Antimatter

The picture that was not reversed

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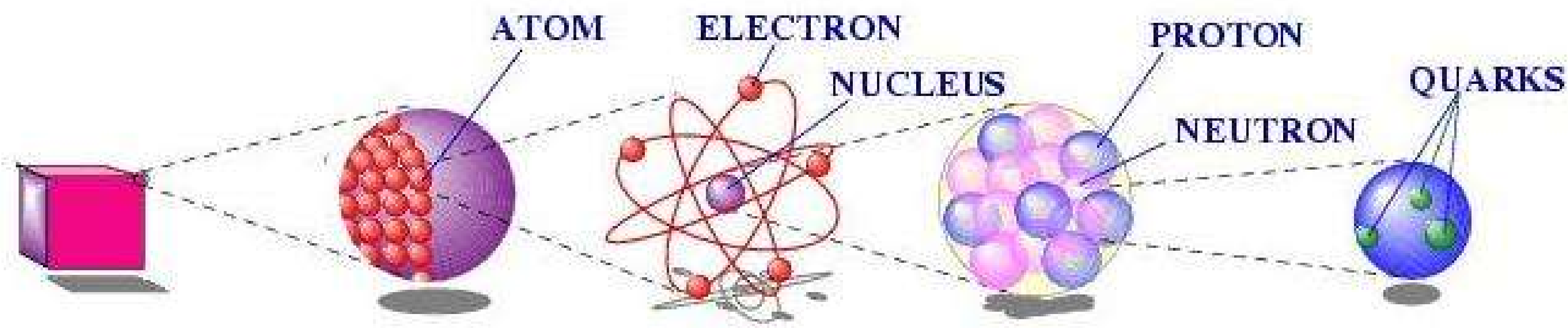
12 March, 2007

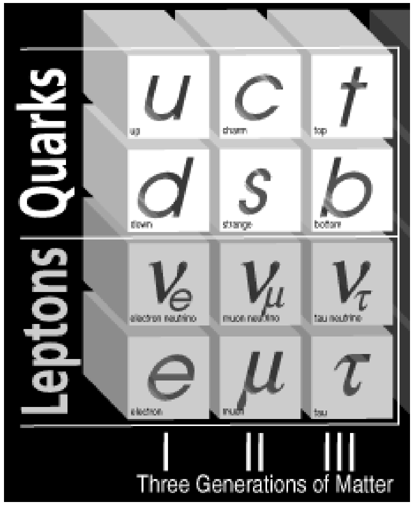
I. The story of everything (abridged)
II. The discovery of antimatter
III. Antimatter in the universe

The particle scale



The current picture

Matter...



+ force carriers...

photon (γ)
$W^\pm$
Z
gluon (g)

+ relativity + quantum mechanics + symmetries...

= "The Standard Model"

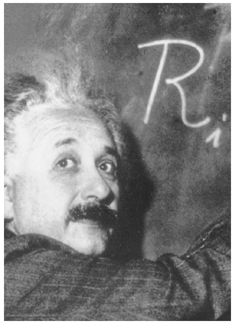
- almost certainly incomplete
- 25 free parameters (!)
- no gravity yet
- agrees with all experimental observations!

Glen Cowan
RHUL Physics

Discovering antimatter

Theoretical ingredients

(1) Special relativity (Einstein, 1905)



Gives correct description when speed close to *c*

New relation between energy, momentum, mass

$$E^2 = p^2c^2 + m^2c^4$$

(2) Quantum mechanics (Heisenberg, Schrödinger, Born, ... 1927)

Probability to find particle ~ $|\psi(\vec{x}, t)|^2$

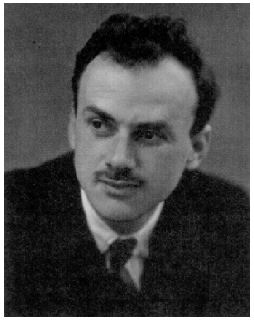
Schrödinger eq. based on $E = \frac{p^2}{2m} + V$ (non-relativistic)

Nature should allow a theory valid for both fast (relativistic) and small (quantum mechanical) systems...

Relativity + QM = antimatter

Dirac (1929) proposes relativistic equation for the wave function

$$\left(i\gamma^\mu \frac{\partial}{\partial x^\mu} - m\right)\psi = -e\gamma^\mu A_\mu \psi$$



The solutions to this equation describe a particle with

mass *m*, electric charge –*e* (e.g., an electron),

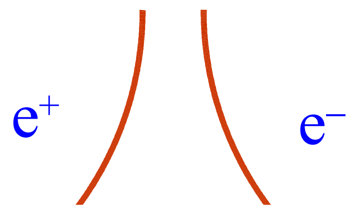
mass *m*, electric charge +*e* ←antimatter!

Some properties of antimatter

For every particle there should be an antiparticle with same mass, opposite charge:

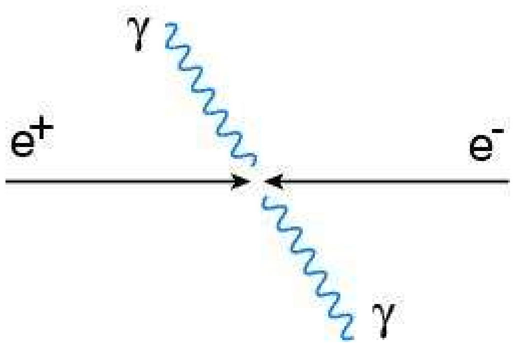
electron (e^-)	$\leftrightarrow$	positron (e^+)
proton	$\leftrightarrow$	antiproton
photon	$\leftrightarrow$	photon (same!)

Because of opposite charge, e^+ and e^- bend oppositely in a magnetic field.



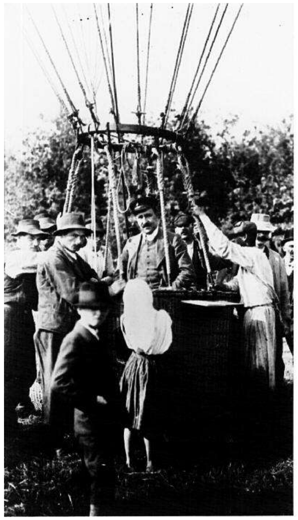
N.B. e^+ from above looks like e^- from below.

