



The CERN Antimatter Factory

Testing the Equivalence Principle, the CPT symmetry, and beyond

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*Nuove frontiere
della fisica nucleare
fondamentale e applicata*



INFN2024

**6° INCONTRO NAZIONALE DI
FISICA NUCLEARE**

26 | 28 Febbraio 2024

TRENTO

	Interactions		
	Strong	EM	Weak
P	yes	yes	no
C	yes	yes	no
CP (or T)	yes	yes	$\sim 10^{-3}$ 1964 : K0 decay 1999 (2012) : Direct T Violation 2001: B decay (BELLE, BaBar) 2013 : strange B decay (LHCb)
CPT	yes	yes	yes

A local, Lorenz invariant theory with canonical spin-statistics relation must be invariant with respect to CPT-transformation

Implications: properties of matter and antimatter particles should be *exactly* the same

- Masses
- Charges
- Magnetic and electric moments
- Binding energies
- Optical transition frequencies

Julian Schwinger, *The Theory of Quantized Fields. I*, Phys. Rev. **82**, 914 (1951)
 Gerhard Lüders, *Proof of the TCP theorem* (1957)



The result of any local non-gravitational experiment is independent from the velocity of an observer in free-fall and his position and time in the Universe

WEP (Weak Equivalence Principle) $\longleftrightarrow m_i = m_g \longrightarrow$ «free-falling trajectories»

LLI (Local Lorentz Invariance) $\longleftrightarrow g_{\mu\nu} \xrightarrow{\text{locally}} \eta_{\mu\nu} \longrightarrow$ «free-falling Lorentz frames»

LPI (Local Position Invariance) $\longleftrightarrow \forall x^\mu \longrightarrow$ «independently of where and when»

~ the Equivalence Principle is at the heart of **any** metric theory of gravity (including GR) ~

What classes models are constrained by an EP test with antimatter?

Hypotetical interactions violating the Equivalence Principle:

$$V = -\frac{G_\infty}{r} m_1 m_2 (1 \mp a e^{-r/v} + b e^{-r/s})$$

attractive/repulsive vector gravitons
attractive scalar gravitons

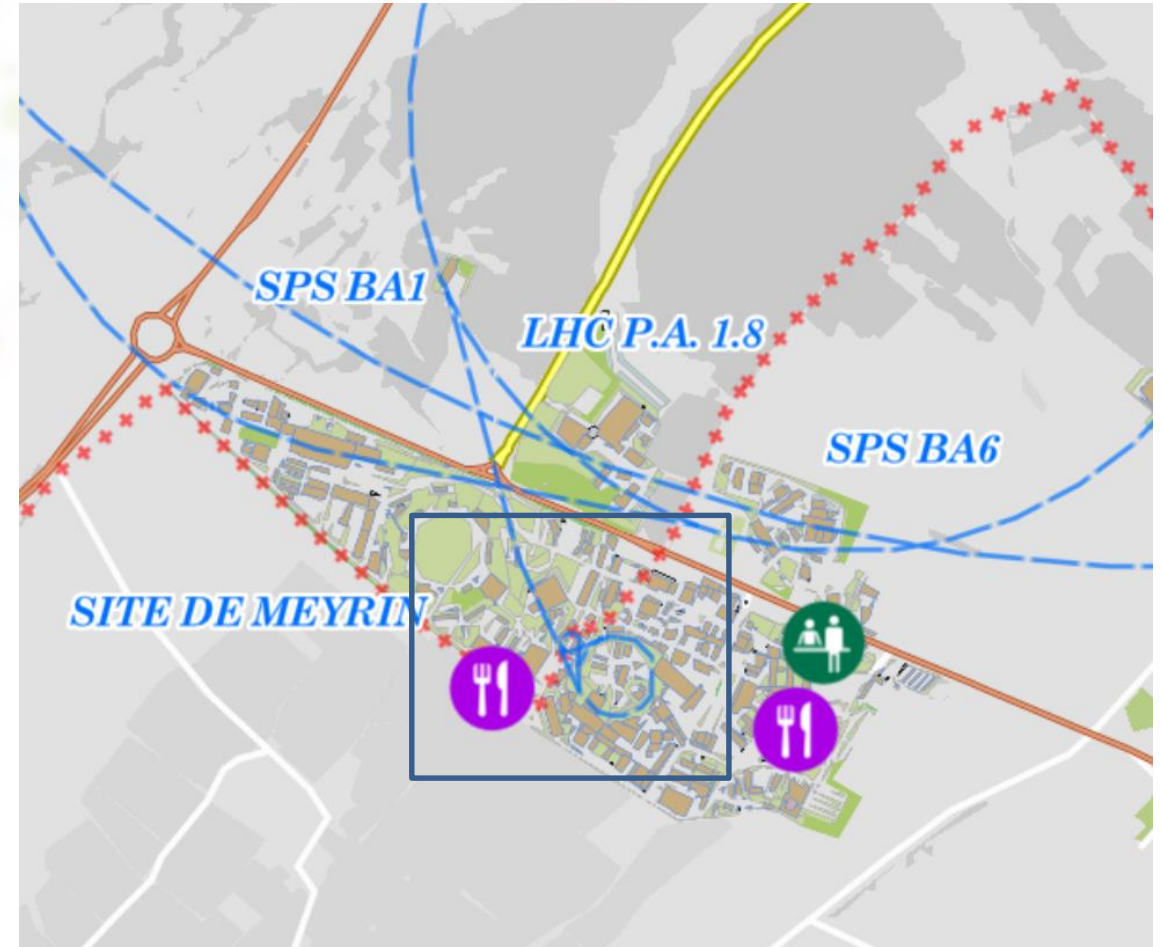
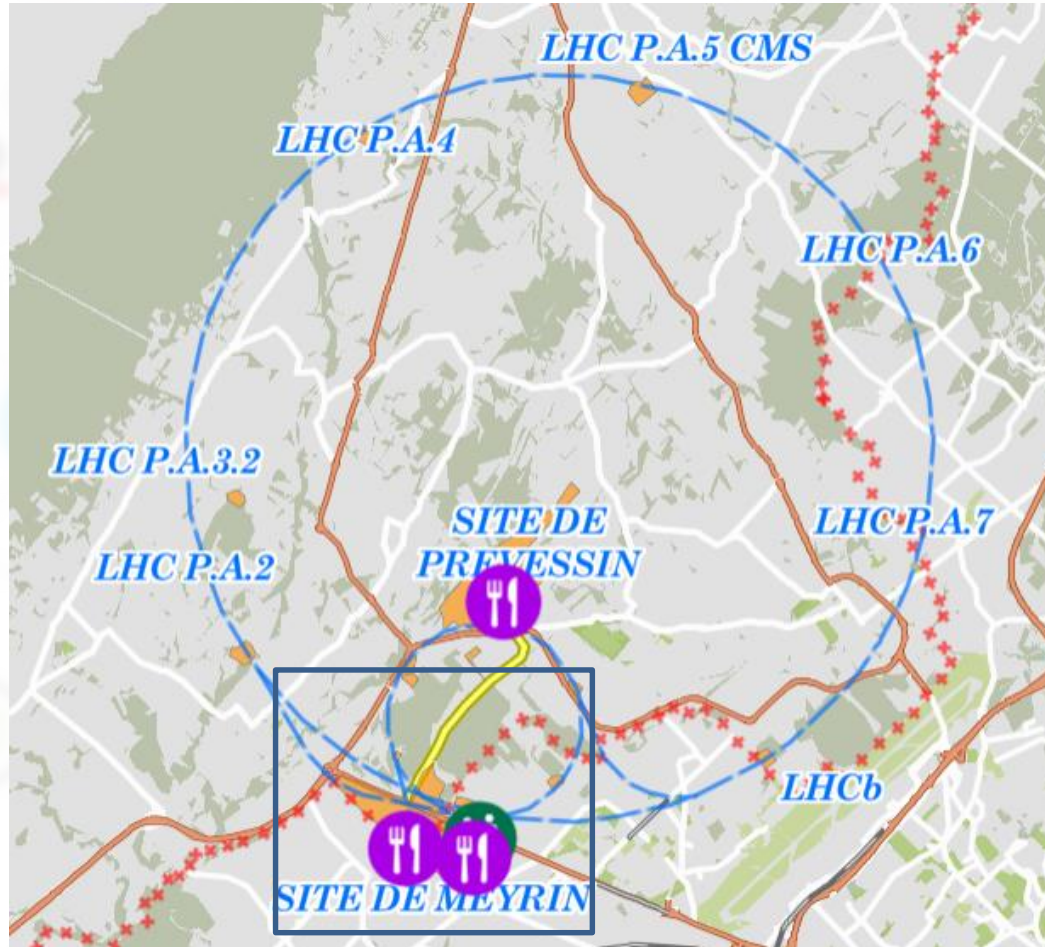
with cancellation effects occuring in matter experiments if $a \sim b$ and $v \sim s$

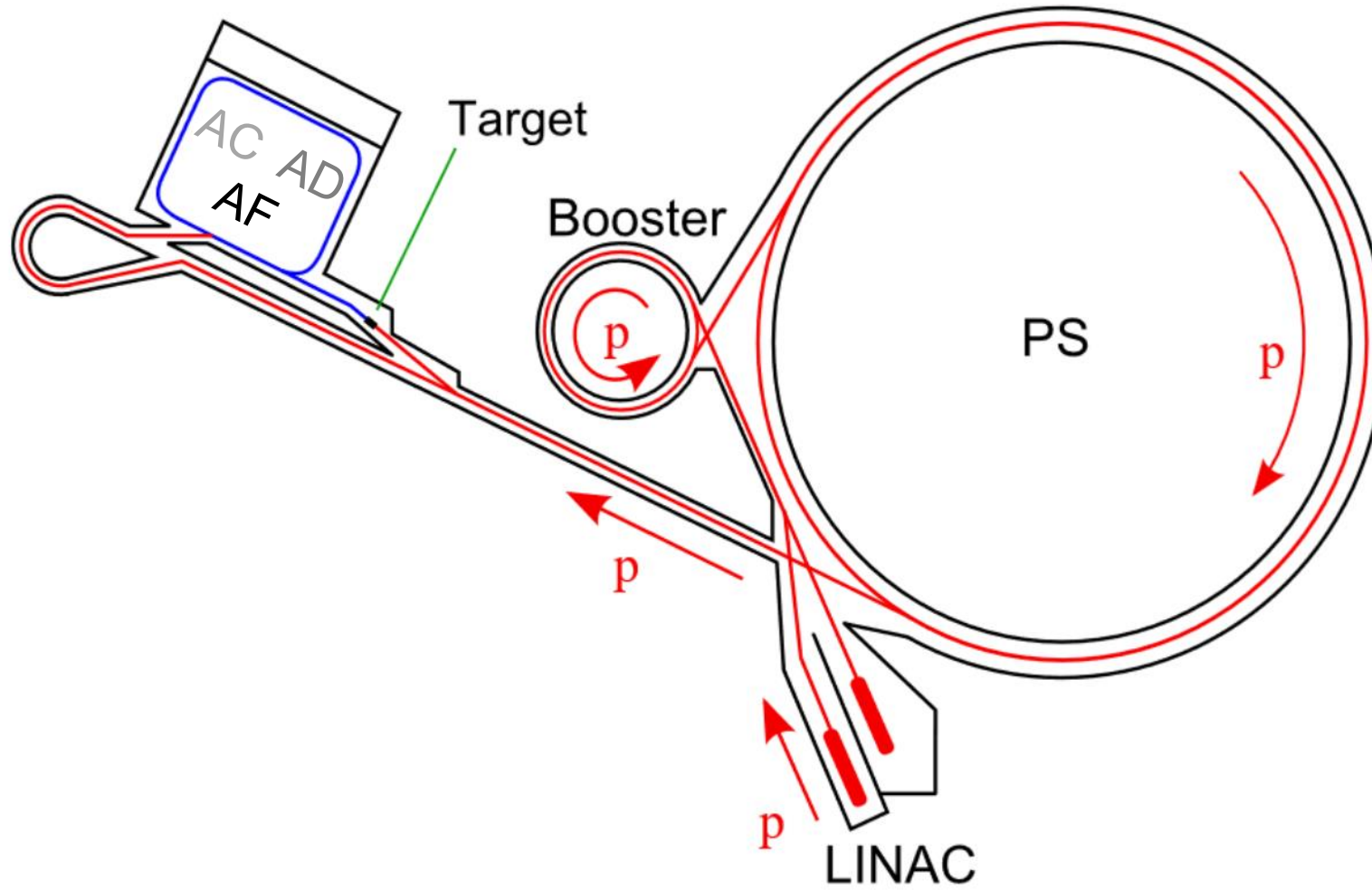
Theoretical considerations on different gravitational couplings of antimatter

1. *Anti-gravity would violate conservation of energy* (Morrison's argument)
2. *Standard Model and gravitational repulsion are incompatible at tree level* (Schiff/Dvali's argument)
3. *Antigravity would cause an unobserved CP violation in kaons oscillations* (Good's argument)
4. *No way to keep EP valid for light, matter and antimatter at the same time in case of anti-gravity, so WEP has to be valid at the level we can verify deflection of light in GR* (Karshenboim's argument)

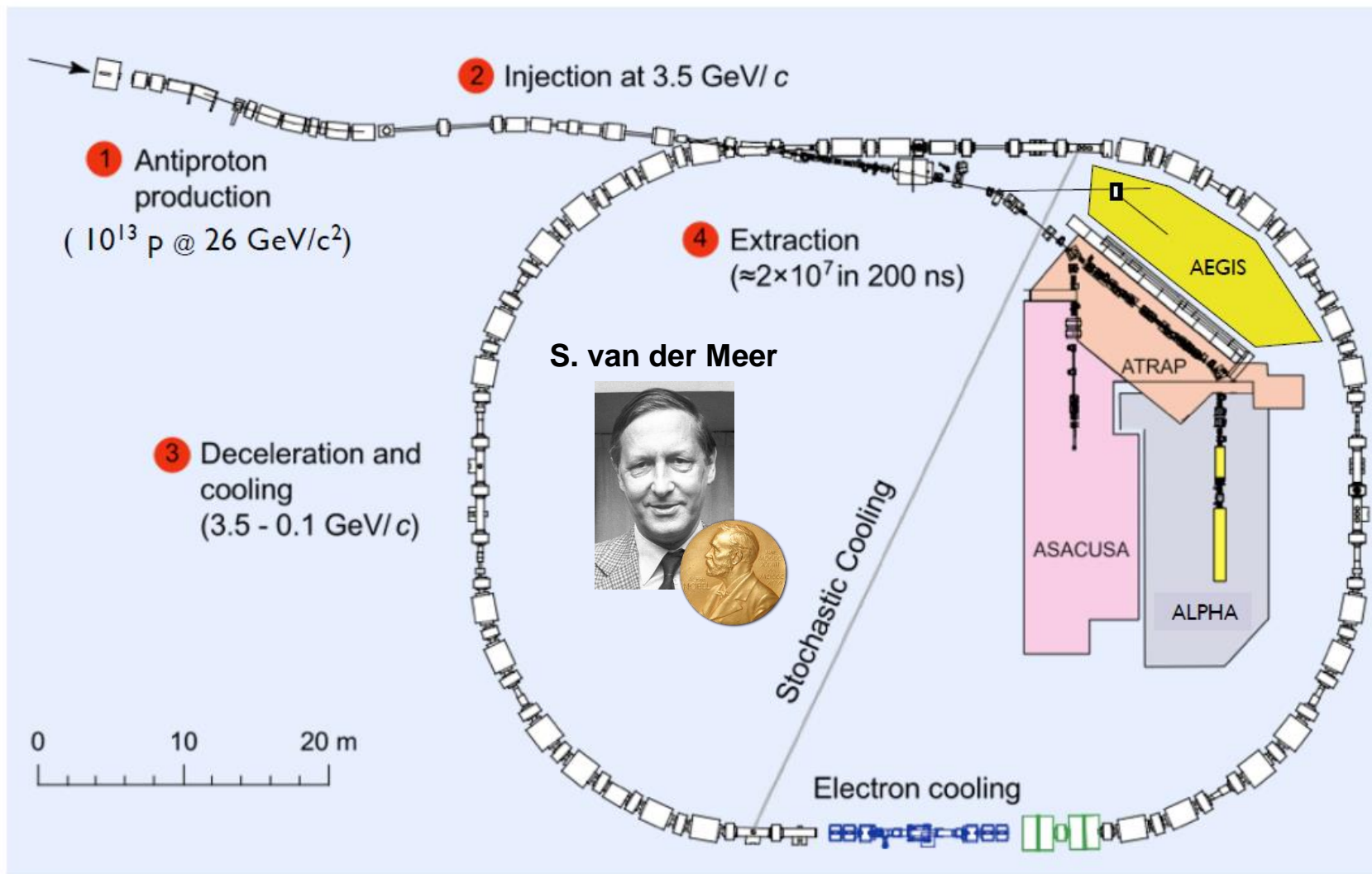
Karshenboim, S. G., talk to 2° Workshop on Antimatter and Gravity (2013)
 M. Nieto and T. Goldman, Phys. Rep. 205,5 221-281 (1992)
 Phys. Rev. D 33 (1986) 2475

