

# Tests of CPT Invariance at the Antiproton Decelerator of CERN

*New Trends in High-Energy Physics,  
12-18 May 2019, Odessa, Ukraine*

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&

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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  $\Rightarrow$  two solutions for electrons ( $x^2 = 4 \Rightarrow x = \pm 2$ ).

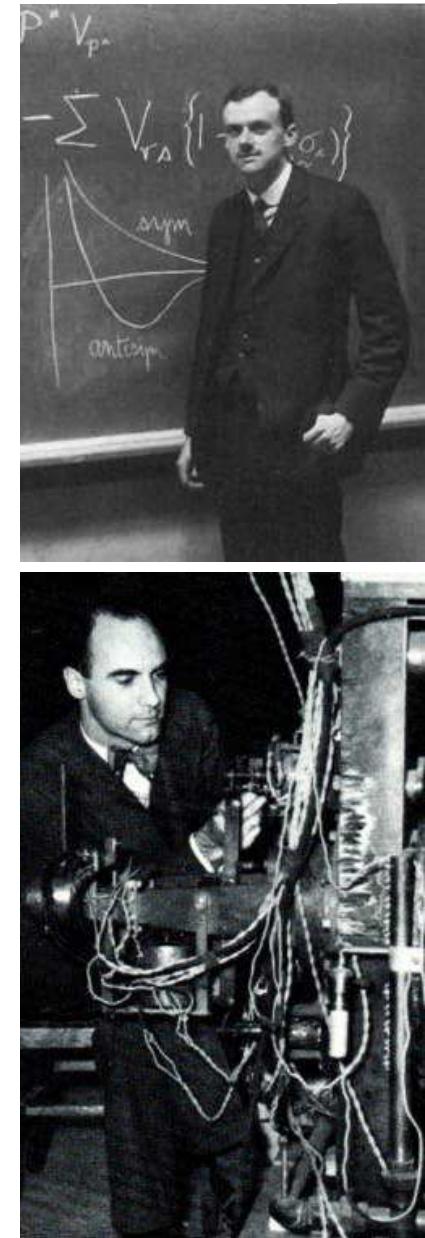
Two kinds of electrons:

- + 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



# Matter–antimatter symmetry

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

**CPT invariance** Space reflection:  $P|\mathbf{p}(r, t)\rangle = |\mathbf{p}(-r, t)\rangle$

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

( $K$ : complex conjugation for  $\exp\{-iEt\}$ )

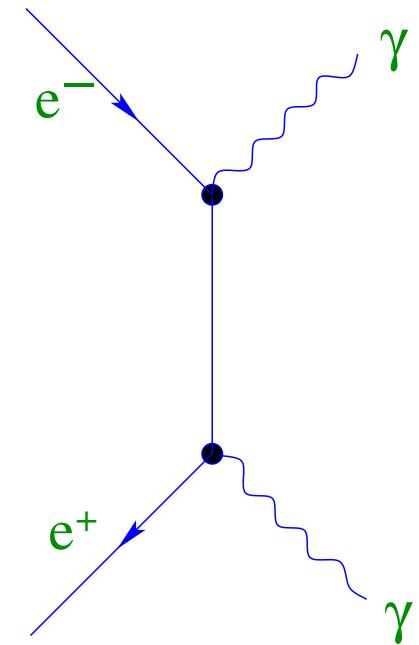
Basic assumption of field theory:

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

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



# 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?

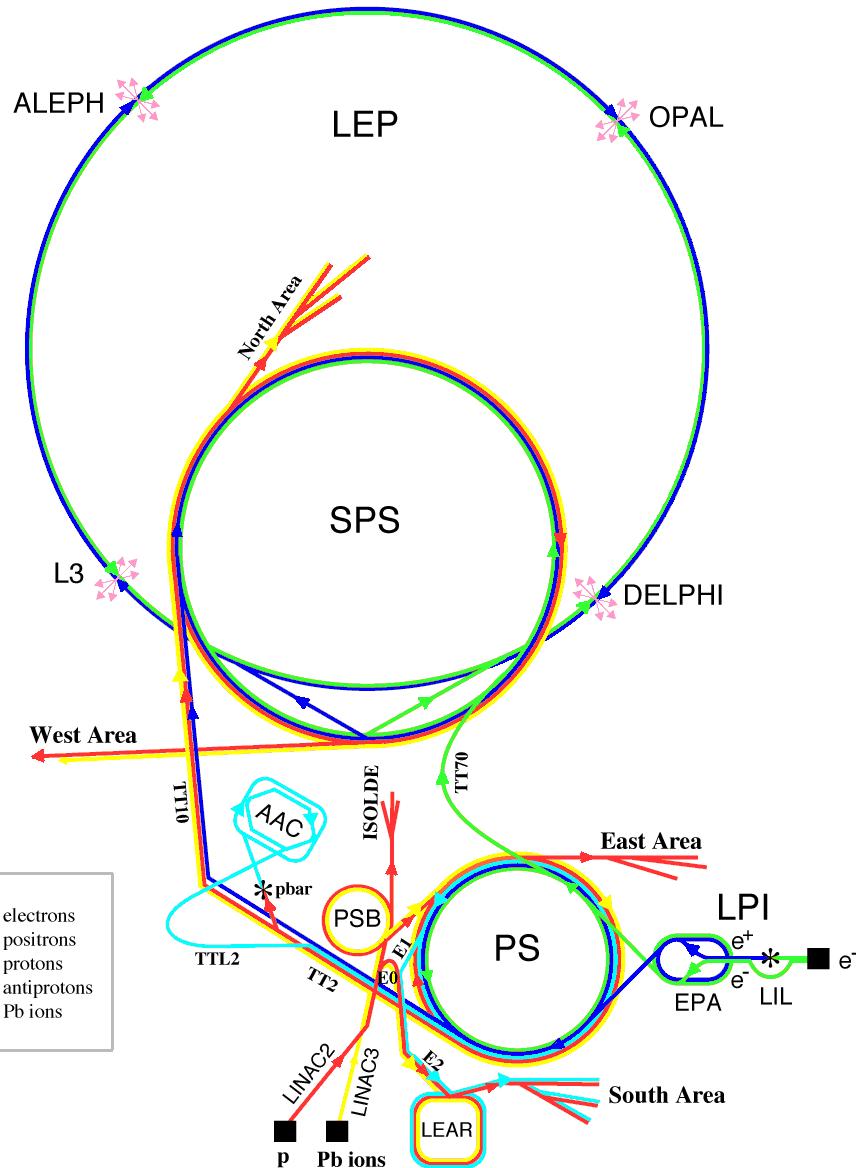
# How to test $CPT$ ?

Particle = – antiparticle ?

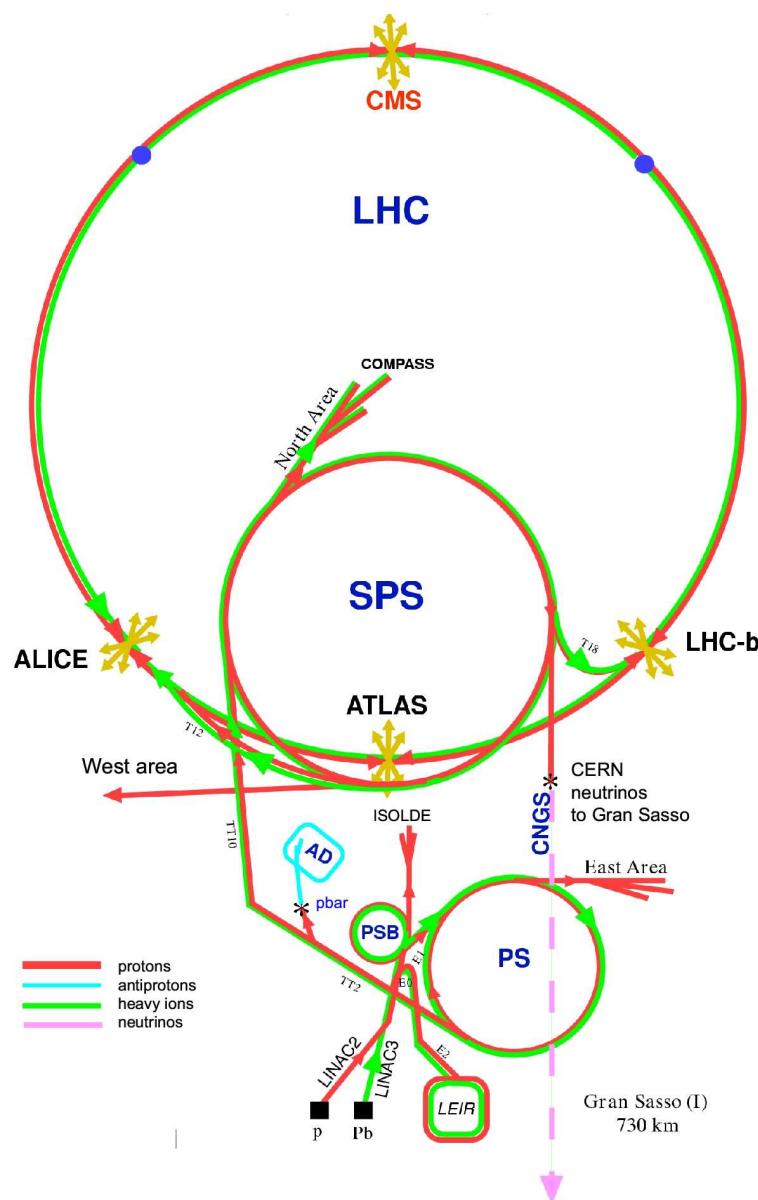
- $[m(K^0) - m(\bar{K}^0)]/m(\text{average}) < 10^{-18}$
- proton ~ antiproton? (compare  $m, q, \vec{\mu}$ )
- hydrogen ~ antihydrogen ( $\bar{p}e^+$ )?  $2S - 1S$ , HFS

# Accelerators at CERN

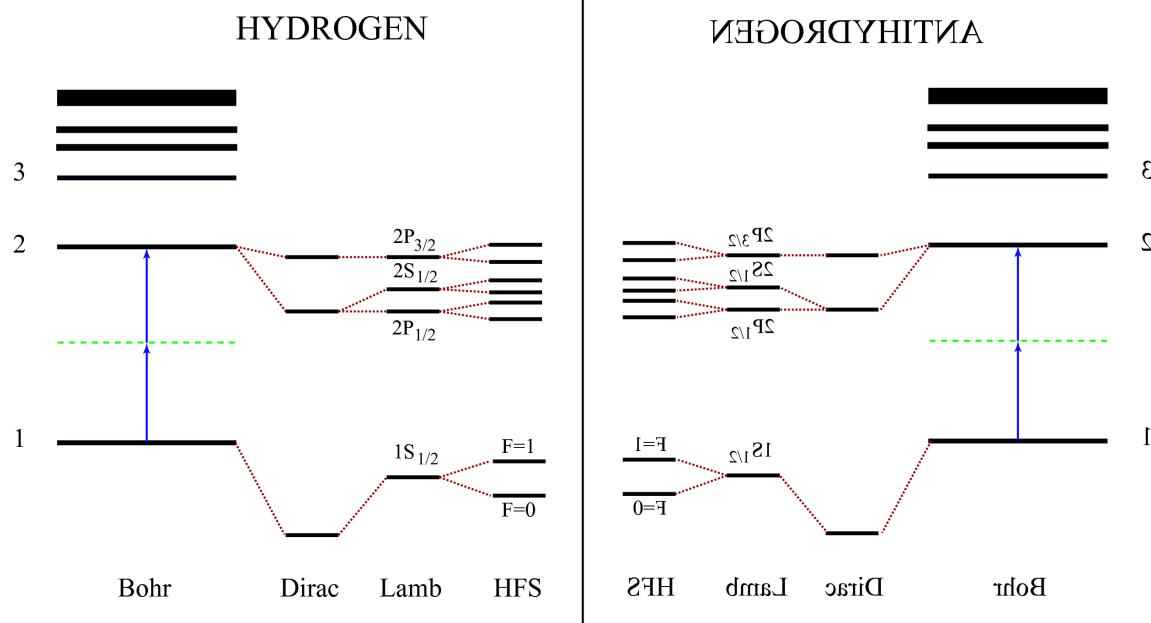
1989–2000



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

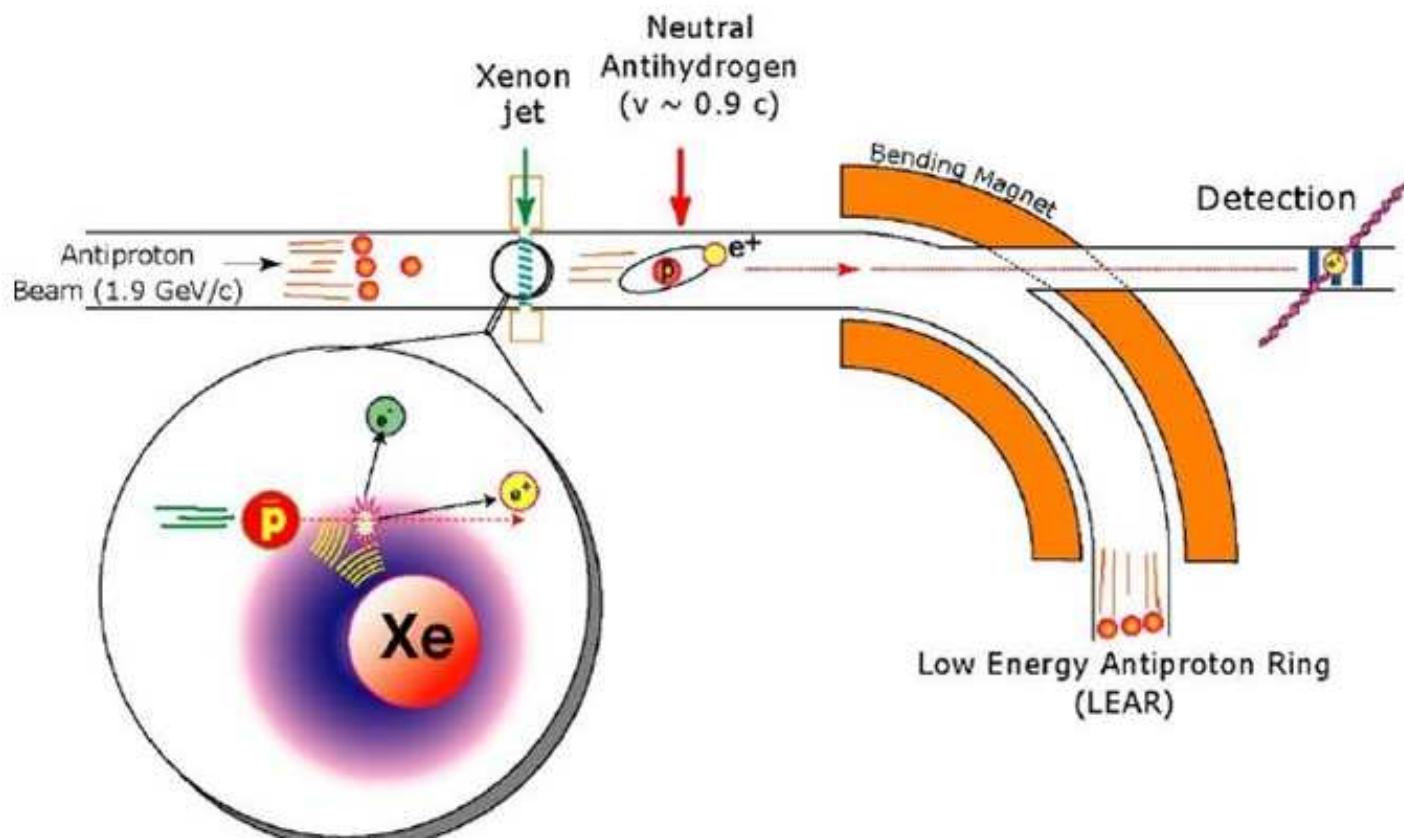
M. Charlton, J. Eades, D. Horváth, R. J. Hughes, C. Zimmermann:  
*Antihydrogen physics*, Physics Reports 241 (1994) 65.

