Antimatter put to the test of gravity at CERN

Pauline Comini

Irfu
Département de Physique des Particules

Bringing antimatter to its (free) fall: a longtime effort

Available:

- a bunch of positrons
- a handful of antiprotons

Free fall experiment on single particles

$$m_e g \approx 5.6\ 10^{-11}\ eV.m^{-1} \qquad m_p g \approx 1.0\ 10^{-7}\ eV.m^{-1}$$

Very slow antiparticles required!

Bringing antimatter to its (free) fall: a longtime effort

In the absence of antiprotons:

NATURE **220**, p.436 (1968)

Experiments to determine the Force of Gravity on Single Electrons and Positrons

by
FRED C. WITTEBORN
WILLIAM M. FAIRBANK
Department of Physics,
Stanford University,
California

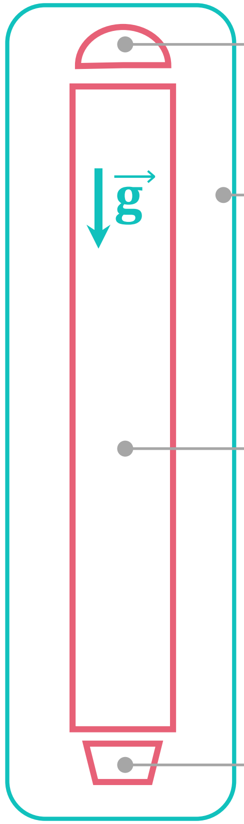
Two experimental methods are described for measuring the gravitational force on electrons falling through vertical metal tubes. A third method is being devised to study the fall of positrons.

Cut-off in time of upward flight

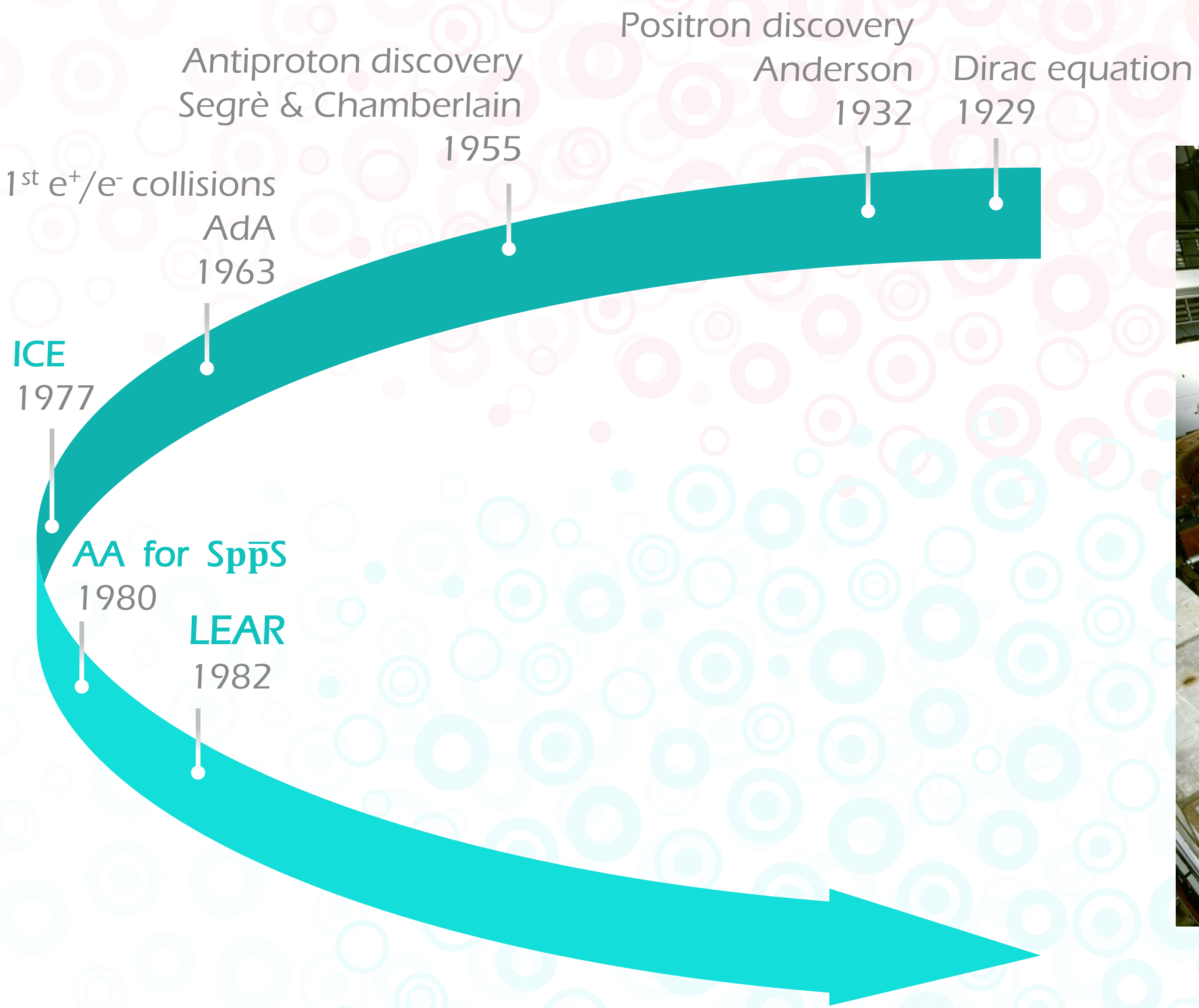
$$t_{max} = \sqrt{\frac{2L}{g}}$$

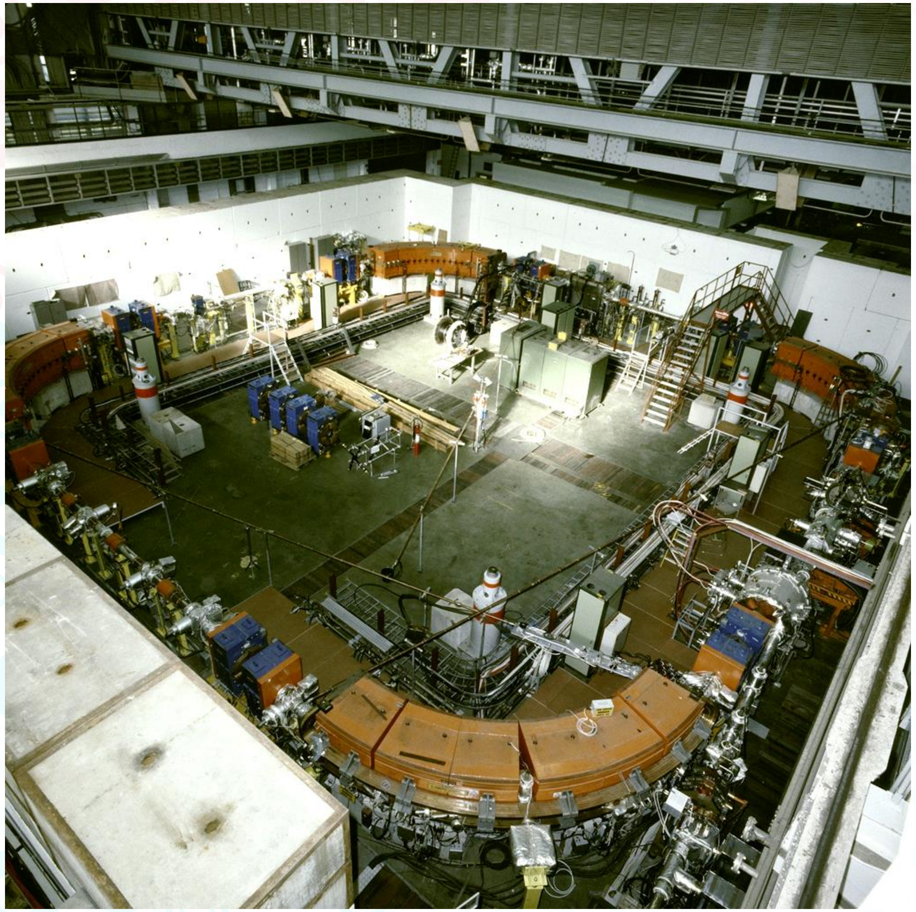
But no source of slow enough positrons...

