Antimatter in the Laboratory 1/2

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CERN

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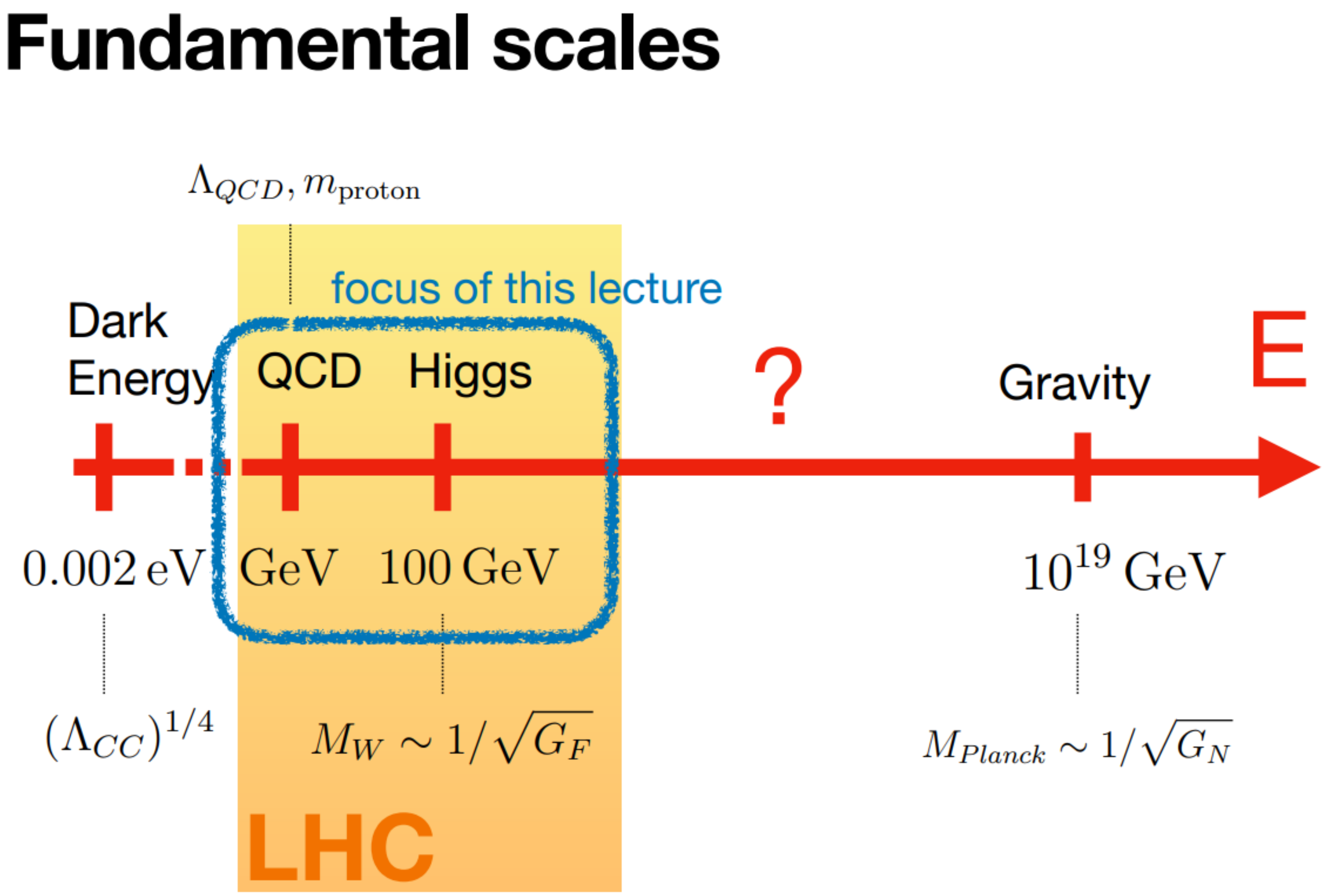
Acknowledgments

I want to acknoledge the contribution of Prof. Stefan Ulmer and Dr. Jack Devlin for providing slides and materials for these lectures.

Introduction

Frontiers of Fundamental Physics -> High energy Frontier



Fundamental scales

$\Lambda_{QCD}, m_{\text{proton}}$

focus of this lecture

Dark Energy

QCD

Higgs

?

Gravity

E

0.002 eV

GeV

100 GeV

10^{19} GeV

$(\Lambda_{CC})^{1/4}$

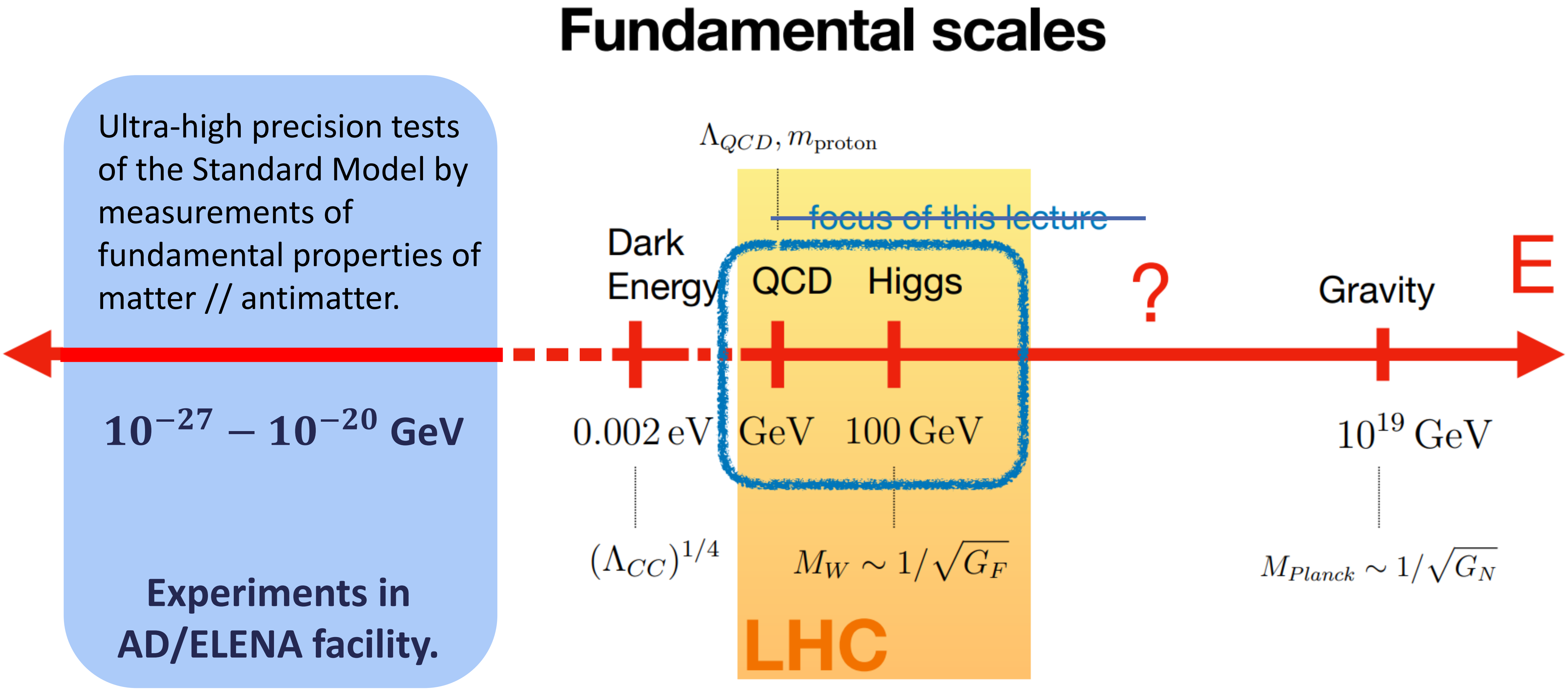
$M_W \sim 1/\sqrt{G_F}$

$M_{Planck} \sim 1/\sqrt{G_N}$

LHC

Screen from the lecture „Standard Model ¼”, Andreas Weiler (TU Munich)

Frontiers of Fundamental Physics -> Ultra High Precision Frontier



Ultra-high precision tests of the Standard Model by measurements of fundamental properties of matter // antimatter.

$10^{-27} - 10^{-20}$ GeV

Experiments in AD/ELENA facility.

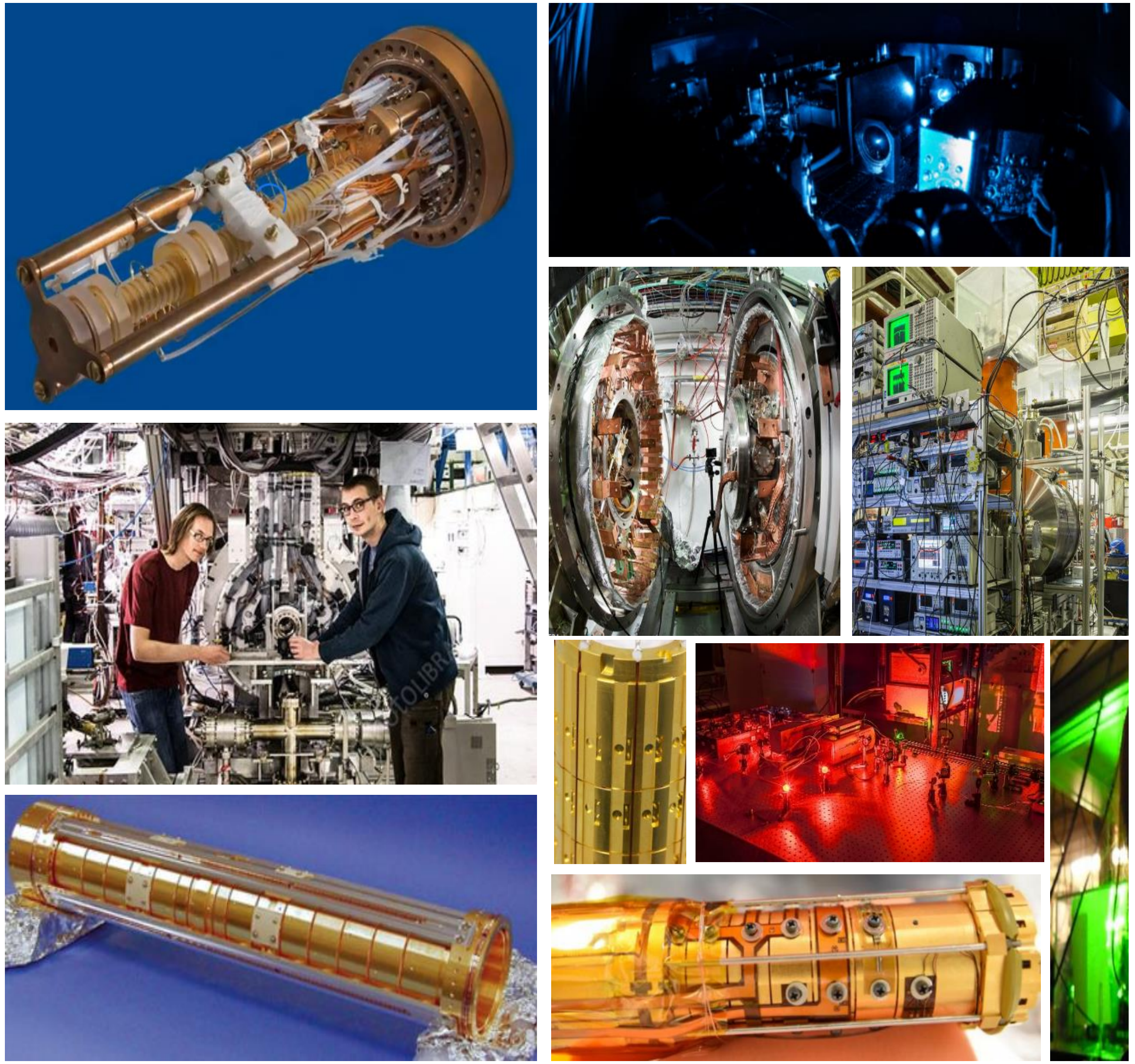
Screen from the lecture „Standard Model ¼”, Andreas Weiler (TU Munich)

Used Techniques: Classical AMO Methods

Clocks

Traps

Lasers



Innovation and Technology

- Trapping of particles
- Penning Traps
- Cooling
- Lasers
- Spectroscopy

matter sector 2016

proton lifetime (direct)	>1.67 e34 y
proton m	90 p.p.t.
proton magn. moment	3.3 p.p.b.
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector 2016

antiproton lifetime	>1.2 y
antiproton m	120 p.p.t.
antiproton m. moment	4.4 p.p.m.
antihydrogen 1S/2S	?
antihydrogen GSHFS	?

matter sector 2021

proton lifetime (direct)	>1.67 e34 y
proton m	**30 p.p.t.**
proton magn. moment	**0.3 p.p.b.**
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector 2021

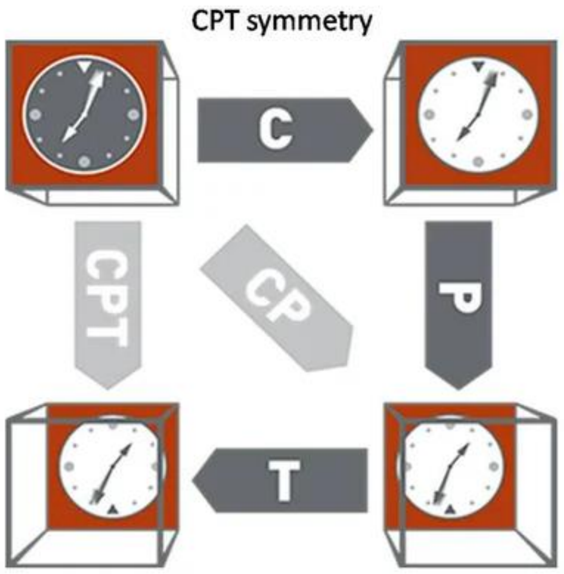
antiproton lifetime	**>30 y**
antiproton m	**30 p.p.t.**
antiproton m. moment	**1.5 p.p.b.**
antihydrogen 1S/2S	**2 p.p.t.**
antihydrogen GSHFS	**400 p.p.m.**

Physics Motivation

Is this interesting?

