Precision Antiproton Spectroscopy at BASE

Jonathan Morgner

BASE Collaboration

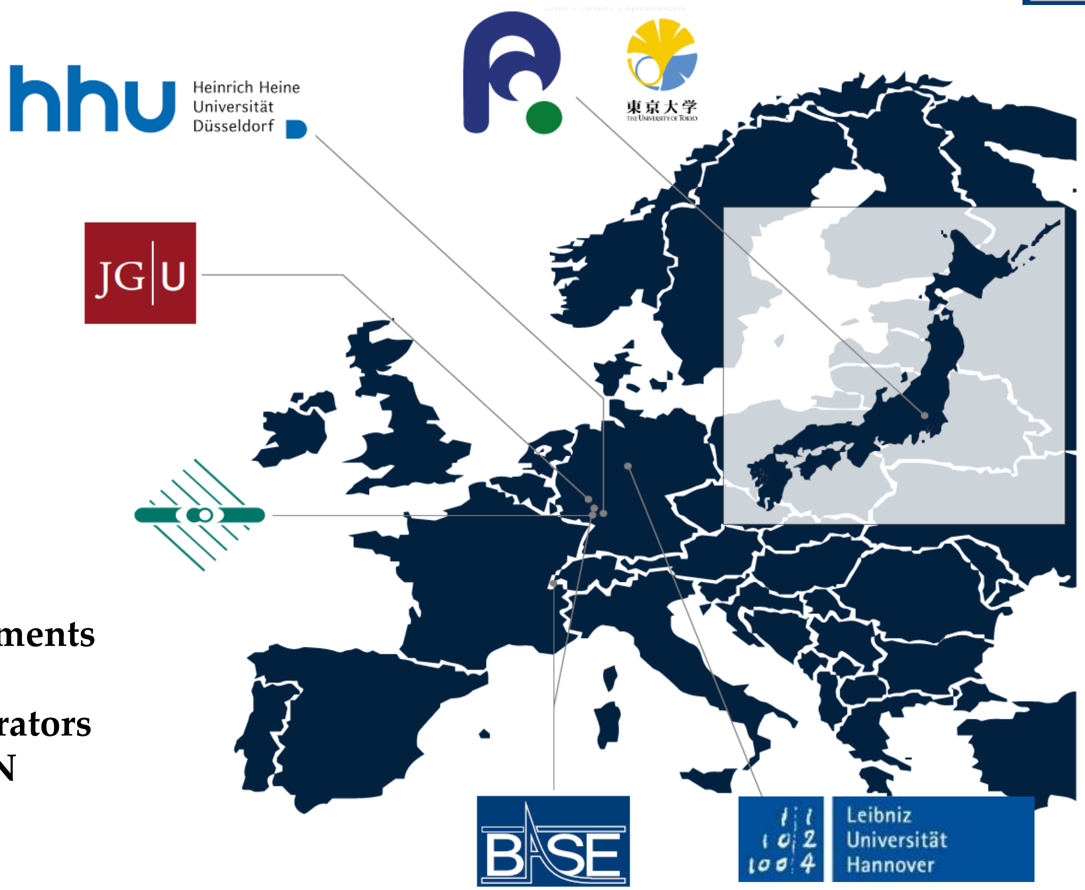
CERN

PSAS 2026

BASE – Collaboration

- **BASE-Mainz:** Proton magnetic moment, new technologies.
- **BASE-CERN:** Antiproton magnetic moment, proton/antiproton q/m ratio
- **BASE-STEP:** Transportable antiproton traps
- **BASE-Hannover/PTB:** BASE-LOGIC / QLEDS laser cooling project, new technologies
- **BASE-HHU:** Offline measurements with transported antiprotons

- **Five experiments**
- **9 institutes**
- **~30 collaborators**
- **~10 at CERN**



Leibniz Universität Hannover

GSI

RIKEN

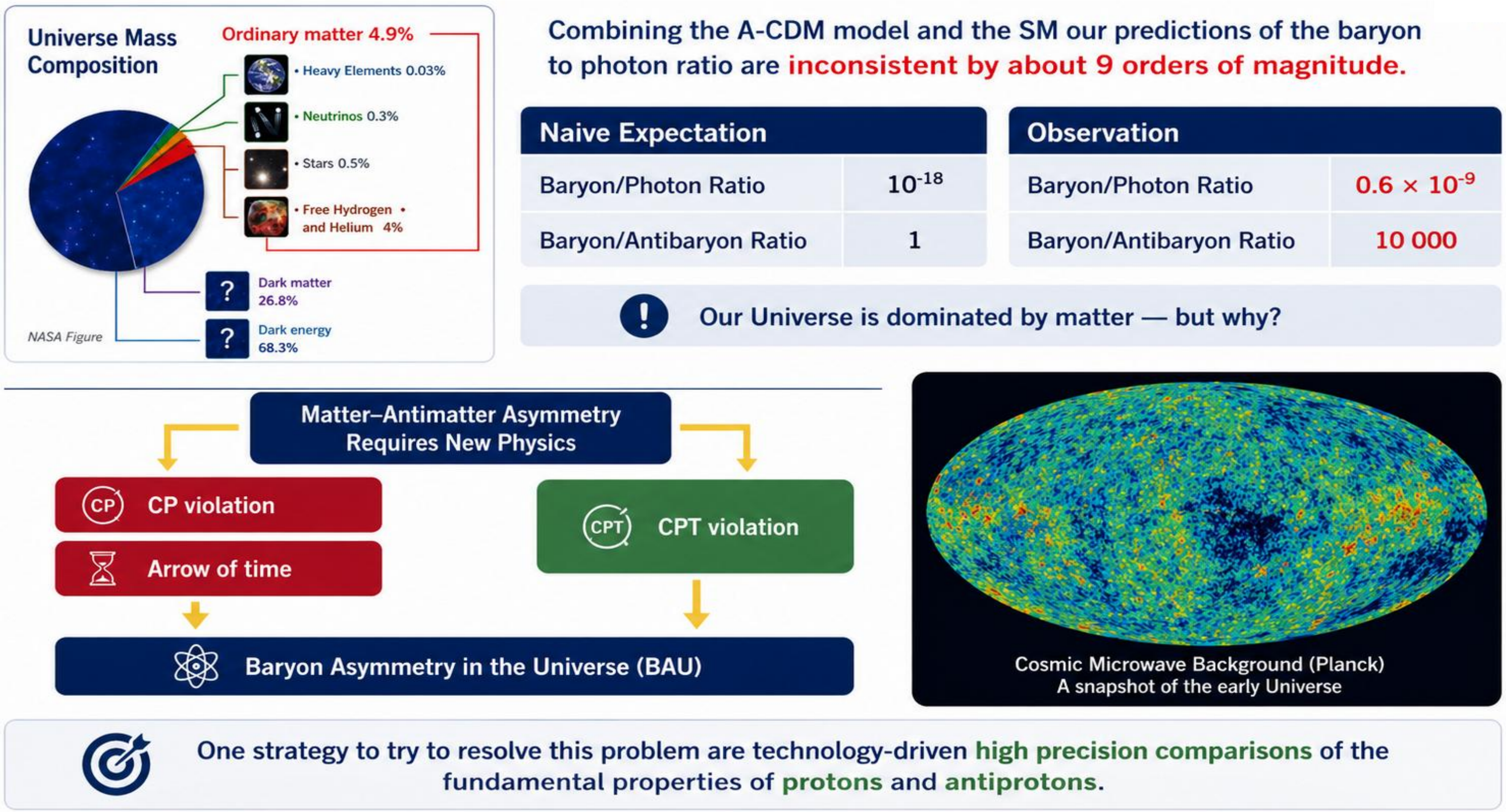
東京大学 THE UNIVERSITY OF TOKYO

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

hhu Heinrich Heine Universität Düsseldorf

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

Matter / antimatter asymmetry



Universe Mass Composition

Ordinary matter 4.9%
- Heavy Elements 0.03%
- Neutrinos 0.3%
- Stars 0.5%
- Free Hydrogen and Helium 4%

? Dark matter 26.8%

? Dark energy 68.3%

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

! Our Universe is dominated by matter — but why?

Matter–Antimatter Asymmetry Requires New Physics

CP violation

Arrow of time

CPT violation

Baryon Asymmetry in the Universe (BAU)

Cosmic Microwave Background (Planck)
A snapshot of the early Universe

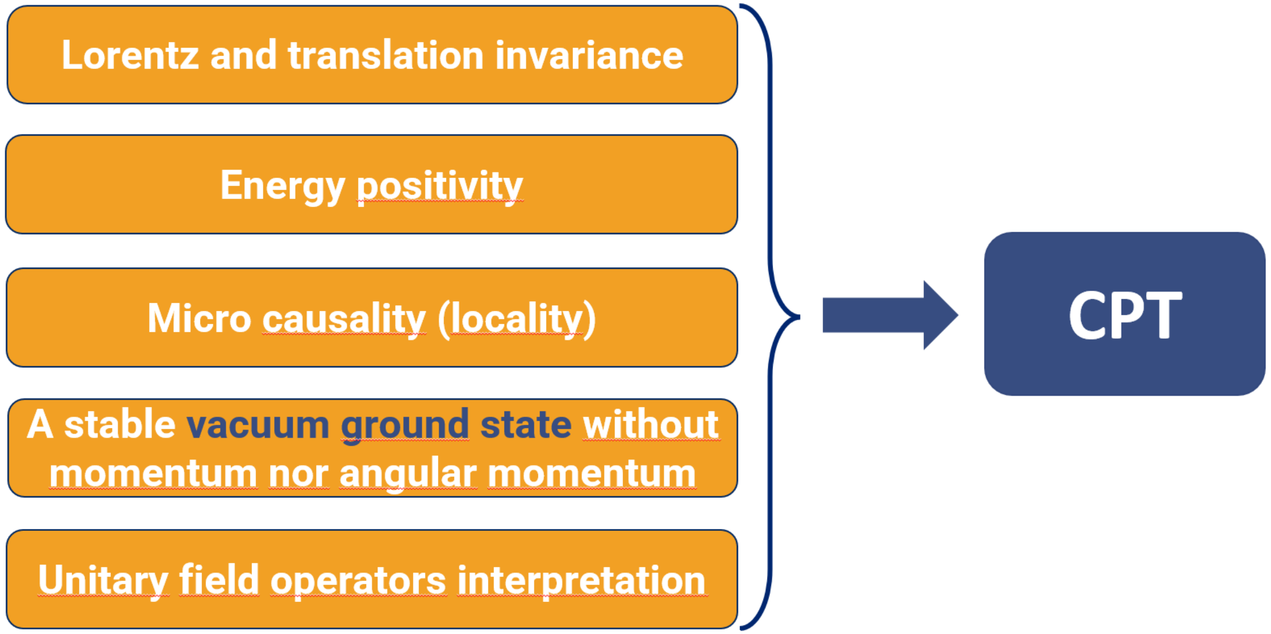
One strategy to try to resolve this problem are technology-driven **high precision comparisons** of the fundamental properties of **protons** and **antiprotons**.

