High precision tests of the matter/antimatter asymmetry

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CERN

Questions:

- What is antimatter?
- What happened at the begining of the Universe?
- How can we produce antimatter?
- How can we store antimatter?
- What are the interesting properties of antimatter?
- How do we measure properties of antimatter?

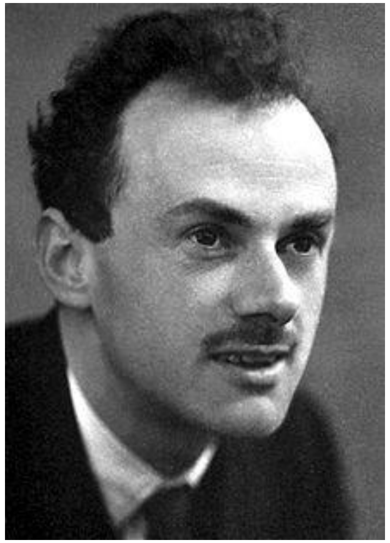
... and many more from your side :-)

Introduction

I think that the discovery of antimatter was perhaps the biggest jump of all the big jumps in physics in the 20th century.

W. Heisenberg in "The physicist's conception of Nature", 1972

1928 – Dirac equation



… one of a very few examples when a theoretician proposed something so spectacular which did not exist before.

Relativistic version of the Schrodinger equation:

$$i\hbar\frac{\partial\psi}{\partial t} = \left(\frac{\hbar c}{i}\alpha^k\partial_k + \beta mc^2\right)\psi \equiv H\psi$$

$$\mathbf{E} = \pm\sqrt{\mathbf{p}^2\mathbf{c}^2 + \mathbf{m}^2\mathbf{c}^4}$$

Dirac found solutions for his equations with „negative energy"

1928

Since half the solutions must be rejected as referring to the charge $+e$ on the electron, the correct number will be left to account for duplexity phenomena.

1930

would fill it, and will thus correspond to its possessing a charge $+e$. We are therefore led to the assumption that *the holes in the distribution of negative-energy electrons are the protons*. When an electron of positive energy drops into

1931

nearly all, of the negative-energy states for electrons are occupied. A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron. We should not expect to find any of

Presumably the protons will have their own negative-energy states, all of which normally are occupied, an unoccupied one appearing as an anti-proton.

1932 – Discovery of antimatter in cloud chamber

How can we know if particle has positive or negative charge?

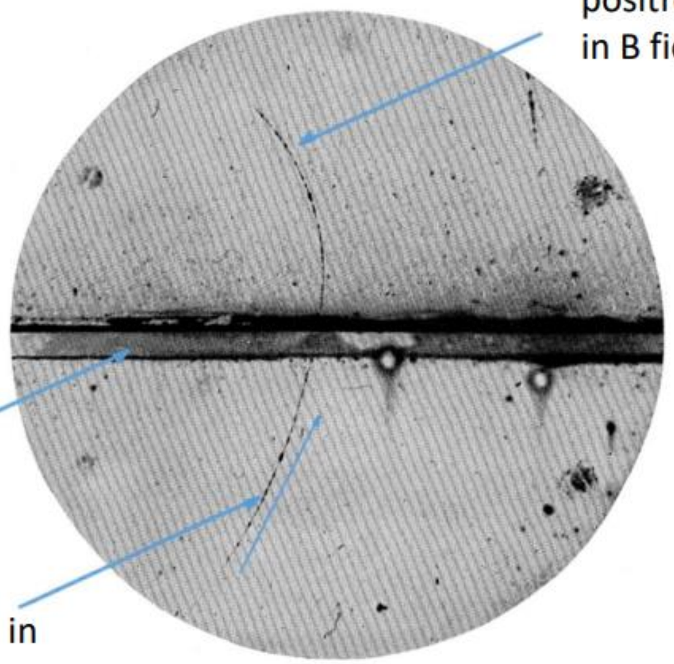
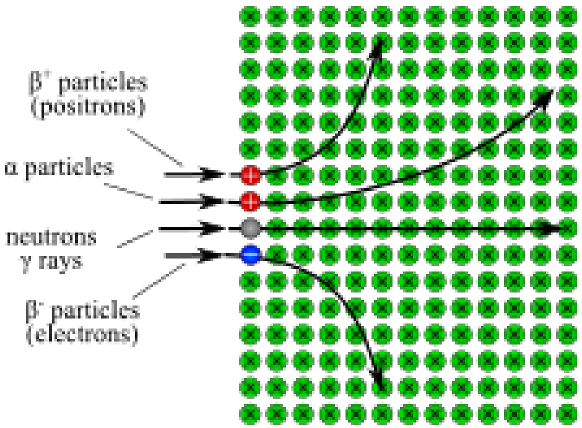
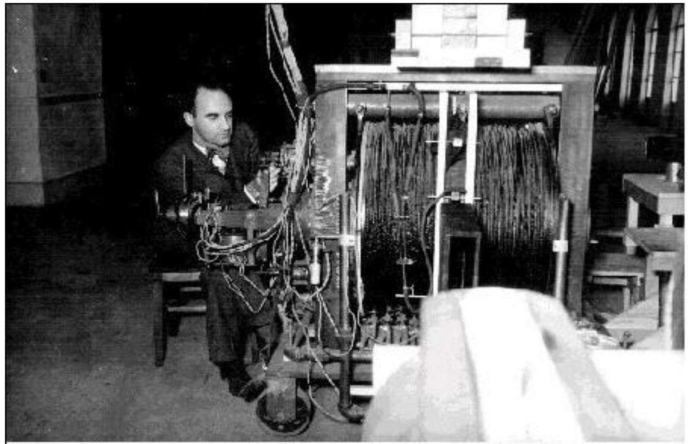


Fig. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

C. D. Anderson, Phys.Rev.43(1933)491





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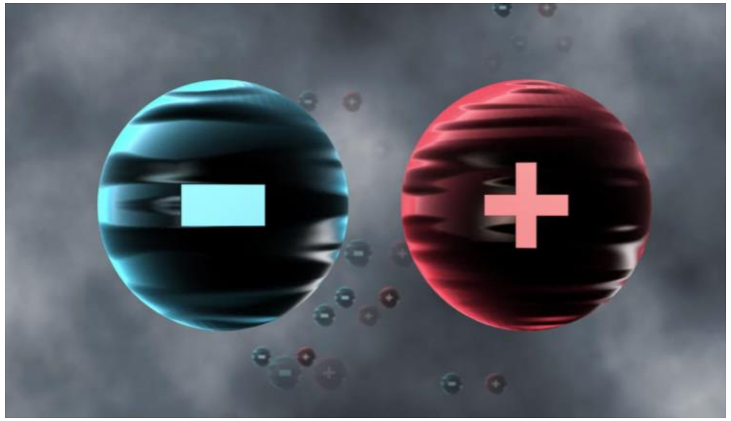
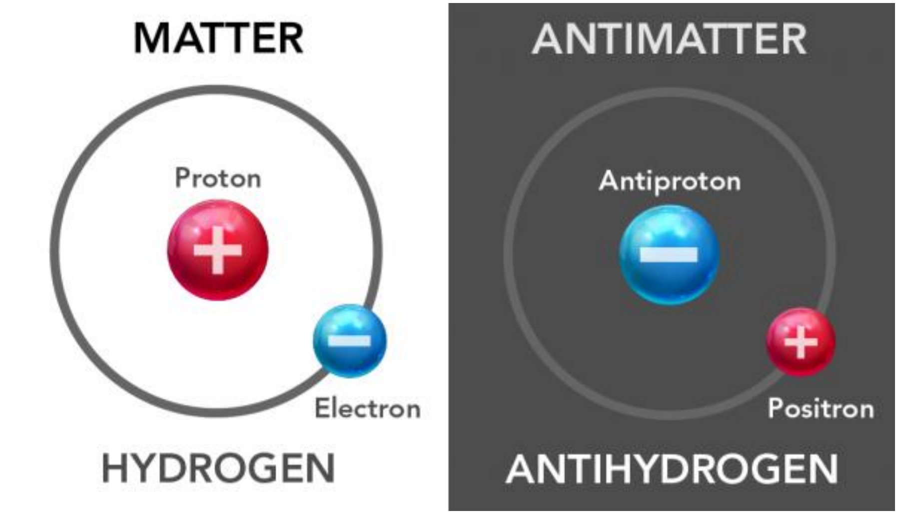
Out of a group of 1300 photographs of cosmic-ray tracks in a vertical Wilson chamber 15 tracks were of positive particles which could not have a mass as great as that of the proton. From an examination of the energy-loss and ionization produced it is concluded that the charge is less than twice, and is probably exactly equal to, that of the proton. If these particles carry unit positive charge the

seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron. Later study of the

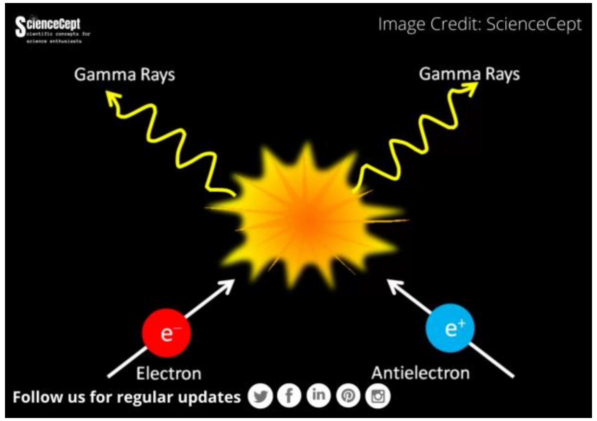
What is antimatter?

- Basic properties:

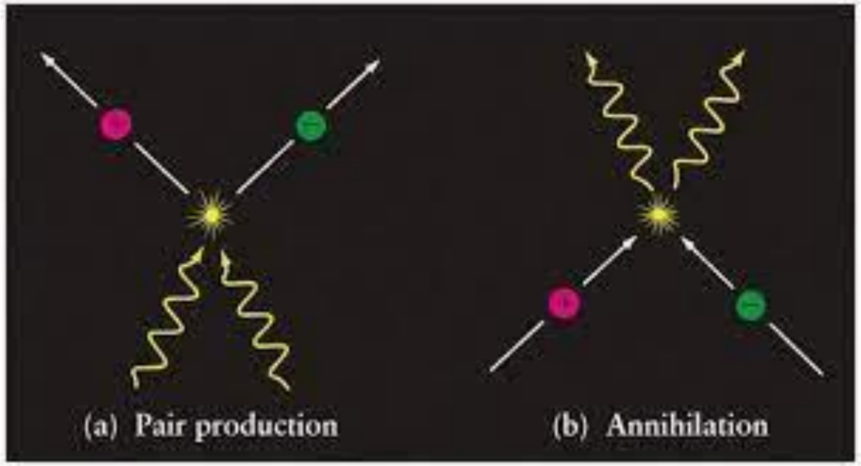




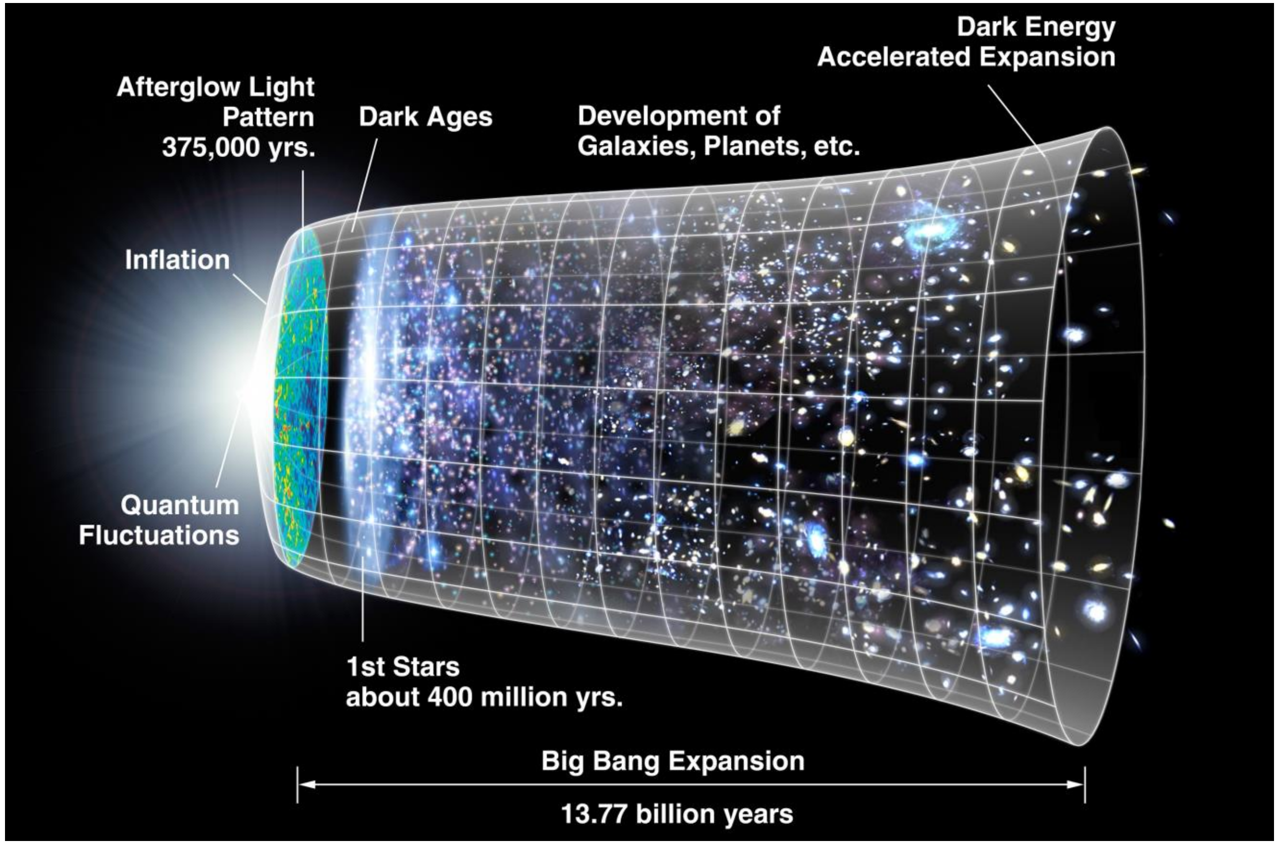
- Annihilation:

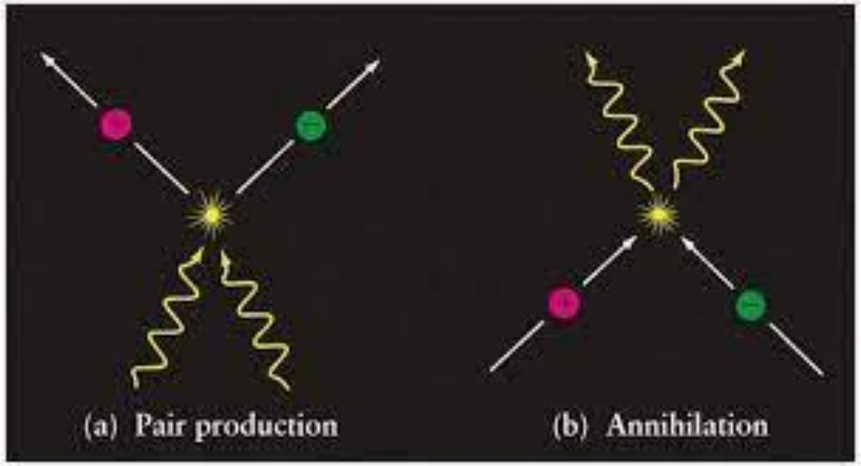


- Creation:



Why we exist?





