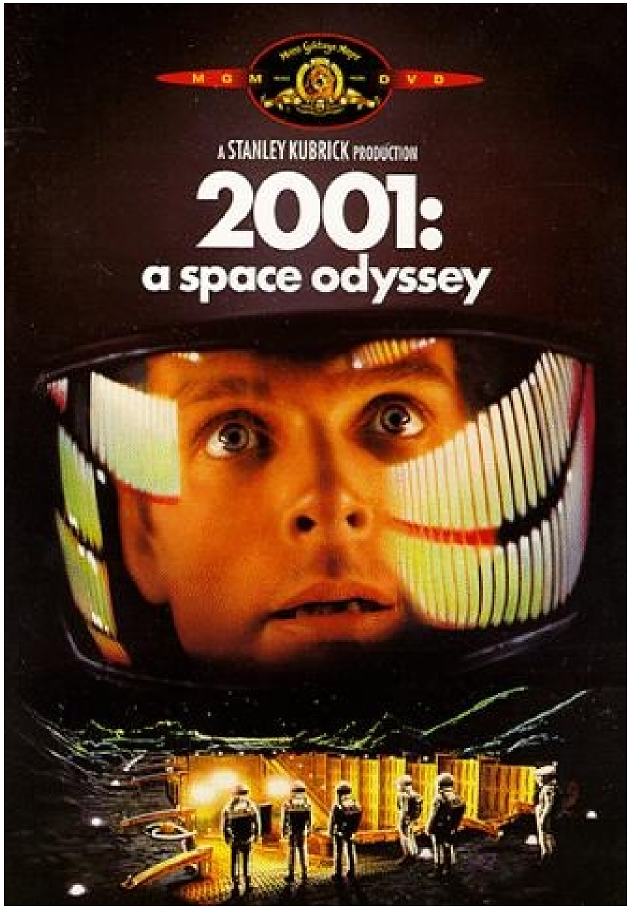
The Particle Physics Odyssey

[Where are we? Where are we going?]



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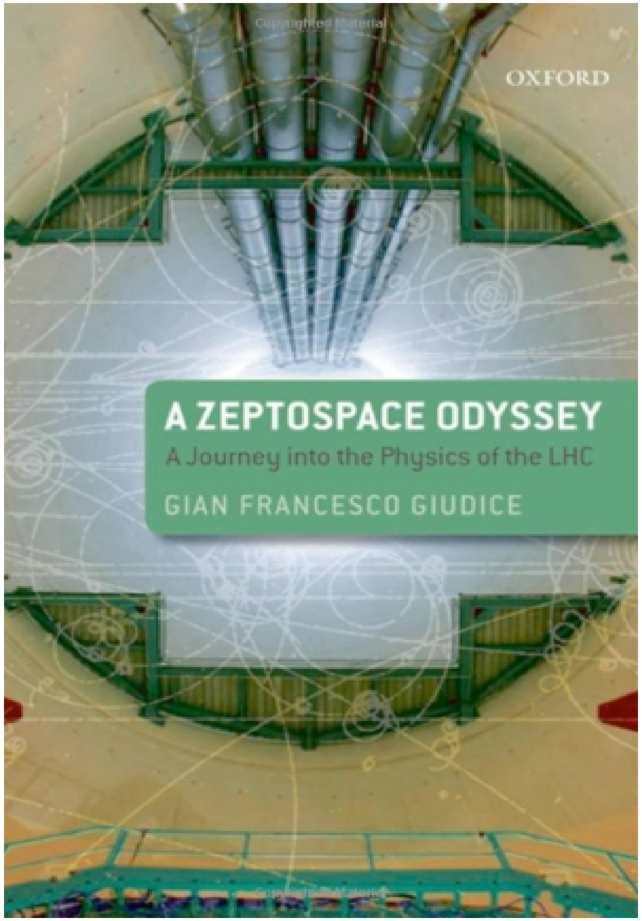

The Particle Physics Odyssey

[Where are we? Where are we going?]

- Introduction
- Mathematical models and fundamental couplings
- The Standard Model
- The Higgs boson
- Open problems
- Beyond the Standard Model
- Conclusions

Introduction

During the last 30 years a highly successful mathematical model has emerged in this field: the so-called Standard Model.

The Standard Model is a relatively simple mathematical theory which describes with success (almost) all the known interactions of matter constituents: from the atomic nuclei to the structure of the stars.

Introduction

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Using the technical jargon, the SM is

A Relativistic Quantum Field Theory based on

Two Fundamental symmetries:
the color symmetry (ruling strong interactions)
and the electro-weak symmetry (ruling weak and electromagnetic interactions)

Three sets of Fundamental Constituents:
the 3 generations (or flavours) of quarks & leptons

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A Relativistic Quantum Field Theory based on

A team game played with a ball...

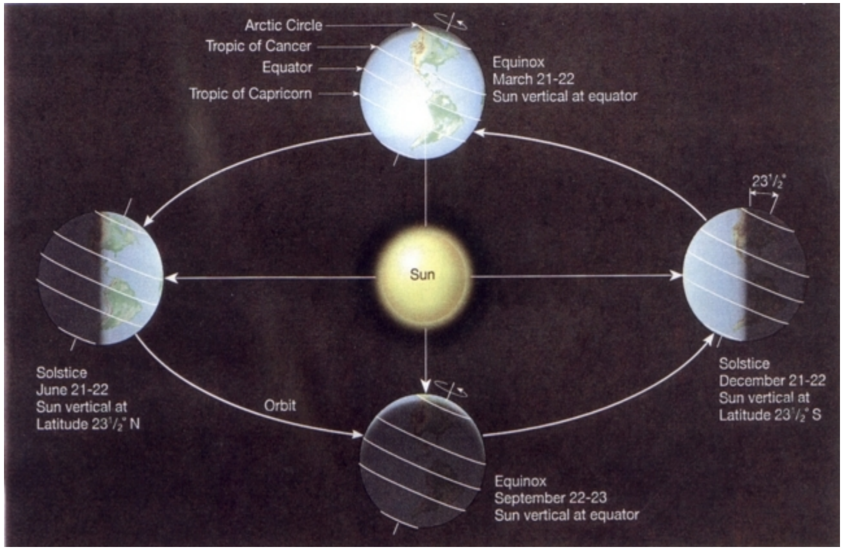
Two Fundamental symmetries:
the color symmetry (ruling strong interactions) and the electro-weak symmetry (ruling weak and electromagnetic interactions)

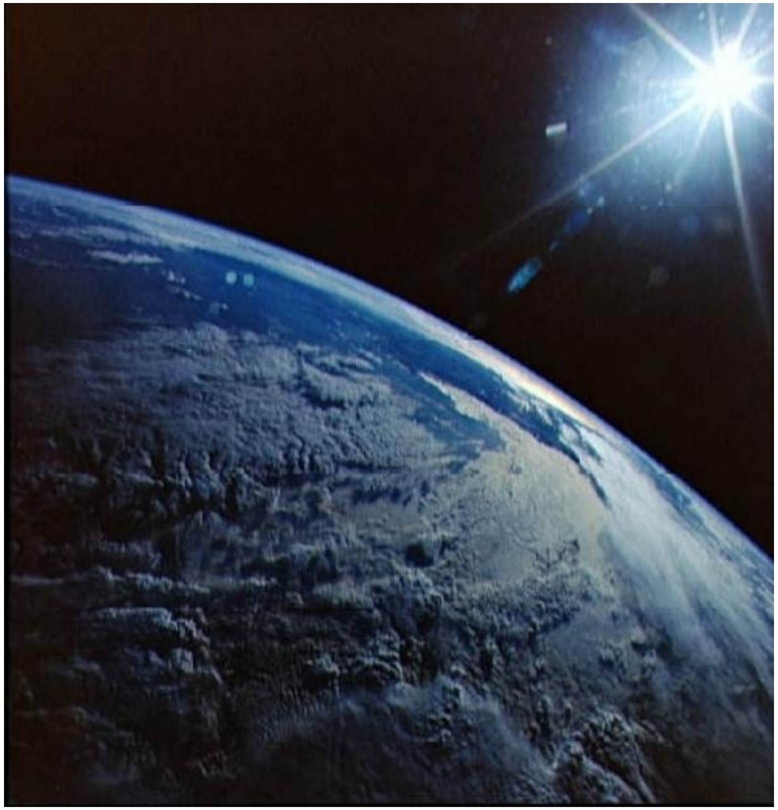
...the ball is spherical and can be touched only by feet...

Three sets of Fundamental Constituents:
the 3 generations (or flavours) of quarks & leptons

...each team has 11 players...

II. Mathematical models & fundamental couplings





Mathematical models & fundamental couplings

As we learned from Galileo, our main purpose, as physicists, is to build mathematical models able to describe (and predict) natural phenomena

Mathematical model = set of logical principles (symmetry laws, etc...)

→ series of mathematical equations for *a-dimensional variables*

↕ Measurement Units

Natural phenomena [*dimensional variables*]

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Example: $h(t) = -\ \frac{1}{2}\, g\, t^2$

Numerical coefficient
[fixed by theory]

Physical coupling
[determined from experiments]

Measurement
Units

Natural phenomena [*dimensional variables*]

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Within an ideal (fundamental) theory all numerical coefficients (a-dimensional couplings) should be calculable,

Measurement Units

while all the measurement units are automatically determined in terms of some universal physical couplings

Natural phenomena [*dimensional variables*]

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[length, time, energy] ↔ 3 fundamental couplings

Natural phenomena [*dimensional variables*]

Mathematical models & fundamental couplings

Nature seems to have chosen three couplings for this purpose:

The velocity of light in vacuum [c]

- Electromagnetism (Maxwell equations)
- Special Relativity ($E = m c^2$, ...)

Planck's constant [ħ]

- Quantum mechanics (electron spin = $\hbar/2$, uncertainty principle: $\Delta x \, \Delta p > \hbar$ & $\Delta E \, \Delta t > \hbar$, ...)

Newton's constant [G]

- Universal law of gravity ($F = G \, m_1 m_2 / r^2$)
- General Relativity

Mathematical models & fundamental couplings

Nature seems to have chosen three couplings for this purpose:

The velocity of light in vacuum [c]

$c = 2.9979... \times 10^{8}$ $\quad$ m s^{-1} $\quad$ [length / time]

Planck's constant [ħ]

$\hbar = 1.0054... \times 10^{-34}$ $\quad$ $m^2\, s^{-1}$ kg $\quad$ [energy × time]

Newton's constant [G]

$G = 6.6742... \times 10^{-11}$ $\quad$ $m^3\, s^{-2}\, kg^{-1}$ $\quad$ [$\text{length}^5 \times \text{time}^{-4} \times \text{energy}^{-1}$]

These 3 couplings have very "unnatural" values in the International System (m kg s), but this is because the SI is a human-based conventional units system.

The universal character of these 3 couplings tell us that in nature there exist some fundamental (non-conventional) units

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Within the Standard Model c & ħ are perfectly integrated as fundamental units, this allows us to measure/describe all phenomena in units of energy:

E.g.: $E = 1\ \text{GeV} \Rightarrow E/c^{2} \approx 2\times10^{-27}\ \text{Kg}$ $\quad \hbar/E \approx 7\times10^{-25}\ \text{s}$ $\quad \hbar c/E \approx 2\times10^{-16}\ \text{m}$

typical binding energy of quarks inside nuclei	proton mass	typical time between collisions of quarks within the proton	proton size

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But we have not understood yet if there is a fundamental scale of energy...