Fayet P., Phys. Rev. D 99 (2019) 055043
 Fischbach E. et al. (2020), arXiv:2012.02862v1
 Caldwell, A. Dvali G. (2019), arXiv:1903.09096

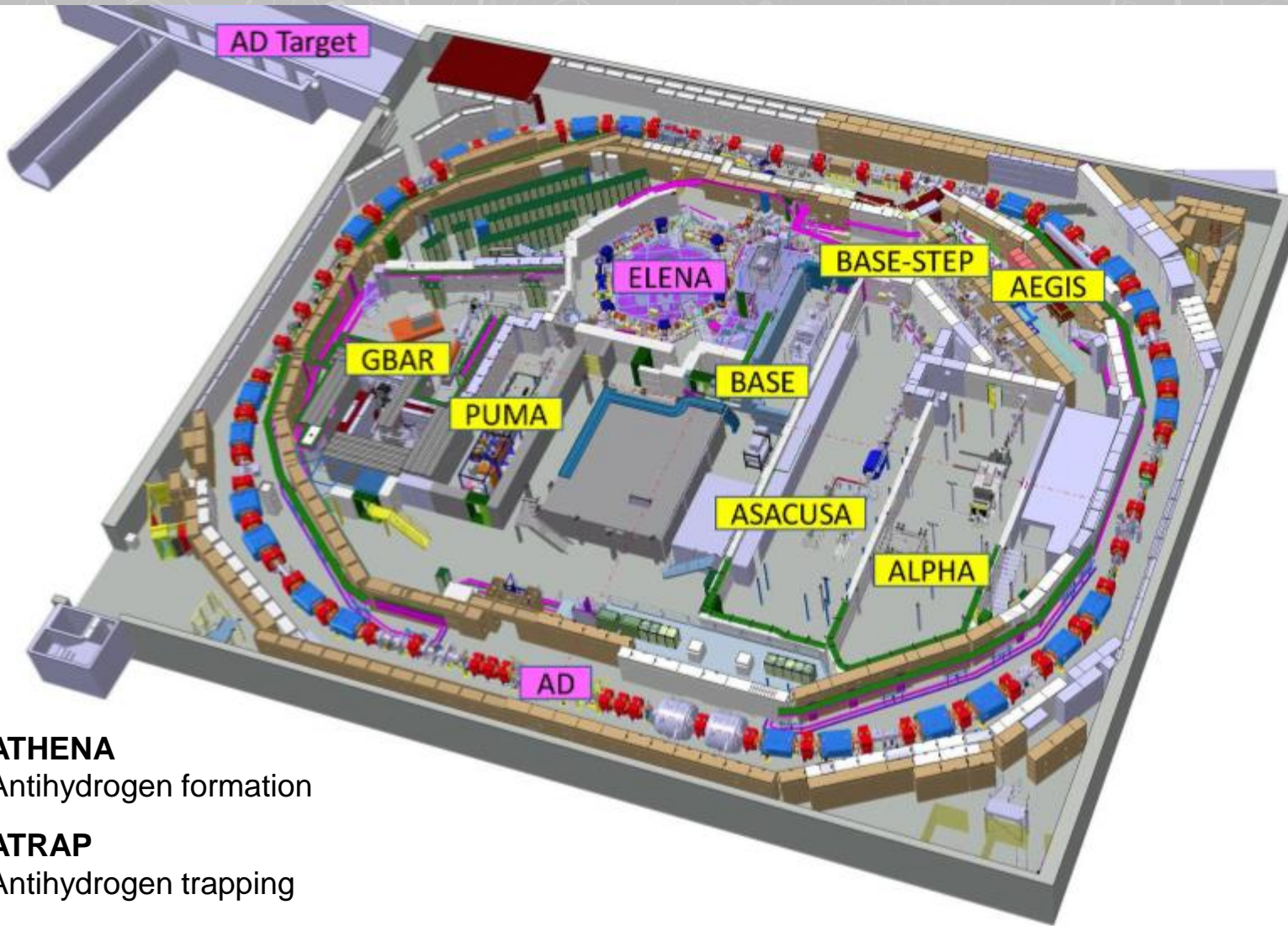




Cold Antiprotons in the Laboratory



The Antimatter Factory, as it looks today



Completed

- ATHENA**
Antihydrogen formation
- ATRAP**
Antihydrogen trapping
- ACE**
Antiproton interaction with cells

Antihydrogen

- ALPHA-2**
Laser spectroscopy
- ASACUSA**
Hyperfine spectroscopy
- AEGIS, GBAR, ALPHA-g**
Free-fall WEP

Antiprotons

- ASACUSA**
Antiprotonic helium spectroscopy
- BASE, BASE-STEP**
proton/antiproton charge, proton/antiproton moment, tests of clock WEP
- PUMA**
Antiproton/nuclei scattering to study neutron skins

Achievements in the Antimatter Factory

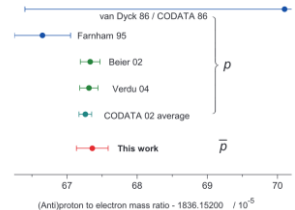


2002

letters to nature

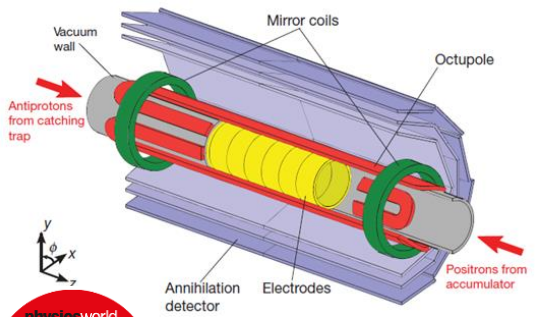
Production and detection of cold antihydrogen atoms

M. Amoretti¹, C. Anisler¹, G. Bonomi^{1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88,89,90,91,92,93,94,95,96,97,98,99,100,101,102,103,104,105,106,107,108,109,110,111,112,113,114,115,116,117,118,119,120,121,122,123,124,125,126,127,128,129,130,131,132,133,134,135,136,137,138,139,140,141,142,143,144,145,146,147,148,149,150,151,152,153,154,155,156,157,158,159,160,161,162,163,164,165,166,167,168,169,170,171,172,173,174,175,176,177,178,179,180,181,182,183,184,185,186,187,188,189,190,191,192,193,194,195,196,197,198,199,200,201,202,203,204,205,206,207,208,209,210,211,212,213,214,215,216,217,218,219,220,221,222,223,224,225,226,227,228,229,230,231,232,233,234,235,236,237,238,239,240,241,242,243,244,245,246,247,248,249,250,251,252,253,254,255,256,257,258,259,260,261,262,263,264,265,266,267,268,269,270,271,272,273,274,275,276,277,278,279,280,281,282,283,284,285,286,287,288,289,290,291,292,293,294,295,296,297,298,299,300,301,302,303,304,305,306,307,308,309,310,311,312,313,314,315,316,317,318,319,320,321,322,323,324,325,326,327,328,329,330,331,332,333,334,335,336,337,338,339,340,341,342,343,344,345,346,347,348,349,350,351,352,353,354,355,356,357,358,359,360,361,362,363,364,365,366,367,368,369,370,371,372,373,374,375,376,377,378,379,380,381,382,383,384,385,386,387,388,389,390,391,392,393,394,395,396,397,398,399,400,401,402,403,404,405,406,407,408,409,410,411,412,413,414,415,416,417,418,419,420,421,422,423,424,425,426,427,428,429,430,431,432,433,434,435,436,437,438,439,440,441,442,443,444,445,446,447,448,449,450,451,452,453,454,455,456,457,458,459,460,461,462,463,464,465,466,467,468,469,470,471,472,473,474,475,476,477,478,479,480,481,482,483,484,485,486,487,488,489,490,491,492,493,494,495,496,497,498,499,500,501,502,503,504,505,506,507,508,509,510,511,512,513,514,515,516,517,518,519,520,521,522,523,524,525,526,527,528,529,530,531,532,533,534,535,536,537,538,539,540,541,542,543,544,545,546,547,548,549,550,551,552,553,554,555,556,557,558,559,560,561,562,563,564,565,566,567,568,569,570,571,572,573,574,575,576,577,578,579,580,581,582,583,584,585,586,587,588,589,590,591,592,593,594,595,596,597,598,599,600,601,602,603,604,605,606,607,608,609,610,611,612,613,614,615,616,617,618,619,620,621,622,623,624,625,626,627,628,629,630,631,632,633,634,635,636,637,638,639,640,641,642,643,644,645,646,647,648,649,650,651,652,653,654,655,656,657,658,659,660,661,662,663,664,665,666,667,668,669,670,671,672,673,674,675,676,677,678,679,680,681,682,683,684,685,686,687,688,689,690,691,692,693,694,695,696,697,698,699,700,701,702,703,704,705,706,707,708,709,710,711,712,713,714,715,716,717,718,719,720,721,722,723,724,725,726,727,728,729,730,731,732,733,734,735,736,737,738,739,740,741,742,743,744,745,746,747,748,749,750,751,752,753,754,755,756,757,758,759,760,761,762,763,764,765,766,767,768,769,770,771,772,773,774,775,776,777,778,779,780,781,782,783,784,785,786,787,788,789,790,791,792,793,794,795,796,797,798,799,800,801,802,803,804,805,806,807,808,809,810,811,812,813,814,815,816,817,818,819,820,821,822,823,824,825,826,827,828,829,830,831,832,833,834,835,836,837,838,839,840,841,842,843,844,845,846,847,848,849,850,851,852,853,854,855,856,857,858,859,860,861,862,863,864,865,866,867,868,869,870,871,872,873,874,875,876,877,878,879,880,881,882,883,884,885,886,887,888,889,890,891,892,893,894,895,896,897,898,899,900,901,902,903,904,905,906,907,908,909,910,911,912,913,914,915,916,917,918,919,920,921,922,923,924,925,926,927,928,929,930,931,932,933,934,935,936,937,938,939,940,941,942,943,944,945,946,947,948,949,950,951,952,953,954,955,956,957,958,959,960,961,962,963,964,965,966,967,968,969,970,971,972,973,974,975,976,977,978,979,980,981,982,983,984,985,986,987,988,989,990,991,992,993,994,995,996,997,998,999,1000}



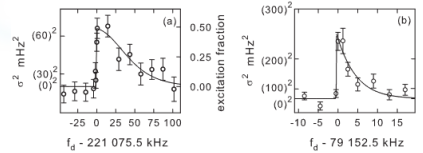
$m_{\bar{p}}/m_e$ 1.5 ppb

Trapped antihydrogen

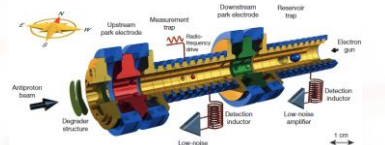


physicsworld
**TOP 10
BREAKTHROUGH
2010**

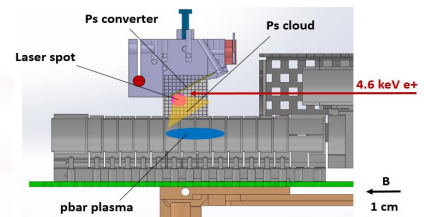
5ppm pbar moment



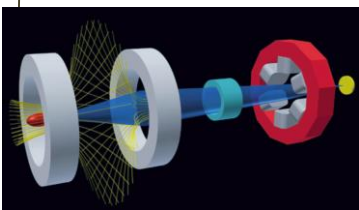
Antiprotons q/m 69 ppt



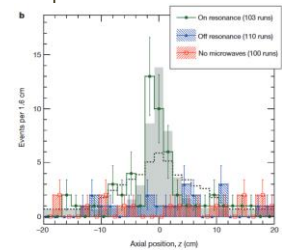
Pulsed production of antihydrogen



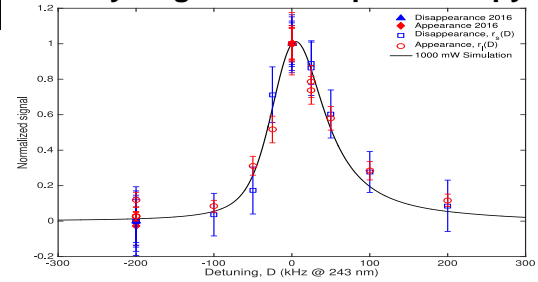
Antihydrogen atoms beam production



Antihydrogen RF spectroscopy



Antihydrogen 1S-2S spectroscopy



2024
2023
2022
2021
2020
2019
2018
2017
2016
2015
2014
2013
2012
2011
2010

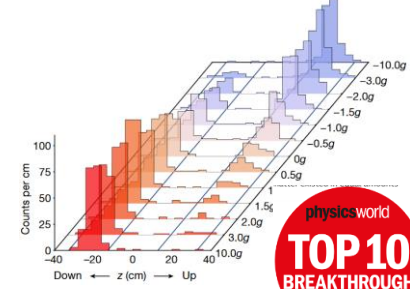
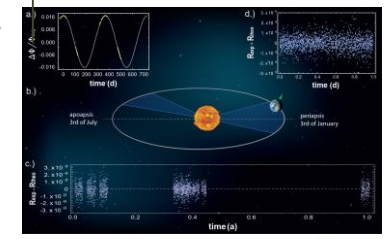