- Once the universe expanded and cooled to a critical temperature of approximately 2×10^{12} K, quarks combined into normal matter and antimatter and proceeded to annihilate up to the small initial asymmetry of about one part in five billion, leaving the matter around us.

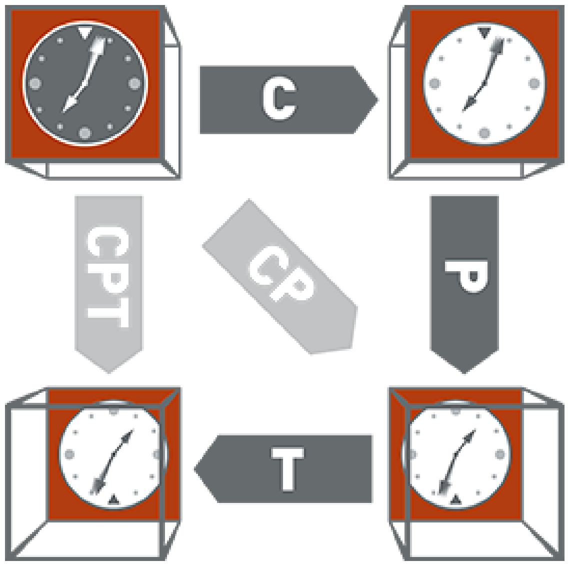
What happened with antimatter?

Standard Model of Particle Physics

Naive Expectations	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

Observations	
Baryon/Photon Ratio	0.6×10^{-9}
Baryon/Antibaryon Ratio	10 000

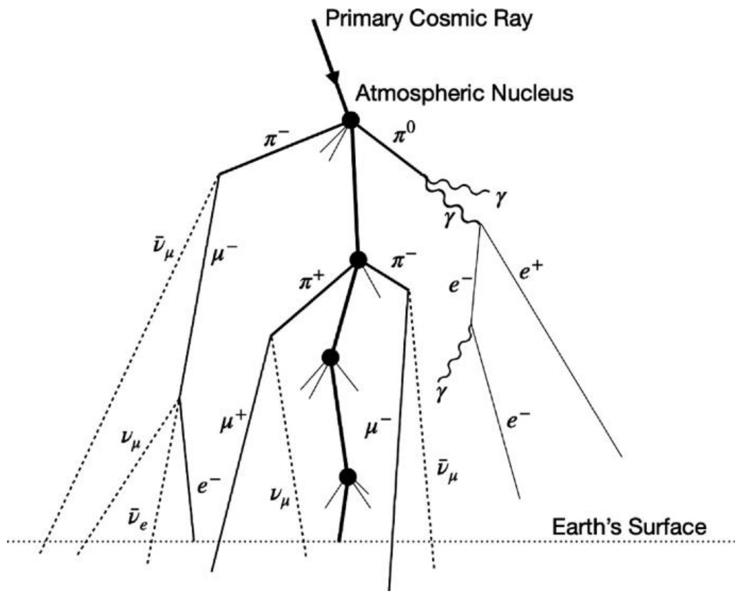
- A. Sakharov presented possible solutions in 1967 . According to his work, the matter-antimatter asymmetry could be explained by simultaneously occurring three conditions:
  - violation of baryon number;
  - C and CP symmetry violation;
  - lack of thermal equilibrium in the expanding Universe (=> direct CPT violation).



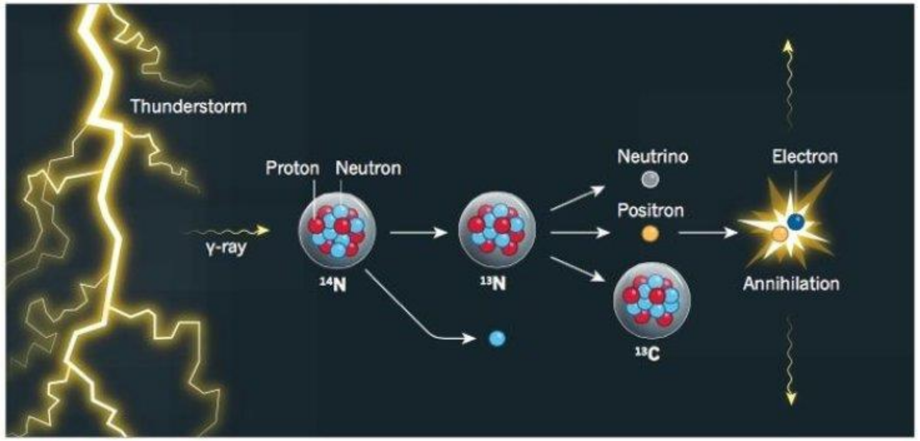
CPT violation? → **Ultra Precise Comparisons of fundamental properties of matter/antimatter conjugate system**

Antimatter around us

- Cosmic radiation

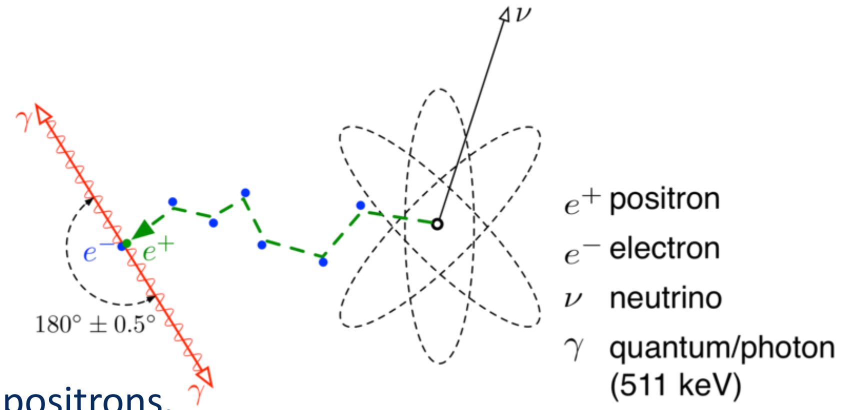


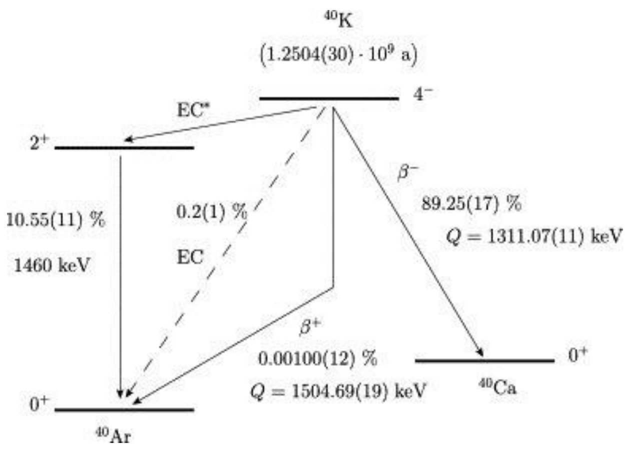
- Lightings:



- Elements which decay via β+ decay:

$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + e^{+} + \nu_e$$



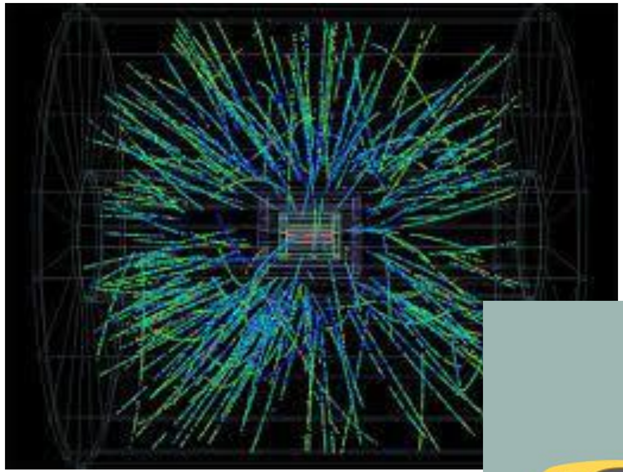


  - Sodium 22 -> the strongest „solid" source of positrons.
  - Potasium 40 -> one banana emits about 1 positron in 75 minutes.

Antimatter research in „controlled” conditions

- **Cosmic observations:**
- The Alpha Magnetic Spectrometer (AMS-02) is a particle physics experiment module mounted on the International Space Station (ISS). The module is a detector that measures antimatter in cosmic rays; this information is needed to understand the formation of the Universe and search for evidence of dark matter.

- **Approach from the perspective of high energy physics:**
- All nuclear reactions produce antimatter.
- Complex nuclei made out of antimatter:
    - LHC – in proton-proton colisions (pp) and lead-lead colisions (Pb–Pb):
        - ALICE – anti- ^{3}He.
- The standard model knows: every particle has an antimatter mirror image with the opposite charge, same mass, same magnetic moment…
- At the level of the Standard Model and elementary particle physics, matter and antimatter annihilate exactly/are created in HEP reactions in exactly the same amount. No violation has yet been found.

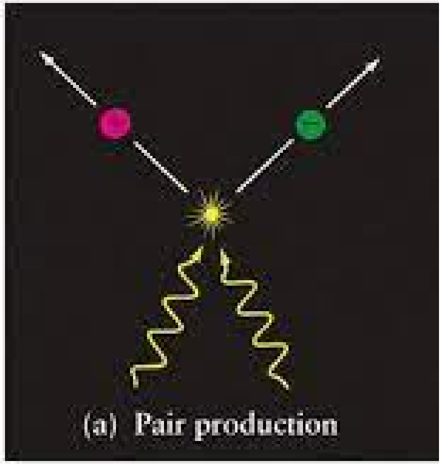


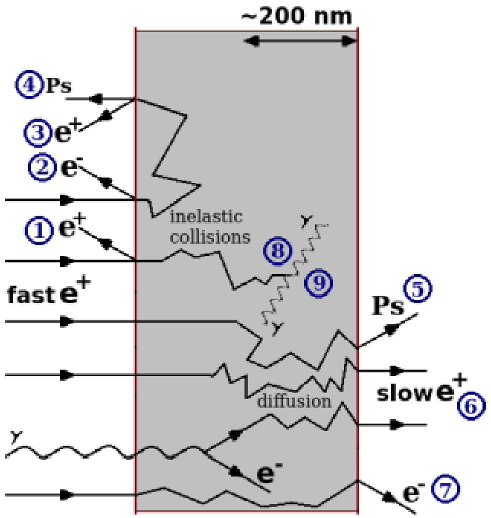
Antimatter production under controlled conditions – Atomic Physics

- Atomic/antimatter physics – the use of frequency measurement techniques provides the highest technologically achievable measurement precision.