SPSLC accepted and CERN approved to build the Antiproton Decelerator

Great technical accomplishment of Dieter Möhl et al.



# First (9) relativistic $\bar{H}$ 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.



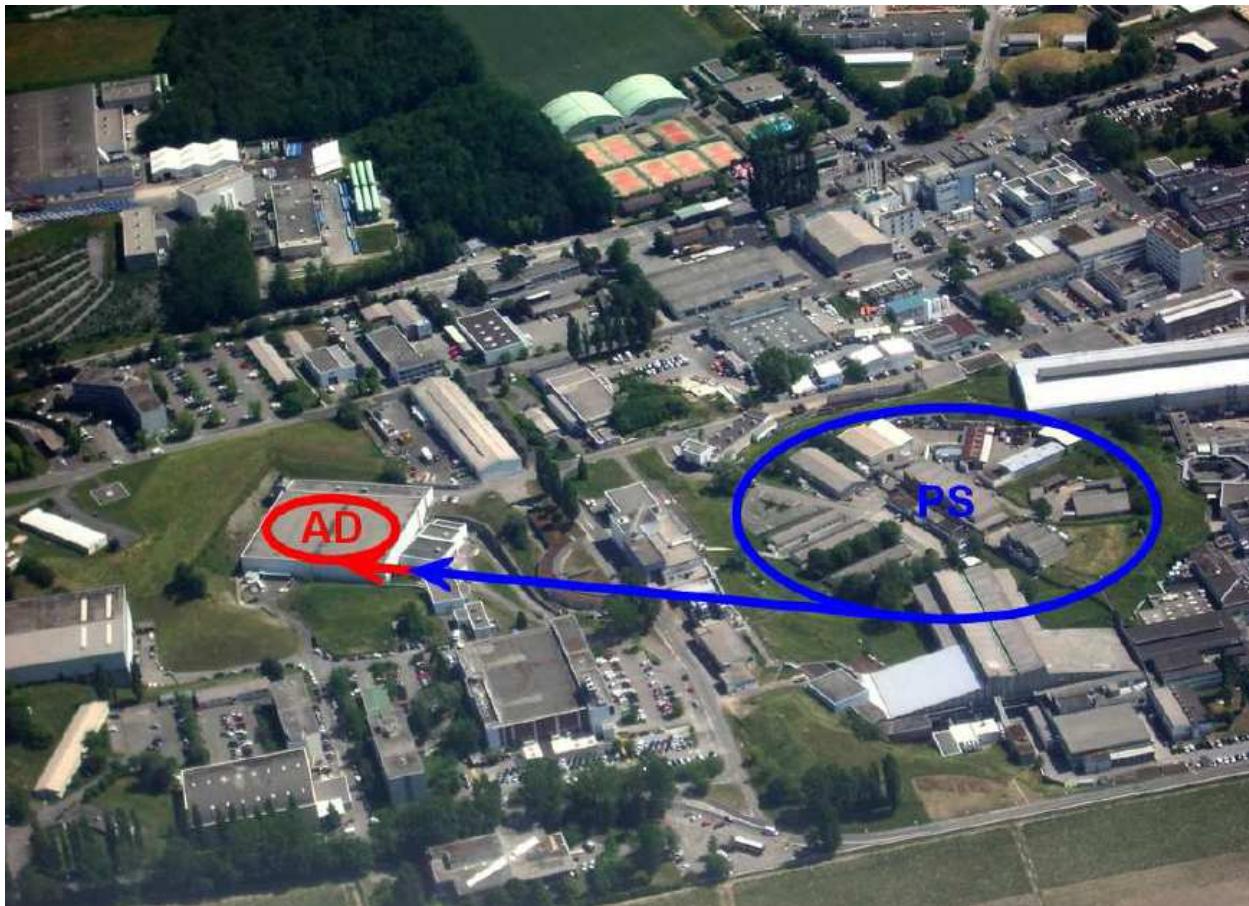
# Antimatter factory at CERN



# The Antiproton Decelerator at CERN

was built in 1997-99 to study antimatter physics

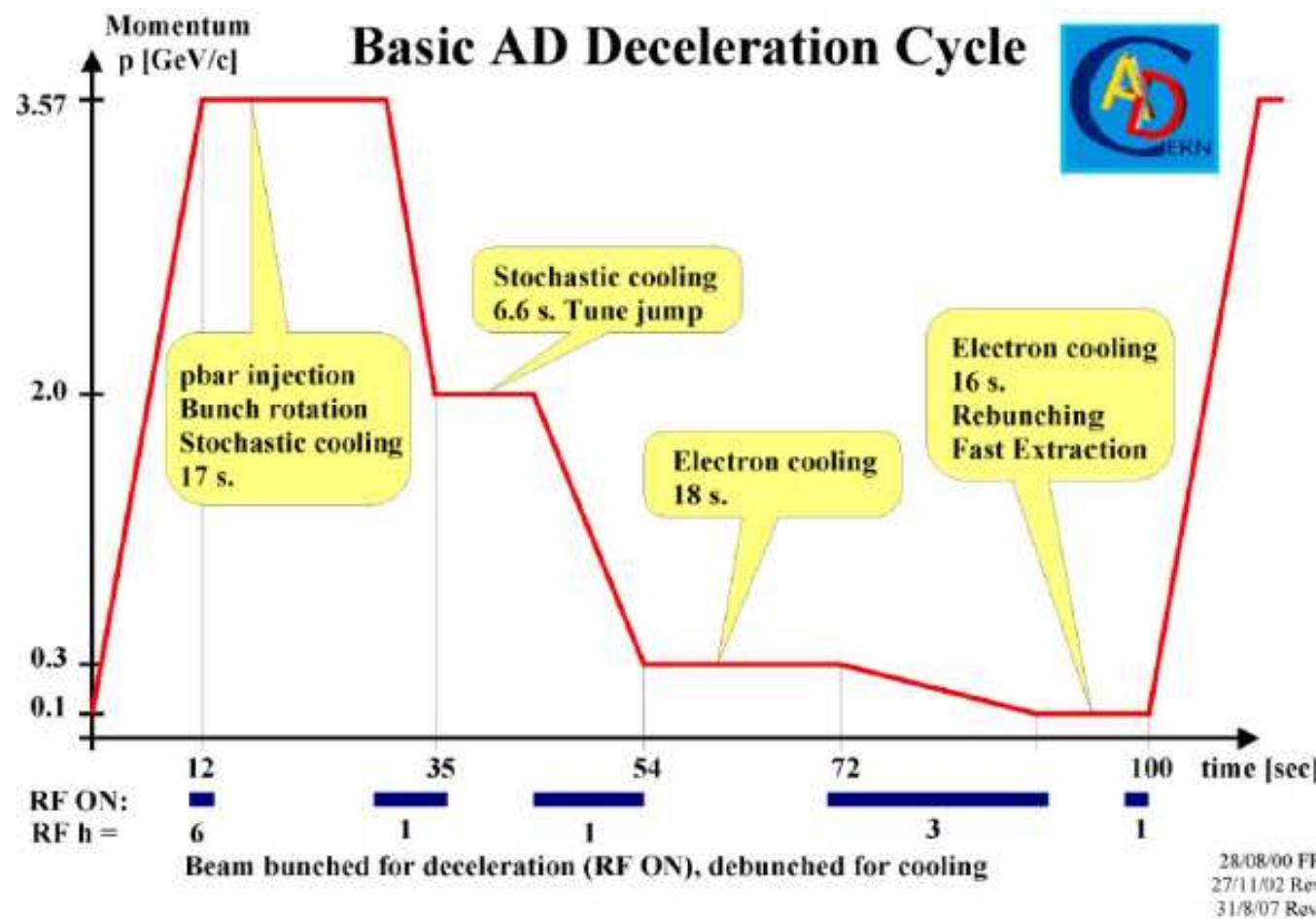
6 expts (3 each) for *CPT* and antigravity



©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

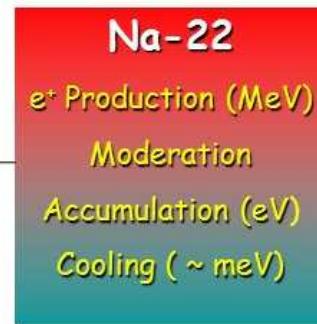
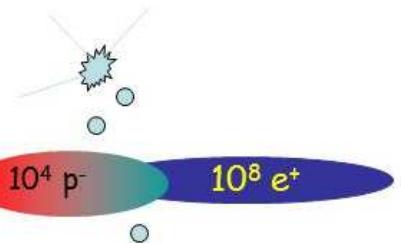
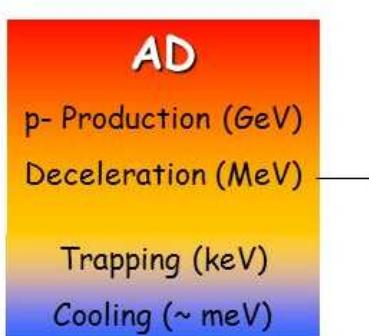


# Antiproton production



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

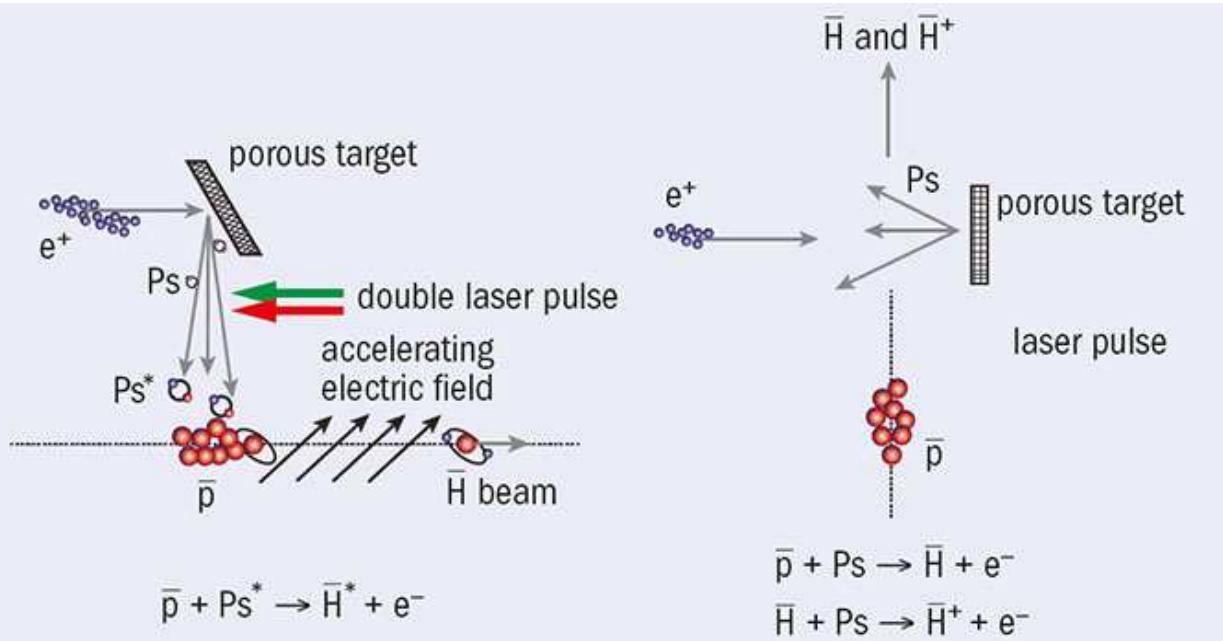
# How to produce antihydrogen?



