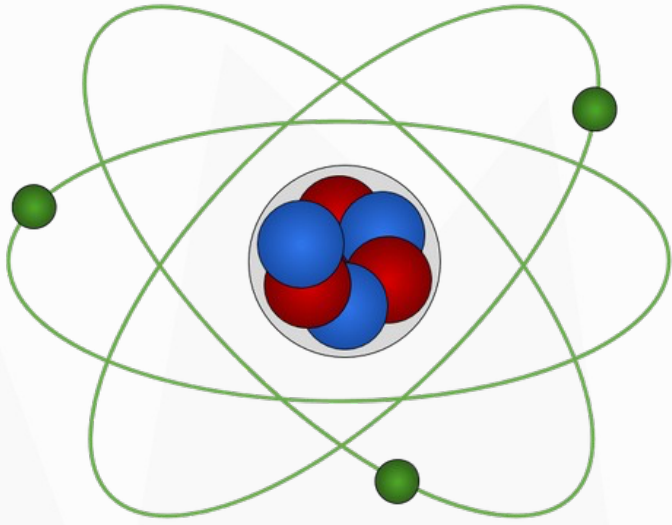




The Universe under a microscope:

Zooming in on particle physics

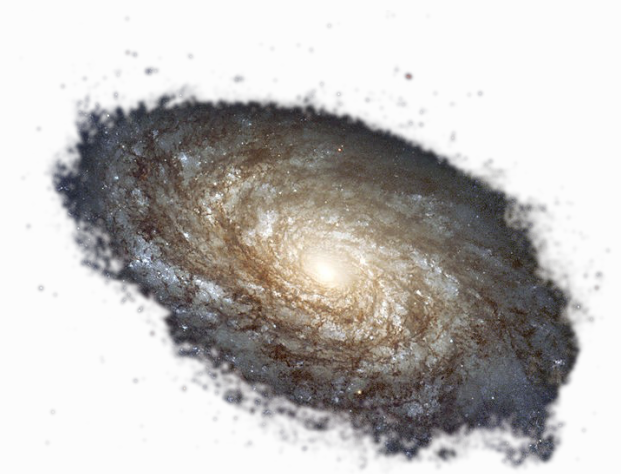
Anca Preda

Division of Particle and Nuclear Physics
Lund University



LUNDS
UNIVERSITET

Have you ever wondered what we're really made of?



The journey



Biology

(large)

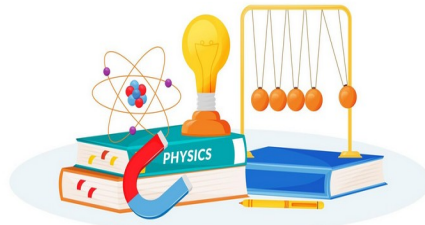


Chemistry

(small)

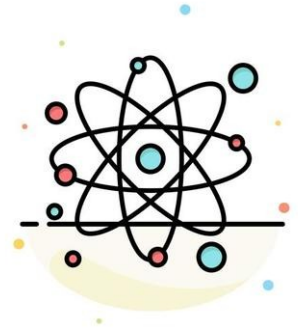
Physics

(smaller)



Particle Physics

(smallest)



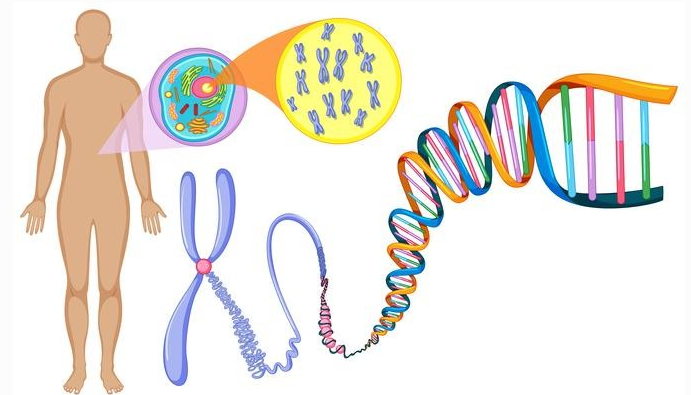
Step 1: Biology

Life starts with **cells**, the smallest units of living organisms.



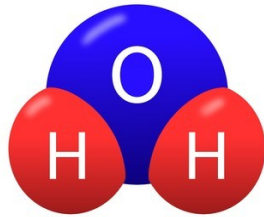
biological functions: growth, repair, reproduction, energy production.

But what are cells made of?

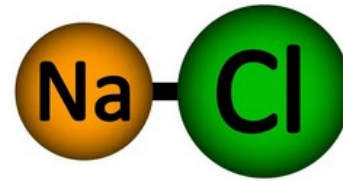


Step 2: Chemistry

- **Zooming in further:** cells are made out of **molecules**, which form the chemistry of life and matter.



H₂O water



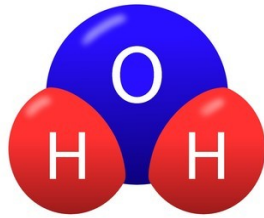
NaCl salt

- Molecules are made of **atoms**, the ingredients of matter.

At this level, Nature is therefore described by atoms!

Step 2: Chemistry

- **Zooming in further:** cells are made out of **molecules**, which form the chemistry of life and matter.



H₂O water

- Molecules are made of **atoms**, which are ingredients of matter.

