Particles and antiparticles

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Outline

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

Birth of antimatter

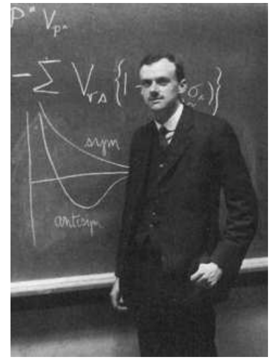
Paul Dirac, 1928: Linear equation for the hydrogen atom.

Square root of a quadratic equation ⇒ two solutions for electrons

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

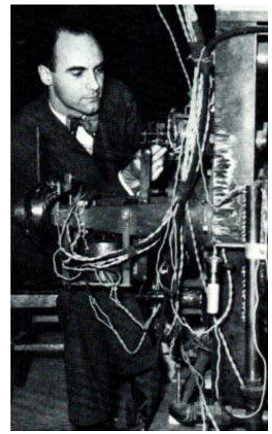
Negative mass non-physical.

Dirac: electron holes in Dirac sea of vacuum.



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

⇒ real existing particle: positron.



Nobel prizes: Dirac: 1933; Anderson: 1936

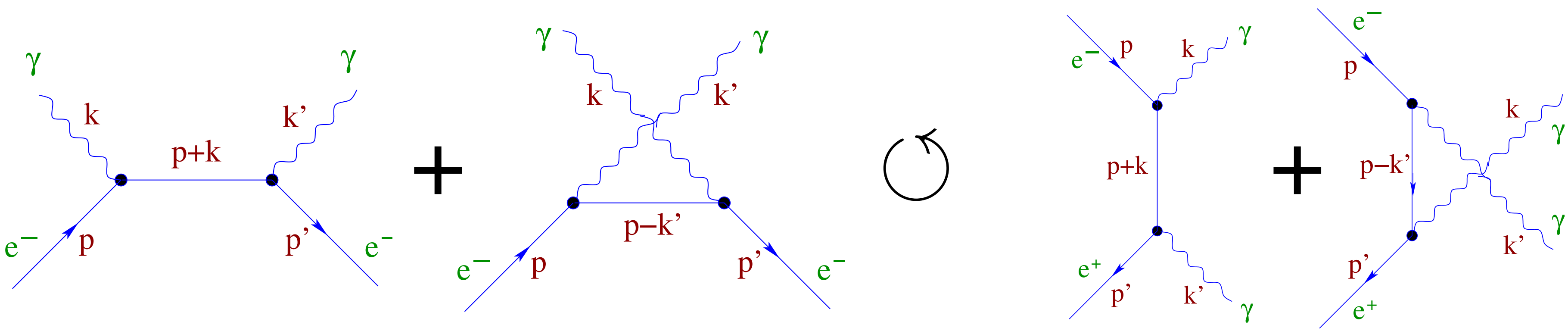
Richard P. Feynman: When I was a young man, Dirac was my hero. He made a breakthrough, a new method of doing physics. He had the courage to simply guess at the form of an equation, the equation we now call the Dirac equation, and to try to interpret it afterwards.

Stückelberg – Feynman interpretation

Feynman (1949) following Ernst Stückelberg (1941):

Dirac's negative energy states *appear in space-time ... as waves traveling away from the external potential backwards in time*.

Application and strong proof: Feynman diagrams



Compton scattering ⟲ positron annihilation

Diagram crossing (rotation)

Matter–antimatter symmetry

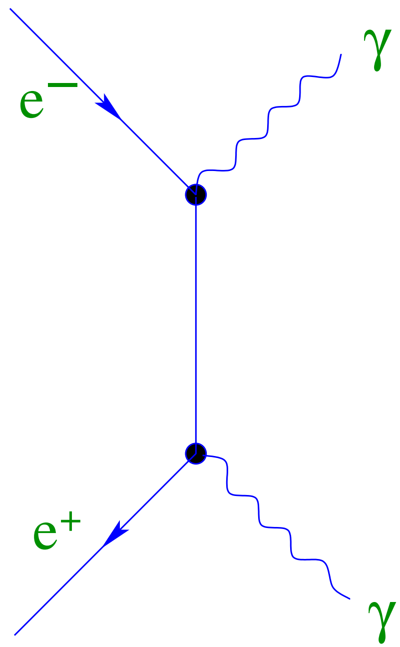
CPT invariance	Charge conjugation:	$C\|\mathrm{p}(r,t)> = \|\overline{\mathrm{p}}(r,t)>$
	Space reflection:	$P\|\mathrm{p}(r,t)> = \|\mathrm{p}(-r,t)>$
	Time reversal:	$T\|\mathrm{p}(r,t)> = \|\mathrm{p}(r,-t)> K$

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

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

What does CPT state?

Equivalence for **free** particles and antiparticles.

Interactions?

- Gravity is OK as long as masses are equal (so far yes).
- 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.

C is the key transformation for particle $\leftrightarrow$ antiparticle

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 is reversed for antiparticles

Fermion $\Rightarrow$ antifermion: Left $\Rightarrow$ Right and Right $\Rightarrow$ Left!

Massive neutrinos??

Antimatter questions

- What does the standard model say about antiparticles, are they really identical apart from the signs of their charges?
- 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? Neutrinos?
- 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: $\mu^+ \rightarrow \mathrm{e}^+ \nu_\mathrm{e} \overline{\nu}_\mu \leftrightarrow \mu^- \rightarrow \mathrm{e}^- \nu_\mu \overline{\nu}_\mathrm{e}$

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.)

Do charges make the difference?

Charges are the sources of interactions.

- Colour $\rightarrow$ strong force, derived from local $SU(3)_C$.
- Weak isospin T, the source of all charged and part of neutral weak currents, derived from local $SU(2)_L$ (where L stands for left-handedness).
- Weak hypercharge: $Y = 2(Q - T_3)$ (Q: electric charge and T_3: weak isospin's 3rd comp.) This is the source of local $U(1)_Y$: electromagnetism and part of neutral weak currents.

E.g. **electron** charge:
In QFT it has nonzero eigenvalues for charge operators:
$Q = -1,\ T_3 = -\frac{1}{2},\ Y = -1$, lepton nr. = +1.

Zero values for baryon nr.,colour, and quark flavour.

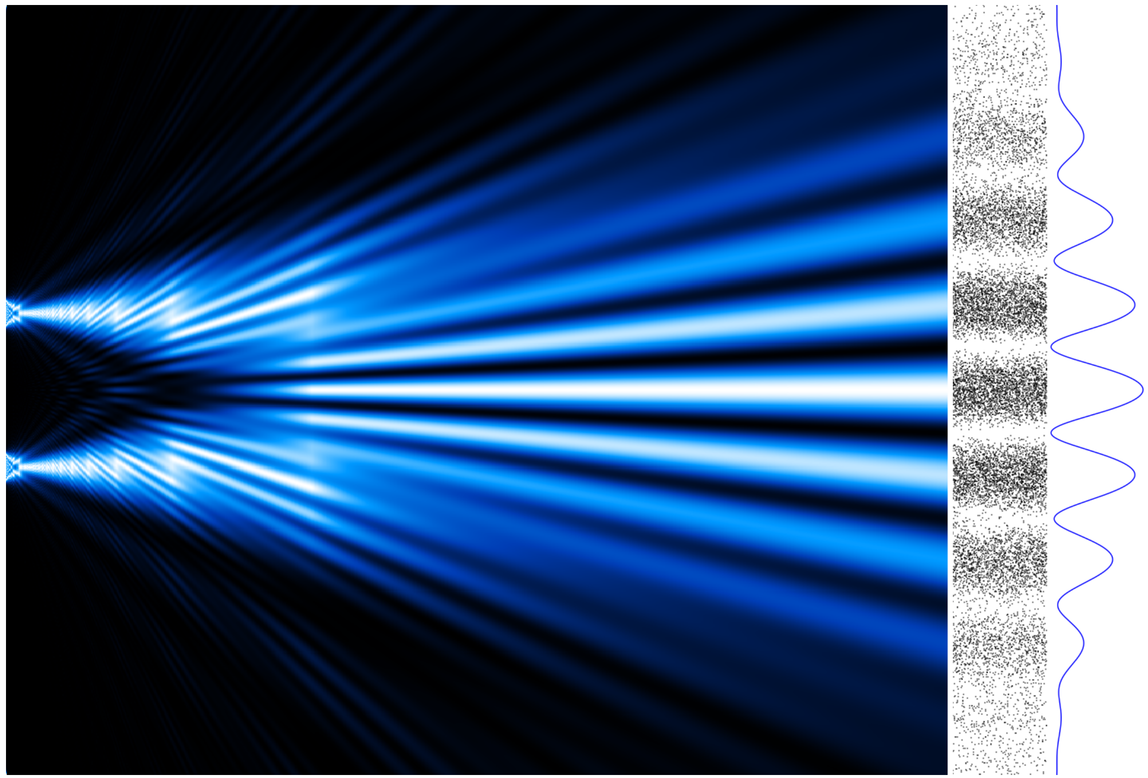
WIGNER

What is the charge?

Parameter coupling the particle with the external field.
Double-slit expt.: electron is in interference with itself.
Its charge is the interaction strength with the field, not an intrinsic physical quantum number (not constant!).

Double-slit interference measurement with single electrons

Jonsson (1974) and Tonomura (1989)