General scheme:



Antiproton decelerators at CERN





Bringing antimatter to its (free) fall: a longtime effort

Interest shifted toward antiprotons:

1986: PS200

Based on time-of-flight technique from Witteborn & Fairbank
+ comparison with H^-

LEAR: 2 MeV (5.3 MeV in fact)
Goal of PS200 : 4 K (~ meV)
Still far from 10^{-7} eV ~ 1.2 mK

NUCL. INST. METH. B **24/25** p.437 (1987)

A MEASUREMENT OF THE GRAVITATIONAL ACCELERATION OF THE ANTIPROTON: AN EXPERIMENTAL OVERVIEW

Nelson JARMIE

Los Alamos National Laboratory, Los Alamos, NM 87545, USA

1. Introduction

An adventurous and difficult experiment to measure the gravitational interaction of antimatter (an antiproton) with matter (the earth) is being planned. The effect

Only a small part of the tail of the thermal distribution would be useful.

And remains the problem of shielding against E field at a 10^{-7} V.m^{-1} level…

Bringing antimatter to its (free) fall: a longtime effort

Antihydrogen could be a better candidate…

HYPERFINE INTERACT. **44**, p.349 (1988)

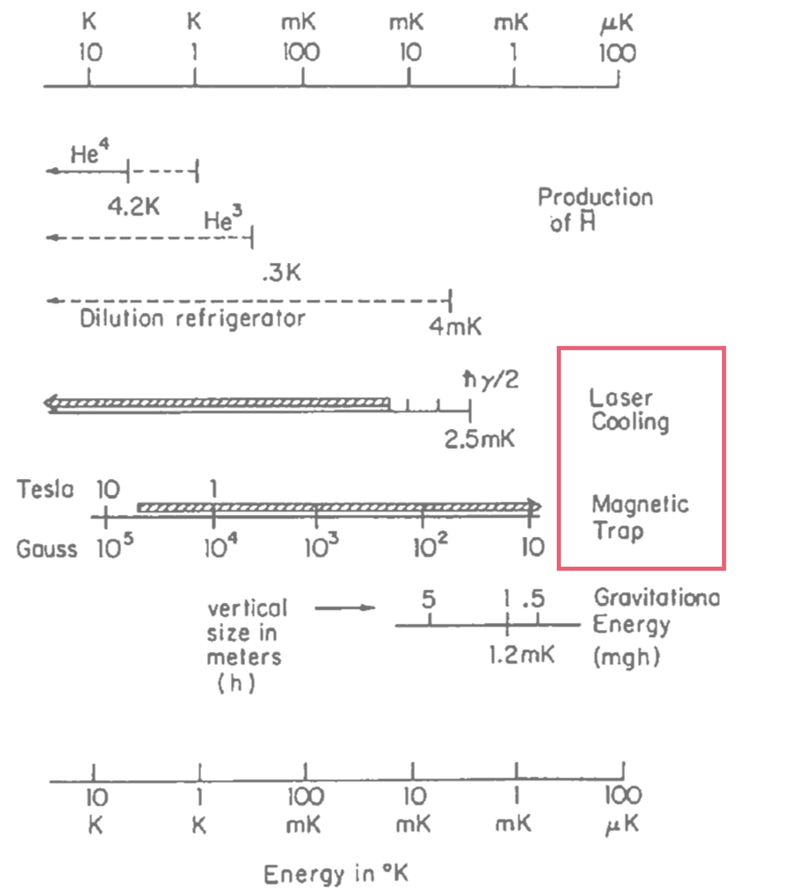
TRAPPED ANTIHYDROGEN FOR SPECTROSCOPY AND GRAVITATION STUDIES: IS IT POSSIBLE?

G. GABRIELSE

Department of Physics, Harvard University, Cambridge, MA 02138, U.S.A.

Possibilities for trapping and cooling antihydrogen atoms for spectroscopy and gravitational measurements are discussed. A measurement of the gravitational force on antihydrogen seems feasible if antihydrogen can be cooled to of order 1 milli-Kelvin. Difficulties in obtaining this low energy are discussed in the hope of stimulating required experimental and theoretical studies.

This contribution surveys an experimental goal which seems worth pursuing even though a complete experimental strategy is not yet clear and the goal may not even be attainable.



… but was yet to be produced!

First antihydrogen production at CERN

1995: PS210

PHYS. LETT. B **368**, p.251 (1996)

Production of antihydrogen

G. Baur [a], G. Boero [b], S. Brauksiepe [a], A. Buzzo [b], W. Eyrich [c], R. Geyer [a], D. Grzonka [a], J. Hauffe [c], K. Kilian [a], M. LoVetere [b], M. Macri [b], M. Moosburger [c], R. Nellen [a], W. Oelert [a], S. Passaggio [b], A. Pozzo [b], K. Röhrich [a], K. Sachs [a], G. Schepers [e], T. Sefzick [a], R.S. Simon [d], R. Stratmann [d], F. Stinzing [c], M. Wolke [a]

[a] *IKP, Forschungszentrum Jülich GmbH, Germany*
[b] *Genoa University and INFN, Italy*
[c] *PI, Universität Erlangen–Nürnberg, Germany*
[d] *GSI Darmstadt, Germany*
[e] *IKP, Universität Münster, Germany*

Received 8 December 1995; revised manuscript received 21 December 1995
Editor: L. Montanet

Abstract

Results are presented for a measurement for the production of the antihydrogen atom $\overline{\mathrm{H}}^0 \equiv \bar{p}e^+$, the simplest atomic bound state of antimatter.

A method has been used by the PS210 collaboration at LEAR which assumes that the production of $\overline{\mathrm{H}}^0$ is predominantly mediated by the e^+e^--pair creation via the two-photon mechanism in the antiproton–nucleus interaction. Neutral $\overline{\mathrm{H}}^0$ atoms are identified by a unique sequence of characteristics. In principle $\overline{\mathrm{H}}^0$ is well suited for investigations of fundamental CPT violation studies under different forces, however, in our investigations we concentrate on the production of this antimatter object, since so far it has never been observed before.

The production of 11 antihydrogen atoms is reported including possibly 2±1 background signals, the observed yield agrees with theoretical predictions.

PACS: 25.43.+t
Keywords: Antihydrogen

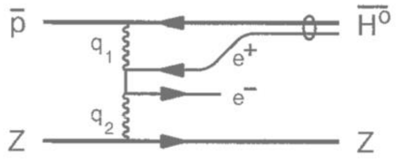
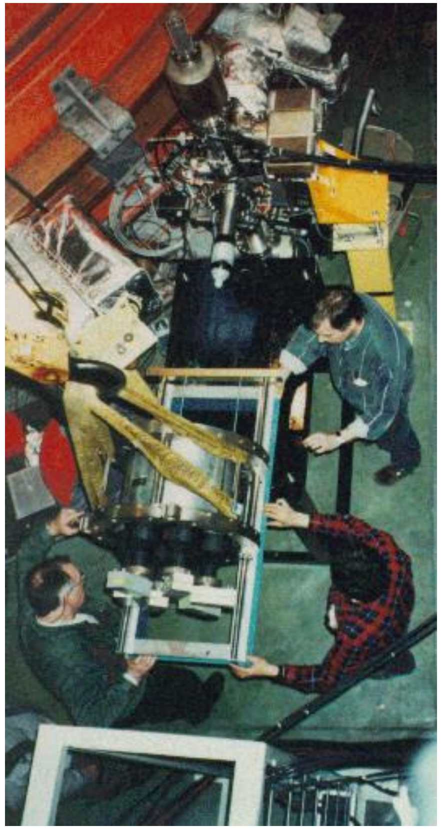


Fig. 1. A schematic view of the two-photon mechanism for e^+e^- and $\overline{\mathrm{H}}^0$ production.

Xe target in LEAR
Fly out
Detection of stripped e+
&
Detection of antiproton

~1.7 GeV $\overline{\mathrm{H}}$:
Not suitable for trapping



Bringing antimatter to its (free) fall: a longtime effort

Calling for cold antihydrogen

PS196 and PS200 developped trapping and cooling method for antiprotons

Antiprotons from LEAR were decelerated in a degrader foil (at the expense of intensity)

~keV antiprotons caught in Penning traps

Electron cooling technique

Next step: trap positrons & antiprotons in the same trap to make antihydrogen.

