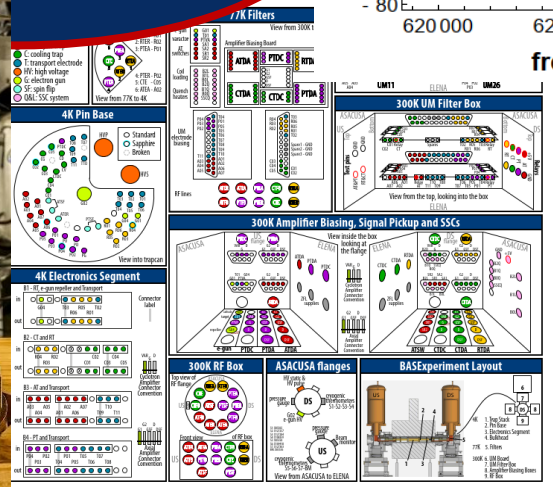


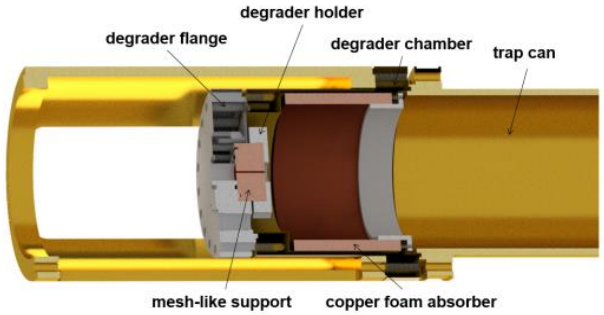


- Many new components developed in 2020 and 2021.

- New trap system
- New electronics layout
- New axial detectors
- New degarder interface
- Improved cryogenic RF noise suppression system
- New magnet shim system

First full 4-trap stack operated in BASE

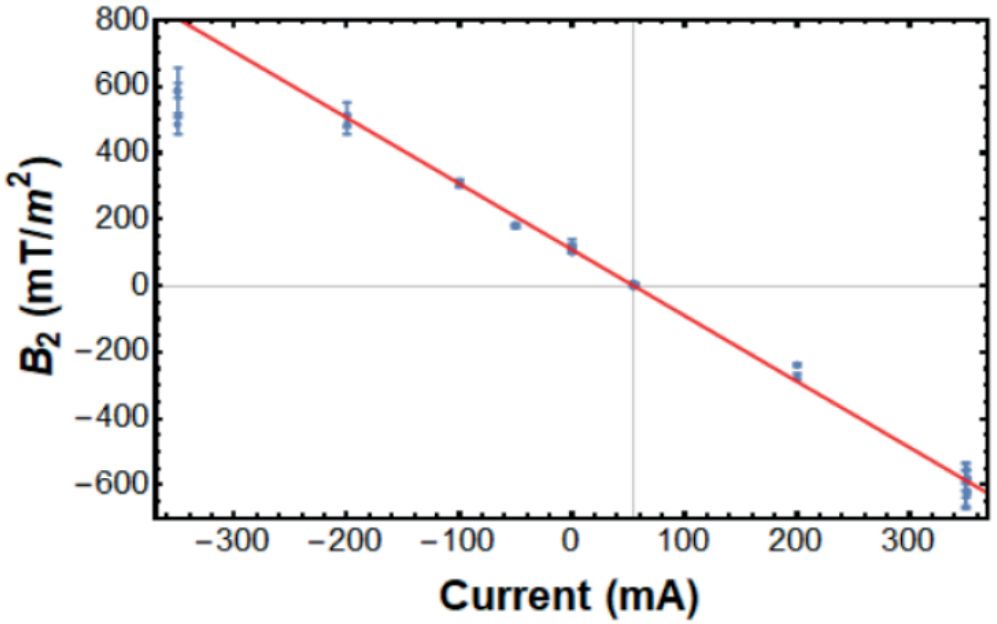




- Phase sensitive detection

Although everything else looks promising, problems with antiproton catching in 2021 (stray fields, misalignment, diagnostics, etc.).

