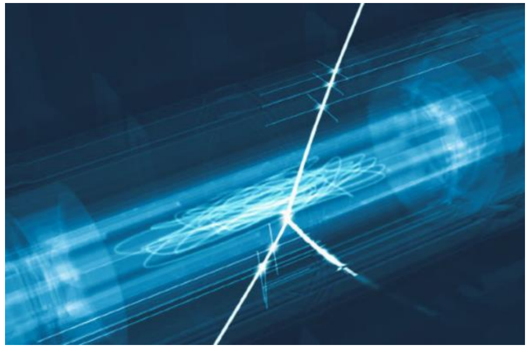
CERN PBC-Workshop – 2024/03/26

Future Perspective of the Experiments at the Antiproton Decelerator / ELENA Facility of CERN



antihydrogen trap

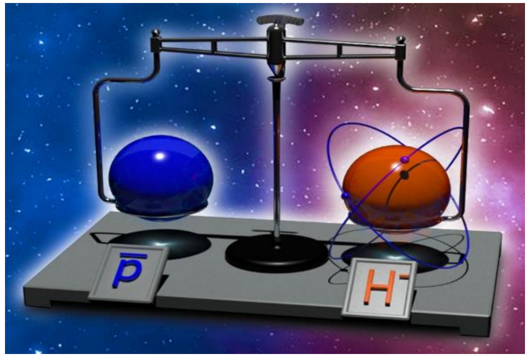
Stefan Ulmer

HHU Düsseldorf,

RIKEN

2024 / 03 / 26

AD-Chair
on behalf of the AD-collaborations

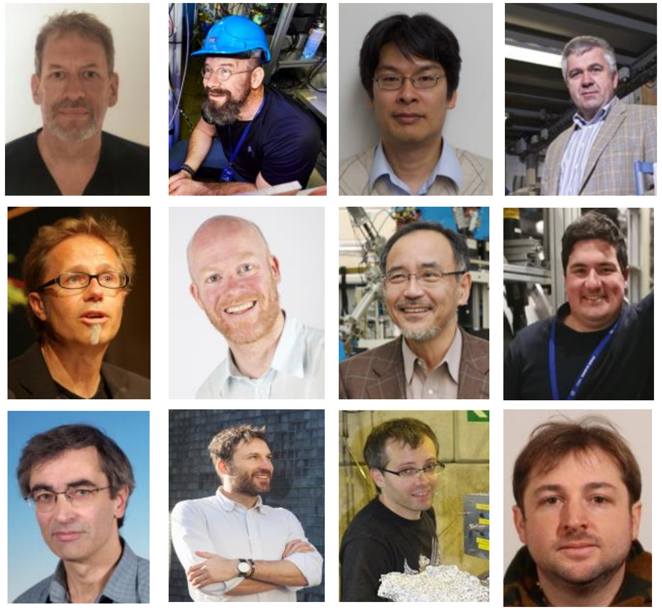


antiproton/proton balance

Outline of Talk

- Introduction and summary of the main achievements made since start of the program
- Report on the status, and in particular give outlook on future plans of the individual collaborations

- **ALPHA**
- **ASACUSA**
- **AEGIS**
- **BASE/BASE STEP**
- **GBAR**
- **PUMA**



facilities and methods

ELENA: Bright Perspectives for Low Energy Antiproton Physics

Introduction

Although incredibly successful, the standard model of particle physics (SM) is known to be glaringly incomplete. For example, it has so far failed in the unification of all known forces, and it includes 19 free parameters that have to be determined by experiments, indications of the phenomenological nature and incompleteness of the theory. Some great triumphs of the SM are the prediction of the Higg and its detection, or the predic detection of the exchange qu the weak interaction. Anoth achievement is the precise cal of the electron's anomalous m dipole moment, which result most precise quantum-electrody based determination of the fin ture constant.

Frustratingly, the success SM is restricted to the descri not more than 5% of the ener tent of our universe, and even damental mechanisms to expl this small fraction came int existence have yet to be und Combining the Λ-Cold Dar ter (Λ-CDM) model and the would expect to find a radiat verse with a baryon/antibary of ≈ 1, and a baryon/photon 10^{-18}. Astrophysical observat dicate on the other hand an exp tal baryon/photon ratio of ~6 challenging our current best standing by a theory/experim agreement of almost nine o magnitude. A possible explana this discrepancy would be a metry between matter and antimatter that has yet to be discovered.

This inspires experiments, such as the ones operated at the Antiproton Decelerator (AD)/Extra Low ENergy Antiproton (ELENA) facility of the European Council for Nuclear Research (CERN), that compare the fundamental properties of stable matter/antimatter conjugates at low energies and with great precision. In recent years, the user community at the AD invented a plethora of cutting edge technologies (see the illustrations in Figure 1) culminating in comparisons

[3], ASACUSA [10, 11], BASE [12], GBAR [6], and PUMA [8].

One of the common workhorses of those experiments is a device called a Penning trap, which is used for trapping charged particles, either for single-particle studies or formation of $\bar{H}$ atoms (see Figure 3).

AEgIS, GBAR, and a part of the ALPHA collaboration are testing the weak equivalence principle by in-

beam quality.

Currently, six active within the A (see Figure 2): Al

Vol. 32, N

facilities and methods

Figure 1. *Image of the installed ELENA ring. Insets clockwise: BASE multi-Penning-trap stack, ASACUSA microwave cavity and laser setup, ALPHA multi-ring electrodes, GBAR positron accumulator, PUMA MR-TOF separator, and AEgIS superconducting magnets.*

The ALPHA collaboration is performing precision measurements on the fundamental properties of $\bar{H}$ using an atom trap. After a development period that required the invention of several innovative plasma manipulation techniques, the collaboration reported in 2010 the first successful demonstration of $\bar{H}$-trapping. Based on this experimental success and by steadily improving their apparatus, ALPHA

hydrogen. The BASE collaboration uses advanced Penning trap systems to compare the fundamental properties of protons and antiprotons. Their trap stack incorporates a purpose-built reservoir trap, in which they have demonstrated antiproton trapping for longer than a year, making the experiment almost independent of accelerator cycles. In fact, most of their precision studies are carried out while

have recently compared the proton-to-antiproton charge-to-mass ratios with a fractional accuracy of 16 parts in a trillion. This measurement also enabled a first differential test of the clock weak equivalence principle in which a fractional accuracy of 0.03 was achieved, similar to the precision goals of experiments that test the free-fall weak equivalence principle studying the ballistics of antihydrogen in

D. Gamba
Beams Department

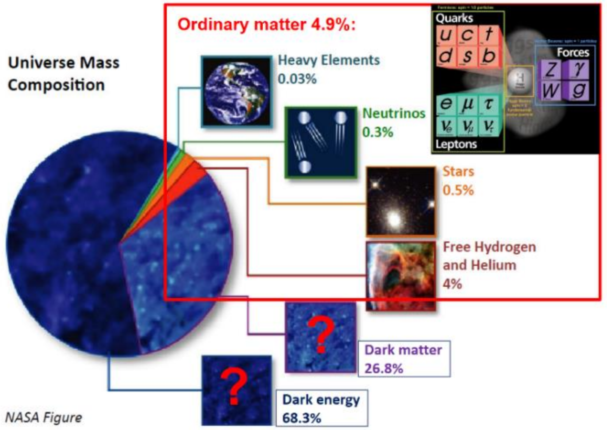
C. Malbrunot
perimental Physics Department

L. Ponce
CERN, Beams Department

C. Carli
CERN, Beams Department

S. Ulmer
RIKEN, Ulmer Fundamental Symmetries Laboratory

Motivation: Matter / Antimatter Asymmetry

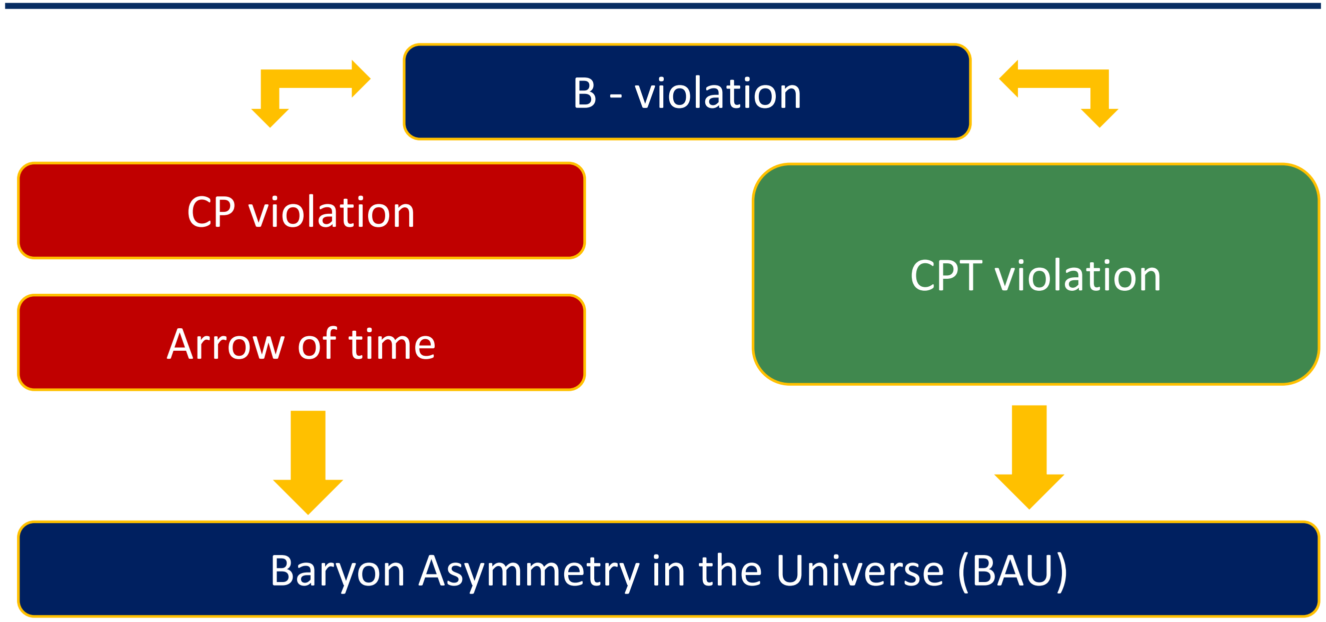


NASA Figure

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

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

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



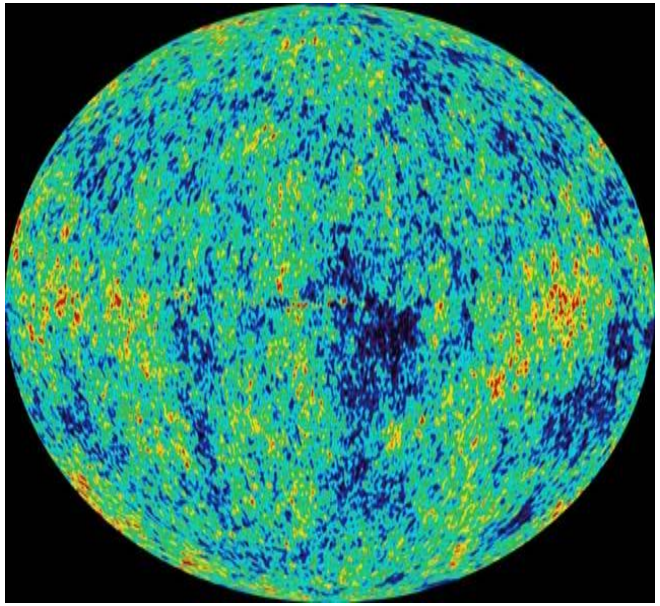
B - violation

CP violation

Arrow of time

CPT violation

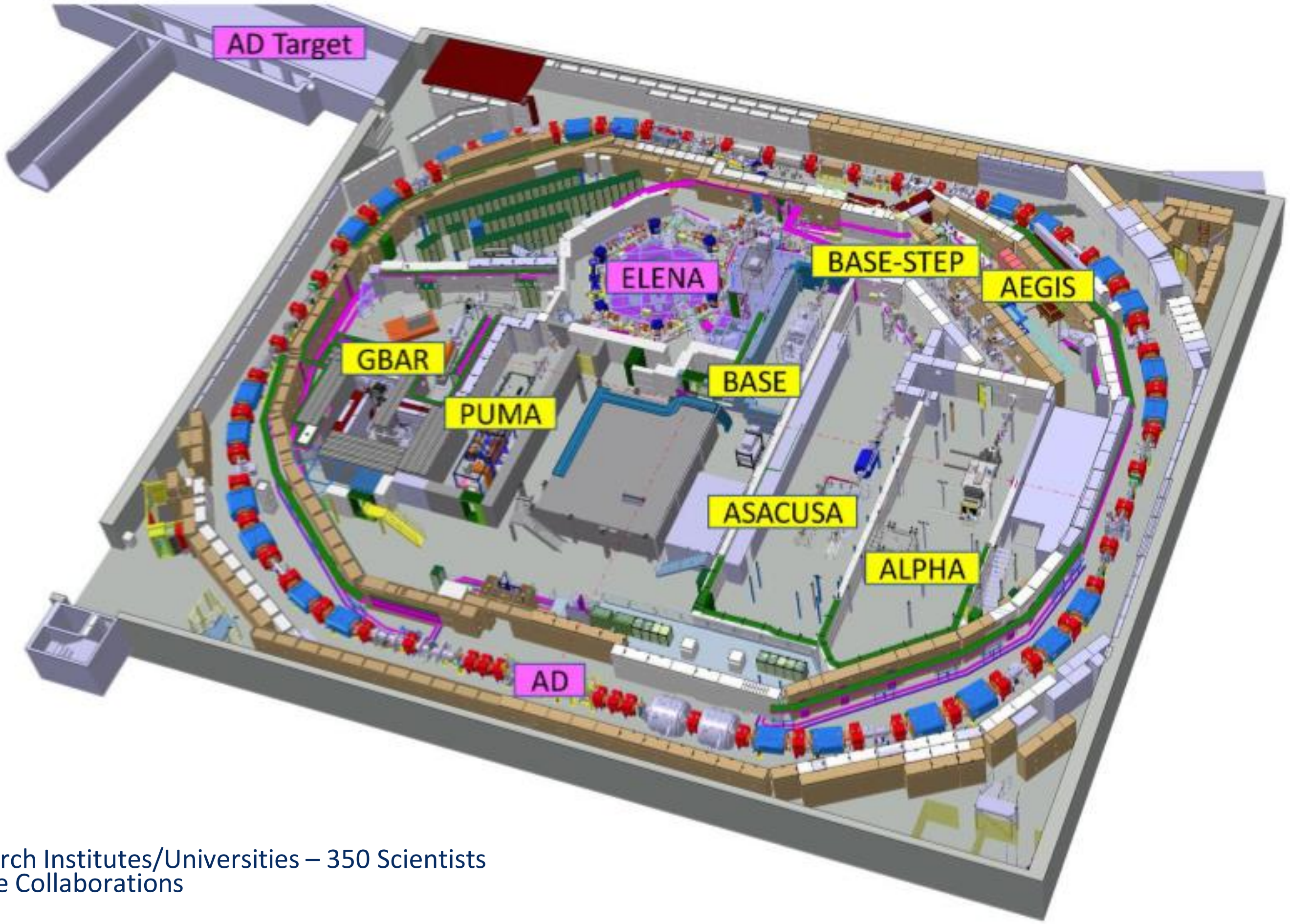
Baryon Asymmetry in the Universe (BAU)



at the AD we are studying these questions using quantum limited mesurement technology of AMO physics.

The AD/ELENA-Facility

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



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

- Tests of CPT symmetry (ALPHA, ASACUSA, BASE)
- Tests of ballistic properties of antihydrogen (ALPHA, GBAR, AEGIS)
- Searches for asymmetric dark matter / antimatter coupling (BASE, ASACUSA)
- Nuclear Physics Projects (PUMA)

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

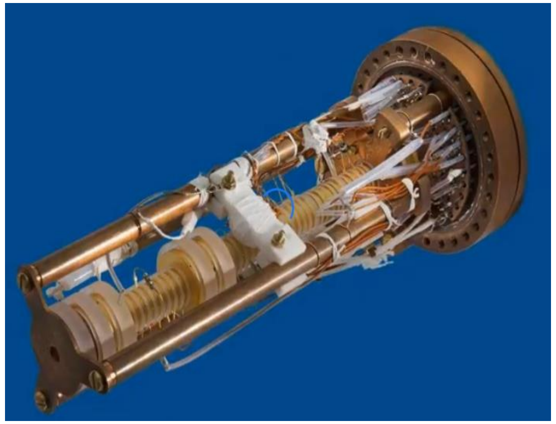
M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).

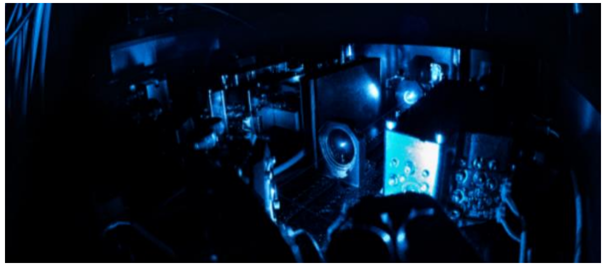
What is Specific about the AD-Experiments

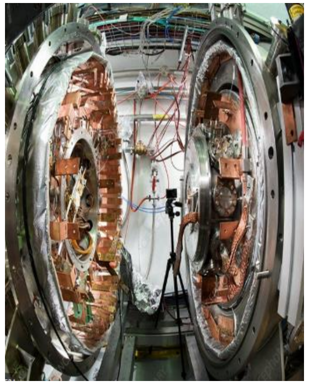
- Very different from the big detectors, the AD experiments are particle physics based AMO experiments

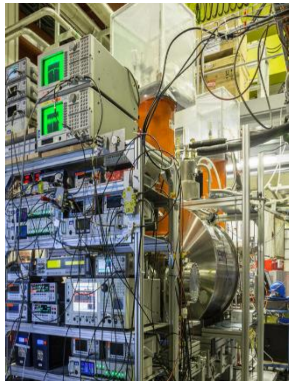
Traps

Clocks



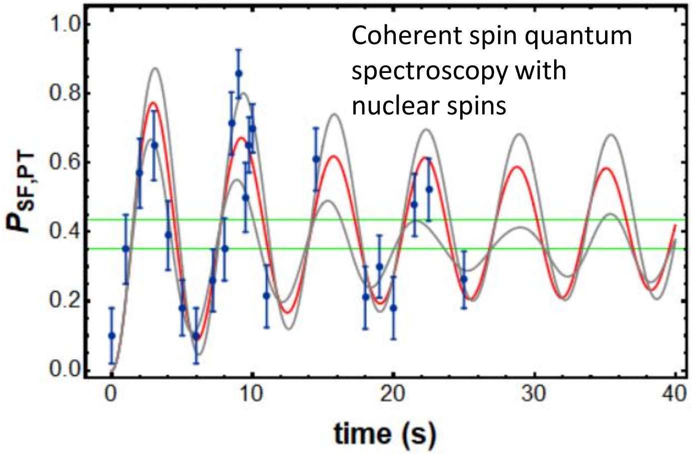




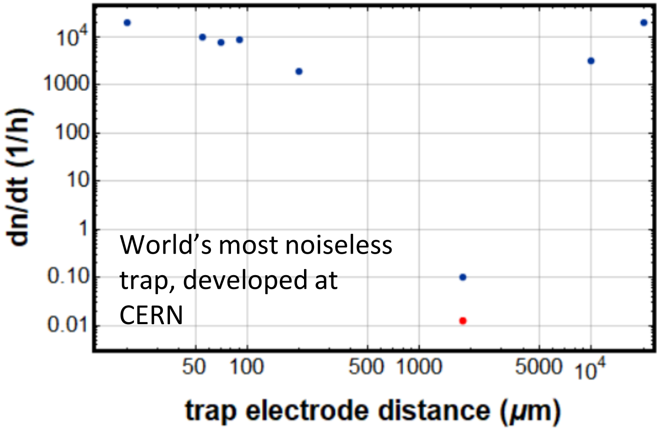


Innovation and Technology

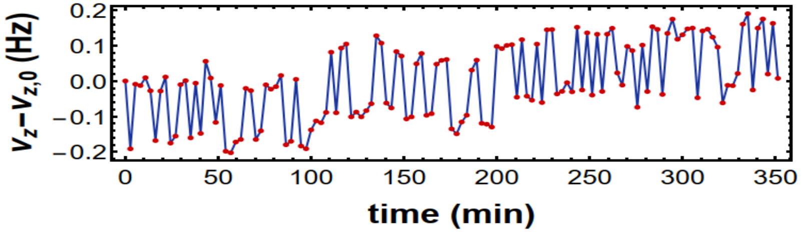
- Antihydrogen traps
- Advanced Multi Penning trap systems
- Ultra-stable ultra-high power lasers
- Transportable antimatter traps and reservoir traps
- **Coherent, quantum limited spectroscopy schemes**
- **Future: Quantum Logic Spectroscopy**

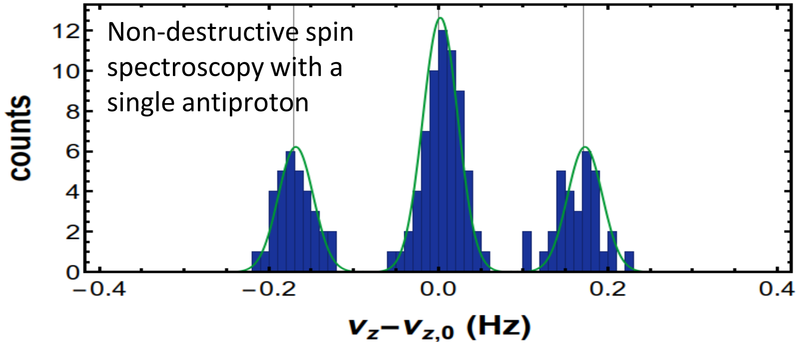


Coherent spin quantum spectroscopy with nuclear spins



World's most noiseless trap, developed at CERN



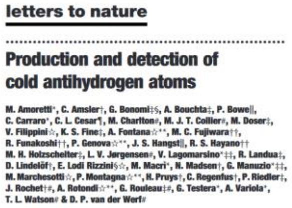


Non-destructive spin spectroscopy with a single antiproton

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



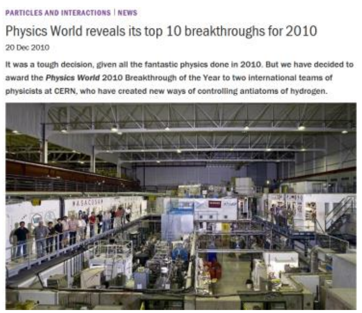
letters to nature

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. 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

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.