The "natural" indication (obtained combining these 3 couplings) leads to an extremely high scale of energy:

$$M_{Planck} = (\hbar c/G)^{1/2} \approx 10^{19}\, M_{proton}$$

Mathematical models & fundamental couplings

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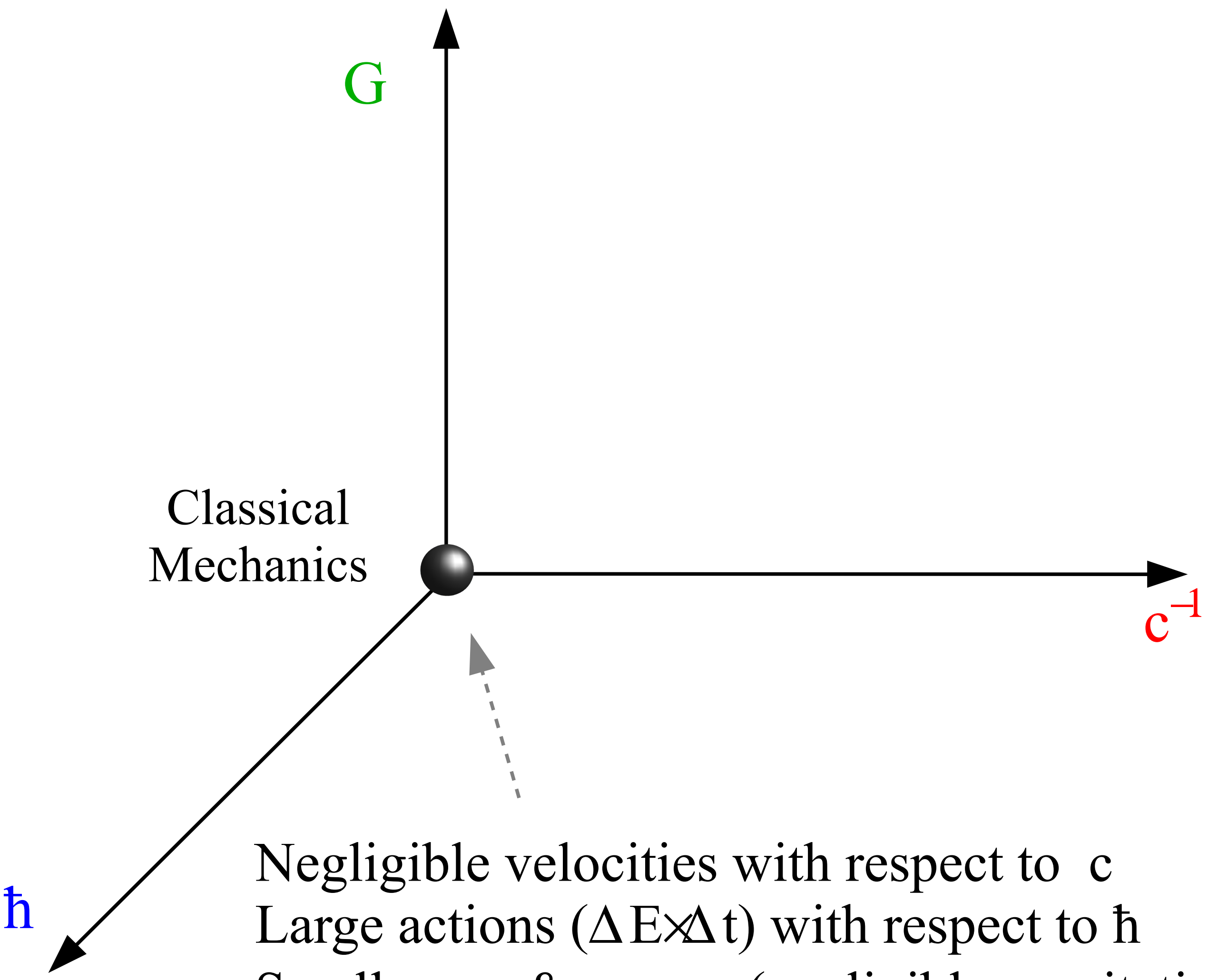
Within the Standard Model c & ħ are perfectly integrated as fundamental units, this allows us to measure/describe all phenomena in units of energy.

But we have not understood yet if there is a fundamental scale of energy...

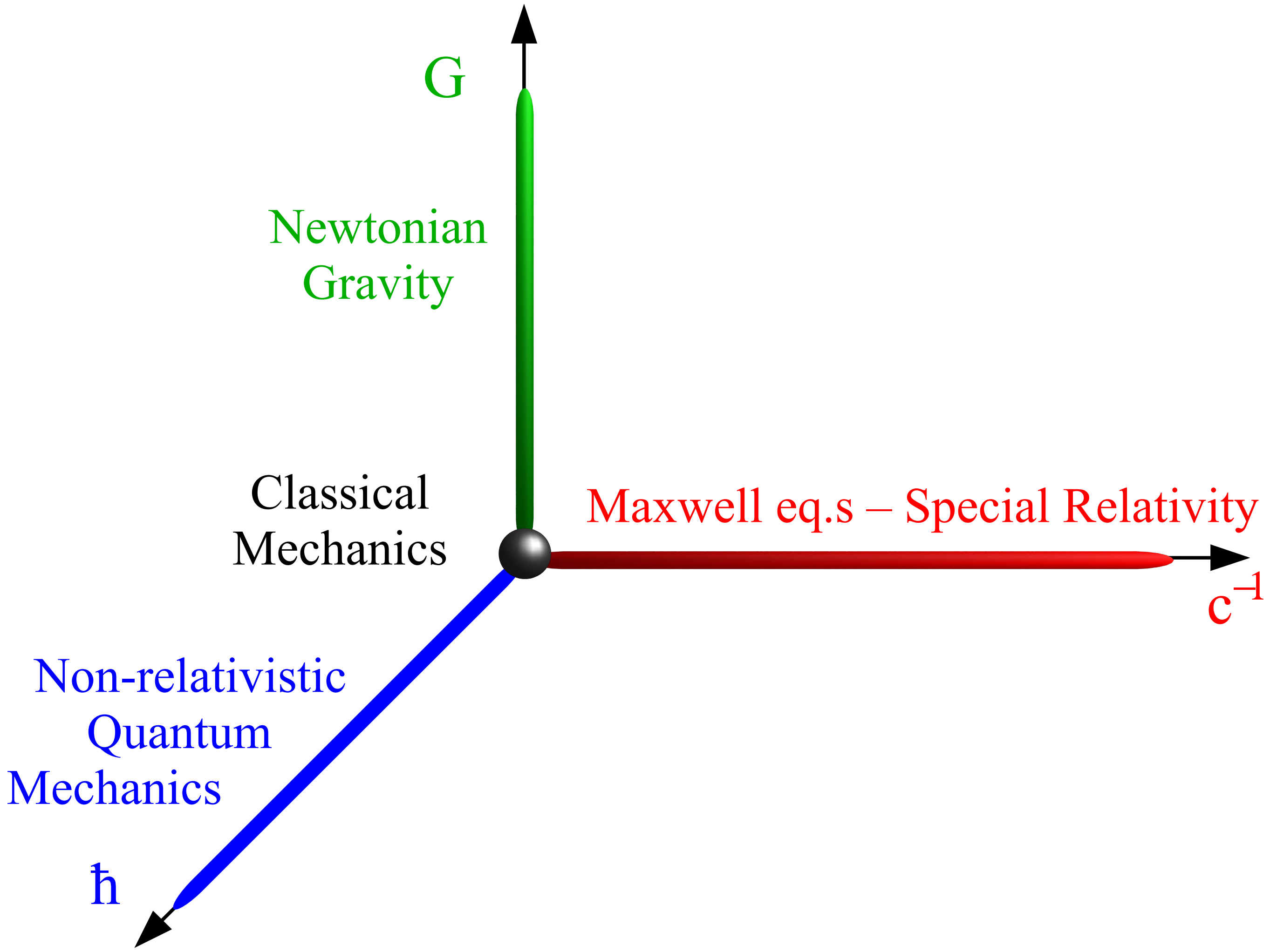
That's the most fascinating and difficult challenge we are facing in particle physics...

▸ Mathematical models & fundamental couplings



Negligible velocities with respect to c
Large actions ($\Delta E \times \Delta t$) with respect to $\hbar$
Small mass & energy (negligible gravitational effects)

Mathematical models & fundamental couplings



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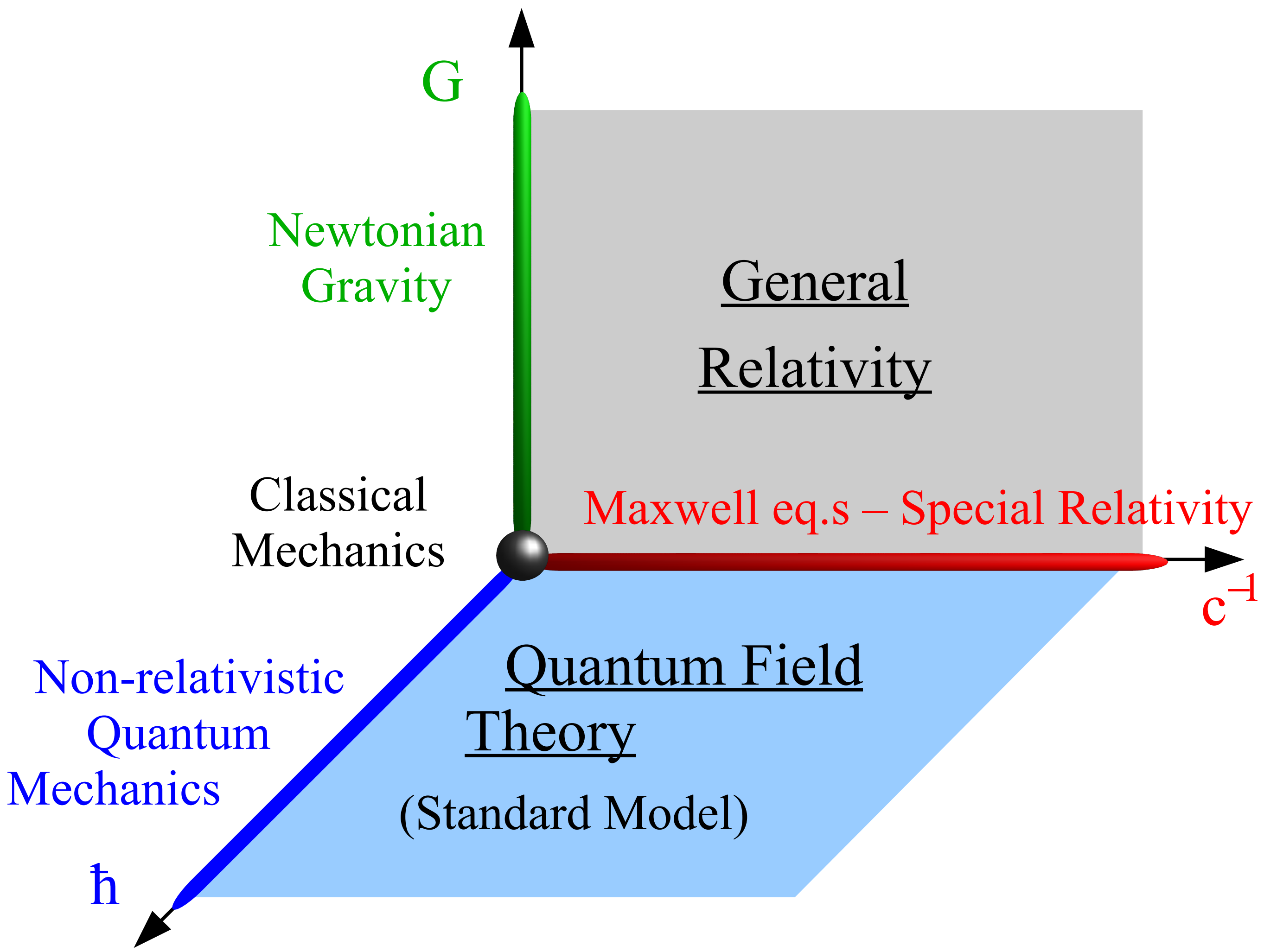