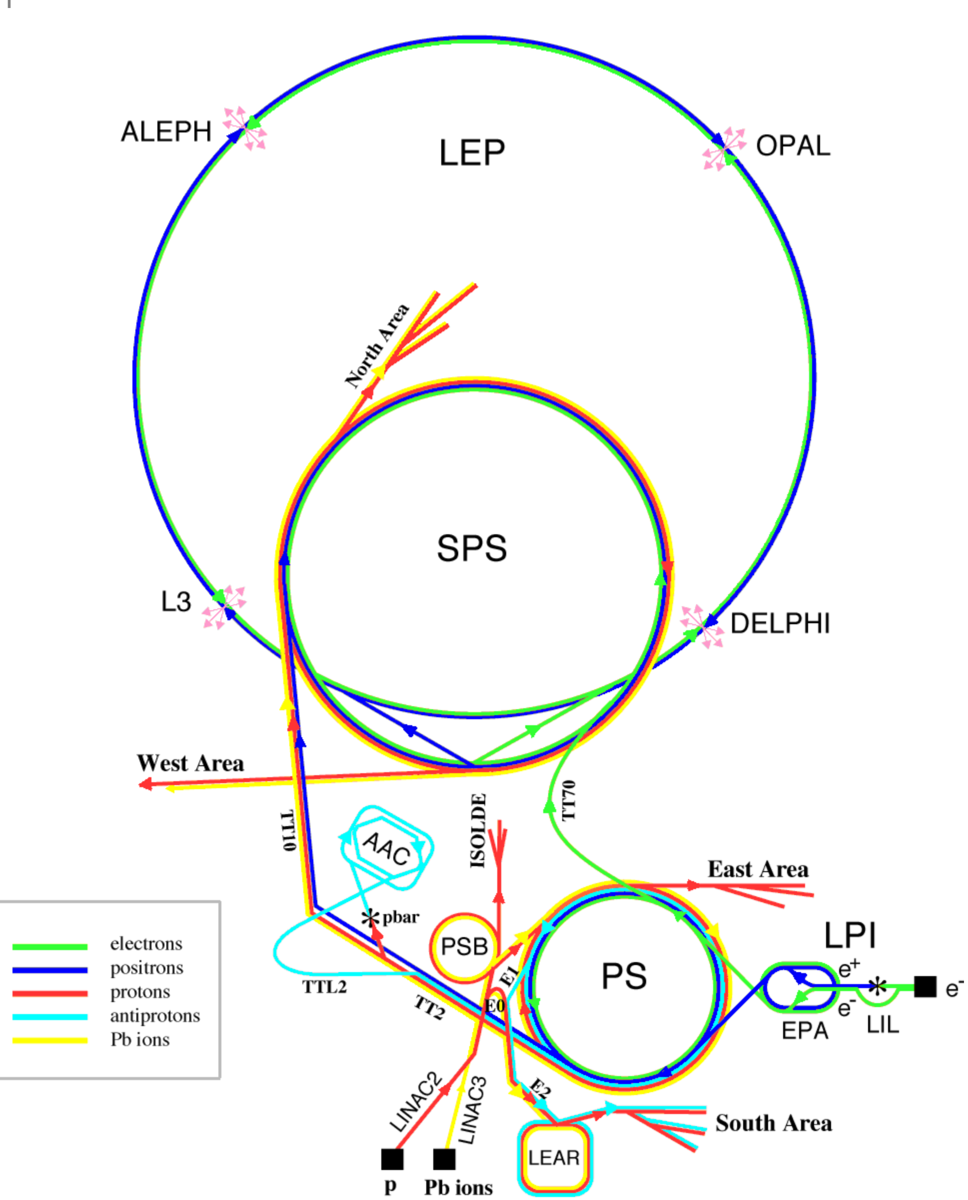
How to test CPT?

Particle = – antiparticle ?

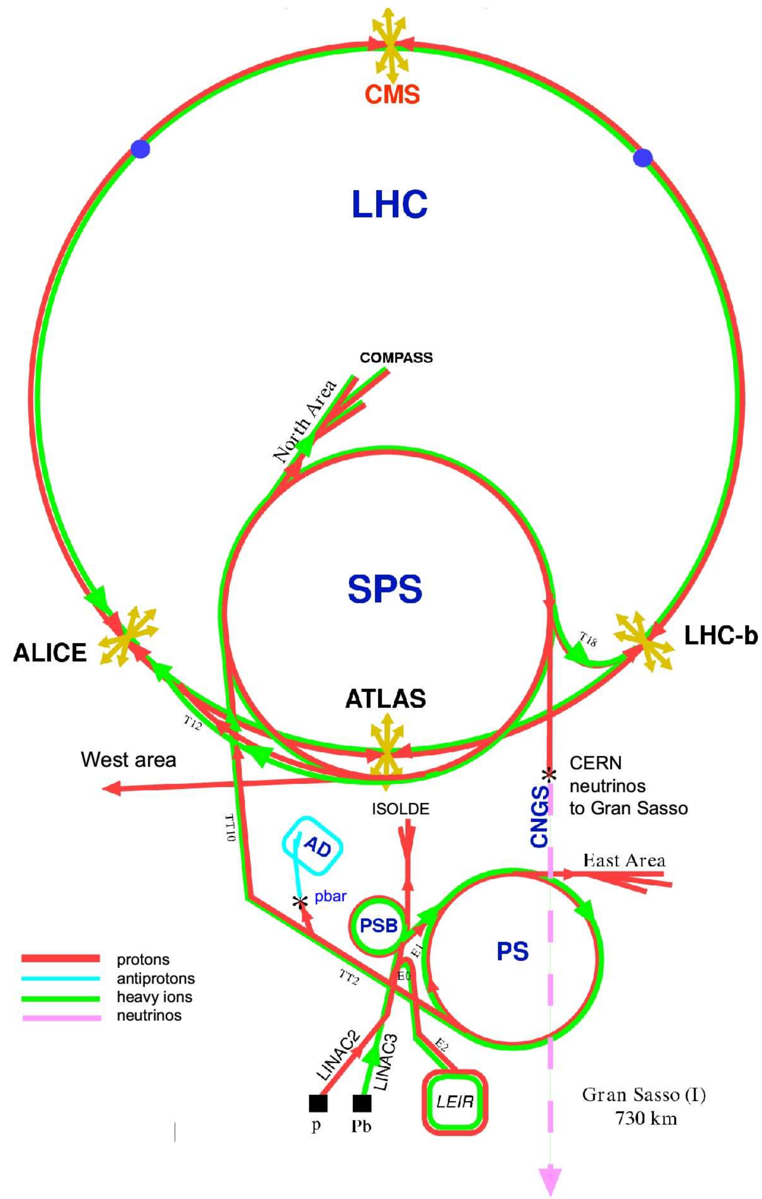
- $[m(\mathrm{K}^0) - m(\overline{\mathrm{K}}^0)]/m(\mathrm{average}) < 10^{-18}$
- proton $\sim$ antiproton? (compare m, q, $\vec{\mu}$)
- hydrogen $\sim$ antihydrogen ($\overline{\mathrm{p}}e^+$)? $2S - 1S$, HFS

Accelerators at CERN

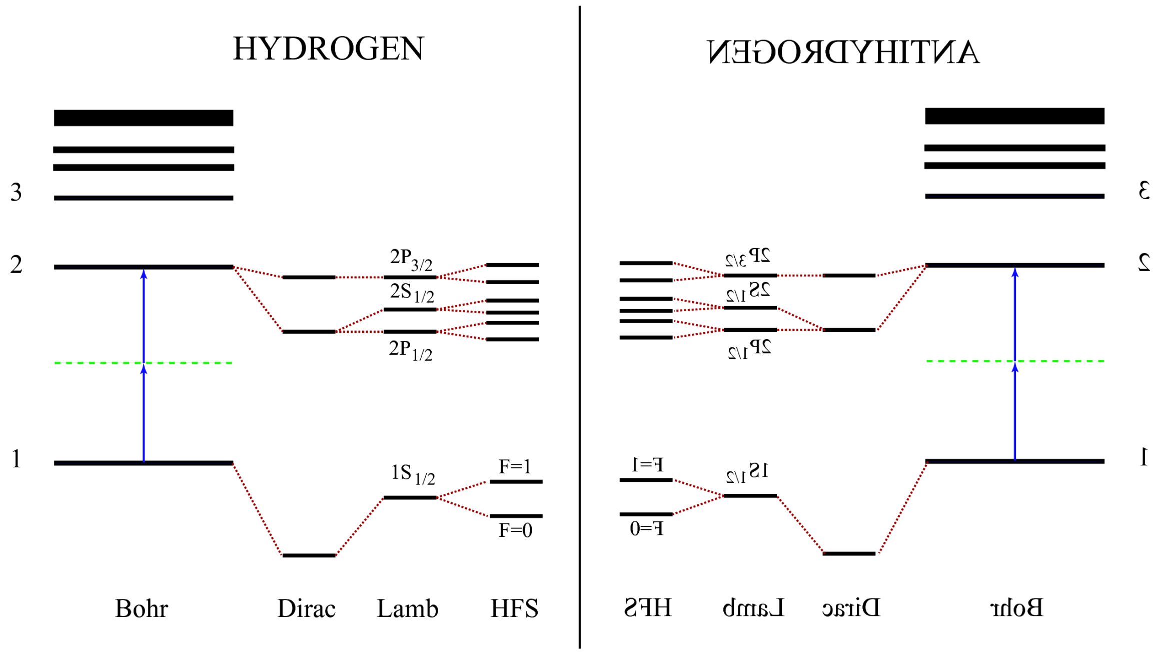
1989–2000



2009–2035??



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



$2S - 1S$ transition

with 2-photons

Long lifetime,

narrow transition,

Doppler-free

spectroscopy

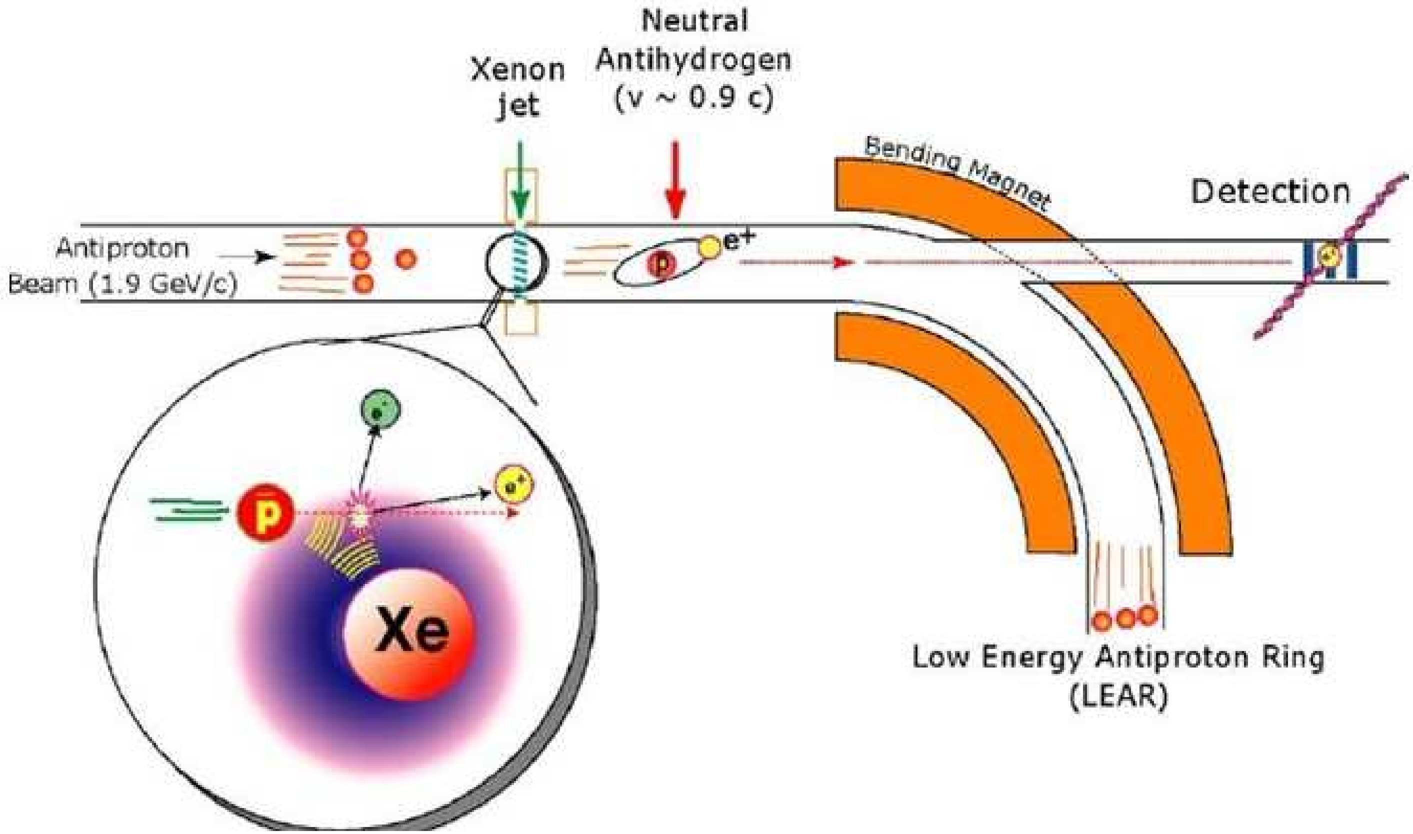
Feasibility study for the SPSL Committee of CERN (1992) converted into