The Physics

Measurements of Proton/Antiproton Fundamental Constants with high precision

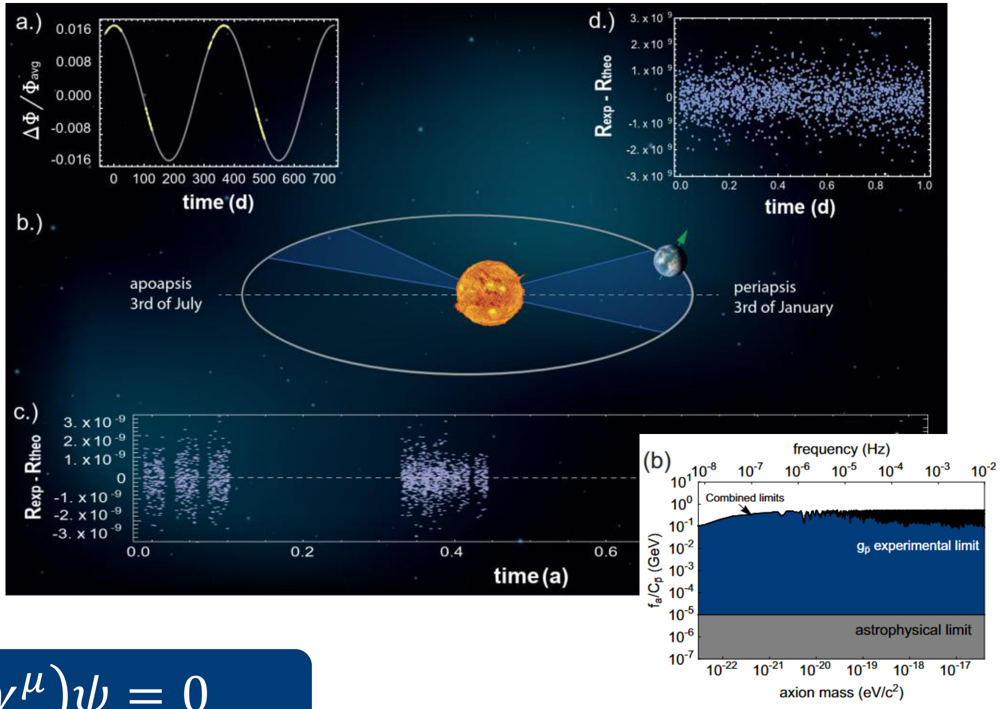
Tests of CPT Invariance

Search for DM and Exotic Interactions



- **Lorentz and translation invariance**
- **Energy positivity**
- **Micro causality (locality)**
- **A stable vacuum ground state without momentum nor angular momentum**
- **Unitary field operators interpretation**

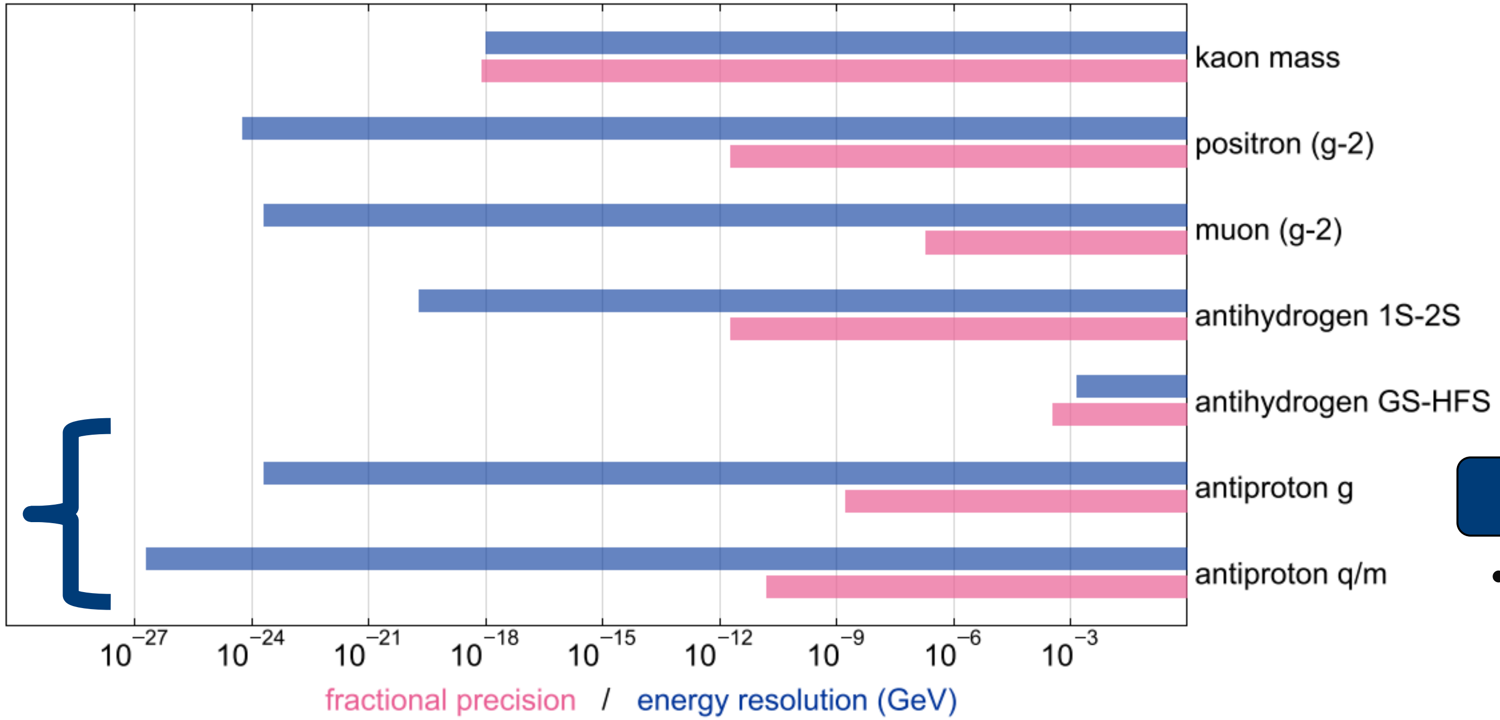
CPT



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

Current most precise tests of CPT invariance with baryons is a BASE measurement (q/m – 16 p.p.t.)

Comparison of existing CPT tests



Antiproton lifetime

- **10.2 years**
  New J. Phys. **19**.8 (2017): 083023

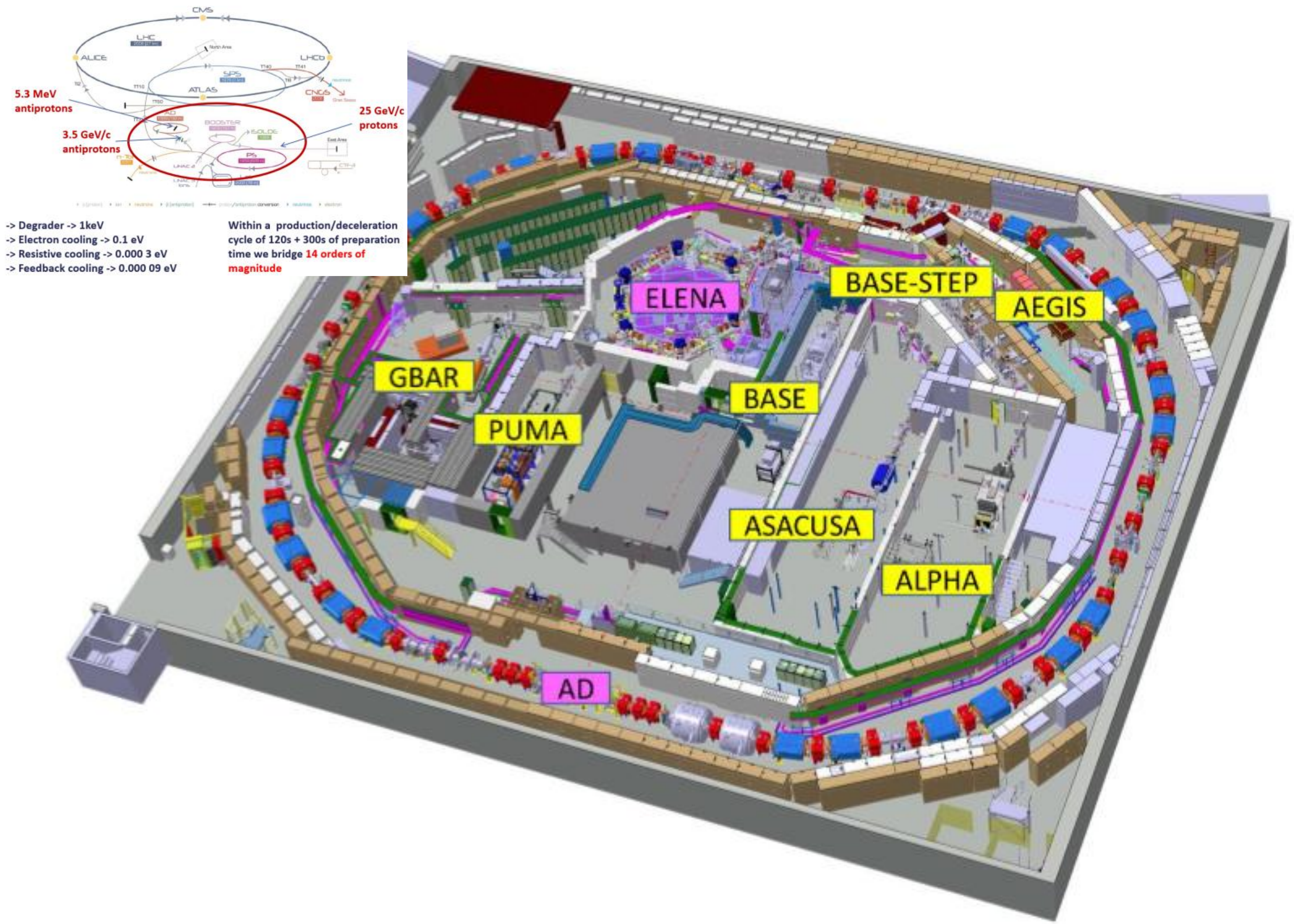
High precision mass spectroscopy

- **16 ppt** antiproton-to-proton **charge–mass ratio** measurement
  Nature **601**.7891 (2022): 53-57.

High precision magnetic moment measurements

- **1.5 ppb** antiproton **magnetic moment** measurement
  Nature 550, 371-374 (2017)
- Towards the first sub 100 ppt measurement

The AD/ELENA-Facility



-> 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

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

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

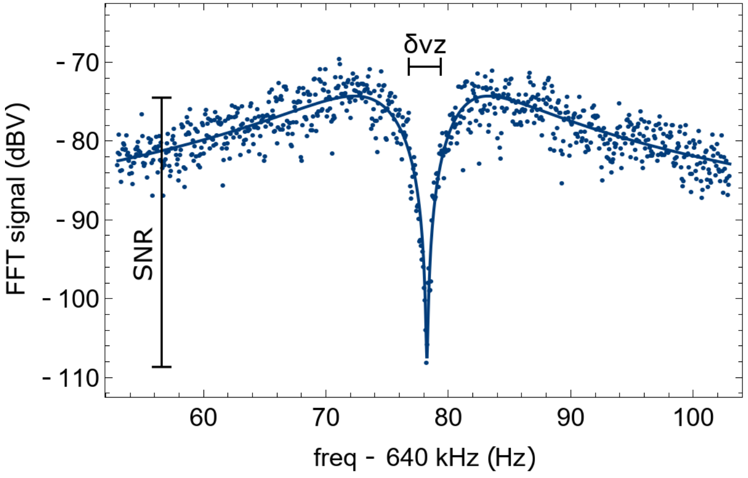
BASE, BASE-STEP
Fundamental properties of the proton/antiproton, tests of clock WEP / tests of exotic physics / antimatter-dark matter interaction, etc...

