

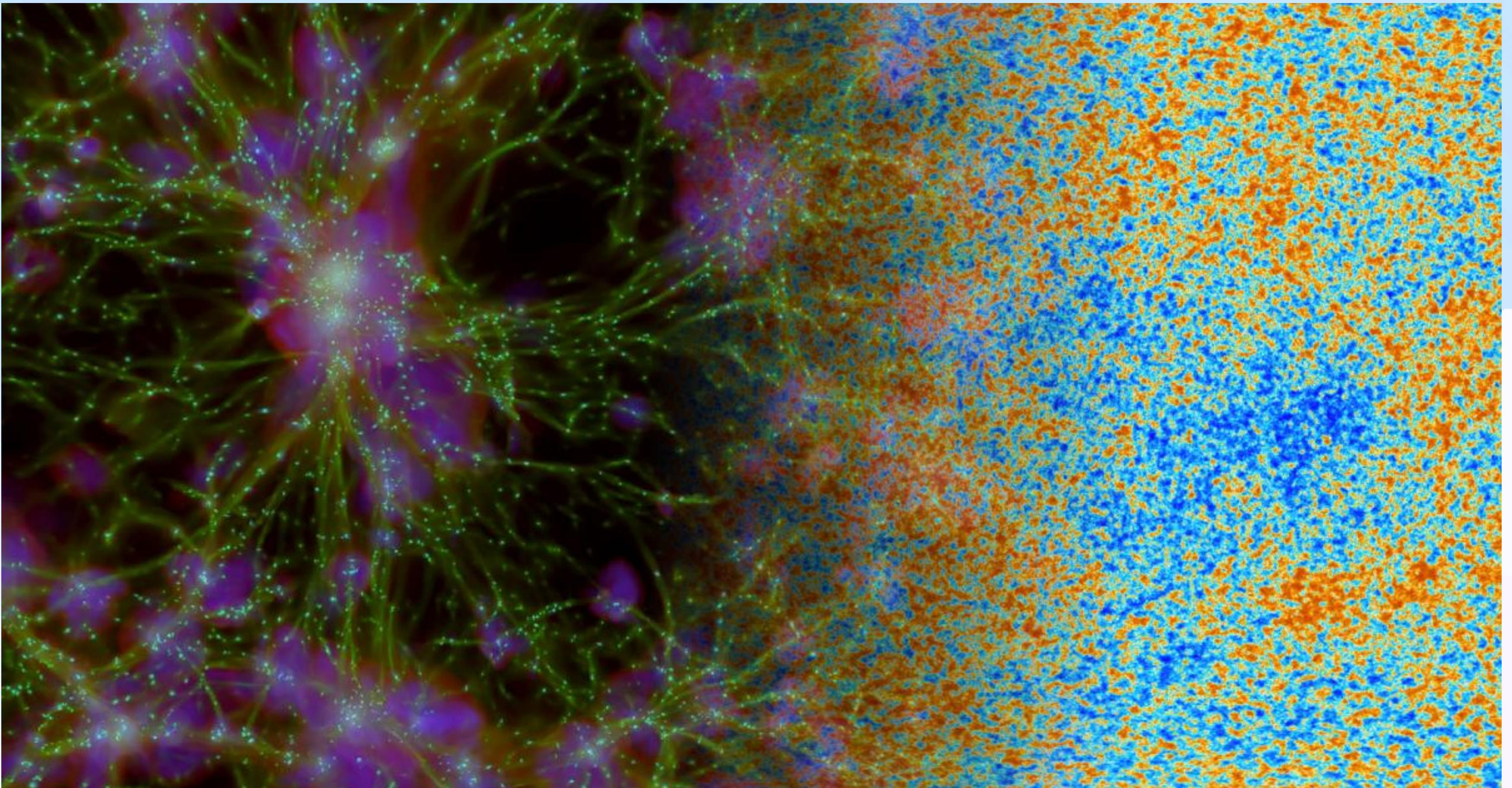
PHYS252 Quantum Physics and Applications

Module 5: Particle Physics

Dr. Shikha Bangar

Module 5

- Particle Physics
- Cosmology

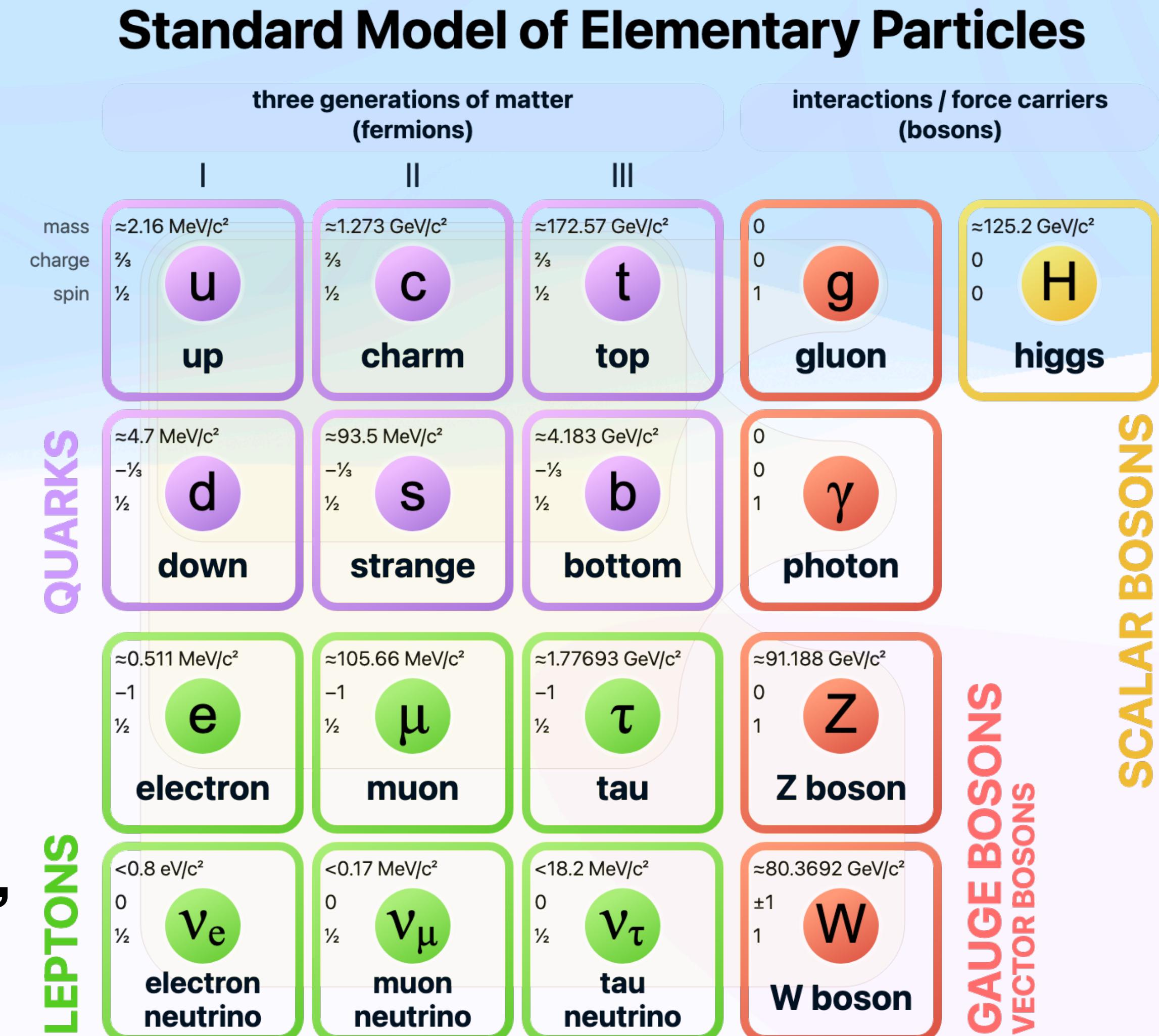


Chapter 14: Elementary Particles and Standard Model

- The four interactions of nature

- Elementary particles
- Conservation laws
- Quark model of hadrons

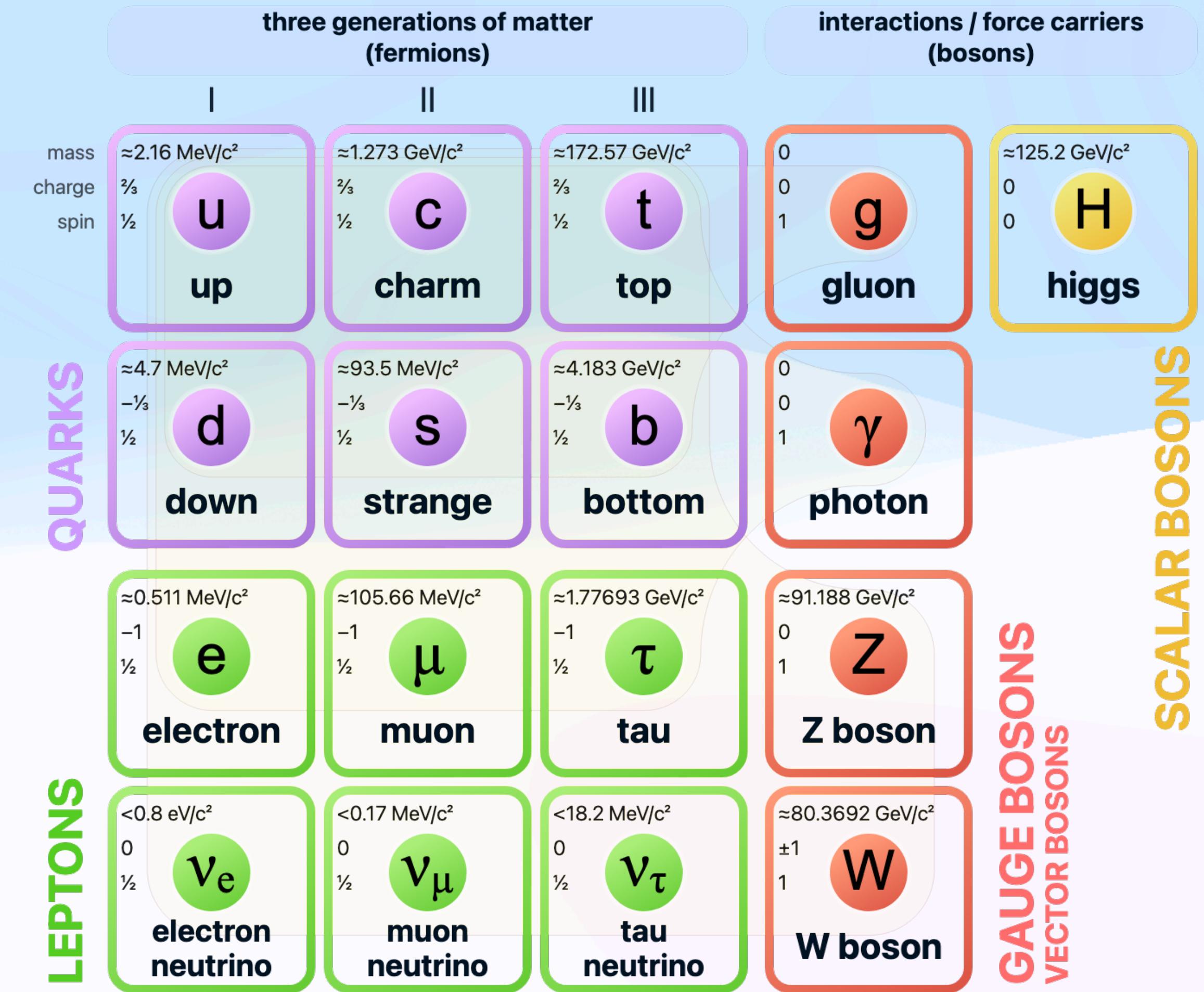
Instead of following this order of topics,
I will give you an overview of everything,
and then we will review this.



Standard Model

- A model to understand everything:
 - What is the universe made of?
 - Elementary particles
 - How do they interact?
 - via 4 fundamental interactions of nature

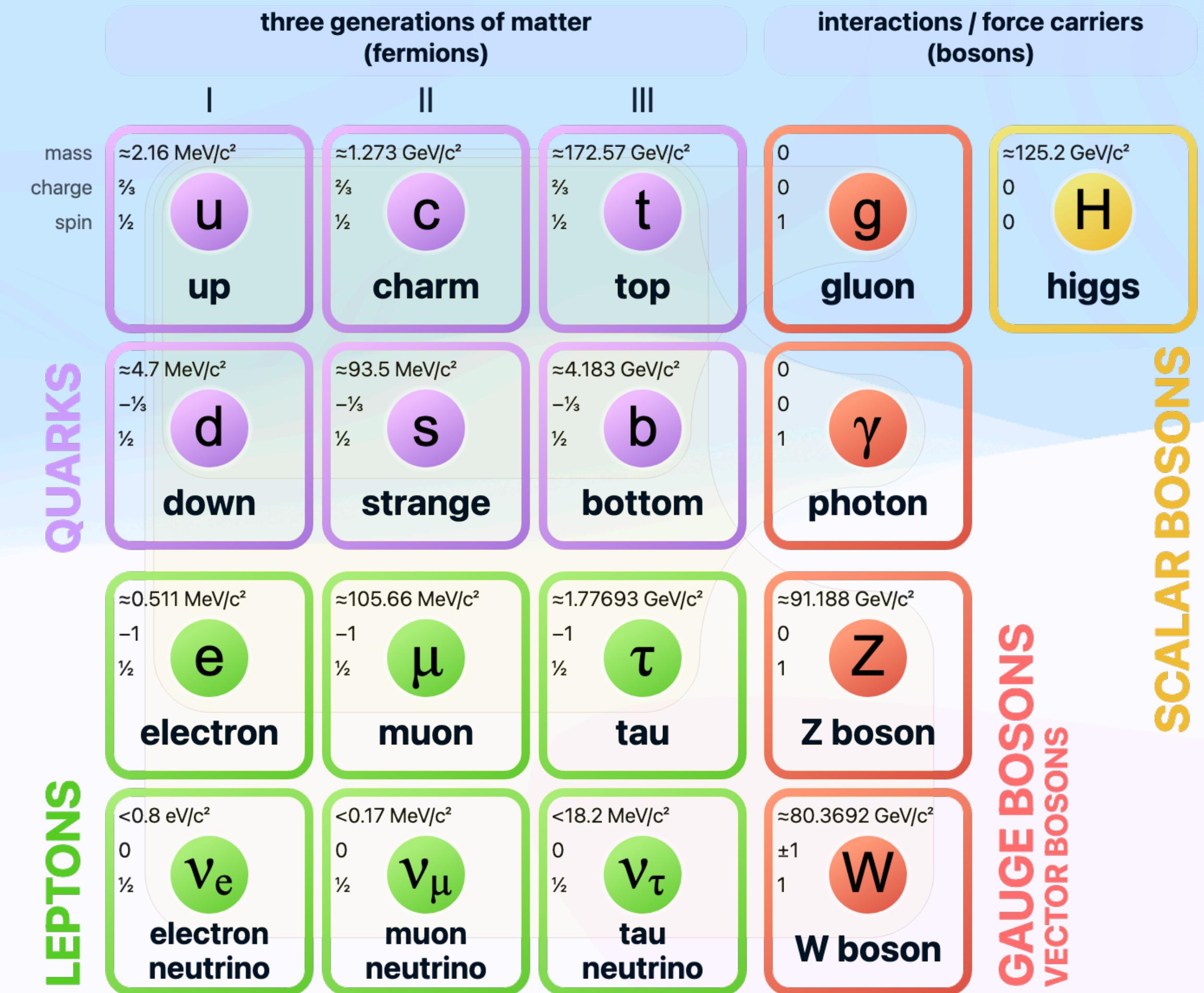
Standard Model of Elementary Particles



Standard Model

- It is written in a language known as Quantum Field Theory
- The matter is made up fields
- But understand this, we will use the language of particles

Standard Model of Elementary Particles



Standard Model

FERMIIONS

LEPTONS

QUARKS

mass
charge
spin

$\approx 2.16 \text{ MeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
u
up

$\approx 1.273 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
c
charm

$\approx 172.57 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
t
top

$\approx 4.7 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
d
down

$\approx 93.5 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
s
strange

$\approx 4.183 \text{ GeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
b
bottom

