Probing Fundamental Physics with Antimatter

Stefan Ulmer (BASE)

RIKEN

Fundamental Symmetries Laboratory

for the AD-Collaborations

Representing the AD Community

currently: 6 collaborations – 60 Research institutes/universities – 350 researchers

THE ALPHA COLLABORATION

Aarhus University, Denmark · University of British Columbia, Canada · University of California Berkeley, USA · University of Calgary, Canada · Imperial College London · University of Liverpool, UK · University of Manchester, UK · NRCN - Nuclear Res. Center Negev, Israel · Purdue University, West Lafayette, USA · Federal University of Rio de Janeiro, Brazil · Stockholm University, Sweden · Simon Fraser University, Canada · TRIUMF, Canada · University of Wales Swansea, UK · Cockcroft Institute, UK · York University, Canada

ATRAP Collaboration

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AEgIS collaboration

IPNL, Lyon · Stefan Meyer Institut, Austria · University Bern, Switzerland · CERN, Switzerland · INFN Genova, Italy · MPI-K, Heidelberg, Germany · U of Heidelberg, Germany · INFN Milano, Italy · Politecnico di Milano, Italy · INR, Moscow, Russia · U of Bergen, Norway · University College London, UK · Laboratoire Aimé Cotton, Orsay, France · U of Oslo, Norway · INFN Pavia/Brescia, Italy · Czech Technical U, Prague, Czech Republic · INFN Padova/Trento, Italy · ETH Zurich, Switzerland

BASE · RIKEN · Programs for Junior Scientists · MAX-PLANCK-GESELLSCHAFT · CERN · 東京大学 · JOHANNES GUTENBERG UNIVERSITÄT MAINZ · GSI · PTB · Leibniz Universität Hannover

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東京大学 THE UNIVERSITY OF TOKYO · SMI · MAX-PLANCK-GESELLSCHAFT · TOKYO UNIVERSITY OF SCIENCE since 1881 · RIKEN · UNIVERSITAS STUDIORUM BRIXIAE

GBAR · Irfu · IPCMS · CSNSM · Laboratoire Kastler Brossel · ETH ZÜRICH · P.N. Lebedev Physical Institute of the Russian Academy of Science · JOHANNES GUTENBERG UNIVERSITÄT MAINZ · Swansea University Prifysgol Abertawe · ILL NEUTRONS FOR SCIENCE Institut Laue-Langevin · UPPSALA UNIVERSITET · Stockholm University · RIKEN · 東京大学 THE UNIVERSITY OF TOKYO · NARODOWE CENTRUM BADAŃ JĄDROWYCH Świerk · 서울대학교 SEOUL NATIONAL UNIVERSITY · ibs Institute for Basic Science

ALPHA · BASE · ATRAP · GBAR · AEgIS

Investigating the properties of antimatter with AMO methods (traps and lasers)

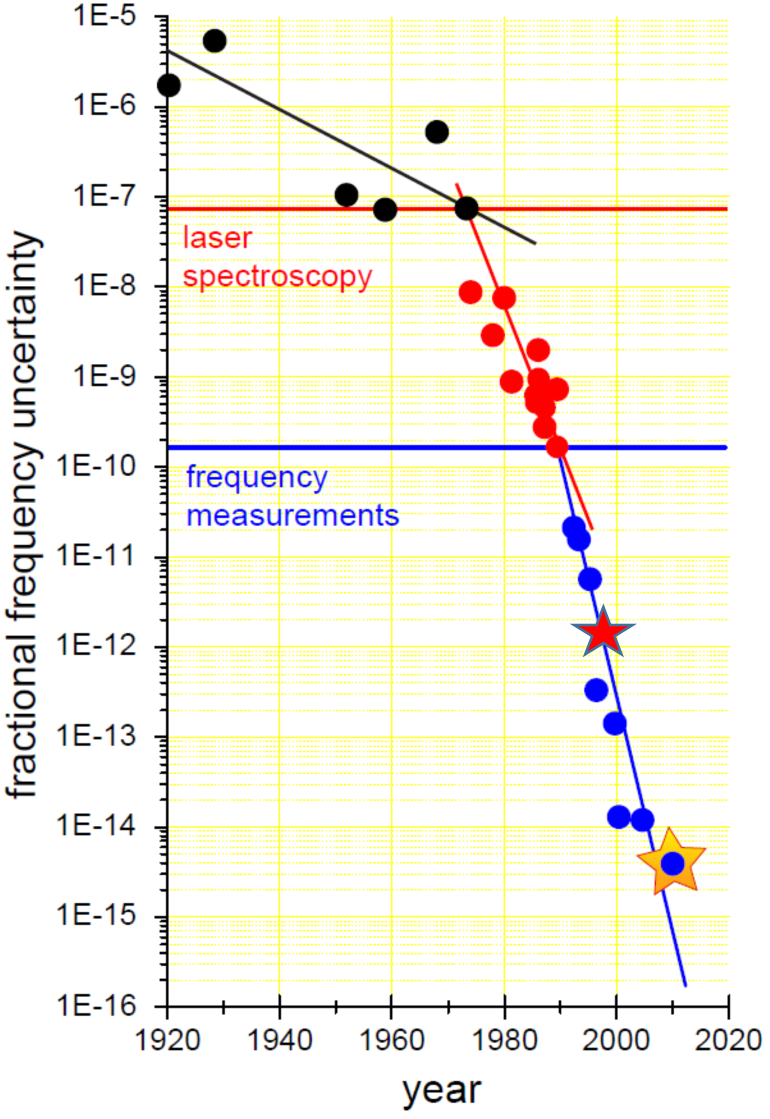
Outline

Introduction: physics motivation and goals

Methods: techniques applied by the AD collaborations

Results: major achievements of recent years

Outlook: physics perspective in the ELENA era



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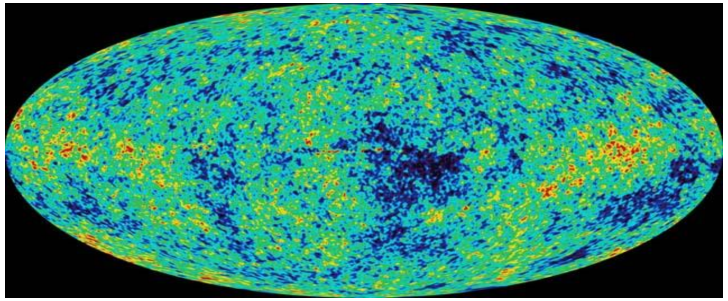
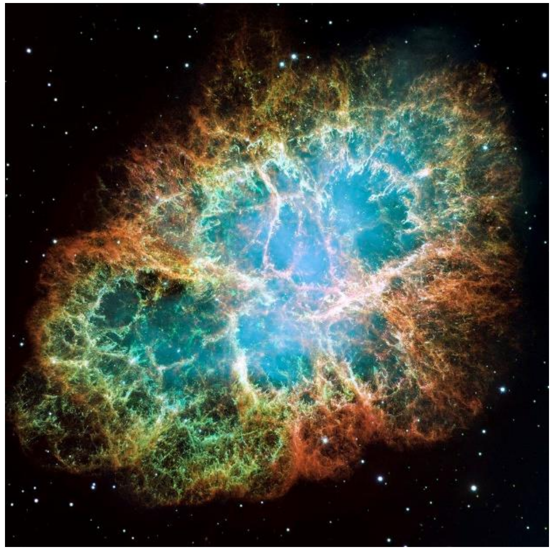
Problem: Big Bang Scenario and Consequences

1. A cosmic microwave background should exist as a fire-ball remnant of the Big Bang
   1. 1965 Penzias and Wilson **observed CMWB with a black body spectrum of 2.73(1)K, by far too intense to be of stellar origin**.

2. Understandable Big Bang nucleosynthesis scenario **describes exactly the observed light element abundances as found in «cold» stellar nebulae**.

3. Using the models which describe 1. and 2.:





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

Observation	
Baryon/Photon Ratio	10^{-9}
Baryon/Antibaryon Ratio	0.0001

Following the current Standard Model of the Universe our predictions of baryon to photon ratio are **wrong by about 9 orders of magnitude** while our baryon/antibaryon ratio is **wrong by about four orders of magnitude**.

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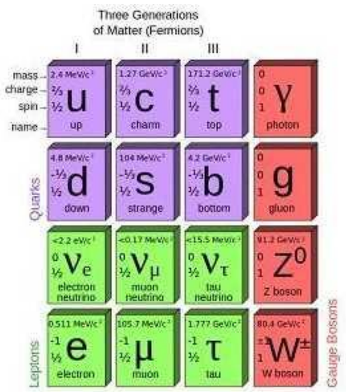
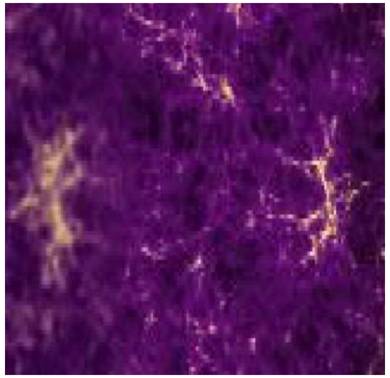
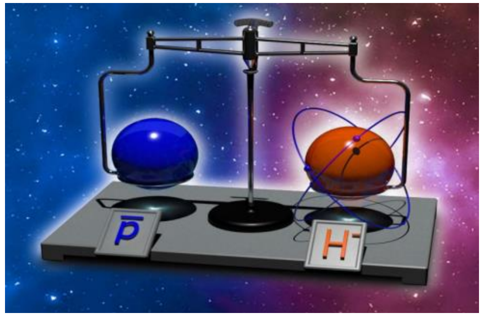
Summary



WE HAVE A PROBLEM



mechanism which created the obvious baryon/antibaryon asymmetry in the universe is not understood



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

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Strategy

- **Use simple well-understood systems** -> provides high sensitivity with respect to potential deviations and new physics.

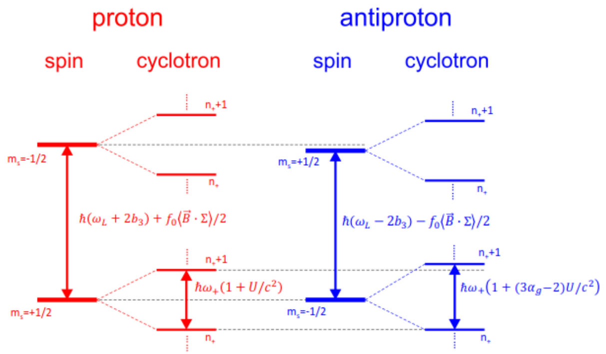
$$H\,\psi = (H_0 + V_{exotic})\,\psi$$

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

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

matter sector

proton lifetime (direct)	>1.67 e34 y
proton m	30 p.p.t.
proton magn. moment	3.3 p.p.b.
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.



In the matter sector, measurements with incredible precision have been demonstrated

Energy Resolution

$$< \psi^*|\Delta V|\psi >= \Delta E$$

$$\mathcal{L}_p = \frac{\lambda}{M}\langle T\rangle\bar{\psi}\Gamma(i\partial)^k\psi$$

Kostelecky et al.

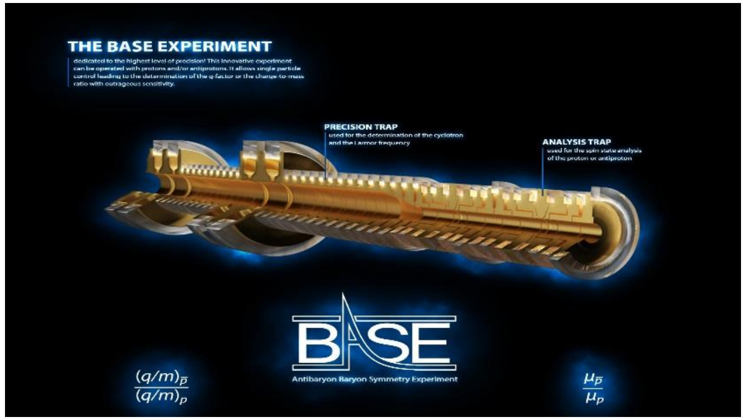
- Absolute energy resolution (normalized to m-scale) might be a more appropriate measure to characterize the sensitivity of an experiment with respect to CPT violation.
- Single particle measurements in Penning traps give high energy resolution.

	Relative precision	Energy resolution	SME Figure of merit
Kaon Δm	$\sim 10^{-18}$	$\sim 10^{-9}$ eV	~ 10^{-18}
p-p̄ q/m	$\sim 10^{-11}$	$\sim 10^{-18}$ eV	~ 10^{-26}
p-p̄ g-factor	$\sim 10^{-6}$	$\sim 10^{-12}$ eV	~ 10^{-21}

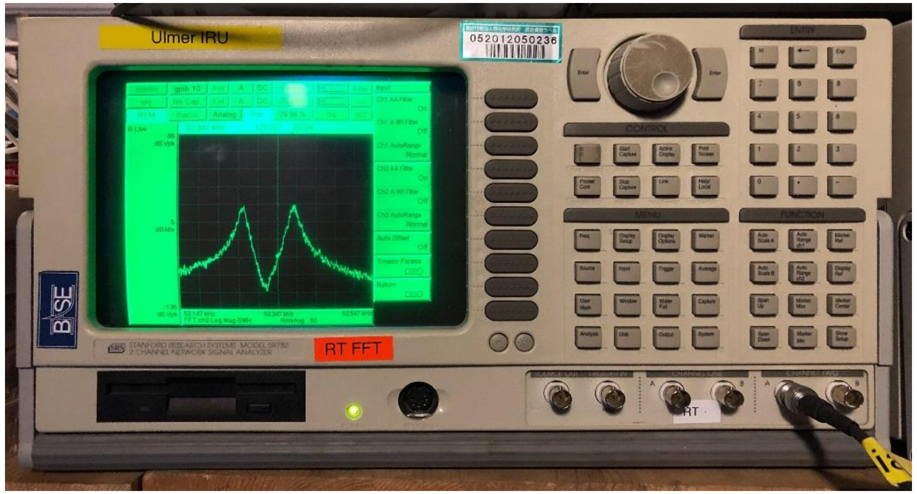
SME has no predictive power / missing link from EFT to particle physics