Ps laser cooling

physicsworld
**TOP 10
BREAKTHROUGH
2022**

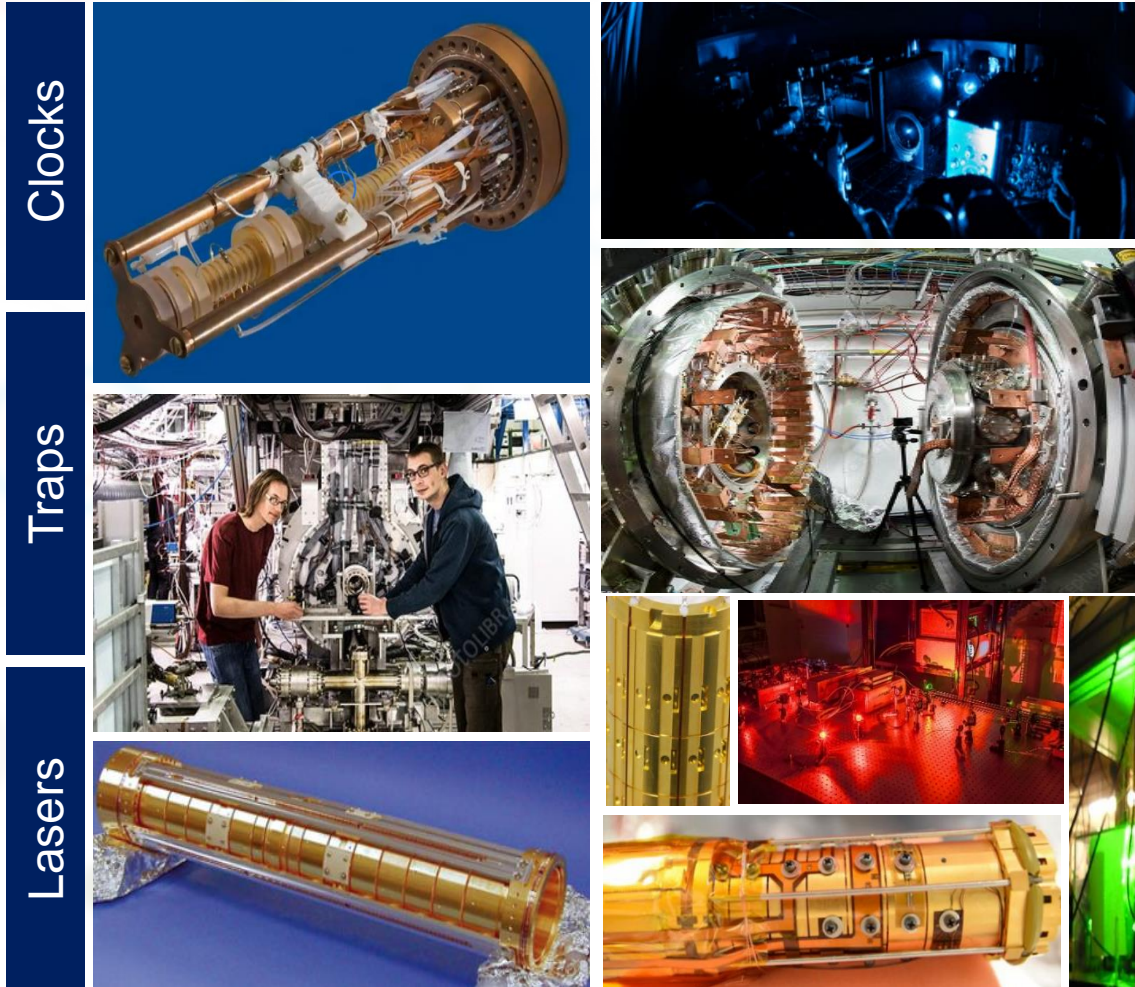
Laser cooled antihydrogen
Sympathetically cooled protons

First WEP tests



physicsworld
**TOP 10
BREAKTHROUGH
2023**

ORIGINAL EXPERIMENTAL TECHNIQUES DEVELOPED AT THE AF



Physics Results are bound to the ability to combine technologies from many fields of experimental physics in the same apparatus.

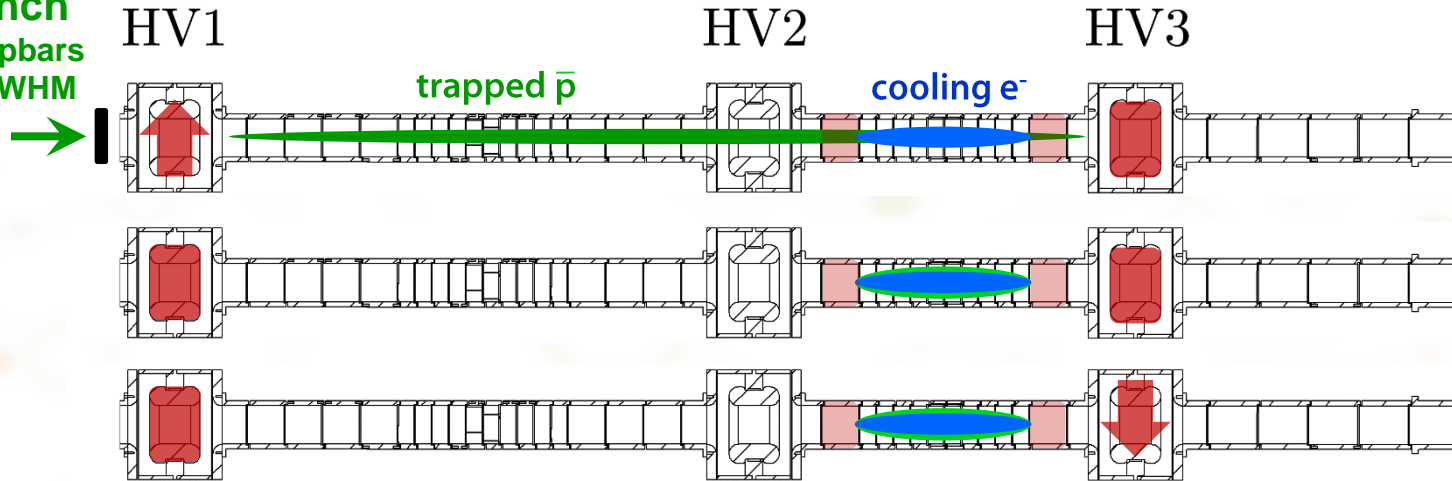
Mixture of expertises from

- Accelerator experiments
- Non-neutral plasmas
- Hybrid neutral and charged particle traps
- Ultra-stable quantum spectroscopy lasers
- Pulsed high-power lasers
- Ultra-high vacuum and superconductors
- Particle Physics detectors

**Non-observational operative experiments:
we are our own «machinists»**

Standards: antiproton catching and cooling

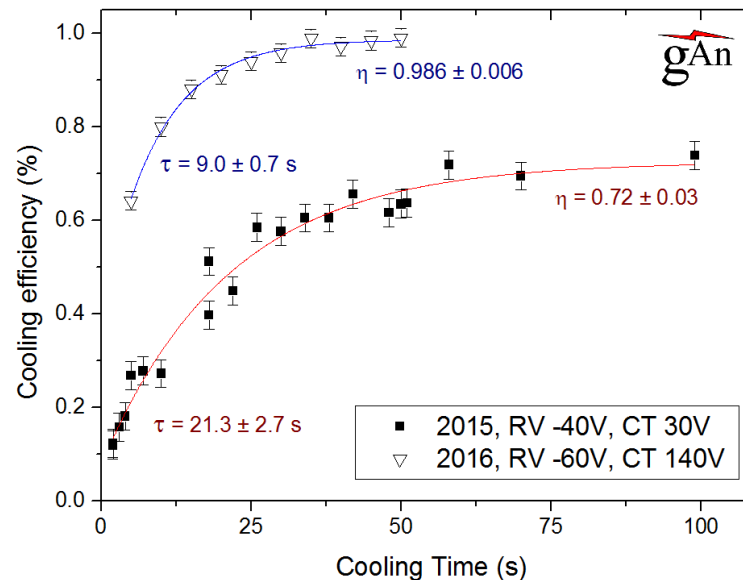
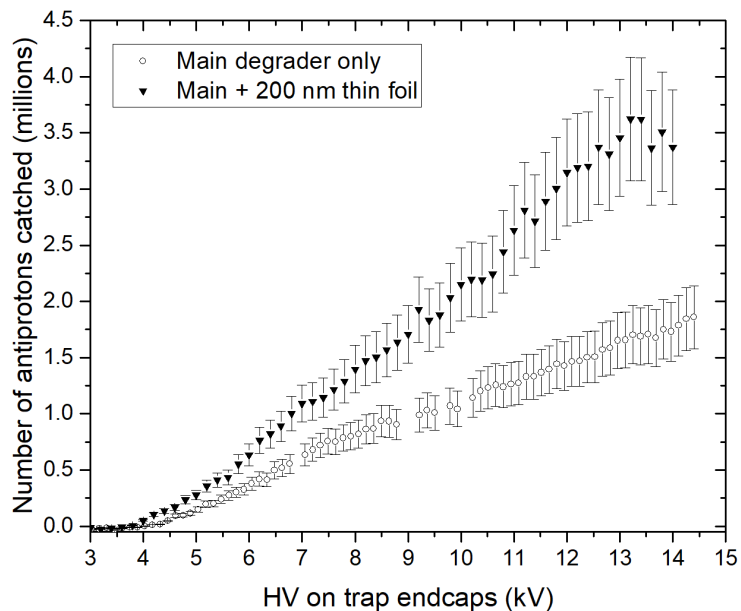
AD bunch
 $3.0 \cdot 10^7$ pbars
 100 ns FWHM