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 $\bar{\text{H}}$ atoms at AD

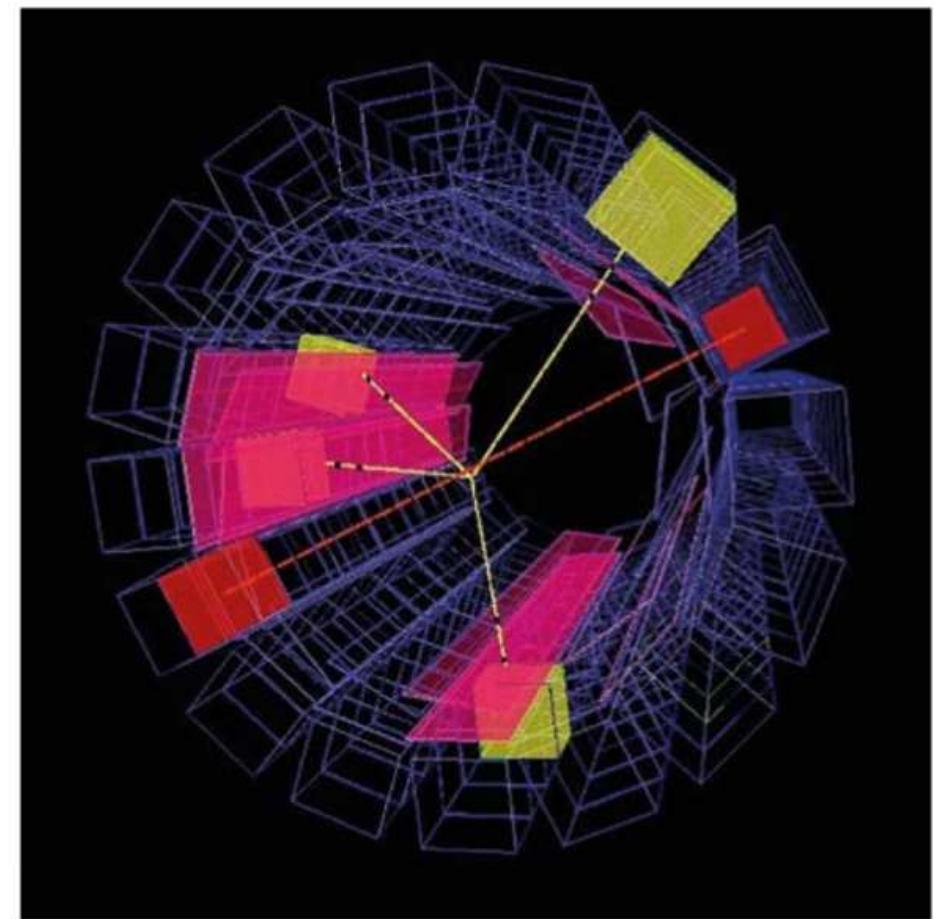
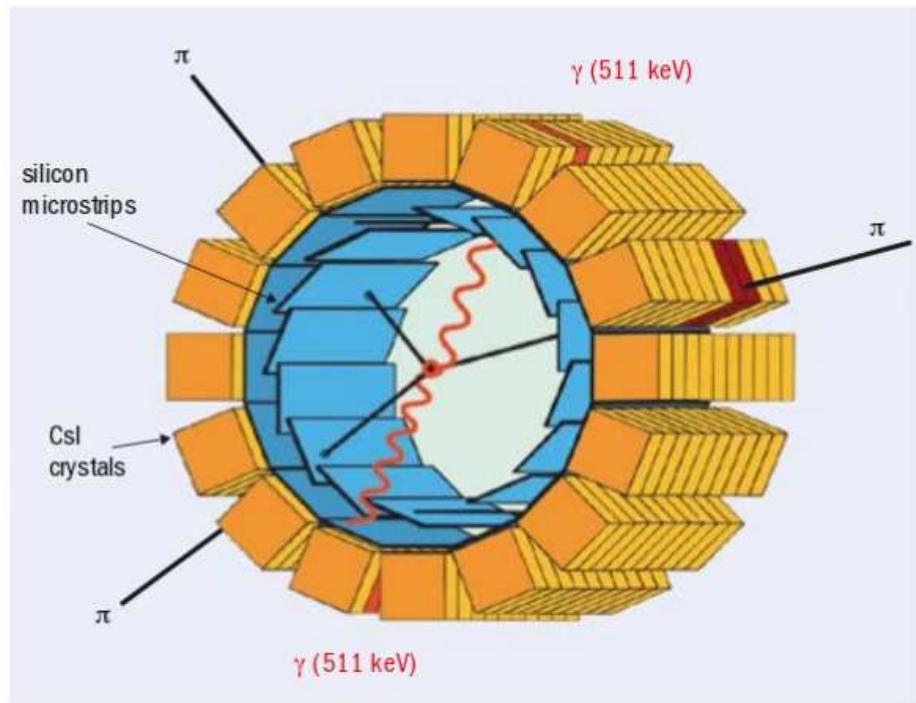


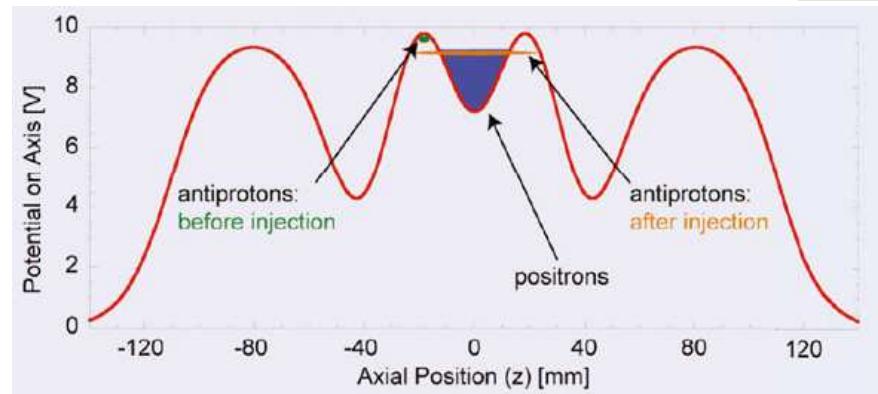
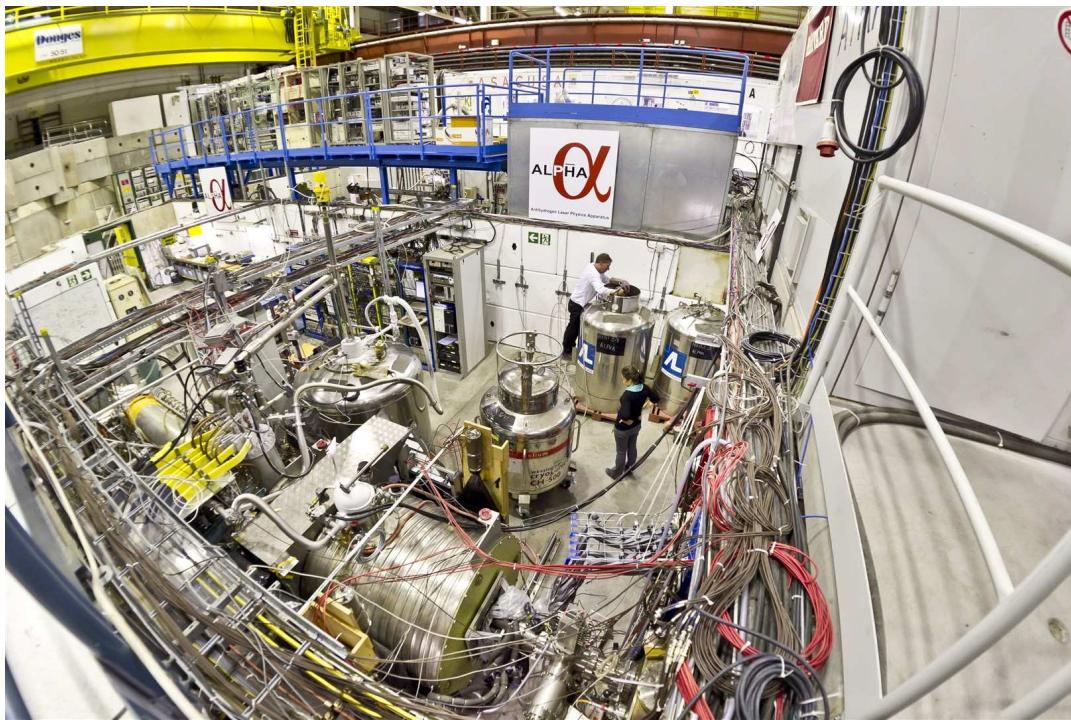
Fig.5. Above: A diagram of the ATHENA antihydrogen detector.  
Right: An antihydrogen annihilation event in ATHENA,  
reconstructing four charged pions (yellow) and two 511 keV  
photons (red). (Image credits: ATHENA Collaboration.)

ATHENA Collaboration (1997 – 2005)  $\Rightarrow$  ALPHA Collaboration



# ALPHA: $\bar{H}$ production

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



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

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

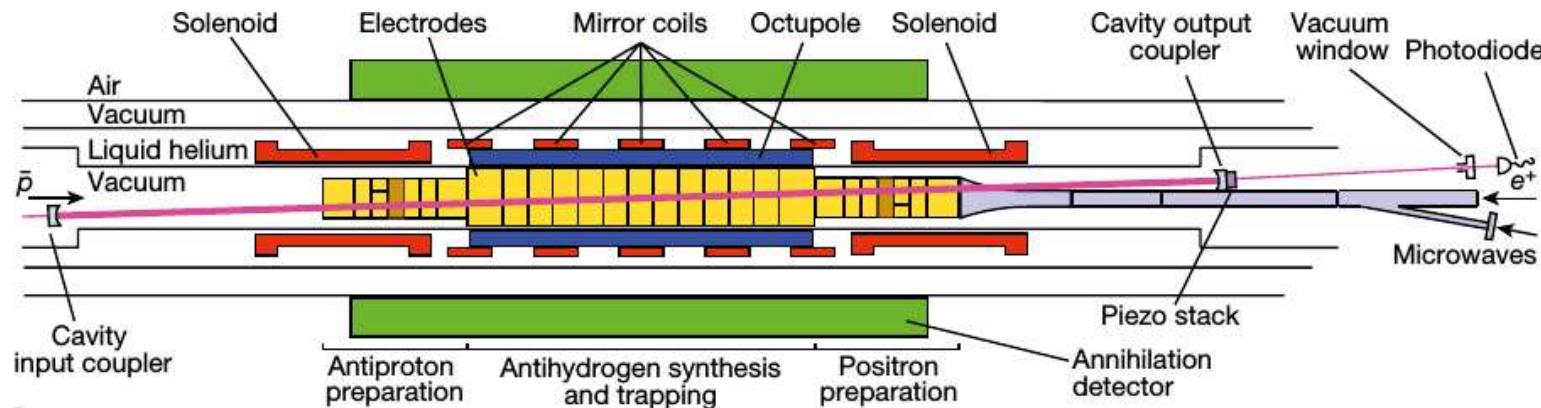
Demonstrated by keeping  $\bar{H}$  for >60 hours.

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

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



# ALPHA: $\bar{H}$ $1S - 2S$ transition



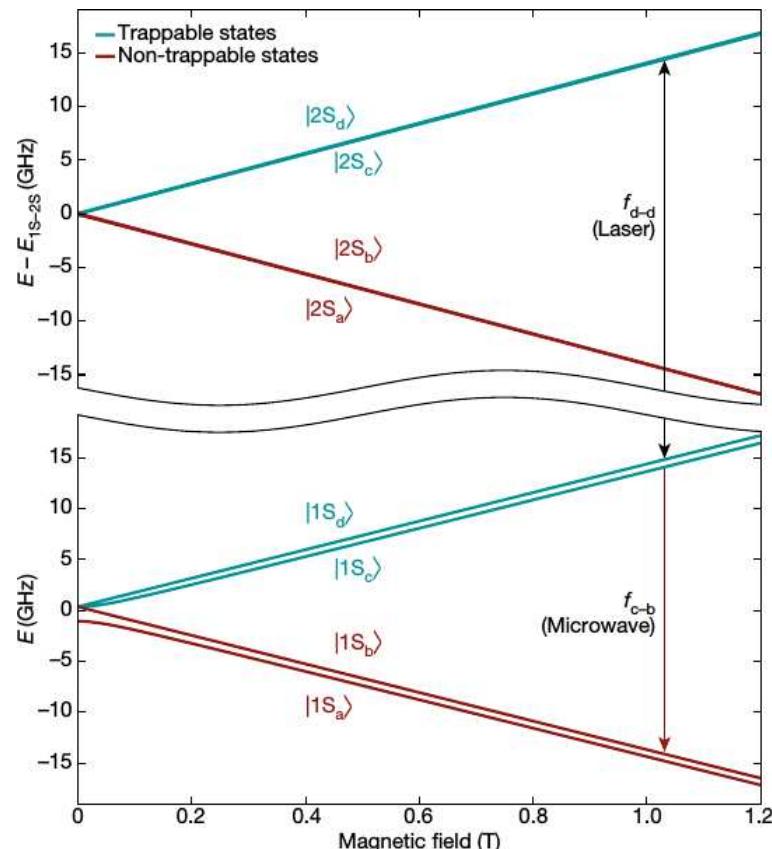
Measure annihilation rates.