[illegible]

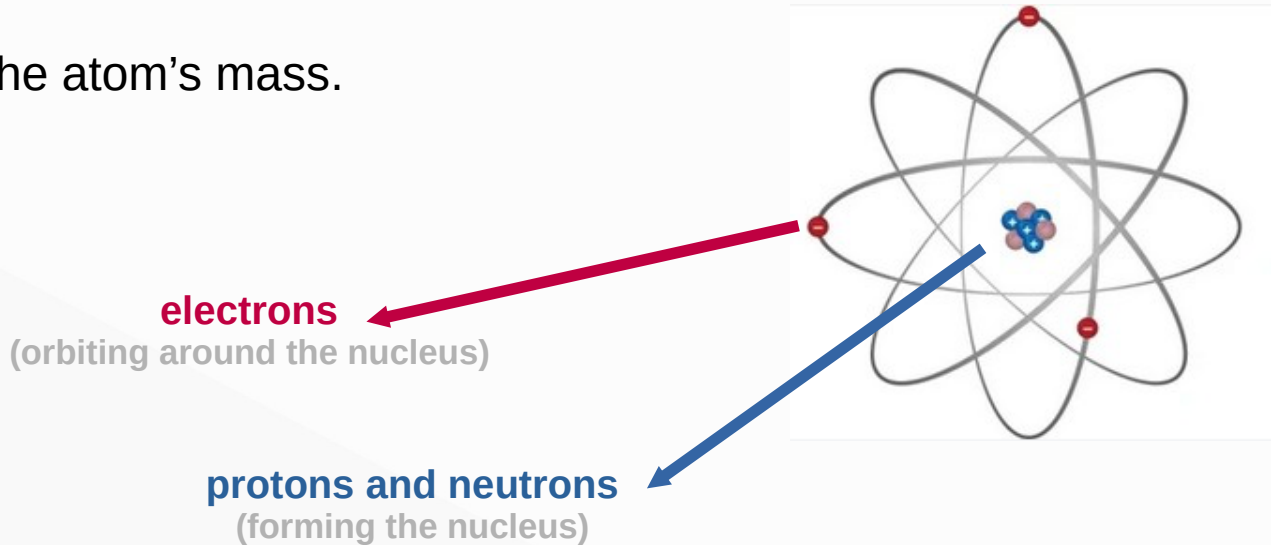
Periodic Table of Elements
Source: Wikipedia

Step 3: Physics

Atoms can be further divided!

- **Zooming in even more:** atoms have a dense nucleus made of **protons** and **neutrons** [E. Rutherford], which are surrounded by **electrons** [J.J. Thomson].
- The nucleus contains nearly all the atom's mass.

!! If we were to stop here, then
Nature would be described in terms
of these three ingredients:
electrons, protons, neutrons



Step 3: Physics

The journey continues...

- **Electrons**: can not be divided further → **fundamental particles** of Nature
- **Protons** and **neutrons**: different story altogether

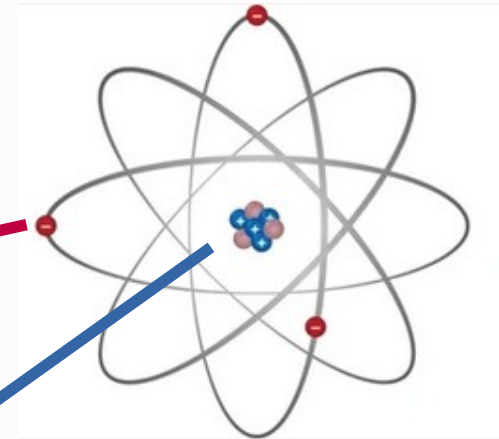


Not fundamental particles

So what are they made of?

electrons
(orbiting around the nucleus)

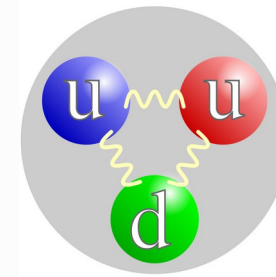
protons and neutrons
(forming the nucleus)



Step 4: Particle Physics

As far as we can go

- We have arrived at the smallest scale, where our description of Nature is the most fundamental (yet!).
- **Protons** and **neutrons**: made out of **quarks**
- There are many different types of quarks: up (u), down (d), strange (s), bottom (b), top (t), charm (c).
- Together with the **electron**, **quarks** are **fundamental particles**!



proton structure:
two up-quarks and
one down-quark

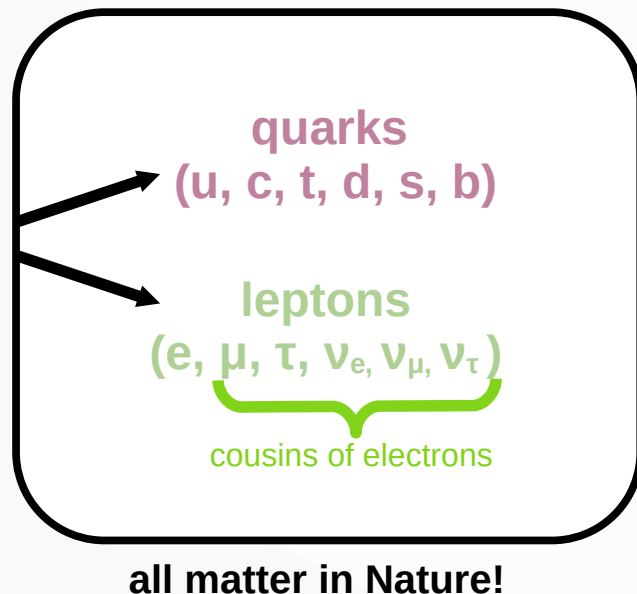
→ That's a
proton!

Step 4: Particle Physics

As far as we can go

Let's summarize...

