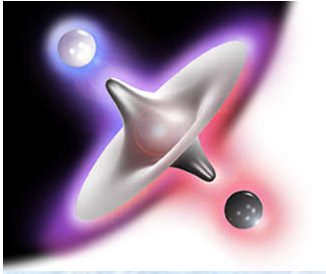


Antimatter in the Laboratory



Rolf Landua
CERN

Summer Student Lectures 2005



Plan

Theory Introduction

Einstein, Dirac, Feynman, CPT

Antimatter 'Factory'

How are antiprotons made?

Trapped antiprotons

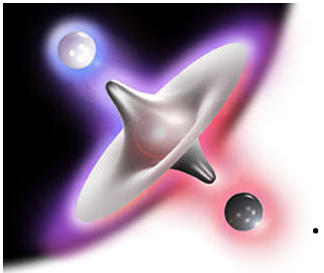
Antiproton charge-to-mass ratio

Antihydrogen

Short history
ATHENA and ATRAP
Making antihydrogen
Future developments

Antimatter technology

PET
Antiproton therapy?
Rocket propulsion??



How CERN *really* became famous

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

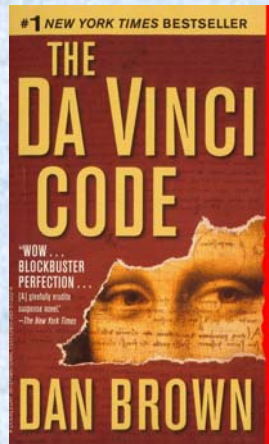
Werner Heisenberg

1996

First Antihydrogen Atoms
Made at CERN

2000

CERNs 'Antimatter Factory' AD

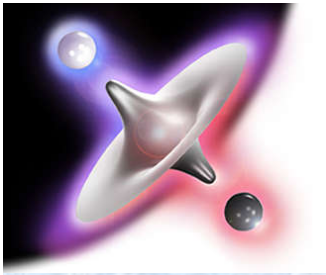


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2001

Angels + Demons





Story Line

Wuminati

Detective story about a secret society which ...



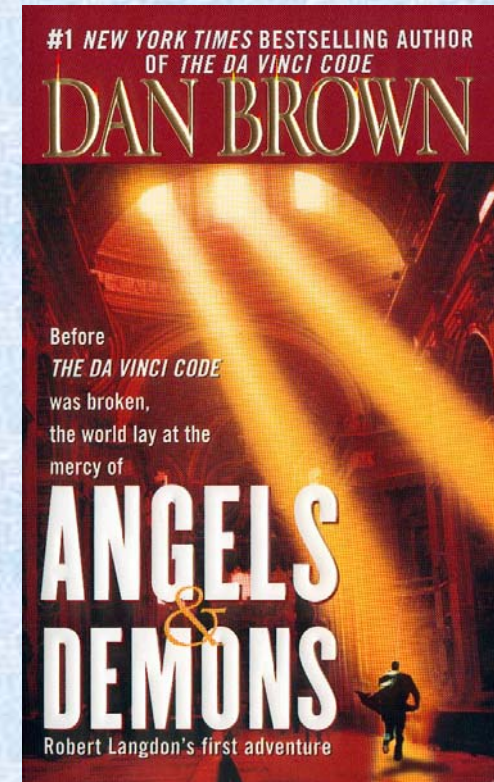
... steals 1 g of antimatter from a place called "CERN" ...



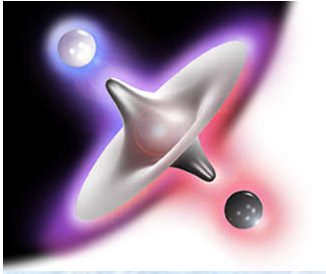
... to blow up the Vatican, an old "enemy of science and CERN".



The DG of CERN owns an 'scram-jet' (Mach-18) airplane



What is true?
What is false?



Frequently asked questions

Can ‘antimatter’ (=anti-atoms) be produced?

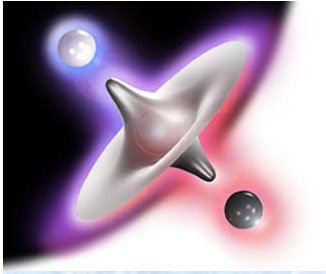
How?

Why are scientists interested?

Is it the energy source of the future?

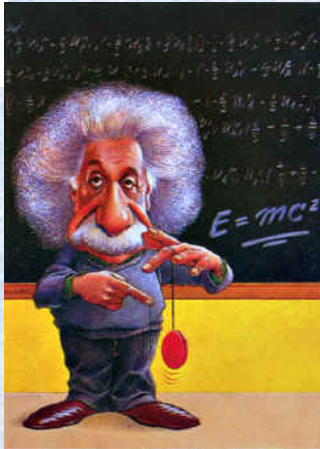
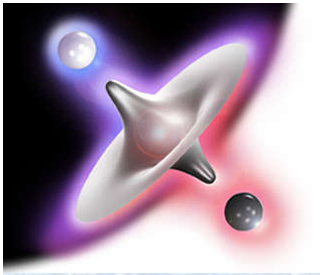
Can it be used as a weapon?

Are there other uses of antimatter?



I. Theoretical Introduction

Theory of special relativity



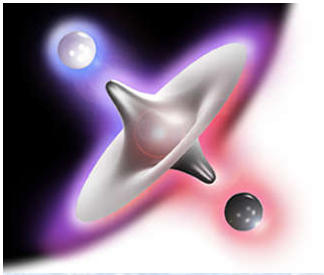
A. Einstein (1905)

$$E=mc^2$$

Mass is condensed energy

(c^2 = exchange rate!)

$$1 \text{ kg} = 9 \cdot 10^{16} \text{ J} = 2.5 \cdot 10^{10} \text{ kWh} = 2.85 \text{ GW} \cdot \text{year}$$



Relativity + Quantum Theory = Antimatter



Paul A.M. Dirac (1928)

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

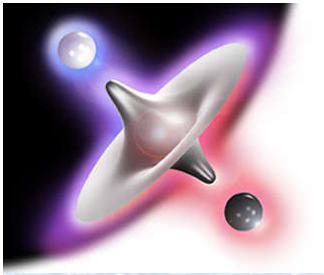
$$\psi_+ = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} \text{ or } \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} e^{-i m t}$$

$$\psi_- = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} \text{ or } \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} e^{+i m t}$$

Electron: spin 1/2

Another spin-1/2 particle??

- For $v \neq 0$, upper and lower components mix
- 1929: Positive electron = proton ????
- 1931: $m(e^-) = m(e^+)$! Annihilation possible ...



Positron discovery- why so late ?



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

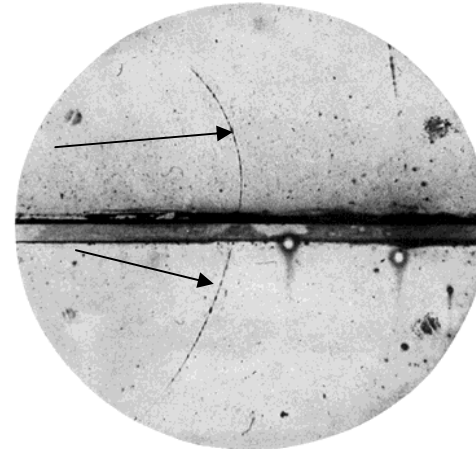


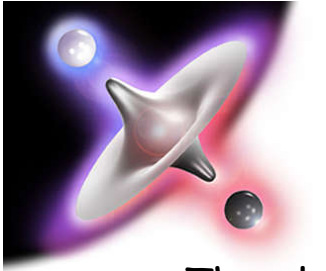
FIG. 1. A 63 million volt positron ($H_p = 2.1 \times 10^6$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H_p = 7.5 \times 10^6$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Dirac (1932):

"Why did the experimentalists not see them? **Because they were prejudiced against them.**

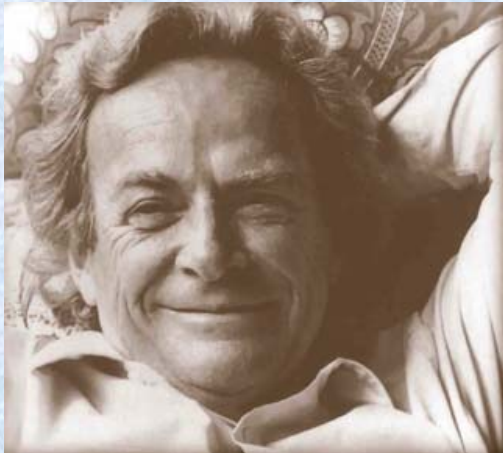
The experimentalists ... sometimes saw the opposite curvature, and interpreted the tracks as electrons which happened to be moving into the source, instead of the positively charged particles coming out.

