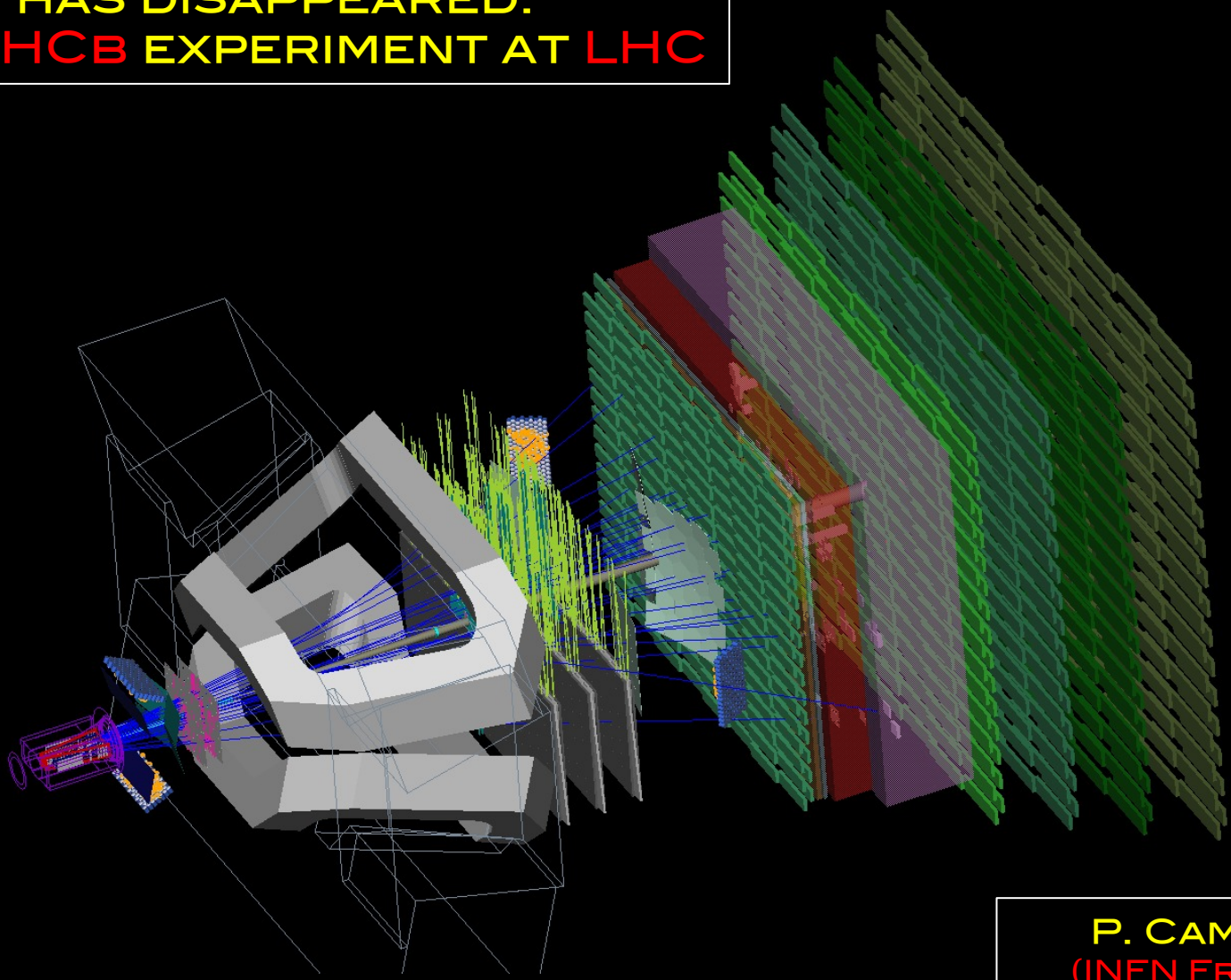
Understanding why antimatter has disappeared: the LHCb experiment at LHC



P. Campana
(INFN Frascati)
Inspyre 2015
19/02/2015 - Frascati

"It's an accident that the Earth and the Solar System are made mostly of negative electrons and positive protons.

It's also possible that some of the stars are made in the opposite way, that is they are constitued of anti-electrons and anti-protons.

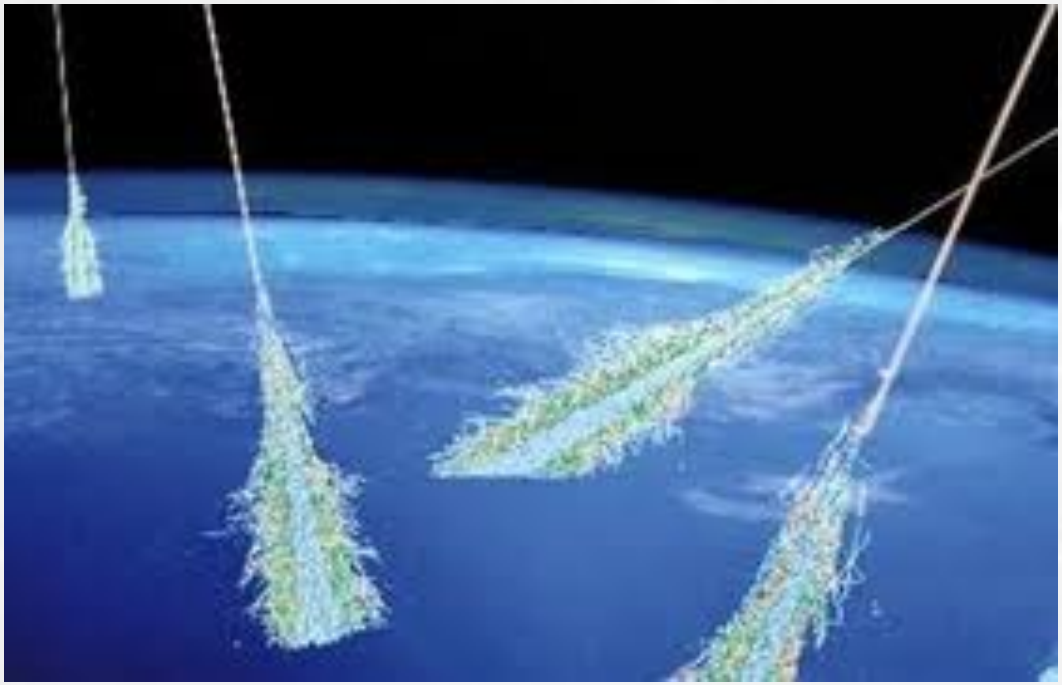
Maybe half of the stars are like this … however it would not be possible to become aware."

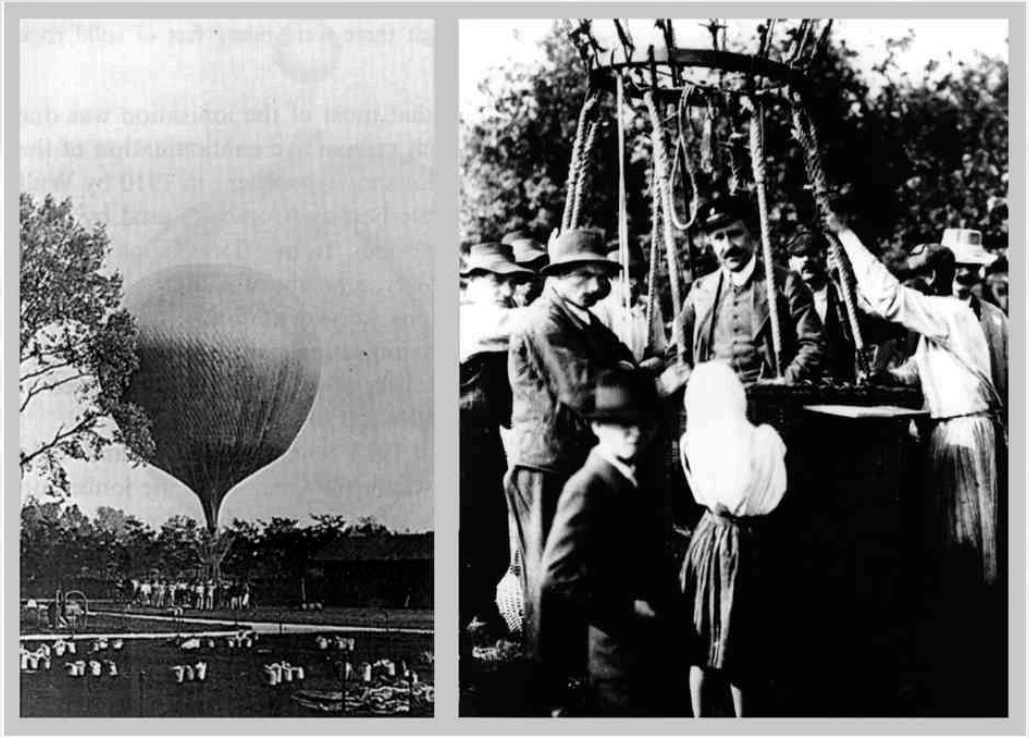
Paul Dirac (1933, Nobel speech)

Items covered in this seminar

1. The discovery of cosmic radiation and the search for antimatter
2. Short history of Big Bang
3. LHC: an accelerator to study the Big Bang
4. Searching for the missing antimatter
5. Future perspectives
6. Epilogue

2. The discovery of cosmic radiation and the search for antimatter





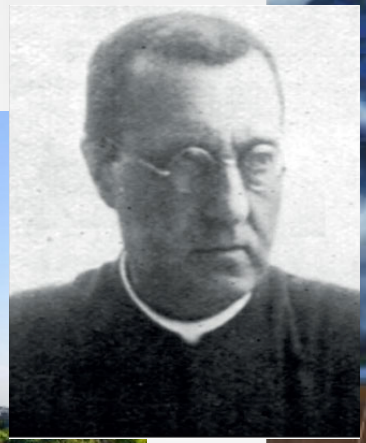
At the beginning of XX century, physicists thought that ambient radioactivity could come also from the sky and not only from the Earth rocks

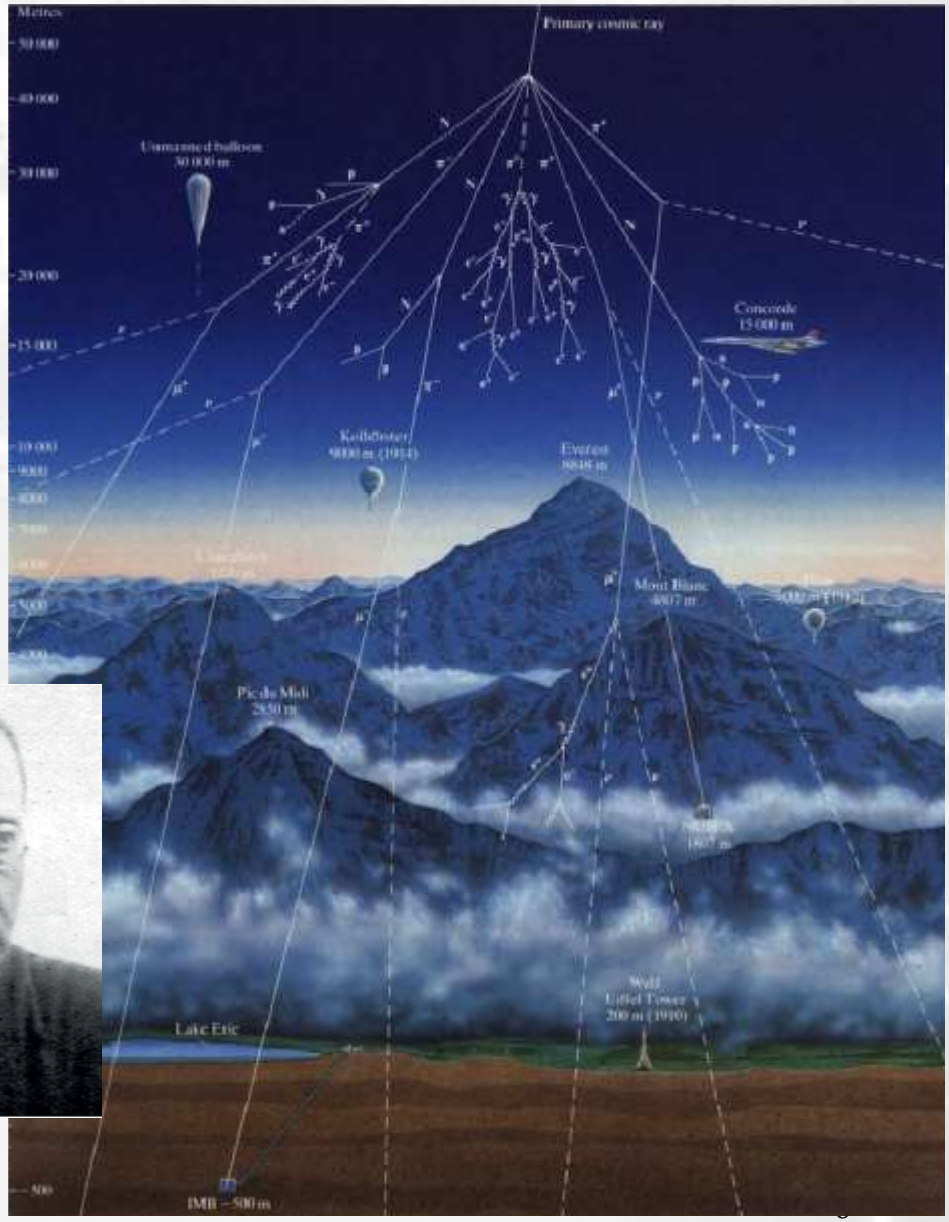
In 1912 V. Hess flew an aerostatic balloon at 6000 m, discovering that the radioactivity increased with height, showing its extra-terrestrial origin

Cosmic Rays had been discovered !

However, 2 years before, the Jesuit priest T. Wulf had noticed that the radio-activity on top of the Tour Eiffel was higher than at the bottom …

But Hess got the Nobel in 1936 for the discovery of Cosmic rays !

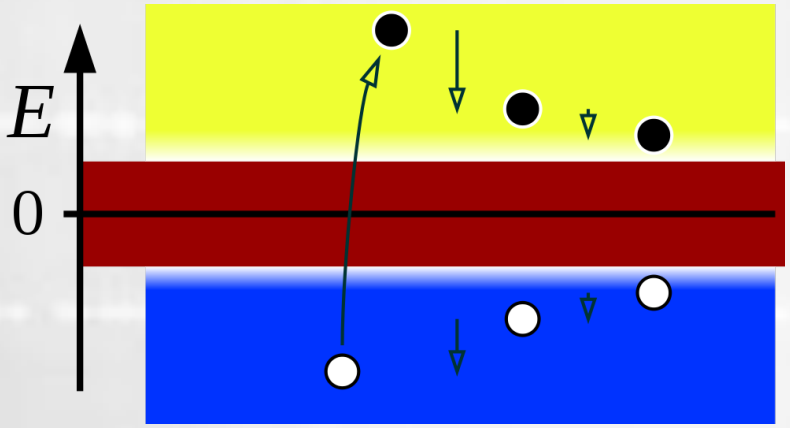




$$(i\gamma\cdot\partial - m)\psi = 0$$

In 1929, P. Dirac tries to combine the effects of the recent born theories on Relativity and Quantum Mechanics (thanks to the work of Planck and Einstein) to explain the behavior of electrons

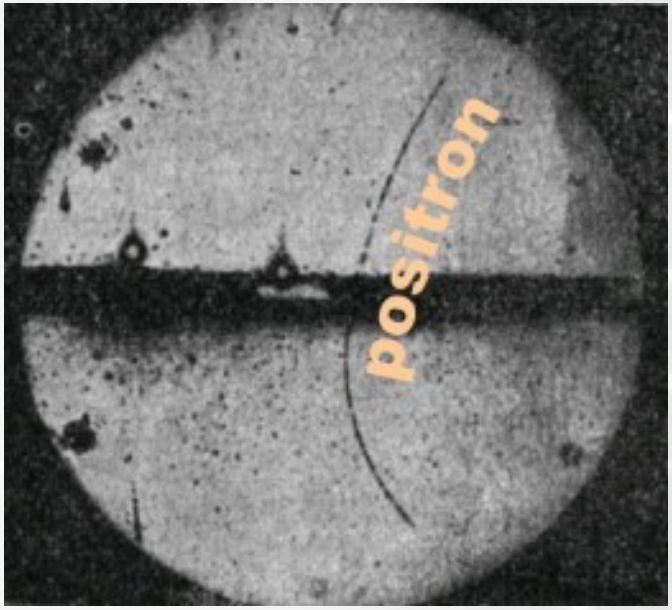
From his theoretical studies, he understood that for each electron (with negative charge) a corresponding positive charged particle of the same mass should exist (the anti-electron or positron).



In 1932 C. Anderson while studying
Cosmic Rays using photographic emulsions,
immersed in a magnetic field,
discovers that some of the tracks similar to
those of electrons show a “wrong curvature”
and can be explained with
the first observation of positrons !

It was the discovery of anti-matter !

