High-Precision Comparisons of the Fundamental Properties of Protons and Antiprotons

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RIKEN

stationed at

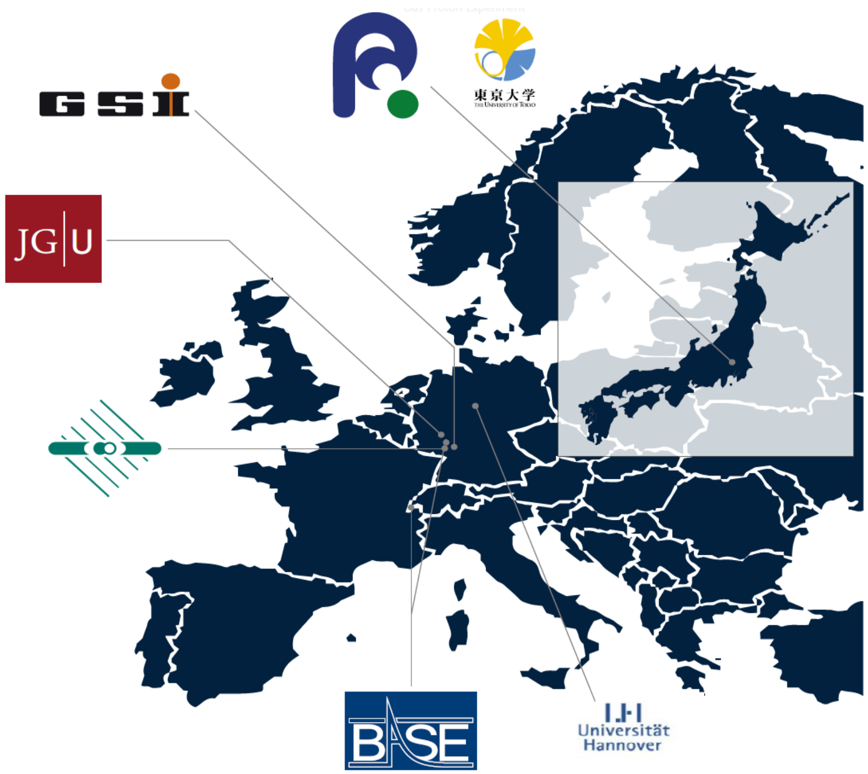
CERN

BASE – Collaboration

- **Mainz:** Measurement of the magnetic moment of the proton (Ulmer, Blaum, Walz, Quint).

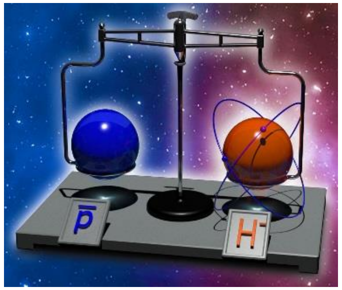
- **CERN-AD:** Measurement of the magnetic moment of the antiproton and proton/antiproton q/m ratio (Ulmer, Yamazaki, Blaum, Matsuda).

- **Hannover/PTB:** QLEDS-laser cooling project (Ospelkaus, Ulmer)

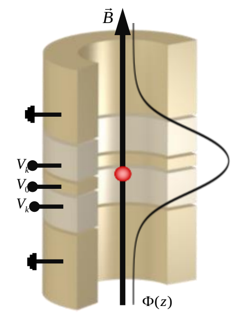


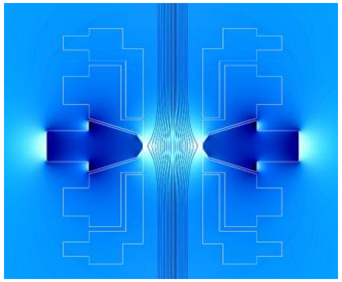
Outline

- Introduction / physics motivation



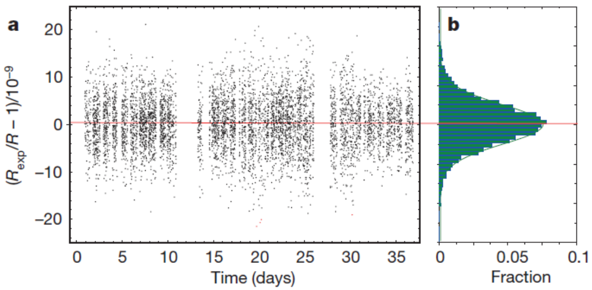
- Experimental principle

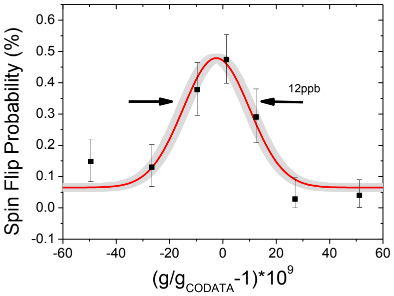




- Measurements:
  – q/m and magnetic moment

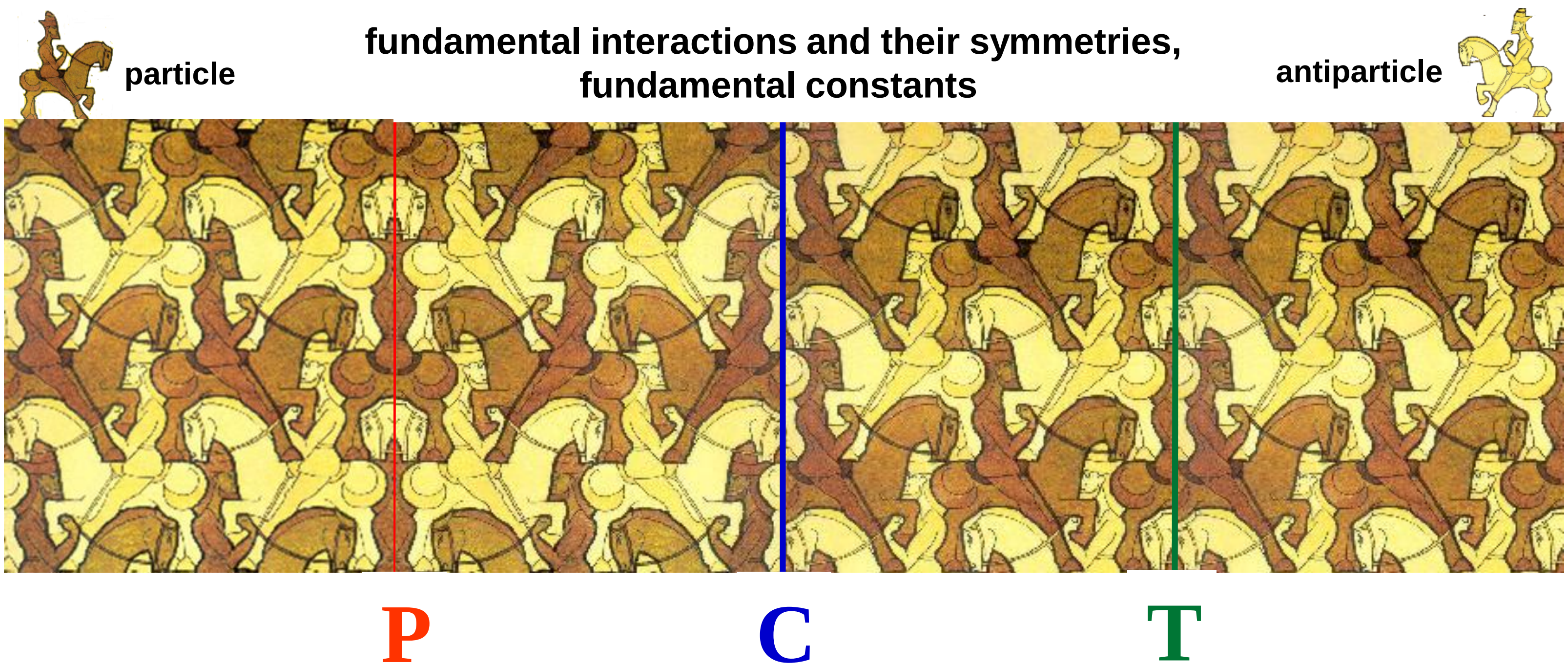
- Results





Testing CPT Invariance

- CPT invariance is the most fundamental discrete symmetry in the Standard Model of particle physics.



- CPT theorem => fundamental properties of matter and antimatter conjugates are identical => Comparing these properties precisely => stringent test of CPT symmetry

Matter / Antimatter Asymmetry

apart from the fundamental nature of CPT symmetry:

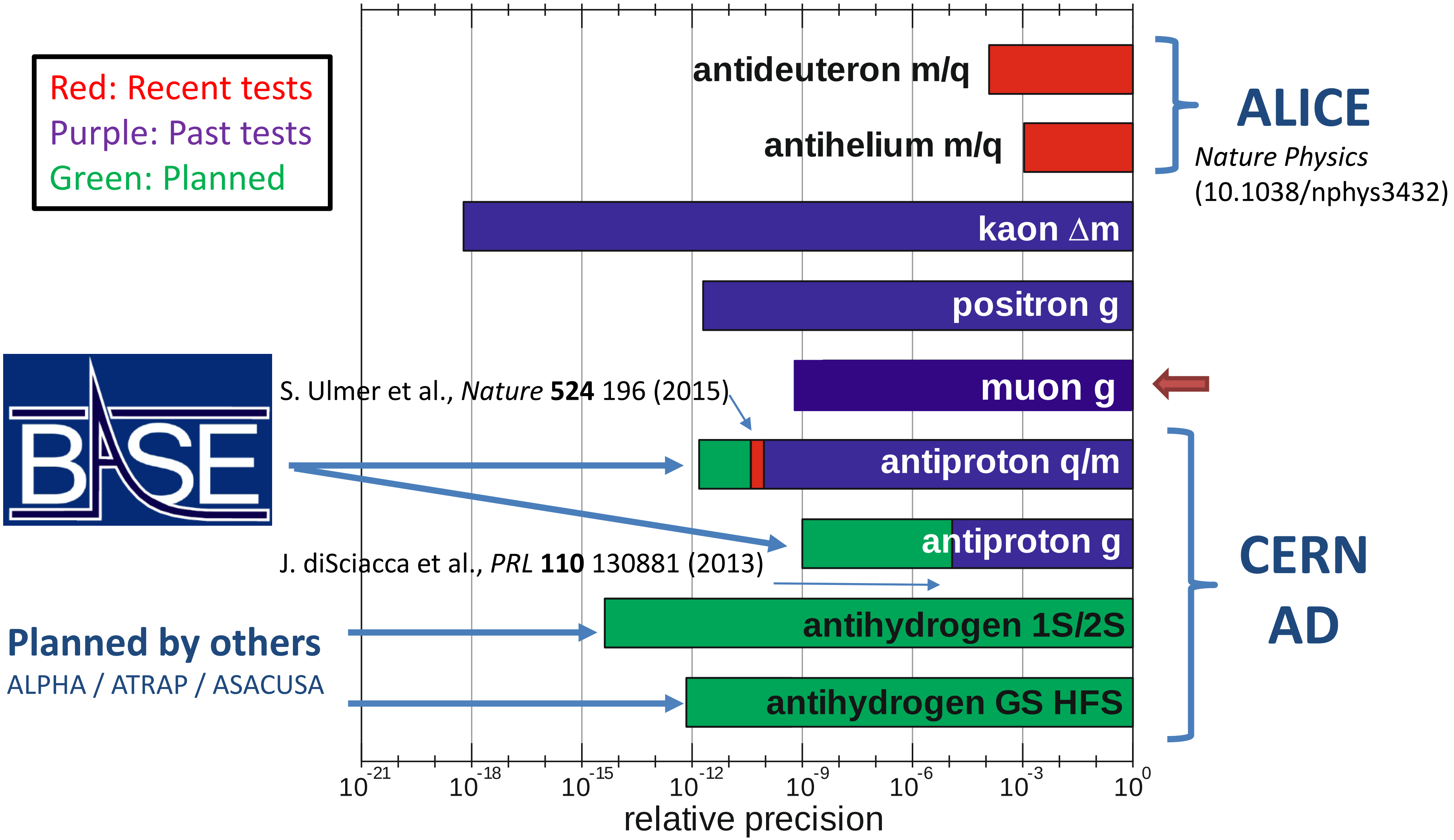
Matter dominance of the Universe, and thus the physics of our existence, has yet to be understood.

Observed SM-CP violation is by **orders of magnitude too small** to explain matter excess observed in our Universe.

CPT violation is (in some models) a possible source for the observed baryon asymmetry.

Different CPT tests

Red: Recent tests
Purple: Past tests
Green: Planned



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

Concept of CPT violation

- Basic idea: Add CPT violating term to a Hamiltonian based on Standard Model and treat as a perturbation theory

  => Absolute energy change ΔE will be derived

$$H' = H_{SM} + \Delta V \quad \Rightarrow \quad < \psi^* | \Delta V | \psi >= \Delta E$$

System based on SM $\rightarrow H_{SM}$

CPT violating term $\rightarrow \Delta V$

different C's

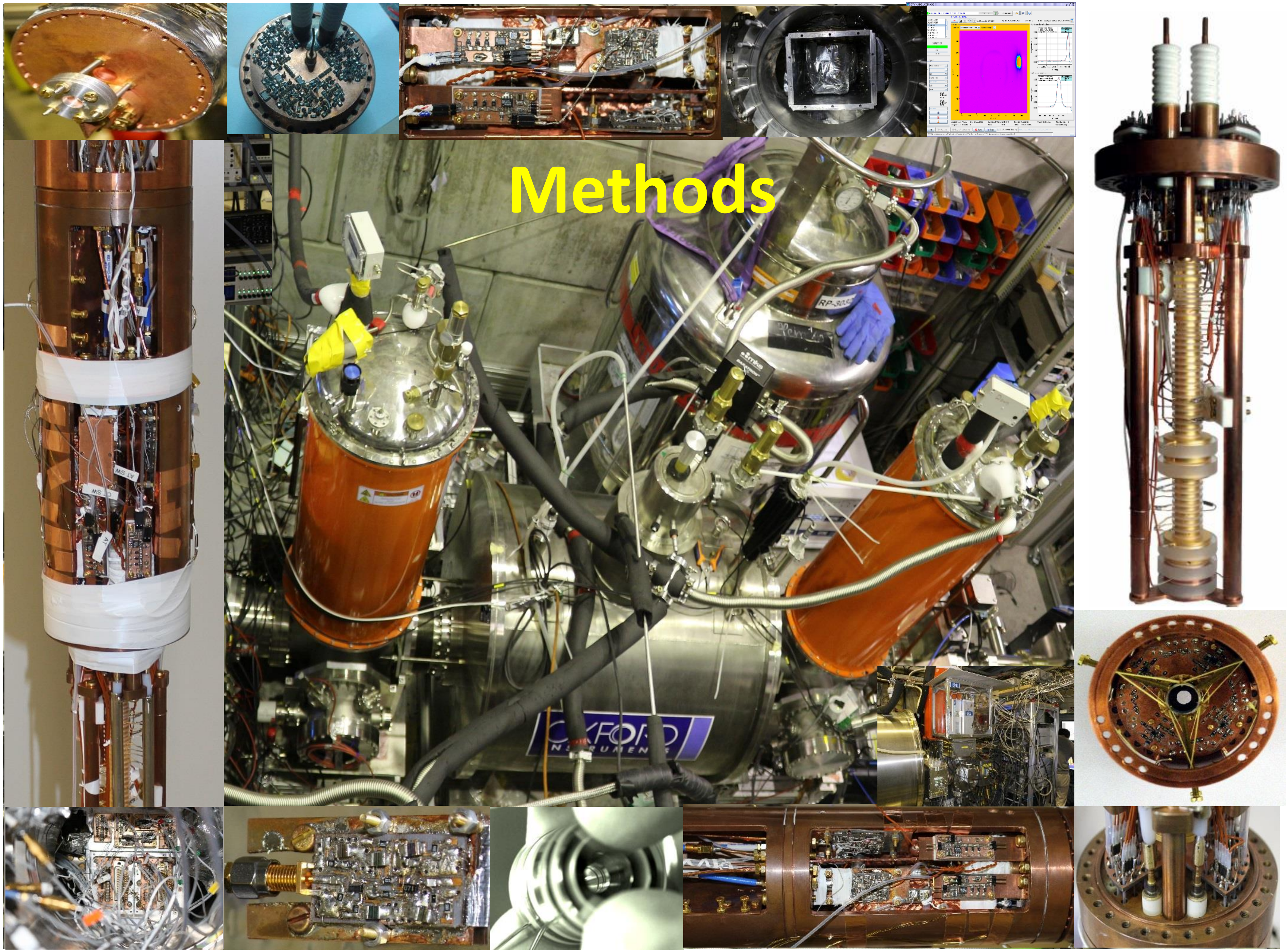
$$\mathcal{L}_p = \frac{\lambda}{M} \langle T \rangle \bar{\psi} \Gamma (i\partial)^k \psi$$