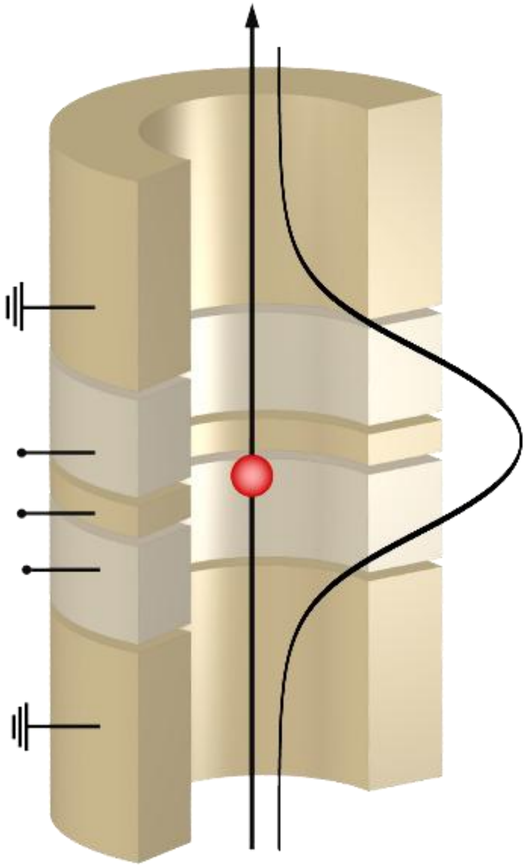
PUMA
Antiproton/nuclei scattering to study neutron skins

TELMAX
Experimental Area for short term experiments with antiprotons

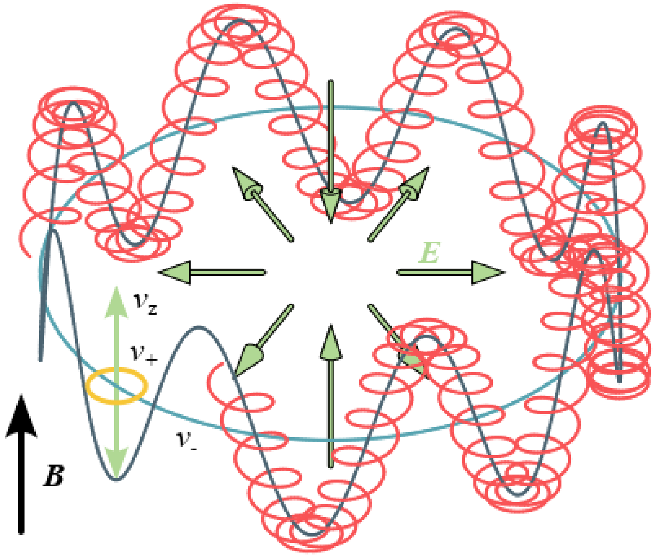
Penning trap

E and ***B*** field confine the particle in the trap
→ Motion can be split into three motional modes:
$\nu_+ \gg \nu_z \gg \nu_-$
Related to the free-space cyclotron frequency:
$\nu_c^2 = \nu_+^2 + \nu_z^2 + \nu_-^2$

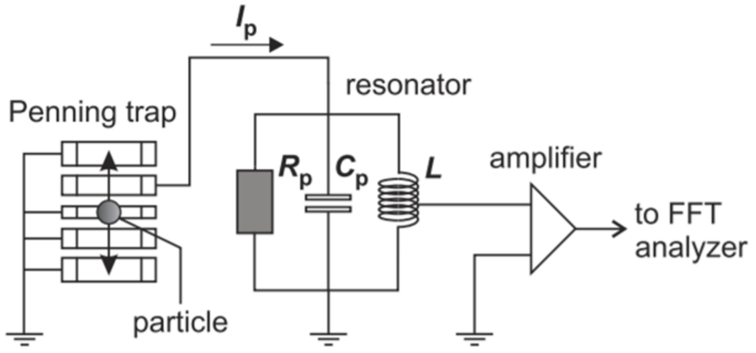


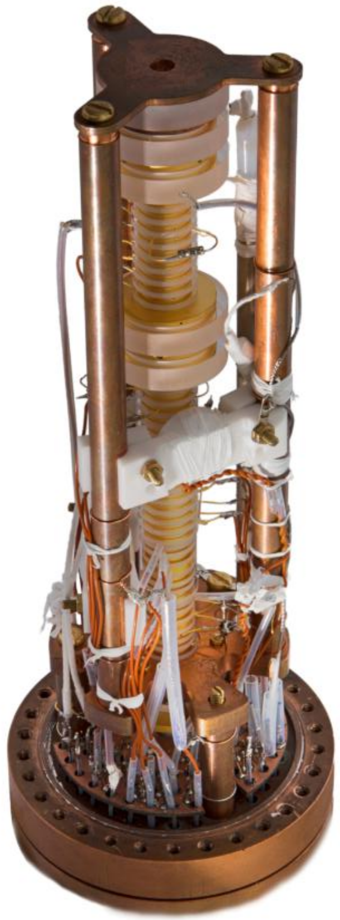


Non-destructive single-particle detection via image-currents

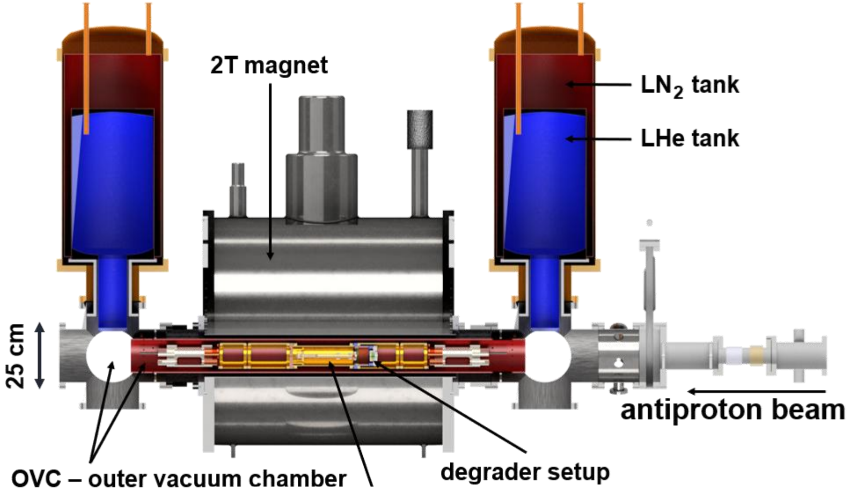


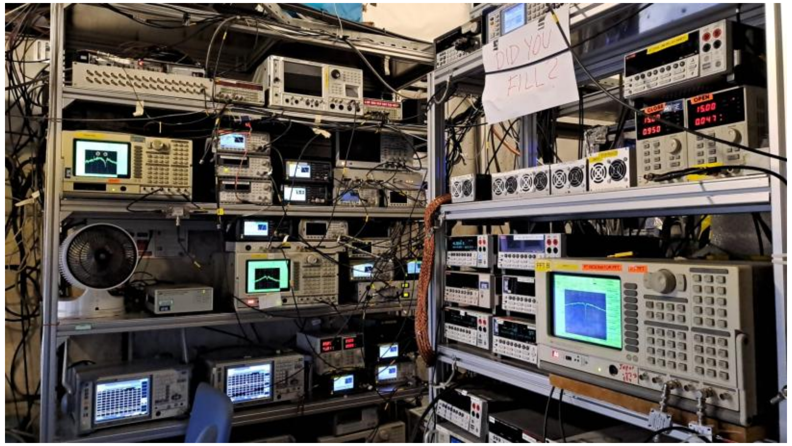
Axial ν_z	639 kHz
Magnetron ν_-	7 kHz
Mod. Cyclotron ν_+	29.6 MHz

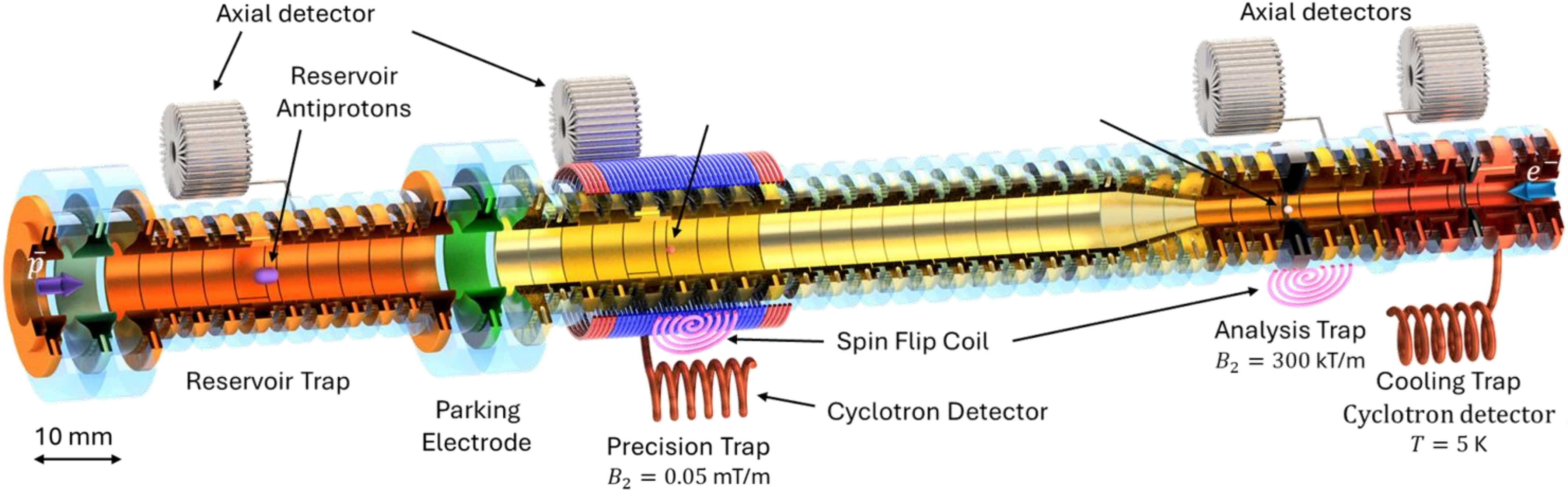




Apparatus


2T magnet
LN$_2$ tank
LHe tank
25 cm
antiproton beam
OVC – outer vacuum chamber
degrader setup