CERN-SPSLC-93-35 (1993)

PROGRESS REPORT ON EXPERIMENT PS200

THE PS200 CATCHING TRAP
A NEW TOOL FOR ULTRA-LOW ENERGY ANTIPROTON PHYSICS

M. H. Holzscheiter[1], R. E. Brown[1], T. Darling[1], P. Dyer[1], T. Goldman[1], K. Hosea[2], R. A. Kenefick[2], N. S. P. King[1], R. A. Lewis[3], M. M. Nieto[1], T. Otto[3], S. P. Parry[4], R. Ristinen[4], J. Rochet[3], M. M. Schauer[1*], G. A. Smith[3], F. C. Witteborn[5]

Phys. Rev. Lett. **63**, 1360 (1989)

Cooling and Slowing of Trapped Antiprotons below 100 meV

G. Gabrielse, X. Fei, L. A. Orozco, and R. L. Tjoelker
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

J. Haas and H. Kalinowsky
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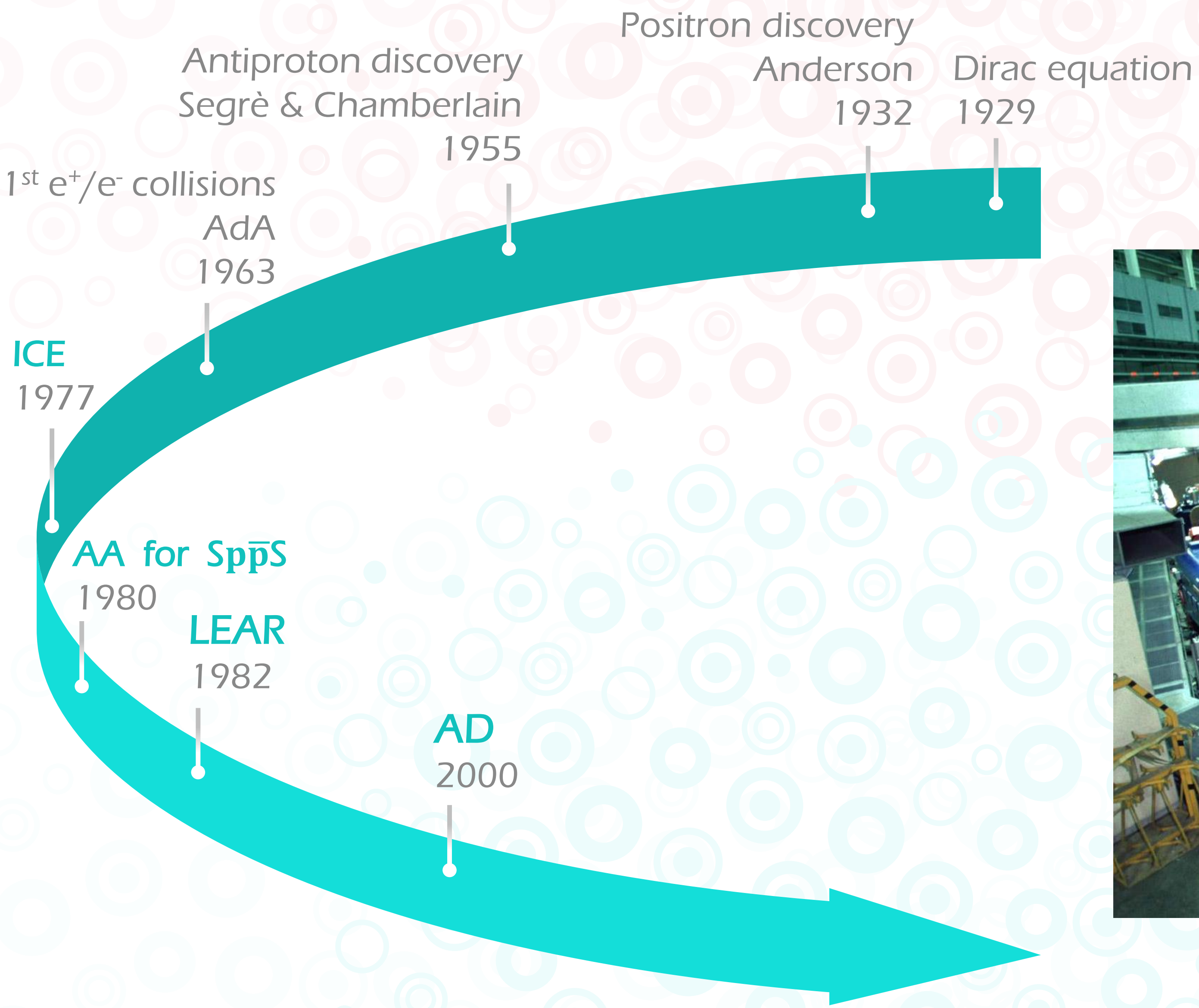
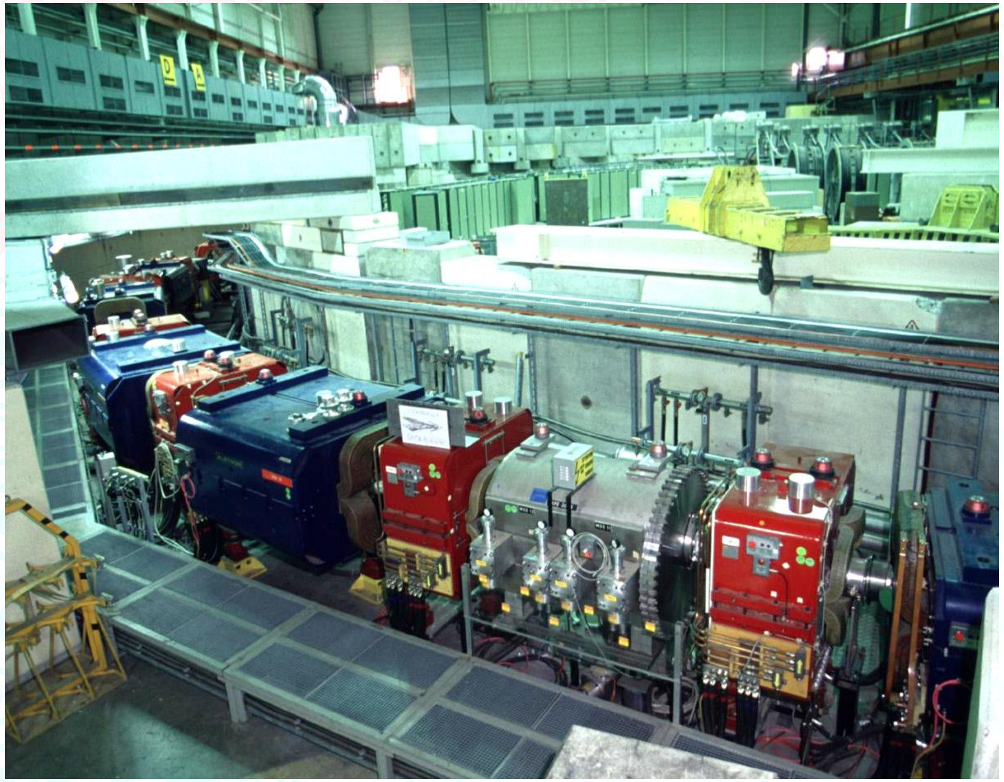
T. A. Trainor
Department of Physics, University of Washington, Seattle, Washington 98195

W. Kells
Institute for Boson Studies, Pasadena, California 91107
(Received 11 May 1989; revised manuscript received 31 August 1989)

Electron cooling of trapped antiprotons allows their storage at energies more than 6×10^7 times lower than is available in any antiproton storage ring. More than 60000 antiprotons with energies from 0 to 3000 eV are stored in an ion trap from a single pulse of 5.9-MeV antiprotons from LEAR. Trapped antiprotons maintain their initial energy distribution over days unless allowed to collide with a cold buffer gas of trapped electrons, whereupon they slow and cool below 100 meV in 10 s. The antiprotons are cooled in a harmonic potential well suited for precision measurements and have remained more than 2 days without detectable particle loss. Energy widths as narrow as 9 meV are directly observed.