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}

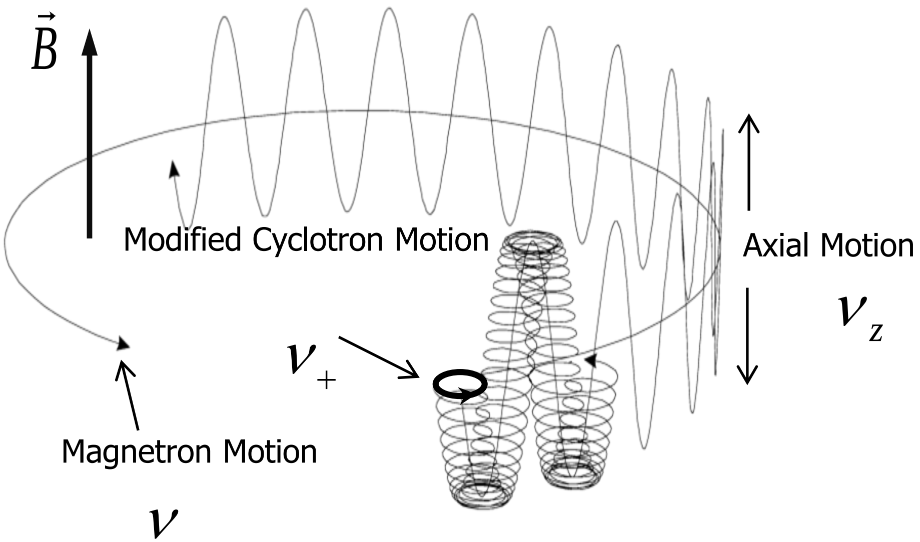
Methods

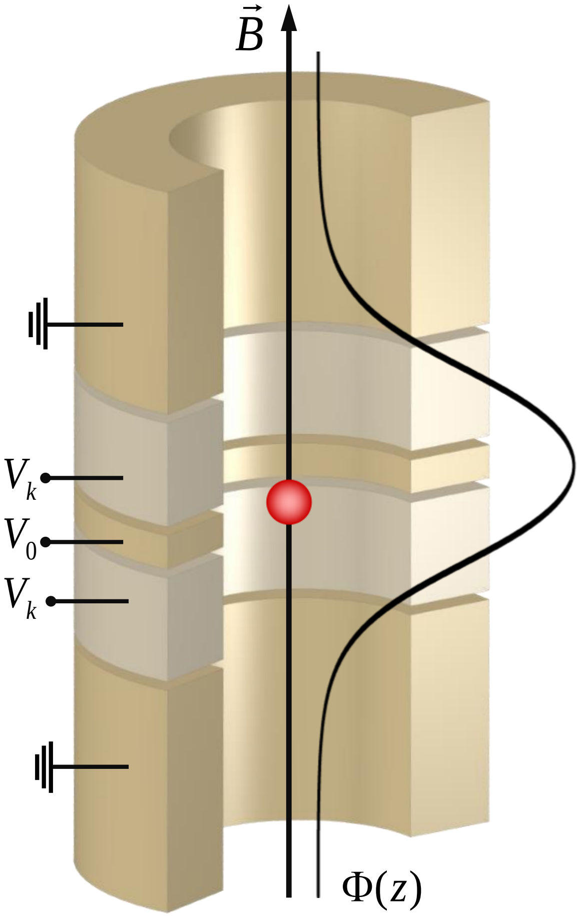


Main Tool: Penning Trap

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

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





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

Invariance-Relation

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

Cyclotron Frequency

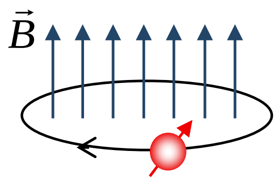
$$\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

Measurements

Experiments performed with single particles in Penning traps

Cyclotron Motion

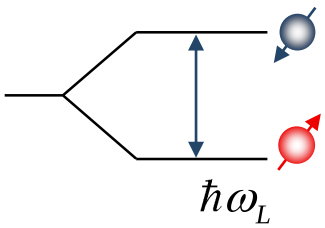
Larmor Precession



g: mag. Moment in units of nuclear magneton

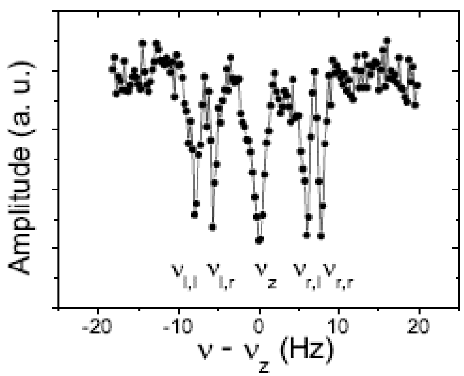
$$\omega_c = \frac{e}{m_p} B$$

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



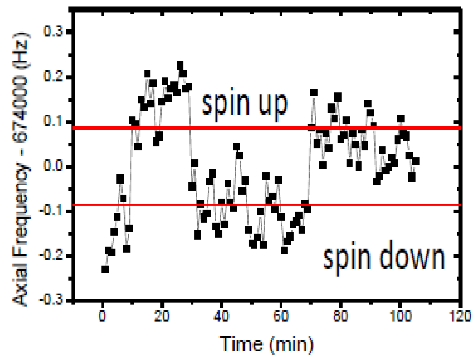
simple

difficult



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

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



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

Determination of the g-factor reduces to measurement of a frequency ratio -> in principle **a very simple** experiment –> **full control, no theoretical corrections**

Non-destructive ion detection

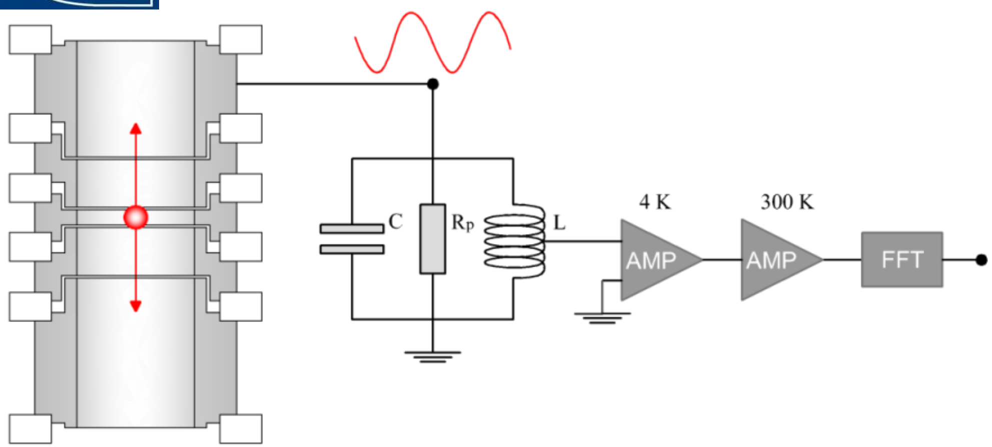


Image current: $I_p = \omega \, q \, \frac{r}{D}$

About 10 fA signal needs to be detected!

Resonance frequency: $\omega_{res} = \frac{1}{\sqrt{L\,C}}$

Matched to one of the particle frequencies

Acts as effective resistance in resonance:

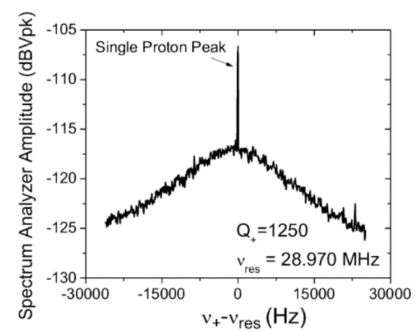
$R_p = \omega \, L \, Q$

Consequences:

- **A signal at the eigenfrequency of the particle can be detected**
- **The particle dissipates energy and is resitively cooled**

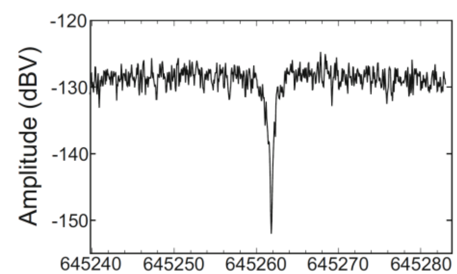
$$U = R_p \, I_p$$

$$\tau = \frac{m \, D^2}{q^2 \, R_p}$$

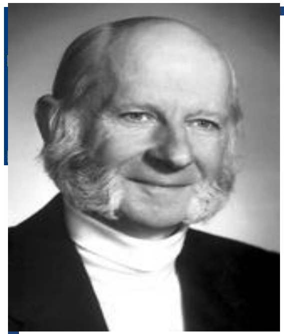


Cooled to Thermal Equilibrium:

- **Particle shorts thermal noise of the detector**
- **Frequency measurements at low amplitudes**

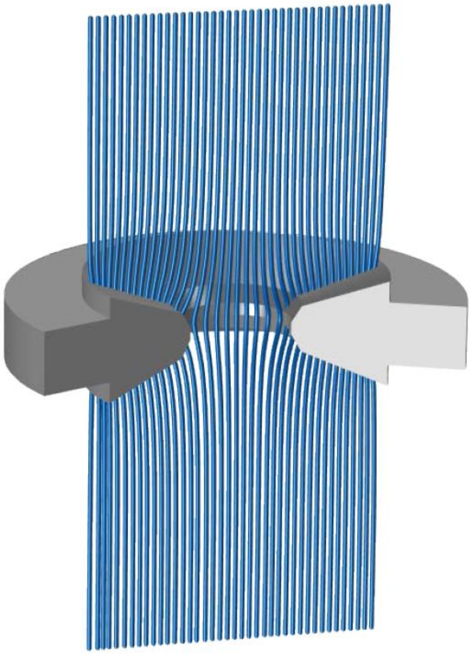


S. Ulmer *et al.*, Phys. Rev. Lett **107**, 130005 (2011).



Larmor Frequency

Measurement based on continuous Stern Gerlach effect.



Energy of magnetic dipole in magnetic field

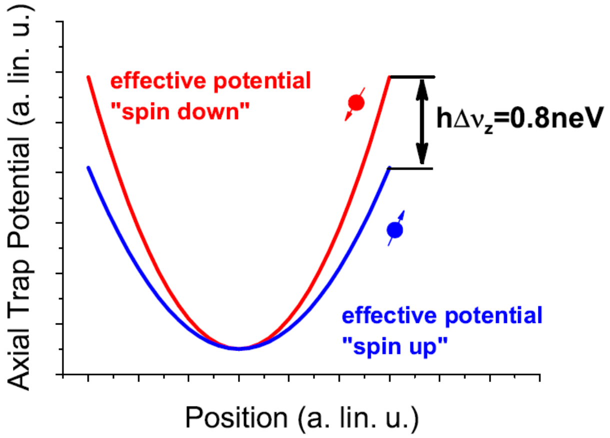
$$\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$$

Leading order magnetic field correction

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

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

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



- Very difficult for the proton/antiproton system.

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

- Most extreme magnetic conditions ever applied to single particle.

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

Observe driven spin transitions -> measurement of resonance

Larmor Frequency Measurement

Measure axial frequency stability:

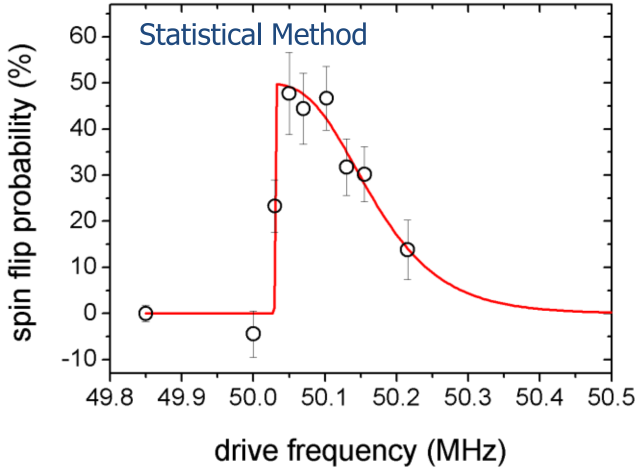
1.) reference measurement with detuned drive on,

2.) measurement with resonant drive on.

Spin flips add up

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

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



g/2 = 2.792 848 (24) Rodegheri et al., NJP 14, 063011, (2012)

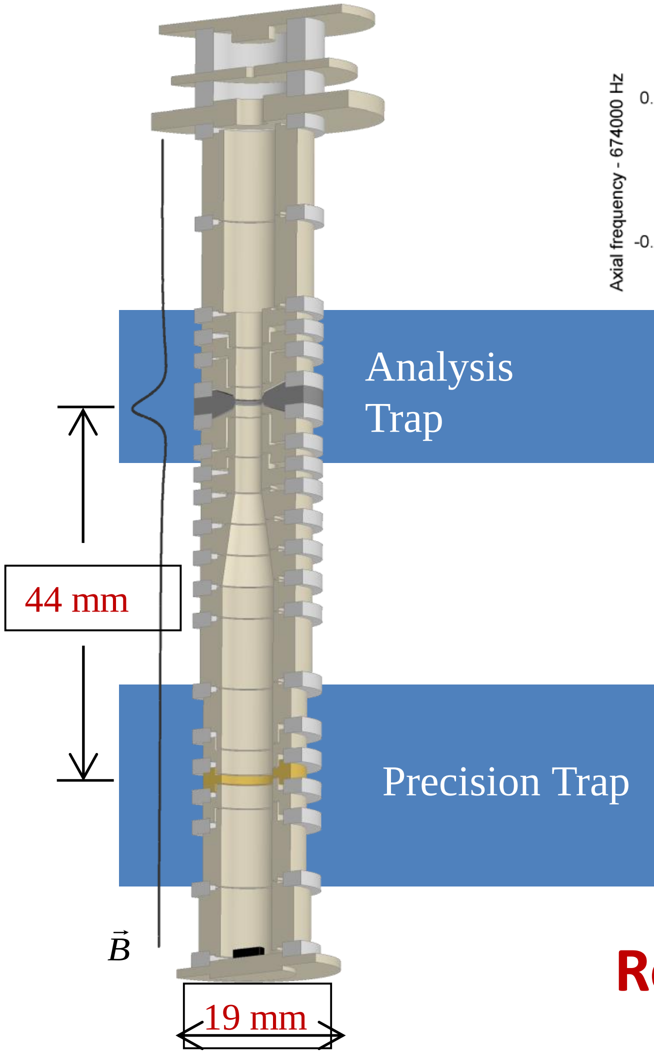
g/2 = 2.792 846 (7) di Sciacca et al., PRL 108, 153001 (2012)

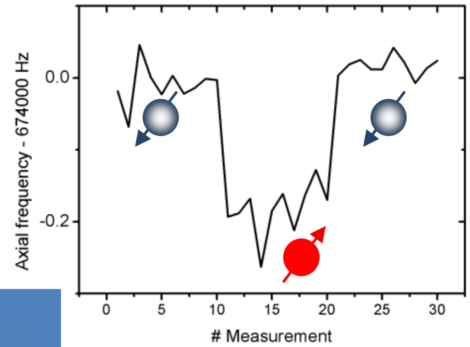
Statistical Method:

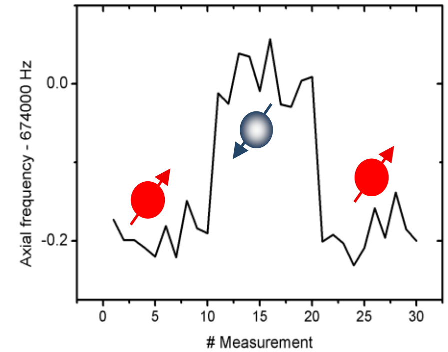
Limited by the strong magnetic bottle.

