Bormio, 2024/01/24

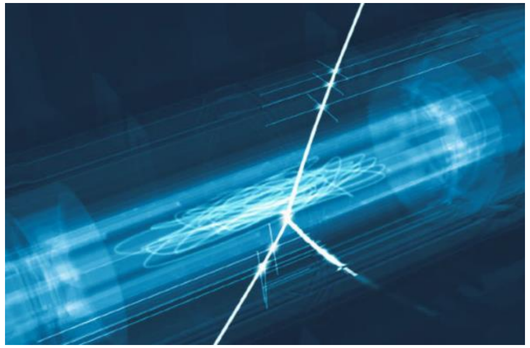
Testing Fundamental Symmetries by High Precision Comparisons of Matter/Antimatter Conjugates

Stefan Ulmer

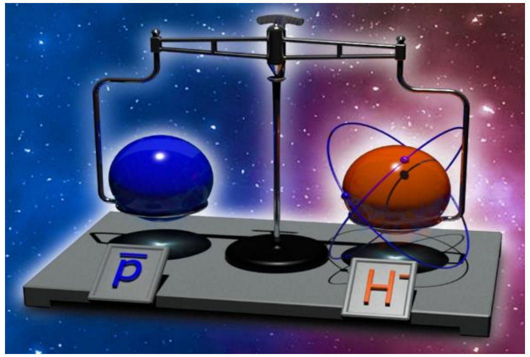
Chair AD Program CERN / Spokesperson BASE

HHU Düsseldorf, Germany
RIKEN, Japan
CERN, Switzerland

2024 / 01 / 24



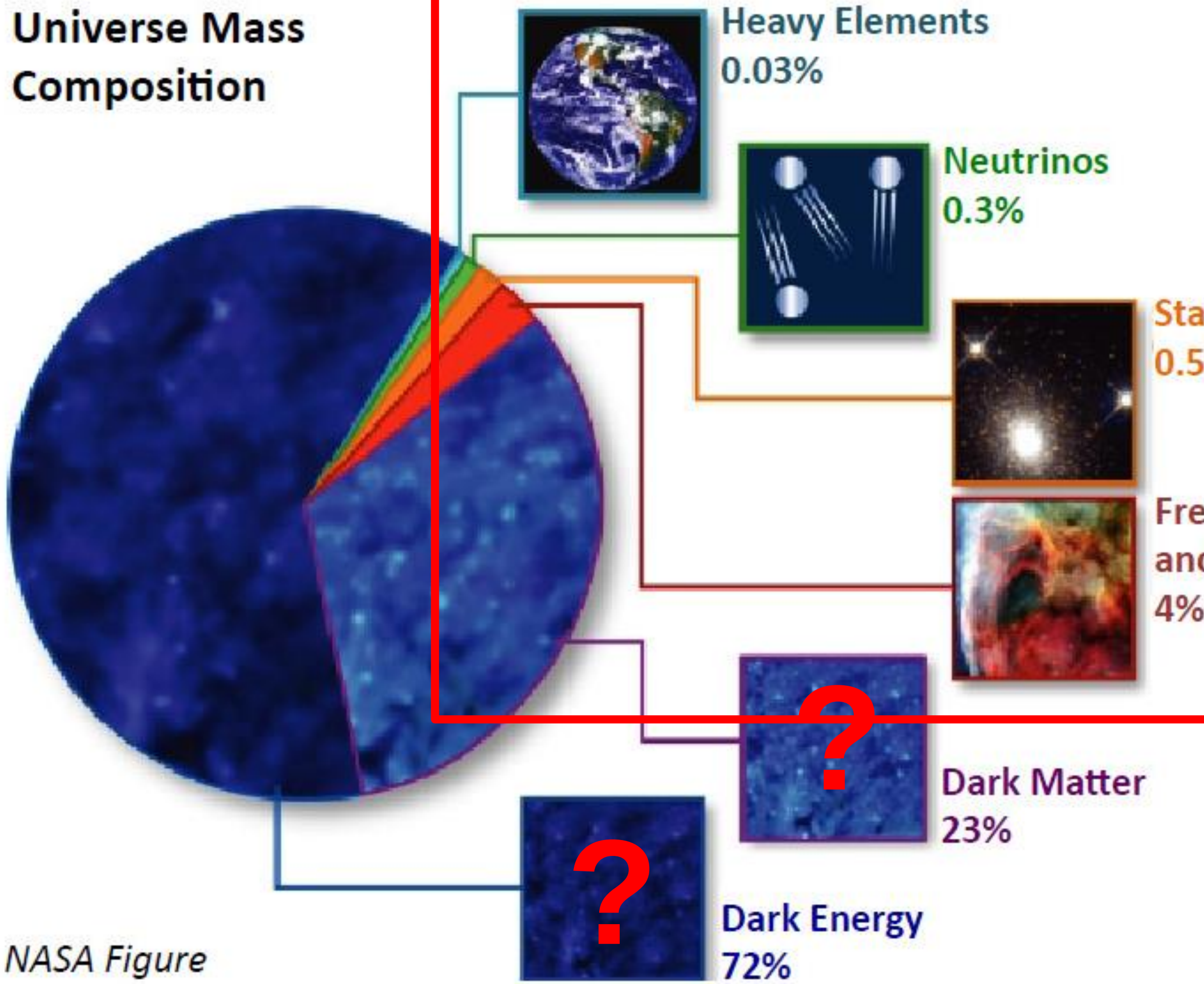
antihydrogen trap



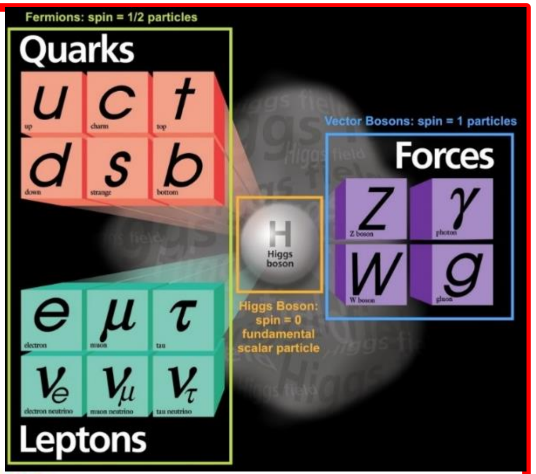
antiproton/proton balance

The Energy Content of our Universe

“Normal” matter



NASA Figure



Experiments at the AD of CERN deal with matter / antimatter symmetry and tests of CPT invariance, antimatter gravity, asymmetric antimatter dark matter couling, and nuclear physics questions.

AEḡIS

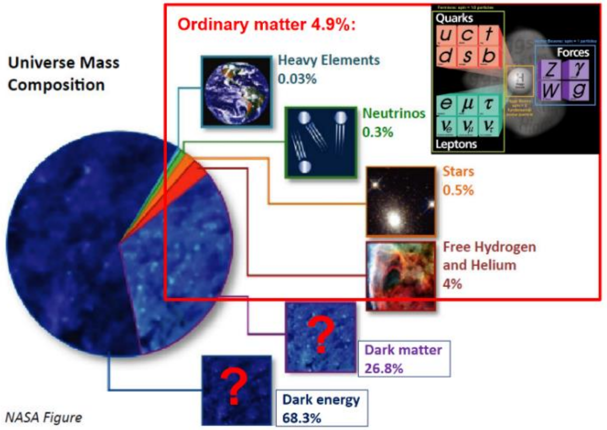
ALPHA

BASE

GBAR

STE p̄

Matter / Antimatter Asymmetry

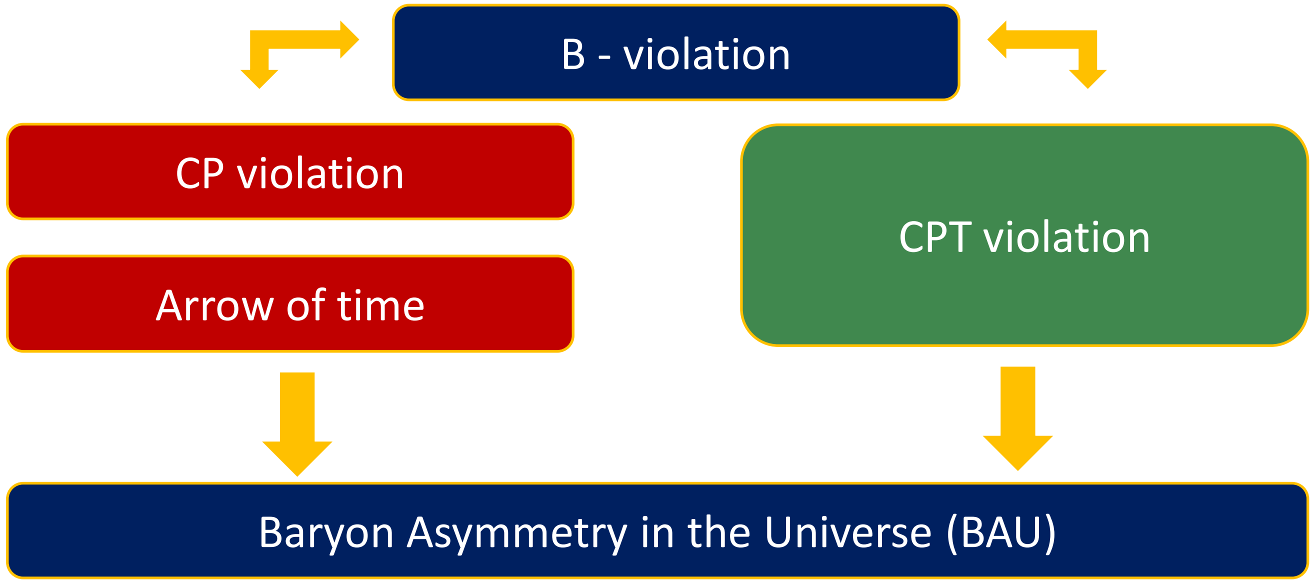


NASA Figure

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



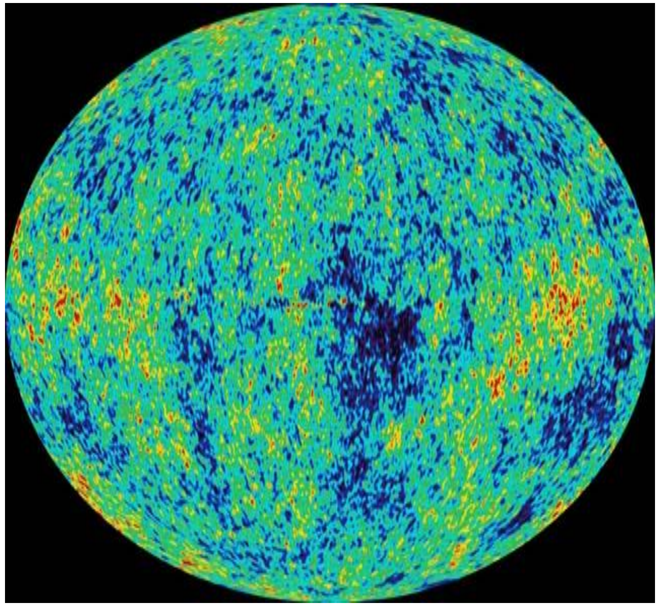
B - violation

CP violation

Arrow of time

CPT violation

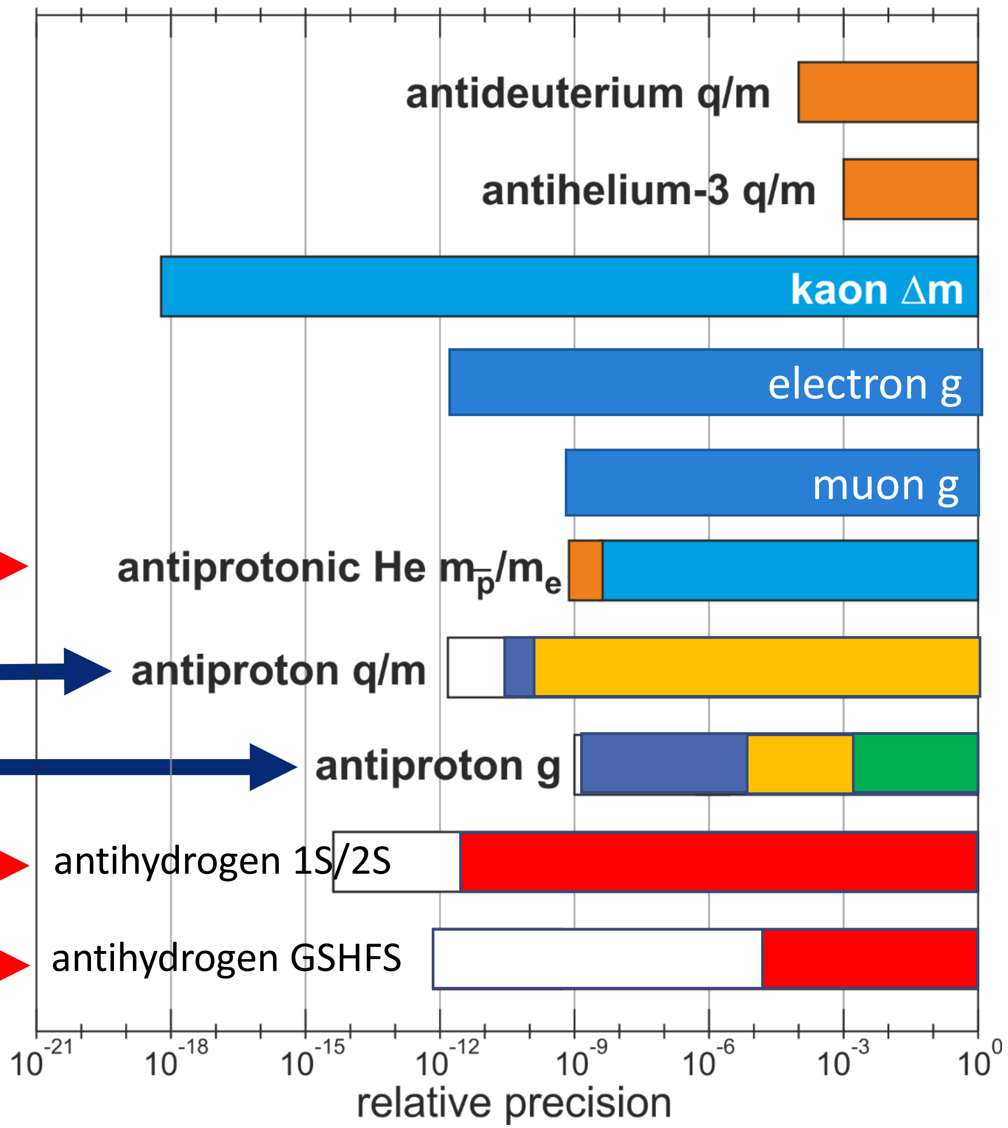
Baryon Asymmetry in the Universe (BAU)



One strategy to try to resolve this problem are technology-driven high precision comparisons of the fundamental properties of protons and antiprotons.

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).

Currently six active collaborations that perform precise tests of fundamental symmetries and gravity with antiprotons, antihydrogen, and antiprotonic helium.