Matter and antimatter can annihilate:

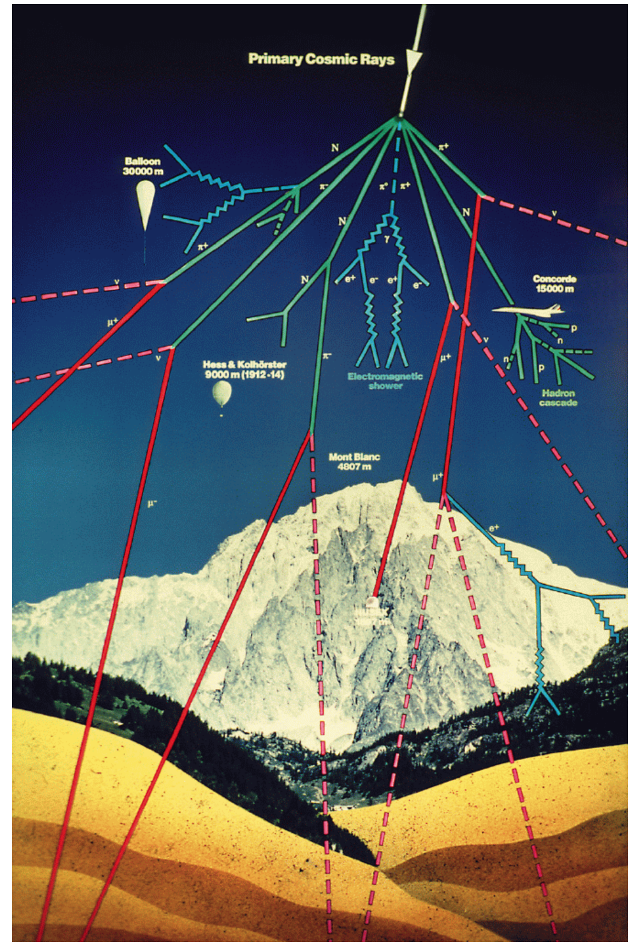


Experimental ingredients

I. Cosmic rays



V. Hess measures ionizing radiation in balloon flights (1912).



More ionizing particles found as balloon ascends to 5 km.

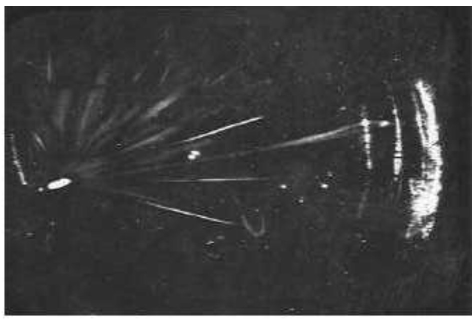
Hess: Particles coming from space.

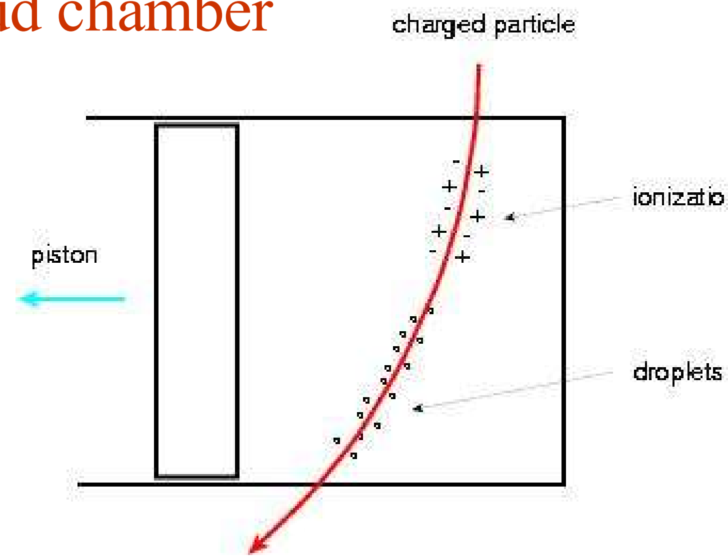
'Shower' of secondary particles mostly absorbed in atmosphere, some make it down to Earth's surface.

Experimental ingredients

II. The cloud chamber

C.T.R. Wilson (1911)





Ionisation seeds droplets $\rightarrow$ visible tracks

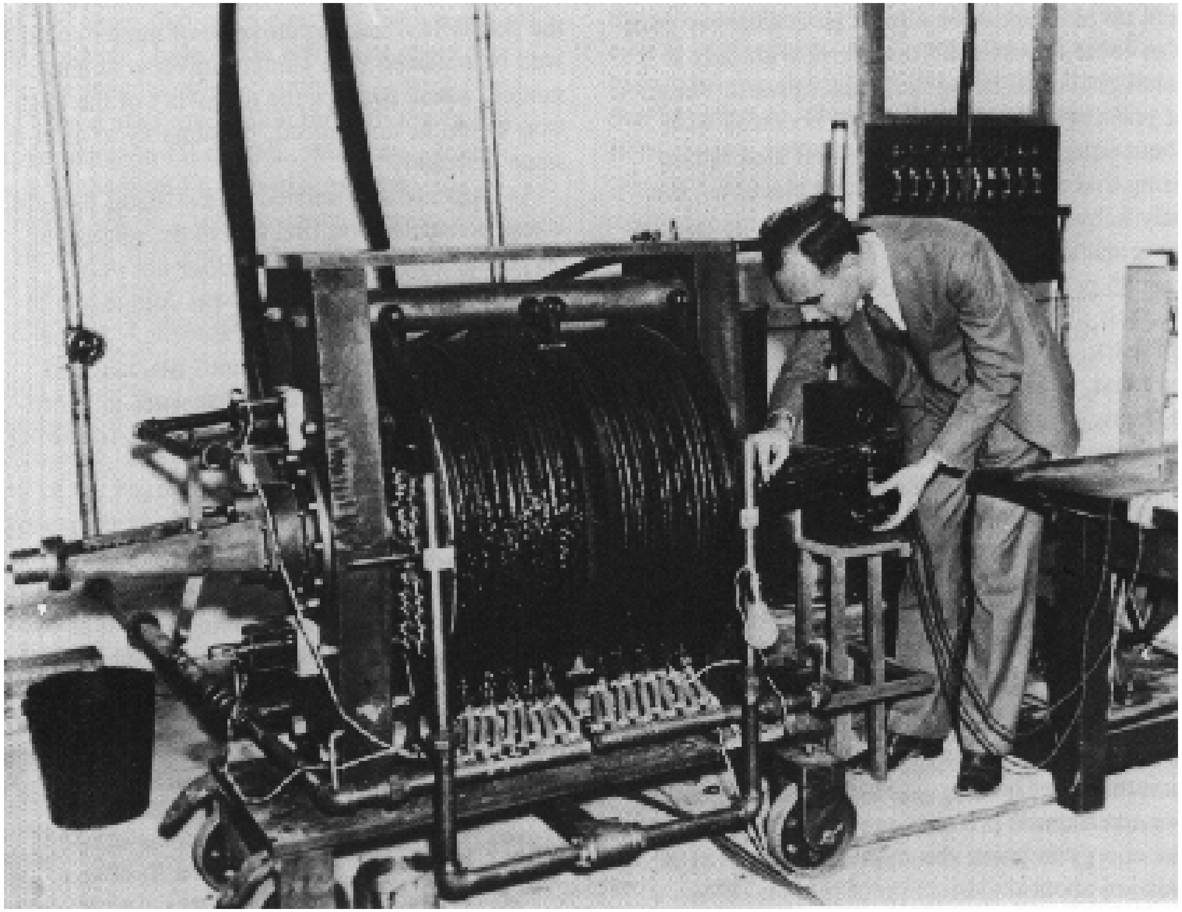
Curvature of track in magnetic field gives momentum.