A skeptical voice:

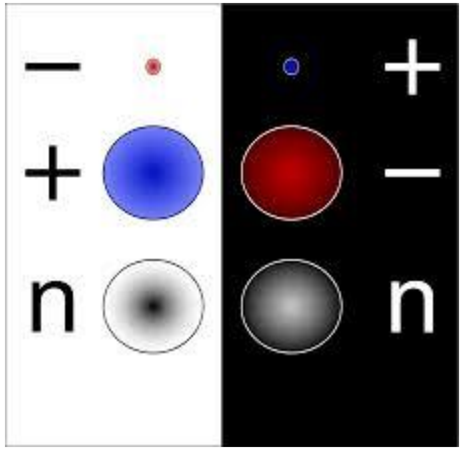
Is it possible for matter and antimatter properties to differ?



A skeptical voice with extensive physics training:

Any “reasonable”, Lorentz-covariant quantum field theory will be CPT symmetric.

CPT symmetry means matter and antimatter properties are the same.



... but it also says...

Why do we want to study antimatter?

- Combining the Λ-CDM model and the SM, our predictions of the baryon to photon ratio are **inconsistent by about 9 orders of magnitude**

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

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

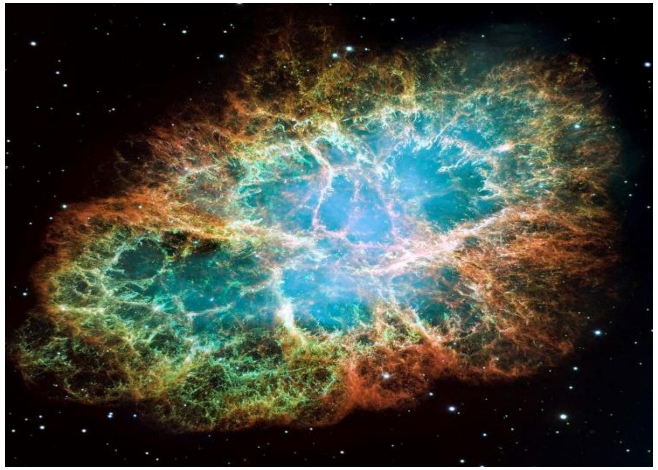
Sakharov conditions (1967):

1.) B-violation (plausible)

2.) CP-violation (observed / too small)

3.) Arrow of time (less motivated)

Maybe lack of thermal equilibrium?



… so maybe the „final” field theory is „not reasonable”?

Or maybe there is much more?

Tackling these problems…

- We need probes for new physics and new discoveries, to get a deeper, additional, complementary understanding.

  - **We should look where noone has looked before!**

    1. Conduct experiments with exotic systems.
    2. Develop new techniques with higher sensitivity.
    3. Scale experiments up.

High Energy Physics
=
Upscaling / Higher Energy

Low Energy Physics
=
New Methods / Better Resolution

We will see in this lecture, that here, trapped antimatter, play a crucial role !!!

Tackling these problems…

- We need probes for new physics and new discoveries, to get a deeper, additional, complementary understanding.

  - **We should look where noone has looked before!**

1. Conduct experiments with exotic systems. => systems with baryons and antibaryons, trapped particles.
2. Develop new techniques with higher sensitivity. => The most sensitive antiproton detector (BASE experiment) has 120 neV sensitivity! This is the most sensitive spectrometer ever built.
3. Scale experiments up. => Make more antiydrogen atoms, make more complex systems, be creative...

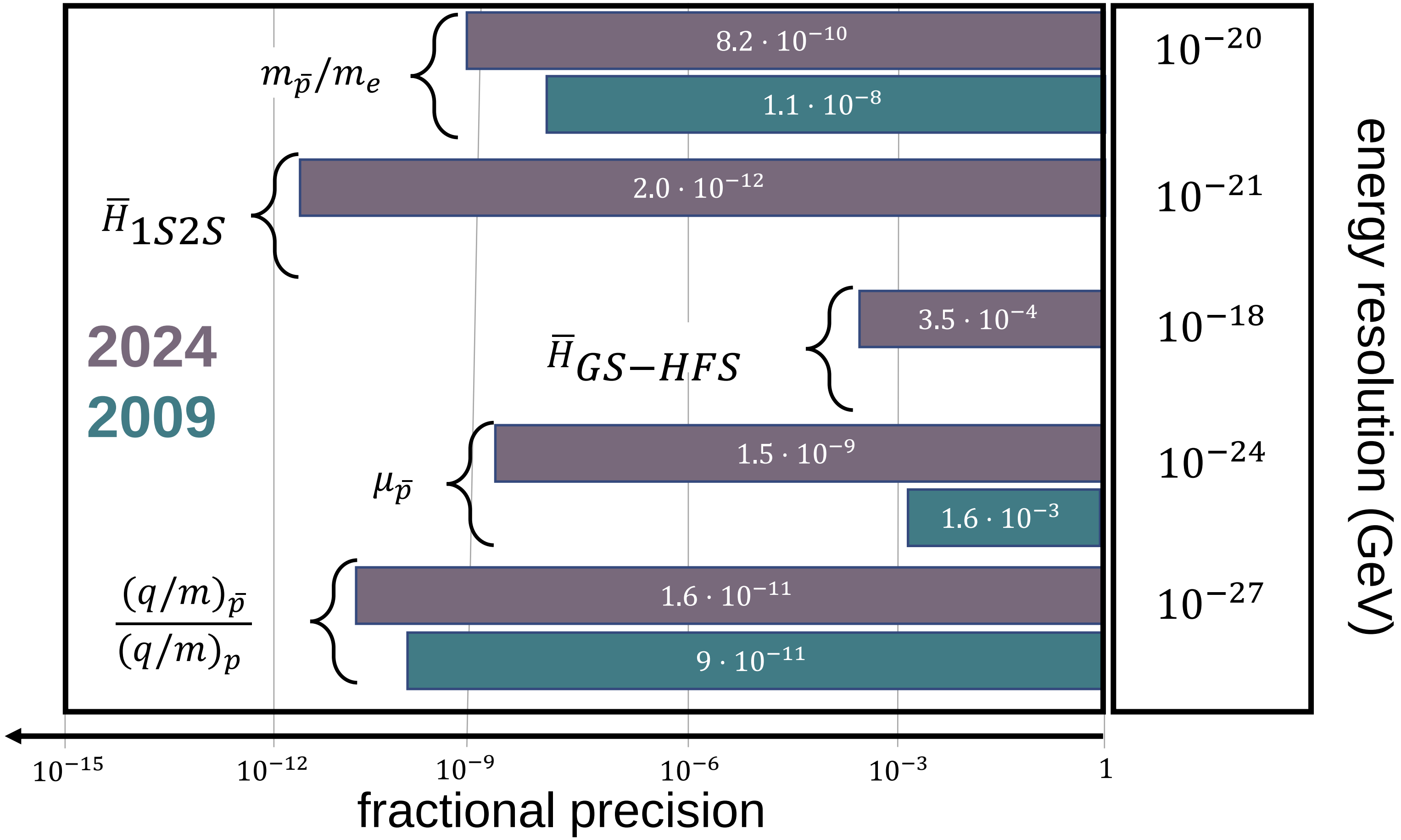
High Energy Physics
=
Upscaling / Higher Energy

Low Energy Physics
=
New Methods / Better Resolution

We will see in this lecture, that here, antimatter AMO physics plays a crucial role !!!

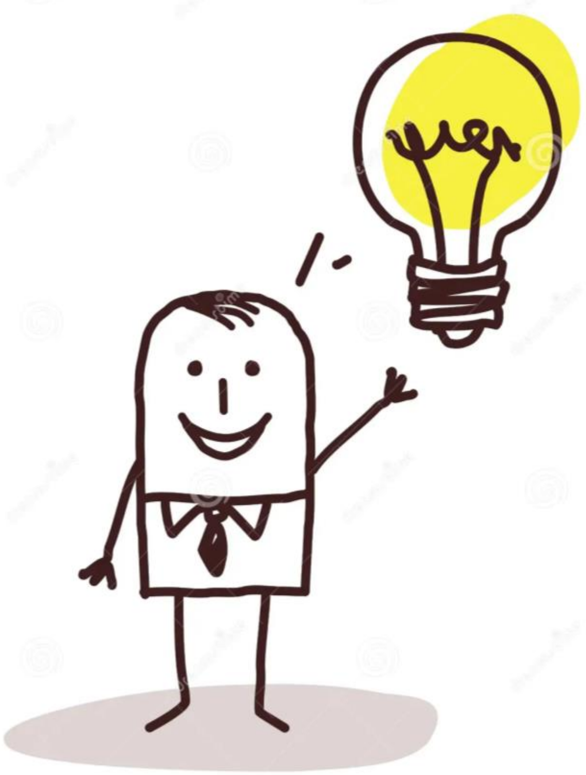
Subject of this lecture -> how to get these numbers?

- AD -> measure fundamental properties of antimatter systems and compare them with theory // matter.



Question to all of you:

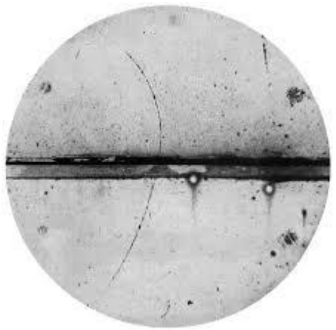
What kind of antimatter system would you propose to study and why?



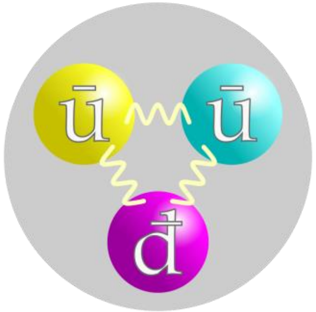
What are the simple systems in antimatter physics

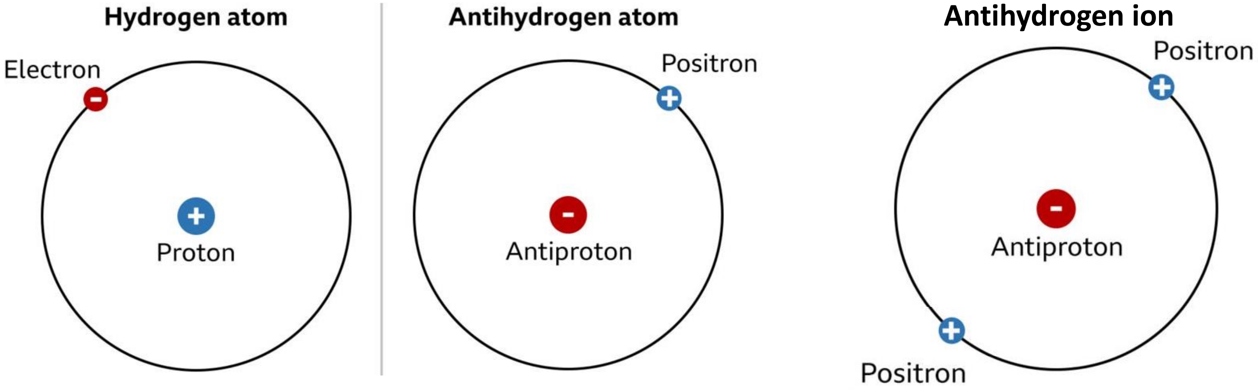
What do we study in the context of antimatter:

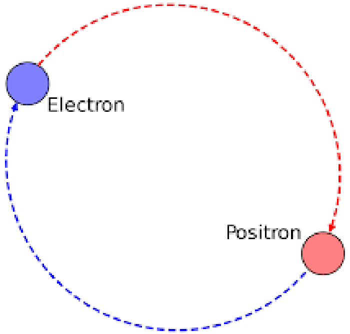
- Single particles:
  - AntiElectron -> positron -> antilepton
  - AntiProton -> antibaryon
  - ~~Neutron~~
- Complex systems:
  - Hydrogen-like system:
    - AntiHydrogen
    - AntiHydrogen Ion
    - Positronium
    - Antiprotonic helium
  - AntiHydrogen molecule

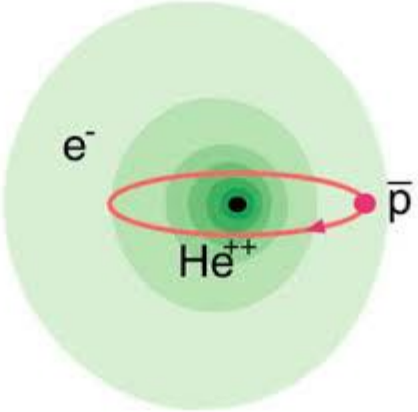


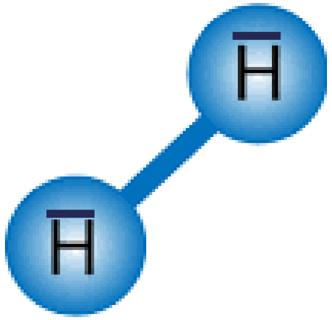
Antiproton





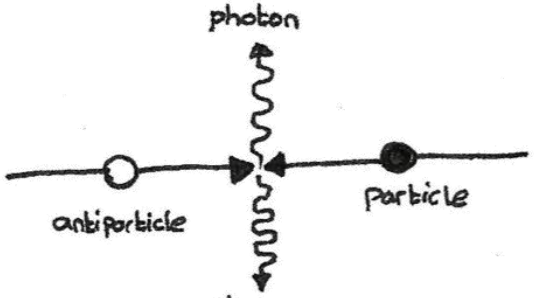




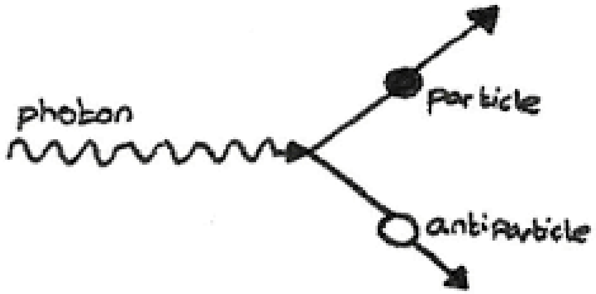


How can we produce antimatter?

Antimatter production



Annihilation

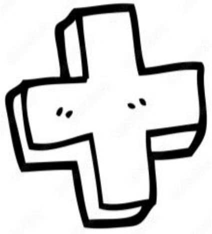


Pair production

$\sigma_{pair\ production} \sim Z^2$

Z - atomic number

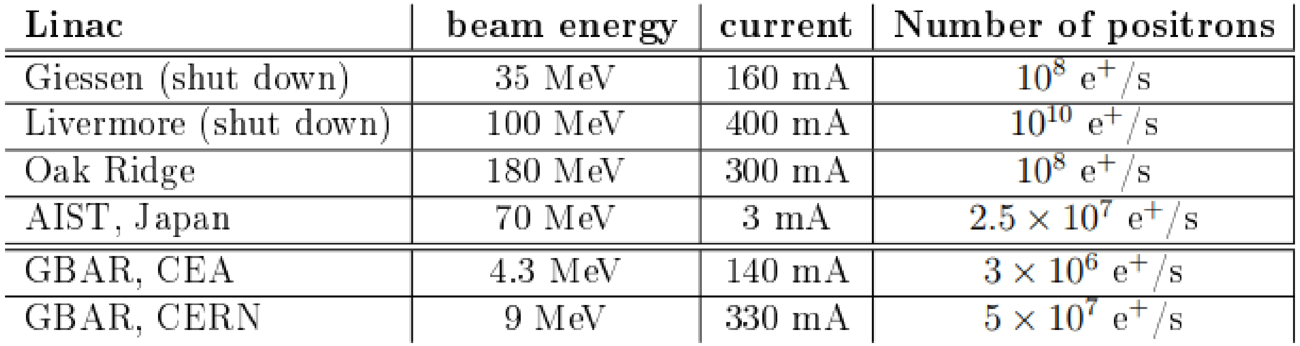
- Aniparticles (natural units c=1):
  - Neutrino: < 1 eV
  - Electron: 511 000 eV
  - Muon: 105 000 000 eV
  - Proton: 938 000 000 eV
  - Higgs Boson: 125 000 000 000 eV



... all the energy needed for particle to go out of the material // to be moderated // to be prepared to be useful.

Positron production

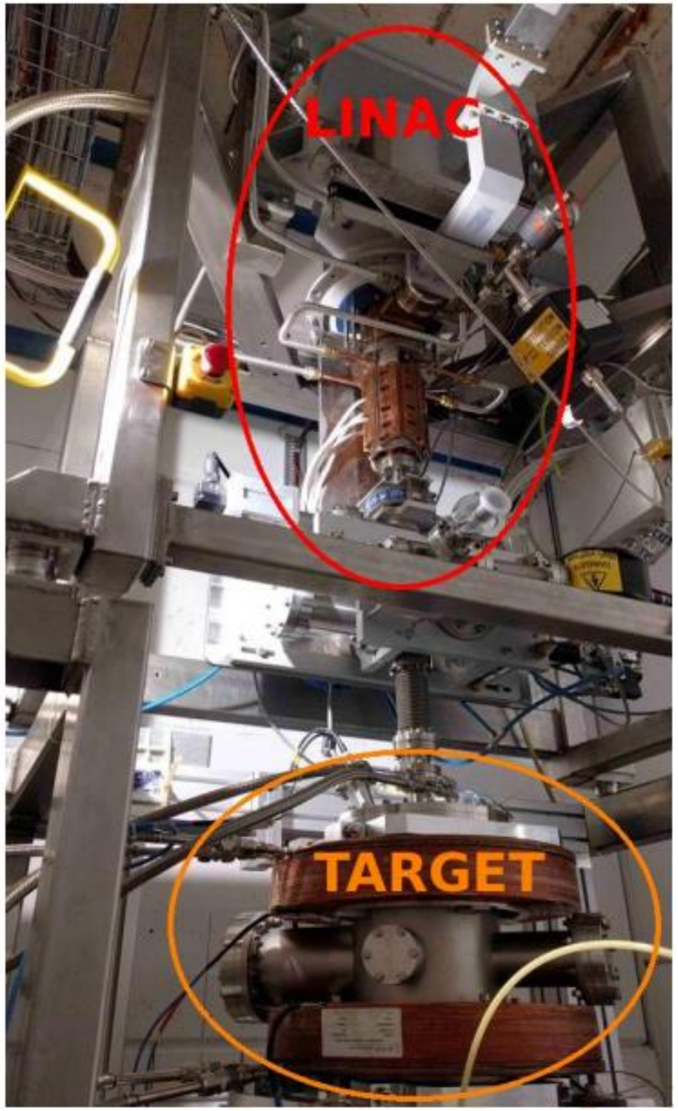
- Positron production:
  - Production using high intensity electron sources:
    - $10^7 - 10^{10}$ e+/s



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

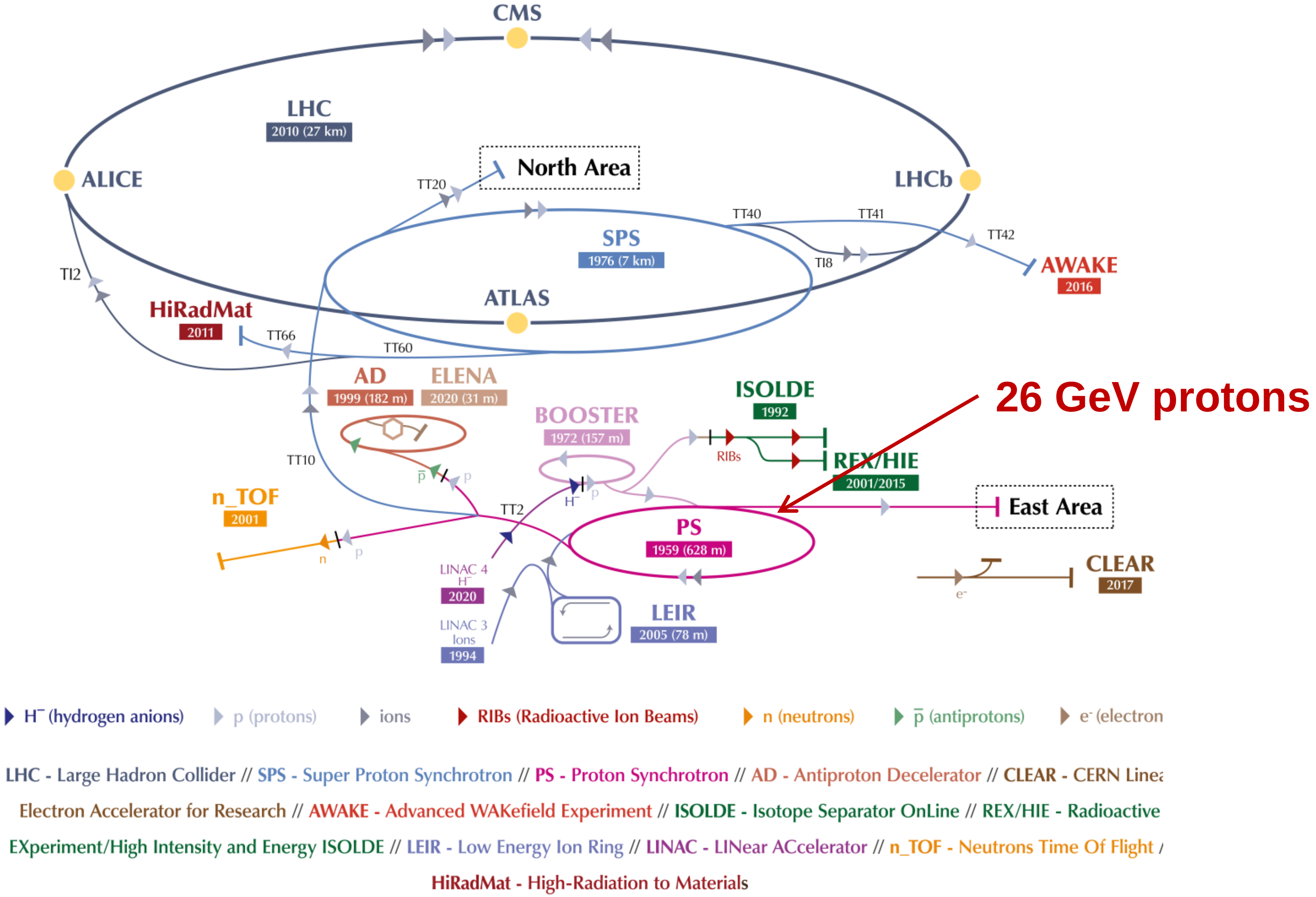
- Catching particles from natural sources
  - ^{22}Na $< 10^7$ e+/s

- Catching particles from nuclear reactors:
  - ^{113}Cd + n → ^{114}Cd + γ, 10^9 e+/s



Antiproton production

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



26 GeV protons

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linea
Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive
EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight /
HiRadMat - High-Radiation to Materials

