Report on Tests of CPT Invariance at CERN

Zimányi School'23, Wigner RCP, 04.12.2023

Dezső Horváth

horvath.dezso@wigner.hu

Wigner Research Centre for Physics,
Institute for Particle and Nuclear Physics, Budapest, Hungary
&
STAR, University Babeș–Bolyai, Cluj–Napoca, Romania

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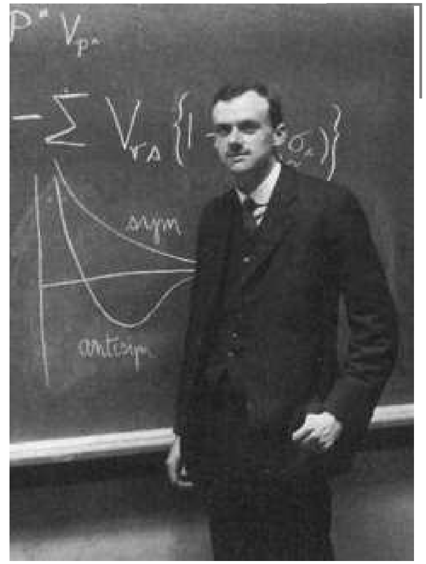
Outline

- Antimatter and its lack in the Universe
- CPT invariance: matter–antimatter symmetry
- Antiparticles vs. particles in the standard model
- Antimatter experiments at CERN
- Antimatter in space

Birth of antimatter

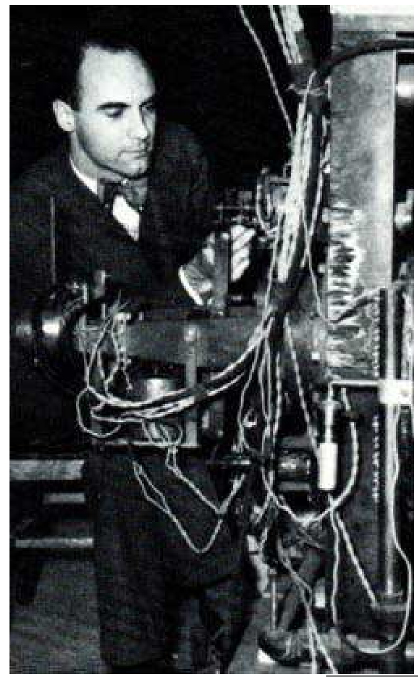


Paul Dirac, 1928: Linear equation for the hydrogen atom.

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

- $+$ 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

Richard P. Feynman: When I was a young man, Dirac was my hero. He made a breakthrough, a new method of doing physics. He had the courage to simply guess at the form of an equation, the equation we now call the Dirac equation, and to try to interpret it afterwards.

Matter–antimatter symmetry

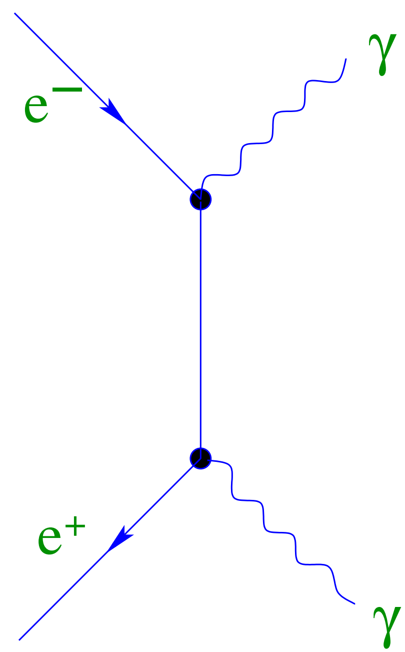
CPT invariance	Charge conjugation:	$C\|\mathrm{p}(r,t)\rangle = \|\overline{\mathrm{p}}(r,t)\rangle$
	Space reflection:	$P\|\mathrm{p}(r,t)\rangle = \|\mathrm{p}(-r,t)\rangle$
	Time reversal:	$T\|\mathrm{p}(r,t)\rangle = \|\mathrm{p}(r,-t)\rangle K$

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

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

What does CPT really state?

Equivalence for **free** particles and antiparticles.

Interactions?

- Gravity is OK as long as masses are equal (so far they are).
- Strong (QCD) is OK as colours and anticolours are attracting the same way.
- Electromagnetism is confused by the repulsion of identical charges, but even there the charges can be switched.
- Weak interaction is problematic as usual.

D. Horváth and Z. Trócsányi, *Particles and antiparticles*
arXiv:2304.10231, MPLA (in print)

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Fermions in the standard model

Particle = – antiparticle ? Not for the weak interaction!

	Family 1	Family 2	Family 3	Charge	T_3
Leptons	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{matrix} 0 \\ -1 \end{matrix}$	$\begin{matrix} +\frac{1}{2} \\ -\frac{1}{2} \end{matrix}$
Quarks	$\begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$	$\begin{matrix} +\frac{2}{3} \\ -\frac{1}{3} \end{matrix}$	$\begin{matrix} +\frac{1}{2} \\ -\frac{1}{2} \end{matrix}$

$e_R, \mu_R.\tau_R, u_R, d'_R, c_R, s'_R, t_R, b'_R : \quad T_3 = 0 \qquad \nu_R$??

Everything reversed for antiparticles

Fermion ⇒ antifermion: Left ⇒ Right and Right ⇒ Left!

Massive neutrinos??

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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 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? Trivial answer: PET.

Antiparticles in the standard model

No complete particle–antiparticle equivalence in weak reactions.

Muon decay: $\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu \leftrightarrow \mu^- \rightarrow e^- \nu_\mu \overline{\nu}_e$

produces left-handed particles and right-handed antiparticles, not invariant under C reversal.

Possible solution: define particle $\rightarrow$ antiparticle conjugation with CP instead of C?

No! Weak forces violate CP, and CPT causes $CP \Rightarrow T$ violation as well (confirmed by expt.)

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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

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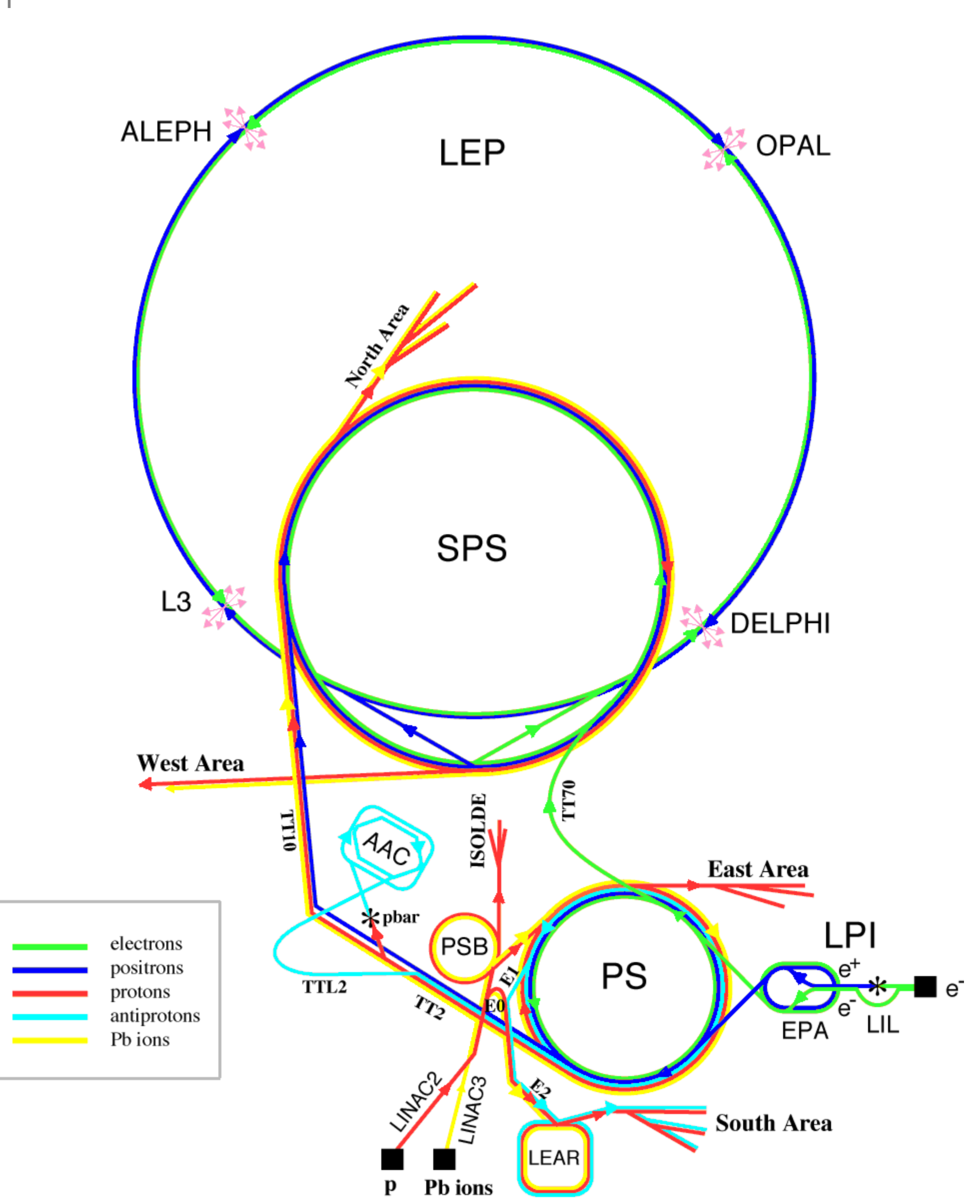
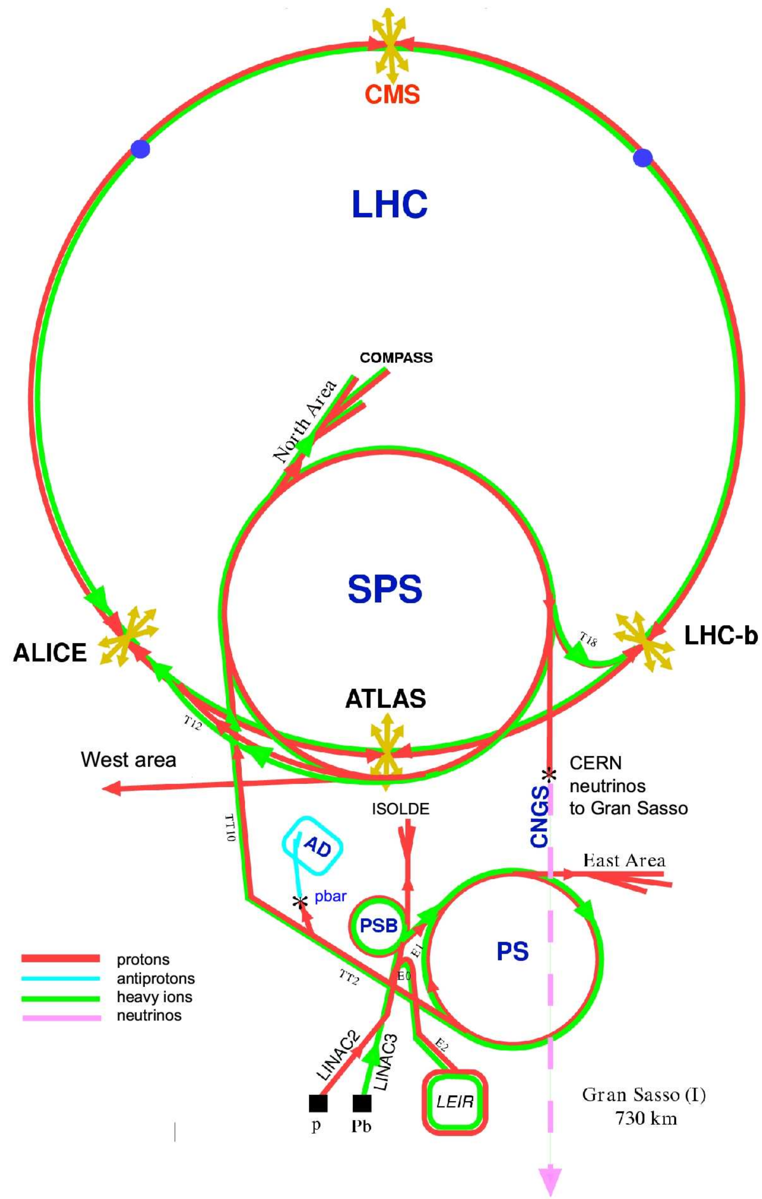
Accelerators at CERN

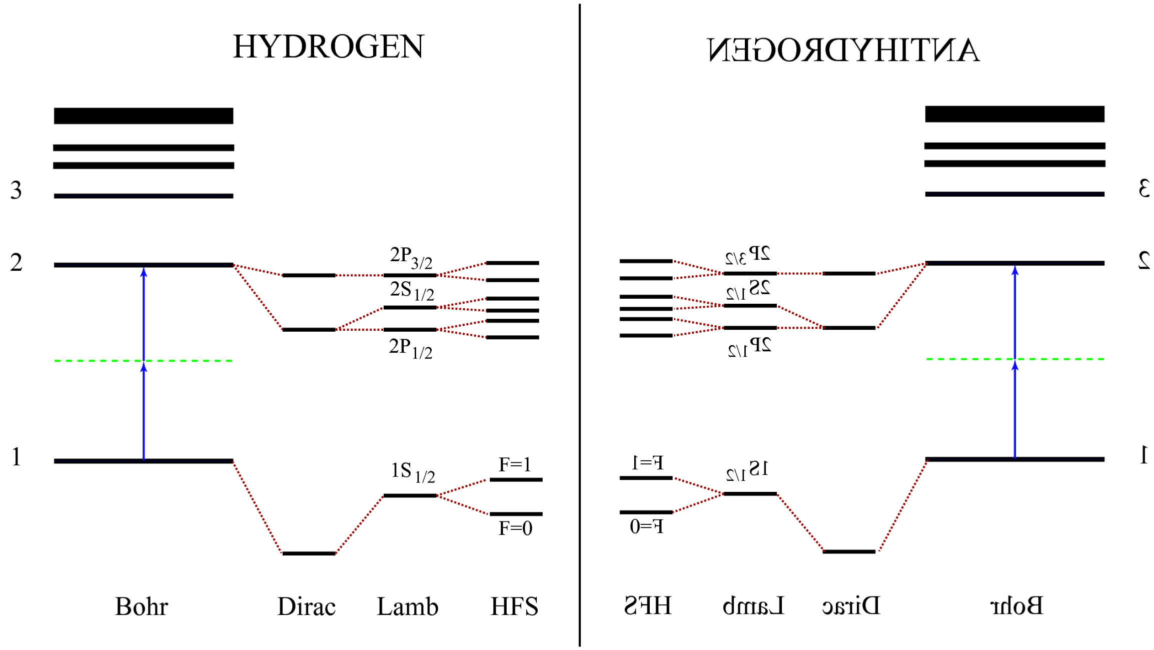
1989–2000



2009–2035??