Momentum related to mass, speed: $$p = \frac{mv}{\sqrt{1 - v^2/c^2}}$$

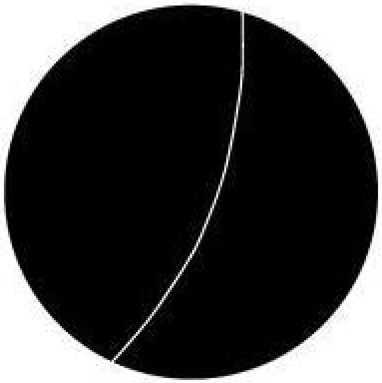
Measure track curvature ($\rightarrow p$) and ionisation rate ($\rightarrow v$)

$\rightarrow$ particle's mass

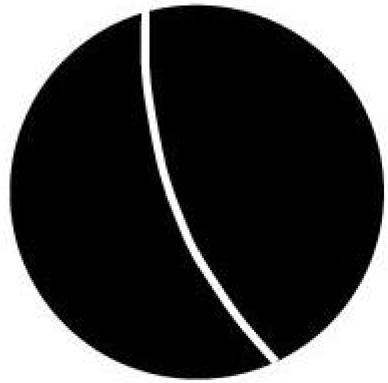
C.D. Anderson and cloud chamber



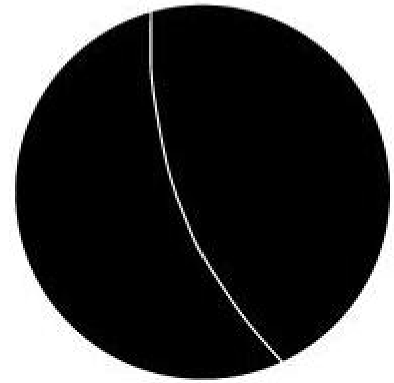
C.D. Anderson observations of cosmic ray tracks



Thin, curved to left,
$m \approx m_e$ and $q = -e$
(if from above).



Thick, curved to right,
$m \approx m_p$ and $q = +e$
(if from above).

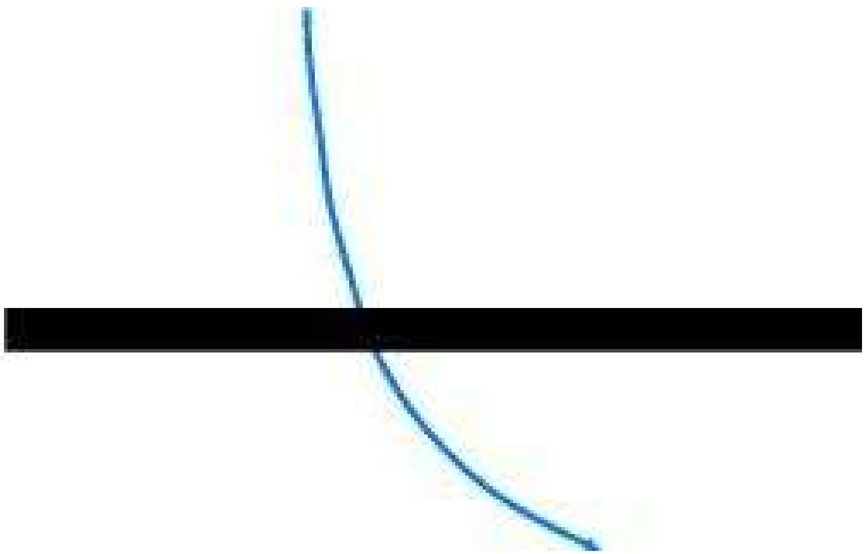


Thin, curved to right,
$m \approx m_e$, $q = ?$
What direction???

Millikan – "Cosmic rays only come from above! Your mass measurement must be wrong."

Anderson – "The mass measurement is reliable: $m \ll m_p$"

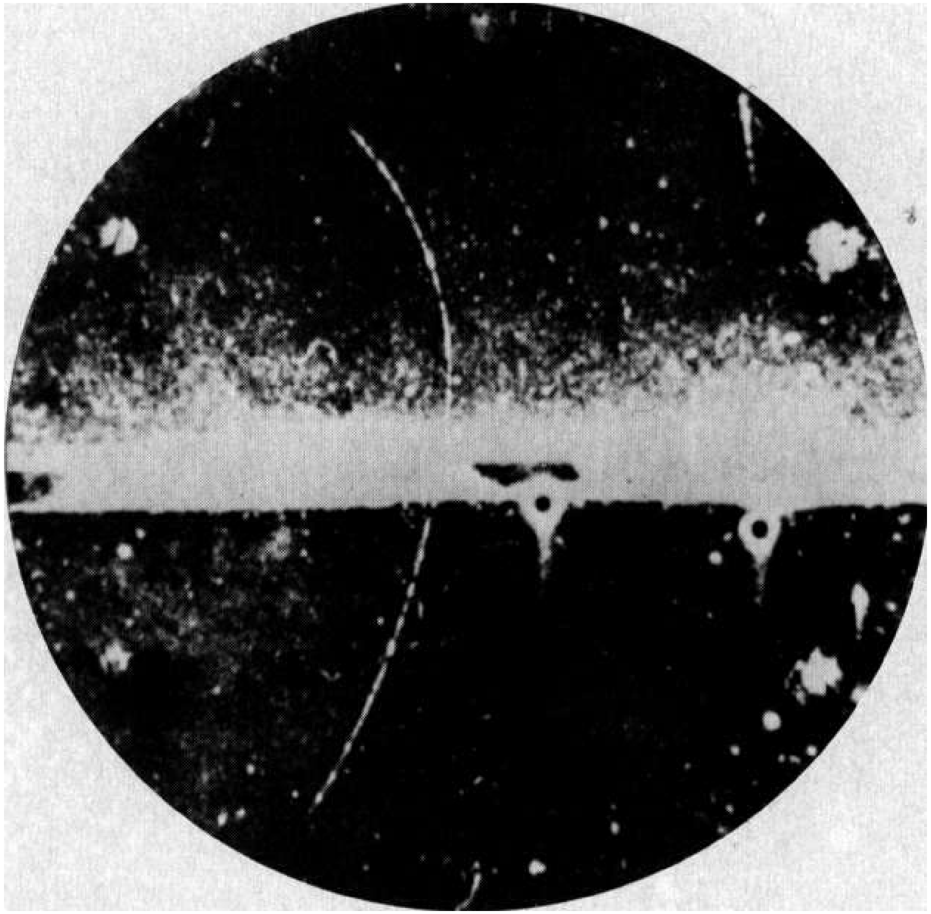
Determining the direction of the cosmic ray



Put 0.5 cm lead
plate in chamber.