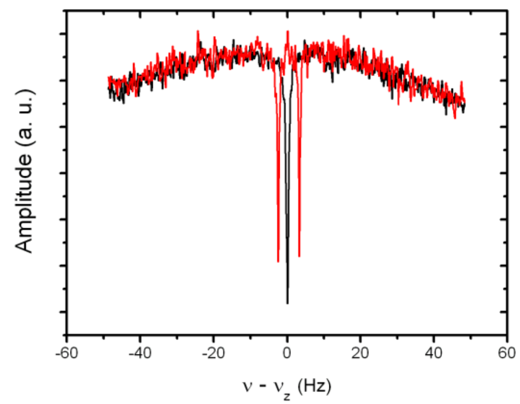
Divide and Conquer - Double Trap Method

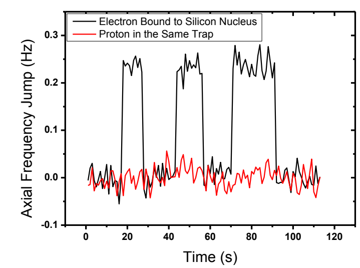
Idea: Separate spin state analysis and precision frequency measurements.











Requires clear identification of the spin state

H. Häffner, Phys. Rev. Lett.85, 5308 (2000)

The Challenge

Typical axial frequency: 700 kHz

$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := 0.4 \cdot \mu Hz \cdot B_2$$

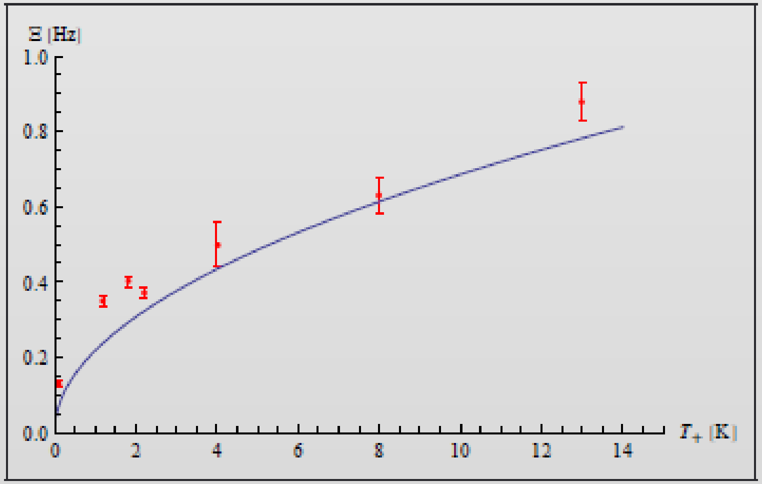
We use: $B_2 = 300000\ T/m^2$

170 mHz out of 740 kHz

Magnetic bottle coupling: $\Delta\nu_z = \frac{1}{4\pi^2 m \nu_z}\frac{B_2}{B_0}(dE_+ + dE_-)$ -> 1 Hz/µeV

One cyclotron quantum jump (70 neV) shifts axial frequency by 70mHz

Tiny heating of the axial mode results in significant fluctuation of the axial oscillation frequency. **-> Three cyclotron quanta (0.2 µeV) -> fidelity to 50%**



Frequency fluctuation as function of T_+

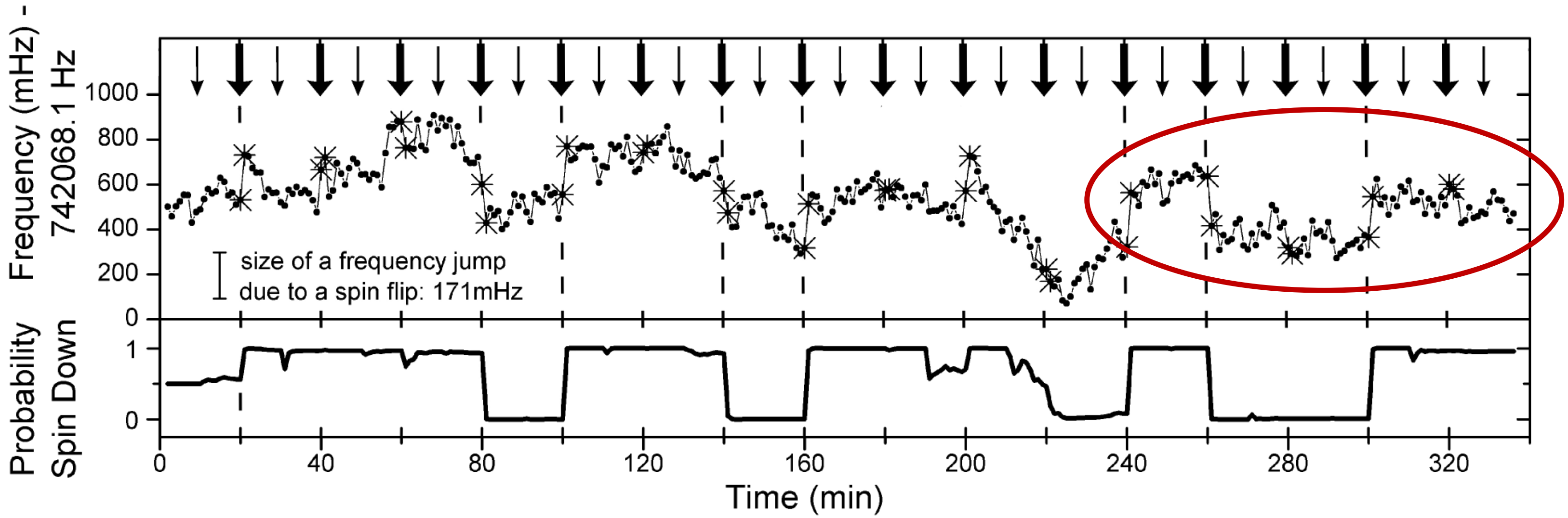
$$R_{n\to n\pm1} = \frac{q^2}{2m_p\hbar\omega}\left(n+\frac{1}{2}\pm\frac{1}{2}\right)\underbrace{\int_{\mathbb{R}}dt'\, e^{\pm i\omega t}\left\langle E^{(1)}(t)E^{(1)}(t+t')\right\rangle}_{S(\pm\omega)}$$

Important message: heating rates scale with the cyclotron quantum number!!!

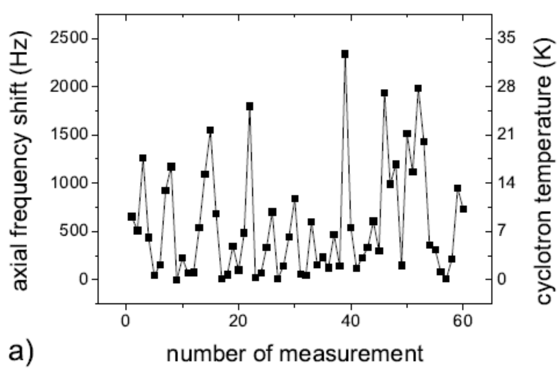
Our heating rates correspond to noise on electrodes of some pV/Hz$^{1/2}$.

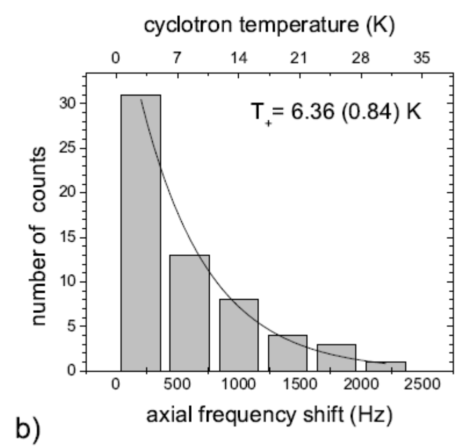
Single Spin Flips and Double Trap Method

- Improvement of apparatus, trap wiring, quality of detection systems (lower noise, faster measuring cycles).
- Based on Bayesian filter -> fidelity of > 90% achieved



A. Mooser, K. Franke, S. Ulmer *et al.* Phys. Rev. Lett. **723**, 78 (2013)



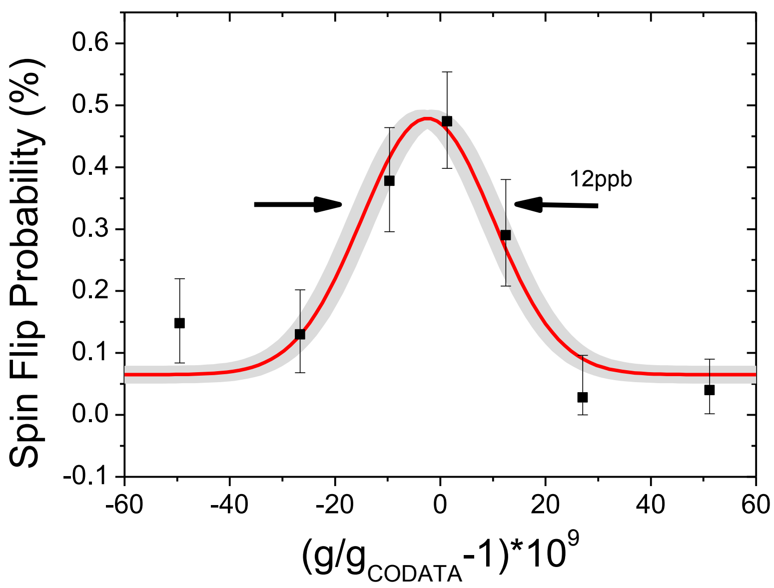


Heating rate: 10 cyclotron quantum jumps in 1h !

preparation procedure for single particle with single spin flip resolution takes 2 hours

The Magnetic Moment of the Proton

- Sweeping excitation frequency -> g factor resonance



LETTER

doi:10.1038/nature13388

Direct high-precision measurement of the magnetic moment of the proton

A. Mooser[1,2]†, S. Ulmer[3], K. Blaum[4], K. Franke[3,4], H. Kracke[1,2], C. Leiteritz[1], W. Quint[5,6], C. C. Rodegheri[1,4], C. Smorra[3] & J. Walz[1,2]

A. Mooser, S. Ulmer, K. Blaum, K. Franke, H. Kracke, C. Leiteritz, W. Quint, C. Smorra, J.Walz, **Nature 509, 596 (2014)**

Measurement listed as one of the top 10 RIKEN research highlights of the last 3 years

Line width:
due to drive-saturation and residual B_2 in the precision trap.

$g/2 = 2.792847350\ (7)\ (6)$

- First direct high precision measurement of the proton magnetic moment.
- Improves 42 year old MASER value by factor of 2.5
- Value in agreement with accepted CODATA value, but 2.5 times more precise
- One measurement -> 4 months

