Experimental techniques in high-energy elementary particle physics

"Dottorato di Ricerca in Ingegneria dell'Informazione"

Lecture Timetable:

Tuesday 21/09/2010 ÷ Friday 24/09/2010 : 9^{00}-13^{00}

Aula Riunioni piano terra, via Caruso

Prof. Rino Castaldi

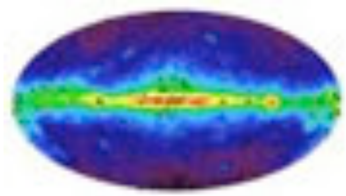
INFN-Pisa

rino.castaldi@pi.infn.it

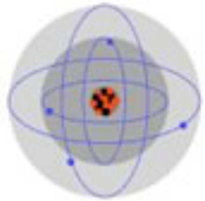
I.N.F.N.

The INFN – the National Institute of Nuclear Physics – is an organization dedicated to the study of the fundamental constituents of matter, and conducts theoretical and experimental research in the fields of subnuclear, nuclear, and astroparticle physics. Fundamental research in these areas requires the use of cutting-edge technologies and instrumentation, which the INFN develops both in its own laboratories and in collaboration with the world of industry. These activities are conducted in close collaboration with the academic world.

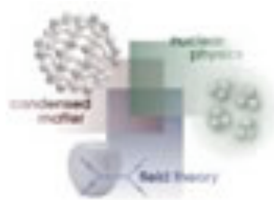
PARTICLE PHYSICS



ASTROPARTICLE PHYSICS



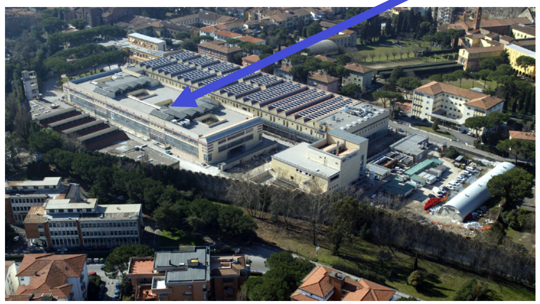
NUCLEAR PHYSICS



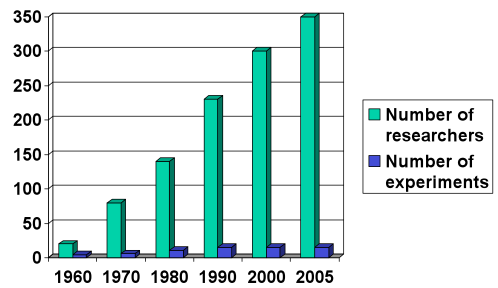
THEORETICAL PHYSICS

TECHNOLOGY RESEARCH

INFN-Pisa Section: Building C



Researchers/Experiments



Experimental techniques in high-energy elementary particle physics

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Abstract
The aim is to introduce the students to the experimental techniques on detectors, data taking and data analysis used in high energy physics. Examples are chosen form modern experiments on elementary particle physics. However the general principles could also be applicable to many other fields of experimental research. As an example of that, the use of these techniques in Medicine and Art&Archaeology will be presented.

Syllabus (15 hours)

- Introduction to the experimental research on elementary particles
- Accelerator techniques
- Interaction by particles in matter creates detector signal
- Calorimetry and lepton identification
- Tracking for momentum measurement and particle identification
- Examples of modern experiment: the CMS and ATLAS at LHC
- Analog and digital processing of detector signals
- Data taking and data analysis techniques
- Techniques from high energy physics used in Medicine and Art&Archaeology

Experimental techniques in high-energy elementary particle physics

"Dottorato di Ricerca in Ingegneria dell'Informazione"

LECTURE 1.

Introduction to the experimental research on elementary particles

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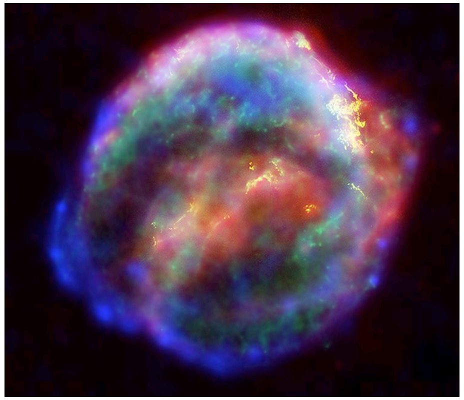
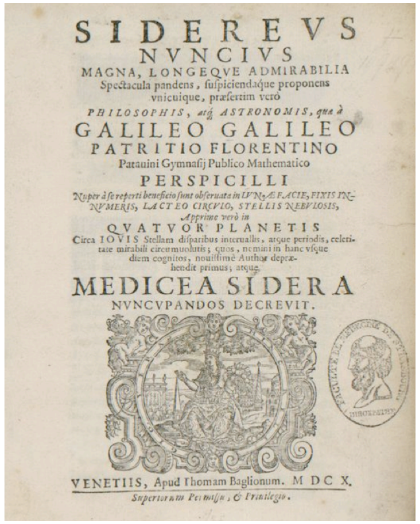
400 years ago



Supernova 1604

On October 9, 1604, a new brilliant star appears in the sky. Many looked at it. One person decided to do it with a new instrument: the telescope. The man was Galileo Galilei. This was the start of our modern world.



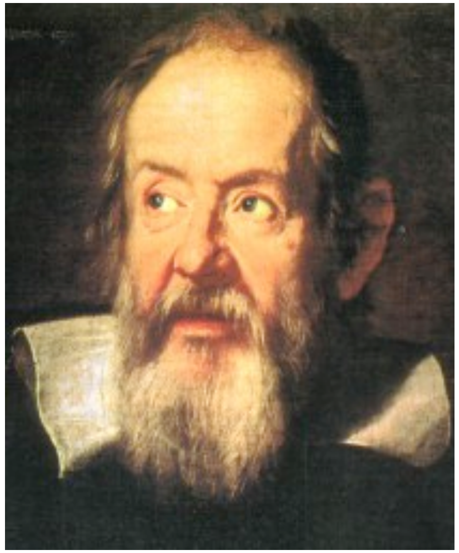
SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

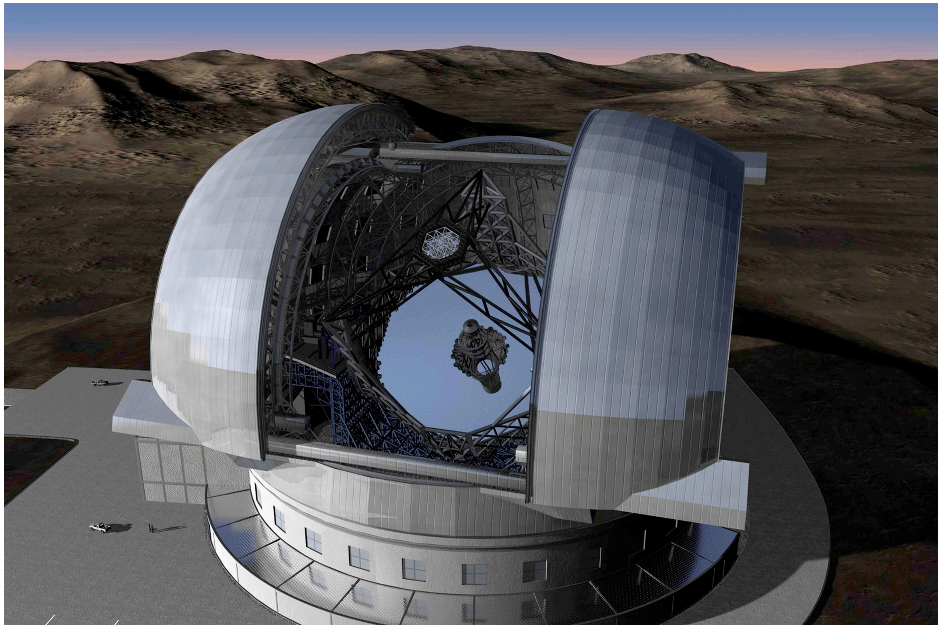
Sidereus Nuncius 1610

After a few years and many observations the picture was clear. Looking at Jupiter in particular a mini-solar system was evidently there. The previous vision of the world must be abandoned.

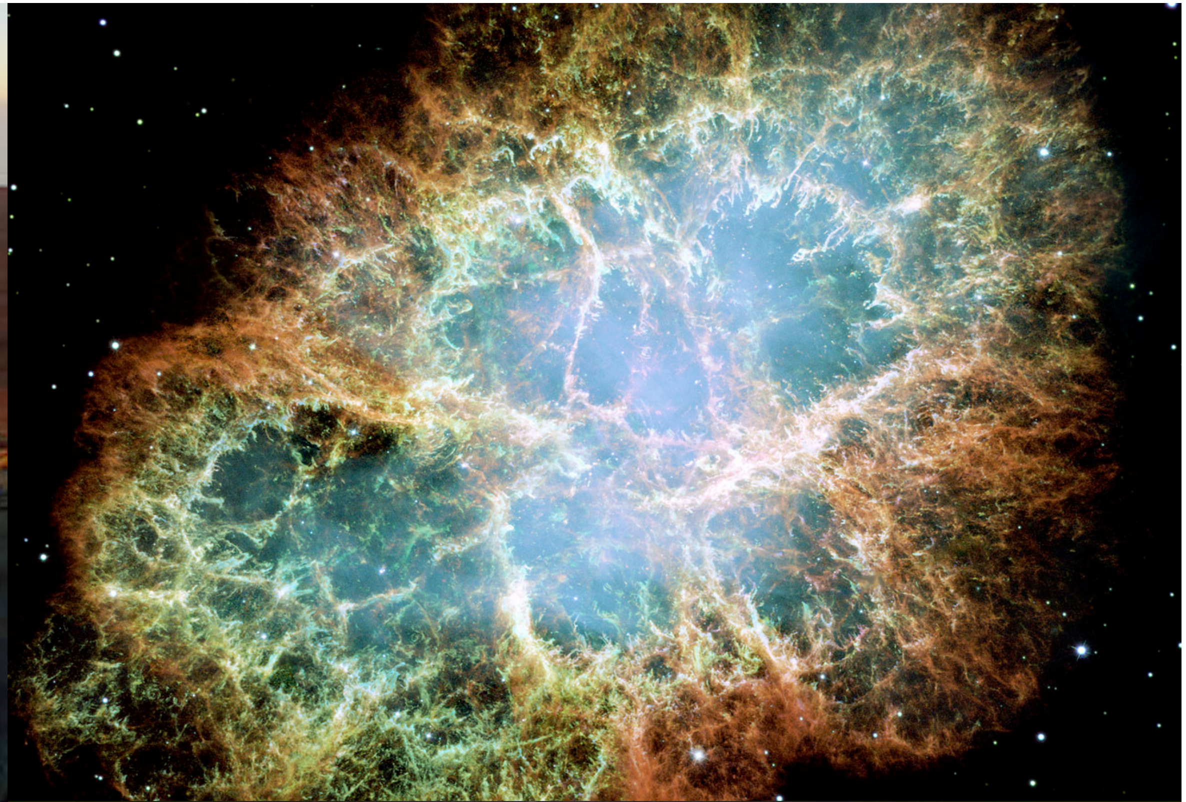
It is the birth of modern science.



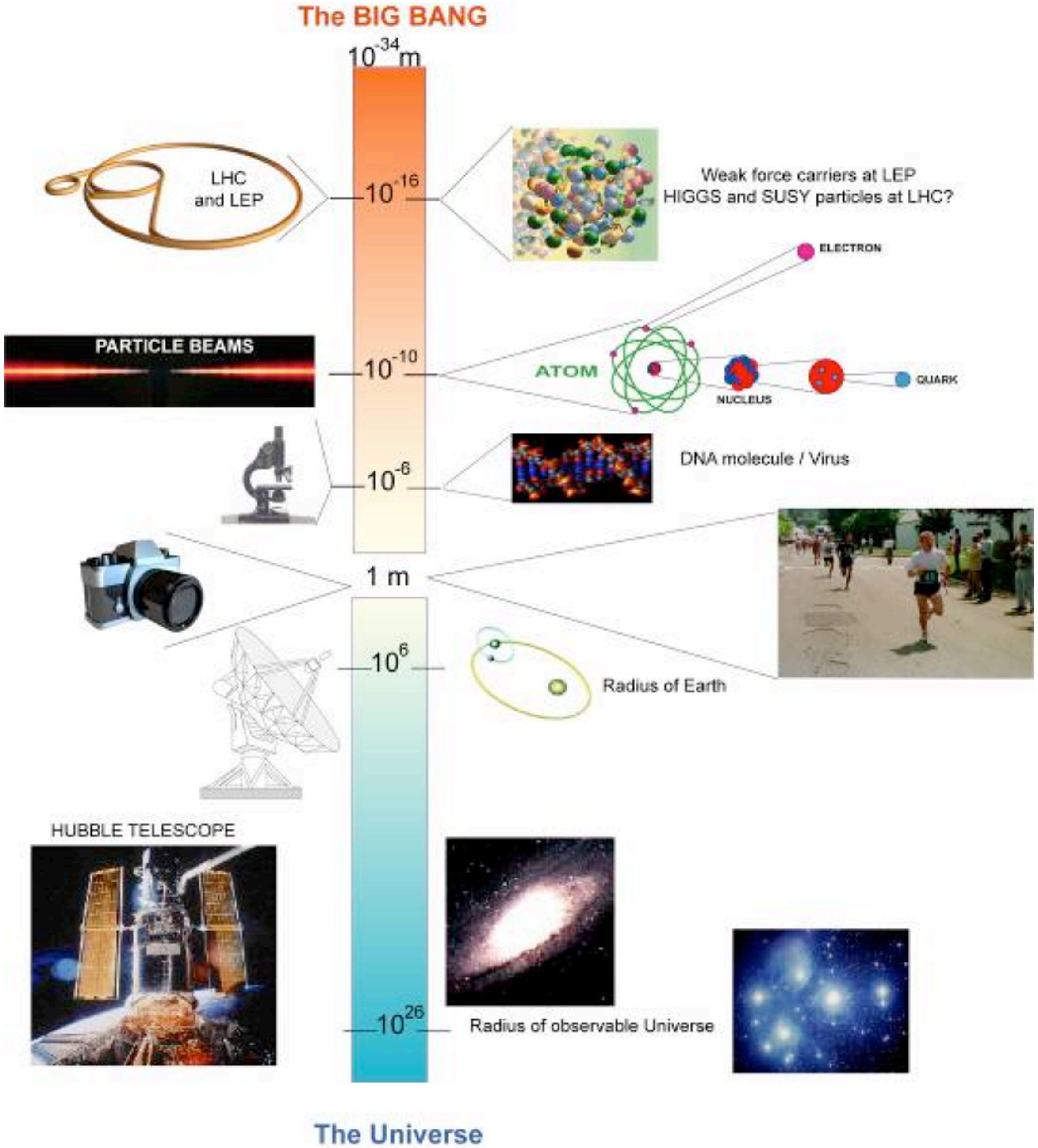
The Galileo Galilei Legacy



European Extremely Large Telescope ELT - 42 m

The right instrument for a given dimension



Different types of equipment are needed to observe different sizes of object

Particle accelerators are needed to explore the tiniest objects in the Universe, while powerful optical&radio telescopes are needed to look at matter in its largest dimensions

Photons

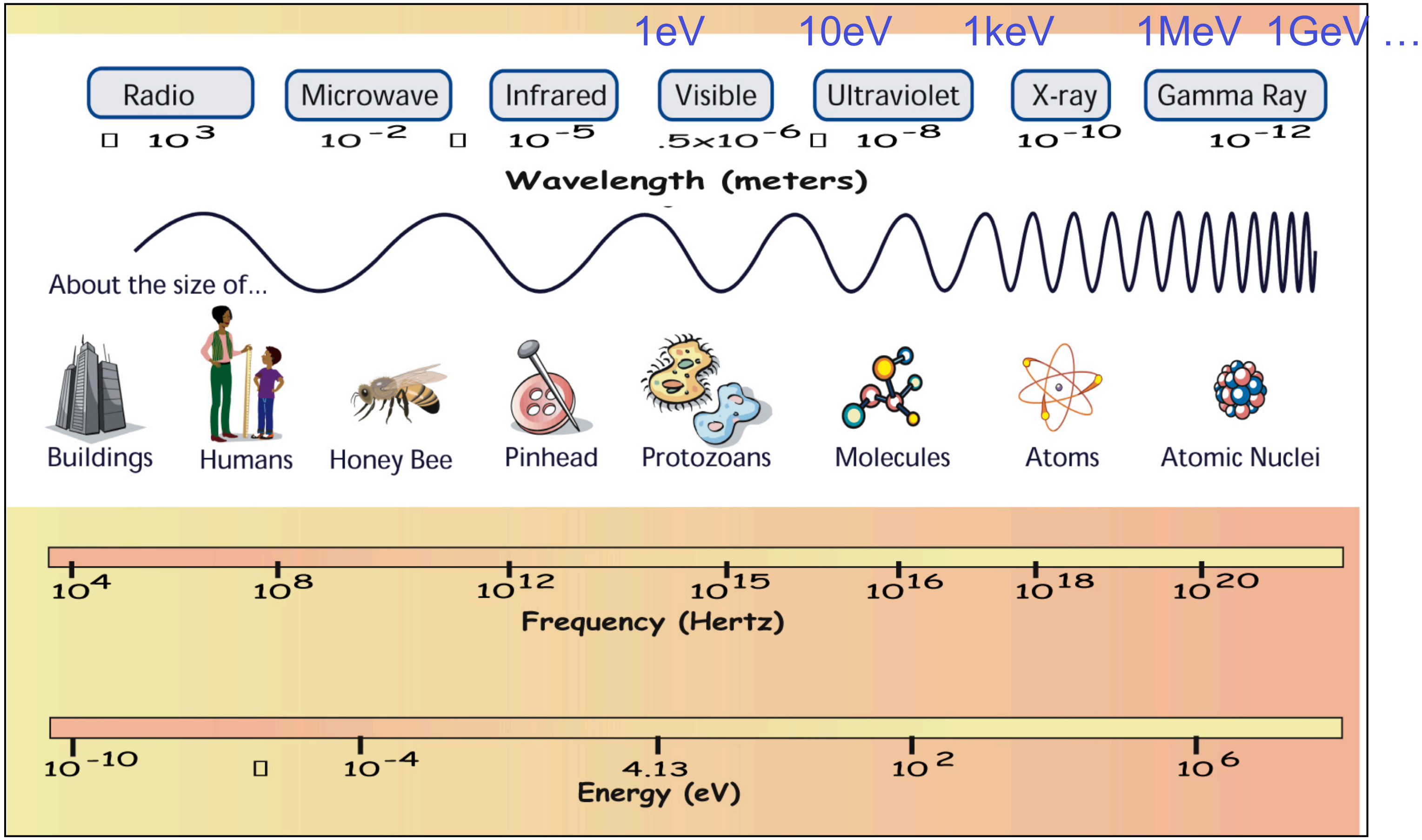
1 keV=1000 eV = 10^3 eV
1 MeV = 10^6 eV
1 GeV = 10^9 eV
1 TeV = 10^{12} eV
1 PeV = 10^{15} eV
1 EeV = 10^{18} eV

Electromagnetic spectrum

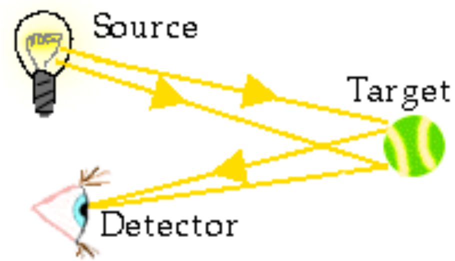
Wavelength (meters)

Frequency (Hz)

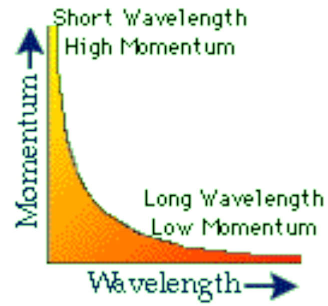
Energy (eV)



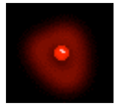
Why use higher and higher energies?

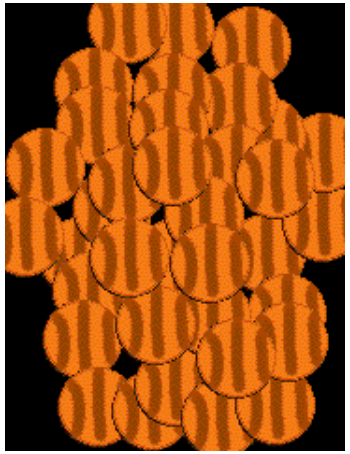
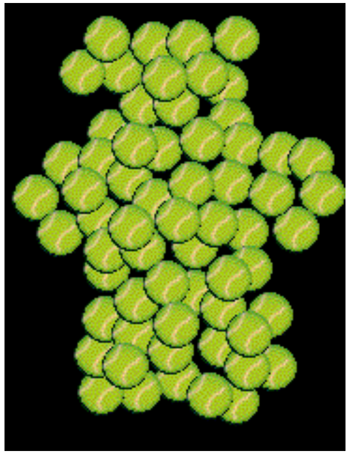
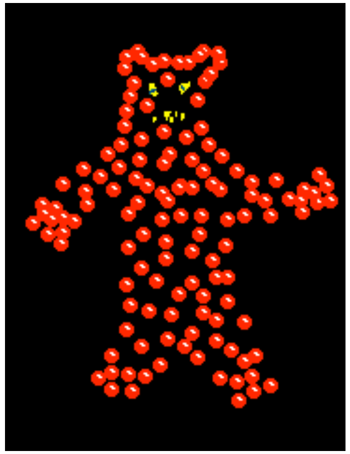


$$\lambda = h/p$$





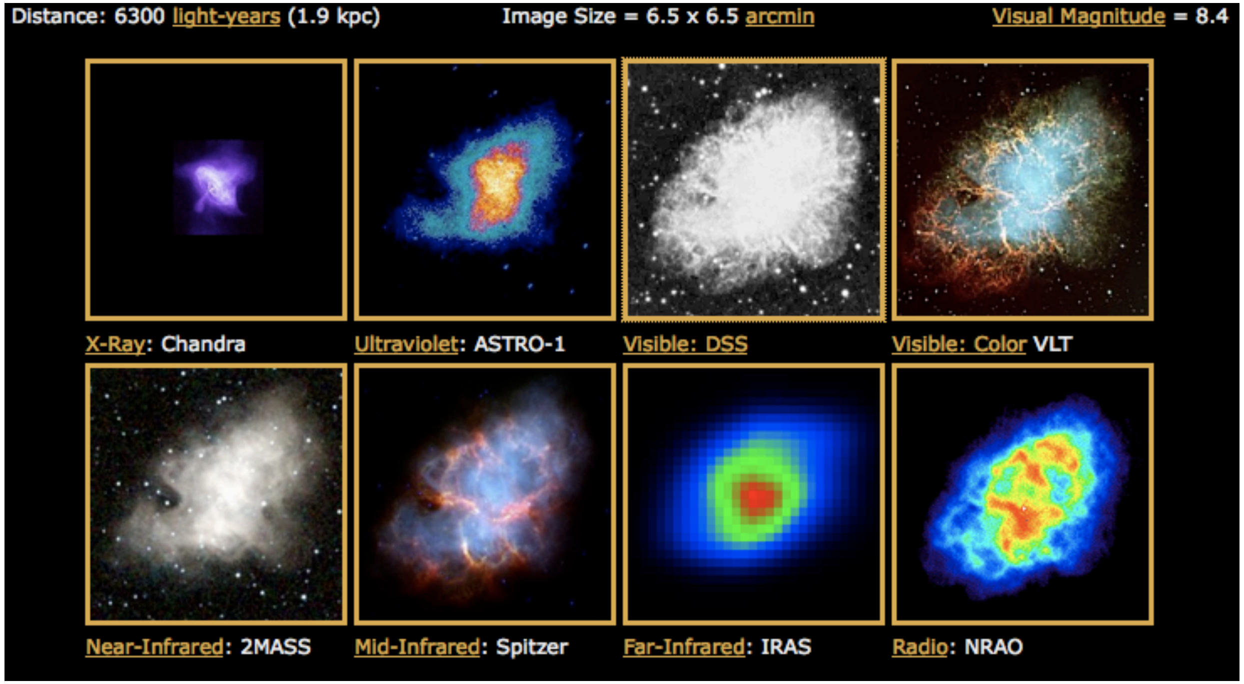


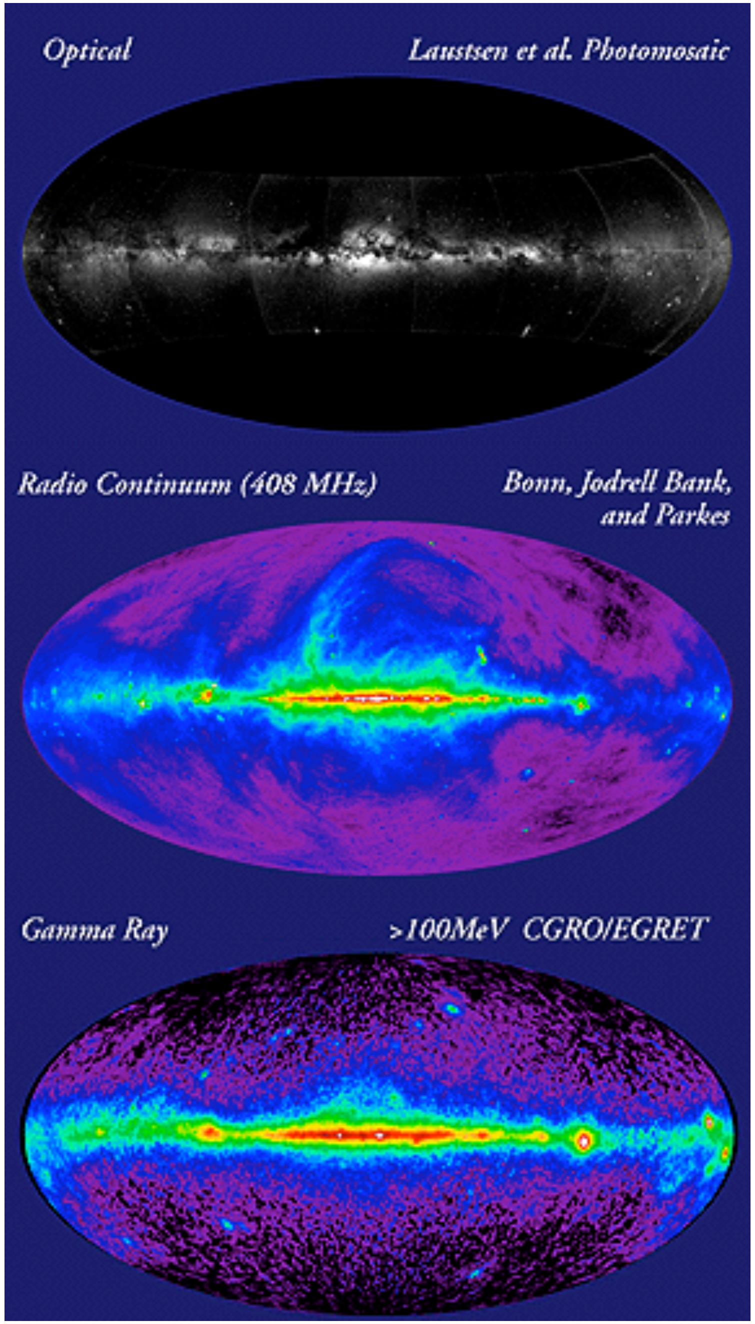




∴ The more energetic the probe, the finer the accessible detail

The Universe not seen by our eyes

Looking at different frequencies (energies) we get very different pictures depending on the emission process at that frequency





Messaggeri cosmici

Fotoni

γ

Neutrini

ν

Raggi cosmici

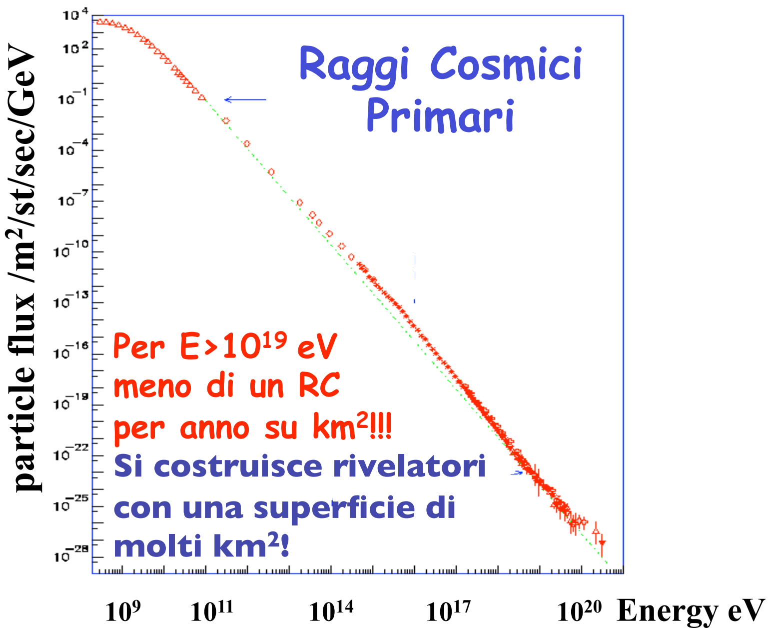
RC

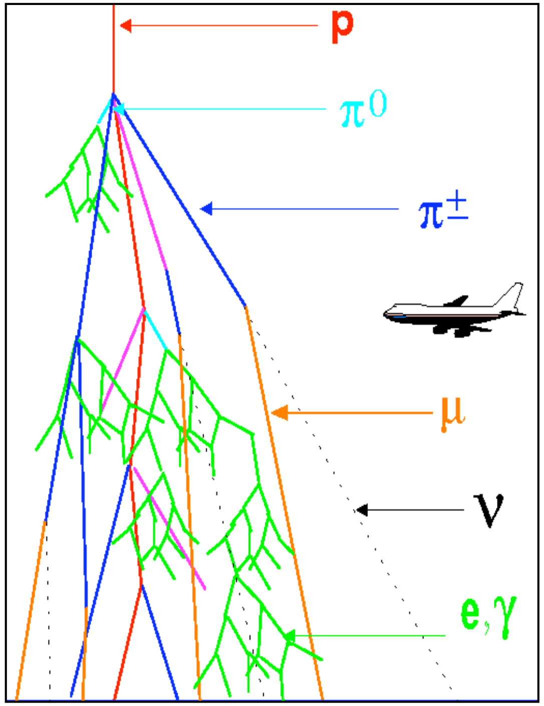
Victor Hess nel 1912
Scopre i Raggi Cosmici
salendo nell' atmosfera
con un elettroscopio

Nobel nel 1936

Raggi Cosmici

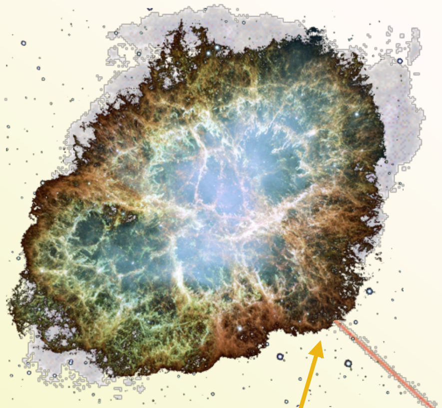
Raggi cosmici primari:
p 80 %, α 9 %, n 8 %
e 2 %, heavy nuclei 1 %
γ 0.1 %, ν 0.1 %



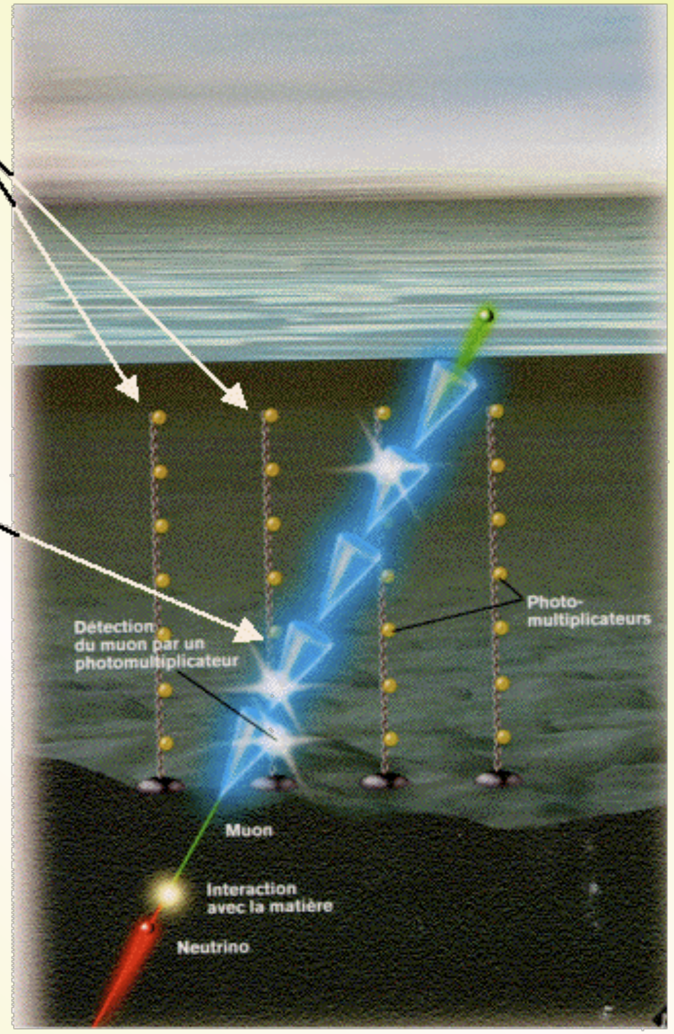


Raggi cosmici secondari sulla superficie della Terra:
ν 68 % ; μ 30 %
p, n, ... 2 %

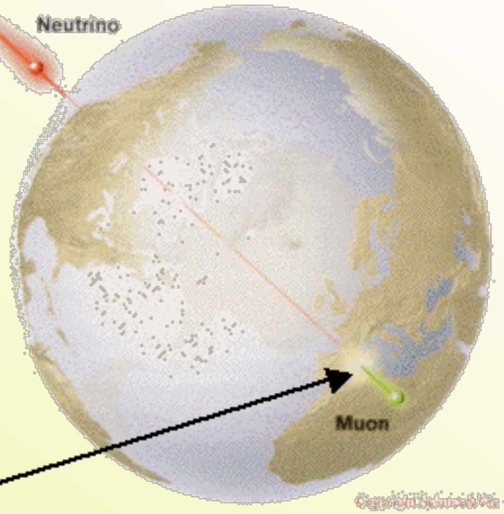
Telescopio di neutrini



Fotoni Cherenkov rivelati da fototubi inseriti in sfere resistenti alle alte pressioni

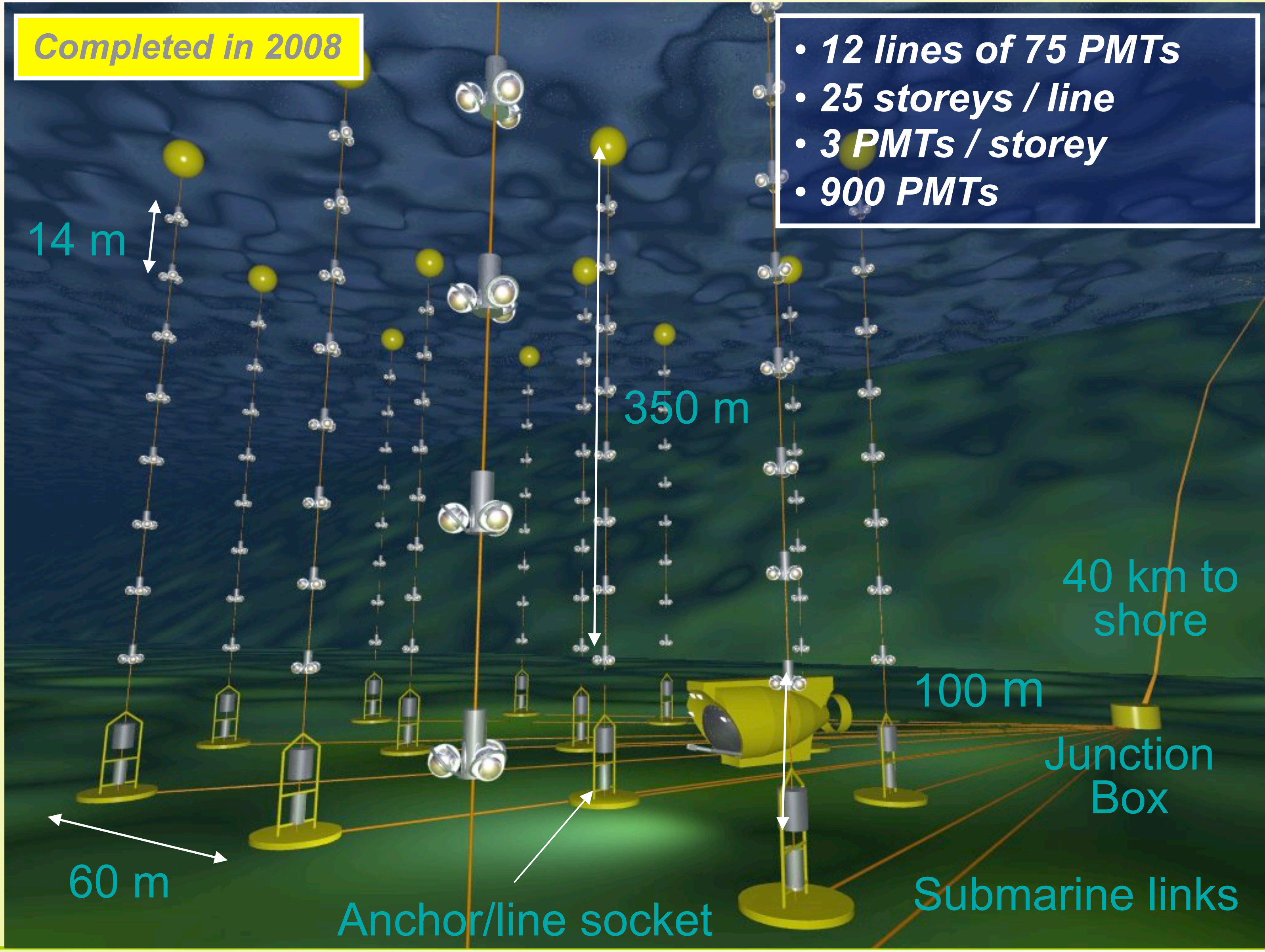


I muoni emettono radiazione Cherenkov nell'acqua di mare



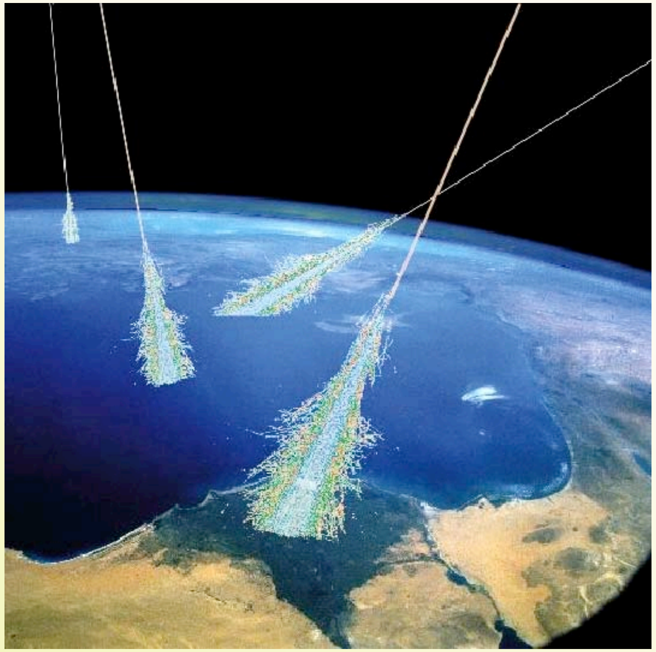
Il neutrino emesso dalla sorgente interagisce con la Terra e produce un muone

ANTARES detector



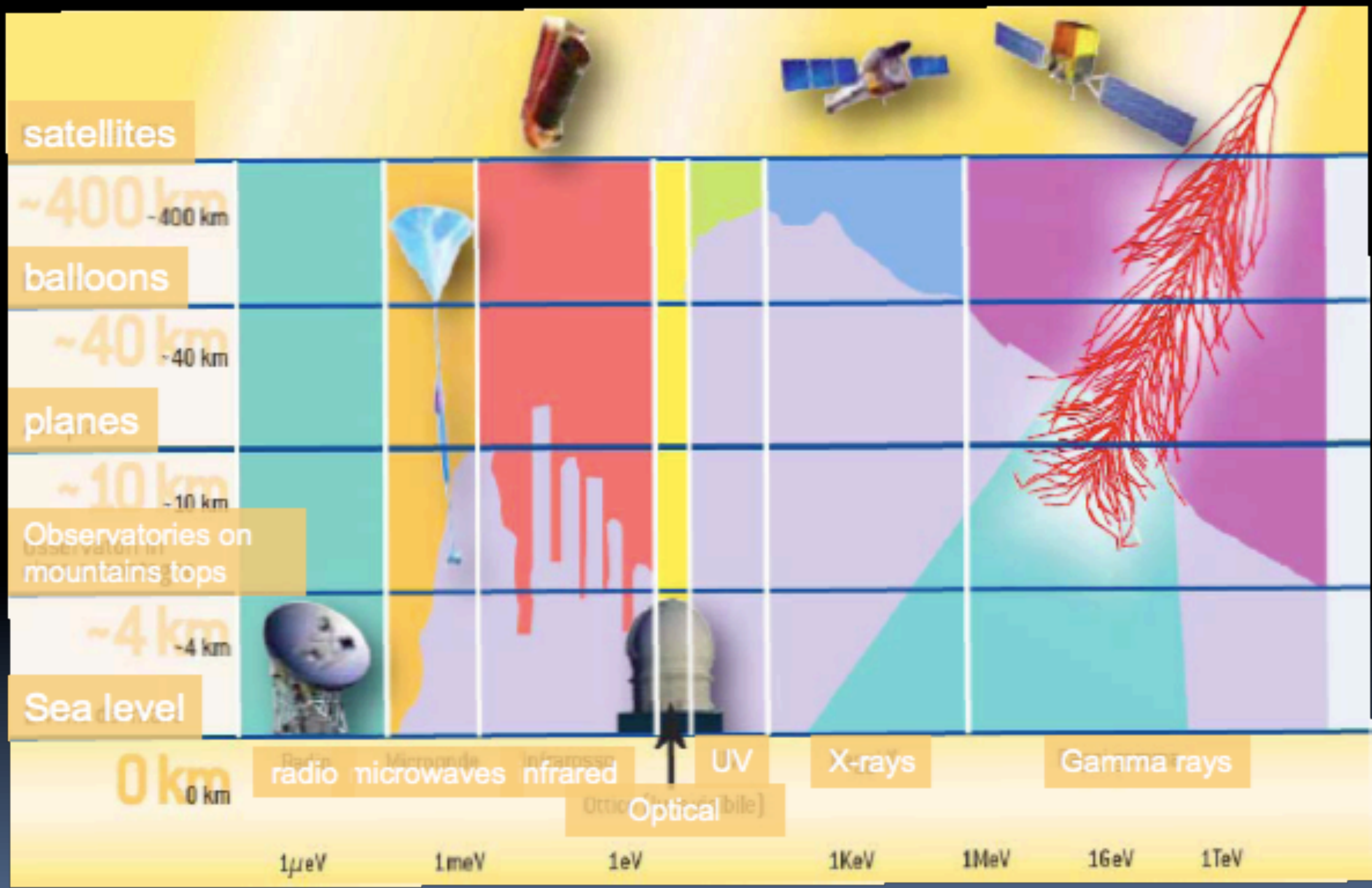
Astronomia da Terra

Atmosfera opaca ai raggi cosmici



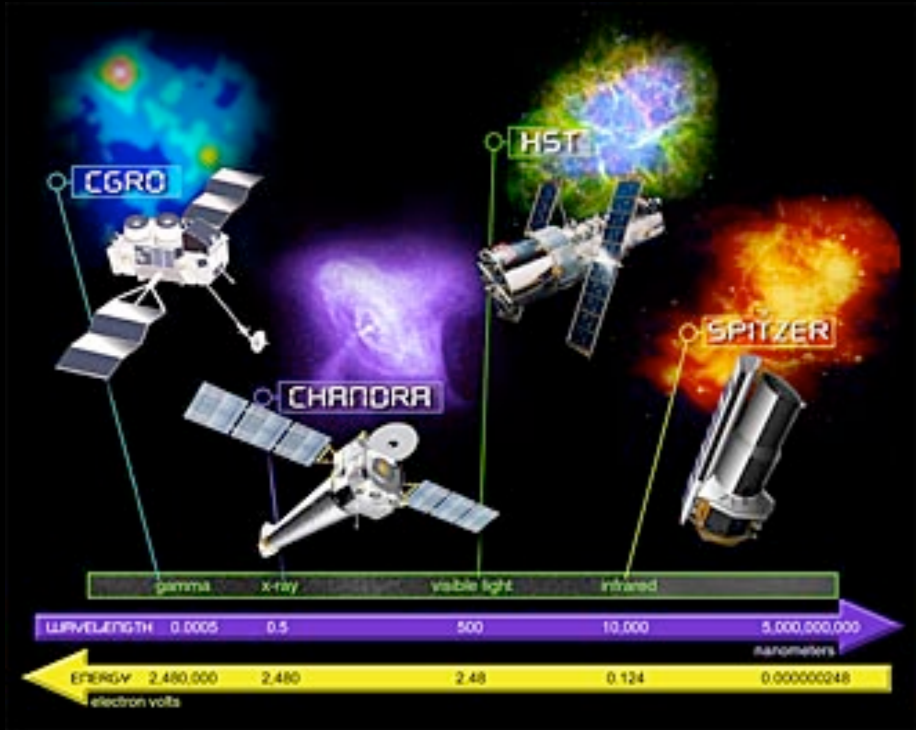
- Si osservano i prodotti dell'interazione con l'atmosfera!

Why satellite astronomy ?