Anderson got the Nobel prize in 1936

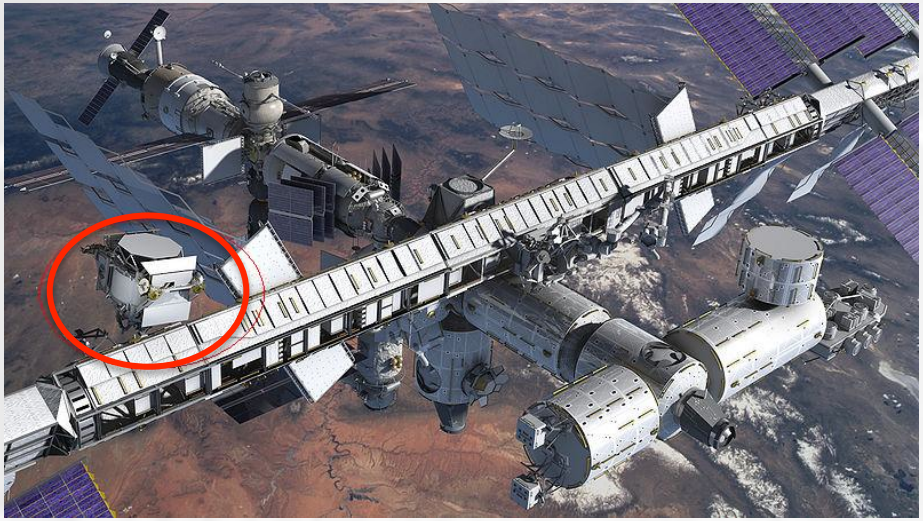


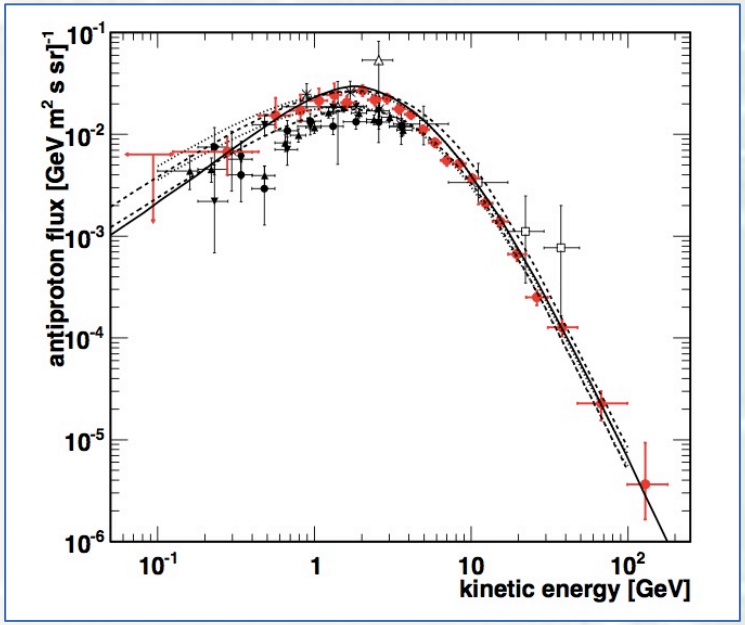
In the ‘50s the developments in technology allow the construction of the first powerful accelerators, where in the collisions of particles of high energy, the first artificial samples of anti-protons (1954) and anti-neutrons (1956) are produced

The road for the study of anti-matter was opened

In the mean time, physicists ask themselves if anti-matter is present in the primary cosmic radiation, the one arriving on top of our atmosphere, before interacting with it

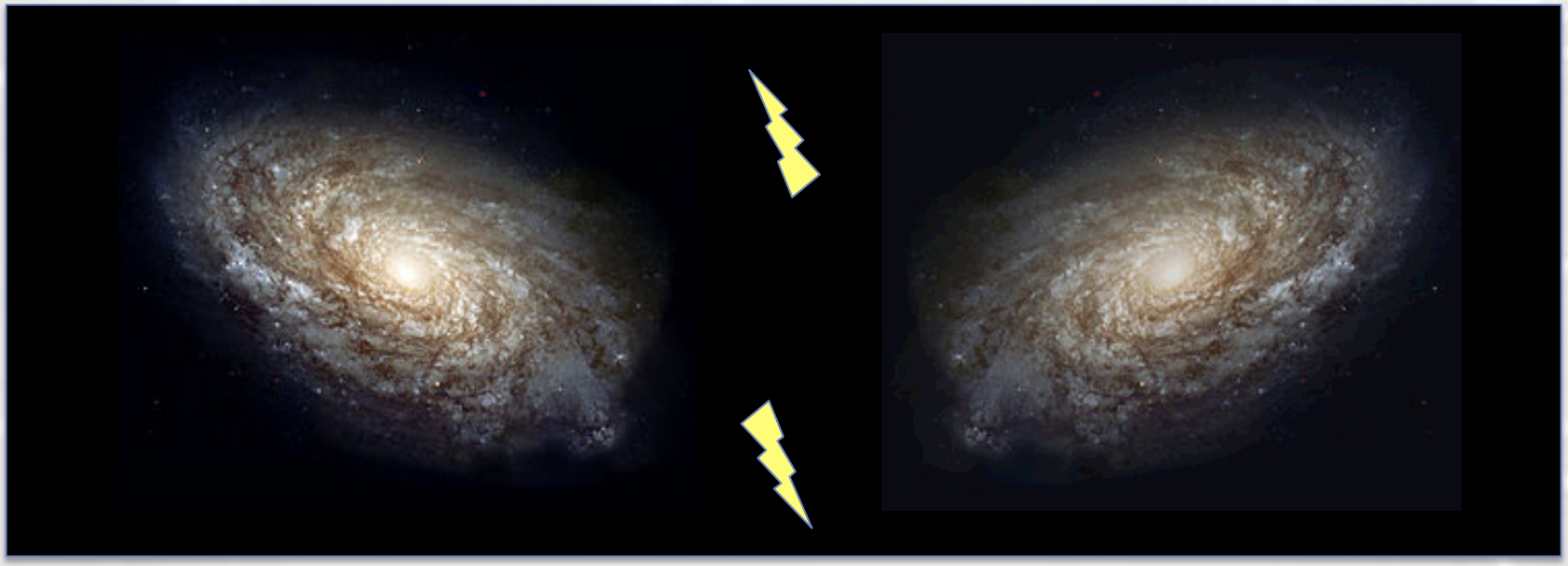
Searches for extra terrestrial anti-matter performed with balloons or satellites, located outside Earth atmosphere, do not show any remarkable flux of anti-particles beyond that coming from interactions of “normal” matter (mainly protons) with the very rare cosmic matter





In particular, the detector AMS mounted on a “arm” of the International Space Station, is performing very precise measurements on this subject (in data taking since 2011)

So, where is the anti-matter in the sky ?
Somebody made the hypothesis that it is “stored” in large clusters of (anti-)galaxies very far away from normal one.
However in this case one would observe continous emission of photons due to collisions of matter and anti-matter in cluster boundary regions



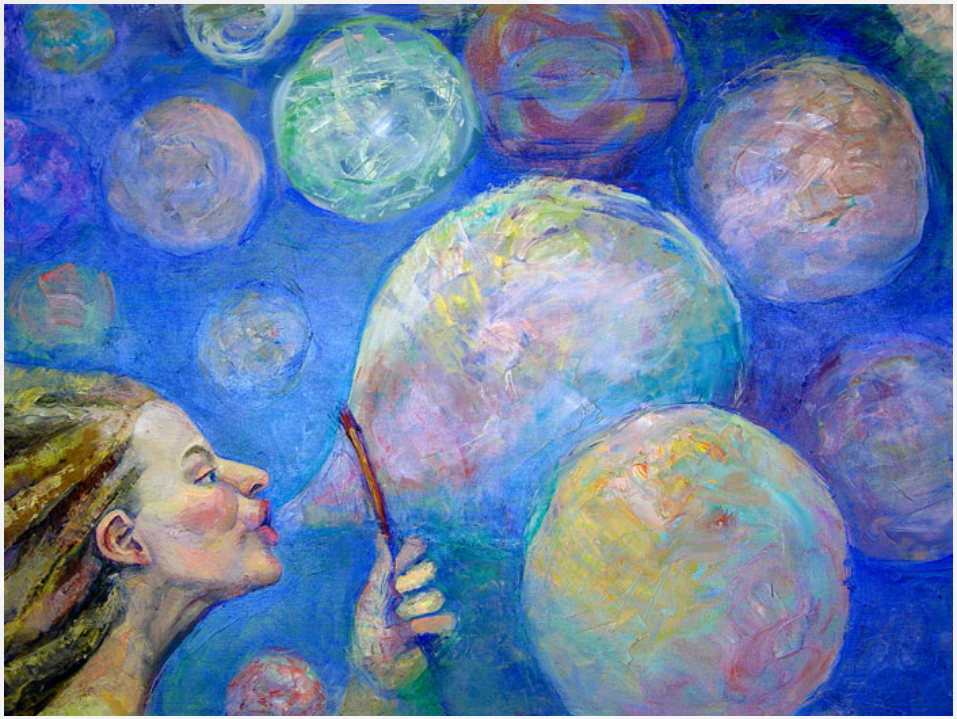
No anomalous fluxes of photons have been observed so far

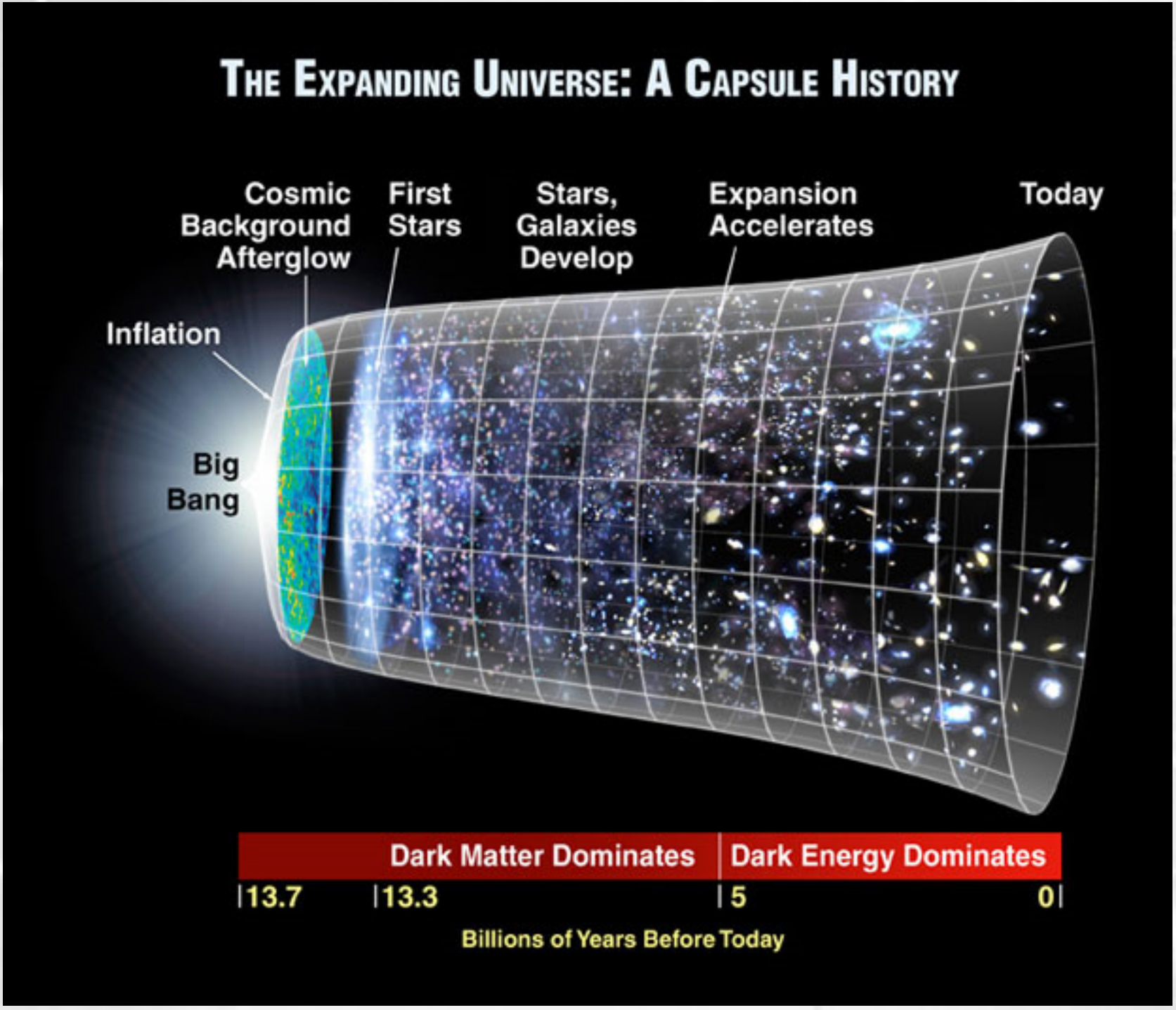
Therefore physicists are asking themselves why there is so little anti-matter around and what was the mechanism for such a suppression

Answering to this question means to go backward in time, at least **13 billions years** ago …

… when we believe everything started

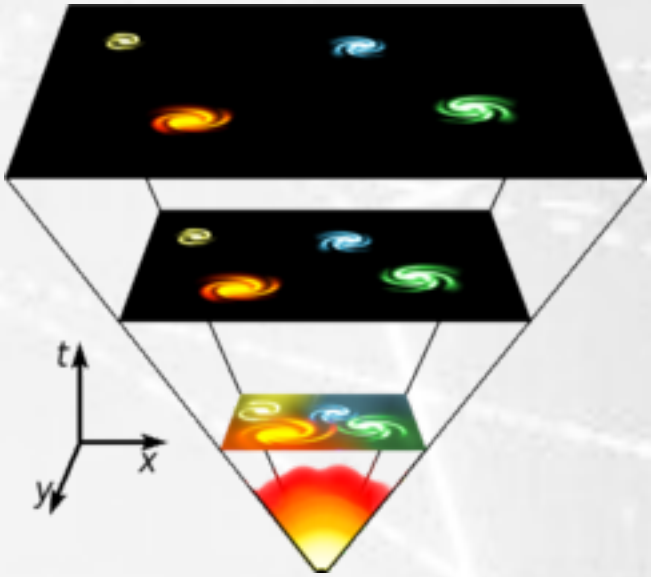
2. A short history of Big Bang




THE EXPANDING UNIVERSE: A CAPSULE HISTORY
Cosmic Background Afterglow
First Stars
Stars, Galaxies Develop
Expansion Accelerates
Today
Inflation
Big Bang
Dark Matter Dominates
Dark Energy Dominates
13.7
13.3
5
0
Billions of Years Before Today

Most accurate determinations of Universe age tell us **13.78 ± 0.06** billions years

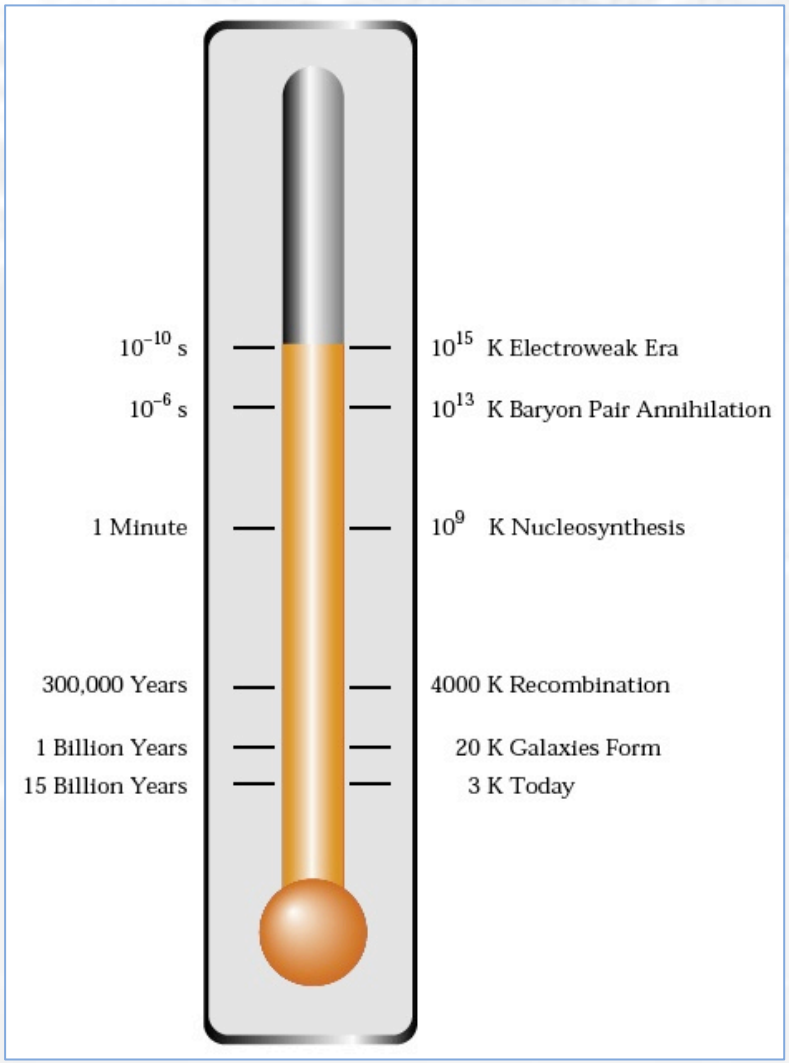
The name **Big Bang** refers to the most complete theory to describe how the Universe has evolved. According to this model, about 14 billions of years ago, the Universe was a "point" extremely hot and dense, that started to expand very rapidly



Soon after this expansion, it cooled down, converting its energy in the creation of protons, neutrons and to give birth to the lightest nuclei, then to the heaviest and then to the formation of stars, galaxies, etc…

From that point onward, the history of the Universe is dominated only by the gravitational energy who produced the shape we know now of galaxies, stars and planetary systems (including ours). **Then life came** …