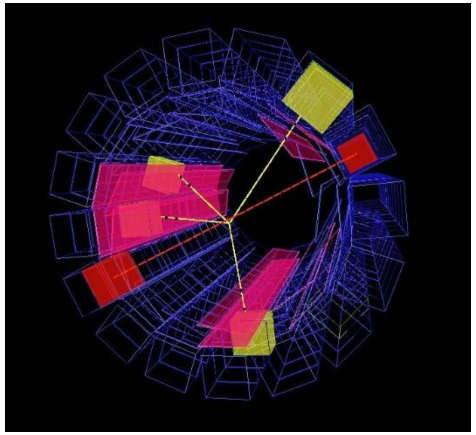
Antiproton decelerators at CERN





Antihydrogen formation by mixing of antiprotons and positrons

2002: ATHENA & ATRAP



NATURE **419**, p.456 (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#

PHYS. REV. LETT. **89**, 213401 (2002)

Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T.W. Hänsch,[4,5] and E. A. Hessels[6]

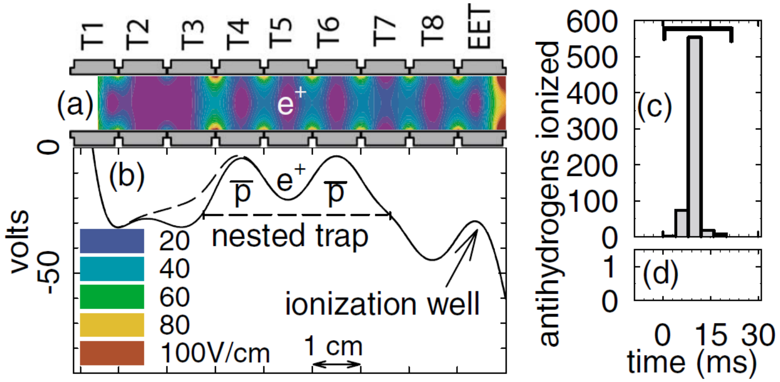


FIG. 2 (color). (a) Electrodes for the nested Penning trap. Inside is a representation of the magnitude of the electric field that strips $\overline{\mathrm{H}}$ atoms. (b) Potential on axis for positron cooling of antiprotons (solid line) during which $\overline{\mathrm{H}}$ formation takes place, with the (dashed line) modification used to launch $\overline{p}$ into the well. (c) Antiprotons from $\overline{\mathrm{H}}$ ionization are released from the ionization well during a 20 ms time window. (d) No $\overline{p}$ are counted when no e^+ are in the nested Penning trap.

First trapped antihydrogen atoms

2010: ALPHA

NATURE **468**, p.673 (2010)

LETTER

doi:10.1038/nature09610

Trapped antihydrogen

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

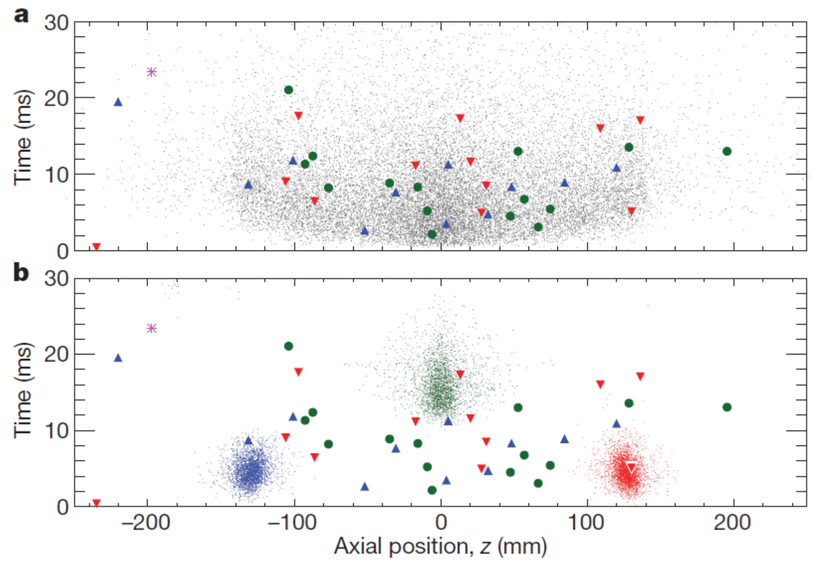
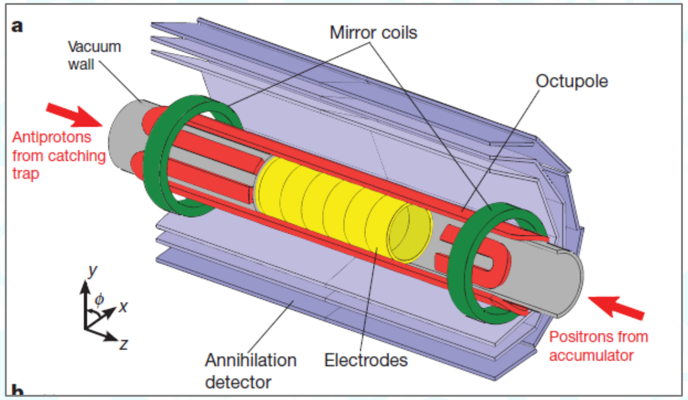


Figure 3 | Distributions of released antihydrogen atoms and antiprotons. **a**, Measured t–z distribution for annihilations obtained with no bias (green circles), left bias (blue triangles), right bias (red triangles) and heated positrons (violet star). The grey dots are from a numerical simulation of antihydrogen atoms released from the trap during the quench. The simulated atoms were initially in the ground state, with a maximum kinetic energy of 0.1 meV. The typical kinetic energy is larger than the depth of the neutral trap, ensuring that all trappable atoms are considered. The 30-ms observation window includes 99% of the 20,000 simulated points. **b**, Experimental t–z distribution, as above, shown along with results of a numerical simulation of mirror-trapped antiprotons being released from the trap. The colour codes are as above and there are 3,000 points in each of the three simulation plots. In both **a** and **b**, the simulated z distributions were convolved with the detector spatial resolution, of ~5 mm.

