Experimental Tests of CPT Invariance at CERN

Szegedi Egyetem, Elm-Fiz. Tanszék, 2018.10.15.

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Outline

- Antimatter and its lack in the Universe
- CPT invariance: matter–antimatter symmetry
- The Antiproton Decelerator at CERN
- Antimatter experiments at CERN
- Antihydrogen: production
- Antihydrogen: spectroscopy
- Antihydrogen: gravity
- Outlook: ELENA
- Use of antimatter in life

Birth of antimatter

Paul Dirac, 1928: Linear equation for the hydrogen atom.

Square root of a quadratic equation $\Rightarrow$ two solutions for electrons ($x^2 = 4 \Rightarrow x = \pm 2$).

Two kinds of electrons:

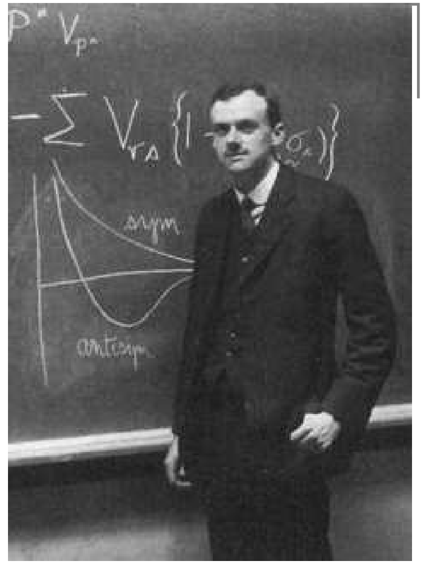
- $+$ mass and $-$ charge (ordinary electron);
- $-$ mass and $+$ charge (anti-electron = positron).

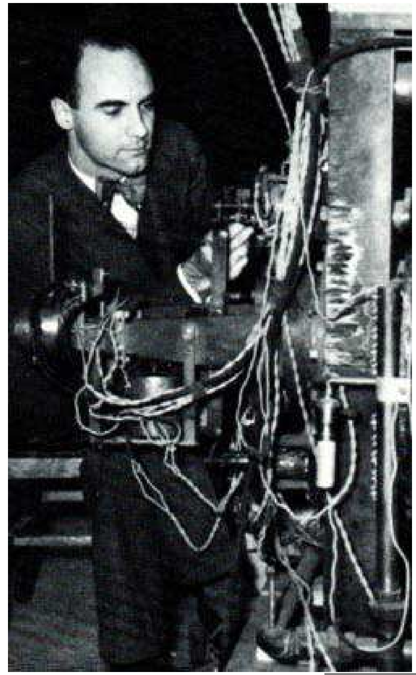
Negative mass non-physical. Dirac: particle holes.

Carl Anderson (1932): e^+ in cosmic rays!

$\Rightarrow$ real existing particle: positron.

Nobel prizes (in 4 years): Dirac: 1933; Anderson: 1936



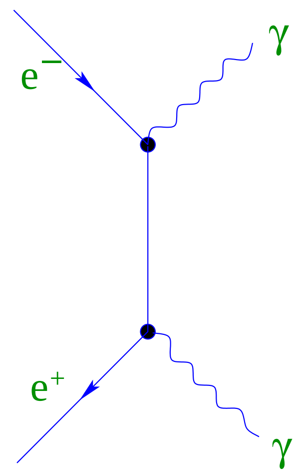


Antiparticles

Every matter particle (fermion) has an antiparticle

Proton (hydrogen nucleus) $\leftrightarrow$ antiproton.

Particles and antiparticles must have the same properties apart from the signs of charges.

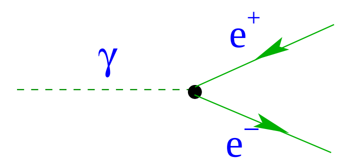


When particle meets its own antiparticle they annihilate to photons or to lighter particles (energy conservation).

A slow positron in matter annihilates with an atomic electron by emitting two (or three) gamma photons.

Converse reaction: radiation in the field of atomic nucleus can produce particle + antiparticle pairs.

Low energy: $\mathrm{e}^- + \mathrm{e}^+$, higher energy ($E > 2M_p$): $\mathrm{p} + \overline{\mathrm{p}}$.



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 curiosity?

Matter–antimatter symmetry

CPT invariance

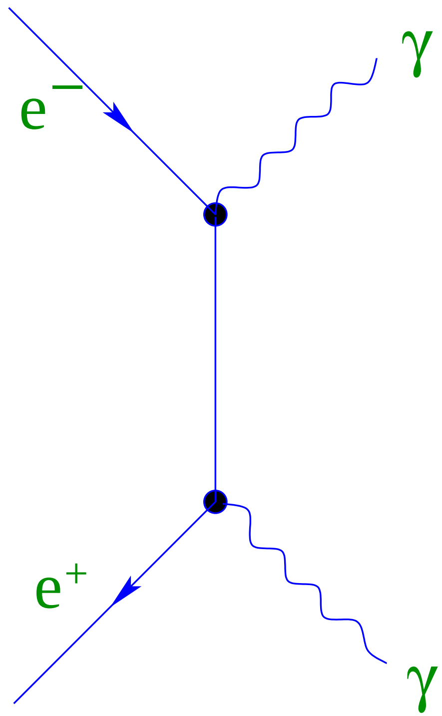
Charge conjugation:	$C\|\mathrm{p}(r,t)\rangle = \|\overline{\mathrm{p}}(r,t)\rangle$
Space reflection:	$P\|\mathrm{p}(r,t)\rangle = \|\mathrm{p}(-r,t)\rangle$
Time reversal:	$T\|\mathrm{p}(r,t)\rangle = \|\mathrm{p}(r,-t)\rangle K$

(K: complex conjugation for $\exp\{-\mathrm{i}Et\}$)

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 is 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

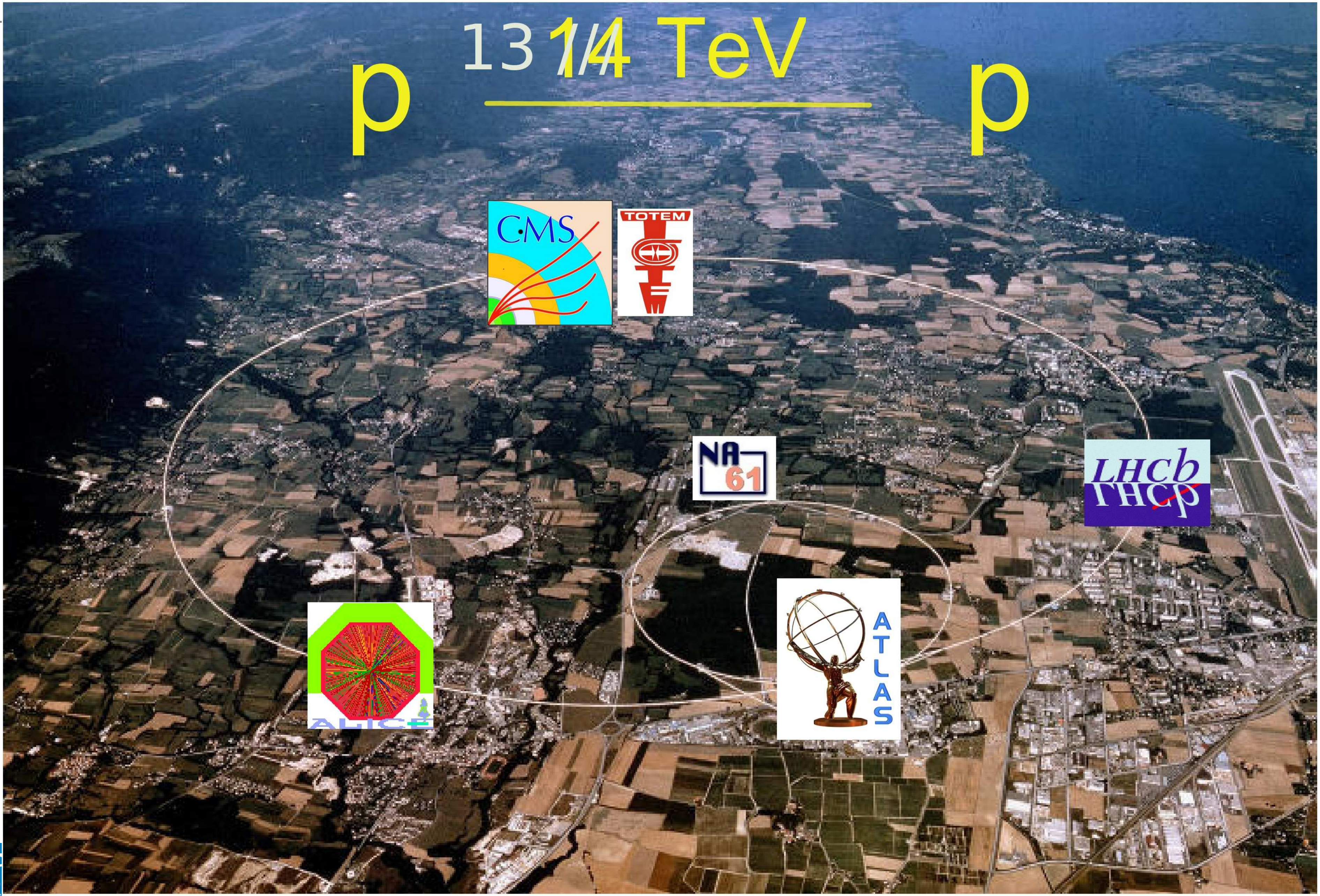
(Alan Kostelecký, F.R. Klinkhamer, N.E. Mavromatos et al)

How to test CPT?

Particle = – antiparticle ?

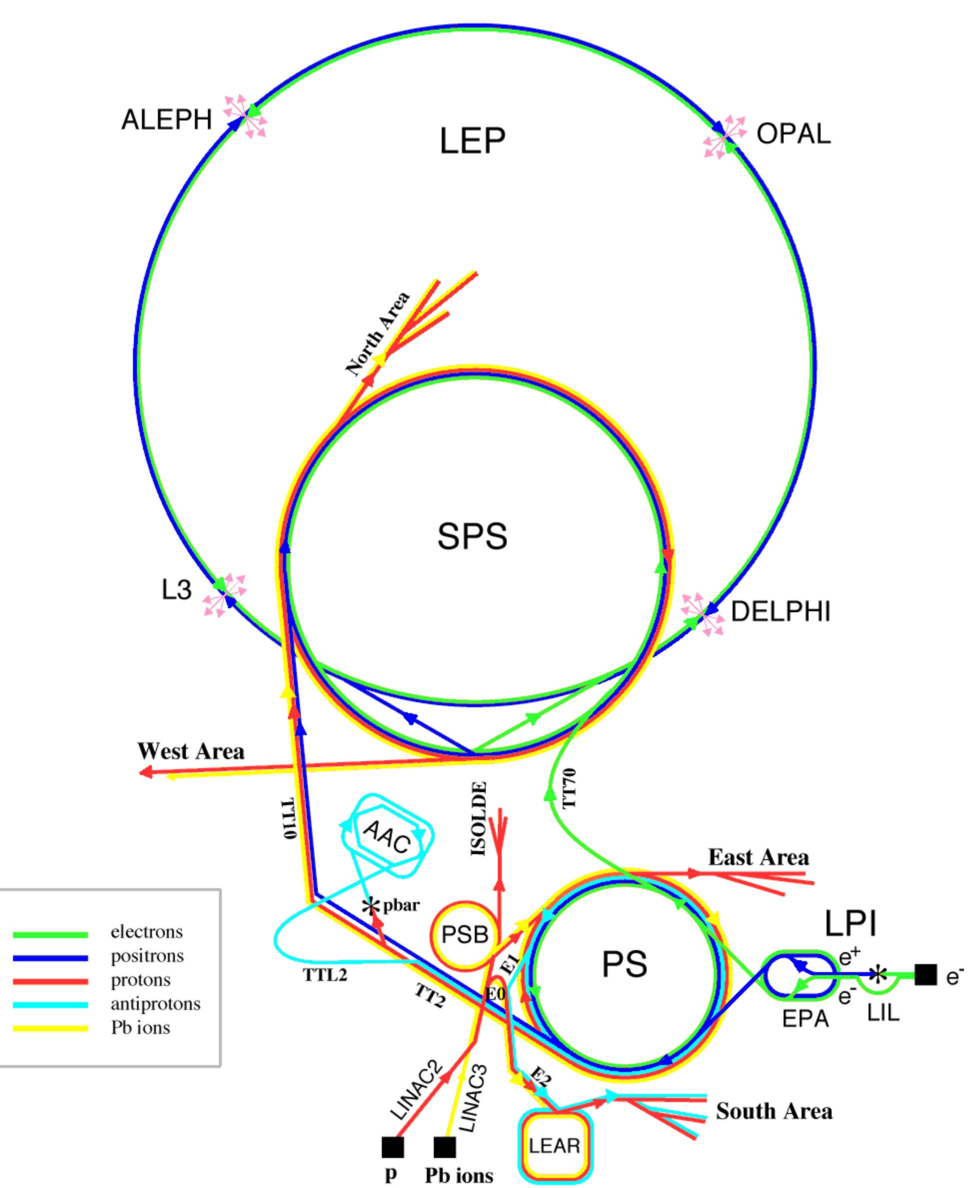
- $[m(\mathrm{K}^0) - m(\overline{\mathrm{K}}^0)]/m(\mathrm{average}) < 10^{-18}$
- proton $\sim$ antiproton? (compare m, q, $\vec{\mu}$)
- hydrogen $\sim$ antihydrogen $(\overline{\mathrm{p}}e^+)$? $2S - 1S$, HFS

CERN: aerial view

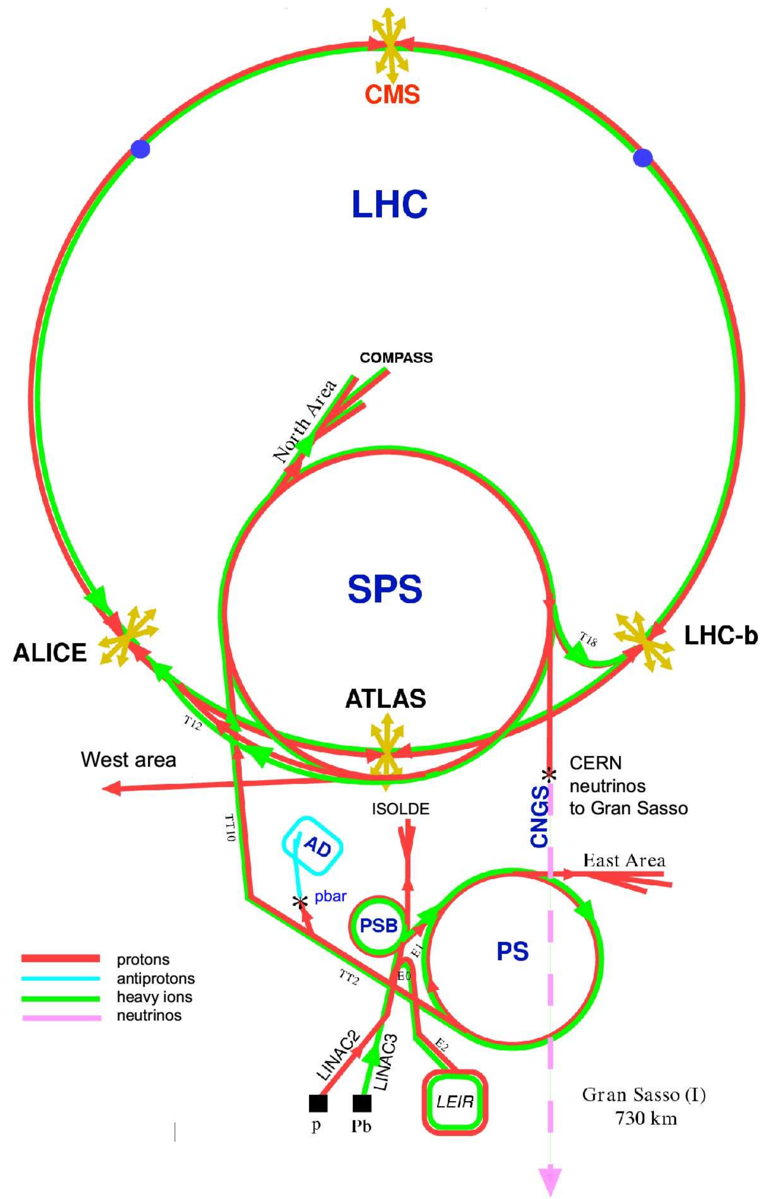


Accelerators at CERN

1989–2000



2009–2025??