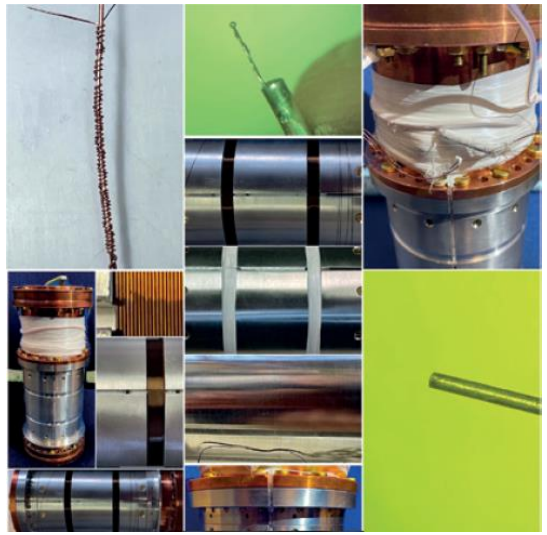
Dominant Systematics / Sampling

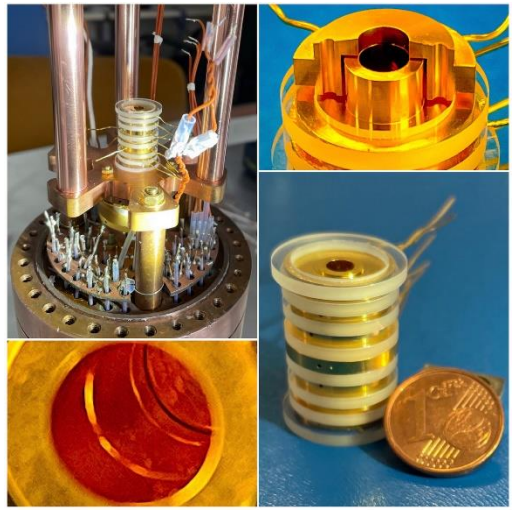



System running successfully in persistent mode.

Able to tune the B2 coefficient to 0 within uncertainties of 0.00006T/m^2

Reduces the dominant systematic uncertainty of the previous magnetic moment measurement by more than a factor of 10000.





Demonstrated in 2022 a 200mK particle preparation time of <10 minutes (60 fold improvement)

Feedback cooling heralds further improvement by a factor of 4. in time, 200mK in 2.5 min.

Parameter	2016 measurement (PT)	2022 measurement (CT)
detector temperature	12.8 K	4.2 K
detection Q	450	1250
R_p	75.000 Ω	360.000 Ω
pickup length (D_{eff})	21.5 mm	4.2 mm
thermalization time τ	380 s	3.2 s
Transport time	78 s	4.6 s
Readout time	120 s	10 s
200 mK preparation time	**15 h**	**8 min**

Recent Achievements – Sympathetic Cooling

- Magnetic moment measurements are limited by particle temperature and would be considerably accelerated by inventing a method beyond resistive cooling

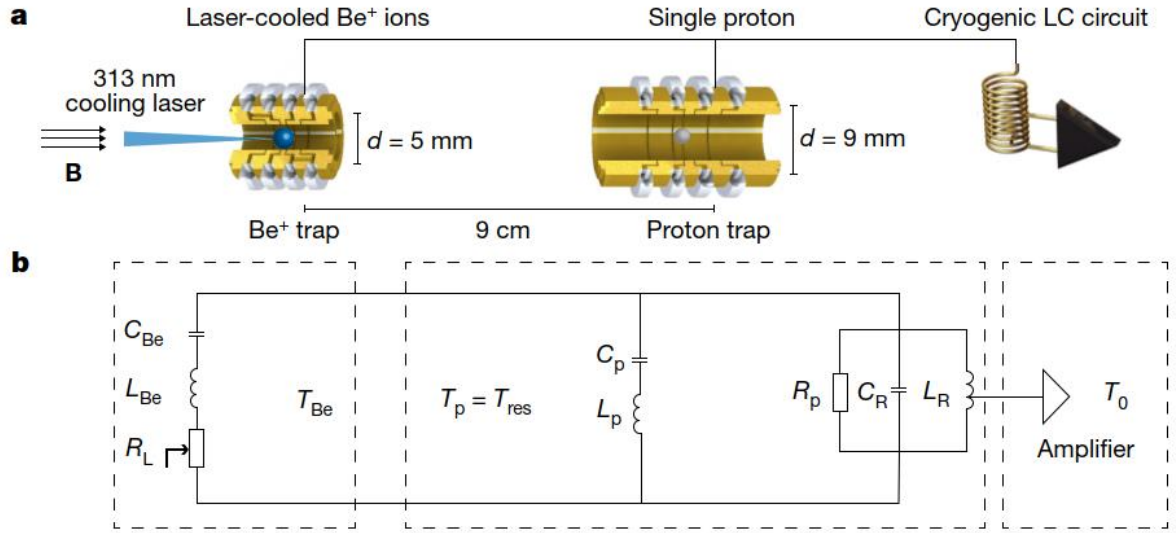
Method proposed by Wineland and Heinzen: Couple particles in different traps via image currents.

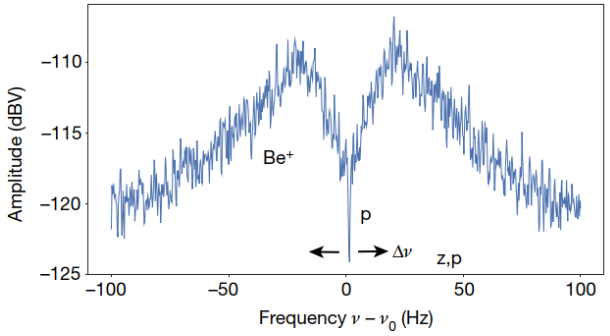
One of the particle types: Laser cooled species
Transfer particle temperatures from one trap to the other.

