KHuK Meeting, Bad Honnef, 2023/12/08

Physics and Perspectives at the AD/ELENA

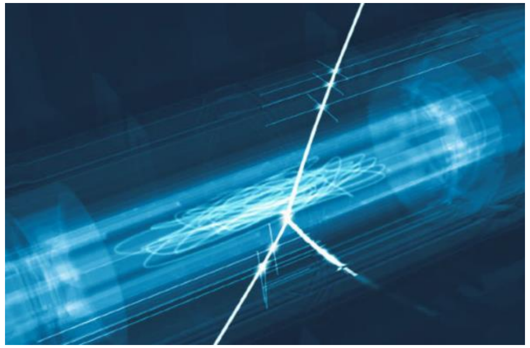
Antimatter Factory of CERN

Stefan Ulmer

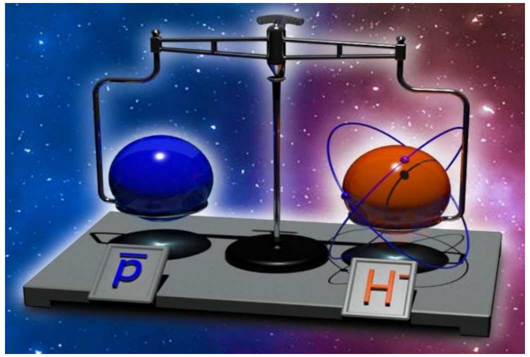
Chair AD Program CERN / Spokesperson BASE

HHU Düsseldorf, Germany
RIKEN, Japan
CERN, Switzerland

2023 / 12 / 08

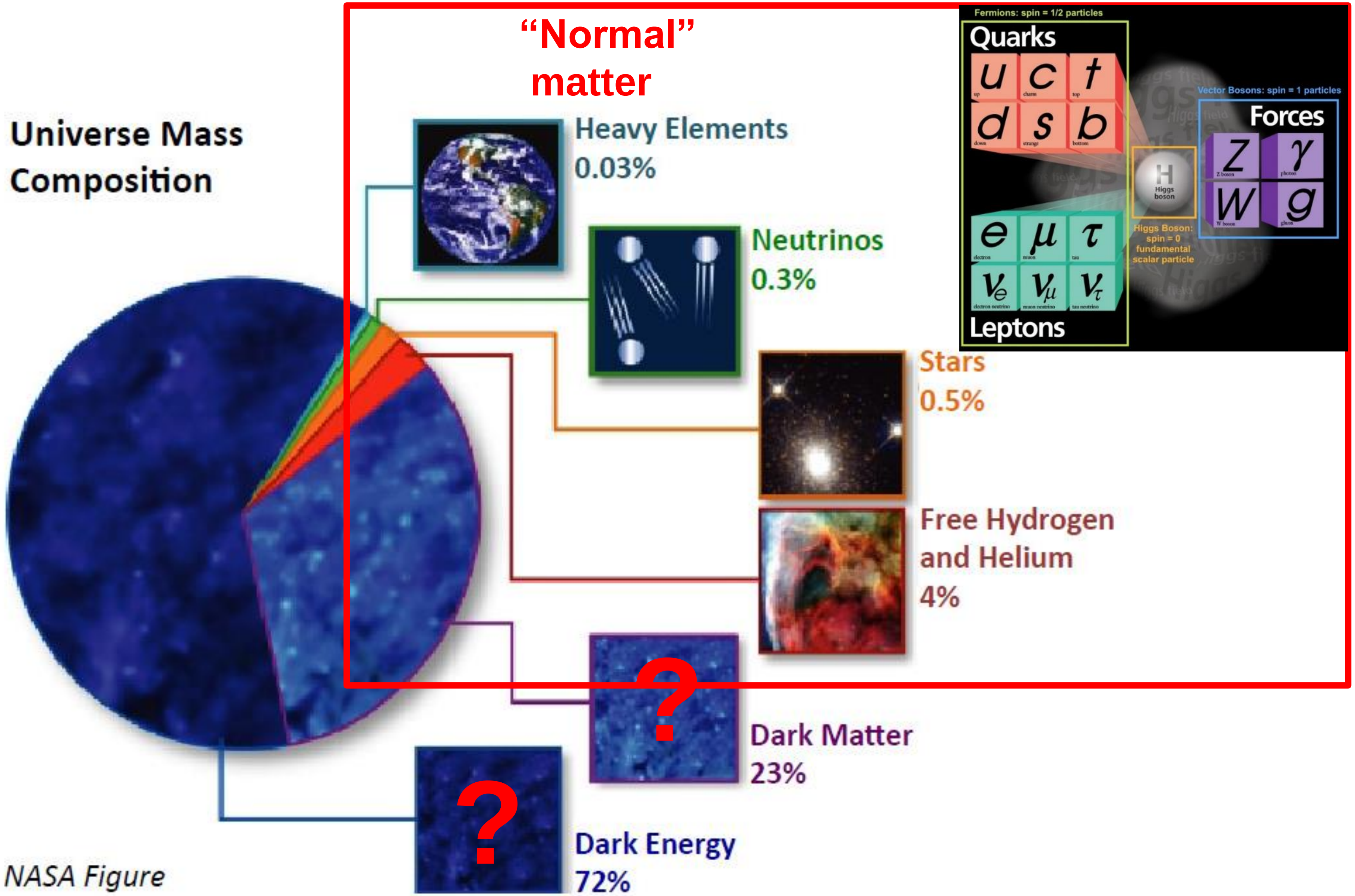


antihydrogen trap



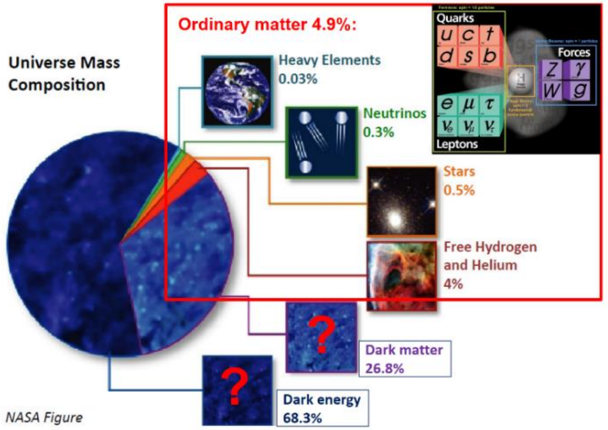
antiproton/proton balance

The Energy Content of our Universe



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

Matter / Antimatter Asymmetry



Combining the Λ-CDM model and the SM our predictions of the baryon to photon ratio are **inconsistent by about 9 orders of magnitude**

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

Observation	
Baryon/Photon Ratio	$0.6 * 10^{-9}$
Baryon/Antibaryon Ratio	10 000

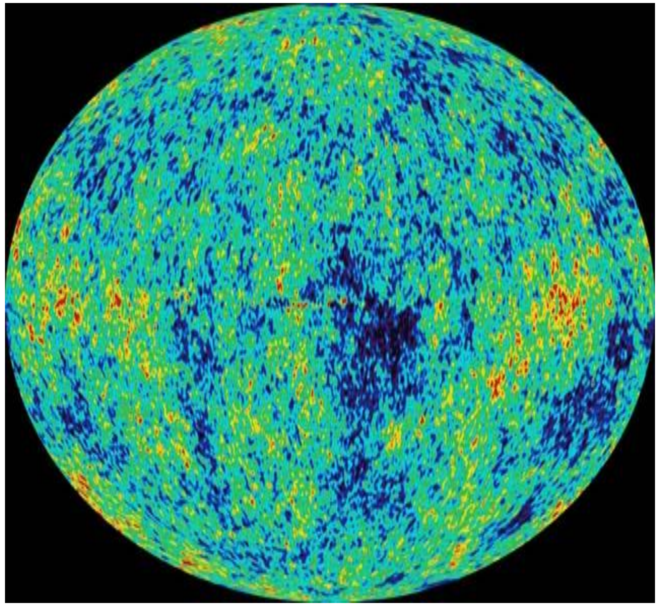
B - violation

CP violation

Arrow of time

CPT violation

Baryon Asymmetry in the Universe (BAU)



AEgIS

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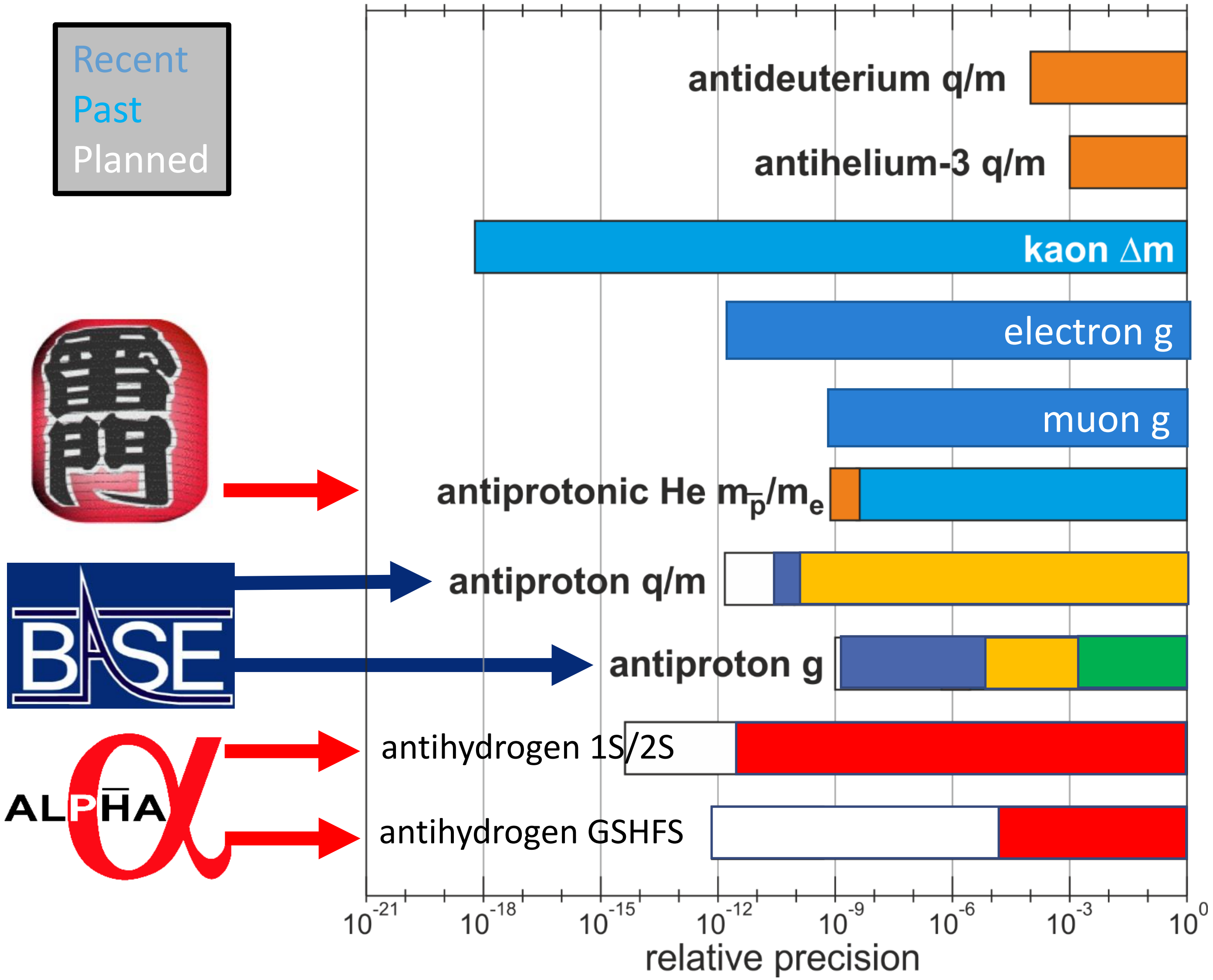
One strategy to try to resolve this problem are technology-driven high precision comparisons of the fundamental properties of protons and antiprotons.

CPT tests based on particle/antiparticle comparisons



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).

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

AEḡIS, ALPHA, BASE, GBAR, STEP̄

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

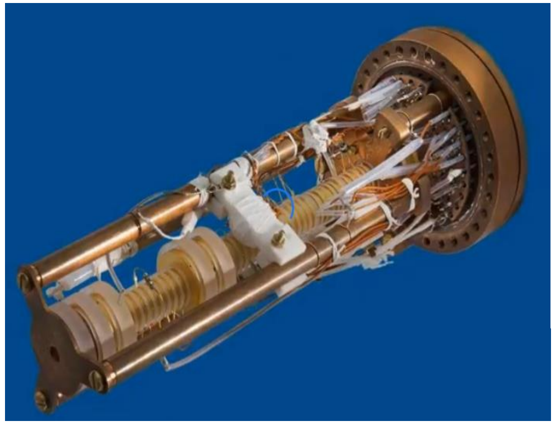
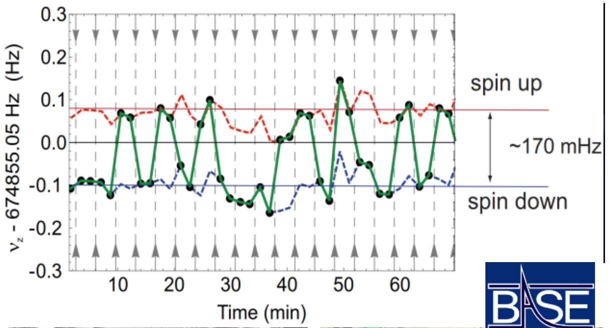
Methods

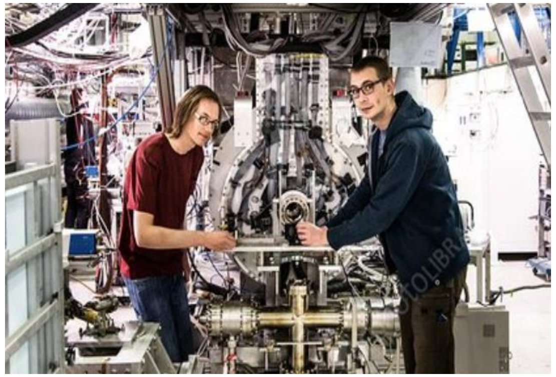
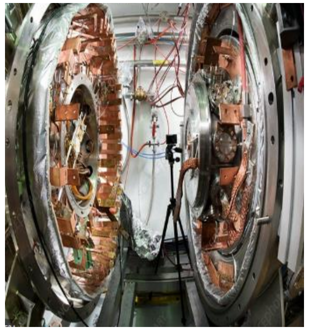
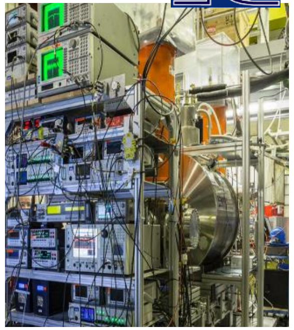
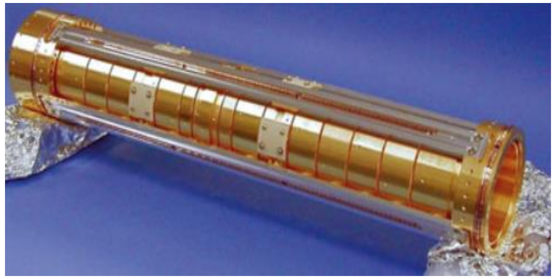
- This community is performing measurements using quantum technologies at world leading precision…

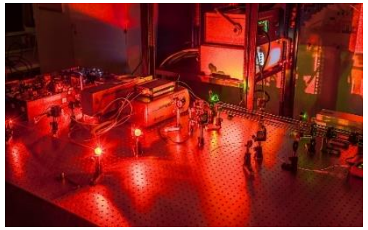
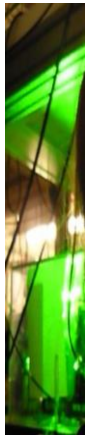
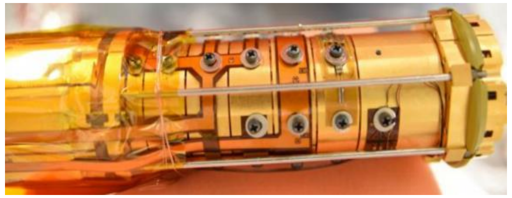
Clocks