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



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

Long lifetime,
narrow transition,
Doppler-free
spectroscopy

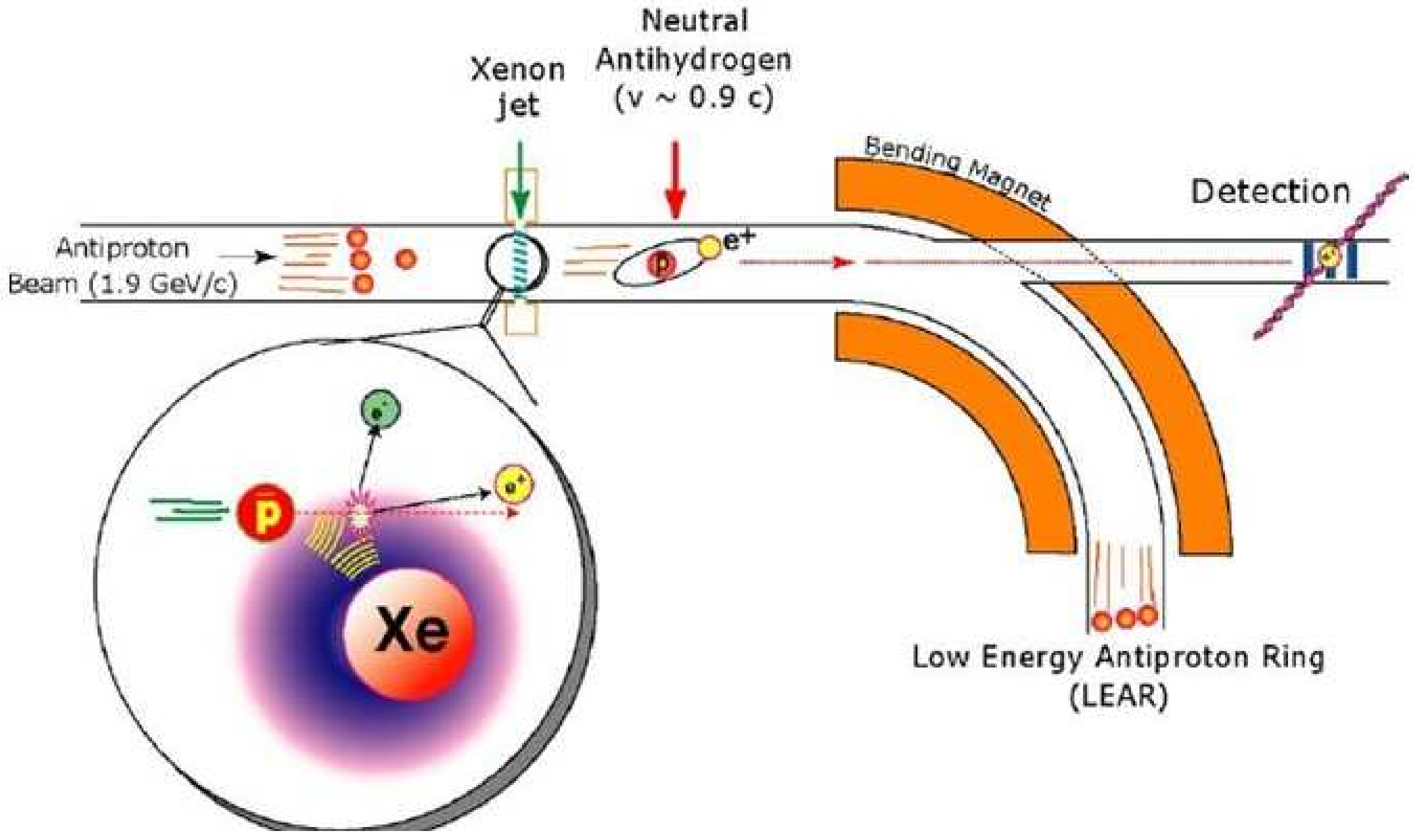
Feasibility study for the SPSL Committee of CERN (1992) converted into

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:

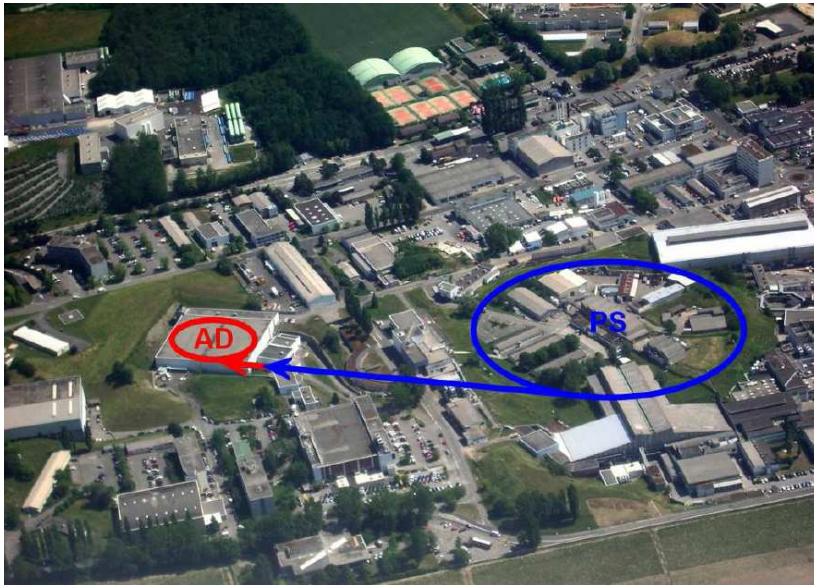
G. Blanford *et al.*, „Observation of atomic anti-hydrogen," Phys. Rev. Lett. **80** (1998) 3037.

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



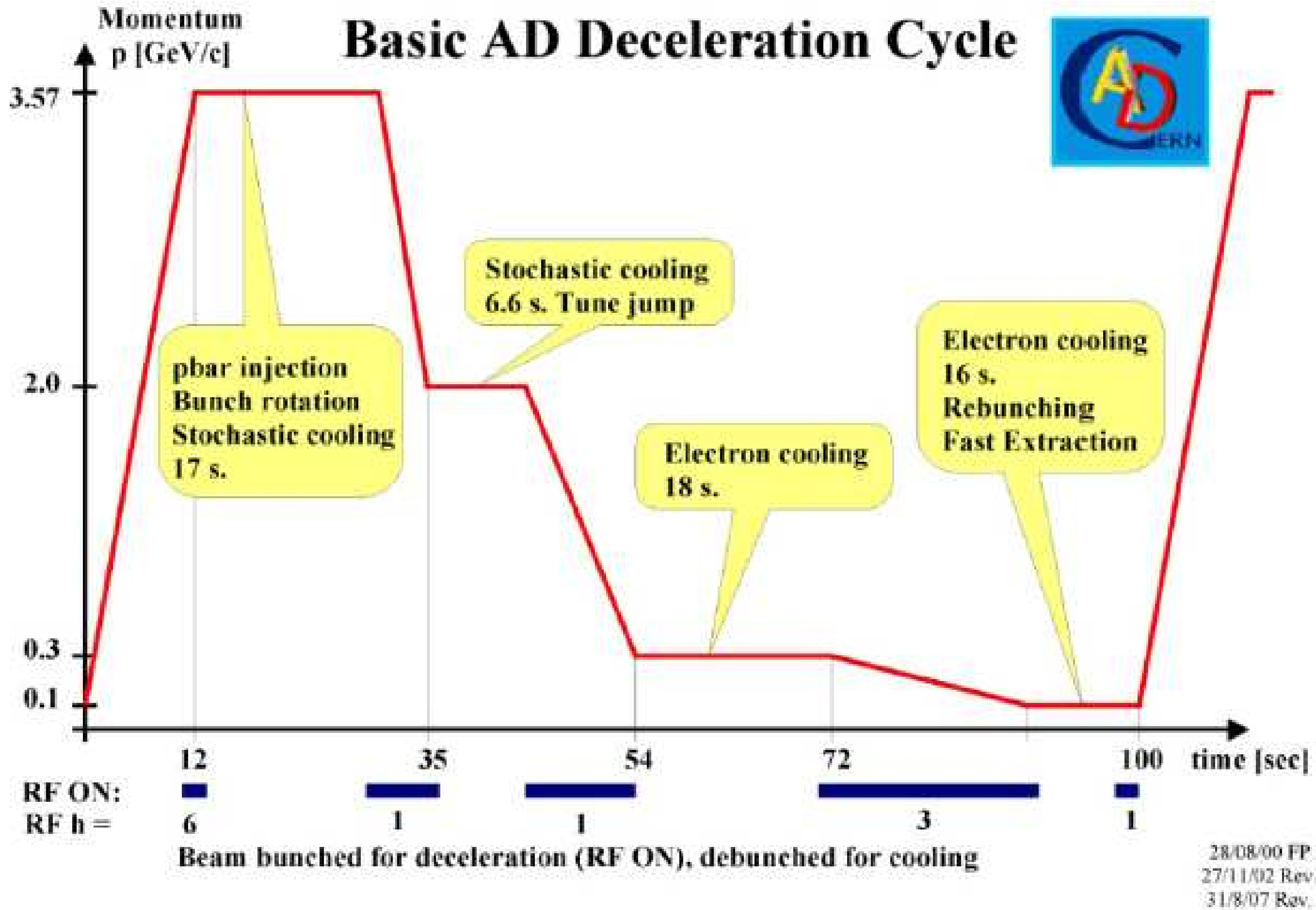
©Ryugo S. Hayano, Tokyo U.