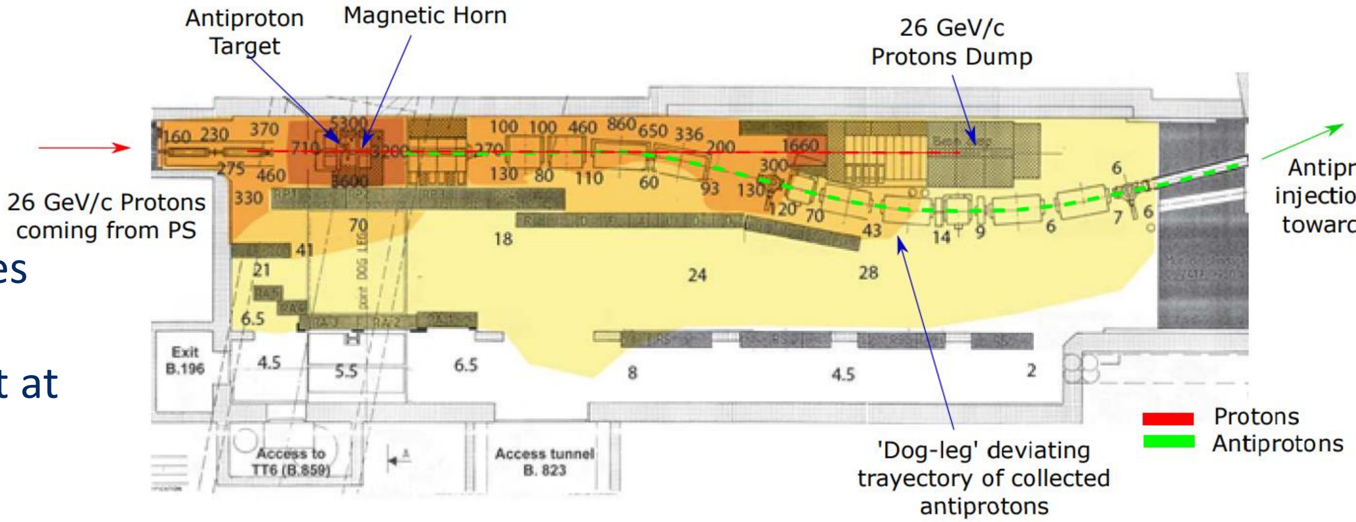
Antiproton production

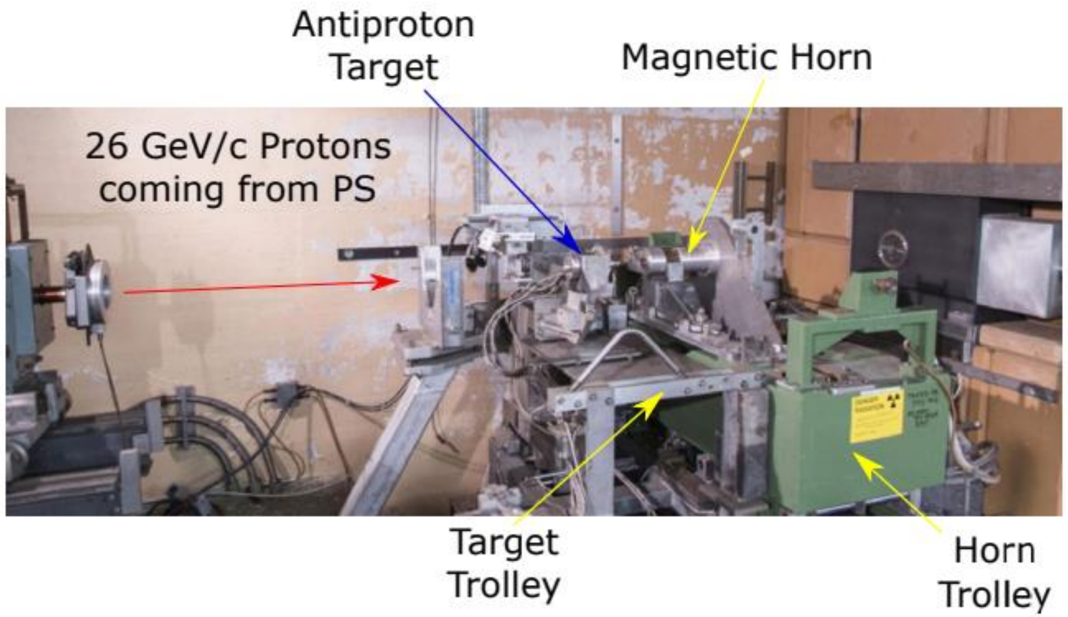
- Production mechanism:

  $p + \text{nucleus}$
  $\rightarrow \text{Excited nucleus} + p + \bar{p} + \text{other particles}$

Threshold for this reaction is at 5.6 GeV, carried out at 26 GeV.

- 1.5×10^{13} protons with 26 GeV energy are used to produce 5×10^{7} antiprotons.
- Indium rod of 5.5 cm length.
- Extreme temperatures: 2000 degrees rise in 0.5 microseconds
- We collect 3.6 GeV antiprotons with momentum spread of $\frac{\Delta p}{p} = 6\%$.
- One bunch every 2 minutes.



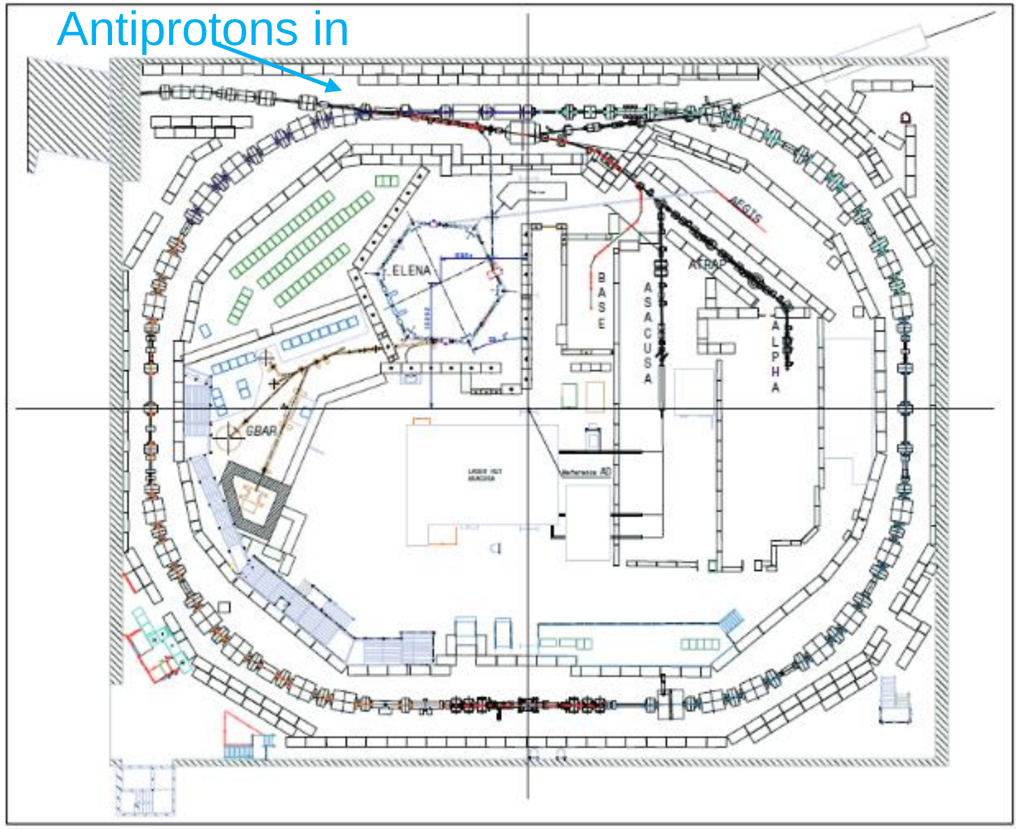


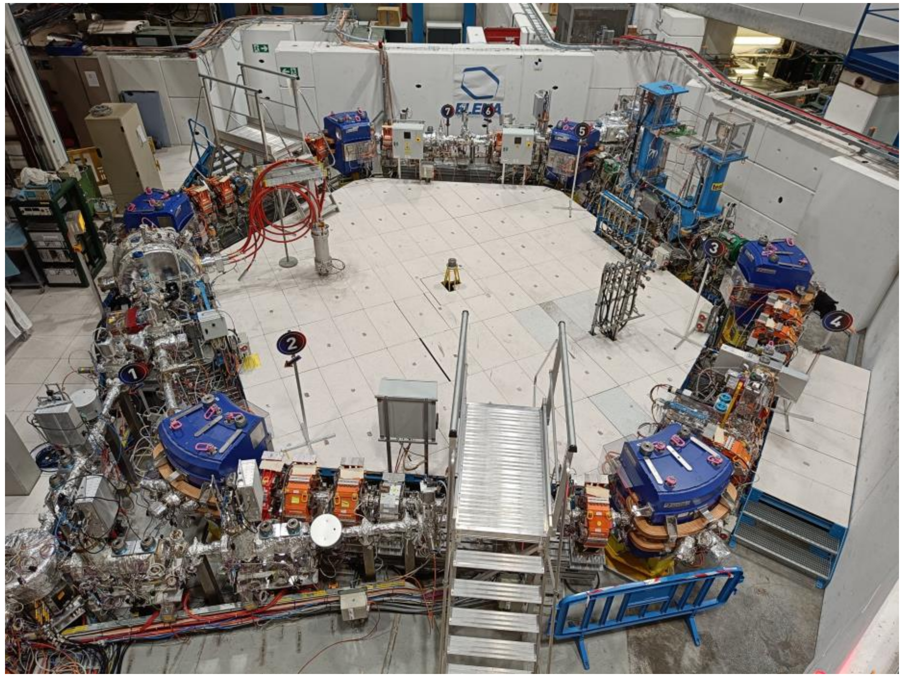
C. Torregrosa Martin, PhD Thesis (CERN-THESIS-2017-357)

The AD and ELENA Decelerators

- Antiproton Decelerator:
    - Slows from 3.6 GeV to 5.3 MeV energy

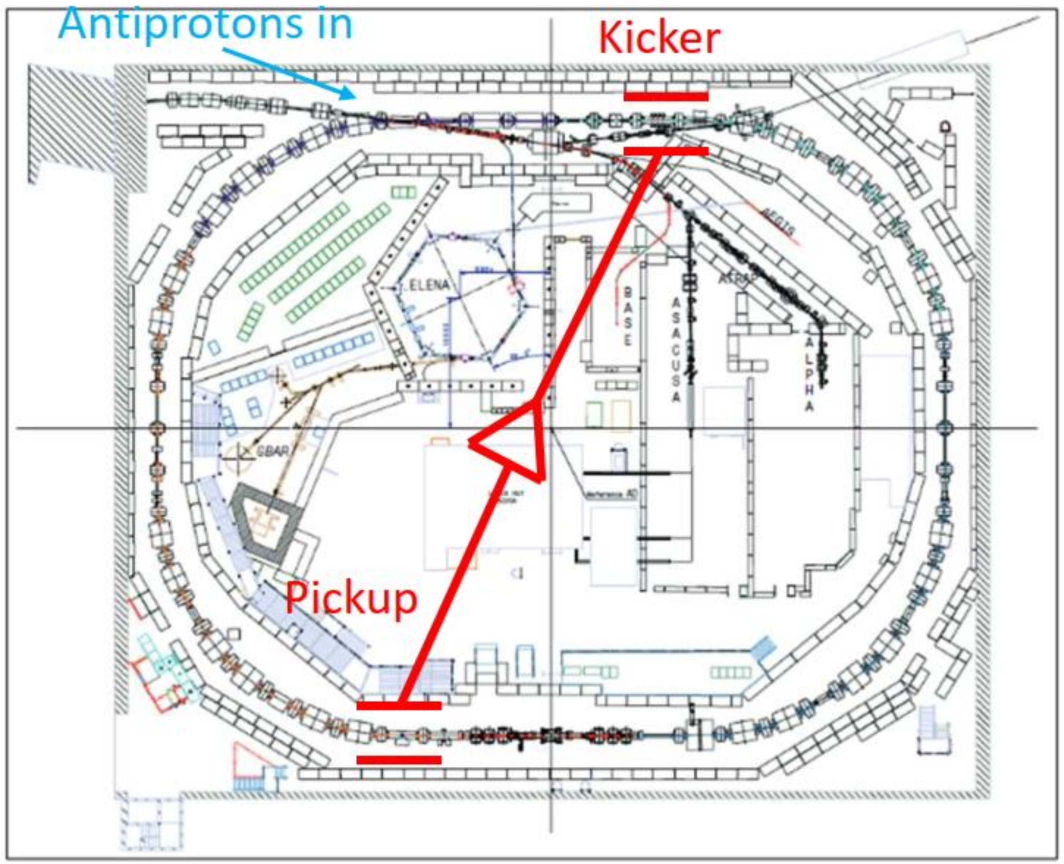
- ELENA - The Extremely Low Energy Antiproton Synchrotron (2018)
    - Slows from 5.3 MeV to 100 keV

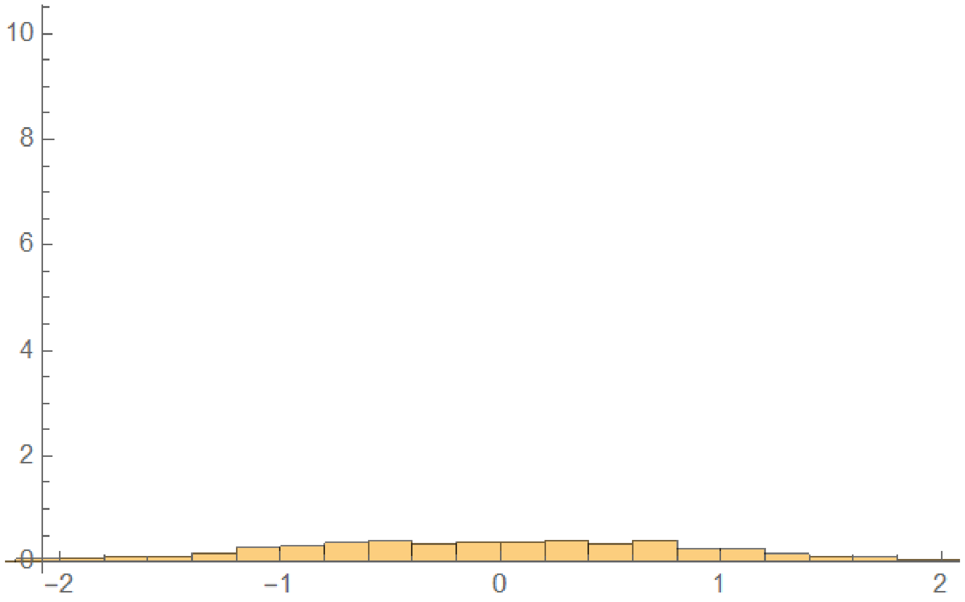

Antiprotons in



1984 - Nobel Prize for antiproton cooling for Simon van der Meer

- The purpose of **stochastic cooling** is to reduce the energy spread and angular divergence of a beam of charged particles. During this process, the particles are “compressed” into a finer beam with less energy spread and less angular divergence. By increasing the particle density to close to the required energy, this technique improved the beam quality.