Use $\bar{H}$ magnetic moment

Trap low field seeking states

Ioffe-Pritchard trap with octupole magnet



Antiproton decelerators at CERN

Positron discovery
Anderson
1932

Dirac equation
1929

Antiproton discovery
Segrè & Chamberlain
1955

1st e^+/e^- collisions
AdA
1963

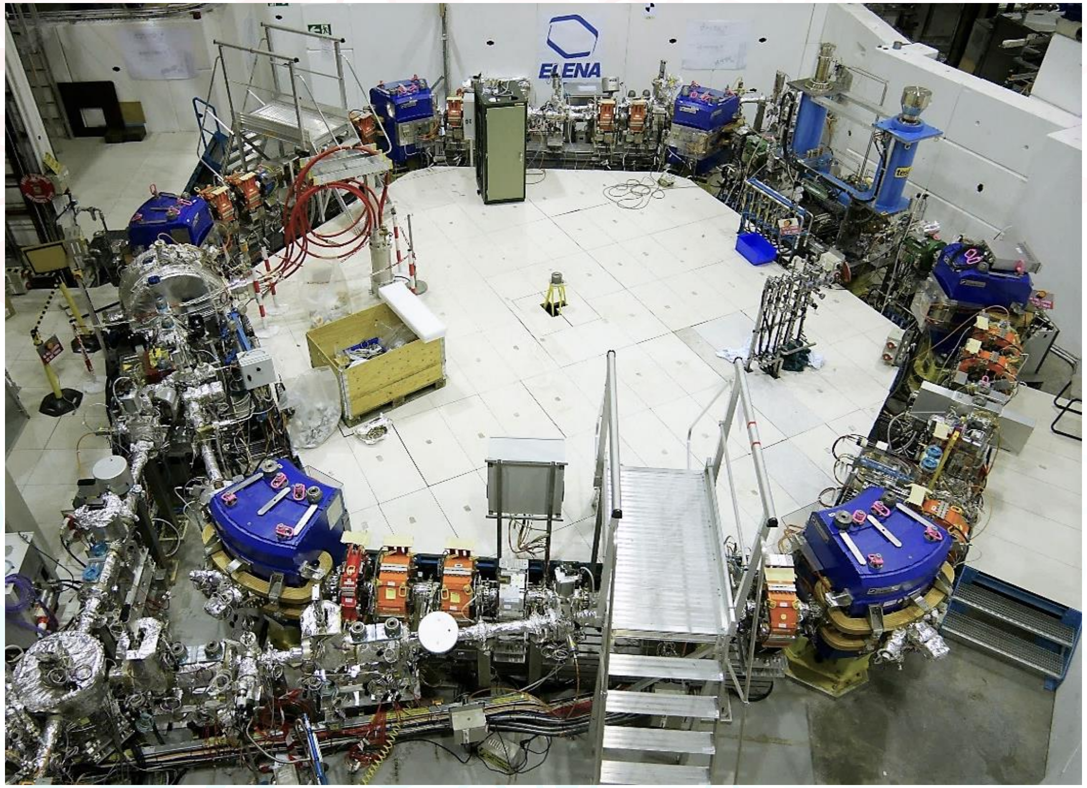
ICE
1977

AA for $Sp\bar{p}S$
1980

LEAR
1982

AD
2000

ELENA
2018



Antiproton decelerators at CERN

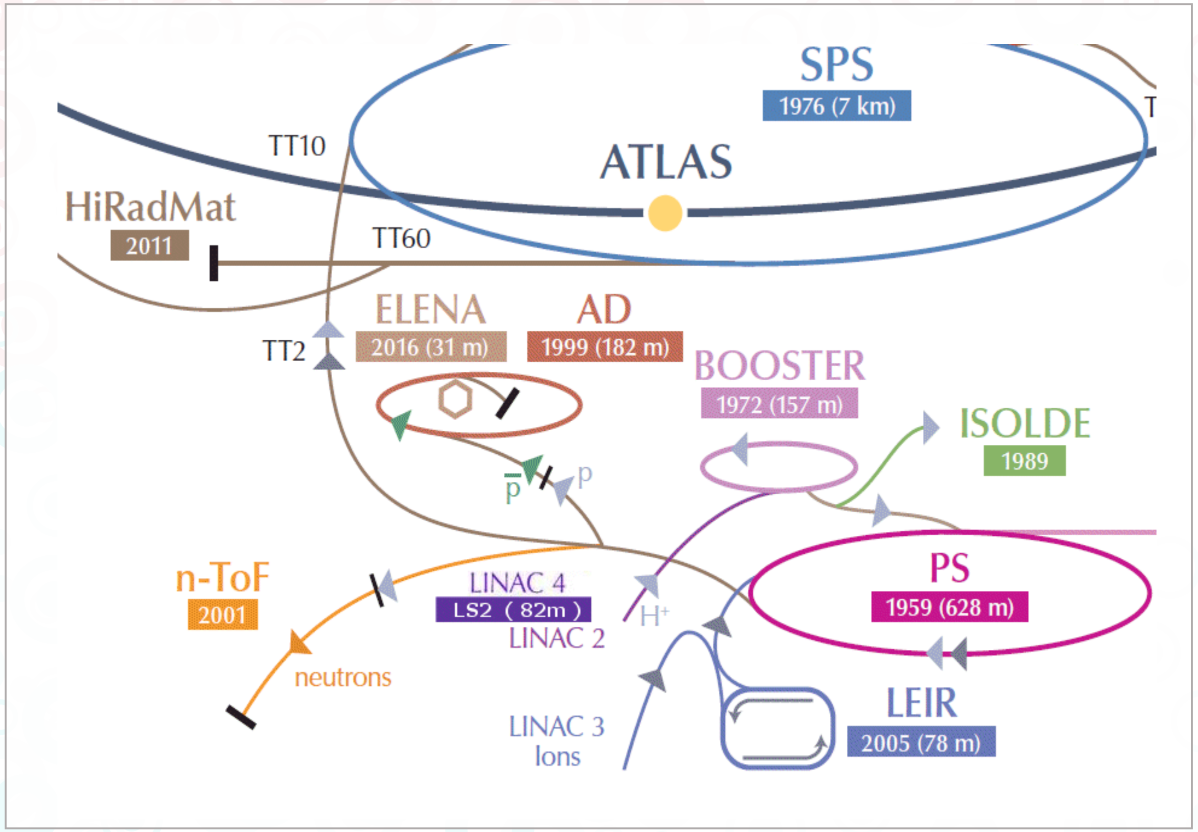
Every 2 minutes:

$1.5\ 10^{13}$ protons from PS at 26 GeV/c on target

$5.\ 10^{7}$ antiprotons in the AD
Down to 5.3 MeV (100 MeV/c)

$3.\ 10^{7}$ antiprotons in ELENA
Down to 100 keV

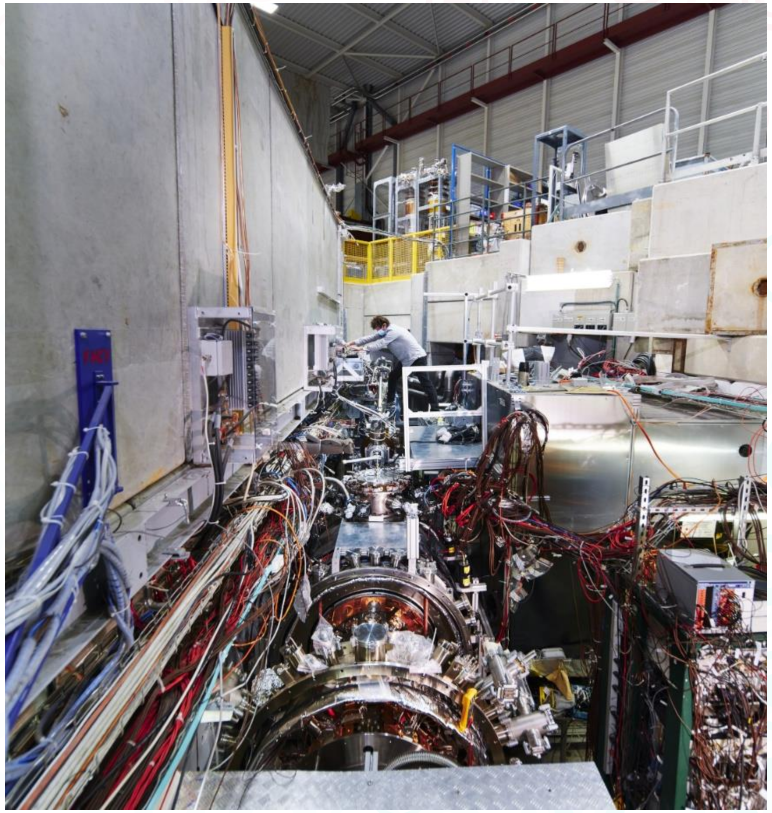
$4 \times 5.5\ 10^{6}$ antiprotons to experiments



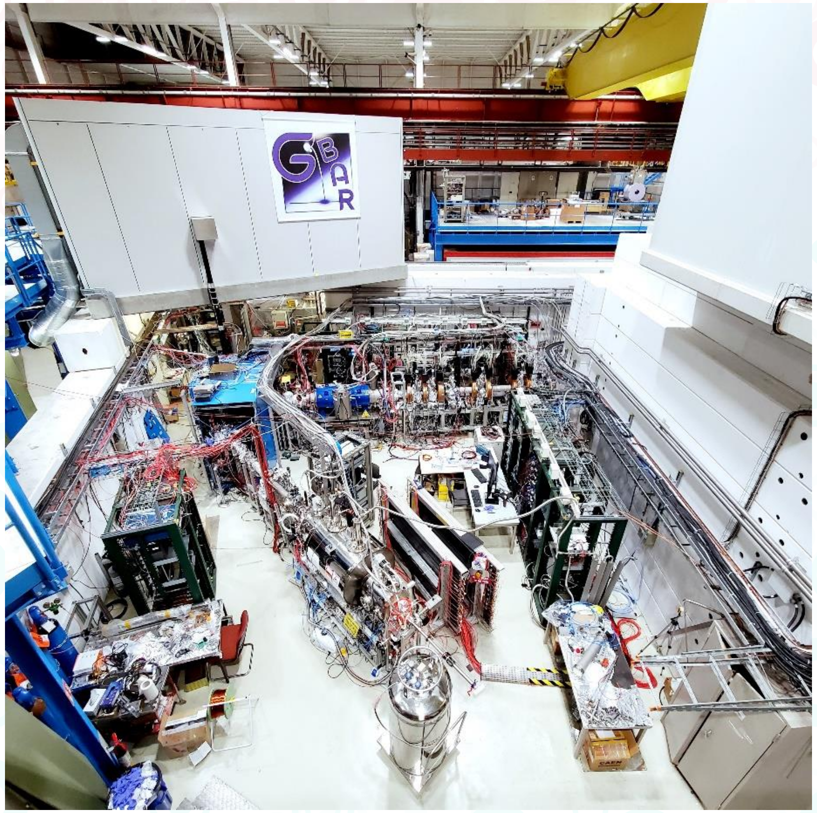
Three Free fall experiments

Primary goal: 1 % precision (~quark mass contribution)

