The Standard Model of Particle Physics and Beyond

or

The Universe of Elementary Particles

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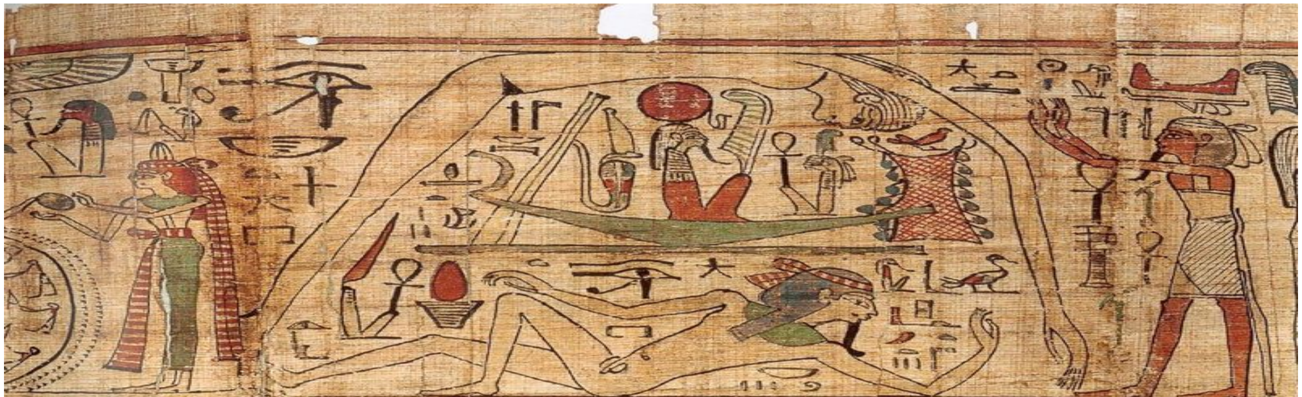
I.1 Particle physics as an explanation of the world

Always, mankind has tried to understand the world that surrounds him:

How did it form? How is it organized? What will it become?

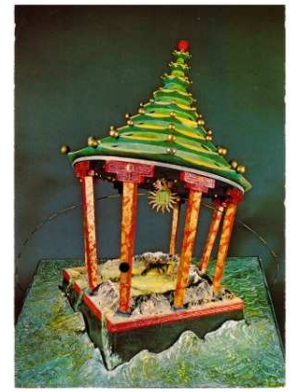
Mesopotamia

Egypt



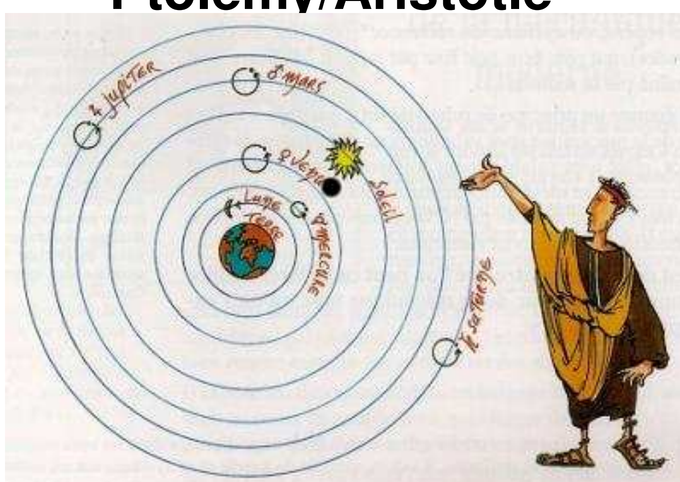
Heaven, Earth, Hell?

China

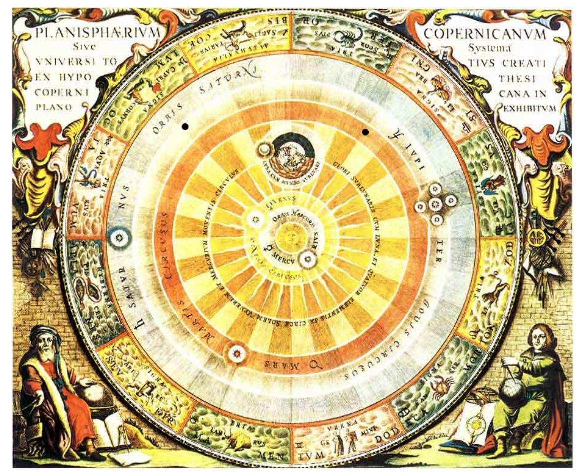


Homer

Ptolemy/Aristotle

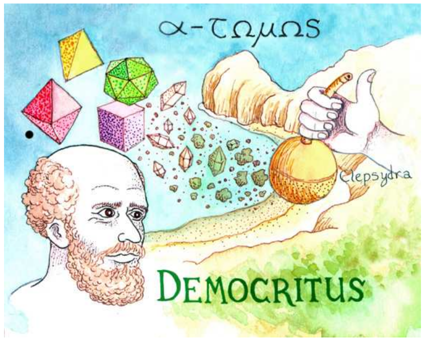


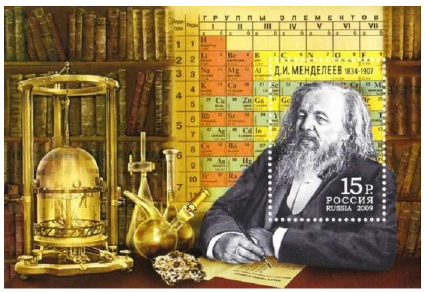
Aristarque of Samos

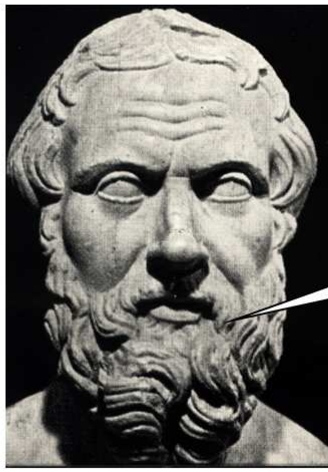


I.1 Particle physics as an explanation of the world

The antique Greeks started to give some naive but plausible answers:



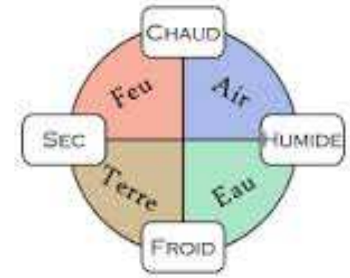




DEMOCRITE

IVème siècle AVJC

La matière est constituée de corpuscules invisibles à cause de leur extrême petitesse, indivisibles et éternels.



ARISTOTE

IVème siècle AVJC

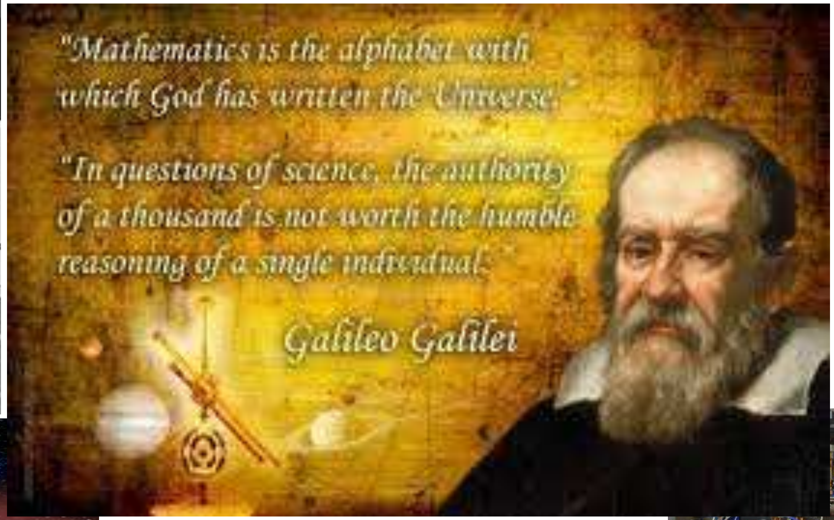
Mais non ! On sait tous que la matière est constituée des quatre éléments: l'eau, la terre, le feu et l'air…

I.1 Particle physics as an explanation of the world

But at least since Galileo, we know the language to answer these questions
Galileo (among others) also gave us the two instruments which help to do it.

The Telescope

Mathematics



The Pisa experiment

The Planck satellite

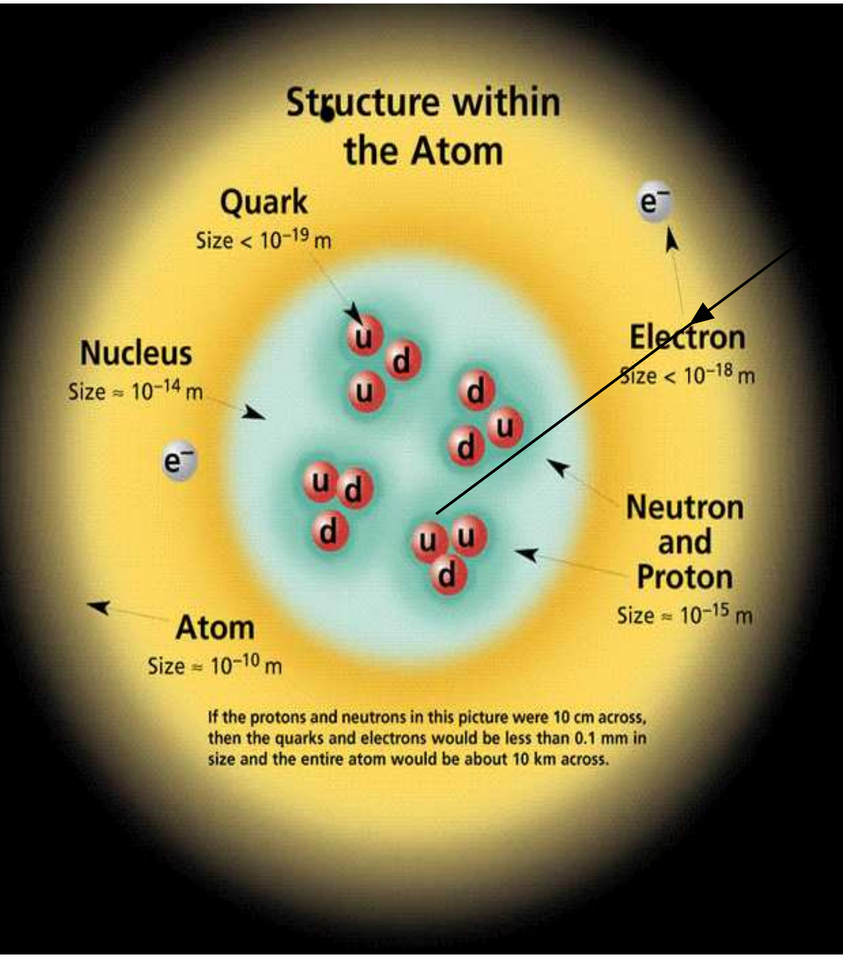
+
Experiment
=
“Physics”