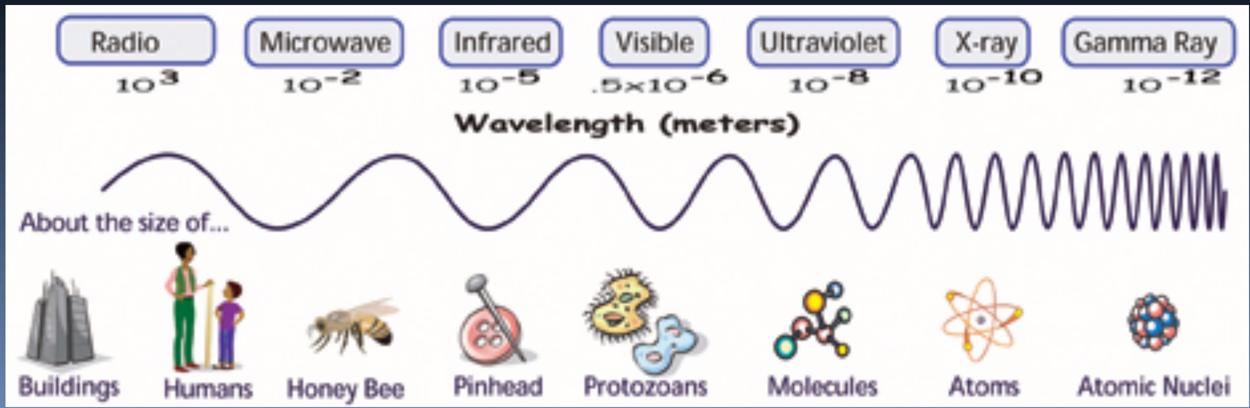


NASA Great Observatories

- Broad EM spectral coverage
- Contemporaneous



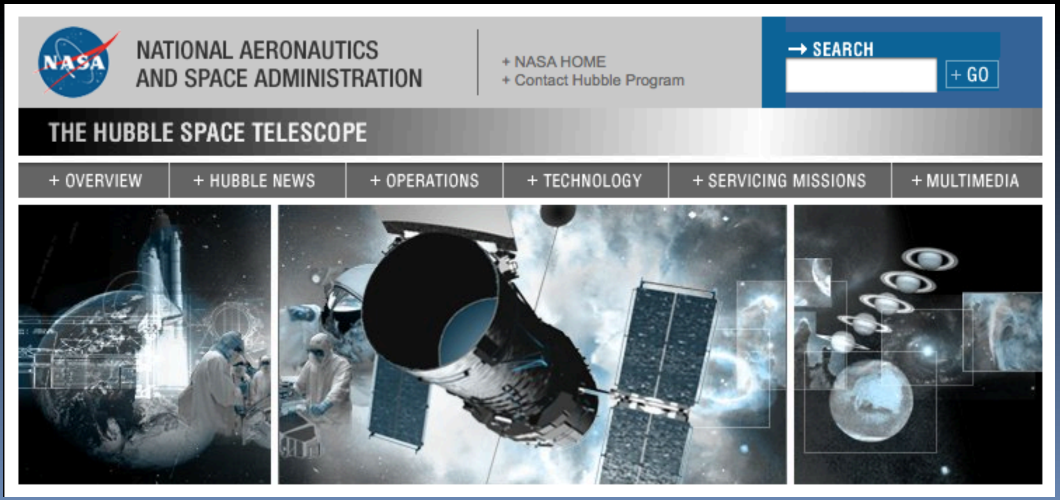
Hubble – Chandra – Spitzer – Compton



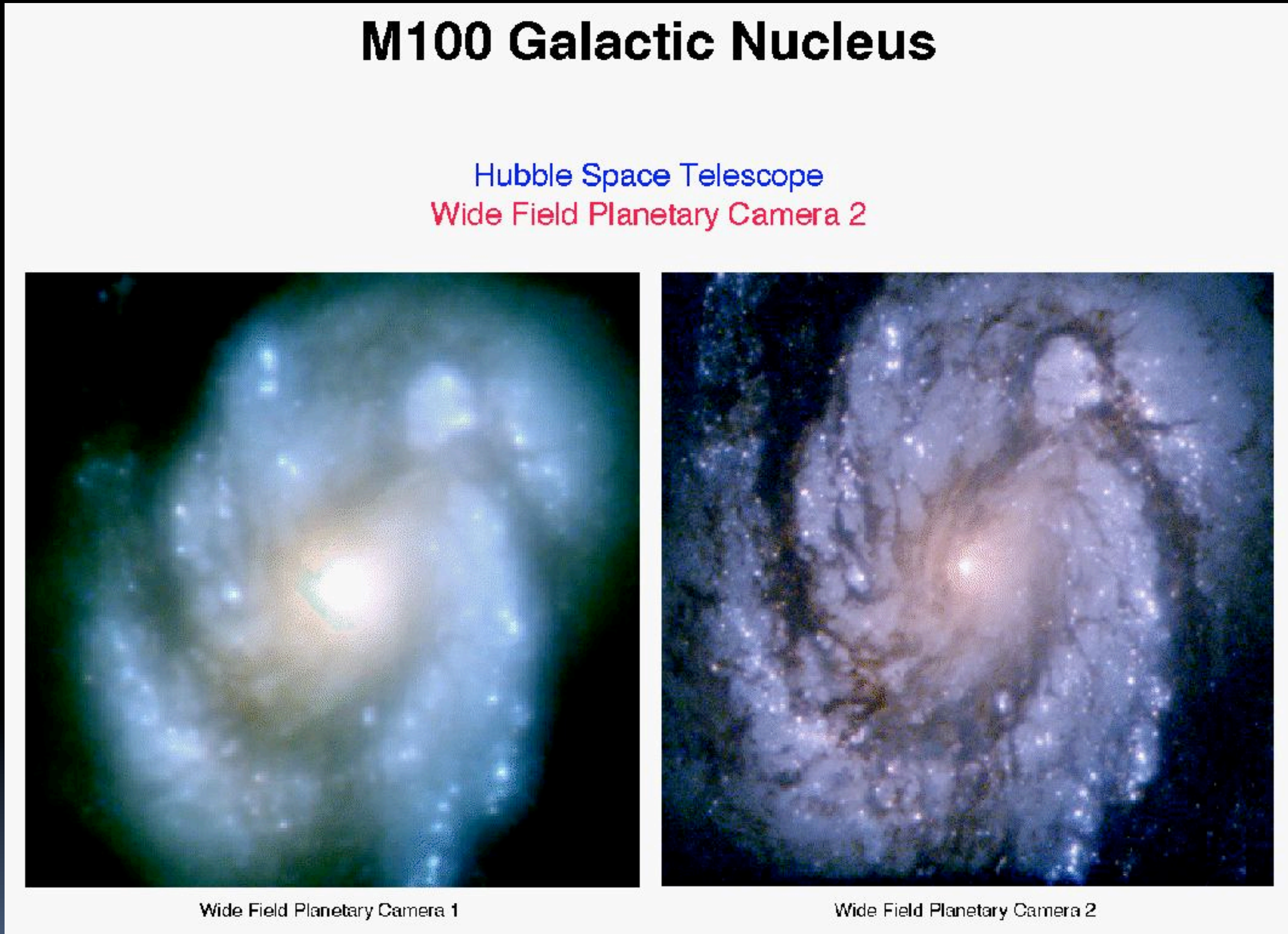
Hubble

- Launch 24 April 1990 with Space Shuttle Atlantis
  - > 100,000 orbits!
  - Multiple instruments

- Service Missions
  - 4 in total
  - Low earth orbit (~500km)



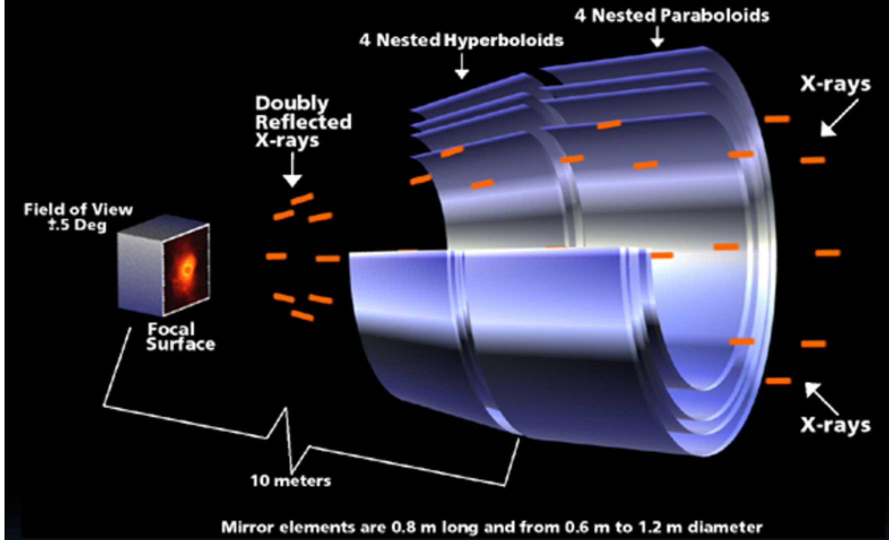
- A world Observatory
  - Multi-agency
  - Public data
  - Huge visibility return with public outreach



January 13, 1994: after SM1, recovery of mirror focusing (COSTAR) and installation of WFPC2

Chandra

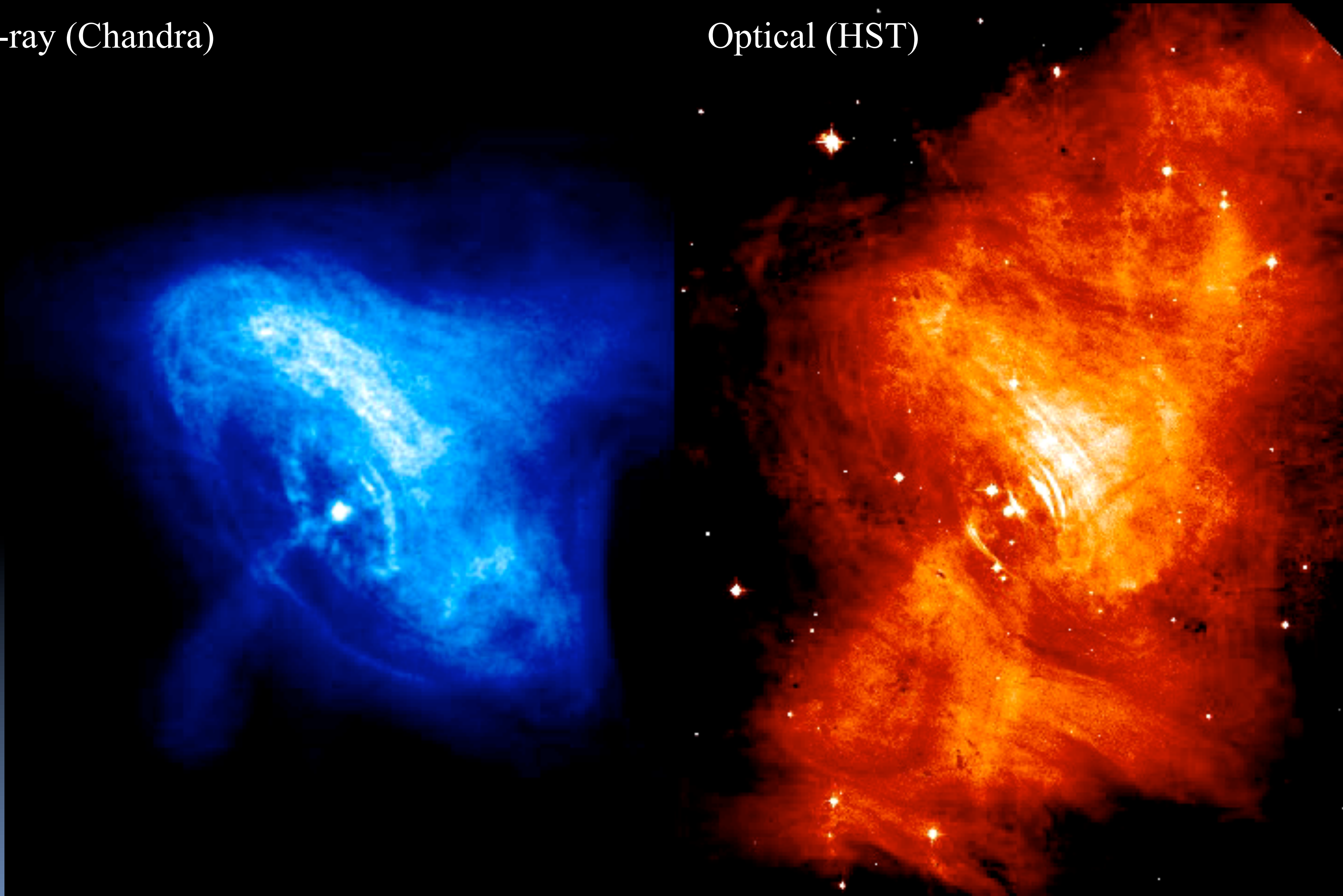
- Launch 23 July 1999 by Space Shuttle Columbia



- X-ray grazing incidence optics

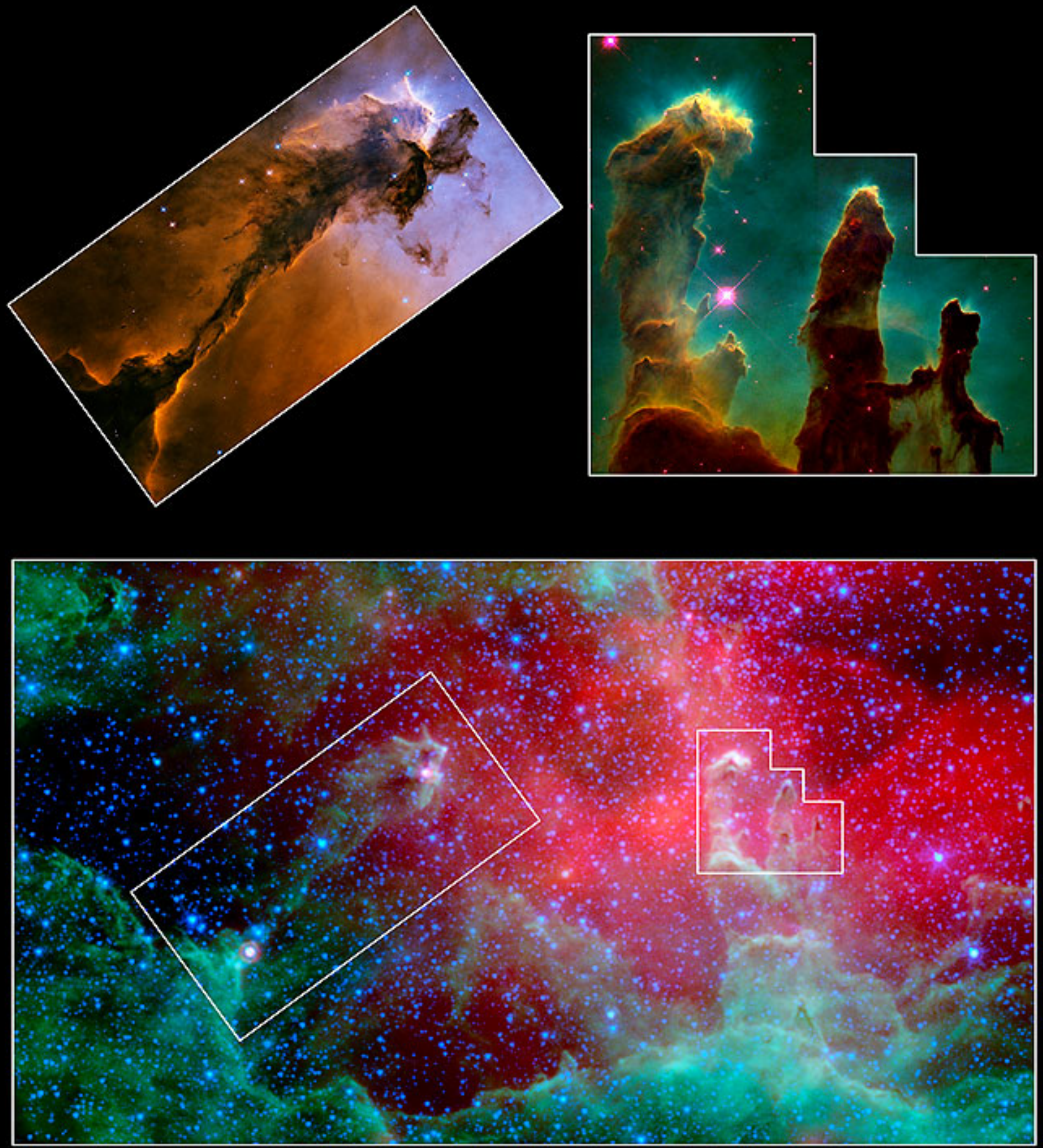
- Elliptical orbit
  - 10000-140000 km from Earth
  - 85% time above Radiation belt

Crab Pulsar Wind Nebula



X-ray (Chandra)

Optical (HST)



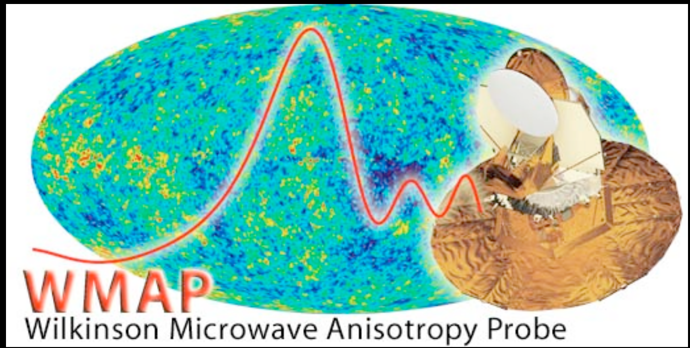
Eagle Nebula (M16) Pillars in Visible and Infrared

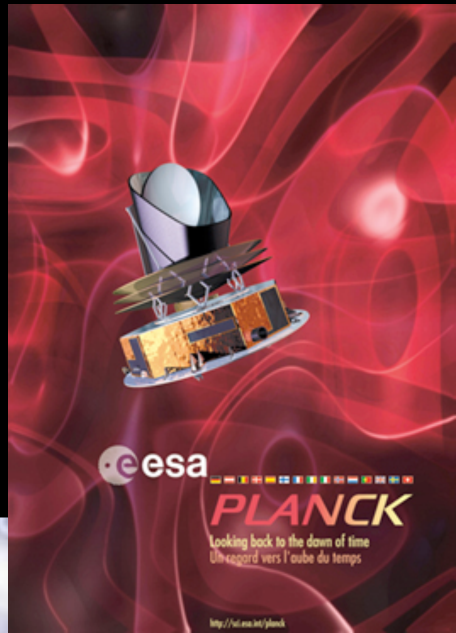
Spitzer Space Telescope • IRAC • MIPS
Hubble Space Telescope (insets)

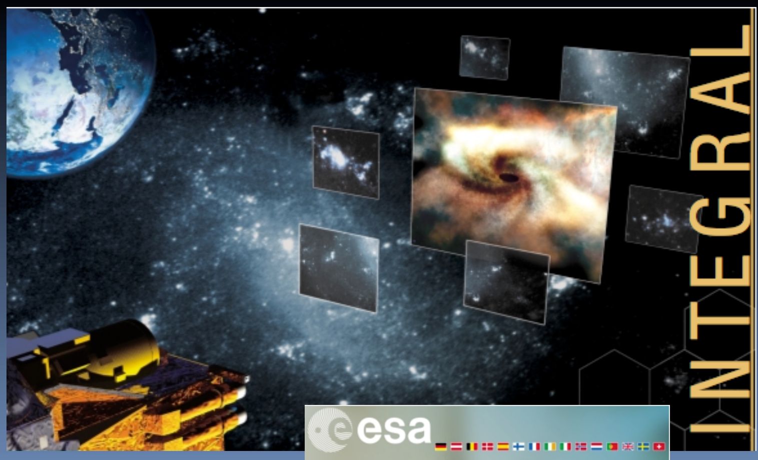
NASA / JPL-Caltech / N. Flagey (SSC/Caltech) & the MIPSGAL Science Team

ssc2007-01d

Many successful missions

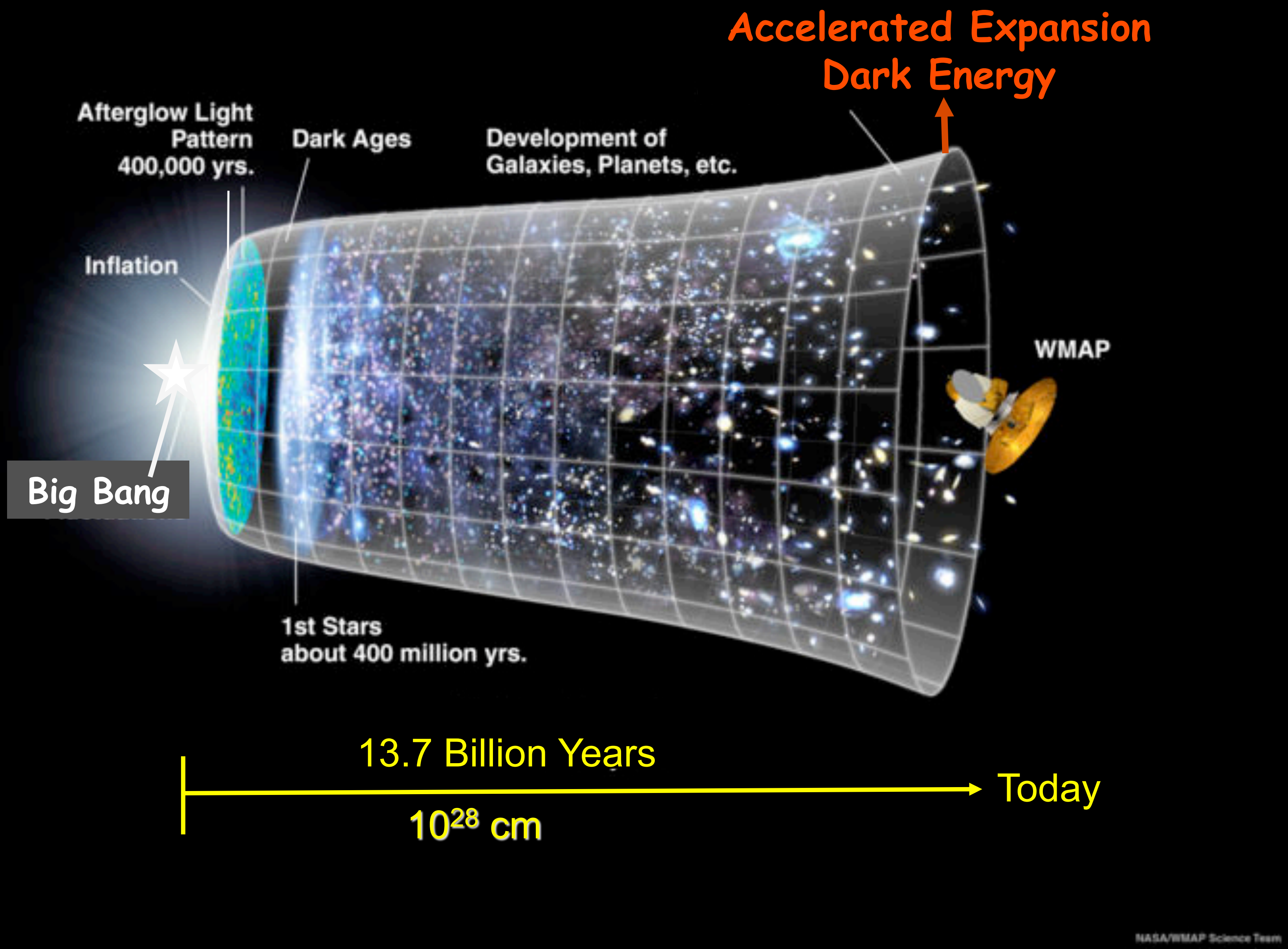




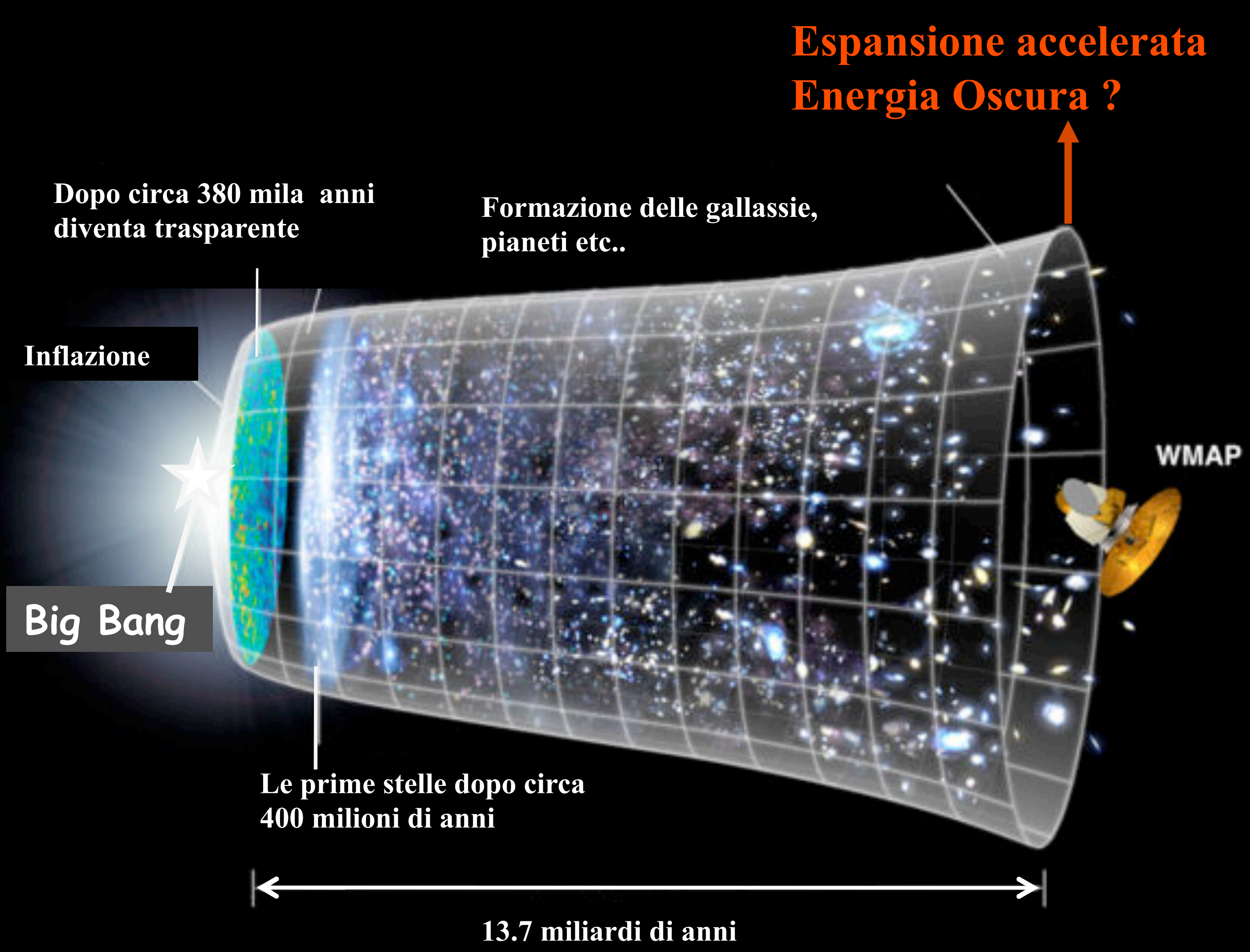


… just to mention a few

Today's Universe: very old and very cold



L'espansione dell'Universo dal Big Bang ad Oggi

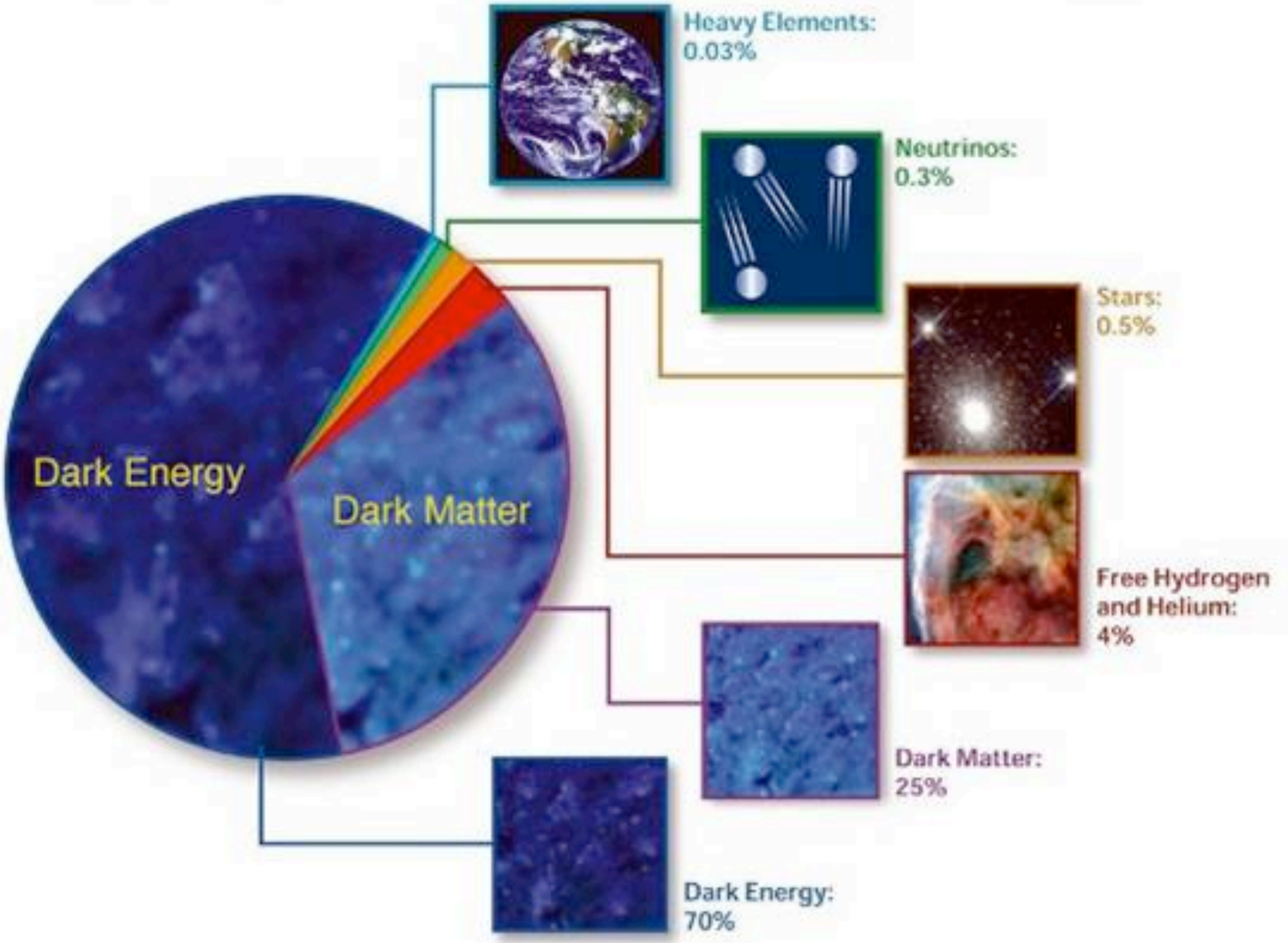


Si ritiene che l'Universo sia iniziato con una singolarità chiamata Big Bang, un evento iniziale che dette origine al tutto: allo spazio, al tempo e all'energia (materia e radiazione). Il modello λ-CDM descrive l'evoluzione dell'Universo da uno stato primordiale denso, caldo e uniforme a quello presente lungo una fascia di tempo di di 13.72±0.12 miliardi di anni.

NASA/WMAP Science Team

Total Energy in the Universe

(stars and planets are a very small part !)



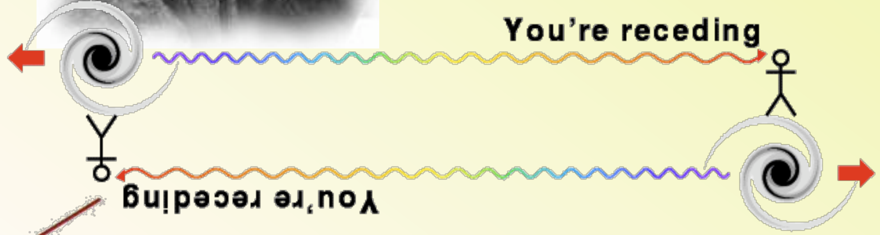
1920: Legge di Hubble

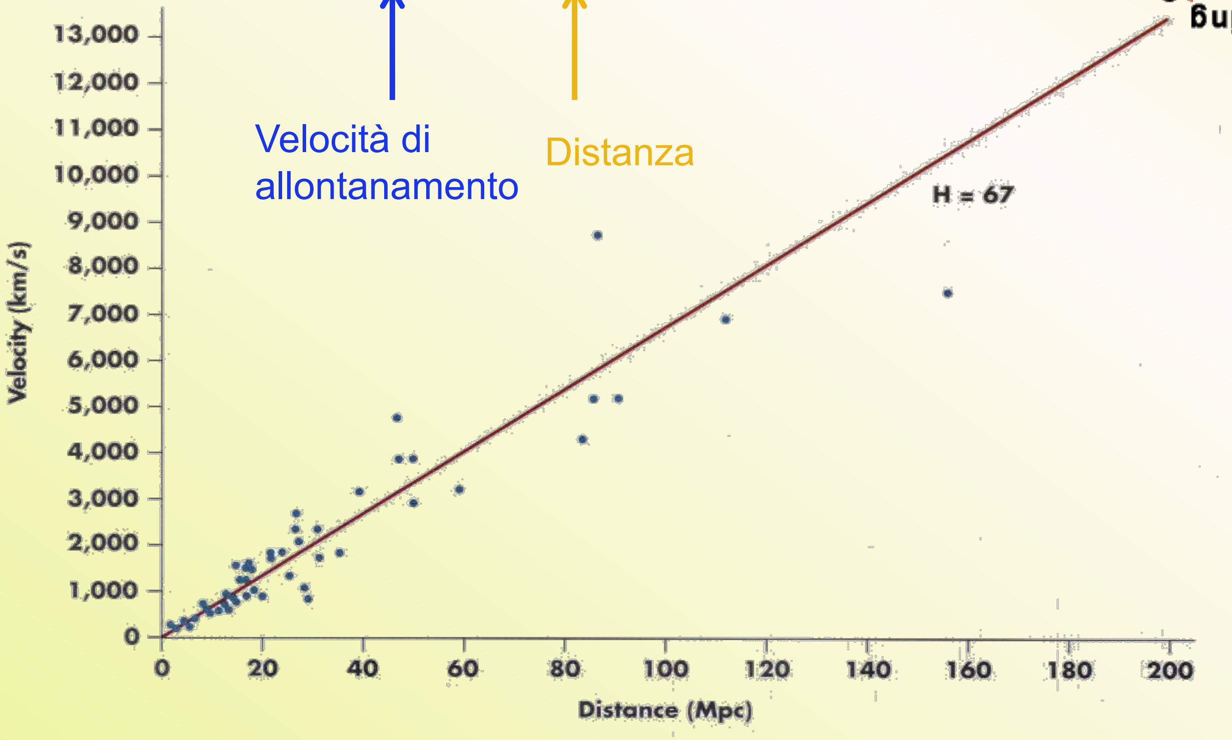
Costante di Hubble

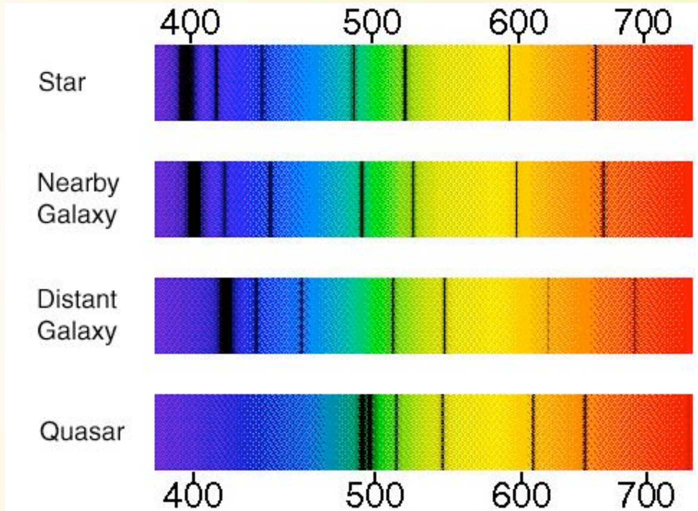
$$V = H_0 d$$

Velocità di allontanamento

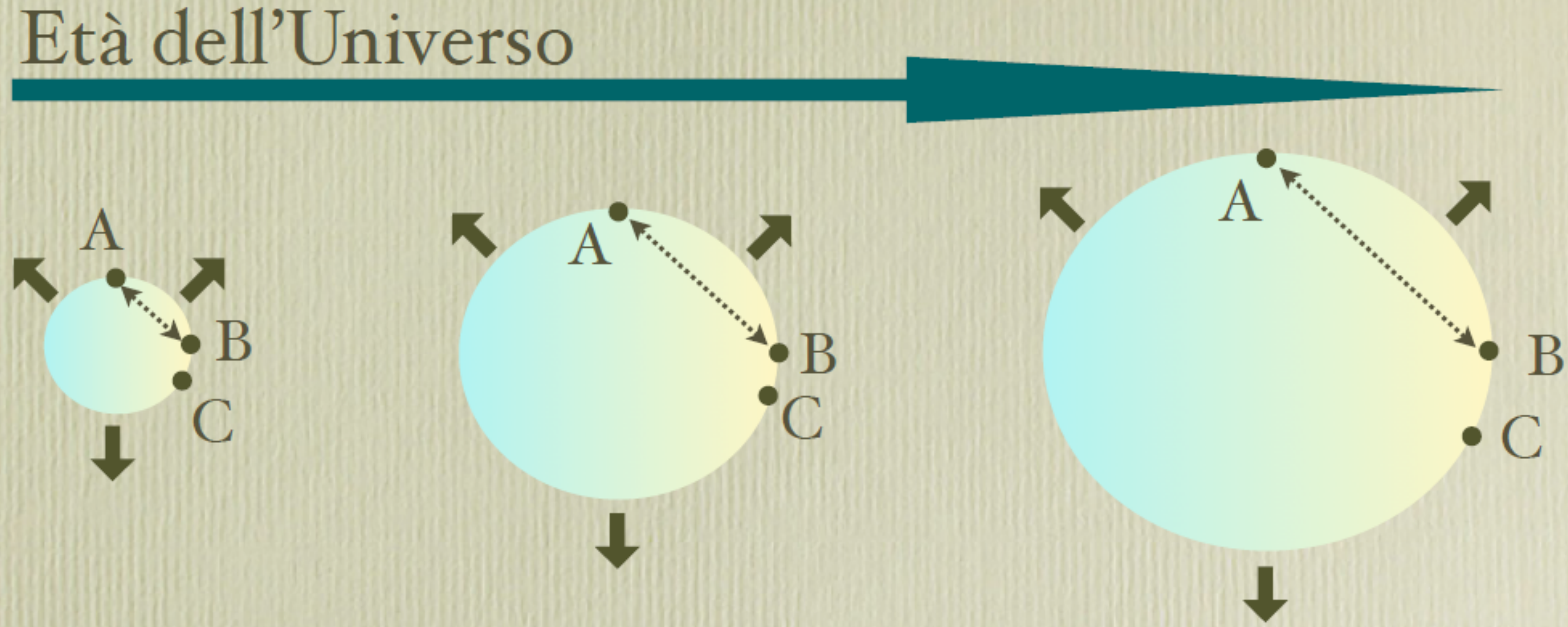
Distanza







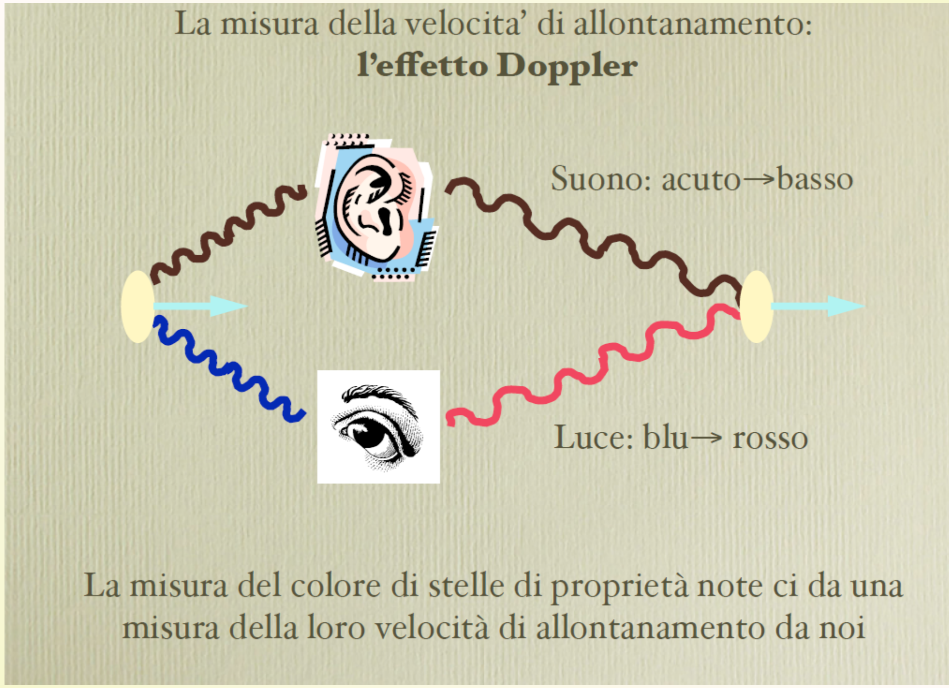
Espansione dell'Universo

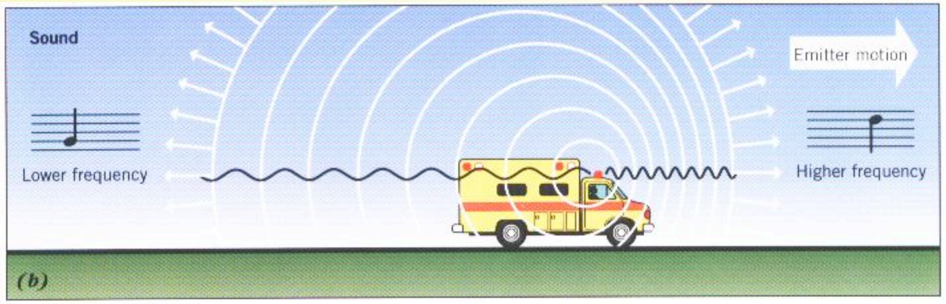


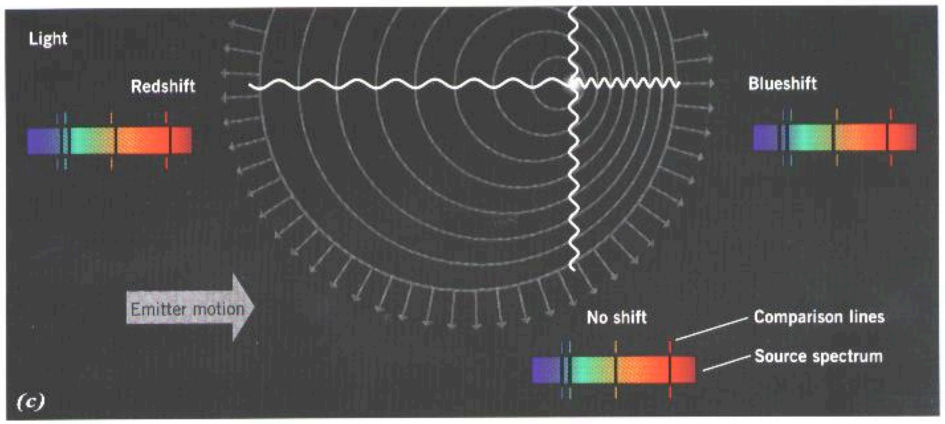
Legge di Hubble:

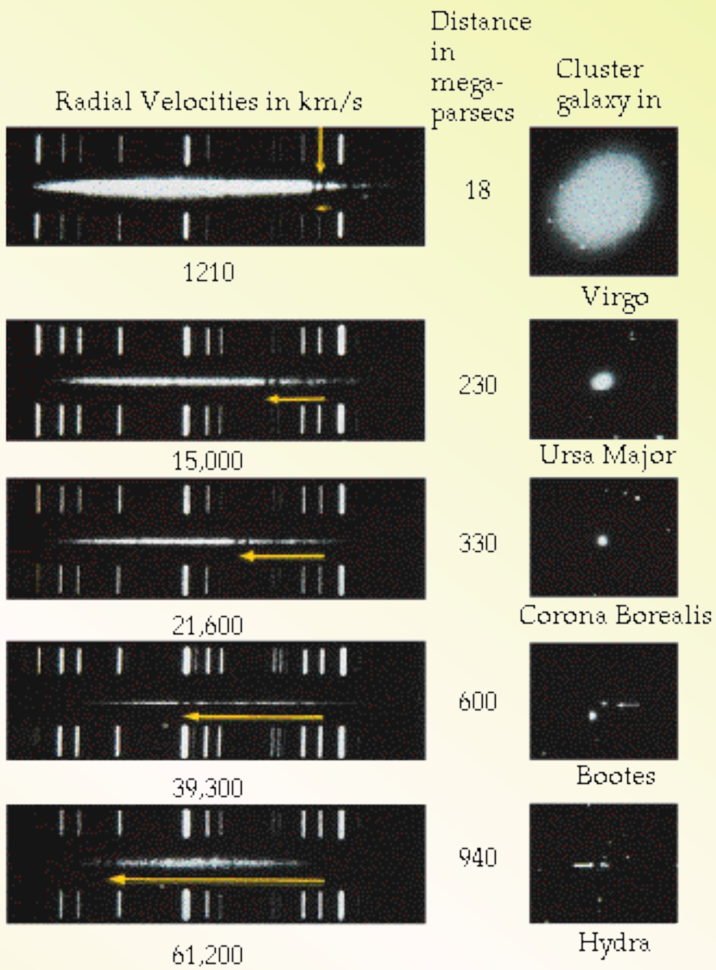
La velocità di allontanamento fra due punti nell'Universo è proporzionale alla distanza che li separa

Effetto Doppler



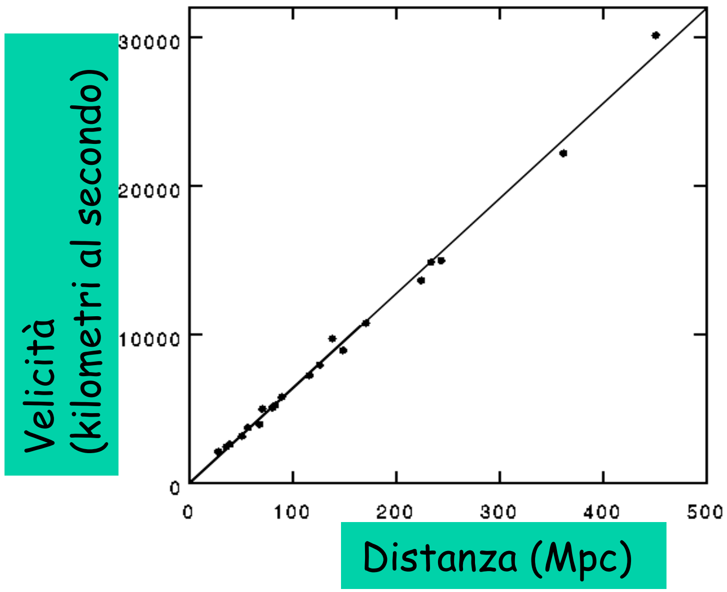


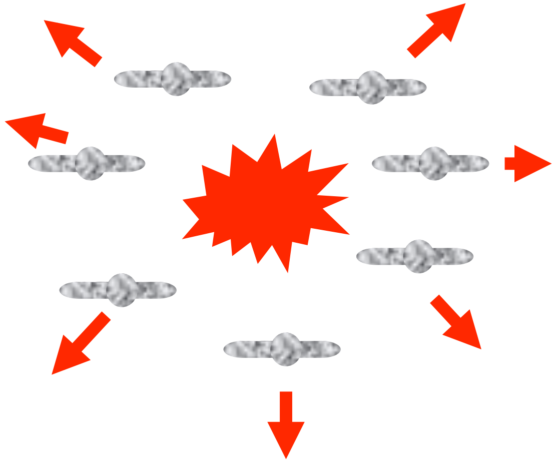


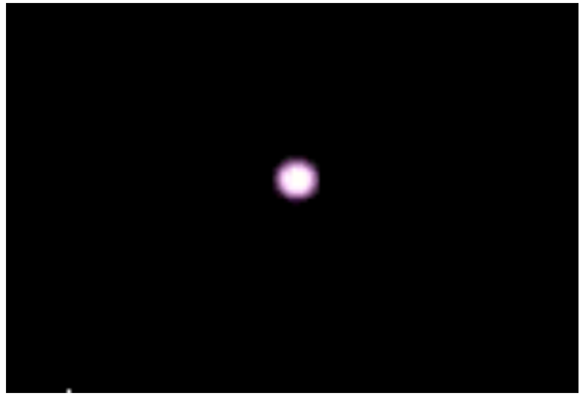


L'Universo è in espansione:

Hubble (1929): le galassie si allontanano con una velocità tanto maggiore quanto maggiore è la loro distanza (H_0=74.2±3.6 Km/sec·Mpc).







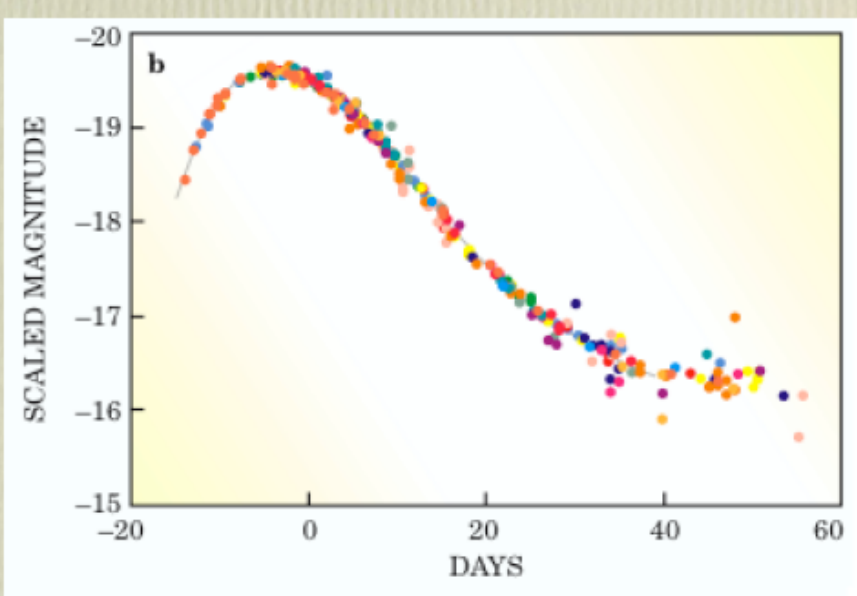
L'Universo si espande come fosse il risultato di una gigantesca esplosione: il **Big Bang**.
Espandendosi la densità di energia diminuisce, cioe' **l'Universo si raffredda**.
La velocità di espansione cresce nel tempo (H_t), cioè **l'espansione è accelerata!**

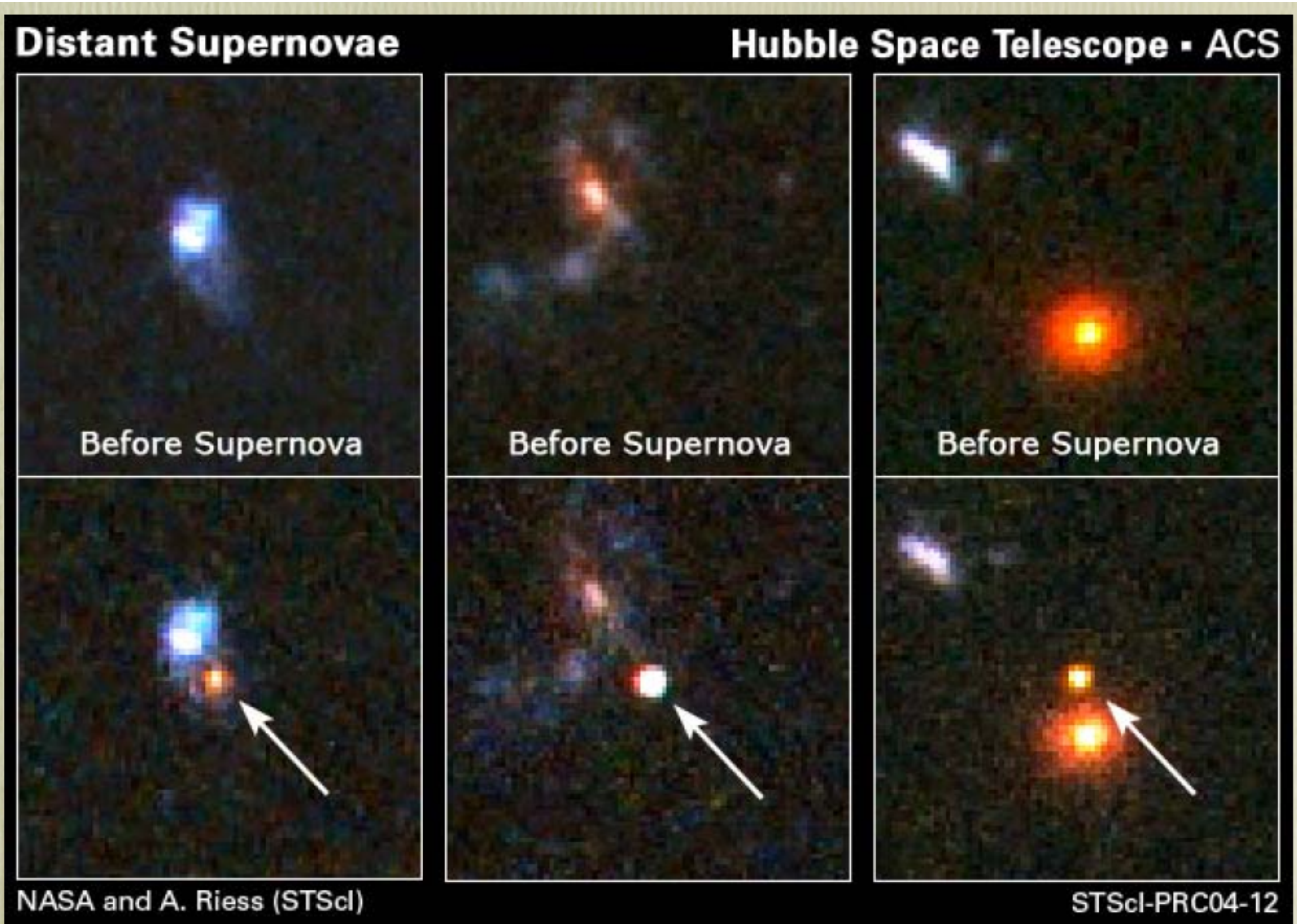
La misura della distanza: Supernovæ

L'intensità della luminosità ricevuta da stelle la cui brillanza assoluta è nota a priori, offre una stima della loro distanza

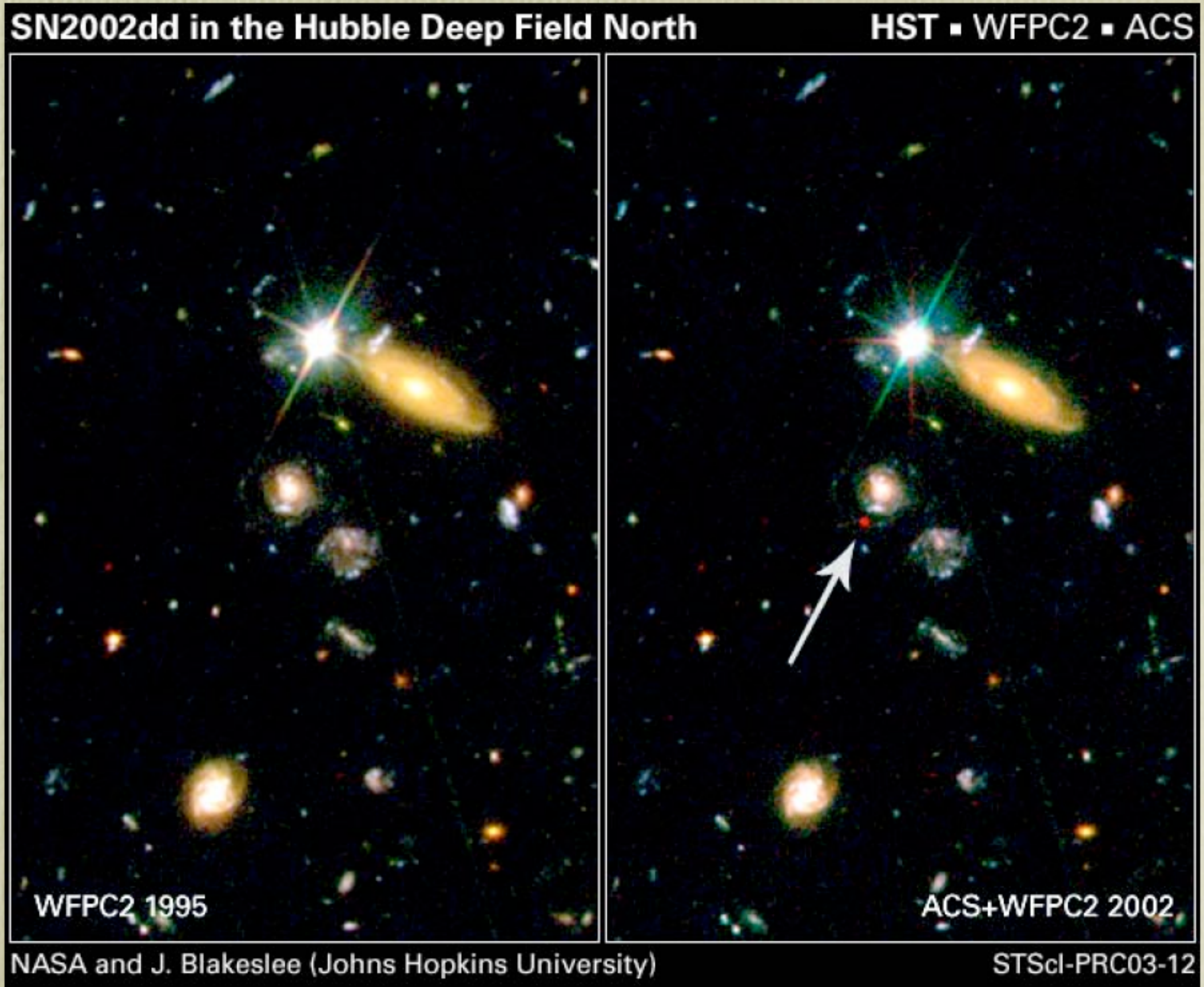
Tali "candele ideali" sono offerte dalle Supernovæ di tipo Ia, il risultato di esplosioni catastrofiche che seguono all'esaurimento del carburante in stelle massicce.

