

Georgian-German Science Bridge

# Structure of Matter (SoM): Lecture 4: Elementary Particles and Forces

October 15, 2013 | Hans Ströher (Forschungszentrum Jülich)

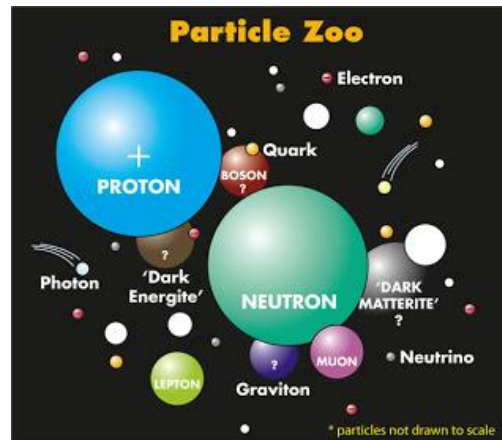


Situation in 1960

Particles are the **fundamental constituents of matter** (i.e. to our current knowledge they have no internal structure); in the context of atoms, nuclei and hadrons, we have discussed:

- **Electron** ( $e$ )
  - Baryons (e.g. **proton** ( $p$ ) and **neutron** ( $n$ ))
  - Mesons (e.g. **pion** ( $\pi$ ) ...)
- } **quarks**

and mentioned some other: **photon** ( $\gamma$ ), **muon** ( $\mu$ ), and **neutrino** ( $\nu$ ).



The question is whether (and how) this all fits together in a common framework (→ **“Standard Model”** of elementary particle physics)

## Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

**FERMIONS** matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2				Quarks spin = 1/2			
Flavor	Mass GeV/c <sup>2</sup>	Electric charge		Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge	
$\nu_e$ lightest neutrino*	{0-0.13}×10 <sup>-9</sup>	0		<b>u</b> up	0.002	2/3	
<b>e</b> electron	0.000511	-1		<b>d</b> down	0.005	-1/3	
$\nu_\mu$ middle neutrino*	{0.009-0.13}×10 <sup>-9</sup>	0		<b>c</b> charm	1.3	2/3	
<b><math>\mu</math></b> muon	0.106	-1		<b>s</b> strange	0.1	-1/3	
$\nu_\tau$ heaviest neutrino*	{0.04-0.14}×10 <sup>-9</sup>	0		<b>t</b> top	173	2/3	
<b><math>\tau</math></b> tau	1.777	-1		<b>b</b> bottom	4.2	-1/3	

\*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ) where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$  joule. The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

### Neutrinos

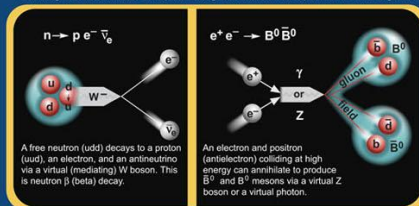
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states  $\nu_e$ ,  $\nu_\mu$ , or  $\nu_\tau$  labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

### Matter and Antimatter

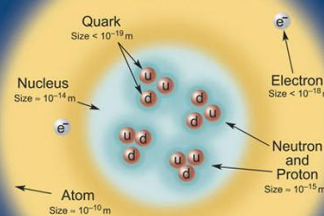
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$ ) are their own antiparticles.

### Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.



### Structure within the Atom



If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

### Properties of the Interactions

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

Property	Gravitational Interaction	Weak Interaction	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at $\left\{ \begin{array}{l} 10^{-18} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{array} \right.$	$10^{-41}$ $10^{-41}$	0.8 $10^{-4}$	1 1	25 60

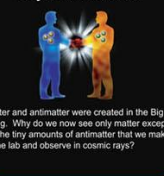
### Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

#### Universe Accelerating?



#### Why No Antimatter?



#### Dark Matter?



#### Origin of Mass?



**BOSONS** force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1			
Name	Mass GeV/c <sup>2</sup>	Electric charge	
$\gamma$ photon	0	0	
$W^-$	80.39	-1	
$W^+$	80.39	+1	
$Z^0$ Z boson	91.188	0	

Strong (color) spin = 1			
Name	Mass GeV/c <sup>2</sup>	Electric charge	
<b>g</b> gluon	0	0	

### Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

### Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature: mesons  $q\bar{q}$  and baryons  $qqq$ . Among the many types of baryons observed are the proton (uud), antiproton ( $\bar{u}\bar{u}\bar{d}$ ), neutron (udd), antineutron ( $\bar{u}\bar{d}\bar{d}$ ), and  $\Lambda$  (uds), and  $\Lambda^0$  ( $\bar{u}\bar{s}\bar{d}$ ). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion  $\pi^+$  (u $\bar{d}$ ), kaon  $K^0$  (d $\bar{s}$ ),  $B^0$  (d $\bar{u}$ ), and  $\eta_c$  ( $c\bar{c}$ ). Their charges are +1, -1, 0, 0, 0 respectively.

Visit the award-winning web feature [The Particle Adventure at ParticleAdventure.org](http://TheParticleAdventure.org)

This chart has been made possible by the generous support of

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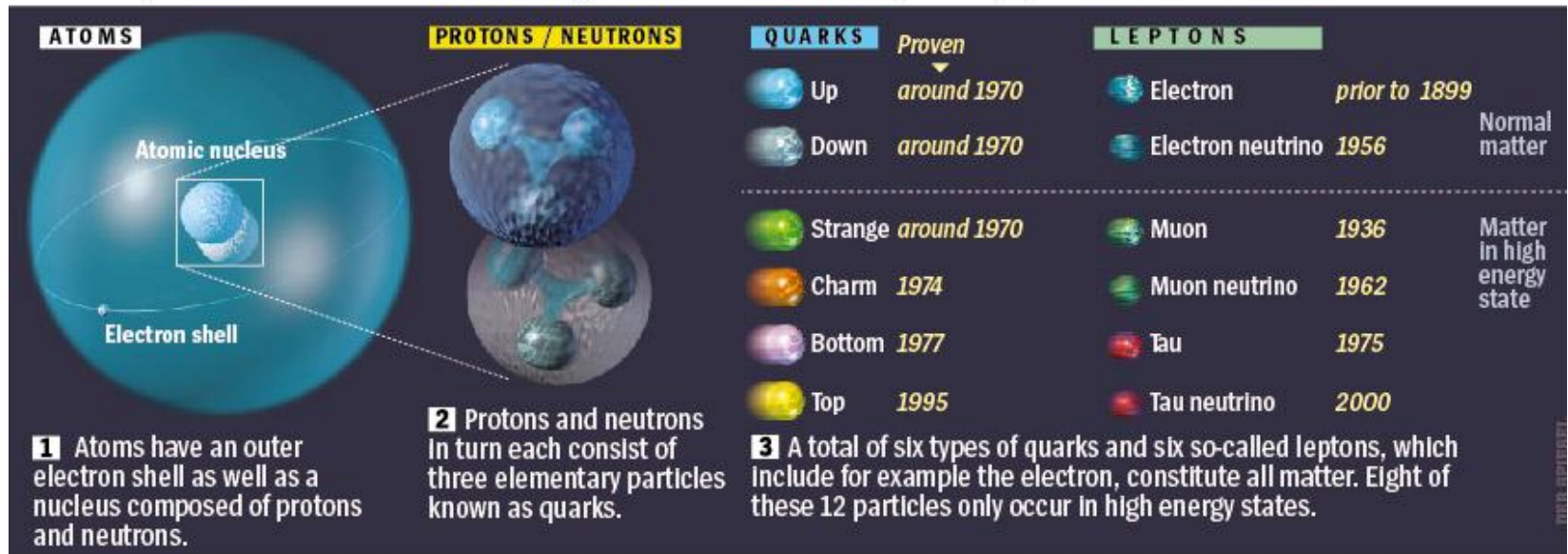
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# Standard Model

In the Standard Model, the **matter particles** are the **quarks** and the **leptons**; each come in 3 “families” or “generations” of charge states and with increasing mass:

## The World of Particles

The makeup of matter and antimatter according to the Standard Model of particle physics



**Normal matter** consists of up- and down-quarks and electron and it's neutrino.



	I	II	III
Mass →	2.4 MeV	1.27 GeV	171.2 GeV
Charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
Spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
Name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top
Quarks	4.8 MeV	104 MeV	4.2 GeV
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV
	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino
	0.511 MeV	105.7 MeV	1.777 GeV
	-1	-1	-1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau

## Standard Model: Matter Particles

One major puzzle is why Nature likes this **repetition** in form of the 2<sup>nd</sup> and 3<sup>rd</sup> generation?

Example: When the **muon** ( $\mu$ ) was discovered, I. Rabi asked: “Who ordered that?” [A similar question can be asked for the **tau** ( $\tau$ )]



Muons have a **mass** about **200 times** the mass of an electron. Since the muon's interactions are very similar to those of the electron, thus a muon can be thought of as a much **heavier version of the electron**.

	muon		muon neutrino		electron		e <sup>-</sup> antineutrino
equation:	$\mu$	$\rightarrow$	$\nu_{\mu}$	+	$e^{-}$	+	$\bar{\nu}_e$
electron number:	0	=	0	+	1	+	-1
muon number:	1	=	1	+	0	+	0
tau number:	0	=	0	+	0	+	0

## Lepton (Quantum) Numbers



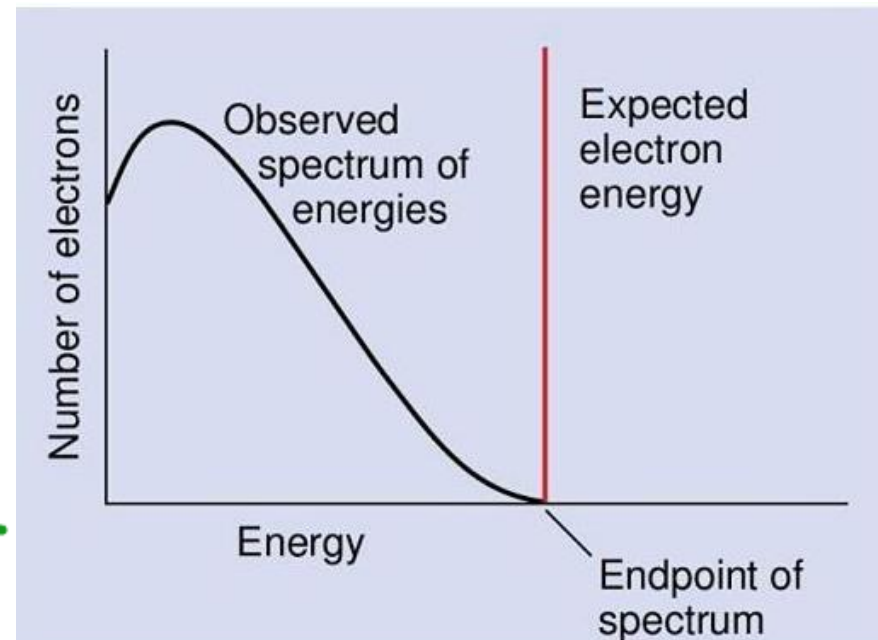
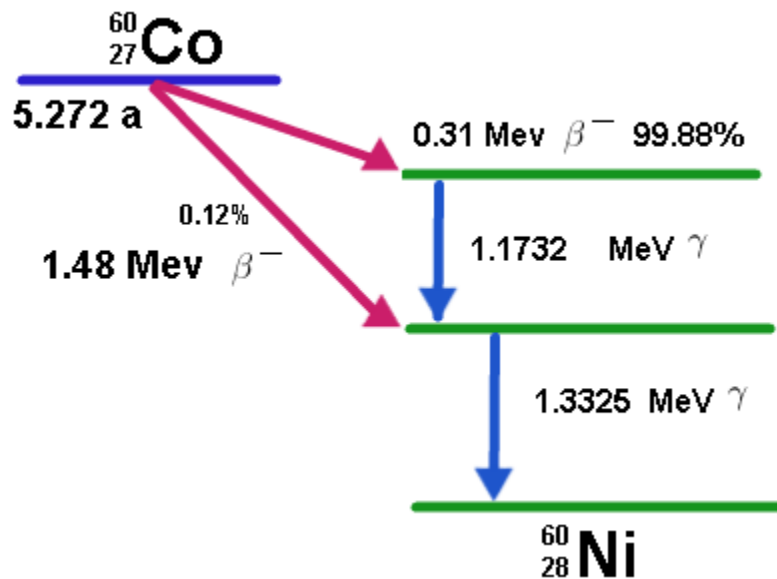


