UNIVERSITY OF BIRMINGHAM

Matter, Antimatter and the Strangeness of CP violation

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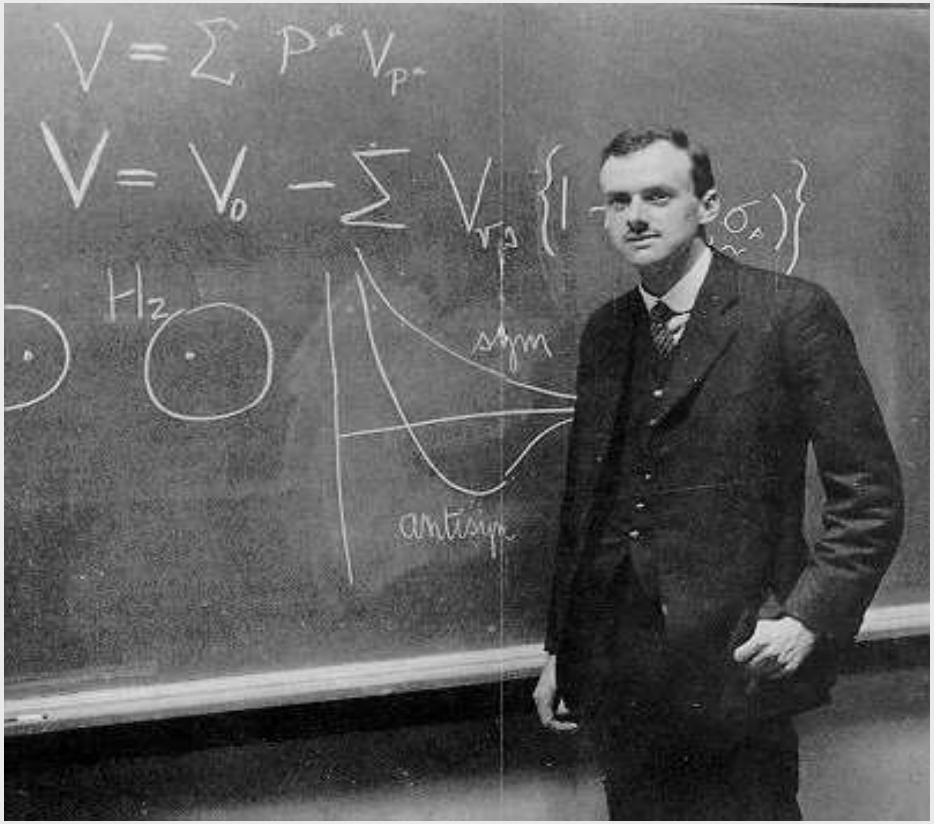
Masterclass 21/04/10

Cambridge, 1928 :

Dirac predicted the existence of the positron e+, same mass but opposite charge to e-



Quantum Mechanics

Special Relativity

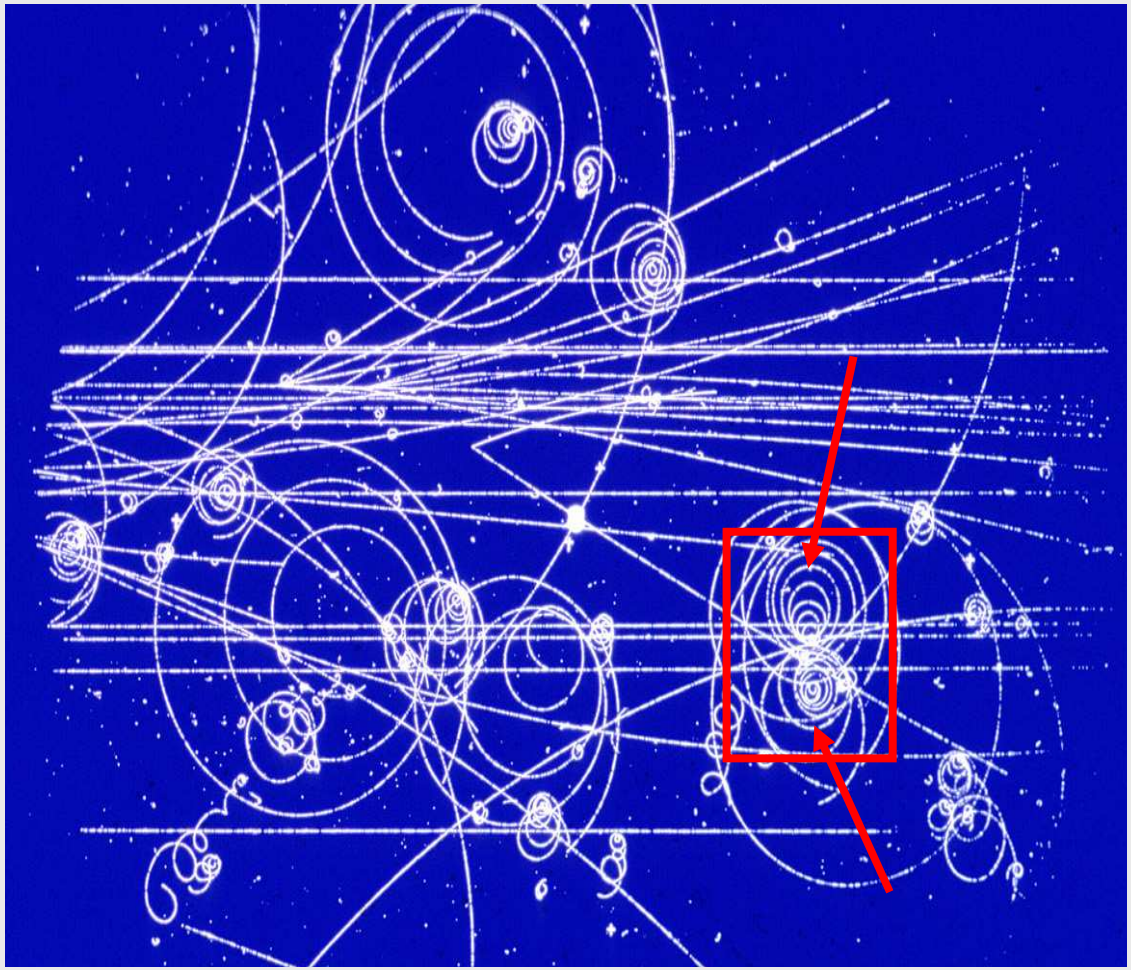
$$\left(i\hbar\gamma^{\mu}\partial_{\mu} - mc\right)\psi = 0$$

The Dirac Equation

Since then, many observations done but mechanism/origin not yet clear

Particle Beam interacting in Hydrogen - Positron discovered by Anderson in 1933

(Nobel Prize for Physics in 1936)



- Positron was then studied in Bubble Chambers

- Charged particles leave a trail of bubbles after they pass through, similar to the trails left by jet airplanes

Electrons and positrons tracks are common !