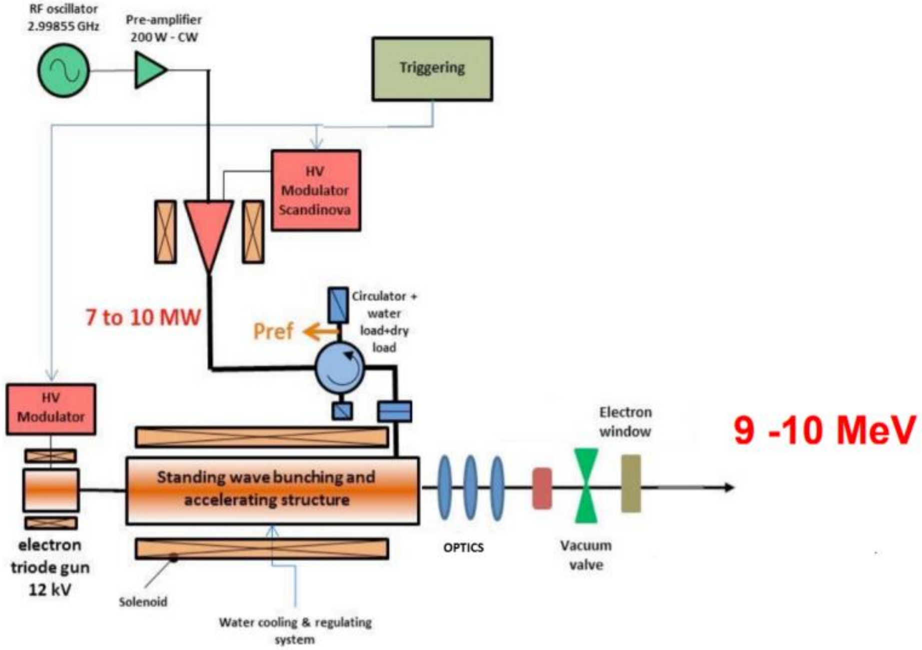
Production of antimatter under controlled conditions

- Aniparticles (natural units c=1):
  - Neutrino: < 1 eV
  - Electron: 511 000 eV
  - Muon: 105 000 000 eV
  - Proton: 938 000 000 eV
  - Higgs Boson: 125 000 000 000 eV





- Positron production:
  - Catching particles from natural sources, ^{22}Na < 10^7 e+/s
  - Catching particles from very intense positron sources:
    ^{113}Cd + n → ^{114}Cd + γ, 10^9 e+/s
  - Production using high intensity electron sources:

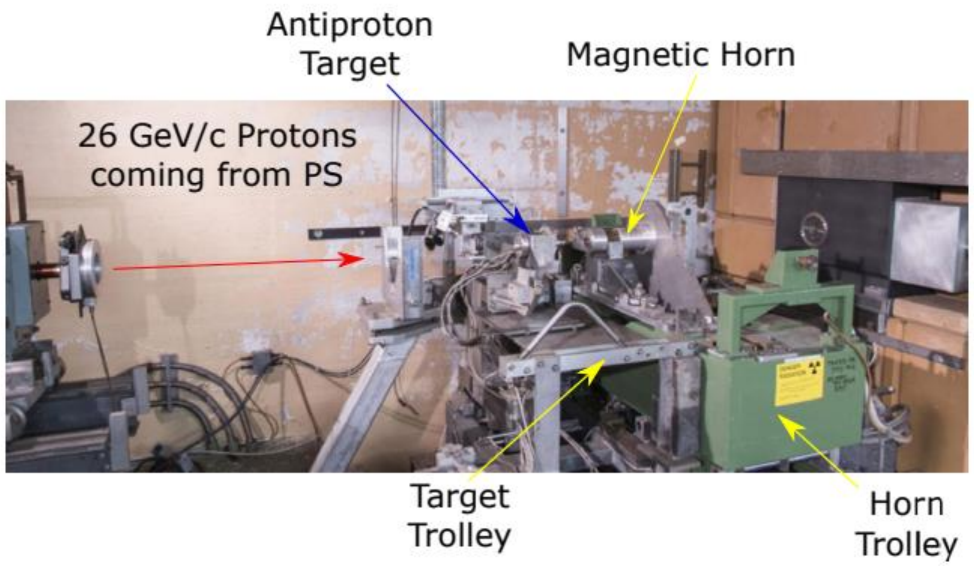


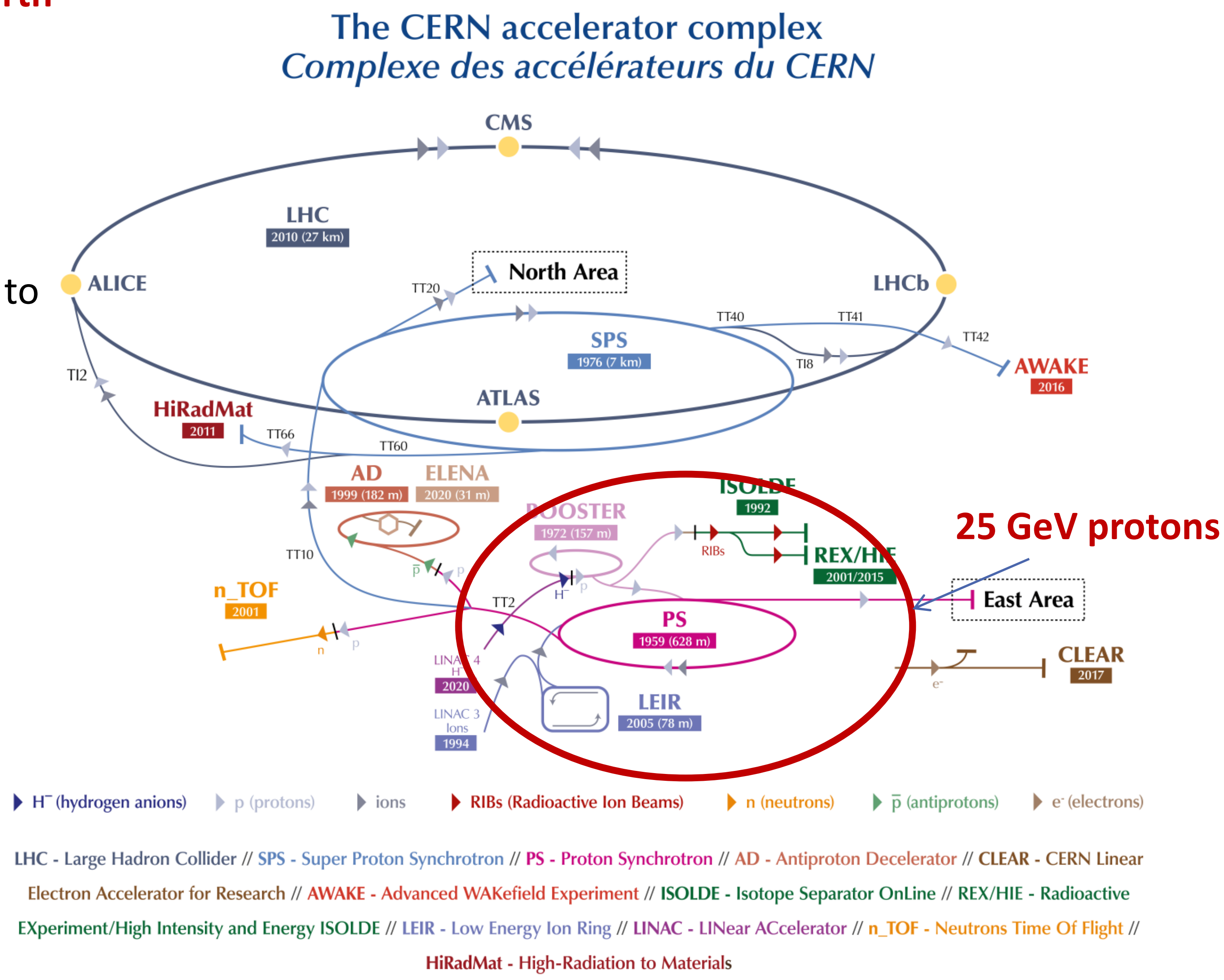
Linac	beam energy	current	Number of positrons
Giessen (shut down)	35 MeV	160 mA	10^8 e$^+$/s
Livermore (shut down)	100 MeV	400 mA	10^{10} e$^+$/s
Oak Ridge	180 MeV	300 mA	10^8 e$^+$/s
AIST, Japan	70 MeV	3 mA	2.5×10^7 e$^+$/s
GBAR, CEA	4.3 MeV	140 mA	3×10^6 e$^+$/s
GBAR, CERN	9 MeV	330 mA	5×10^7 e$^+$/s

How do we produce antiprotons?

- **CERN's antimatter factory – the only place on Earth where low-energy antiprotons are produced.**

- 1.5×10^{13} protons with 26 GeV energy are used to produce 5×10^{7} antiprotons.
- One bunch every 2 minutes.
- Indium rod of 5.5 cm length.
- We collect 3.5 GeV antiprotons.

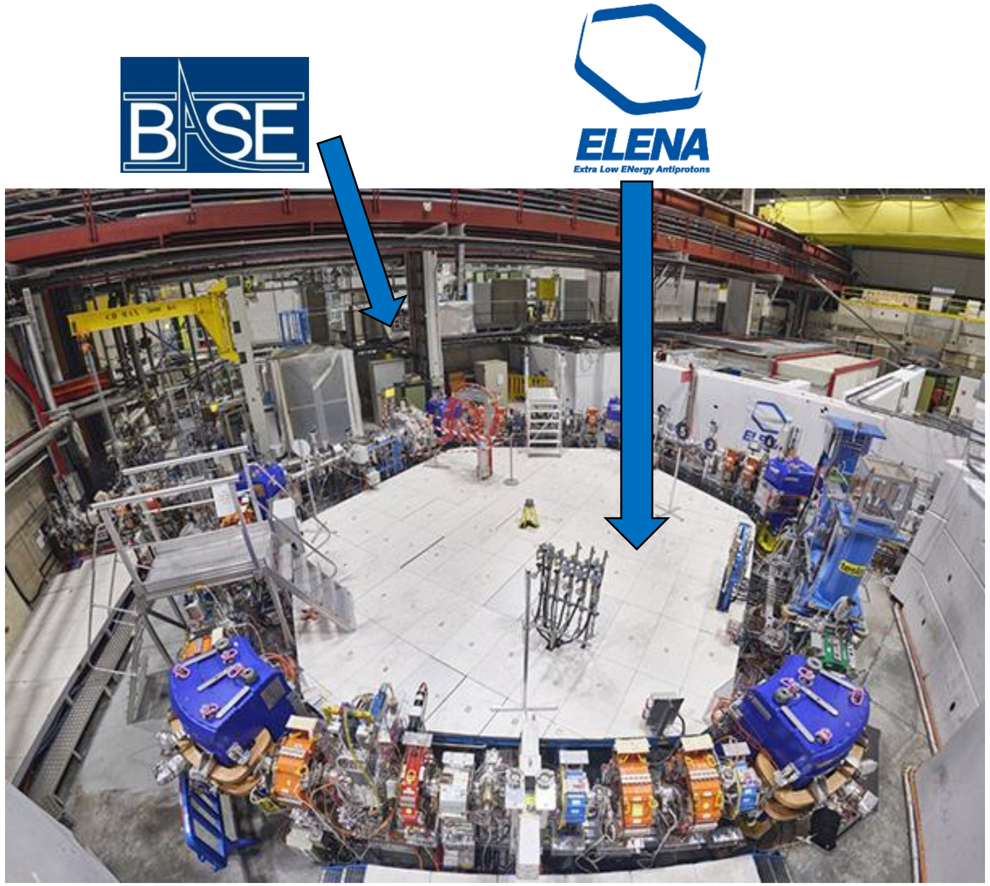


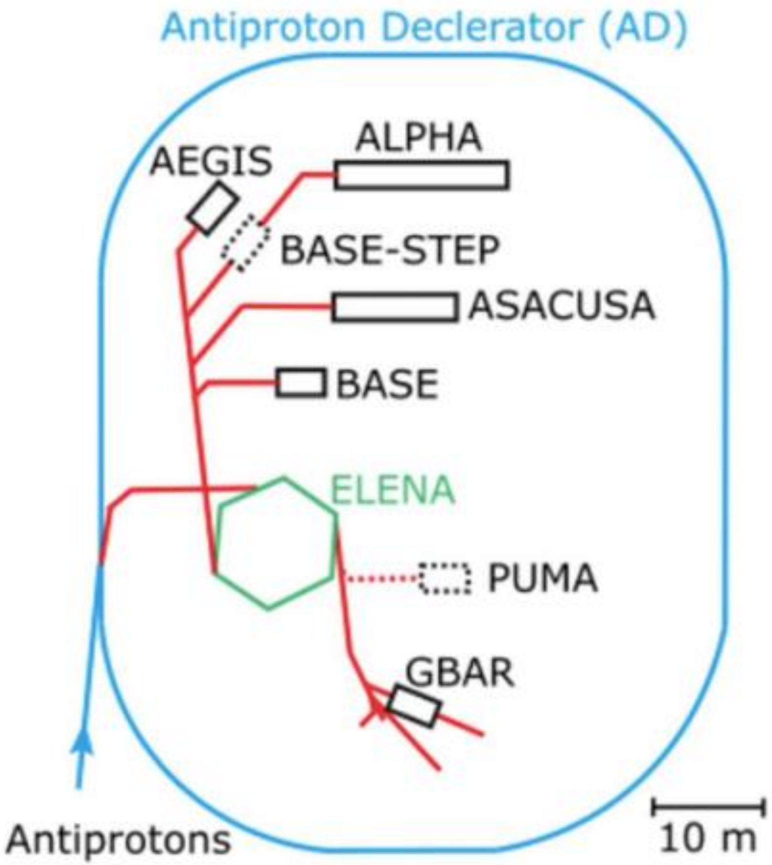


Slowing down antiprotons

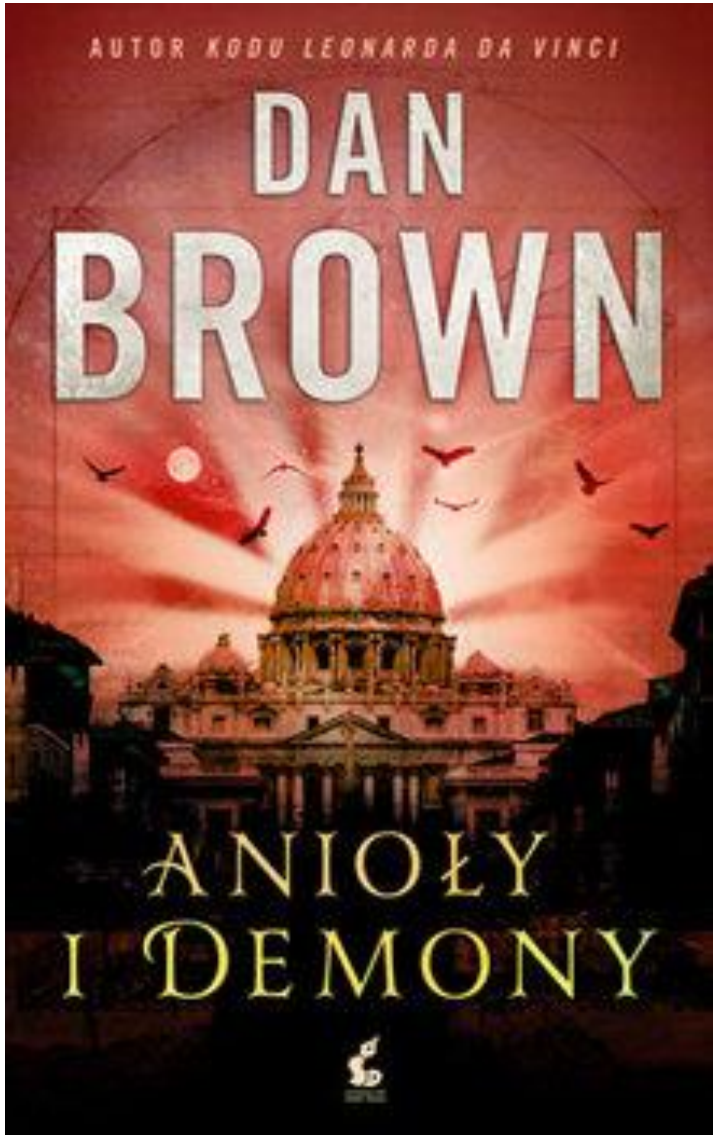
- Antiproton Decelerator – 5.3 MeV.

