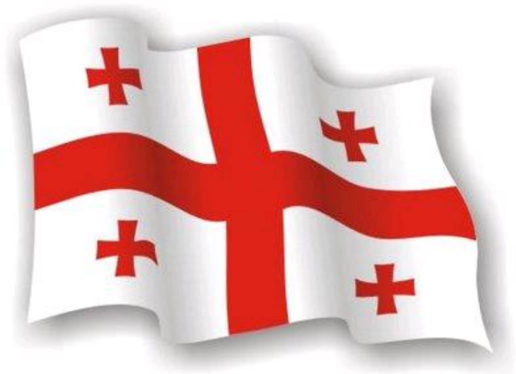

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Georgian-German Science Bridge

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

October 15, 2013 | Hans Ströher (Forschungszentrum Jülich)


Situation in 1960

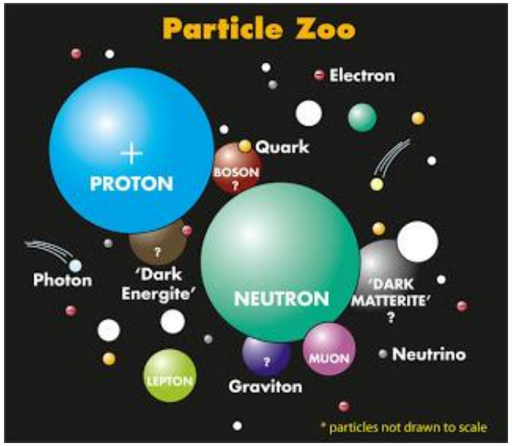
# Lecture 4 – **Particles** – Introduction

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** ($\pi$) …)

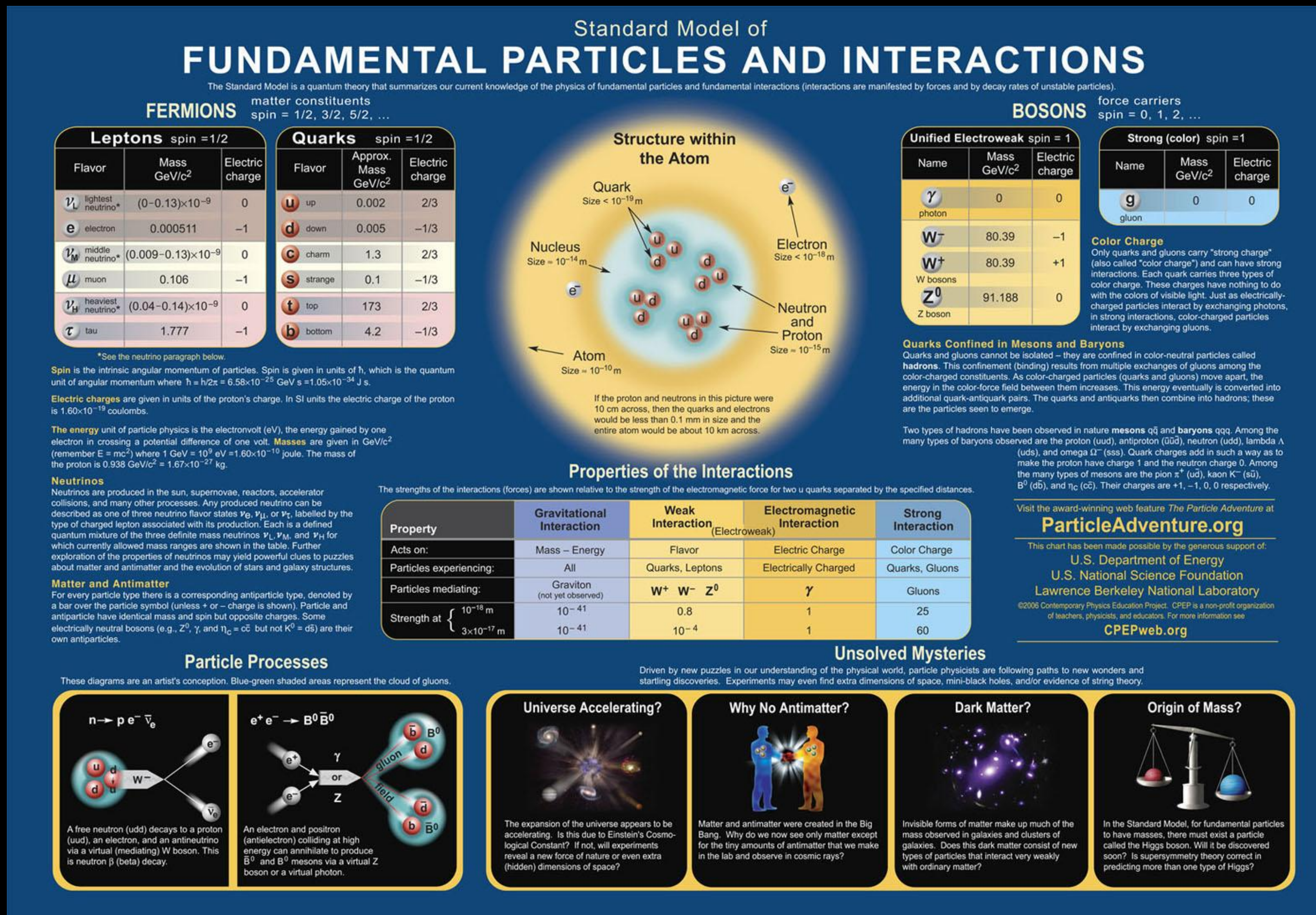
} **quarks**

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)

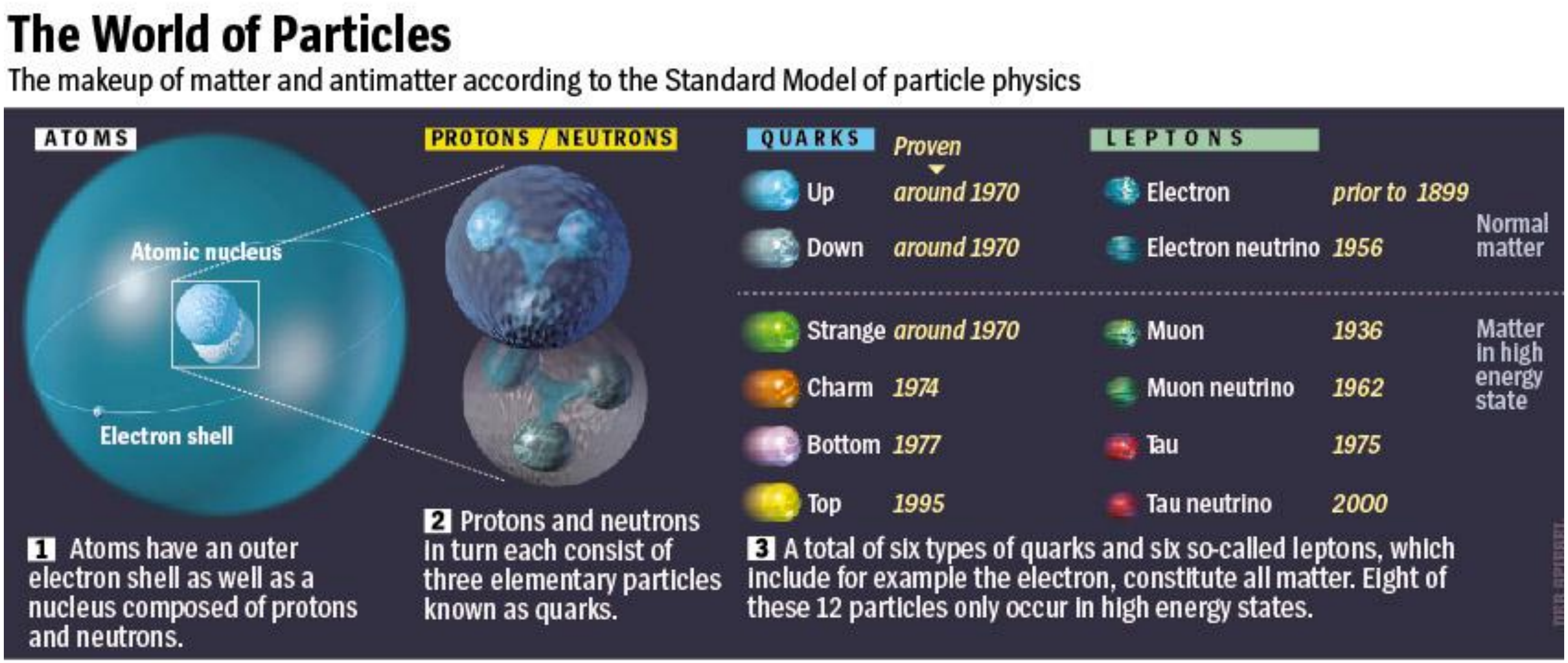
# Lecture 4 – **Particles** – Introduction