THE BASE EXPERIMENT

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

BASE

Antibaryon Baryon Symmetry Experiment

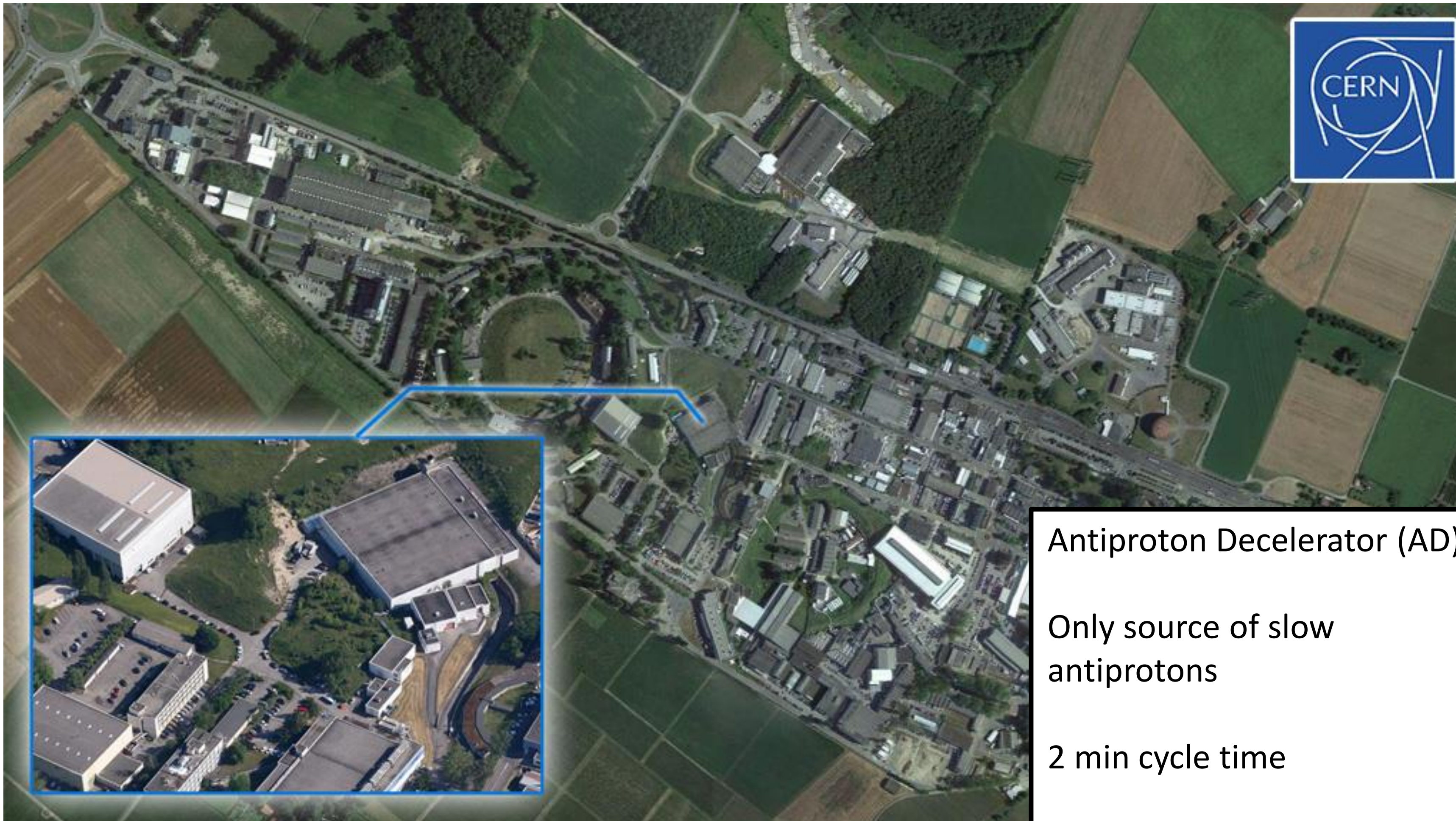
$$\frac{(q/m)_{\bar{p}}}{(q/m)_{p}}$$

$$\frac{\mu_{\bar{p}}}{\mu_{p}}$$

RIKEN

RIKEN

BASE at CERN



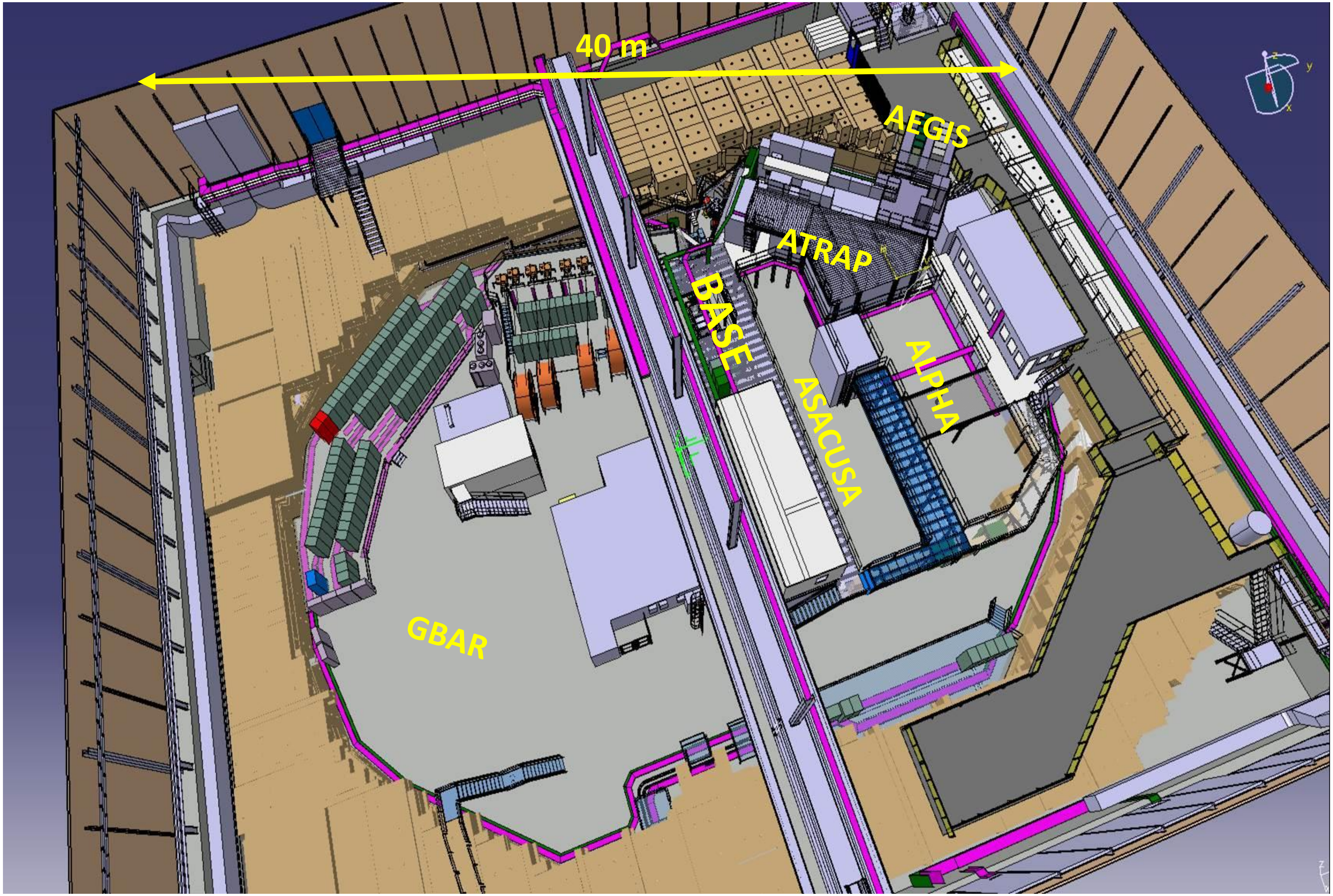
Antiproton Decelerator (AD)

Only source of slow antiprotons

2 min cycle time

35 million antiprotons
5.3 MeV kinetic energy
150 ns pulse length

BASE in the AD-facility

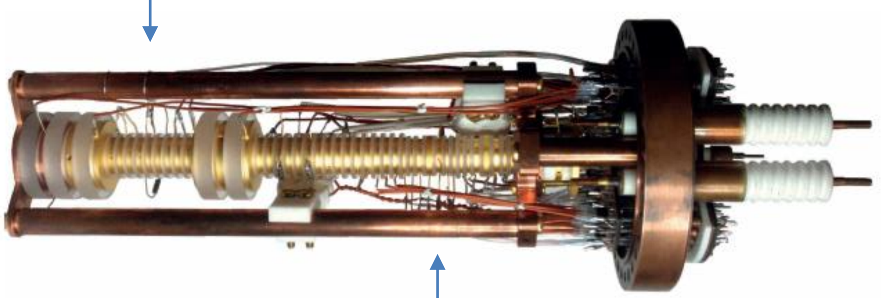


New Requirements / New Concept

Access to beamline

Particles not continuously available

Fix cyclotron cooling issues

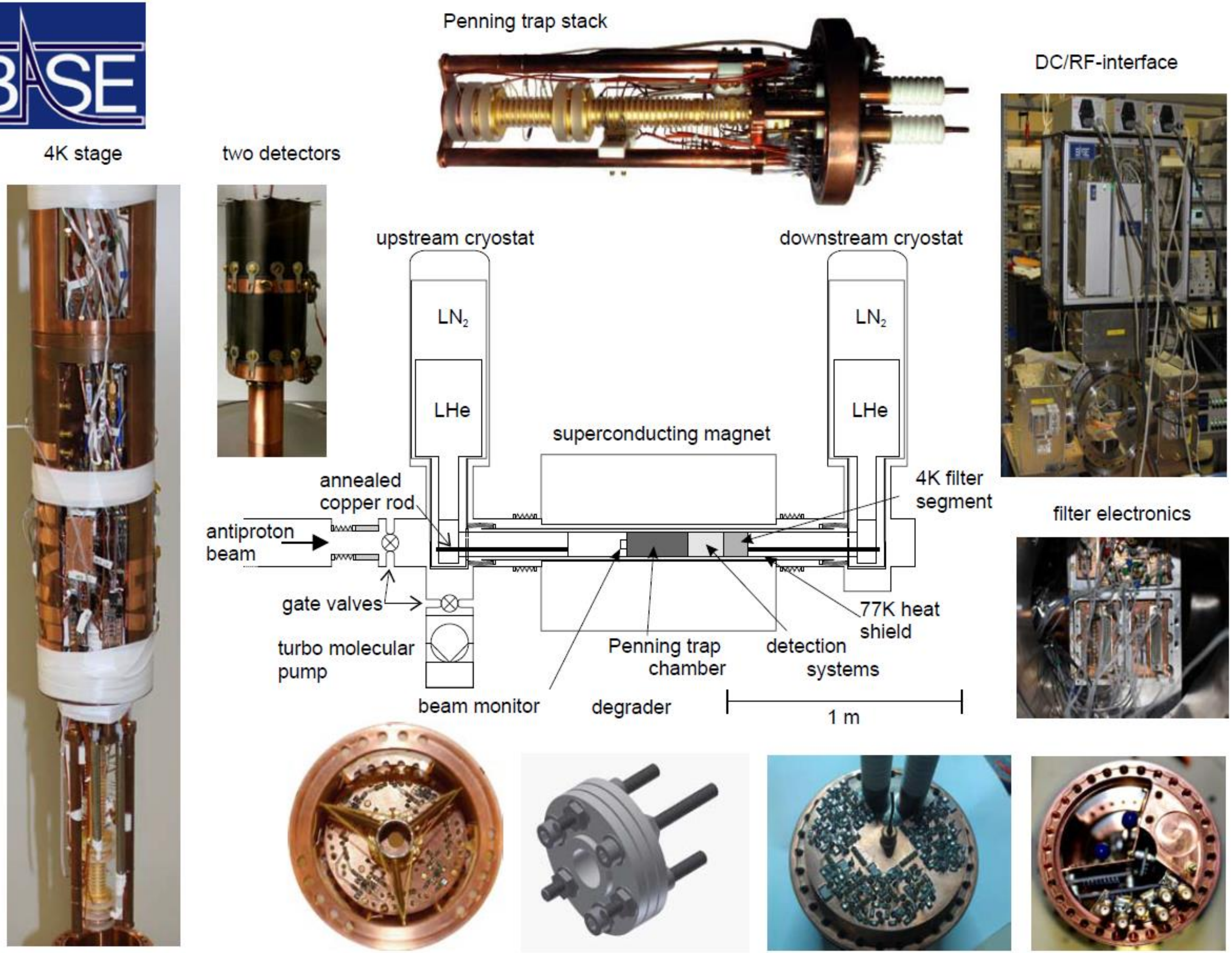


Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.
Trap is "power failure save".

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

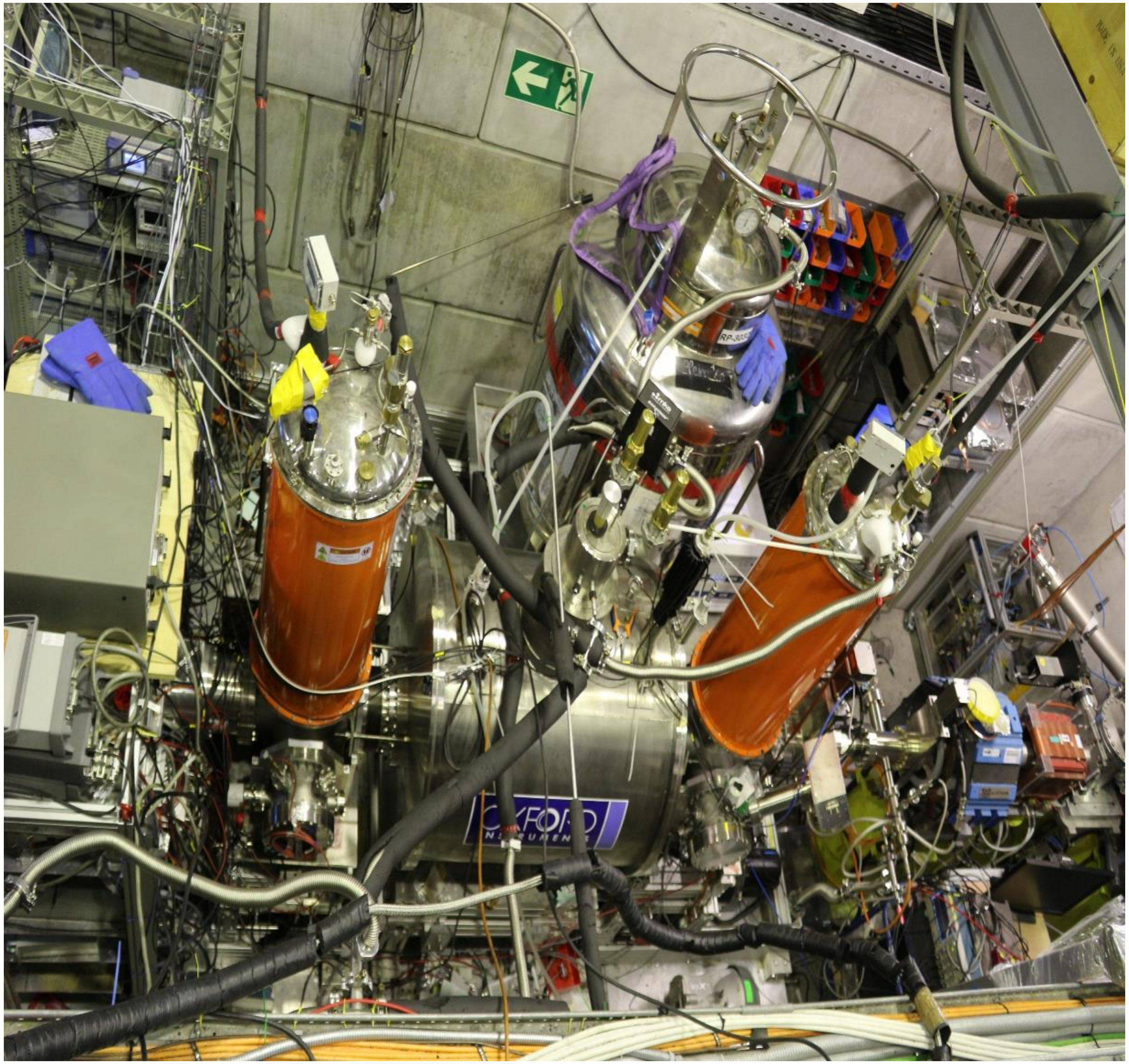
Cooling Trap: Fast cooling of the cyclotron motion, $1/\gamma < 4$ s **(10 x improved)**

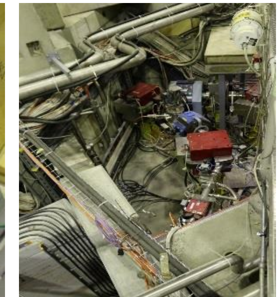
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300$ mT / mm^2

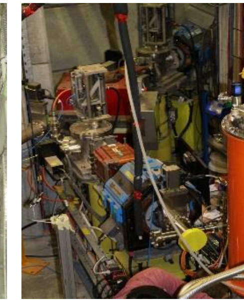


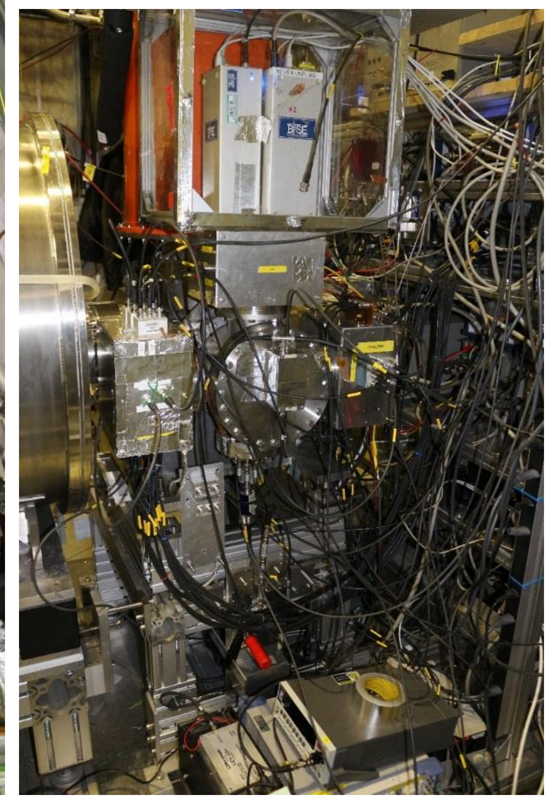
Penning trap stack
DC/RF-interface
4K stage
two detectors
upstream cryostat
downstream cryostat
LN2
LHe
LN2
LHe
superconducting magnet
annealed copper rod
4K filter segment
filter electronics
antiproton beam
gate valves
turbo molecular pump
77K heat shield
Penning trap chamber
detection systems
beam monitor
degrader
1 m