Wait for 10 s to reach  $\bar{H}(1S)$  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: $\bar{H}$ $1S - 2S$ spectroscopy

Result using 15000  $\bar{H}$  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):  $2 \times 10^{-12}$

ALPHA Coll.,

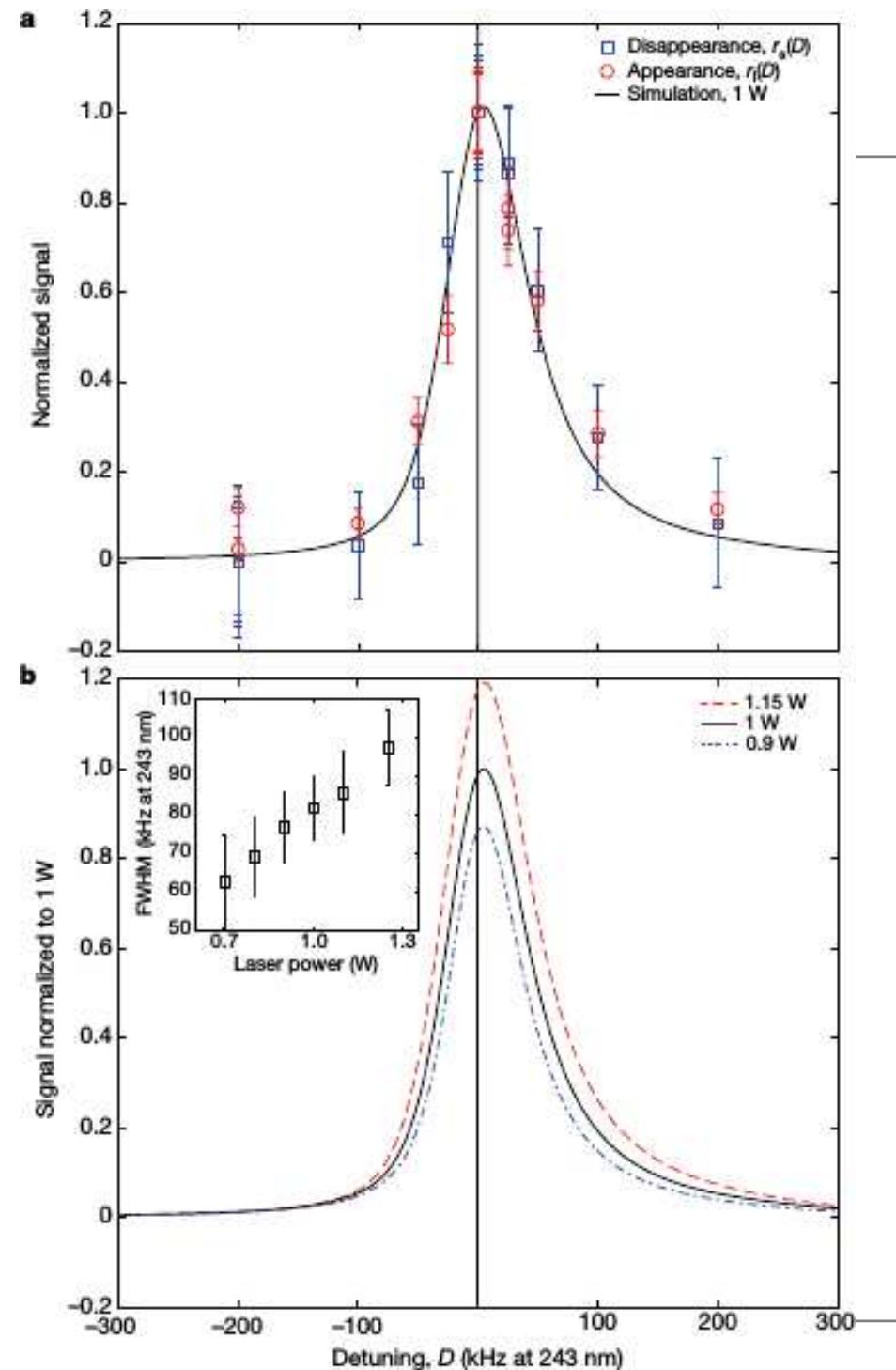
*Observation of the  $1S-2S$  transition in trapped antihydrogen,*

**Nature** 541 (2017) 506.

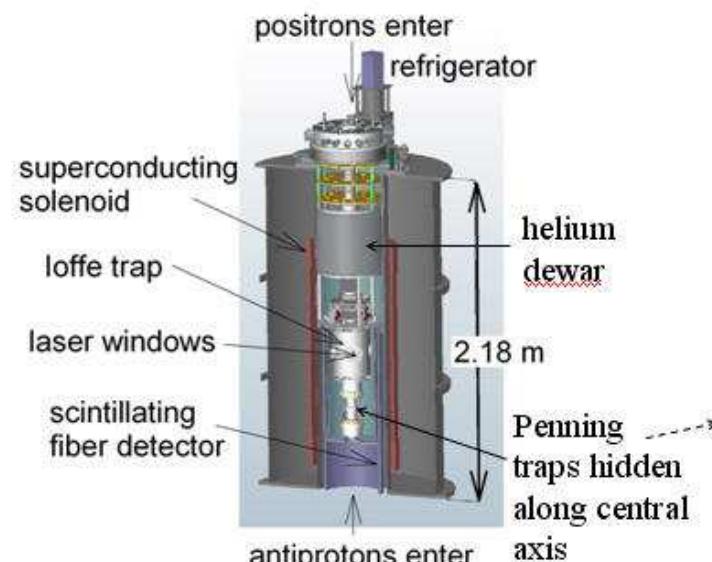
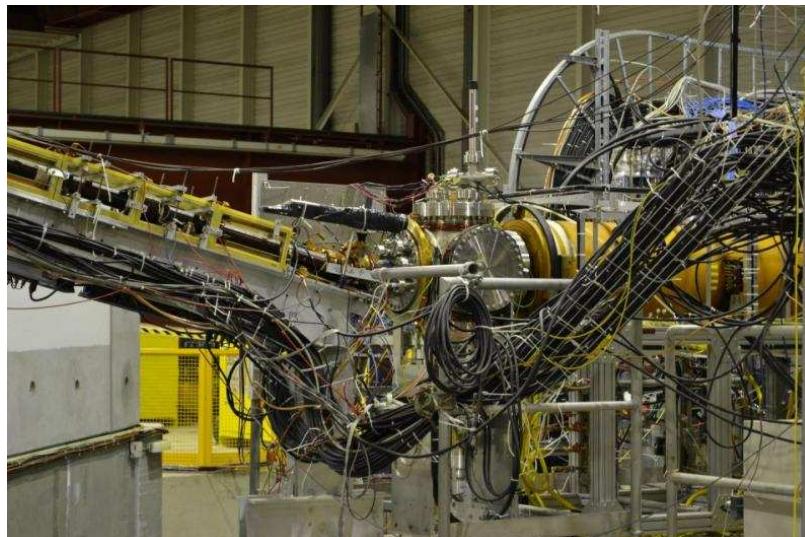
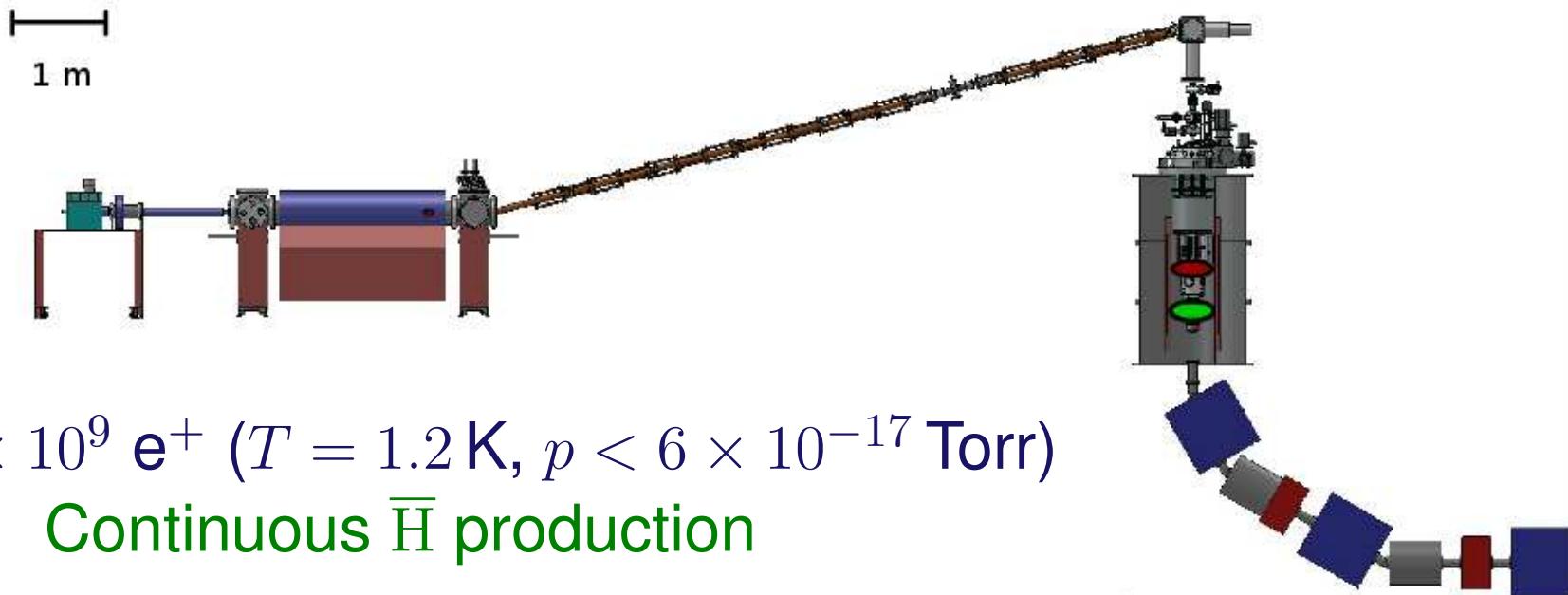
ALPHA Coll.,

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

**Nature** 557 (2018) 74.



# ATRAP: Antimatter trap



# Antimatter gravity



I read a book on anti-gravity



I couldn't put it down!

Negative mass  $\Rightarrow$  repulsive gravity??

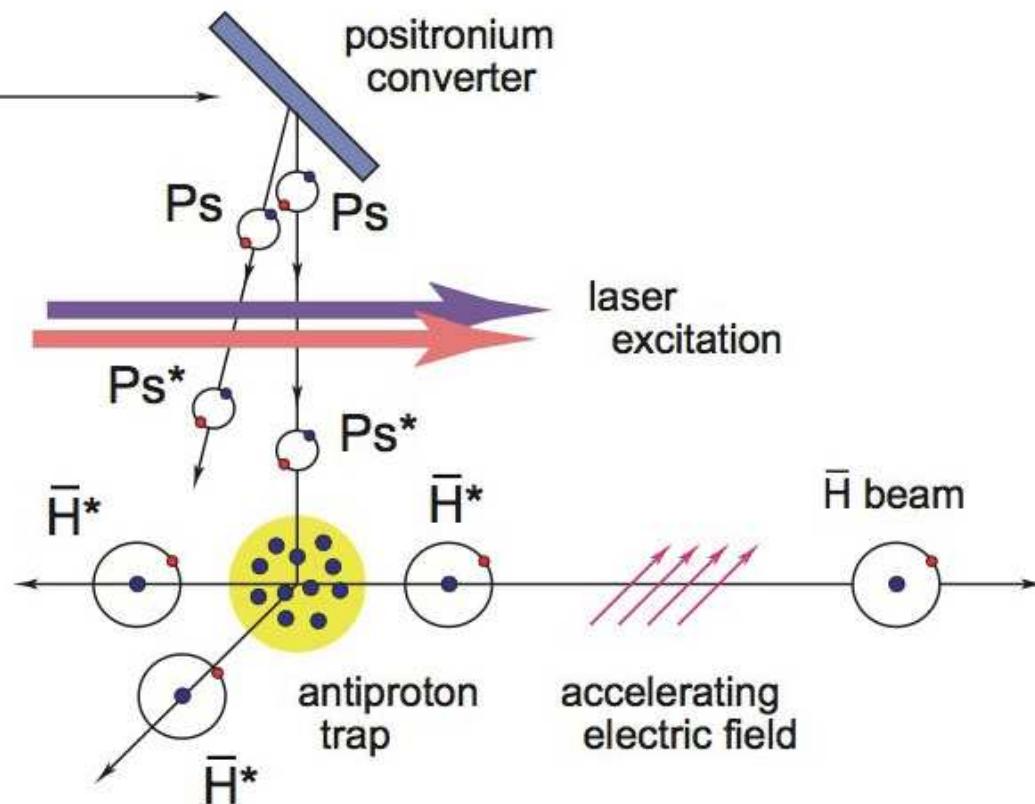
95 % of nucleon mass is energy, small grav. diff. between H and  $\bar{H}$

Not *CPT*: weak equivalence principle

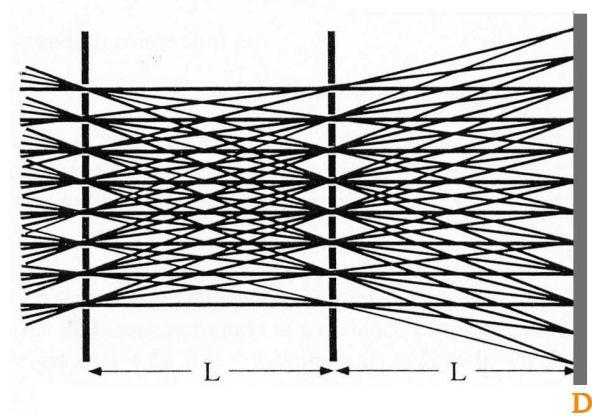


# AEGIS: antimatter gravity

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



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

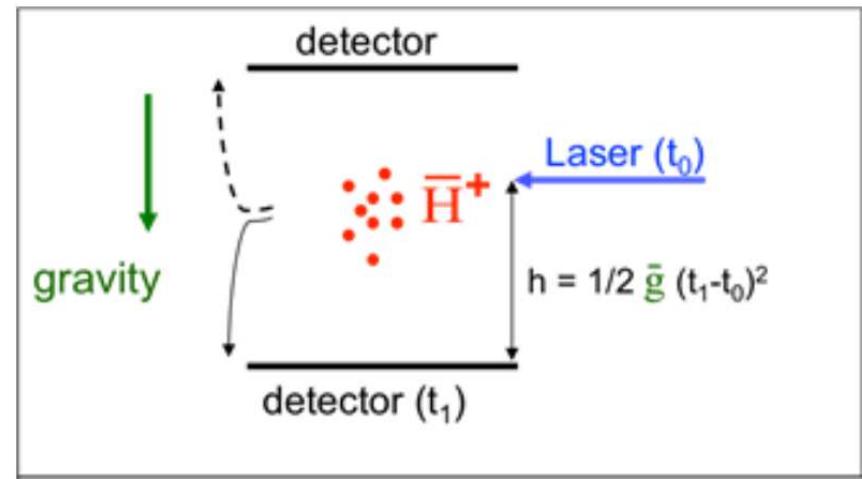
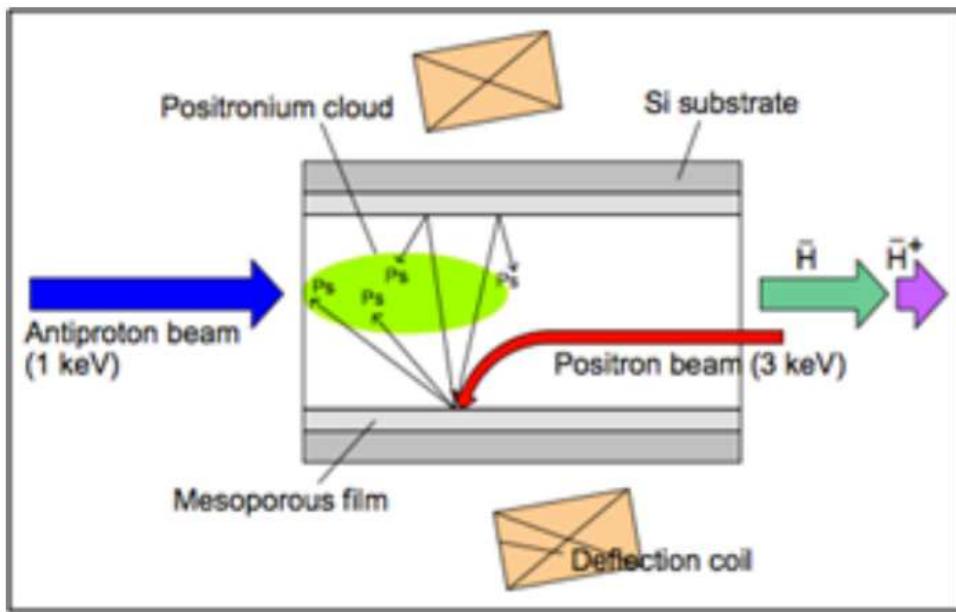