Traps

Lasers

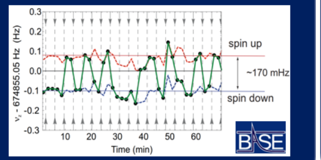





Innovation and Technology

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

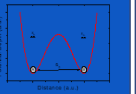
Non-destructive spin transition spectroscopy



Single spin spectroscopy in a Penning trap

Sympathetic Cooling

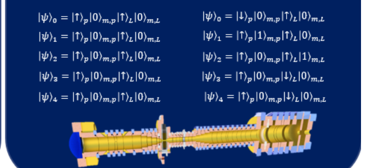
Quantum logic inspired sympathetic cooling of antiprotons, Hbar +, and positrons to laser-cooled Be+ ions



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

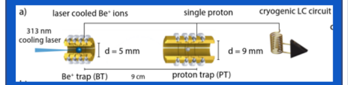
Quantum Logic Spectroscopy

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



Laser Cooled Superconductors

coupled Penning traps with common SC-LC

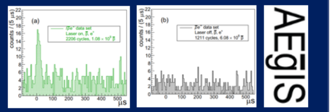


Demonstrated reduction of SC-LC circuit temperature to sub-1K level

Axion detection / precision frequency measurements

Production of Hbar via Charge Exchange with Laser Excited PS

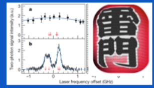
$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$



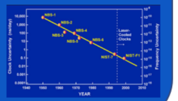
Similar methods to be applied for production of Hbar+-ion / H2+bar

More Quantum Methods

Deep UV two photon spectroscopy in antiprotonic helium



Atomic fountain microwave clocks

AEḡIS

ALPHA

BASE

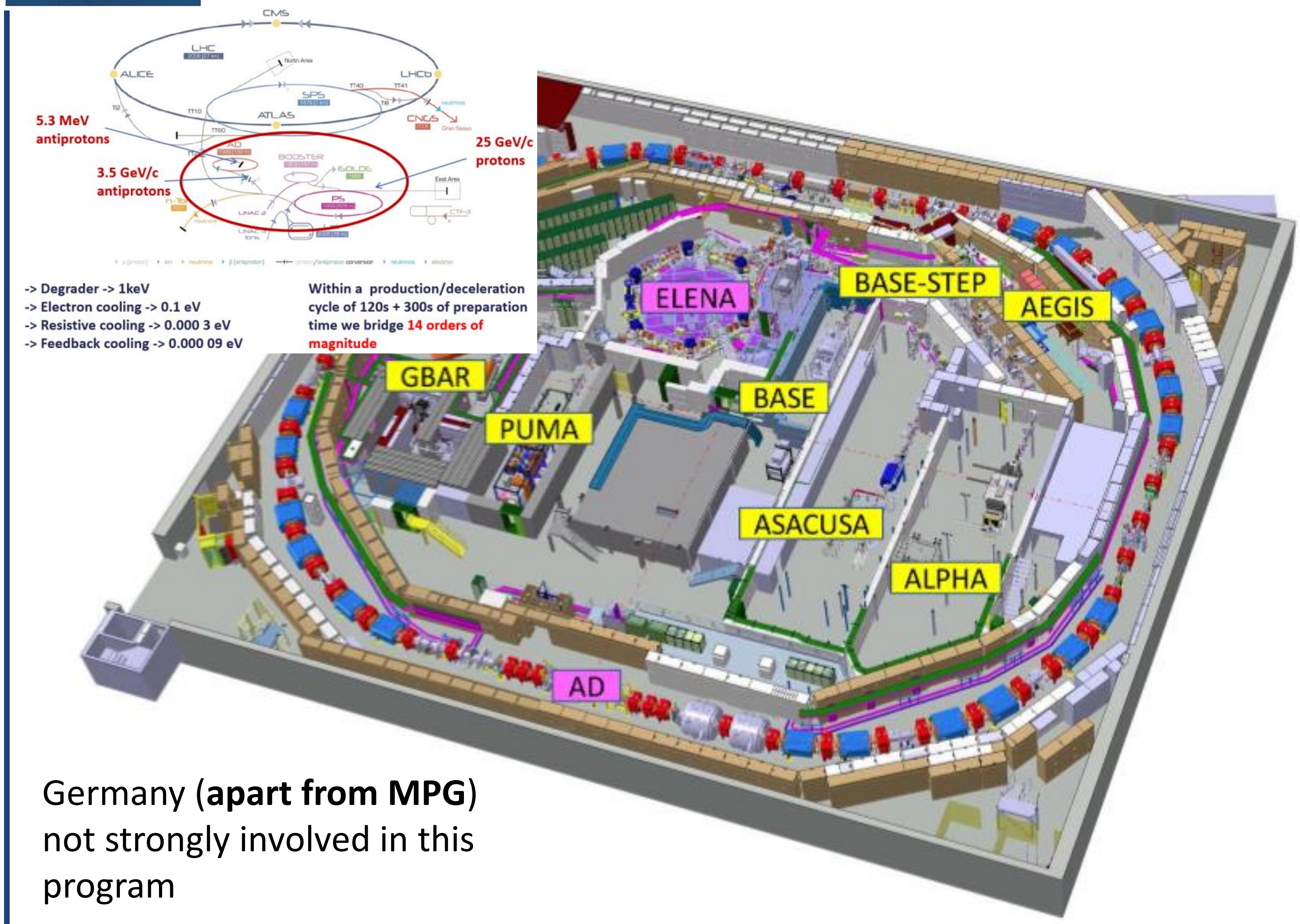
GBAR

STEp

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

The AD/ELENA-Facility

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



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

antihydrogen

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

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

antiprotons

ASACUSA
Antiprotonic helium spectroscopy

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

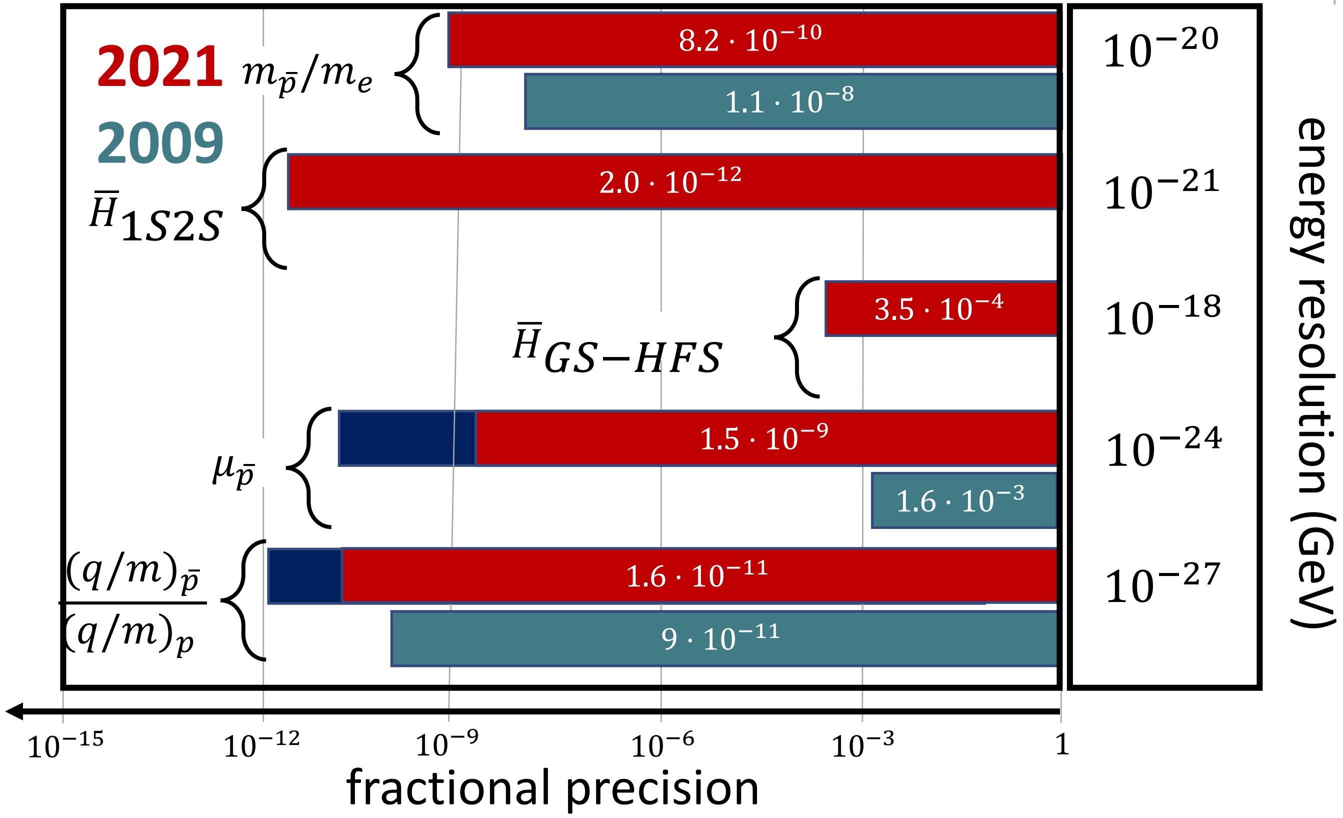
PUMA
Antiproton/nuclei scattering to study neutron skins

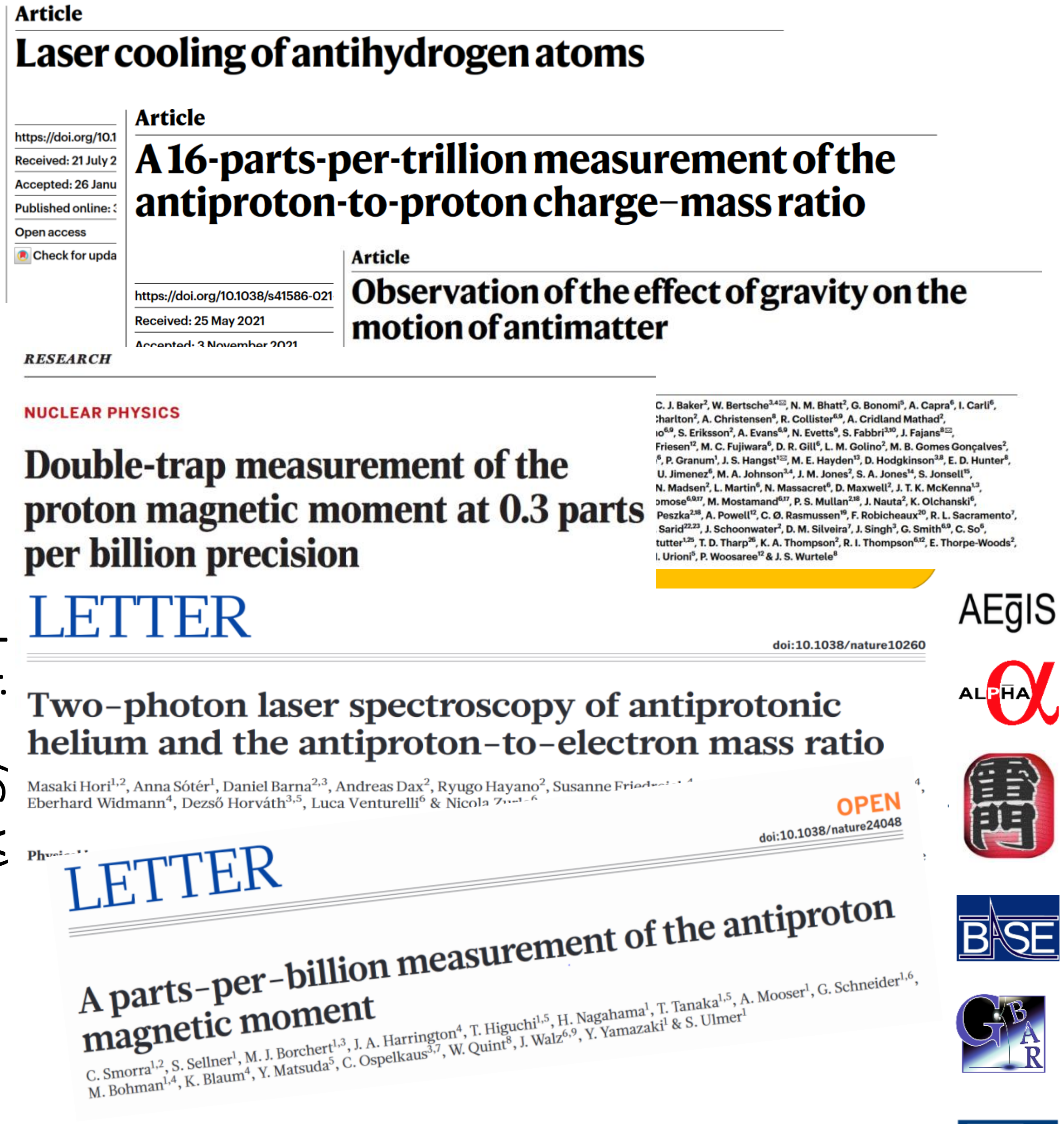
60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations

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

Progress

- Progress made since LS1





dramatic progress in experimental resolution since the program was started

Some Groups Active

Hannover (BASE)
Ion and atom traps / clocks / QI

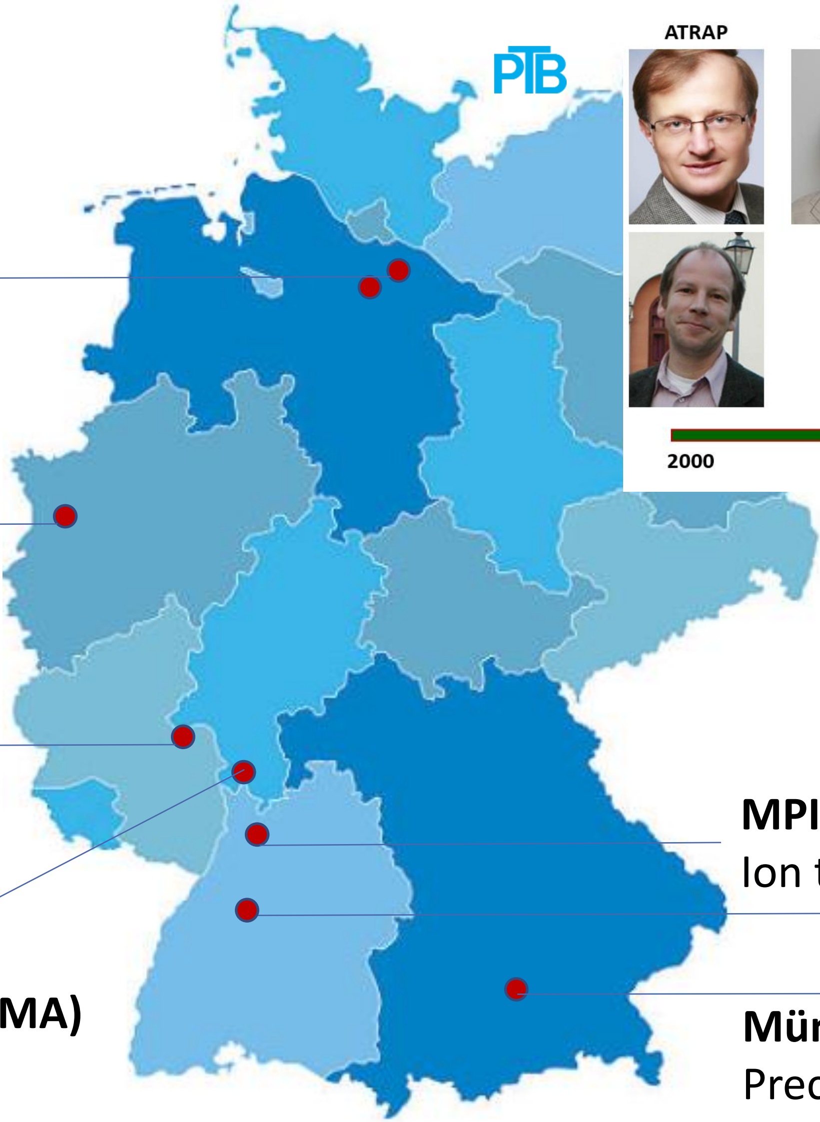
Düsseldorf (BASE)
Ion traps / antimatter / molecules / clocks

Mainz (BASE / ASACUSA / GBAR)
Ion traps / Magnetometers / QI

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

GSI (BASE) / Darmstadt (PUMA)