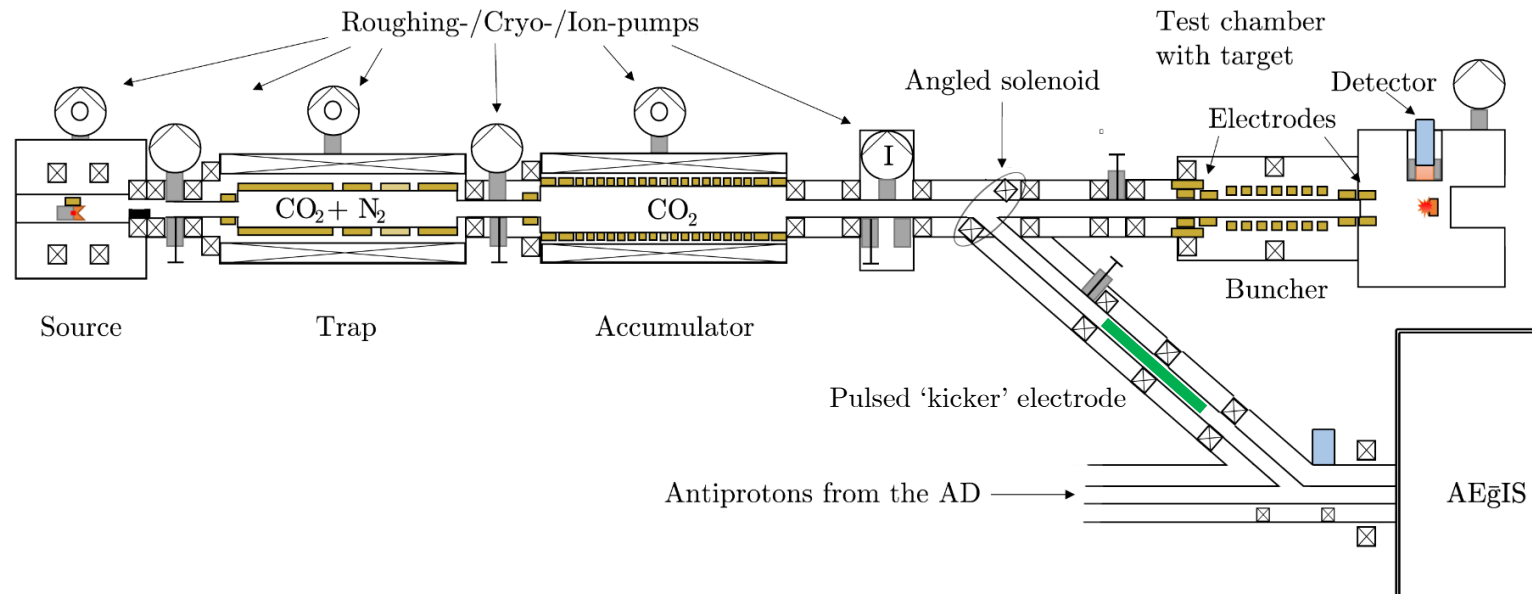
Capture

Electron cooling

Hot fraction release

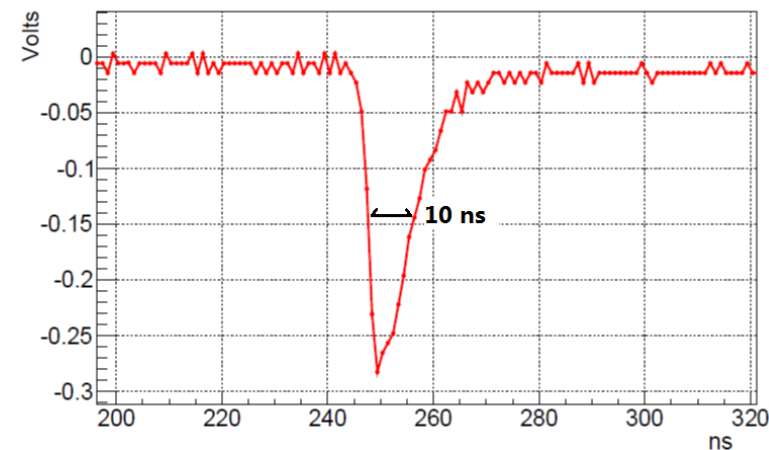


gAn



Positron bunch preparation

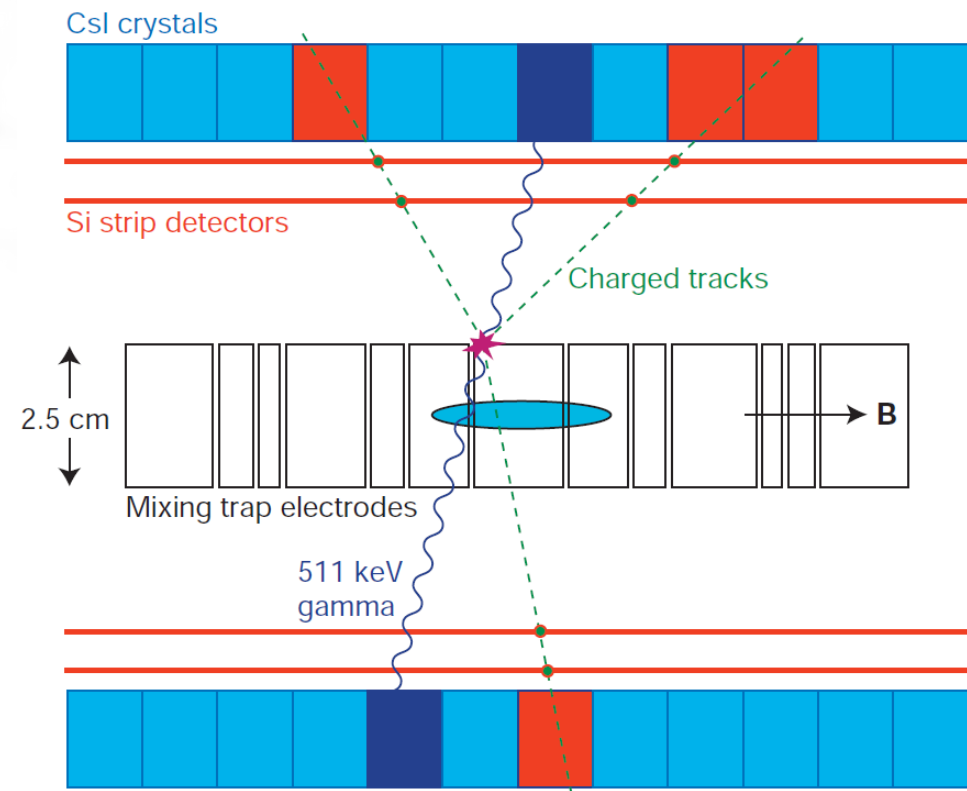
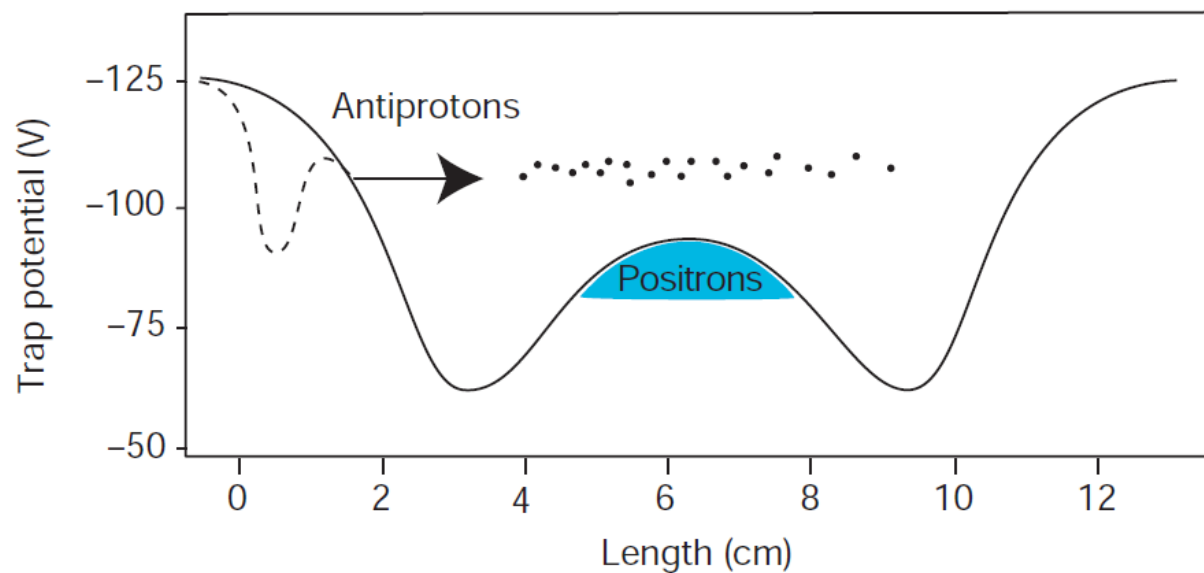
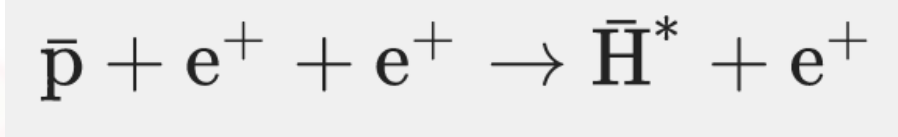
- Solid-neon-moderated ^{22}Na source (activity 25 mCi)
- Buffer-gas Surko-type e^+ trap (spills of $4 \cdot 10^5 e^+ / 0.17\text{s}$)
- Magnetic accumulator (lifetime up to 7000 spills)
- Nanosecond extraction at 300 eV with magnetic t.line
- Acceleration with pulsed 'kicker' electrode to 4.6 keV
- Steering with horizontal/vertical t.line coils



Letter | Published: 18 September 2002

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. Holzschteiter, L. V. Jørgensen, V. Lagomarsino, R. Landua, D. Lindelöf, E. Lodi Rizzini, ... D. P. van der Werf [+ Show authors](#)



Letter | [Published: 17 November 2010](#)

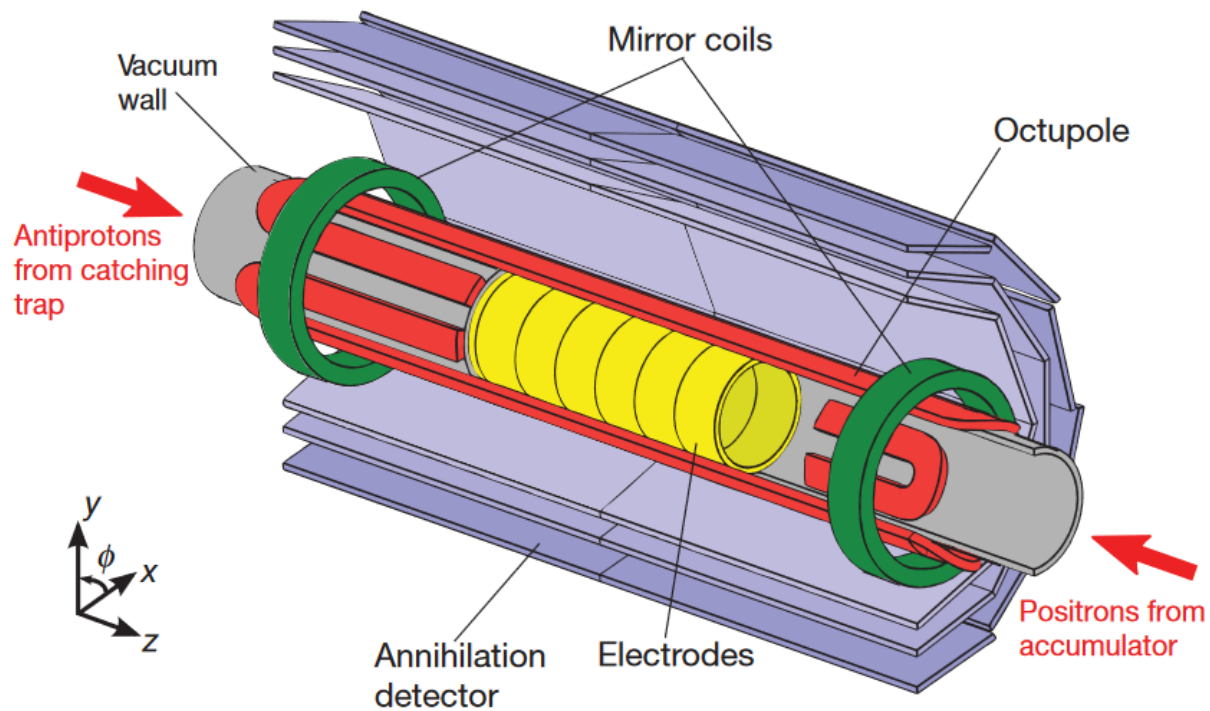
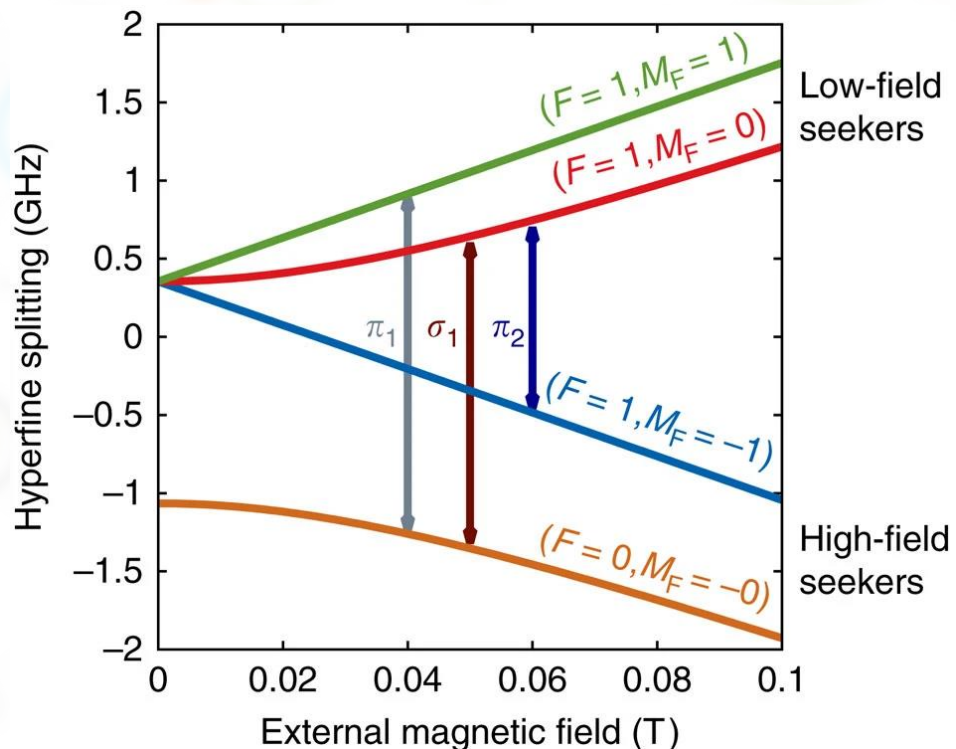
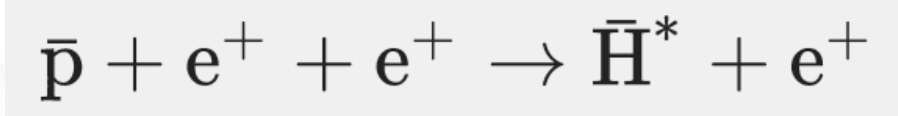
Trapped antihydrogen

[G. B. Andresen](#), [M. D. Ashkezari](#), [M. Baquero-Ruiz](#), [W. Bertsche](#), [P. D. Bowe](#), [E. Butler](#), [C. L. Cesar](#), [S.](#)

[Chapman](#), [M. Charlton](#), [A. Deller](#), [S. Eriksson](#), [J. Fajans](#), [T. Friesen](#), [M. C. Fujiwara](#), [D. R. Gill](#), [A. Gutierrez](#), [J. S.](#)



[Hangst](#) , [W. N. Hardy](#), [M. E. Hayden](#), [A. J. Humphries](#), [R. Hydromako](#), [M. J. Jenkins](#), [S. Jonsell](#), [L. V.](#)

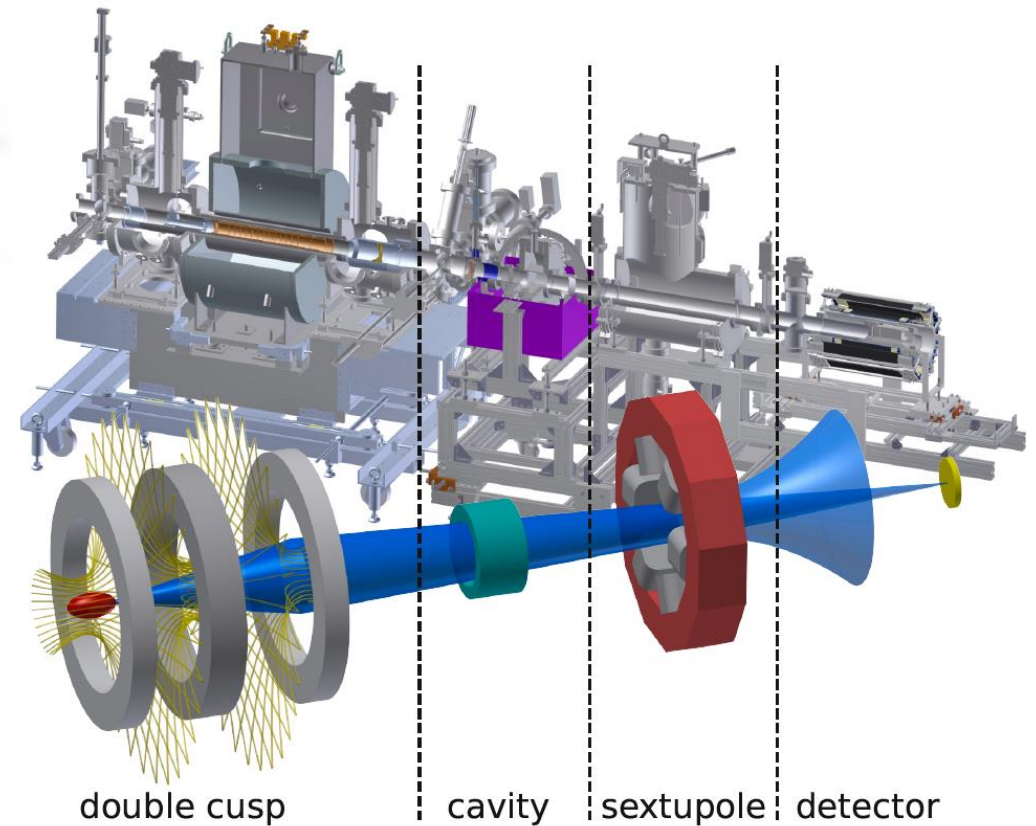
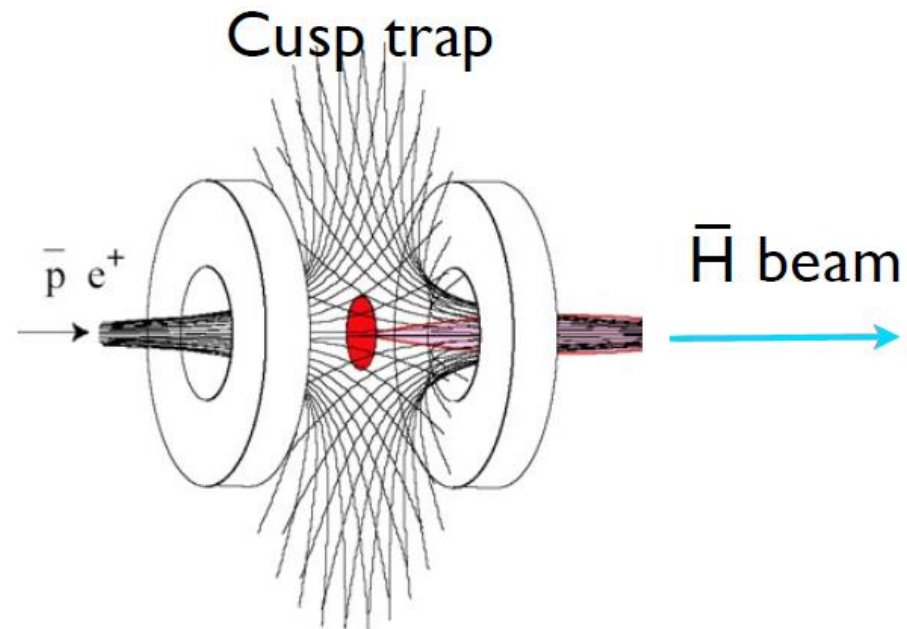
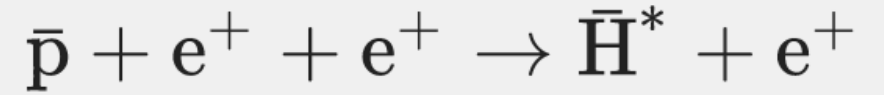
[Jørgensen](#), ... [Y. Yamazaki](#) + Show authors