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

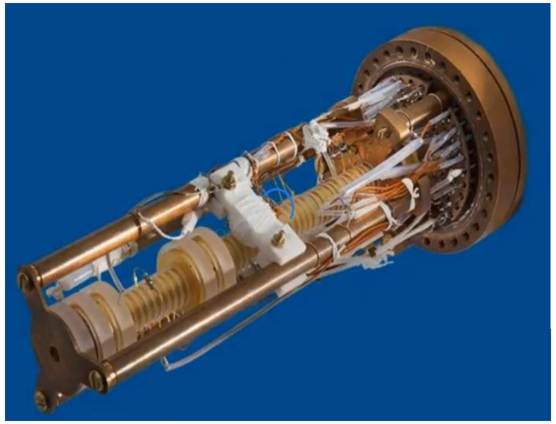
Methods

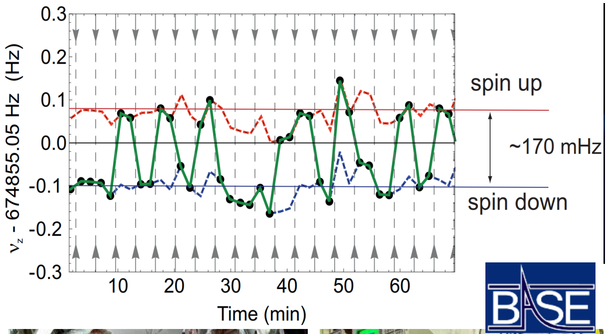
- This community is performing measurements using quantum technologies at world leading precision…

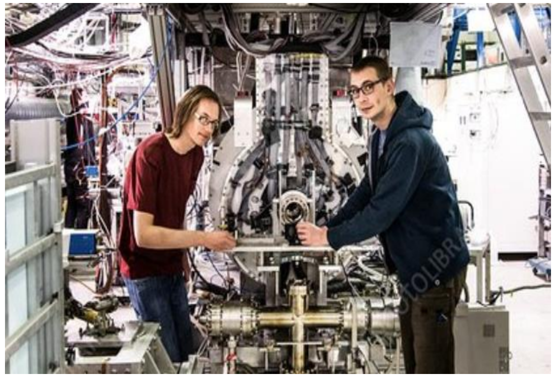
Clocks

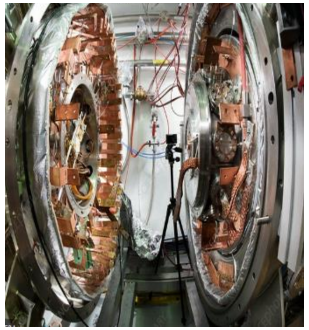
Traps

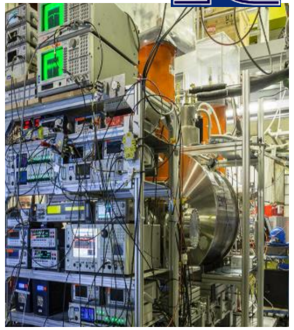
Lasers

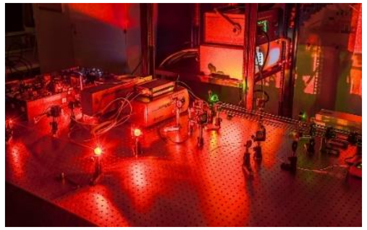


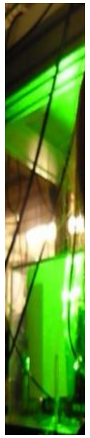


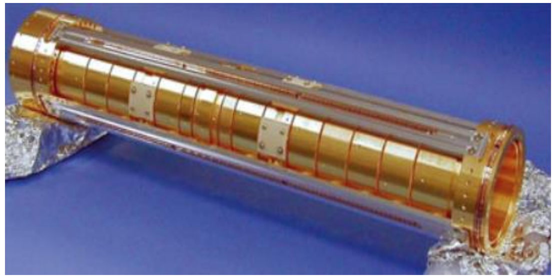


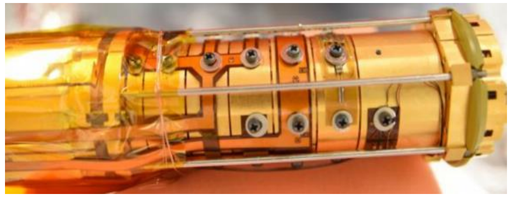








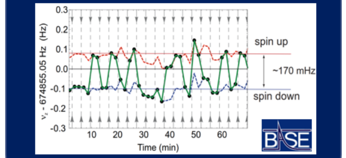




Innovation and Technology

- Antihydrogen traps
- Advanced multi-Penning trap systems
- Ultra-stable ultra-high power lasers
- Transportable antimatter traps and reservoir traps
- Non-destructive spin quantum transition spectroscopy
- quantum logic spectroscopy

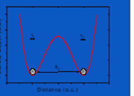
Non-destructive spin transition spectroscopy



Single spin spectroscopy in a Penning trap

Sympathetic Cooling

Quantum logic inspired sympatethic cooling of antiprotons, Hbar +, and positrons to laser-cooled Be+ ions



Improves

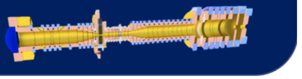
- spin detection fidelity
- Anihydrogen yield
- Resolution in test of WEP

Quantum Logic Spectroscopy

Use Wineland Al-clock quantum-logic algorithm to measure antiproton spin

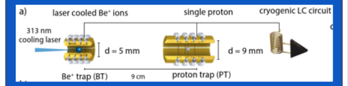
$|\psi\rangle_0 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$
$|\psi\rangle_1 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$
$|\psi\rangle_2 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$
$|\psi\rangle_3 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$
$|\psi\rangle_4 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$

$|\psi\rangle_0 = |\downarrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$
$|\psi\rangle_1 = |\uparrow\rangle_p|1\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$
$|\psi\rangle_2 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|1\rangle_{m,L}$
$|\psi\rangle_3 = |\uparrow\rangle_p|0\rangle_{m,p}|\downarrow\rangle_L|0\rangle_{m,L}$
$|\psi\rangle_4 = |\uparrow\rangle_p|0\rangle_{m,p}|\downarrow\rangle_L|0\rangle_{m,L}$



Laser Cooled Superconductors

coupled Penning traps with common SC-LC

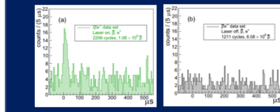


Demonstrated reduction of SC-LC circuit temperature to sub-1K level

Axion detection / precision frequency measurements

Production of Hbar via Charge Exchange with Laser Excited PS

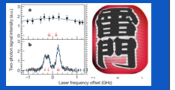
$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$



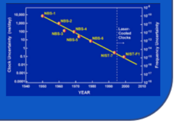
Similar methods to be applied for production of Hbar+-ion / H2+bar

More Quantum Methods

Deep UV two photon spectroscopy in antiprotonic helium



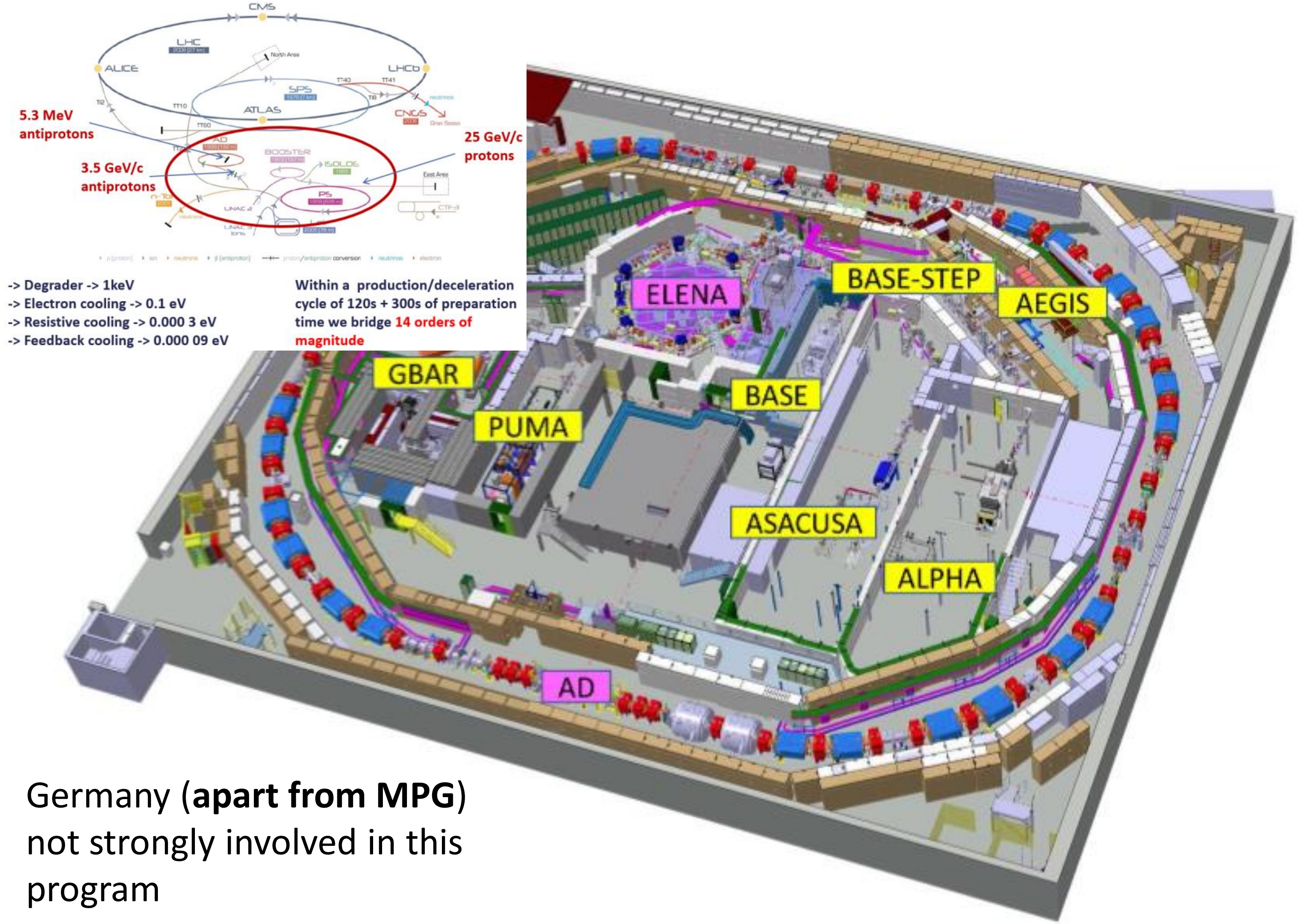
Atomic fountain microwave clocks



…and is a vital part of the low energy precision physics community…

The AD/ELENA-Facility

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.



-> Degrader -> 1keV
-> Electron cooling -> 0.1 eV
-> Resistive cooling -> 0.000 3 eV
-> Feedback cooling -> 0.000 09 eV

Within a production/deceleration cycle of 120s + 300s of preparation time we bridge 14 orders of magnitude

Germany (**apart from MPG**) not strongly involved in this program

antihydrogen

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ALPHA, AEgIS, GBAR
Test free fall weak equivalence principle with antihydrogen

antiprotons

ASACUSA
Antiprotonic helium spectroscopy

BASE, BASE-STEP
Fundamental properties of the proton/antiproton, tests of clock WEP / tests of exotic physics / antimatter-dark matter interaction, etc...

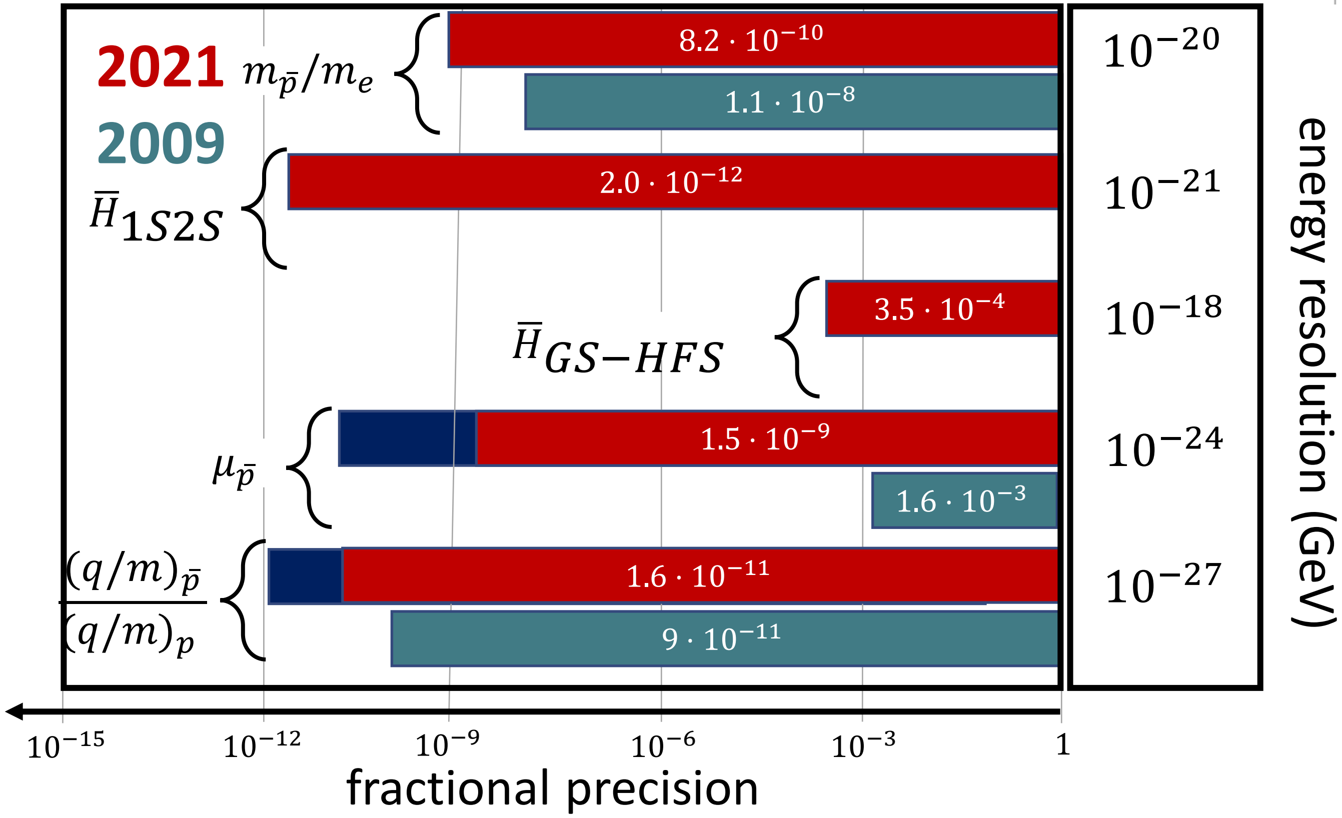
PUMA
Antiproton/nuclei scattering to study neutron skins

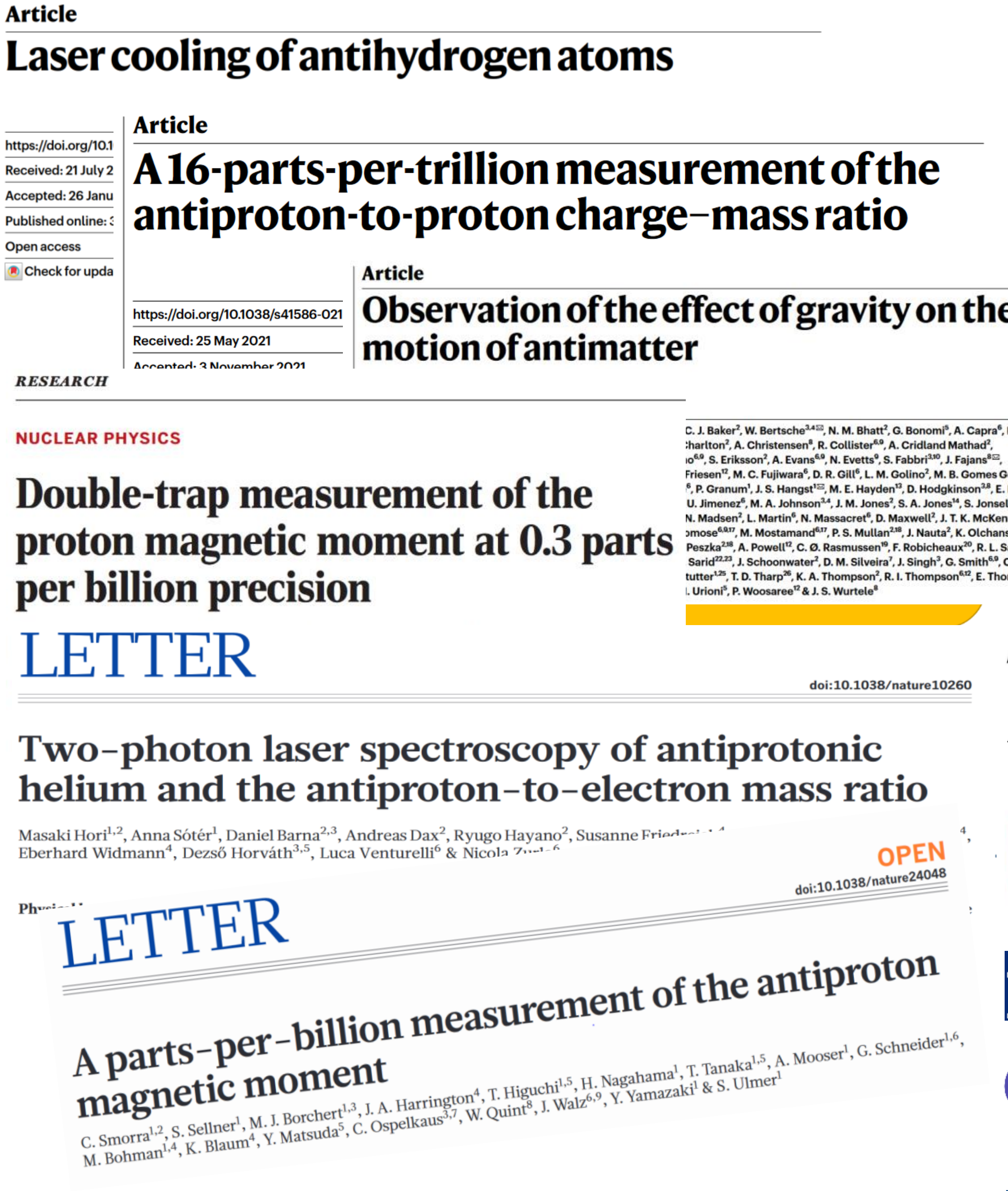
60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations

M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).