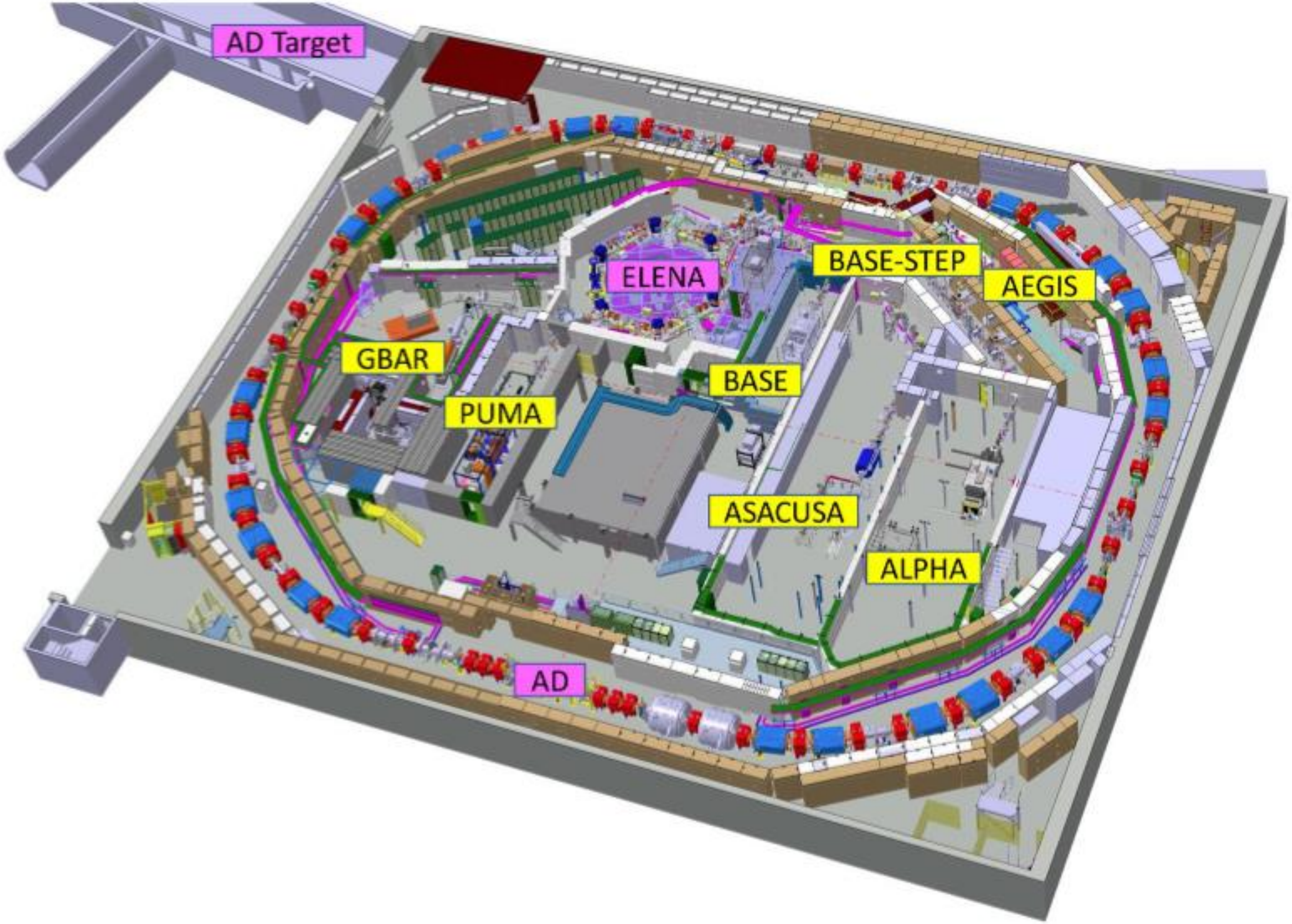




- 2 stages of stochastic cooling reduces momentum spread (4σ) from 1%->0.1%->0.015%

P. Belochitskii, T. Eriksson, and S. Maury, Nucl. Instrum. Meth. Phys. Res. A **214** (2004)

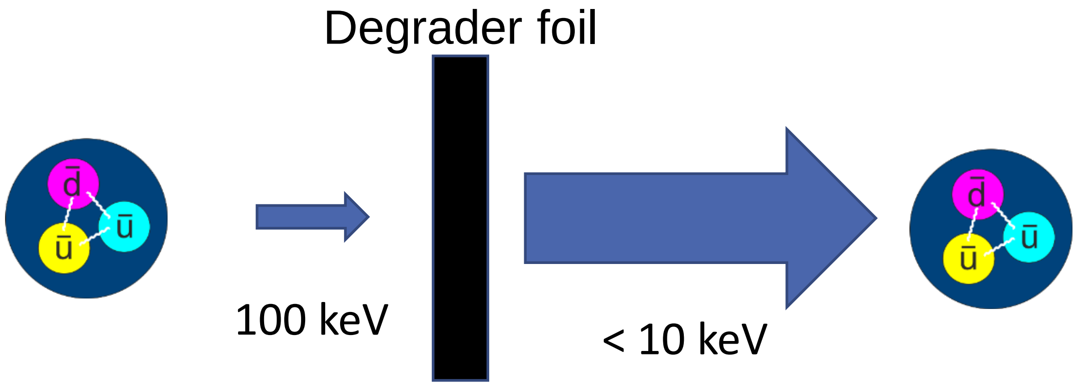
The AD/ELENA-Facility

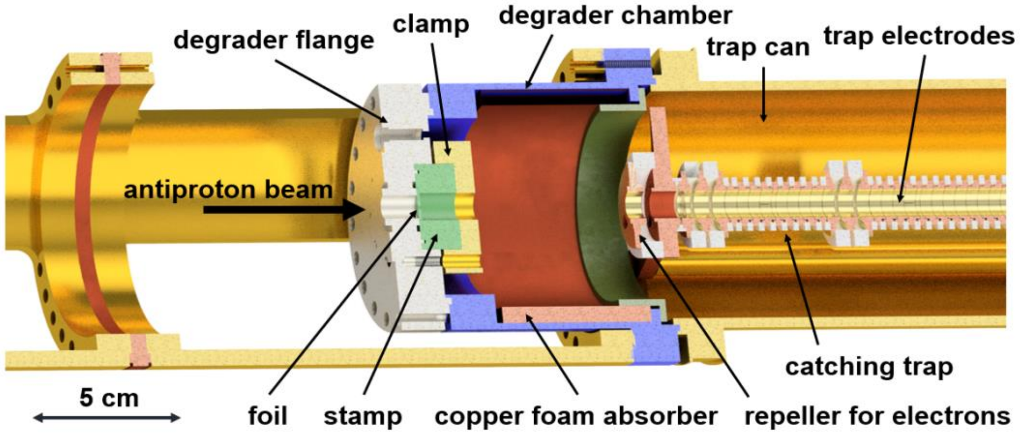


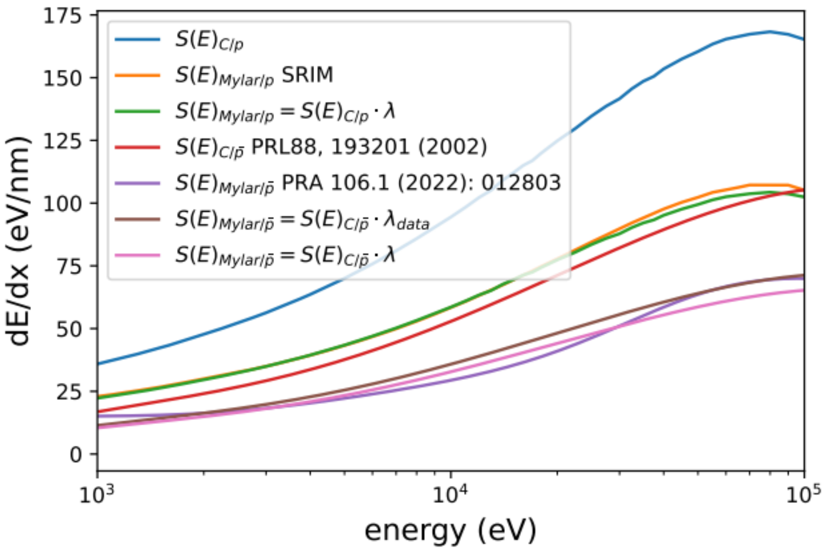
60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations

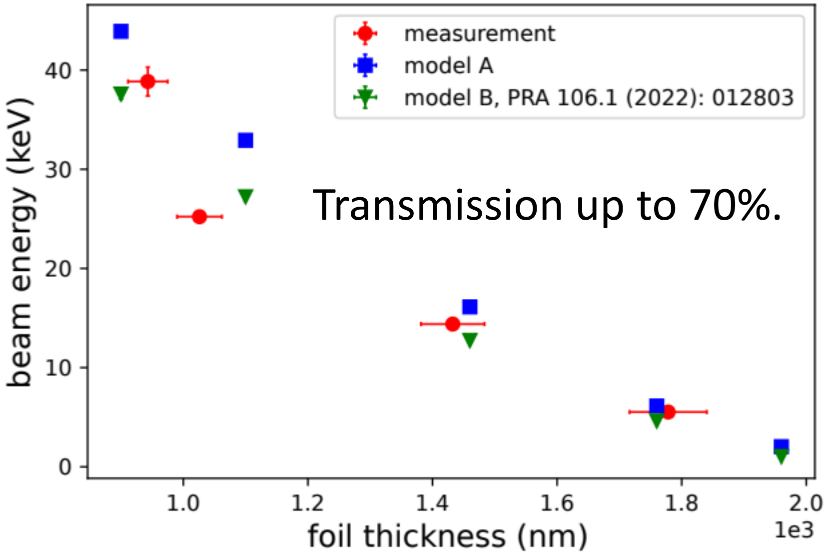
Final step of slowing

- 100 keV energy is still to high to be able to trap antiprotons.
- Final stage of deceleration is done using the degrader foil.
- Lose of energy comes from the sum of scattering from electrons and Rutherford scattering from nuclei









Transmission up to 70%.

What’s the cost of a gram of antimatter?