Article | [Open access](#) | [Published: 21 January 2014](#)

A source of antihydrogen for in-flight hyperfine spectroscopy

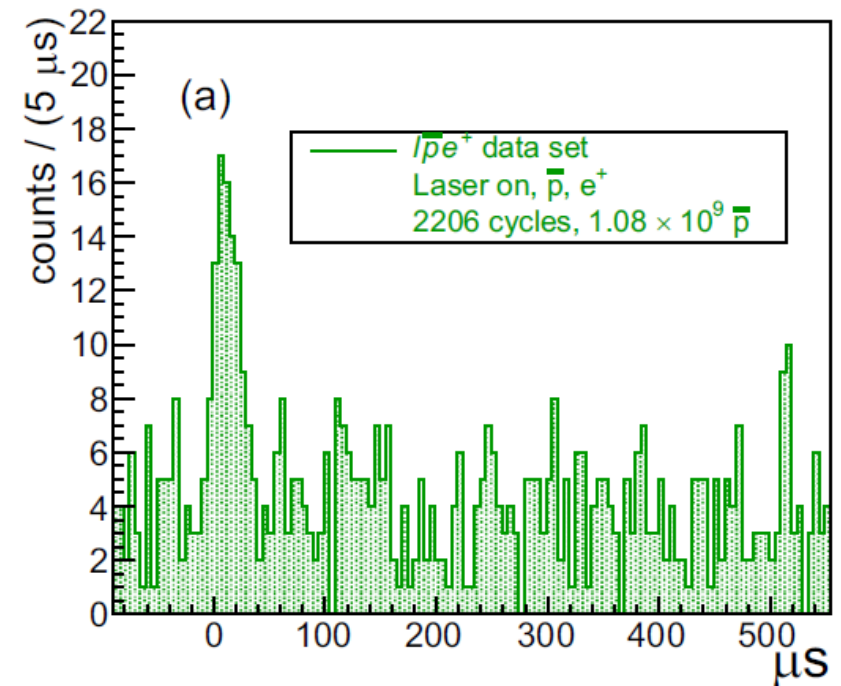
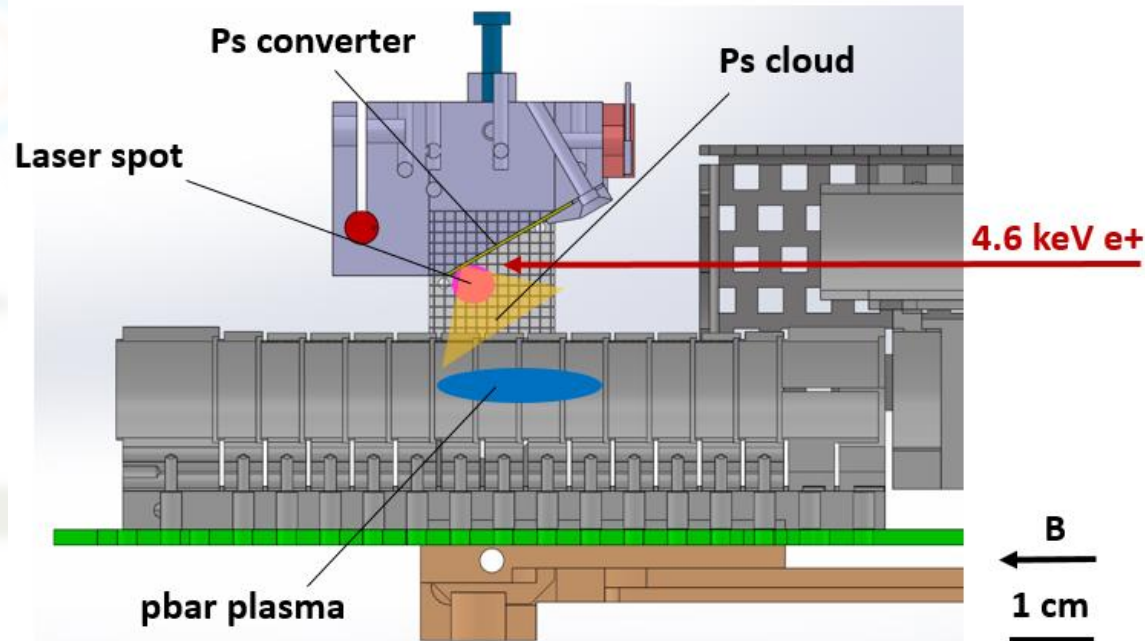
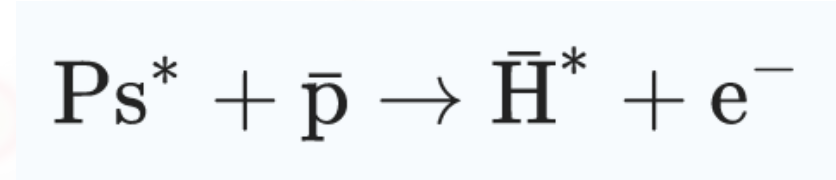
[N. Kuroda](#) , [S. Ulmer](#), [D. J. Murtagh](#), [S. Van Gorp](#), [Y. Nagata](#), [M. Diermaier](#), [S. Federmann](#), [M. Leali](#), [C. Malbrunot](#), [V. Mascagna](#), [O. Massiczek](#), [K. Michishio](#), [T. Mizutani](#), [A. Mohri](#), [H. Nagahama](#), [M. Ohtsuka](#), [B. Radics](#), [S. Sakurai](#), [C. Sauerzopf](#), [K. Suzuki](#), [M. Tajima](#), [H. A. Torii](#), [L. Venturelli](#), [B. Wu](#) , [... Y. Yamazaki](#)



Article | [Open access](#) | Published: 08 February 2021

Pulsed production of antihydrogen

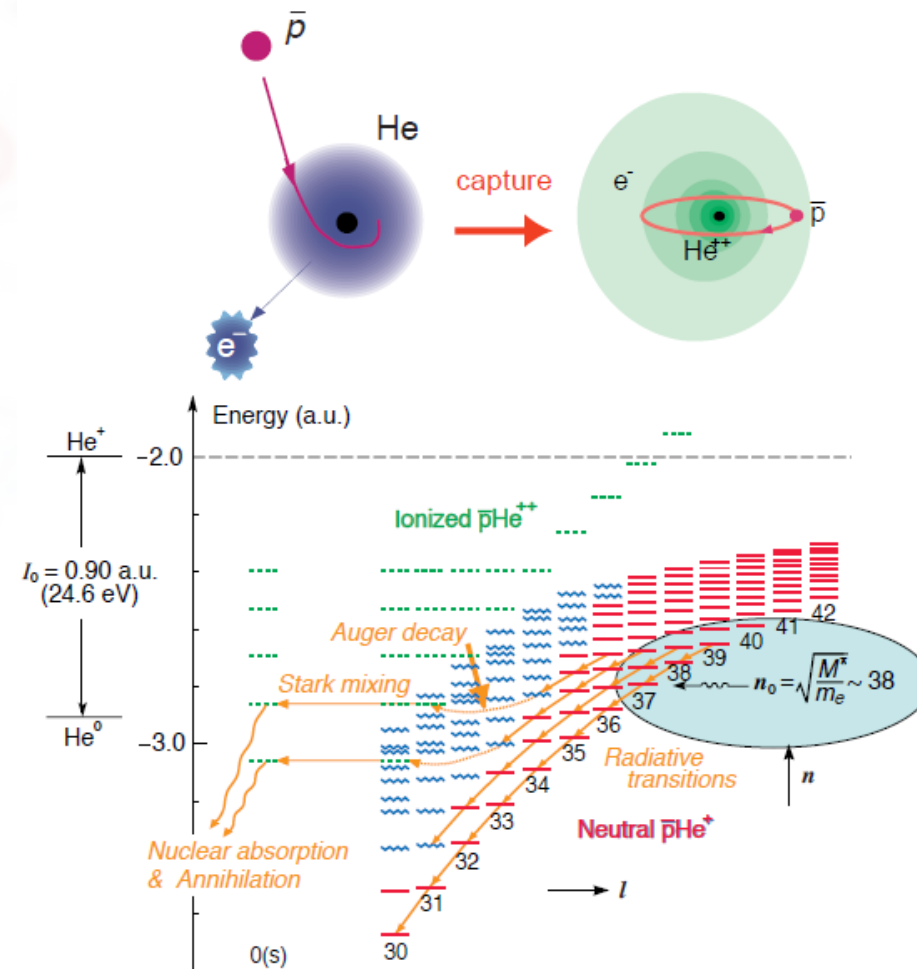
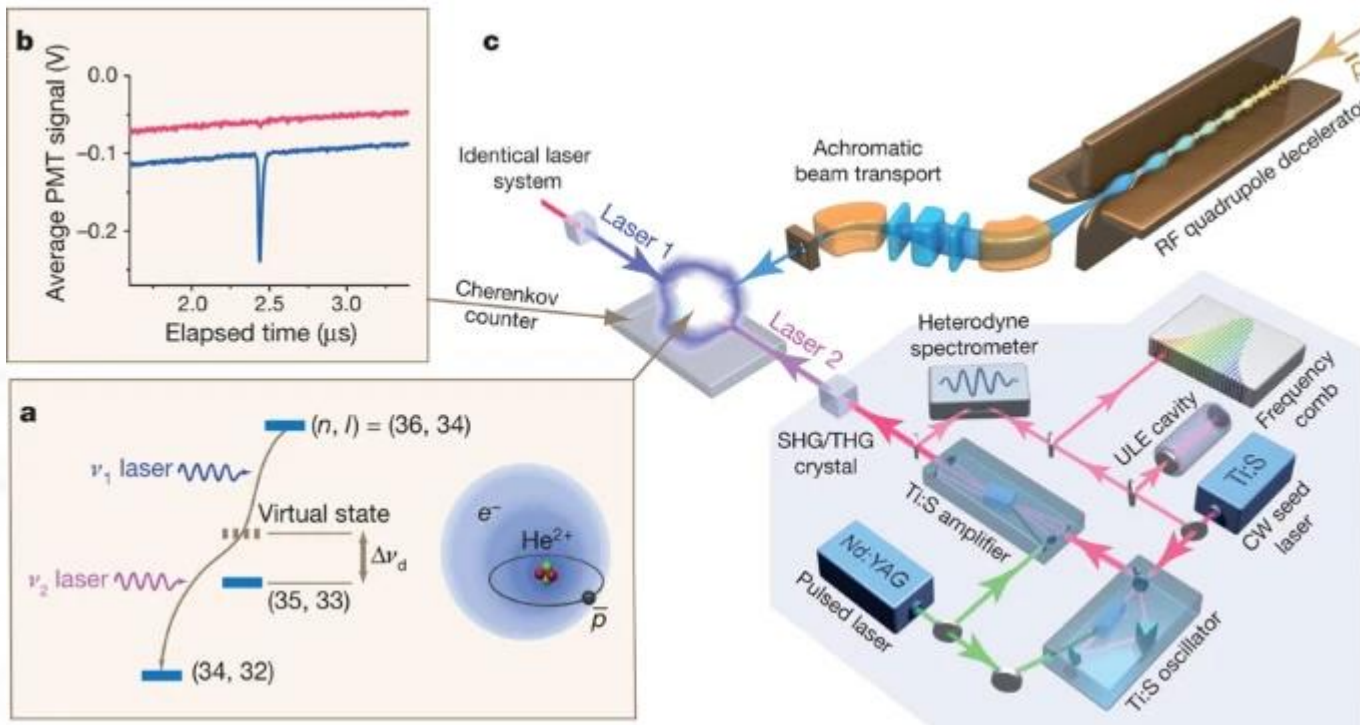
[Claude Amsler](#), [Massimiliano Antonello](#), [Alexander Belov](#), [Germano Bonomi](#), [Roberto Sennen Brusa](#), [Massimo Caccia](#), [Antoine Camper](#), [Ruggero Caravita](#), [Fabrizio Castelli](#), [Patrick Cheinet](#), [Daniel Comparat](#), [Giovanni Consolati](#), [Andrea Demetrio](#), [Lea Di Noto](#), [Michael Doser](#), [Mattia Fani](#), [Rafael Ferragut](#), [Julian Fesel](#), [Sebastian Gerber](#), [Marco Giammarchi](#), [Angela Gligorova](#), [Lisa Theresa Glöggler](#), [Francesco Guatieri](#), [Stefan Haider](#), ... [Nicola Zurlo](#) [+ Show authors](#)



TESTING CPT AND WEP AT THE ANTIMATTER FACTORY

Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio

Masaki Hori, Anna Sótér, Daniel Barna, Andreas Dax, Ryugo Hayano, Susanne Friedreich, Bertalan Juhász, Thomas Pask, Eberhard Widmann, Dezső Horváth, Luca Venturelli & Nicola Zurlo

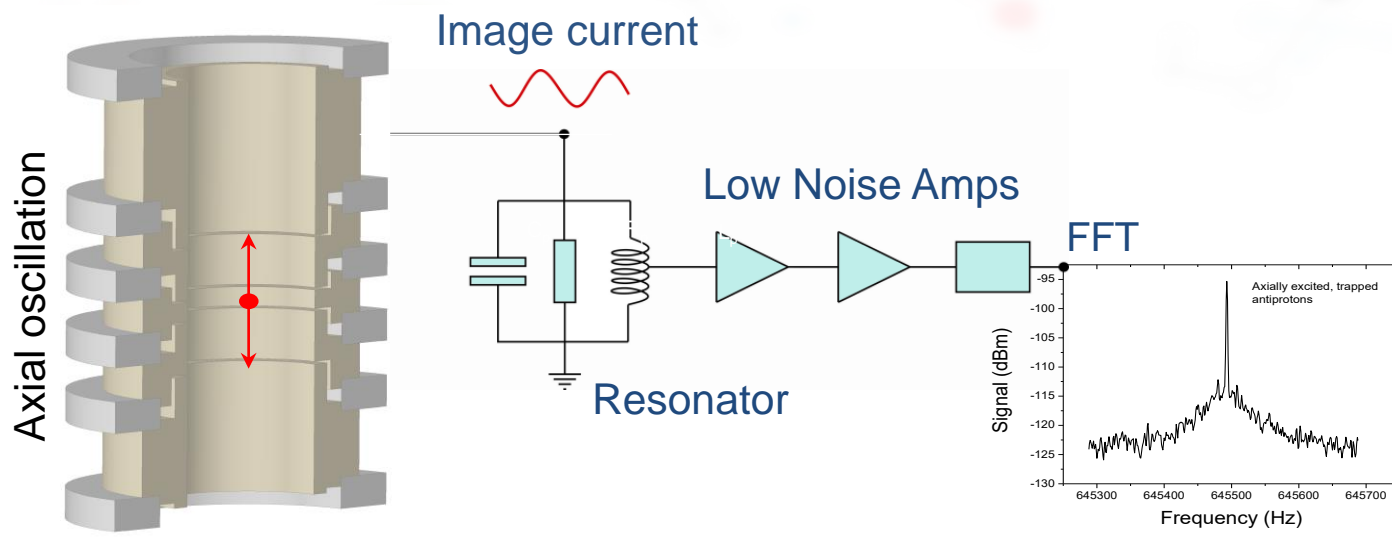


Measured frequencies agree with calculations at the $(2-5) \times 10^{-9}$ level

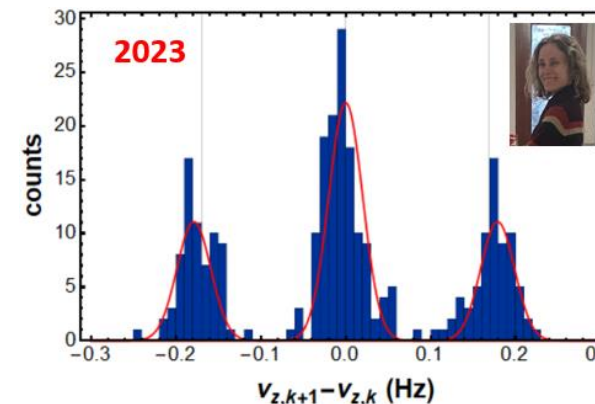
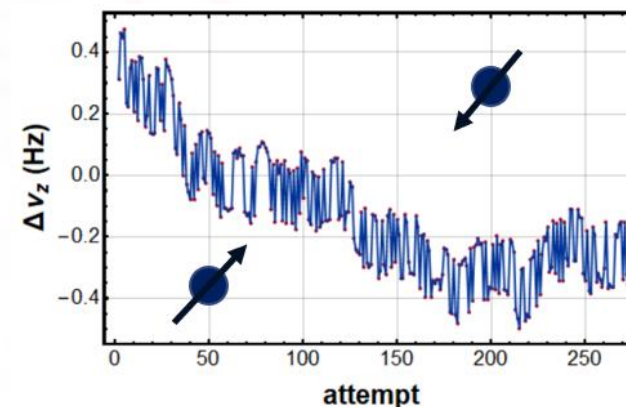
Letter | [Open access](#) | [Published: 12 August 2015](#)