Antimatter

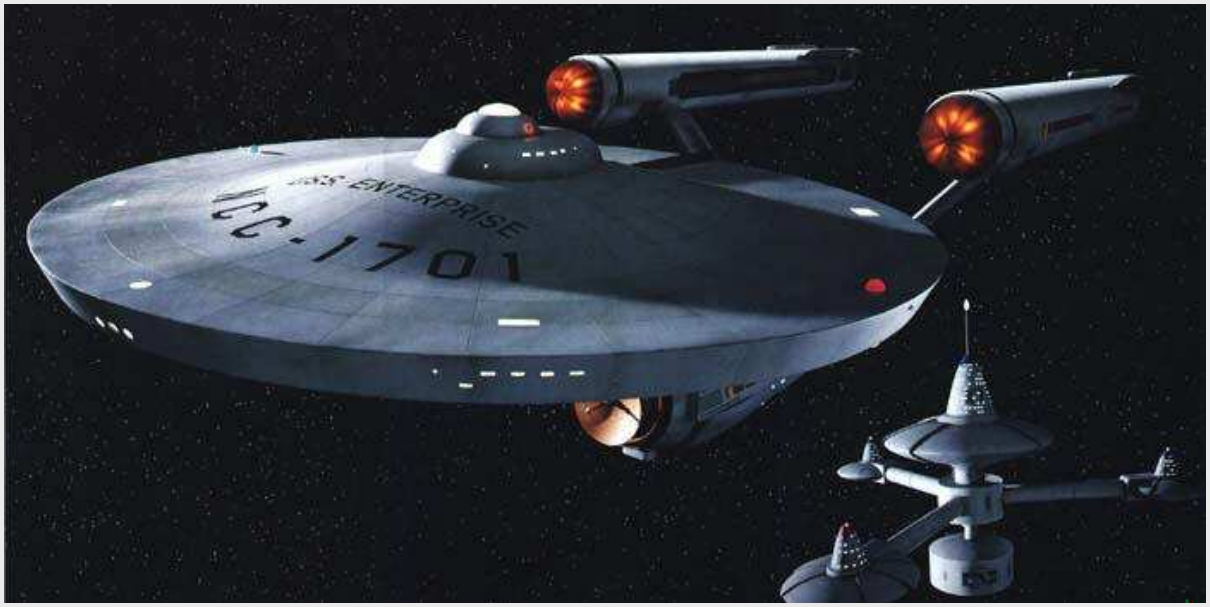
- Every fundamental particle has its antiparticle.
  - These have the same mass but opposite charge.

electron e^- e^+ **positron**

up quark $u^{+2/3}$ $\bar{u}^{-2/3}$ **up anti-quark**

and, if they are unstable : the same lifetime

If Antimatter exists…



Where is the largest concentration of antimatter in the known Universe?

Particle accelerators !!!

Antimatter

- If a particle and antiparticle each of mass (m) collide they annihilate with the production of energy (E) in the form of radiation – the total mass (2m) is converted into energy.
  - $E = 2mc^2$ (using the famous equation: $E = mc^2$)

The opposite is also true; given enough energy, one can create matter with equal amounts of antimatter.

Antimatter in the story of

ANGELS & DEMONS

In the Angels and Demons story, the bad guys go to a laboratory called "CERN".

They steal half a gram of antimatter in a canister, which they then take to Rome to use as a bomb.

A feather weigths about ½ gram.

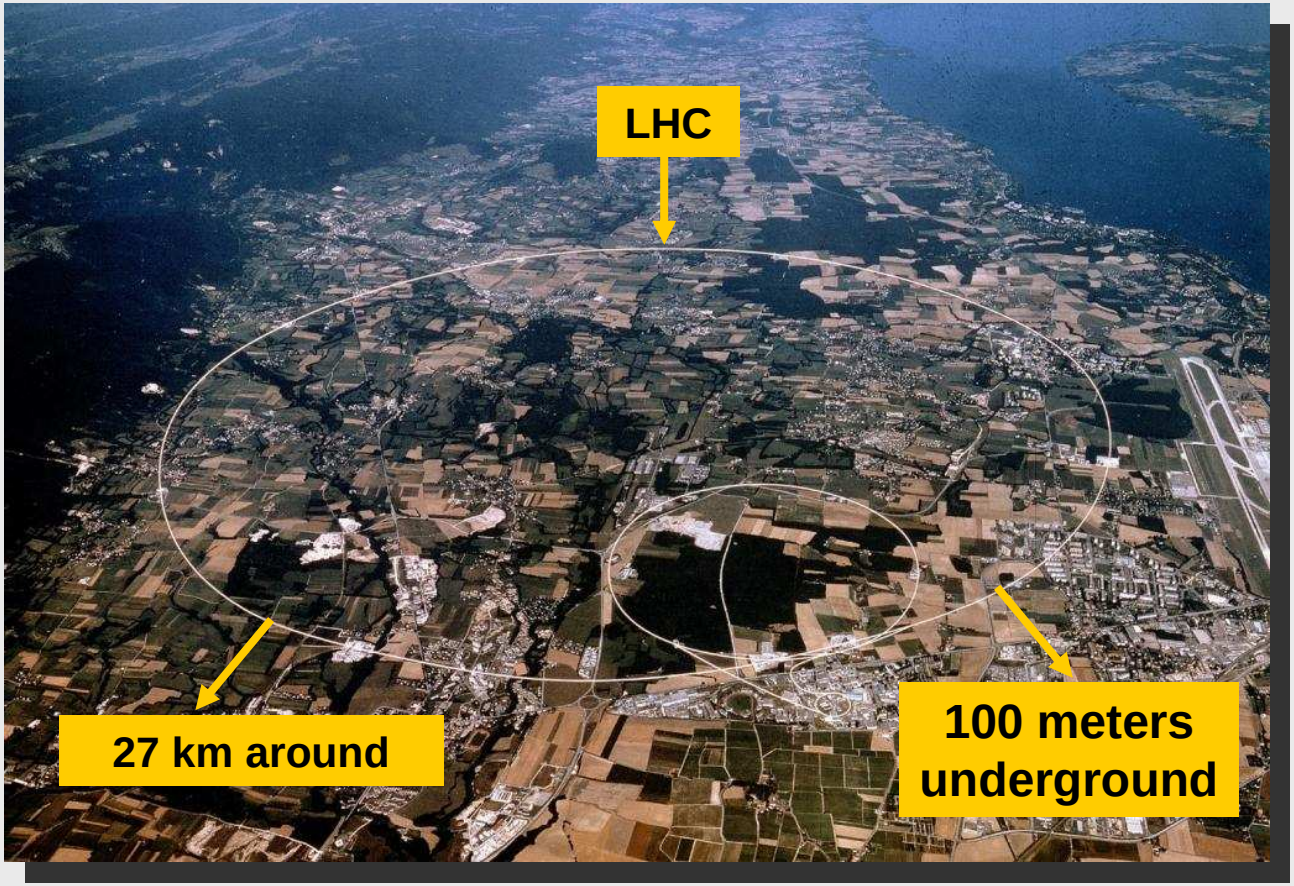
CERN is indeed a real-life lab located in Geneva, Switzerland