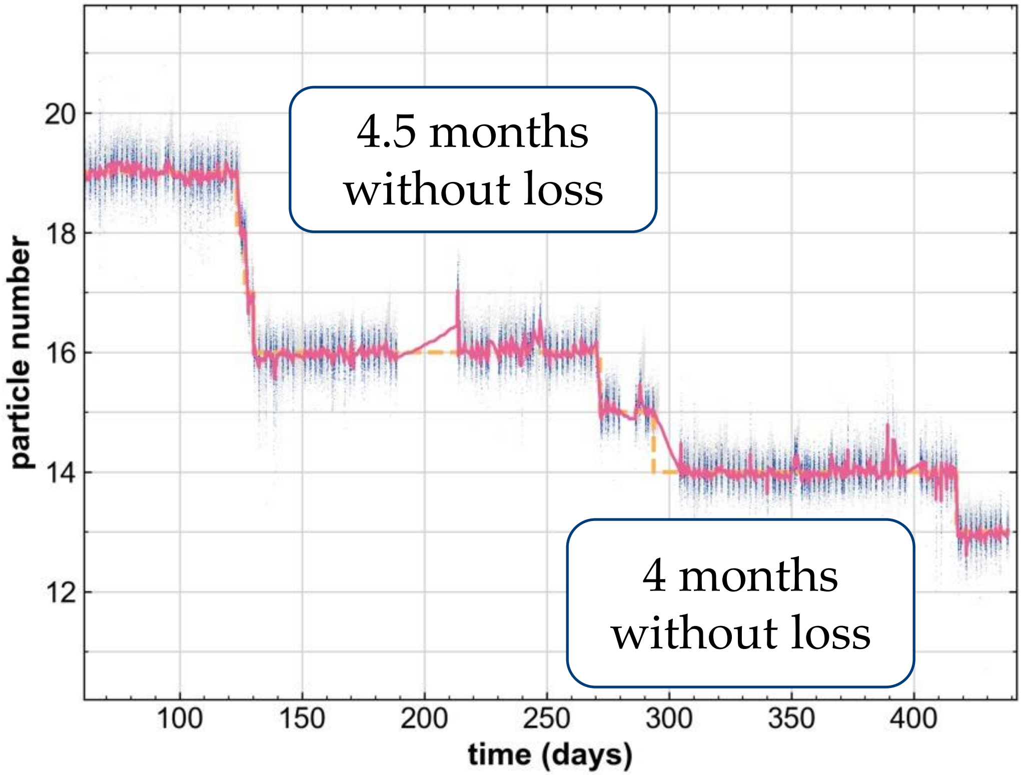

Axial detector
Reservoir Antiprotons
Axial detectors
$\bar{p}$
e^-
Reservoir Trap
Parking Electrode
Spin Flip Coil
Cyclotron Detector
Precision Trap
$B_2 = 0.05$ mT/m
Analysis Trap
$B_2 = 300$ kT/m
Cooling Trap
Cyclotron detector
$T = 5$ K
10 mm

Antiproton lifetime

We just captured **~300 antiprotons** on the 8th of May

- No observed loss of Antiprotons

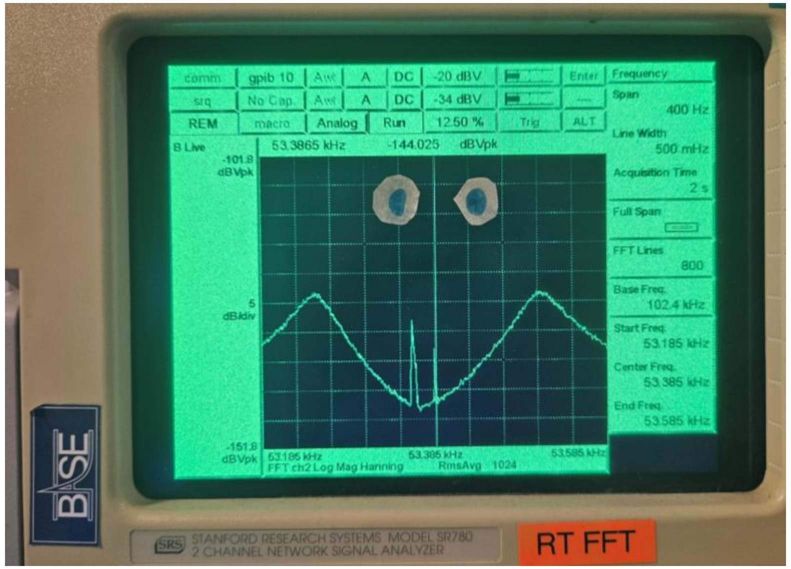
  → Pressure in the system $< 1.04 \cdot 10^{-18}$ mbar
- We kept **antiprotons** from 27th of October 2023 till the 2nd of July 2025
- Trapped for 614 days → **oldest antimatter** ever created on Earth.



4.5 months without loss

4 months without loss

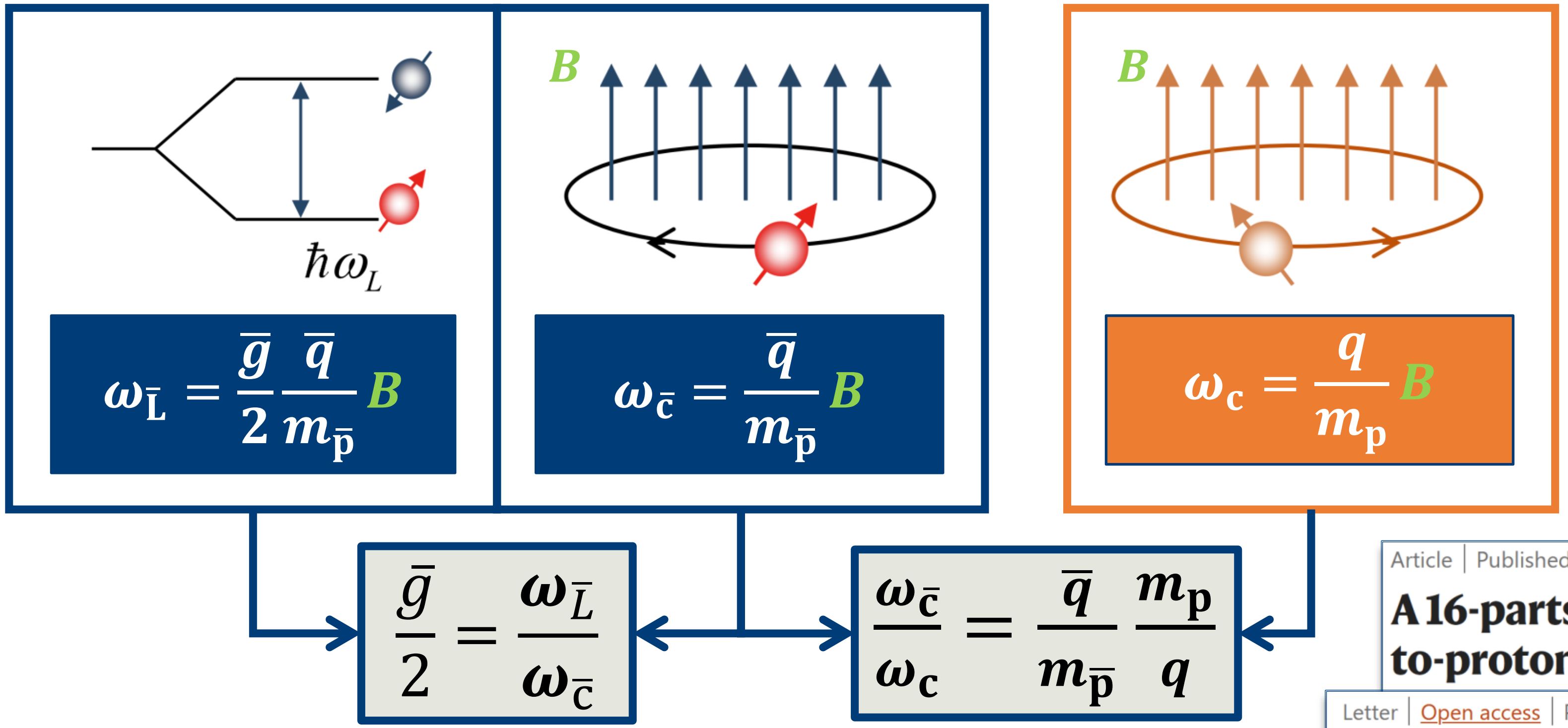
6 antiprotons used during the entire 2024 campaign



Antiproton lifetime data collected since 2014: **> 55 y**

Submitted, under revision

Measurements



Antiproton

$$\omega_{\bar{L}} = \frac{\bar{g}}{2}\frac{\bar{q}}{m_{\bar{p}}}B$$

$$\omega_{\bar{c}} = \frac{\bar{q}}{m_{\bar{p}}}B$$

Proton

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

$$\frac{\bar{g}}{2} = \frac{\omega_{\bar{L}}}{\omega_{\bar{c}}}$$

Determine
magnetic moment

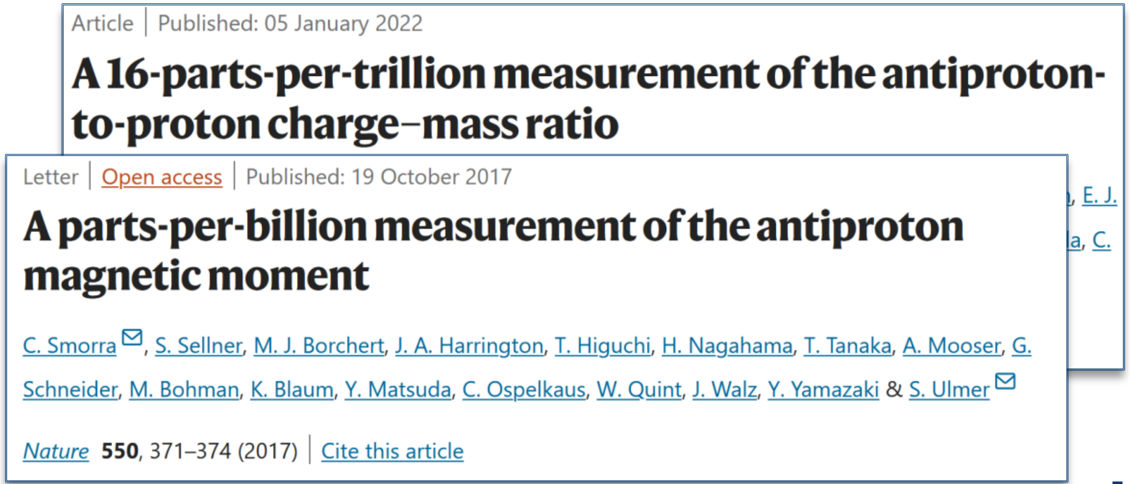
$$\frac{\omega_{\bar{c}}}{\omega_c} = \frac{\bar{q}}{m_{\bar{p}}}\frac{m_p}{q}$$

Antiproton-to-proton
charge-to-mass ratio

Ideally *B* cancels out
→ Limited by the magnetic
field stability

Compare **Antiproton** with
Proton to test **CPT**

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



Article | Published: 05 January 2022

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

, E. J.

a, C.

