The CERN Antimatter Factory

Testing the Equivalence Principle, the CPT symmetry, and beyond

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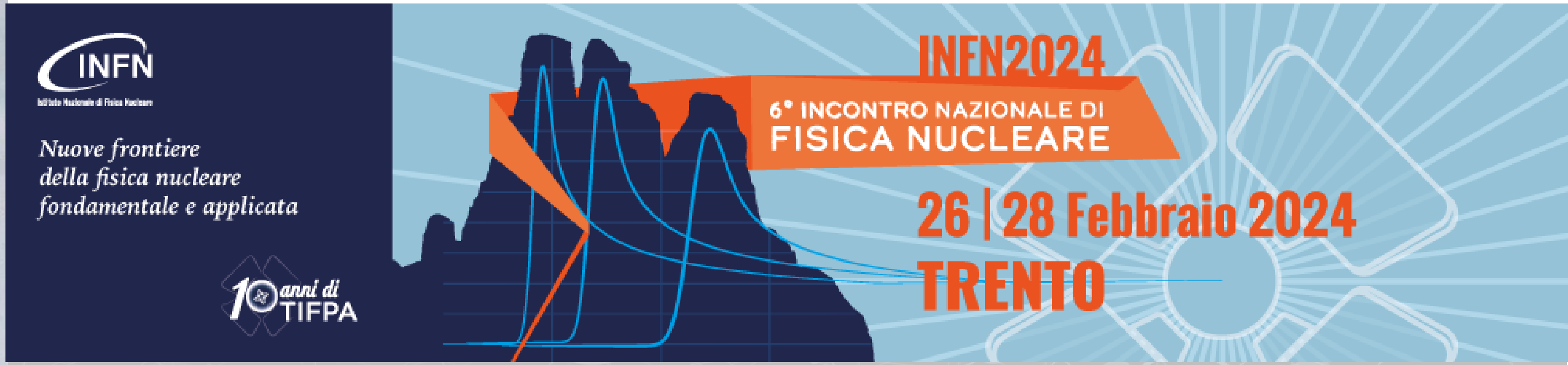
*INFN – TIFPA, Trento (IT)



Motivation 1: testing the CPT symmetry

	Interactions		
	Strong	EM	Weak
P	yes	yes	no
C	yes	yes	no
CP (or T)	yes	yes	~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) ~

Clifford M. Will, *Theory and experiment in gravitational physics* (1993)

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

Hypotetical interactions violating the Equivalence Principle:

attractive/repulsive vector gravitons — attractive scalar gravitons

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

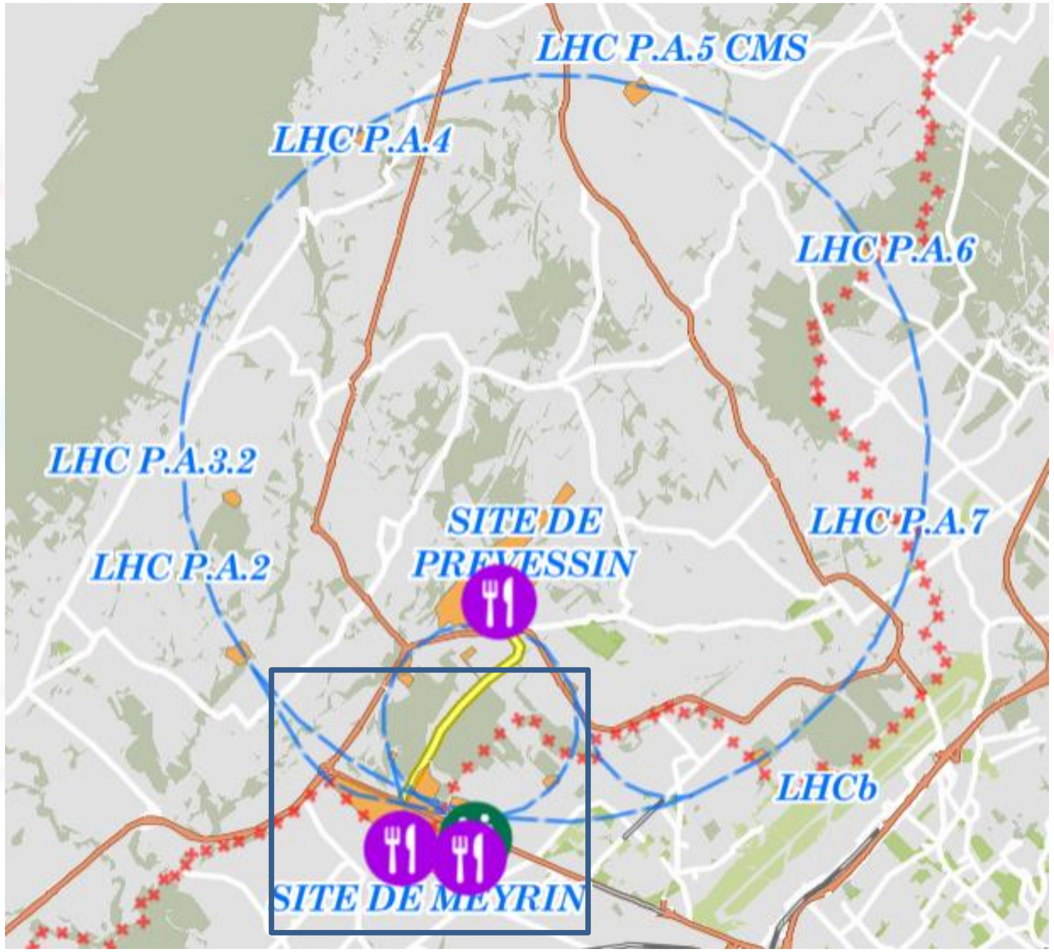
with cancellation effects occuring in matter experiments if a ~ b and v ~ s

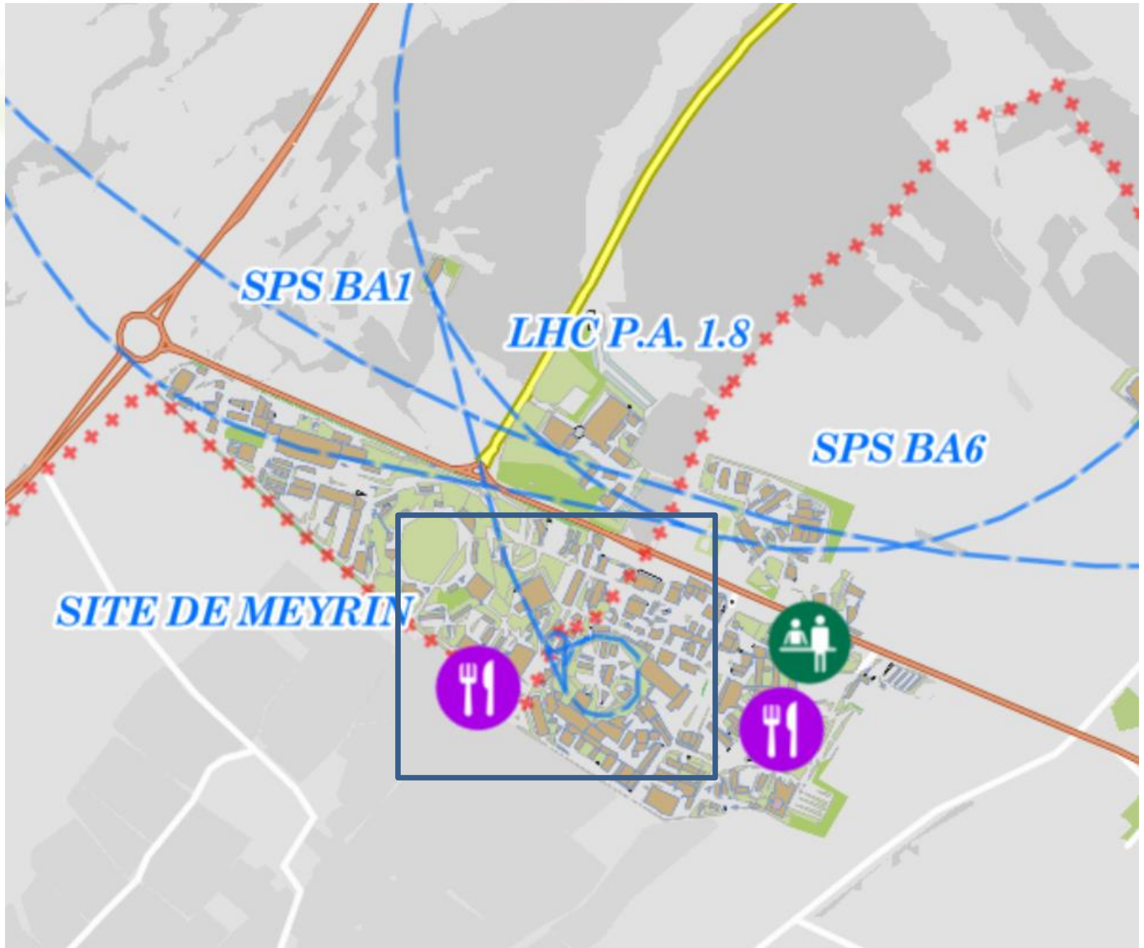
Theoretical considerations on different gravitational couplings of antimatter

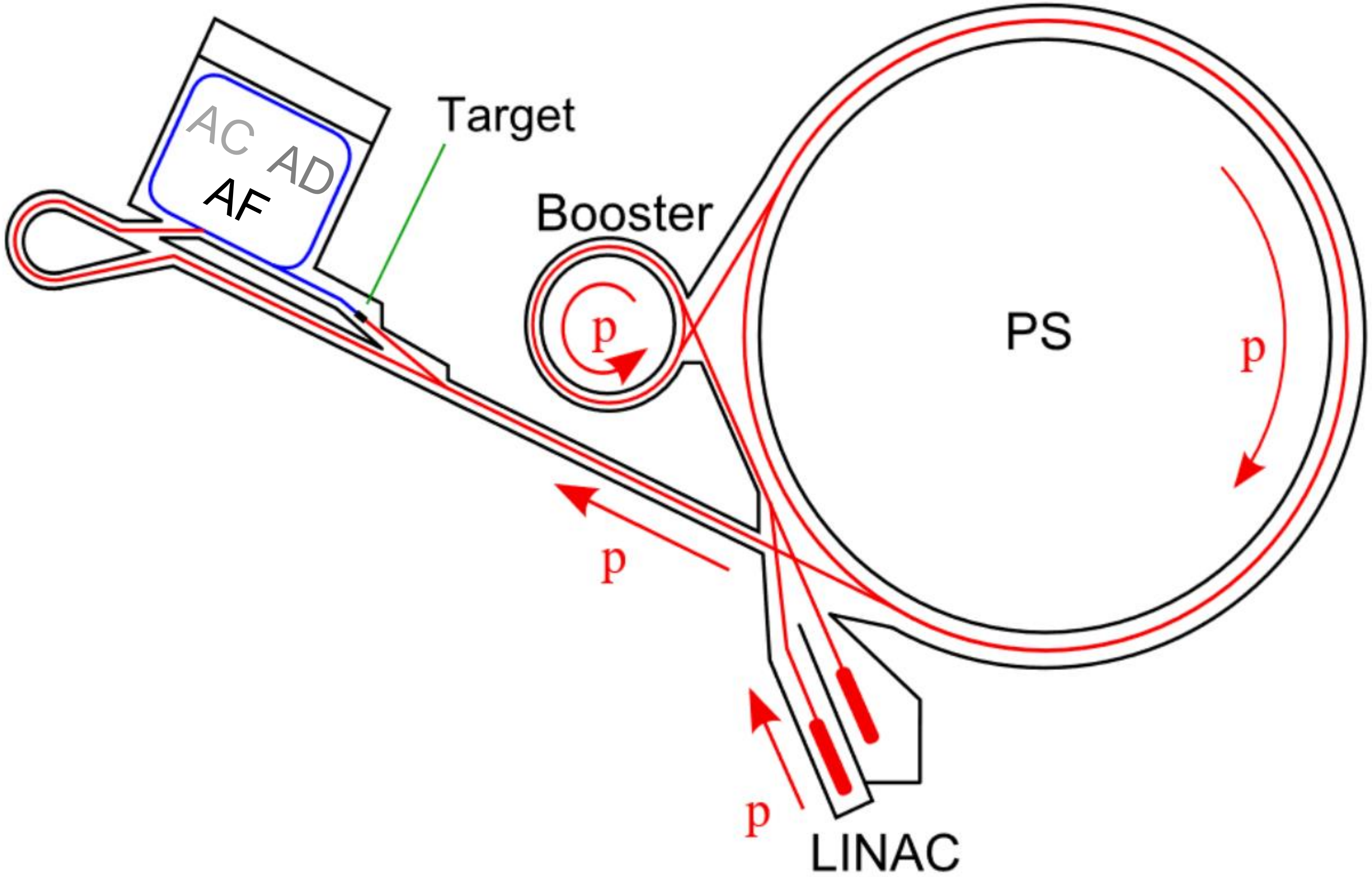
1. *Anti-gravity would violate conservation of energy* (Morrison's argument)
2. *Standard Model and gravitational repulsion are incompatible at tree level* (Schiff/Dvali's argument)
3. *Antigravity would cause an unobserved CP violation in kaons oscillations* (Good's argument)
4. *No way to keep EP valid 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