Progress

- Progress made since LS1





Article

Laser cooling of antihydrogen atoms

https://doi.org/10.1
Received: 21 July 2
Accepted: 26 Janu
Published online:
Open access
Check for upda

Article

A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio

https://doi.org/10.1038/s41586-021
Received: 25 May 2021
Accepted: 3 November 2021

Article

Observation of the effect of gravity on the motion of antimatter

C. J. Baker[2], W. Bertsche[3,4], N. M. Bhatt[2], G. Bonomi[5], A. Capra[6], I. Carli[6],
harlton[2], A. Christensen[8], R. Collister[6,9], A. Cridland Mathad[2],
o[6,9], S. Eriksson[2], A. Evans[6,9], N. Evetts[9], S. Fabbri[3,10], J. Fajans[8],
Friesen[12], M. C. Fujiwara[6], D. R. Gill[6], L. M. Golino[2], M. B. Gomes Gonçalves[2],
[6], P. Granum[1], J. S. Hangst[1], M. E. Hayden[13], D. Hodgkinson[3,8], E. D. Hunter[8],
U. Jimenez[6], M. A. Johnson[3,4], J. M. Jones[2], S. A. Jones[14], S. Jonsell[15],
N. Madsen[2], L. Martin[6], N. Massacret[6], D. Maxwell[2], J. T. K. McKenna[1,3],
omose[6,9,17], M. Mostamand[6,17], P. S. Mullan[2,18], J. Nauta[2], K. Olchanski[6],
Peszka[2,18], A. Powell[12], C. Ø. Rasmussen[19], F. Robicheaux[20], R. L. Sacramento[7],
Sarid[22,23], J. Schoonwater[2], D. M. Silveira[7], J. Singh[3], G. Smith[6,9], C. So[6],
tutter[1,25], T. D. Tharp[26], K. A. Thompson[2], R. I. Thompson[6,12], E. Thorpe-Woods[2],
. Urioni[5], P. Woosaree[12] & J. S. Wurtele[8]

RESEARCH

NUCLEAR PHYSICS

Double-trap measurement of the proton magnetic moment at 0.3 parts per billion precision

LETTER

doi:10.1038/nature10260

Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio

Masaki Hori[1,2], Anna Sótér[1], Daniel Barna[2,3], Andreas Dax[2], Ryugo Hayano[2], Susanne Fried
Eberhard Widmann[4], Dezső Horváth[3,5], Luca Venturelli[6] & Nicola Z

OPEN

doi:10.1038/nature24048

LETTER

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

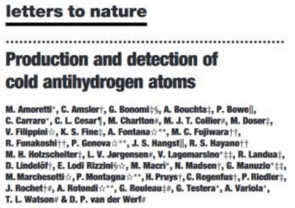
C. Smorra[1,2], S. Sellner[1], M. J. Borchert[1,3], J. A. Harrington[4], T. Higuchi[1,5], H. Nagahama[1], T. Tanaka[1,5], A. Mooser[1], G. Schneider[1,6],
M. Bohman[1,4], K. Blaum[4], Y. Matsuda[5], C. Ospelkaus[3,7], W. Quint[8], J. Walz[6,9], Y. Yamazaki[1] & S. Ulmer[1]

dramatic progress in experimental resolution since the program was started

Achievements Since the Start of the Program

- Advanced charged plasma control techniques
- Advanced magnetic trapping
- High power UV-laser technology
- Non-destructive quantum-transition spectroscopy
- Ultra-low-noise trapping techniques
- Sympathetic cooling and quantum-logic spectroscopy

2002

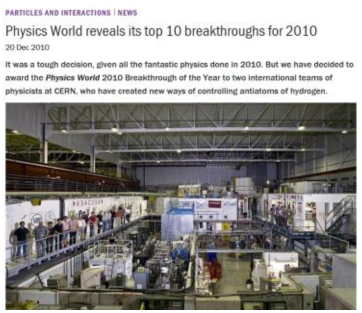


letters to nature

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe‖, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst‖, R. S. Hayano†† M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macri*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#

Start of antihydrogen physics



PARTICLES AND INTERACTIONS | NEWS

Physics World reveals its top 10 breakthroughs for 2010

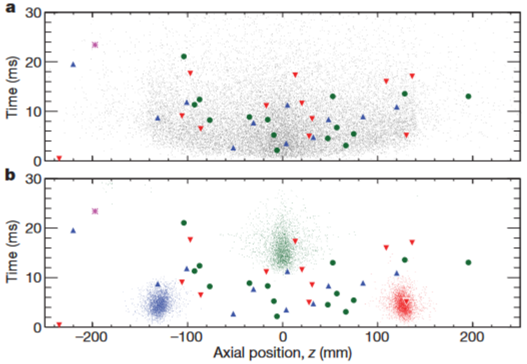
20 Dec 2010

It was a tough decision, given all the fantastic physics done in 2010. But we have decided to award the *Physics World* 2010 Breakthrough of the Year to two international teams of physicists at CERN, who have created new ways of controlling antiatoms of hydrogen.

physicsworld TOP 10 BREAKTHROUGH 2010

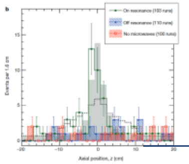
ALPHA
ASACUSA

2010



trapped antihydrogren

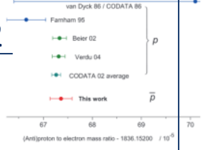
2011



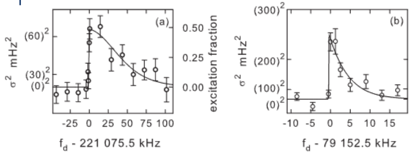
Resonant quantum transitions in Hbar

2012

$m_{\bar{p}}/m_e$ at 1.5 ppb

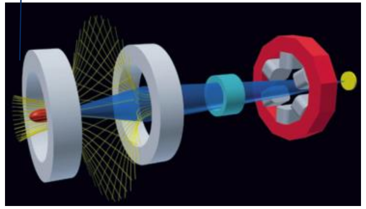


2013



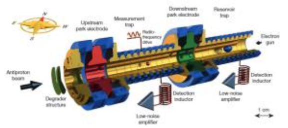
5ppm pbar moment

2014



Production of a beam of antihydrogen atoms

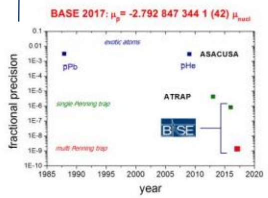
2015



69 p.p.t. proton/antiproton q/m comparison

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

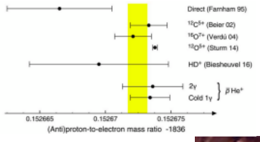
2017



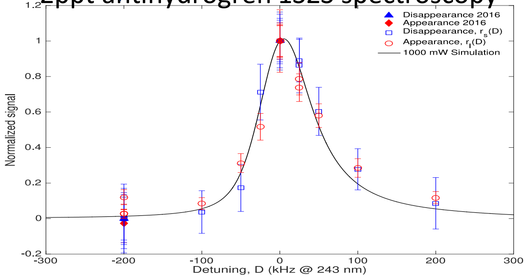
1.5ppb pbar moment

2018

$m_{\bar{p}}/m_e$ at 0.8ppb

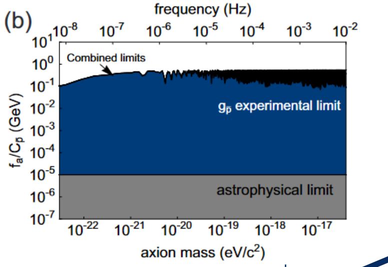


2ppt antihydrogren 1S2S spectroscopy

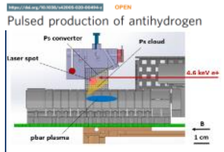


2019

antimatter/dark matter coupling



2020

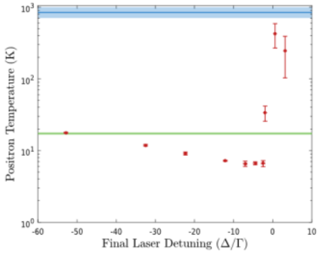


2021

ALPHA
BASE

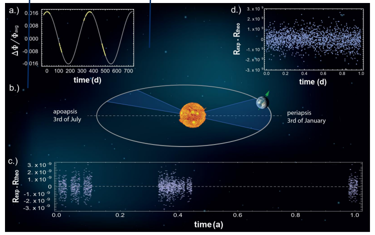
physicsworld TOP 10 BREAKTHROUGH 2022

laser-cooled antihydrogren and sympathetically cooled protons



Laser cooled positrons

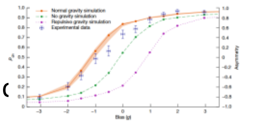
2022



WEP test with clocks

2023

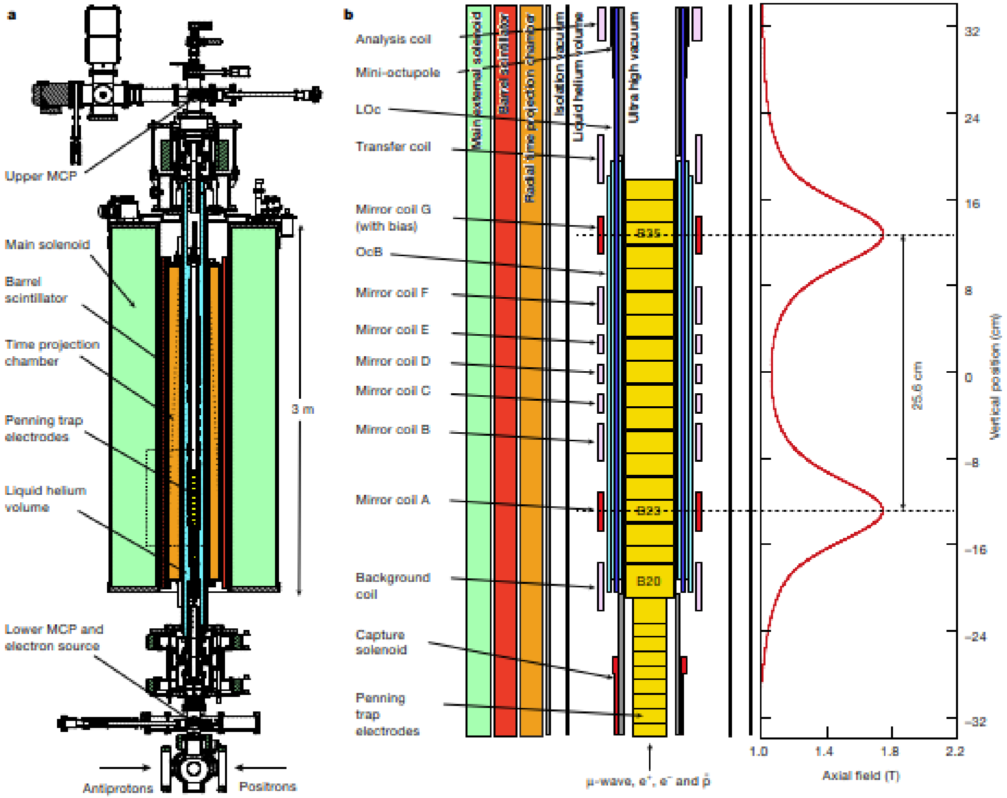
Hbar produc



physicsworld TOP 10 BREAKTHROUGH 2023

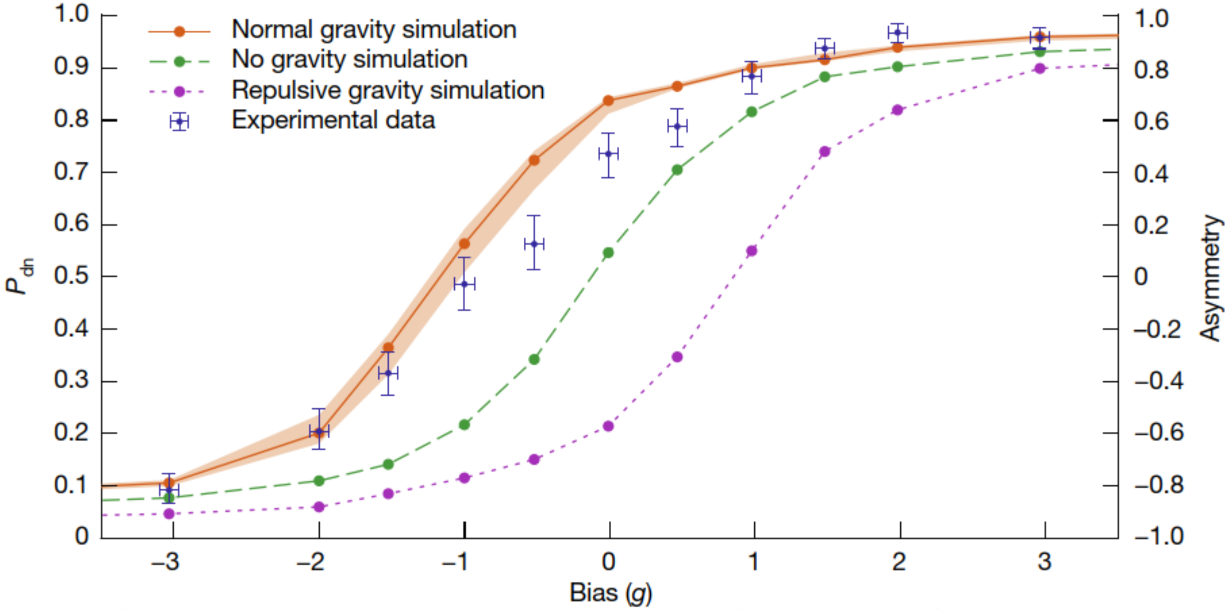
2023 – AD/ELENA – Facility News

- Does antimatter fall up?
- Sudied with the ALPHA-g experiment



https://www.nature.com/articles/s41586-023-06527-1

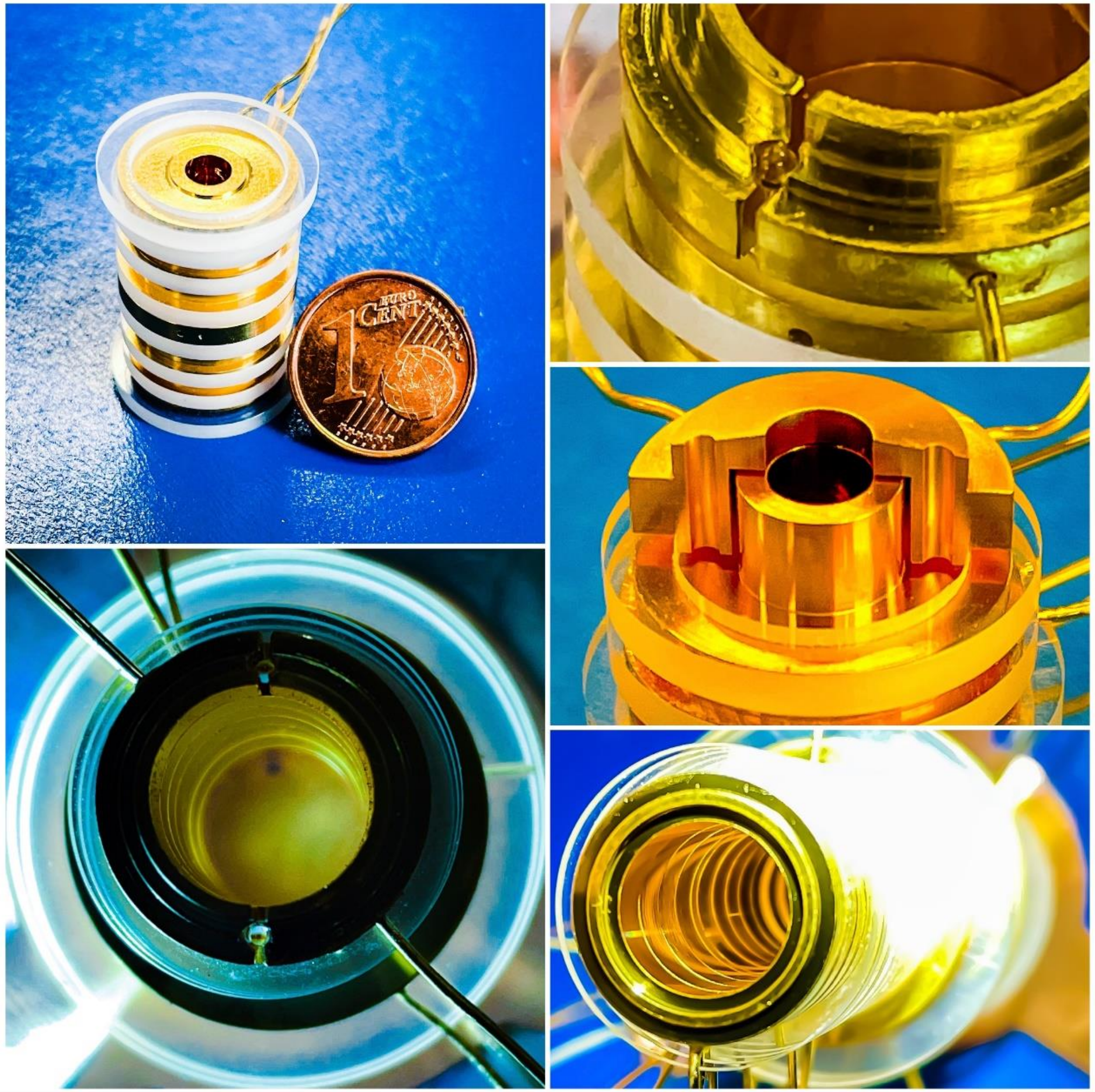
- Experiment principle: Study antimatter gravity by applying a magnetic bias to the trap, and releasing the trap. Count what is being detected as a function of position.



