Antimatter in a classroom

Benoît Clément

Johann Collot

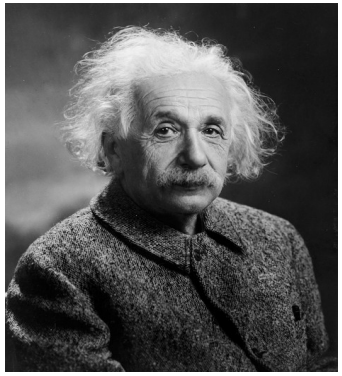
Christophe Furget

Laboratoire de Physique Subatomique et de Cosmologie de Grenoble (LPSC)

université Grenoble Alpes, CNRS/IN2P3

Experiment

How does it work ?



Albert Einstein
1879 - 1955

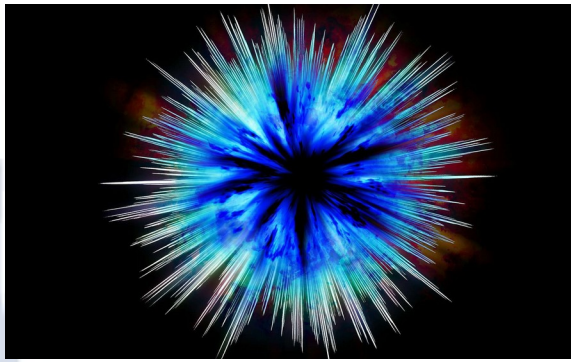
Energy materialization

$$E = m\,c^2$$

Energy — mass — velocity of light in vacuum

Annihilation (dematerialization) of matter

Big Bang



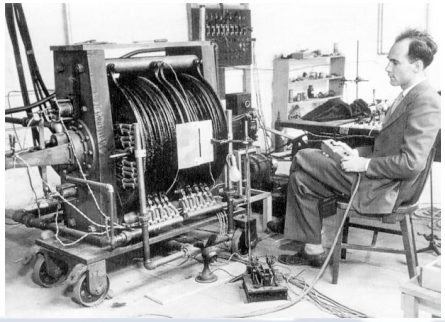
At the beginning (13.7 billion years ago), there was only energy.

Energy materialized, obeying the fundamental laws of physics as e.g. electric charge conservation.

The whole universe initially was neutral, and then is still neutral.

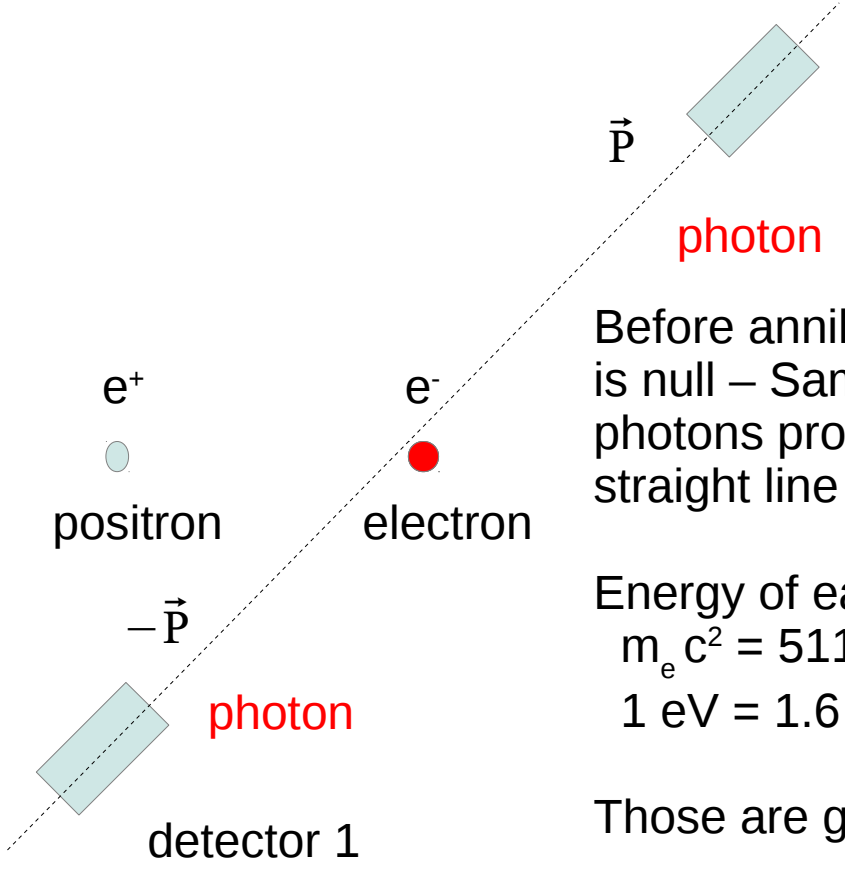
If an electron materializes, then a particule of the same absolute charge but positive, must also materialize. This is a positron, e^+ , the electron antiparticule.
The positron has the same mass as the electron : 9.109 10^{-31} kg

The positron was discovered in 1932 by Carl David Anderson in USA.