Letter | Open access | Published: 19 October 2017

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

C. Smorra ✉, S. Sellner, M. J. Borchert, J. A. Harrington, T. Higuchi, H. Nagahama, T. Tanaka, A. Mooser, G. Schneider, M. Bohman, K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki & S. Ulmer ✉

Nature **550**, 371–374 (2017) | Cite this article

Spin state detection

usw Stern Gerlach Effect:

Force on antiproton:

$$\boldsymbol{F} = \nabla(\boldsymbol{\mu}_{\mathrm{p}} \cdot \boldsymbol{B})$$

Introduce magnetic-field gradient into the trap:

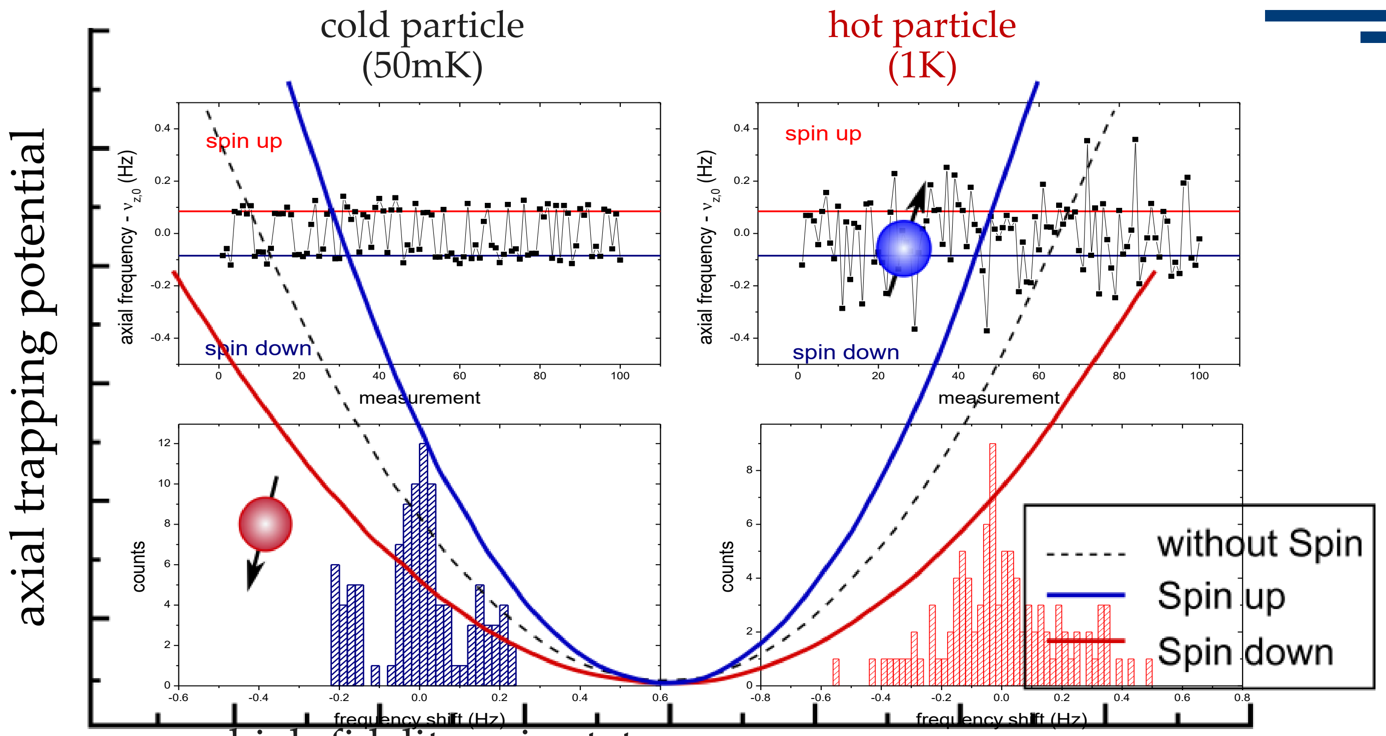
$$B = B_0 + B_2 \cdot z^2 + \cdots$$

Axial frequency is Spin state dependent:

$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} \propto n_+$$

In our apparatus with $\mathrm{B}_2 = 300000 \, \frac{\mathrm{T}}{\mathrm{m}^2}$:

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



high-fidelity spin state resolution

fidelity at 65%, not useful for measurements

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

We need a cold particle to resolve spin state

Spin state detection

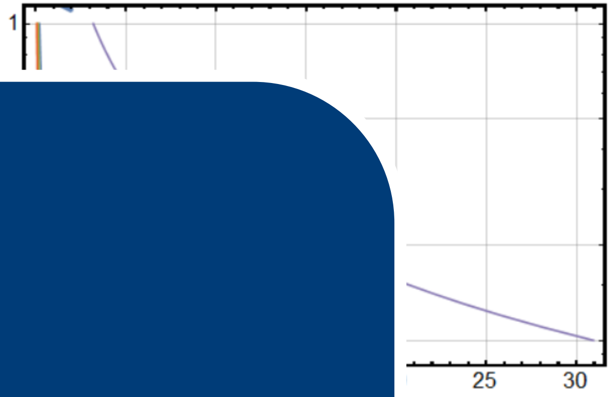
- **Recent game c**

  → er

  •Re
- Ongoing : pl

  - Dip meth
    C. Smorra
    769 (2017

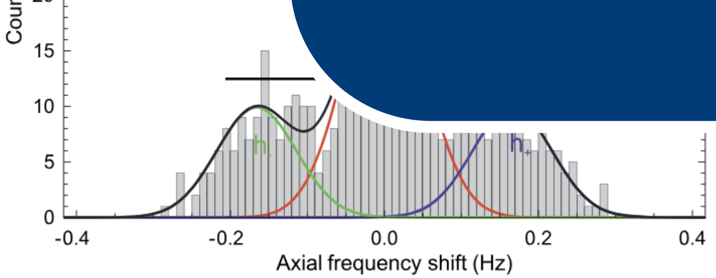
ase methods –
t, P. Geissler, et al.)

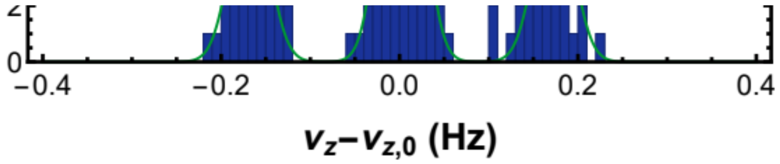


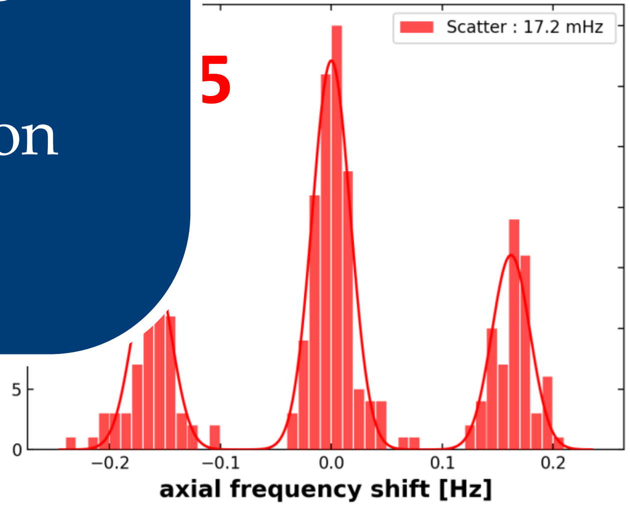
Next goal:
Frequency switch

Enables to decouple the detector during the phase accumulation time

→ Faster state-detection by a factor of 5







Two trap and two particle method

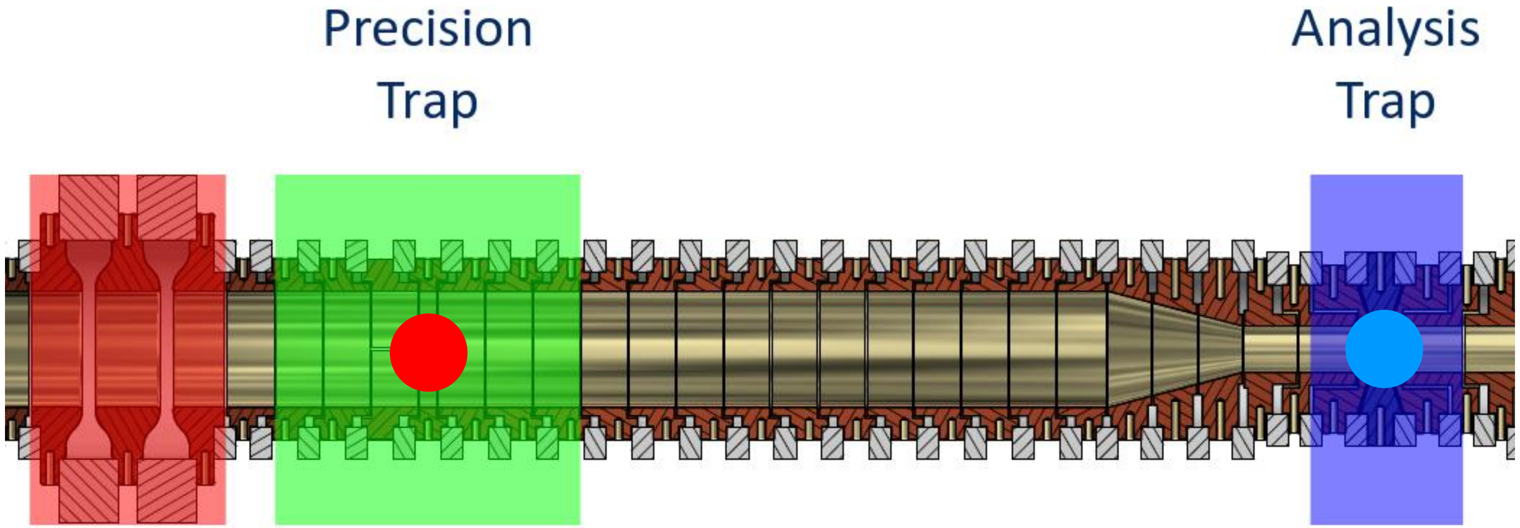
Analysis Trap - high B_2 / Cold →

Precision Trap - low B_2 / Hot →

$$\frac{\omega_L}{\omega_{\bar{c}}} = \frac{g}{2}$$

One cold $\bar{\mathrm{p}}_{\mathrm{cold}}$ for state detection
One Hot $\bar{\mathrm{p}}_{\mathrm{hot}}$ for measuring the $\omega_{\bar{c}}$

1. Determine spin state of $\bar{\mathrm{p}}_{\mathrm{cold}}$
2. Measure $\omega_{\bar{c}}$ of $\bar{\mathrm{p}}_{\mathrm{hot}}$ in the Precision Trap
3. Shuttle particles
4. Excite $\bar{\mathrm{p}}_{\mathrm{cold}}$ spin in Precision Trap
5. Shuttle particles
6. Determine spin state of $\bar{\mathrm{p}}_{\mathrm{cold}}$
7. repeat



Cycletime between 15 to 45 min.