ASACUSA: Atomic Spectroscopy And Collisions Using Slow Antiprotons

Tokyo, Aarhus, Vienna, Brescia, Budapest, Debrecen, Munich

BARNA Dániel, RADICS Bálint, JUHÁSZ Bertalan, SÓTÉR Anna, HORVÁTH Dezső

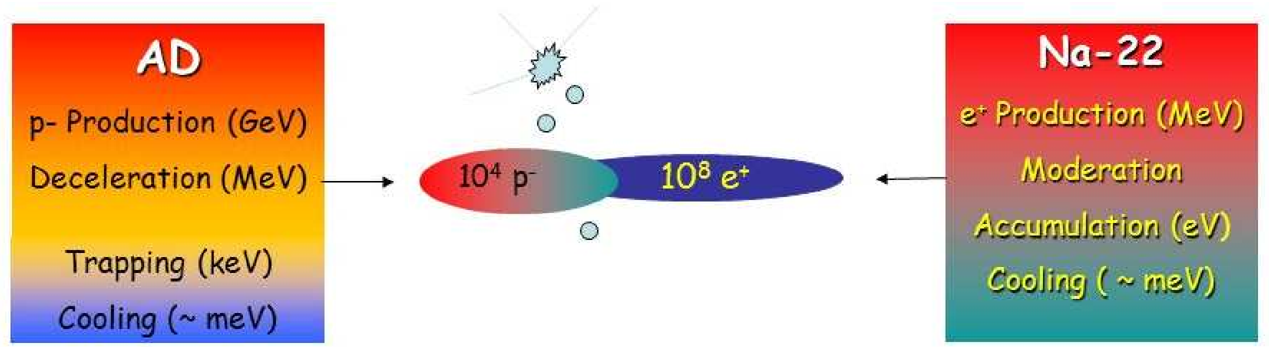
The Antiproton Decelerator: cooling



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

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

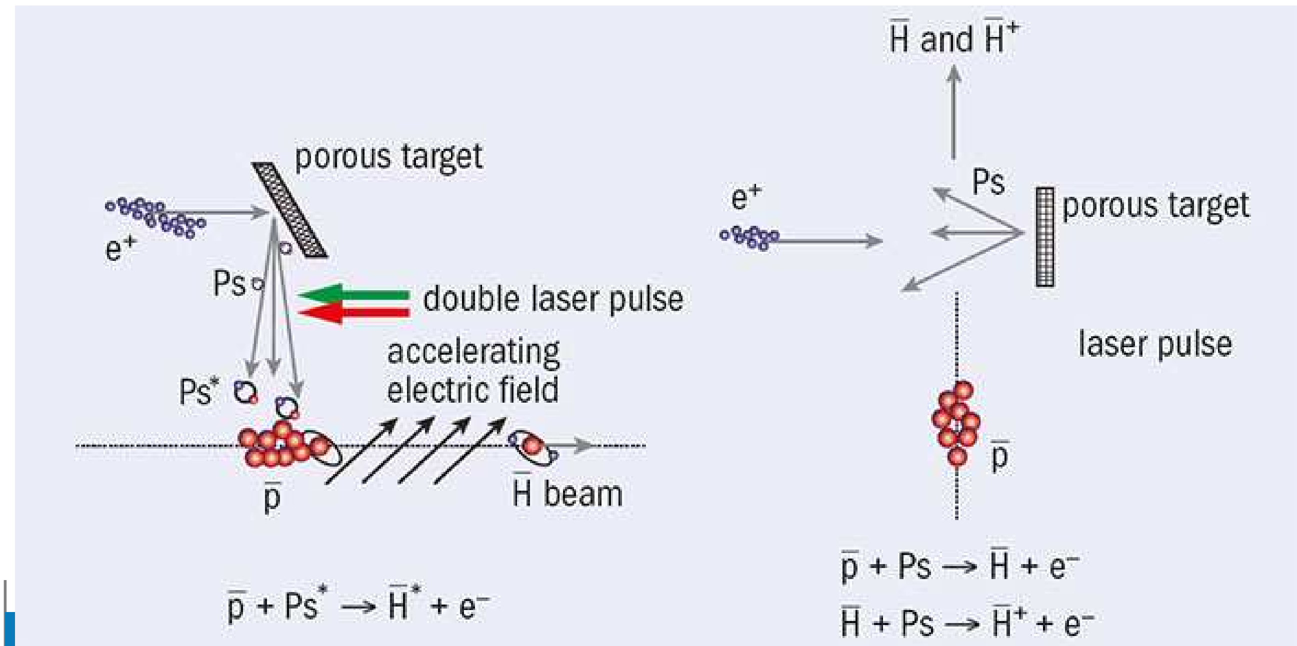
How to produce antihydrogen?



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

3-body $(\overline{p}e^+e^+)$: 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

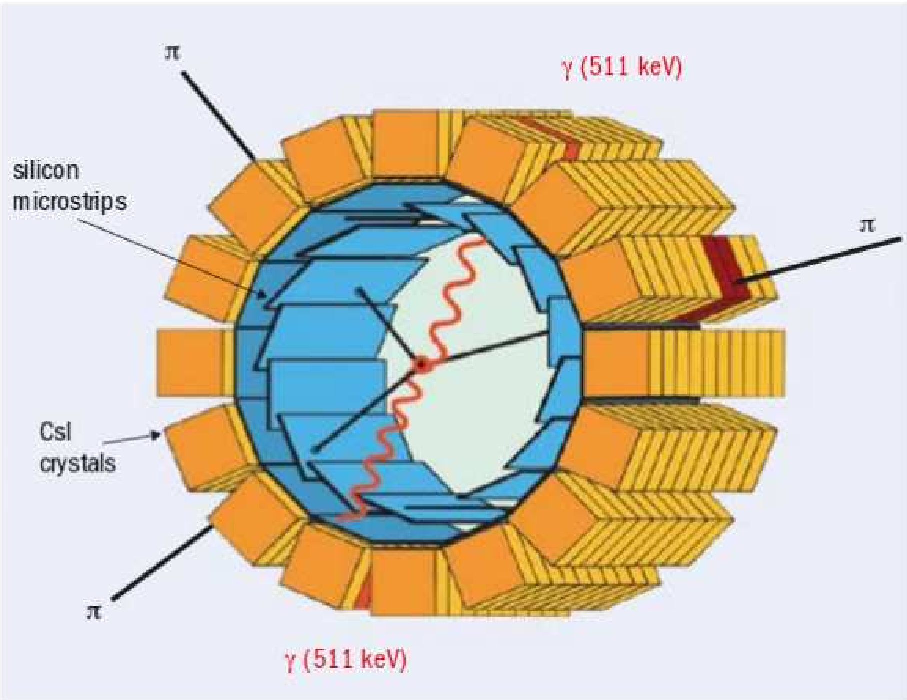
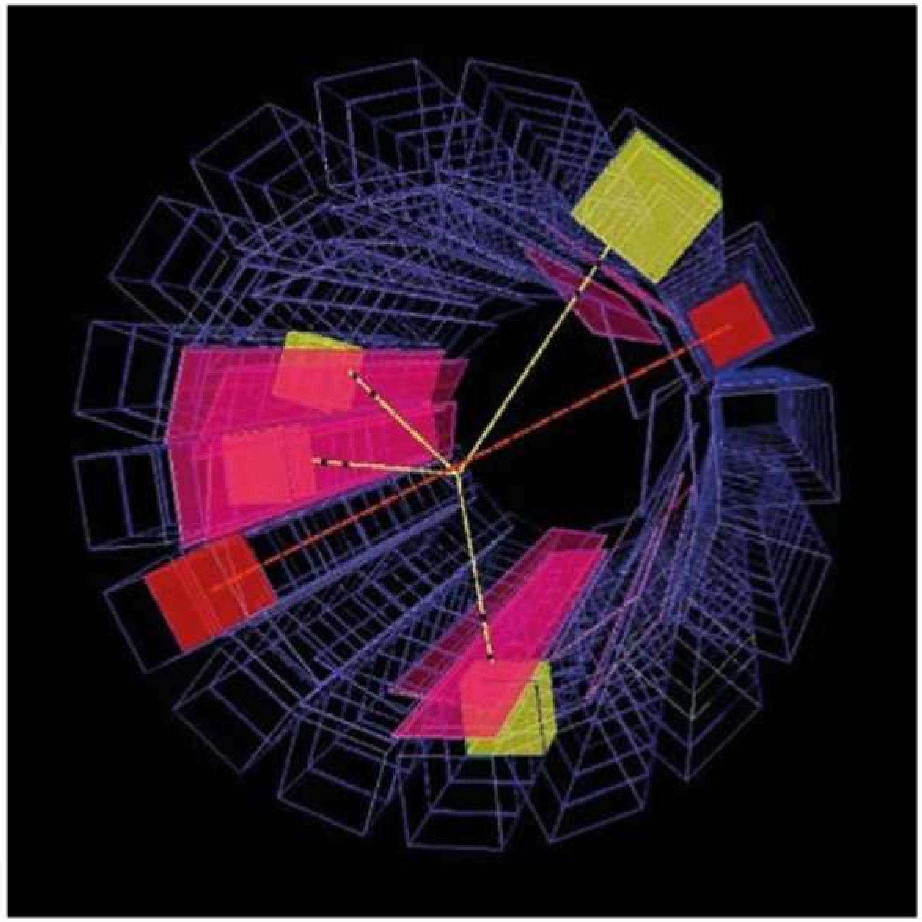


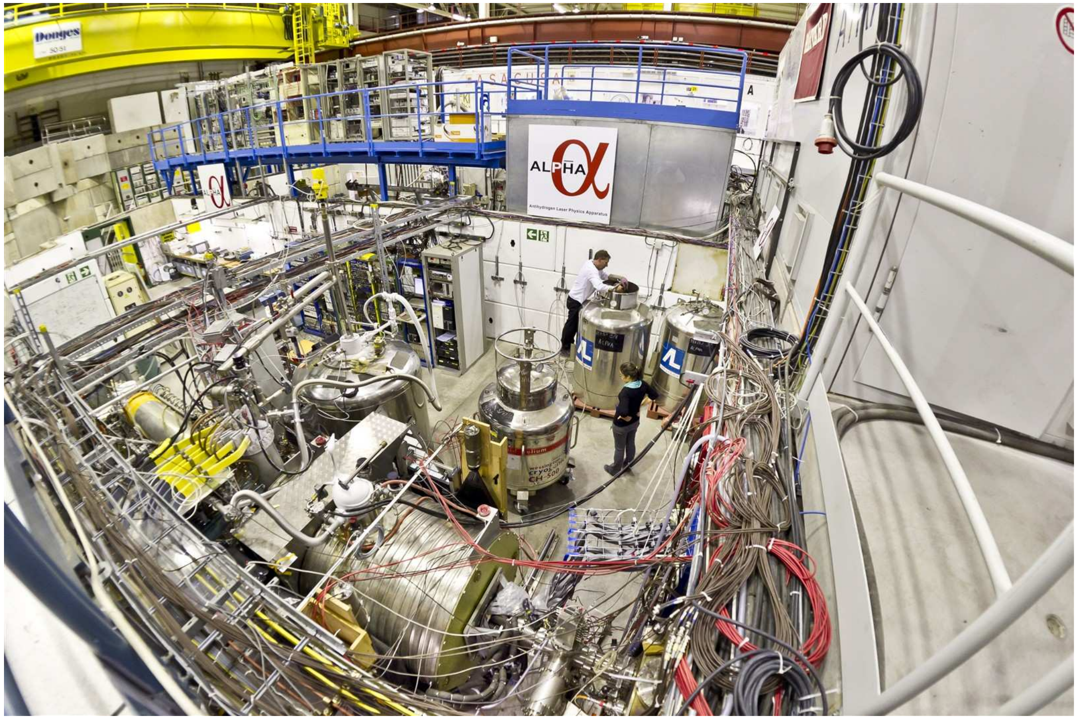
Fig.5. Above: A diagram of the ATHENA antihydrogen detector. Right: An antihydrogen annihilation event in ATHENA, reconstructing four charged pions (yellow) and two 511 keV photons (red). (Image credits: ATHENA Collaboration.)

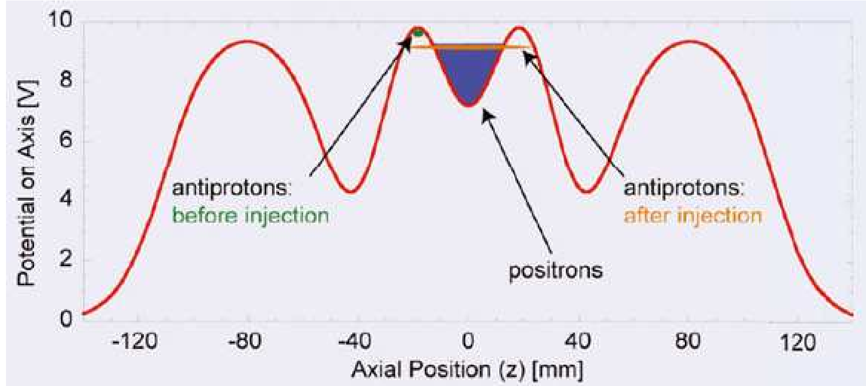


ATHENA Collaboration (1997 – 2005) ⇒ ALPHA Collaboration

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

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





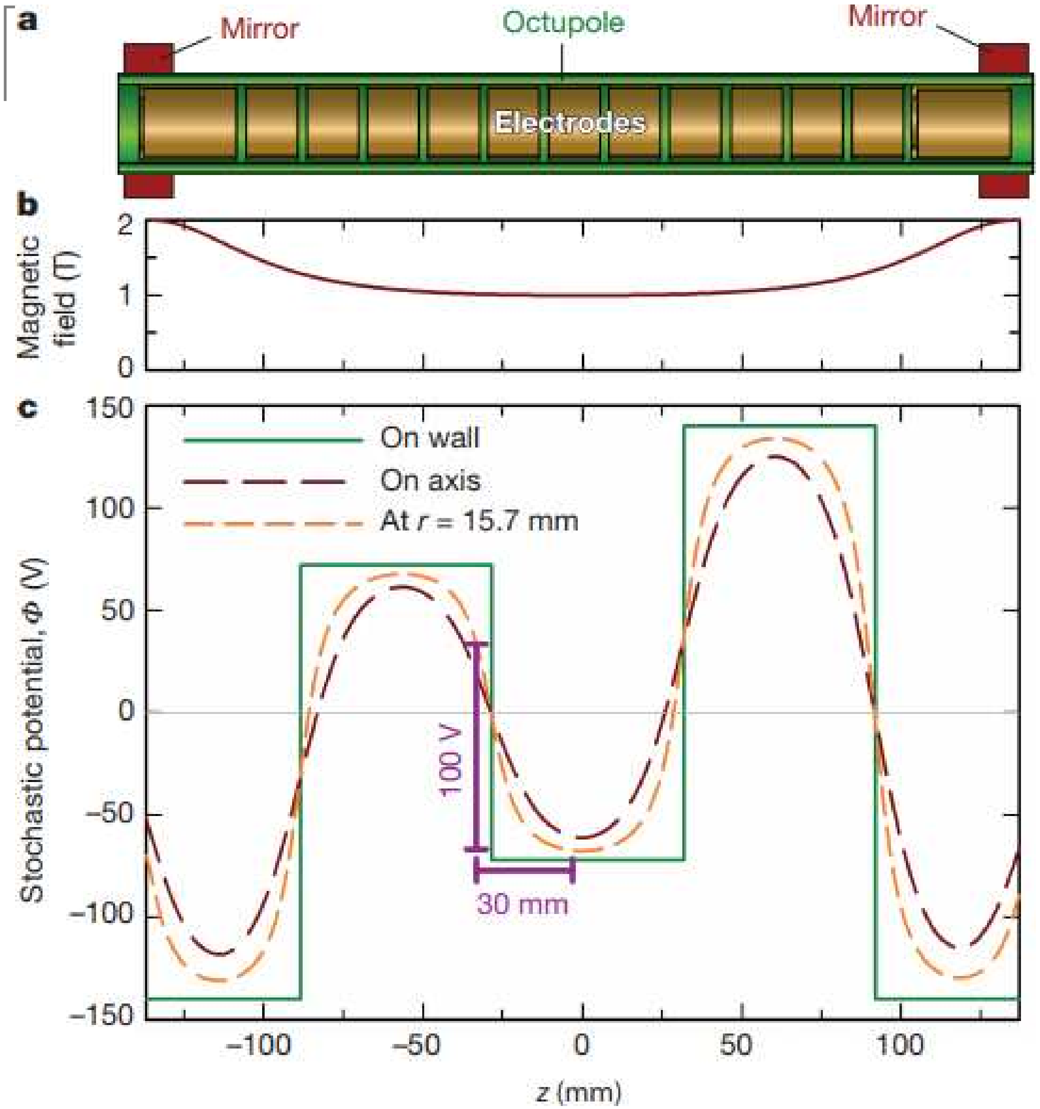
- Capture 90,000 antiprotons.
- Mix with 3 million positrons.
- Produce 50,000 $\overline{\mathrm{H}}$ atoms.
- Remove charged particles.
- Trap 20 $\overline{\mathrm{H}}$ at $T = 0.54$ K.