- Such experiments were proposed already in the 1970ies.
- Initiative to study gravity with antiprotons failed in the 1990ies
- Numerous cosmological models that require repulsive gravity or no gravity ruled out by this measurement.

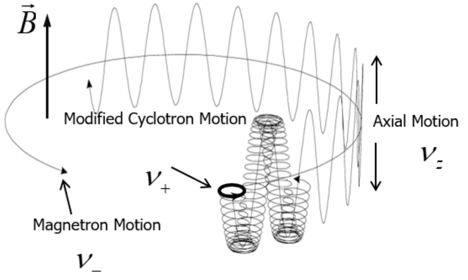
$\alpha_g = 0.75(20)$ so there is headroom for anomalous gravity for antimatter – which would change our understanding of physics

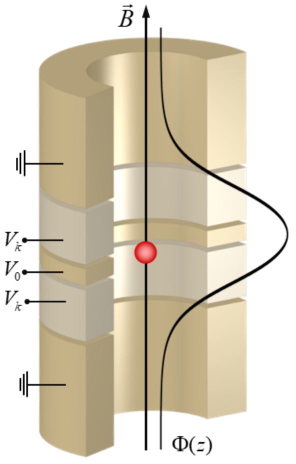
BASE – Penning Traps - Antiprotons



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

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

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

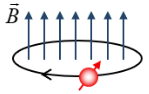
$$\nu_- = \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$

Invariance Theorem

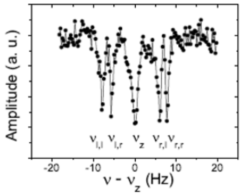
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

Gives undisturbed access to cyclotron frequencies $\nu_c = \frac{1}{2\pi}\frac{q_{ion}}{m_{ion}} B$

Cyclotron Motion



simple



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

g: mag. Moment in units of nuclear magneton

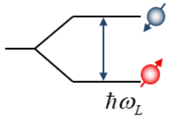
$$\omega_c = \frac{e}{m_p} B$$

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

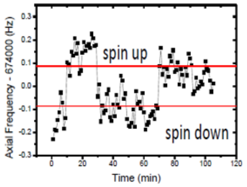
$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

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

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.**

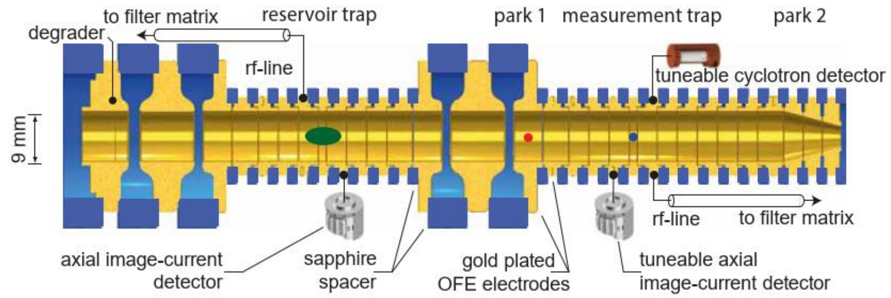
High Precision Mass Spectrometry

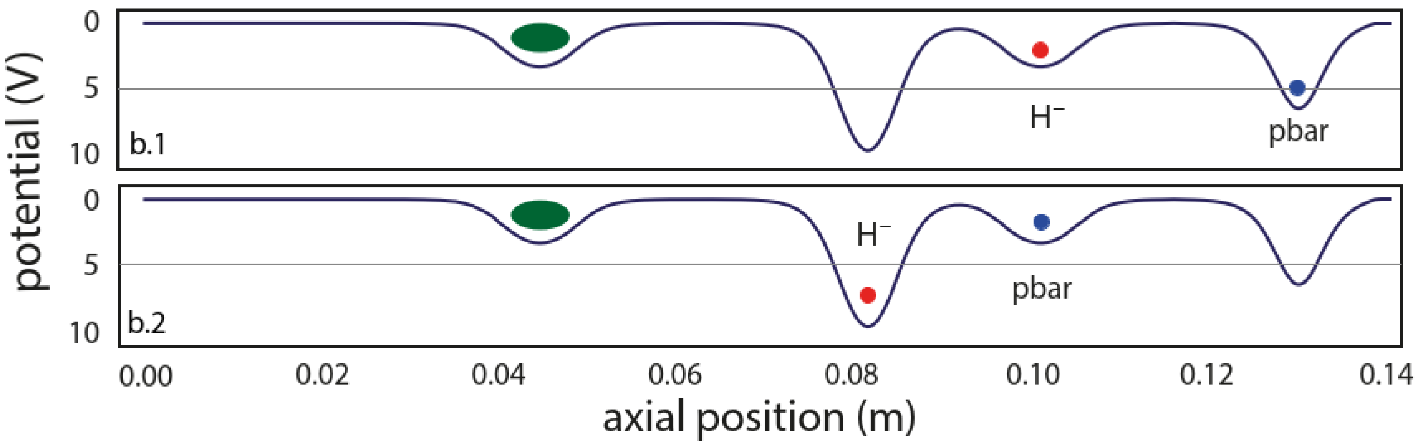
High Precision Magnetic Moment Measurements

Charge-to-Mass Ratio Measurement

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

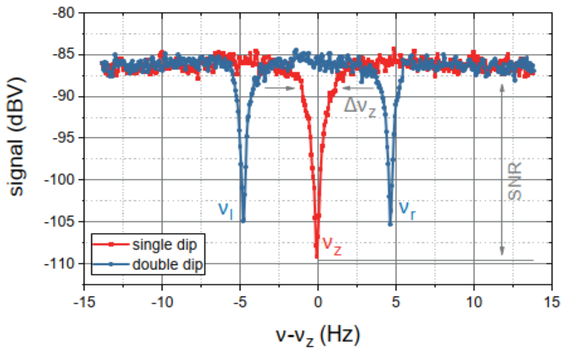
First Measurement: S. Ulmer, et al., **Nature 524, 196 (2015)**





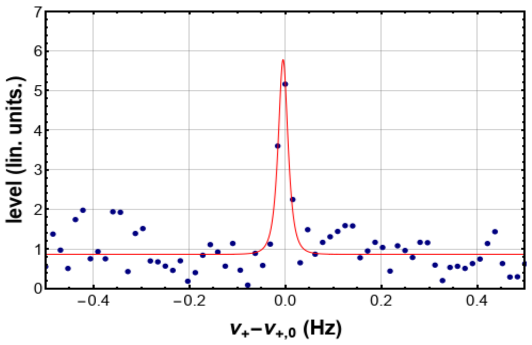
BASE is the first experiment which has implemented this method, now also used by many others

- 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

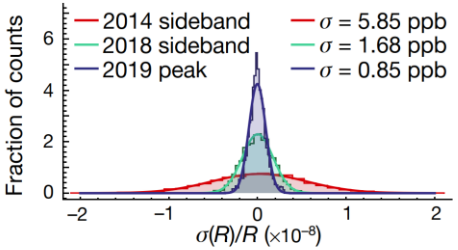
Improvements and Acquired Data Set

Previous BASE Measurement (2015):

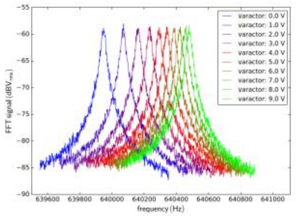
$R_{exp,c}$ = 1.001 089 218 755 (69)

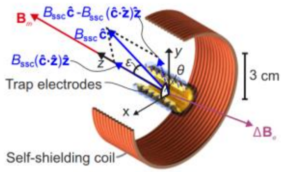
$$\boxed{\frac{(q/m)_{\bar{p}}}{(q/m)_{p}}+1 = 1(69)\times 10^{-12}}$$

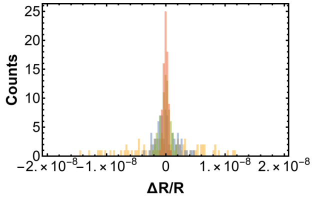
S. Ulmer et al., *Nature* **524** 196 (2015)



Technical Improvements:

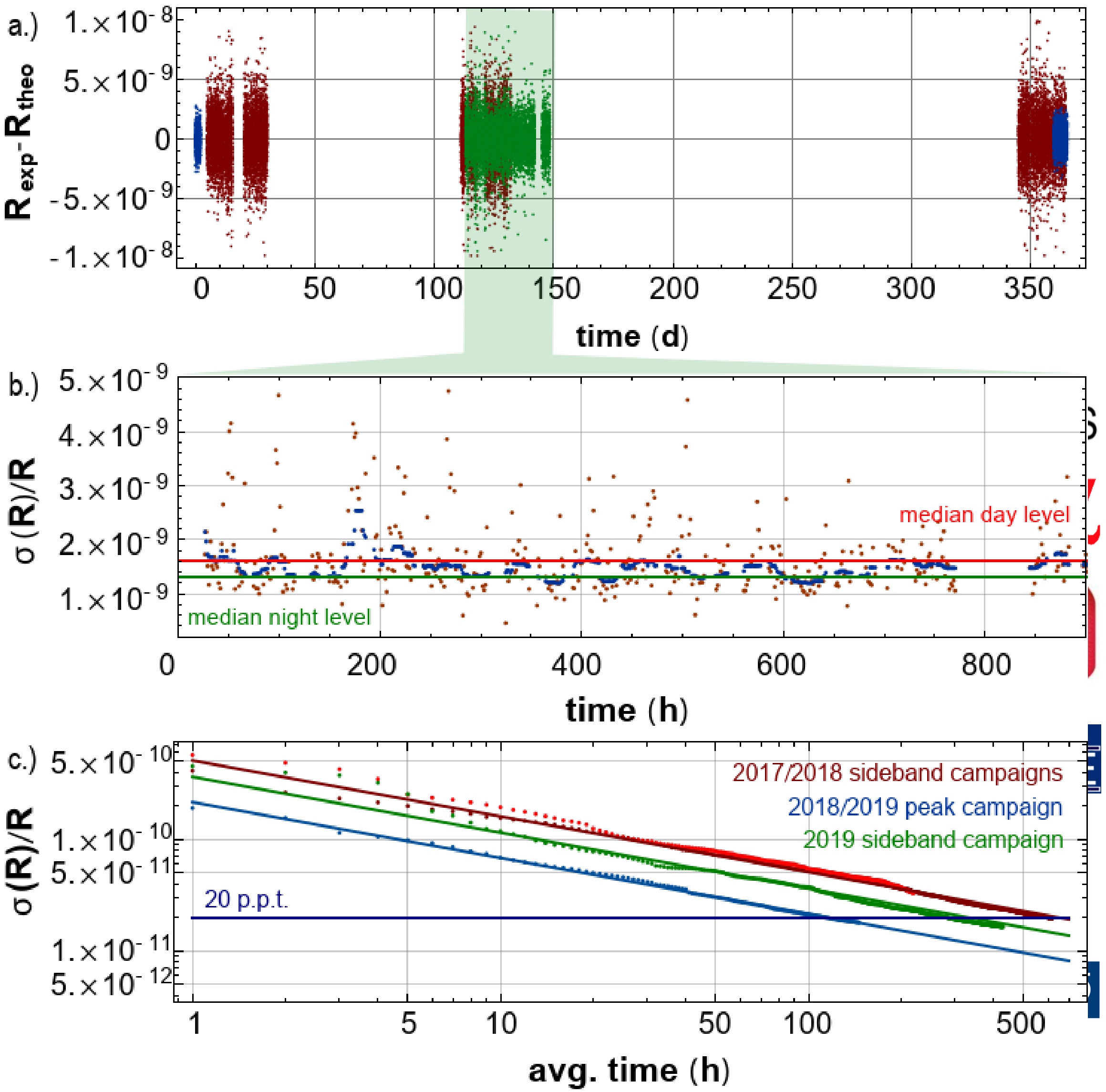




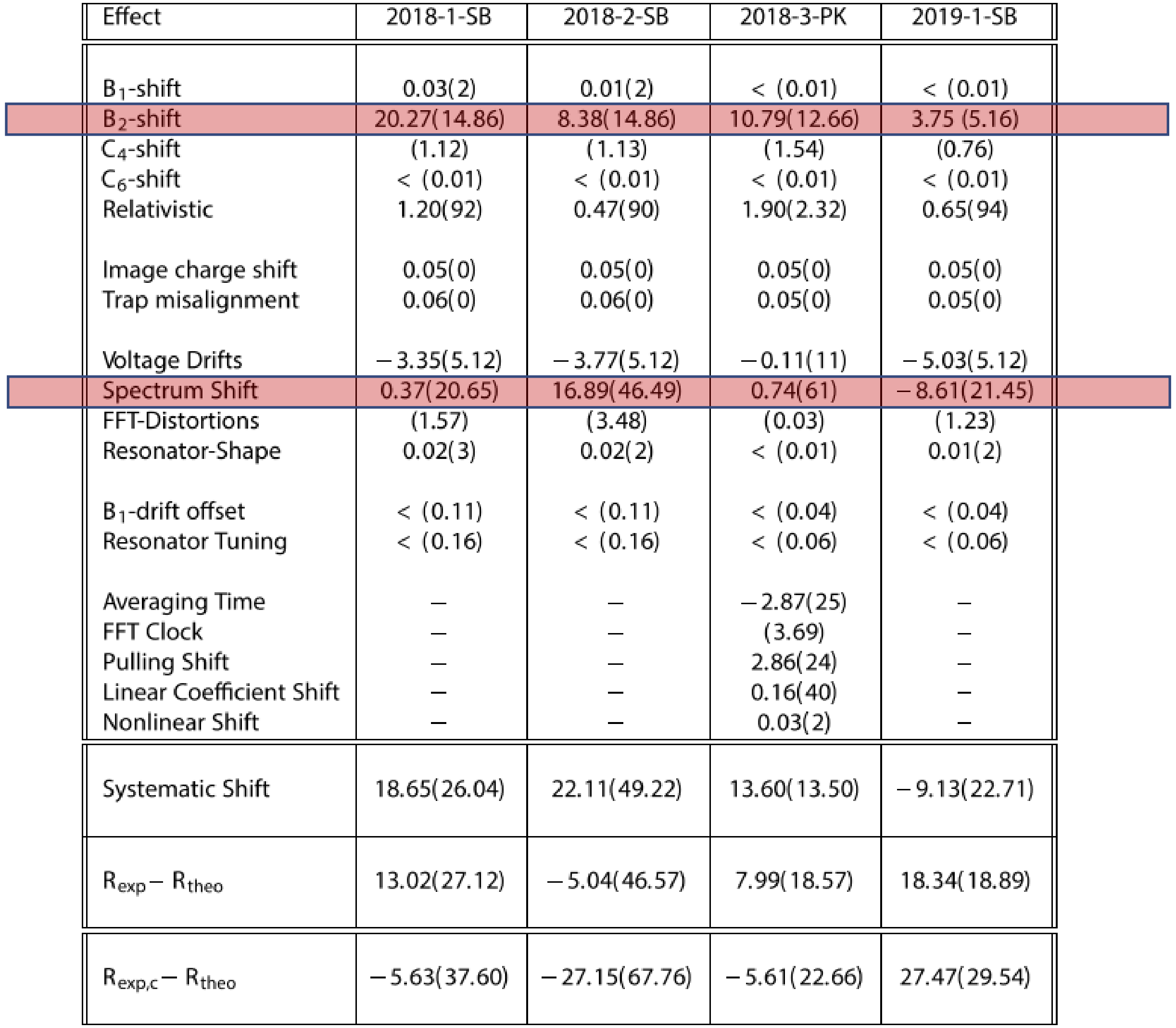


- Systematics by resonant particle tuning **-> Tuneable Detectors**
- Accelerator imposed magnetic field fluctuations **-> Multi layer shielding systems / reservoir trap**
- Intrinsic magnetic field stability limitation **-> redesign of cryo-inlay of the apparatus**
- **Implementation** of direct frequency measurement techniques for lower measurement fluctuation (work once AD is off).