Target
AC
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p
p
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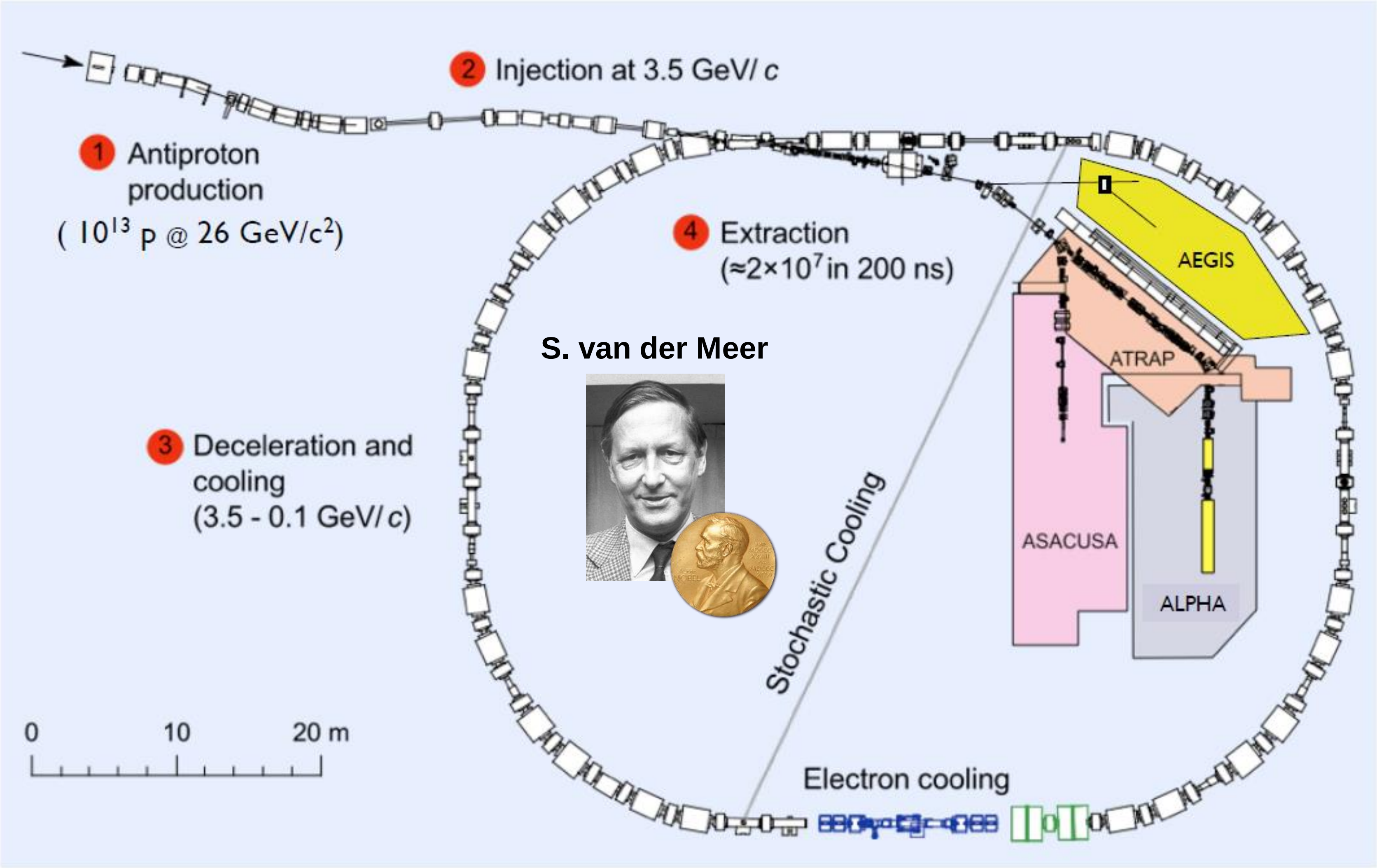
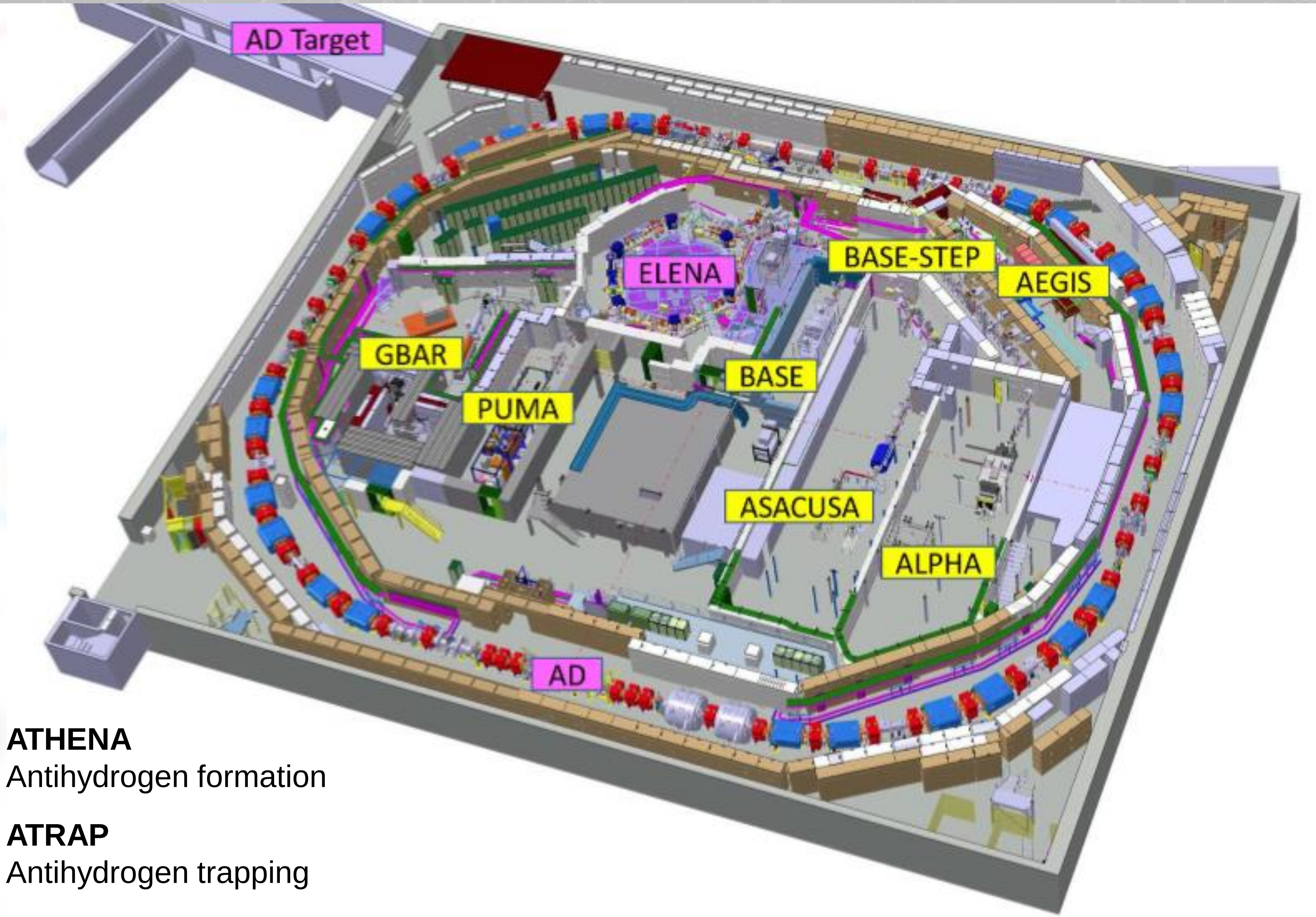
Cold Antiprotons in the Laboratory



S. van der Meer

The Antimatter Factory, as it looks today



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

Completed

ATHENA
Antihydrogen formation

ATRAP
Antihydrogen trapping

ACE
Antiproton interaction with cells

Achievements in the Antimatter Factory

2002

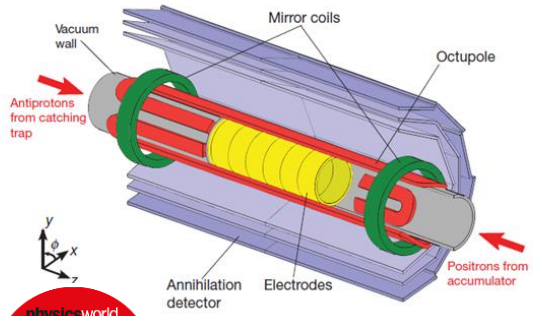
letters to nature

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. Macri*, 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#

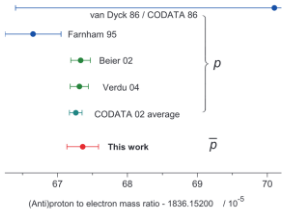
2010

Trapped antihydrogren



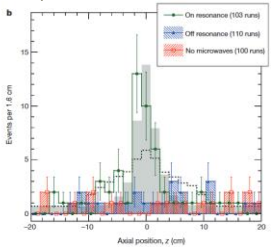
physicsworld TOP 10 BREAKTHROUGH 2010

2011



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

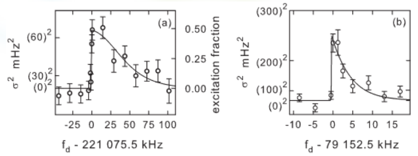
2012



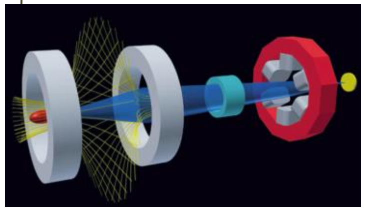
Antihydrogen RF spectroscopy

2013

5ppm pbar moment

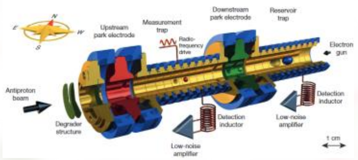


2014



Antihydrogen atoms beam production

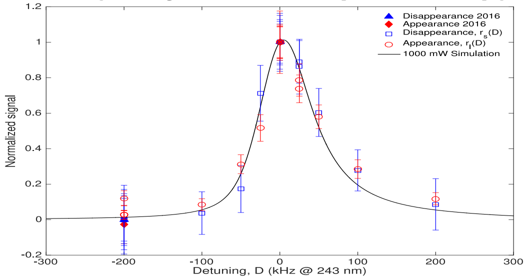
2015



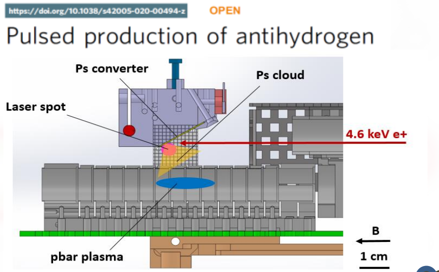
Antiprotons q/m 69 ppt

2017

Antihydrogren 1S-2S spectroscopy



2019



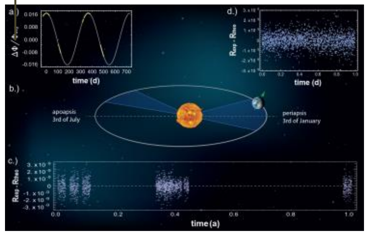
2022

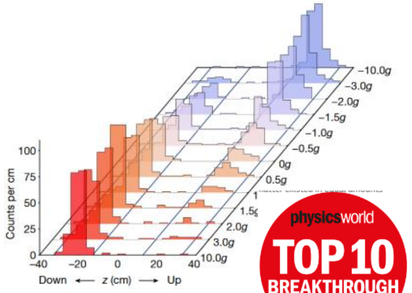
physicsworld TOP 10 BREAKTHROUGH 2022

Laser cooled antihydrogren
Sympathetically cooled protons

2023

First WEP tests



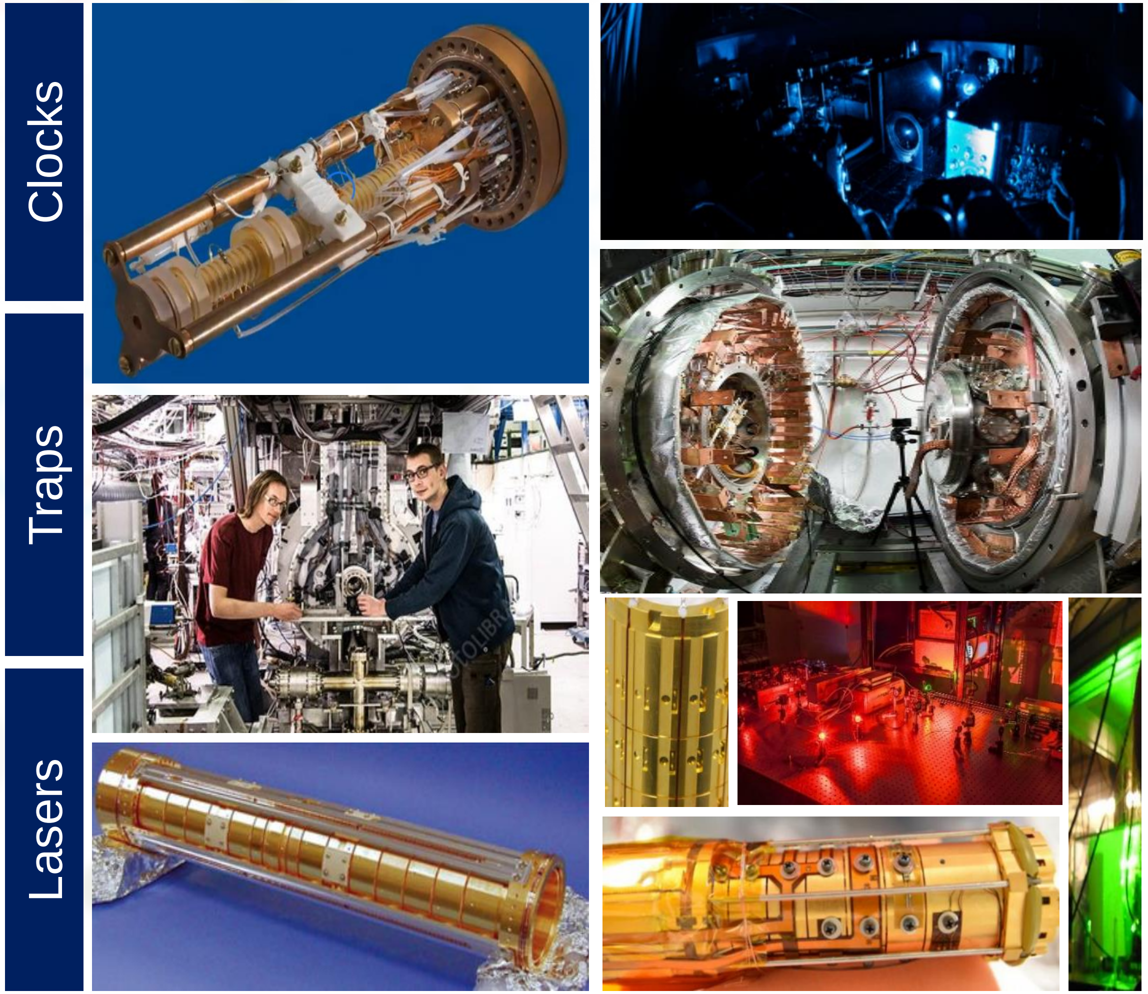


physicsworld TOP 10 BREAKTHROUGH 2023

2024

Ps laser cooling

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.