$\approx 0.511 \text{ MeV}/c^2$
 -1
 $\frac{1}{2}$
e
electron

$\approx 105.66 \text{ MeV}/c^2$
 -1
 $\frac{1}{2}$
 μ
muon

$\approx 1.77693 \text{ GeV}/c^2$
 -1
 $\frac{1}{2}$
 τ
tau

$<0.8 \text{ eV}/c^2$
 0
 $\frac{1}{2}$
 ν_e
electron neutrino

$<0.17 \text{ MeV}/c^2$
 0
 $\frac{1}{2}$
 ν_μ
muon neutrino

$<18.2 \text{ MeV}/c^2$
 0
 $\frac{1}{2}$
 ν_τ
tau neutrino

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

BOSONS

0
 0
 1
g
gluon

0
 0
 1
 γ
photon

$\approx 91.188 \text{ GeV}/c^2$
 0
 1
Z
Z boson

$\approx 80.3692 \text{ GeV}/c^2$
 ± 1
 ± 1
W
W boson

Standard Model

FERMIOS

They form the matter
particles

BOSONS

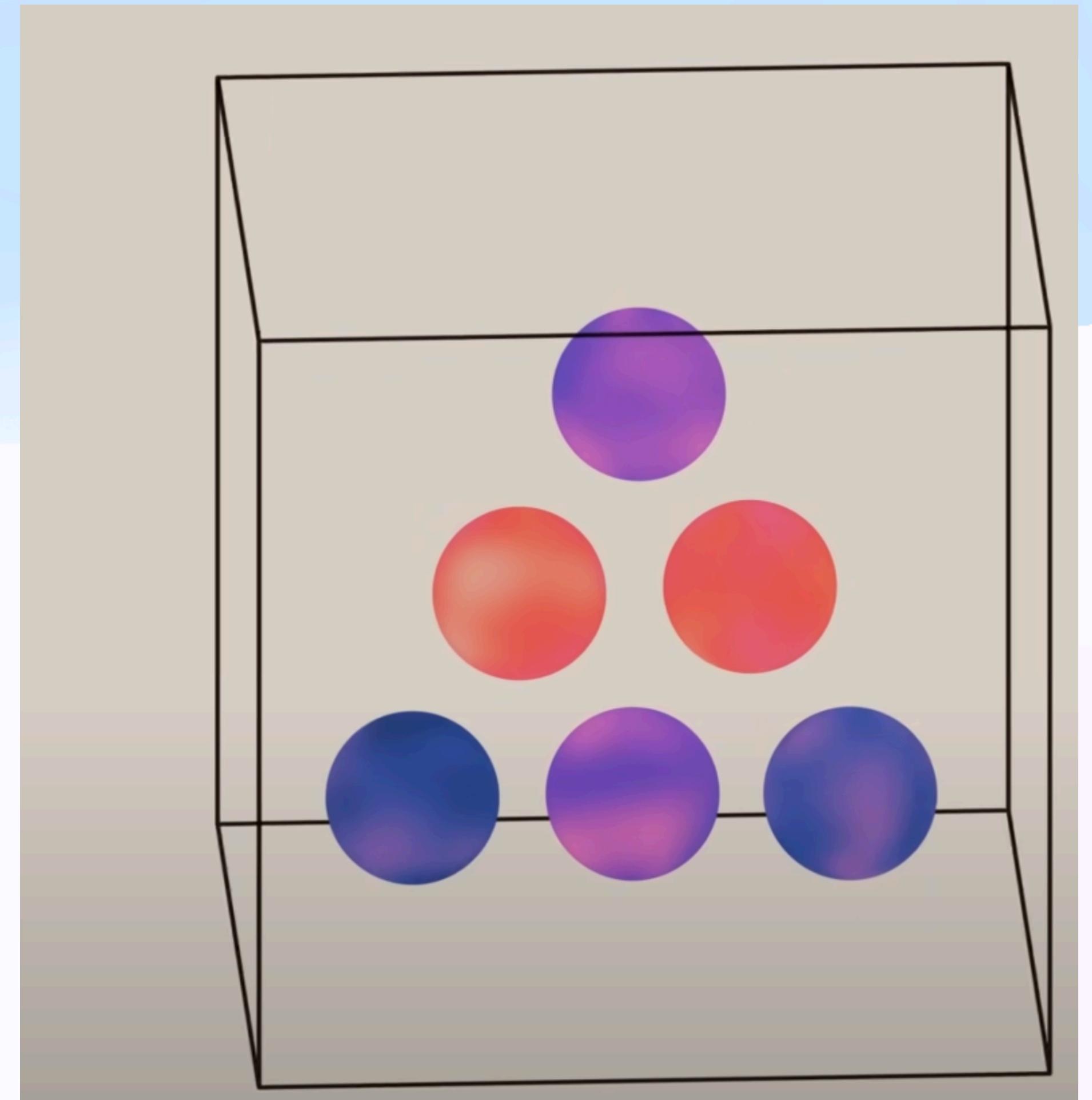
They form the force
interaction particles

Standard Model

FERMIOS

They form the matter particles

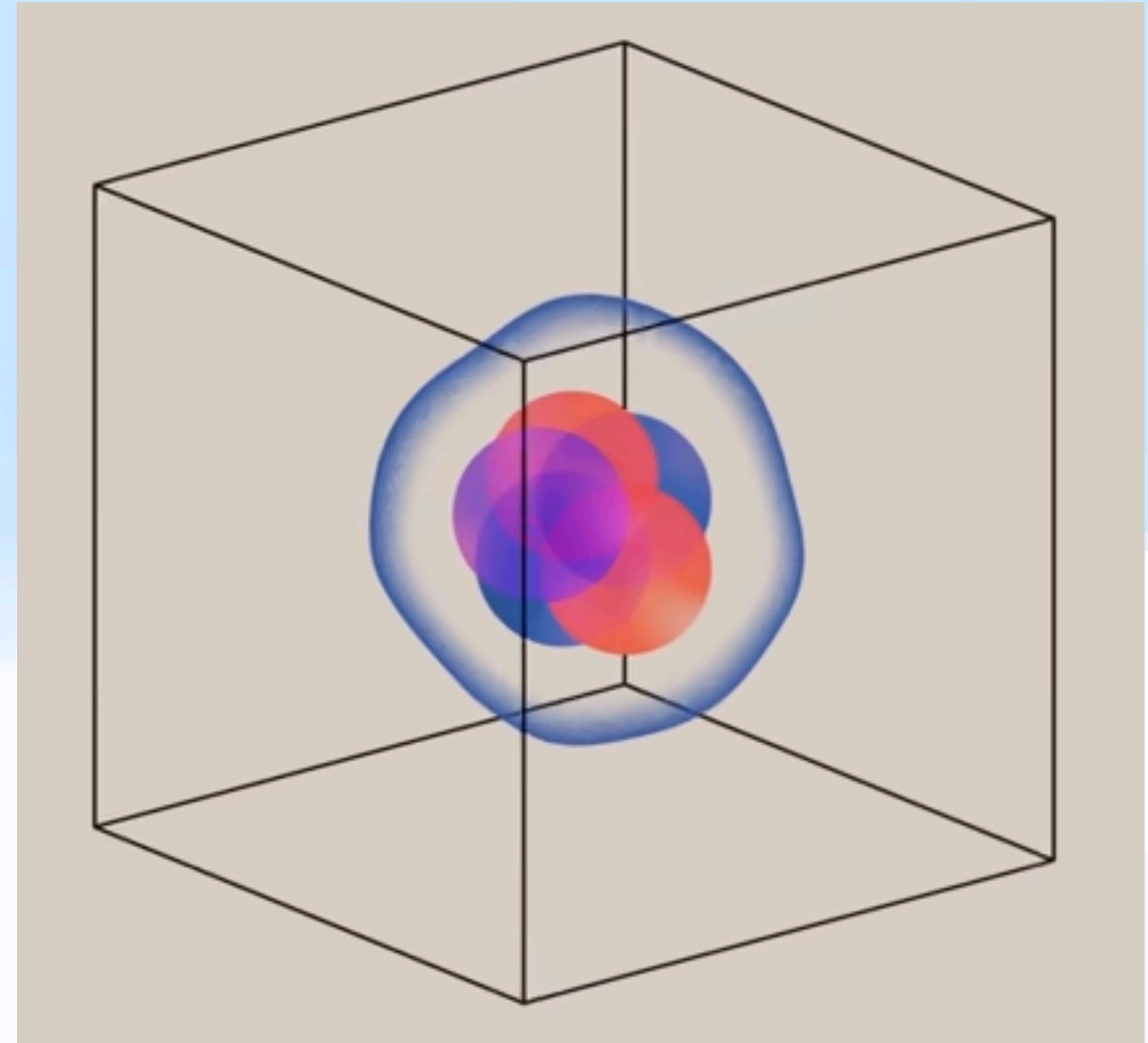
PAULI EXCLUSION PRINCIPLE



Standard Model

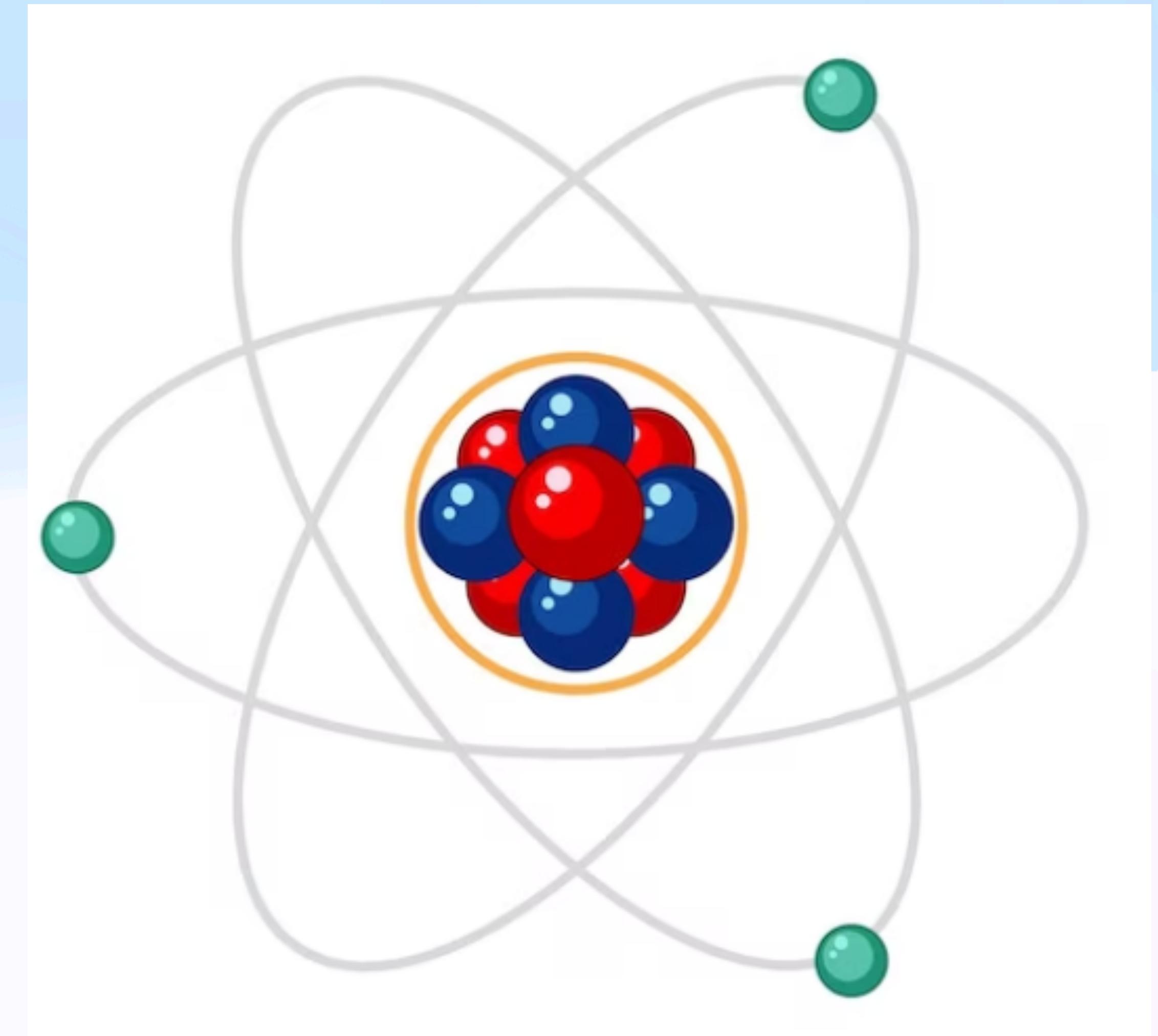
BOSONS

They form the force interaction particles



Fundamental building blocks

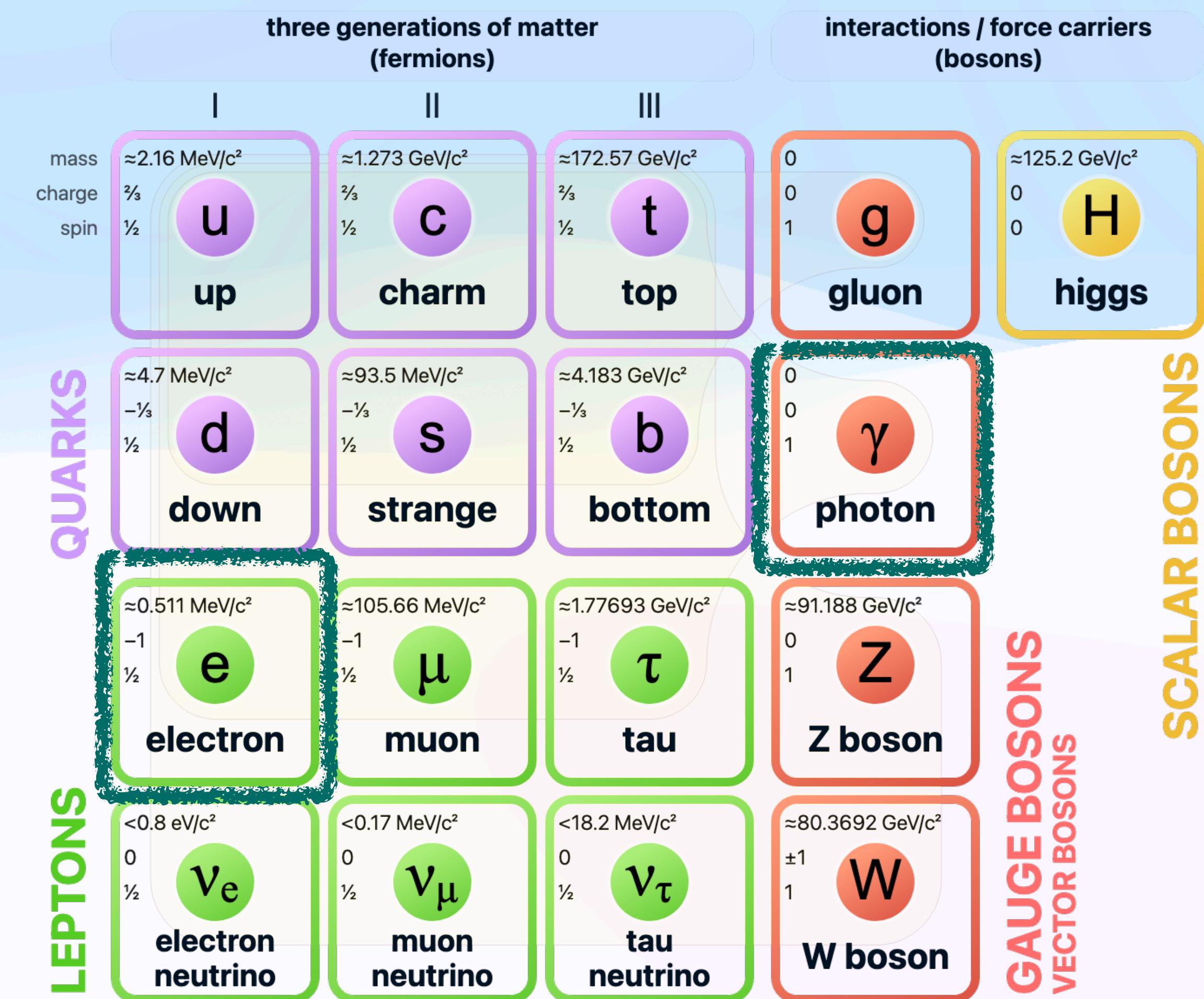
- Atoms are building blocks of matter
- They look something like this:
 - Electrons
 - Protons
 - Neutrons



Fundamental building blocks

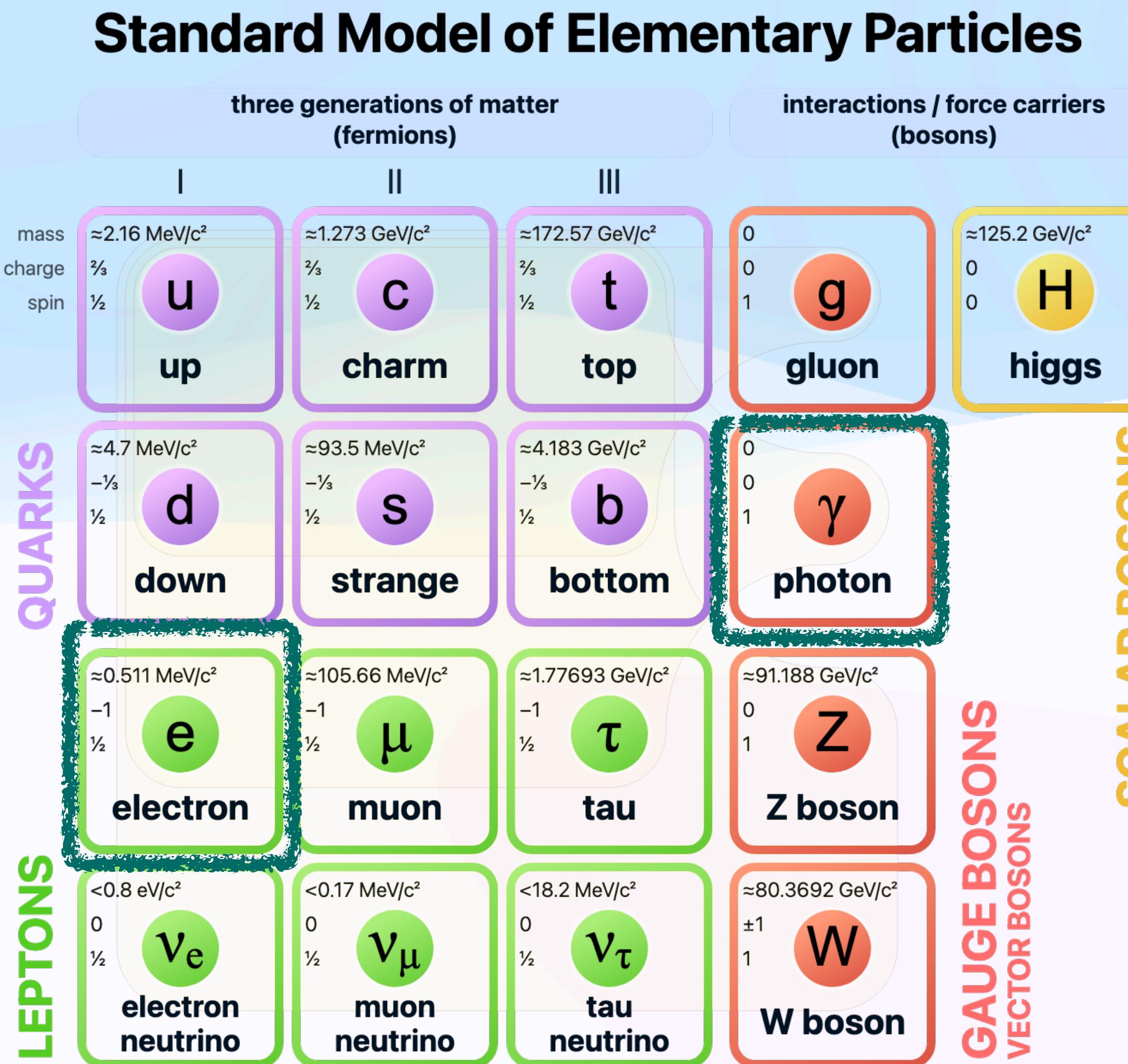
- An electron is a fundamental particle.
- It interacts via electromagnetic force
- It can emit and absorb a photon which is the particle for EM force