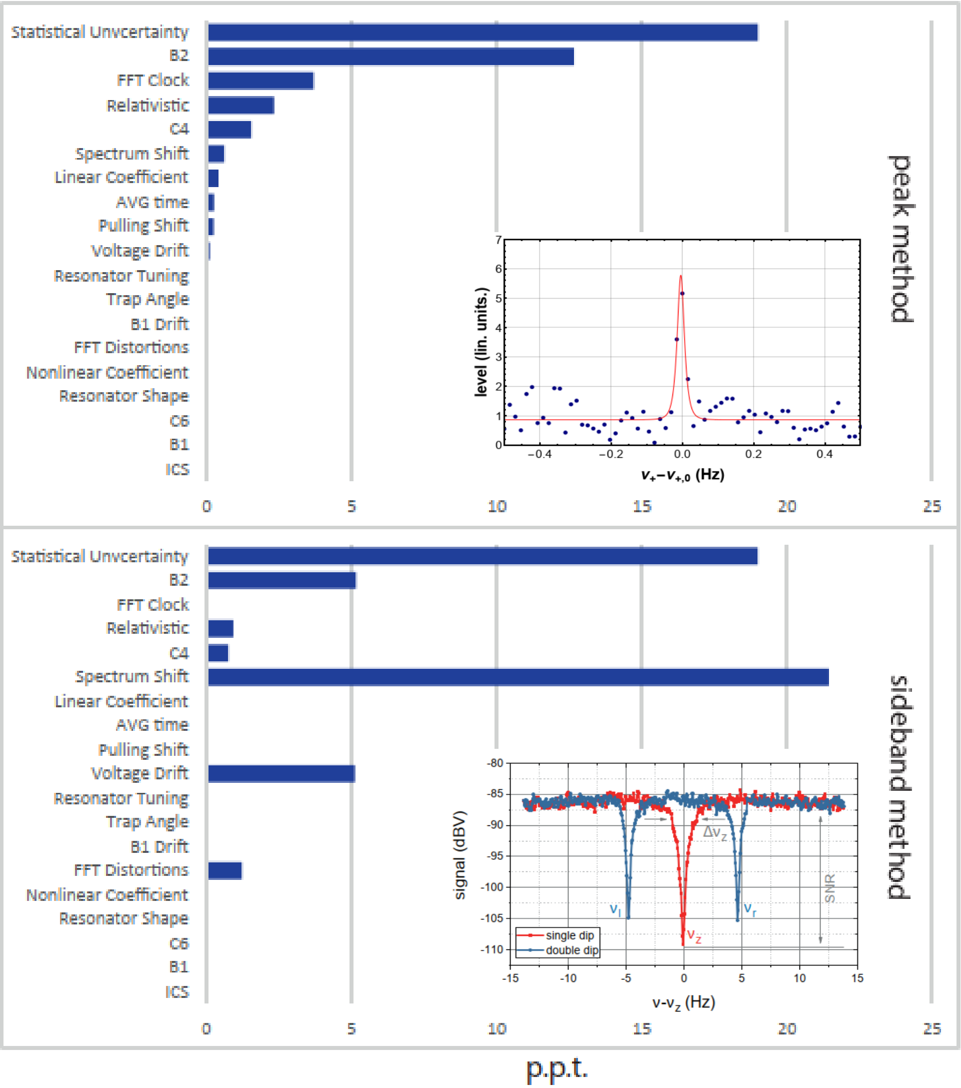
Improved measurement (2018/2019):



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)



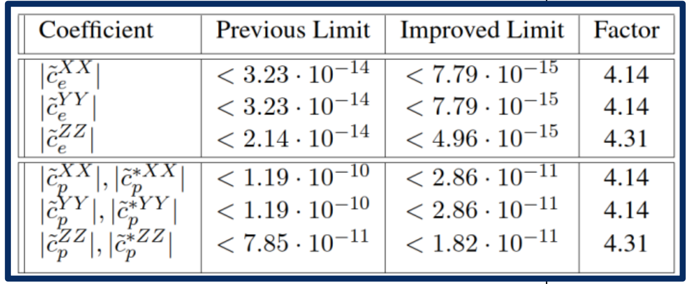
The Result

- Most precise test of CPT invariance in the baryon sector

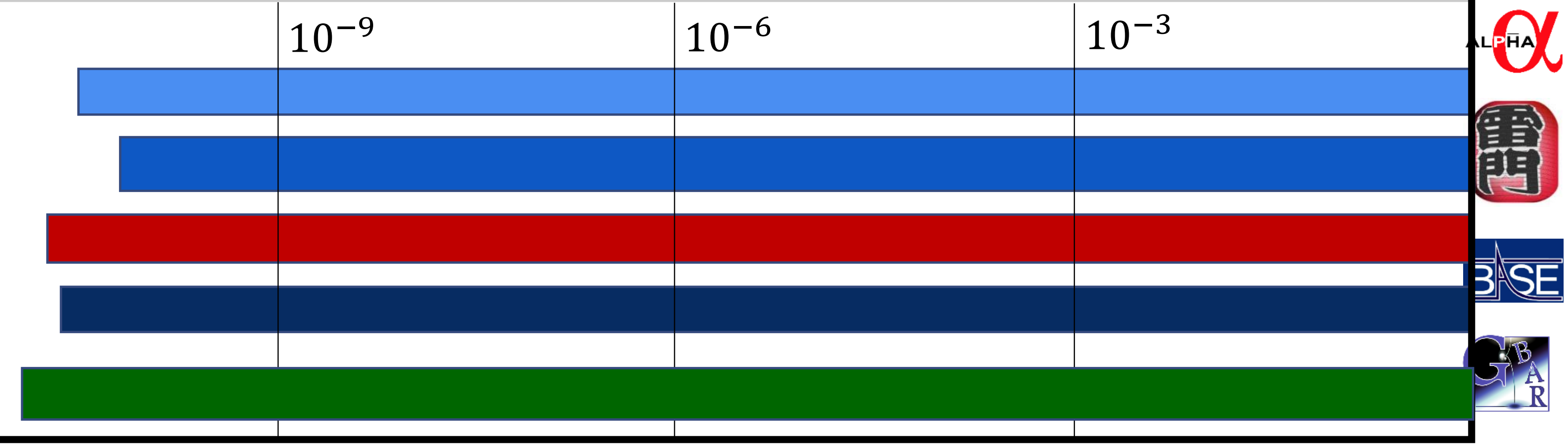
Campaign	R_{exp}	$\sigma(R)_{stat}$	$\sigma(R)_{sys}$
2018-1-SB	1.001089218748	$27 * 10^{-12}$	$27 * 10^{-12}$
2018-2-SB	1.001089218727	$47 * 10^{-12}$	$49 * 10^{-12}$
2018-3-PK	1.001089218748	$19 * 10^{-12}$	$14 * 10^{-12}$
2018-1-SB	1.001089218781	$19 * 10^{-12}$	$23 * 10^{-12}$
Result	1.001 089 218 757 (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
$\|\tilde{c}_e^{XX}\|$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\|\tilde{c}_e^{YY}\|$	$< 3.23 \cdot 10^{-14}$	$< 7.79 \cdot 10^{-15}$	4.14
$\|\tilde{c}_e^{ZZ}\|$	$< 2.14 \cdot 10^{-14}$	$< 4.96 \cdot 10^{-15}$	4.31
$\|\tilde{c}_p^{XX}\|, \|\tilde{c}_p^{*XX}\|$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\|\tilde{c}_p^{YY}\|, \|\tilde{c}_p^{*YY}\|$	$< 1.19 \cdot 10^{-10}$	$< 2.86 \cdot 10^{-11}$	4.14
$\|\tilde{c}_p^{ZZ}\|, \|\tilde{c}_p^{*ZZ}\|$	$< 7.85 \cdot 10^{-11}$	$< 1.82 \cdot 10^{-11}$	4.31



Result consistent with CPT invariance

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

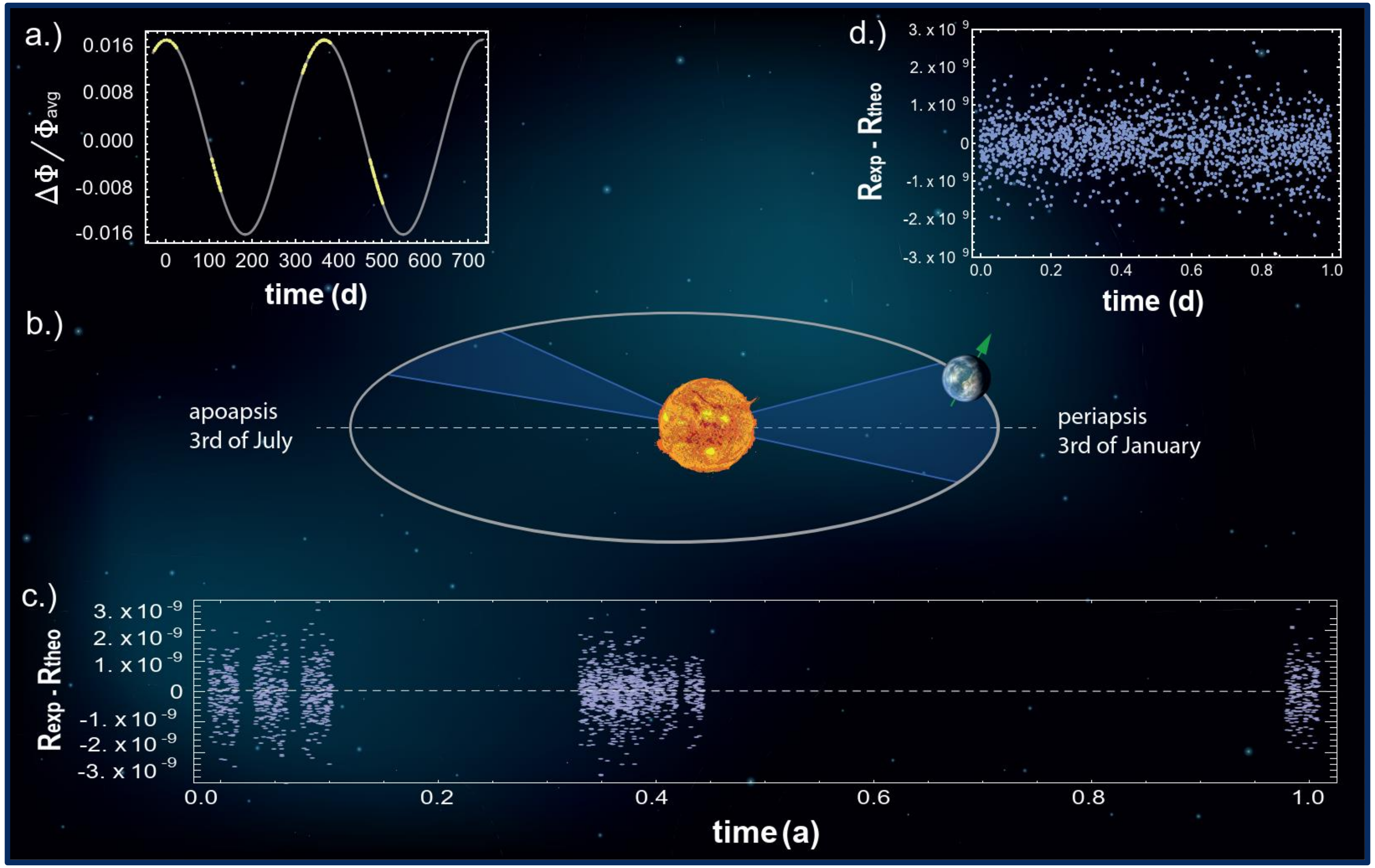
Ding et al., Phys. Rev. D 102, 056009 (2020)

STEp̄

Interpretation

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

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



- Derived limits for global and differental considerations

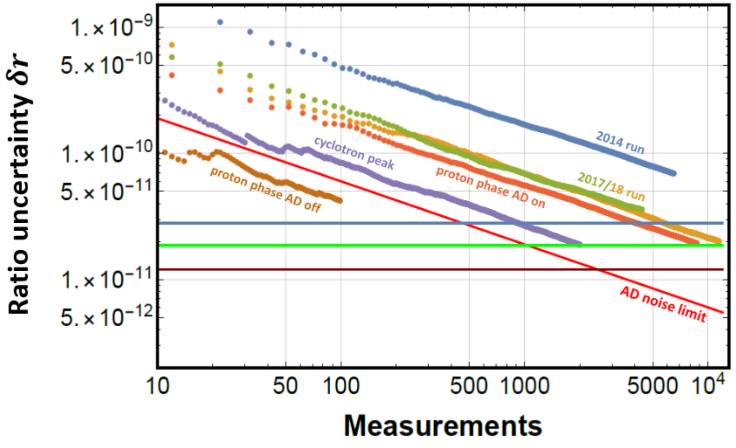
Property	Limit
$\alpha_g - 1$	$< 1.8 * 10^{-7}$
$\alpha_{g,D} - 1$	< 0.03

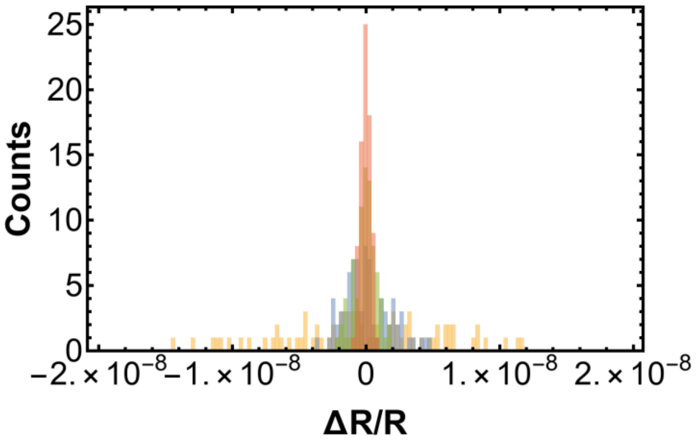
- Constraints set limits similar to goals of experiments that drop antihydrogen in the gravitational field of the earth.
- Looking forward to these results, rapid progress in ALPHA-g and GBAR, stay tuned for beamtime 2022 / 2023.

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

Outlook

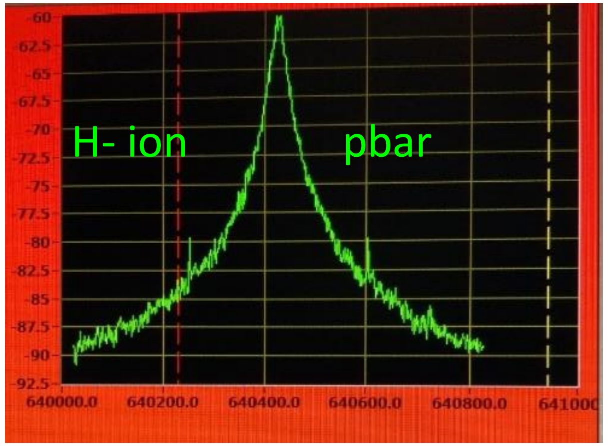
- Using phase sensitive methods





- Recent development: Two Particle Method (similar to MIT/FSU experiments (Pritchard/Myers) and recent MPIK-results (Blaum/Sturm)), «simple» for Q/M ratios, very difficult for nuclear moments

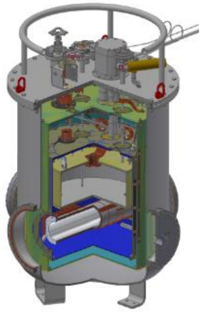
Antiproton: Two particles in one trap



- Current problem: Magnetic field fluctuations imposed by the antiproton decelerator.

- **Masterplan:** Develop transportable antiproton traps and perform offline spectroscopy e.g. at HHU Düsseldorf

STEp̄



Transportable antiproton traps coming soon (see also PUMA)

AEḡIS

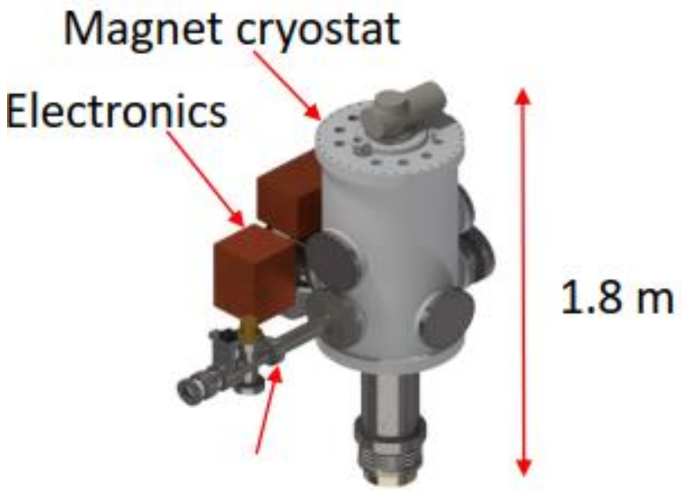
ALPHA

erc

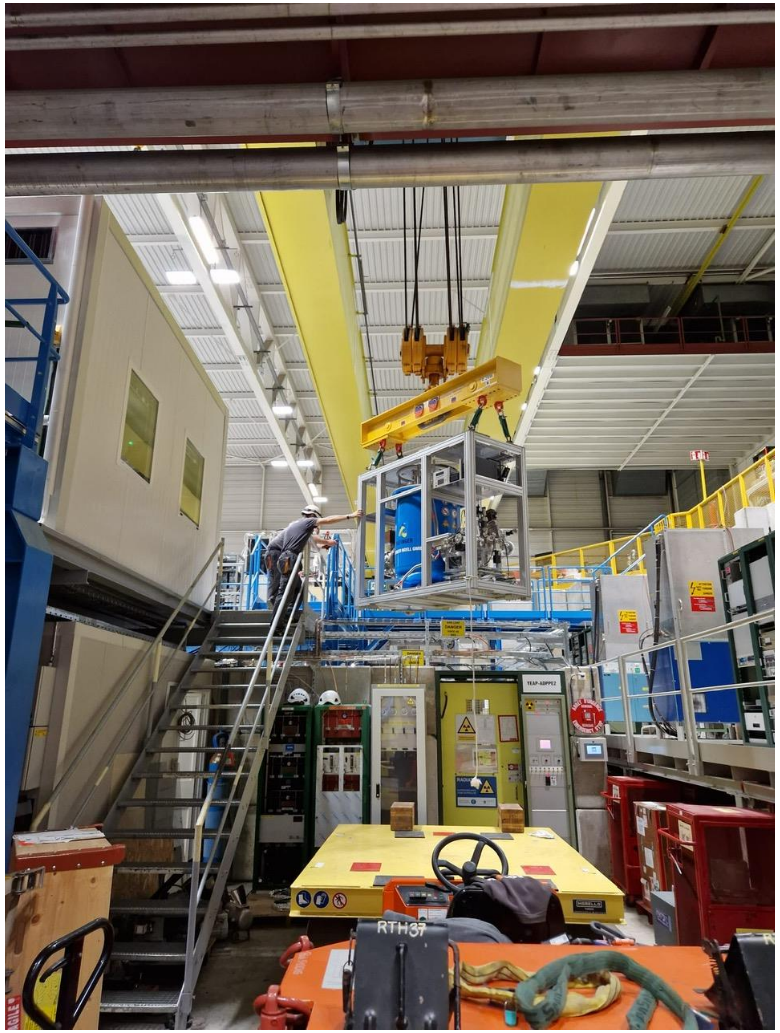
20 p.p.t. / 24h , but only possible during accelerator shutdown

To make these experiments better….