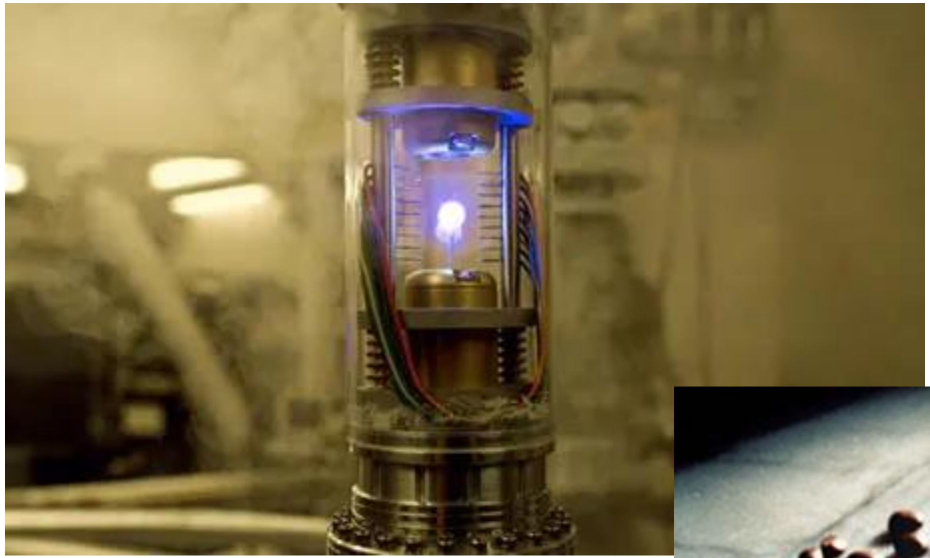
- Since 2021: ELENA (Extra low energy antiproton decelerator) – 100 keV antiprotons, $5 \times 10^{7}\ \bar{p}$ in one pulse.





„Angels and Demons” Dan Brown





... but actually all the antimatter produced so far would heat only one cup of coffee by 1 degree Celsius.

… but if we would have to estimate…

CERN produces $3x10^7 \bar{p}$/cycle ~ $10^{15} \bar{p}$/yr

1.67 pg per year

Fat Man:

20 kt TNT = $8.4 \cdot 10^{13}$ J
0.5 g antimatter
+ 0.5 g matter

Efficiency: 10^{-9}

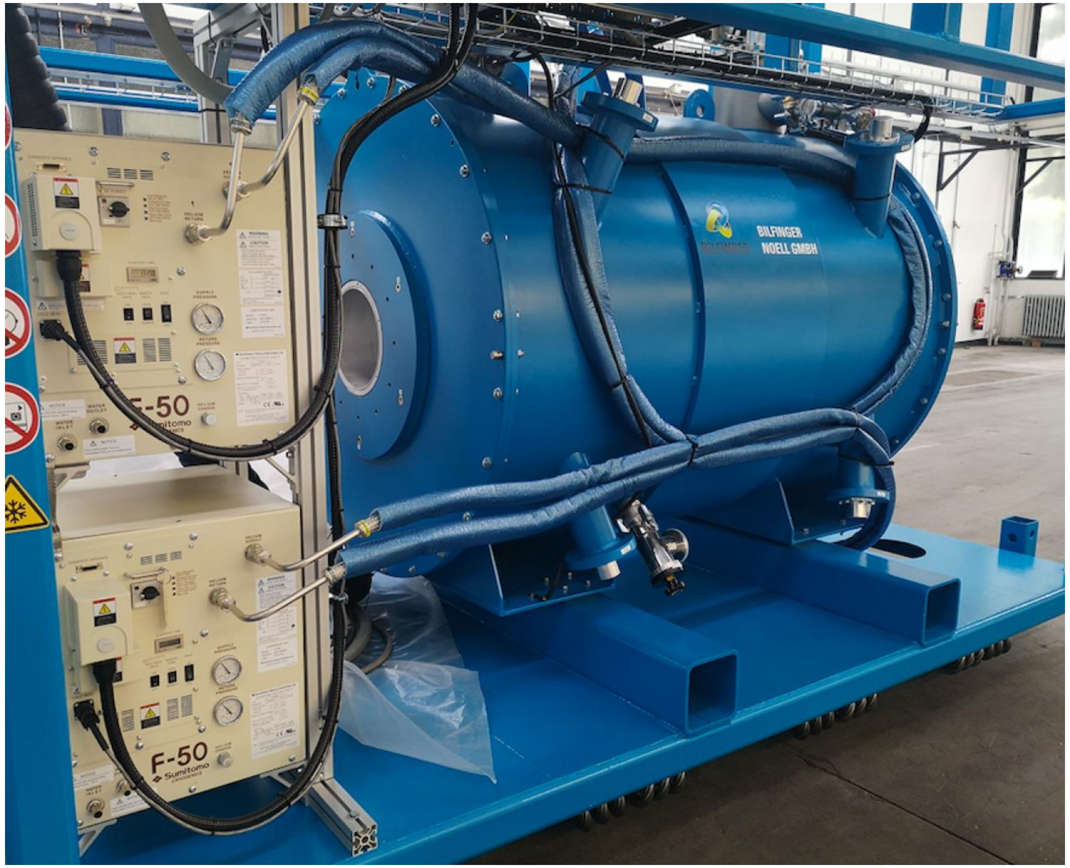
Cost of electrocity: 1kWh = $3.6*10^6$ J = 0.1 Euro

Cost: 1 250 000 000 000 000 Euro

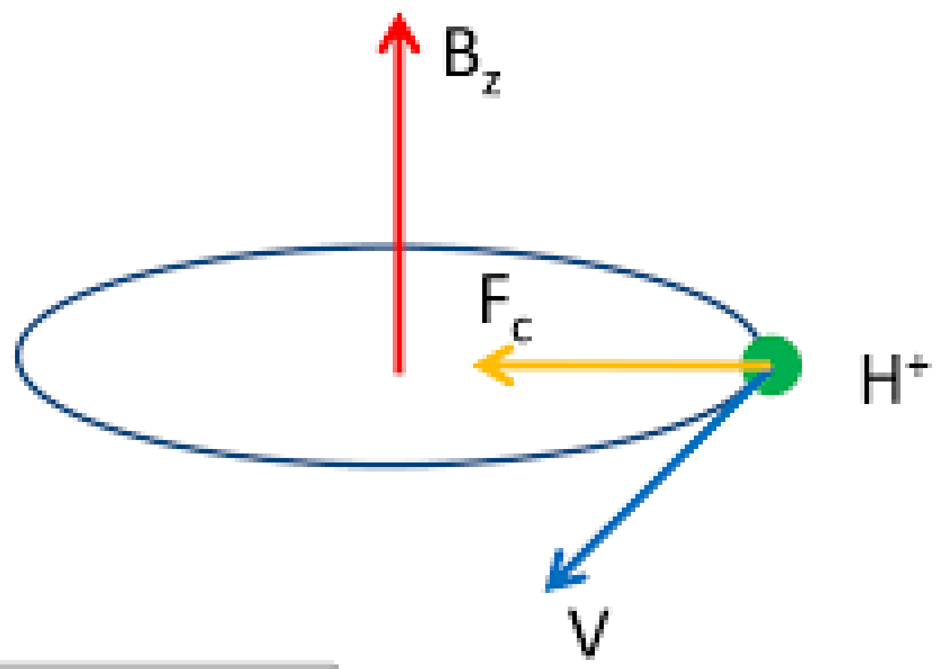
Production time: 300 000 000 years

Antimatter transport

- BASE-STEP and PUMA experiments



Cyclotron frequency



$$\frac{mv^2}{r} = qvB \Rightarrow \omega = \frac{v}{r} = \frac{qB}{m}$$

Penning trap

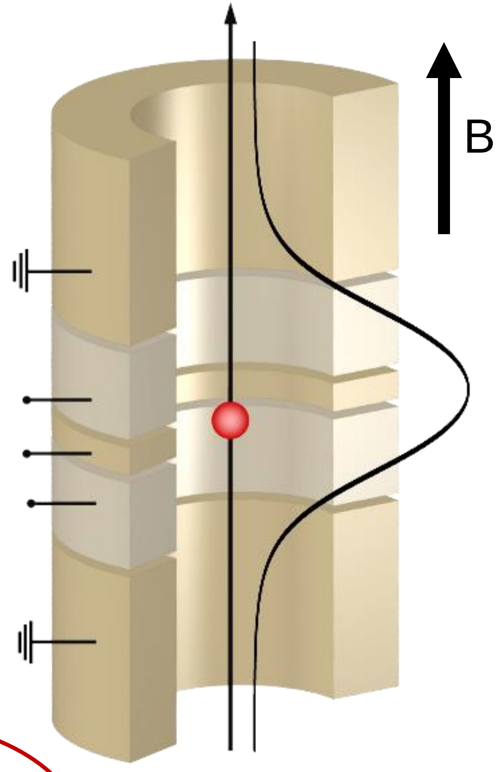
- **Penning trap with:**
  -> radial confinement: $\vec{B} = B_0 \hat{z}$

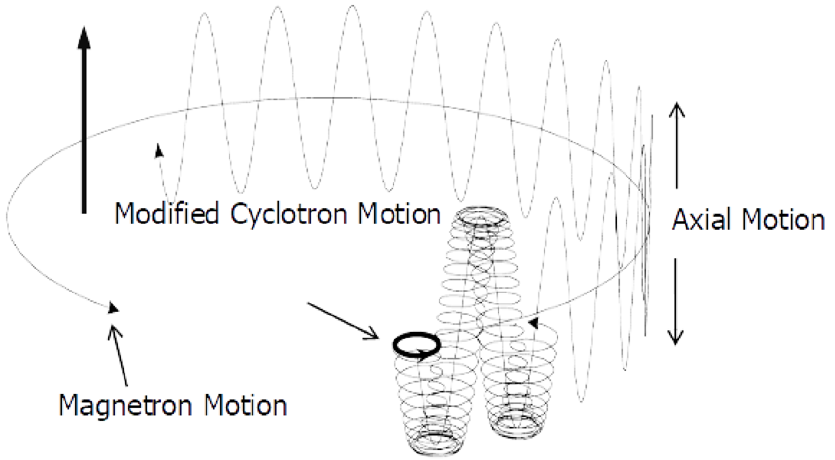
  -> axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$

- **Invariance theorem:**
Cyclotron frequency of a particle

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2} \longleftrightarrow \nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

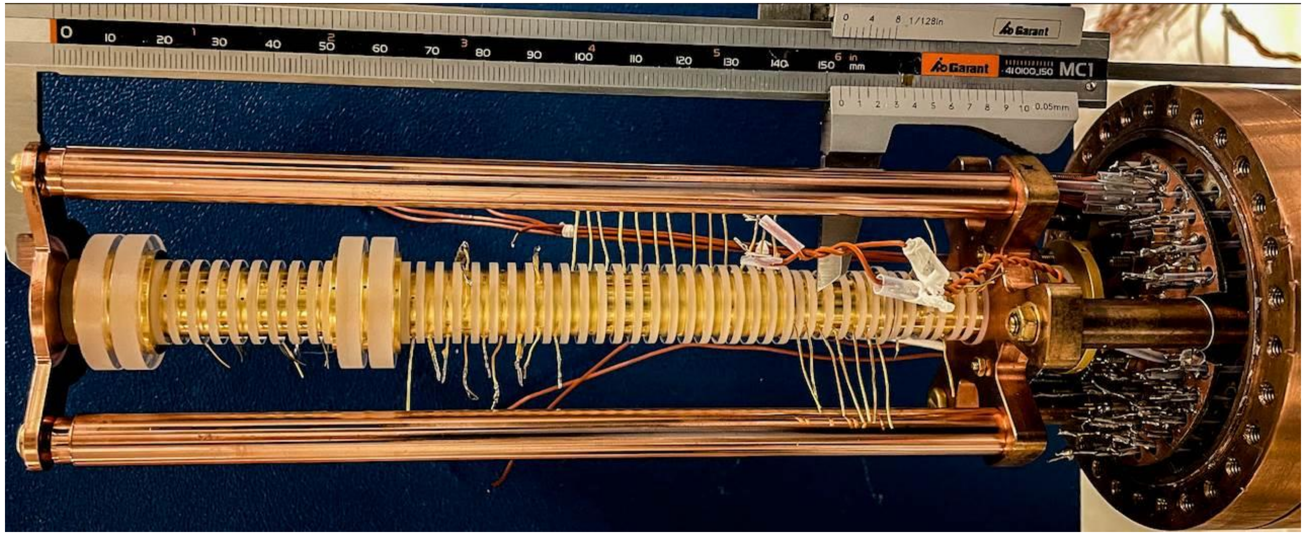
which is correct also for any small angle misalignment of the trap or quadratic imperfections of the field (G. Gabrielse)!

