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PARTICLE PHYSICS 粒子物

BRIEF HISTORY OF ANTIMATTER FROM THE DISCOVERY TO RESEARCH AND APPLICATIONS

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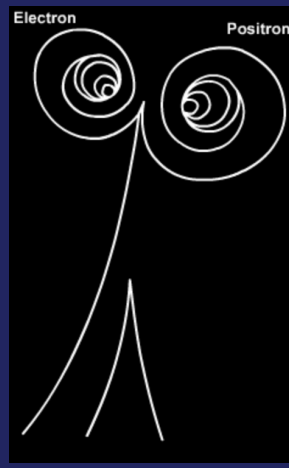

Track

A brief history of antimatter

- P.A.M. Dirak

- Andreson and Wilson's bubble chamber

- Big Bang and Standard model

- Cosmic rays & antimatter PAMELA a modern experiment and its results

- Dark Matter? Friz Zwiky and Vera Rubin

- Natural radioactivity, Antimatter & Positron Emission Tomography

From Galileo Galilei “Il Saggiatore”

Philosophy is written in the grand book
– I mean the universe –

which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written.

It is written in the language of mathematics, and its characters are triangles, circles and other geometrical figures, without which it is humanly impossible to understand a single word of it;
without these one is wandering about in a dark labyrinth.

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The Quantum Theory of the Electron.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 2, 1928.)

The new quantum mechanics, when applied to the problem of the structure of the atom with point-charge electrons, does not give results in agreement with experiment. The discrepancies consist of "duplexity" phenomena, the observed number of stationary states for an electron in an atom being twice the number given by the theory. To meet the difficulty, Goudsmit and Uhlenbeck have introduced the idea of an electron with a spin angular momentum of half a quantum and a magnetic moment of one Bohr magneton. This model for the electron has been fitted into the new mechanics by Pauli,* and Darwin,† working with an equivalent theory, has shown that it gives results in agreement with experiment for hydrogen-like spectra to the first order of accuracy.

The question remains as to why Nature should have chosen this particular model for the electron instead of being satisfied with the point-charge. One would like to find some incompleteness in the previous methods of applying quantum mechanics to the point-charge electron such that, when removed, the whole of the duplexity phenomena follow without arbitrary assumptions. In the present paper it is shown that this is the case, the incompleteness of the previous theories lying in their disagreement with relativity, or, alternatively, with the general transformation theory of quantum mechanics. It appears that the simplest Hamiltonian for a point-charge electron satisfying the requirements of both relativity and the general transformation theory leads to an explanation of all duplexity phenomena without further assumption. All the same there is a great deal of truth in the spinning electron model, at least as a first approximation. The most important failure of the model seems to be that the magnitude of the resultant orbital angular momentum of an electron moving in an orbit in a central field of force is not a constant, as the model leads one to expect.

* Pauli, 'Z. f. Physik,' vol. 43, p. 601 (1927).
† Darwin, 'Roy. Soc. Proc.,' A, vol. 116, p. 227 (1927).

The Quantum Theory of the Electron. Part II.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received February 2, 1928.)

In a previous paper by the author* it is shown that the general theory of quantum mechanics together with relativity require the wave equation for an electron moving in an arbitrary electromagnetic field of potentials, A_0, A_1, A_2, A_3 to be of the form

$$F\psi \equiv \left[p_0 + \frac{e}{c}A_0 + \alpha_1\left(p_1 + \frac{e}{c}A_1\right) + \alpha_2\left(p_2 + \frac{e}{c}A_2\right) + \alpha_3\left(p_3 + \frac{e}{c}A_3\right) + \alpha_4 mc\right]\psi = 0. \quad (1)$$

The α's are new dynamical variables which it is necessary to introduce in order to satisfy the conditions of the problem. They may be regarded as describing some internal motion of the electron, which for most purposes may be taken to be the spin of the electron postulated in previous theories. We shall call them the spin variables.

The α's must satisfy the conditions

$$\alpha_\mu^2 = 1, \qquad \alpha_\mu\alpha_\nu + \alpha_\nu\alpha_\mu = 0. \qquad (\mu \neq \nu.)$$

They may conveniently be expressed in terms of six variables ρ_1, ρ_2, ρ_3, σ_1, σ_2, σ_3 that satisfy

$$\left.\begin{aligned} &\rho_r^2 = 1, \quad \sigma_r^2 = 1, \quad \rho_r\sigma_s = \sigma_s\rho_r, \quad (r, s = 1, 2, 3) \\ \text{and} \quad &\rho_1\rho_2 = i\rho_3 = -\rho_2\rho_1, \quad \sigma_1\sigma_2 = i\sigma_3 = -\sigma_2\sigma_1 \end{aligned}\right\}, \quad (2)$$

together with the relations obtained from these by cyclic permutation of the suffixes, by means of the equations

$$\alpha_1 = \rho_1\sigma_1, \quad \alpha_2 = \rho_1\sigma_2, \quad \alpha_3 = \rho_1\sigma_3, \quad \alpha_4 = \rho_3.$$

The variables σ_1, σ_2, σ_3 now form the three components of a vector, which corresponds (apart from a constant factor) to the spin angular momentum vector that appears in Pauli's theory of the spinning electron. The ρ's and σ's vary with the time, like other dynamical variables. Their equations of motion, written in the Poisson Bracket notation [ ], are

$$\dot{\rho}_r = c\,[\rho_r, F], \qquad \dot{\sigma}_r = c\,[\sigma_r, F].$$

* 'Roy. Soc. Proc.,' A, vol. 117, p. 610 (1928). This is referred to later by *loc. cit.*

P.A.M. Dirac

Two articles February and March 1928

What are quantum waves capable of describing electrons? And what are the wave equations that govern the dynamics of these equations by satisfying the conditions of relativity and capable of giving reasonable predictions of physics?

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

Dirac e Schroedinger shared the Nobel Prize for Physics in 1933

Erwin Schrödinger
Prize share: 1/2

Paul Adrien Maurice
Prize share: 1/2

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Dirac's papers on the quantum theory of the electron were published in the *Proceedings of the Royal Society (London) A* in 1928.

Any solution of the equation where the electron had a positive energy had a counterpart where the energy was negative.

It gradually became clear that *these counterpart solutions could be interpreted as representing a new particle*, similar to the electron but *with positive rather than negative* charge; *Dirac called it an "anti-electron"*, but it soon came to be known as the positron.

If an electron encounters a positron, Dirac predicted, *the two charges cancel and the pair annihilates, with the combined mass transforming into radiation in the most dramatic expression of Einstein's celebrated equation* $E = mc^2$.

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Since, however, no such particles had been found Dirac formulated the hypothesis that it might be that in other parts of the universe positive and negative charge were reversed.

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Thus was antimatter predicted!!

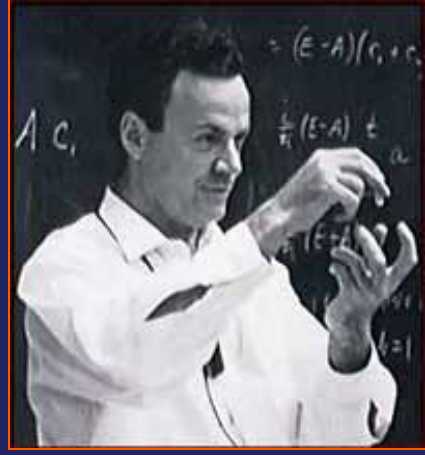
Quantum mechanics is one of the major revolutions in 20th century Physics.

It is probably the closest science has come to a fundamental description of the underlying nature of reality.

And yet it is totally bizarre it is against all our intuition and common sense.

In 1928 Paul Dirac, introduces a relativistic and quantum description of the electron which also implies negative energy states that appear as particles with inverse quantum numbers to the "normal" matter

(Proc. R. Soc. London, A, 117, (1928), 610)

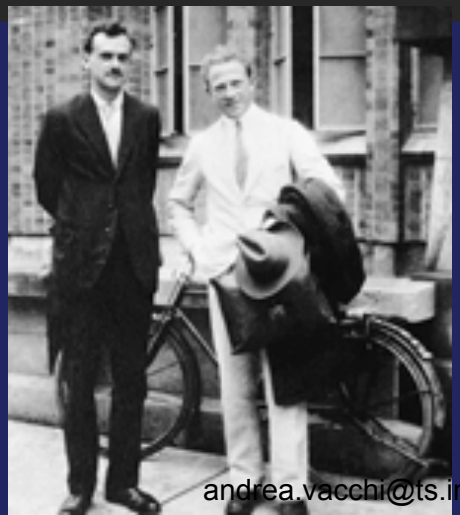


$$(i\gamma\cdot\partial - m)\psi = 0$$

- In 1932 Anderson in the USA makes an exemplary discovery linked to the study of cosmic rays is the ANTIELELTRTRON OR POSITRON;
- and immediately afterwards also Blacket and Occhialini in Cambridge proved that the swarms produced by cosmic rays contain positive electrons.

"I think this discovery of antimatter was, perhaps, the greatest leap in the great leaps in the physics of our century"

Heisemberg 1972



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Paul Dirac equation combined quantum mechanics and Einstein's Special relativity to describe the behavior of an electron moving at a relativistic speed. The equation which won him the Nobel Prize in 1933 and posed a problem.

$$(\beta mc^2 + c\vec{\alpha}.\vec{p})\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t}$$

m *is the rest mass of the electron,*

c *is the speed of light,*

p *is a momentum operator as described by Schrodinger wave mechanics,*

ψ (x,t) *is a Space time wave function,*

ħ *is a reduced planck constant.*

Dirac's equation could have two solutions, one for an electron with positive energy, and one for an electron with negative energy. But classical physics and our common sense prescribed that the energy of a particle must always be a positive number.

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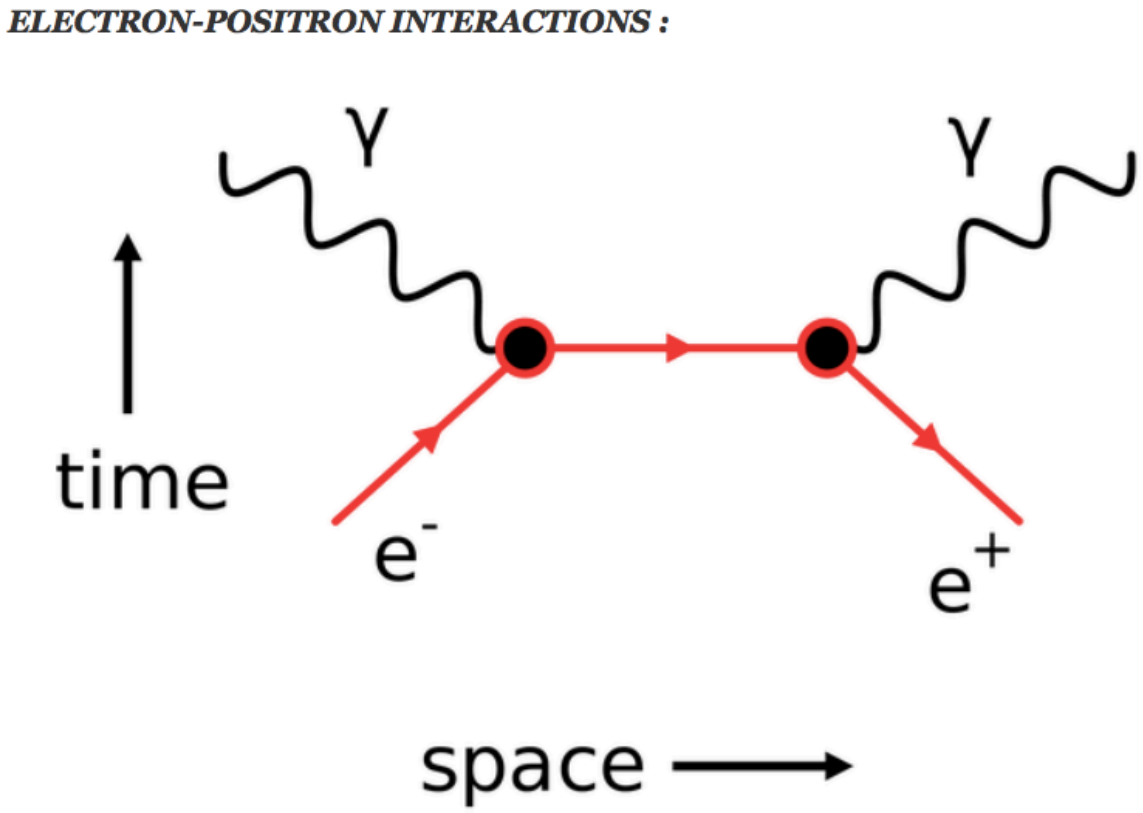
Dirac interpreted the equation to mean that for every particle there exists a corresponding antiparticle, exactly matching the particle but with opposite charge.



Dirac was a student at Bristol University between 1918 and 1923, first in electrical engineering and then in applied mathematics. Much later, he said:

"I owe a lot to my engineering training because it [taught] me to tolerate approximations. Previously to that I thought...one should just concentrate on exact equations all the time. Then I got the idea that in the actual world all our equations are only approximate. We must just tend to greater and greater accuracy.

In spite of the equations being approximate, they can be beautiful."

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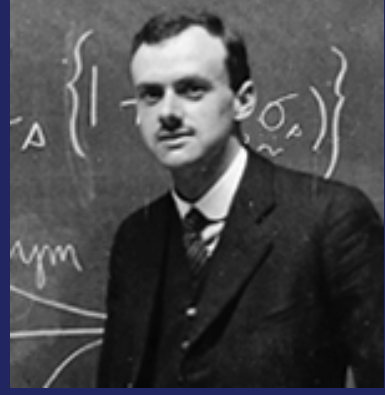
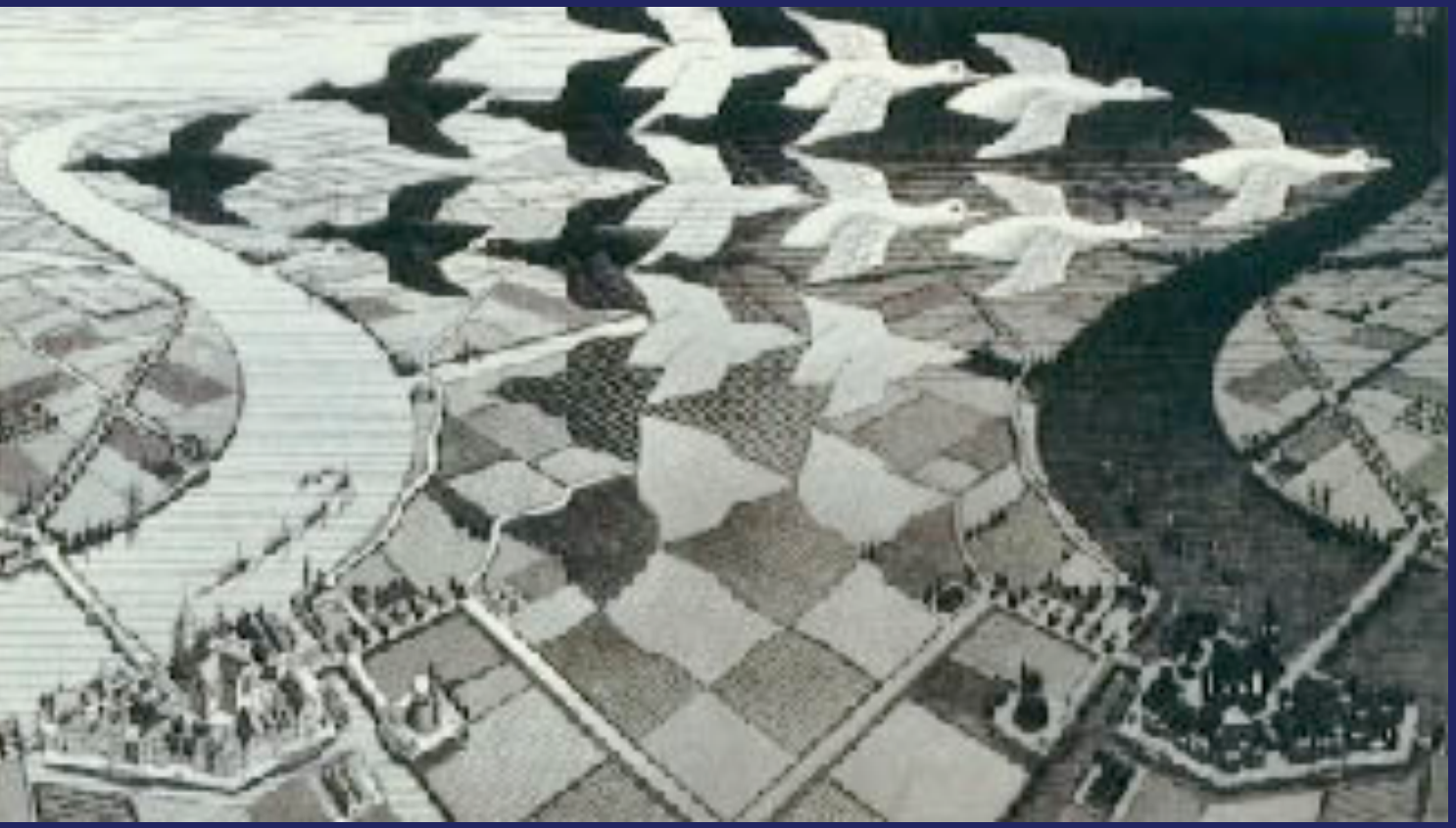
"A great deal of my work is just playing with equations and seeing what they give."

Paul Dirac pubblicò il primo dei suoi lavori novanta anni fa nel 1928.

"The Quantum Theory of the Electron"





"...we must just tend to greater and greater accuracy. In spite of the equations being approximate, they can be beautiful."

negative energy states that appear as particles with inverse quantum numbers to the "normal" matter

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In fact, at roughly the same time that quantum mechanics first began to suggest that *very small* things defy our intuition,

Einstein was proposing his special theory of relativity which shows that *very fast* things defy our intuition;

and then his general theory of relativity, which concerns the odd behavior of *very big* things.

It seems that, more and more, the only way to understand the world is to apply the math.

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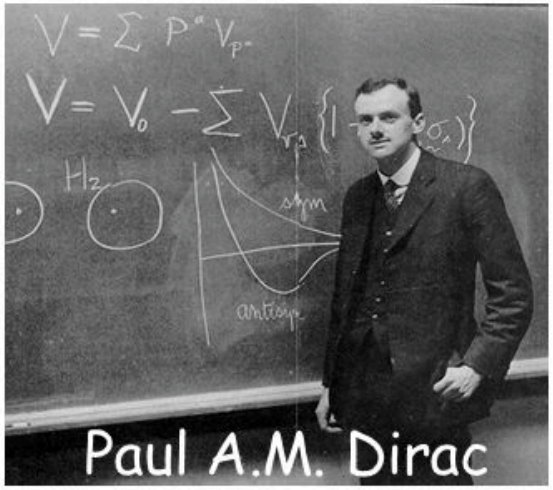
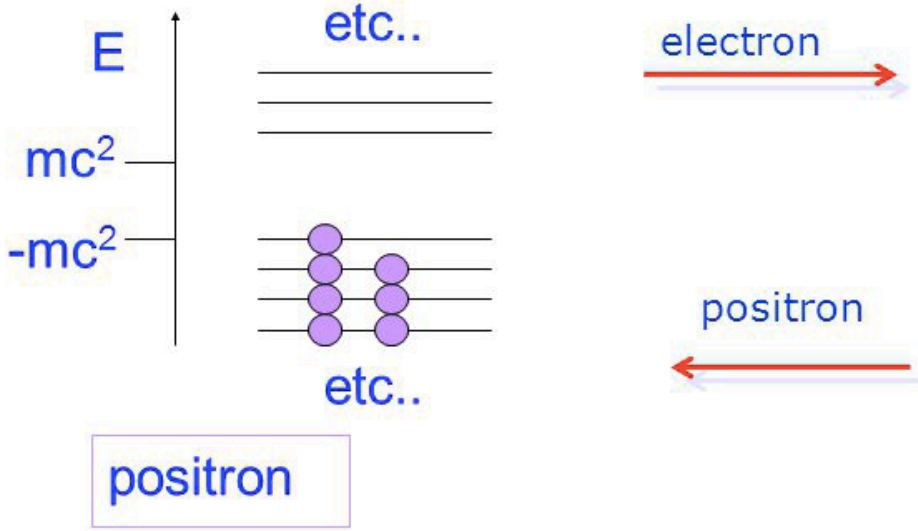
Antiparticles – Interpretation of negative energy solutions



- **Dirac**:
  in terms of 'holes' like in semiconductors
- **Feynman & Stückelberg**:
  as particles traveling backwards in time,
  equivalent to antiparticles traveling forward in time

- **both lead to the prediction of antiparticles !**



Dirac's interpretation: the vacuum corresponds to all the negative energy states that are full, with the Pauli exclusion principle that prevents electrons from falling into negative energy states. The holes in the negative energy states correspond to the anti-particles of positive energy with opposite charge. Provides an image for torque production and annihilation.

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Covariant Notation: the Dirac γ Matrices

- The Dirac equation can be written more elegantly by introducing the four Dirac gamma matrices:

$$\gamma^0 \equiv \beta;\ \ \gamma^1 \equiv \beta\alpha_x;\ \ \gamma^2 \equiv \beta\alpha_y;\ \ \gamma^3 \equiv \beta\alpha_z$$

Premultiply the Dirac equation by β

$$i\beta\alpha_x\frac{\partial\psi}{\partial x} + i\beta\alpha_y\frac{\partial\psi}{\partial y} + i\beta\alpha_z\frac{\partial\psi}{\partial z} - \beta^2 m\psi = -i\beta\frac{\partial\psi}{\partial t}$$

$$i\gamma^1\frac{\partial\psi}{\partial x} + i\gamma^2\frac{\partial\psi}{\partial y} + i\gamma^3\frac{\partial\psi}{\partial z} - m\psi = -i\gamma^0\frac{\partial\psi}{\partial t}$$

using $\partial_\mu = \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$ this can be written compactly as:

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

★ NOTE: it is important to realise that the Dirac gamma matrices are <u>not</u> four-vectors - they are constant matrices which remain invariant under a Lorentz transformation. However it can be shown that the Dirac equation is itself Lorentz covariant

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Theoretical Physicists

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a little like in the movies of terror Nosferatu of Murnau

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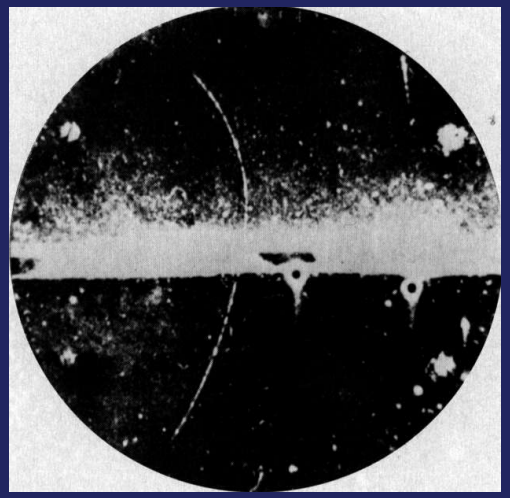
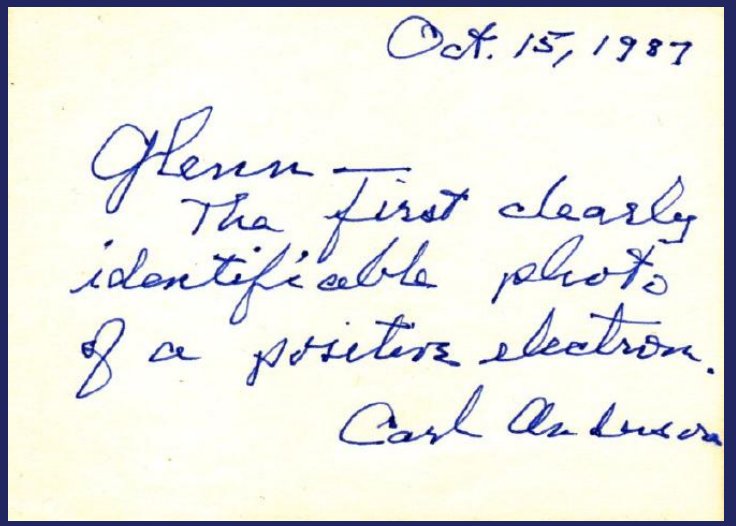
On August 2, 1932, during the course of photographing cosmic-ray tracks produced in a vertical Willson chamber (magnetic field of 15,000 gauss) designed in the summer of 1930 by Professor R. A. Millikan and the writer, the tracks shown in Fig. 1 were obtained, which seemed to be interpretable only on the basis of the existence in this case of a particle carrying a positive charge but having a mass of the same order of magnitude as that normally possessed by a free negative electron.





..It is concluded, therefore, that the magnitude of the charge of the positive electron which we shall henceforth contract to positron is very probably equal to that of a free negative electron which from symmetry considerations would naturally be called a negatron." -Carl Anderson

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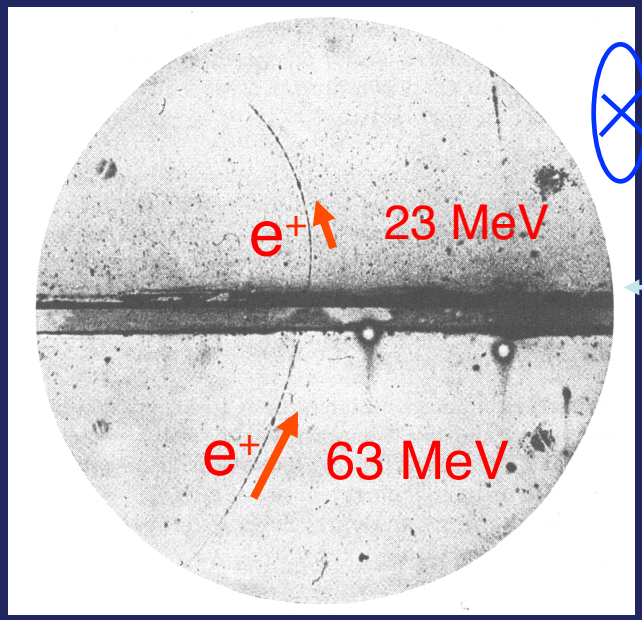
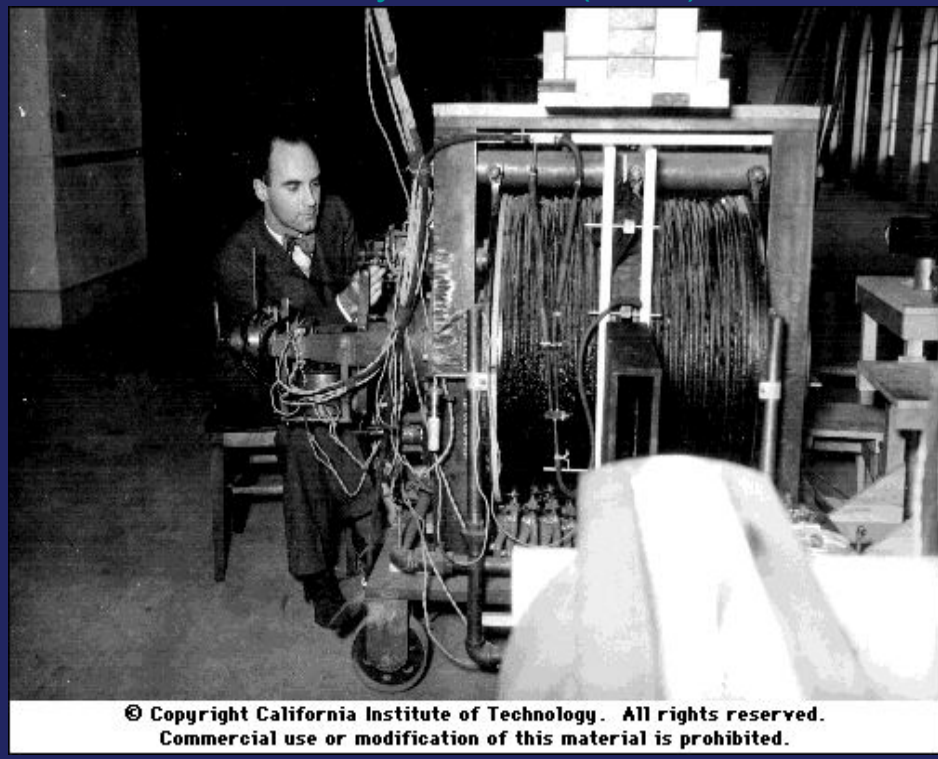
Discovery of the Positron

★Cosmic ray track in cloud chamber:



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



- e^+ enters at bottom, slows down in the lead plate – know direction
- Curvature in B-field shows that it is a positive particle
- Can't be a proton as would have stopped in the lead

Provided Verification of Predictions of Dirac Equation

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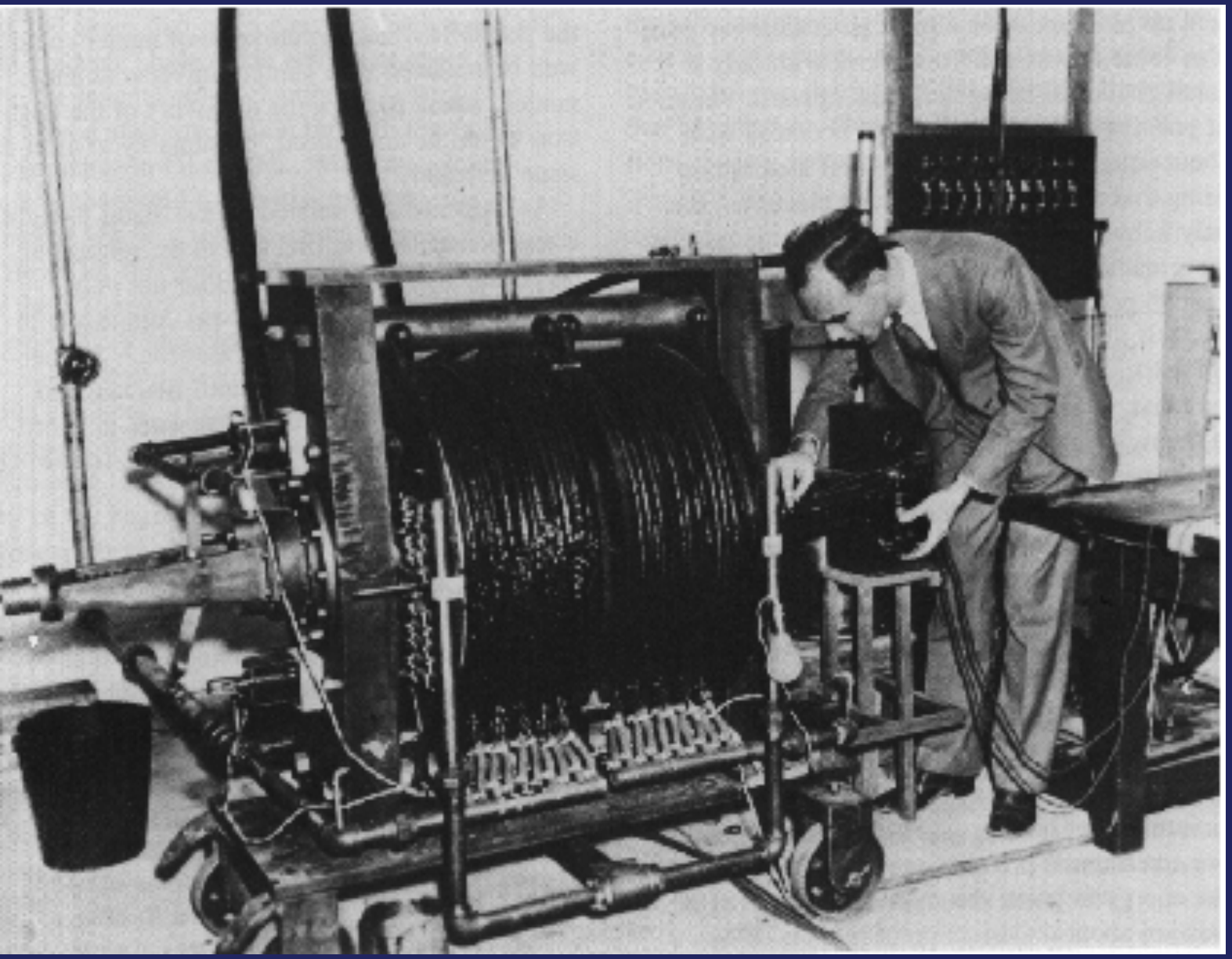
CD. Anderson and the bubble chamber? ????