The “thermometer” of the time of the Universe

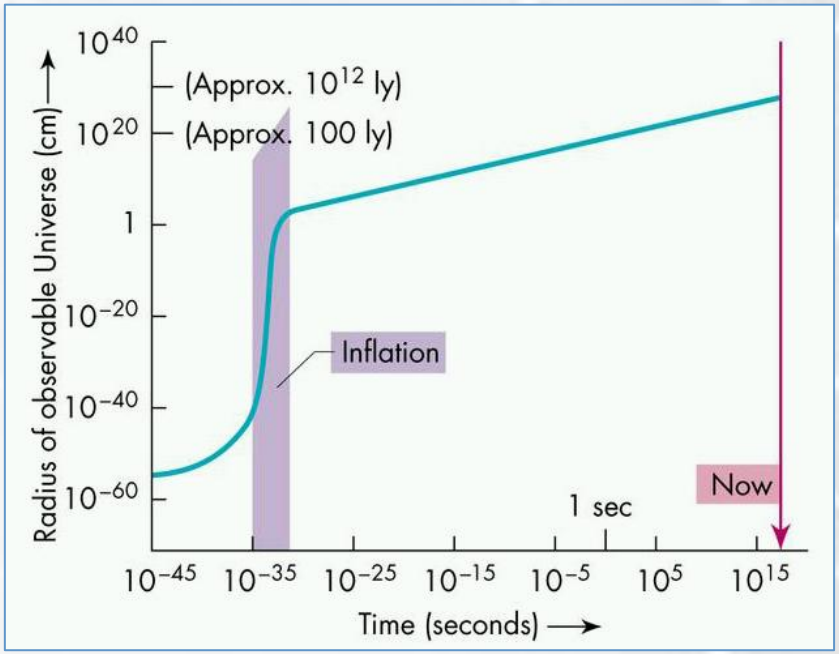


$t < 10^{-36}$ s

We know very little about: everything was collapsed in a point with a nearly infinite temperature
In these conditions, the physics laws we know are no longer valid

10^{-36} s < t < 10^{-32} s

The Universe expands very rapidly (~10^{78} times in size, "**inflation**" mechanism) and also in a very homogeneous way (isotropy).
We do not know exactly the mechanisms, but we know that this hypothesis is confirmed by experimental observations from satellites and telescopes



10^{-32} s < t < 1 s

The matter is very hot, but it it cooling very slowly.
Quarks and leptons are free in a sort of "primordial soup"
Matter, antimatter and photons are in equilibrium

$$p + \bar{p} \leftrightarrow \gamma + \gamma \qquad n_\gamma \approx n_p, n_{\bar{p}}$$

As cooling continues, quarks can recombine and give origin to protons (and anti-protons), neutrons (and anti-neutrons) and to many other particles (and anti-particles). Matter and anti-matter is continuously created and destroyed. However, an unknown mechanism generates a very small **asymmetry** matter-antimatter

Anti-matter (30,000,000)

Matter (30,000,001)

This very tiny difference has catastrophic consequences, generating the so-called "**baryogenesis**" – the creation of baryons, which are the particles constituting the matter (protons and neutrons)

In fact in this period of Universe evolution, the available energy is so low that after the annihilations (collisions among baryon and anti-baryons) that result in their disappearance and in the generation of photons, they are no longer re-generated and the effects are the following:

- A decrease in the amount of matter and the increase in the no. of photons

$$\frac{n_{baryon} - n_{\overline{baryon}}}{n_\gamma} \sim O(10^{-10})$$

- The definite disappearance of anti-matter (due to the unbalance shown in the previous slide)

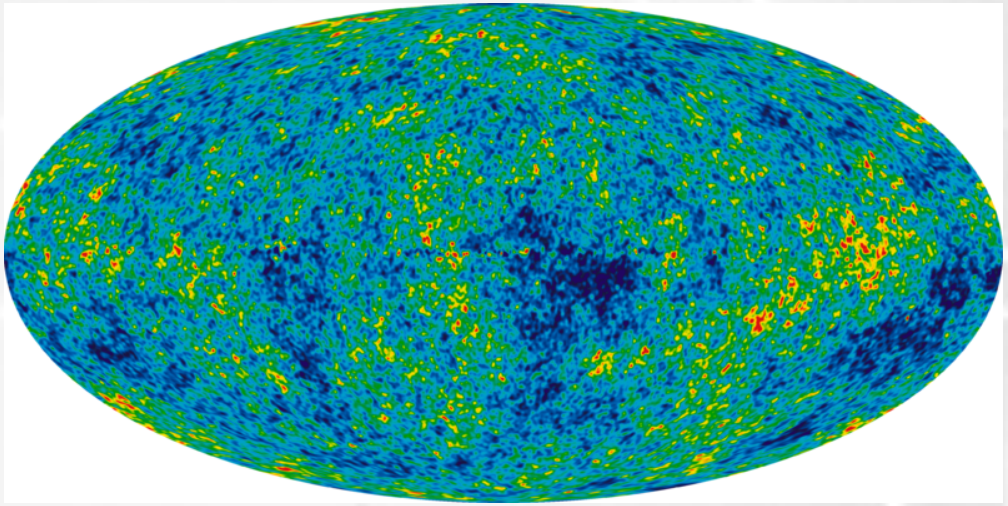
The same mechanism holds for leptons ("**leptogenesis**") in which positrons disappear

1 s < t < 380,000 y

The matter continues to cool down
The lightest nuclei ^{4}He and ^{2}D start to be built ("**nucleosynthesis**")

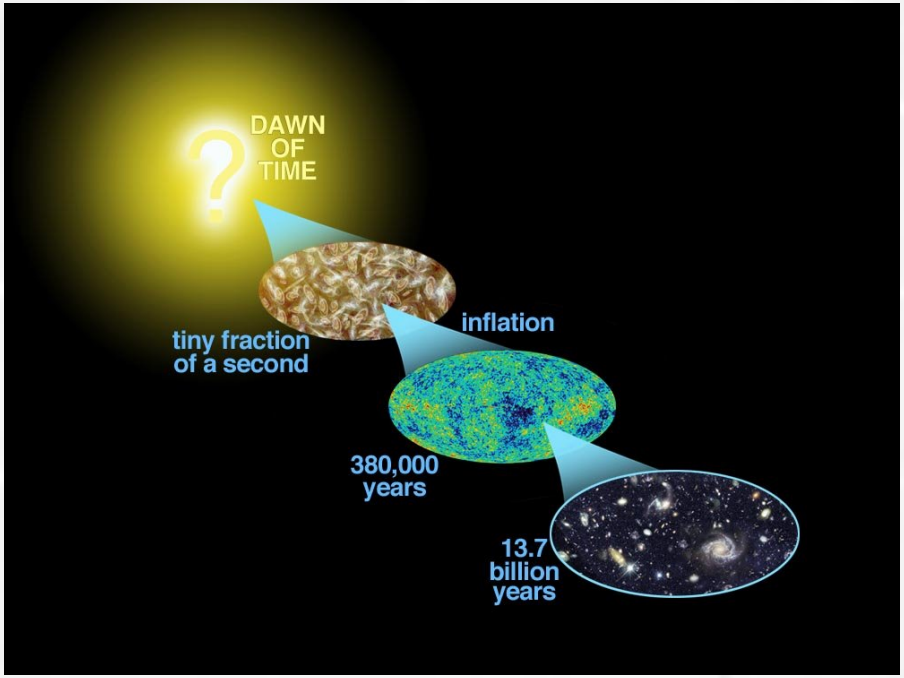
The Universe that was opaque to the electromagnetic radiation (photons) due to its density, starts to be transparent.
Photons come out of this "fog", creating a sort of radiography of the Universe at an age of 380,000 years: this is the first echo of the Big bang, a sort of background sound that we can "hear" still today (T=2.7 K or a frequency of 160 GHz, used in communications)

The **Cosmic Background Radiation** was discovered in 1964 by Penzias e Wilson (they got the Nobel in 1978)

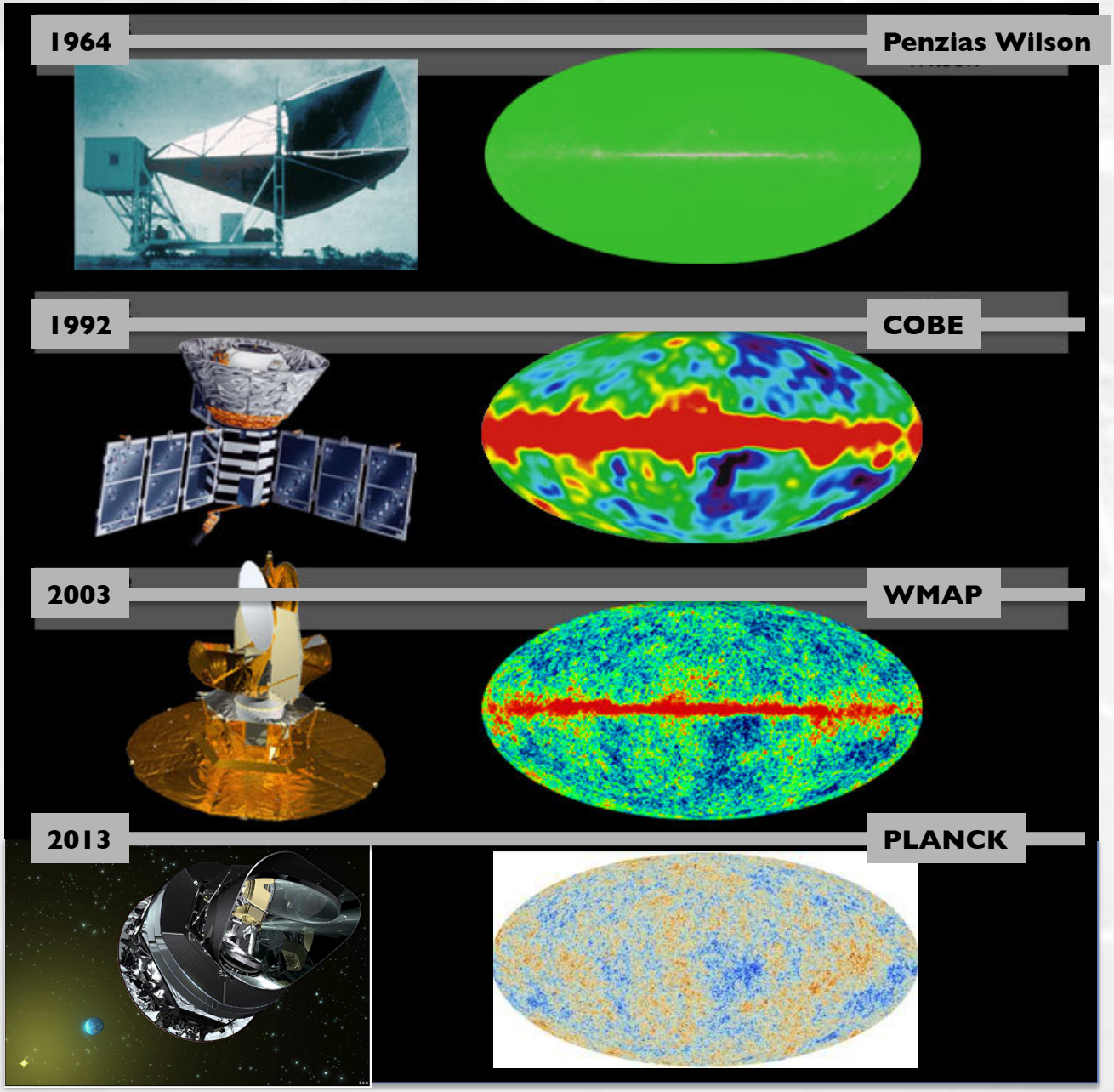


The theory of inflation and the spectrum of the 3K radiation can explain in detail all the Universe evolution

The Cosmic Background Radiation shows an impressive homogeneity (~1/10000) which would be difficult to explain with the effect of the sole gravitational effects (inflation explain this effect)
However, in the 3K map there are all the primordial seeds ("fluctuations") that gave birth to everything we observe now (clusters, galaxies, etc…)



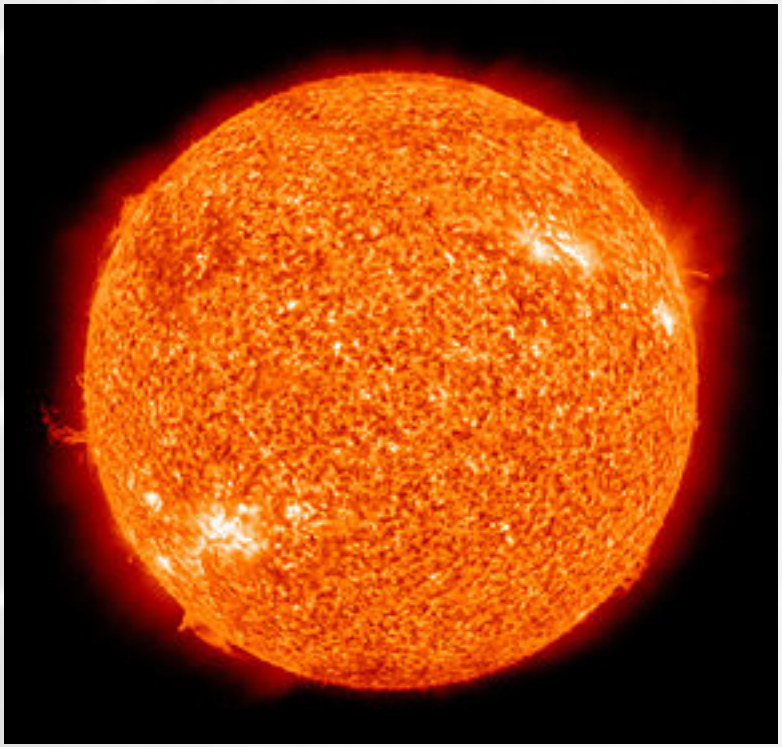
The impressive technological evolution of the 3K background map



t > 380,000 y (till today)

The Universe is in continous expansion and gravitational effects are dominant. Big masses accumulate and collide, giving rise to galaxies, stars, and solar systems

Sun and Earth are generated about **5 billions** years ago



… and so, having observed that
anti-matter disappeared
in the first moments of the Universe,
how do we study in Laboratory
what happened just after the Big Bang ? …

3. The Large Hadron Collider at CERN

Experimentation at LHC plans to give an answer to basic questions:

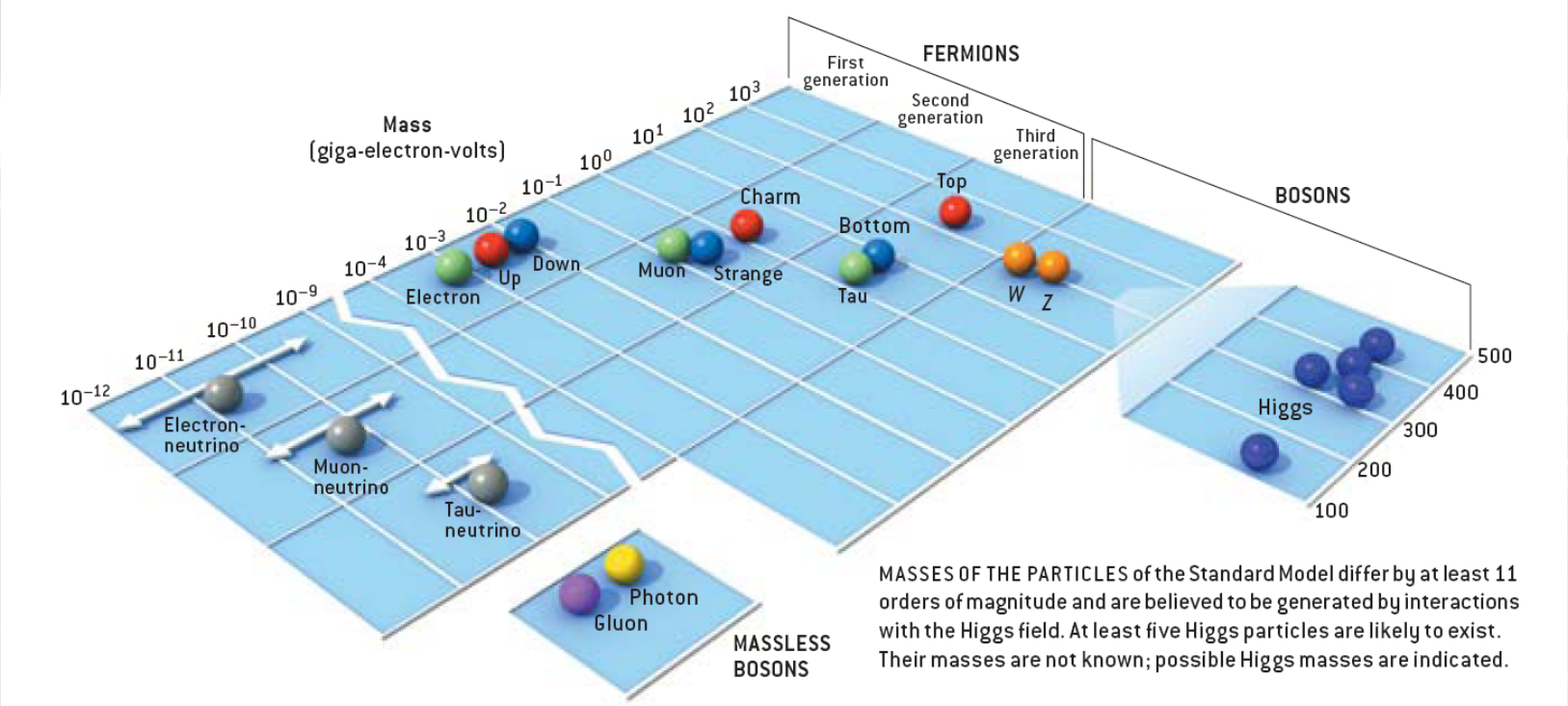
- how the Universe evolved ?
- which are the building blocks of the matter around us ?
- which are the forces acting on matter ?
- how matter and forces determine the properties of the Universe ?