People were so prejudiced against new particles that they never examined the statistics of these particles entering the source to see that there were really too many of them."

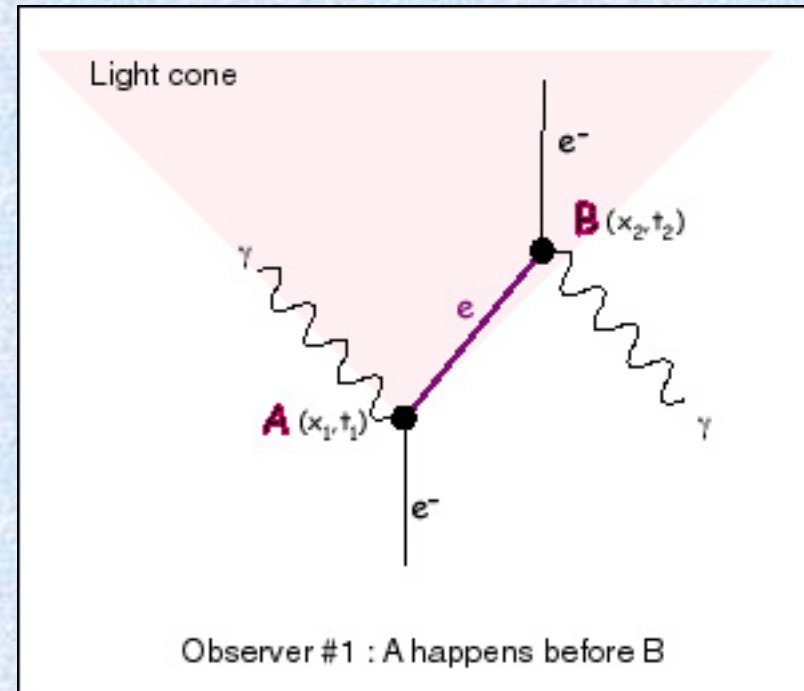


Antimatter in Quantum Field Theory

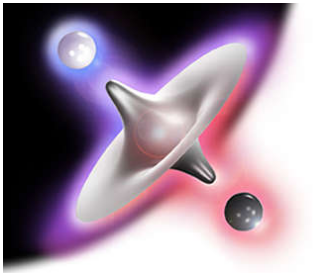
The electron (field) is no longer described by a wave function but an operator that creates and destroys particles. All energies are positive.



R. P. Feynman

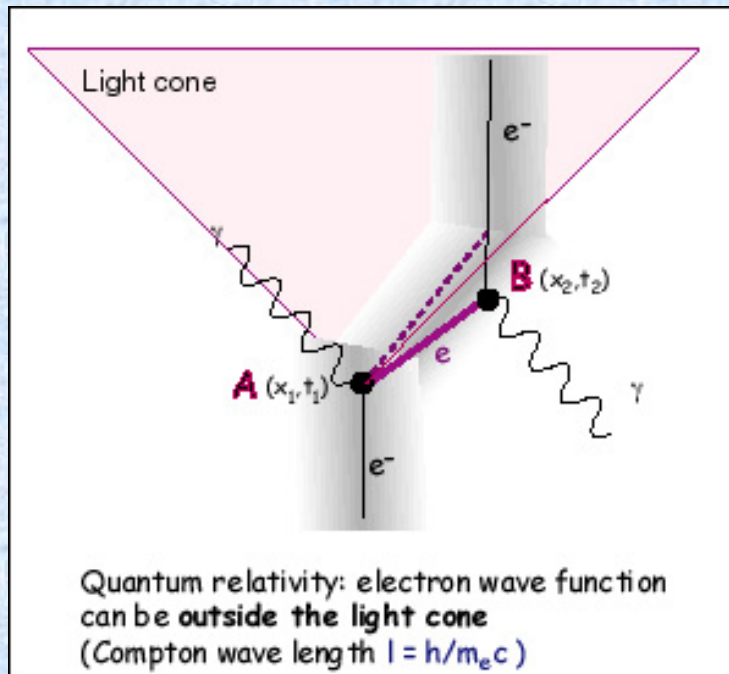


An electron can emit a photon at A, propagate a certain distance, and then absorb another photon at B.

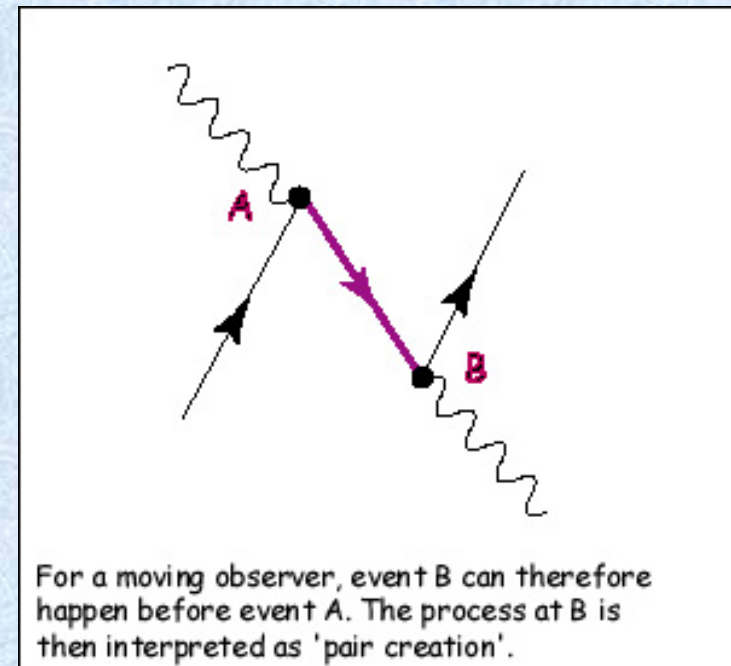
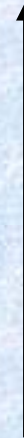


Why antimatter must exist in quantum theory

Wave function only localized within Compton wave length ($\lambda \sim 1/m$).