TECHNISCHE UNIVERSITÄT DARMSTADT



MPIK-Heidelberg (BASE)
Ion traps

München (MPQ - ASACUSA)
Precision Laser-Spectroscopy

RIKEN
DFG
erc

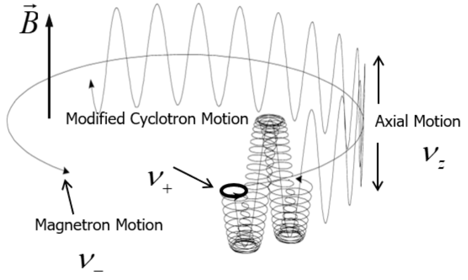
Continously increasing community in the German hemisphere

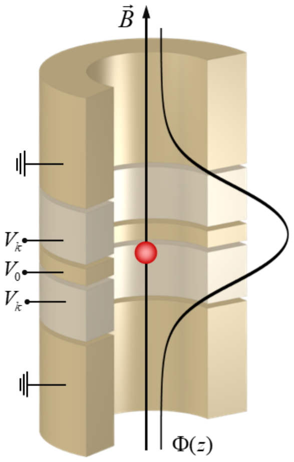
AEgIS
ALPHA
BASE
STEP

BASE – Penning Traps - Antiprotons

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

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





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

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

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

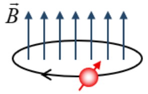
Invariance Theorem

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

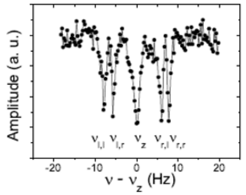
Gives undisturbed access to cyclotron frequencies $\nu_c = \frac{1}{2\pi}\frac{q_{ion}}{m_{ion}} B$

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

Cyclotron Motion



simple



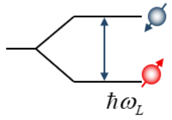
S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)

g: mag. Moment in units of nuclear magneton

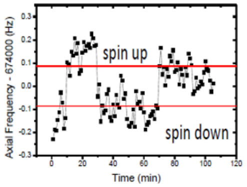
$$\omega_c = \frac{e}{m_p} B \qquad \omega_L = g \frac{e}{2m_p} B$$

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} \qquad \frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

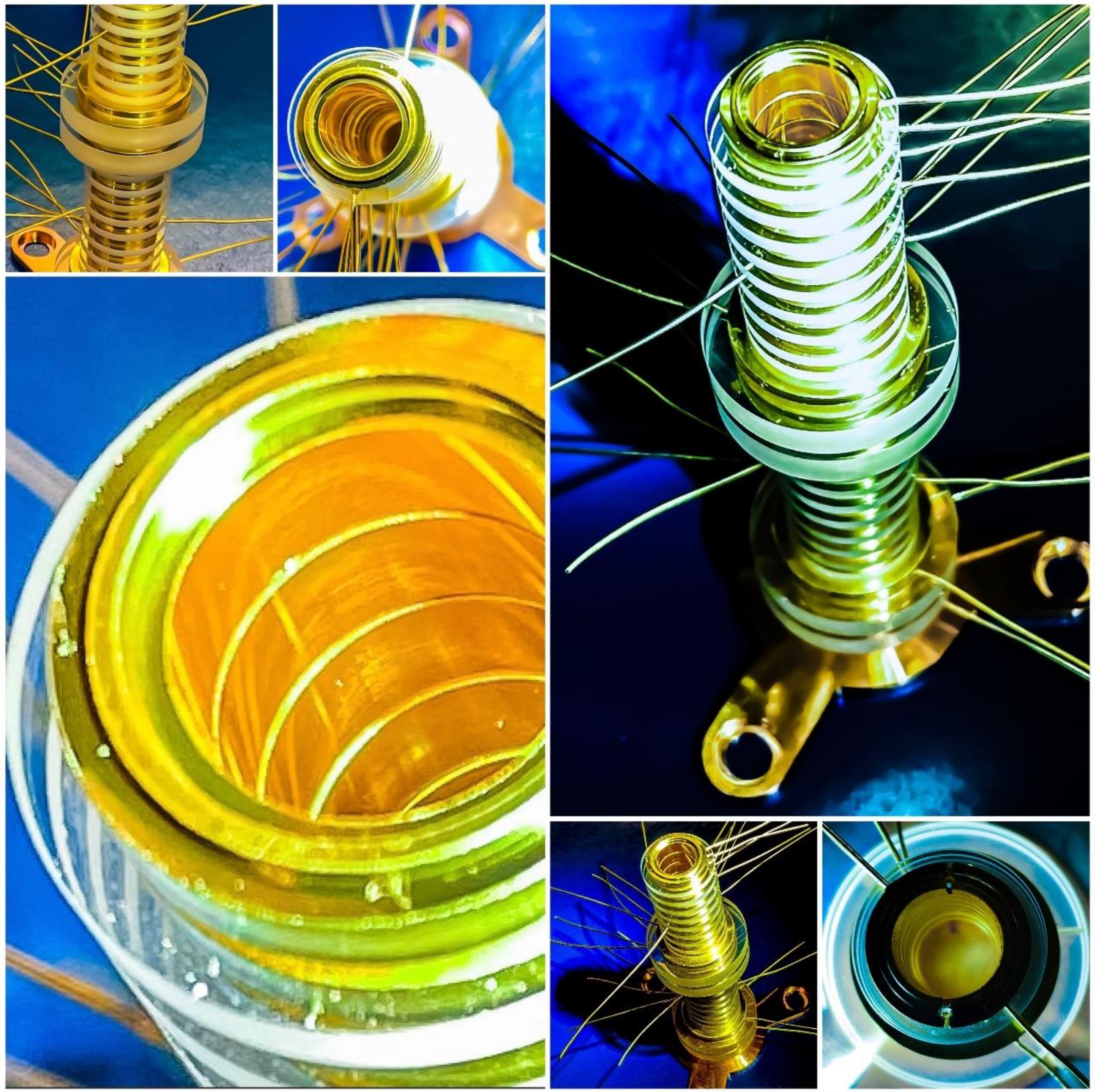
Larmor Precession



difficult



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

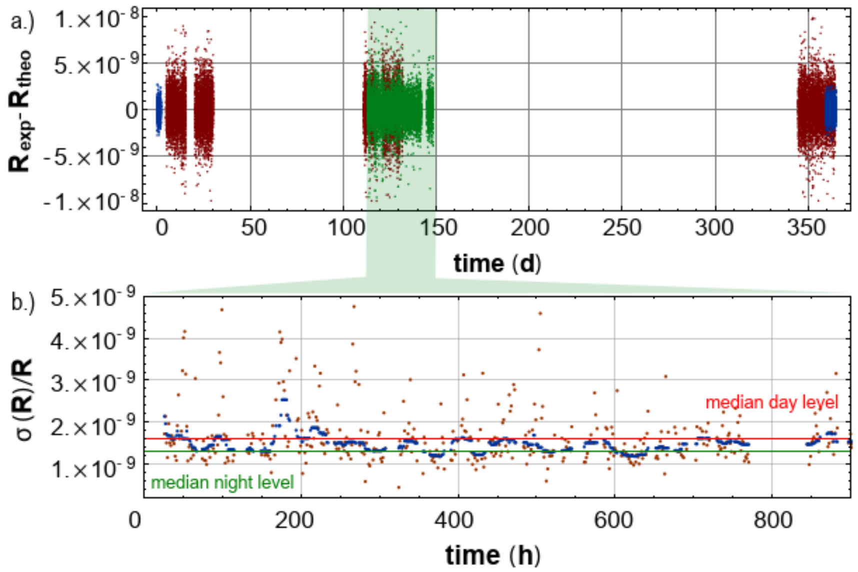


Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

High Precision Mass Spectrometry

High Precision Magnetic Moment Measurements

BASE Measurements – Proton to Antiproton Q/M



Result of 6500 proton/antiproton Q/M comparisons:

$R_{exp,c}$ = 1.001 089 218 757 (16)

$$\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} + 1 = 3(69) \times 10^{-12}$$

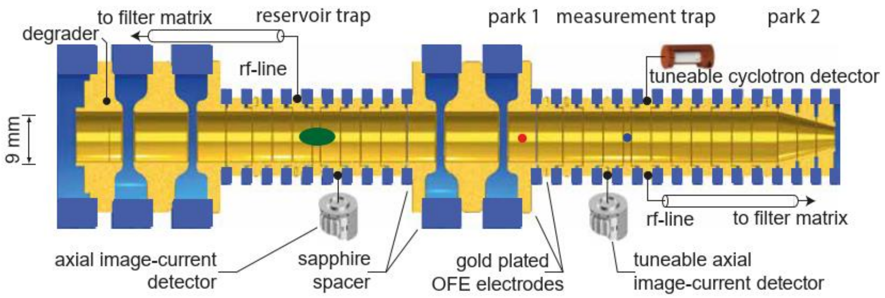
Stringent test of CPT invariance with Baryons.

Consistent with CPT invariance

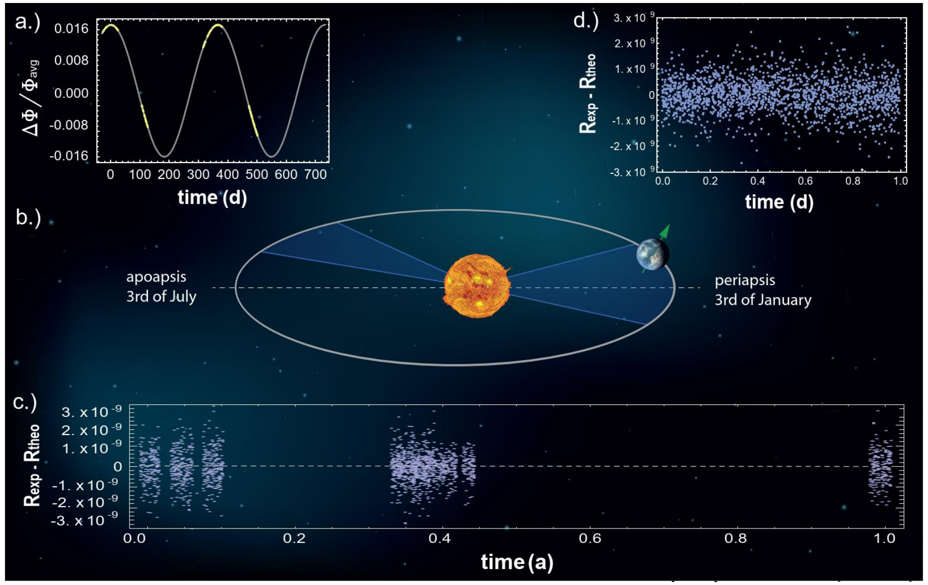
S. Ulmer et al., ***Nature* 524** 196 (2015)
M. Borchert et al, **Nature 601,** 53 (2022)

- Set differential constraints on the weak equivalence principle by measuring charge-to-mass ratio as a function of gravitational potential at surface of earth.
- Final data analysis is work in progress.

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



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



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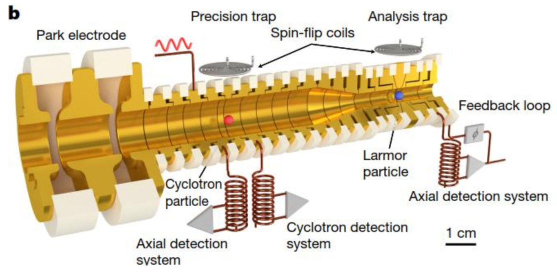
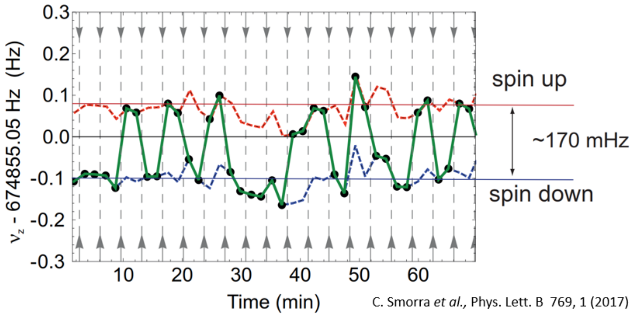
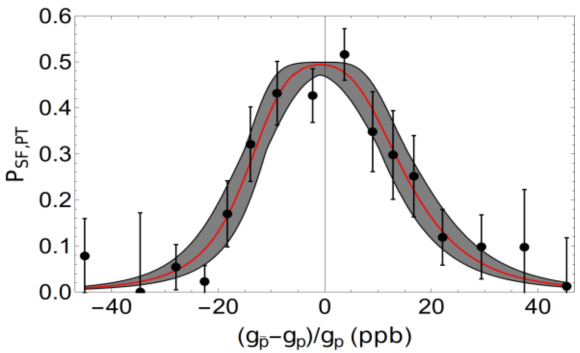
3000-fold Improved Antiproton Moment Measurement

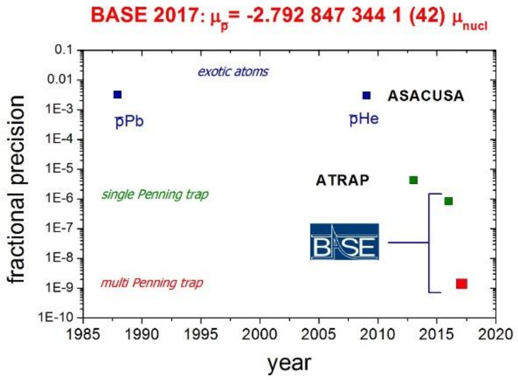
New idea: divide measurement to two particles



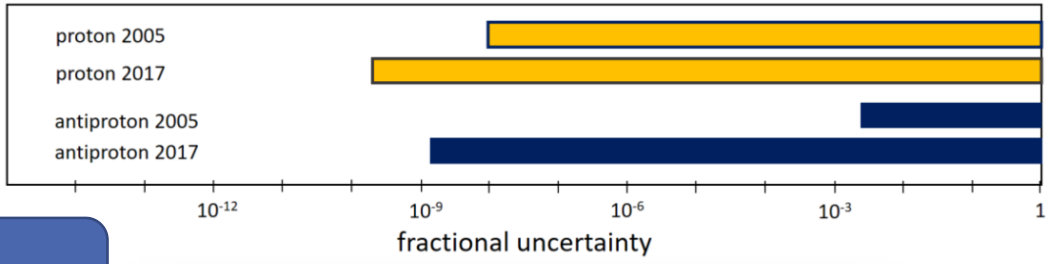


win: 60% of time usually used for sub-thermal cooling useable for measurements



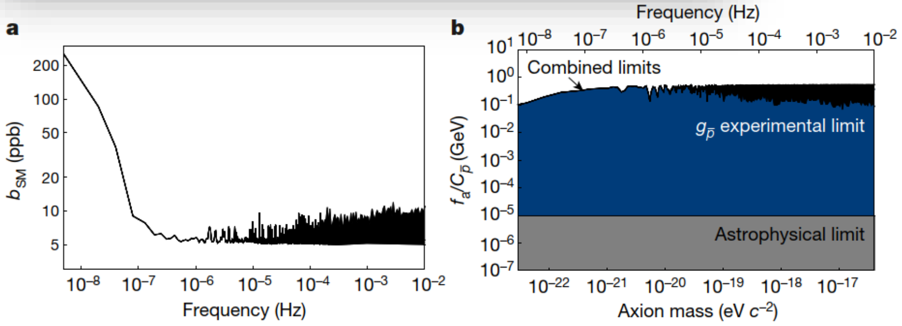


Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	Collaboration	Method
2011	2.792 847 353 (28)	2.786 2 (83)	Pask (ASACUSA)	MASER / Exotic Atoms
2012	2.792 846 (7)		diSciacca (ATRAP)	Single Penning-trap
2013		2.792 845 (12)	diSciacca (ATRAP)	Single Penning-trap
2014	2.792 847 349 8 (93)		Mooser (BASE)	Double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