Example: the BASE trap - a special place

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



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



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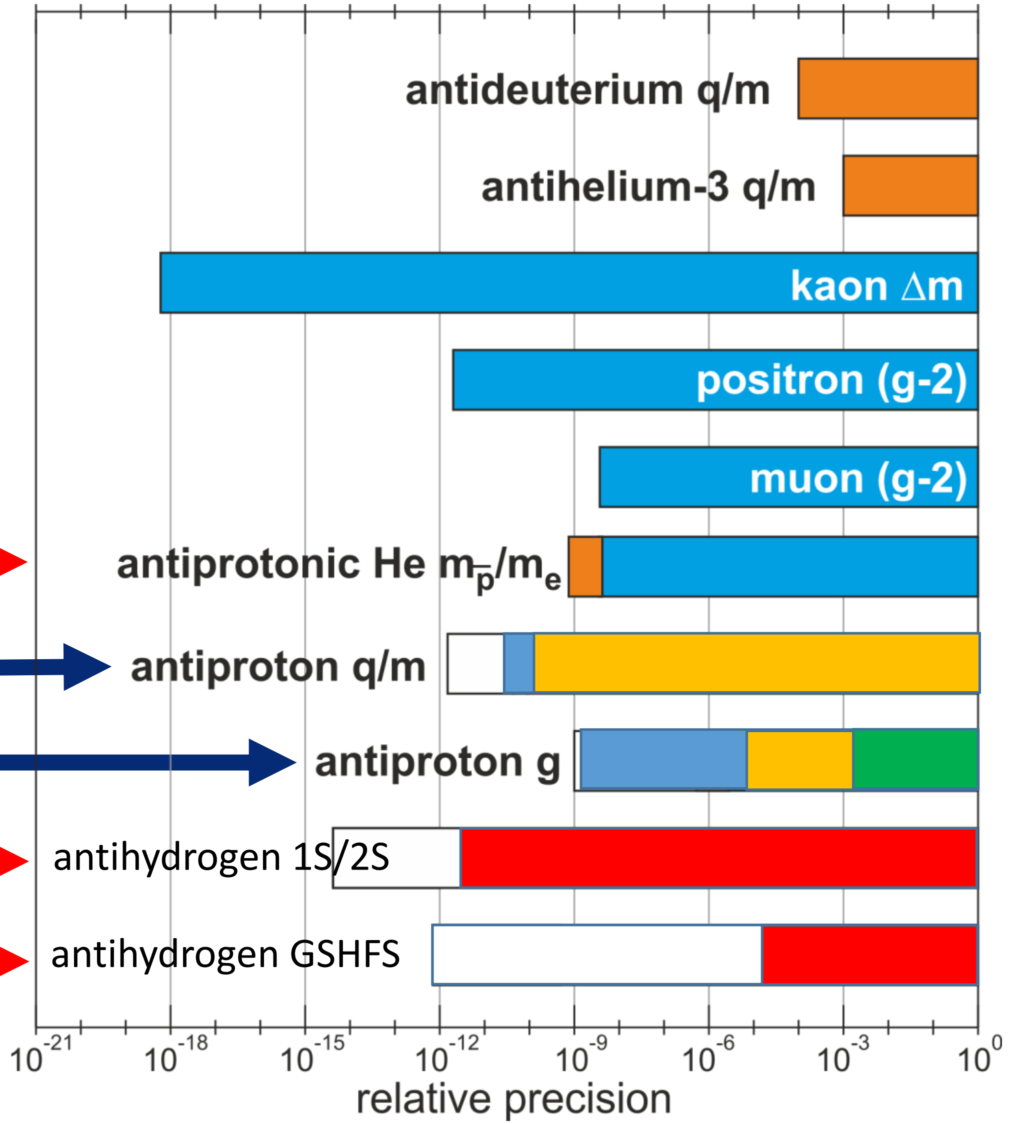
With this instrument: Investigate properties of antimatter very precisely

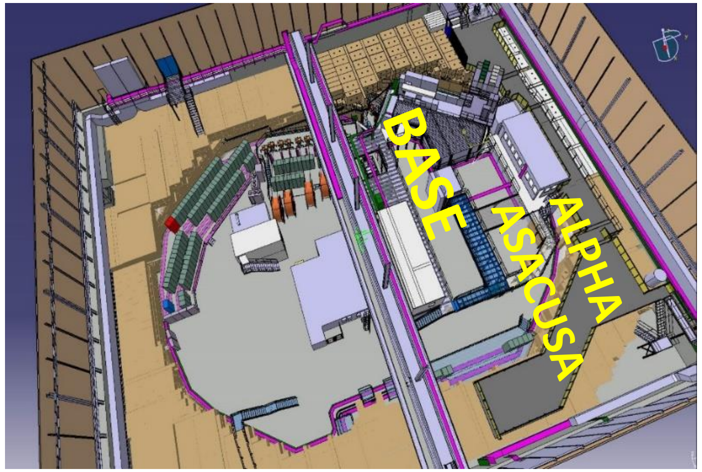
CPT tests based on particle/antiparticle comparisons

Recent
Past
Planned



CERN
ALICE

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).



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Momentum in the AD community

matter sector

proton lifetime (direct)	>1.67 e34 y
proton m	30 p.p.t.
proton magn. moment	3.3 p.p.b.
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector 2013

antiproton lifetime	> 0.3 y
antiproton m	120 p.p.t.
antiproton m. moment	0.002
antihydrogen 1S/2S	-
antihydrogen GSHFS	-

antimatter sector 2019

antiproton lifetime	> 10.6 y
antiproton m	70 p.p.t.
antiproton m. moment	1.5 p.p.b.
antihydrogen 1S/2S	2 p.p.t.
antihydrogen GSHFS	350 p.p.m.

- **Recent rapid progress towards a better understanding of antimatter.**

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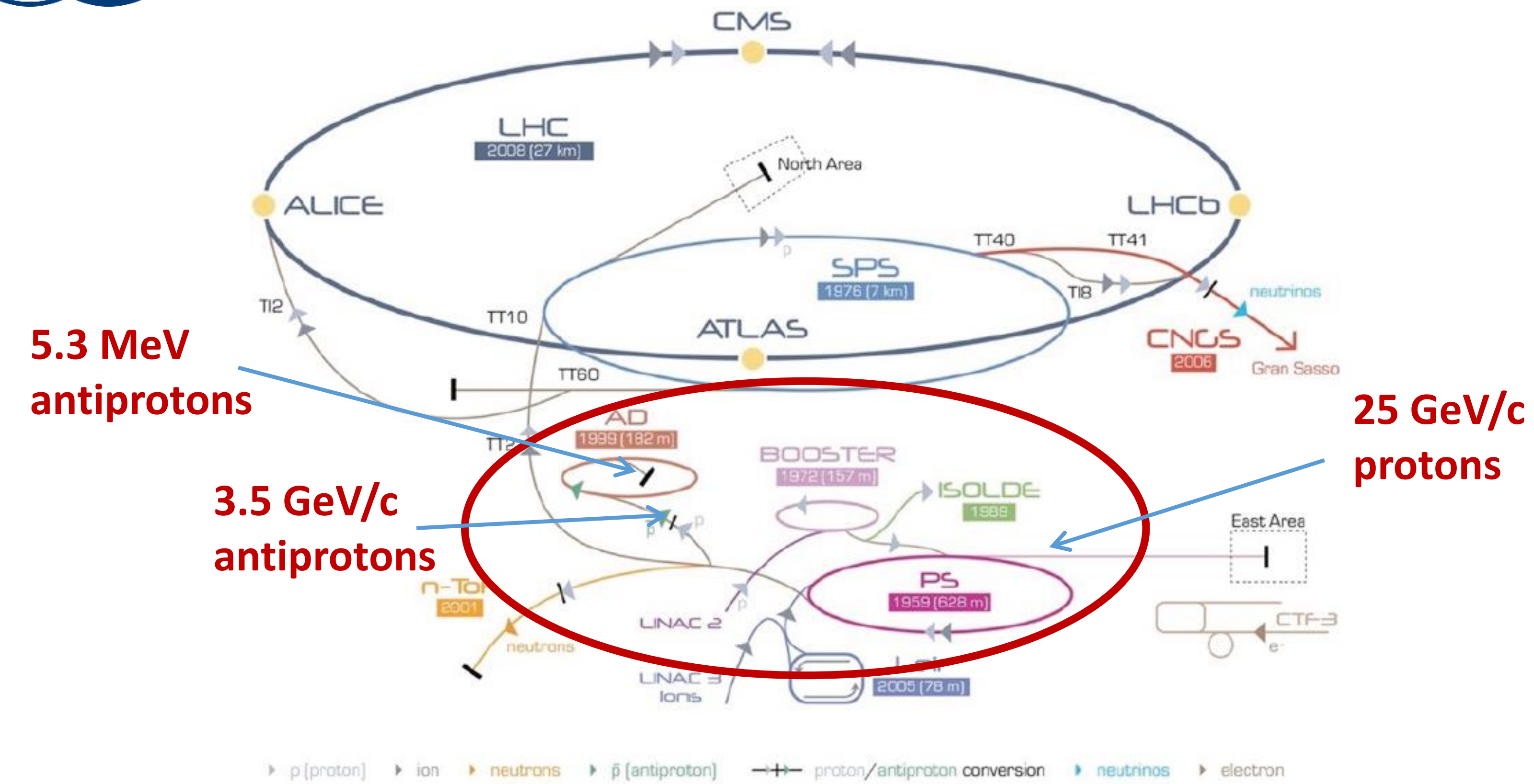
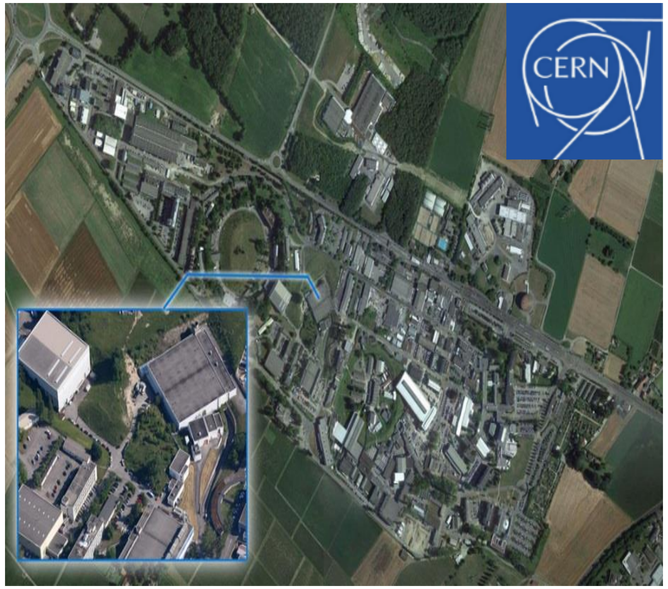
Antiprotons – CERN





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

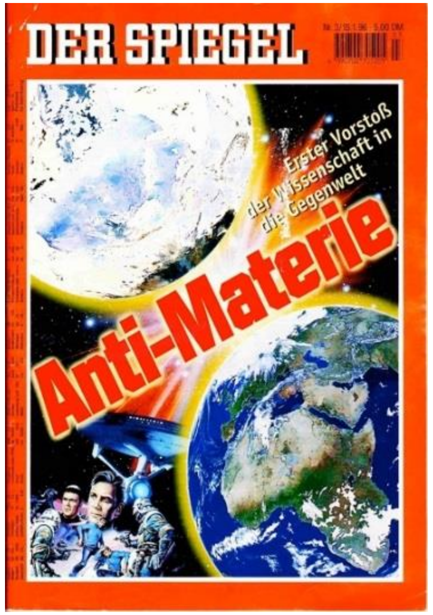
Within a production/deceleration cycle of 120s + 300s of preparation time we bridge **14 orders of magnitude**

Most of these methods were pioneered and first demonstrated by the TRAP collaboration (Gabrielse et al.)

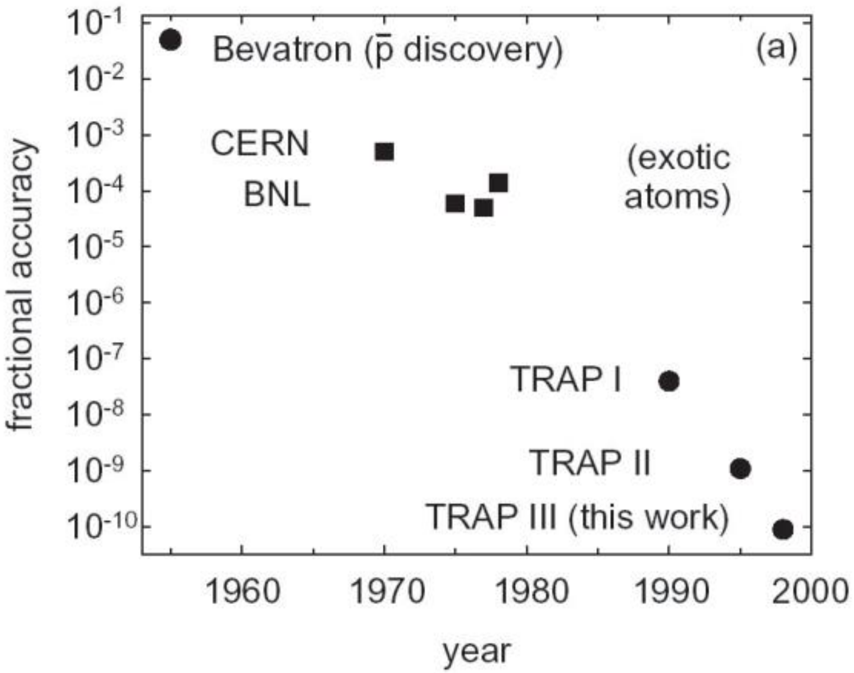
Pioneering Highlights

Production of 11(2) relativistic antihydrogen atoms at LEAR (PS210) in 1995.