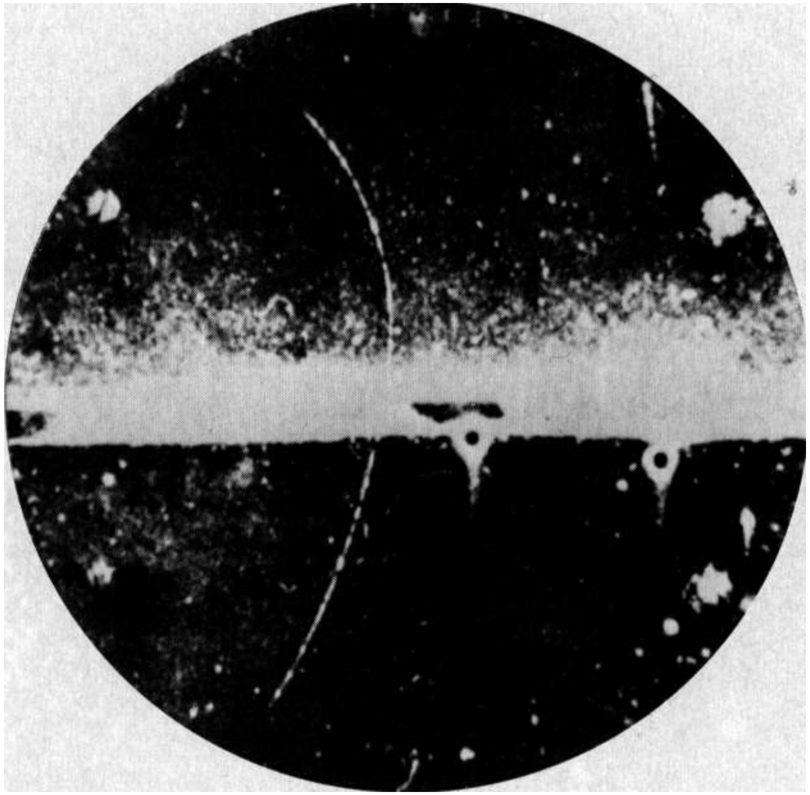
Particle loses energy traversing plate,
smaller radius of curvature must be outgoing side.

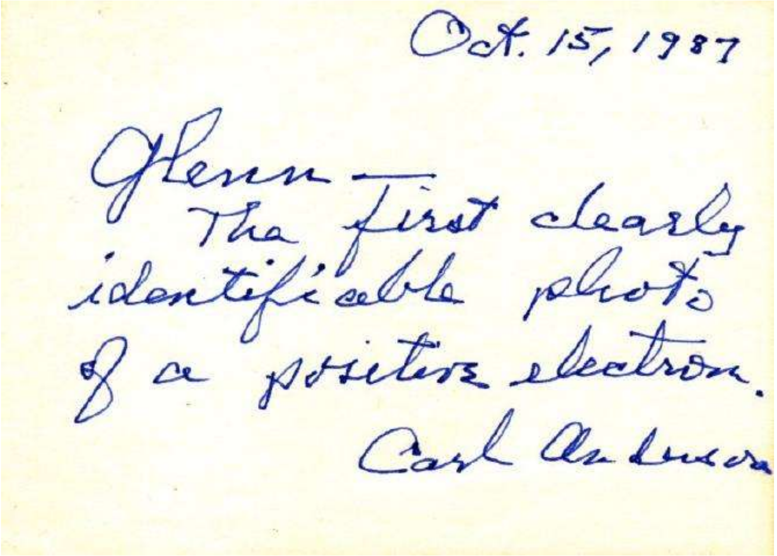
The first positron



C.D. Anderson
2 August, 1932

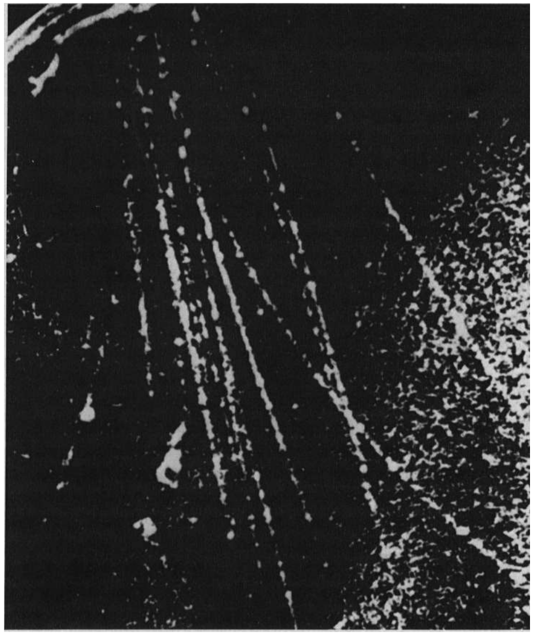
The first positron



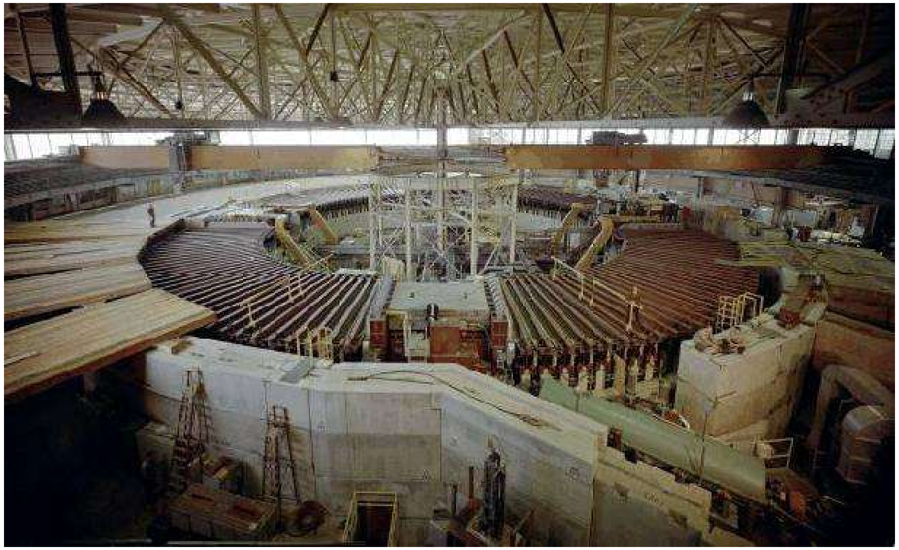

Oct. 15, 1987

Glenn —
The first clearly identifiable photo of a positive electron.
Carl Anderson

More antimatter



Electron-positron shower seen by Blackett and Occhialini, 1933.