First constraints on antimatter/dark matter coupling

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



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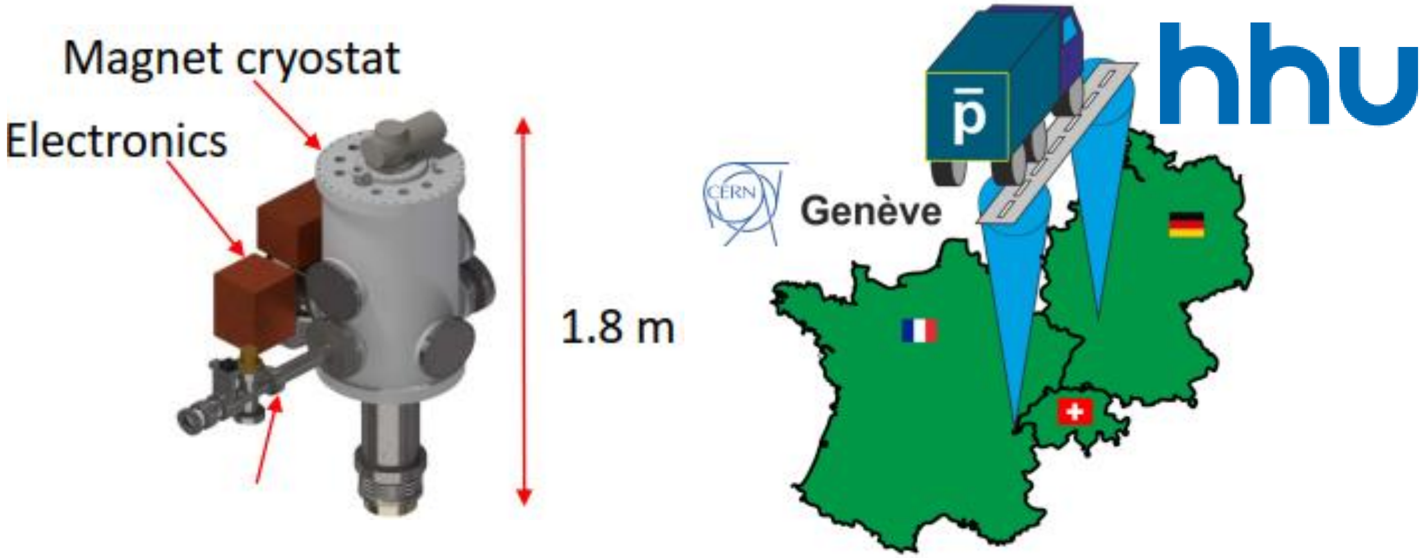
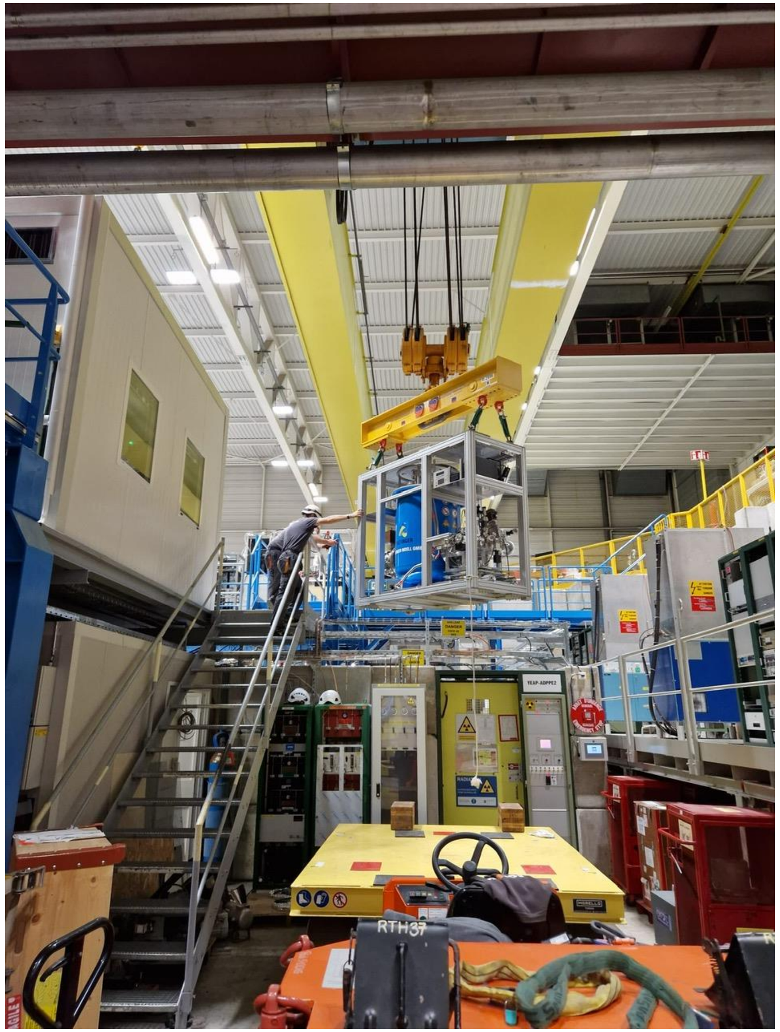
first measurement more precise for antimatter than for matter...

Smorra *et al. (BASE)*, **Nature 550**, 371 (2017) Schneider *et al. (BASE)*, Science 358, 1081 (2017) *Smorra et al.(BASE)*, **Nature 575**, 310 (2019)

To make these experiments better….

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



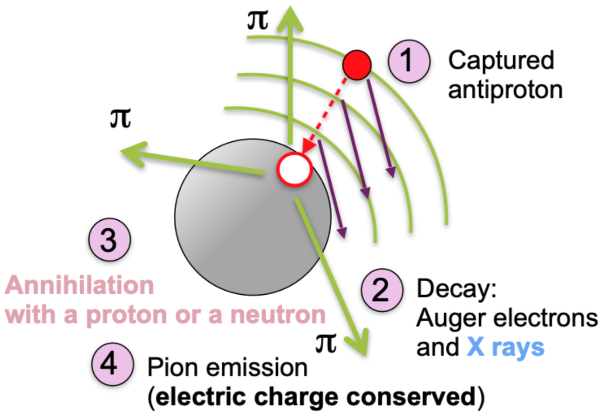


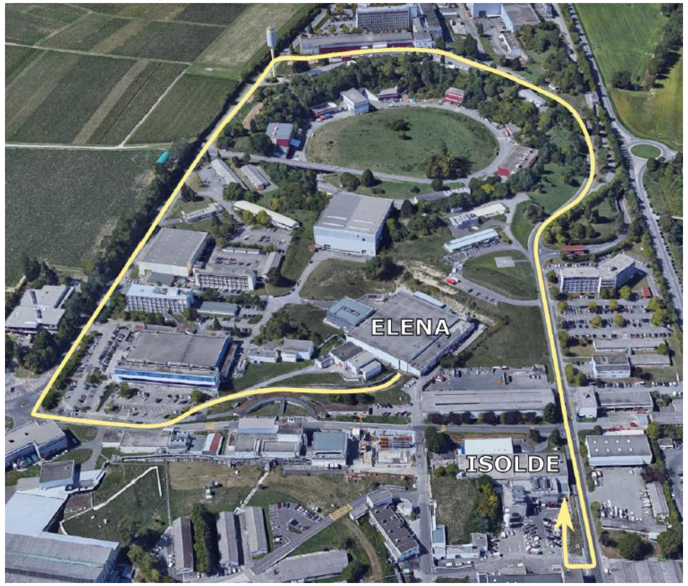
- Antiproton transport to dedicated precision laboratory space at HHU Düsseldorf.

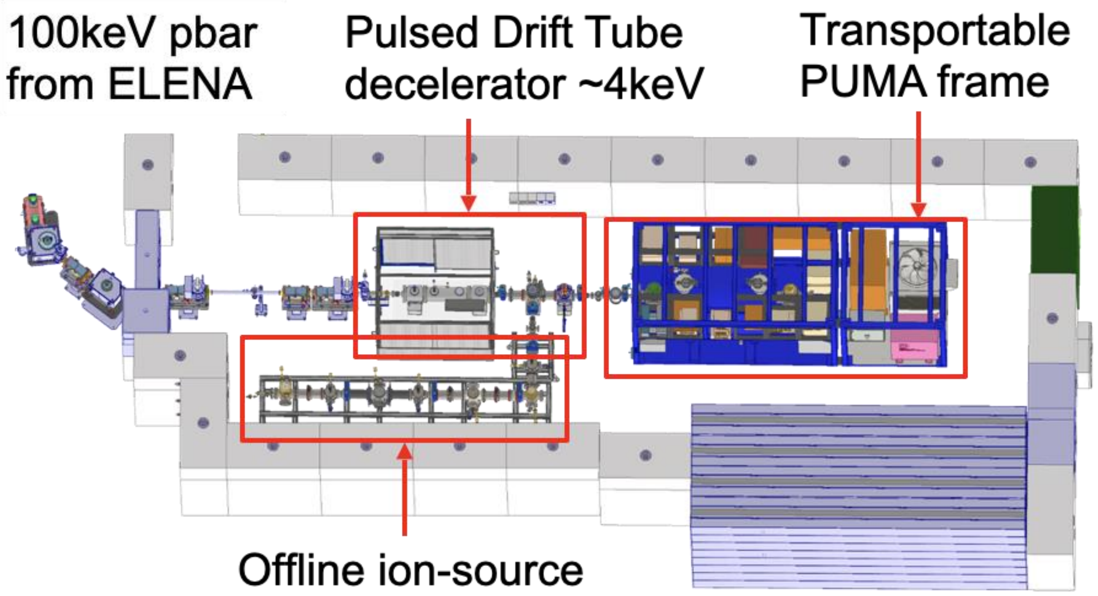
- New chair to support BASE Physics created at HHU in 2022 – clear long-term perspective of BASE Physics program
- SFB-TR (DFG), with several BASE-related projects involved, in preparation (HHU/Mainz).

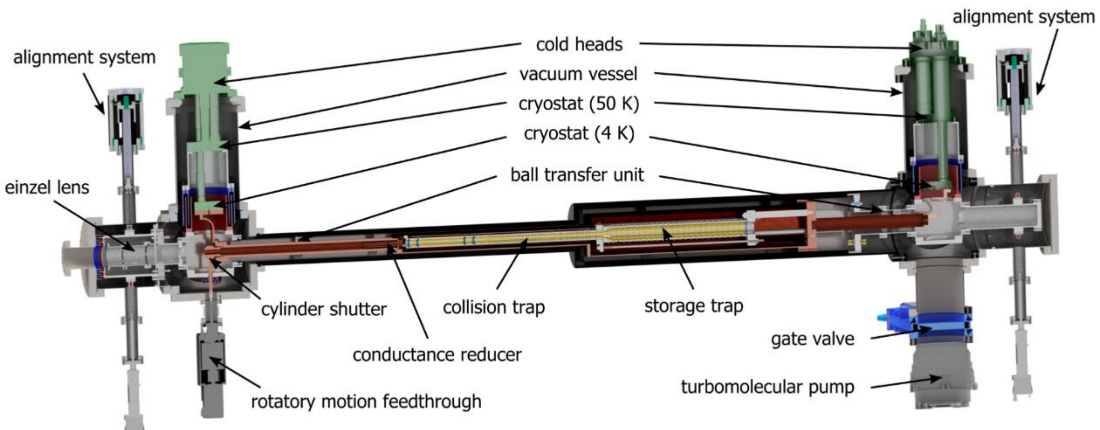
Overview – PUMA Collaboration

- **General:** Low-energy antiprotons to probe the neutron-to-proton content of the radial density tail of stable (ELENA) and unstable (ISOLDE) nuclei
- **Main tools:** transportable Penning trap and time projection chamber for tracking of charged pions





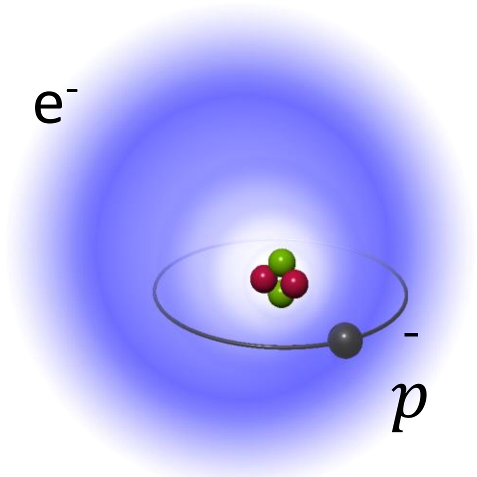




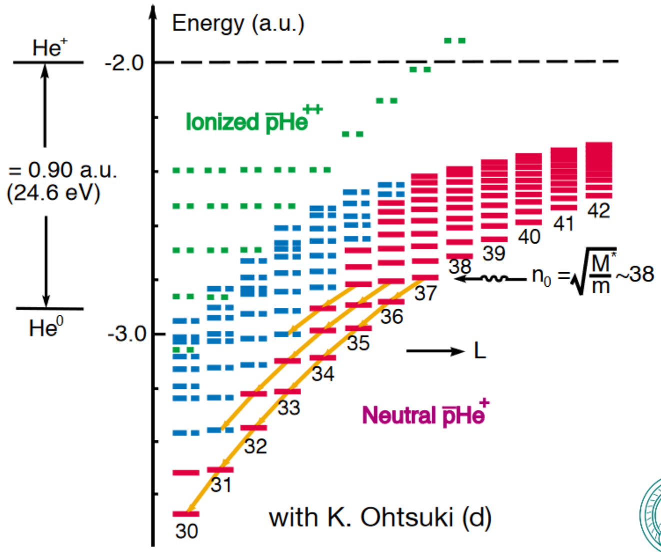
- **ADUC** hopes to see trapped antiprotons in PUMA in the 2024 run.
- **Rich physics program beyond LS3**

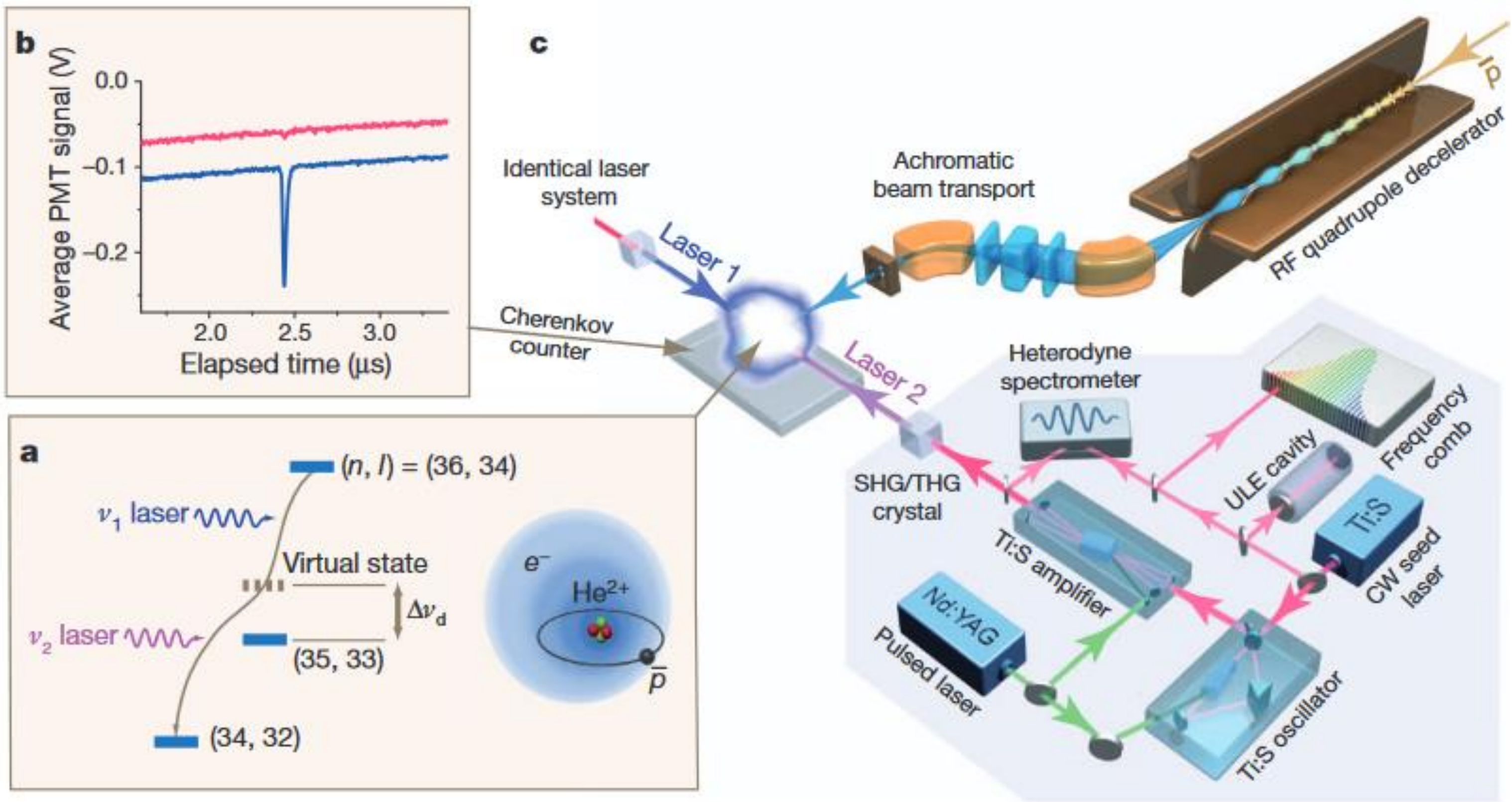
explained in detail by Norbert Pietralla

Laser spectroscopy of antiprotonic/pionic helium



$\overline{p}He^+$: antiprotonic helium





2003: Laser spectroscopy with 80 keV beam of radiofrequency quadrupole decelerator — *PRL* 91, 123401 (2003)

2005: Synthesis of cold two-body Rydberg antiprotonic helium ions — *PRL* 94, 063401 (2005)

2006: First accelerator experiment to use femtosecond optical frequency comb — *PRL*. 96, 243401 (2006)

2011: First sub-Doppler two-photon laser spectroscopy of antiprotonic atom — *Nature* 475, 484 (2011)

2016: Gas buffer cooling of two billion atoms and antiproton-to-electron mass ratio — *Science* 354, 610 (2016)

2020: First laser spectroscopy of an atom containing a meson: pionic helium atoms — *Nature* 581, 37 (2020)

2022: Narrowing of spectral lines of antiprotonic atoms in superfluid helium — *Nature* 603, 411 (2022)

2023: Dedicated group established in Mainz and Imperial College London to carry out research to around **2040**.