Coherent spin-state spectroscopy

- Lineshape parameter:

$$\Delta\nu_L = \nu_L \frac{B_2}{B_0}\frac{k_B T_z}{m\omega_z^2}$$

$$T_z = 8.5(3)\ \mathrm{K}$$
$$\nu_z = 636712\ \mathrm{Hz}$$
$$\nu_L = 82.794\ \mathrm{MHz}$$
$$B_0 = 1.945\ \mathrm{T}$$

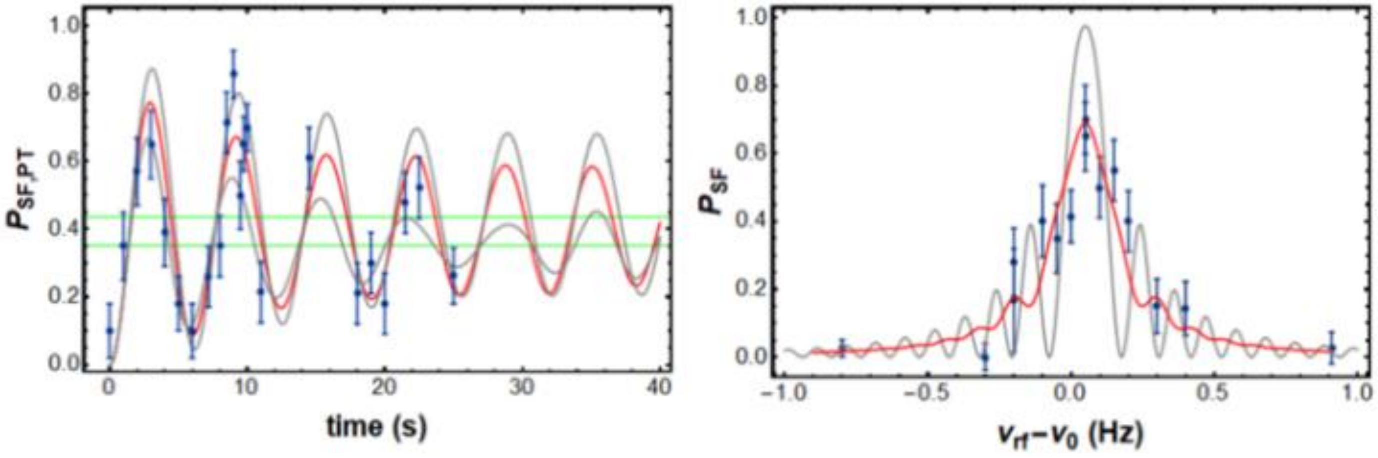
- Rabi resonance shape:

$$P_{\mathrm{SF,PT}}(\Omega_0, \Delta, t) = \frac{\Omega_0^2}{\Omega_0^2+\Delta^2} \times \sin^2\left(\pi\sqrt{\Omega_0^2+\Delta^2} \times t\right)$$

- Convolution with Gaussian:

$$L(\Omega_0, \Delta, t) = \int_{-\infty}^{\infty} P_{\mathrm{SF,PT}}(\Omega_0, \Delta+\sigma, t)\, G(\sigma; \mu, \sigma)\, \mathrm{d}\sigma$$

- Each „bin” is average of 20 points, single point takes 15 min



physicsworld
TOP 10
BREAKTHROUGH
2025

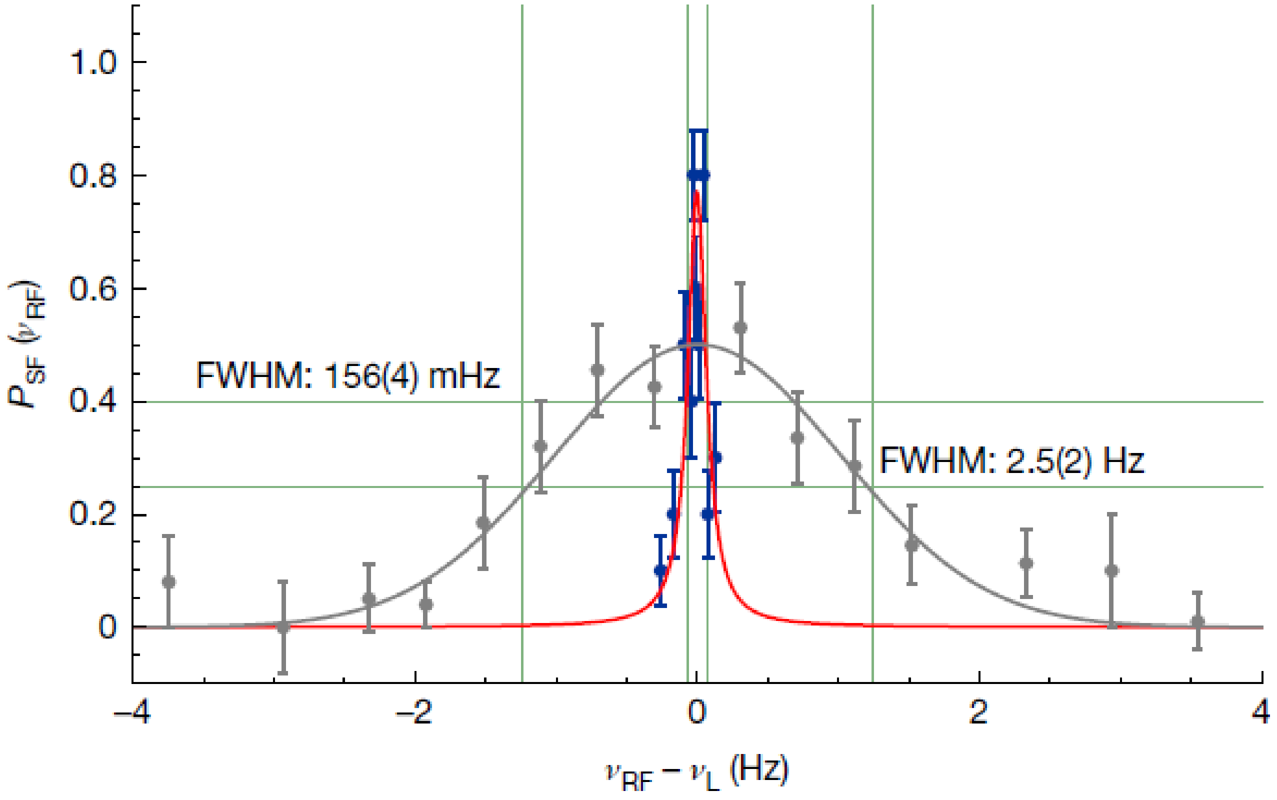
We observe a coherent spin-state with a single antiproton for the first time ever!!

Nature **644**, pages 64–68 (2025)

Frequency sweep at maximum inversion

- *At Ω*/(2π) ≈ 50 mHz and a drive time of 16 s

Inversion 2016: 0.5 → Incoherent
Inversion 2023: 0.77 → Coherent



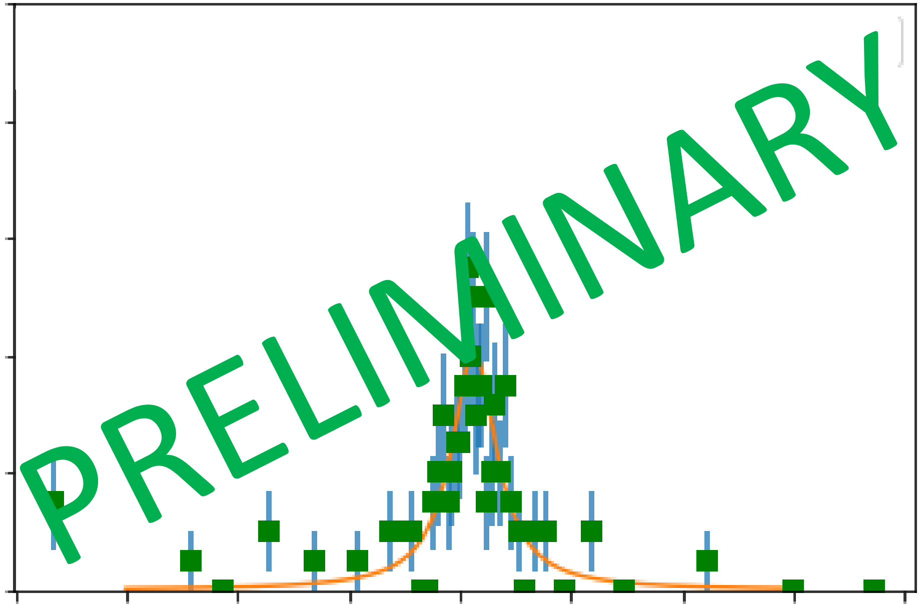
FWHM reduced by factor of **16**

~77(4) % spin state inversion in the center

Nature **644**, pages 64–68 (2025)

Antiproton / proton measurements

- Antiproton:
  - First run: data collected between 28.12.2023 and 26.01.2024
  - Second run: data collected between 22.12.2024 and 10.02.2025
- Proton: measurement carried out May to July 2023

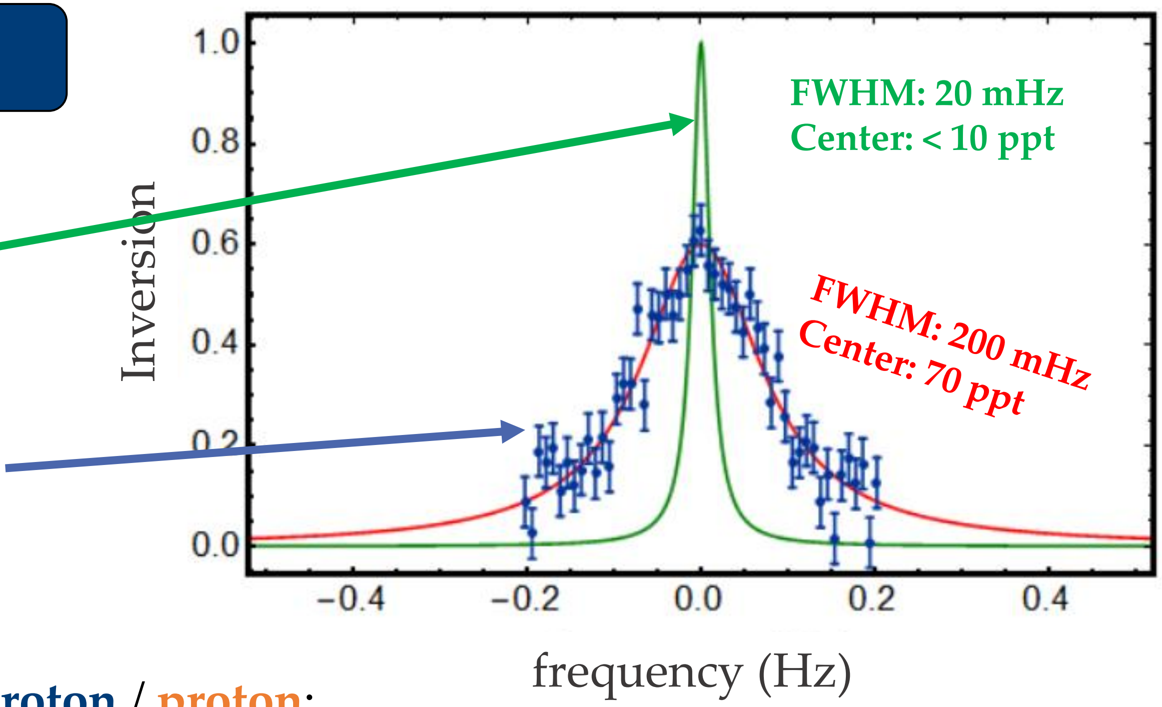


	2016	2024/2025
FWHM	2.5 Hz	< 200 mHz
Sigma (stat)	123 mHz	< 10 mHz

- Statistical line center resolution at about **100 ppt precision** - 15 times better.
- Systematic studies ongoing (tough at this accuracy in the AD).