High-precision comparison of the antiproton-to-proton charge-to-mass ratio

[S. Ulmer](#) , [C. Smorra](#), [A. Mooser](#), [K. Franke](#), [H. Nagahama](#), [G. Schneider](#), [T. Higuchi](#), [S. Van Gorp](#), [K. Blaum](#),
[Y. Matsuda](#), [W. Quint](#), [J. Walz](#) & [Y. Yamazaki](#)



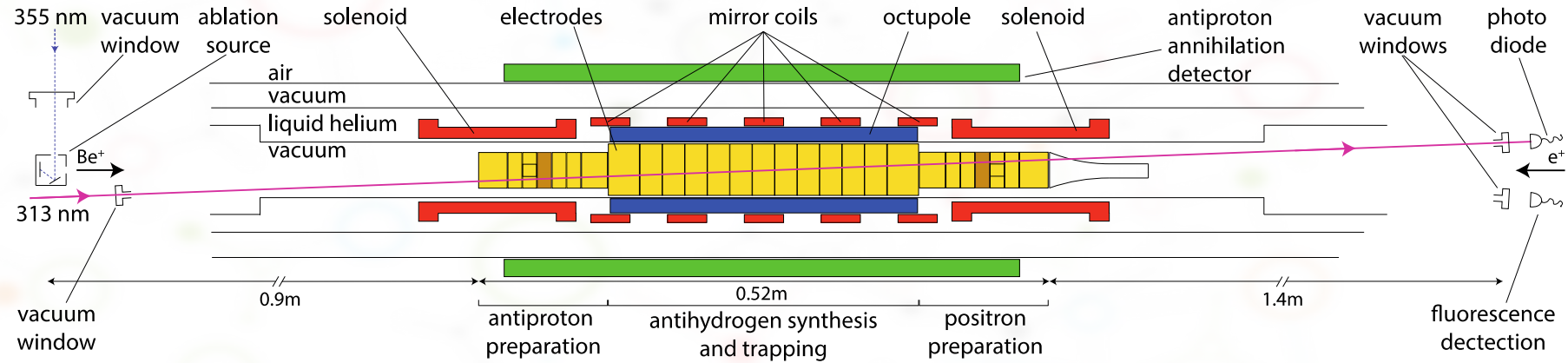
Quantum Jump Spectroscopy



Thousandfold improvement in the measured antiproton mass

G. Gabrielse, X. Fei, L. A. Orozco, R. L. Tjoelker, J. Haas, H. Kalinowsky, T. A. Trainor, and W. Kells
 Phys. Rev. Lett. **65**, 1317 – Published 10 September 1990

CPT test at 1.7×10^{-12}



Letter | [Open access](#) | Published: 19 December 2016

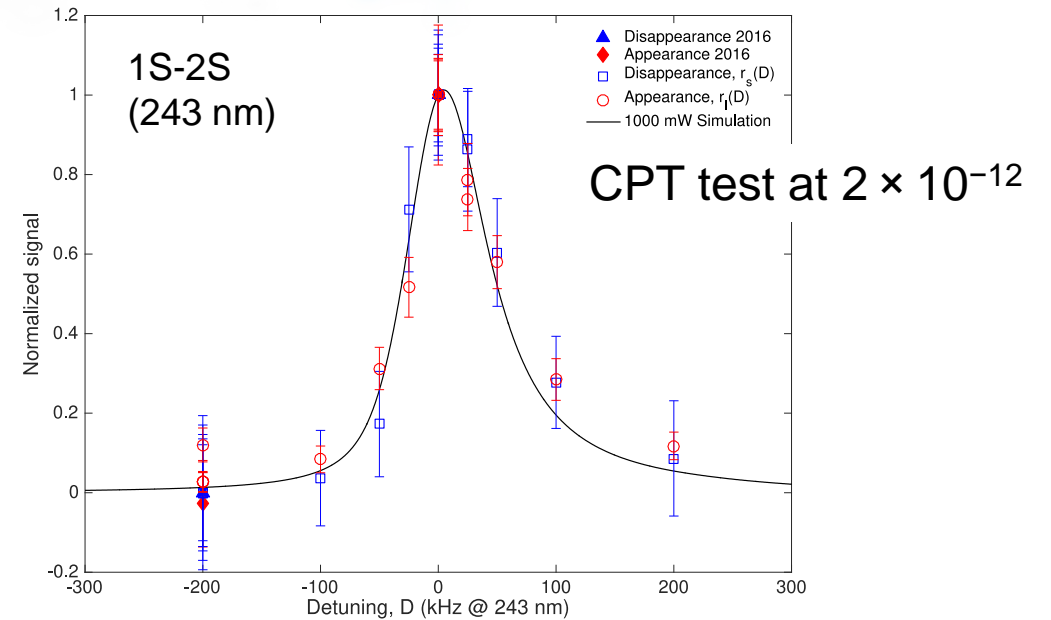
Observation of the 1S–2S transition in trapped antihydrogen

[M. Ahmadi](#), [B. X. R. Alves](#), [C. J. Baker](#), [W. Bertsche](#), [E. Butler](#), [A. Capra](#), [C. Carruth](#), [C. L. Cesar](#), [M. Charlton](#), [S. Cohen](#), [R. Collister](#), [S. Eriksson](#), [A. Evans](#), [N. Evetts](#), [J. Fajans](#), [T. Friesen](#), [M. C. Fujiwara](#), [D. R. Gill](#), [A. Gutierrez](#), [J. S. Hangst](#) , [W. N. Hardy](#), [M. E. Hayden](#), [C. A. Isaac](#), [A. Ishida](#), ... [J. S. Wurtele](#) [+ Show authors](#)

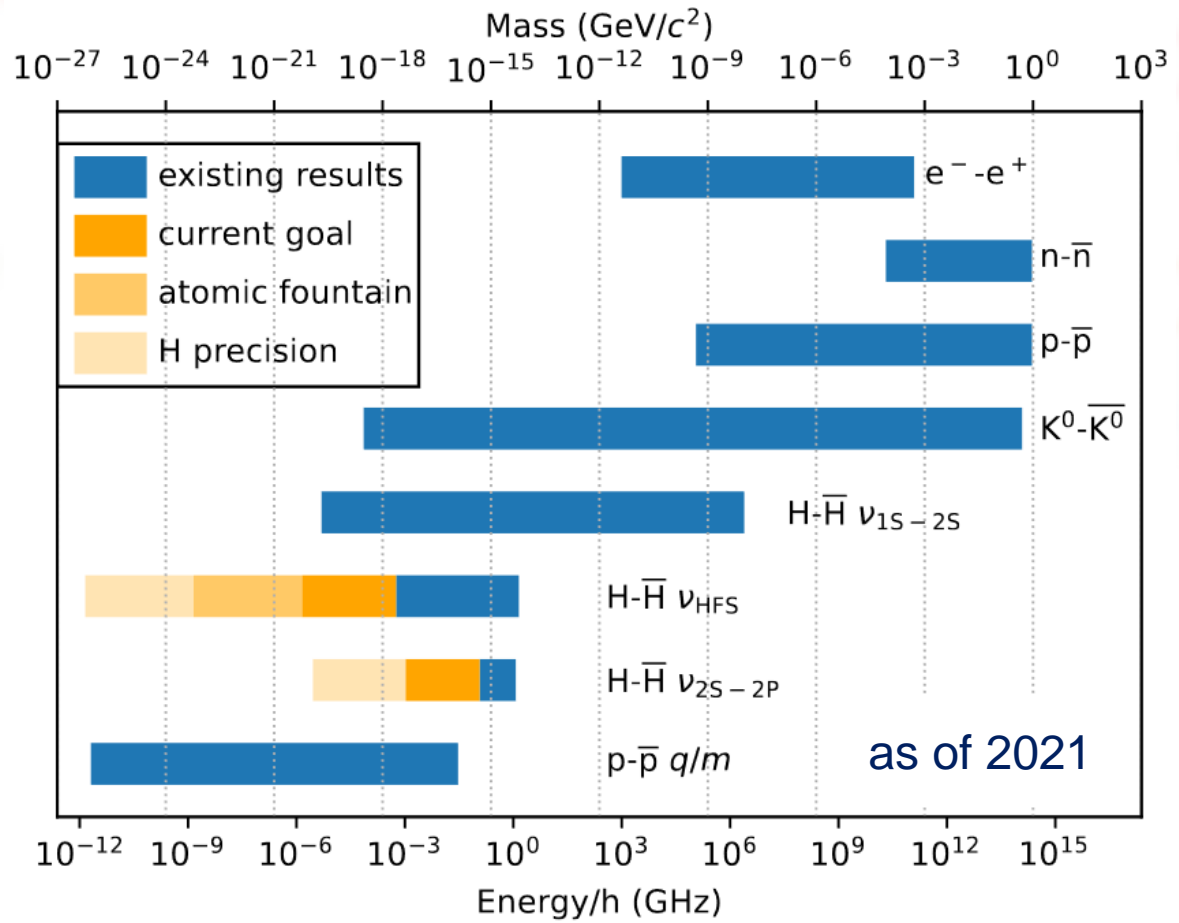
Letter | [Open access](#) | Published: 04 April 2018

Characterization of the 1S–2S transition in antihydrogen

[M. Ahmadi](#), [B. X. R. Alves](#), [C. J. Baker](#), [W. Bertsche](#), [A. Capra](#), [C. Carruth](#), [C. L. Cesar](#), [M. Charlton](#), [S. Cohen](#), [R. Collister](#), [S. Eriksson](#), [A. Evans](#), [N. Evetts](#), [J. Fajans](#), [T. Friesen](#), [M. C. Fujiwara](#), [D. R. Gill](#), [J. S. Hangst](#) , [W. N. Hardy](#), [M. E. Hayden](#), [C. A. Isaac](#), [M. A. Johnson](#), [J. M. Jones](#), [S. A. Jones](#), ... [J. S. Wurtele](#) [+ Show authors](#)



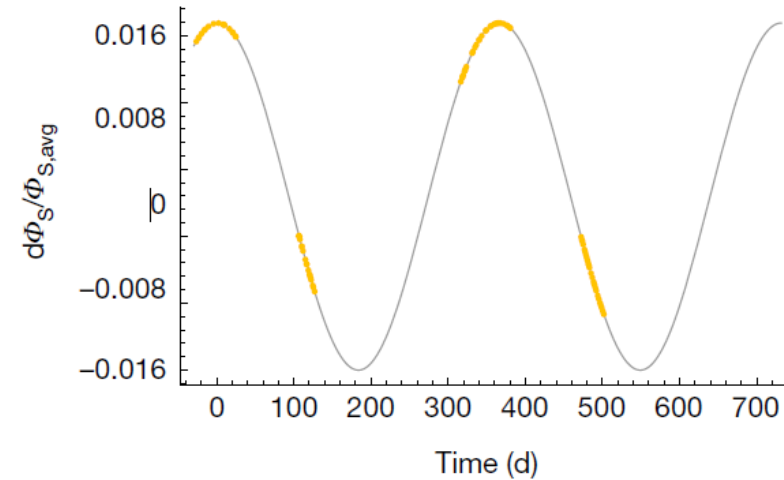
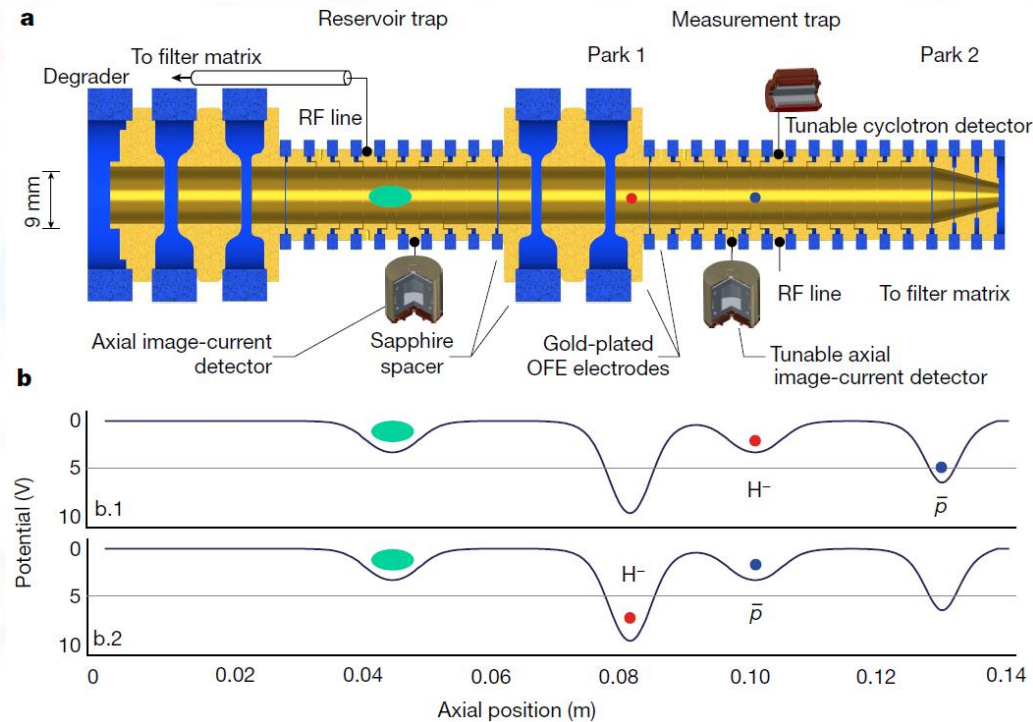
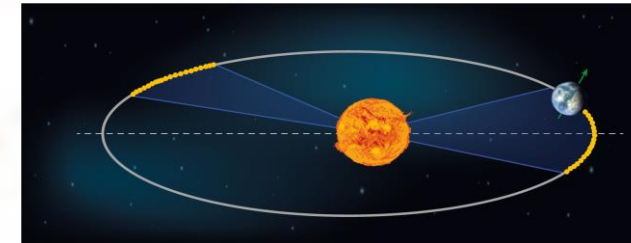
Overview on the direct tests of the CPT symmetry