Particle Physics, Astrophysics and Cosmology have the goal of explaining in a single unified view what we experimentally measure at the accelerators, at the telescopes, on satellites or in underground laboratories

In the last 50 years, physicists and astrophysicists have set up a theoretical frame of Particle Physics which explains in an outstanding way the experimental data and describes the evolution of the Universe after the Big Bang: the so called **Standard Model (SM)**

As example, the **SM** is capable to predict and describe the production mechanisms of the element abundances in the Universe, starting from the evolution models (nucleosynthesis)

The synthesis of SM: Elementary Particle's table

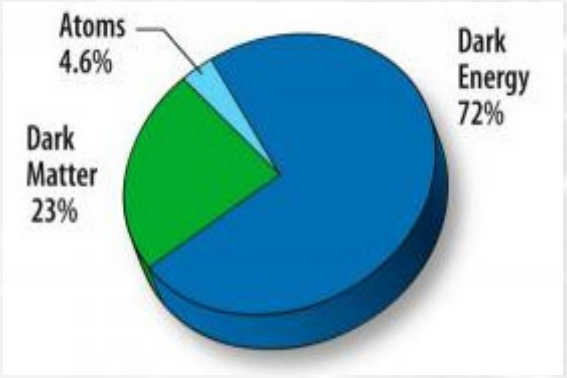


The puzzle elements: **6 quarks (UP, DOWN, strange, charm, beauty, top), 6 leptons (ELECTRON, muon, tau e 3 NEUTRINOS), 4 forces (weak, gravitational, nuclear, electromagnetic) with their messengers (photon, W, Z, gluon, graviton) and the Higgs boson**

This is all you need to build the Universe !

However, since many years physicists know that the SM cannot be the **Final Theory** (as Maxwell equations weren't for the electromagnetism)
The SM shows some problems, as it does not explain some experimental facts:

- The **dark matter** observed in the Universe
- The **dark energy** responsible for the Universe expansion
- The **baryonic asymmetry** (antimatter has gone)
- The **non zero mass** of neutrinos



There are also unsolved theoretical problems:
- particles have a large variety in masses
- forces have a quite different variety in strength
- family of particles behave differently
- Gravity is not described by a Quantum Mechanical Theory

As of today, there are no experimental signs that the SM does not work
Even the recent (2012) observation of the **Higgs boson** is a triumph of the SM

Since the '70s, theorists have tried to think to something beyond the SM, to solve the above problems
One of these models goes under the name of **Supersymmetric Theory**

Scientific goals of LHC

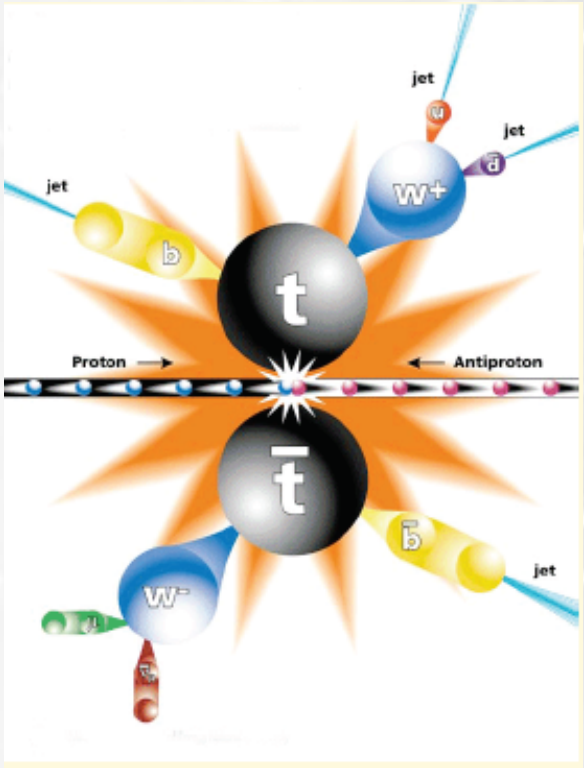
LHC is a **27 km** long accelerator in which collisions at the highest possible energy (14 TeV) among beams of protons may reveal new states of matter, never seen before, and maybe produced only in the first moments of Big Bang

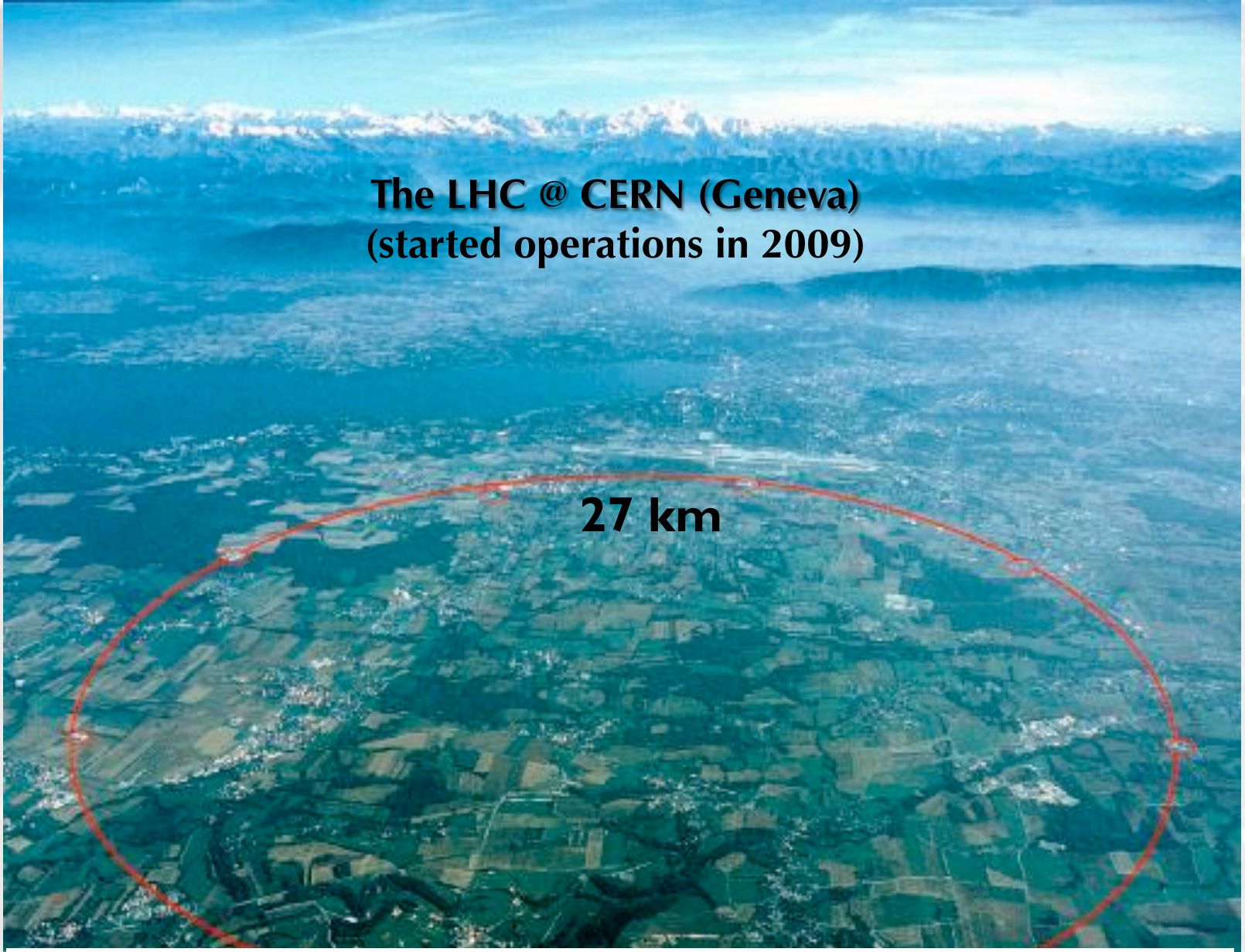
Why building such a machine ?

- Discovery the **Higgs boson** (and it happened …)
- Look for **new particles** (perhaps supersymmetric ?)
- Study if quarks and leptons are **elementary**
- Find the candidates for the **Dark Matter**

And also give hints on new theoretical models, among the many possibilities, which can solve at best the problems of SM

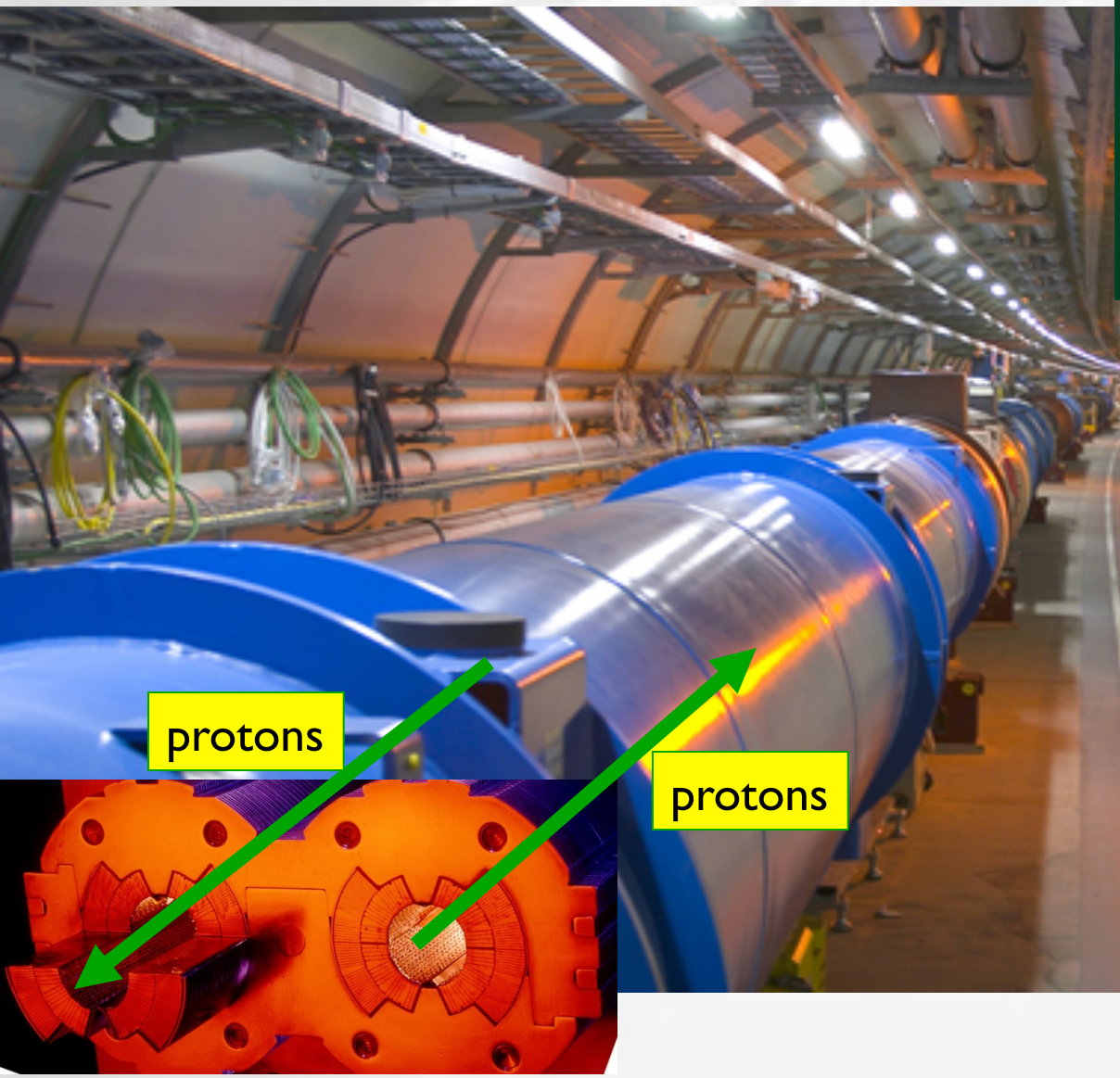
However, reality could be more complex, and maybe LHC experimental results alone are not enough: we need a large spectrum of other precision measurements to discover New Physics

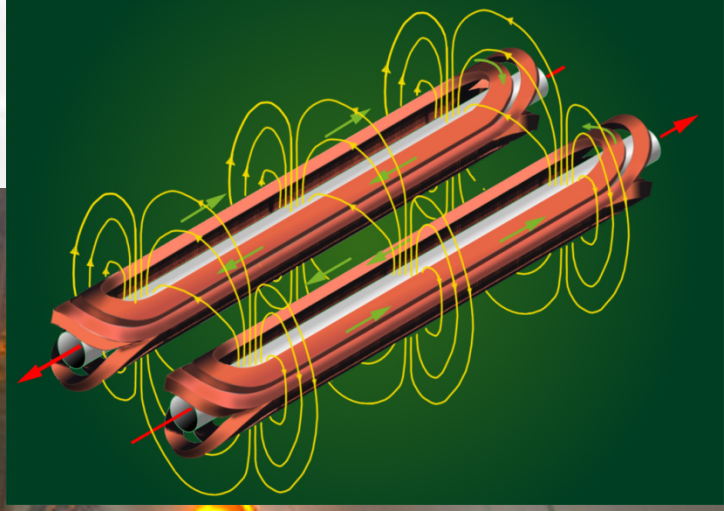




In 2009-2012 operated at 7 and 8 TeV
(the largest available energies)
In 2015 energy will be 13 TeV – Run starting this summer

The LHC tunnel

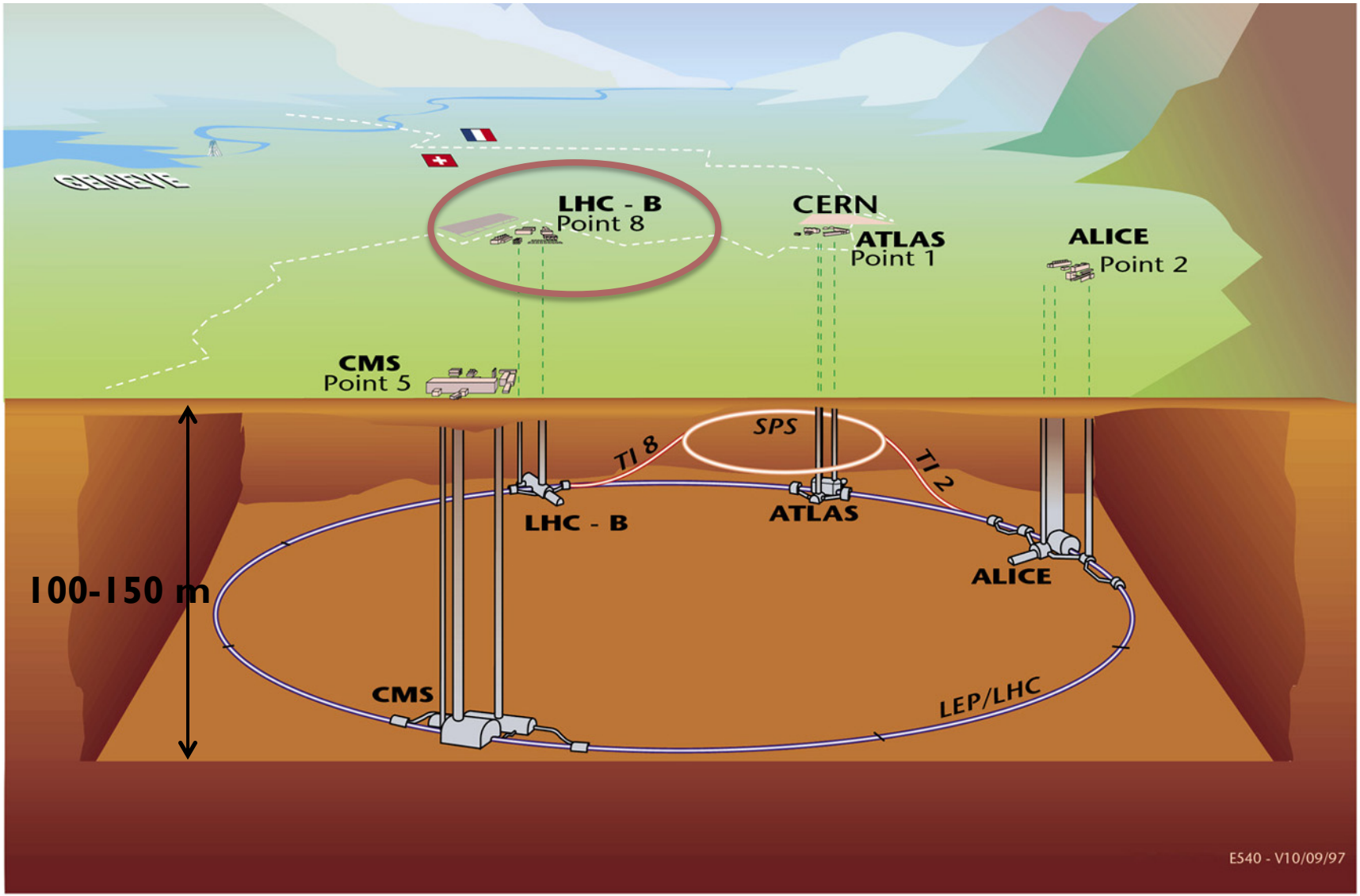




ATLAS e CMS, general purpose (very large detectors)