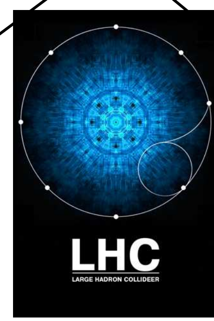
Le LHC accelerator

I.1 Particle physics as an explanation of the world

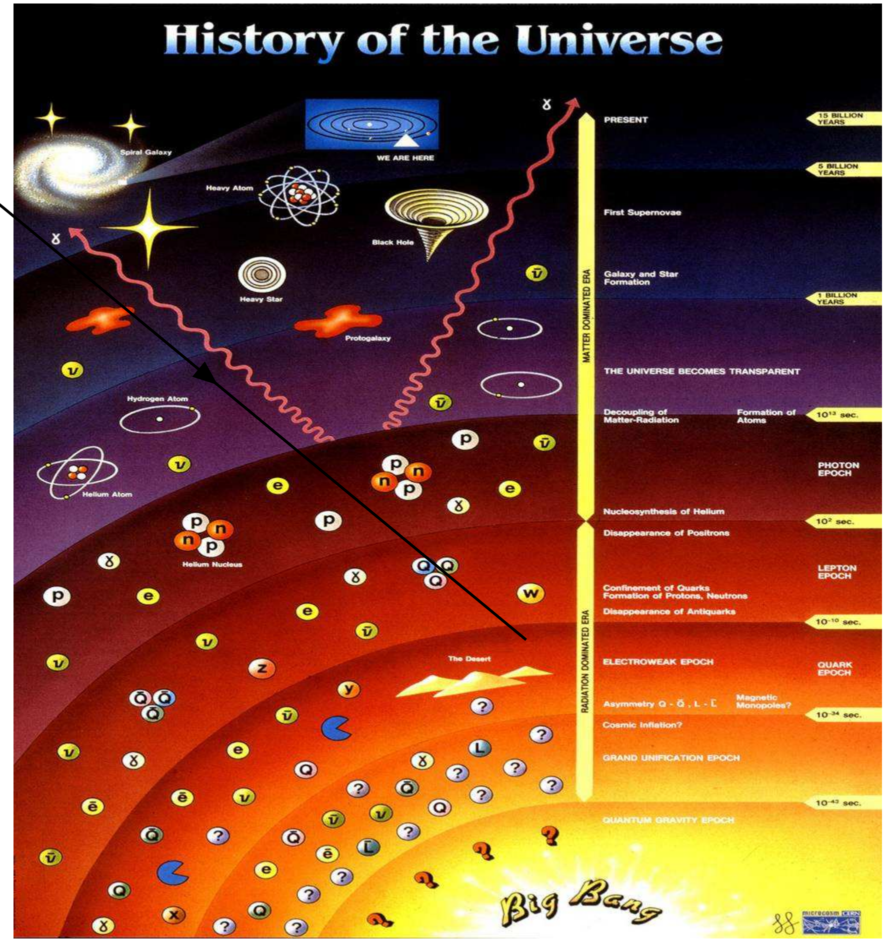
The experiment in Laboratory, from Galileo to LHC led to:

The observation of the sky from then to the Planck satellite led :