Standard Model

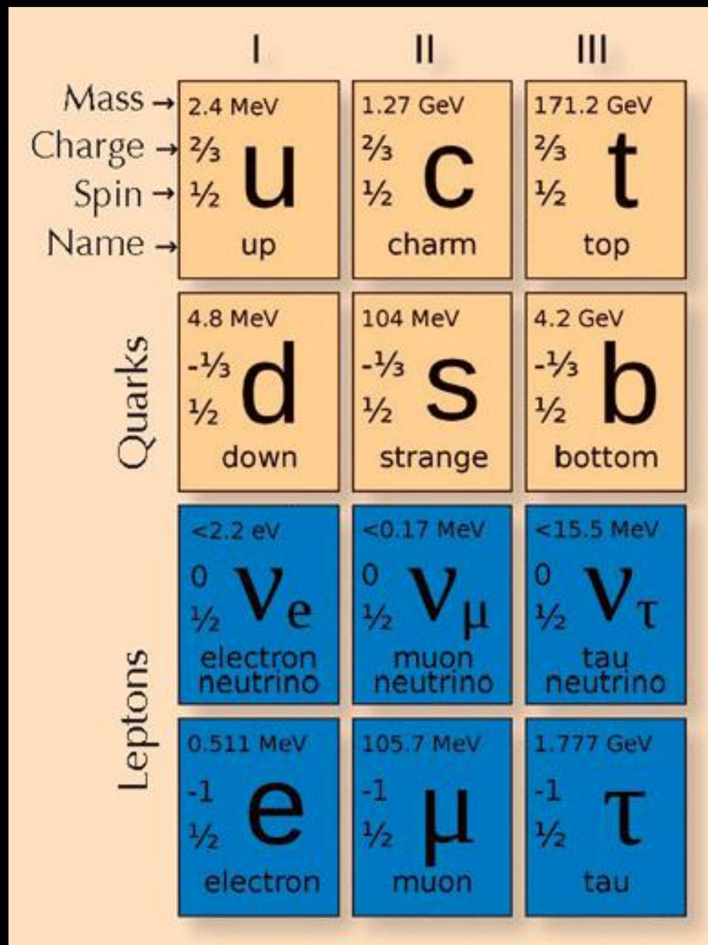
# Lecture 4 – **Particles** – Constituents

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:




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

# Lecture 4 – **Particles** – Constituents




Standard Model: Matter Particles

# Lecture 4 – **Particles** – Constituents

One major puzzle is why Nature likes this **repetition** in form of the 2$^{nd}$ and 3$^{rd}$ generation?

Example: When the **muon** (μ) was discovered, I. Rabi asked: "Who ordered that?" [A similar question can be asked for the **tau** (τ)]


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**.

# Lecture 4 – **Particles** – Constituents

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| | muon | | muon neutrino | | electron | | $e^-$ 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

# Lecture 4 – **Particles** – Constituents

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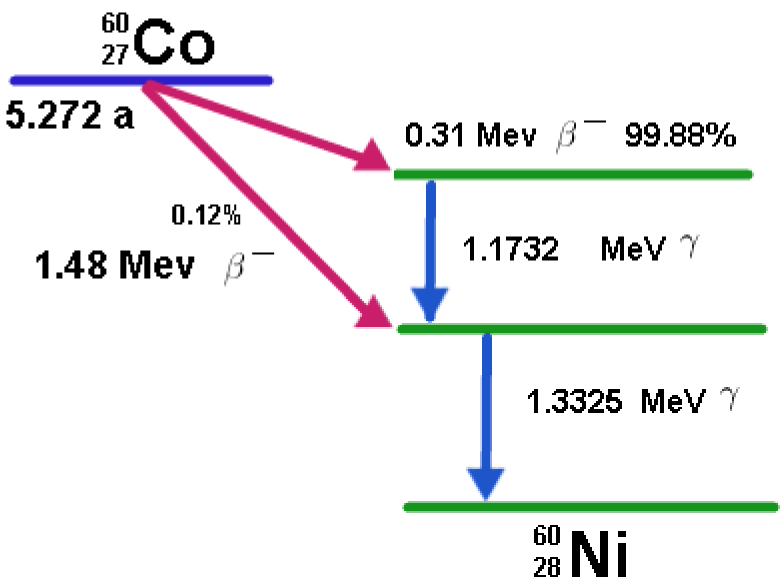
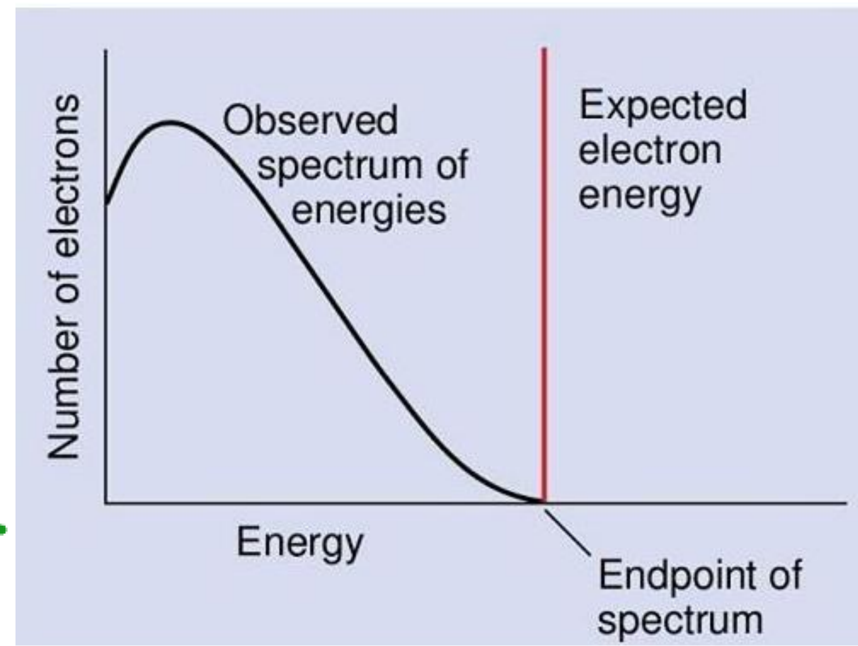
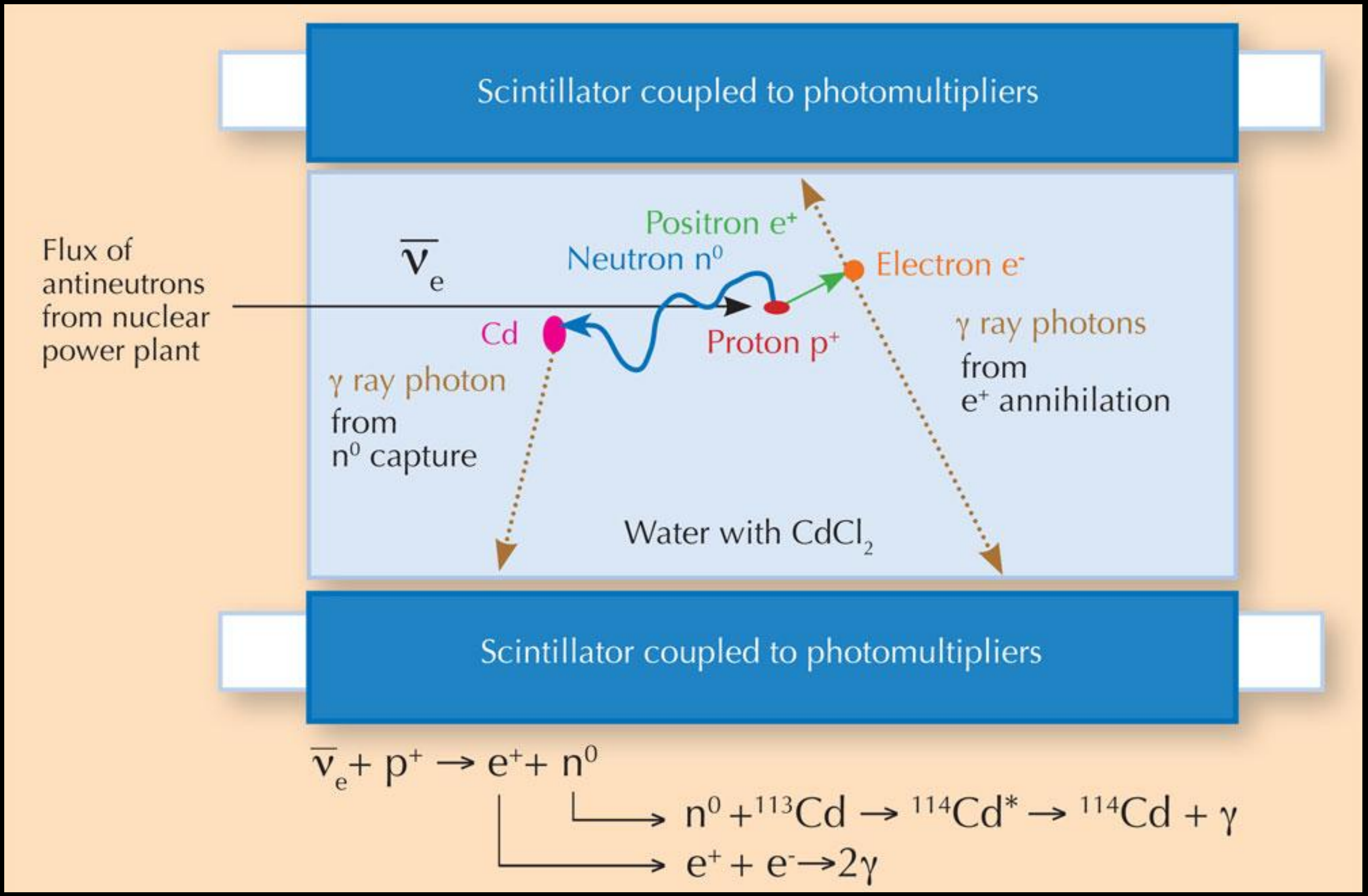
**Neutrinos** are the electrically neutral leptons, affiliated with the corres-ponding charged ones: e - $\nu_e$, μ - $\nu_\mu$, τ - $\nu_\tau$

