Antimatter Experiments at CERN

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Outline

- CPT Invariance and its Tests
- The Antiproton Decelerator at CERN
- ASACUSA: Atomic Spectroscopy And Collisions Using Slow Antiprotons
- ALPHA: Antimatter Laser PHysics Apparatus
- ATRAP: Antimatter trap
- AEGIS: Antimatter gravity
- ACE: Antimatter Cell Experiment
- AMS2: Alpha Magnetic Spectrometer
- Outlook: ELENA

Antimatter mysteries

- Why there is practically no antimatter in our Universe? At the Big Bang particles and antiparticles should have been produced together. Where did antimatter go?
- Could they be hiding in parts of the Universe inaccessible for us?
- Could there be a tiny difference between particle and antiparticle to cause this asymmetry?
- Are there particles which are their own antiparticles (Majorana particles)? Could the dark matter of the Universe consist of such particles?
- Can antimatter be used for something in everyday life or is it just an expensive curiousity?

CPT Invariance

Charge conjugation: $C|\mathrm{p}(r,t)\rangle = |\overline{\mathrm{p}}(r,t)\rangle$

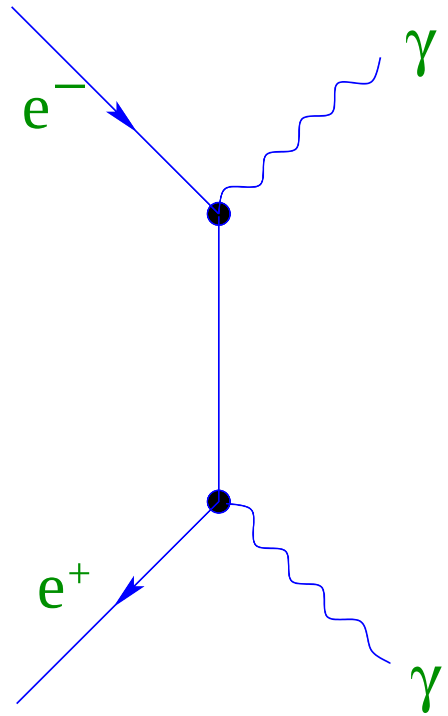
Space reflection: $P|\mathrm{p}(r,t)\rangle = |\mathrm{p}(-r,t)\rangle$

Time reversal: $T|\mathrm{p}(r,t)\rangle = |\mathrm{p}(r,-t)\rangle$

Basic assumption of field theory:

$CPT|\mathrm{p}(r,t)\rangle = |\overline{\mathrm{p}}(-r,-t)\rangle \sim |\mathrm{p}(r,t)\rangle$

meaning free antiparticle $\sim$ particle going backwards in space and time.



Giving up CPT one has to give up:

- locality of interactions $\Rightarrow$ causality, or
- unitarity $\Rightarrow$ conservation of matter, information, ... or
- Lorentz invariance

CPT-violating theories

Weak interaction violates P and CP symmetry
Theoreticians in general: CPT **cannot** be violated

- Standard Model valid up to Planck scale ($\sim 10^{19}$ GeV).
  Above Planck scale new physics $\Rightarrow$
  Lorentz violation possible
- Quantum gravity: fluctuations $\Rightarrow$ Lorentz violation
  loss of information in black holes $\Rightarrow$ unitarity violation

Motivation for testing CPT at low energy

- Quantitative expression of Lorentz and CPT invariance needs violating theory
- low-energy tests can limit possible high energy violation

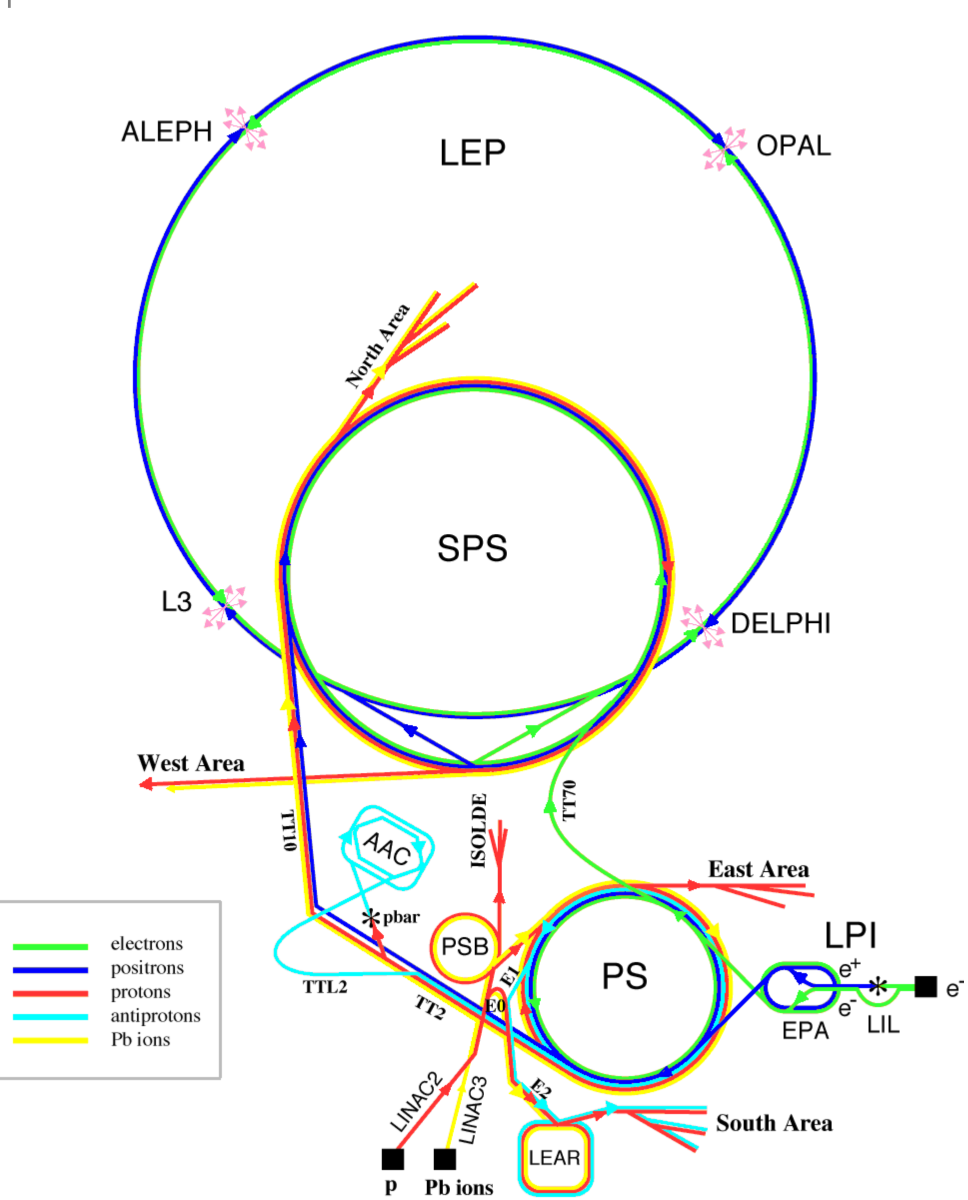
How to test CPT?