Future: Fully coherent single particle measurement

- Achieved coherence time of **50.2(4.8) s**



Possible based on 50s spin coherence time measurement

Measured subset of 2024/2025 with AD-OFF

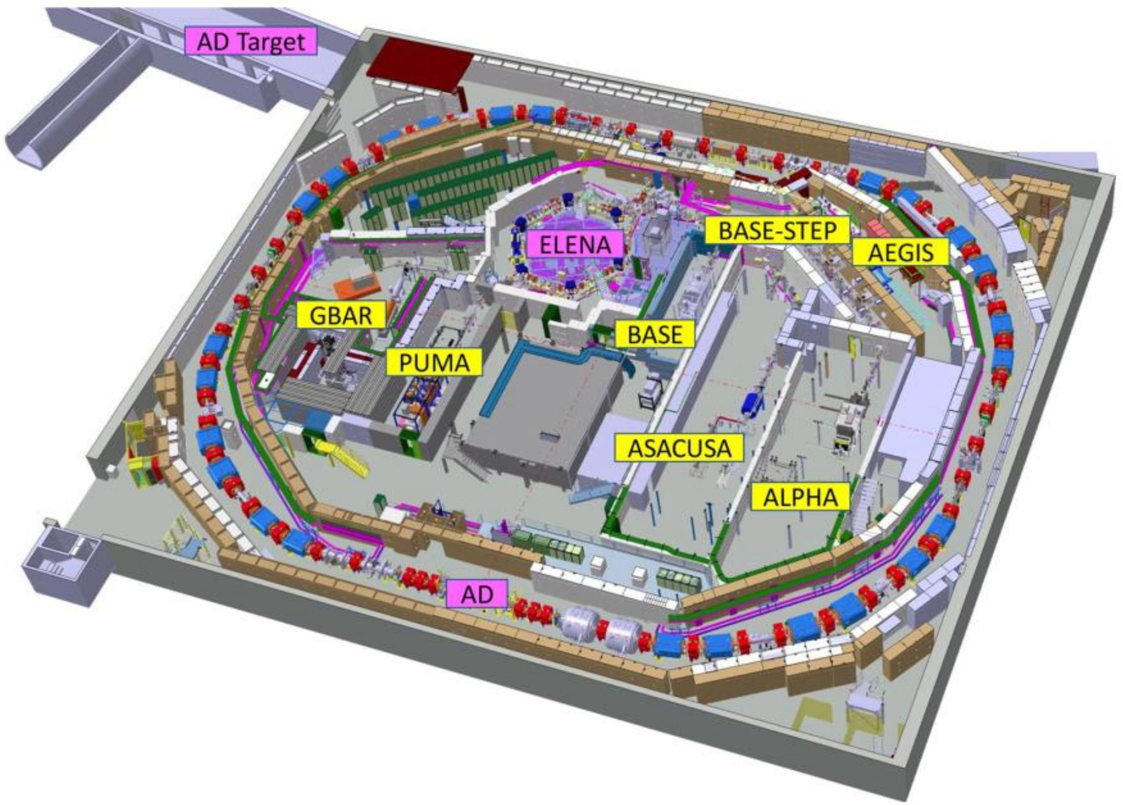
Plan: Magnetic moment measurement with single **antiproton** / **proton**:

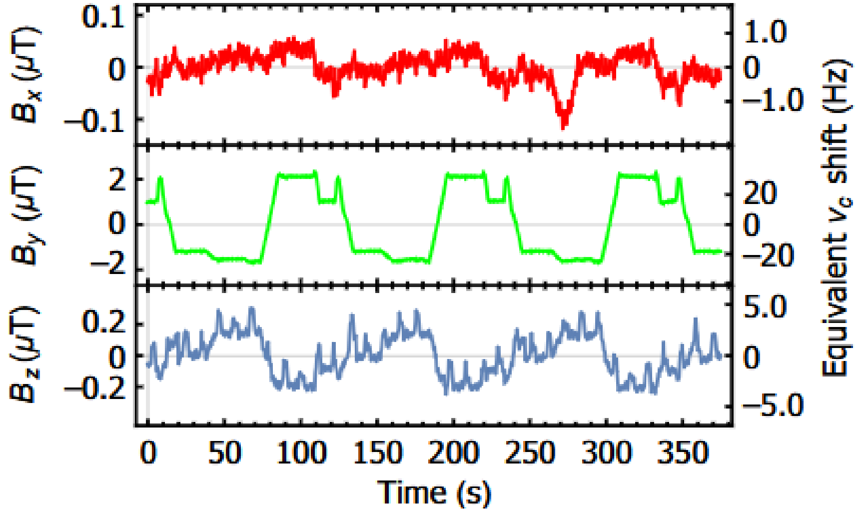
- Phase sensitive cylotron frequency measurements:
- Phase sensitive detection in the AT
- Fast particle cooling in the CT

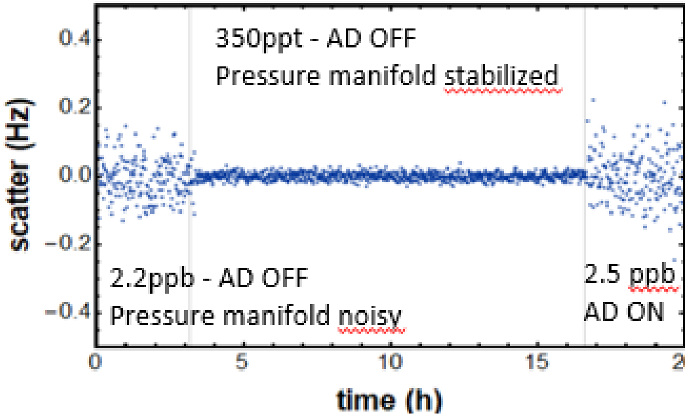
→ **Achieve 10 ppt precision**

The big limitation

AD fluctuations for 8 months of the year







- While AD is running no high-precision Measurement possible.

→ Use the upcoming long shutdown!

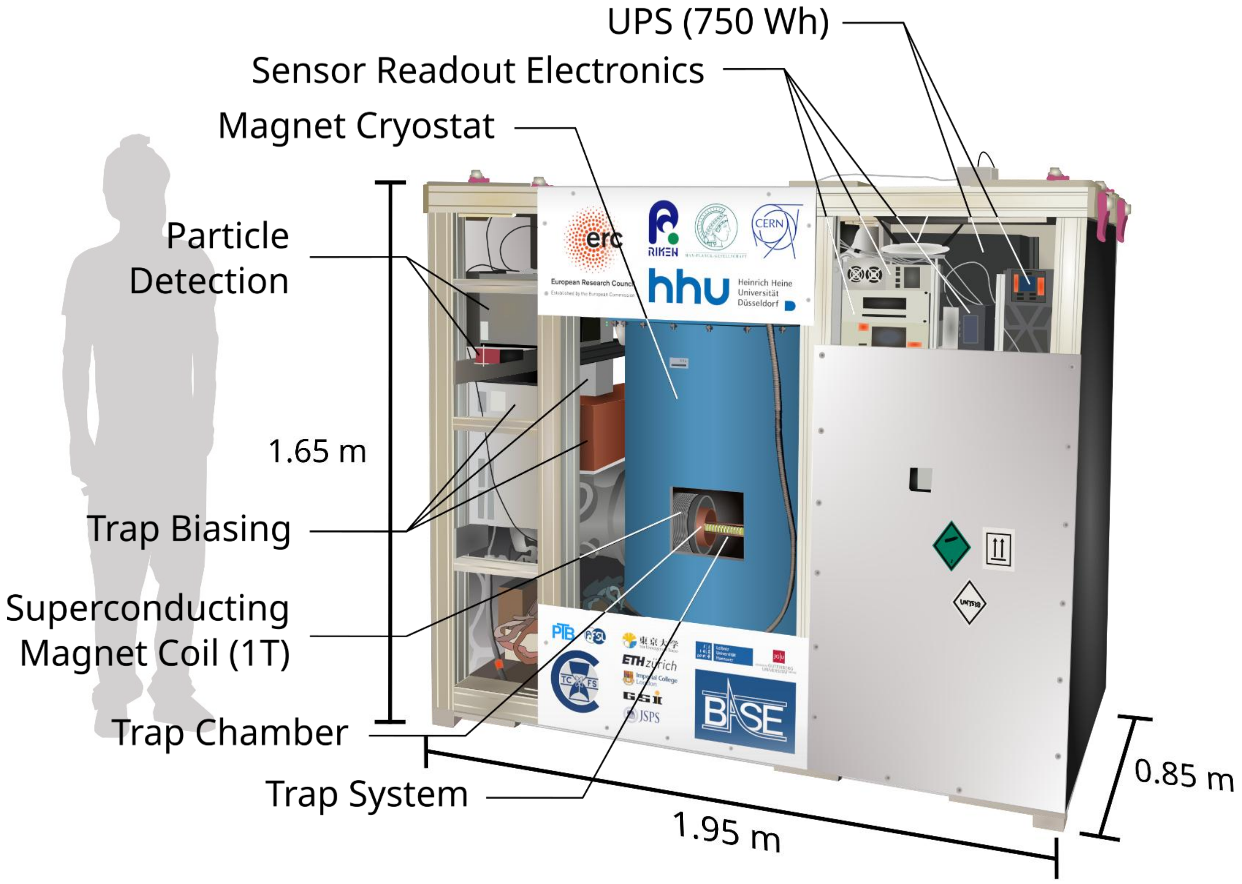
→ Move antiprotons out of the antimatter factory

Charge-to-Mass Ratio Measurements

- **Next precision goal is the p.p.t. level**

	AD/ELENA-ON	BASE best (AD/ELENA OFF)	BASE best (Offline Laboratory)	Best Penning Traps
Fluctuation	2000ppt / 60mHz / 4nT (shielded)	200ppt / 6mHz / 0.4nT	200ppt / 6mHz / 0.4nT	70ppt / 2.2mHz / 0.13nT
Precision goal	2 ppt	2 ppt	2 ppt	2ppt
Measurements	1.000.000	10.000	10.000	820
Realistic Sampling	**23 years**	**3 months**	**3 months**	**2.5 days**
Total measurement time	**> 1 lifetime of an Exp.Phys.**	**3 years (AD)**	**9 months**	**2 weeks?**

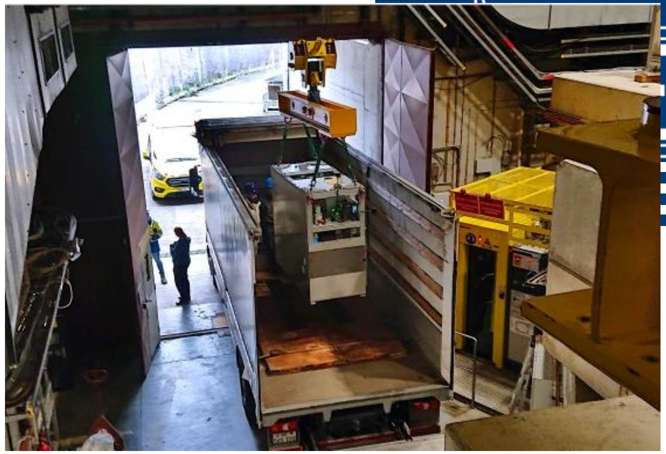
BASE-STEP apparatus



- Transport antiprotons from the only available source
- Use in offline laboratories to multiply experiments on antiprotons
- Crucial technology, not only for **antiproton** transport but also for future spectroscopy of $\overline{H}_2^-$.