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

Example:





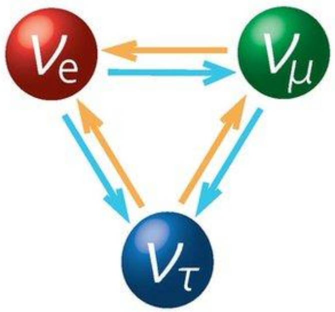

# (First) Neutrino Detection

# Lecture 4 – Particles – Constituents

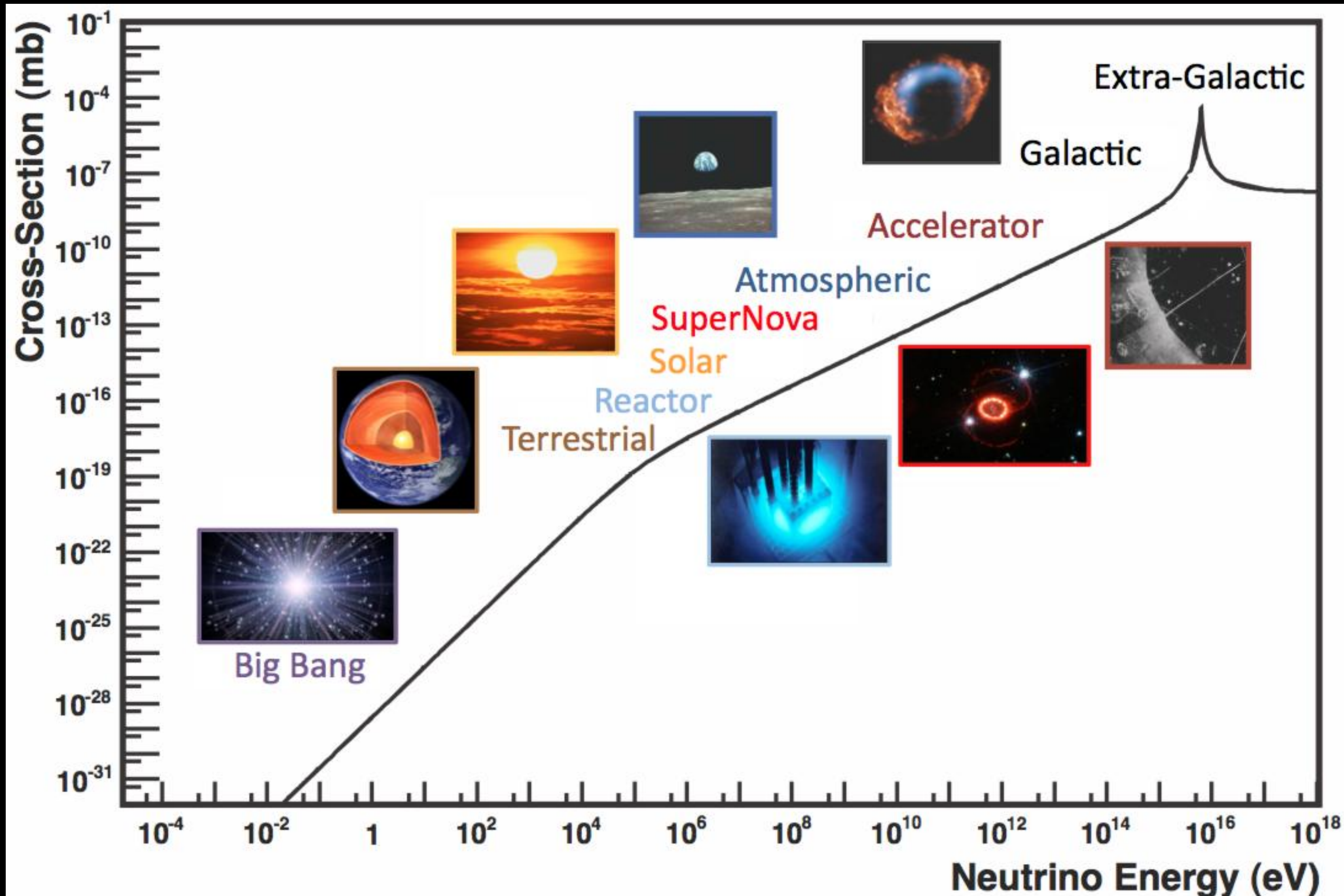
**Neutrinos are very abundant** in the Universe (second most after photons): **~ 37 ν´s per cm$^3$**; the neutrino flux from the **sun** is calculated to be **5 x 10$^6$ cm$^{-2}$ s$^{-1}$** ; every second trillions of neutrinos pass our bodies

Neutrinos **interact very little** with matter (→ reason why they were discovered so late); gigantic detectors have been built to measure their properties: AMANDA (Mediteranian 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"):



# Lecture 4 – Particles – Constituents




Neutrino Cross Section

# Lecture 4 – **Particles** – Constituents


Neutrino Detectors

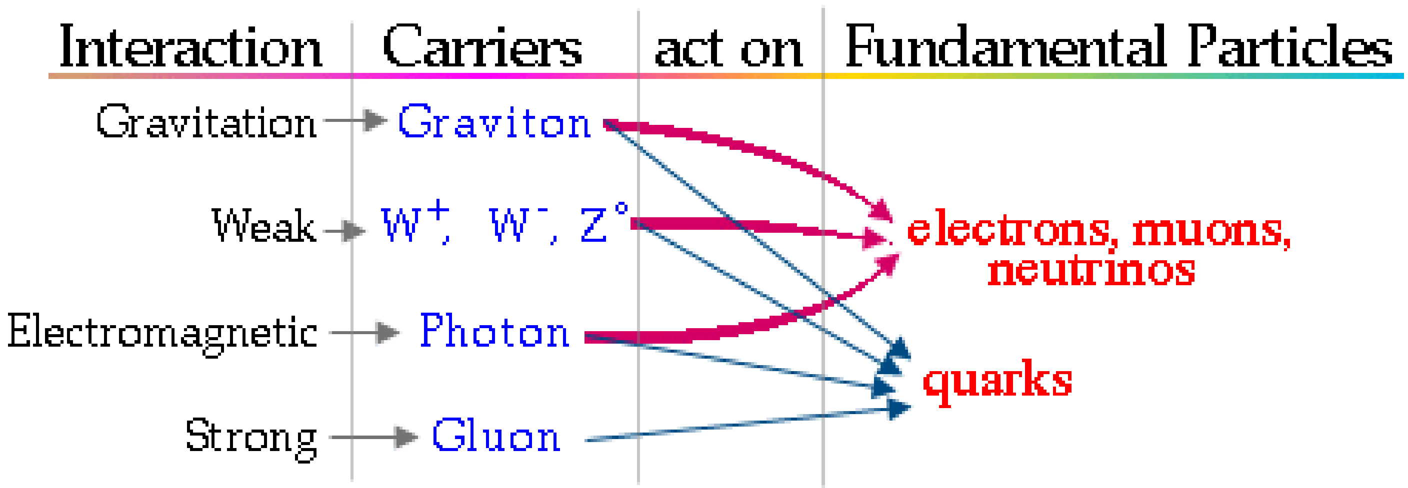
# Lecture 4 – Particles – Force Carriers