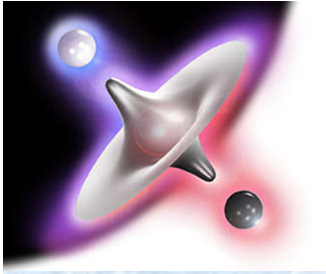


†



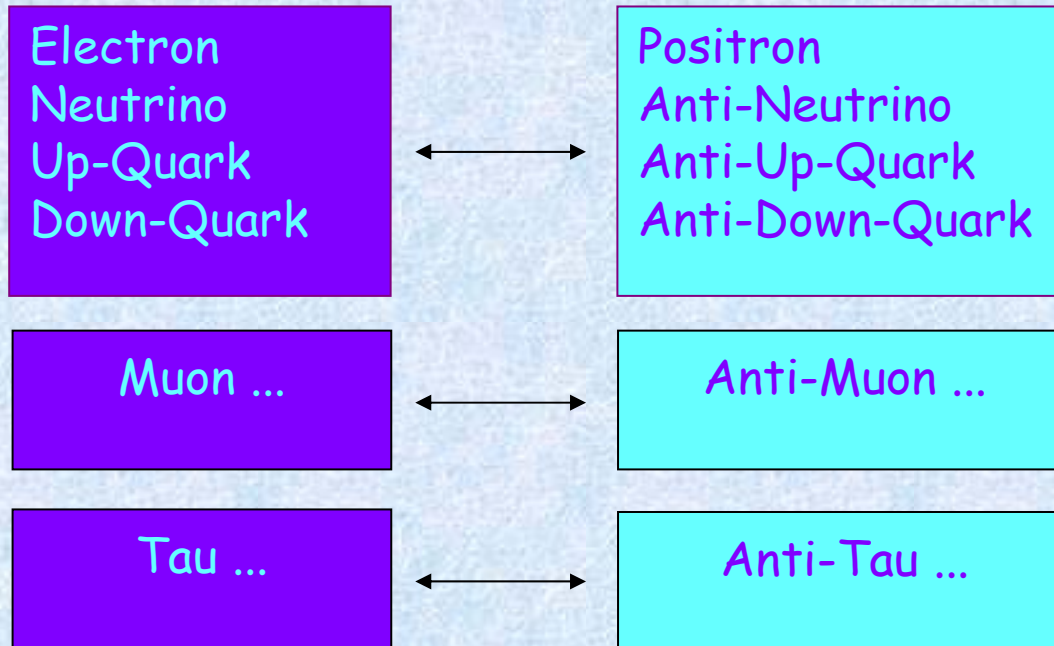
"One observer's electron is the other observer's positron".

The presence of antiparticles is necessary to restore the **causal structure** to the process seen in another inertial system.

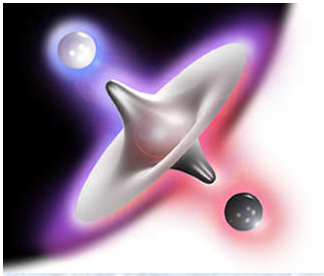


Therefore:

Every particle has an antiparticle

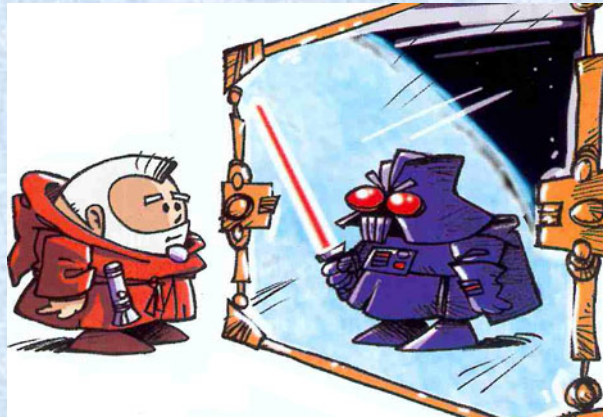


After Dirac, the fundamental spectrum of particles doubled
In 1973, supersymmetry made a similarly bold prediction ...



Particles and antiparticles

How can we imagine an 'anti-particle'?

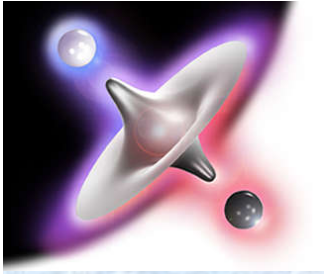


Electron

Positron



Particles and anti-particles are two manifestations of the same underlying, but yet unknown, physical structure (superstrings??).



CPT Theorem *

IF :

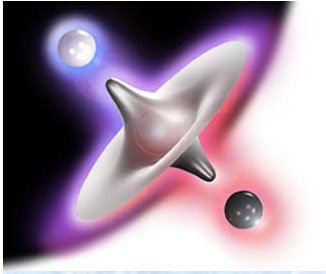
- | | |
|----------------------------------|--|
| 1) Locality | (no action at a distance) |
| 2) Lorentz invariance | (all inertial frames are equivalent) |
| 3) Causality | (no interaction between two space-time points outside each other's light cone) |
| 4) Vacuum is lowest energy state | (spin-statistics connection) |

Then:

Particles and antiparticles must have

- equal masses
- equal lifetimes
- equal magnitude (opposite sign) of quantum numbers, e.g. charge
- equal energy levels of bound states

*1955 - Proof of CPT theorem by Pauli (following work by Schwinger and Lüders)



COSMIC ANTIMATTER

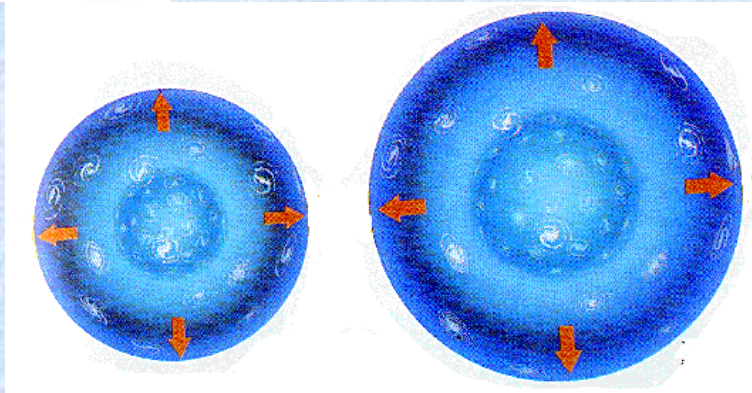
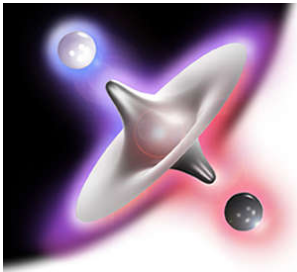
1933 Dirac's Vision

"If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of Nature, we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about, these stars being built up mainly of positrons and negative protons. **In fact, there may be half the stars of each kind.** The two kind of stars would both show exactly the same spectra, and there would be no way of distinguishing them by present astronomical methods."

From his Nobel lecture (12 December 1933)

- 1) Symmetric Universe?
- 2) Where is the antimatter gone?
- 3) Antihydrogen spectrum?

The lopsided Universe



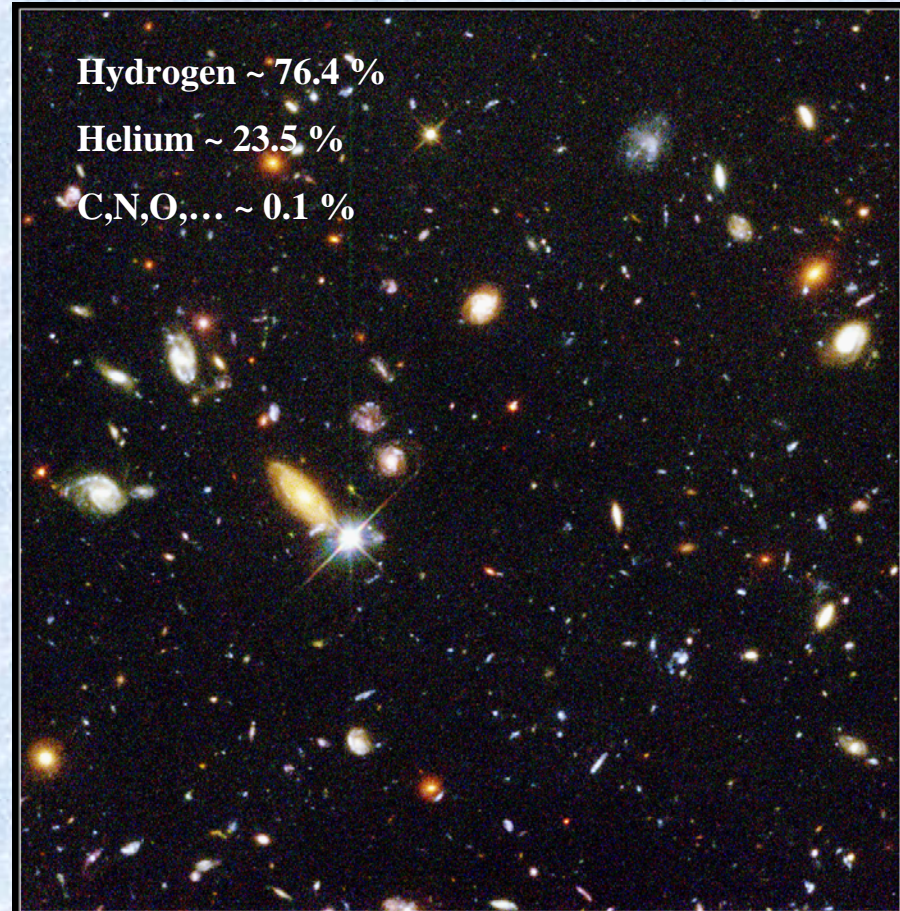
13.7 billion years ago:

- The Universe expands from the size of needle tip
- Matter and antimatter are created in equal quantities
- Something happens
- Only matter is left

Hydrogen ~ 76.4 %

Helium ~ 23.5 %

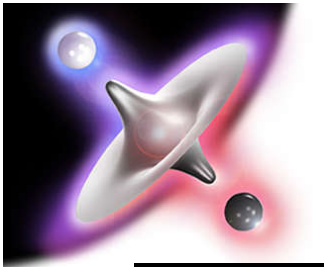
C,N,O,... ~ 0.1 %



Hubble Deep Field
Hubble Space Telescope • WFPC2

PRC96-01a - ST ScI OPO - January 15, 1995 - R. Williams (ST ScI), NASA

How do we know that the antimatter has disappeared?



The Scale of Burt

I'm not made of antimatter. I don't know about these guys.

The Solar Scale

We're not!

Forgetaboutit

Nope

Look here buddy

Uhh...I don't know

Not me

No

The Whole Enchilada

The Galaxy Scale

H

E

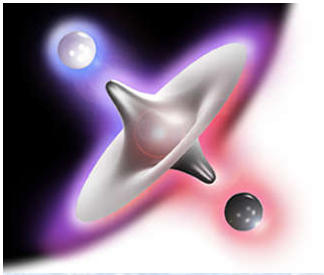
L

L

O

N

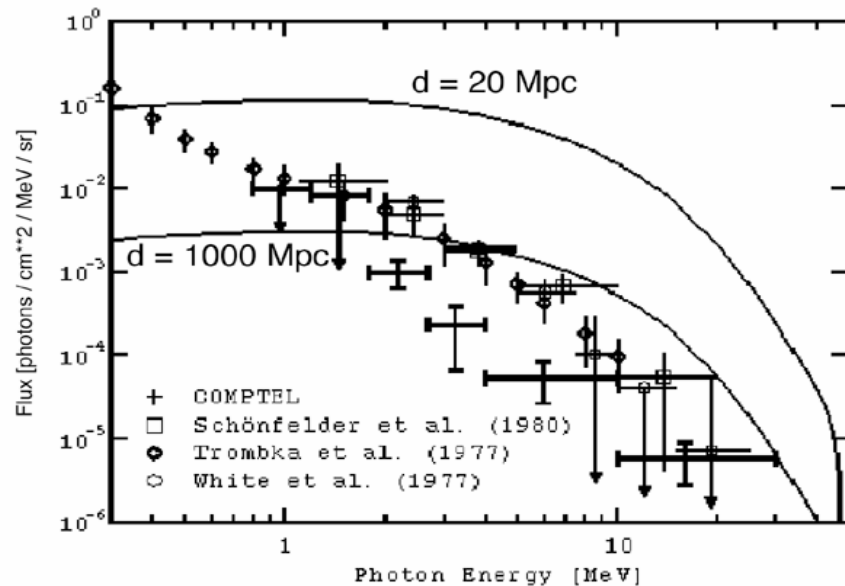
!



Gamma-ray and Cosmic Background Radiation

Is the Universe divided into matter and antimatter 'domains' of diameter d ?

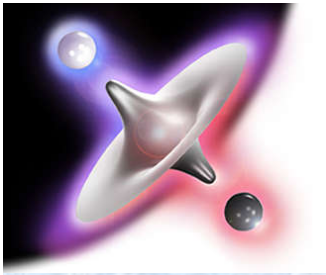
Annihilations at boundaries --> *Cosmic Diffuse Gamma spectrum* (0.1 - 10 MeV region):



Scars on Cosmic Background Radiation?

Inhomogeneity from pre-recombination annihilation could lead to 'local' heating and distort CBR

**PRESENT LIMIT ~
1/3 SIZE OF UNIVERSE**



Where is the antimatter gone?

Possible explanation:

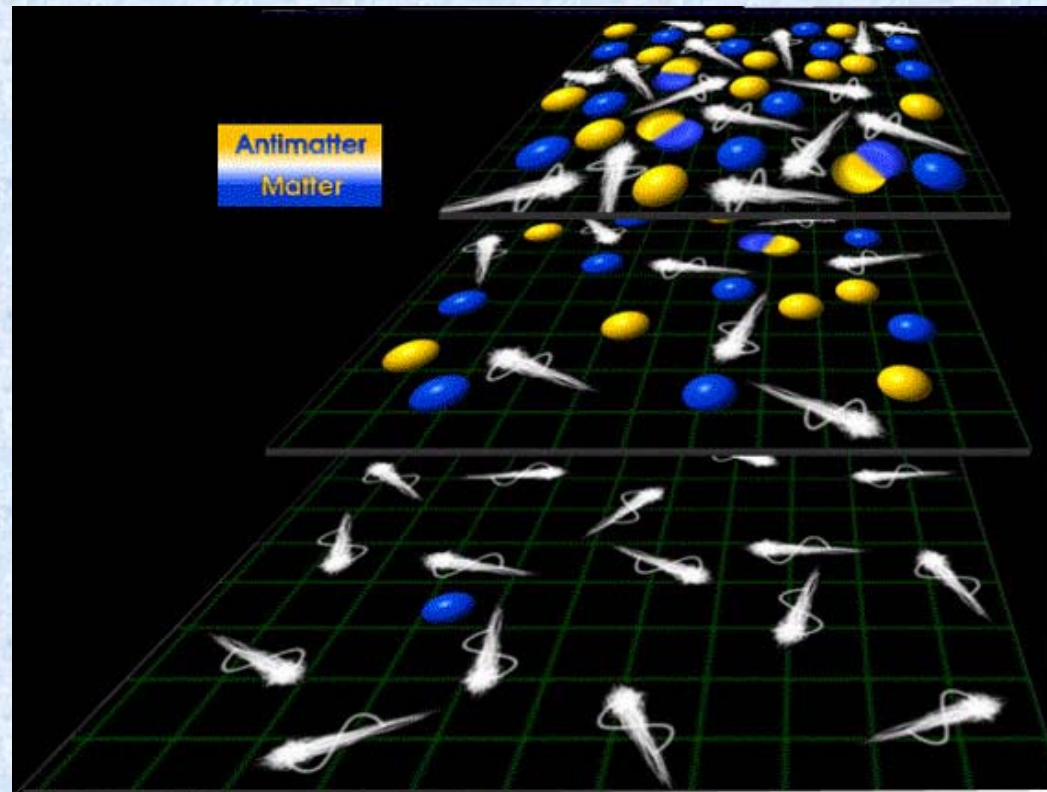
- **CP Violation:** slight **excess** of baryons vs antibaryons
- **Thermal non-equilibrium** during rapid expansion phase
- **Baryon number violation** (very small)