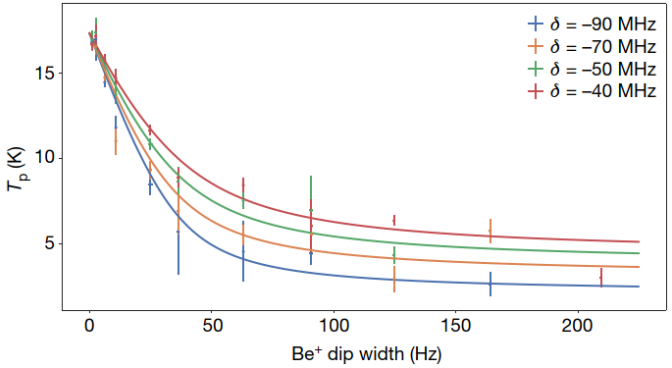
First proof of principle demonstration successful!!!

Demonstrated proton temperature reduction by about a factor of 8.

New trap geometries under development for more efficient cooling







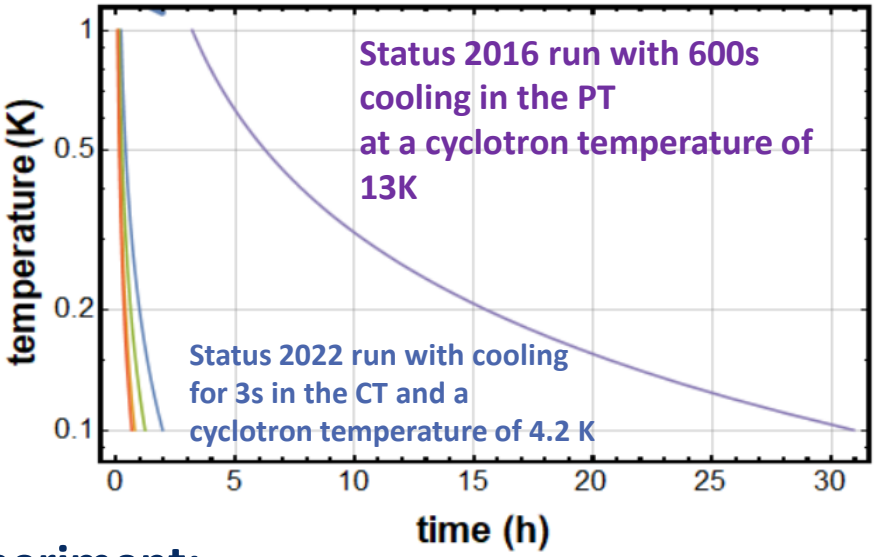
Simulations: Optimized procedures will enable 20 mK temperatures in 10 s.

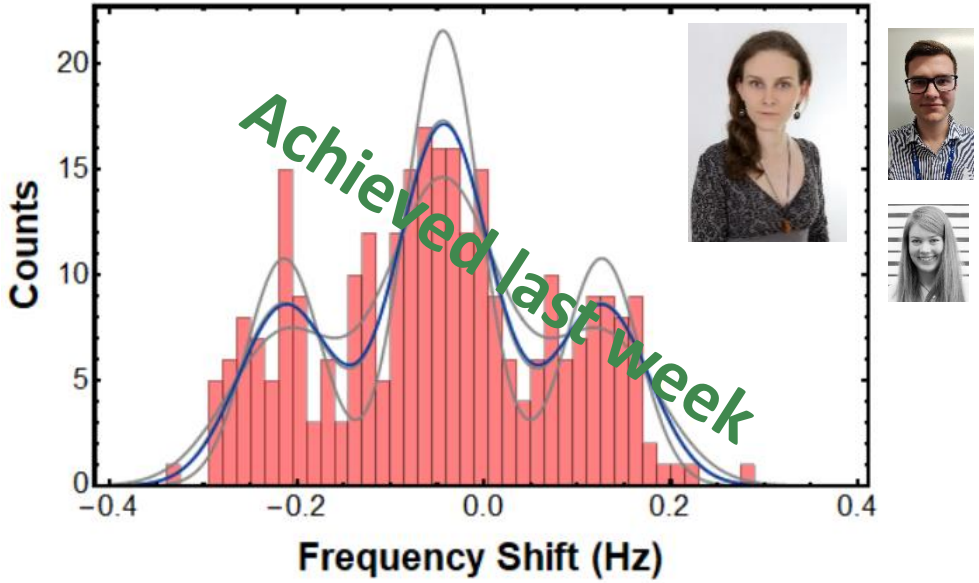
Bohman et al., Nature **596**, 514 (2021)

The single spin flip 2022

- With
  - dedicated cooling trap implemented
  - optimized fast particle transport
  - optimized detector/particle coupling

-> prepare a particle with >90% spin state detection fidelity in 10 minutes (still some headroom)…



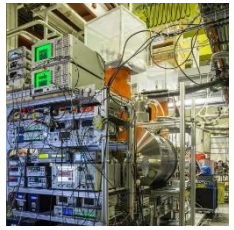


- **Current experiment:**
  - considerably improved particle cooling, thus much higher sampling rate
  - Double trap measurements possible now -> reduced systematics
  - Ultra homogeneous magnetic field
  - Ultra stable experiment magnet
  - Coherent methods and phase methods

Very optimistic to improve the antiproton moment measurement by >factor of 5

The «Perfect» Penning Trap Experiment

- Vision: Build at new HHU-D labs a world-leading Penning trap laboratory which features all essential aspects of all lessons learned in the last 10 years, supplied by BASE STEP.