1 TeV $\approx 10^{-12}$**s** $\approx 10^{16}$**K**

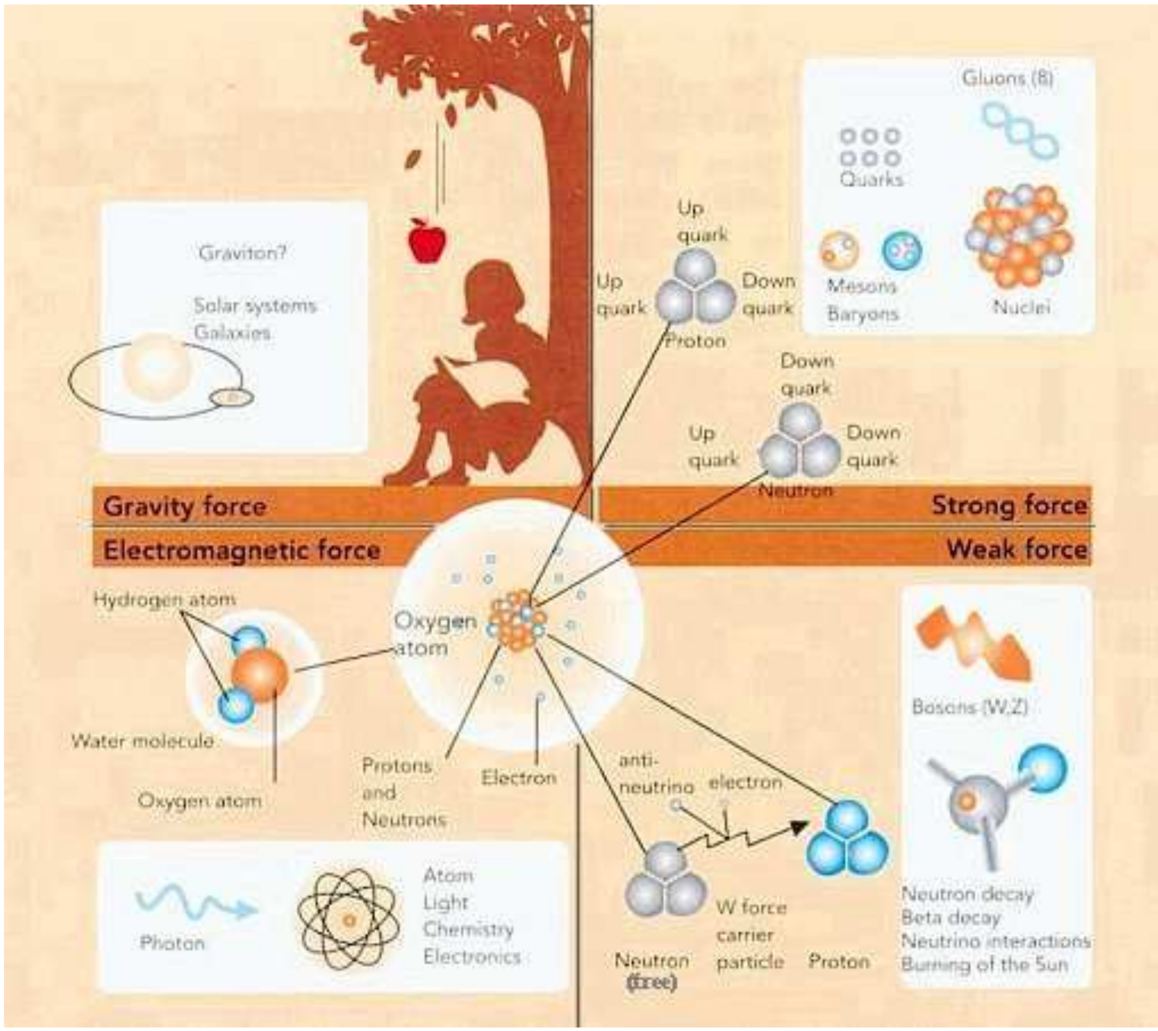


.. and the two – the infinitely and infinitely big – meet...

I.2 The elementary particles and their interactions

We have observed only four fundamental interactions in Nature:

the gravitational, electromagnetic, nuclear strong and nuclear weak forces.

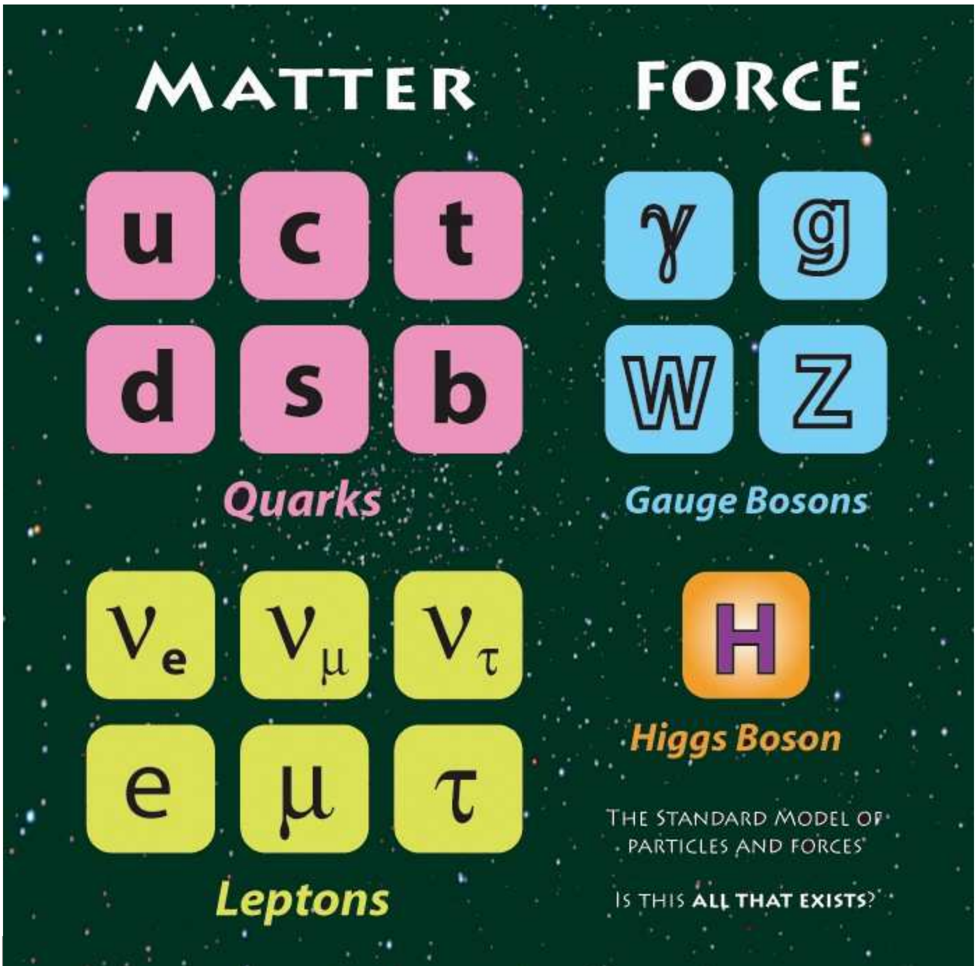


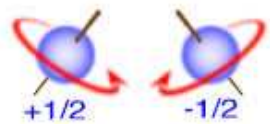
I.2 The elementary particles and their interactions

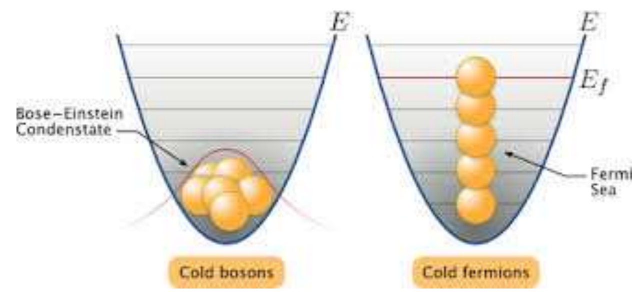
We have a theory, the Standard Model (SM), that describes this microcosm:

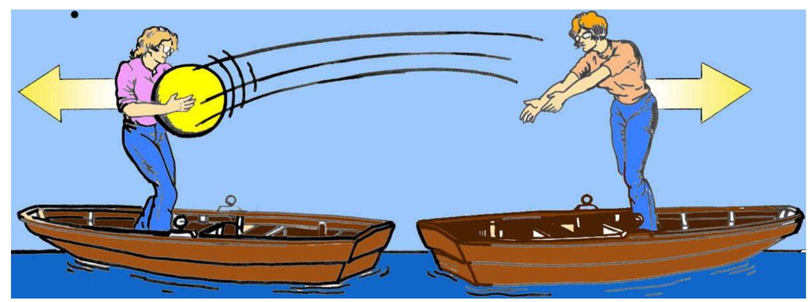
three of fundamental interactions in Nature (excluding the gravitational one):

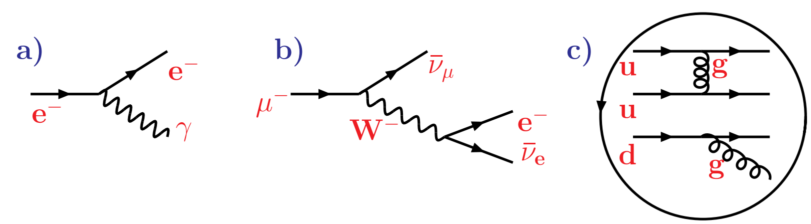
interactions of matter particles (s=$\frac{1}{2}$) via exchange of force particles (s=1).







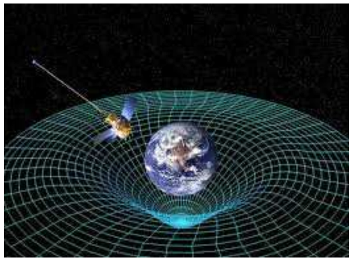


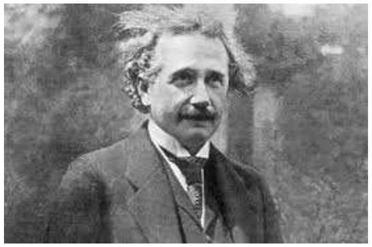


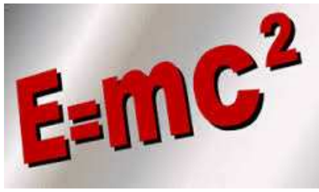
I.2 The elementary particles and their interactions

The SM uses the language of Mathematics and three pillars of Physics:

A. The theory obeys the laws of Einstein's special relativity (1905).







- The physical laws are the same in any inertial frame of reference (not subject to an acceleration): there is no absolute/privileged frame.
- The speed of light in vacuum, denoted c, is a universal constant: c = 300.000 km/s (or 1 billion km/h) and cannot be exceeded.

It has major implications for physics; here are some of them:

- the end of absolute time and absolute space: space-time vector x=($\vec{x}$,t),
- at very high speed, close to c, time dilatation and length contraction,
- only particles without a mass, like the photon, can travel at v=c,
- equivalence between the mass and the energy; at rest, one has E=mc^2.

$\Rightarrow$ At high energies (LHC), elementary particles travel at a speed at v$\approx$c.

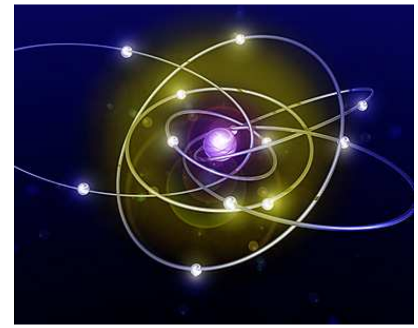
I.2 The elementary particles and their interactions

B. The theory obeys the laws of Quantum Mechanics (years 1920–1930).

- **The wave particle duality: fields**

– **electron:** $\mathrm{e} \Rightarrow \mathbf{\Psi}(\vec{x},t) \equiv \mathbf{\Psi}(\mathbf{x})$

– **photon :** $\gamma \Rightarrow \mathbf{A}(\vec{x},t) \equiv \mathbf{A}(\mathbf{x})$



Particles non-localized: probabilistic view.
Schrödinger's cat: dead and alive?

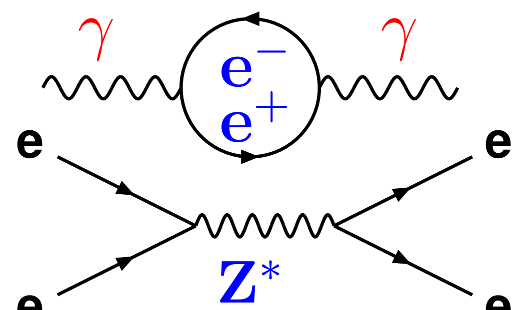
- **Heisenberg uncertainty principle :**

$$\left.\begin{array}{l} \Delta\vec{x}\Delta\vec{p} \geq \frac{1}{2}\hbar \\ \mathbf{\Delta t \Delta E} \geq \frac{1}{2}\hbar \end{array}\right. \Rightarrow \mathbf{\Delta x \cdot \Delta p} \geq \frac{1}{2}\hbar.$$

Large uncertainty possible on x, p.

- **Quantum fluctuations:**

during an infinitesimal time ($\mathbf{\Delta t} \ll \frac{1}{2}\hbar$**)**
possible violation of conservation laws
for energy ($\mathbf{\Delta E} \gg \frac{1}{2}\hbar$**) and momentum.**



Quantum corrections: emission and absorption of very heavy particles.
whatever happens in intermediate state is called virtual effect or state.