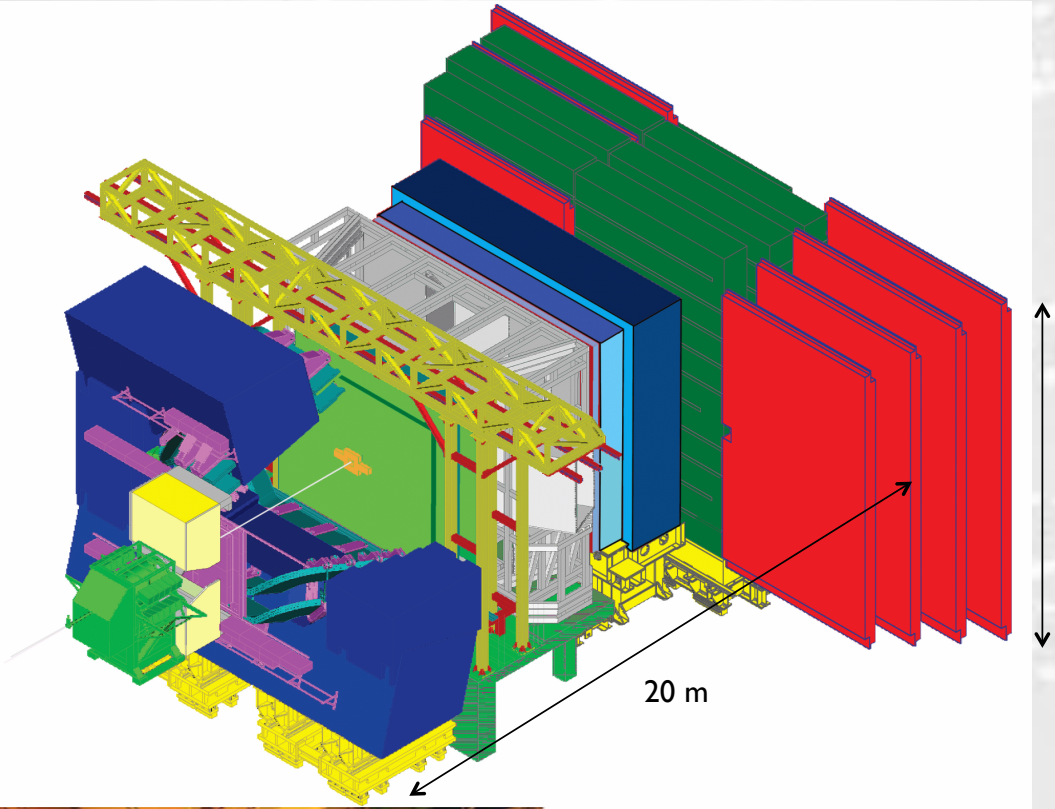
LHCb, to study matter anti-matter asymmetry

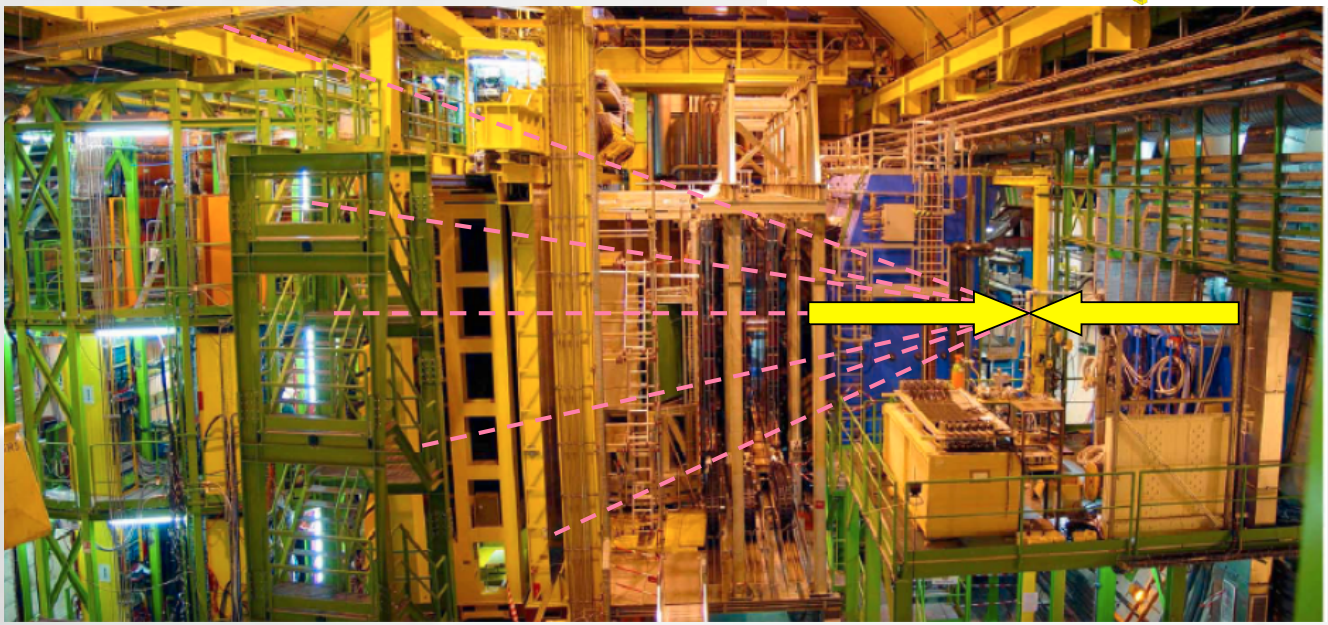
ALICE, to study the early moments of Big Bang



LHCb
International collaboration
800 physicists
70 institutes

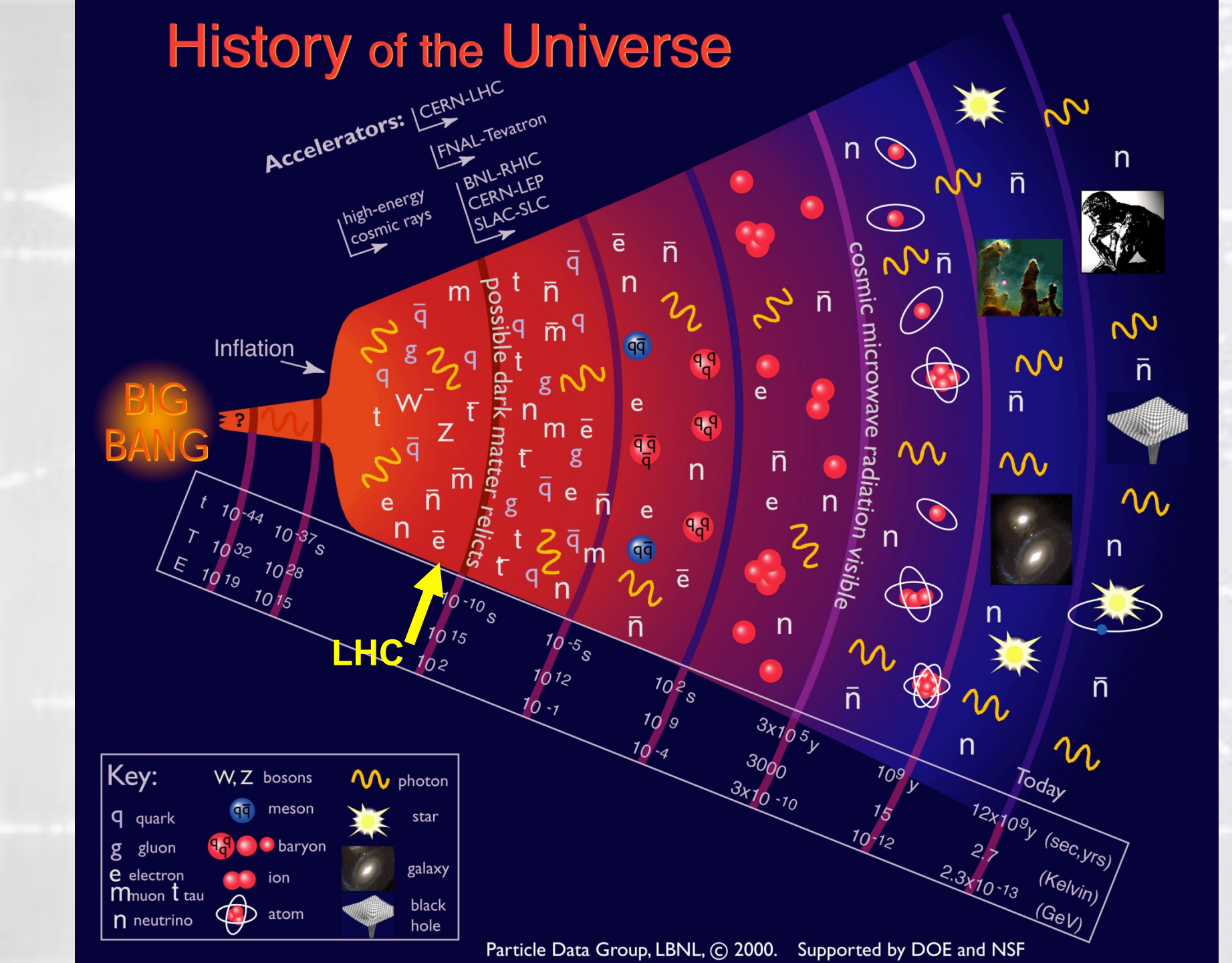
Lhcb-public.web.cern.ch





The asymmetric shape
is optimized
to collect as many
as possible
B mesons to study
CP violation

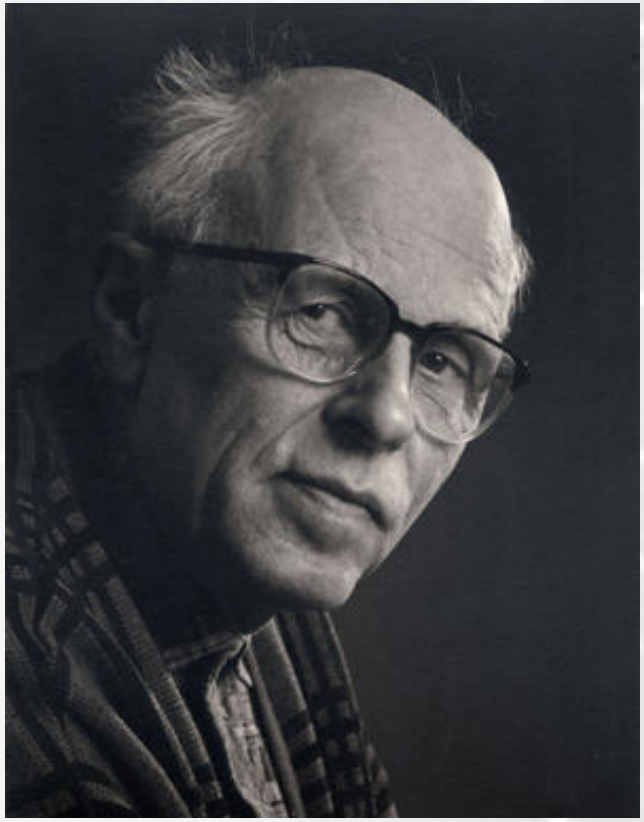
4. Searching for the missing anti-matter


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
LHC
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
10 15
10 2
10-5 s
10 12
10 -1
102 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
109 y
15
10-12
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Let's come back to the moment when the **inflation** (rapid expansion of the Universe) has finished: matter and anti-matter are in **equilibrium**

At that point a mechanism generates an asymmetry, and today we believe that it is the combination of various facts

In 1967 A. Sakharov (father of USSR atomic Bomb, political opponent and Peace Nobel Prize in 1975), made the hypothesis that 3 are the conditions for the start of baryogenesis (i.e. the victory of matter over antimatter):



- **the violation of CP symmetry**
- **the possibility of creating baryons violating some conservation rules**
- **a system which is undergoing a rapid variation of state**

CP violation

In 1964, an experiment in the US discovered that the **CP symmetry** was violated in the decays of a special particle: **the neutral K meson**

What is the CP symmetry ? It comes from the application of 2 transformations:

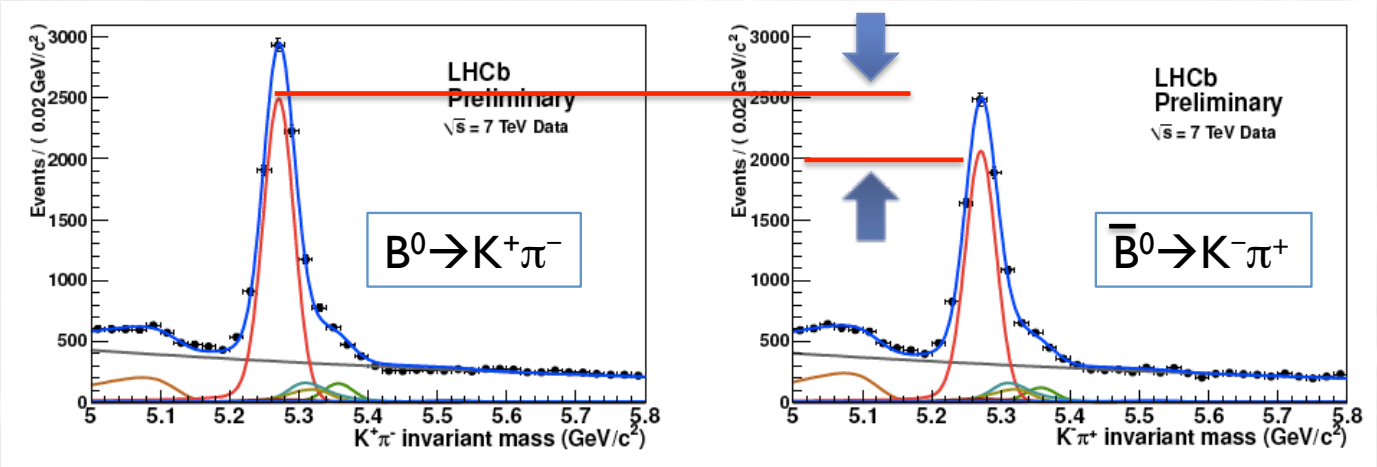
1) Parity [P] – Reverses the axis (x,y,z)→(-x,-y,-z) (like in a mirror, but also up/down)

2) Charge conjugation [C] – Inverts the charges (transforming a particle into an anti-particle and vice-versa)

Until 1964, physicist thought CP was conserved: the discovery was a big surprise for everybody, but a mechanism for generating asymmetries was now there !

Afterwards, the violation of CP has been observed (in 2000) also in neutral and charged **B mesons** (particles with a quark b inside) which are the ideal laboratory for studying matter anti-matter asymmetry

These particles are studied with large statistics and in detail in LHCb, as they are created in pp collisions, in particular in the forward direction
One way of measuring the asymmetry is to count "how many times" a neutral B or an anti-neutral B decays in a specific channel
The asymmetry can be seen "by eye" (**look to the red plot**)



Unfortunately, what we know now from K and B CP violation decays is that the amount of the effect is too small to explain the large effect needed to generate the asymmetry between matter and anti-matter
Therefore the search continues …

… wrap-up …

It is believed that the CP violation has determined the evolution of the Universe as the Big Bang has produced an equal amount of matter and anti-matter.
However today we observe a large asymmetry as the Universe is dominated by matter and there are no traces of antimatter

The unsolved problem is that the amount of CP violation observed experimentally is by far too small to explain the asymmetry

Therefore the experiments at LHC (such as LHCb, a dedicated one, but also ATLAS and CMS) are looking for the possible observation of New Physics beyond the SM, which will allow us to explain this mystery with new sources of matter anti-matter asymmetry

… and future perspectives …

LHC has still many years to go ! In 2015 a new run at nearly the highest energy will start and we hope to find surprises ! LHC is planning his activity at least until 2030

We have not yet observed **New Physics** effects (such those predicted by Supersymmetric theories or by other more exotic models)

The **Higgs boson** has been discovered and the value of its mass is a critical ingredient for further studies on the evolution of the Universe

The disappearance of anti-matter is still a mystery: the Standard Model is not capable of explaining it. More data is needed: we must be patient …

5. Epilogue

(why we do fundamental research ?)

Sometime straw man asks:
Why Fundamental Research ? Which are the benefits for the Society ?
Are costs well justified ?

Anwering to basic question of human being is already a significant goal !