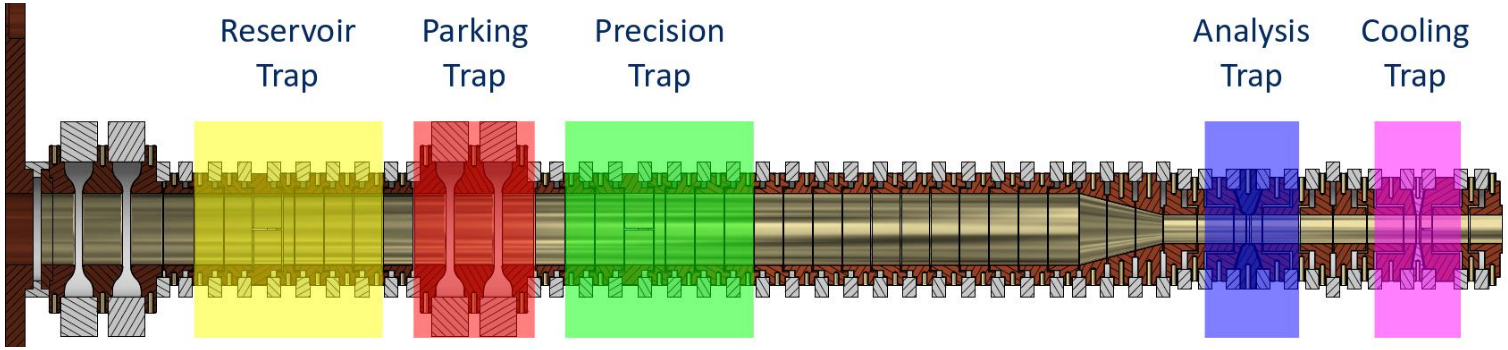




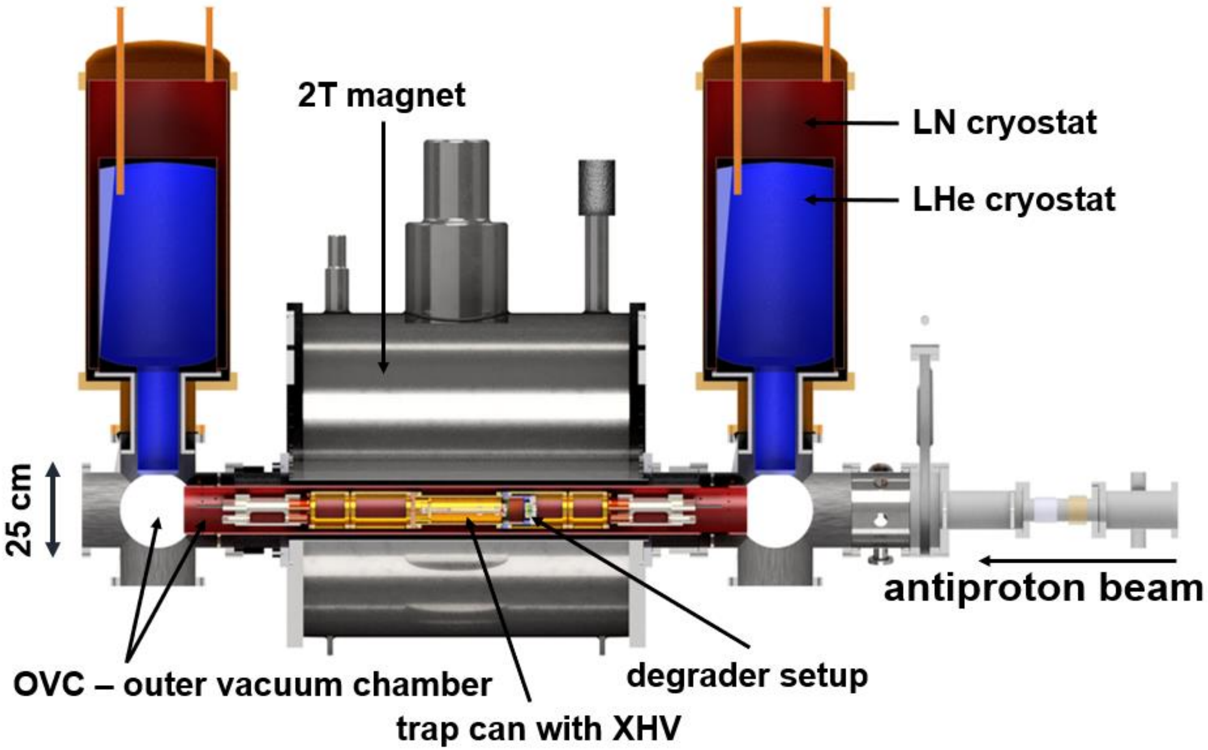
Axial	680 kHz	$\nu_z = \frac{1}{2\pi} \sqrt{\frac{2 C_2 q V_0}{m}}$
Magnetron	8 kHz	$\nu_- = \frac{1}{2} \left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2} \right)$
Modified Cyclotron	28.9 MHz	$\nu_+ = \frac{1}{2} \left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2} \right)$

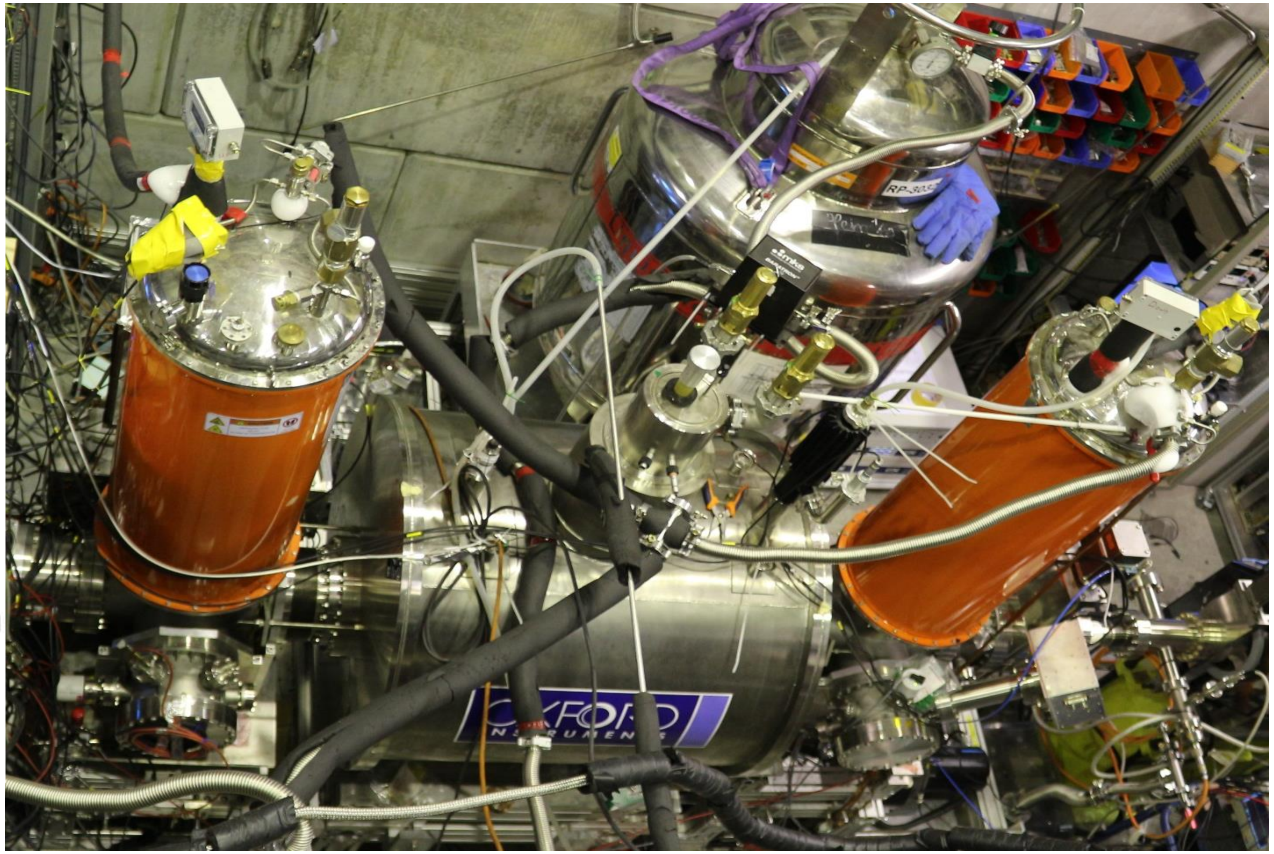
Penning Trap System in the BASE experiment





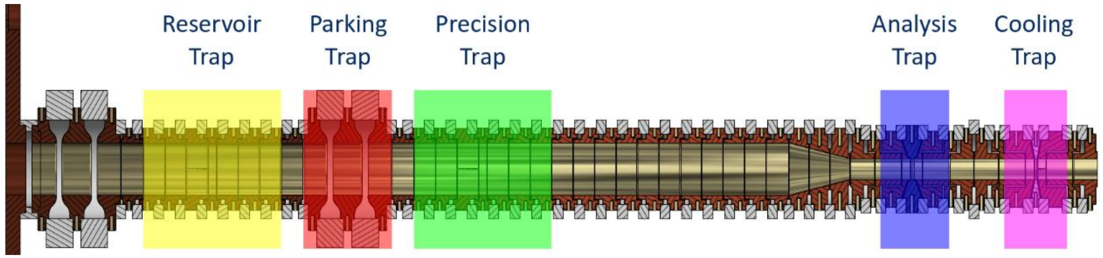
Penning Trap - Magnet



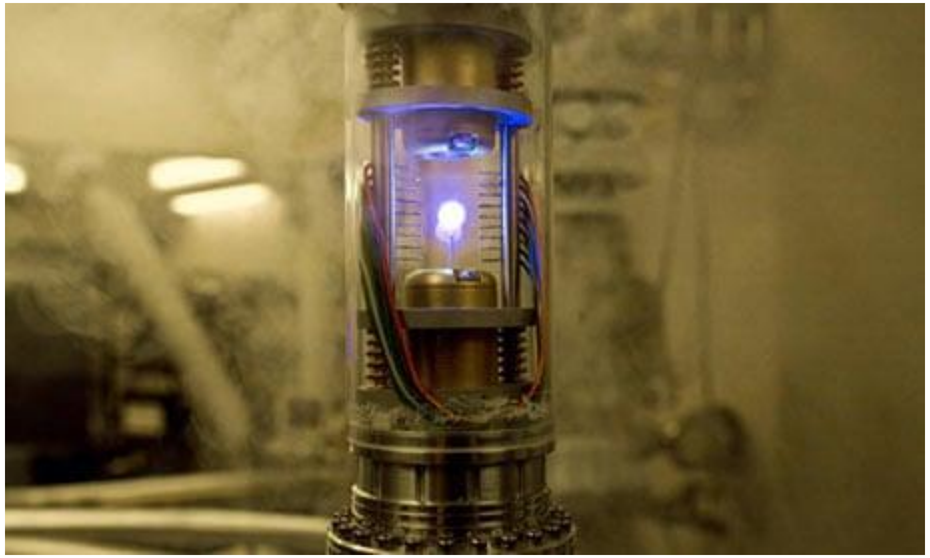


A special place (in the Universe?) – BASE Reservoir trap

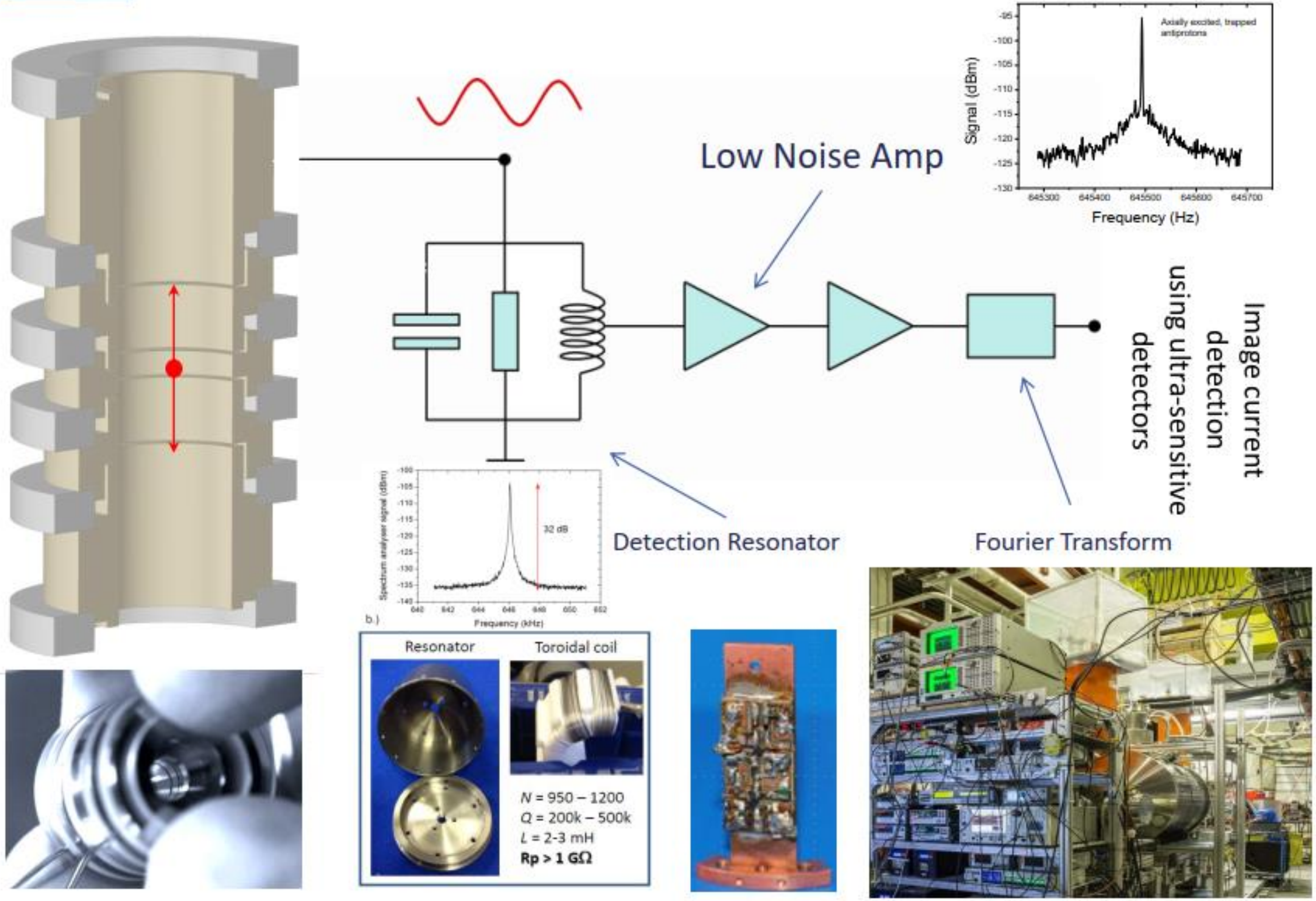
- BASE Reservoir trap:
  - **Pressure:** $p_H < 0.46 \times 10^{-18}$ **mbar** and $p_{He} < 1.04 \times 10^{-18}$ **mbar**.
  - best characterized vacuum on Earth, comparable to pressures in the interstellar medium
  - Antiproton storage time is 10s of years -> 405 days.
  - Not more than 3000 atoms in a vacuum volume of 0.5 l
  - Order 100 to 1000 trapped antiprotons
  - A local inversion of the baryon asymmetry