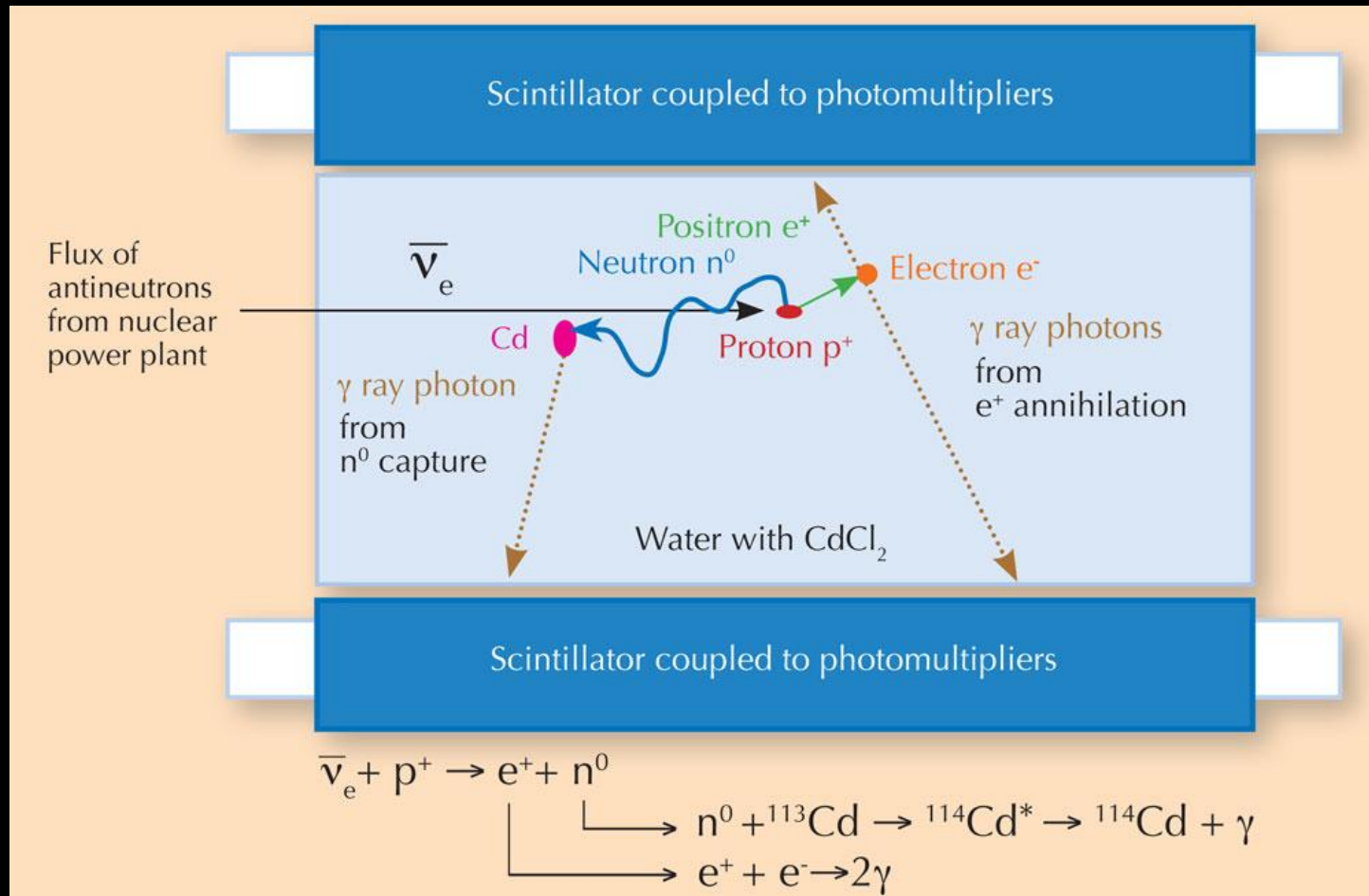
## Cosmic Ray Muons

**Neutrinos** are the electrically neutral leptons, affiliated with the corresponding charged ones:  $e - \nu_e$ ,  $\mu - \nu_\mu$ ,  $\tau - \nu_\tau$

The neutrino was postulated first by Wolfgang Pauli in 1930 to explain how nuclear  **$\beta$ -decay** could **conserve energy, momentum, and spin**;

Example:



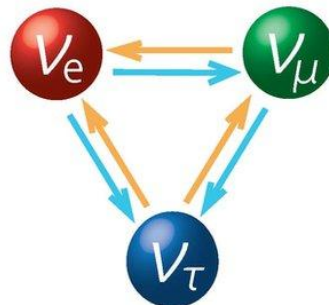


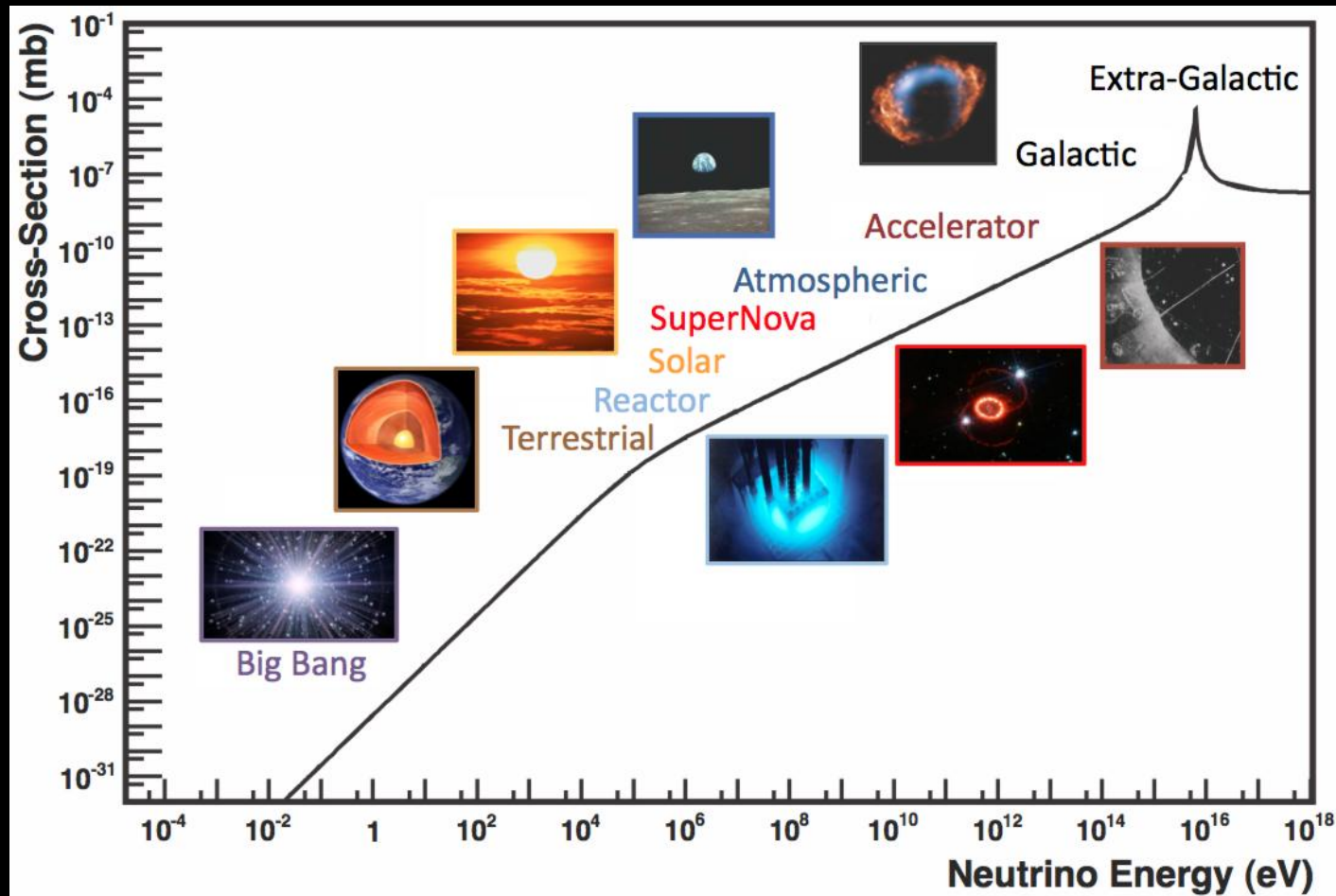
# (First) Neutrino Detection

**Neutrinos are very abundant** in the Universe (second most after photons):  $\sim 37 \nu$ 's per  $\text{cm}^3$ ; the neutrino flux from the **sun** is calculated to be  $5 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ ; every second trillions of neutrinos pass our bodies

Neutrinos **interact very little** with matter ( $\rightarrow$  reason why they were discovered so late); gigantic detectors have been built to measure their properties: AMANDA (Mediterranean Sea), IceCube (Antartica), Super-Kamiokande (Japan), ...

Neutrinos **have a mass**  $> 0$  (although no finite neutrino mass has been measured yet; this is inferred from the fact that the different neutrino flavors can change into others (“**neutrino oscillations**”)):





## Neutrino Cross Section





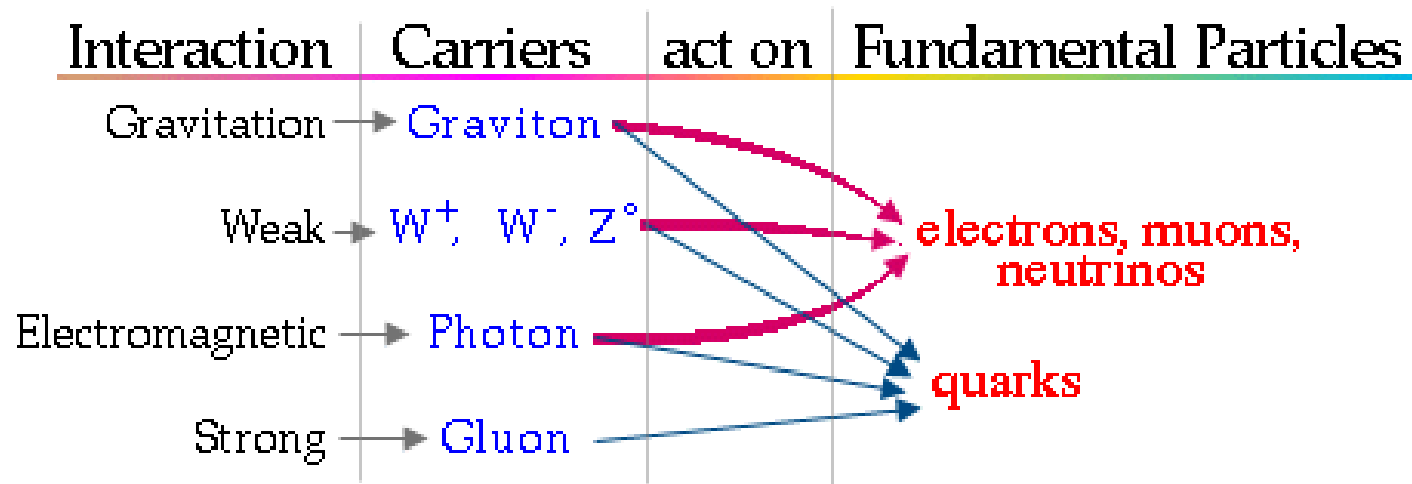
## Neutrino Detectors

The Standard Model particles have to be extended by **force carriers**, i.e. particles which mediate the **interactions** between particles:

force	boson	
	symbol	name
strong	$g$	<i>gluon</i>
electromagnetic	$\gamma$	<i>photon</i>
weak	$W^+, W^-$	<i>W bosons</i>
	$Z^0$	<i>Z boson</i>

Scientists have discovered force carriers for three of the four known forces: **electromagnetism**, the **strong force** and the **weak force**. (They are still searching for experimental evidence of the force carrier for the fourth force, **gravity**. Note: gravitation will not be discussed here further.)

Not all fundamental particles take part in all of the interactions:

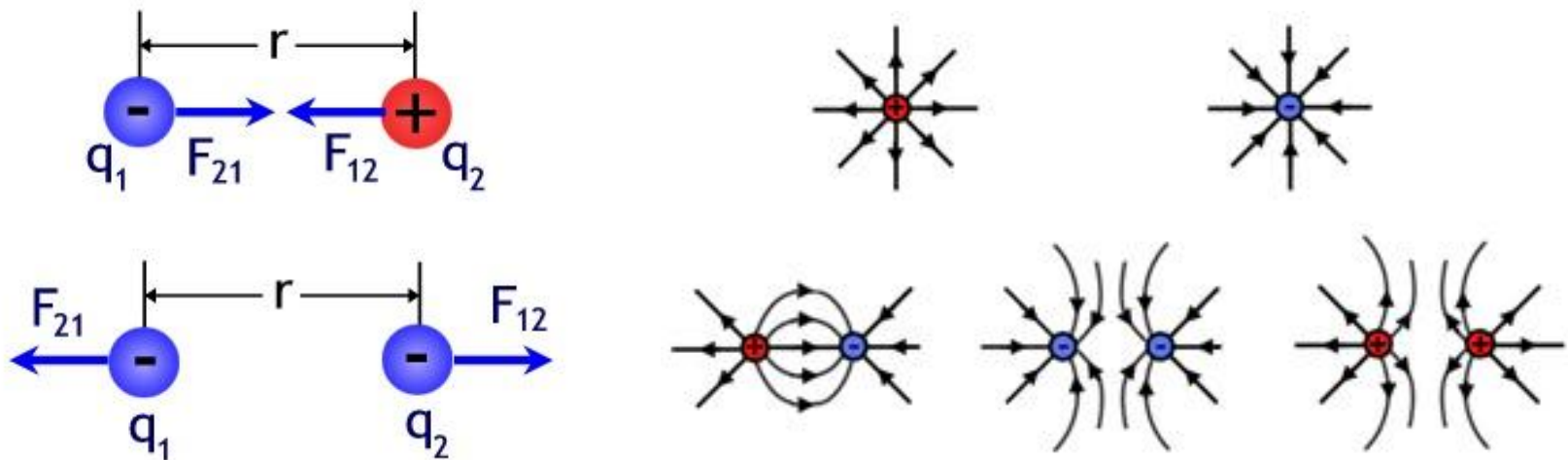


The **strong interaction** only acts between quarks, the **electromagnetic interaction** does not influence the uncharged neutrinos, but the **weak** and the **gravitational interaction** act on all fundamental particles.

	I	II	III	(forces)
Mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
Charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
Spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon electromagnetic force
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon strong force
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z</b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force

## A more complete Table of SM Particles

The **electromagnetic force** is a fundamental interactions in nature; it is described by electromagnetic fields, and has innumerable physical instances including the interaction of electrically **charged particles**:



The electromagnetic force is the interaction responsible for almost all the phenomena encountered in daily life, with the exception of gravity: molecular and atomic binding, electromagnetic waves (light) ...