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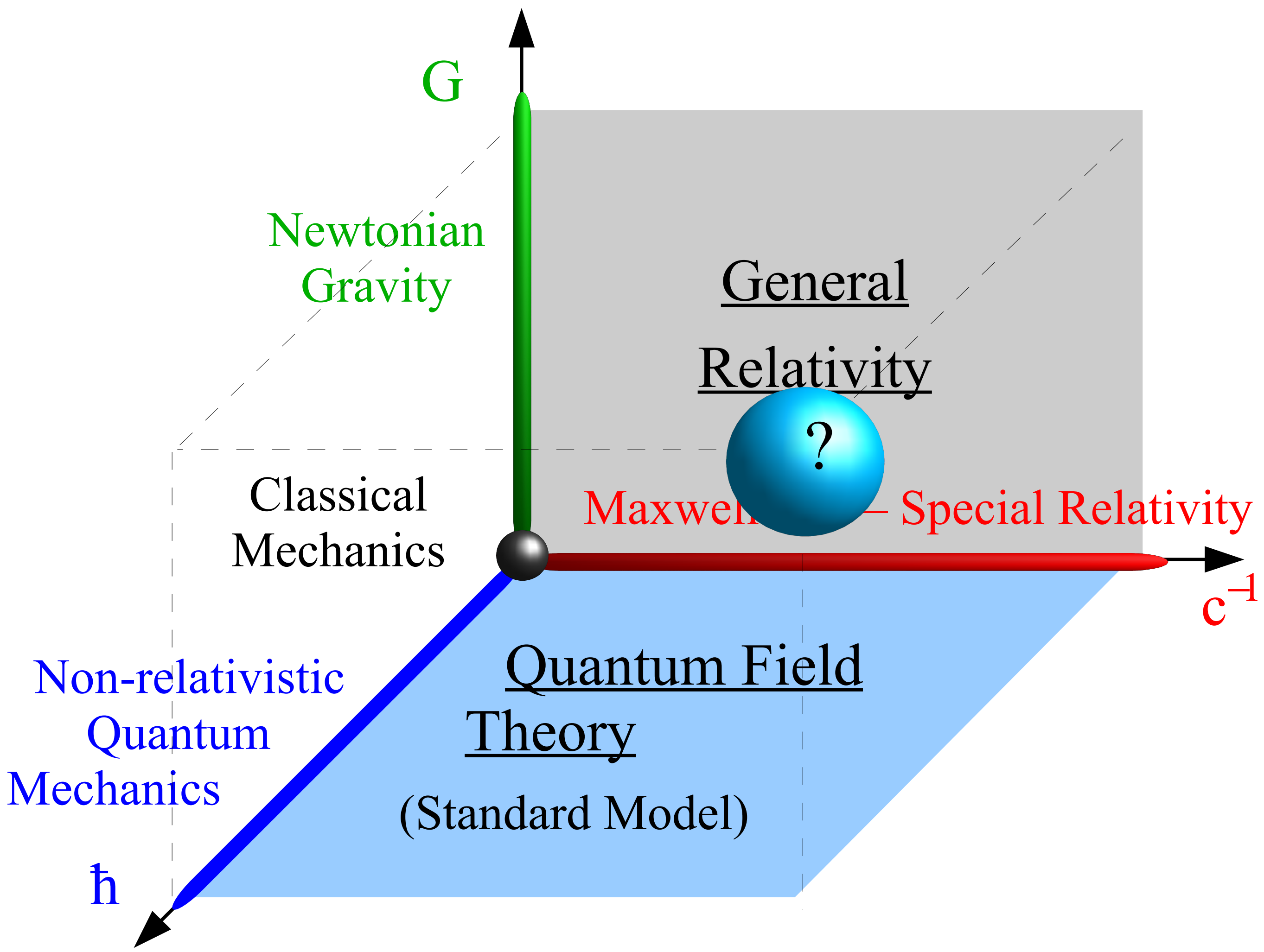
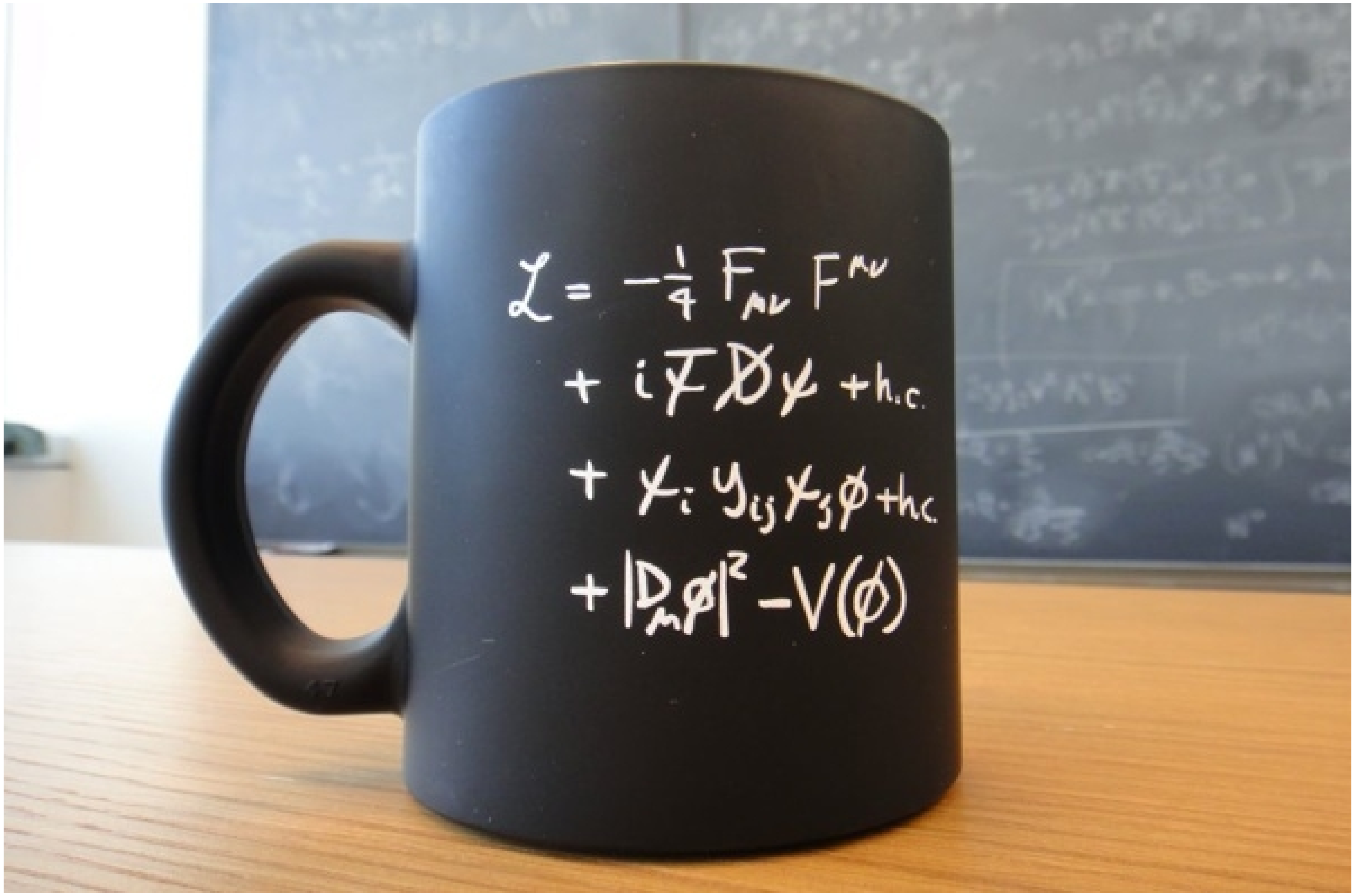


III. The Standard Model



The Standard Model

The two main pillars on which *quantum field theory* is based are the two "revolutionary" theories developed at the beginning of last century:

Quantum Mechanics
[Uncertainty principle $\Delta E \, \Delta t > \hbar$]

- No more "classical trajectory" for processes with $\Delta E \, \Delta t \sim \hbar$
- Deterministic determination of the probabilities for the occurrence of physical processes

→ Quantum Field Theory ←

Special Relativity
[Equivalence of mass & energy $E = m\, c^2$]

- No more "absolute" space and "absolute" time: unified description of the space-time, where the velocity of light is the same for all the observers

▶ The Standard Model

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Quantum Mechanics
[Uncertainty principle $\Delta E \, \Delta t > \hbar$]

Quantum Field Theory

Special Relativity
[Equivalence of mass & energy $E = m\, c^2$]

QFT generalises and combines these two theories (*it is the most advanced theoretical tool we have to describe natural phenomena...*)

To achieve this goal, the last classical concept that has to be abandoned is the idea that the number of the matter constituents is conserved: all elementary particles (including the electron) are described by *excitations* of specific *fields.*

All particles can be created and destroyed transforming mass in energy and viceversa (*they are like "waves"*) → resolution of the particle/wave dualism of non-relativistic quantum mechanics.

The Standard Model

The SM is a specific type of QFT.
To define it, we have to specify which are the fields and how they interact.

Two main categories of fields:

- Matter fields (electron, ...) (spin=1/2)
- Force carriers (photon, ...) (spin=1)

Transformation property of the field under "rotations" of the space-time coordinates

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To which recently we added a third one:

- Scalar fields (the Higgs boson) (spin=0)

The Higgs boson is the only excitation of a fundamental scalar field so far observed.

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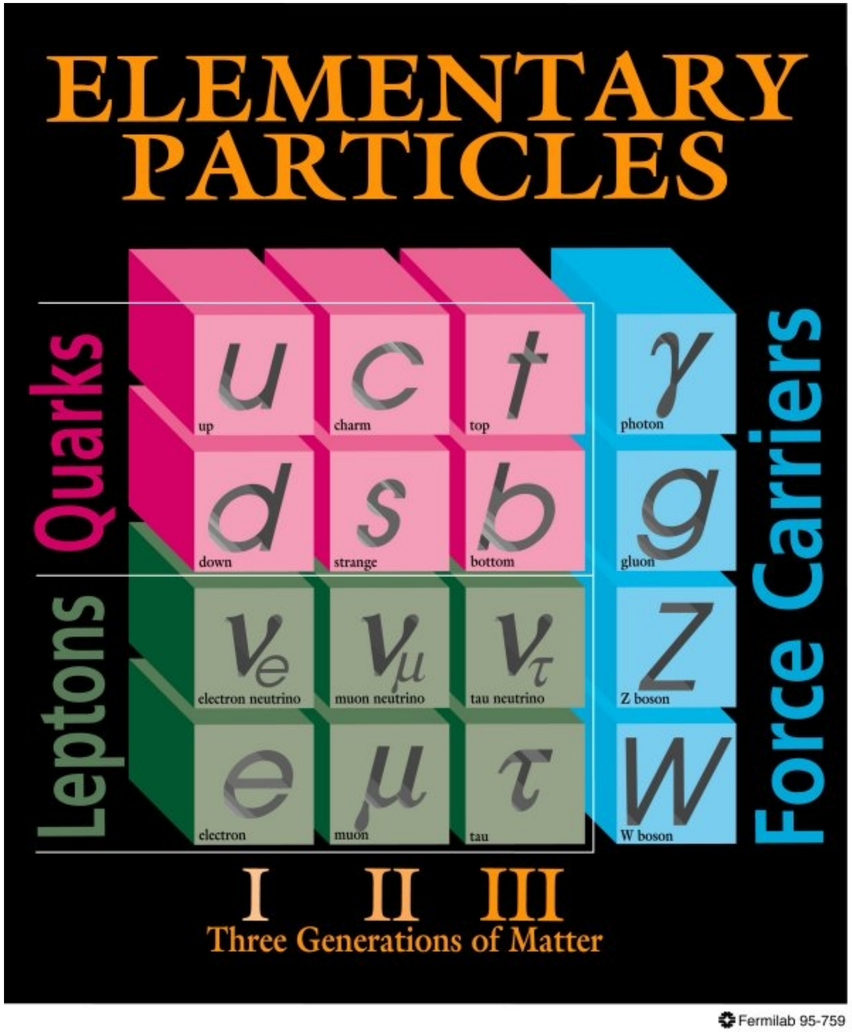
The matter fields are organised in 3 families (*whose internal structure is determined by symmetry principles*)