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:

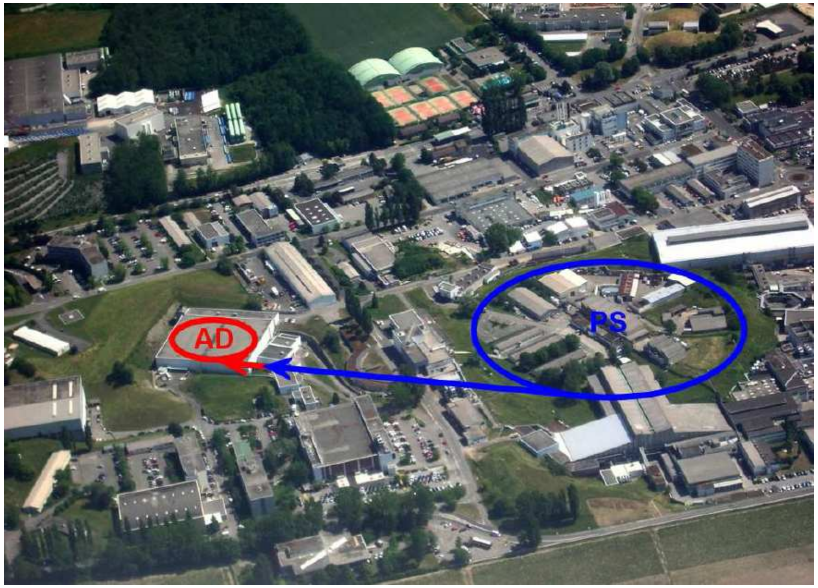
G. Blanford *et al.*, „Observation of atomic anti-hydrogen," Phys. Rev. Lett. **80** (1998) 3037.

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



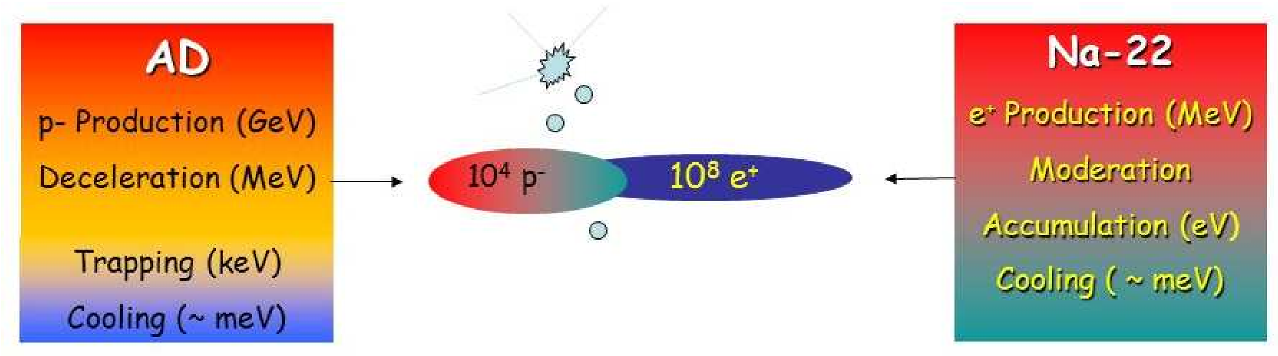
©Ryugo S. Hayano, Tokyo U.

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

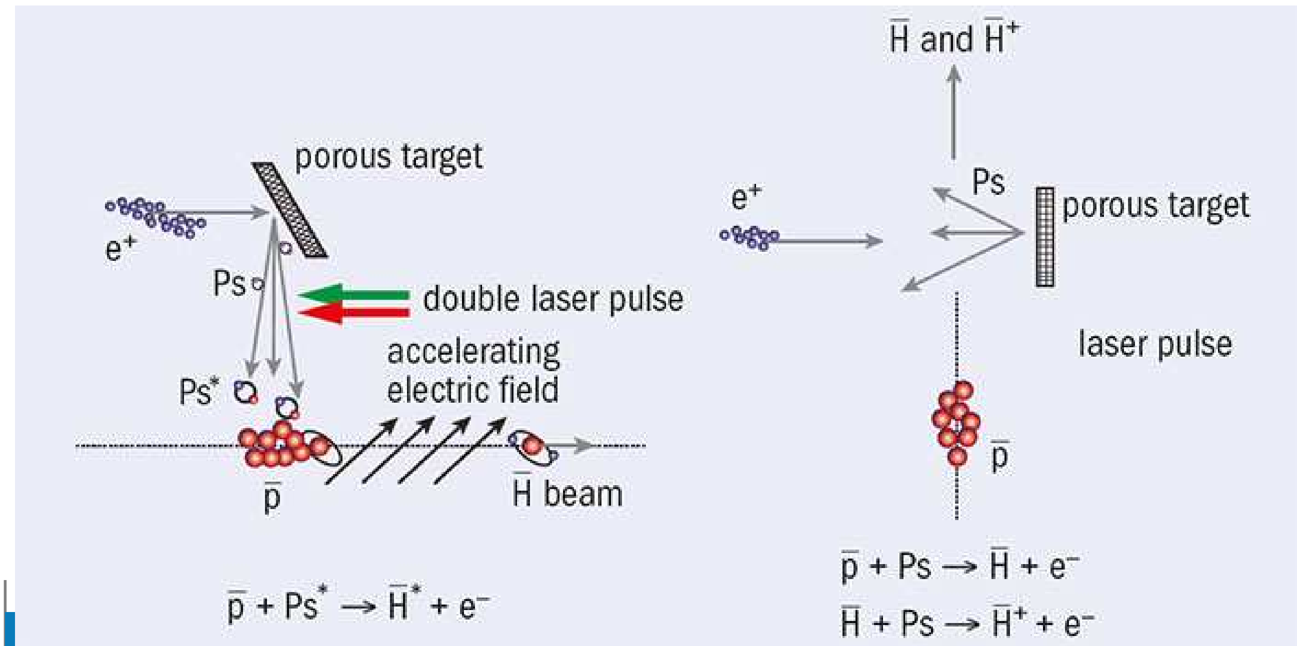
How to produce antihydrogen?



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

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

Proposed by G. Gabrielse, ATRAP & Harvard U.

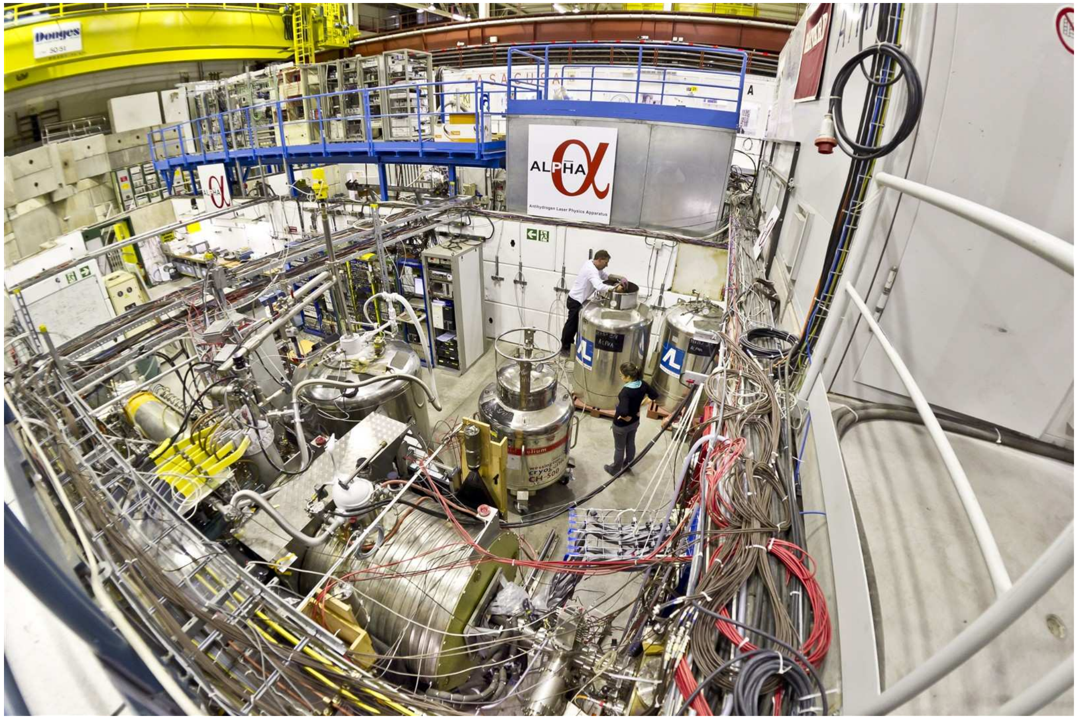


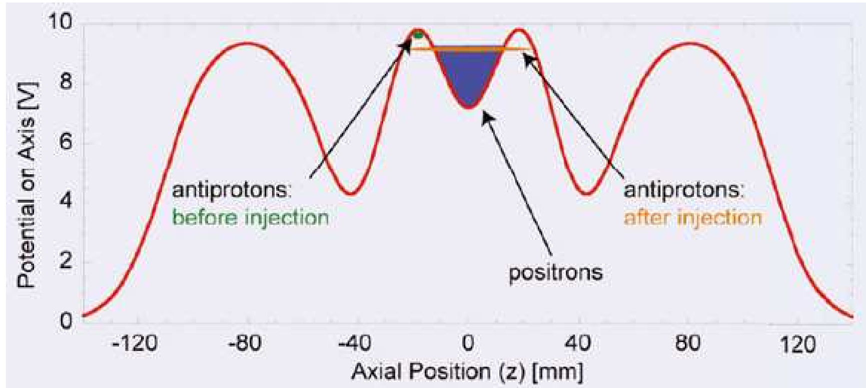
With excited positronium: high rate, deep bond (planned)

Proposed by B. Deutch et al., Aarhus

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.