Particle = – antiparticle ?

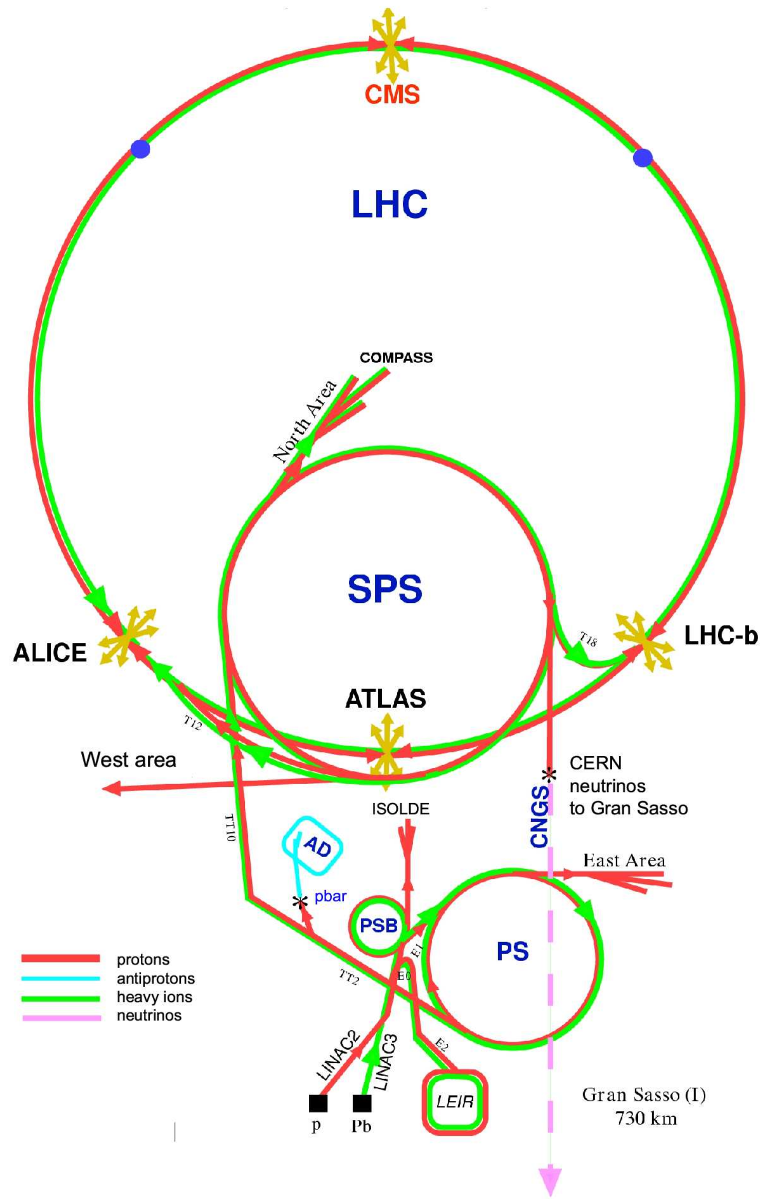
- $[m(\mathrm{K}^0) - m(\overline{\mathrm{K}}^0)]/m(\text{average}) < 10^{-18}$
- proton $\sim$ antiproton? (compare m, q, $\vec{\mu}$)
- hydrogen $\sim$ antihydrogen? ($2S - 1S$, HFS)

Accelerators at CERN

1989–2000



2009–2025??



The Antiproton Decelerator at CERN

has been built to test *CPT* invariance

Three experiments test CPT:

ATRAP: $q(\overline{\mathrm{p}})/m(\overline{\mathrm{p}}) \leftrightarrow q(\mathrm{p})/m(\mathrm{p})$

$\overline{\mathrm{H}}(2S-1S) \leftrightarrow \mathrm{H}(2S-1S)$

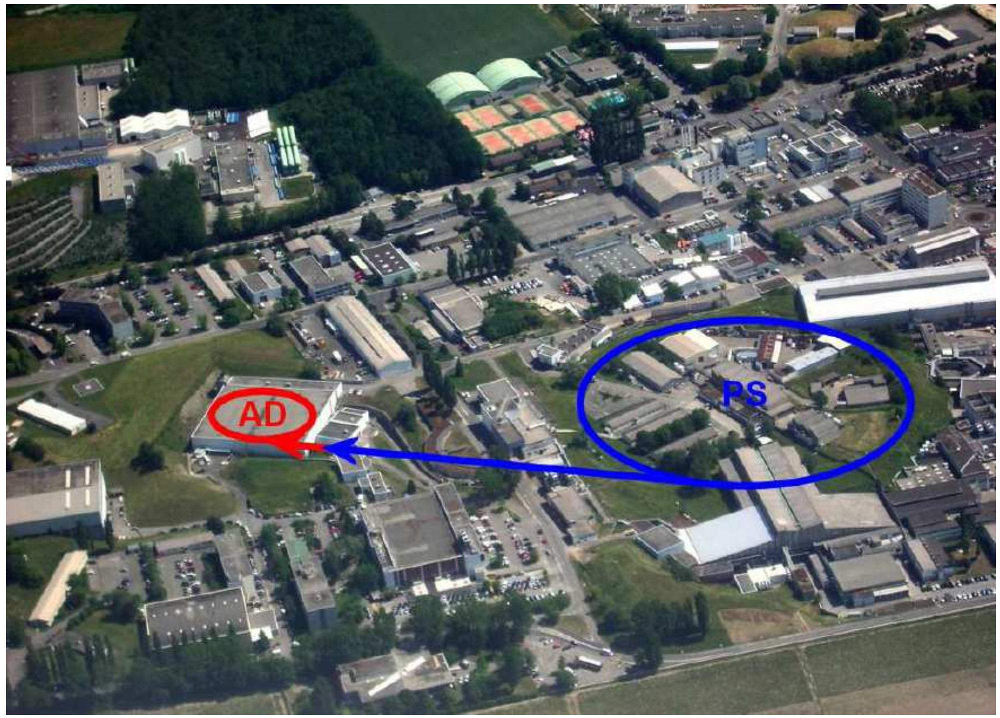
ALPHA: $\overline{\mathrm{H}}(2S-1S) \leftrightarrow \mathrm{H}(2S-1S)$