AEgIS



GBAR



ALPHA-g

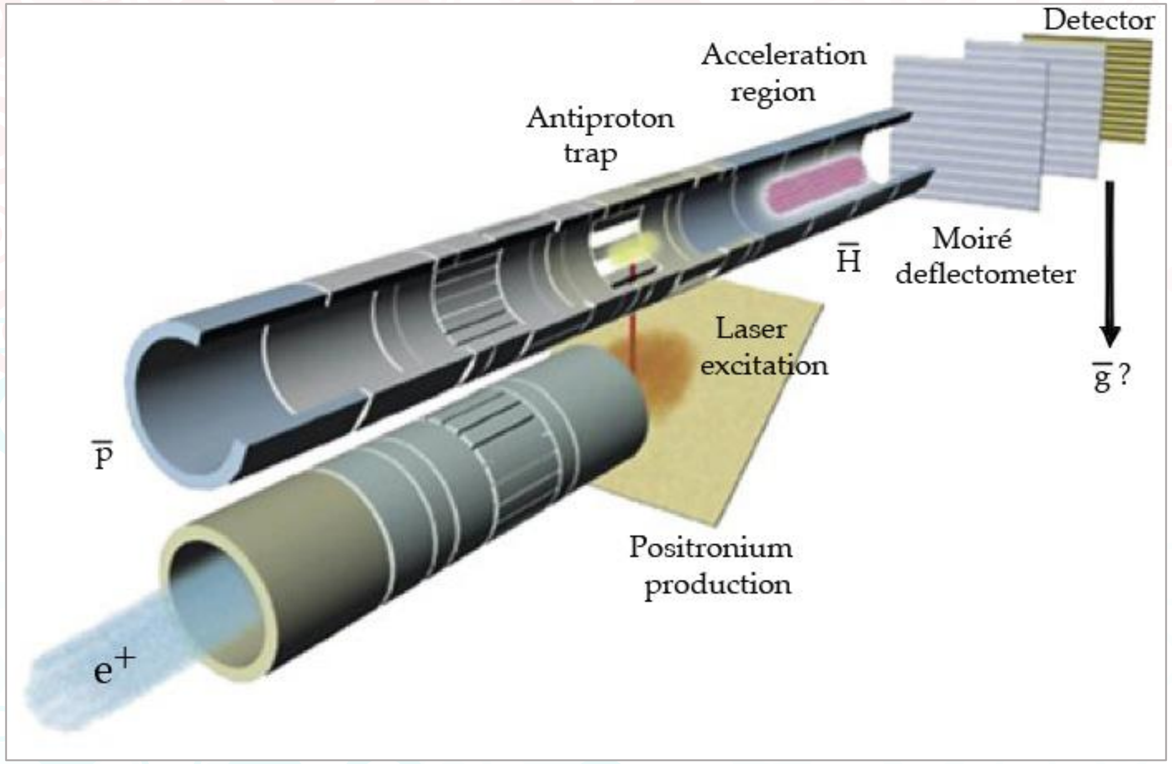
AEGIS experiment

No $\overline{\mathrm{H}}$ trapping!

Accelerate Rydberg Stark states of cold antihydrogen

Observe the beam deflection
(10 μm over 1 m distance if $\bar{g} = g$)
Moiré deflectometer

See next talk by Antoine Camper



ALPHA experiment

First attempt at a direct free fall observation

NAT. COMMUN. **4**, 1785 (2013)

ARTICLE

Received 14 Jan 2013 | Accepted 22 Mar 2013 | Published 30 Apr 2013 DOI: 10.1038/ncomms2787 OPEN

Description and first application of a new technique to measure the gravitational mass of antihydrogen

The ALPHA Collaboration* & A.E. Charman[1]

Release of trapped antihydrogens

Observation of the distribution of annihilation vertices

Limits: $$-65 < F = \frac{m_g}{m_i} < +110$$

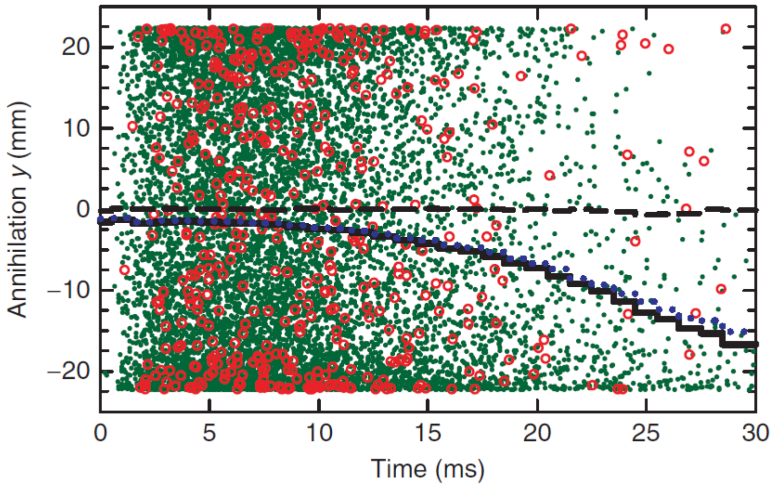


Figure 2 | Annihilation locations. The times and vertical (y) annihilation locations (green dots) of 10,000 simulated antihydrogen atoms in the decaying magnetic fields, as found by simulations of equation 1 with $F = 100$. Because $F = 100$ in this simulation, there is a tendency for the anti-atoms to annihilate in the bottom half ($y < 0$) of the trap, as shown by the black solid line, which plots the average annihilation locations binned in 1 ms intervals. The average was taken by simulating approximately 900,000 anti-atoms; the green points are the annihilation locations of a sub-sample of these simulated anti-atoms. The blue dotted line includes the effects of detector azimuthal smearing on the average; the smearing reduces the effect of gravity observed in the data. The red circles are the annihilation times and locations for 434 real anti-atoms, as measured by our particle detector. Also shown (black dashed line) is the average annihilation location for ~840,000 simulated anti-atoms for $F = 1$.

ALPHA-g experiment

Vertical trap

Release from mirror coils
Top-bottom experiment

To go to 1 %:
Adiabatic cooling
Field compensation
+ counting

CERN-SPSC-2023-010 (2023)

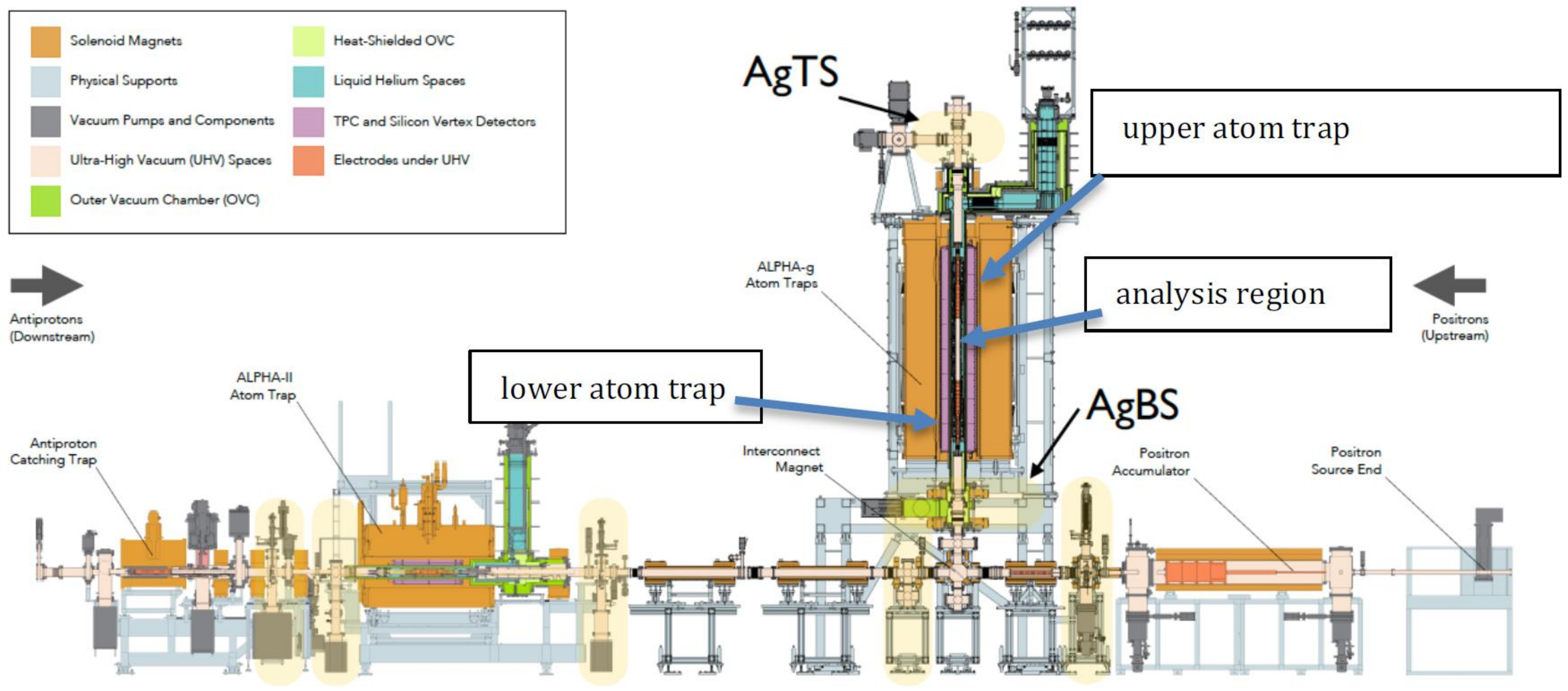


Figure 6. Schematic of the complete ALPHA apparatus.