$\overline{\mathrm{H}}$ kept trapped for 10 s $\Rightarrow$ 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.

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 $\Delta E > E_{\text{well}}$

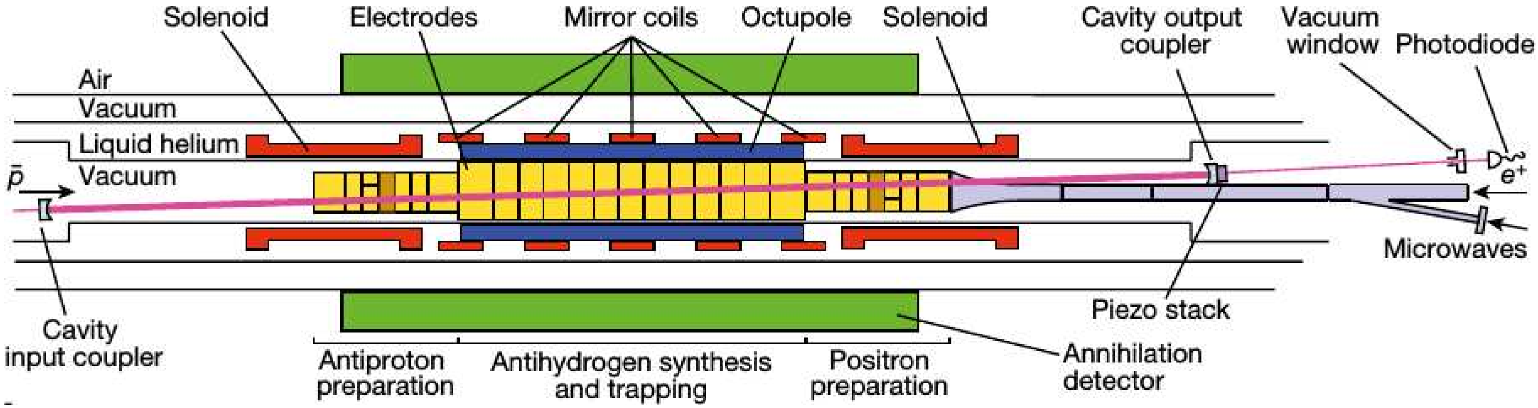
Result: $|Q| < 0.71 \times 10^{-9}$

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

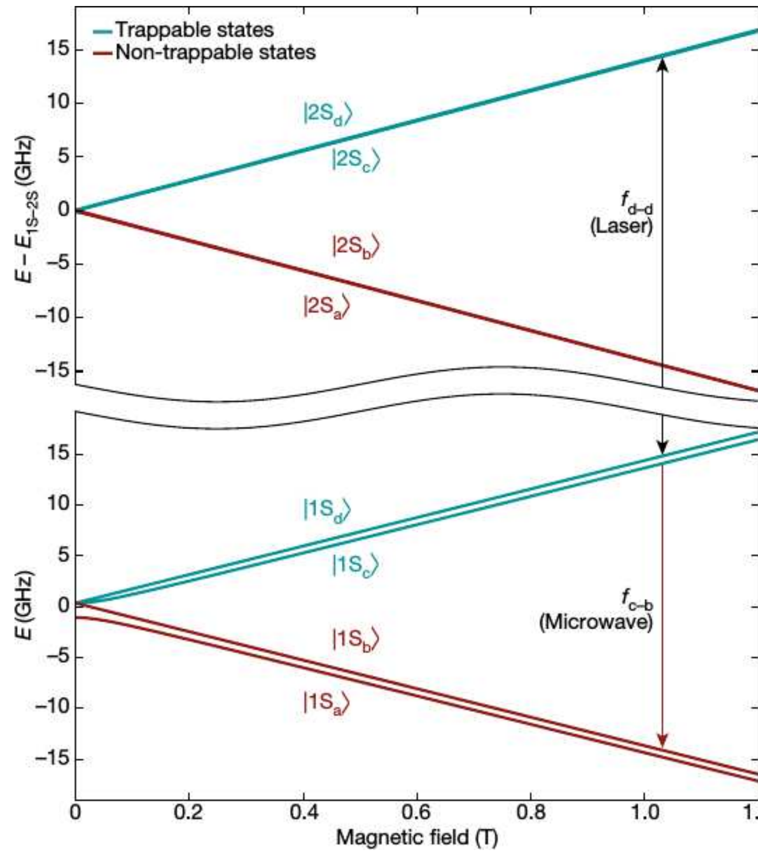
(standing wave for 300 s) tuned around

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:

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

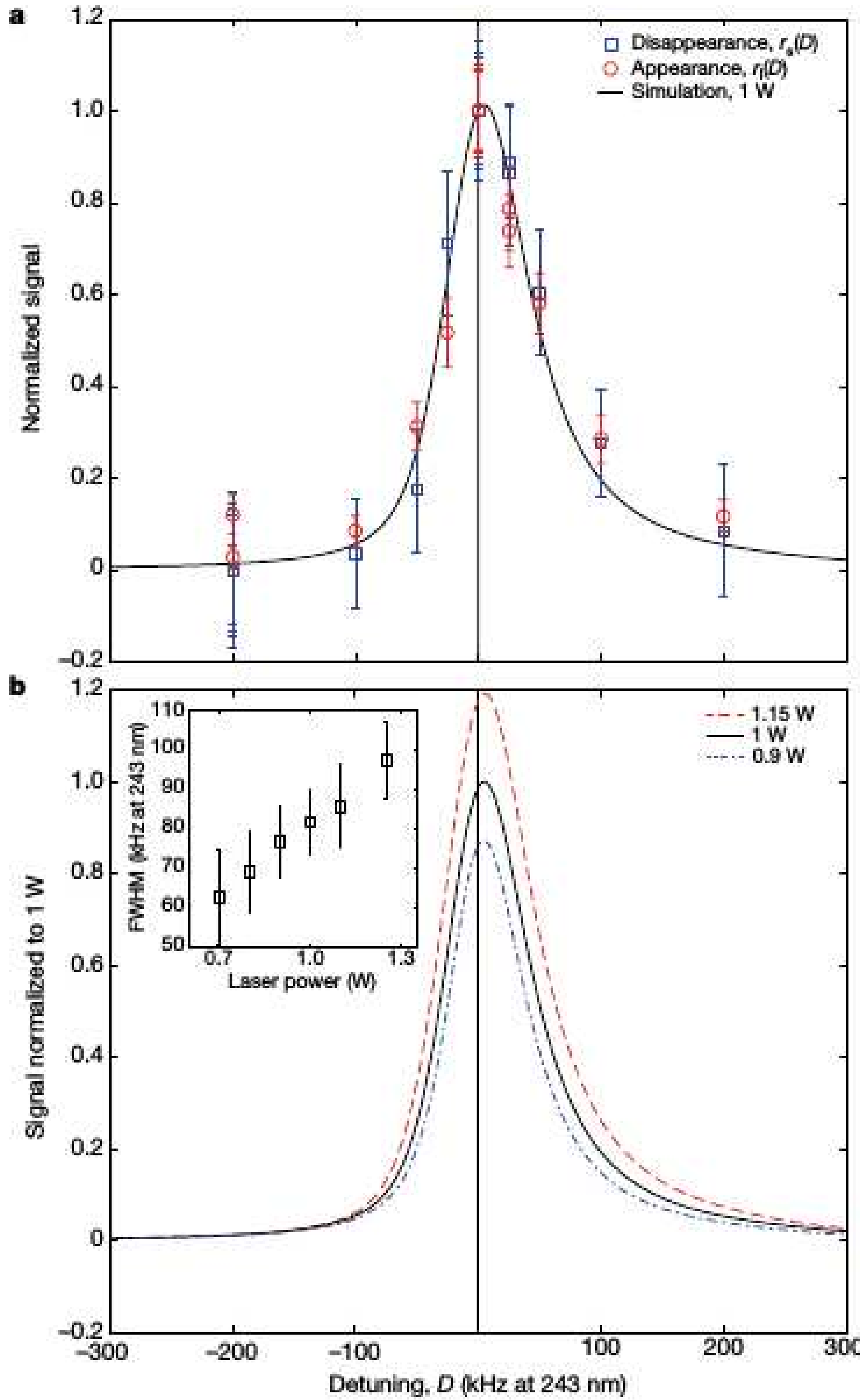
For hydrogen:

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

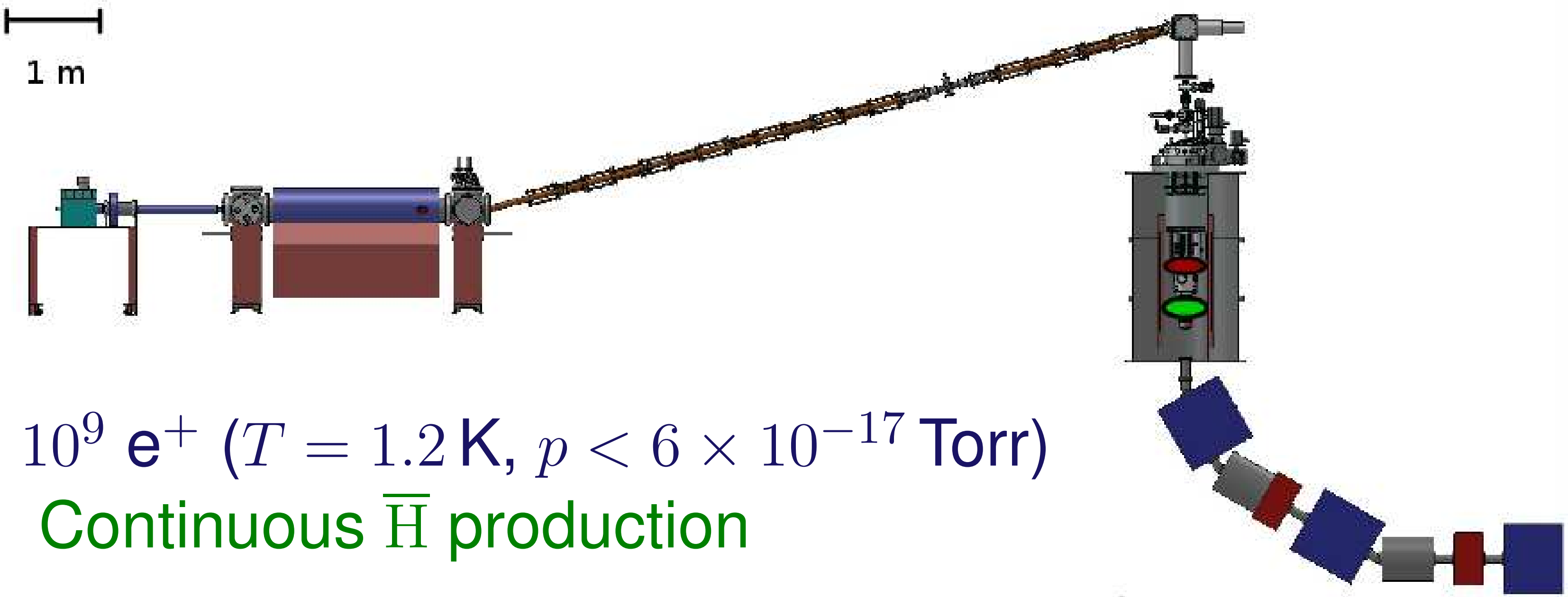
Difference (CPT test): 2×10^{-12}

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.