Low Energy Antiproton Ring (LEAR)

1992: CERN wants to stop it
when CPLEAR finishes data taking.

Save LEAR! Munich workshop, 1992

1993

ANTIHYDROGEN

Proceedings of the
Antihydrogen Workshop

Ludwig Maximilian University
Munich, Germany
30-31 July 1992

J.C. Baltzer AG

SCIENCE PUBLISHERS
BASEL - SWITZERLAND

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Save LEAR! feasibility study, 1992

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN SPSLC 92-45
SPSLC M-505
August 27, 1992

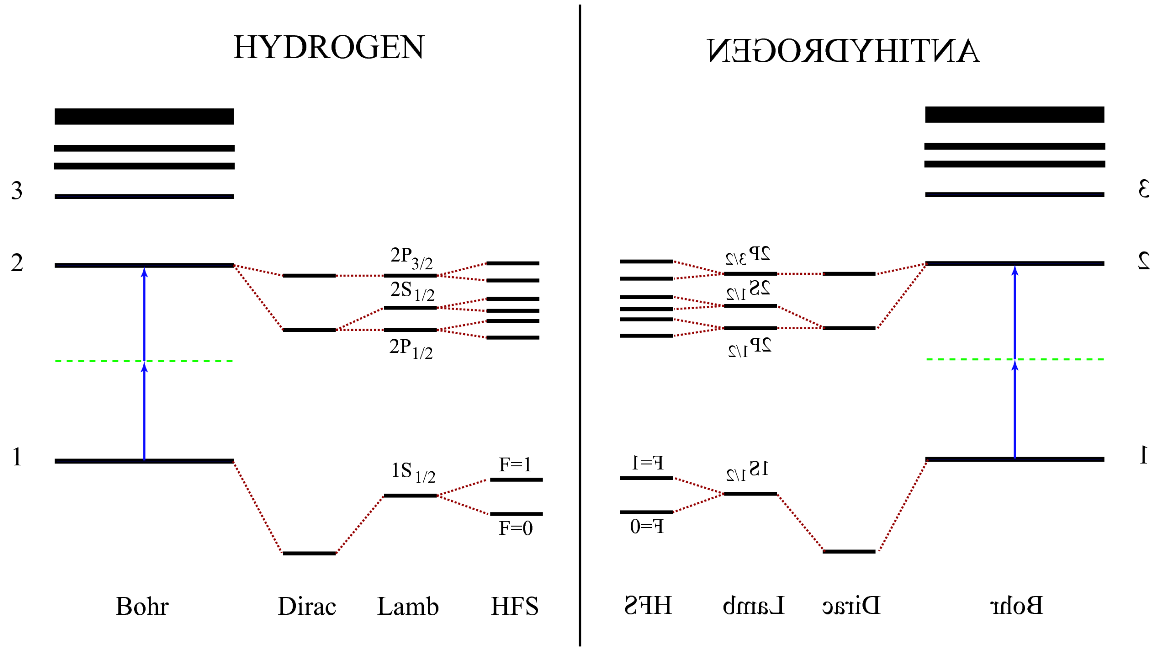
MEMORANDUM TO THE CERN SPSL COMMITTEE

ANTIHYDROGEN FORMATION AND SPECTROSCOPY AT LEAR

M. Charlton[1)], J. Eades[2)], D. Horváth[3,4)] and R. J. Hughes[5)]

CERN extended LEAR until 1996
(when CPLEAR finished data taking).

Antihydrogen, e^+–$\bar{p}$ atom, 1993



$2S - 1S$ transition

with 2-photons

Long lifetime,

narrow transition,

Doppler-free

spectroscopy

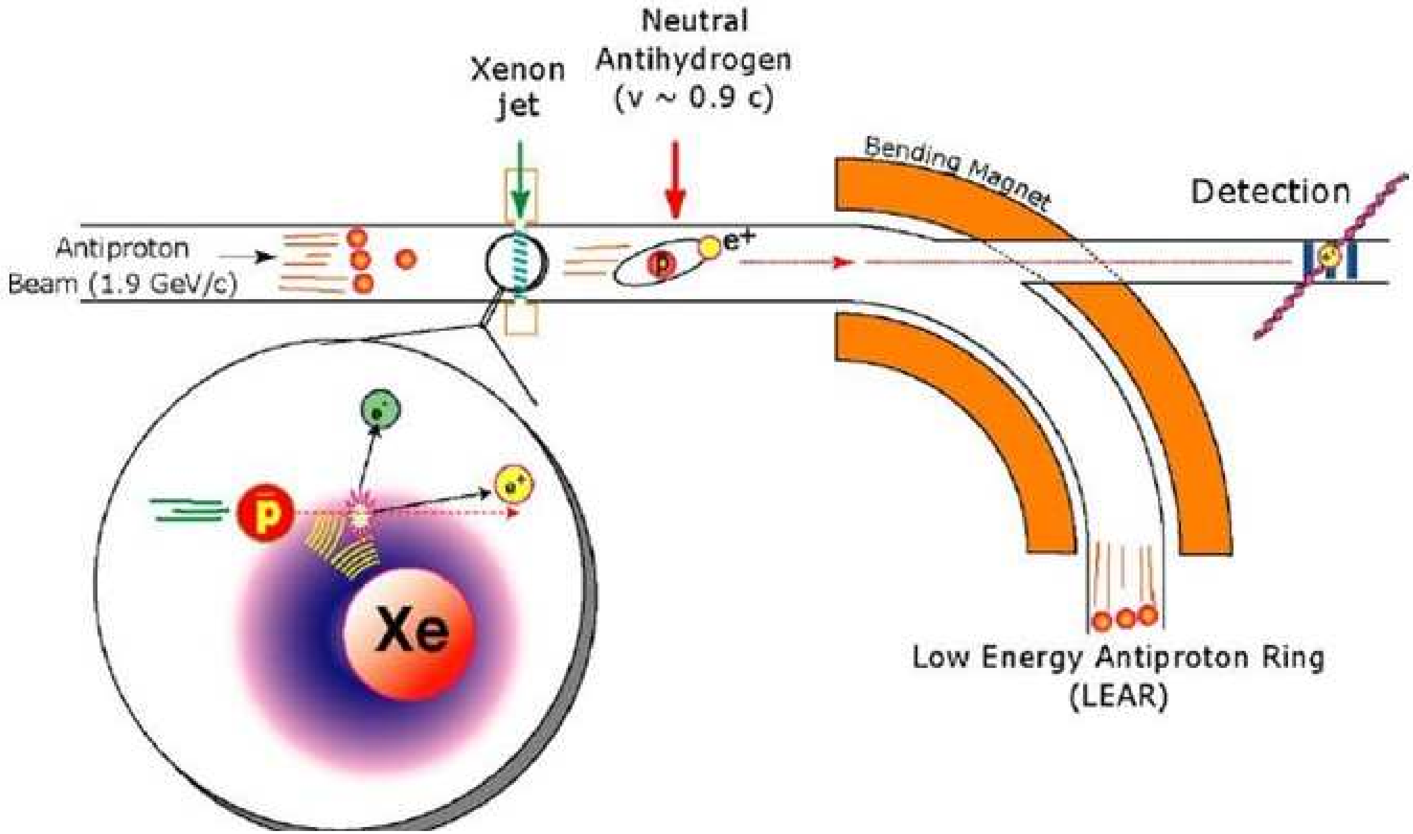
Feasibility study for the SPSL Committee of CERN (1992) converted into

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

SPSLC accepted and CERN approved to build the Antiproton Decelerator

Great technical accomplishment of Dieter Möhl et al.

First (9) relativistic $\overline{\mathrm{H}}$ atoms at LEAR



G. Baur *et al.*, „Production of anti–hydrogen," Phys. Lett. B **368** (1996) 251.

Later also at FERMILAB:

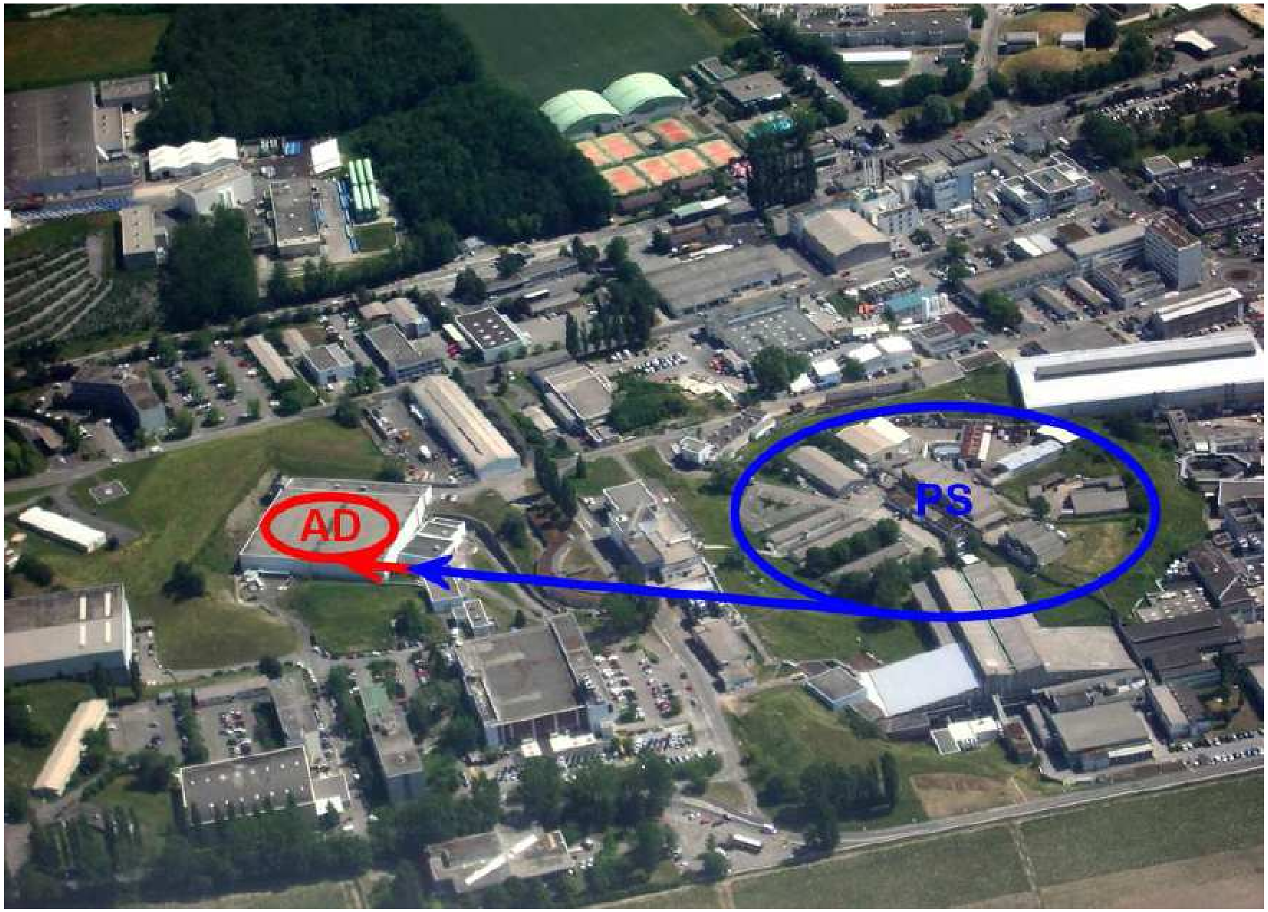
G. Blanford *et al.*, „Observation of atomic anti-hydrogen," Phys. Rev. Lett. **80** (1998) 3037.

Antimatter factory at CERN

The Antiproton Decelerator at CERN

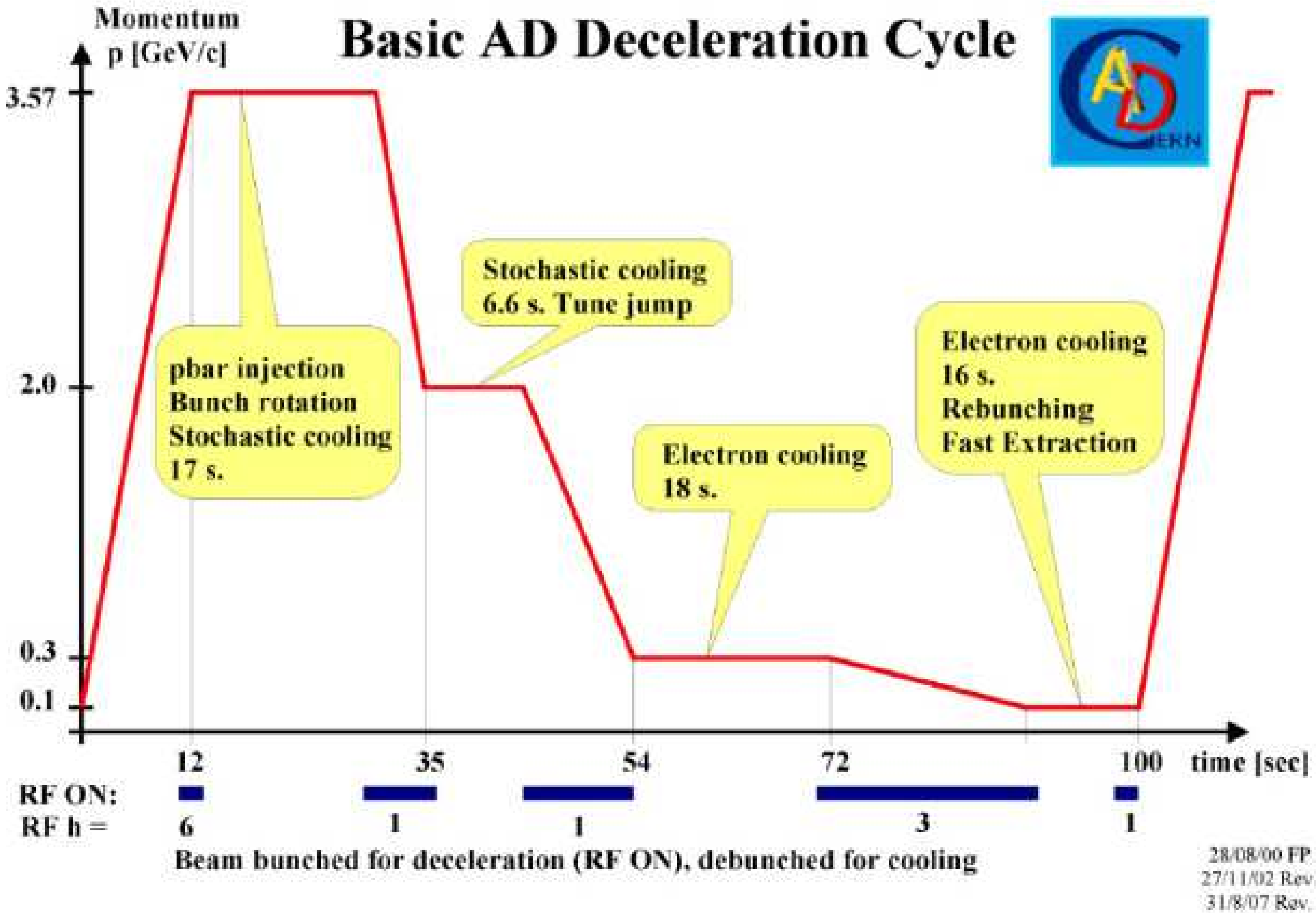
was built in 1997-99 to study antimatter physics

6 expts (3 each) for *CPT* and antigravity



©Ryugo S. Hayano, Tokyo U.

