Modern Physics

An open discussion on some basic concepts

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Overview (First Part)

- The Scientific Approach - the importance of time
- What is a Scientific Theory?
- mathematical models of linear systems
- Linearisation of a complex system
- The Nature, The measurement, The error
- Introduction to SM

Overview (Second Part)

- What is Standard Model? introduction to some basic concepts
- Quanta
- Discretisation (?)
- Fields
- Spin

Overview (Second Part)

- Matter and gauge fields
- Constraints of Relativity
- Force carriers and SM

Scientific Approach

Physical Science

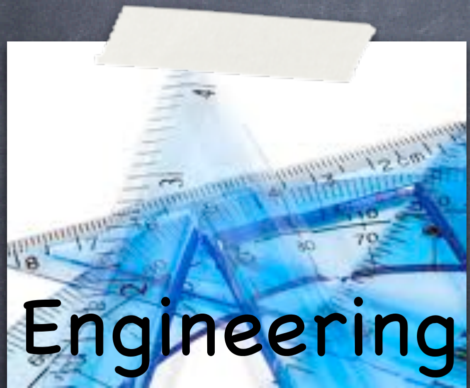
- In the next slides we will discuss about physical sciences
- What is a physical science?
- Simply a science based on physics

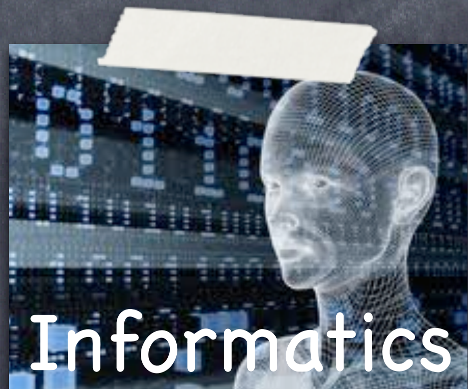
Physical Science

- The concept of physics is strictly related with the concept of time
- So...

The basic concept

- The basic concept which unify all physical sciences branch is only one

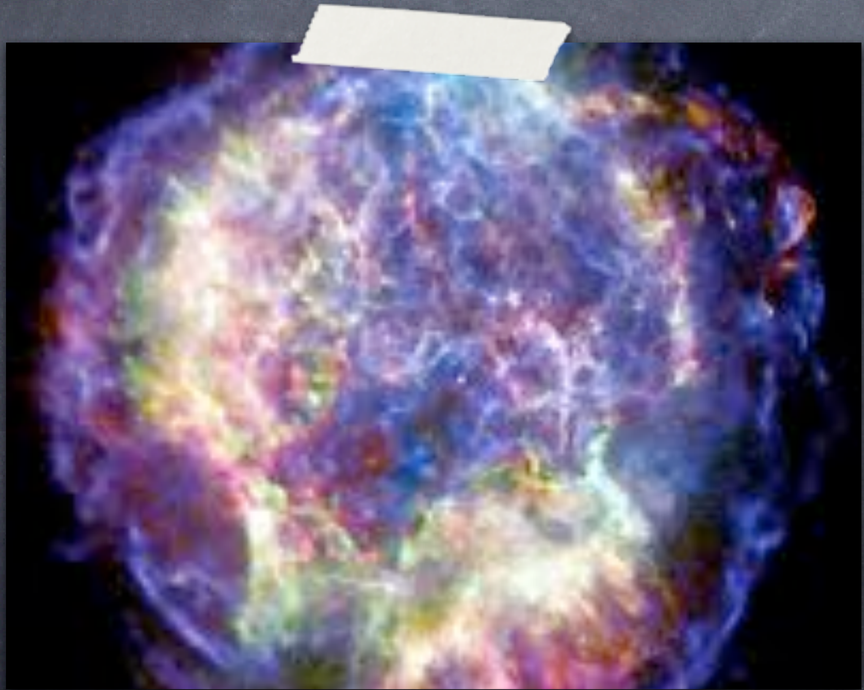




WHY?

What is Science?

What is the aim of a physical science?
(usefulness)



What is the pillar of a physical science?

Scientific Theories

- In your point of view what is a scientific theory?
- What should it do?
- What thing makes a Theory "Scientific" ?

Predictability (time)

- The aim of a scientist is the same aim of a wizard, or of an stargazer:
- Make previsions on the future!

- <u>This is the reason why in history astrology and science were often the same thing</u>

- But Why today no stargazer or wizard works, for example, at LHC?
- Why we can trust in a scientific theory and we are less confident with an horoscope?

Basic questions

- A Scientific theory answer to a precise question: Giving a physical system right here and now, what will be its evolution?

- But you can say that even an horoscope can answer to a similar question: giving a human being born in an certain date (physical system right here and now), how will be its love affairs in a week? (evolution)

So, where is the difference?

Errors!

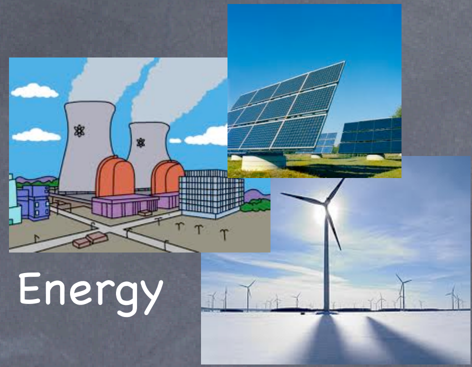
The errors! A scientific theory ever knows how much big is its error in the previsions!

Is possible to quantify the errors with numbers!

You cannot say the same thing for an horoscope!

Effects of this difference

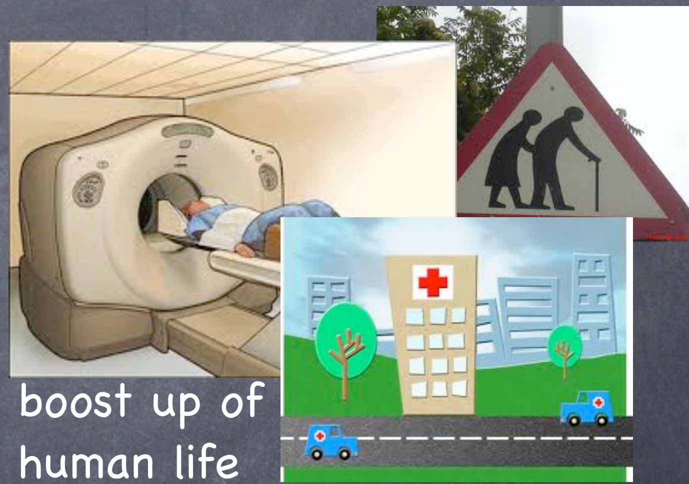
- From science today we have:
- Nobody here says that thrusting horoscope is wrong...
- But surely is not useful!!! and not of our interest!!!
- Thanks to the science our life is more simple and surely more comfortable!



Energy

Light, heat

food



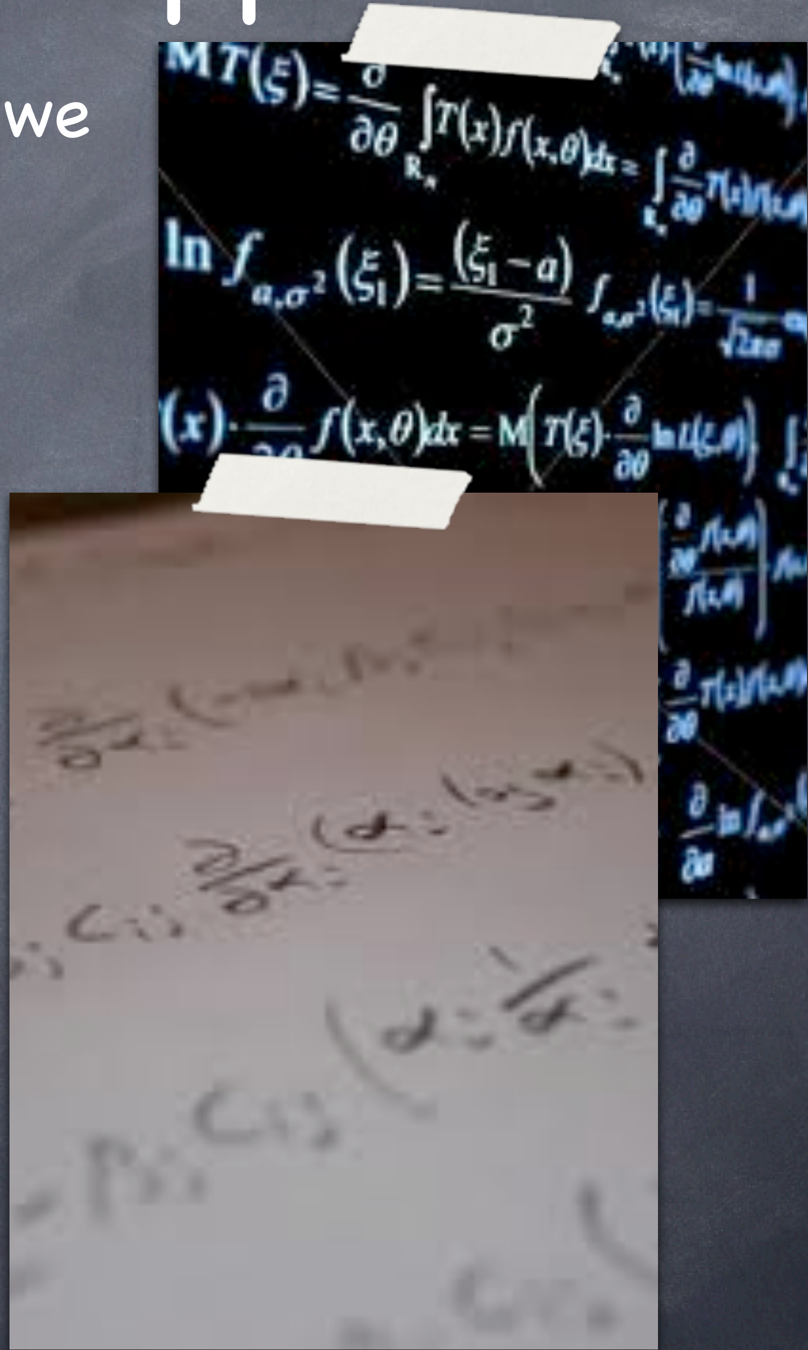
boost up of human life

computers, cells, tvs

Mathematical models

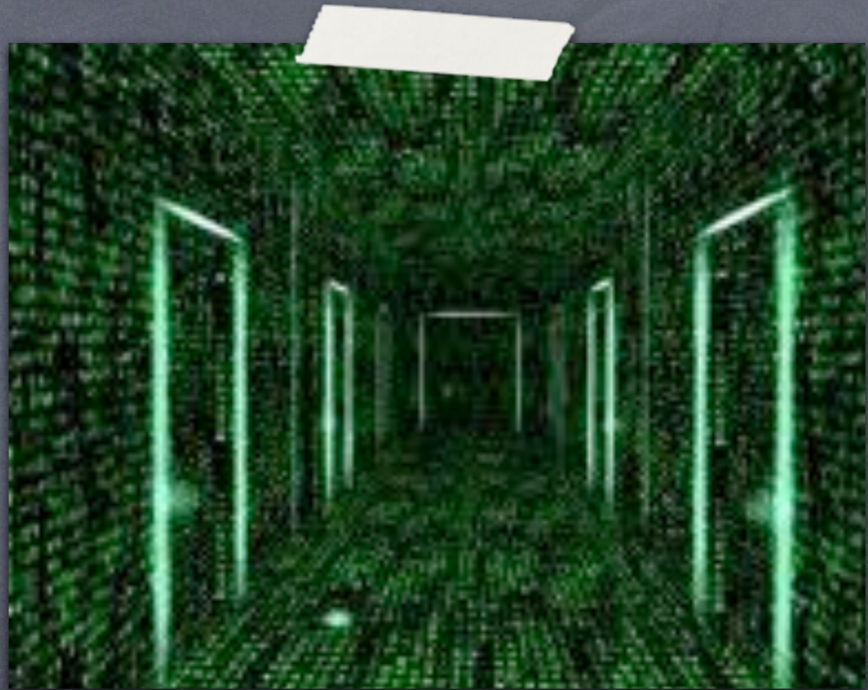
Mathematical approach!