In 2018

Electricity used cost 67 million Swiss Franc, and uses 1.25 TWh per year when running

10% spent on Proton Synchrotron, AD takes ~2.4 s/112 s= 2% of cycles

Costs ~130,000 CHF in electricity per year to produce antiprotons

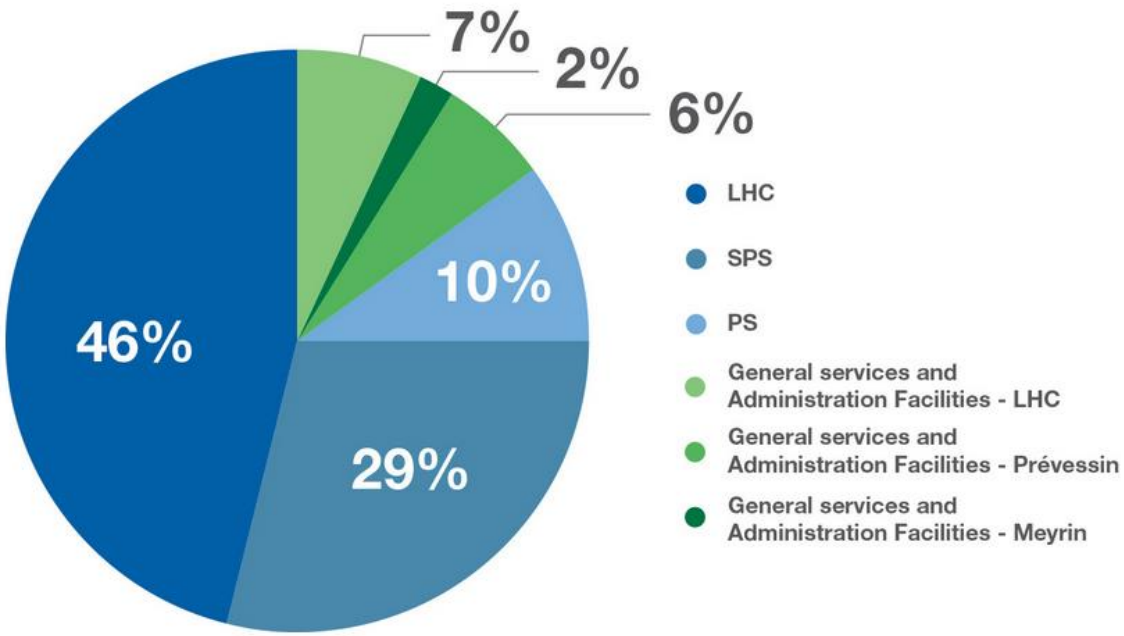
~10 trillion antiprotons produced per year ~12 picograms

Cost per gram ~**8000 trillion Swiss Franc (100x world GDP/y)**

- Not including people to operate the machine!

Not a cheap way to make lots of antimatter

Or looking at it another way – cost per particle
12 nano Swiss Francs or 40 cents per shot



CERN Financial Budget 2018
https://hse.cern/environment-report-2017-2018/energy

Trapping antimatter

The Earnshaw Theorem

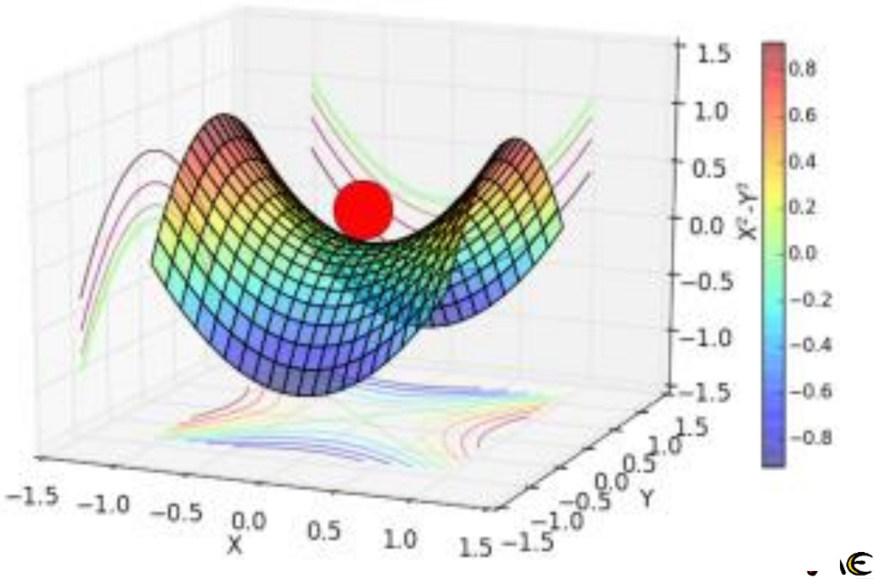
- **Earnshaw's theorem** -A charged body cannot be held in stable stationary equilibrium by electrostatic forces from other charged bodies. This was first proven by British mathematician Samuel Earnshaw in 1842.

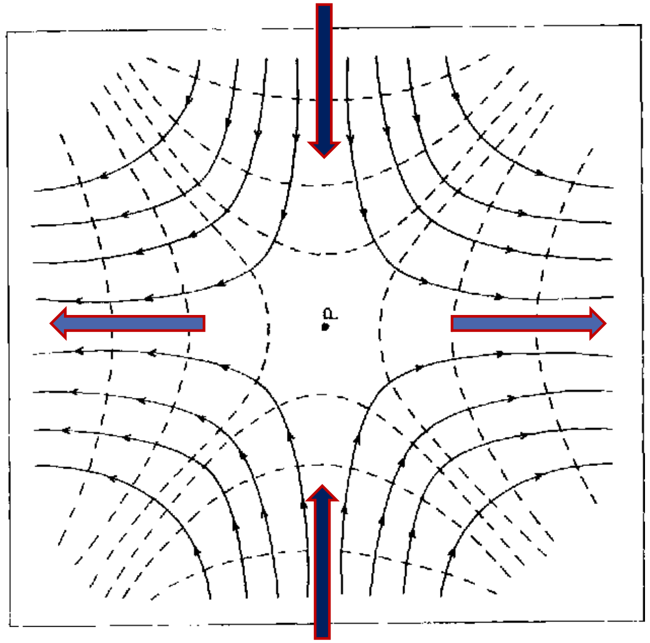
- **Earnshaw's theorem** in its simplest shape:

$$\nabla^2\Phi(x,y,z) = 0$$

Therefore, there are no local minima or maxima of the field potential in free space, only saddle points.

- Simplest solution would be harmonic: $\Phi(x,y,z) = C_2\left(z^2 - \frac{x^2+y^2}{2}\right)$
- The electric quadrupole potential is the simplest harmonic, stationary solution to the Laplace equation, and **fulfils the Earnshaw theorem**.



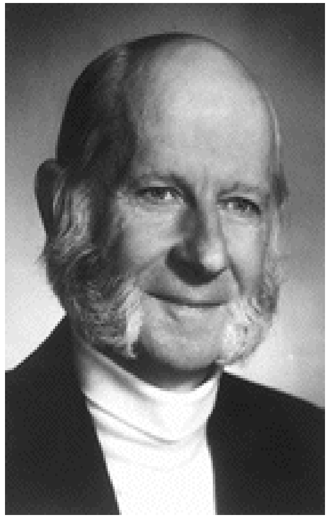


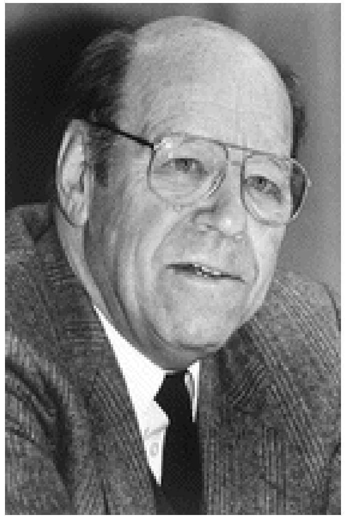
Overcoming The Earnshaw Theorem

Static

Dynamical

Hans Dehmelt
(1922 - ...)





Wolfgang Paul
(1913 - 1993)

Nobel Prize in Physics in 1989 to

Hans Dehmelt und Wolfgang Paul

„for the development of the ion trap technique“.

Penning Trap

Paul Trap

The Two Solutions

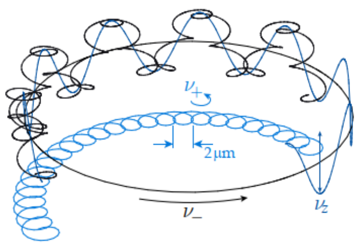
- The Penning Trap

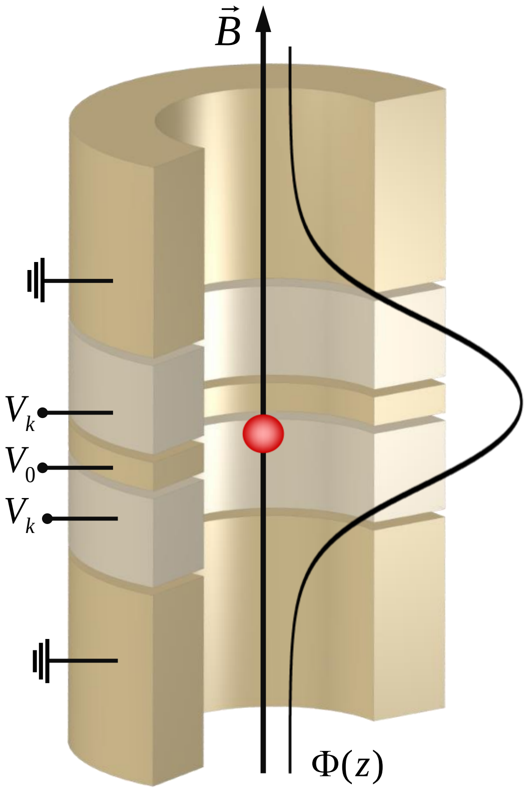
- Static potential

$$\phi(z,\rho) = V_0 C_2 \left(z^2 - \frac{\rho^2}{2}\right)$$

- Static magnetic field

$$\boldsymbol{B} = B_0 \boldsymbol{e_z}$$





- Used in measurements of fundamental properties such as masses, magnetic moments, etc…

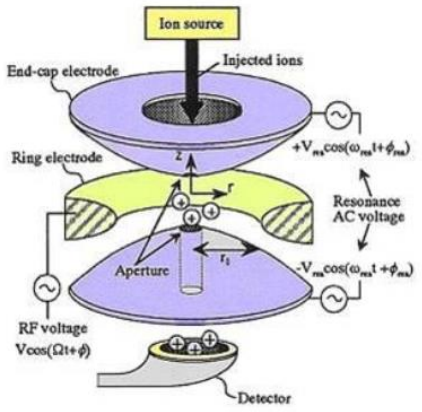
EXPENSIVE

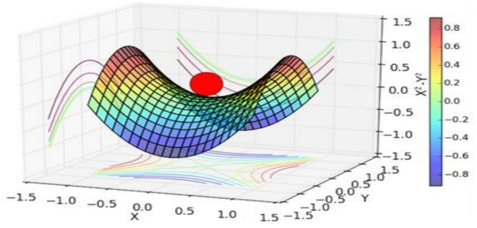
- The Paul Trap

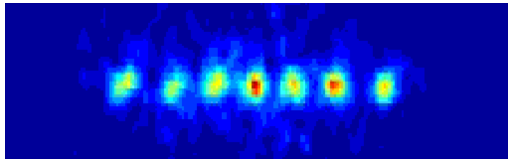
- Dynamical potential

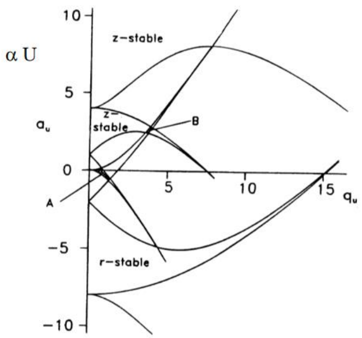
$$\phi_0(z,\rho) = C_2 \left(z^2 - \frac{\rho^2}{2}\right)$$

$$\phi(z,\rho,t) = \phi_0(z,\rho)(V_0 + U_0 \cos(\Omega t))$$









- Used in measurements and manipulations, where intrinsic degree of freedom of the trapped particle is of interest.