Standard Model of Elementary Particles



Fundamental building blocks

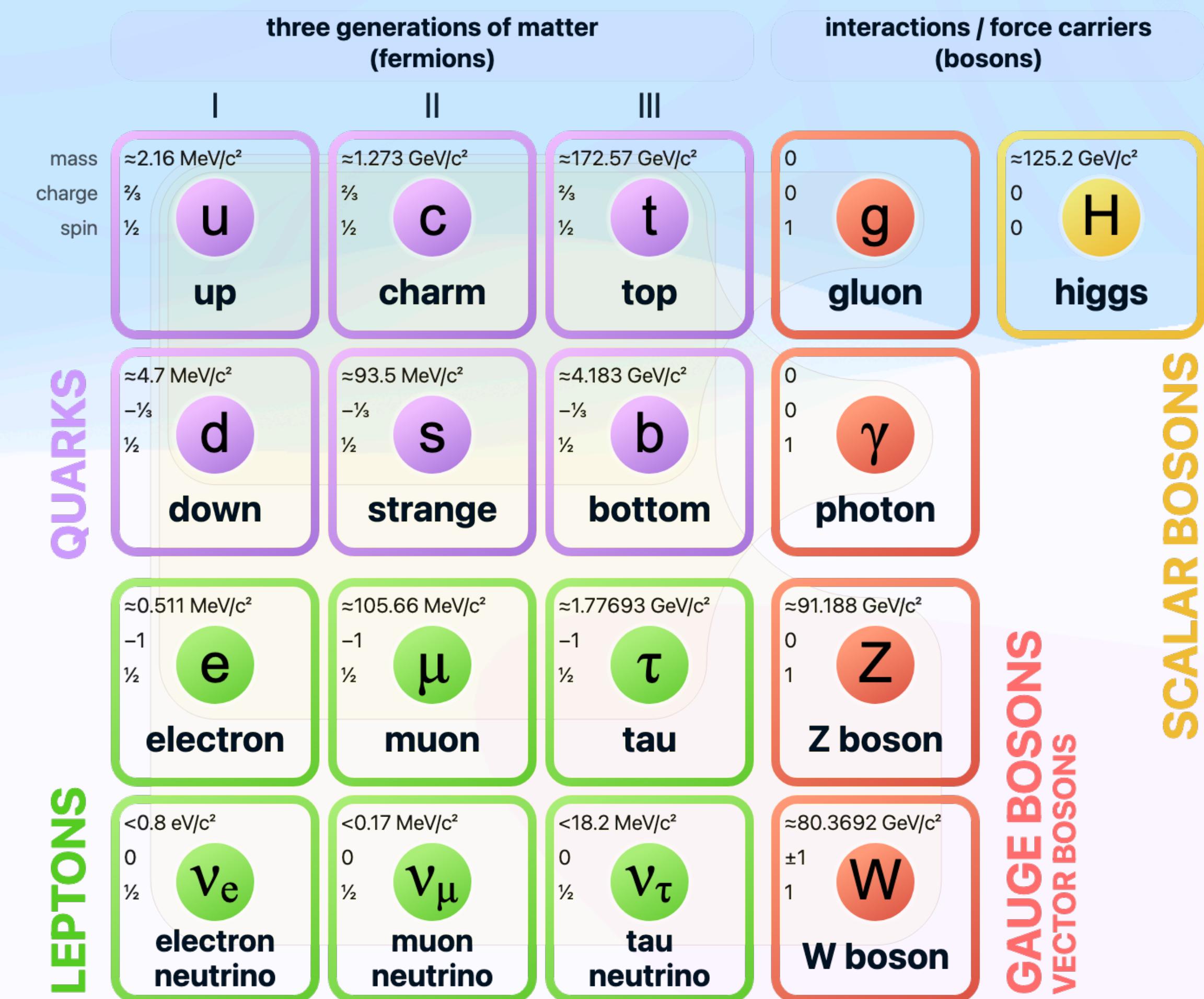
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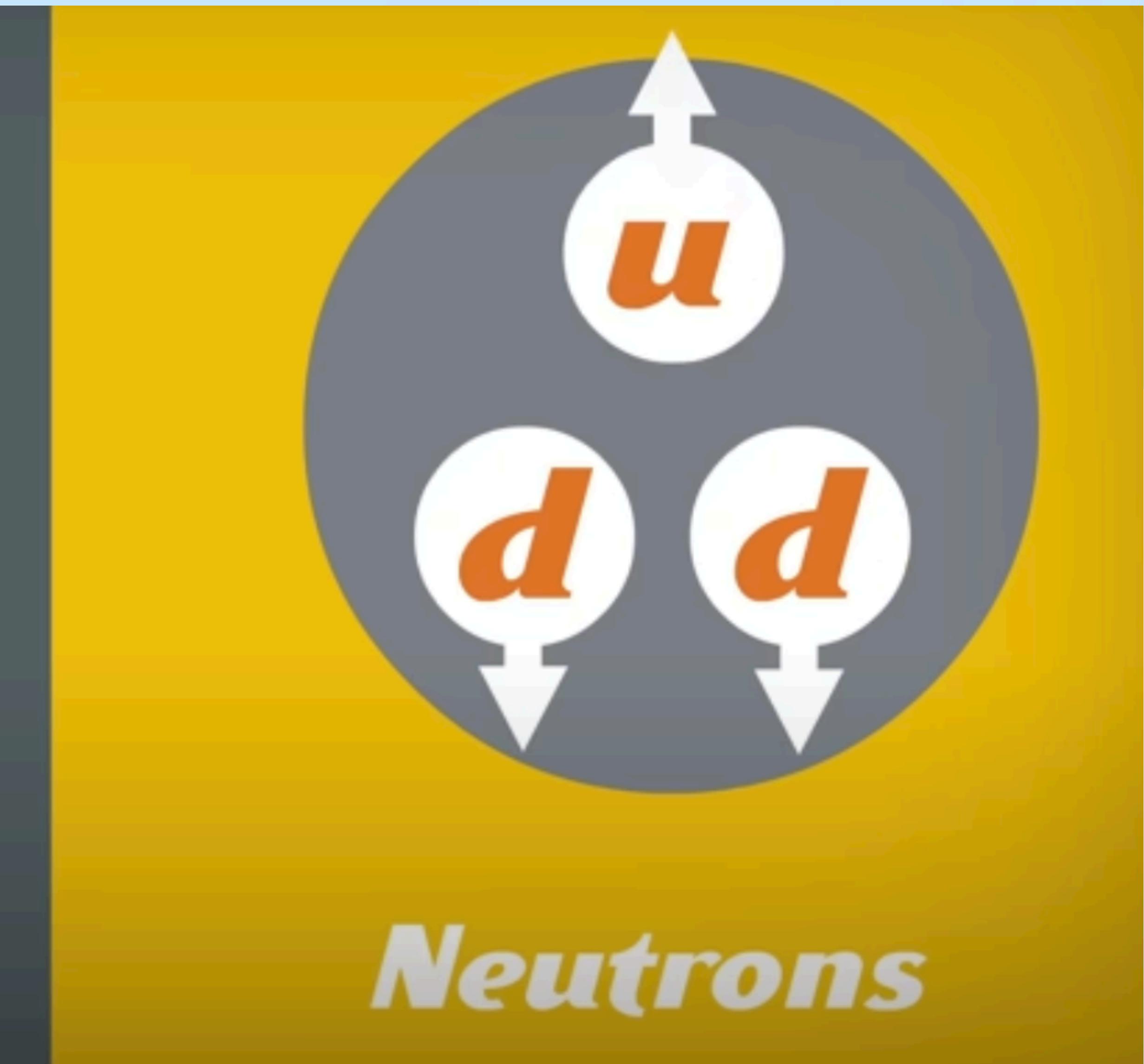
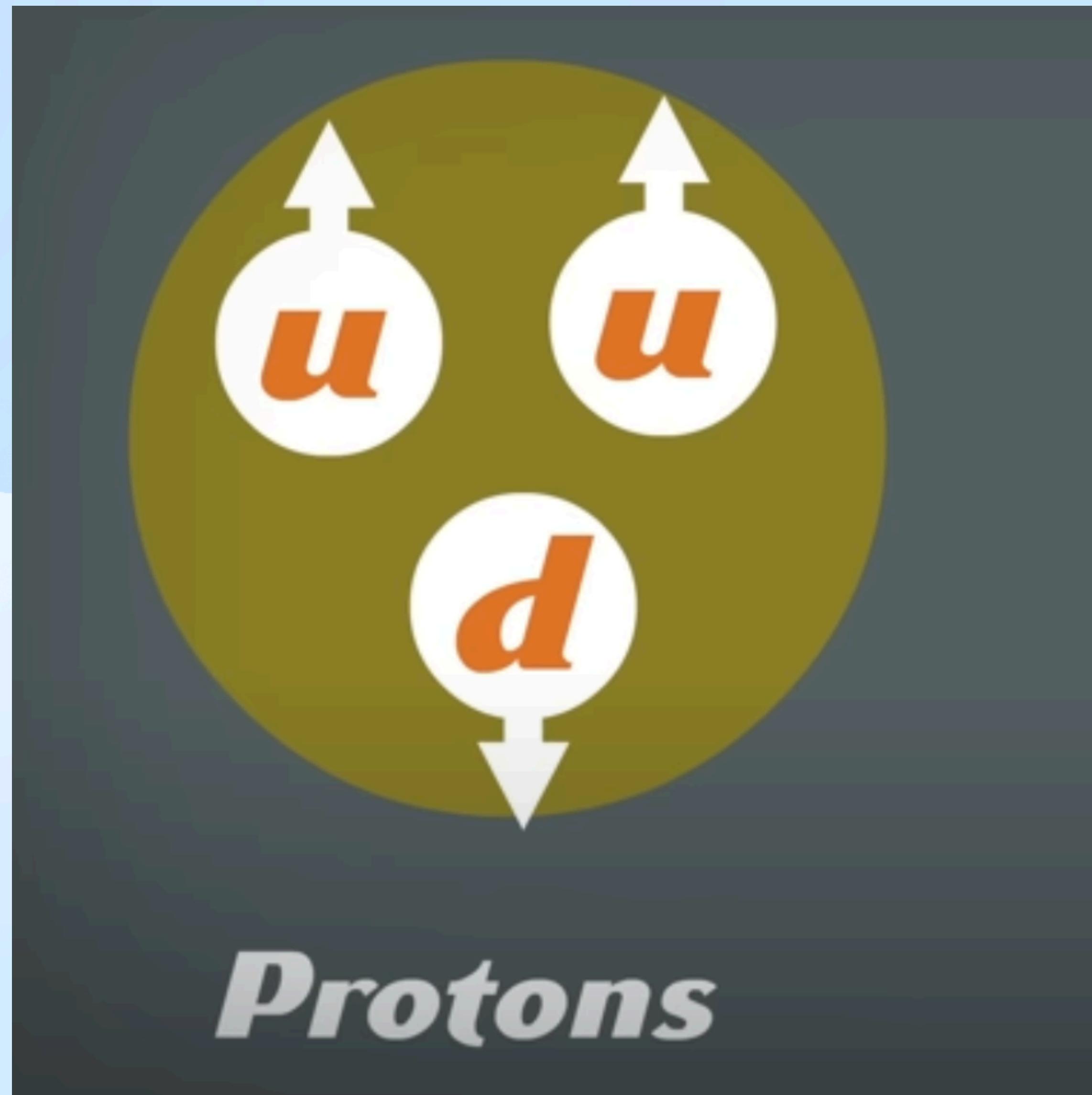
Fundamental building blocks

- The nucleus of the atom is made-up of proton and neutrons
- Historically, they were thought to be fundamental particles
- But that is not true

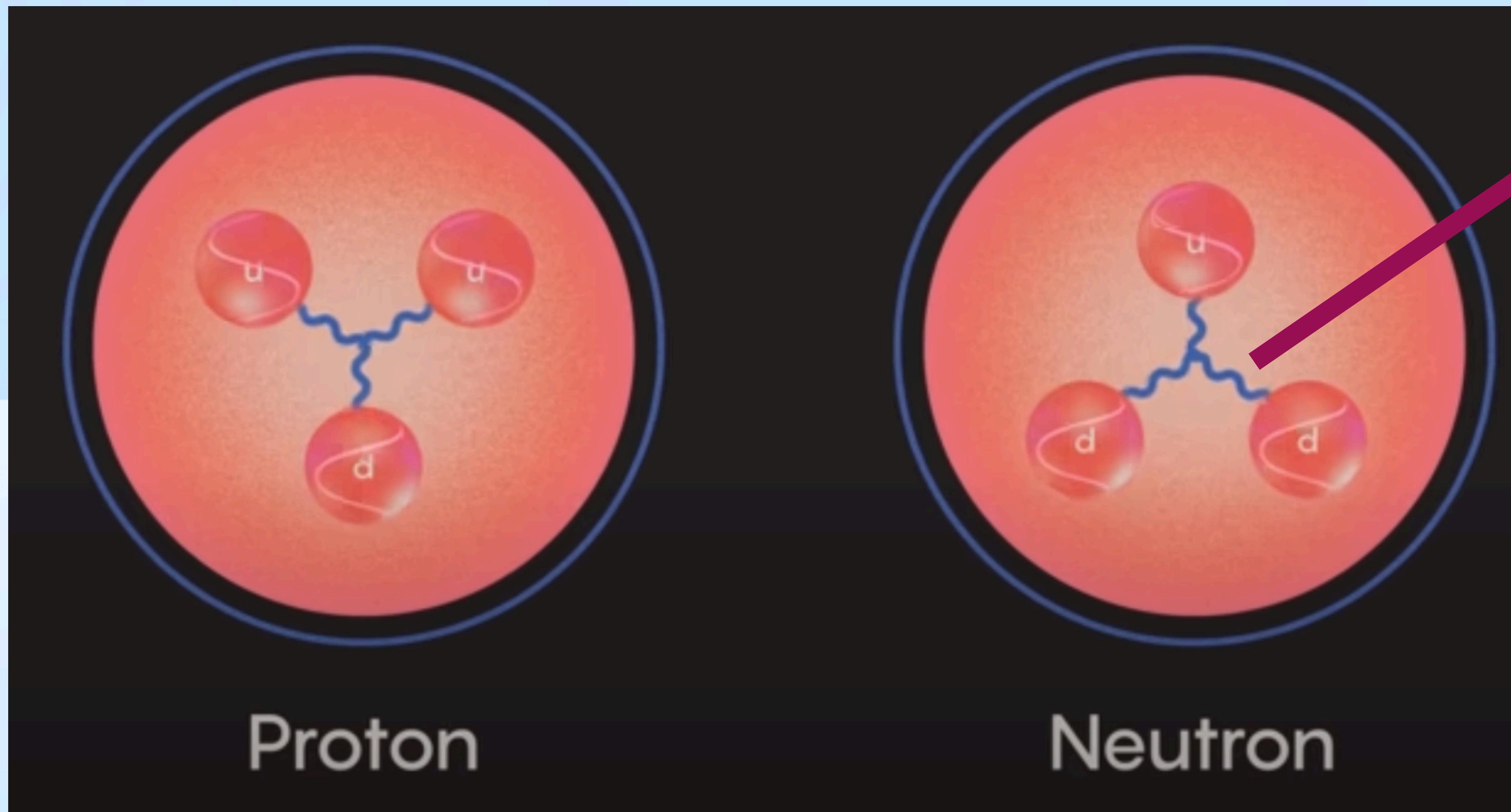
Standard Model of Elementary Particles



Fundamental building blocks



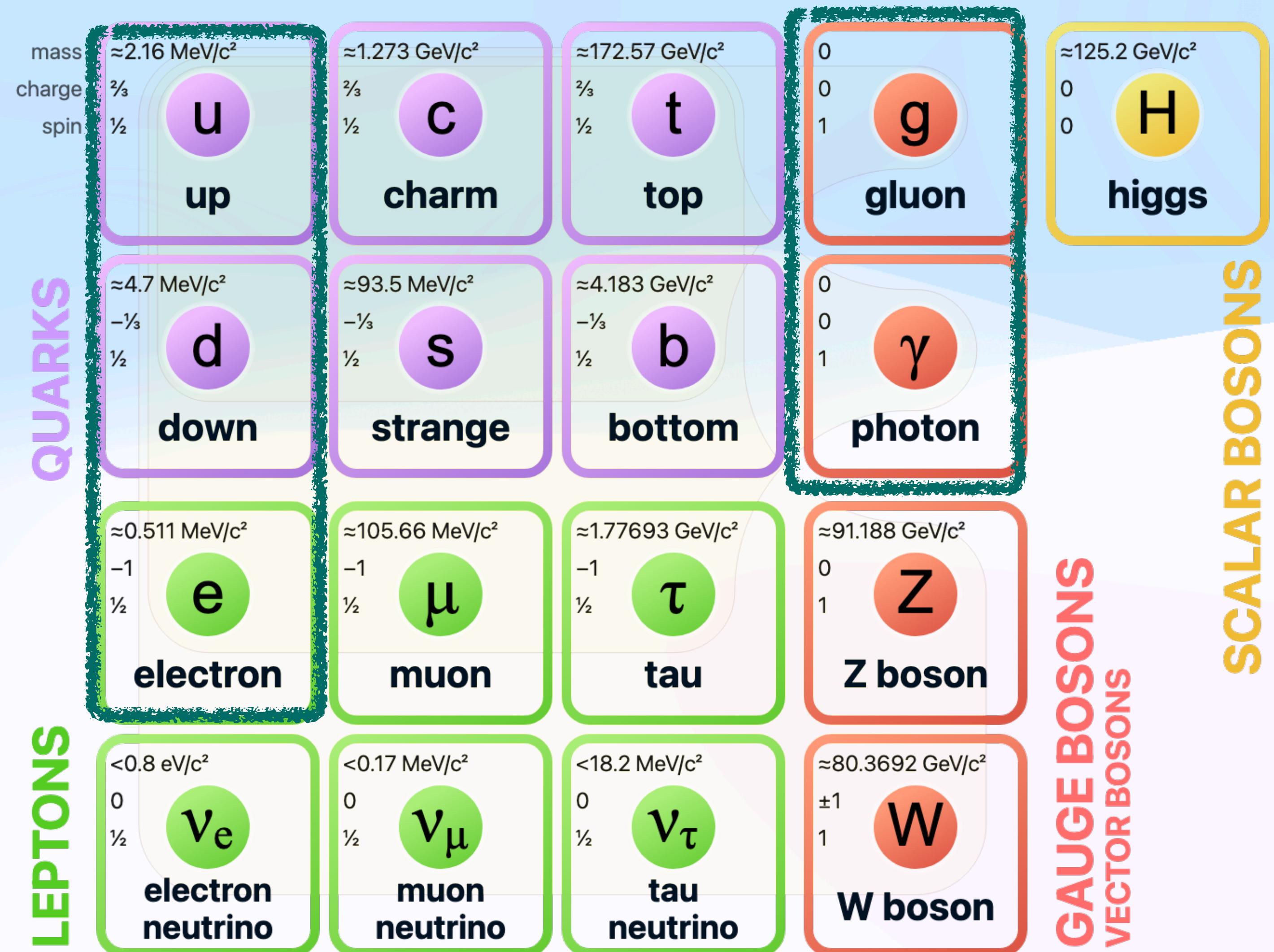
Fundamental building blocks



Gluon -
particle for
Strong force

Fundamental building blocks

- All the matter which you can see around you is made-up of just 3 fundamental particles
- They are just arranged in different ways to make the matter