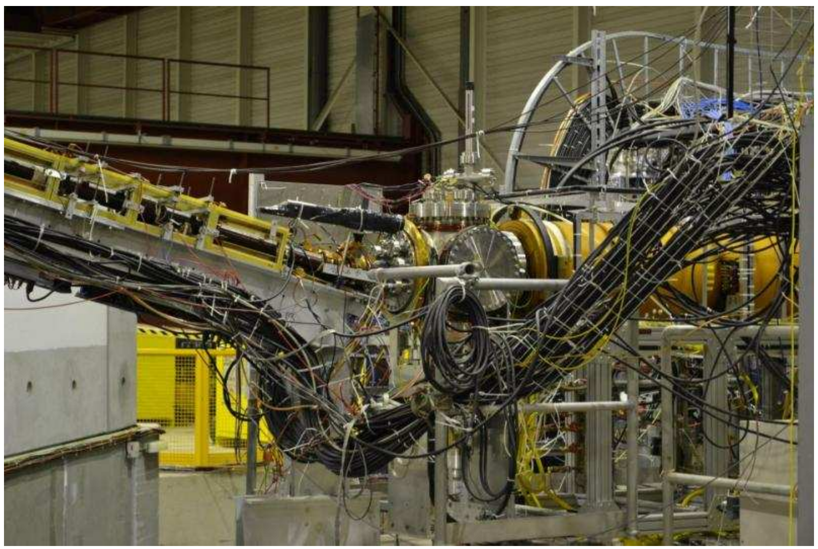


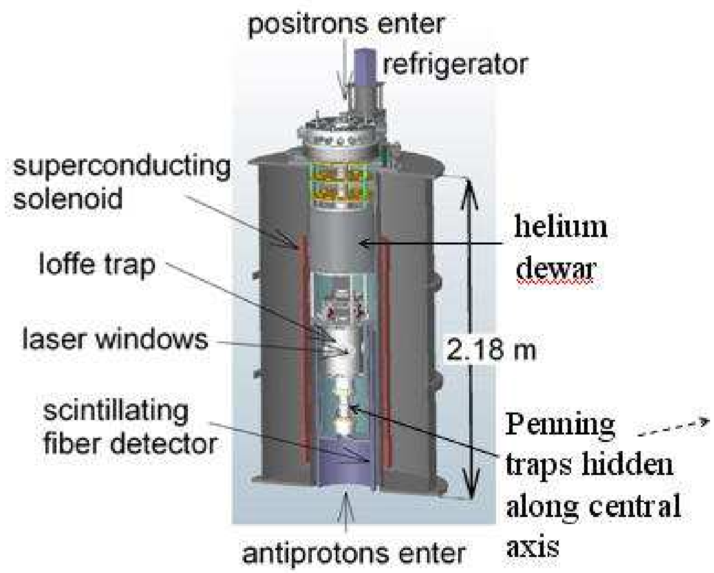
ATRAP: Antimatter trap



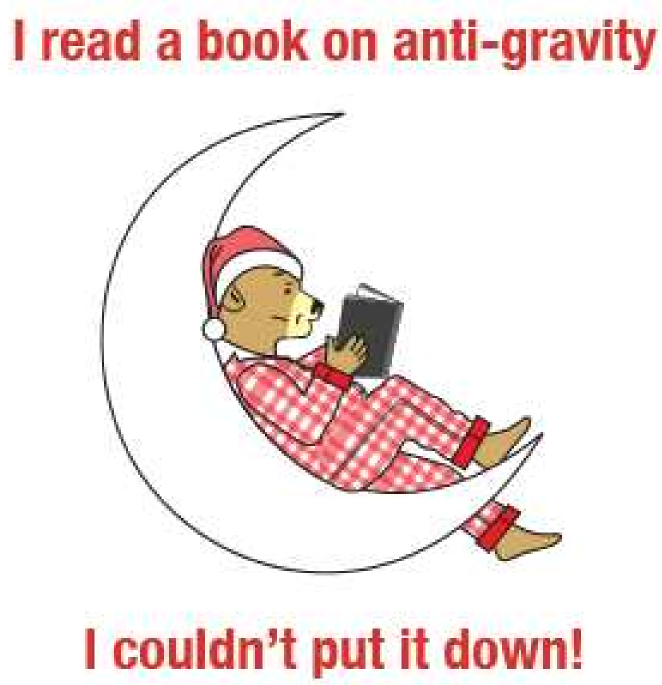
4×10^9 e$^+$ ($T = 1.2$ K, $p < 6 \times 10^{-17}$ Torr)

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





Antimatter gravity



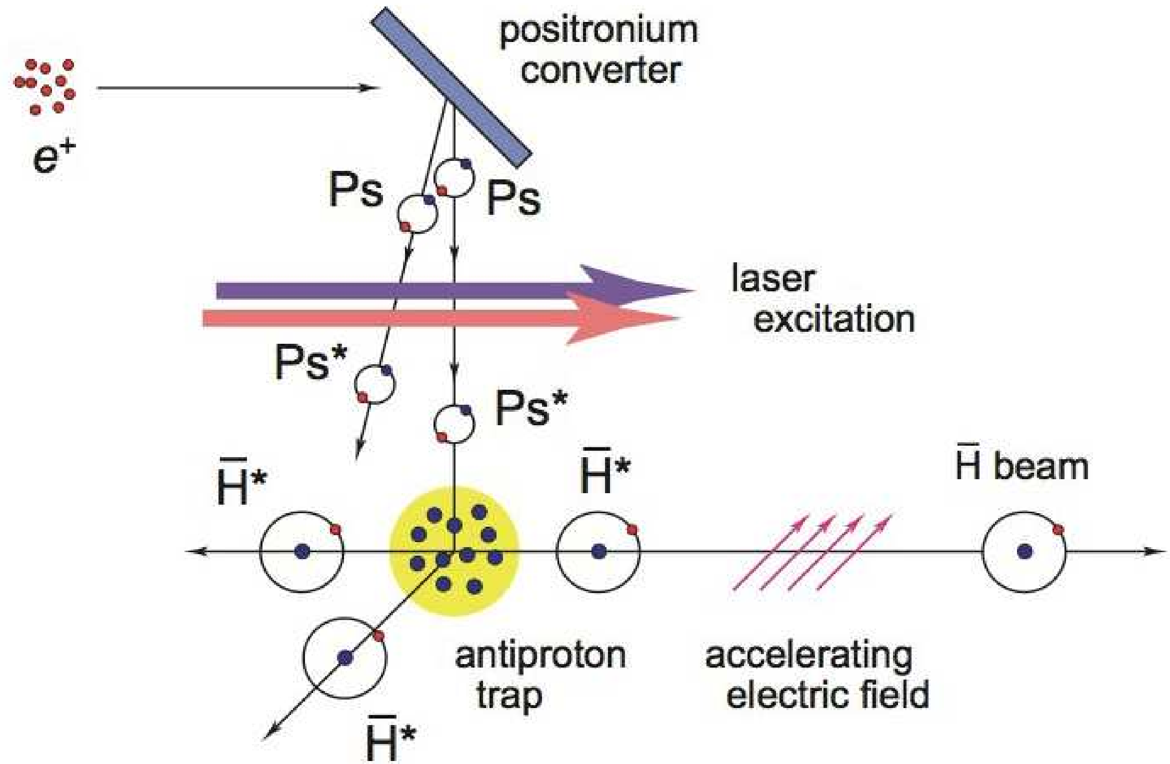
Negative mass $\Rightarrow$ repulsive gravity??

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

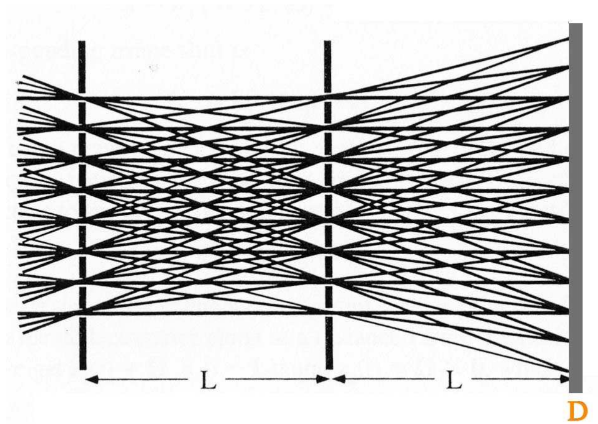
Not CPT: weak equivalence principle

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

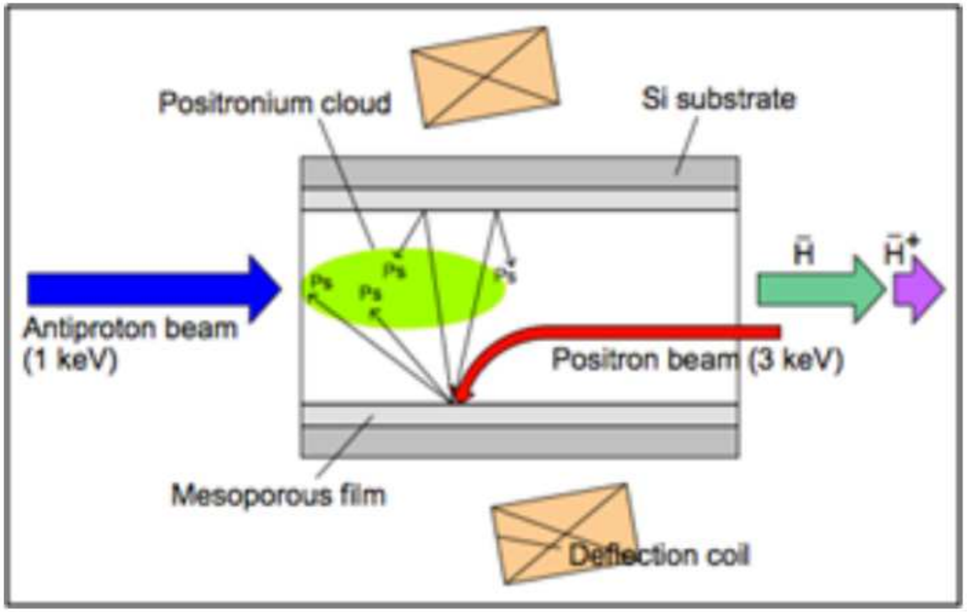


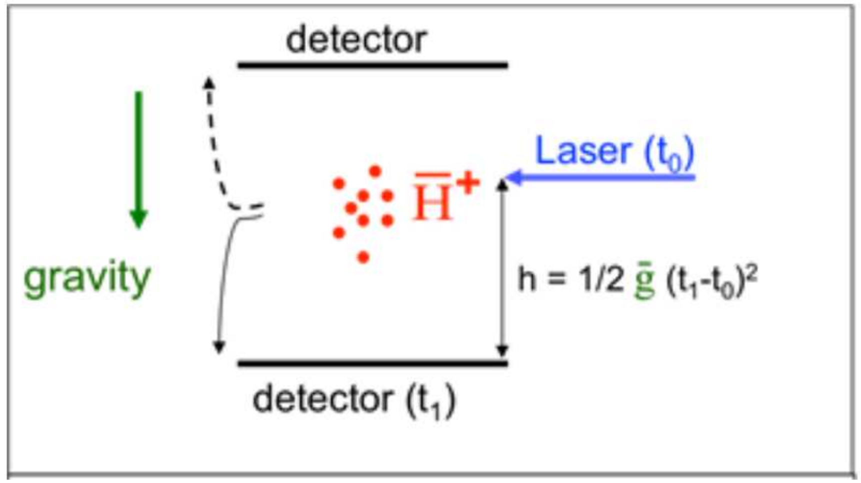
$\overline{\mathrm{H}}$ production with Ps proven

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

GBAR

Gravitational Behaviour of Antihydrogen at Rest
(in preparation)

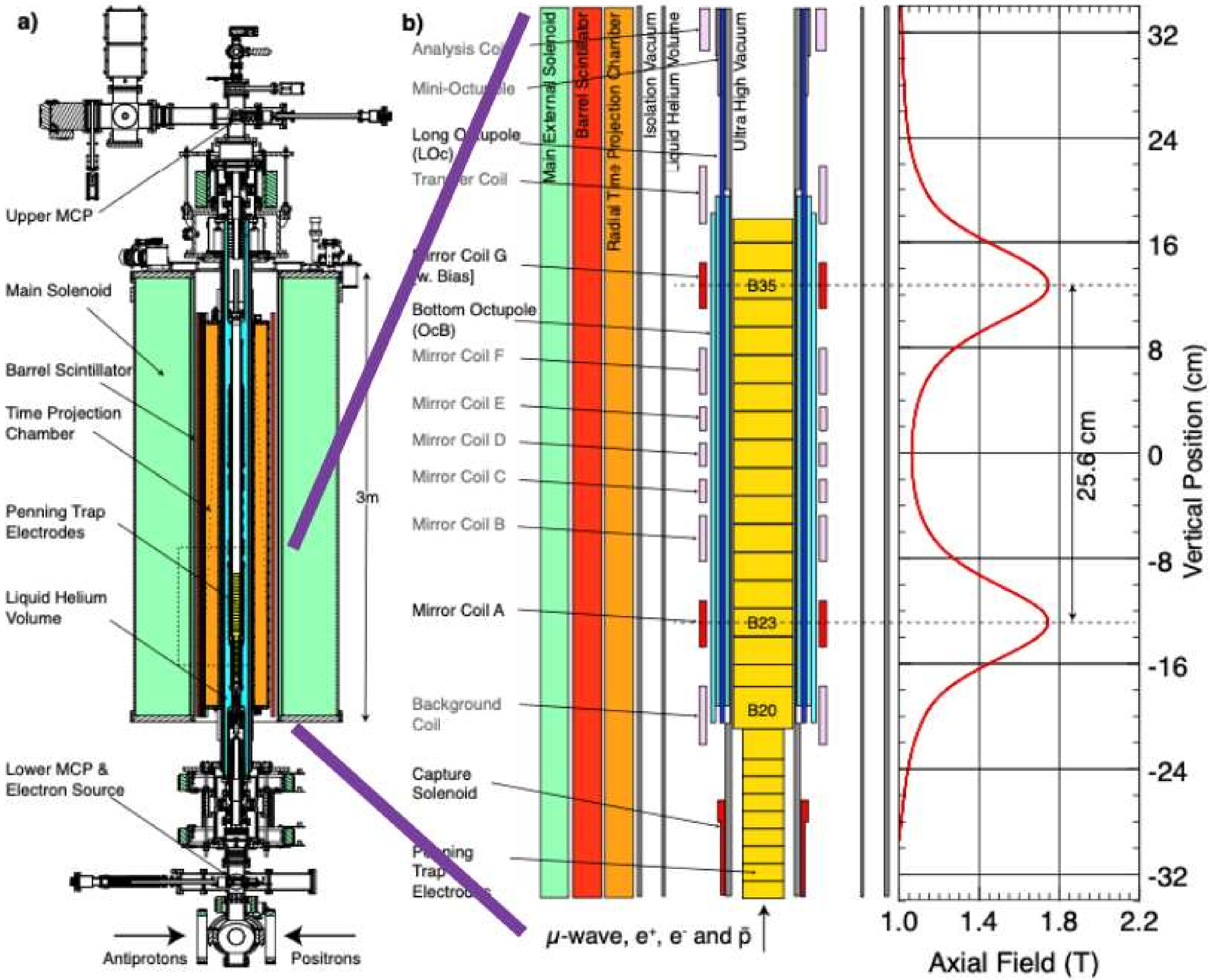




$\overline{\mathrm{p}}$ + Ps $\to \overline{\mathrm{H}}$; $\overline{\mathrm{H}}$ + Ps $\to \overline{\mathrm{H}}^+$ (cooling); back to $\overline{\mathrm{H}}$: let it fall