- fundamental particles



Standard Model of Elementary Particles

three generations of matter (fermions)						interactions / force carriers (bosons)	
I		II		III			
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.2 \text{ GeV}/c^2$		
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0		
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0		
QUARKS	 up	 charm	 top	 gluon	 higgs		
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$	0			
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
	 down	 strange	 bottom	 photon			
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.77693 \text{ GeV}/c^2$	$\approx 91.188 \text{ GeV}/c^2$			
	-1	-1	-1	0			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
	 electron	 muon	 tau	 Z boson			
	$< 0.8 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.3692 \text{ GeV}/c^2$			
	0	0	0	± 1			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
	 electron neutrino	 muon neutrino	 tau neutrino	 W boson			
					GAUGE BOSONS VECTOR BOSONS		
					SCALAR BOSONS		

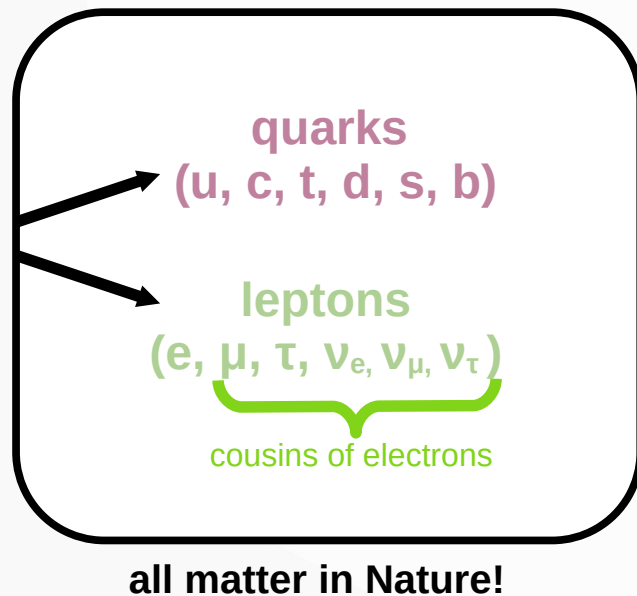
source: Wikipedia

Step 4: Particle Physics

As far as we can go

Let's summarize...

- fundamental particles



- gauge bosons: help particles interact

↓
“carry” the fundamental forces

Standard Model of Elementary Particles

three generations of matter (fermions)						interactions / force carriers (bosons)	
I			II			III	
mass charge spin	$\approx 2.16 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.273 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 172.57 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 93.5 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.183 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 125.2 \text{ GeV}/c^2$ 0 0 0
QUARKS	u up	c charm	t top	d down	s strange	b bottom	g gluon
							γ photon
							Z Z boson
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	$\approx 1.77693 \text{ GeV}/c^2$ -1 $\frac{1}{2}$	e electron	μ muon	τ tau	$\approx 91.188 \text{ GeV}/c^2$ 0 0 1
	$< 0.8 \text{ eV}/c^2$ 0 $\frac{1}{2}$	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$\approx 80.3692 \text{ GeV}/c^2$ ± 1 1
							W W boson
							SCALAR BOSONS

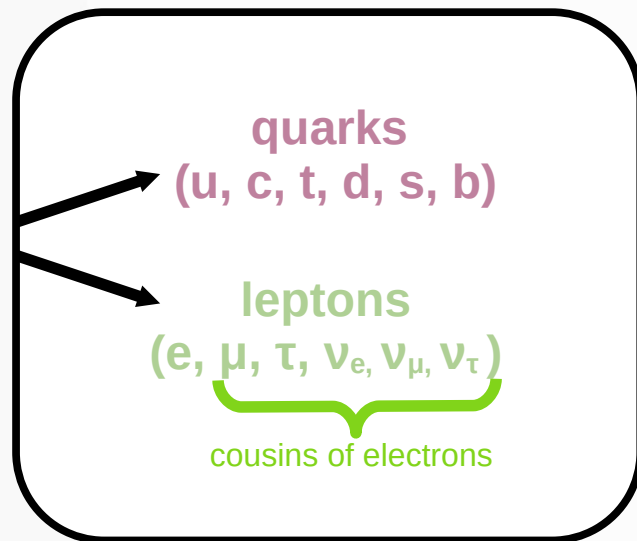
source: Wikipedia

Step 4: Particle Physics

As far as we can go

Let's summarize...

- fundamental particles



all matter in Nature!