However, it is historically proven that Fundamental Research has always important technological fall-outs that enter in everyday life several decades afterwards

The radar, the pacific use of nuclear energy, the transistor, the X rays and the nuclear medicine, the magnetic resonance, the laser, the superconductivity, the telecommunications, the WEB, etc…
mentioning only those driven by Research in Physics

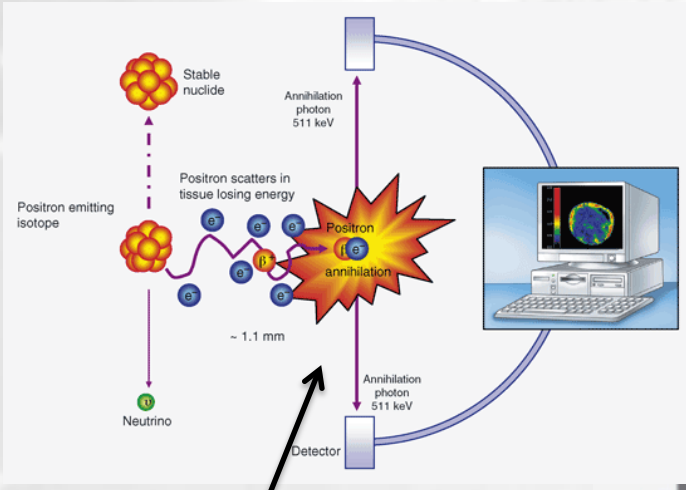
While studying a problem, accidentally, something important is discovered

***Serendipity**, or "always making discoveries, by accidents and sagacity, of things which they were not in quest of"*

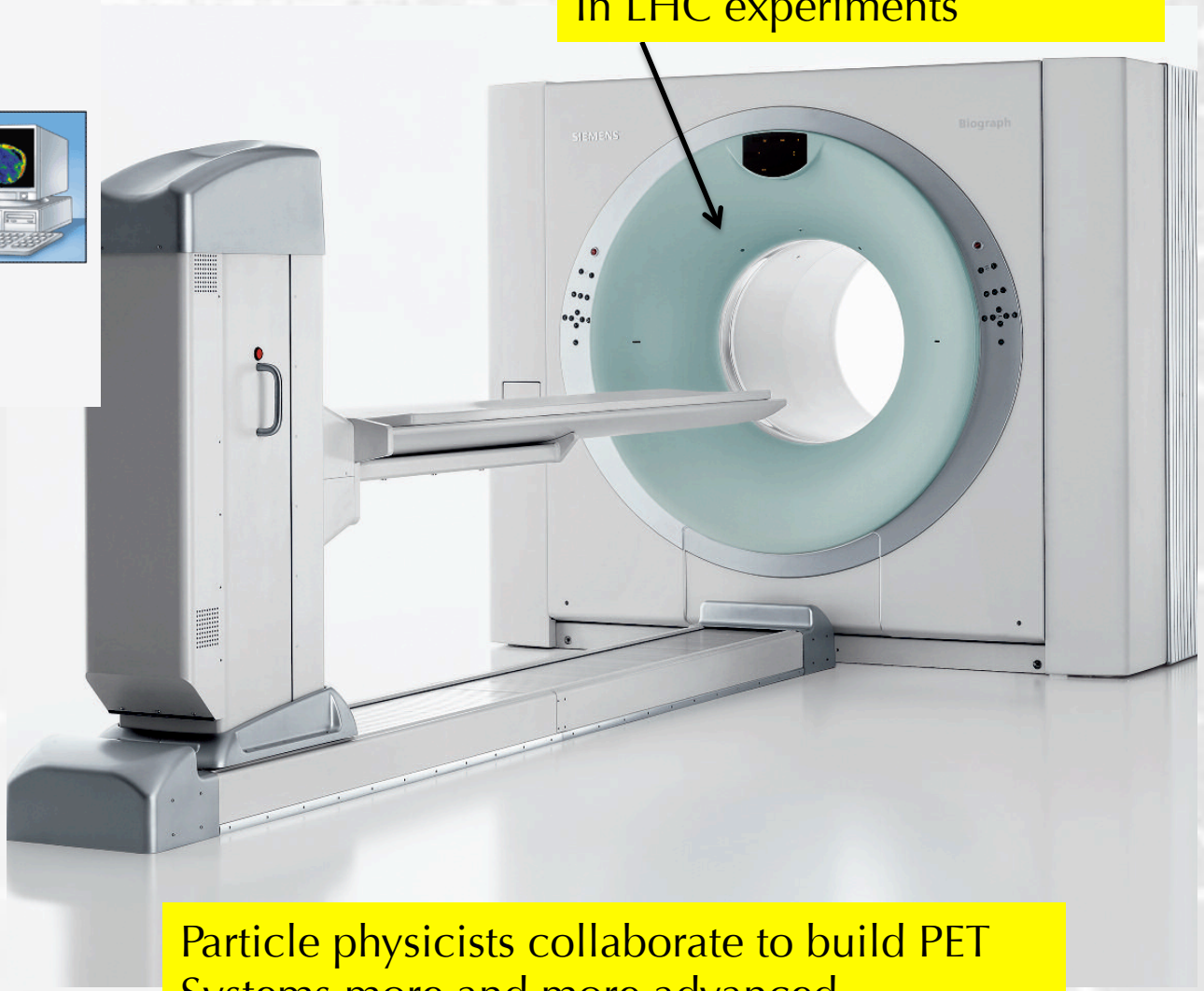
Flute, Homo sapiens, Germany (35,000 years ago)

Cave art, Homo sapiens (France, 25,000 years ago)

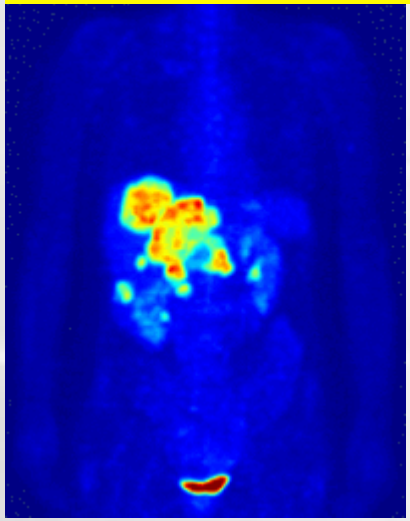
Example no. 1
Positron Emission Tomography for early detection of cancer



Here we have crystals used
In LHC experiments



Antimatter (positrons)
at work !

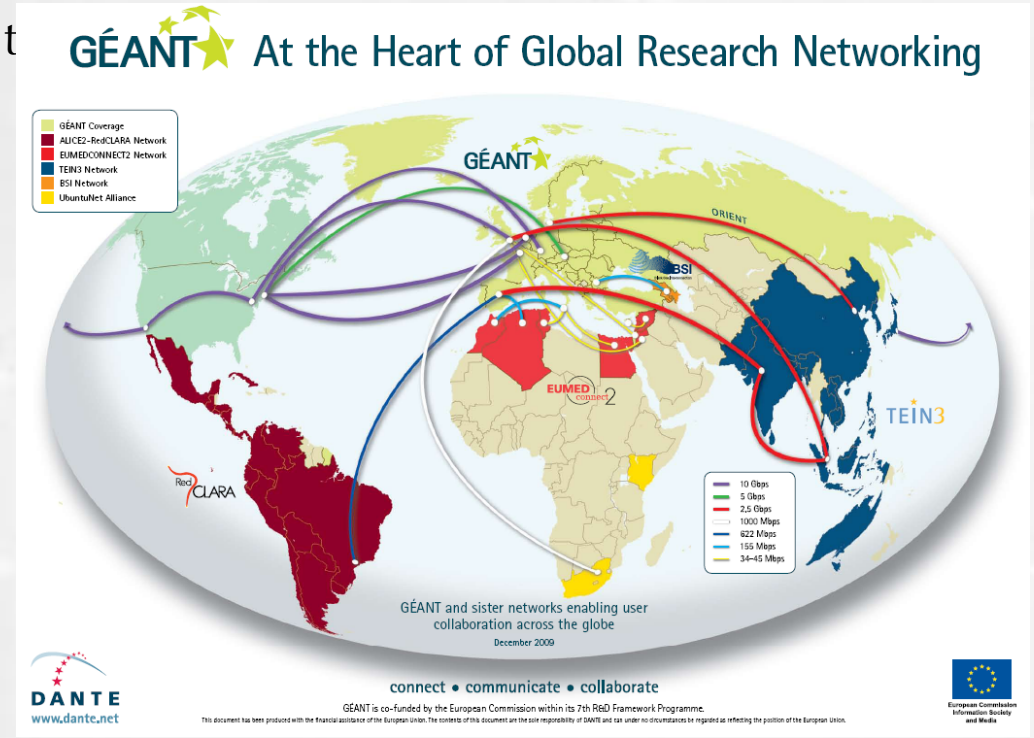


Particle physicists collaborate to build PET
Systems more and more advanced

Example n. 2 – The World Wide Web

Web has born on August 6th, 1991. Tim Berners-Lee published online the first web page at CERN. At the beginning only used by physicists to exchange data, on April 30th 1993, CERN decided to open freely the access to the software.
Everyone could use it freely usato solo dai fisici delle particelle, il 30 aprile 1993 il CERN decide di rendere pubblica la tecnologia permettendo a chiunque di usarla e svilupparla ***gratuitamente.*** Il resto e' noto a tutti.

Could we think t

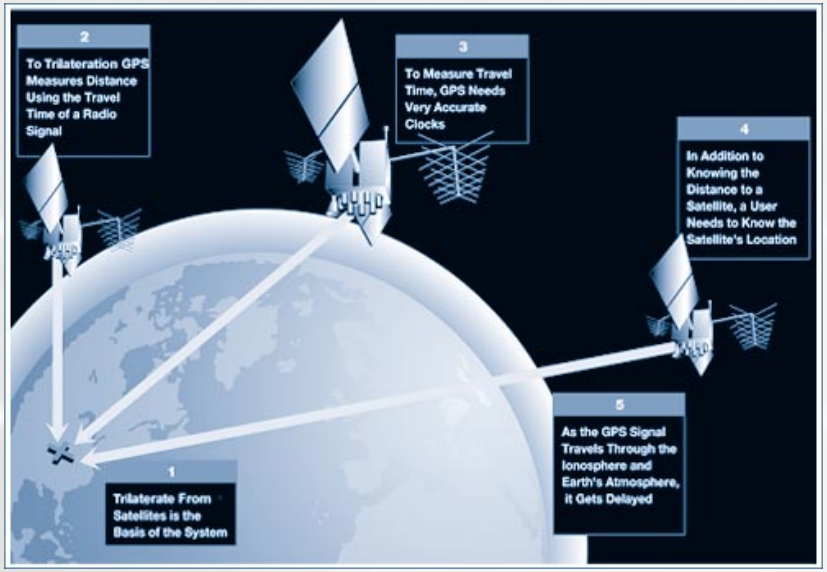


Example no. 3 – The GPS and Einstein's General Relativity

GPS satellites are orbiting around the Earth at a speed of 14,000 km/h.
Einstein's theory tells us that clocks slow down when are moving (the famous "twin paradox"): **- 7 μs each day**

GPS satellites are at an orbit of 20,000 km far from the Earth.
The gravitational force there is 4 times less strong than on the Earth and the clocks (due to Einstein's theory) accelerate: **+ 48 μs each day**

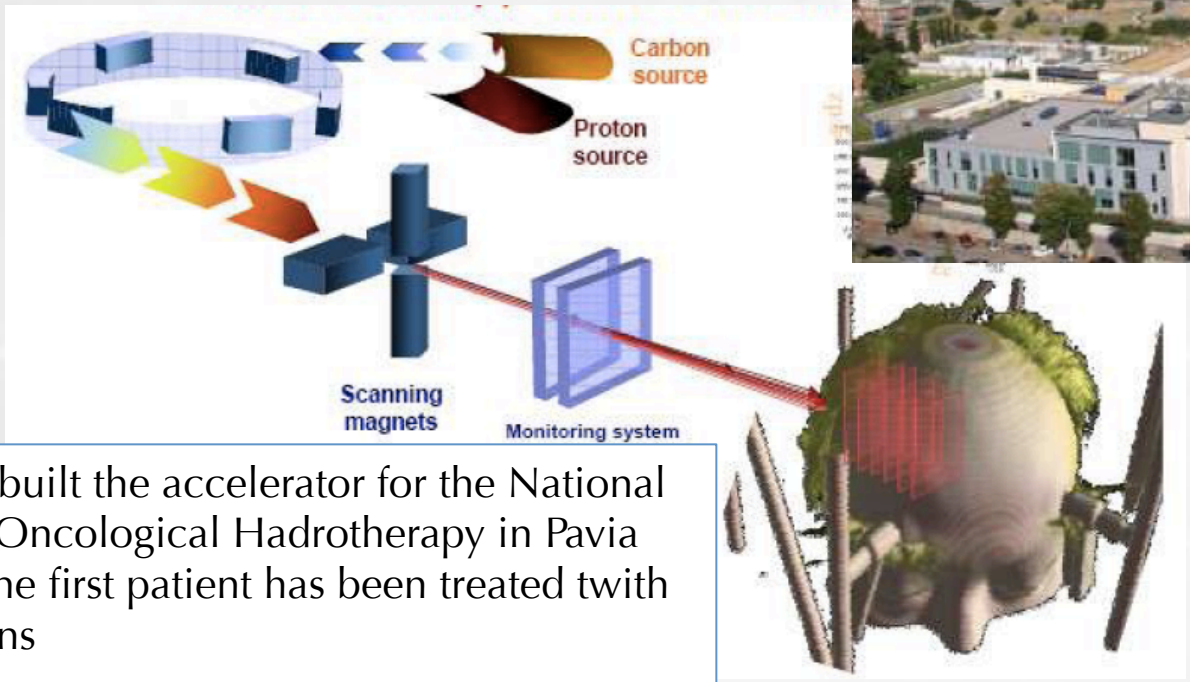
Total effect +35 μs → 11 km of error. Without the correction due to gravitational effects the GPS could not provide the current accuracy (**15 m error)**



Example no. 4 – Accelerators for cancer therapy

There are **26,000** accelerators installed in the world: **1% for research**, **44%** for radiotherapy, **55%** for industrial applications

A technological frontier is represented by **hadrotherapy**: destroy tumors in a more efficient way, hitting only damaged tissues and leaving untouched the rest of the body, especially in deep tumors, which are inaccessible.
Beams of **protons** or better of **ions** are sent very precisely on cancer tissue



INFN has built the accelerator for the National Centre of Oncological Hadrotherapy in Pavia
In 2012, the first patient has been treated twith Carbon ions

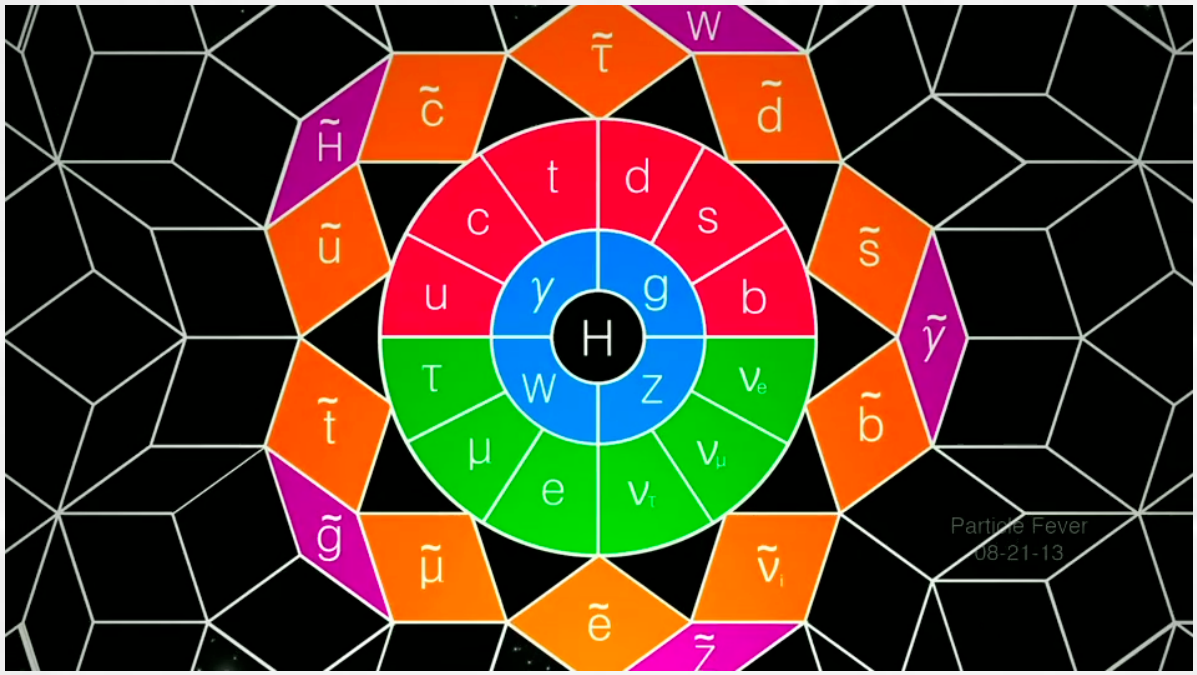
Fundamental research (or “curiosity driven”) has soon or later applied fallouts, sometime after many years, to everyday life and therefore contributes to the economic wealth of a country

Money spent in knowledge will make,
some day in the future, everyone’s life better

(… *remember this when you will become Prime Minister* …)