C. The theory makes extensive use of the symmetries of Nature (aesthetical..)

There are at least three types of symmetries that play an important role in SM:

- **Space-time symmetries:**

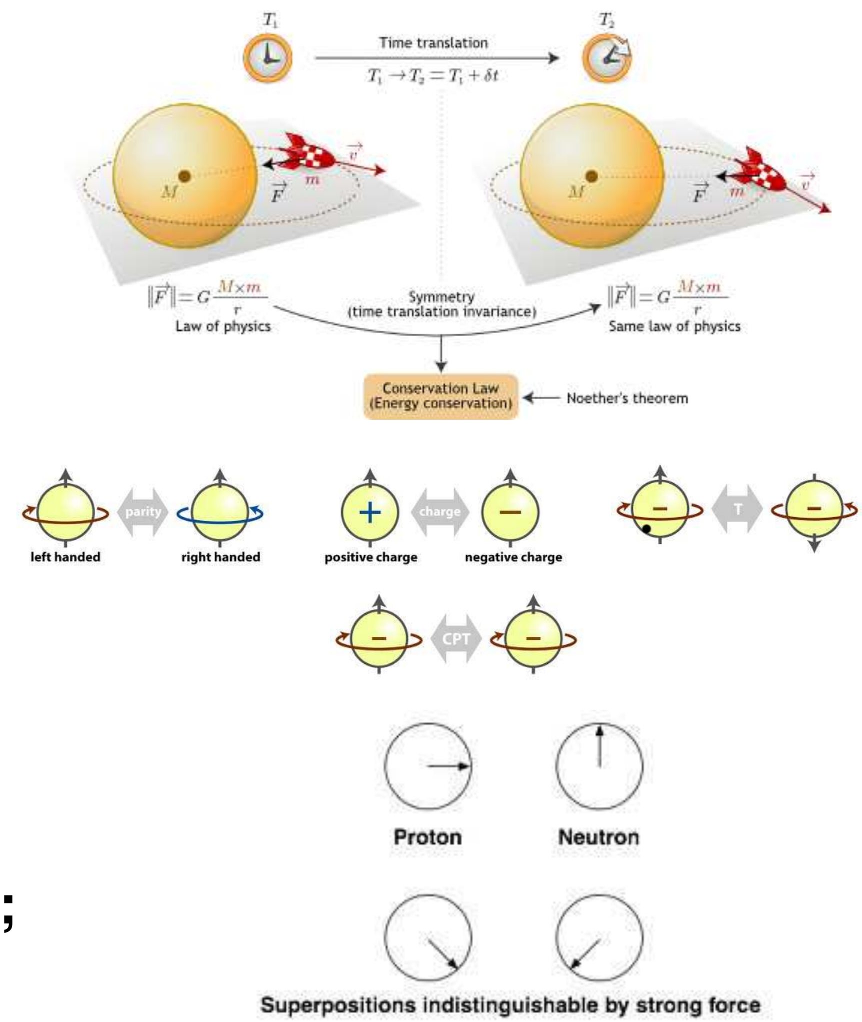
translations $(t, \vec{x})$, rotations, etc..
known continuous symmetries.
Noether: conservation of $\mathrm{E}, \tilde{\mathrm{p}}, \tilde{\omega}$, ...

- **Discrete symmetries:**

parity-P, charge-C et T-reversal;
quantum number conservation.
CPT is always conserved.

- **Internal symmetries:**

“rotations” in an internal space,
ex: proton$\equiv$neutron for strong force;
same physics in interchange of p$\leftrightarrow$n;
isospin symmetry: doublet $\mathrm{N} \equiv \binom{\mathrm{p}}{\mathrm{n}}$.



I.2 The elementary particles and their interactions

C. The theory makes extensive use of the symmetries of Nature (aesthetical..)

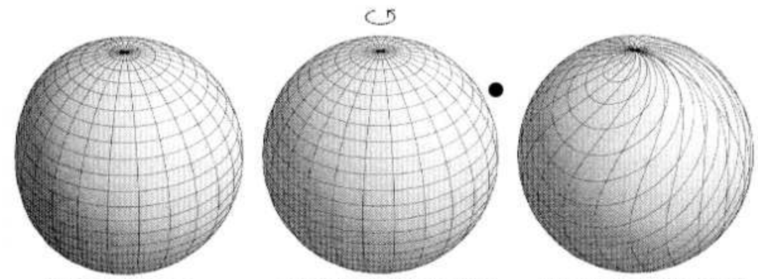
- **Gauge symmetries:**

isospin: global internal transformation

transf. x dependent $\Rightarrow$ local symmetry

$$\Psi(x) \to \Psi'(x) = T(x)\Psi(x)$$

more general and has a huge impact.



Prototype of symmetry: Quantum Electro-Dynamics (QED);

invariance under local phase transformations: $U(1)_Q$ group;

- transf. of electron field: $\Psi(x) \to \Psi'(x) = e^{iQ\alpha(x)}\Psi(x)$,
- transf. of photon field: $A(x) \to A'(x) = A(x) - \frac{1}{Q}\partial_\mu \alpha(x)$.

$\Rightarrow$ the physics (or system) is invariant under these transformations,

$\Rightarrow$ the quantity conserved by the symmetry is the electric charge Q,

$\Rightarrow$ once symmetry group chosen: interaction and number of bosons fixed,

$\Rightarrow$ the invariance implies massless gauge bosons (like photons).

Gauge Theories: aesthetical/geometry, simplicity/minimality, predictivity,

should possibly be extended to all known interactions!

I.3 The Standard Model for Pedestrians

The Standard Model describes the electromagnetic, weak and strong interaction

The electromagnetic interaction (QED):

– subjects: electrically charged particles
– mediator: the massless photon,
– conserves P, C, T... and of course Q.