- gauge bosons: help particles interact

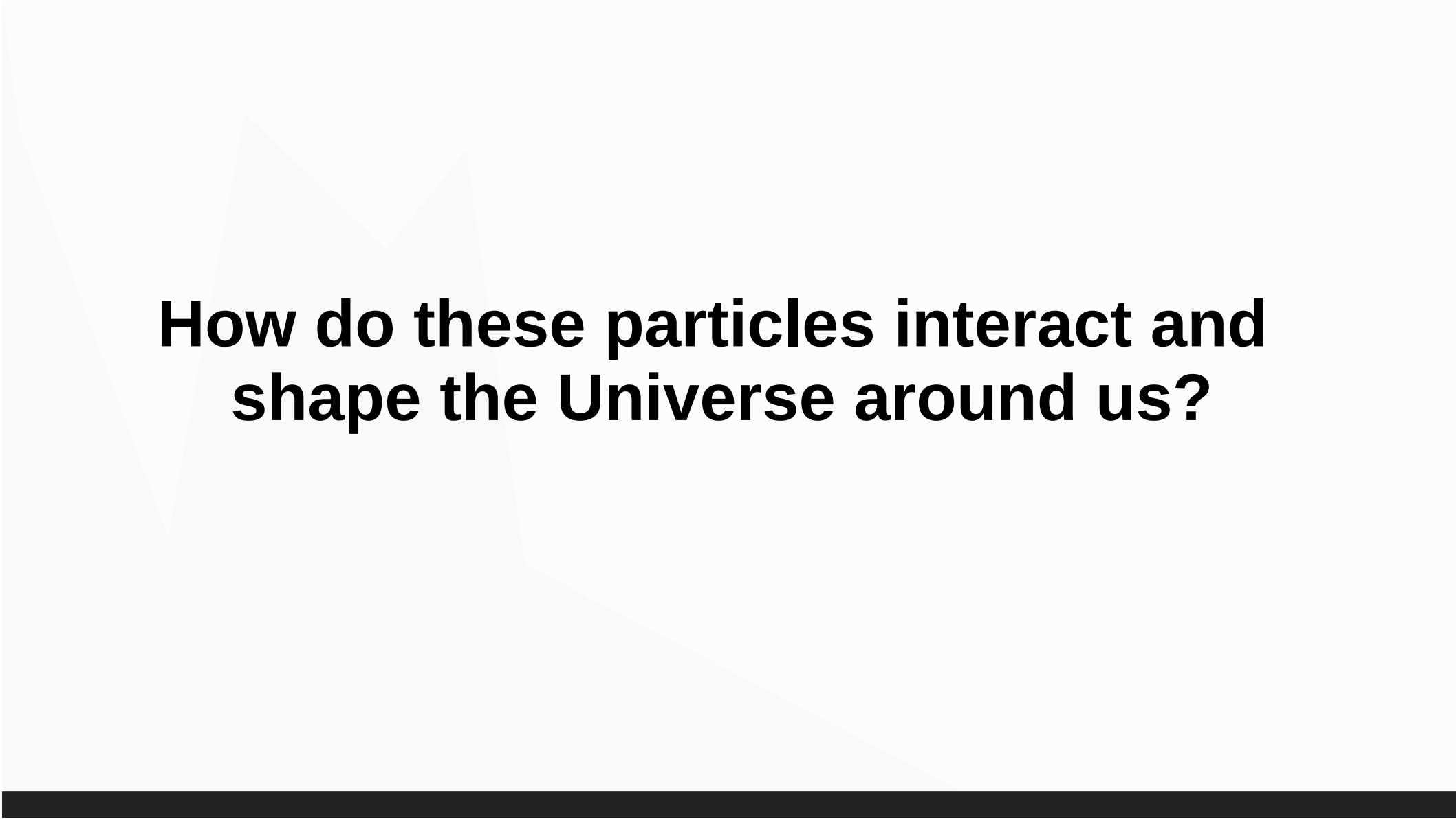
↓
“carry” the fundamental forces

gives particles mass!

Standard Model of Elementary Particles

three generations of matter (fermions)						interactions / force carriers (bosons)	
I			II			III	
mass charge spin	$\approx 2.16 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 1.273 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 172.57 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 93.5 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.183 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$
u up			c charm			t top	
d down			s strange			b bottom	
e electron			μ muon			τ tau	
ν_e electron neutrino			ν_μ muon neutrino			ν_τ tau neutrino	
g gluon			γ photon			Z Z boson	
H higgs			W W boson				

source: Wikipedia



**How do these particles interact and
shape the Universe around us?**

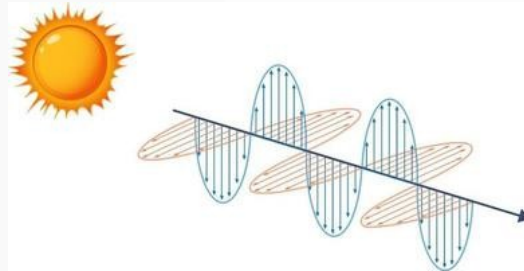
Forces and interactions

The universe operates under four fundamental forces, each with a unique role!

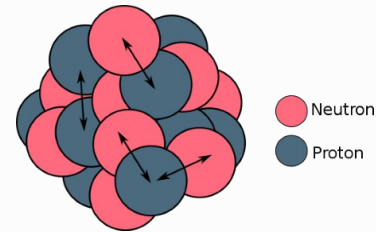
“invisible rules of the game”



