Tests of CPT Invariance at the Antiproton Decelerator of CERN

Zimányi School'19, Wigner RCP, 02-06.12.2019

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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 studies
- Antiproton mass
- Antimatter in space
- Outlook: ELENA

Birth of antimatter

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

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

Two kinds of electrons:

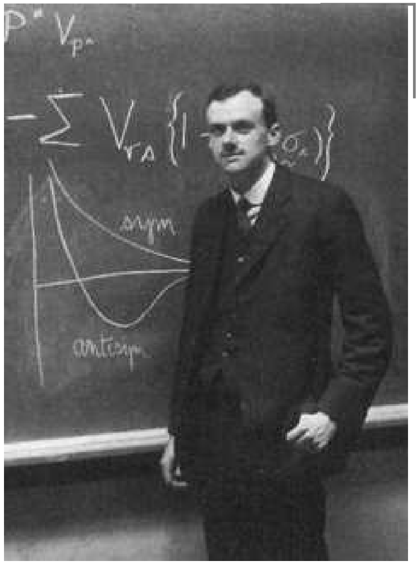
- $+$ mass and $-$ charge (ordinary electron);
- $-$ mass and $+$ charge (anti-electron = positron).

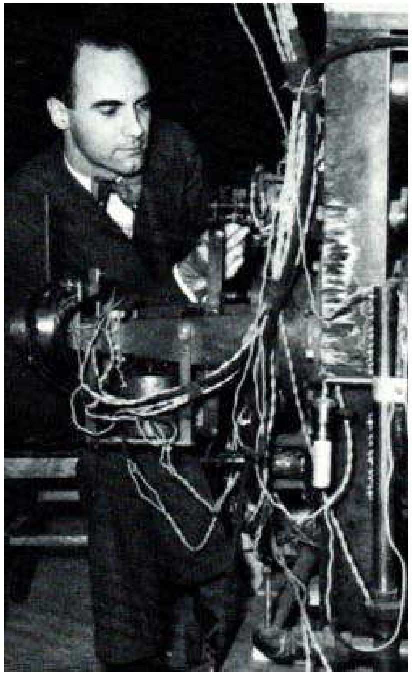
Negative mass non-physical. Dirac: particle holes.

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

⇒ real existing particle: positron.

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





Matter–antimatter symmetry

CPT invariance

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

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

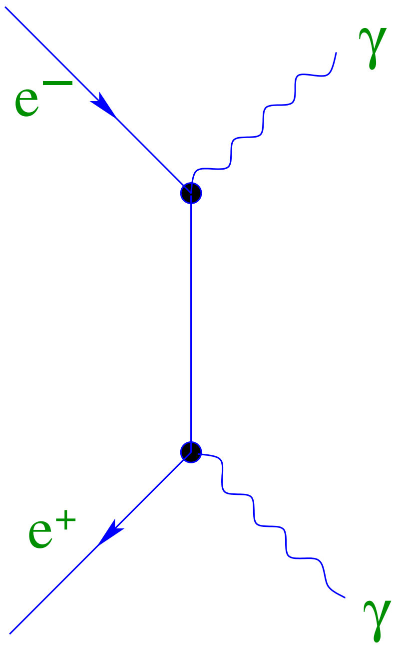
Time reversal: $T|\mathrm{p}(r,t)> = |\mathrm{p}(r,-t)>K$

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

Basic assumption of field theory:

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

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



Giving up CPT one has to give up:

- locality of interactions ⇒ causality, or
- unitarity ⇒ conservation of matter, information, ...
- or Lorentz invariance

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?

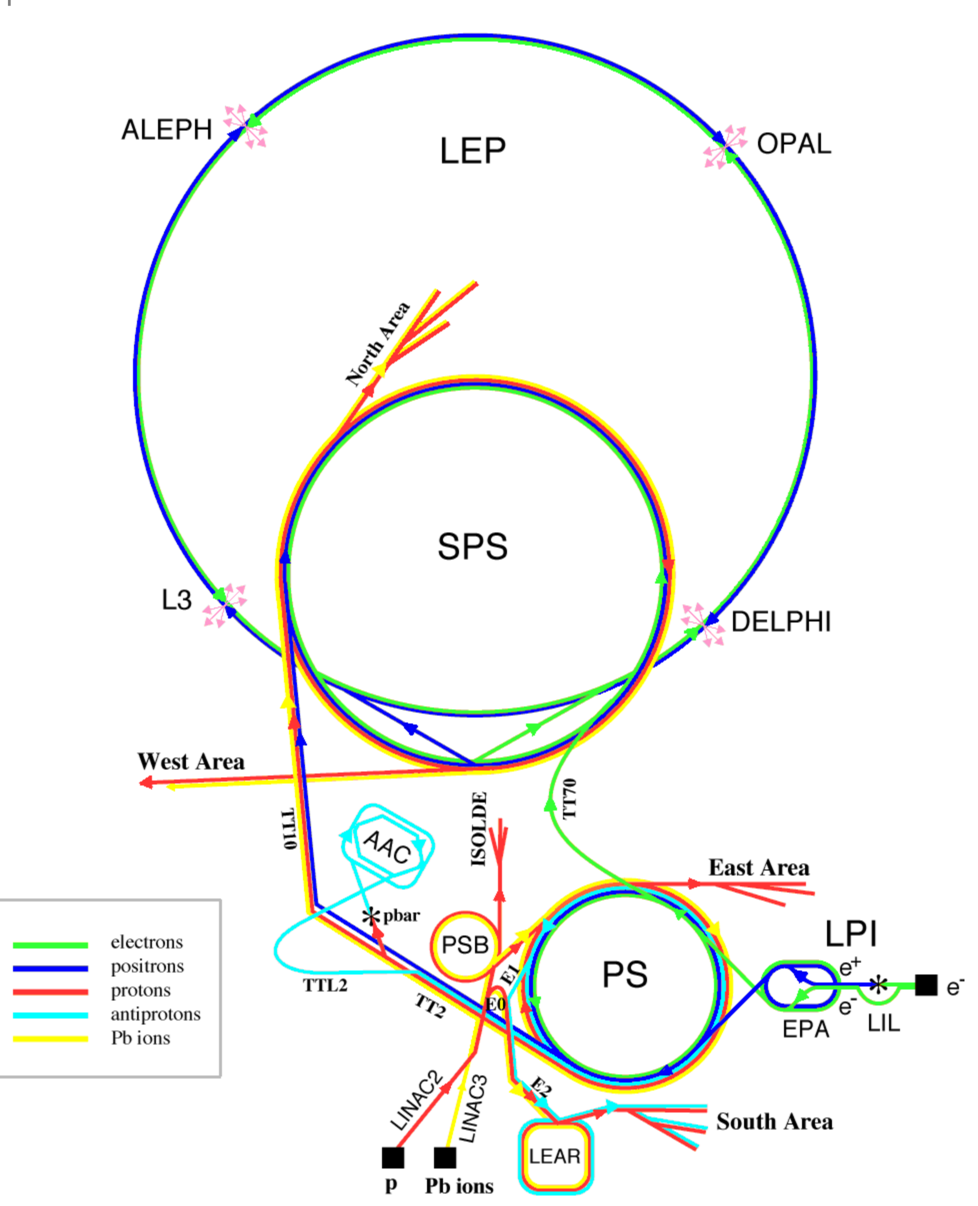
How to test CPT?

Particle = – antiparticle ?

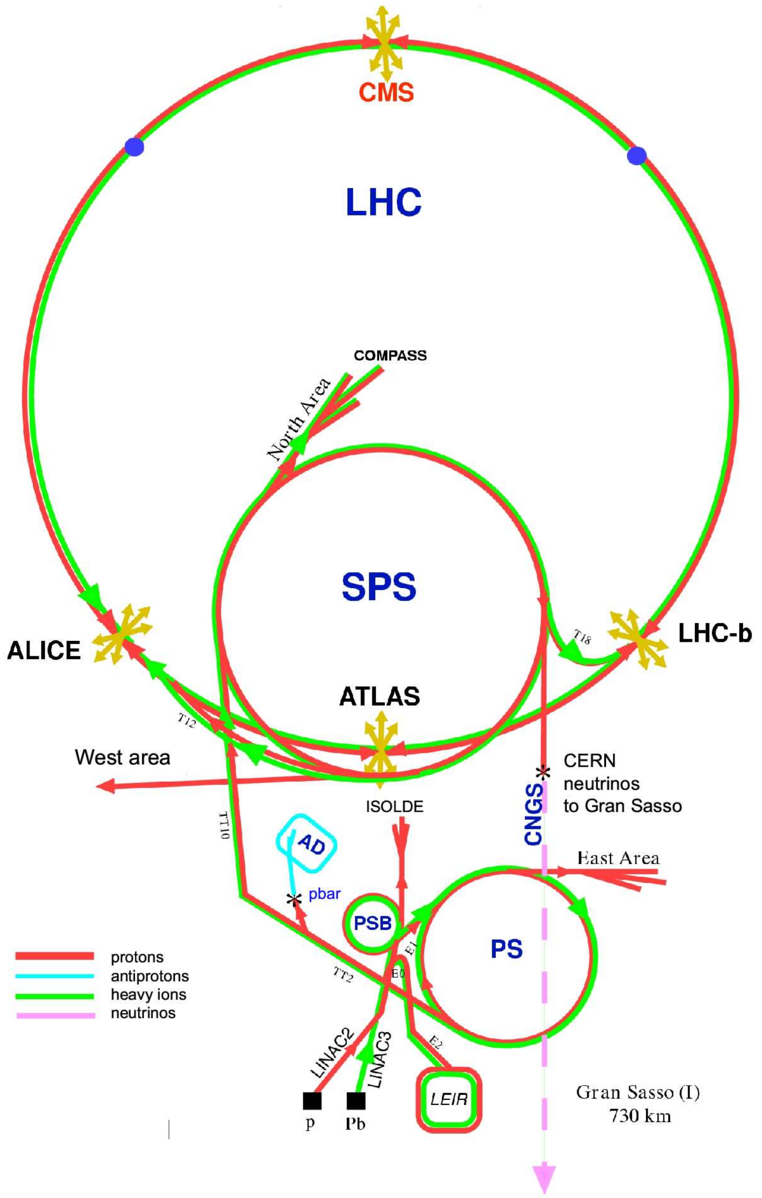
- $[m(\mathrm{K}^0) - m(\overline{\mathrm{K}}^0)]/m(\mathrm{average}) < 10^{-18}$
- proton $\sim$ antiproton? (compare m, q, $\vec{\mu}$)
- hydrogen $\sim$ antihydrogen ($\overline{\mathrm{p}}e^+$)? $2S - 1S$, HFS

Accelerators at CERN

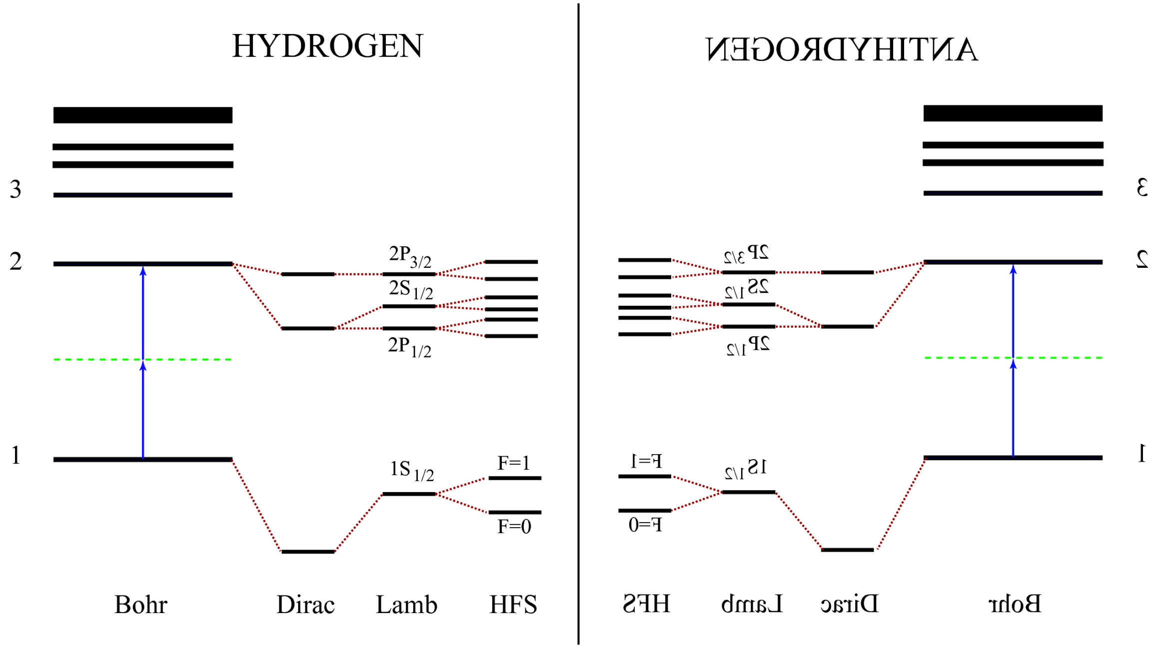
1989–2000



2009–2025??