Carl David Anderson
1905-1991

Positron-electron annihilation

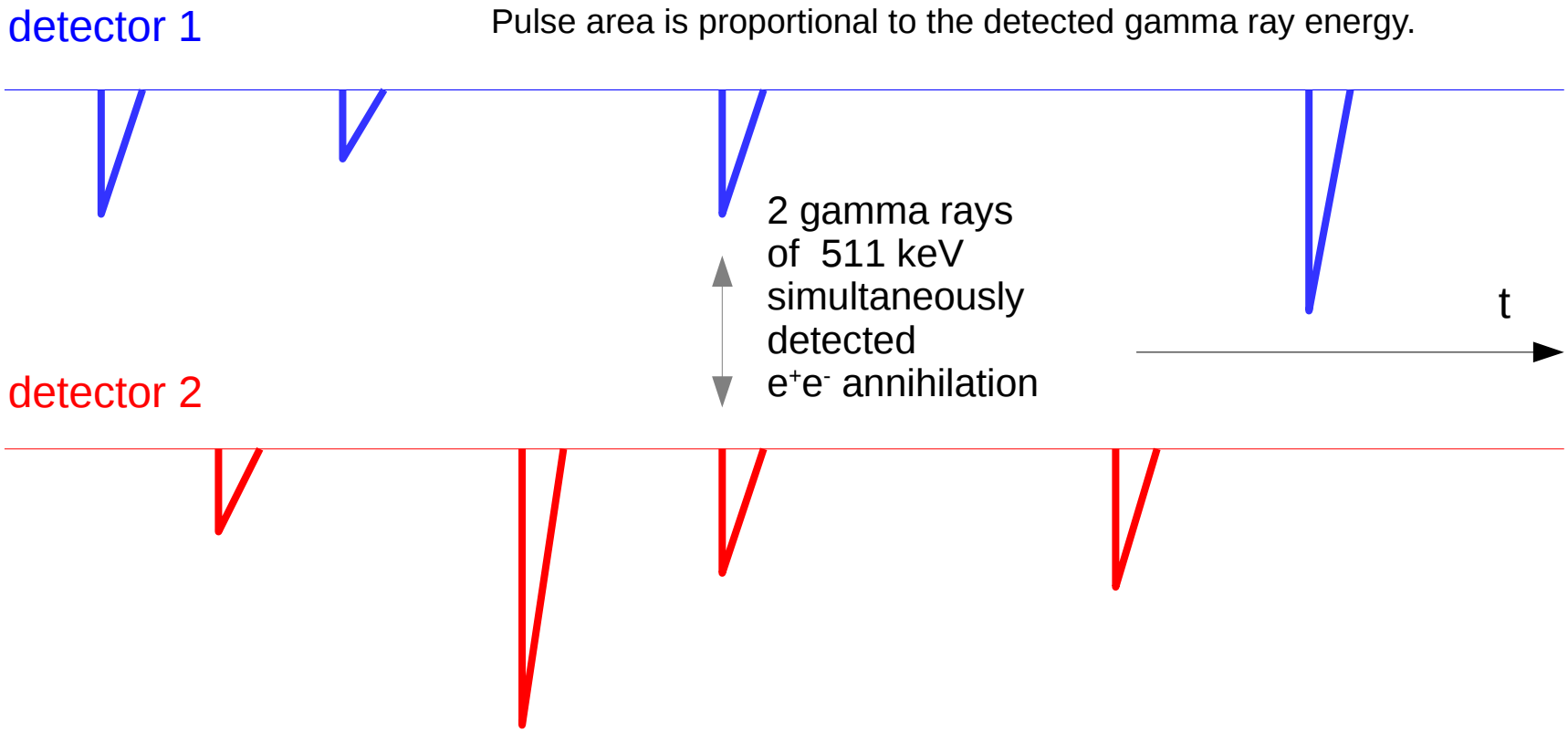


Before annihilation, total momentum is null – Same thing after. Both photons propagate on the same straight line in opposite directions.