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

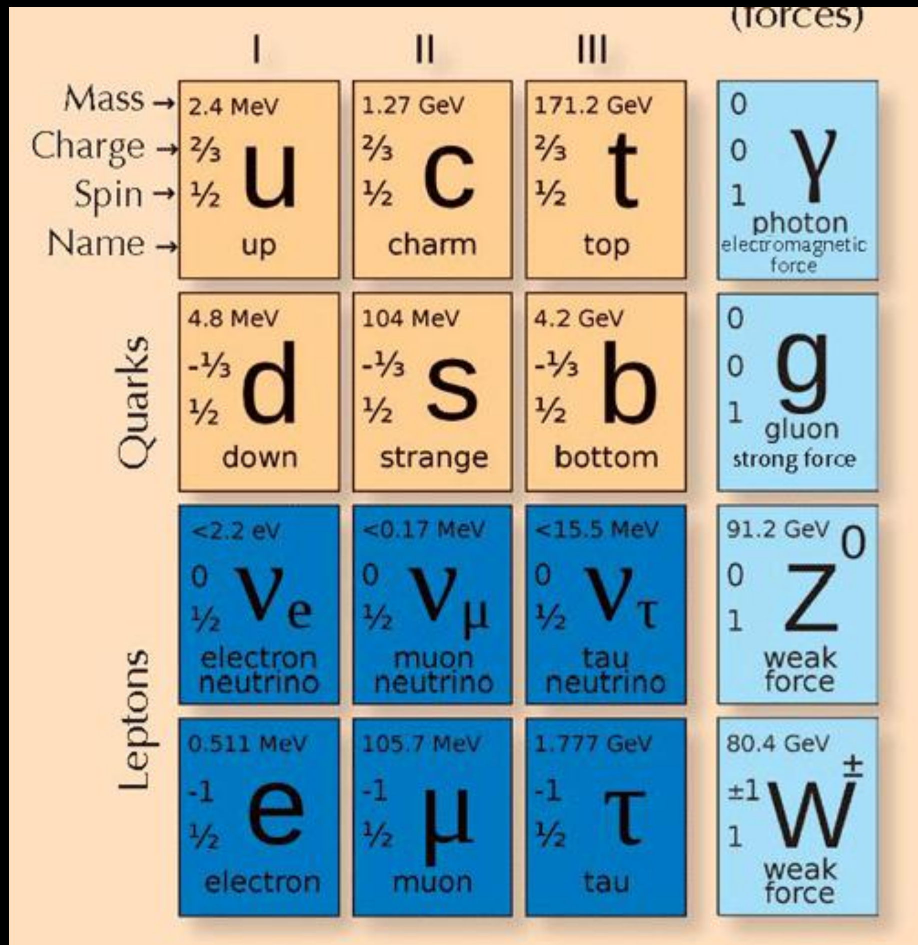
| force | boson symbol | boson name |
| --- | --- | --- |
| strong | g | *gluon* |
| electromagnetic | $\gamma$ | *photon* |
| weak | $W^+$, $W^-$ | *W bosons* |
| | $Z^0$ | *Z boson* |

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:

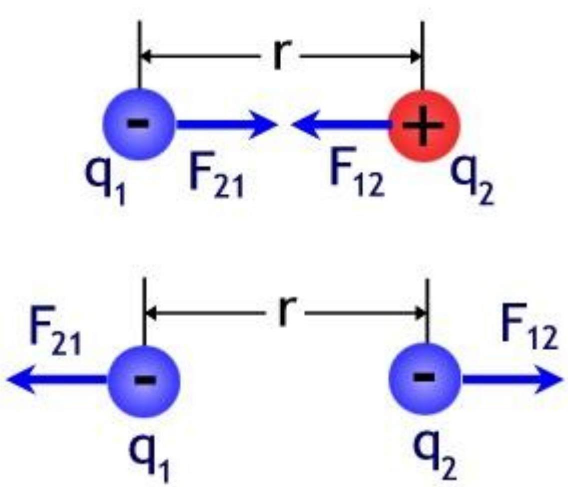


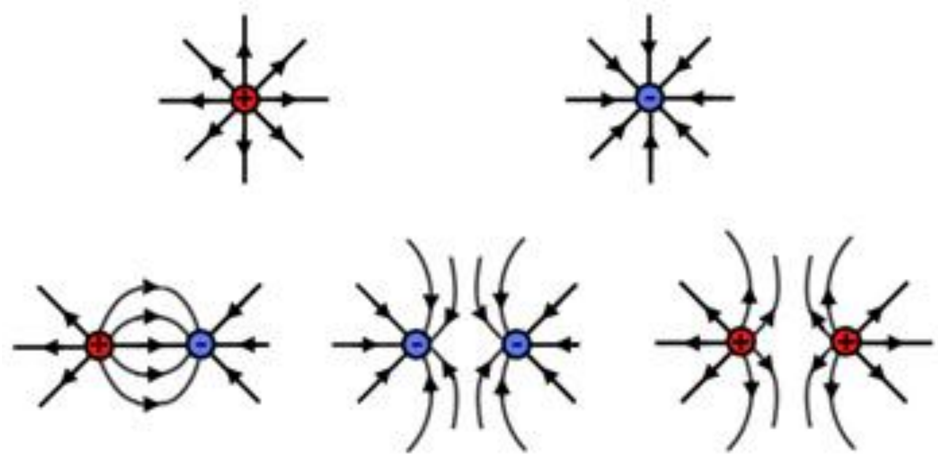

The **strong interaction** only acts between quarks, the **electromagnetic interaction** does not influence the uncharged neutrinos, but the **weak** and the **gravitational interaction** act on all fundamental particles.




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"