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



$2S - 1S$ transition

with 2-photons

Long lifetime,

narrow transition,

Doppler-free

spectroscopy

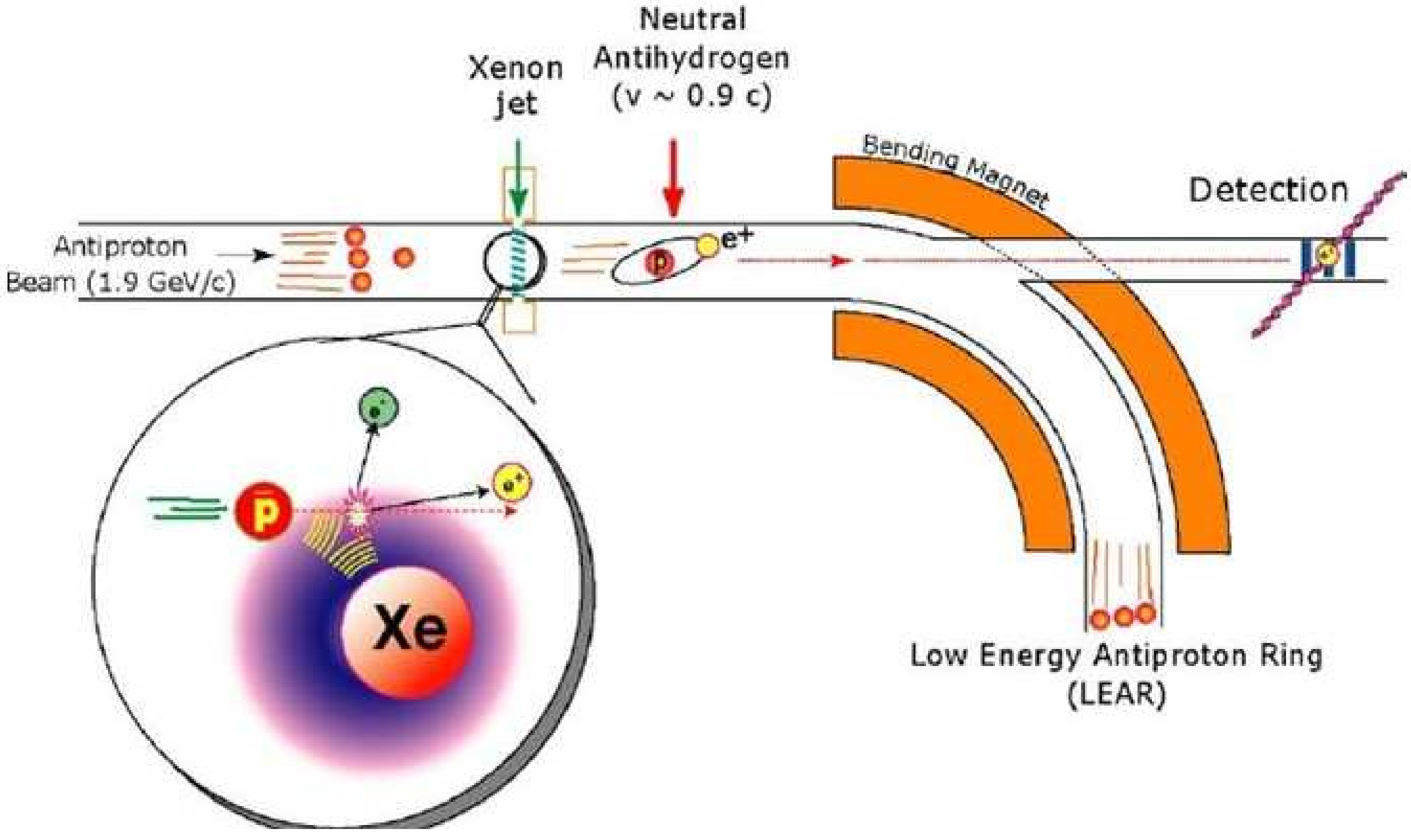
Feasibility study for the SPSL Committee of CERN (1992) converted into

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:

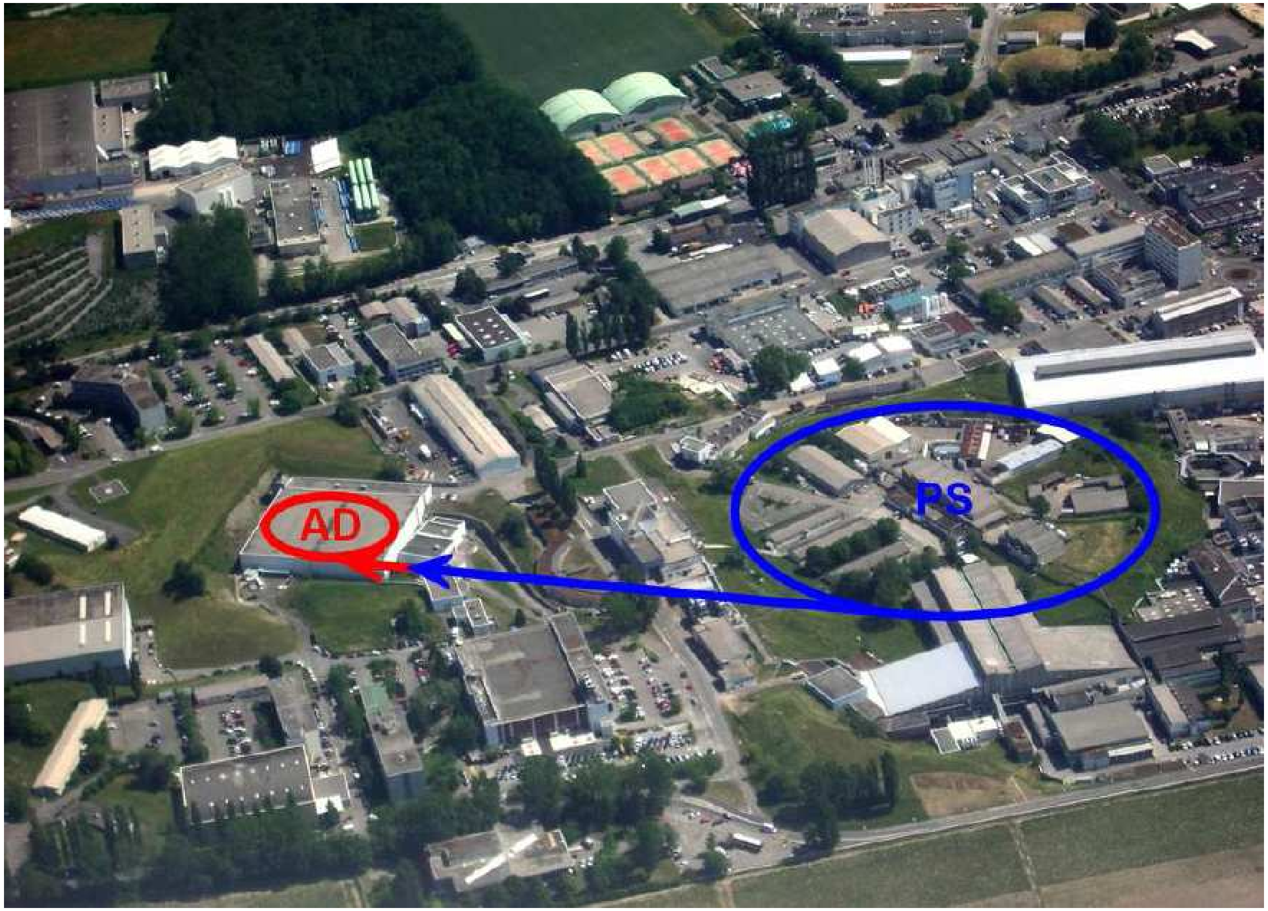
G. Blanford *et al.*, „Observation of atomic anti-hydrogen," Phys. Rev. Lett. **80** (1998) 3037.

Antimatter factory at CERN

The Antiproton Decelerator at CERN

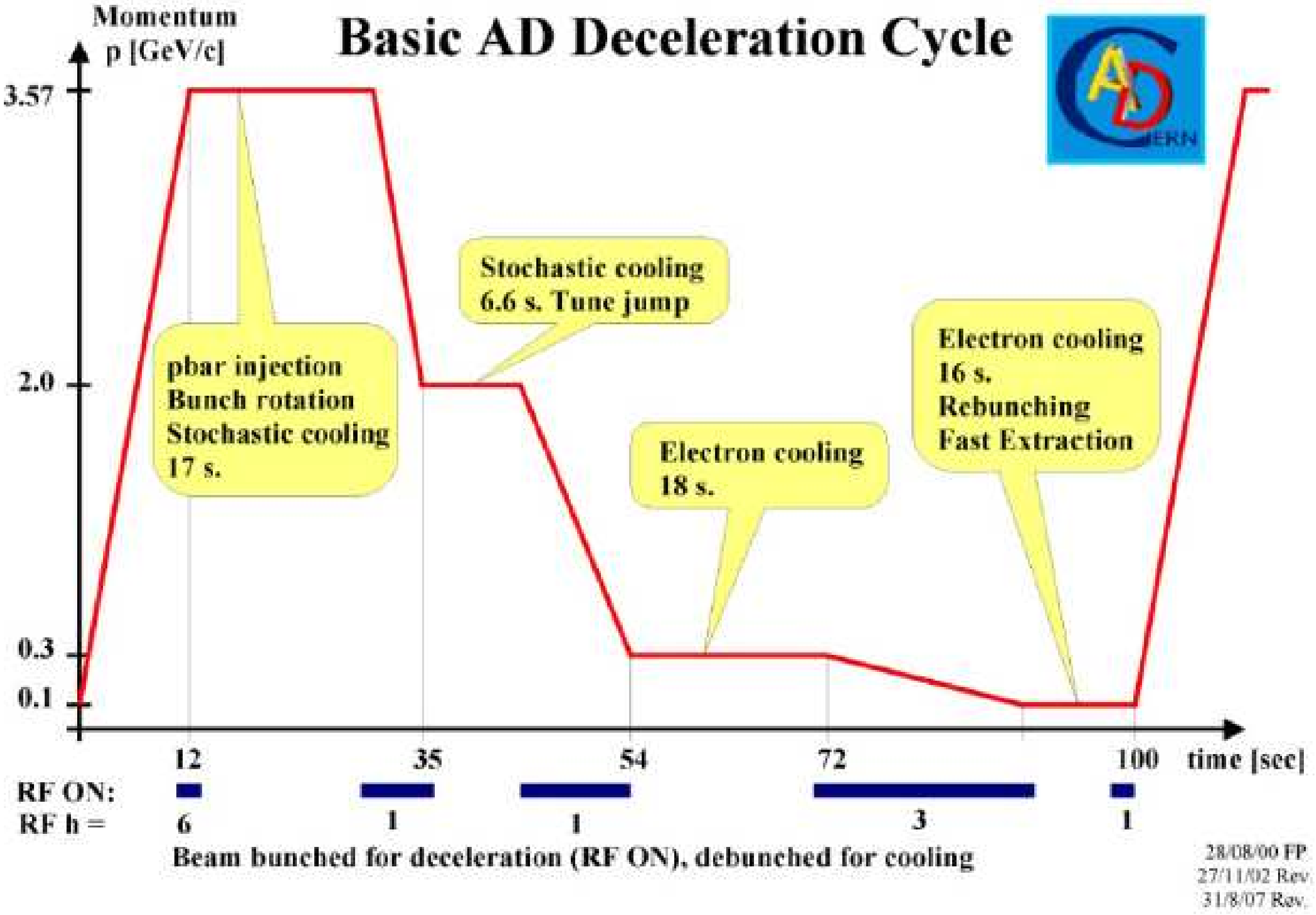
was built in 1997-99 to study antimatter physics

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



©Ryugo S. Hayano, Tokyo U.

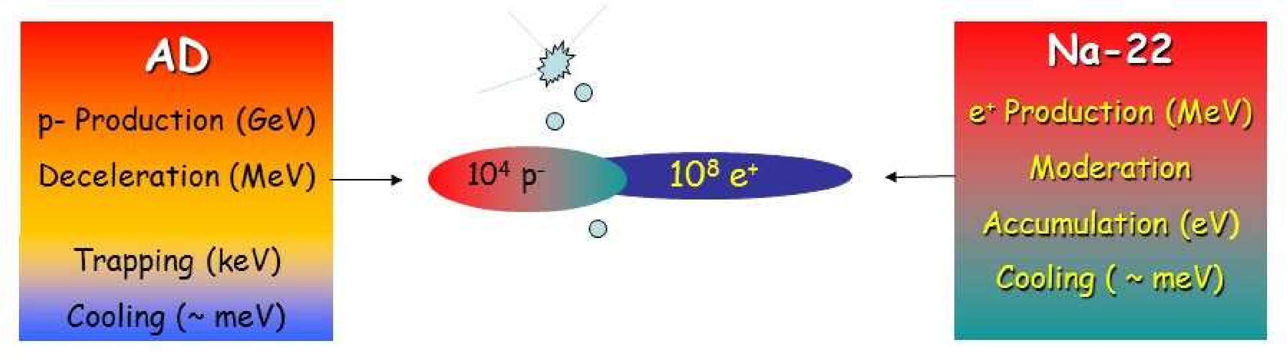
The Antiproton Decelerator: cooling



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

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

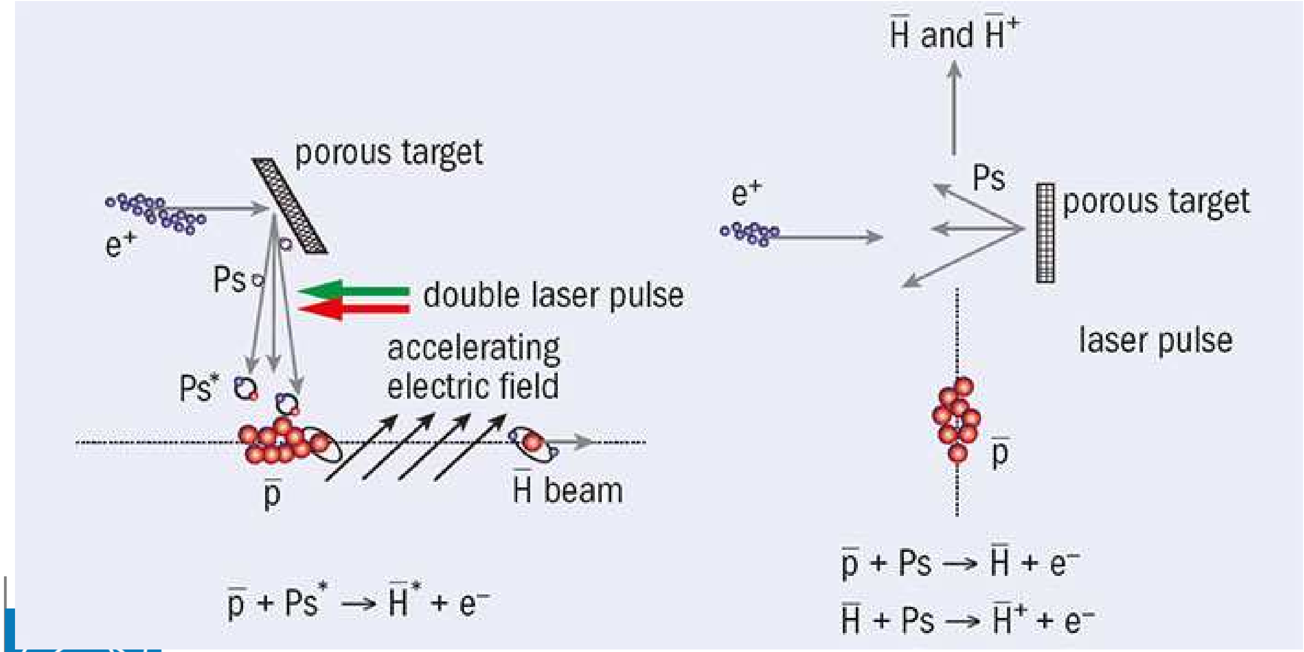
How to produce antihydrogen?