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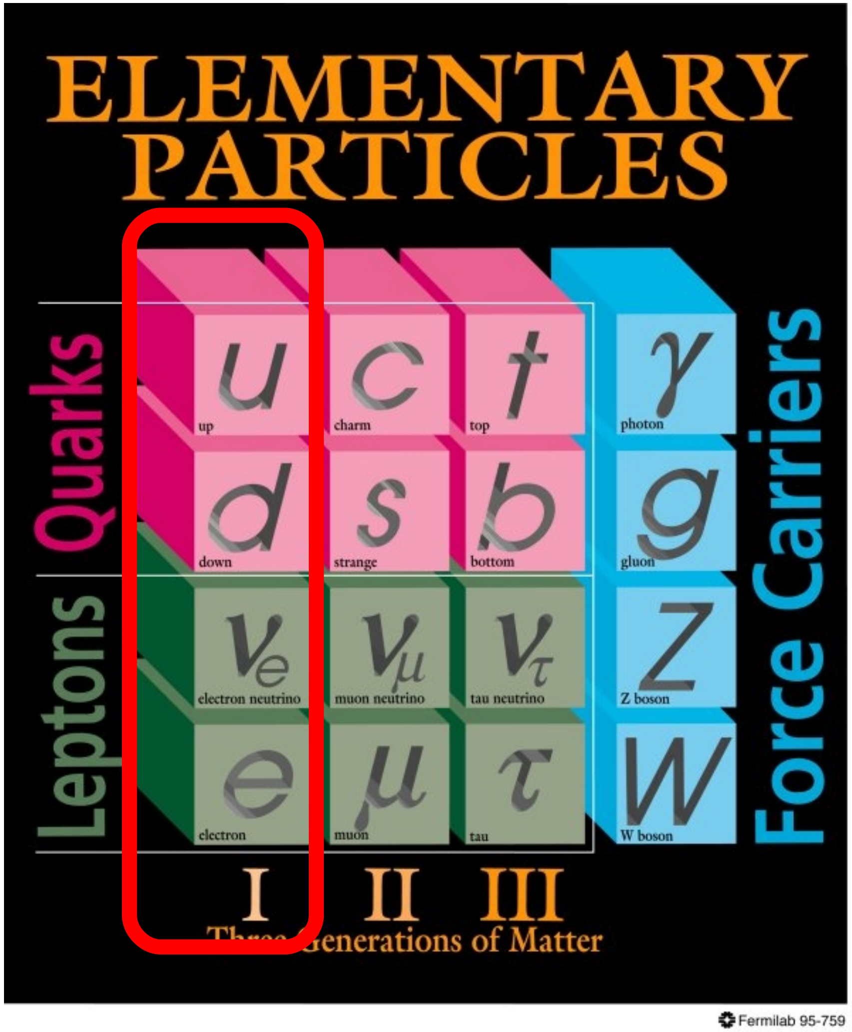
- The 1st family is composed by up & down quarks (*constituents of protons & neutrons*), the electron & the electron neutrino: all the forms of matter we observe around us are composed by these basic constituents



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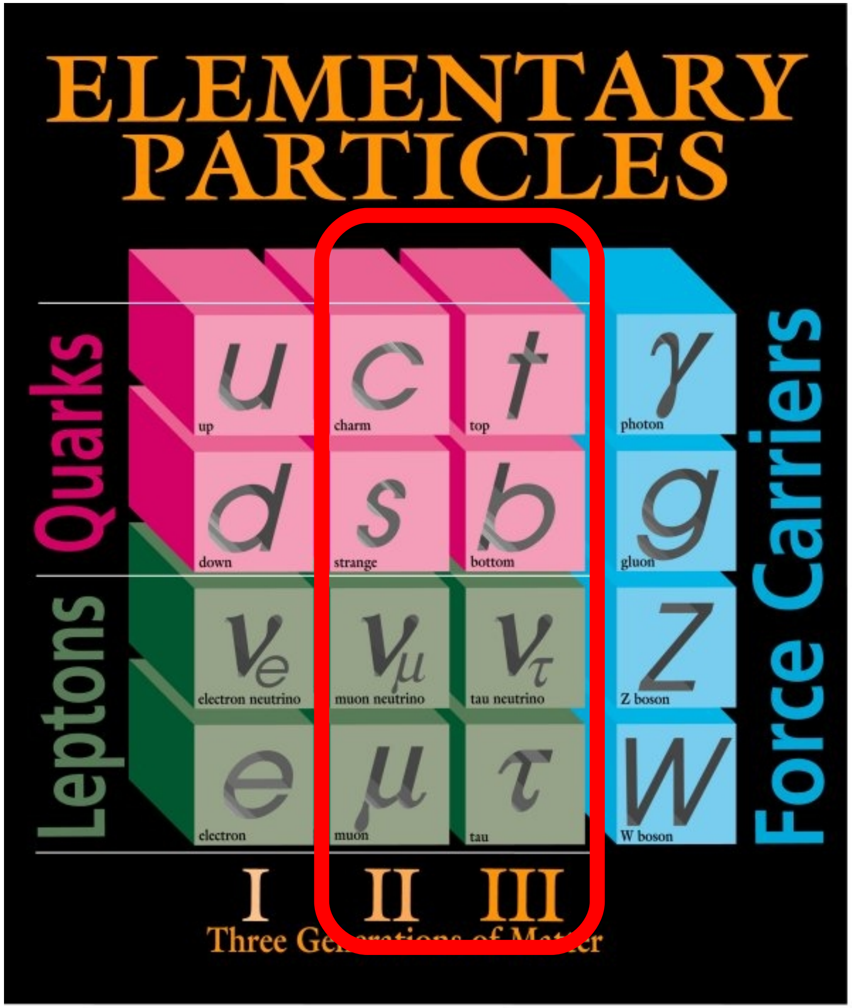
- The 2nd & 3rd families are identical copies except for different masses for the various constituents



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The Standard Model

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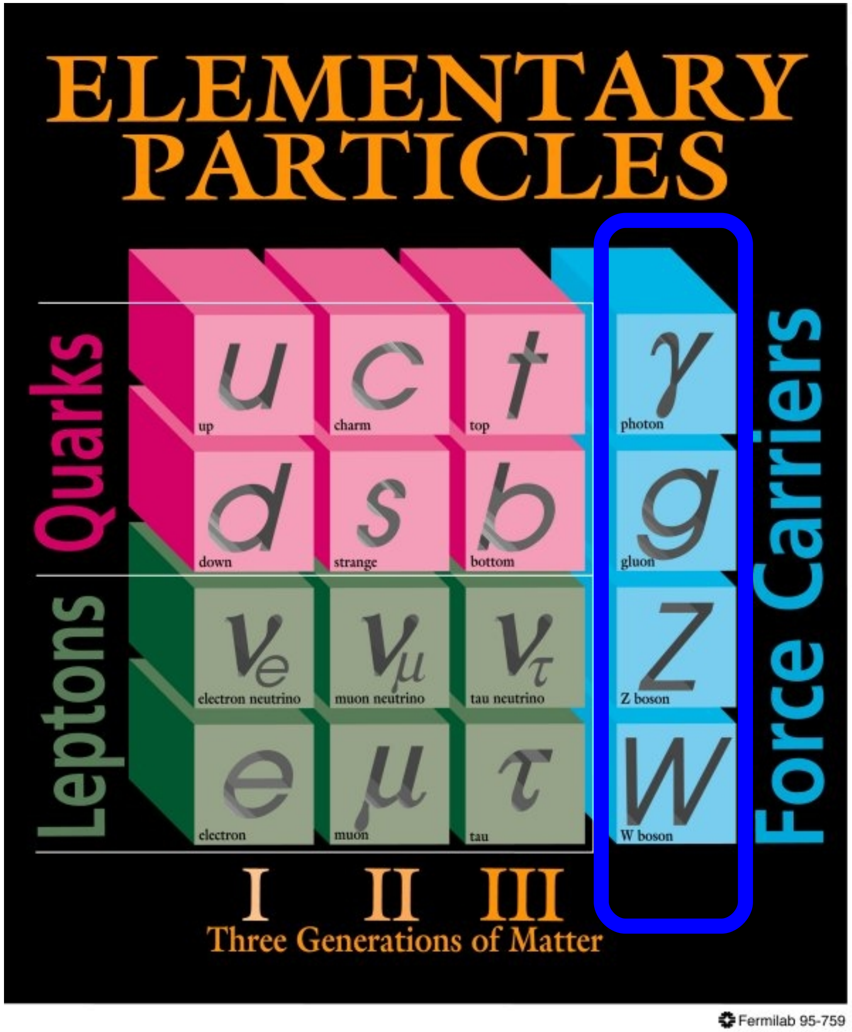
To define it, we have to specify which are the fields and how they interact.

Two main categories of fields:

- Matter fields (electron, ...)
- Force carriers (photon, ...)

The number and the properties of the force carriers are completely specified by two symmetries:

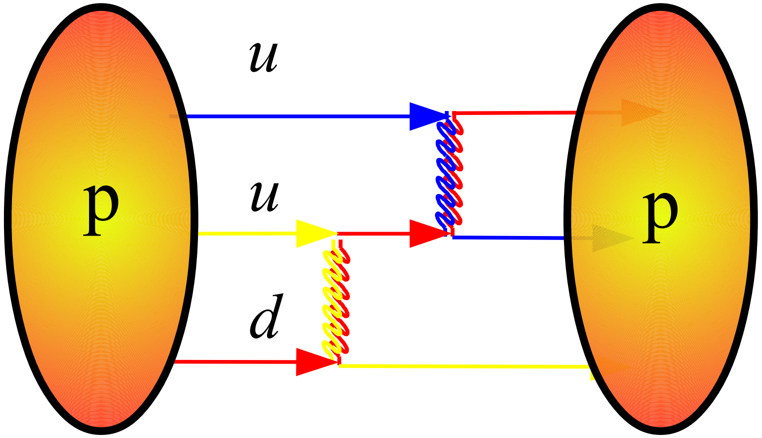
- The color symmetry (ruling strong interactions)
- The electro-weak symmetry (ruling electromagnetic and weak interactions)

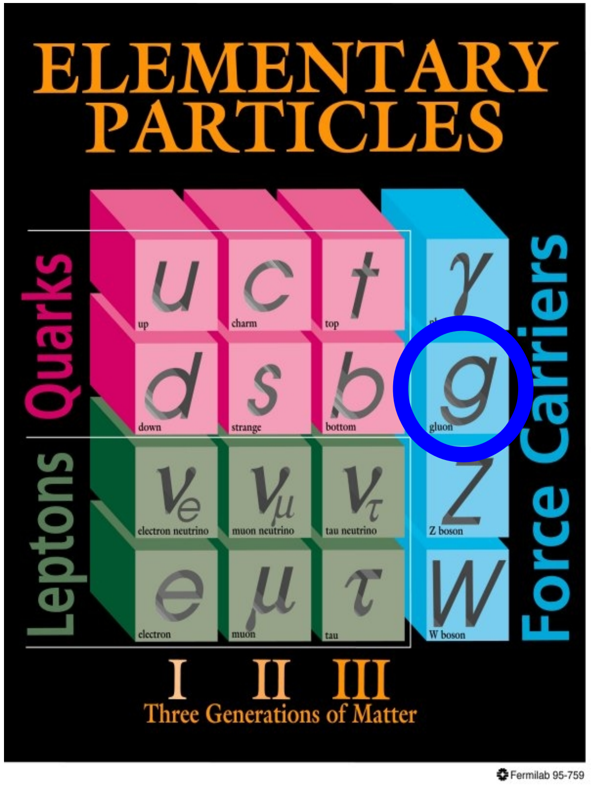


The Standard Model

The color symmetry is responsible of the strong bounding force which keeps the quarks bounded inside the atomic nuclei (*confinement mechanism*):