Per tali stelle, esiste una relazione precisa fra la loro luminosità assoluta, e la variazione della luminosità nel periodo successivo all'esplosione:



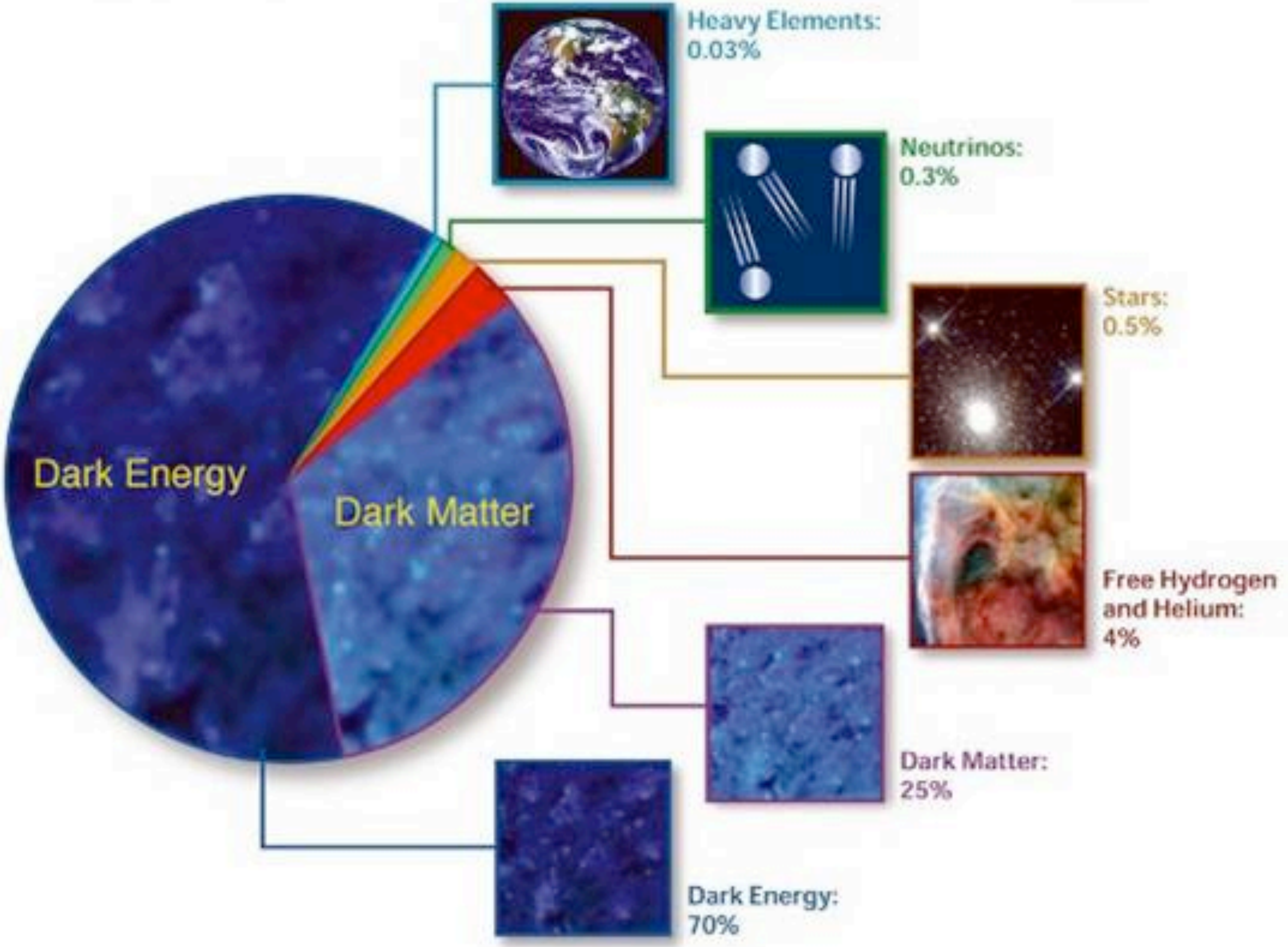


Immagini di tre delle supernove più distanti note, scoperte dall' Hubble Space Telescope. Le supernove esplosero circa 6 miliardi di anni fa, dunque prima che il sistema solare si formasse! La loro immagine, tuttavia, viaggiando nello spazio e nel tempo ci raggiunge solo ora (e non dura che pochi giorni!!).


SN2002dd in the Hubble Deep Field North
HST ▪ WFPC2 ▪ ACS
WFPC2 1995
ACS+WFPC2 2002
NASA and J. Blakeslee (Johns Hopkins University)
STScI-PRC03-12

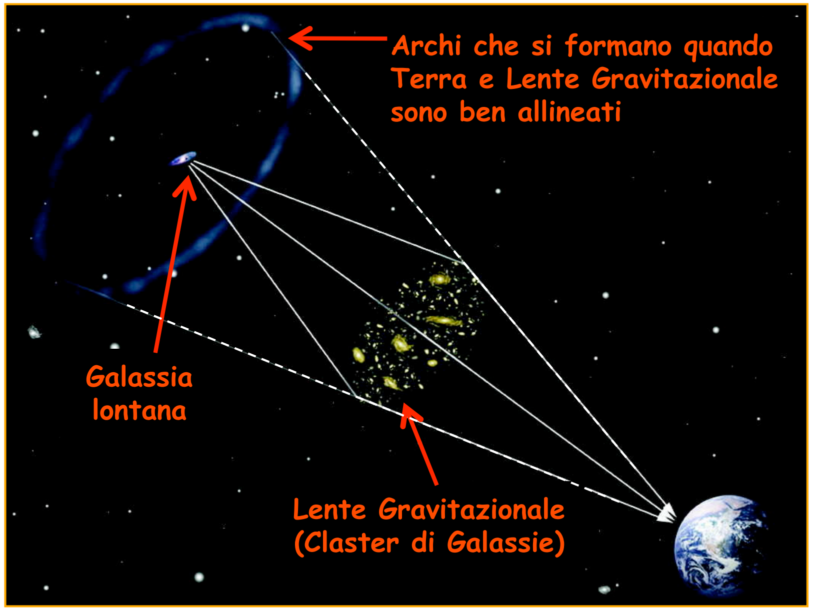
Total Energy in the Universe

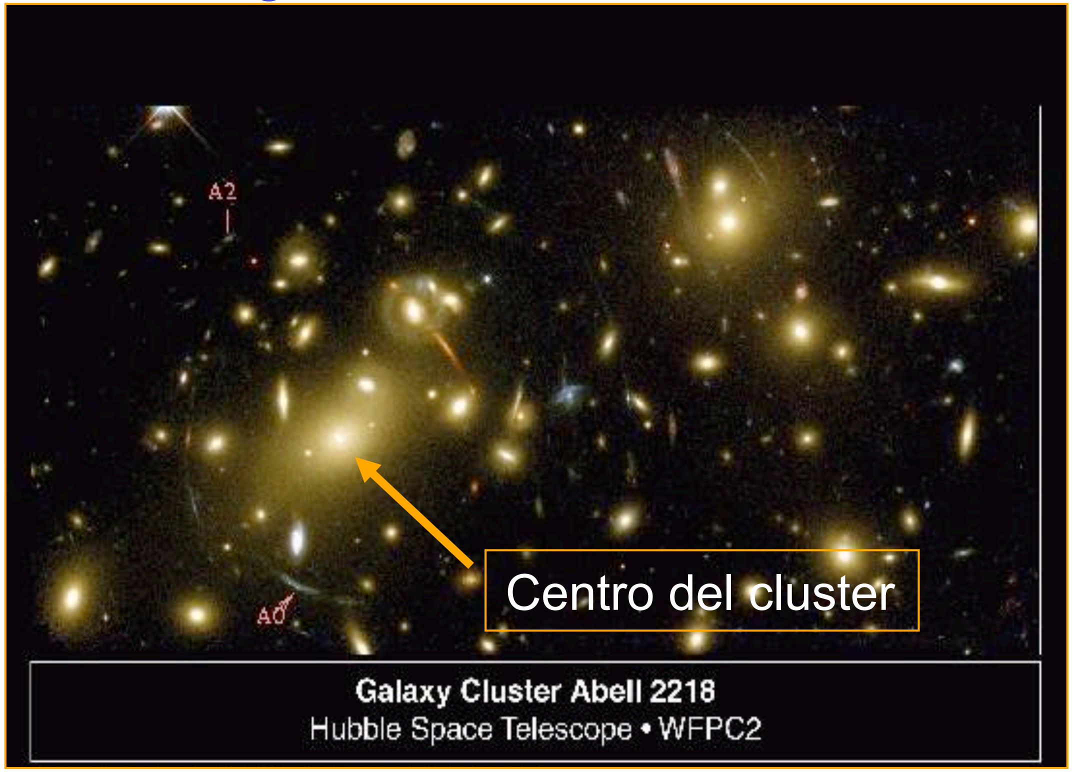
(stars and planets are a very small part !)



La Materia come Lente Gravitazionale

effetto predetto dalla teoria della relatività generale di A.Einstein nel 1936



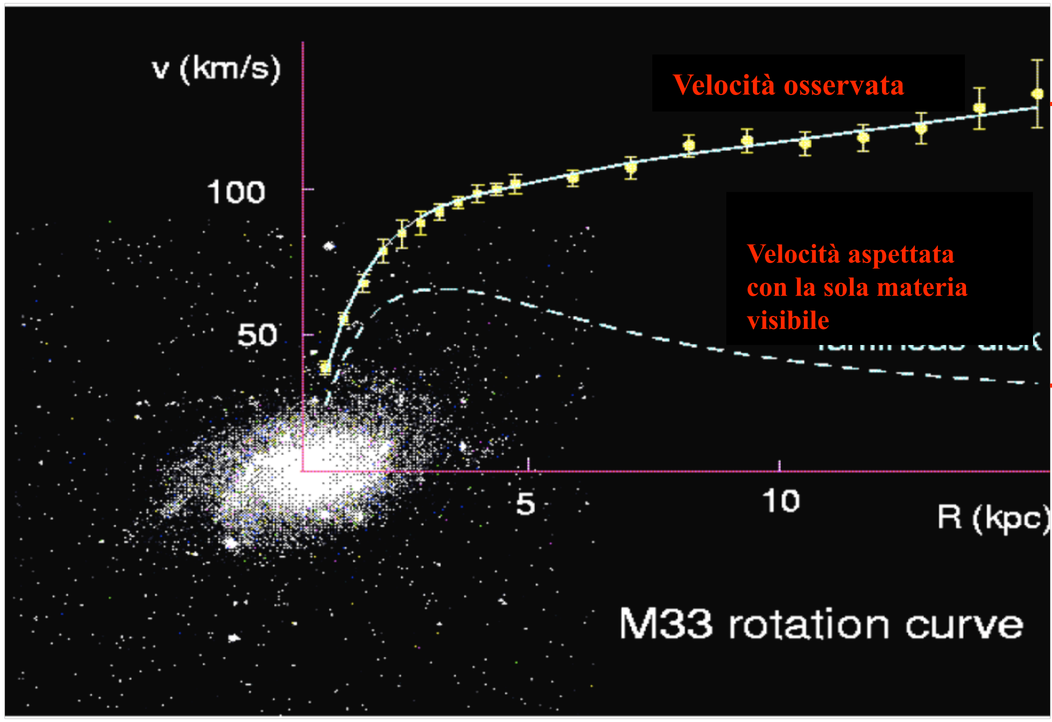


Le immagini multiple di una stessa galassia (per es. A0 e A2) vengono identificate confrontando gli spettri di luce dei diversi archi. Con così tante immagini è possibile fare un modello preciso della distribuzione di masse del cluster della lente gravitazionale.

Ma l'effetto e' molto piu' forte di quello spiegabile con la massa della Materia Visibile da cui l'ipotesi dell'esistenza della Materia Oscura (cioe' invisibile)

Manifestazioni della Materia Oscura

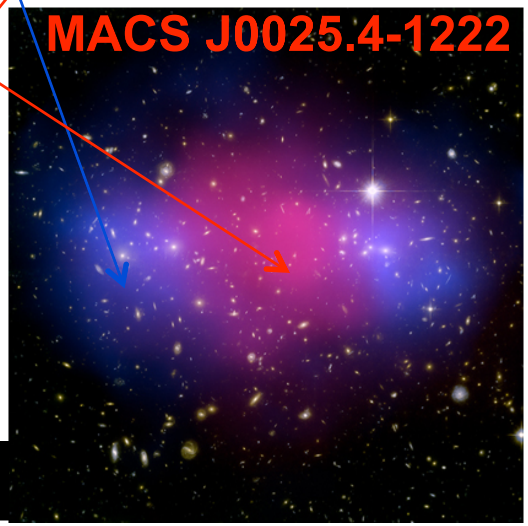
Galassia M33
Velocità di rotazione



Materia oscura?

Gas ad alta temperatura

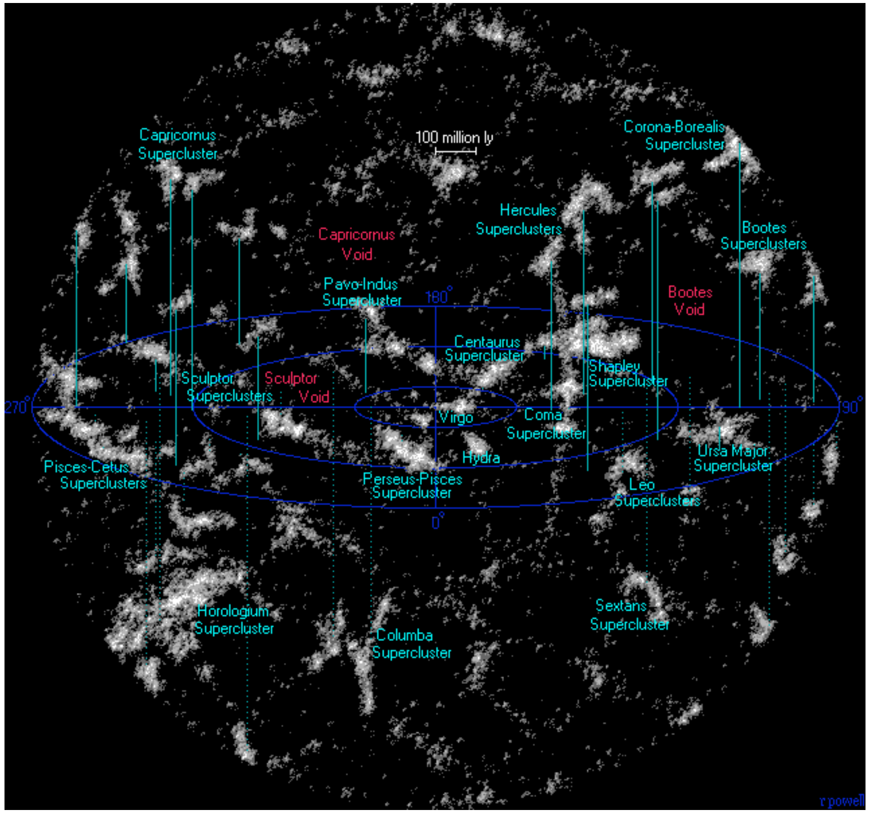
Il "Bullet Cluster"
Formatosi dalla collisione di due grandi cluster di galassie



Chandra X-ray Observatory and Hubble Space Telescope

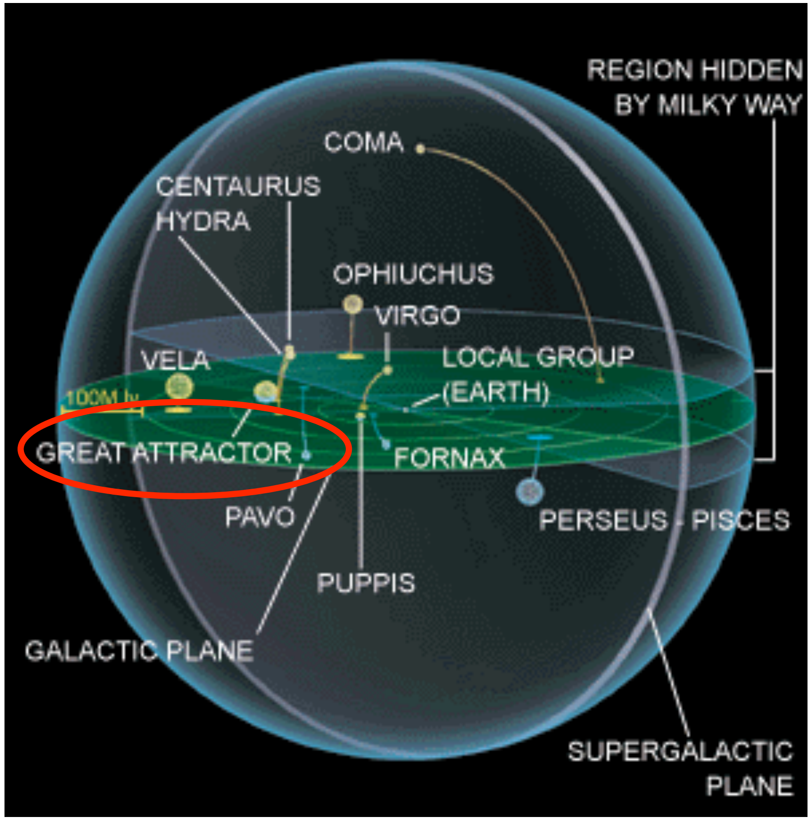
La Materia Oscura sembra essere costituita da particelle di grande massa che interagiscono debolmente

why the LHC?



Why are there huge voids and clusters of galaxies in outer space?

Could the LHC find new forces and extra 'hidden' dimensions ?



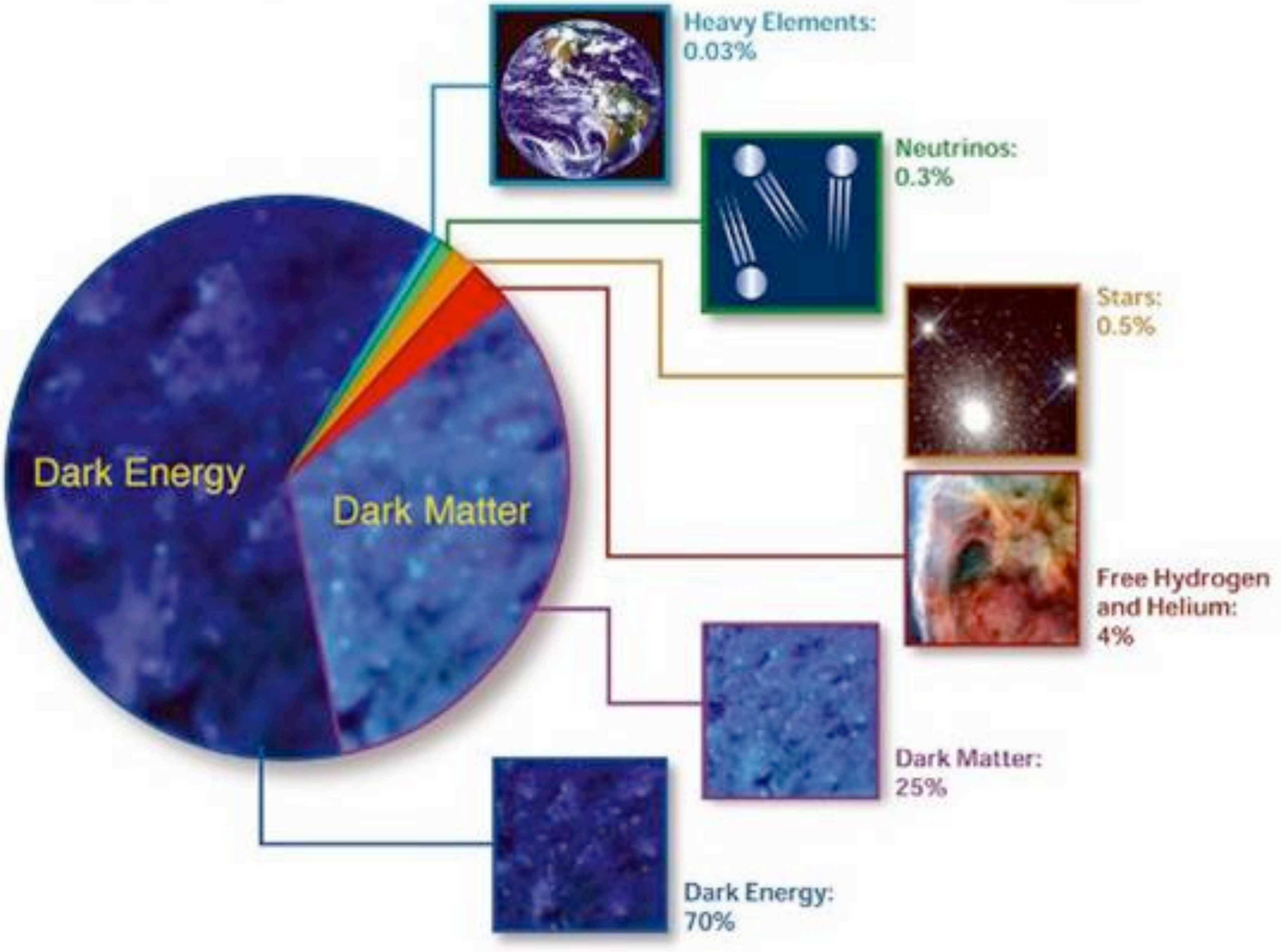
What is the Great Attractor ?
It corresponds to the pull of 10^{16} suns

Only 10% can be accounted for with the visible stars and galaxies

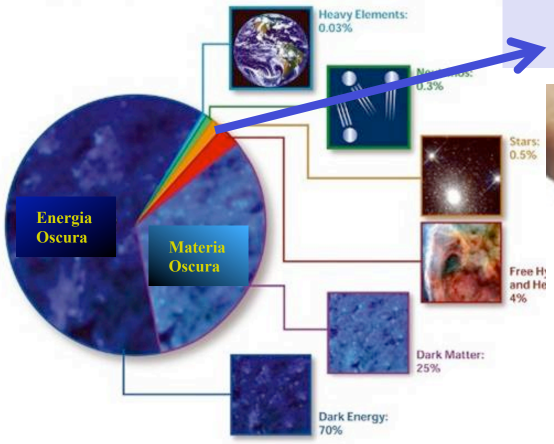
Is the rest due to Dark Matter Particles ?

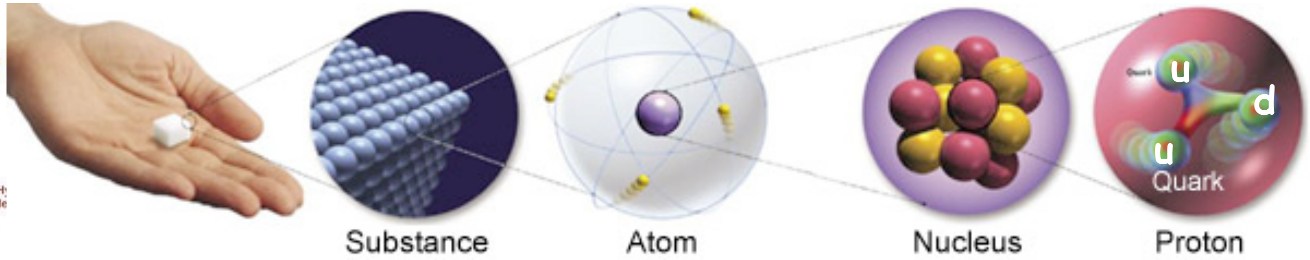
Total Energy in the Universe

(stars and planets are a very small part !)



La materia ordinaria (~5%)





Anassimene
Talete
(VI-V a.C.)

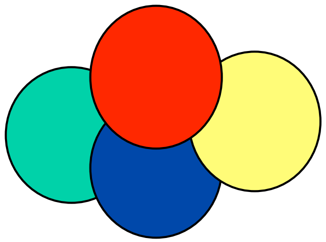
Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	— VII —			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

Naming conventions of new elements

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

D. Mendeleev
J.L.Meyer
(1869 d.C.)



atomos

Leucippo
Democrito
(V-IV a.C.)

Fermions

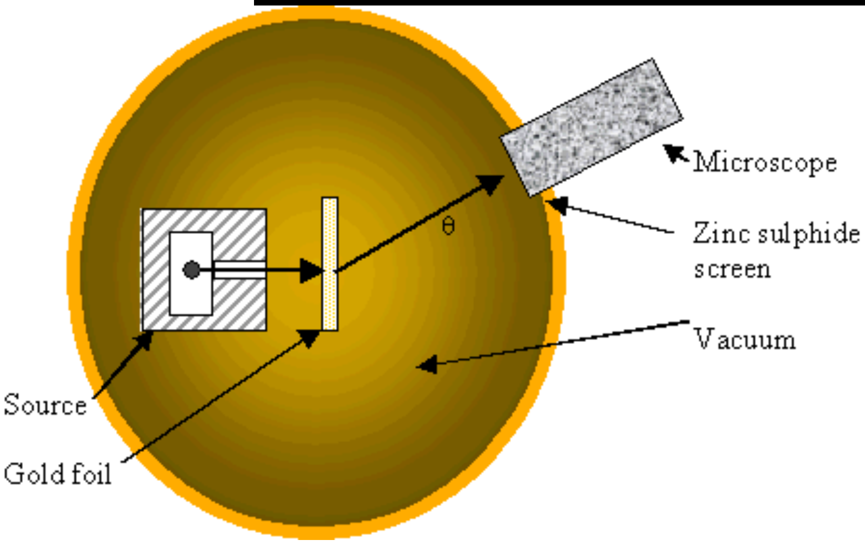
		I	II	III
I-materia ordinaria	Quarks	u up	c charm	t top
	Quarks	d down	s strange	b bottom
II,III materia instabile	Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	Leptons	e electron	μ muon	τ tau

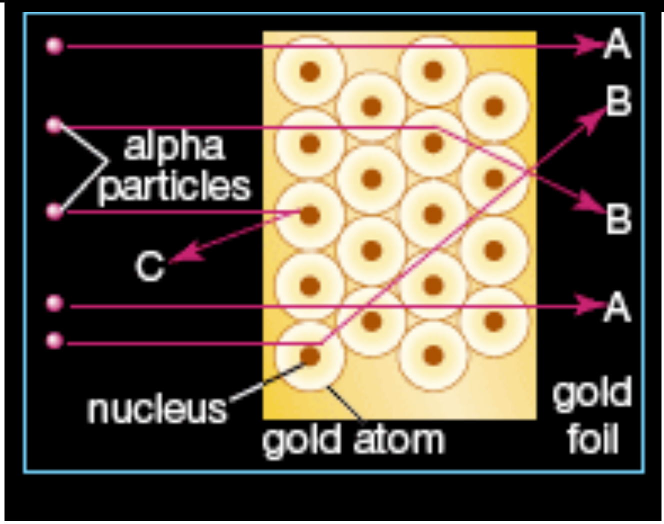
Modello
Standard
(XX d.C.)

(nuova tavola
periodica)

Rutherford: atoms are not elementary particles!

1911
Rutherford found a nucleus in the atom by firing alpha particles at gold and observing them bounce back



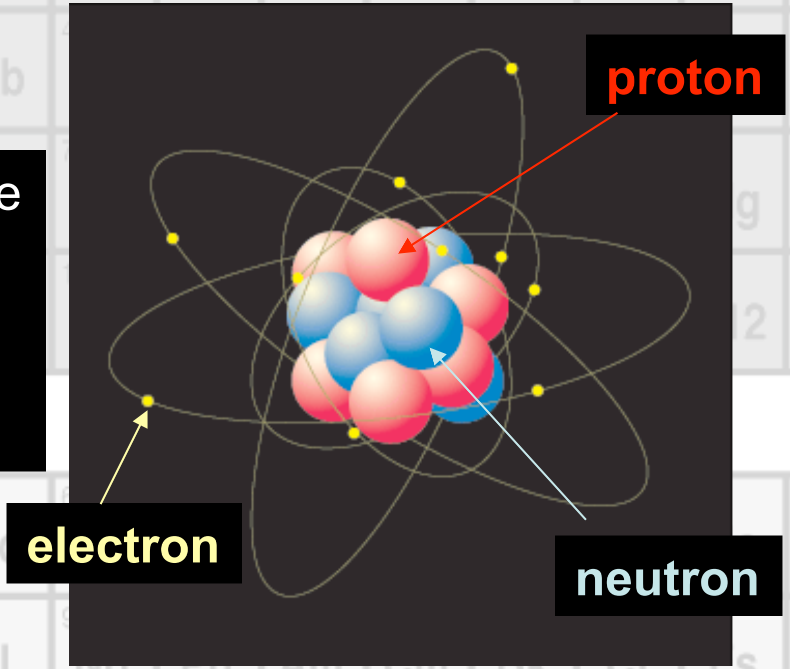


Precursor of modern scattering experiments at accelerator

Atoms

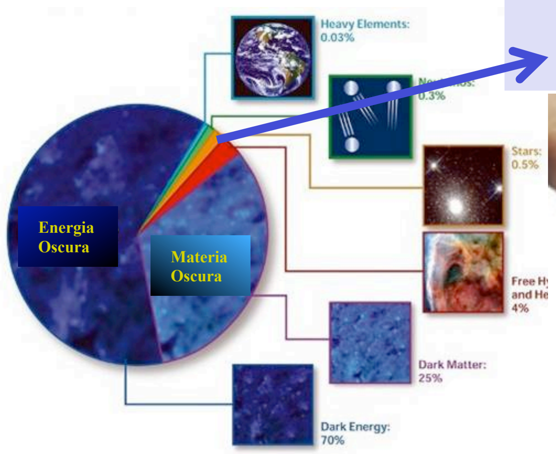
Atoms are all similarly made of:
- protons and neutrons in the nucleus
- electrons orbiting around

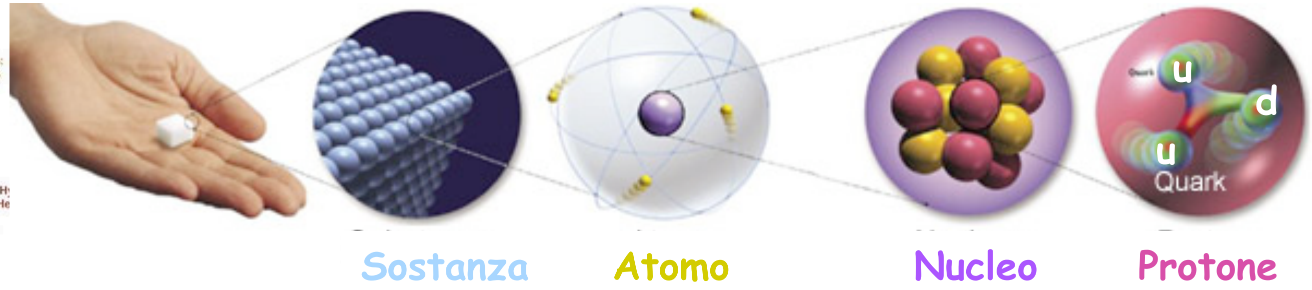
The electron was the first elementary particle to be discovered
(JJ Thomson 1897)

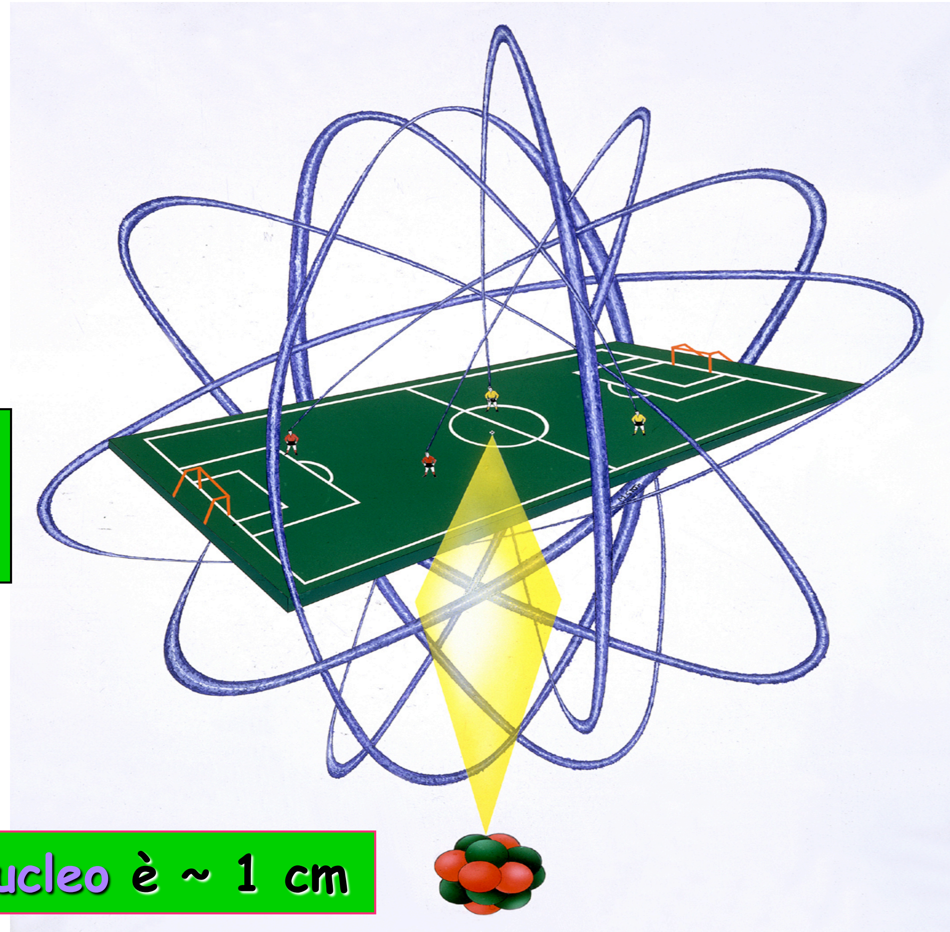


Protons, neutrons are made up of quarks

La materia ordinaria (~5%)





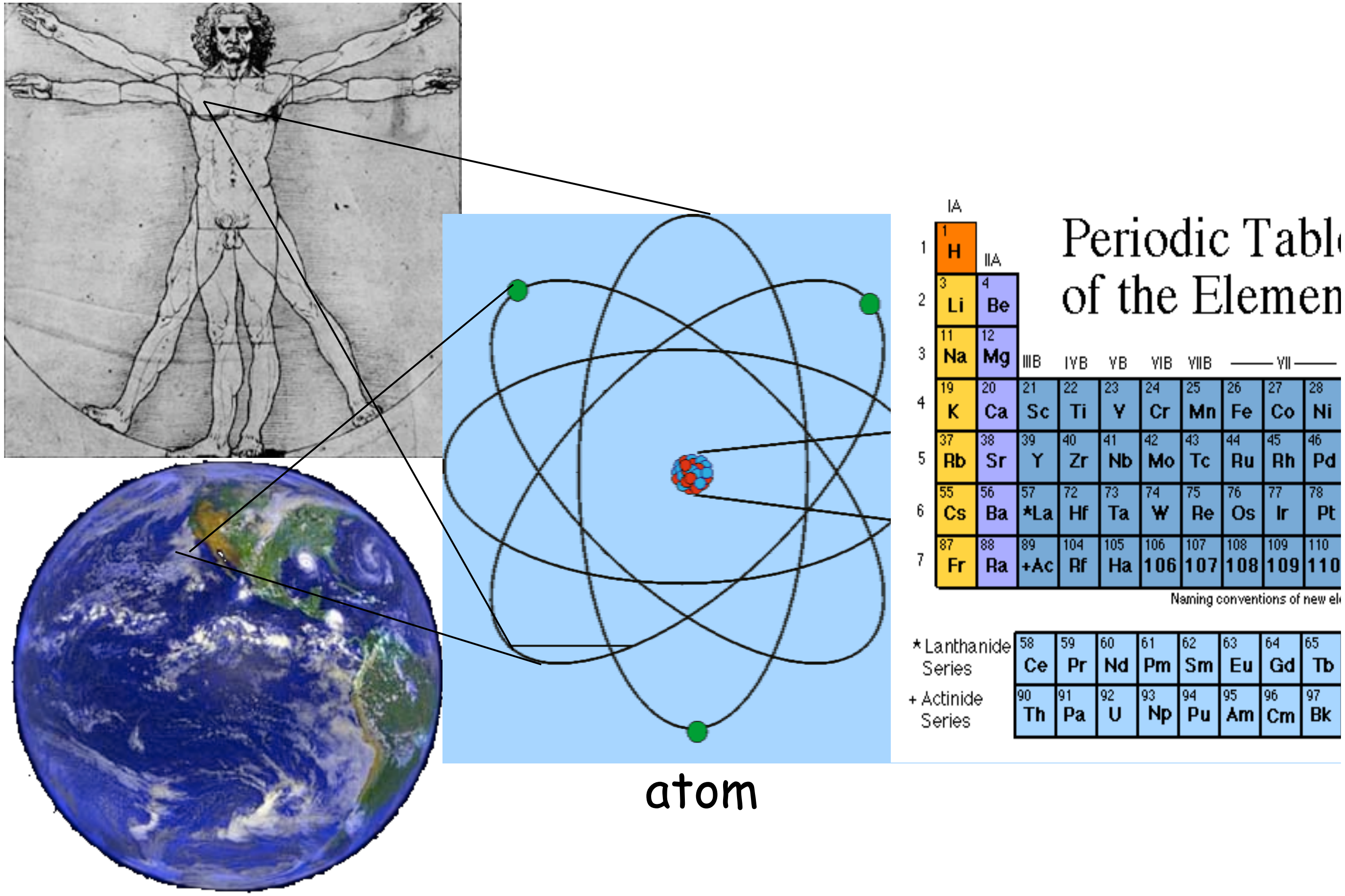


Atomo

(ingrandito mille milliardi di volte)

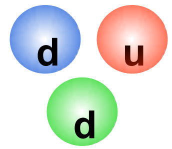
A questa scala, il Nucleo è ~ 1 cm

Elementary particles



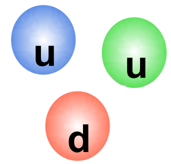
atom

neutrons



quarks

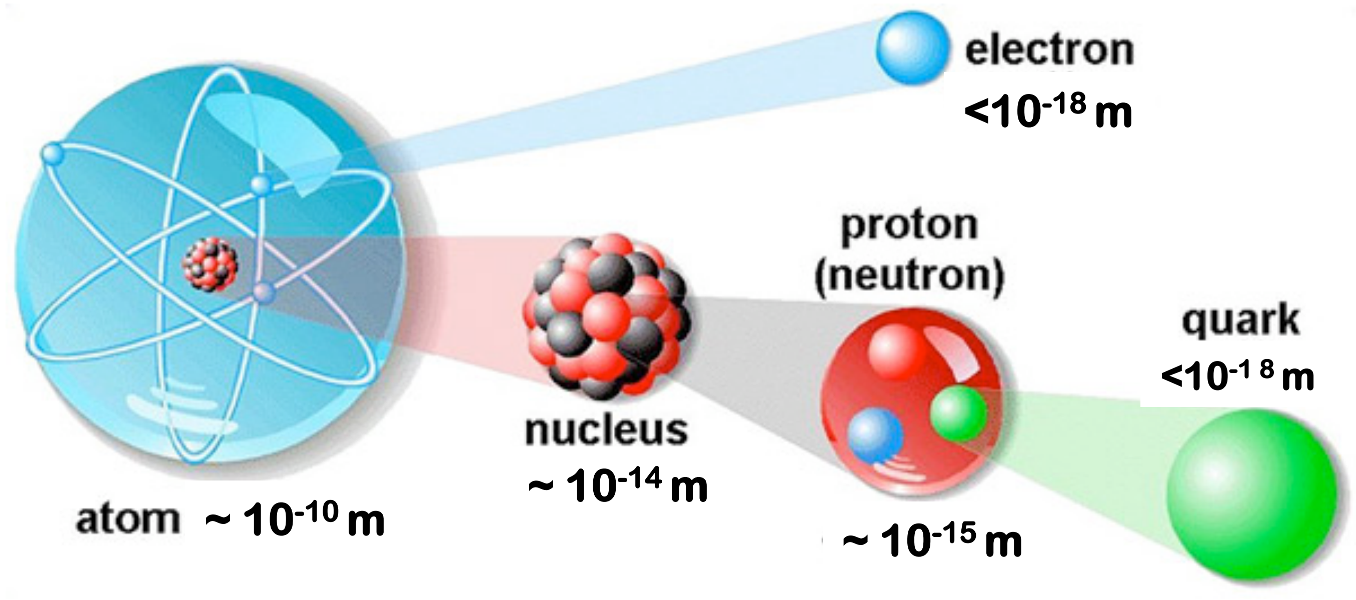
protons



quarks

From the atom to the quark

How small are the smallest constituents of matter?



Atoms and sub-atomic particles are much smaller than visible light wave-length
Therefore, we cannot really "see" them (all graphics are artist's impressions)
To learn about the sub-atomic structure we need particle accelerators

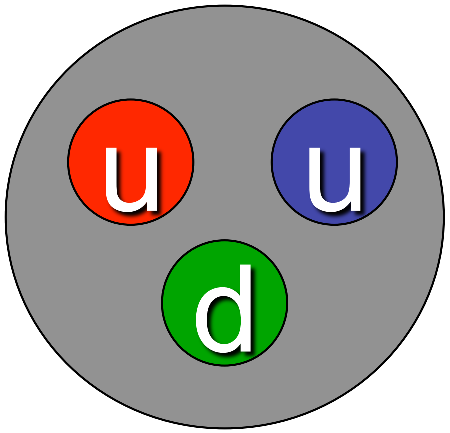
Protons and neutrons in the quark model

Quarks have fractional electric charge!

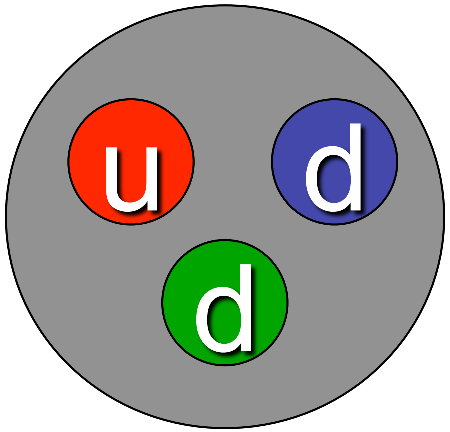
u electric charge + 2/3

d electric charge -1/3

proton (charge +1)



neutron (charge 0)



$$u\left(+\frac{2}{3}\right)u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)=p(+1)$$

$$u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)d\left(-\frac{1}{3}\right)=n(0)$$

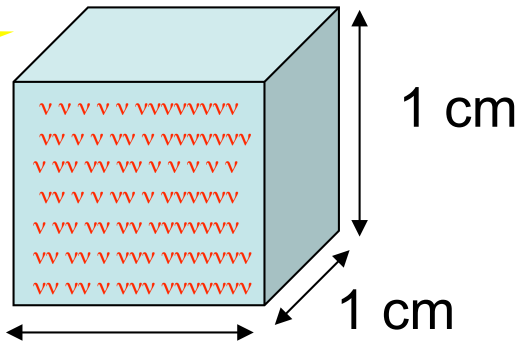
Is the whole Universe made only of quarks and electrons?

No! There are also neutrinos! ν

Electron, proton and neutrons are rarities!
For each of them in the Universe there is 1 billion neutrinos

Neutrinos are the most abundant matter-particles in the Universe!

Within each cm^3 of space: ~300 neutrinos from Big Bang

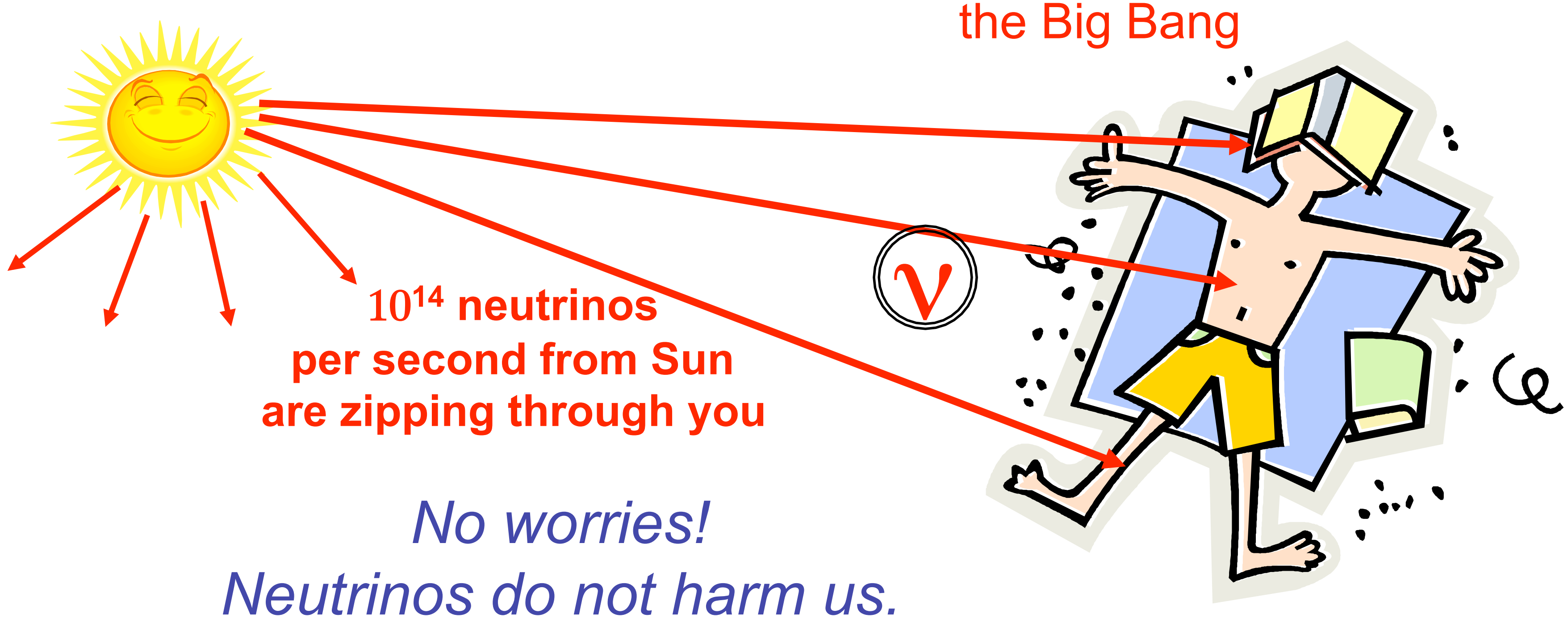


Neutrinos are everywhere!
in the outer space, on Earth, in our bodies..

Neutrinos get under your skin!