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

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

Unification of electricity and magnetism

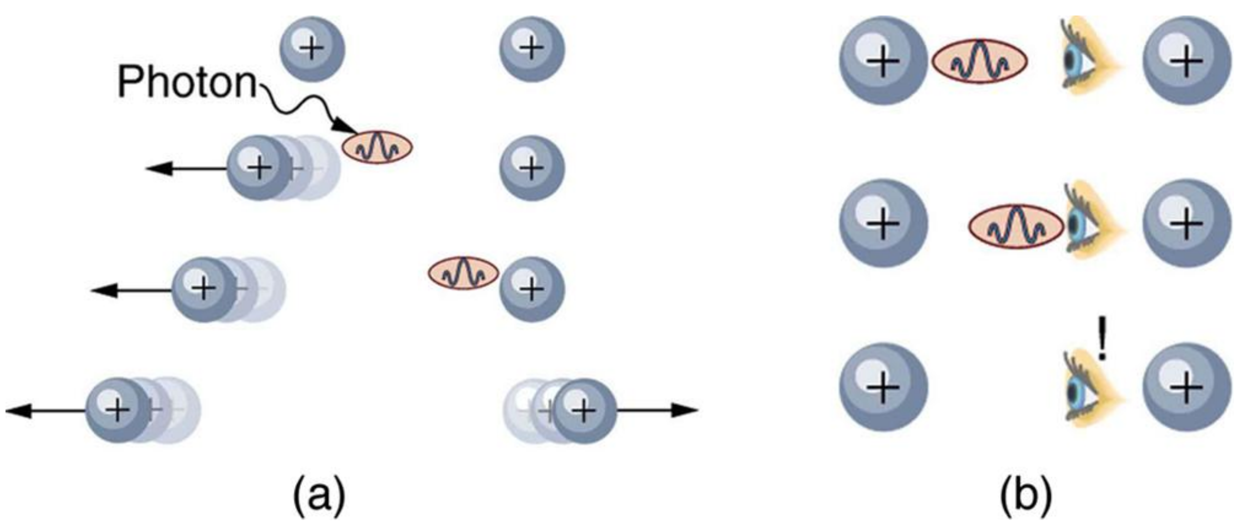
Prediction of electromagnetic waves

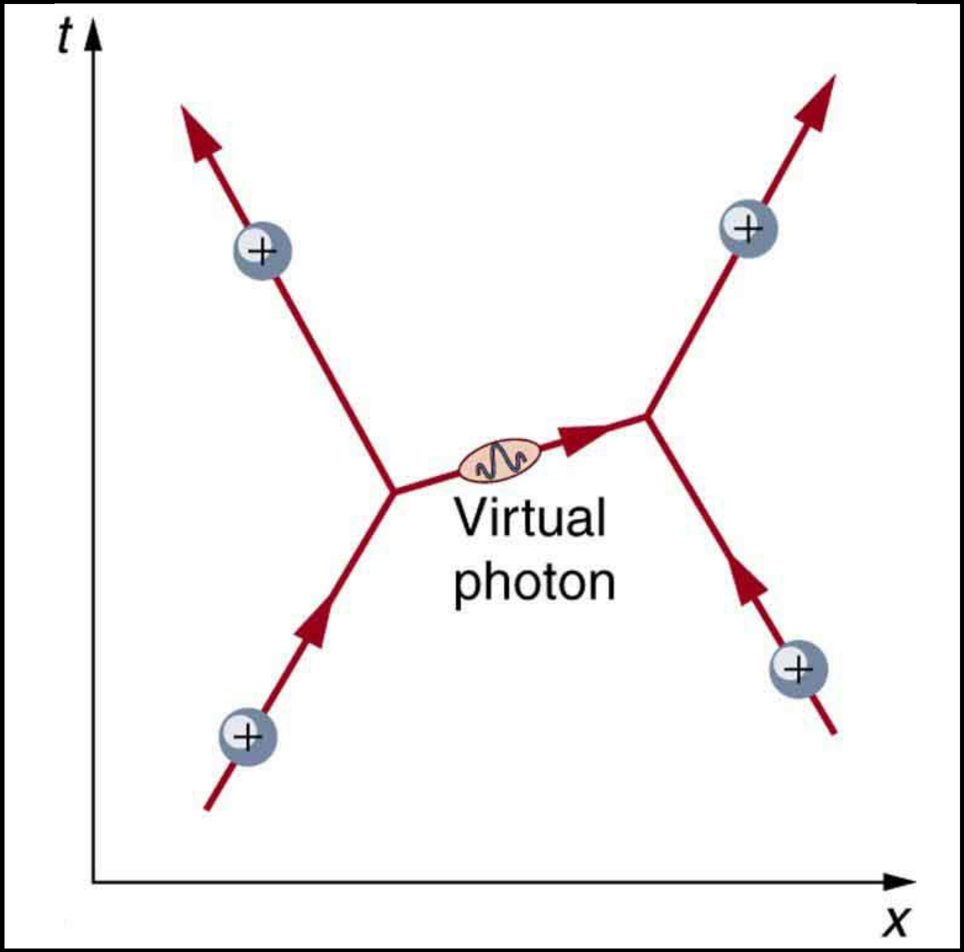
# Maxwell Equations

# Lecture 4 – Particles – Force Carriers

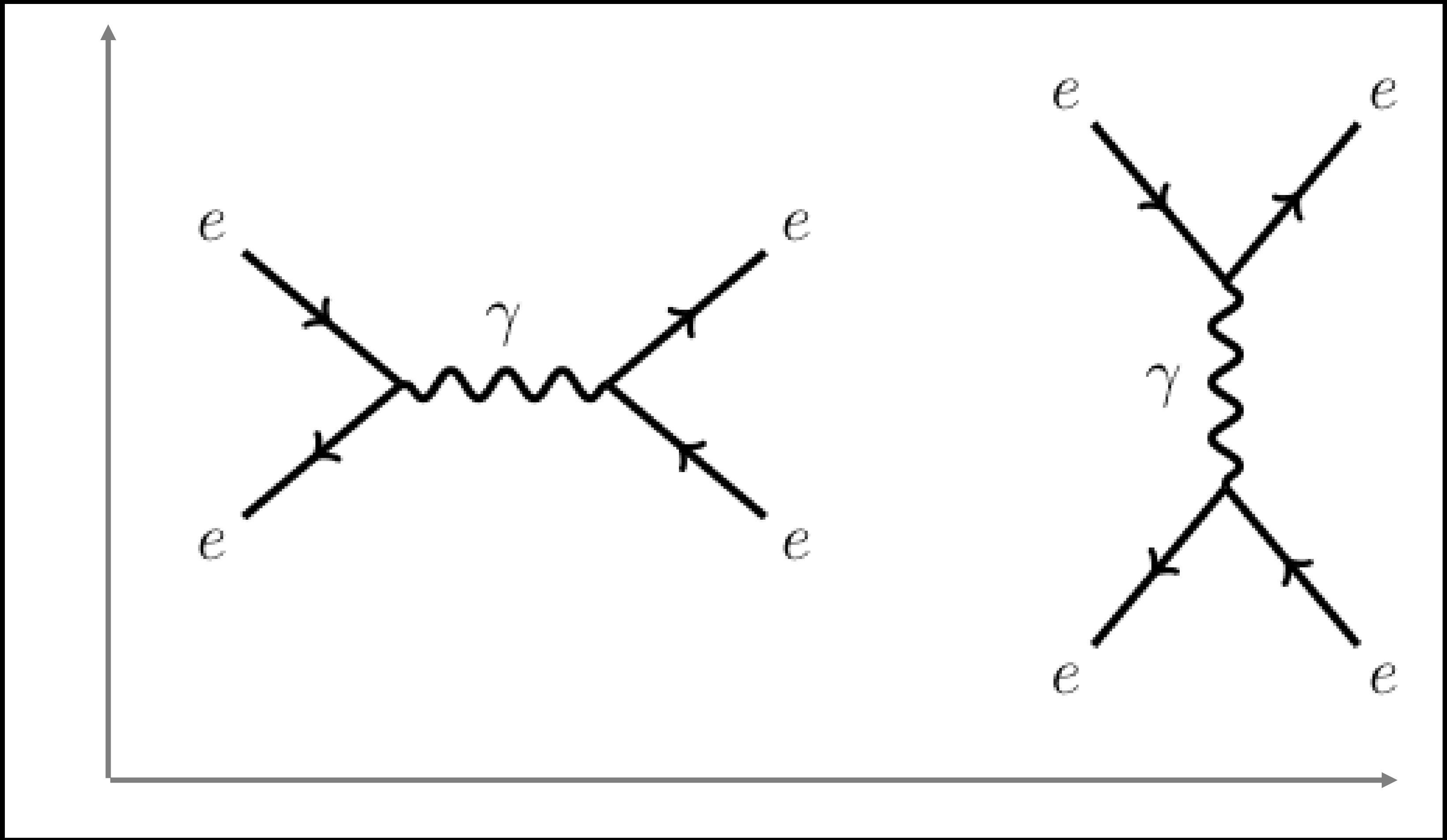
**Maxwell's equations** (along with the rest of classical electromagnetism) are extraordinarily successful at explaining and predicting a large variety of phenomena; however, they are **not exact laws** of Nature, but merely **approximations**; for example, Maxwell's equations do not involve "**photons**".

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**:





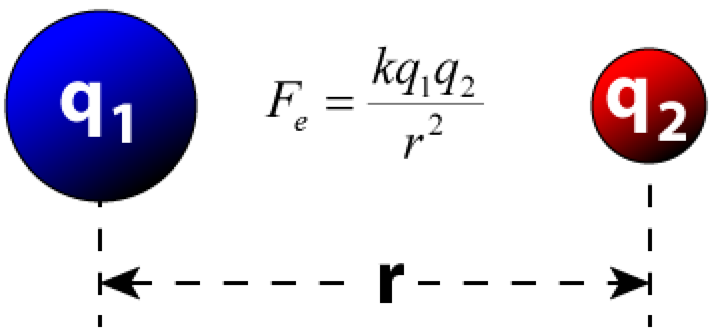

Feynman Diagram: Repulsion



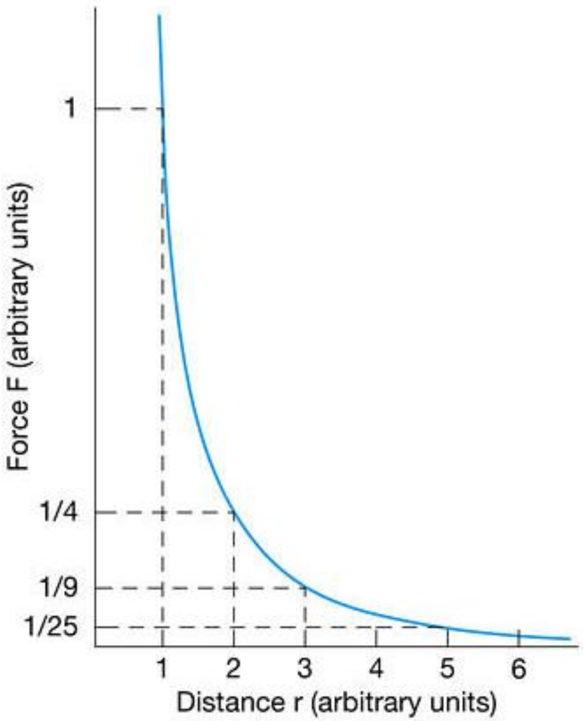

# Feynman Diagrams: Interaction, Annihilation

# Lecture 4 – Particles – Force Carriers

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




$$F_e = \frac{kq_1q_2}{r^2}$$



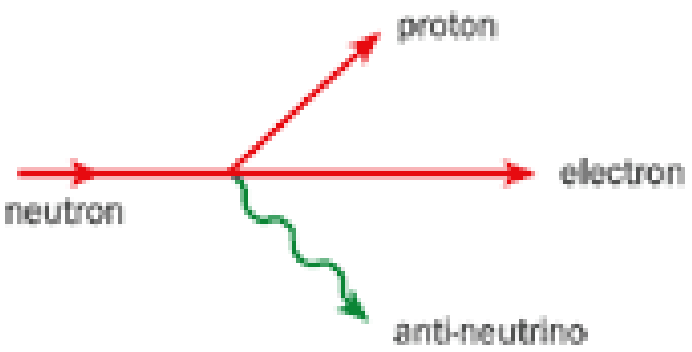

Charged particles interact, because there is a **continuous exchange of photons**