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

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

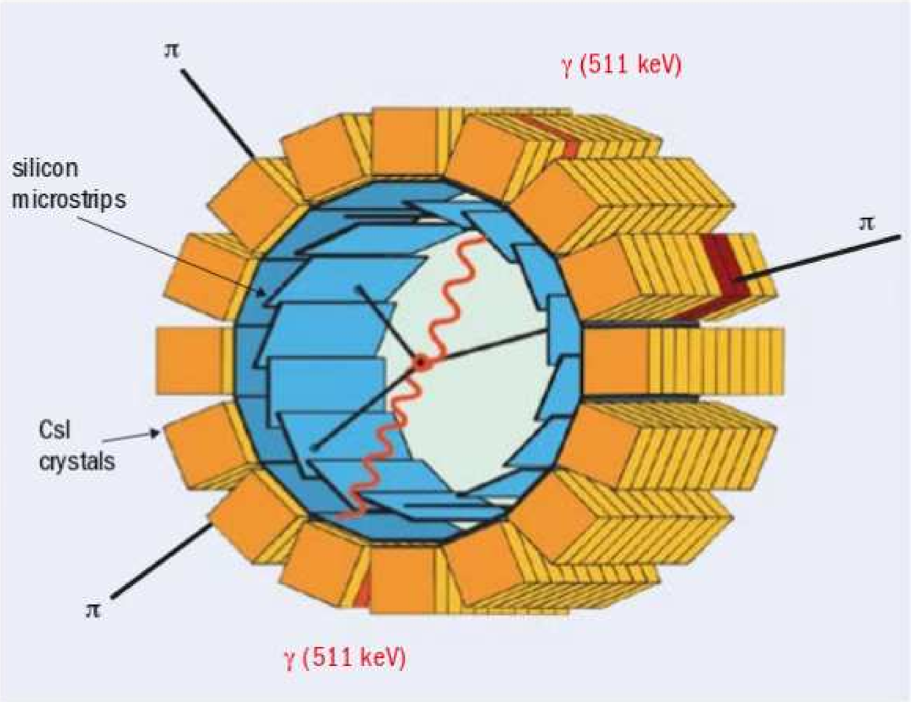
Proposed by G. Gabrielse, ATRAP & Harvard U.



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

Proposed by B. Deutch et al., Aarhus

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



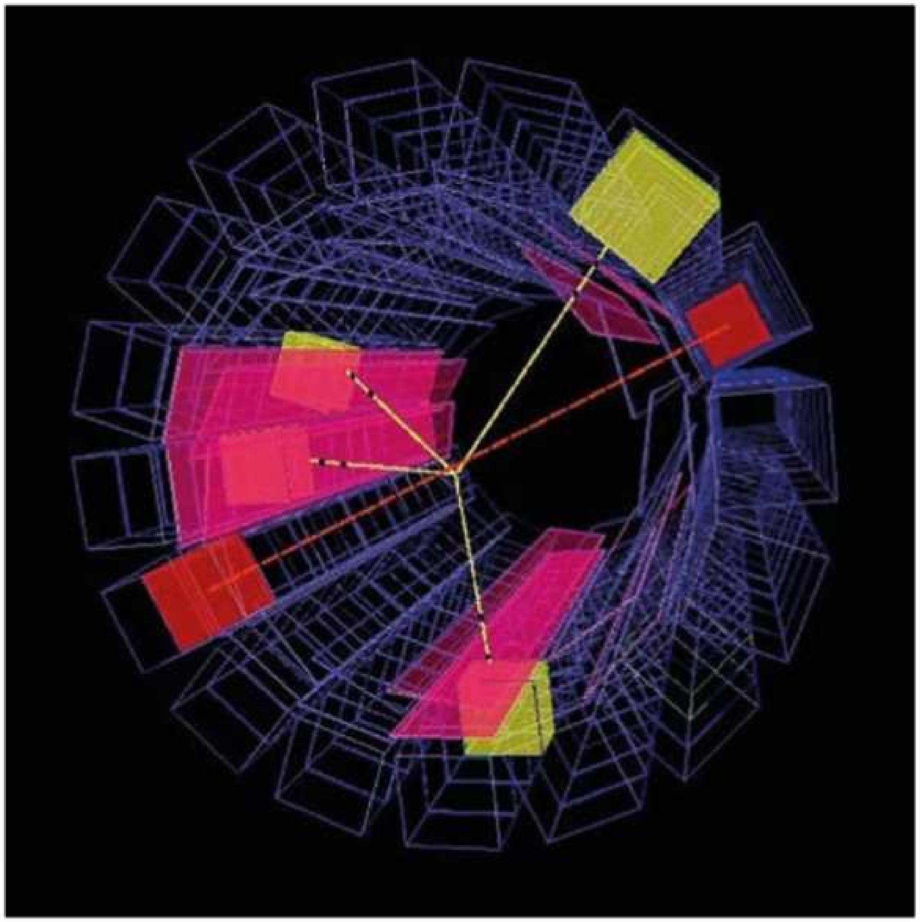
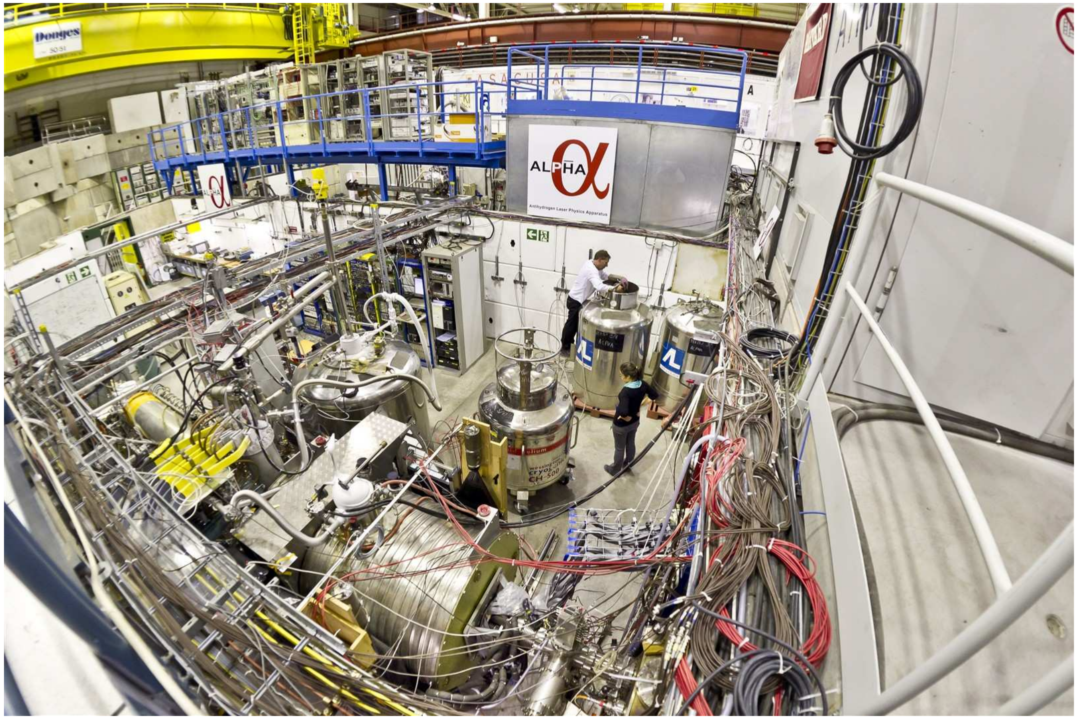


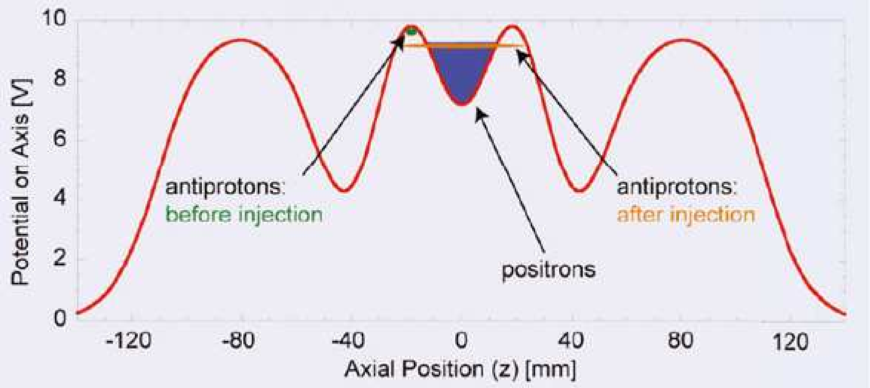
Fig.5. Above: A diagram of the ATHENA antihydrogen detector. Right: An antihydrogen annihilation event in ATHENA, reconstructing four charged pions (yellow) and two 511 keV photons (red). (Image credits: ATHENA Collaboration.)

ATHENA Collaboration (1997 – 2005) ⇒ ALPHA Collaboration

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

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





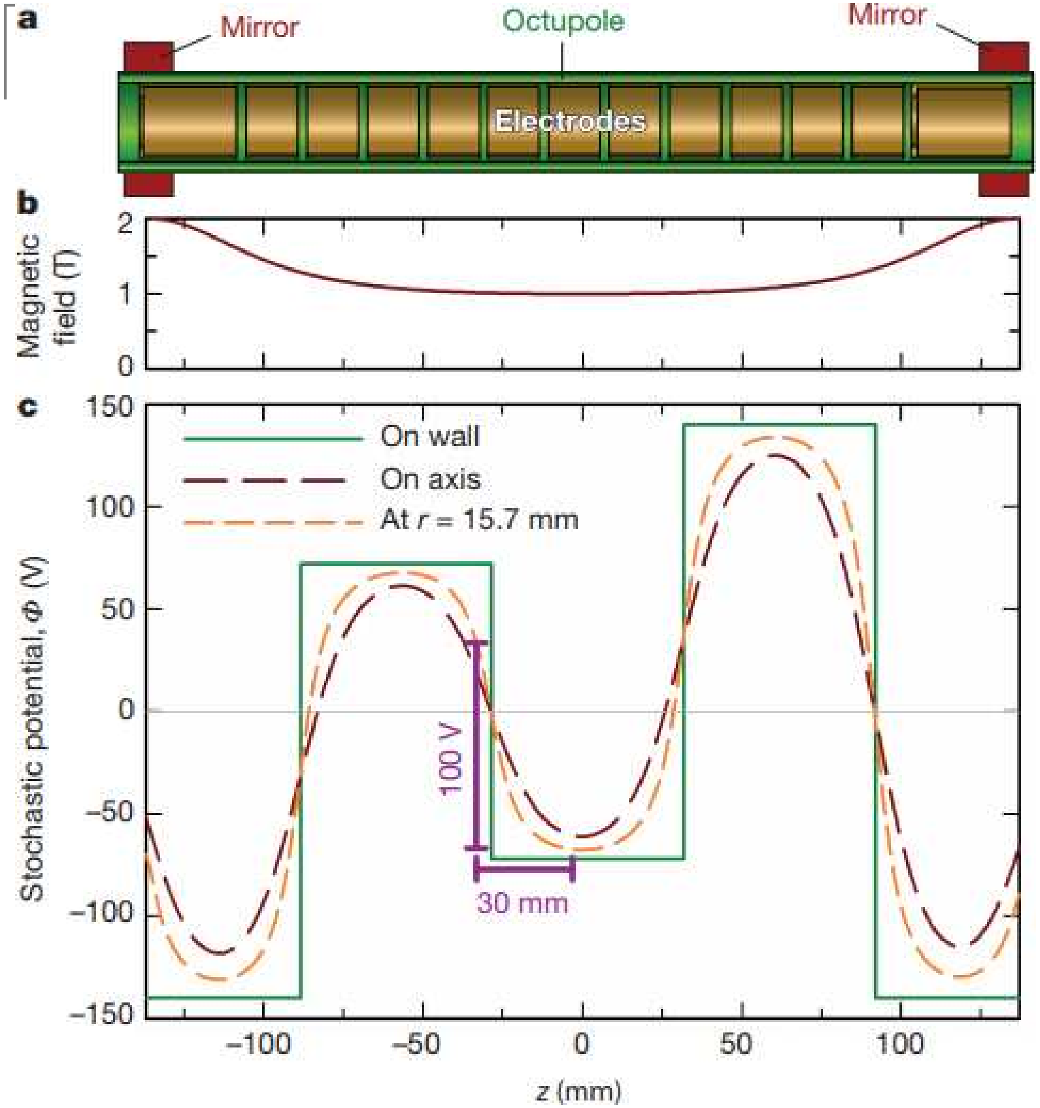
- Capture 90,000 antiprotons.
- Mix with 3 million positrons.
- Produce 50,000 $\overline{\mathrm{H}}$ atoms.
- Remove charged particles.
- Trap 20 $\overline{\mathrm{H}}$ at $T = 0.54$ K.

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

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

Detected and measured by dropping $B = 1$ T ⇒ annihilation.

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



$\overline{\mathrm{H}}$ trapped in $B = 1\,$T at $T = 0.1\,$K

Randomly kicked with $\Delta\Phi \sim 100\,$V

After $N = 84900$ kicks $\overline{\mathrm{H}}$ of charge Qe gains energy:

$$\Delta E \sim |Q| e \Delta\Phi \sqrt{N}$$

$\overline{\mathrm{H}}$ annihilates if $\Delta E > E_{\text{well}}$

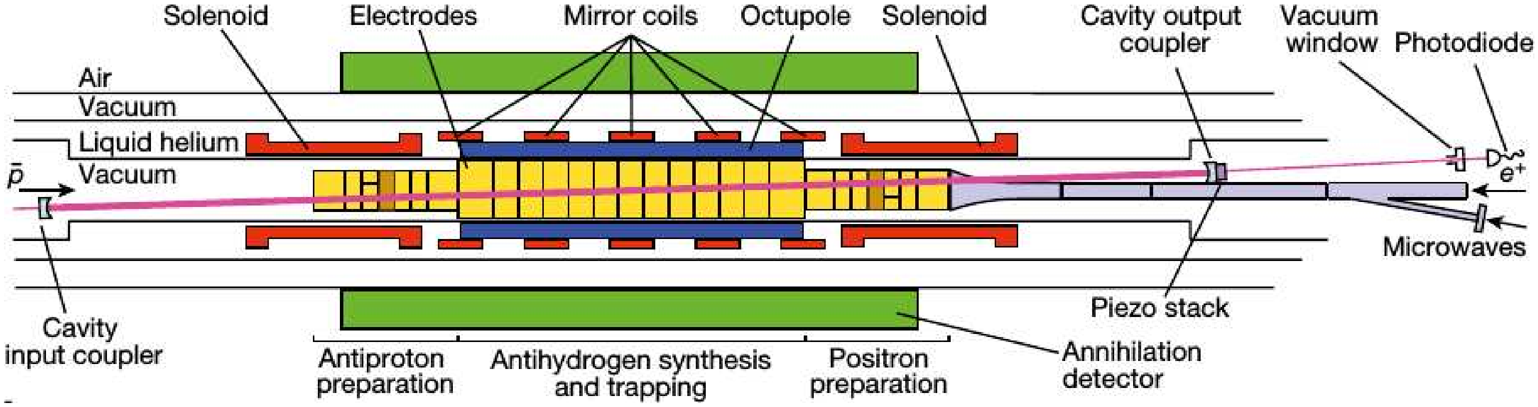
Result: $|Q| < 0.71 \times 10^{-9}$

ALPHA Coll.,

An improved limit on the charge of antihydrogen from stochastic acceleration,

Nature 529 (2016) 373.