Energy of each photon =
$m_e c^2 = 511$ keV
1 eV = $1.6\ 10^{-19}$ J

Those are gamma rays.

Detection time diagram of gamma rays

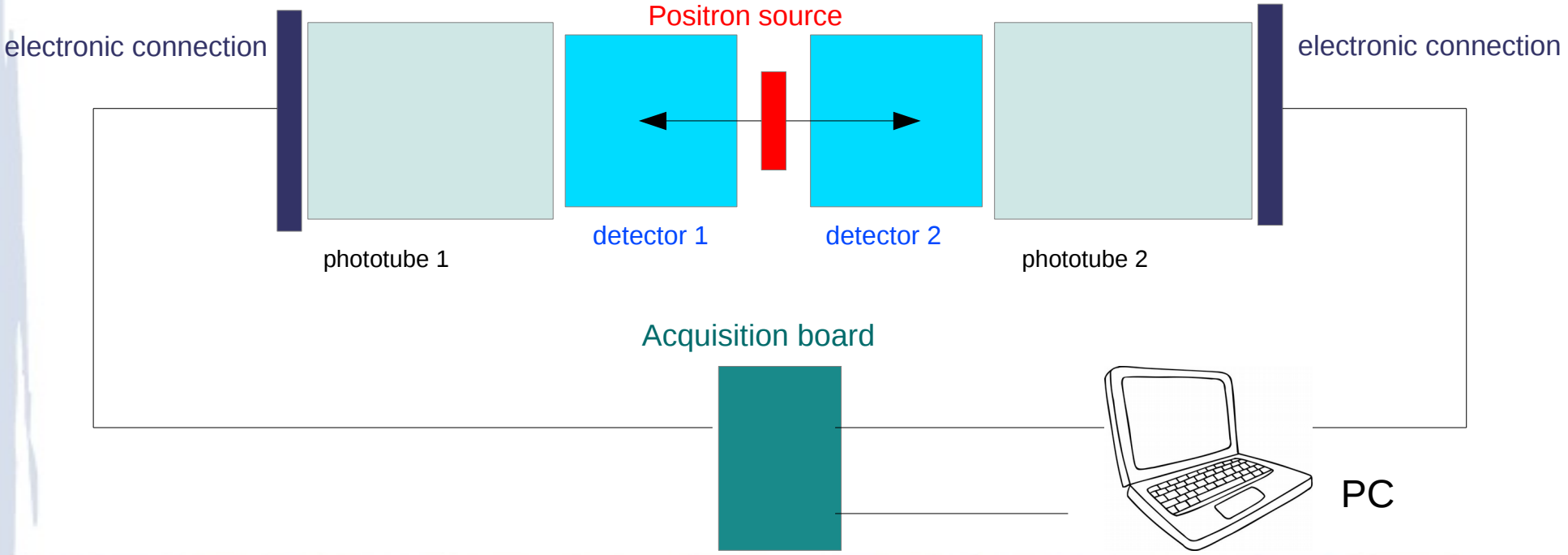


The experiment

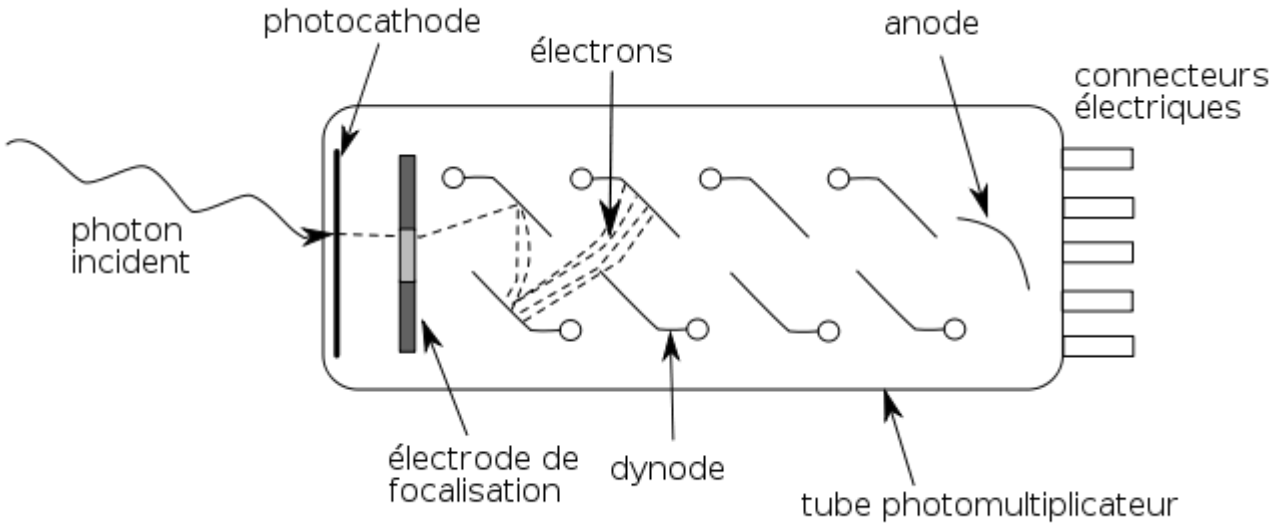
The detectors absorb gamma rays (photoelectric effect) and convert their energy into visible light.