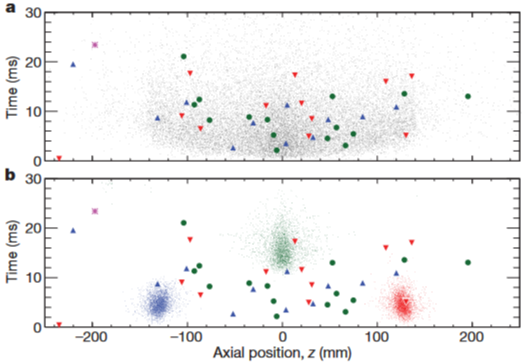
physicsworld TOP 10 BREAKTHROUGH 2010

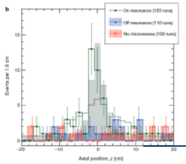
ALPHA

ASACUSA

2011

trapped antihydrogren

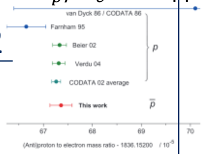




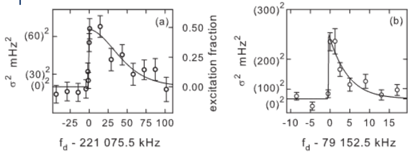
Resonant quantum transitions in Hbar

2012

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

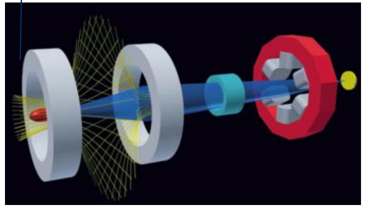


2013



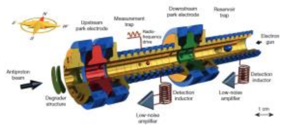
5ppm pbar moment

2014



Production of a beam of antihydrogen atoms

2015

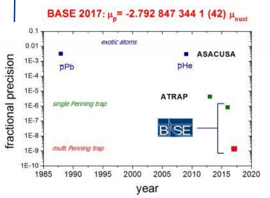


69 p.p.t. proton/antiproton q/m comparison

$$1+\frac{(q/m)_{\bar{p}}}{(q/m)_p}=1(69)\times10^{-12}$$

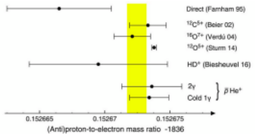
2017

1.5ppb pbar moment

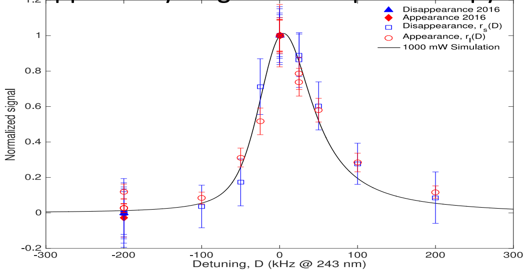


2018

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

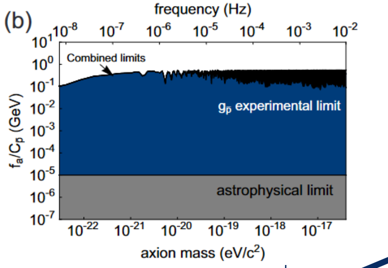


2ppt antihydrogren 1S2S spectroscopy

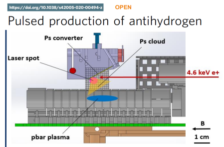


2019

antimatter/dark matter coupling



2020



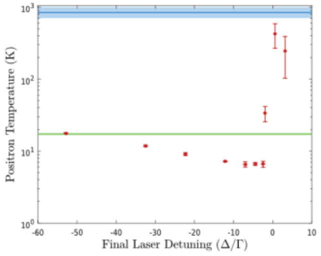
2021

ALPHA

BASE

physicsworld TOP 10 BREAKTHROUGH 2021

laser-cooled antihydrogren and sympathetically cooled protons



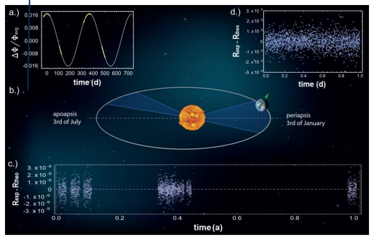
Laser cooled positrons

2022

Hbar production in GBAR

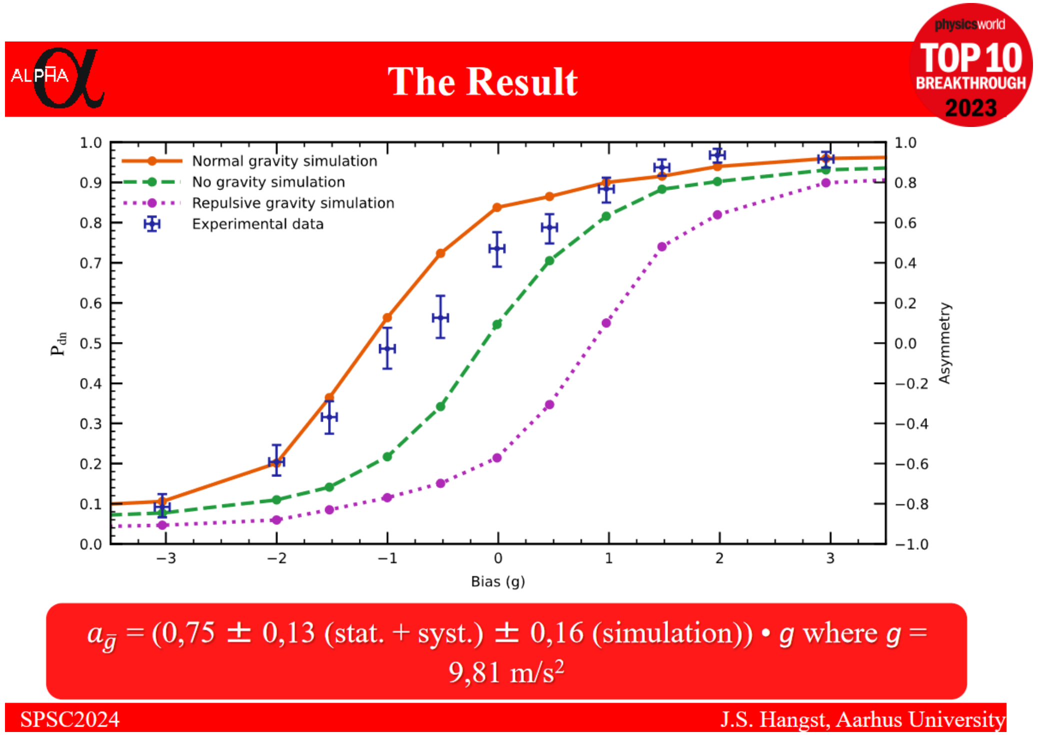
Gravity Measurement

2023



WEP test with clocks

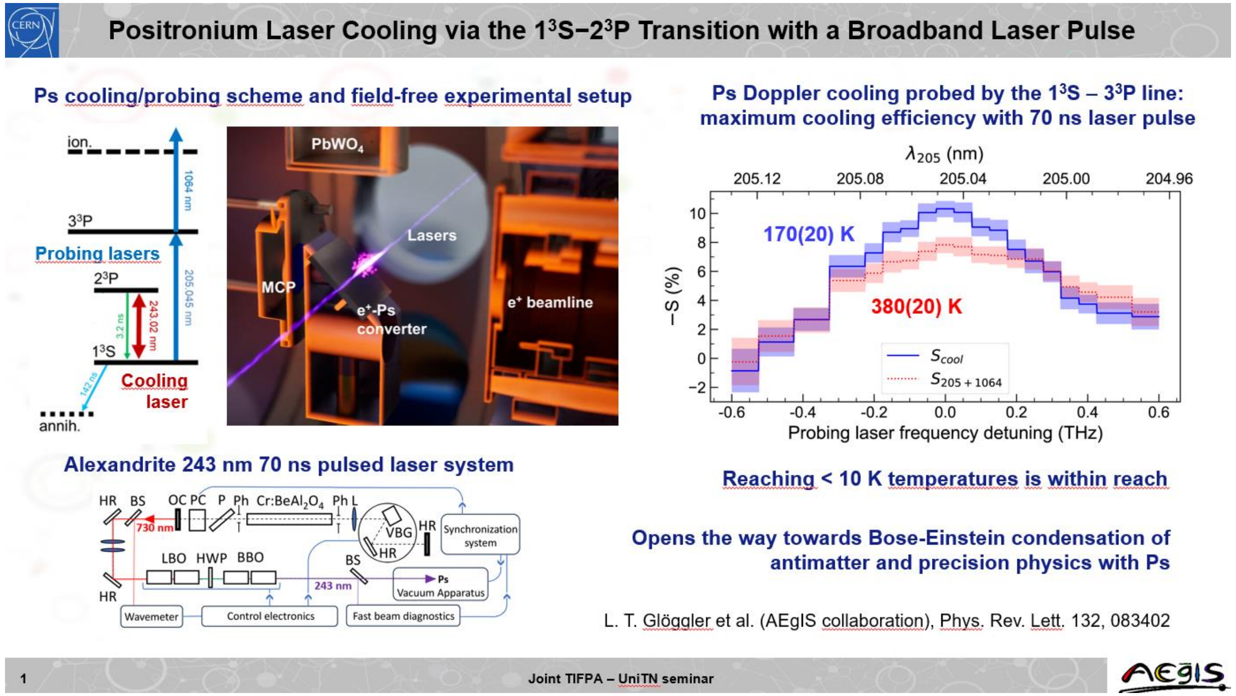
Very Recent Highlights



The Result

$a_{\bar{g}}$ = (0,75 ± 0,13 (stat. + syst.) ± 0,16 (simulation)) • g where g = 9,81 m/s^2

SPSC2024 J.S. Hangst, Aarhus University



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

Ps cooling/probing scheme and field-free experimental setup

Ps Doppler cooling probed by the 1^3S – 3^3P line: maximum cooling efficiency with 70 ns laser pulse

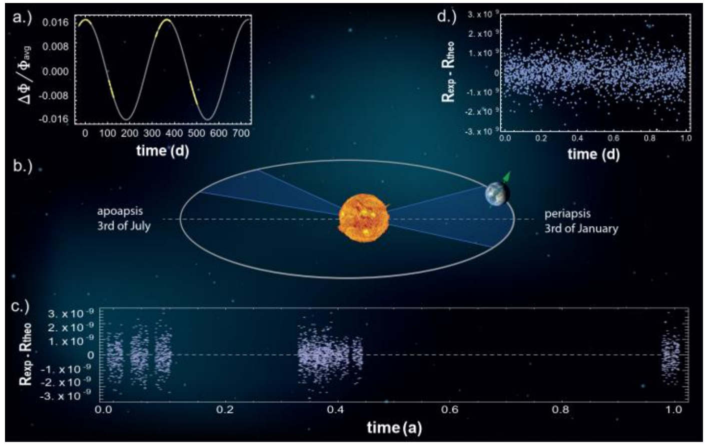
Alexandrite 243 nm 70 ns pulsed laser system

Reaching < 10 K temperatures is within reach

Opens the way towards Bose-Einstein condensation of antimatter and precision physics with Ps

L. T. Glöggler et al. (AEgIS collaboration), Phys. Rev. Lett. 132, 083402

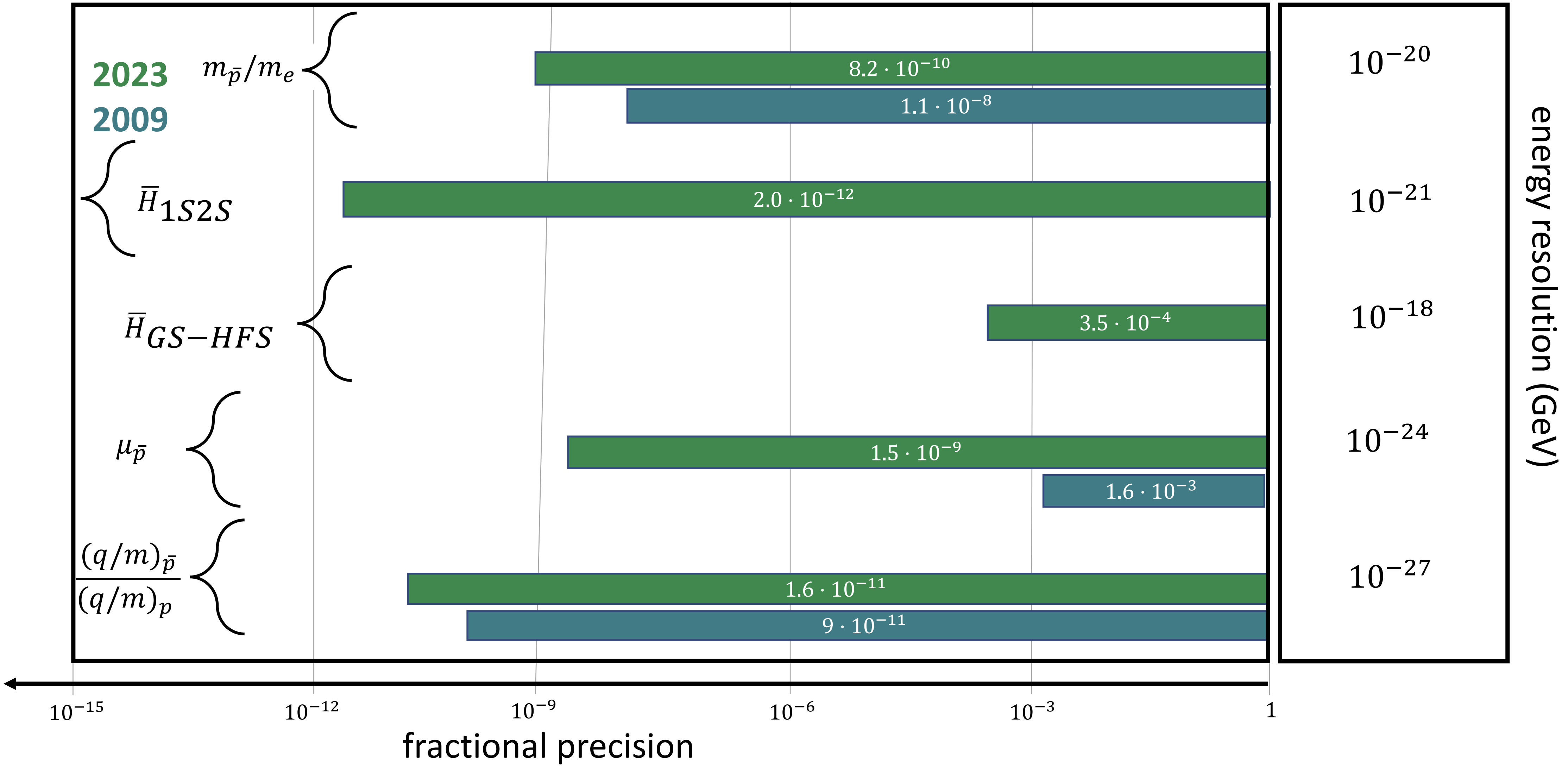
1 Joint TIFPA – UniTN seminar



- **ALPHA:** First measurement of the ballistic properties of antihydrogen in the gravitational field of the earth.
- **AEgIS:** First demonstration of laser cooling of positronium atoms.
- **BASE:** Most precise test of CPT invariance in the baryon sector.

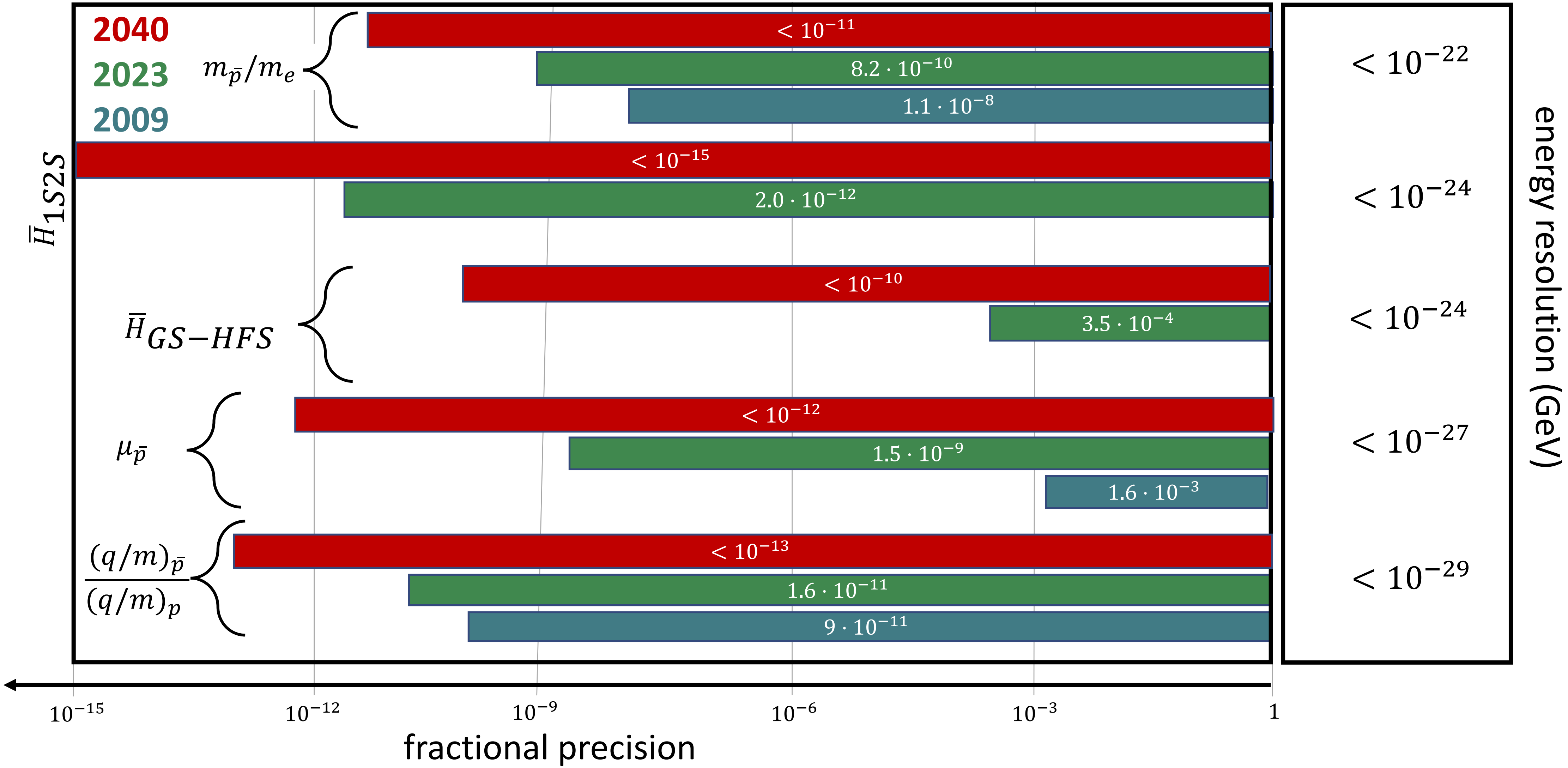
Achievements in Fundamental Constants

dramatic progress in experimental resolution since the program was started



…and many ideas around how to improve…

Future Perspective – Towards 2040 and beyond



…are looking forward to invitations by the SPSC to submit new proposals (invitation promised for 2024)

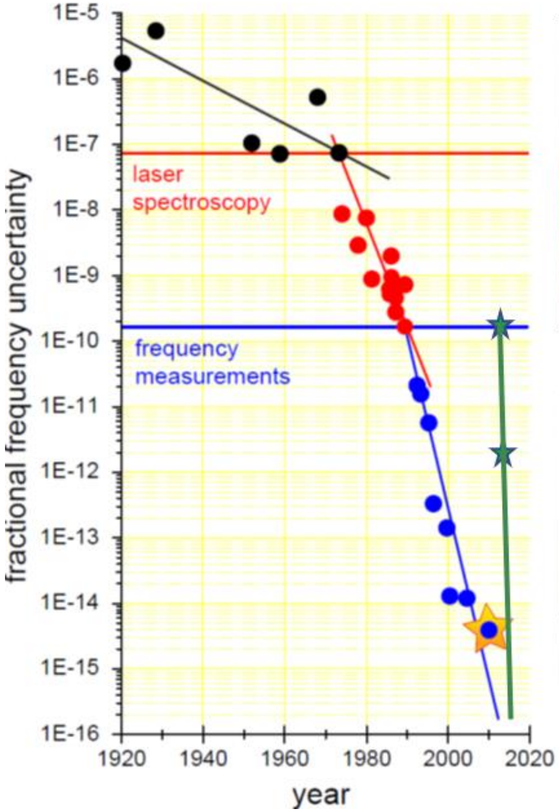
Moore’s Law in Precision Physics

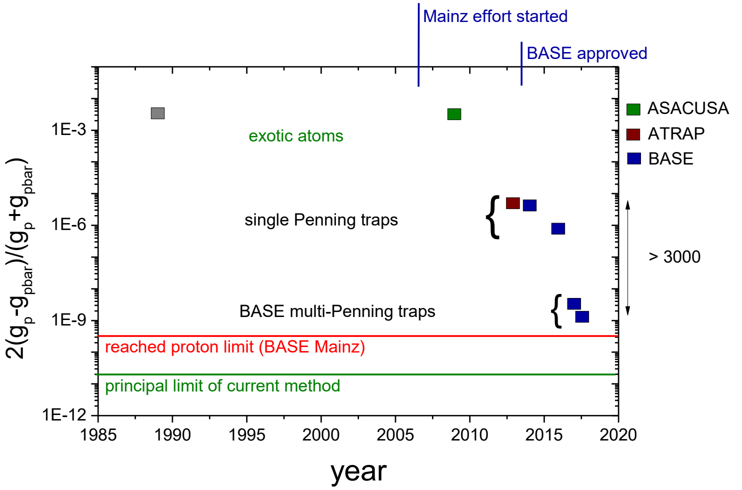
- **There is the rough estimate that precision improves by one order of magnitude per decade.**

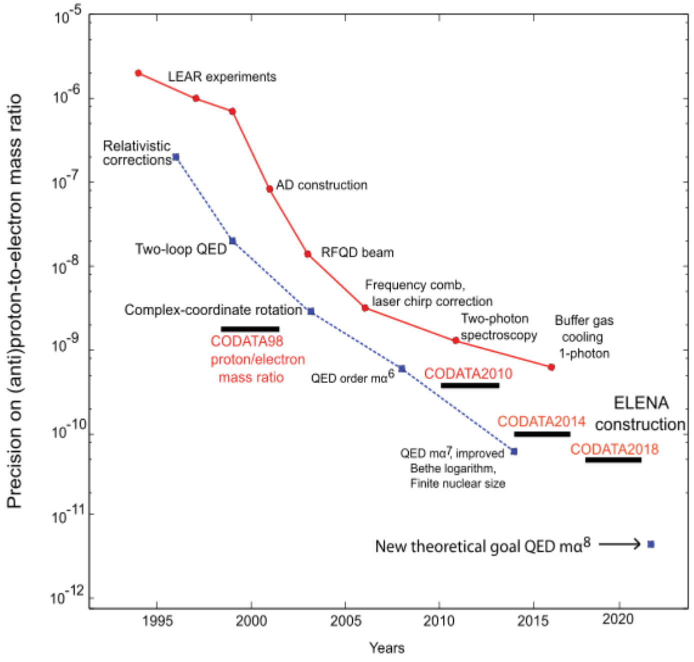
ALPHA: ppt measurements 5 years after first antihydrogen trapping

BASE: six orders of magnitude in an operation time of 7 years.