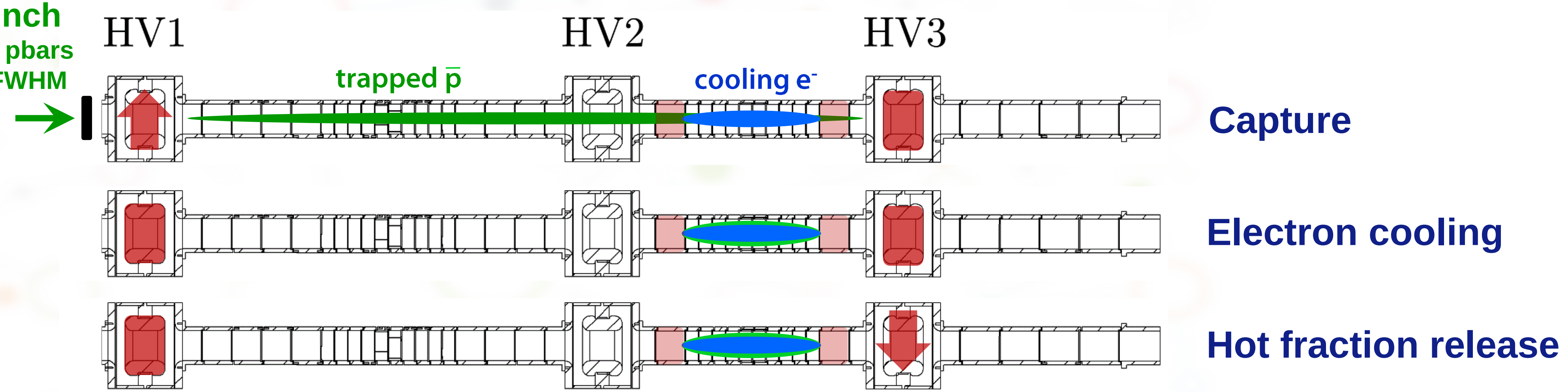
Mixture of expertises from

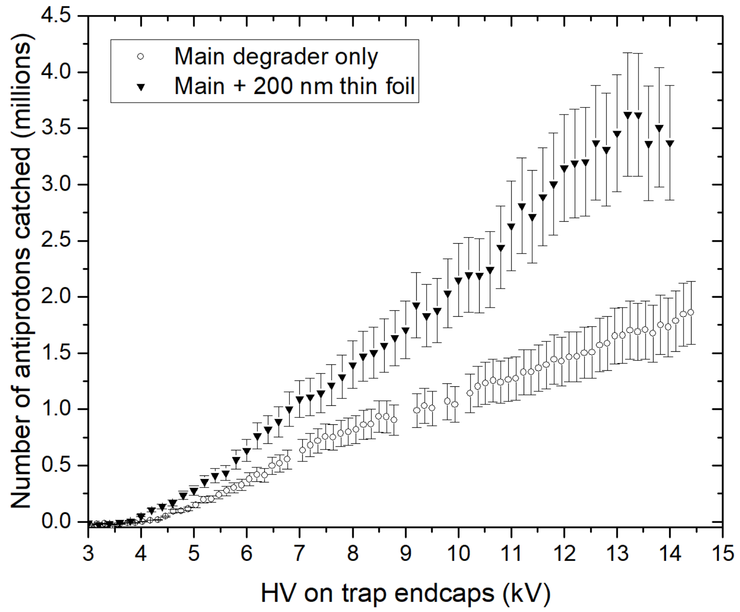
- Accelerator experiments
- Non-neutral plasmas
- Hybrid neutral and charged particle traps
- Ultra-stable quantum spectroscopy lasers
- Pulsed high-power lasers
- Ultra-high vacuum and superconductors
- Particle Physics detectors

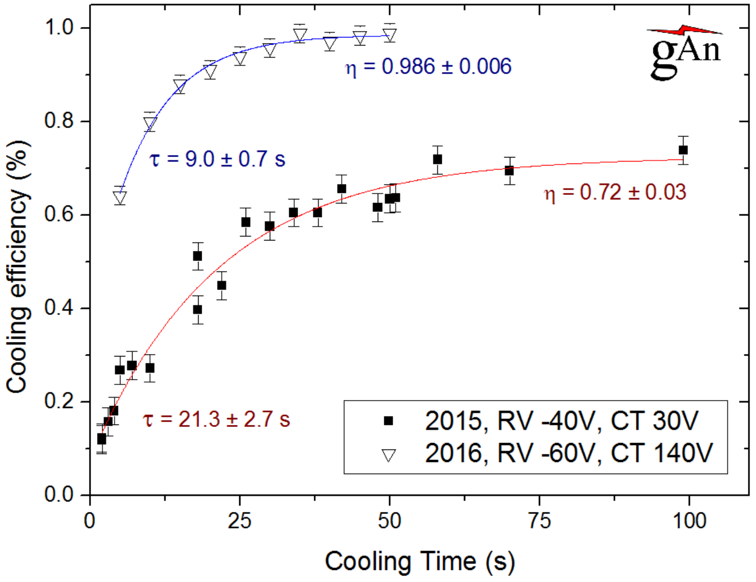
Non-observational operative experiments: we are our own «machinists»

Standards: antiproton catching and cooling

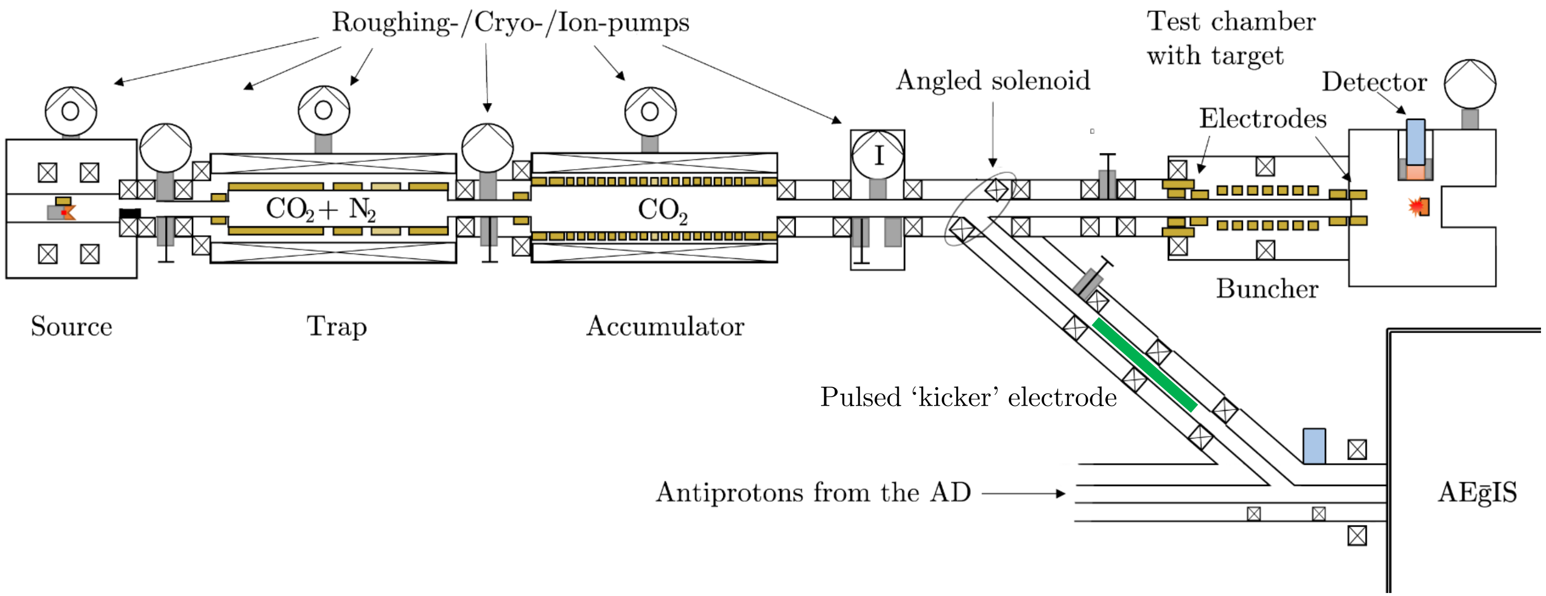
AD bunch
3.0 · 10^7 pbars
100 ns FWHM





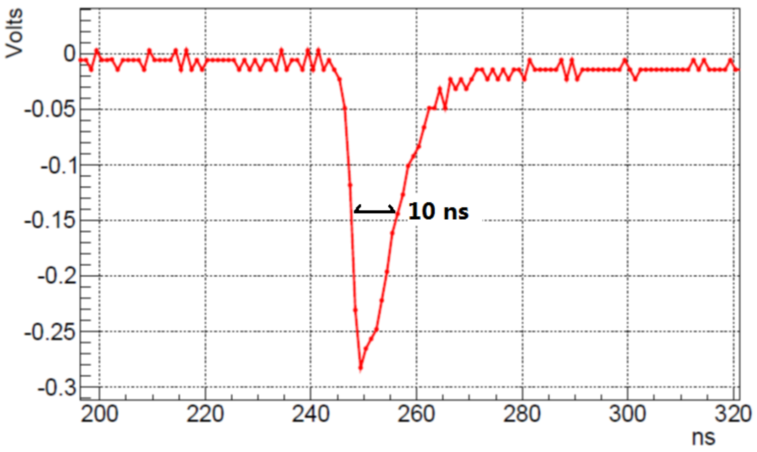


Standards: positron accumulation and transfer



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^+ / 0.17s)
- 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



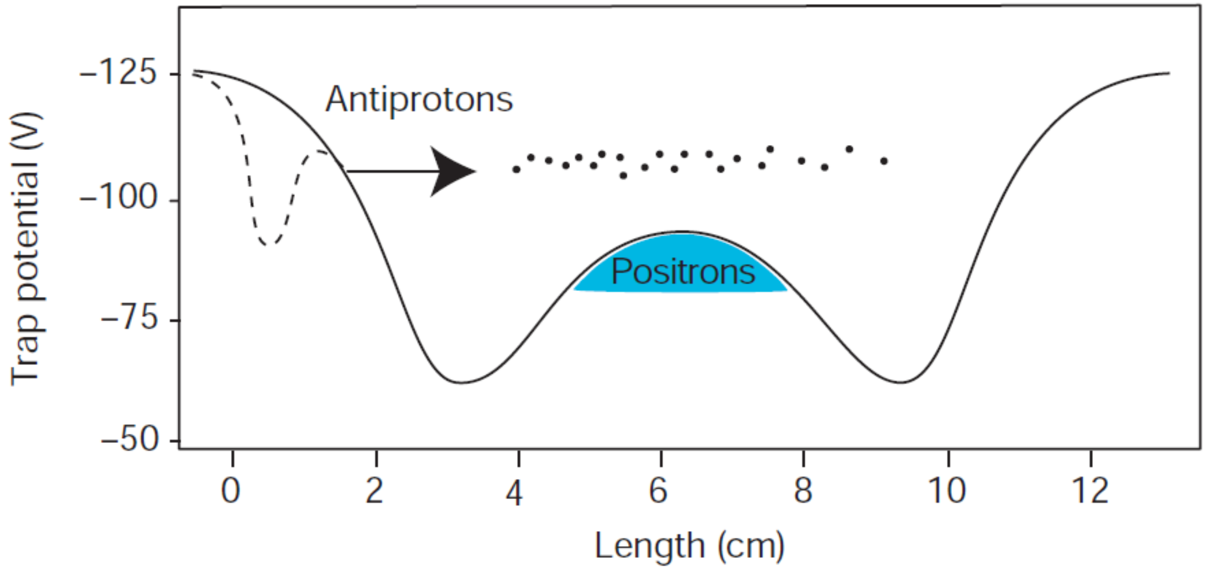
ATHENA and ATRAP: cold antihydrogen production