BASE ANTIMATTER INVERSION	
local volume	0.0001^3 m^3
Baryons in local trap volume	$1.65*10^{-7}$
Antibaryon in local trap volume	100
Antibaryon/Baryon Ratio	**$5.9*10^8$**



How to listen to antimatter



Induced Current:

$$I_p = \frac{1}{\sqrt{2}} \frac{q}{D_{eff}} \omega\rho \rightarrow fA$$

Detection Resonator:

$$R_p = Q\omega L \rightarrow 100M\Omega$$

Voltage Drop

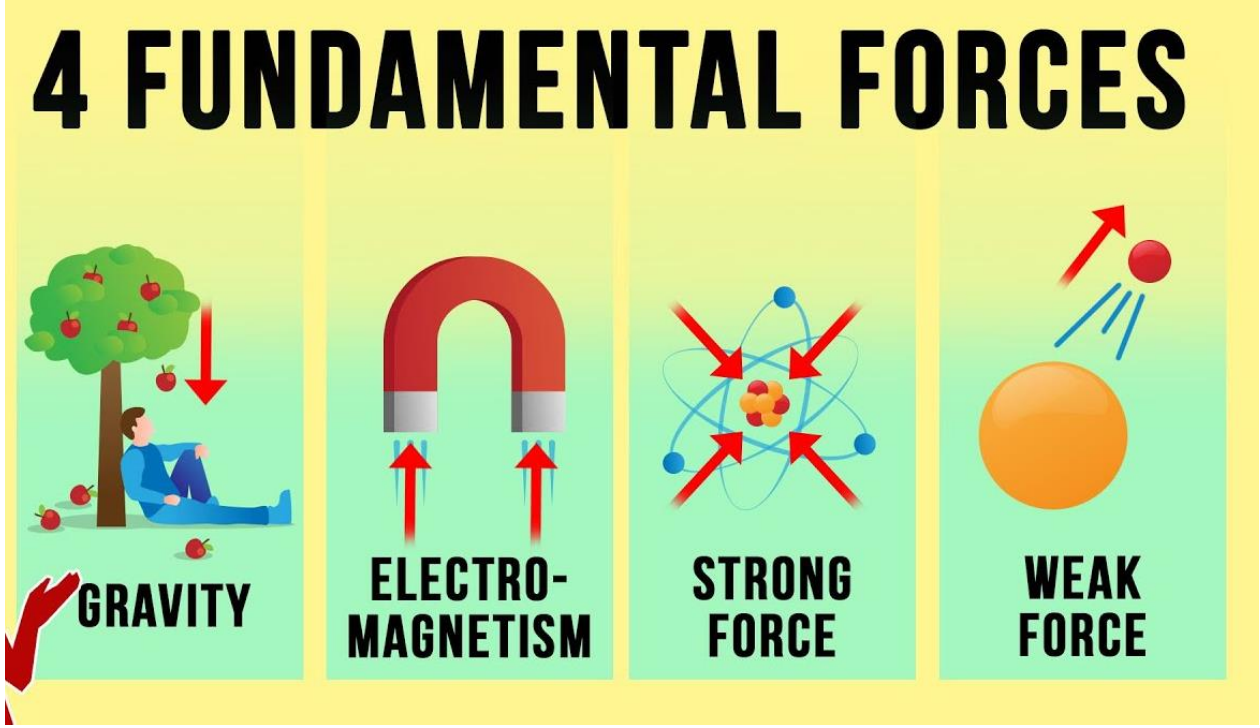
$$u_p = \frac{Q\omega L}{\sqrt{2}} * \frac{q}{D_{eff}} \omega \rho$$

100 nV

Testing antimatter

- Fundamental properties like: mass, charge, magnetic moment

- Testing fundamental interactions:

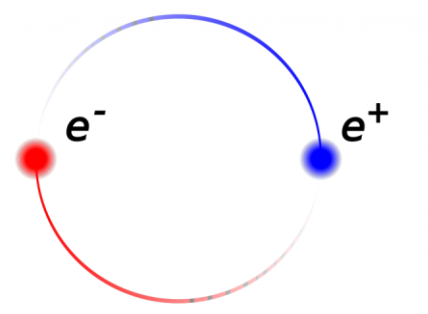


Tested systems

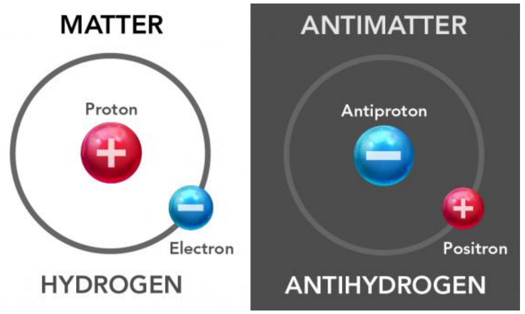
Fundamental particles:
- Positrons
- Antiprotons (BASE)

„Complex” systems:

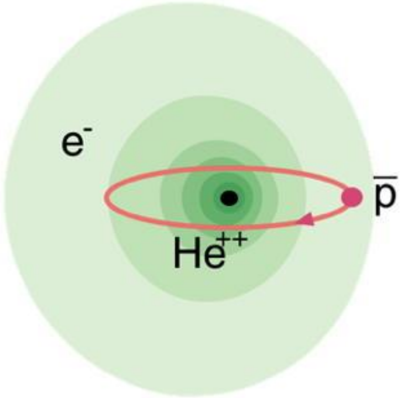
- Positronium



- Antihydrogen (ATRAP, AEgIS, ALPHA, ASACUSA, GBAR)



- Antiprotonic Helium (ASACUSA II)



Baryon/Antibaryon Symmetry Experiment

CPT violation?

Ultra Precise Comparisons of fundamental properties of protons and antiprotons

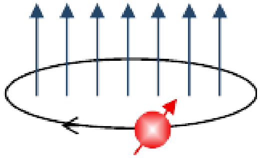
BASE

High precision mass spectroscopy of antiprotons and protons

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Cyclotron Motion

$$\omega_c = \frac{e}{m_p} B$$

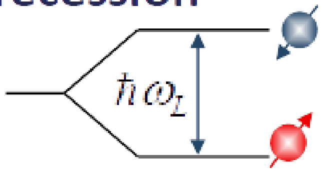


High precision magnetic moment measurements

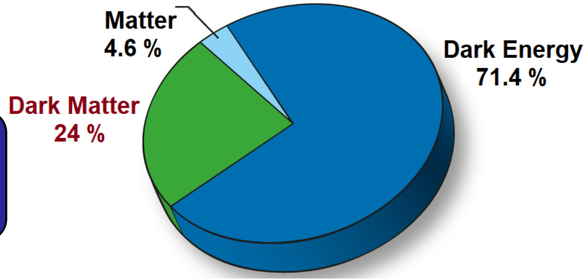
$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

Larmor Precession

$$\omega_L = g \frac{e}{2m_p} B$$



Dark Matter Searches



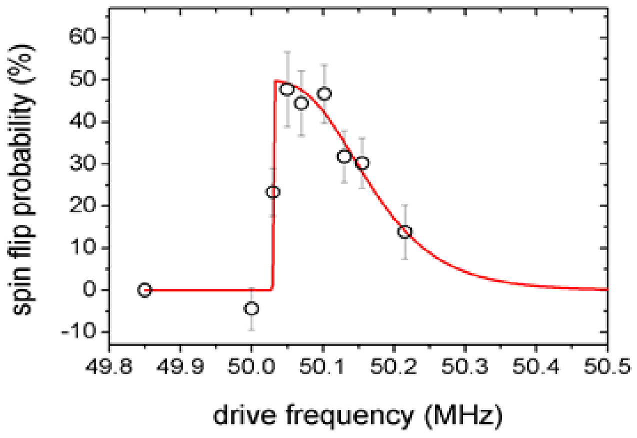
g factor

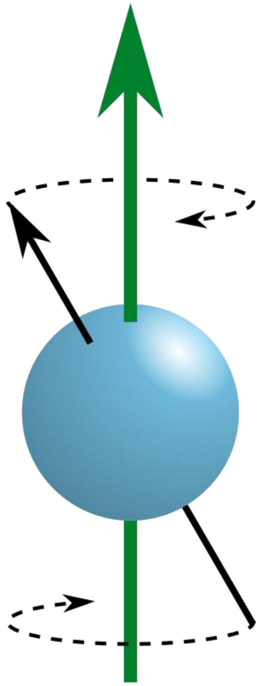
- Magnetic moment and a spin of a particle are related through a dimentionless parameter called g-factor:

$$\boldsymbol{\mu} = g\frac{q}{2m}\mathbf{S} \quad \Rightarrow \quad \mu = \frac{g}{2}\mu_{\mathrm{N}}$$

- (Anti)Proton / electron spin S = ½
- Larmor frequency – spin precession in a given magnetic field:

$$\omega_L = g\frac{e}{2m_p}B$$



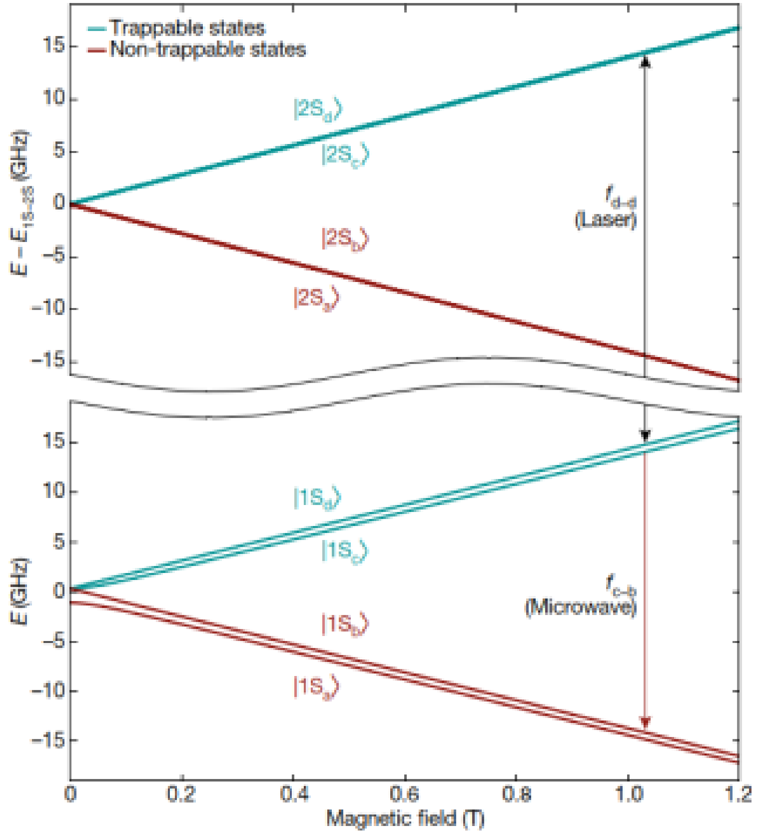


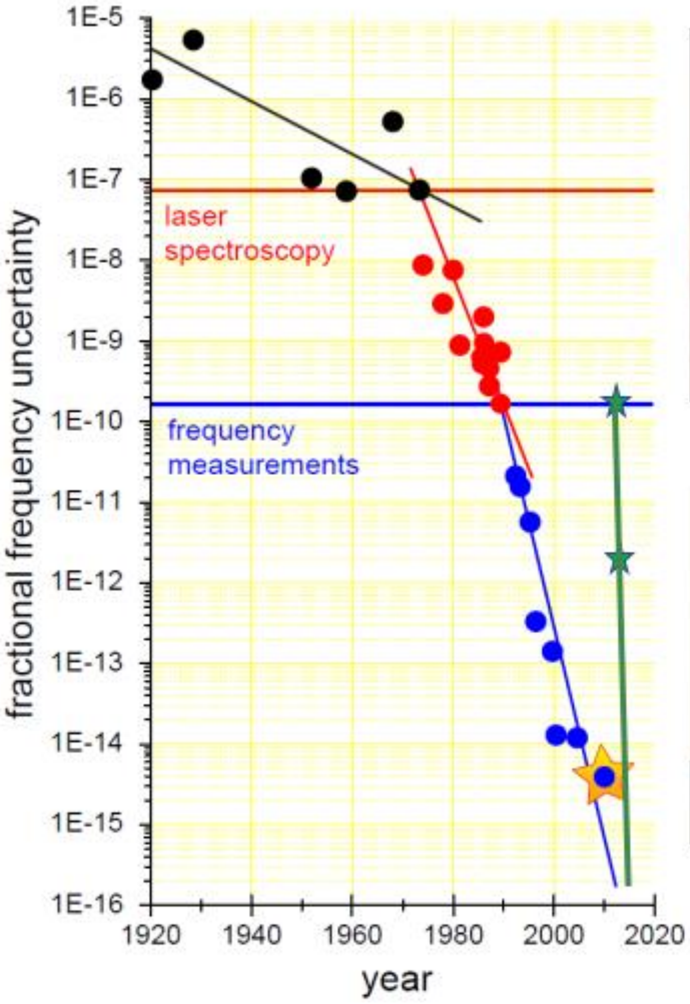
- g factors:

Particle	g-factor	Relative standard uncertaintity
Electron	−2.00231930436256(35)	1.7×10^{-13}
Muon – (experiment-world-average-2021)	−2.002 331 84121(82)	4.1×10^{-10}
Proton	5.5856946893(16)	$\mathbf{2.9 \times 10^{-10}}$
Antiproton	5.5856946906(60)	$\mathbf{1.5 \times 10^{-9}}$

Spectroscopy of antihydrogen 1S-2S

- The 1S–2S transition is useful because of the long lifetime (about 1/8 s) of the 2S state and the associated narrow transition frequency width (a few hertz at 2.5 × 10^15 Hz)

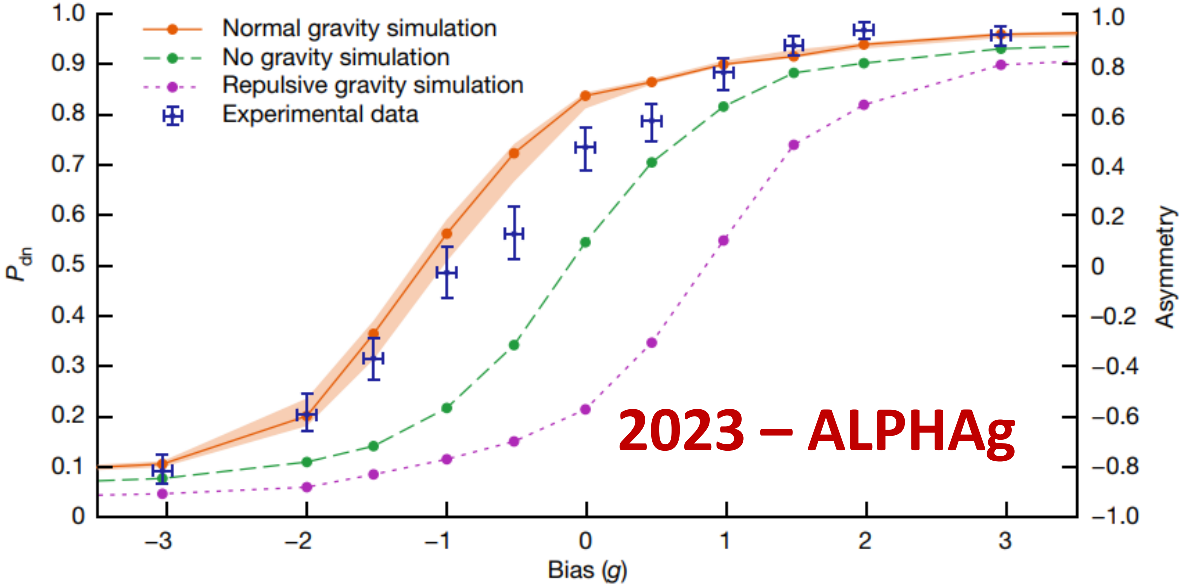


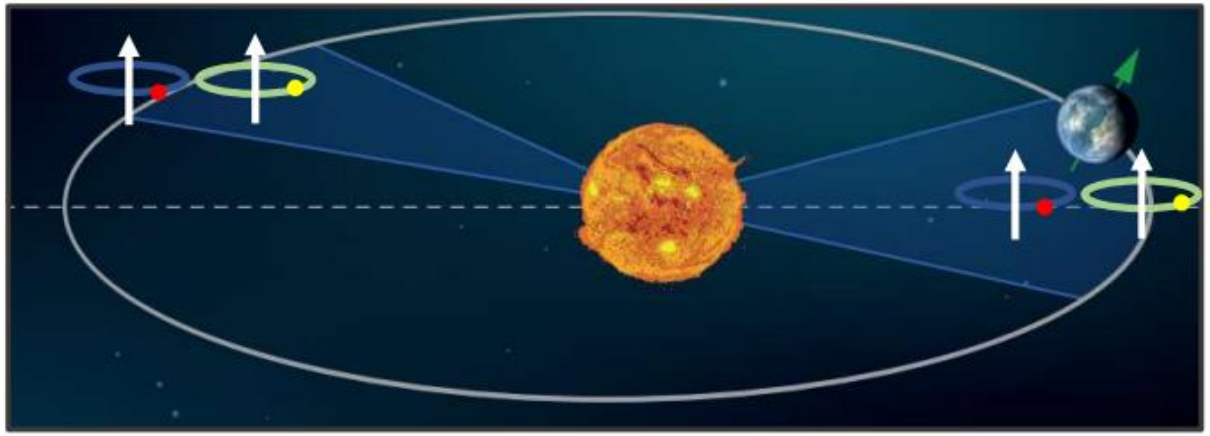


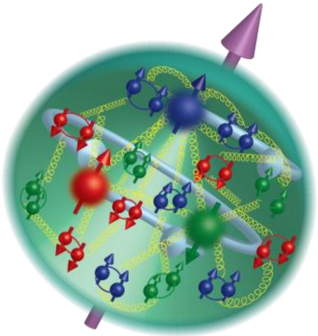
$$f_{d-d} = 2{,}466{,}061{,}103{,}064(2)\ \text{kHz}$$
$$f_{c-c} = 2{,}466{,}061{,}707{,}104(2)\ \text{kHz}$$

Nature **volume 541**, pages506–510 (2017)

Measurement of the gravitational interaction





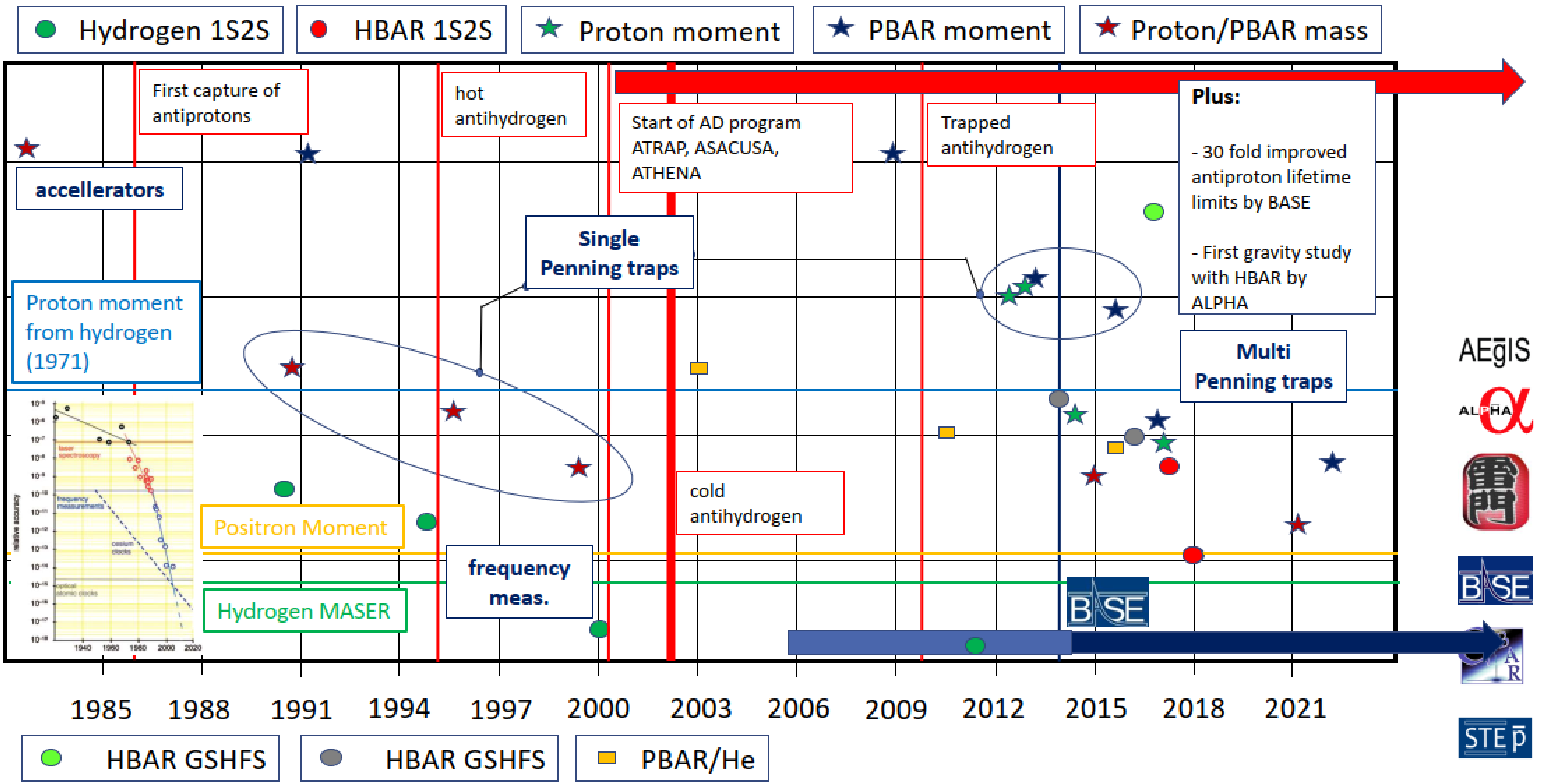


Comaring matter and antimatter clocks:

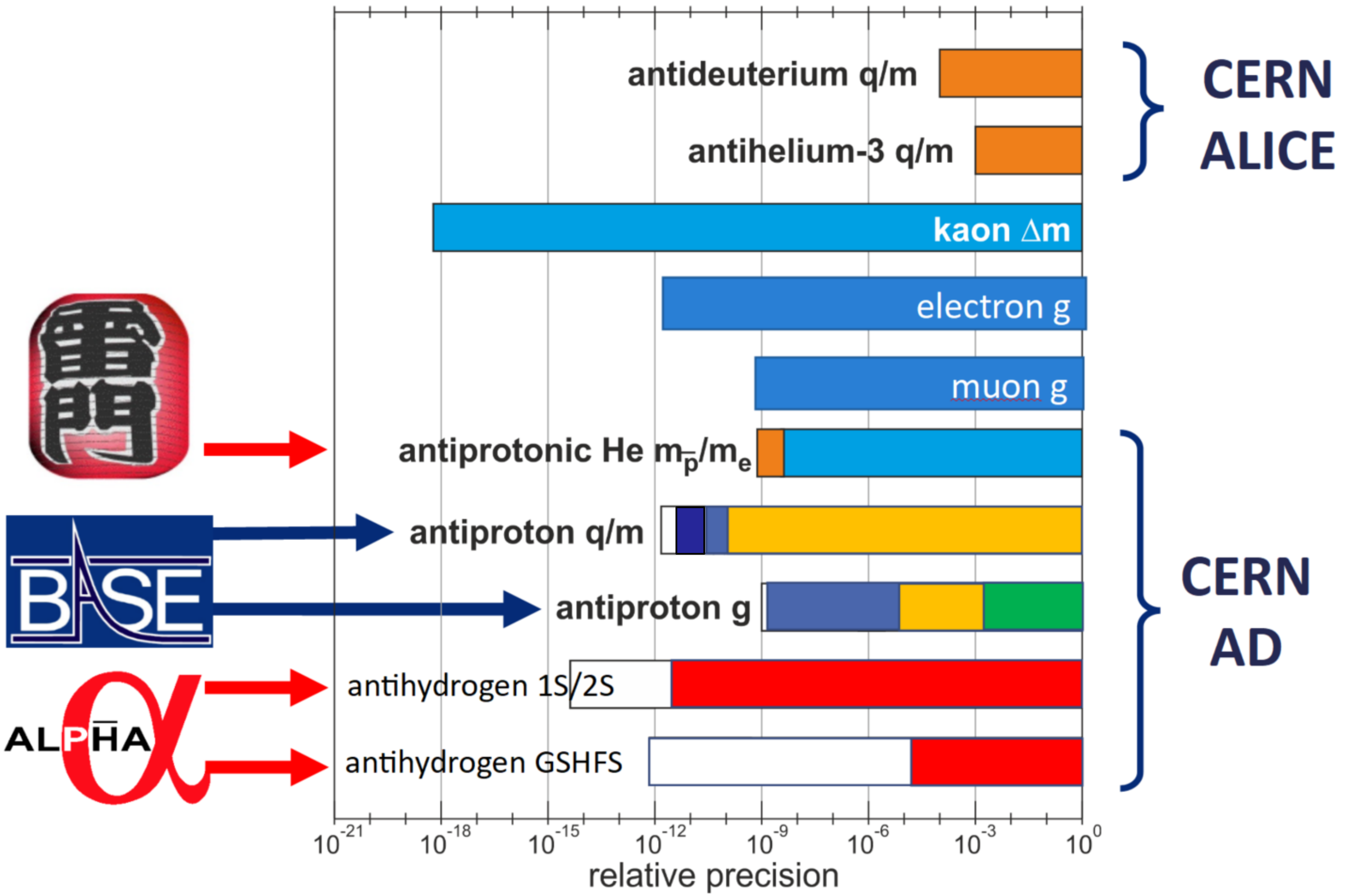
- **BASE – result: |αg,D − 1| < 0.030**

- In antiproton, only 1% of the energy is made our of antimatter -> we need very high precission.