The Antiproton Decelerator: cooling



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

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

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

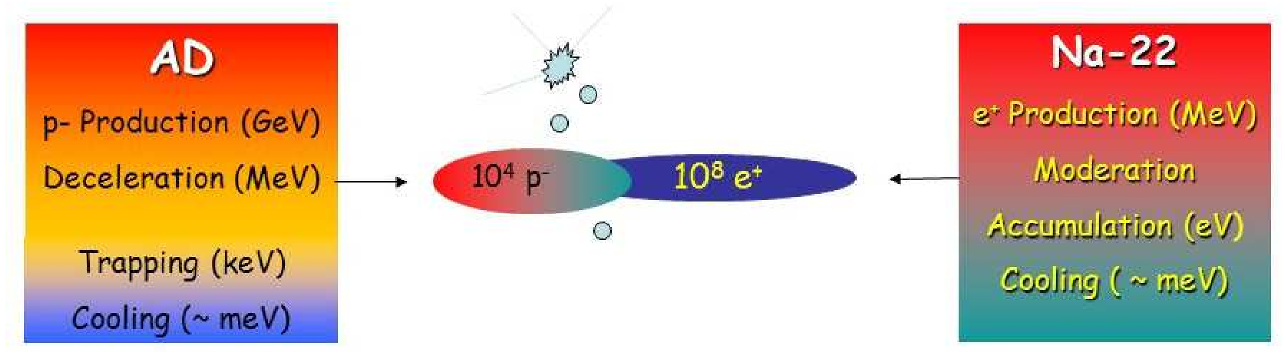
- Putting antiprotons ($\overline{\mathrm{p}}$) in electromagnetic trap
- Trapping and cooling antiprotons
- Cooling slow positrons (e^+ from ^{22}Na) in trap
- Mixing $\overline{\mathrm{p}}$ and e^+ $\rightarrow$ recombination in $e^+e^+\overline{\mathrm{p}}$ collisions (G. Gabrielse, ATRAP & Harvard U.)
- Trapping antihydrogen, waiting for deexcitation
- Cooling antihydrogen
- Laser spectroscopy on antihydrogen

2017: done by the ALPHA Collaboration!

Antiproton production

CERN exhibition in Globe: $\overline{\mathrm{p}}$ production target at AD

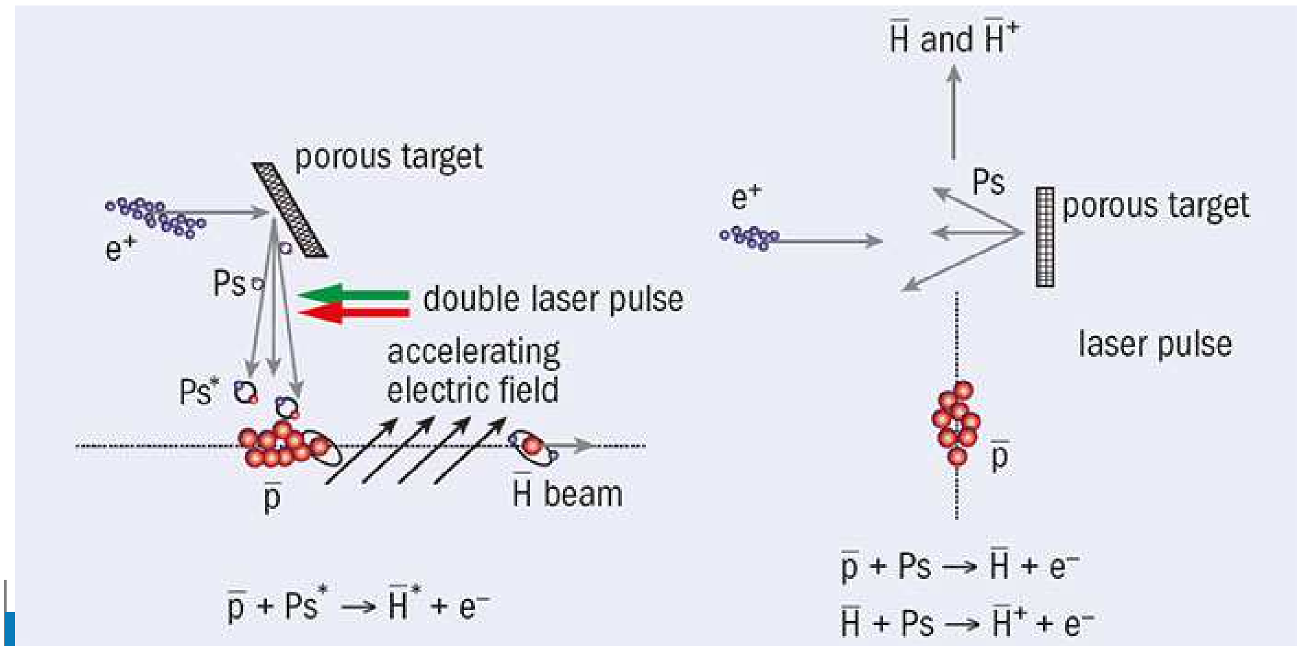
How to produce antihydrogen?



Radiative $(\bar{\mathrm{p}}\mathrm{e}^+\gamma)$: deep bonding, low rate (hopeless)

3-body $(\bar{\mathrm{p}}\mathrm{e}^+\mathrm{e}^+)$: shallow bond, high rate

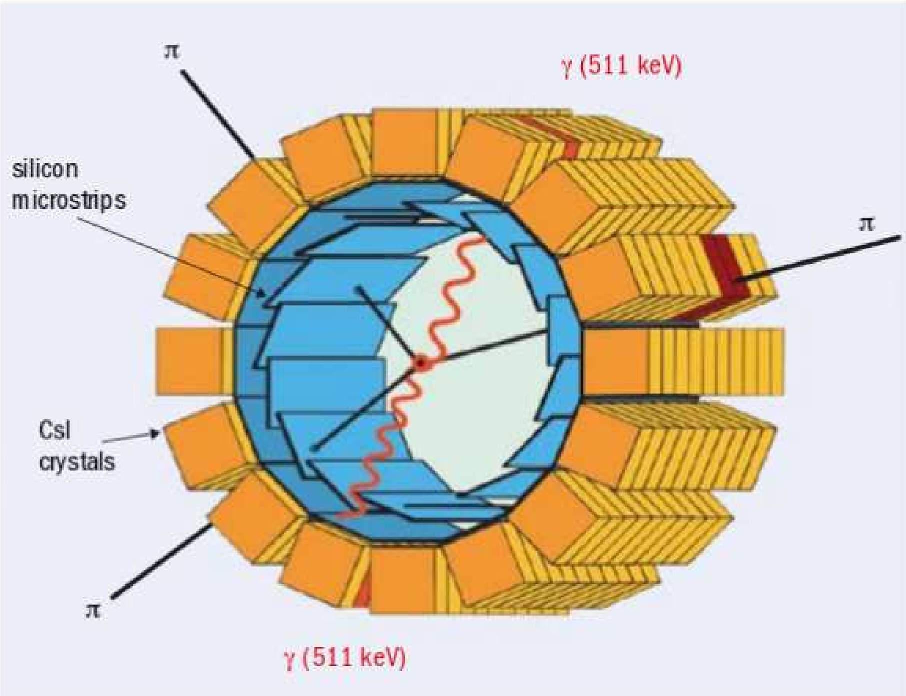
Proposed by G. Gabrielse, ATRAP & Harvard U.



With excited positronium: high rate, deep bond (planned)

Proposed by B. Deutch et al., Aarhus

ATHENA: first cold $\overline{\mathrm{H}}$ atoms at AD



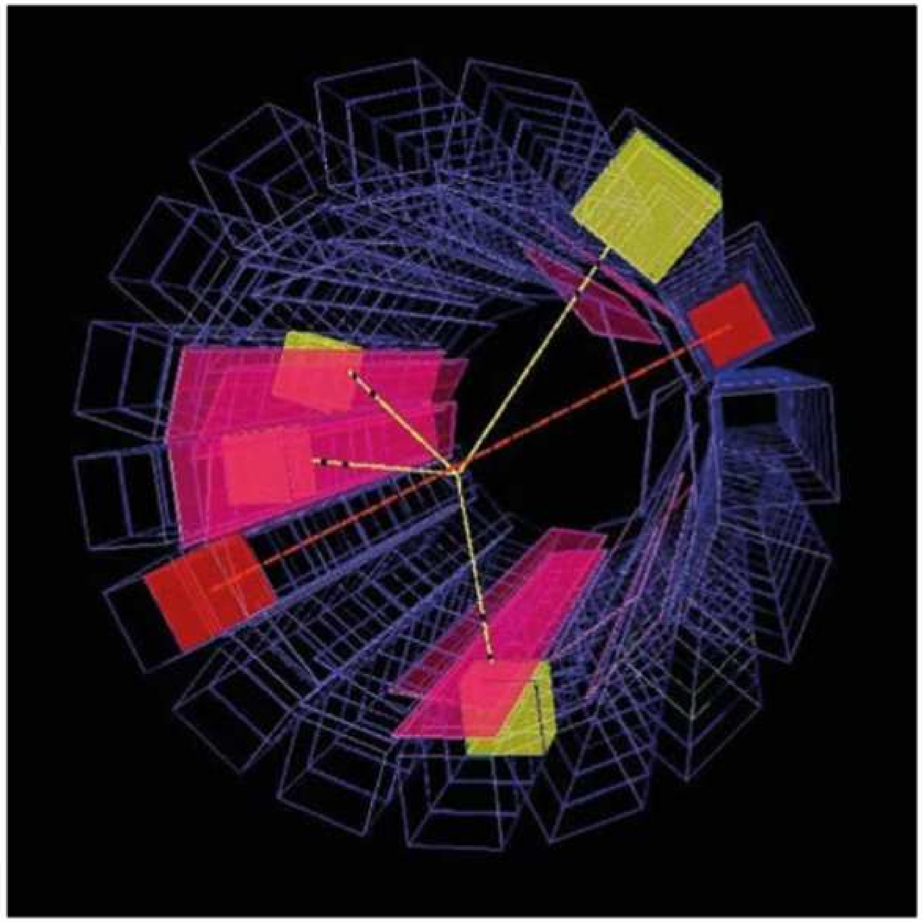
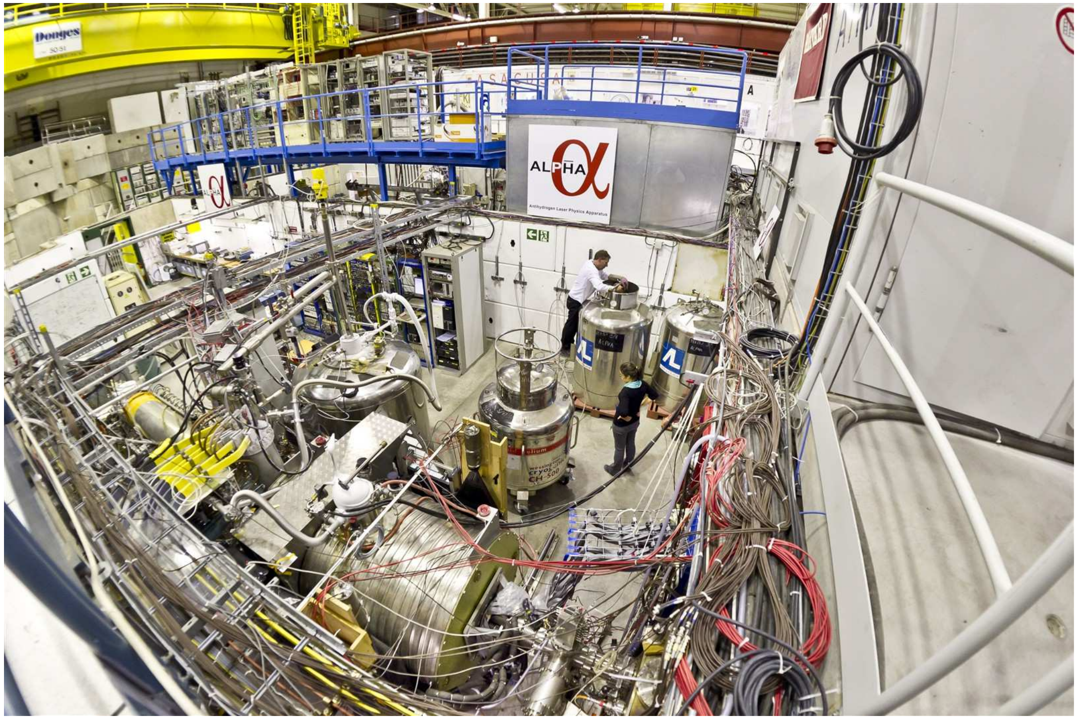


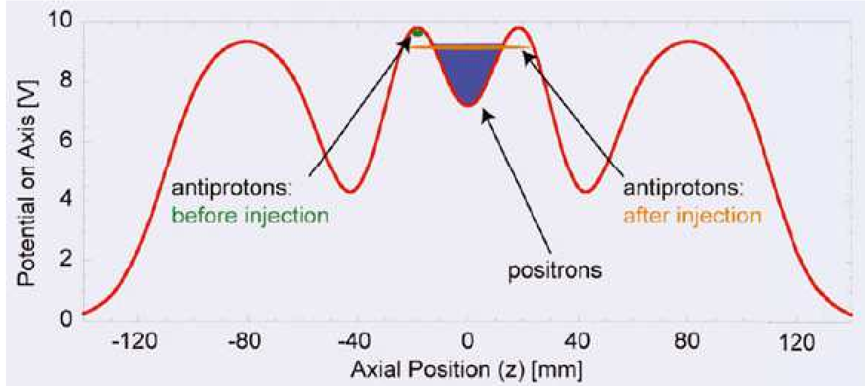
Fig.5. Above: A diagram of the ATHENA antihydrogen detector. Right: An antihydrogen annihilation event in ATHENA, reconstructing four charged pions (yellow) and two 511 keV photons (red). (Image credits: ATHENA Collaboration.)

ATHENA Collaboration (1997 – 2005) ⇒ ALPHA Collaboration

ALPHA: $\overline{\mathrm{H}}$ production

ALPHA: Antimatter Laser PHysics Apparatus (19 institutes of 9 countries)





- Capture 90,000 antiprotons.
- Mix with 3 million positrons.
- Produce 50,000 $\overline{\mathrm{H}}$ atoms.
- Remove charged particles.
- Trap 20 $\overline{\mathrm{H}}$ at $T = 0.54\,$K.

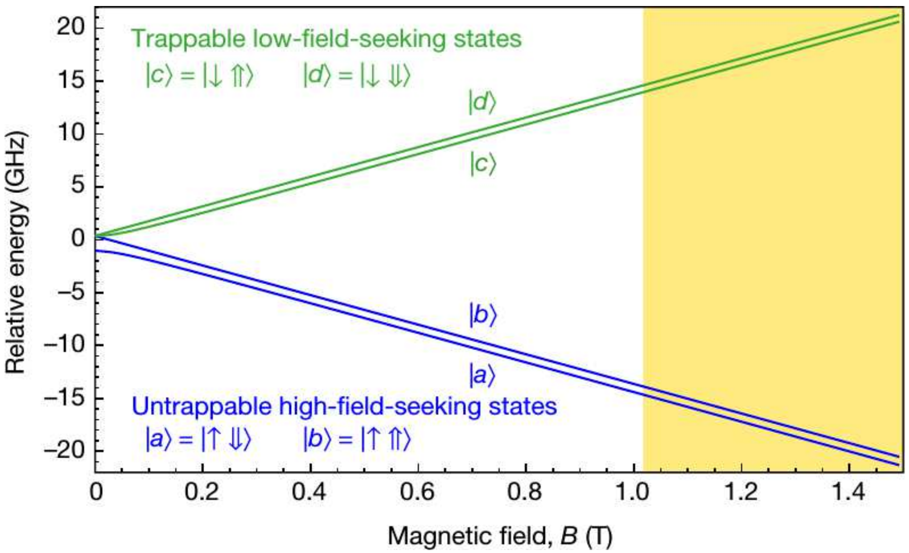
$\overline{\mathrm{H}}$ kept trapped for 10 s $\Rightarrow$ waiting deexcitation to $1S$ ground state.