Stark acceleration (electric dipole in inhom. E-field) of  
excited  $\bar{H}$



# GBAR

## Gravitational Behaviour of Antihydrogen at Rest (in preparation)

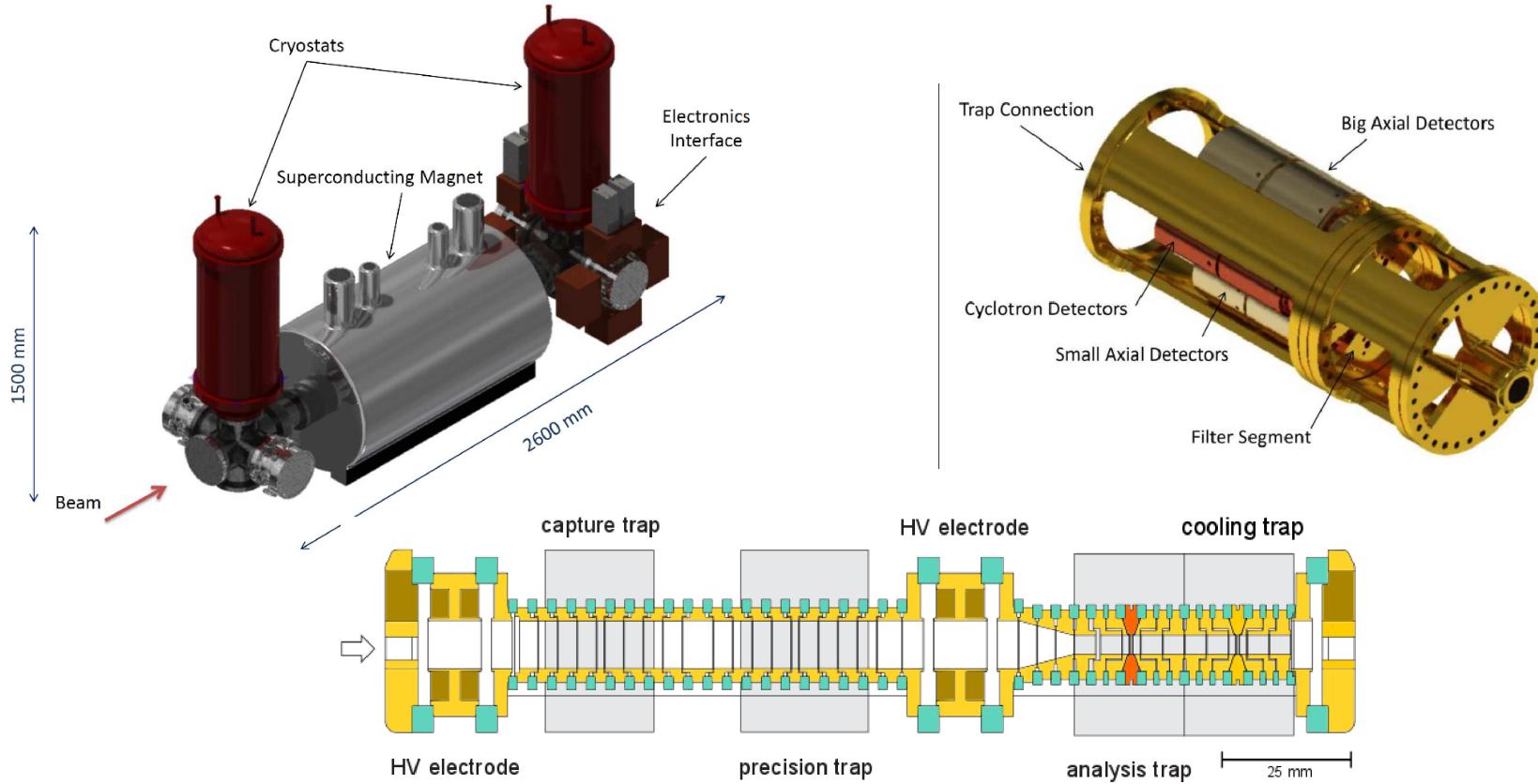


$\bar{p} + \text{Ps} \rightarrow \bar{H}; \bar{H} + \text{Ps} \rightarrow \bar{H}^+ \text{ (cooling); back to } \bar{H}: \text{ let it fall}$



# BASE: Baryon Antibaryon Symmetry Experiment

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



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

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  $\sim$  1640

5.8 MeV  $\bar{p}$  injected into RFQ

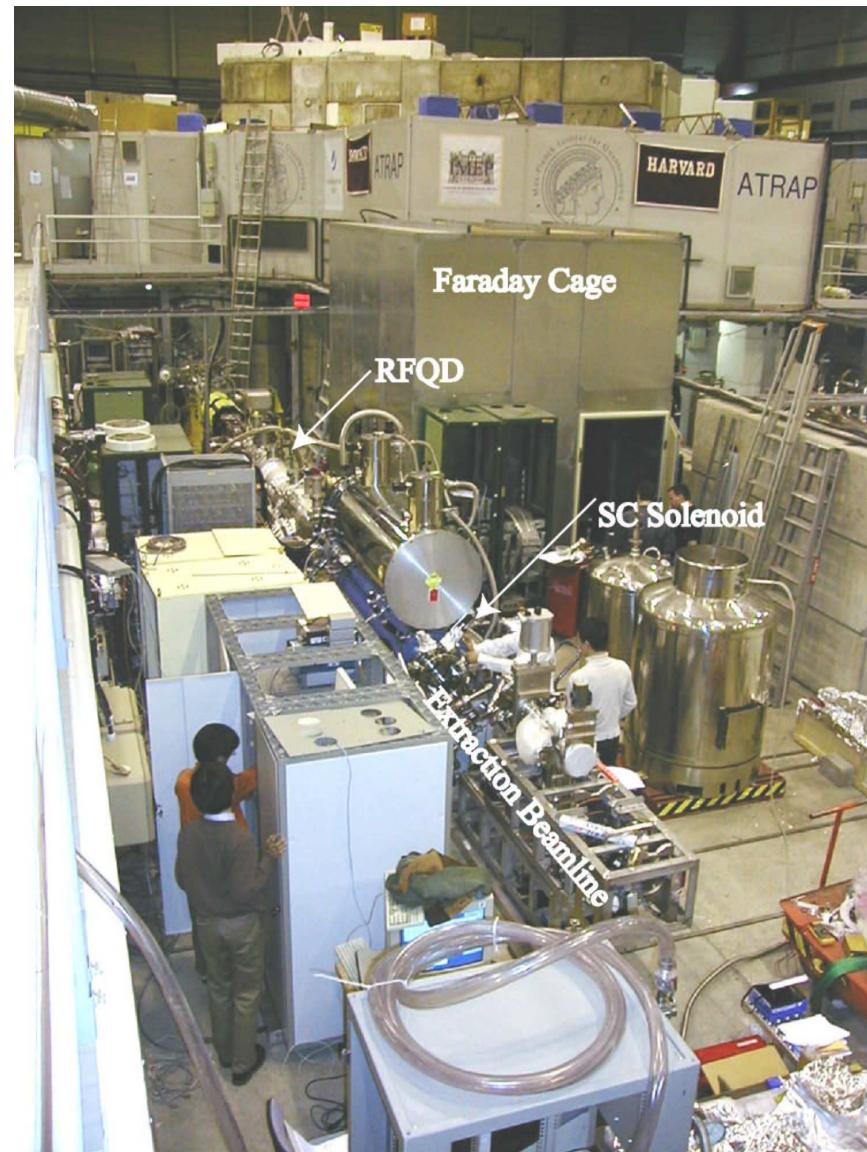
100 keV  $\bar{p}$  injected into trap

$10^6 \bar{p}$  trapped and cooled (2002)

$\sim 350000$  slow  $\bar{p}$  extracted (2004)

Cold  $\bar{p}$  compressed in trap (2008)