- How is it possible? How can we have knowledge of errors?
- Primary question: Why do errors exist?
- Answer: because we use mathematical models to study the nature and make previsions!
- Key concept: measurability of the nature -> measurements allow us to express through numbers physical phenomena!



Nature: a complex system

Making mathematical model of the nature is very difficult!

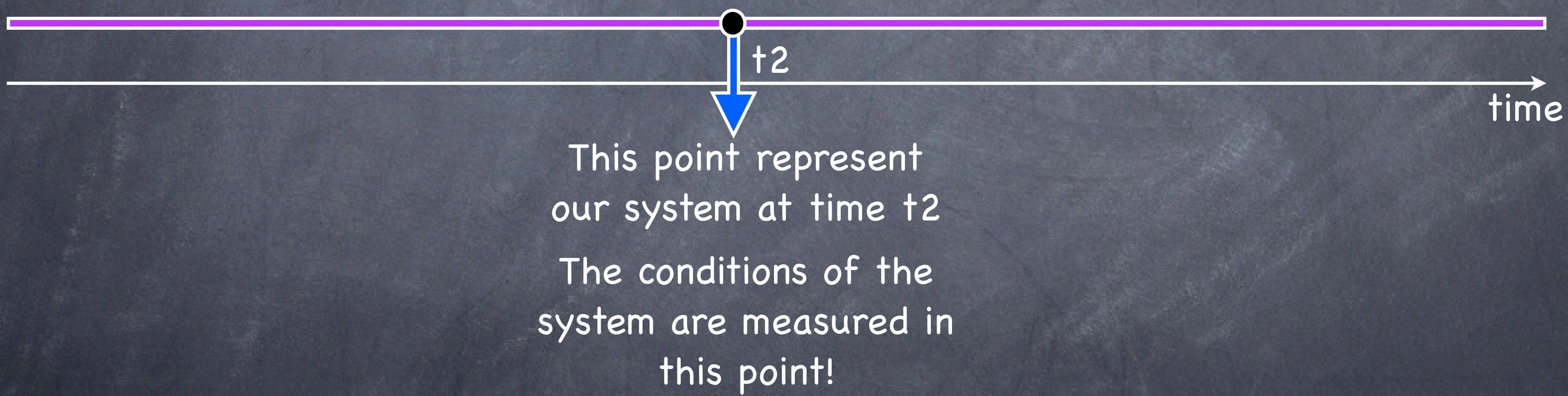


We succeeded to apply mathematics only to simple systems:

Linear systems

Linear System

- What is it? Consider a line which represent the physical system at different times



Linear System

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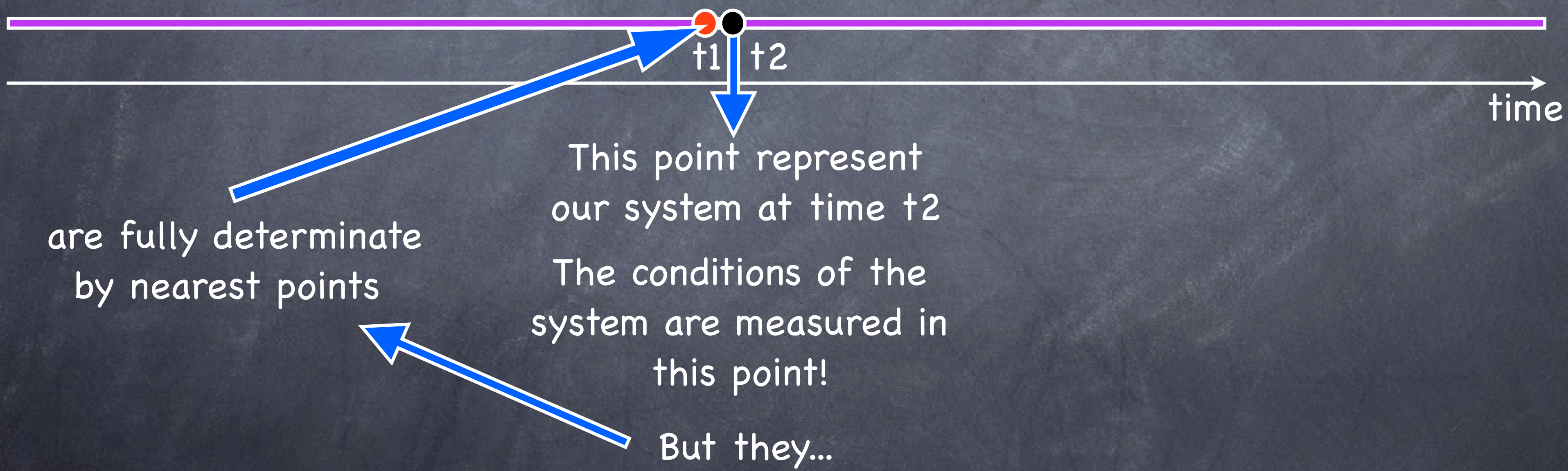
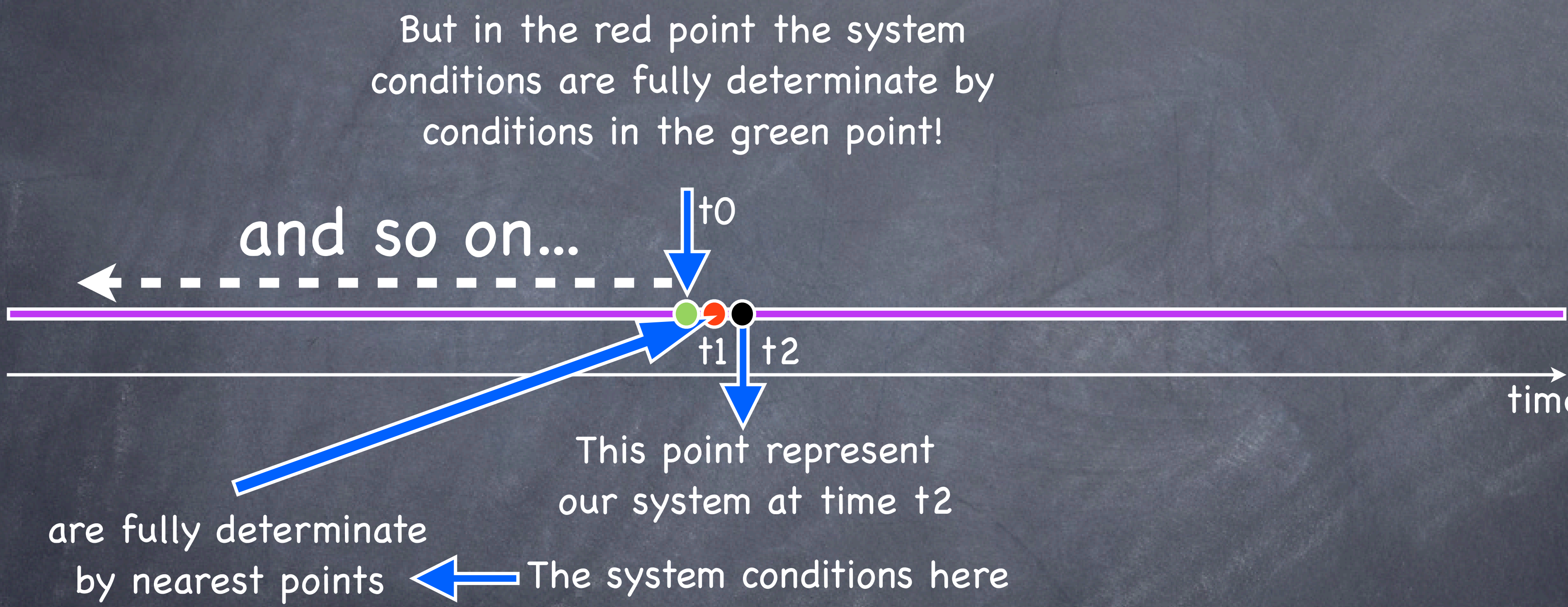


Linear System

- What is it? Consider a line which represent the physical system at different times



So, if we are able to write an equation for the small evolution between two point...

We can know all the system conditions at every time: in the past, in the present, and in the future!

Note that the equations for the small evolutions will have all the same form!

Birth of errors

- Up to now we haven't errors. But now we have to make a consideration
- Nature isn't a linear system! Is a complex system (holistic)
- What does it mean?
- Consider the line of the previous case, and think the line like a wire which we stretch by hands
- Nature is made of a lot of this wire rolled together

- Roll

- So Nature is made of a lot of systems collected together, which interact each other

Studying the roll...

- We can study the roll applying mathematical approach as we see for linear systems?

- <u>In general no!</u>
- If we consider a single wire of the roll and focusing our attention on one point of the wire (say p1), the conditions are determinate not only by nearest points on the wire, but also by nearest points of other wires close to p1!
- Making some mathematical model is too complicated!
- How to solve the problem?

Linearisation!

- What is it?
- Recipe for linearisation:

  - Take the roll
  - take the end of one wire
  - pull till the extraction of the wire from the roll
  - Stretch the wire by hands
  - And then goes to study the wire!!!!
- Now we are able to build some mathematical model of the system
- But these models are approximations... why?