The BASE Machine

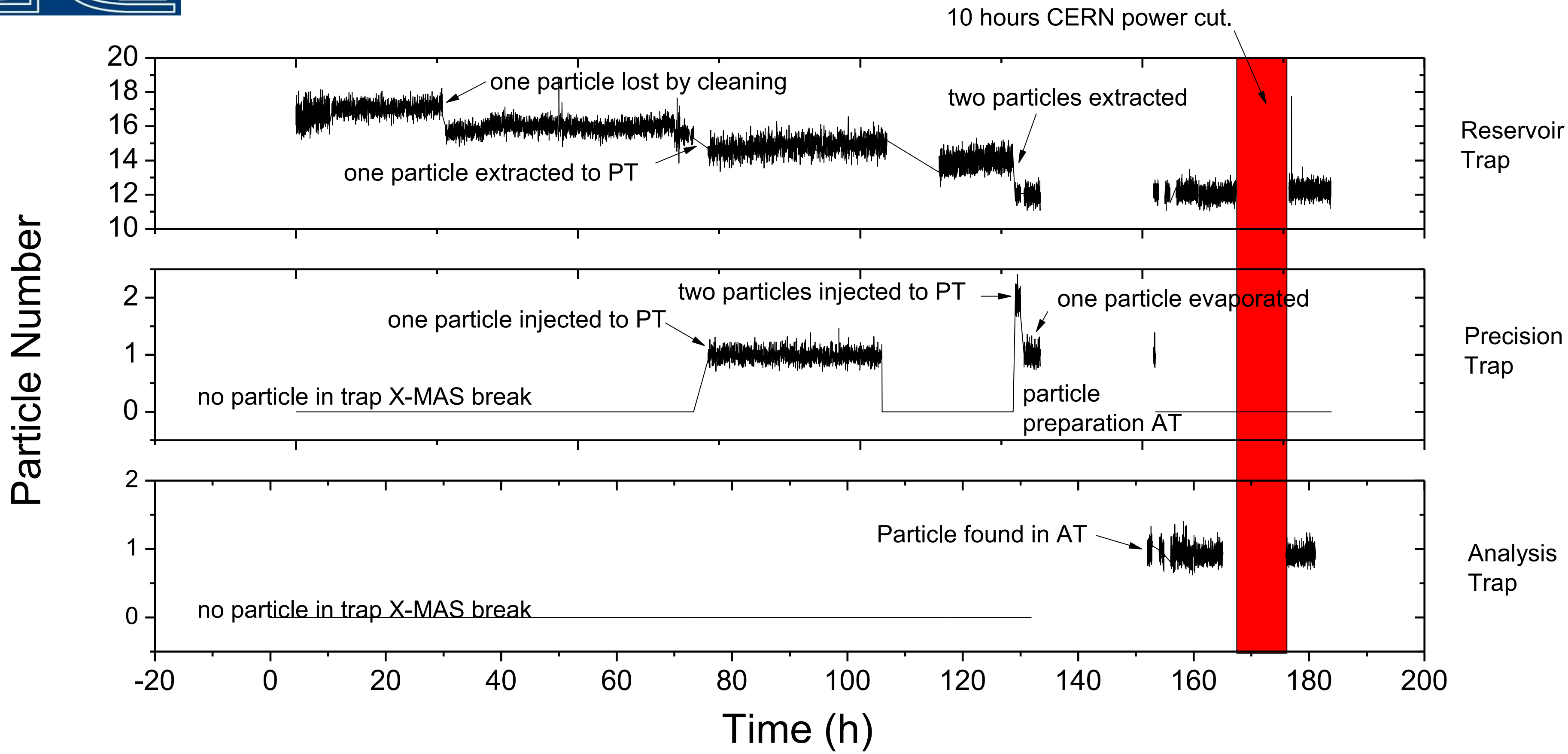








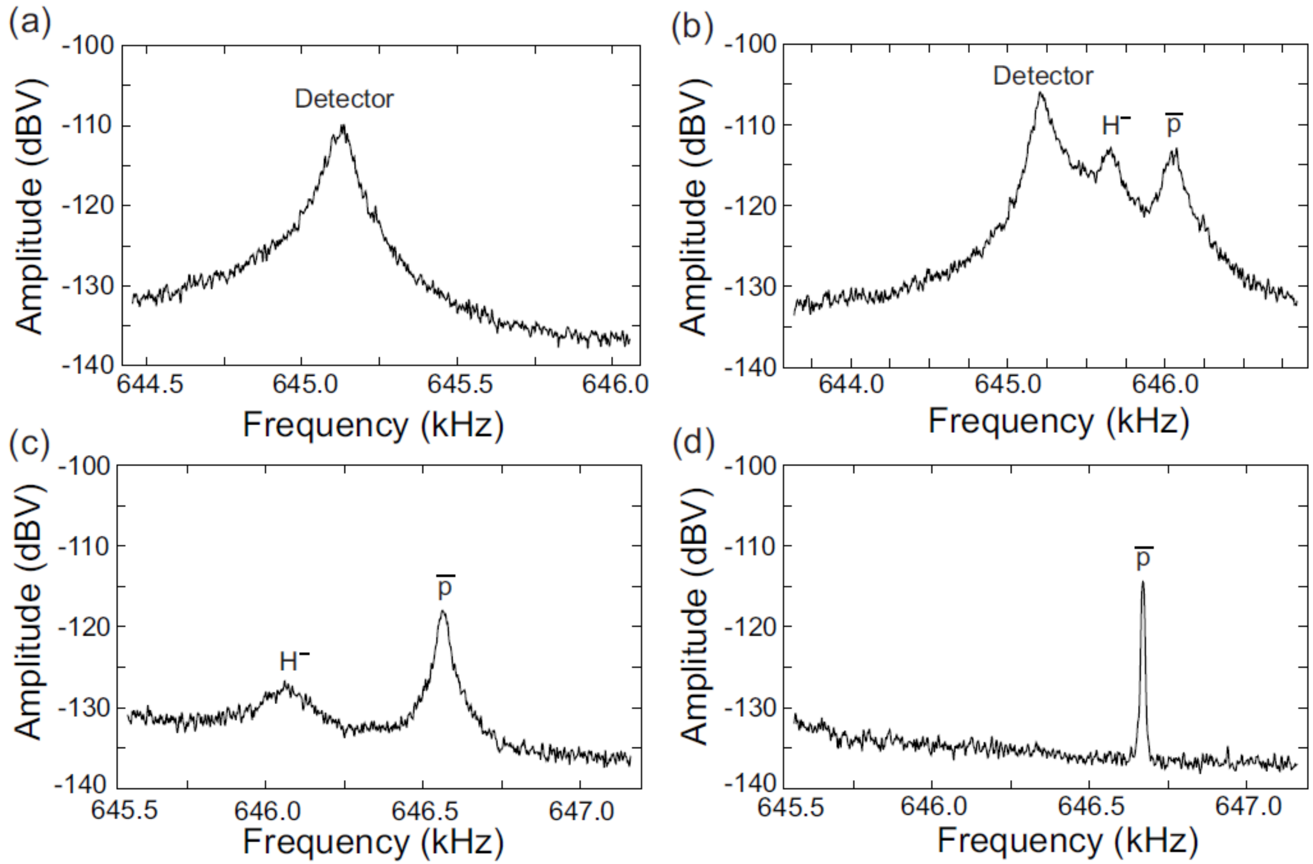
Reservoir Operation Mode



- Experiment still running.
- Consume typically 1 particle per month (mainly software glitches and human errors).

C. Smorra et al., A reservoir trap for antiprotons, Int. Journ. Mass. Spec. 389, 10 (2015).

H^- ions



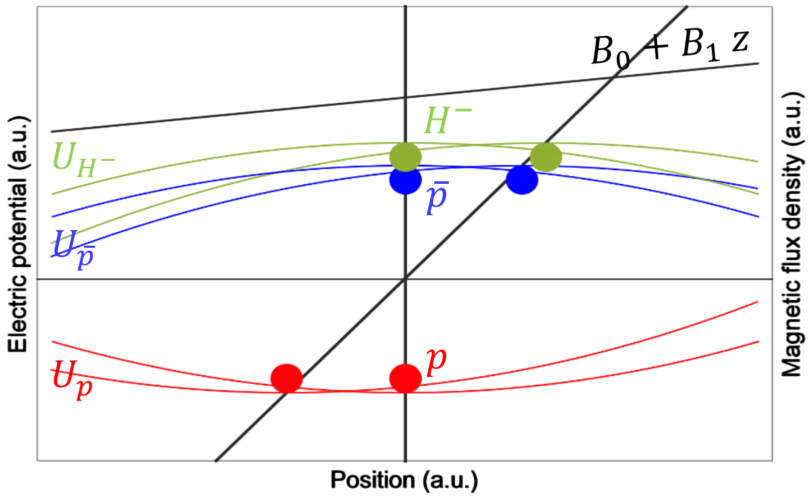
- details of H^- trapping have yet to be understood.
- managed to prepare a clean composite cloud of H^- and antiprotons.

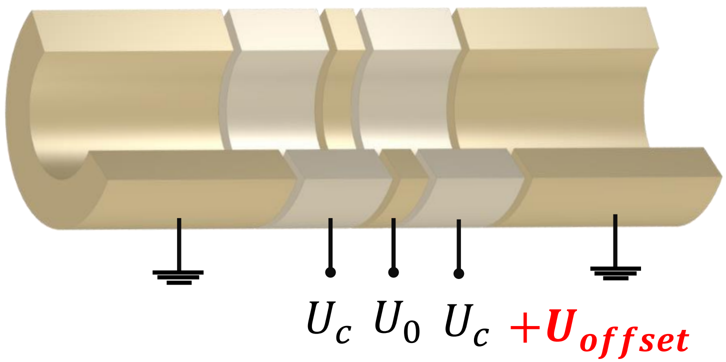
Benefits of H^- ions

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

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

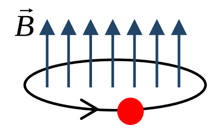
- For protons (polarity inversion (dV=10V)) much larger as for H- ions (dV=0.005V).



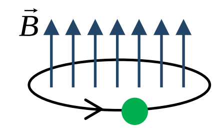


H^- ions: perfect proxies for protons

- Measure free cyclotron frequencies of antiproton and H^- ion.



antiproton



H^- ion

*using proton=>opposite charge=>position in the trap changes

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

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

Magnetic field cancels out!

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

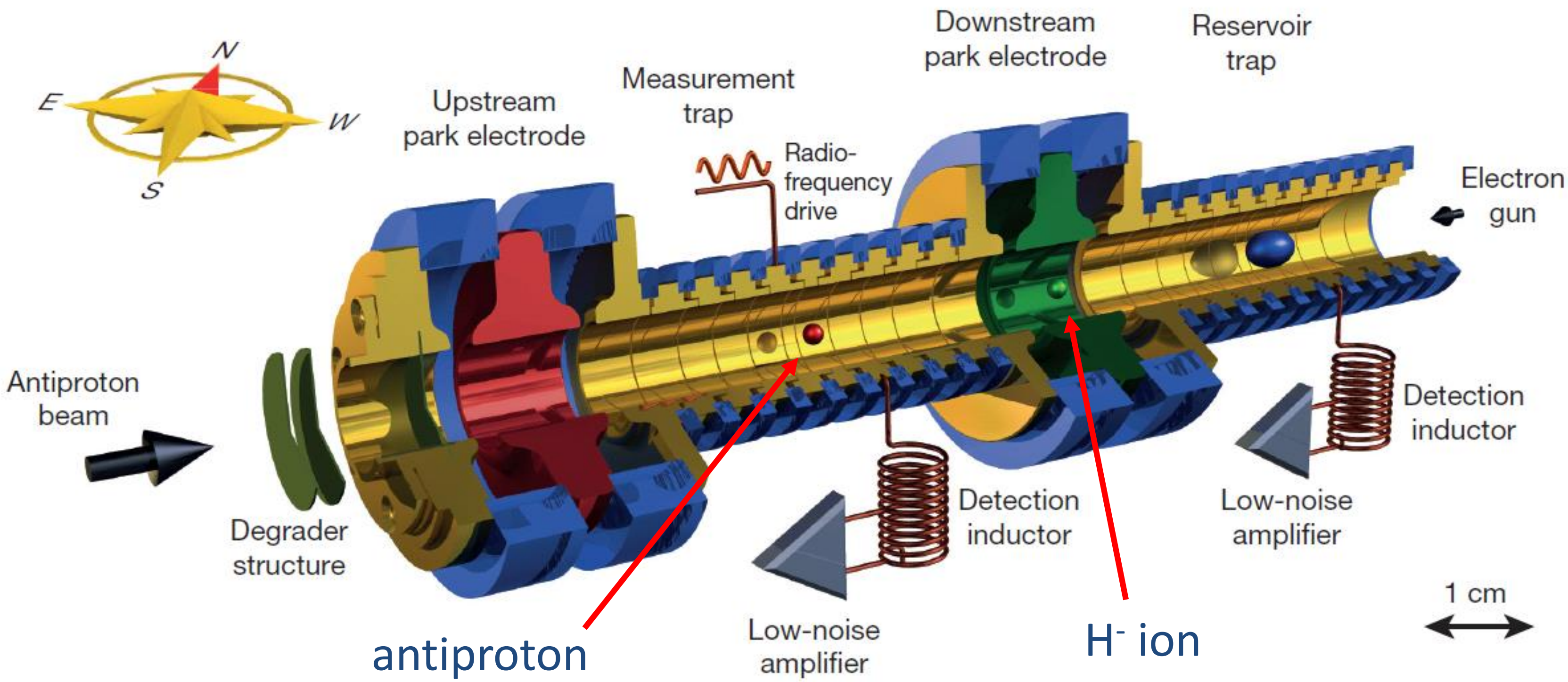
$$R_{theo} = 1.0010892187542(2)$$

Comparable measurements were carried out by the TRAP collaboration in 1990 to 1998

G. Gabrielse, A. Khabbaz, D.S. Hall, C. Heimann, H. Kalinowsky, and W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

Elegant Techniques

Based on reservoir extraction technique and developed methods to prepare negative hydrogen ions we prepared an interesting set of initial conditions

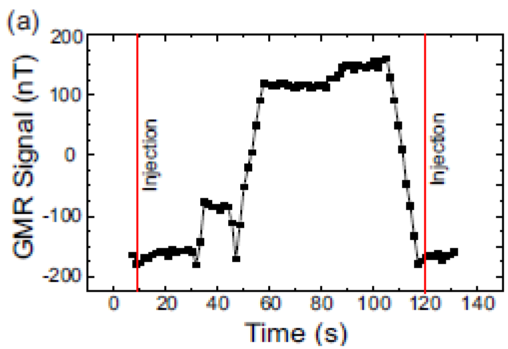


Comparison of proton/antiproton cyclotron frequencies: achieved in a not fully optimized single night test measurement a precision of 400 ppt!!!