Requires extremely precise measurement of magnetic field.

Data aquisition in 2022…

GBAR

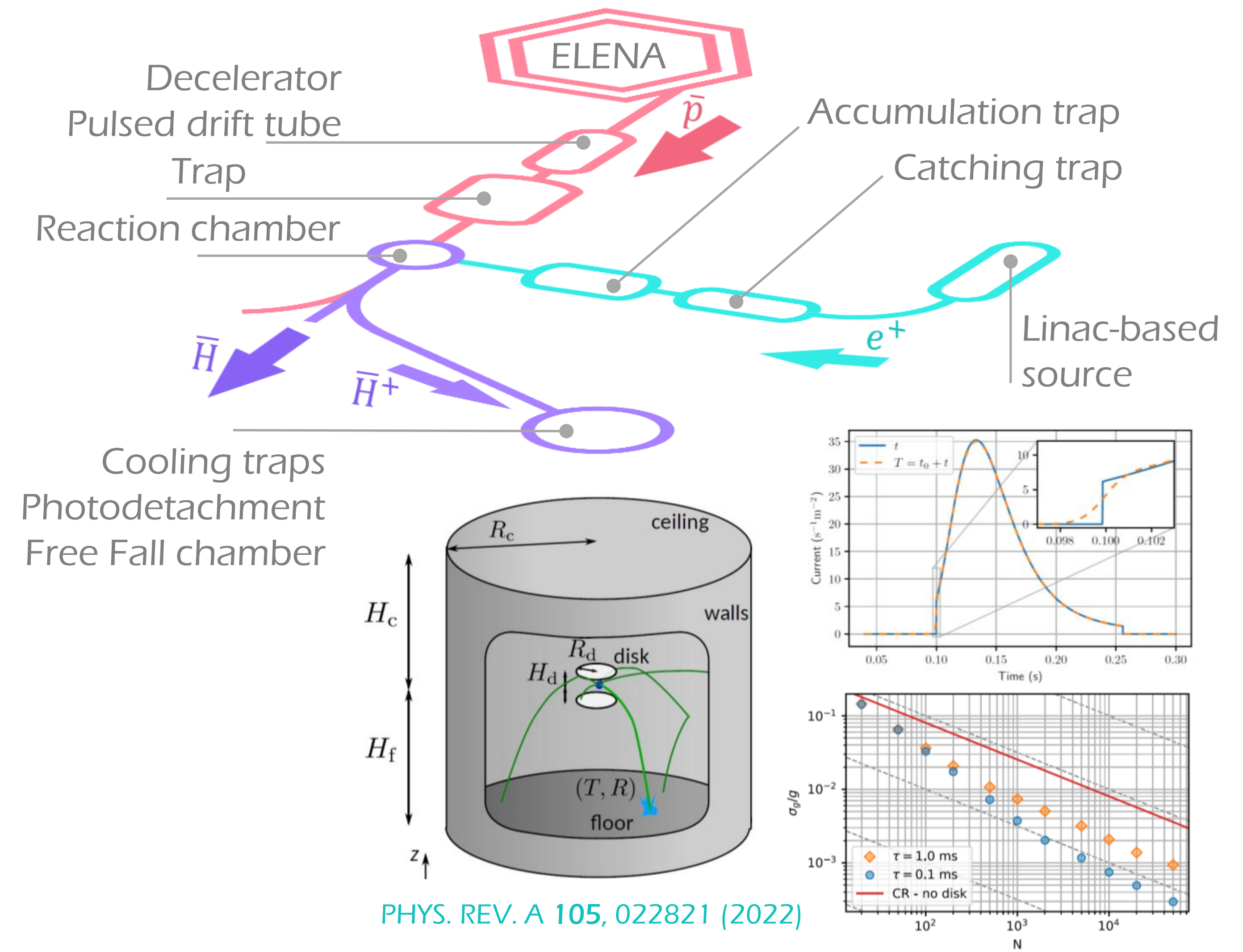
Goal: 1 neV, ~10 μK, 1 m.s $^{-1}$

Sympathetic cooling of $\bar{H}^+$
Doppler cooling of Be^+
+ ground state cooling

Production:

1) $\bar{p} + Ps \rightarrow \bar{H} + e^-$
2) $\mathbf{\bar{H} + Ps \rightarrow \bar{H}^+ + e^-}$

$\sim 10^{10}\, e^+ + 10^6\, \bar{p}$

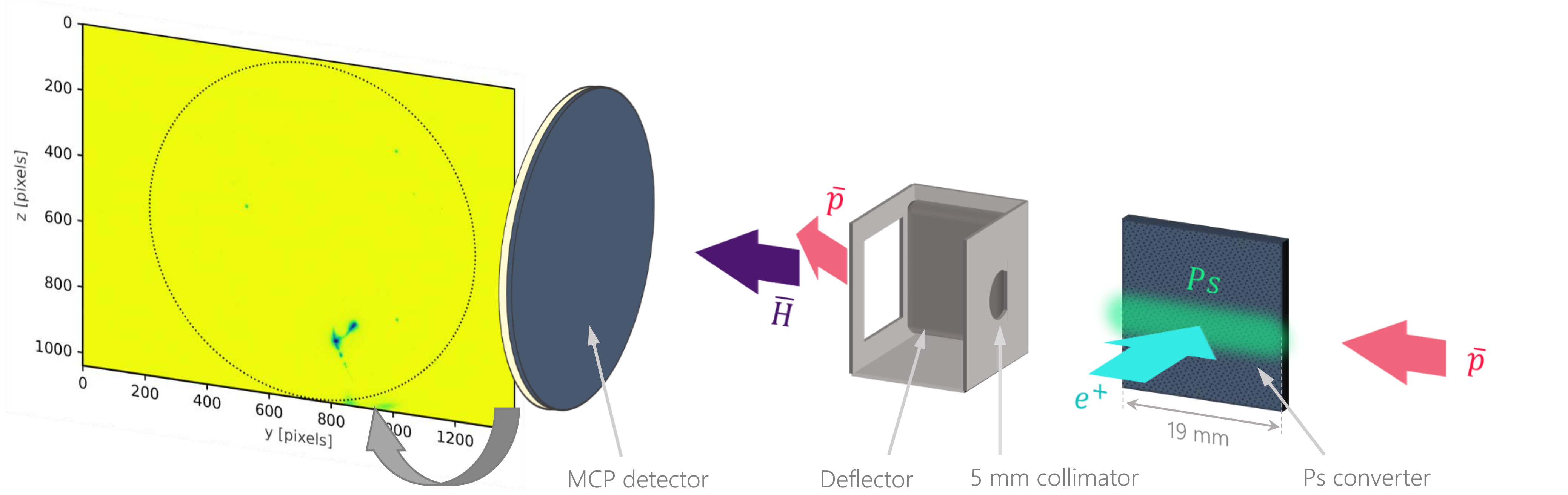


PHYS. REV. A **105**, 022821 (2022)

GBAR

Status:
Demonstrated 1st production of $\bar{H}$ from 6 keV antiprotons and Ps(1S)

Figure adapted from 2023 pre-print CERN-EP-2023-120



Many steps remain, from $\bar{H}^+$ production to sympathetic cooling

Going better than 1 % ? Interferometry

ALPHA-g: Cold antiatom gravimeter

Laser cooling (20 mK) NATURE **592**, p.35 (2021)
Anti-atomic fountain

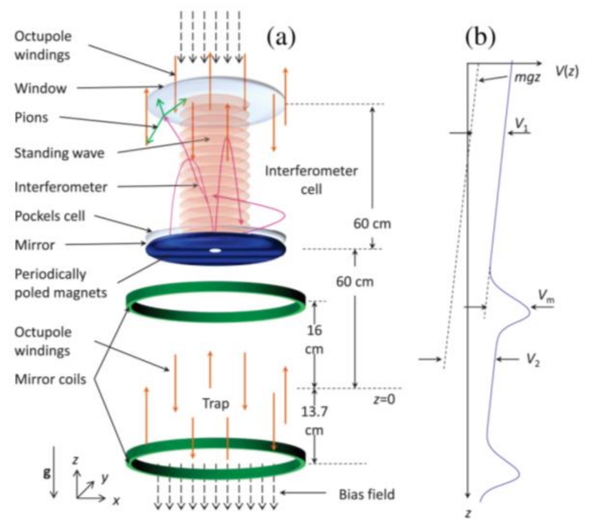
Precision: 10^{-3} with 250 events
10^{-6} with apparatus upgrade