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



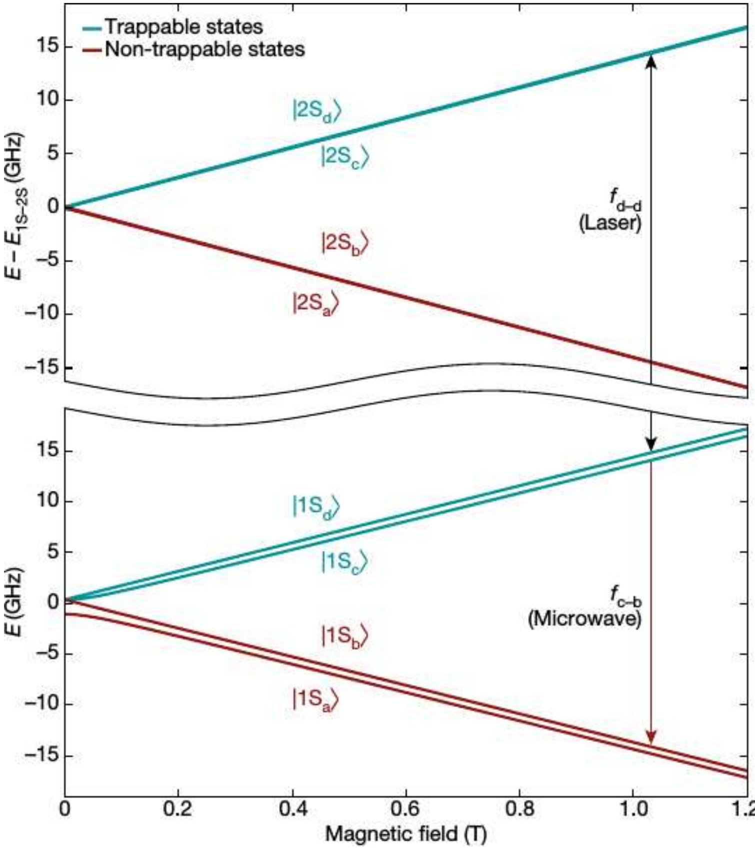
Measure annihilation rates.

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

Excite $1S{\rightarrow}2S$ 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:

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

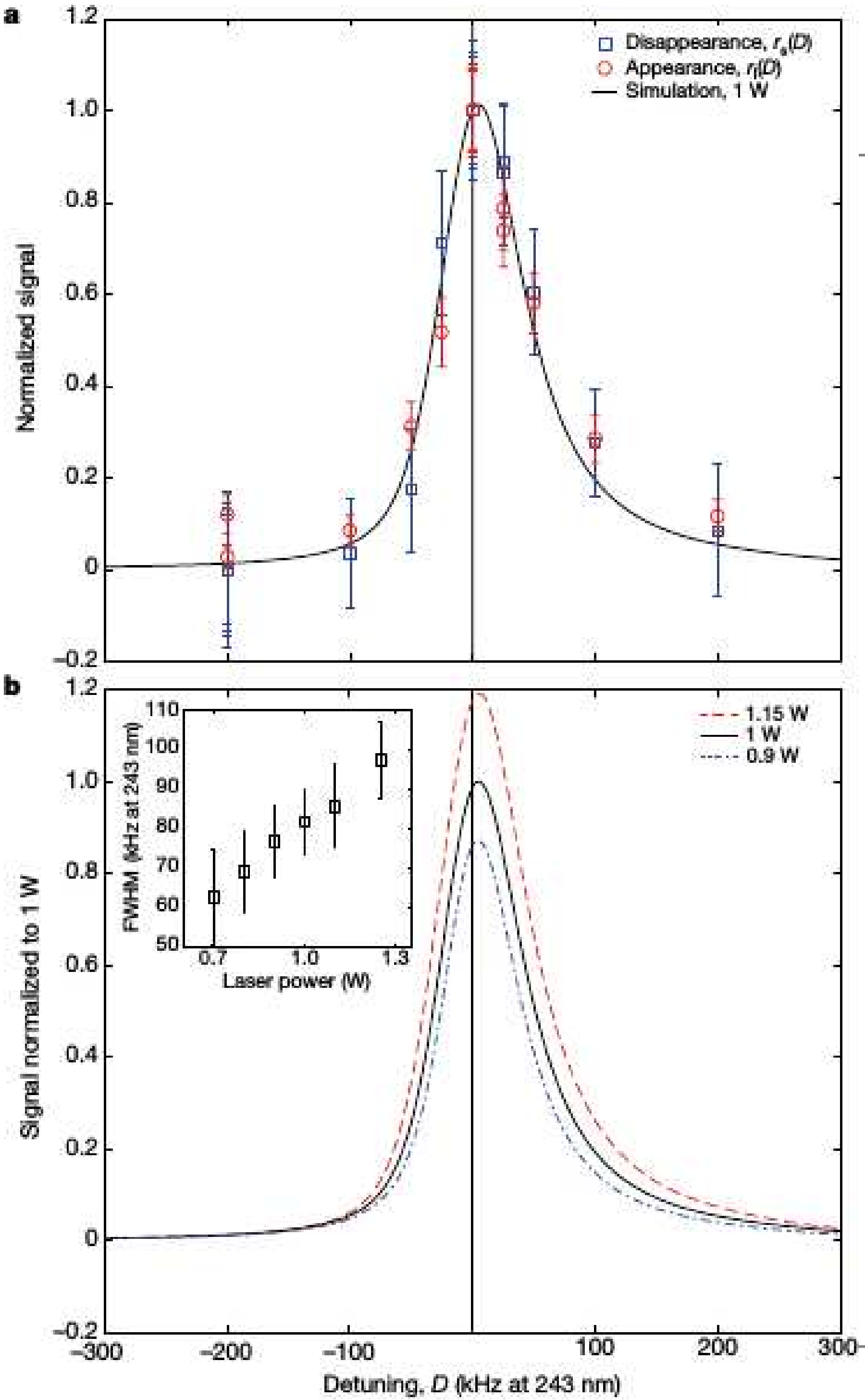
For hydrogen:

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

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.

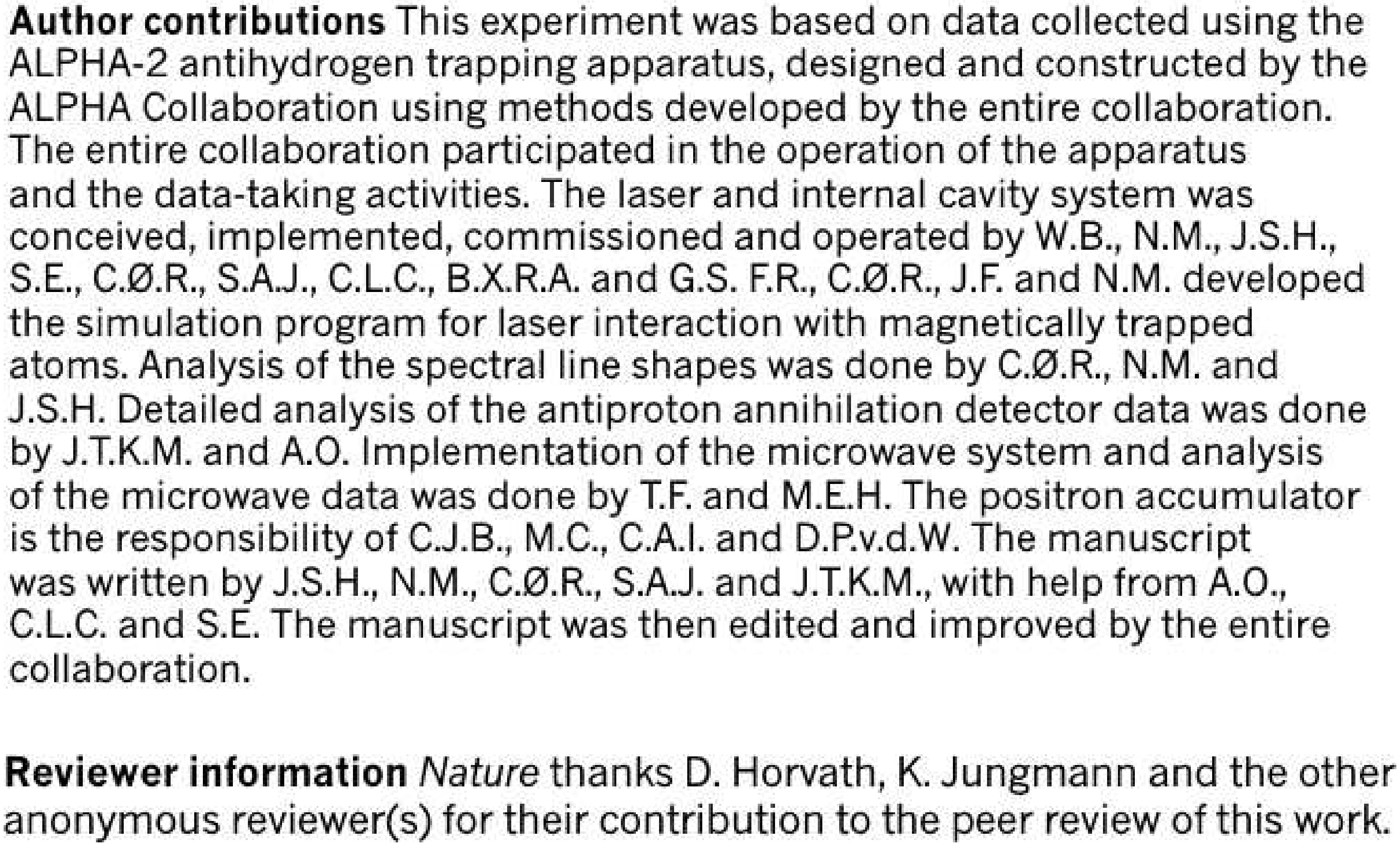


ALPHA: $\overline{\mathrm{H}}$ $1S-2S$ transition

ALPHA Collaboration (49 authors),

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

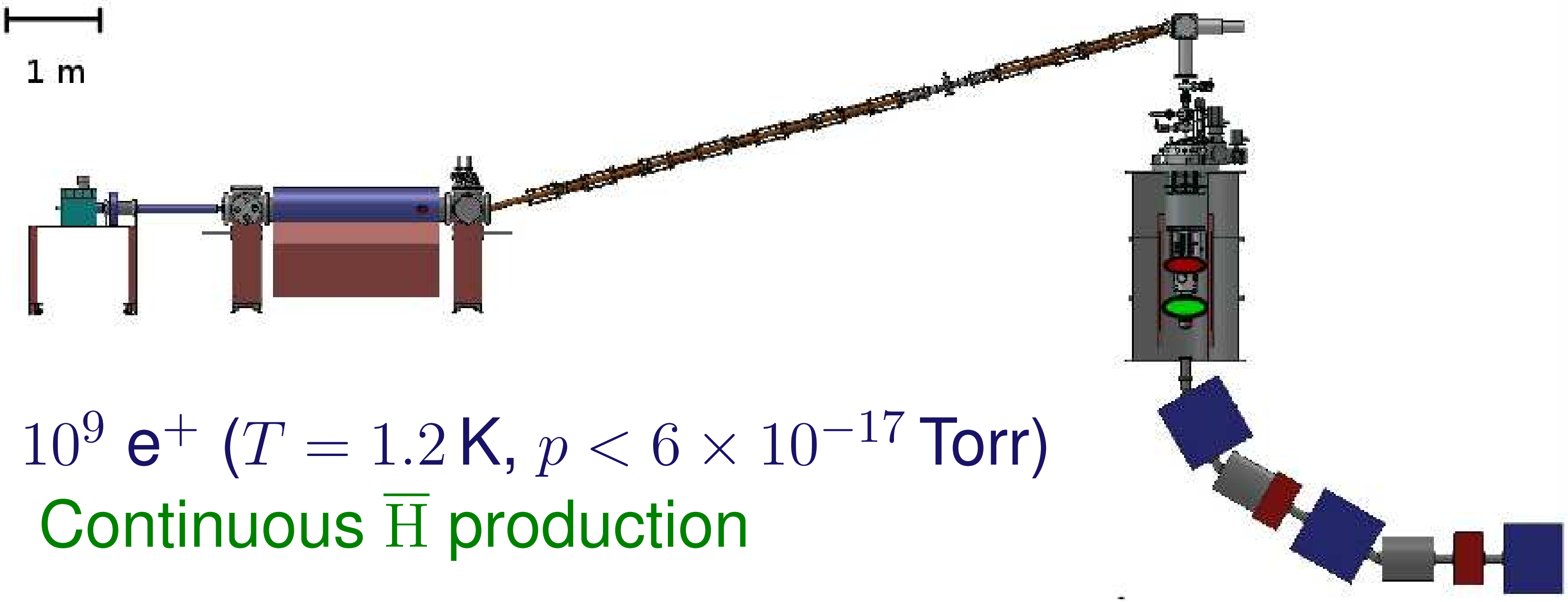
Nature 557 (2018) 74.



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.

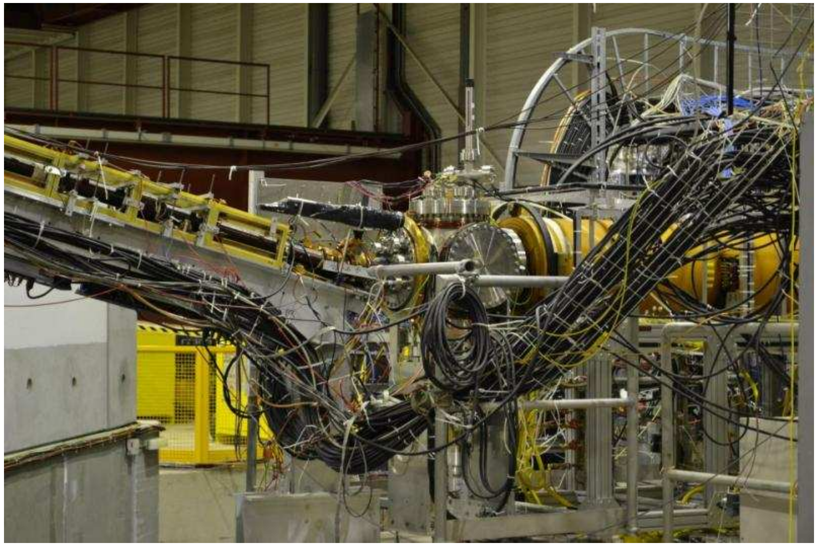
Reviewer information *Nature* thanks D. Horvath, K. Jungmann and the other anonymous reviewer(s) for their contribution to the peer review of this work.