The phototubes convert visible light into fast electronic signals (1 µs) and amplify them.

The acquisition board applies an energy threshold, counts the signals arriving at the same time (in coincidence) and visualize their energy spectrum.



Phototube



Produces up to 10^6 electrons per incident photon

Can detect a single photon !

Beta plus radioactivity

Discovery

Irène : 1897-1956
Frédéric : 1900-1958

In 1934, Irène & Frédéric Joliot-Curie announce the premiere production of an artificial atom of phosphorus 30 decaying by beta plus radioactivity.

$$\alpha + {}^{27}_{13}Al \rightarrow {}^{30}_{15}P + n$$

By exposing various elements to α particles or light nuclei, many other atoms, decaying by beta plus radioactivity, can be produced, among which ^{22}Na.

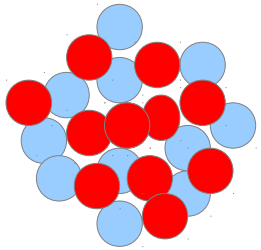
Beta plus decay

Nuclei are made of protons (●) and neutrons (●).

e^+ : positron

^{22}Na

^{22}Ne

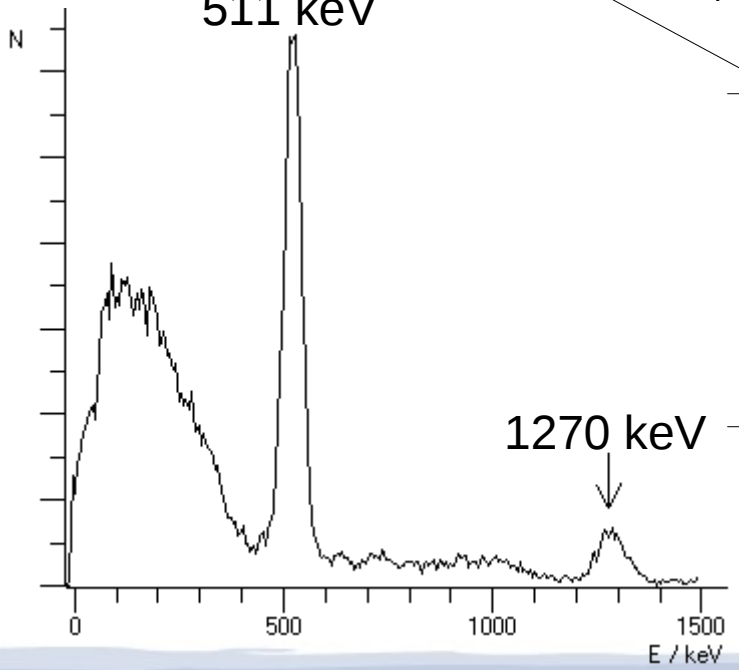


Many beta plus emitting nuclei exist. Some like ^{18}F , ^{15}O .... are used in medicine

ν_e : electronic neutrino

Neutron-deficient light nuclei convert a proton into a neutron while simultaneously emitting a positron & an electronic neutrino.

^{22}Na gamma ray spectrum (energy distribution)



^{22}Na half-life = 2.6 y

e^+ , ν_e followed by $e^+ + e^-$ -> γ (511 keV) + γ (511 keV)

^{22}Ne* half-life 3.6 ps

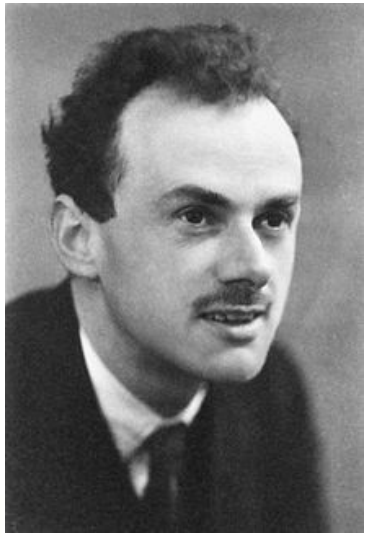
γ (1270 keV)

^{22}Ne stable

All in all, a 1270 keV gamma ray followed by two 511 keV gamma rays from the annihilation.