# Lecture 4 – Particles – Force Carriers

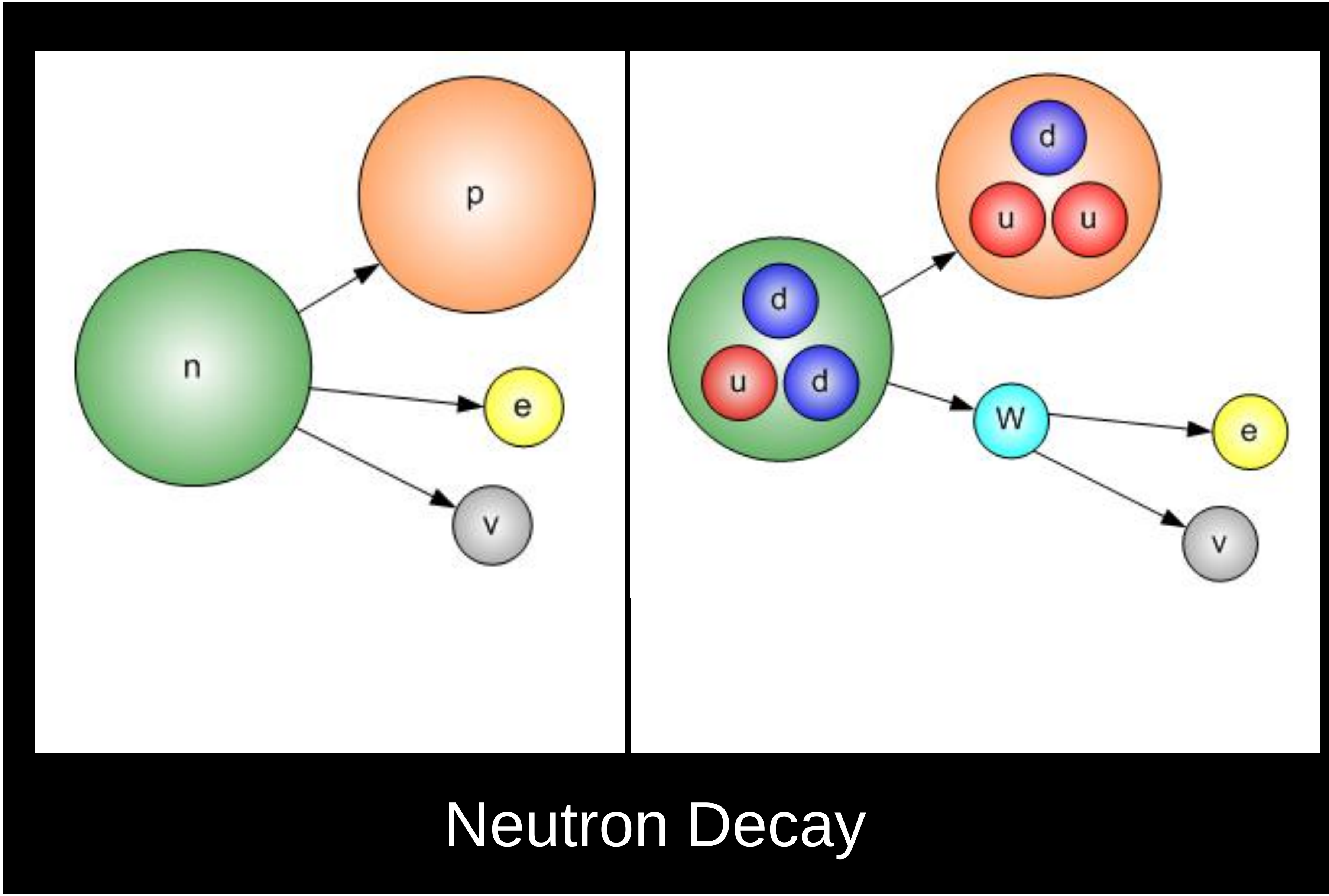
The **weak force** underlies some forms of **radioactivity** (ß-decay), governs the **decay of unstable** subatomic **particles** (such as mesons), and initiates the nuclear **fusion reaction** (e.g., in the Sun)

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

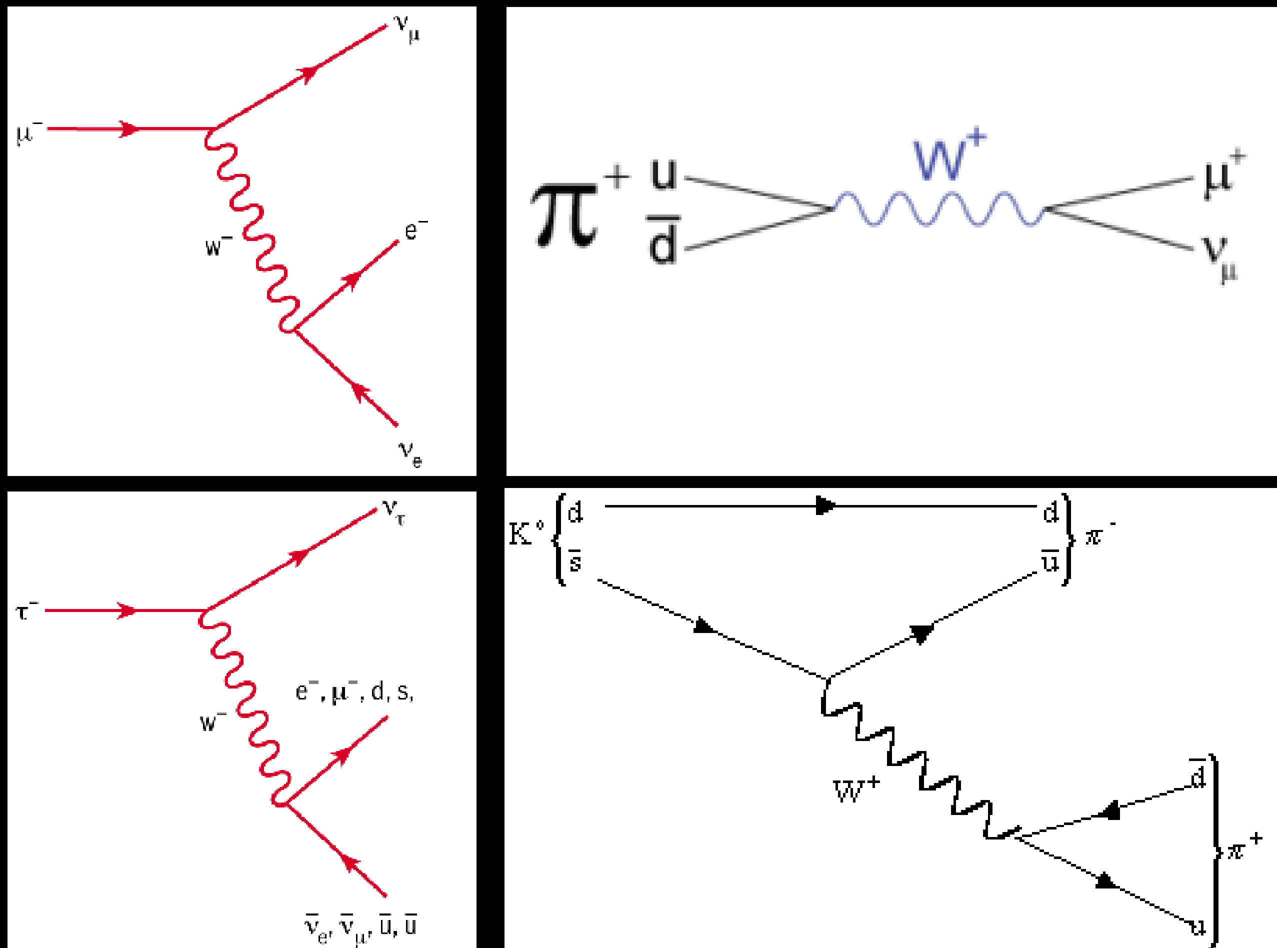
**Enrico Fermi** proposed the first theory of the weak interaction, known as Fermi's interaction by suggesting that beta decay could be explained by a four-fermion interaction, involving a contact force with no range; example: **neutron-decay**



# Lecture 4 – Particles – Force Carriers



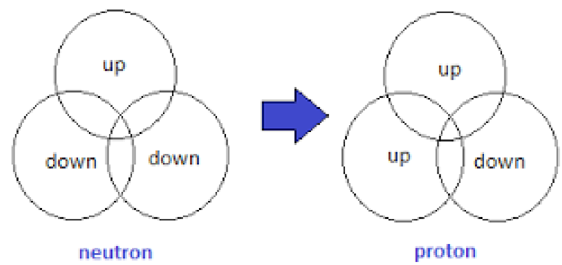
# Lecture 4 – **Particles** – Force Carriers




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)



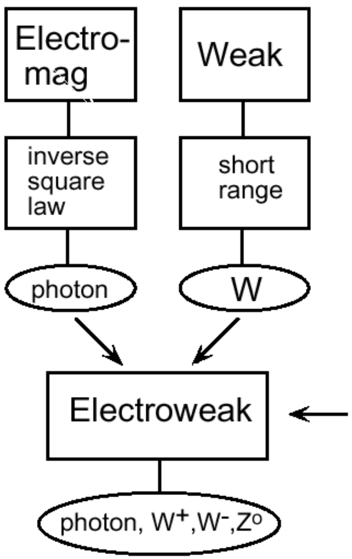

- It is the only interaction which **violates P** or parity-symmetry. It is also the only one which violates **CP symmetry**