In one night 3 times more precise than 1996 TRAP value

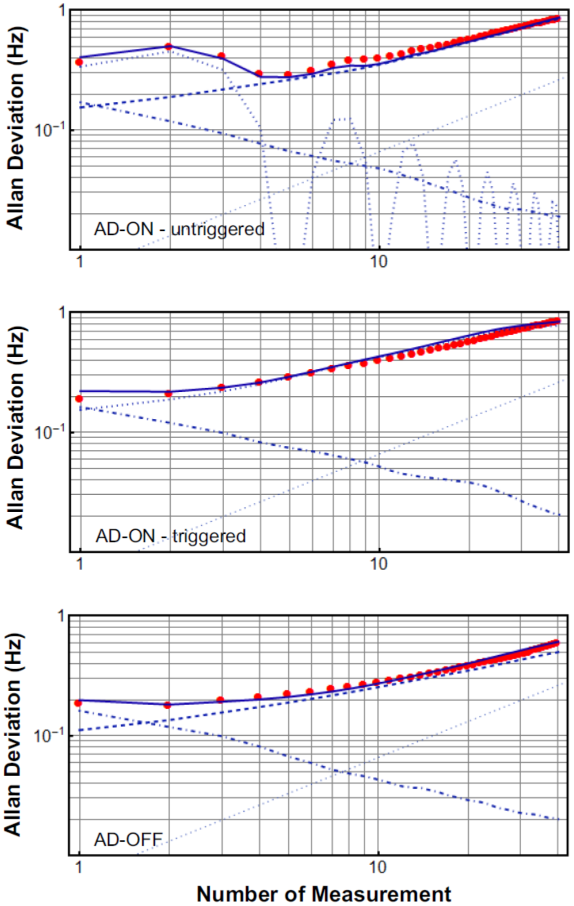
Systematic Studies

AD – Magnetic Noise



100 ppb fluctuation by the AD
Reduced by self-shielding factor of 10

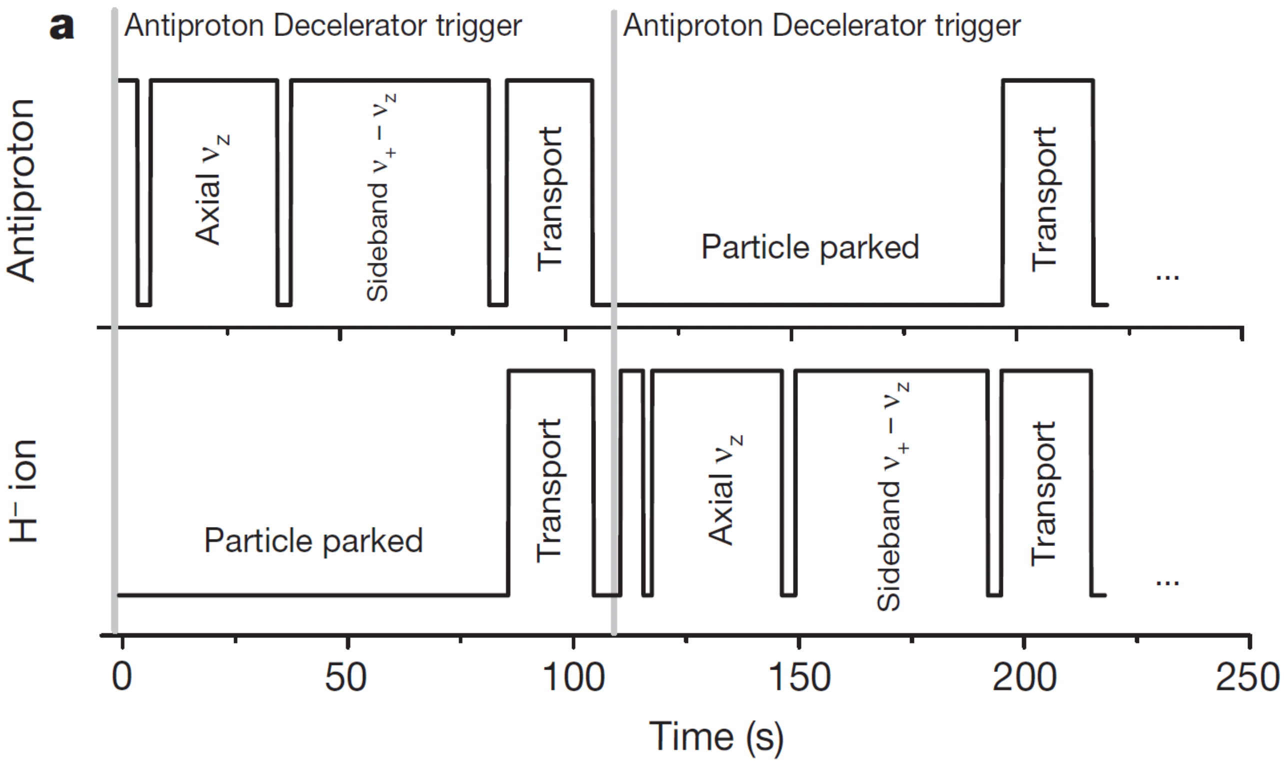
- High sampling rate enables us to perform detailed systematic studies
- Magnetic field fluctuations are the most significant uncertainty contribution

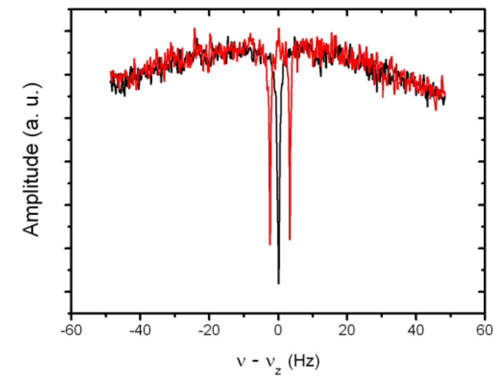


Measurement

$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$

AD cycle





$$\nu_l = \nu_z - \frac{\delta}{2} - \frac{\Omega}{4\pi}$$

$$\nu_r = \nu_z - \frac{\delta}{2} + \frac{\Omega}{4\pi}$$

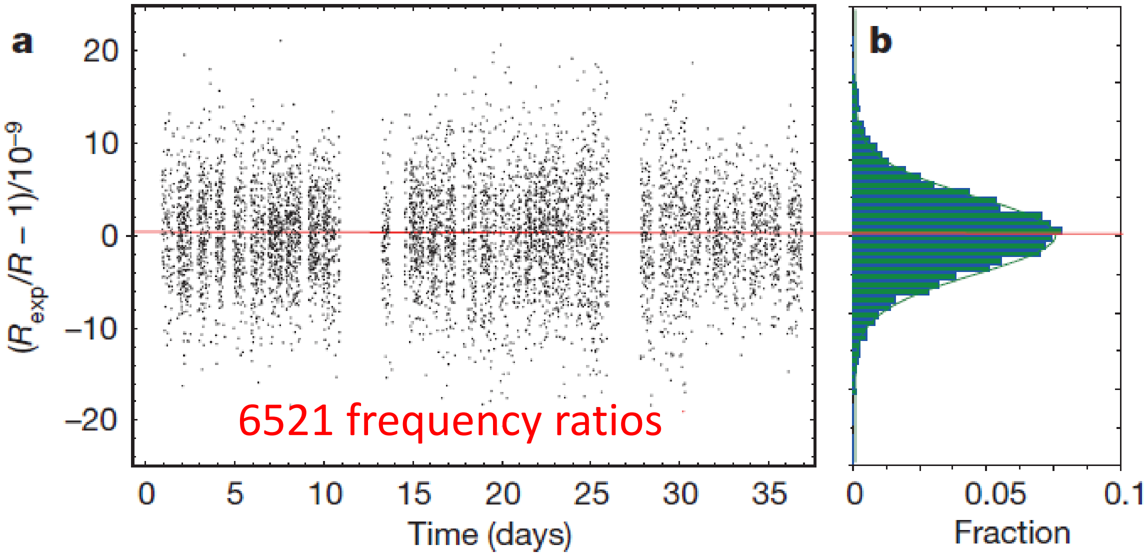
$$\nu_l + \nu_r = \nu_z + \nu_{rf} - \nu_\pm$$

Measurement cycle is triggered by the antiproton injection into the AD

One BASE charge-to-mass ratio measurement is by 50 times faster than achieved in previous proton/antiproton measurements.

First high-precision mass spectrometer which applies this fast shuttling technique

The Antimatter "Clock"



Shot/Shot:
150mHz frequency scatter

Absolute resolution:
2mHz

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

- Experimental result:

$$R_{exp} = 1.001\ 089\ 218\ 872\ (64)$$

- Cyclotron frequency ratios for $\bar{\mathrm{p}}$-to-$\bar{\mathrm{p}}$ and H^--to-H^- R_{id} are also evaluated

$$R_{id} - 1 = -3(79) \times 10^{-12}$$ ← Consistent with 1

Systematic Corrections

- Major systematic correction due to shift of particle in the magnetic B1 gradient caused by spin-flip bottle.

  – Particle shift and magnetic gradient can be determined very precisely

  dR_{B1} = -114(26) p.p.t.

  – Slight re-adjustment of the trapping potential: dR_{C4} = -3(1) p.p.t.

final experimental result: **$R_{exp,c}$ = 1.001 089 218 755 (64) (26)**

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

- In agreement with CPT conservation
- Exceeds the energy resolution of previous result by a factor of 4.

most precise test of CPT invariance with baryons

Antiproton charge-to-mass ratio

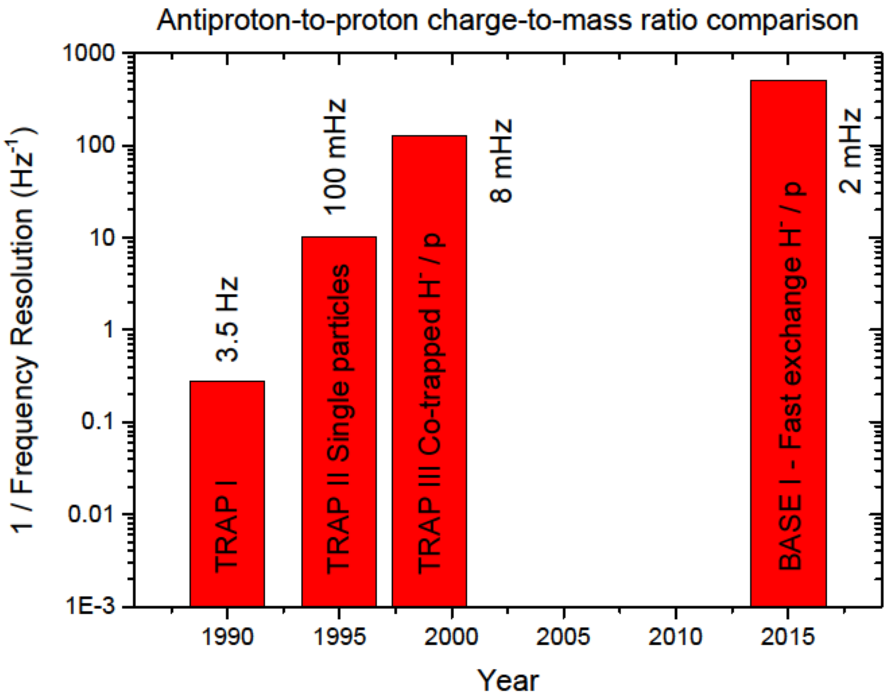
TRAP I: 100 protons vs. 100 antiprotons (40 ppb)
Limit: Coulomb interaction

TRAP II: 1 proton vs. 1 antiproton (1.1 ppb)
Limit: Magnetic field gradient
“Trap Asymmetry”

TRAP III: Co-trapped negative hydrogen ion (H^-) and antiproton (90 ppt)
Limit: Magnetic field stability,
extrapolation to zero energy

BASE I: Fast exchange of 1 H^- ion and 1 antiproton (69 ppt)
Limit: Magnetic field stability, trap asymmetry

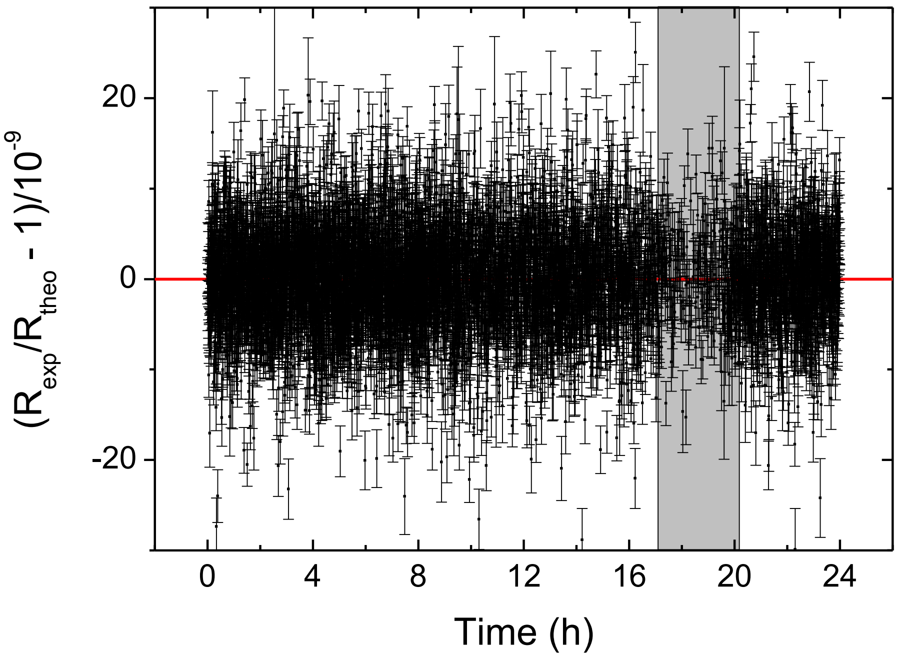
$$\frac{(q/m)_{\bar{p}}}{(q/m)_p} + 1 = 1(64)(26) \times 10^{-12}$$

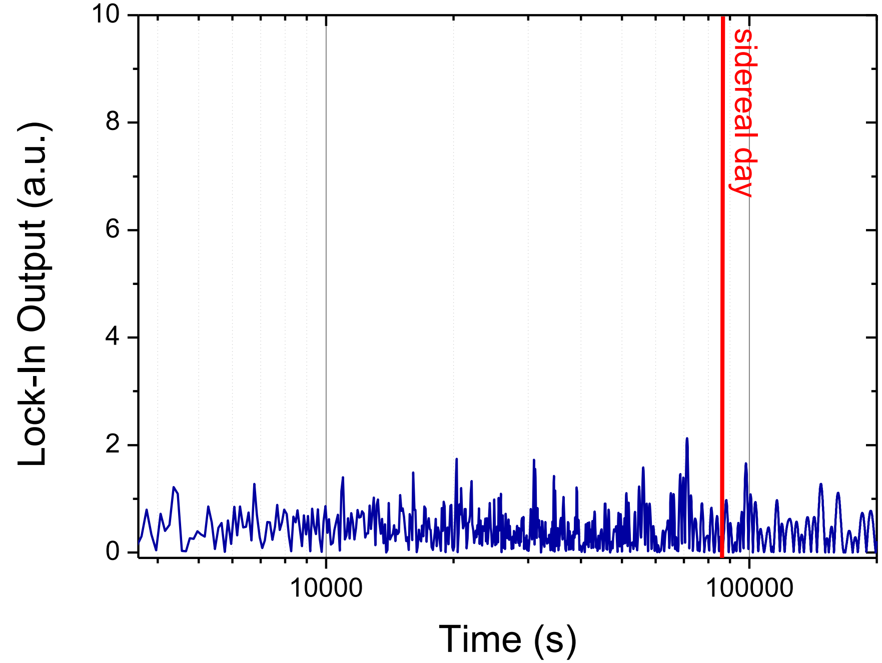


G. Gabrielse et al., Phys. Rev. Lett. 82, 3198 (1999).
G. Gabrielse, Int. J. Mass Spectr. 251, 273-280 (2006).
S. Ulmer, C. Smorra et al., Nature 524, 196-199 (2015).