ASACUSA: three orders of magnitude in an operation time of about 20 years.







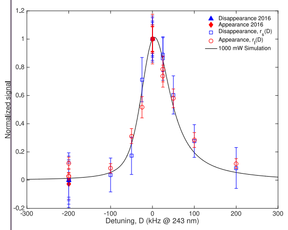
AD-experiments have proven that they usually outperfom Moore’s law

Physics Plans of Individual Collaborations

ALPHA – Collaboration

2024 2030 2035 2040

Study and refine laser-cooling of antihydrogen



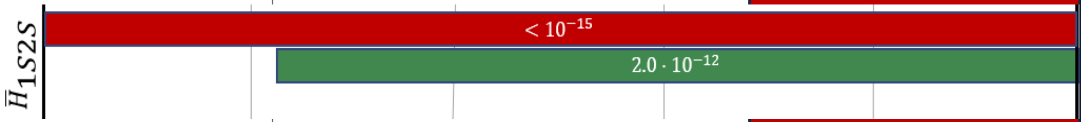
Integrate new metrology tools into the experimental program

Integrate sympathetic cooling of prositrons for enhanced Hbar production yield

Improve precision in ground state hyperfine splitting (ppm)

LS3
2026
2027

GOAL: achieve hydrogen-like precision for the 1S-2S transition (~10^{-15}). laser-cooled positrons, laser-cooled antihydrogen, better frequency metrology,…etc…



GOAL: direct **measurement of the Lamb shift** in antihydrogen

GOAL: Measurement of the antiproton charge radius using antihydrogen spectral lines.

ALPHA-g

- continue systematic characterisation of the three distinct ALPHA-g traps.
- implement laser cooling in ALPHA-g.
- best possible measurements of g-bar in ALPHA-g.
- begin integration of in-trap NMR resonator for driving transitions in antihydrogen.

LS4
2033
2034

Studies of anti-deuterium - spectroscopy and gravity, feasibility under consideration

Rich Spectrum of additional Ideas:

- antihydrogen atomic fountain spectroscopy
- field-free antihydrogen spectroscopy
- Spectroscopy of hydrogen and antihydrogen in the same trap

Gravity measurements with ppm resolution

Contributions to spectroscopy of H2+-bar

AEgIS

ALPHA

BASE
STEP

GBAR

AEgIS – Collaboration

2024 | 2030 | 2035 | 2040

Before LS3
(2023-2025)

Improve antihydrogen source flux by x100

Direct WEP test with antihydrogen in a magnetic field

Establishing laser cooling of positronium
Characterize Ps emission from transmission targets via Doppler spectroscopy

Form Rydberg antiprotonic ions in traps

LS3
2026
2027

After LS3

- Precise antihydrogen WEP test in a null magnetic field at 1% level
- Ps 1^3S-2^3S,1^3S-3^3S spectroscopy with a laser cooled source
- Spectroscopy of Rydberg antiprotonic atoms
- Time-of-flight mass spectrometry of trapped nuclear isotopes

Towards improved gravity exp.

LS4
2033
2034

Gravity measurements with ppm resolution

Studies of anti-deuterium - spectroscopy and gravity, feasibility under consideration

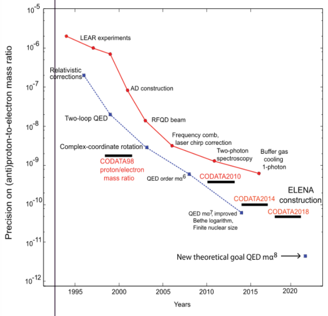
Rich Spectrum of additional Ideas:

- Spectroscopy search for an antiproton EDM in antiprotonic molecules
- DM search via pbar-^{3}He in traps
- Anti-^{3}He synthesis by fusion between anti-p and anti-d

ASACUSA Collaboration

2024 2030 2035 2040

First Rabi GS-HFS measurement before LS3

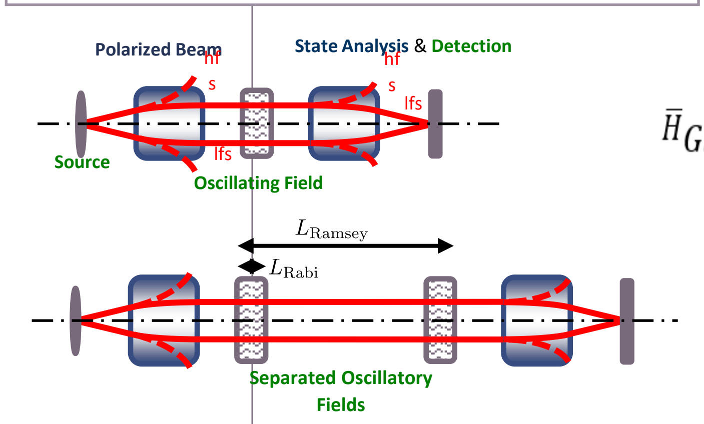


Use cooled antiproton beam of ELENA instead of uncooled beam of RFQD

Determine the antiproton-to-electron mass ratio

LS3
2026
2027

Rabi GS-HFS measurement after LS3 with ppm resolution, afterwards application of a Ramsey scheme with goal to reach 10 ppb resolution



Test QED of antiprotons with **10 to 100x higher precision than before.** (trap precision level)

Determine upper limits on beyond Standard Model fifth forces and spin-dependent forces.

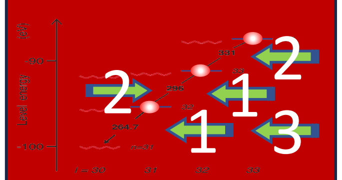
More experiments with superfluid pbarHe

LS4
2033
2034

Long term vision: Atomic fountain spectroscopy, requires however an entirely new setup. – towards ppt-spectroscopy

Rich Spectrum of additional Ideas:

- Spectroscopy of Rydberg antihydrogen
- Antiproton annihilation studies on different targets
- Antiprotonic atom formation studies
- Studies of Pontecorvo reactions

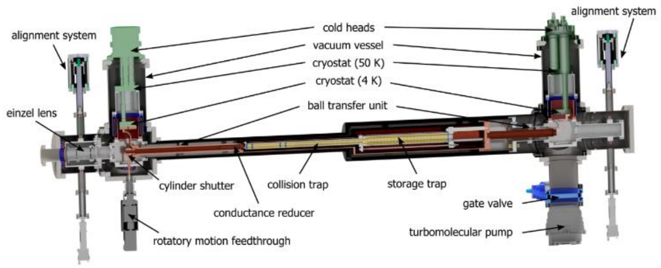


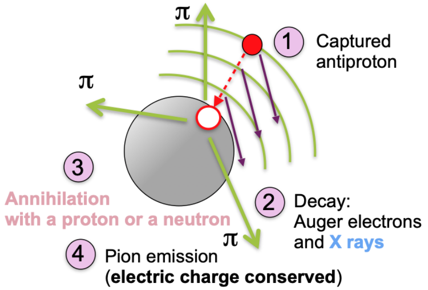
- Measure additional narrow sub-doppler transitions

program using slow extracted antiprotons for nuclear / hadron physics as well as atomic collisions

PUMA and GBAR Collaborations

- **PUMA 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





The physics program of PUMA for **order 10 years (2036/2037)**, including the development of the method and setup optimisation at ELENA, and measurements at ISOLDE (just approved by the SPSC).

- PUMA is investigating the feasibility and interest of hypernuclei physics at ELENA, if the idea becomes reality, this could last **until 2040** (proposal/LoI to be submitted).

GBAR: Collaboration successfully produced antihydrogen in their apparatus.

Main project after LS3: precision measurement of the gravitational acceleration of antimatter

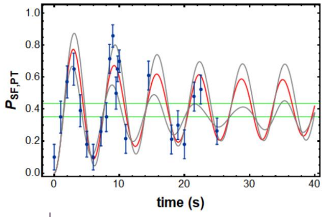
- first: below 10 % $\bar{g}$ measurement with 100 detected cold antiatoms
- second: 10^{-2} - 10^{-3} precision with increased statistics (1000 events)
- next steps: QGS interferometry, toward a sub 10^{-5} precision *EPJD **76**, 209 (2022)*

- **Continuity of ongoing side-projects**
  - Lamb shift precision measurement and antiproton charge radius *PRD **94**, 052008 (2016)*
  - Cross sections measurements ($\overline{\mathrm{H}}, \overline{\mathrm{H}}^{+}, \overline{\mathrm{H}}_2^{-}$) at low energies
- **Other projects under discussion and ideas for after LS4**
  - Further in-flight antihydrogen spectroscopy (n=2 fine structure)
  - Production of antihydrogen molecular ion spectroscopy (more stringent CPT test than $\overline{\mathrm{H}}$) *PRA **98**, 010101(R) (2018)*
  - Ultracold antihydrogen in optical trap (*Hyp. Int. **214**, 60 (2020)*) / atom chip trap, for single anti-atom spectroscopy

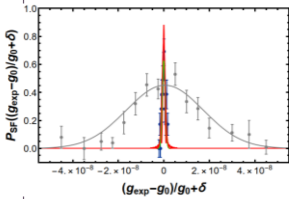
BASE – Collaboration

2024 2030 2035 2040

Coherent Spin Spectroscopy

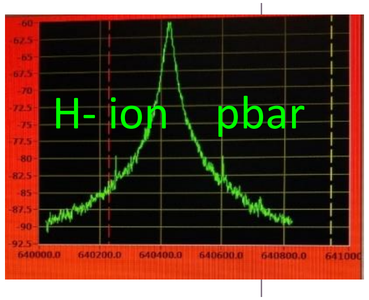


GOAL: Measurement of the antiproton magnetic moment with 10 p.p.t. precision



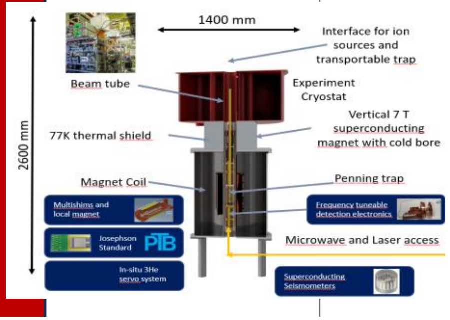
LS3
2026
2027

Antiproton/H- ion crystal spectroscopy



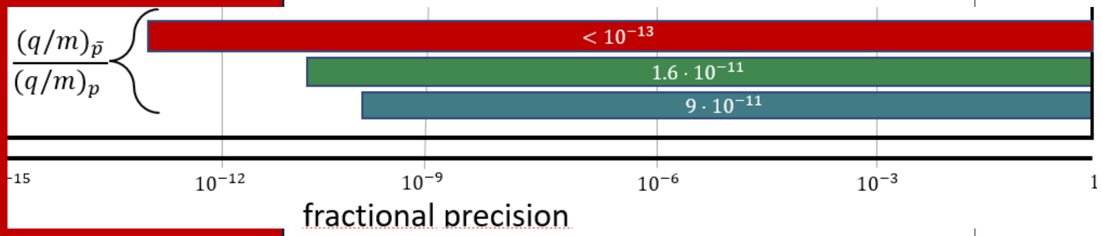
Simultaneous spectroscopy on two particles on magnetron.locked trap orbits for decoherence-free subspace measurements

GOAL: Measurement of the proton/antiproton charge/mass ratio with sub-p.p.t. precision.



Offline laboratory operation

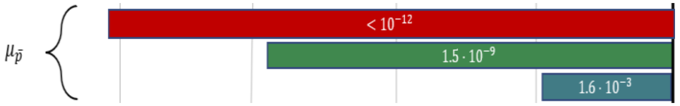
LS4
2033
2034



Quantum logic spectroscopy with single trapped antiprotons

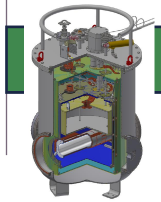
GOAL: Measurement of the antiproton magnetic moment with sup-p.p.t. precision

Considered: Constraining the EDM of the antiproton by spin spectroscopy in inhomogeneous magnetic fields.



Preparation of g-factor ratio measurements

Contributions to spectroscopy of H2+-bar



Offline Antiproton Experiment Operation using the transportable trap **BASE-STEP**

BASE-CDM and BASE-LEPTON

Potential New Proposals

New Proposals - CPT test via comparison of H_2^+ with anti-H_2^+

Input by Schiller et al.

- Hydrogen to antihydrogen comparisons test among others

$$\frac{E_h}{\bar{E}_h} \propto \frac{(q_e)^2(q_p)^2\, m_e}{(q_{\bar{e}})^2(q_{\bar{p}})^2\, m_{\bar{e}}} = 1\,?$$

(dependence on $(m_e/m_p)/\,(m_{\bar{e}}/m_{\bar{p}})$ suppressed by 3 oom (red. mass))

- Compare one vibrational frequency in H_2^+ with the same in anti-H_2^+

$$\frac{f_{\mathrm{vib}}}{\bar{f}_{\mathrm{vib}}} \propto \frac{(q_e)^2(q_p)^2(m_e)^{3/2}(m_p)^{-1/2}}{(q_{\bar{e}})^2(q_{\bar{p}})^2(m_{\bar{e}})^{3/2}(m_{\bar{p}})^{-1/2}} = 1\,?$$

- Only system which gives direct access to antiproton/antiproton interaction.

$$\frac{f_m/f_n}{\bar{f}_m/\bar{f}_n} = 1\,? \quad \rightarrow \quad \frac{m_p/m_e}{m_{\bar{p}}/m_{\bar{e}}} = 1\,?$$

Ratios of different vibrational frequencies depend only on m_p/m_e (neglecting higher-order effects)

Accuracy: *potentially at the 10^{-17} level **

- **Statement:** Not a serious proposal yet, since engineering of a feasible source is outstandingly difficult.
  - requires an instrument similar to **ALPHA**, providing higher antihydrogen yield, plus one additional mixing stage, plus an experiment similar to **BASE**, with laser access (as prepared in the BASE-logic setup) or transportable trap (as BASE-STEP, FUNDING?).
  - **ALPHA** and **BASE** considering to join forces (very long term >10 years) with H_2^+ spectroscopy experts from Düsseldorf (Schiller).
  - Ideas by Schiller / Myers / Sturm currently probed with HD_2^+ at ALPHATRAP (MPIK) and H_2^+ at HHU (Schiller) and ETH (Kienzler / Home / Crivelli)

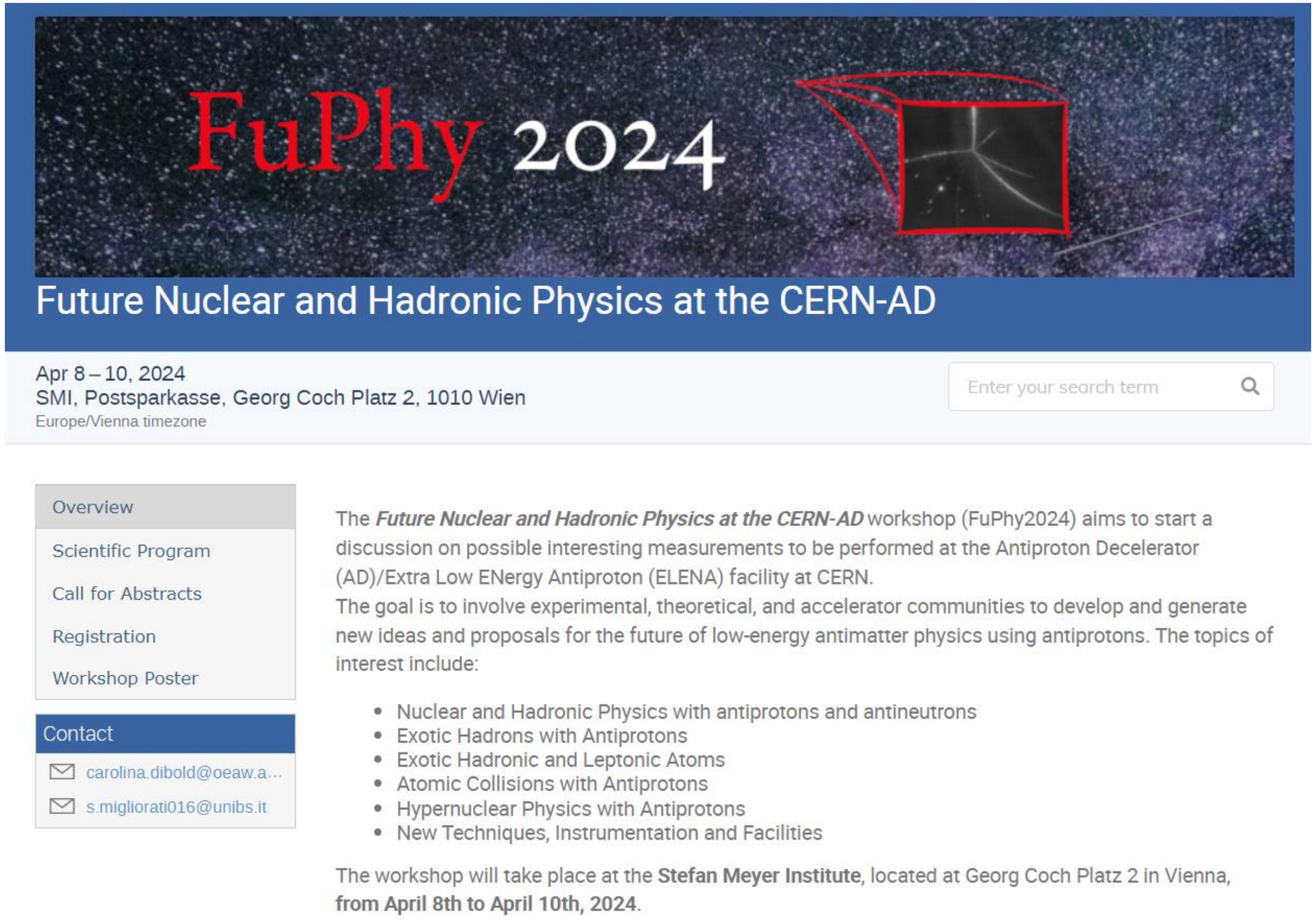
[1] Dehmelt, Phy. Scr. T59, 432 (1995)
[2] Myers, PRA 98, 010101(R) (2018)
[3] Schiller and Korobov, PRA 71, 032505 (2005)

* Schiller et al., PRL 113, 023004 (2014)
Karr, J. Mol. Spec. 300, 37 (2014)

More to Come

Solid ideas to develop hydrogen optical lattice clock in collaboration of MPQ-Garching and RIKEN -> translate these ideas, once worked-out and available, to the spectroscopy of anthydrogen (fractional resolution of lattice clocks is at the 10^{-18}level)

- Initiative to establish at CERN-AD a program for Nuclear and Hadronic Physics
- Workshop at SMI Vienna in April 2024
- Register here: Future Nuclear and Hadronic Physics at the CERN-AD (8-April 10, 2024): Overview · Indico



FuPhy 2024

Future Nuclear and Hadronic Physics at the CERN-AD

Apr 8 – 10, 2024
SMI, Postsparkasse, Georg Coch Platz 2, 1010 Wien
Europe/Vienna timezone

carolina.dibold@oeaw.a…
s.migliorati016@unibs.it

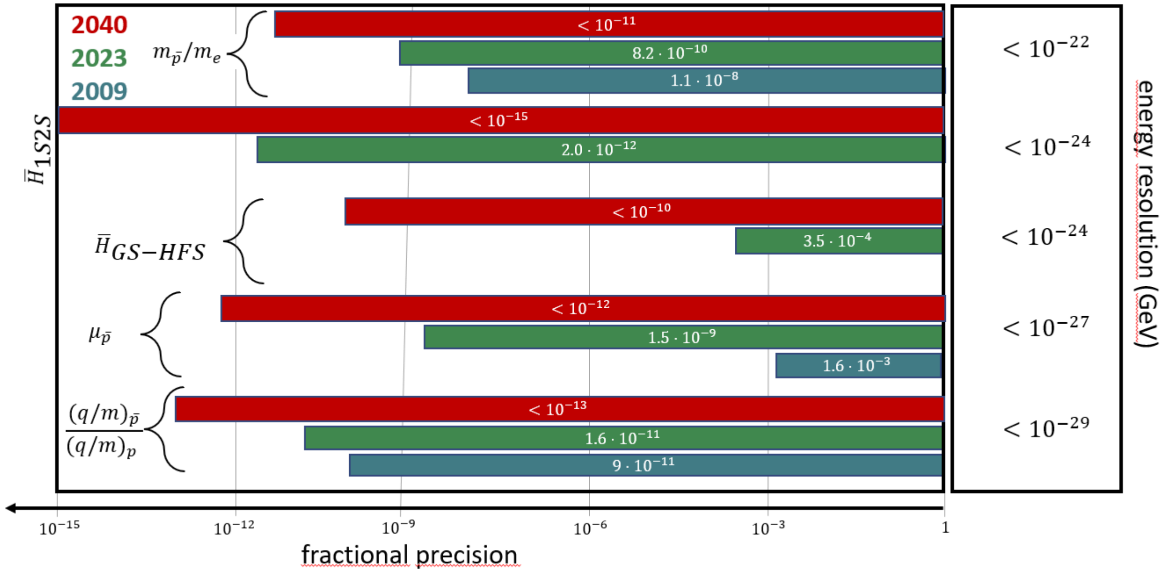
The *Future Nuclear and Hadronic Physics at the CERN-AD* workshop (FuPhy2024) aims to start a discussion on possible interesting measurements to be performed at the Antiproton Decelerator (AD)/Extra Low ENergy Antiproton (ELENA) facility at CERN.
The goal is to involve experimental, theoretical, and accelerator communities to develop and generate new ideas and proposals for the future of low-energy antimatter physics using antiprotons. The topics of interest include:

- Nuclear and Hadronic Physics with antiprotons and antineutrons
- Exotic Hadrons with Antiprotons
- Exotic Hadronic and Leptonic Atoms
- Atomic Collisions with Antiprotons
- Hypernuclear Physics with Antiprotons
- New Techniques, Instrumentation and Facilities

The workshop will take place at the **Stefan Meyer Institute**, located at Georg Coch Platz 2 in Vienna, **from April 8th to April 10th, 2024**.