ASACUSA: $q(\overline{\mathrm{p}})^2 m(\overline{\mathrm{p}}) \leftrightarrow q(\mathrm{p})^2 m(\mathrm{p})$

$\mu_\ell(\overline{\mathrm{p}}) \leftrightarrow \mu_\ell(\mathrm{p})$

$\overline{\mathrm{H}} \leftrightarrow \mathrm{H}$ HF structure

RED: done, GREEN: planned



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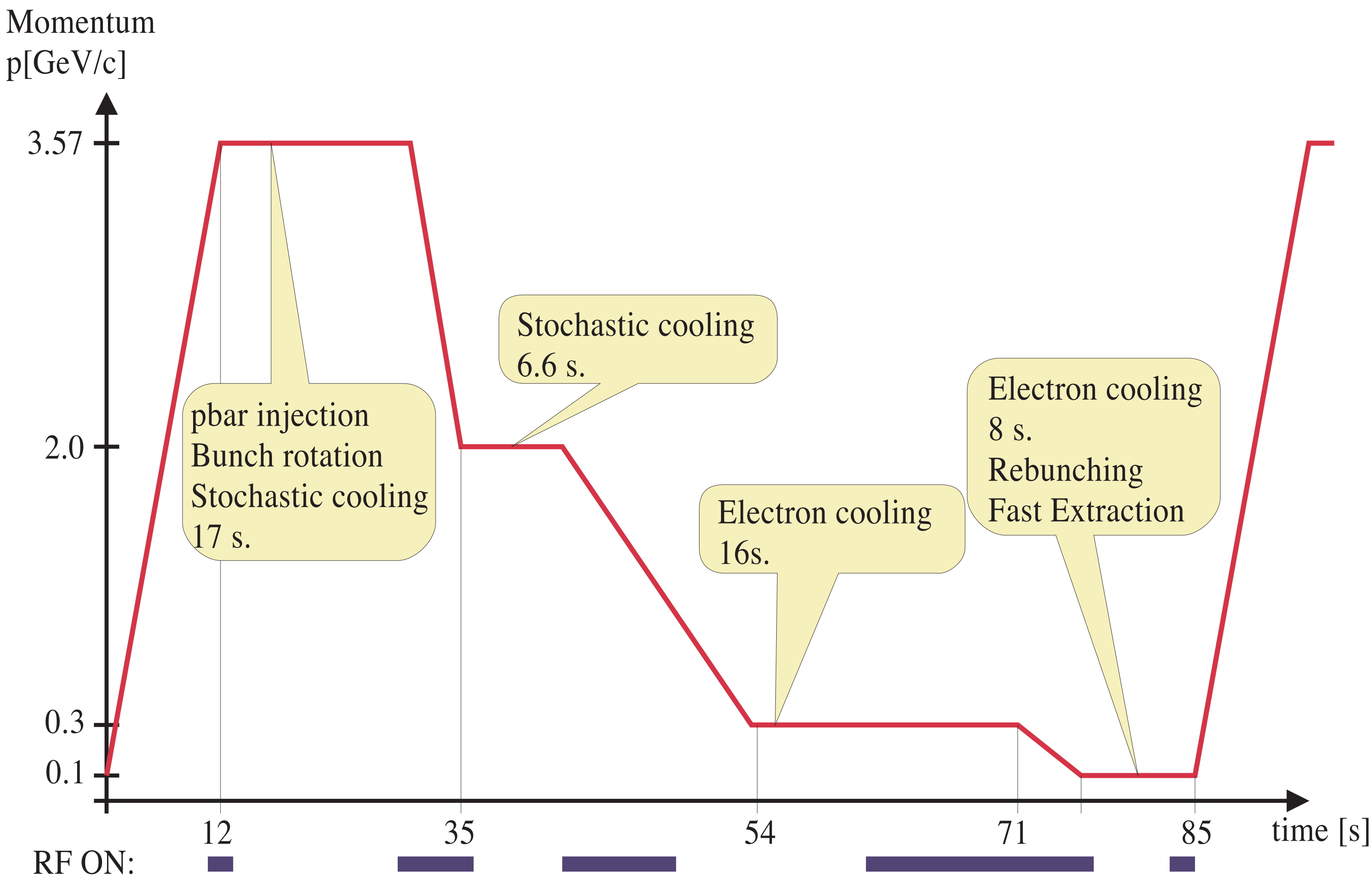
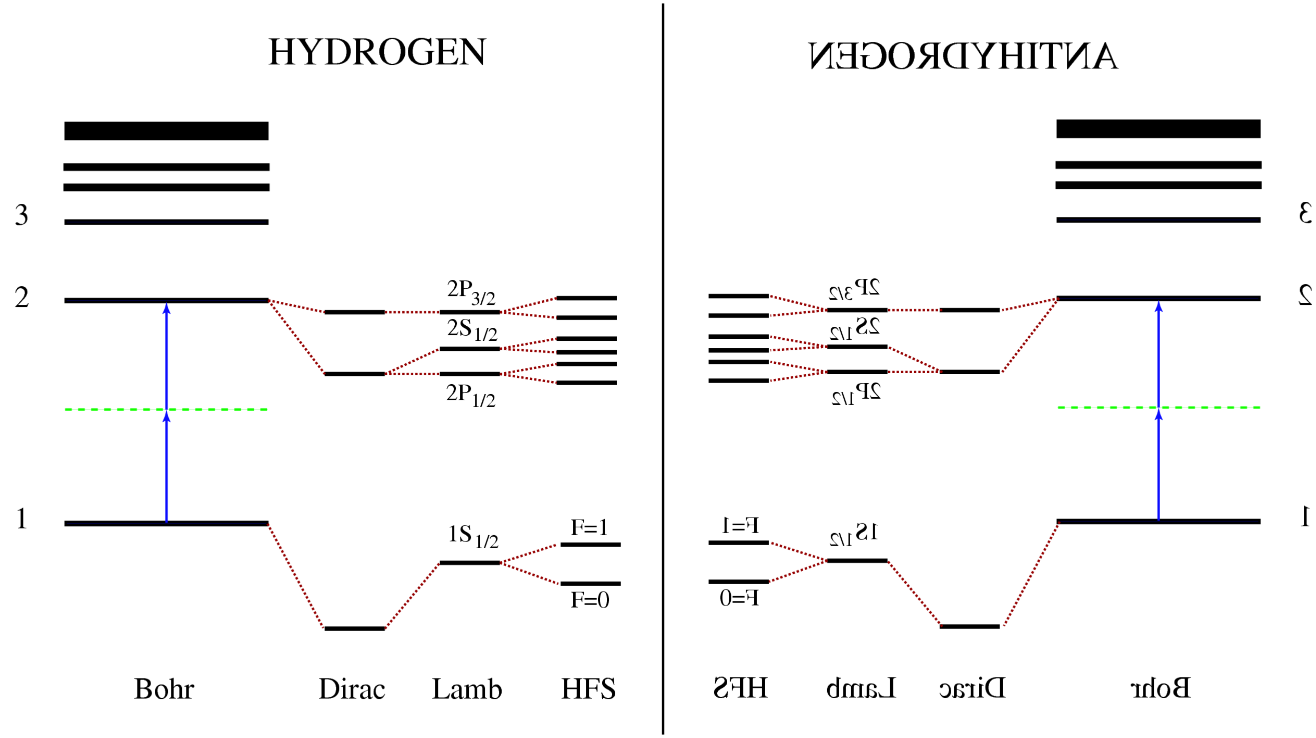
The Antiproton Decelerator: cooling