Eberhard Widmann, *Hyperfine spectroscopy of antihydrogen, hydrogen, and deuterium*, Phys. Part. Nucl. **53** (2022)

Article

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



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

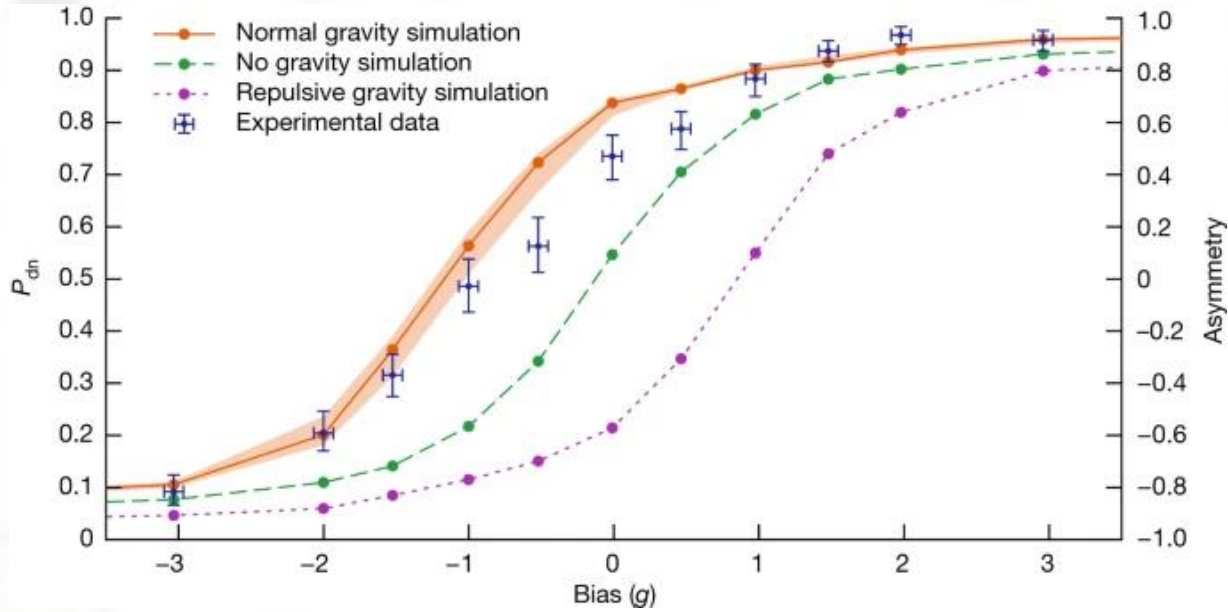
$$O(t) = D_p (1 - \epsilon^2) / [1 + \epsilon \cos((2\pi/t_{sid})t)].$$

$$|\alpha_{g,D} - 1| < 0.03.$$

Gravitational redshift comparison with hydrogen/antihydrogen

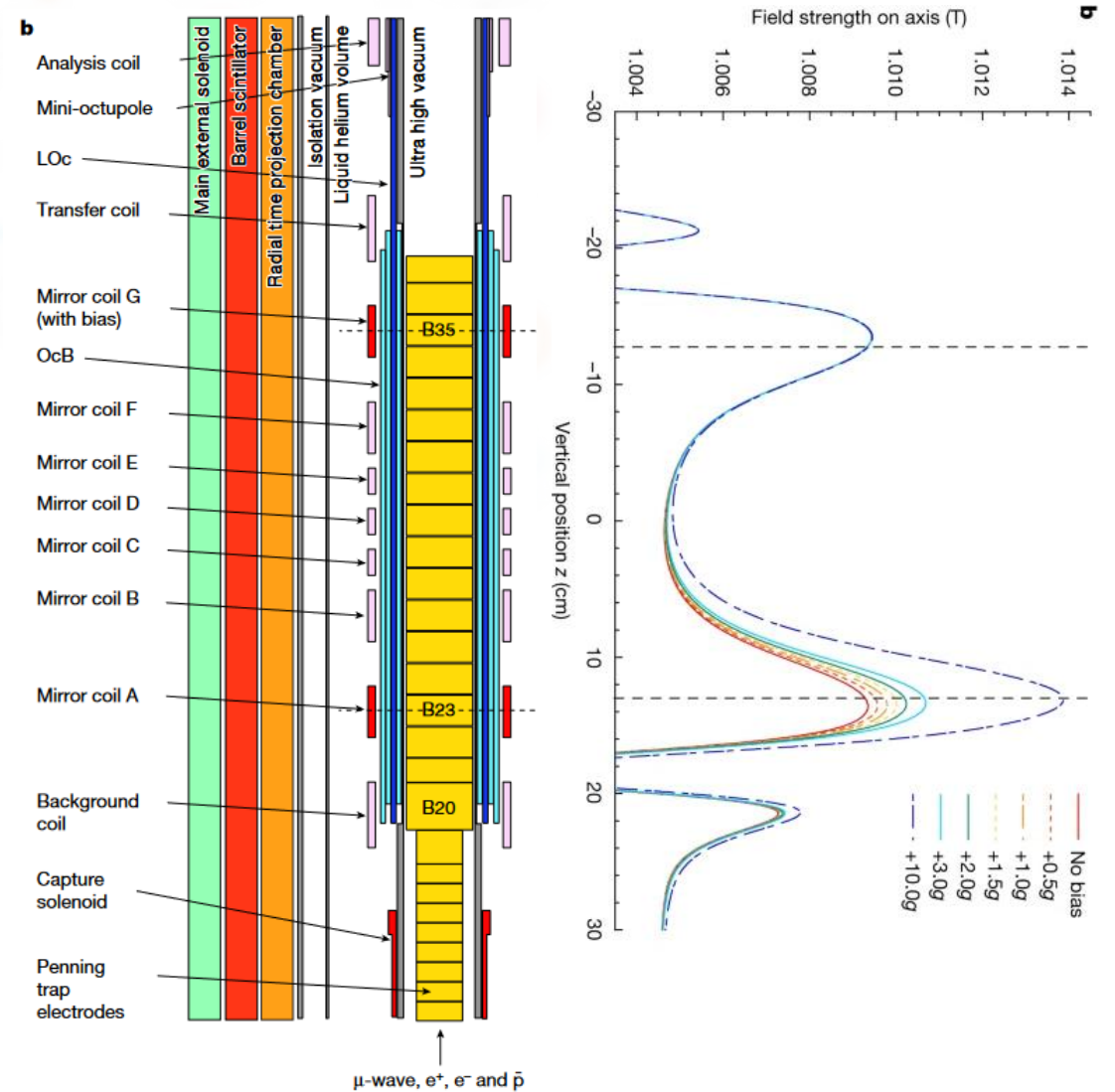
Article

Observation of the effect of gravity on the motion of antimatter



$$a_g = (0.75 \pm 0.13_{stat+sys} \pm 0.16_{sim}) g$$

Excluded a positive sign of g



FUTURE PROSPECTS AND NEW TECHNOLOGIES

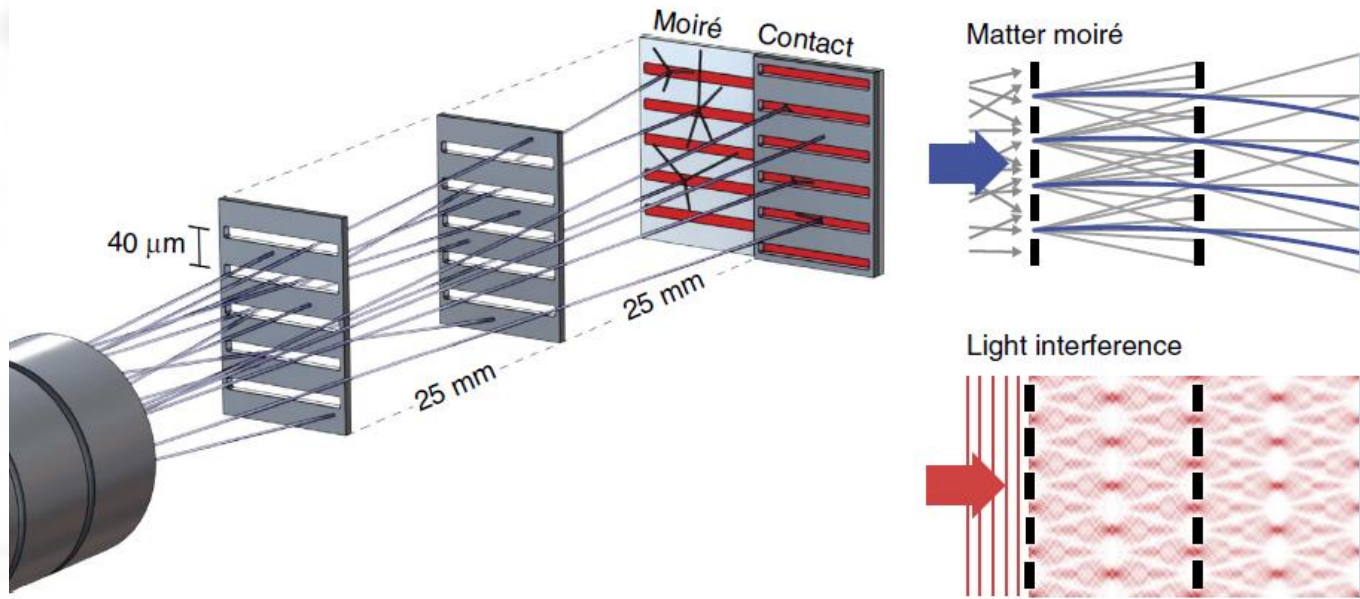
ARTICLE

Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014

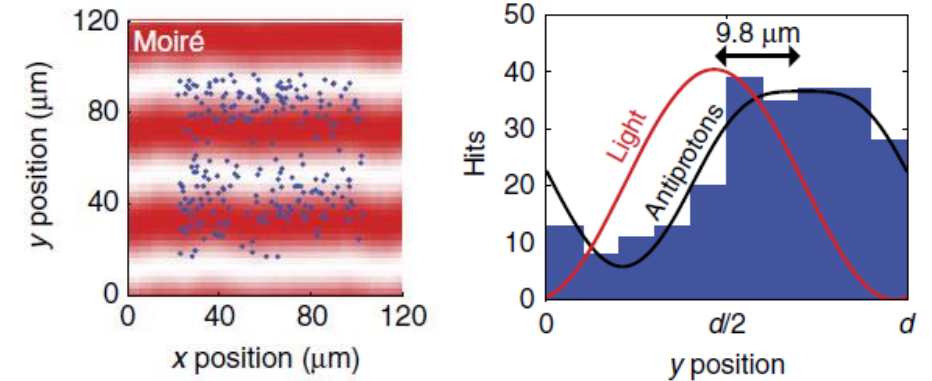
DOI: 10.1038/ncomms5538

OPEN

A moiré deflectometer for antimatter



Tested with 10-50 keV antiprotons



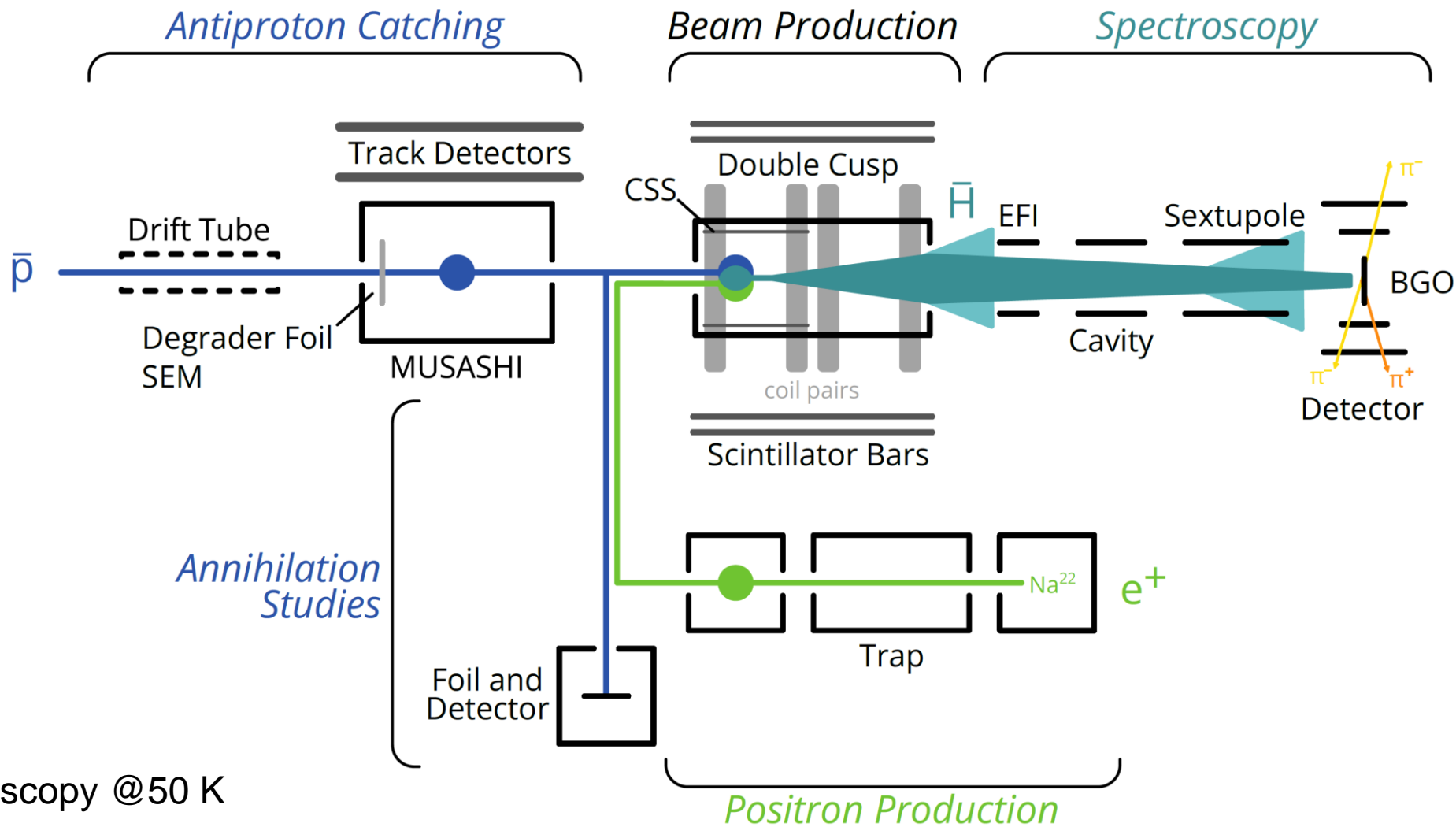
$$y = gt^2$$

$$\delta g = t^{-2} \delta y - 2gt^{-1} \delta t$$

$$\begin{cases} t = 1 \text{ ms} \\ \delta g/g = 10\% \end{cases} \rightarrow \begin{cases} \delta y \ll 1 \mu\text{m} \\ \delta t \ll 50 \mu\text{s} \end{cases}$$