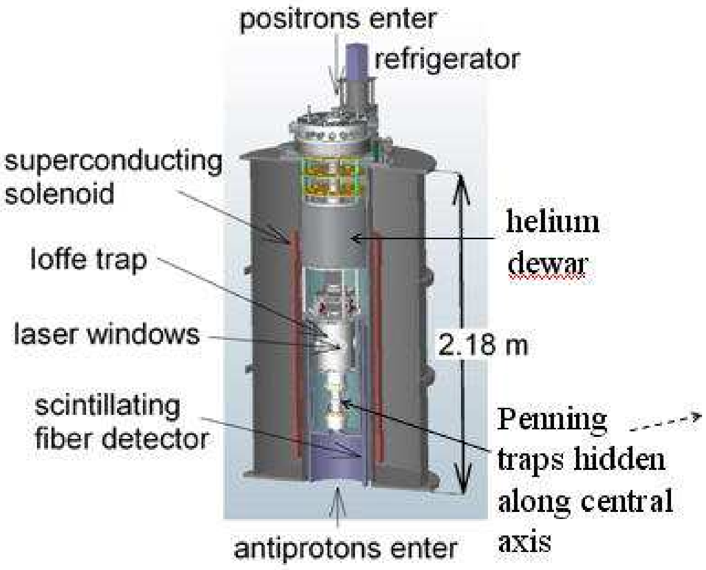
ATRAP: Antimatter trap



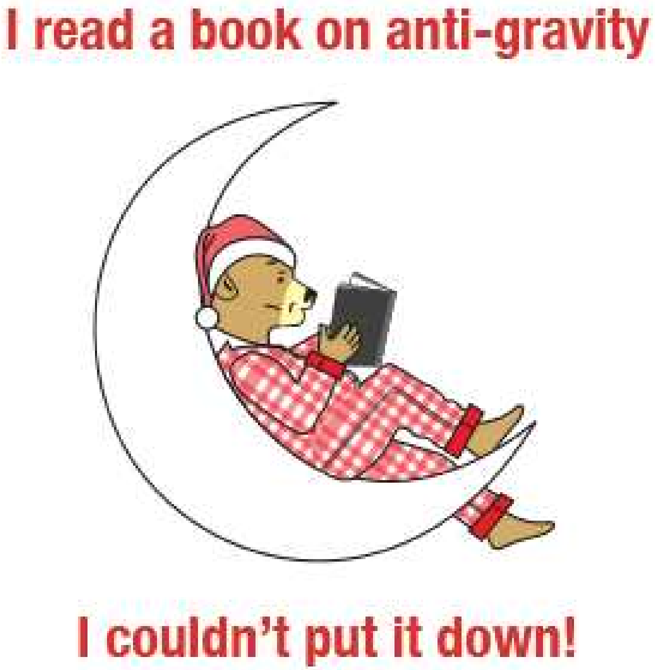
4×10^9 e$^+$ ($T = 1.2$ K, $p < 6 \times 10^{-17}$ Torr)

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





Antimatter gravity



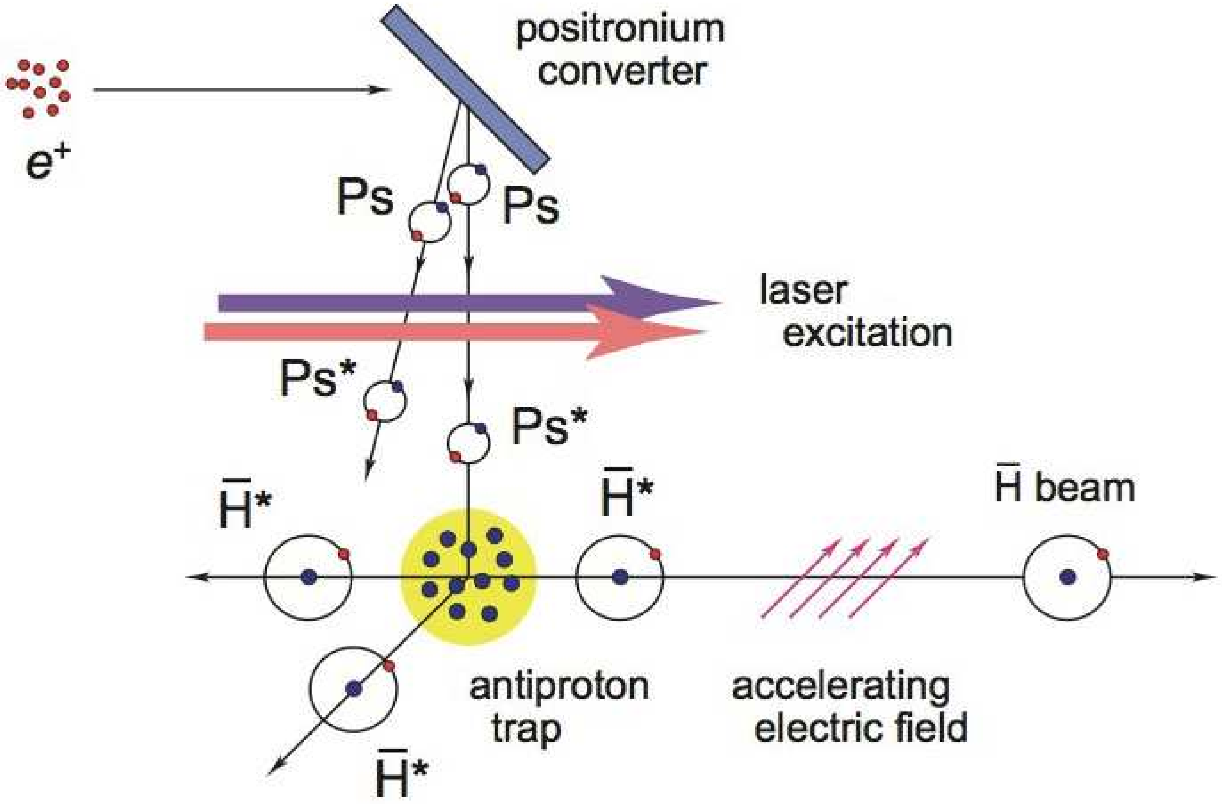
Negative mass ⇒ repulsive gravity??

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

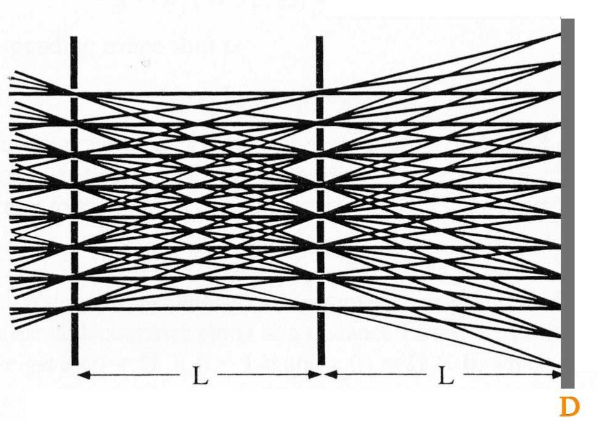
Not CPT: weak equivalence principle

AEGIS: antimatter gravity

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



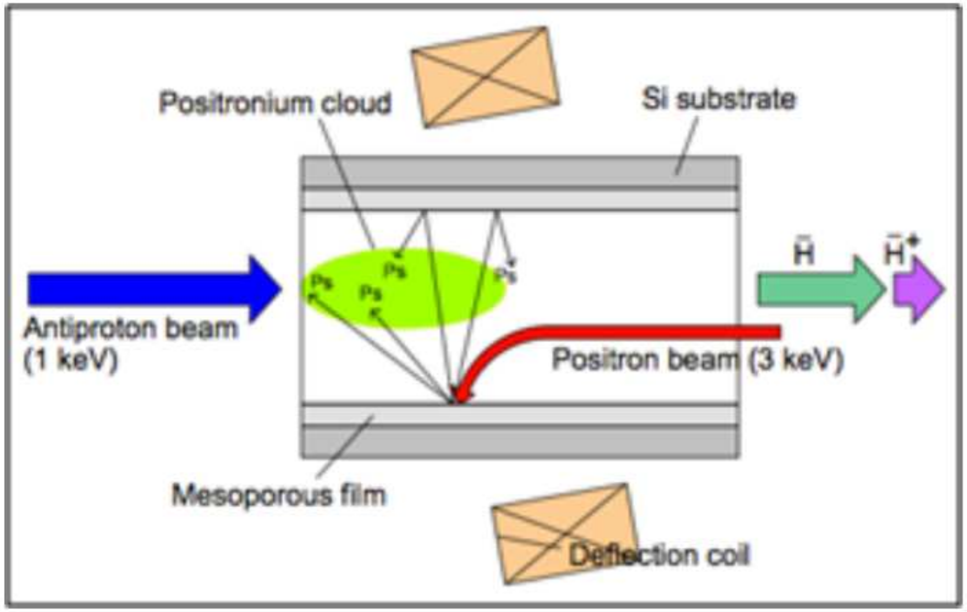
Moiré deflectometry: gravitational falling of collimated $\overline{\mathrm{H}}$ as compared to light

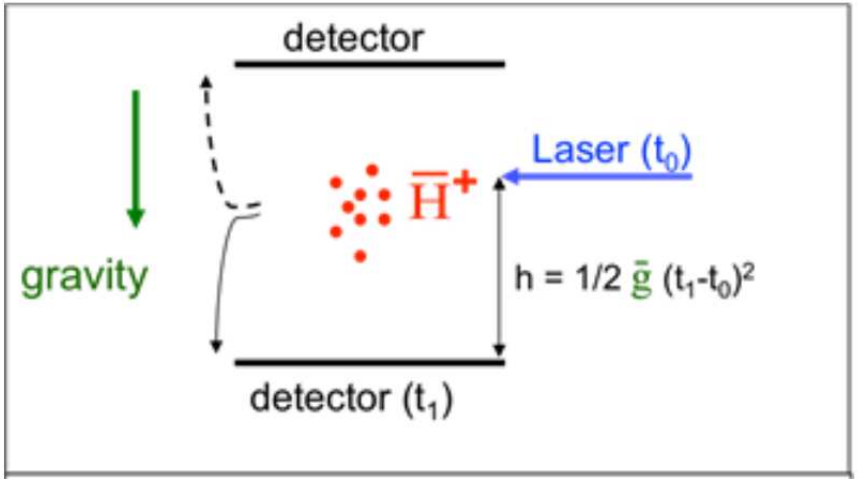


Stark acceleration (electric dipole in inhom. E-field) of excited $\overline{\mathrm{H}}$

GBAR

Gravitational Behaviour of Antihydrogen at Rest
(in preparation)

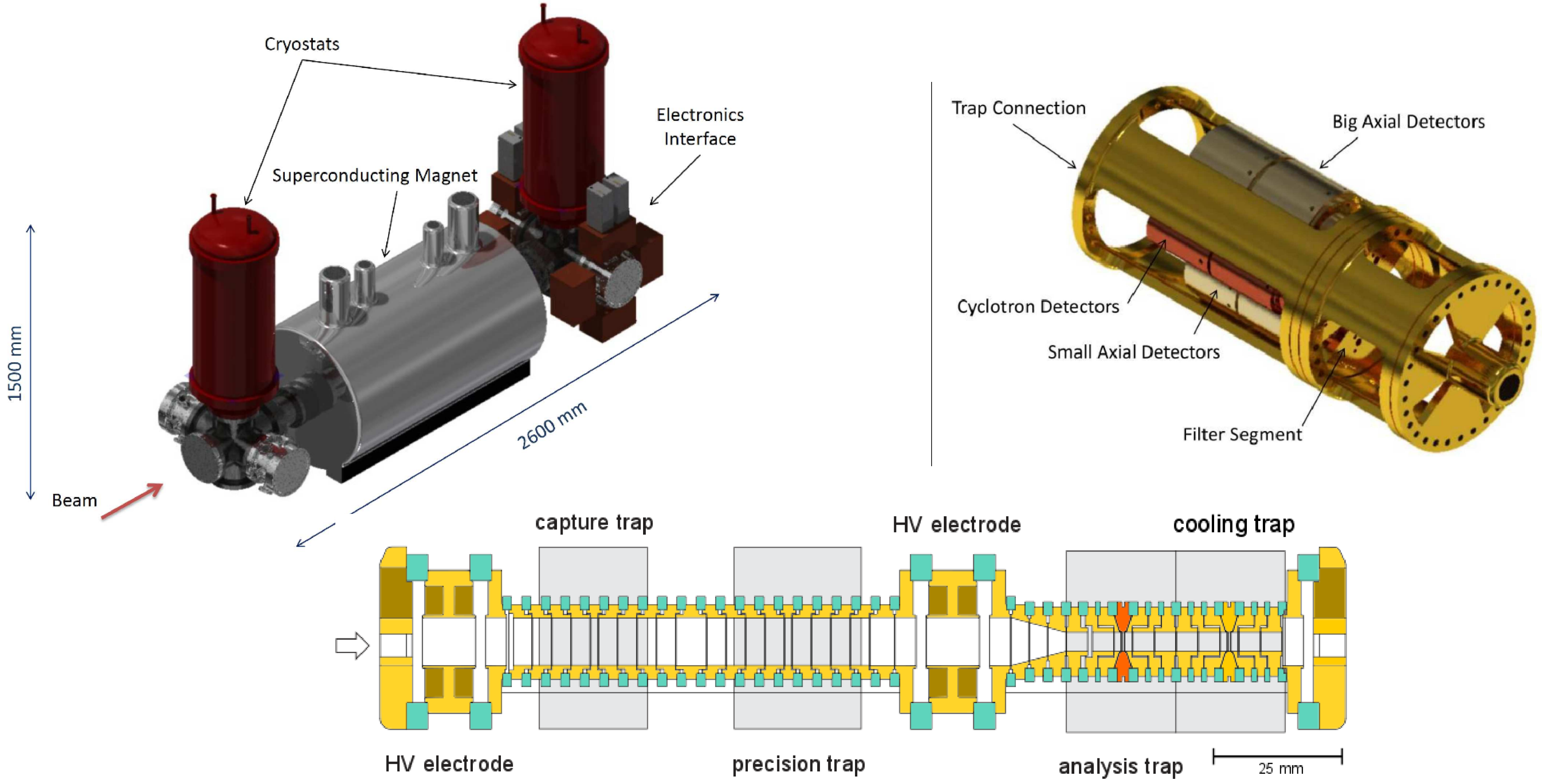




$\bar{p}$ + Ps $\rightarrow$ $\overline{H}$; $\overline{H}$ + Ps $\rightarrow$ $\overline{H}^+$ (cooling); back to $\overline{H}$: let it fall

BASE: Baryon Antibaryon Symmetry Experiment

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



$$g(\overline{\mathrm{p}})/2 = 2.7928465(23) \leftrightarrow g(\mathrm{p})/2 = 2.792847350(9)$$

H. Nagahama *et al.* [BASE Collaboration], „Sixfold improved single particle measurement of the magnetic moment of the antiproton," Nature Commun. 8 (2017) 14084.