G. Baur et al., Phys. Lett. B 368 (1996) 251



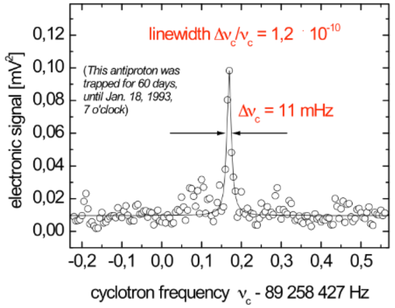
W. Oelert (Juelich)



Comparison of the proton to antiproton charge to mass ratio at fractional precision of 90 p.p.t.

$$\frac{Q_{\bar{p}}}{M_{\bar{p}}} \Big/ \frac{Q_p}{M_p} = -0.999'999'999'91(9)$$

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



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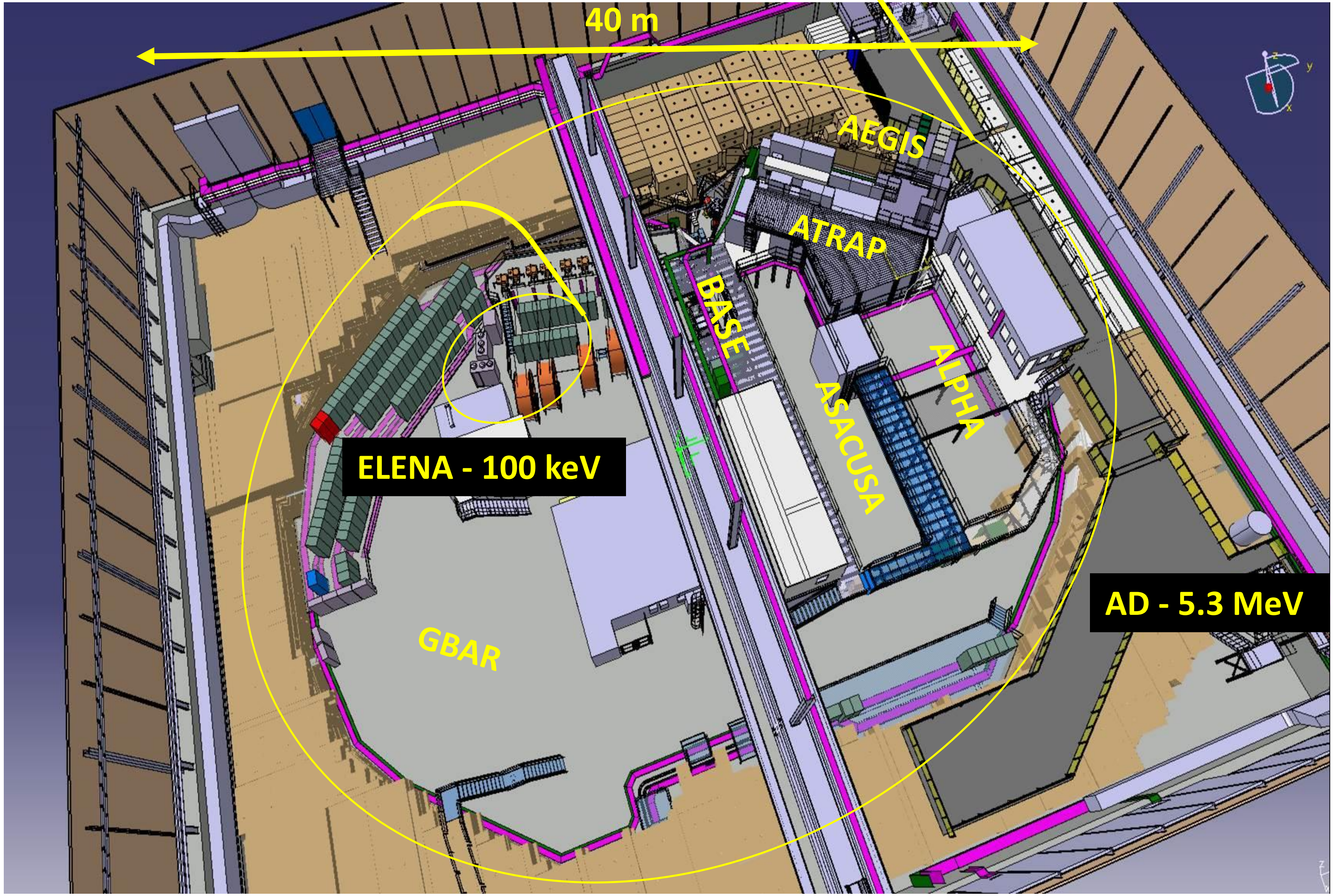
Together with the discovery of antiprotonic helium by T. Yamazaki / R. Hayano / Iwasaki *et al.* ...

Convinced CERN to start the AD program.

The AD/ELENA-facility

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



BASE, ATRAP,
Fundamental properties of the antiproton

ALPHA, ATRAP,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

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

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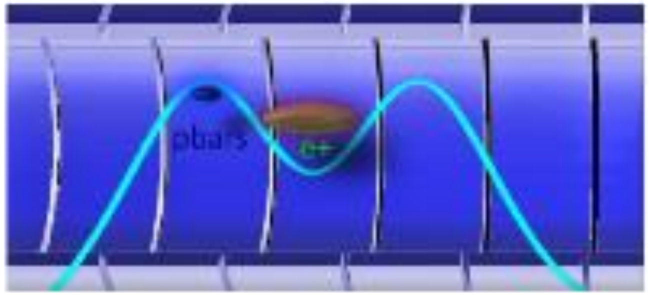
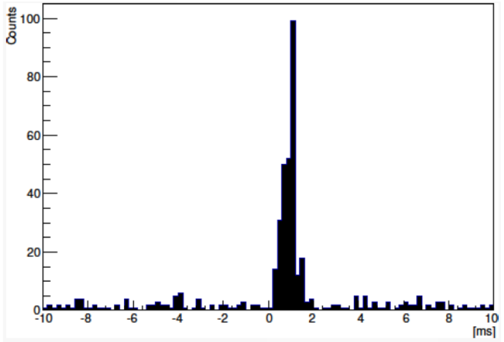
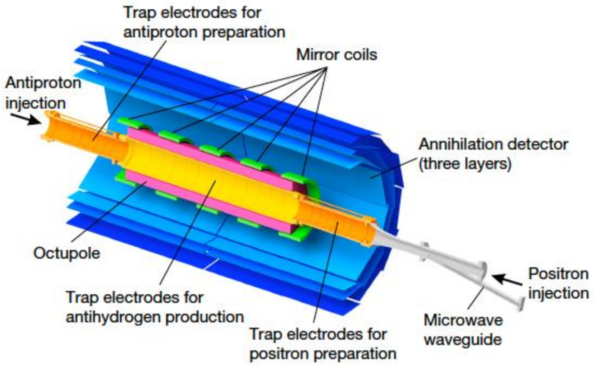
M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).

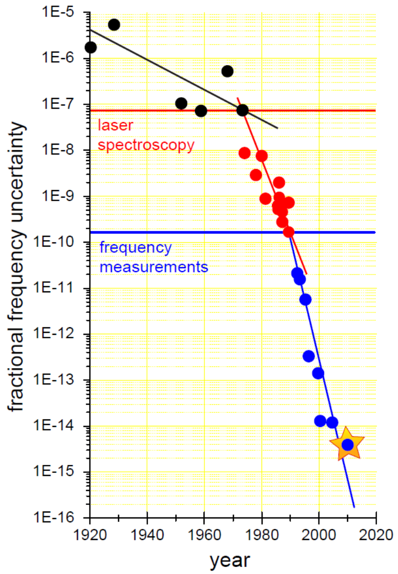
Antihydrogen

- Idea: Investigate the electro-magnetic spectrum of antihydrogen
- Problem: antihydrogen does not exist -> needs to be synthesized









First Demonstration: M. Amoretti, Nature 419 (2002) 456, ATHENA collaboration

- Problem: ...and trapped...being the difficult part because

electric force: $\vec{F} = q \cdot \vec{\nabla}\phi$

magnetic force: $\vec{F} = \overrightarrow{\mu_e} \cdot \vec{\nabla}B$

typical trap depth

$$\frac{E}{k_B} = 1000K \ to \ 100000K$$

$$\frac{E}{k_B} = 0.1K \ to \ 0.5K$$

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- Alternative: Produce antihydrogen by antiproton/positronium interaction

Antihydrogen Physics

- Electronic Structure of Antihydrogen

Measured by G. Gabrielse (Harvard) and Holger Mueller (Berkeley)

Measured by BASE / ASACUSA

ALPHA

$$E_{nlm} = R_{\infty}\left(-\frac{1}{n^2} + f_{nlm}\left(\alpha, \frac{m_e}{m_p}, xxx\right) + \frac{16\,\pi^2 m_e^2 c^2 \alpha^2}{3n^3h^2} r_p{}^2\right)$$

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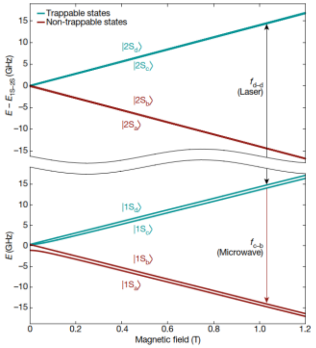
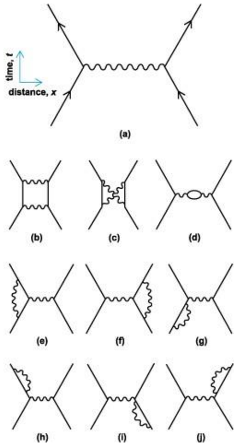
$$\frac{1}{2} m_e c^2 \frac{\alpha^2}{hc}$$



Tests / Measurements of

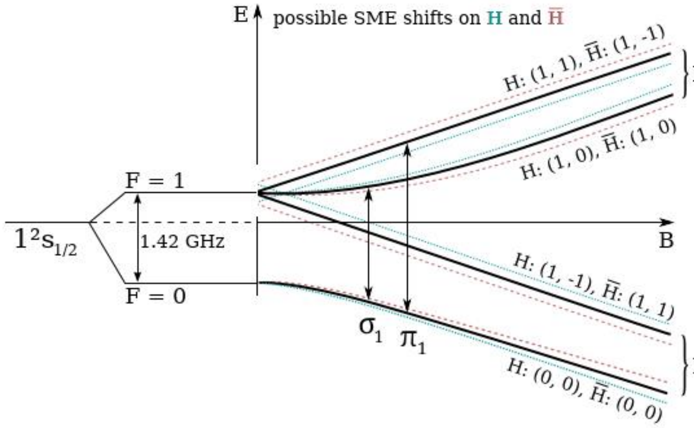
- Properties of the positron
- Antimatter interactions
- QED tests with antimatter
- **Antiprotons charge radius**



Rather insensitive to the properties of the antiproton

- GSHFS of Antihydrogen

ALPHA



$$\nu_G = \frac{16}{3}\left(\frac{m_p}{m_p + m_e}\right)^3 \frac{m_e}{m_p}\frac{\mu_e}{\mu_B}\frac{\mu_p}{\mu_N}\frac{m_e(\alpha^2 c)^2}{h}$$

$$\times\ (1 + \Delta_{QED} + \Delta_{HAD} + \Delta_{ST})$$

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Sensitive to antiproton substucture

antihydrogen milestone – trapping (2010)

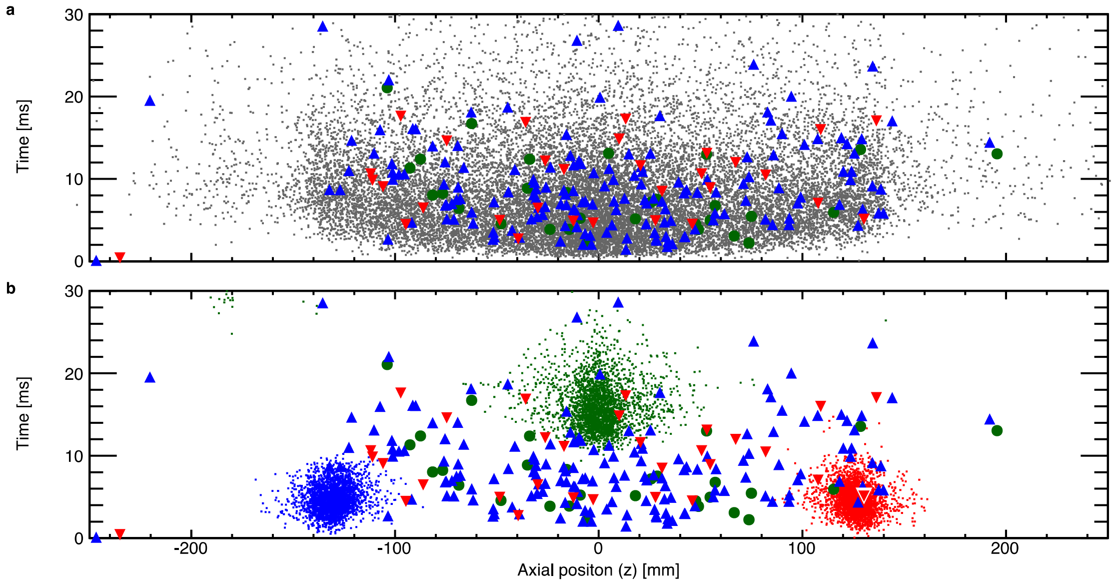
- After almost 10 years of R'n'D
  - plasma compression
  - evaporative plasma-cooling
  - autoresonance excitation

LETTER

doi:10.1038/nature09610

Trapped antihydrogen

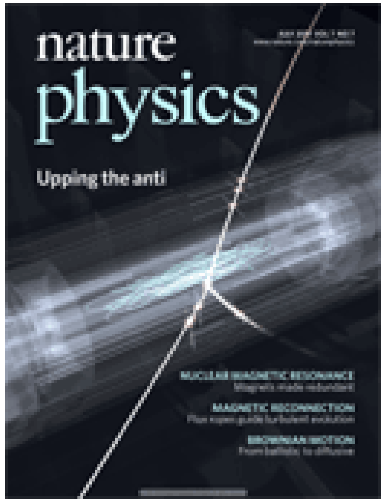
G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]



HBAR simulation

left bias
right bias
no bias

PBAR simulations



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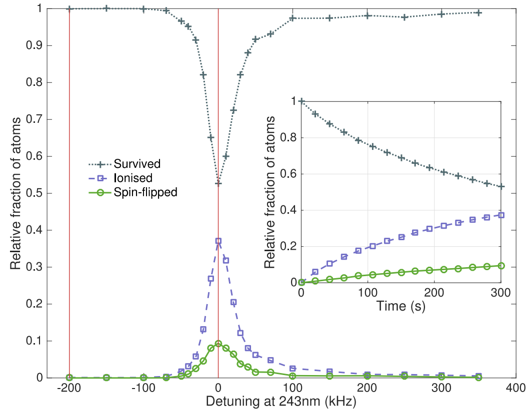
At that time, about 0.7 hbar atoms per mixing cycle

antihydrogen milestone – spectroscopy

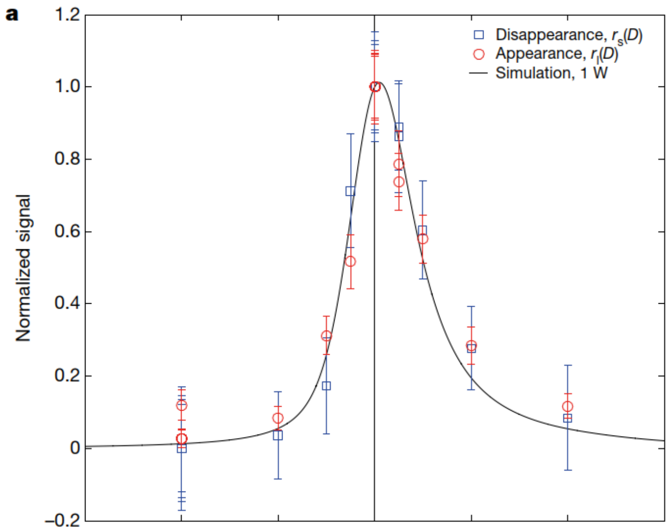
- since 2010 -> trapping rate increased by a factor of 20
- But how can experimentalists perform optical spectroscopy in 20 to 100 particles?



Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12

Single-sided constrain:

200 p.p.t.