The foundation of **classical electrodynamics** is provided by the “**Maxwell Equations**”



The now called „Maxwell Equations“ were first written down in complete form by physicist **James Clerk Maxwell** during the 19<sup>th</sup> century:

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot d\mathbf{S} = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho dV$	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot d\mathbf{S} = 0$	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E} \cdot d\boldsymbol{\ell} = -\frac{d}{dt} \iint_{\Sigma} \mathbf{B} \cdot d\mathbf{S}$	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's correction)	$\oint_{\partial\Sigma} \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 \iint_{\Sigma} \left( \mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right) \cdot d\mathbf{S}$	$\nabla \times \mathbf{B} = \mu_0 \left( \mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$

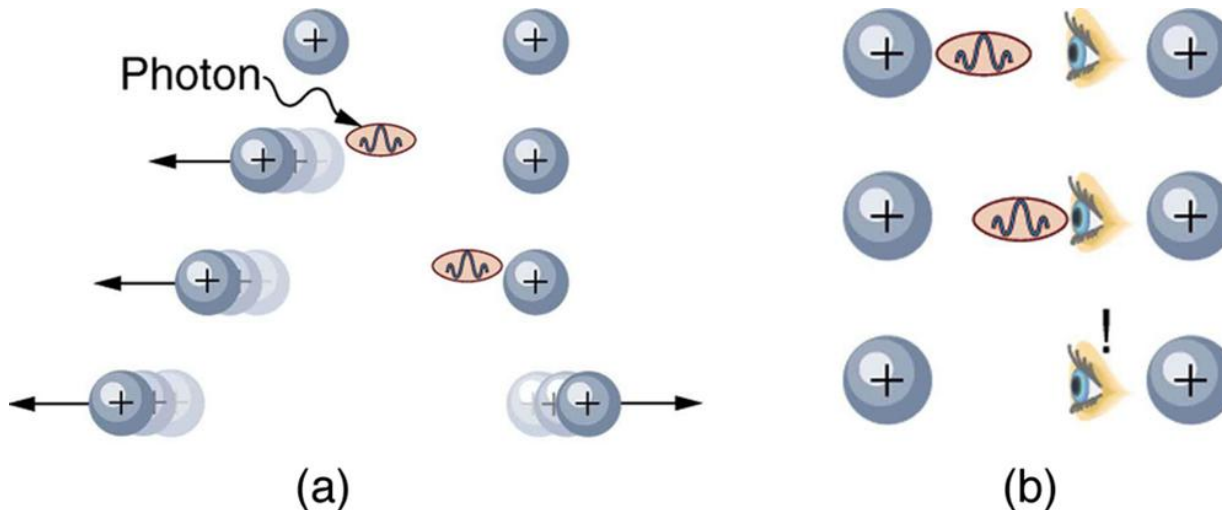
Unification of electricity and magnetism

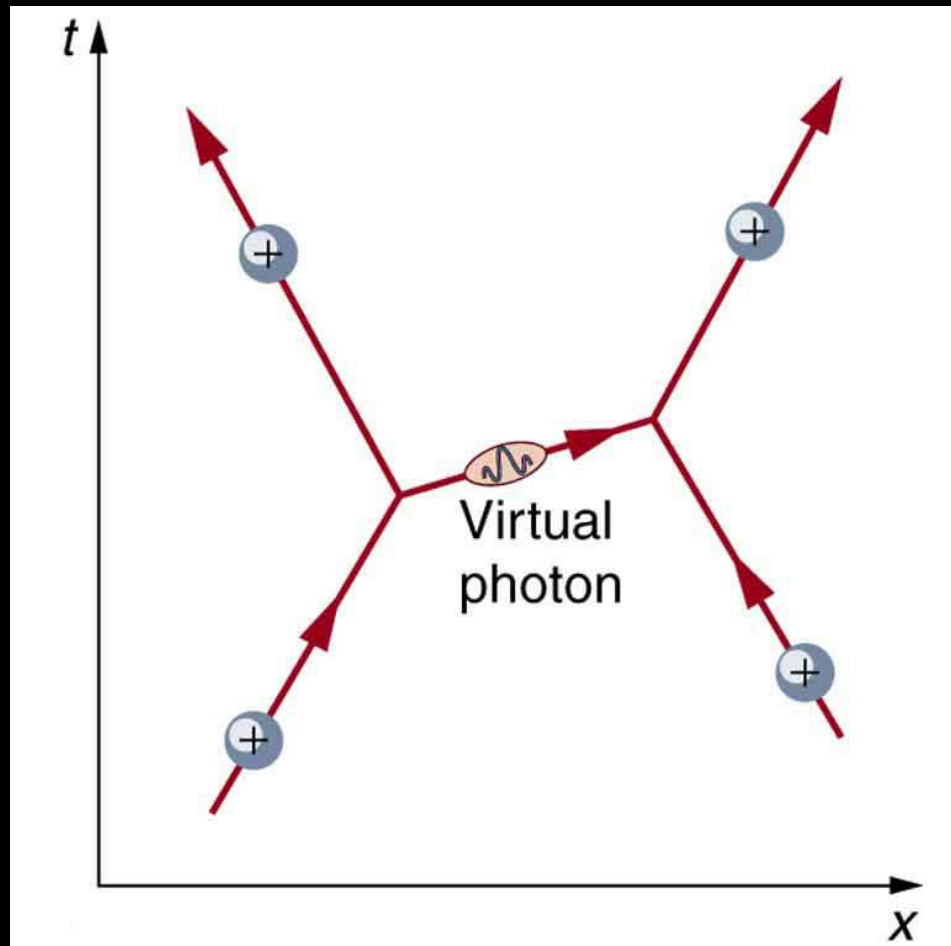
Prediction of electromagnetic waves

## Maxwell Equations

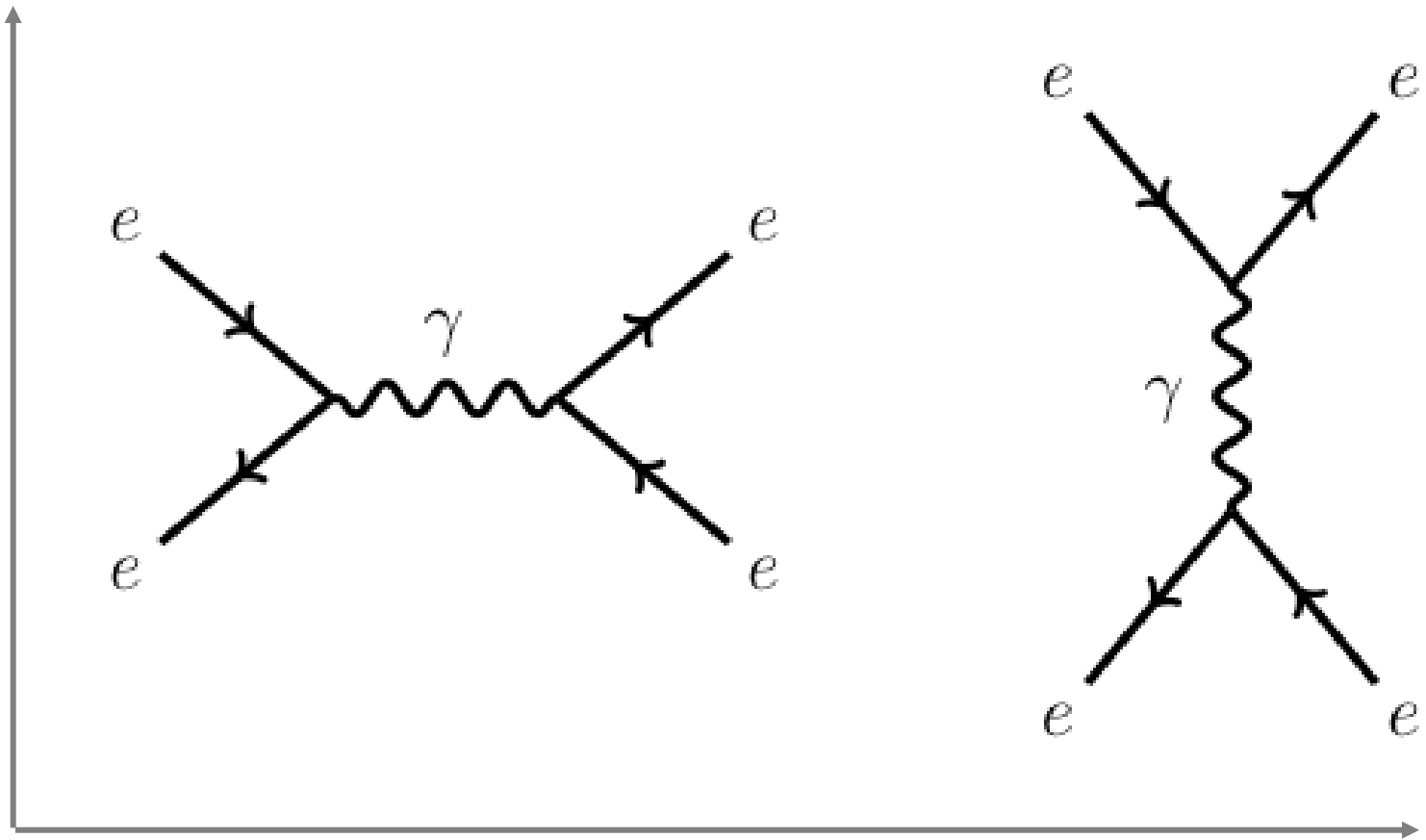
**Maxwell's equations** (along with the rest of classical electromagnetism) are extraordinarily successful at explaining and predicting a large variety of phenomena; however, they are **not exact laws** of Nature, but merely **approximations**; for example, Maxwell's equations do not involve “**photons**”.

For accurate predictions in all situations, Maxwell's equations have been superseded by **quantum electro-dynamics** (QED): the interaction happens by the **exchange** of force carrier bosons called **photons**:



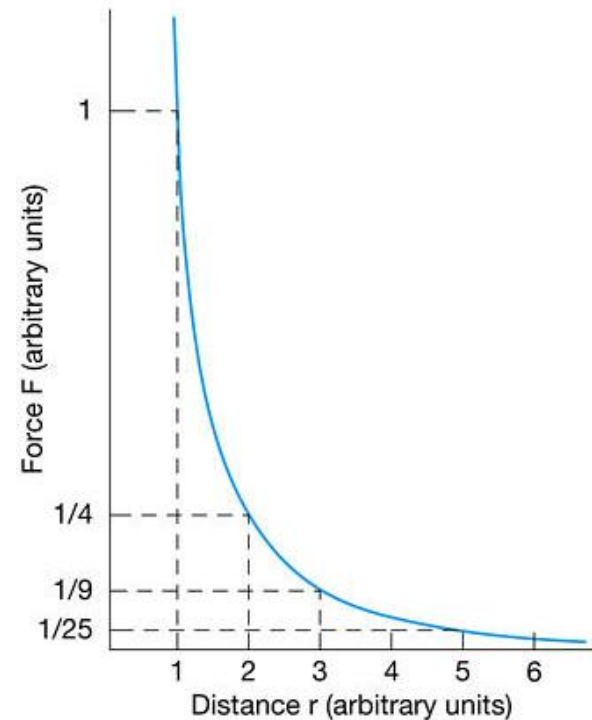
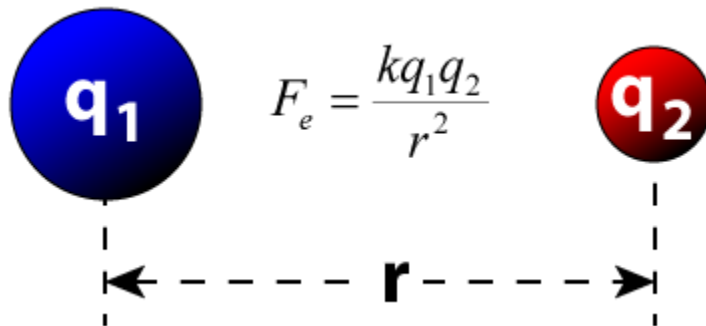


## Feynman Diagram: Repulsion



## Feynman Diagrams: Interaction, Annihilation

Electromagnetic interactions are **long range** attractions or repulsions between any particles or antiparticles that have charge:



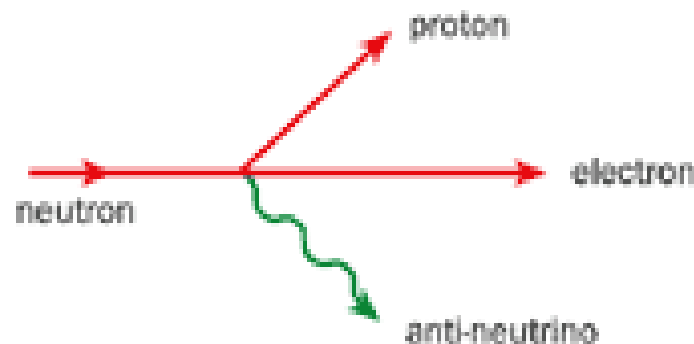
Charged particles interact, because there is a **continuous exchange of photons**