In order to study subatomic particles you need a method of detecting them. Over the years physicists have developed devices that can show the presence of particles and reveal their properties by the tracks that they leave.

- Two of the most important early detecting devices were **cloud** and **bubble chambers**.
- In modern high-energy research these devices are now obsolete. Spark and drift chambers are used as faster alternatives.

All of these devices work on a common principle:

- **charged** particles that pass through leave a path of detectable **ionised** particles.
- The technical details of each detector are slightly different but this principle is true nonetheless.

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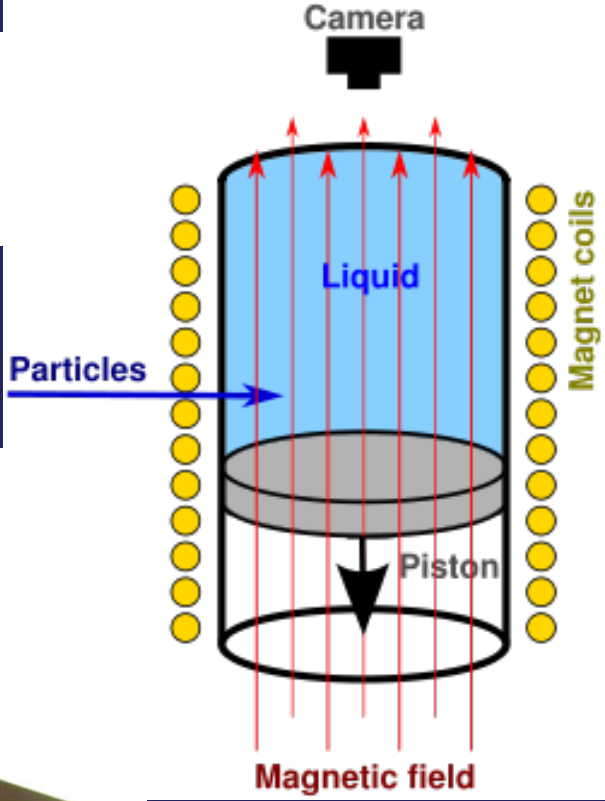
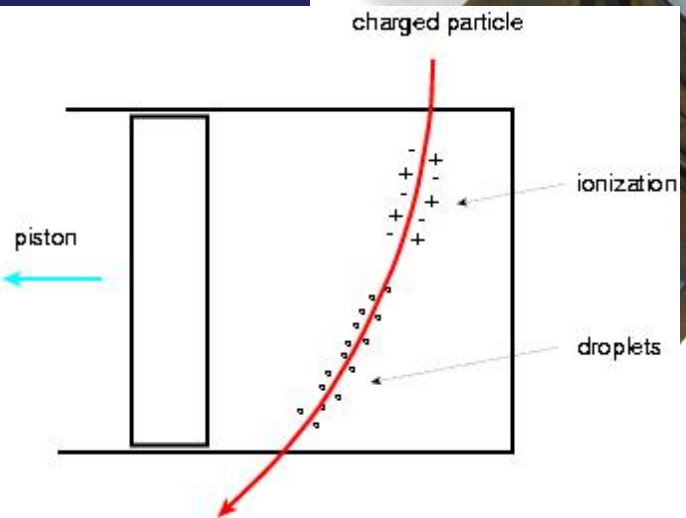
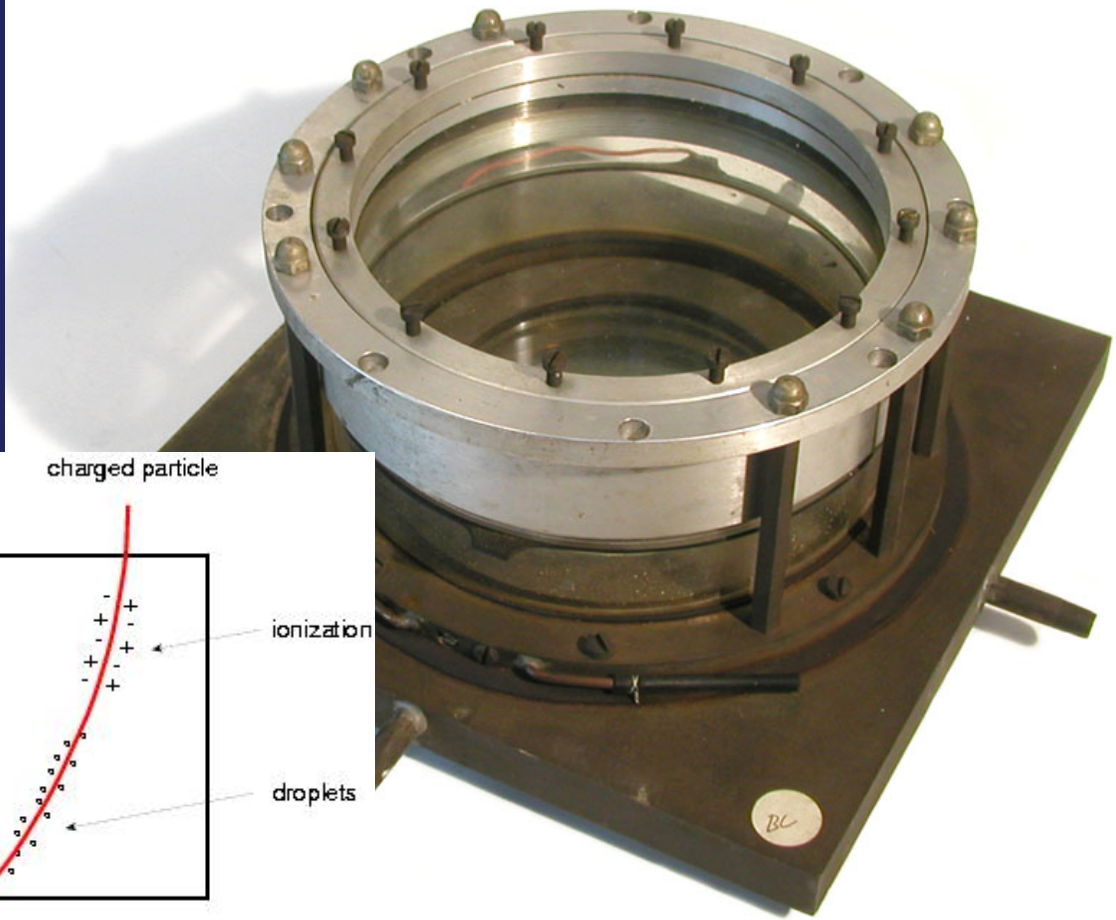
Charles Wilson

Nobel con Compton 1927







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The **bubble chamber** was the main tool for research in the 1950s and 60s. In consists of a tank of superheated liquid hydrogen kept just on the verge of boiling. When a particle moves through it can cause ions in the hydrogen around which tiny bubbles form. The tank is kept in a strong **magnetic field** so charged particles follow **curved** paths.

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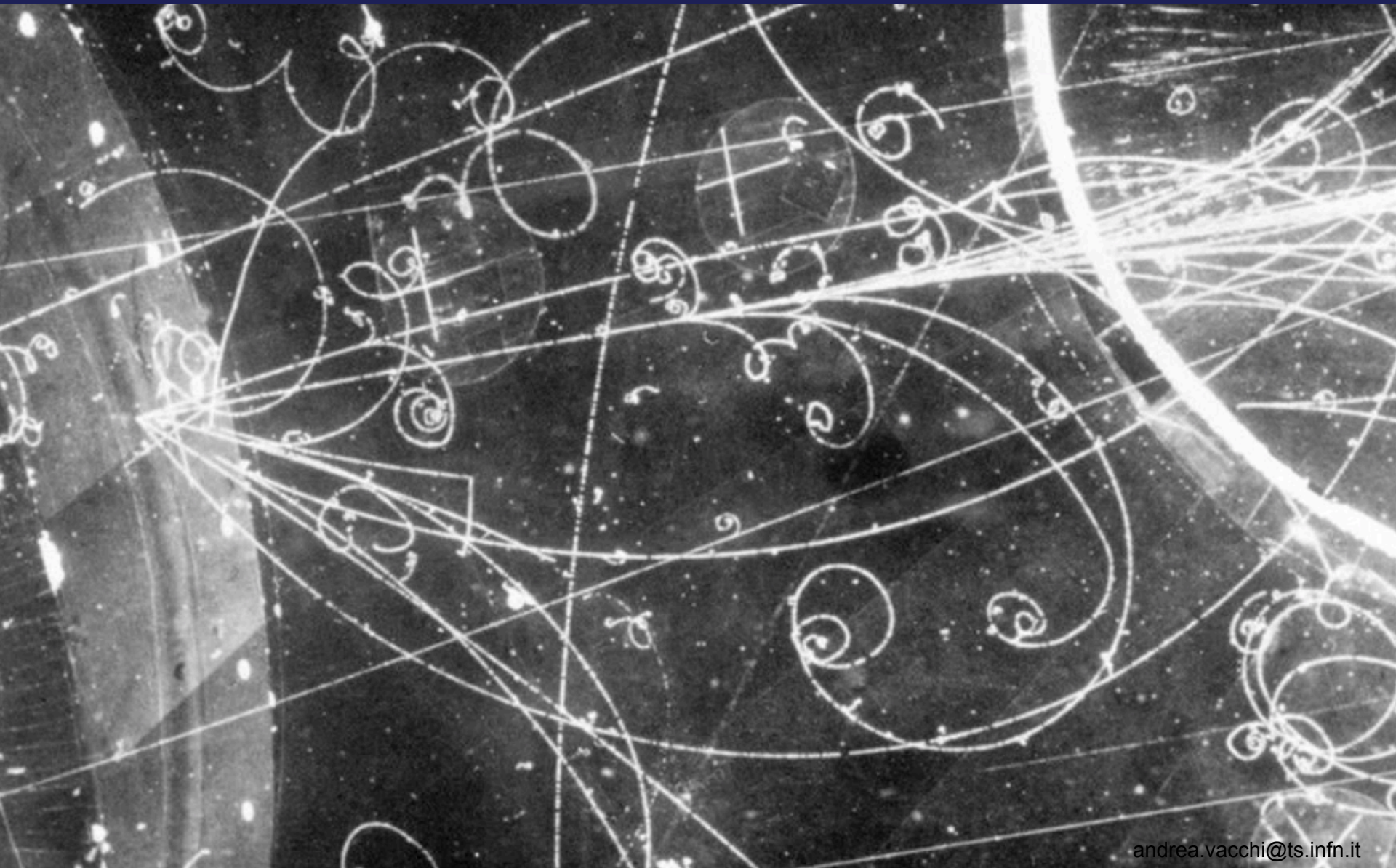
High-energy collisions of particles can create matter-antimatter pairs or photons, while matter-antimatter pairs annihilate to produce photons as well, as these bubble chamber tracks show. But what determines whether a particle is matter or antimatter? Image credit: Fermilab.



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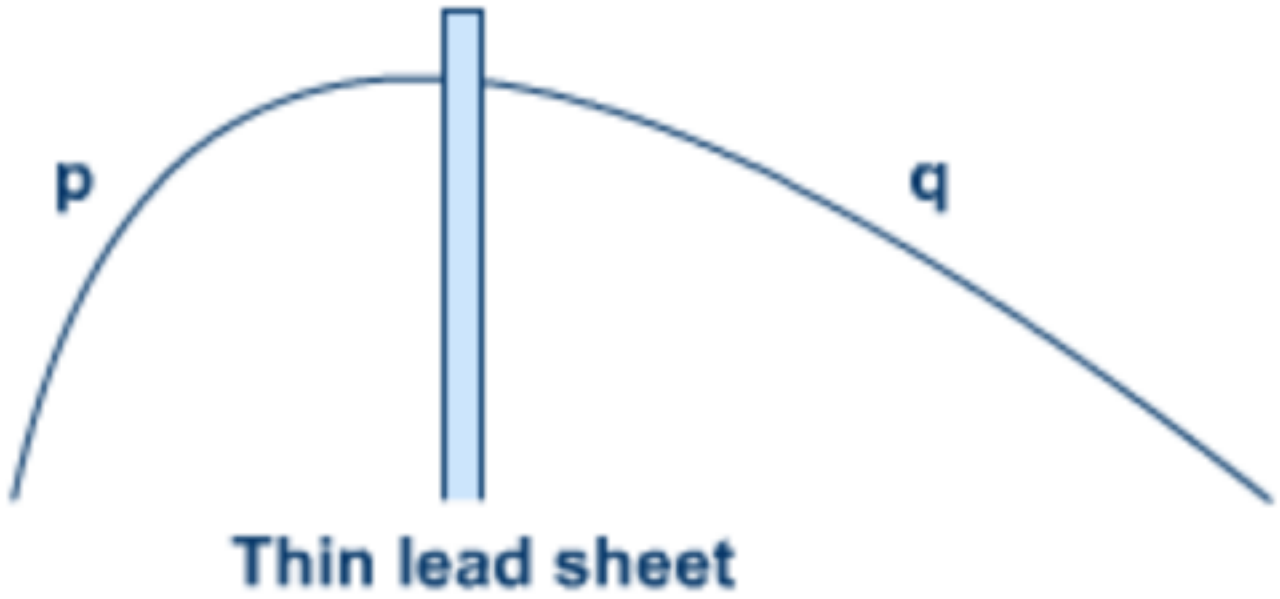

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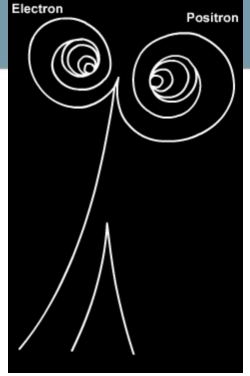

The pathways left in the detectors above are complex to analyse but much information can be gleaned by noticing a few simple points about particle paths within a magnetic field:

- The momentum of particle is proportional to the radius of its track. If the field is directed into the paper, negative particles curve clockwise; positive particles curve anticlockwise.
- Neutral particles do not leave tracks because they produce very little ionisation. They travel in straight lines and their paths can often be inferred from the presence of gaps between visible tracks. It is possible to determine their momentum by applying the principle of conservation of mometum.
- The two spiralling tracks in this bubble-chamber diagram were made by an electron and a positron. These particles were created by a high-energy gamma ray in a collision with the electron of a hydrogen atom in the bubble chamber. The long slightly curved downward track was made by the recoiling electron.

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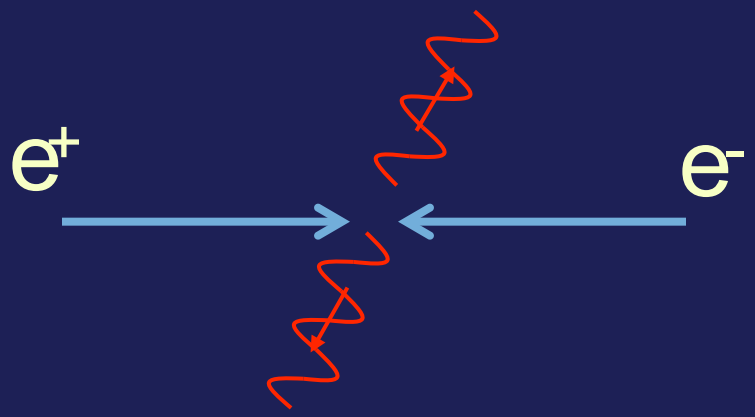
$E = mc^2$



Electrons and positrons annihilate to produce gamma rays => energy

Not only is it true for electrons and positrons, it also occurs for quarks and anti-quarks and more complicated objects such as protons and anti-protons.
You'd be in trouble if you met your anti-you.
However; only in 1996 was the anti-hydrogen, the simplest anti-atom, been produced.

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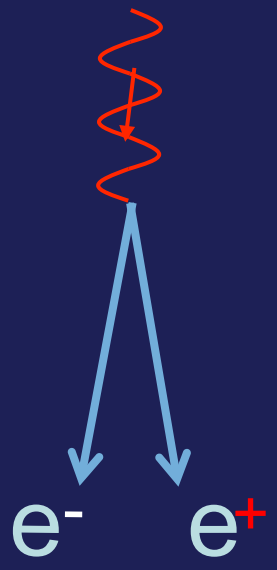
Pair production e^+e^-

The inverse process also occurs, rays g having sufficient energy become electron - positron pairs



The inverse to the annihilation process also occurs and γ-rays with sufficient energy can convert to matter and antimatter.

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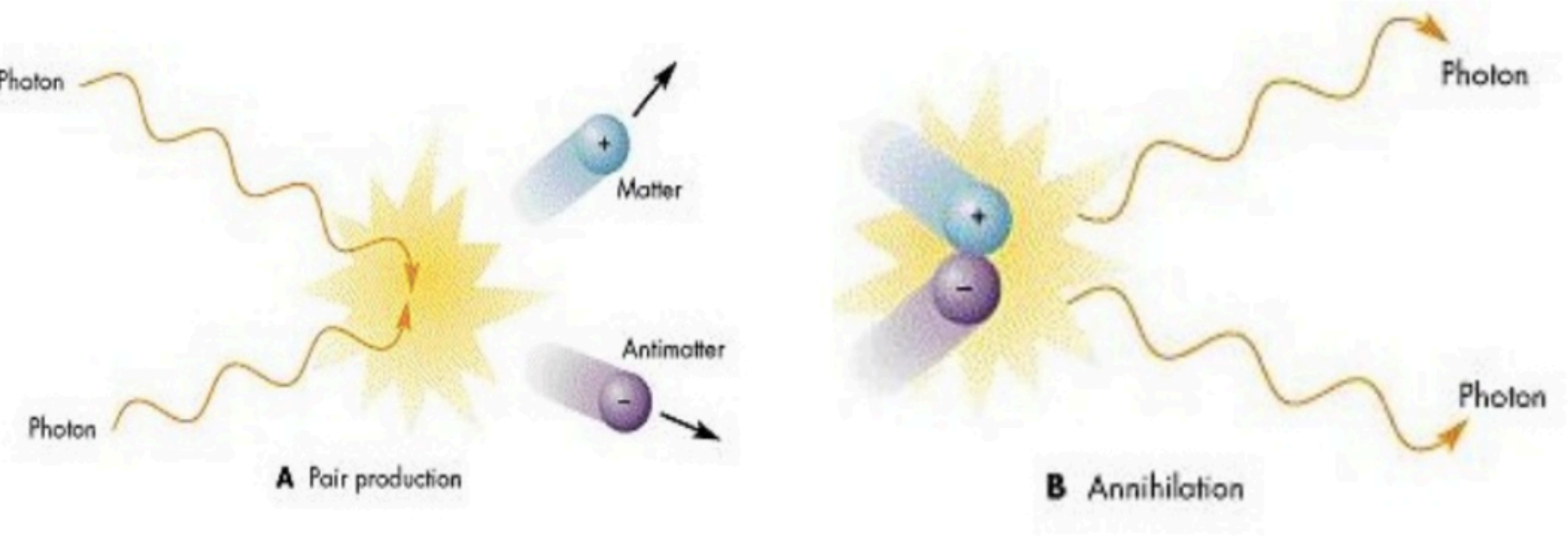
Pair Producion and annihilation



- **Pair Production:** When the photon with energy in excess of 1.02 MeV passes close to the nucleus of an atom, the photon disappears, and a positron and an electron appear.

- **Annihilation:** These two particles collide, converting to 2 photons with equal energy of 511 kev.

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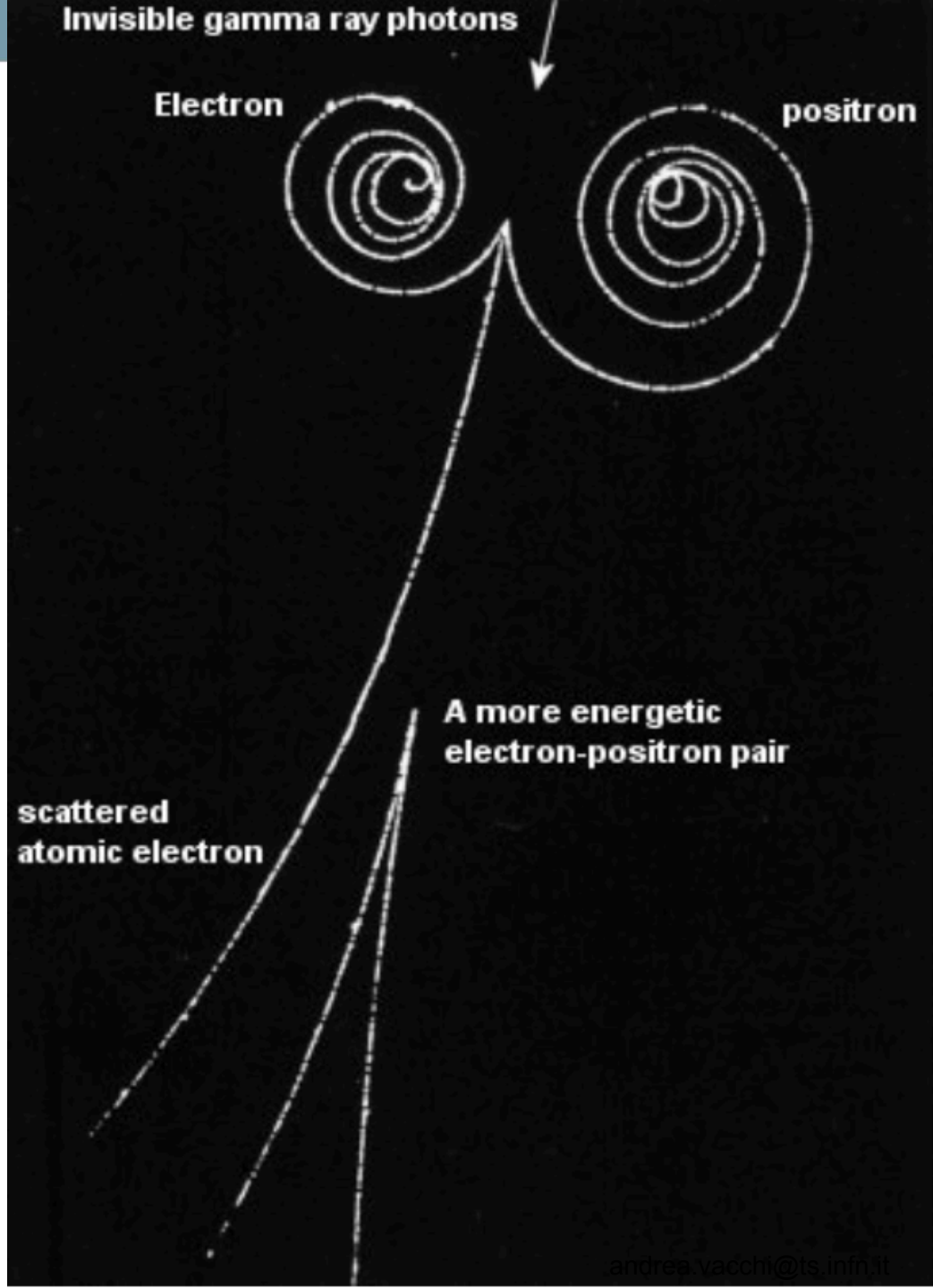
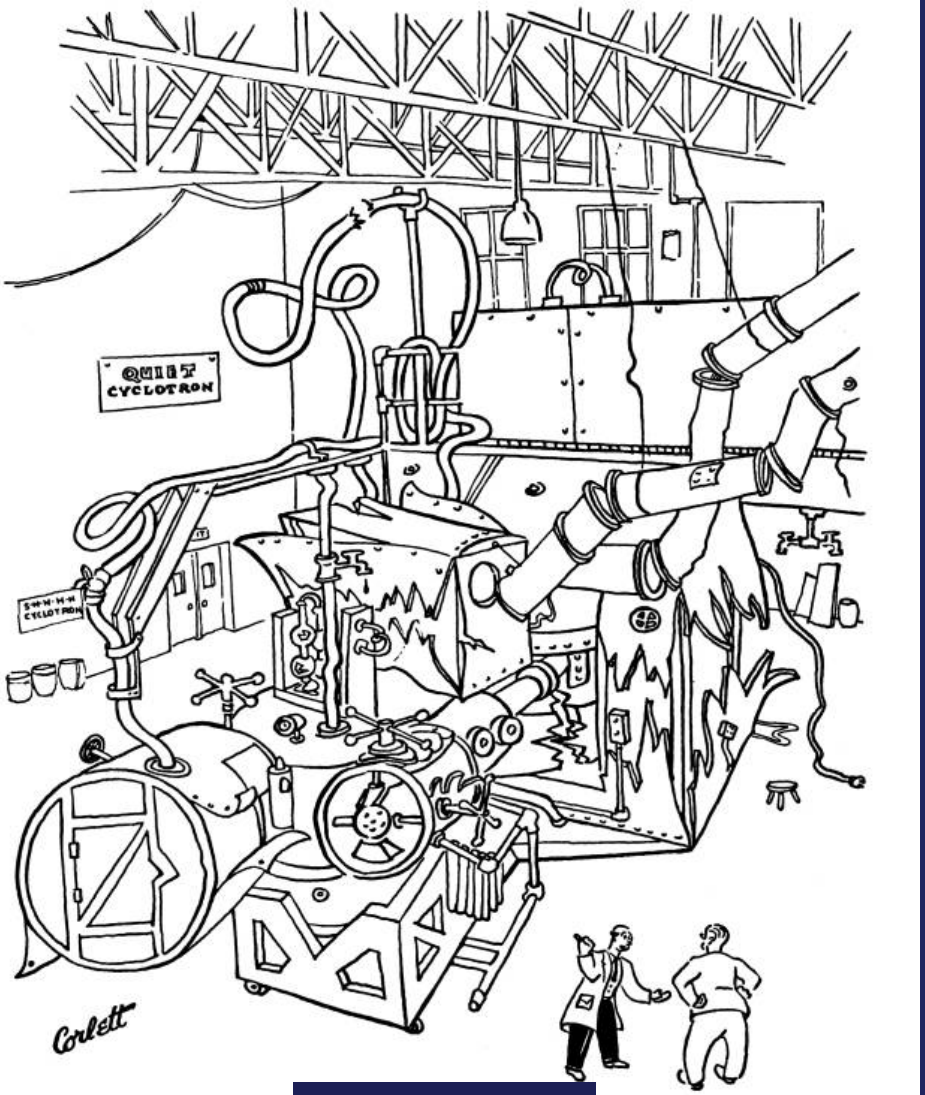
The two spiralling tracks in this bubble-chamber diagram were made by an electron and a positron. These particles were created by a high-energy gamma ray in a collision with the electron of a hydrogen atom in the bubble chamber. The long slightly curved downward track was made by the recoiling electron.