Antimatter

Dirac theory



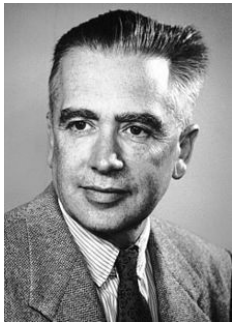
Paul Dirac : 1902-1984

From 1928 to 1932, Paul Dirac works out a quantum & relativistic theory of the electron. After several hesitations, in 1931, he postulates the existence of a particle featuring the same mass as that of the electron, but carrying an opposite charge : + |e|

The positron will be experimentally discovered a year after, in a totally independent way by Carl Anderson, and confirmed shortly after by Patrick Blackett & Giuseppe Occhialini

During the XXth century, the existence of antiparticles will be generalized. Today one knows that each particle has its antiparticle (that sometimes can be the same particle, as this is the case for photons and some other electrically neutral particles)

Antimatter in laboratories



Emilio Segrè : 1905-1989

In 1955, Chamberlain, Segrè & colleagues discover antiproton that opens the door to the production of hydrogen antiatoms.

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

Owen Chamberlain : 1920-2006

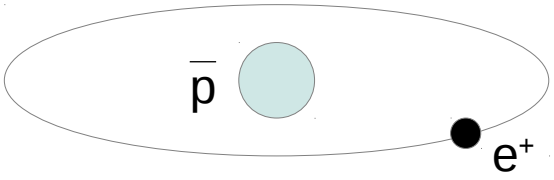
In 1956, Bruce Cork et al. discover antineutron.

$$p + p \rightarrow p\ p\ p\ \pi^-\ \bar{n}$$

Bruce Cork et al.

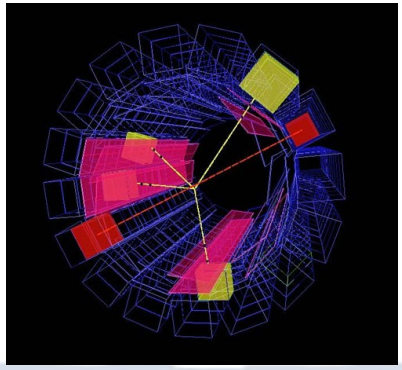
First artificial antiatoms

In 1995, a team at CERN lead by Walter Oelert announces to have produced the first hydrogen antiatoms : 9 in total !



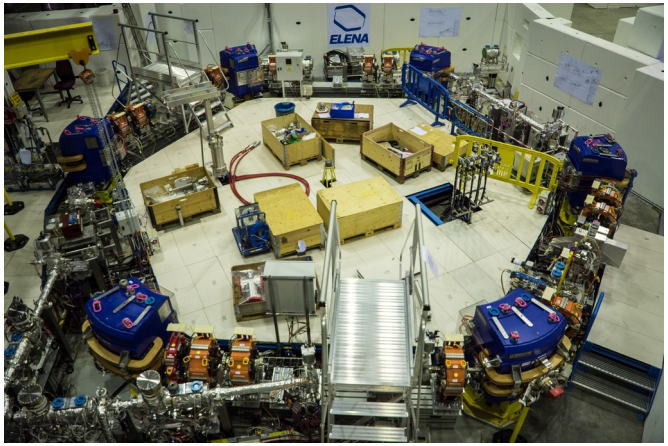
Walter Oelert : 1942 -

In 2011, 300 hydrogen antiatoms are trapped for 16 minutes at CERN.



Annihilation of a H antiatom in the ATHENA detector

Study of antimatter goes on



ELENA (Extra Low ENergy Antiprotons)
at CERN in Geneva.

Spectroscopy of hydrogen antiatoms & study of their gravitational properties :

- is the optical spectrum of antiatoms the same as that of atoms ?

- do antiatoms fall the same way in the earth gravity as atoms ?