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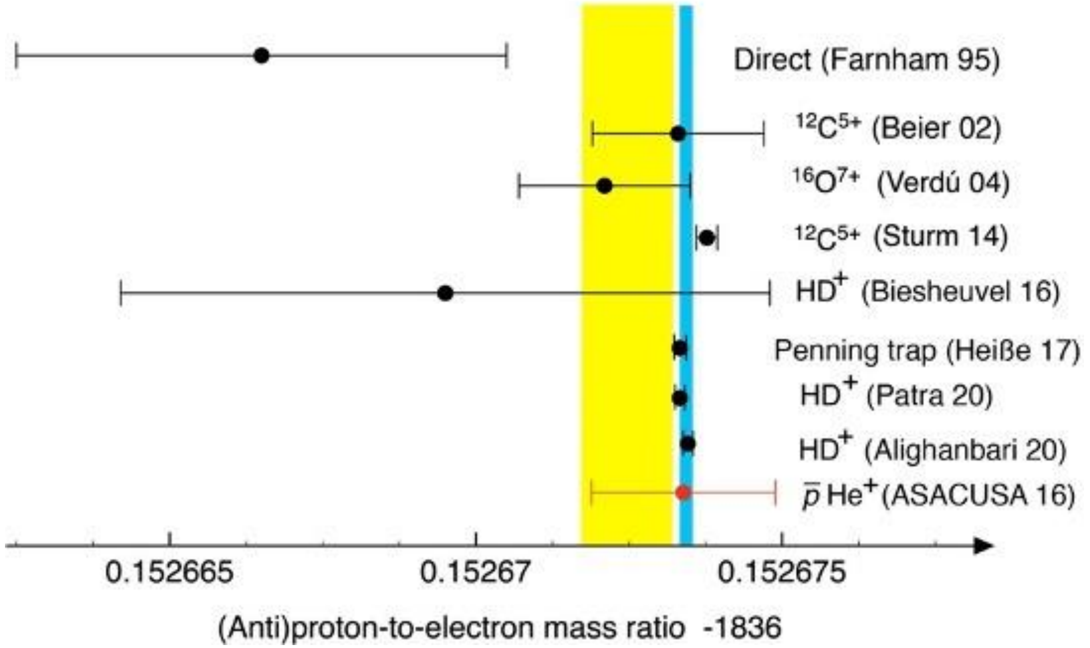
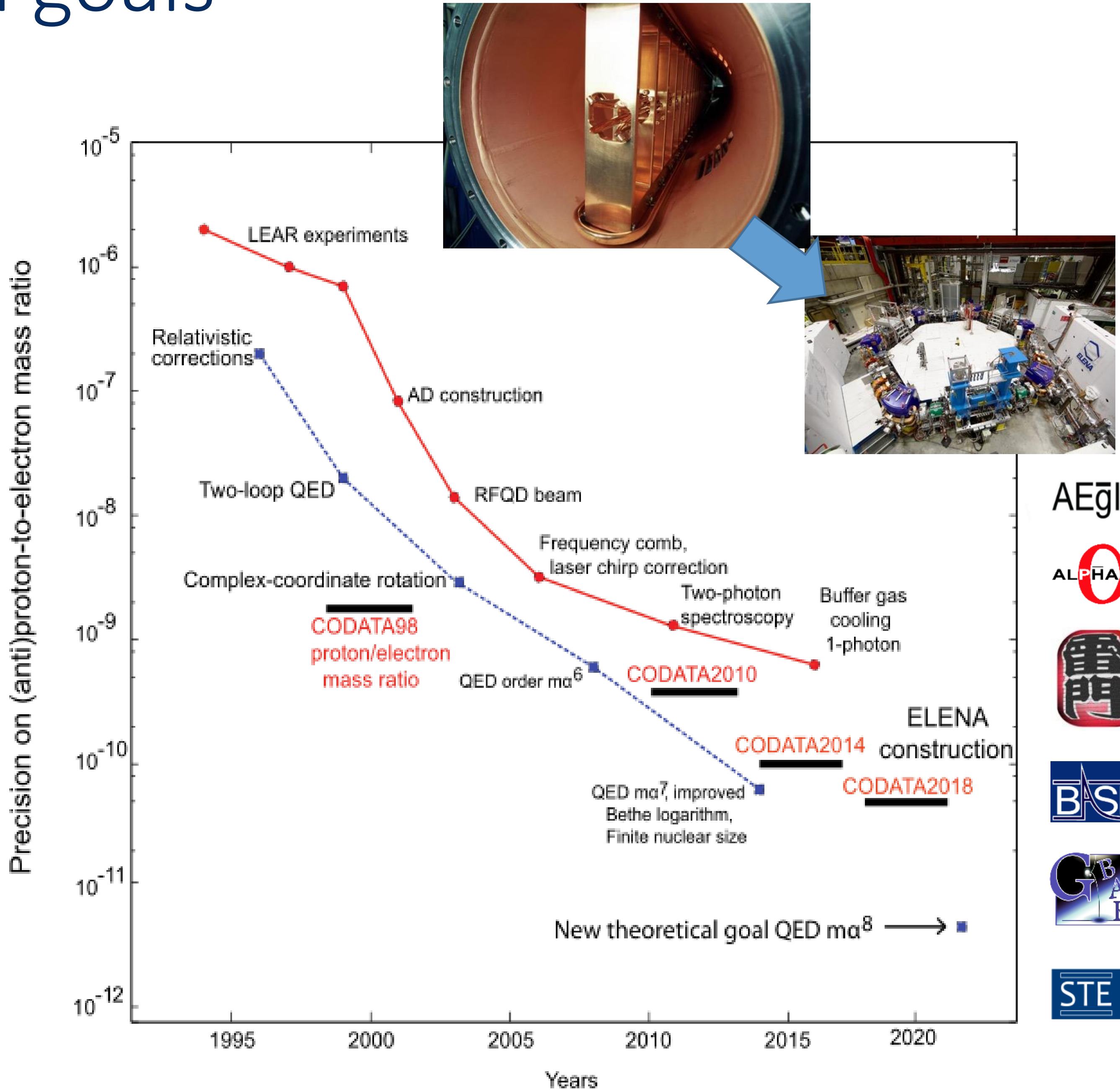
Short/medium term goals

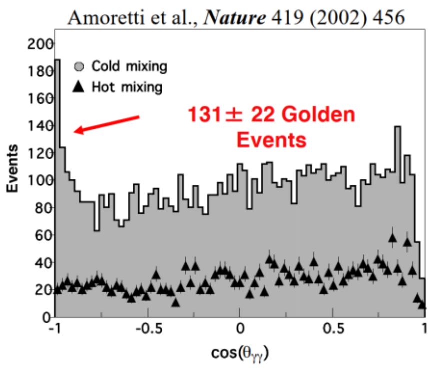
- Use cooled antiproton beam of ELENA instead of uncooled beam of RFQD
- Determine the antiproton-to-electron mass ratio 1836.1526734 (15).
- Test QED of antiprotons with **100x higher precision than before.** (trap precision level)
- Determine upper limits on beyond Standard Model fifth forces and spin-dependent forces.





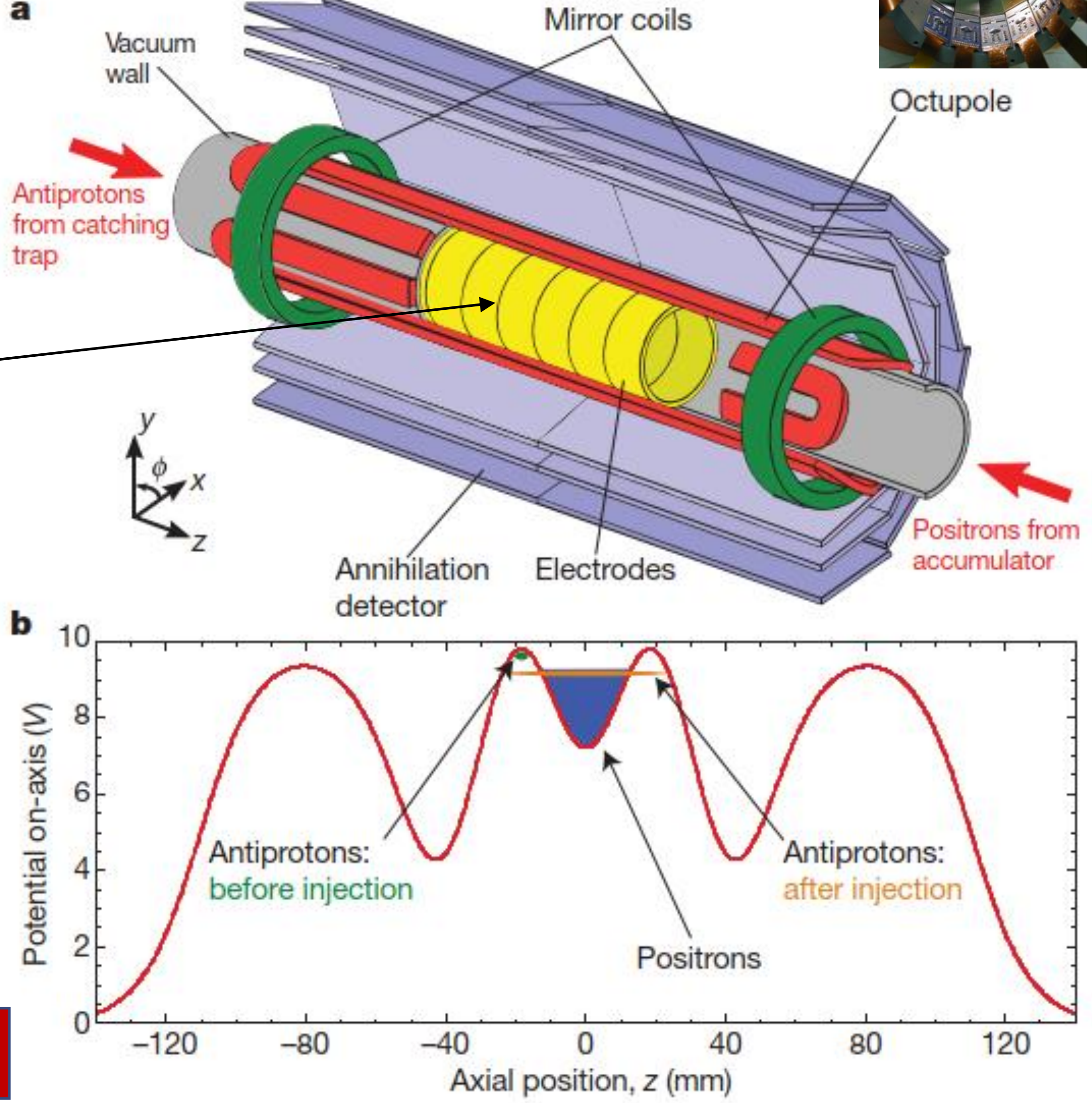
Antihydrogen Production and Trapping

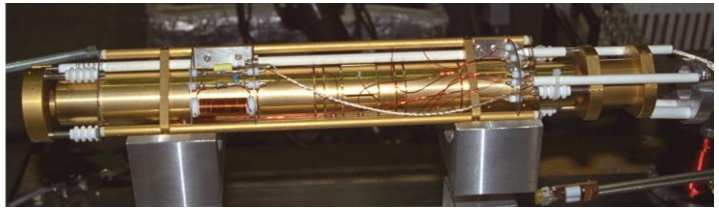
Cold antihydrogen

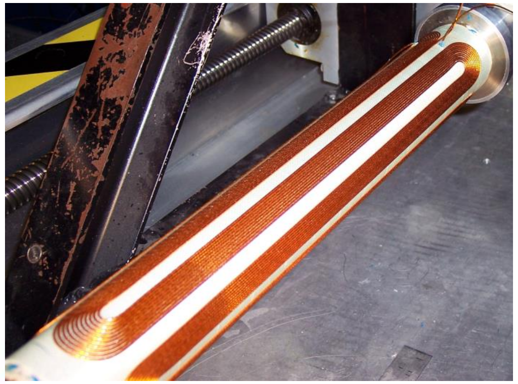


«simple»

trap electrodes







Nested Penning Trap with

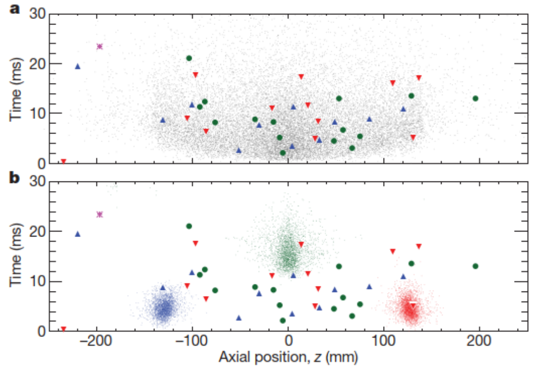
- Antiprotons and
- Positrons

trapped close to each other.

Different antiproton/positron injection methods

!!! difficult !!!

Trapped Antihydrogen



Initially: less than one atom per attempt

ALPHA collaboration: Nature **468**, 673 (2010)

ALPHA – 1S2S Spectroscopy

Spectroscopy idea: Annihilation as a function of laser frequency.