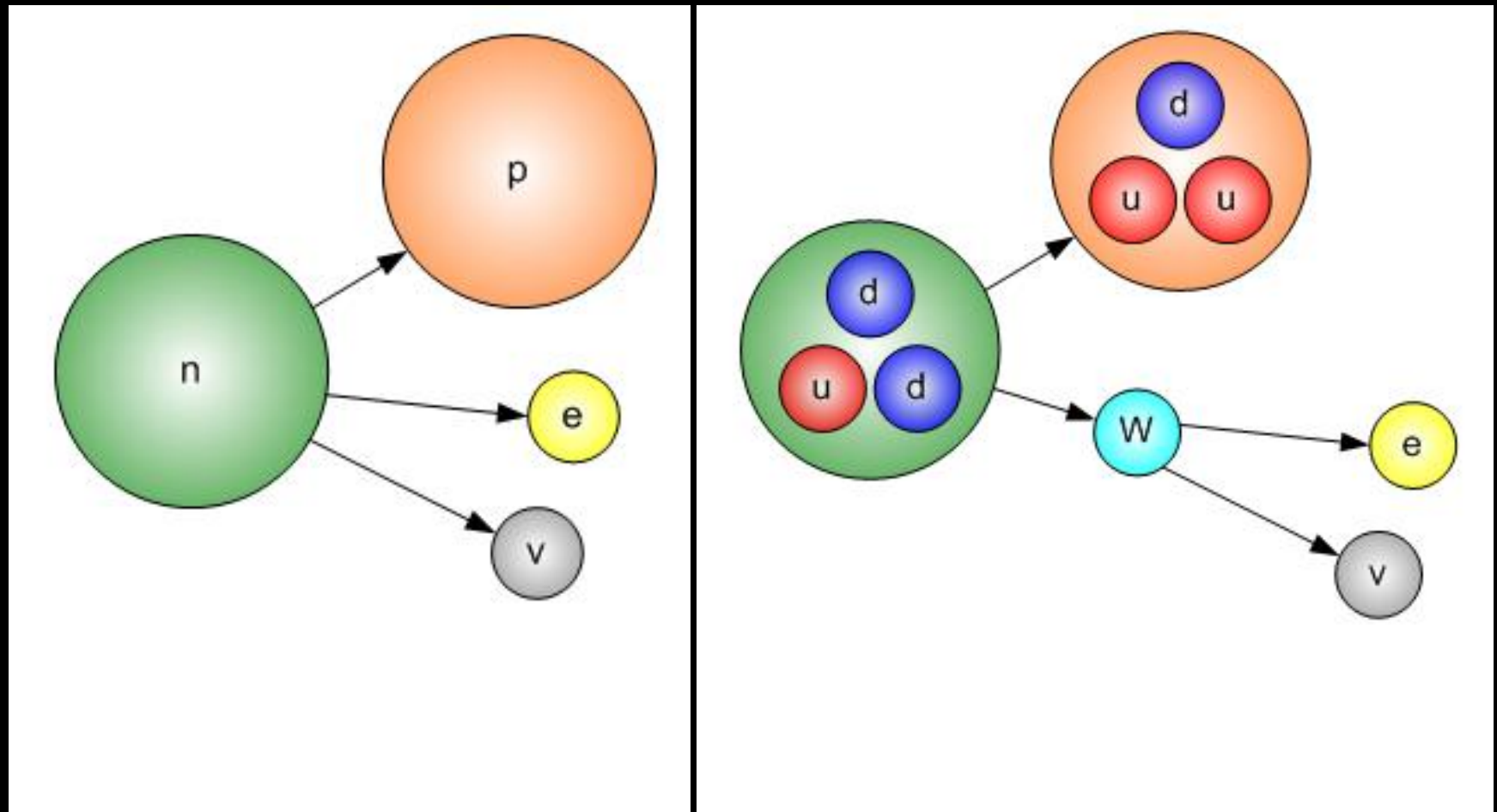


The **weak force** underlies some forms of **radioactivity** ( $\beta$ -decay), governs the **decay of unstable** subatomic **particles** (such as mesons), and initiates the nuclear **fusion reaction** (e.g., in the Sun)

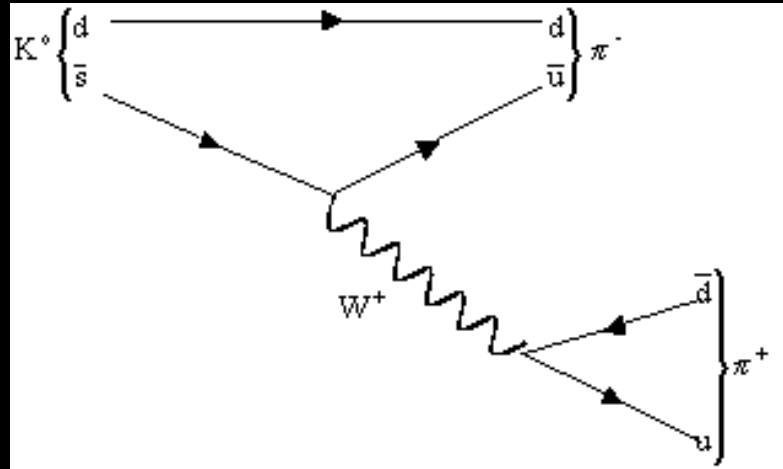
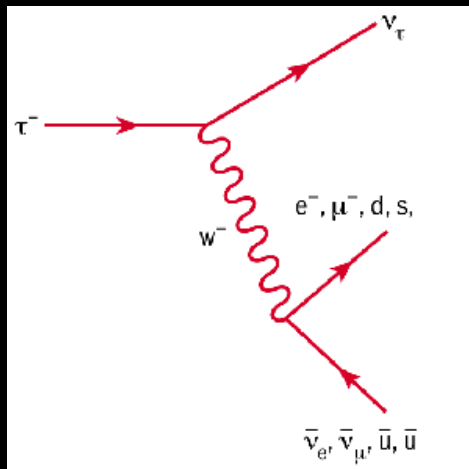
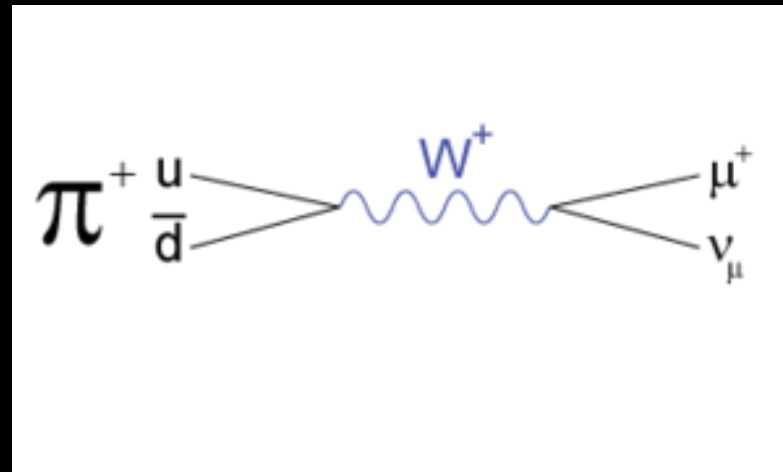
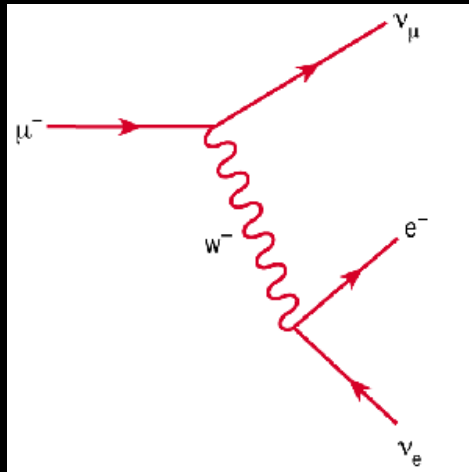
The weak force **acts upon all known fermions**, i.e., elementary particles with half-integer values of intrinsic angular momentum (spin)

**Enrico Fermi** proposed the first theory of the weak interaction, known as Fermi's interaction by suggesting that beta decay could be explained by a four-fermion interaction, involving a contact force with no range; example: **neutron-decay**





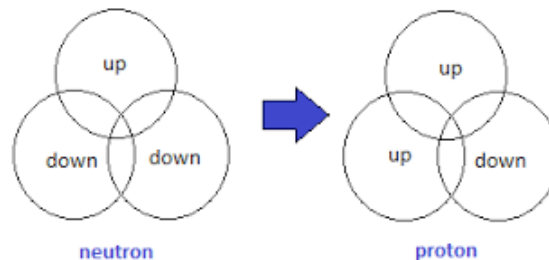
## Neutron Decay



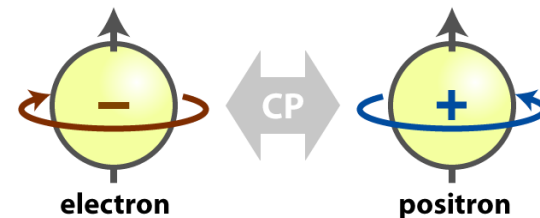
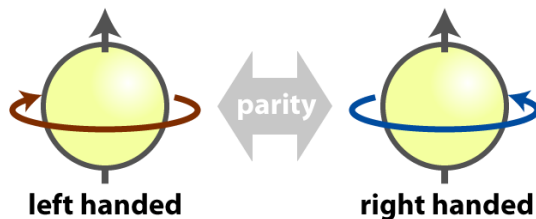
## Weak Decays

The **weak force** is unique in a number of respects:

- It is the only interaction capable of **changing the flavor of quarks** (i.e., of changing one type of quark into another)



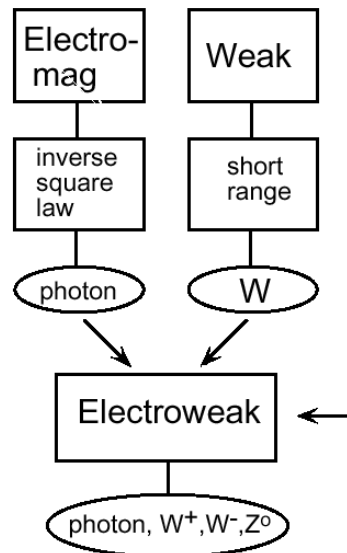
- It is the only interaction which **violates P** or parity-symmetry. It is also the only one which violates **CP symmetry**

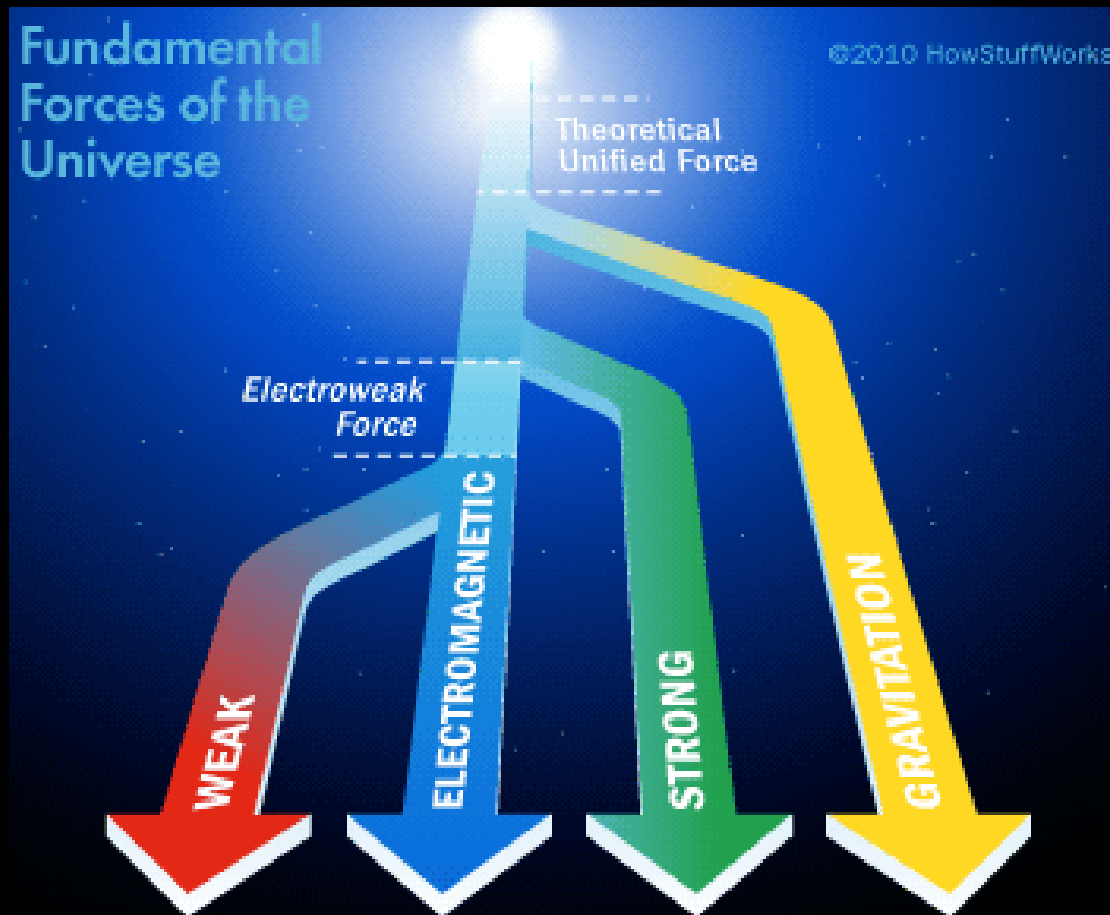


- It is propagated by carrier particles (known as **gauge bosons**) that have significant masses ( $\sim 100 \times$  mass of the nucleon)

The **weak force** is confined to a distance range of  $10^{-17}$  m, which is about 1 percent of the diameter of a typical atomic nucleus, because of the large mass of the force carriers ( $W^+$ ,  $W^-$  and  $Z^0$ )