1400 mm

2600 mm

Interface for ion sources and transportable trap

Beam tube

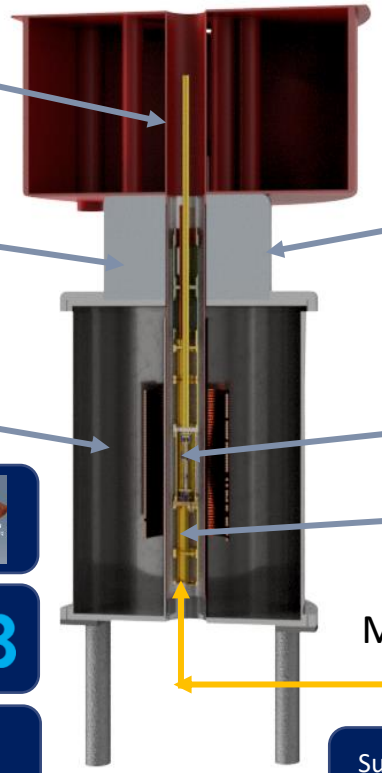
Experiment Cryostat

Vertical 7 T superconducting magnet with cold bore

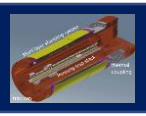
77K thermal shield

Magnet Coil

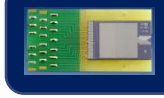
Penning trap



Multishims and local magnet



Frequency tuneable detection electronics



Josephson Standard

PTB

Microwave and Laser access

In-situ 3He servo system

Superconducting Seismometers

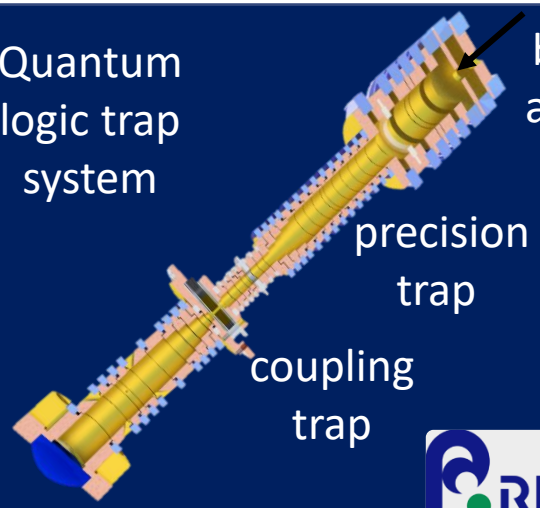
Quantum logic trap system

beam access

precision trap

coupling trap

fluorescence readout



RIKEN

PTB

Leibniz Universität Hannover

Be pump lasers

Developments will allow general improvement of Penning trap spectrometers to sub-p.p.t. precision

Summary

- Talked about recent precision measurements in BASE, with the flag-results 16ppt measurement of the antiproton/proton charge-to-mass ratio, and a 1.5ppb measurement of the proton magnetic moment.

- Some searches for more exotic physics.

- Future plans:

  - Improved measurement of the antiproton moment – excellent progress
  - Improved measurements by developing transportable antimatter traps
  - Improved measurements by implementing new technologies

Promising future experiments possible

Summary of SME Limits by BASE

- Magnetic Moment Measurements

Coefficient	Limit
$\lvert\tilde{b}_p^{Z}\rvert$	$< 1.8 \cdot 10^{-24}$ GeV
$\lvert\tilde{b}_p^{XX} + \tilde{b}_p^{YY}\rvert$	$< 1.1 \cdot 10^{-8}$ GeV^{-1}
$\lvert\tilde{b}_p^{ZZ}\rvert$	$< 7.8 \cdot 10^{-9}$ GeV^{-1}
$\lvert\tilde{b}_p^{*Z}\rvert$	$< 3.5 \cdot 10^{-24}$ GeV
$\lvert\tilde{b}_p^{*XX} + \tilde{b}_p^{*YY}\rvert$	$< 7.4 \cdot 10^{-9}$ GeV^{-1}
$\lvert\tilde{b}_p^{*ZZ}\rvert$	$< 2.7 \cdot 10^{-8}$ GeV^{-1}

Coefficient	Limit
$\tilde{b}_p^{*X}$	$< 9.7 \cdot 10^{-25}$ GeV
$\tilde{b}_p^{*Y}$	$< 9.7 \cdot 10^{-25}$ GeV
$\lvert\tilde{b}_p^{*XX} - \tilde{b}_p^{*YY}\rvert$	$< 5.4 \cdot 10^{-9}$ GeV^{-1}
$\tilde{b}_p^{*XZ}$	$< 3.7 \cdot 10^{-9}$ GeV^{-1}
$\tilde{b}_p^{*YZ}$	$< 3.7 \cdot 10^{-9}$ GeV^{-1}
$\tilde{b}_p^{*XY}$	$< 2.7 \cdot 10^{-9}$ GeV^{-1}