Summary

- AD collaborations produced dramatic progress in recent years,
  - Several milestones achieved:
    - Trapping of antihydrogen
    - Spectroscopy of antihydrogen
    - Laser-cooling of antihydrogen
    - Production of a beam of antihydrogen
    - 2 photon spectroscopy of antiprotonic helium
    - Non-destructive spin quantum spectroscopy with antiprotons
    - Axion/antimatter coupling
    - Antihydrogen production via charge exchange
- …and **have outlined plans to operate until 2040 at least**.
- Detailed proposals that outline the plans until 2040 **AND BEYOND** will be submitted on invitation by the SPSC, this invitation was promised to come **early 2024 and to be evaluated in 2025**.



- Potential new big long-term projects that would last beyond 2040:
  - Spectroscopy of antihydrogen molecular ions
  - Towards Anti-deuterium
  - Antihydrogen lattice-clocks
  - …to be discussed in the next evaluation round of the SPSC….

Thanks…

- …in the name of all collaborations, thanks very much to CERN and the awesome team of AD operators which make this physics program possible!!!

- …and thanks to many more which support the program
  - **Cryolab !!!**
  - Vacuum group,….
  - Engineering department….and many more…

General happiness by the users about great support and the fantastic new ELENA machine

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
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

ASACUSA collaboration

C. Amsler[a], D. Barna[b], H. Breuker[c], M. Bumbar[a], S. Chesnevskaya[a], G. Costantini[d], R. Ferragut[e], M. Giammarchi[f], A. Gligorova[a], G. Gosta[d], H. Higaki[g], M. Hori[h,i*], E. D. Hunter[a], Y. Kanai[j], C. Killian[a], V. Kletzl[a], V. Kraxberger[a], N. Kuroda[k], A. Lanz[a], M. Leali[d], V. Mäckel[a,c], G. Maero[l], C. Malbrunot[m], V. Mascagna[d], Y. Matsuda[k], S. Migliorati[d], D. J. Murtagh[a], Y. Nagata[n], A. Nanda[a], L. Nowak[m], F. Parnefjord Gustafsson[a], E. Pasino[l], W. Pirkl[h], M. Romé[l], M. C. Simon[a], M. Tajima[j], V. Toso[e], U. Uggerhøj[o], S. Ulmer[c], L. Venturelli[d], A. Weiser[a], E. Widmann[a*], T. Wolz[m], Y. Yamazaki[c], J. Zmeskal[a]

[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

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

PUMA collaboration

T. Aumann, N. Azaryan, W. Bartmann, A. Bouvard, O. Boine-Frankenheim, A. Broche, F. Butin, D. Calvet, J. Carbonell, P. Chiggiato, H. De Gersem, R. De Oliveira, T. Dobers, E. Ehm, J. Ferreira Somoza, **J. Fischer**, M. Fraser, **E. Friedrich**, M. Gomez-Ramos, J.-L. Grenard, G. Hupin, K. Johnston, **C. Klink**, M. Kowalska, **Y. Kubota**, P. Indelicato, R. Lazauskas, S. Malbrunot-Ettenauer, N. Marsic, W. Müller, S. Naimi, N. Nakatsuka, R. Necca, D. Neidherr, A. Obertelli, Y. Ono, S. Pasinelli, N. Paul, E. C. Pollacco, D. Rossi, H. Scheit, **M. Schlaich**, R. Seki, **A. Schmidt**, L. Schweikhard, S. Sels, E. Siesling, T. Uesaka, M. Wada, **F. Wienholtz**, S. Wycech, **C. Xanthopoulou**, **S. Zacarias**

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

60 Research Institutes/Universities – 339 scientists – 6 Collaborations

All Collaborations: *DURING* LS3

Very important:** All collaborations can make significant progress without pbars; the community needs **helium and services as much as possible.

- Magnetometry studies in ALPHA-g – crucial for future precision gravity measurements.
- Microwave B-field component measurements using Be^+ spin flips.
- Establish trapping of HYDROGEN in ALPHA-2 and ALPHA-g for direct comparisons.
- Shutdown antiproton measurements in BASE (significantly improved stability conditions / BASE can work on reservoir), during LS3.
- Proton mass and magnetic moment measurements in BASE.
- Positron physics in GBAR.
- Positronium physics in AEgIS.
- Hydrogen beam measurements in ASACUSA.

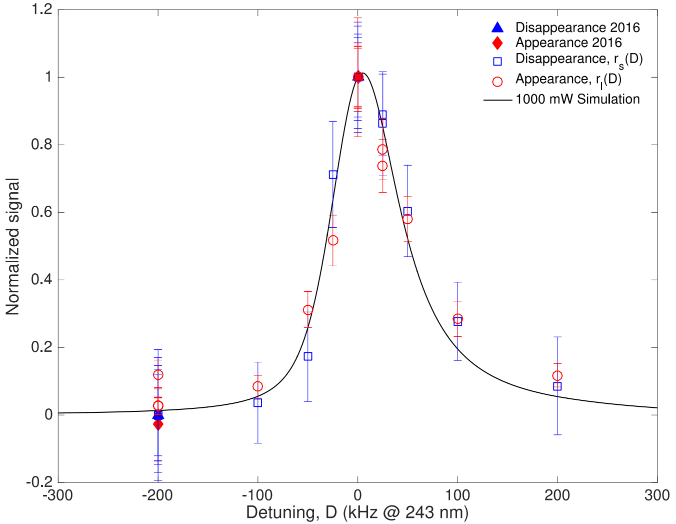
ALPHA Collaboration

Antihydrogen in ALPHA - highlights

The only experiment which traps antihydrogen (very difficult), and has access to «non-destructive» measurements on antihydrogen (long observation times).

- **Prior to LS1**
  - **Trapped antihydrogen**. Nature **468**, 673–676 (2010). https://doi.org/10.1038/nature09610
  - Confinement of antihydrogen for 1,000 seconds. Nature Phys **7**, 558–564 (2011). https://doi.org/10.1038/nphys2025
  - **Resonant quantum transitions in trapped antihydrogen atoms**. Nature **483**, 439–443 (2012). https://doi.org/10.1038/nature10942
  - Description and first application of a new technique to measure the gravitational mass of antihydrogen. Nat Commun **4**, 1785 (2013). https://doi.org/10.1038/ncomms2787
  - An experimental limit on the **charge of antihydrogen**. Nat Commun **5**, 3955 (2014). https://doi.org/10.1038/ncomms4955

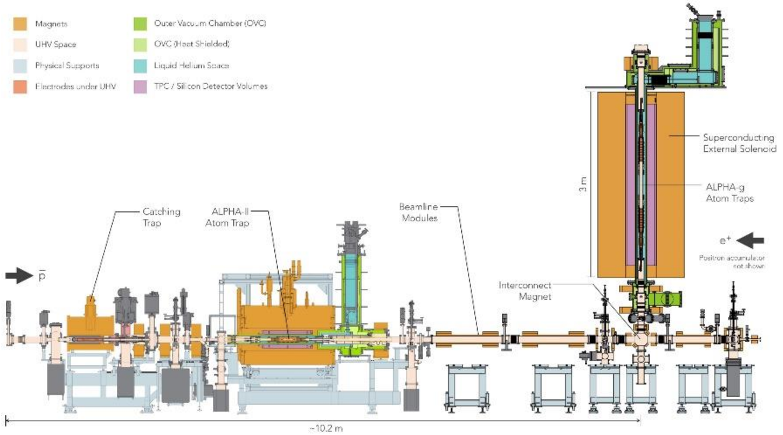
- **Since LS1**
  - An improved limit on the charge of antihydrogen from stochastic acceleration. Nature **529**, 373–376 (2016). https://doi.org/10.1038/nature16491
  - **Observation of the 1S–2S transition in trapped antihydrogen**. Nature **541**, 506–510 (2017). https://doi.org/10.1038/nature21040



consistent with expectations for hydrogen to about 2 x 10^{-12}

Antihydrogen in ALPHA - highlights

- Observation of the hyperfine spectrum of antihydrogen. Nature **548**, 66–69 (2017). https://doi.org/10.1038/nature23446
- Antihydrogen accumulation for fundamental symmetry tests. Nat Commun **8**, 681 (2017). https://doi.org/10.1038
- **Characterization of the 1S–2S transition in antihydrogen**. *Nature* **557**, 71–75 (2018). https://doi.org/10.1038/s41586-018-0017-2
- Observation of the 1S–2P Lyman-α transition in antihydrogen. Nature **561**, 211–215 (2018). https://doi.org/10.1038/s41586-018-0435-1



- **ALPHA-g installed (2018)**

  - Investigation of the fine structure of antihydrogen. Nature **578**, 375–380 (2020). https://doi.org/10.1038/s41586-020-2006-5
  - **Laser cooling of antihydrogen atoms**. Nature **592**, 35–42 (2021). https://doi.org/10.1038/s41586-021-03289-6
  - Sympathetic cooling of positrons to cryogenic temperatures for antihydrogen production. Nat Commun **12**, 6139 (2021). https://doi.org/10.1038/s41467-021-26086-1


The international journal of science / 1 April 2021

outlook Sports science

nature

LASER-COOLED ANTIMATTER

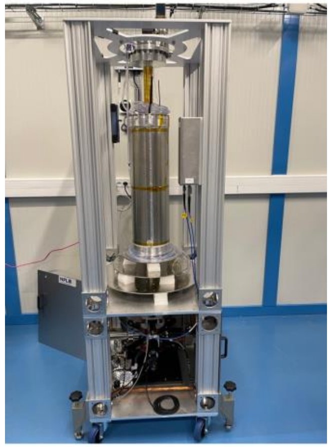
Ultraviolet beam manipulates and cools antihydrogen atoms

Coronavirus The race to improve indoor air quality to help curb COVID-19

Heart of glass Full atomic structure of amorphous solid determined in 3D

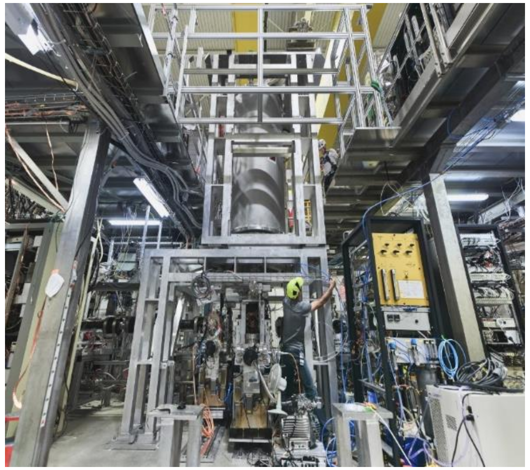
Tumour targets Bacterial peptides help flag melanoma cells to the immune system

Goals before LS3



- **ALPHA-2/3**
  - study and refine laser cooling of antihydrogen.
  - integrate new metrology tools into the experimental program.
  - **achieve hydrogen-like precision** for the 1S-2S transition (~10^{-15}).
  - direct **measurement of the Lamb shift** in antihydrogen.
  - improve precision on the **ground state hyperfine spectrum.**
  - investigate other laser-spectral lines; implement fluorescence detection; antiproton charge radius; anti-rydberg (ALPHA-3).
  - integrate sympathetic cooling of positrons by laser-cooled Be ions to antihydrogen production.

- **ALPHA-g**
  - continue systematic characterisation of the three distinct ALPHA-g traps.
  - implement laser cooling in ALPHA-g.
  - best possible measurements of g-bar in ALPHA-g.
  - begin integration of in-trap NMR resonator for driving transitions in antihydrogen.



Perspectives after LS3

- improvements in precision of existing measurements
- direct comparisons of hydrogen and antihydrogen in the same trap
- antihydrogen NMR spectroscopy
- fountain experiments with antihydrogen – gravitational interferometry
- extraction of antihydrogen into field-free space for spectroscopy
- possible investigation of the antihydrogen molecular ion $\overline{H}_2^-$

↓

speculative and preliminary, discussions about feasibility between **ALPHA and BASE** started.

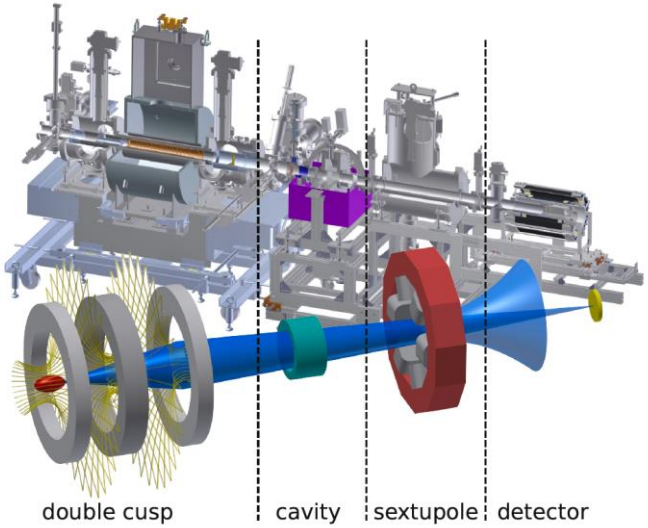
(see detail-slide below)

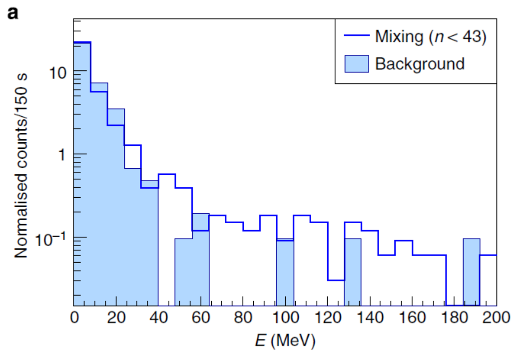
ALPHA has a very bright future ahead and more the problem to decide what to do FIRST

ASACUSA Collaboration

ASACUSA Cusp experiment - status

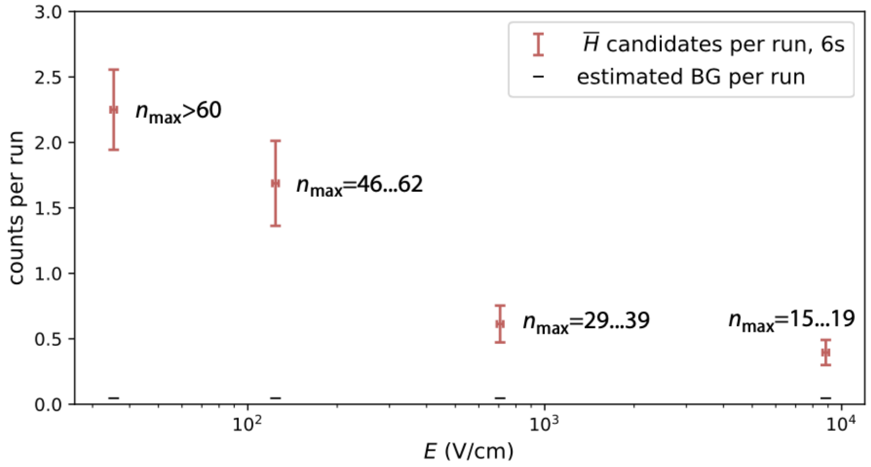
- **$\bar{\mathrm{H}}$ ground-state hyperfine splitting** measurement in a beam
  - Polarized $\bar{\mathrm{H}}$ beam from Cusp trap
  - Rabi-type spectroscopy
  - Compared to ALPHA: Field free region
    - Sensitive to different physics couplings.





N. Kuroda et al, *Nat. Commun.* **5,** 3089 (2014).

- **Achieved Milestones**
  - 2010 1st production of $\bar{\mathrm{H}}$.
  - 2014 1st $\bar{\mathrm{H}}$ beam observed 2.7 m downstream of formation region.
  - 2016 ppb-scale measurement of H hyperfine splitting using same apparatus.
  - 2021 measurement of $\bar{\mathrm{H}}$ principal quantum number distribution in a beam.

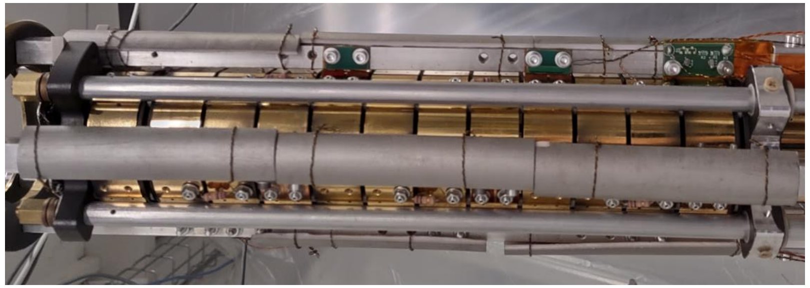


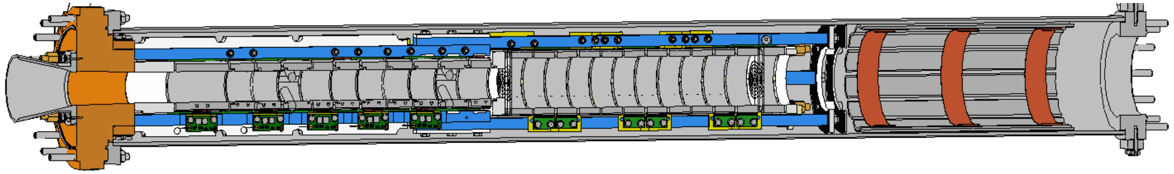
B. Kolbinger et al., *EPJ D* 75, (2021) 91.

Developments and Achievements after LS2

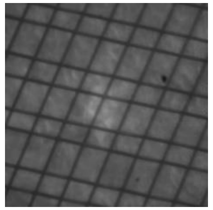
- **New Cusp cold bore**

Ceramic “bracelet” to absorb cyclotron radiation from the plasma

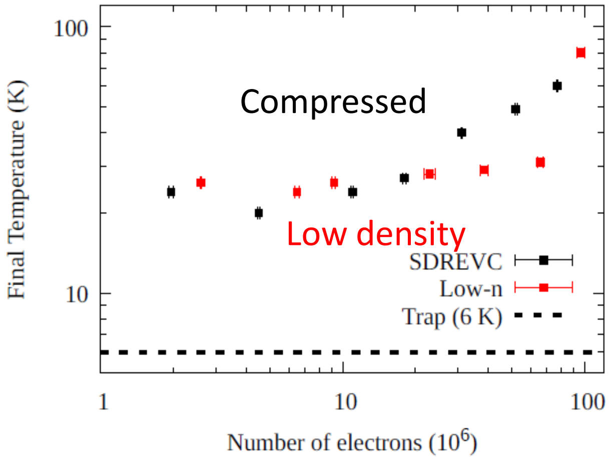


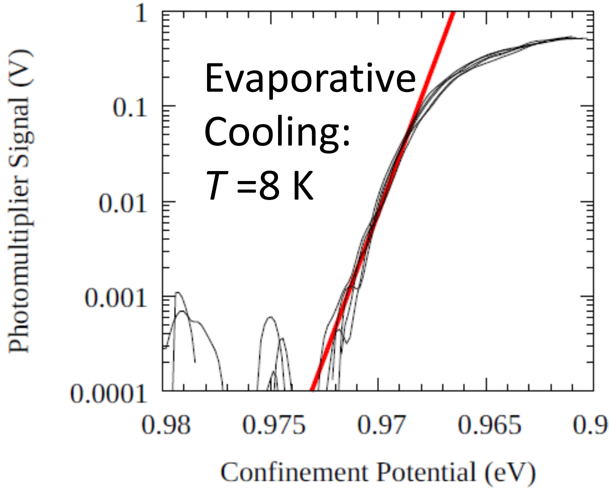


High transparency <u>copper mesh</u> to reflect incoming microwaves
0.25 mm pitch
0.03 mm wire diameter
>20 dB attenuation at 60 GHz



- **100 K colder electron plasmas** compared to before
- **SDREVC** implemented
  - Improved reproducibility



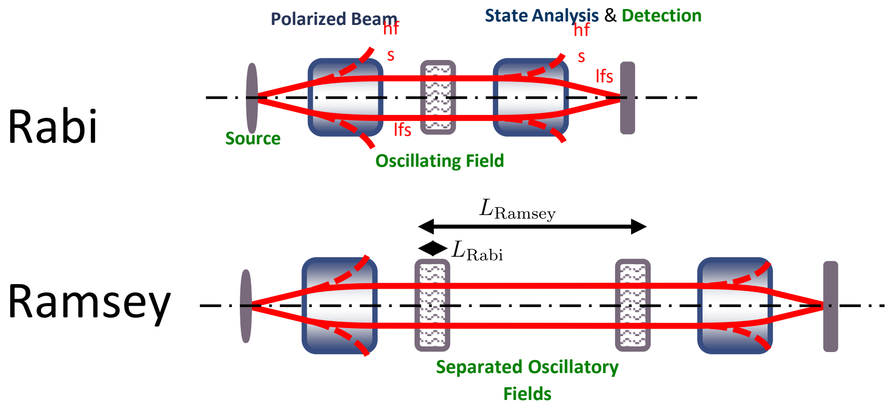


E. Hunter et al., *EPJ Web Conf.* 262 01007 (2022)
C. Amsler et al., *Physics of Plasmas* 29 (2022) 08330

Performance of upgrades looks very good, to be confirmed it pays off with increased production yield