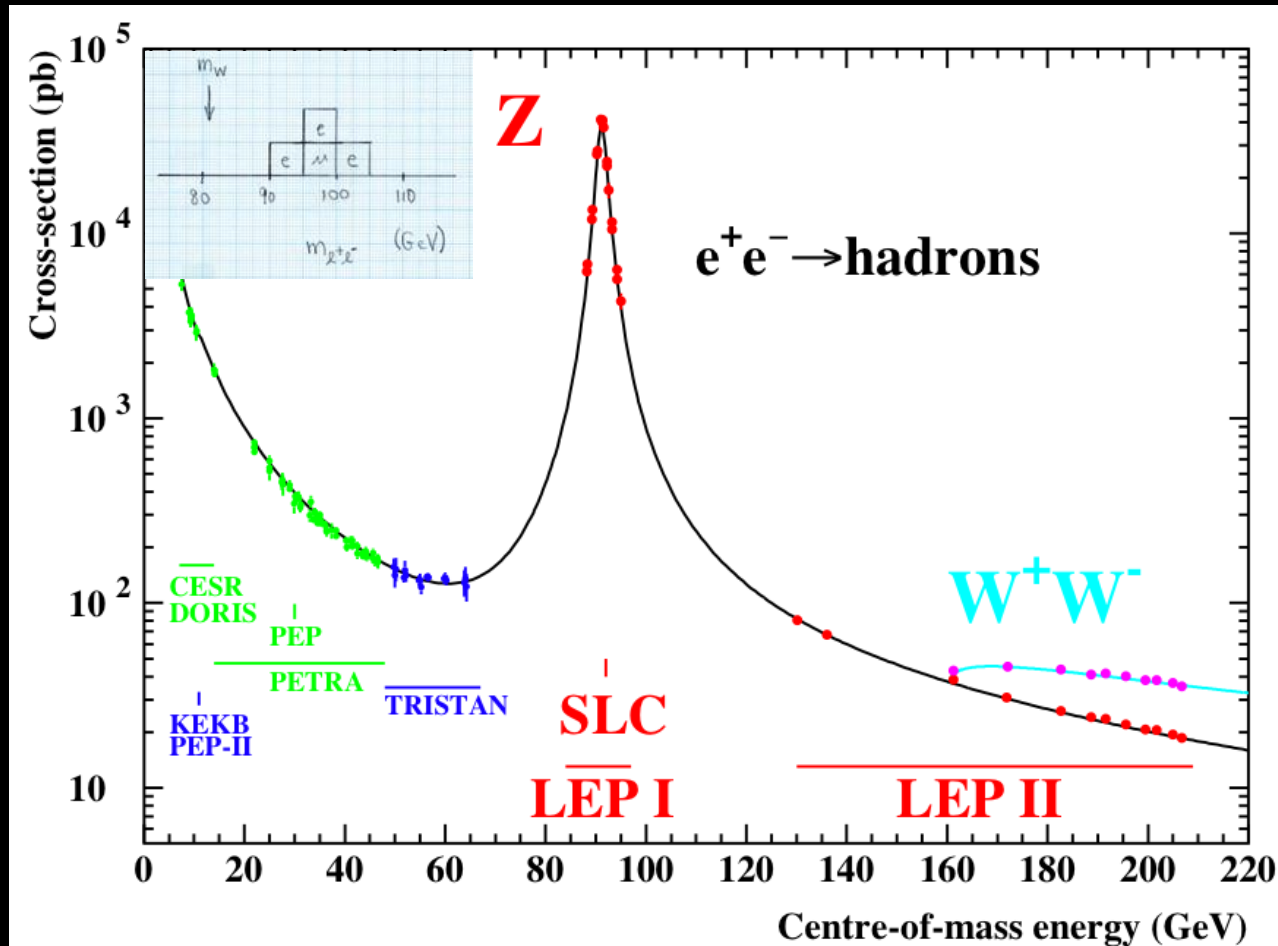
In radioactive decays the **strength** of the weak force is about 100,000 times less than the strength of the electromagnetic force. However, the weak force has intrinsically the same strength as the electromagnetic force, and these two apparently distinct forces are known to be different manifestations of a **unified electroweak force**:





## Unification of Forces

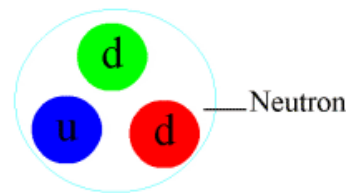
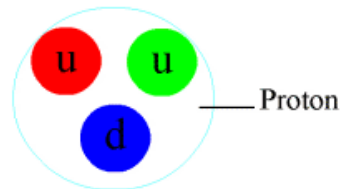




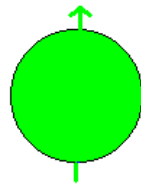
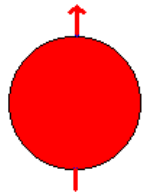
## Discovery of Gauge Bosons

The **strong force** (interaction) is observable in two areas:

- on a larger scale (about 1 to 3 femtometers (fm)), it is the force that binds protons and neutrons (nucleons) together to form the nucleus of an atom - in this form, it is often referred to as the **nuclear force**
- on the smaller scale (less than about 0.8 fm, the radius of a nucleon), it is the force (carried by “**gluons**”) that holds quarks together to form protons, neutrons and other hadron particles (→ **color force**)



Quark-quark takes place by  
colored gluon-exchange:

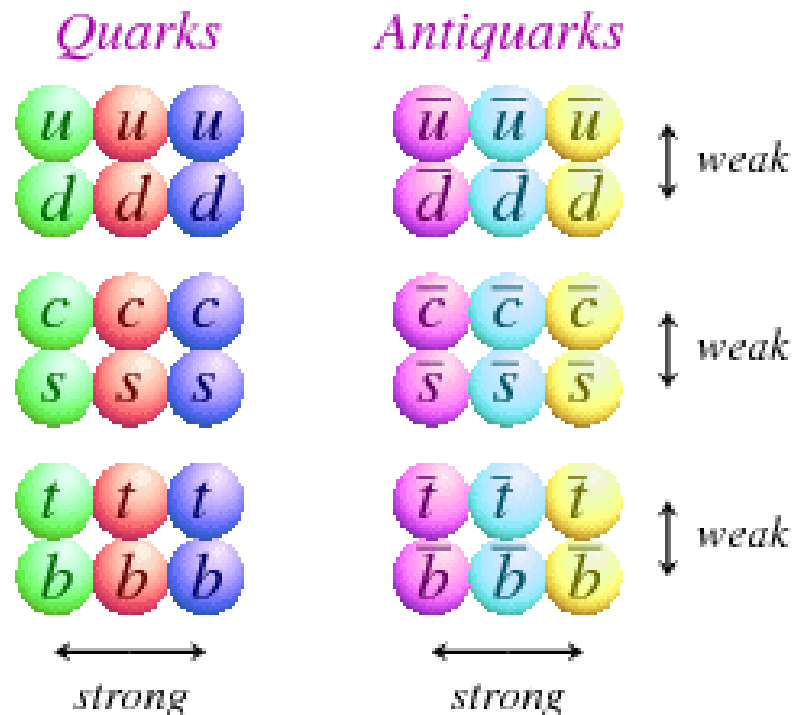


Gluons have color-anticolor  
(in this case **red-antigreen**)

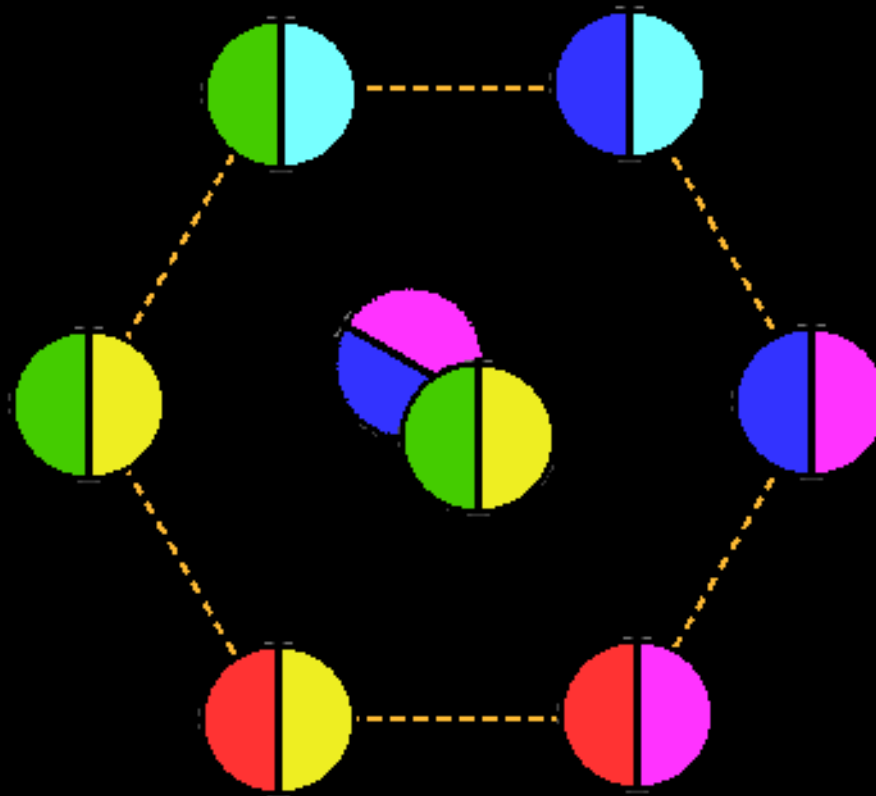


## Strong Interaction (Gluon Exchange)

The **strong force** (interaction) acts between the **colored quarks** and antiquarks:

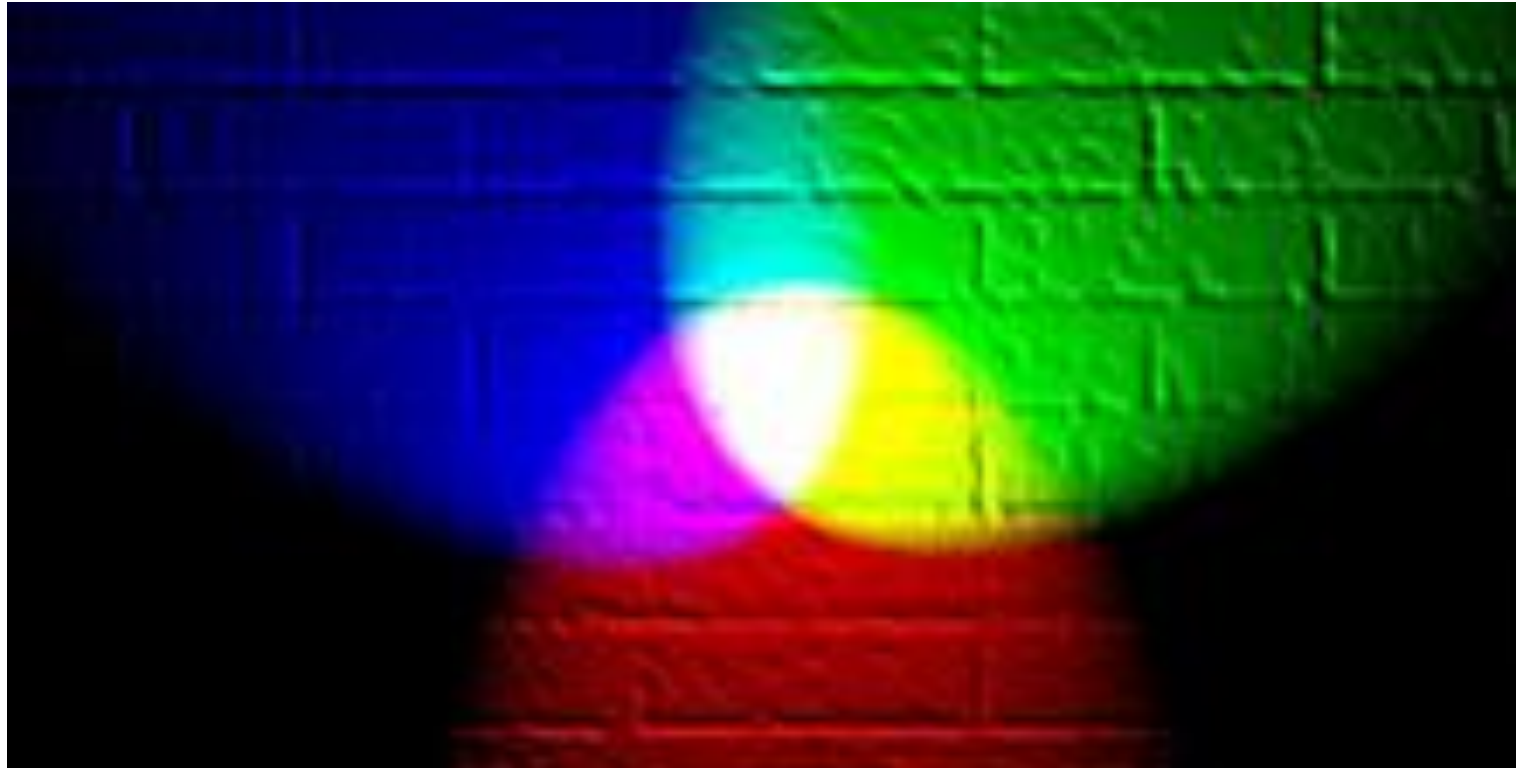


... in such a way that the color (-charge) is conserved (i.e. the overall does not change!)



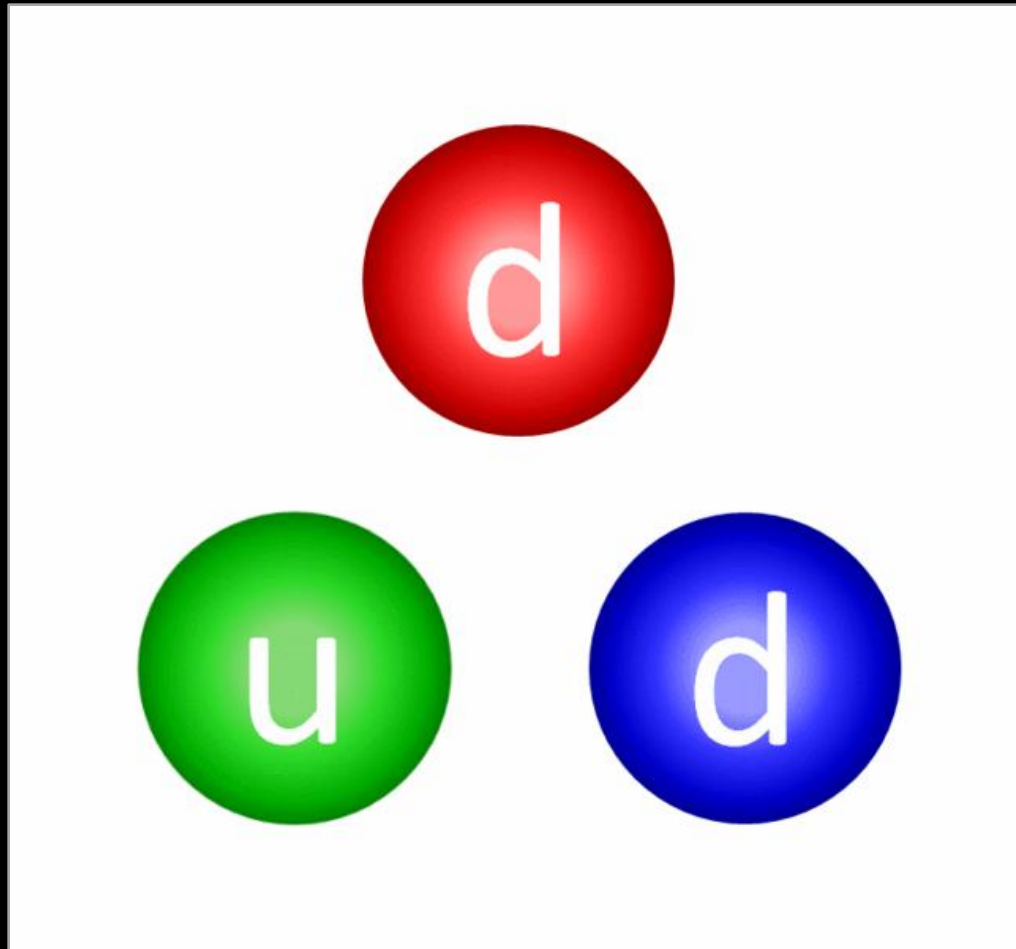
## Strong Interaction (8 Gluons)