- It is propagated by carrier particles (known as **gauge bosons**) that have significant masses (~ 100 x mass of the nucleon)

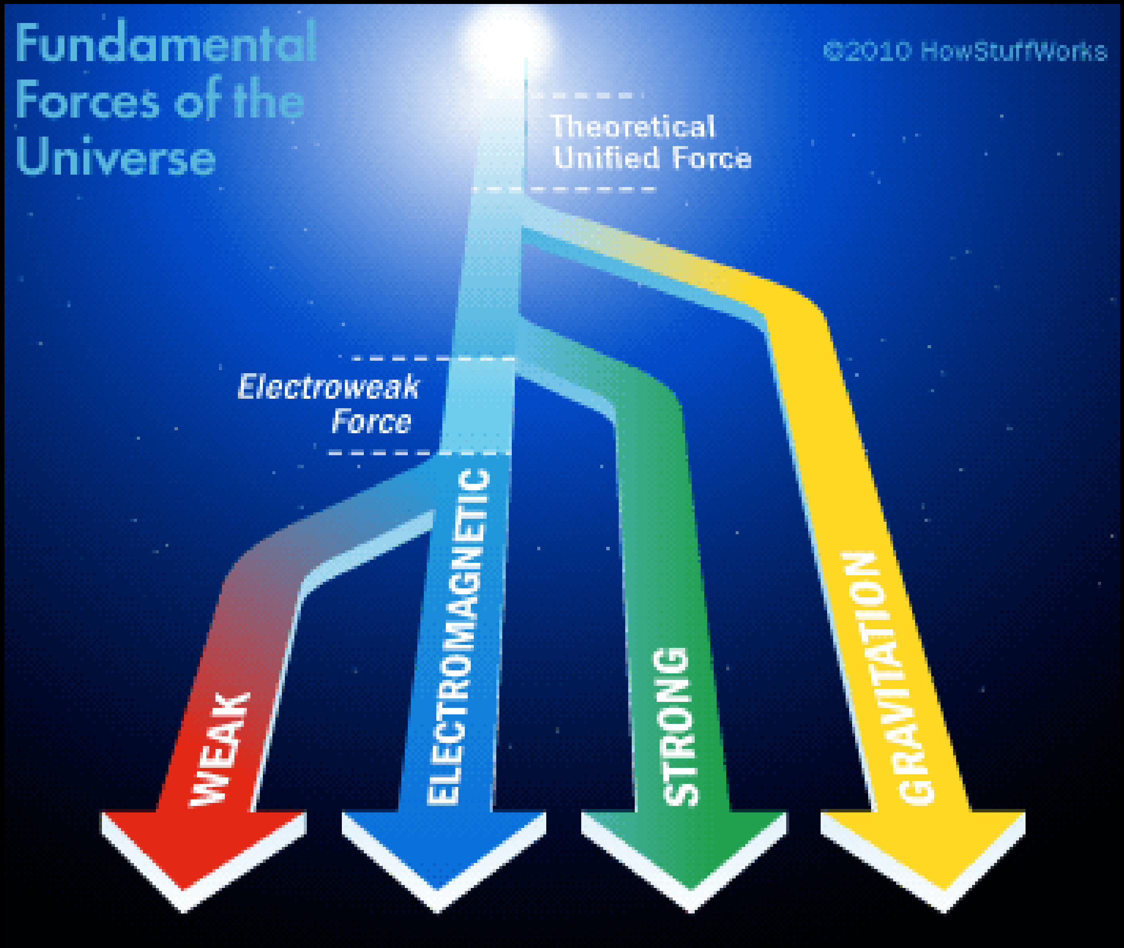
# Lecture 4 – Particles – Force Carriers

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**:



# Lecture 4 – **Particles** – Force Carriers




Unification of Forces

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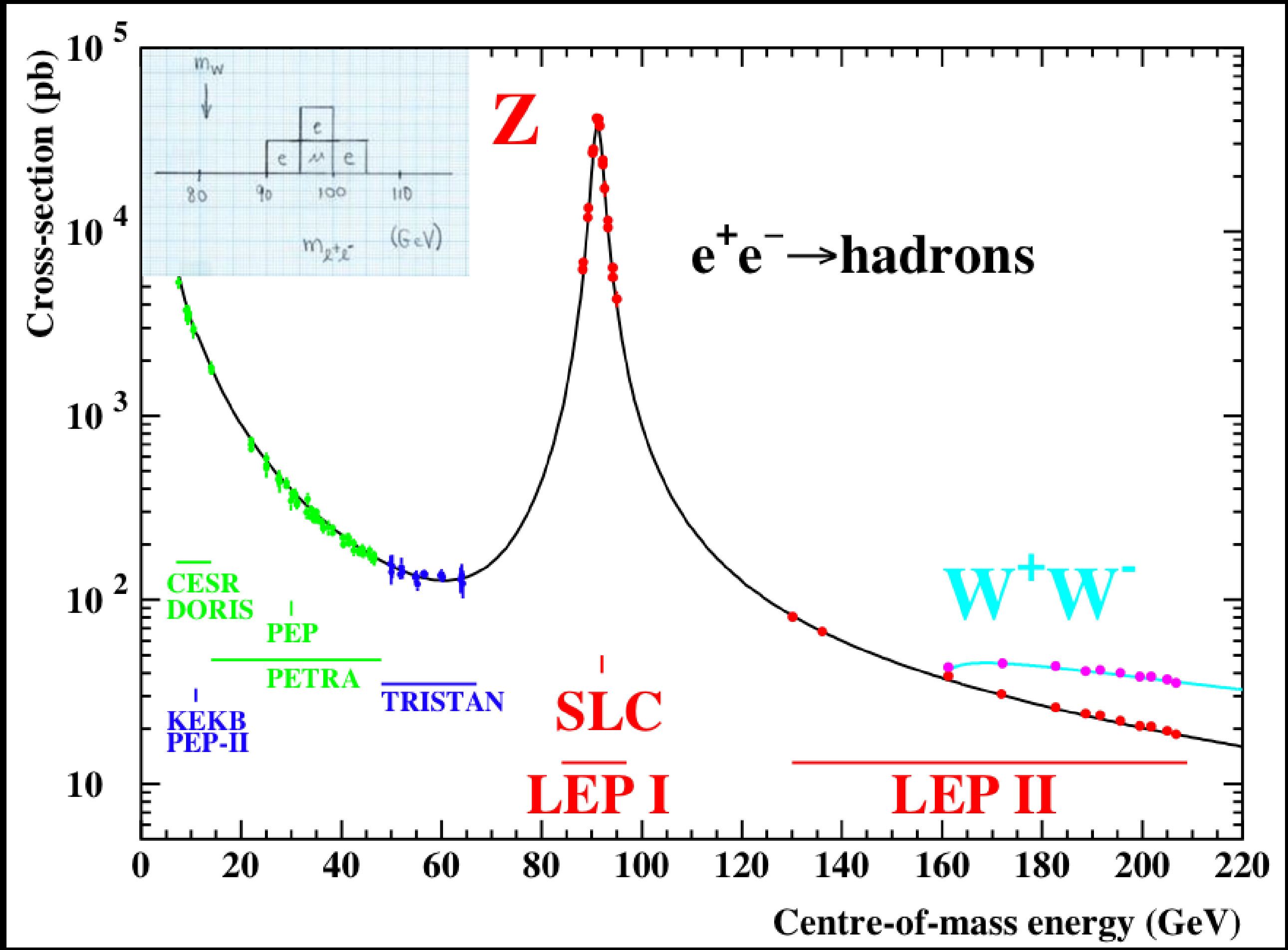
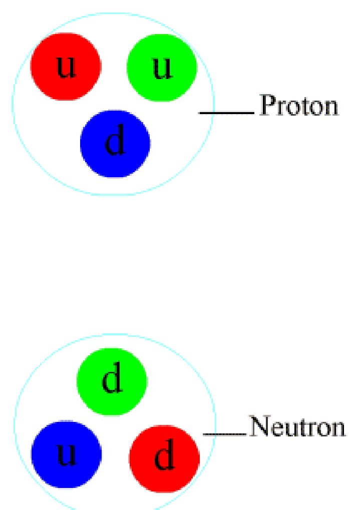