- Combined moiré deflectometer and Talbot-Lau interferometer
- High resolution detector referenced with light patterns
- Time-of-flight knowledge from external scintillator detectors

ASACUSA: towards hyperfine spectroscopy of ground state antihydrogen

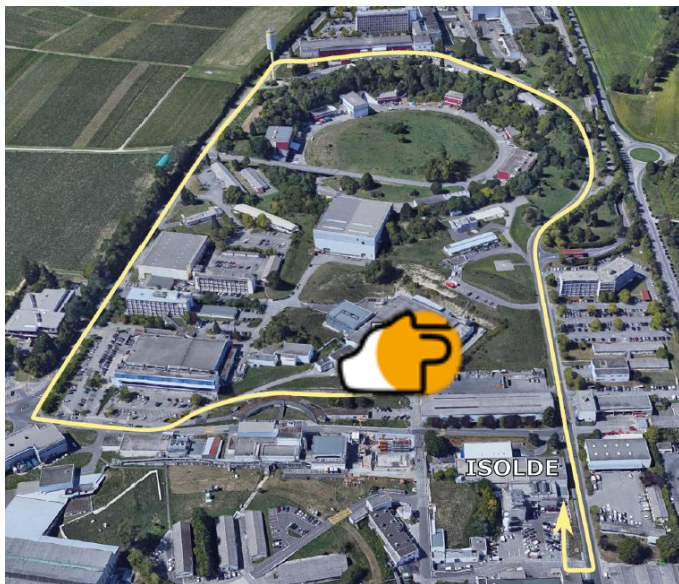


Rabi spectroscopy @50 K

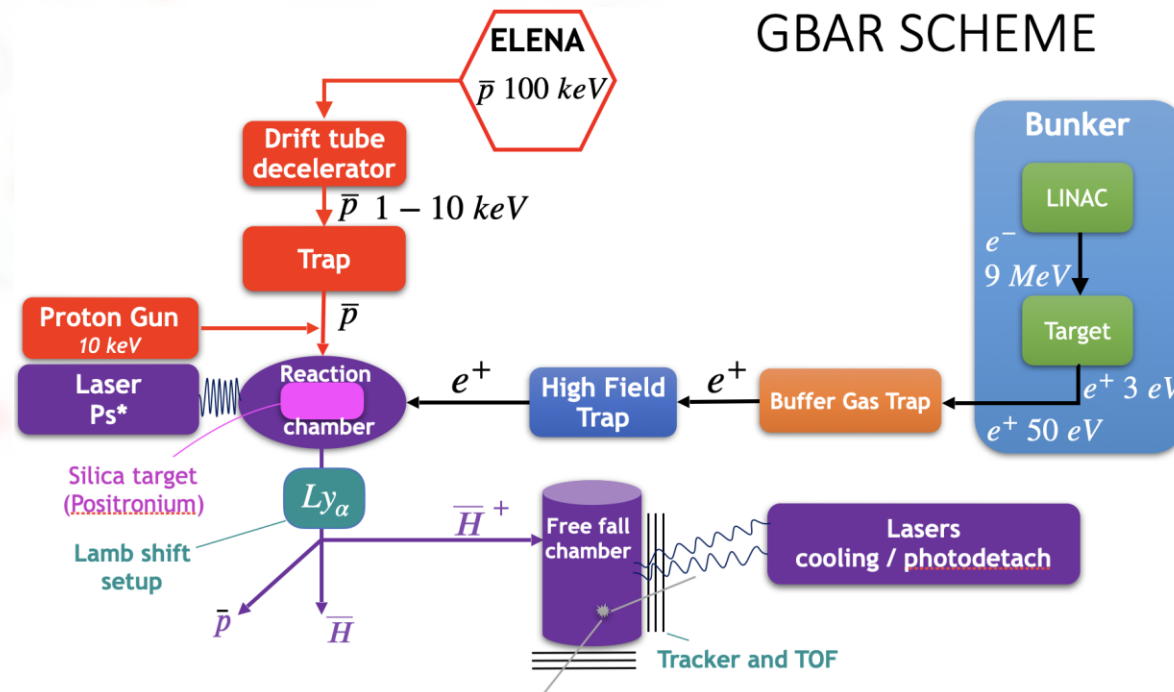
Line width ~10 kHz: precision ~ppm

PUMA and BASE-STEP

- Transportable Penning traps for antiprotons
- Higher precision measurements of the antiproton charge-to-mass radius and momentum
- Nuclear physics at ISOLDE with antiprotons

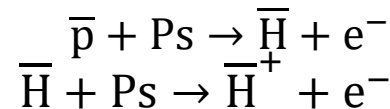


GBAR SCHEME

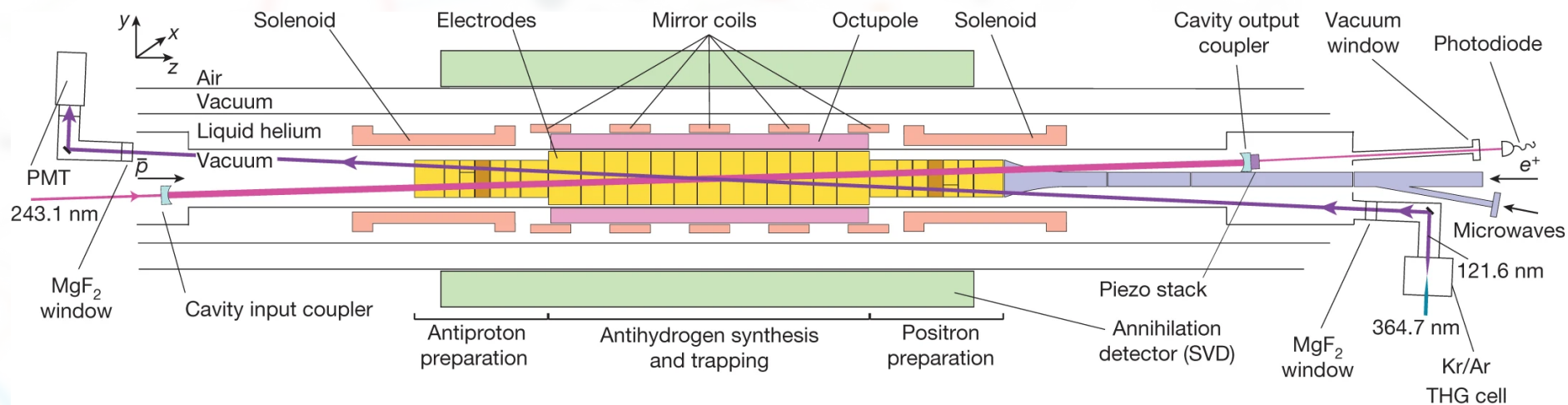


GBAR

- Produce keV beams of antihydrogen atoms and ion



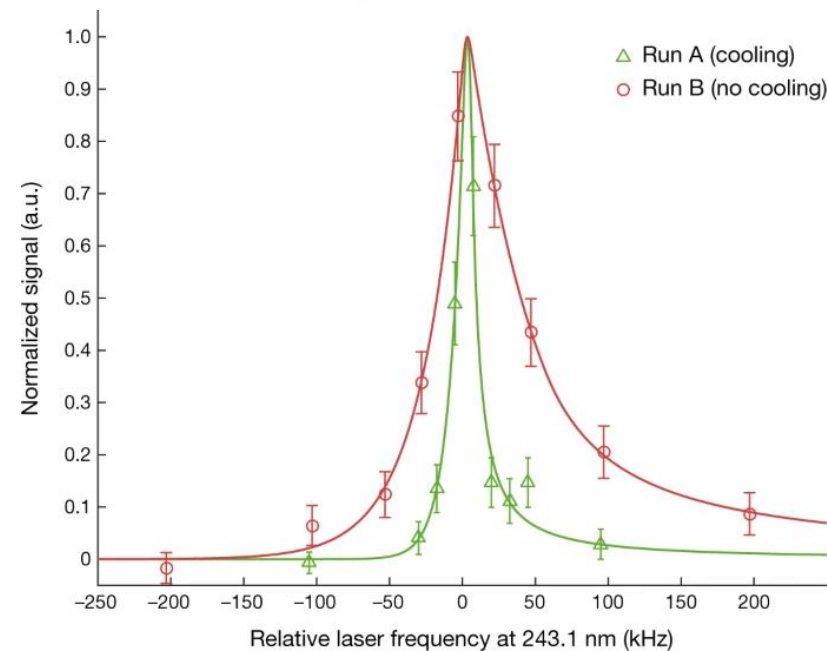
- Cool $\bar{\text{H}}^+$ to $10 \mu\text{K}$ and photo detach
- Measure $\bar{\text{H}}$ free fall



Article | [Open access](#) | [Published: 31 March 2021](#)

Laser cooling of antihydrogen atoms

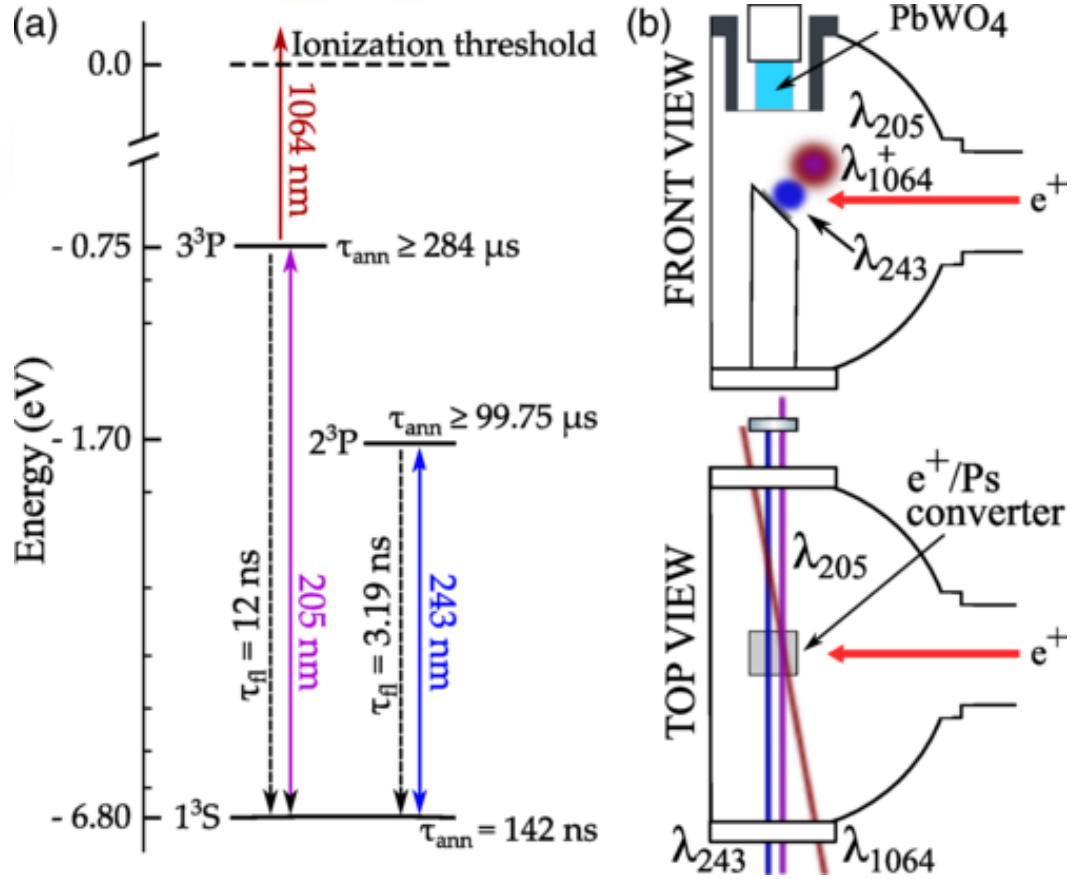
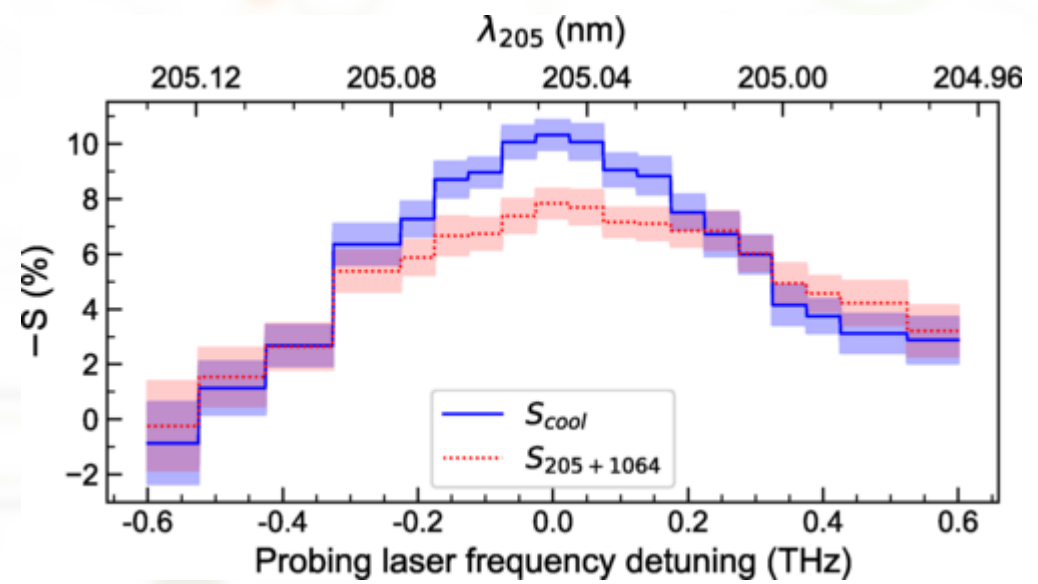
[C. J. Baker](#), [W. Bertsche](#), [A. Capra](#), [C. Carruth](#), [C. L. Cesar](#), [M. Charlton](#), [A. Christensen](#), [R. Collister](#), [A. Cridland Mathad](#), [S. Eriksson](#), [A. Evans](#), [N. Evetts](#), [J. Fajans](#), [T. Friesen](#), [M. C. Fujiwara](#) , [D. R. Gill](#), [P. Grandemange](#), [P. Granum](#), [J. S. Hangst](#) , [W. N. Hardy](#), [M. E. Hayden](#), [D. Hodgkinson](#), [E. Hunter](#), [C. A. Isaac](#)



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Positronium Laser Cooling via the 1^3S-2^3P Transition with a Broadband Laser Pulse

L. T. Glöggler *et al.* (AEgIS Collaboration)
 Phys. Rev. Lett. **132**, 083402 – Published 22 February 2024



Milestone towards Bose-Einstein condensation of antimatter and stimulated gamma-ray sources

- The Antimatter Factory is a vibrant community of 7 collaborations and > 300 physicists
- Aiming at performing tests of the CPT symmetry and the Weak Equivalence Principle
- Working primarily with antiprotons, positrons, positronium and antihydrogen

- Many progresses in the last 20 years
 - Development of techniques to manipulate cold antiparticles
 - Many tests of CPT with increasing precision and broad energy range, exclude violations at 10^{-12} level
 - Indirect tests of the Weak Equivalence Principle exclude violations at 3 % level
 - Direct tests of the Weak Equivalence Principle exclude a different sign of gravity

New cooling technologies at the horizon to enhance the accuracy of existing experiments



Thank you for your attention!



Istituto Nazionale di Fisica Nucleare