- 2016/2017 -> trapping rate further increased
- Improved detector code & more time

$$\nu_{1S2S} = 2\,466\,061\,103\,080.3\ (0.6)\ \mathrm{kHz}$$

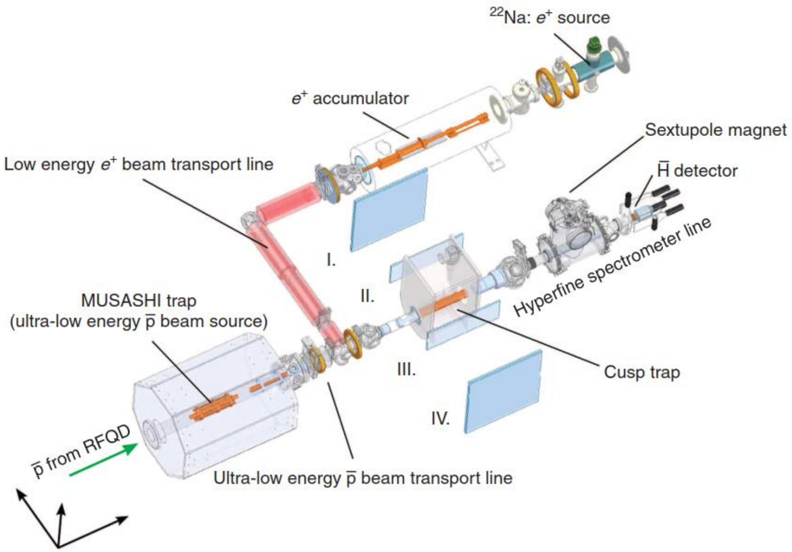
- Additional headroom – laser cooling / laser waist / 0-field measurements etc…

ALPHA collaboration, *Nature* **541**, 506 (2017)

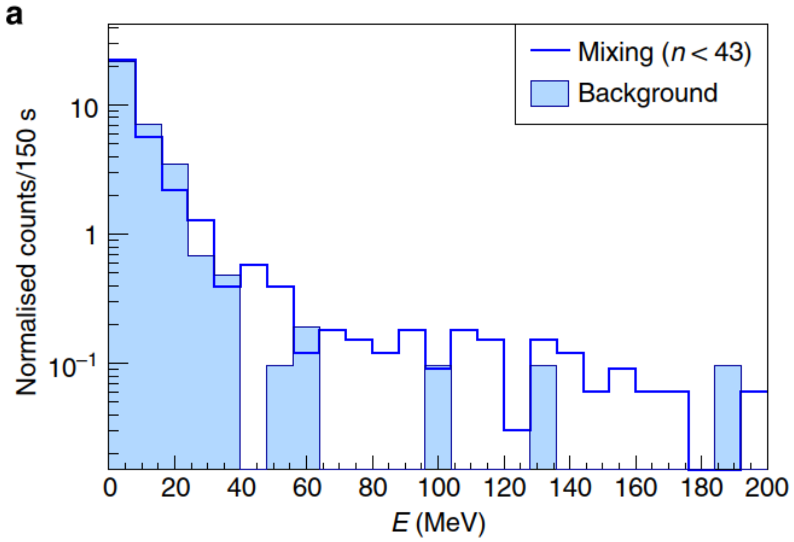
ATRAP

ASACUSA CUSP – Beam of Antihydrogen

- Apparatus



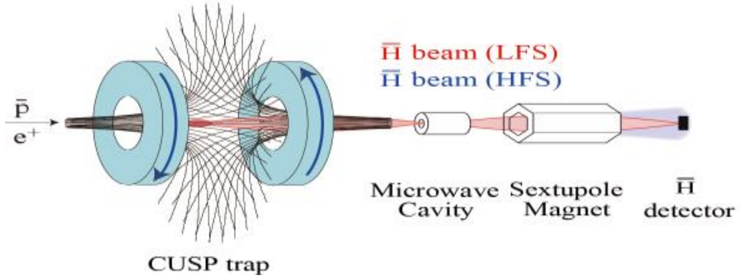
- Signal on antihydrogen detector



- Basic idea is to conduct a Rabi type measurement of antihydrogen GSHFS

production

polarized beam



very successful measurements **on hydrogen beam** demonstrated in SMI group (Widmann et al.)

$$\nu_{HFS} = \mathbf{1,420,405,748.4\ (3.4)}Hz\ \ \mathbf{(2.7}\ p.p.b.\mathbf{)}$$

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BASE

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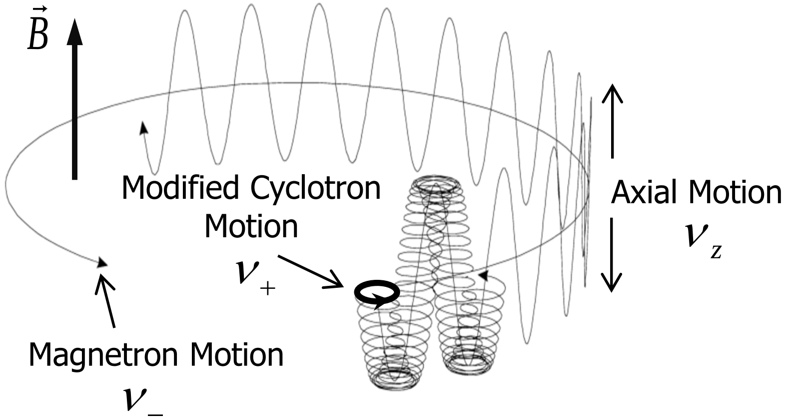
M. Diermaier et al., *Nat. Commun.*, **8** (2017) ARTN 15749 .

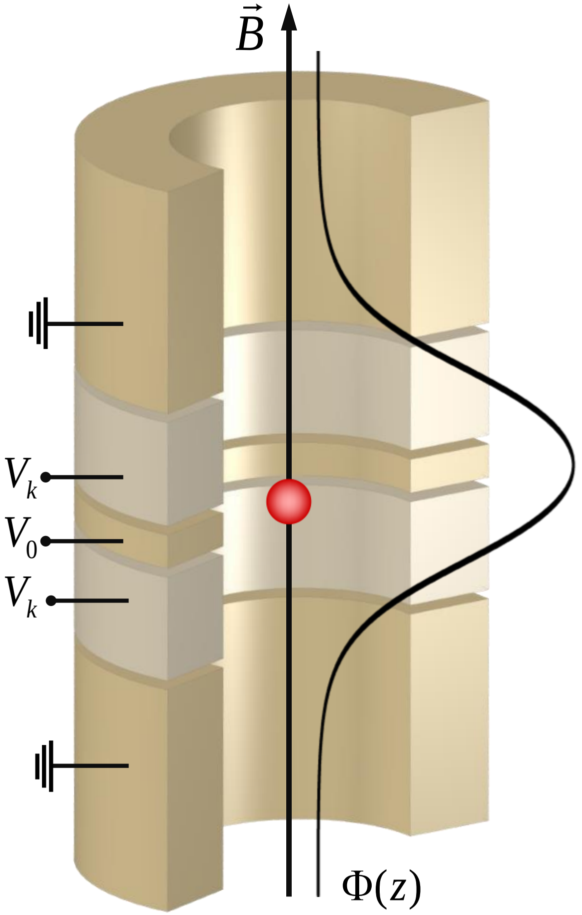
Penning trap

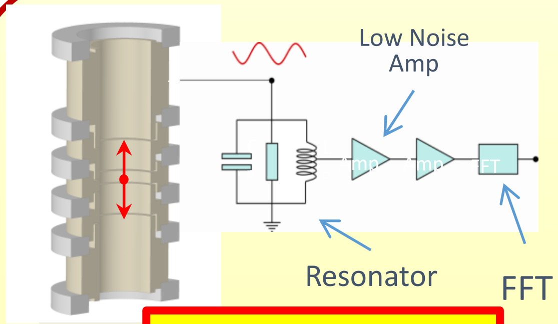
radial confinement: $\vec{B} = B_0 \hat{z}$

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

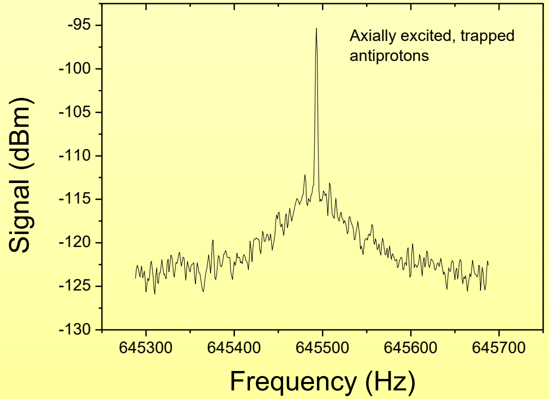


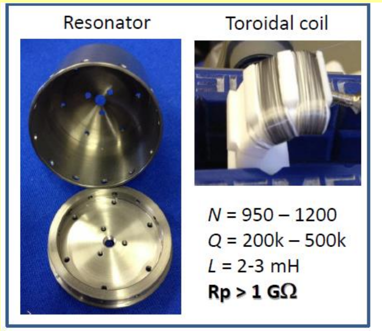
Axial	$\nu_z = 680\,\mathrm{kHz}$
Magnetron	$\nu_- = 8\,\mathrm{kHz}$
Modified Cyclotron	$\nu_+ = 28{,}9\,\mathrm{MHz}$





currents: 1 fA





ATRAP

Invariance-Relation

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

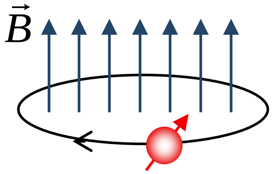
Cyclotron Frequency

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

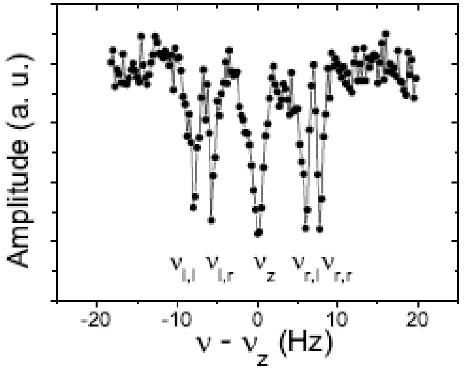
Cyclotron frequency relates measurable quantity to fundamental properties of trapped charged particle

Measurements in Penning traps

Cyclotron Motion



simple



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

g: mag. Moment in units of nuclear magneton

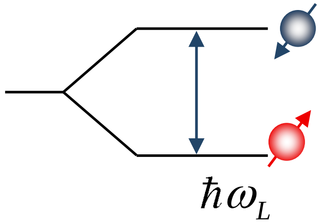
$$\omega_c = \frac{e}{m_p} B$$

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

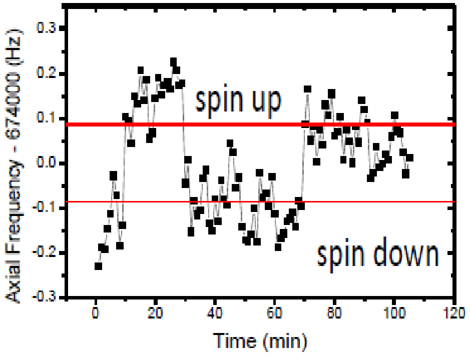
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

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

Larmor Precession



difficult



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

ALPHA

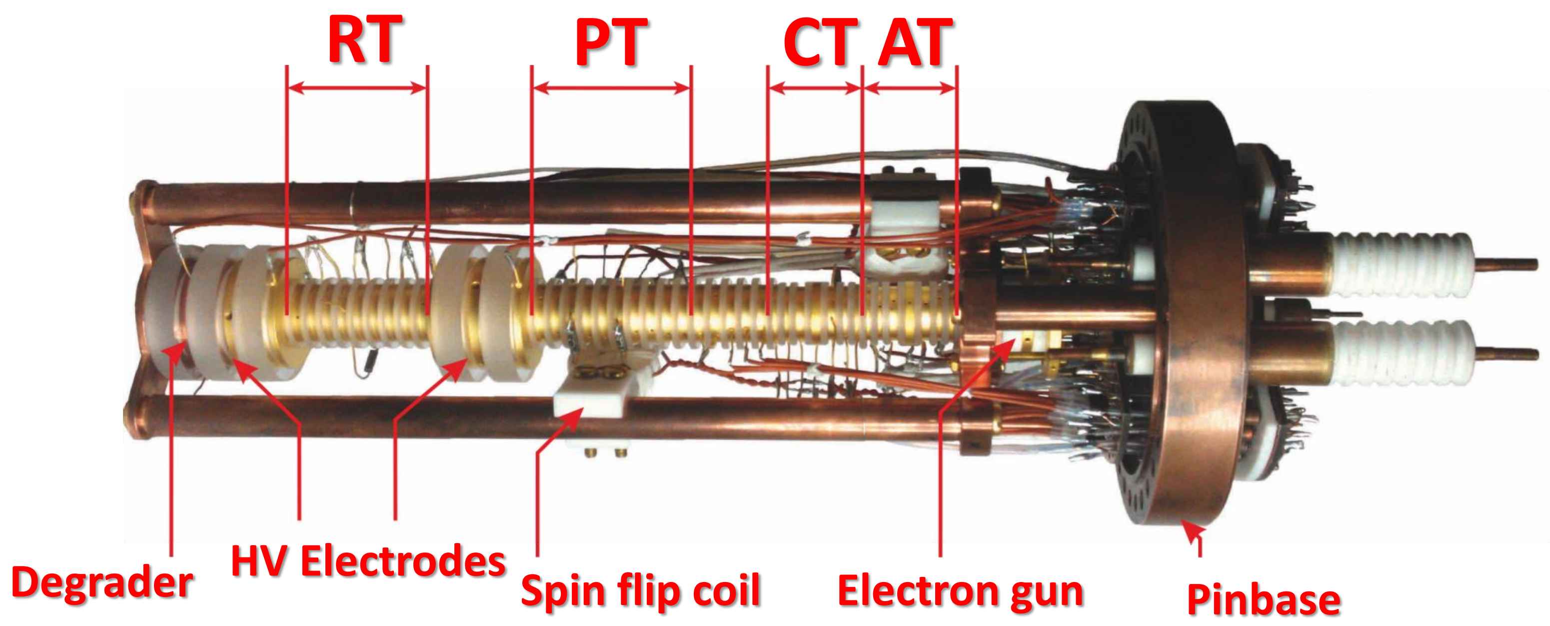
ATRAP

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.**

the BASE trap



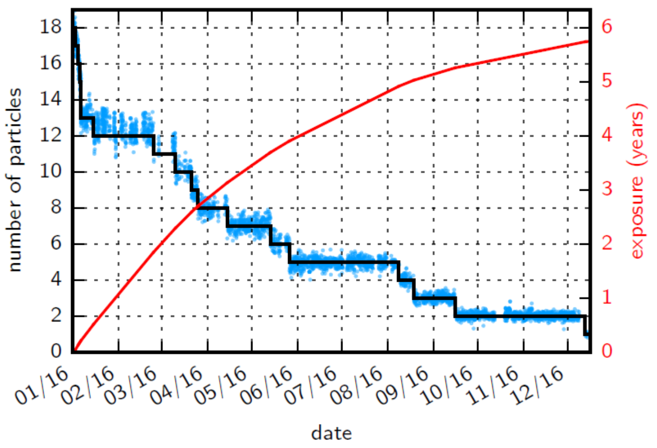
Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.
Trap is “power failure save”.

Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$

Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4$ s

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

- Lifetime measurement



trapping of antiprotons for > 400 days

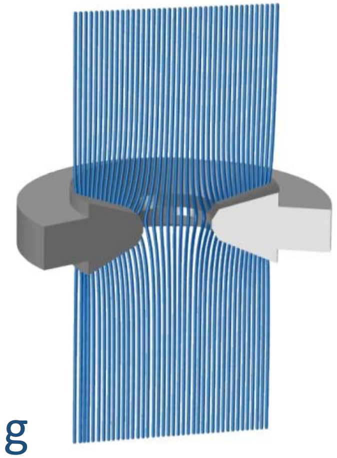
antiproton lifetime limit

$t_{1/2} > 10.2$ a

Sellner, S. *et al.*, *New J. Phys.* **19**, 083023 (2017).

ATRAP

magnetic moment measurement



- Larmor frequency measurement by spin quantum transition spectroscopy – QND measurements using the continuous Stern Gerlach effect

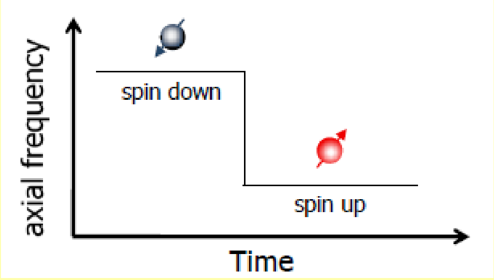
Magnetic bottle adds a spin dependent quadratic axial potential -> Axial frequency becomes function of spin state

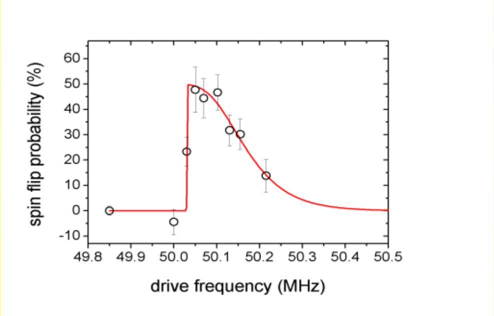
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- **Extremely difficult** for the proton due to μ/m scaling
  - Extremes:
    - Strongest magnetic bottle ever superimposed to a Penning trap
    - Smalles precision Penning trap
    - Lowest rms-noise ever measured

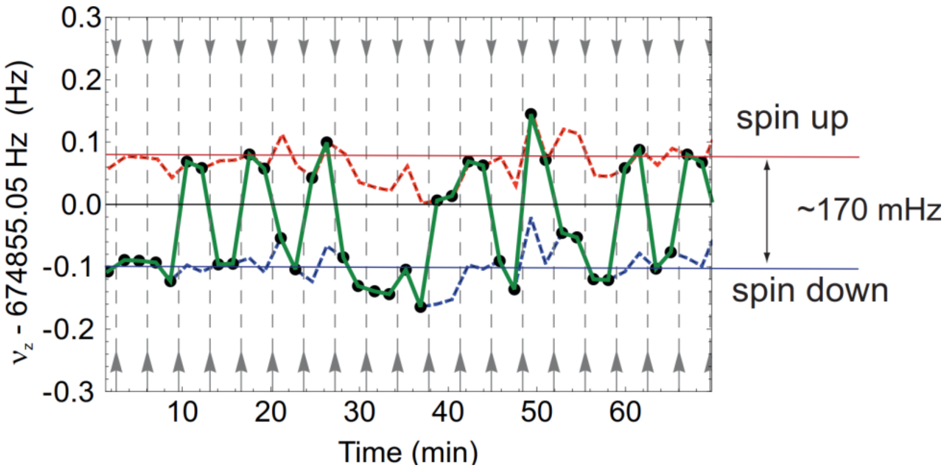
Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement





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



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

Single trap measurements are limited to the p.p.m. level.

$\mathbf{g_{\bar{p}}/2 = 2.792846\,(14)}$

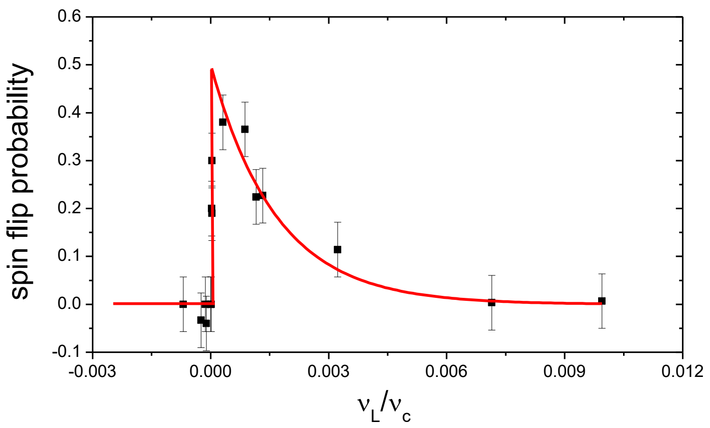
ATRAP 2013

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

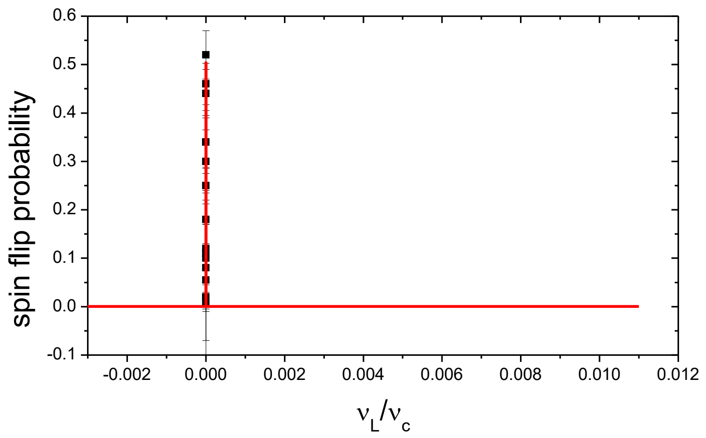
BASE 2016

ATRAP

??? Can we overcome current limitations ???



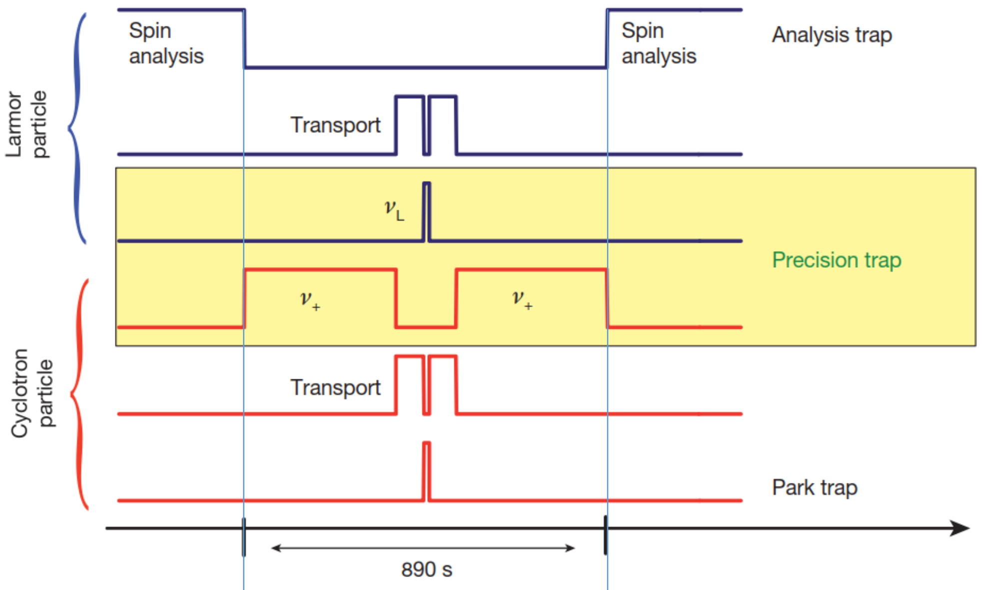
???



ATRAP

Invented: Two-Particle/Triple-Trap Method

- ...single spin quantum resolution gives possibility to measure g in an advanced scheme



Initialize the spin state

Measure frequencies in homogeneous trap

Analyze the spin state

- Two particle scheme reduces measurement time by a factor of 5
- **350-fold improved measurement** of the antiproton magnetic moment

BASE

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

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

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

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

- **At that time the antiproton magnetic moment was more precise than the proton magnetic moment.**

ALPHA

ATRAP

AEgIS

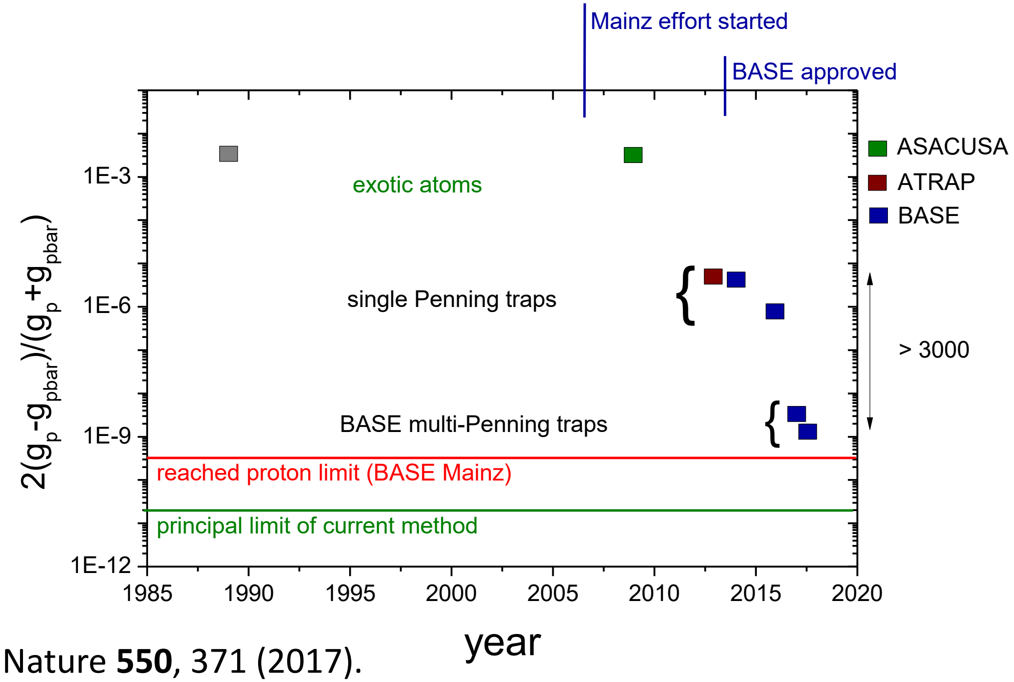
The Antiproton Magnetic Moment

LETTER

OPEN
doi:10.1038/nature24048

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

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



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

CERN Courier March 2018

BASE

Experiment of the moment

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

The BASE setup at CERN's Antiproton Decelerator.

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.

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[illegible] 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.

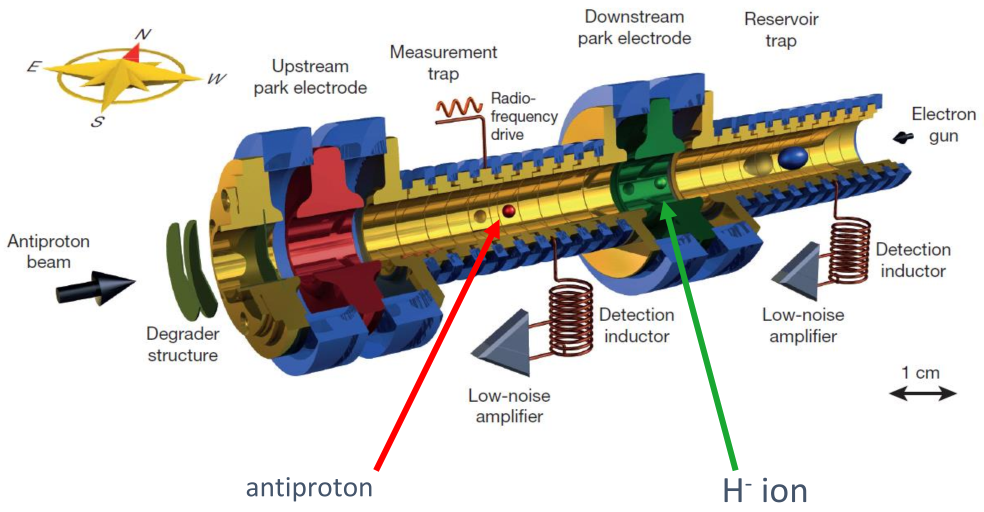
CERN COURIER, 3 / 2018.

ALPHA

ATRAP

Measurement configuration

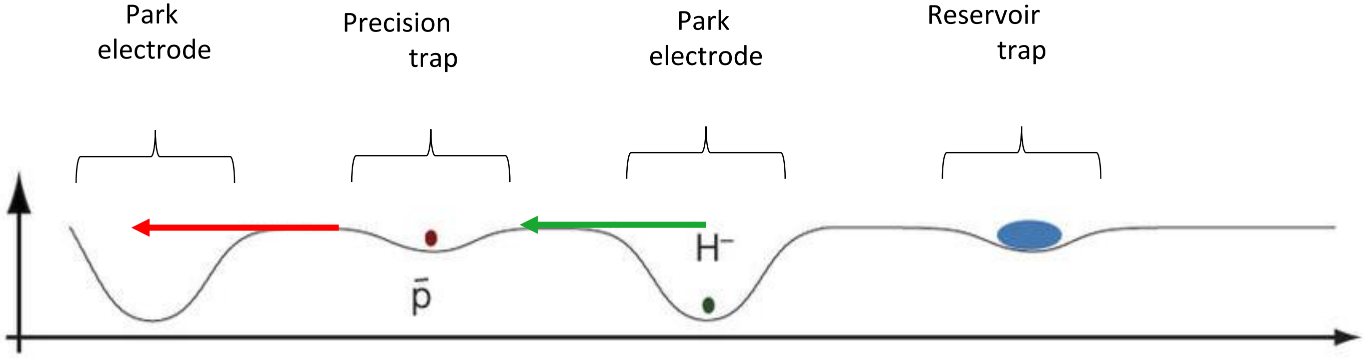
Extract antiprotons and H⁻ ions, compare cyclotron frequencies



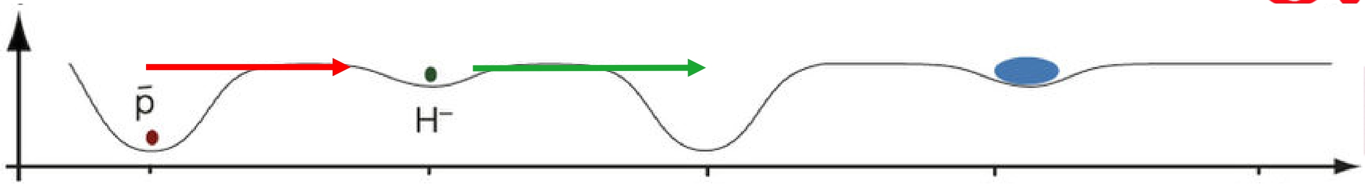
$$R = \frac{\nu_{c,\bar{p}}}{\nu_{c,H^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \times \frac{B/2\pi}{B/2\pi} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$

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

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



Measure ν_z & $\nu_+ \Rightarrow \nu_c$



Measure ν_z& $\nu_+ \Rightarrow \nu_c$

Comparison of H-/antiproton cyclotron frequencies:

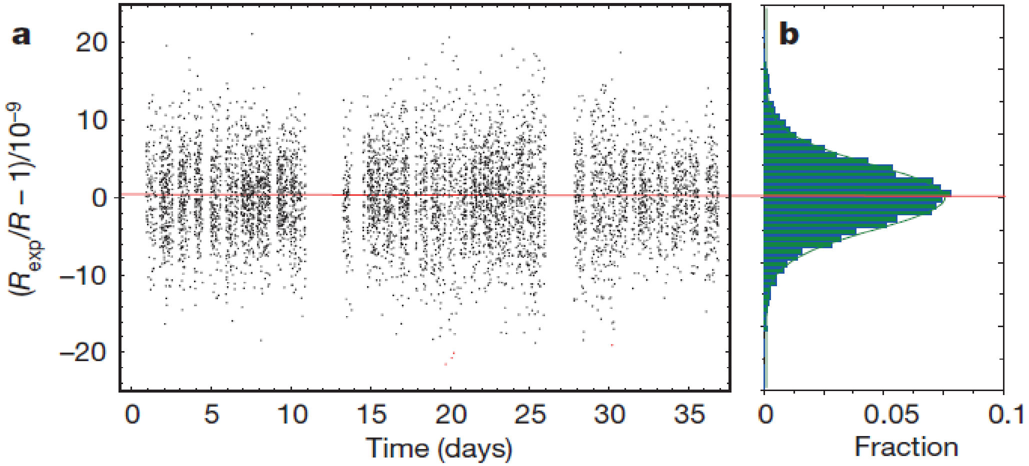
One frequency ratio per 4 minutes with ~ 6 ppb uncertainty

ATRAP

Pioneering Ideas: G. Gabrieslе et al., PRL **82**, 3199 (1999).