ANGELS&DEMONS at the Large Hadron Collider

The

Large Hadron Collider

(LHC) is an accelerator located at CERN



Protons circulate in opposite directions and collide inside experimental areas

If We Could Accumulate It

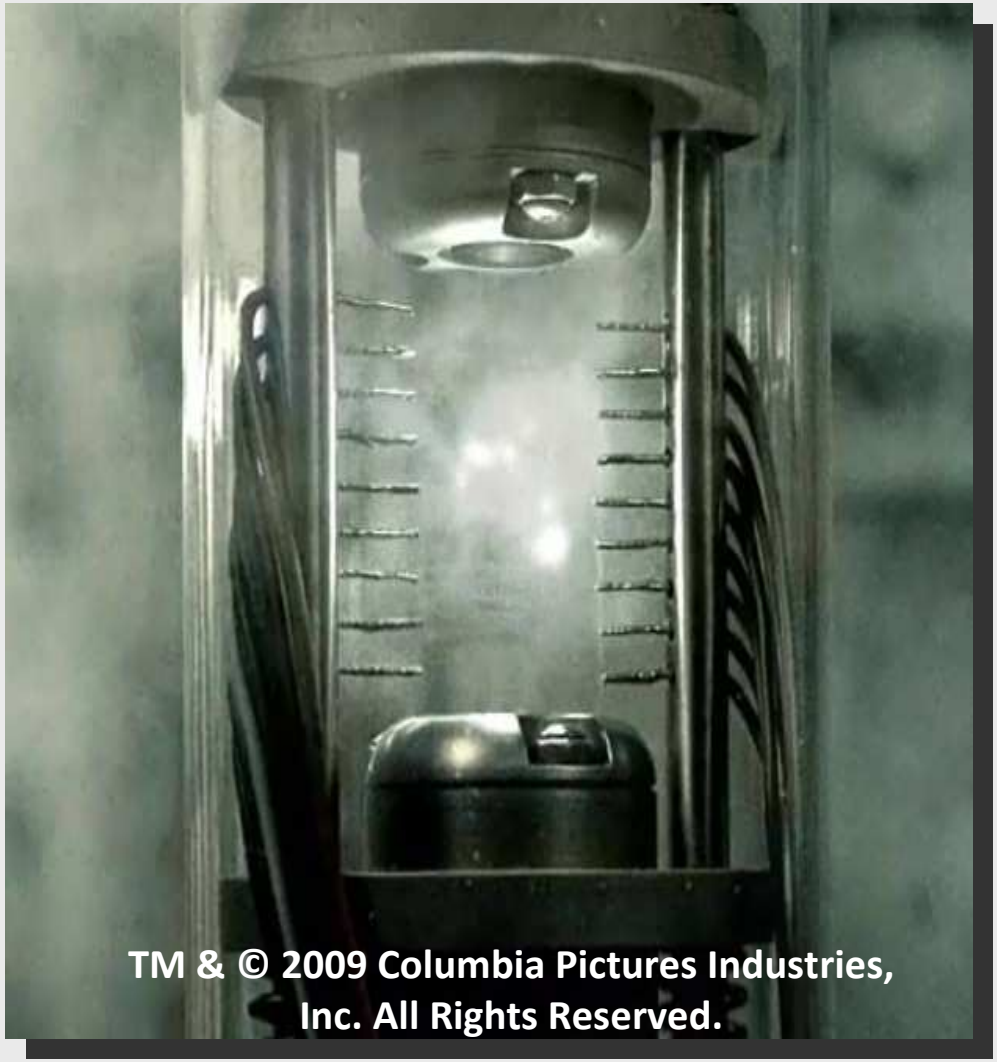
If we had some means to accumulate half a gram and

if we could put it in a container and

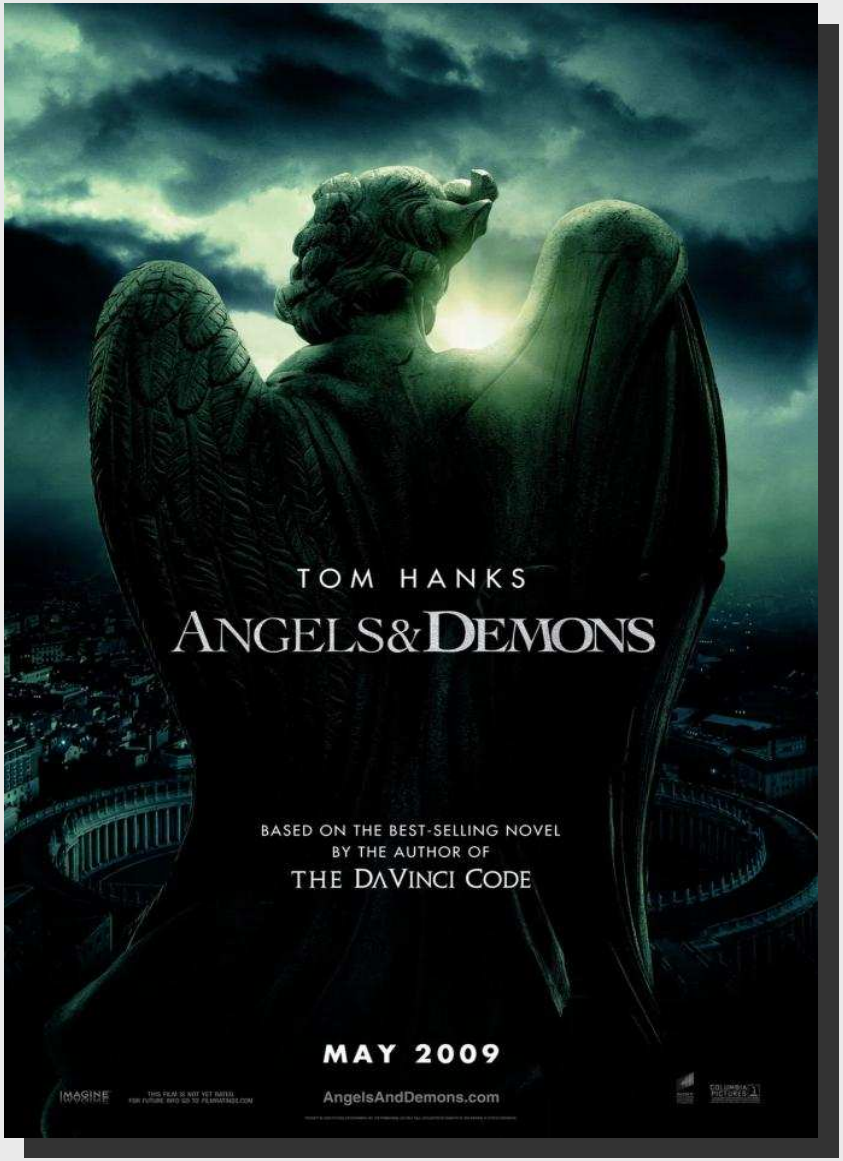
if we could transport it safely to another site,

it would indeed be a powerful bomb as in

ANGELS&DEMONS



How Long to Get Half a Gram?



All the antimatter produced in accelerators annihilates within a fraction of a second.

If LHC could somehow accumulate all the antimatter it produced,

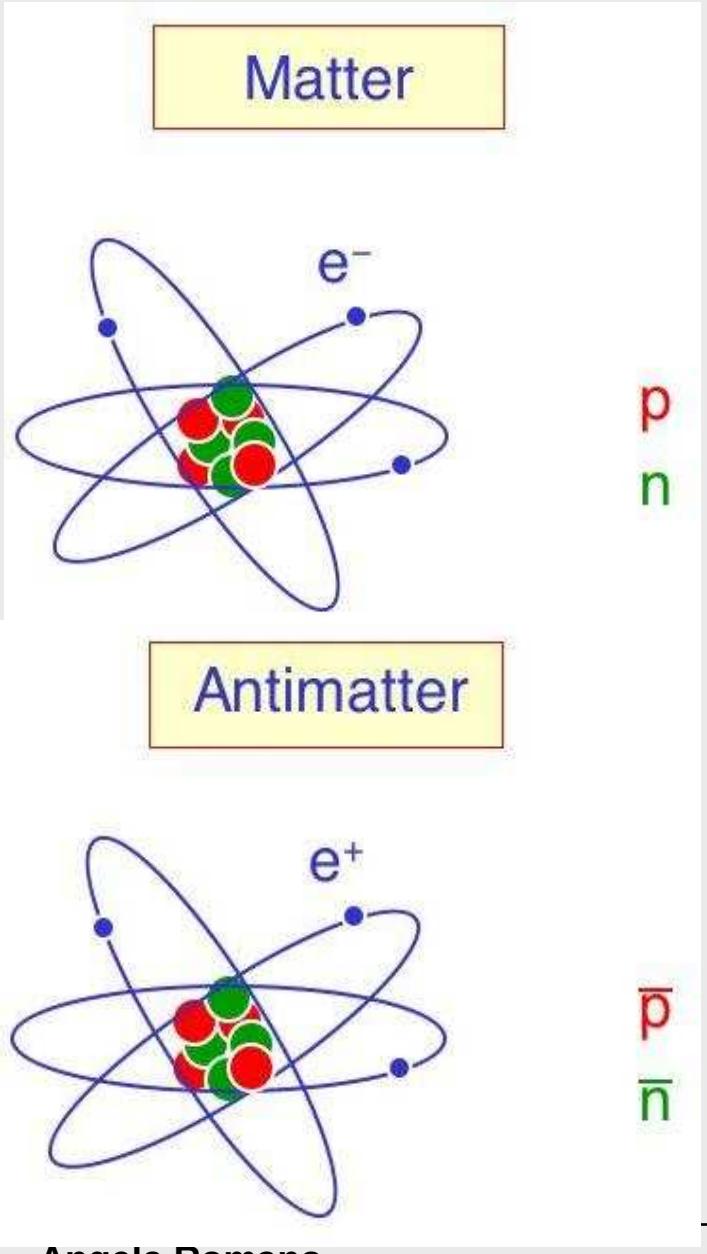
It would take 10 million years to get $\frac{1}{2}$ a gram of antimatter.