The first particle accelerators

"E. O. Lawrence was a pathfinder not just for Lawrence Livermore and Berkeley laboratories. He created the model for large-scale science throughout the world."

—Bruce Tarter



The toughest atom I ever saw

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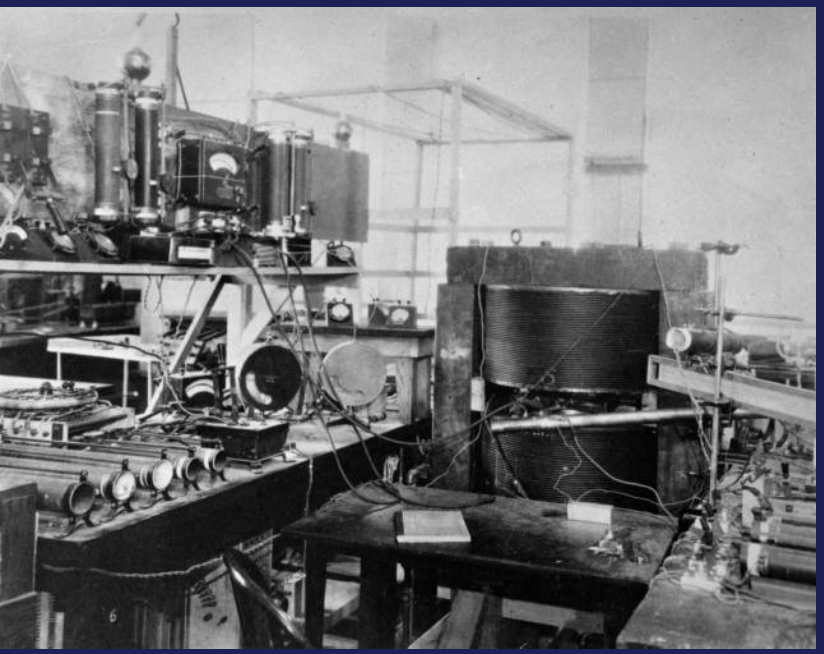
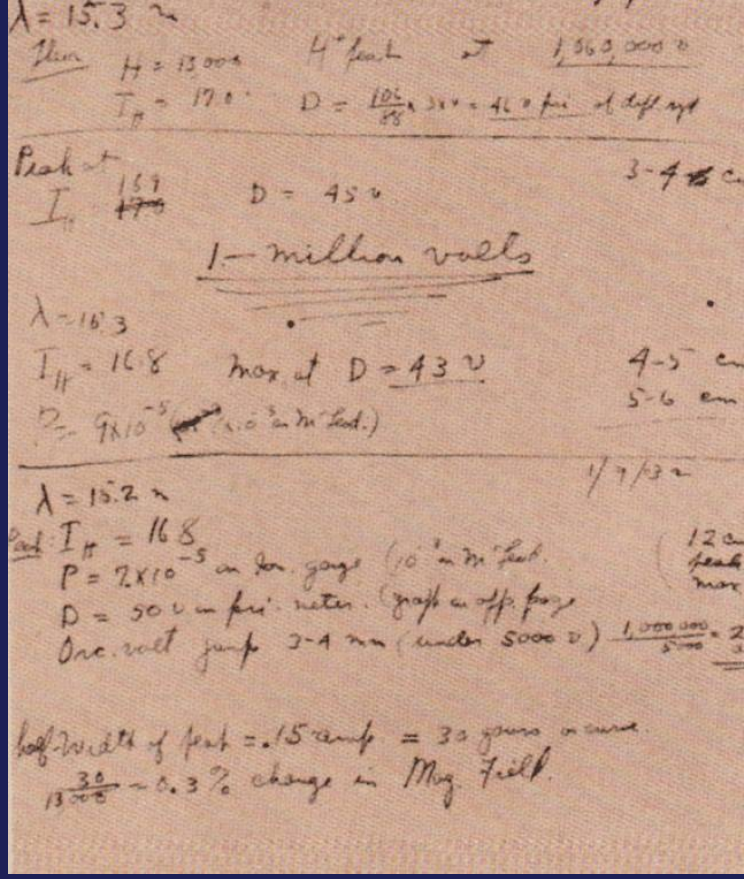
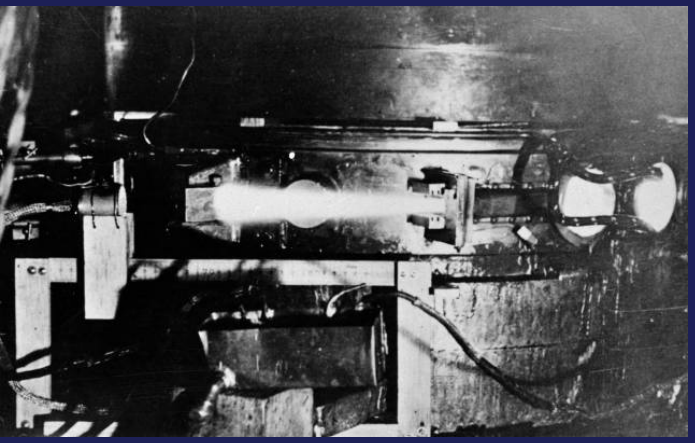
First accelerators





The 11-inch cyclotron accelerated up to 1 million electronvolts



."letizia". "joy". The first proton-antiproton annihilation star (an event nicknamed "Letizia") found by Roman physicists in November 1955 in one of the emulsions exposed in August preceding the Bevatron proton beam in Berkeley, as part of the collaboration between the research groups by Edoardo Amaldi and Emilio Segrè.

O. Chamberlain, W. W. Chupp, G. Goldhaber, E. Segrè and C. Wiegand - *Berkeley*
E. Amaldi, G. Baroni, C. Castagnoli, C. Franzinetti and A. Manfredini - *Rome*

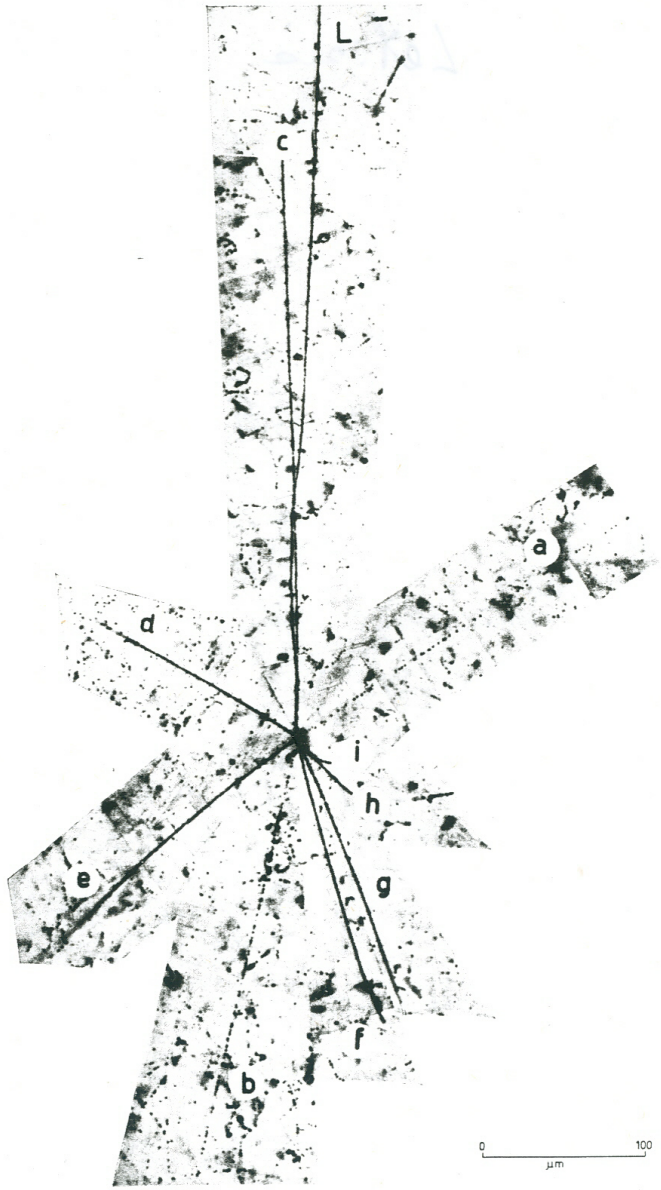
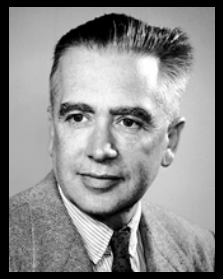


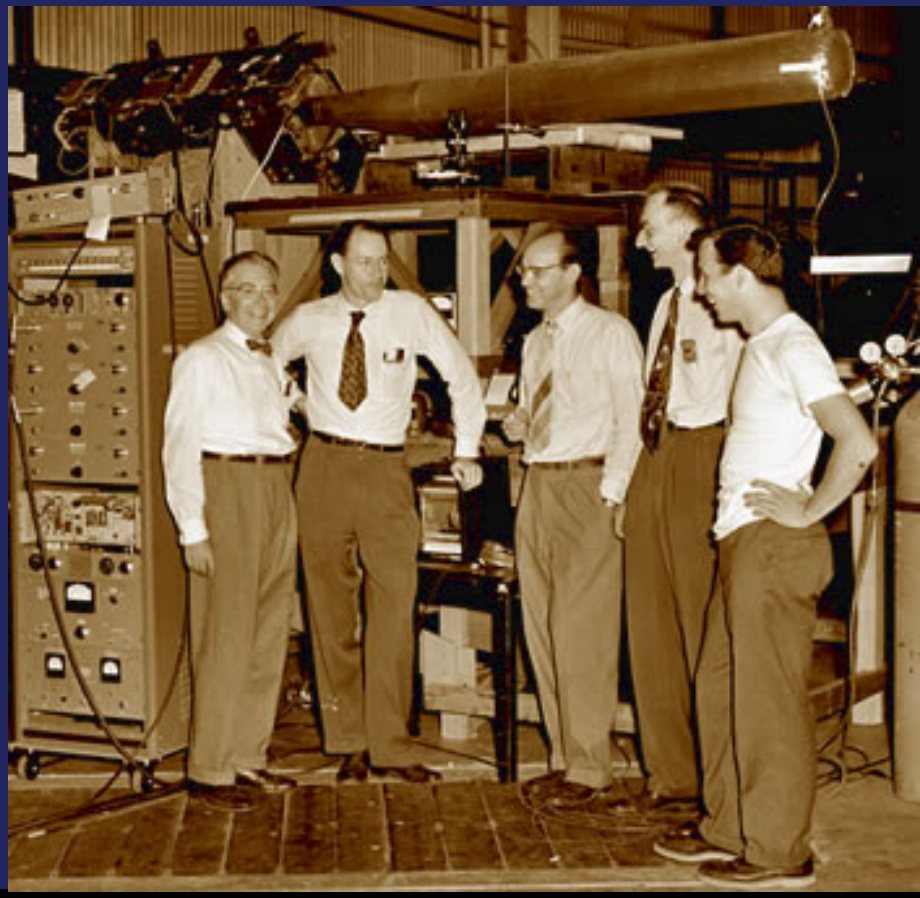
Fig. 6. – The star. *L* indicates the incoming antiproton track. Tracks *a* and *b* are pions, and *c* is a proton. The remaining tracks could be protons or α-particles.

AT THE BEVATRON ACCELERATOR IN 1955
THE DISCOVERY OF THE ANTIPROTON
SEGRÈ, CHAMBERLAIN, WIEGAND, YPSILANTIS

That there should exist a particle of mass equal to the proton but of negative charge, and that this particle was indeed an antiproton (ie capable of annihilating in the encounter with a proton, similarly to what was known to happen between an electron and a positron) it was a conjecture suggested by the possibility of extending Dirac's theory even to heavy particles



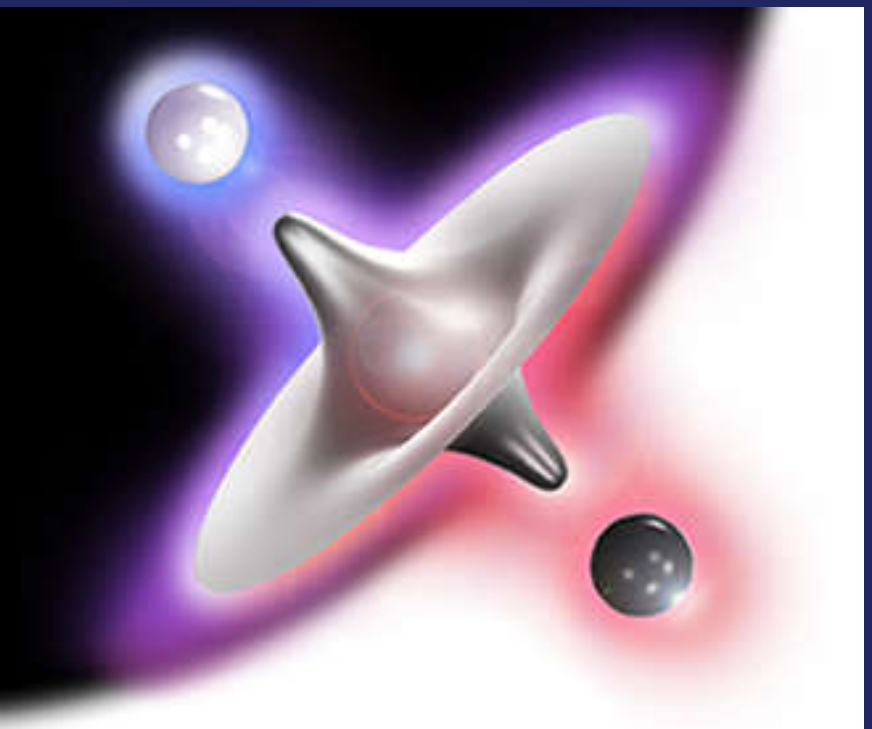
Emilio Segrè Nobel1959



Produce and detect antiprotons in quantity, artificially creating proton-antiproton pairs in the collisions between the proton beam produced by the accelerator and a fixed target. Bevatron (accelerated protons up to 6 GeV) had been designed by the Lawrence group with enough energy to produce proton pairs of antiproton

When we print a coin from a metal profile, we get our coin and the hole in the profile.

This hole we could call it anticoin!



This is the case when energy becomes matter. The experiments show that only pairs formed by a particle and its mirror image called antiparticle are produced.

The particle or antiparticle production alone does not occur.

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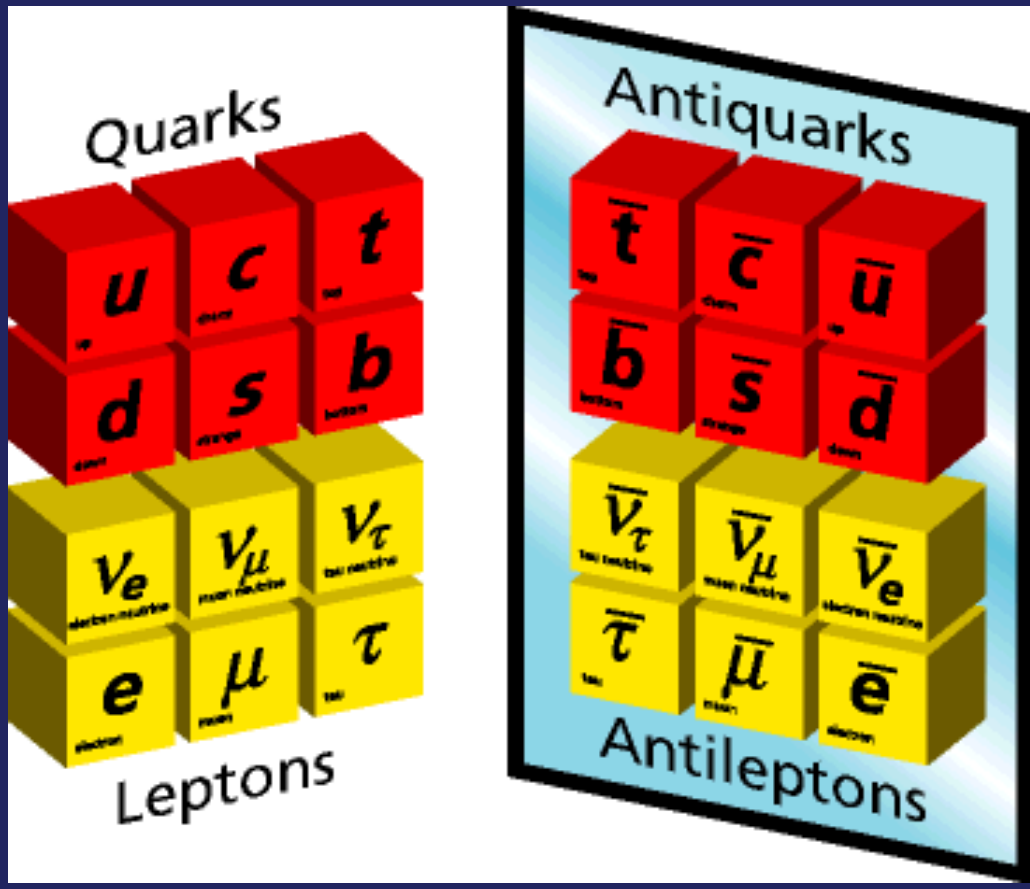
STANDARD MODEL describes the fundamental structure of matter



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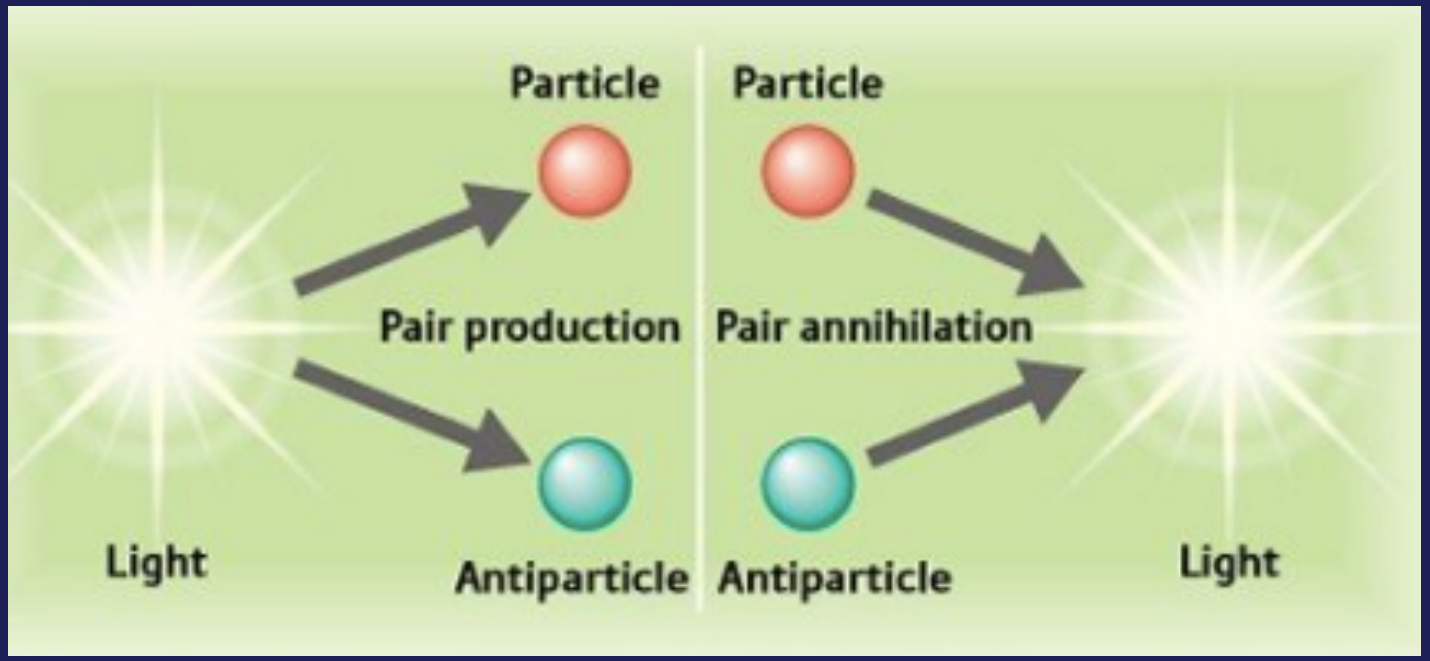

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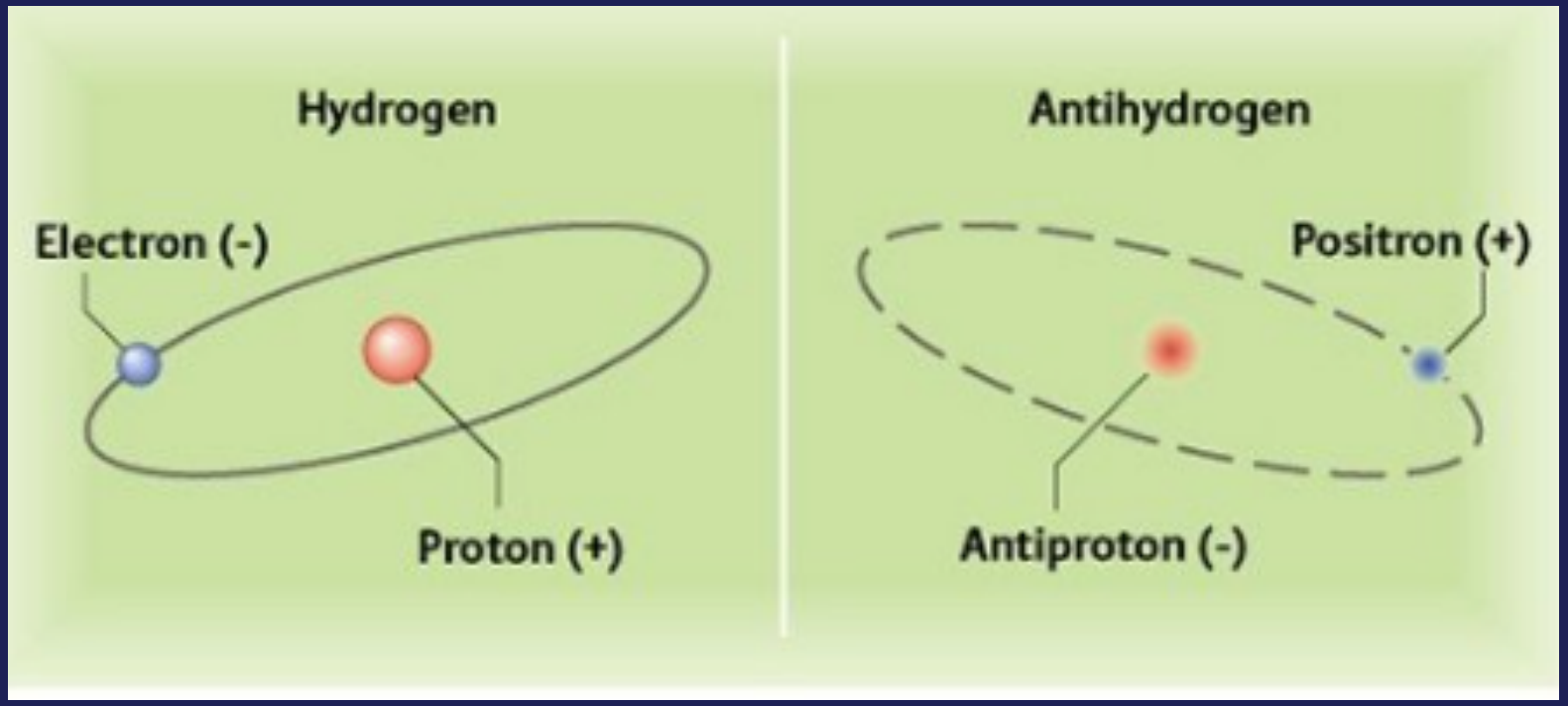

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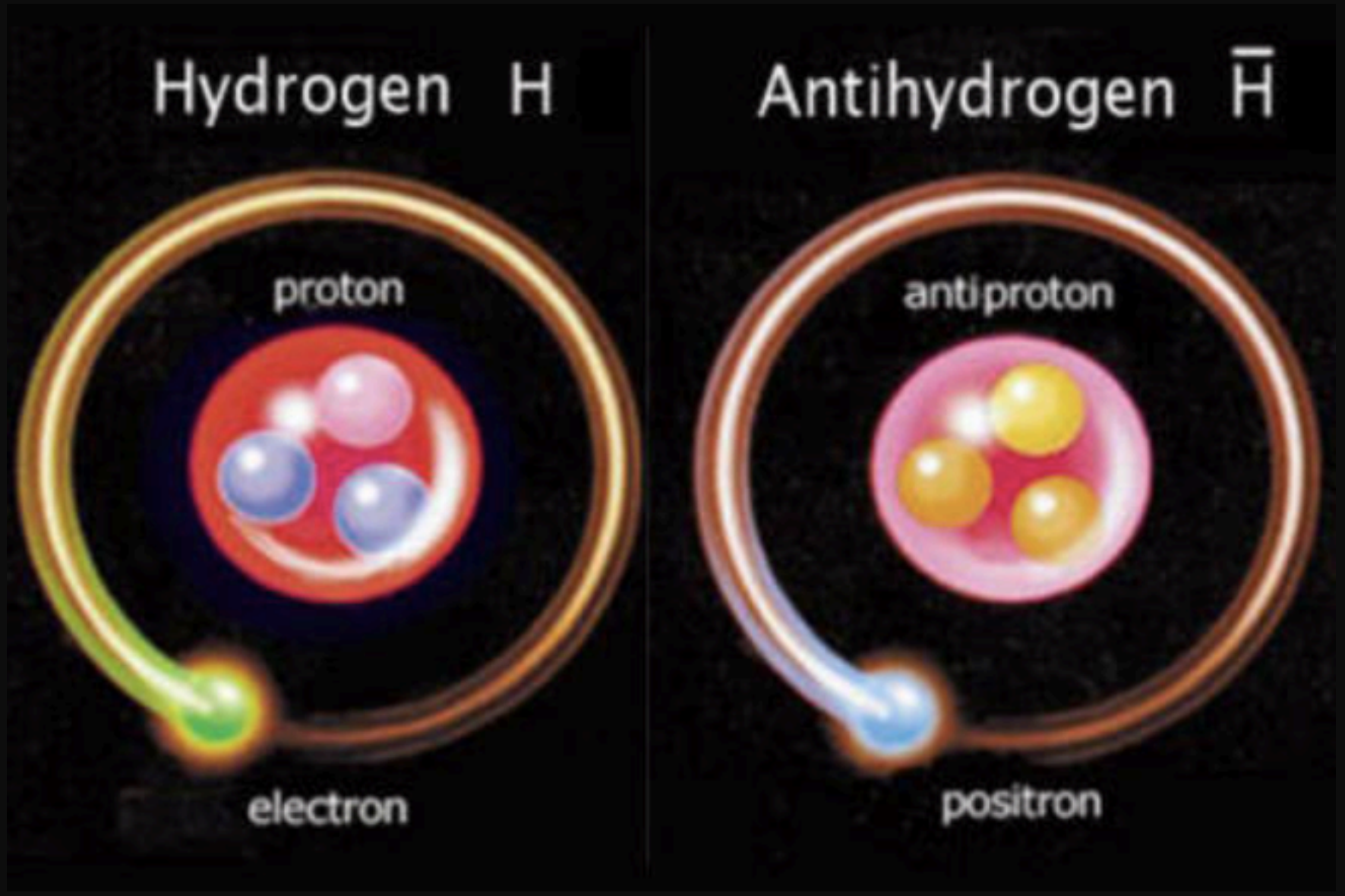
Hydrogen H
proton
electron
Antihydrogen $\bar{H}$
antiproton
positron

- *When the Big Bang created the universe out of nothing, scientists believe that the explosion created equal amounts of **matter and anti-matter**.*
- *But today, everything we observe from the smallest forms of life on the planet Earth to the largest stellar objects like **galaxies** is made almost entirely of **ordinary matter**.*
- *Comparatively, there is not much antimatter to be found. Something must have happened to tilt the balance.*
- *One of the greatest challenges in physics is to figure out what happened to the antimatter, or why we see an asymmetry between matter and antimatter.*
- ***During the first fractions of a second of the Big Bang**, the hot and dense universe was buzzing with particle-antiparticle pairs popping in and out of existence.*
- *If matter and antimatter are created and destroyed together, it appears that the universe should only contain the leftover energy. Nevertheless, a very little portion of matter, **about one particle per billion managed to survive**. This is what we are witnessing now.*

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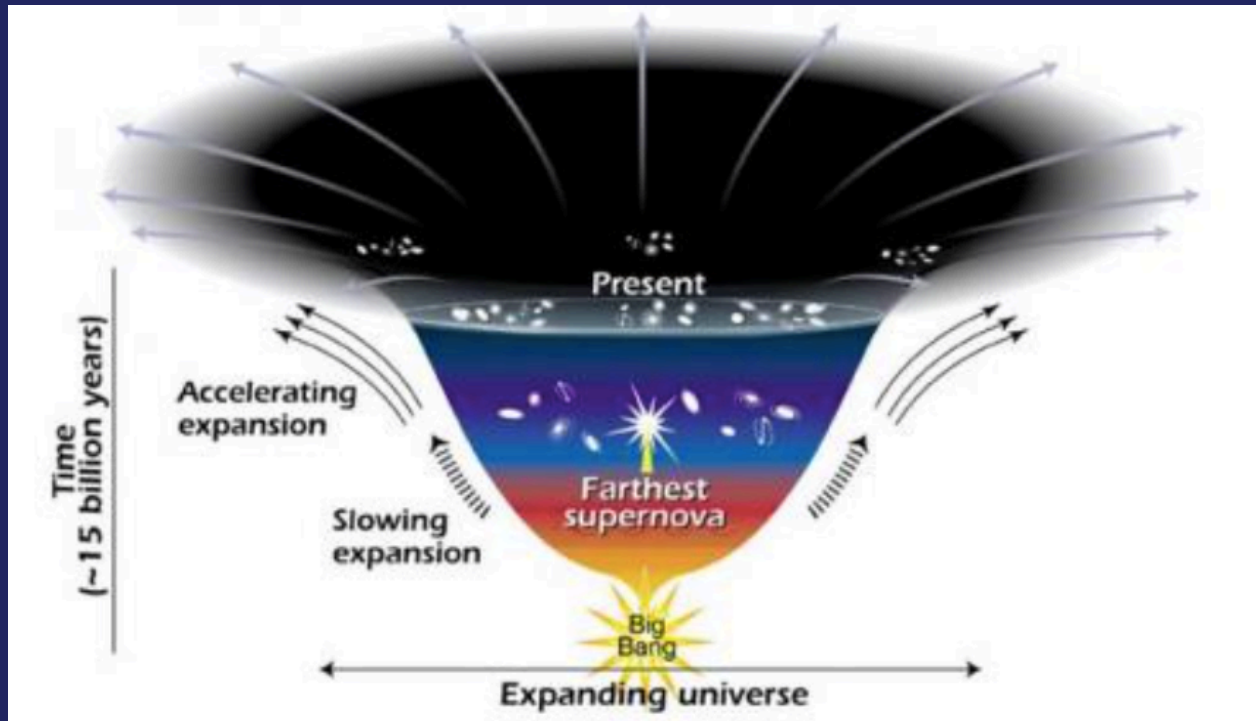
Existence of antimatter in the Universe

The Big Bang theory on the origins of the Universe requires that in the initial instant - very hot and very dense - matter and antimatter are equally abundant



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The Big Bang model describes the formation of the Universe

Experimental tests have been assessed;

- The recession of galaxies
- The existence of cosmic background radiation
- The relative amount of light isotopes in the Universe

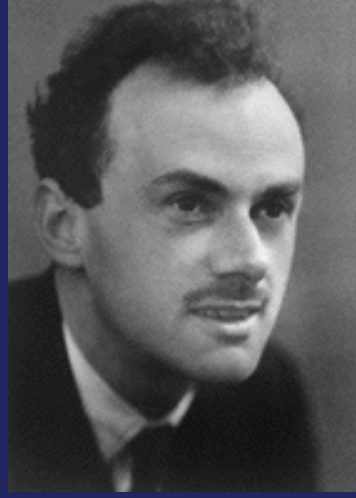
matter and antimatter must exist in equal quantities but until now .....

no trace of antimatter in the Universe

nor near our planet nor in the solar system nor in the galaxy

Where is antimatter ?