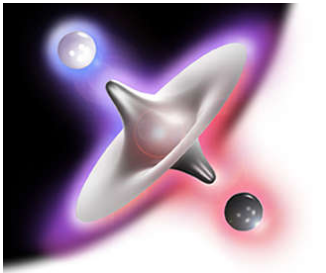


A.D. Sakharov,
JETP Lett. 5, 24
(1967)

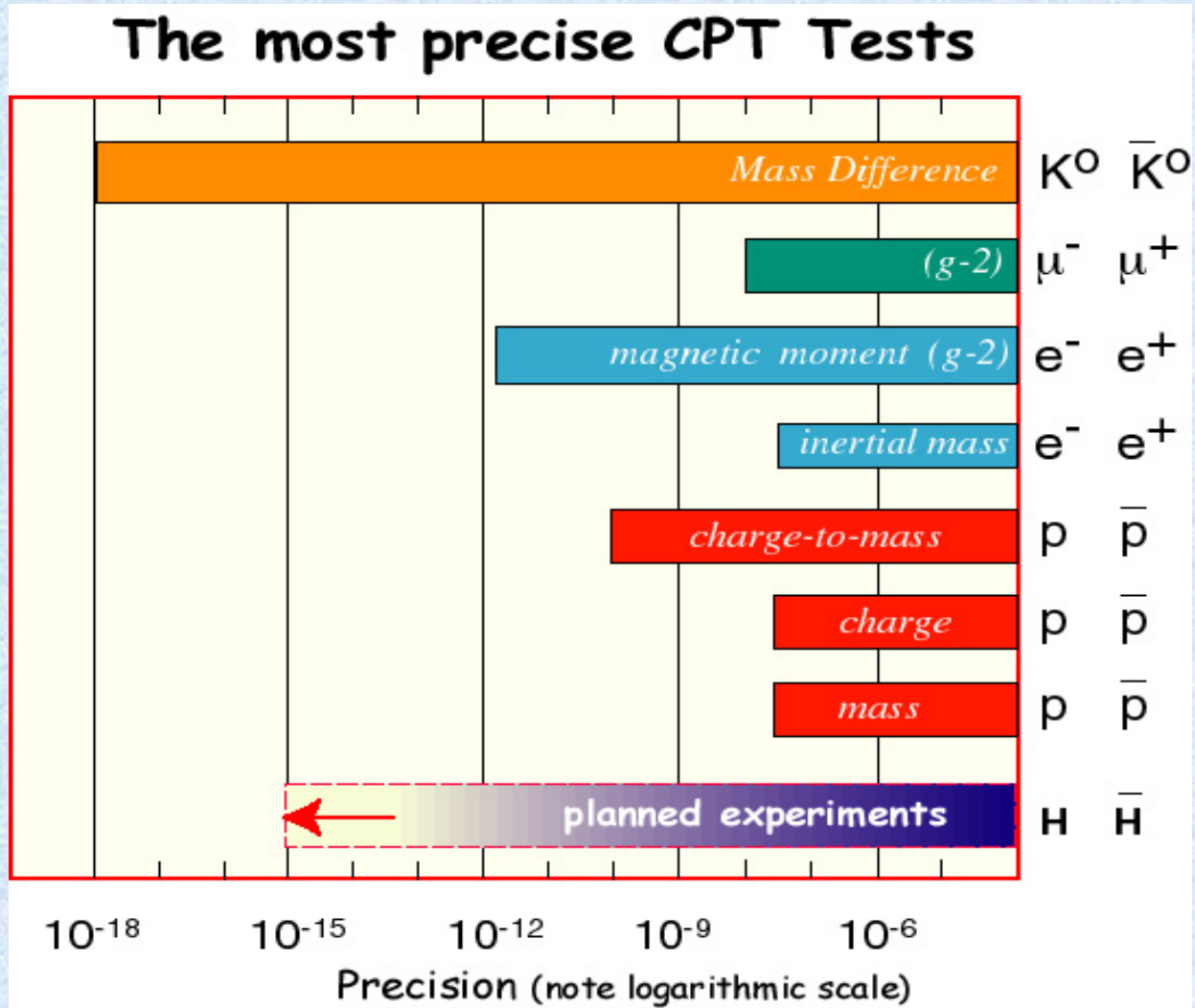
But: known CP-violating effects
not strong enough !

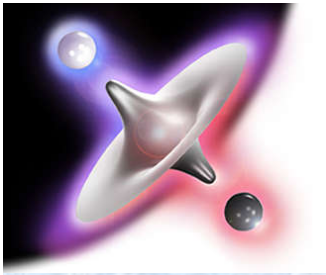
CPT violation?
Antimatter-matter gravity?





Precise comparisons of particles and antiparticles





Antimatter gravitation ?

Einstein's equivalence principle:

The world-line of a free falling body is independent of its composition or structure

Gravitational = Inertial mass

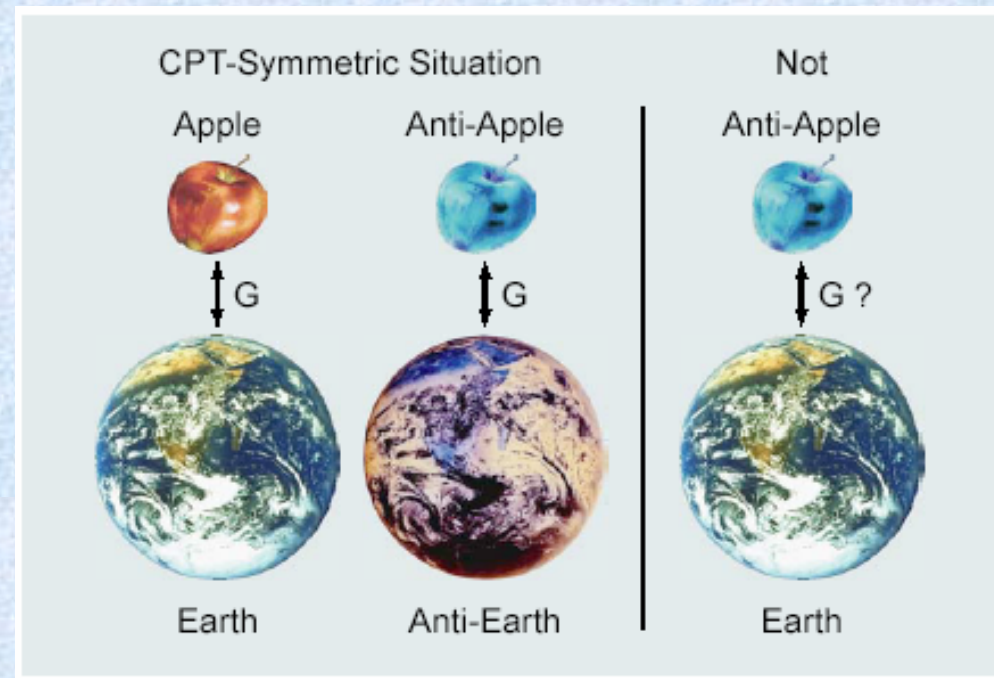
Possible violations:

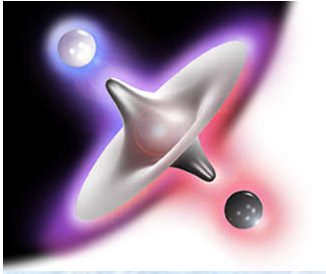
- Additional components of gravitational field (baryon number dependent)
- Short-range deviations (\ll mm) from inverse square-law (e.g. due to extra-dimensions)