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

Results and interpretation



Result of 6500 proton/antiproton Q/M comparisons:

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

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

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

Consistent with CPT invariance

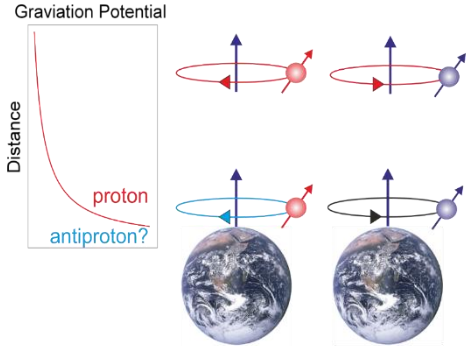
Limit of sidereal (diurnal) variations < 0.72 ppb/day

Constrain of the gravitational anomaly for antiprotons:

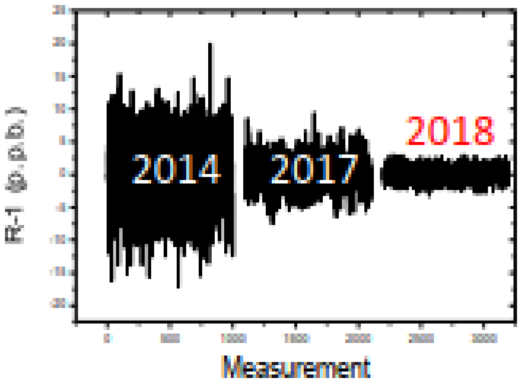
$$\frac{\omega_{c,p} - \omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1)\, U/c^2$$

Our 69ppt result sets a new upper limit of

$$|\alpha_g - 1| < 8.7 \times 10^{-7}$$



Progress:

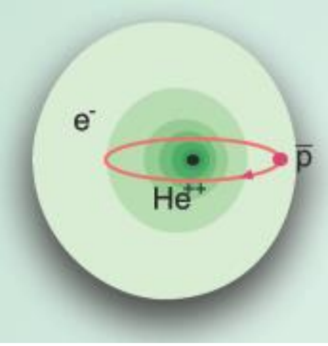


Next step: Spectroscopy on two particles in one trap.

ATRAP

Potential CPT/WEP compensation to be performed by **AEgIS**, **ALPHA-g** and **GBAR** in the ELENA era

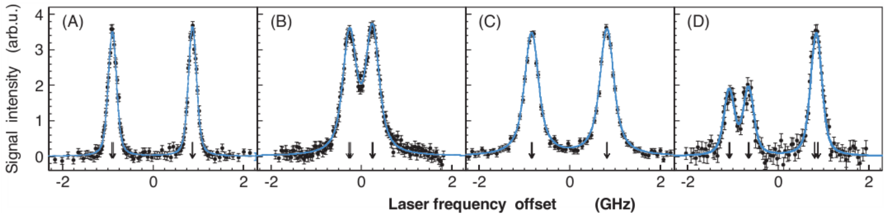
antiprotonic Helium spectroscopy

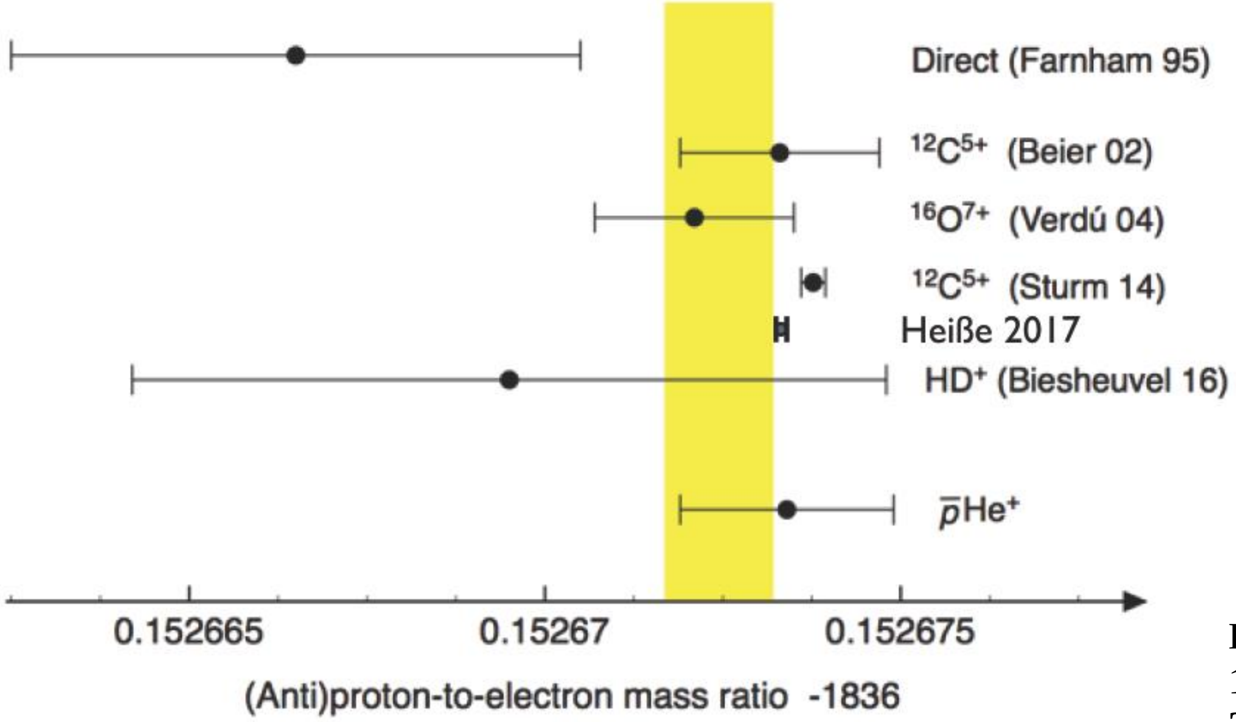


electron in 1s state

pbar in «long-lived» (us) circular state

Induce transitions to non-circular state and watch annihilation signals





Antiproton-to-electron mass ratio

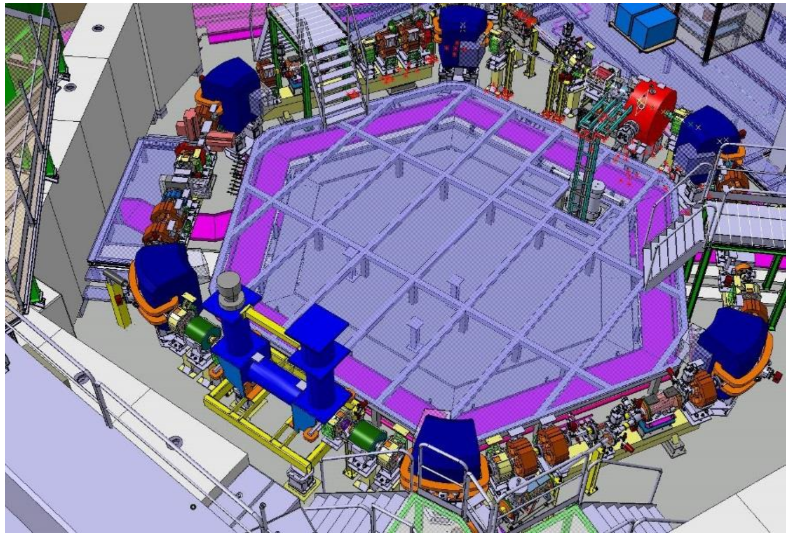
1 836.152 673 4 (15)

Hori, M. *et al.*, Buffer-gas cooling of antiprotonic helium to 1.5 to 1.7 K, and antiproton-to-electron mass ratio, *Science* **354**, 610 (2016).

ATRAP

ELENA

- Antiprotons are caught in Penning traps using degraders – 99.9% of particles are lost.
- ELENA provides antiprotons decelerated to 100keV – compared to the AD – at improved beam emittance.
- Degrading at low particle energies is much more efficient



Experiment	ELENA Gain Factor
ALPHA	100
ATRAP	100
ASACUSA	10
AEgIS	100
BASE	X
GBAR	GO

- **ELENA will be able to deliver beams almost simultaneously to all experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone**

ALPHA

BASE

ATRAP

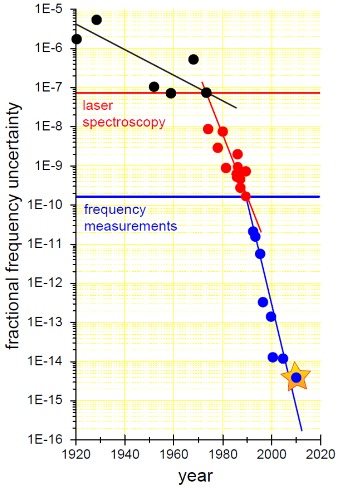
GBAR

AEgIS

Provides bright future perspective for antiproton-physics at CERN

Future AD Program – old collaborations

Antihydrogen Experiments

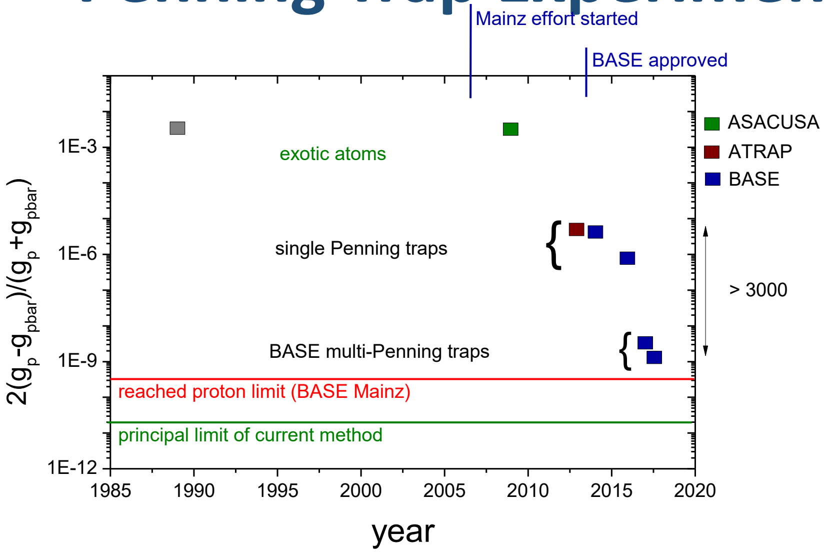


achieved fractional precision of 2 p.p.t. in 1S/2S

Measurements conducted with hydrogen define the next steps

Work on further increase of production yield and preparation of colder antihydrogen

Penning Trap Experiments



20-fold improved measurement to pbar g-factor is possible

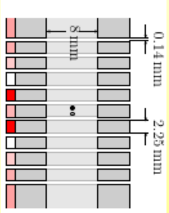
sympathetic cooling of positrons and pbars

ALPHA: Overlap positrons with laser cooled Be ions

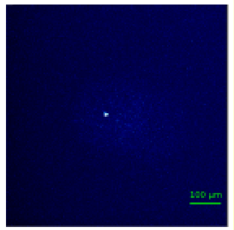
$$\text{Rate} \propto n_{e^+}^2 / T_{e^+}^{9/2}$$

AEgIS: Cool antiprotons by sympathetic interaction with laser cooler C2- ions (Doser / Gerber / Borealis)

PTB Quantum Logic Spectroscopy of pbars



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



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

Antiprotonic Helium group is optimistic for 10 to 100 fold improved measurements in the future

Future Projects

GBAR – Test of the weak eqivalence principle with hbar

Idea:

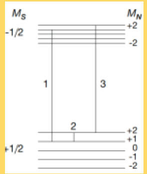
1.) Produce the antihydrogen ion (pbar / 2 positrons)

2.) Cool the system sympathetically to the Doppler limit using Be ions in an rf-trap based Coulomb lattice in a hollow beam.

3.) Laser-ionize the system and drop the neutral antihydrogen atom

Molecular Spectroscopy

Penning trap experiment for spectroscopy of the antihydrogen molecular ion

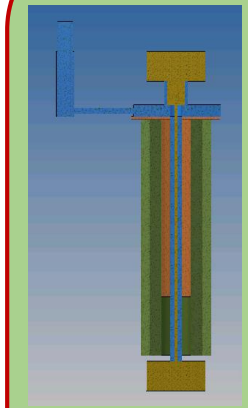


Positron magnetic moment

Mass ratios from ro-vibrational spectroscopy.

E. G. Myers et al. MAX Project (in GBAR?)

ALPHA-g



6 m instrument constructed to test weak equivalence principle with antihydrogen

Apparatus can be upgraded to fountain spectroscopy

…and atomic beam interferometry

Transportable Traps (Smorra)

Scheme to extract single antiprotons from a reservoir has been developed recently

Trapping of antiprotons for > 1 year has been demonstrated

First step towards transportable antiproton traps.

C. Smorra et al., Int. Journ. M.S. ***114*** *213001 (2014)*

Space for more experiments

See contributions by

PUMA Project

A. Obertelli et al.

ALPHA

BASE

ATRAP

GBAR

AEgIS

Summary

- Since the startup of the AD program, CERN's antimatter collaborations made excellent progress towards their experiment goals.