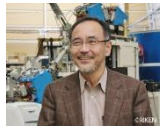
- 2022 Charge-to-Mass Ratio Measurement

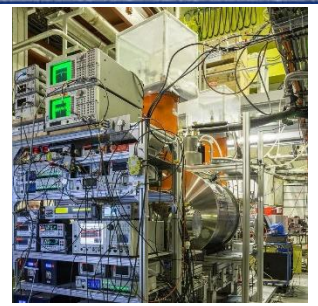
Coefficient	Previous Limit	Improved Limit	Factor
$\lvert\tilde{c}_e^{XX}\rvert$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\lvert\tilde{c}_e^{YY}\rvert$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\lvert\tilde{c}_e^{ZZ}\rvert$	$< 2.14 \cdot 10^{-14}$	$< 4.96 \cdot 10^{-15}$	4.31
$\lvert\tilde{c}_p^{XX}\rvert, \lvert\tilde{c}_p^{*XX}\rvert$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\lvert\tilde{c}_p^{YY}\rvert, \lvert\tilde{c}_p^{*YY}\rvert$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\lvert\tilde{c}_p^{ZZ}\rvert, \lvert\tilde{c}_p^{*ZZ}\rvert$	$< 7.85 \cdot 10^{-11}$	$< 1.82 \cdot 10^{-11}$	4.31

- Time-base Charge-to-Mass analysis ongoing

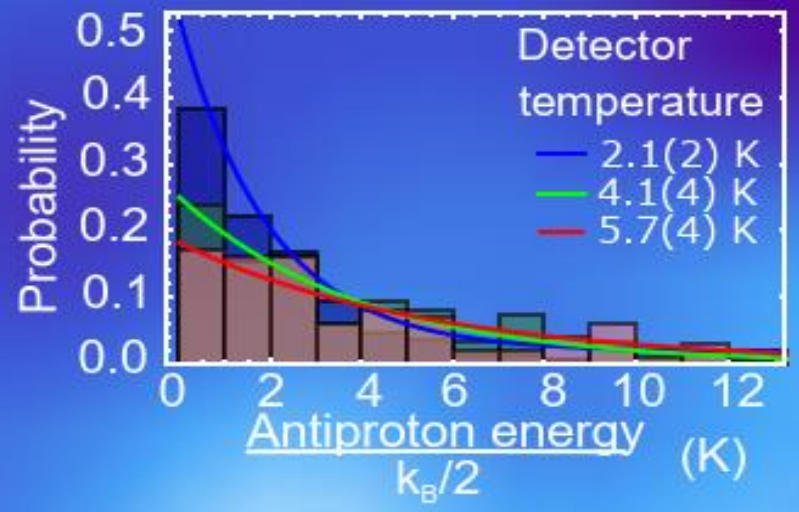
Work in progress, to be finished within the next 3 months.