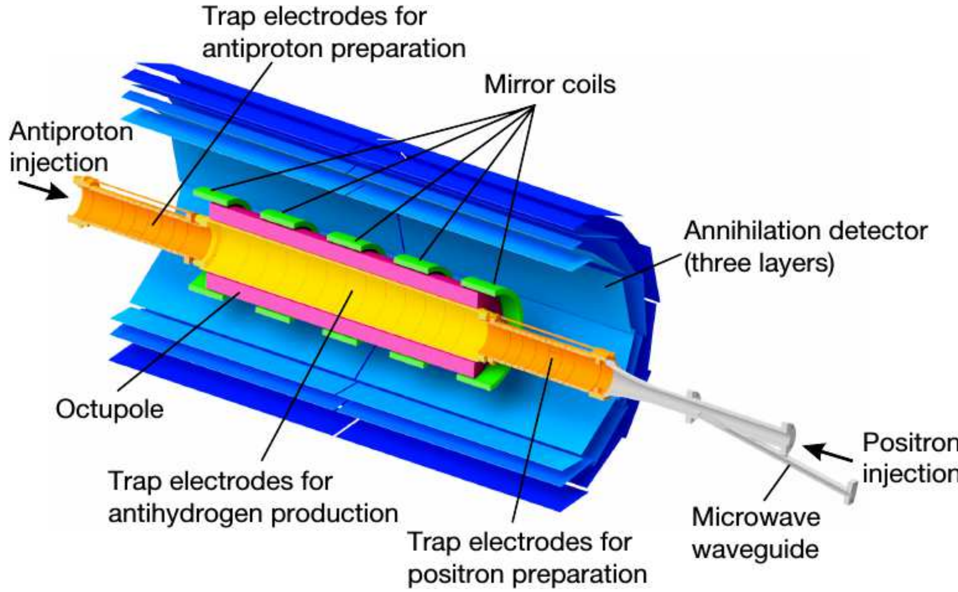
Demonstrated by keeping $\overline{\mathrm{H}}$ for >60 hours.

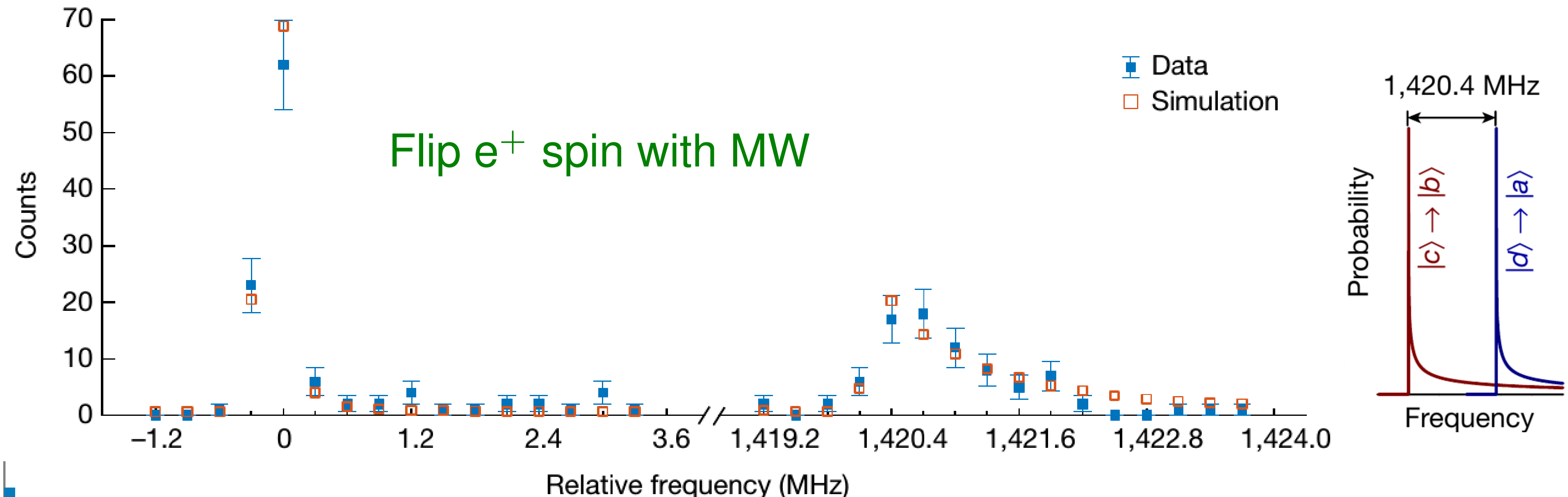
Detected and measured by dropping $B = 1\,$T $\Rightarrow$ annihilation.

Measured magnetic moment by hyperfine splitting on $\overline{\mathrm{H}}$

ALPHA: $\overline{\text{H}}$ hyperfine spectrum

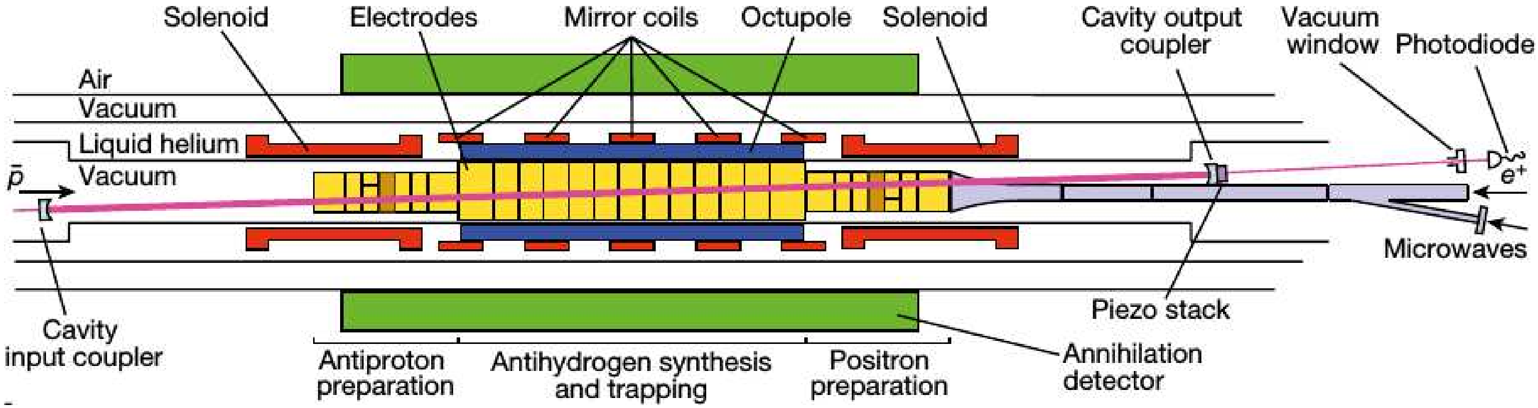






ALPHA Coll., „Observation of the hyperfine spectrum of antihydrogen," Nature 548 (2017) 66.

ALPHA: $\overline{\mathrm{H}}$ $1S - 2S$ transition



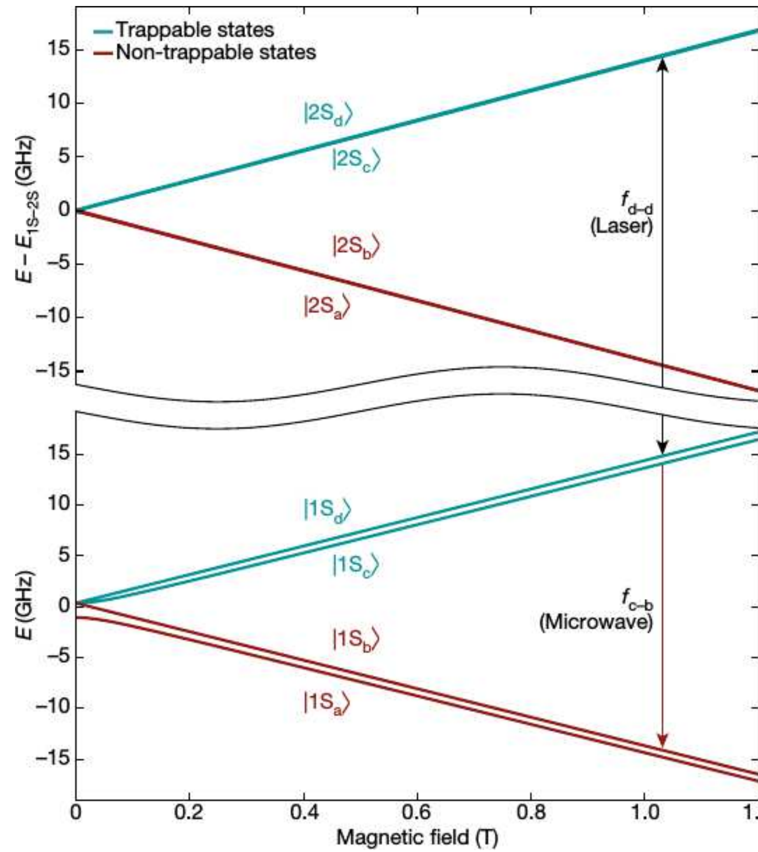
Measure annihilation rates.

Wait for 10 s to reach $\overline{\mathrm{H}}(1S)$ state.

Excite $1S \to 2S$ with two 243 nm photons (standing wave for 300 s) tuned around resonance (appearance).

Use microwave to remove residual $1S$ atoms (disappearance).

Flush trap by dropping B (residuals).



ALPHA: $\overline{\mathrm{H}}$ $1S - 2S$ spectroscopy

Result using 15000 $\overline{\mathrm{H}}$ atoms:

$$f_{d-d} = 2,466,061,103,079.4 \pm 5.4 \text{ kHz}$$

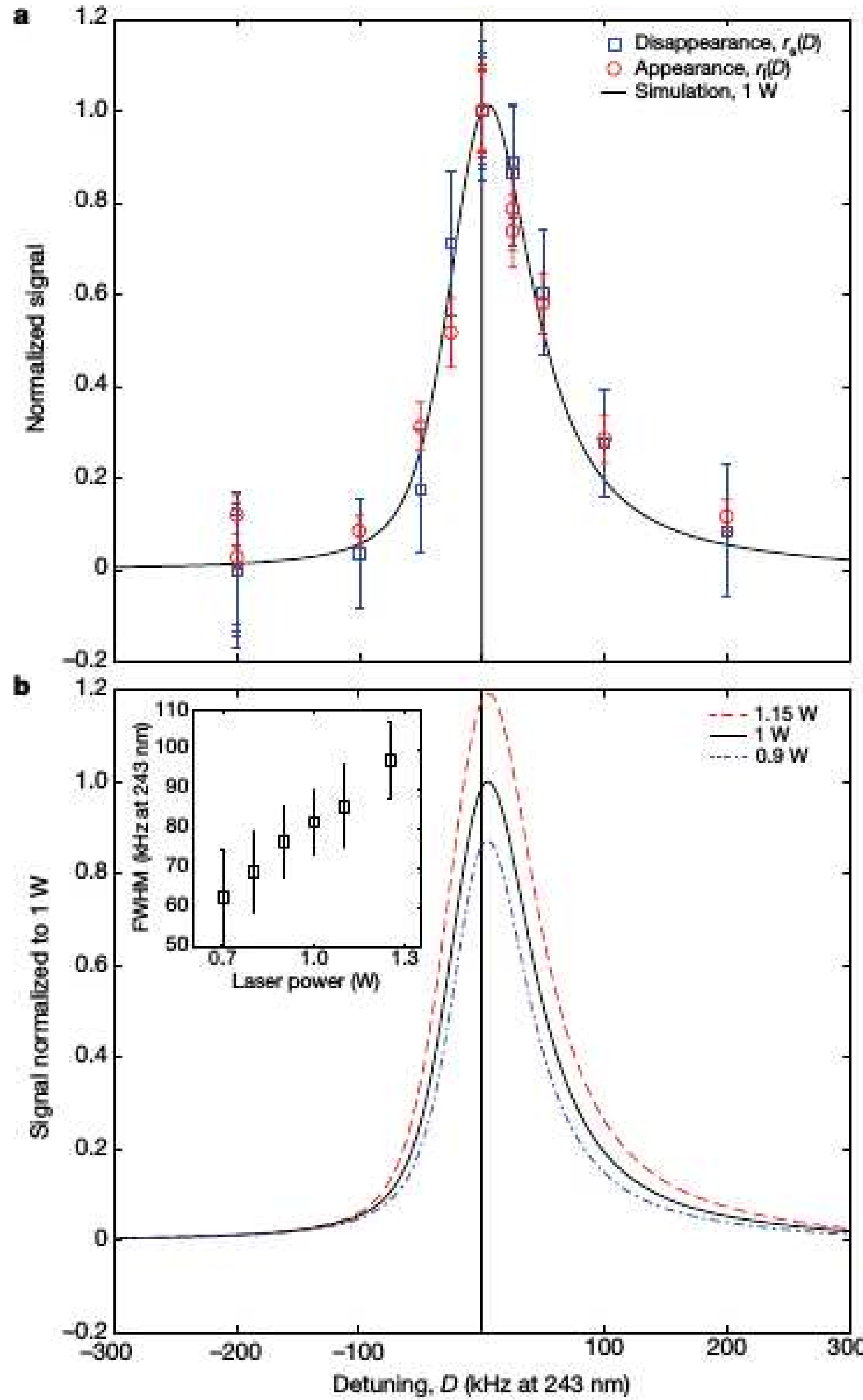
For hydrogen:

$$f_{d-d} = 2,466,061,103,080.3 \pm 0.6 \text{ kHz}$$

Difference (CPT test): 2×10^{-12}

ALPHA Coll.,
Observation of the 1S-2S transition in trapped antihydrogen,
Nature 541 (2017) 506.

ALPHA Coll.,
Characterization of the 1S-2S transition in antihydrogen,
Nature 557 (2018) 74.



ALPHA: $\overline{\mathrm{H}}$ $1S - 2S$ transition

ALPHA Collaboration (49 authors),

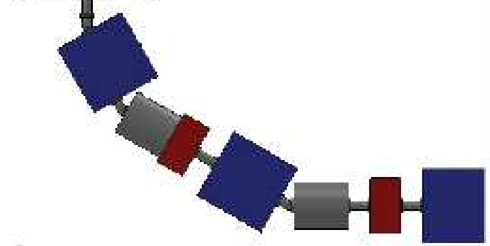
Characterization of the 1S-2S transition in antihydrogen,

Nature 557 (2018) 74.

Author contributions This experiment was based on data collected using the ALPHA-2 antihydrogen trapping apparatus, designed and constructed by the ALPHA Collaboration using methods developed by the entire collaboration. The entire collaboration participated in the operation of the apparatus and the data-taking activities. The laser and internal cavity system was conceived, implemented, commissioned and operated by W.B., N.M., J.S.H., S.E., C.Ø.R., S.A.J., C.L.C., B.X.R.A. and G.S. F.R., C.Ø.R., J.F. and N.M. developed the simulation program for laser interaction with magnetically trapped atoms. Analysis of the spectral line shapes was done by C.Ø.R., N.M. and J.S.H. Detailed analysis of the antiproton annihilation detector data was done by J.T.K.M. and A.O. Implementation of the microwave system and analysis of the microwave data was done by T.F. and M.E.H. The positron accumulator is the responsibility of C.J.B., M.C., C.A.I. and D.P.v.d.W. The manuscript was written by J.S.H., N.M., C.Ø.R., S.A.J. and J.T.K.M., with help from A.O., C.L.C. and S.E. The manuscript was then edited and improved by the entire collaboration.

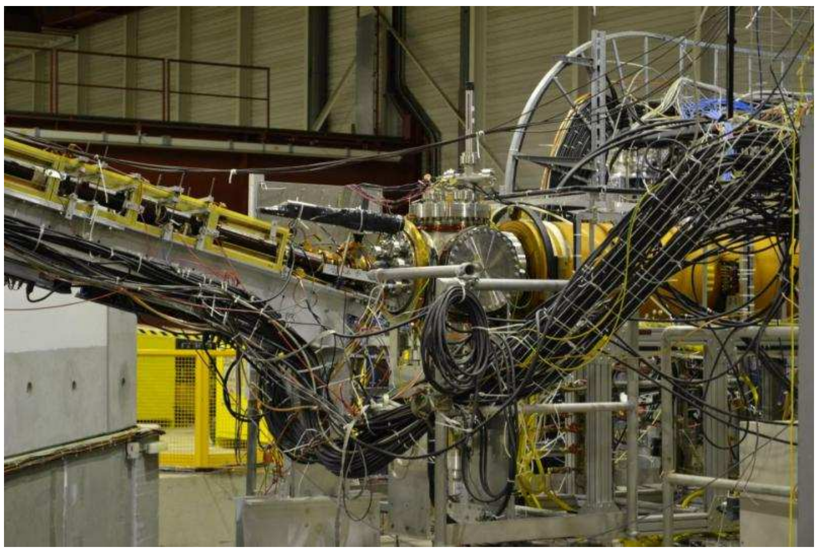
Reviewer information *Nature* thanks D. Horvath, K. Jungmann and the other anonymous reviewer(s) for their contribution to the peer review of this work.