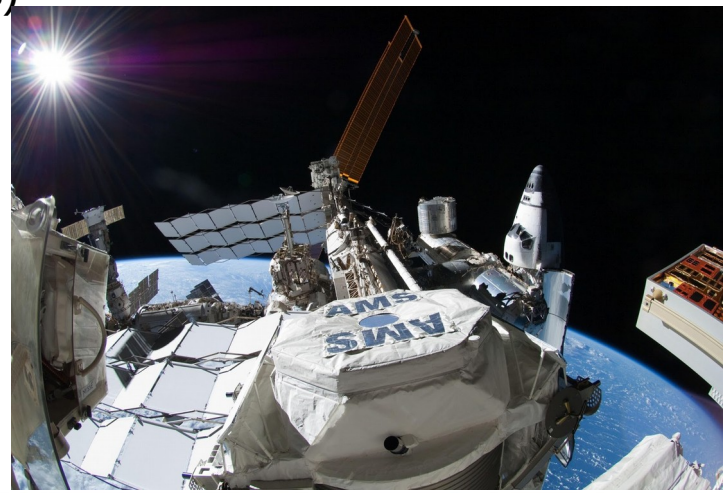
Natural antimatter in the Universe

Only natural positrons and antiprotons were detected in our Universe.

Till now no natural antinucleus was ever detected (and confirmed) in our Universe.

If a natural carbon antiatom were detected, it would prove that antistars exist !
(since carbon is only produced at the center of stars)

But if the same number of particles and antiparticles were produced during the Big Bang, where has antimatter gone since ? This constitutes one of the most challenging enigmas of contemporary physics.