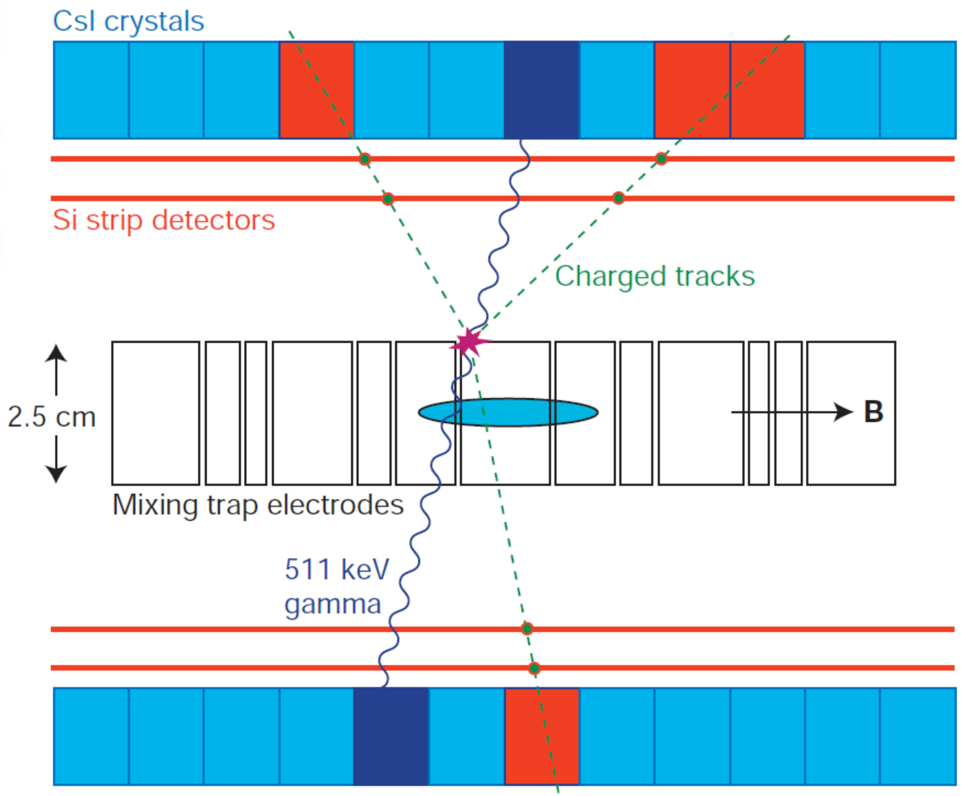
Letter | Published: 18 September 2002

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. Holzscheiter, L. V. Jørgensen, V. Lagomarsino, R. Landua, D. Lindelöf, E. Lodi Rizzini, ... D. P. van der Werf + Show authors

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





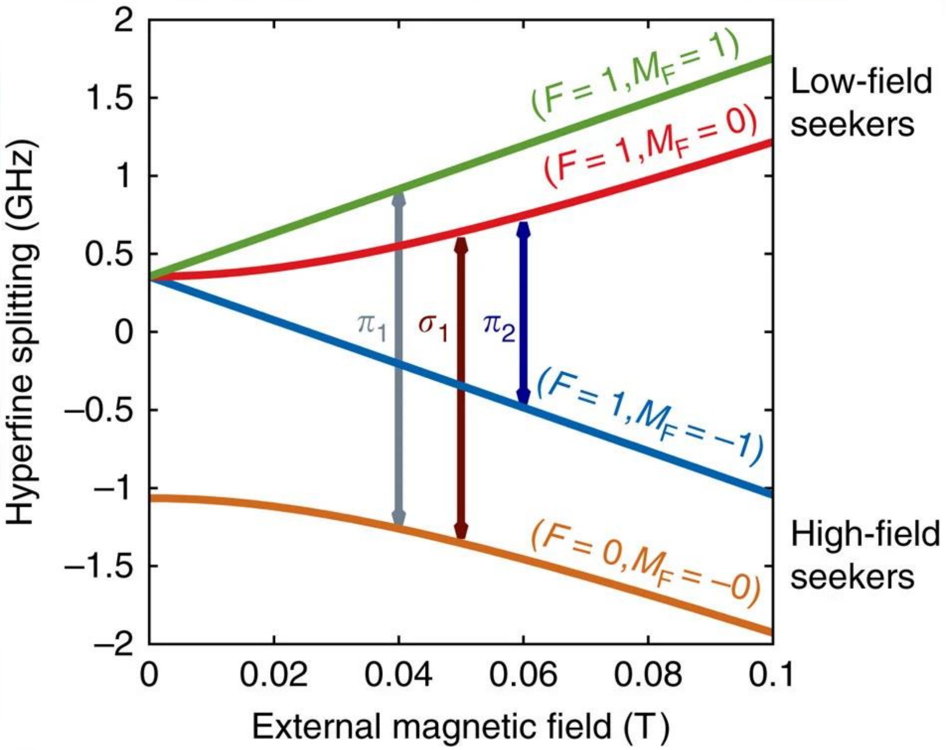
ALPHA and ATRAP: cold antihydrogen trapping

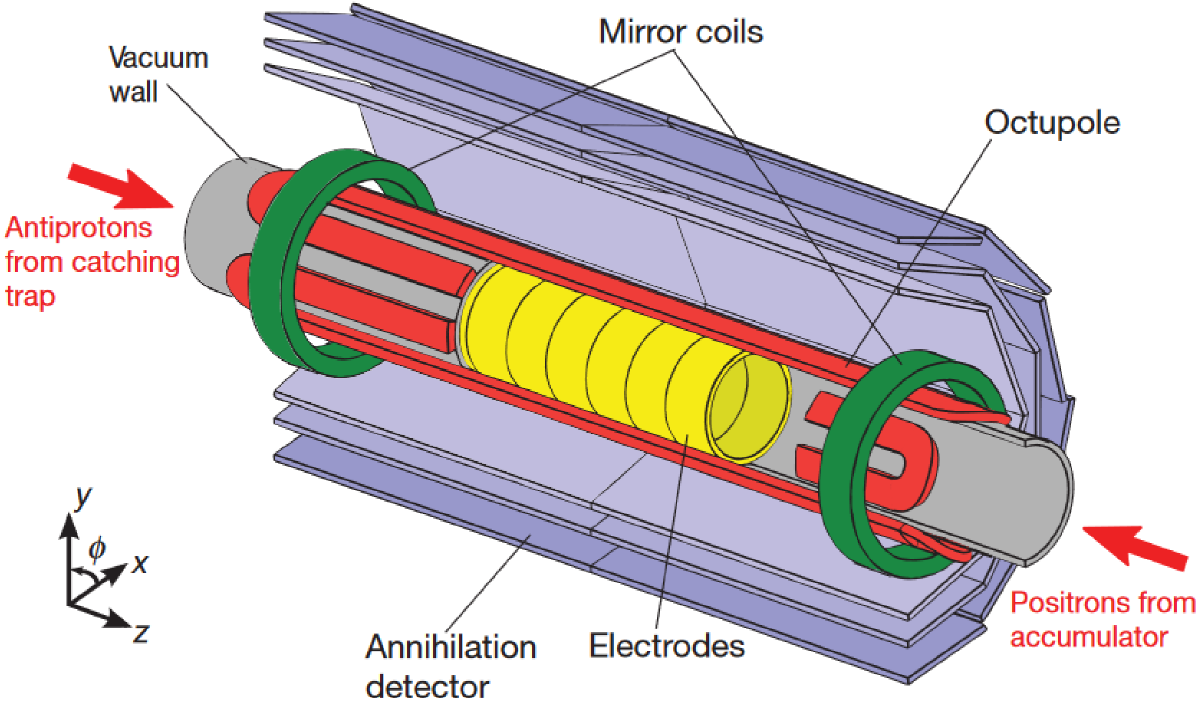
Letter | Published: 17 November 2010

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. Hydomako, M. J. Jenkins, S. Jonsell, L. V. Jørgensen, ... Y. Yamazaki + Show authors

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





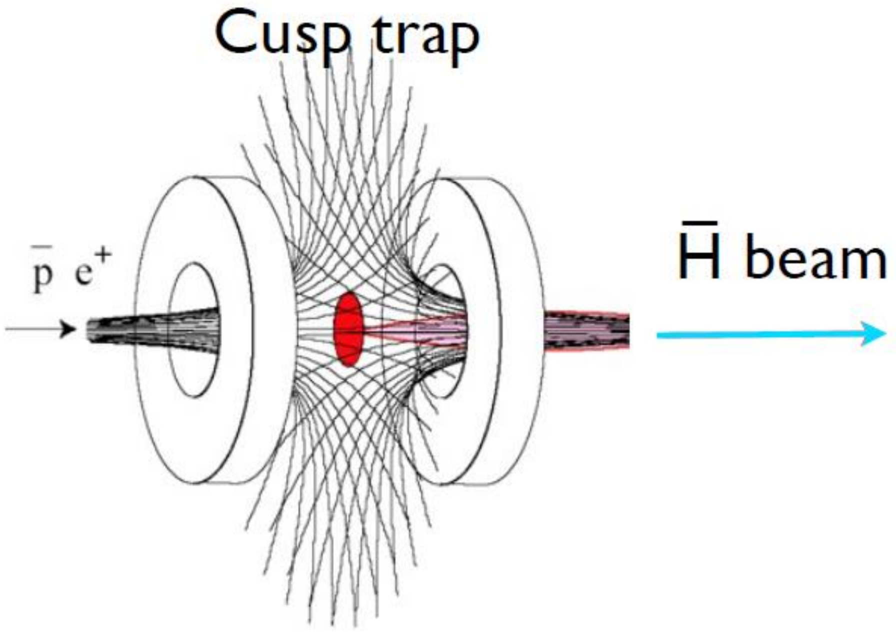
ASACUSA: a continuous beam of antihydrogen

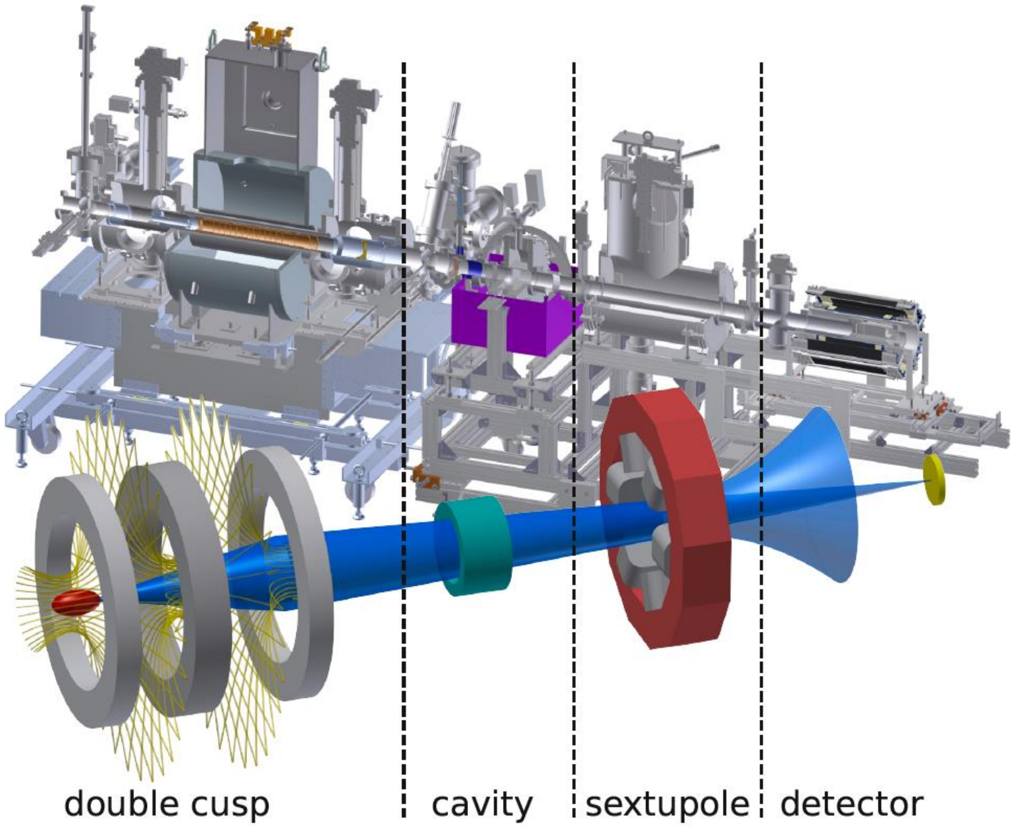
Article | Open access | Published: 21 January 2014