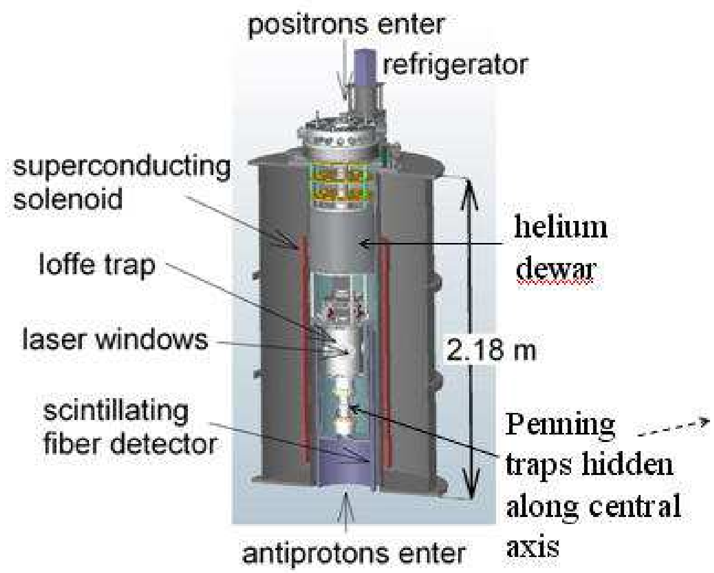
ATRAP: Antimatter trap



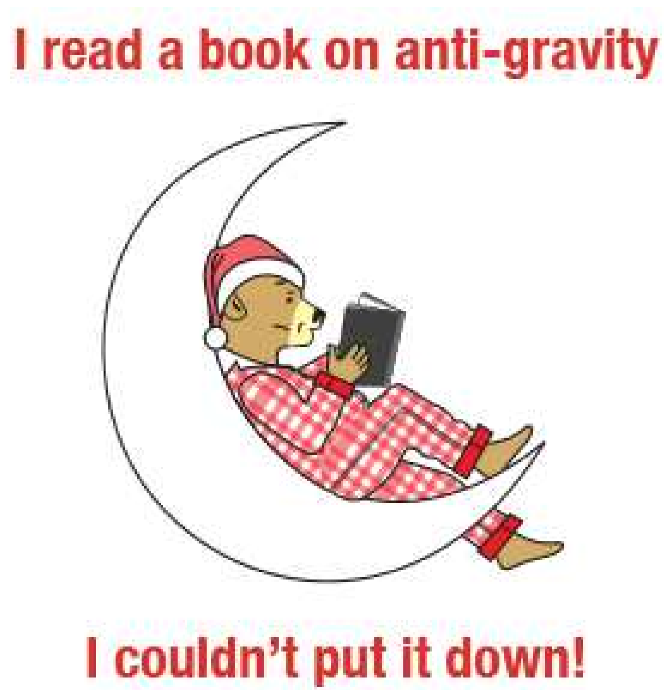
4×10^9 e$^+$ ($T = 1.2$ K, $p < 6 \times 10^{-17}$ Torr)

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





Antimatter gravity



Negative mass $\Rightarrow$ repulsive gravity??

95 % of nucleon mass is energy, small grav. diff. between H and $\overline{\mathrm{H}}$

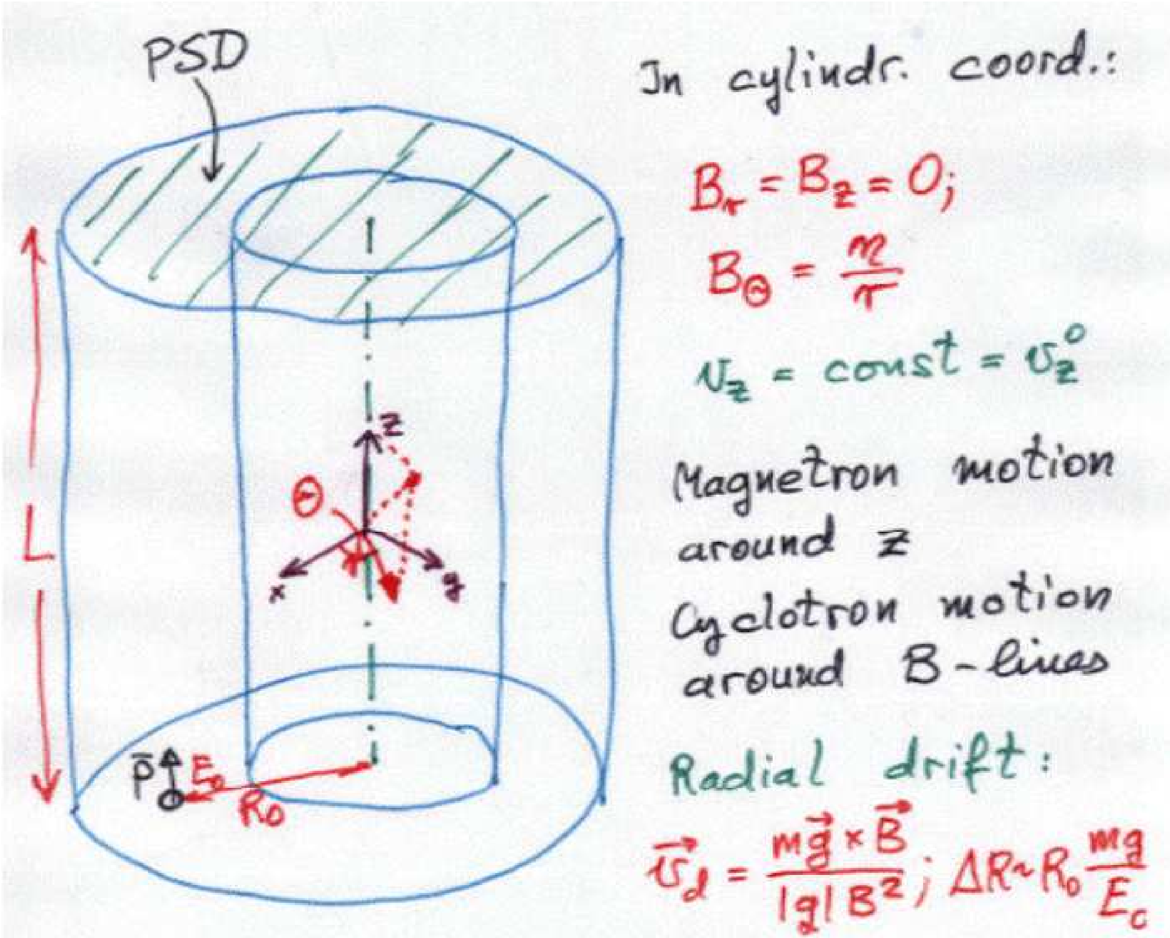
Not CPT: weak equivalence principle

Antimatter gravity = supergravity?

Einstein's gravity does not depend on baryon charge
One needs a vector force for that. Supergravity?
Exact supersymmetry cancels even p–p gravity $\Rightarrow$ broken
Trouble: $\overline{\mathrm{p}}$ weight on Earth $\simeq \mathrm{e}+-\mathrm{e}+-$ at 12 cm
For a 1 % measurement no point charge at 1 m!

Separate gravity effect from the initial motion of $\overline{\mathrm{p}}$:
Magnetron method: J. Eades et al, CERN/PSCC/98-30, 1989

Antiproton gravity: magnetron method?



(DH, RIKEN, 1998)

Simulations, Pisa, 1993:

Patch effect kills it.

Random potentials on clean metal surface:

$\pm 0.01 \ldots 0.1 V$ on $1 - 10\,\mu$m patches.

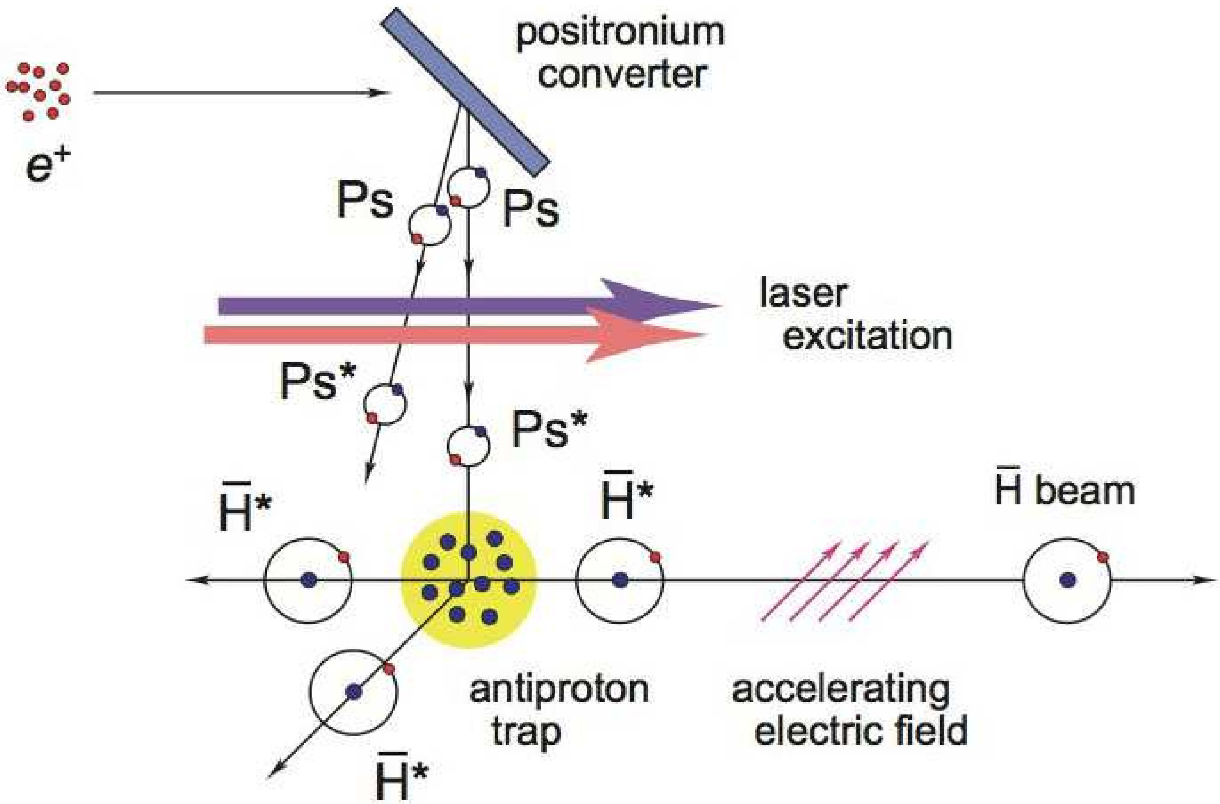
For fast $\overline{\mathrm{p}}$ it averages, but no grav. drift

For slow $\overline{\mathrm{p}}$ initial patch condition dominates.

Must use neutral probe: antihydrogen

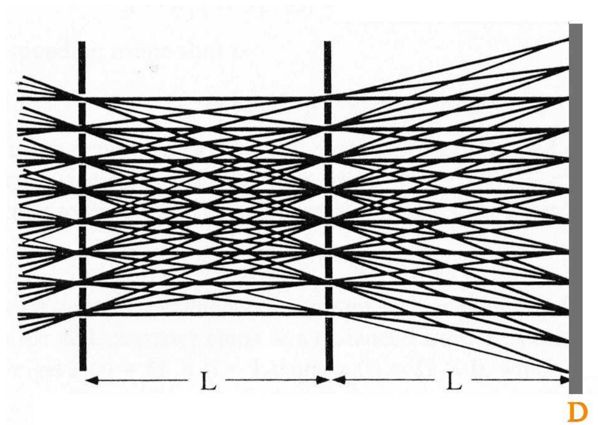
AEGIS: antimatter gravity

Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy (in preparation, 77 authors)



Moiré deflectometry:

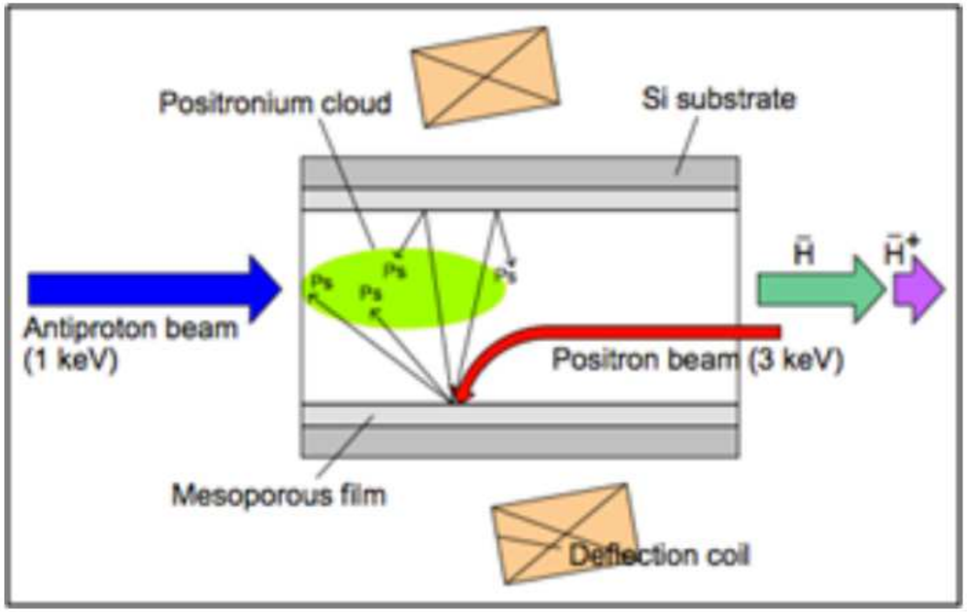
gravitational falling of collimated $\overline{\mathrm{H}}$ as compared to light

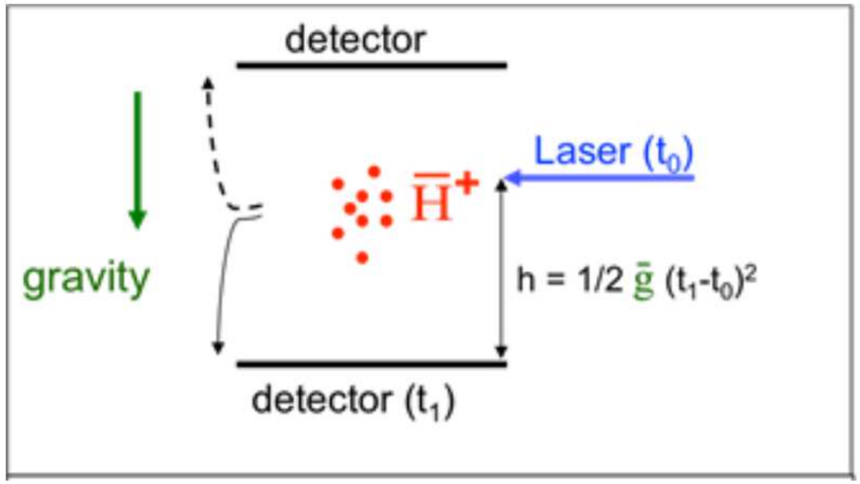


Stark acceleration (electric dipole in inhom. E-field) of excited $\overline{\mathrm{H}}$

GBAR

Gravitational Behaviour of Antihydrogen at Rest
(in preparation)