- BASE experiments limited by fluctuations imposed by the CERN accelerator chain



- Antiproton transport to dedicated precision laboratory space at HHU Düsseldorf.



- New chair to support BASE Physics created at HHU in 2022 – clear long-term perspective of BASE Physics program
- SFB-TR (DFG), with several BASE-related projects involved, in preparation (HHU/Mainz).

The Antiproton Magnetic Moment

A milestone measurement in antimatter physics

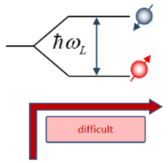
LETTER

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]



Continuous Stern Gerlach Effect

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

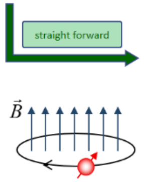
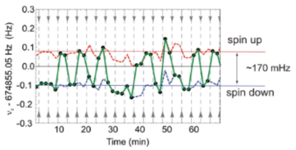
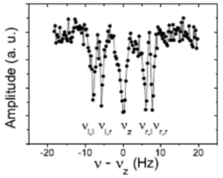


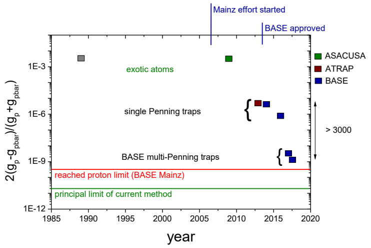
Image Current Measurements

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





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



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.

AEḡIS

ALPHA

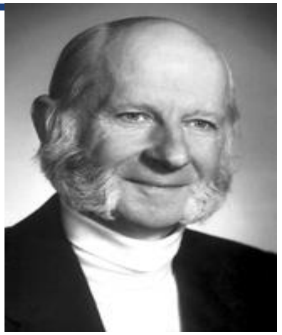
BASE

STEp̄

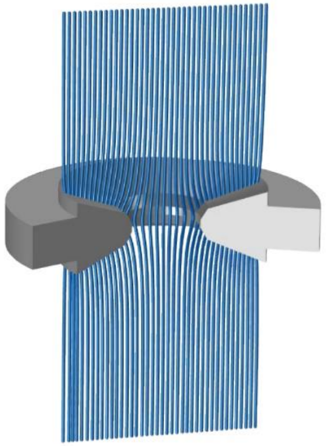
C. Smorra et al., Nature **550**, 371 (2017).

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

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

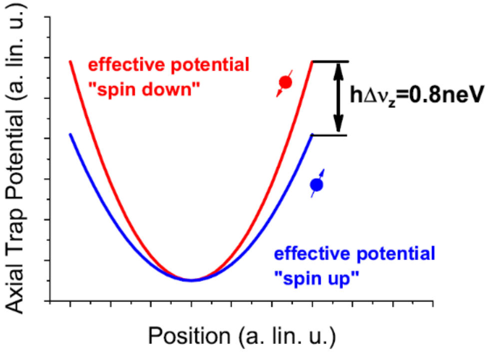
the curse (and blessing): 1000 times harder than electron experiments

- Very difficult for the proton/antiproton system.

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

- Most extreme magnetic conditions ever applied to single particle.

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

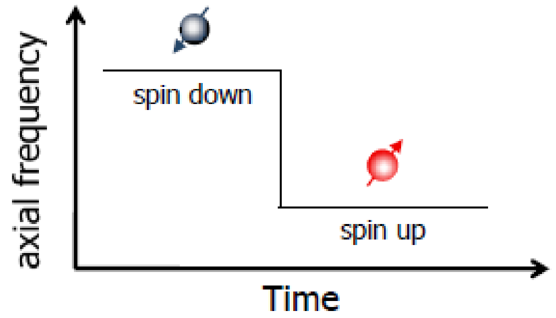


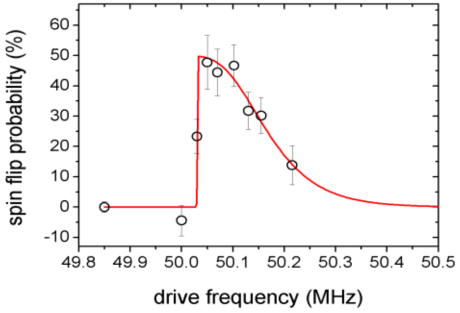
Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

Limited to p.p.m level

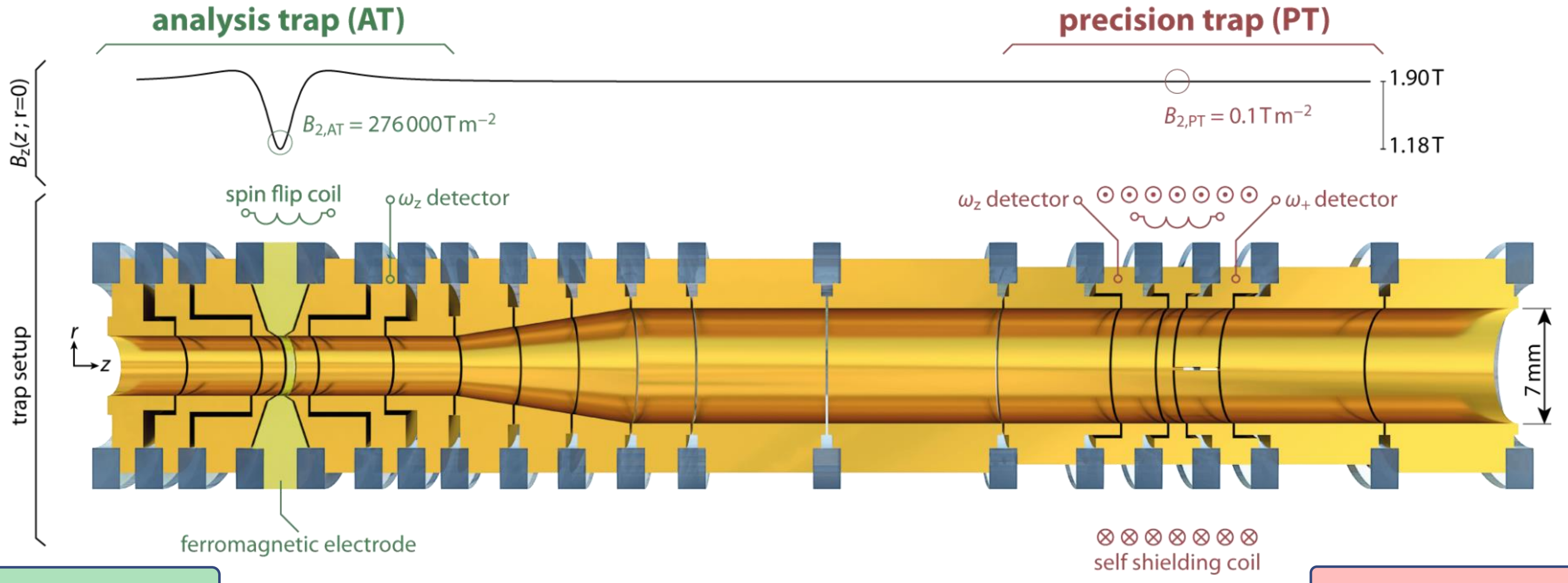


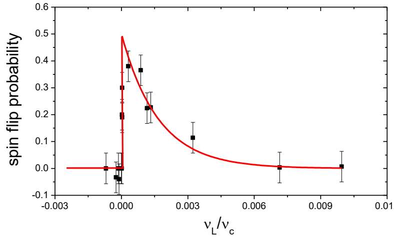


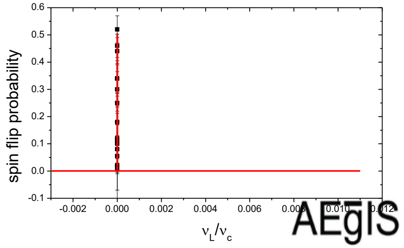
S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

Multi Penning-Trap Methods

Invented by **H. Haeffner**, in group of **G. Werth** also highly relevant in electron mass measurements and tests of BS QED (Blaum / Sturm et al.)







Initialize the spin state

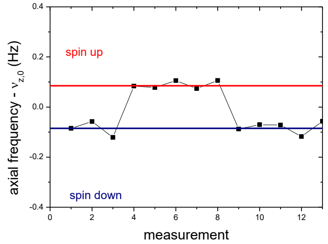
particle transport

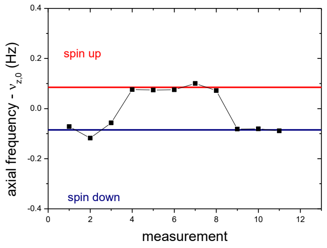
1.) measure cyclotron ν_c

2.) drive spin transition at ν_{rf}

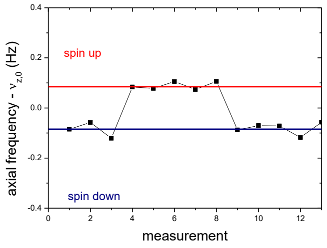
analyze the spin state

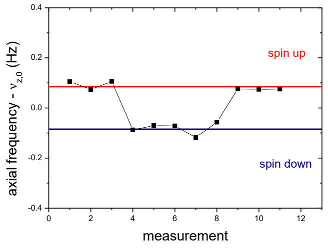
no spin-flip in PT

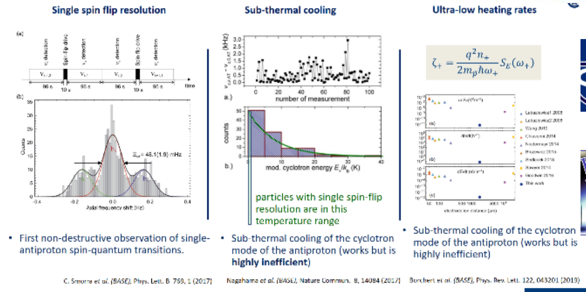




spin flipped in PT







Single spin flip resolution

Sub-thermal cooling

Ultra-low heating rates

particles with single spin-flip resolution are in this temperature range

$$\zeta_+ = \frac{q^2 n_+}{2 m_{\bar{p}} \hbar \omega_+} S_E(\omega_+)$$

- First non-destructive observation of single-antiproton spin-quantum transitions.
- Sub-thermal cooling of the cyclotron mode of the antiproton (works but is **highly inefficient**)
- Sub-thermal cooling of the cyclotron mode of the antiproton (works but is highly inefficient)

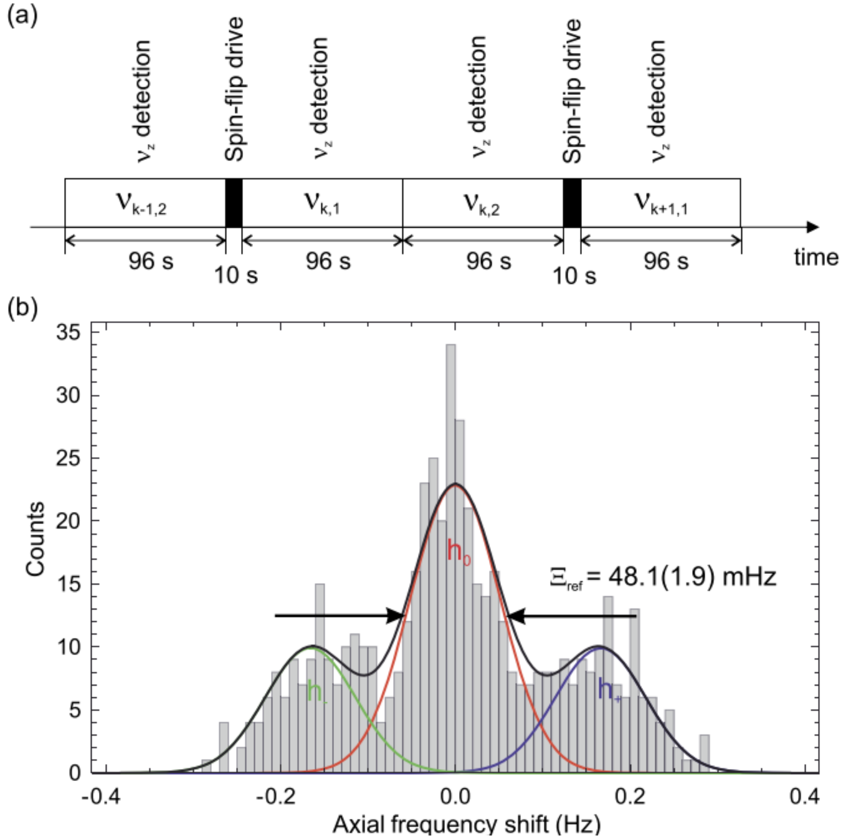
C. Smorra *et al. (BASE)*, Phys. Lett. B 769, 1 (2017)

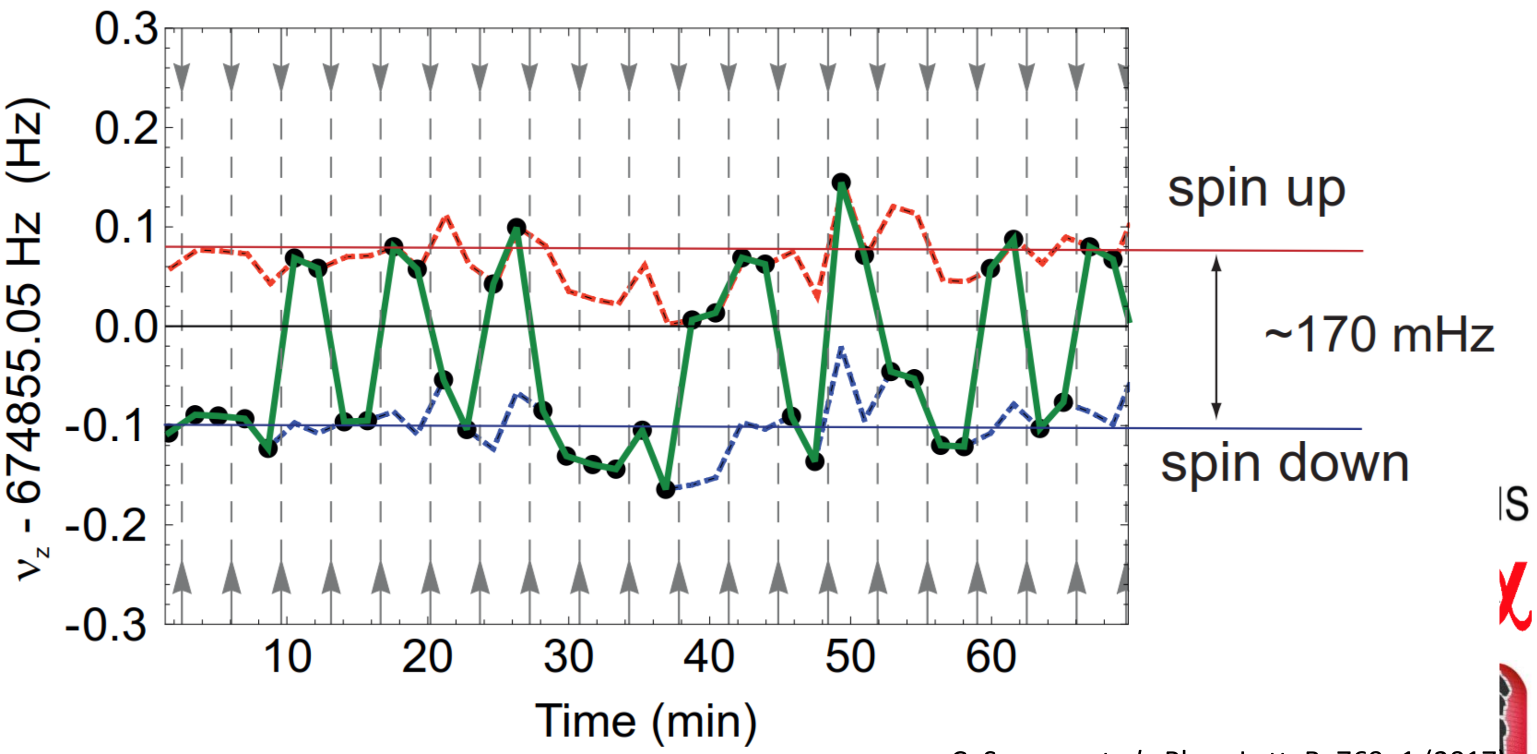
Nagahama *et al. (BASE)*, Nature Commun. 8, 14094 (2017)

Borchert *et al. (BASE)*, Phys. Rev. Lett. 122, 043201 (2019)

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)

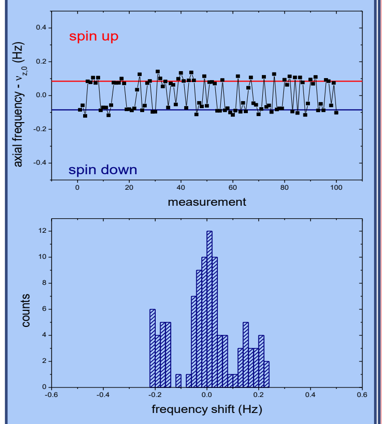
- First non-destructive observation of single-antiproton spin-quantum transitions.
- **This is one of the hardest measurements you can do in a Penning trap!**
- **Double trap method ultimately requires single spin-flip detection with high fidelity.**

First Ingredient: Single Spin Flip Resolution

- **Multi trap:** Need to be able to identify the spin state in one single measurement attempt.
- **To identify spin flip:** Cannot accept more than 2 cyclotron quantum jumps in a spin state identification cycle (4 min).