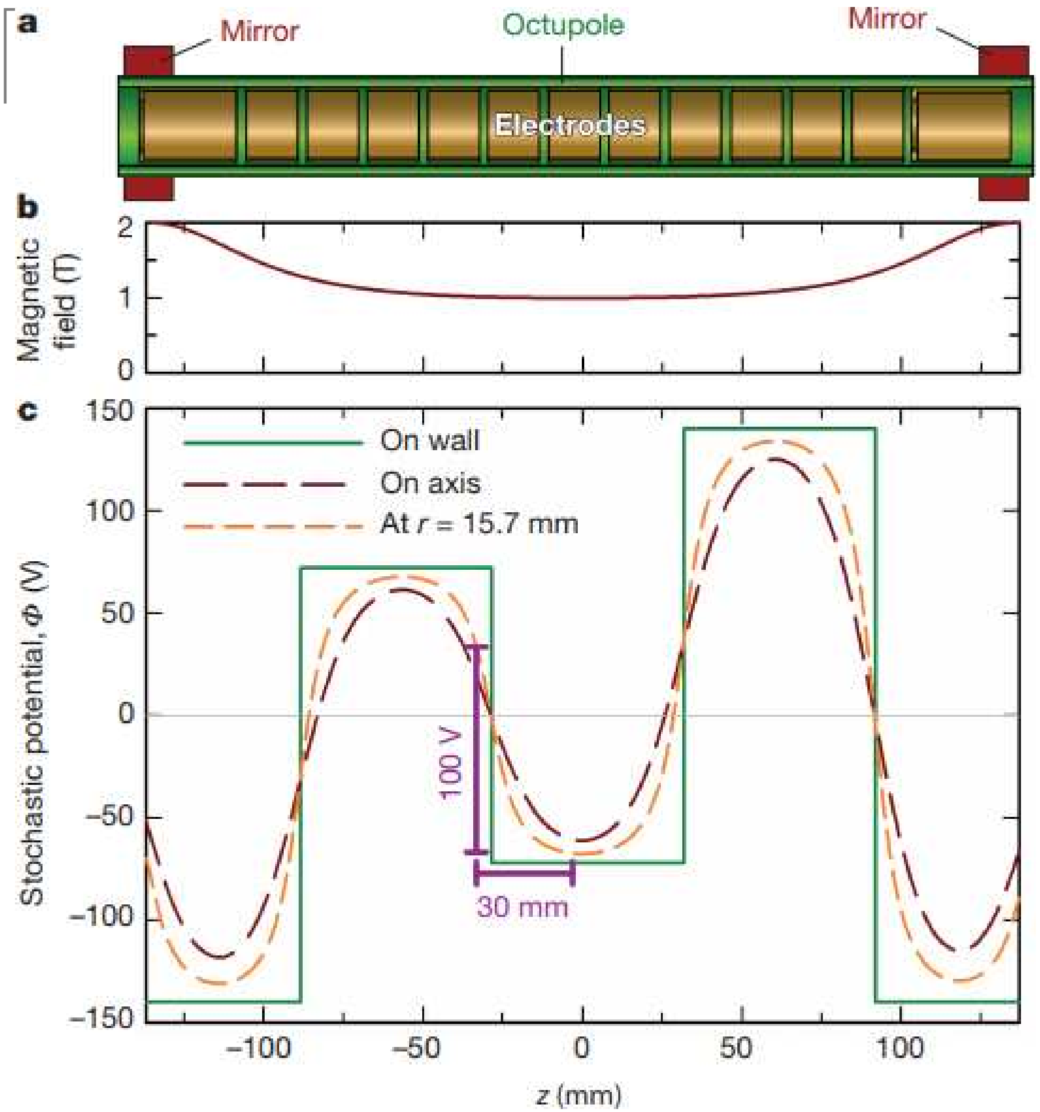
$\overline{\mathrm{H}}$ kept trapped for 10 s $\Rightarrow$ waiting deexcitation to $1S$ ground state.

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

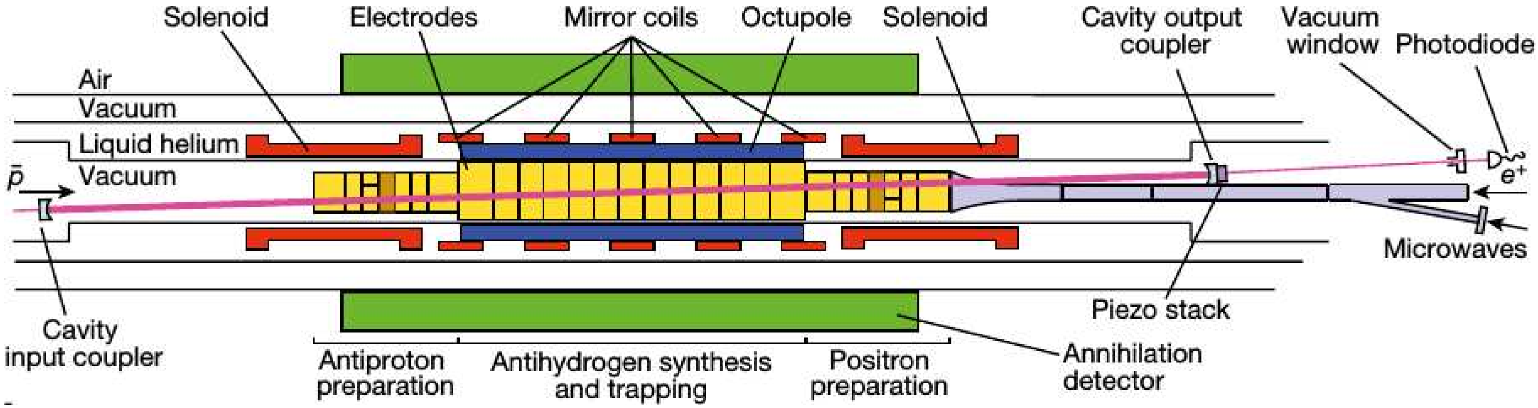
Result: $|Q| < 0.71 \times 10^{-9}$

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

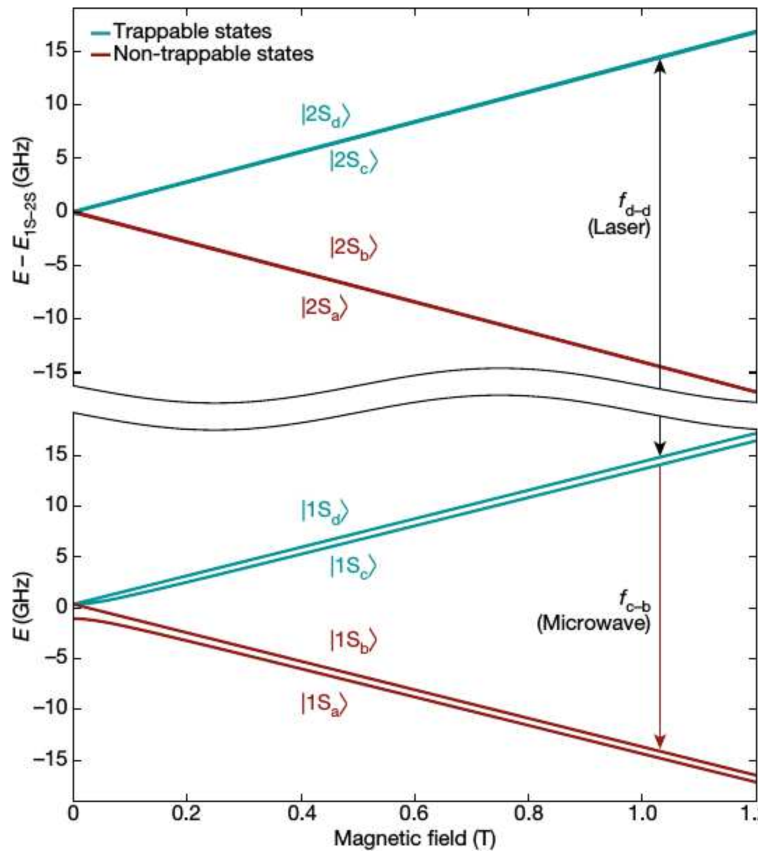
(standing wave for 300 s) tuned around

resonance (appearance).

Use microwave to remove residual $1S$ atoms

(disappearance).

Flush trap by dropping B (residuals).



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

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

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

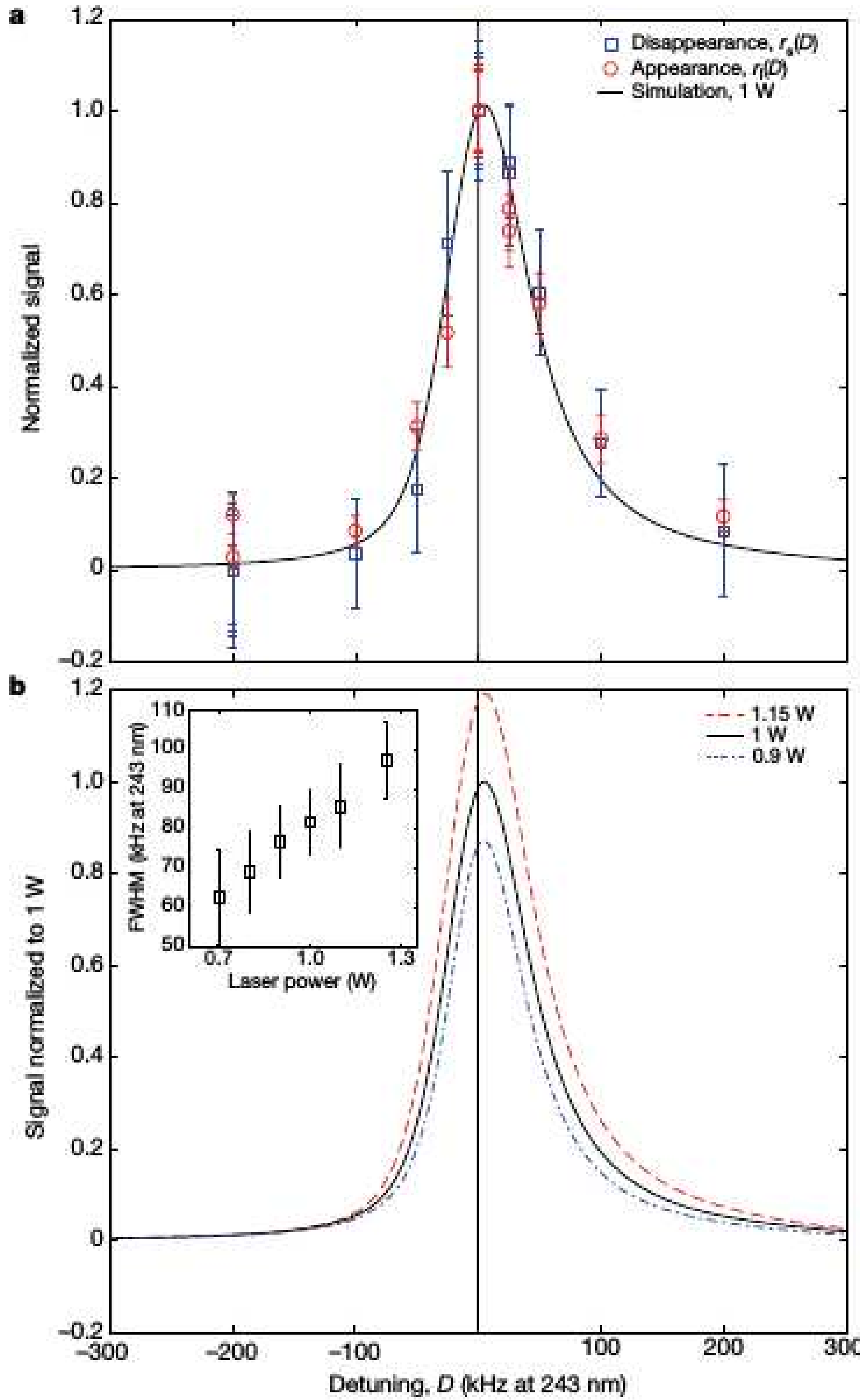
For hydrogen:

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

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),

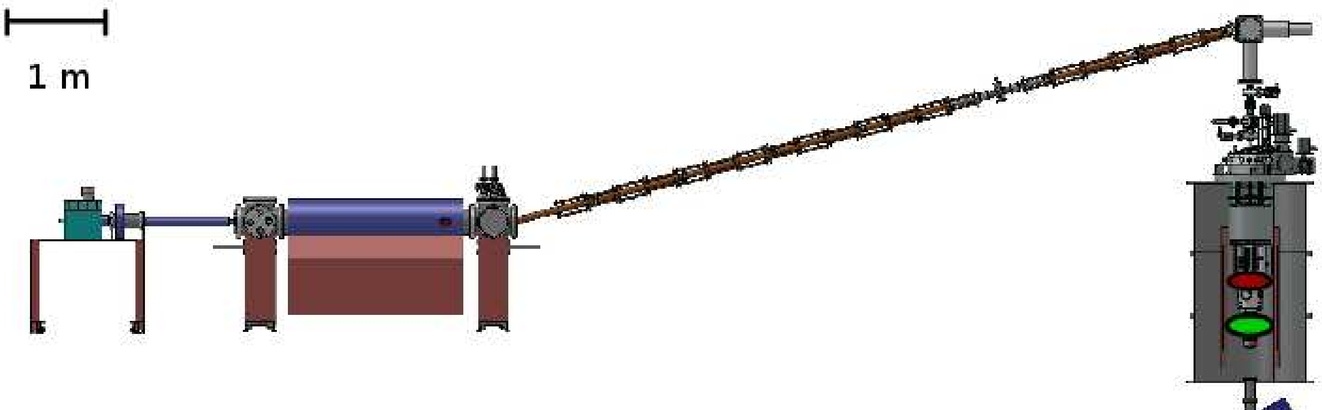
Characterization of the 1S-2S transition in antihydrogen,

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.

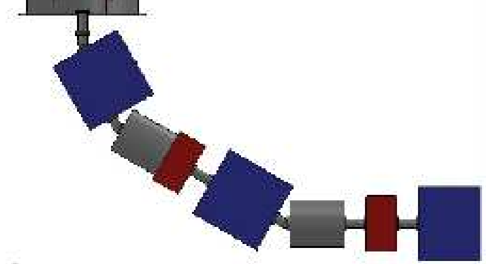
Reviewer information *Nature* thanks D. Horvath, K. Jungmann and the other anonymous reviewer(s) for their contribution to the peer review of this work.

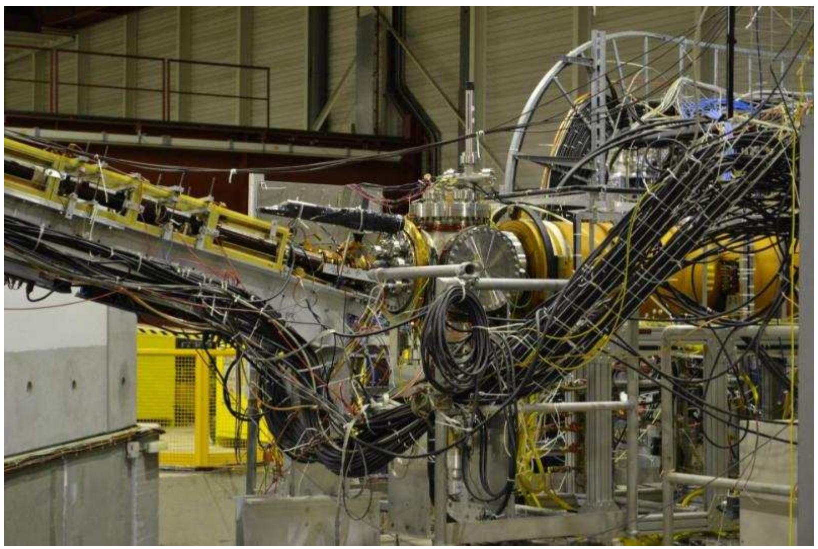
ATRAP: Antimatter trap

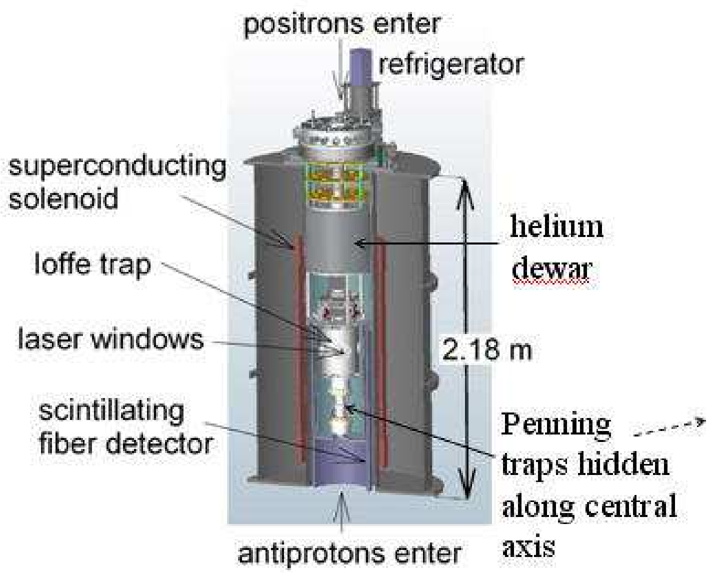


4×10^9 e$^+$ ($T = 1.2$ K, $p < 6 \times 10^{-17}$ Torr)

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

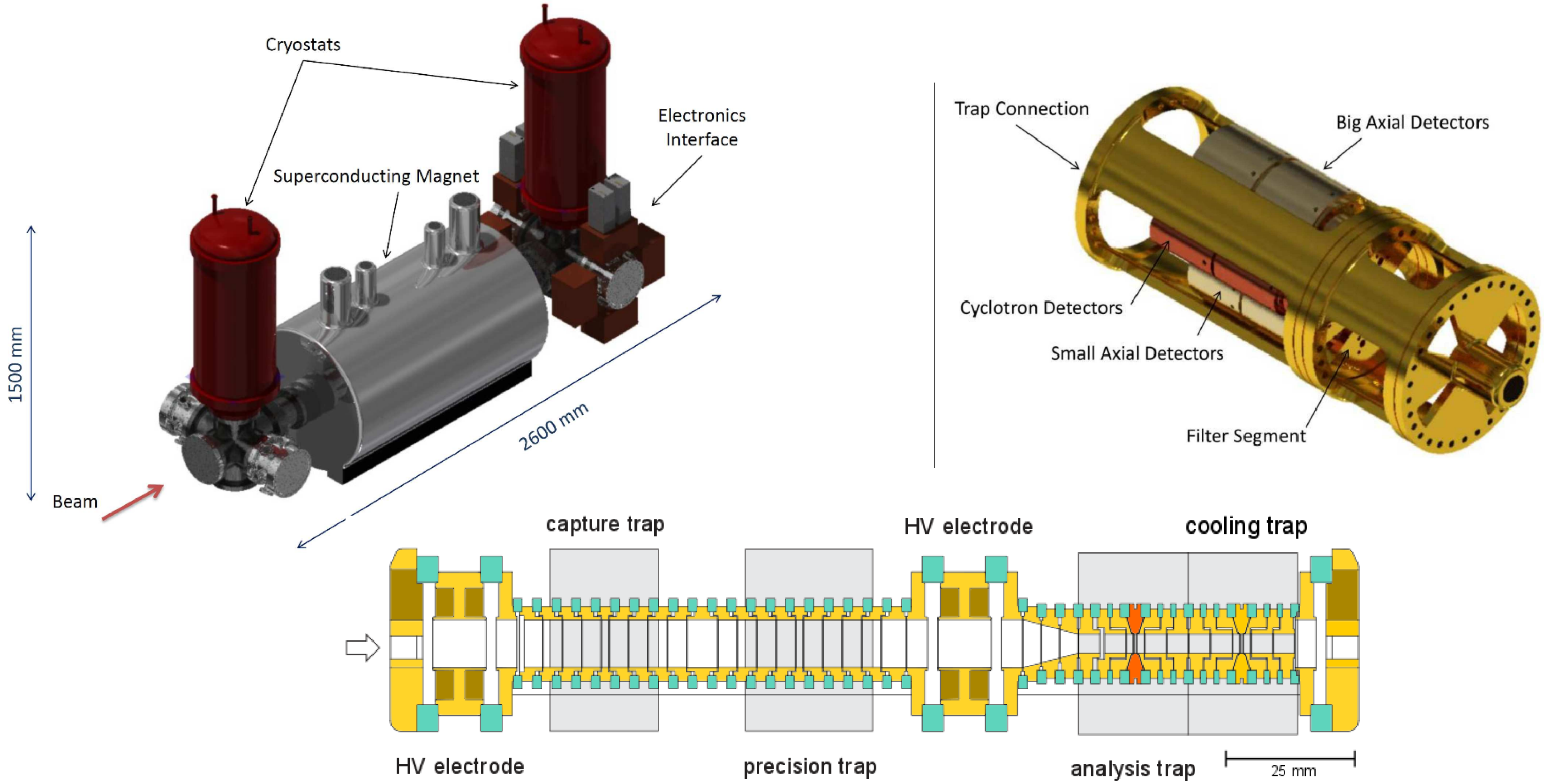






BASE: Baryon Antibaryon Symmetry Experiment

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

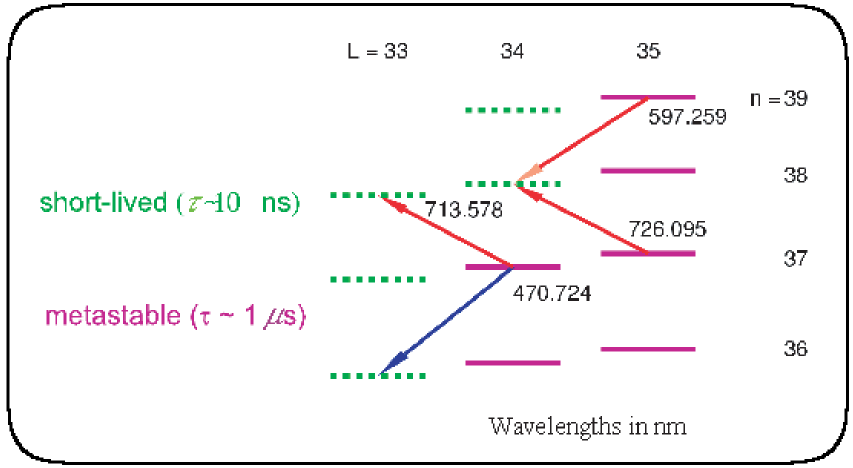
5.8 MeV $\overline{\mathrm{p}}$ injected into RFQ
100 keV $\overline{\mathrm{p}}$ injected into trap
10^6 $\overline{\mathrm{p}}$ trapped and cooled (2002)
~ 350000 slow $\overline{\mathrm{p}}$ extracted (2004)
Cold $\overline{\mathrm{p}}$ compressed in trap (2008)
$(5 \times 10^5\ \overline{\mathrm{p}},\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