Fundamental building blocks

- All the matter which you can see around you is made-up of just 3 fundamental particles
- They are just arranged in different ways to make the matter

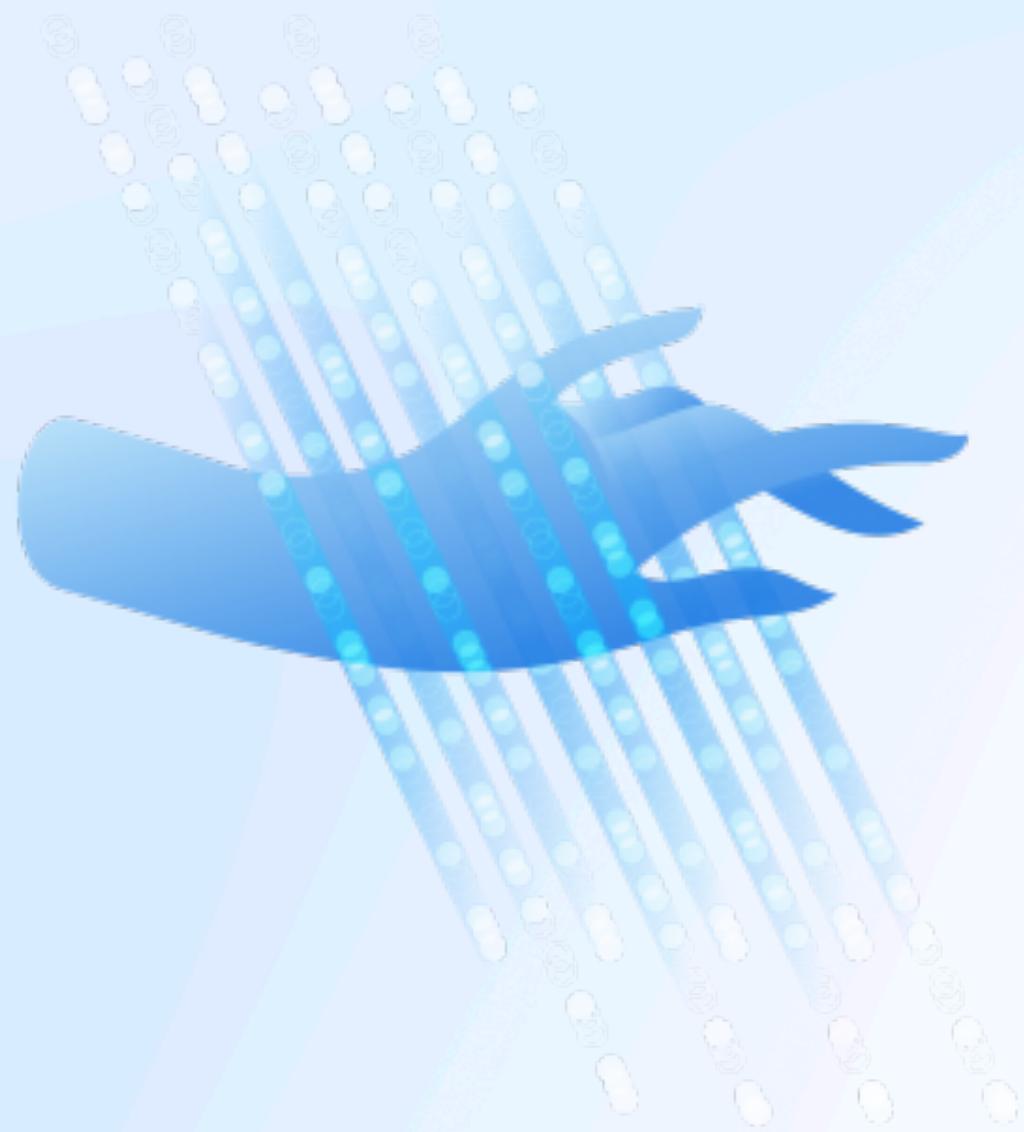
PERIODIC TABLE OF THE ELEMENTS

The periodic table displays elements in a grid of colored squares. Elements are color-coded into groups: alkali metals (red), alkaline earth metals (orange), transition metals (yellow), post-transition metals (green), noble gases (light blue), chalcogens (purple), and halogens (pink). A single square for element 117, Ts (Tennessee), is highlighted in green, standing out from the rest of the table.

1 H	Hydrogen	2 He	Helium
3 Li	Lithium	4 Be	Beryllium
11 Na	Sodium	12 Mg	Magnesium
19 K	Potassium	20 Ca	Calcium
37 Rb	Rubidium	38 Sr	Sr
55 Cs	Ce	56 Ba	Ba
87 Fr	Fr	88 Ra	Ra
90 Th	Th	91 Pa	Pa
92 U	U	93 Np	Np
94 Pu	Pu	95 Am	Am
96 Cm	Cm	97 Bk	Bk
98 Cf	Cf	99 Es	Es
100 Fm	Fm	101 Md	Md
102 No	No	103 Lr	Lr
117 Ts	Tennessee		
5 B	Boron	6 C	Carbon
13 Al	Aluminum	14 Si	Silicon
31 Ga	Gallium	32 Ge	Germanium
51 In	In	52 Sn	Tin
53 Te	Te	54 Sb	Antimony
55 I	Iodine	56 Po	Poison
57 At	Atmosphere	58 Rn	Radiation
59 Ce	Cerium	60 Pr	Praseodymium
61 Nd	Nd	62 Pm	Promethium
63 Sm	Sm	64 Eu	Europium
65 Gd	Gd	66 Tb	Terbium
67 Dy	Dy	68 Ho	Holmium
69 Er	Er	70 Tm	Tulium
71 Yb	Yb	72 Lu	Lutetium

Fundamental building blocks

- The fourth matter particle is neutrino
- They are almost non-interacting particles and, hence, very hard to detect
- But they are huge in numbers
- And constantly following through us



Fundamental building blocks

These three make-up all the matter

LEPTONS

mass charge spin	particle	mass charge spin	particle	mass charge spin	particle	mass charge spin	particle	mass charge spin	particle	mass charge spin	particle
$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	e electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$	μ muon	$\approx 1.77693 \text{ GeV}/c^2$ -1 $\frac{1}{2}$	τ tau	$\approx 91.188 \text{ GeV}/c^2$ 0 $\frac{1}{2}$	Z Z boson	$\approx 80.3692 \text{ GeV}/c^2$ ± 1 1	W W boson	$\approx 125.2 \text{ GeV}/c^2$ 0 0	H higgs
$<0.8 \text{ eV}/c^2$ 0 $\frac{1}{2}$	ν_e electron neutrino	$<0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	ν_μ muon neutrino	$<18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$	ν_τ tau neutrino	0 0 1	g gluon	0 0 1	γ photon	0 0 1	
$\approx 2.16 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	u up	$\approx 1.273 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	c charm	$\approx 172.57 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$	t top						
$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	d down	$\approx 93.5 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	s strange	$\approx 4.183 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$	b bottom						

SCALAR BOSONS

GAUGE BOSONS VECTOR BOSONS

A peculiar cosmic ghost which follows through us

Fundamental building blocks

But this is not it, we have 2 more copies of these 4 particles, which are called the “next generation”

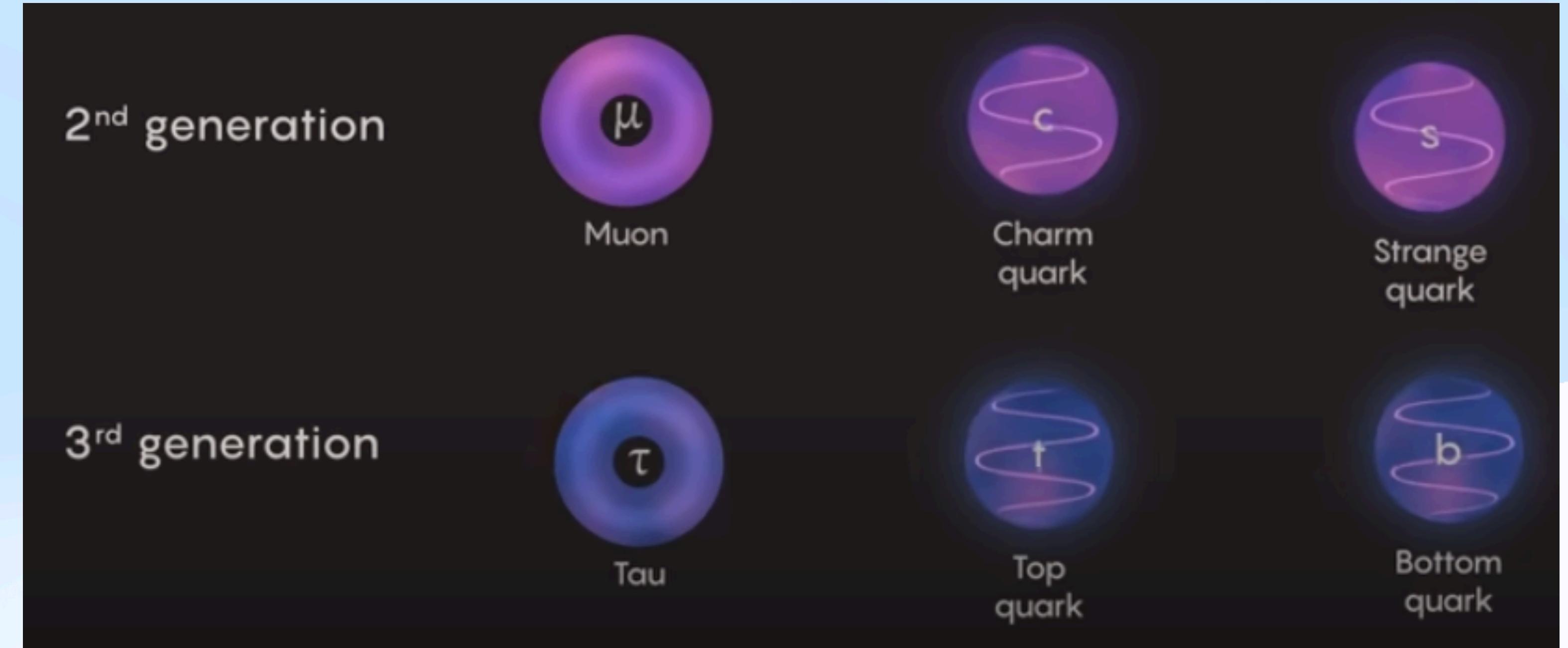
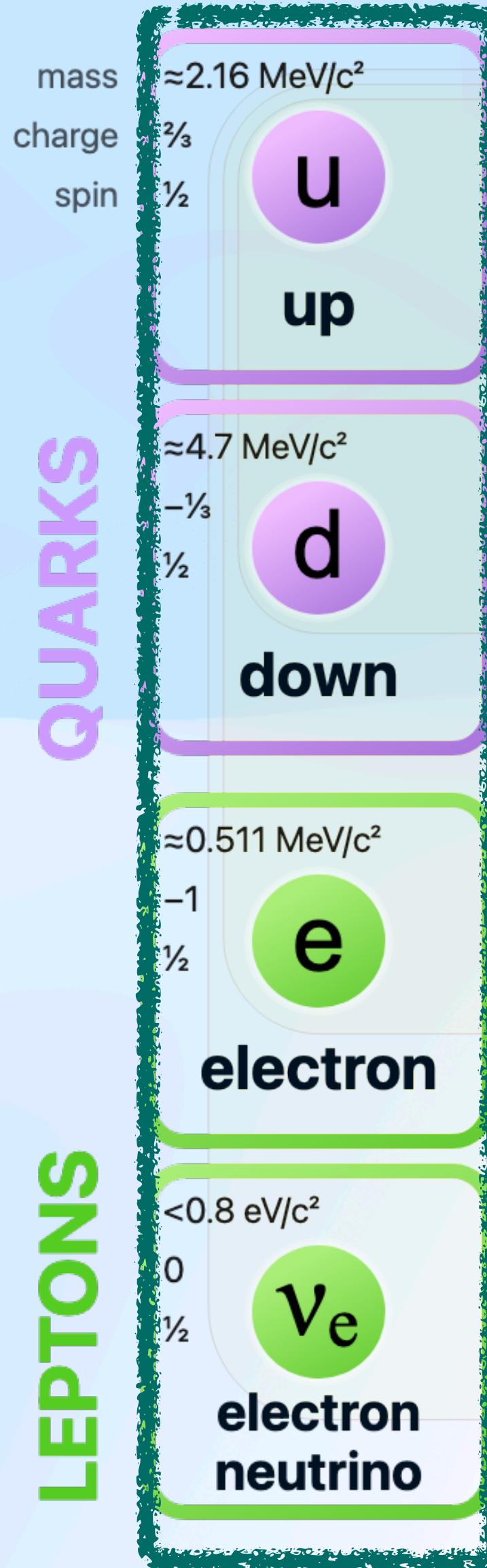
We don't know the reason for this

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

Fundamental building blocks

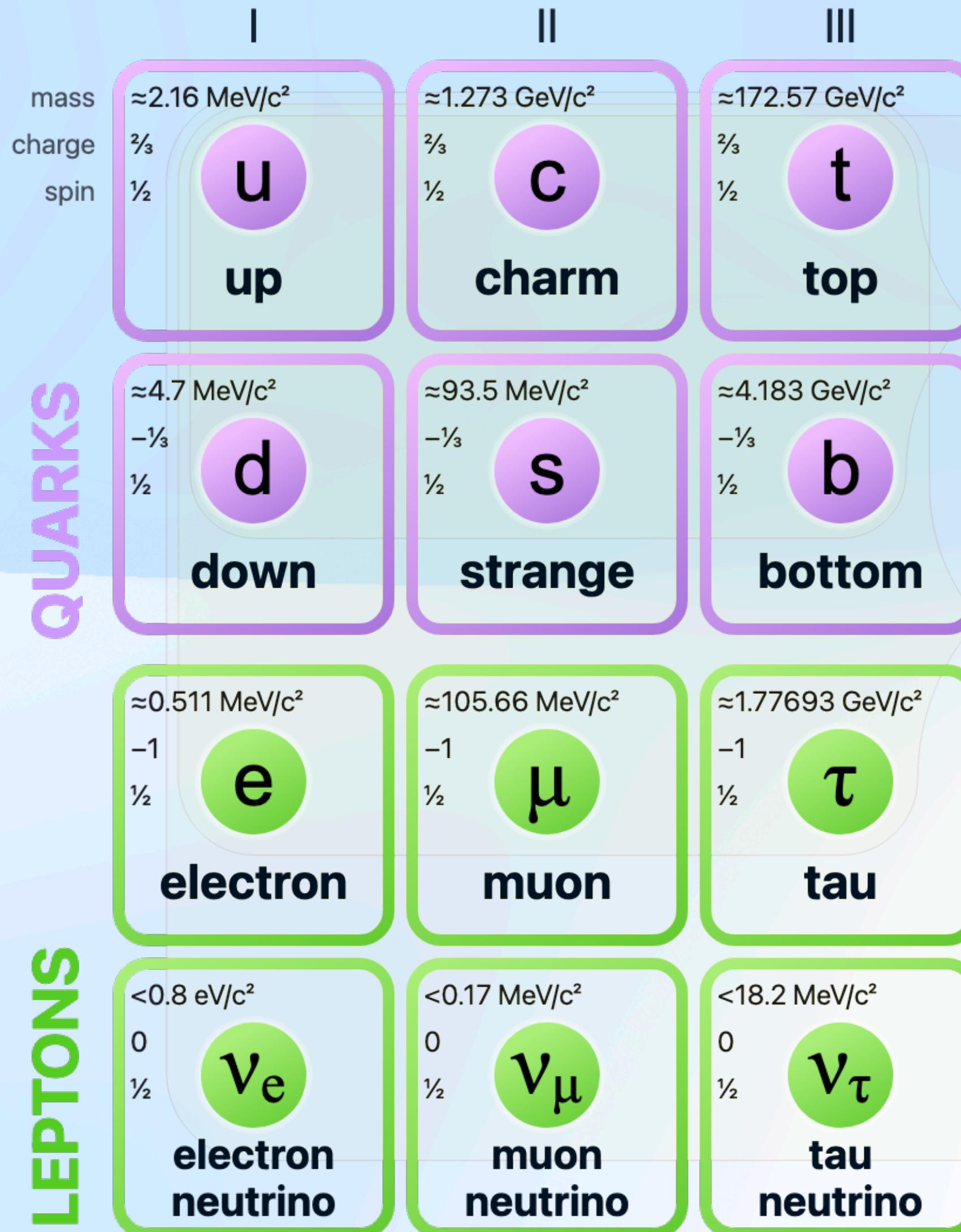
	mass $\approx 2.16 \text{ MeV}/c^2$	mass $\approx 1.273 \text{ GeV}/c^2$	mass $\approx 172.57 \text{ GeV}/c^2$
charge $\frac{2}{3}$	u	c	t
spin $\frac{1}{2}$	up	charm	top
QUARKS			
charge $-\frac{1}{3}$	d	s	b
spin $\frac{1}{2}$	down	strange	bottom
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.77693 \text{ GeV}/c^2$
-1	e	μ	τ
$\frac{1}{2}$	electron	muon	tau
LEPTONS			
	$<0.8 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<18.2 \text{ MeV}/c^2$
0	ν_e	ν_μ	ν_τ
$\frac{1}{2}$	electron neutrino	muon neutrino	tau neutrino