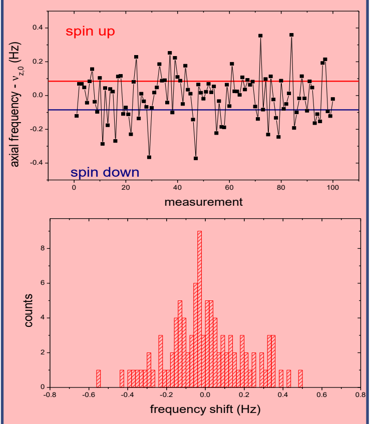
$$\zeta_+ = \frac{q^2 n_+}{2m_{\bar{p}}\hbar\omega_+} S_E(\omega_+)$$

cold particle (50mK)



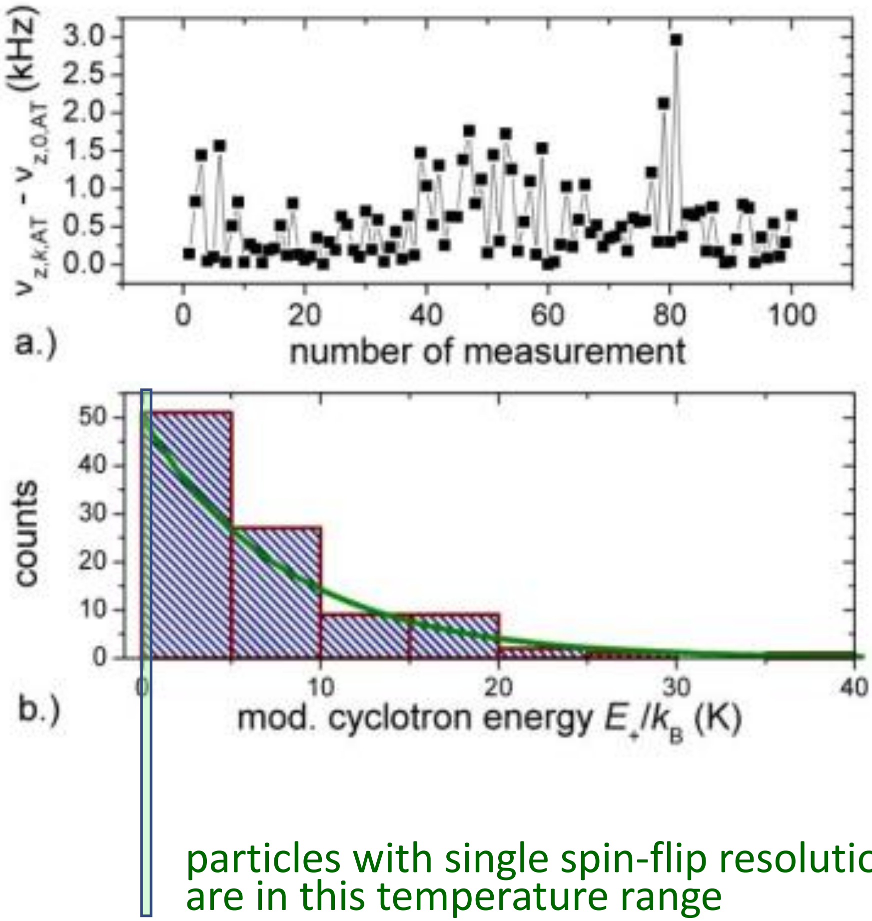
high-fidelity spin state resolution

hot particle (1K)



fidelity at 65%, not useful for measurements

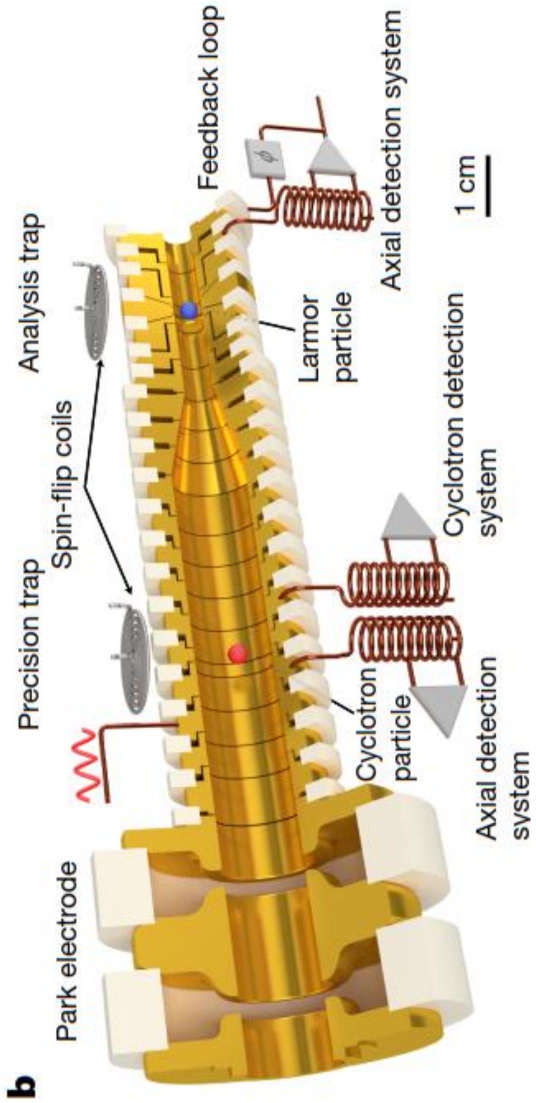
- Particle at 0.1K cyclotron temperature allows for spin state detection with 90% fidelity
- Particle preparation by resistive cooling
- Took in 2016 about 15h to prepare such a cold antiproton

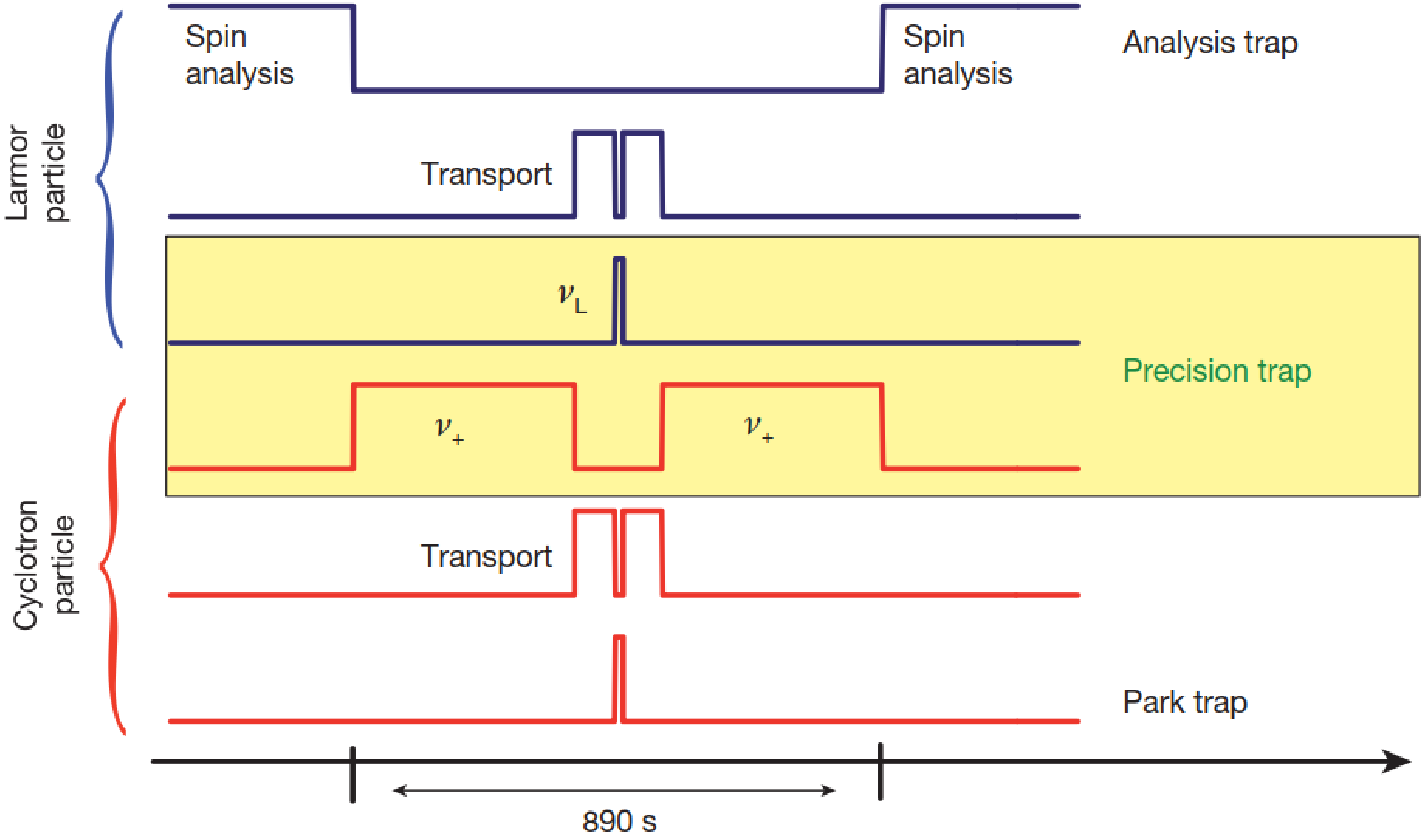


particles with single spin-flip resolution are in this temperature range

- Cyclotron frequency measurement in double trap cycle heats the cyclotron mode of the particle

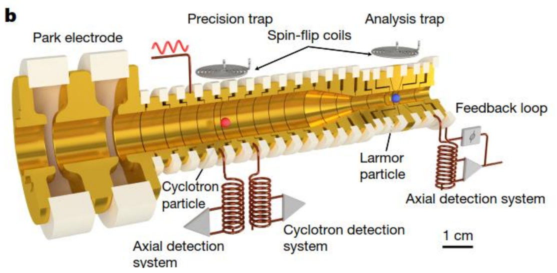
TTM – Triple Trap Method – Divide and Conquer

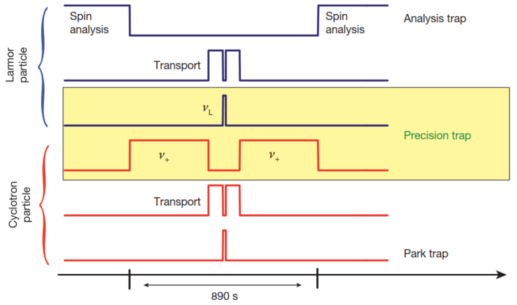




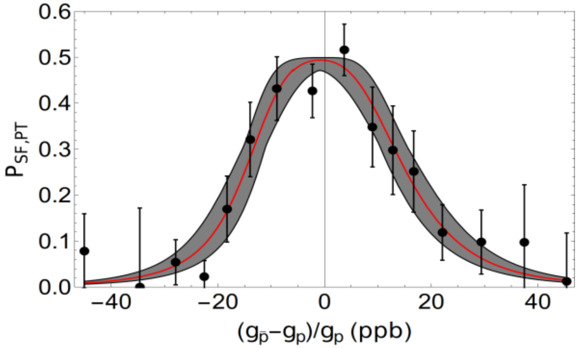
3000-fold Improved Antiproton Moment Measurement

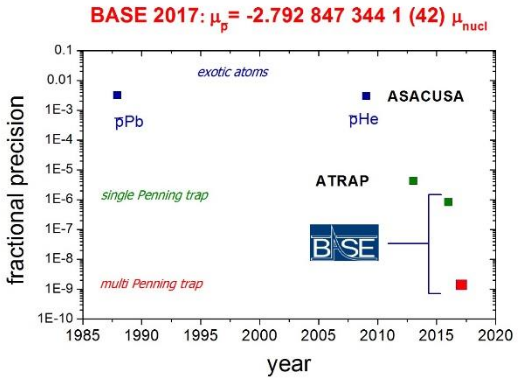
New idea: divide measurement to two particles



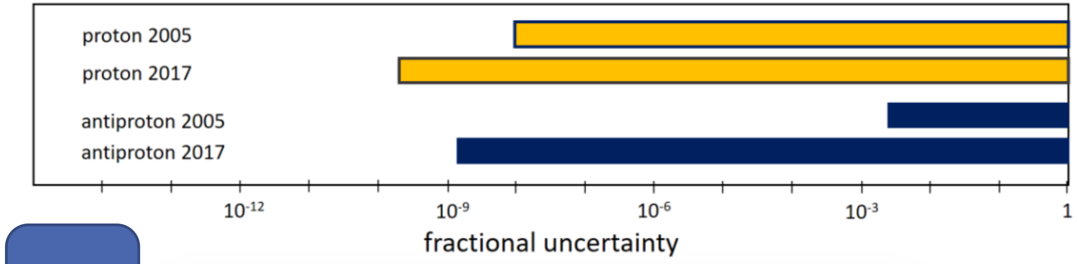


win: 60% of time usually used for sub-thermal cooling useable for measurements



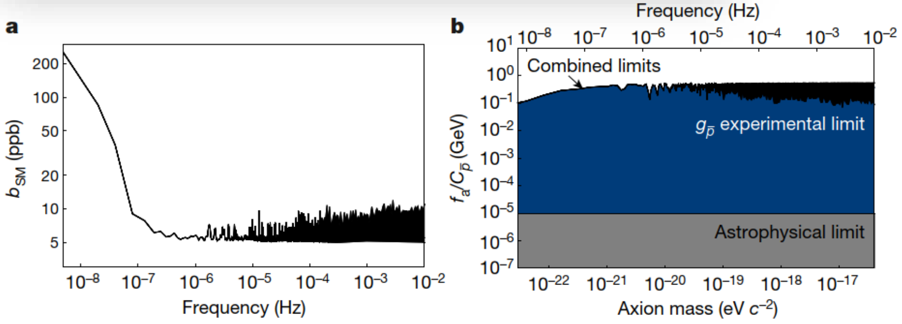


Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	Collaboration	Method
2011	2.792 847 353 (28)	2.786 2 (83)	Pask (ASACUSA)	MASER / Exotic Atoms
2012	2.792 846 (7)		diSciacca (ATRAP)	Single Penning-trap
2013		2.792 845 (12)	diSciacca (ATRAP)	Single Penning-trap
2014	2.792 847 349 8 (93)		Mooser (BASE)	Double 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



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...

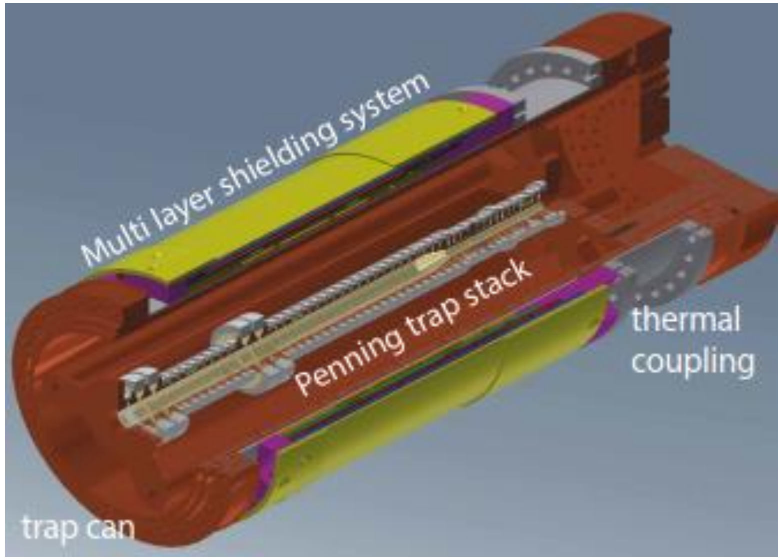
Smorra *et al. (BASE),* Nature 550, 371 (2017)

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

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

Dominant Systematic Trap – Uncertainty

Designed and developed in the BASE e-laboratory

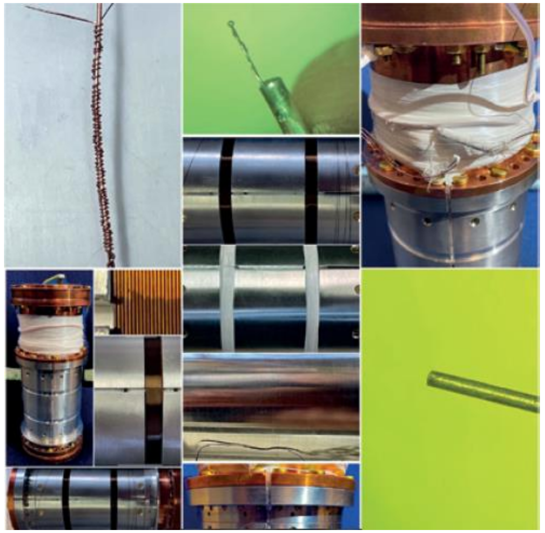


Dominant shift from trap systematics at our current magnetic field properties:

$$\frac{\Delta\nu_c}{\nu_c} = \frac{\nu_+}{\nu_c^2}\Delta\nu +_{+} \frac{\nu_z}{\nu_c^2}\Delta\nu_z \approx \frac{1}{4\pi^2 m_0 \nu_z^2}\frac{B_2}{B_0}k_B T_z = -23.5(1.5)\,\frac{\text{p.p.t.}}{\text{K}},$$

Need to get rid of this scaling in future runs -> local tuning magnets need to be implemented.