Christian Smorra

BASE-STEP apparatus



Open system for injection and ejection while keeping good vacuum

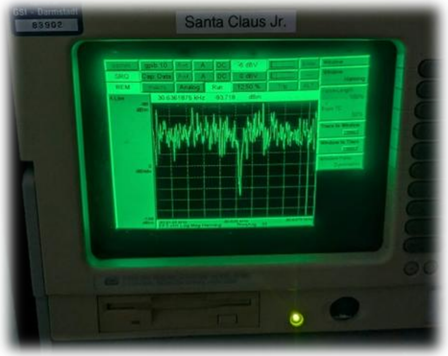
Multi-trap-system for controlled separation

- **First proton transport in 2024 (*Nature* 641, 871–875 (2025))**

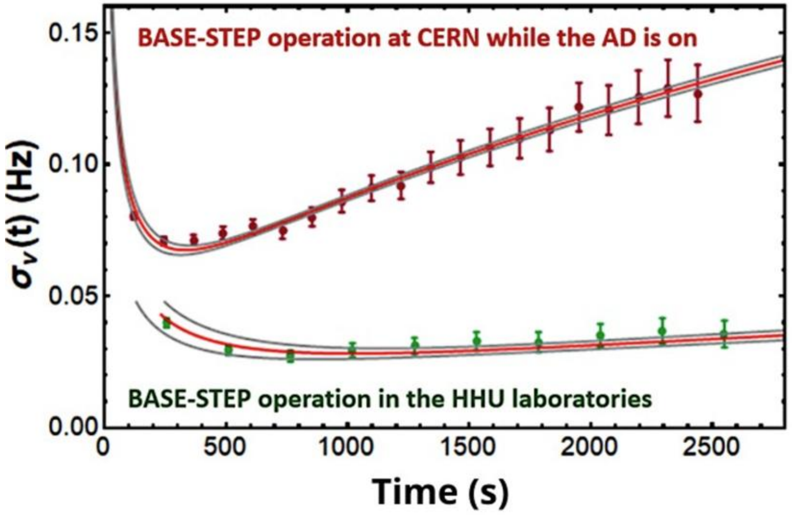
BASE-STEP upgrades in 2025

- ▶ BASE-STEP transported to Düsseldorf

Single-Proton Precision Measurement



December 2024 to February 2025



Clear potential for considerably improved experiments in the offline laboratories at HHU

April to August 2025: System Upgrades

BASE-STEP capture

14.10.2025: STEP connected to Beamline

2 Month of commissioning and beam steering

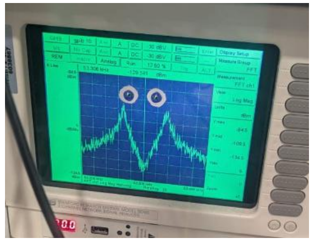
December 2025:
First antiproton
capture in BASE-STEP

- 100 keV antiprotons from ELENA are injected into BASE-STEP
- Degrader reduces kinetic energy to the keV range
- Capture at these low energies by pulsing electric confining potentials.

No observed vacuum-related antiproton loss in 2025

First Antiproton Road Transport

24th of March 2026



92 antiprotons were successfully transported

Not a single antiproton lost

Excellent vacuum conditions
→ No losses observed in the last half year

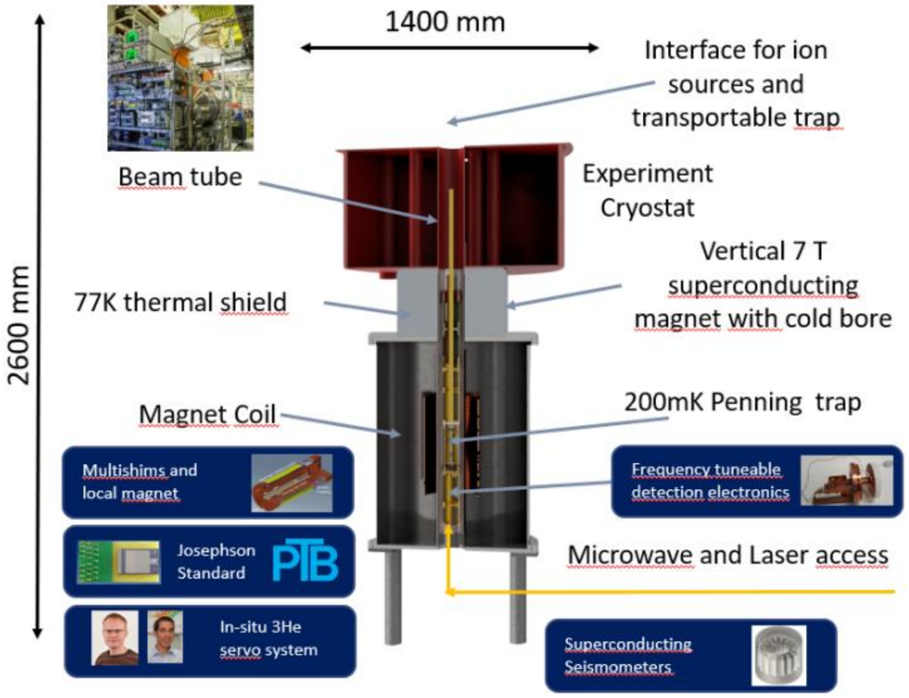
First Antiproton Road Transport

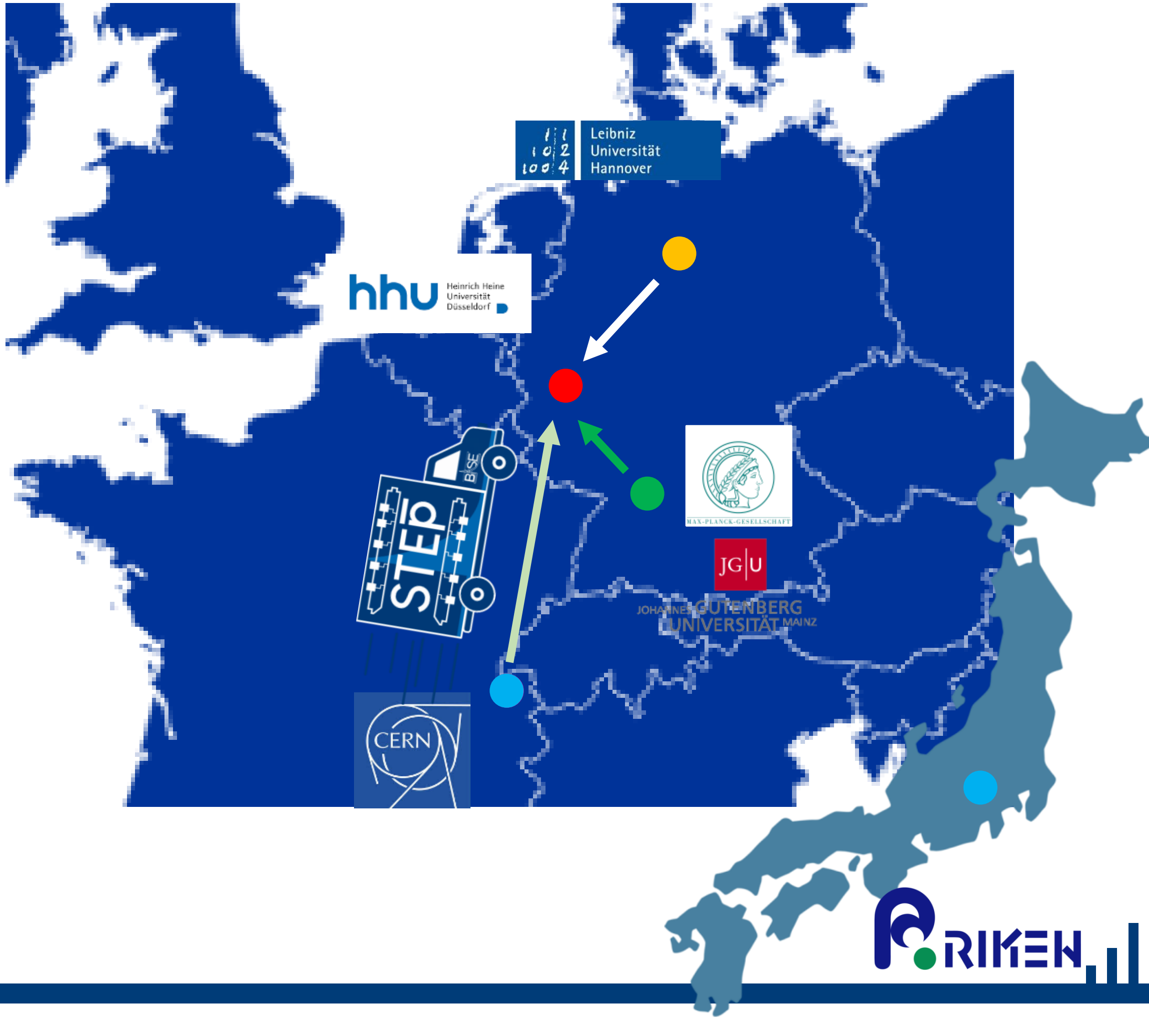
24th of March 2026

- Transport took place around the CERN campus
- Took in total ~3 hours
- Liquid Helium cooled
- Connection to a cold head during transport planned in the future for long distance transport

Antiprotons on the road 2027 and beyond

- BASE–CERN → offline laboratory?!?
- BASE–HHU:
  - New generation of Penning-Trap experiments in commissioning





Thanks for your attention

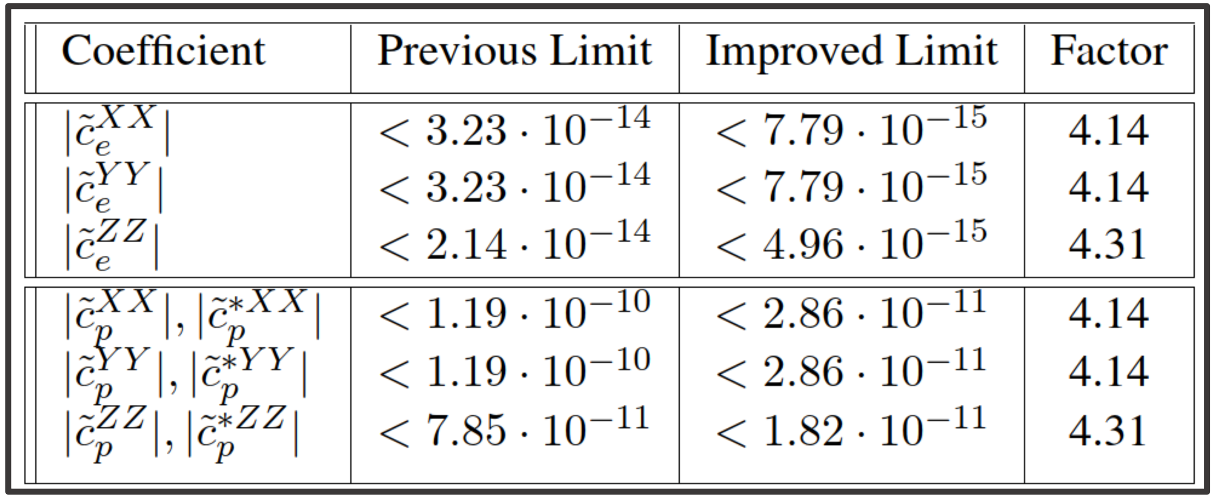
Summary of SME limits by BASE

- Magnetic Moment Measurements

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

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

- 2022 Charge-to-Mass Ratio Measurement



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

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