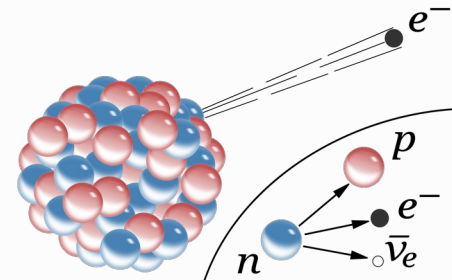
Gravity



Electromagnetism



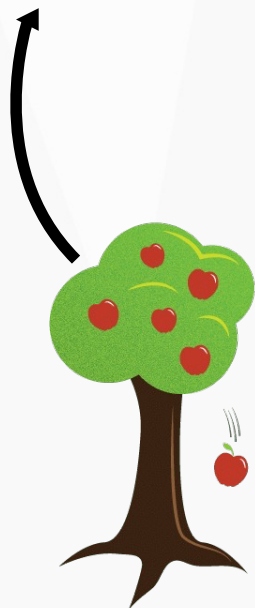
Strong force



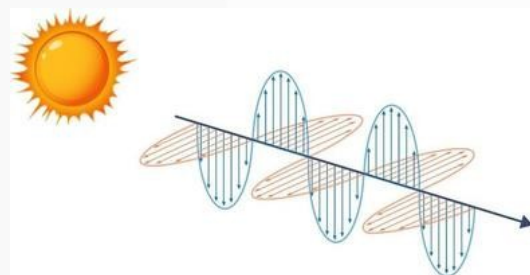
Weak force



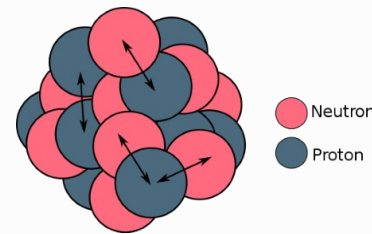
Large scale
Shapes galaxies and planets



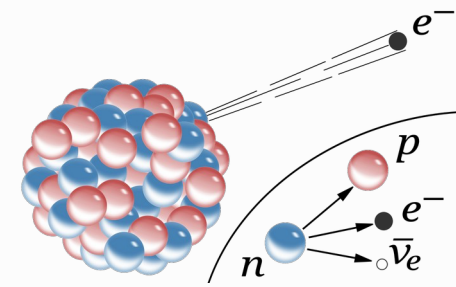
Gravity



Electromagnetism



Strong force



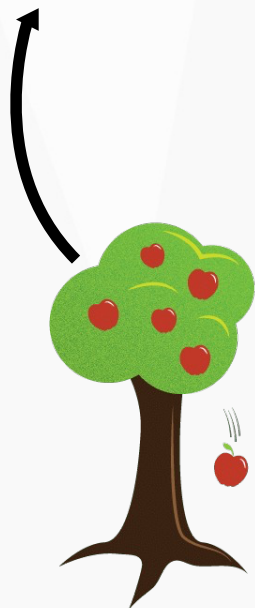
Weak force



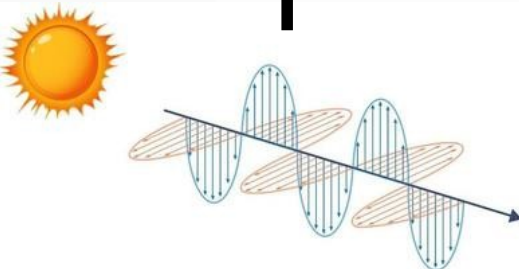
Large scale
Shapes galaxies and planets



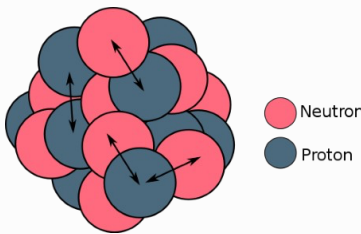
Describes light,
electronics,
magnetism..



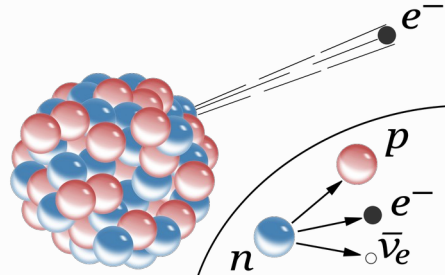
Gravity



Electromagnetism



Strong force



Weak force

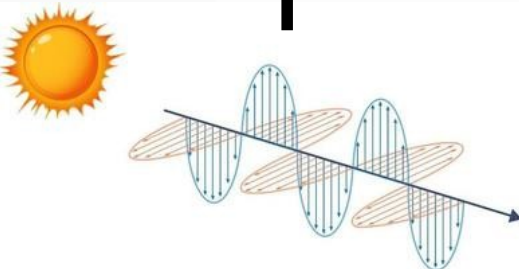


Large scale
Shapes galaxies and planets

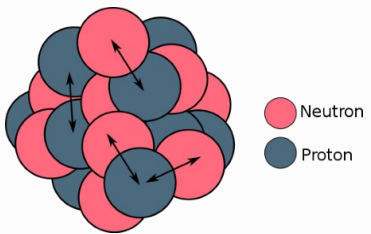


Describes light,
electronics,
magnetism..