Each quark has a "color" charge, which can assume 3 values (R,Y,B), and which can be exchanged continuously among the other quarks by means of the 8 gluon fields (the force carriers). The only macroscopically stable states are those which are "color neutral" (superposition of R + Y + B)



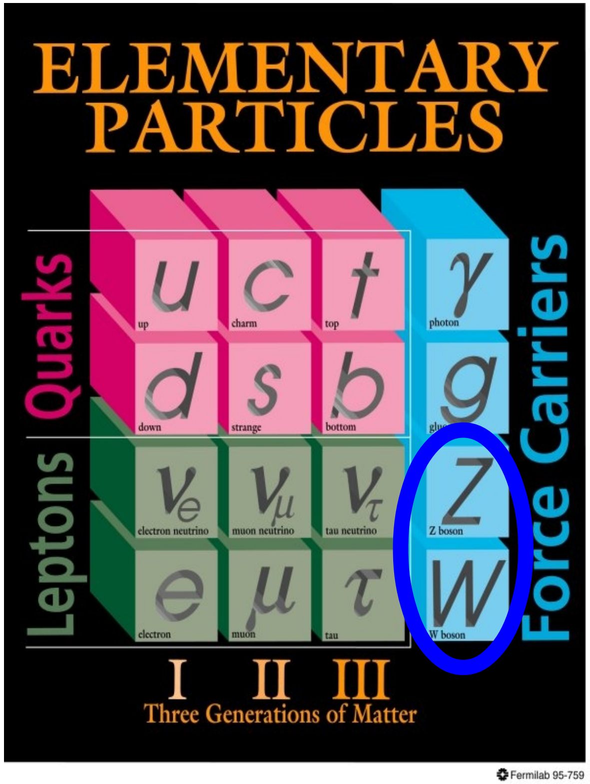


M_{proton} = bounding energy of the quarks

The Standard Model

The weak interaction is responsible for nuclear weak decays, but also for the nuclear-fusion processes which occur inside the stars.

It is the only interaction which is felt by neutrinos and which can mix the three different generations of quarks and leptons



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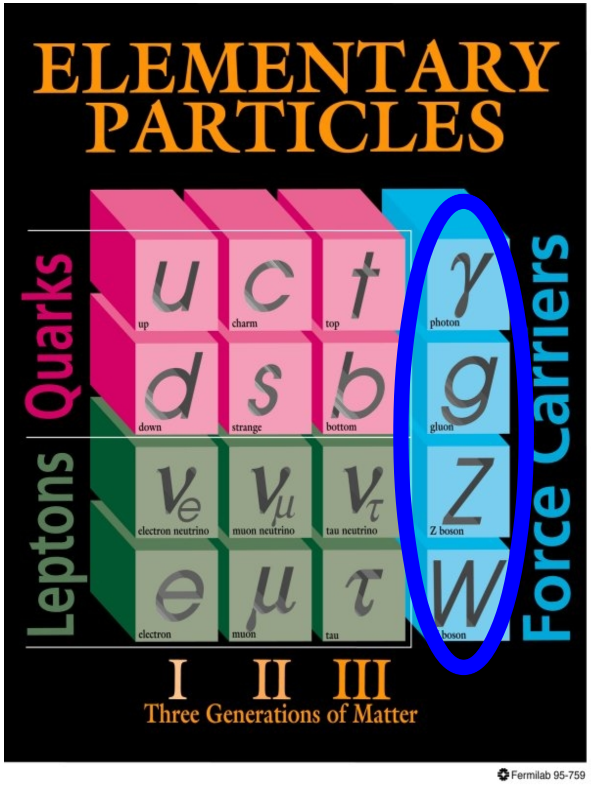
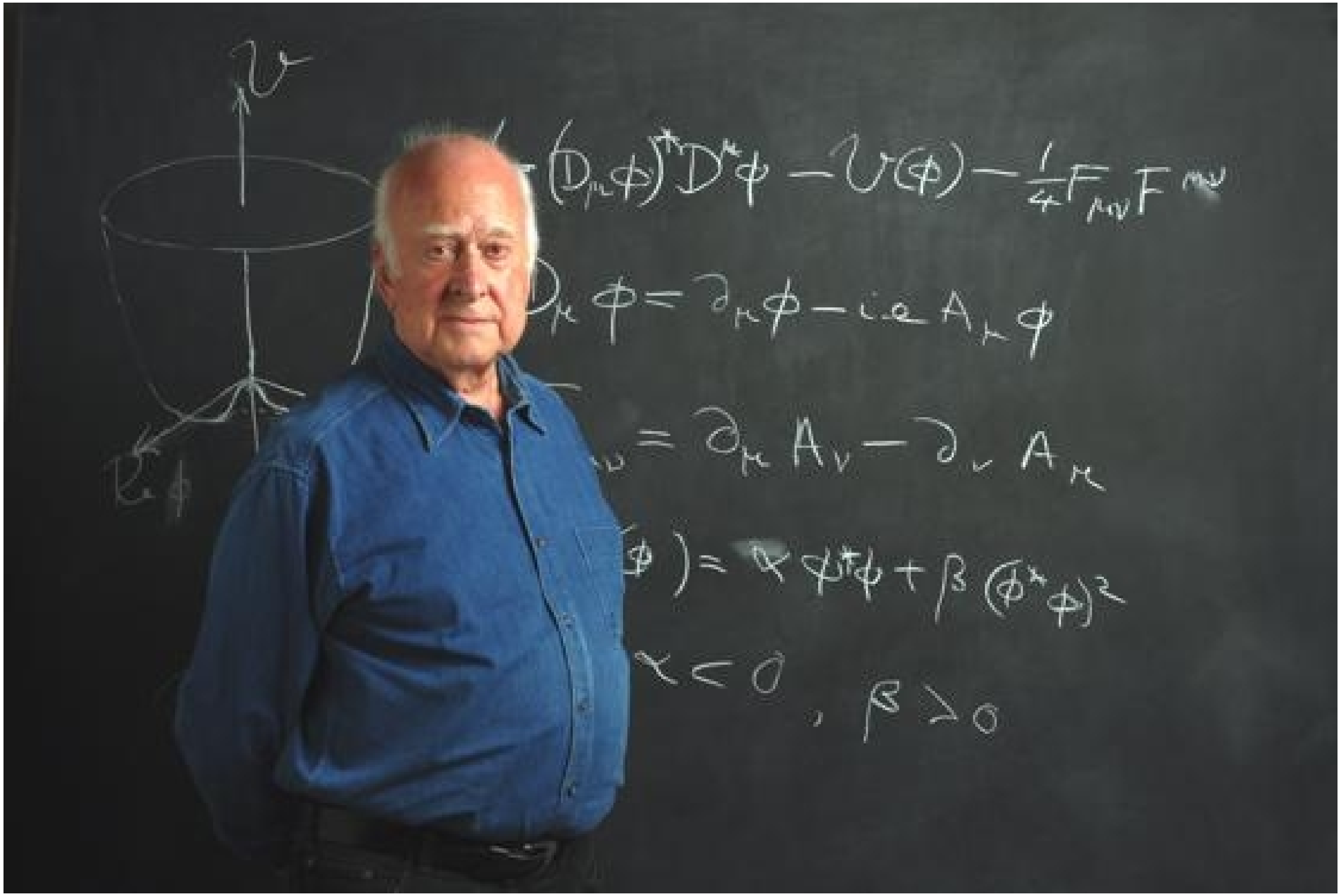
The strength of the various interactions is quite different at low energies, but it becomes very similar at energies where we can neglect all masses:

	E ~ 1 GeV	E ~ 100 GeV
g_{strong}	~ 3	~ 1.2
g_{weak}	~ 0.01	~ 0.4
$g_{e.m.}$	~ 0.2	~ 0.3



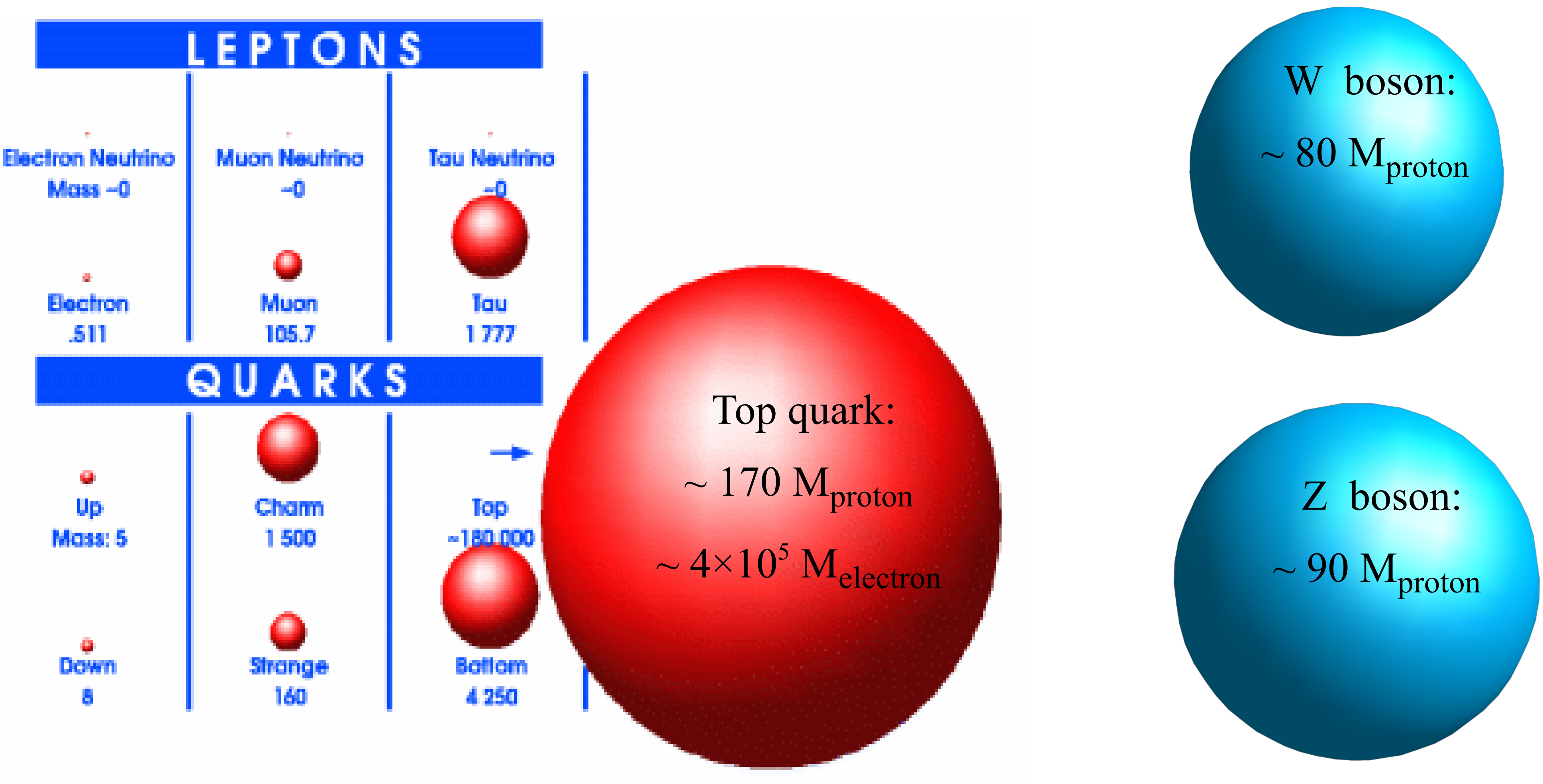
IV. The Higgs boson



The Higgs boson

The electroweak symmetry implies that none of the SM fields (quarks & leptons, and force carriers) can have a mass.