Future program beyond LS3

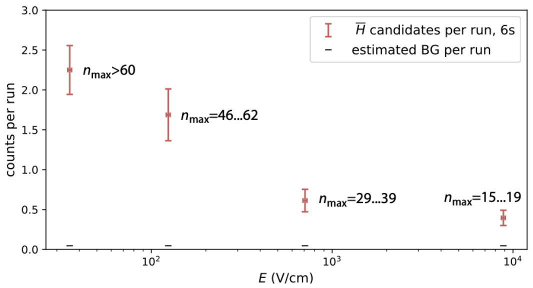
- **$\overline{\mathrm{H}}$ ground-state hyperfine splitting**
  - In-beam: complementary to in-trap
  - 1st Rabi measurement before LS3
  - After LS3:
    - <1 ppm with Rabi measurement
    - Ramsey: factor ~ 20
    - Better resolution: colder $\overline{\mathrm{H}}$
      - Trapping, cooling, extraction



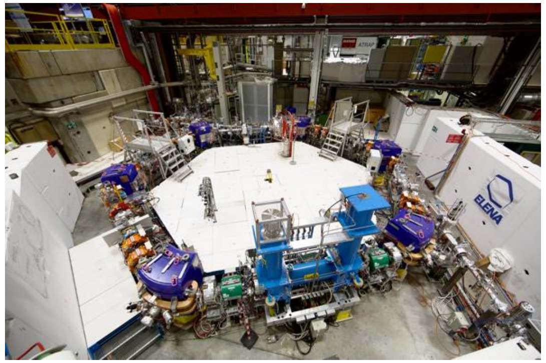
- **Spectroscopy of Ry-$\overline{\mathrm{H}}$**
  - Initially copiously produced
- Existing techniques used with matter will allow us to control Rydberg states of antihydrogen [1]
- Spectroscopy can be performed using Ramsey separated oscillating field techniques [2]
- Spectroscopy of $\overline{\mathrm{H}}$ and H can take place in the same apparatus
- It may be possible to produce cold samples (~150 mK) of antihydrogen [3]
- Maybe interesting to investigate 5th forces [4]

[1] Vliegen E, Merkt F (2006) *Stark deceleration of hydrogen atoms*. J Phys B: At Mol Opt Phys 39: 241.
[2] De Vries, Joel Christopher, 1993, PhD Thesis http://hdl.handle.net/1721.1/8292

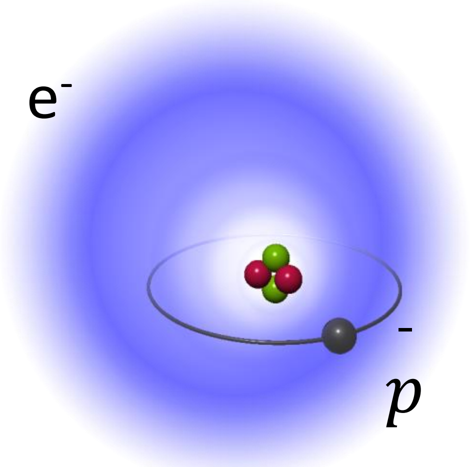
[3] Hogan SD, Merkt F (2008) *Demonstration of three-dimensional electrostatic trapping of state-selected Rydberg atoms.* Phys Rev Lett 100: 043001.
[4] Matthew P. A. Jones and Robert M. Potvliege, *Probing new physics using Rydberg states of atomic hydrogen*, Phys. Rev. Res. 2, 013244 (2020)



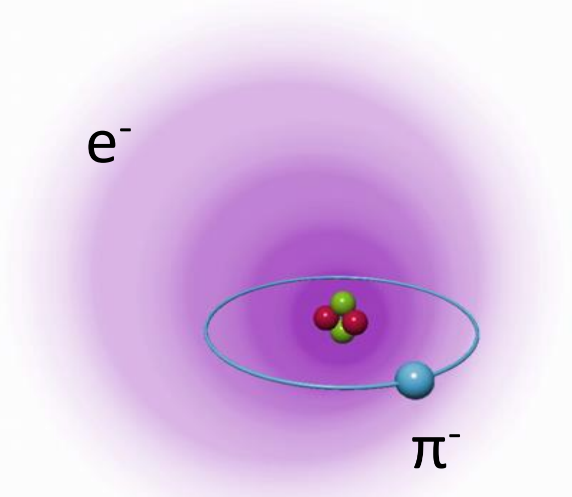
Laser spectroscopy of antiprotonic/pionic helium



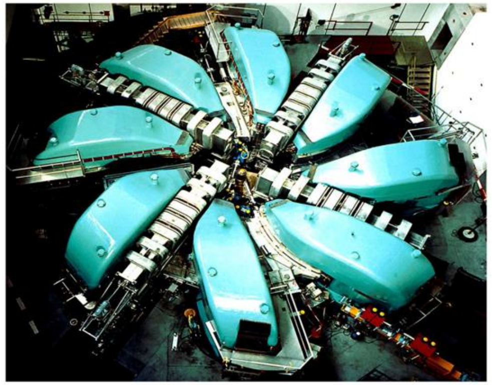
ELENA



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



πHe$^+$: pionic helium



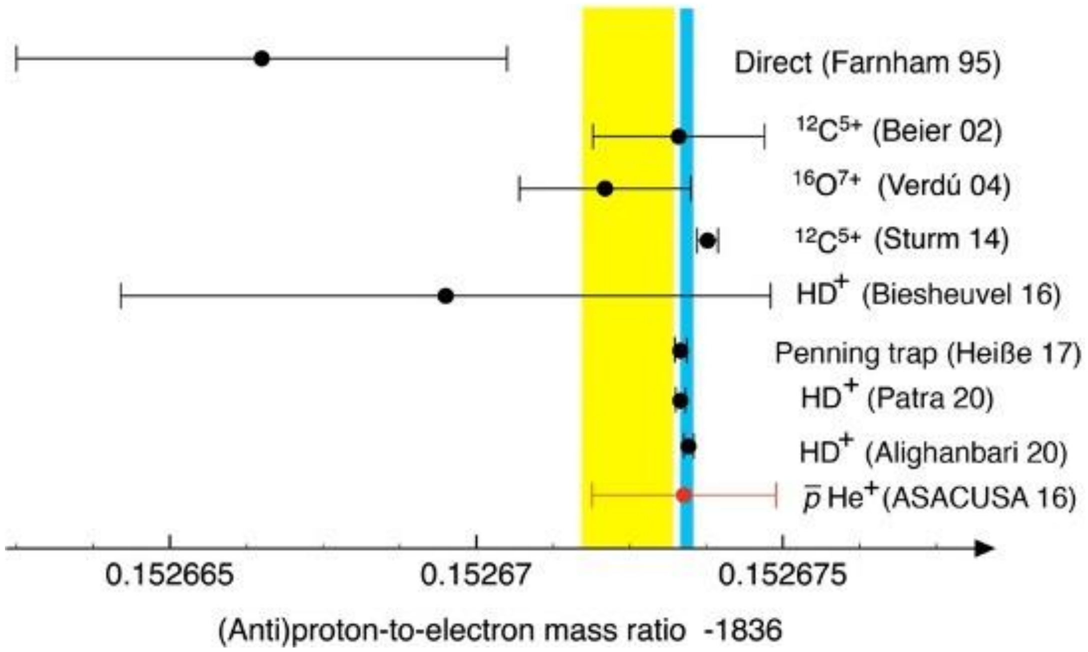
PSI

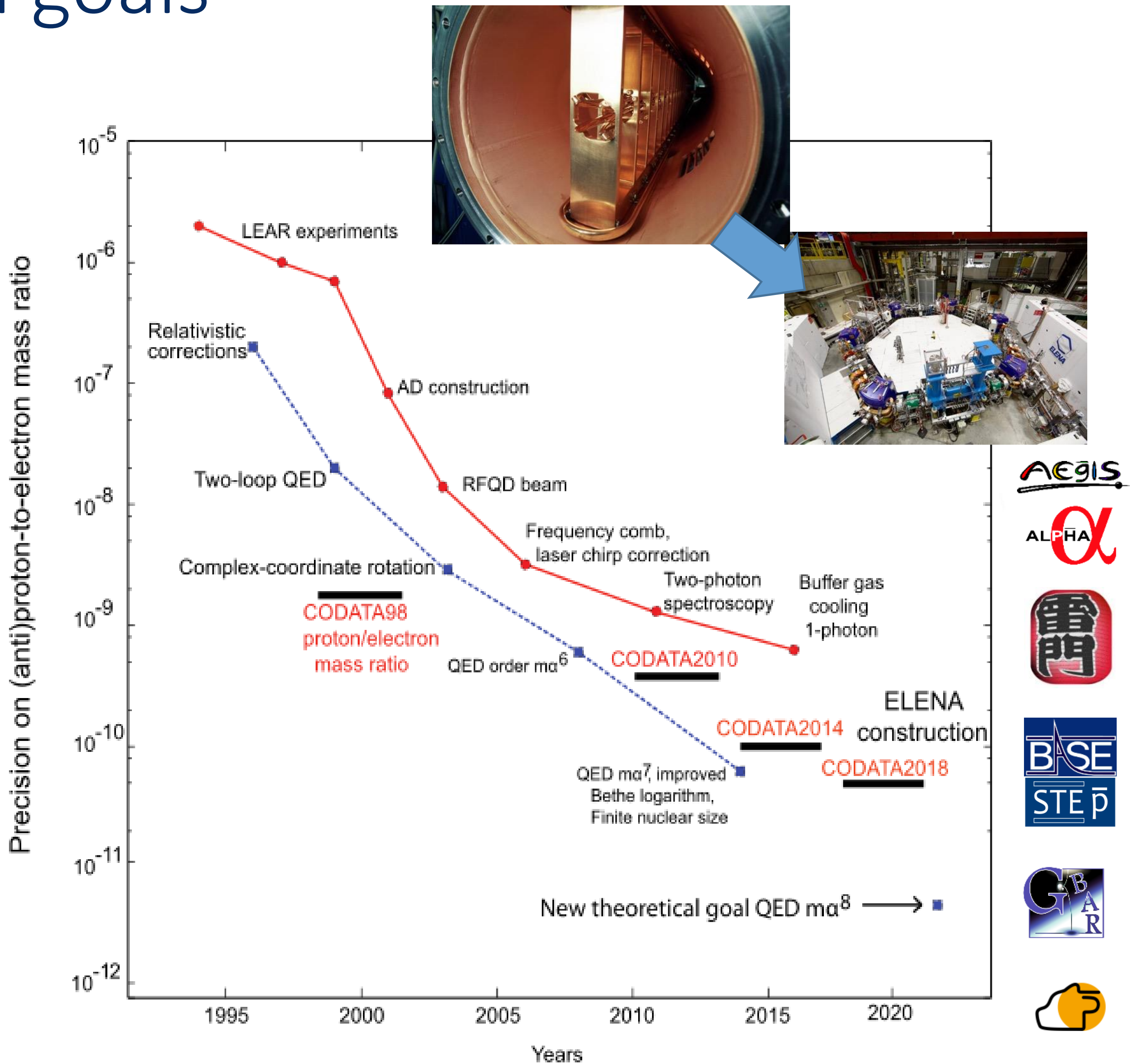
2003: Laser spectroscopy with 80 keV beam of radiofrequency quadrupole decelerator	*PRL* 91, 123401 (2003)
2005: Synthesis of cold two-body Rydberg antiprotonic helium ions	*PRL* 94, 063401 (2005)
2006: First accelerator experiment to use femtosecond optical frequency comb	*PRL*. 96, 243401 (2006)
2011: 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**.

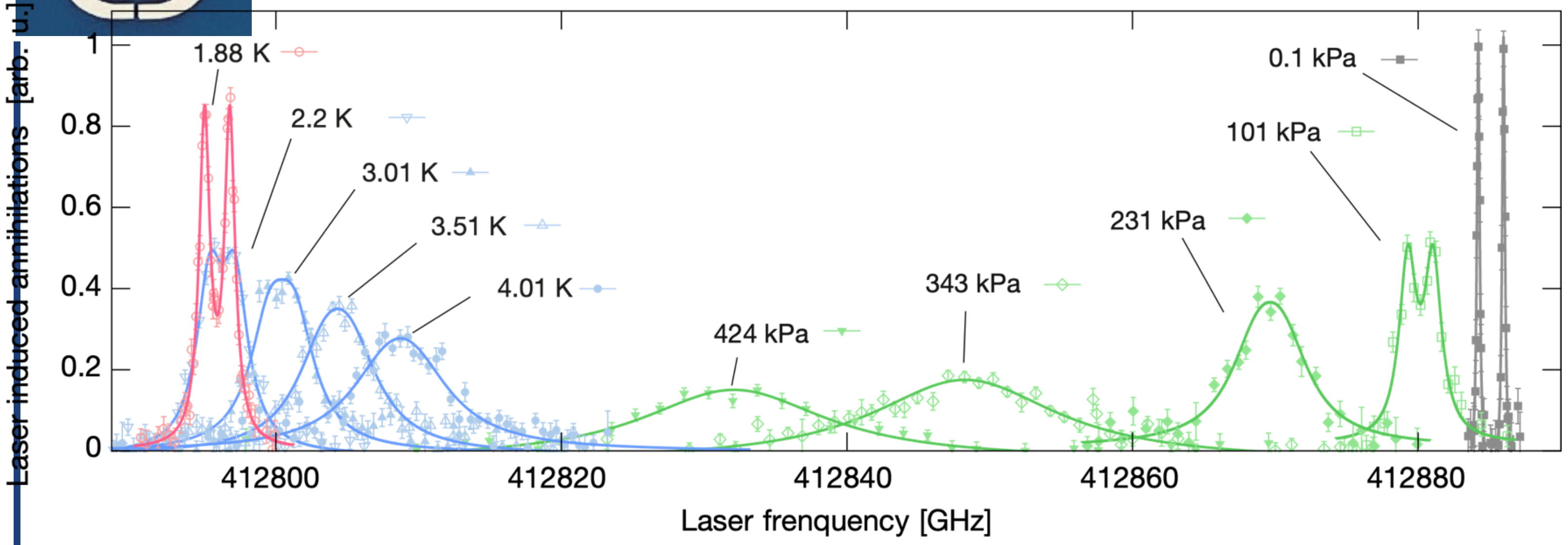
Short/medium term goals

- 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.

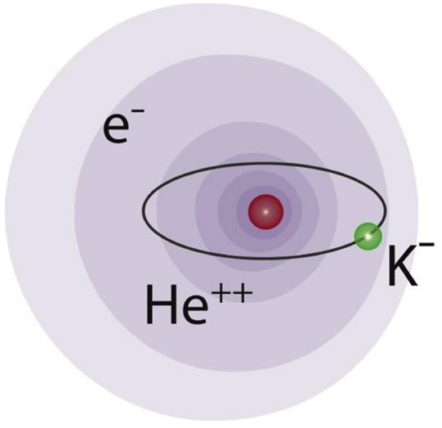




Condensed matter research and new exotic atoms

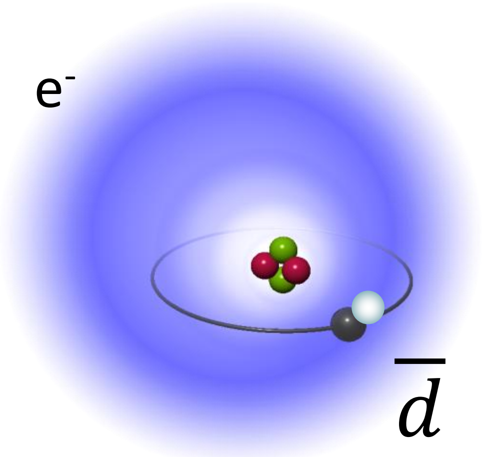


- Condensed matter research using superfluid and solid helium of temperature < 0.1 K, microscopic quasi-particle excitations.
- Needs 0.4 to few MeV pbar beam, “reaccelerator” installation in ASACUSA studied.
- Laser spectroscopy of kaonic and antideuteronic helium atoms
- Needs antideuteron beam, studied by CERN in 1989 in the context of AAC + PS
- “200 antideuterons per pulse (1e13 protons) in the AC”
- GSI-ESR can measure one ion.

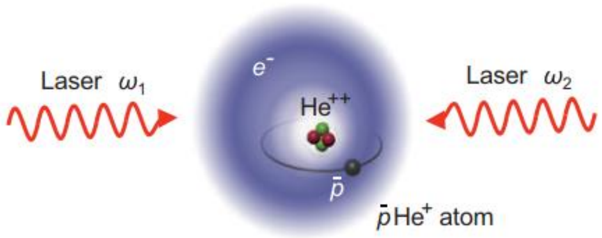


Kaonic helium

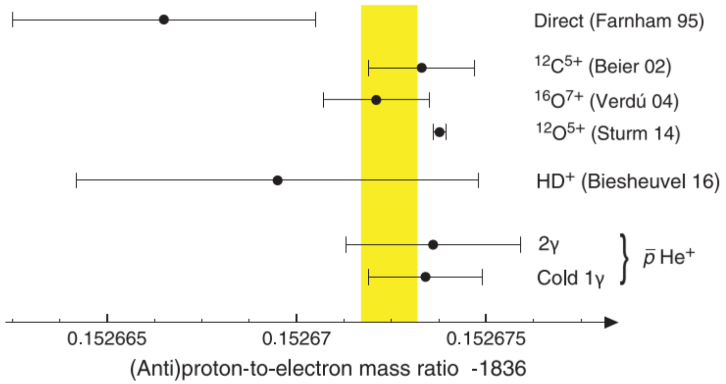
(contains strange quark!)



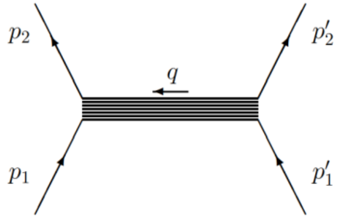
Antiprotonic Helium (ASACUSA)



- 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**)

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

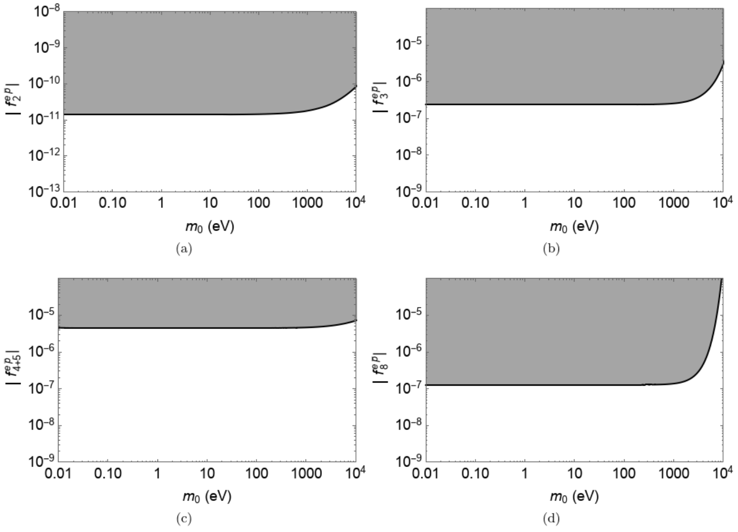
$$V_3 = f_3^{e\bar{p}} \frac{\hbar^3}{\pi m_e^2 c} \left[\mathbf{s}_{\bar{p}} \cdot \mathbf{s}_e \left(\frac{1}{\bar{\lambda} r^2} + \frac{1}{r^3} + \frac{4\pi}{3} \delta^3(r) \right) - (\mathbf{s}_{\bar{p}} \cdot \mathbf{r})(\mathbf{s}_e \cdot \mathbf{r}) \left(\frac{1}{\bar{\lambda}^2 r^3} + \frac{3}{\bar{\lambda}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

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

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

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

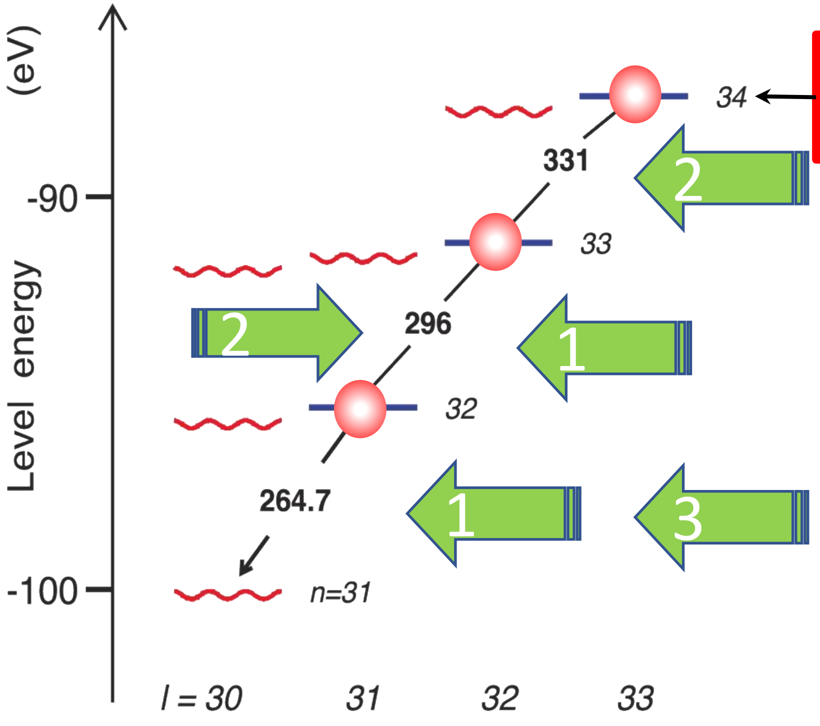
Interactions would modify atomic potential and lead to shifts in wavelengths



(a) (b) (c) (d)

- First limits on exotic antimatter/axion coupling derived

Precision quantum optics measurements before/after LS3



GPS

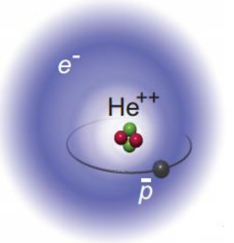
Hydrogen Maser

Comb

Ti:S

1560 nm SubHz

ULE cavity



- Five laser beams used to excite and measure narrow sub-Doppler two-photon transitions.
- New optical frequency comb and quantum optics techniques needed.
- ELENA antiprotons vastly increase the data acquisition rate and signal-to-noise ratio.
- Induction decelerator developed with KEK 30 GeV PS-MR accelerator group and Mainz HIM.
- Spectroscopy in radiofrequency traps.