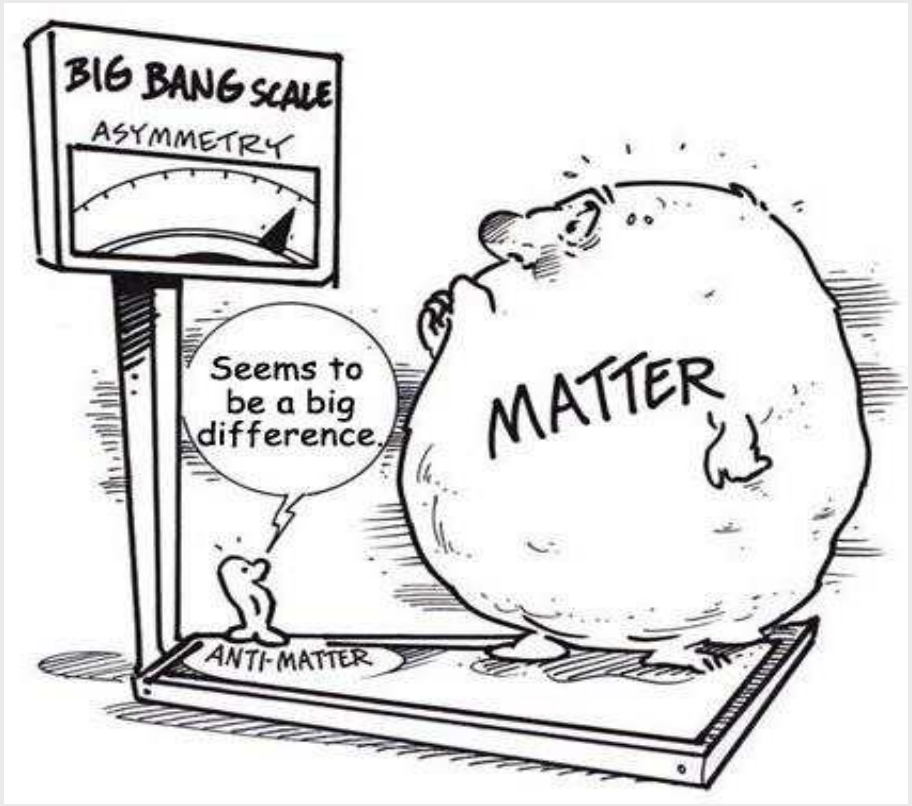
Big Bang

- So far, our experiments show that equal amounts of matter and anti-matter are produced when energy is converted into matter – for every up quark created, an up anti-quark is also created etc.

- So, equal amounts of matter and anti-matter should have been created during the Big Bang.

Matter and Anti-matter

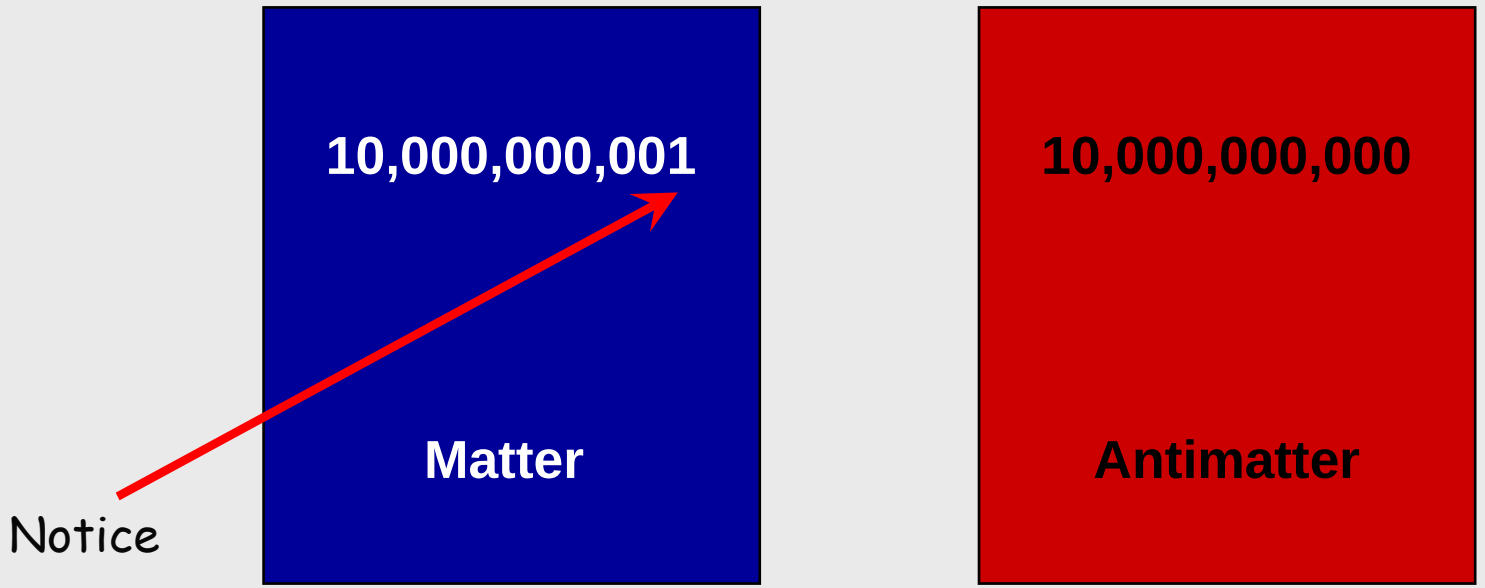




- But we live in a universe made from matter.
- Where did all the anti-matter go?

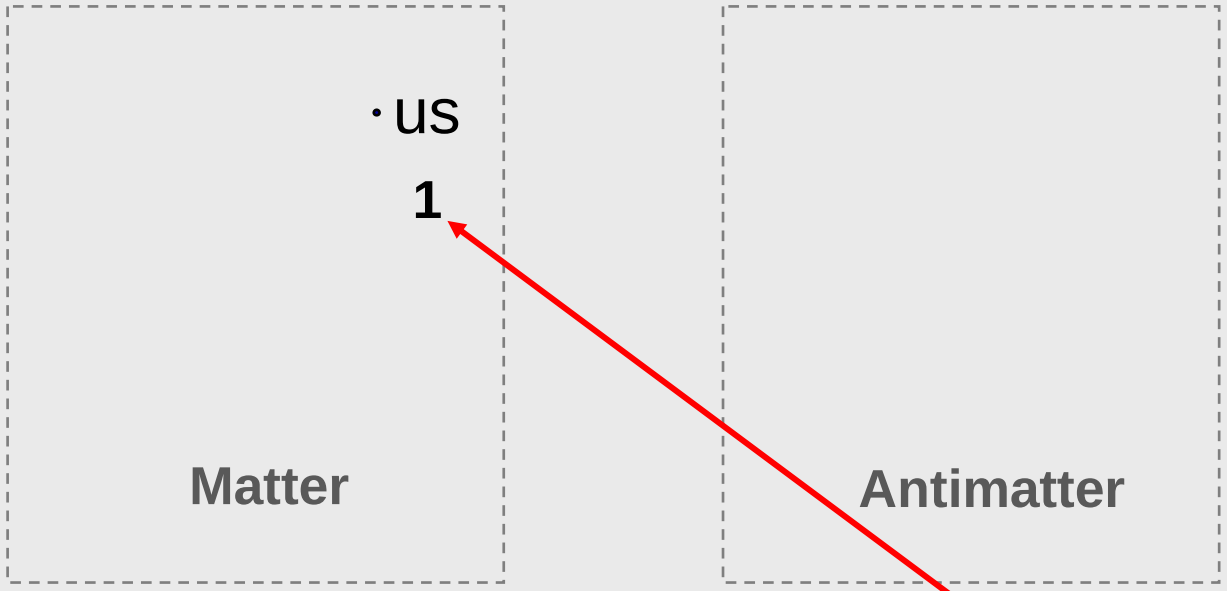
We are lucky because…

Immediately after the Big Bang,
the matter and antimatter… were NOT exactly equal



The Great Annihilation followed !!!