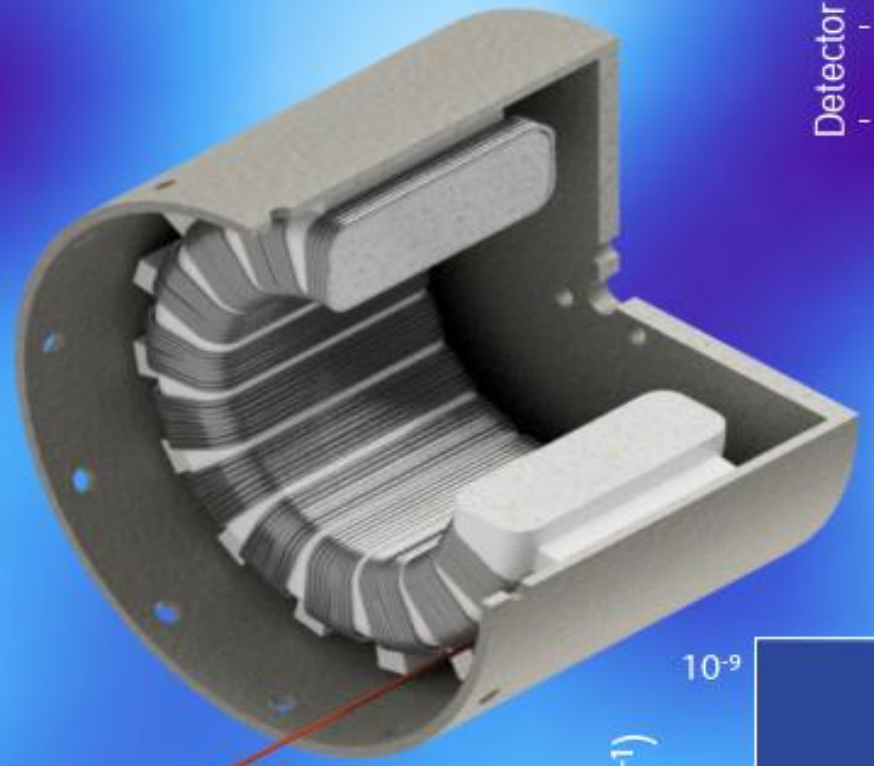
Thanks for your attention

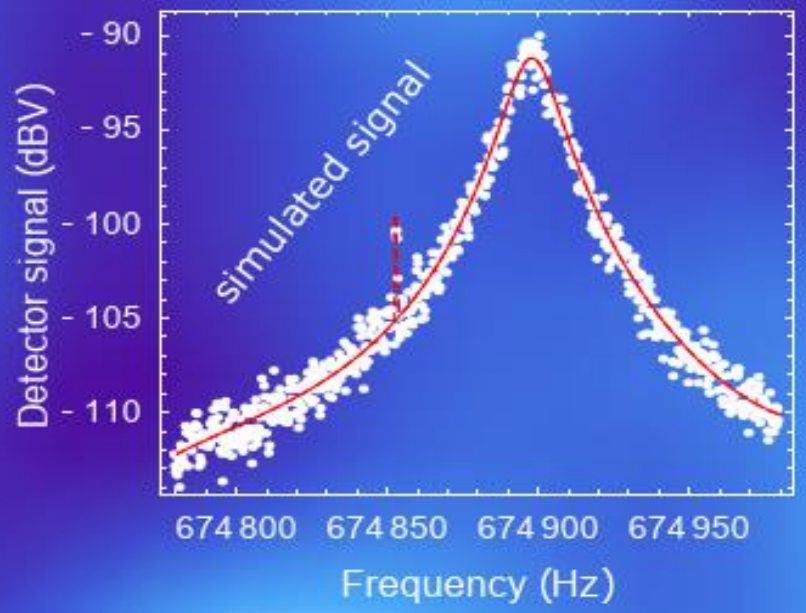


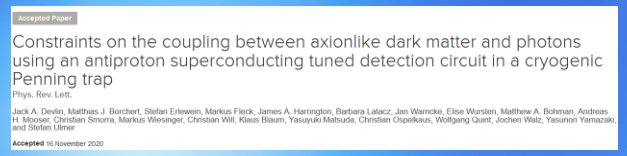


AXION SEARCH








Accepted Paper

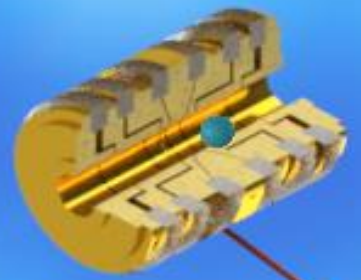
Constraints on the coupling between axionlike dark matter and photons using an antiproton superconducting tuned detection circuit in a cryogenic Penning trap

Phys. Rev. Lett.

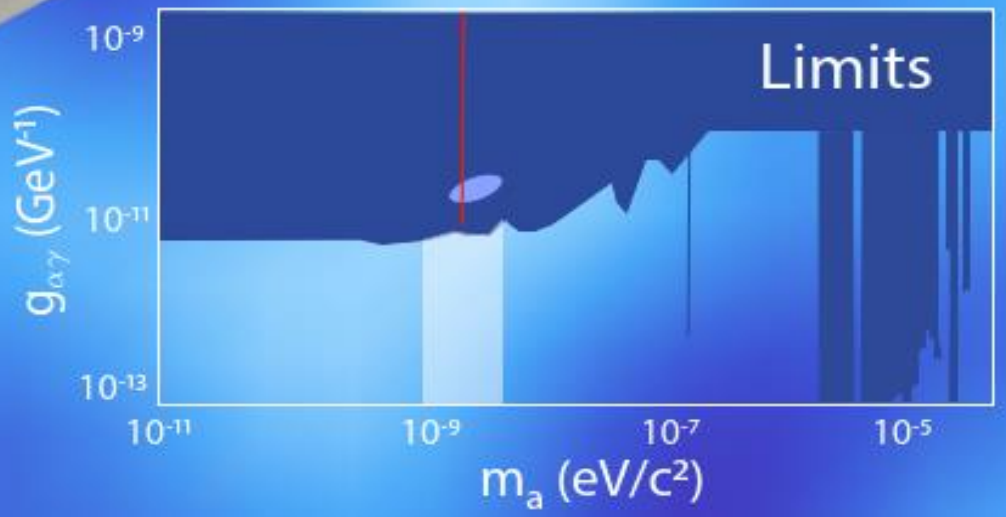
Jack A. Devlin, Matthias J. Borchert, Stefan Erlewein, Markus Fleck, James A. Harrington, Barbara Latacz, Jan Warncke, Elise Wursten, Matthew A. Bohman, Andreas H. Mooser, Christian Smorra, Markus Wiesinger, Christian Will, Klaus Blaum, Yasuyuki Matsuda, Christian Ospelkaus, Wolfgang Quint, Jochen Walz, Yasunori Yamazaki, and Stefan Ulmer