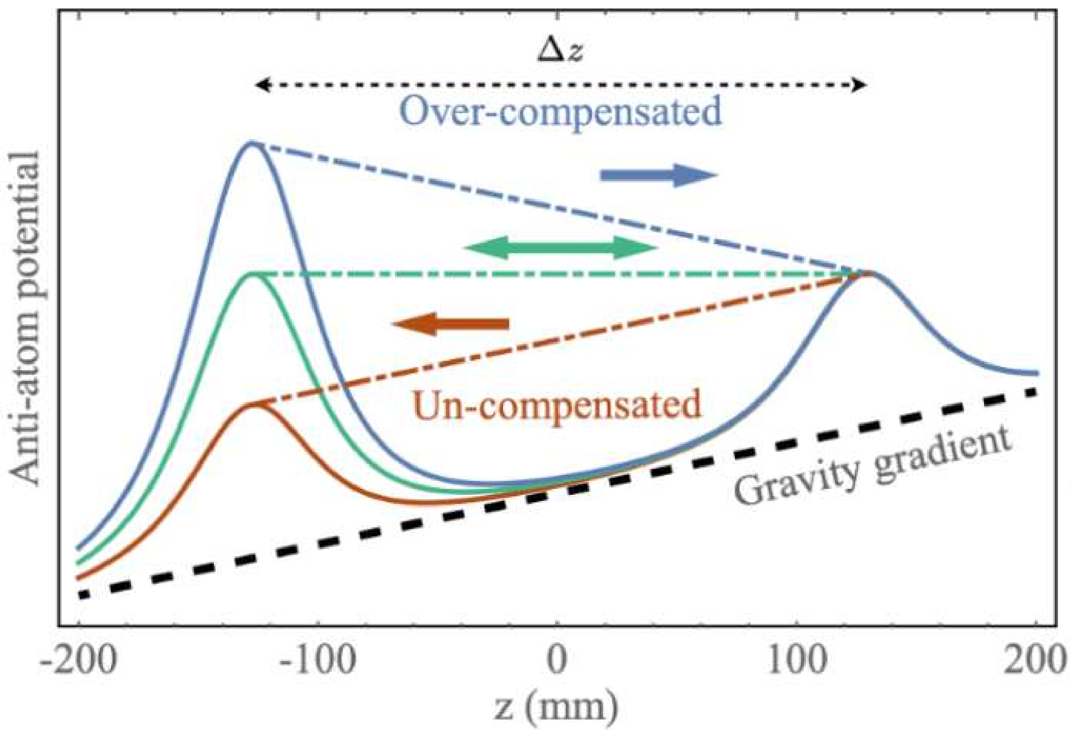
ALPHA-gravity: setup

ALPHA-gravity trap (2023)



ALPHA-gravity measurement (2023)

ALPHA-g Measurement Scheme



Up/Down Test:

When balanced:

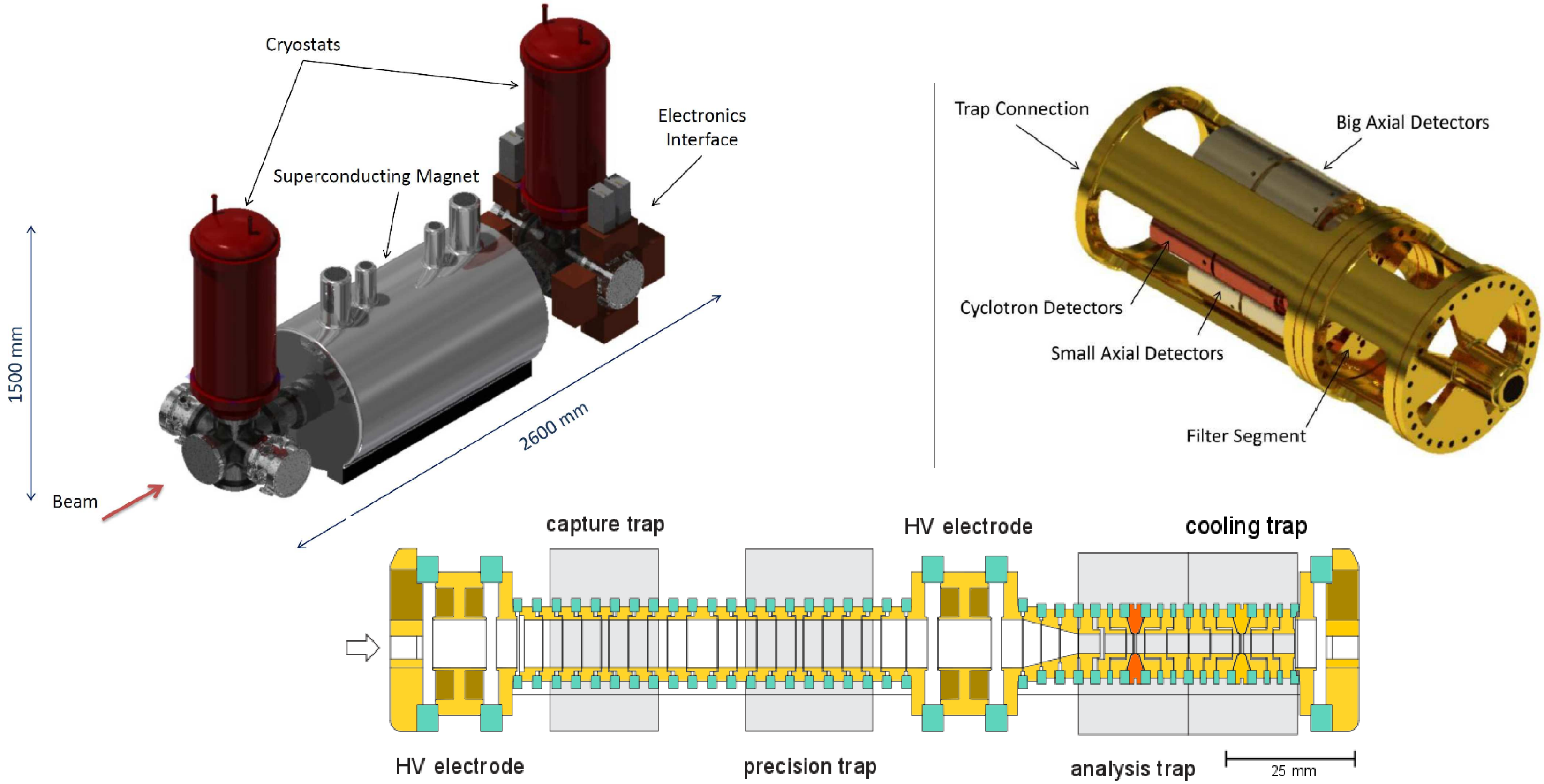
500 mK Hbar,
~20% up, ~80% down

Result (2023): $\overline{g}/g = 0.75 \pm 0.13$ (stat+syst) ± 0.16 (simulation)

Antigravity out. Aim: 1 % measurement.

BASE: Baryon Antibaryon Symmetry Experiment

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



$$(q/m)_{\mathrm{p}}/(q/m)_{\overline{\mathrm{p}}} = 1.000000000003(16)$$

M. J. Borchert *et al.* [BASE], „A 16-parts-per-trillion measurement of the antiproton-to-proton charge/mass ratio,” Nature **601** (2022) no.7891, 53-57.

Antihydrogen beam

ASACUSA: MUSASHI

Monoenergetic
Ultra
Slow
Antiproton
Source for
High–precision
Investigations

Musashi Miyamoto self-portrait ~ 1640

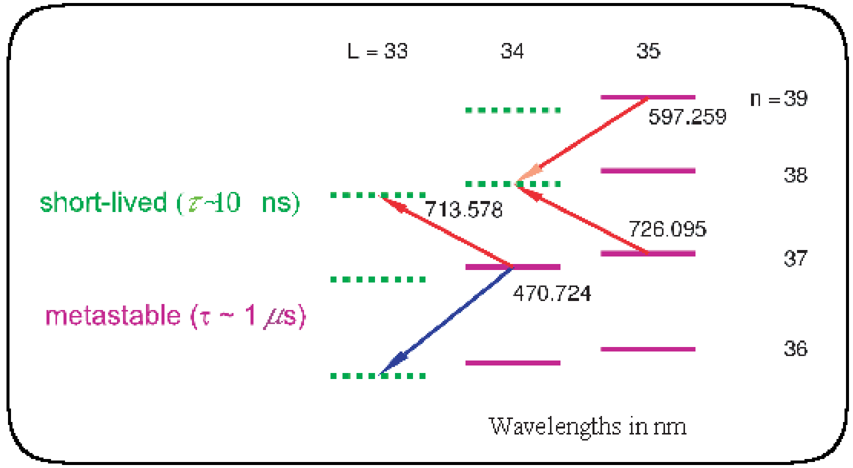
5.8 MeV $\overline{\mathrm{p}}$ injected into RFQ
100 keV $\overline{\mathrm{p}}$ injected into trap
10^6 $\overline{\mathrm{p}}$ trapped and cooled (2002)
~ 350000 slow $\overline{\mathrm{p}}$ extracted (2004)
Cold $\overline{\mathrm{p}}$ compressed in trap (2008)
(5×10^5 $\overline{\mathrm{p}}$, $E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

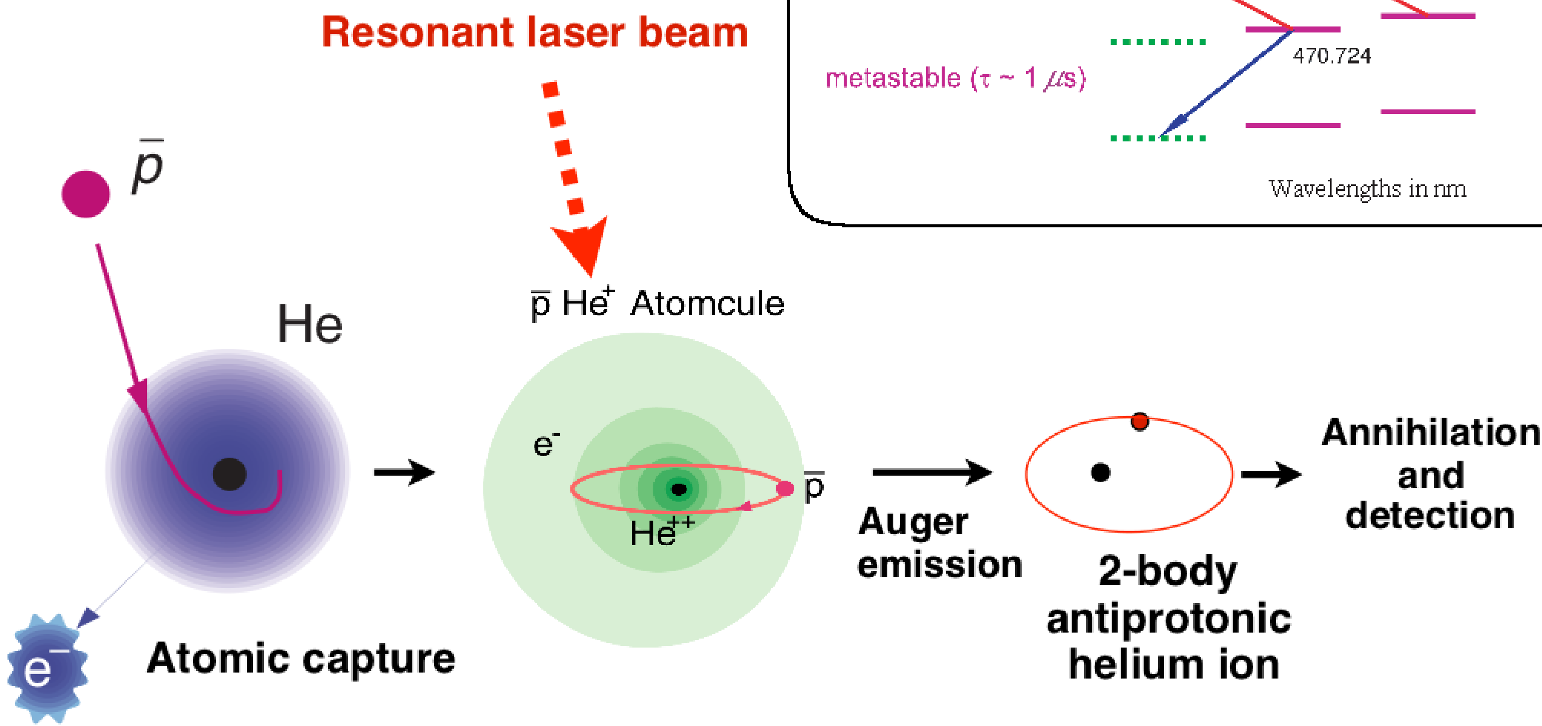
N. Kuroda *et al.*, Nature Commun. **5** (2014) 3089.