GBAR: Gravitational Quantum states

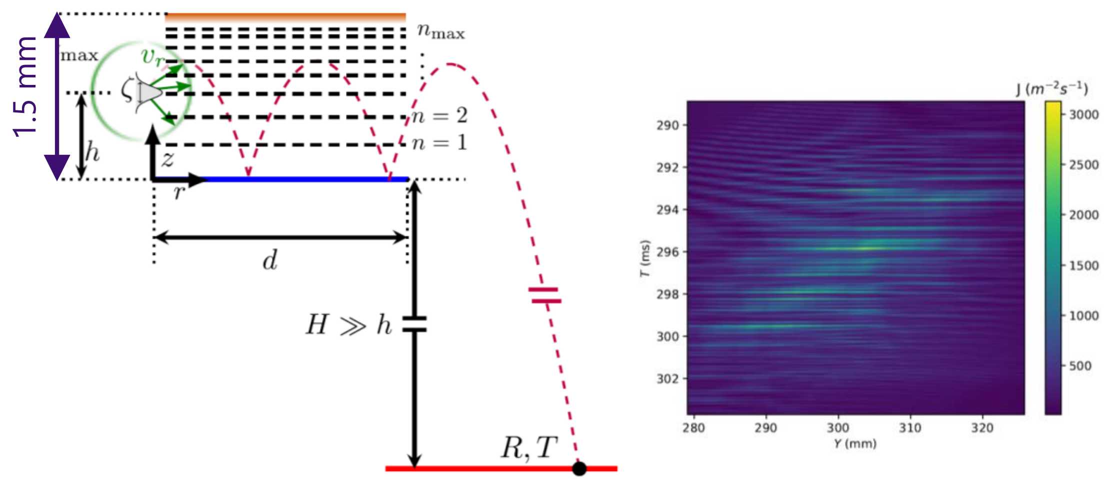
$\overline{H}$ trapped between gravitational potential & Casimir-Polder potential of a mirror

Precision: 10^{-5} – 10^{-6} with 1000 events

PHYS. Rev. Lett. **112**, 121102 (2014)



EUR. PHYS. J. D **76**, 209 (2022)



Antiproton’s comeback

BASE experiment

NATURE **601**, p.53 (2022)

Article

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

https://doi.org/10.1038/s41586-021-04203-w
Received: 25 May 2021
Accepted: 3 November 2021
Published online: 5 January 2022

M. J. Borchert[1,2,3], J. A. Devlin[1,4], S. R. Erlewein[1,4,5], M. Fleck[1,6], J. A. Harrington[1,5], T. Higuchi[1,6], B. M. Latacz[1], F. Voelksen[1,7], E. J. Wursten[1,4,5], F. Abbass[8], M. A. Bohman[1,5], A. H. Mooser[5], D. Popper[8], M. Wiesinger[1,5], C. Will[5], K. Blaum[5], Y. Matsuda[6], C. Ospelkaus[2,3], W. Quint[7], J. Walz[8,9], Y. Yamazaki[1], C. Smorra[1,8] & S. Ulmer[1]✉

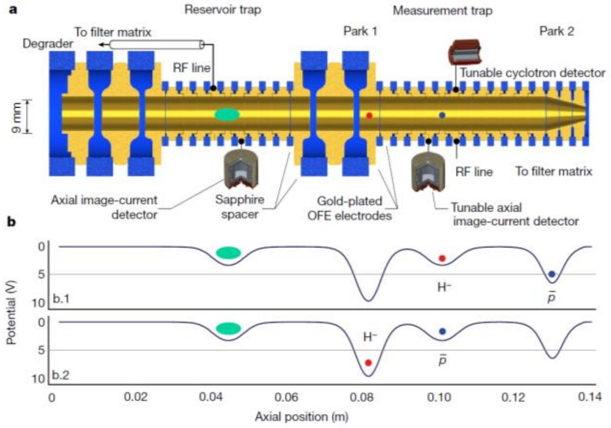


Fig. 1 | Elements of the experiment to determine the antiproton-to-H⁻ charge-to-mass ratio.

$$R = \frac{-\left(\frac{q}{m}\right)_p}{\left(\frac{q}{m}\right)_{\bar{p}}} = 1.000000000003(16)$$

WEP for clocks

Gravitation redshift of the cyclotron frequency
Varies during the year

$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3GM_{\mathrm{sun}}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right) \qquad (\alpha_{g,D} - 1) < 0.03$$

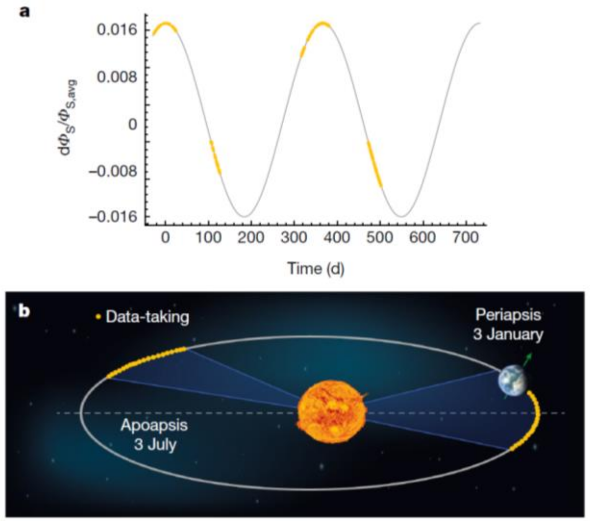


Fig. 3 | Trajectory of the Earth on its orbit around the Sun. a, Variation of the gravitational potential in the BASE laboratory, sourced by the elliptical orbit of the Earth around the Sun. The yellow scatter points represent the data-taking windows. **b**, Scaled orbit; the blue shaded areas indicate the trajectorial fraction covered by the measurement reported here.

Conclusion

CERN is the only provider of slow antiprotons

Attempts to measure
the gravitational behaviour of antimatter
have been ongoing for almost 60 years!

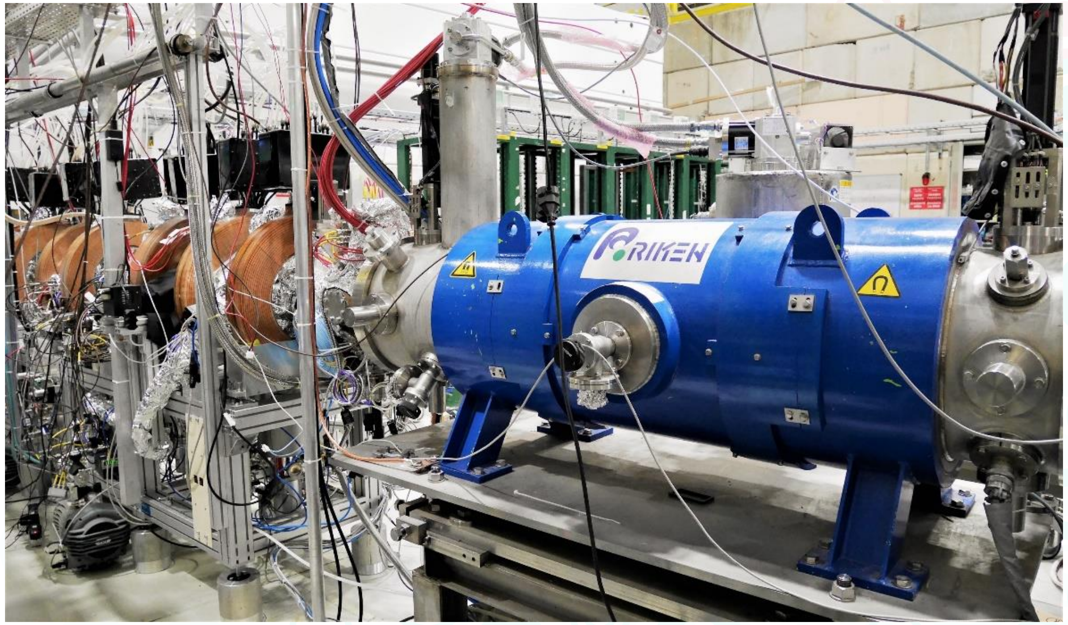
Very challenging

Many techniques developped on the road

No lack of ideas to improve the precision

A direct free fall measurement: never been so close?

Picture credits:
LEAR: CERN PhotoLab
PS210: Forschungszentrum Jülich / PS210 Collaboration
AD: CERN / L. Guiraud
AEgIS & ALPHA-g: CERN / M. Brice, J. Ordan
AEgIS scheme: AEgIS Collaboration
ELENA & GBAR: CERN / P. Comini



@GBAR_Experiment

@gbar_experiment