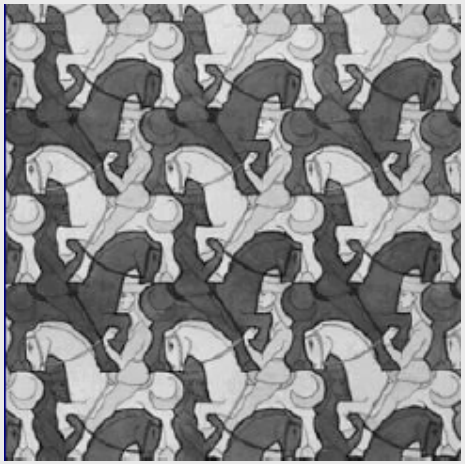
After the Great Annihilation…



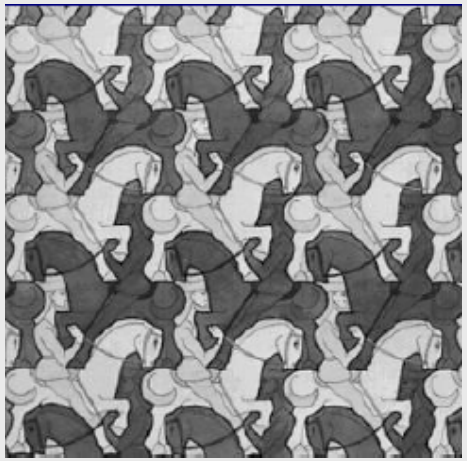
All the antimatter, and all but a tiny part of the matter were gone … and that tiny part is us

CP violation is one of the necessary conditions for the imbalance matter/antimatter to happen

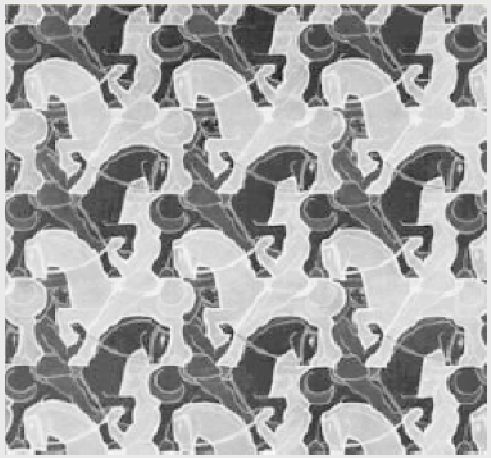
CPV: optical analogy ⇒ { *P (parity) = mirror*; *C (charge conjugation) = anti-image* }



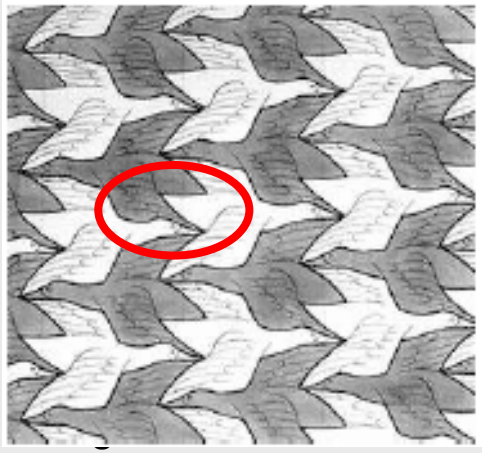
P



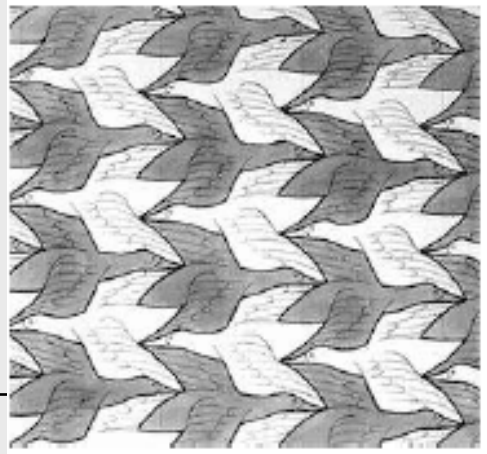
C



CP



P



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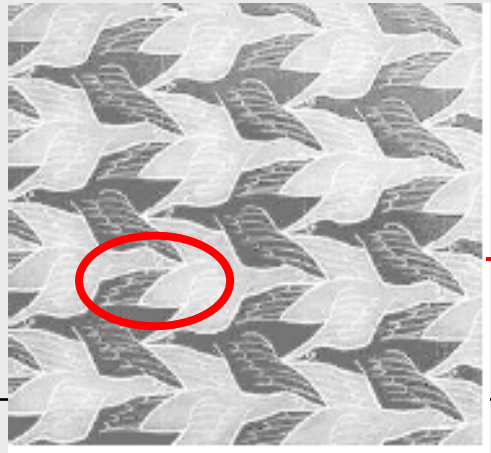


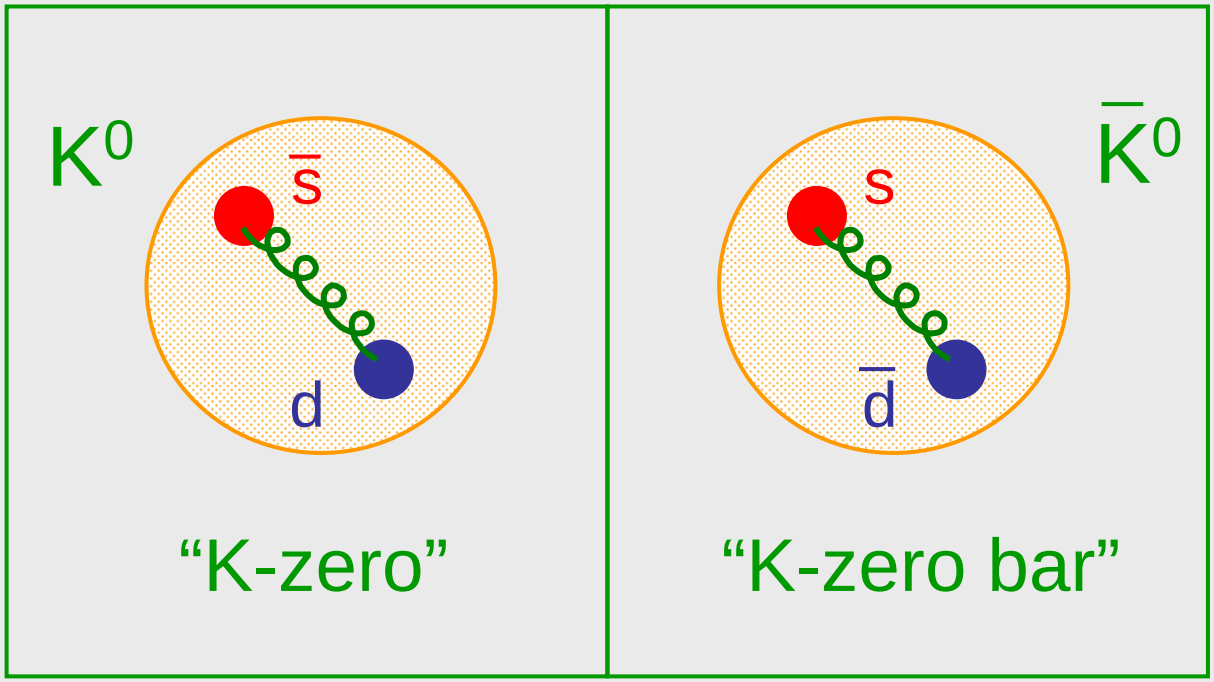
CP
Violation

How do we study CP violation ?