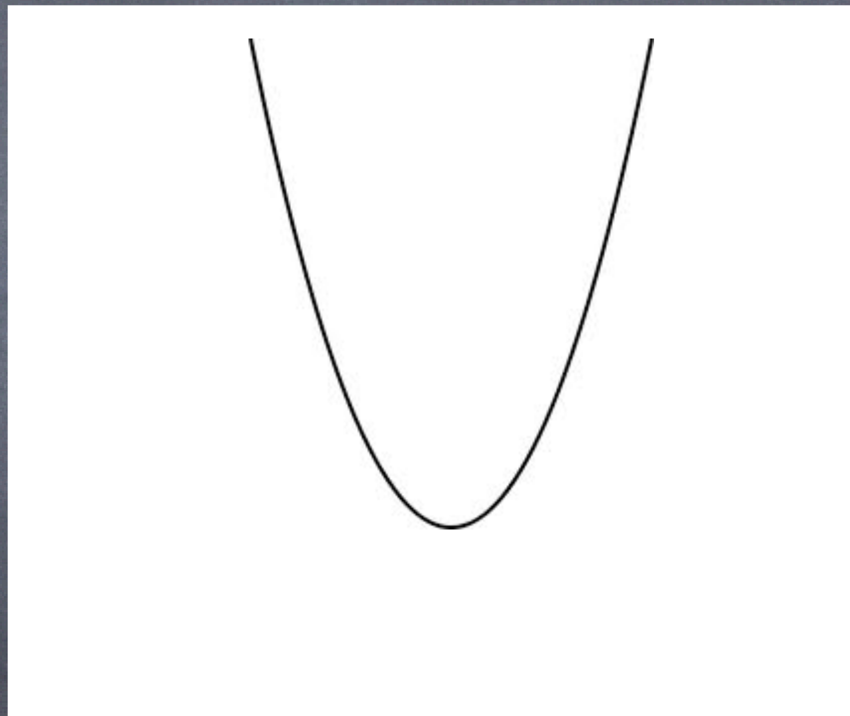
Approximation

Approximation because we aren't considering the other points of the other wires close to p1, which affect our system

We have a good approximation if the effects induced by these other points are smaller than the effects generated by nearest points to p1 on the wire

Approximation: mathematical point of view

Considering a physical system described by this parabola



Suppose that we don't know the parabola equation

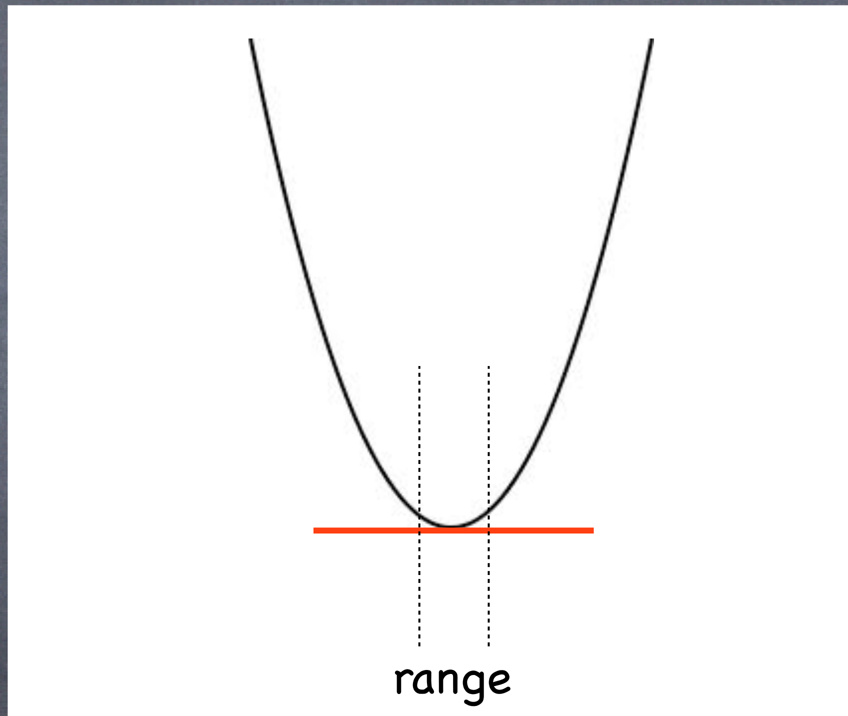
but we know only line equation...

Approximation: mathematical point of view

Considering a physical system described by this parabola

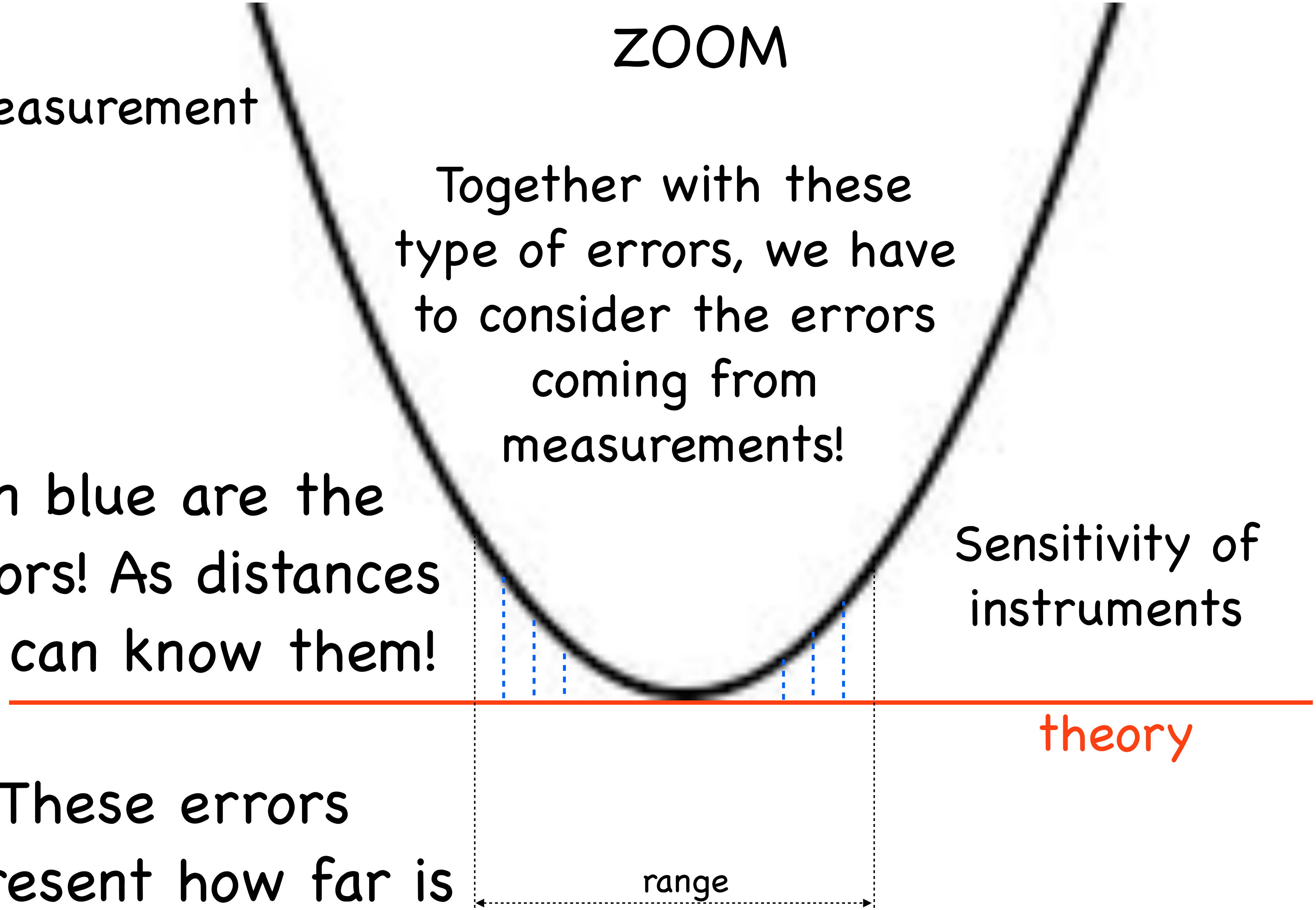
Suppose that we don't know the parabola equation

but we know only line equation...



We can approximate the parabola in a little range with a line!

ZOOM



Together with these type of errors, we have to consider the errors coming from measurements!

In blue are the errors! As distances we can know them!

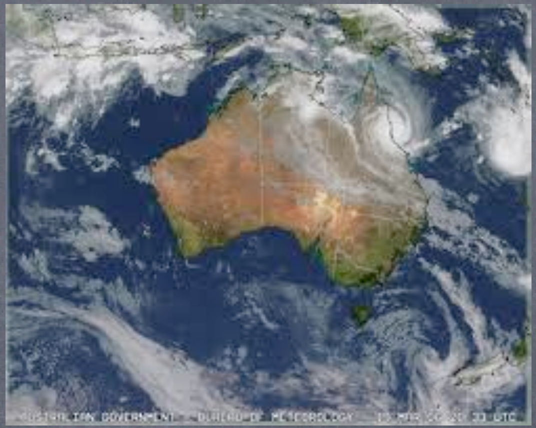
Sensitivity of instruments

These errors represent how far is our theory from the real system!

<u>In other words how good will be our previsions!</u>

Meteorology

- From the previous case we can understand why meteorological previsions are reliable only in a range of one or two days...



- If we expand the range of the approximation (time), errors blow up!

Goodness of a scientific theory

- A scientific theory is good if it makes good previsions with small errors!
- From this definition a question:
- Suppose that I build a scientific theory which explains the attraction between two planets...
- ...and the basic mathematical model which I use is a set of equations which describes two giant smurfs playing at tug-of-war planet by planet...

- Smurfs
- Tug-of-war

Goodness of a scientific theory

- And this theory allows to make very precise predictions on the evolution of two planets system...
- ...with errors smaller than the errors of newton equation...
- Is this theory good or not? Is scientific?
- And do the smurfs exist?

Goodness of a scientific theory

- This is a key concept to understand scientific theories!
- In principle you cannot say that the things described by a scientific theory are the same which are going on in nature! (in general yes, this is a little science philosophy!)

- Remind that science explain the "how", not the "why" something happen!
- If you want to know the "why", you have to go to a priest, to a rabbi or to a guru... or...

Anthropic principle

- I cannot answer to the question: "why" gravity exist! I can just explain "how" it works!

A possible answer to the Why: Because it is God's will

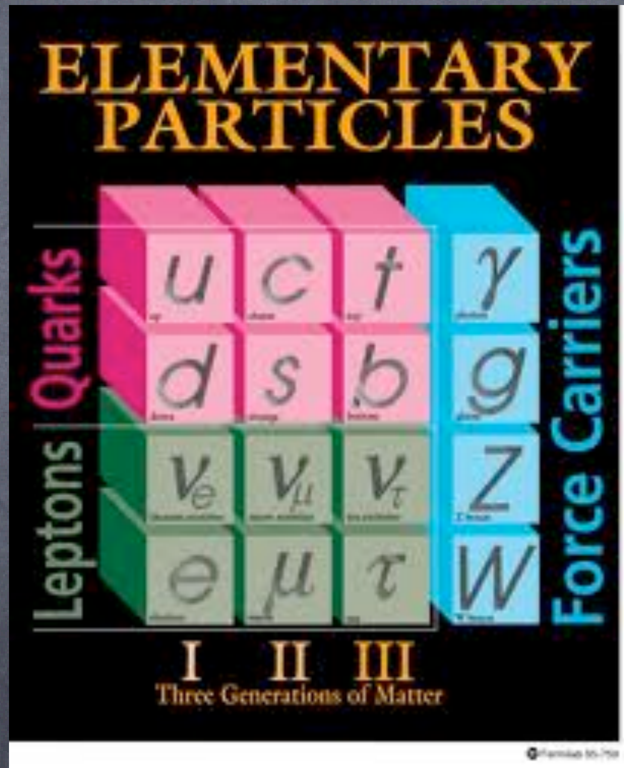
Another answer coming from Anthropic principle: the Universe (and hence the fundamental parameters on which it depends) must be such as to admit the creation of observers within it at some stage

- The key point of this discussion is: "why" isn't in the scientific interest, because we haven't any tool to understand and discover!