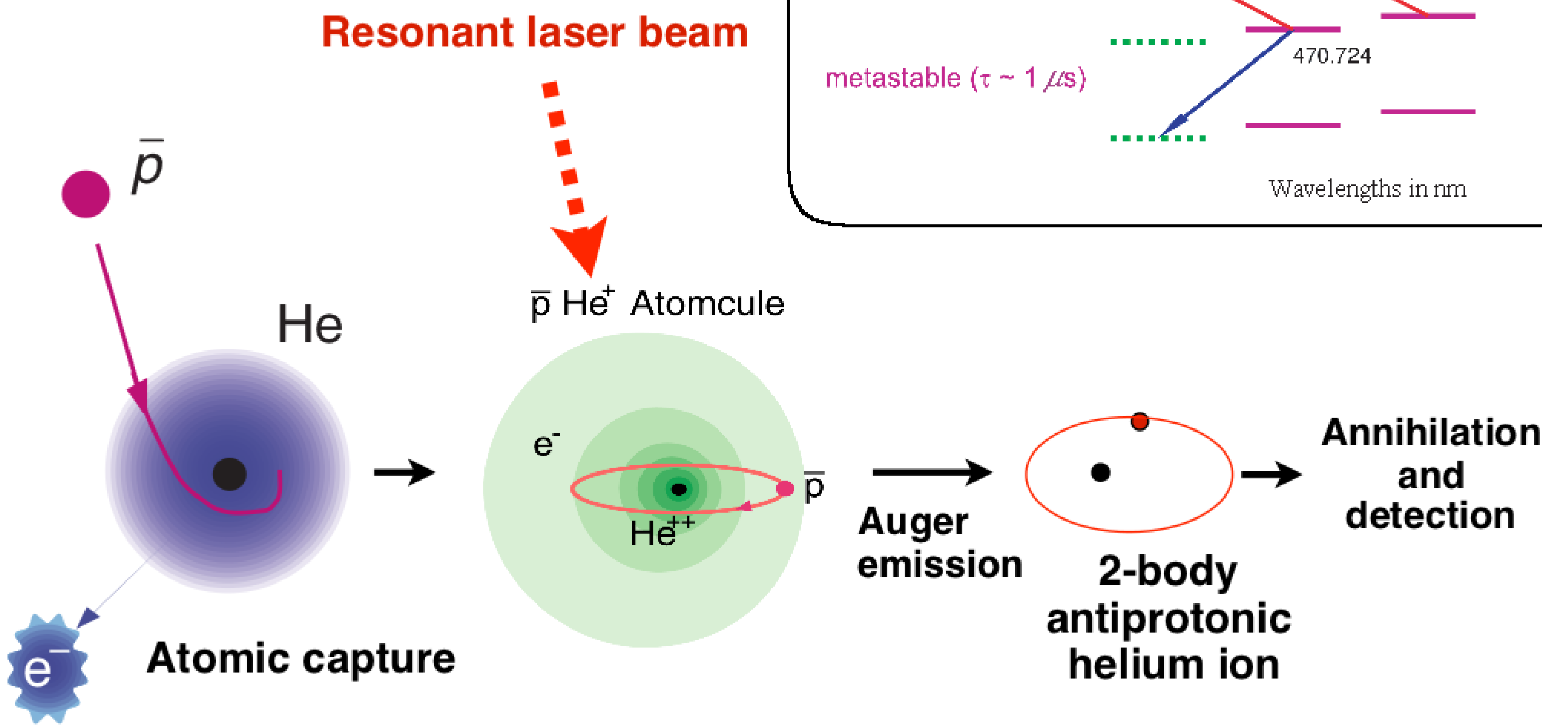
N. Kuroda *et al.*, Nature Commun. **5** (2014) 3089.

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 $\Rightarrow$ prompt annihilation

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

Negative masses?

Particle masses are due to interactions,
masses are couplings in energy units (Hamiltonian).

Negative masses for antiparticles: math. artifacts

The BEH mechanism allows us to add mass terms to the Lagrangians for the quarks and charged leptons (not for the neutrinos) with arbitrary couplings. We choose the same positive values for particles and antiparticles (CPT !). The masses of the elementary bosons are determined and of the hadrons are mostly energy-related.

Wrong-handed (sterile) neutrinos have no interaction in the SM, so should have neither attached charged leptons, nor masses. Possible solutions: Majorana neutrinos or additional interaction.

Majorana particle: its own antiparticle. No observation in double beta-decay expts.

However, negative masses sound exciting, especially for gravity.

Antimatter gravity?

Flying saucer steals a cow

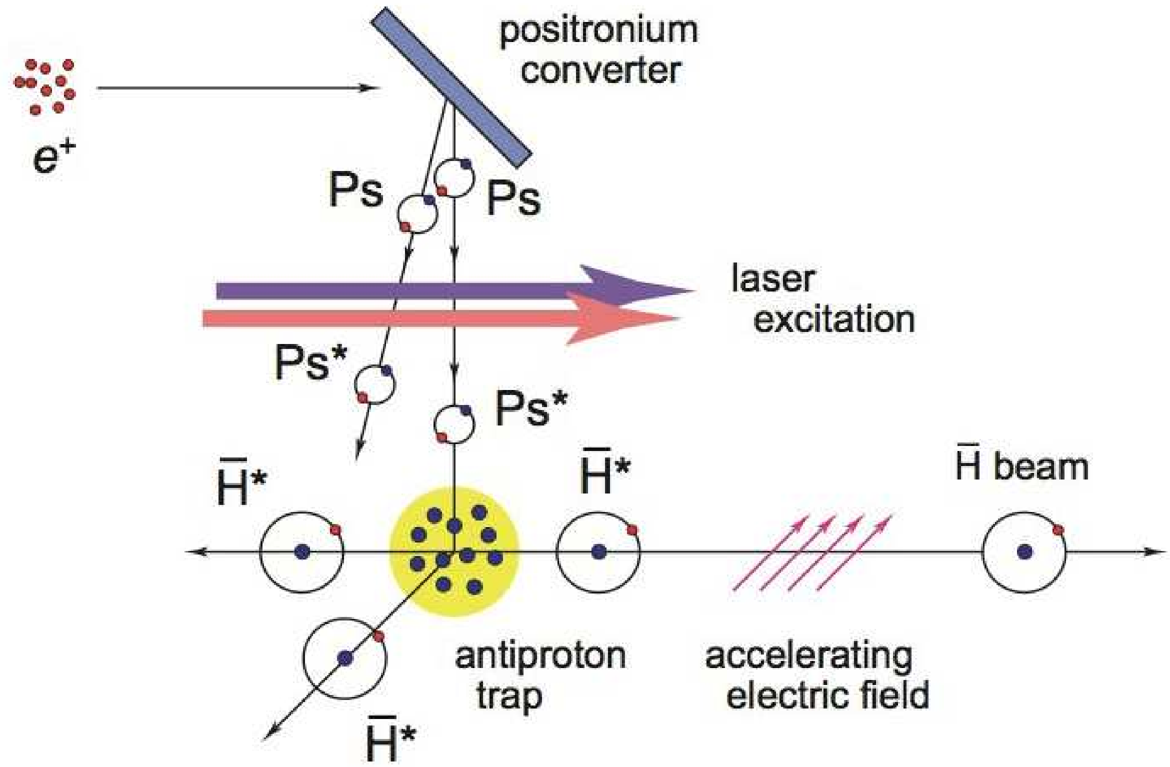
Negative mass $\Rightarrow$ repulsive gravity??

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

Not CPT: weak equivalence principle

AEGIS: antimatter gravity

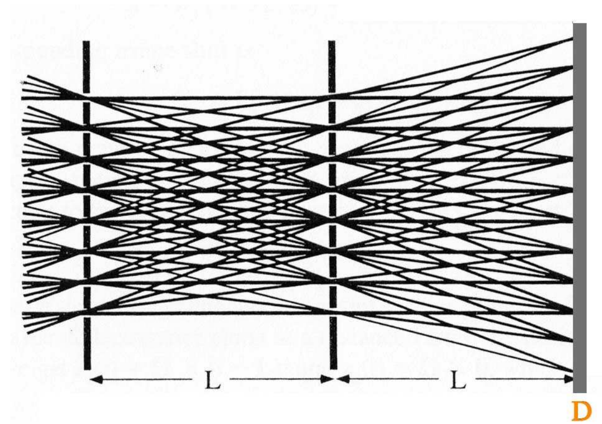
Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy (in preparation, 77 authors)