- Discovery of CP Violation in 1964
- Nobel Prize for Physics in 1980 - James Cronin, Val Fitch

Neutral Kaons:

neutral particles containing a strange quark or antiquark

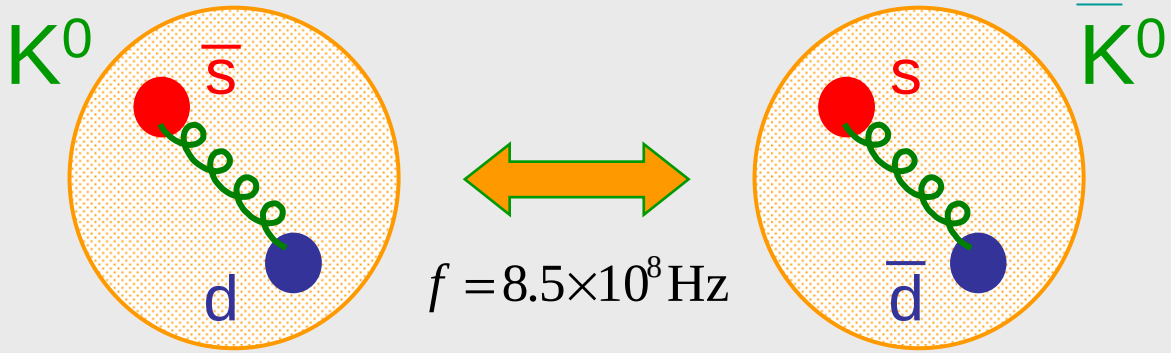


Kaon mass :

$$\frac{m_K}{m_e} = 974$$

Despite many searches, no other manifestation of CP violation until 1990

The neutral kaons can "mix" :



The particles we see decaying are :

K_S "K-short"

$$K_S \approx \frac{1}{\sqrt{2}}\left(K^0 + \bar{K}^0\right)$$

K_L "K-long"

$$K_L \approx \frac{1}{\sqrt{2}}\left(K^0 - \bar{K}^0\right)$$

A Quantum mechanical mixture of

K^0 and $\bar{K}^0$

K_S and K_L have very different lifetimes :

K_S : $\tau_S = 0.9 \times 10^{-10}$ sec

K_L : $\tau_L = 5.2 \times 10^{-8}$ sec

e.g. For a beam of energy 100 GeV :

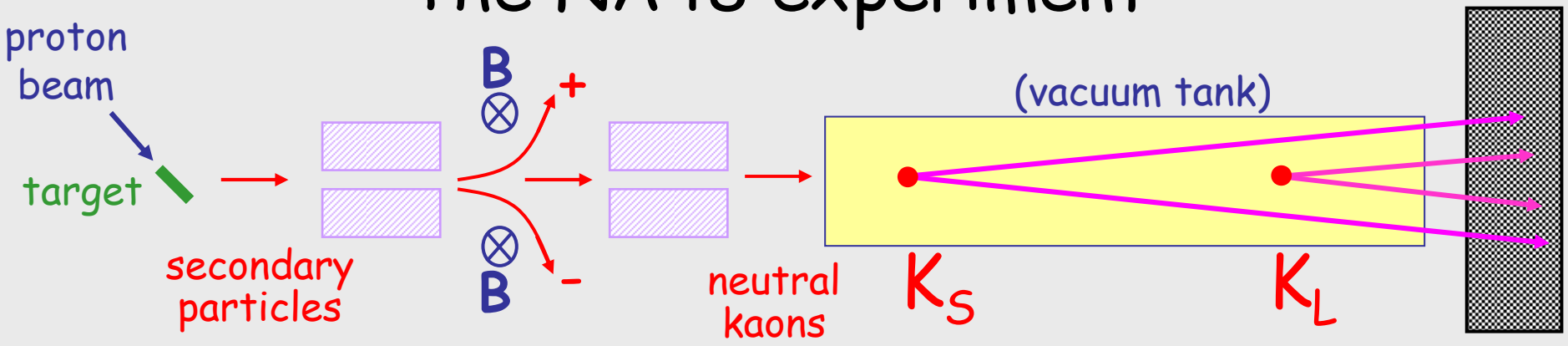
Average distance travelled before decay is