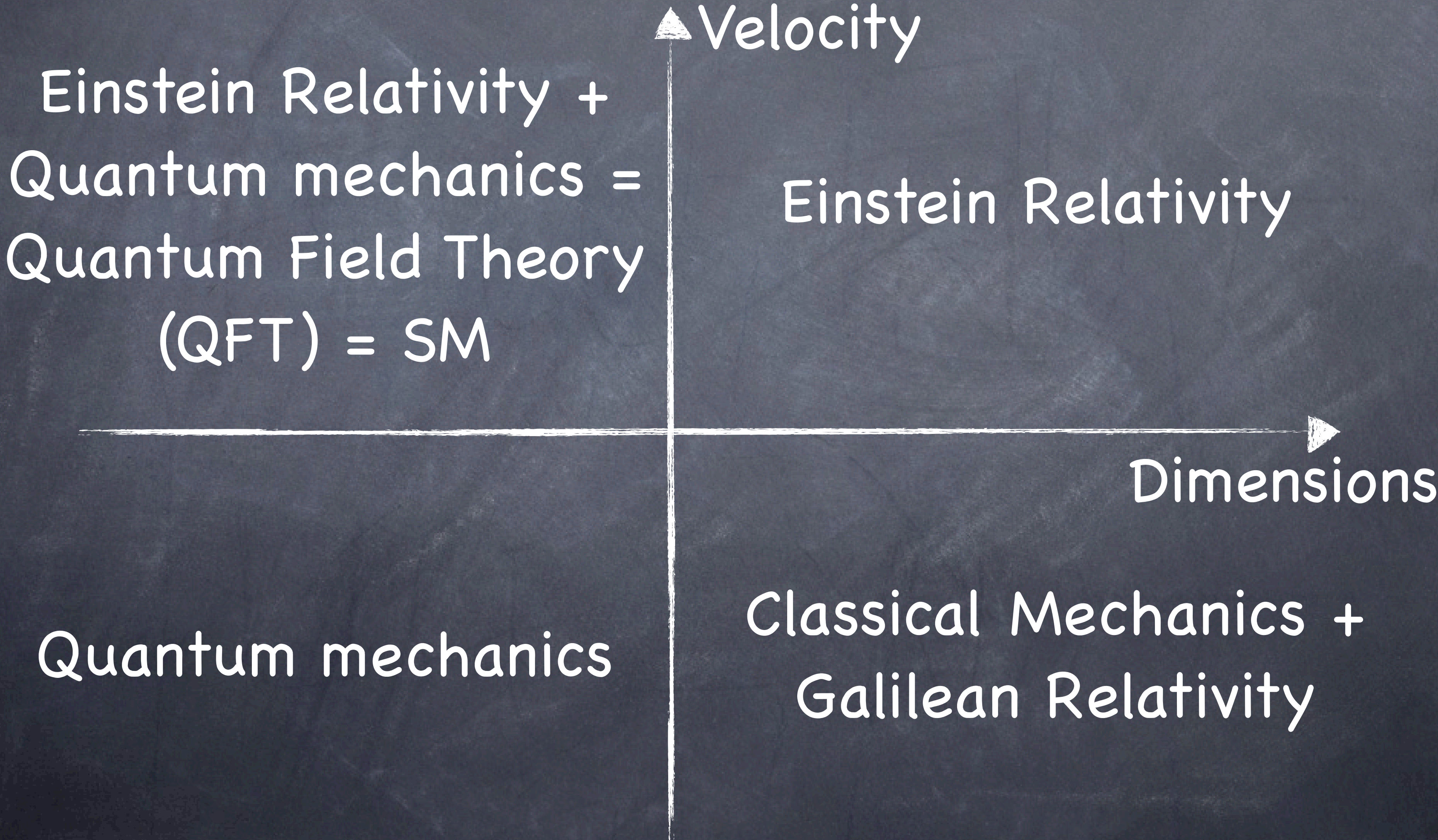
Basic concept of modern physics: pillars of SM

Standard Model (SM)

- Scientific Theory (mathematical model) which explain three of the four fundamental forces in nature...
- What are the fundamental forces in nature?



SM = Quantum Mechanics + Relativity



SM: basic concepts

Quanta

The smallest blocks of the nature

Quanta

- Suppose that our entire universe is this lego house

- And suppose you want to study the structure of our universe
- To do so, we start to disassemble the house... we find a lot of blocks of different dimensions

- The smallest block is a quantum! Nothing in our universe is smaller than a quantum!

Quanta

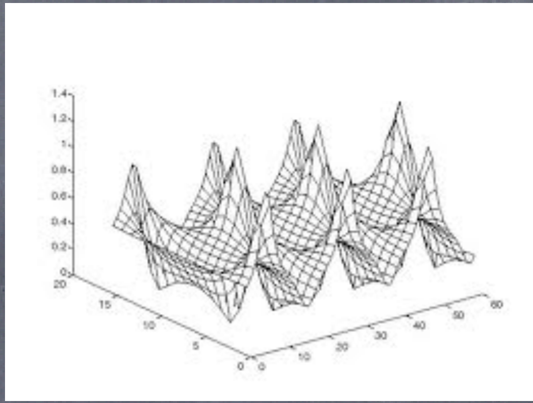
- But, how much small?
- In mathematics a key concept is a quantity which can be as small as you like (called ε)... You can say that ε is near to 0 as much as you want! ε could be 0,001 or 0,000000001 or 0,00000000000000000000000005... (we say that ε is INFINITESIMAL)
- Can we associate ε with a quantum in nature? NO!
- Why not? In nature quantum is the smallest block, but it isn't as small as you want! It has finite dimensions (the smallest block of lego is small, but it has precise dimensions!!!!)!!!
- In Nature we speak about ENERGY QUANTA! Energy quantum is a very small energy. Very small, but FINITE!!!

Discretisation

Making a mathematical model of a discrete system

Starting to build...

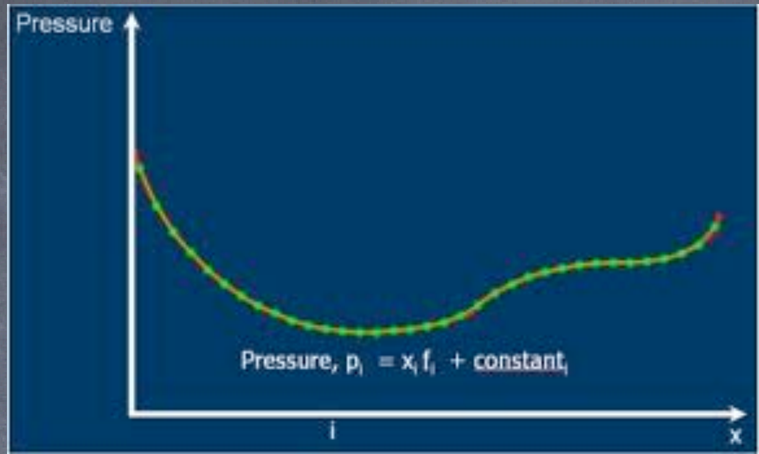
- In its infinitesimal structure, our universe has a discrete structure (is made of the smallest lego blocks - quanta)



- So we have to build some mathematical model reproducing this discrete structure
- From the mathematical point of view it isn't a trivial problem.
- In general, when we start from mathematics, a key concept is the CONTINUUM
- The concept of continuum make mathematics a very powerful tool, especially to study the nature!

Continuum

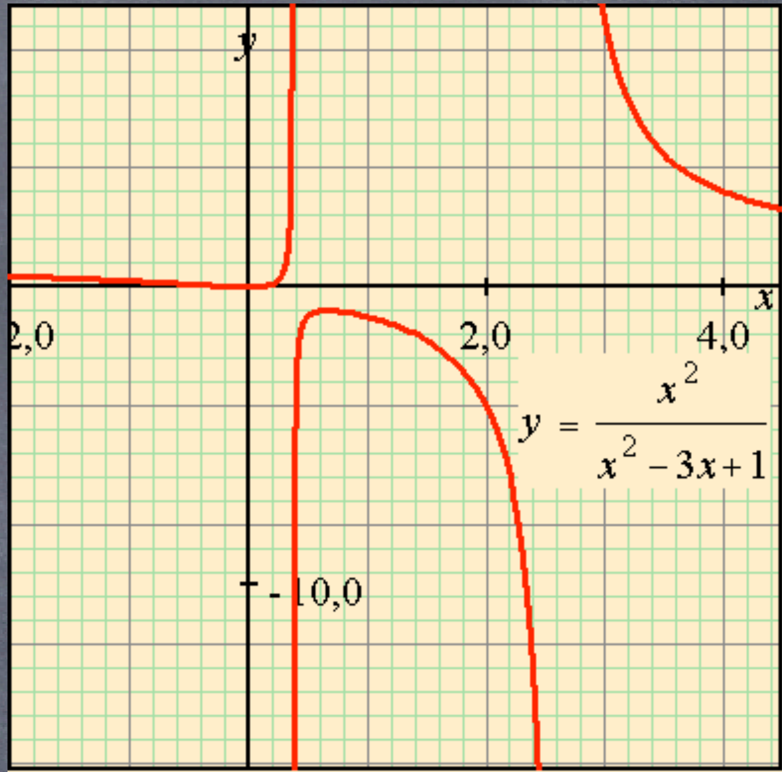
- What is the concept of continuum?



- Essentially, continuum tell us that in mathematics exists the concept of "as small as you like it"!
- In other words, in mathematics the quantity ε exists!!!
- You can say : "...and so? "

Continuum

- The existence of ε allows us, for example to draw a continuos function in the cartesian plane!
- A continuos function is a function that you can draw without raising up your pen from the sheet



- Without the existence of ε, every function which you draw, is only a sequence of disconnected strokes
- So the problem in describing the structure of nature is: starting from some continuos stuff (mathematics), how can I describe something discrete (made of smallest lego blocks)?