Fundamental building blocks



We can create these particles, but they are unstable. They decay into the 1st generations particles very quickly

Fundamental building blocks



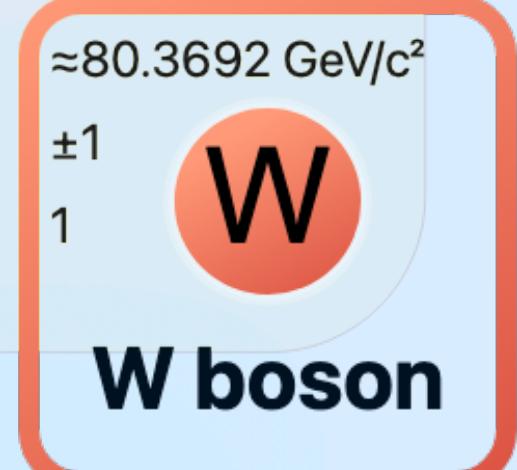
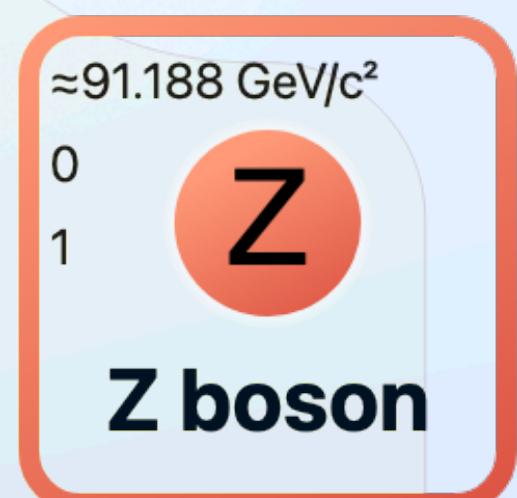
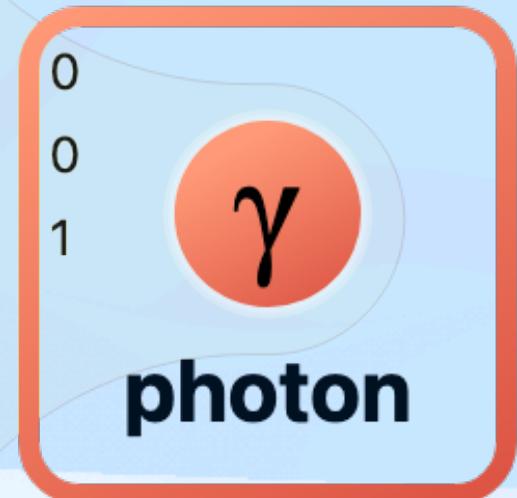
- Here are all the fundamental particles that make matter
- We understand a few things about them but there are still many mysteries
- Why 3 generations?

Fundamental building blocks

	I	II	III
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
QUARKS	u up	c charm	t top
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	d down	s strange	b bottom
LEPTONS	e electron	μ muon	τ tau
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.77693 \text{ GeV}/c^2$
	-1	-1	-1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

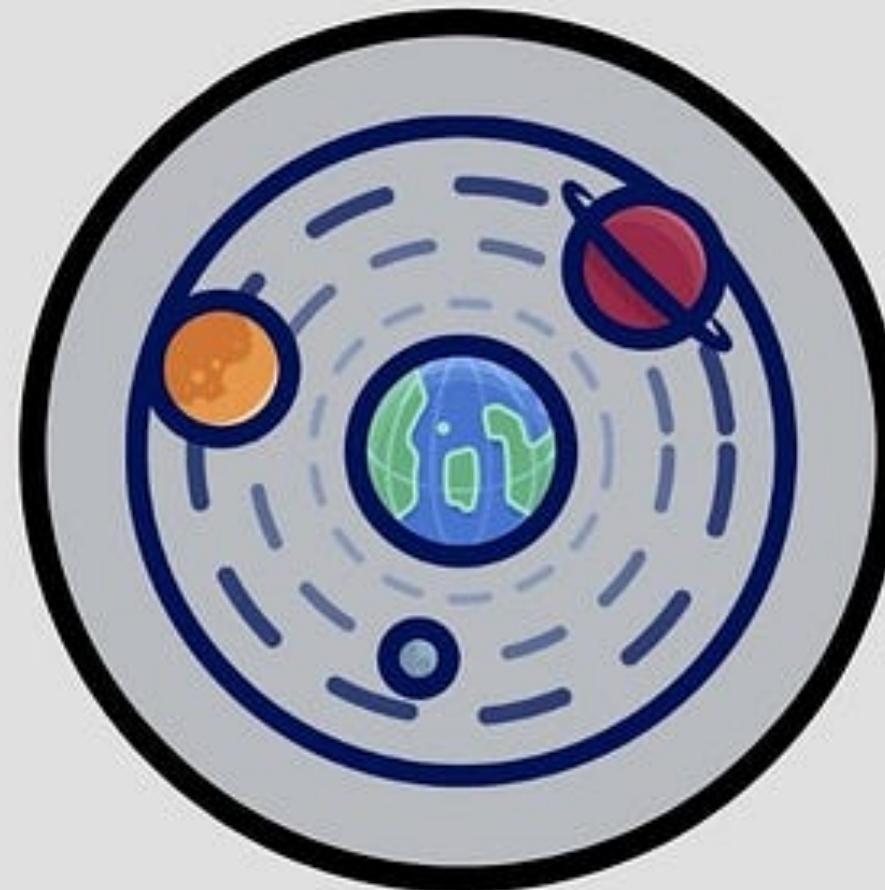
- What about the forces?

Fundamental building blocks

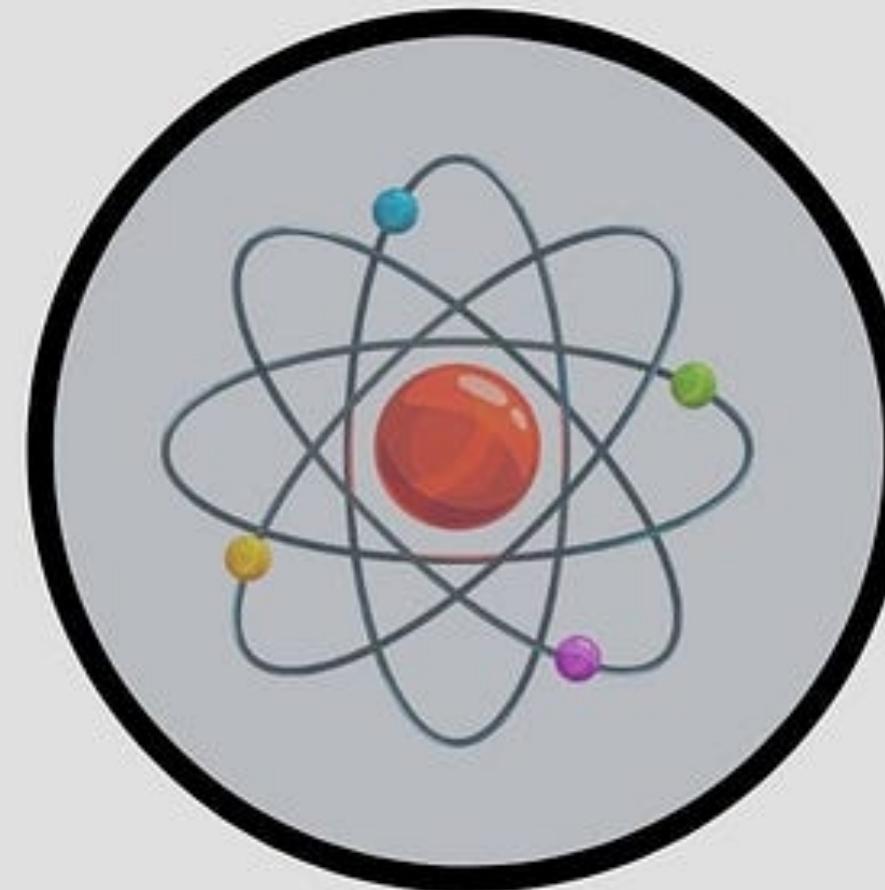


- What about the forces?
- There are 4 fundamental forces in nature and we have 3 of them here in the Standard Model
- All 3 forces have an associated particle through which the matter particles interact.
- All force particles are bosons in nature

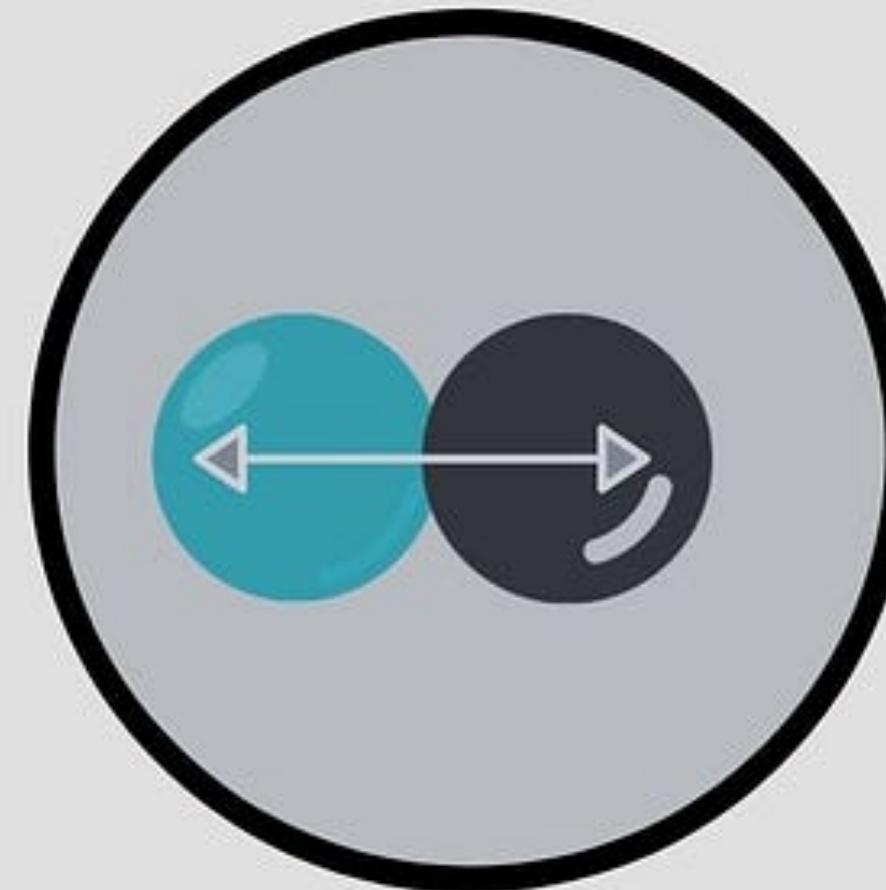
Four Basic Forces



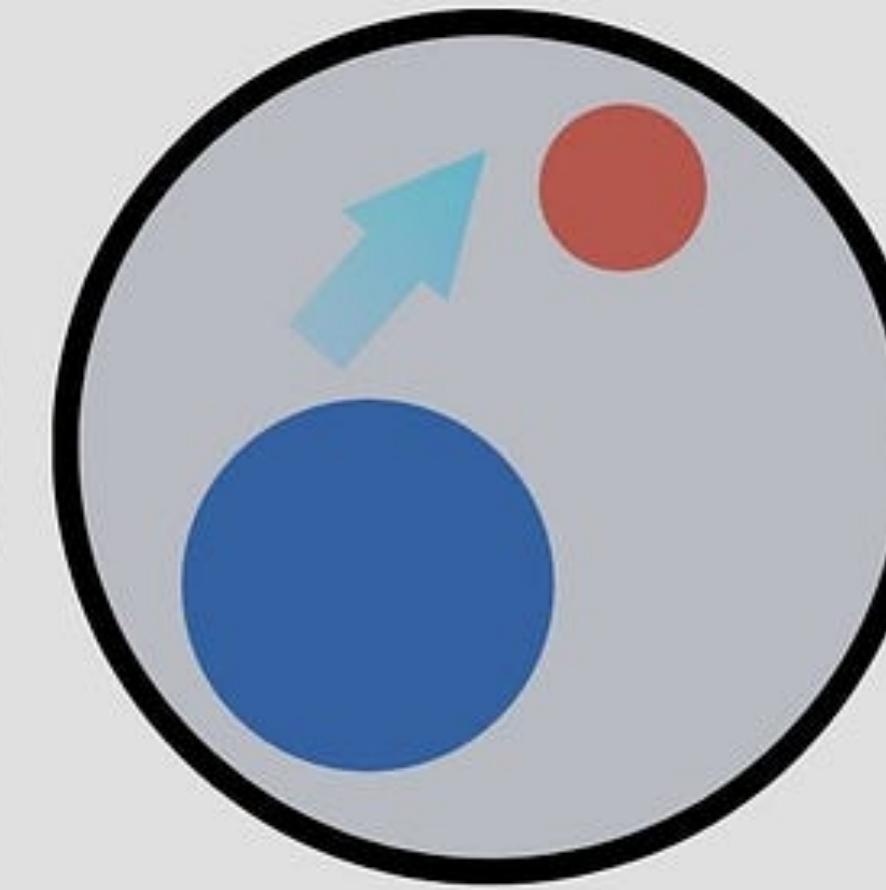
Gravitation



Elecctro-magnetism



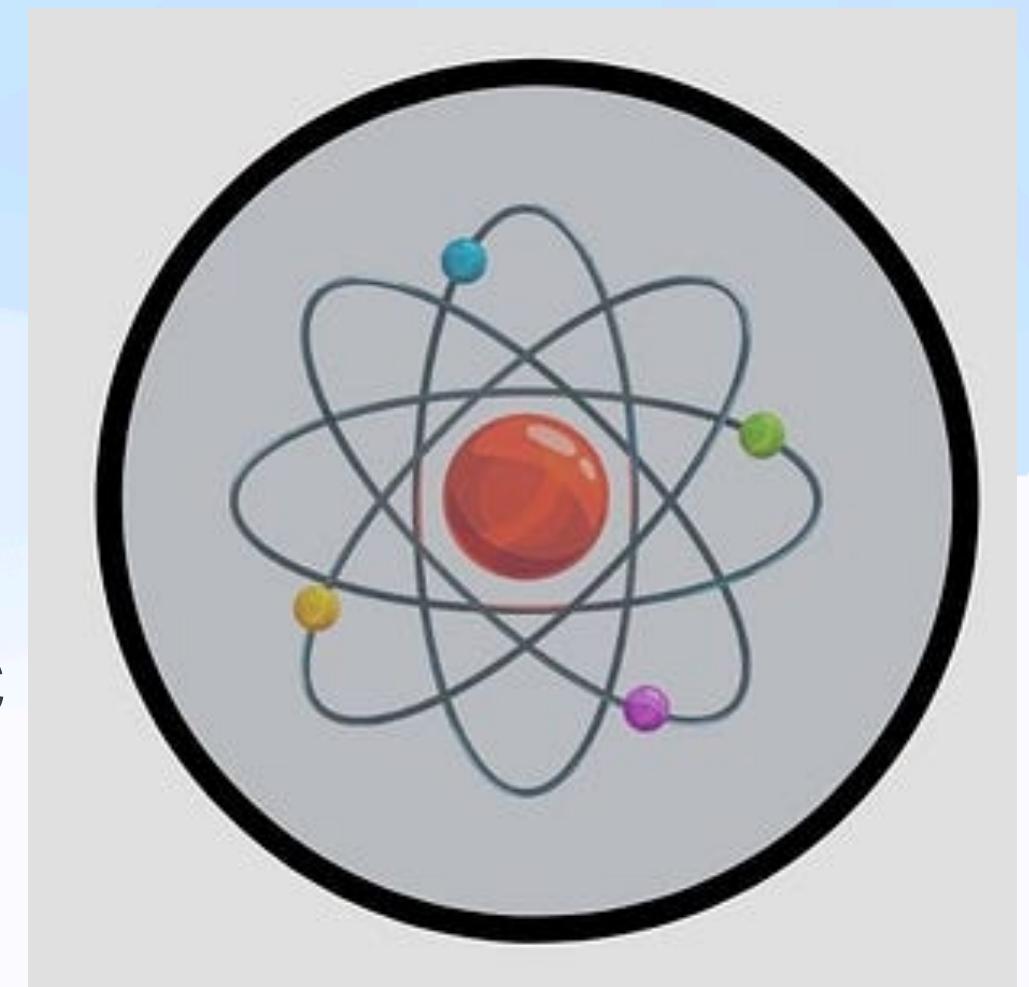
Strong Force



Weak Force

Electromagnetic(EM) Interaction

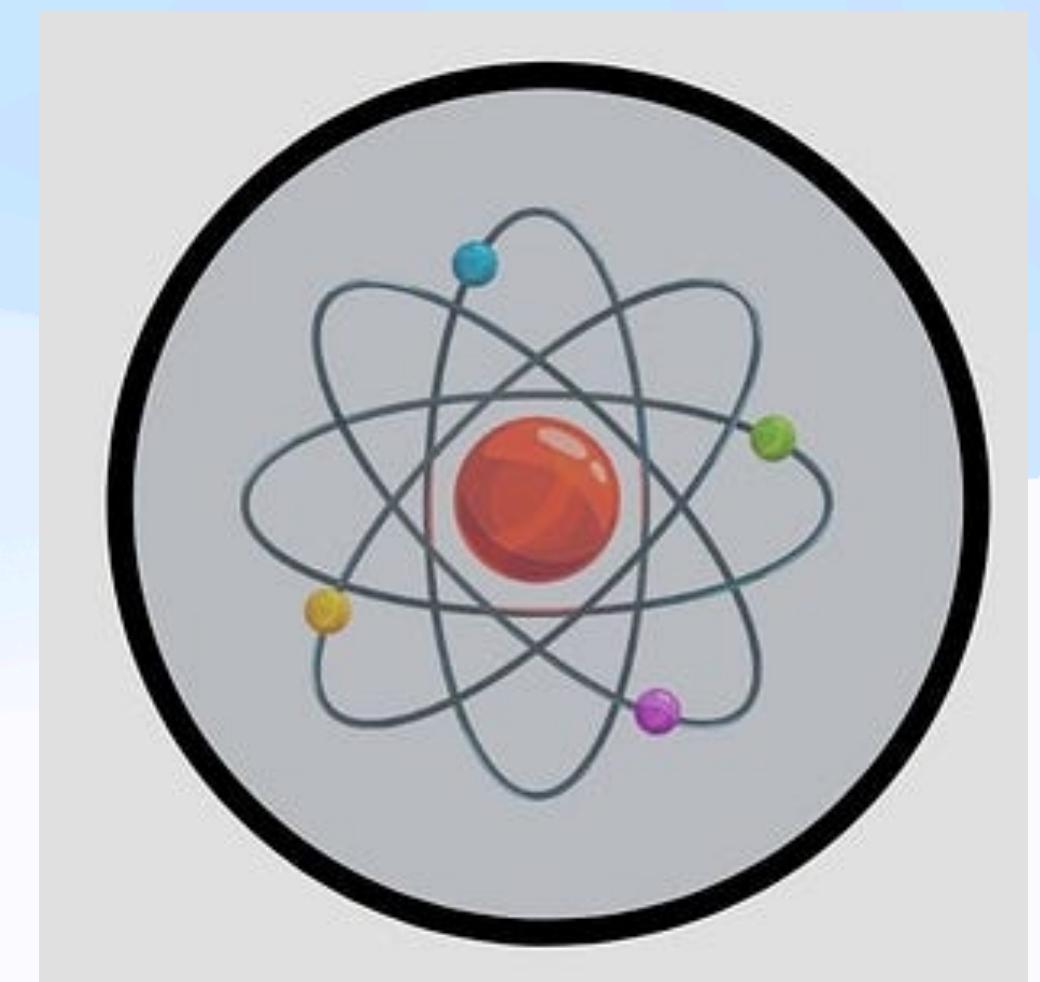
- Responsible for the structure and the interactions of the fundamental particles
- Within the atom, EM forces dominate
- Many common macroscopic forces (such as friction, air resistance, drag, and tension) are due to EM forces at the atomic level
- Between two protons in the nucleus, EM is about 10^{-2} of strong force with an infinite range
- According to QED, the mediator of the electromagnetic force is the photon.