$\sim 4 \times 10^7$ 100 MeV/c antiprotons every 85 s

Pavel Belochitskii: AIP Conf. Proc. 821 (2006) 48

Antihydrogen, e^+–$\bar{p}$ atom



$2S - 1S$ transition with 2-photons

Long lifetime, narrow transition, Doppler-free spectroscopy

M. Charlton, J. Eades, D. Horváth, R. J. Hughes, C. Zimmermann: *Antihydrogen physics*, **Physics Reports** *241* (1994) 65.

M.H. Holzscheiter, M. Charlton, M.M. Nieto: *The route to ultra-low energy antihydrogen*, **Physics Reports** *402* (2004) 1.

Steps toward $\overline{\mathrm{H}}$ spectroscopy

- Putting antiprotons ($\overline{\mathrm{p}}$) in electromagnetic trap
- Trapping and cooling antiprotons
- Cooling slow positrons (e^+ from ^{22}Na) in trap
- Mixing $\overline{\mathrm{p}}$ and $e^+ \rightarrow$ recombination
- Trapping antihydrogen, waiting for deexcitation

2014

- Cooling antihydrogen
- Laser spectroscopy on antihydrogen

Future

ASACUSA: Mass of the antiproton

Proton's well (?) known:

$m(\mathsf{p})/m(\mathrm{e}) = 1836.15267245(75)$

$q(\mathrm{e}) = 1.602176565(35) \times 10^{-19}$ C

Precision: $4 \cdot 10^{-10}$ and $2 \cdot 10^{-8}$

Relative measurements: proton vs. antiproton

Cyclotron frequency in trap $\rightarrow q/m$

TRAP $\Rightarrow$ ATRAP collaboration

Harvard, Bonn, München, Seoul

$\overline{\mathrm{p}}$ and H^- together $\Rightarrow 10^{-10}$ precision

Atomic transitions:

$E_n \approx -m_{\mathrm{red}} c^2 (Z\alpha)^2/(2n) \rightarrow m \cdot q^2$

PS-205 $\Rightarrow$ ASACUSA collaboration

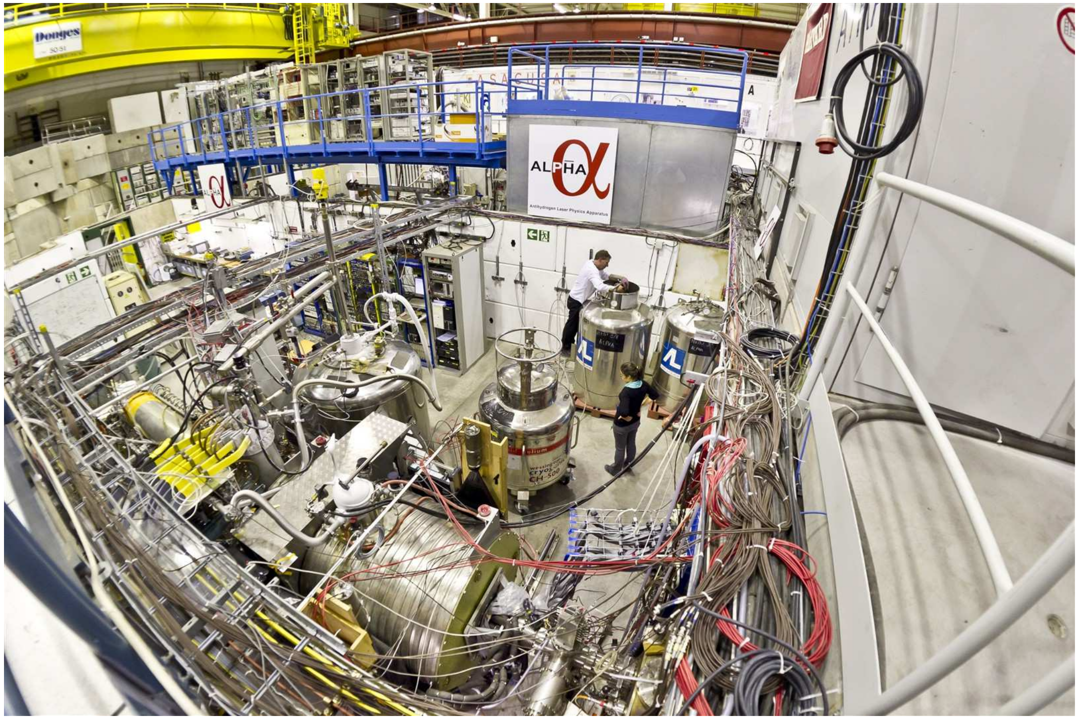
Tokyo, Brescia, Budapest, Debrecen, Munich, Vienna

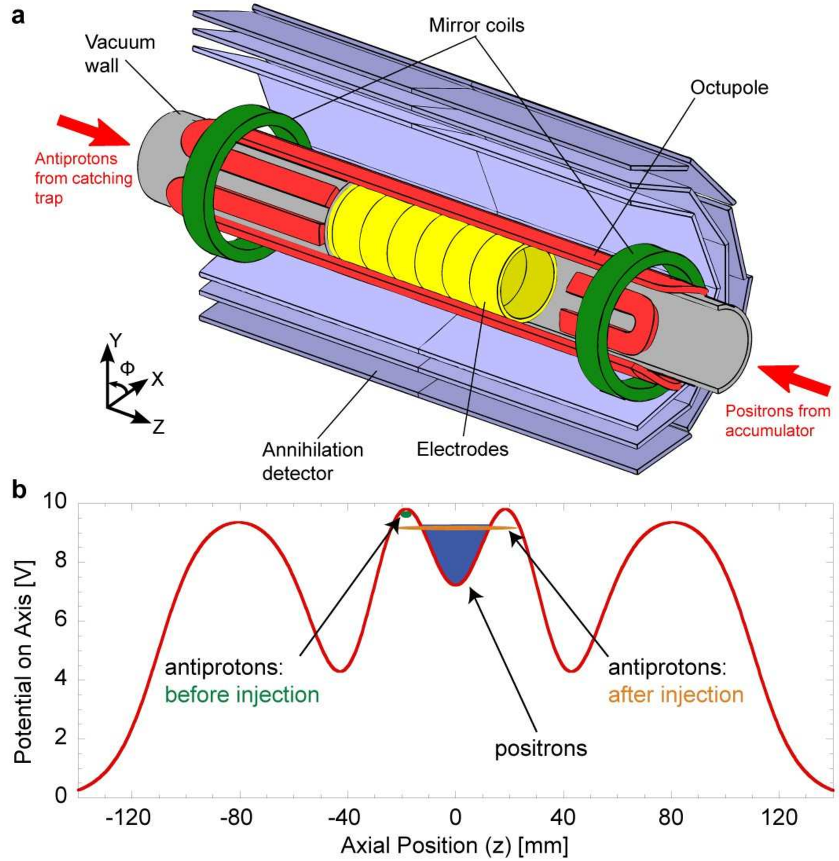
Atomic
Spectroscopy
And
Collisions
Using
Slow
Antiprotons