Short range
Holds matter together

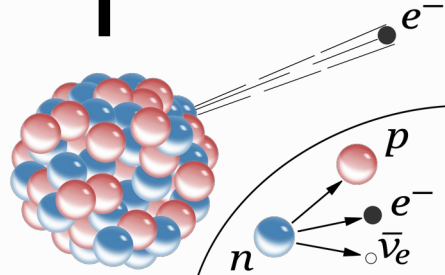


Electromagnetism

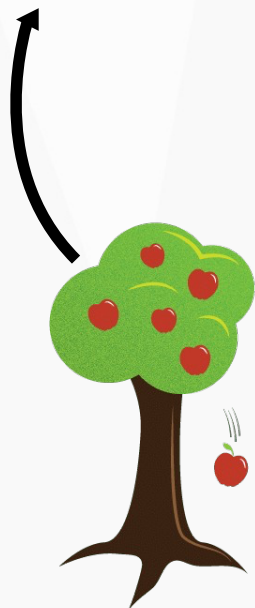


Strong force

Short range
Nuclear processes



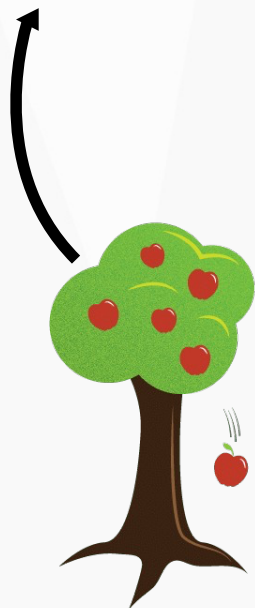
Weak force



Gravity



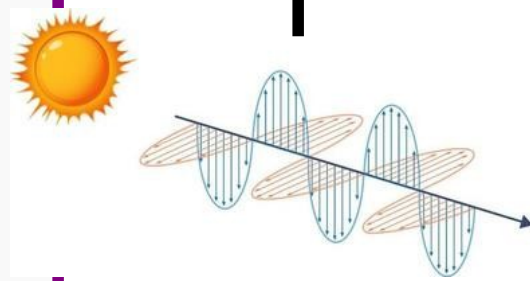
Large scale
Shapes galaxies and planets



Gravity



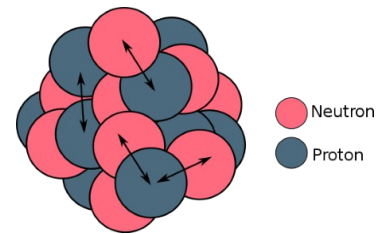
Describes light,
electronics,
magnetism..



Electromagnetism

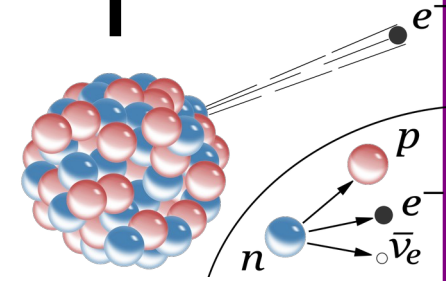
**Vital at very small distances!
Described by the Standard Model**

Short range
Holds matter together



Strong force

Short range
Nuclear processes



Weak force

Let's summarize

Theoretical side

Particles

Forces

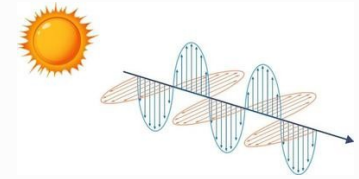
Standard Model of Elementary Particles

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u up	c charm	t top	g gluon	H higgs
$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 93.5 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	$\approx 4.183 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	0 0 1	
d down	s strange	b bottom	γ photon	
$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	$\approx 1.77693 \text{ GeV}/c^2$ -1 $\frac{1}{2}$	0 0 1	
e electron	μ muon	τ tau	Z Z boson	
$< 0.8 \text{ eV}/c^2$ 0 $\frac{1}{2}$	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	$\approx 80.3692 \text{ GeV}/c^2$ ± 1 1	
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

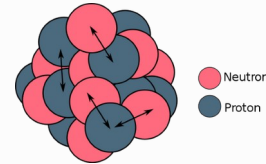
source: Wikipedia



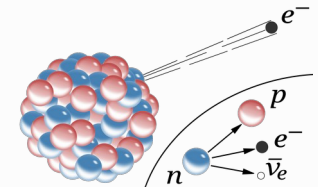
Gravity



Electromagnetism



Strong force



Weak force

Let's summarize

Theoretical side

Particles

Standard Model of Elementary Particles

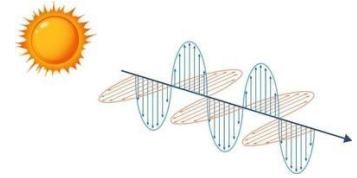
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spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.77693 \text{ GeV}/c^2$	$\approx 91.188 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 0.8 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.3692 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