This is in sharp contradiction to what we find in experiments:



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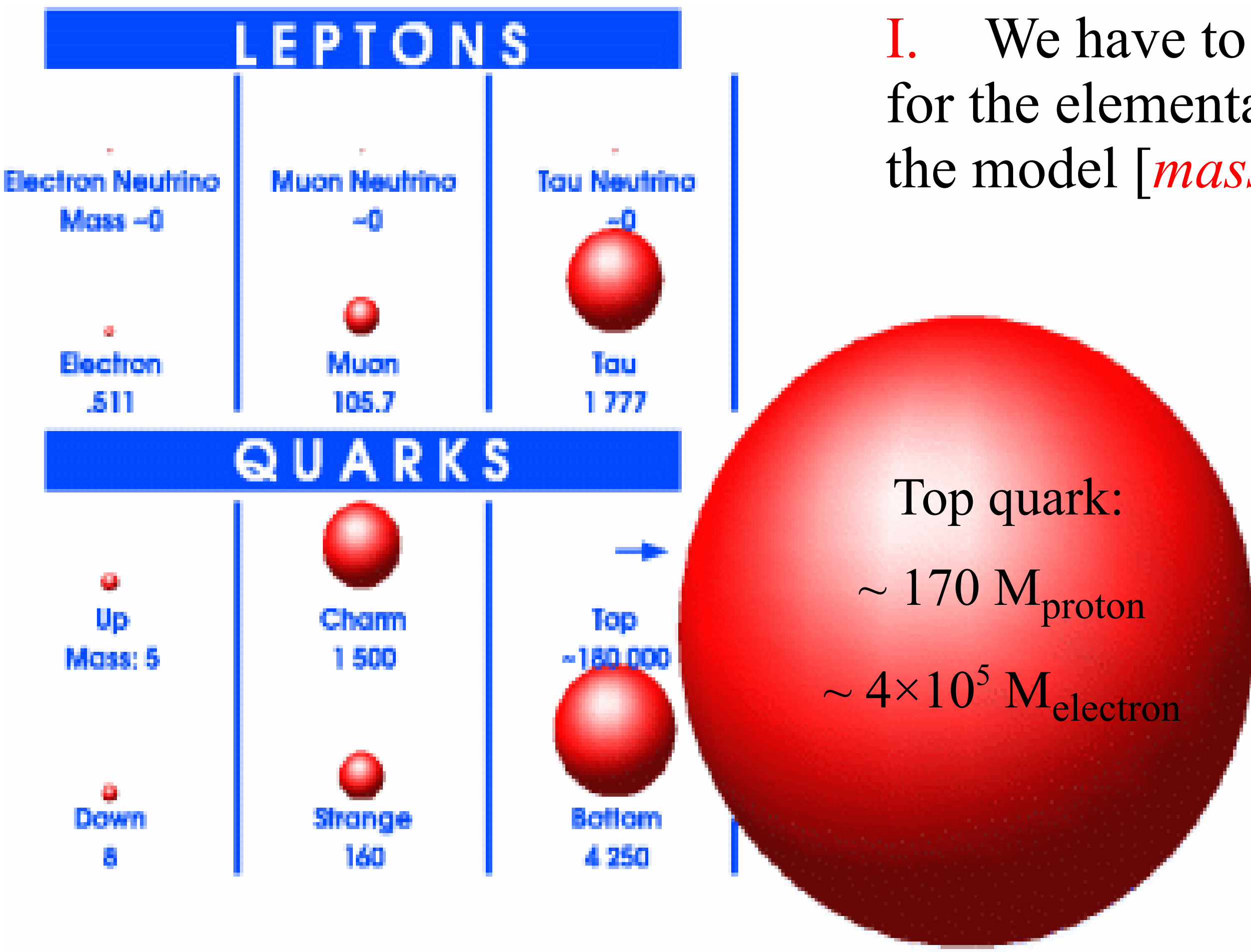

I. We have to understand how mass terms for the elementary fields can be included in the model [*mass problem*]

II. We have to understand why the 3 generations of quarks and leptons have so different masses [*flavor puzzle*].

The Higgs boson

Within the "Standard" version of the model, the mass problem is solved introducing a new field: the Higgs field

Elementary particle masses are then described as the result of the interaction of the various elementary fields with the background value of the Higgs field (~ *propagation in non-trivial medium*).

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Although this solution works from the technical point of view, it is not very satisfactory:

- The Higgs field is essentially a new interaction. However, contrary to the four "standard forces", it is not based on a symmetry principle. This is why the Higgs mechanism does not solve the problem of why each particle has a different mass (*it does not allow us to predict/compute particle masses*) and this is why we suspect it is only an *effective description* of something more fundamental.

The Higgs boson

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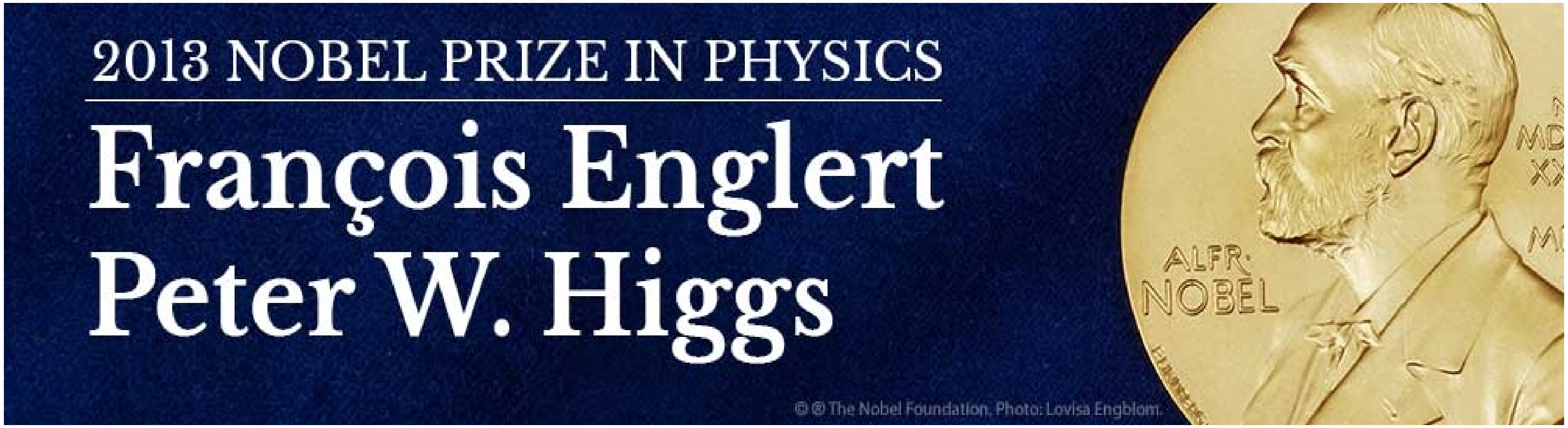
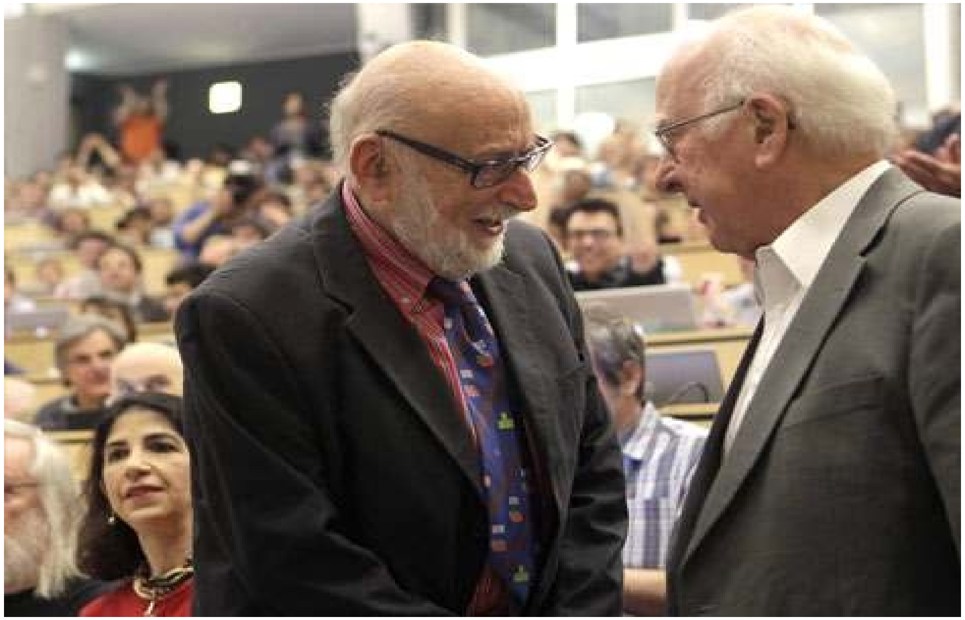
For several years alternative theories have been proposed, but the the 4th of July 2012 the LHC experiments at CERN have finally demonstrated the existence of a particle compatible with the excitation of such filed, the famous Higgs boson (*the "wave" of the "Higgs field"*...)



The Higgs boson

Pictures from the 4th of July 2012 at CERN...



V. Open problems

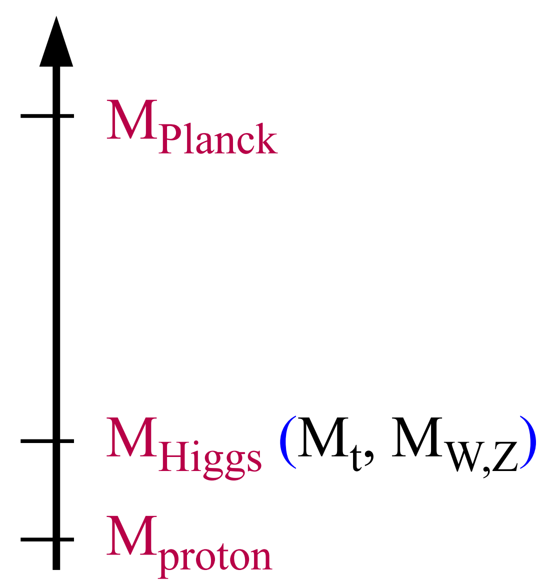
The origin of mass

The discovery of the Higgs boson is certainly a great triumph for the Standard Model. But there are a few important questions that are still open:

The Higgs boson mass (non predicted within the model) turns out to be $M_{Higgs} \sim 126$ GeV. This is the only fundamental scale of energy within the Standard Model.