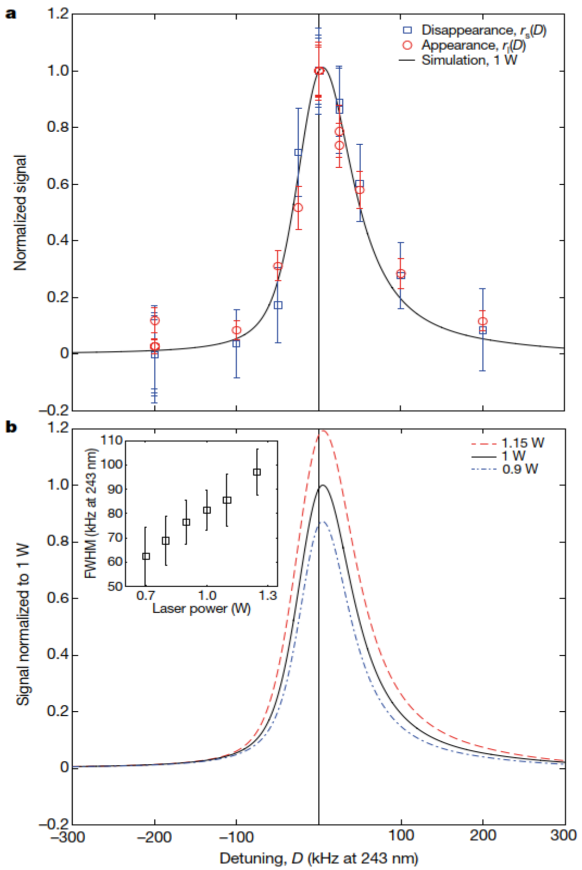
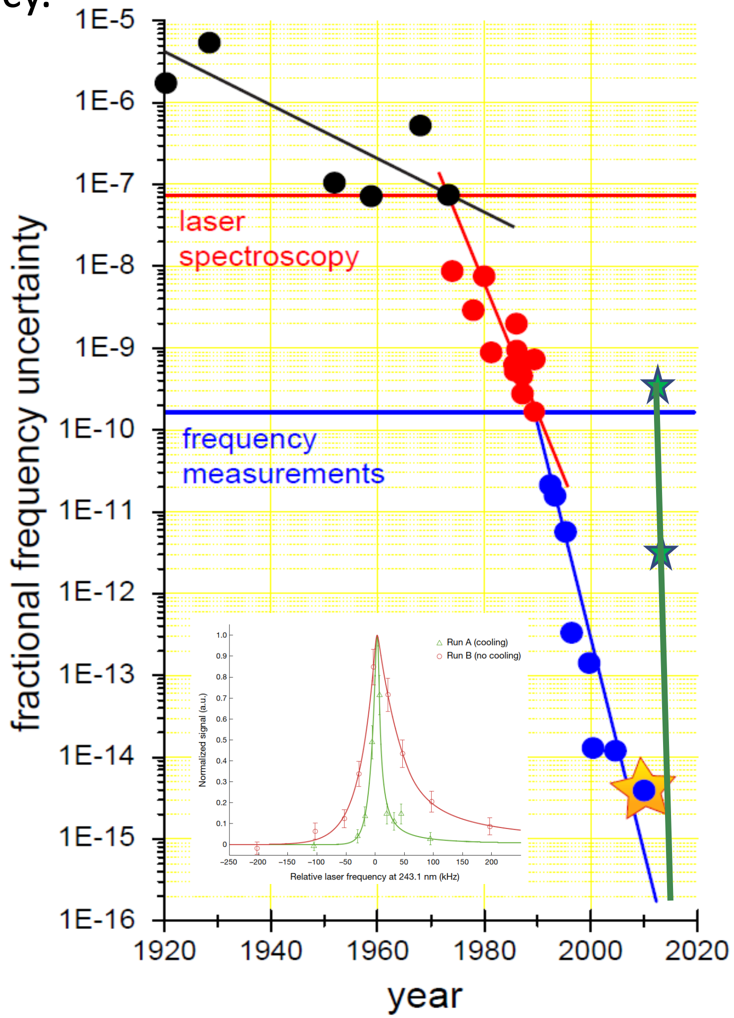


Table 1 | Antihydrogen atom counts

	Laser detuning, D (kHz)	Number of trials	Atoms lost during laser exposure, L	Atoms lost during microwave exposure, M	Surviving atoms, S	Initially trapped atoms, N_i
Set 1	−200	21	7±7	383±23	504±25	894±35
	−100	21	22±9	415±24	494±24	931±35
	0	21	264±24	423±24	217±16	904±38
	+100	21	75±14	411±23	424±23	910±35
Set 2	−200	21	26±9	394±23	466±24	886±34
	−25	21	113±16	423±24	326±20	862±35
	0	21	219±22	390±23	269±18	878±37
	+25	21	173±20	438±24	296±19	907±37
Set 3	−200	23	8±7	354±22	479±24	841±33
	0	23	303±26	454±25	248±17	1,005±40
	+50	23	176±20	390±23	339±20	905±37
	+200	23	36±11	446±24	459±23	941±35
Set 4	−200	21	7±7	525±26	541±25	1,073±37
	−50	21	86±15	475±25	495±24	1,056±38
	0	21	274±25	480±25	275±18	1,029±40
	+25	21	202±21	516±26	305±19	1,023±38
Total		344	1,991	6,917	6,137	15,045

$$f_{d-d} = 2{,}466{,}061{,}103{,}080.3(0.6)\ \mathrm{kHz}$$



Hydrogen
Hänsch Plot

Antihydrogen
Hangst Plot

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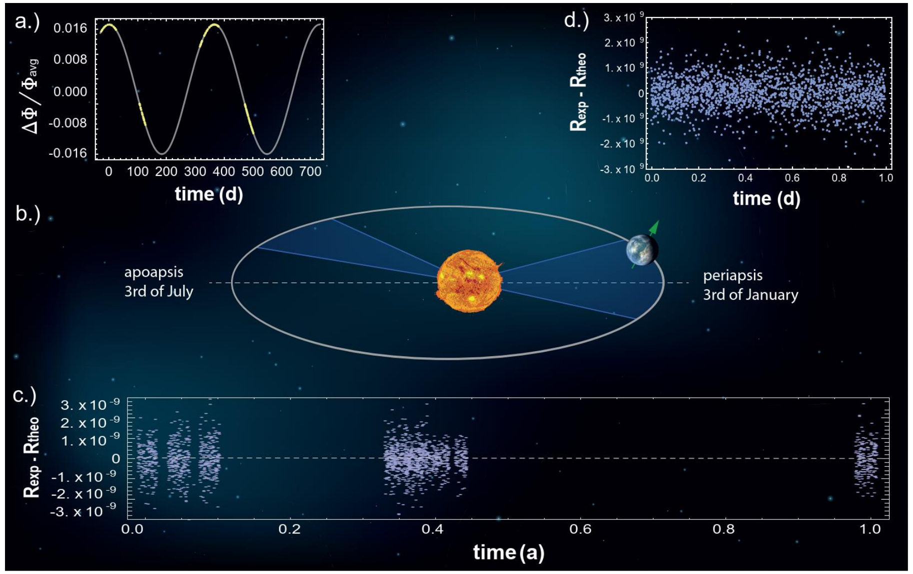
Tests hydrogen/antihydrogen CPT invariance with a fractional precision of 2 p.p.t.

Future perspective: **Laser cooling of antihydrogen just demonstrated**

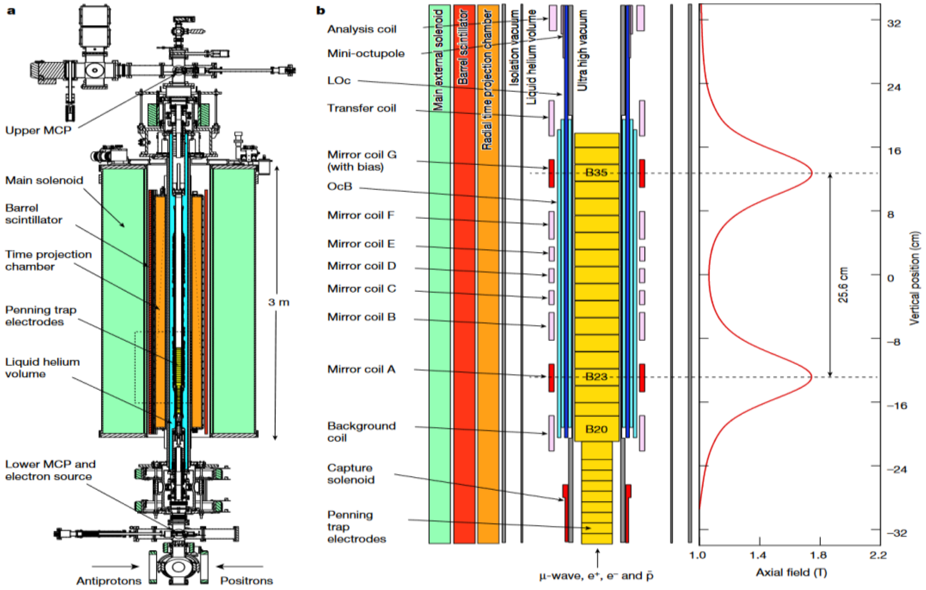
ALPHA collaboration, Nature 592, 35 (2021)

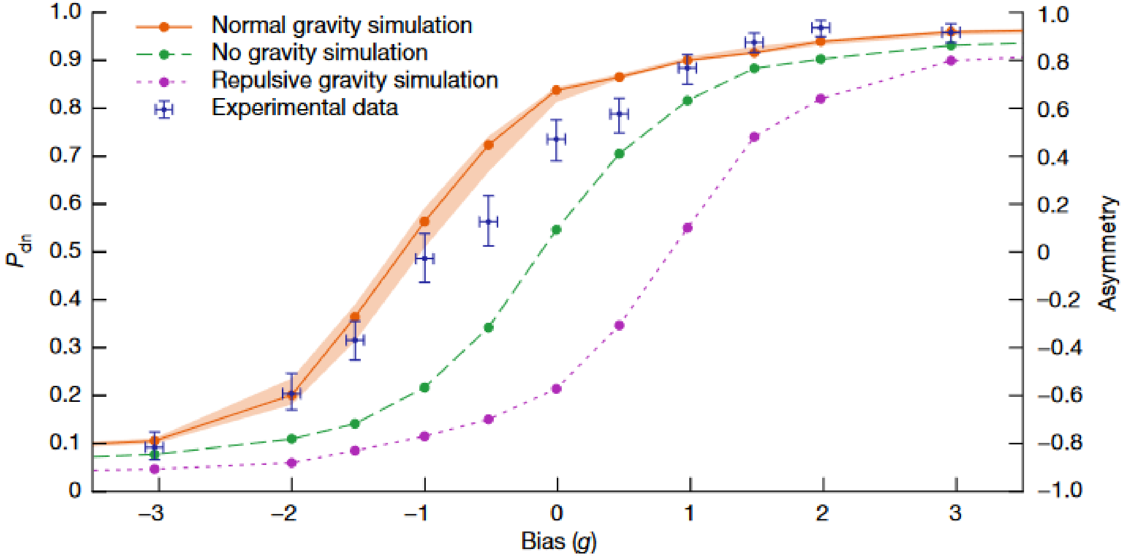
First Ballistic Gravity Measurement of Antihydrogen

- **Repulsive anti-gravity** is an essential part of **some alternative cosmological models**, such as e.g. Dirac Milne, etc…
- Direct gravity measurements with antimatter waited since the substance was discovered.
  - Dropping charged antimatter inconclusive due to 38 oom difference in gravity/em interaction strength.
  - Clock-WEP tests done by TRAP collaboration are model dependent.
  - First differential clock-WEP tests by BASE in 2022.



BASE-Collaboration, **Nature 601,** 53 (2022)



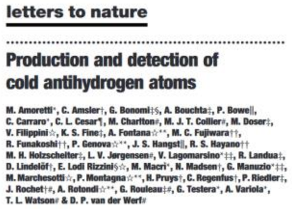


ALPHA-Collaboration, **Nature 621,** 716 (2023)

Achievements Since the Start of the Program

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

2002

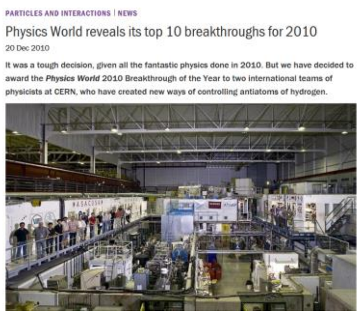

letters to nature

Production and detection of cold antihydrogen atoms

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

2010

Start of antihydrogen physics


PARTICLES AND INTERACTIONS | NEWS

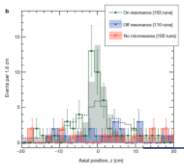
Physics World reveals its top 10 breakthroughs for 2010

20 Dec 2010

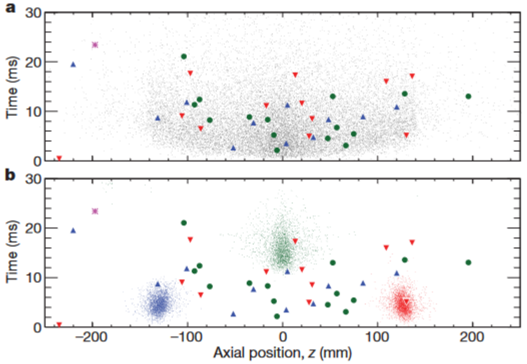
It was a tough decision, given all the fantastic physics done in 2010. But we have decided to award the Physics World 2010 Breakthrough of the Year to two international teams of physicists at CERN, who have created new ways of controlling antiatoms of hydrogen.

physicsworld TOP 10 BREAKTHROUGH 2010

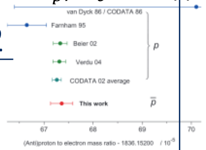
ALPHA
ASACUSA


Resonant quantum transitions in Hbar

2011

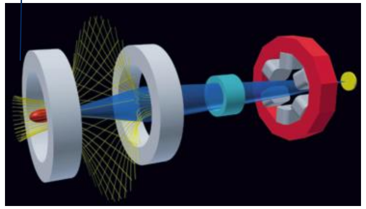

trapped antihydrogren

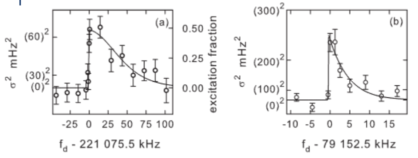
2012

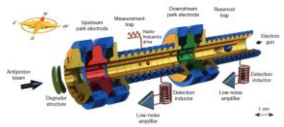

$m_{\bar{p}}/m_e$ at 1.5 ppb

2013

2014


Production of a beam of antihydrogen atoms

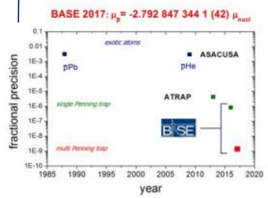

5ppm pbar moment


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

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

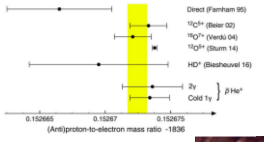
2015

2017

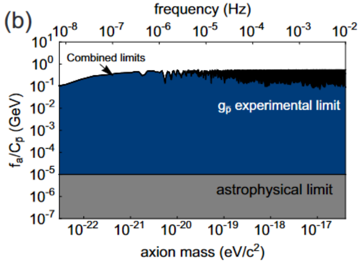

1.5ppb pbar moment

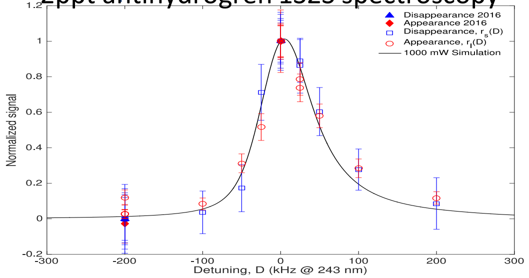
2018

2019

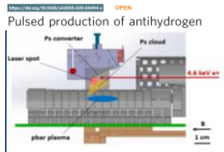

$m_{\bar{p}}/m_e$ at 0.8ppb

antimatter/dark matter coupling




2ppt antihydrogren 1S2S spectroscopy

2020



2021

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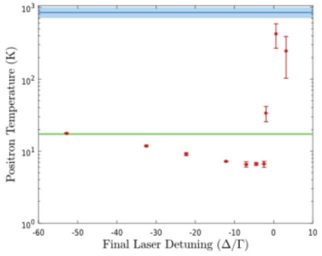
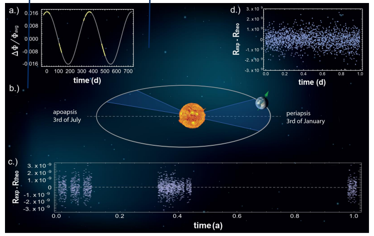
physicsworld TOP 10 BREAKTHROUGH 2022

laser-cooled antihydrogren and sympathetically cooled protons

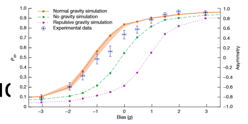

Laser cooled positrons

2022


WEP test with clocks

2023

Hbar produc



physicsworld TOP 10 BREAKTHROUGH 2023

Thank you very much for your attention

THE ALPHA COLLABORATION

Aarhus University, Denmark; University of Brescia, Italy; University of British Columbia, Canada; University of California Berkeley, USA; University of Calgary, Canada; CERN

University of Groningen, Holland; University of Manchester, UK; NRCN - Nuclear Res. Center Negev, Israel; Purdue University, USA; Federal University of Rio de Janeiro, Brazil; University of Pisa Italy

Stockholm University, Sweden; Simon Fraser University, Canada; TRIUMF, Canada; University of Wales Swansea, UK; Cockcroft Institute, UK; York University, Canada