CHEAP

Penning trap

$$\vec{F} = m\ddot{\vec{r}} - q_0\left(\vec{\nabla}\Phi(\vec{r}) + \dot{\vec{r}} \times \vec{B}\right) = 0$$

- **Penning trap with:**
  - -> radial confinement: $\vec{B} = B_0\hat{z}$
  - -> axial confinement: $\Phi(\rho, z) = V_0 c_2\left(z^2 - \frac{\rho^2}{2}\right)$

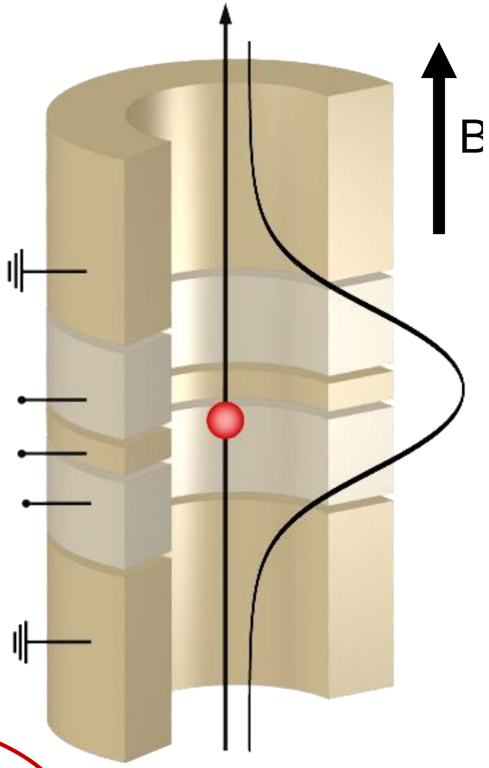
- **Invariance theorem:**

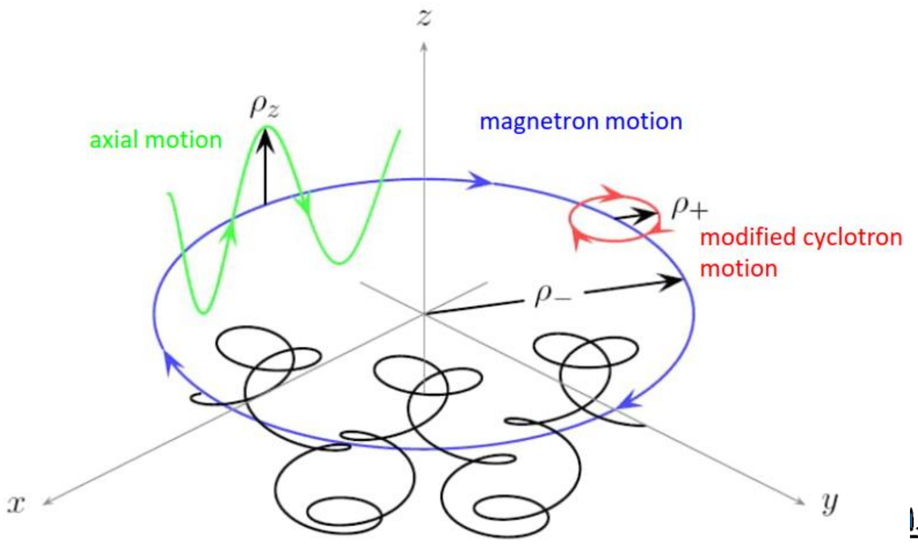
Cyclotron frequency of a particle

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

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

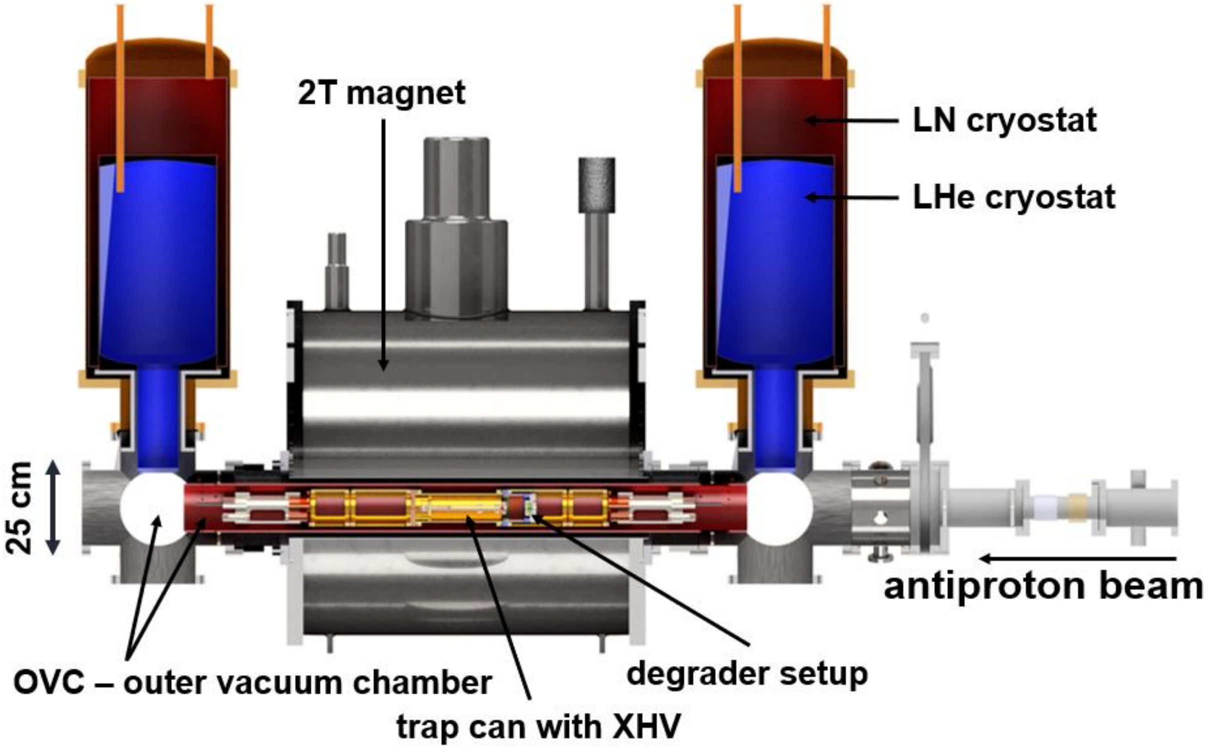
A single fundamental particle in a Penning trap is one of the simplest systems you can think of!

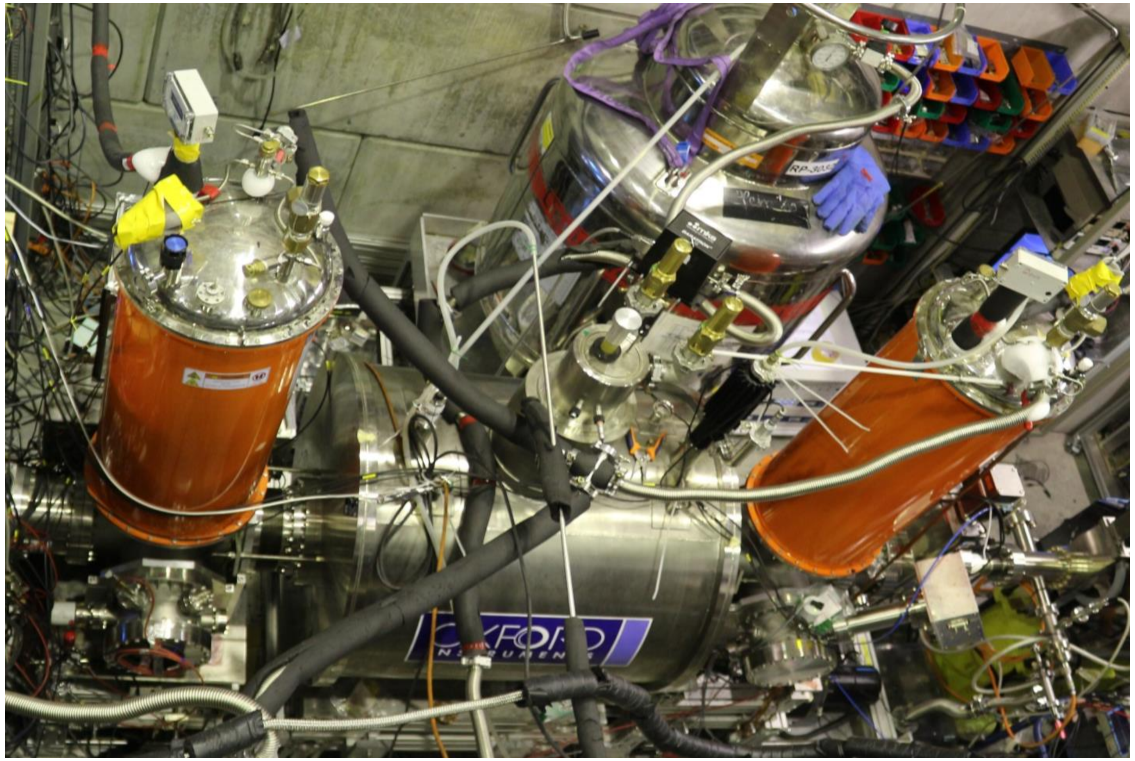




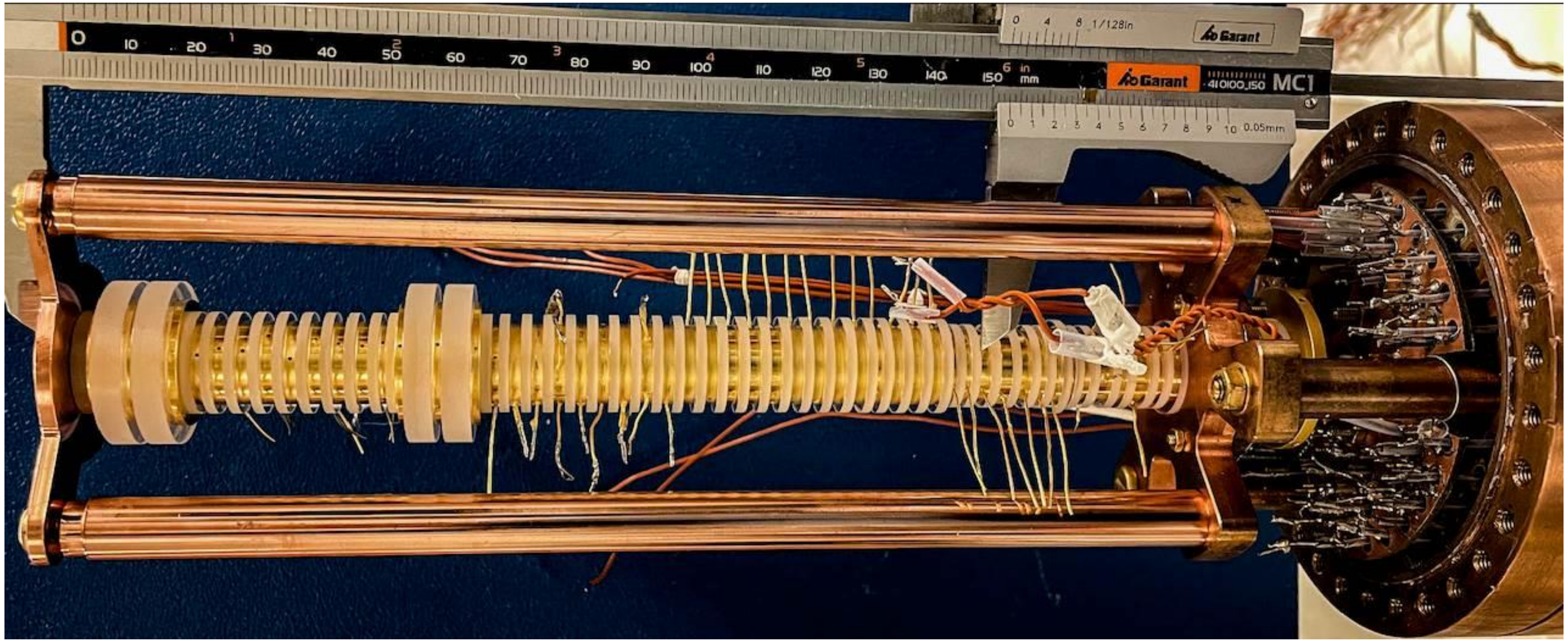
Axial	680 kHz	$\nu_z = \frac{1}{2\pi}\sqrt{\frac{2C_2qV_0}{m}}$
Magnetron	8 kHz	$\nu_- = \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)$
Modified Cyclotron	28.9 MHz	$\nu_+ = \frac{1}{2}\left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)$