Moiré deflectometry:

gravitational falling of collimated $\overline{\mathrm{H}}$

as compared to light

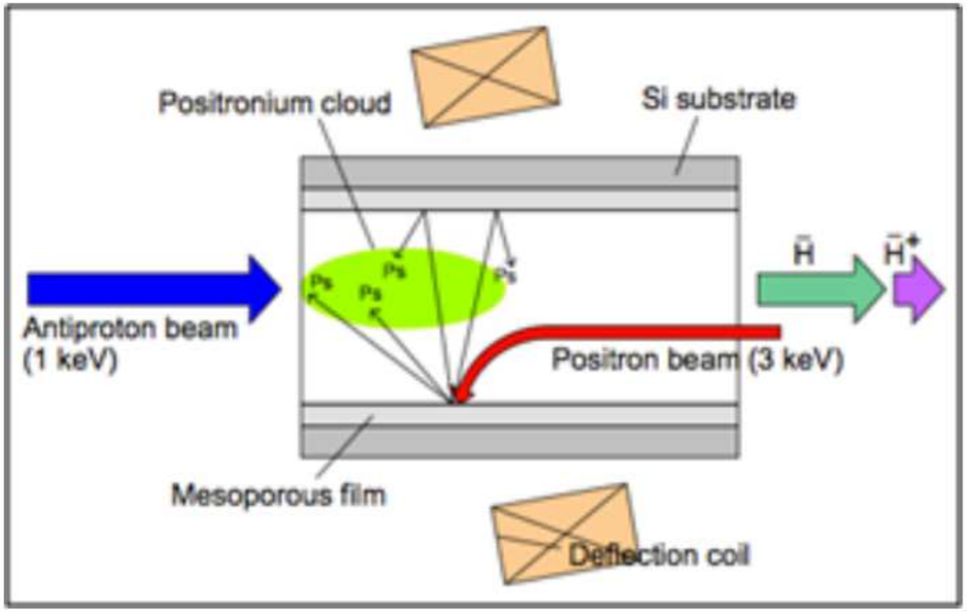


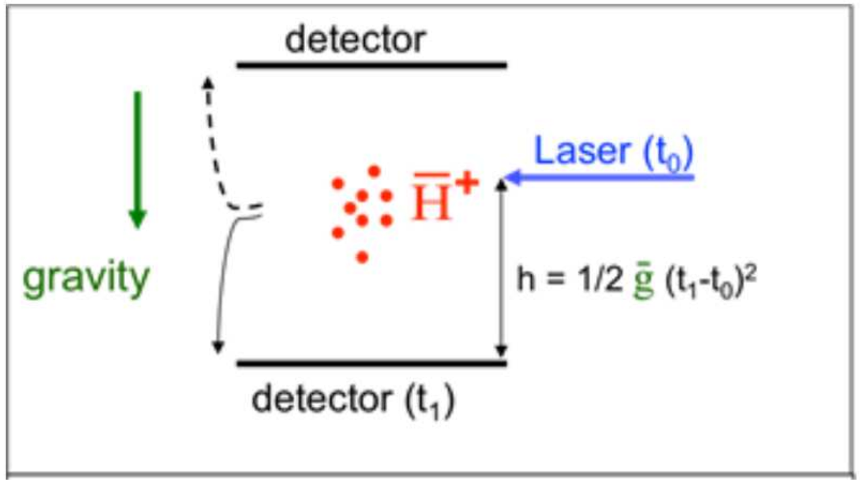
$\overline{\mathrm{H}}$ production with Ps proven

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

GBAR

Gravitational Behaviour of Antihydrogen at Rest
(in preparation)

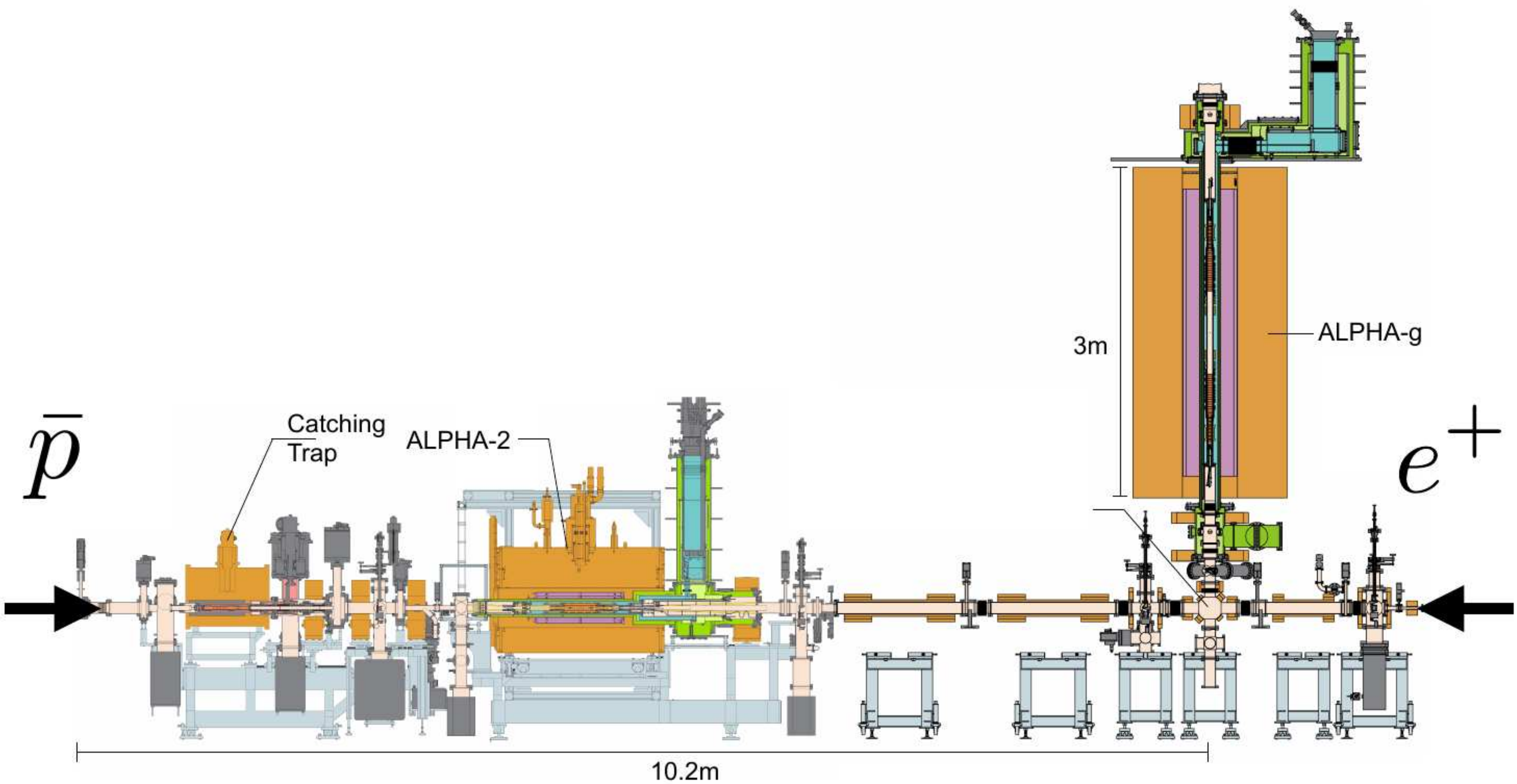




$\overline{p}$ + Ps $\rightarrow \overline{H}$; $\overline{H}$ + Ps $\rightarrow \overline{H}^+$ (cooling); back to $\overline{H}$: let it fall