The symmetry of the Universe



- ”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“

- Dirac, 1933 Nobel acceptance speech

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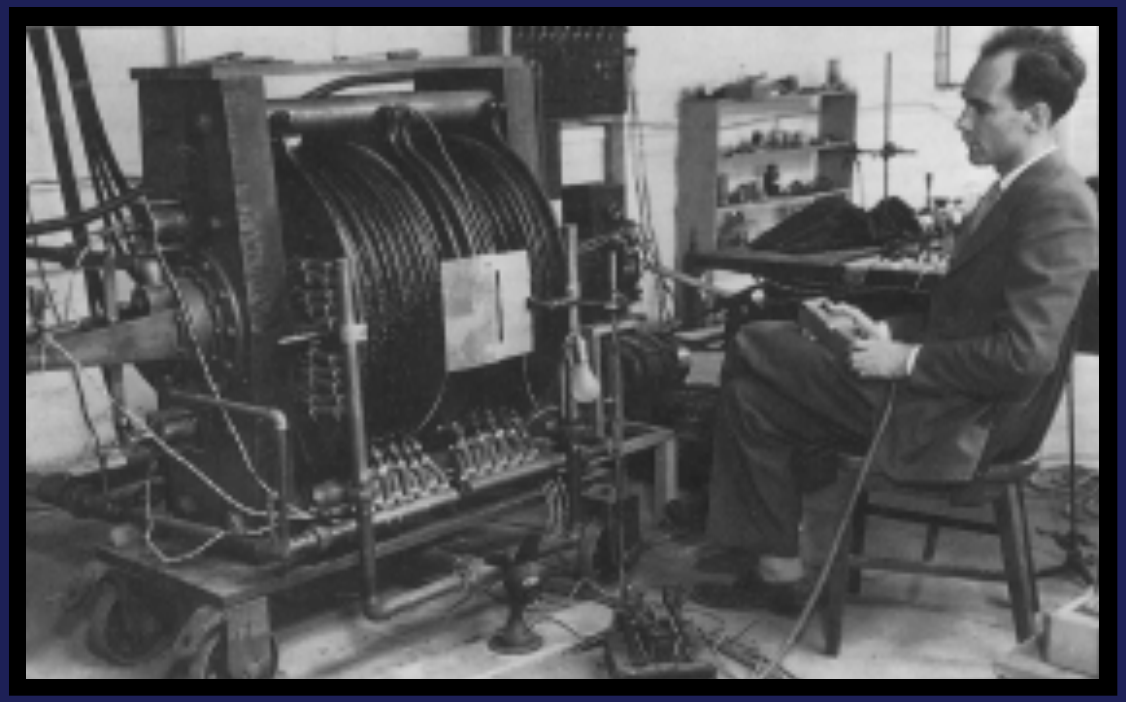
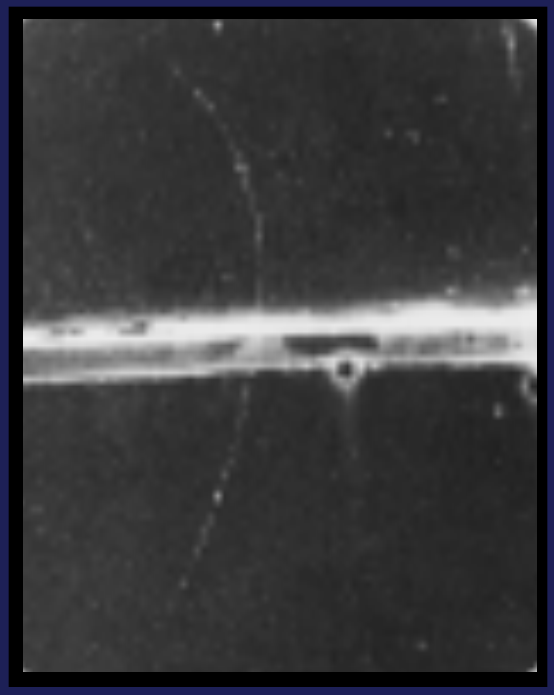
Anderson (1932) - The discovery of antimatter

in cosmic rays





COSMIC RAYS ??????? nice name but ,,, what are they?

At six o'clock in the morning of August 7, 1912, a aerostatic balloon carrying three men took off from a camp near the Austrian city of Aussig, one of them was the young physicist Victor Hess, he he carried with him three very sensitive ionization measuring devices.

Hess tried to find out something about the origin of a mysterious radiation that the physicists had identified for some time. The balloon climbed up to 5000 meters, Hess discovered that the radiation was much stronger at that height than at sea level.
Once the data analysis was performed, he announced:

La prima scoperta della radiazione cosmica.

<The results of my observations are perfectly explained by supposing that a radiation of great penetrating power comes from above into our atmosphere ... ..>

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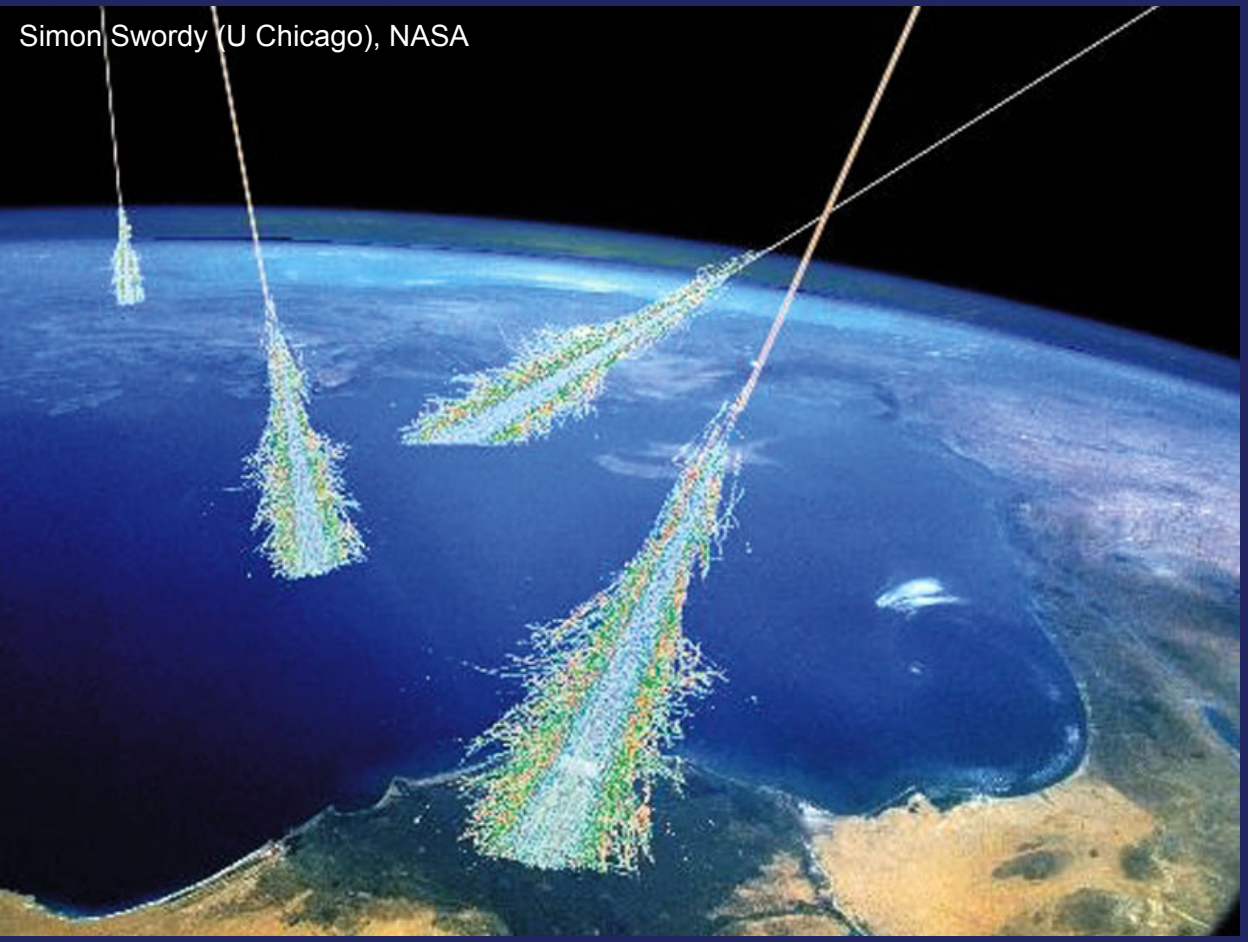
Cosmic Rays

High energy particles, Mainly protons of cosmic origin (sun, supernovae, galaxies)



E = mc2
Energy can be converted into matter and vice versa

In the clash with atomic nuclei of the atmosphere the cosmic particles are converted into swarms of secondary particles

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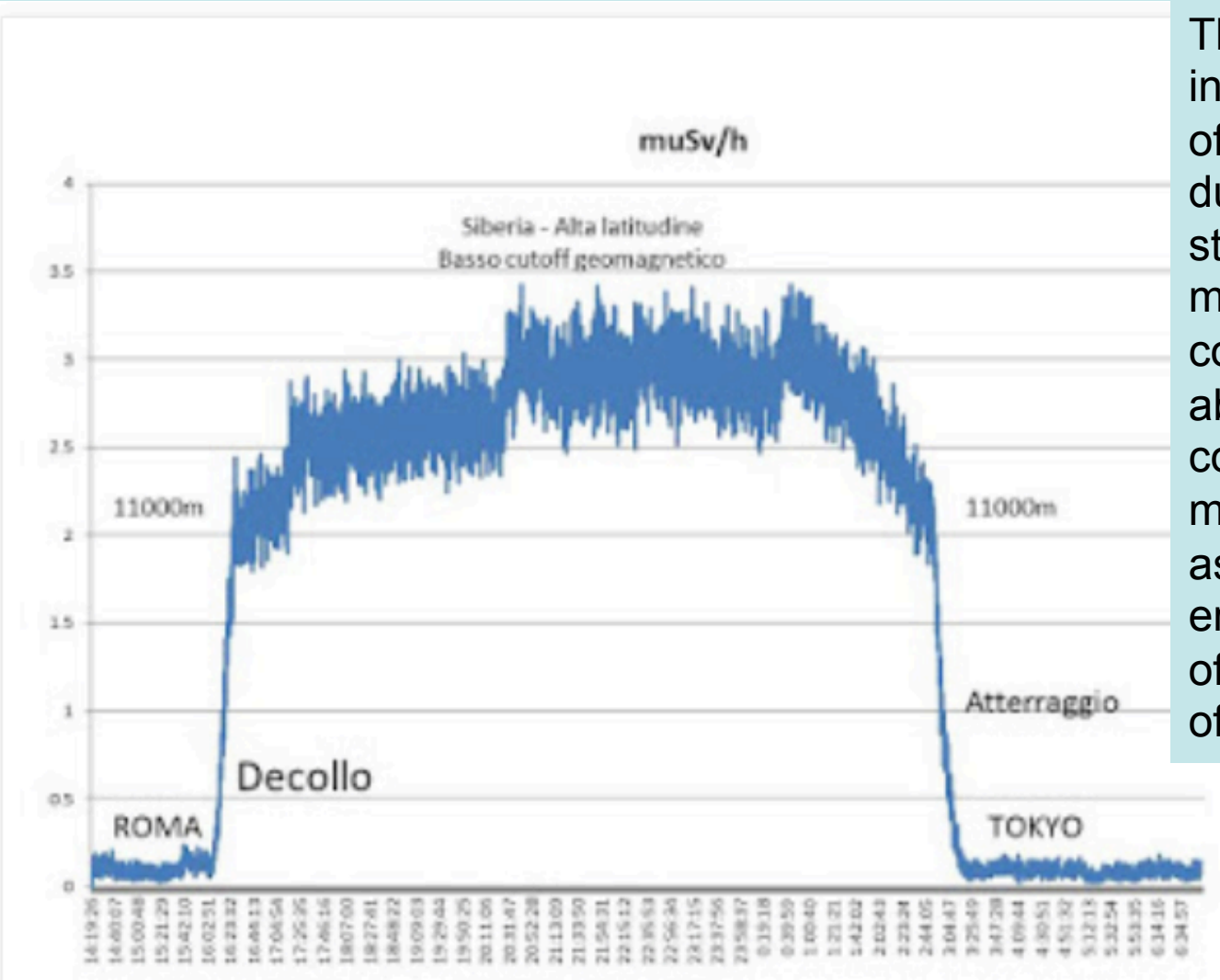
cosmic rays during a Flight



Il flusso di raggi cosmici, convertito in microSv/h

The oscillations in the number of counts are due to the statistics: 2 microSv / hour correspond to about 1000 counts per minute. The associated error is the root of the number of counts.

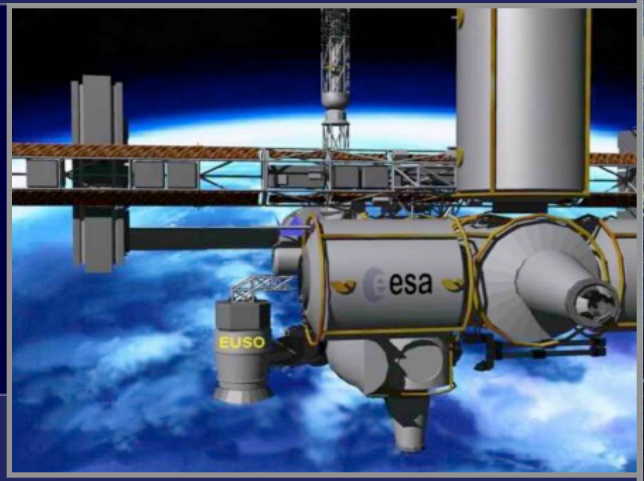
How are the Cosmic Rays revealed today?

The Primary:

- the observers are in space
- They study primary particles without interference with the atmosphere.
- They are expensive and small! Many of the studies are instead on rare particlesv

Secondary swarms:

- Observatories on the ground
- Less expensive can have larger surfaces
- Of must be able to reconstruct the primary and identify it, difficult but possible



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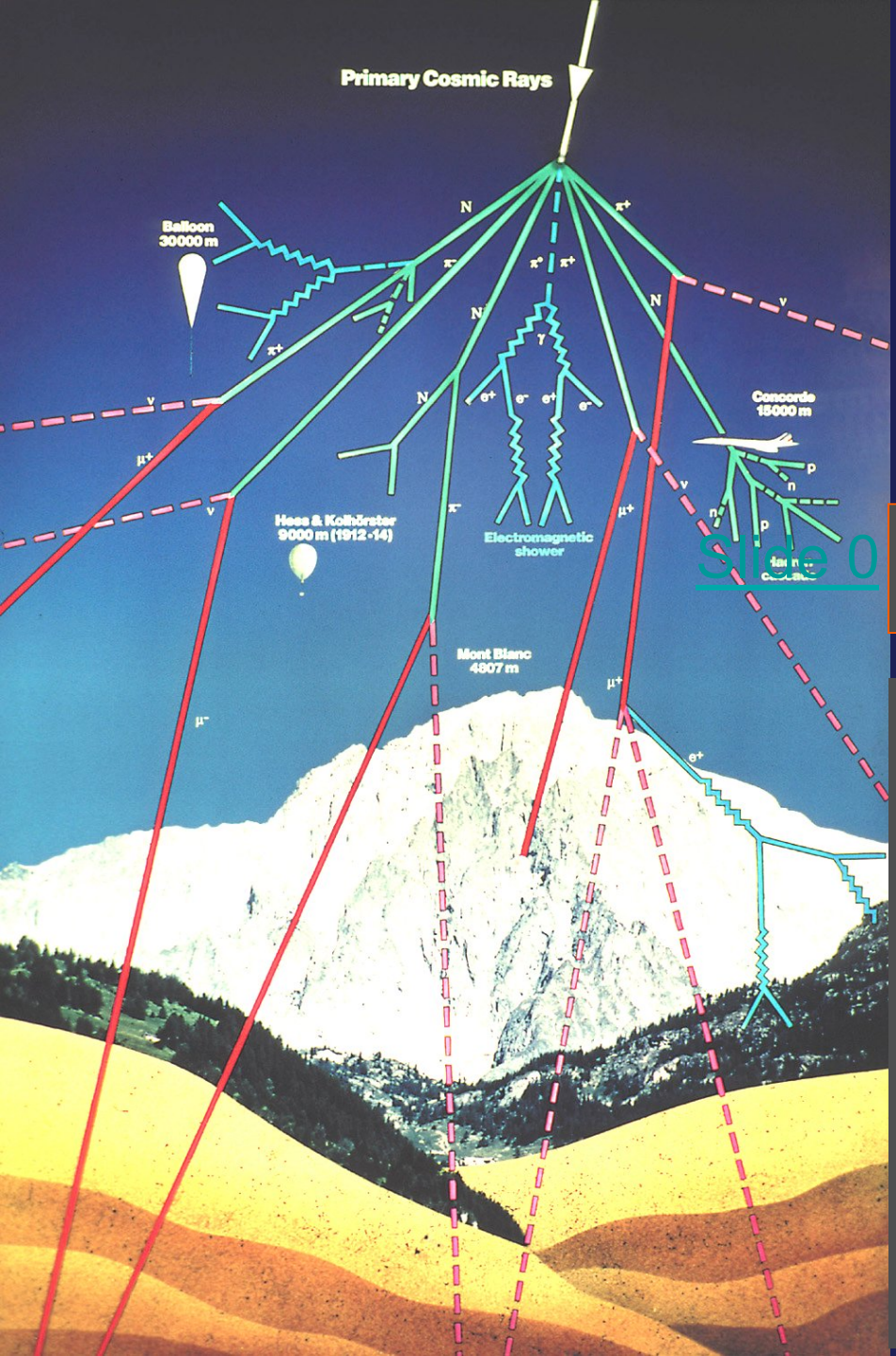


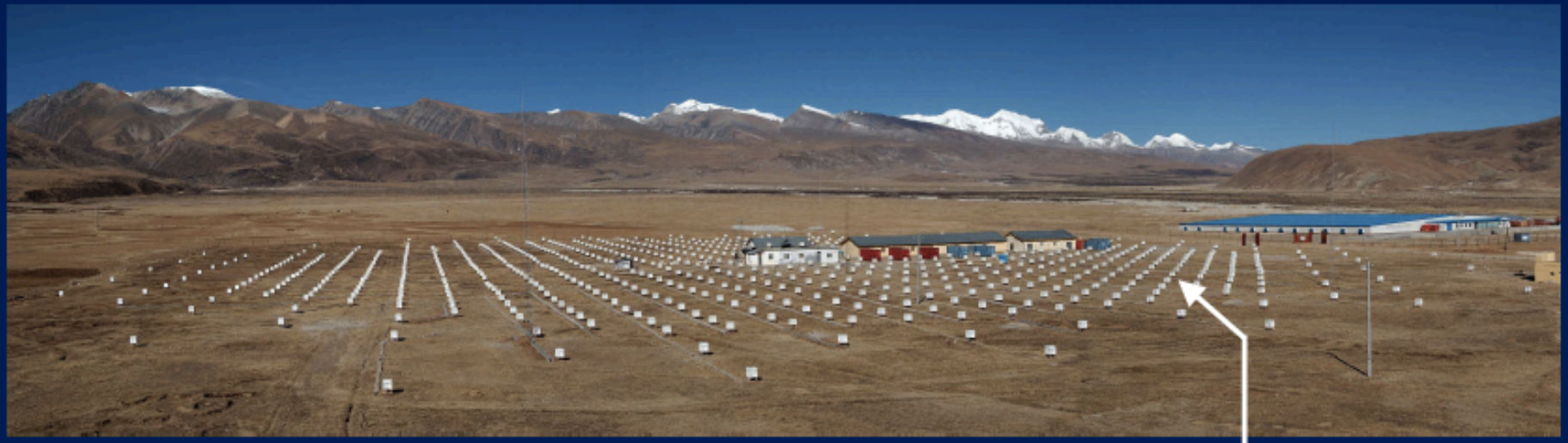
Costruzione dell' osservatorio del Pic du Midi dove fu *scoperto il pione*

Le particelle avvicinandosi alla Terra sentono:

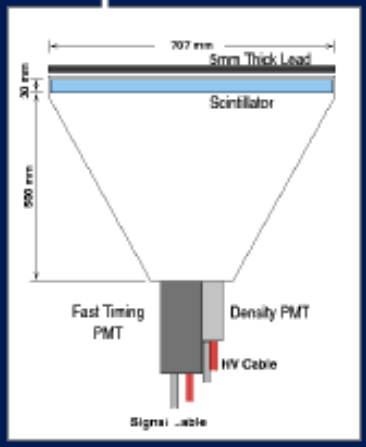
- prima l'azione del suo campo magnetico che le deflette, più o meno secondo la loro energia,
- poi, nell'atmosfera, urtando contro le molecole dell'aria, la particella primaria produce un vero sciame di particelle secondarie.

La natura dei raggi cosmici muta mano a mano che essi si sprofondano nell'atmosfera o che giunti al livello del mare penetrano entro la crosta terrestre.

Tibet Air Shower (AS) Array



Tibet China (90.522°E, 30.102°N) 4300 m a.s.l.



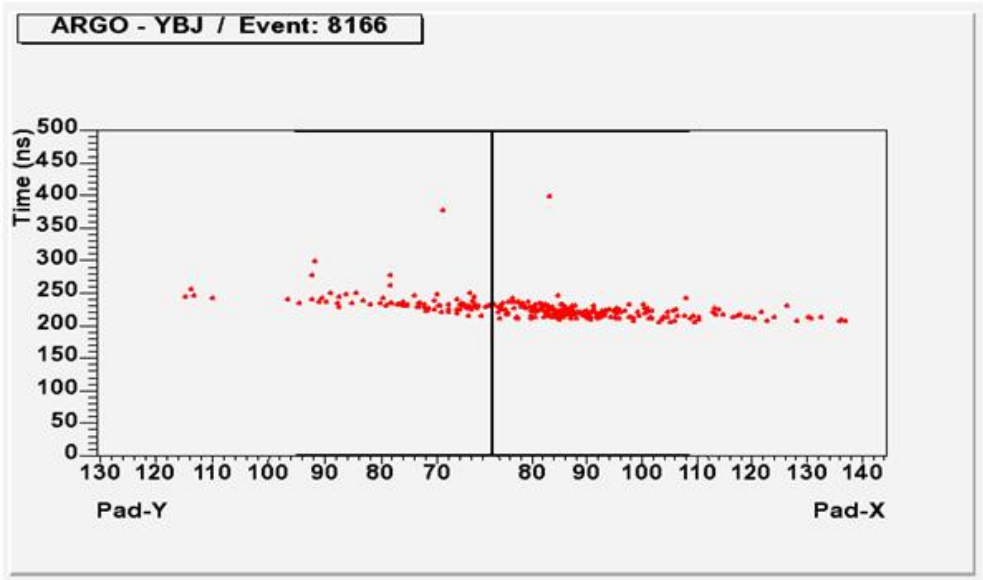
☐ Number of Scinti. Detectors	0.5 m^2 x 789
☐ Effective Area for AS	~37,000 m^2
☐ Energy region	~TeV - 100 PeV
☐ Angular Resolution	~0.4° @10 TeV
(for Gamma 1ry)	~0.2° @100 TeV
☐ Energy Resolution	~70% @10 TeV
(for Gamma 1ry)	~40% @100TeV
☐ Pointing Error	< 0.01°
☐ Absolute Energy Error	~10%
☐ F.O.V.	~2 sr

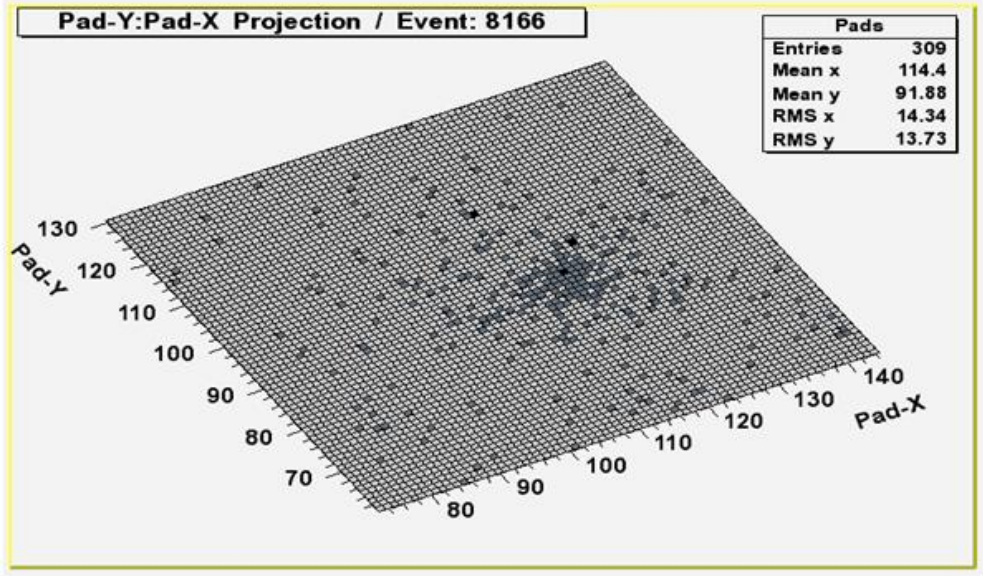
In Tibet, 4300 m asl
The experiment

Gamma-ray
Observation
with the Tibet ASγ
Experiment

Detector of swarms
of particles
produced by the
Cosmic Rays

18500 detectors
cover an area as big
as a soccer field.