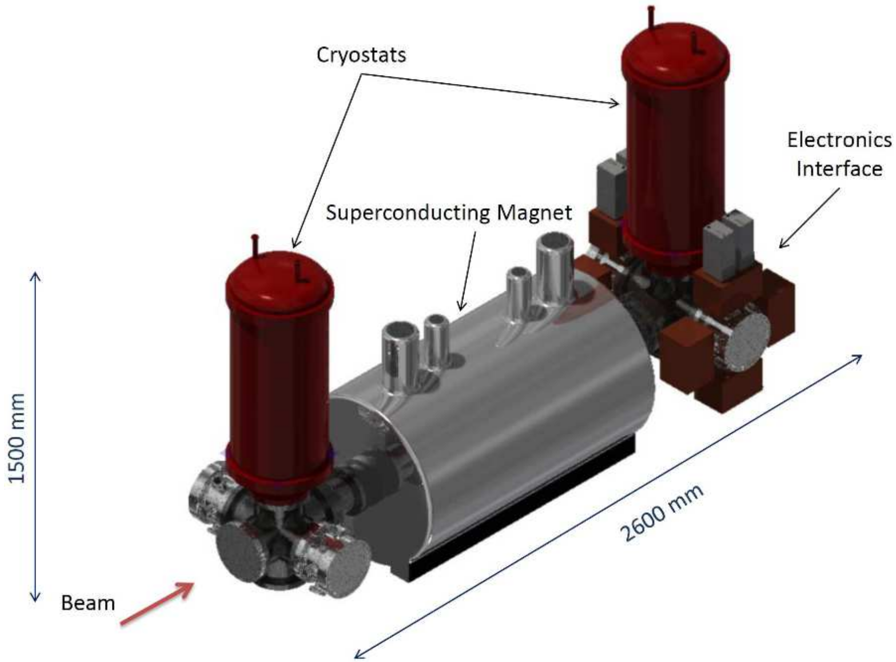


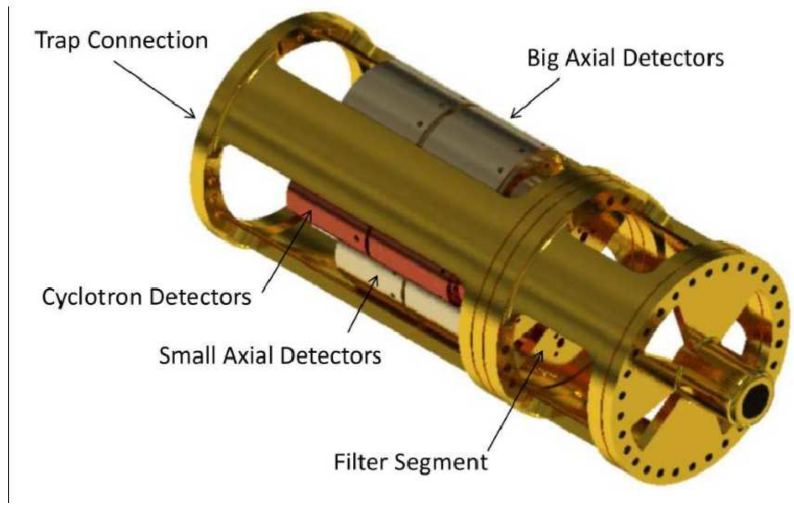


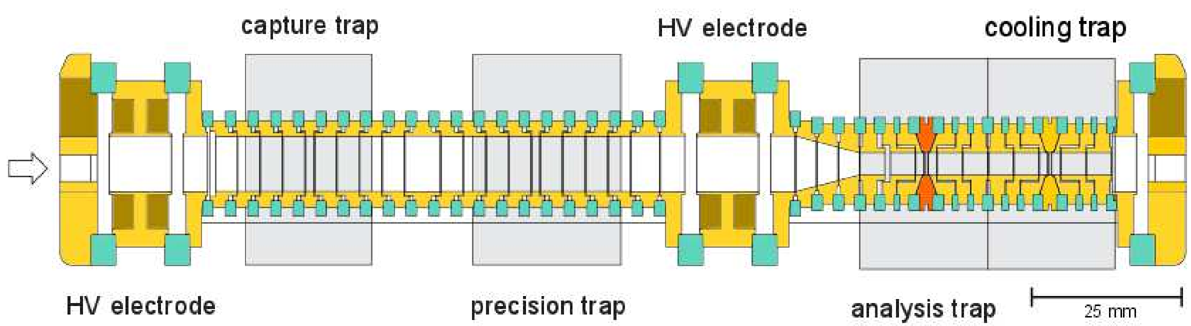
$\overline{\mathrm{p}}$ + Ps $\to \overline{\mathrm{H}}$; $\overline{\mathrm{H}}$ + Ps $\to \overline{\mathrm{H}}^+$ (cooling); back to $\overline{\mathrm{H}}$: let it fall

BASE: Baryon Antibaryon Symmetry Experiment

Direct high-precision measurement of the magnetic moment of a single antiproton stored in a cryogenic Penning trap







(in preparation)

Antihydrogen beam

ASACUSA: MUSASHI

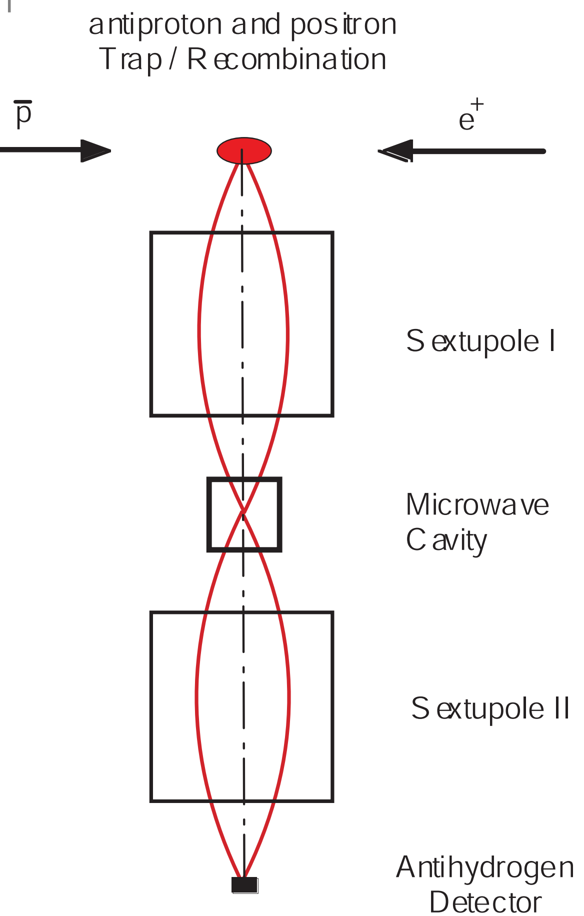
Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

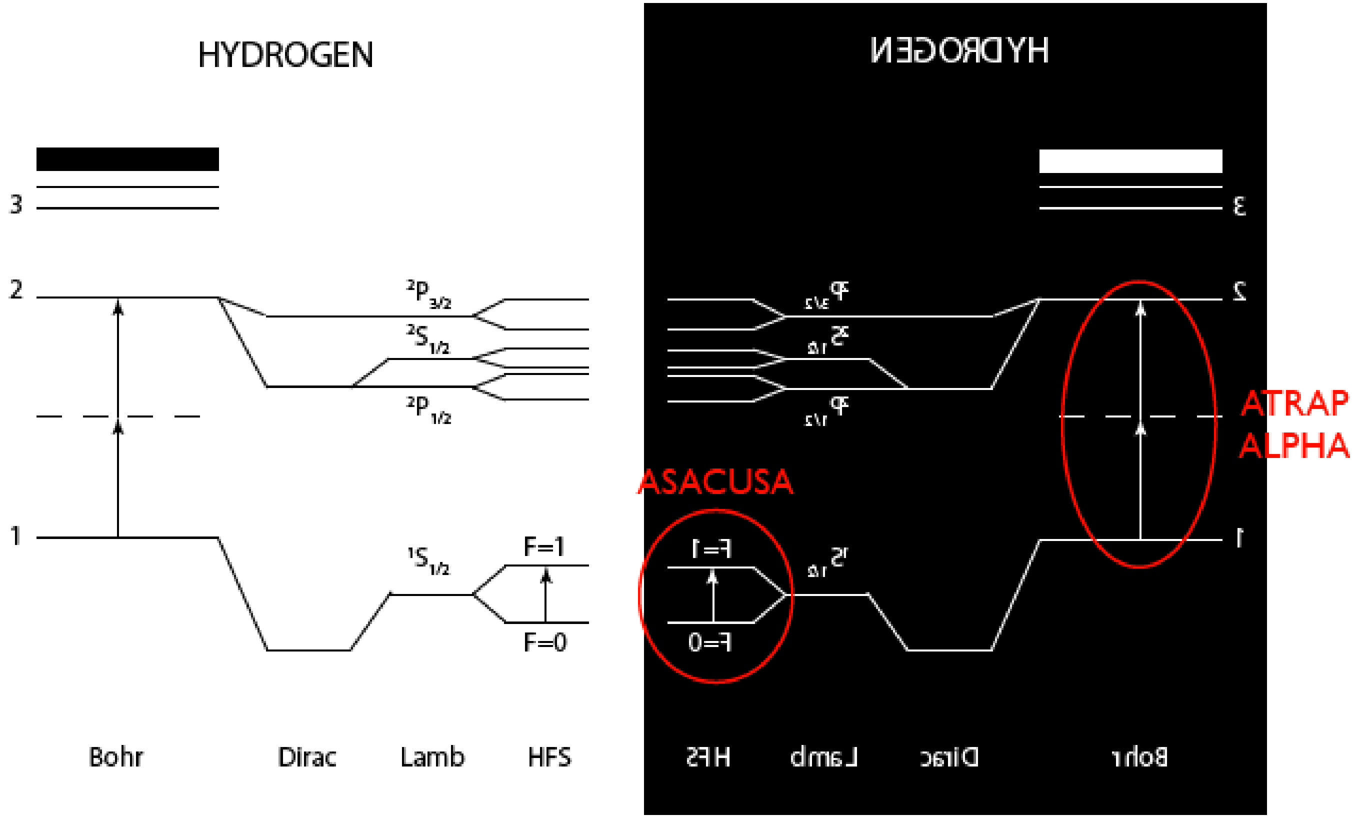
Musashi Miyamoto self-portrait ~ 1640

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

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)

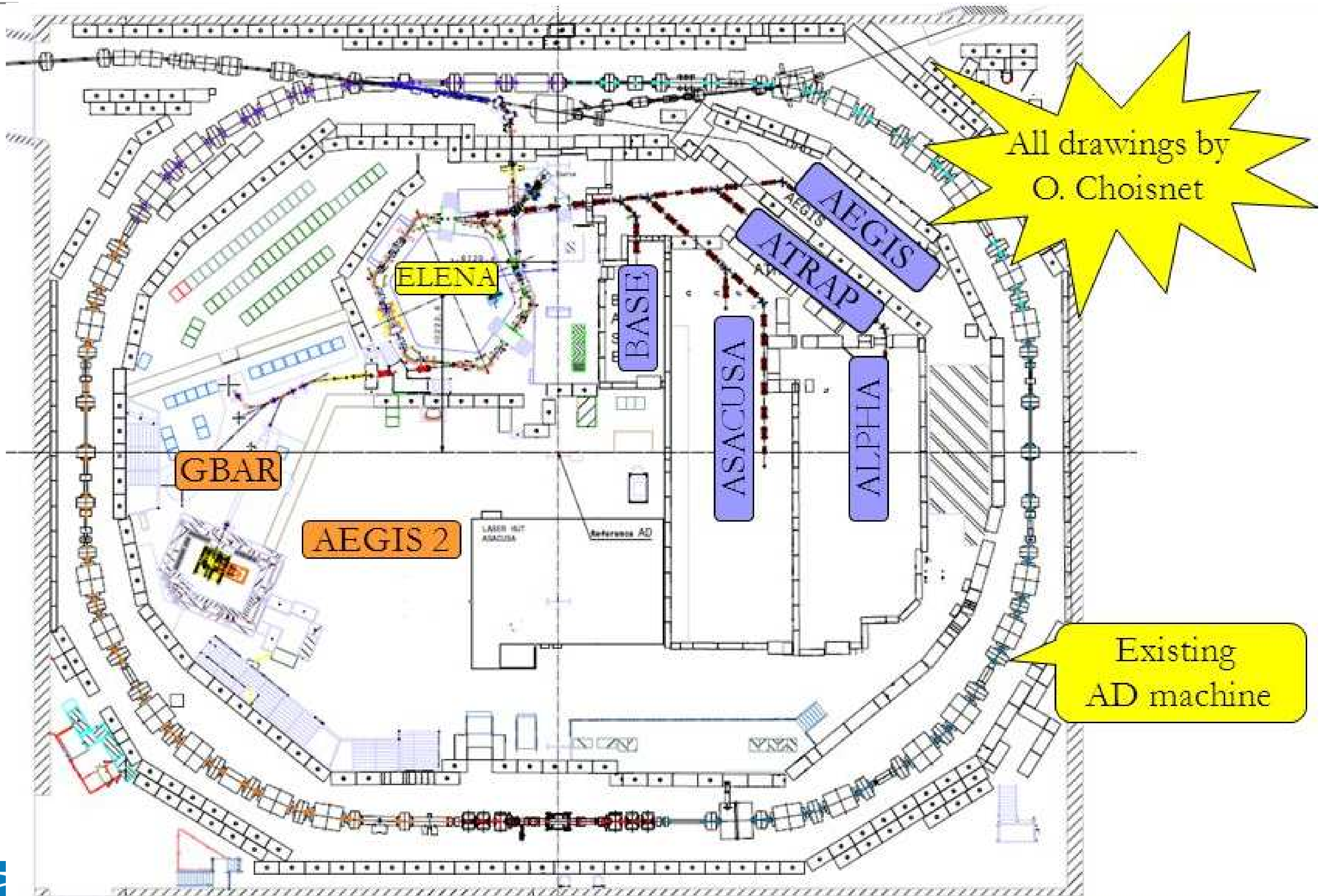
Physics Motivation

- 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)

Dániel BARNA (Wigner RCP) participated in its development

ELENA at the AD: plan



F. Butin / ELENA collaboration, 2017.

Antimatter in Space

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

Mass: 8500 kg,
1200 kg perm. magnet

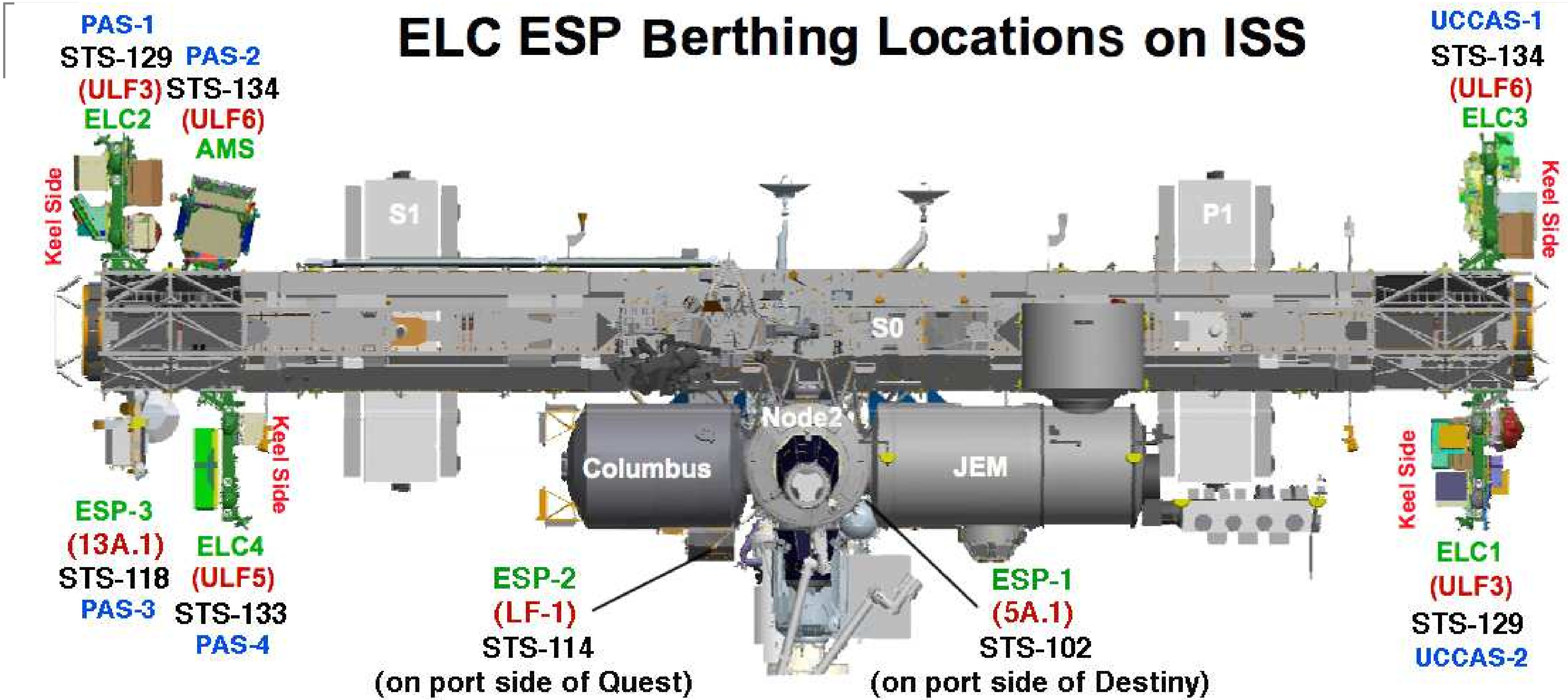
Father: Sam Ting, cost: 2 G$

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.