AEgIS Collaboration

Overview – AEgIS Collaboration

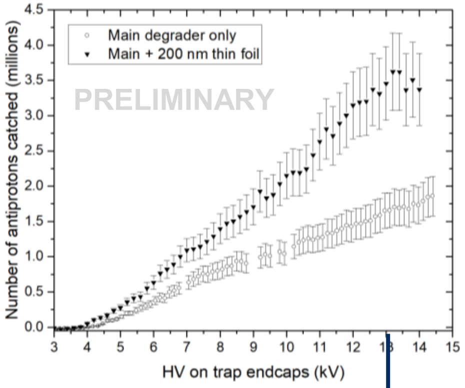
$\text{AEgIS}_{\text{Hbar}}$

AEgIS_{Ps}

$\text{AEgIS}_{\text{pion}}$

- **General:** use diverse atomic systems with antimatter constituents to test the Weak Equivalence Principle and perform spectroscopic studies
- **Main tools:** laser-controlled charge-exchange reactions with Rydberg Ps atoms, cold and dense plasmas in Malmberg-Penning traps, inertial sensors

Efficient catching from ELENA



PROPOSAL

2008

2012

2014

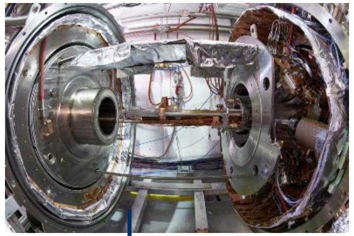
2016

2017

2019

2020

2023

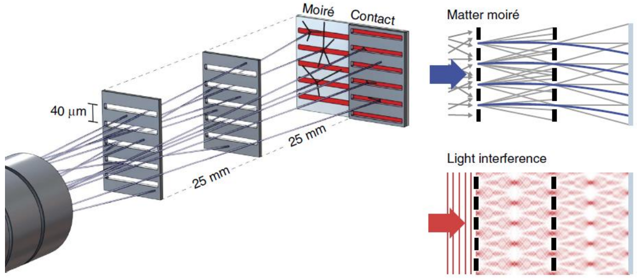


Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014

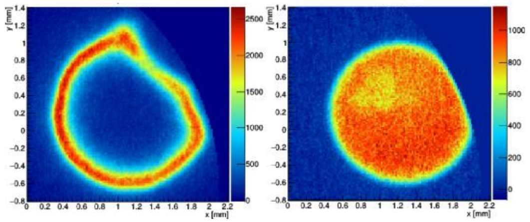
DOI: 10.1038/ncomms5538

OPEN

A moiré deflectometer for antimatter

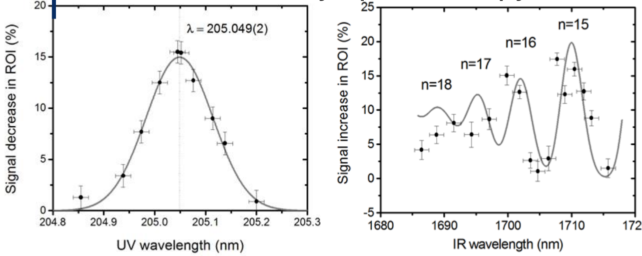


Pbar compression to mm radius



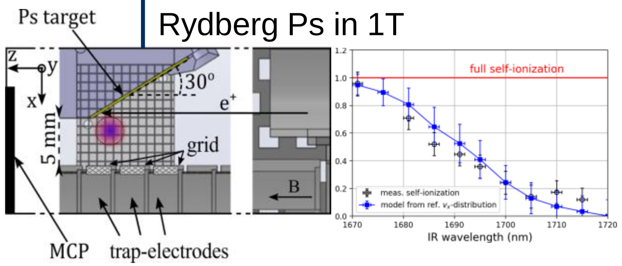
S. Aghion et al., Eur. Phys. J. D (2018) 72: 76

Ps 1S-3P-Ry spectroscopy



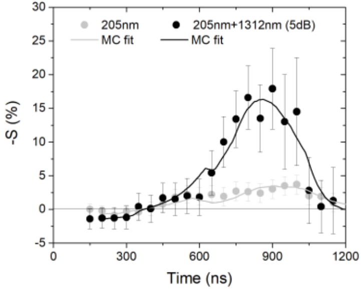
S. Aghion et al., PRA **94,** 012507 (2016)

Rydberg Ps in 1T



M. Antonello et al., PRA **102,** 013101 (2020)

Ps 2S-3P spectroscopy

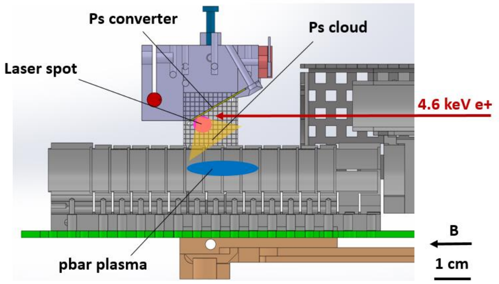


M. Antonello et al., PRA **100,** 063414 (2019)

https://doi.org/10.1038/s42005-020-00494-z

OPEN

Pulsed production of antihydrogen



Highlights – AEgIS

Inertial detector for WEP testing

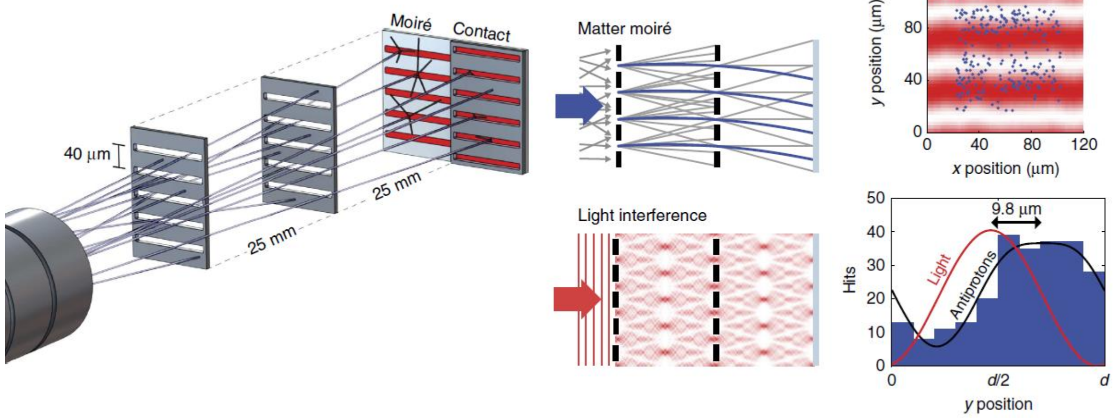
- 500 aN sensitivity with 100 keV antiprotons and emulsion detectors
- Talbot-Lau interferometry as alignment tool and un-deflected reference

$$\Delta y = \frac{F_{\parallel}}{m}\tau^2 \longrightarrow F_{min} \approx 5\cdot 10^{-16}\,\mathrm{N}$$

-: viable detector for WEP tests :-

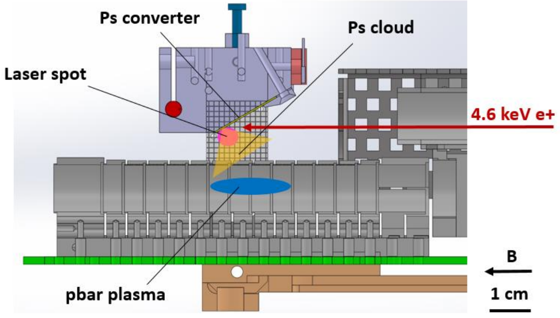
Received 5 Nov 2013 | Accepted 27 Jun 2014 | Published 28 Jul 2014 DOI: 10.1038/ncomms5538 OPEN

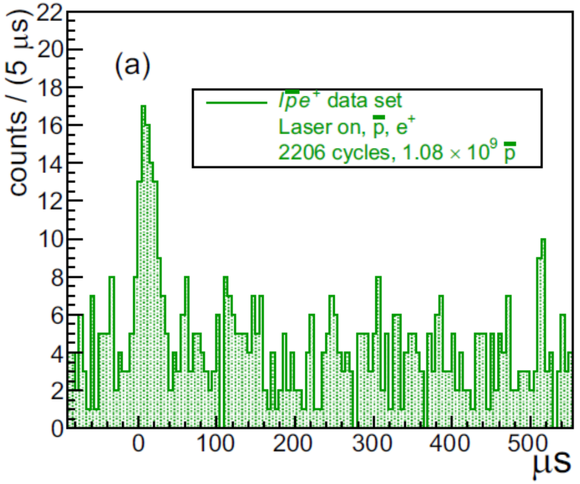
A moiré deflectometer for antimatter

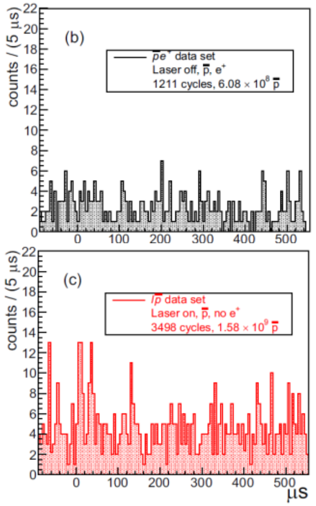


https://doi.org/10.1038/s42005-020-00494-z OPEN

Pulsed production of antihydrogen





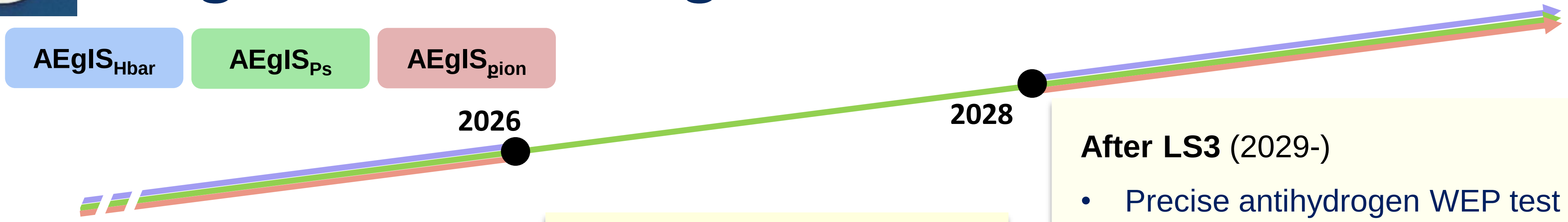


Cold pulsed Hbar source

- 100 $\overline{\mathrm{H}}^*$ produced within a time window of ~100 ns
- The annihilation time distribution suggest temperatures much below the initial plasma 300 K

-: first pulsed source available :-

AEgIS - Future Program



Before LS3 (2023-2025)

- **Improve antihydrogen source flux by x100**
- Direct WEP test with antihydrogen in a magnetic field
- Establishing laser cooling of positronium
- Characterize Ps emission from transmission targets via Doppler spectroscopy
- Form Rydberg antiprotonic ions in traps

During LS3 (2026-2028)

- Apparatus upgrade for Ps transmission targets
- Ps 1^3S-2^3P and 1^3S-3^3P spectroscopy with a laser-cooled source
- Ps HFS on n=2 and n=3
- Inertial sensing with 2^3S and Rydberg Ps
- Two-photon spectroscopy of Ps n^3S Rydberg states
- Positron affinity of neutralized anions via charge-exchange

After LS3 (2029-)

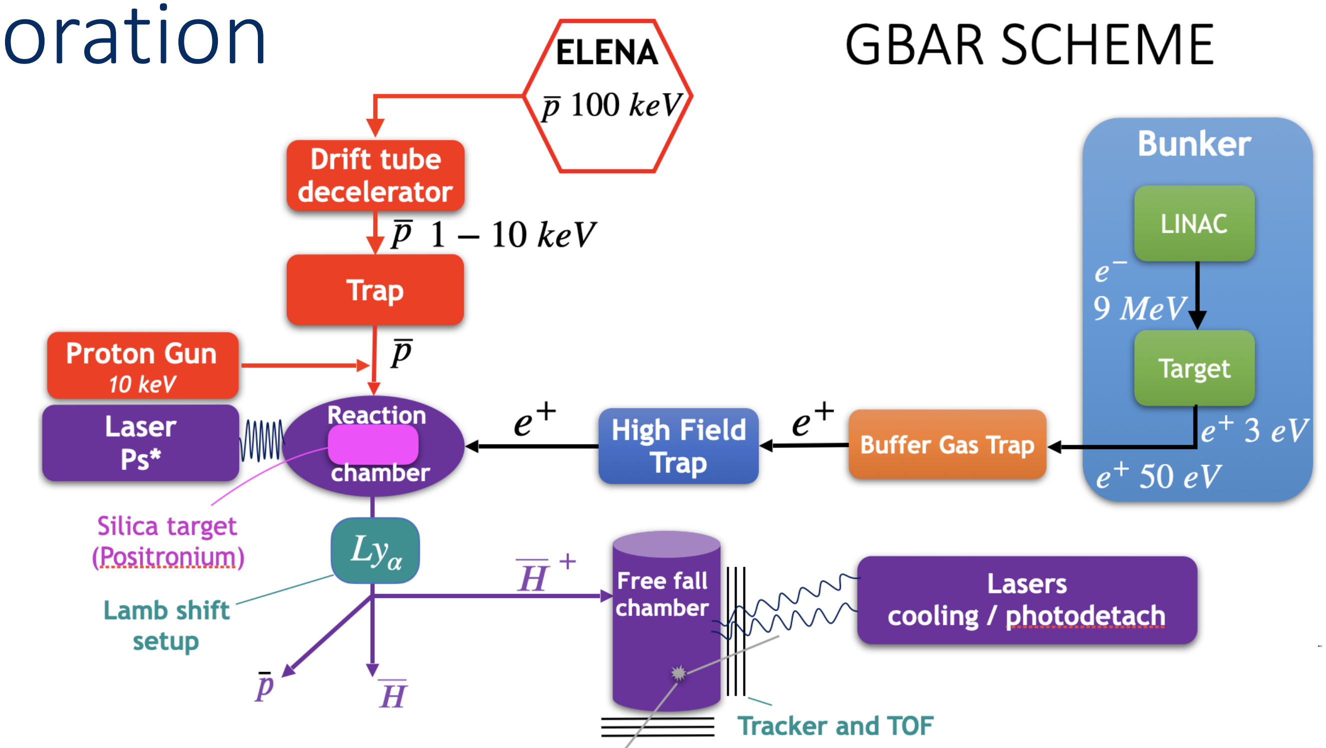
- Precise antihydrogen WEP test in a null magnetic field
- Ps 1^3S-2^3S, 1^3S-3^3S spectroscopy with a laser cooled source
- Spectroscopy of Rydberg antiprotonic atoms
- Time-of-flight mass spectrometry of trapped nuclear isotopes
- Inertial sensing with antiprotonic atoms
- Spectroscopy search for an antiproton EDM in antiprotonic molecules
- DM search via pbar-^{3}He in traps
- Anti-^{3}He synthesis by fusion between anti-p and anti-d

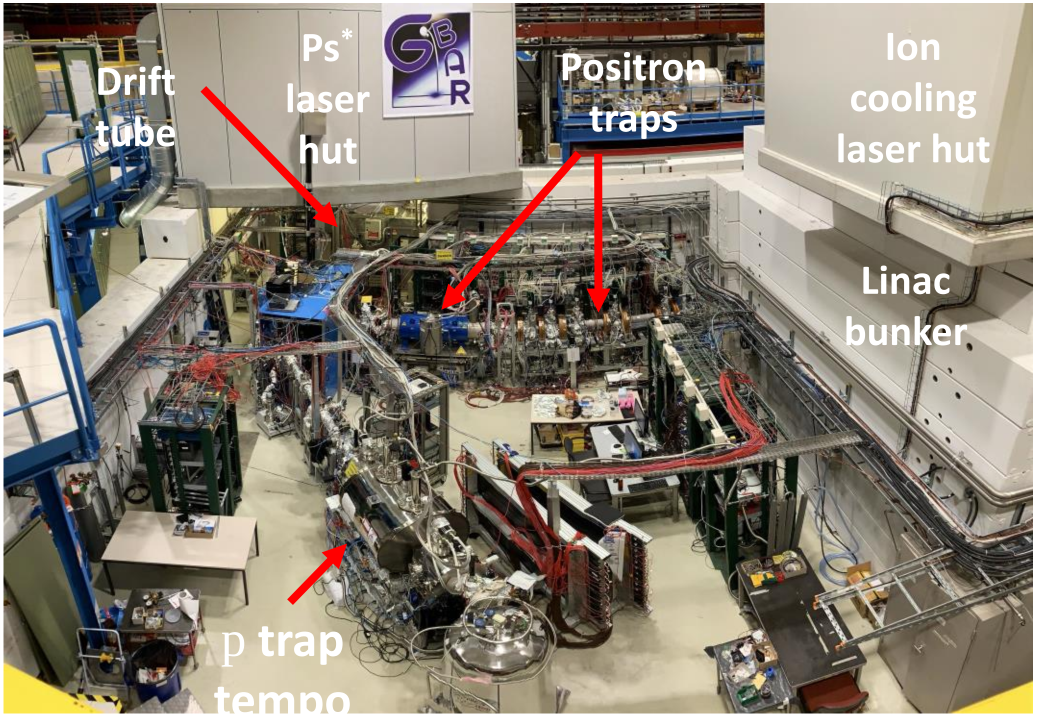
GBAR Collaboration

Overview – GBAR Collaboration

Main goal

- Produce keV beams of antihydrogen atoms and ions
  - $\bar{\mathrm{p}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}} + \mathrm{e}^-$ & $\bar{\mathrm{H}} + \mathrm{Ps} \rightarrow \bar{\mathrm{H}}^+ + \mathrm{e}^-$
- **Measure $\bar{H}$ Lambshift —> radius of antiproton**
- Cool $\bar{\mathrm{H}}^+$ to 10 μK and photo detach —> ultra cold $\bar{\mathrm{H}}$
- Measure $\bar{\mathrm{H}}$ free fall





In construction, with intermediate milestones

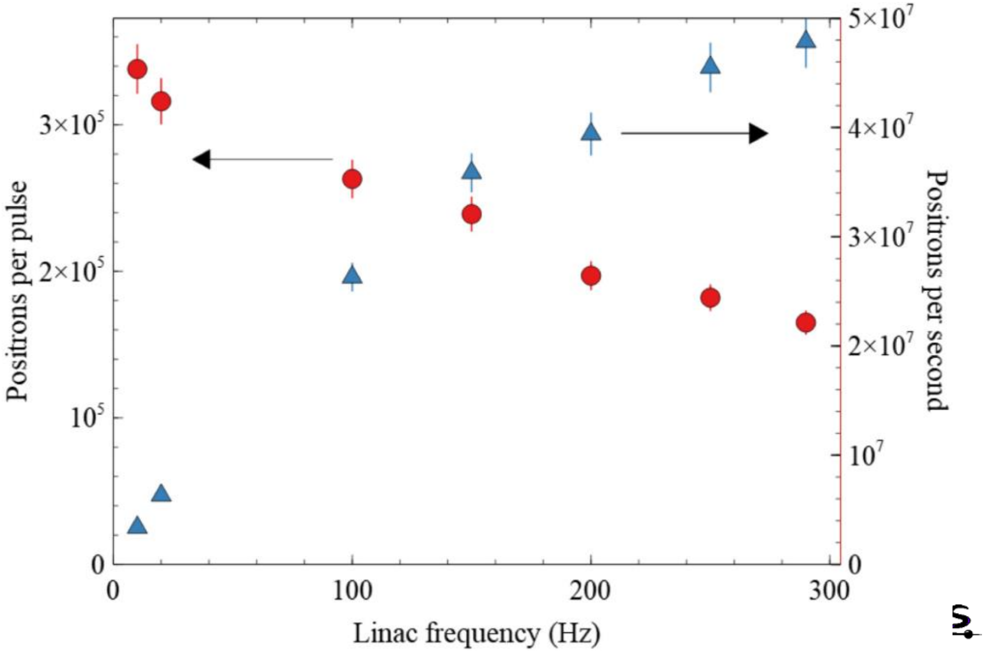
- Linac —> $5 \times 10^7 e^+/s$ M. Charlton et al., NIMA 985, 164657 (2021)
- traps —> $1 \times 10^9 e^+/1000s$ P. Blumer et al., NIMA 1040, 167263 (2022)
- drift tube —> 100 keV -> 6 keV A. Husson et al., NIMA 1002, 165245(2021)
- **$\bar{H}$ production —> evidence in 2022 run**

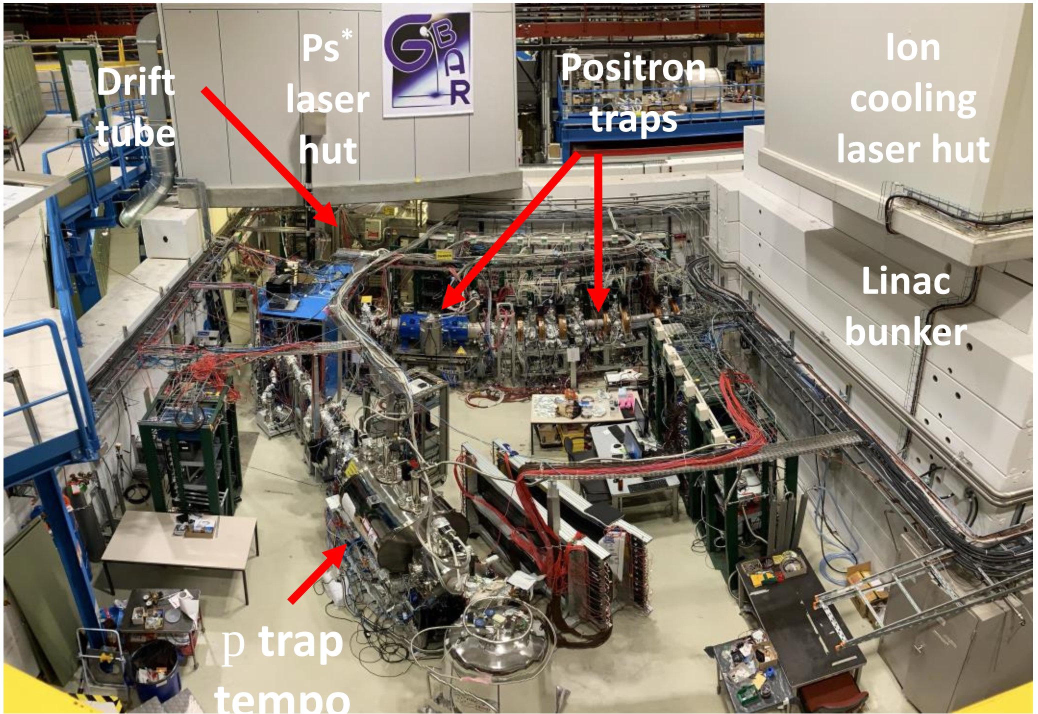
Improve yield and focus before LS3 on Lamb shift measurement