  - 1000 antihydrogen atoms can now be trapped and investigated routinely
    - First spectroscopic measurements were performed.
    - ALPHA is prepared to further advance their ultra-high precision measurements.

  - Antiproton parameters have been measured to
    - Magnetic Moment: p.p.b. level has been achieved, 100 p.p.t. level in reach
    - Q/M: 70 p.p.t. measurement completed, 10 p.p.t. to 20 p.p.t. possible

- **CERN continues supporting this branch of physics by the dedicated new machine ELENA, which opens up a bright future for antimatter physics at CERN.**

ATRAP

Thanks very much for your attention

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Imperial College London
University of Liverpool, UK
University of Manchester, UK
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Federal University of Rio de Janeiro, Brazil
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Max Planck Institute for Quantum Optics	Max-Planck-Gesellschaft	Garching	Germany	(TL) HORI, MASAKI
Gruppo Collegato Di Brescia	Universita e INFN, Pavia	Pavia	Italy	(TL) VENTURELLI, LUCA

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PTB
GSI
Leibniz Universität Hannover

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

GBAR
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IPCMS
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Possibilities

antiprotons → free → charge-to-mass ratio; magnetic moment

antiprotons → bound

fundamental properties

pbarHe — fundamental properties and e/m interactions

antihydrogen — spectroscopy; gravity

antihydrogen ions

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Strategy

- Precise comparisons of the fundamental properties of **simple baryonic matter/antimatter** conjugates at **low energy** and with **high precision**.
- Such comparisons provide **stringent tests of CPT invariance**.
- Simple systems are well-understood -> provides sensitivity with respect to potential deviations.

$$(i\,\gamma^{\mu}\partial_{\mu} - m_X)\psi = 0 \qquad (i\,\gamma^{\mu}\partial_{\mu} - m_X - a_{\mu}^{X}\gamma^{\mu} - b_{\mu}^{X}\gamma_5\gamma^{\mu} + f(H_{\mu\nu}^{X}, c_{\mu\nu}^{X}, d_{\mu\nu}^{X}))\psi = 0$$

matter sector

proton lifetime (direct)	>1.67 e34 y
proton m	30 p.p.t.
proton magn. moment	3.3 p.p.b.
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector

antiproton lifetime	> 10.6 y
antiproton m	70 p.p.t.
antiproton m. moment	1.5 p.p.b.
antihydrogen 1S/2S	0.8 p.p.b.
antihydrogen GSHFS	350 p.p.m.

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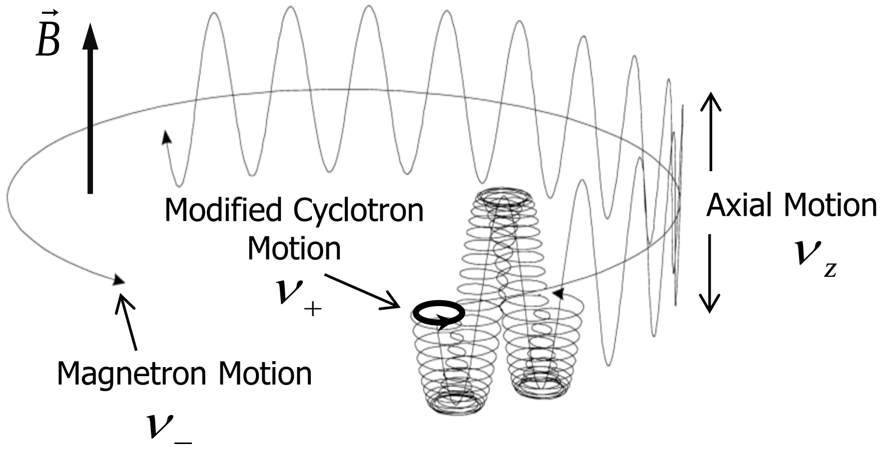
Methods: Workhorse Penning Trap

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

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

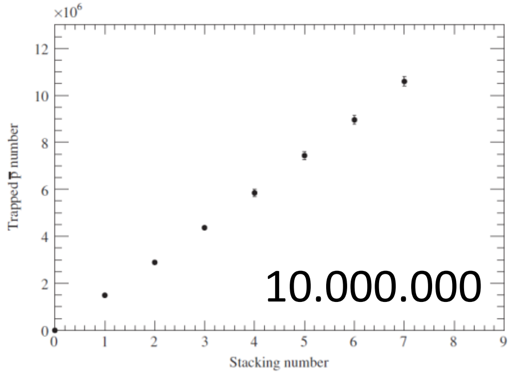


Measurements

$\omega_c = \frac{e}{m_p} B$ charge-to-mass ratios

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

- accumulation and compression of antiproton / positron plasmas



N. Kuroda, Phys. Rev. ST **15** (2012) 024702.

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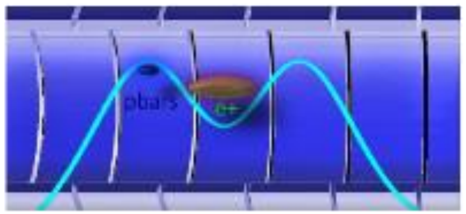
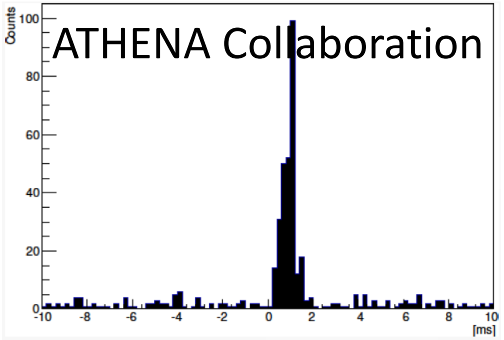
- antihydrogen formation using a nested trap scheme.

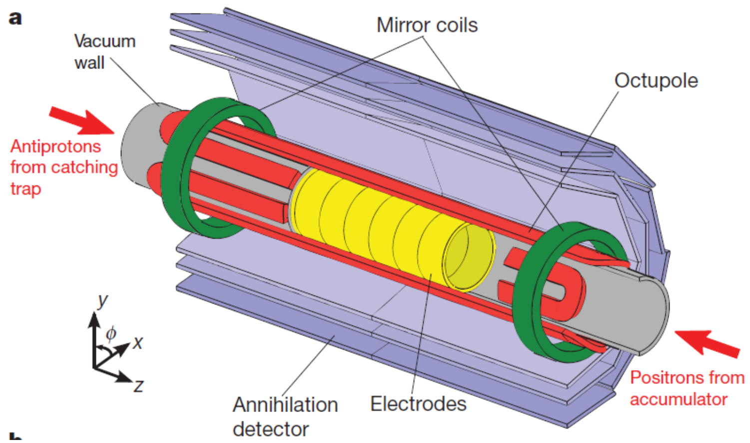
Proposed: G. Gabrielse, Phys. Lett. A **129** (1988) 38.

First Demonstration: M. Amoretti, Nature **419** (2002) 456.





Physics Measurements



- Antihydrogen 1S/2S laser spectroscopy in magnetic trap.
- Hydrogen in trap: 5 p.p.t.
- Trapping via atomic magnetic moment, Challenge: shallow trap (0.5 K)

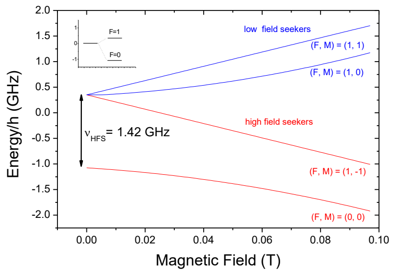
C. L. Cesar, Phys. Rev. Lett. **77** (1996) 255.

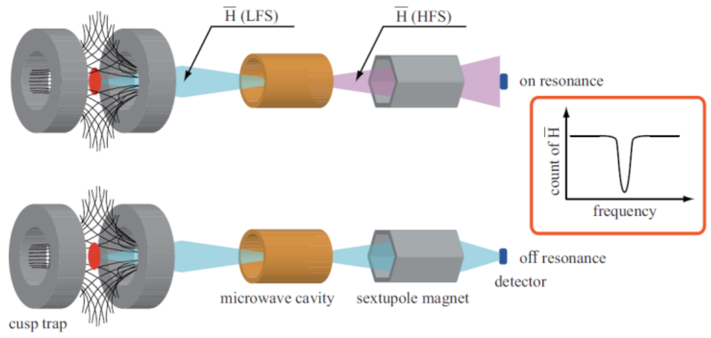
- Antihydrogen beam spectroscopy (ASACUSA Scheme)

1ppb

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

<1ppb





- extract antiproton magnetic moment
- probe antiproton substructure
- Test SME coefficients

Achieved 3.3 p.p.b. using hydrogen beam (Widmann Group in ASACUSA)

A. Mohri and Y. Yamazaki, Europhys. Lett. **63** (2003) 207.

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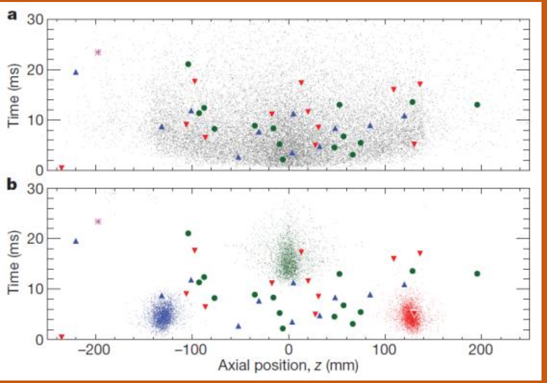
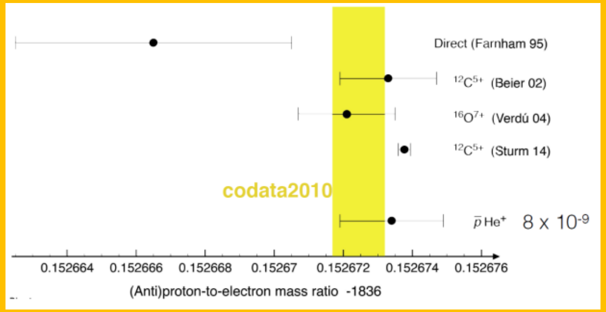
Highlights – CPT Sector

trapped antihydrogen



ALPHA, Nature 468, (2010) 674.
sim. res. ATRAP, PRL (2012)

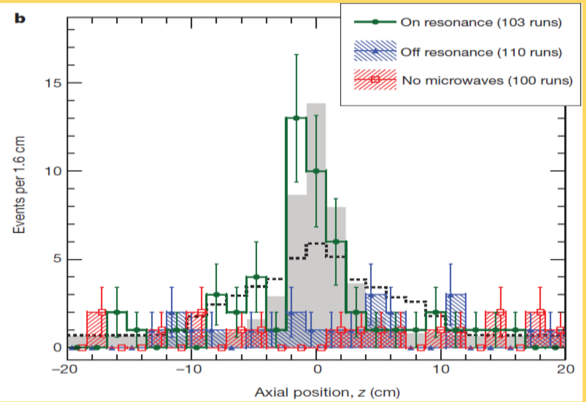
antiproton/electron mass ratio



2-photon spectroscopy of anti-protonic helium / 8 p.p.b.

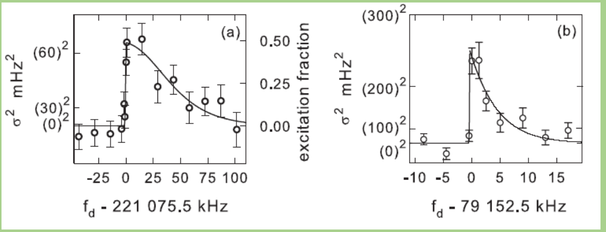
ASACUSA, Nature **484** (2011) 475.

«rf-spectroscopy»



ALPHA, Nature 483, (2012) 442.

antiproton mag. moment



4.4 p.p.m. measurement using single Penning trap technique

ATRAP, Phys. Rev. Lett **110** (2013) 130810

Antihydrogen Beam

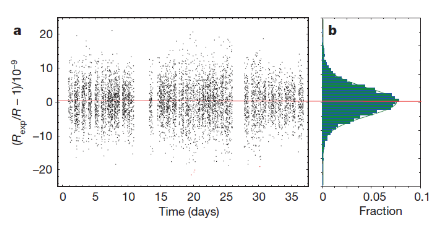
Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	Scheme 1	Scheme 2	Background
Measurement time (s)	4,950	2,100	1,550
Double coincidence events, N_t	1,149	487	352
Events above the threshold (40 MeV), $N_{>40}$	99	29	6
Z-value (profile likelihood ratio) (σ)	5.0	3.2	—
Z-value (ratio of Poisson means) (σ)	4.8	3.0	—

Major step towards planned antihydrogen spectroscopy.

ASACUSA, Nature Comm. **3** (2014) 475.

antiproton/proton Q/M ratio



69 p.p.t. measurement using two particle Penning trap technique

BASE, Nature **493** (2014) 502.

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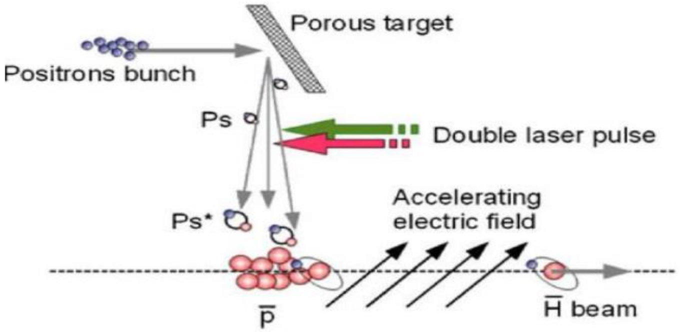
Tests of the weak equivalence principle

- AEgIS Scheme (Moire Defl.)



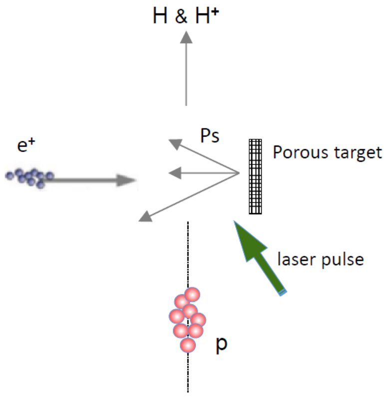
$$\bar{p} + Ps^* \rightarrow \bar{H}^* + e^-$$

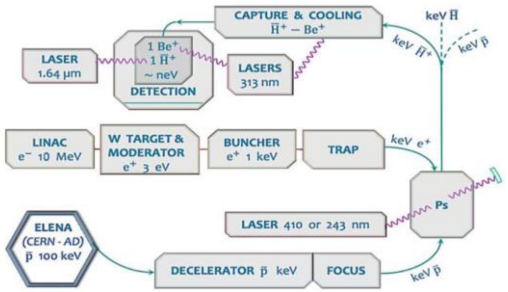
Demonstration: AEgIS, Nature. Comm. **5** (2014) 4538.

precision goal: order %

Goal: First gravity measurement before LS2

- GBAR Scheme





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

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

precision goal: order %

Status: Under construction / beam in 2017

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Production of the antihydrogen ion is highly promising

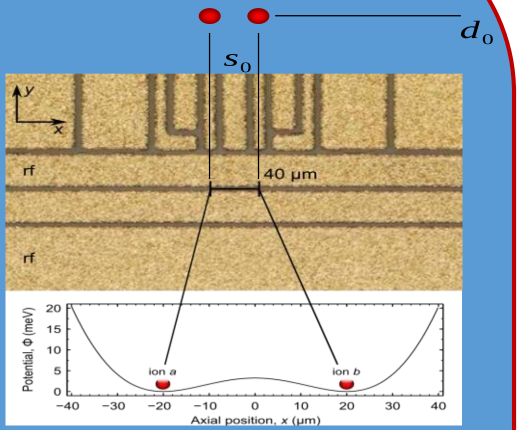
Potential of the antihydrogen ion

Charged particle

Sympathetic cooling has been demonstrated in Paul traps

Doppler temperatures can be reached easily

Stripping by «resonant» lasers is a routine.