Historical Milestones



CPT with particle/antiparticle comparisons



-> Absolute energy resolution normalized to m-scale.

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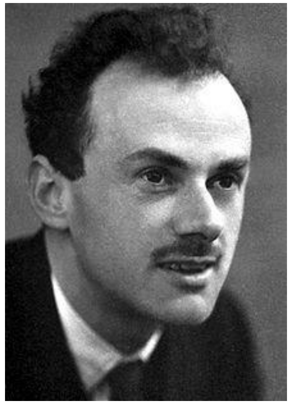
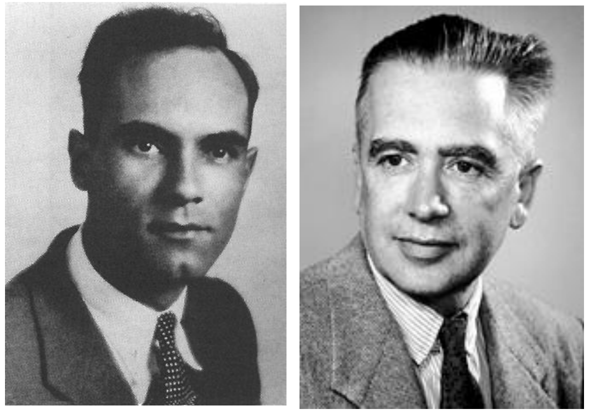
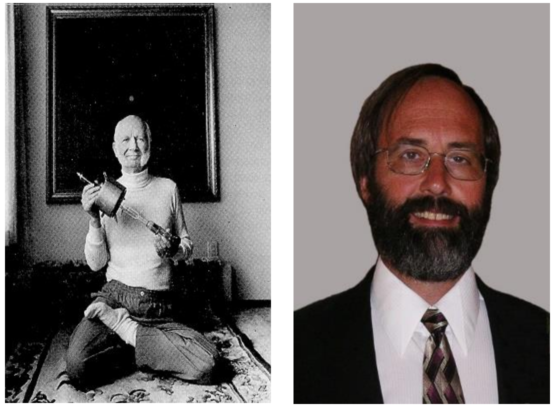


Theretical idea - Paul Dirack



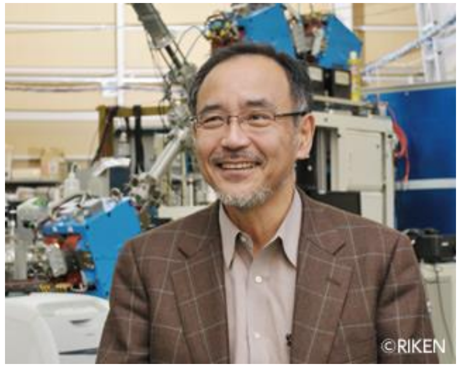
Discovery – Carl Anderson, Emilio Segrè



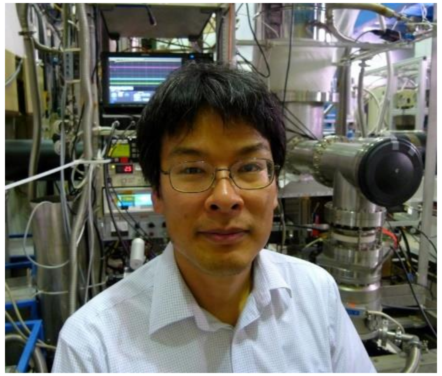
Trapping of antimatter - Hans Dehmelt, Gerald Gabrielse

First antihydrogen -Walter Oelert

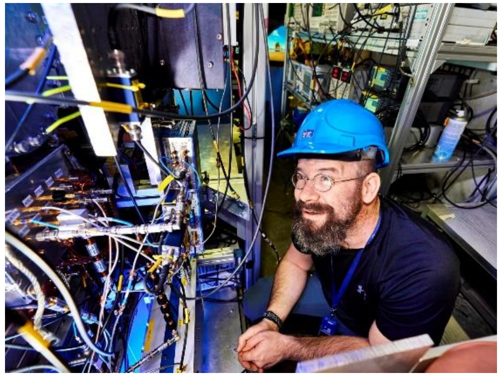
First trapped antihydrogen- Jeffrey Hangst (ALPHA experiment)



First beam of antihydrogen - Yasunori Yamazaki (ASACUSA experiment)

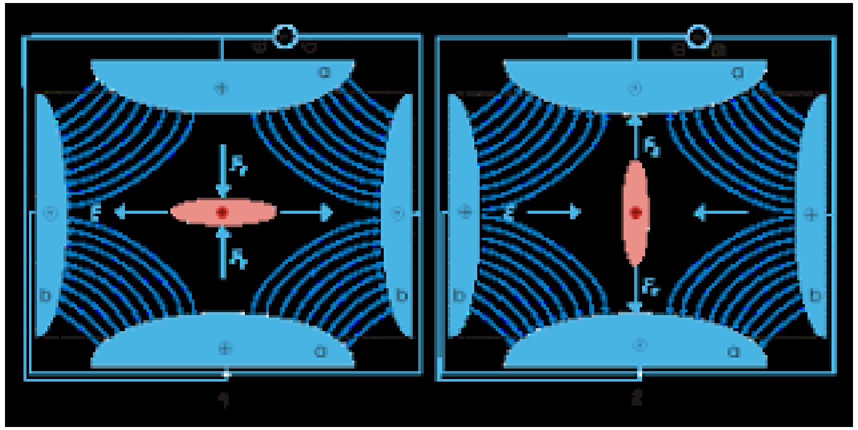


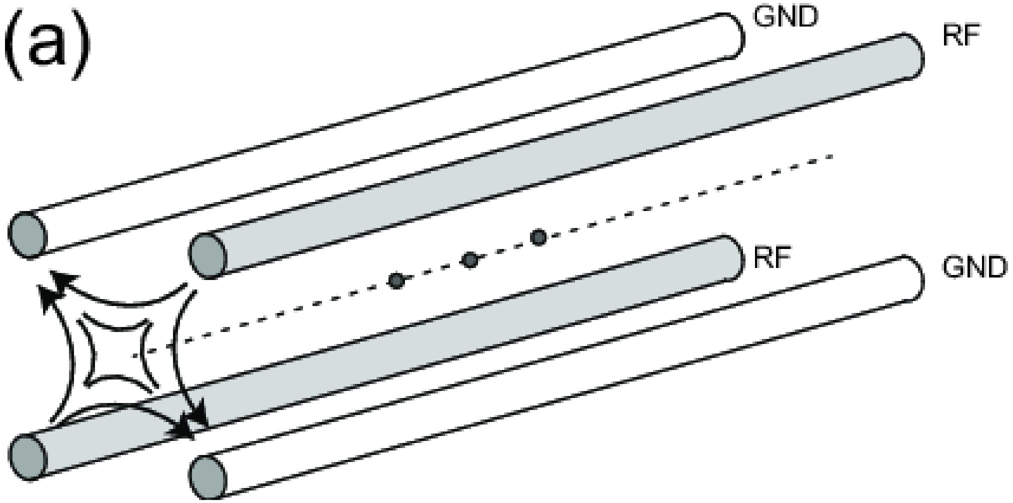
Antiprotonic helium spectroscopy – Masaki Hori (ASACUSA II experiment)

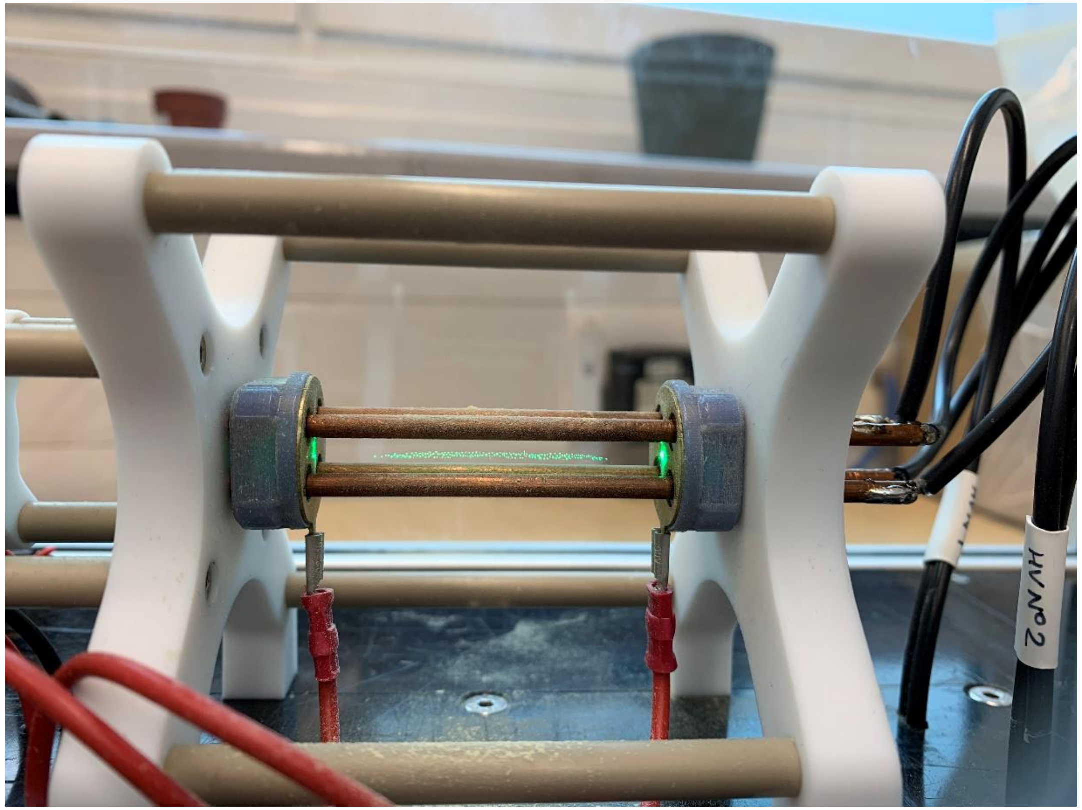


The most precise CPT tests for antimatter – Stefan Ulmer (BASE experiment)

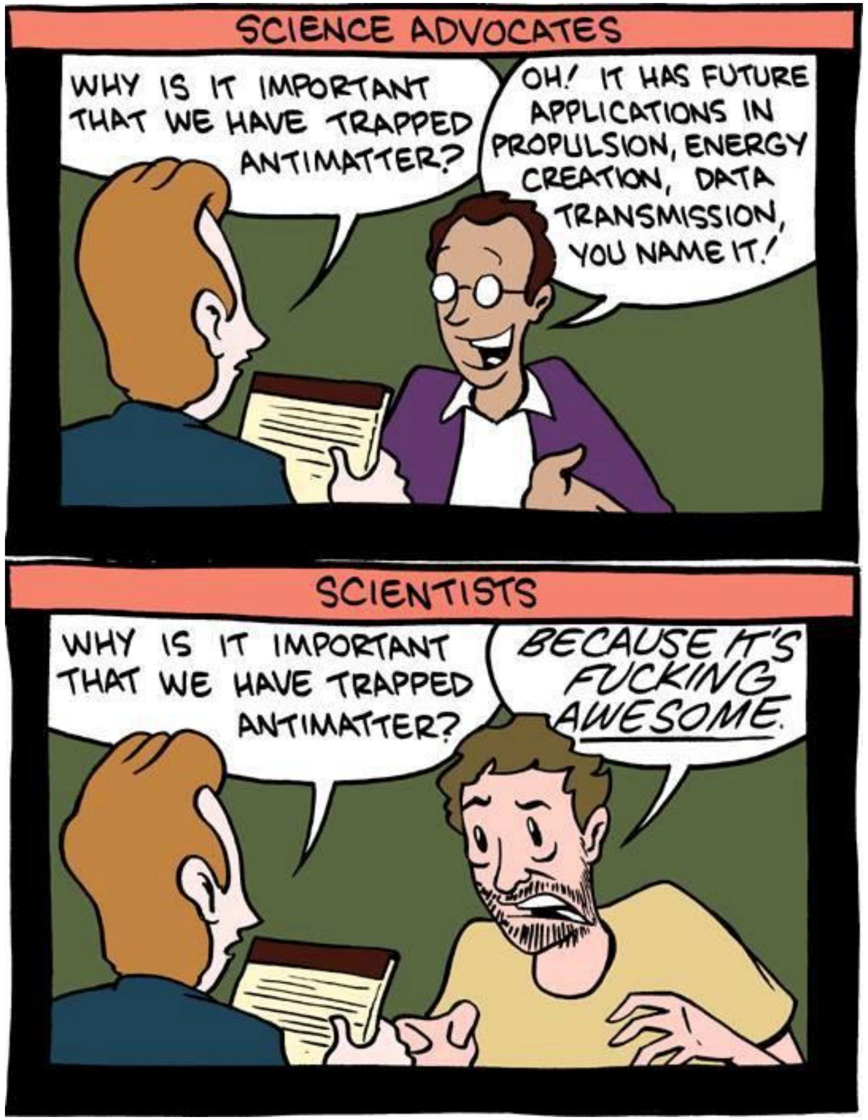
Paul trap







Thank you for your attention!



Thanks to Stefan Ulmer and Jack Devlin for sharing material for this lecture.