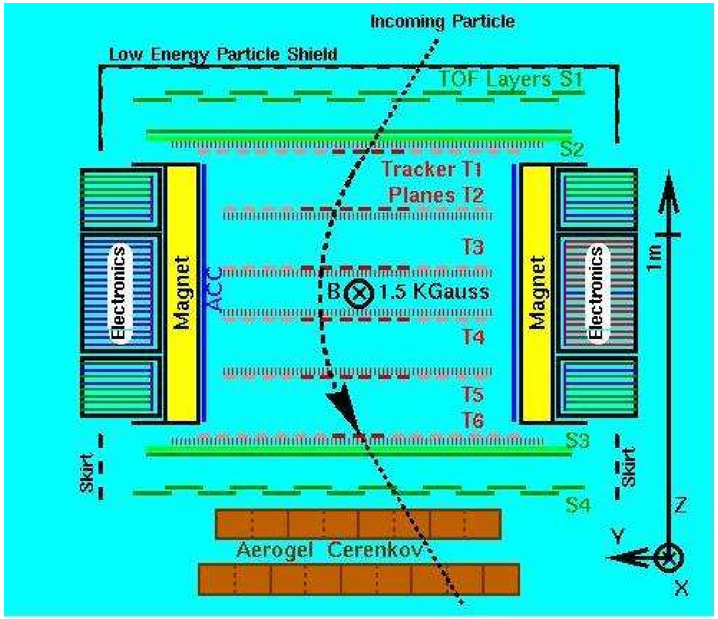
Antiproton discovered by Segrè, Chamberlin et al., 1955.

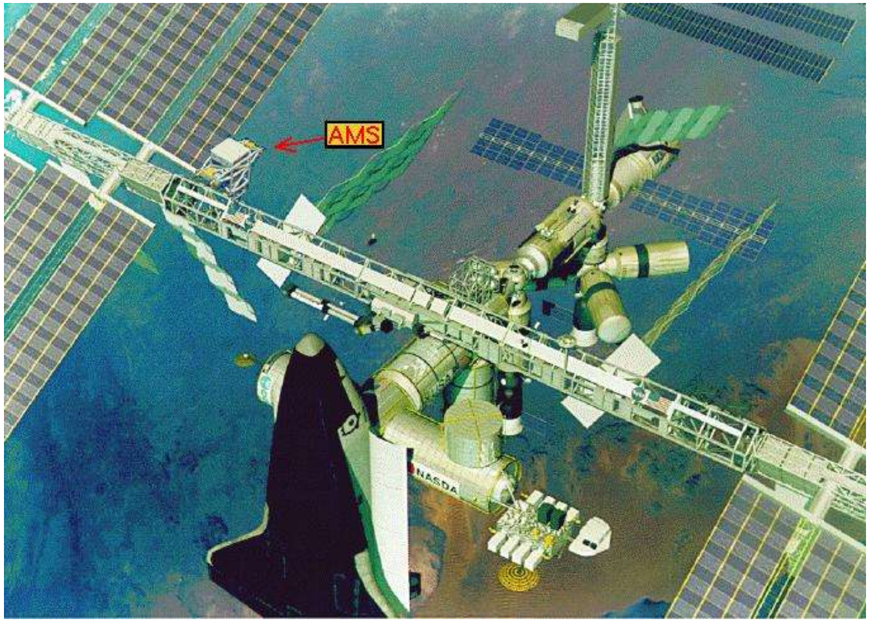
Experiment vs. Theory

Experiment	particle	theory
1932	positron	predicted 1929
1936	muon	Rabi – 'Who ordered that?'
1947	kaon	unexpected
1959	neutrino	predicted 1930
1969	partons (quarks)	predicted 1964
1974	c quark	predicted 1970
1975	τ lepton	unexpected
1977	b quark	unexpected
1979	gluon	predicted 1972
1983	$W^{\pm}$, Z	predicted 1971
1995	t quark	expected since b quark
2000 – 2008 (???)	Higgs boson	predicted mid 1960s
2008 – ?	SUSY particles	predicted mid 1970s
???	???	???

Searching for antimatter in cosmic rays

The Alpha Magnetic Spectrometer

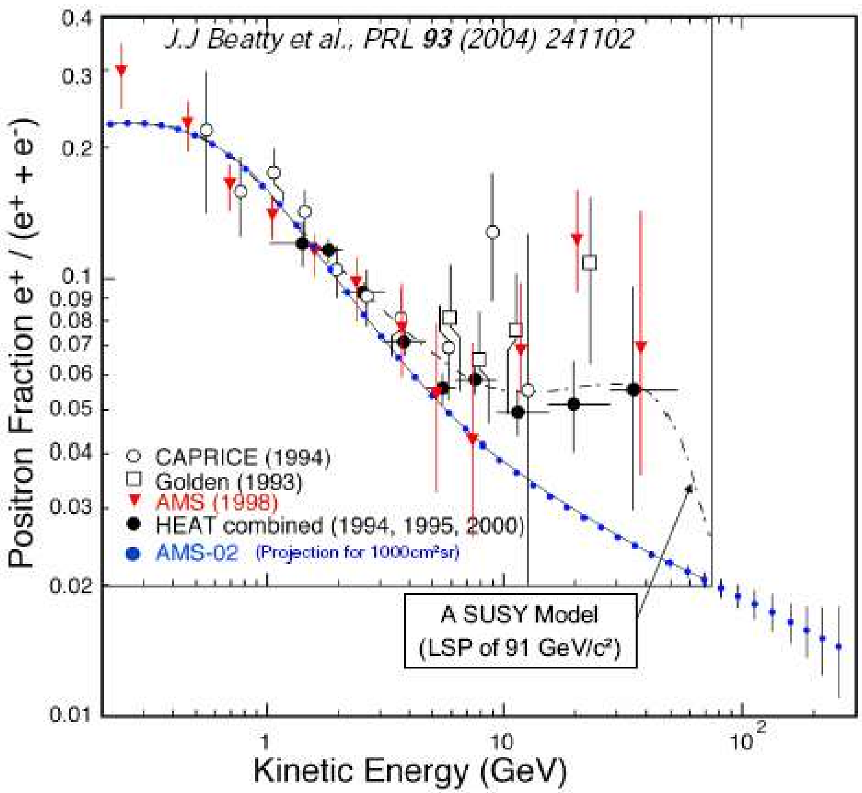




Currently no evidence that the universe contains ‘antiworlds’.