Diurnal Variations (LV)

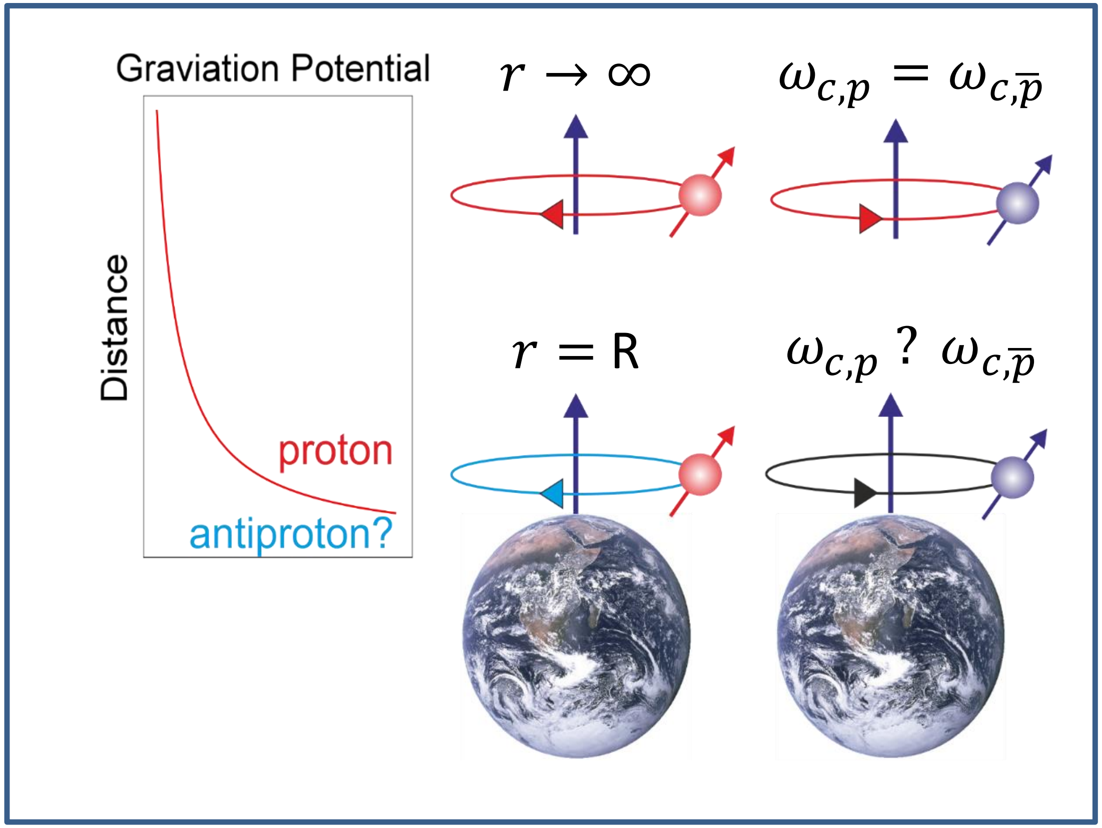
- Understanding: cosmological background field couples to particles -> Sidereal variations could be observed.





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

Antiproton gravitational redshift



- Constrain of the gravitation 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

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

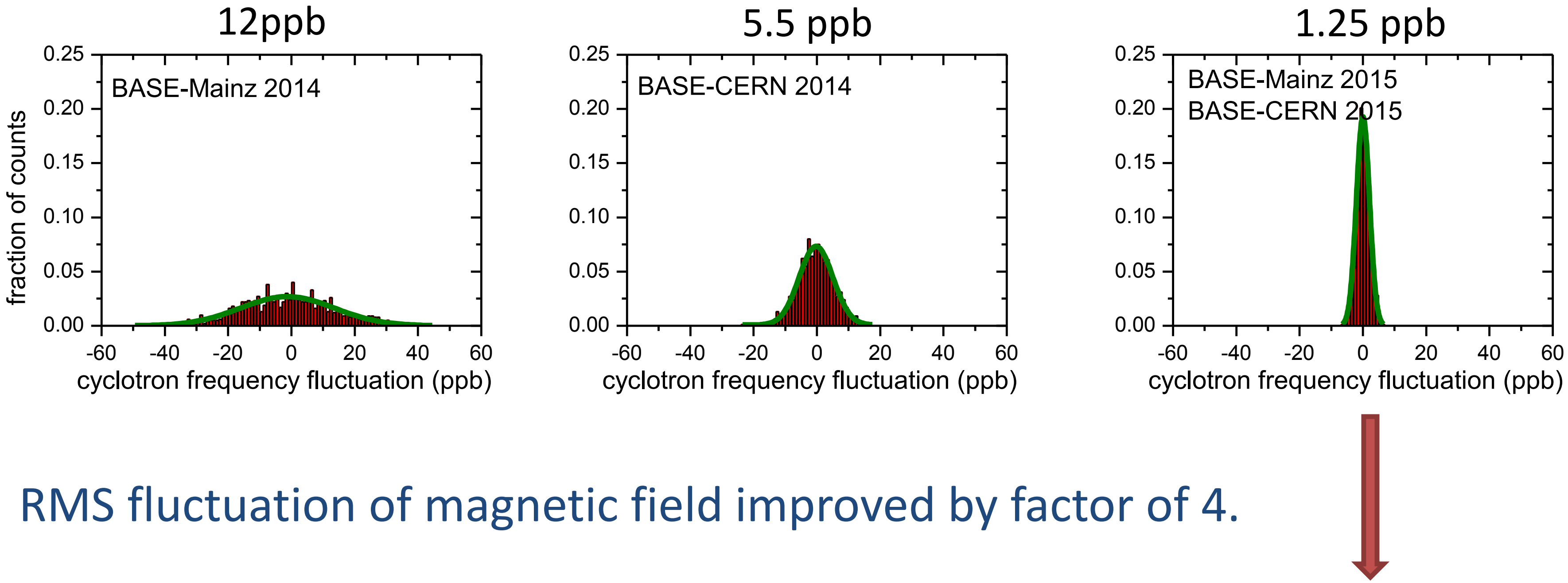
S. Ulmer et al., *Nature* **524** 196 (2015)

Assuming that CPT Invariance holds, we can compare the proton/antiproton gravitational redshift.

R. J. Hughes, & M. H. Holzscheiter, Phys. Rev. Lett. 66, 854-857 (1991).
R. J. Hughes, Contemporary Physics, 34:4, 177-191 (1993).

Progress – BT 2015

Implementation of a self-shielded solenoid and increase of homogeneity in the measurement trap

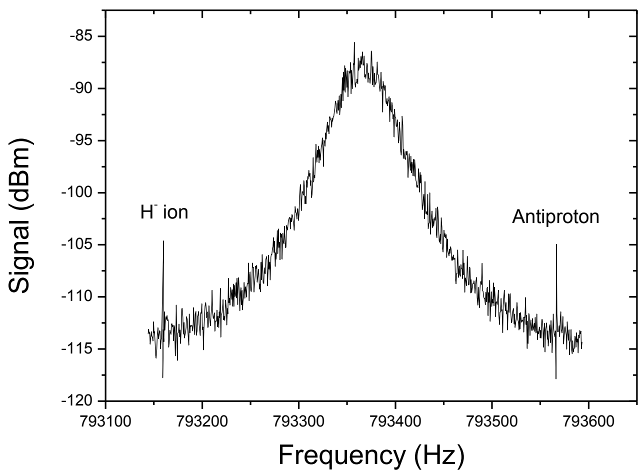


RMS fluctuation of magnetic field improved by factor of 4.

With conditions of beamtime 2014 **-> Q/M comparison at level of 10 ppt possible.**

Outlook - Simultaneously trapped particles

- **Dave Pritchard scheme:** Perform simultaneous measurement on antiproton and hydrogen ion -> improved precision of q/m ratio



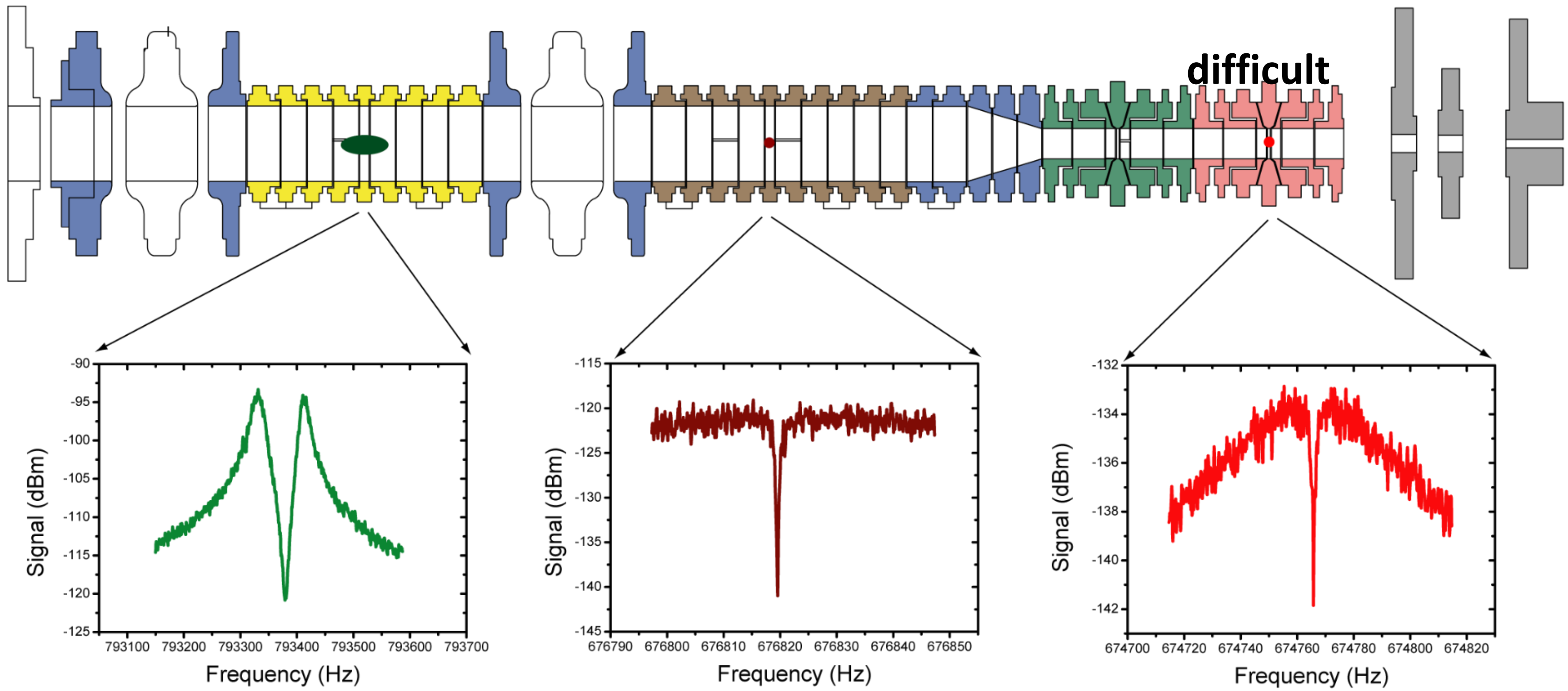
- During a measurement the particles will experience exactly the same magnetic field fluctuations -> ppt level.
- Systematics due to particle / particle interaction.
- Difficult. Requires further R'n'D.

Ultimate precision goal: 1ppt (several years)

Antiproton Magnetic Moment

Beamtime 2015: Shuttling along entire trap stack (20cm/5s) established.

Current situation:



50 antiprotons in reservoir trap

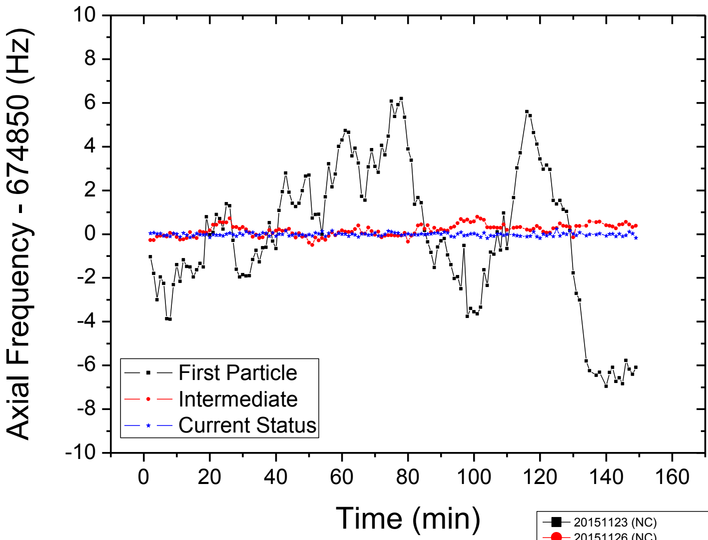
Single antiproton in precision trap

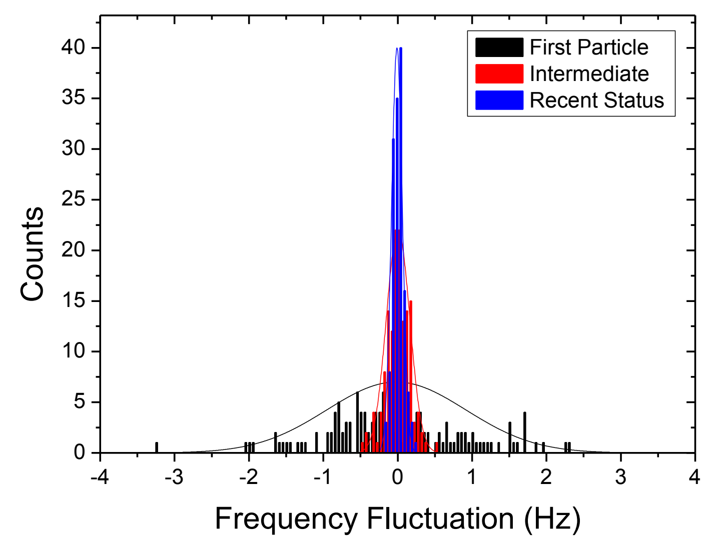
Single antiproton in analysis trap

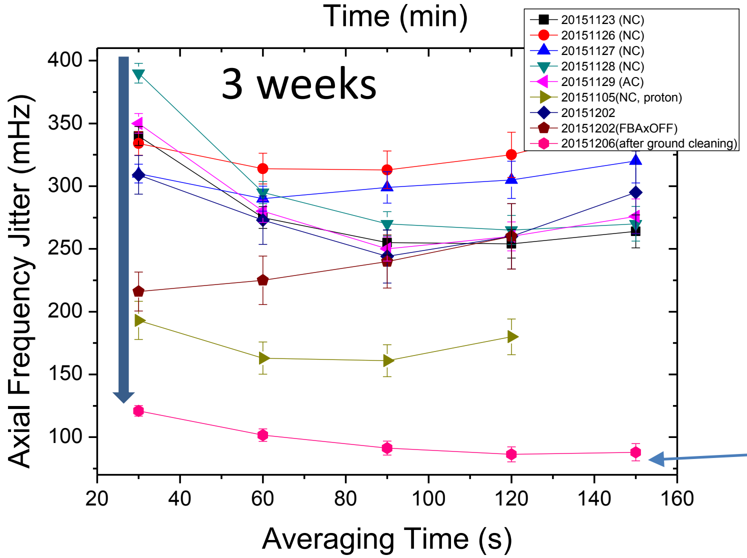
C. Smorra et al., *The BASE Experiment*, EPJ-Special Topics **224**, 3055 (2015)