K_S : 5.4 m

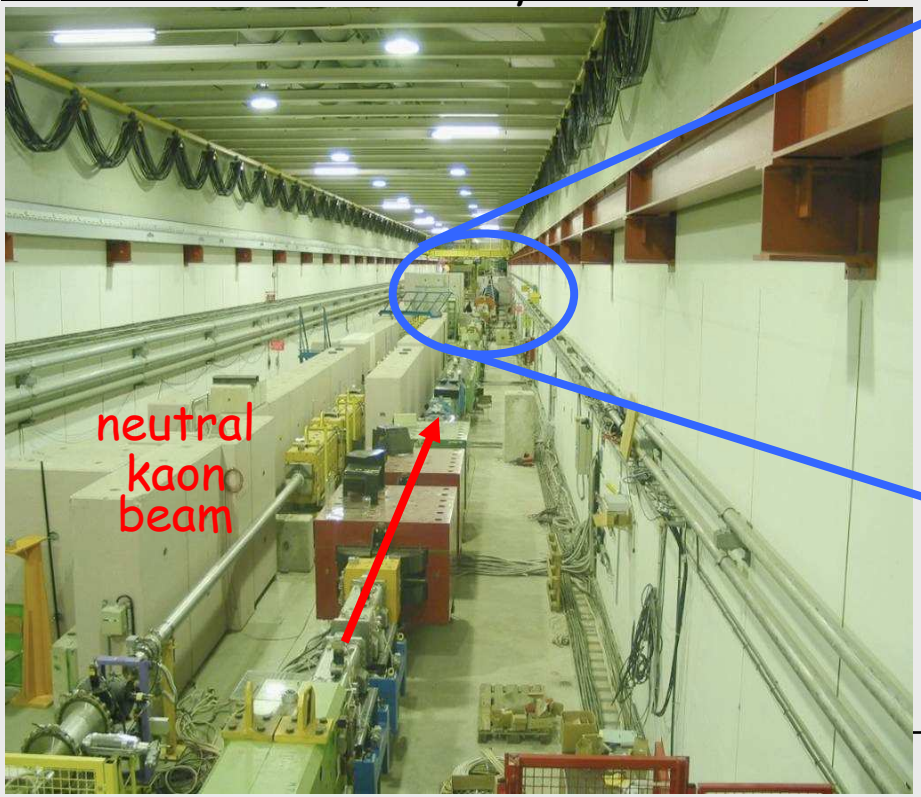
K_L : 3.1 km

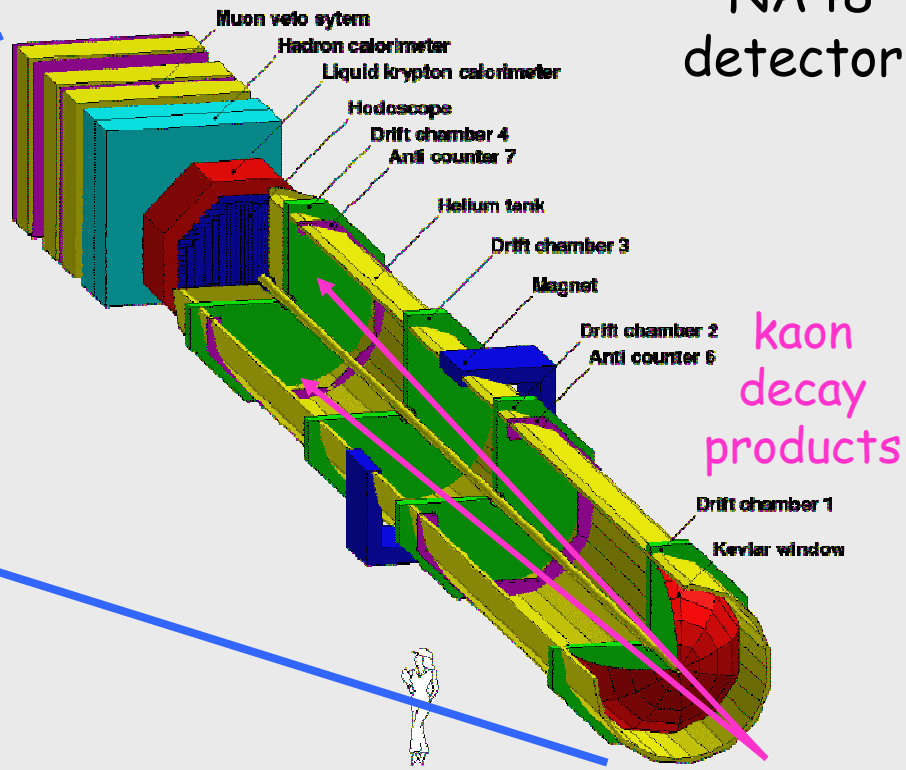
The beam starts out as an equal mix of K_S and K_L but eventually only K_L are left

The NA48 experiment



A view of the NA48 experimental area





CP violation

The K-Long has revealed subtle differences between matter and antimatter

For example, the decay $K_L \to \pi^- e^+ \nu_e$

occurs slightly (0.3%) more often than $K_L \to \pi^+ e^- \bar{\nu}_e$

More e^+ than e^- in K-long decays

allows unambiguous definition of matter and antimatter

In an Anti-world :

In the NA48 experiment at CERN ....

The neutral kaon beams starts out with **opposite** amounts of K^0 and $\overline{K^0}$

But, just as in our world :

the neutral kaon beam still starts out as an equal mix of K_S and K_L and eventually becomes pure K-long

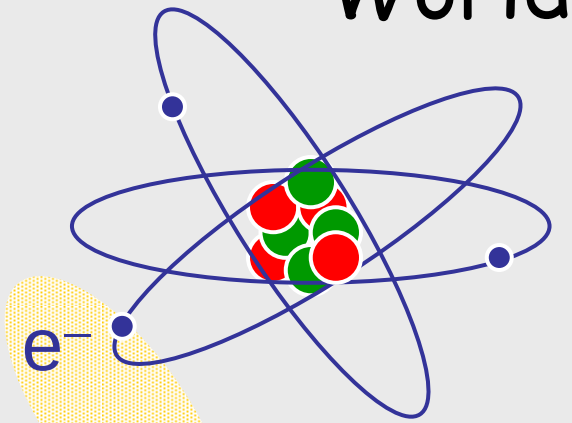
And, the decay:

$$K_L \rightarrow \pi^- e^+ \nu_e$$

still occurs slightly (0.3%) more often than:

$$K_L \rightarrow \pi^+ e^- \overline{\nu}_e$$

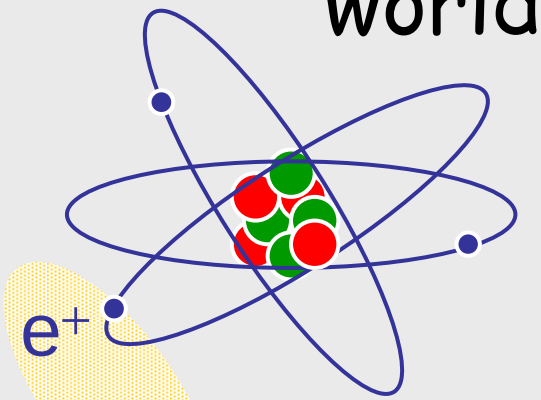
Our World



p
n

more e^+ than e^- in K-long decays

An Anti-world



$\bar{p}$
$\bar{n}$

more e^+ than e^- in K-long decays

MYSTERIES OF THE EARLY UNIVERSE

the Universe was born with
equal amounts of matter and antimatter

$t = 0$

CP violation :

(and B violation and
phase transitions)

the Universe contains
slightly more matter than antimatter

$t \sim 1\mu\,\mathrm{sec}$

Particles and anti-particles annihilate :

the Universe contains only matter
(and lots of photons)