Scheme has been demonstrated for two co-trapped laser-cooled Be-ions.

Is planned to be established and applied to antihydrogen ions by the gbar collaboration and to antiprotons by the BASE collaboration.

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

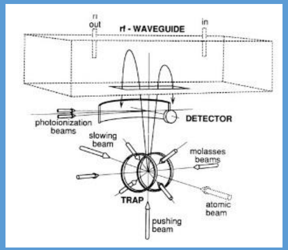
See also: M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel, Nature **471**, 200 (2011).

Production of a high-quality beam

Cool particles sympathetically.

Accelerate particles with electric field.

Strip one positron.

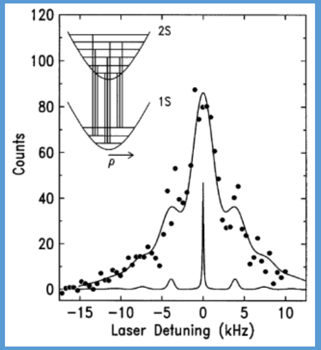


Apply to ASACUSA ideas (Rabi / Ramsey beam-scheme)

1S/2S spectroscopy at improved temperature distribution

Apply the «classical» ideas by ALPHA and ATRAP however with drastically improved initial temperature distribution

Smaller gradient traps, higher precision



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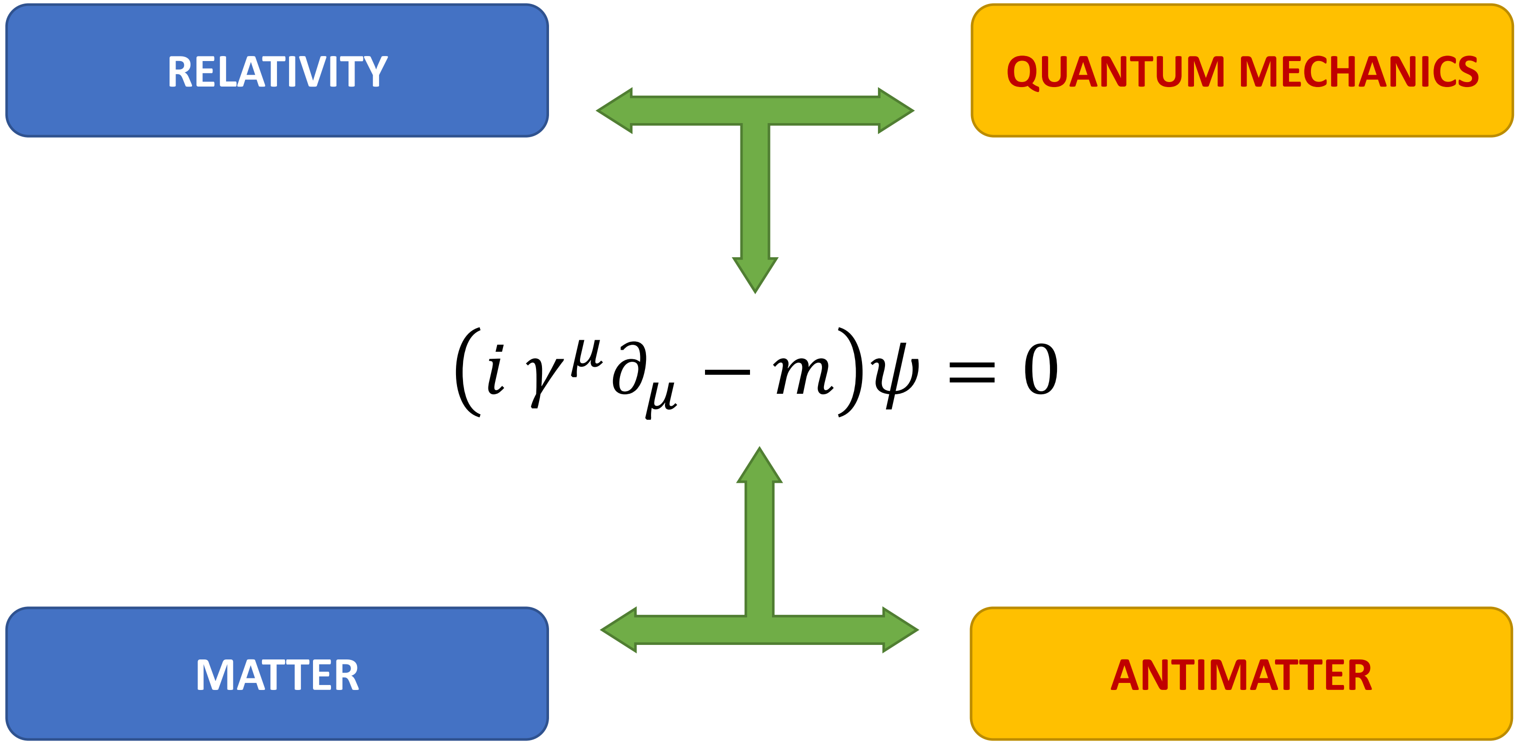
ANTIMATTER

- The prediction of the existence of antimatter is one of the great successes of theoretical physics in the 20th century



$$\left(i\,\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$$

IT WAS NOT THAT EASY

The process of cognition

Since half the solutions must be rejected as referring to the charge + *e* on the electron, the correct number will be left to account for duplexity phenomena.

1928

would fill it, and will thus correspond to its possessing a charge + *e*. We are therefore led to the assumption that *the holes in the distribution of negative-energy electrons are the protons.* When an electron of positive energy drops into

1930

nearly all, of the negative-energy states for electrons are occupied. A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. We should not expect to find any of

1931

Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton.

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there is a strong reason that this process took 3 years....

!!! In our current universe the baryonic antimatter is gone !!!

- **Quantitative:** Baryon asymmetry in the universe (BAU)

$$\eta = \frac{N_B}{N_\gamma}\Big]_{T=3K} = \frac{N_B - N_{\bar{B}}}{N_\gamma}\Big]_{T=3K} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}\Big]_{T>1GeV} = 0.580(27) \cdot 10^{-9}$$

- **Obvious conclusion:** It is a bit too simple minded to define matter and antimatter to be “symmetric”

Need sources which produce BAU: e.g. CP violation / B-violation / T-arrow

-> known SM-CP violation produces $\eta = \frac{N_B}{N_\gamma}\Big]_{T=3K} \sim 10^{-18}$

Need additional sources which produce BAU:

- more CP violation
- CPT violation
- ...other BSM physics

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SME coefficients constrained by BASE

Using BASE proton g-factor measurements, possible to constrain the following b coefficients:

	Coefficient or combination	Limit BASE (Smorra 2017)	Limit BASE (Nagahama 2017)	Previous Limits (DiSciacca 2013)
Minimal SME	$\lvert\tilde{b}_Z\rvert$	< 1.8 × 10^{-24} GeV	< 2.1 × 10^{-22} GeV	< 2 × 10^{-21} GeV
Minimal SME	* $\lvert\tilde{b}_Z\rvert$	< 3.5 × 10^{-24} GeV	< 2.6 × 10^{-22} GeV	< 6 × 10^{-21} GeV
Non-minimal SME	$\lvert\tilde{b}_{F,p}^{XX}+\tilde{b}_{F,p}^{YY}\rvert$	< 1.1 × 10^{-8} GeV^{-1}	< 1.2 × 10^{-6} GeV^{-1}	< 1 × 10^{-5} GeV^{-1}
Non-minimal SME	$\lvert\tilde{b}_{F,p}^{ZZ}\rvert$	< 7.8 × 10^{-9} GeV^{-1}	< 8.8 × 10^{-7} GeV^{-1}	< 1 × 10^{-5} GeV^{-1}
Non-minimal SME	* $\lvert\tilde{b}_{F,p}^{*XX}+\tilde{b}_{F,p}^{YY}\rvert$	< 7.4 × 10^{-9} GeV^{-1}	< 8.3 × 10^{-7} GeV^{-1}	< 2 × 10^{-5} GeV^{-1}
Non-minimal SME	* $\lvert\tilde{b}_{F,p}^{ZZ}\rvert$	< 2.7 × 10^{-8} GeV^{-1}	< 3.0 × 10^{-6} GeV^{-1}	< 8 × 10^{-6} GeV^{-1}

3 orders of magnitude improvement in limits

A. Mooser *et al.*, Nature **509**, 596 (2014).
J. DiSciacca et al., PRL **110**, 130801 (2013).
Y. Ding and V. A. Kostelecký Phys. Rev. D 94, 056008 (2016).
V. A. Kostelecký, N. Russell, arXiv:0801.0287v12 (2019).
C. Smorra et al., Nature **550**, 371 (2017).
H. Nagahama et al., Nat. Comm. **8**, 14084 (2017).

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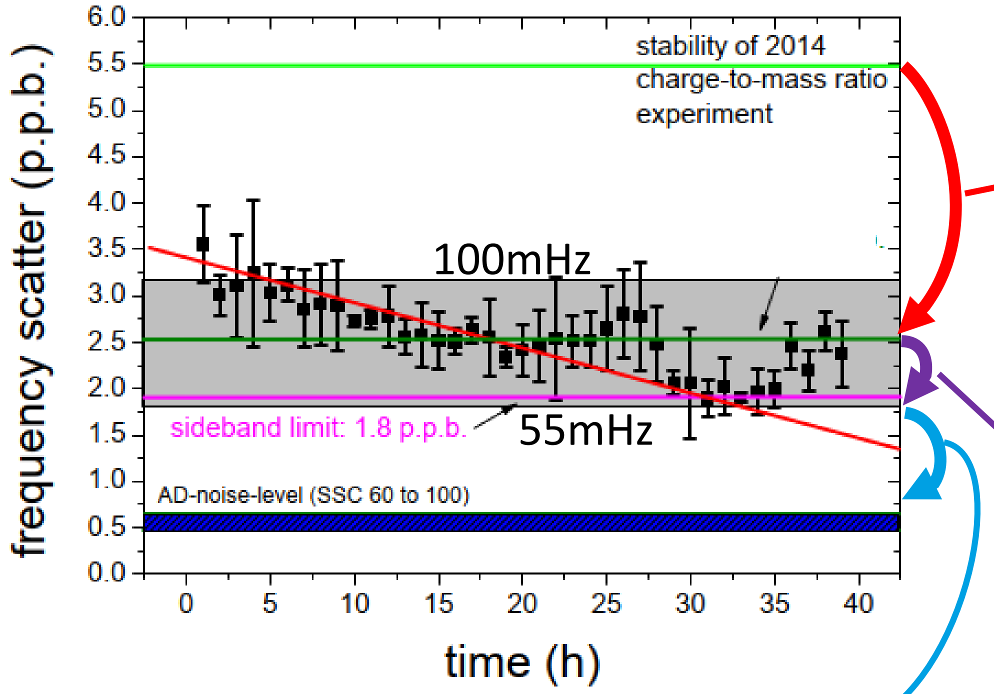
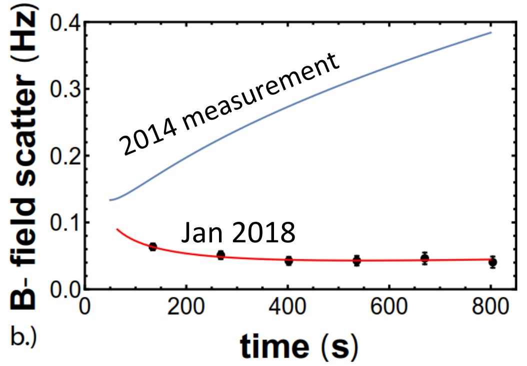
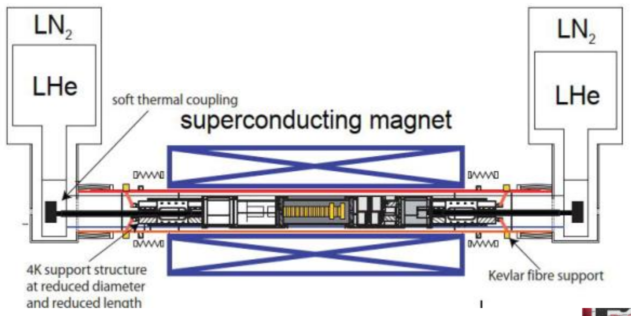
Progress towards a better q/m measurement



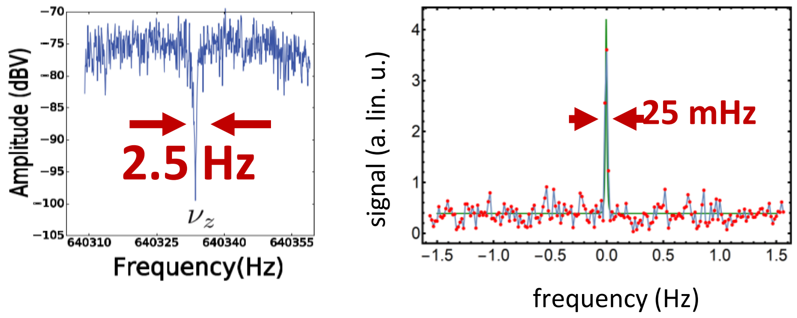
Better stabilisation of cryoliquid pressure, temperature improves magnetic stability



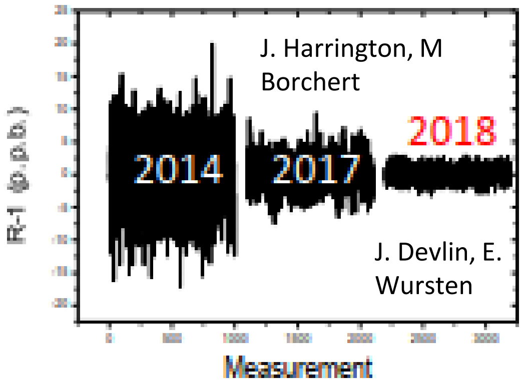
Mechanical upgrade more stable and lower heat load means fewer vibrations



peak measurement technique



Also, tunable axial detector removes dominant 2014 systematic



Next step: Spectroscopy on two particles in one trap.

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