Asakusa, Tokyo

ALPHA

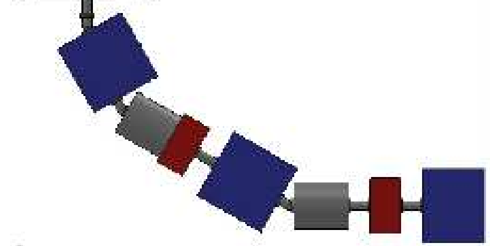
ALPHA: Antimatter Laser PHysics Apparatus



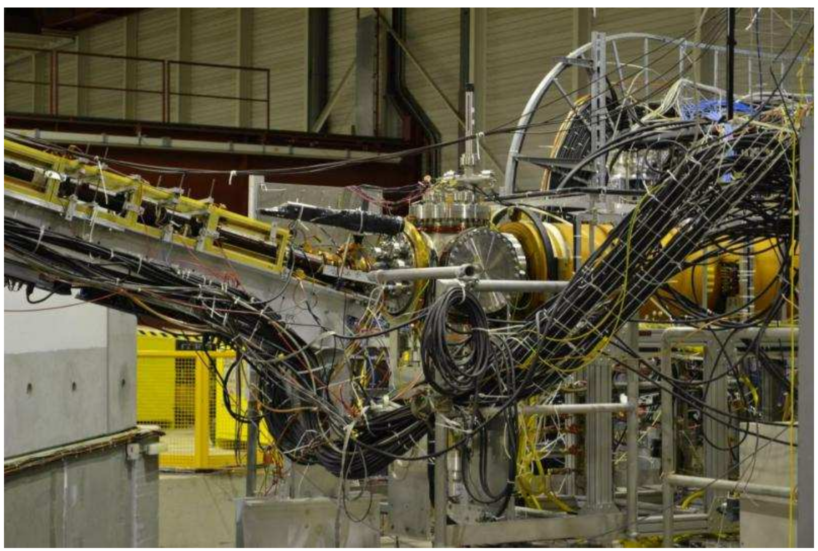


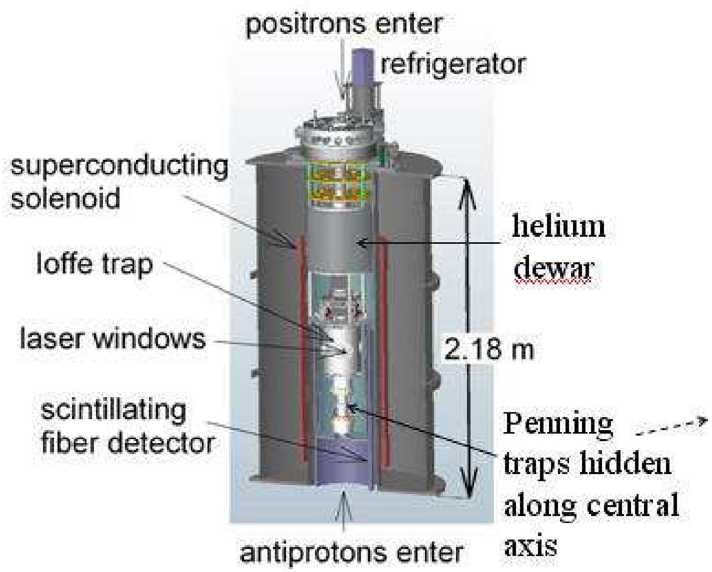
$\overline{\mathrm{H}}$ trapped for 1000 s; resonant HF transition induced; limit on $\overline{\mathrm{H}}$ charge; proposal for gravity measurement.

ATRAP: Antimatter trap



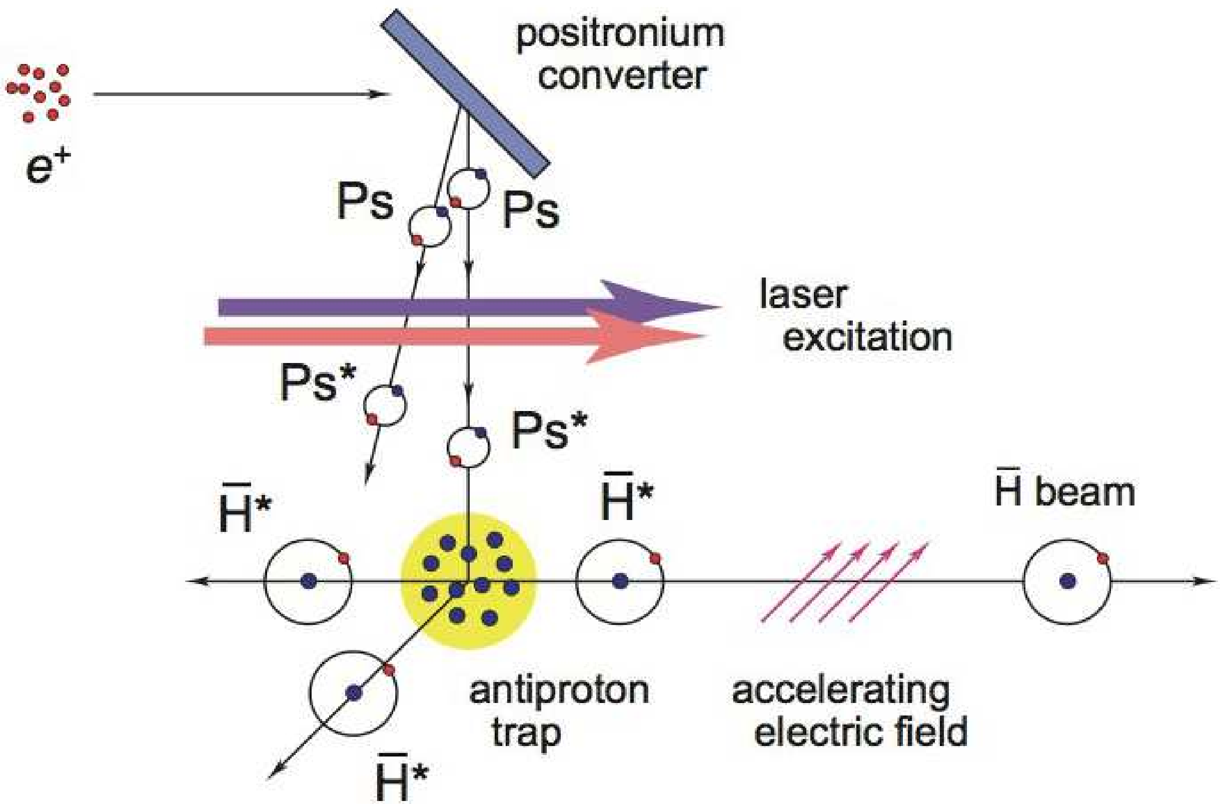
Continuous $\overline{\mathrm{H}}$ production