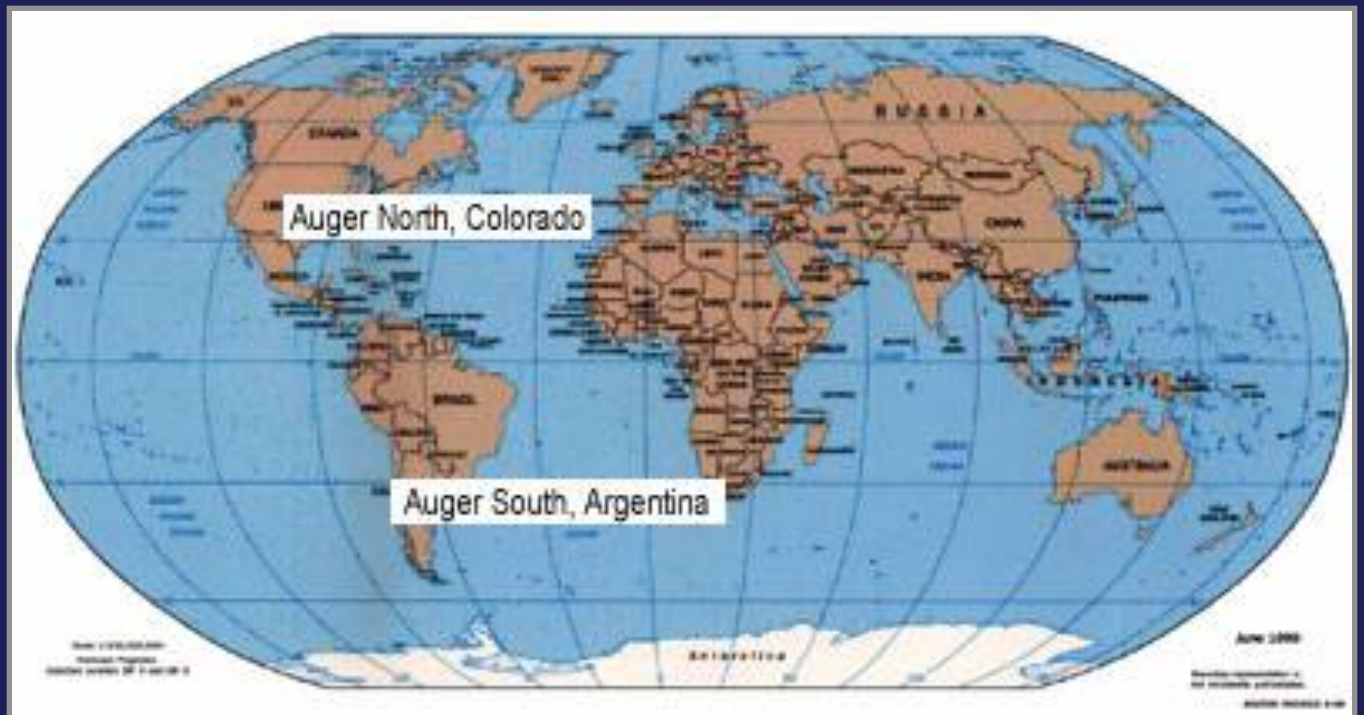
Cherenkov light large observatories

STACEE: Albuquerque, New Mexico

Air Showers observed on ground

Pierre Auger

The Auger Project observes more than 500 showers/day



Modern Experiments with balloons - other steps in the search for antimatter in cosmic rays

- The typical ascent times are between 2 and 3 hours and reach 40 km in height. Bringing up to 3000Kg of experimental apparatus,
- Main disadvantages: short measurement period with consequent problems (low statistics), little or no control of the flight profile and consequent difficulty in comparing the results with the simulations.

The P A M E L A Satellite experiment

Payload for Antimatter / Matter Exploration and Light-nuclei Astrophysics

Cosmic-ray positrons are a sensitive probe of the local astrophysical environment, and may be produced by the annihilation of dark matter particles which are gravitationally bound to our galaxy.

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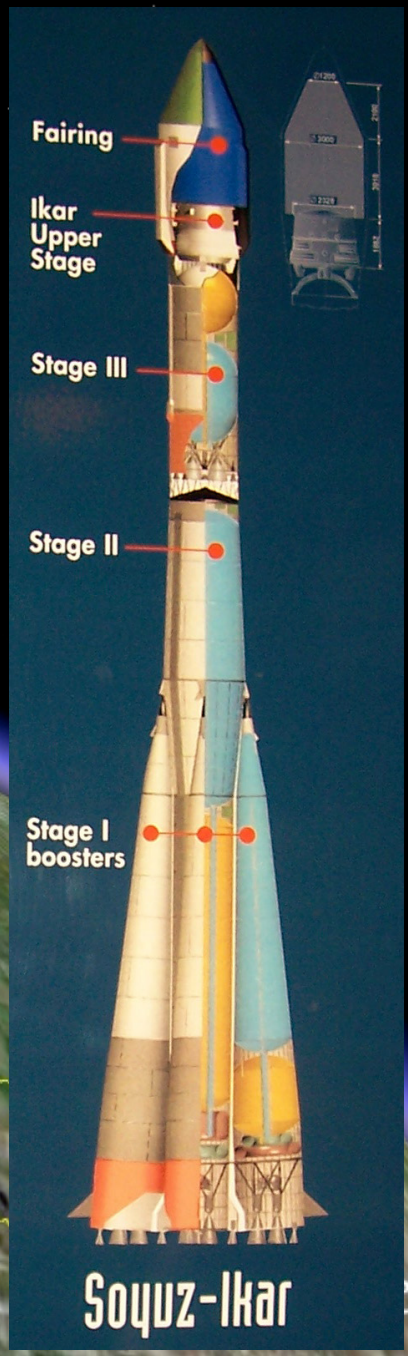
Total height	43.4 m
Main stage diameter	2.65 m
Lift-off mass	305 000 kg
Fairing diameter	3.3 m
Ikar Upper Stage:	
Dry mass	2 352 kg
Propellant mass up to	900 kg
Propellant	UDMH/N_2O_4
Engine	17D61
Soyuz-Ikar Performance:	
(Circular Orbits, 51.8° inclination)	
Altitude 450 km	4 100 kg
Altitude 1400 km	3 300 kg



Pointer 68° 01'48.95"N 29° 04'08.15"E Streaming 100%

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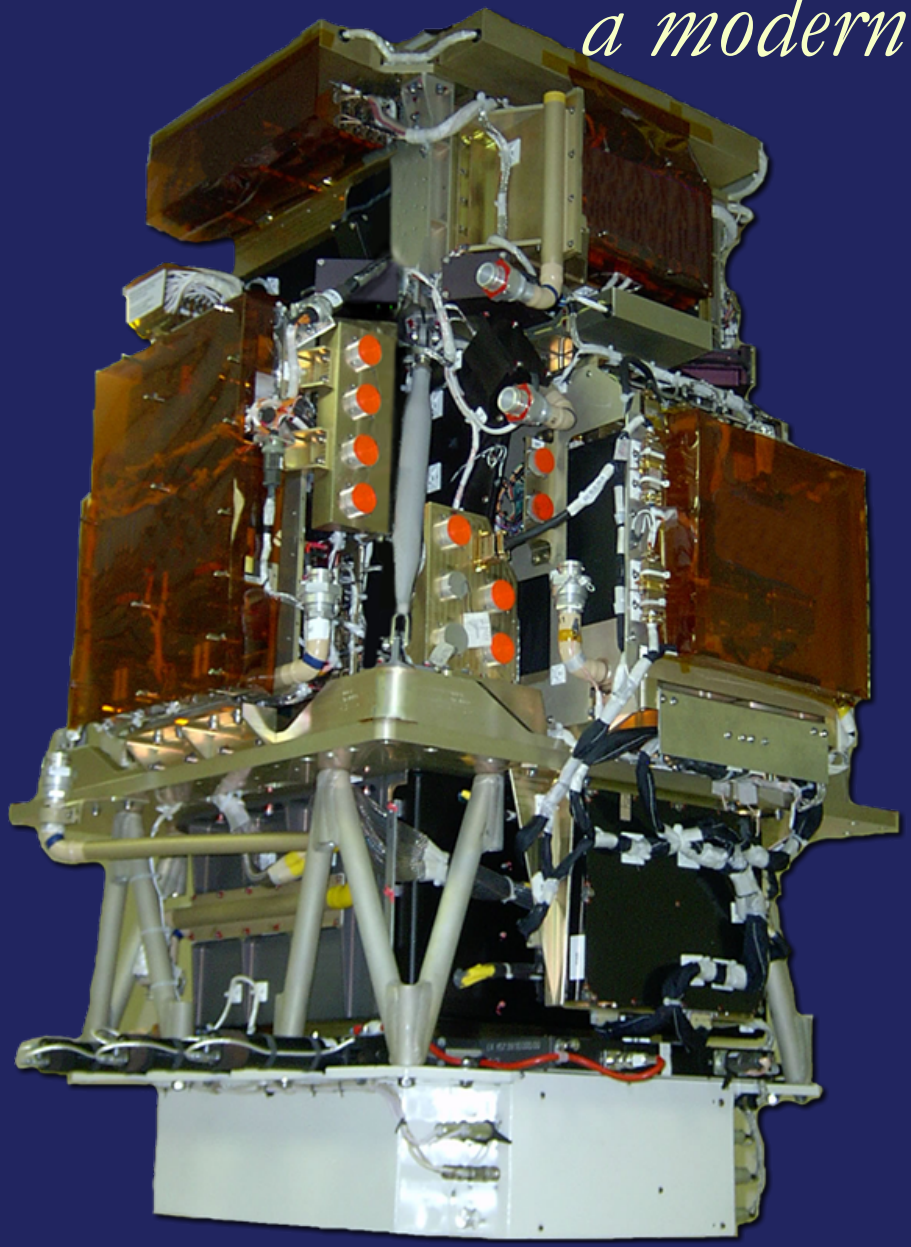
PAMELA
a modern Instrument



GF ~21.5 cm^2sr

Mass: 470 kg

Size: 130x70x70 cm^3

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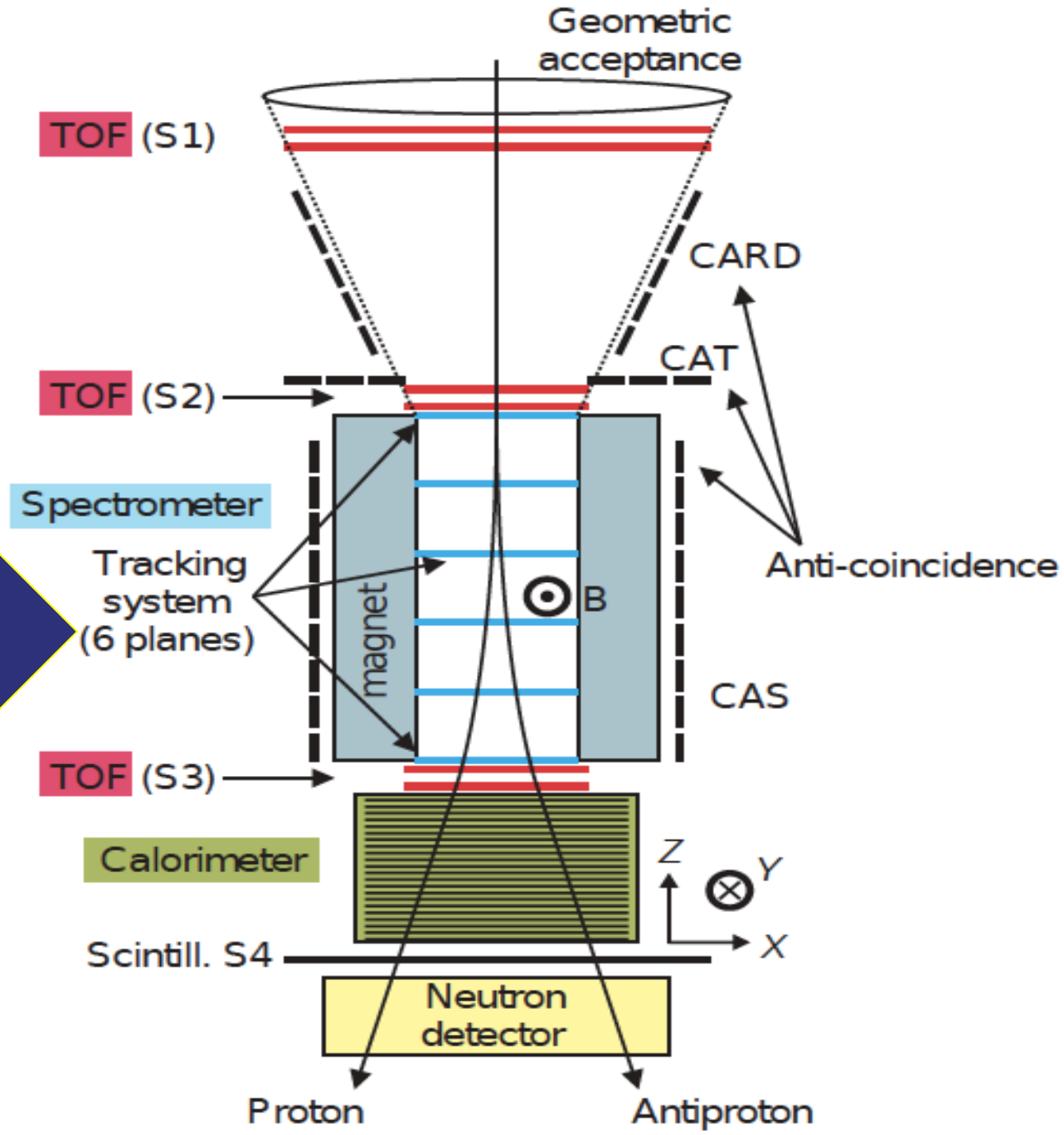
The principle is not very different from Anderson's detector:

- magnetic filed
- and particle's track



Scheme of the detectors composing the PAMELA satellite experiment.

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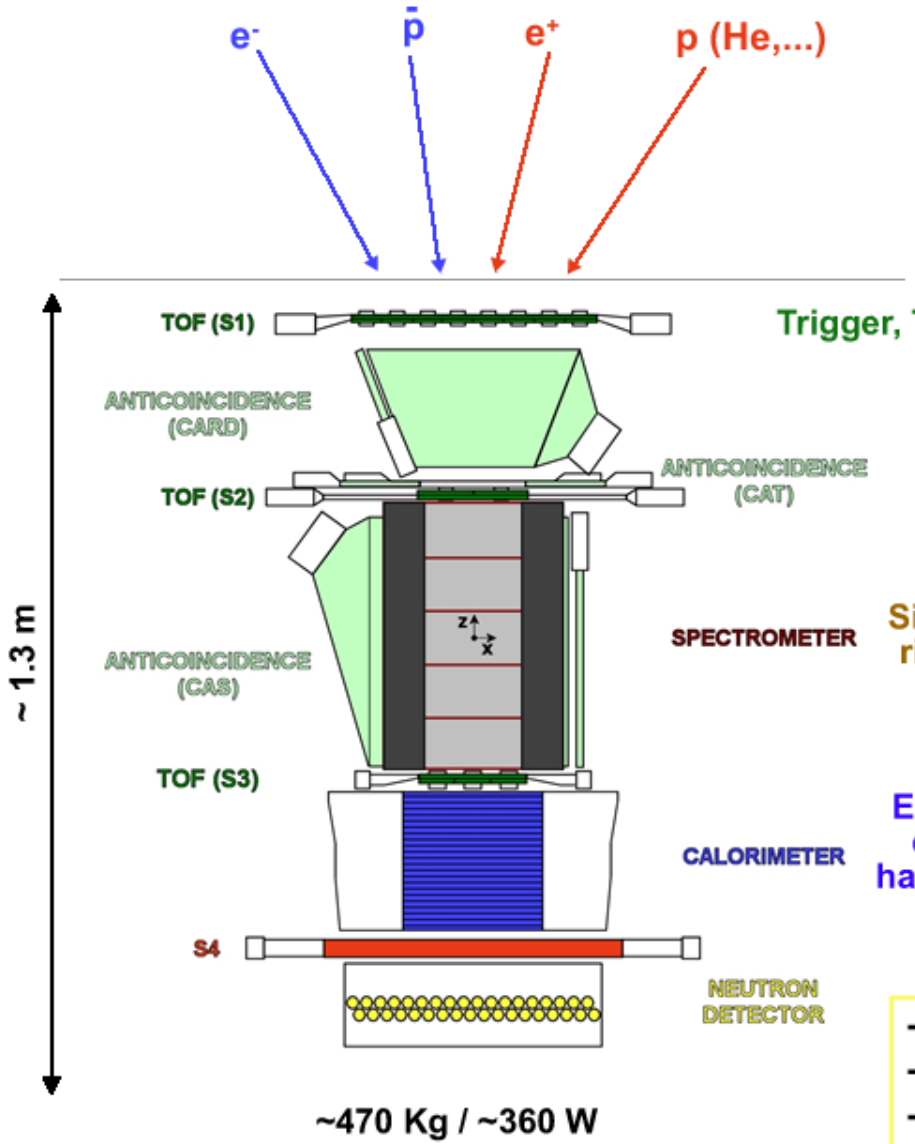
PAMELA Instrument



Trigger, ToF, dE/dx

- S1, S2, S3; double layers, x-y
- plastic scintillator (8mm)
- ToF resolution ~300 ps (S1-3 ToF >3 ns)
- lepton-hadron separation < 1 GeV/c
- S1.S2.S3 (low rate) / S2.S3 (high rate)

Sign of charge, rigidity, dE/dx

- Permanent magnet, 0.43 T
- 21.5 cm^2 sr
- 6 planes double-sided silicon strip detectors (300 μm)
- 3 μm resolution in bending view → MDR

MDR 1.2 TeV

Electron energy, dE/dx, lepton-hadron separation

- 44 Si-x / W / Si-y planes (380)
- 16.3 X0 / 0.6 L
- dE/E ~5.5 % (10 - 300 GeV)
- Self trigger > 300 GeV / 600 cm^2 sr

- 36 ^{3}He counters
- ^{3}He(n,p)T; E_p = 780 keV
- 1 cm thick poly + Cd moderator
- 200 μs collection

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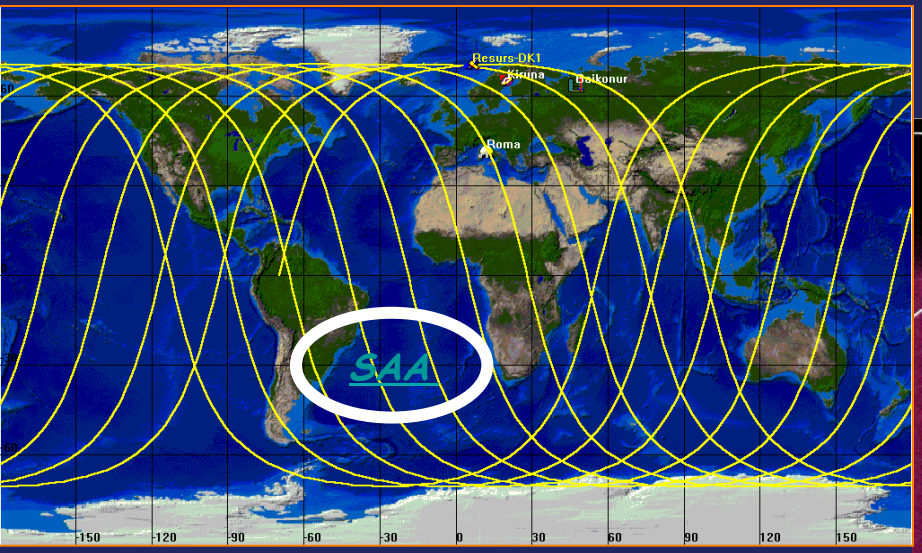
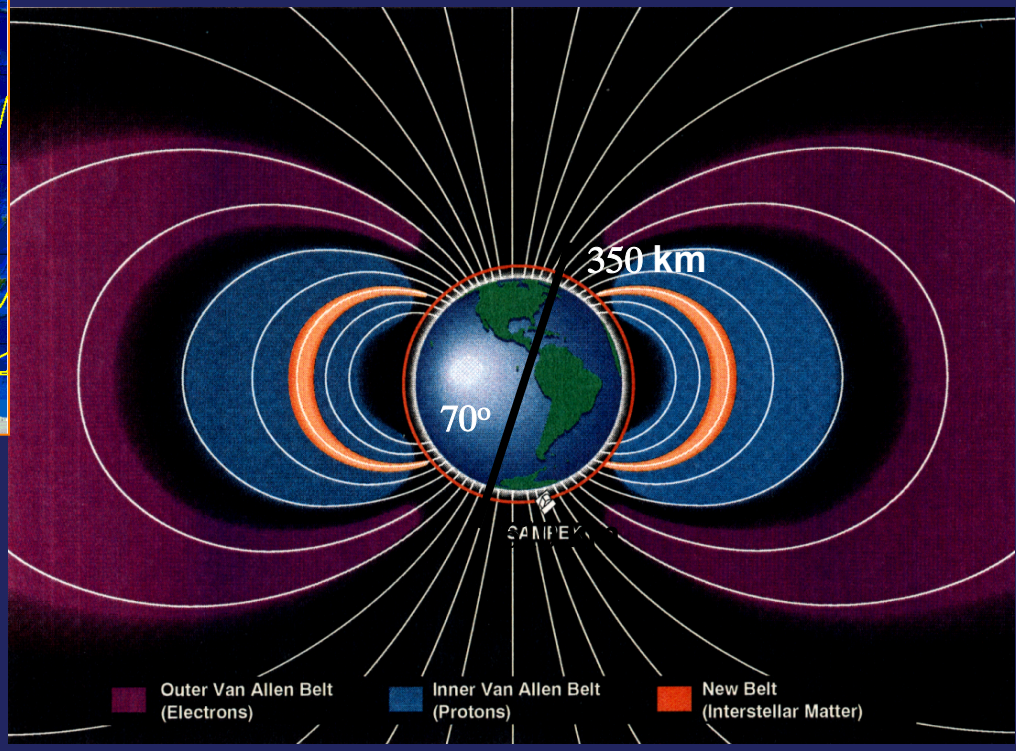
Orbit Characteristics





- Low-earth elliptical orbit
- 350 – 610 km
- Quasi-polar (70° inclination)
- SAA crossed

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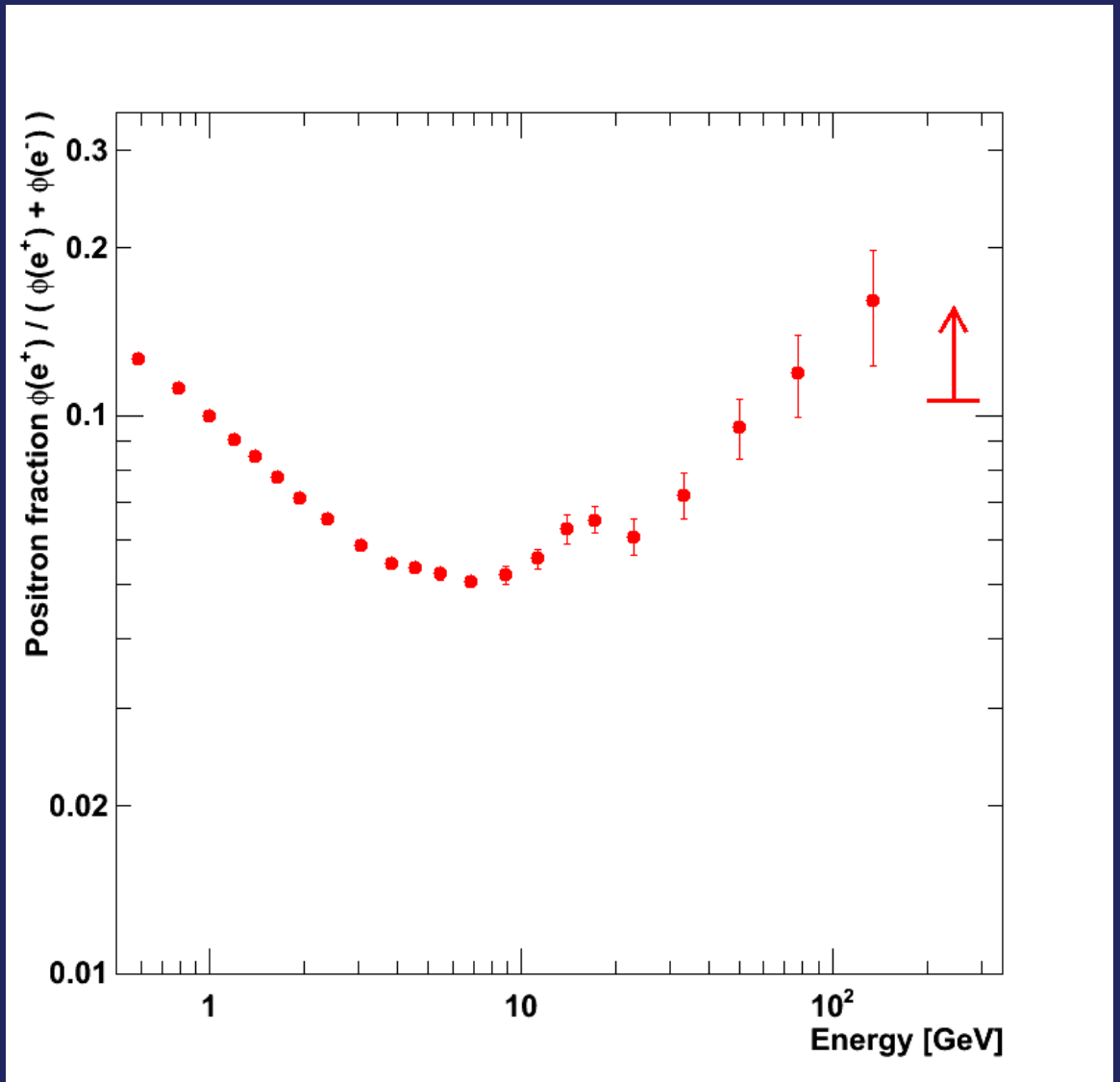
Positron Fraction as a ratio of fluxes



New result

$(e^+)/(e^+ + e^-)$

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Positron to all electron ratio
PAMELA results

Nature 458, 697, 2009

$$R(E) = \frac{\Phi_{e+}}{\Phi_{e+} + \Phi_{e-}}$$

The measured points are very much different from the theoretical prediction and could be explained by the annihilation of dark matter particles

Theoretical prediction
Secondary production
Moskalenko & Strong 98

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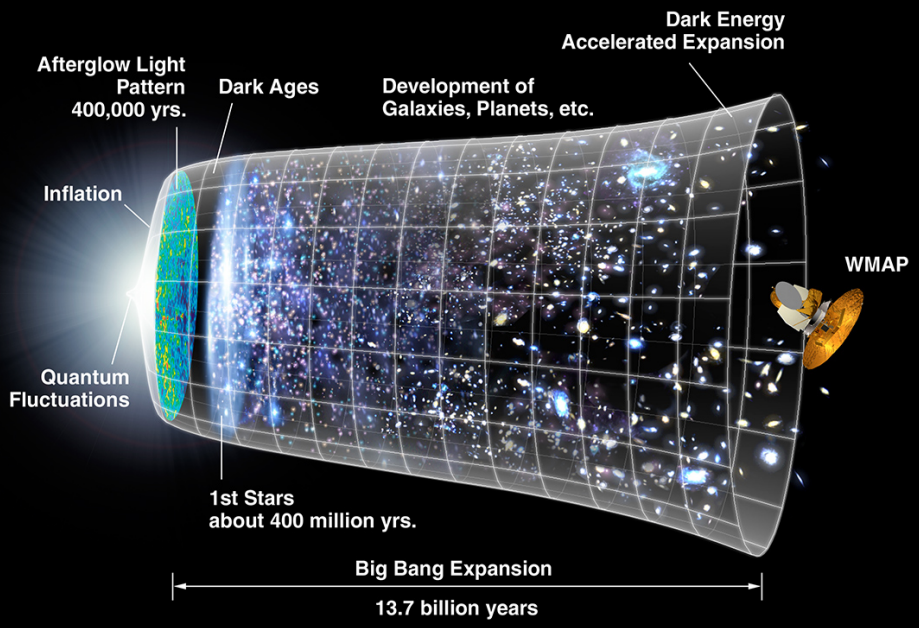
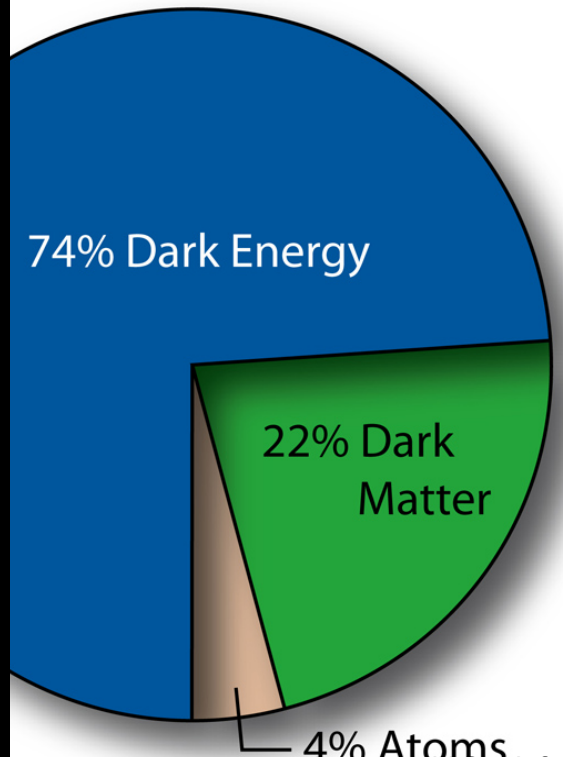
What does the Universe contain? The PLANK satellite finds

4% of atoms, the basic components of stars and planets.