Every cm^2 of Earth surface is crossed every second by more than 10 billion (10^{10}) neutrinos produced in the Sun

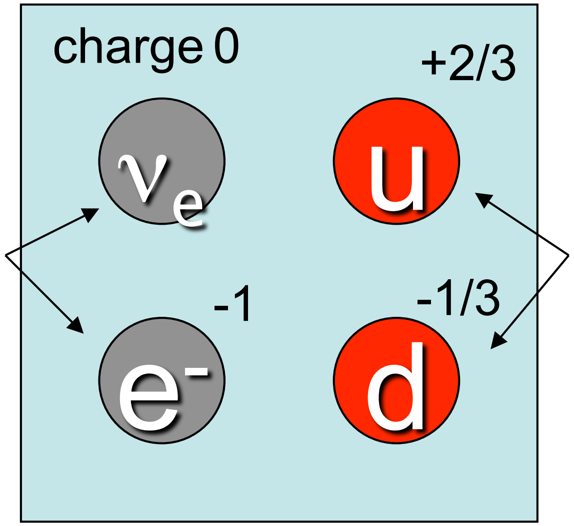
Within your body at any instant: roughly 30 million neutrinos from the Big Bang



No worries!
Neutrinos do not harm us.
Our bodies are transparent to neutrinos

The particles of ordinary matter

Leptons:
ν = neutrino
e = electron

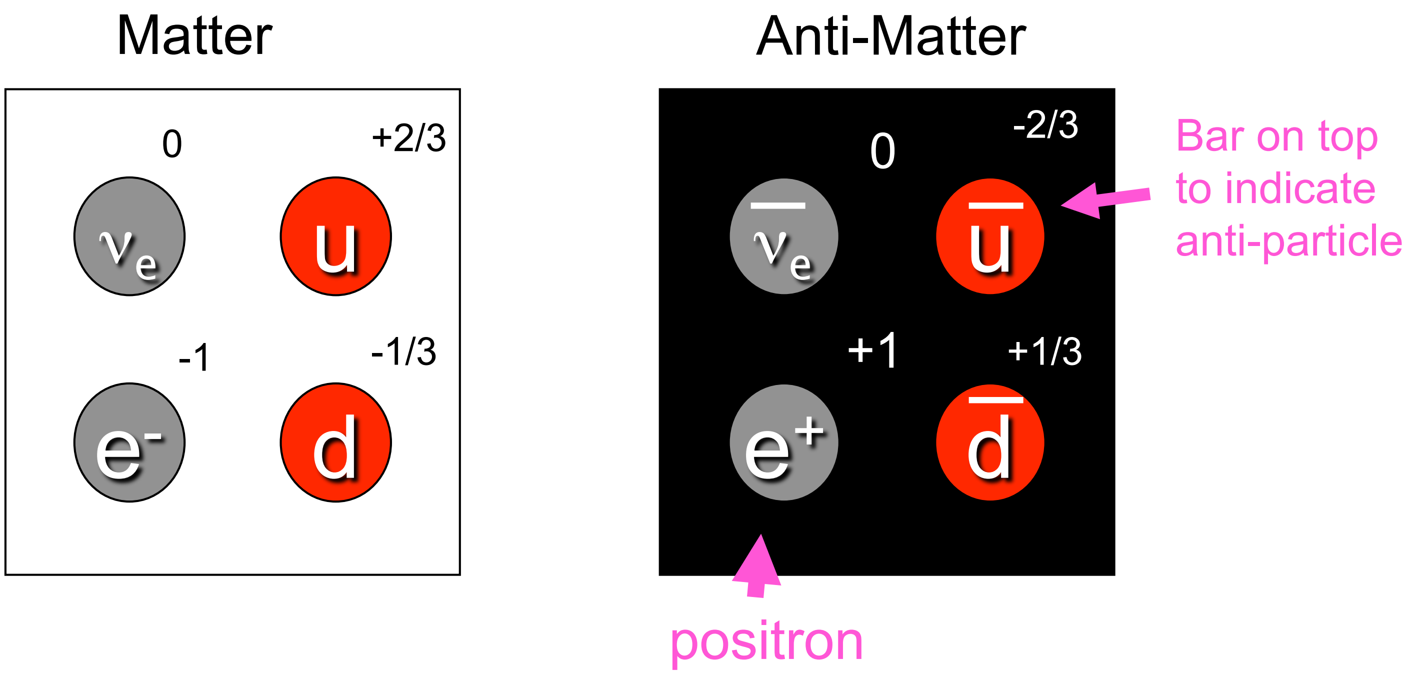


Quarks:
u = up
d = down

All stable matter around us
can be described using
electrons, neutrinos, u and d "quarks"

Anti-matter

- For every fundamental <u>particle</u> of matter there is an <u>anti-particle</u> with same mass and properties but opposite charge



- Correspondent anti-particles exist for all three families
- Anti-matter can be produced using accelerators

Elementary Particles

■ The Antiparticles:

A chaque particule est associée une antiparticule :

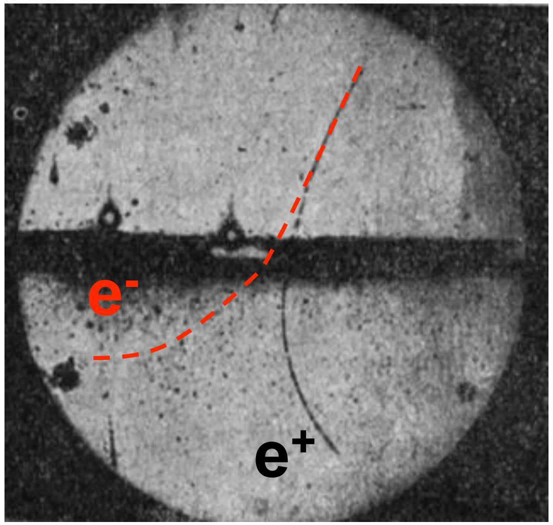
$p \rightarrow \bar{p}$ = antiproton   charge -

$n \rightarrow \bar{n}$ = antineutron   charge 0

$e^- \rightarrow \overline{e^-} = e^+$ = positron

même masse, même temps de vie,

charges opposées.



1932 découverte de l'antimatière,
prédite par la théorie (Dirac) :
le positron.

Matter-antimatter pair creation

- Electron-positron pair created out of photons hitting the bubble-chamber liquid

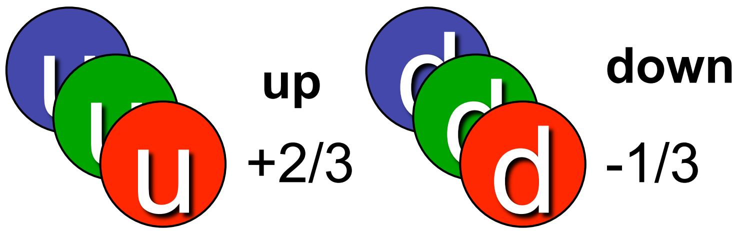
- Example of conversion of photon energy into matter and anti-matter

- Matter and anti-matter spiral in opposite directions in the magnetic field due to the opposite charge

- Energy and momentum is conserved

Quarks and colour

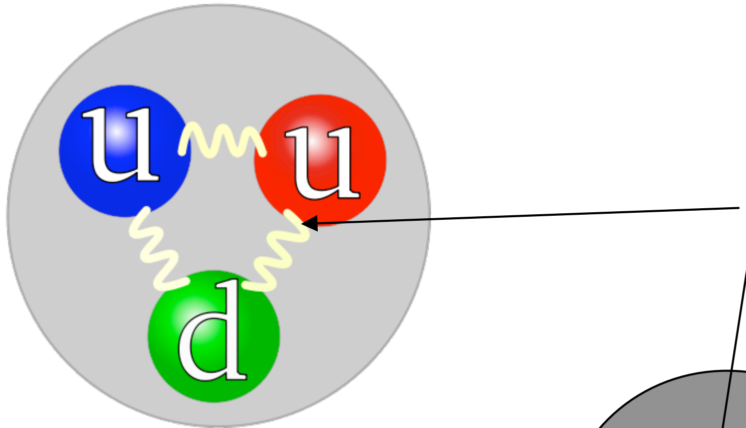
All quark flavours come in 3 versions, called "colours"



Quarks combine together to form colourless particles

-***Baryons*** (three quarks: red+ green + blue = white)

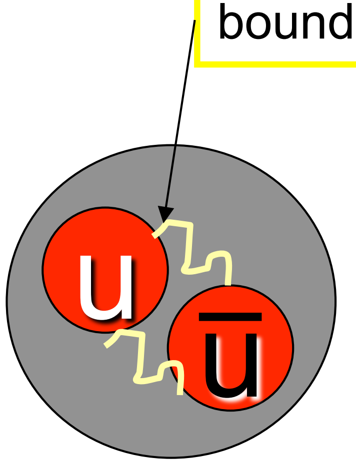
proton
p

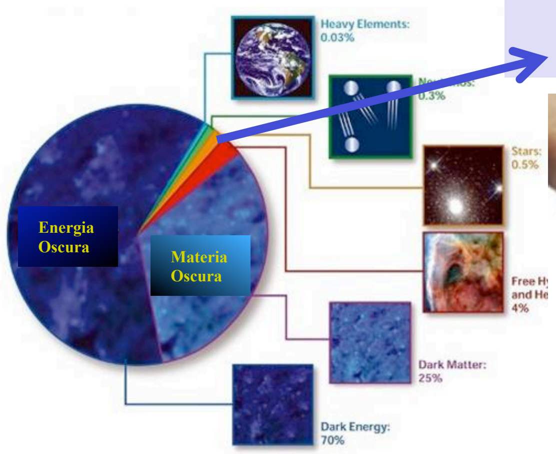


Strong forces "glue" quarks together in bound states

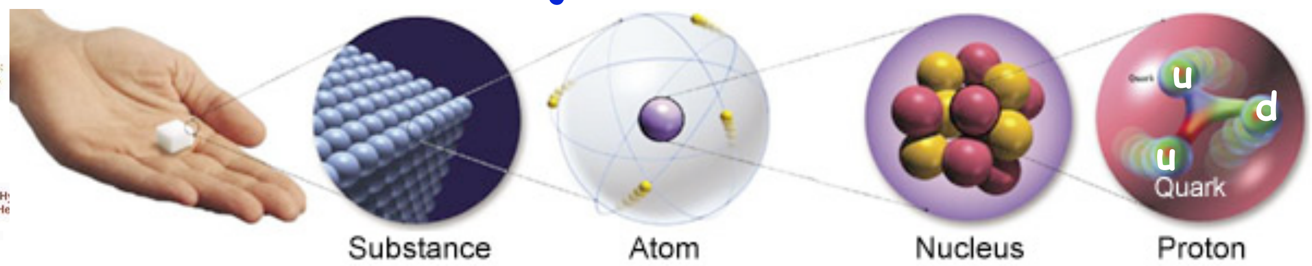
-***Mesons*** (quark-antiquark pair)
such as red+anti-red u-ubar state

pion
π

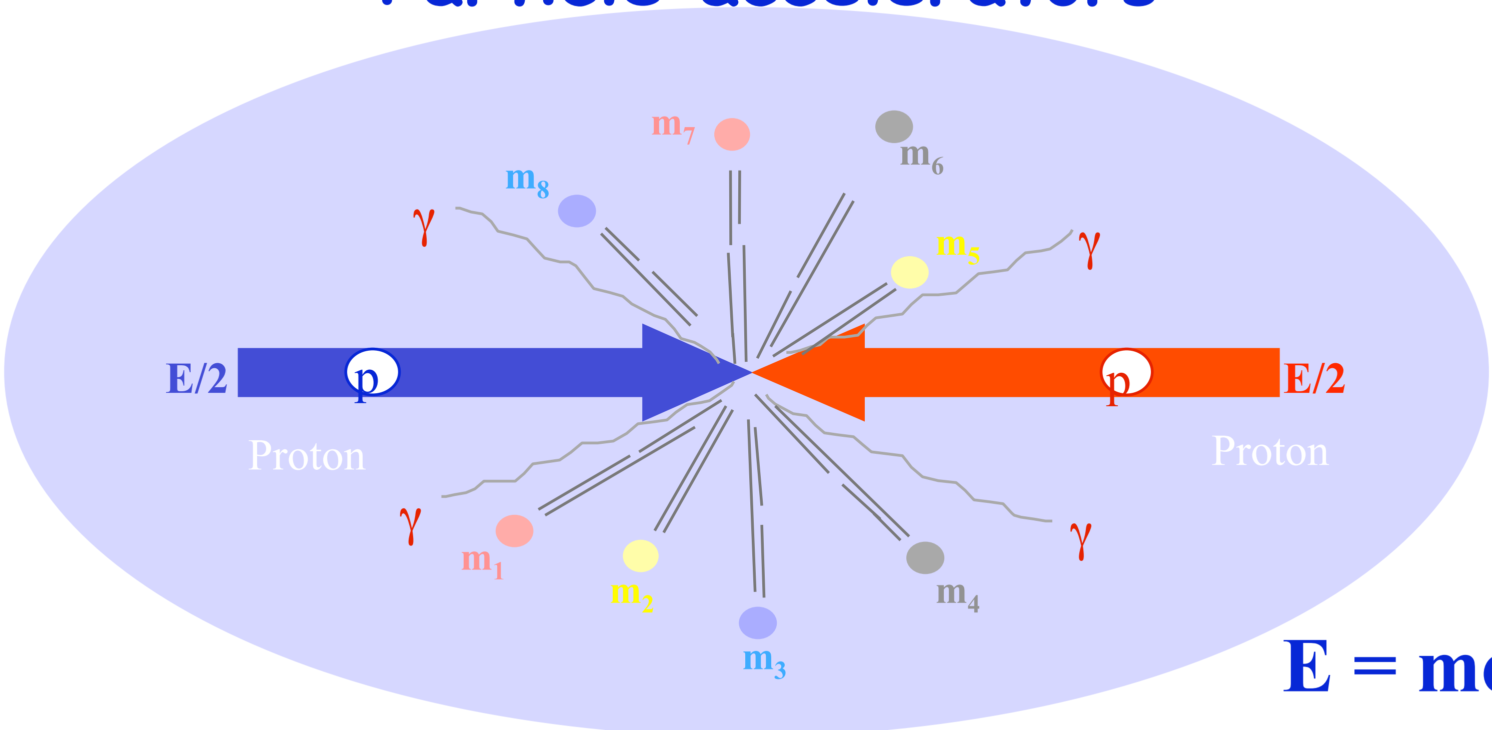




Ordinary Matter (~5%)



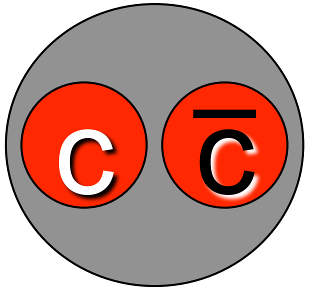
Particle accelerators



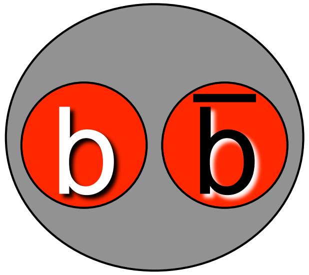
$$E = mc^2$$

In an high energy collision many particles can be produced both of matter and antimatter

Building more particles

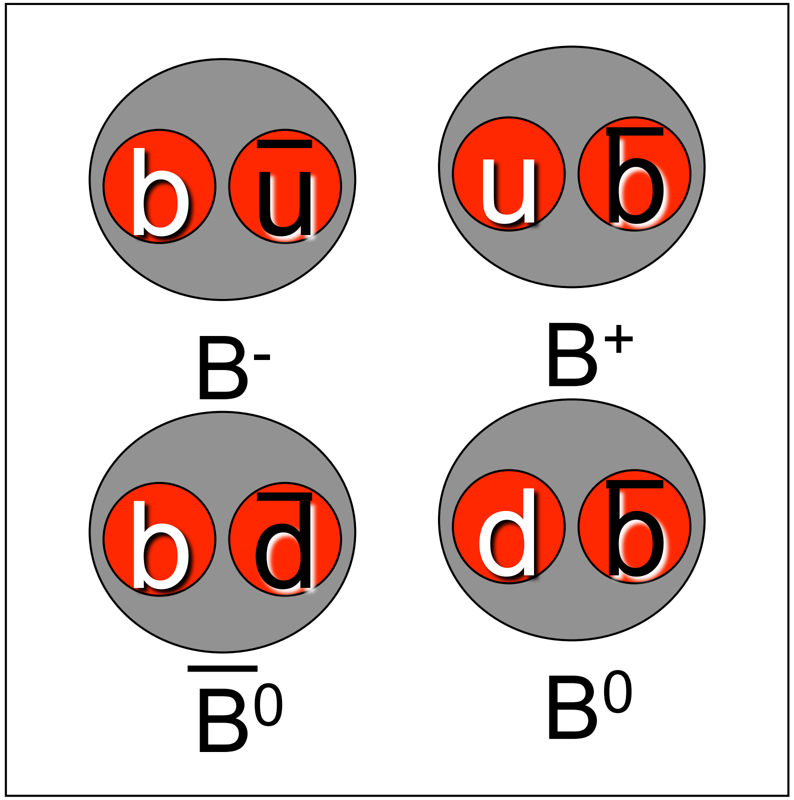


J/ψ



Υ

B mesons ($b\bar{q}$)



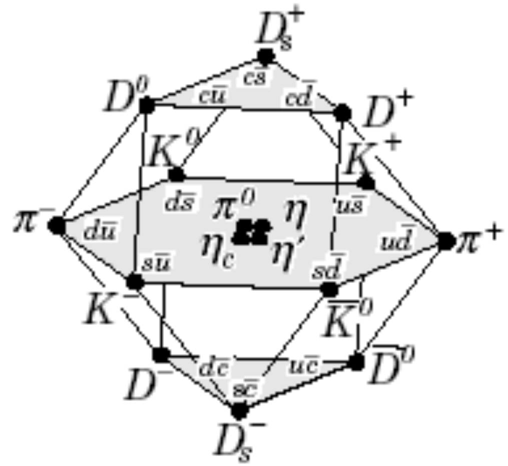
Many more mesons and baryons…

MESONS $\equiv q_1 \bar{q}_2$

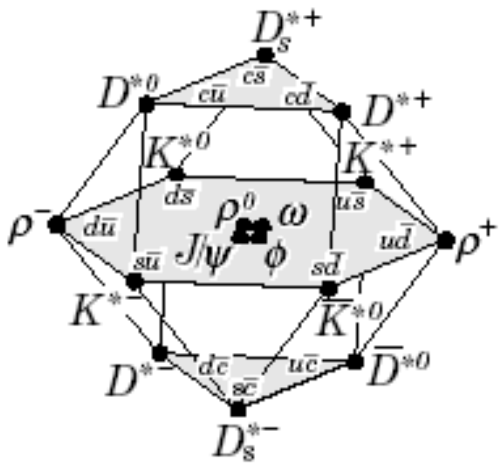
Spin: $\frac{1}{2} \otimes \frac{1}{2} \rightarrow J = 0, 1$

SU(4): u, d, s, c $(L = 0)$

$J = 0$



$J = 1$



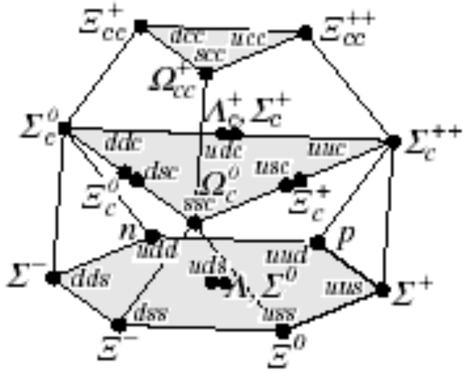
BARYONS $\equiv q_1 q_2 q_3$

Baryon Number: $B(q_i) = \frac{1}{3}$

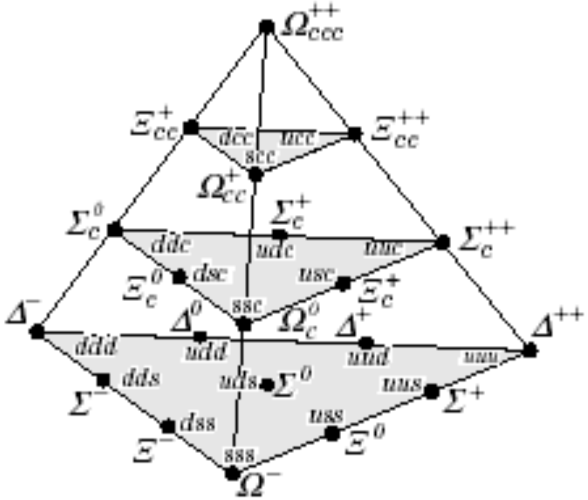
Spin: $\frac{1}{2} \otimes \frac{1}{2} \otimes \frac{1}{2}$ ➡ $J = \frac{1}{2}, \frac{3}{2}$

SU(4): u, d, s, c $(L = 0)$

$J = \frac{1}{2}$



$J = \frac{3}{2}$



"Young man, if I could remember the names of these particles, I would have been a botanist!"

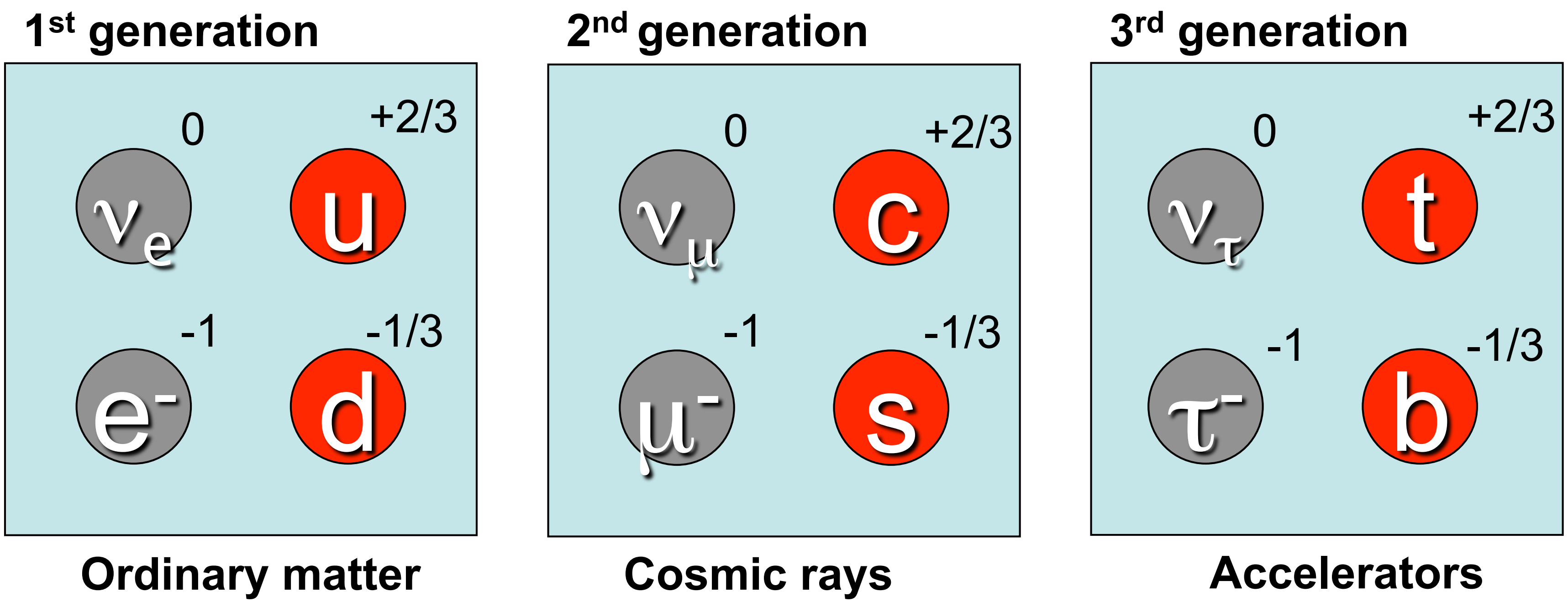
E.Fermi to his student L. Lederman (both Nobel laureates)

The Particle Physicist's Bible: Particle Data Book

https://pdg.lbl.gov

Most particles are not stable and can decay to lighter particles..

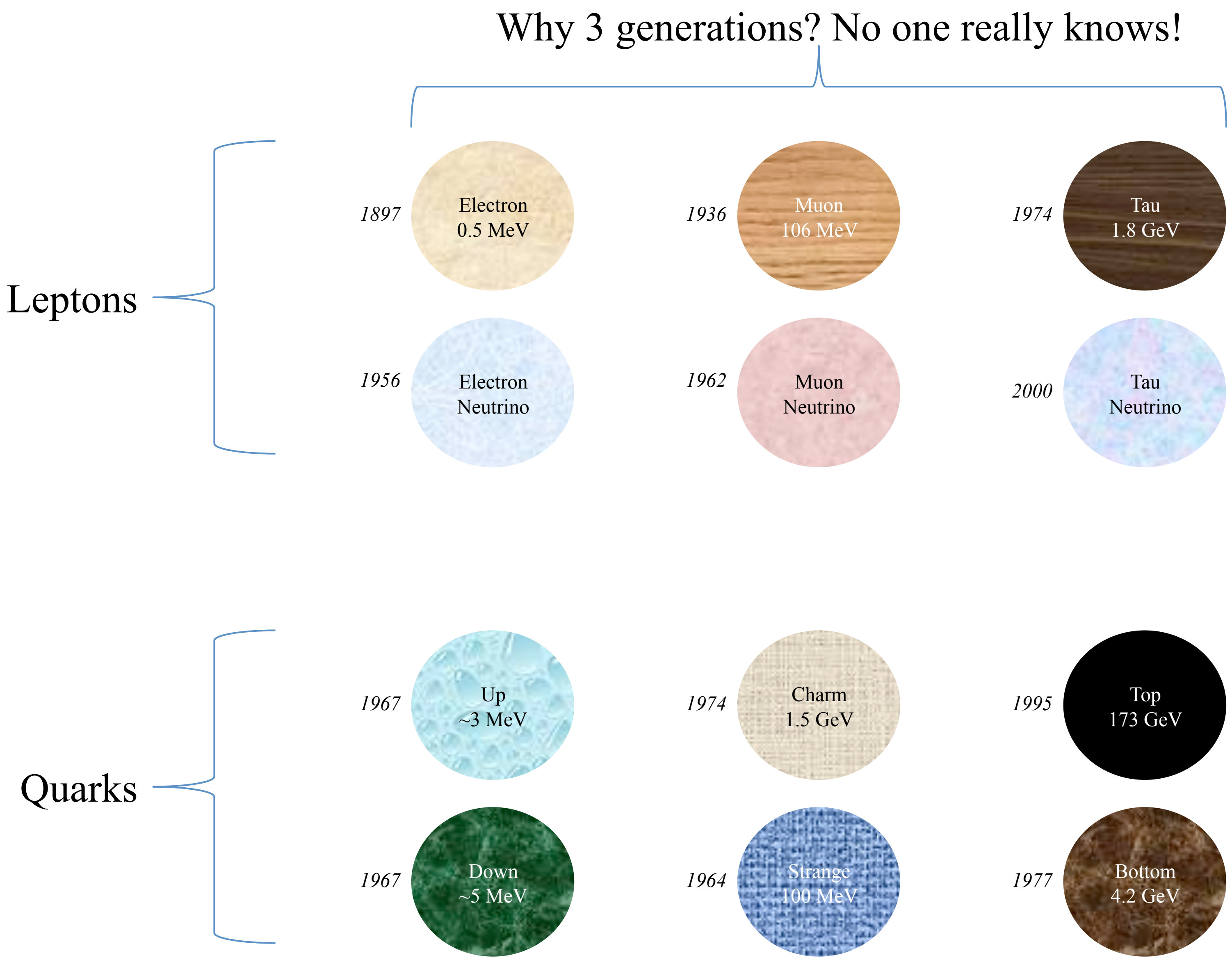
3 Families (or Generations)



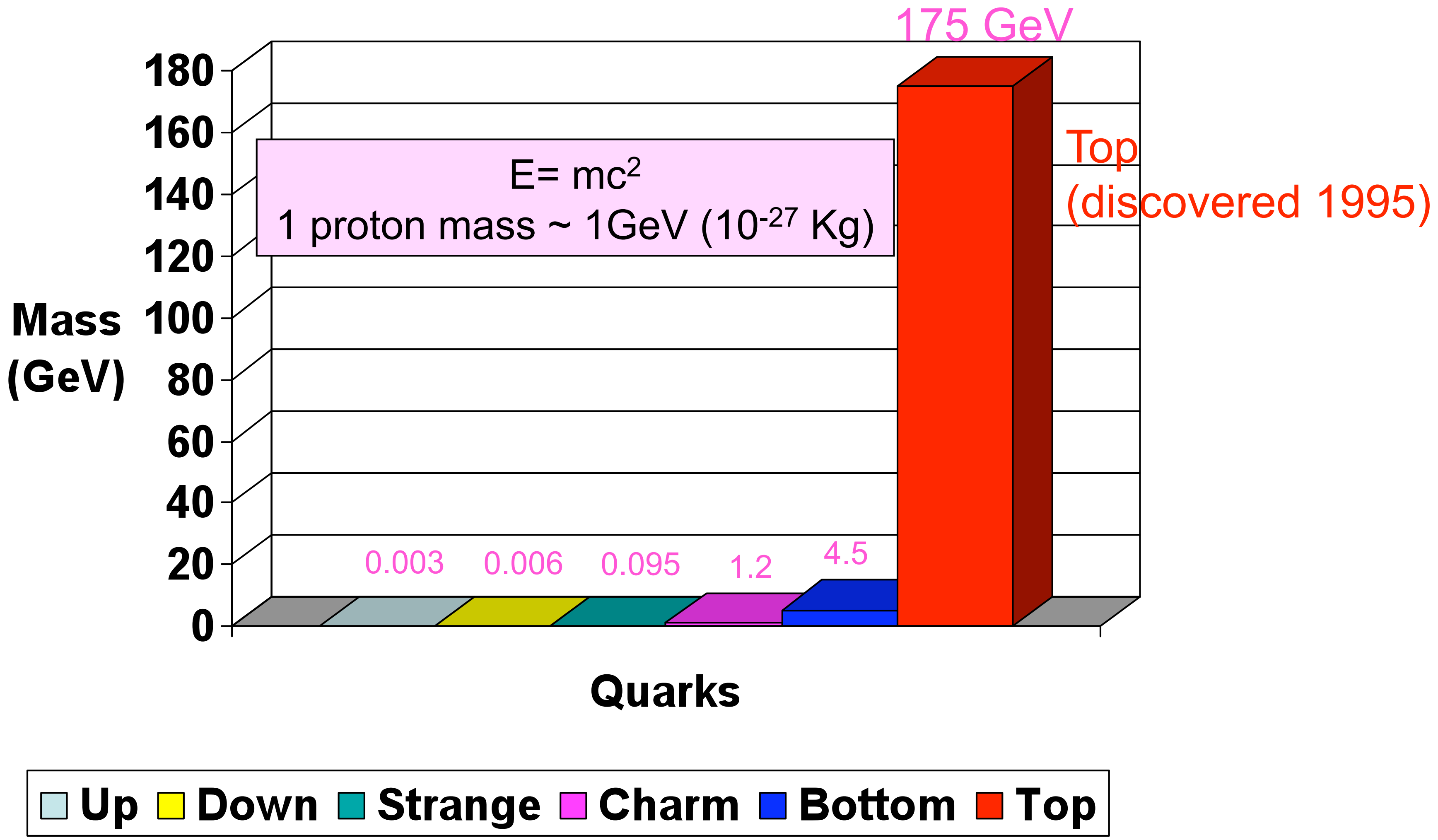
3 generations in everything similar but the mass

We believe these to be the fundamental building blocks of matter

What is everything made of?

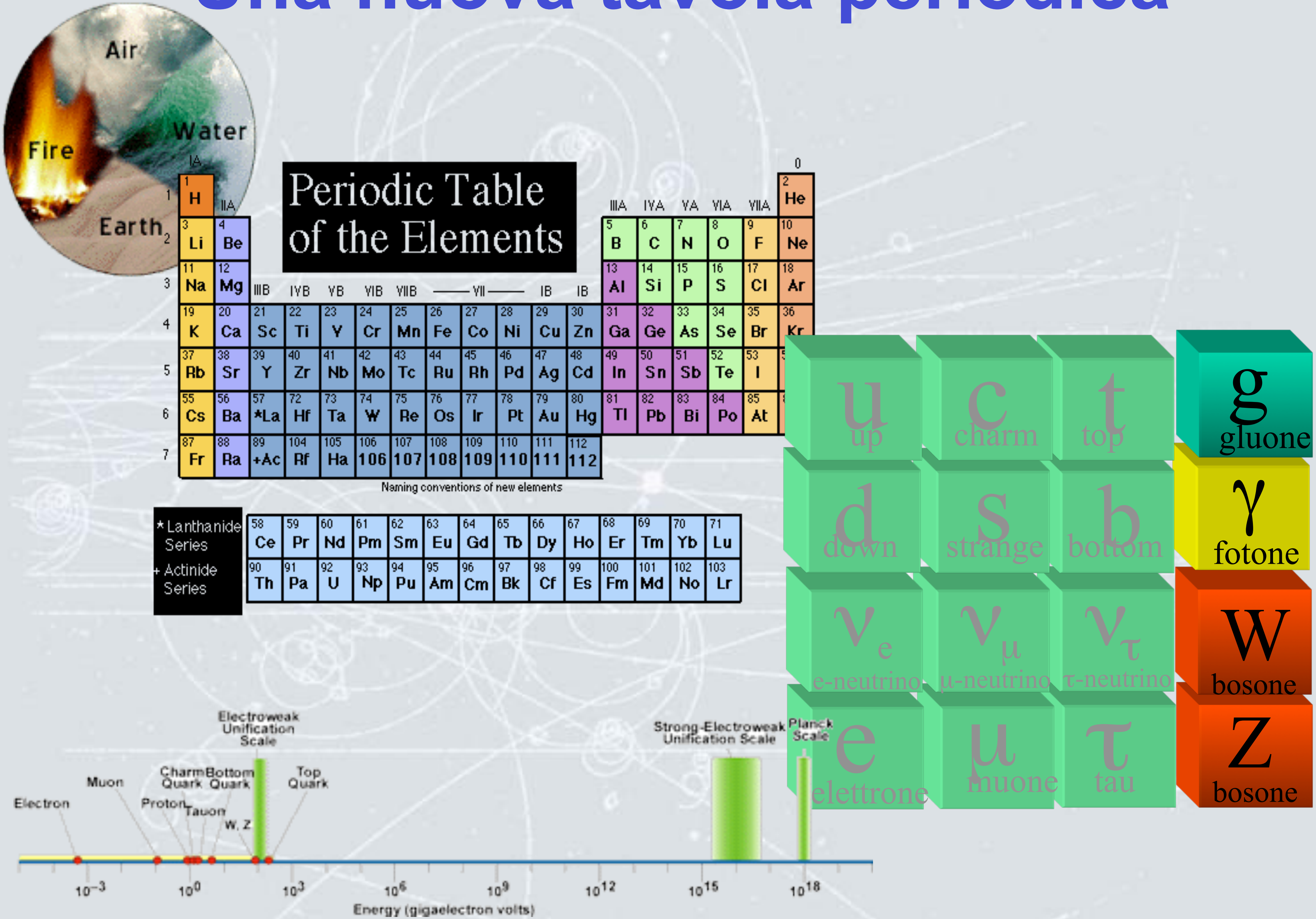


Quark masses



The mass grows larger in each successive family

Una nuova tavola periodica



Exchange Particles

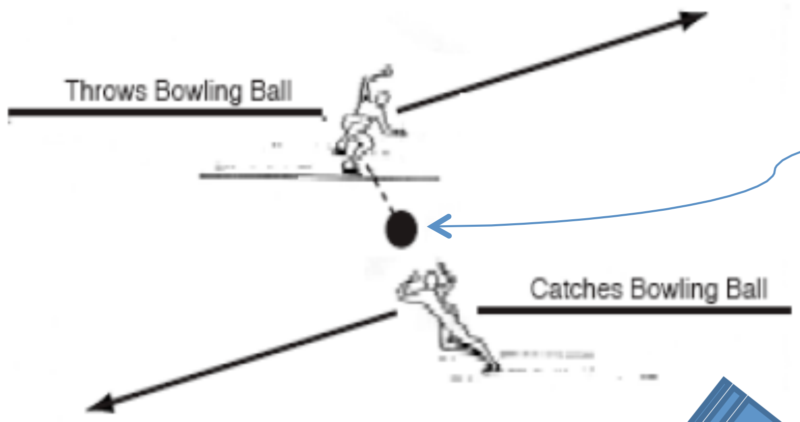
By exchanging the ball, the skaters are forced apart.

If you didn't see the ball you would think there was a repulsive force between them.

The range of the force is related to the mass of the exchanged particle

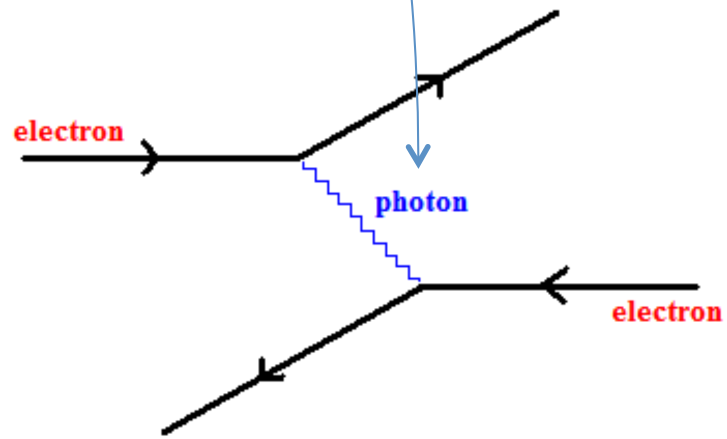
Forces as Interactions

All forces can be thought of as interactions between elementary particles.



All forces are mediated by a force-carrying particle.

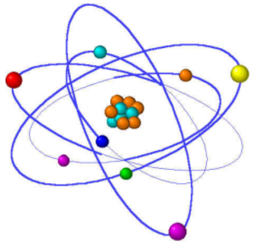
Richard Feynman

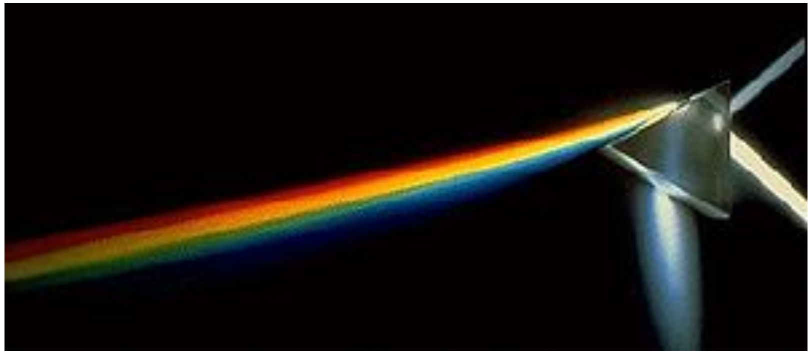


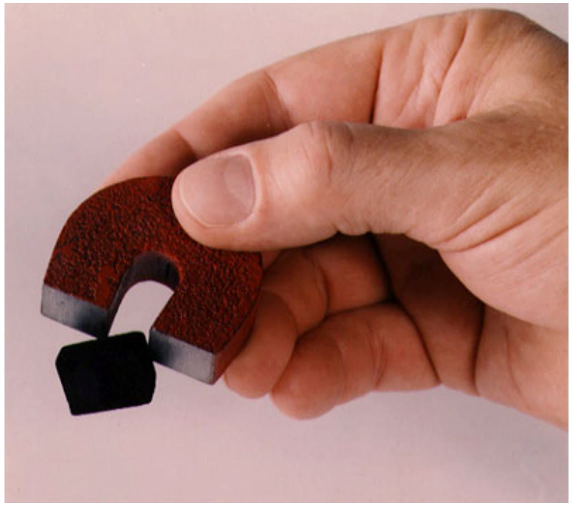
A Feynman Diagram for two electrons repelling each other

What holds everything together? – Electromagnetism


Electricity


Chemistry


Light

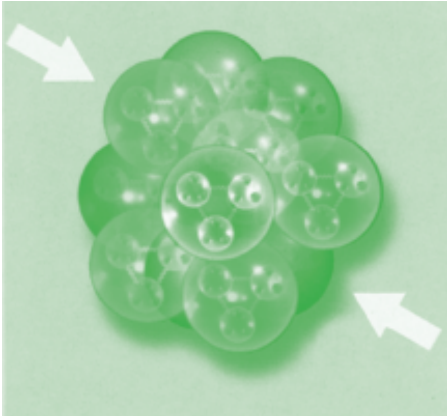

Magnetism

The Electromagnetic Force

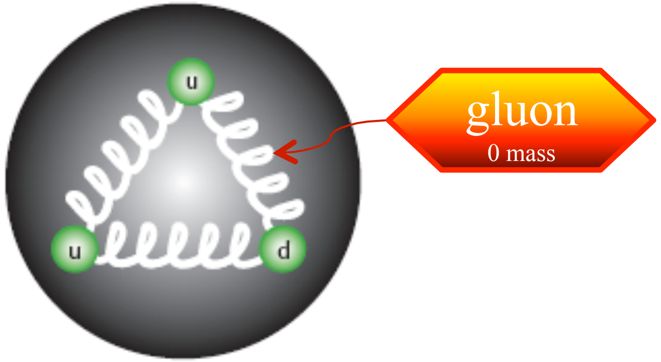
- Felt by all charged particles
- Carried by particles called *photons* in the quantum theory

Photon
0 mass

What holds everything together? – Strong Nuclear Force



Binds protons and neutrons together to form atomic nuclei



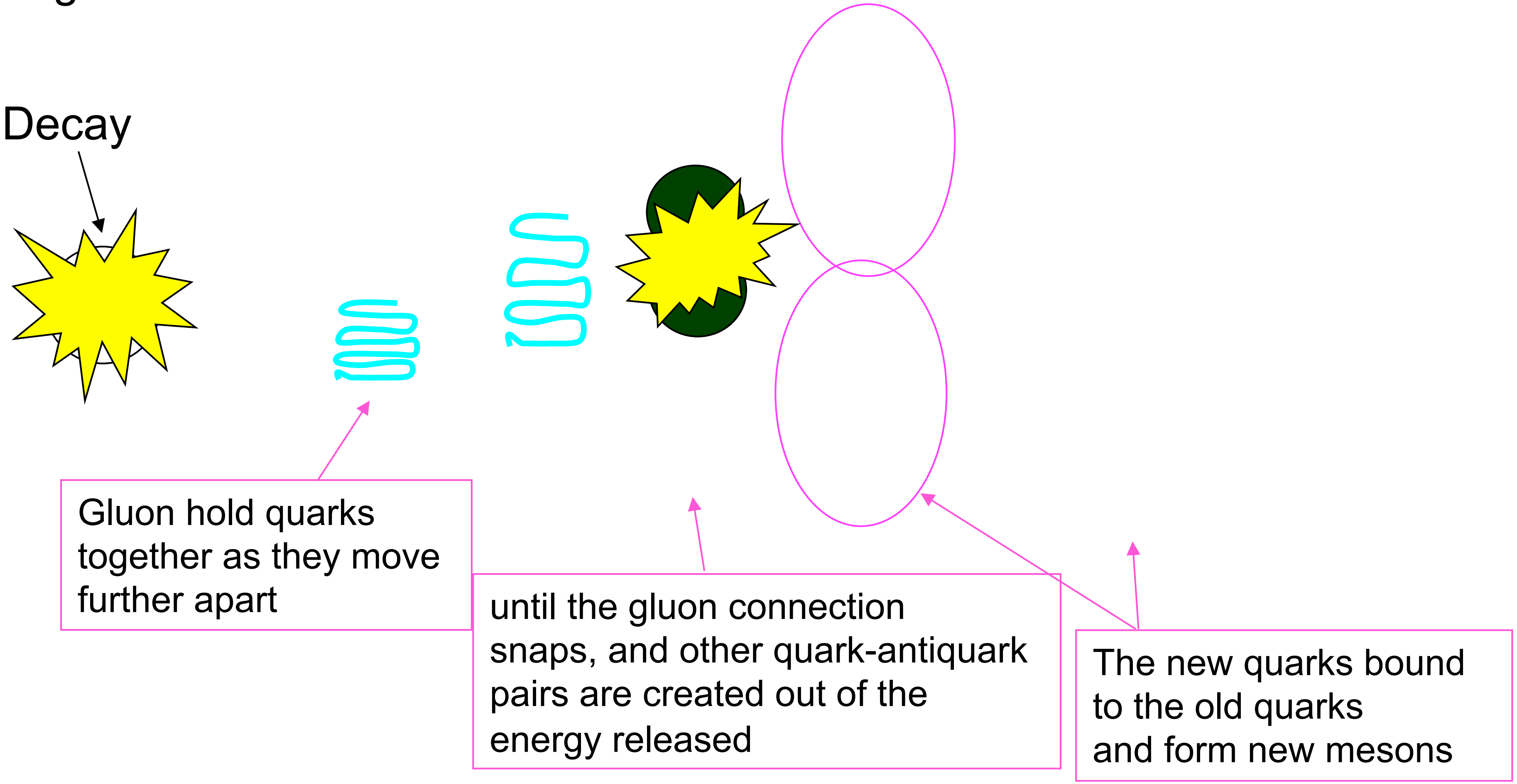
Binds quarks together to form protons and neutrons

The Strong Nuclear Force

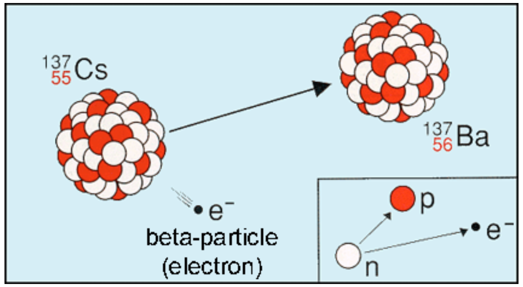
- Holds nuclei and nucleons together.
- Quarks and gluons feel this force
- Mediated by particles called *gluons*
- Very short in range

Quark confinement

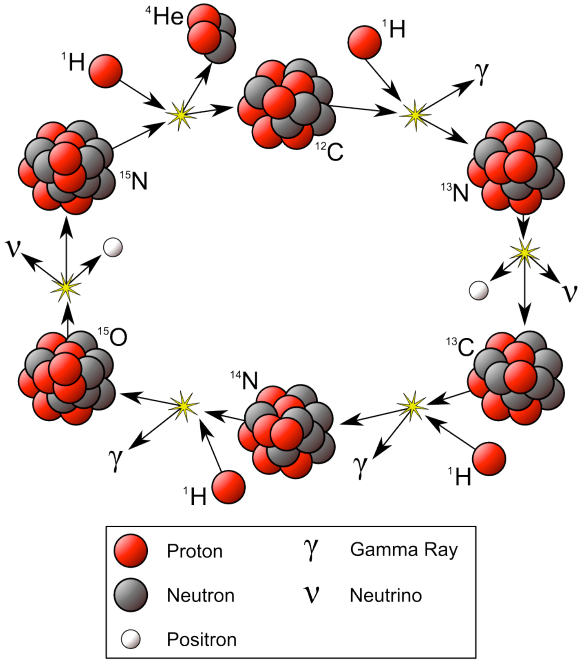
• There are no free quarks, quarks and antiquarks are “confined” in colourless doublet (mesons) or triplets (baryons) by the exchange of gluons



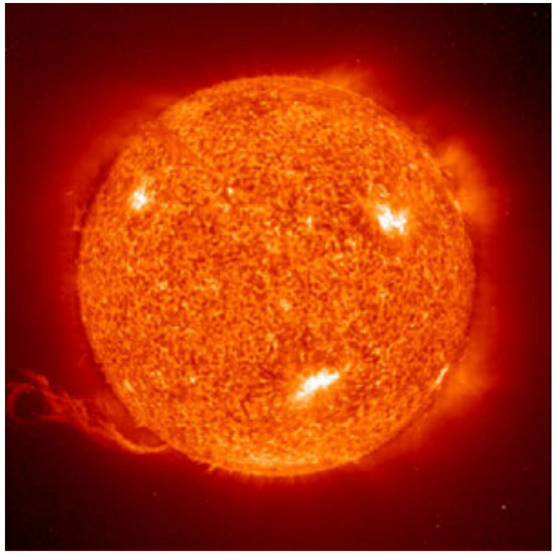
What holds everything together? – Weak Nuclear Force



Officiates nuclear (beta) decays



Give us CNO nuclear cycles…



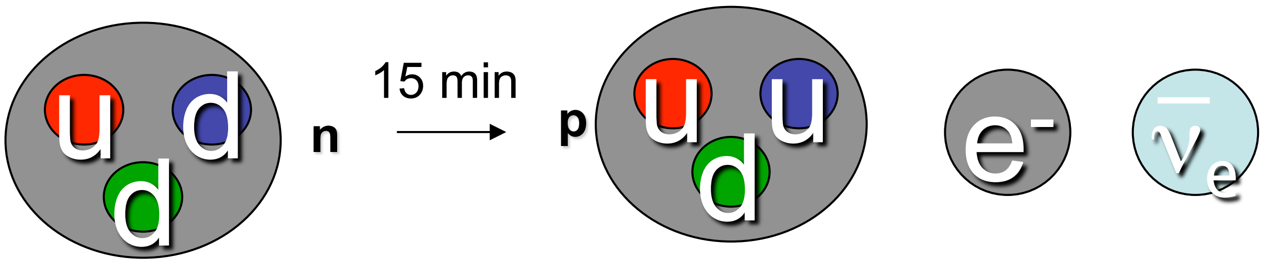
… that powers our sun and other stars.