Supplemental material

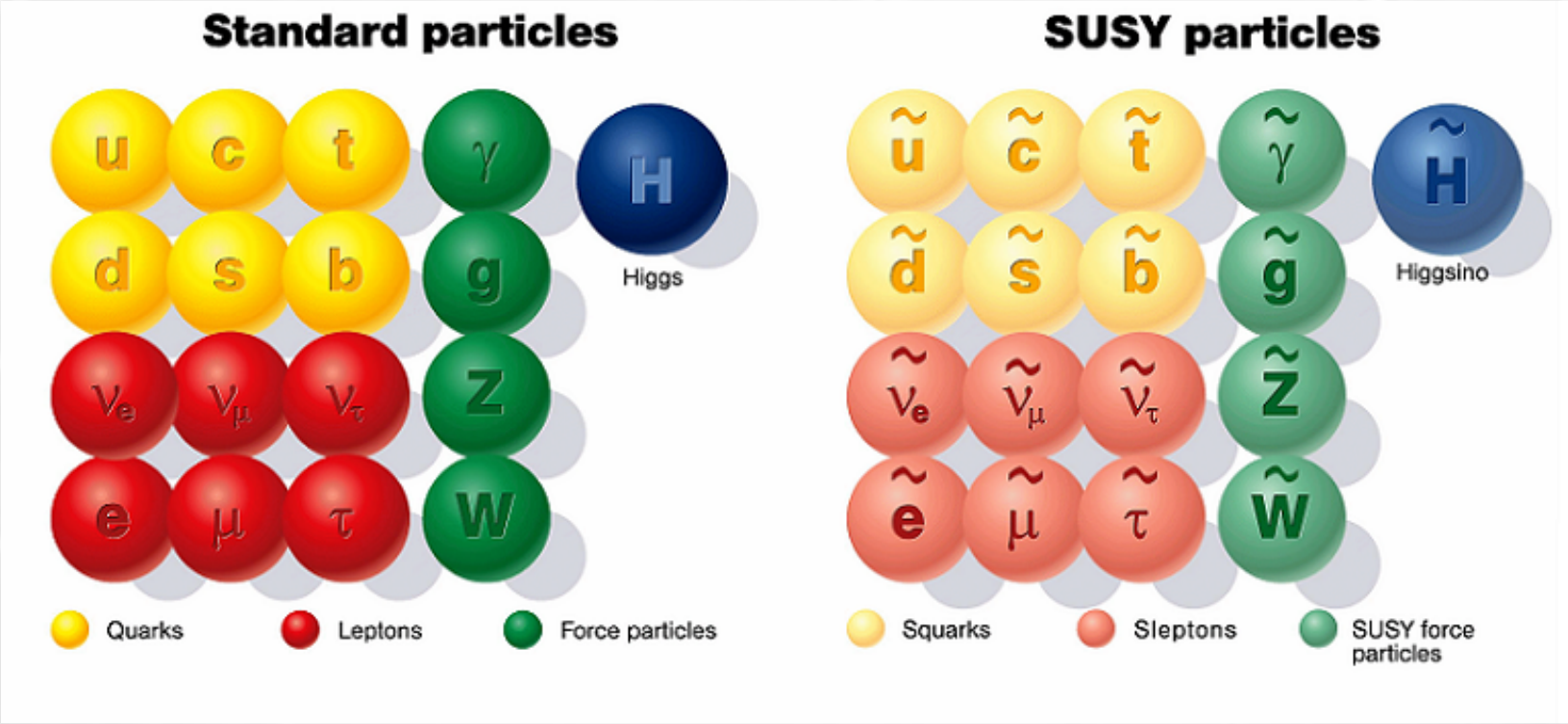
Il mondo Supersimmetrico



Le Teorie Supersimmetriche (SUSY) (I)

Sono uno delle possibili ampliamenti del Modello Standard. Accanto alle particelle note esiste un **Supermondo** di particelle che hanno spin intero (o semintero): *s-particelle*

Quarks (s=1/2) → sQuarks (s=1) Fotone (s=1) → sFotone (s=1/2)
Leptoni (s=1/2) → sLeptoni (s=1) Bosoni (s=1) → Gaugini (s=1/2)

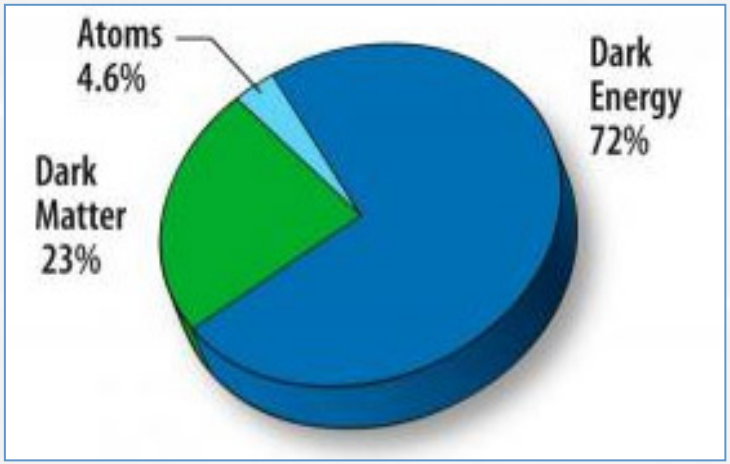


Le Teorie Supersimmetriche (II)

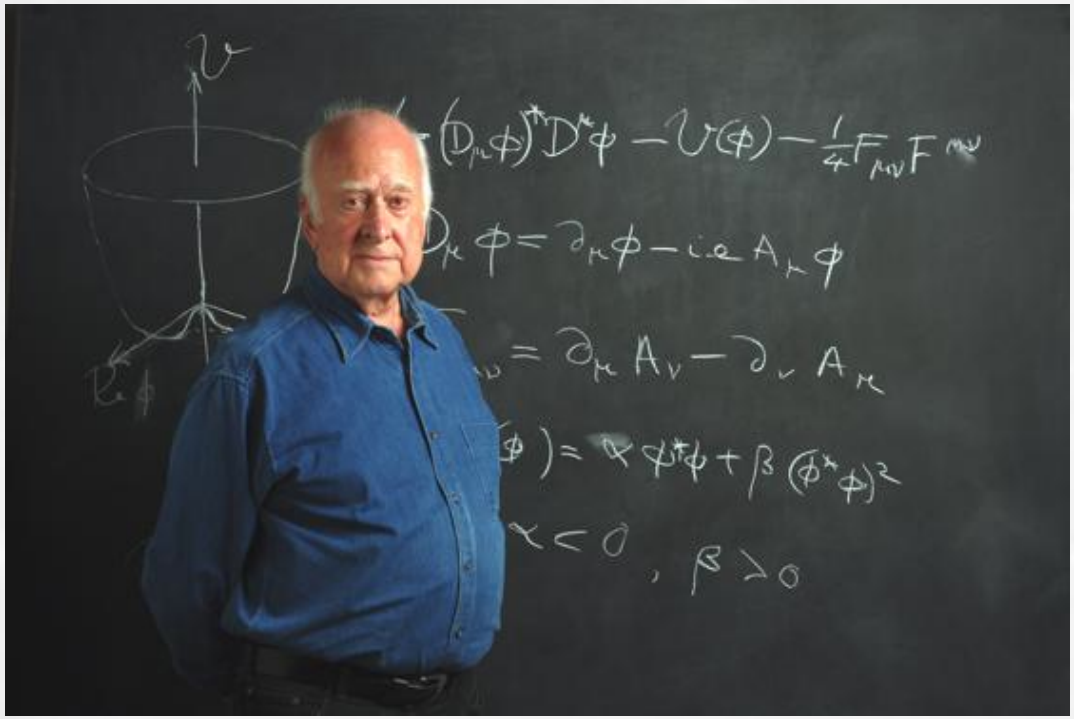
Le particelle Supersimmetriche hanno uno spettro di massa ad energie alte (forse qualche centinaio di GeV): questo e' il motivo per il quale non sono state osservate (ma potrebbero essere state prodotte nel Big Bang).

Le TEORIE SUSY permettono di risolvere alcuni problemi del MODELLO STANDARD, in particolare per il mistero della MATERIA OSCURA, che potrebbe essere costituita da una delle particelle supersimmetriche creata nel Big Bang ed arrivata "intatta" sino ad oggi

Non e' facile osservare sperimentalmente queste particelle: LHC ha gia' messo dei limiti, ma la ricerca continuera' con energia piu' elevata



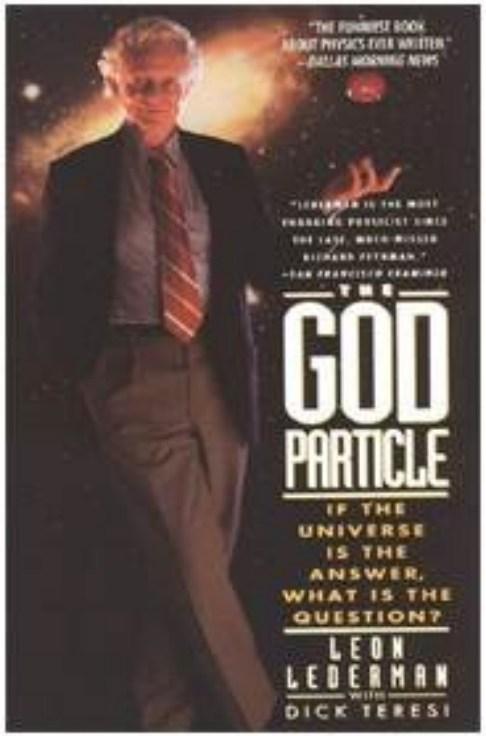
Il meccanismo di Higgs



Il Meccanismo di Higgs

Esisteva pero' ancora un elemento da verificare nel Modello Standard: la scoperta della ***particella di Higgs***

Il meccanismo di Higgs e' un elemento cruciale della teoria. Ha la funzione di:
- ***rompere la simmetria*** (quella che unifica le interazioni fondamentali);
- ***dare massa alle particelle***.



Si e' osservato sperimentalmente che il meccanismo funziona, il ***bosone di Higgs*** e' stato recentemente scoperto, ad una massa di circa 125 GeV

Nel 1993 il Ministro inglese della Scienza, *William Waldegrave*, mise in palio una bottiglia di champagne per il fisico che fosse stato capace di spiegargli su un solo foglio di carta, come funzionasse il meccanismo di Higgs (e a cosa servisse scoprirlo…)

Il prof. David Miller vinse con il seguente esempio...

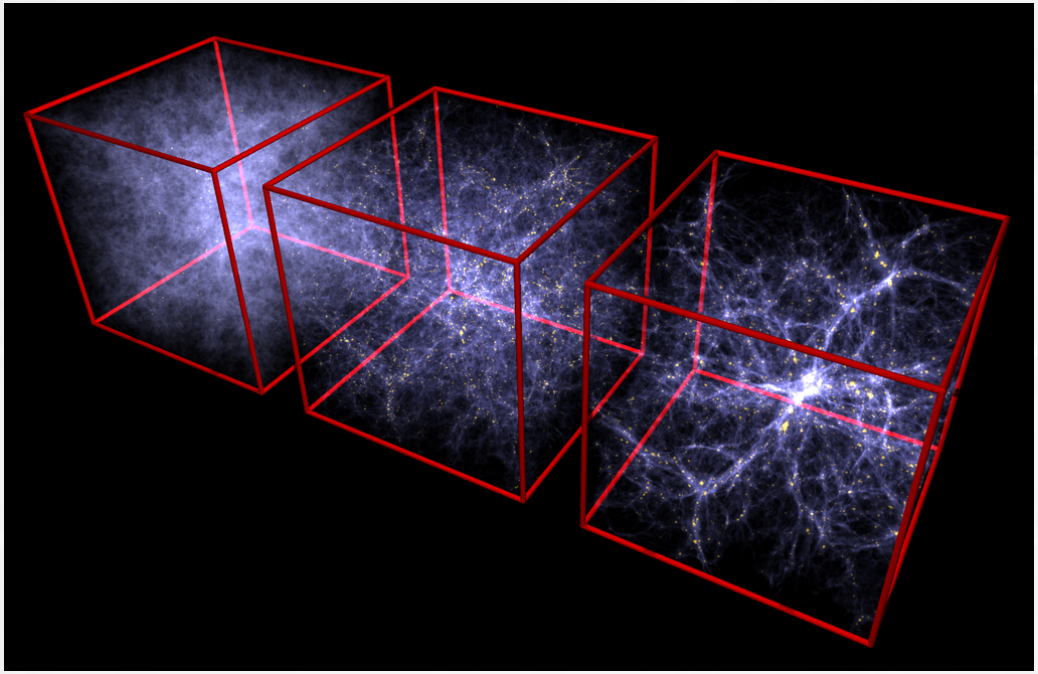
...un gruppo di politici alla buvette del Parlamento...

...improvvisamente arriva il Primo Ministro...

...tutti si affollano intorno a lui...
(questo spiega come le particelle acquistano la massa)

Un altro modo per immaginare il Meccanismo di Higgs: lo spazio e' permeato di acqua (= campo di Higgs) che determina le caratteristiche di mobilita' (= massa) degli elementi che vi transitano (pesci = particelle)

La materia oscura e l'energia oscura

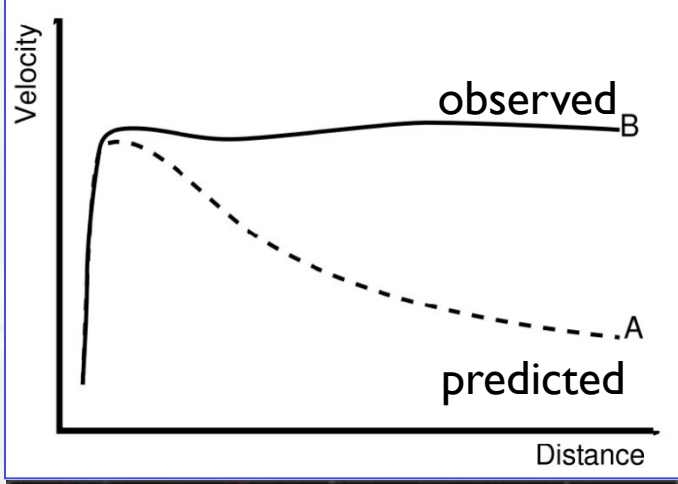


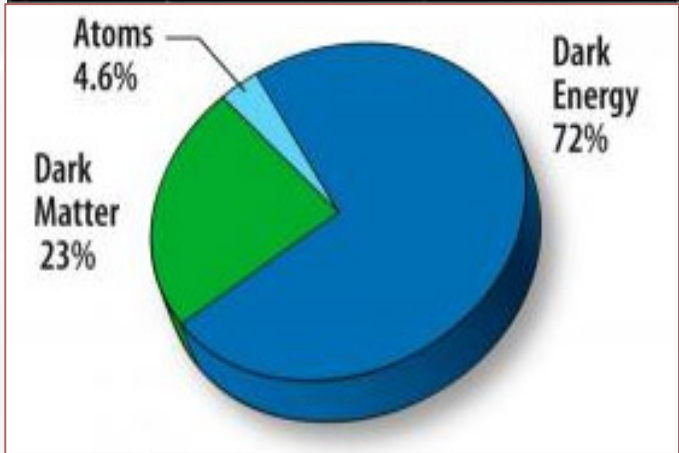
Il Problema della Materia Oscura

I cosmologi, che a partire dagli anni '60 hanno tentato di calcolare il contenuto di massa dell'Universo.
Dalle misure della velocita' delle stelle periferiche delle Galassie a Spirale, si puo' determinarne – attraverso la meccanica classica – la massa.

Le osservazioni sperimentali ci dicono che c'e' **molta piu' materia nell'Universo** di quanta se ne osservi (Galassie, gas intergalattico, raggi cosmici = **Materia Barionica**). Lo spazio e' permeato di Materia Oscura (almeno 5 volte quella visibile).

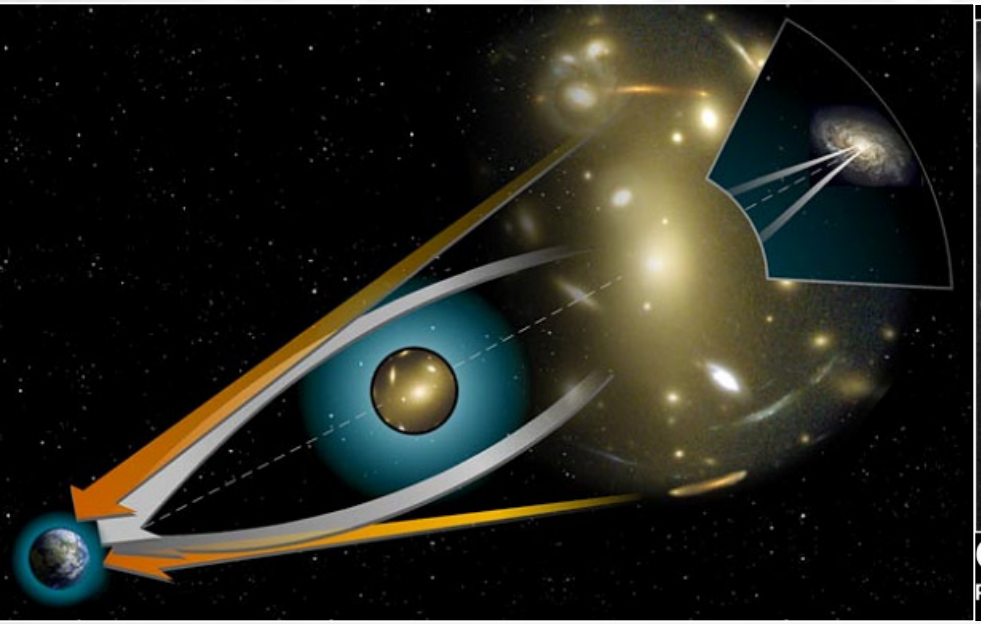
Da cosa e' costituita questa materia oscura ?
Per molti anni si e' pensato che fosse dovuta ad una massa – piccola – dei neutrini. Le misure sperimentali pero' rendono non percorribile questa ipotesi.
Ora si ipotizza che sia formata da particelle di grande massa (~1 TeV), debolmente interagenti, generate nel BigBang e da allora imprigionate nell'Universo.