$t \sim 1\,\mathrm{sec}$

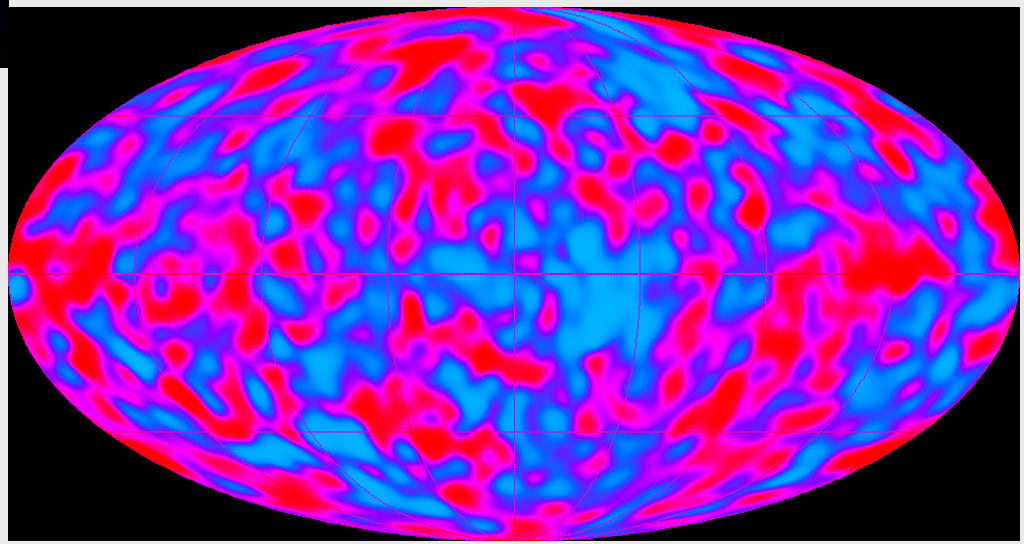
After 14-billion years

~ 10^{80} protons

$p + \bar{p} \rightarrow \gamma + \gamma$

~ 10^{9} photons

for every proton



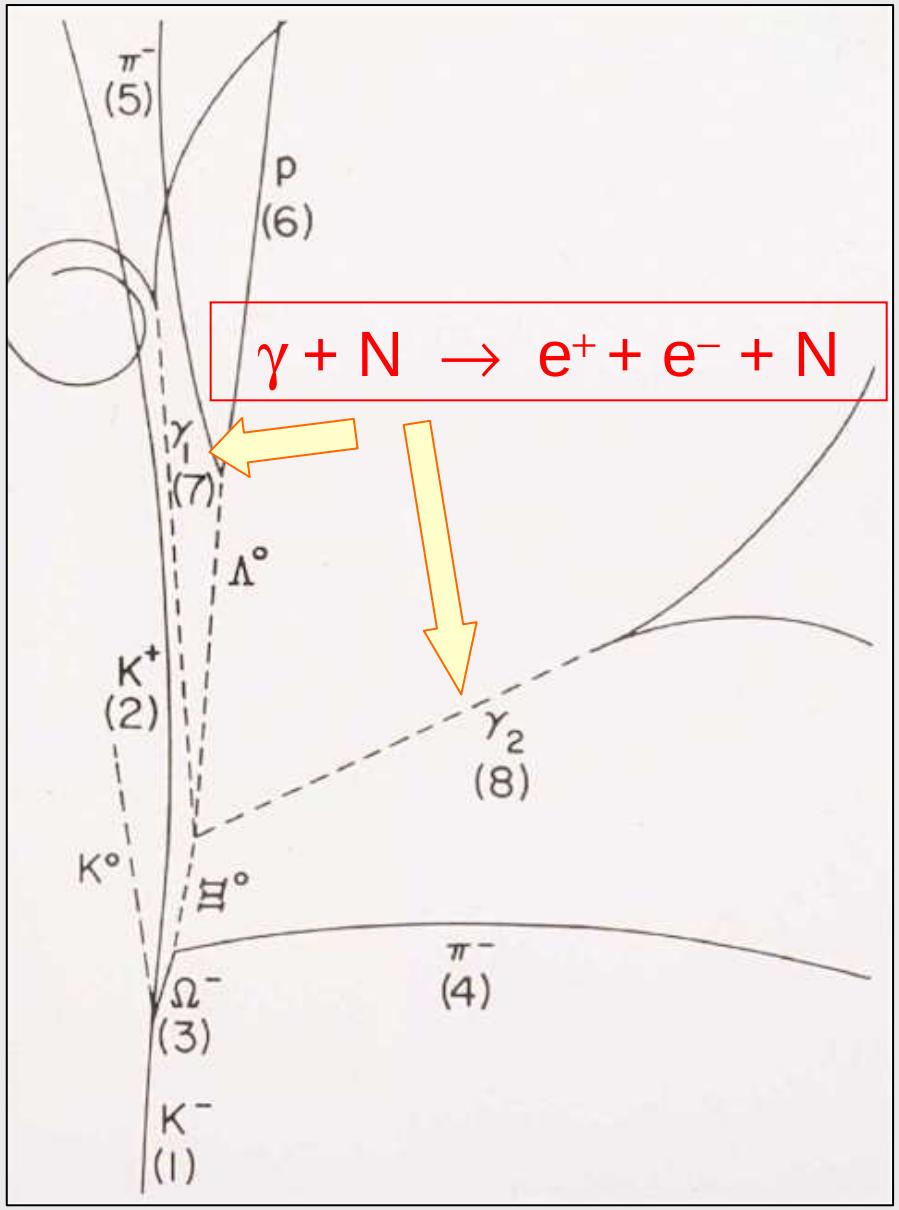
Open questions:

What is the origin of CP violation ?

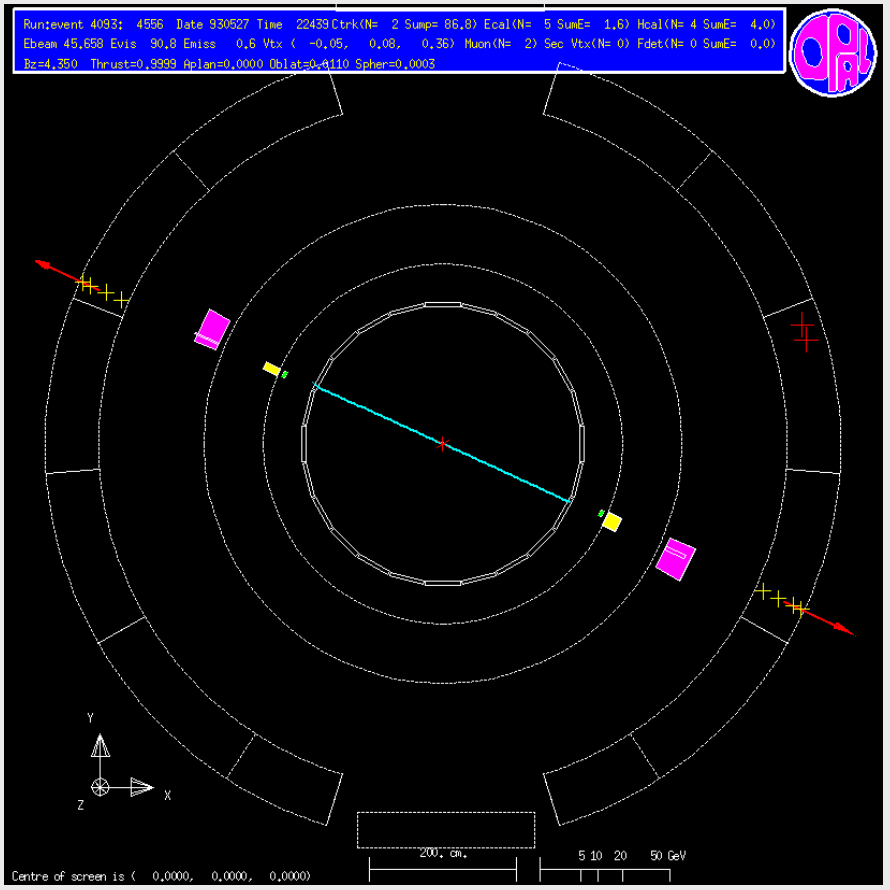
Is the CP violation we see what is needed in the Big Bang ?

Do aliens or anti-aliens exist ?

Spares:



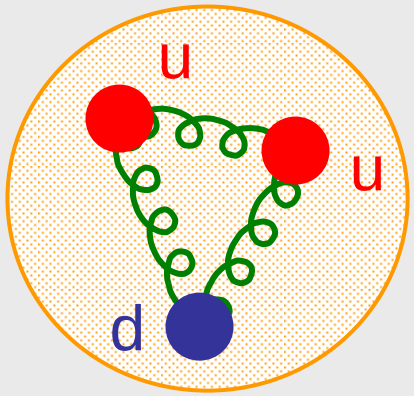
$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$



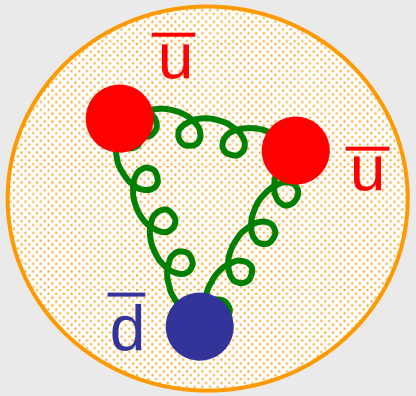
Hadrons are made up by quarks

qqq

p

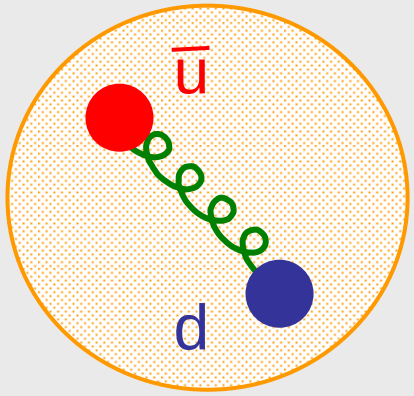


$\bar{p}$

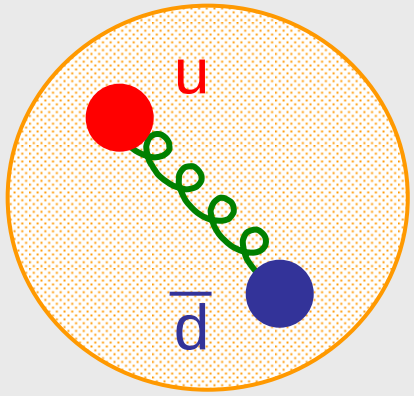


$q\bar{q}$

π^-



π^+



$$t \sim 1\,\mu\ \text{sec}$$

A hot, expanding "particle soup" :

e^+ , e^- , γ , p, $\bar{p}$, n, $\bar{n}$ (T ~ 10^{13} K)

with a small excess of particles :

$10^9 + 1$	protons
10^9	antiprotons

After particle - antiparticle annihilation :

$$p + \bar{p} \rightarrow \gamma + \gamma$$

1	proton
0	antiprotons
2 x 10^9	photons