$(5 \times 10^5 \bar{p}, E = 0.3 \text{ eV}, R = 0.25 \text{ mm})$

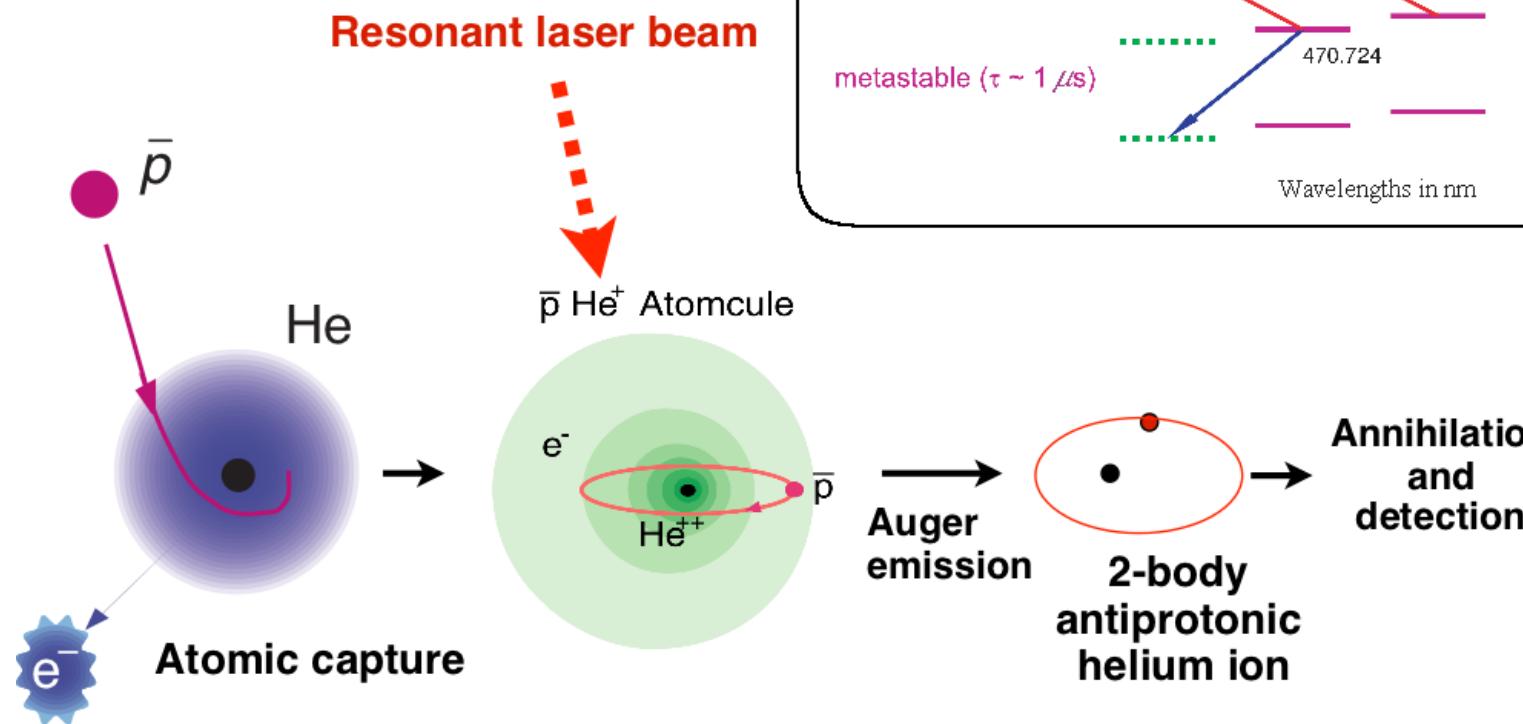


N. Kuroda *et al.*, Nature Commun. 5 (2014) 3089.

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

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

Laser spectroscopy of antiprotonic helium



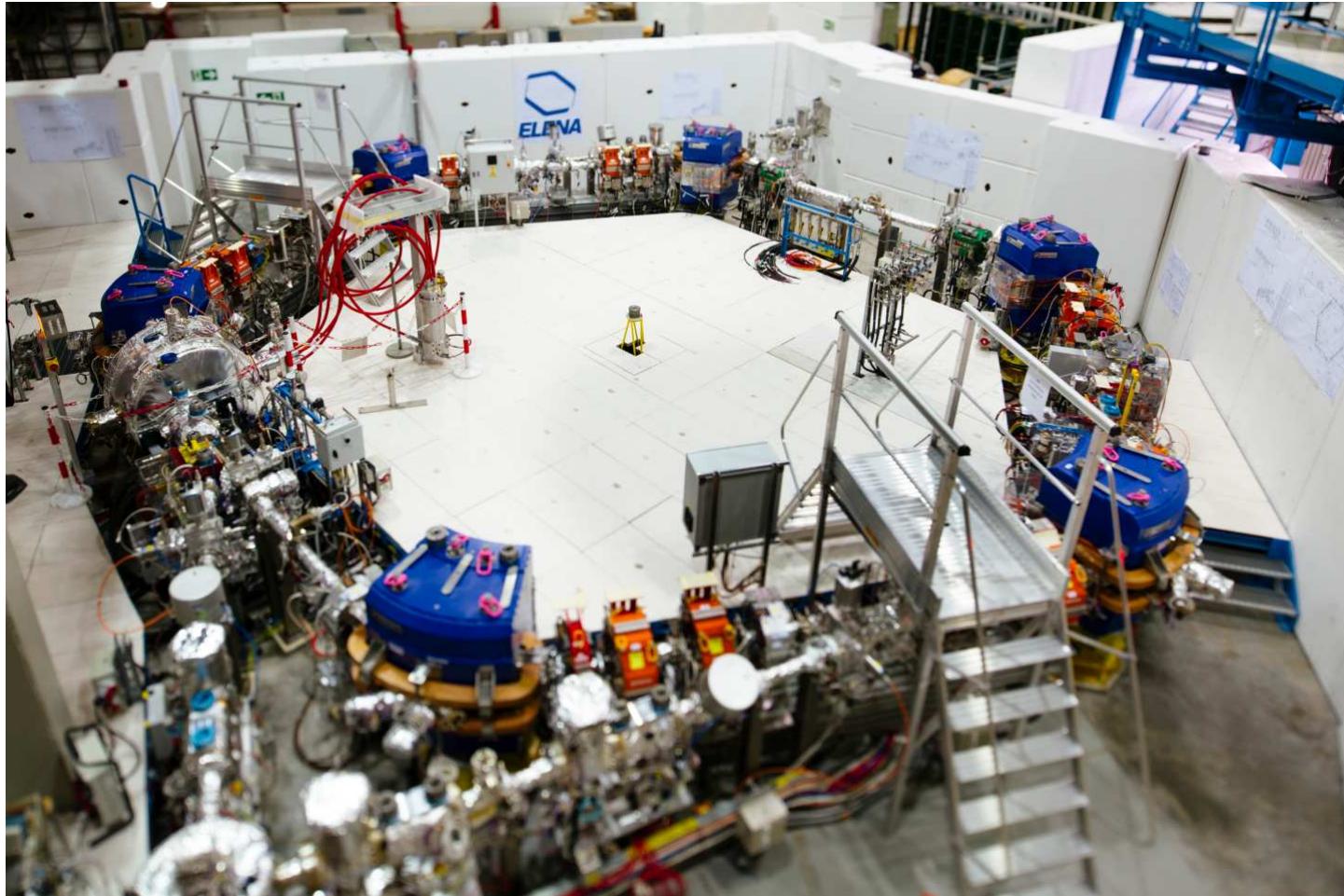
Transition between long- and short-lived states  $\Rightarrow$  prompt annihilation

Theory: Vladimir Korobov (Dubna)  $\Rightarrow \Delta M_{\bar{p}} \sim 10^{-12}$



# Extra Low ENergy Antiprotons (ELENA)

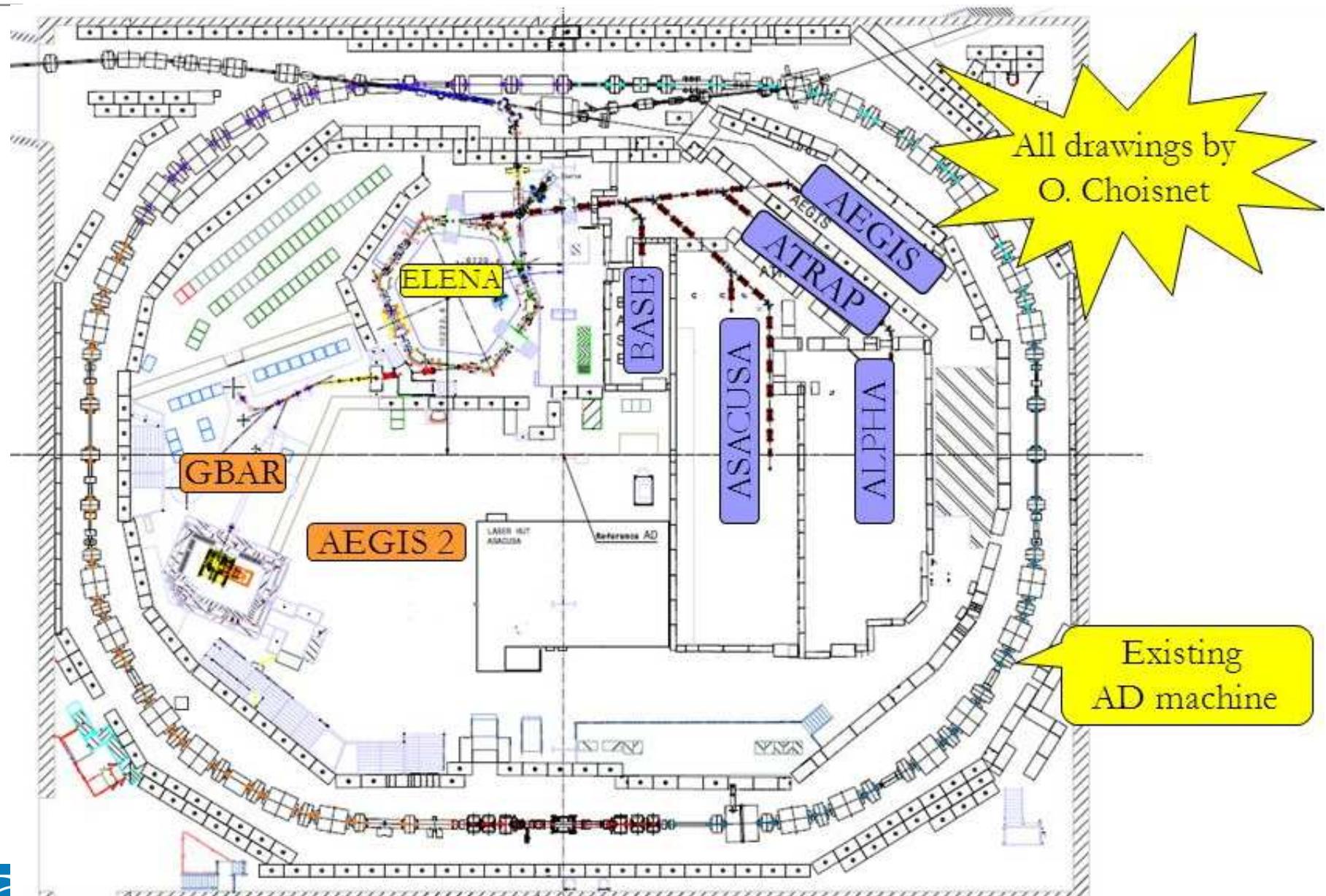
New deceleration ring at CERN: 100 keV  $\bar{p}$  for trapping



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



# ELENA at the AD: plan



F. Butin / ELENA collaboration, 2017.

Dezső Horváth: CPT Tests at CERN

NewHEP, Odessa, 13 May 2019 – p. 27

# 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\$

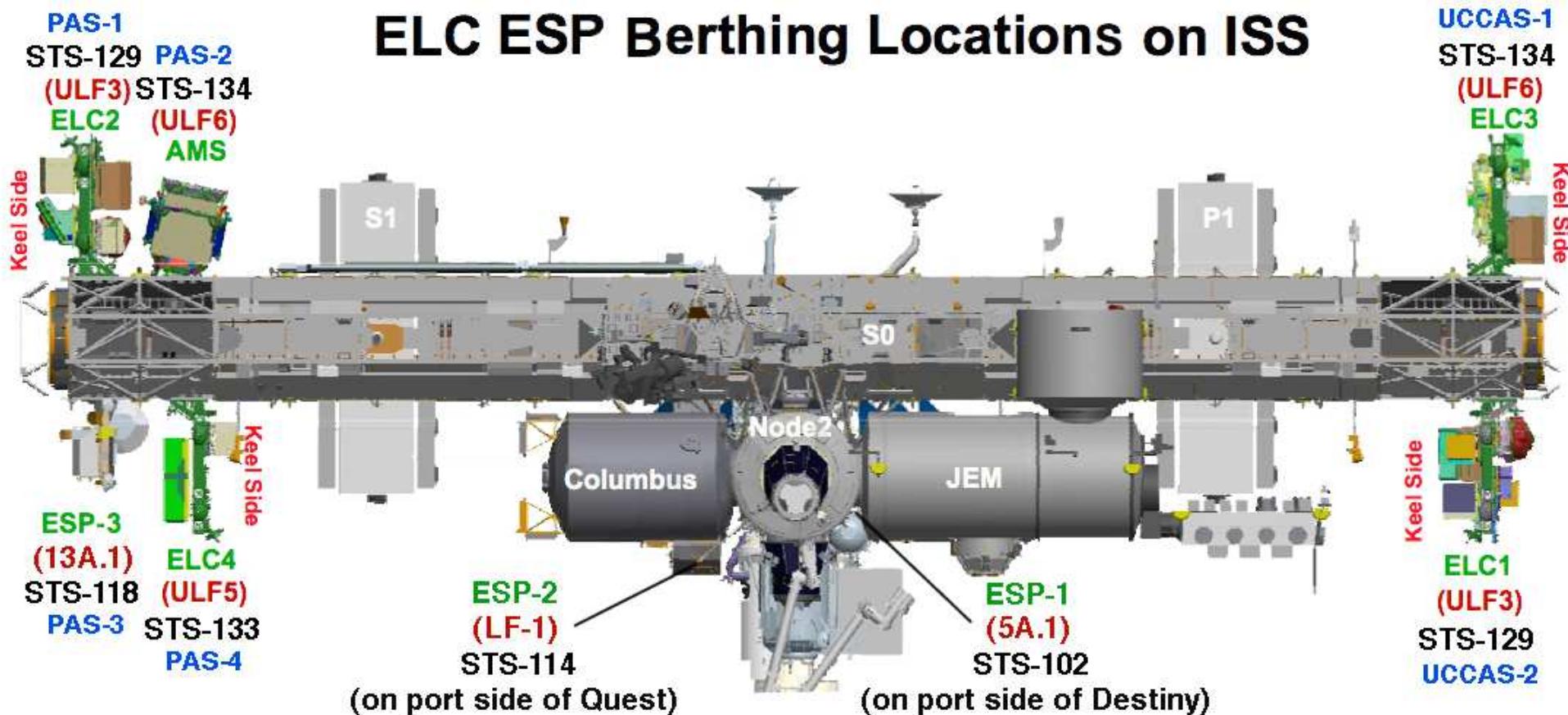
Construction: CERN

Launch: May 2011, USA

Control room: CERN



# AMS-2: Alpha Magnetic Spectrometer



First results (2015):

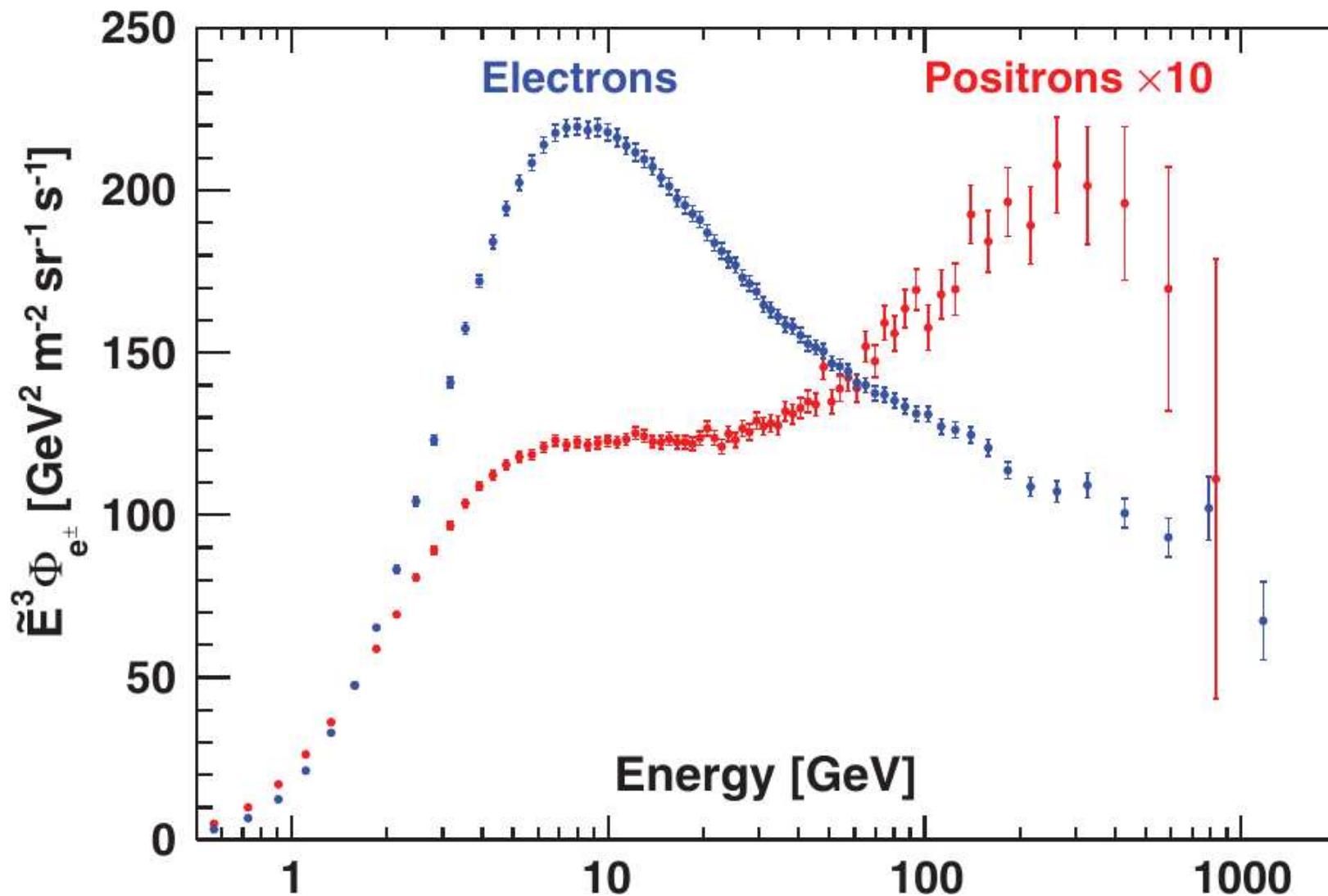
No antihelium observed.