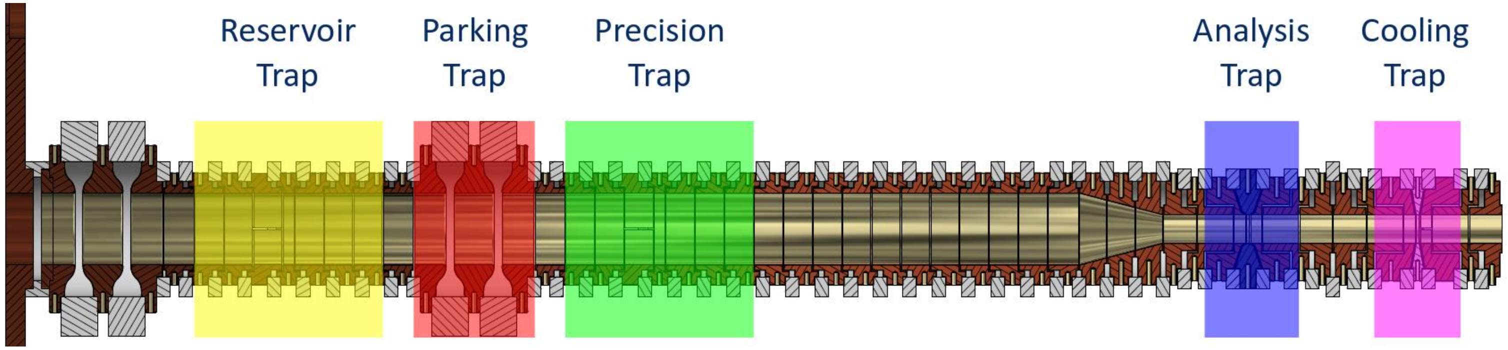
Penning Trap – superconducting magnet





Typical precision Penning Trap System




Reservoir Trap

Parking Trap

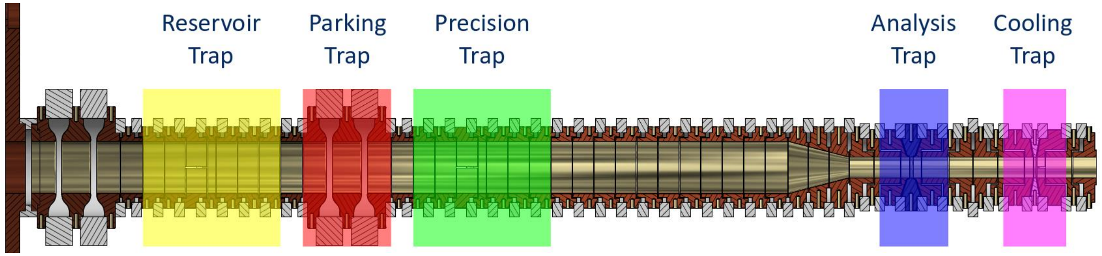
Precision Trap

Analysis Trap

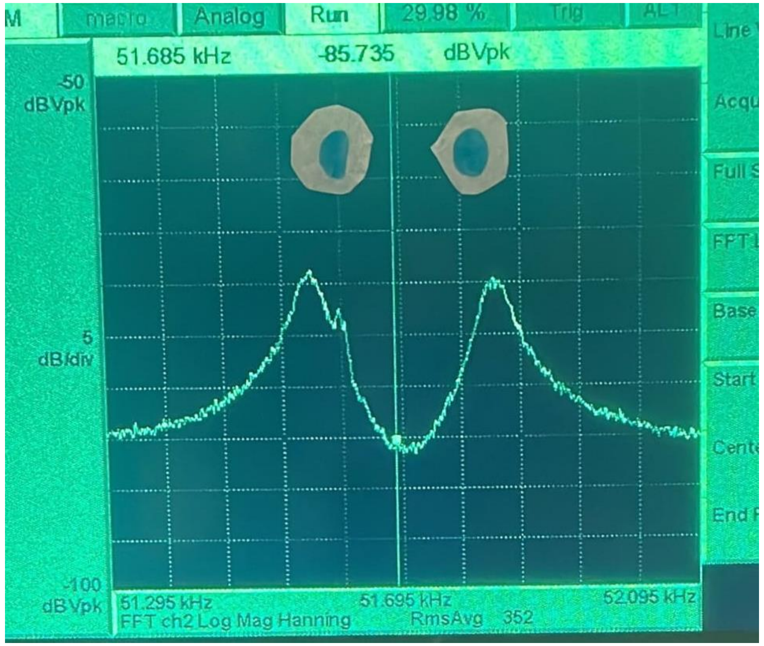
Cooling Trap

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

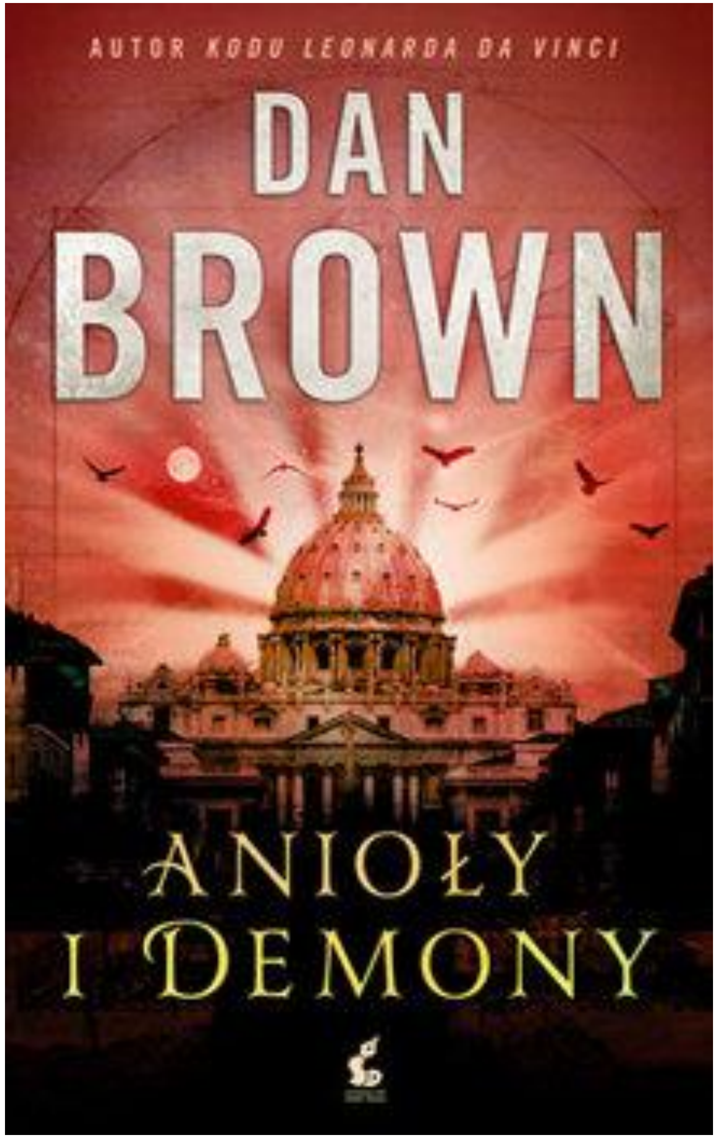
- BASE Reservoir trap:
  - **Pressure: $p_H < 0.46 \times 10^{-18}$ mbar** and **$p_{He} < 1.04 \times 10^{-18}$ mbar**.
  - best characterized vacuum on Earth, comparable to pressures in the interstellar medium
  - Antiproton storage time is 10s of years -> 405 days.
  - Not more than 3000 atoms in 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	**$5.9*10^8$**



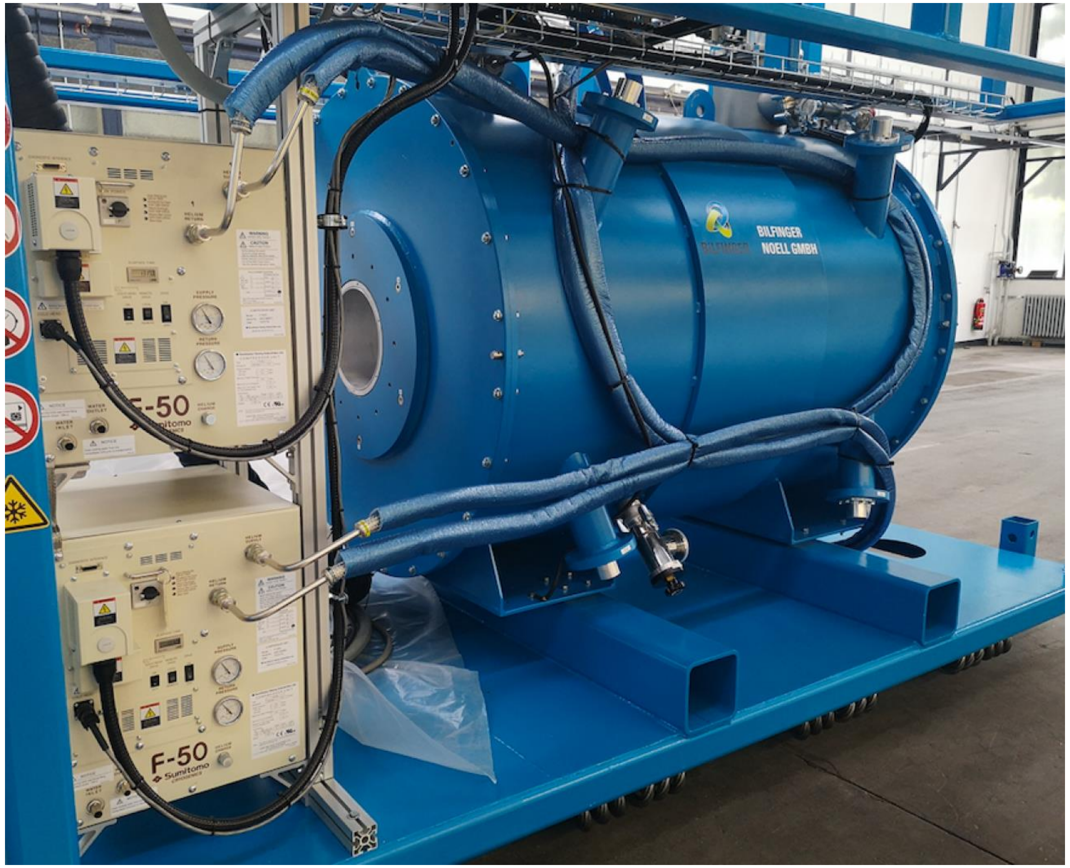
„Angels and Demons” Dan Brown



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

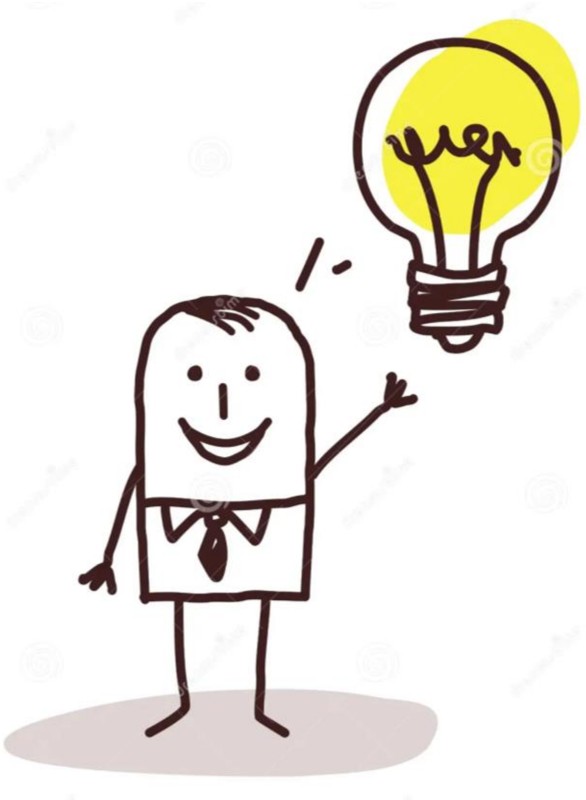
Antimatter transport

- BASE-STEP and PUMA experiments



Question to all of you:

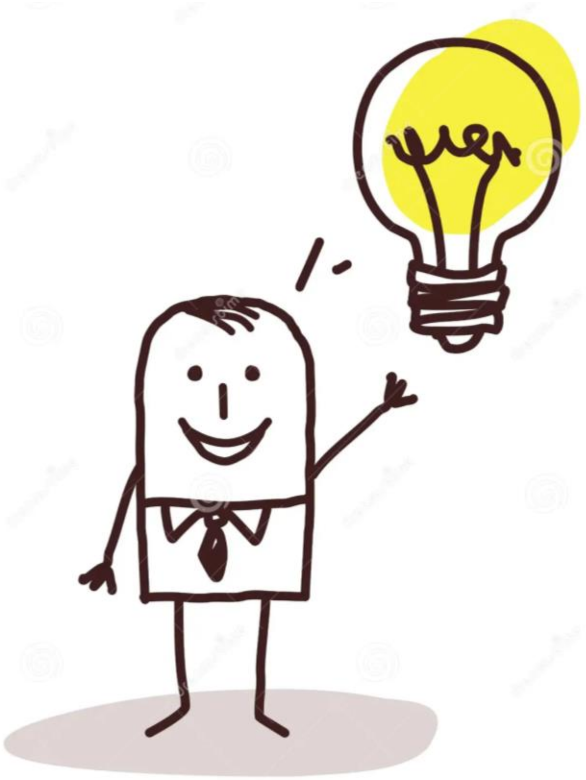
Do you know what is the most precise test of the Standard Model?



Question to all of you:

Do you know what is the most precise test of the Standard Model?

... it was made in a Penning Trap...
Think about this until tomorrow!



Thank you for your attention!

- Summary of Lecture 1:
    - Baryon-antibaryon assymetry as a motivation to measure fundamental properties of antimatter.
    - High-energy physics vs Low-energy physics approach.
    - Different „simple” antimatter system.
    - Production of positrons.
    - Production of antiprotons.
    - Antiproton decelerators.
    - Particles trapping, in particular Penning Trap.
    - Antiproton storage.
    - Antiproton transport.
    - BASE-STEP.
    - Nuclear physics with antimatter with PUMA experiment.

- Lecture 2:
    - Precision measurements with antimatter systems.