Electromagnetic(EM) Interaction

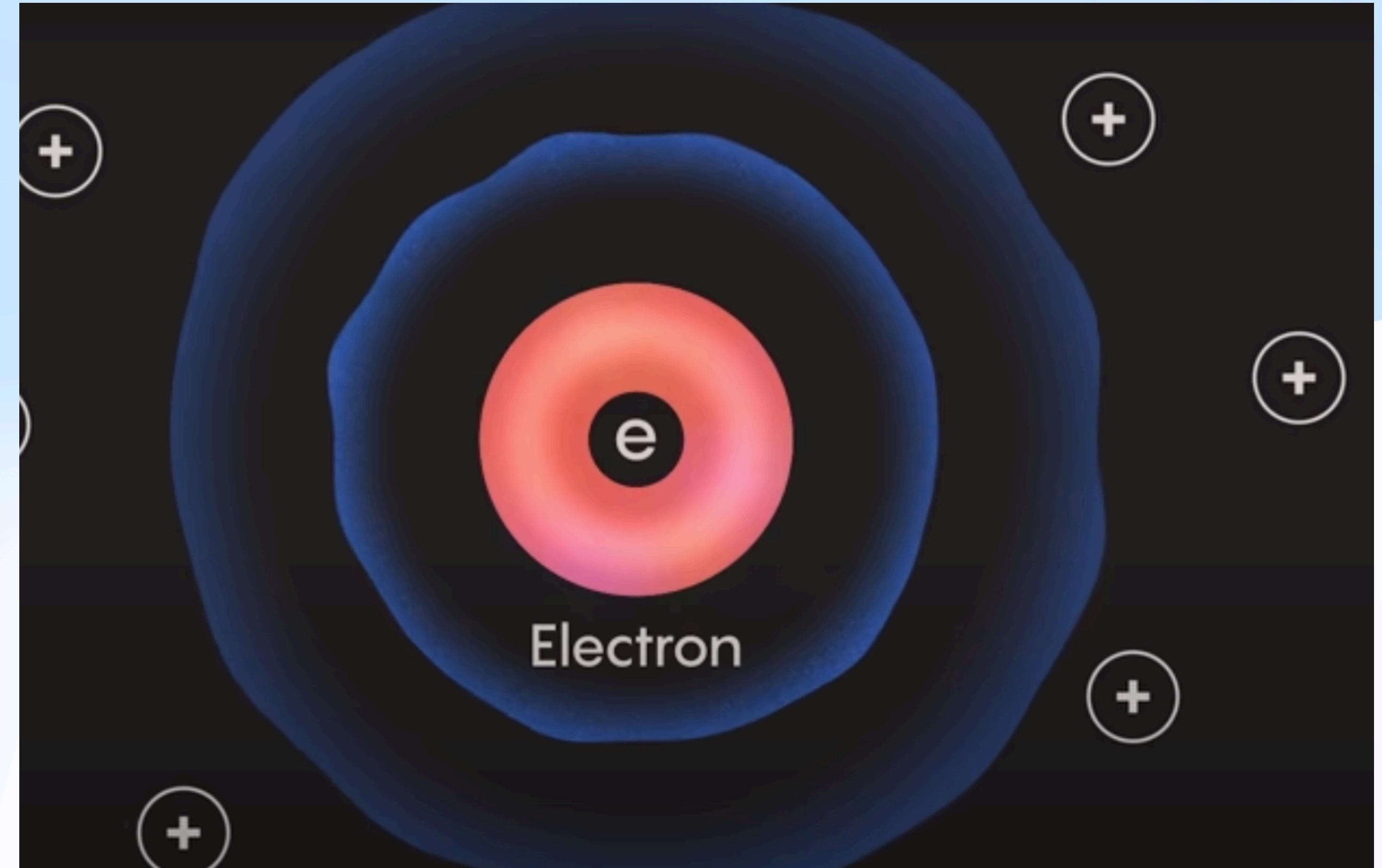
- EM force is felt by all the matter particles except the neutrinos (as they are neutral)

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



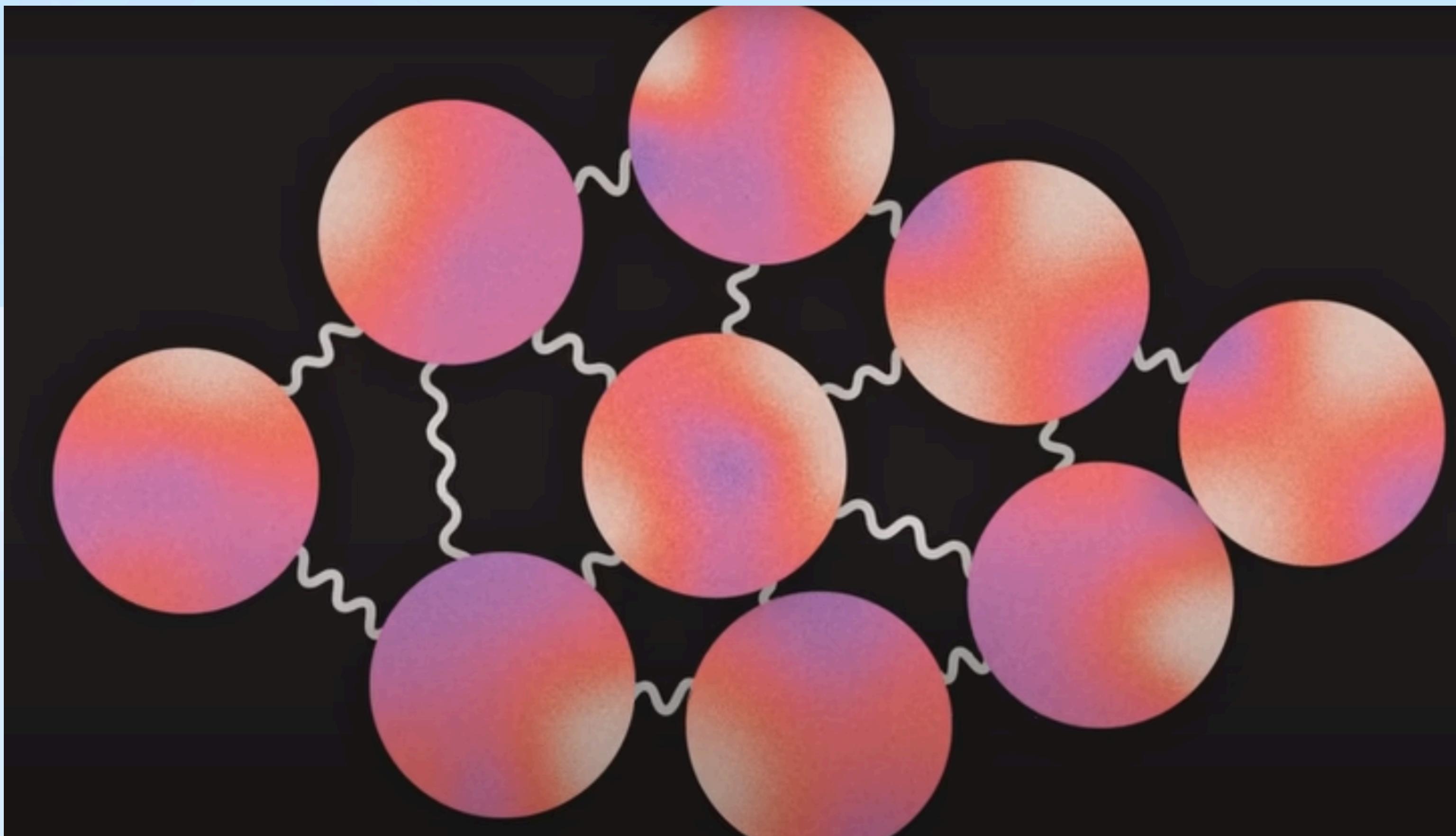
Electromagnetic(EM) Interaction

- EM force is applied **radially**



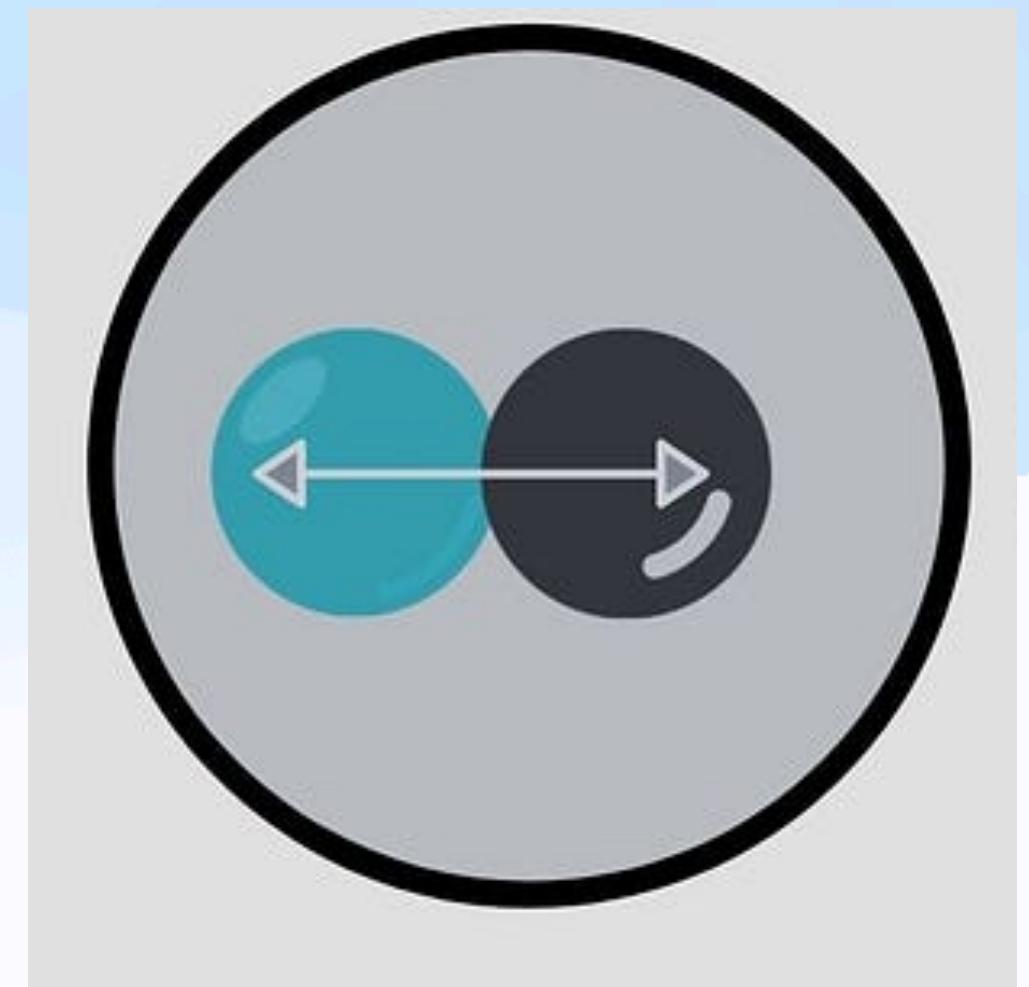
Strong Interaction

- Responsible for binding the nucleus together



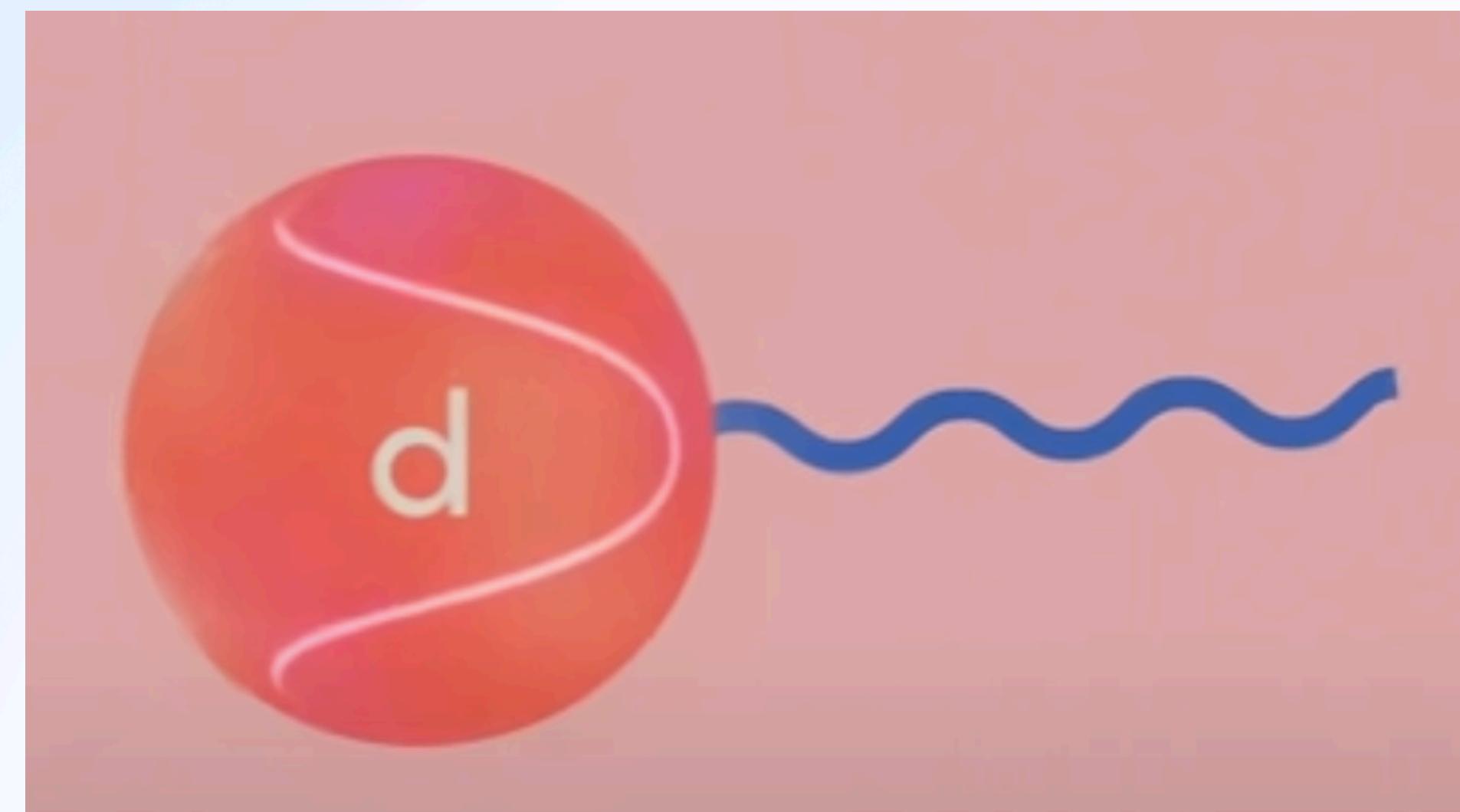
Strong Interaction

- Responsible for binding the nucleus together
- It is the dominant one in the reactions and decays of most of the fundamental particles
- The strong force is 10^7 times stronger for two protons touching.
- The mediator of the strong force is the gluon.
- Within the framework of the Standard Model, the strong force is due to color charge, analogous to the electromagnetic force being due to electric charge.