Accepted 16 November 2020

https://journals.aps.org/prl/accepted/15071Y2dJe514a63281b1498fe4274156d3788acc



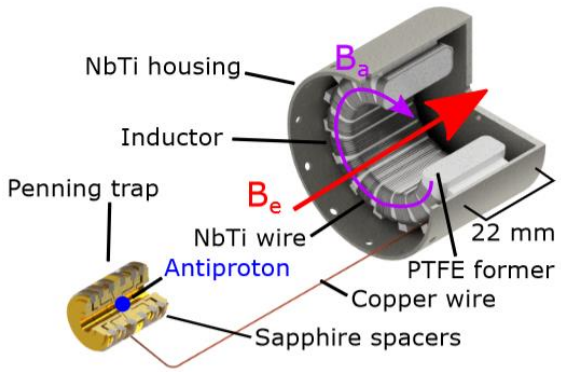
calibrated with a trapped antiproton



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

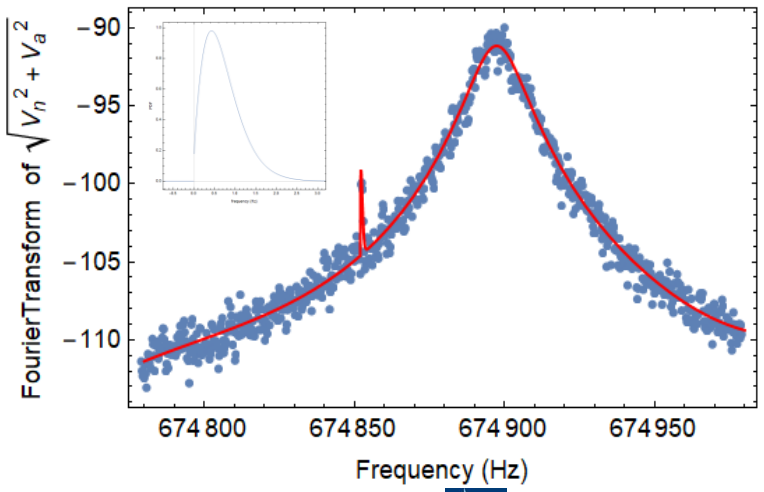


- Important feature: cold axions and axion like particles oscillate at their Compton frequencies

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

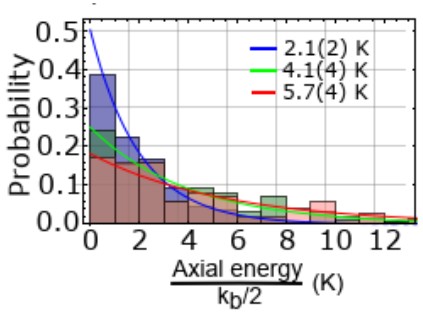
- In a strong external magnetic field **axions can convert into photons** via the inverse Primakoff effect.

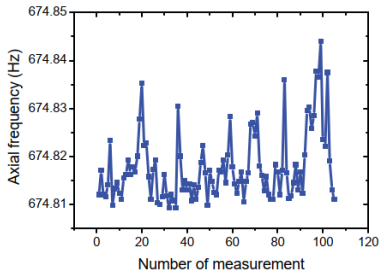
$$\boldsymbol{B_a} = -\frac{1}{2} g_{a\gamma} r \sqrt{\rho_a c_0 \hbar} B_e \boldsymbol{e_\phi}$$

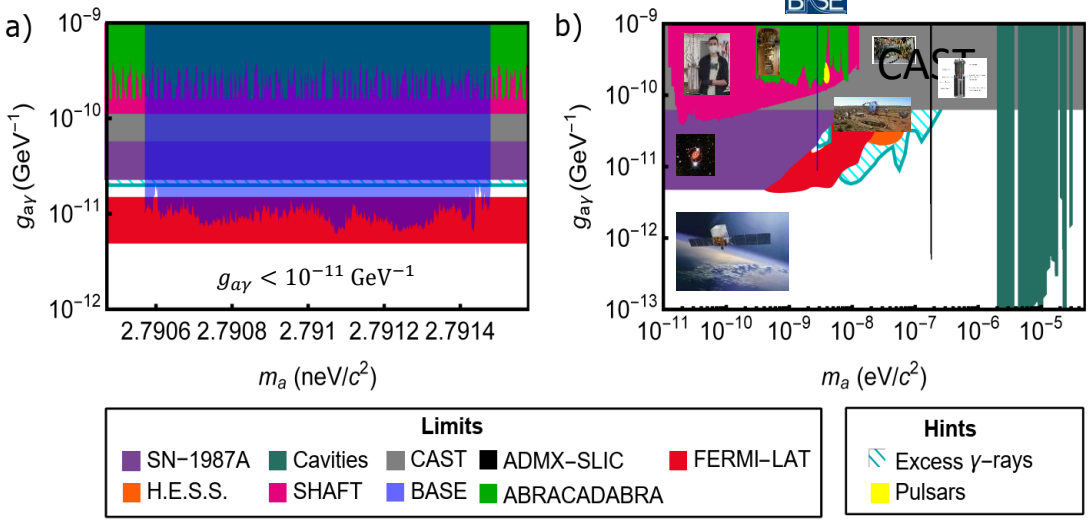


- Axion signal: $V_a = \frac{\pi}{2} g_{a\gamma} \nu_a \sqrt{\rho_a \hbar c_0} * Q \sqrt{\tau(\nu, Q, p)} \kappa N_T (r_2^2 - r_1^2) B_e$
- Noise-Floor: $V_n = \sqrt{e_n^2 \Delta\nu + 4 k_B T_z R_p \tau(\nu, Q, p) \kappa^2 \Delta\nu}$