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¨nschek, ... Y. Yamazaki

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



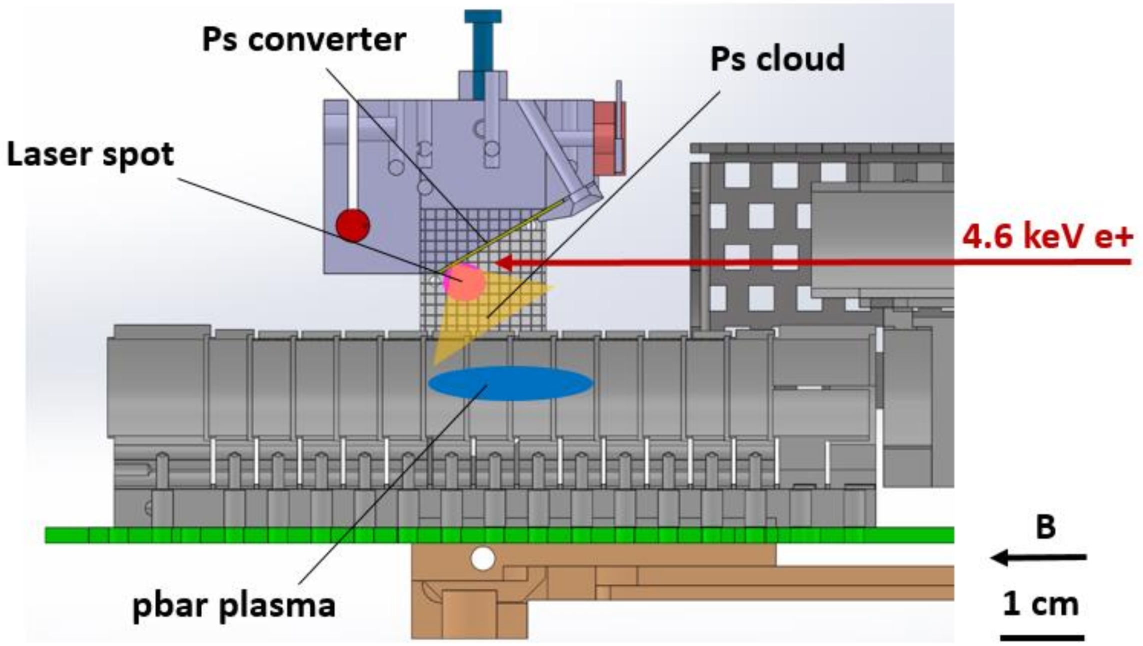


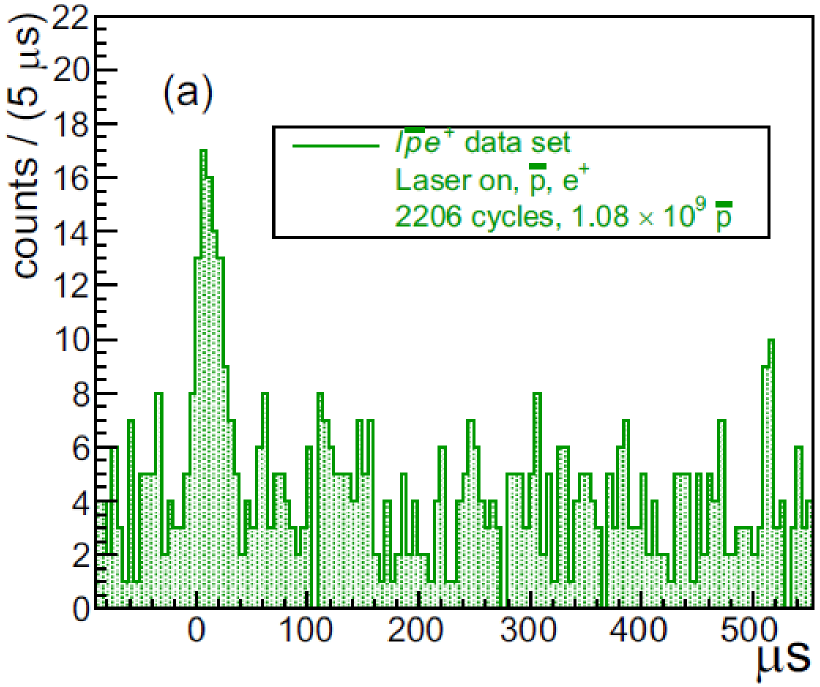
Article | Open access | Published: 08 February 2021

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 Fanì, Rafael Ferragut, Julian Fesel, Sebastian Gerber, Marco Giammarchi, Angela Gligorova, Lisa Theresa Glöggler, Francesco Guatieri, Stefan Haider, ... Nicola Zurlo + Show authors

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



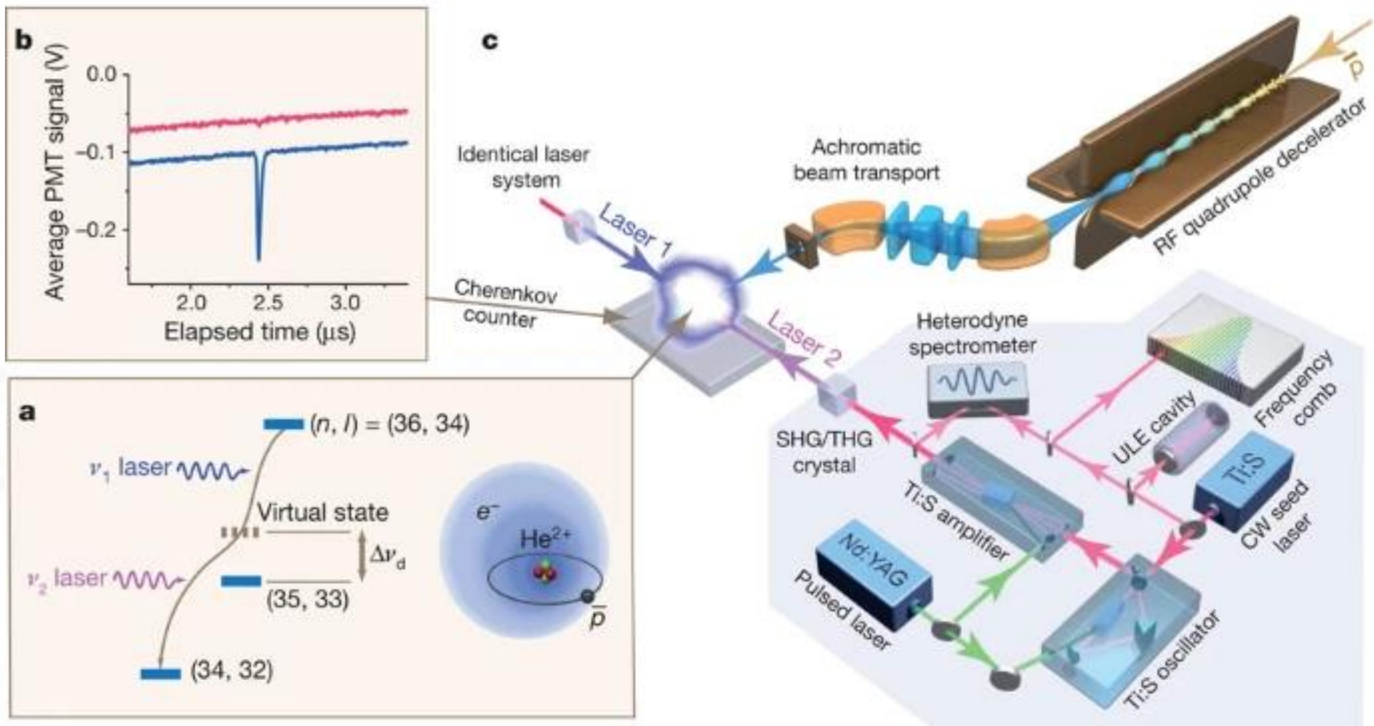


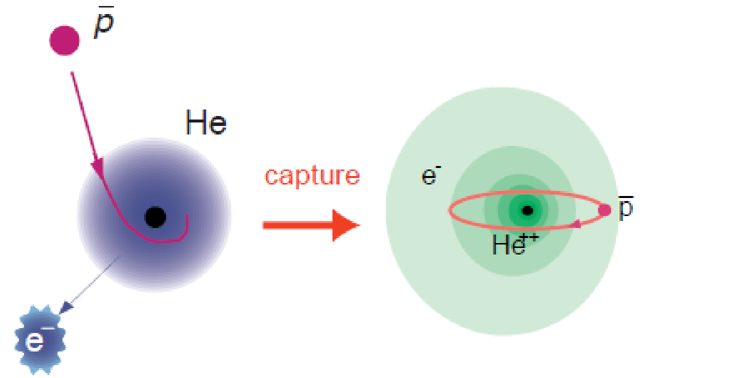
TESTING CPT AND WEP
AT THE ANTIMATTER FACTORY

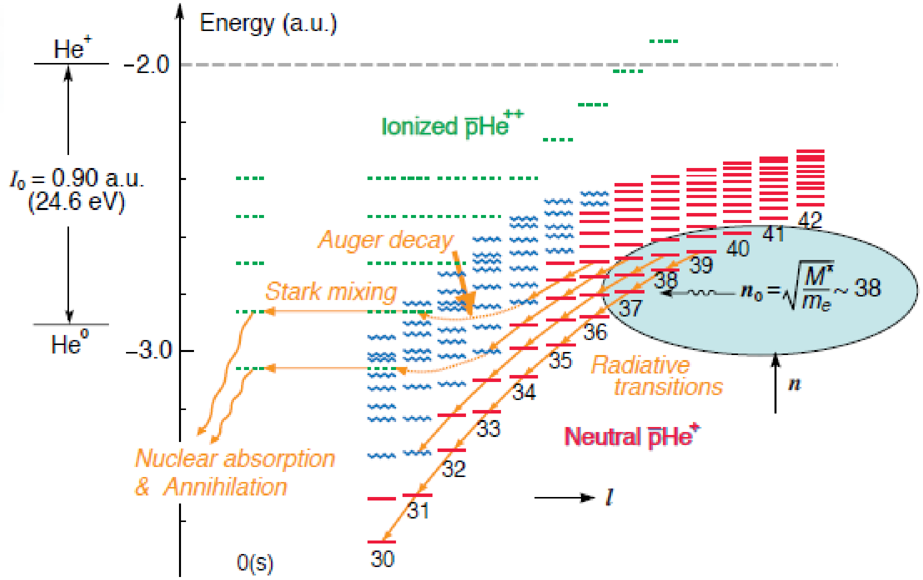
ASACUSA: spectroscopy of antiprotonic helium

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







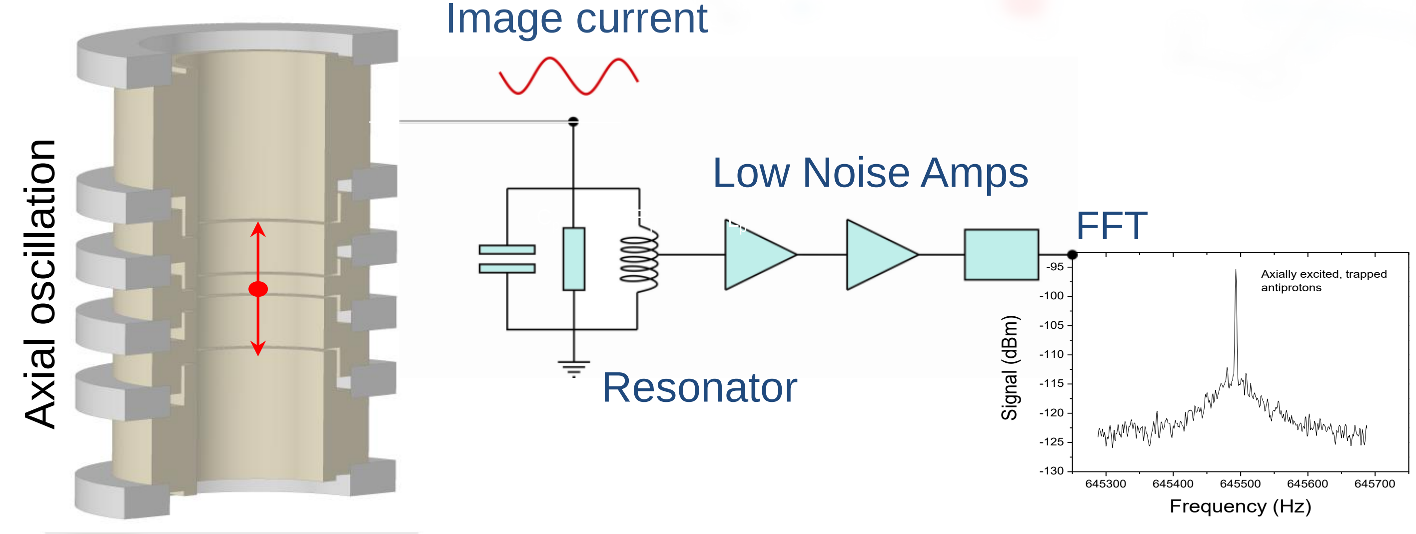
Measured frequencies agree with calculations at the $(2–5) \times 10^{-9}$ level

ATRAP and BASE: proton/antiproton charge-to-mass ratio

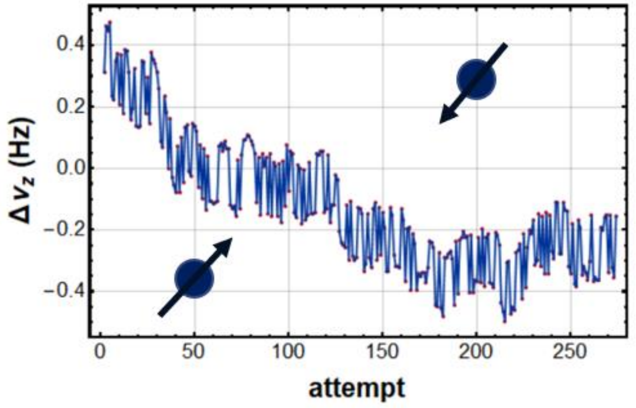
Letter | Open access | Published: 12 August 2015

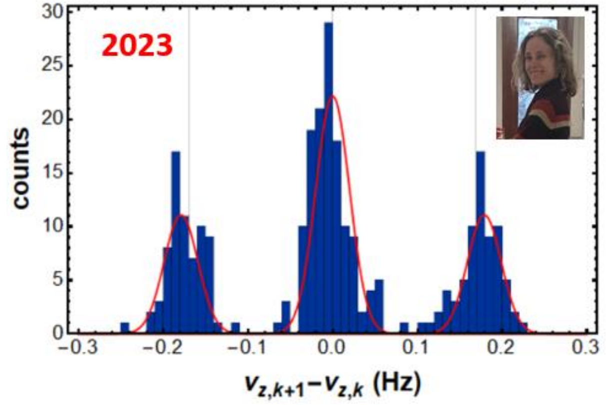
High-precision comparison of the antiproton-to-proton charge-to-mass ratio