The strong nuclear interaction (QCD):

– quarks appear in triplets q,q ,q,
– interact via the exchange of color,
– mediators: the massless gluons,
– conserves P, C, T and color number;
– color=attraction $\Rightarrow$ confinement.

Nuclear weak interaction:

– subjects: all known fermions;
– mediators: massive W^+, W^-, Z
(only interaction with short range),
– does not conserve parity: $f_L \neq f_R$;
(ex: there is no $\nu_R \Rightarrow \nu$ massless);
– does not conserve CP: $n_P \gg n_{\bar{P}}$.

Particules de: matière (s=1/2) force (s=1)

3 familles de fermions bosons-jauge

c→ Q→ m→	quark up ^{3}u $+2/3$ $\sim$5 MeV	quark charm ^{3}c $+2/3$ 1.6 GeV	quark top ^{3}t $+2/3$ 172 GeV	gluon ^{8}g 0 0
	quark down ^{3}d $-1/3$ $\sim$5 MeV	quark strange ^{3}s $-1/3$ 0.2 GeV	quark bottom ^{3}b $-1/3$ 4.9 GeV	photon γ 0 0
	neutrino e ν_e 0 ~ 0	neutrino μ ν_μ 0 ~ 0	τ neutrino ν_τ 0 ~ 0	boson Z Z^0 0 91.2 GeV
	electron e -1 0.5 MeV	muon μ -1 0.1 GeV	tau τ -1 1.7 GeV	bosons W $W^\pm$ ± 1 80.4 GeV

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

I.3 The Standard Model for Pedestrians

Standard Model based on $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$ gauge symmetry.

- The local $\mathrm{SU(3)_C}$ symmetry group describes strong interactions:
  - strong interaction between q,q,q which are color triplets of SU(3),
  - mediated by 8 gluons, which correspond to 8 generators of SU(3).
- $\mathrm{SU(2)_L \times U(1)_Y}$ is for the unified electromagnetic+weak interactions:
  - acts on quarks/leptons of isospin Left (doublets) and Right (singlets),

$$\binom{\nu}{\mathrm{e}}_{\mathrm{L}} \, , \; \mathrm{e}^{-}_{\mathrm{R}} \, , \; \binom{\mathrm{u}}{\mathrm{d}}_{\mathrm{L}} \, , \; \mathrm{u_R} \, , \; \mathrm{d_R} \, , \; \cdots$$

idem for the other families; neutrinos are massless $\Rightarrow$ there are no ν_{R};

  - mediated by the bosons W_1, W_2, W_3 generators of SU(2) and B of U(1):

(W_1,W_2) and (W_3,B) then combine to form the (W^+,W^-) and (Z,γ) bosons.

Major problem: the photon is massless but the weak bosons are massive!

Naive inclusion of a mass for W/Z bosons and also fermions breaks invariance with respect to gauge symmetry and loss of nice theory properties.

Former major problem of Particle Physics: how to generate these masses?

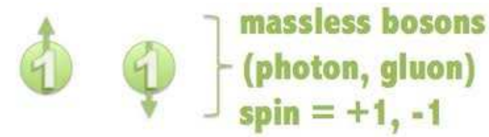
$\Rightarrow$ the Higgs-Englert-Brout mechanism of electroweak symmetry breaking!

I.3 The Standard Model for Pedestrians

How to render a gauge boson massive without violating gauge symmetry?

Recall:

- **Photon: massless spin-1:** two degrees of freedom $\mathrm{P_x}, \mathrm{P_y}$, or transverse polarizations.

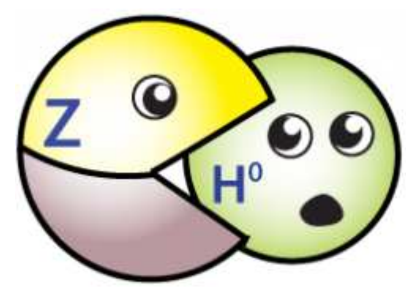


- **Massive boson of spin–1:** three degrees of freedom (x,y,z): i.e. +longitudinal polarization.

- **Scalar boson of spin-0:** has no polarization at all: one degree of freedom...

"Trick":

to make a massive spin-1 particle (with three degrees of freedom): make absorb a scalar (one dof) to a massless spin-1 (two dof). The "longitudinal" component of W/Z bosons can be scalars,



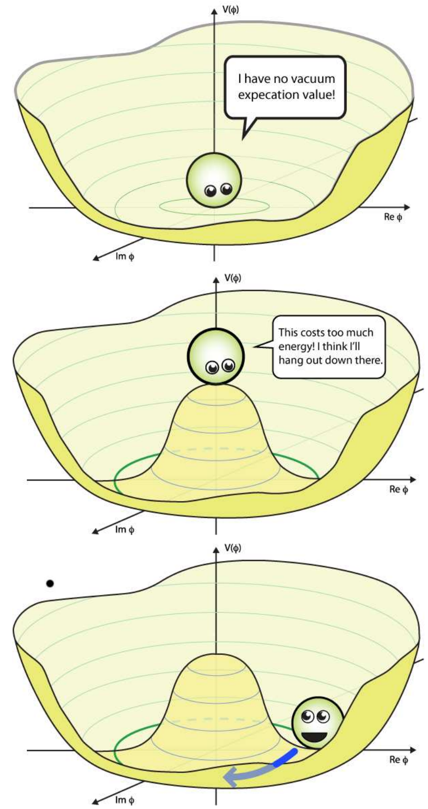
All of this is done without altering the symmetry...