The **strong force** (interaction) only allows **bound systems** that don't have color (-charge); they are **color-neutral** (“white”):



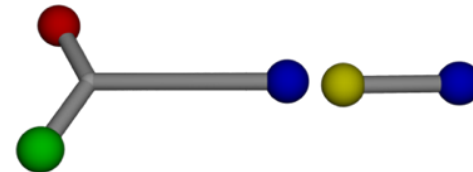
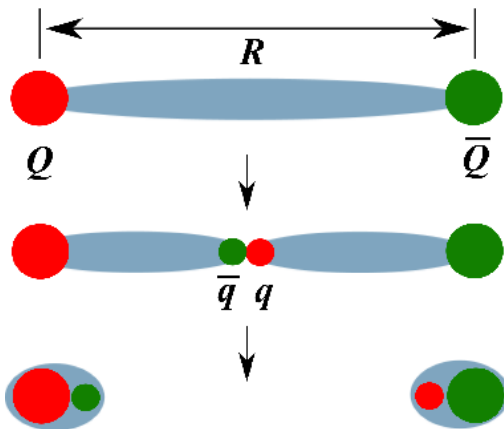
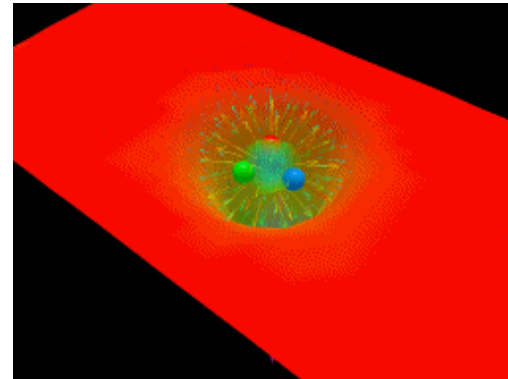
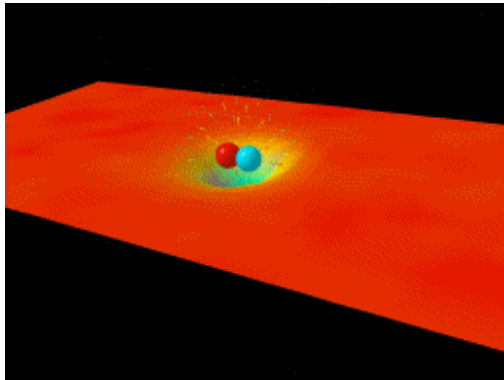
→ quark-antiquarks (“**mesons**”); 3 quarks (“**baryons**”), ...



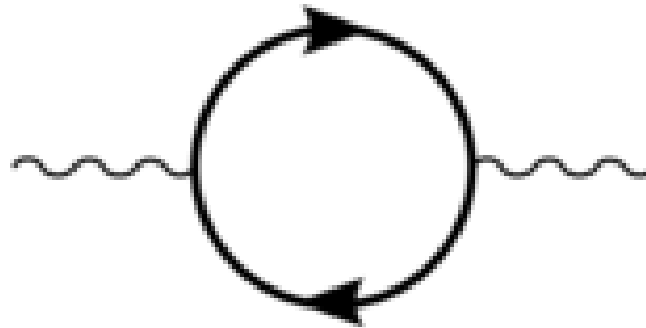


Bound System (e.g. Neutron)

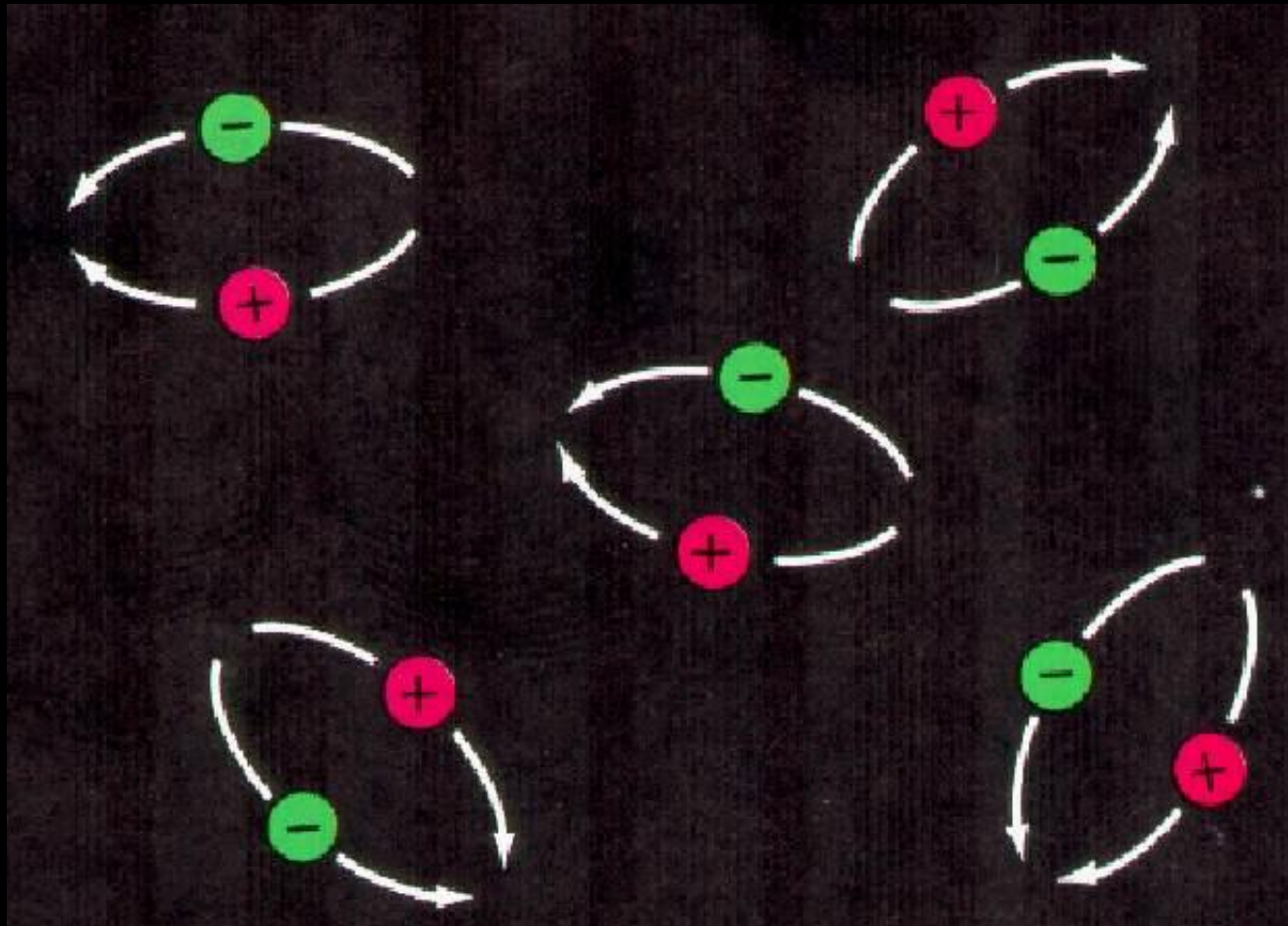
A consequence of the fact that gluons are colored is, that **free quarks** are not allowed – quarks are “**confined**” inside hadrons; as examples: separation of quarks in a meson or a baryon:



Quantum mechanics allows, and indeed requires, temporary **violations of conservation of energy** in quantum fluctuations, so one particle can become a pair of heavier particles (the so-called “**virtual particles**”), which quickly rejoin into the original particle as if they had never been there:

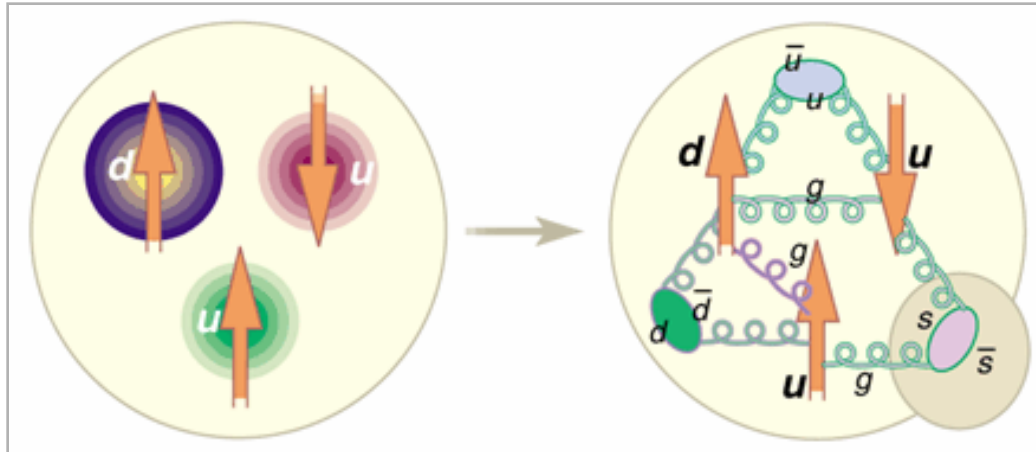


While the virtual particles are briefly part of our world they can interact with other particles, and that leads to a number of tests of the quantum-mechanical predictions about virtual particles: one example is the **Lamb-shift** in hydrogen (see: “atoms”).

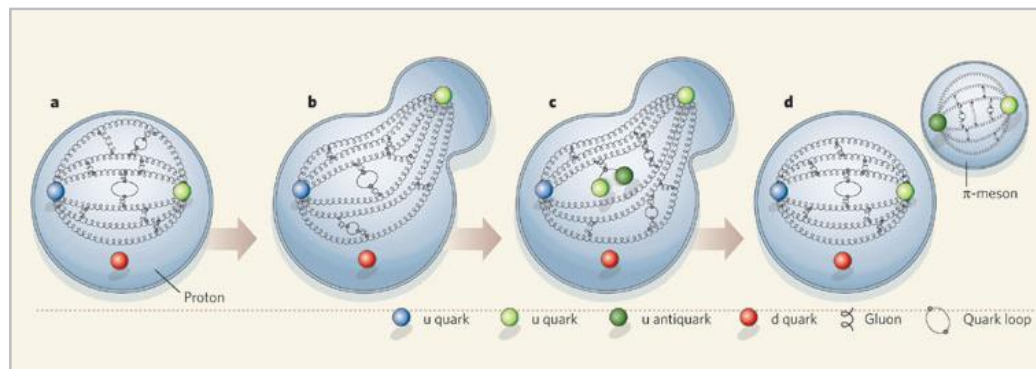


## Vacuum Fluctuations

Hadrons are thus much more **complicated multi-particle systems**;  
Example: proton



... and **meson production** can be “more realistically” pictured as:





## Forces

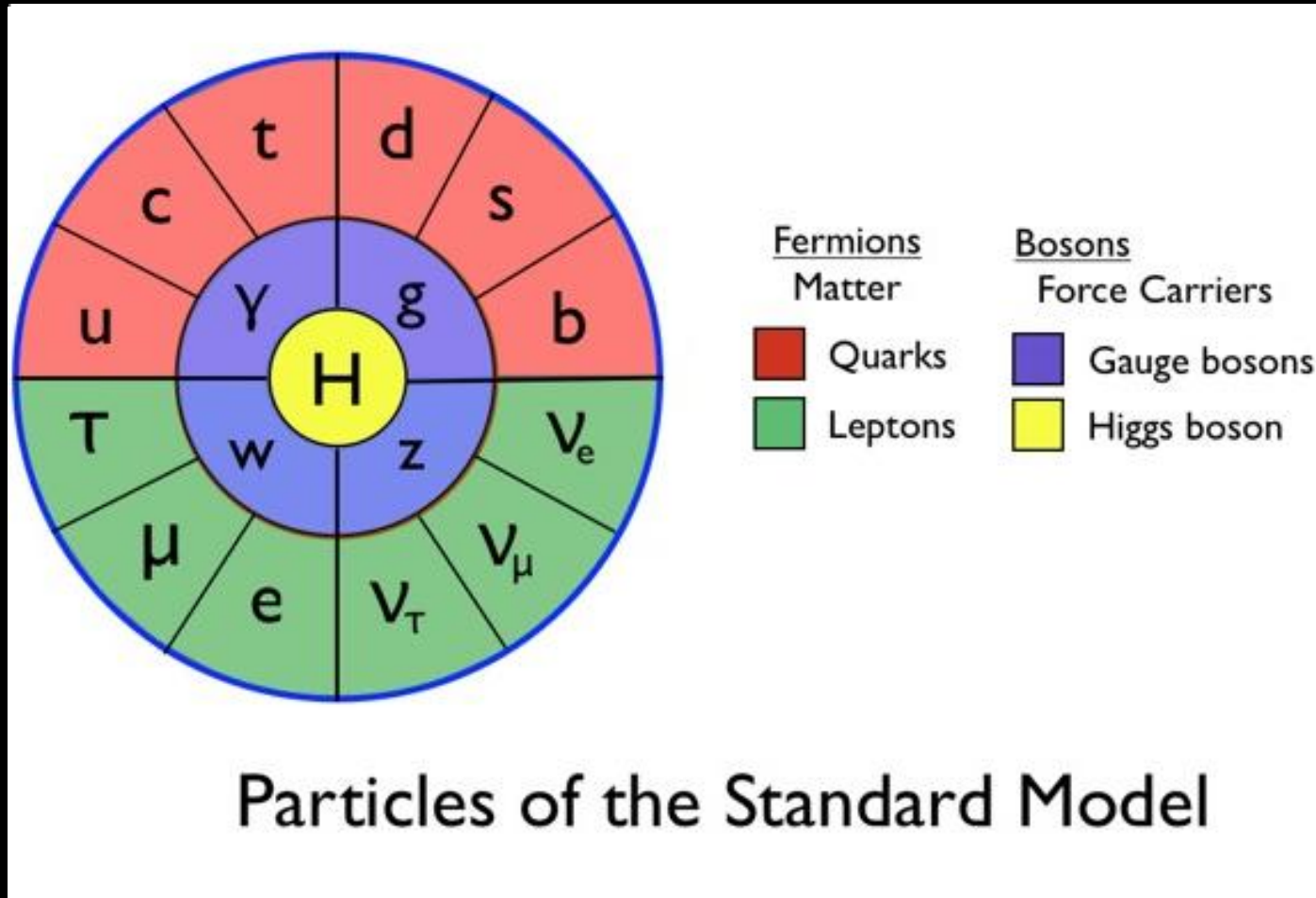


**Table S4.2 The Four Forces**

Force	Relative Strength Within Nucleus*	Relative Strength Beyond Nucleus	Exchange Particles	Major Role
Strong	100	0	Gluons	Holding nuclei together
Electromagnetic	1	1	Photons	Chemistry and biology
Weak	$10^{-5}$	0	Weak bosons	Nuclear reactions
Gravity	$10^{-43}$	$10^{-43}$	Gravitons	Large-scale structure

\* The force laws for the strong and weak forces are more complex than the inverse square laws for the electromagnetic force and gravity; hence the numbers given for the strong and weak forces are very rough.