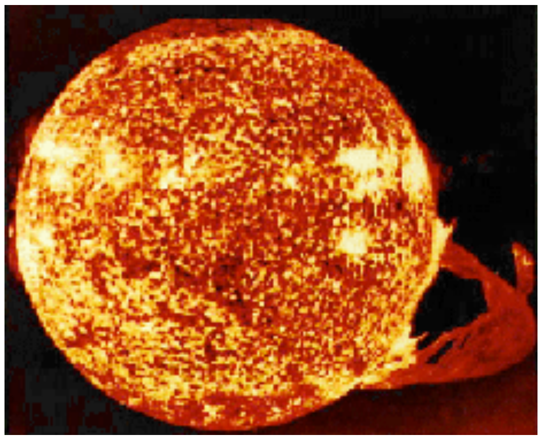
The Weak Nuclear Force

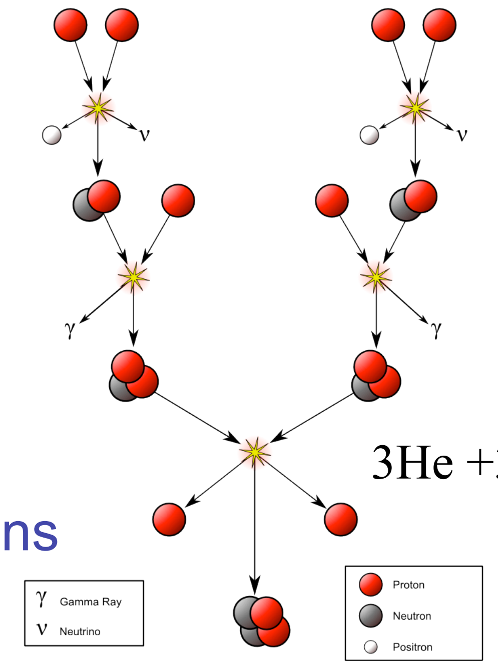
- All matter particles feel this force
- Mediated by particles called *W and Z bosons*
- Short ranged

Neutron β-decay

At quark level: $d \rightarrow u\, e^- \,\bar{\nu}_e$







$^1H + {}^1H \rightarrow {}^2H + e^+ + \nu_e$

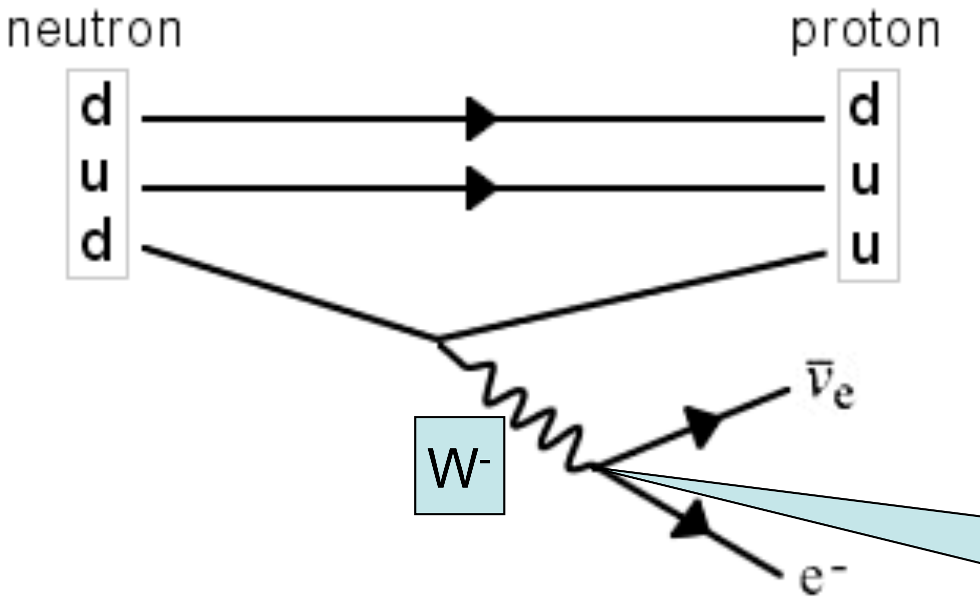
$^2H + {}^1H \rightarrow {}^3He + \gamma + 5.49$ MeV

$^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H + 12.86$ MeV

without such weak interactions

the Sun would shut down!

Weak force: W^-, W^+, Z^0



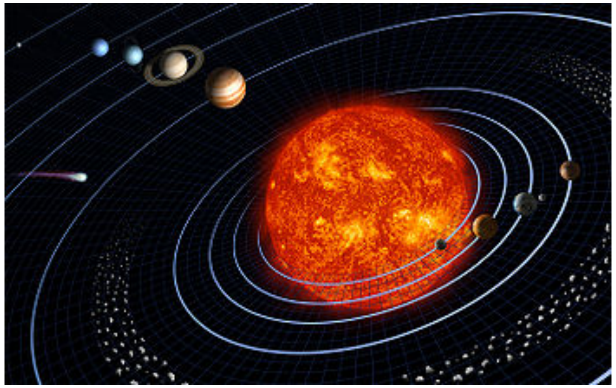
Beta radioactive decay via the weak interaction

β-decay

$n \rightarrow p e \overline{\nu}_e$

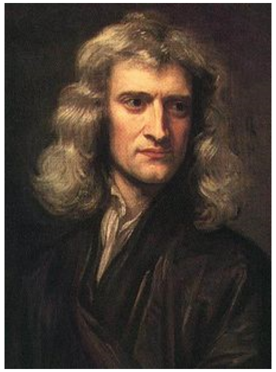
Electric charge conserved at each vertex

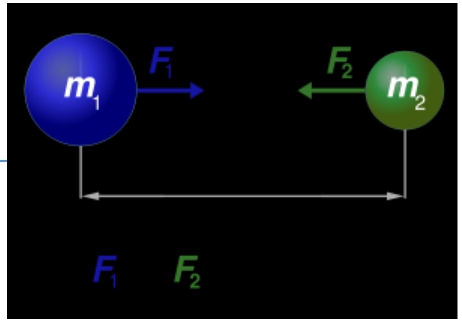
What holds everything together? – Gravitation



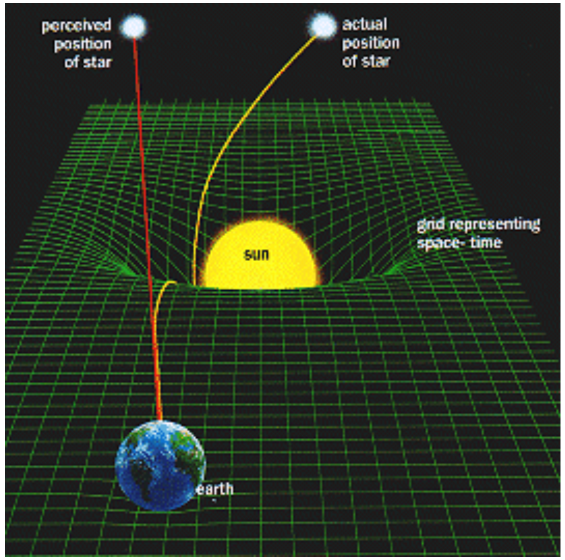
Celestial Gravitation

Terrestrial Gravitation



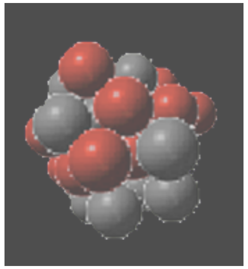


Newton's Law of **Universal Gravitation**



Einstein's **General Theory of Relativity**

Le interazioni fondamentali tra particelle



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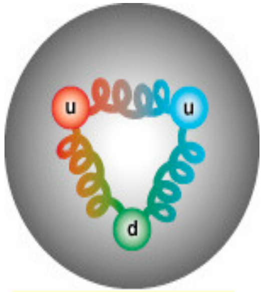
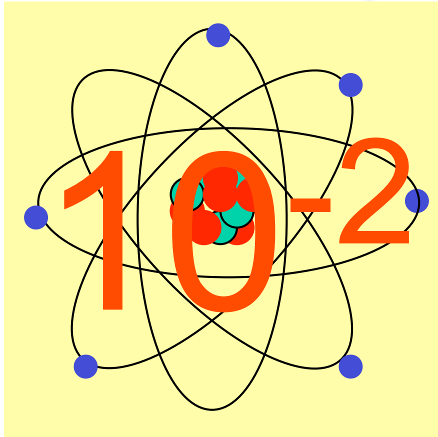


Forza forte

g (Gluone)

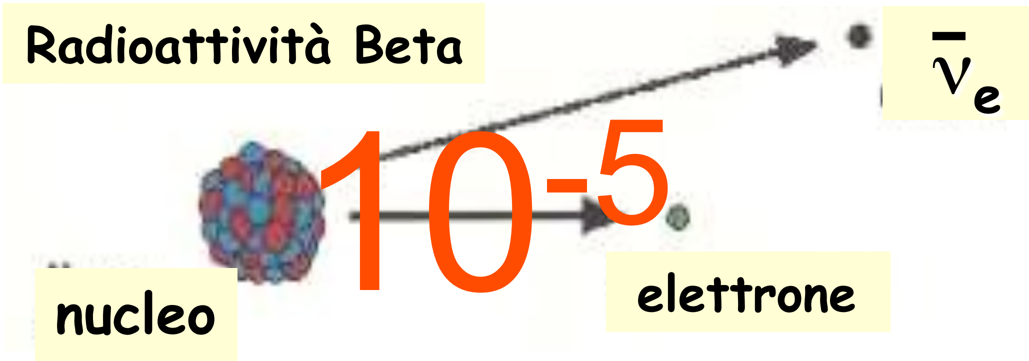


Forza elettromagnetica

γ (Fotone)

Forza gravitazionale

(Gravitone)



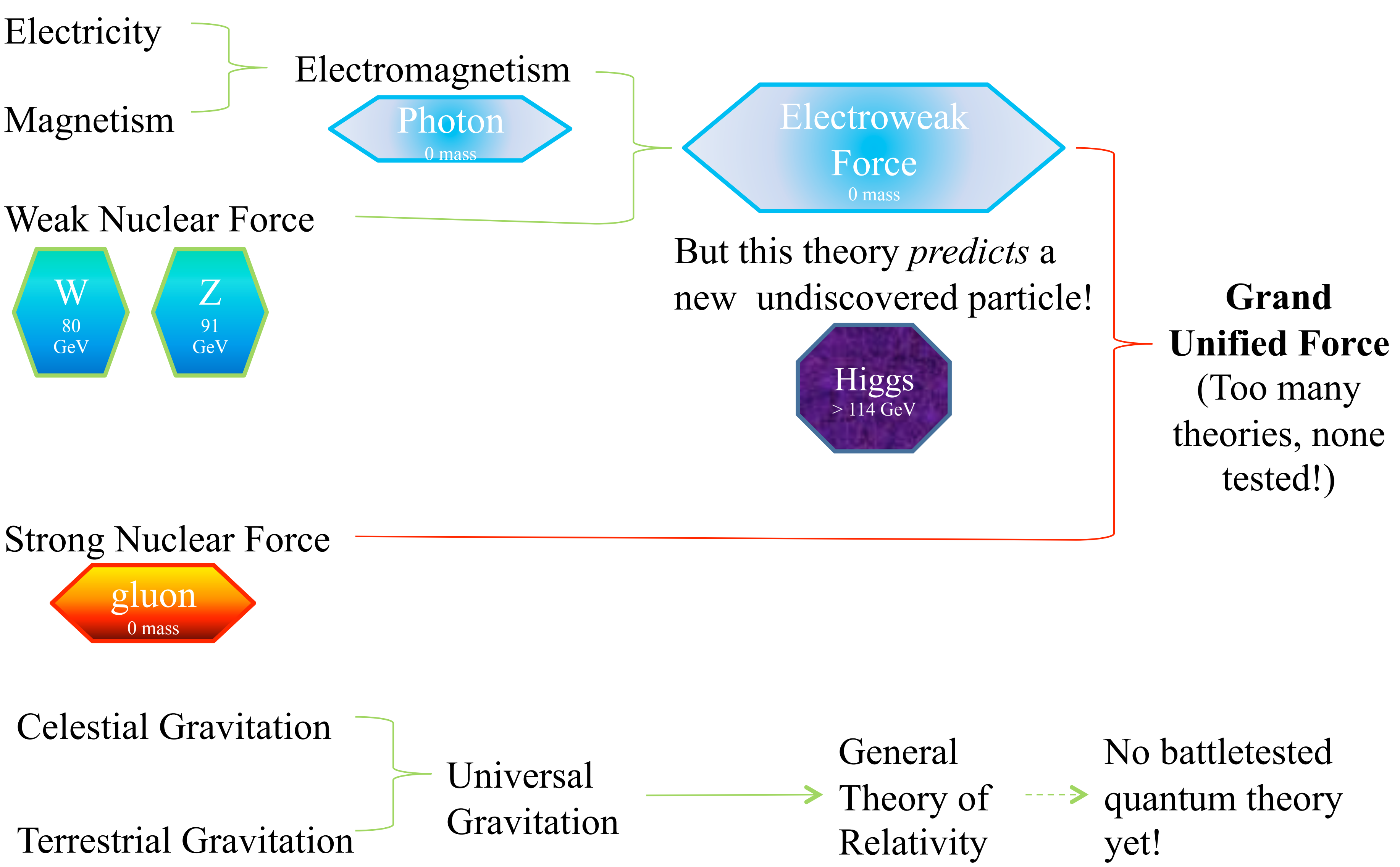
Forza debole

Z, W$^{\pm}$ (Bosoni)

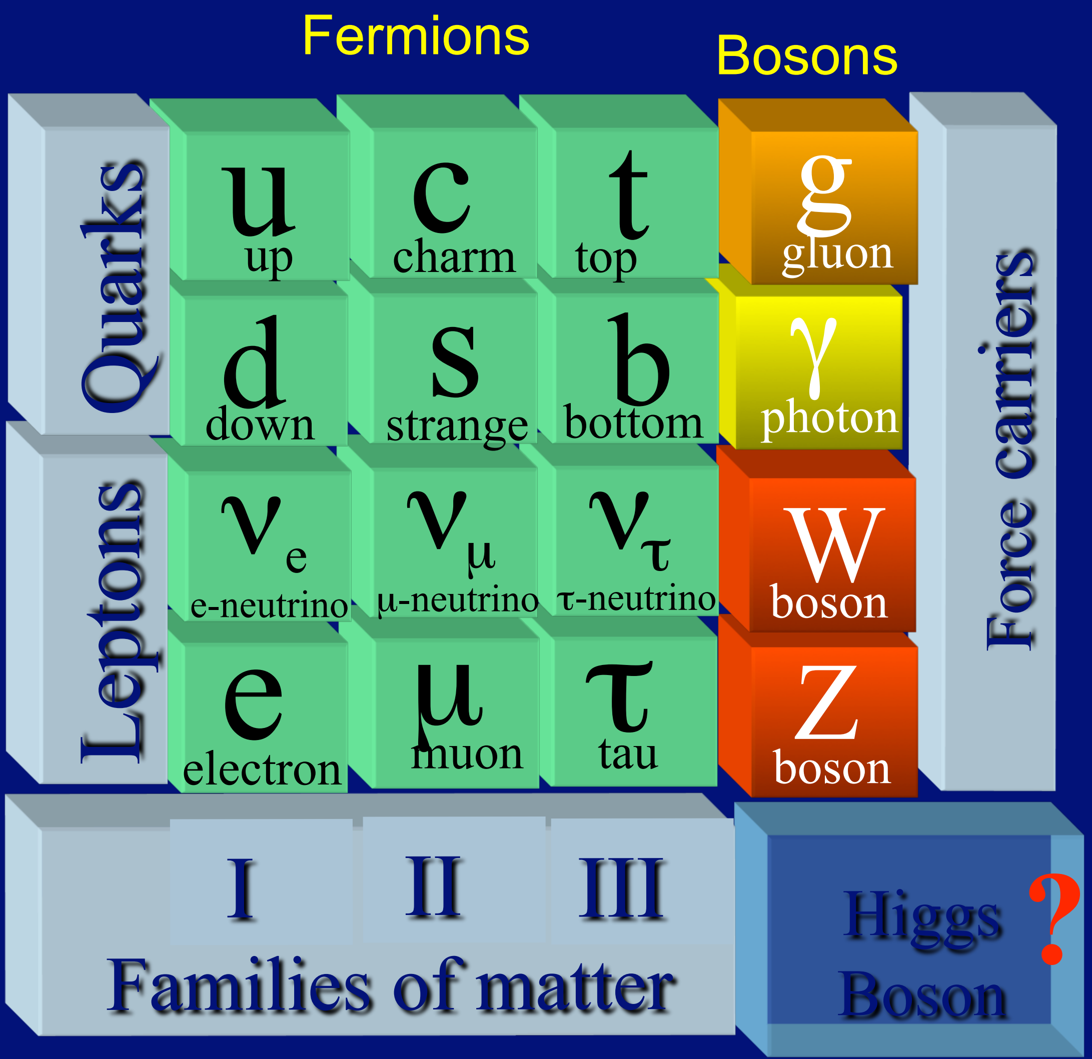
$n \rightarrow p + e^- + \bar{\nu}_e$

$d \rightarrow u + e^- + \bar{\nu}_e$

The Quest for Unification



The Standard Model



Questions:
why masses of matter particles and forces carriers are so different ?
The bare SM could be consistent with massless particles but matter particles range from almost 0 to about 170 GeV while force carriers range from 0 to about 90 GeV.

The simplest solution:
all particles are massless !!
A new scalar field pervades the Universe (the Higgs field). Particles interacting with this field acquire mass: the stronger the interaction the larger the mass...

BUT

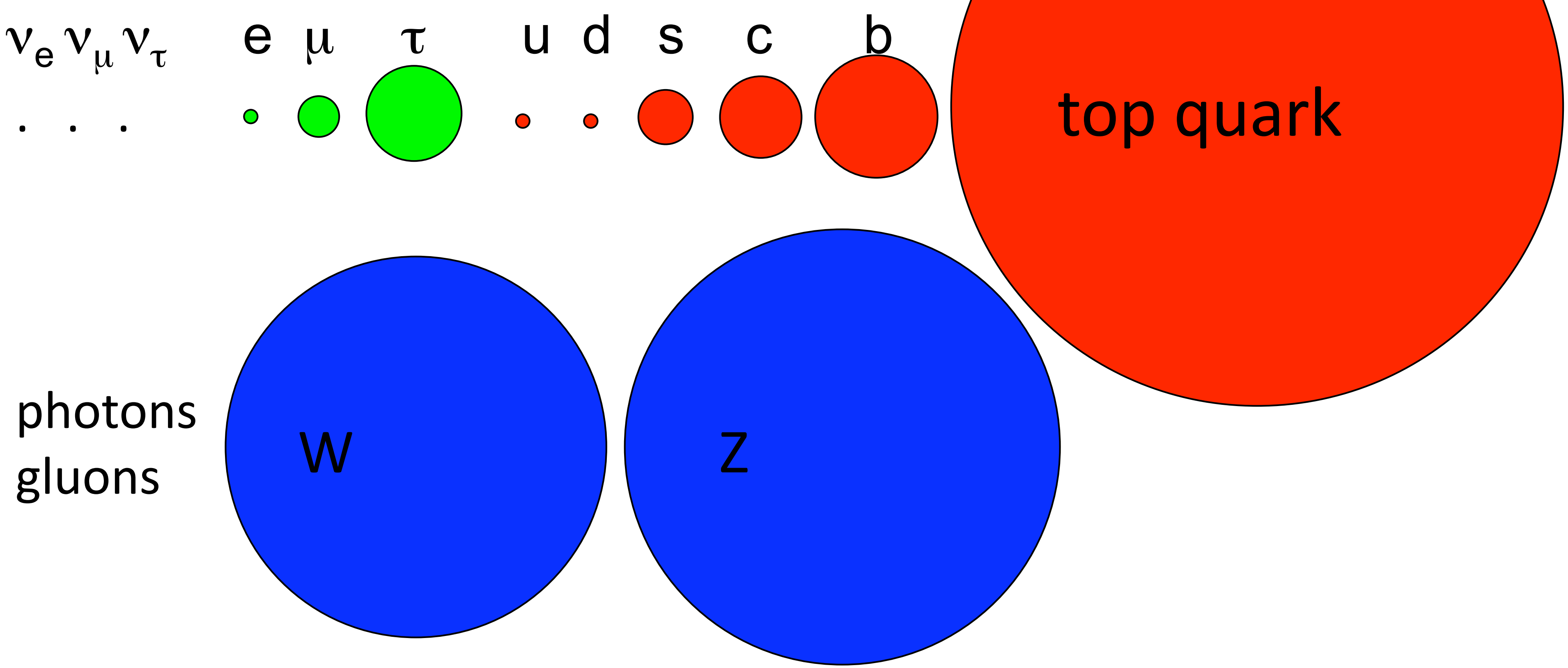
the Higgs boson have not yet been found !

ELEMENTARY PARTICLE MASSES

$E = mc^2$

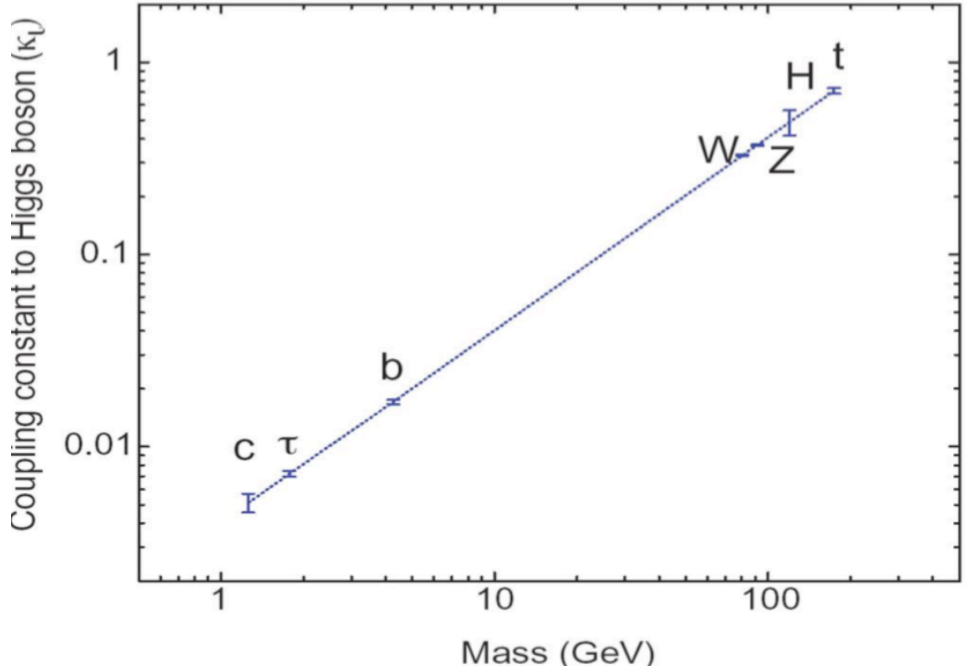
1 proton mass ~ 1GeV/c^2 (10^{-27} Kg)

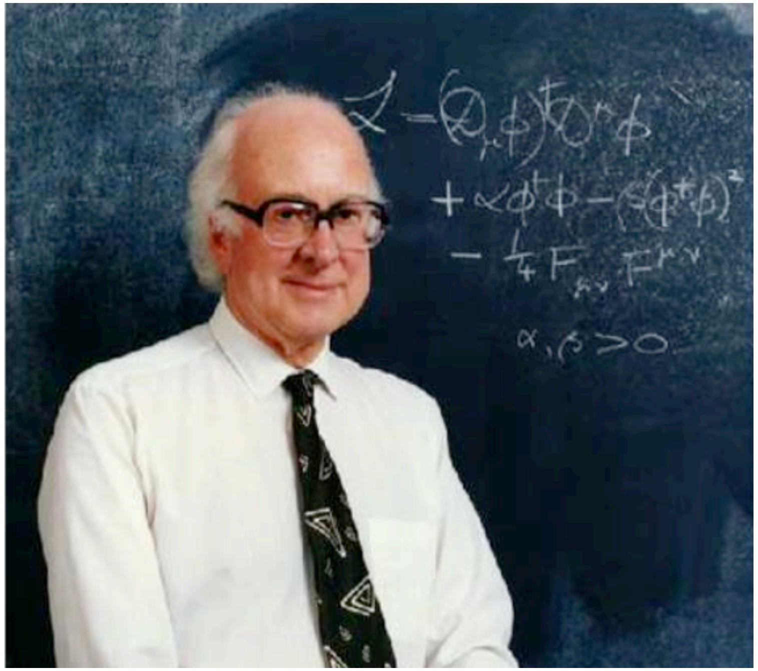
Mass proportional to area:



Are these made of something else? Are there more quark-, neutrino-,and electron-like particles?

The Higgs mechanism





The theory is elegant, coherent, and consistent with all observations….. but nobody has been able so far to identify this new particle.

Unfortunately the theory does not constrain significantly the mass of the boson. M_H can be considered as a free parameter. The Higgs boson can live anywhere between a few 10 GeV and many 100 GeV.

A definitive answer can come only from careful experiments.

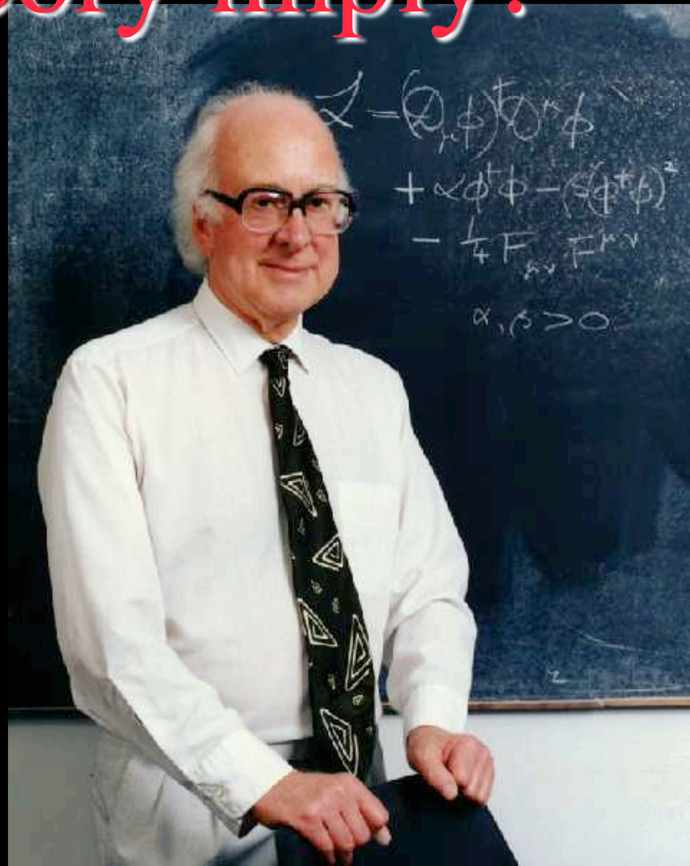
What does Higgs theory imply?

Higgs' mechanism gives mass to W and Z bosons, and to the matter particles.

Mass of the W predicted

We can check it

It also predicts one extra particle:
The Higgs boson



The Higgs Boson mass is *not* predicted

The Waldegrave Higgs challenge

In 1993, the then UK Science Minister, William Waldegrave, issued a challenge to physicists to answer the questions:

'What is the Higgs boson, and why do we want to find it?'

on one side of a sheet of paper.

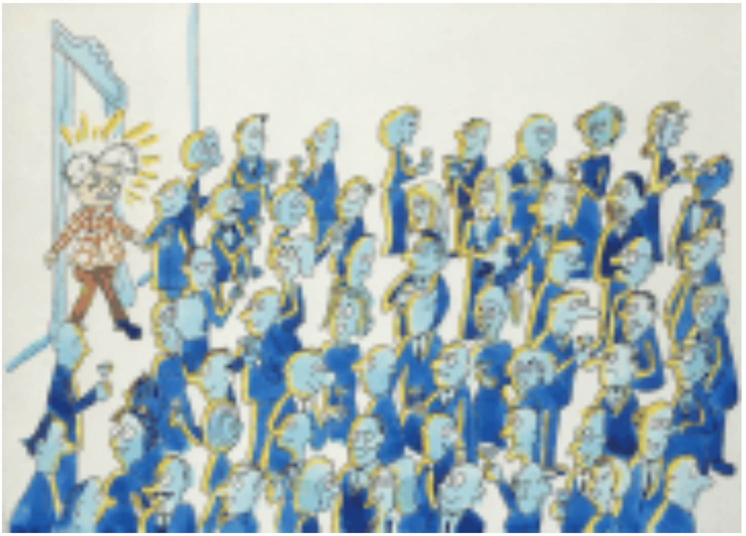
David Miller of UCL won a bottle of champagne for the following:

The Waldegrave Higgs challenge

Imagine a room (the Universe) full of political activists (the Higgs field) talking to each other

A famous Person like the Prime Minister (one Particle) walks in, trying to cross the room

More famous is that Person (highier is the mass of the Particle) more difficult is his movement in the room (higher is his inertia)

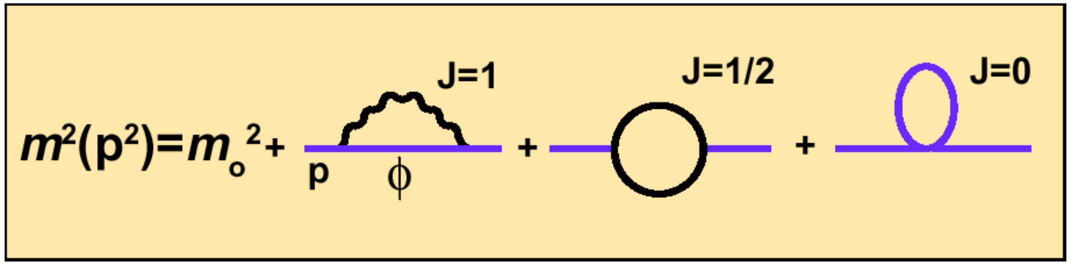


The Standard Model is one of the most successful theories tested so far but many questions are still without an answer.

* *What is the origin of the mass of quarks, leptons and force carriers ?*
* *Why matter is made of fermions and force carriers of bosons ?*
* *What is the dark matter (and dark energy), which pervades the Universe ?*
* *Why our World is made with matter and how the antimatter disappeared ?*
* *Why the interactions are so different in strenght and why Gravity cannot be included in our SM theory?*
* *Are quarks and leptons fundamental particles or have they internal structures ?*

We believe that the answer to some of these questions is probably hidden in the so far unexplored TeV region which will become accessible with the CERN Large Hadron Collider (LHC)

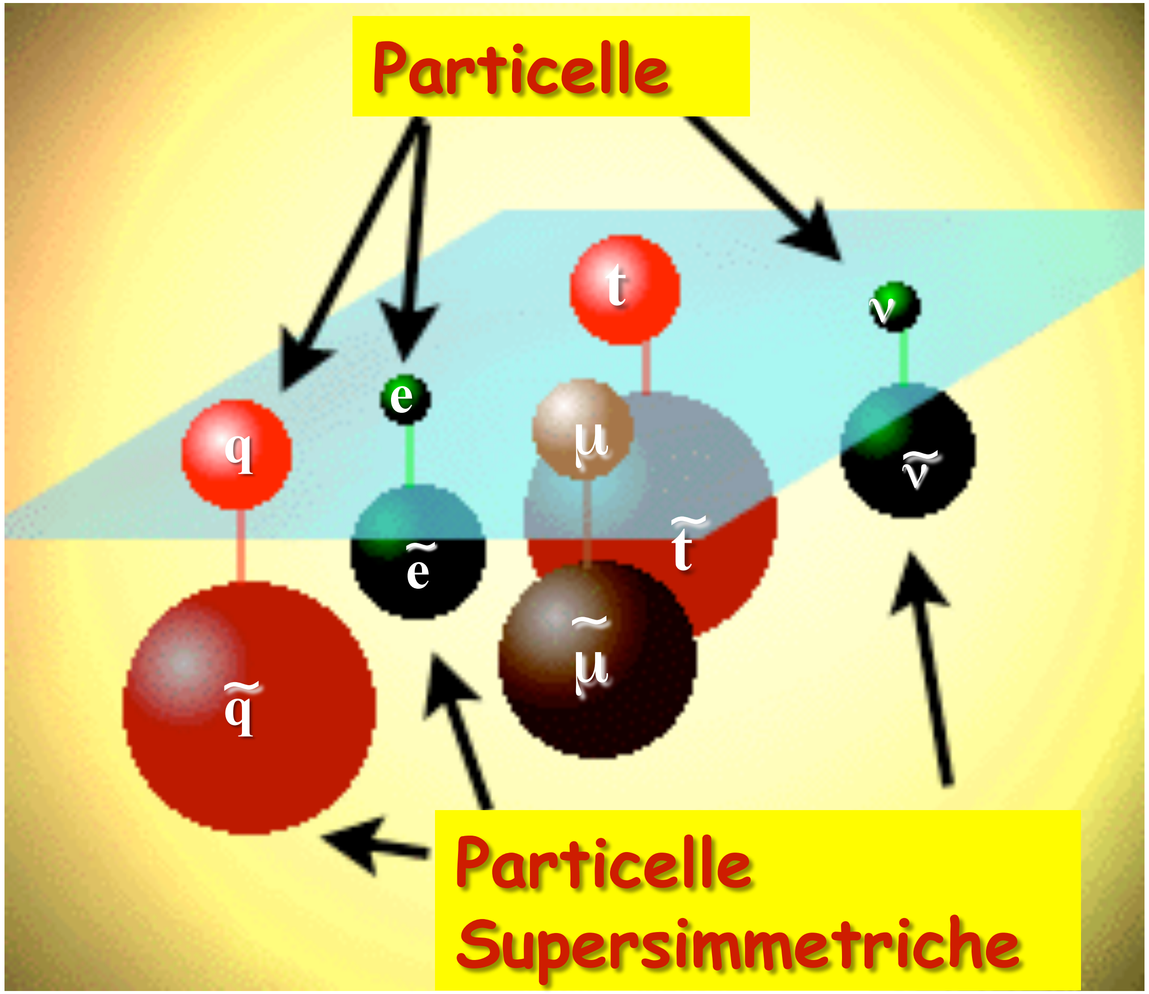
Problema con lo Higgs dello Standard Model



$$m^2(p^2) = m^2(\Lambda^2) + Cg^2 \int_{p^2}^{\Lambda^2} dk^2$$

- La massa dello Higgs tende a divergere mentre deve restare bassa perchè la teoria continui a fare senso.
- Questa contraddizione può essere eliminata con la supersimmetria.

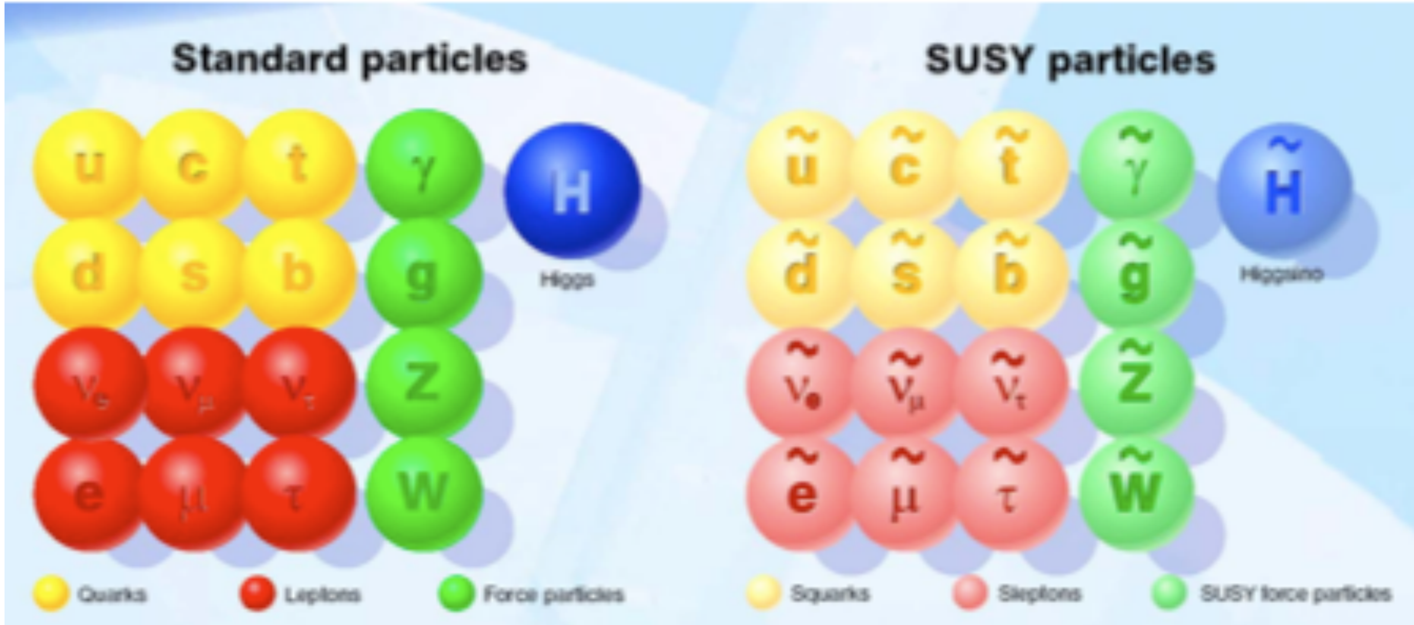
L'inconsistenza del modello potrebbe essere risolta se esistesse un mondo di particelle supersimmetriche corrispondente al mondo delle particelle standard ma con masse molto più grandi (e che per questo motivo non sono ancora state osservate).



$$m_{\widetilde{sp}} >> m_p$$

Super-symmetry

Each SM particle could have a super-symmetric (SUSY) partner with spin 1/2 difference. In super-matter the carriers of the interactions are fermions and the particles are bosons. Elegant and nice symmetry of nature (similar to matter-antimatter where the spin plays the role of the charge).



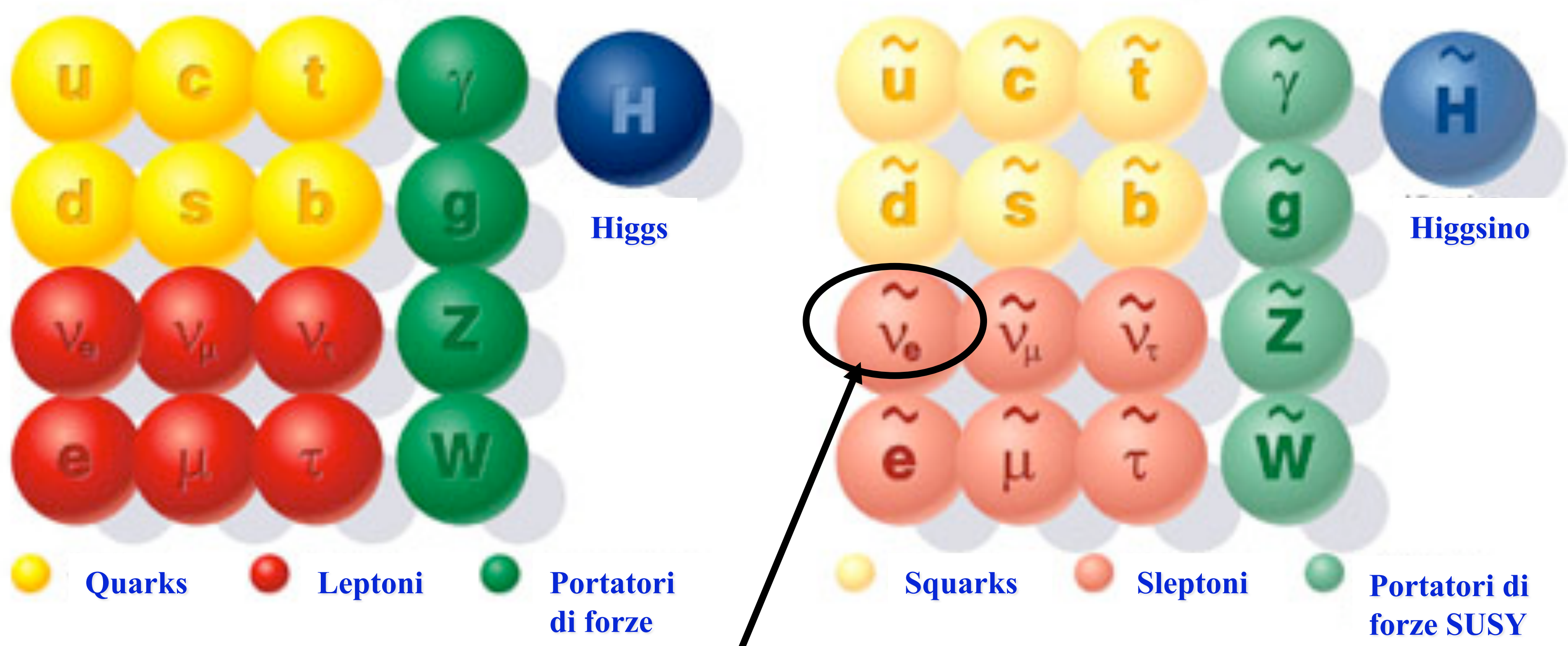
Since none of them have been discovered yet they must be heavy and SUSY must be a broken symmetry! But if SUSY is supposed to solve the issue of naturalness they must populate the TeV mass region:

$|M^2_{spart} - M^2_{part}| < O\,(1\ \text{TeV}^2)$

La **Materia Oscura** e’ dovuta all’esistenza di **Particelle Supersimmetriche** ? Tali particelle potrebbero non essere state scoperte fino ad oggi perché hanno masse molto più grandi delle masse delle particelle standard.

Particelle Standard

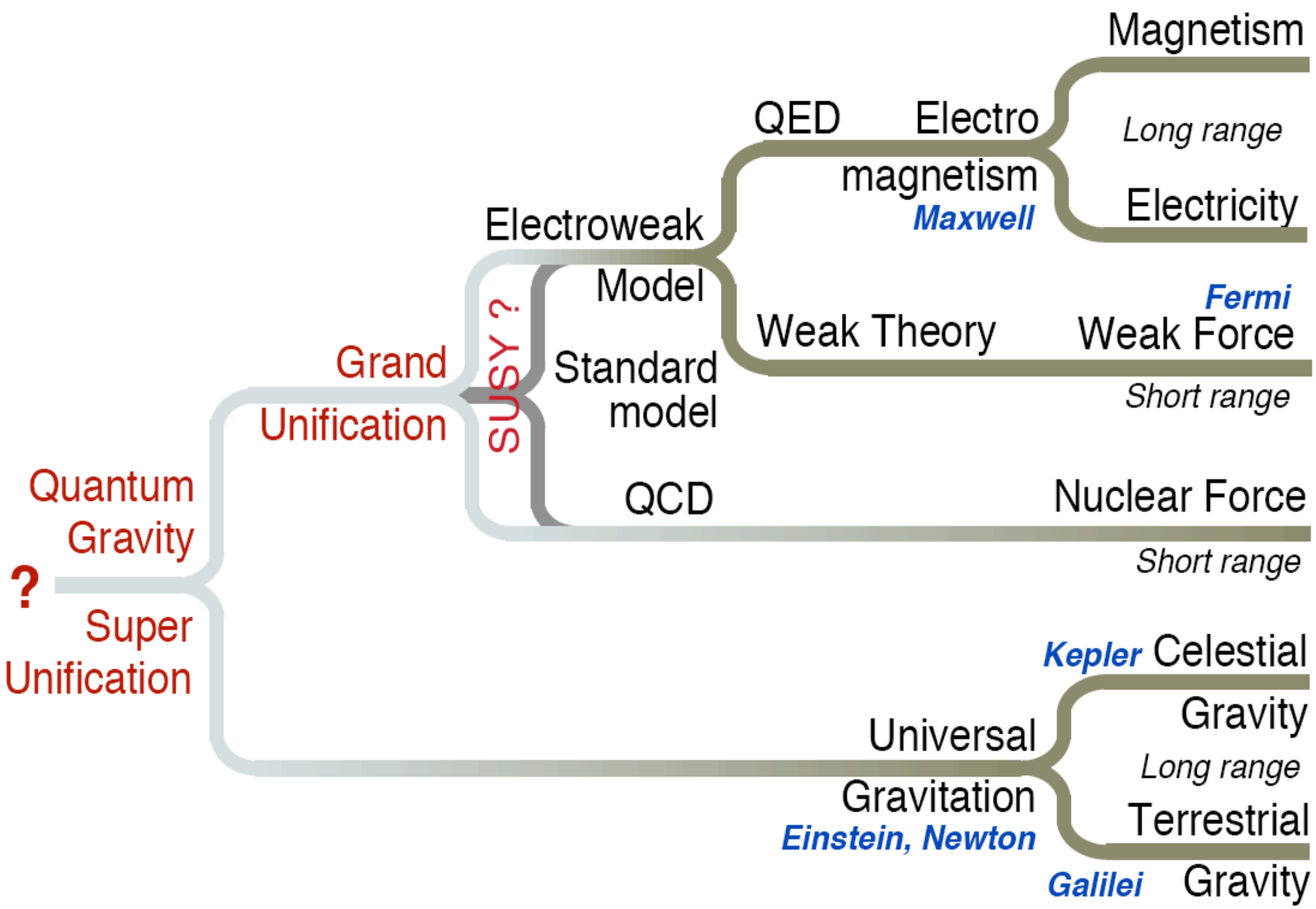
Particelle Supersimmetriche (SUSY)



Possibile candidato come particella che forma la Materia Oscura. LHC potrebbe avere l’energia per produrla

The unification of all forces of nature.

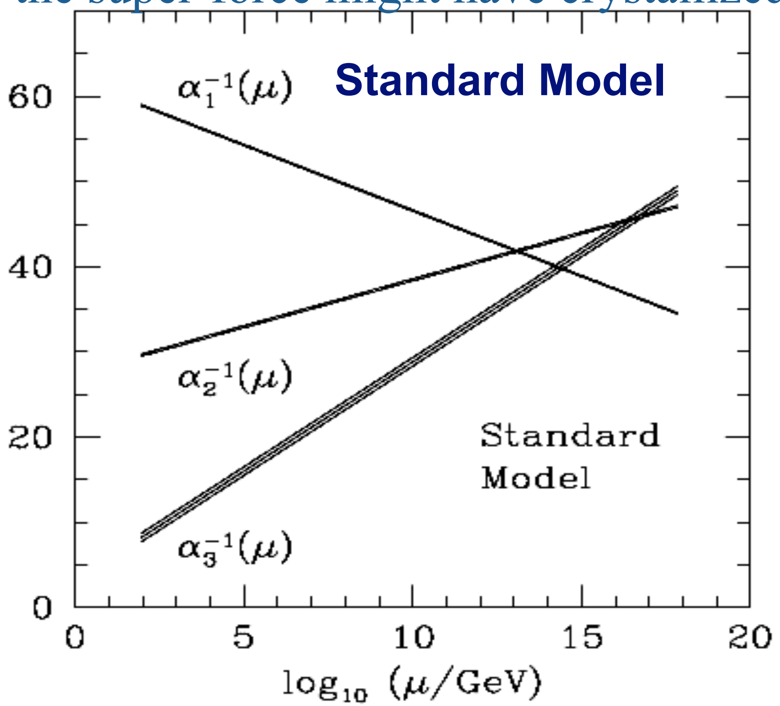
The dream of all physicists, the“mother” of all challenges

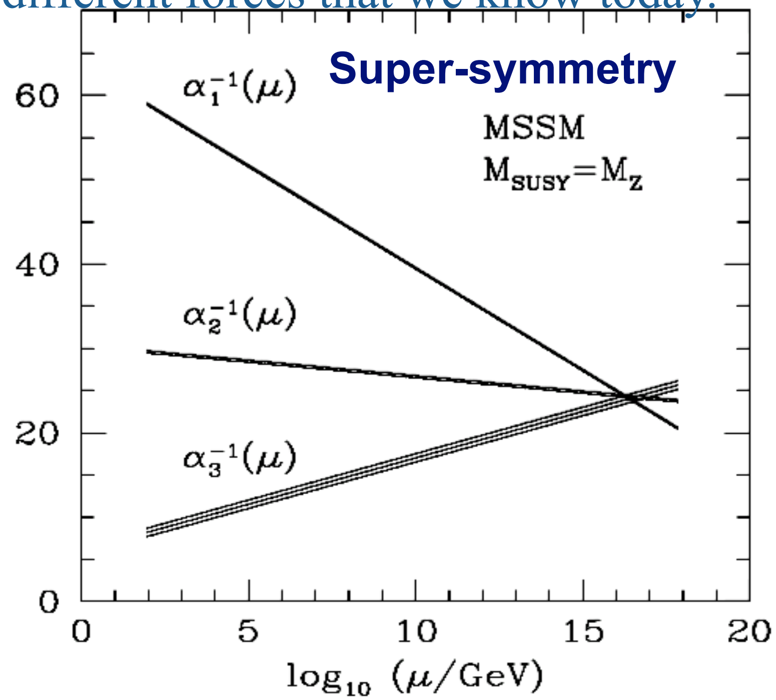


Super-symmetry could bring us closer to the unification of the forces

The coupling constants "run" in quantum field theories due to vacuum fluctuations. For example, in EM the e charge is shielded by virtual γ fluctuations into e^+e^- pairs on a distance scale set by, $l_e \sim 1/m_e$. Thus α increases as M decreases, $\alpha(0) = 1/137$, $\alpha(M_Z) = 1/128$.

All known interactions could be considered sort of daughters of a single primordial super-force. Passing from the extreme temperatures of the “baby” universe to the cold and old universe of today the super-force might have crystallized in the different forces that we know today.





Extradimensions

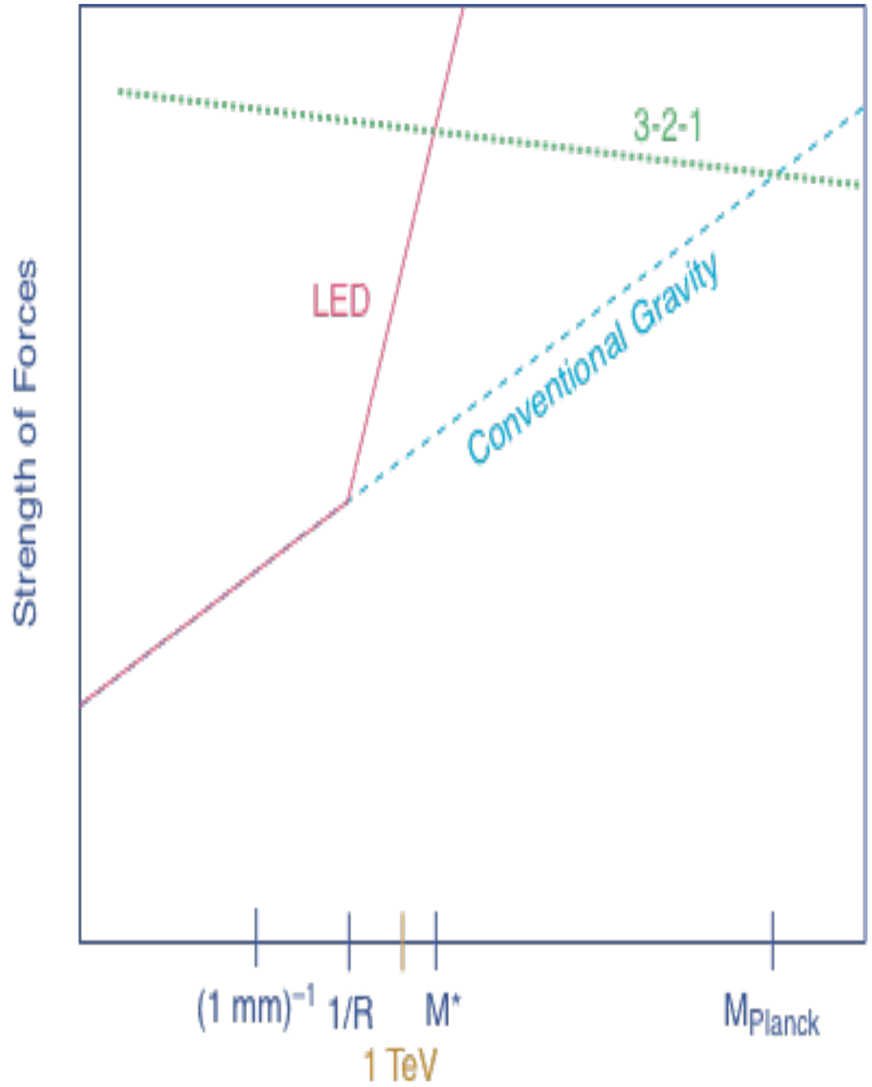
Things are not too bad… but gravity is not yet in the picture. It is still too weak.