I.3 The Standard Model for Pedestrians

Question: how can one do that in practice for the weak interactions?

– Total energy of a system = kinetic energy + potential energy.
– Least action: minimal energy $\Rightarrow$ at rest and minimum of potential.

- In general the potential is a well: the minimum of Φ is called "vacuum" (at the bottom of the well in this case).
  Everything is still symmetric...
- Imagine now a different potential, like, for instance, this Mexican hat: symmetry $\Rightarrow$ Φ on top of the bump; non-minimal and costs some energy.
- Potential energy minimal $\Rightarrow$ Φ at bottom of the potential well. Minima in a circle of radius v called non-zero vacuum expectation value: "spontaneously" broken symmetry.



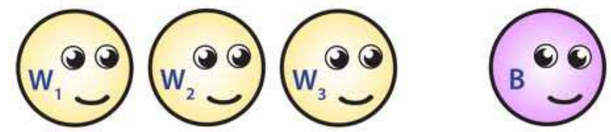
- Look at phenomena from the point of equilibrium = true vacuum.

zero vev or symmetric: field Φ is real and the "photon" massless.
non-zero or asymmetric phase: Φ absorbed and "photon" massive!

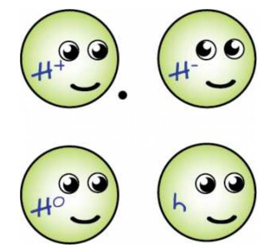
I.3 The Standard Model for Pedestrians

Application to the weak interaction:

- we have an SU(2)xU(1) symmetry,
1 gauge boson for U(1): B field,
3 gauge bosons for SU(2): W_1,W_2,W_3,
all four bosons are non-massive.

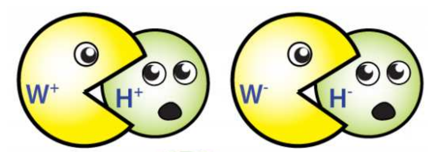


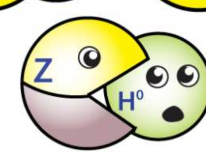
- We need 3 spin-1 massive bosons:
i.e. ≥ 3 degrees of freedom more.
Most economical: scalar complex field.
SU(2) doublet: 4 degrees of freedom.

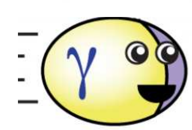


$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \begin{pmatrix} H^+ + iH^- \\ h \;+ iH^0 \end{pmatrix}$$

- Spontaneous symmetry breaking:
$\Rightarrow$ some scalar fields are absorbed
$W_1, W_2 \oplus H^+, H^- \Rightarrow W^+, W^-$
comb. of $W_3, B \oplus H^0 \Rightarrow Z$
comb. of W_3, B, still hungry $\Rightarrow \gamma$





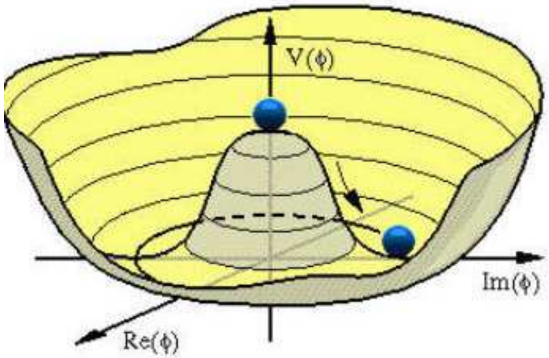


- But one scalar field is not absorbed,
it remains a physical field, a new state:

$\Rightarrow$ **it is the Higgs boson!**

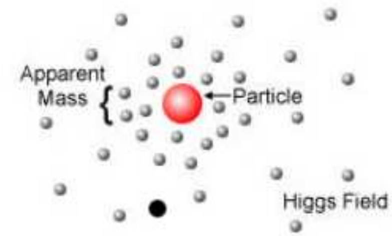
I.3 The Standard Model for Pedestrians

Another (more “colorful”) way to see things:



The field Φ fills all space:
(exp.value$\neq$0 in vacuum)

gives inertia,
(slows down....)



confers a mass!
(inertia = mass)

- **The field Φ and the gauge bosons:**

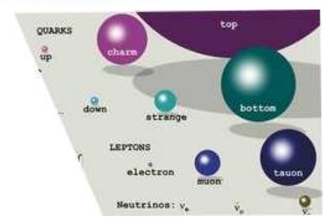
– interacts more with $W^{\pm}$, Z $\Rightarrow$: very massive!
– does not interact with γ $\Rightarrow$: stays massless.

- **It does the same thing with the fermions:**

– interacts more with 3d than 2d than 1st families;
– interacts much more with top quark: very heavy;
– interacts little with the electron: extremely light;
– does not interact with neutrinos: non–massive.

- **The Higgs boson also interacts with itself:**

– the Higgs boson is a massive particle,
– but the theory does not predict its mass.



I.3 The Standard Model for Pedestrians

To recap: the Standard Model is base on three pillars:

- it is a theory that obeys to special relativity and quantum mechanics;
- a theory based on invariance with respect to gauge symmetries;
- uses the Higgs (or HEB, or EWSB) mechanism for mass generation.

and before then advent of LHC, had only one unknown: the H boson mass.

- The theory is mathematically consistent:

$\Rightarrow$ can make extremely precise predictions.

- Multiple experiments since 5 decades,

$\Rightarrow$ tests with extremely high accuracy.

- Predictions match measurements at 0.01%:

$\Rightarrow$ **an extremely satisfactory theory!**

10 years ago, only remaining problem:

- verify the Higgs mechanism,
- discover the famous Higgs boson
- or the ingredient that does its job....

LHC was just devised for that!