Excess of positrons in primary cosmic rays?

Measurements from AMS (1998) and high-altitude balloon experiments show more positrons in primary cosmic rays (above the atmosphere) than expected at high energies.



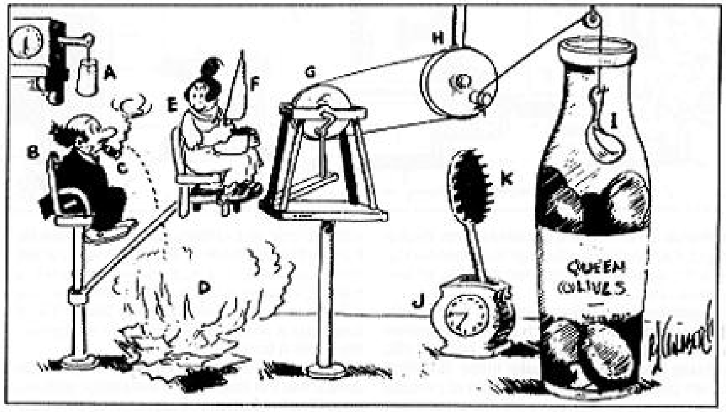
This is well described by models where the neutralino (a particle predicted by supersymmetric theories) constitutes a significant fraction of the Dark Matter of the universe.

No claim as yet for the 'discovery' of the neutralino but an interesting hint.

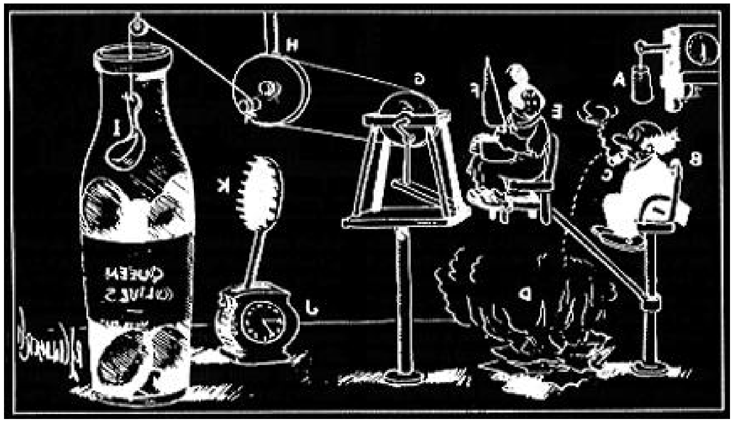
Antimatter and the rest of Particle Physics

Laws of physics 'symmetric' with respect to matter/antimatter?

An experiment



Its antimatter ("CP") equivalent



Will the two experiments behave the same?
Since 1964 we know the answer is no.

(And the Standard Model explains at least part of this, as long as we have 3 families of quarks and leptons.)

Timeline of the Big Bang

time (s)	temperature (GeV)	(K)	era
10^{-43}	10^{19}	10^{32}	Planck scale (quantum gravity)
10^{-39}	10^{16}	10^{29}	GUT scale, beginning of inflation(?)
10^{-37}	10^{15}	10^{28}	End of inflation(?)
10^{-10}	10^{2}	10^{15}	Electroweak unification
10^{-5}	1	10^{13}	Quarks confined to protons, neutrons
1	10^{-3}	10^{10}	$e^+e^- \rightarrow \gamma\gamma$; almost all antimatter gone.
10^{2}	10^{-4}	10^{9}	Synthesis of He, D, Li
10^{13}	10^{-9}	10^{4}	Neutral hydrogen, formation of Cosmic Microwave Background
...	...	...	...
10^{18}	10^{-13}	1	WOLAS established

$(13.8 \times 10^9$ y)

(more precisely, 2.75 K)

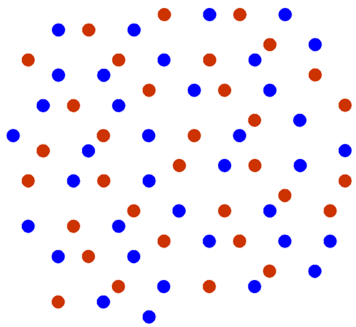
Size of the matter/antimatter asymmetry

At very early times, there were almost equal amounts of matter and antimatter, constantly being created and destroyed, e.g.

$e^+e^- \to \gamma\gamma$

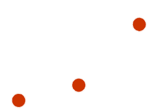
$\gamma\gamma \to e^+e^-$

At T > 1 MeV, rates almost equal



For every 10^9 antiparticles, there are $10^9 + 3$ 'normal' matter particles

At T < 1 MeV, inverse reaction $\gamma\gamma \to e^+e^-$ stops, almost all of the matter and antimatter annihilate; tiny bit left over to make the matter we see around us.



Antimatter and the Big Bang

So if the universe is made of matter (not a mixture of matter and antimatter) then was this asymmetry there at the beginning?

Best guess: no – it started symmetric, and the asymmetry developed in the first instants after the Big Bang.

For this to happen, several criteria must be fulfilled including matter/antimatter (CP) asymmetry (Sakharov).

So the detailed behaviour of antimatter turns out to have fundamental consequences for the evolution of the universe.

Current research on antimatter

The Stanford Linear Accelerator Center's two-mile e^+e^- linac.

The PEP-II e^+e^- collider

~1/2 mile diameter tunnel at end of linear accelerator houses separate beam lines for counter-rotating e^+ and e^- beams.