Great idea some years ago.

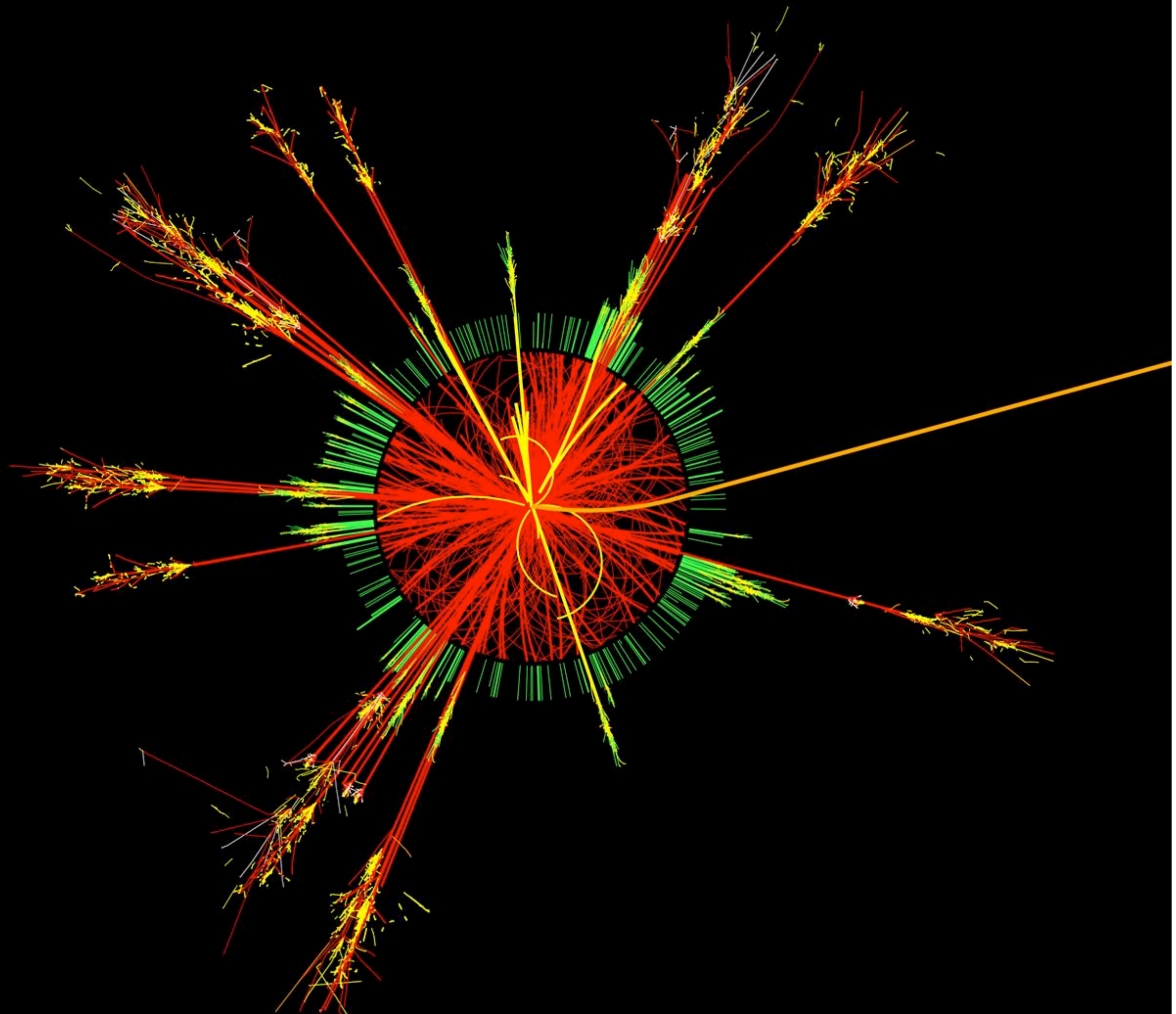
Gravity is NOT weak, it appears weak to us because we observe it in a 4-dimensional world. **If we assume that our universe can really evolve in 5-10 dimensions**, immediately gravity becomes much stronger than the simple 4-dimensional projection that we are used to deal with.

The Great Unification of Forces can be proven at lower energies.

But if this theory is correct there would be new massive particle populating the TeV region.

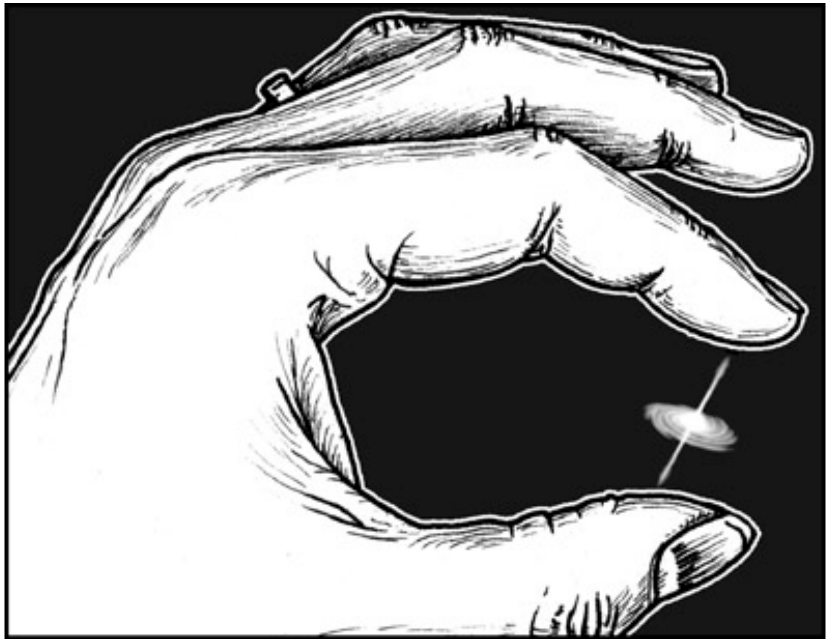


Se esistessero in natura delle dimensioni nascoste accessibili solo alla gravità, oltre alle 4 dimensioni del nostro spazio tempo, alle energie di LHC si potrebbero creare dei piccoli "Black Hole" che potrebbero essere rivelati dagli apparati sperimentali come eventi del tipo simulato in figura



Evento di "Black Hole" a LHC

Black Holes a LHC



I black holes che potrebbero essere prodotti a LHC sono di massa piccolissima e decadrebbero immediatamente in particelle normali ben misurabili dai nostri rivelatori

I black holes a LHC non sono niente di simile ai black holes super-massivi (~100.000 volte la massa del sole) che si trovano sparsi nell'Universo

La paura che a LHC possa venir creato un piccolo ma vorace Buco Nero in cui la Terra venga inesorabilmente inghiottita è totalmente priva di senso !

All these are elegant theories

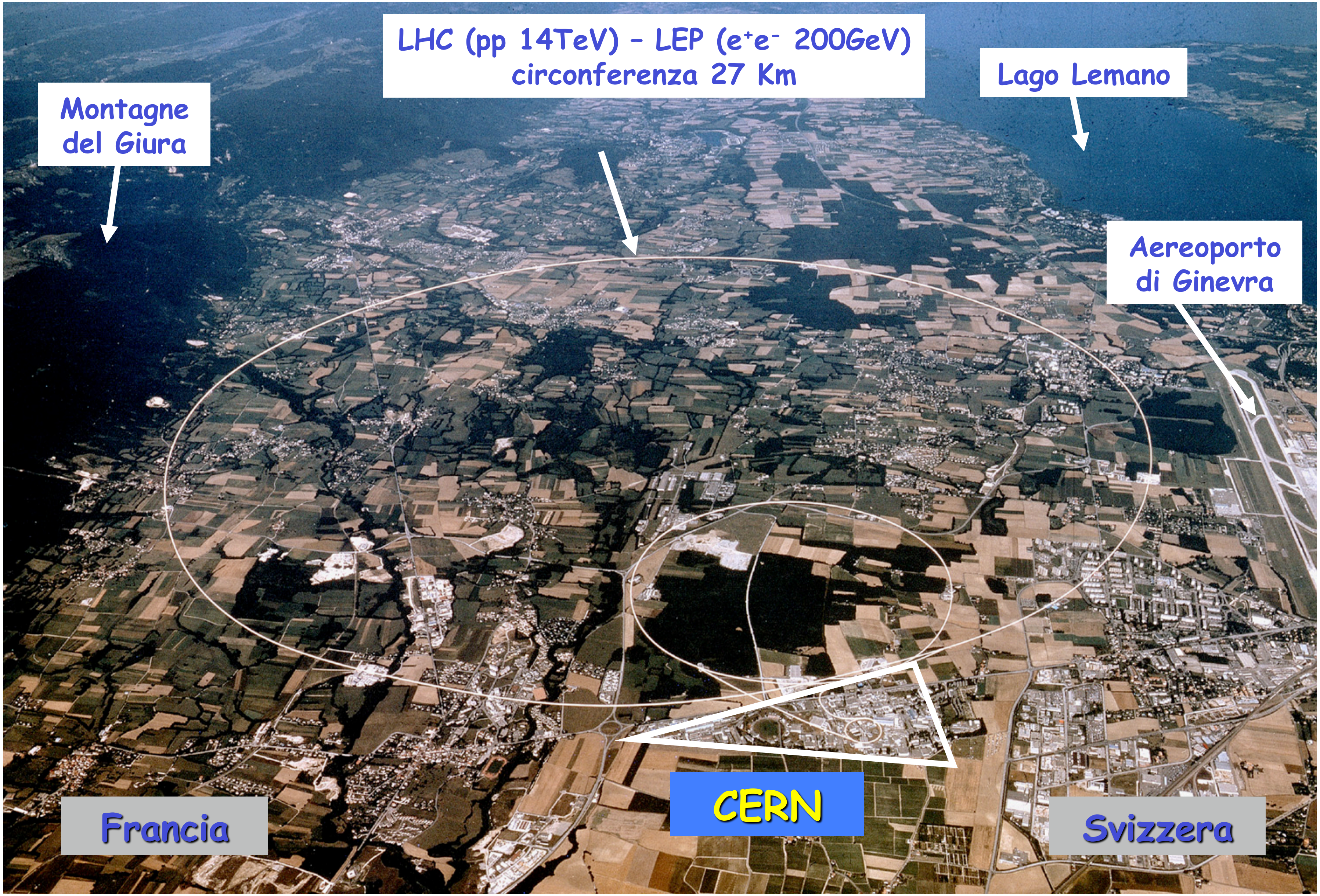
But to verify them we need to discover the Higgs, the supersymmetric particles and the very massive particles predicted by extradimensional theories (100GeV to severalsTeV)

All these particles have escaped detection so far.
This could be due to the fact that:
a)The theories are wrong or
b)We have not been able to produce them so far because the energy of previous accelerators was not high enough.

We should remember that to produce a mass m we need an energy $E=mc^2$. So far the modern experiments have produced and studied particles up to masses ~100GeV.

Let’s try to produce and study masses ~TeV

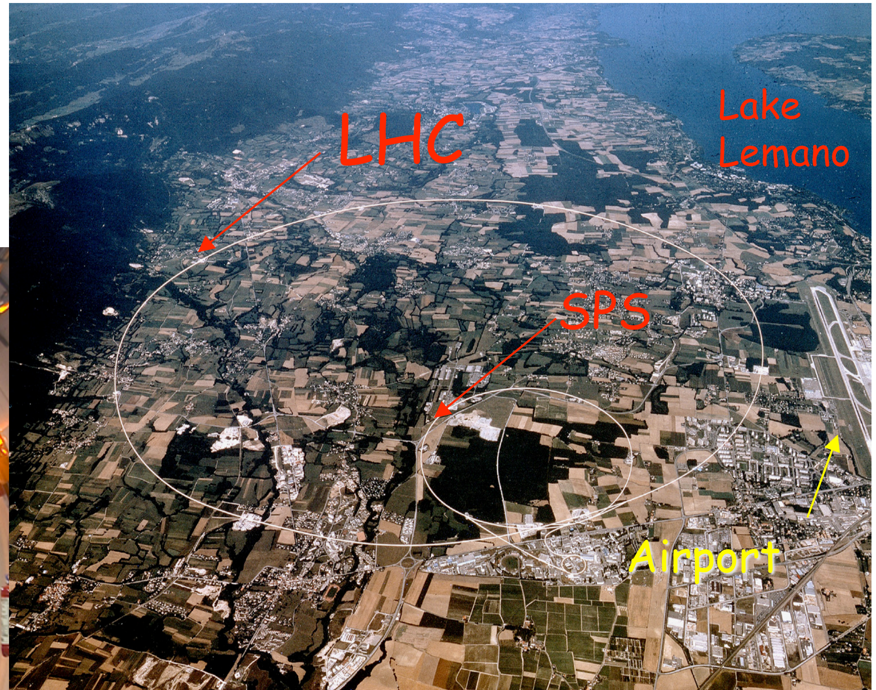
CERN (Centro Europeo Ricerche Nucleari)

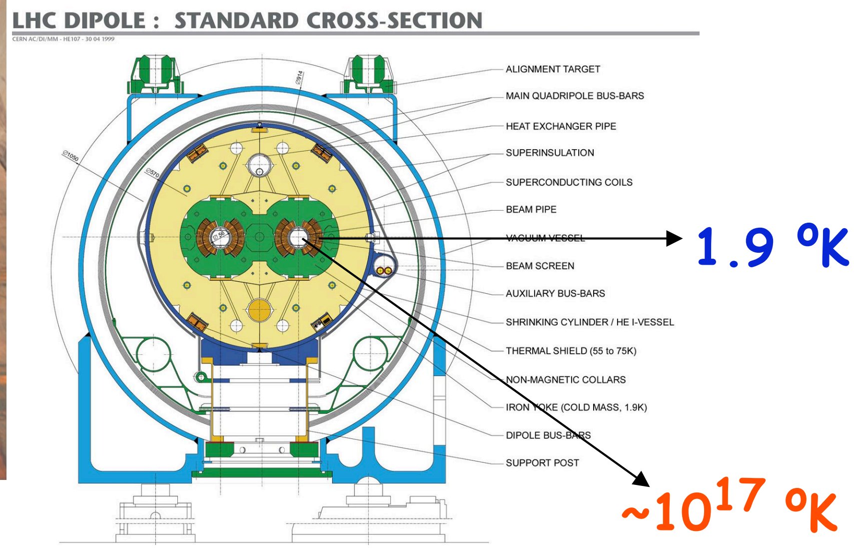


The CERN Large Hadron Collider

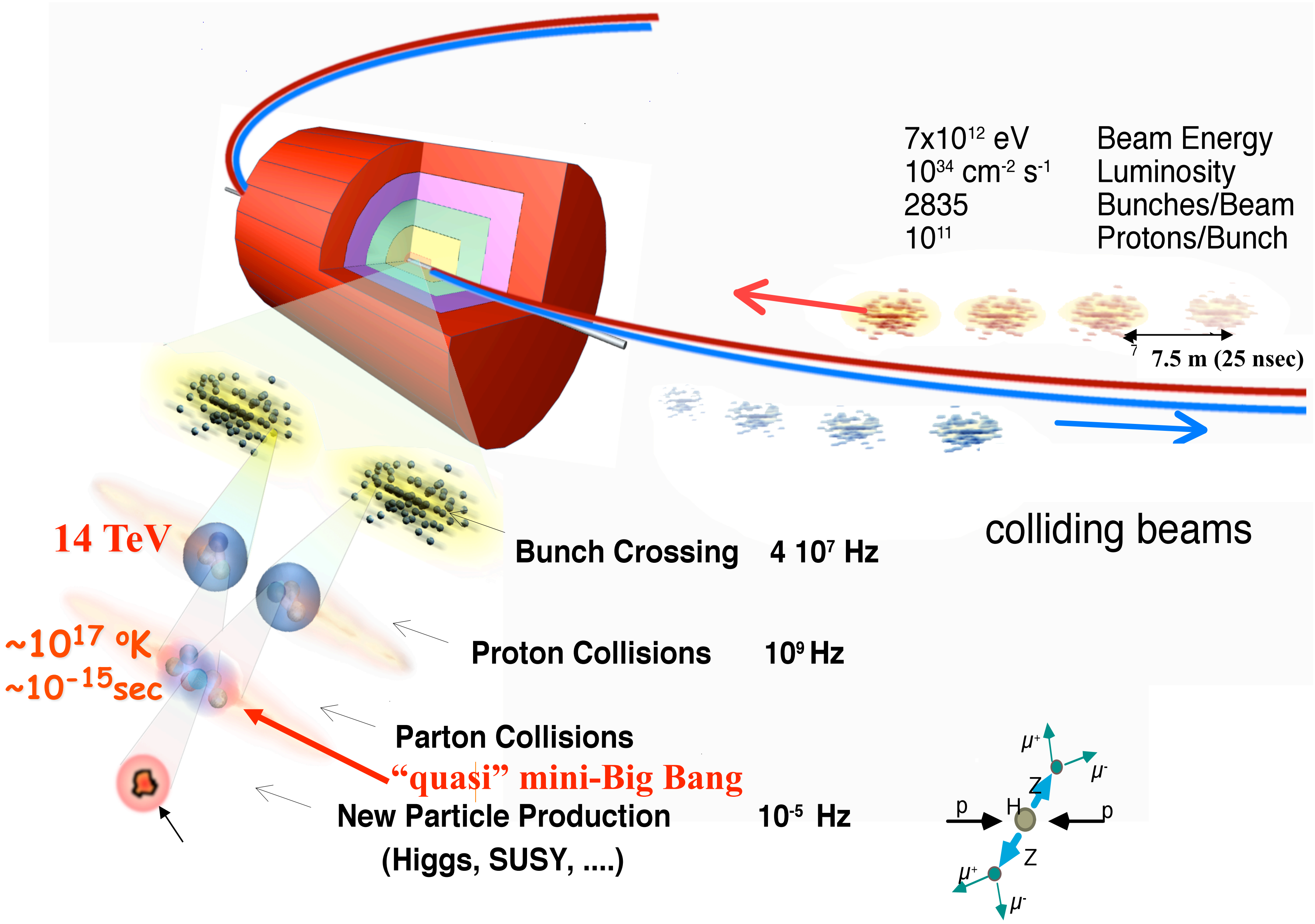
first collisions in Autumn 2009

9300 Superconductor magnets
1232 Dipoles (15m, 1.9^{o}K) 8.4Tesla 11700 A
448 Main Quads, 6618 Correctors.
Circonference 26.7 km

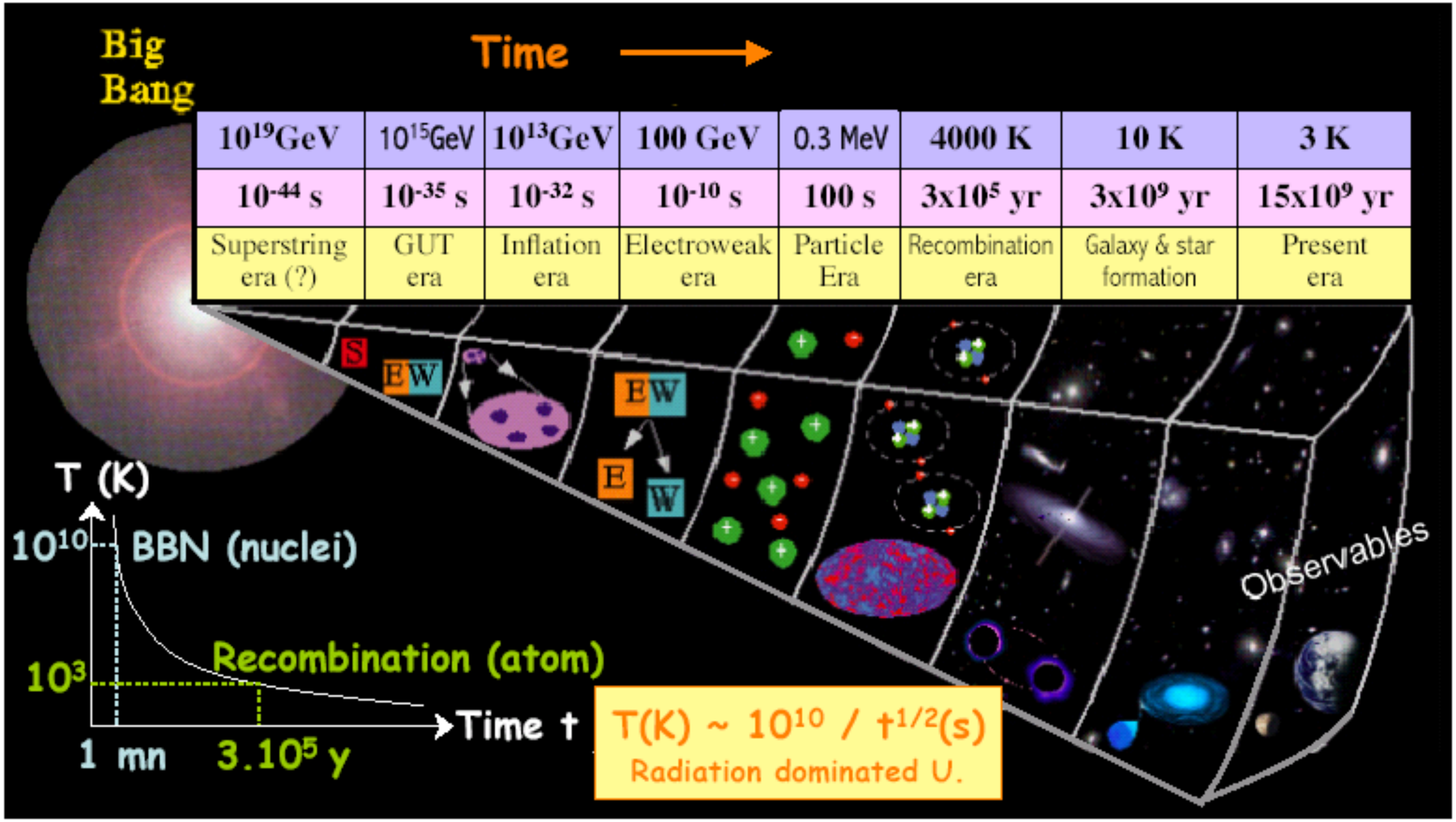




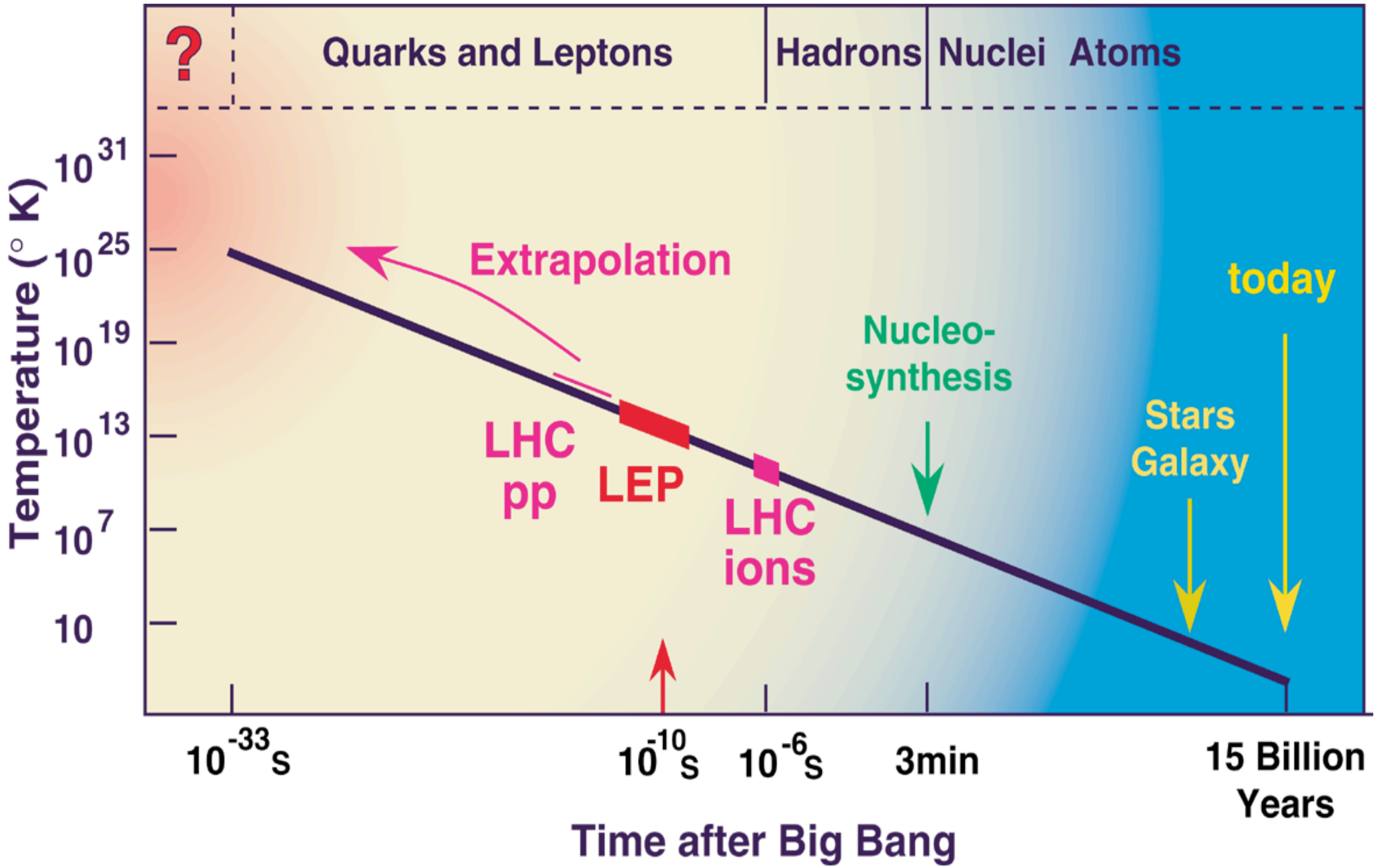
LHC : proton-proton collisions at 14 TeV



The two frontiers of physics:
high energy physics with particle accelerators

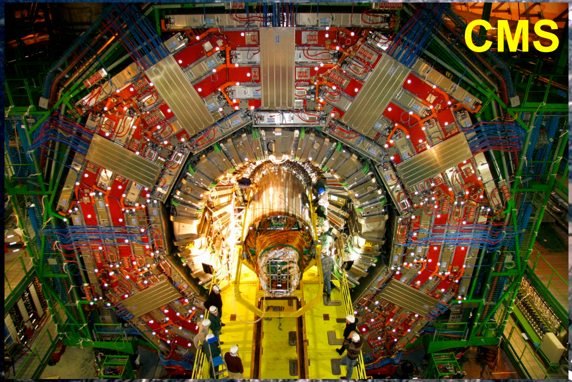


LHC: towards the origin of the Universe

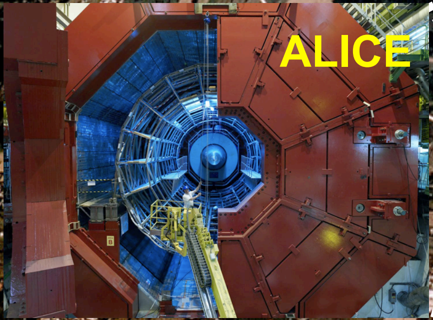


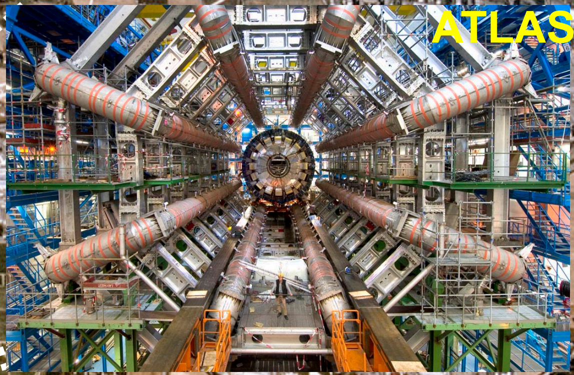
With LHC we are entering a New Era in Fundamental Science

The Large Hadron Collider (LHC), one of the largest and truly global scientific projects ever, is a turning point in modern physics.

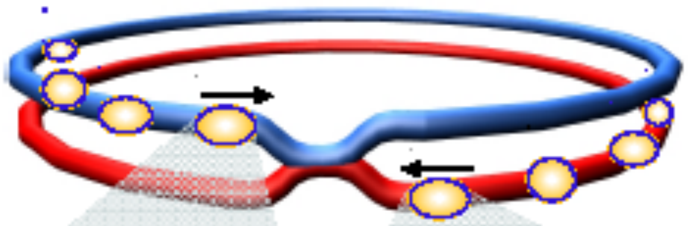


The exploration of a new energy frontier just started

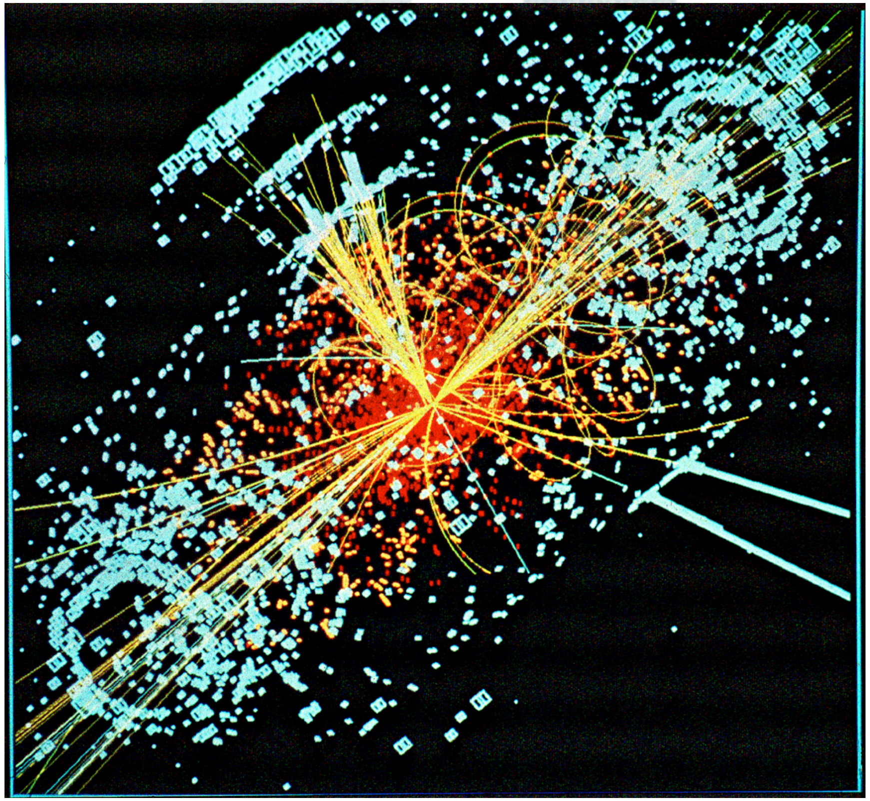




proton-proton collisions at LHC

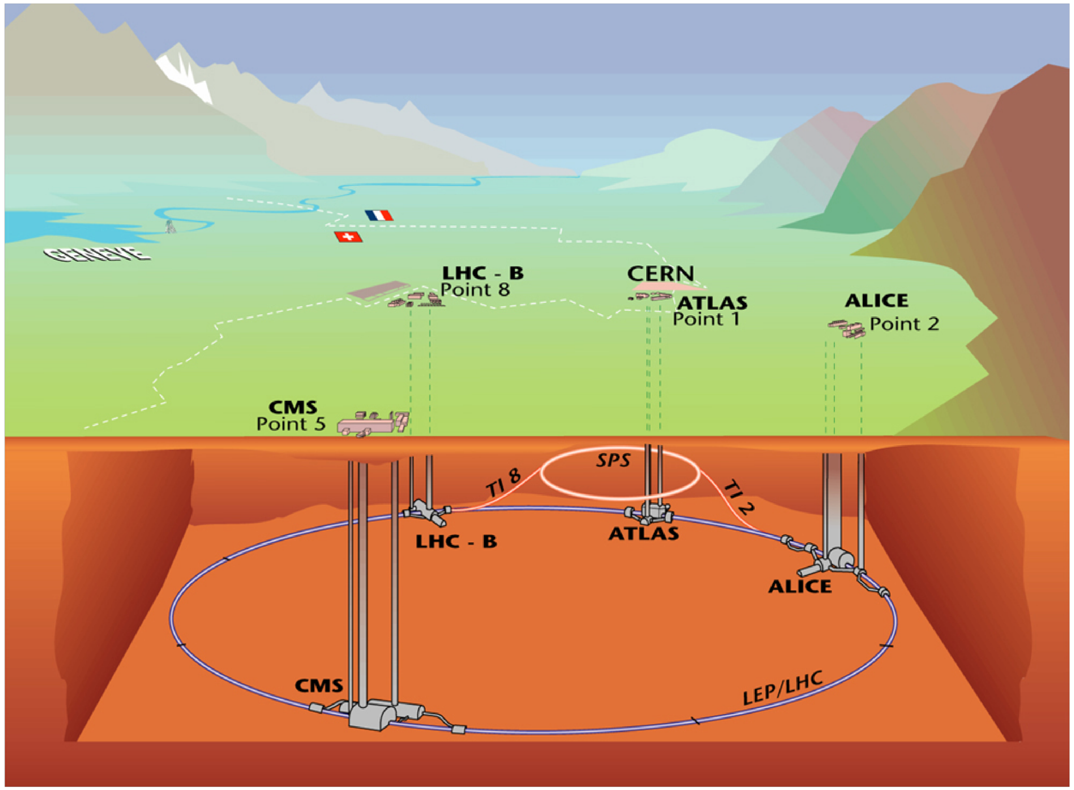


~100 millions events per second
~60 billions particles per second
~1600 particles every 25 ns
Select 1 event over ten thousand billions



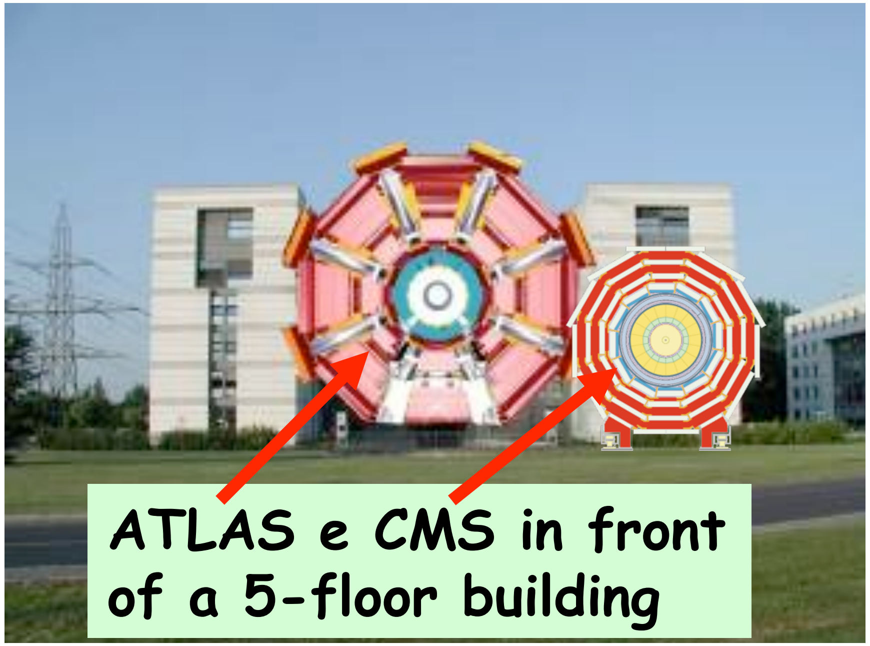
"quasi" mini-Big Bang

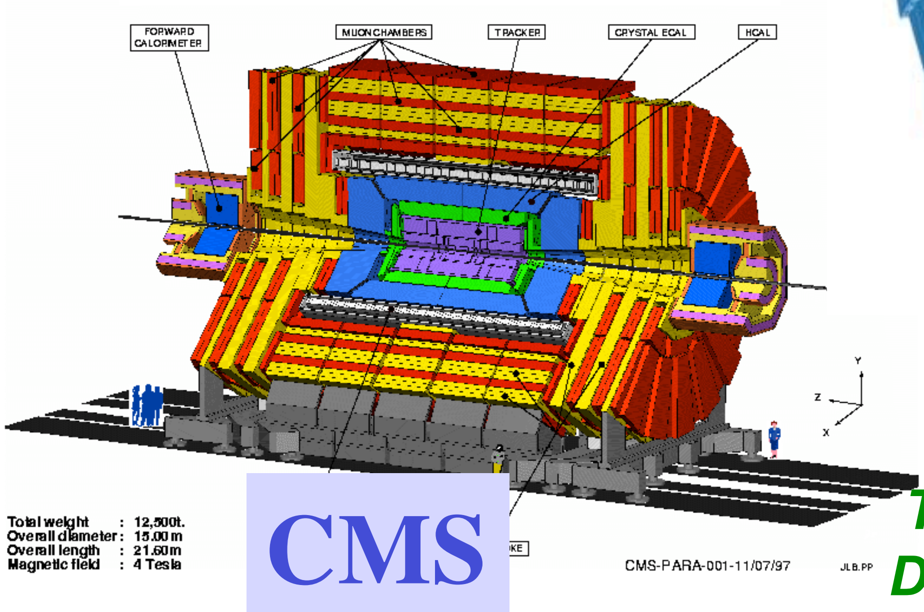
$\sim 10^{17}$ °K , $\sim 10^{-15}$ sec

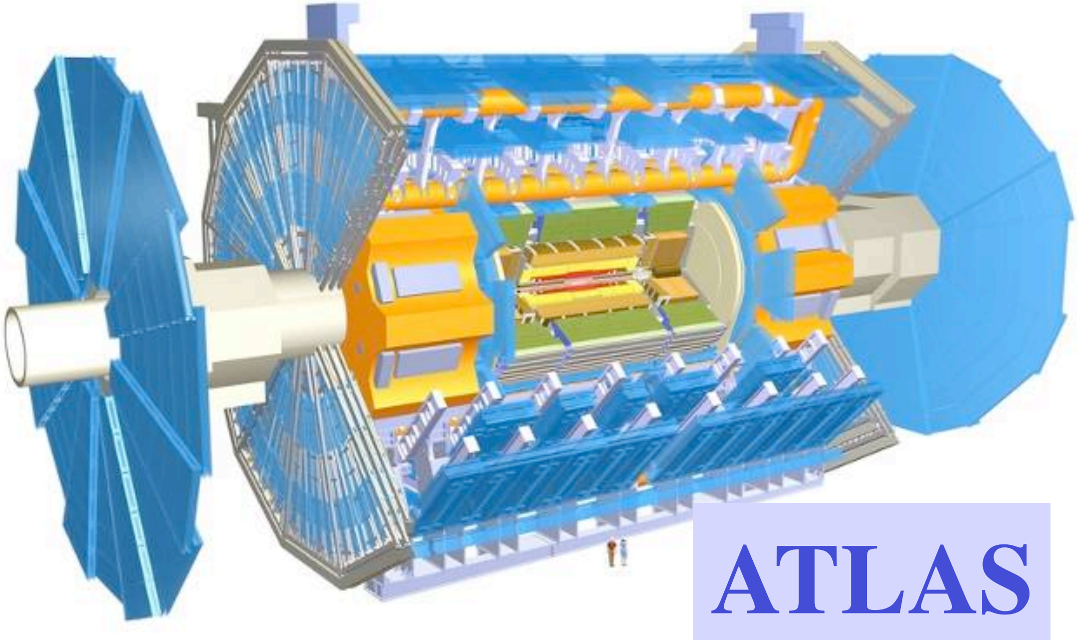


⇒ Highly performant detectors

How big are ATLAS e CMS?

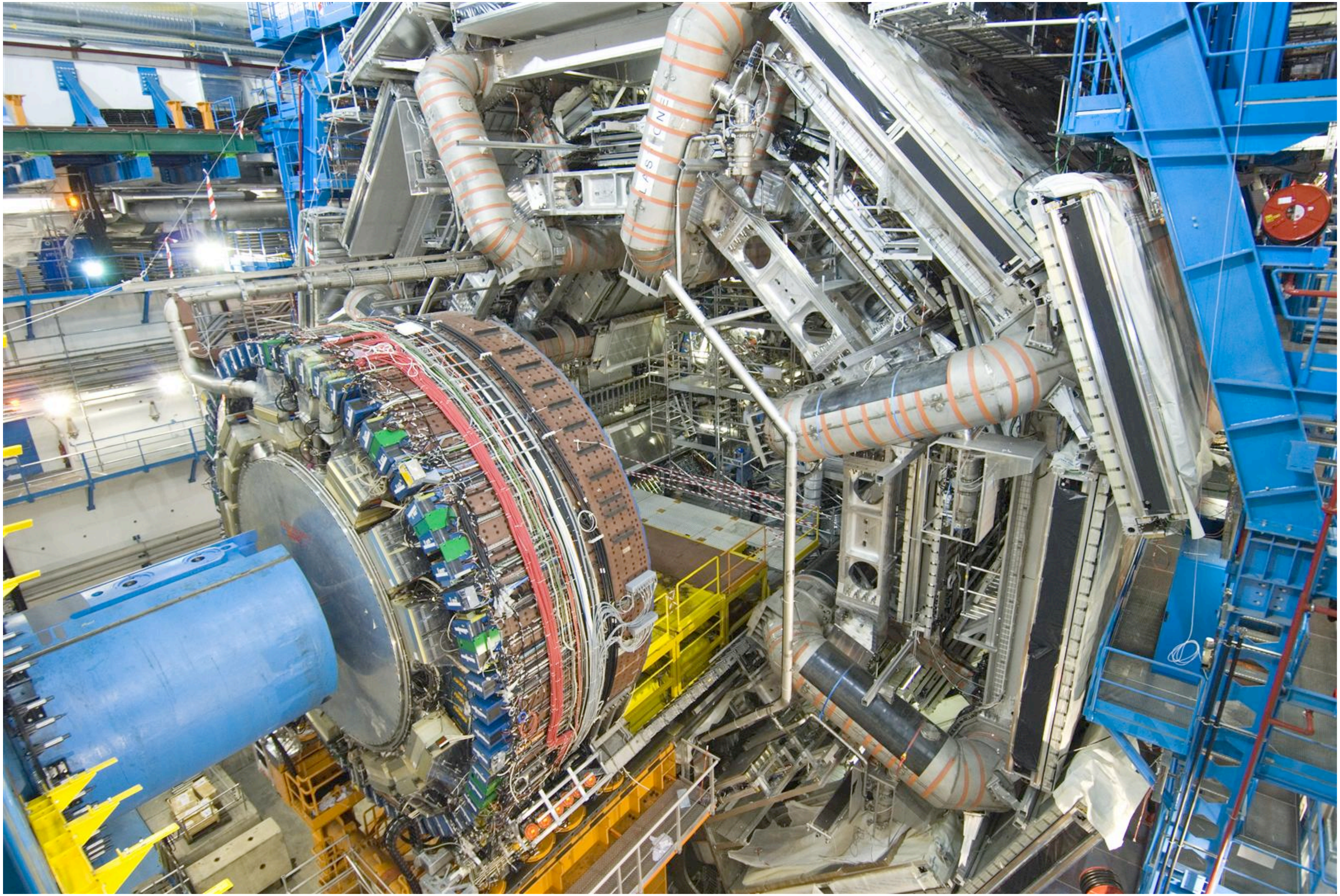




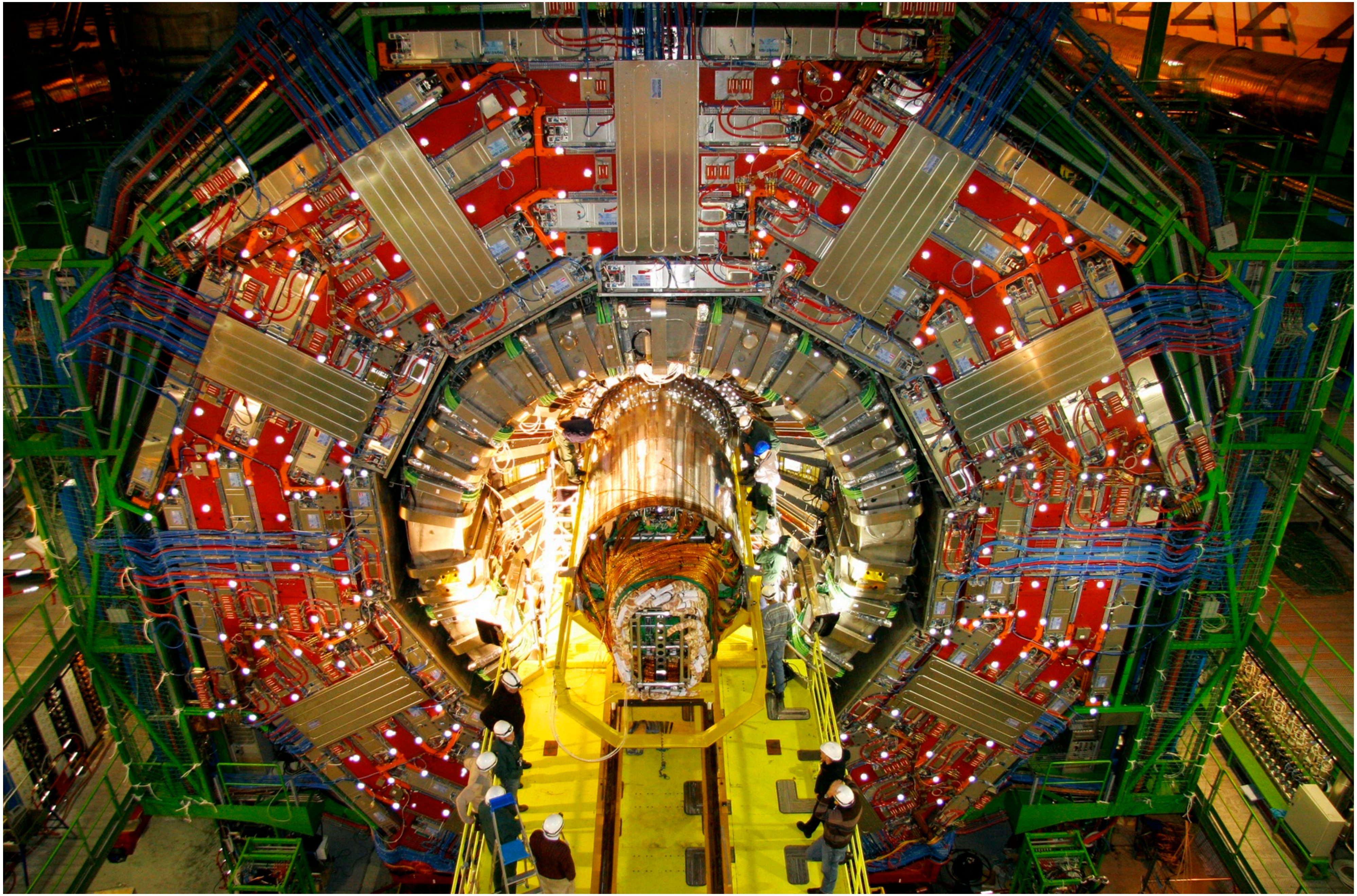


	ATLAS	CMS
Total weight (tons)	7000	12500
Diameter	22 m	15 m
Lenght	46 m	22 m
Magnetic field	2 T	4 T

The ATLAS Detector



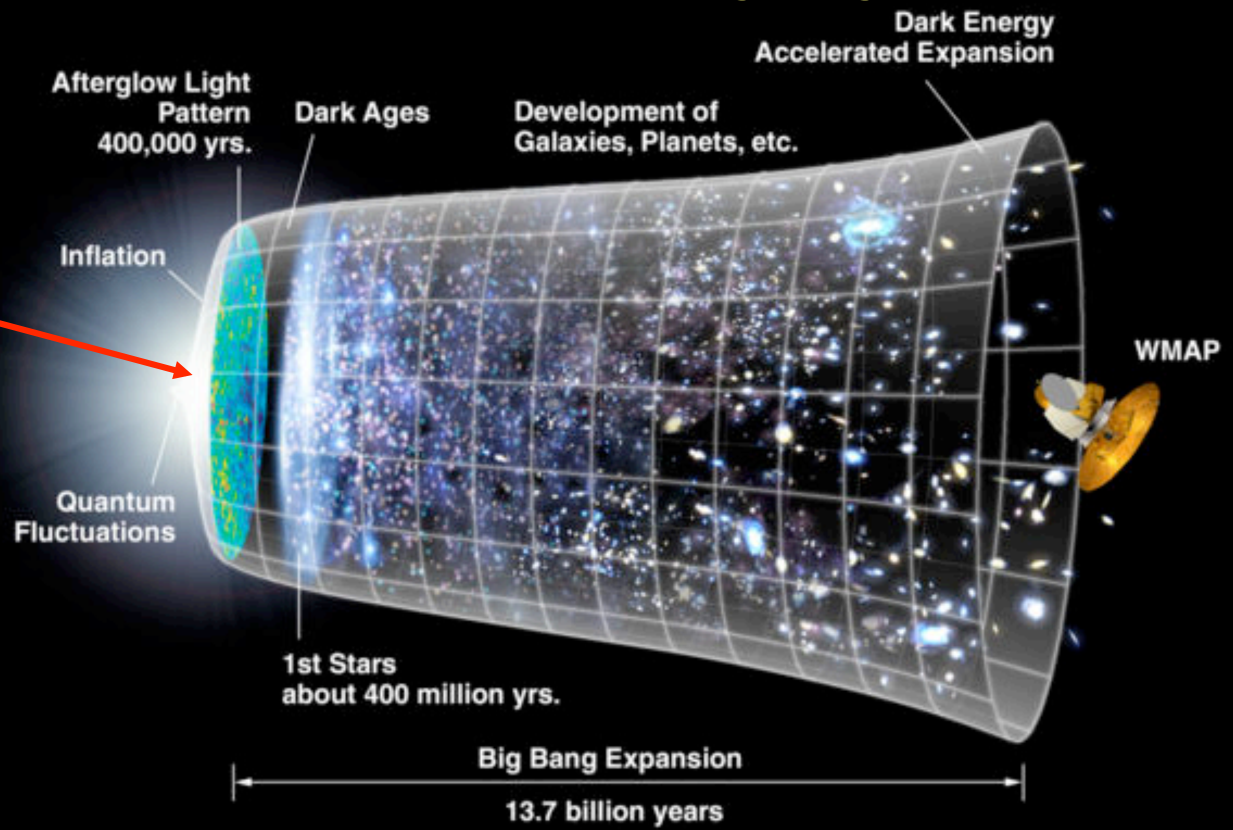
The CMS Detector



The two frontiers of physics

Particle accelerators (like LHC) will recreate the conditions prevailing in the first moments of the Universe after the Big Bang