Measurement of gravitational acceleration by dropping atoms

Achim Peters, Keng Yeow Chung & Steven Chu

Physics Department, Stanford University, Stanford, California 94305-4060, USA

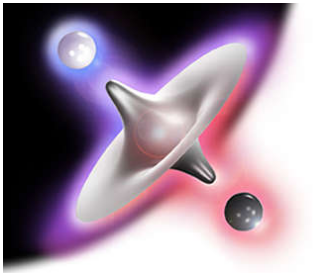




AD

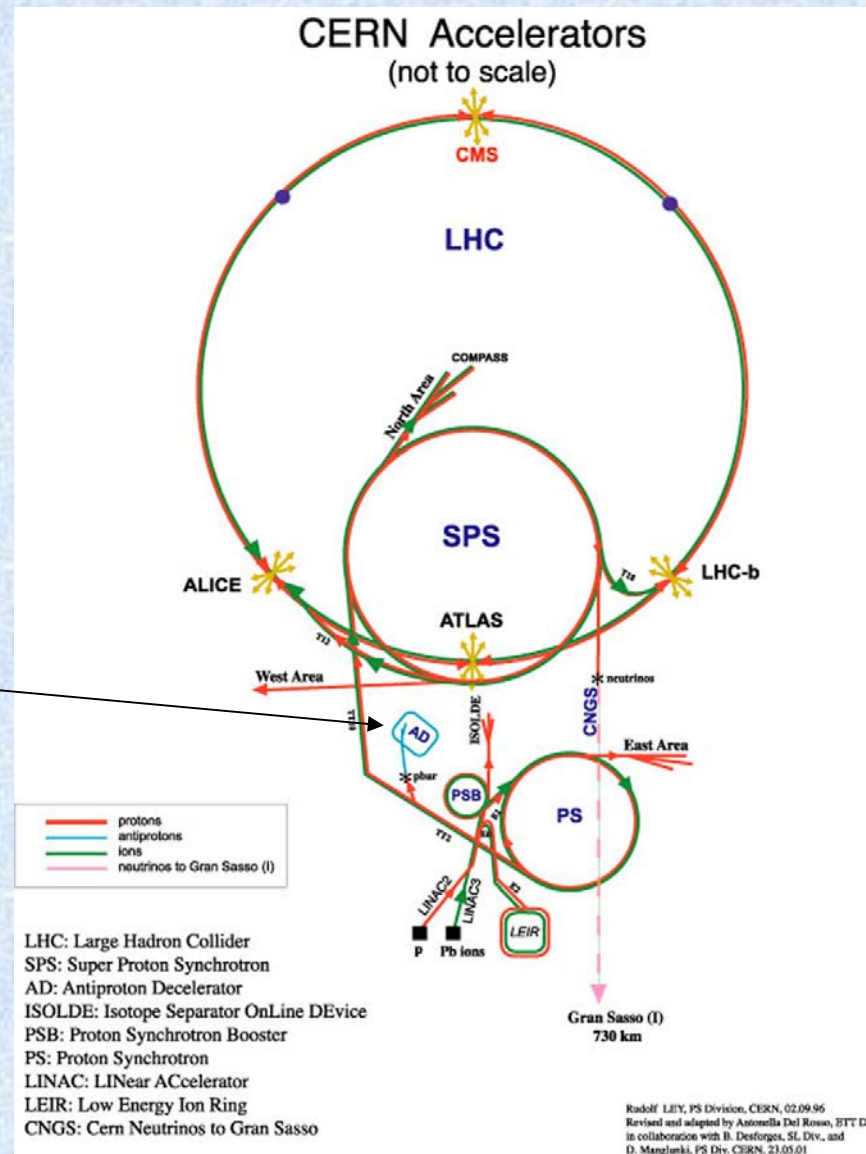
II. ANTIMATTER 'FACTORY'

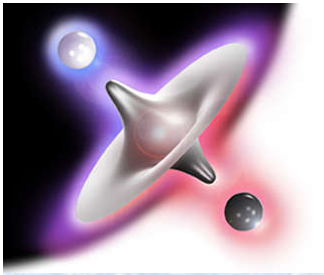
How are antiprotons made?



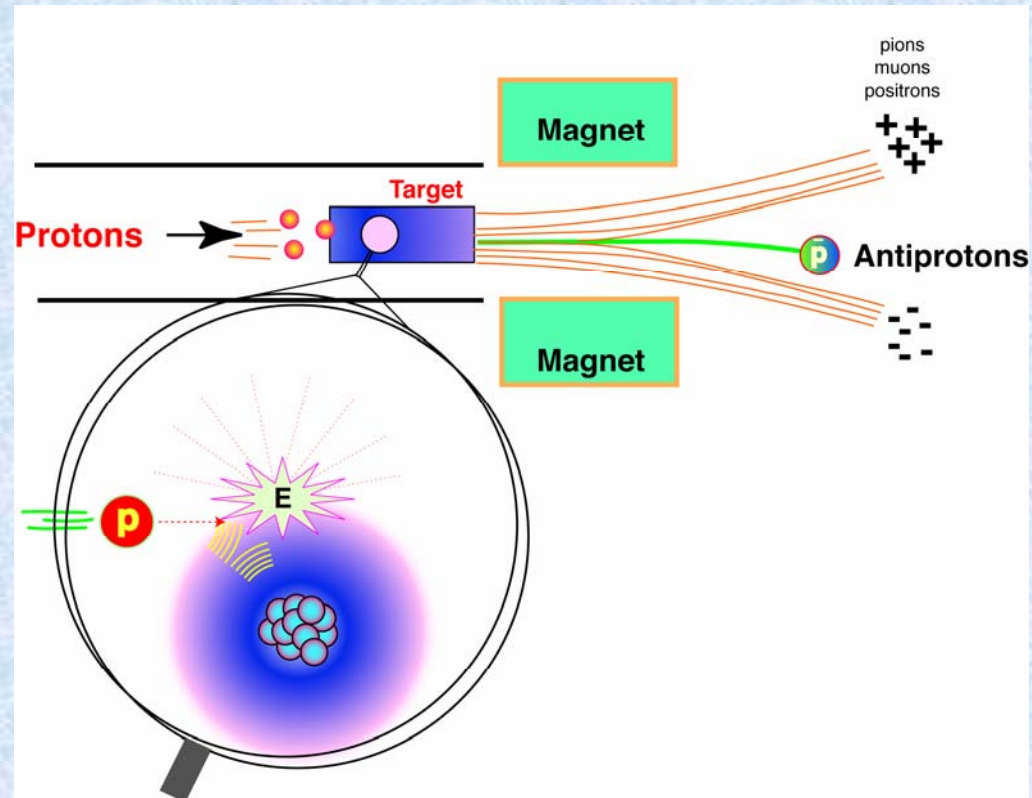
The Antiproton Decelerator (AD)

QuickTime™ and a GIF decompressor are needed to see this picture.