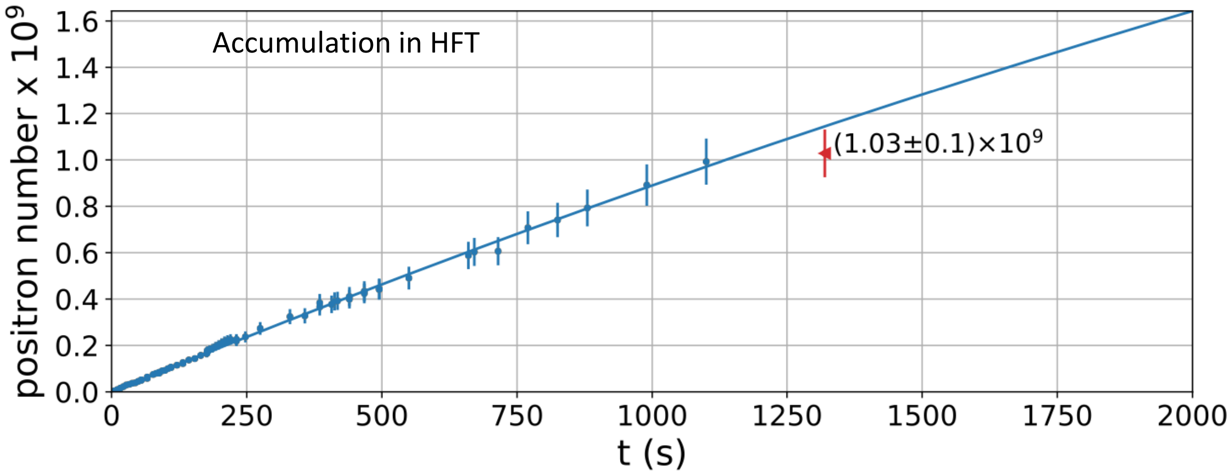
Overview – GBAR Collaboration

In construction, with intermediate milestones

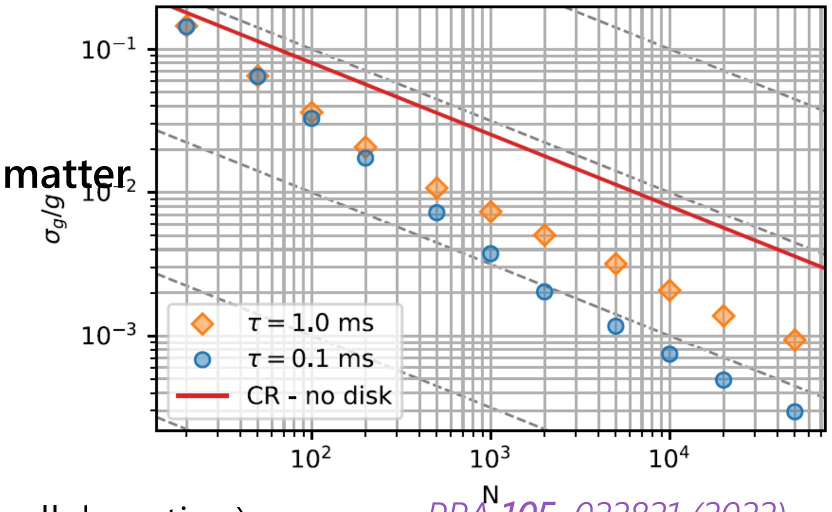
- Linac —> $5 \times 10^7 e^+/s$ M. Charlton et al., NIMA 985, 164657 (2021)
- traps —> $1 \times 10^9 e^+/1000s$ P. Blumer et al., NIMA 1040, 167263 (2022)
- drift tube —> 100 keV -> 6 keV A. Husson et al., NIMA 1002, 165245(2021)
- **$\overline{H}$ production —> evidence in 2022 run**







GBAR - Future Program



Main project after LS3: precision measurement of the gravitational acceleration of antimatter

- first: below 10 % $\bar{g}$ measurement with 100 detected cold antiatoms
- second: 10^{-2} - 10^{-3} precision with increased statistics (1000 events)
- or at least 1 % precision with QGS interferometry (10 events)
- next steps: QGS interferometry, toward a sub 10^{-5} precision *EPJD **76**, 209 (2022)*

PRA **105**, 022821 (2022)

- + GBAR collaborators involved in "mirror" measurement with Hydrogen (GRASIAN collaboration)

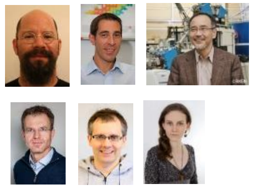
- **Continuity of ongoing side-projects**
  - Lamb shift precision measurement and antiproton charge radius *PRD **94**, 052008 (2016)*
  - Cross sections measurements ($\overline{\mathrm{H}}, \overline{\mathrm{H}}^+, \overline{\mathrm{H}}_2^-$) at low energies
  - X-ray spectroscopy of antiprotonic atoms (QED, comparison with PUMA on stable nuclei) *PRL **126**, 173001 (2021)*

- **Other projects under discussion and ideas for after LS4**
  - Further in-flight antihydrogen spectroscopy (n=2 fine structure)
  - **Production of antihydrogen molecular ion spectroscopy** (more stringent CPT test than $\overline{\mathrm{H}}$) *PRA **98**, 010101(R) (2018)*
  - Ultracold antihydrogen in optical trap (*Hyp. Int. **214**, 60 (2020)*) / **atom chip trap**, for single anti-atom spectroscopy
  - Investigation of the Casimir force with antimatter (demonstration of the reflection, QGS spectroscopy and shift), with possible application of BSM short-range interaction investigation

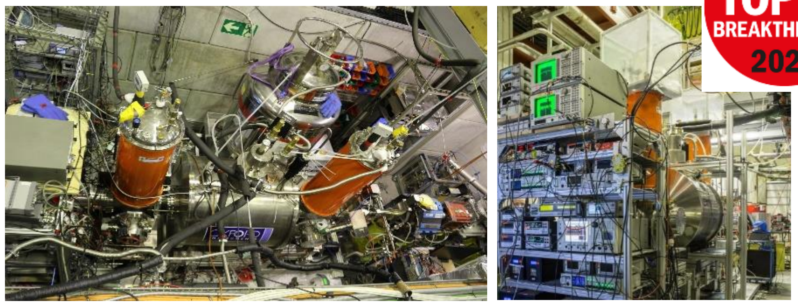
BASE Collaboration

Overview – BASE Collaboration

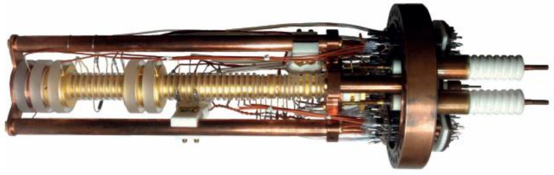
- BASE-CERN
- BASE-Mainz
- BASE-Logic
- BASE-STEP
- BASE-CDM
- BASE-Lepton
- Exotics
- He moment



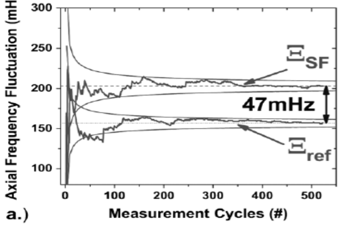
- **General:** Use ultra-high precision methods to measure fundamental constants and study fundamental symmetries with highest fractional accuracy
- **Main tools:** advanced Penning trap systems



physicsworld TOP 10 BREAKTHROUGH 2022

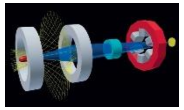


2011



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

2012



2013

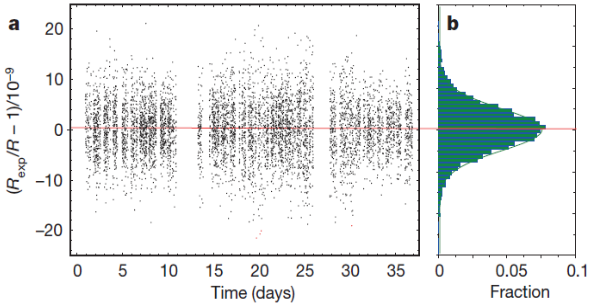
3ppb proton moment

2014

A. Mooser, S. Ulmer, et al., **Nature 509, 596 (2014)**

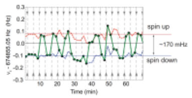
2015

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

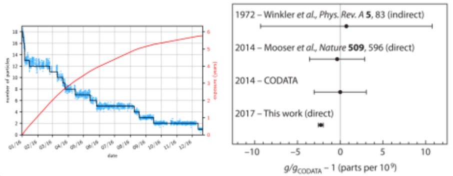


S. Ulmer, et al., **Nature 524, 196 (2015)**

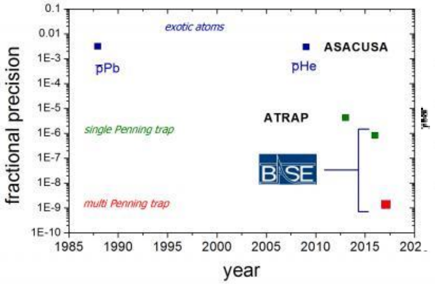
2016

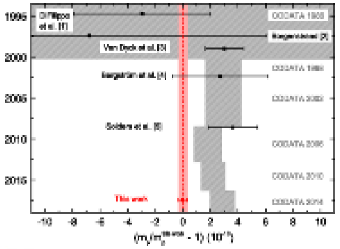


2017 pbar moment, proton moment, pbar lifetime, proton mass



BASE 2017: μ_p = -2.792 847 344 1 (42) μ_{nucl}

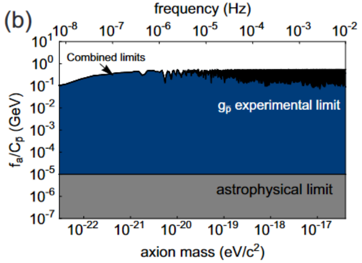




G. Schneider et al., Science **358**, 1081 (2017).

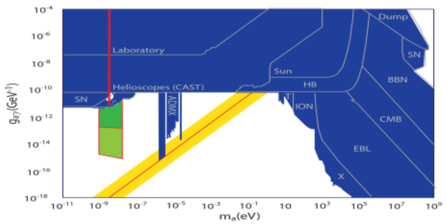
C. Smorra *et al.*, Nature **550**, 371 (2017)

2019

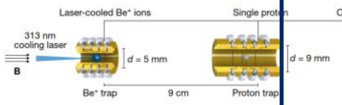


BASE, Nature **575**, 310 (2019)

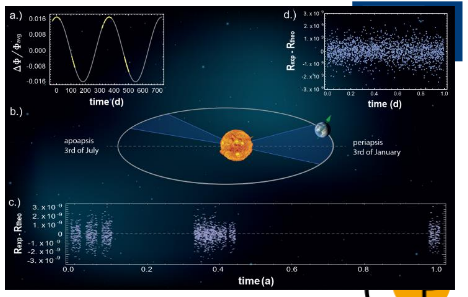
2021



J. A. Devlin, et al., **PRL, accepted (2021)**



M. A. Bohman, et al., **Nature 596, 514 (2021)**

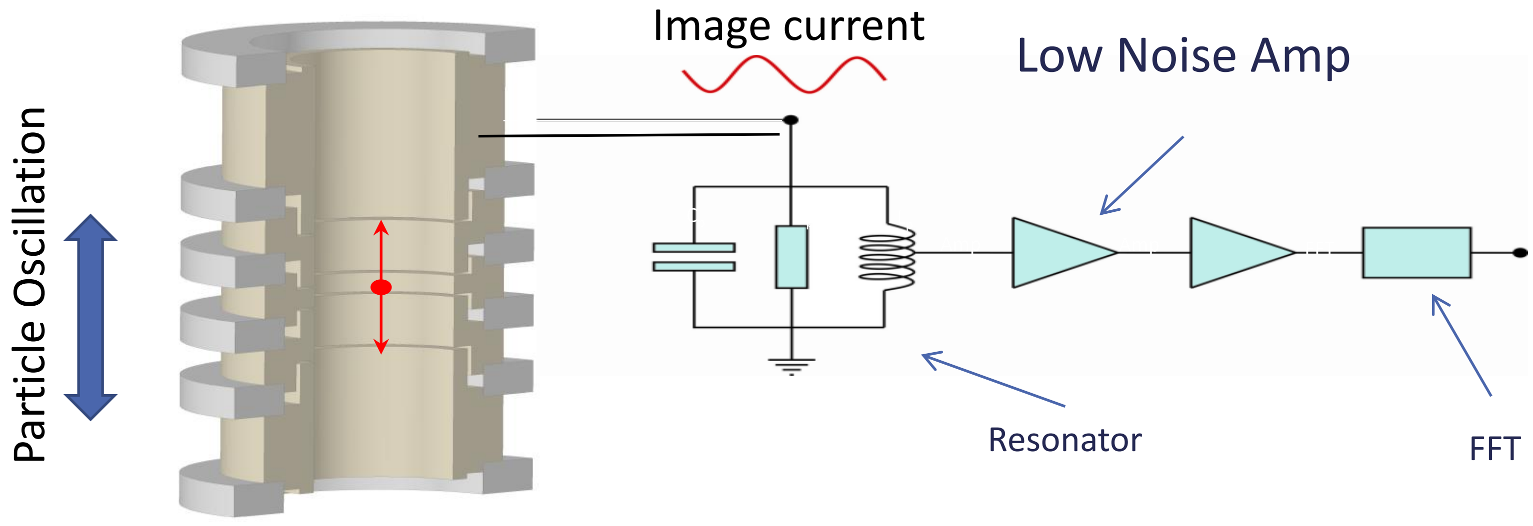


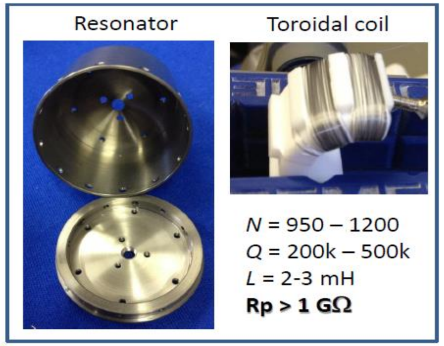
S. Ulmer, et al., **Nature, accepted (2021)**

2022

The Sound of Antimatter

- Concept of image current detection



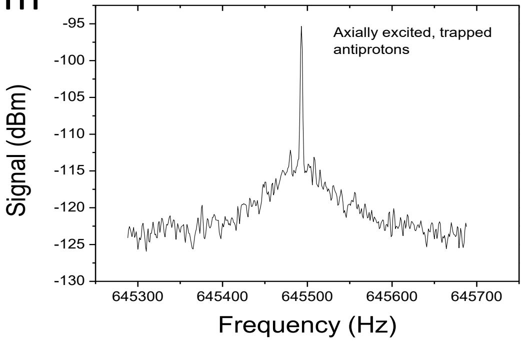


N = 950 – 1200
Q = 200k – 500k
L = 2-3 mH
Rp > 1 GΩ

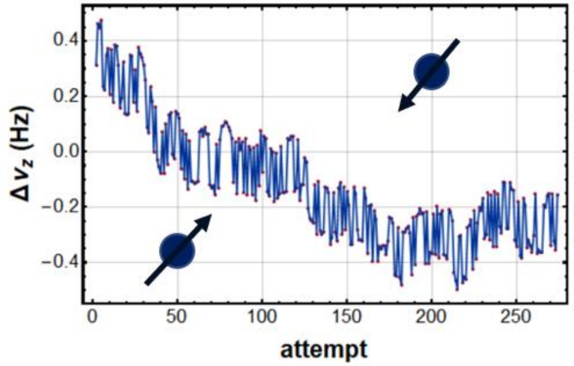
Inductor compensates system capacitance

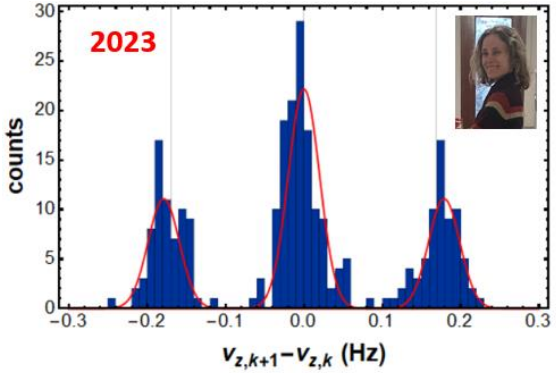
$$I_{p,x} \sim \frac{q}{D_{eff}}(2\pi\nu_x)x$$

$$I_{p,x} \sim 0.1\ fA\ /(MHz\ \mu m)$$



- Non-destructive Quantum Transition Spectroscopy with Antimatter





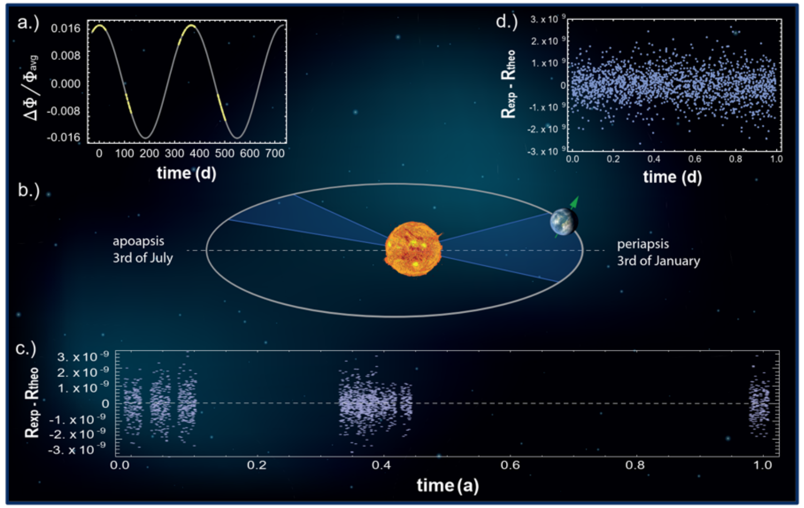
Maybe the «most quantum» experiment at CERN

In the AD we are «listening» to the sound of extremely simple, well understandable Antimatter systems to detect exotic physics , **which appears as changes in pitch / frequency beating**

Highlights – BASE

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

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



- 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 -> time dependent coefficients

- 3000-fold improved measurement of the antiproton magnetic moment, by inventing a new two particle / three trap technique in a multi-Penning-trap system

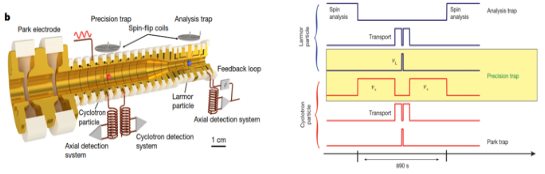
$$g_{\bar{p}} = 2.792\,847\,344\,1\;(42)$$

$$g_p = 2.792\,847\,344\,62\;(82)$$

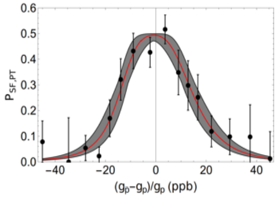
- Most precise test of CPT invariance in the baryon sector by comparing the proton/antiproton charge-to-mass ratio with a fractional accuracy of 16 parts in a trillion

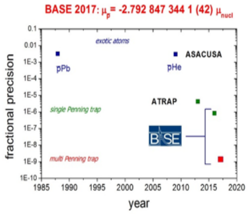
$$R_{\bar{p},p} = -1.000\,000\,000\,003\;(16)$$

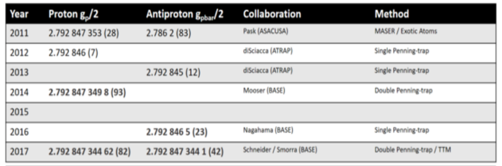
New idea: divide measurement to two particles



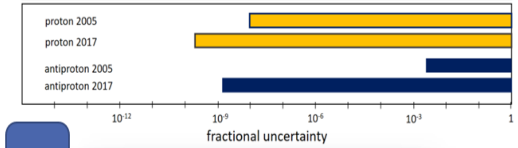
win: 60% of time usually used for sub-thermal cooling useable for measurements





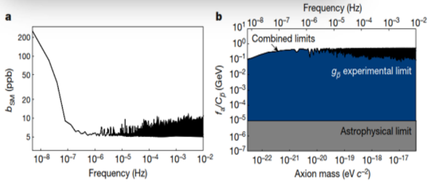


Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	Collaboration	Method
2011	2.792 847 353 (28)	2.786 2 (83)	Pask (ASACUSA)	MASER / Exotic Atoms
2012	2.792 846 (7)		diSciacca (ATRAP)	Single Penning-trap
2013		2.792 845 (12)	diSciacca (ATRAP)	Single Penning-trap
2014	2.792 847 349 8 (93)		Mooser (BASE)	Double 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

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



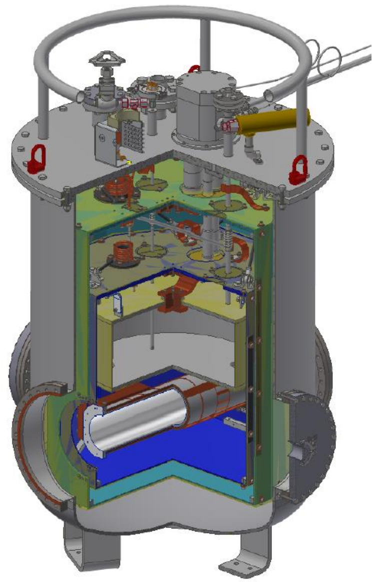
first measurement more precise for antimatter than for matter...