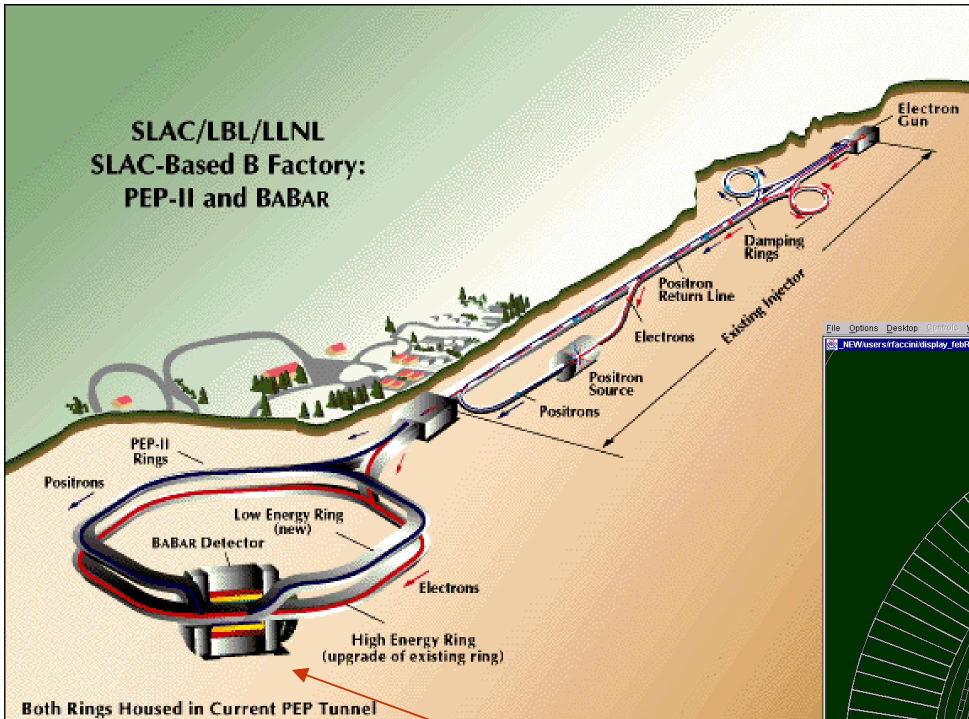
PD_001 PEP-II Dedication 10/26/98

The BaBar Experiment

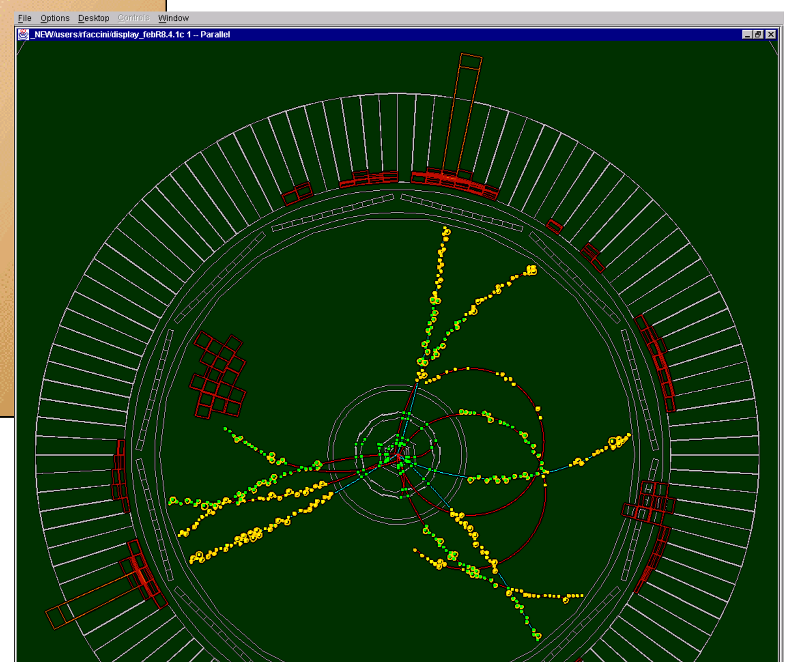
~700 physicists, ~84 universities and labs, 10 countries.

The PEP-II collider and BaBar experiment

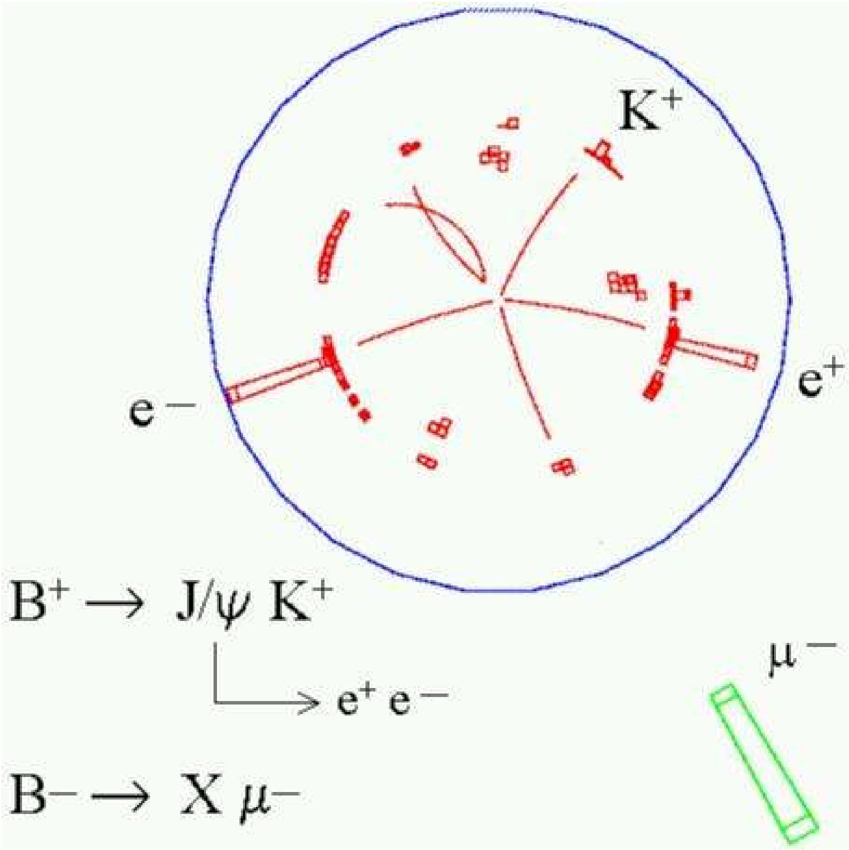
Electrons and positrons collide to produce B and anti-B mesons, which rapidly decay into other particles.



$$e^+e^- \rightarrow B^0\bar{B}^0$$



Studying CP asymmetries with B-meson decays



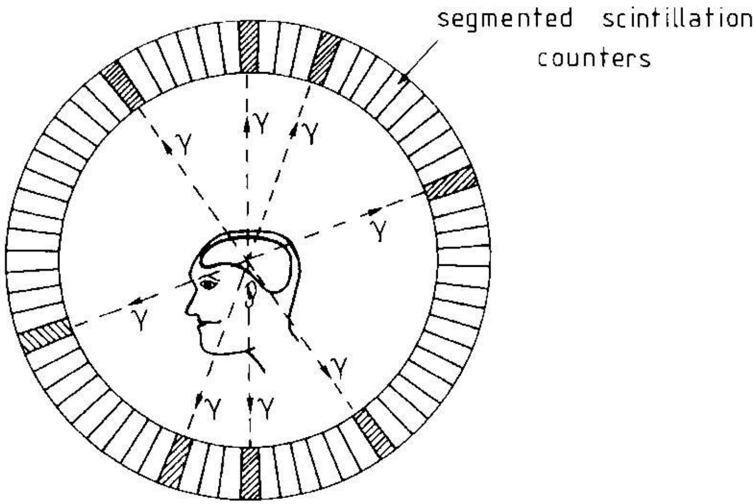
By measuring the decay times of many (~10^8) B mesons, we can study Nature's matter/antimatter symmetry.