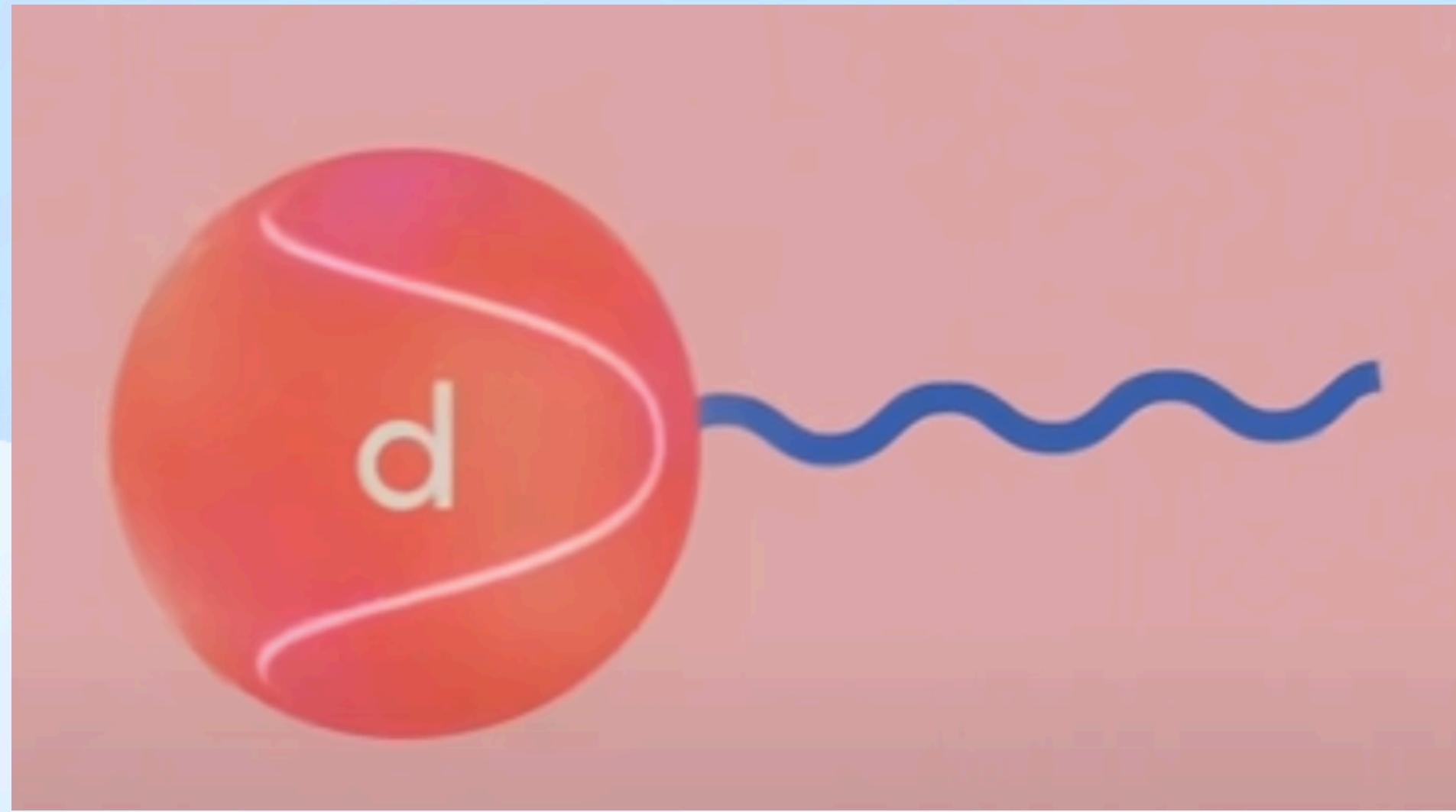


Strong Interaction

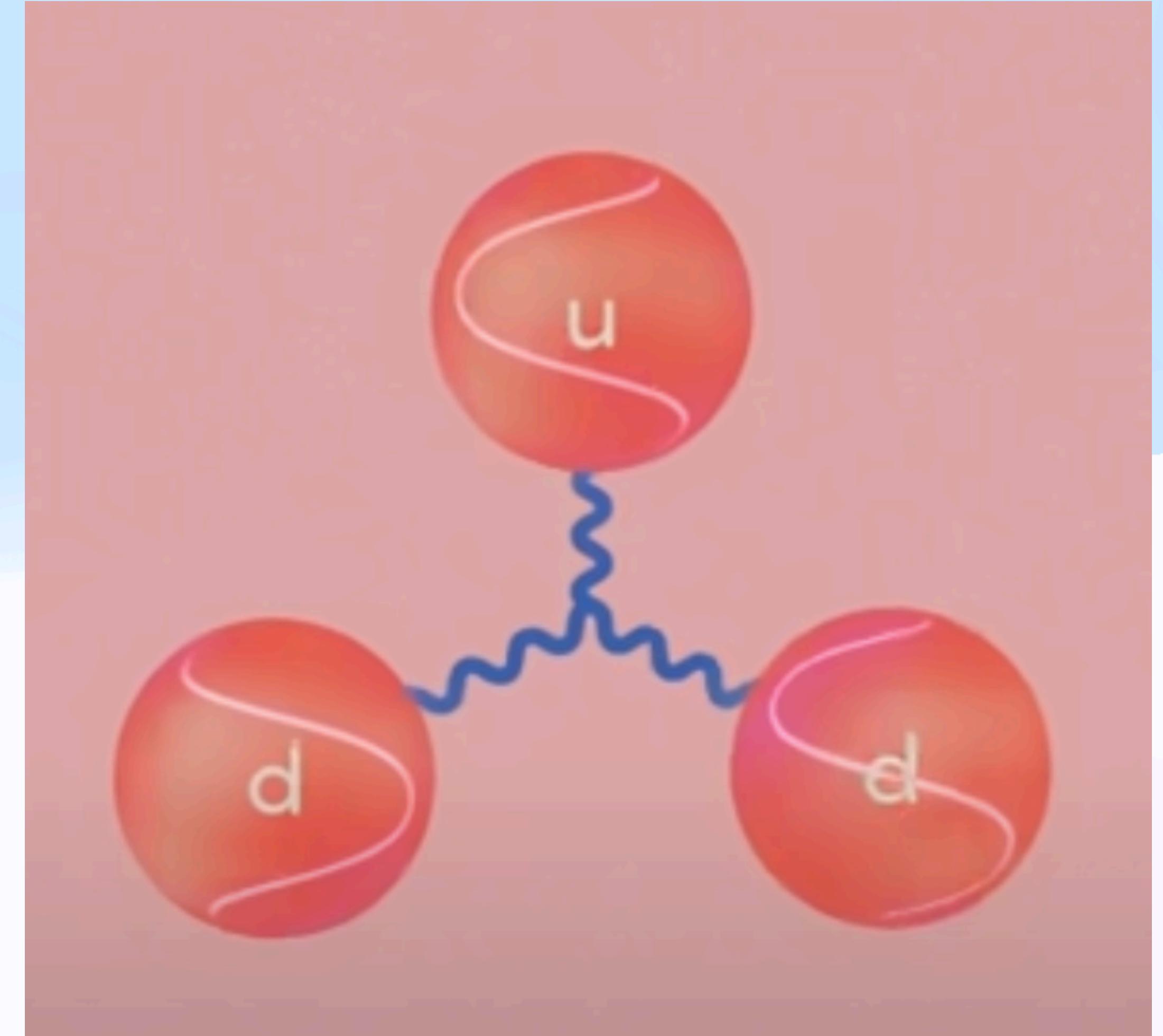
- Gluons - glues the quarks together to make protons and neutrons
- But gluons and strong force are very different than EM force
- It does not spread out radially
- There is thin string-like object which only ends when it meets the other quark



Strong Interaction



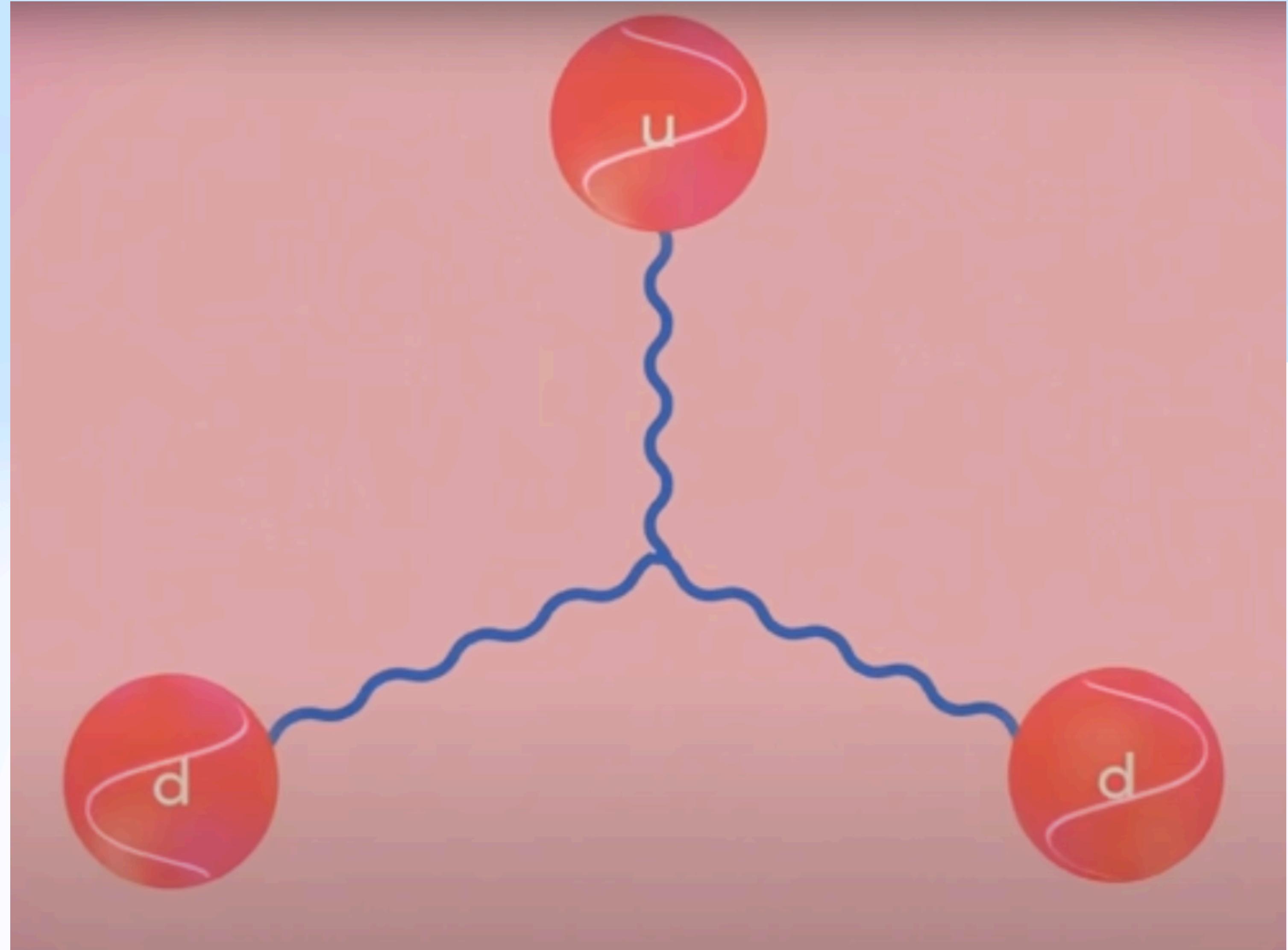
This makes strong force -
strong



Strong Interaction

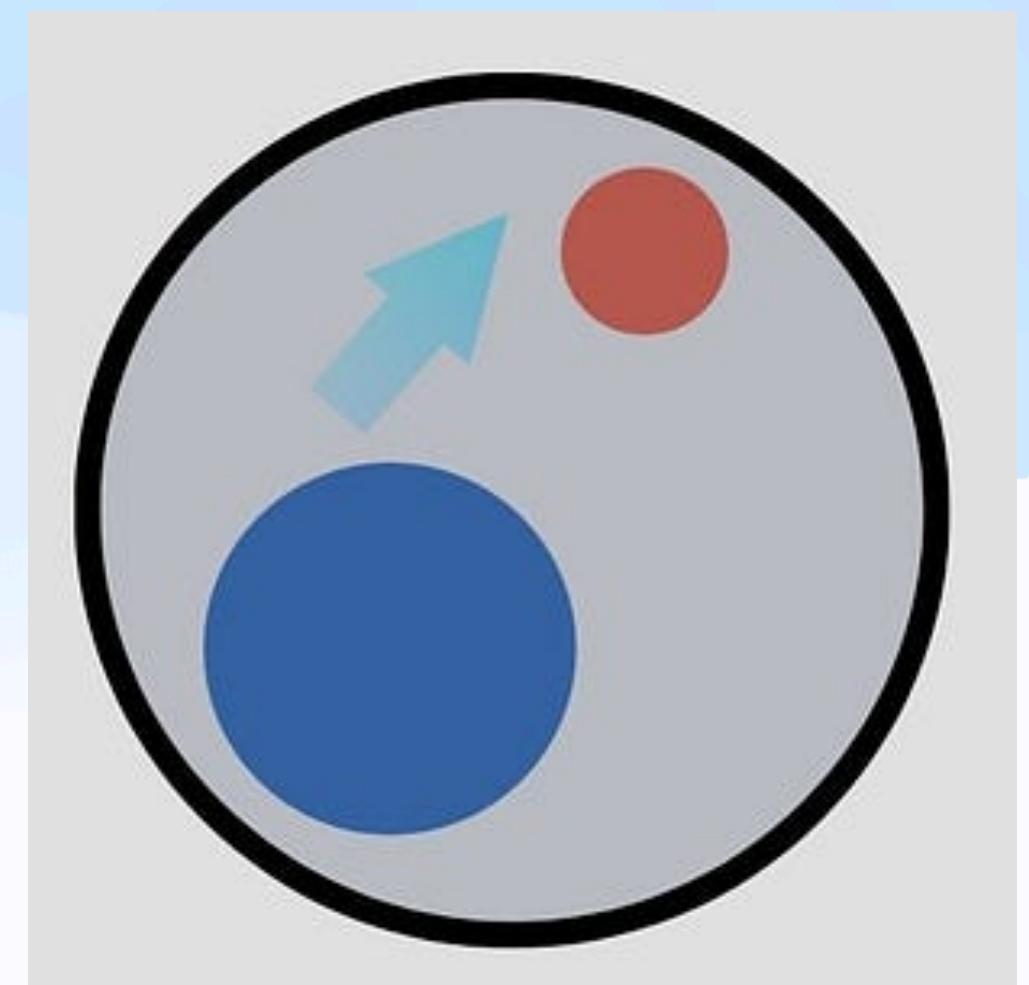
This makes strong force - strong.

It would require much energy to break these connections

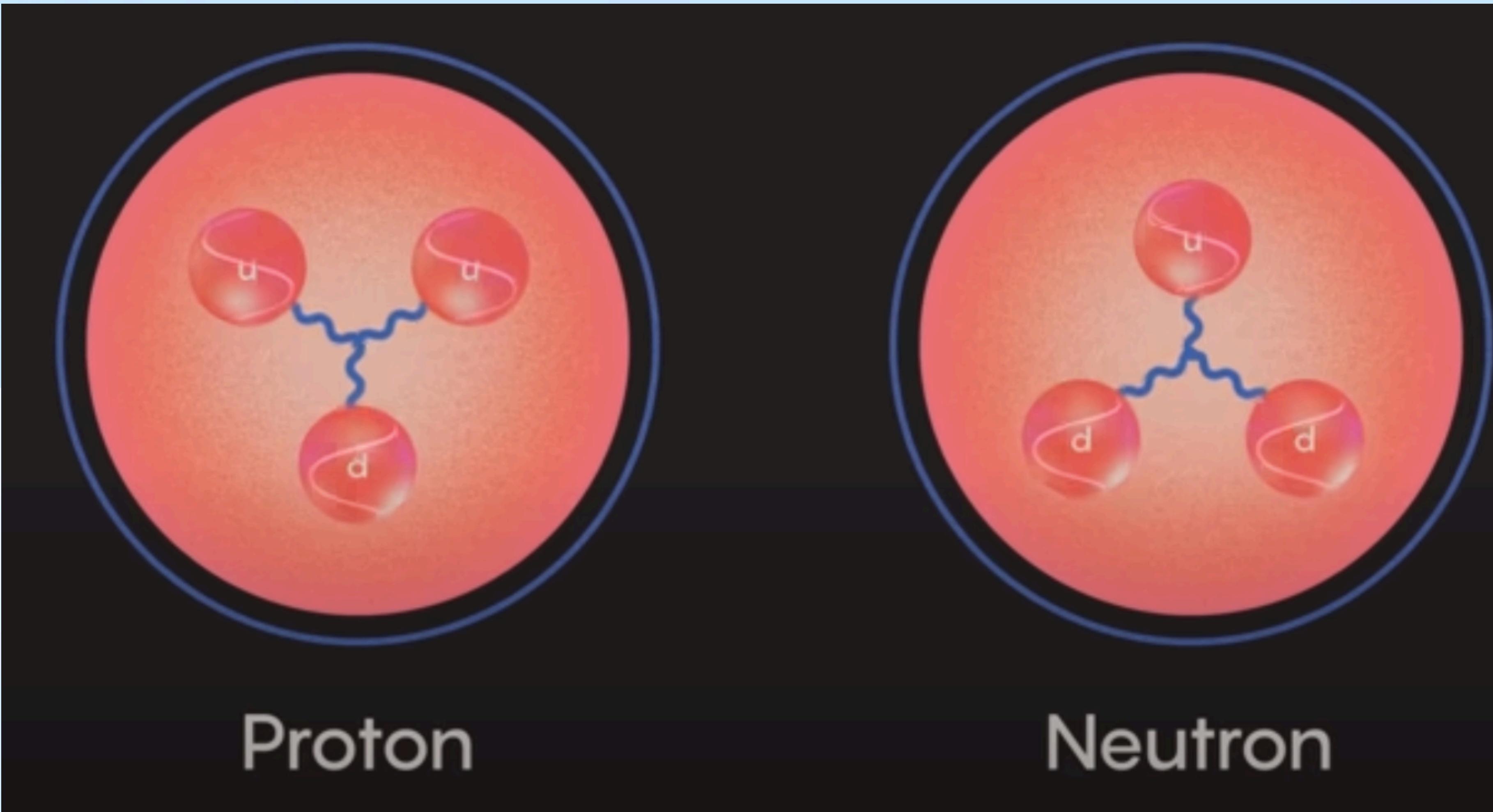


Weak Interaction

- Responsible for nuclear beta decay and other processes.
- It does not play a major role in binding the nucleus together.
- The strong force is 10^7 times stronger for two protons touching.
- Three particles carry the weak force:
 - the charged weak force by the W^+ and W^- and
 - the neutral weak force by the Z^0
 - All three have spin 1 and thus are bosons