## Forces

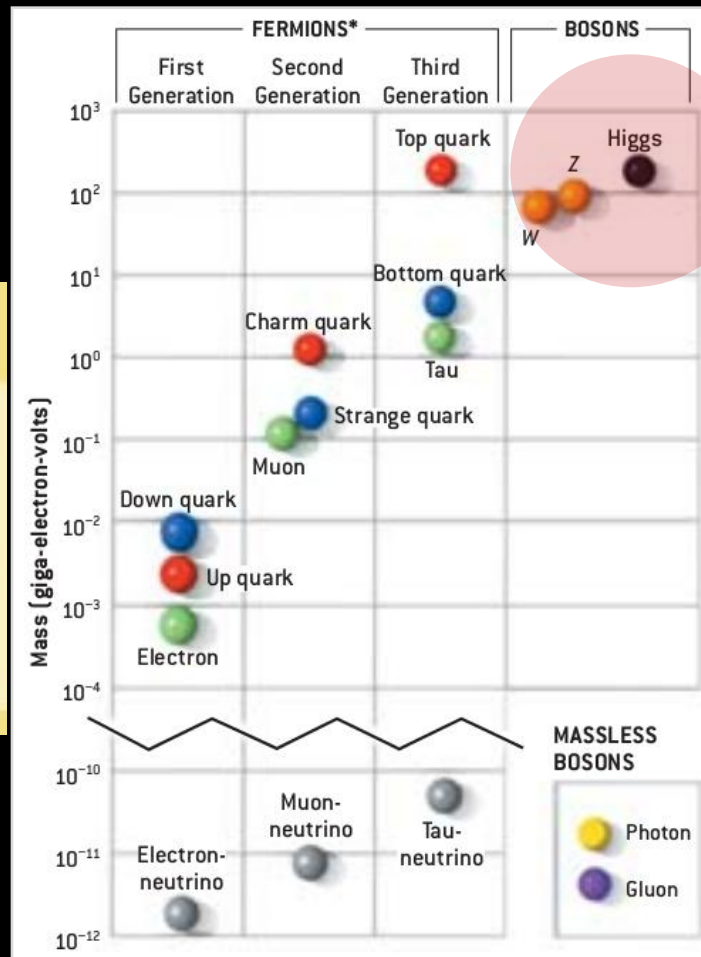


## Standard Model

**Fermions**

Leptons and Quarks      Spin =  $\frac{1}{2}$

Baryons (qqq)      Spin =  $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \dots$



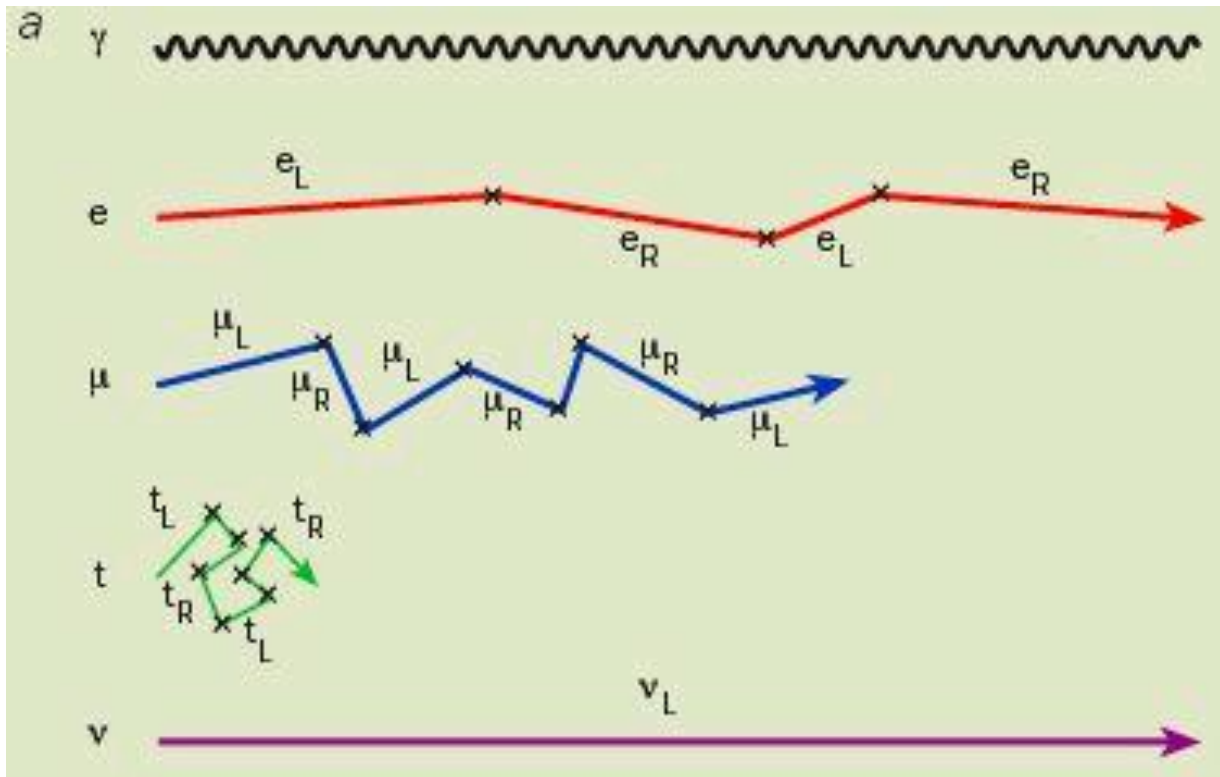
**Bosons**

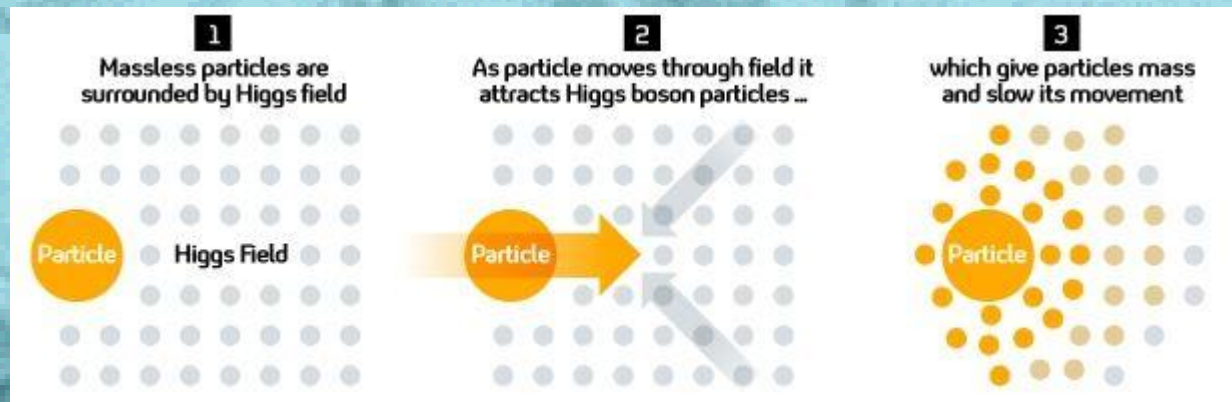
Spin =  $1^*$       Force Carrier Particles

Spin =  $0, 1, 2, \dots$       Mesons ( $q\bar{q}$ )

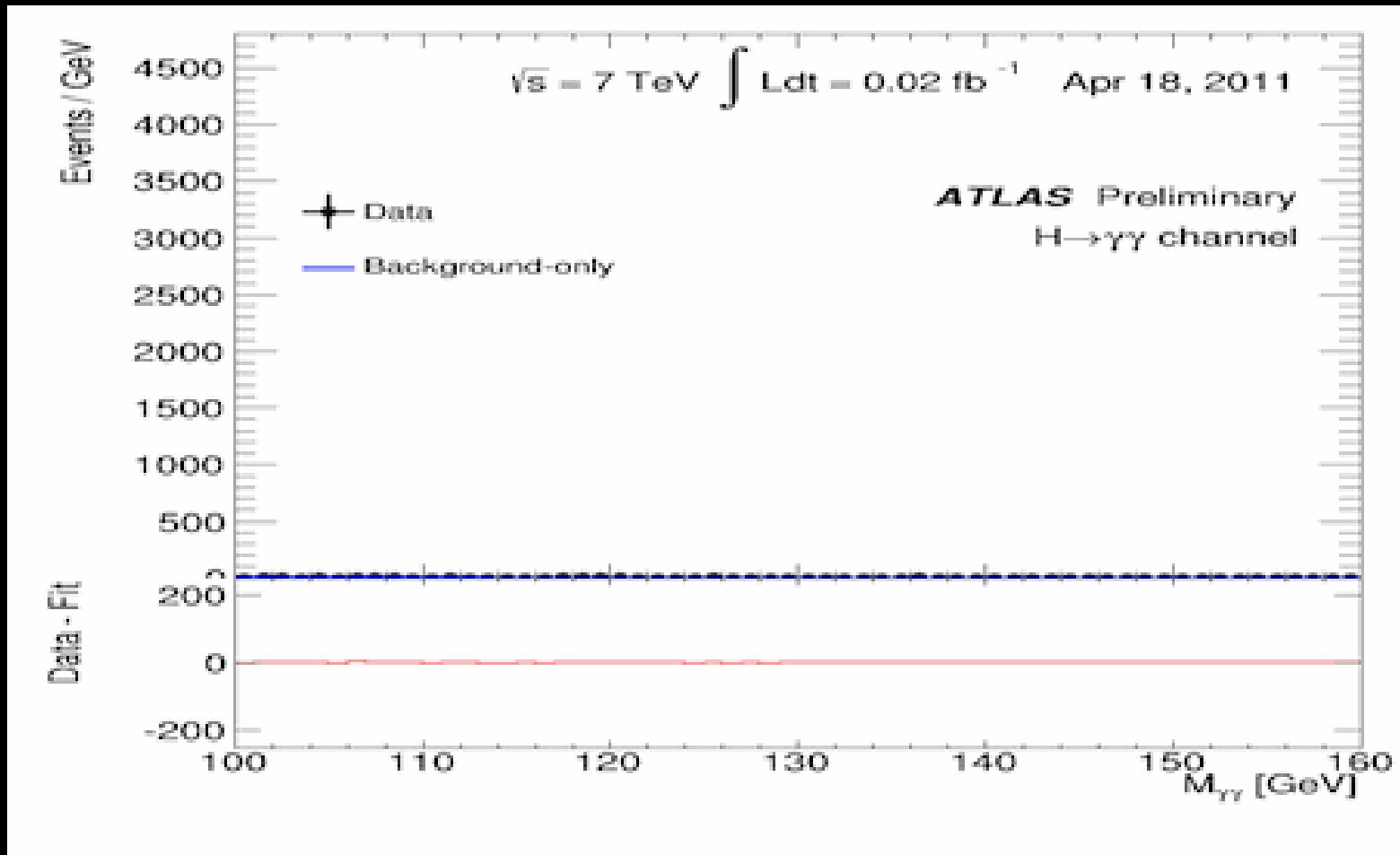
## Masses of Fundamental Particles

The **Higgs boson** or **Higgs particle** is an elementary particle, which is associated with the **Higgs field** and is pivotal to the Standard Model, since it explains why some fundamental particles have **mass** and why the **weak force** has a much shorter range than the electromagnetic force:





## Higgs Field



## Higgs Discovery at CERN (July 4, 2012)



The **Standard Model** of elementary particle physics is a triumph of 20<sup>th</sup> century science – but it is not without problems; for one thing it has too many elementary constituents:

$$18 = (6 \times 3)$$

quarks

$$6 = (2 \times 3)$$

leptons

8

gluons

3

gauge bosons

1

photon

1 (at least)