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



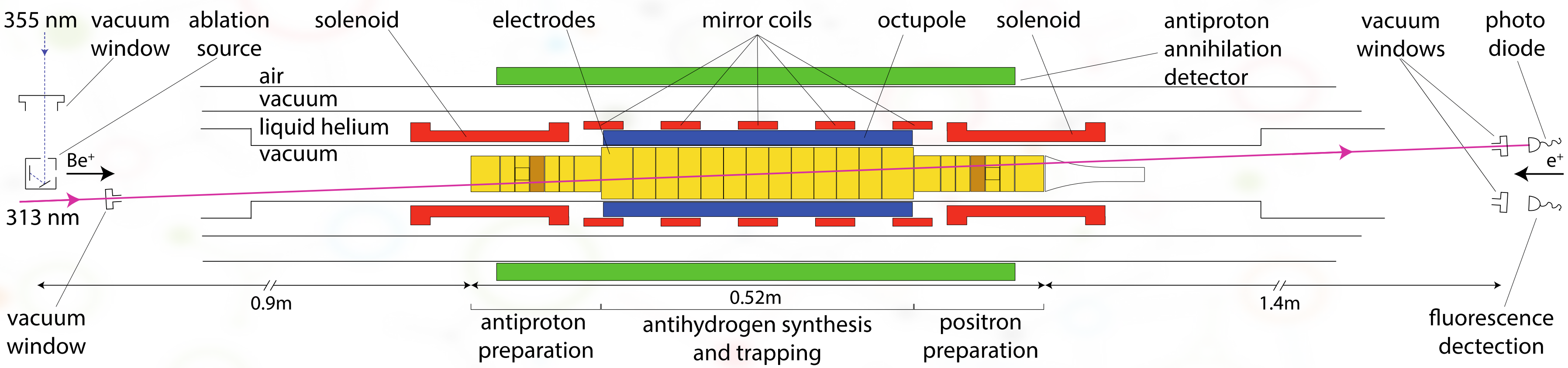


Thousandfold improvement in the measured antiproton mass

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}

ALPHA: spectroscopy of antihydrogen



Letter | Open access | Published: 19 December 2016

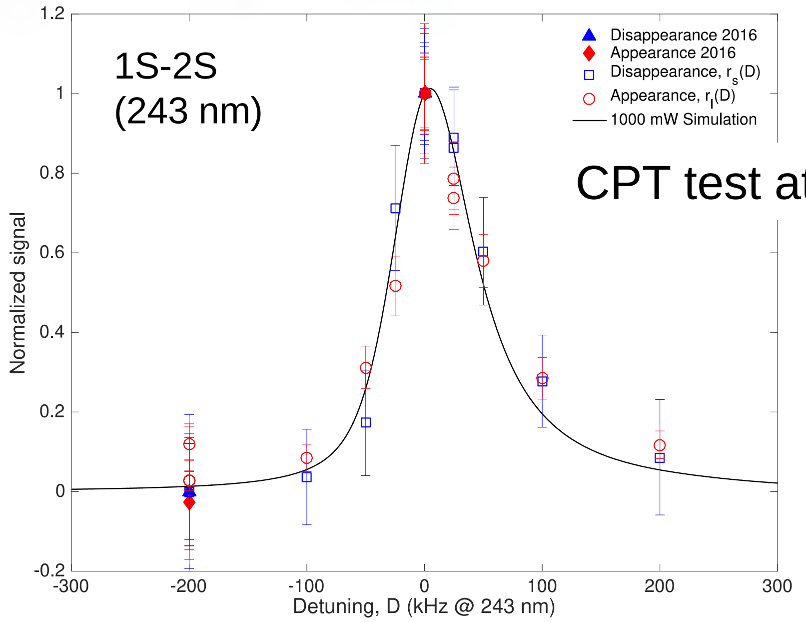
Observation of the 1S–2S transition in trapped antihydrogen

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

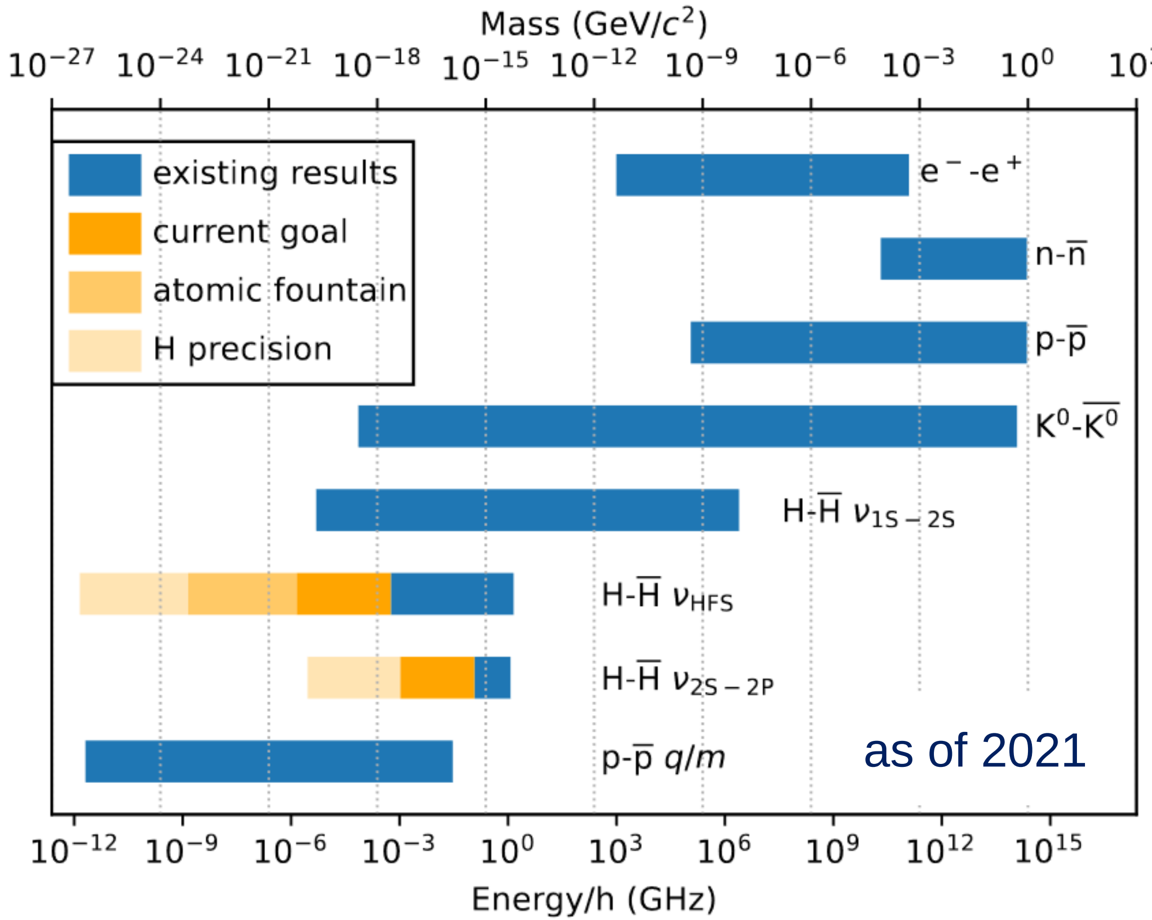
Letter | Open access | Published: 04 April 2018

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



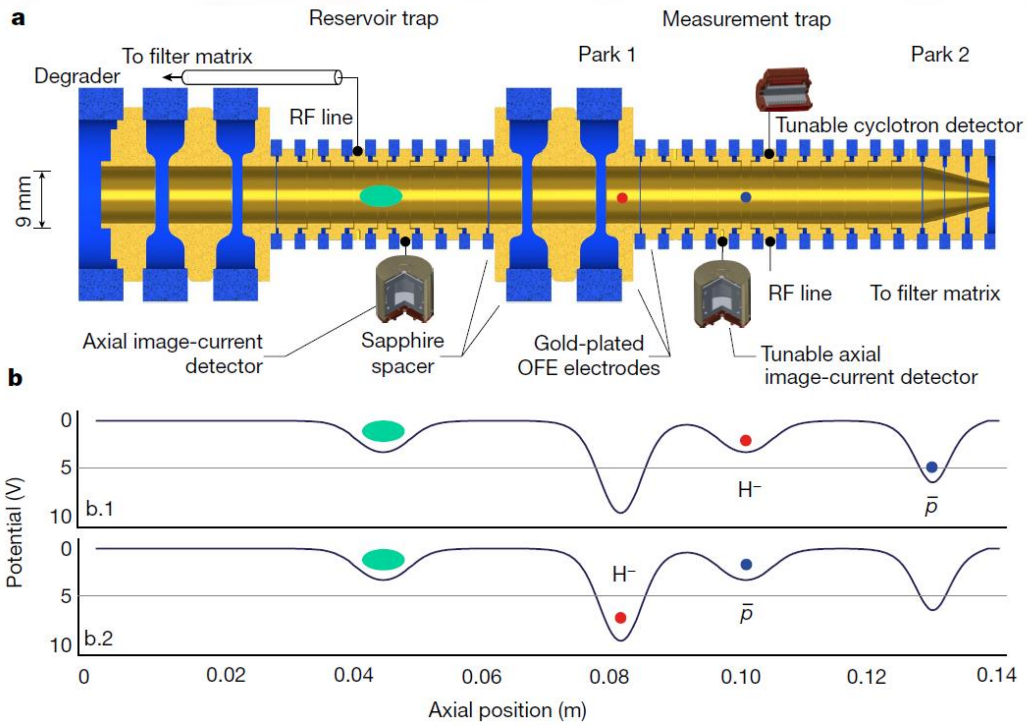
CPT test at 2×10^{-12}

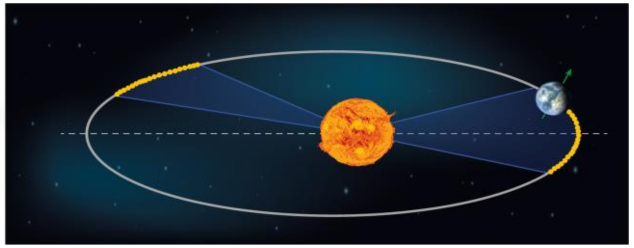


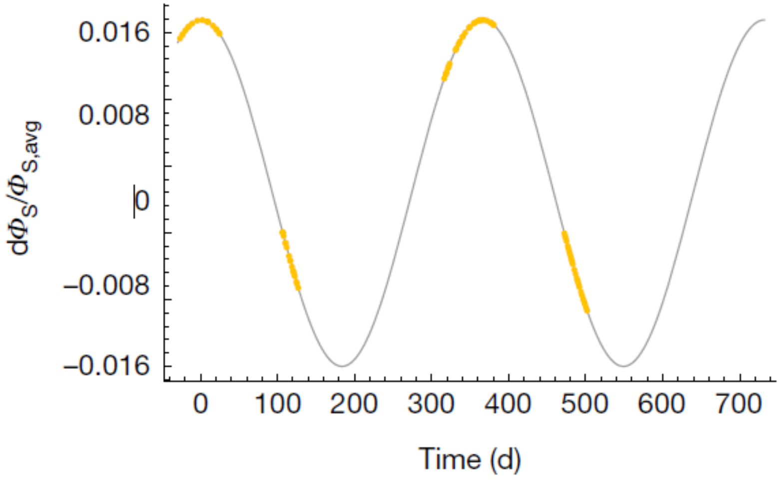
Eberhard Widmann, *Hyperfine spectroscopy of antihydrogen, hydrogen, and deuterium*, Phys. Part. Nucl. **53** (2022)