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

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

Laser spectroscopy of antiprotonic helium



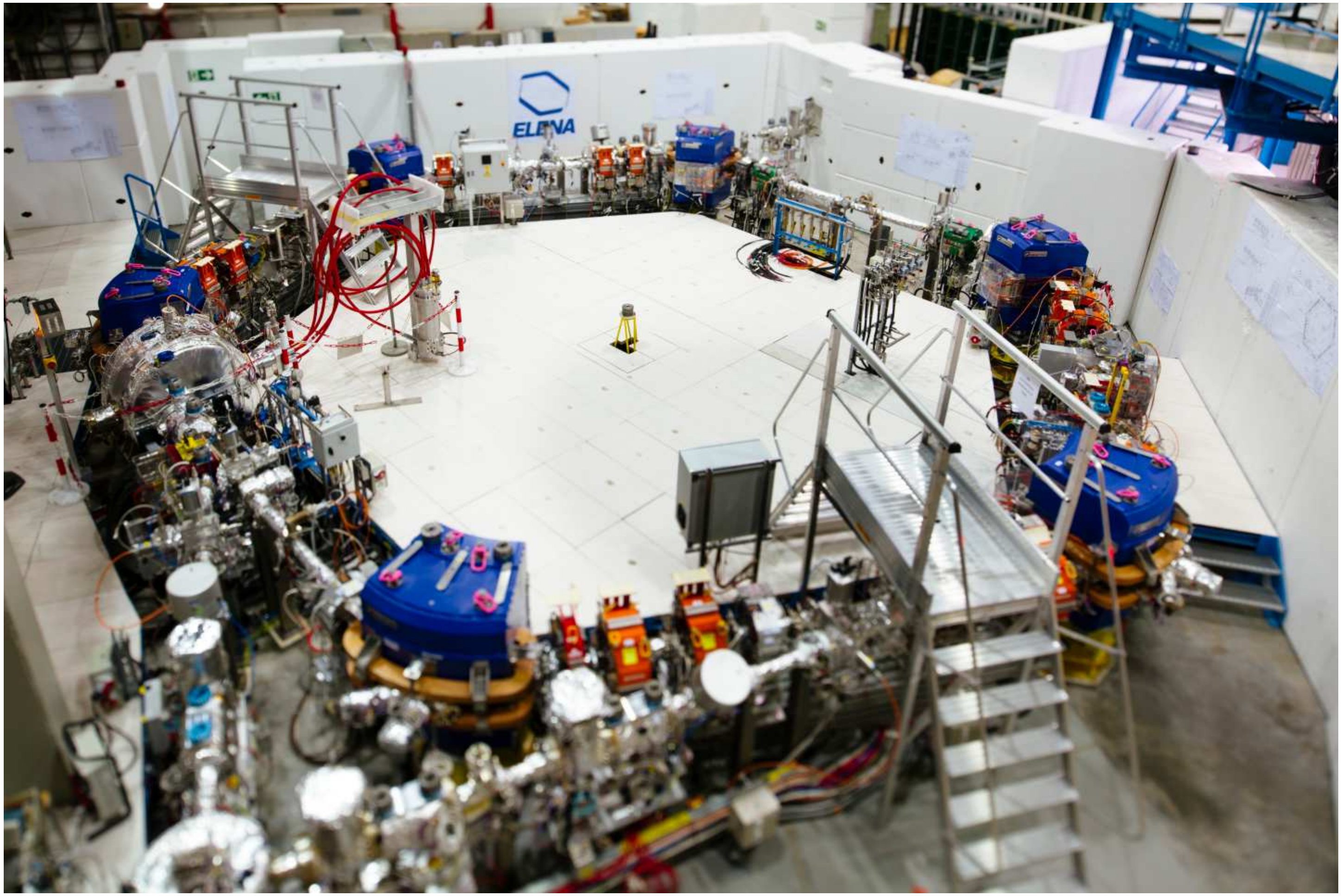


Transition between long- and short-lived states ⇒ prompt annihilation

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

Extra 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)

Antimatter in Space

AMS-2: Alpha Magnetic Spectrometer

to discover antimatter (anti-helium!) and dark matter

Mass: 8500 kg,

1200 kg perm. magnet

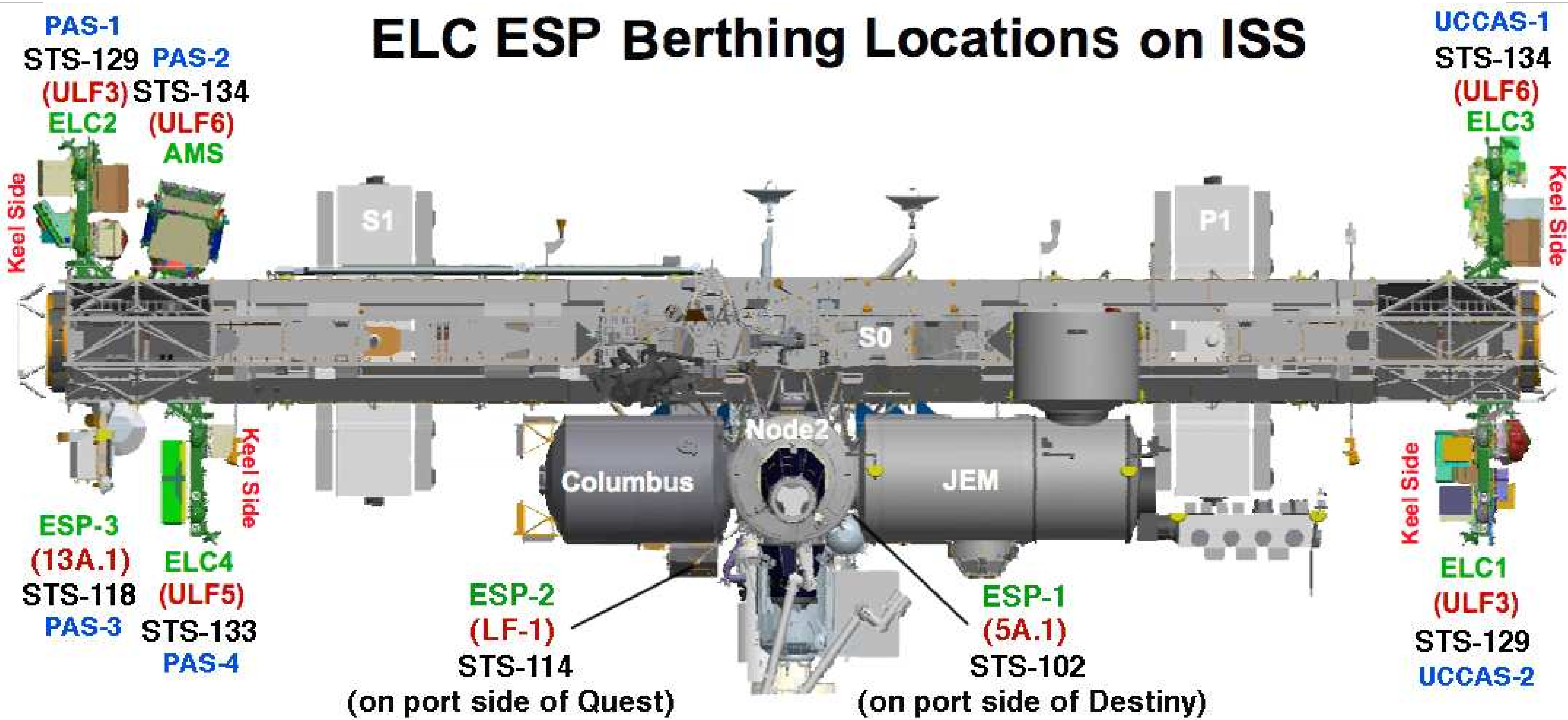
Father: Sam Ting, cost: 2 G$

Construction: CERN

Launch: May 2011, USA

Control room at CERN

AMS-2: Alpha Magnetic Spectrometer



First results (2015-17):

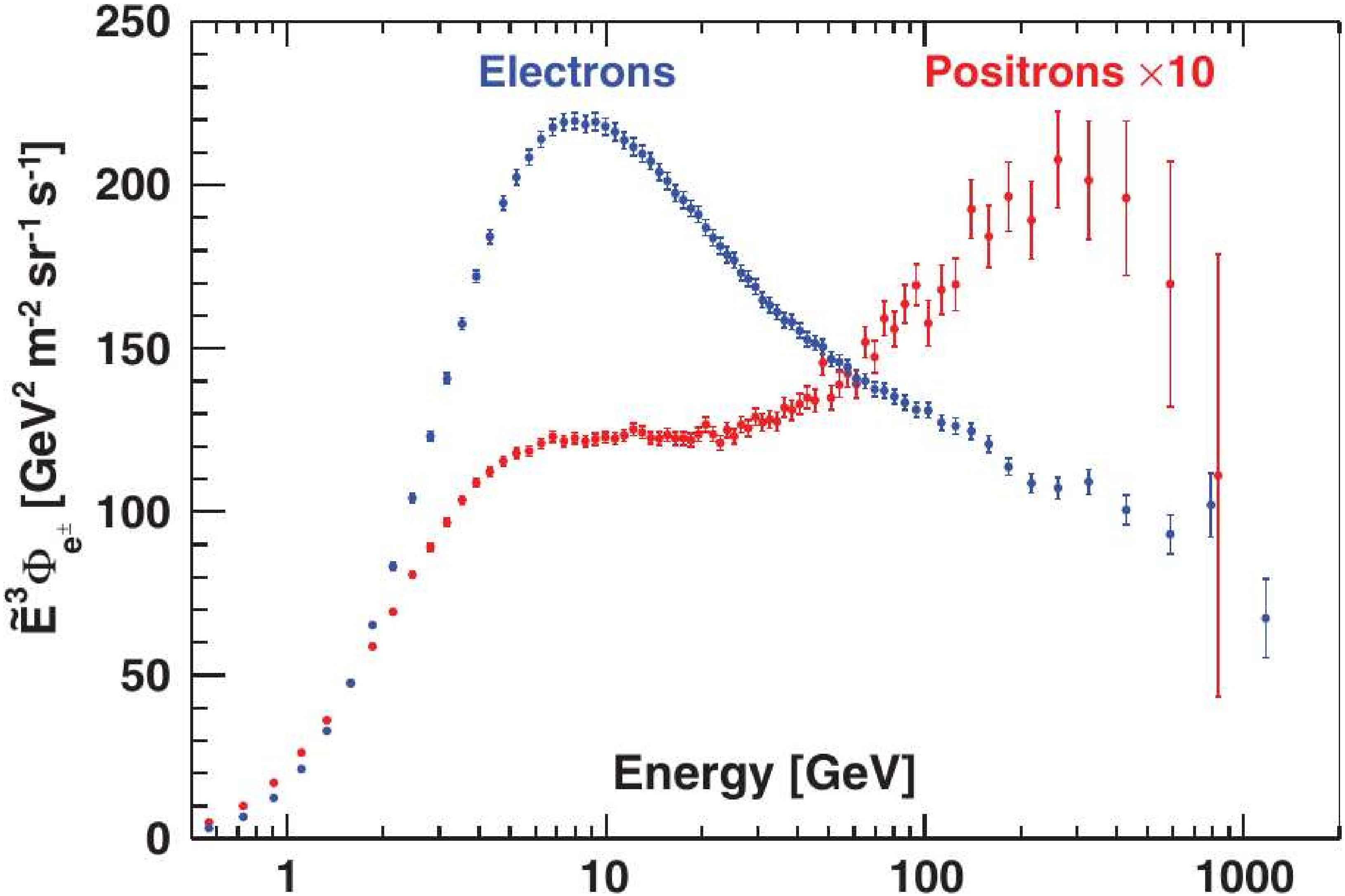
Very few antihelium atoms observed.