source: Wikipedia

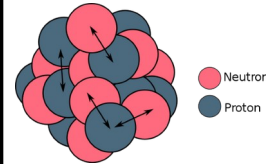
Forces



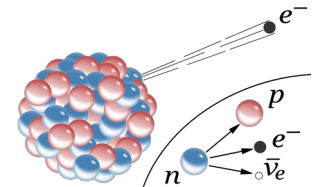
Gravity



Electromagnetism



Strong force

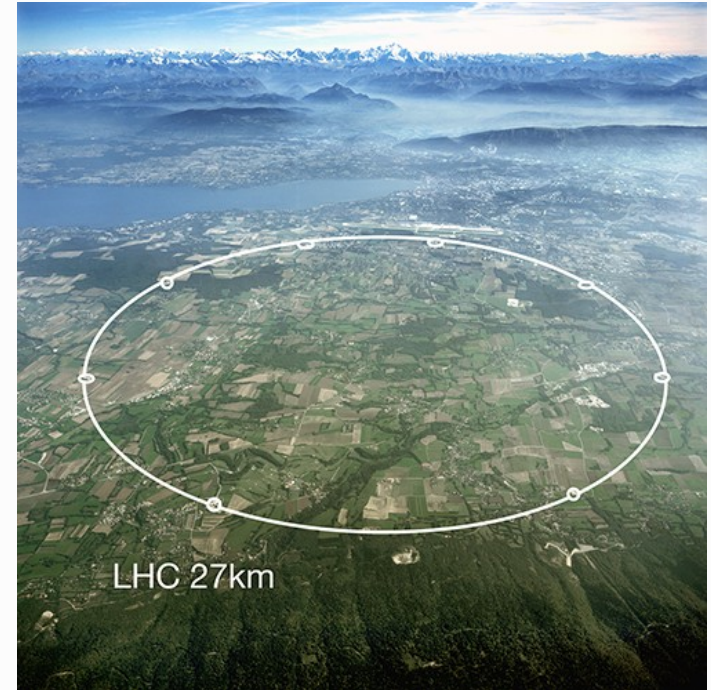


Weak force

Let's summarize

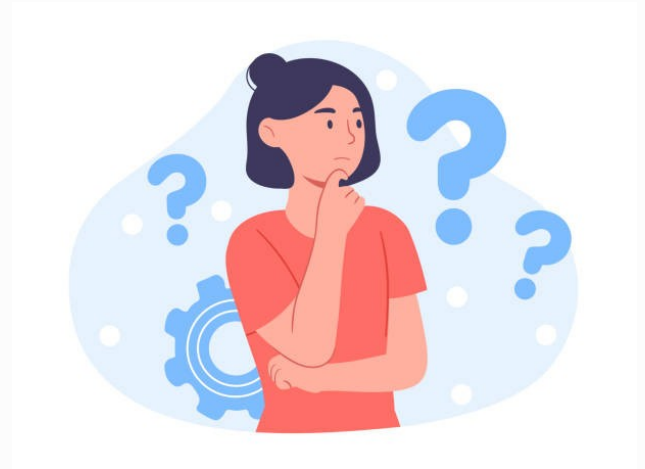
Experimental side

- Standard Model has been tested successfully in high-energy experiments at CERN and beyond.
- LHC played a crucial role in these tests (**Higgs discovery**)
- Collide protons at large speeds and form new particles and processes.
- Physicists compare experimental data with Standard Model predictions to look for differences.
- So far...no (major) difference from theory!



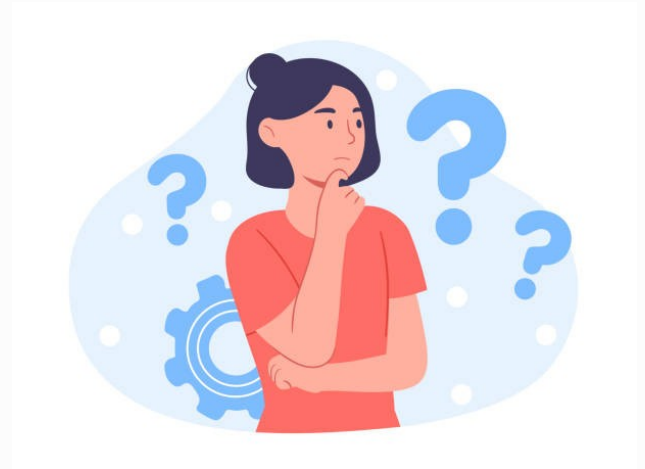
The Large Hadron Collider (LHC) at CERN

Do we know everything?

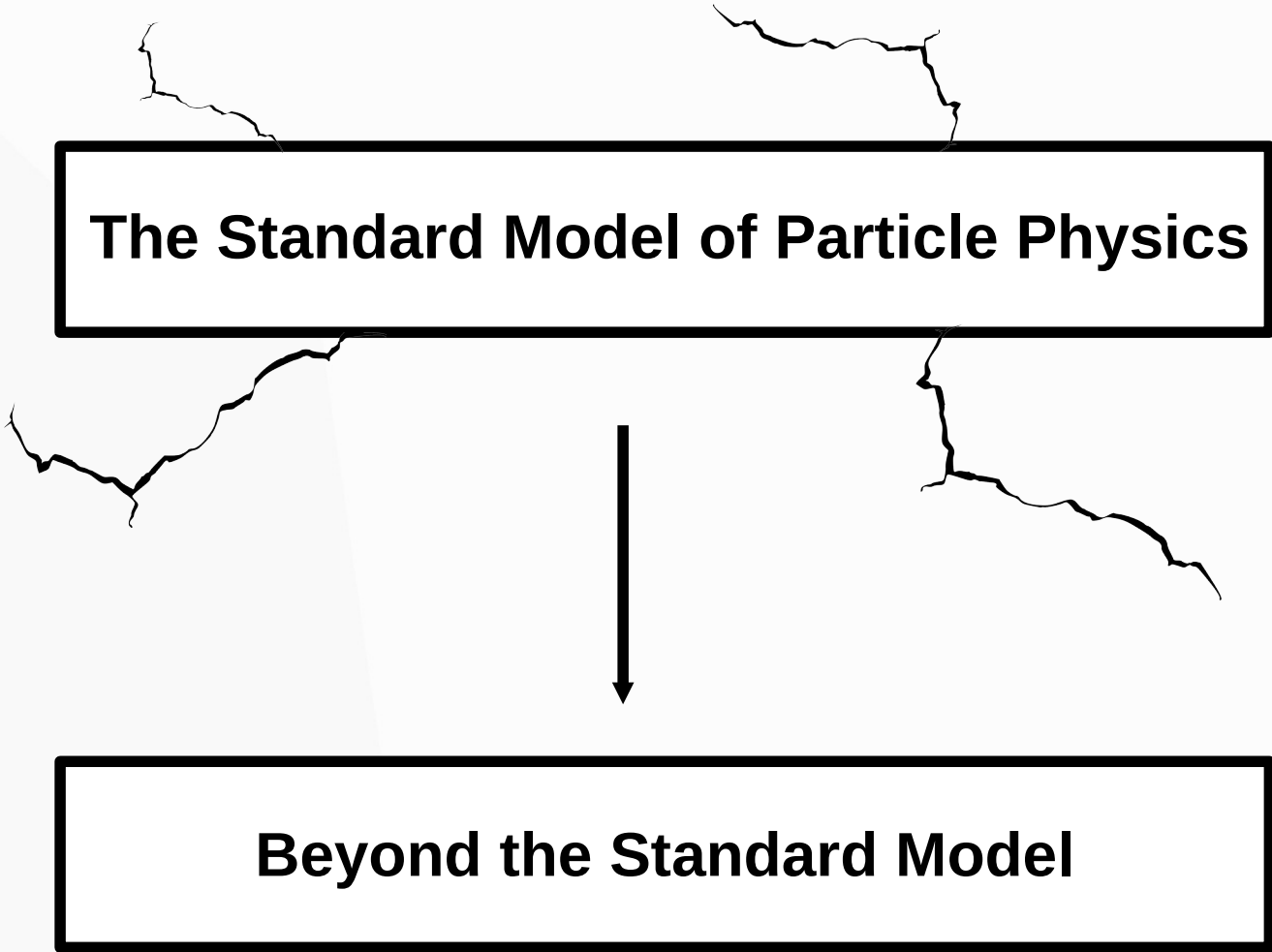


Do we know everything?