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

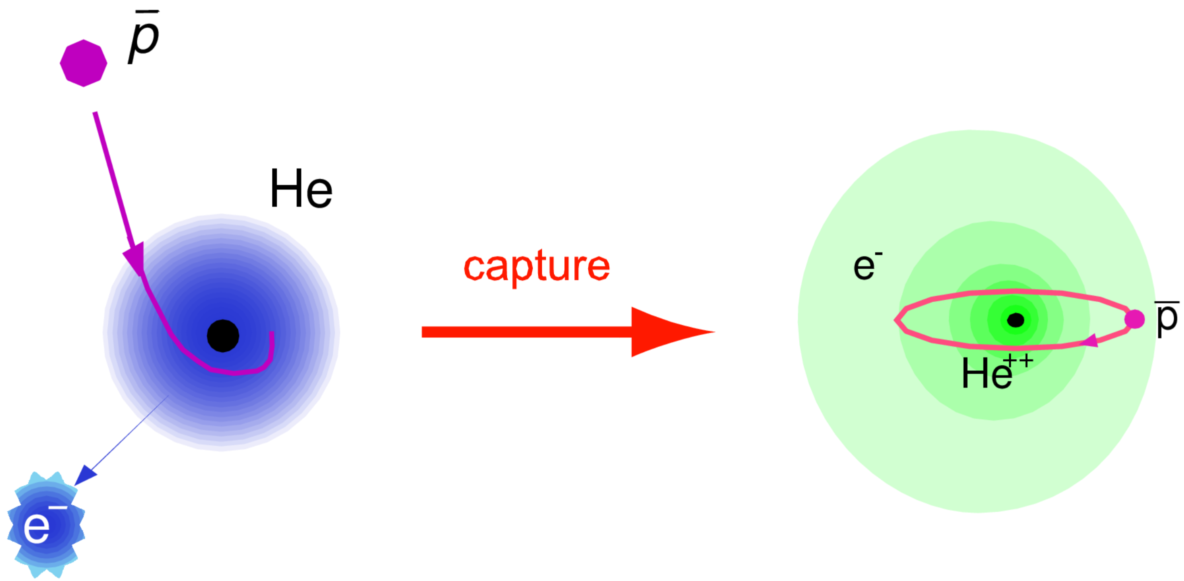
Atomic
Spectroscopy
And
Collisions
Using
Slow
Antiprotons

Asakusa, Tokyo

Metastable hadronic atoms

In matter (gas, liquid, solid) τ(hadron) $\tau \sim 1$ ps

except $\sim 3\%$ of X^-He: K^-, π^-: decay lifetime; $\overline{\mathrm{p}}$: 3–4 μs



Metastable 3-body system

Auger suppressed, slow radiative transitions only

Electron *cloud* protects $\overline{\mathrm{p}}$ against collisions

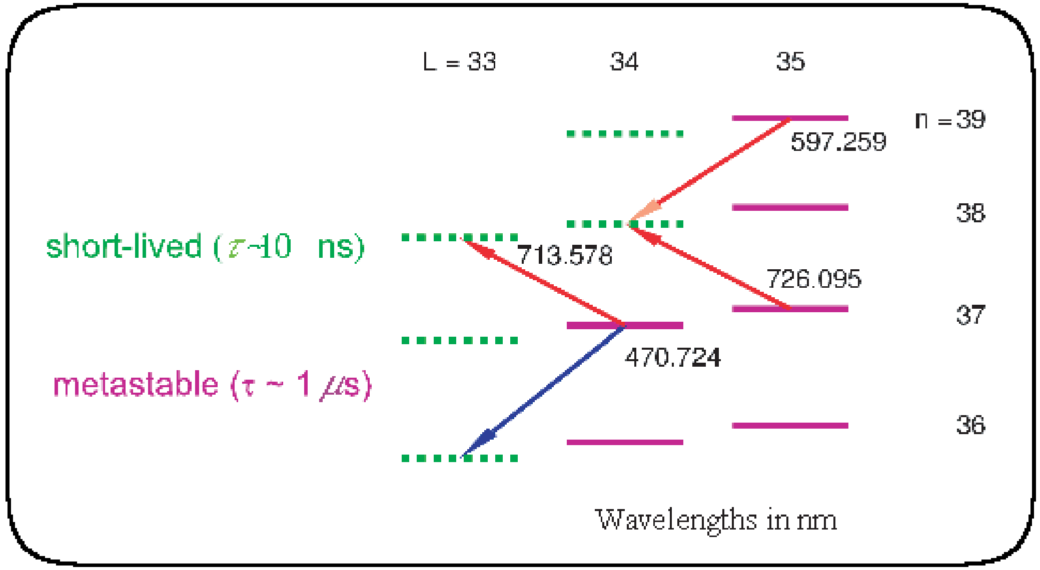
Electron tightly bound: $1S$

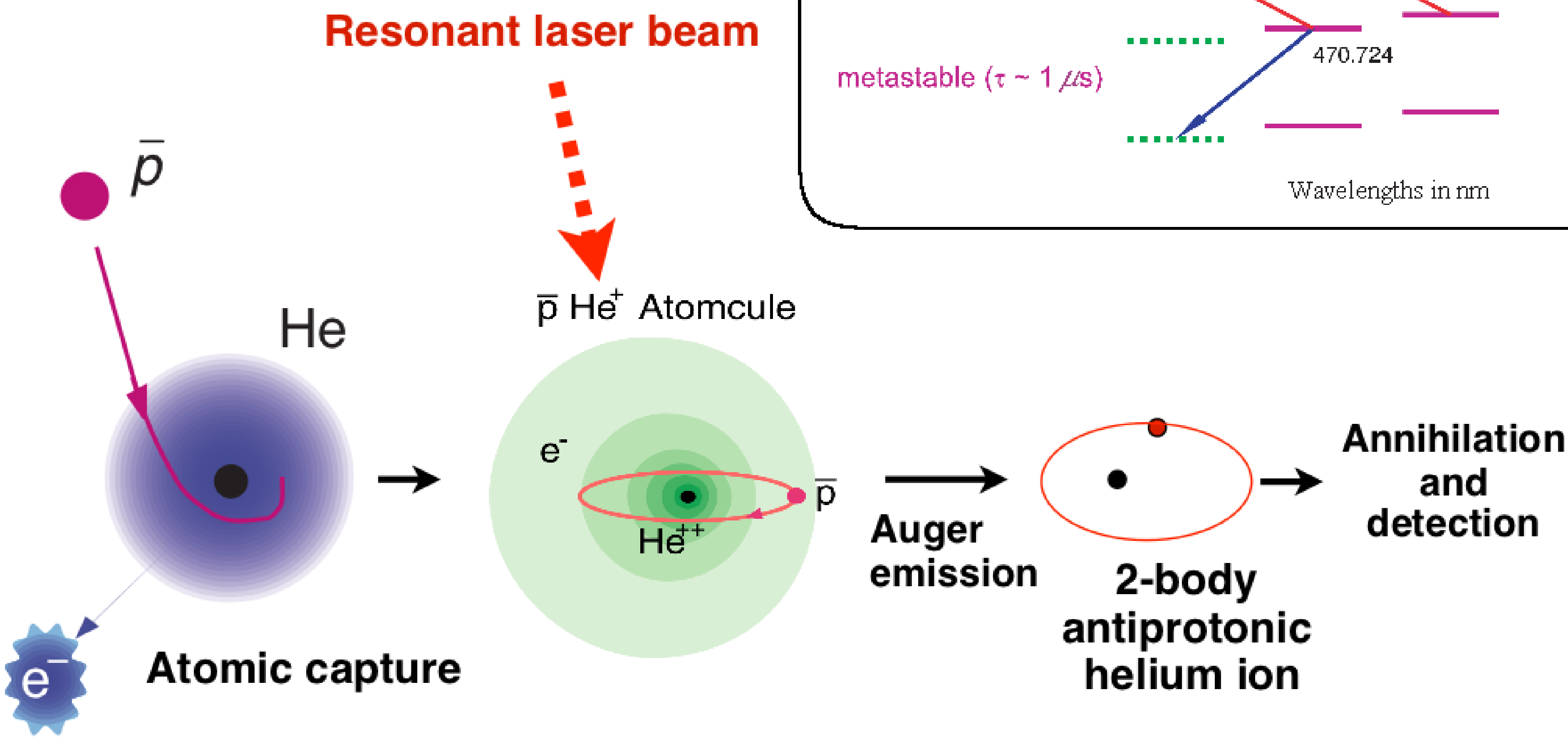
$\overline{\mathrm{p}}$He: $n \sim 40$, $l \sim n-1$, Rydberg state

$\overline{\mathrm{p}}$-He^{+}: spectroscopy motivation

- Vladimir Korobov calculates $\overline{\mathrm{p}}$ transition frequencies in $\overline{\mathrm{p}}$-He^{+} with the precision of $\sim 10^{-9}$
- Determination of antiproton-to-electron mass ratio to 1.3×10^{-9}.
  $\longrightarrow$ Dimensionless fundamental constant of nature.
- Determination of electron mass in a.u. to 1.3×10^{-9}
  $\longrightarrow$ One of the data points for CODATA2010 average.
- When combined with cyclotron frequency of antiprotons in a Penning trap measured by the TRAP collaboration, comparison of antiproton and proton mass and charge to 7×10^{-10}
  $\longrightarrow$ Particle Data Group: CPT consistency test.

Laser spectroscopy of antiprotonic helium





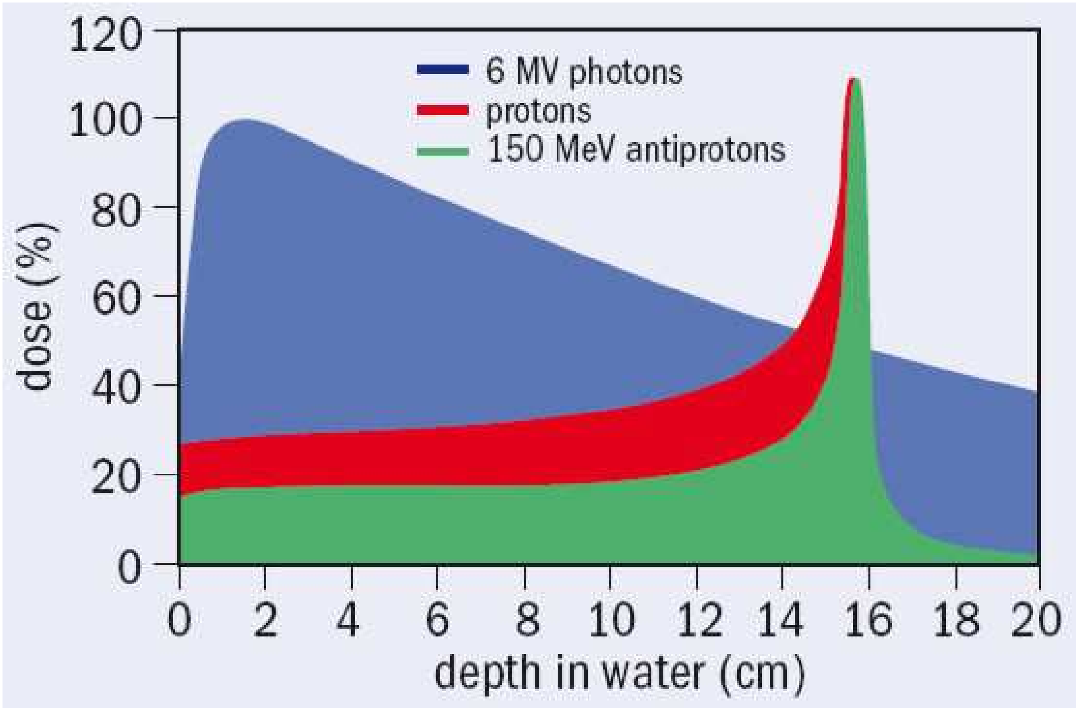
Induce transition between long-lived and short-lived states

⇓

Force prompt annihilation

ACE: Antimatter Cell Experiment

Cancer therapy research (USA) at AD of CERN



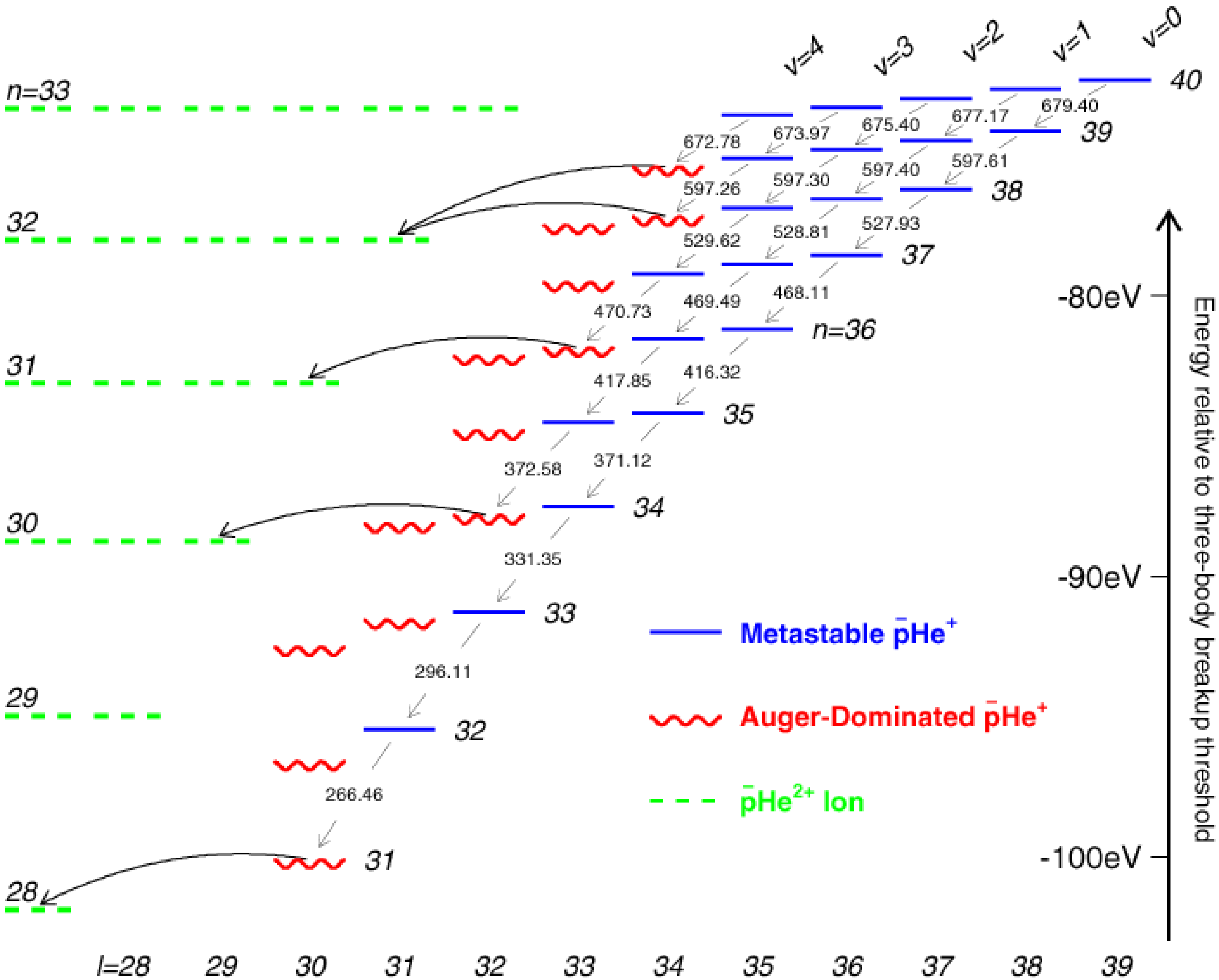
Advantage: Antiprotons lose energy in very small volume, choosing the right energy concentrates damage in tumor.