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



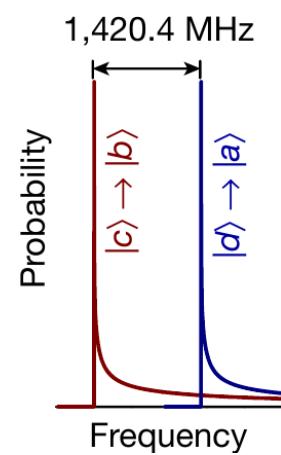
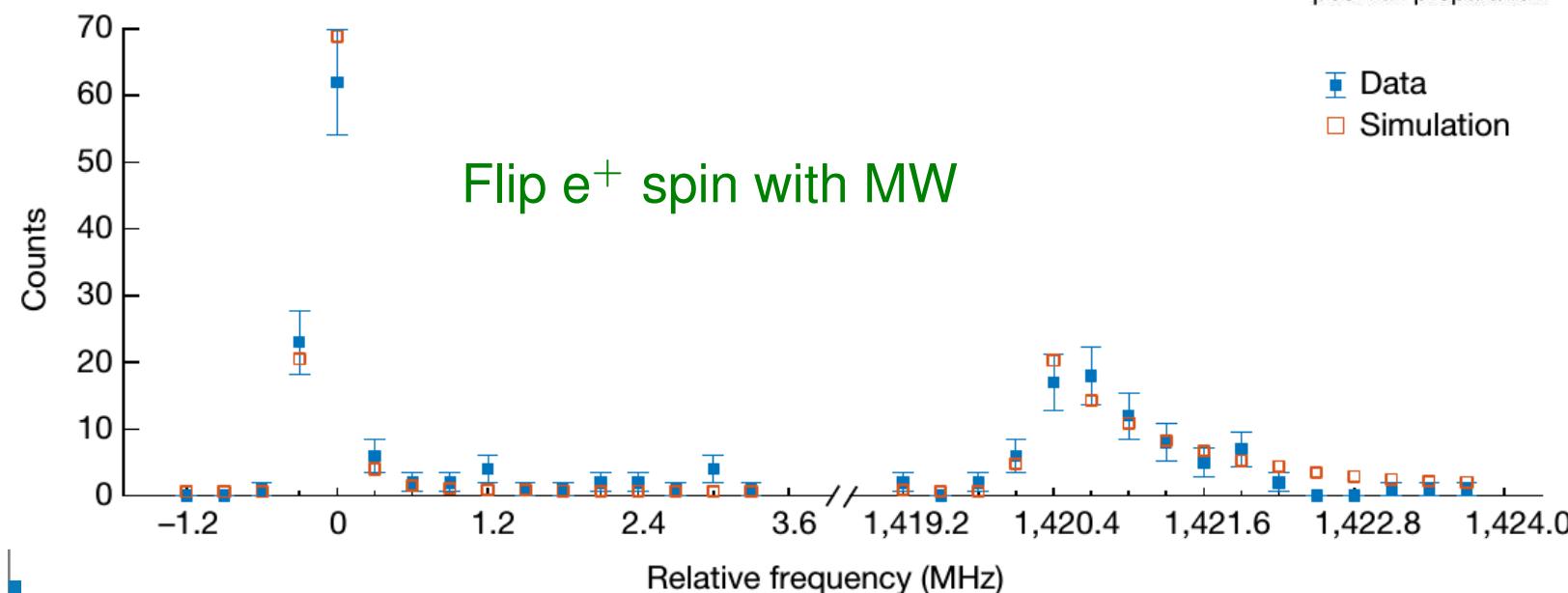
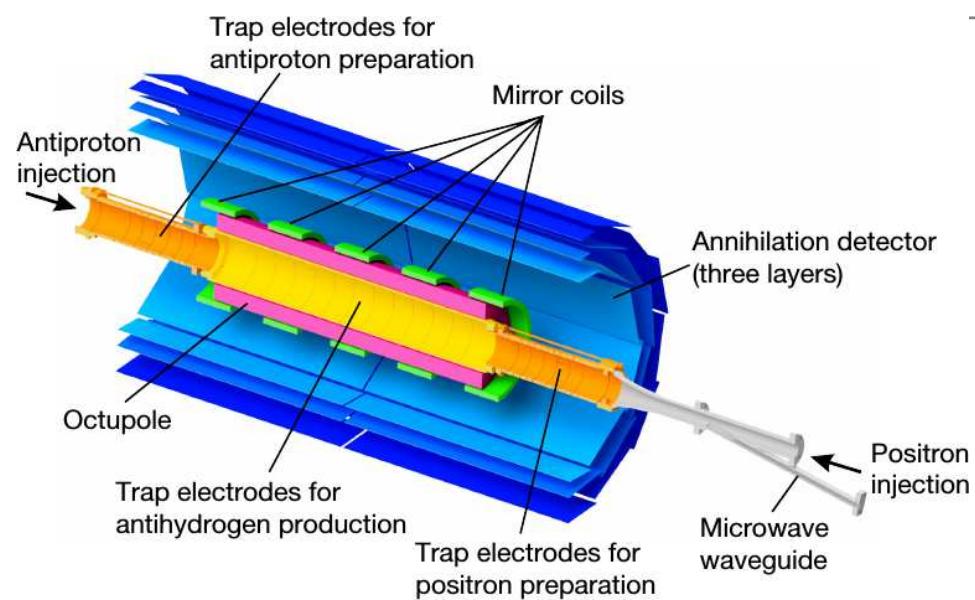
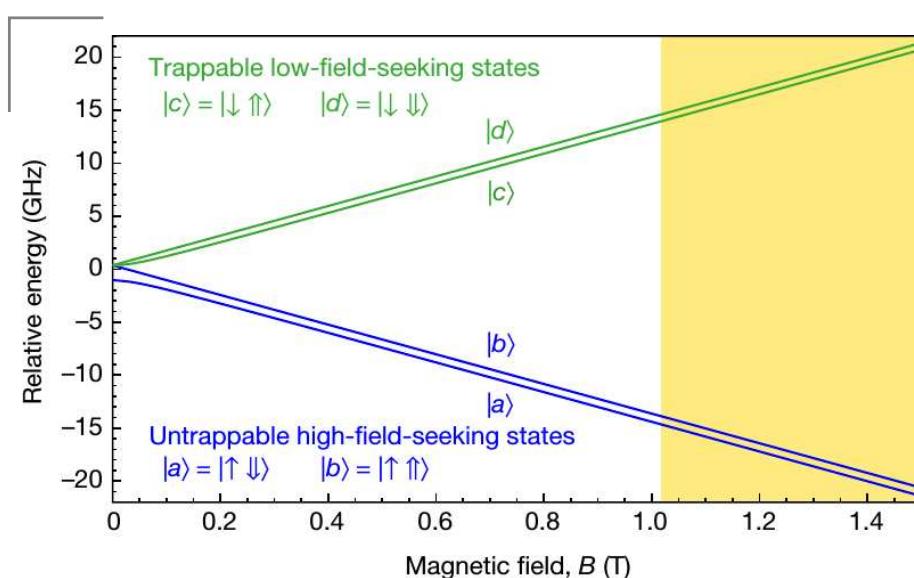
# Steps toward $\bar{H}$ spectroscopy

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

2017: done by the ALPHA Collaboration!



# ALPHA: $\bar{H}$ hyperfine spectrum



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

# ALPHA: $\bar{\text{H}}$ $1S - 2S$ transition

ALPHA Collaboration (49 authors),

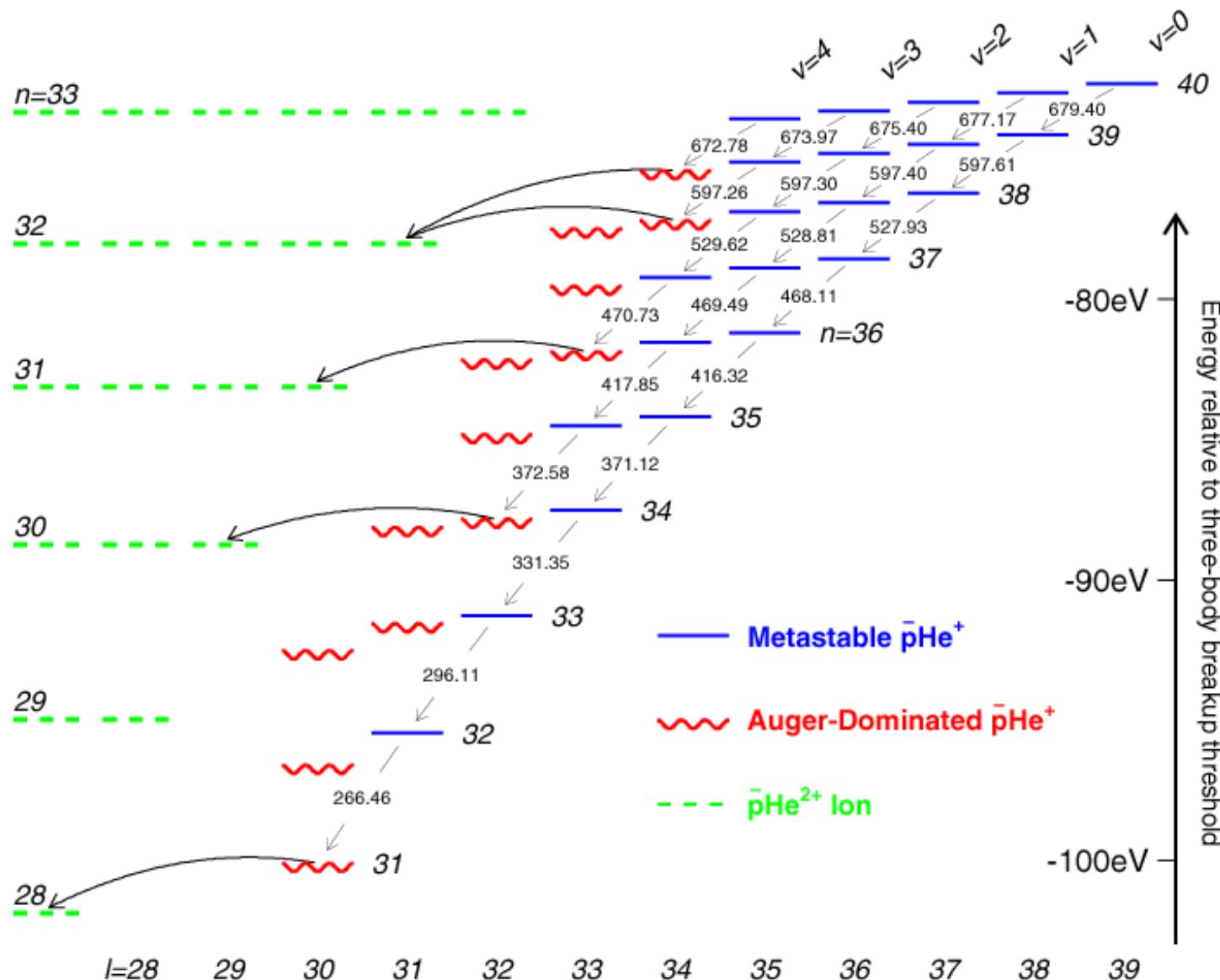
*Characterization of the  $1S$ - $2S$  transition in antihydrogen,  
Nature* 557 (2018) 74.

**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.



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



Level energies in eV, transition wavelengths in nm

# MUSASHI: slow antiproton beam



Monoenergetic  
Ultra  
Slow  
Antiproton  
Source for  
High-precision  
Investigations

Musashi Miyamoto self-portrait  $\sim$  1640

5.8 MeV  $\bar{p}$  injected into RFQ

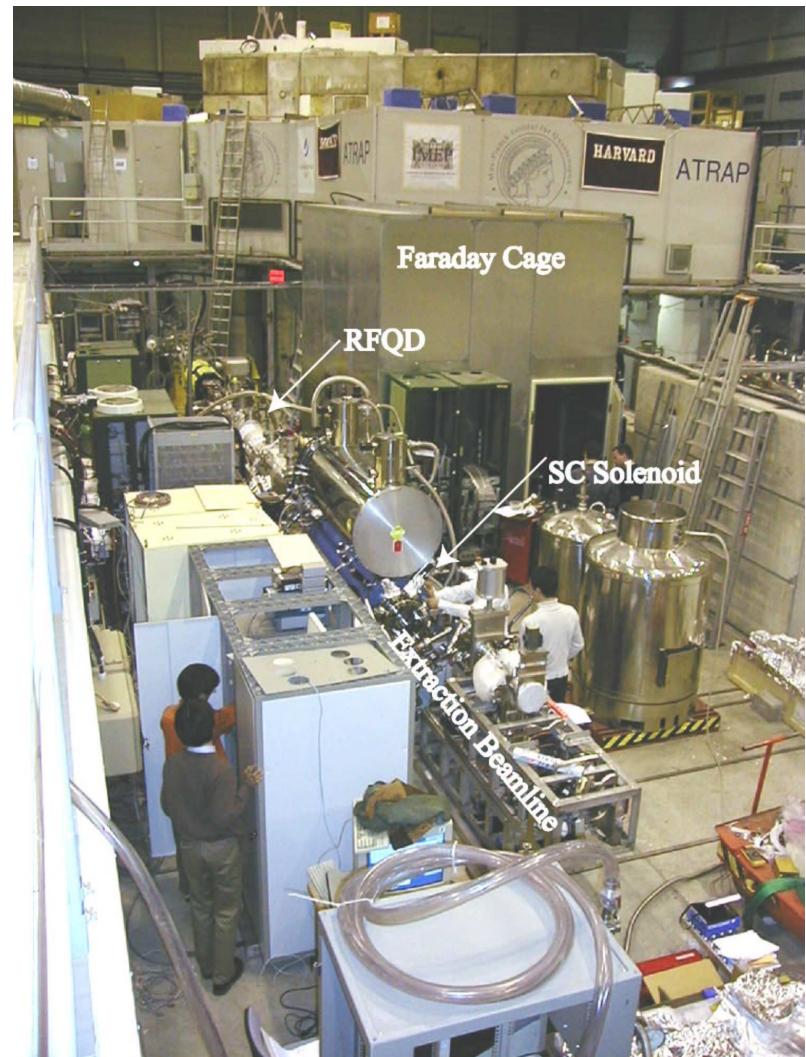
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$(5 \times 10^5 \bar{p}, E = 0.3 \text{ eV}, R = 0.25 \text{ mm})$



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<sup>+</sup> and the antiproton-to-electron mass ratio*, Nature 475 (2011) 484-488,  
Few Body Syst. 54 (2013) 917-922.