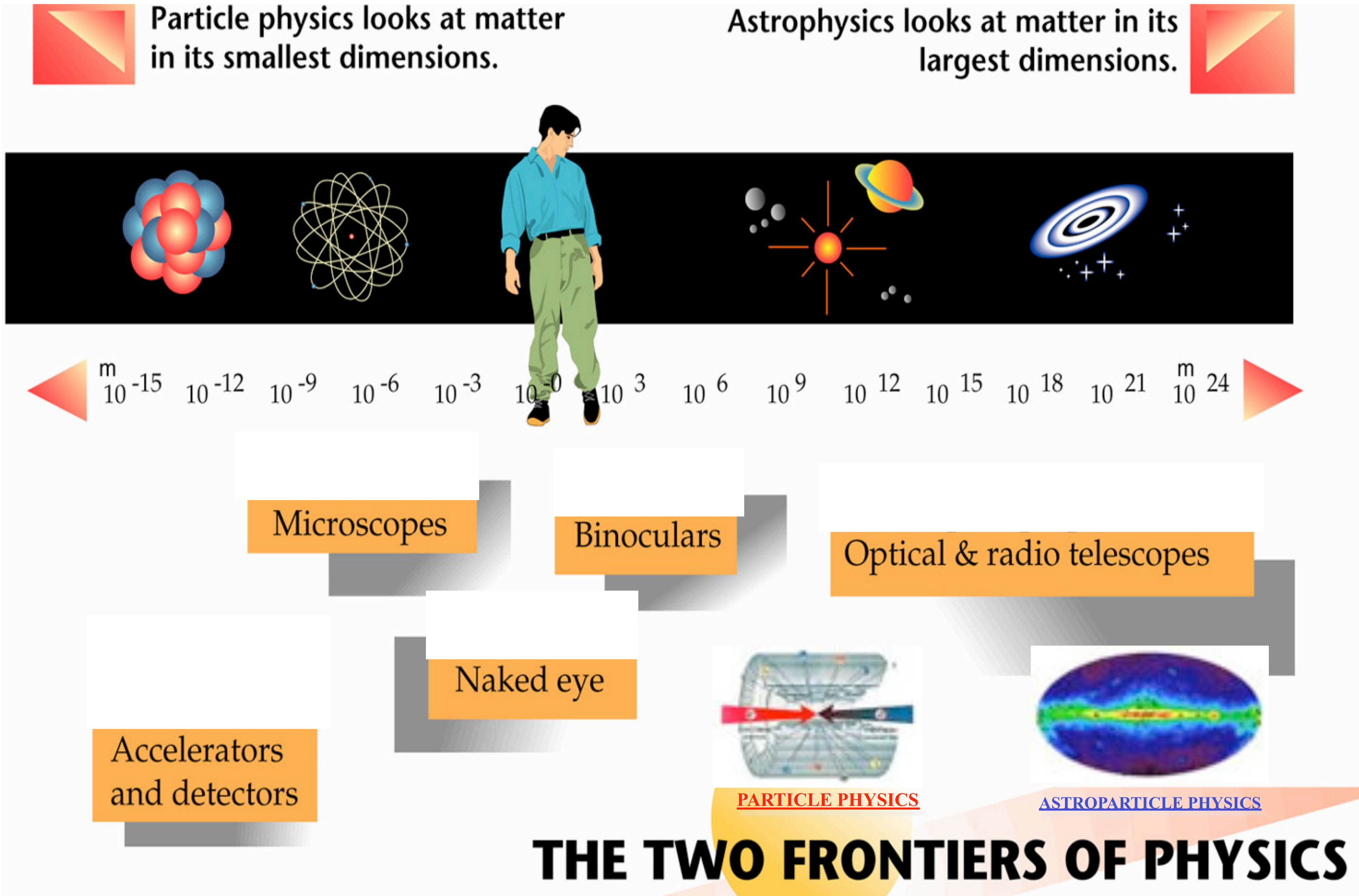
LHC
$\sim 10^{-15}$
seconds
after the
Big Bang

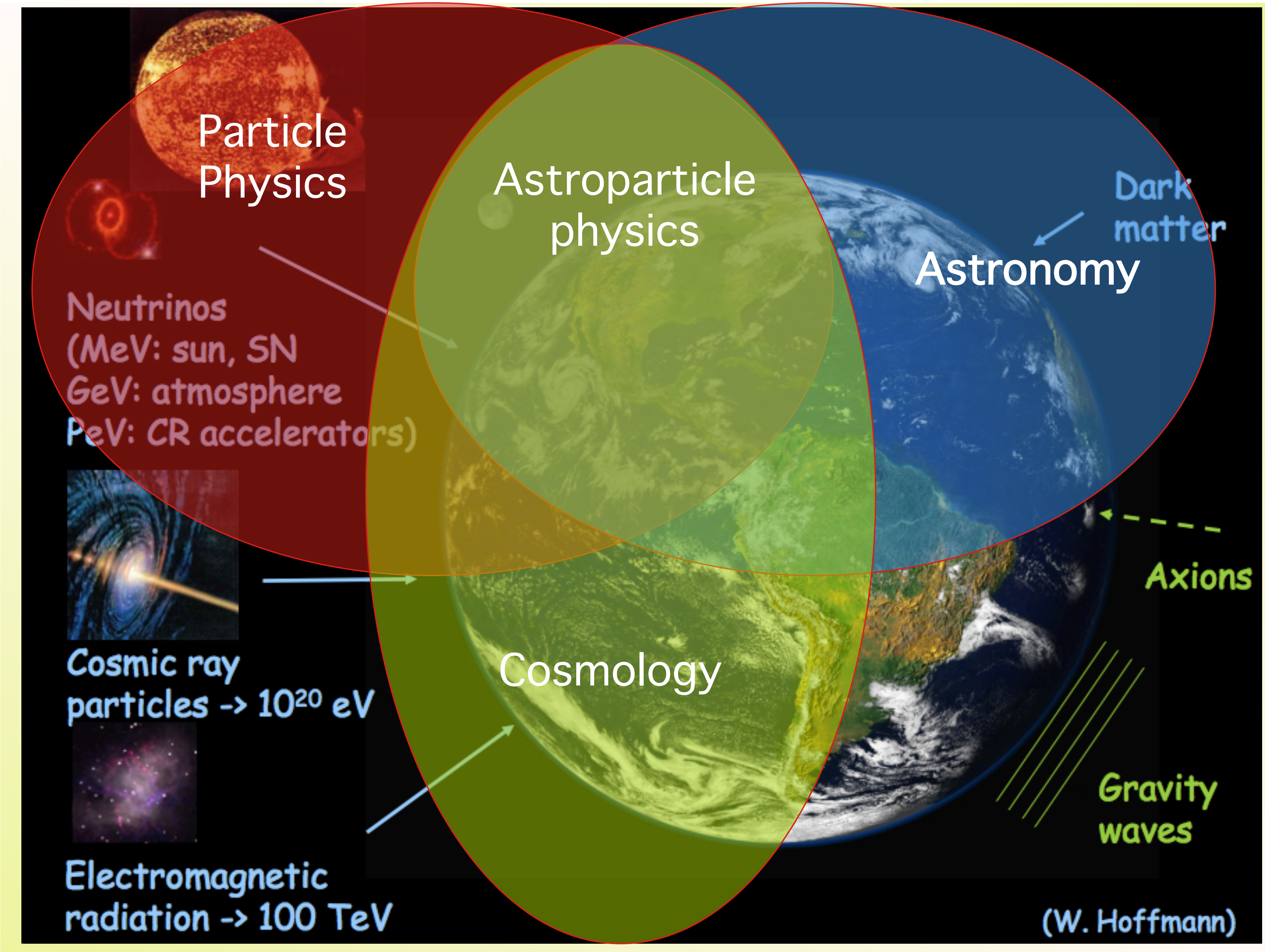


At the LHC the particles will be at an equivalent temperature of 10^{17} K
= 100 thousand, million, million degrees = hot !!

The sun is only 16 million degrees at its core
(and only a piddly 6000 degrees on its surface)

NASA/WMAP Science Team


Particle physics looks at matter in its smallest dimensions.
Astrophysics looks at matter in its largest dimensions.
m
10 -15
10 -12
10 -9
10 -6
10 -3
10 0
10 3
10 6
10 9
10 12
10 15
10 18
10 21
m
10 24
Microscopes
Binoculars
Optical & radio telescopes
Naked eye
Accelerators and detectors
PARTICLE PHYSICS
ASTROPARTICLE PHYSICS
THE TWO FRONTIERS OF PHYSICS


Particle Physics
Astroparticle physics
Astronomy
Dark matter
Neutrinos (MeV: sun, SN GeV: atmosphere PeV: CR accelerators)
Cosmic ray particles -> 10^20 eV
Electromagnetic radiation -> 100 TeV
Axions
Cosmology
Gravity waves
(W. Hoffmann)

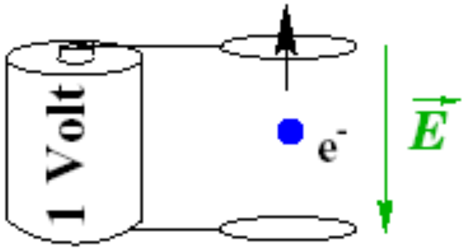
ALTRE SLIDES

Units

Energy Gain:

1 eV

→ *(1.6 * 10^{-19} J)*



Common Units: *keV, MeV, GeV, TeV*

(10^3, 10^6, 10^9, 10^{12})

Total Particle Energy:

- ***Relativity:*** $E = mc^2$; $m = \gamma * m_0$

  $\gamma = 1/\sqrt{1 - \beta^2}$; $\beta = v/c$

- ***Electron:*** $m_0 = 9.11*10^{-31}$ kg; **0.51 MeV**

- ***Proton:*** $m_0 = 1.67*10^{-27}$ kg; **0.94 GeV**

1 eV is a tiny portion of energy. 1 eV = $1.6\cdot10^{-19}$ J

m_{bee} = 1g = $5.8\cdot10^{32}$ eV/c^2

v_{bee} = 1m/s → E_{bee} = 10^{-3} J = $6.25\cdot10^{15}$ eV

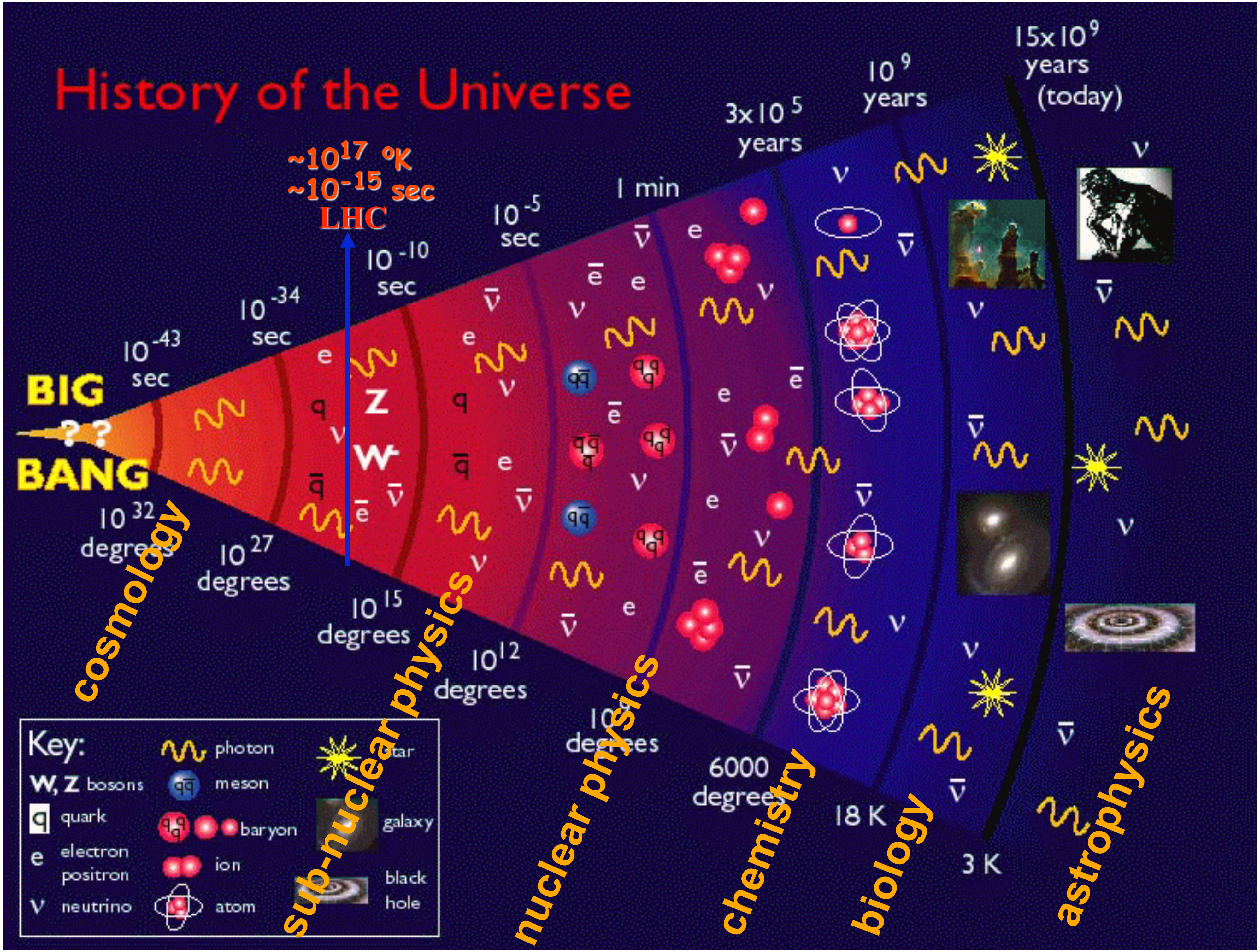
E_{LHC} = $14\cdot10^{12}$ eV

To rehabilitate LHC…

Total stored beam energy:

10^{14} protons * $14\cdot10^{12}$ eV ≈ $1\cdot10^{8}$ J

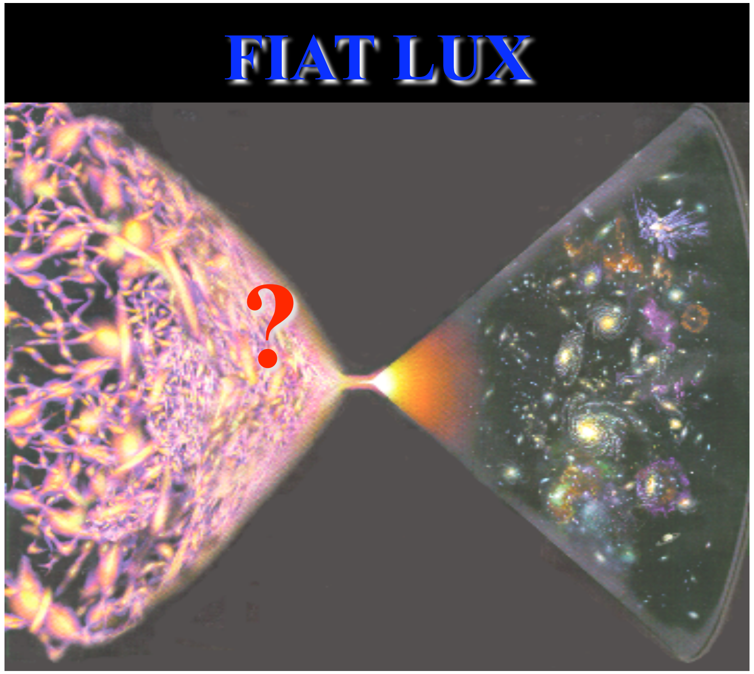
this corresponds to a  m_{truck} = 100 T, v_{truck} = 120 km/h


History of the Universe
~10^17 ºK
~10^-15 sec
LHC
BIG BANG
10^-43 sec
10^-34 sec
10^-10 sec
10^-5 sec
1 min
3x10^5 years
10^9 years
15x10^9 years (today)
10^32 degrees
10^27 degrees
10^15 degrees
10^12 degrees
10^10 degrees
6000 degrees
18 K
3 K
cosmology
sub-nuclear physics
nuclear physics
chemistry
biology
astrophysics
Key:
W, Z bosons
q quark
e electron positron
ν neutrino
photon
meson
baryon
ion
atom
star
galaxy
black hole

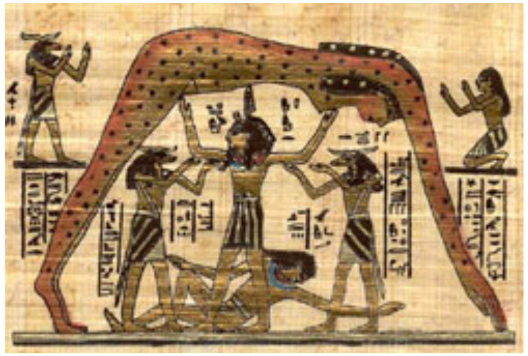
Mitologia Norrea (scandinava): Quando il ghiaccio di Niflheim entra in contatto con il fuoco di Muspell, il gigante Ymir e la mucca cosmica, Auohumla emergono dal ghiaccio. Ymir si nutre del latte della mucca e genera i giganti, la mucca lecca il ghiaccio e genera gli dei…

Zoroastrismo. Ahura Mazda creò 16 terre che fossero sorgente di bene; Angra Mainyu intervenne con una contro-creazione introducendo il male.

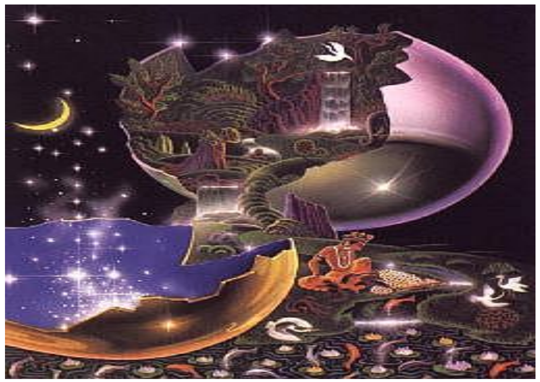
Creazione Giudeo-Cristiana-Islamica. All'inizio Dio creò il cielo e la terra….



Una storia di creazione cinese: Phan Ku nacque da un uovo e crebbe per 18.000 anni. La parte più leggera del guscio formò il cielo e quella più pesante la terra. Quando morì ed i suoi resti divennero il sole e la luna. Gli uomini sono i parassiti del suo corpo.

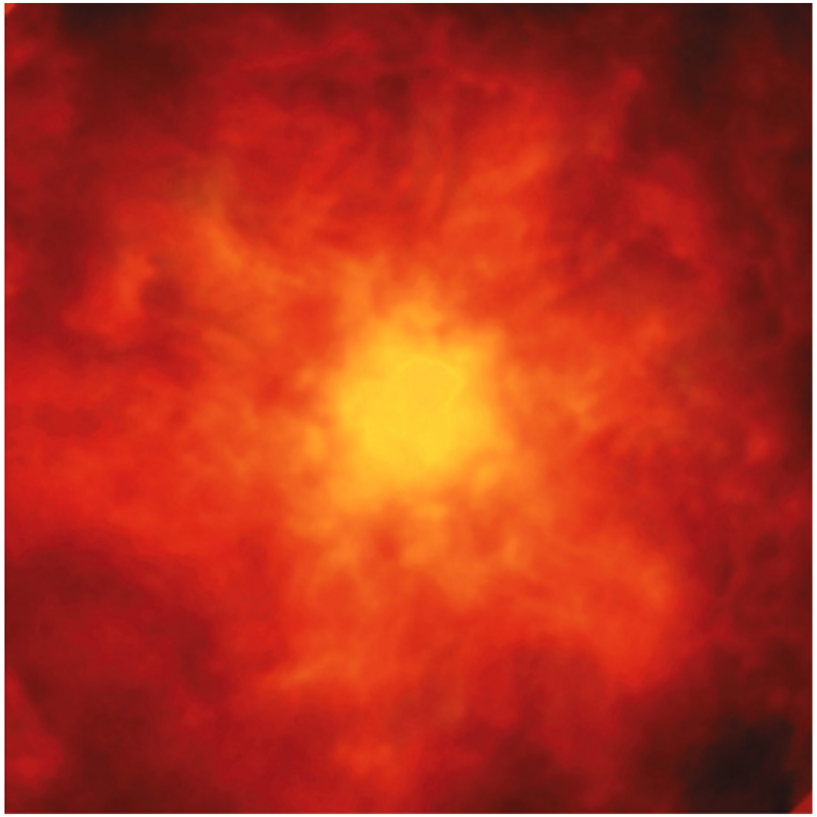


Una storia di creazione egiziana. Da Nun, il caos, emerse Ra. Ra generò un pantheon di dei, cioè la terra, il cielo etc.. Gli umani sono le lacrime di Ra.



Una storia di creazione indù: Brahma nacque da un uovo e i resti dell'uovo divennero l'Universo.

There was a Bang

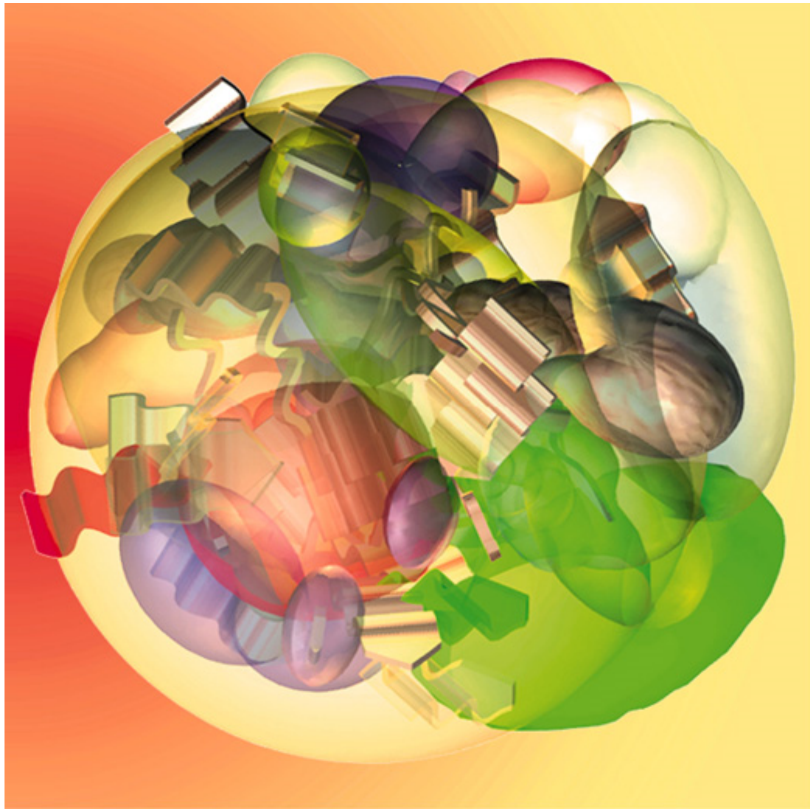


The Era of Quantum Gravity (10^{-43} sec, 10^{32} K)

• All particles, quarks, leptons, force carriers and other undiscovered particles existed in thermal equilibrium.

•Gravity "froze out" in a phase transition to be a force distinct from the strong nuclear, weak nuclear and electromagnetic forces by the end of this era.

In the Beginning... the Grand Unified Force degenerated



The Era of Inflation (10^{-35} sec, 10^{27} K)

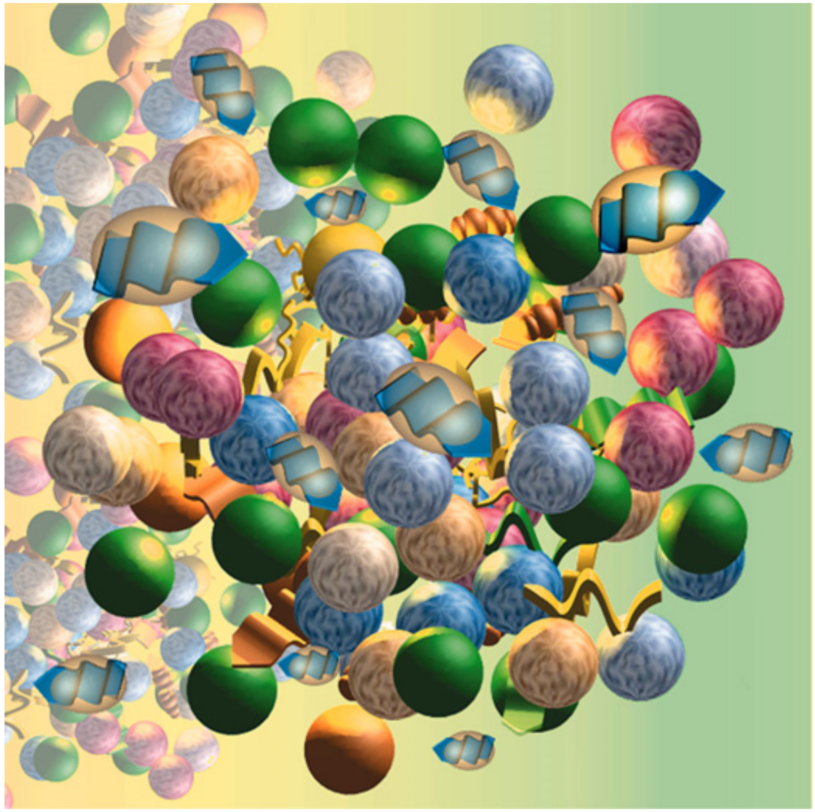
• The universe *inflates* by a factor of 10^{50} in ~ 100 seconds. It reaches a total size of 10^{23} m.

Degeneration of the Grand Unified Force
(10^{-32} sec)

•The strong nuclear force "freezes out" as distinct from the electroweak force.
•A billion to one excess of matter over antimatter develops

(The LHC can reproduce this era!)

In the Beginning... the Electroweak Force degenerated



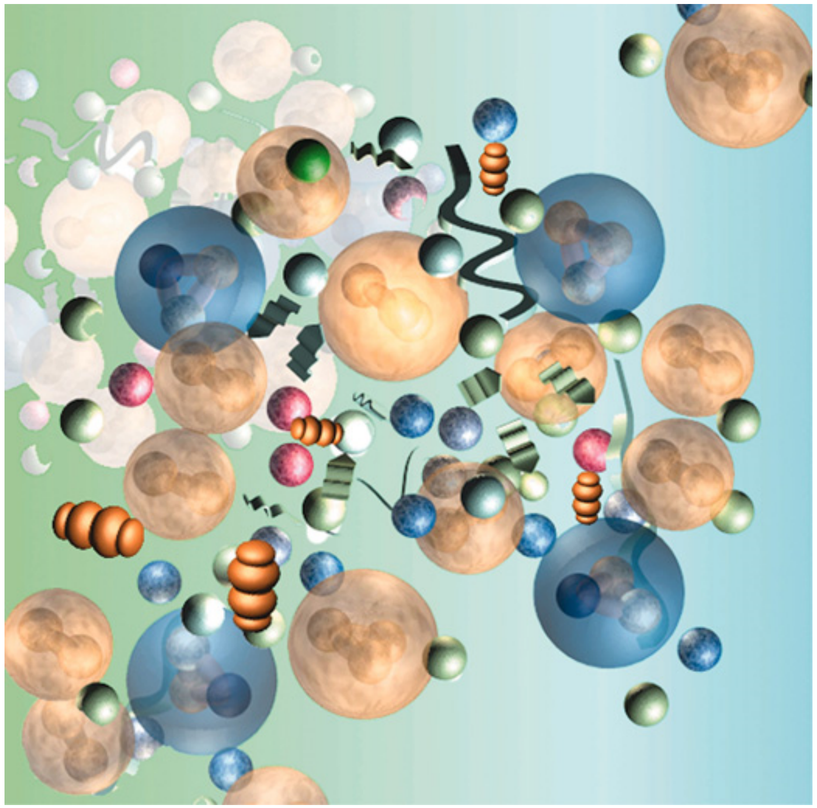
Electroweak Degeneration Era (10^{-10} sec, 10^{15} K)

• The weak nuclear force separates from the electromagnetic force. The W & Z bosons put on weight while the photon remains massless.

•Quarks annihilates with anti-quarks, leaving a tiny excess of quarks.

(These conditions have been reproduced and studied in previous experiments like the LEP)

Protons and Neutrons formed



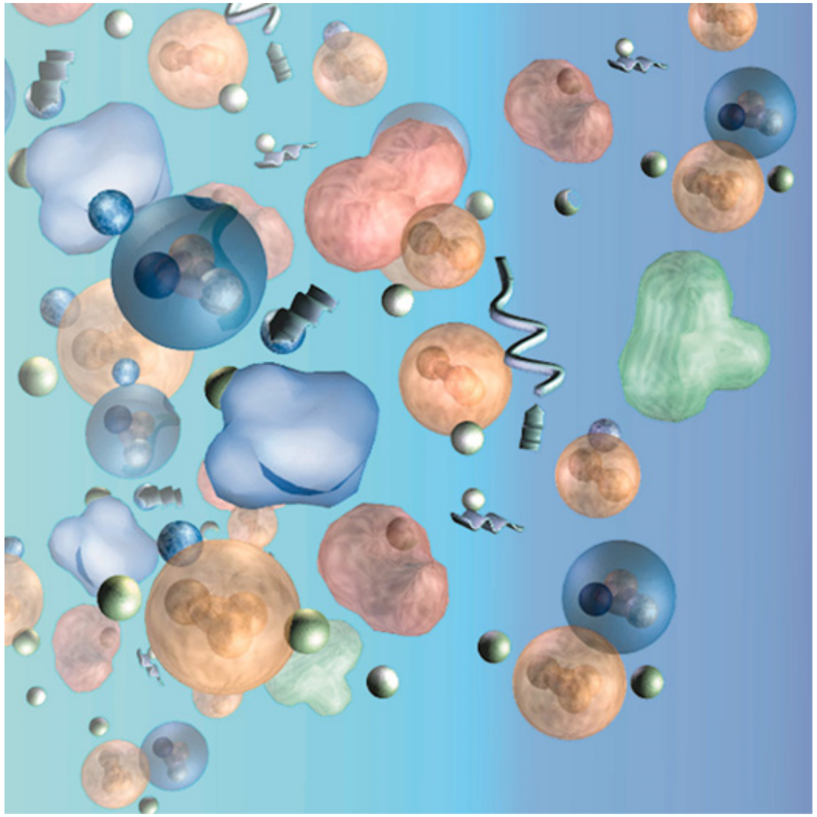
Protons and Neutrons form (10^{-4} sec, 10^{13} K)

• Quarks remaining from the annihilation bind with each other under the influence of the strong nuclear force to form protons and neutrons

Neutrinos decouple (10^{-4} sec, 10^{10} K)

•Neutrinos shy away from further interactions
•Electrons and positrons annihilate till a slight excess is left
•Neutron:Proton ratio shifts from 50:50 to 25:75

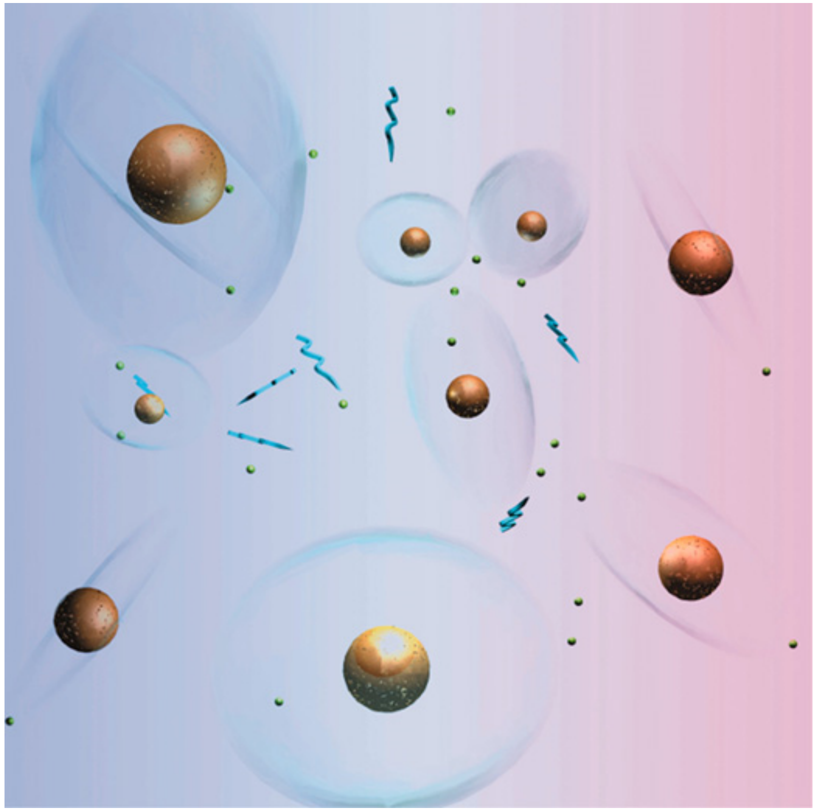
Atomic Nuclei formed



Helium Age (100 sec, 10^9 K)

- Helium nuclei can form now. Conditions similar to stars or hydrogen bombs.
- Atoms cannot form as yet.

Atoms formed and Light could travel freely

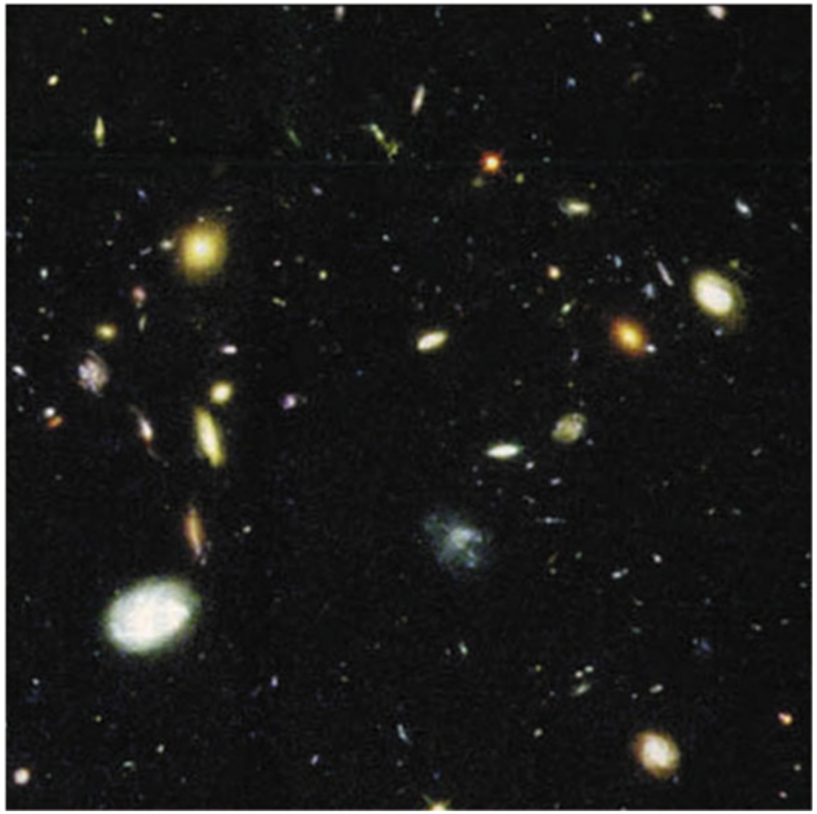


Atoms form (300,000 years, 6000 K)

• Light particles (photons) are not strong enough to break up atoms anymore. So, stable atoms of hydrogen and helium can form.

•The universe becomes transparent to radiation and finally there is light!

Stars and Galaxies formed

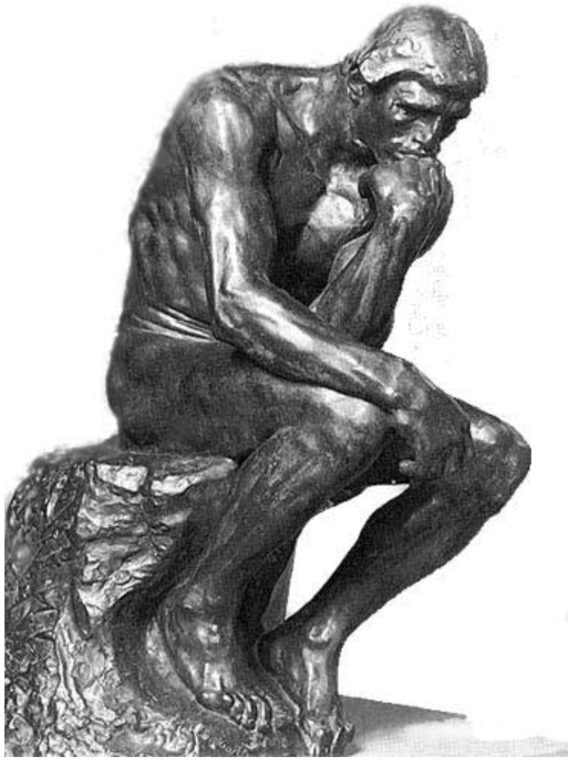


Stars and Galaxies form (1 billion years, 18 K)

• Stars begin to glow, turning lighter elements into heavier ones (of which planets and ourselves are going to be made of)

•Galaxies of stars begin to form

Life has arisen to soak in the Mystery



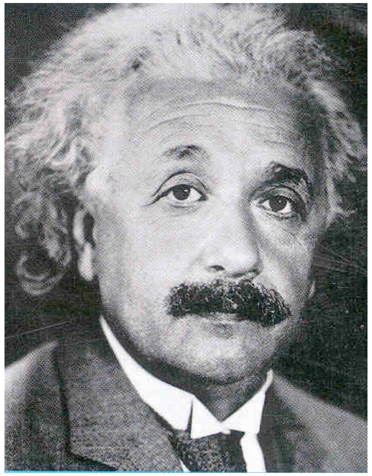
Today (13.7 billion years, 3 K)

• The dust of stars spewed out in supernovae explosions accumulate into planets

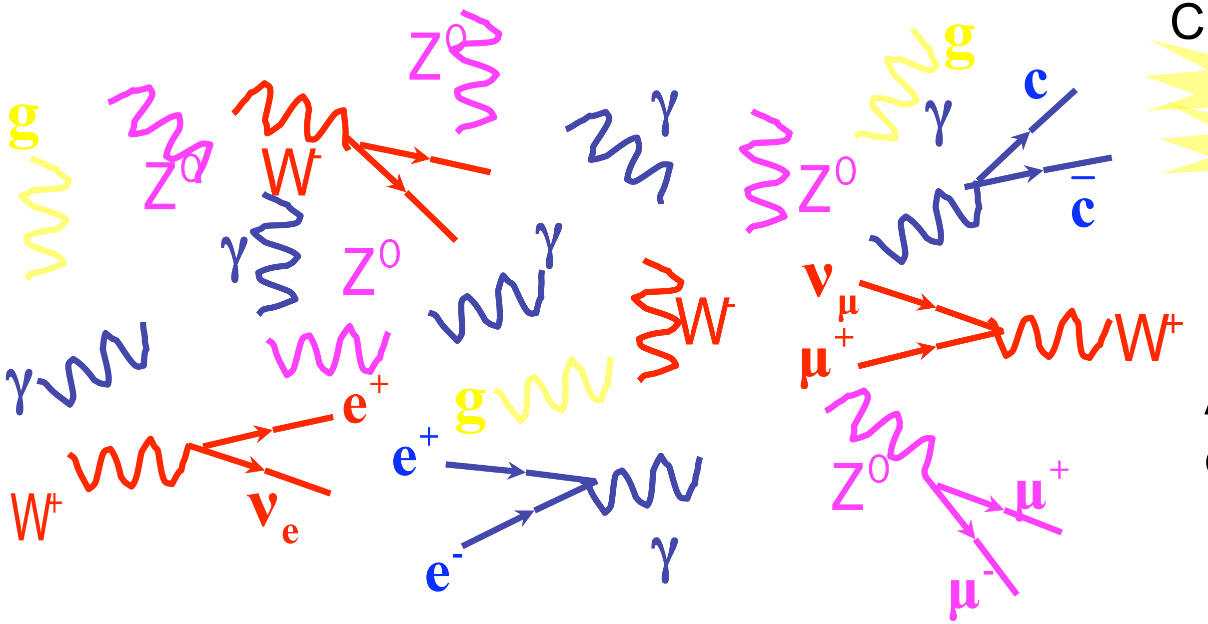
•Carbon atoms concatenate into complex molecules while the relentless energy from stars animate their ever-more-sophisticated dance of self-replication.

•And out of the stardust living creatures emerge to observe the universe and ponder its mystery

L'evoluzione dell'Universo



- 1^0 tappa : l'inflazione
  - **t_0: big-bang : énergia infinita concentrata in un punto.**
    inflazione : l'Universo cresce di un fattore 10^{30} in 10^{-35} s
  - **$t_0 + 10^{-12}$ s: 1000 GeV**



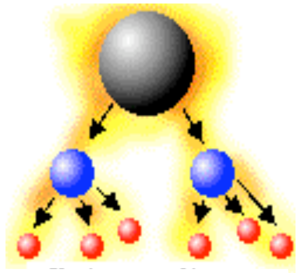
Creazione di coppie
énergia → $e^+ + e^-$
énergia → $q + \bar{q}$

$E = mc^2$, Einstein

Annichilazioni:
$e^+ + e^-$ → energia
$q + \bar{q}$ → energia

Leggera asimmetria materia antimateria : $N_q \approx 1,000000001 N_{\bar{q}}$

L’évolution de l’univers



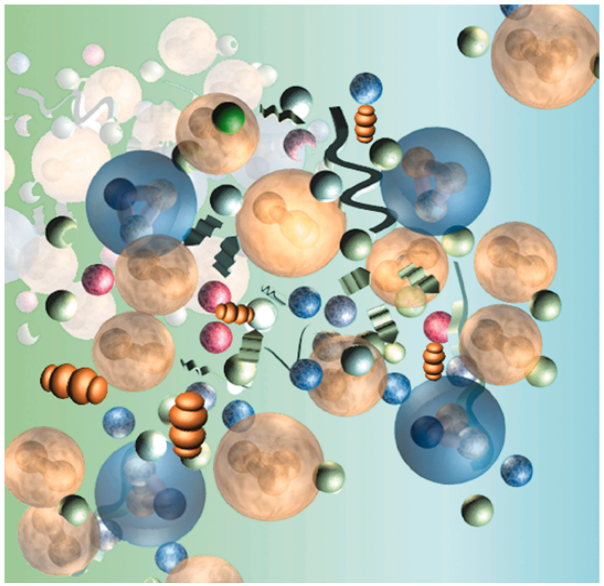
- Etape 2 : baryogénèse
  - **$t_0 + 10^{-10}$ s: 100 GeV**

Il n’y a plus assez d’énergie pour créer une paire quark-antiquark, seuls restent quelques quarks en excès,

les plus légers, up et down, les autres s’étant désintégrés.

  - **$t_0 + 10^{-4}$ s: 1 GeV**

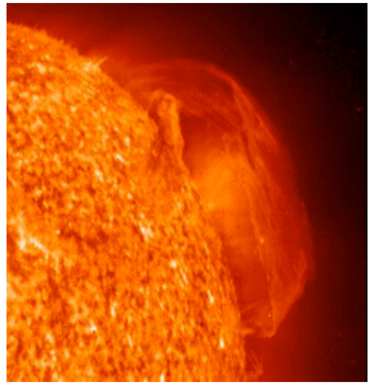
Ils s’assemblent sous l’effet de la force de couleur pour former des protons et des neutrons (ce sont des baryons).



Univers : protons, neutrons, électrons,

neutrinos et radiation.

L'évolution de l'univers



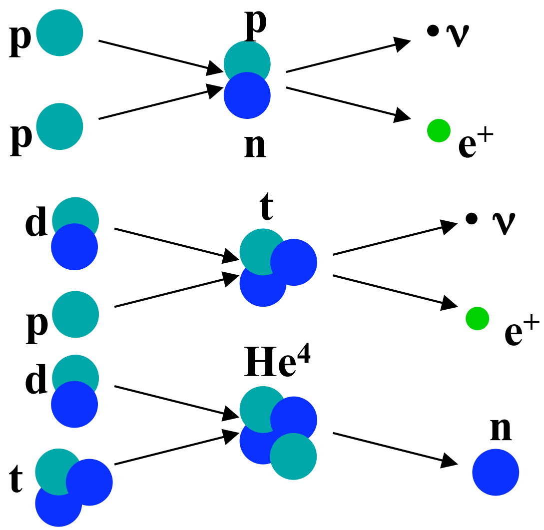
- Etape 3 : nucléosynthèse
  - **t_0 +100s: 100 eV   1 milliard de degrés**

Les premiers noyaux d'He^4 avec des traces de H^2, He^3 et de Li^7 se forment :

$$p + p \rightarrow d + e^+ + \nu$$

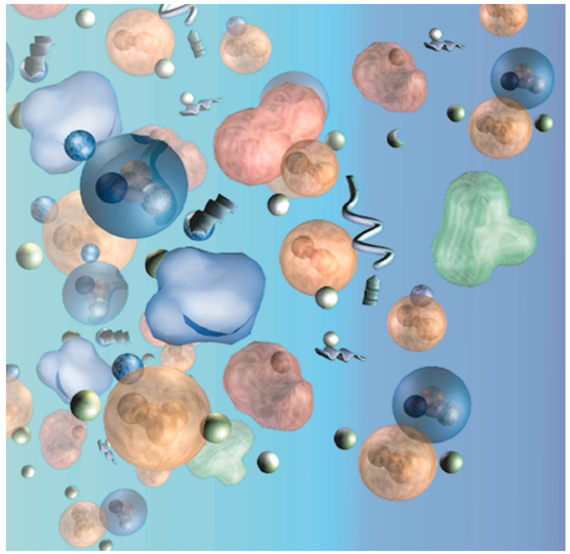
$$p + d \rightarrow t + e^+ + \nu$$

$$d + t \rightarrow He^4 + n$$



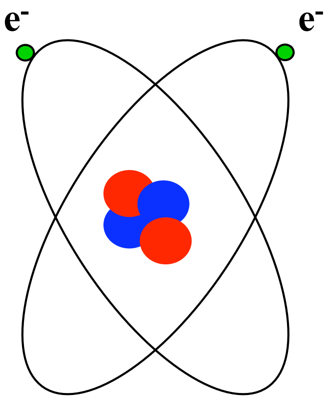
- **t_0 +30 minutes:**

Univers : noyaux légers, électrons, neutrinos et radiation.

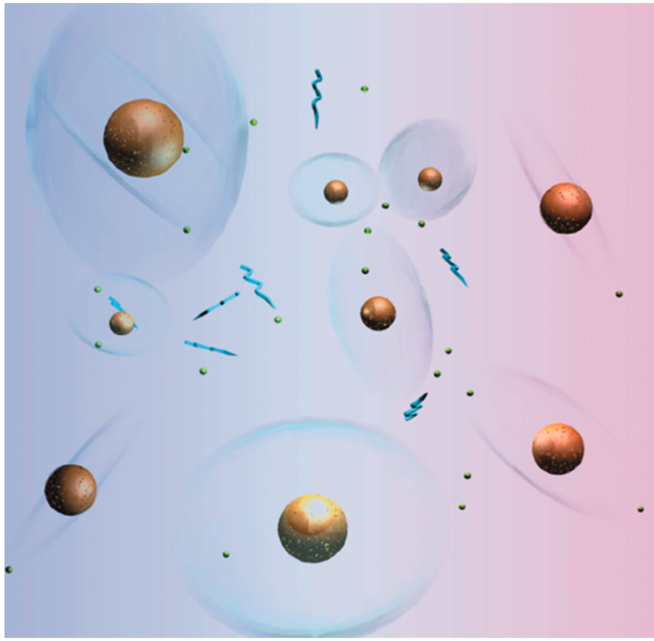


L'évolution de l'univers

- Etape 4 : formation des atomes
  - **t_0 +700.000 ans:** **3000 degrés**



Les atomes les plus simples se forment sous l'effet de la force é.m. : H^1 et He^4 avec des traces de H^2, He^3 et de Li^7

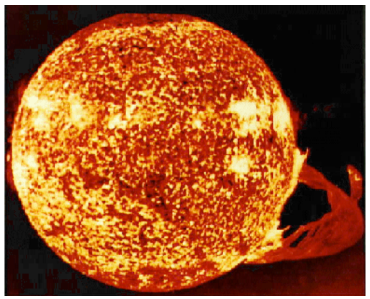


Univers : atomes légers, neutrinos et radiation.

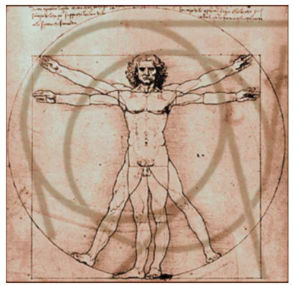
L’évolution de l’univers

- Etape 4 : formation de la matière
  - puis, plus tard: formation des agglomérats de matière sous l’effet de la force gravitationnelle:….étoiles, …. galaxies, ….amas, ...planètes, ….la vie!
  - **t_0 + 13,7 milliards d’années :** aujourd’hui



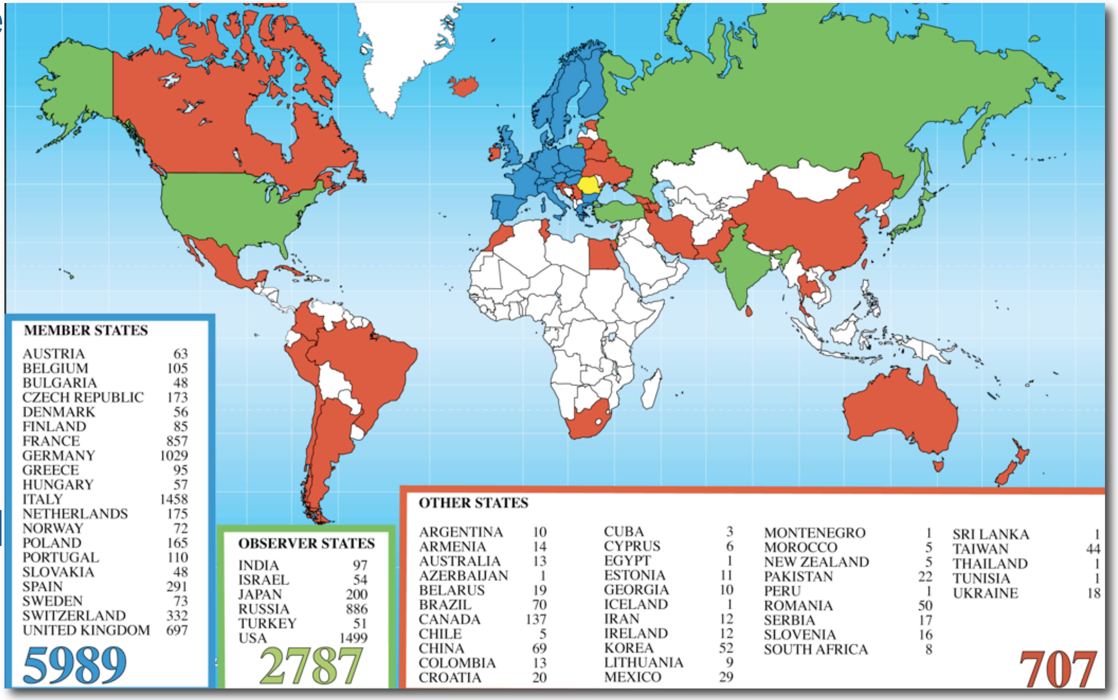






3) an appropriate organization: CERN

- ~ 3,000 personnel (2265 staff) some of the best specialists in all conceivable technologies.
- ~ 10,000 users coming from 63 different countries.
- ~ 1,100 MCHF yearly budget.
- Most of the most brilliant young minds of the planet sharing the same curiosity and the same passion for technical and intellectual challenges.