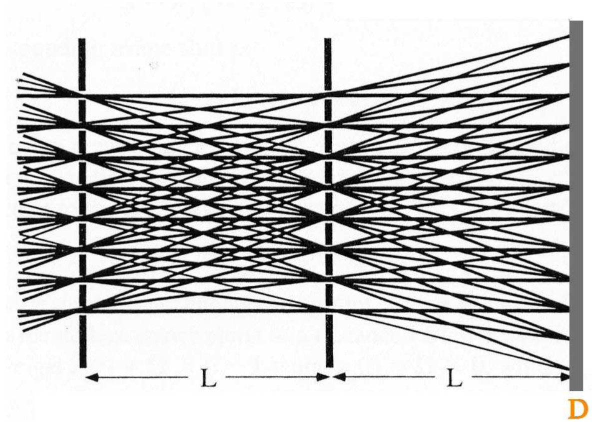
AEGIS: antimatter gravity

Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy



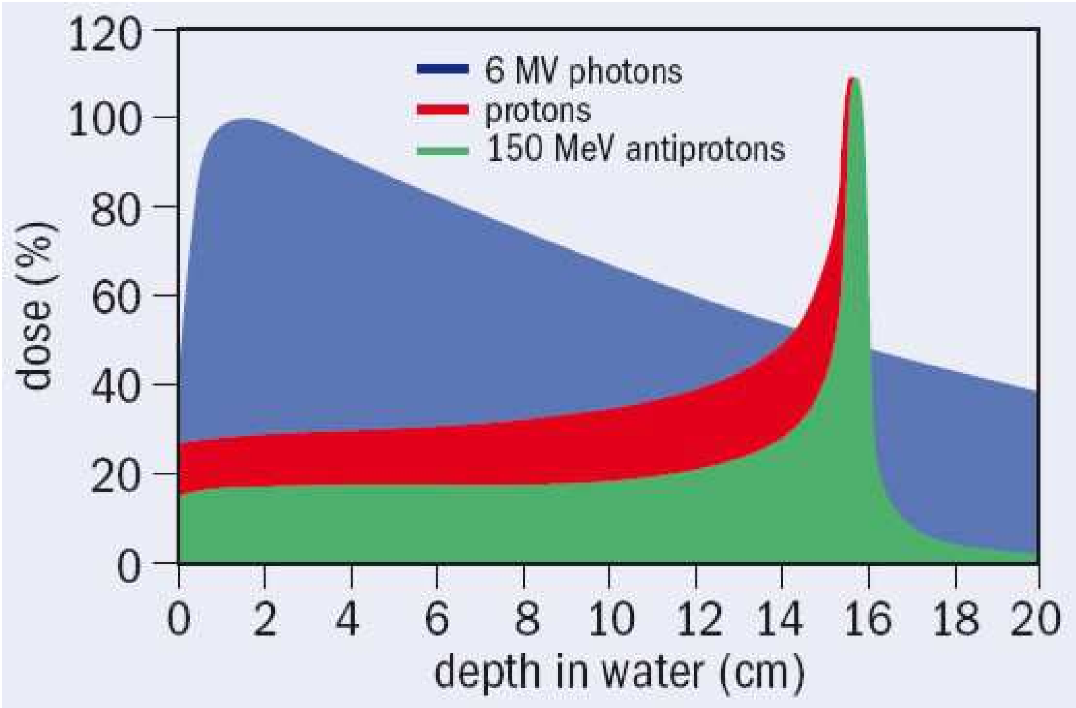
Moiré deflectometry:

gravitational falling of collimated $\overline{\mathrm{H}}$ as compared to light



ACE: Antimatter Cell Experiment

Cancer therapy research (USA) at AD of CERN



Advantage: Antiprotons lose energy in very small volume, choosing the right energy concentrates damage in tumor.

Disadvantage: Antiprotons are very expensive and annihilation radiation damages as well.