Reservoir Trap and SME Limits

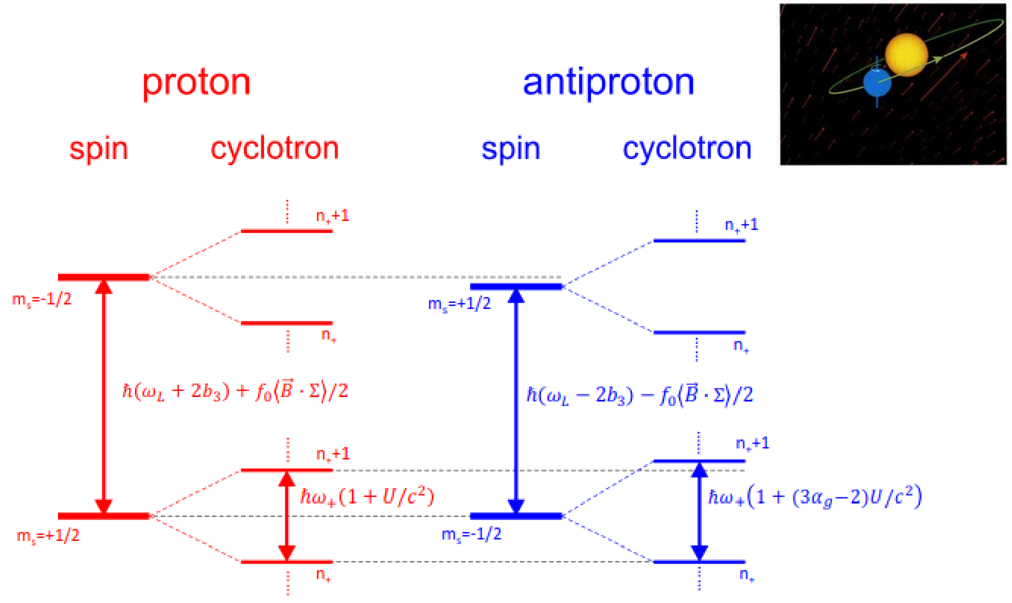
BASE Reservoir

BASE ANTIMATTER INVERSION	
local volume	0.0001^3 m^3
Baryon pressure	$5*10^{-19}$ mbar
Antibaryons in local trap volume	100
Antibaryon/Baryon Ratio	**$5.9*10^8$**
Ratio Inversion	**$3.8*10^{12}$**

- Pbar consumption (excl. steering and trap loading):
  - Since 2014: 68 particles lost
  - Since 2014: 34 particles lost due to exp. Mistakes
- Average loss rate is at 1 particle in 2.5 months.
- **Demonstrated antiproton trapping for > 1 year**
- **Direct lifetime limits: t > 26.5a** (80-fold impr.)



Summary of BASE - SME Limits



- Magnetic Moment Measurements

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

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

- 2022 Charge-to-Mass Ratio Measurement

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

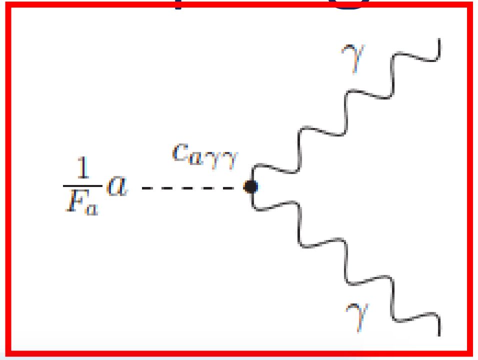
- Time-base Charge-to-Mass analysis ongoing

BASE measurements improved a total of 22 constraints on coefficients of the standard model extension.

Investigating Antimatter / Dark Matter Coupling

- Frist of all: a quick comment on axion , fermion coupling

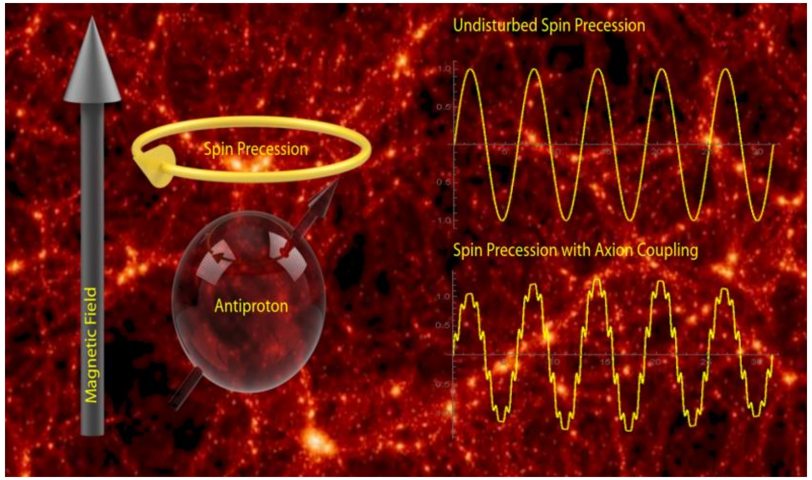
$$
\begin{aligned}
\mathcal{L}_\theta = {} & \frac{1}{2} f_S^2 \partial^\mu\theta\partial_\mu\theta - \frac{1}{4g_c^2} G^a_{\mu\nu}G^{a\mu\nu} + (\bar q_L i \not{D} q_L + \bar q_R i \not{D} q_R) \\
& + c_1(\partial_\mu\theta)\bar q\gamma^\mu\gamma_5 q - (\bar q_L\; m\; q_R e^{ic_2\theta} + \text{h.c.}) \\
& + c_3 \frac{\theta}{32\pi^2} G^a_{\mu\nu}\tilde G^{a\mu\nu} \ (\text{or } \mathcal{L}_{\rm det}) \qquad (19) \\
& + c_{\theta\gamma\gamma}\frac{\theta}{32\pi^2} F^i_{{\rm em},\mu\nu}\tilde F^{i\mu\nu}_{\rm em} + \mathcal{L}_{{\rm leptons},\theta}
\end{aligned}
$$

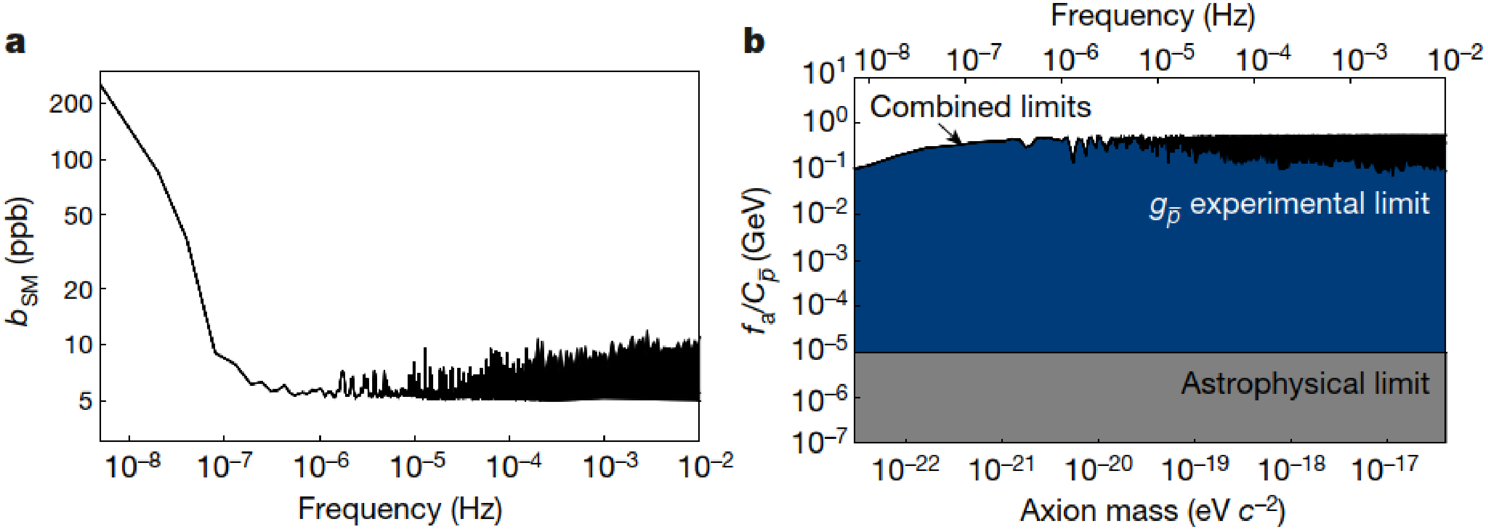


J. Kim, G. Carosi, https://arxiv.org/pdf/0807.3125.pdf

this “derivative interaction” would induce a pseudo magnetic field and a modulation of the antiproton spin transition frequency at the “Compton frequency” of CDM

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





Improves previous antiproton/axion limits by 5 orders of magnitude

By 4 o.o.m. less stringent than current best matter limits

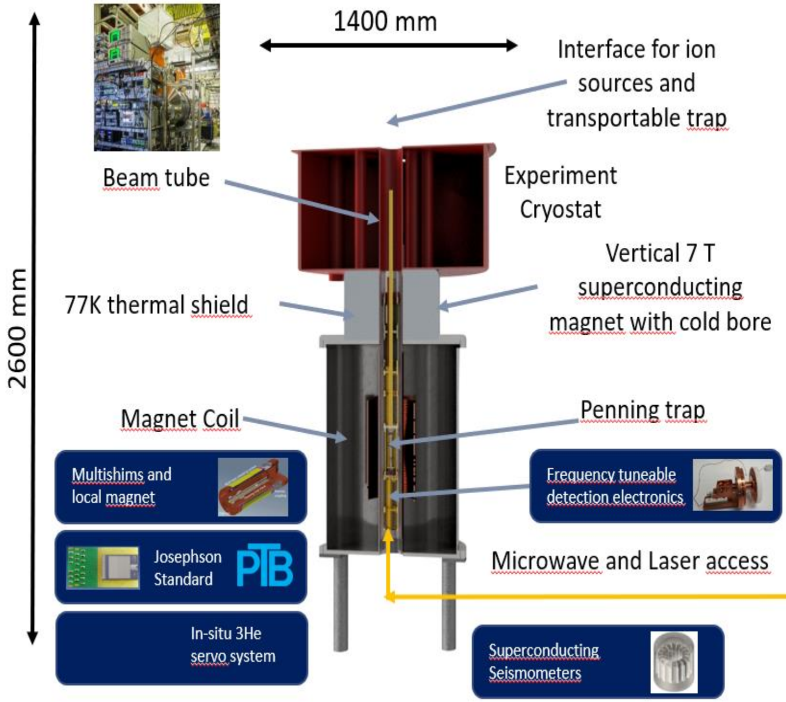
C. Smorra, Y. Stadnik, Nature **(575)**, 310 (2019)

BASE - Future Program

- **Before LS3:**
  - At least 10-fold improved proton / antiproton / H- magnetic moment measurements (now running 2023 / 2024 / 2025), precision target: <100 p.p.t. or 15-fold improvement.
  - Demonstration of antiproton transport in 2023 / 2024.
  - Construction of BASE-CDM Experiment (not installed at CERN)
  - Magnetic-Moment and Charge-to-Mass ratio measurements on simultaneously trapped particles on magnetron locked orbits.

- **LS3 Projects:**
  - Proton mass
  - Magnetic moment of He^{2+}
  - Construction of BASE-Offline Experiment (2025 ff.)

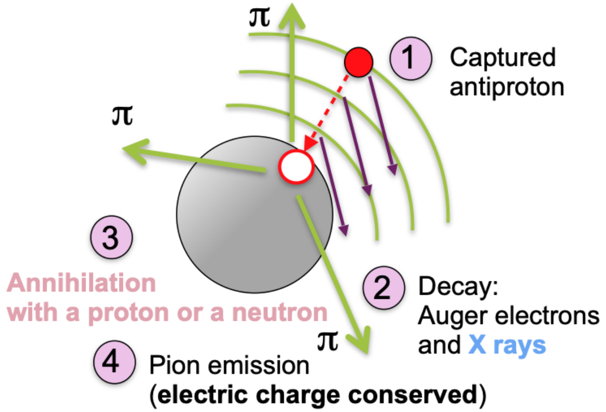
- **Beyond LS3**
  - Operation of BASE-offline laboratory, AD/ELENA used as “filling station”
  - Exotic Physics (BASE-CDM / BASE-MCP).
  - Future Perspective: **BASE-LEPTON** (electron/positron moments).
  - Contributions of BASE-members to H2+_bar spectroscopy.
  - Quantum logic spectroscopy with antiprotons.

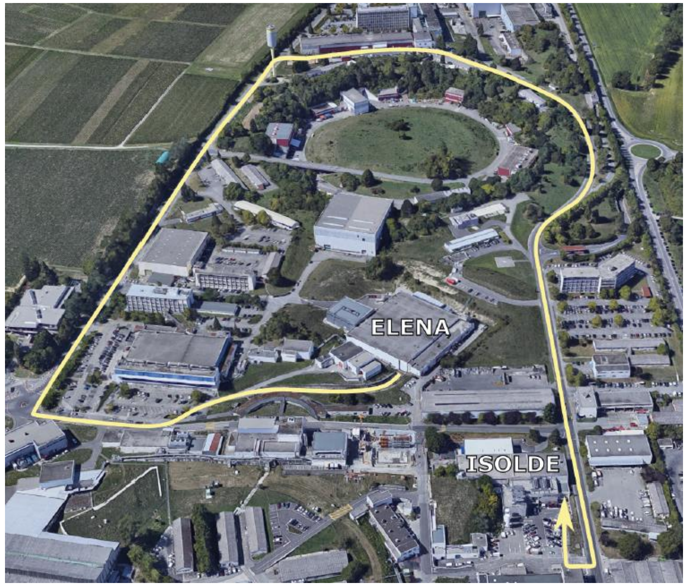


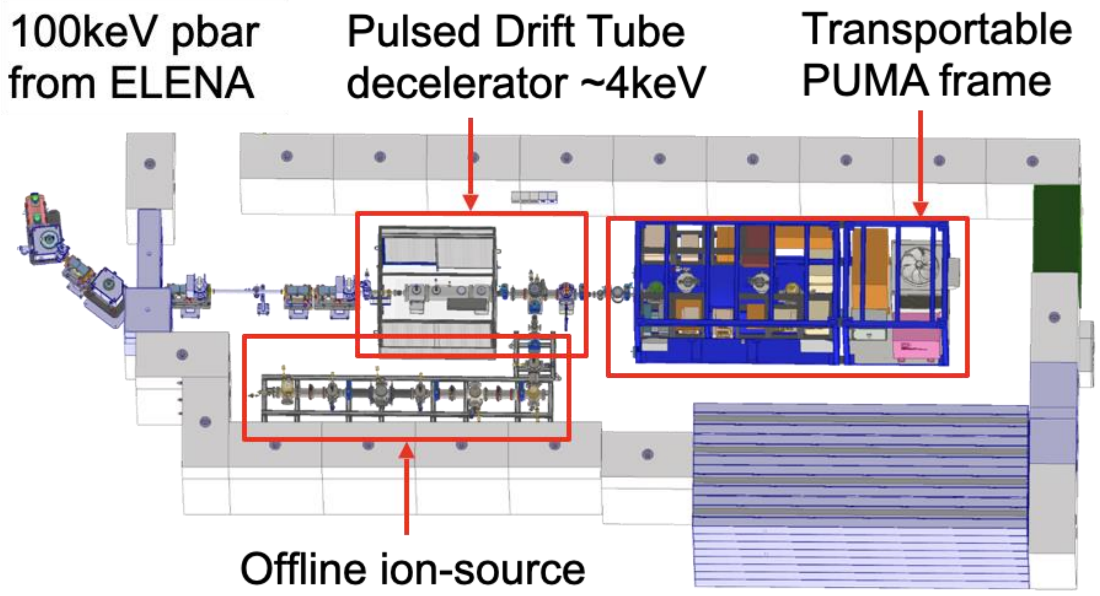
PUMA Collaboration

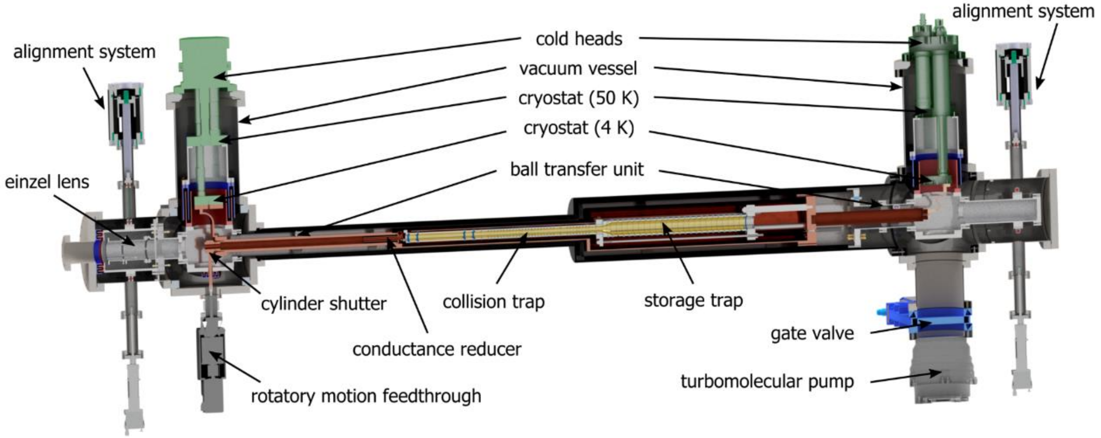
Overview – PUMA Collaboration

- **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



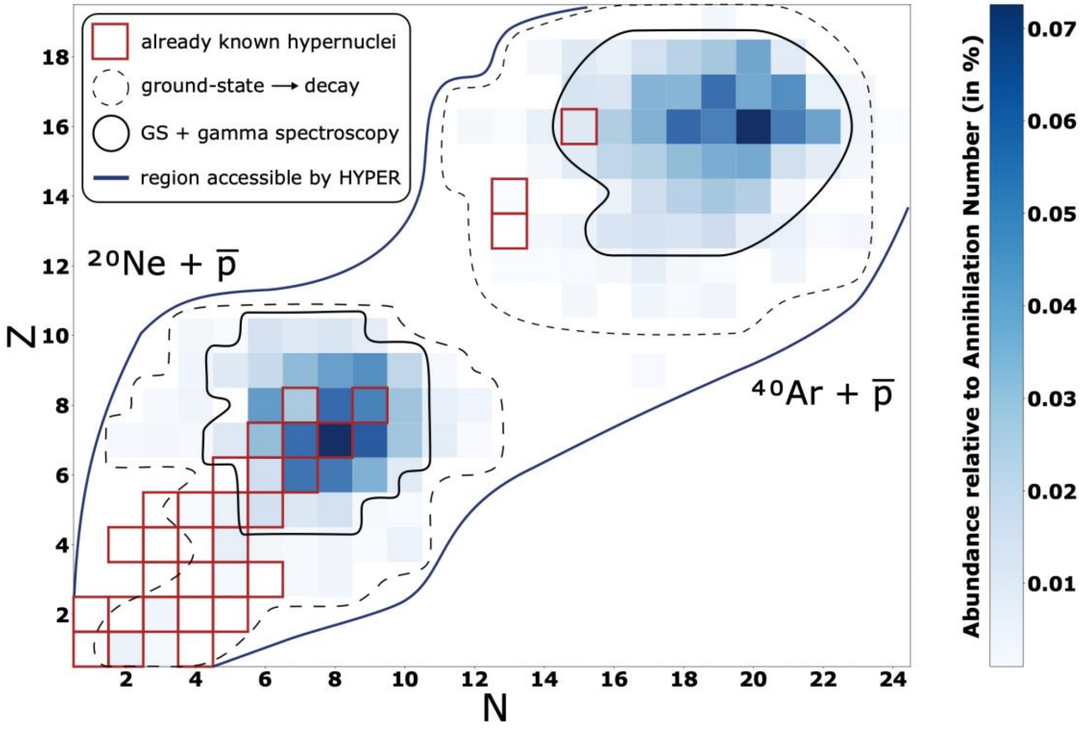


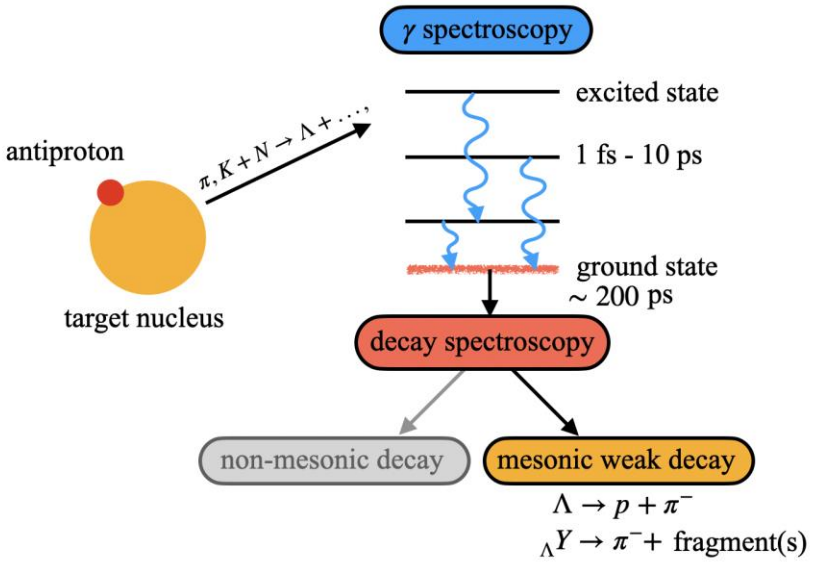




PUMA - Future Program

- Stable nuclei measurements at ELENA from 2023/2024
- Antiproton transport and physics at ISOLDE (2024/2025 – beyond LS3)
- Future Perspective: production of **hypernuclei** and spectroscopy at ELENA (beyond LS3). Letter of intent to be submitted to SPSC in 2024.





γ spectroscopy

antiproton

$\pi, K + N \to \Lambda + \ldots,$

target nucleus

excited state

1 fs - 10 ps

ground state

~ 200 ps

decay spectroscopy

non-mesonic decay

mesonic weak decay

$\Lambda \to p + \pi^-$

$_{\Lambda}Y \to \pi^- +$ fragment(s)