The problem of Representation

Nature - Discrete - (No ε)

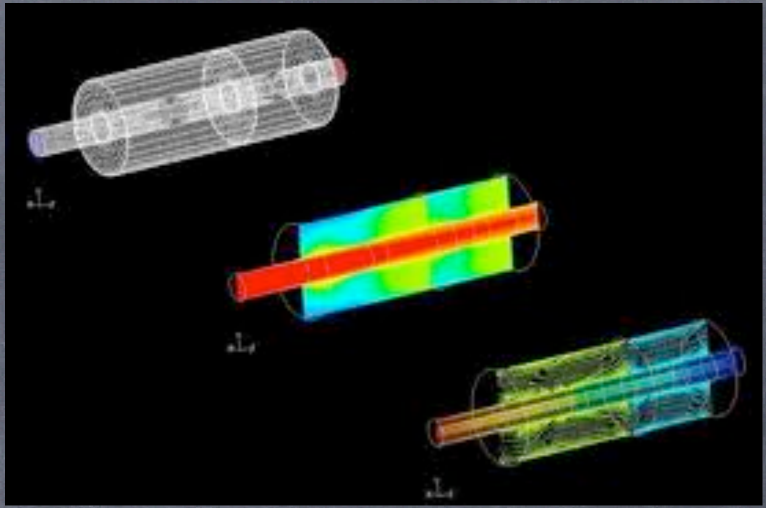
Representation

Problem! make a model of something discrete (nature) using a continuos tool (mathematics)

Mathematics - Continuos - (ε)

Discretisation

- To build the model we use the concept of discretisation



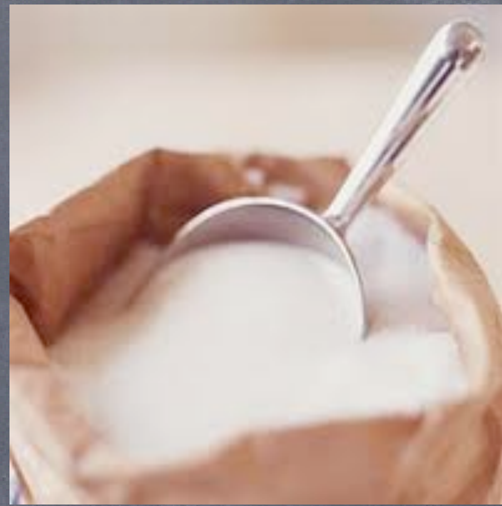
- Let's see How mathematics works...
- ATTENTION!!!! As we know, mathematics could work in a different way from how the nature works!!!
- Our interest are only the predictions of our mathematical model
- To understand the concept, let's see an example... a sweet example!

Discretisation

- Suppose to have a lot of sugar, say 100 Kg (continuum system), and you decide to sell it.

- In this way for example I can come to you and buy 100 g of sugar, or 467,4657383 g (with a very precise balance!), or 1,2378934 g, or what I want (In a continuos system ε exist!)...

Discretisation



- Suppose now that you decide to put the sugar into 100 bags of one kilo, and sell the bags.
- In this way I can buy 1, 2, 3 or n 1 Kg bags of sugar, but no 1,2378934 g of sugar!
- Using the bags you have discretised a continuum system - the same concept is used in the mathematical approach

Fields

Our representation of particles

The field

When someone will explain you SM, you will ear the word FIELD

What is a field?

To answer, consider what SM describes... SM predicts interactions between elementary particles

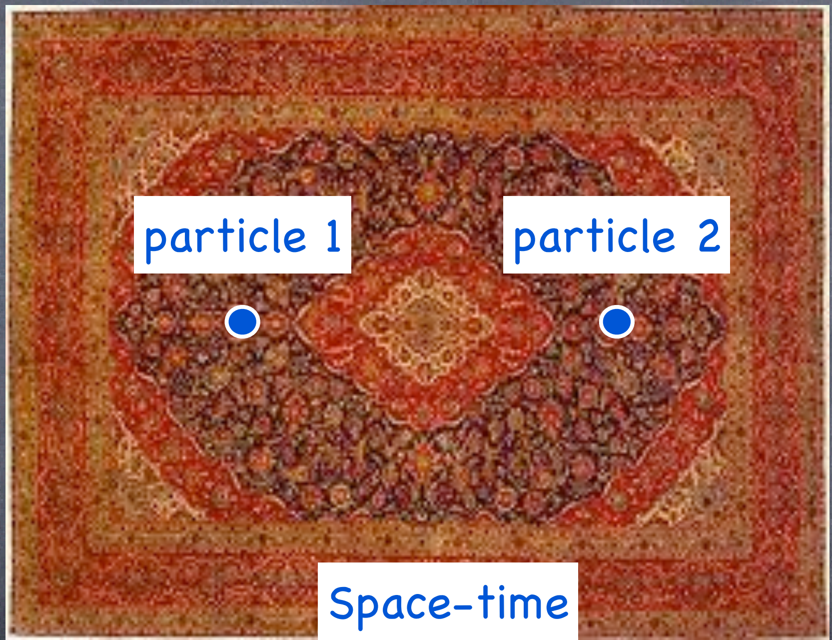
To do so, the starting point is the mathematical representation of the elementary particles...

A field is the mathematical representation of an elementary particle

To perform calculations about what's going on between two particles which interact each other, is a very useful concept...

Space-time

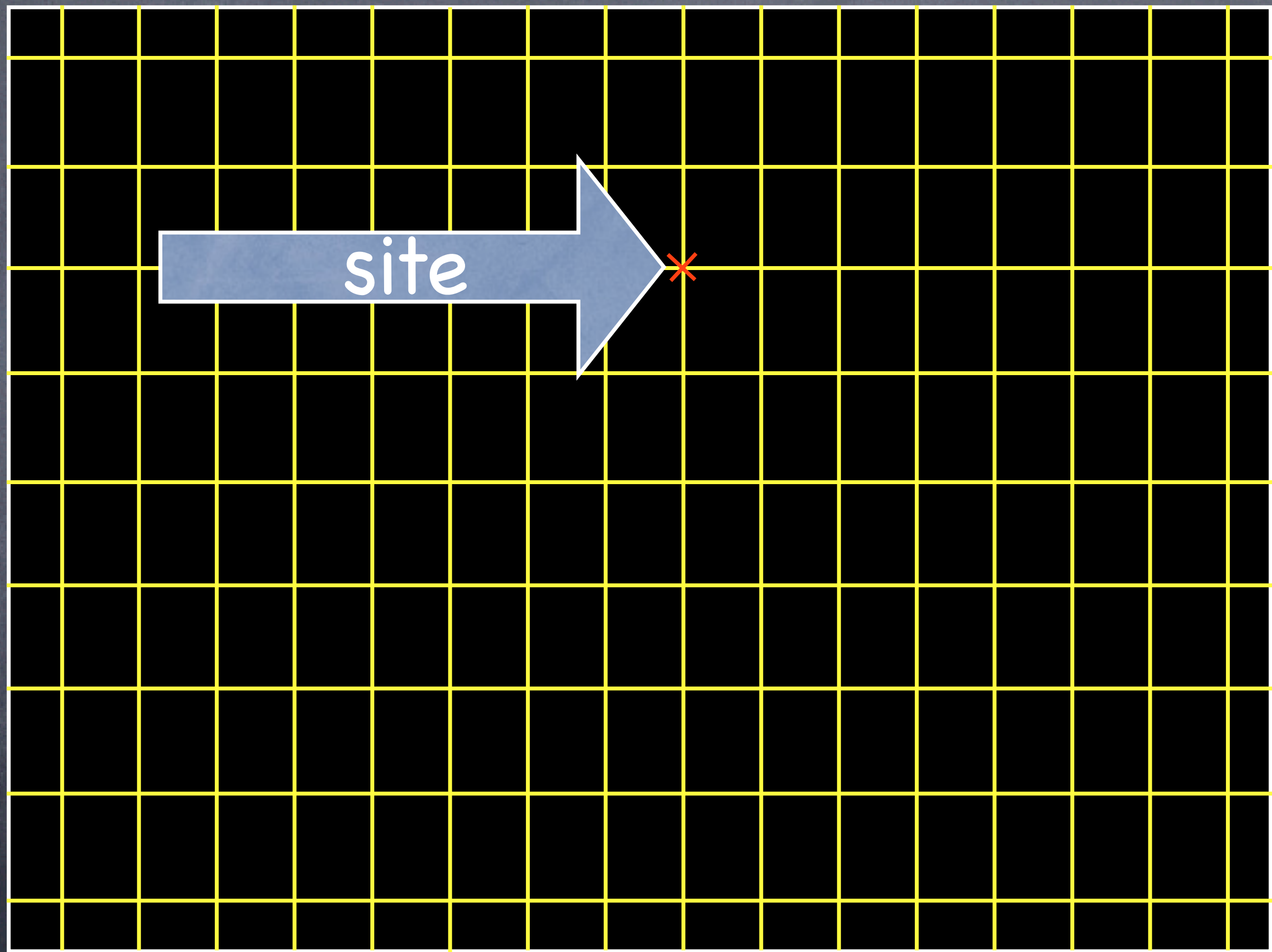
- Imagine the space-time as a big carpet, on which we have two particles...



- We have to start to build a mathematical model of the carpet...

Tha space-time

- We represent the carpet with the following lattice



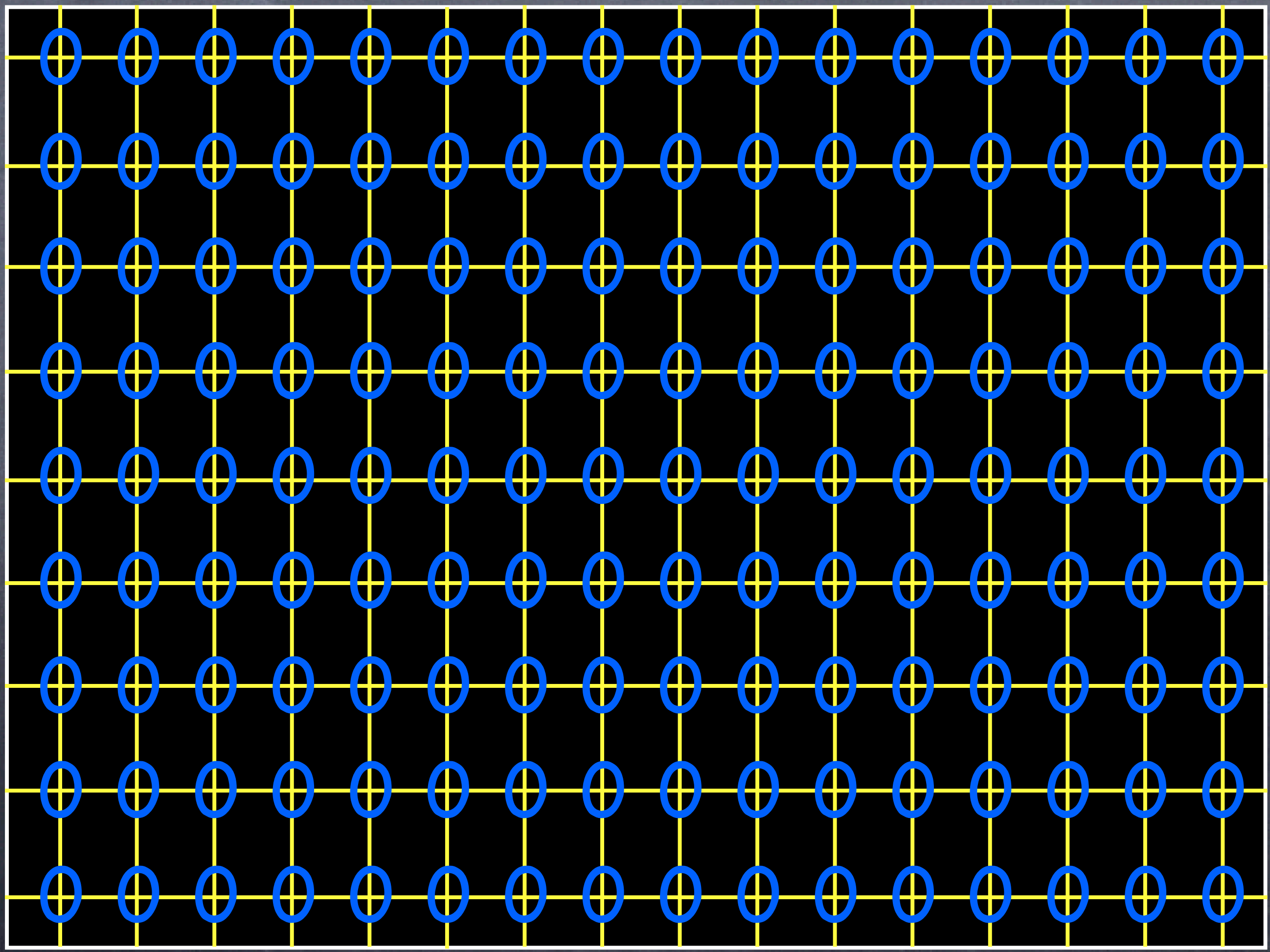
- Every site represent a point in the space-time...