Antihydrogen beam

ASACUSA: MUSASHI

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

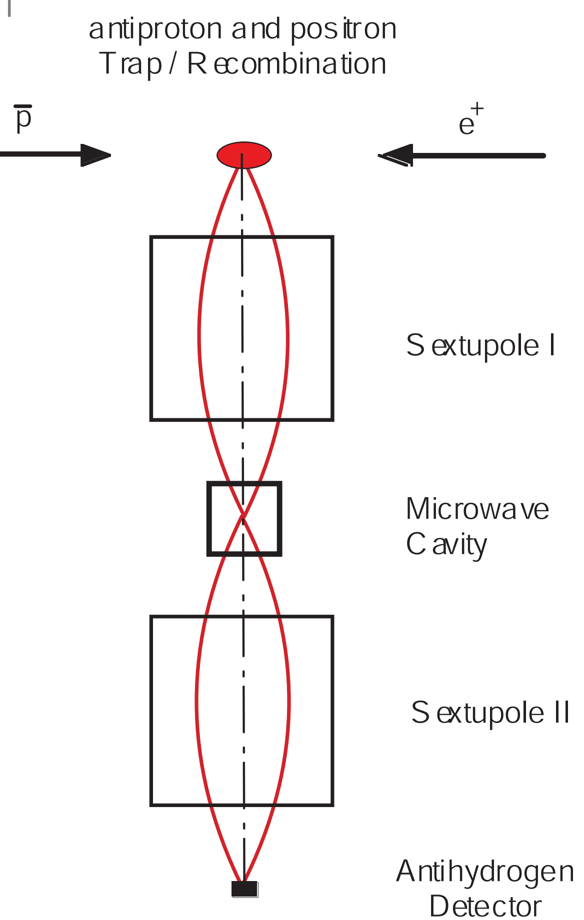
Musashi Miyamoto self-portrait ~ 1640

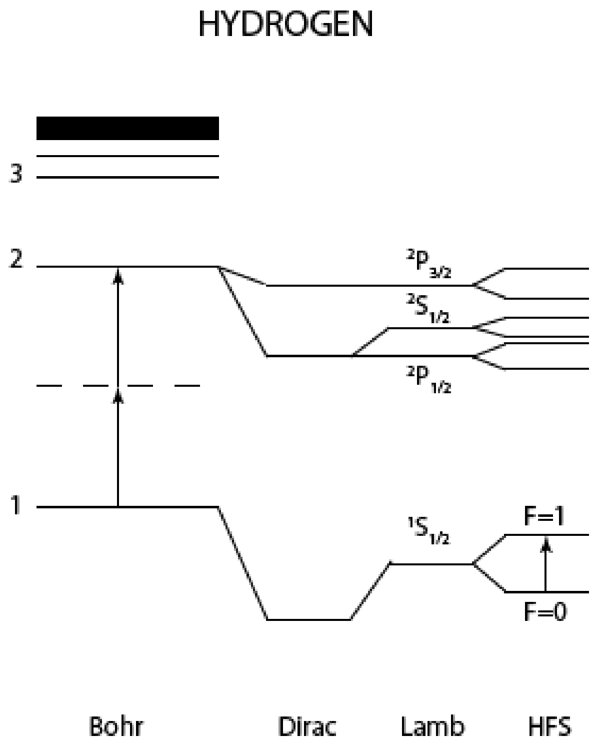
5.8 MeV $\overline{\mathrm{p}}$ injected into RFQ
100 keV $\overline{\mathrm{p}}$ injected into trap
10^6 $\overline{\mathrm{p}}$ trapped and cooled (2002)
~ 350000 slow $\overline{\mathrm{p}}$ extracted (2004)
Cold $\overline{\mathrm{p}}$ compressed in trap (2008)

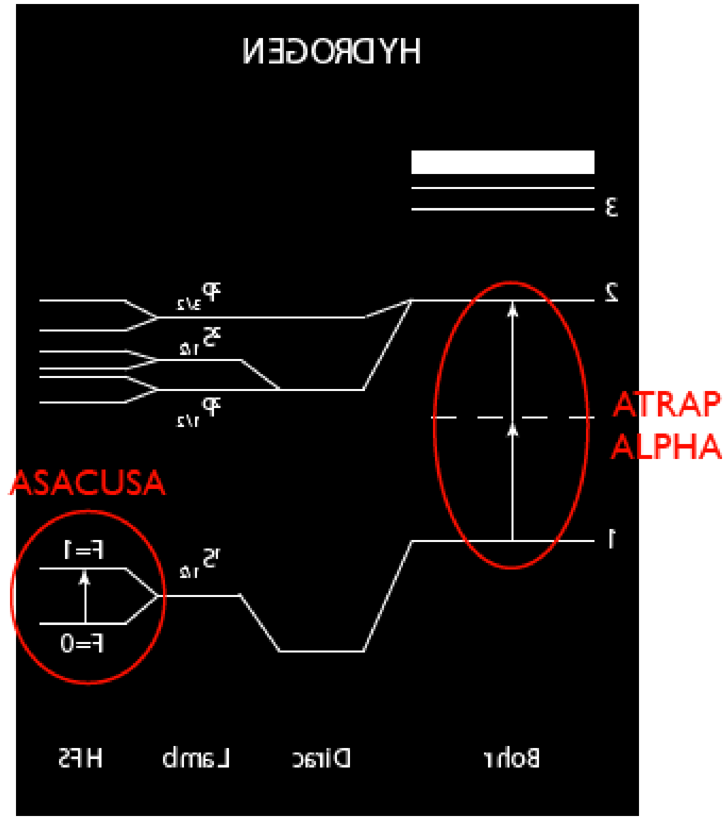
(5×10^5 $\overline{\mathrm{p}}$, $E = 0.3$ eV, $R = 0.25$ mm)

$\overline{\mathrm{H}}$-beam formed: ASACUSA, 2010–2012

Spectroscopy with $\overline{\mathrm{H}}$-beam







$\overline{\mathrm{H}}$-beam path: polariser, resonator, analyser

Analogy to polarised light

R.S. Hayano, M. Hori, D. Horváth, E. Widmann, **Rep. Progr. Phys.** *70* (2007) 1995.

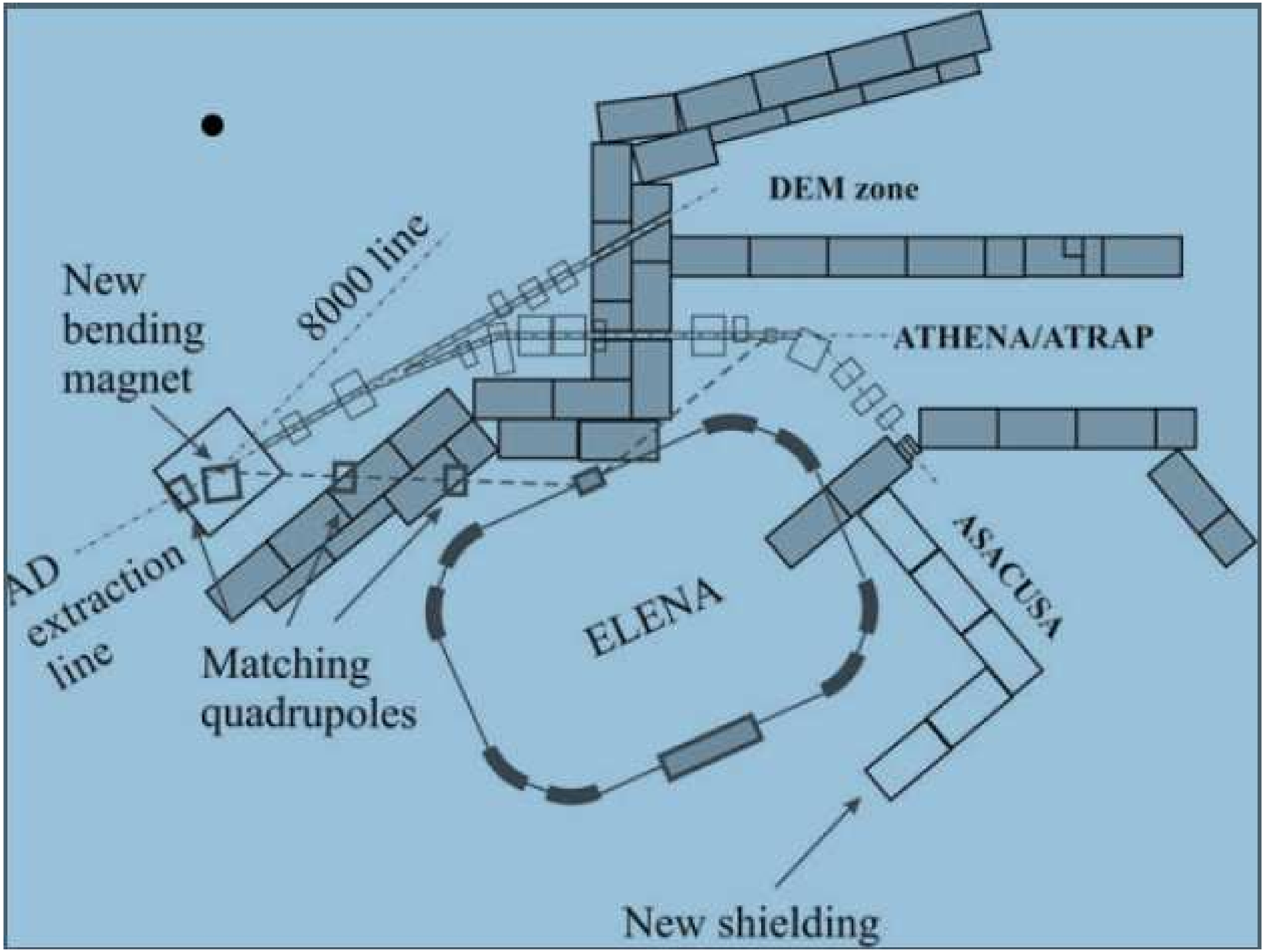
Extra Low ENergy Antiprotons (ELENA)