J.S Hangst for the ALPHA Collaboration

AEgIS

INFN; Università di Trento; Paul Scherrer Institut PSI; University of Liverpool; TIFPA Trento Institute for Fundamental Physics and Applications; CERN; Nicolaus Copernicus University in Toruń; Lyon 1; RRI

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[a]Stefan Meyer Institute, [b]Wigner Research Centre for Physics, [c]Ulmer Fundamental Symmetries Laboratory, RIKEN, [d]Dipartimento di Ingegneria dell'Informazione, Università degli Studi di Brescia and INFN Pavia, [e]Politechnico di Milano, [f]INFN Milano, [g]Graduate School of Advanced Sciences of Matter, Hiroshima University, [h]Max-Planck-Institut für Quantenoptik, [i]Fakultät für Physik, Ludwig-Maximilians-Universität München, [j]Nishina Center for Accelerator-Based Science, RIKEN, [k]Institute of Physics, the University of Tokyo, [l]Dipartimento di Fisica, Università degli Studi di Milano and INFN Milano, [m]Experimental Physics Department, CERN, [n]Department of Physics, Tokyo University of Science, [o]Department of Physics and Astronomy, Aarhus University

* Co-spokespersons

RIKEN; CERN; Aarhus University; Wigner; 東京大学; Hiroshima University; MPQ; LMU

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

BASE

GBAR

Irfu; Laboratoire Kastler Brossel; ETH Zürich; Johannes Gutenberg Universität Mainz; Swansea University Prifysgol Abertawe; Neutrons for Science Institut Laue-Langevin; Uppsala Universitet; Stockholm University; RIKEN; 東京大学 The University of Tokyo; IPCMS; CSNSM; Narodowe Centrum Badań Jądrowych Świerk; 서울대학교 Seoul National University; ibs Institute for Basic Science

PUMA collaboration

Technische Universität Darmstadt

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Technische Universität Darmstadt; CERN; TRIUMF; IJCLab Irène Joliot-Curie; LKB; IPHC

03.12.2022 I JAPW | PUMA | A. Obertelli I TU Darmstadt I 1

AEgIS; ALPHA; BASE; GBAR; STEP

60 Research Institutes/Universities – 350 scientists – 6 Collaborations

Fundamentality of CPT Invariance

- **A relativistic theory which conserves CPT requires only five basic ingredients (Axioms):**

Lorentz and translation invariance

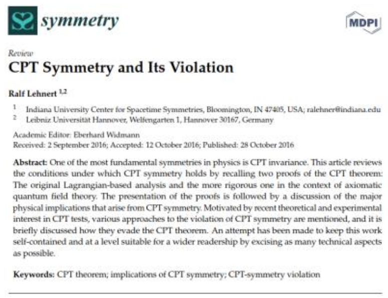
Energy Positivity

Micro Causality (Locality)

A stable vacuum ground state without momentum nor angular momentum

Unitary Field Operators Interpretation

READ: R. Lehnert, CPT Symmetry and its violation, *Symmetry* 8 (2016) 11, 114


symmetry
MDPI
Review
CPT Symmetry and Its Violation
Ralf Lehnert [1,2]
1 Indiana University Center for Spacetime Symmetries, Bloomington, IN 47405, USA; ralehner@indiana.edu
2 Leibniz Universität Hannover, Welfengarten 1, Hannover 30167, Germany
Academic Editor: Eberhard Widmann
Received: 2 September 2016; Accepted: 12 October 2016; Published: 28 October 2016
Abstract: One of the most fundamental symmetries in physics is CPT invariance. This article reviews the conditions under which CPT symmetry holds by recalling two proofs of the CPT theorem: The original Lagrangian-based analysis and the more rigorous one in the context of axiomatic quantum field theory. The presentation of the proofs is followed by a discussion of the major physical implications that arise from CPT symmetry. Motivated by recent theoretical and experimental interest in CPT tests, various approaches to the violation of CPT symmetry are mentioned, and it is briefly discussed how they evade the CPT theorem. An attempt has been made to keep this work self-contained and at a level suitable for a wider readership by excising as many technical aspects as possible.
Keywords: CPT theorem; implications of CPT symmetry; CPT-symmetry violation

→ **CPT**

Parameterized in the Standard Model Extension

	$\bar{\psi}\psi$	$i\bar{\psi}\gamma^5\psi$	$\bar{\psi}\gamma^\mu\psi$	$\bar{\psi}\gamma^5\gamma^\mu\psi$	$\bar{\psi}\sigma^{\mu\nu}\psi$	∂_μ
C	$+1$	$+1$	-1	$+1$	-1	$+1$
P	$+1$	-1	$(-1)^\mu$	$-(-1)^\mu$	$(-1)^\mu(-1)^\nu$	$(-1)^\mu$
T	$+1$	-1	$(-1)^\mu$	$(-1)^\mu$	$-(-1)^\mu(-1)^\nu$	$-(-1)^\mu$
CPT	$+1$	$+1$	-1	-1	$+1$	-1

The Standard Model Extension

Motivation

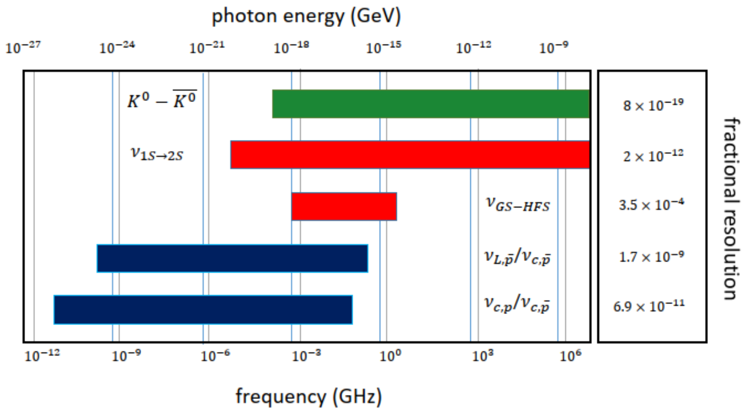
- KK and String theories
- Loop-Quantum Gravity
- Non-commutative FT
- Brane scenarios
- Random dynamics models

→ **CPT-V**

- Which type of **measureable** signatures of these «BSM» theories would be imprinted onto the structure of the vacuum-box of relativistic quantum field theories.

$$\mathcal{L} = ?$$

- Construct effective field theory which features:
  - microcausality
  - positivity of energy
  - energy and momentum conservation
  - standard quantization methods



Kostelecký, V. Alan; Samuel, Stuart (1989-01-15). "Spontaneous breaking of Lorentz symmetry in string theory". Physical Review D. ***39*** *(2): 683–685.*

- SME contains the Standard Model and General Relativity, but adds CPT violation

Expectation value / Mass Scale / Coupling strength

$$\mathcal{L}' \supset \frac{\lambda}{M^k}\langle T\rangle \cdot \overline{\psi}\Gamma(i\partial)^k\psi + \text{h.c.}$$

Lorentz bilinear

- E.g. k=2 produces attractive baryogenesis scenario

AEḡIS ALPHA BASE GBAR STEp̄

Laser-cooling of Antihydrogen (ALPHA-collaboration)

Culmination point of several decades of work by the ALPHA collaboration

- Laser (doppler)-cooling is one of the the workhorses in AMO physics.
- Idea:
  - Directional absorption, unidirectional emission of **red-detuned** photons
  - Cools particles to a recoil «Doppler temperature»
  - 3-D cooling by parasitic coupling of motional modes in trap

Article

Laser cooling of antihydrogen atoms

https://doi.org/10.1038/s41586-021-03289-6
Received: 21 July 2020
Accepted: 26 January 2021
Published online: 31 March 2021
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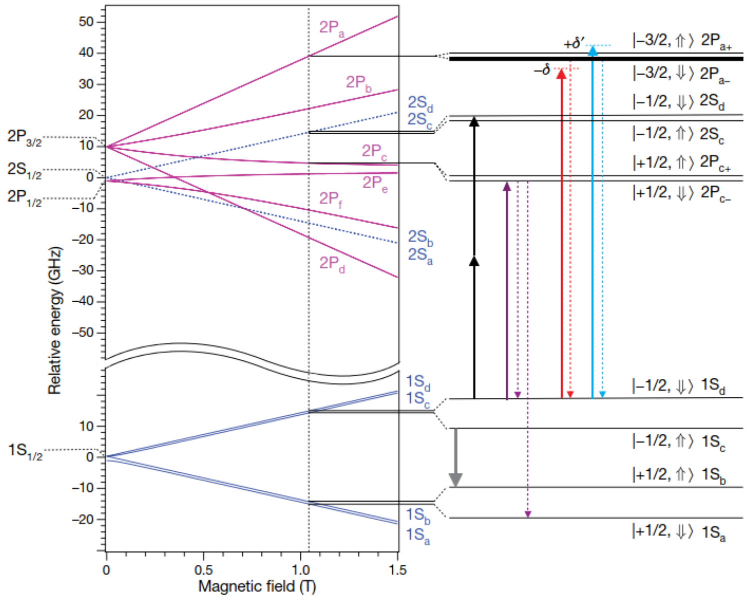
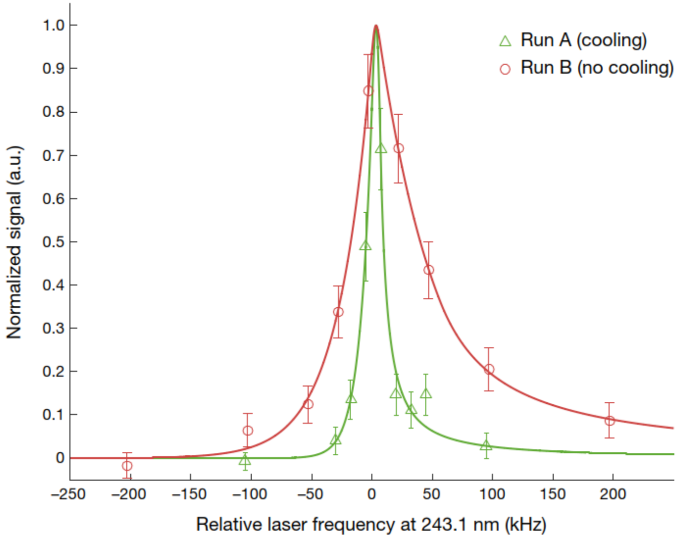


red/blue: Cycling transition

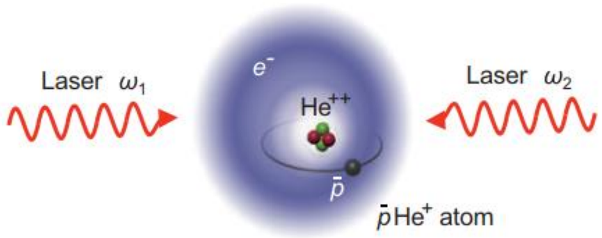
black: dipole forbidden spectroscopy transition



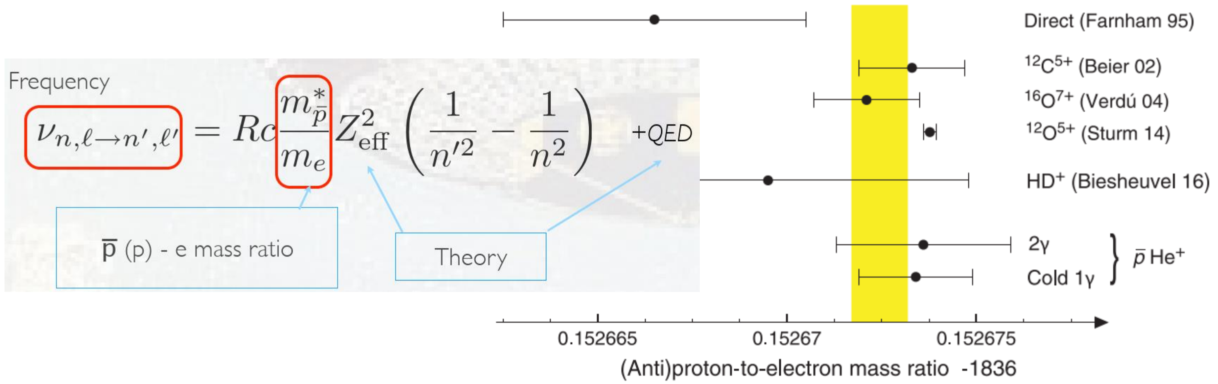
AEgIS
ALPHA
BASE
GBAR
STEP

Reduction of 1S/2S transition line width by a factor of 4. Heralds antihydrogen CPT tests at the sub p.p.t. level

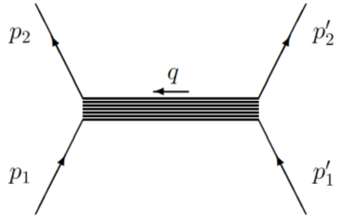
Antiprotonic Helium (ASACUSA)



- Helium atom with one of the electrons replaced by an antiproton



- Elegant and technically challenging experiments on circular states lead to measurements of the antiproton-to-electron mass ratio (0.6 p.p.b.)



- For exotic spin-1 bosons: general approach assuming rotational invariance -> 16 spin dependent interactions (**Moody-Wilczek-Dobrescu-Mocioiu formalism**)

$$V_2 = f_2^{e\bar{p}} \frac{\hbar c}{\pi} (\mathbf{s}_{\bar{p}} \cdot \mathbf{s}_e) \frac{e^{-r/\lambda}}{r},$$

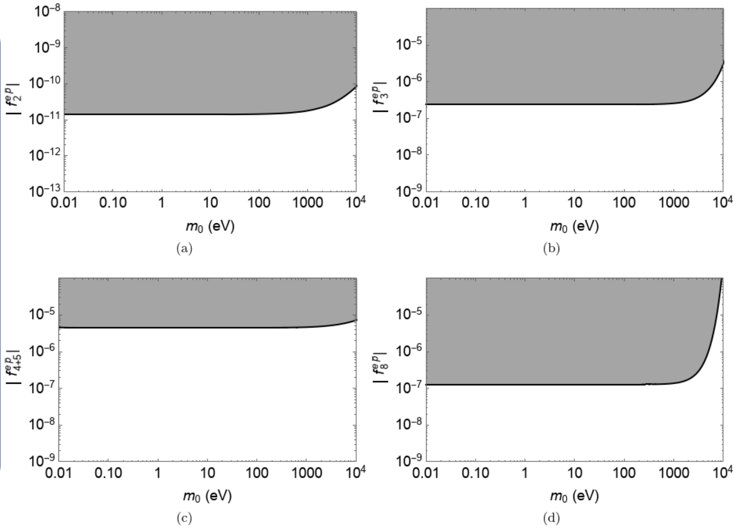
$$V_3 = f_3^{e\bar{p}} \frac{\hbar^3}{\pi m_e^2 c} \left[\mathbf{s}_{\bar{p}} \cdot \mathbf{s}_e \left(\frac{1}{\lambda r^2} + \frac{1}{r^3} + \frac{4\pi}{3}\delta^3(r) \right) - (\mathbf{s}_{\bar{p}} \cdot \mathbf{r})(\mathbf{s}_e \cdot \mathbf{r}) \left(\frac{1}{\lambda^2 r^3} + \frac{3}{\lambda r^4} + \frac{3}{r^5} \right) \right] e^{-r/\lambda},$$

$$V_{4-5} = f_{4-5}^{e\bar{p}} \frac{i\hbar^3}{4 m_e^2 c} \mathbf{s}_{\bar{p}} \cdot \left[\left(\frac{m_e}{m_{\bar{p}} + m_e} \nabla_{\bar{p}} - \frac{m_{\bar{p}}}{m_{\bar{p}} + m_e} \nabla_e \right) \times \mathbf{r}, \left(\frac{1}{r^3} + \frac{1}{\lambda r^2} \right) e^{-r/\lambda} \right]_+,$$

$$V_{4+5} = f_{4+5}^{e\bar{p}} \frac{i\hbar^3}{4 m_e^2 c} \mathbf{s}_e \cdot \left[\left(\frac{m_e}{m_{\bar{p}} + m_e} \nabla_{\bar{p}} - \frac{m_{\bar{p}}}{m_{\bar{p}} + m_e} \nabla_e \right) \times \mathbf{r}, \left(\frac{1}{r^3} + \frac{1}{\lambda r^2} \right) e^{-r/\lambda} \right]_+,$$

$$V_8 = -f_8^{e\bar{p}} \frac{\hbar^3}{4\pi m_e^2 c} \left[\mathbf{s}_e \cdot \left(\frac{m_e}{m_{\bar{p}} + m_e} \nabla_{\bar{p}} - \frac{m_{\bar{p}}}{m_{\bar{p}} + m_e} \nabla_e \right), \left[\mathbf{s}_{\bar{p}} \cdot \left(\frac{m_e}{m_{\bar{p}} + m_e} \nabla_{\bar{p}} - \frac{m_{\bar{p}}}{m_{\bar{p}} + m_e} \nabla_e \right), \frac{e^{-r/\lambda}}{r} \right]_+ \right]_+$$