22% of the universe consists of "dark matter". This matter, different from atoms, does not emit and absorbs light. It was only revealed indirectly by the action of its gravity.

74% of the Universe consists of "dark energy", this acts as a kind of antigravity and is responsible for accelerating the expansion of the universe.





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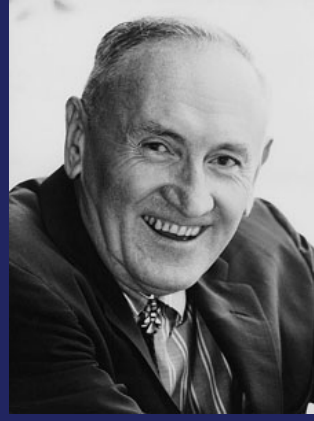
Missing Matter

Fritz Zwicky's Extraordinary Vision



The galaxies were flying around too fast (as measured by the Doppler effect) for their visible mass to keep them together, so he proposed dark matter was present.

- Zwicky, the most unrecognized genius of twentieth century astronomy, measured (1933) the radial velocities for eight galaxies in the Coma cluster and found an unexpectedly large velocity dispersion of ~1000 km/s.
- He used the Virial Theorem to deduce that the mass density of Coma would have to be ~400 times that of the luminous matter -- although he assumed a Hubble parameter of ~500 km/s/Mpc. For present day value of Hubble parameter mass discrepancy of ~50.
- What caused this mass discrepancy? What could resolve it?

Fritz Zwicky (1898–1974). A bold and visionary scientist, Zwicky was far ahead of his time in conceiving of supernovas, neutron stars, dark matter, and gravitational lenses.

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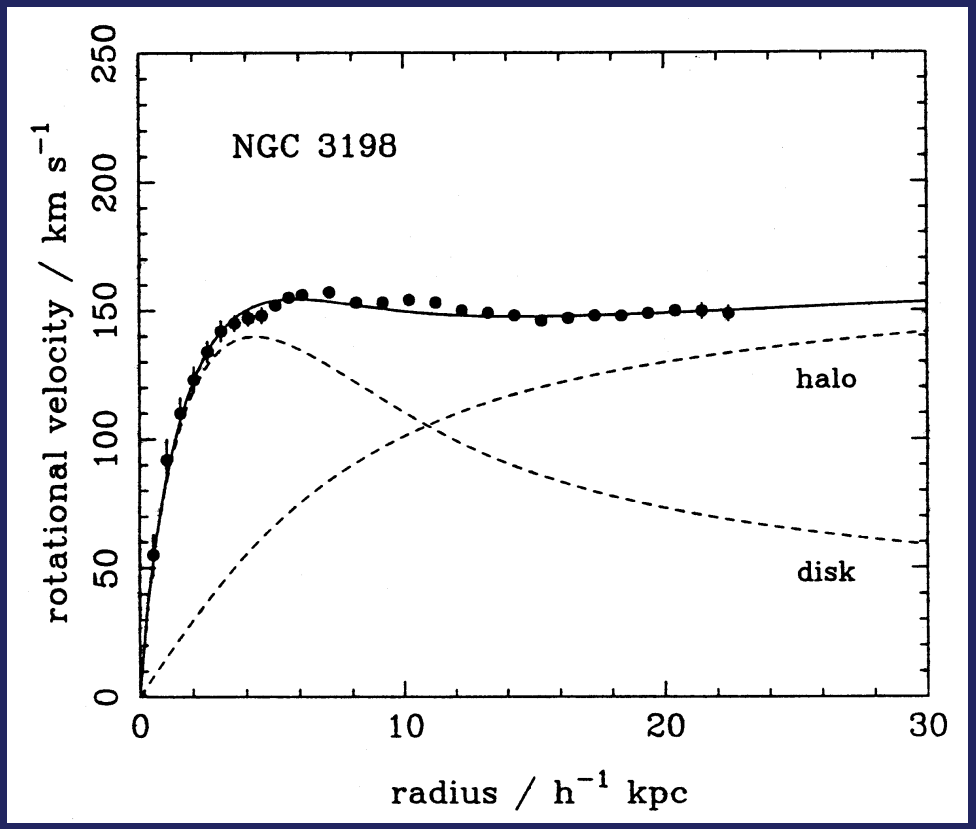
~1970: Vera Rubin, Ken Freeman and others explore rotation curves and (re-)find the need for dark matter (formerly called *missing matter*).



spiral galaxies contain a large fraction of dark matter

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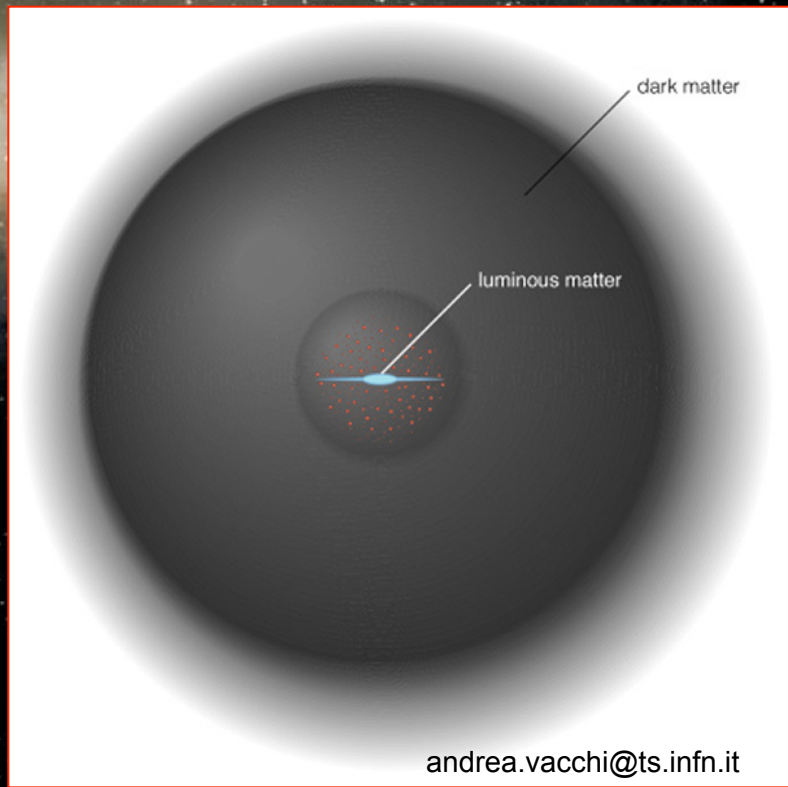
Orbital velocity stays almost constant as far out as we can track it Means that enclosed mass increases linearly with distance… expected?

Mass continues to increase, even beyond the radius where the starlight stops

So, in these outer regions of galaxies, the mass isn't luminous…

This is DARK MATTER.



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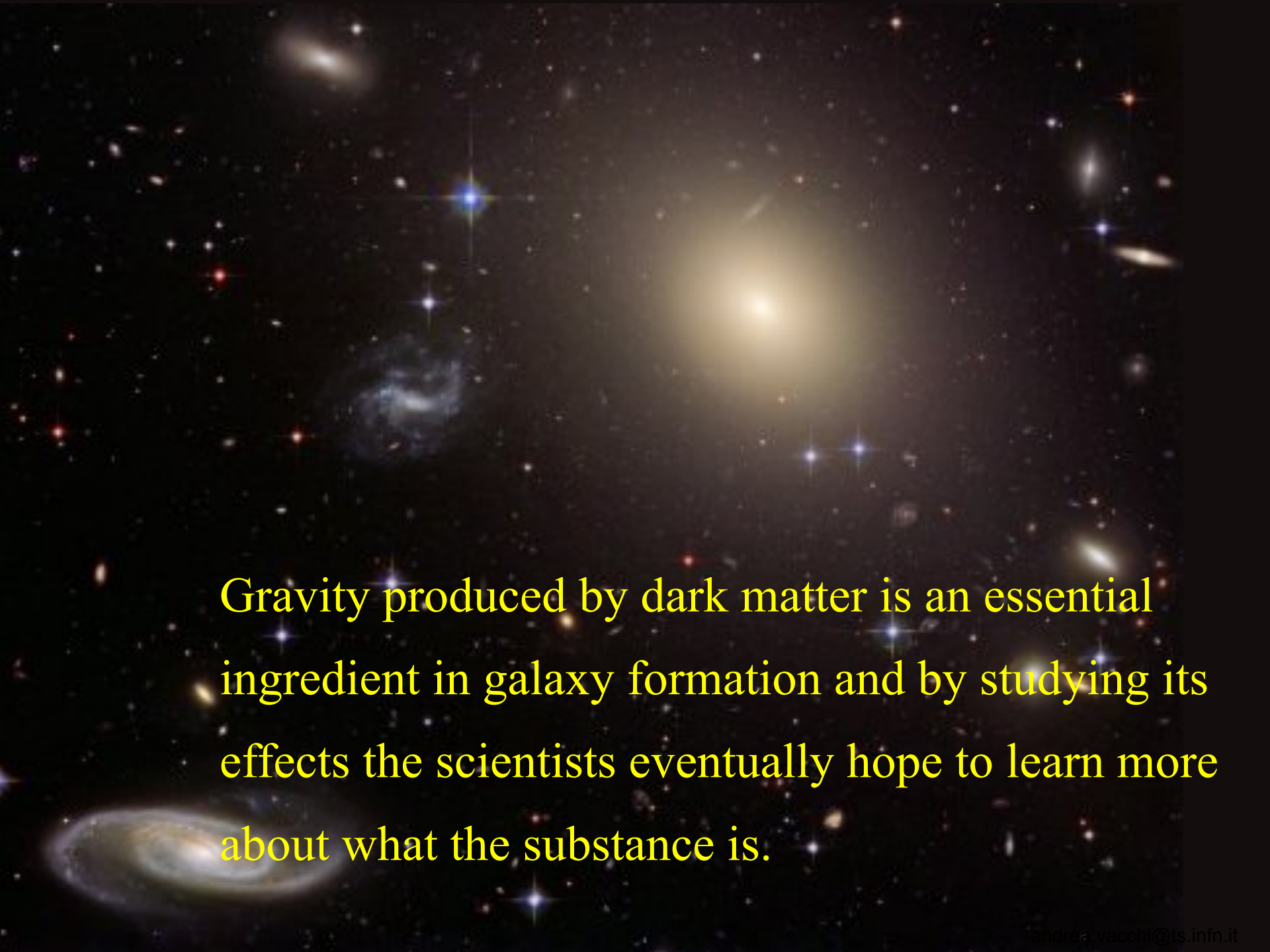

Gravity produced by dark matter is an essential ingredient in galaxy formation and by studying its effects the scientists eventually hope to learn more about what the substance is.

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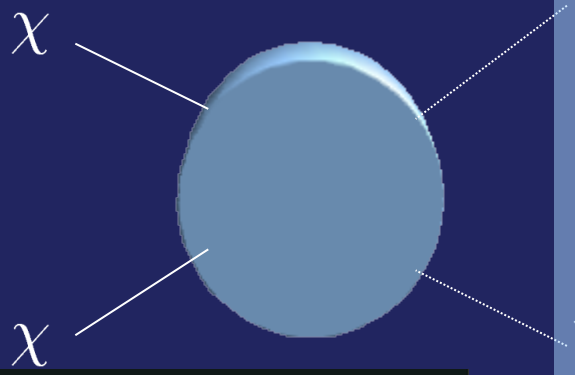
A possible hypothesis

Neutralino may be the component of halos around galaxies.

Their annihilation would produce an indirect signature of high-energy cosmic rays
Cusp of dark matter at centre of Galaxy is expected, Annihilation of DM particles in the Galactic Halo could produce energetic particles:

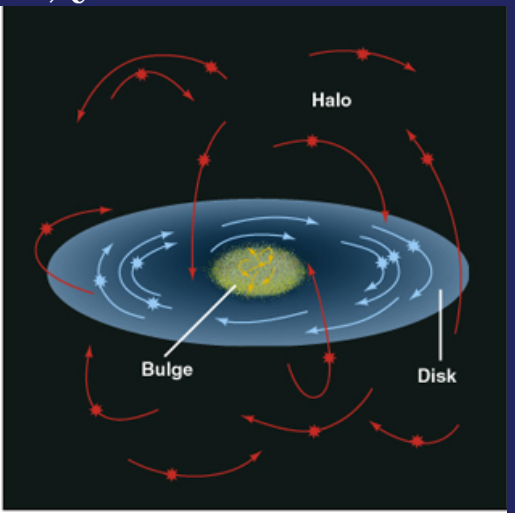
- Antiprotons
- Positrons
- Gamma-rays lines

Annihilation signal ~ density



$W^-, Z^0, b, \tau^-, t, h^0, \ldots$ $\Rightarrow$ $e^{\mp}, p^{(-)}, D^{(-)}, \ldots$

$W^+, Z^0, \bar{b}, \tau^+, \bar{t}, h^0, \ldots$ $\Rightarrow$ $e^{\pm}, p^{(-)}, D^{(-)}, \ldots$



Primary annihilation channels

Decay

Final states

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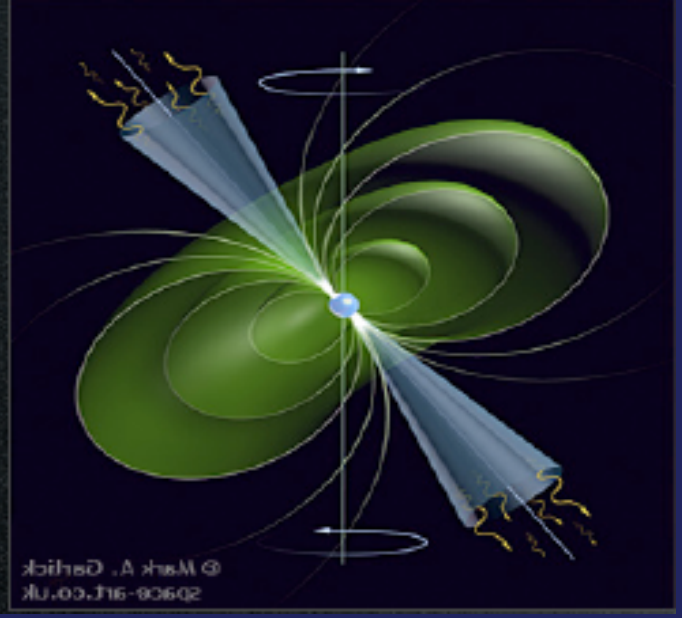
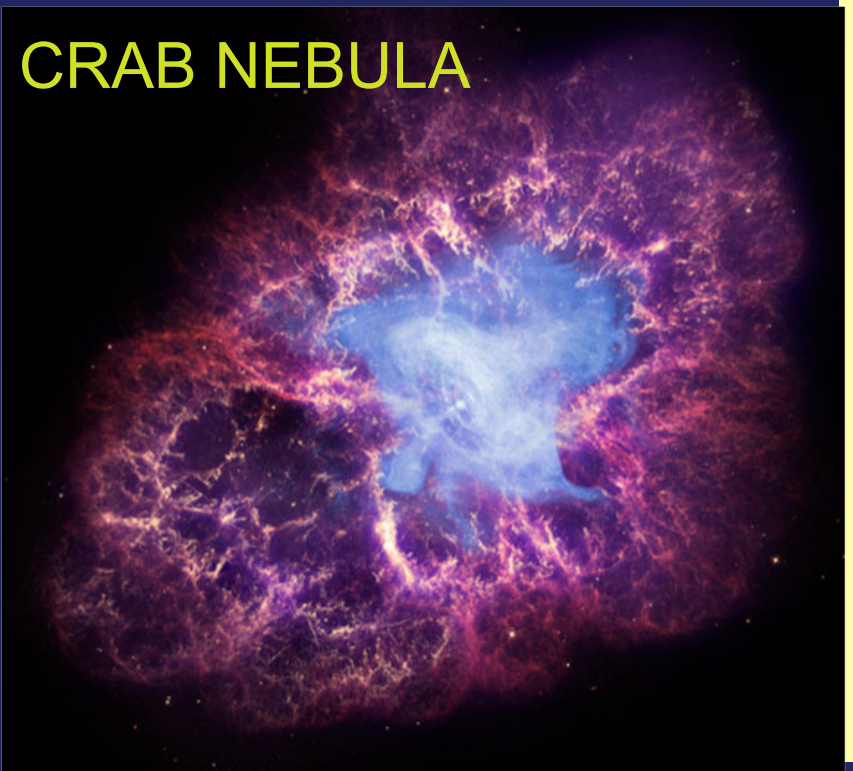


There are also Astrophysical Explanation as for instance Pulsars



- Mechanism: the spinning B of the pulsar strips e^- that accelerated at the polar cap or at the outer gap emit γ that make production of $e^{\pm}$ that are trapped in the cloud, further accelerated and later released at $\tau \sim 10^5$ years.

- Young ($T < 10^5$ years) and nearby (< 1kpc)
- If not: too much diffusion, low energy, too low flux.

- Geminga: 157 parsecs from Earth and 370,000 years old
- B0656+14: 290 parsecs from Earth and 110,000 years old.

- Diffuse mature pulsars

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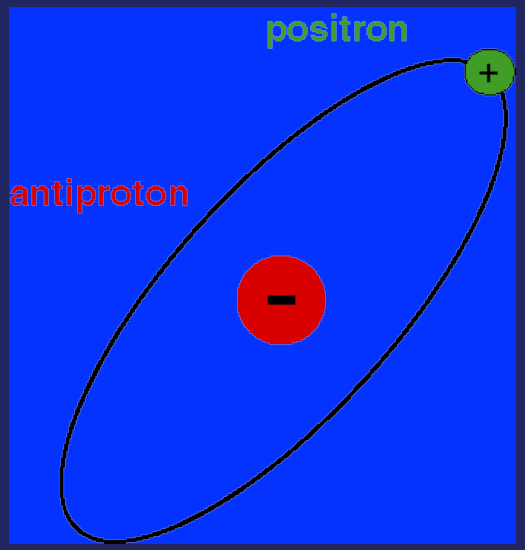
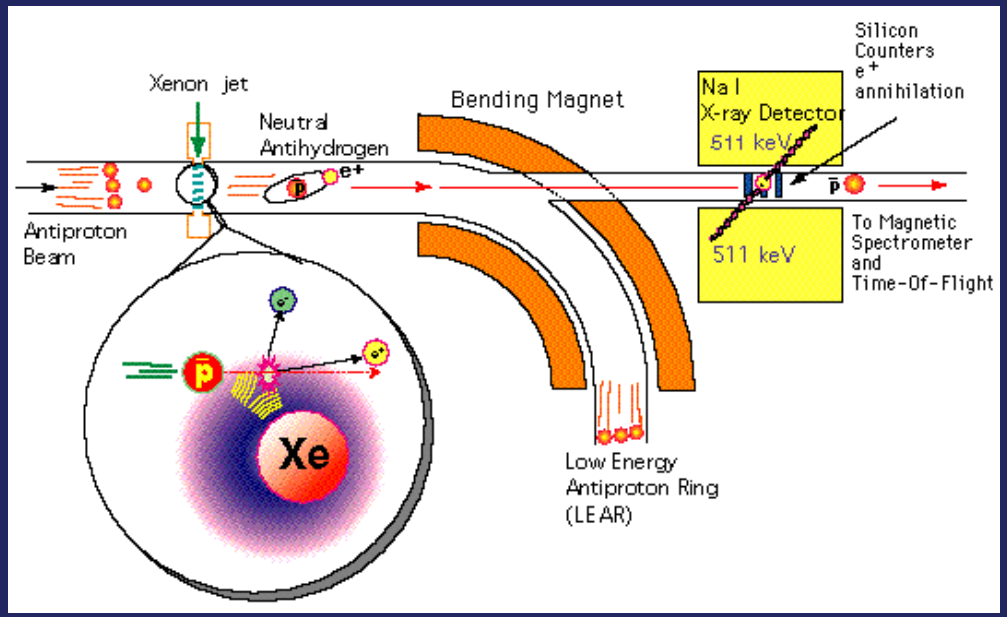
1995 CERN antiatom





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PET Definition

Positron emission tomography

Positron emission tomography is a nuclear medicine technique that produces three-dimensional images of functional processes in the body

It is not a person who has developed PET but it is the story of a scientific development made by many contributions that has led to today's PET

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How it works?

A short-living radioactive isotope is incorporated into a biologically active molecule and injected into the patient through the bloodstream.

There is a waiting period for the active molecule to be incorporated into the tissue of interest.

When the radioisotope decays with the emission of a positron

After a distance of about one millimeter, the positron meets an electron

$$e^+ + e^- \rightarrow \gamma + \gamma$$

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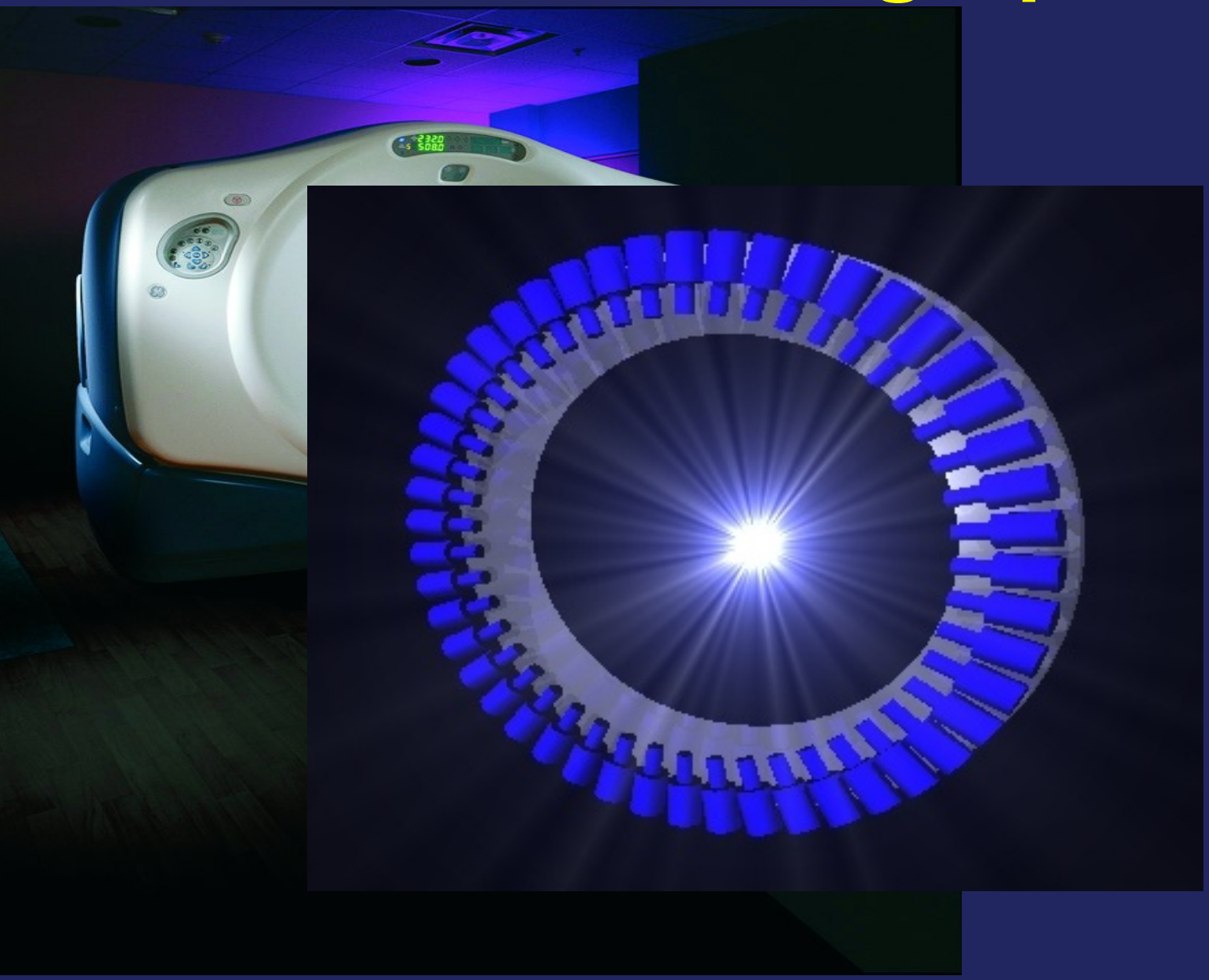
PET Tomograph



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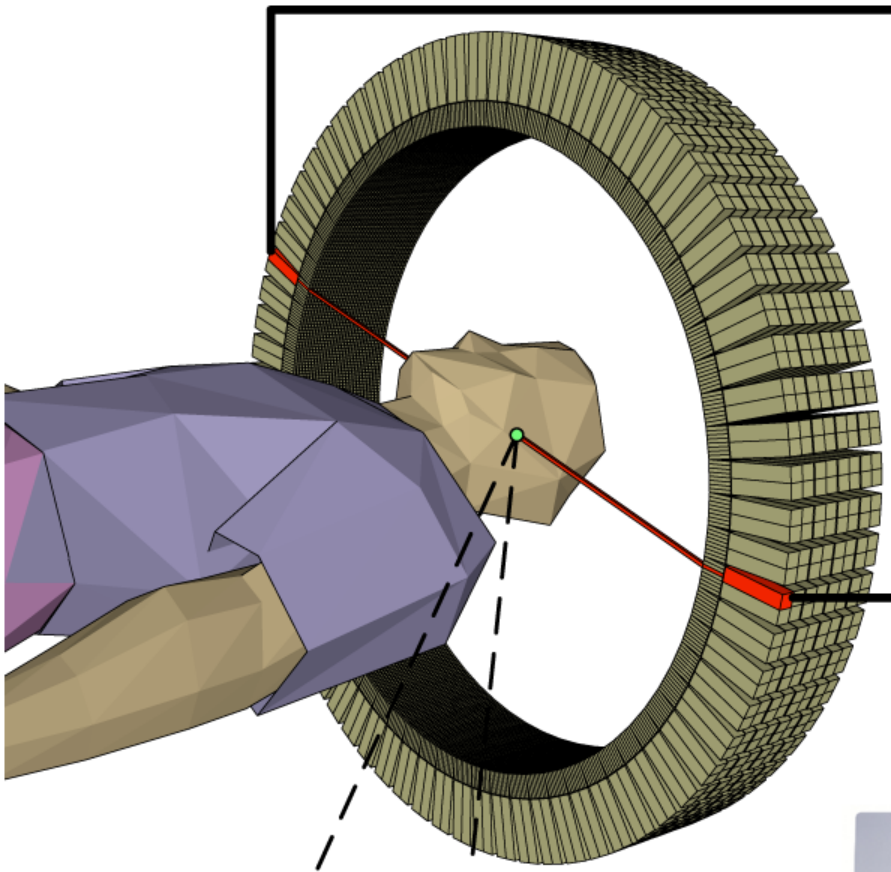
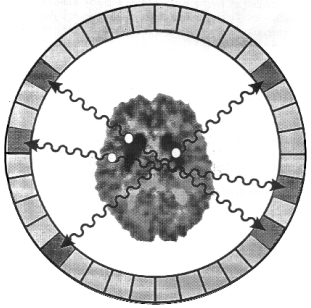
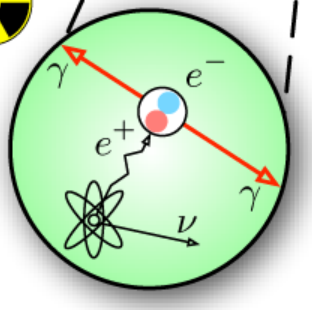