Article

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





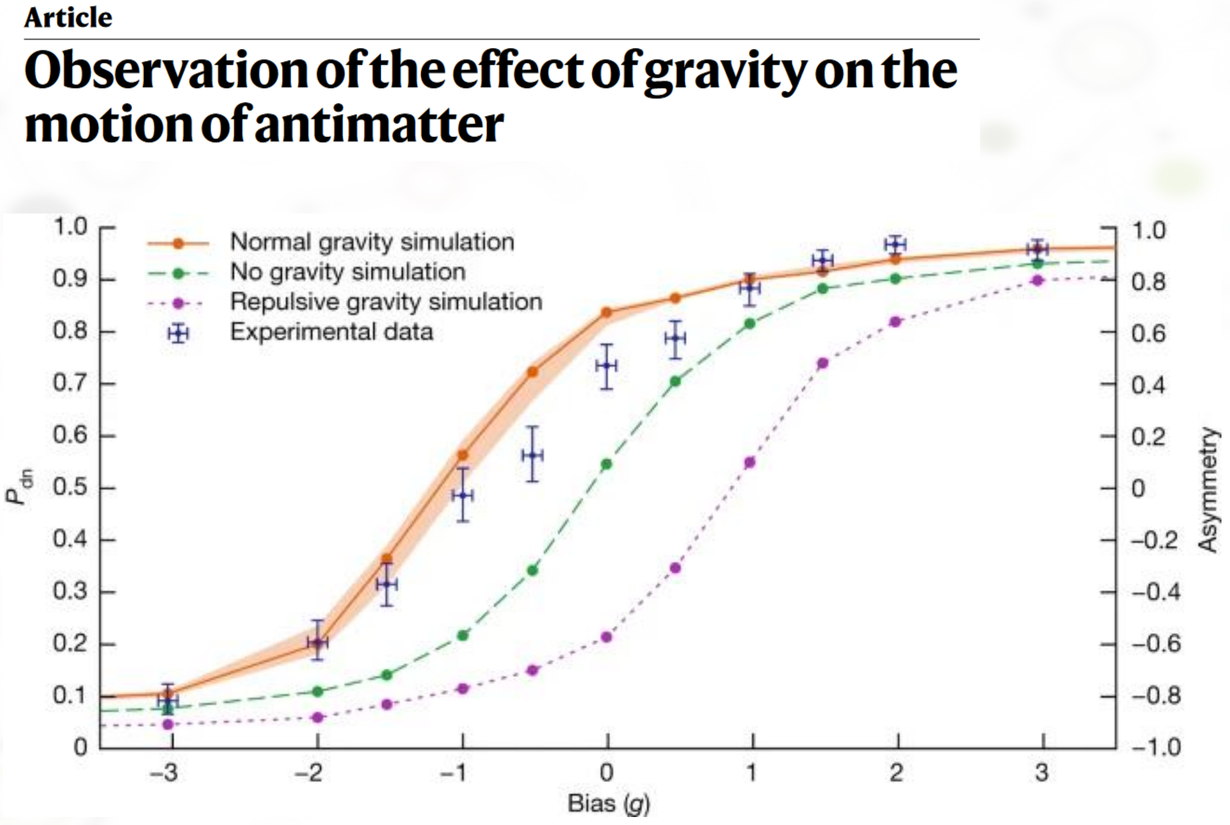


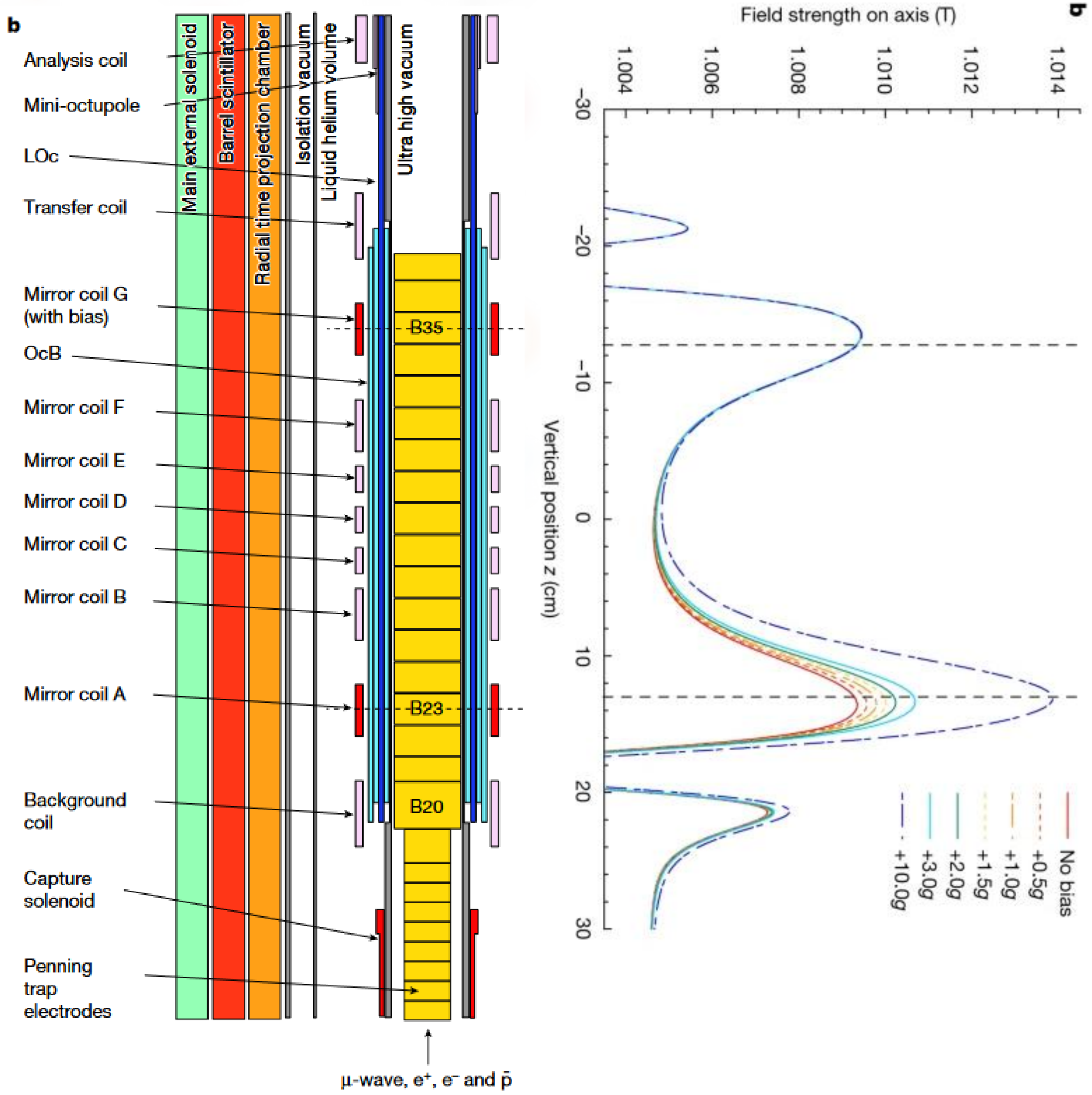
$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3GM_{\mathrm{sun}}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right),$$

$$O(t) = D_{\mathrm{p}}(1-\varepsilon^2)/[1+\varepsilon\cos((2\pi/t_{\mathrm{sid}})t)]$$

Gravitational redshift comparison with hydrogen/antihydrogen

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





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

Excluded a positive sign of g

FUTURE PROSPECTS AND NEW TECHNOLOGIES

AEgIS: gravity with a pulsed beam of antihydrogen in no magnetic field

ARTICLE

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

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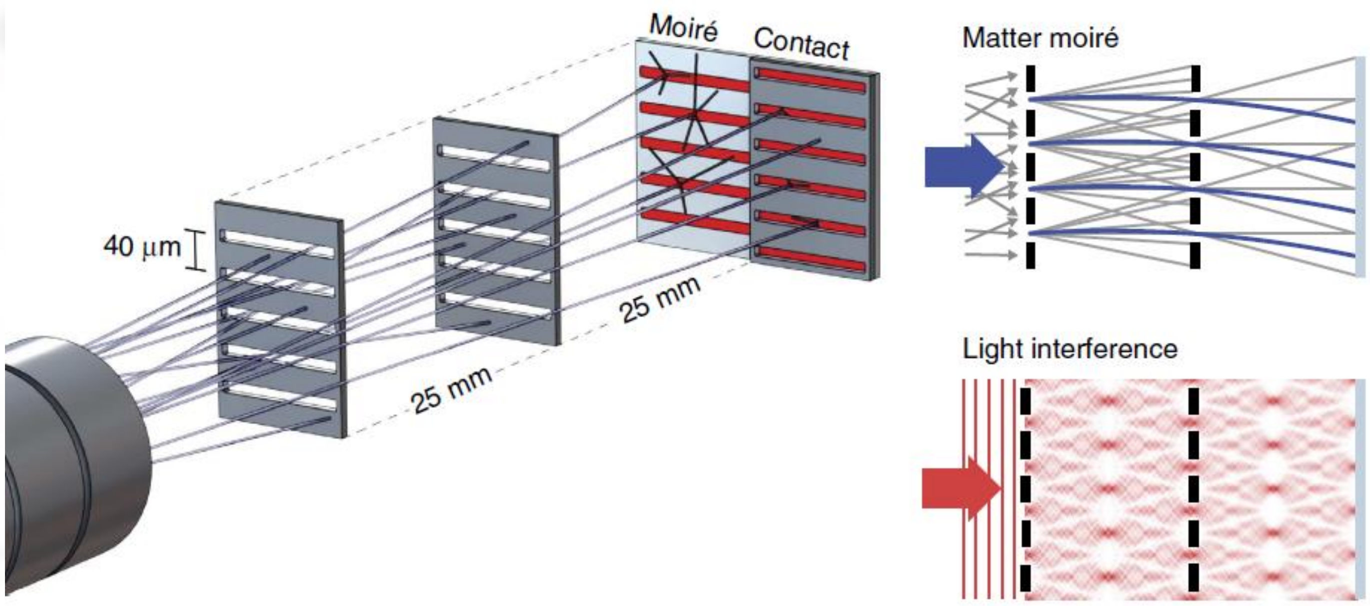
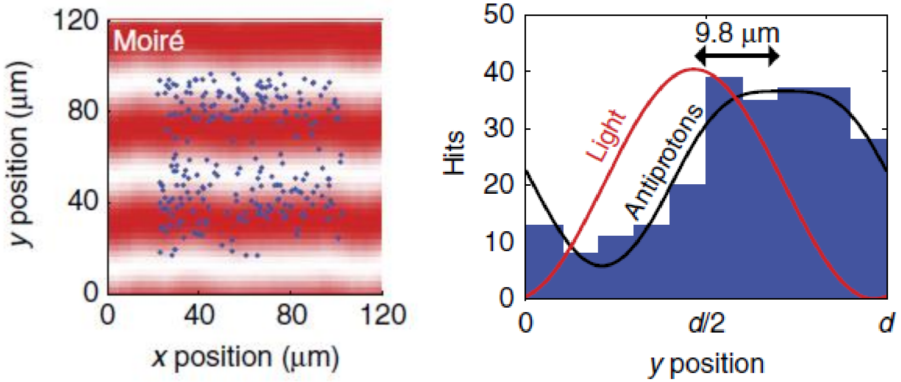
OPEN

A moiré deflectometer for antimatter



Tested with 10-50 keV antiprotons

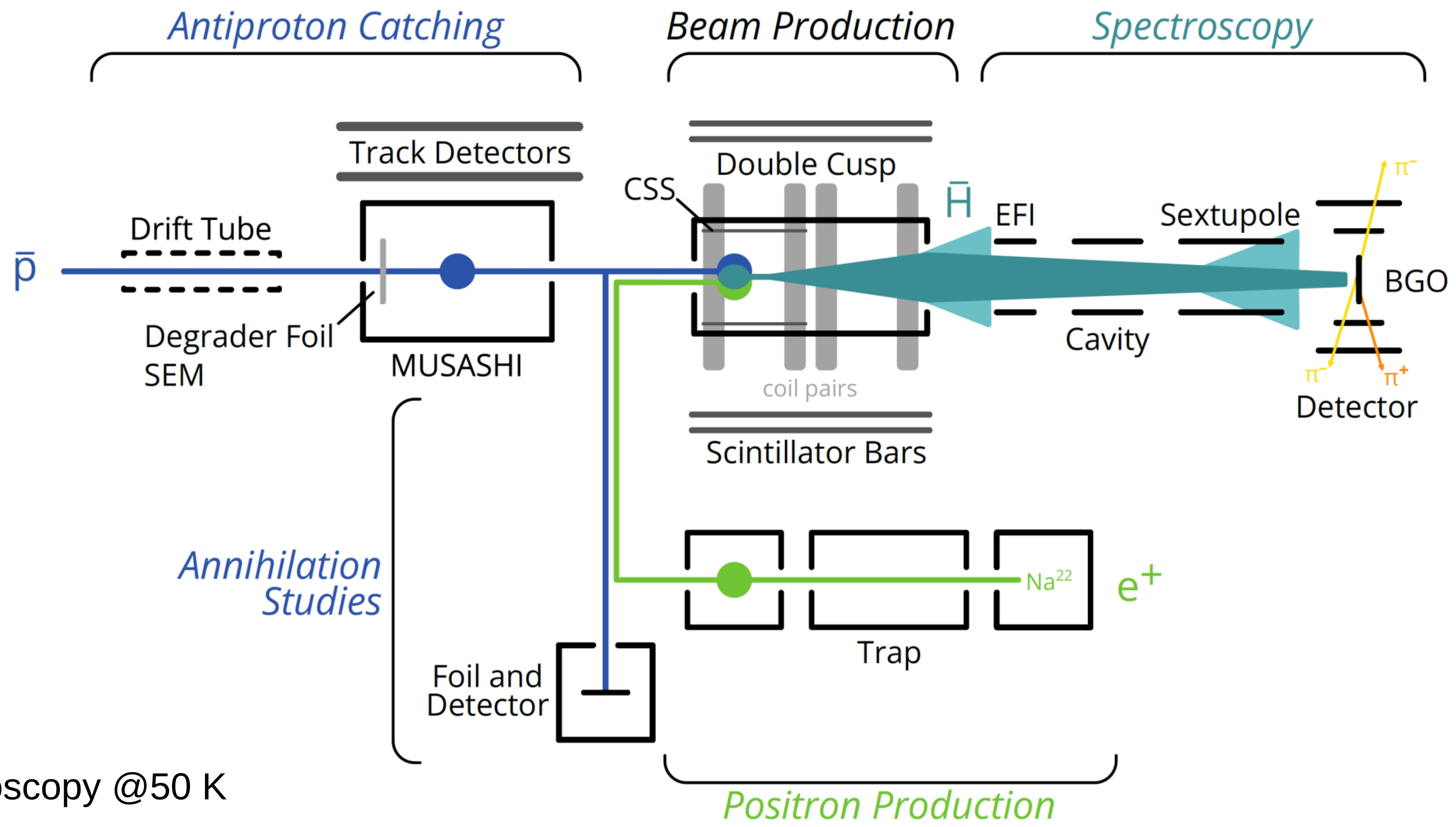


- Combined moiré deflectometer and Talbot-Lau interferometer
- High resolution detector referenced with light patterns
- Time-of-flight knowledge from external scintillator detectors