Weak Interaction



Responsible
for conversions
from proton to
neutron and
vice-versa

Weak Interaction

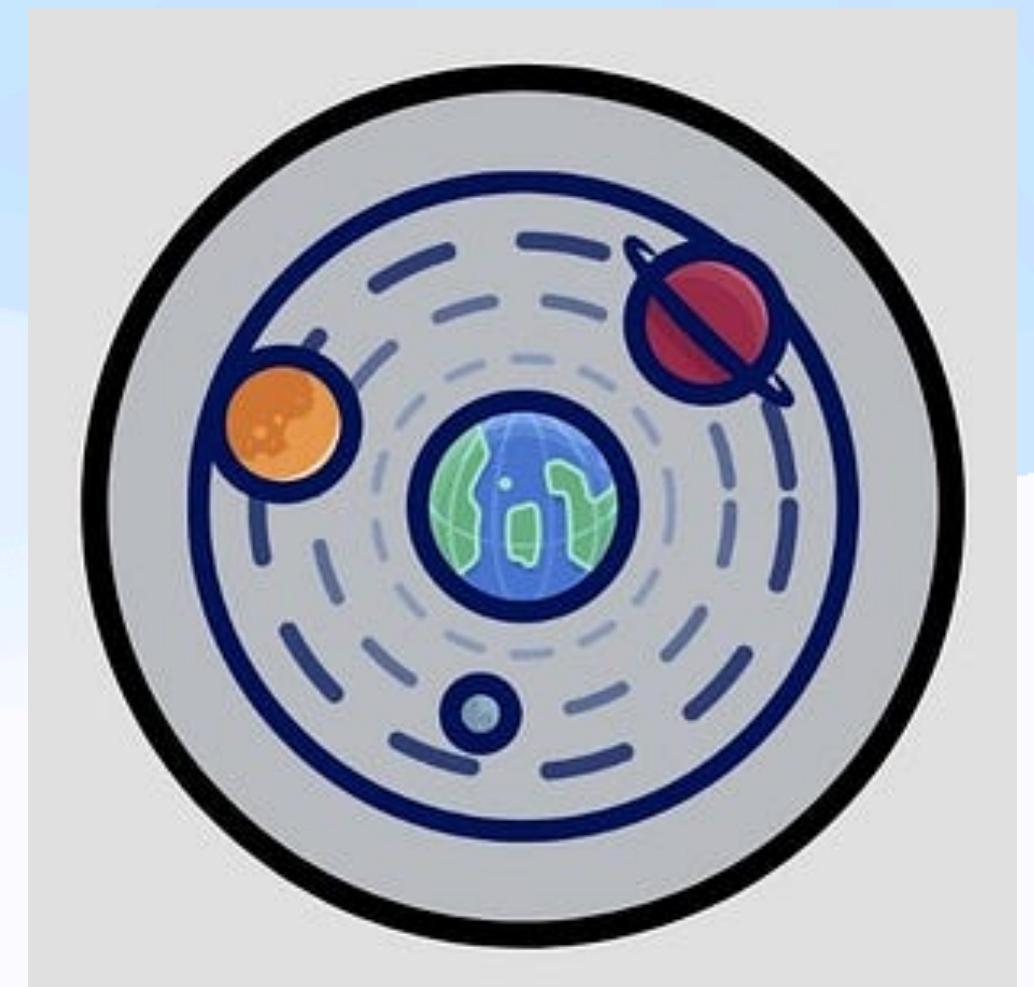
QUARKS	mass charge spin	particle	mass charge spin	particle	mass charge spin	particle	mass charge spin	particle																												
	up	≈2.16 MeV/c ² 2/3 1/2	charm	≈1.273 GeV/c ² 2/3 1/2	top	≈172.57 GeV/c ² 2/3 1/2	gluon	≈4.7 MeV/c ² -1/3 1/2	down	≈93.5 MeV/c ² -1/3 1/2	strange	≈4.183 GeV/c ² -1/3 1/2	bottom	≈0.511 MeV/c ² -1 1/2	e	electron	≈105.66 MeV/c ² -1 1/2	μ	muon	≈1.77693 GeV/c ² -1 1/2	τ	tau	≈91.188 GeV/c ² 0 1	Z	Z boson	≈0.8 eV/c ² 0 1/2	ν _e	electron neutrino	≈0.17 MeV/c ² 0 1/2	ν _μ	muon neutrino	≈18.2 MeV/c ² 0 1/2	ν _τ	tau neutrino	≈80.3692 GeV/c ² ±1 1	W

Responsible for conversions from proton to neutron and vice-versa

All matter particles can interact via weak interaction

Gravitation

- Gravity is essential for macroscopic objects (from the solar system to the humans)
- It is not important for the elementary particles. Two protons just touching experience a force that is 10^{38} times stronger than gravity.
- The mediating particle for this force is the graviton, which is expected to be uncharged, massless, and has spin 2.
- This particle has not yet been observed, nor does the experimental capability to do so yet exist.



Gravitation

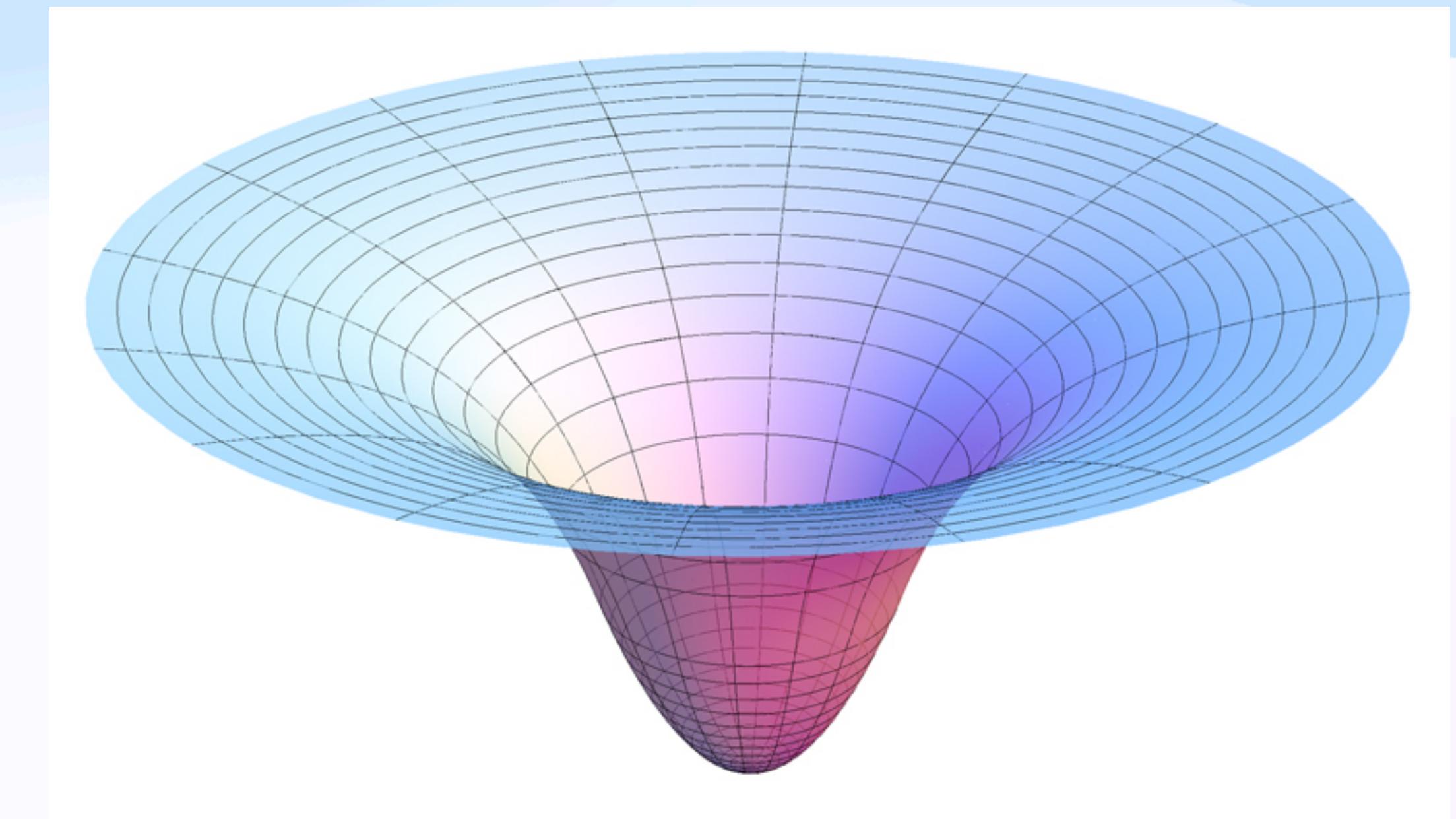
	I	II	III		
mass	$\approx 2.16 \text{ MeV}/c^2$	$\approx 1.273 \text{ GeV}/c^2$	$\approx 172.57 \text{ GeV}/c^2$	0	$\approx 125.2 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 93.5 \text{ MeV}/c^2$	$\approx 4.183 \text{ GeV}/c^2$	γ	
	d down	s strange	b bottom	photon	
LEPTONS	e electron	μ muon	τ tau	Z Z boson	
	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.77693 \text{ GeV}/c^2$		
	-1 $\frac{1}{2}$	-1 $\frac{1}{2}$	-1 $\frac{1}{2}$	0 1	
	v _e electron neutrino	v _{μ} muon neutrino	v _{τ} tau neutrino		
GAUGE BOSONS VECTOR BOSONS					
SCALAR BOSONS					

Where is gravity in this?

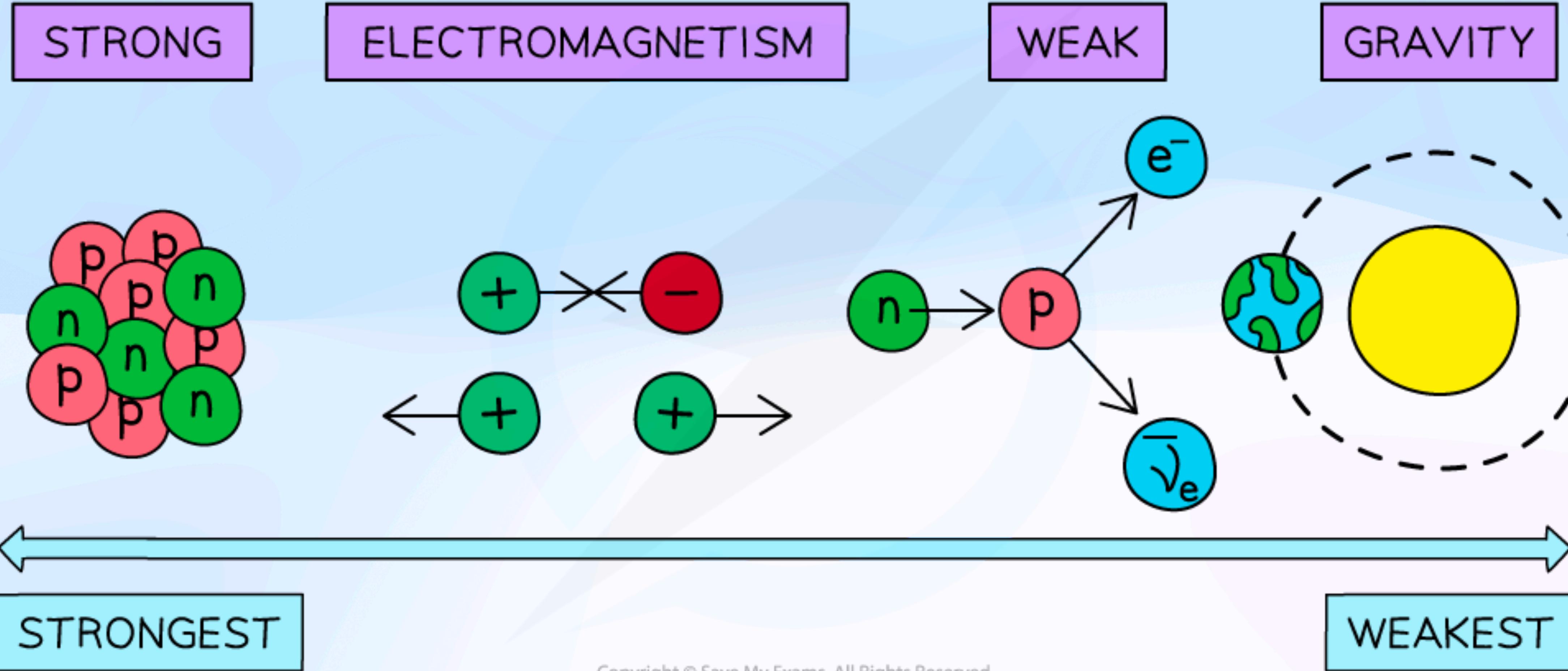
Why is it missing from the Standard Model?

Gravitation

- The Standard Model is written in the language of quantum field theory.
- We can easily view gravity as a field, but we don't understand how to study it on the quantum level



Four Interactions

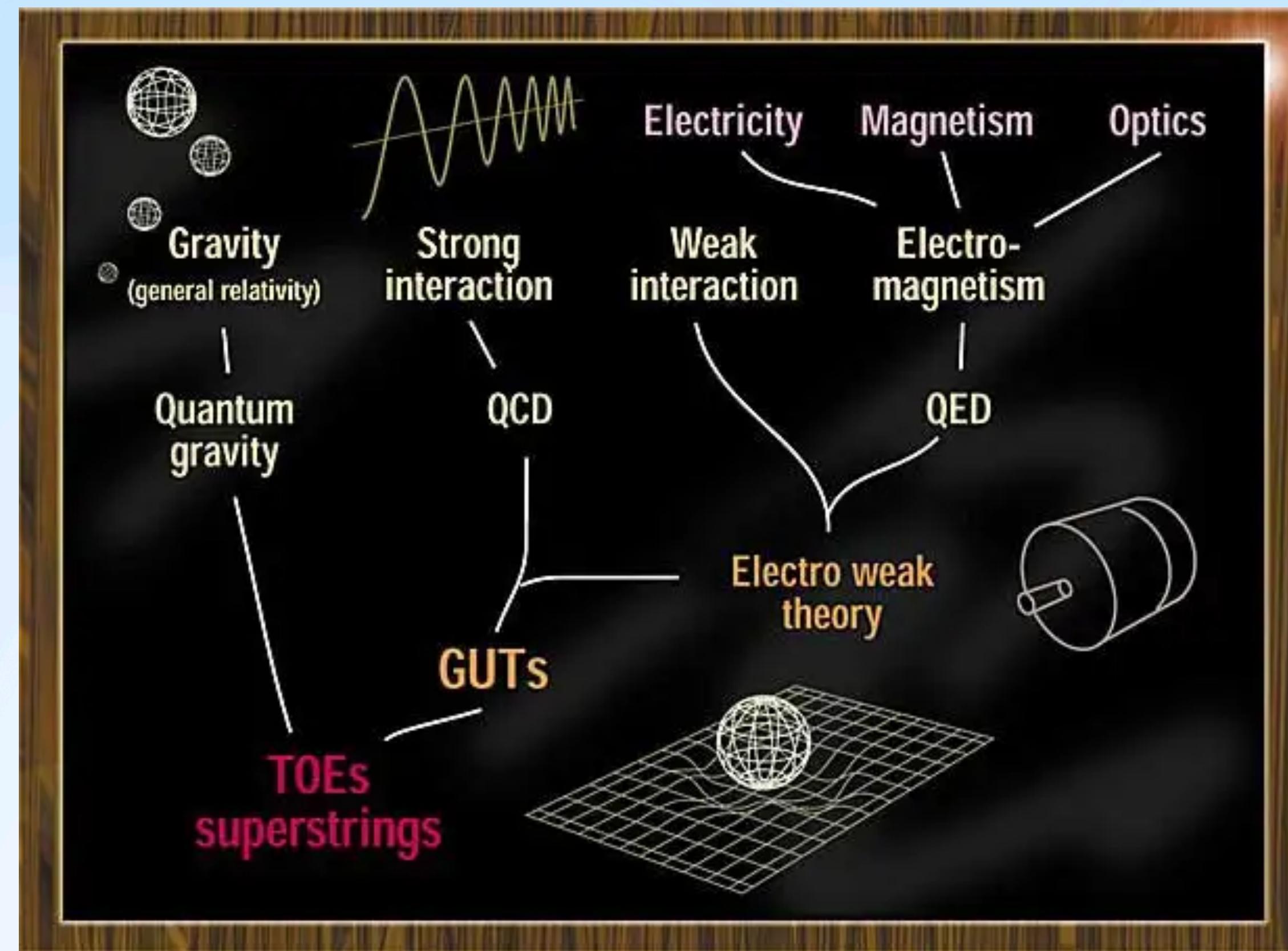


Four Interactions

- The fundamental forces may not be truly “fundamental” but may actually be different aspects of the same force.
- Electric + magnetic forces = electromagnetic force
- In the 1970s unified the electromagnetic force with the weak nuclear force into an **electroweak force**.

Four Interactions

- Any scientific theory that attempts to unify the electroweak force and strong nuclear force is called a **grand unified theory**, and any theory that attempts to unify all four forces is called a **theory of everything**.



Four Interactions

Type	Range	Relative Strength	Characteristic Time	Typical Particles
Strong	1 fm	1	$< 10^{-22}$ s	π, K, n, p
Electromagnetic	∞	10^{-2}	$10^{-14} - 10^{-20}$ s	e, μ, π, K, n, p
Weak	10^{-3} fm	10^{-7}	$10^{-8} - 10^{-13}$ s	All
Gravitational	∞	10^{-38}	Years	All

- Characteristic time: If we bring two particles close enough together, it takes much longer for the weak force to cause a decay or a reaction than the strong force.

Four Interactions

Force	Field Particle	Symbol	Charge (e)	Spin (\hbar)	Rest Energy (GeV)
Strong	Gluon	g	0	1	0
EM	Photon	γ	0	1	0
Weak	Weak Boson	W^+, W^- , Z^0	± 1 0	1	80.4 91.2
Gravitational	Graviton	Not yet observed	0	2	0