The concept of the field

- A field is simply a function which couple every site with a number (or more...)

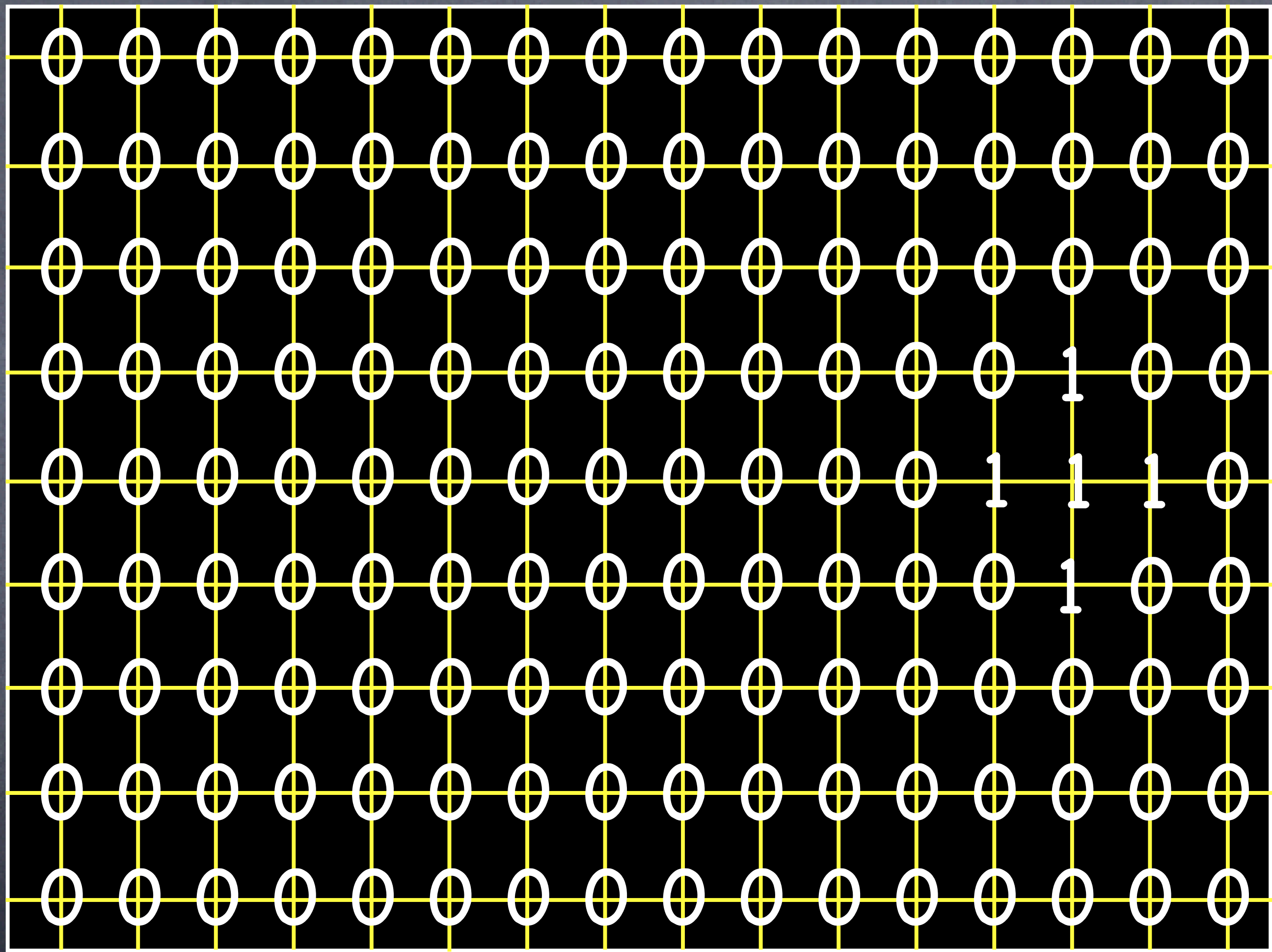
The vacuum field

- As an example, we can think to the vacuum field as the function which couple every site with a zero!



Particle field

- The particle field it isn't only the group of 1, but it is all! 0 and 1!

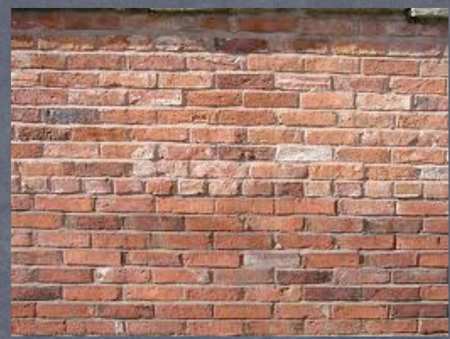


- A particle field is not localised in only one point of space time! it is extended to every point of space time!

Fundamental fields in nature

2 fundamentals fields in nature!

Matter fields (fermions)



Gauge fields (bosons)

The spin

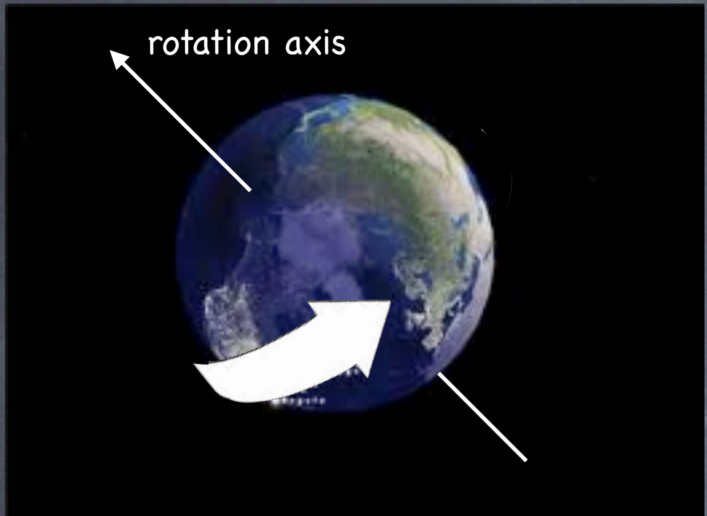
The difference between Fermions and Bosons...

Quantum numbers

- In order to describe particles we use the concept of the field
- To different kind of particle correspond different kind of field with different properties
- To describe field properties we use special numbers called QUANTUM NUMBERS (QN)
- The most famous quantum number is the SPIN

Fermions and bosons

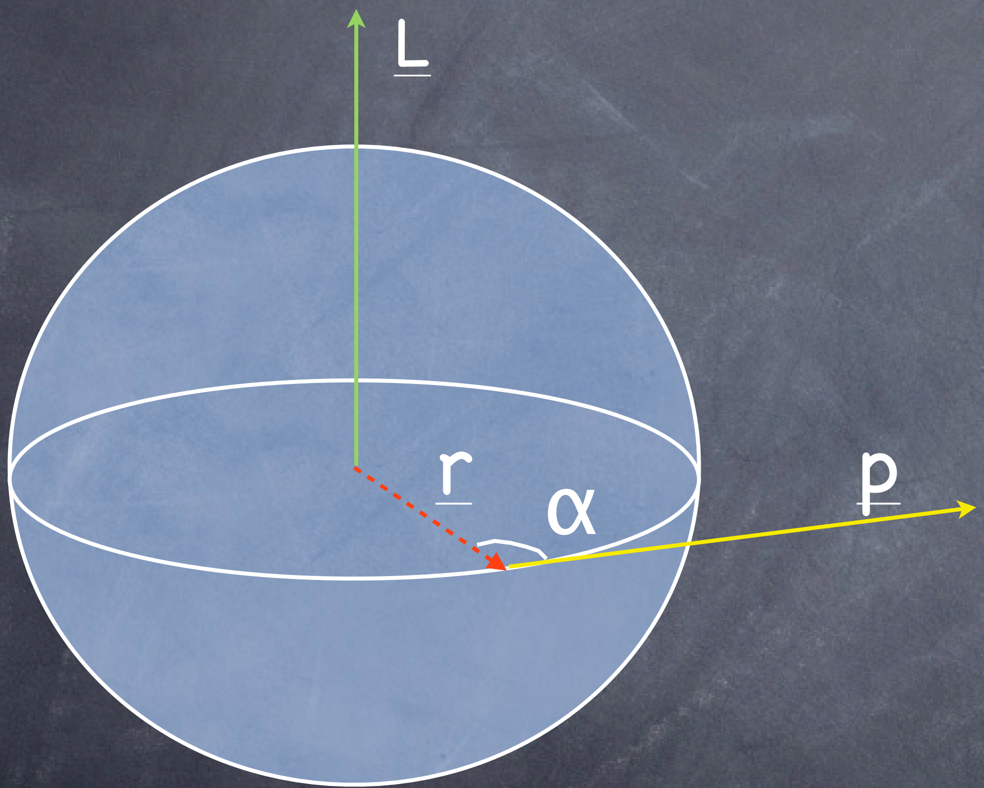
- Fermions and Bosons differ in the spin!



- What is the spin?
- Spin is the quantum analogous of angular momentum L
- What is L: Consider the Earth. It turns around its rotation axis
- We use the concept of angular momentum to quantify the rotation (remind the measurability of the nature!)
- definition: $\underline{L} = \underline{r} \wedge \underline{p}$
- L is a vector! (an arrow in the space with a definite length!)

Vector product

$\underline{L} = \underline{r} \wedge \underline{p} = r \cdot p \cdot \sin(\alpha)$ What does it mean?

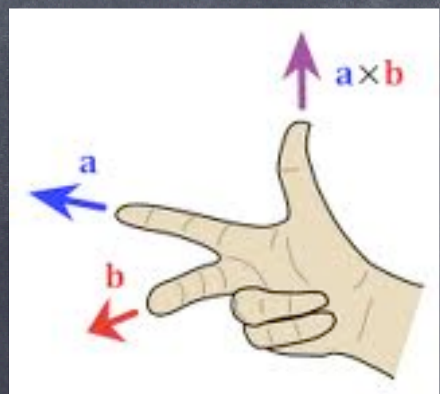


When I write:

$\underline{L}$, $\underline{r}$ and $\underline{p}$ are vectors: with their lengths and a precise direction in the space!

L, r and p are only the lengths of the vectors

L is ever orthogonal to r,p plane!