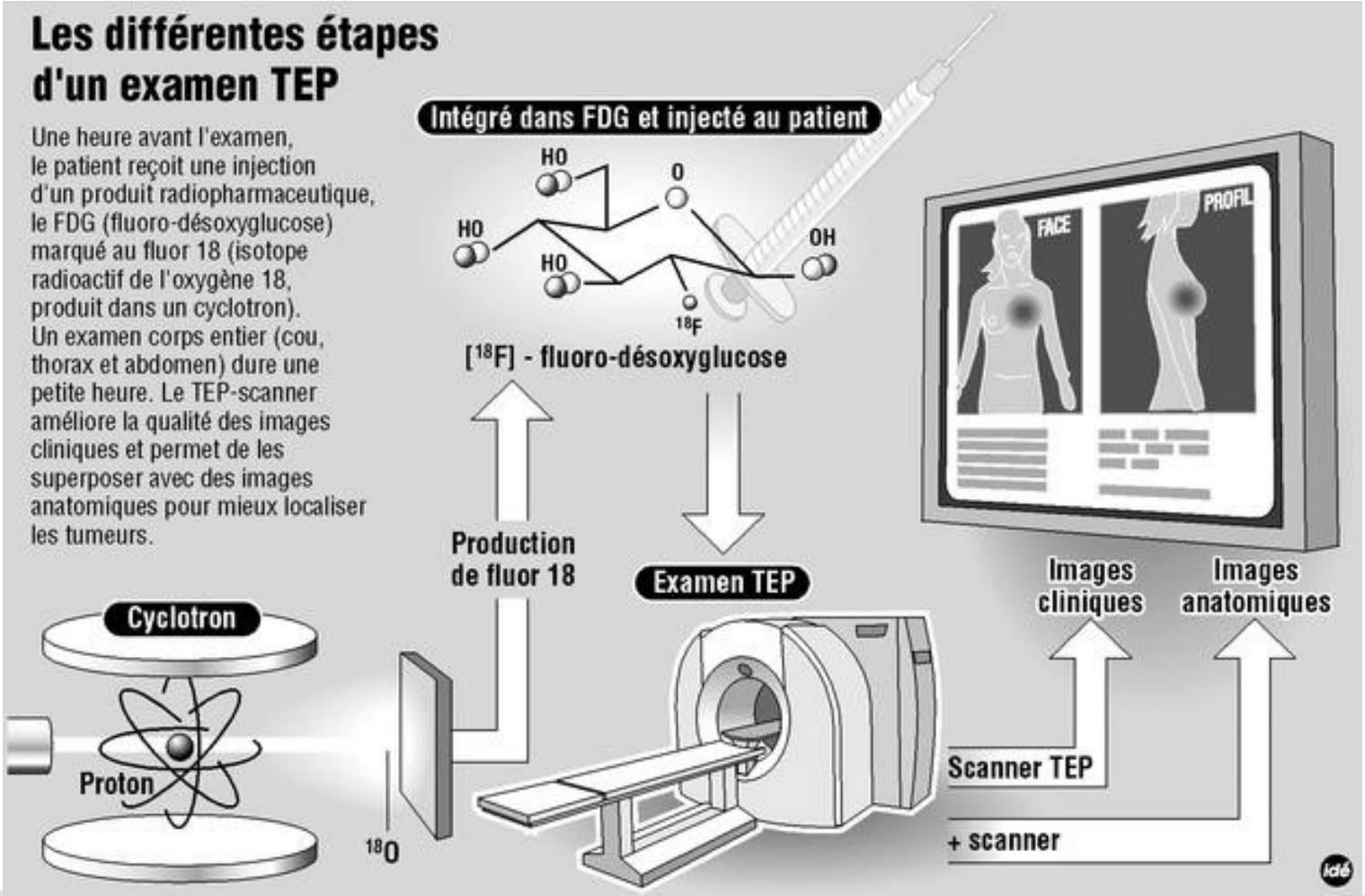


Antimatter in hospitals

Positron emission tomography : the concept

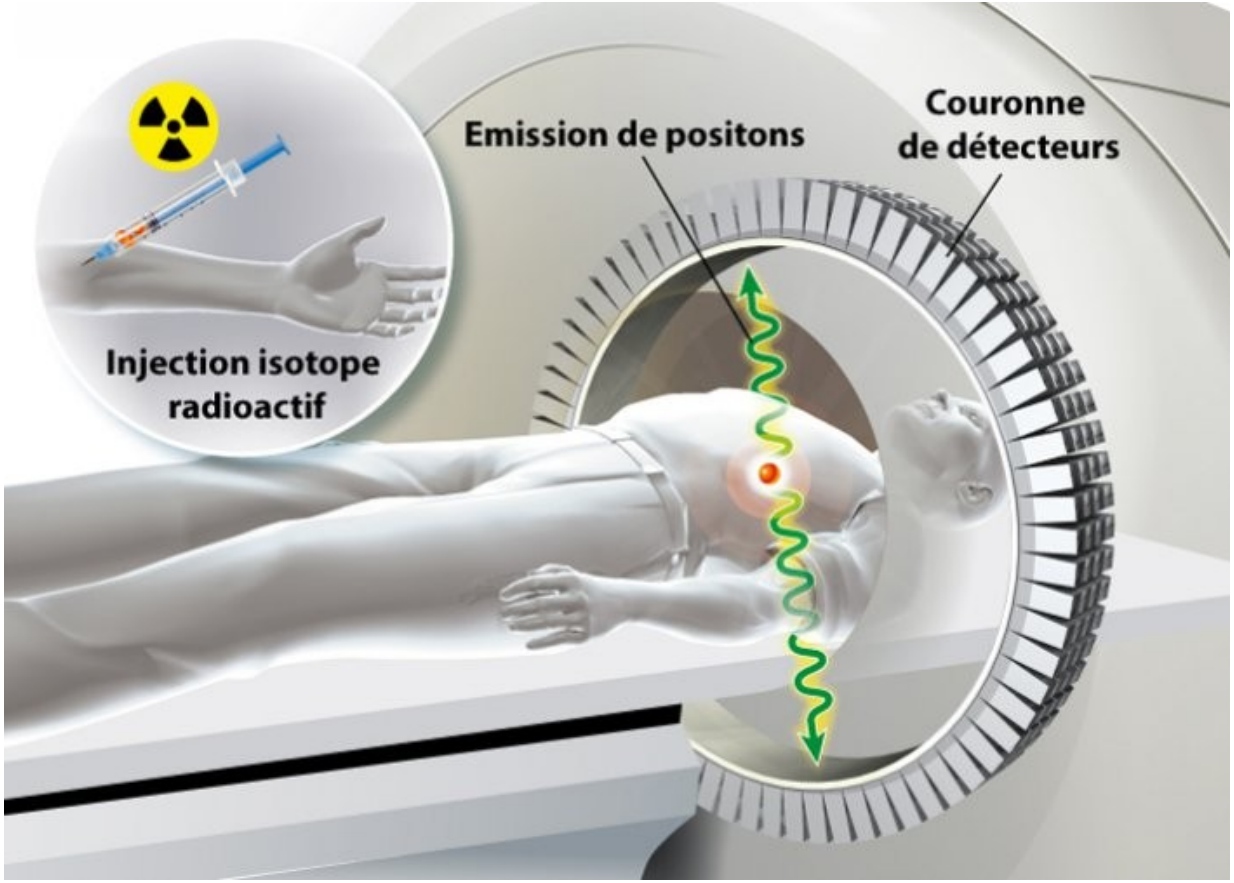
- Cancerous cells feature an exacerbated metabolism : they consume more glucose than healthy cells.
- Some glucose (FDG) is marked with fluorine 18 atoms that emit positrons with a half-life of 2h.
- ^{18}FDG is injected to the patient.
- A tumor more strongly metabolizes radioactive glucose. ^{18}F atoms get fixed to this tumor more than on other healthy tissues.
- Thanks to the detection of the annihilation gamma rays, one may image the metabolized glucose.
- A « hot » point on the image may signal a tumor.