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

Thanks for your attention

Spare slides for discussion

Energy levels of $\bar{p}He^4$



Level energies in eV, transition wavelengths in nm

MUSASHI: slow antiproton beam

Musashi Miyamoto self-portrait ~ 1640

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

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)

N. Kuroda,...D. Barna, D. Horváth, Y. Yamazaki: **Phys. Rev. Lett.** *100* (2008) 203402.

Two-photon spectroscopy

In low density gas main precision limitation: thermal Doppler broadening even at $T < 10$ K

Excite $\Delta\ell = 2$ transition with 2 photons

Two counterpropagating photons with $\nu_1 \sim \nu_2$ eliminate 1st order Doppler effect

Laser linewidth should not overlap with resonance

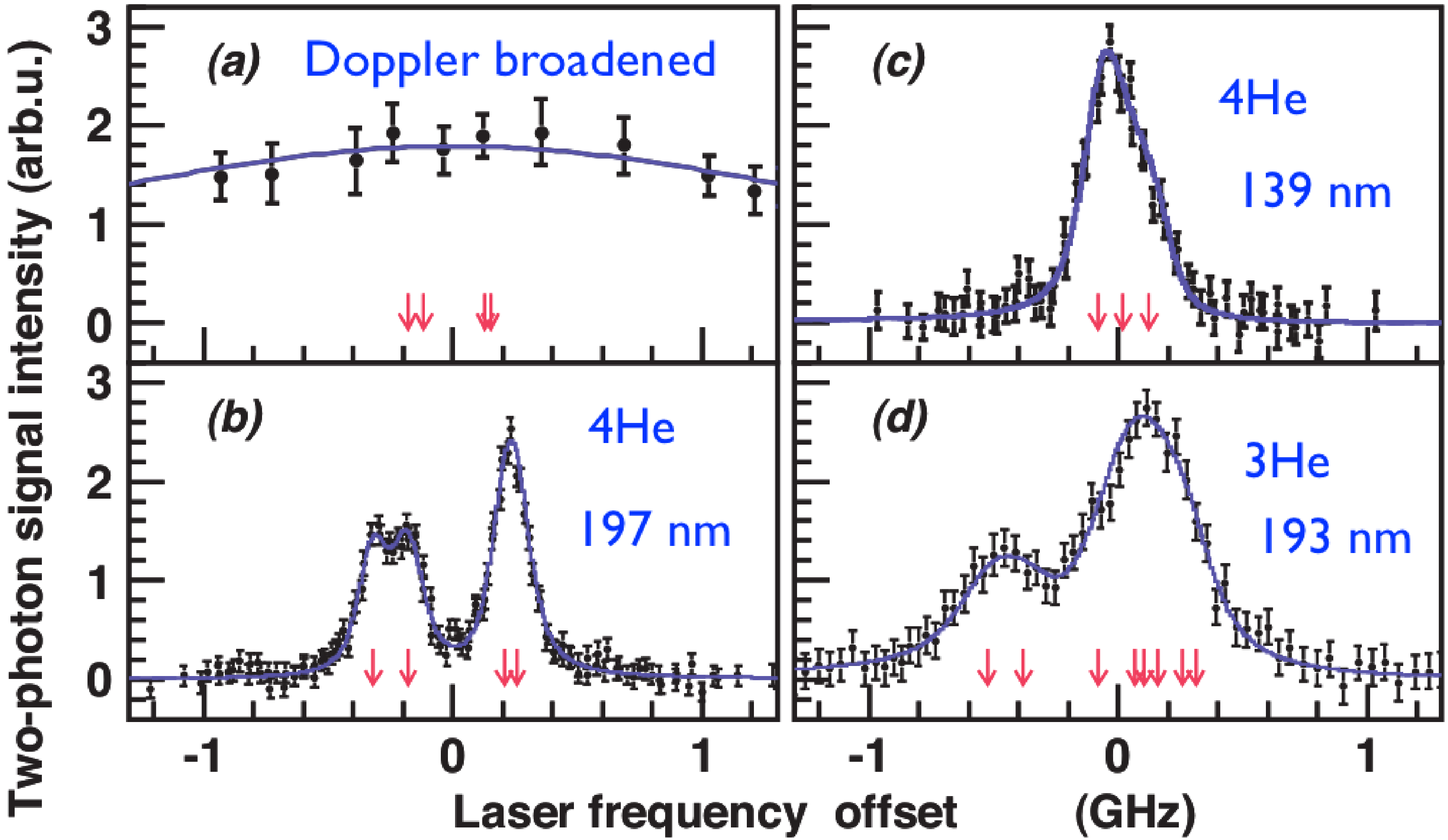
M. Hori, et al., A. Sótér, D. Barna, A. Dax, R.S. Hayano, S. Friedreich, B. Juhász, T. Pask, E. Widmann, D. Horváth, L. Venturelli, N. Zurlo: *Two-photon laser spectroscopy of pbar-He$^+$ and the antiproton-to-electron mass ratio*, **Nature** 475 (2011) 484-488,
Few Body Syst. *54* (2013) 917-922.

Two-photon spectroscopy: parameters

- Precision of lasers: $< 1.4 \times 10^{-9}$.
- 7×10^6 $\overline{\mathrm{p}}$/pulse, $E \approx 70$ keV, 200 ns long, Ø20 mm.
- Target: He gas, $T \approx 15$ K, $p = 0.8 - 3$ mbar
- Laser beams: $\lambda_1 = 417$ nm, $\lambda_2 = 372$ nm, $P \approx 1$ mJ/cm^2
- Transition: (n=36, l=34) $\rightarrow$ (n=34, l=32); $\Delta\nu = 6$ GHz
- Measured linewidth: ≈ 200 MHz
- Width: Residual Doppler broadening, hyperfine structure, Auger lifetime, power broadening.

M. Hori, A. Sótér, D. Barna, A. Dax, R.S. Hayano, S. Friedreich, B. Juhász, T. Pask, E. Widmann, D. Horváth, L. Venturelli, N. Zurlo: „Two-photon laser spectroscopy of pbar-He$^+$ and the antiproton-to-electron mass ratio"
Nature 475 (2011) 484-488

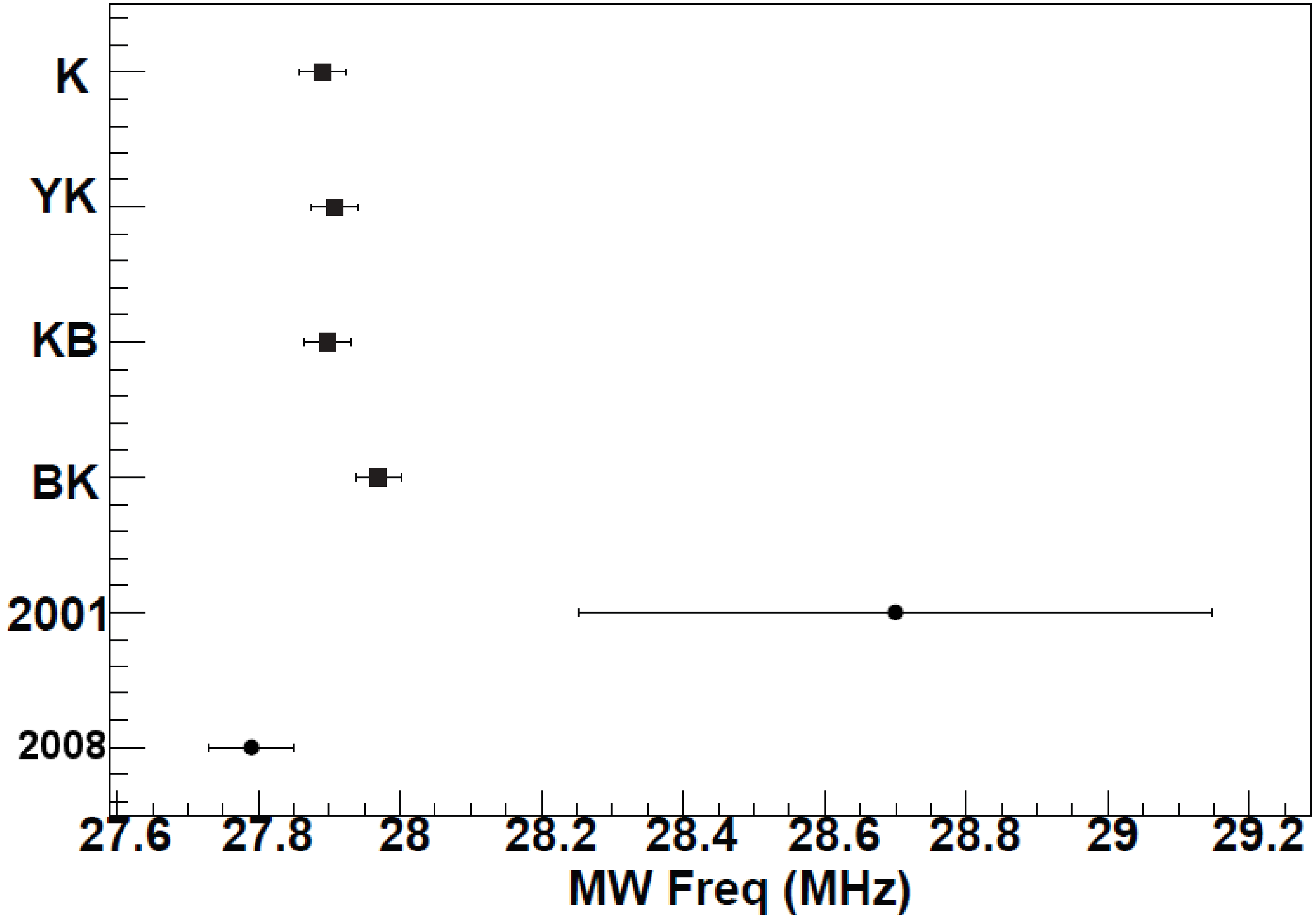
Two-photon spectroscopy: spectra



M. Hori et al., **Nature** 475 (2011) 484-488

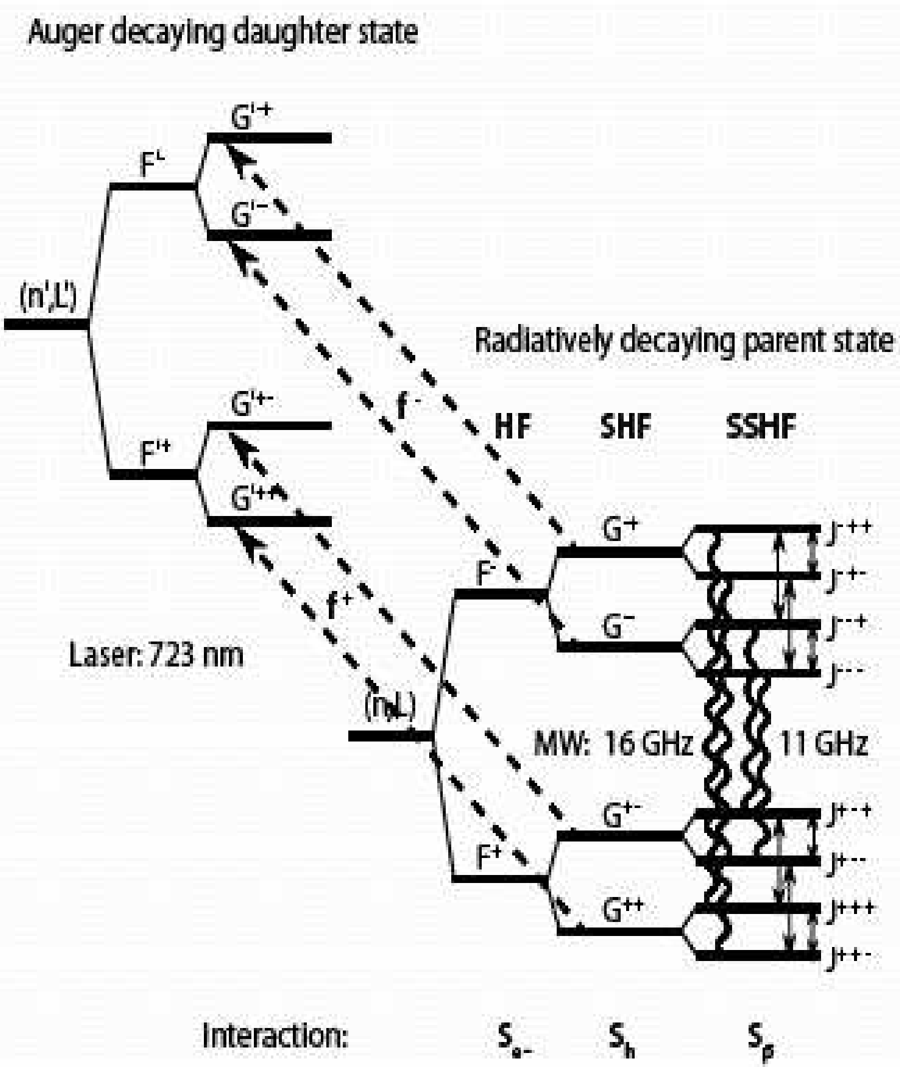
Arrows: hyperfine transitions

$\overline{p}^4$He HF structure: expt vs. theory

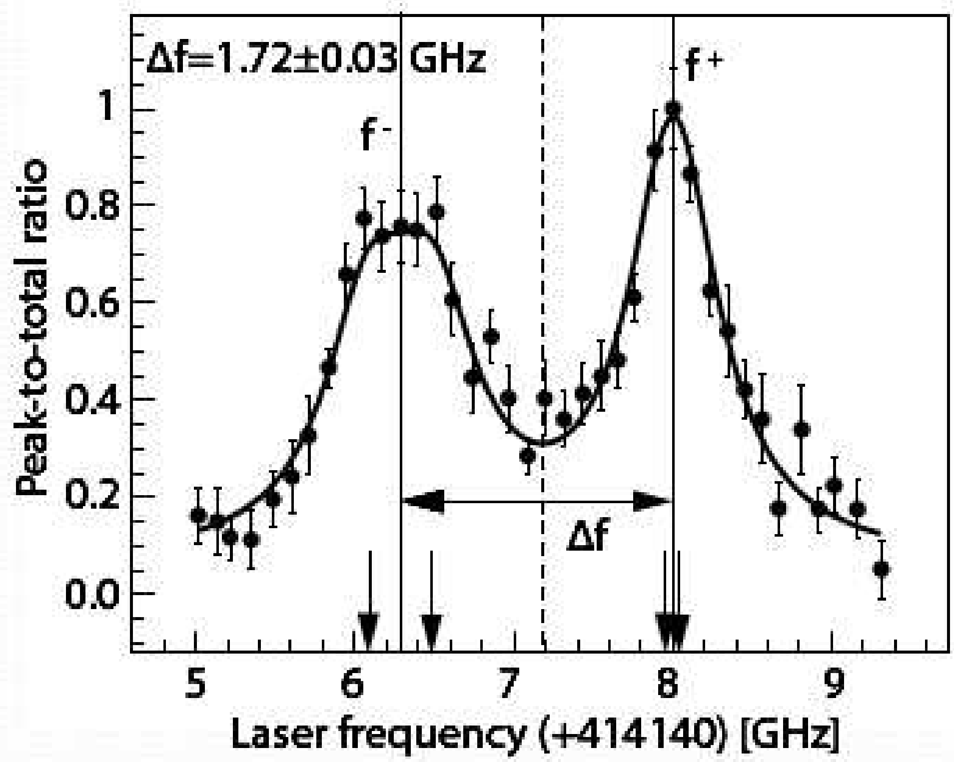


Th. Pask et al., Phys. Lett. B 678 (2009) 55.

$\bar{p}^3$He HF structure: laser scan



- verify splitting of laser transition lines
- determine laser resonance frequency



- fit with 4 Voigt functions plus constant for signal background

S. Friedreich et al., Physics Letters B 700 (2011) 1.