Antihydrogen beam

ASACUSA: MUSASHI

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

Musashi Miyamoto self-portrait ~ 1640

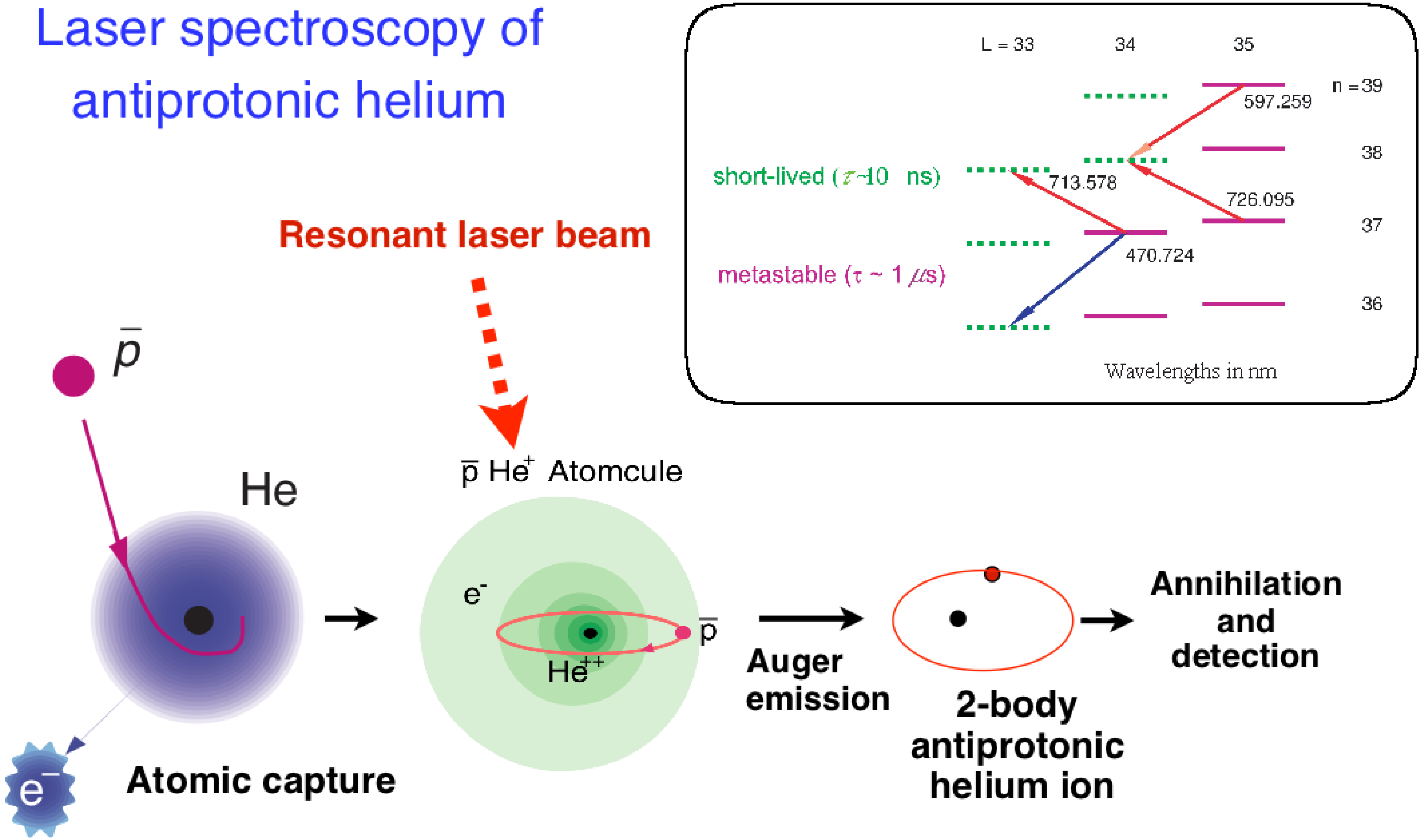
5.8 MeV $\overline{\mathrm{p}}$ injected into RFQ
100 keV $\overline{\mathrm{p}}$ injected into trap
10^6 $\overline{\mathrm{p}}$ trapped and cooled (2002)
~ 350000 slow $\overline{\mathrm{p}}$ extracted (2004)
Cold $\overline{\mathrm{p}}$ compressed in trap (2008)
(5×10^5 $\overline{\mathrm{p}}$, $E = 0.3$ eV, $R = 0.25$ mm)

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

E. Widmann *et al.*, Hyperfine Interact. **240** (2019) 5

ASACUSA: measuring $\bar{\mathrm{p}}$ mass

Laser spectroscopy of antiprotonic helium

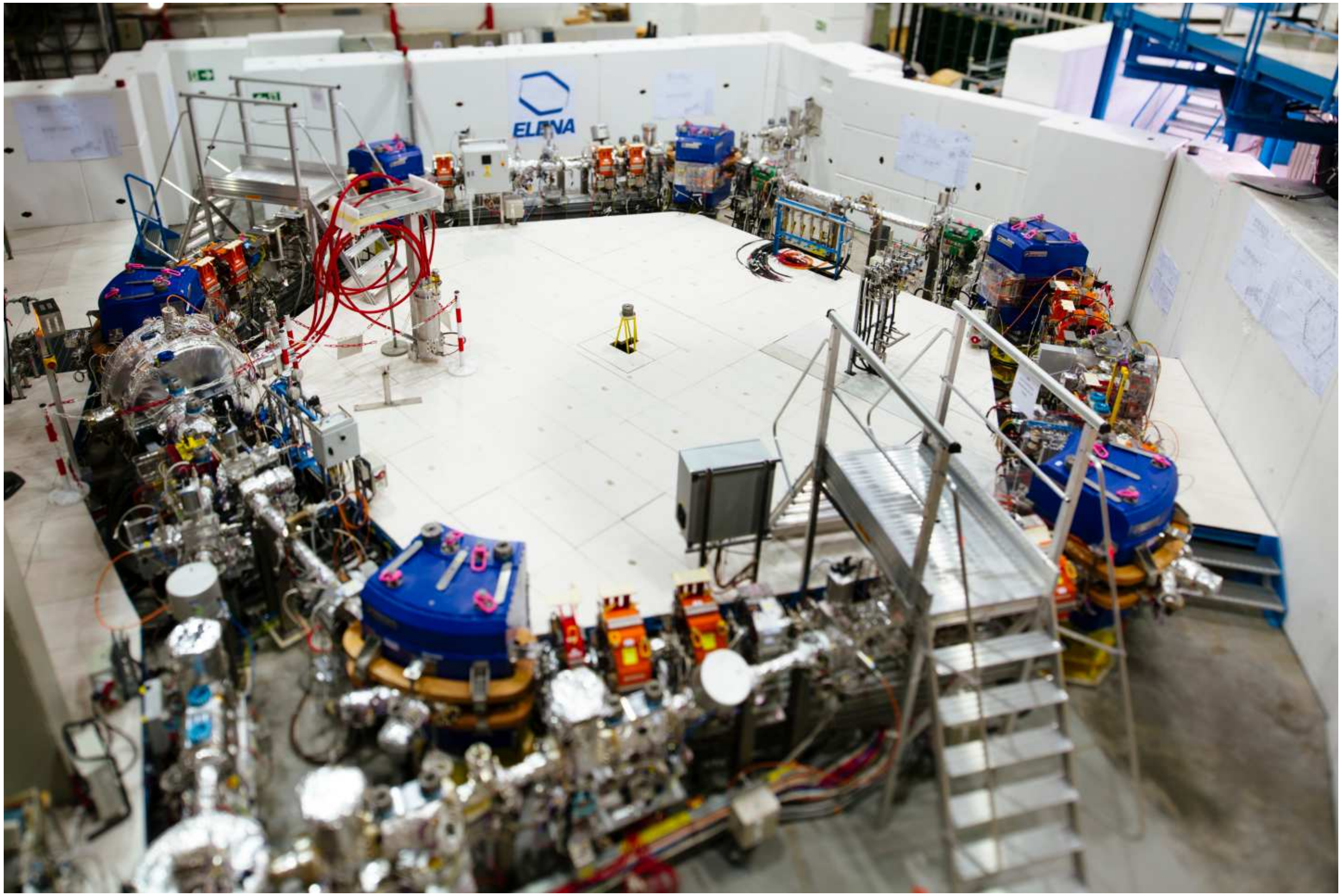


Transition between long- and short-lived states ⇒ prompt annihilation

Theory: Vladimir Korobov (Dubna) ⇒ $\Delta M_{\overline{\mathrm{p}}} \sim 10^{-12}$

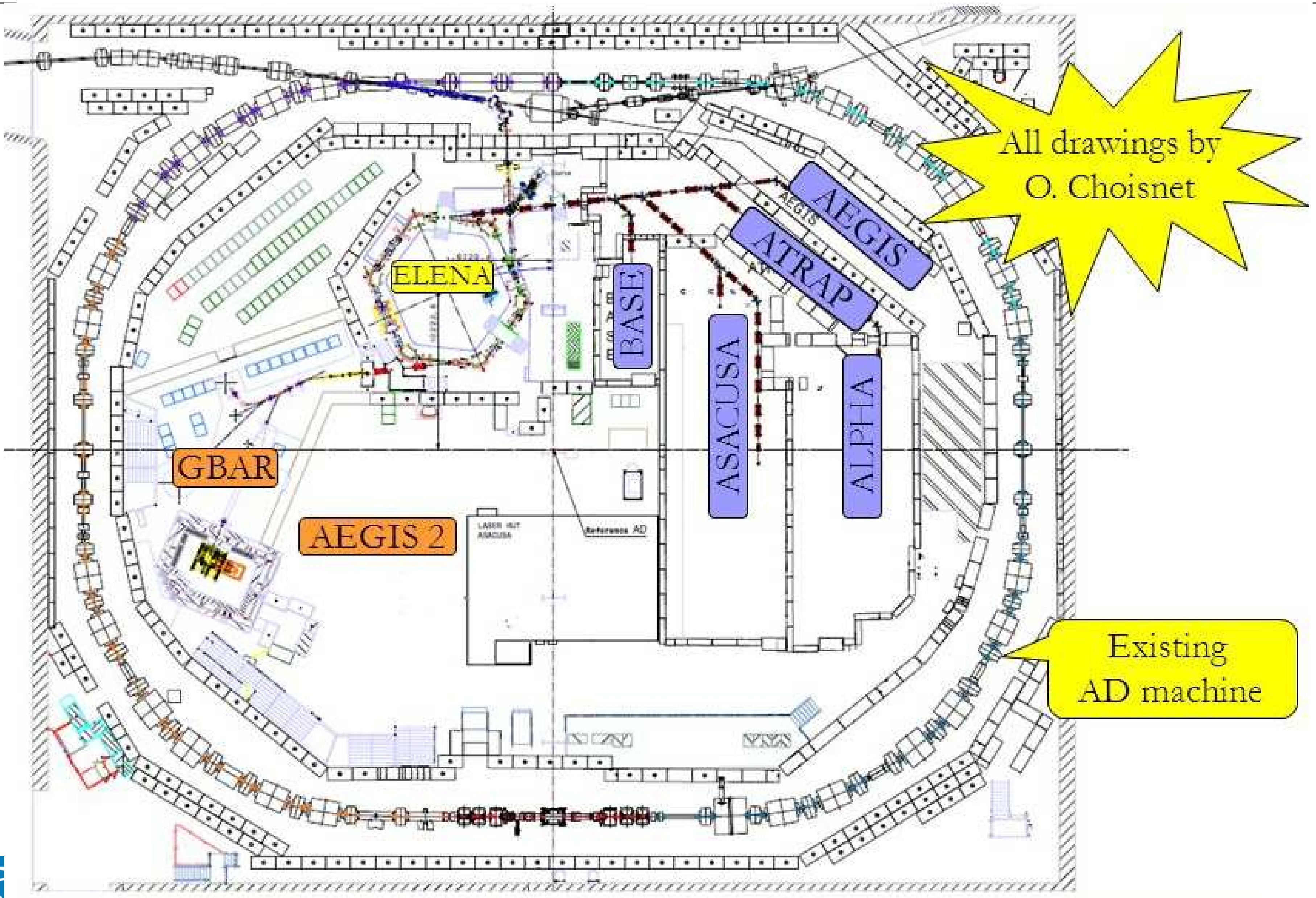
xtra Low ENergy Antiprotons (ELENA)

New deceleration ring at CERN: 100 keV $\overline{\mathrm{p}}$ for trapping



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

ELENA at the AD: plan



All drawings by O. Choisnet

Existing AD machine

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

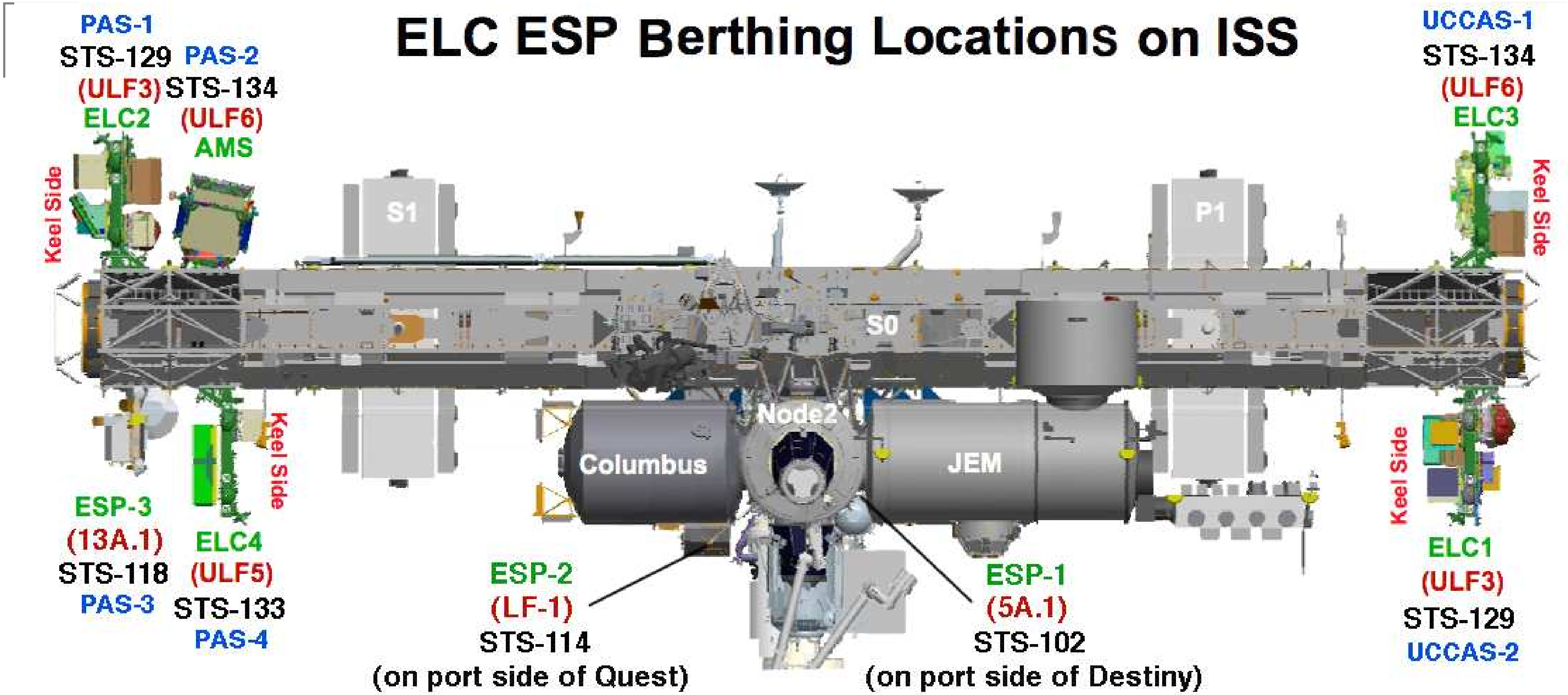
Father: Sam Ting, cost: 2 G$

Construction: CERN

Launch: May 2011, USA

Control room: CERN

AMS-2: Alpha Magnetic Spectrometer



First results (2015):