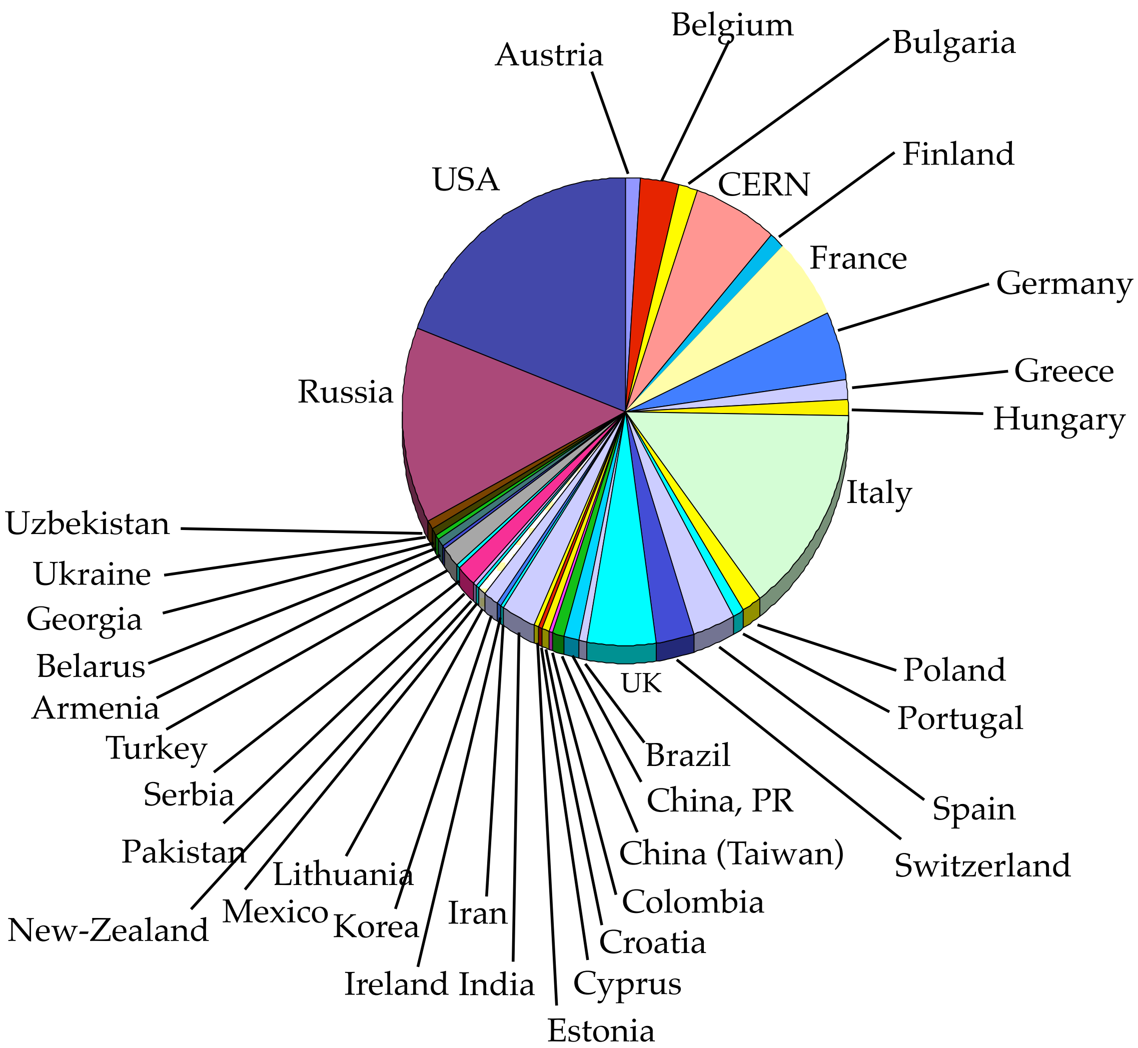


CMS Collaboration (2007)

	Number of Laboratories
Member States	59
Non-Member States	67
USA	49
Total	175

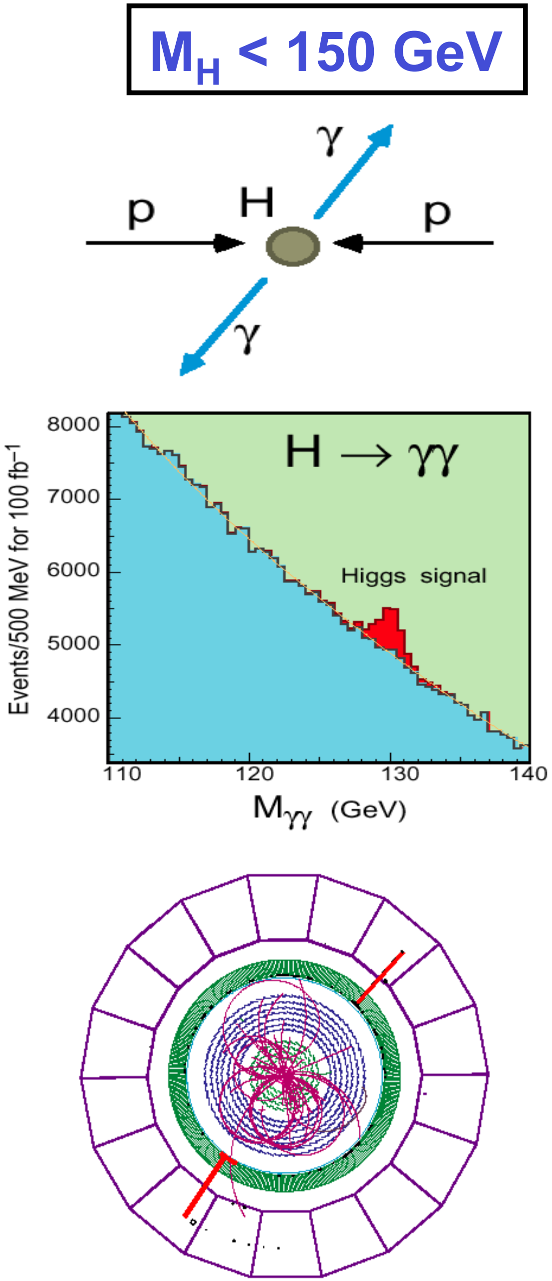
	# Scientific Authors
Member States	1084
Non-Member States	503
USA	723
Total	2310

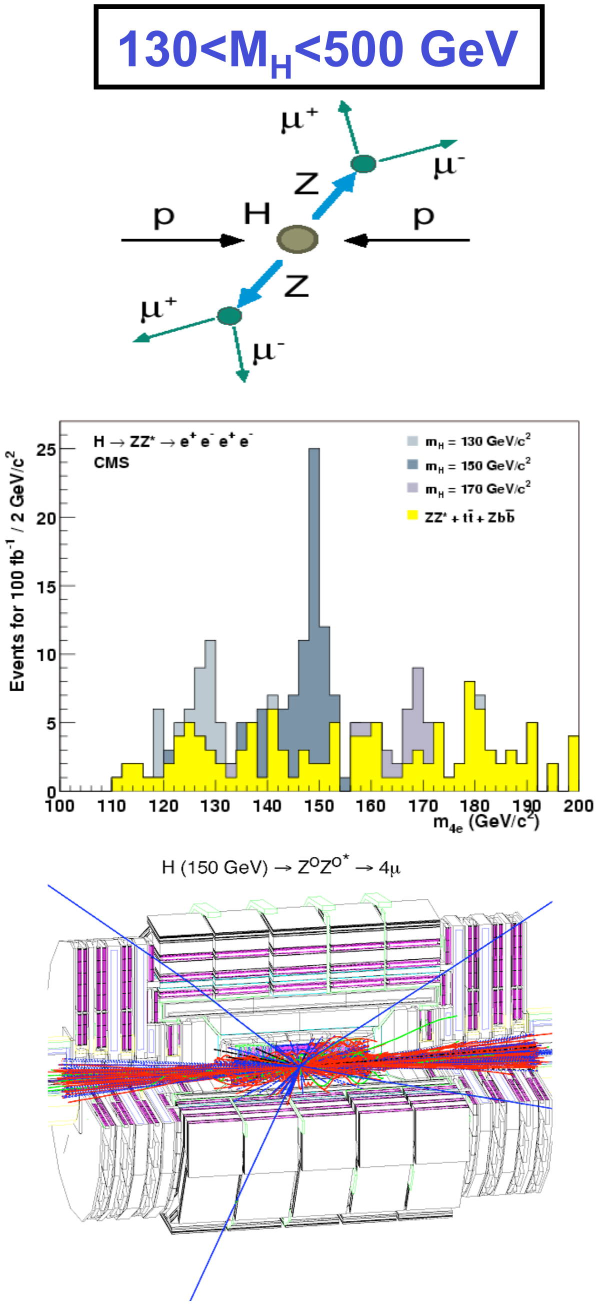
Associated Institutes	
Number of Scientists	62
Number of Laboratories	9

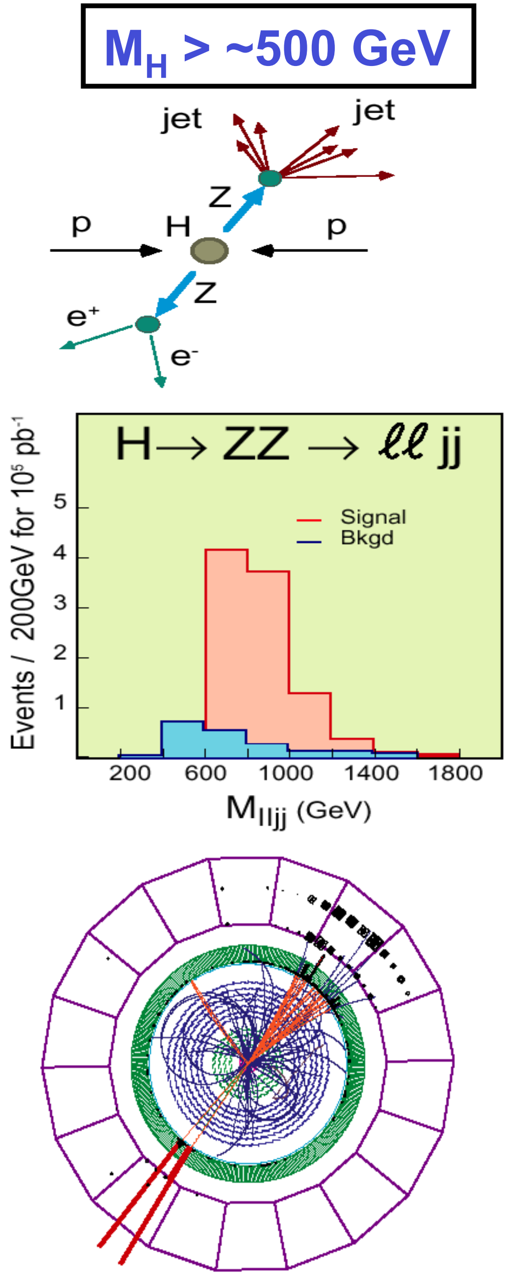


Oct. 3rd 2007/gm

Higgs Events in CMS

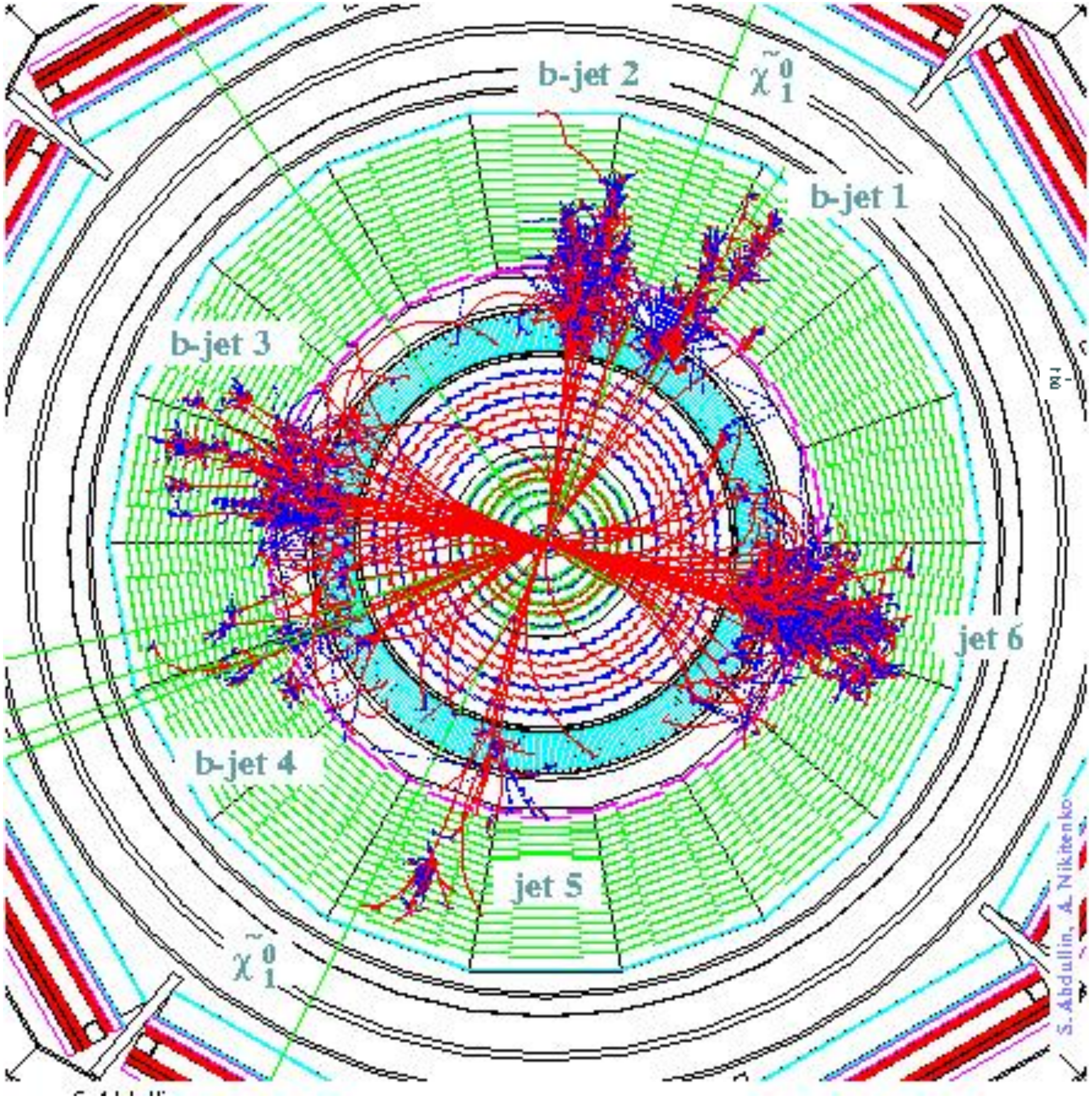






Evento di SUSY in CMS : $pp \rightarrow \tilde{u}_L + \tilde{g}$

mSUGRA: m_0=1000 GeV; $m_{1/2}$ =500 GeV; A_0=0; tanβ =35; μ>0



$\tilde{g} \rightarrow \tilde{t}_1 + \bar{t}$

↳ $W^- + \bar{b}$ (jet 4, E_t=113 GeV)

↳ s (jet 5, E_t=79 GeV) + $\bar{c}$

↳ $\tilde{\chi}_2^+ + b$ (jet 3, E_t=536 GeV)

↳ $\tilde{\chi}_1^+ + Z \rightarrow \nu\,\bar{\nu}$

↳ $\tilde{\chi}_1^0 + W^+ \rightarrow \nu\tau^+$

↳ $e^+ \nu$

$\tilde{u}_L \rightarrow \tilde{\chi}_2^0 + u$ (jet 6, E_t=1200 GeV)

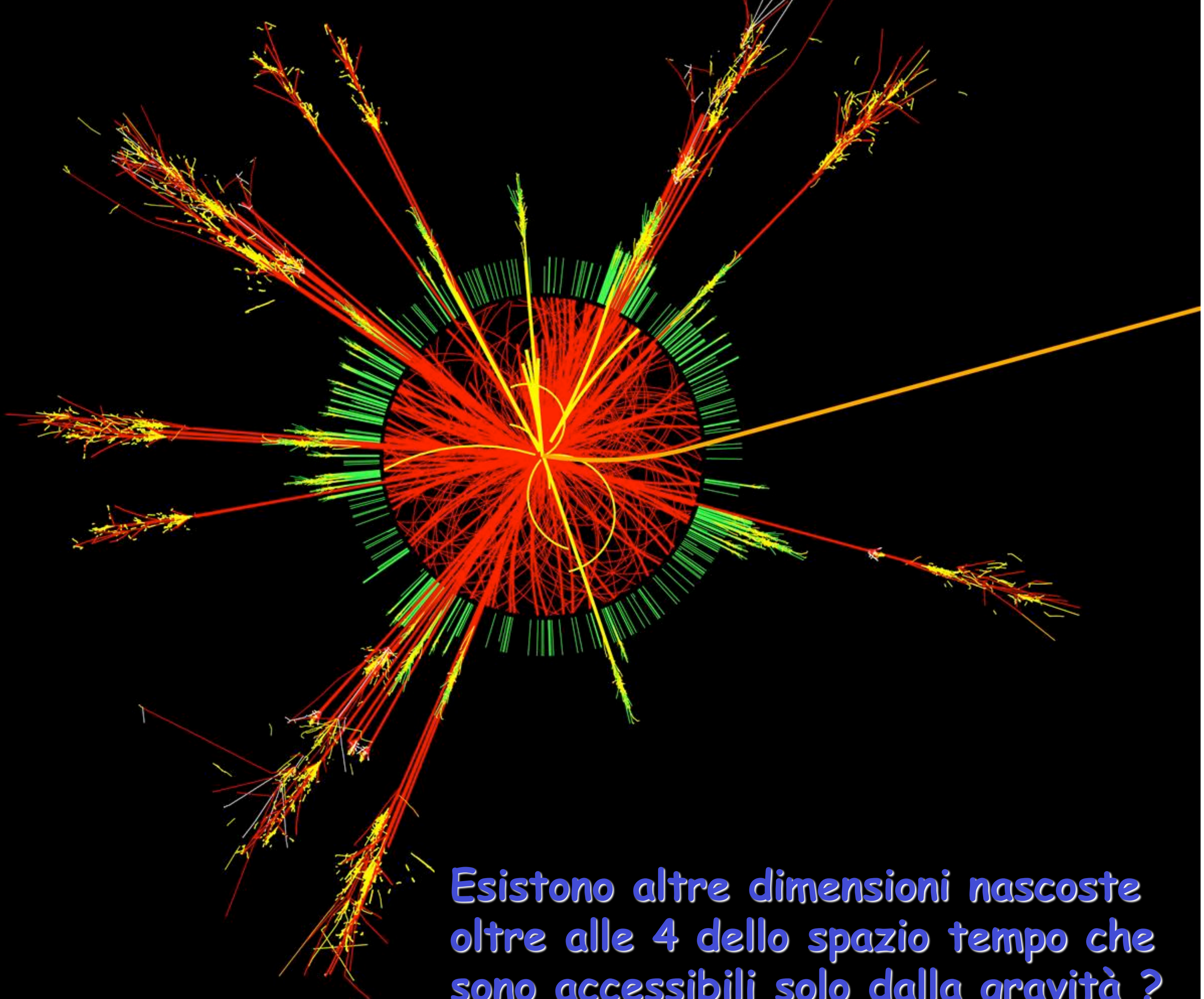
↳ $\tilde{\chi}_1^0 + h \rightarrow b\,\bar{b}$ (jet 1, E_t=206 GeV; jet 2, E_t=320 GeV)

$m(\tilde{g})$=1266 GeV ; $m(\tilde{t}_1)$=1026 GeV

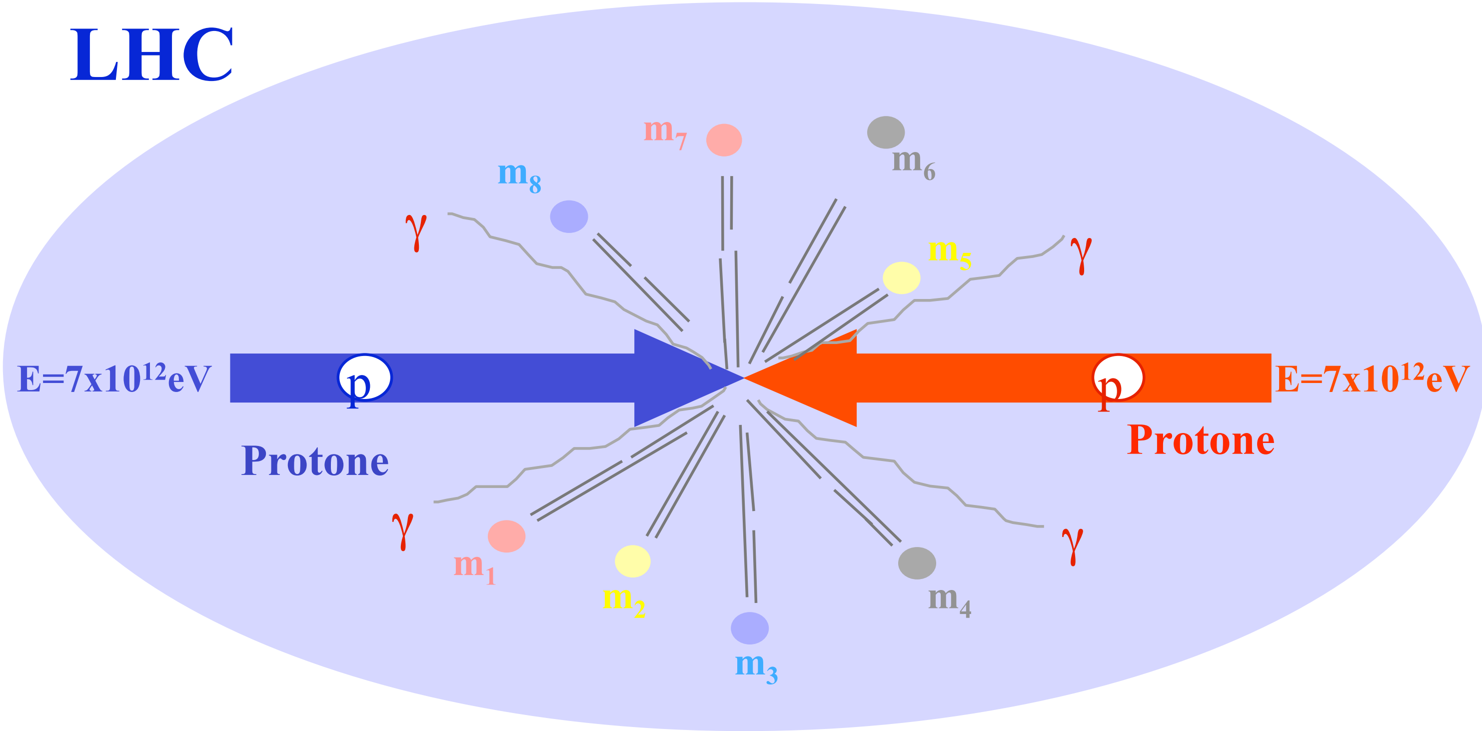
$m(\tilde{u}_L)$=1450 GeV; $m(\tilde{\chi}_2^0)$=410 GeV;

$m(\tilde{\chi}_1^0)$=214 GeV; m(h)=119 GeV

Evento di “Black Hole” a LHC

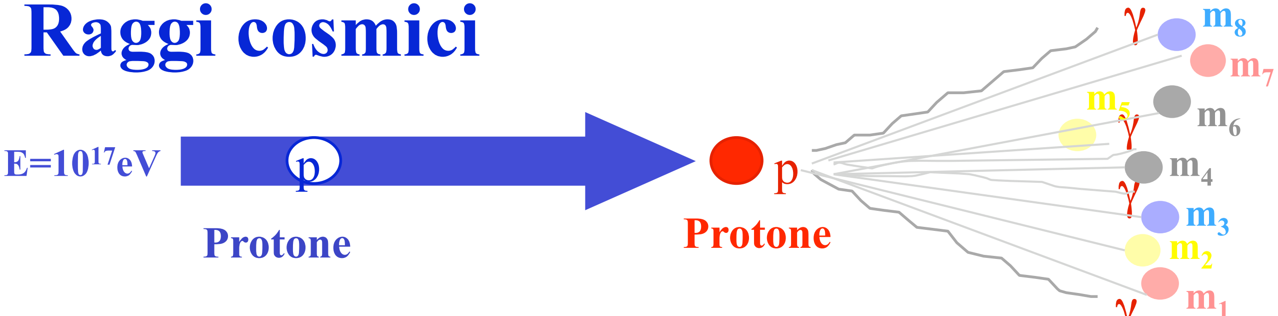


Esistono altre dimensioni nascoste oltre alle 4 dello spazio tempo che sono accessibili solo dalla gravità ?



$$E_{CM} = 14\ \text{TeV}$$

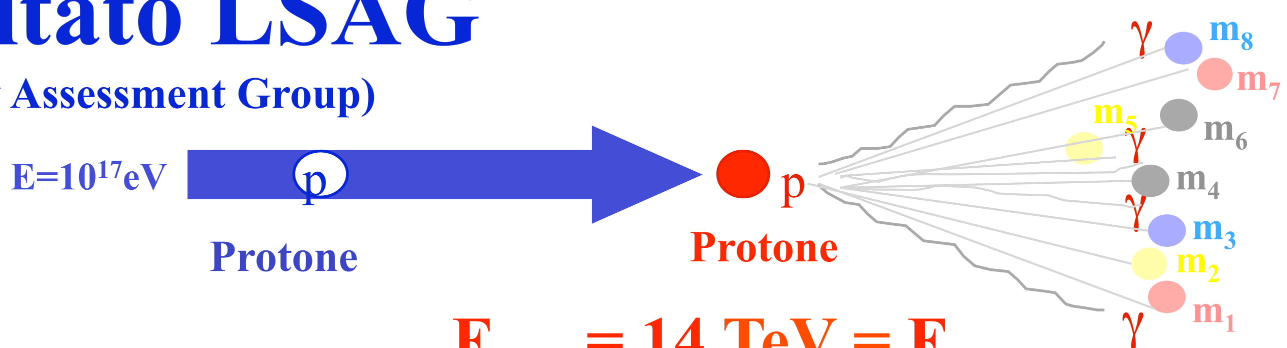
Raggi cosmici



Nelle due collisioni vengono prodotti gli stessi tipi di eventi

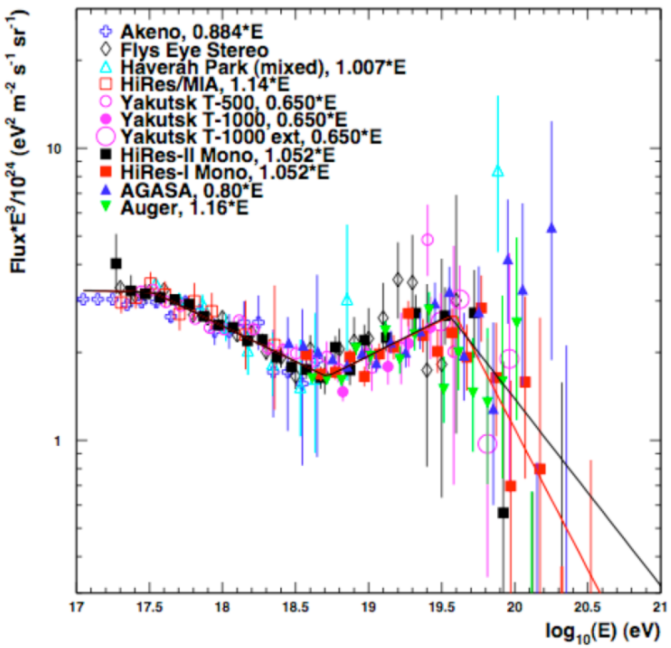
Comitato LSAG

(LHC Safety Assessment Group)



E_{CM} = 14 TeV = E_{LHC}

Flusso misurato sulla Terra di raggi cosmici con E≥10^{17}eV= $5x10^{-14}sec^{-1}cm^{-2}$



1.Superficie della Terra è circa $5x10^{18}cm^2$ 2.La Terra esiste da 4.5 miliardi di anni quindi più di $3x10^{22}$ raggi cosmici con E≥10^{17}eV hanno colpito la Terra e quindi sono già stati fatti più di centomila esperimenti come LHC

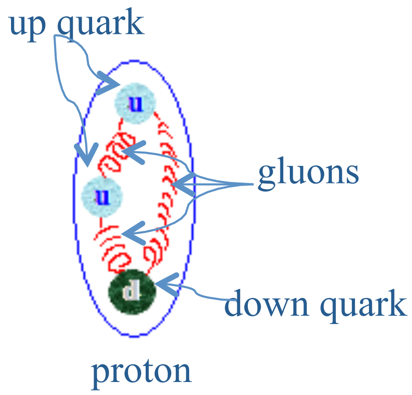
Superficie del Sole=diecimila volte la superficie della Terra, quindi sul Sole sono già stati fatti circa un milione di esperimenti come LHC

La nostra galassia ha più di 10^{11} stelle
Nell'Universo ci sono più di 10^{11} galassie, quindi sulle stelle eistenti sono già stati fatti circa 10^{31} esperimenti come LHC e ne vengono completati ben $3x10^{13}$ ogni secondo!!

e la Terra, il Sole e le Stelle continuano ad esitere da miliardi di anni !

LHC non produrrà eventi pericolosi né per l'umanita né per la terra...

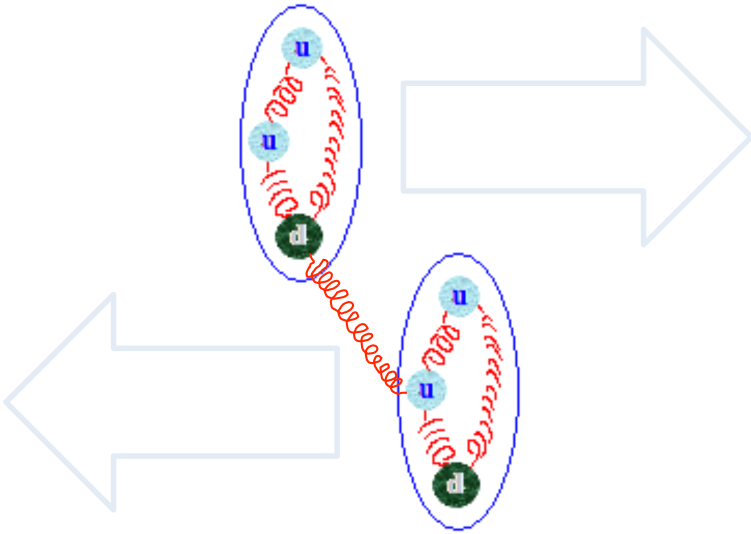
Collision Point



Travelling at 99.999999% the speed of light,
carrying 7000 GeV of energy each.

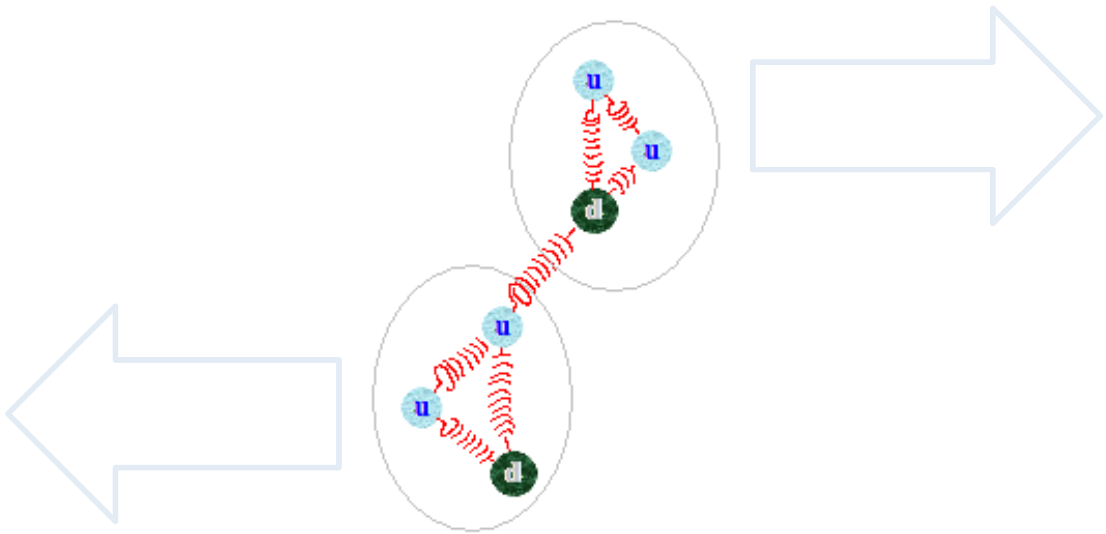
The energy allows them to overcome their mutual electromagnetic repulsion and **allows their quarks and gluons to interact** via the strong nuclear force.

The Crash – Approach



Quarks of different protons begin to feel each other through gluons because they are so close!

The Crash – Interaction



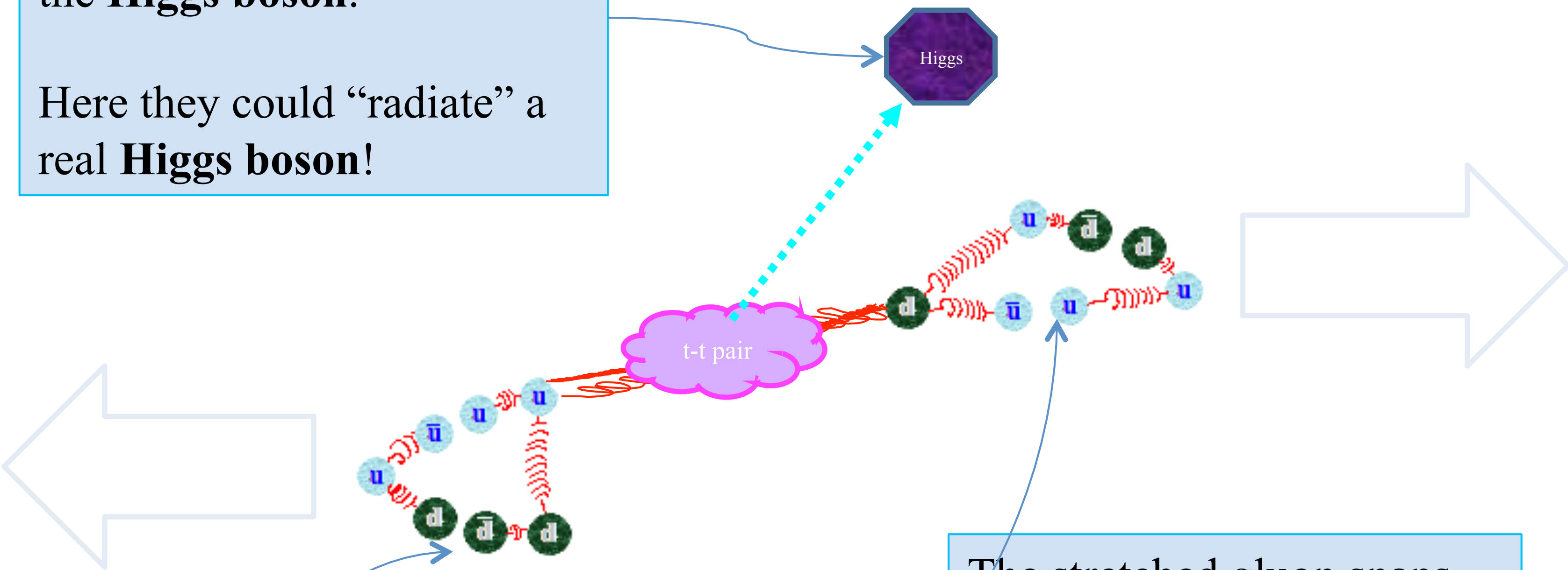
The newly formed gluon is under high tension now!

And so may be the other gluons since the whole protons received a tremendous shock.

The Crash – Production of New Particles!

Top quarks are quite heavy and hence couple strongly to the **Higgs boson**.

Here they could “radiate” a real **Higgs boson**!

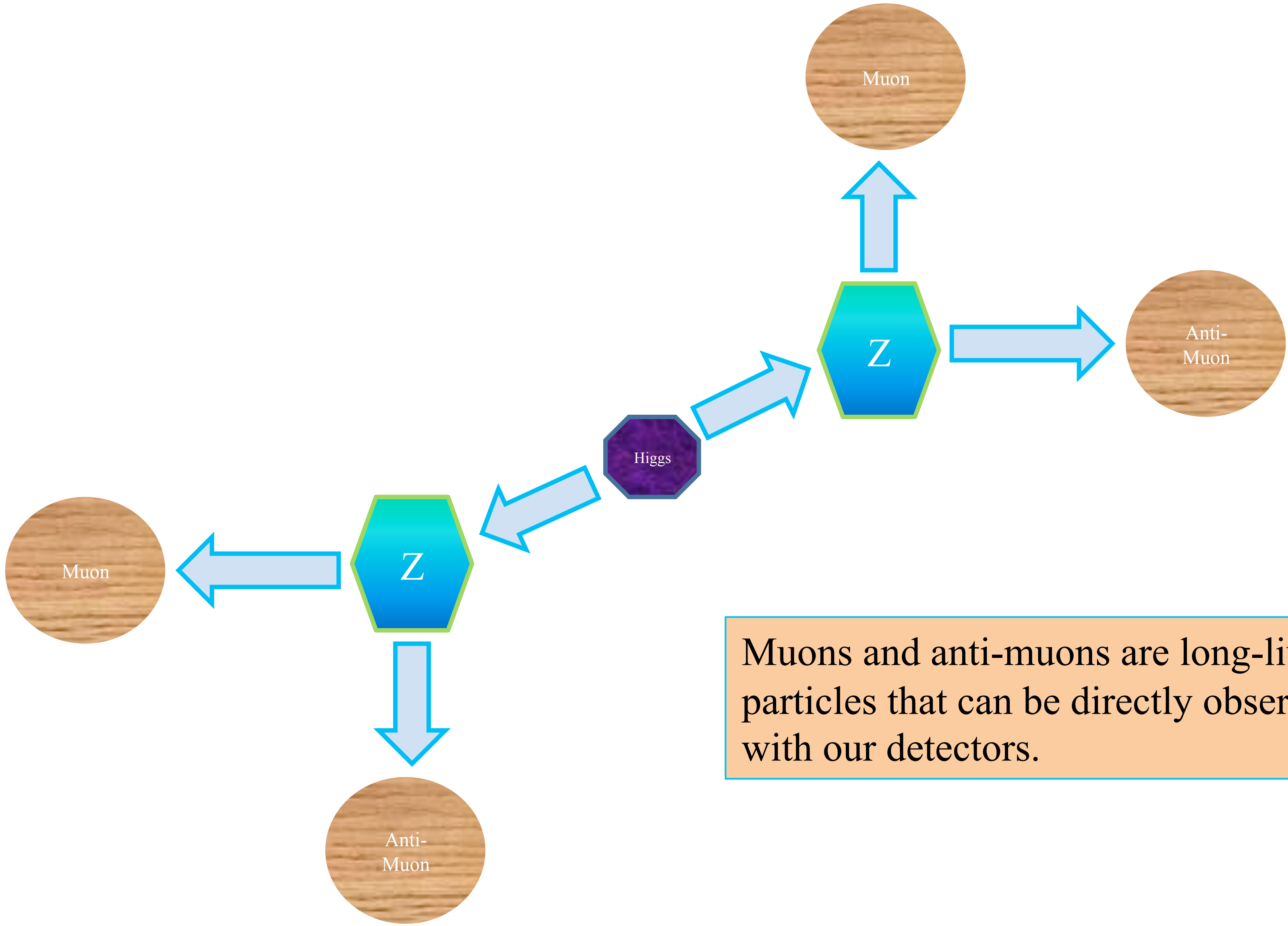


The stretched gluon snaps into a **top & antitop** quark pair of virtual particles!

Gluons snap forming **quark – antiquark pairs**!

Protons fragment into sprays of newly formed hadronic debris. Don’t interest us usually.

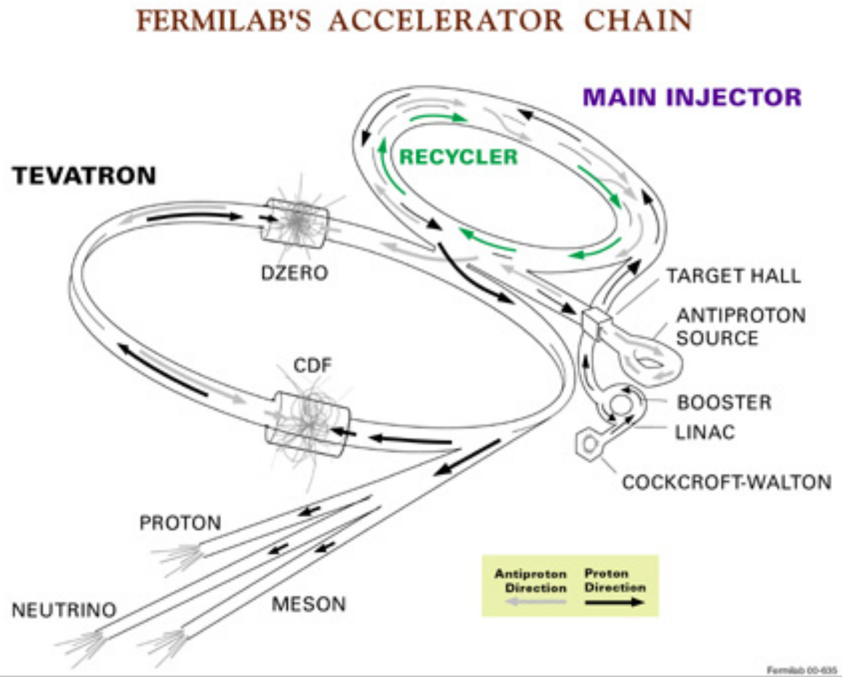
The Higgs Boson Decays into Muons



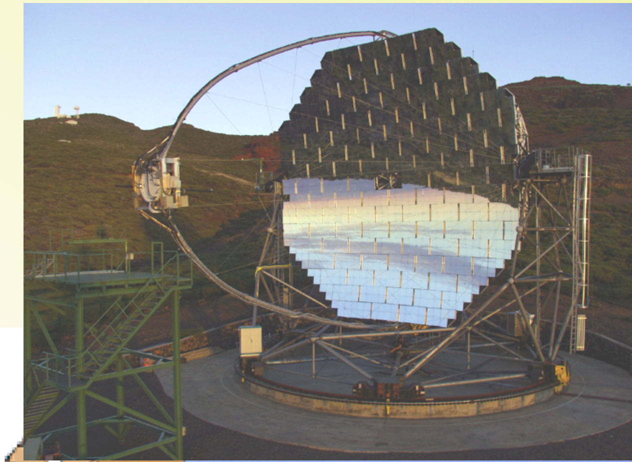
Muons and anti-muons are long-lived particles that can be directly observed with our detectors.

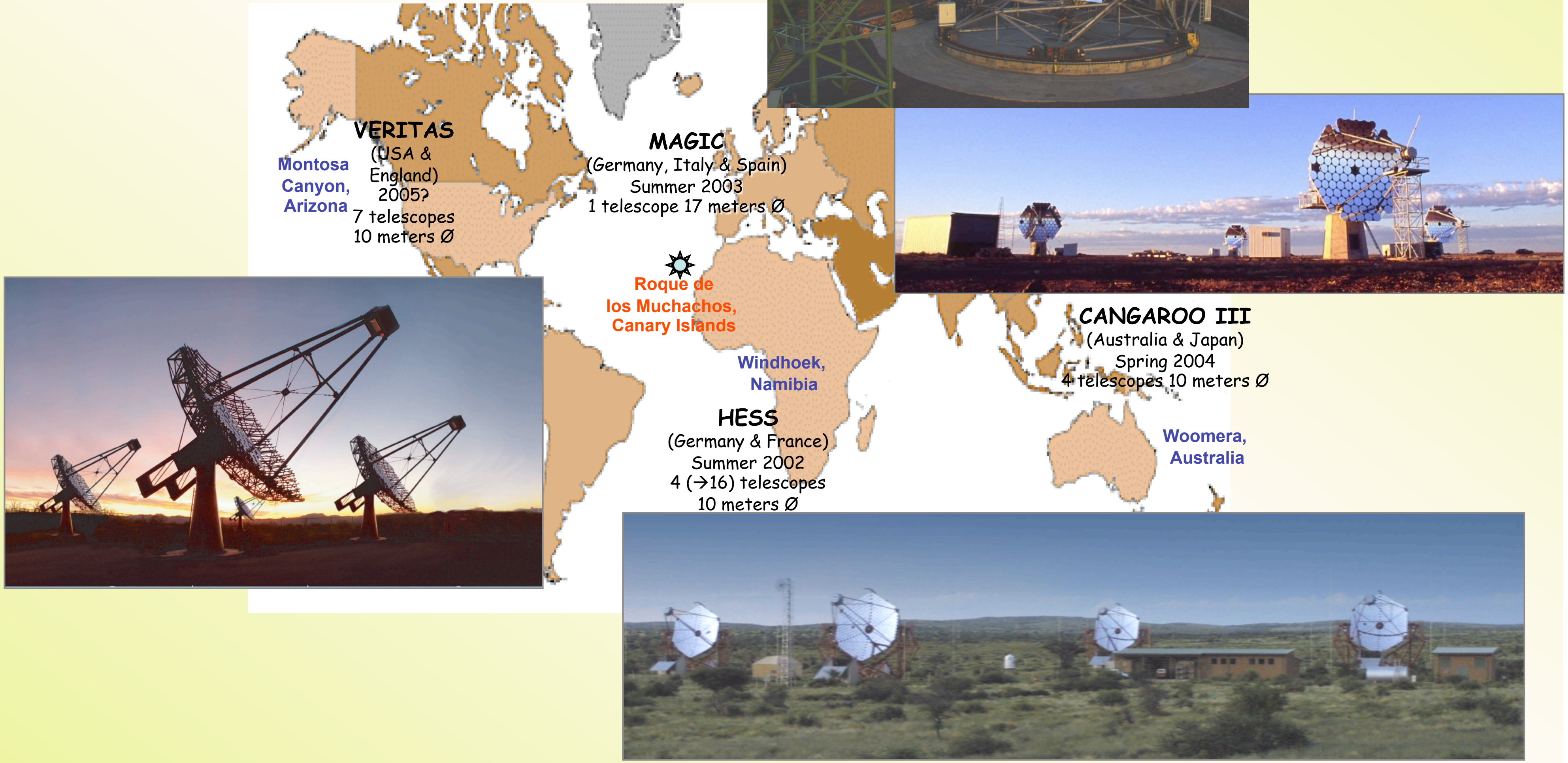
Fermilab

protone-antiprotone a 2 TeV

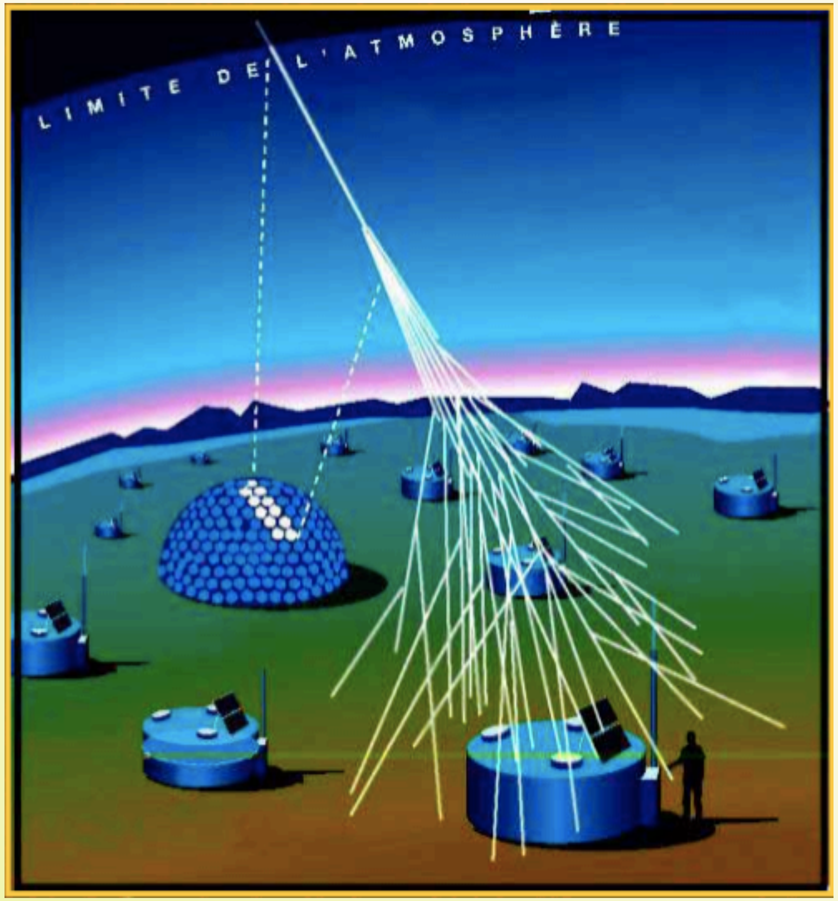


the four big telescopes for γ rays





AUGER



- Operativo dal 2004
- ~3000 km^2, Argentina
- 4 Rivelatori di fluorescenza e 1500 rivelatori Cherenkov in acqua
- Energia: 10^{18}-10^{20} eV