Right hand rule

Units of measurement

- $\underline{L}$ have to quantify the rotation (of our planet in this case)

- What are the right units of measurements of $\underline{L}$?

$$\underline{L} = \underline{r} \wedge \underline{p} = r \cdot p \cdot \sin(\alpha)$$

r = distance = m

p = momentum = m·v

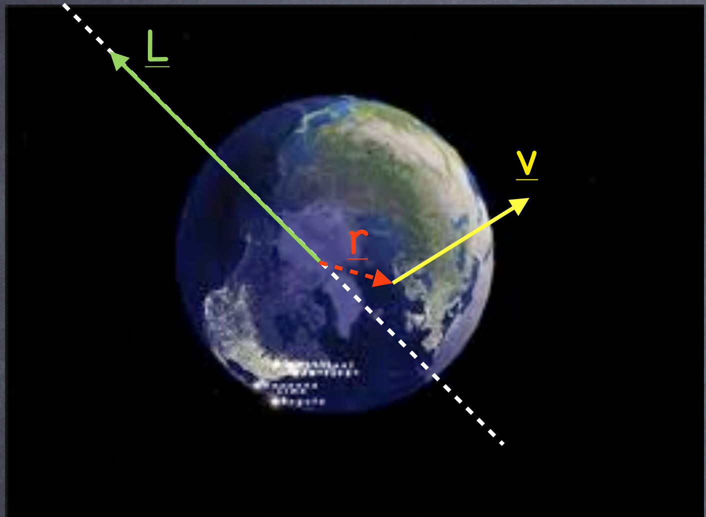
= m·r·1/t = Kg·m·1/s

adimensional

$$m \cdot Kg \cdot m \cdot 1/s = Kg \cdot m^2/s$$

So, when we speak about the length of vector $\underline{L}$, we measure this length in $Kg \cdot m^2/s$

Earth Angular momentum



So we have found L!

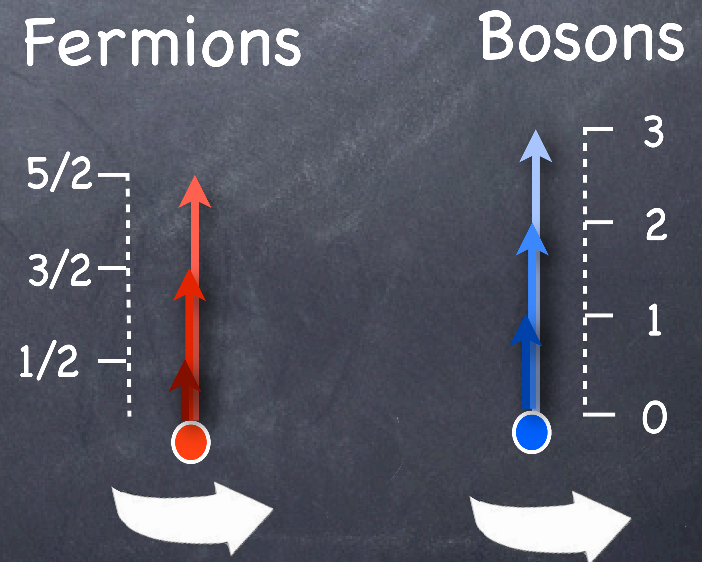
In general, for every body in rotation we can calculate L.

L length could be any value in $Kg \cdot m^2/s$ (continuos quantity, ε)

As the Earth we can imagine elementary particles as little spheres which turn around their rotation axis (why? because it is useful!)

Spin

- But when we speak about elementary particles, we have to consider that we are speaking of infinitely small, and we have to remind that we have quantised structure
- "Spin is the quantum analogous of L" means that S is like L, but with discrete values of lengths
- Two possible classes of spin values exist:
- half-integer: 1/2, 3/2, 5/2 and so on...
- integer: 0, 1, 2, 3 and so on...



The spin and the field

- As we have saw, in SM exist two kinds of field, matter and gauge field
- Matter is made of elementary particles called fermions (leptons and quarks)
- Fermions fields will be related to an half-integer value of spin (S=1/2)
- The second kind of field is the gauge field, which represent particles called bosons (related to the interactions, as we will see)
- Bosons fields will be related to an integer value of spin (e.g. S=1)

Spin as a label…

- In the Standard Model we use QUANTUM NUMBERS (in particular the spin) like labels, to distinguish different kind of particles

- Labels like the clothes label!
- Thanks to clothes label we can know all about the the clothes: PRICE, MATERIAL, HOW TO WASH…

- We use QUANTUM NUMBERS following the same philosophy!

Standard Model

The structure

Standard Model

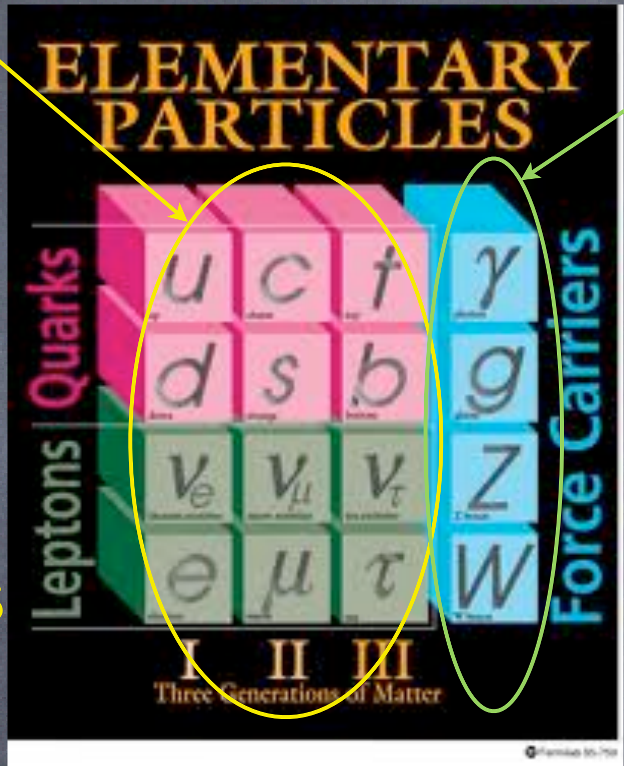
Fermions

The matter is made of fermions

Think to the atoms: atomic nucleus is made of protons and neutrons

Protons and neutrons are made of quarks

Around the nucleus we find the electrons, which give to the atom its chemical properties



Bosons

particles related to the interaction an atom is made of fermions which interact each other through the exchange of bosons!

Different interactions (em,w,s, or g) -> different kind of bosons

Gauge Fields

Why do we need them?

Gauge fields (bosons)

- From relativity arises up the existence of bosons like force carriers...
- ... because nothing in the universe can go faster than light (velocity c)!
- Where is the problem with the classical physics?
- Let's go to see an example...

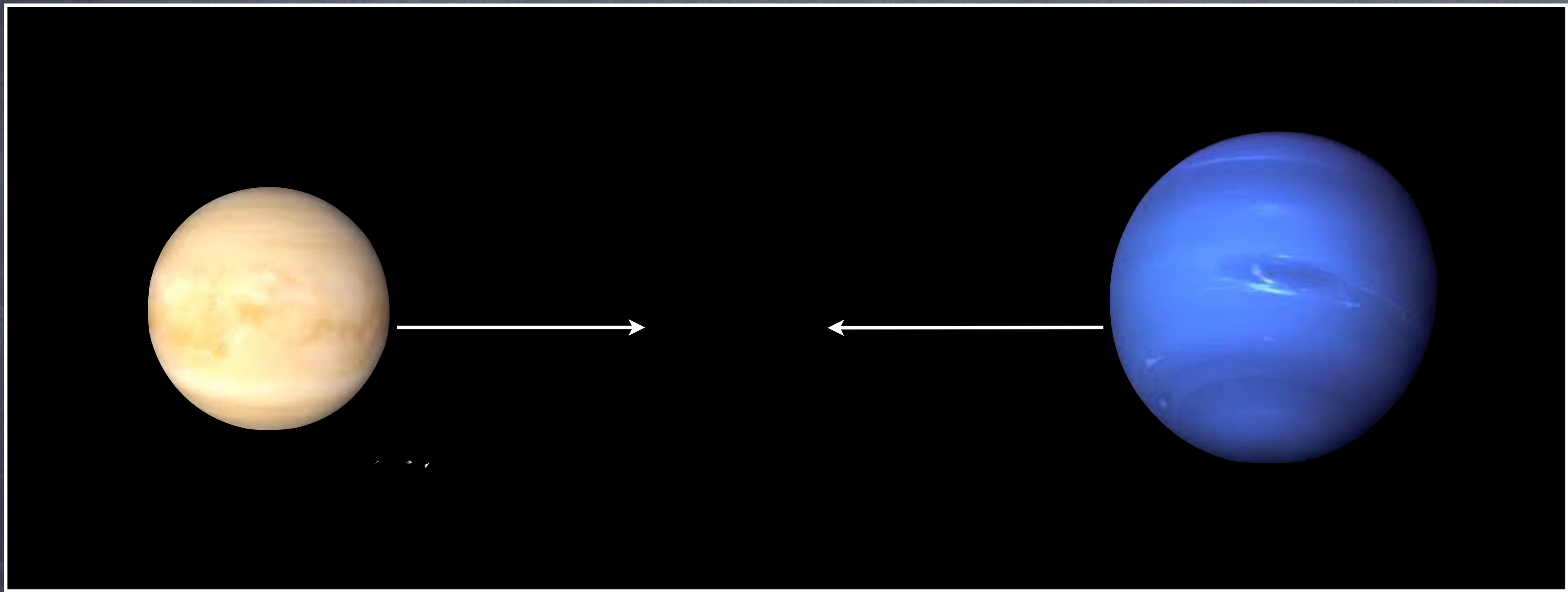
Force carriers

- Consider two planets at distance r and suppose that there is no gravity

Gravity (off)

Force carriers

- When we switch on gravity each planet feel instantly other planet attraction!