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

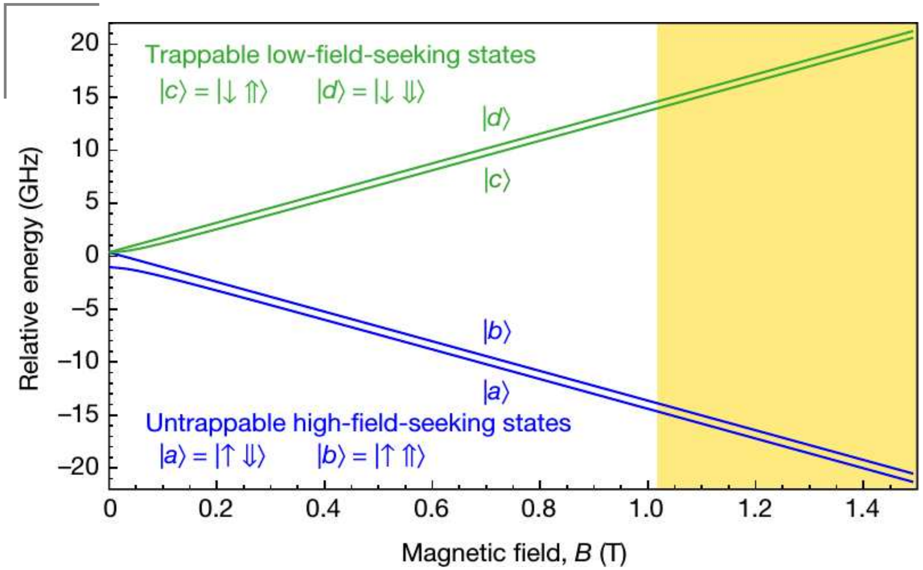
CERN exhibition in Globe: $\overline{\mathrm{p}}$ production target at AD

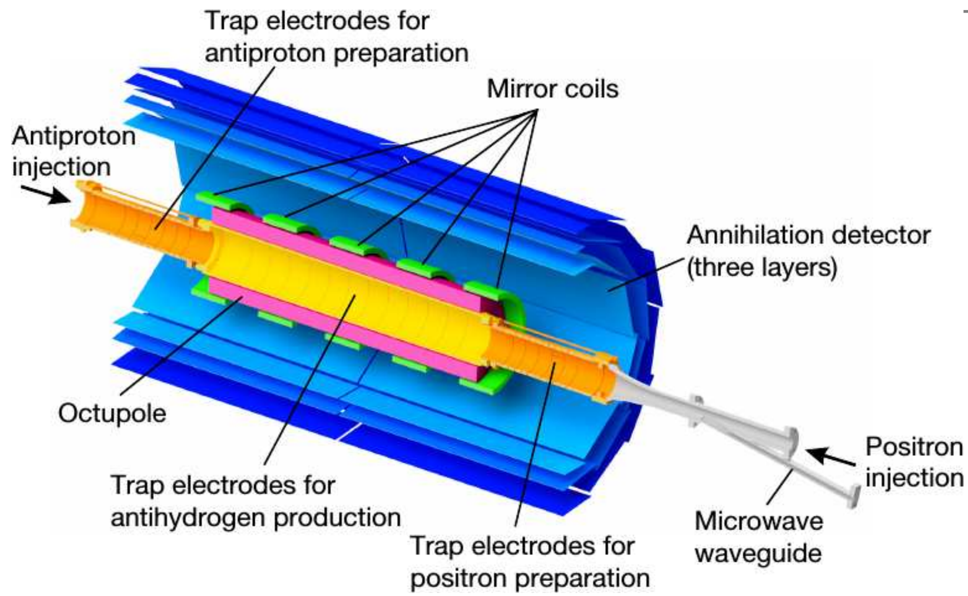
Steps toward $\overline{\mathrm{H}}$ spectroscopy

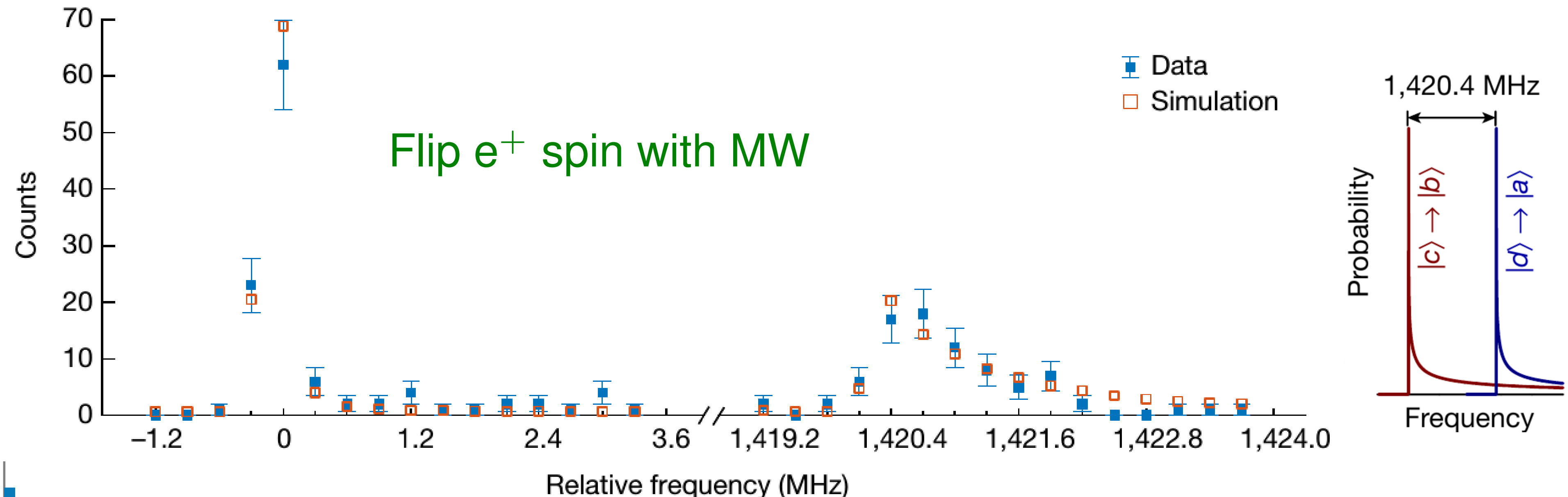
- Putting antiprotons ($\overline{\mathrm{p}}$) in electromagnetic trap
- Trapping and cooling antiprotons
- Cooling slow positrons (e^+ from ^{22}Na) in trap
- Mixing $\overline{\mathrm{p}}$ and e^+ $\rightarrow$ recombination in $e^+e^+\overline{\mathrm{p}}$ collisions (G. Gabrielse, ATRAP & Harvard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

2017: done by the ALPHA Collaboration!

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

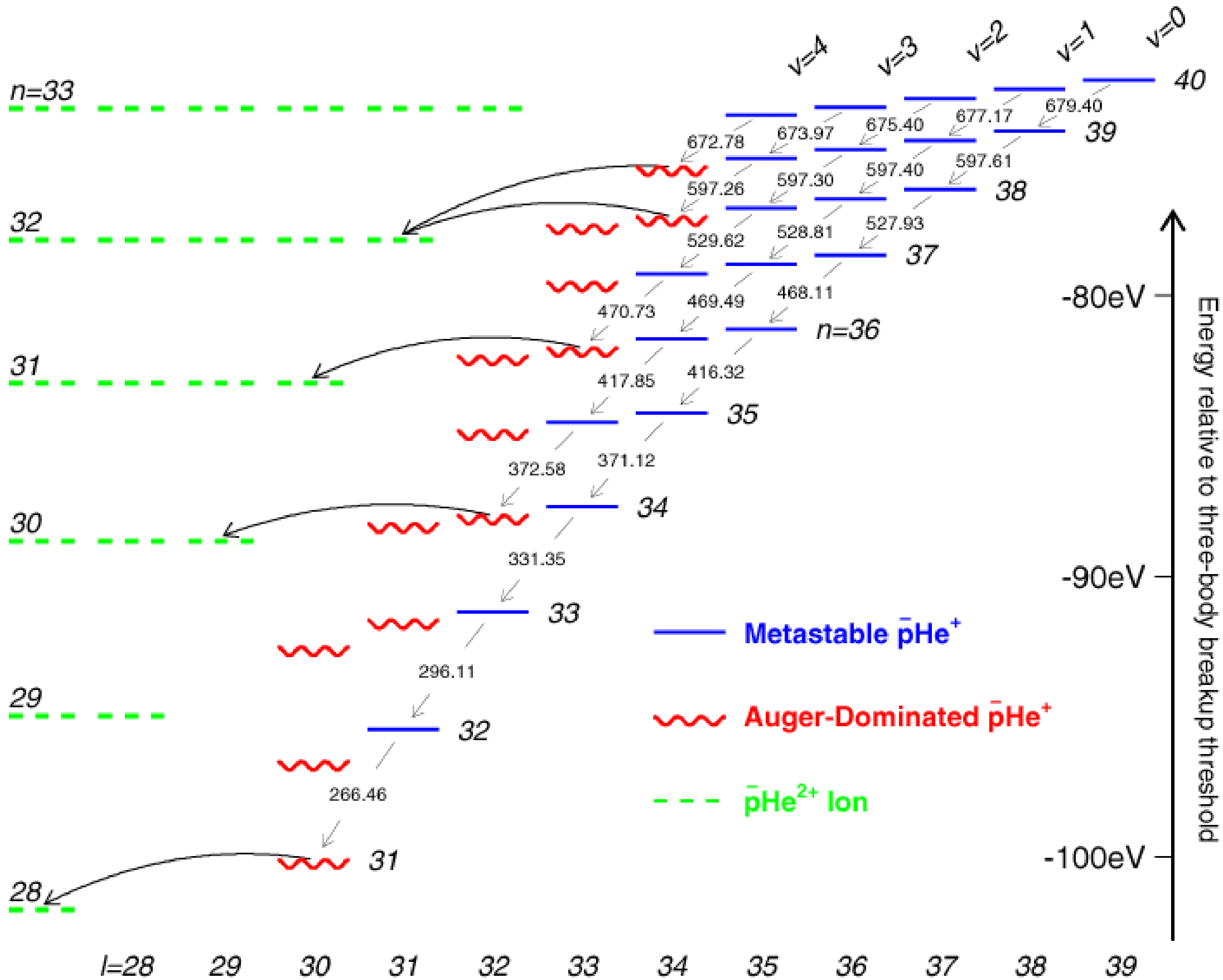






ALPHA Coll., „Observation of the hyperfine spectrum of antihydrogen," Nature **548** (2017) 66.

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



Level energies in eV, transition wavelengths in nm

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) $\rightarrow$ (n=34, l=32); $\Delta\nu = 6$ GHz
- Measured linewidth: ≈ 200 MHz
- Width: Residual Doppler broadening, hyperfine structure, Auger lifetime, power broadening.

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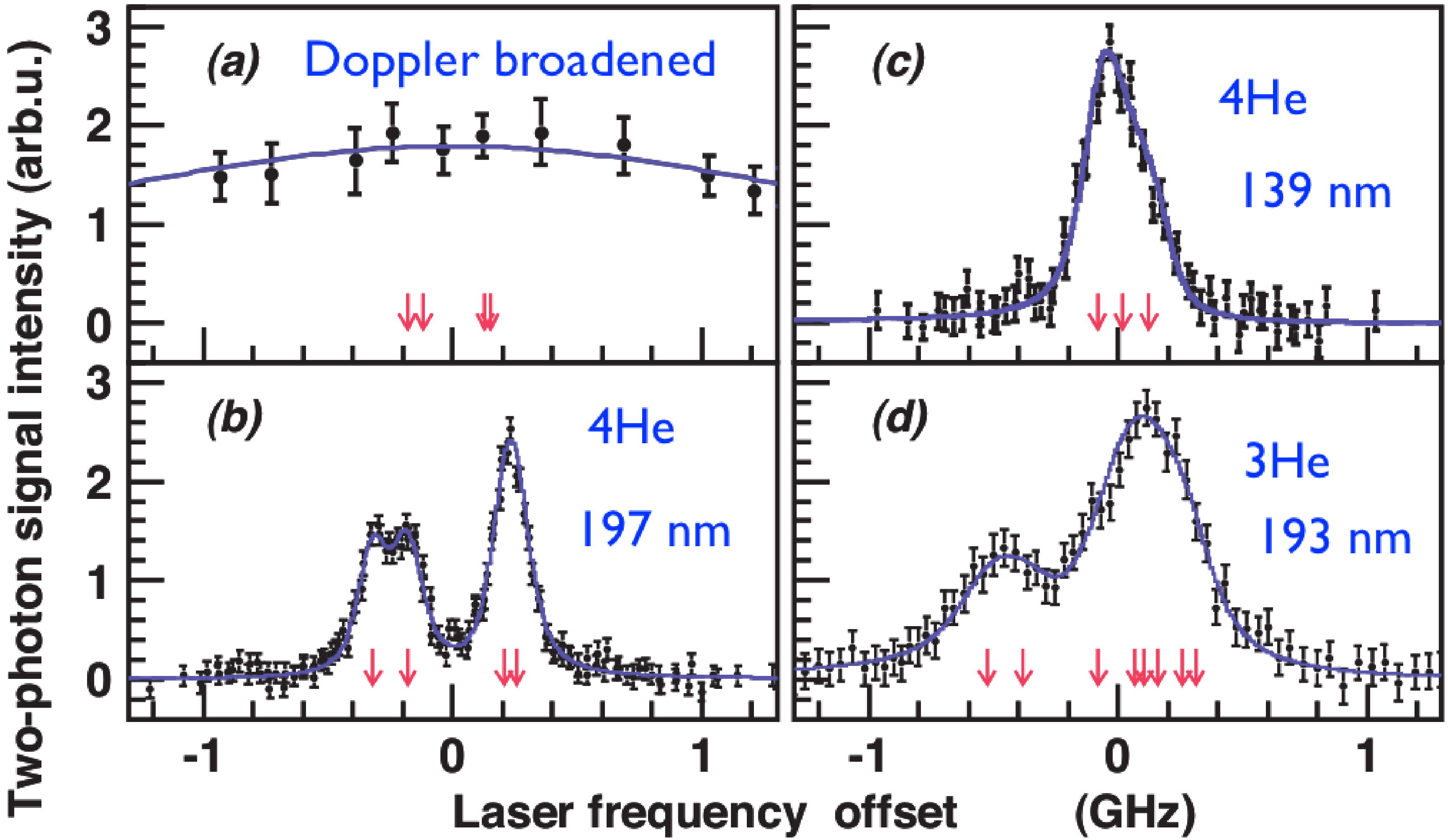
Two-photon spectroscopy: spectra



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

Arrows: hyperfine transitions