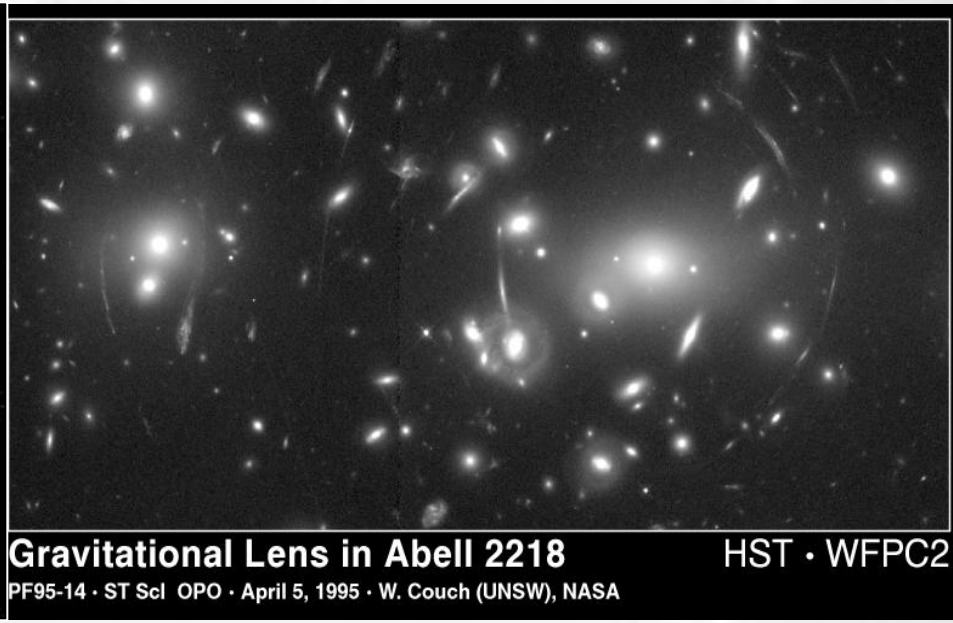




Una spettacolare indicazione sperimentale della Materia Oscura

La teoria della Gravitazione di Einstein prevede che il campo di un oggetto molto massivo possa deviare significativamente la luce (Lenti Gravitazionali).

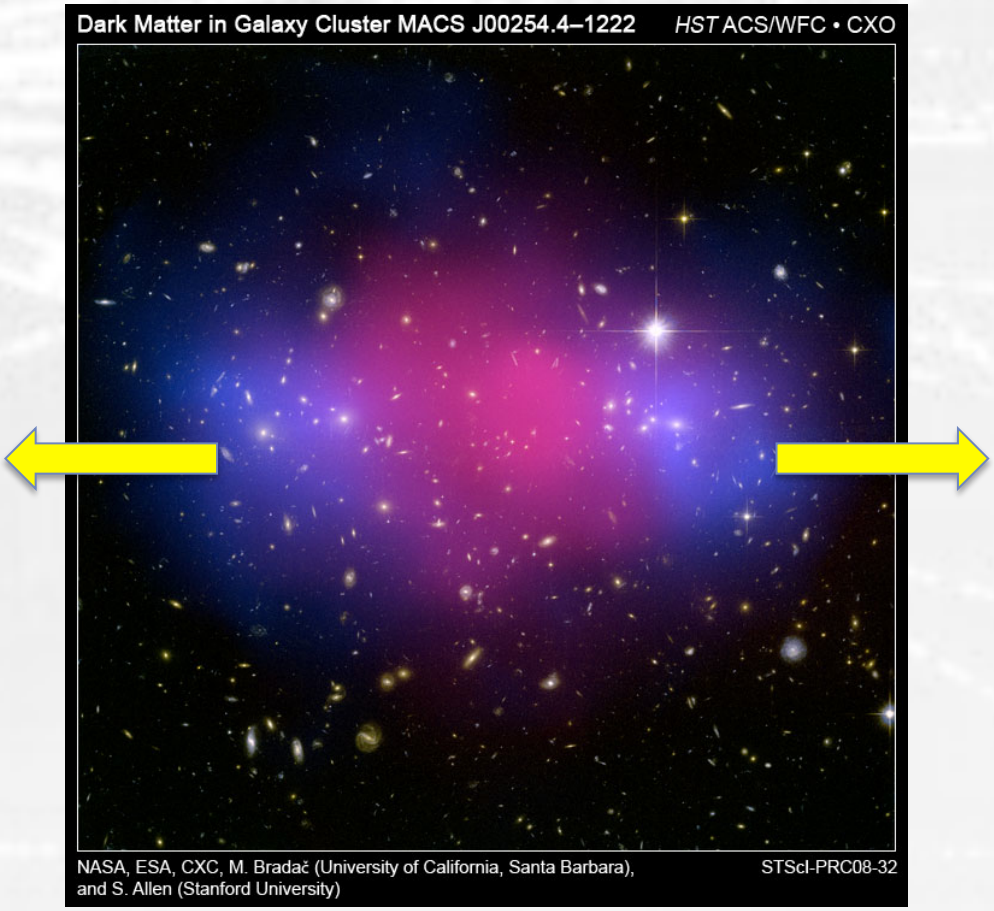




Ci sono ormai molte evidenze di oggetti celesti dei quali si osservano immagini speculari ed anelli di luce dovuti a questi effetti e causati da materia oscura che si frappone tra noi e l'oggetto osservato.

Il merito di molti dei progressi in Cosmologia va all'Hubble Space Telescope

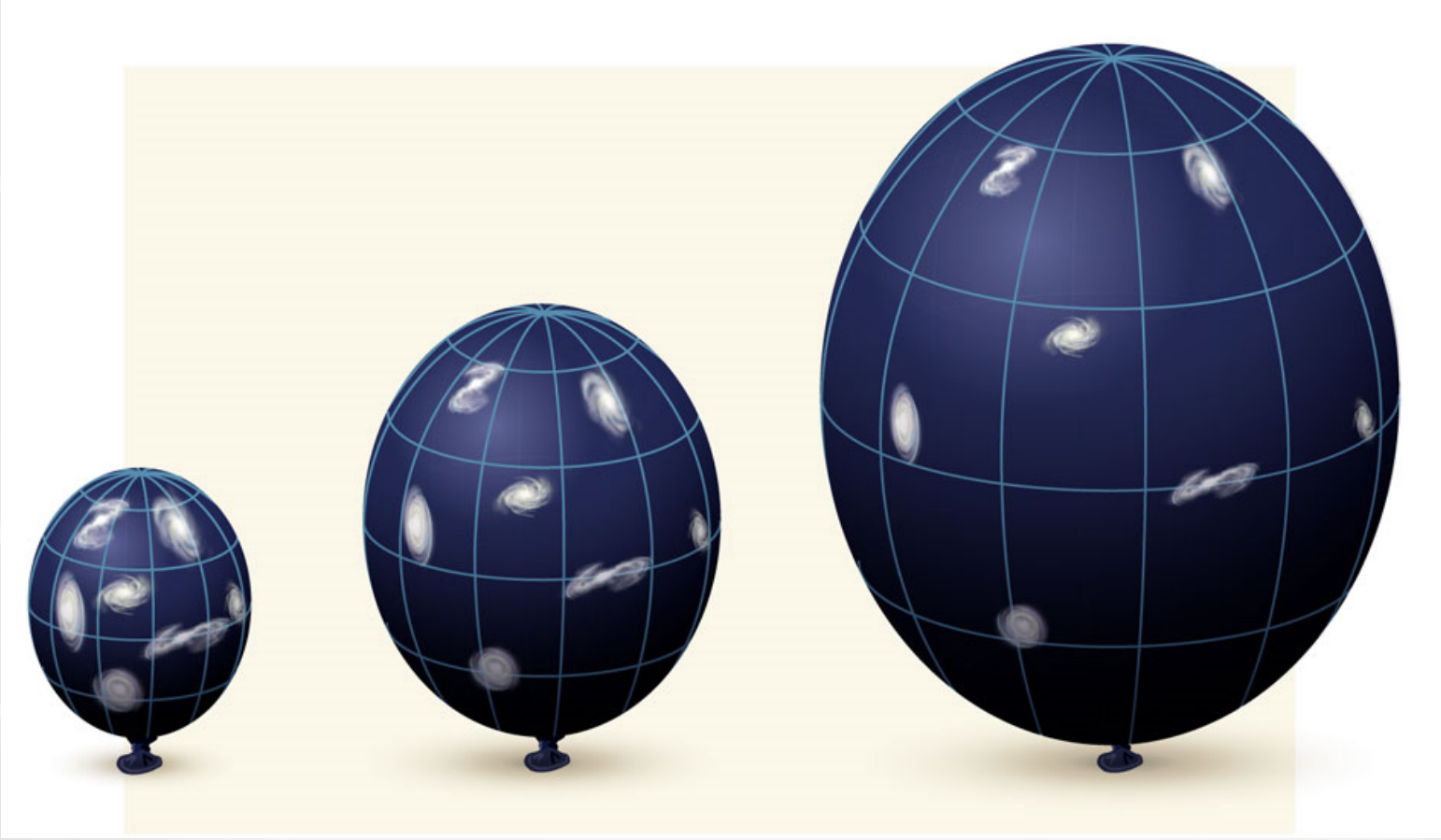
Un'altra spettacolare indicazione sperimentale della Materia Oscura

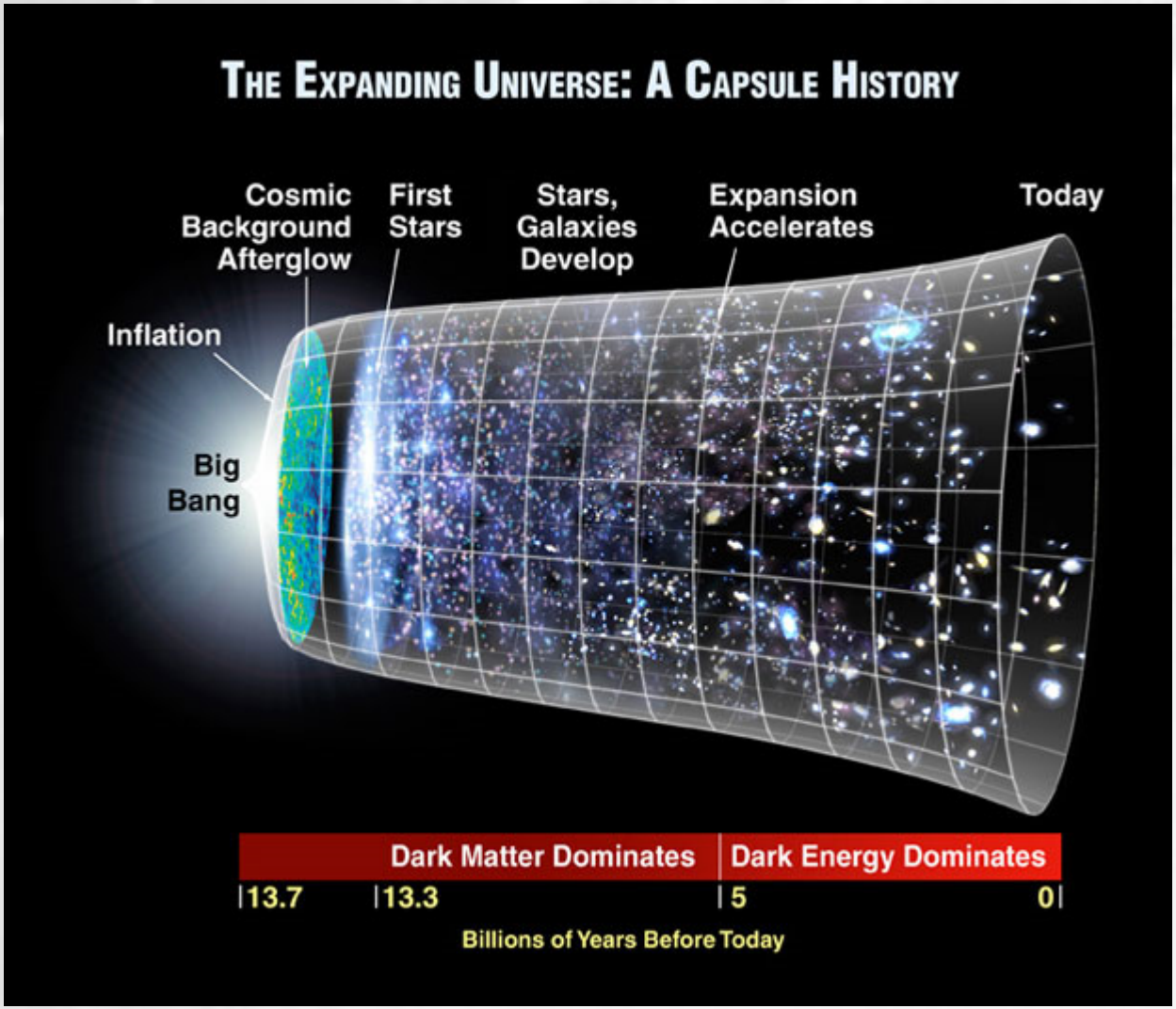


Due galassie si attraversano, ma nel passaggio, la materia "oscura" (IN BLU)sopravanza la materia "barionica" (IN ROSSO) che rimane "indietro" perche' piu' interagente e quindi piu' lenta.

Una questione piu “oscura” della Materia Oscura: l’Energia Oscura

Nel 1998 un gruppo di ricercatori americani, studiando le distanze tra le Supernovae molto lontane si e' accorto che – contrariamente a quanto si pensava dalla teoria di Einstein in poi – l'Universo e' in espansione e sta accelerando, sotto la spinta di una forza repulsiva ingente e sconosciuta ("Energia Oscura").

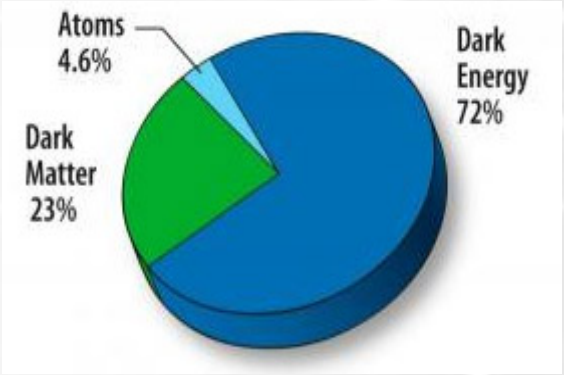




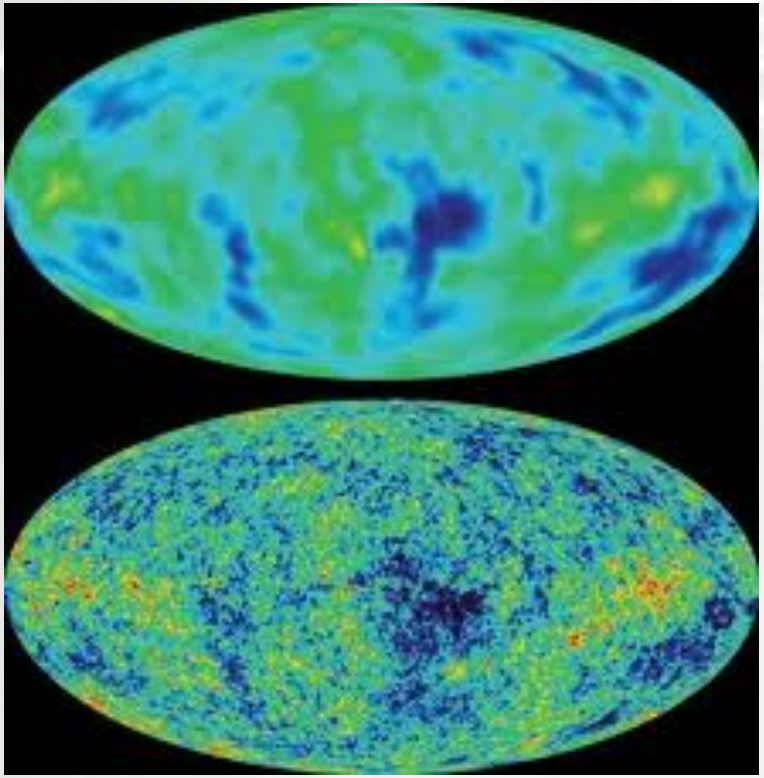
Dalle misure si deduce che:

- la materia oscura rappresenta circa il 20% della materia esistente
- l'energia oscura rappresenta oltre il 70% della materia dell'Universo

Sino ad oggi non si sa quale siano l'origine e le caratteristiche di questa forza misteriosa che si oppone alla gravitazione e allontana tra loro le Galassie



Einstein e la Costante Cosmologica Λ



Anche altre misure, *quali quelle sulla distribuzione della radiazione di fondo a 2.7 K* e lo studio dei Cluster a grande scala, confermano che il nostro Universo sta accelerando nella sua espansione

Nel 1917, Einstein aveva predetto che, ipotizzando un Universo statico, era necessario introdurre "ad hoc" una forza repulsiva (Costante Cosmologica) che controbilanciasse l'attrazione gravitazionale

Nel 1929 Hubble scopri' che le Galassie si stanno allontanando (metodo del red shift) e quindi Einstein abbandono' l'ipotesi della costante cosmologica, definendola come "una delle sue peggiori sciocchezze" !

Oggi non si sa dare una spiegazione coerente. Vi sono molte ipotesi.
Una suggestiva e' quella per la quale Λ potrebbe essere causata dalle fluttuazioni del vuoto (un fenomeno tipicamente quantistico) che potrebbero "generare" un'energia non nulla nello spazio. Il problema e' che la stima differisce per 120 ordini di grandezza...