It seems not!



The Standard Model of Particle Physics



The Standard Model of Particle Physics

A diagram illustrating the progression of particle physics. At the top, a rectangular box with a thick black border contains the text 'The Standard Model of Particle Physics'. Below this box, a thick black arrow points downwards. At the bottom, another rectangular box with a thick black border contains the text 'Beyond the Standard Model'. The background features faint, light gray geometric shapes and several jagged, black, lightning-like lines that appear to be tearing or cracking the surface, particularly around the boxes and the arrow.

Beyond the Standard Model

What are the missing pieces of the puzzle?

Dark matter and Dark energy

mass of neutrinos

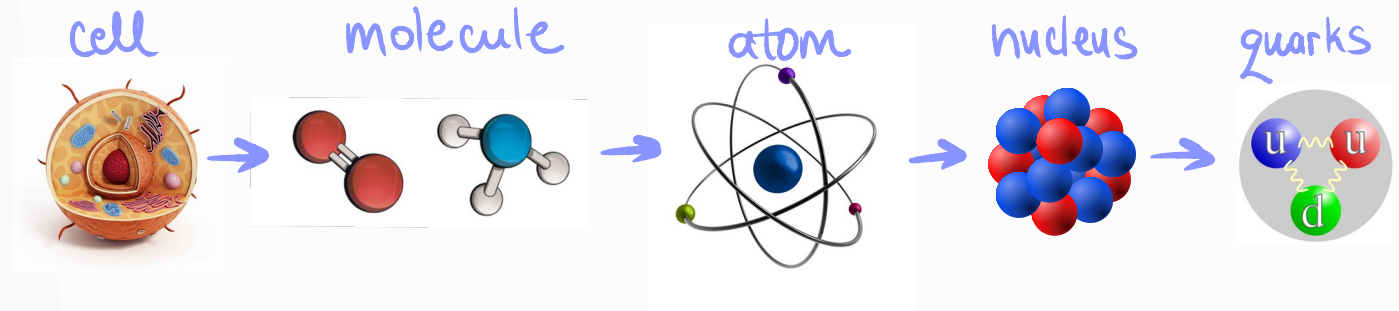


matter-antimatter asymmetry

does not include gravity

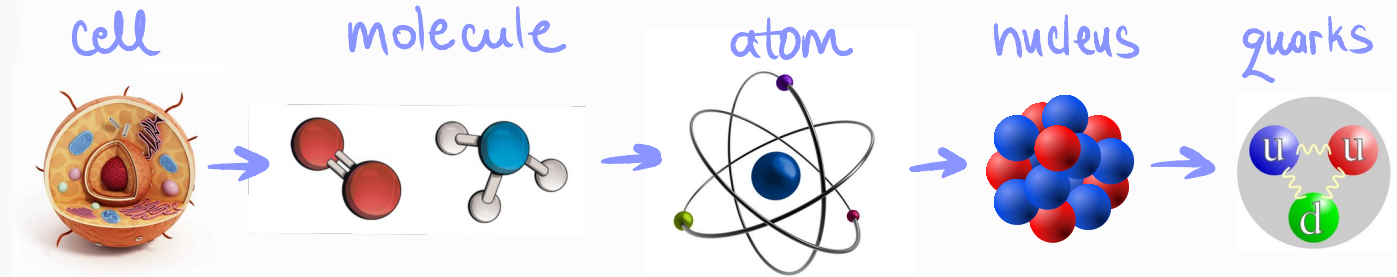
Final thoughts...

1. Nature is layered



Final thoughts...

1. Nature is layered

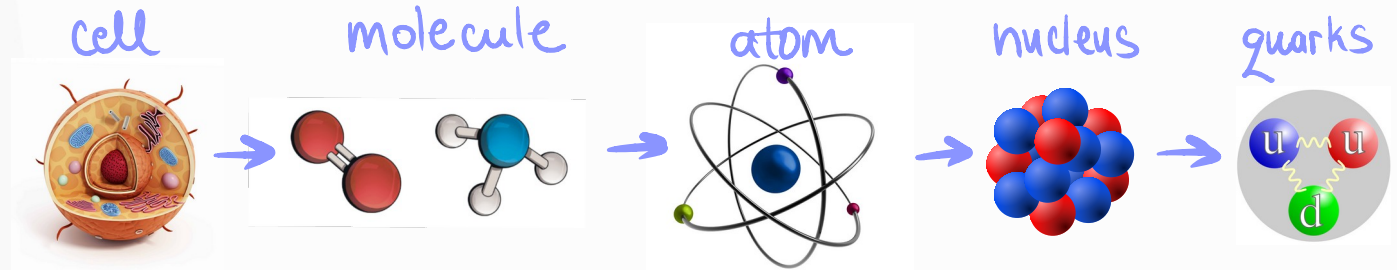


2. The Standard Model is our best map



Final thoughts...

1. Nature is layered



2. The Standard Model is our best map



3. The map is incomplete

- dark matter, neutrino masses, matter-antimatter asymmetry, and gravity still point beyond it.