Interactions would modify atomic potential and lead to shifts in wavelengths

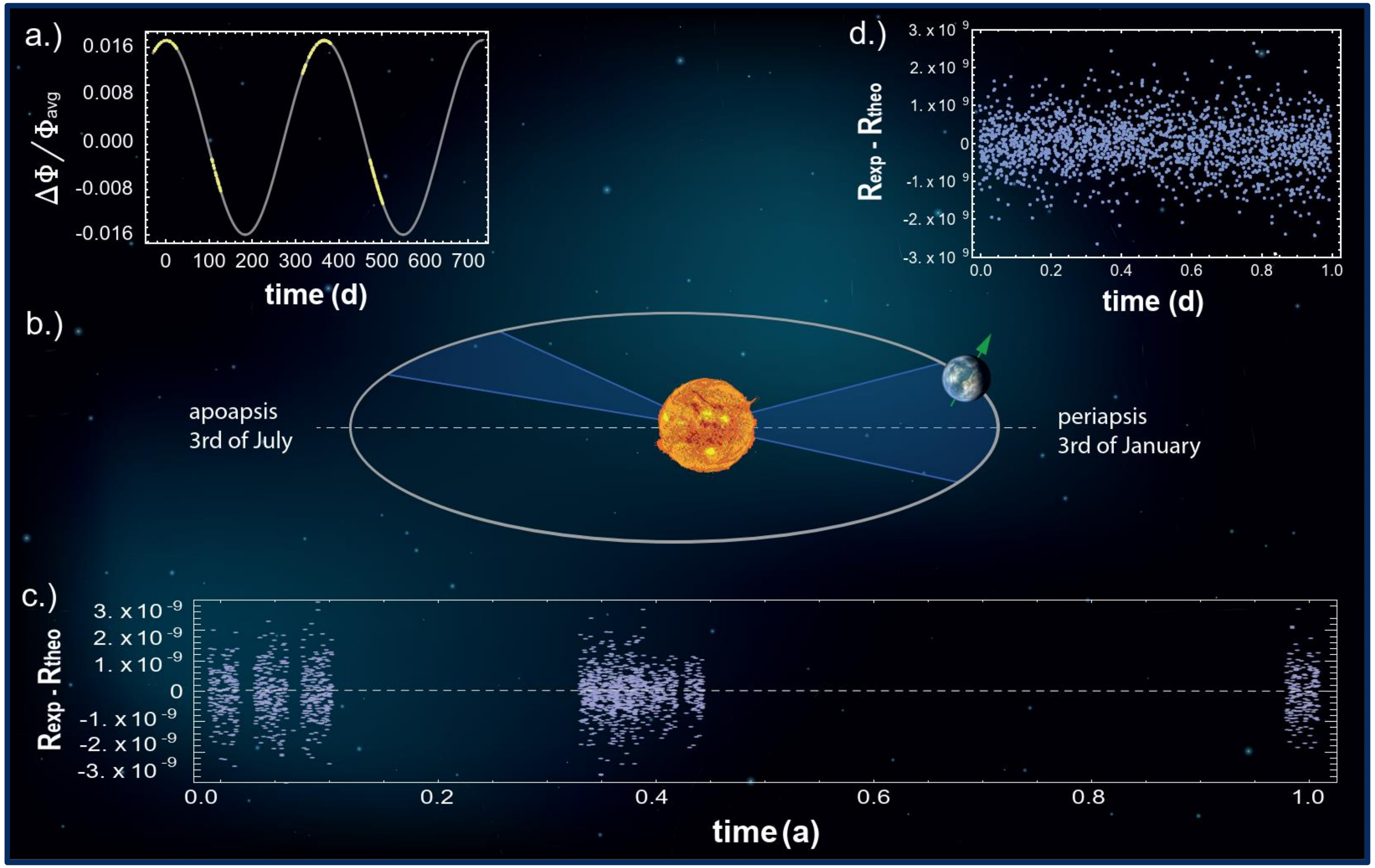


- First limits on exotic antimatter/axion coupling derived

Interpretation

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

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



- Derived limits for global and differental considerations

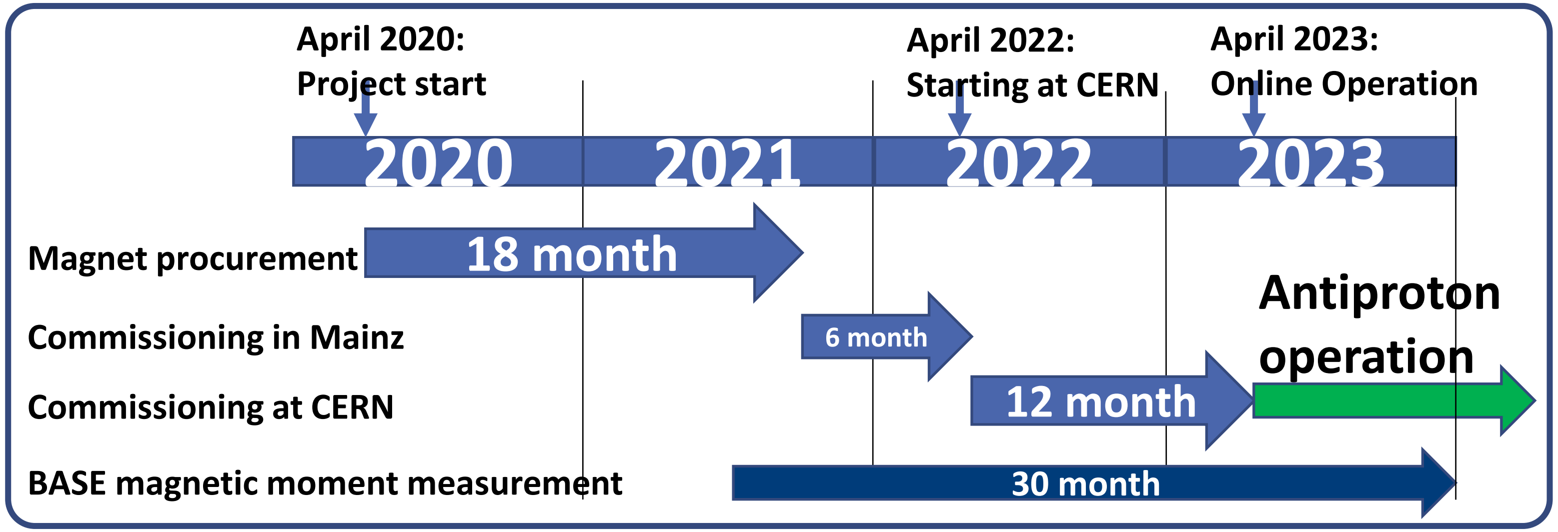
Property	Limit
$\alpha_g - 1$	$< 1.8 * 10^{-7}$
$\alpha_{g,D} - 1$	< 0.03

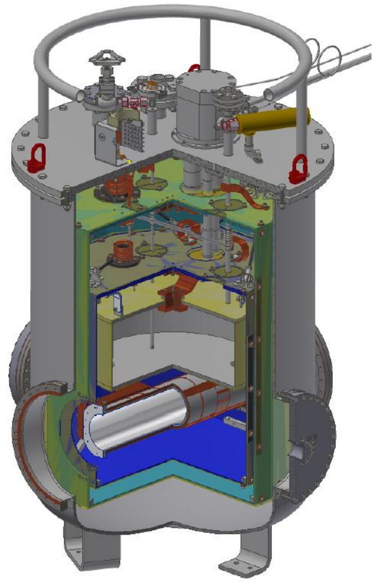
- Constraints set limits similar to goals of experiments that drop antihydrogen in the gravitational field of the earth.
- Looking forward to these results, rapid progress in ALPHA-g and GBAR, stay tuned for beamtime 2022 / 2023.

Broad band time base analysis is under evaluation

BASE STEP – C. Smorra – ERC HHU

Under development at University of Mainz



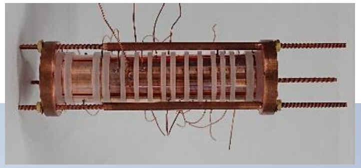


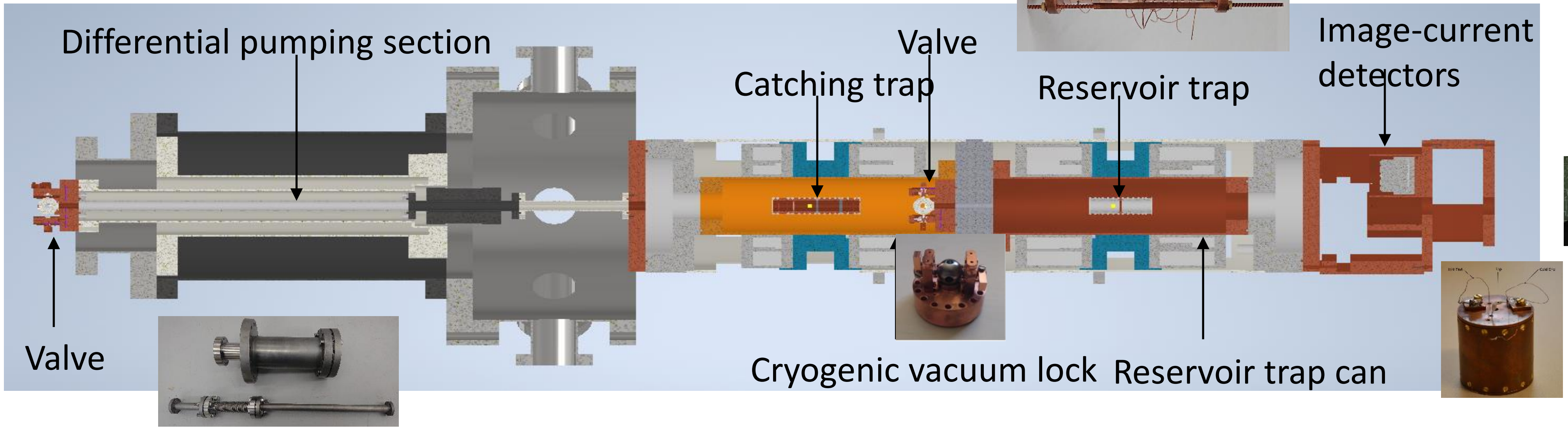
Magnet is ordered

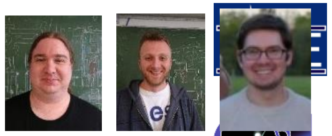
Expected delivery window 12/21 to 03/22

- Apparatus has been developed, currently in the workshop, likely operational late 2021 / early 2022.

Approved by CERN







Developed by Smorra group

C. Smorra

BASE Measurements – Proton to Antiproton Q/M

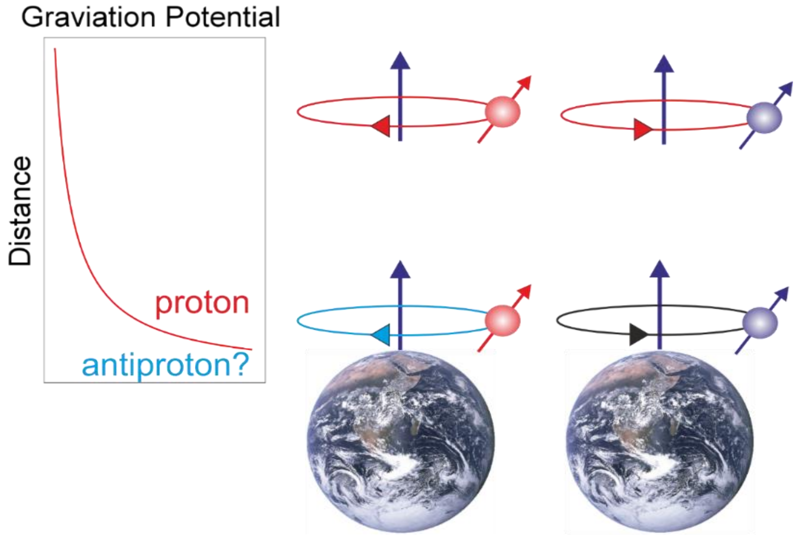
- Constrain of the gravitational anomaly for antiprotons:

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

Our recent result sets an upper limit of

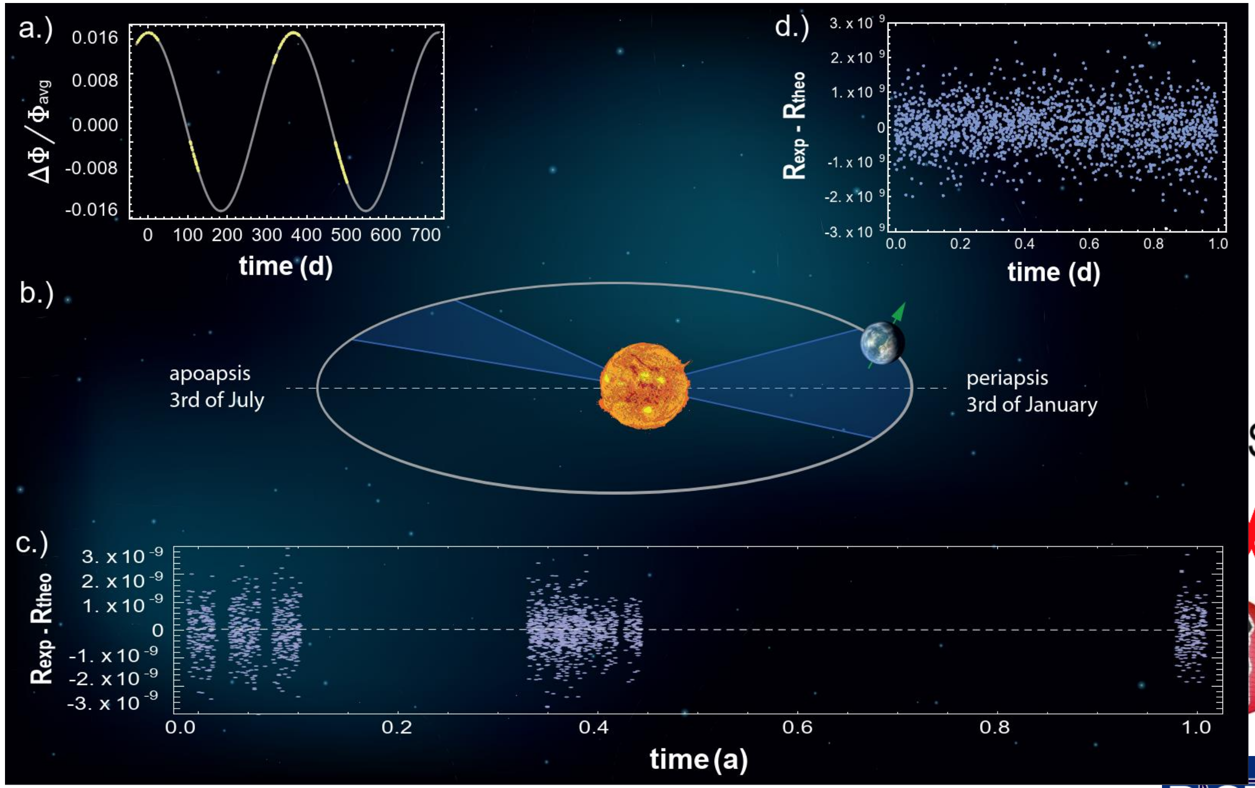
$$|\alpha_g - 1| < 1.9 \times 10^{-7}$$

tests WEPcc, in aspects (vectors) different to WEPff



- Direct experiments planned by Aegis, GBAR, ALPHA

- Planned Longer Term Measurements



- Set differential constraints on the weak equivalence principle by measuring charge-to-mass ratio as a function of gravitational potential at surface of earth.
- Final data analysis is work in progress.

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