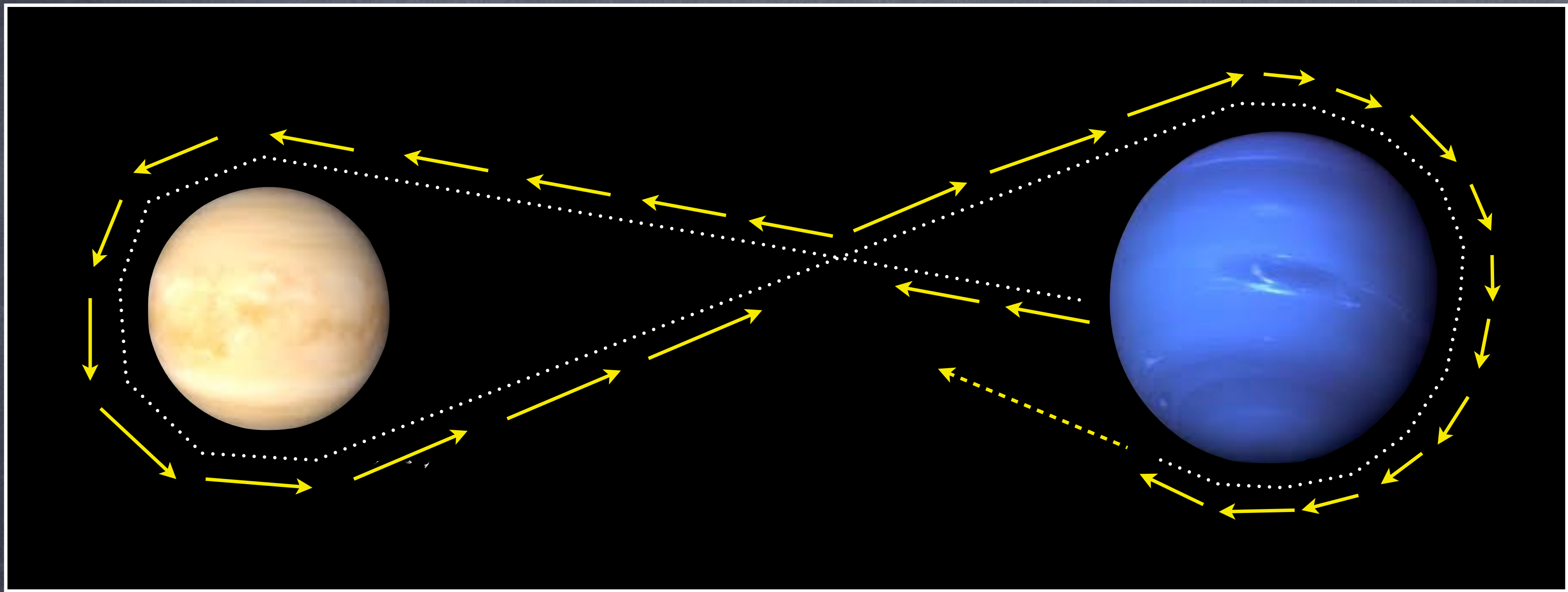


Gravity (on)

- AND INSTANTLY IS FASTER THAN THE VELOCITY C!!!!

Force carriers

- Way to solve: see the gravitational interaction as an exchange between the two planet of a particle



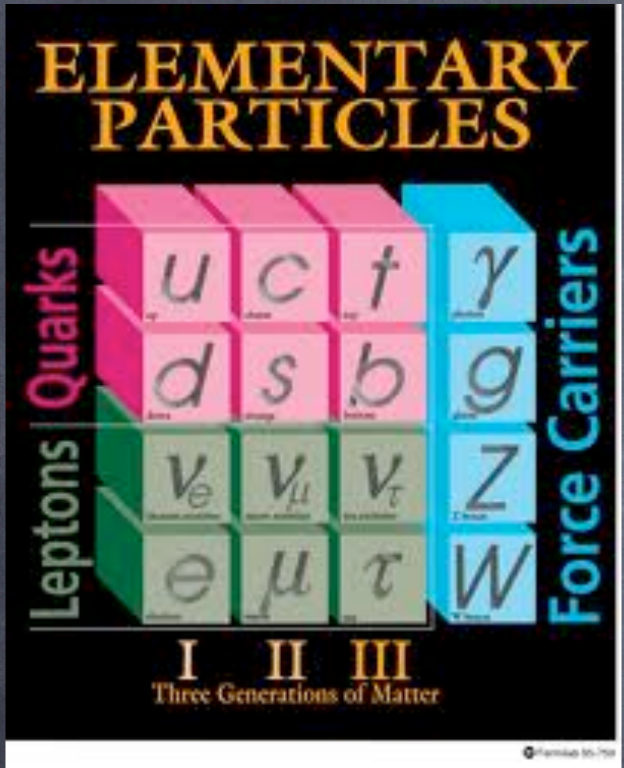
Gravity (on)

- THE VELOCITY OF THIS PARTICLE IS C!!!!!

Fundamental Interactions

three of four: a good result

Force carriers

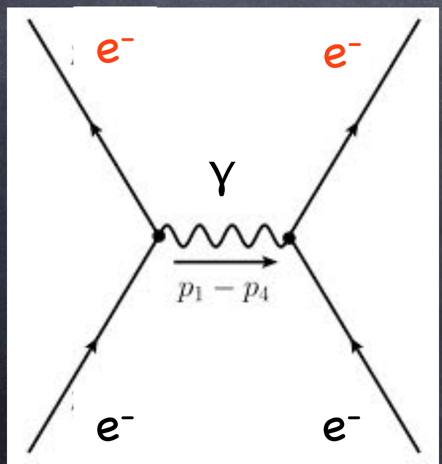


In this way we have:

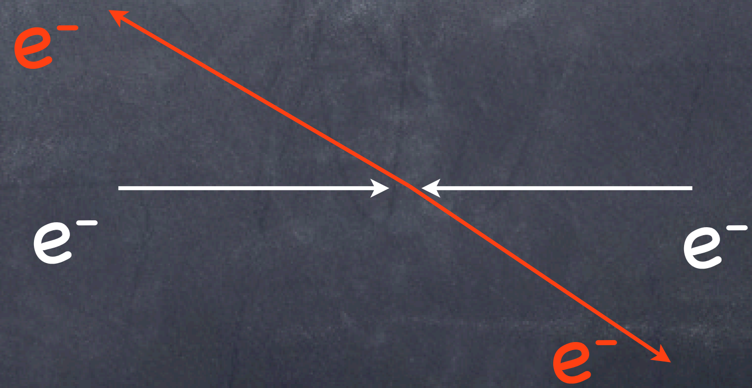
Electromagnetic force carrier

PHOTON γ

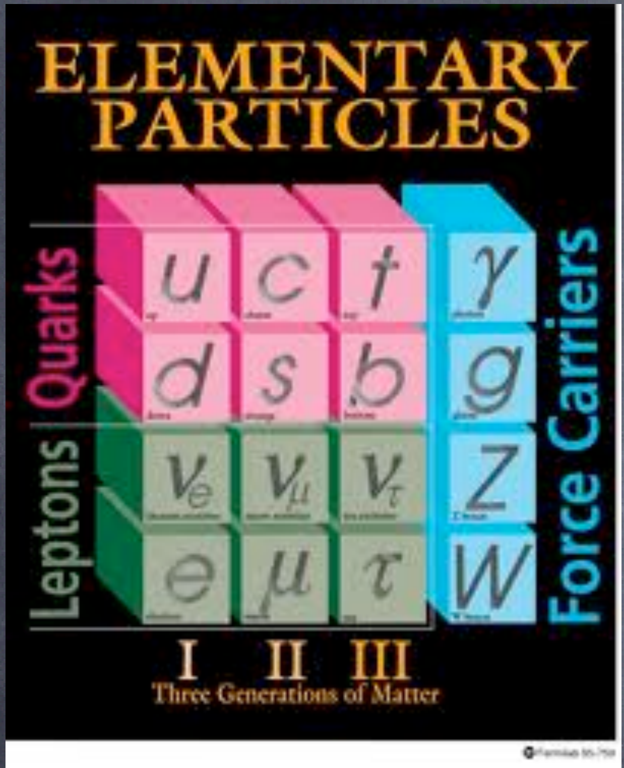
Two charged particles that interact each other via em force, exchange a photon

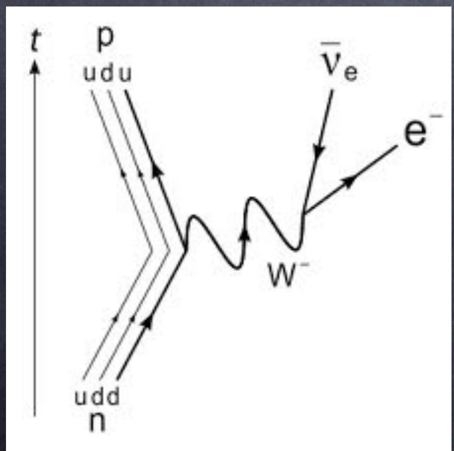


$e^- e^- \rightarrow e^- e^-$



Force carriers





In this way we have:

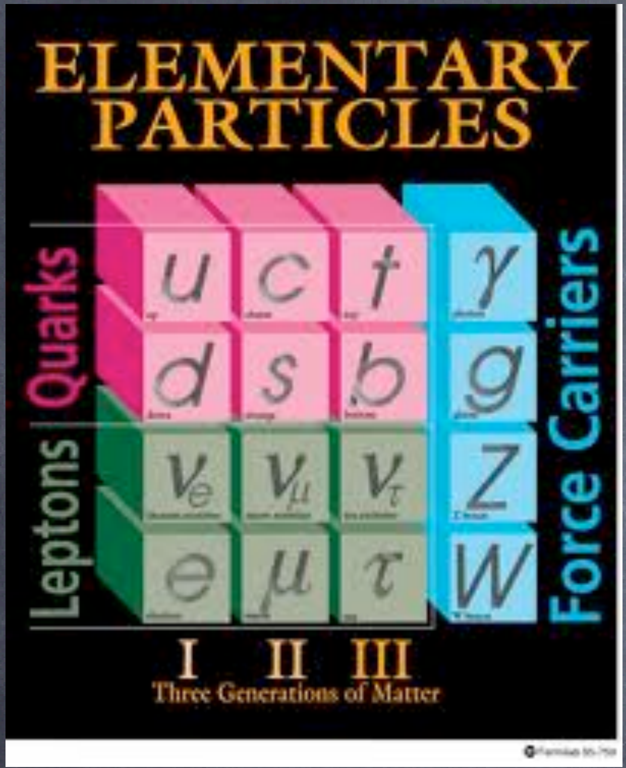
weak force carriers

Bosons W^+,W^- and Z^0

We find weak interactions for example in radioactive phenomena like beta decay

$n \to p + e^- + \nu$

Force carriers



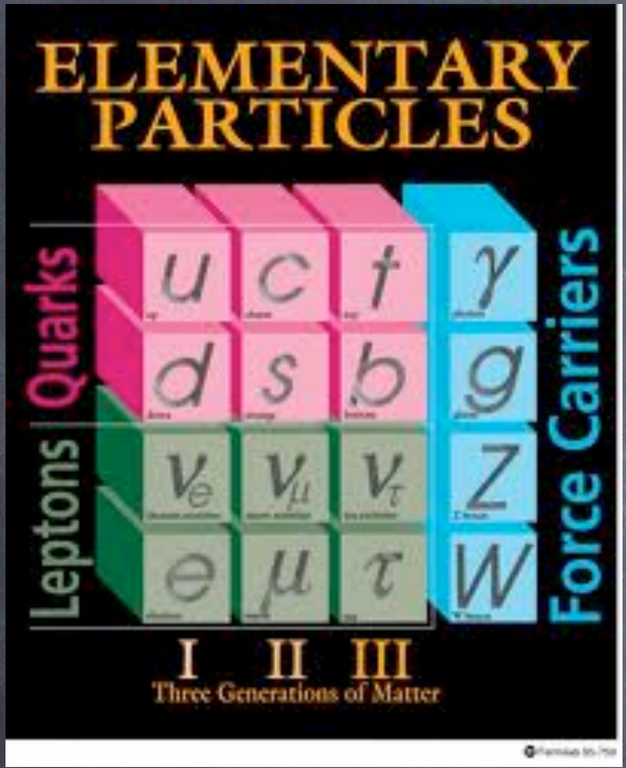
In this way we have:

strong force carriers

gluons g

Strong interactions glue quarks together to form hadrons, like protons and neutrons

Force carriers



In SM today we aren't able to describe gravity too

But from the constraints of relativity, we know that must exist the graviton, force carrier of gravity...

We are still looking for it!

Thank you for your attention