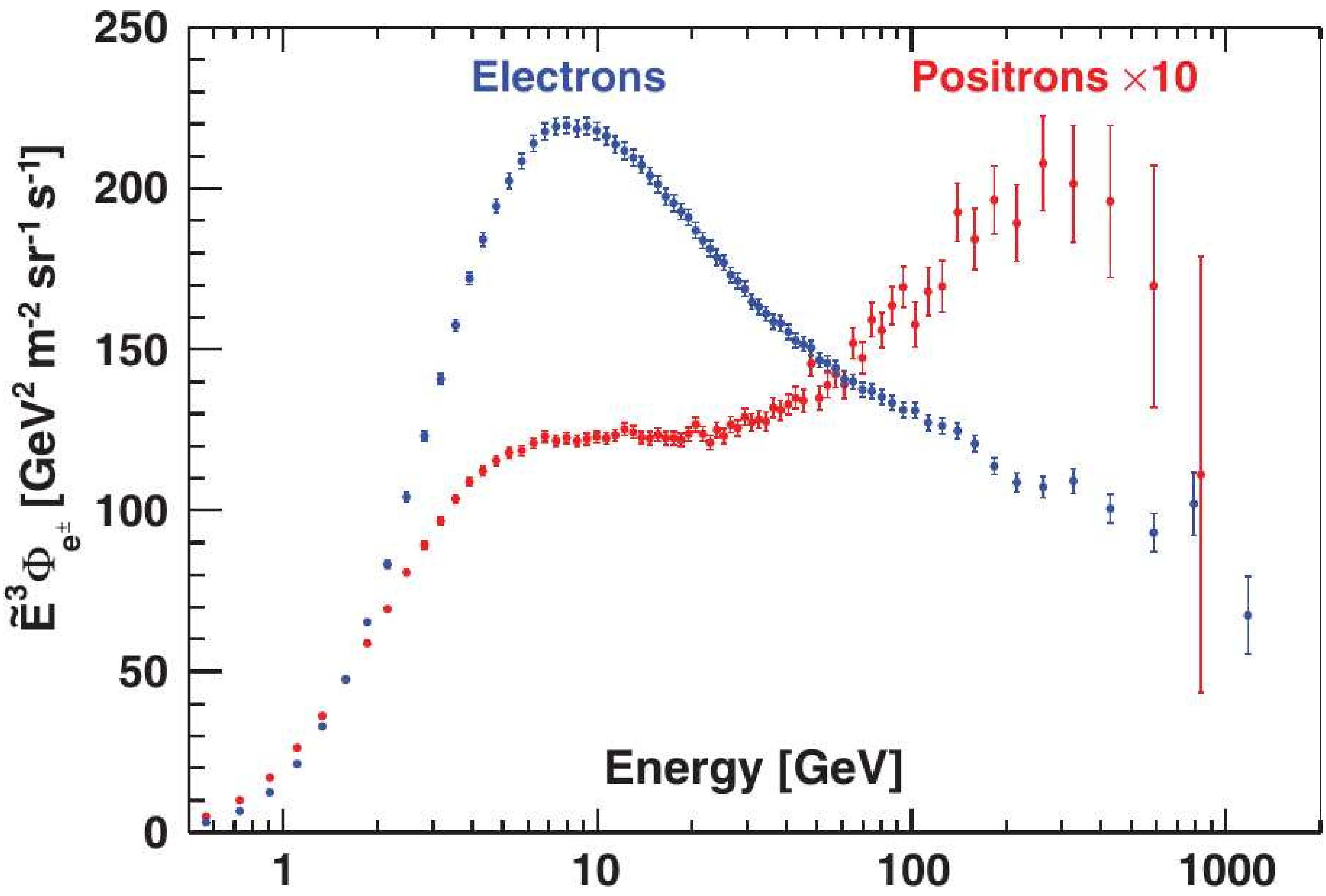
No antihelium observed.

High energy electrons and positrons have different sources.

Could come from dark matter or pulsars.

AMS2 will collect data for 10–15 years.

AMS-2: Electrons vs. positrons



Thanks for your attention

Spare slides for discussion

Antiproton production

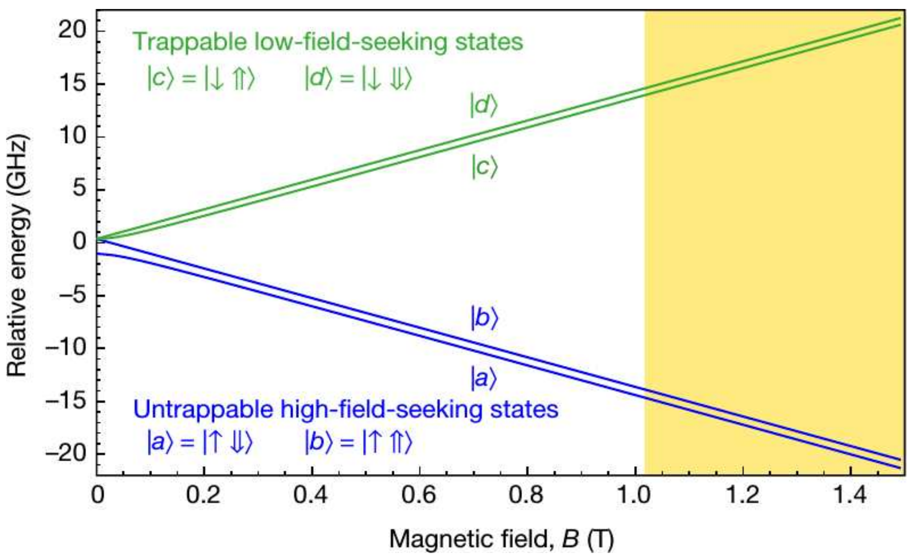
CERN exhibition in Globe: $\overline{\mathrm{p}}$ production target at AD

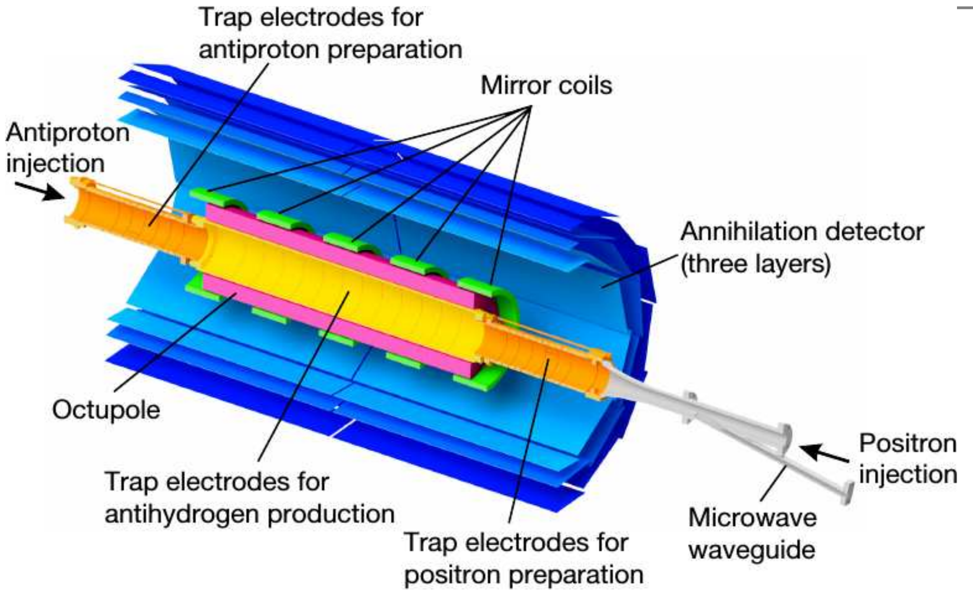
Steps toward $\overline{\mathrm{H}}$ spectroscopy

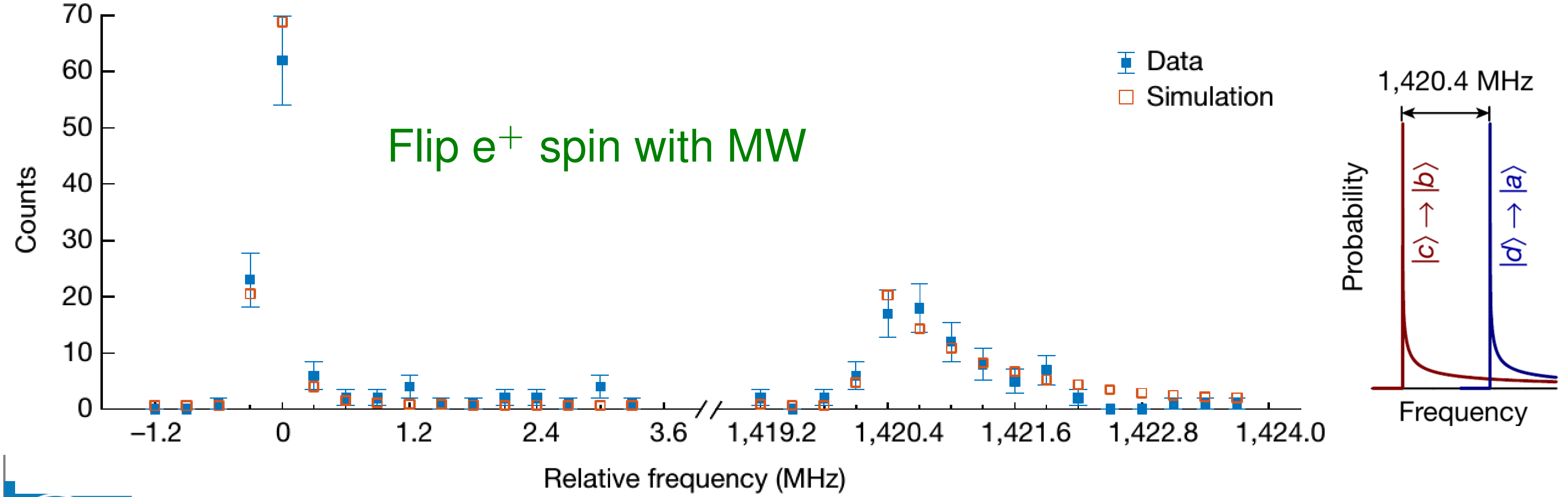
- Putting antiprotons ($\overline{\mathrm{p}}$) in electromagnetic trap
- Trapping and cooling antiprotons
- Cooling slow positrons (e^+ from ^{22}Na) in trap
- Mixing $\overline{\mathrm{p}}$ and e^+ $\rightarrow$ recombination in $\mathrm{e}^+\mathrm{e}^+\overline{\mathrm{p}}$ collisions (G. Gabrielse,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

2017: done by the ALPHA Collaboration!

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



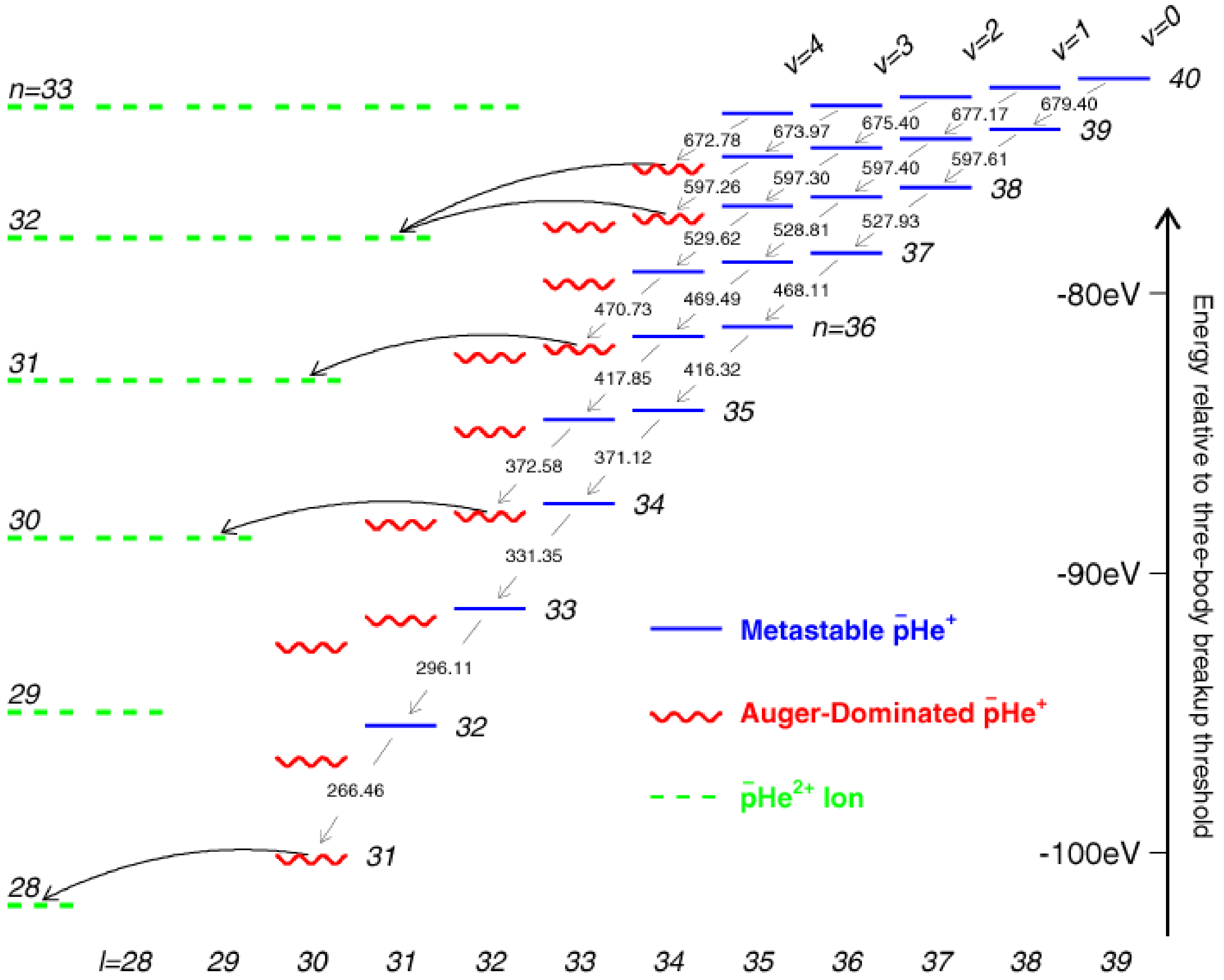




Flip e$^+$ spin with MW

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

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

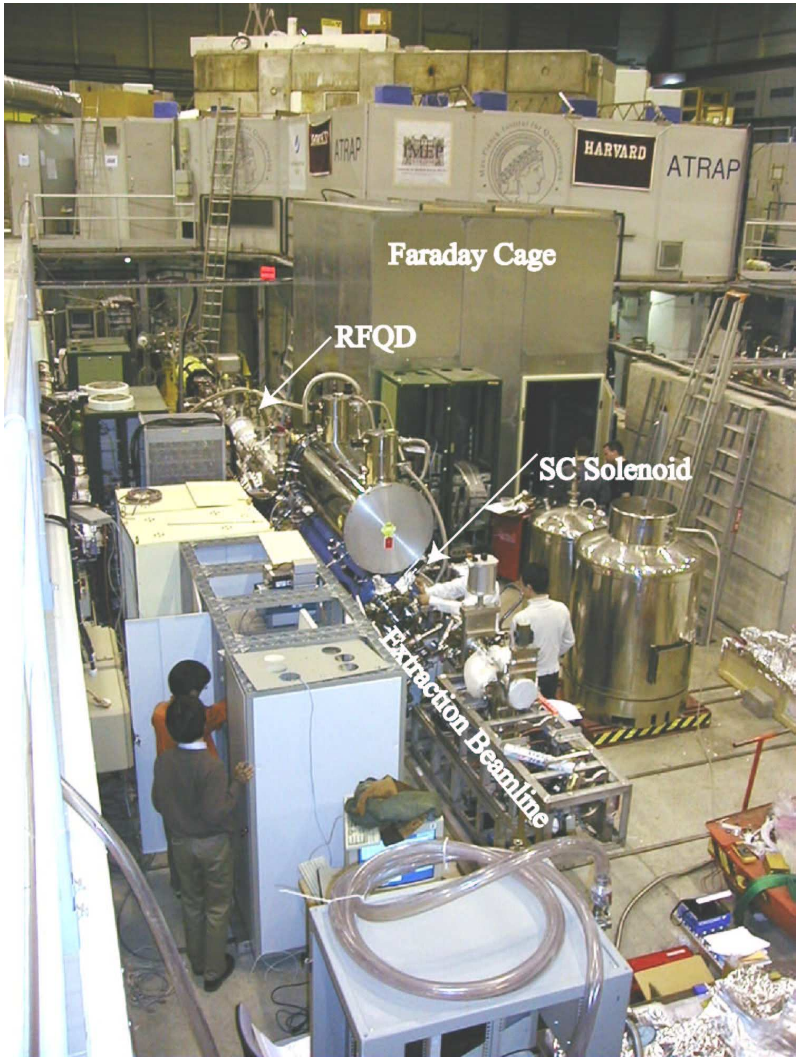


Level energies in eV, transition wavelengths in nm

MUSASHI: slow antiproton beam

Musashi Miyamoto self-portrait ~ 1640

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations



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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, 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.