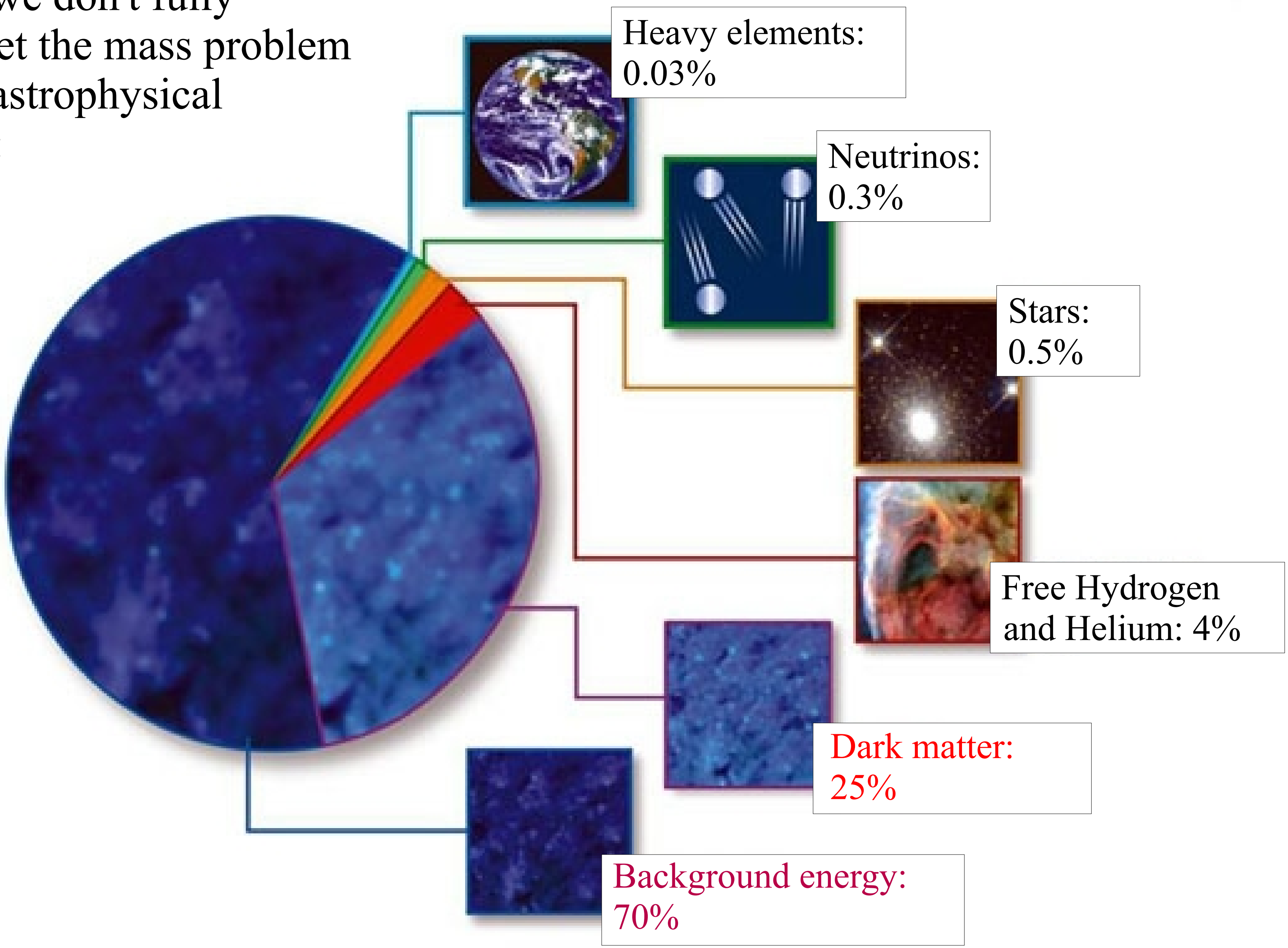
This energy scale is much higher compared to the proton mass, but is still well below $M_{Planck} \sim 10^{19}$ GeV (*the universal energy scale associated to gravity*)

- Why $M_{Higgs} << M_{Planck}$?
- Can we extend the validity of the model up to energies $\sim M_{Planck}$?
- What determines the coupling of the Higgs boson to the various particles?
- ...



▶ The origin of mass

A clear clue we don't fully understand yet the mass problem comes from astrophysical observations:



The origin of mass

Hopefully, a more accurate study of the properties of the Higgs boson will allow us to shed some light on some of these questions (*or at least to some of them...*).

A first interesting answer has been obtained by the precise measurement of the Higgs-boson mass:

- Can we extend the validity of the model up to energies ~ M_{Planck} ?

The answer is “yes”

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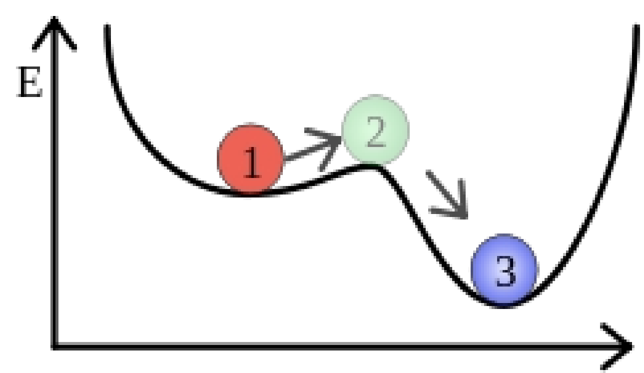
The answer is "yes"... but the situation is rather peculiar:

The Higgs-boson mass is the last "free parameter" of the Standard Model. Knowing it, we can now compute how the model behave at large energies. And the measured value is very peculiar:

- In absence of new phenomena (or new fields) <u>*the Standard Model is unstable:*</u> the Higgs field could move to a different configuration, more favorable from the energetic point of view (*with dramatic consequences for the whole Universe...*)



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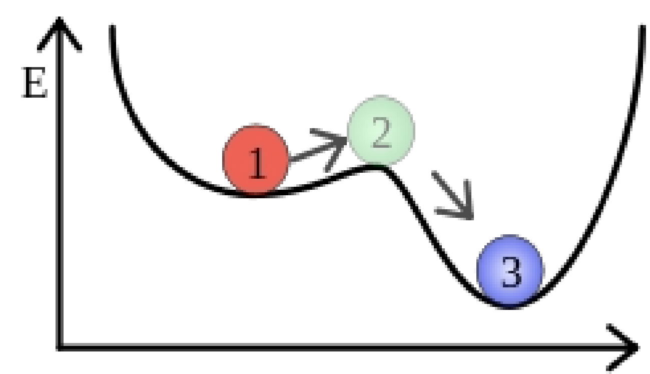
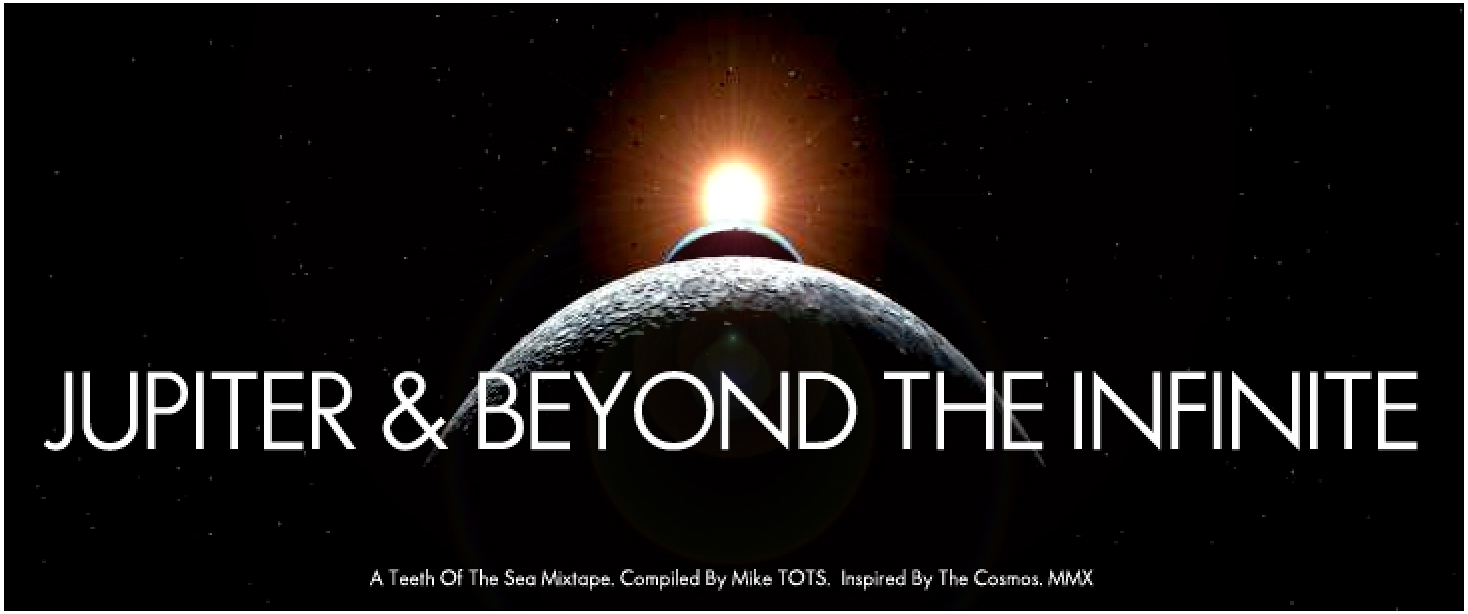
- In absence of new phenomena (or new fields) *the Standard Model is unstable*
- *But the life-time* of this (unstable) configuration *is much longer than the present age of the Universe.* So the model can survive up to very high energies without problems.



VI. Beyond the Standard Model



Beyond the Standard Model

Two main directions:

The anthropic principle

("Chance and Necessity" [J. Monod])

New symmetries

("The book of nature is written in a mathematical language, where the characters are triangles, circles, and other geometircal figures..." [G. Galilei])

Beyond the Standard Model

Two main directions:

The anthropic principle

The two basic ideas of this approach are the following:

1) The "free parameters" of the Standard Model are unpredictable dynamical variables that can change giving rise to different universes.

2) The presently measured values of such couplings are what they are, because only for such values is possible to develop an "Anthropic Universe".

New symmetries

So far, the identification of universal symmetry principles has been the main road to understand, simplify, and predict, natural phenomena (*starting from Galileo...*)

Proceeding along this way, it is natural to expect that the free parameters of the Standard Model, and particularly the couplings of the Higgs field, are "calculable" in terms of new symmetry principles (*non yet identified*)

→ *new interactions* & *new particles*

Beyond the Standard Model

Two main directions:

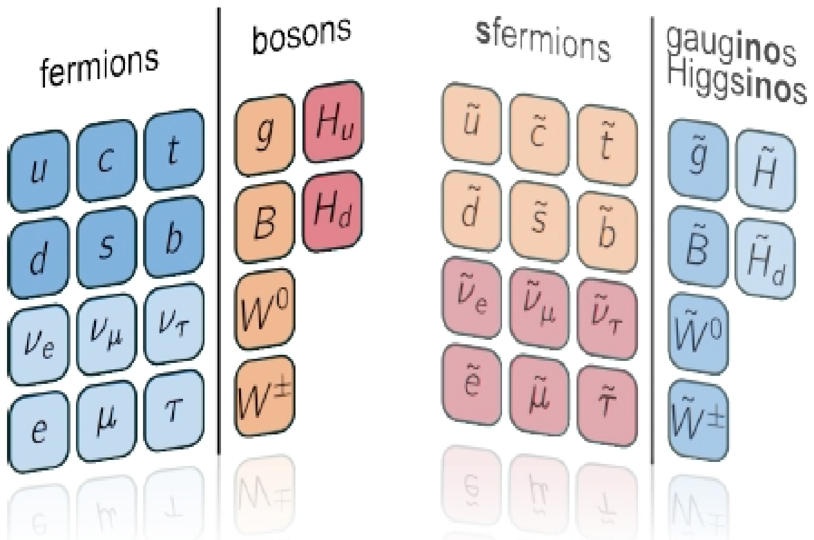
The anthropic principle

New symmetries

The so-called "super-symmetry" is probably the most interesting idea among the proposals to extend the model introducing new symmetries

The "super-symmetric" extension of the Standard Model implies that

- For each SM particle there exists a new particle with same properties but different spin [e.g.: electron (s=1/2) ↔ s-electron (s=0)]
- These new particles should have masses in the 1000 GeV range: if this hypothesis is correct, they could be observed at the LHC in the near future.