# Two-photon spectroscopy: parameters

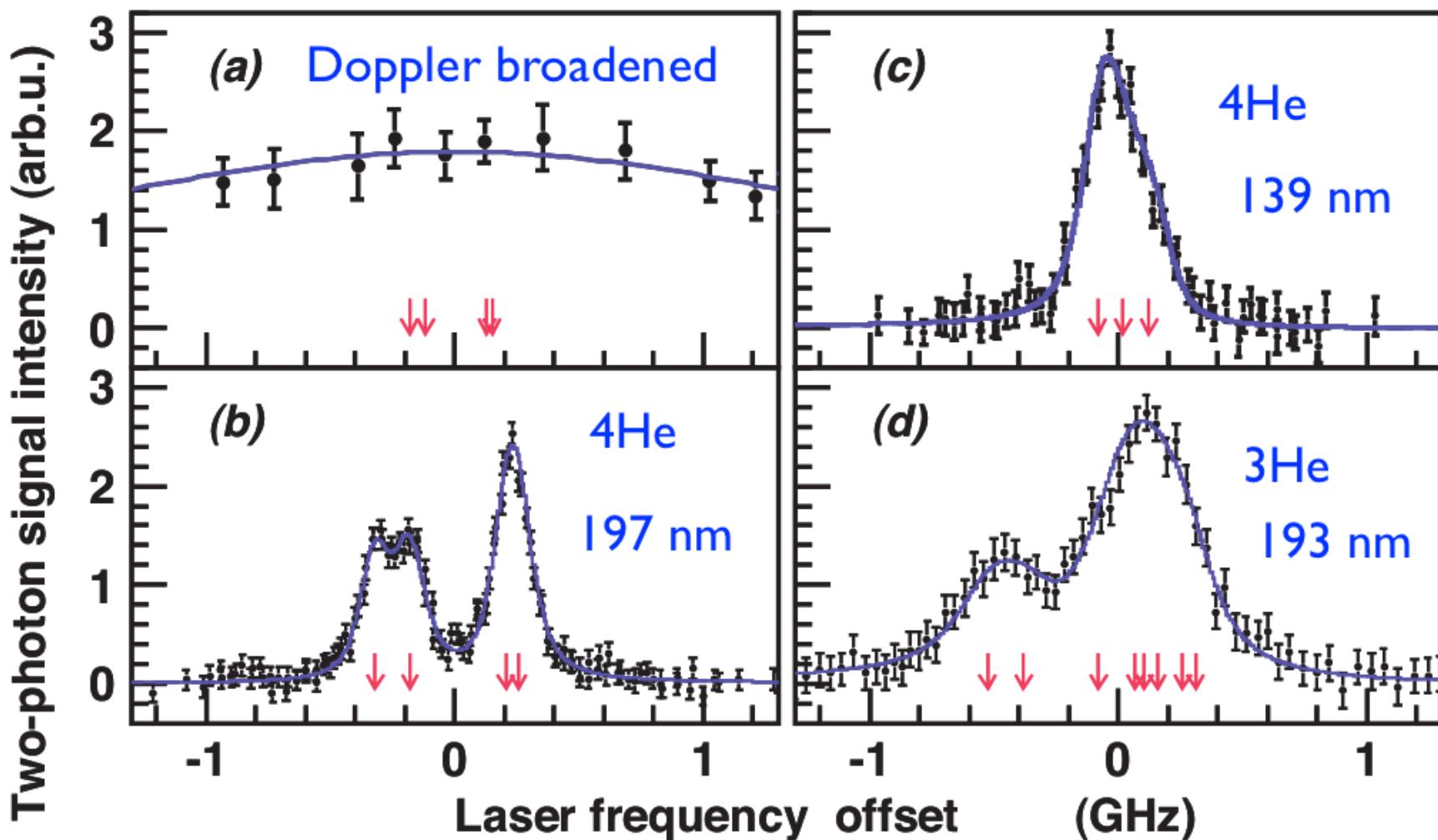
- Precision of lasers:  $< 1.4 \times 10^{-9}$ .
- $7 \times 10^6 \bar{p}/\text{pulse}$ ,  $E \approx 70 \text{ keV}$ , 200 ns long, Ø20 mm.
- Target: He gas,  $T \approx 15 \text{ K}$ ,  $p = 0.8 - 3 \text{ mbar}$
- Laser beams:  $\lambda_1 = 417 \text{ nm}$ ,  $\lambda_2 = 372 \text{ nm}$ ,  $P \approx 1 \text{ mJ/cm}^2$
- Transition: (n=36, l=34)  $\rightarrow$  (n=34, l=32);  $\Delta\nu = 6 \text{ GHz}$
- Measured linewidth:  $\approx 200 \text{ MHz}$
- 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<sup>+</sup> and the antiproton-to-electron mass ratio”

Nature 475 (2011) 484-488



# Two-photon spectroscopy: spectra

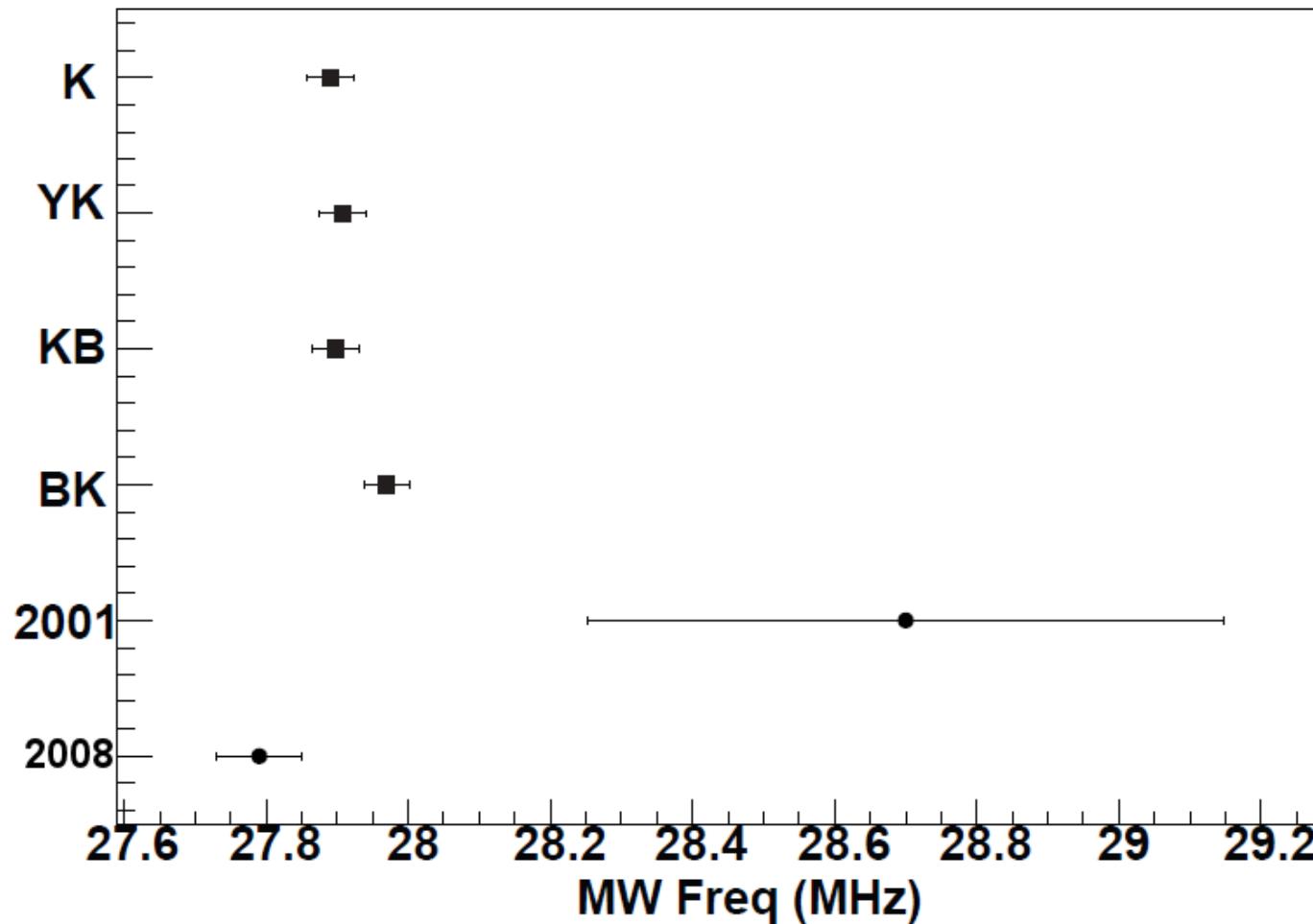


M. Hori et al., Nature 475 (2011) 484-488

Arrows: hyperfine transitions



# $\bar{p}^4\text{He}$ HF structure: expt vs. theory

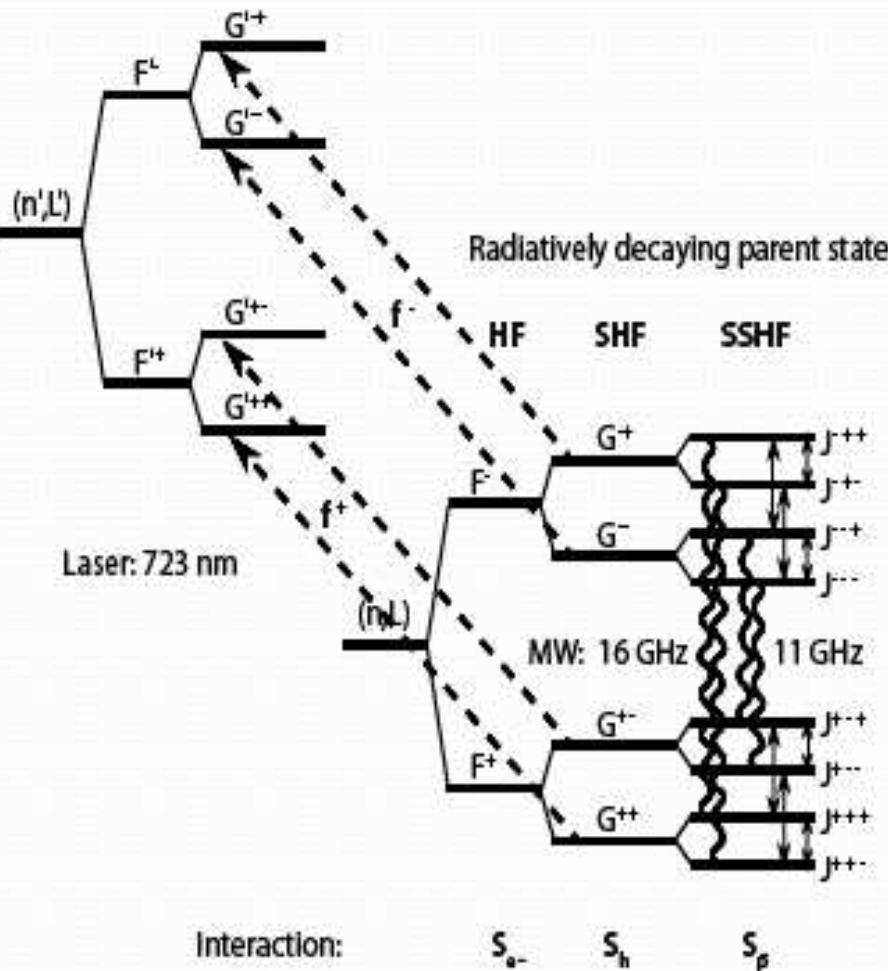


Th. Pask et al., Phys. Lett. B 678 (2009) 55.

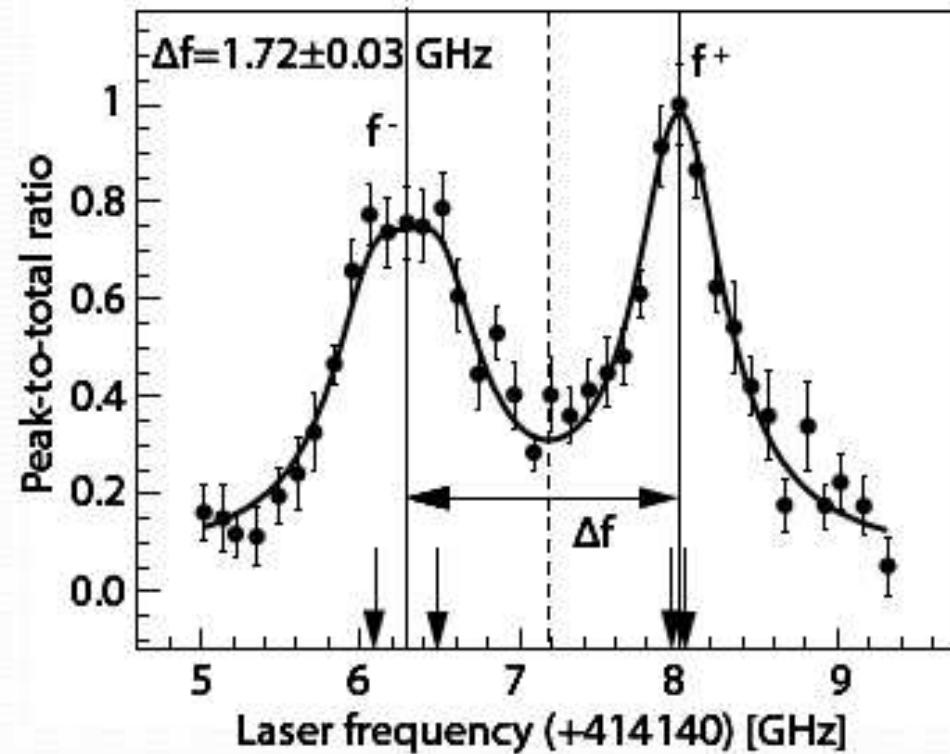


# $\overline{p}^3\text{He}$ HF structure: laser scan

Auger decaying daughter state



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



- fit with 4 Voigt functions plus constant for signal background

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