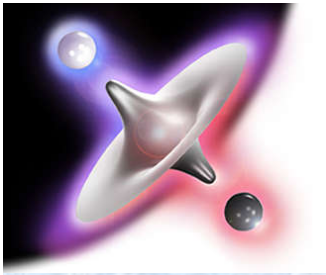


An accelerator 'condenses' energy in collisions



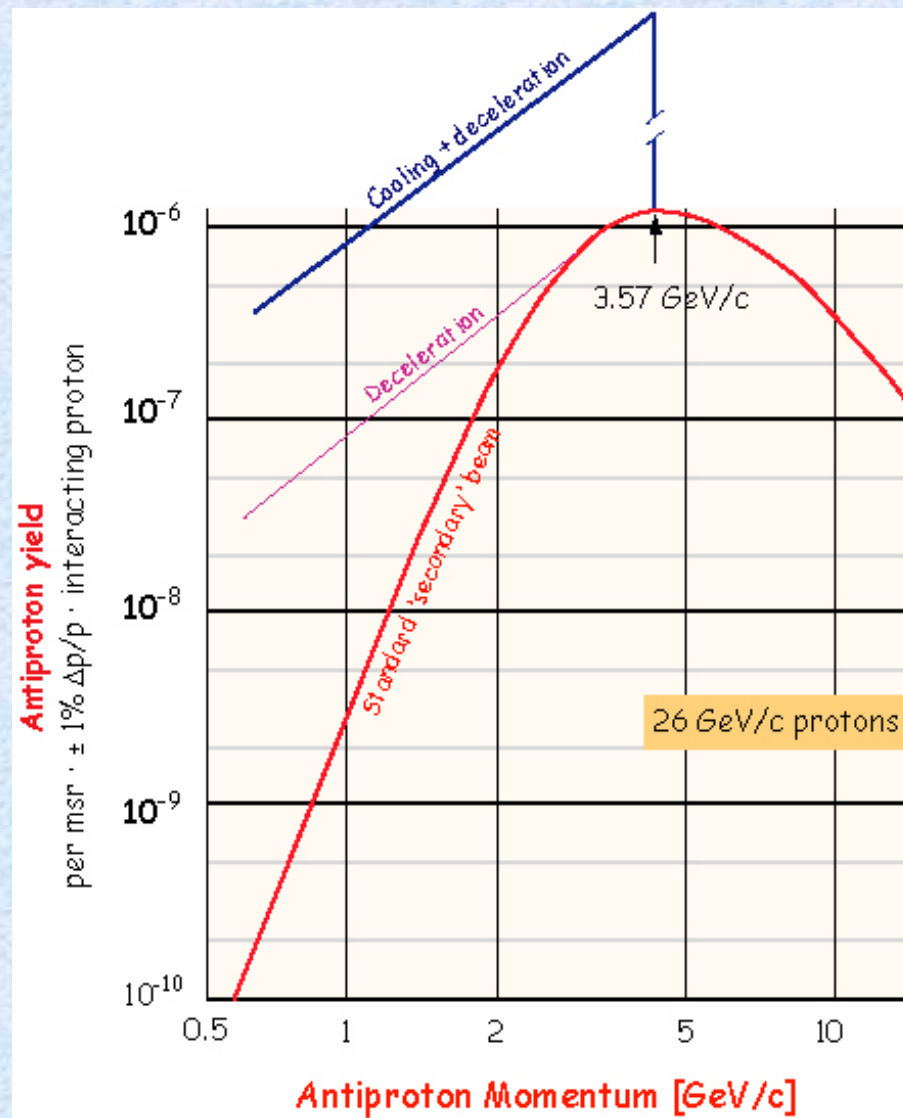
Peak production at CERN ~ 200,000,000,000,000 antiprotons/year

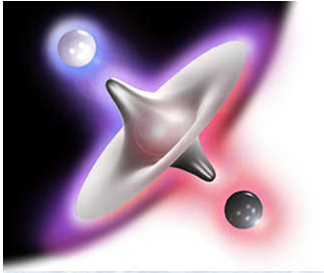
= 0.3 nano-gram



Efficiency of antiproton production (at 26 GeV/c)

~ few 10^{-6}
(per proton-on-target)





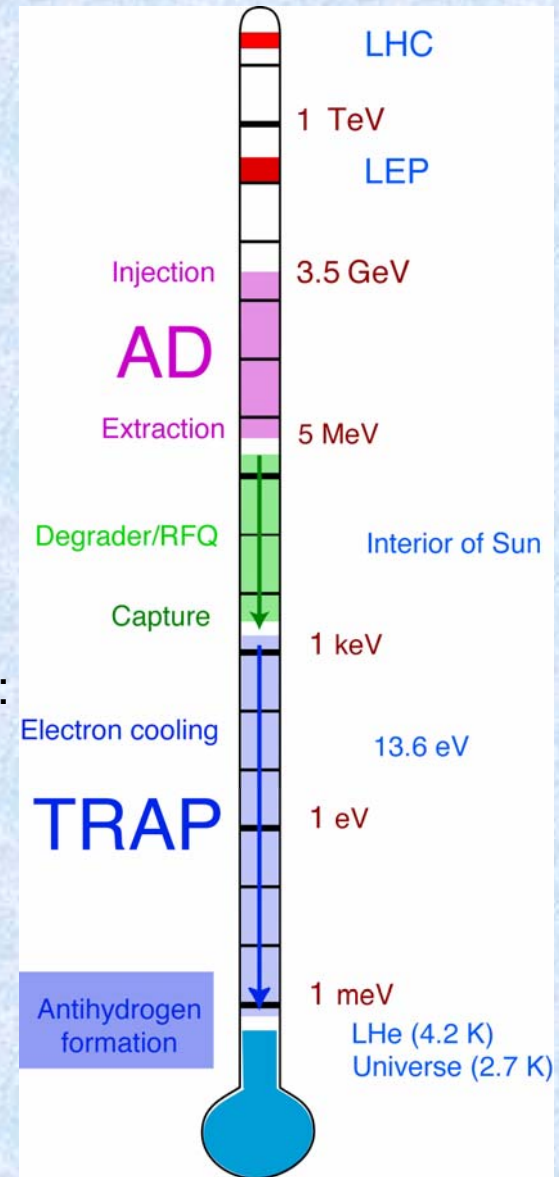
Challenge of antihydrogen production

Antiprotons are produced 'hot'

Cooling by 12 orders of magnitude!

Hydrogen atom is a weakly bound system:
- 0.000 000 013 6 GeV

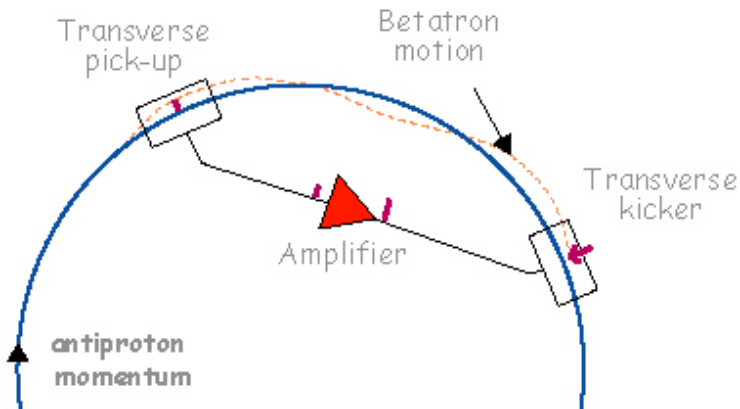
Antiprotons (and positrons) need to chill
before becoming attached