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







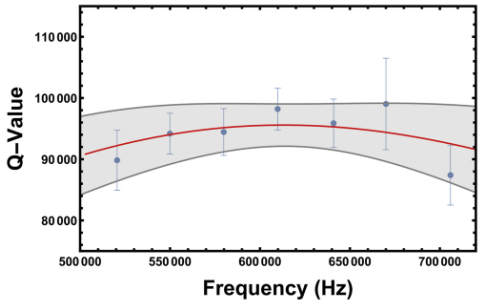
Penning trap: calibrated by single particle quantum thermometry

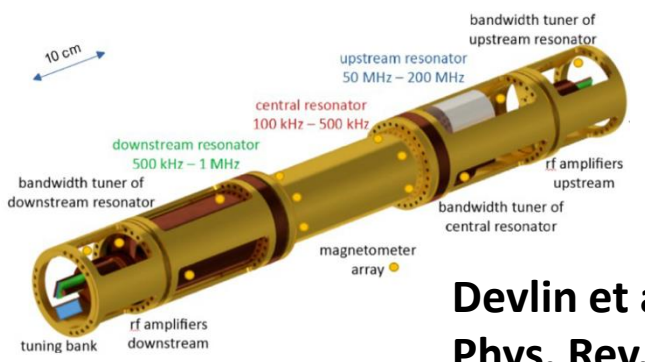
Future Projection

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

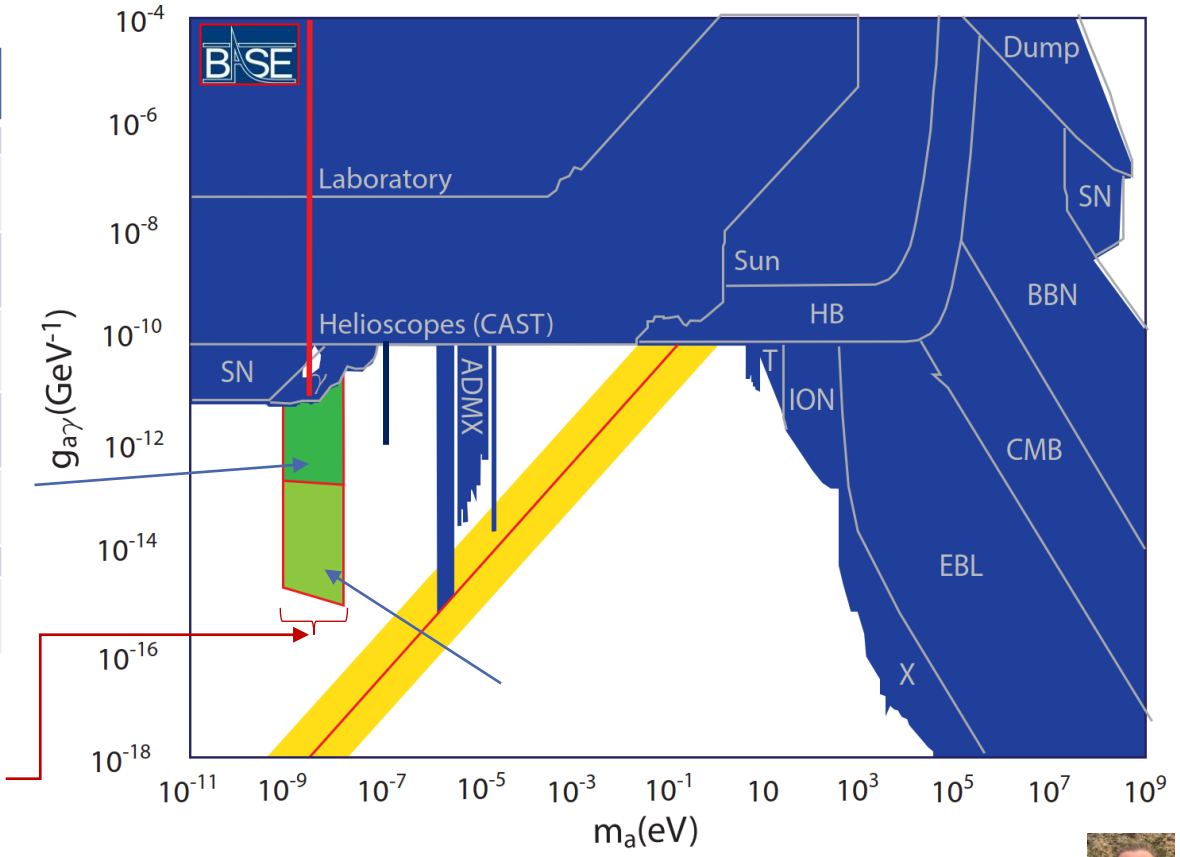
$$\frac{V_a}{V_n} \propto \frac{\pi}{2} g_{a\gamma}\sqrt{\nu_a \rho_a \hbar c_0} * \sqrt{\frac{f(Q)}{4k_B g(T_z)}}\sqrt{(r_2 - r_1)}(r_2 + r_1)^{3/2} B_e$$

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





Devlin et al., BASE, Phys. Rev. Lett. 126, 041301



Bandwidth-gain: x 3000

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