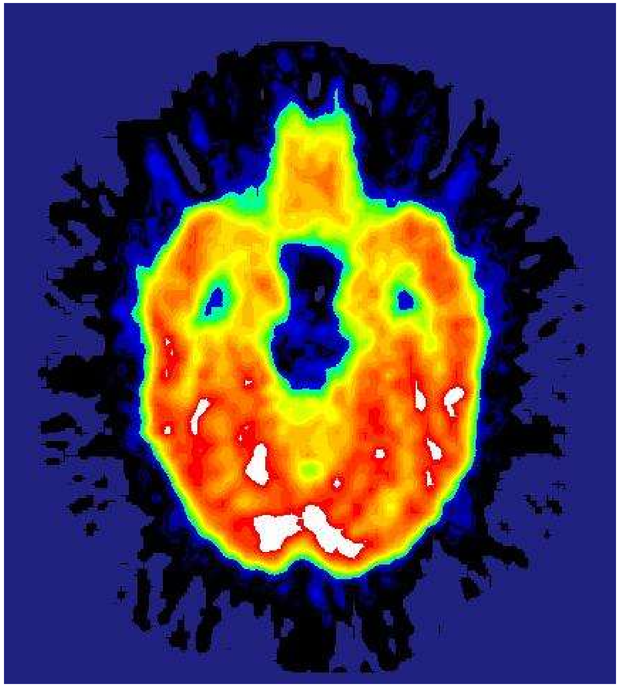
The observed 'CP asymmetry' is found (so far) to agree with the Standard Model, but doesn't yet explain the matter/antimatter asymmetry of the universe.

This is a strong indication that our current picture of CP violation is incomplete.

Antimatter and technology

Positron Emission Tomography (PET)





PET scan of a brain

Does it matter?

The story of antimatter combines

theory and experiment,

particle physics and cosmology,

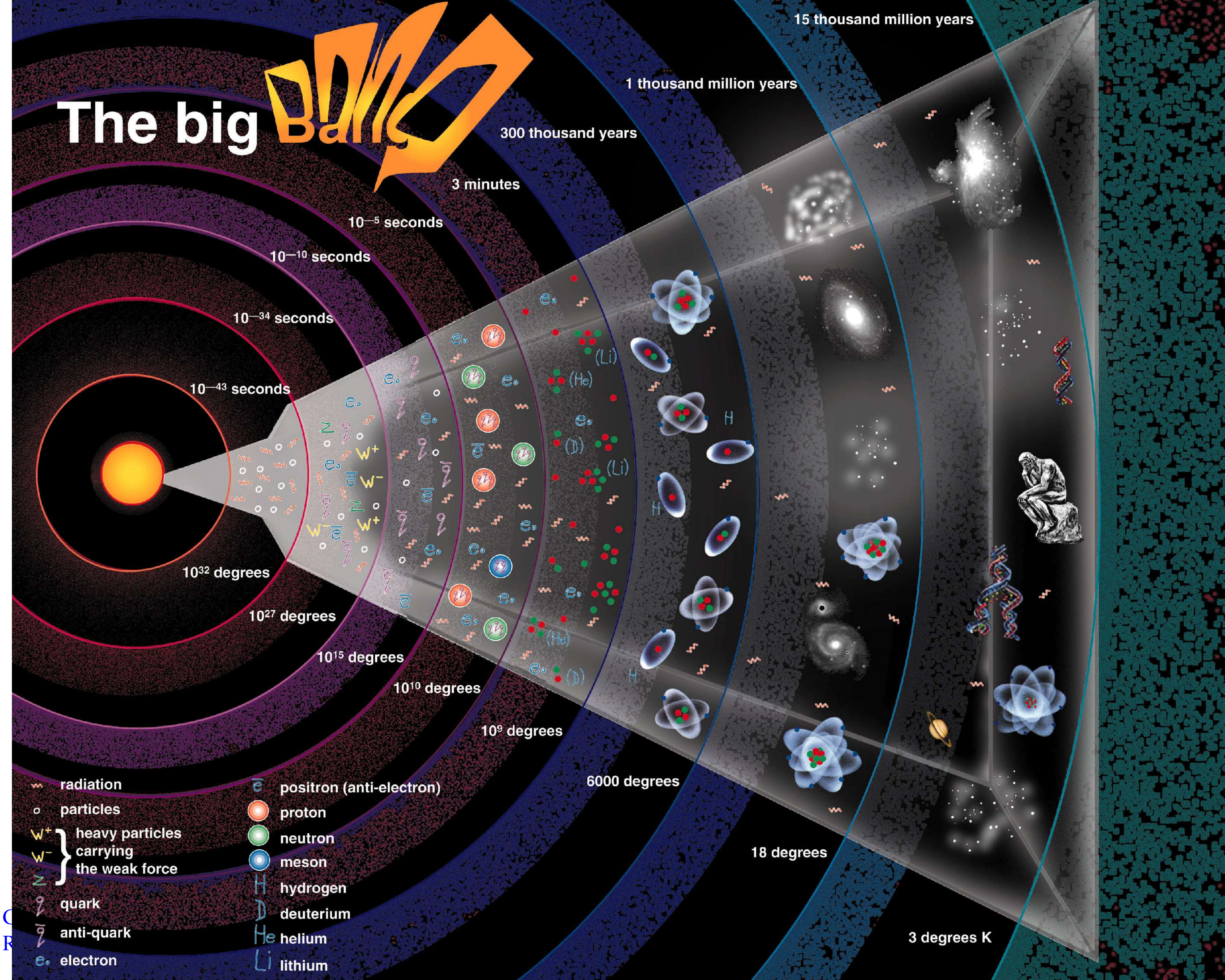
science and technology,

the insignificant and the crucial.

Antimatter is almost completely decoupled from the ordinary processes of daily life,

but its detailed properties have had a major influence on the evolution of the universe.

Extra slides


The big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
10^{-5} seconds
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium

C
R

The Large Hadron Collider (CERN)

The ATLAS experiment at the LHC