Higgs boson

+ anti-particles

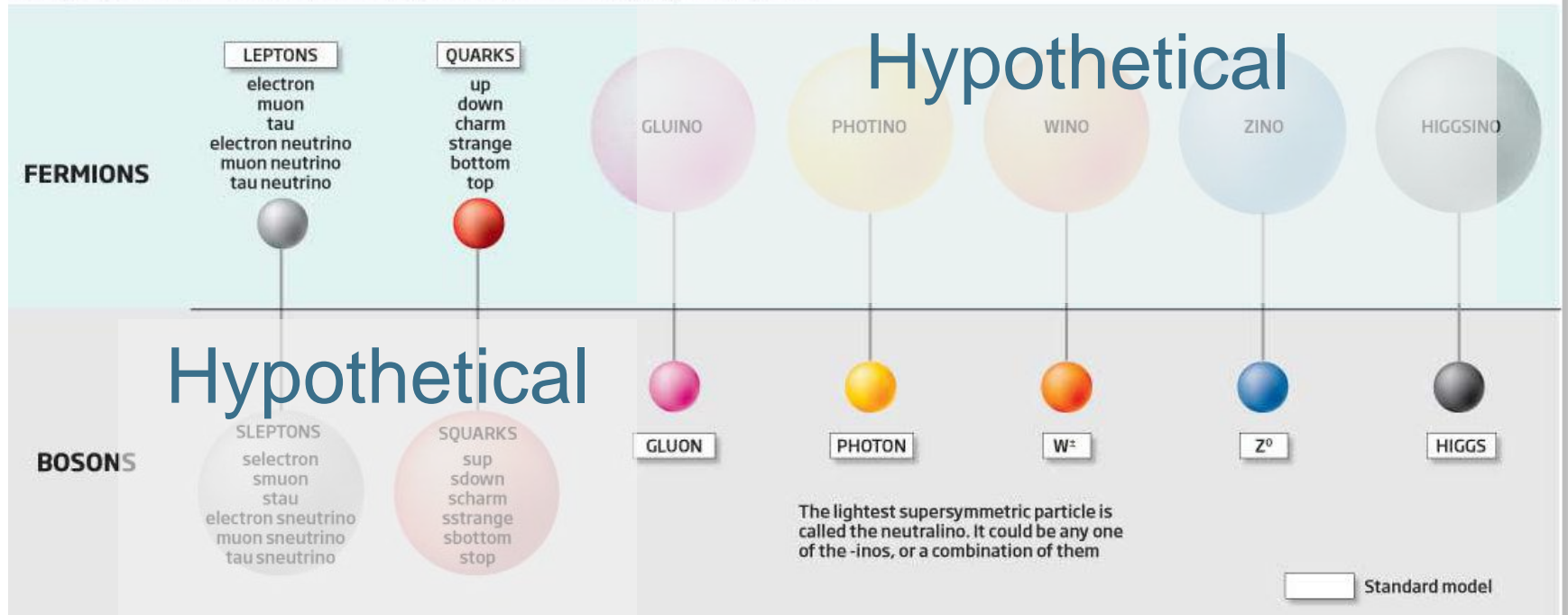
**61**

It does not attempt to explain **gravitation**; it needs to be modified in order to accommodate the fact that **neutrinos have mass**, and it cannot explain “**dark matter**” – there must be “**physics beyond the Standard Model**” (BSM) ...

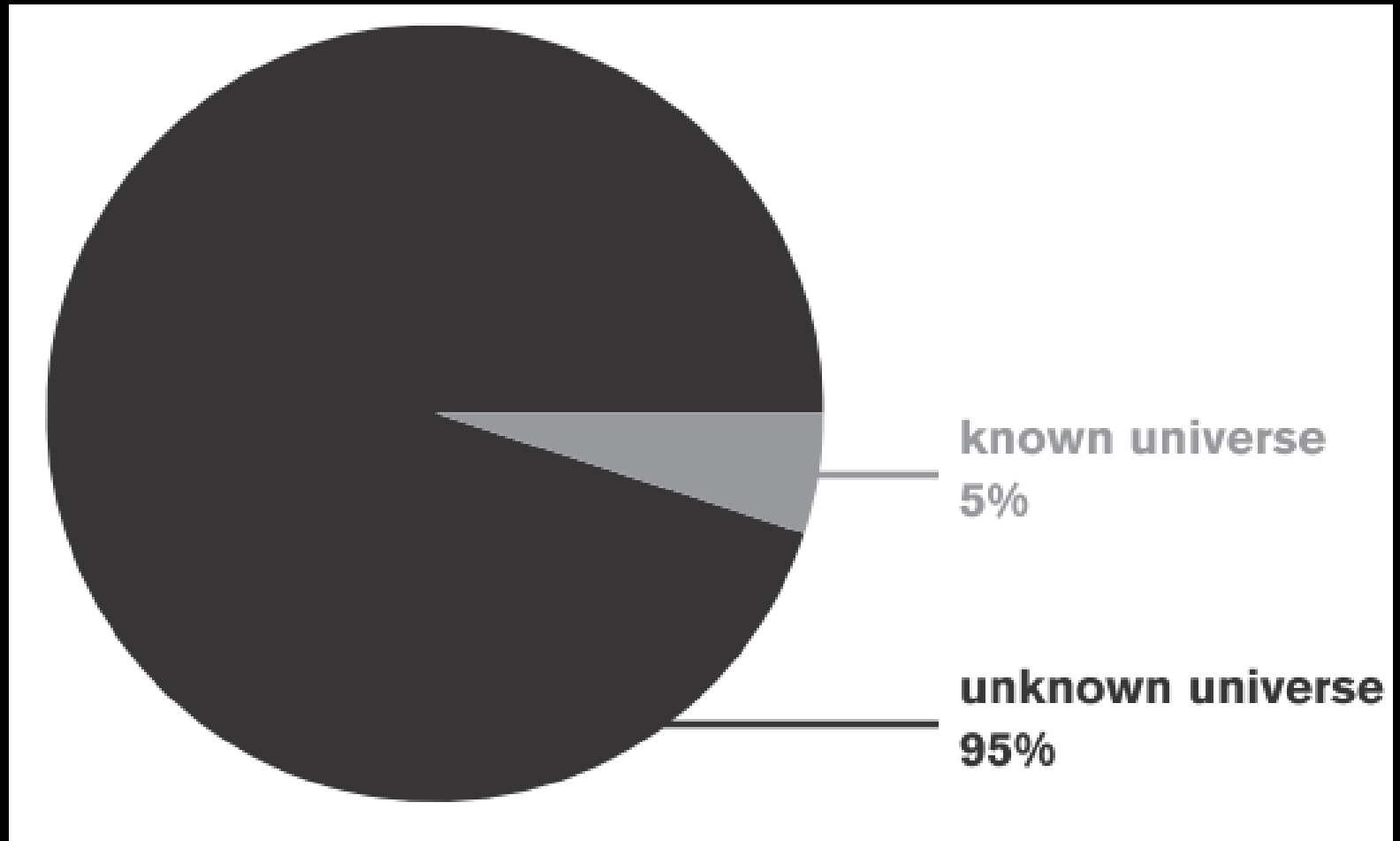
## Particle zoo

©NewScientist

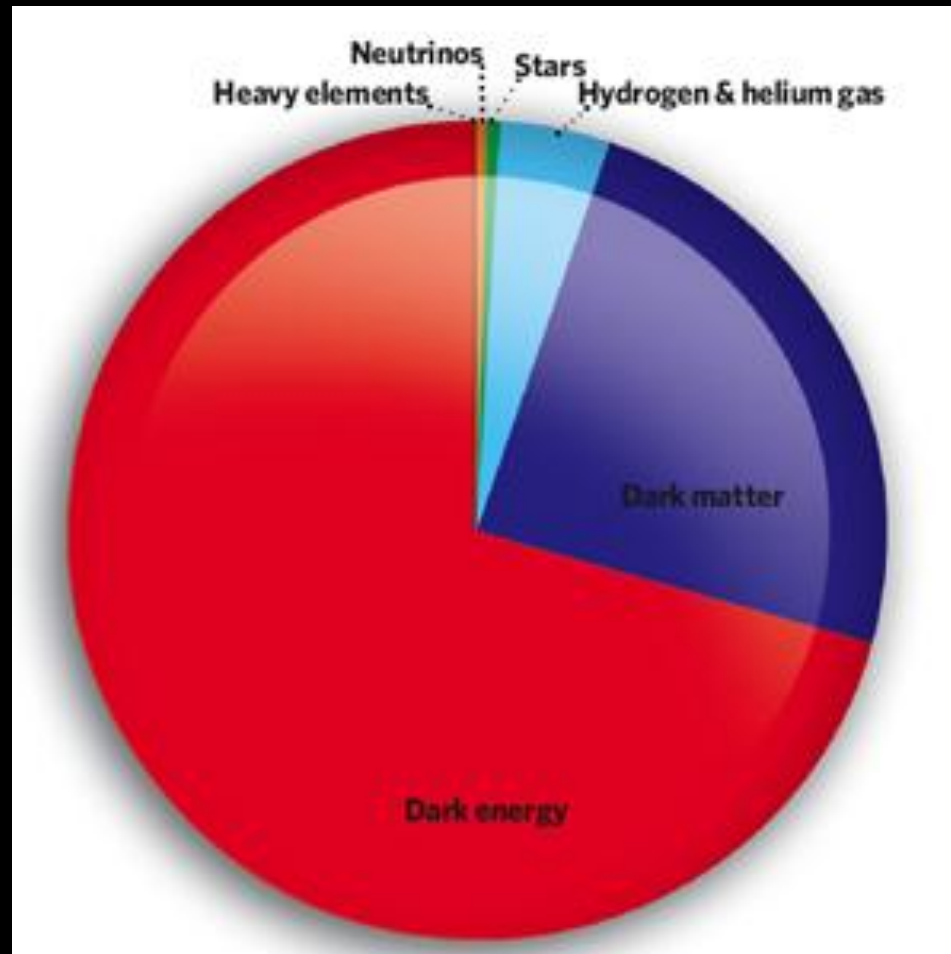
Particles are divided into two families called bosons and fermions. Among them are groups known as leptons, quarks and force-carrying particles like the photon. Supersymmetry doubles the number of particles, giving each fermion a massive boson as a super-partner and vice versa. The LHC is expected to find the first supersymmetric particle



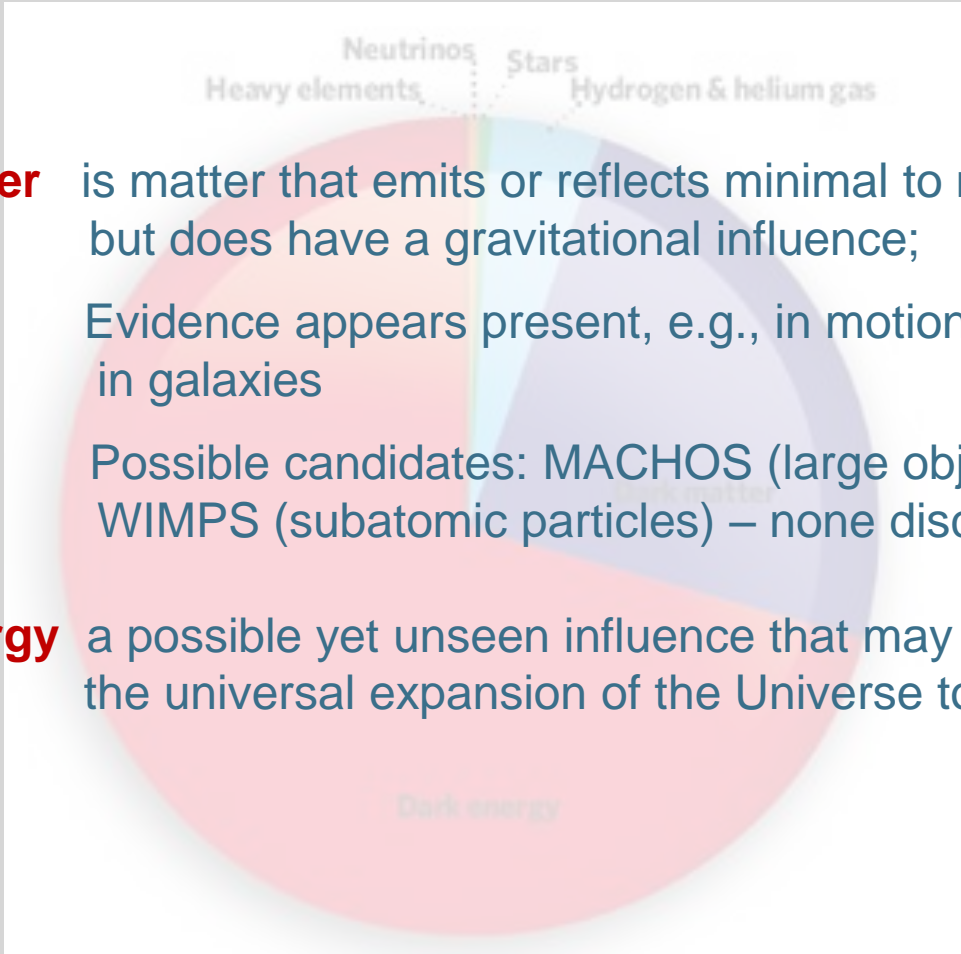
## Supersymmetry (SUSY) ?



„Dark Universe“



„Dark Universe“

- 
- Dark Matter** is matter that emits or reflects minimal to no light, but does have a gravitational influence;  
Evidence appears present, e.g., in motion of the stars in galaxies  
Possible candidates: MACHOS (large objects) or WIMPS (subatomic particles) – none discovered yet!
- Dark Energy** a possible yet unseen influence that may be causing the universal expansion of the Universe to accelerate.

„Dark Universe“

Nine key questions define the field of particle physics.

## EINSTEIN'S DREAM OF UNIFIED FORCES

1 ARE THERE UNDISCOVERED PRINCIPLES  
OF NATURE : NEW SYMMETRIES, NEW  
PHYSICAL LAWS?

2 HOW CAN WE SOLVE THE MYSTERY OF  
DARK ENERGY?

3 ARE THERE EXTRA DIMENSIONS  
OF SPACE?

4 DO ALL THE FORCES BECOME ONE?

## THE PARTICLE WORLD

5 WHY ARE THERE SO MANY KINDS OF  
PARTICLES?

6 WHAT IS DARK MATTER? HOW CAN WE  
MAKE IT IN THE LABORATORY?

7 WHAT ARE NEUTRINOS TELLING US?

## THE BIRTH OF THE UNIVERSE

8 HOW DID THE UNIVERSE COME TO BE?

9 WHAT HAPPENED TO THE ANTIMATTER?

# Key Questions

**“MAKE EVERYTHING AS SIMPLE  
AS POSSIBLE, BUT NOT SIMPLER.”**

*Albert Einstein*





გმადლობთ