$$y = gt^2$$

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

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

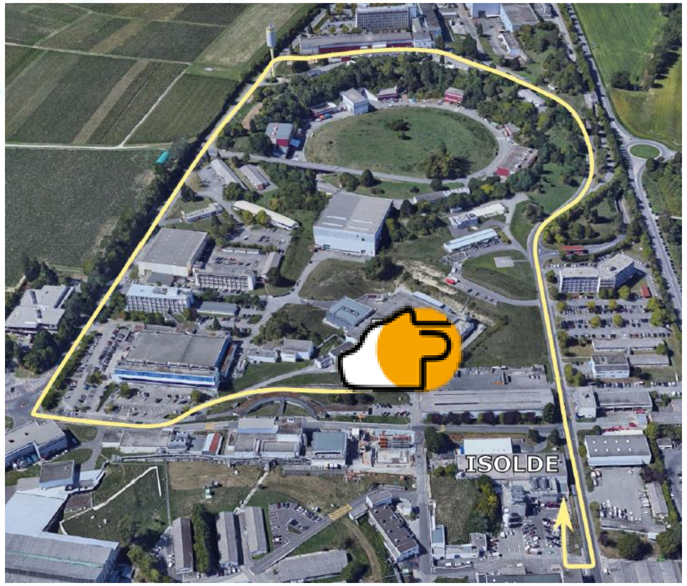


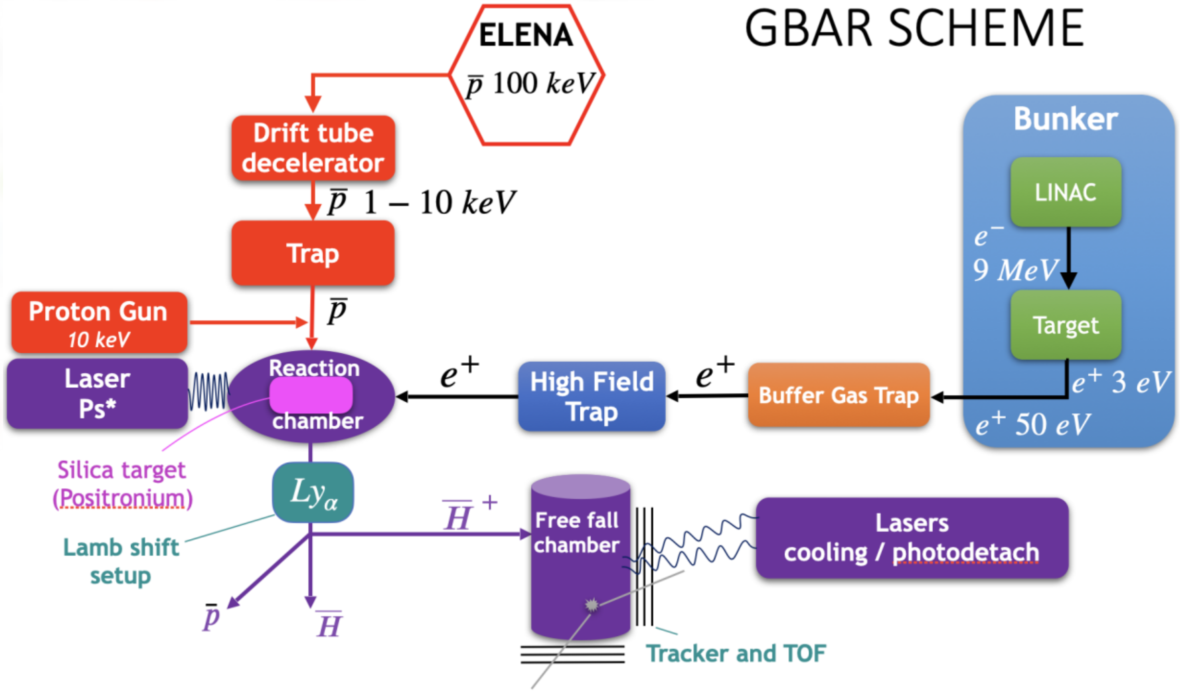
Rabi spectroscopy @50 K

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





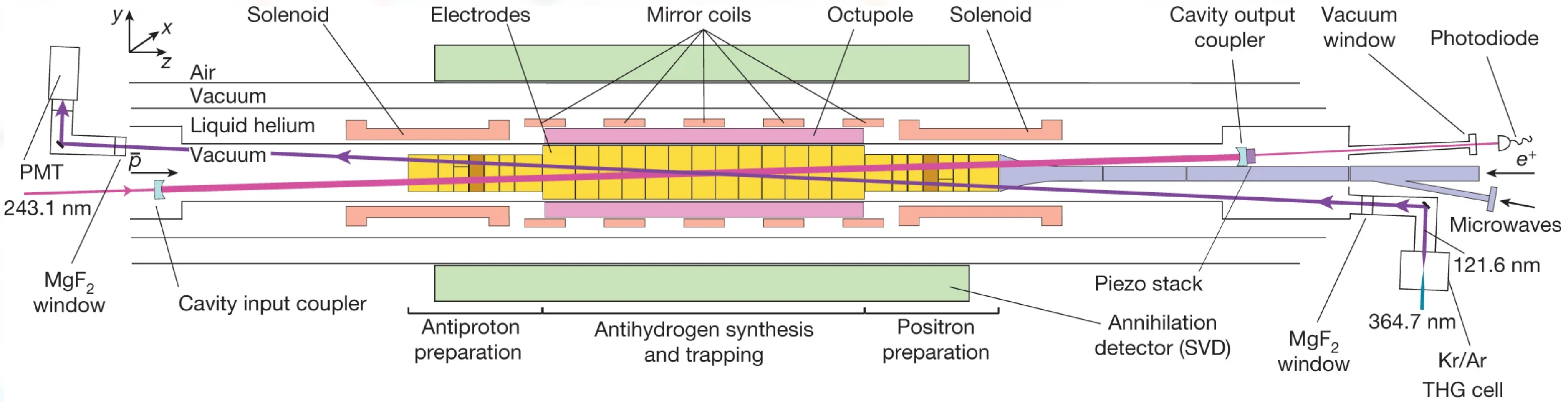
GBAR

- Produce keV beams of antihydrogen atoms and ion

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

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

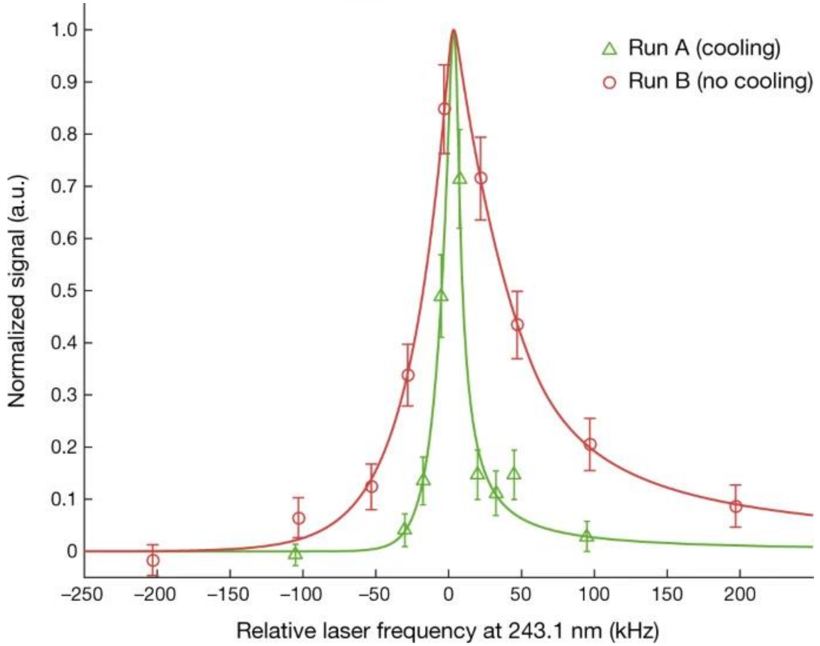
ALPHA: laser cooled antihydrogen



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,



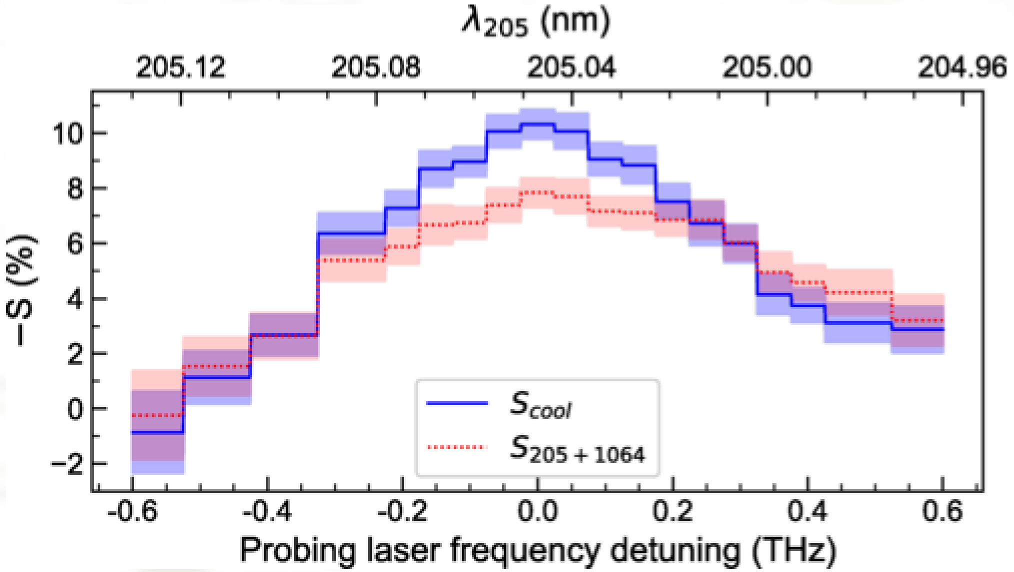
AEgIS: laser cooling of positronium

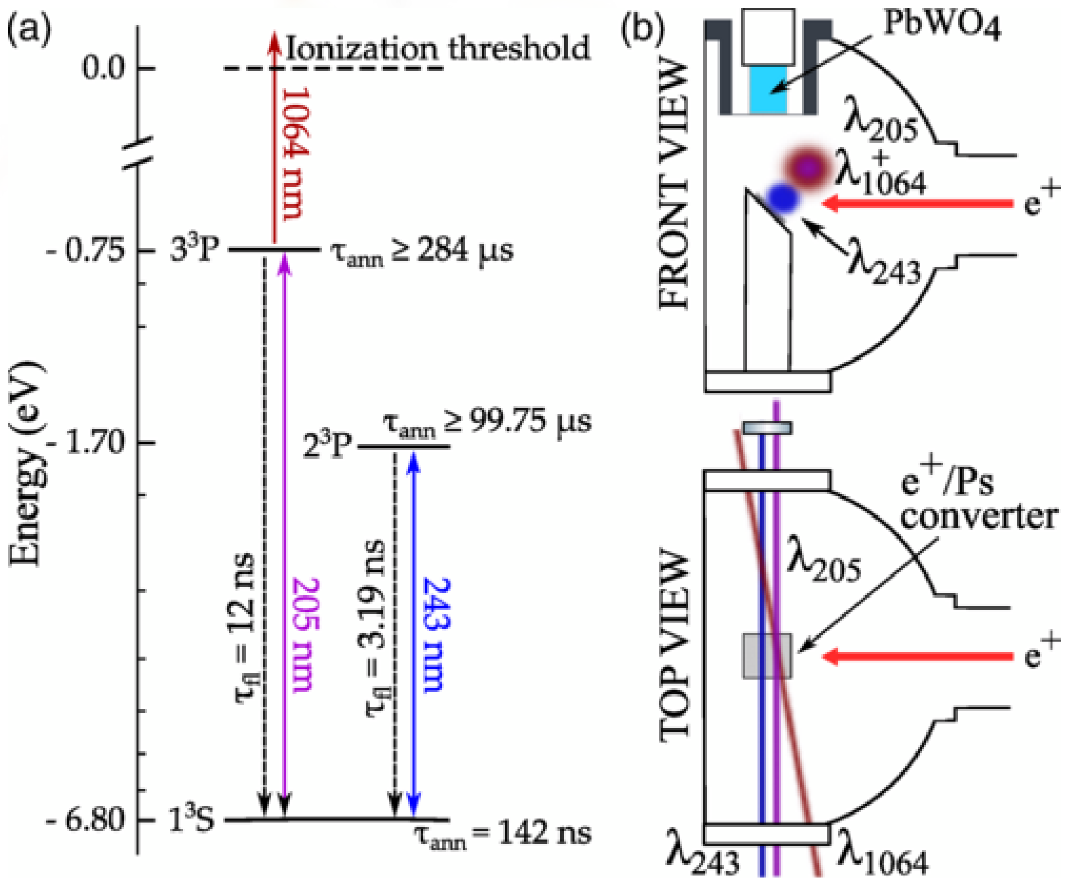
Featured in Physics | Editors' Suggestion | Open Access

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

L. T. Glöggler *et al.* (AEḡIS Collaboration)

Phys. Rev. Lett. **132**, 083402 – Published 22 February 2024





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

Conclusions

- 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 horizion to enhance the accuracy of existing experiments

Thank you for your attention!

Istituto Nazionale di Fisica Nucleare