Positron emission tomography



Positron emission tomography

150 TEP scanners
TEP in France for
500 000 medical
examinations per year !



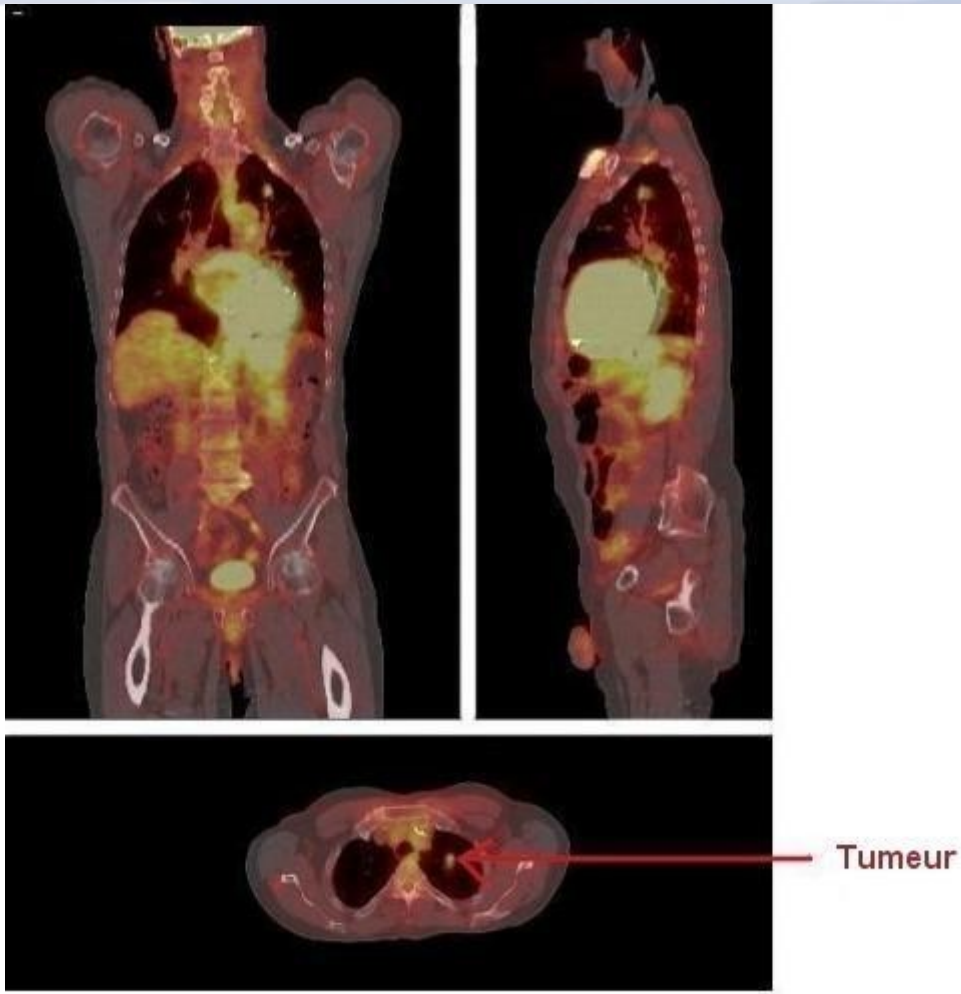


Image par Pet-scan - Cancer du poumon

Conclusion

- With time, all fundamental discoveries, albeit very abstract, lead to applications in many domains ....
- Antimatter discovered in 1932 does not escape the rule.
- Does antimatter feature the same properties as matter ?
- If yes, why doesn't antimatter seem to exist in our Universe in abundant amount ?
- The first articial antiatoms were produced at CERN in 1995 .
- Their ongoing study could unveil dissimilarities and help us elucidate why antimatter seems to have disappeared.