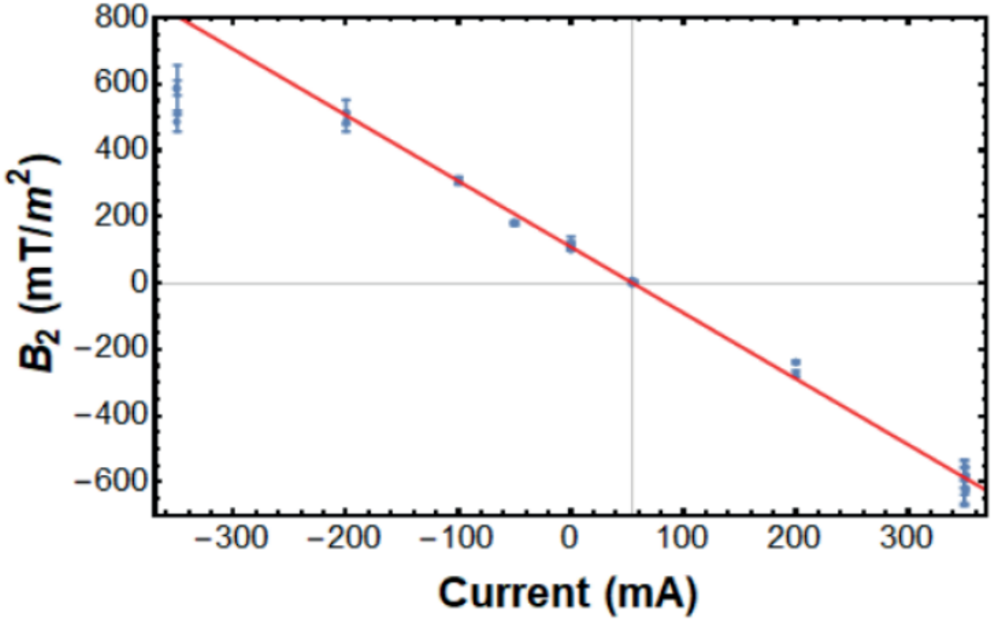
AEḡIS



System running successfully in persistent mode.

Able to tune the B2 coefficient to 0 within uncertainties of 0.0006 T/m^2

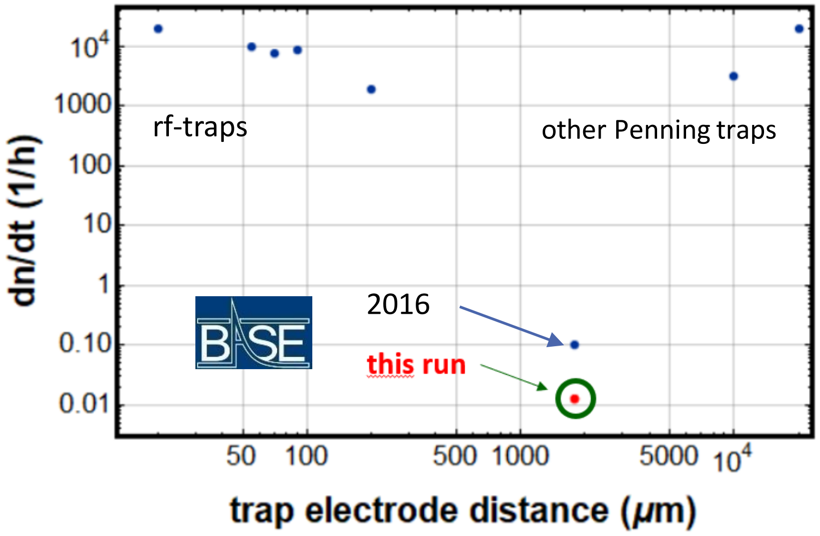
Reduces the dominant systematic uncertainty of the previous magnetic moment measurement by more than a factor of 10000.

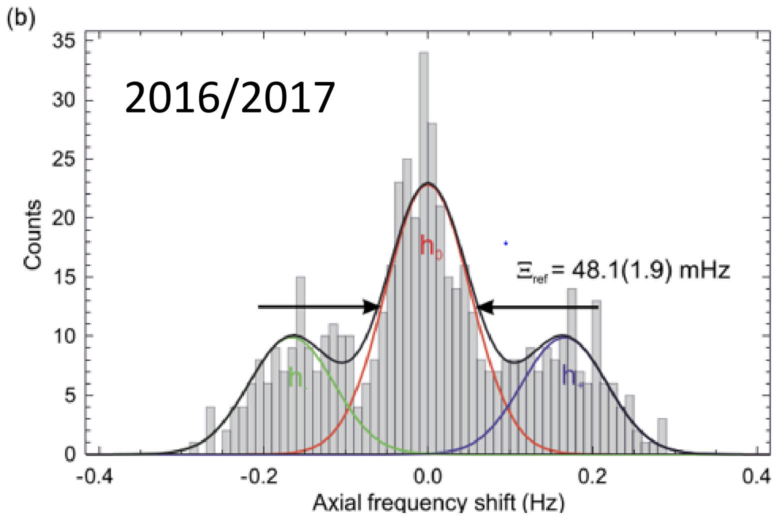


Yet open: B1 coil below expected limits… (16mT/m)

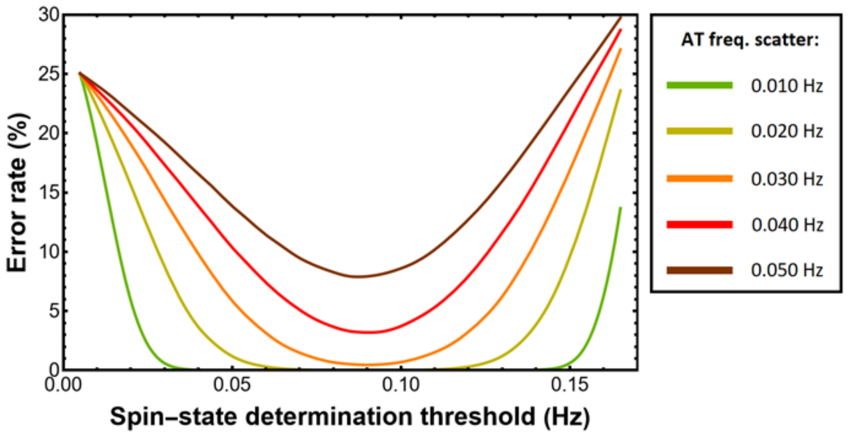
The single spin flip 2022

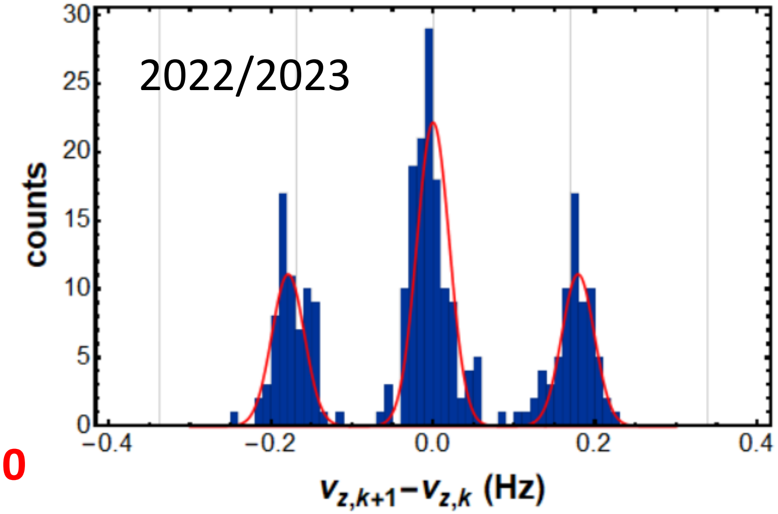
- **Current experiment:**
  - considerably improved particle cooling, thus much higher sampling rate
  - Double trap measurement cycles demonstrated -> reduced systematics
  - Ultra homogeneous magnetic field
  - Ultra stable experiment magnet
  - Coherent quantum spectroscopy methods and phase methods available.





- **Successful detection of spin transitions with 99.95% detection fidelity**
  - Much faster experiment cycles possible.
  - Threshold initialization not required anymore.





Very optimistic to improve the antiproton moment measurement by >factor of 10

Possibilities: Direct measurement of 3He2+ / 10 fold improved limits on MCP / 20neV absolute energy resolution

Recent Achievements – Sympathetic Cooling

physicsworld TOP 10 BREAKTHROUGH 2021

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

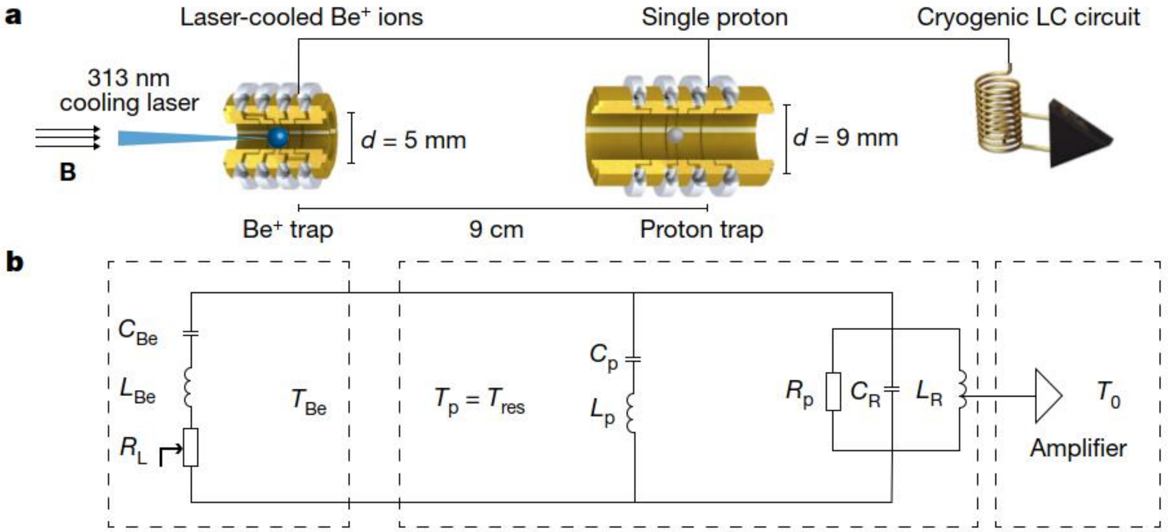
Method proposed by Wineland and Heinzen: Couple particles in different traps via image currents.

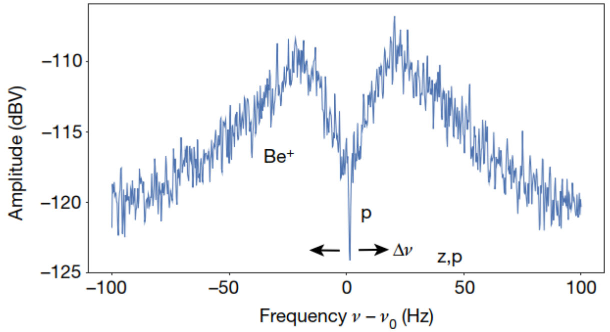
One of the particle types: Laser cooled species
Transfer particle temperatures from one trap to the other.

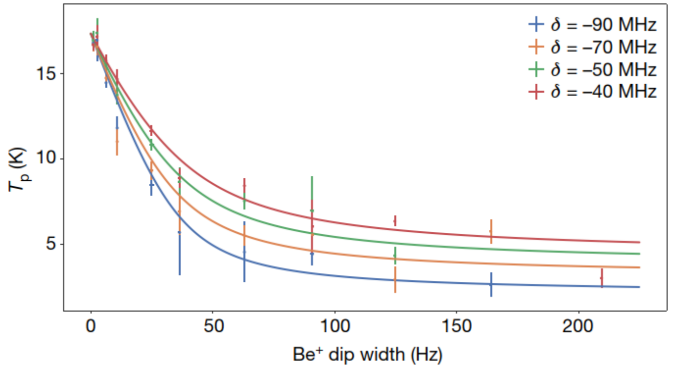
First proof of principle demonstration successful!!!

Demonstrated proton temperature reduction by about a factor of 8.

New trap geometries under development for more efficient cooling



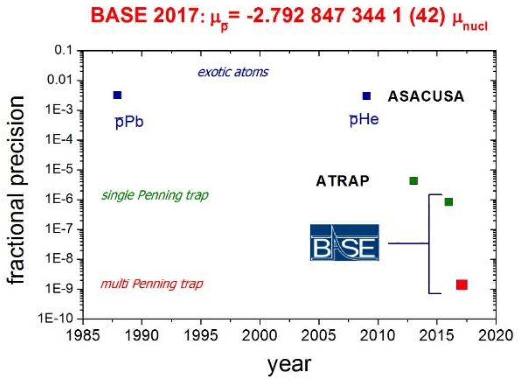




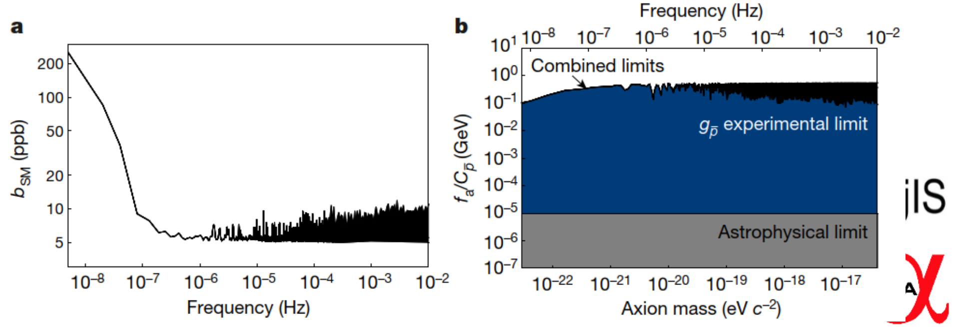
Simulations: Optimized procedures will enable 20 mK temperatures in 10 s.

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

Summary

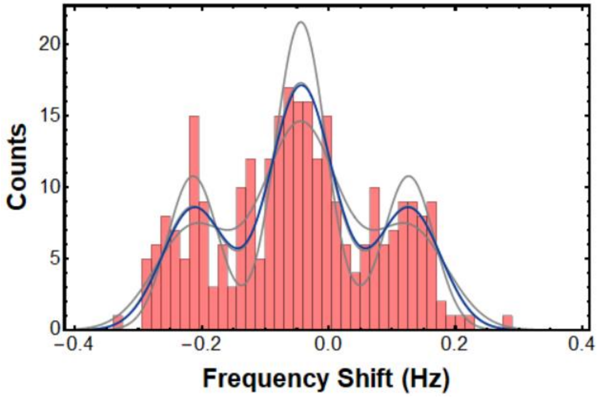


- Talked about recent precision measurements in BASE, with the flag-results 16ppt measurement of the antiproton/proton charge-to-mass ratio, and a progress towards a considerably improved measurement of the antiproton/proton magnetic moment.



- Some searches for more exotic physics.

- **Future plans:**
  - Considerably improved measurement of the antiproton moment in reach – excellent progress
  - Improved measurements by developing transportable antimatter traps
  - Improved measurements by implementing new technologies



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Promising future experiments possible

Thank you very much for your attention

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- Aarhus University, Denmark
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- University of British Columbia, Canada
- University of California Berkeley, USA
- University of Calgary, Canada
- University of Groningen, Holland
- University of Manchester, UK
- NRCN - Nuclear Res. Center Negev, Israel
- Purdue University, USA
- Federal University of Rio de Janeiro, Brazil
- University of Pisa Italy
- Stockholm University, Sweden
- Simon Fraser University, Canada
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J.S Hangst for the ALPHA Collaboration

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M. Hori / E. Widmann SPSC144 18 Jan 2022 1

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60 Research Institutes/Universities – 350 scientists – 6 Collaborations