Progress Analysis Trap 2015

In the magnetic bottle: need to resolve spin flip induced axial frequency jumps of 200mHz:



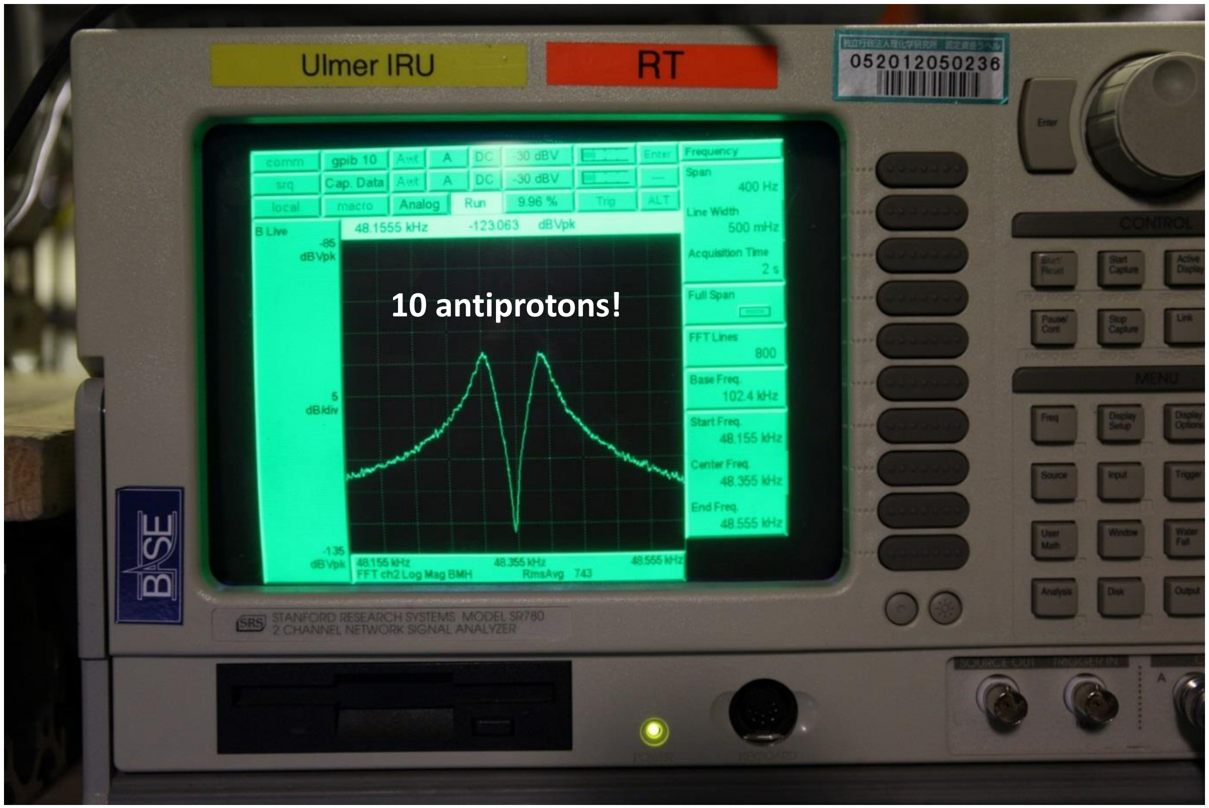




- Trap cleaning
- Ground loops
- RF tricks
- Feedback cooling

Cyclotron heating rate:
< 1 quantum transition in 240s
In this case: Single spin flip resolution

Current Status



Antibaryon density: ~ $10^8/cm^3$
$V < (50\ \mu m)^3$

Baryon density: ~ $10^7/cm^3$
$p < 10^{-15}$ Pa

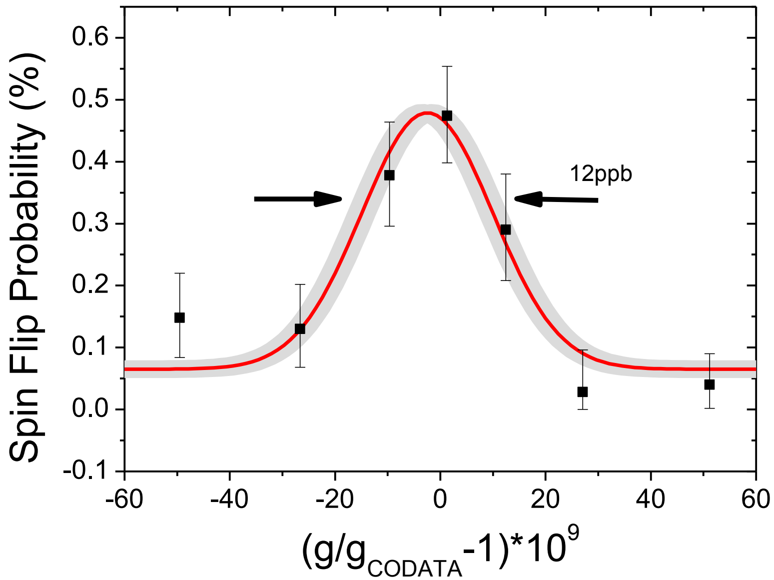
Loss/consumption rate:
1 particle/month

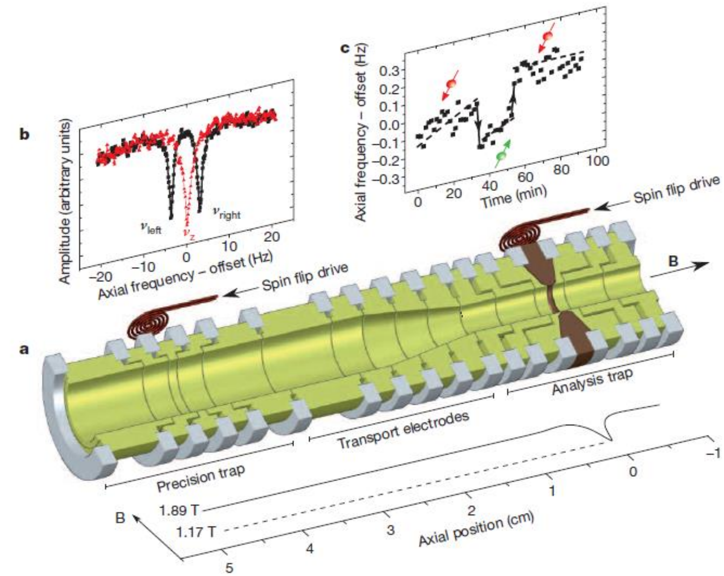
Baryon Asymmetry Slightly Inverted

Goal 2016

GOAL:

- Apply double trap scheme to the antiproton





LETTER

doi:10.1038/nature13388

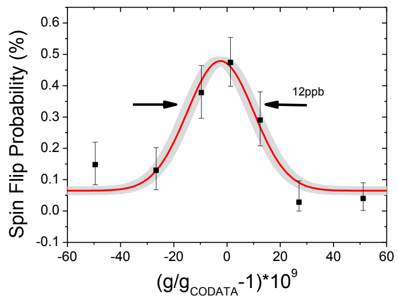
Direct high-precision measurement of the magnetic moment of the proton

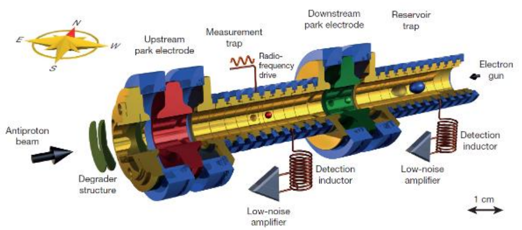
A. Mooser[1,2]†, S. Ulmer[3], K. Blaum[4], K. Franke[3,4], H. Kracke[1,2], C. Leiteritz[1], W. Quint[5,6], C. C. Rodegheri[1,4], C. Smorra[3] & J. Walz[1,2]

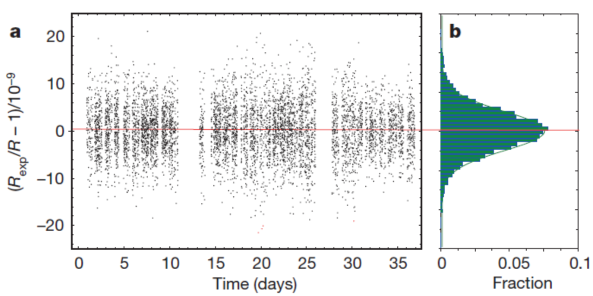
A. Mooser, S. Ulmer, K. Blaum, K. Franke, H. Kracke, C. Leiteritz, W. Quint, C. Smorra, J.Walz**, Nature 509, 596 (2014)**

g/2 = 2.792847350 (7) (6)

Summary



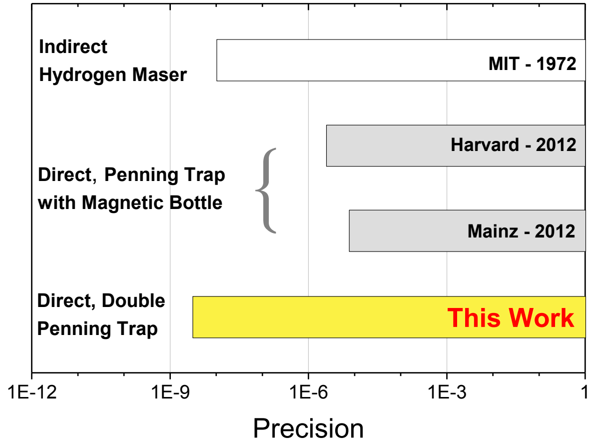


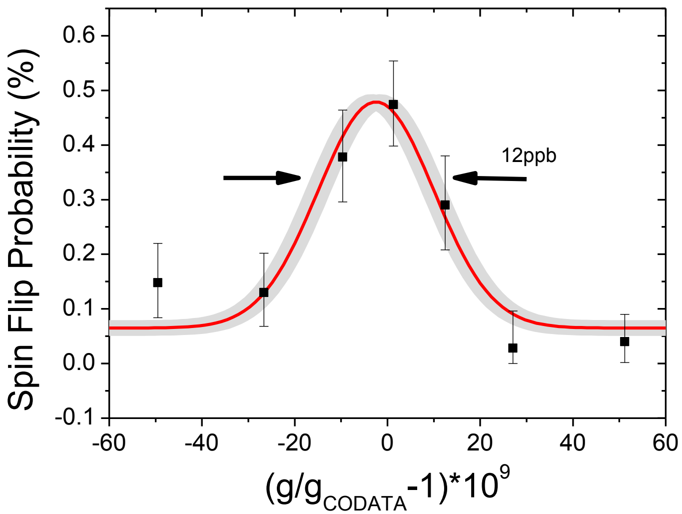


- …measured the magnetic moment of the proton with a fractional precision of 3.3ppb, which is the **most precise measurement to date.**
- …established new collaboration at AD of CERN.
- …commissioned an entirely new 4-Penning trap experiment (only running 4 trap experiment to date).
- …invented reservoir trap technique for antiprotons
- …applied fast shuttling and performed the **most precise test of CPT symmetry** with baryons using this new machine.
- …prepared to improve this test to 10 p.p.t..
- …current status: commissioning of antiproton magnetic moment measurement. Full 4 trap system running. Required frequency resolution for ppm achieved. GOAL: p.p.b. precision.

BASE Precision Measurements

Magnetic Moment of the Proton

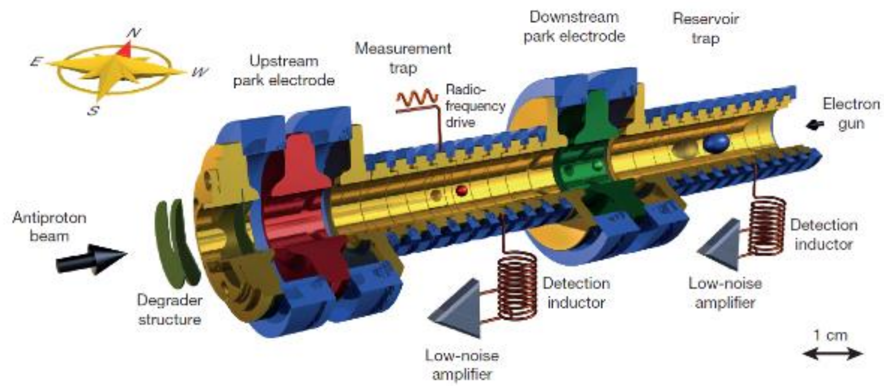


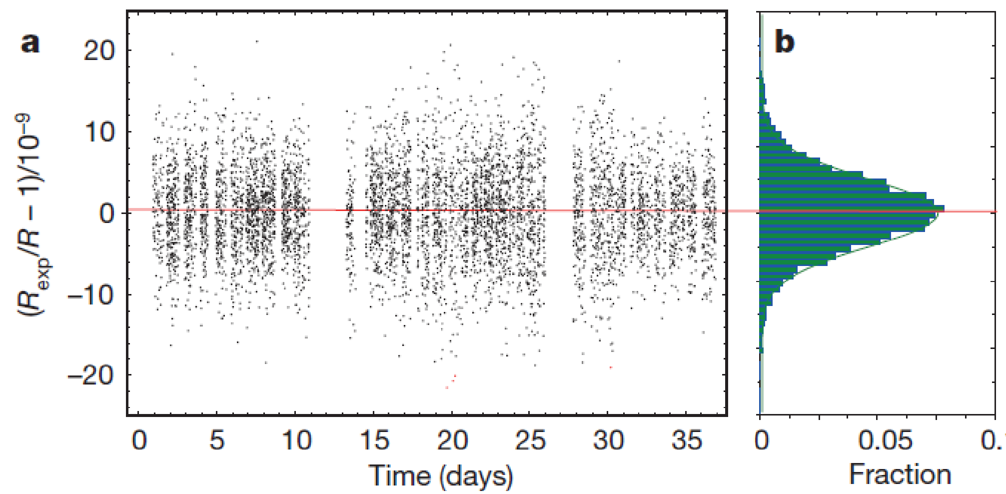


g/2 = 2.792847350 (7) (6)

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

Antiproton/Proton Charge-to-Mass Ratio





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

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

BASE - Overview Article

THE EUROPEAN PHYSICAL JOURNAL ST

Special Topics

is a continuation of Journal de Physique IV

BASE – The Baryon Antibaryon Symmetry Experiment

C. Smorra, K. Blaum, L. Bojtar,
M. Borchert, K.A. Franke, T. Higuchi,
N. Leefer, H. Nagahama, Y. Matsuda,
A. Mooser, M. Niemann, C. Ospelkaus,
W. Quint, G. Schneider, S. Sellner,
T. Tanaka, S. Van Gorp, J. Walz,
Y. Yamazaki and S. Ulmer

Published with the support of the Centre National de la Recherche Scientifique

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

Thanks for your attention!

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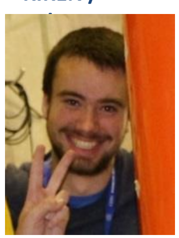

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