Physics Motivation

- Test the Standard Model and General Relativity for antimatter
- Test SM extensions for antimatter (Lorentz-violation, black holes, new interactions, ...)
- Stringent CPT tests with antihydrogen
- Antimatter gravity measurement (weak equivalence)
- Added precision for physical constants (CODATA) assuming CPT invariance

All existing AD experiments profit, new ones made possible
(gravity, X-rays, nuclear studies)

ELENA at the AD: plan



M.-E.Angoletta et al: *ELENA: A Preliminary Cost And Feasibility Study*, CERN-AB-2007-079.

Antimatter in Space

AMS-2: Alpha Magnetic Spectrometer
to discover antimatter (anti-helium!) and dark matter

Mass: 8500 kg,
1200 kg perm. magnet

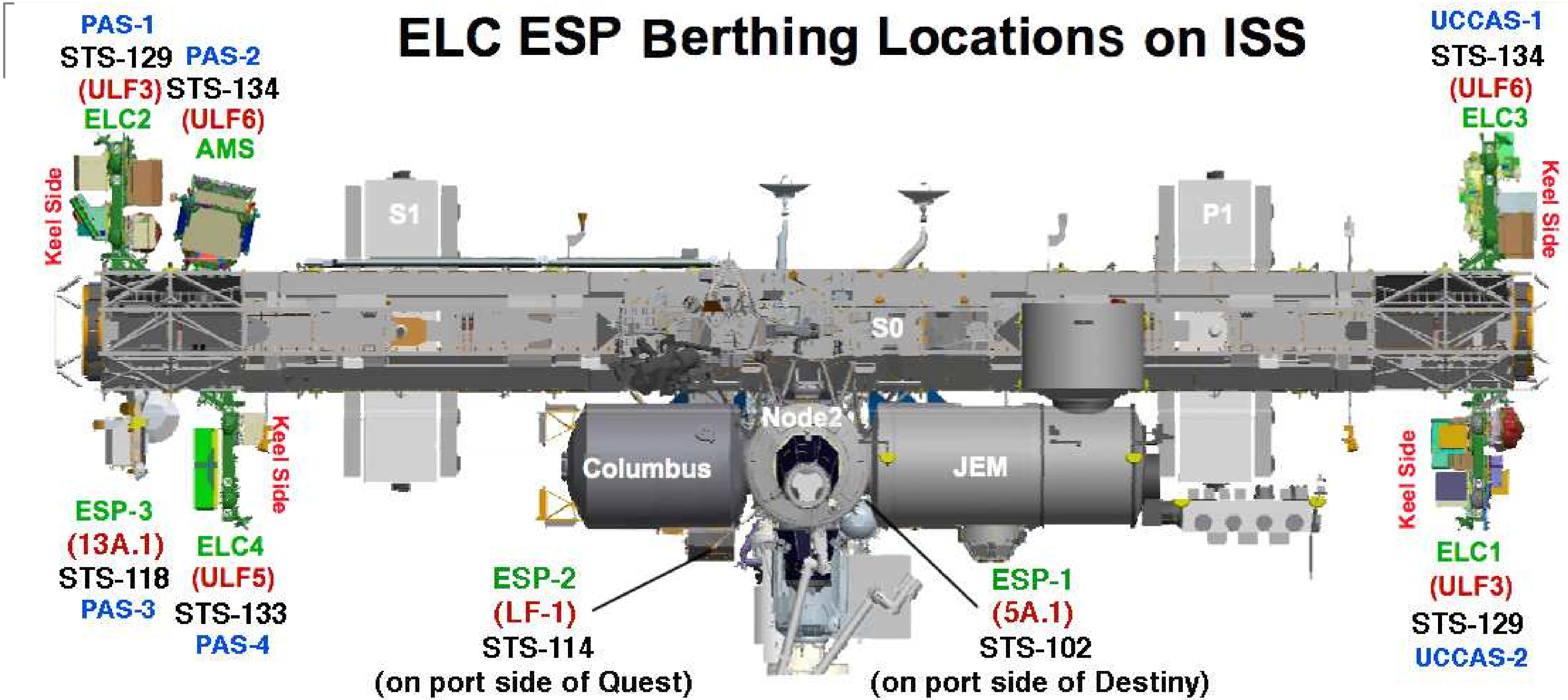
Father: Sam Ting, cost: 2 G$

Construction: CERN

Launch: May 2011, USA

Control room: CERN

AMS-2: Alpha Magnetic Spectrometer



First results (2013-14):

No antihelium observed.

High energy positrons everywhere.

Could come from dark matter or pulsars.

AMS2 will collect data for 10–15 years.

Conclusion

ASACUSA at AD

- Two-photon spectroscopy of antiprotonic helium: results agree with 3-body calculations.
- Determined $M_{\overline{\mathrm{p}}}/m_{\mathrm{e}}$ ratio to 1.3 ppb. Result agrees with CODATA proton value (0.4 ppb).
- Further improvement partially hindered by theoretical uncertainty.

Future prospects

- Colder atoms, better lasers, better detectors.
- ELENA (colder antiproton beams at 100 keV of higher luminosity).
- Spectroscopy with trapped antihydrogen and with antihydrogen beam.
- AMS2 delivers more and more data on antimatter in space.

Next: ASACUSA, antiprotonic helium