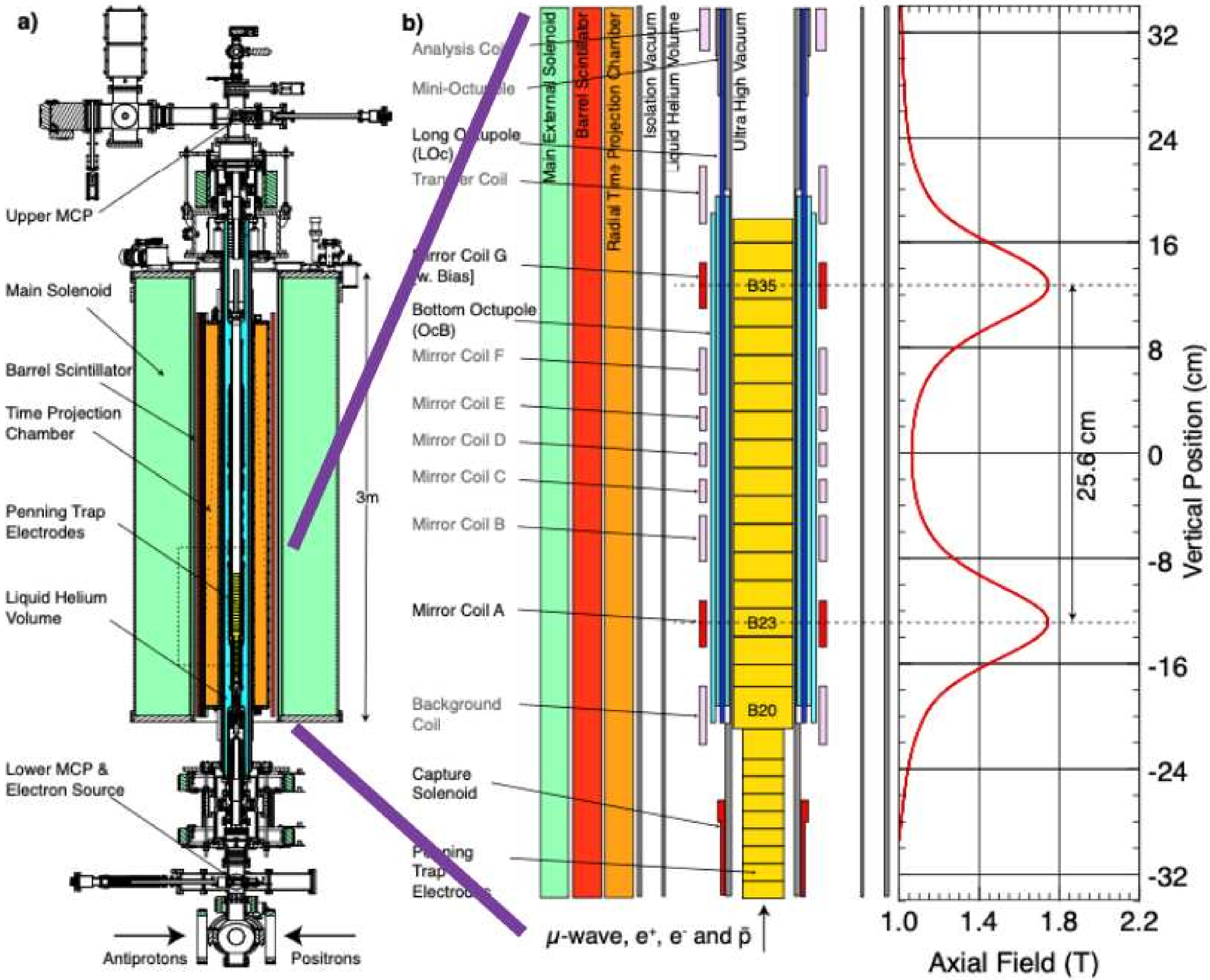
ALPHA setup, 2022

ALPHA as installed, 2022



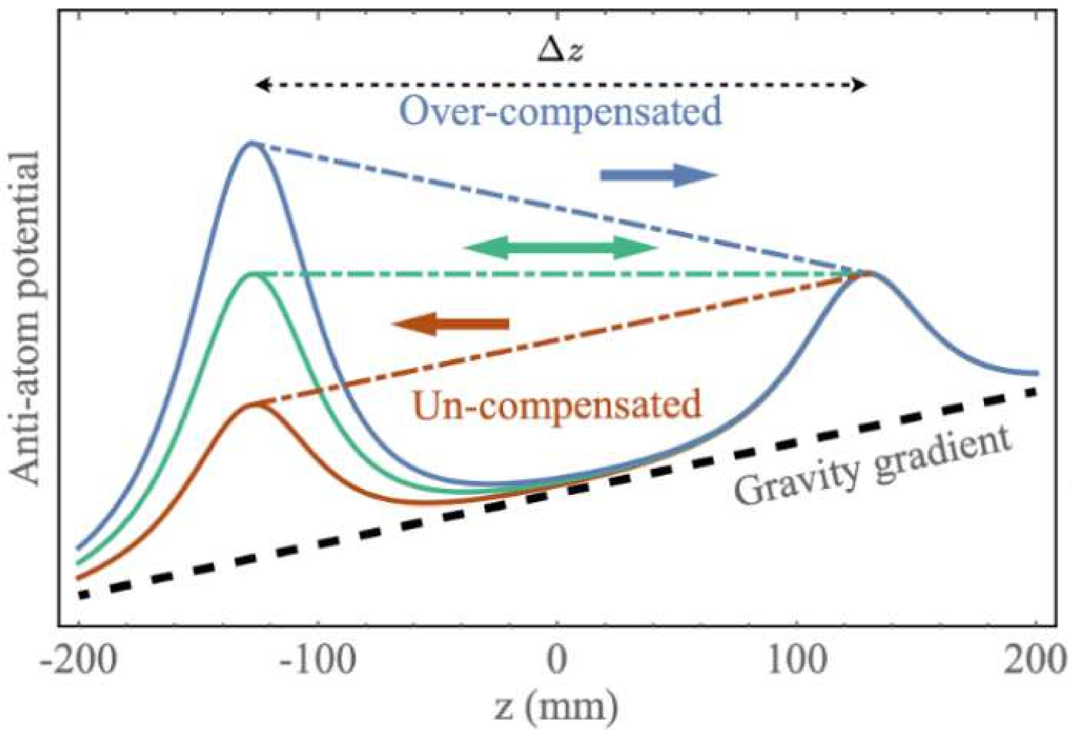
ALPHA-gravity: setup

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.

Dark matter

25 % of gravity of the Universe is due to dark matter.
Cannot be ordinary neutrinos: too light and too mobile.
Beyond the standard model.

Supersymmetric extensions produce such particles: neutralinos, fermion partners of our bosons. Problem: fermions do, elementary bosons do not have antiparticles, so neutralinos must be Majorana particles. That is why they do not form dark stars or black holes.

Sterile neutrino is good, too, with large enough mass.

Lack of antimatter in the universe

Where did it go after the radiation stage?

6×10^{-10} parts more particles than antiparticles had to be created in our universe.

Many extensions of the SM, some even assuming a little CPT violation.

In addition to the CERN antiproton experiments, KLOE-2 looks at the kaon sector for CPT violation.

Antimatter in Space

AMS-2: Alpha Magnetic Spectrometer

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

Mass: 8500 kg,

1200 kg perm. magnet

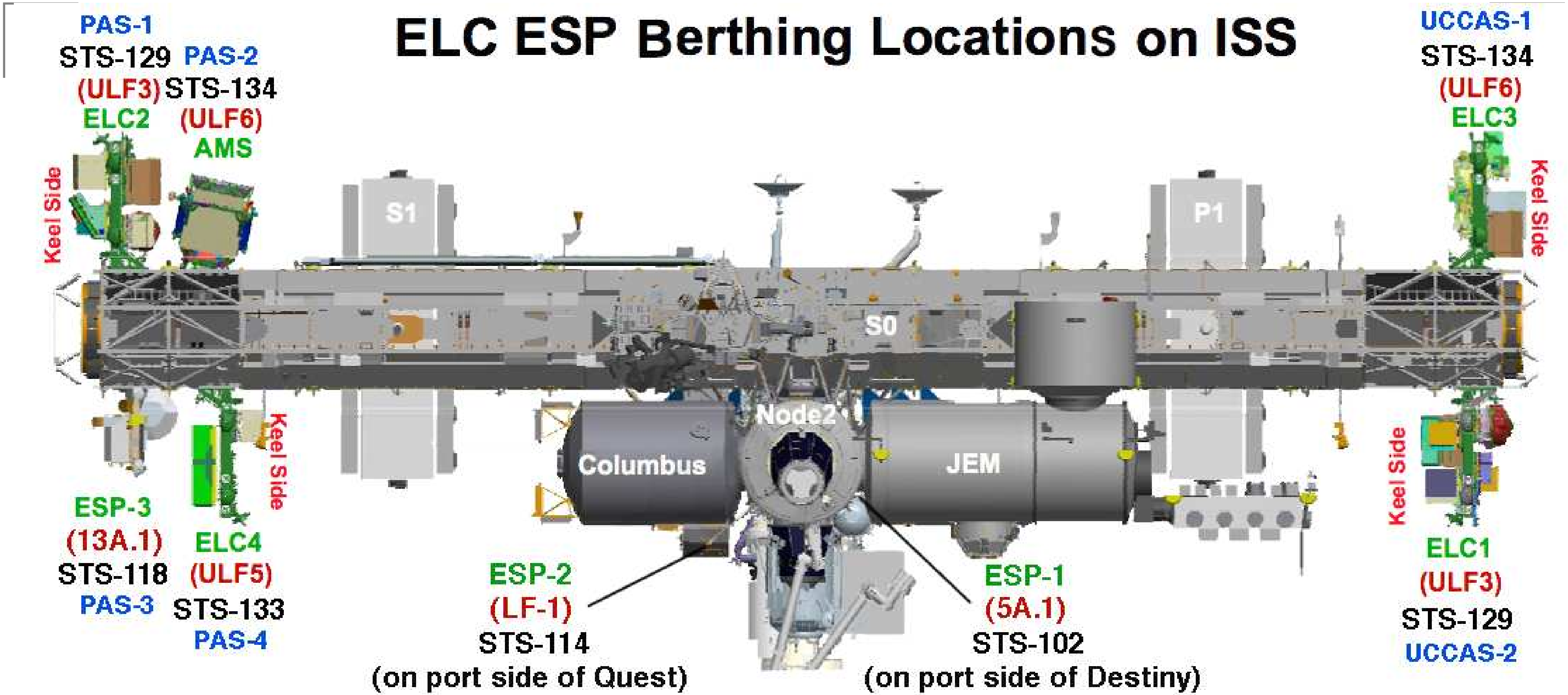
Father: Sam Ting, cost: 2 G$

Construction: CERN

Launch: May 2011, USA

Control room at CERN

AMS-2: Alpha Magnetic Spectrometer



First results (2015-17):

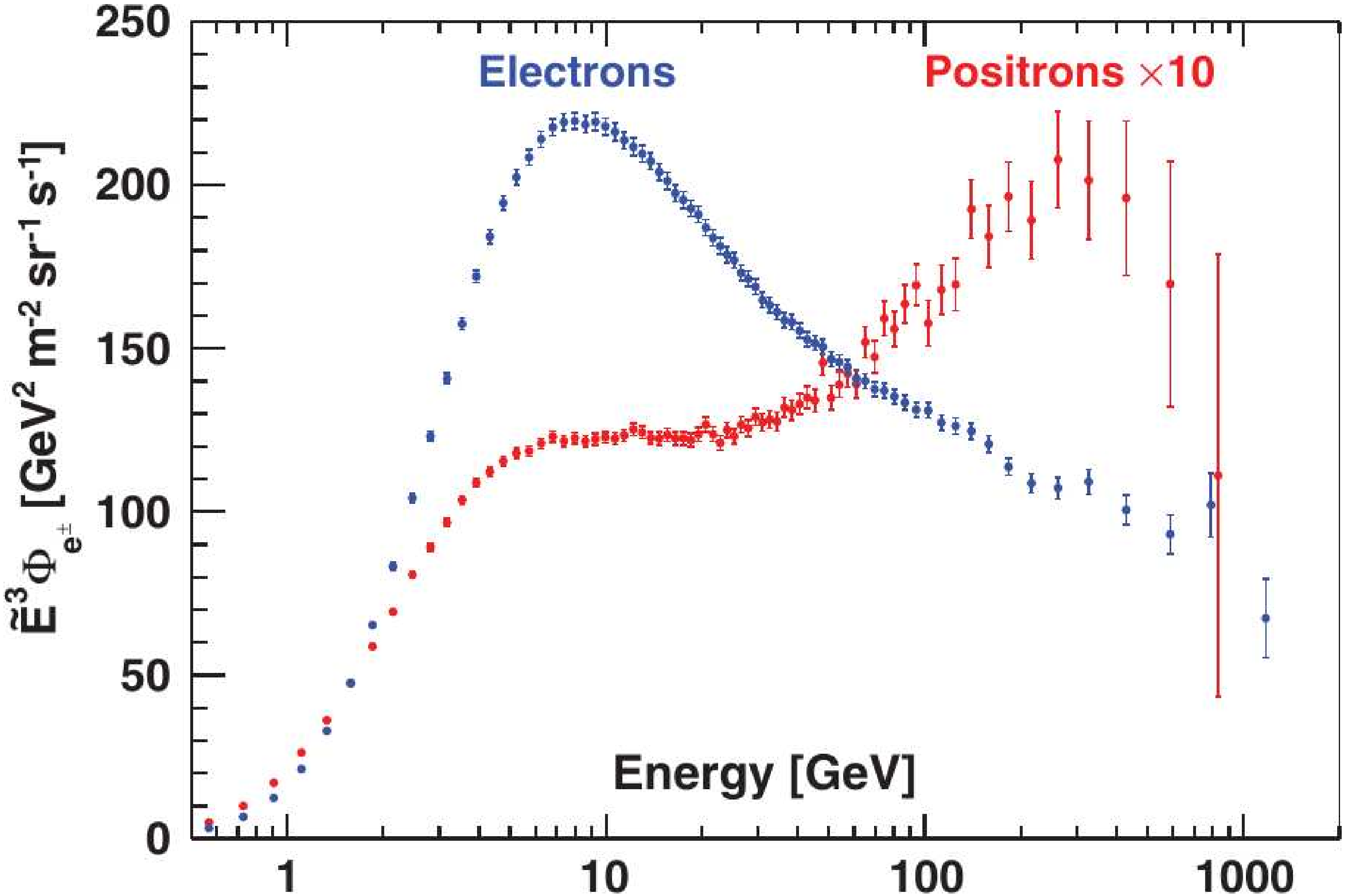
Very few antihelium atoms observed.

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



Conclusion

The standard model hiccups a bit when treating antiparticles. Moreover, it cannot account for the masses of the neutrinos, the lack of antimatter, and the presence of dark matter in the Universe. All those problems will be solved somehow, by introducing new symmetries or interactions.

Thanks for your attention