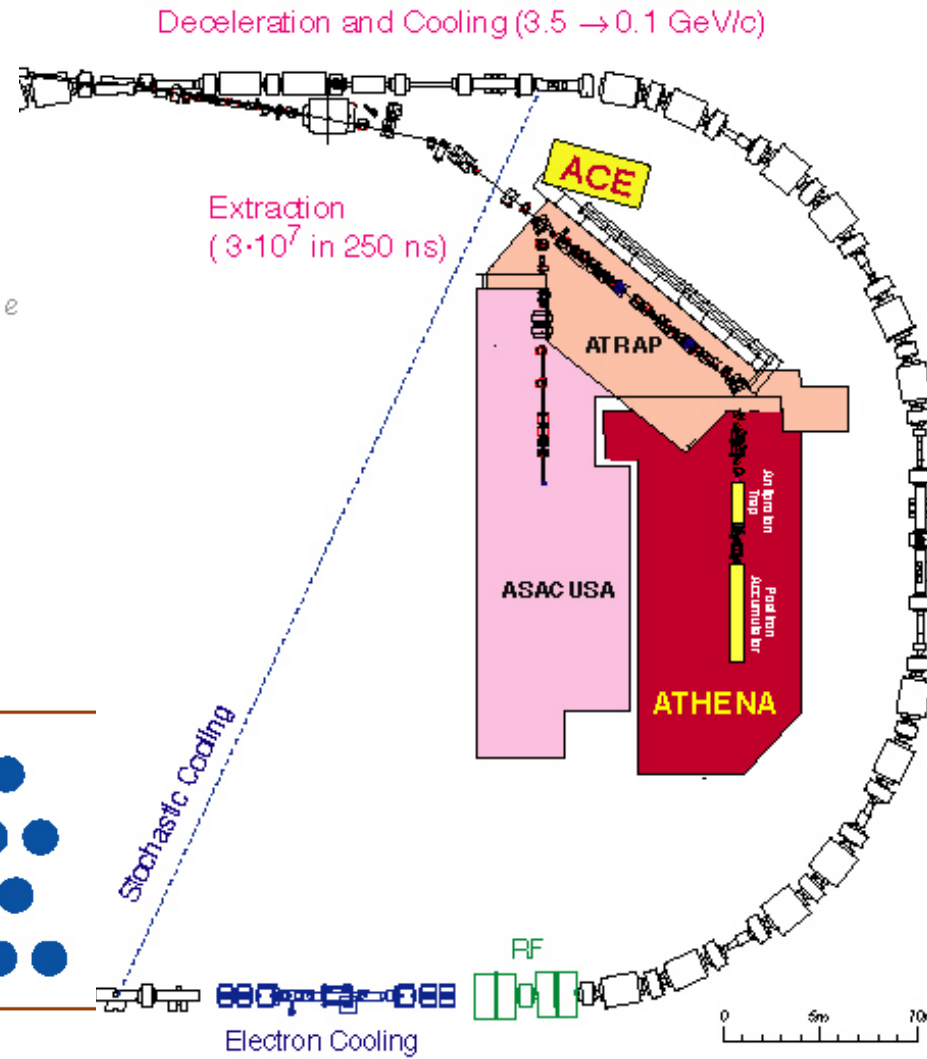
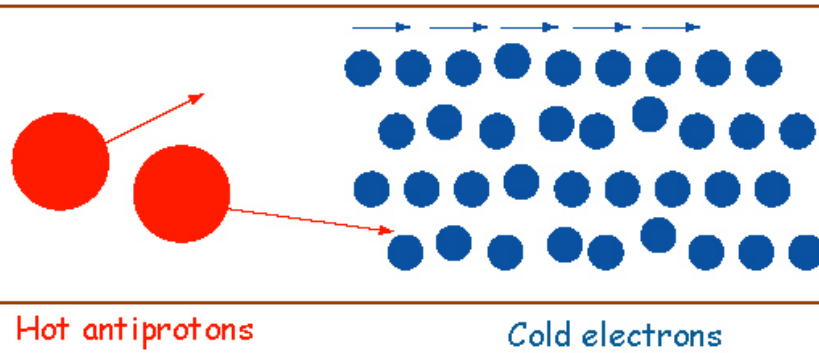
The Antiproton Decelerator (AD)

Principle of stochastic cooling



Principle of electron cooling

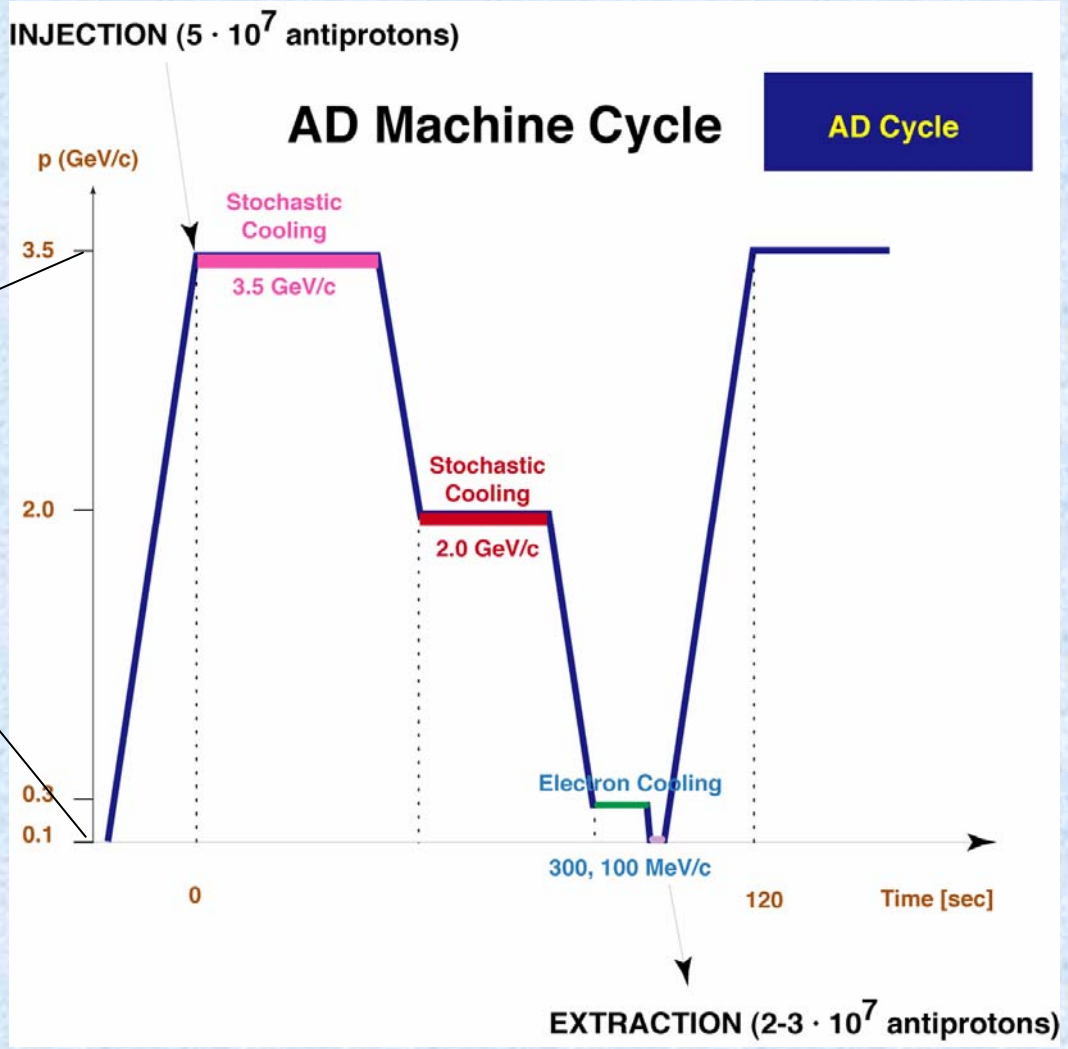
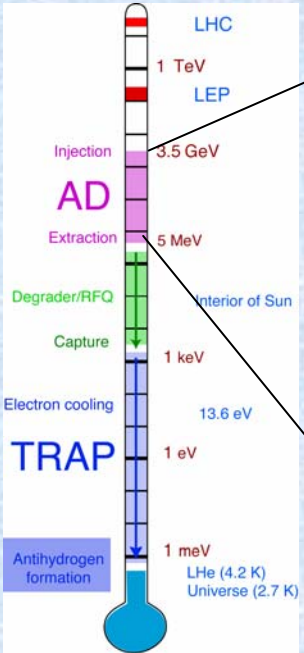
$$\langle v(\text{antiprotons}) \rangle = \langle v(\text{electrons}) \rangle$$

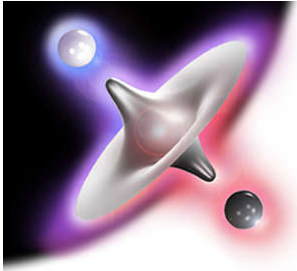




QuickTime™ and a GIF decompressor are needed to see this picture.

The Antiproton Decelerator (AD)





Antiproton Decelerator (Photos)