Beyond the Standard Model

Two main directions:

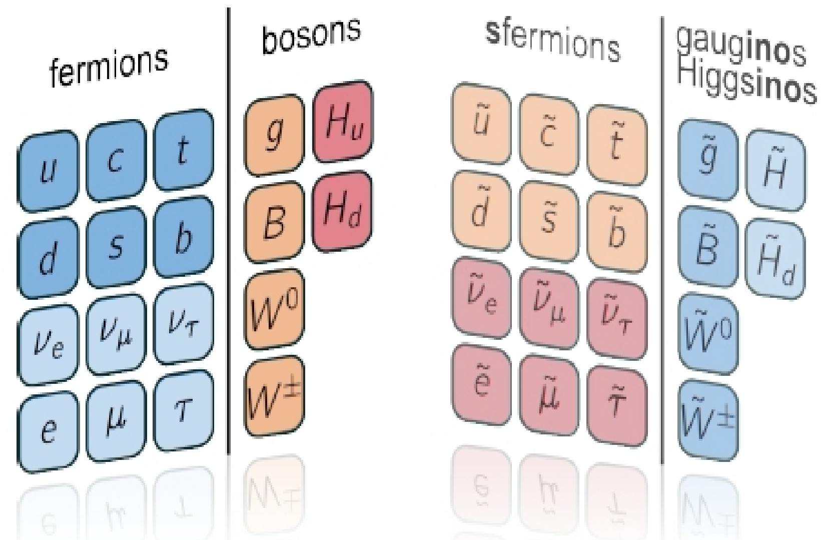
The anthropic principle

New symmetries

The so-called "super-symmetry" is probably the most interesting idea among the proposals to extend the model introducing new symmetries

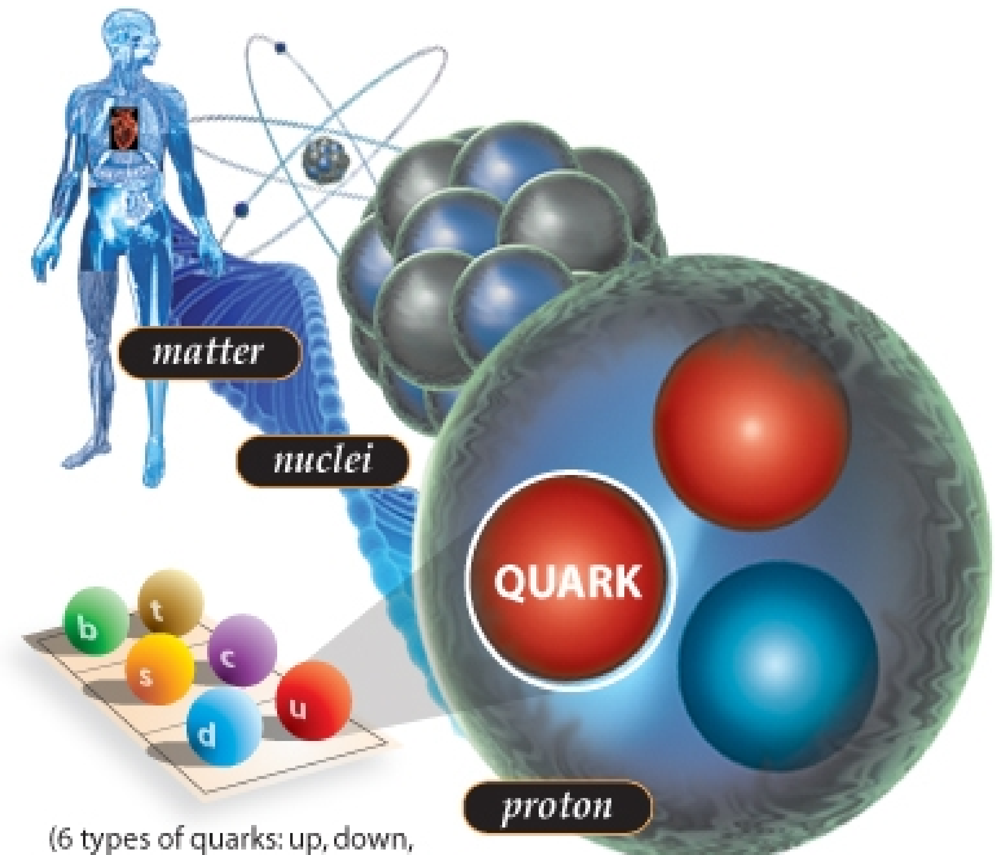
The "super-symmetric" extension of the Standard Model implies that

- For each SM particle there exists a new particle with same properties but different spin [e.g.: electron (s=1/2) ↔ s-electron (s=0)]
- These new particles should have masses in the 1000 GeV range: if this hypothesis is correct, they could be observed at the LHC in the near future.

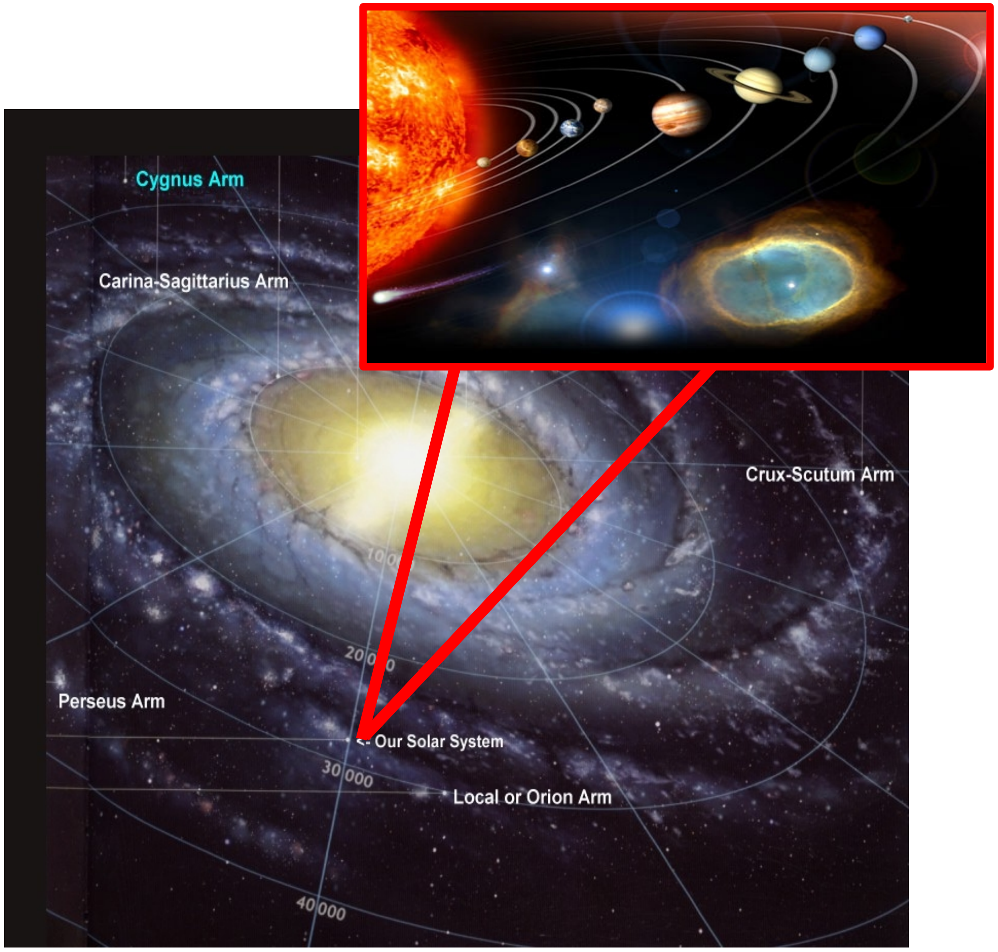


...but right now this is only a theoretical speculation !

VI. Conclusions



(6 types of quarks: up, down, charm, strange, top and bottom)



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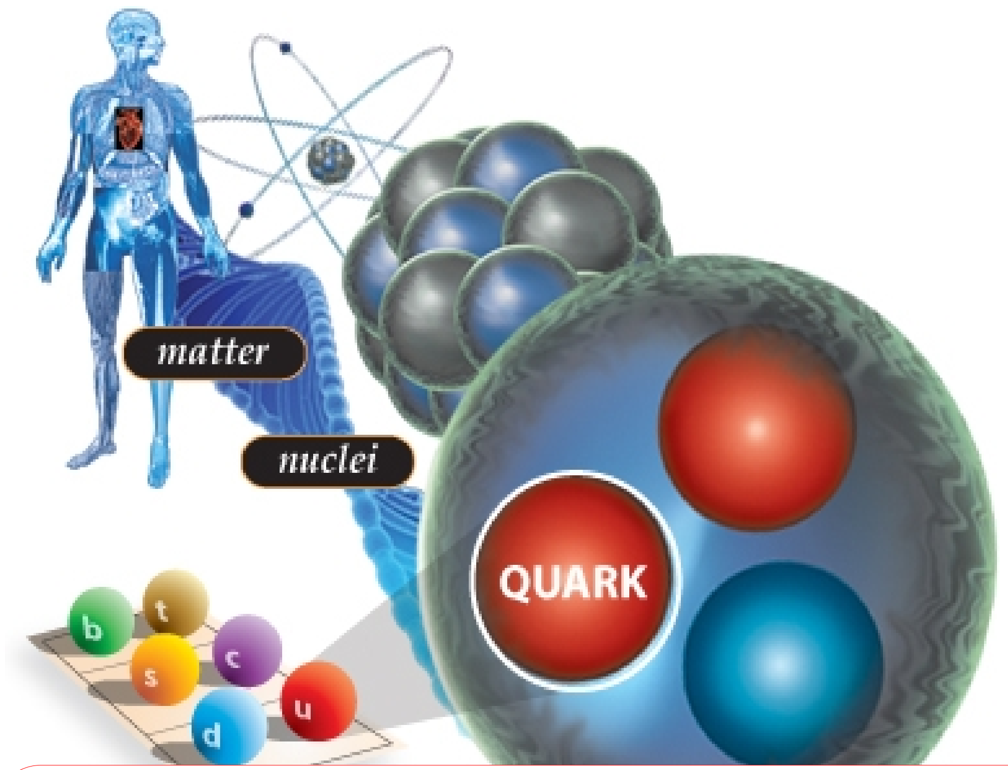

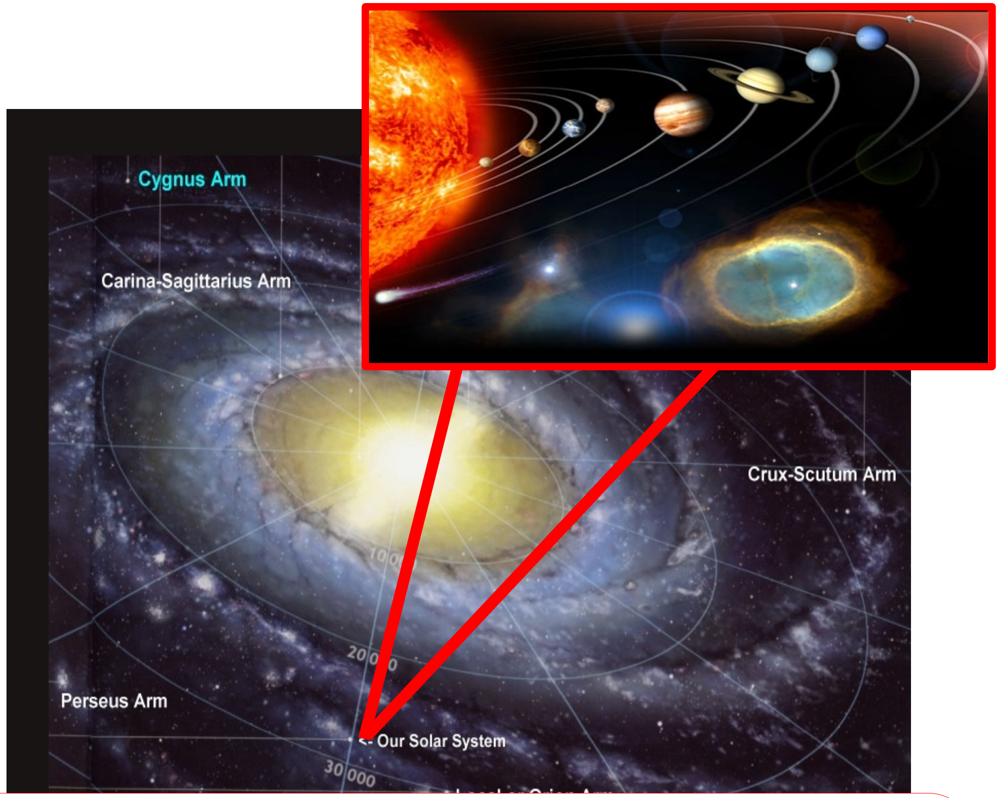

We are crossing a frontier in the study of fundamental interactions:
We don't know yet what's beyond the frontier, and even how difficult will be to cross it... but it is clear that there is still a lot to learn!