Coincidence
Processing Unit

Sinogram/
Listmode Data





Annihilation

Image Reconstruction

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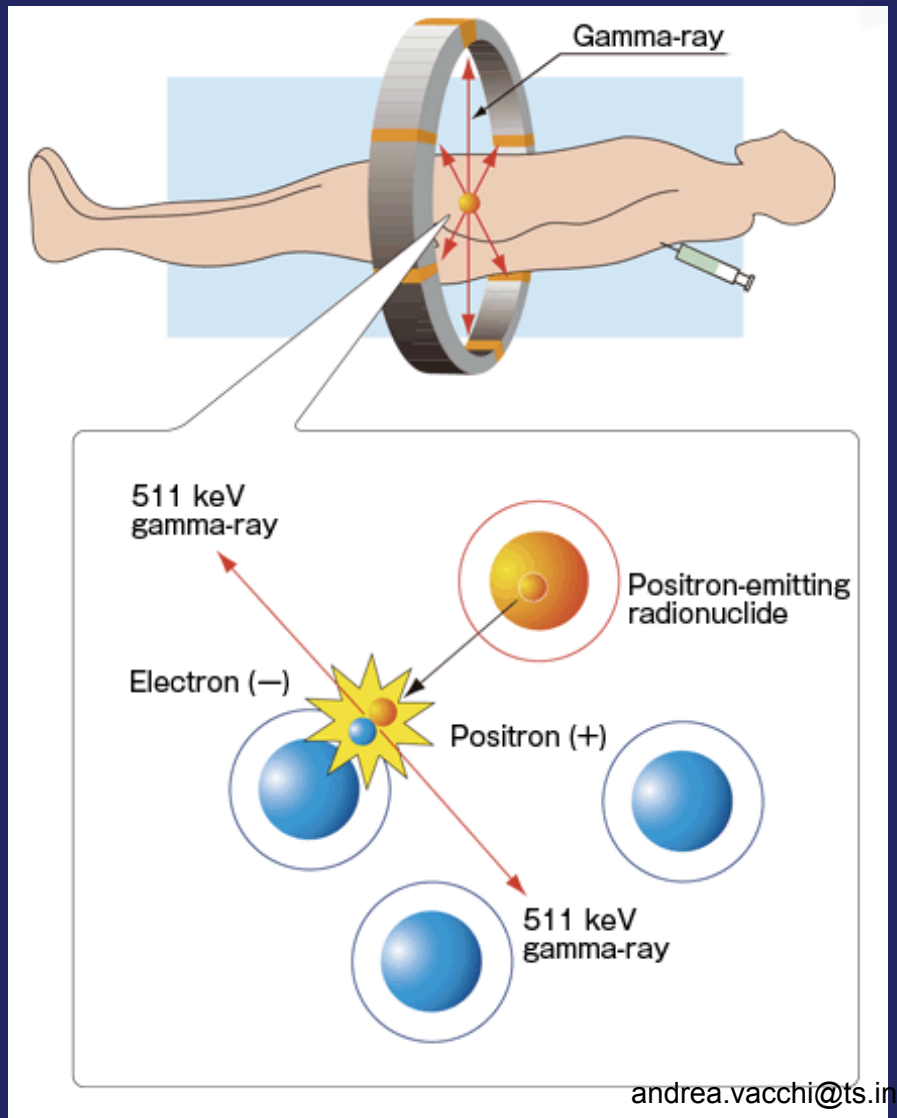
A unique diagnosis tool

Positron-emitting radionuclide and half-life

Nuclide	Half-life
^{11}C (carbon-11)	20 min
^{13}N (nitrogen-13)	10 min
^{15}O (oxygen-15)	2 min
^{18}F (florine-18)	110 min



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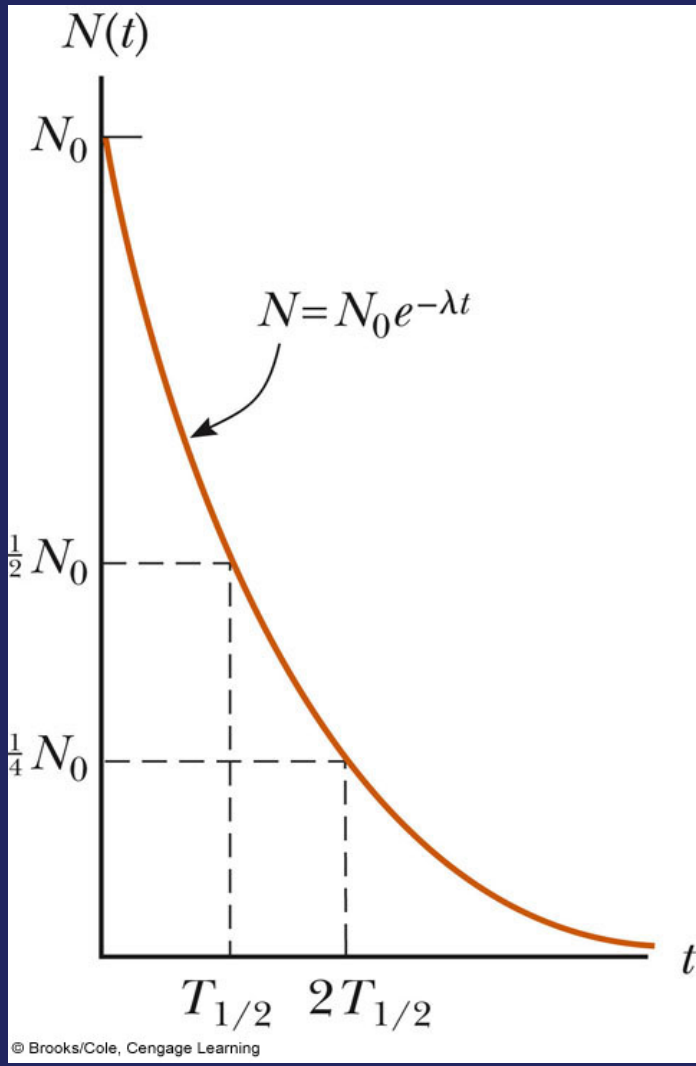
Decay constant λ and half-life

- The rate of decays is the number of decays per second λ the decay constant
- The unit is the Curie (Ci) or Becquerel (Bq)
- The decay is exponential
- - The average life is the time necessary to halve the number of decays



$$1\,\text{Ci} \equiv 3.7 \times 10^{10}\ \text{decays/s}$$

$$1\,\text{Bq} = 1\,\text{decay/s}$$

$$R = \left|\frac{\Delta N}{\Delta t}\right| = \lambda N \quad [29.3]$$

$$N = N_0 e^{-\lambda t} \quad [29.4a]$$

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda} \quad [29.5]$$

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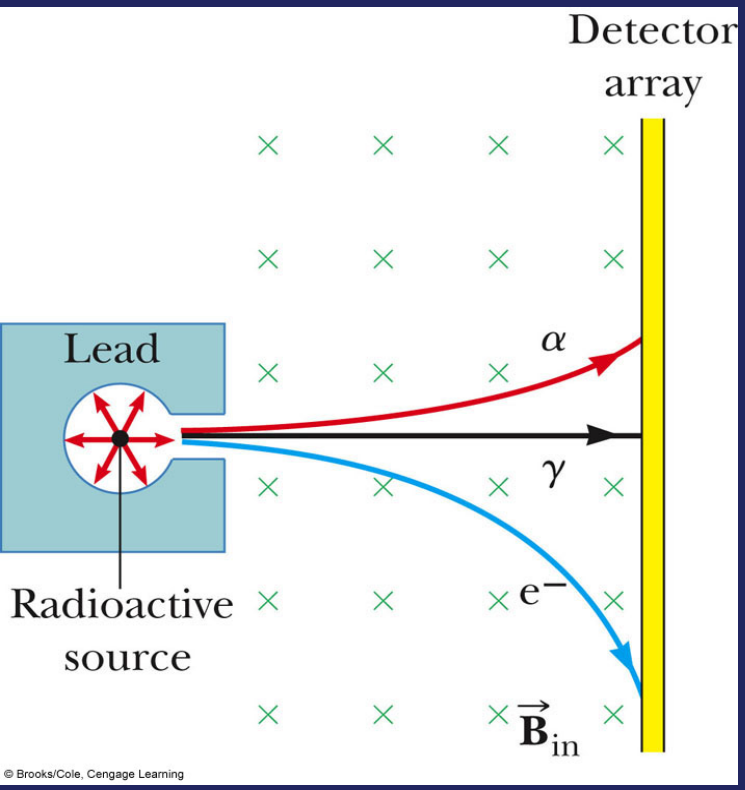
Radioattivity

- Unstable nuclei decay into more stable nuclei
- They can emit three types of radiation



α particles : ${}^4_2\mathrm{He}$ nuclei

β particles : e^- or e^+

γ rays : high energy photons

A positron (e^+) is the antiparticle of the electron (e^-)

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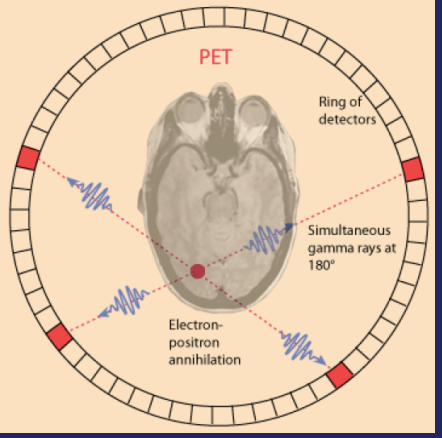
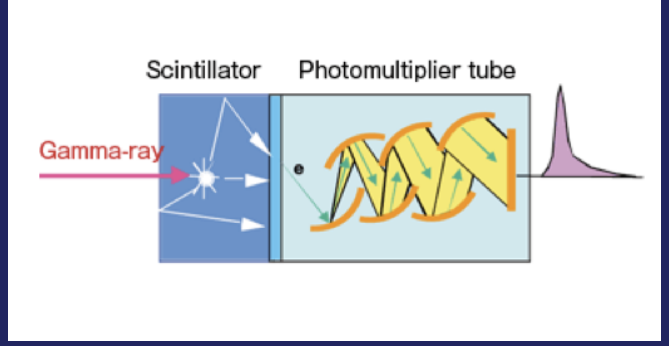
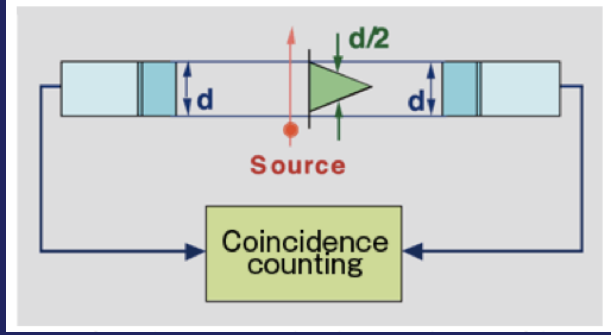


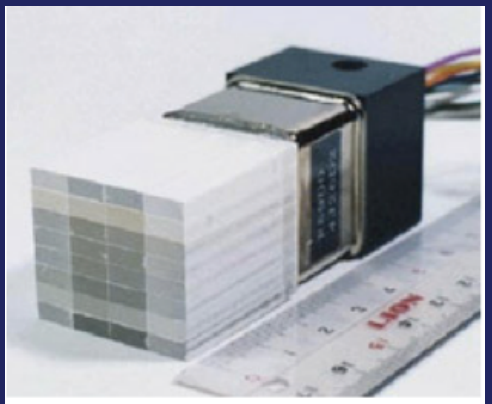


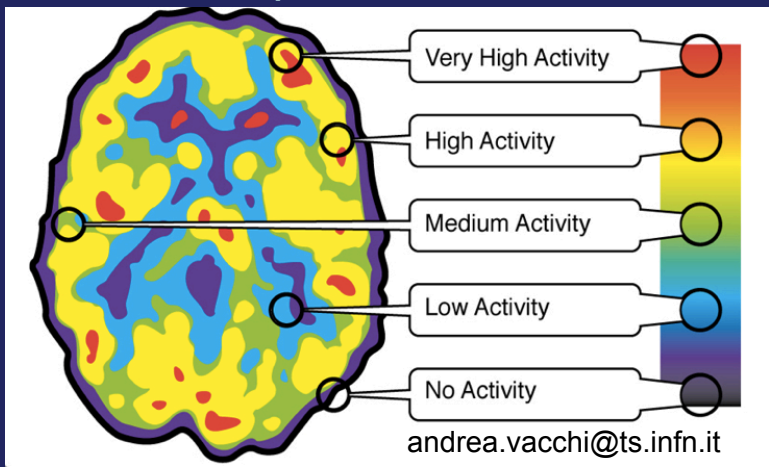


producing photons (gamma) that move in opposite directions

the scintillator crystals of the detector create a stream of light collected by the photomultiplier

From this it is possible to extract the image of the organ or the part of the most active organ part that has absorbed the radioisotope.


Compact PS-PMT



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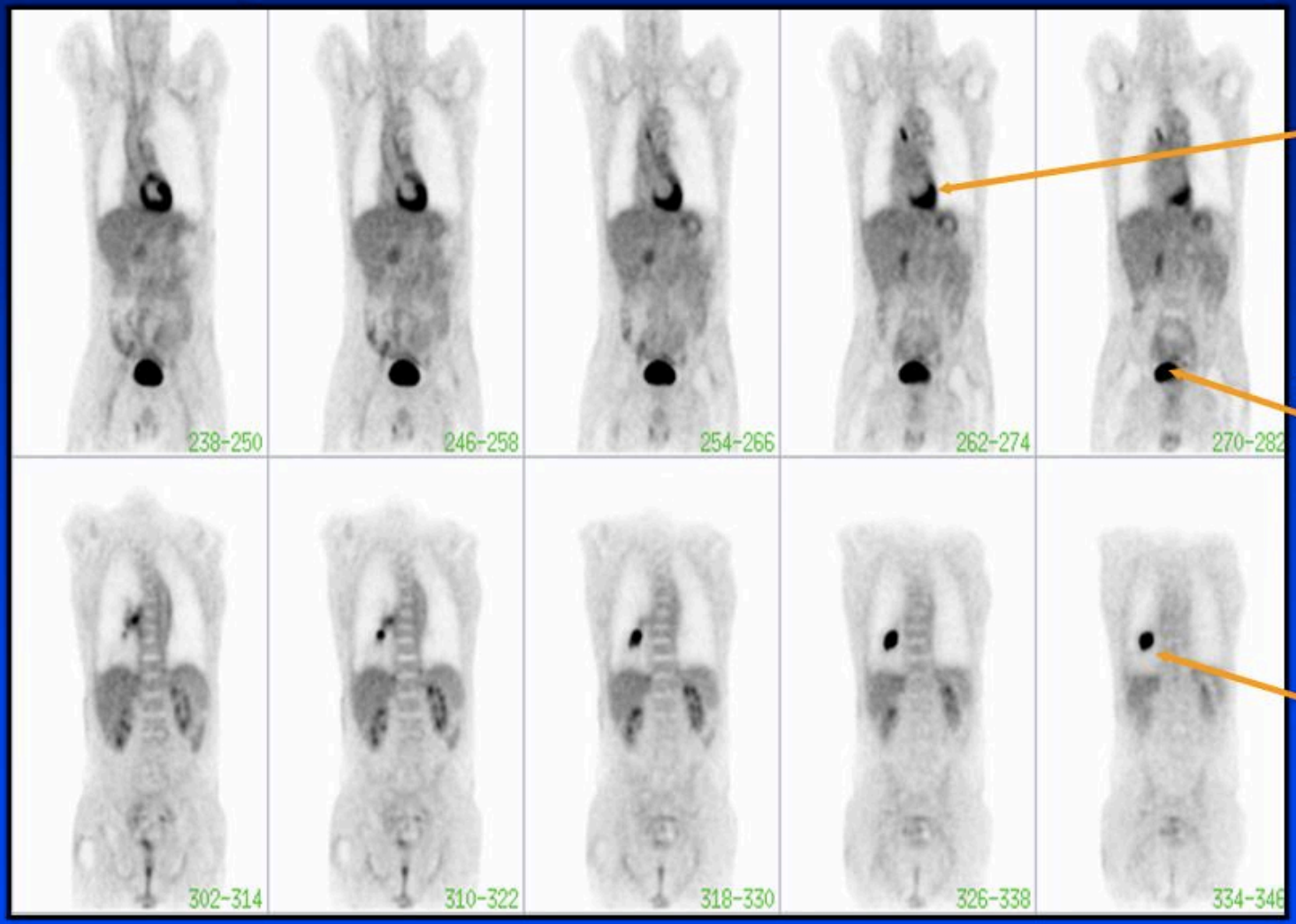
PET SCAN



Heart activity (normal)

Tracer in bladder (normal)

Lung Cancer (abnormal)

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Tracer

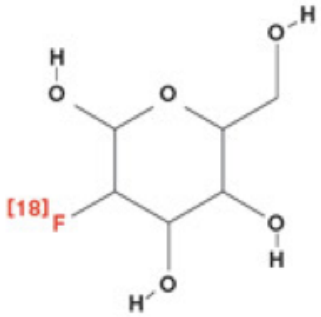

Figure 1. **FDG (fluorodeoxyglucose) Molecule.**

- Radioisotopes used in PET are isotopes of coal, nitrogen, oxygen and fluorine.
- Only radio nuclides of natural elements that pass without damaging the body.
- The type of element employed depends on what the doctor wants to measure. For the research of a tumor, for example, a marked radio glucose is used and it is seen how it spreads.

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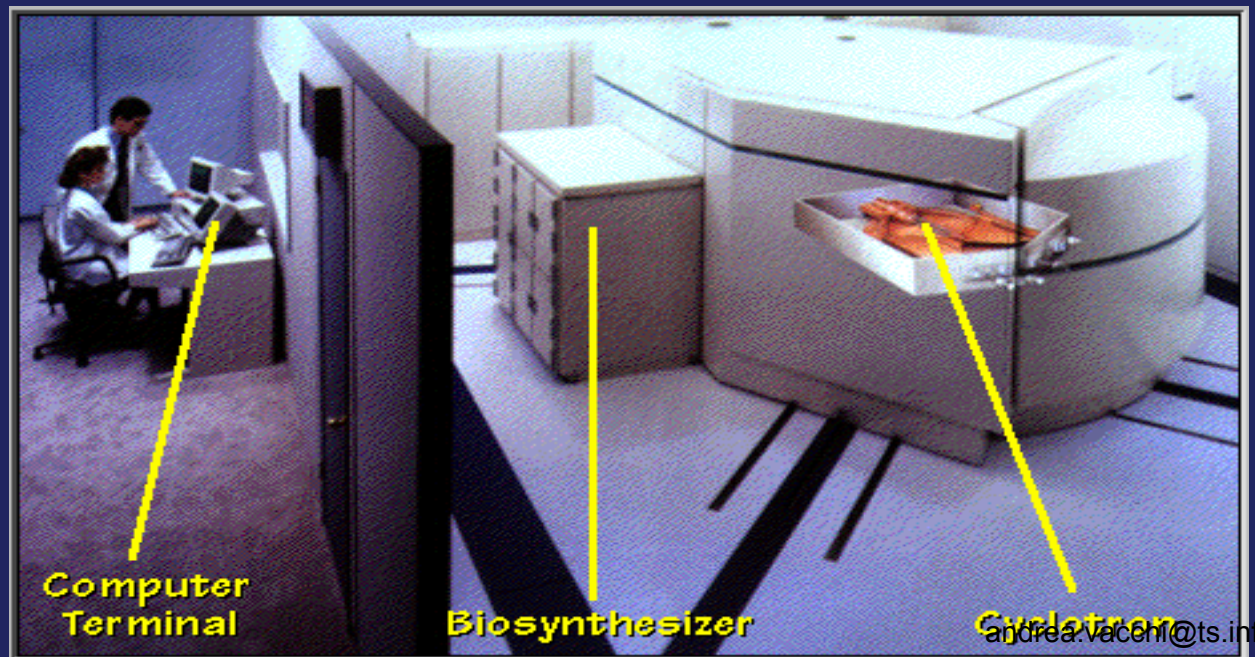
Cyclotron

Accelerators of charged particles.

High Energy particles hit the target material and are absorbed into the nucleus converting the target into several nuclear species.

For example, a proton strikes and is absorbed in ^{18}O-water and converts it into ^{18}F-fluoride with the emission of a neutron and other particles for the energy balance.



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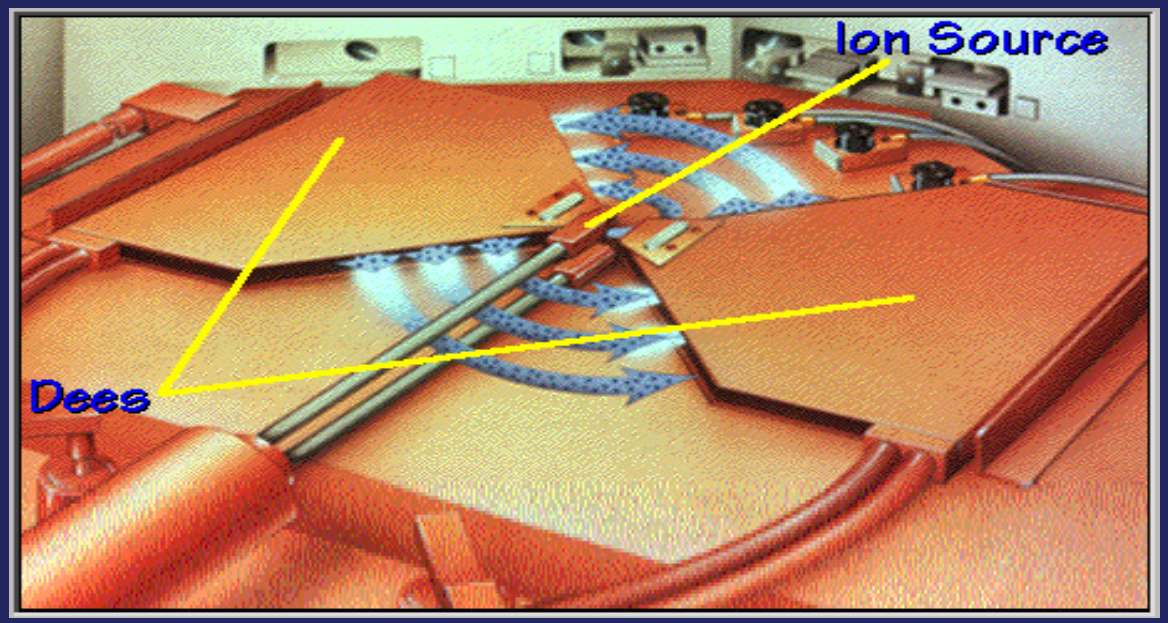
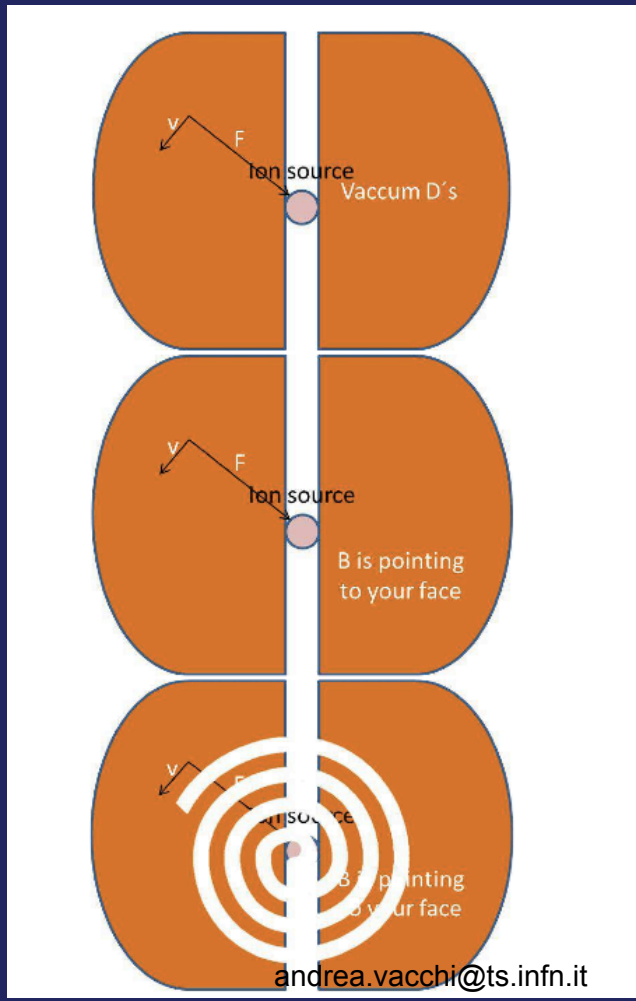
A cyclotron consists of two hollow and semicircular electrodes positioned in the poles of a large electromagnet (not visible here). These electrodes are separated by a small space. At the center an ion source generates charged particles (an arc device that generates a discharge in a gas)



$$\vec{B} = \vec{v} x \vec{F}$$



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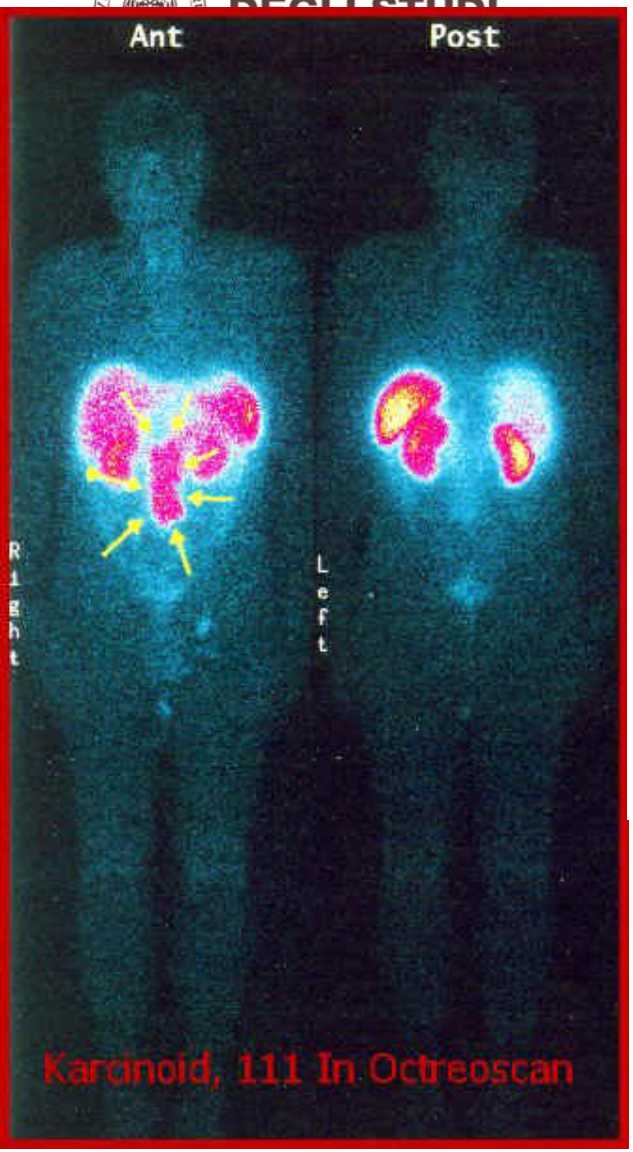

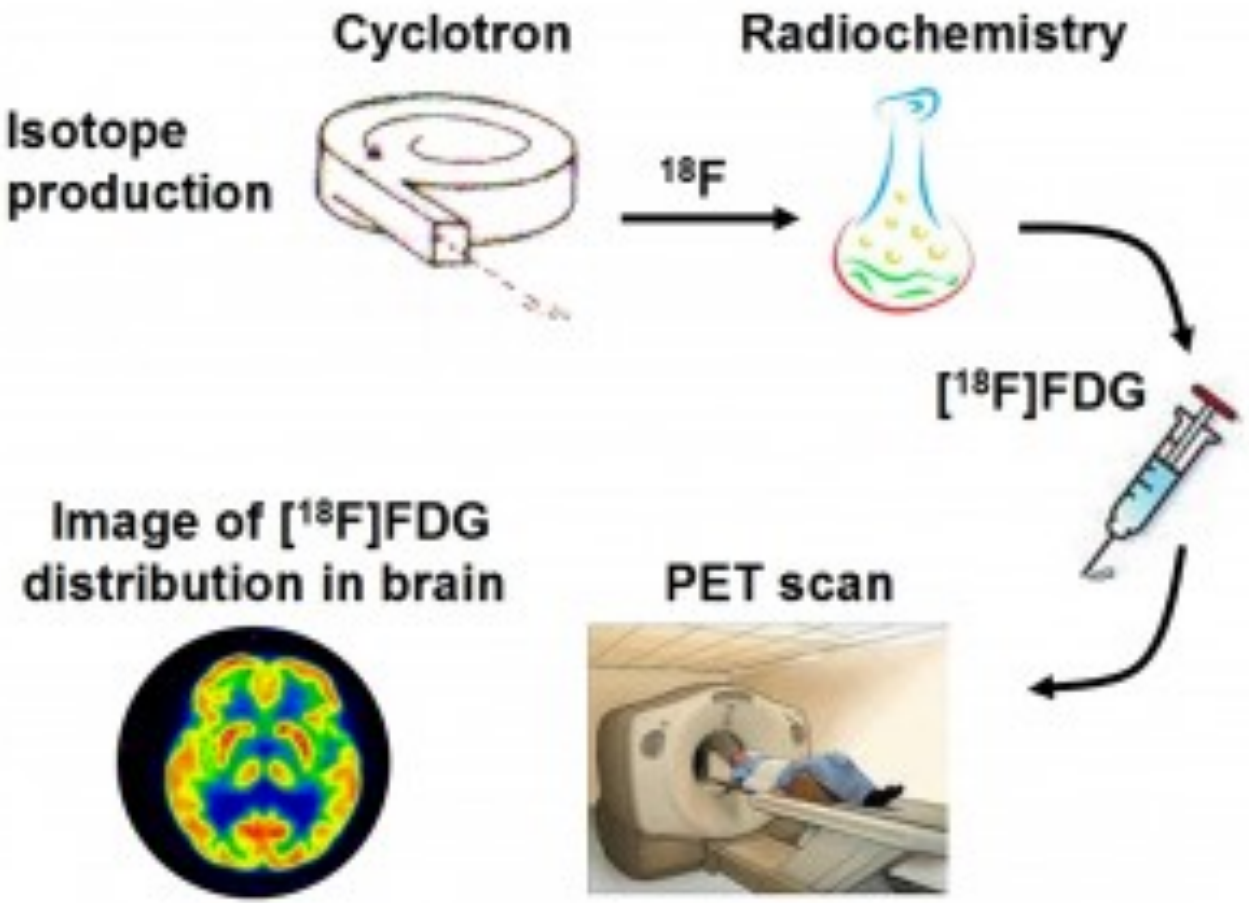

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radiopharmaceuticals

- Drugs that contain a radioactive substance used in the diagnosis and treatment of cancer in the management of pain and bone metastases.