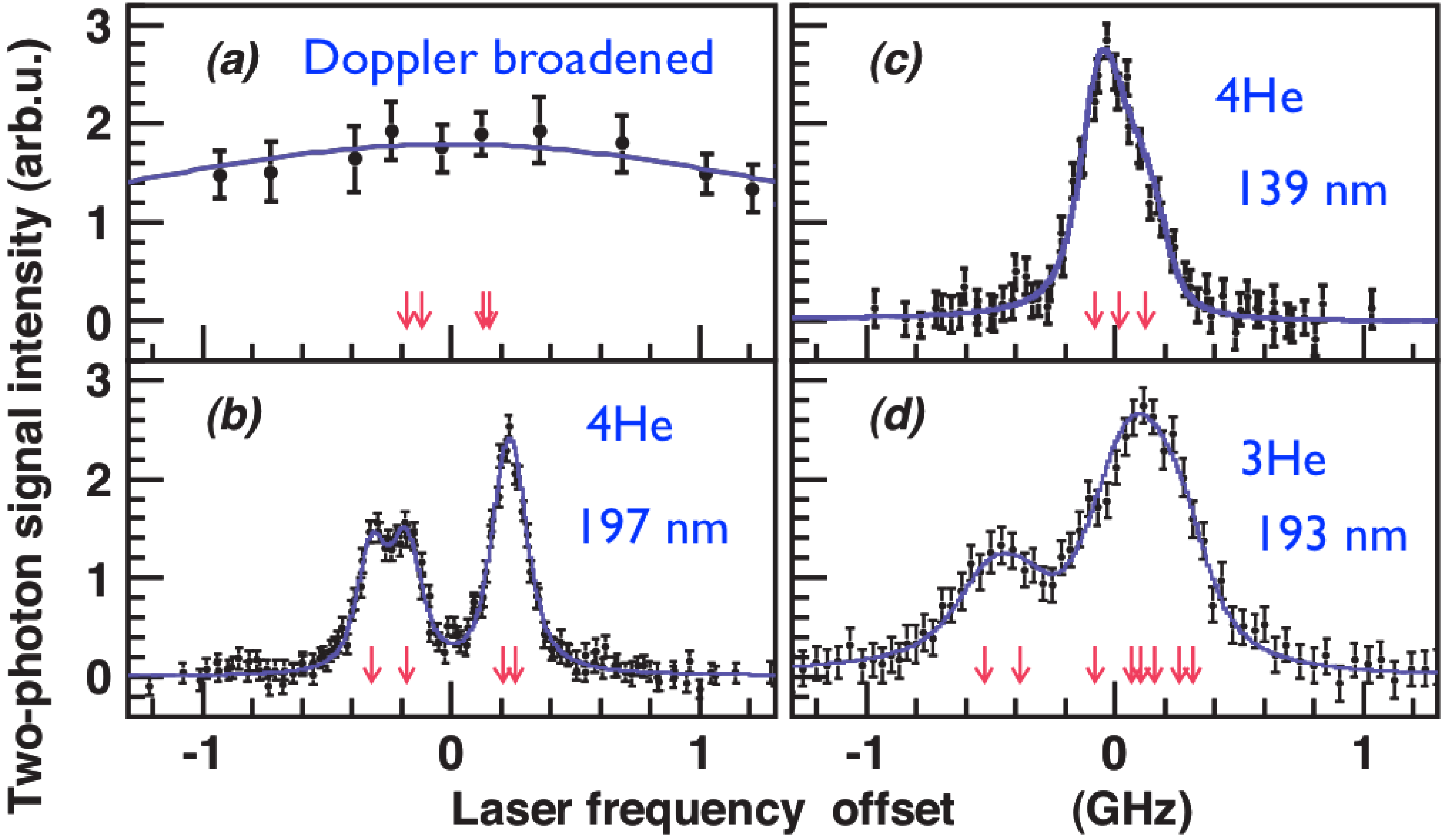
Two-photon spectroscopy: parameters

- 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) → (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

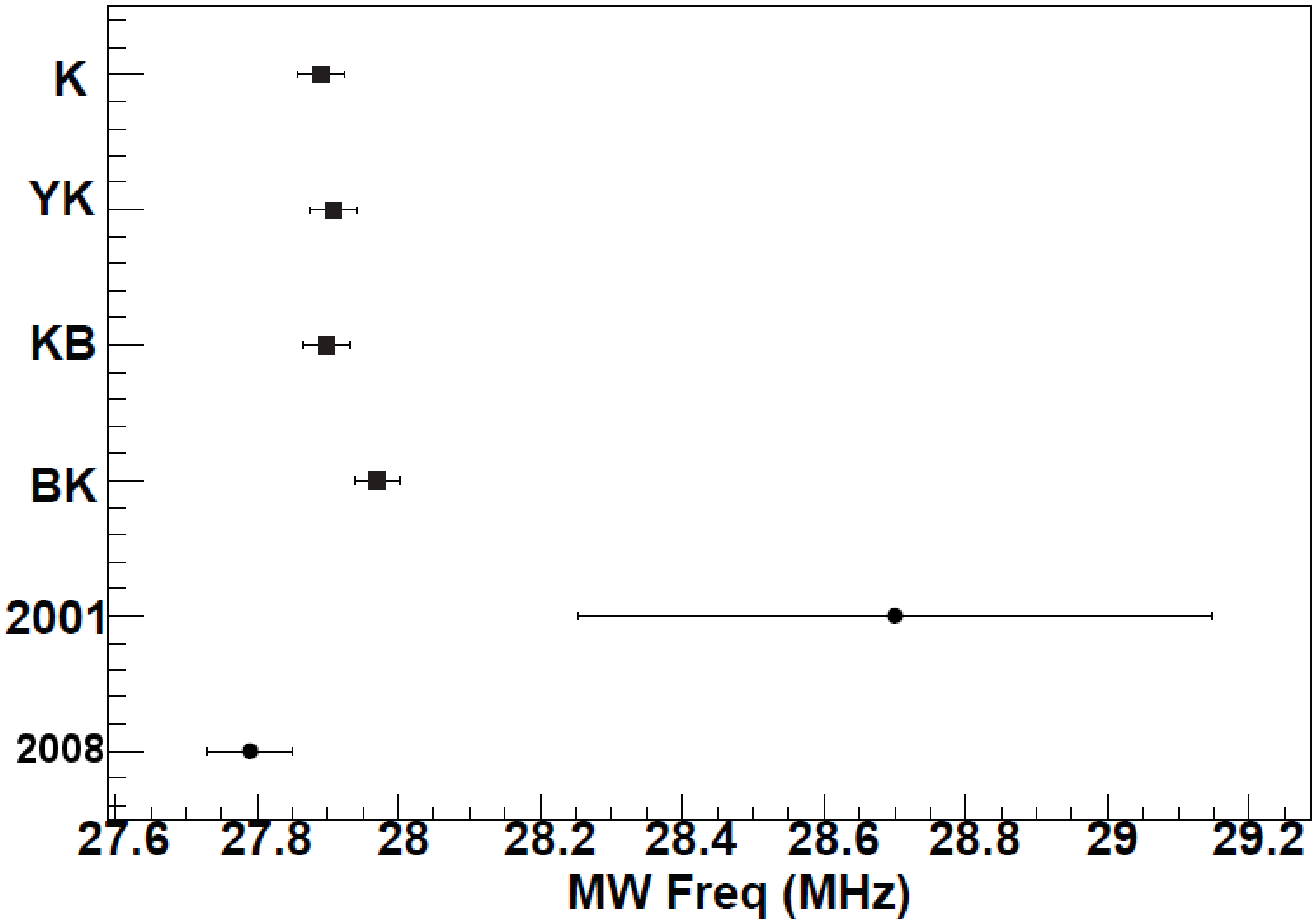
Two-photon spectroscopy: spectra



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

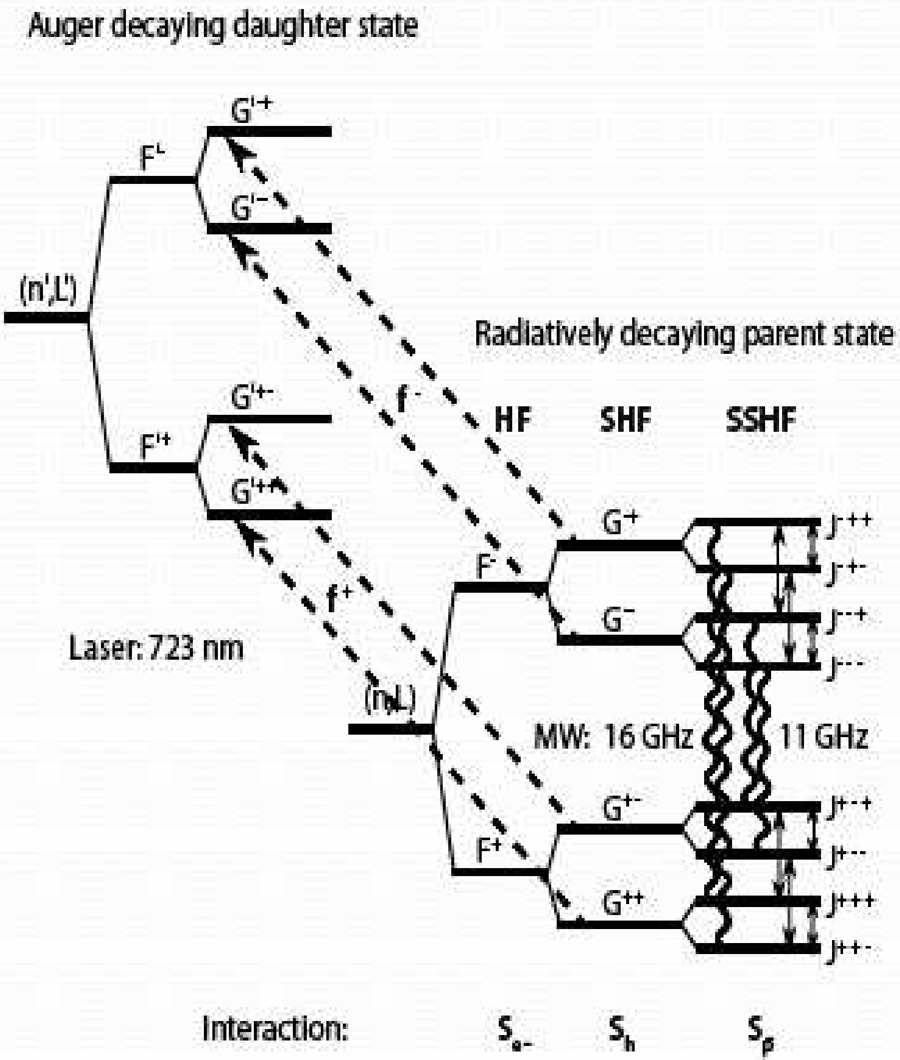
Arrows: hyperfine transitions

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

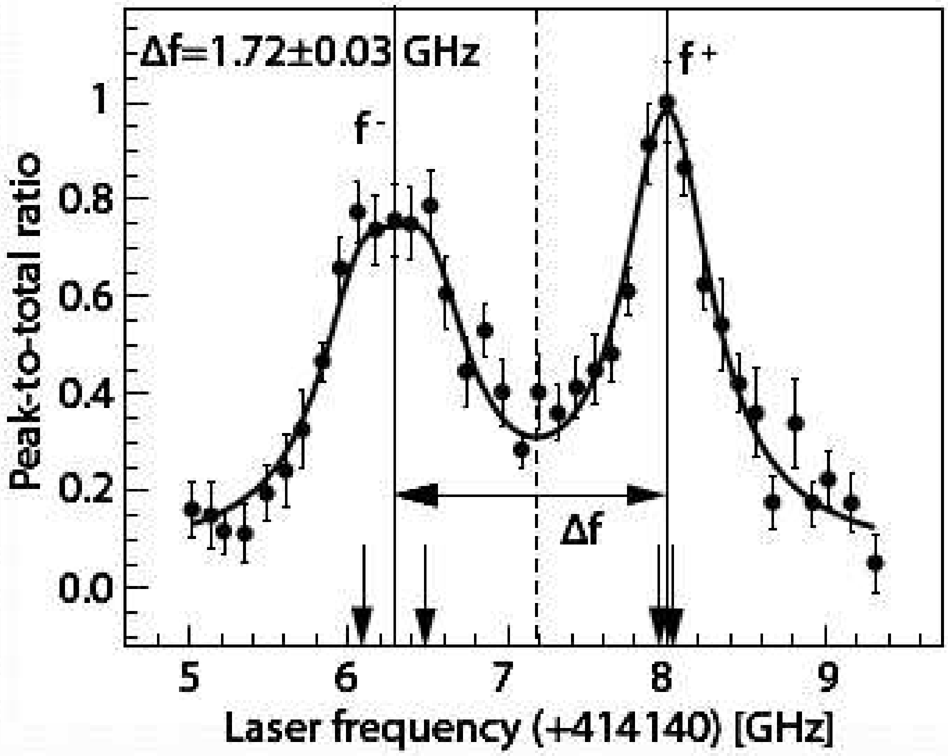


Th. Pask et al., Phys. Lett. B 678 (2009) 55.

$\overline{\mathrm{p}}^3$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.