- Medical products that bring radioactivity into the patient. They are mainly used for diagnostic purposes. They allow to obtain images of the distribution of medicinal products and their progression in the body.
- Radio drugs important for the imaging of endocrine tumors (somatostatin receptors)
- Gallium + DOTA + NOC = 68Ga-DOTA-NOC = Radipharmaceutical
- ([1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid] -1-Nal3-Octreotide)

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Benefits of PET

- The information provided by nuclear medicine is unique and often unattainable with other imaging techniques.
- For many diseases the analysis done with nuclear medicine provides the most useful information necessary to make diagnoses or determine the most appropriate treatments.
- Nuclear medicine is less expensive and can lead to information of higher quality than exploratory surgery.
- By identifying changes in the body at the cellular level, the PET image can reveal the onset of the disease well before this becomes evident in other image examinations such as CT and MRI

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Some of the uses

- Revealing tumors.
- Analyze the level of diffusion
- Verify the efficiency of the treatment plan
- Check for any relapses
- Visualize the flow of blood in the heart
- Check the effects of a heart attack
- Identify areas of the heart that could benefit from an intervention (coronary or arterial bypass angioplasty ....).
- Evaluate abnormalities of the brain
- Provide images of normal brain and heart function

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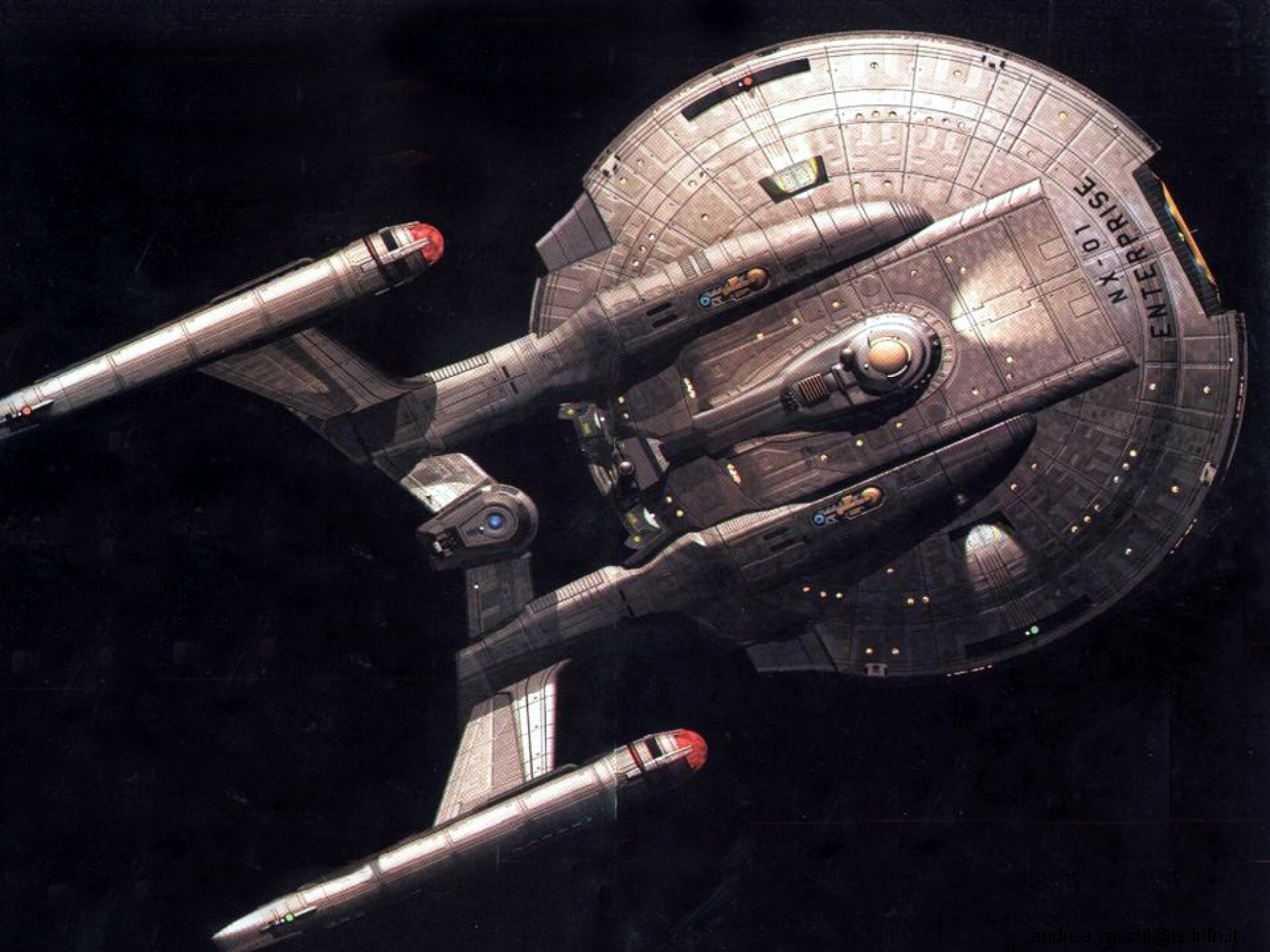

SCIENCE FICTION!!!

In the Star Track episode Doctor Who, an antimatter universe is discovered and used as a fuel source.

In the film, a scientist exposed to antimatter turns into an "anti-man" !!!!

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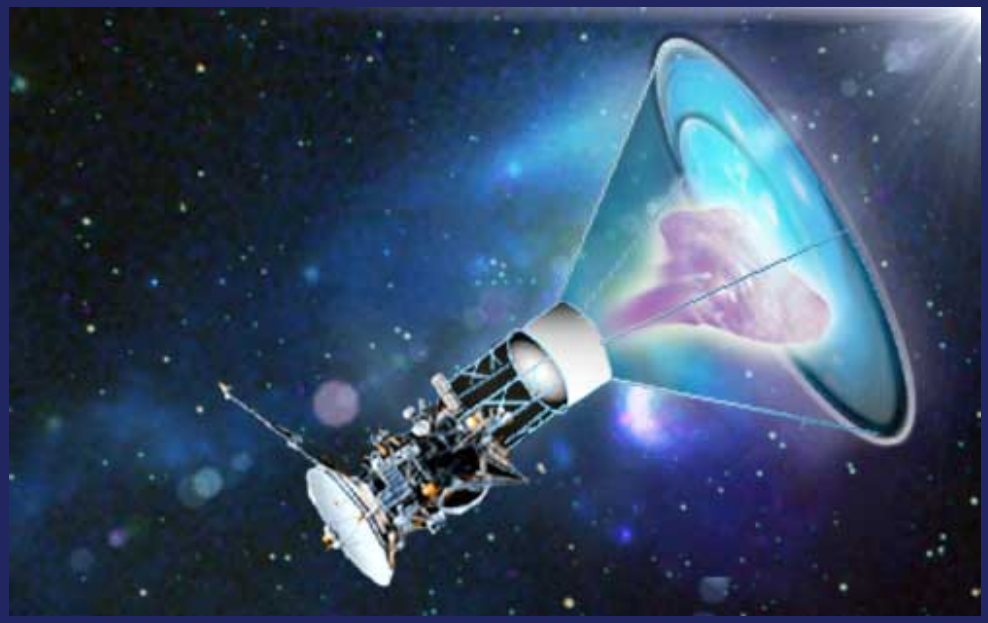
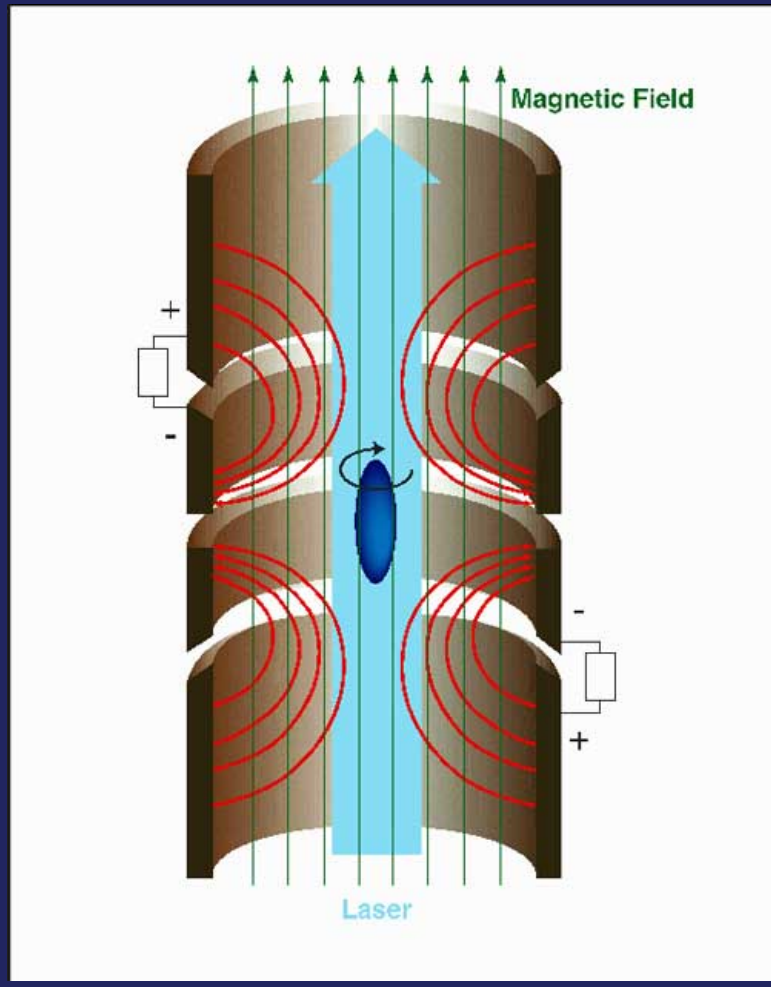
http://www.space.com/businesstechnology/technology/antimatter_sail_021029.html





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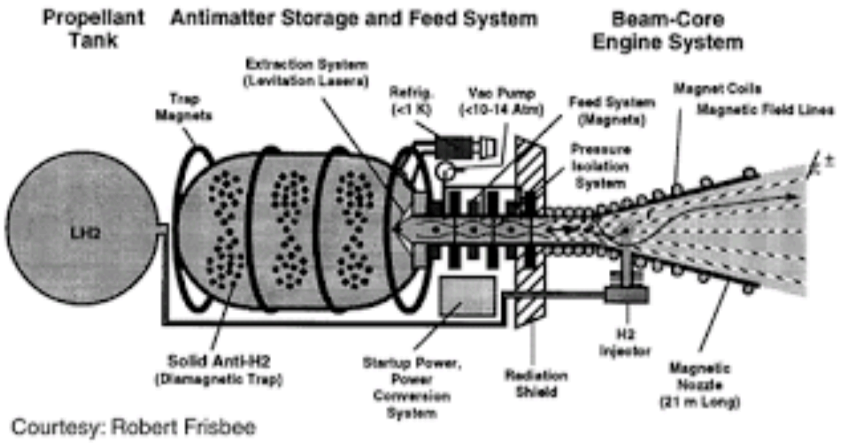
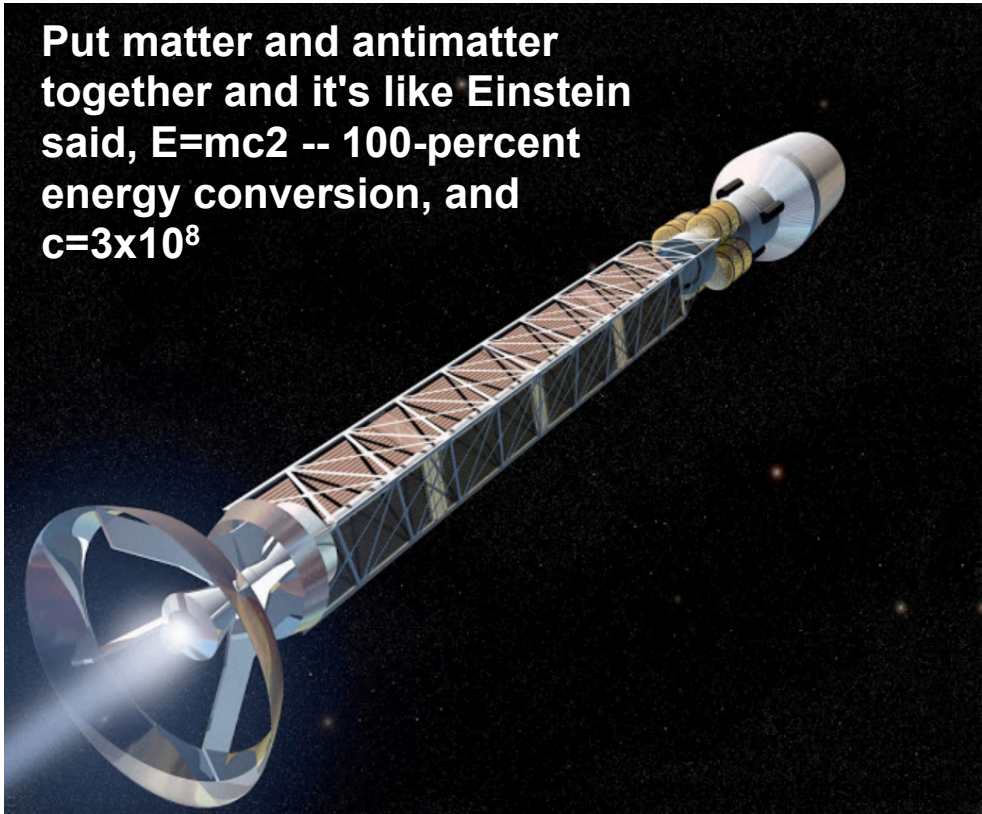
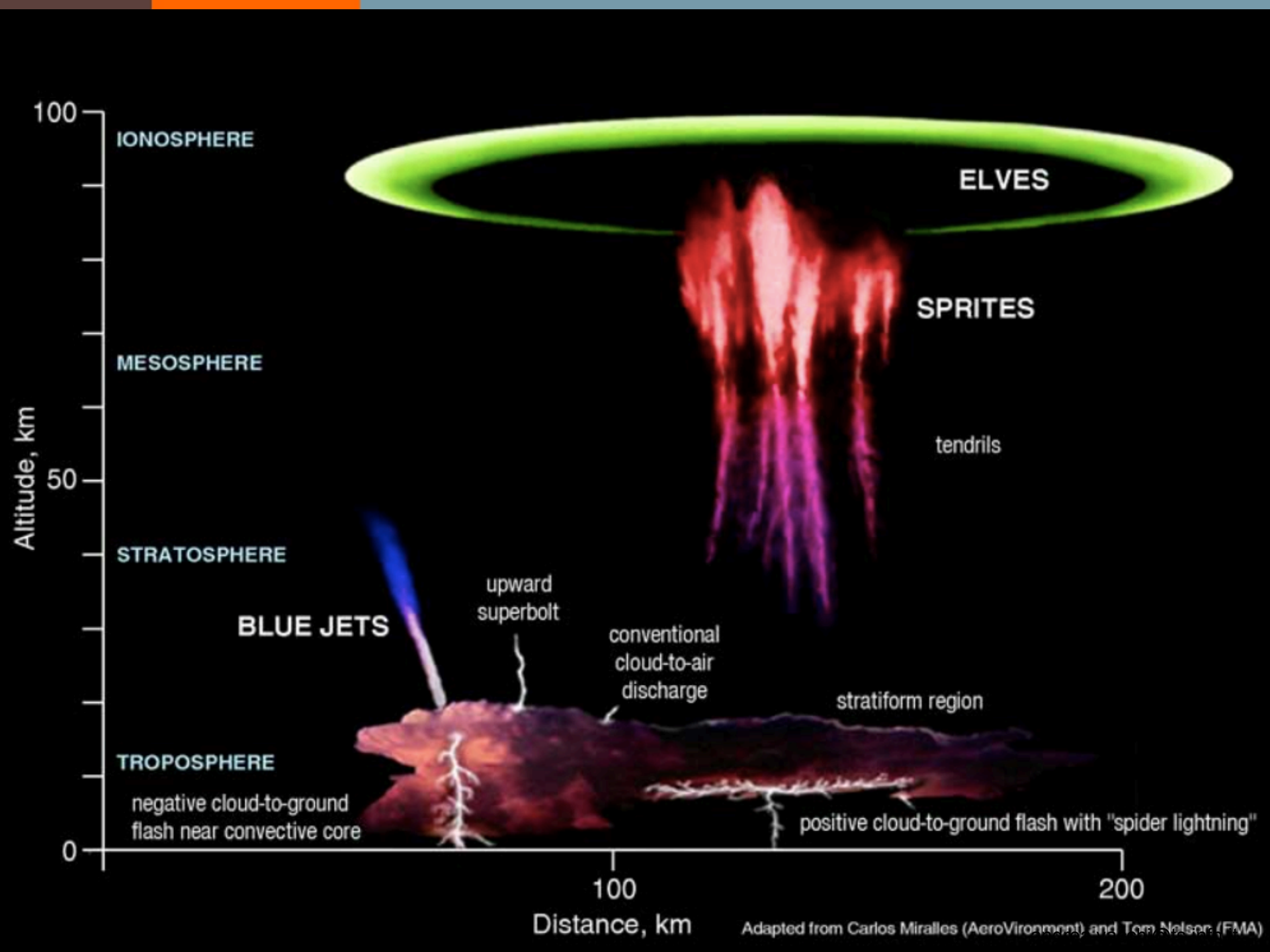
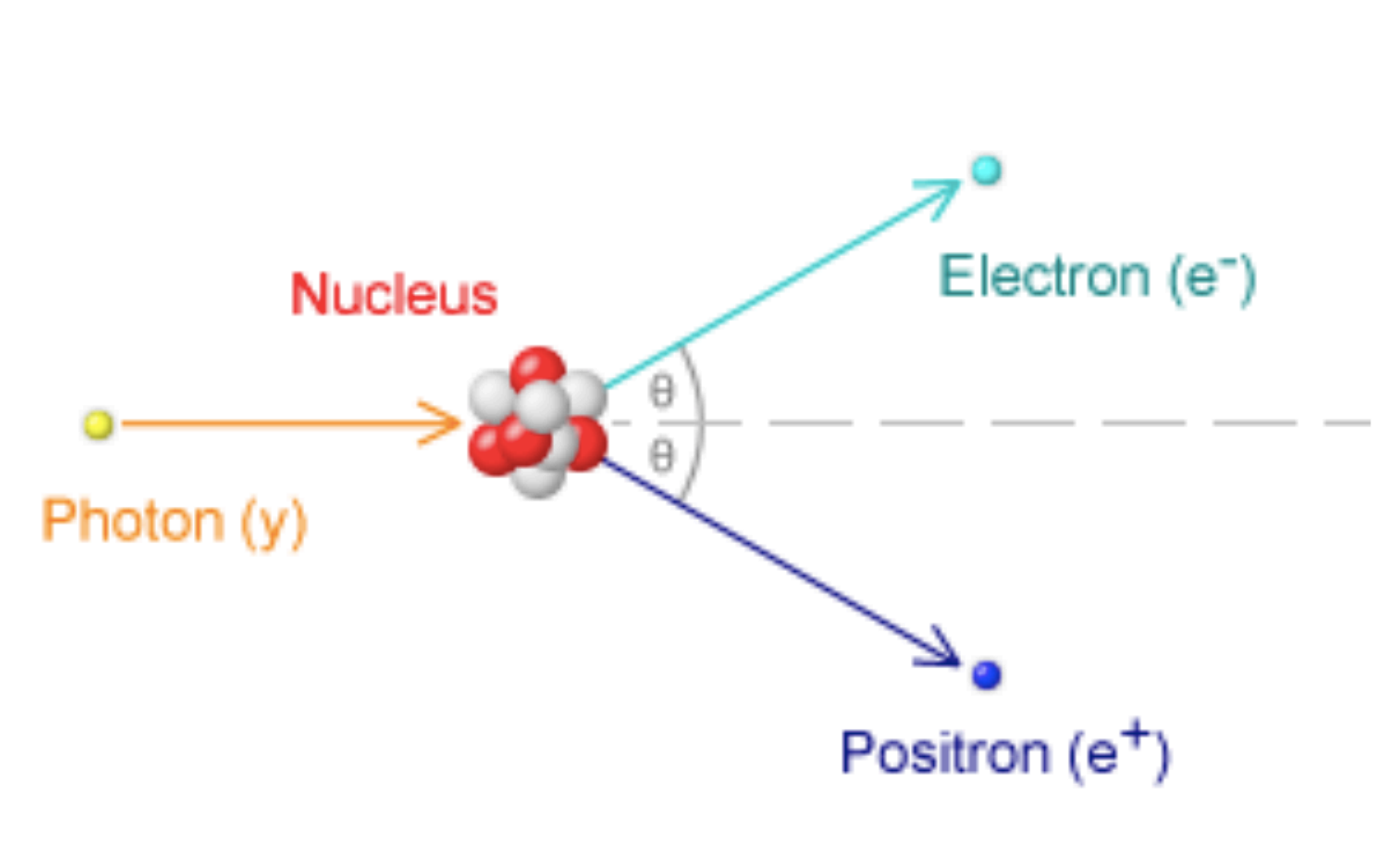
Antimatter Fuel for Rocket is Theoretically Possible

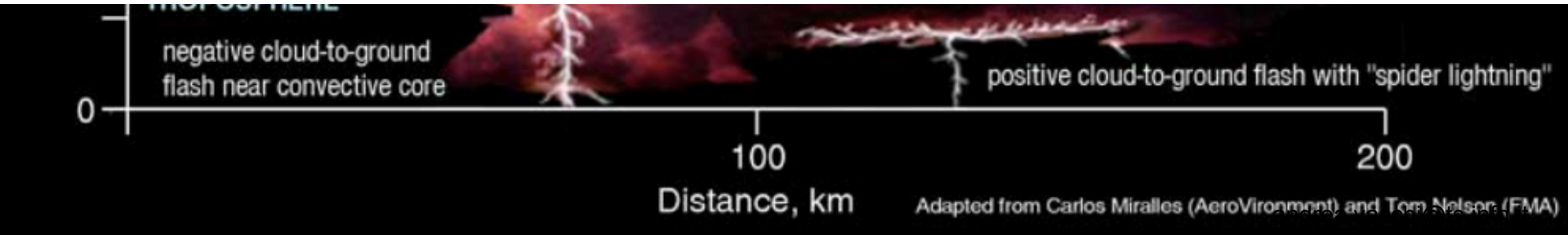


Courtesy: Robert Frisbee

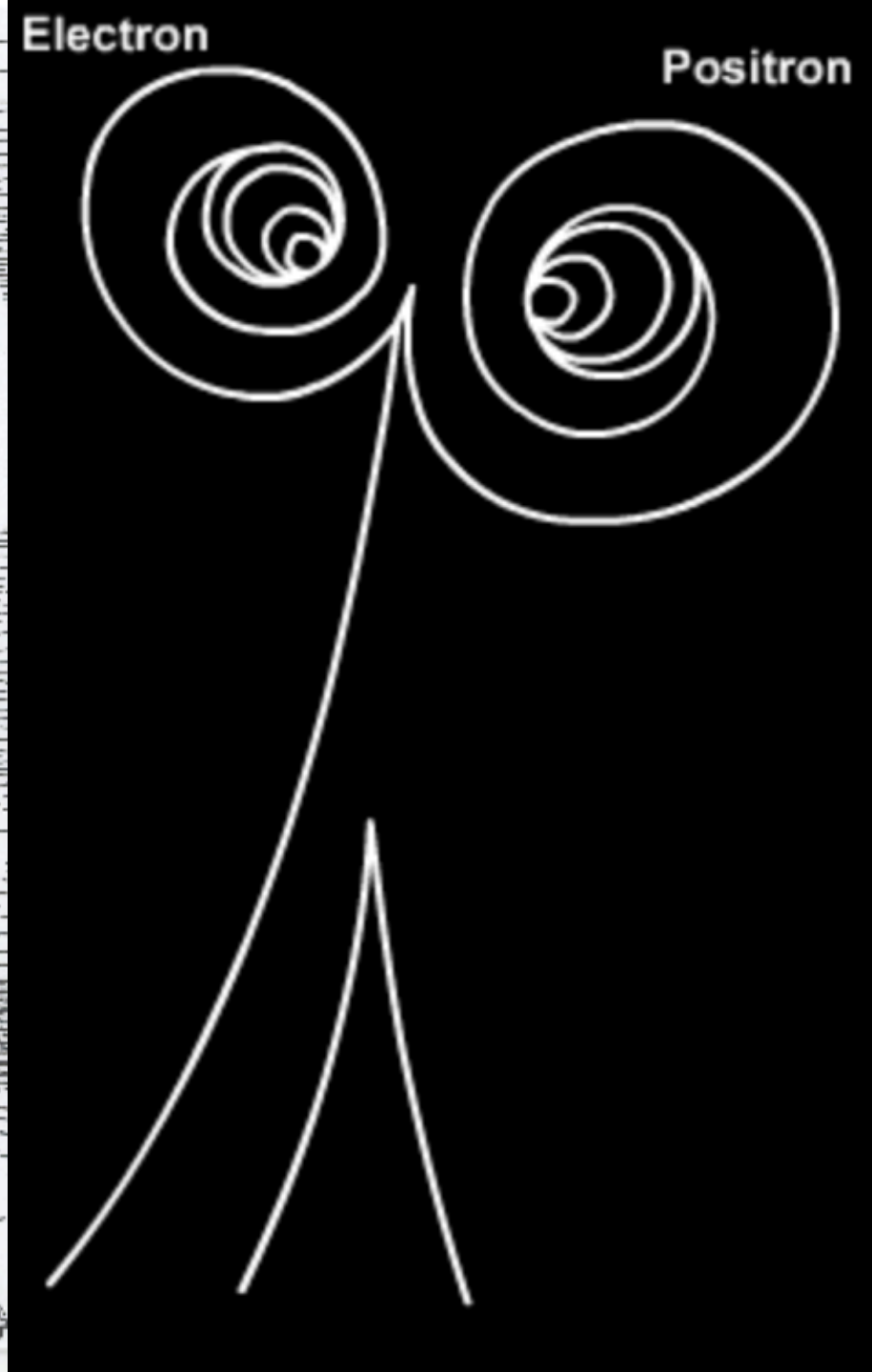



100
IONOSPHERE
ELVES
SPRITES
MESOSPHERE
tendrils
50
Altitude, km
STRATOSPHERE
upward
superbolt
BLUE JETS
conventional
cloud-to-air
discharge
stratiform region
TROPOSPHERE
negative cloud-to-ground
flash near convective core
positive cloud-to-ground flash with "spider lightning"
0
100
200
Distance, km
Adapted from Carlos Miralles (AeroVironment) and Tom Nelson (FMA)


Nucleus
Electron (e^-)
θ
θ
Photon (γ)
Positron (e^+)


negative cloud-to-ground
flash near convective core
positive cloud-to-ground flash with "spider lightning"
0
100
200
Distance, km
Adapted from Carlos Miralles (AeroVironment) and Tom Nelson (FMA)


General
physics


Electron
Positron

The surprises are always lurking, Andreson wrote:

"I knew of Dirac's theory ... .. but I did not know the details of that work I was too busy to make the instrument work to have time to read his articles"

Anderson

The discovery of the positron was completely accidental

Thank you of your attention

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