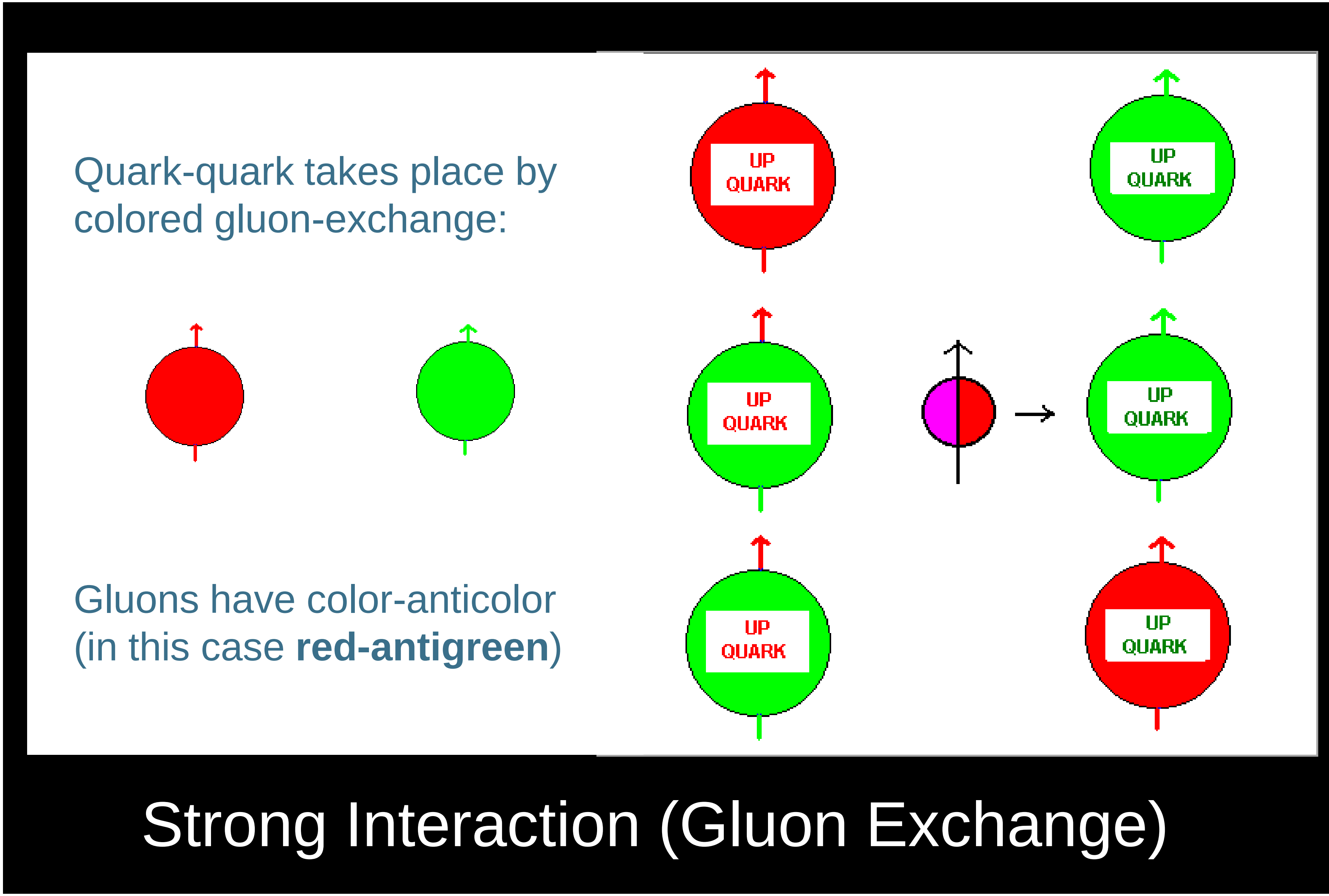

# Discovery of Gauge Bosons

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**)

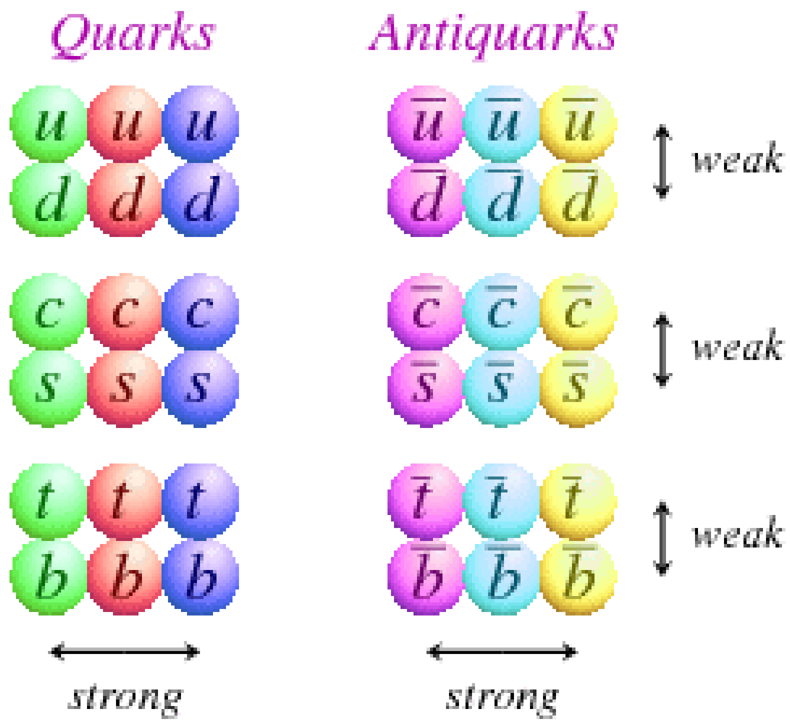


# Lecture 4 – **Particles** – Force Carriers

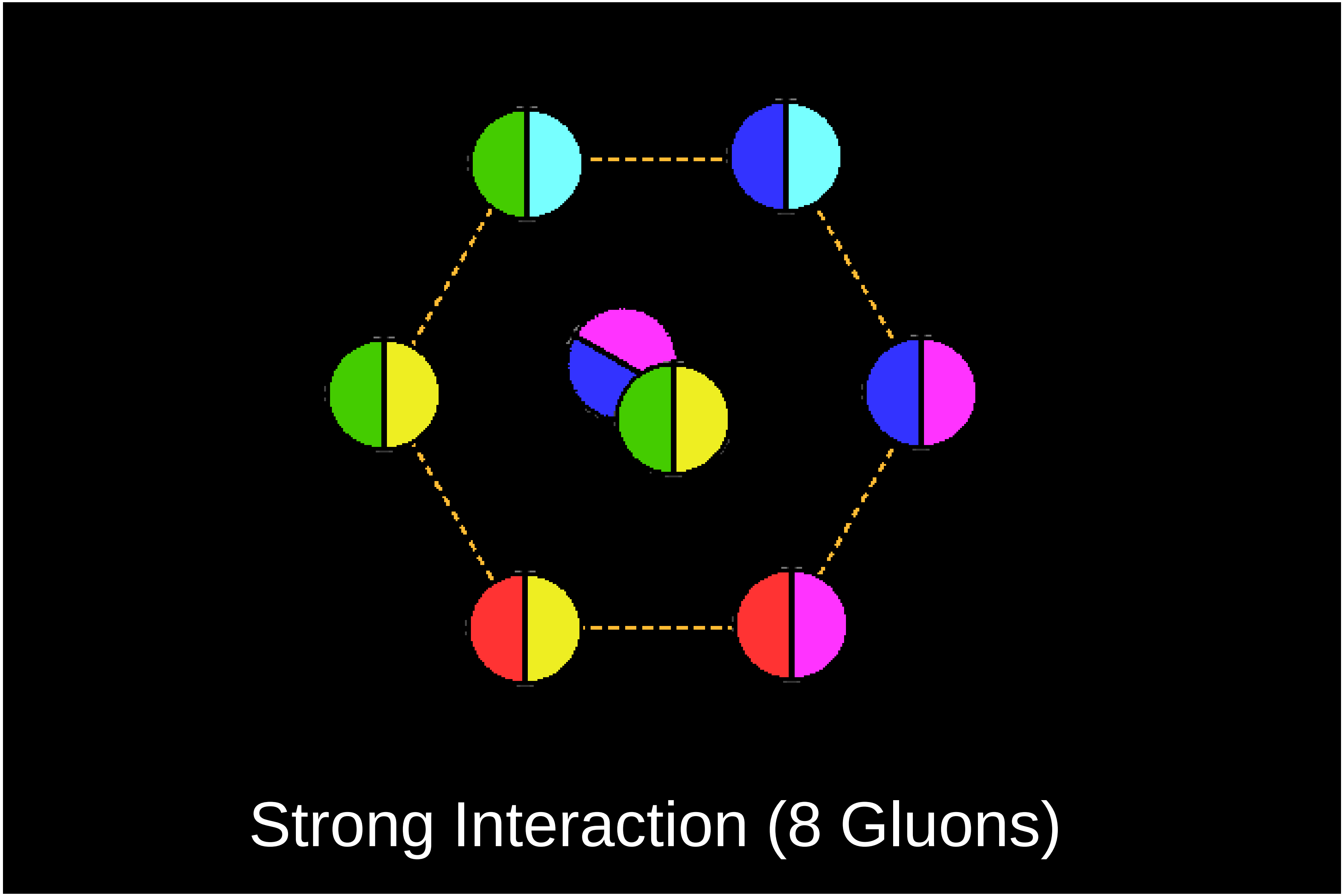


# Lecture 4 – **Particles** – Force Carriers

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

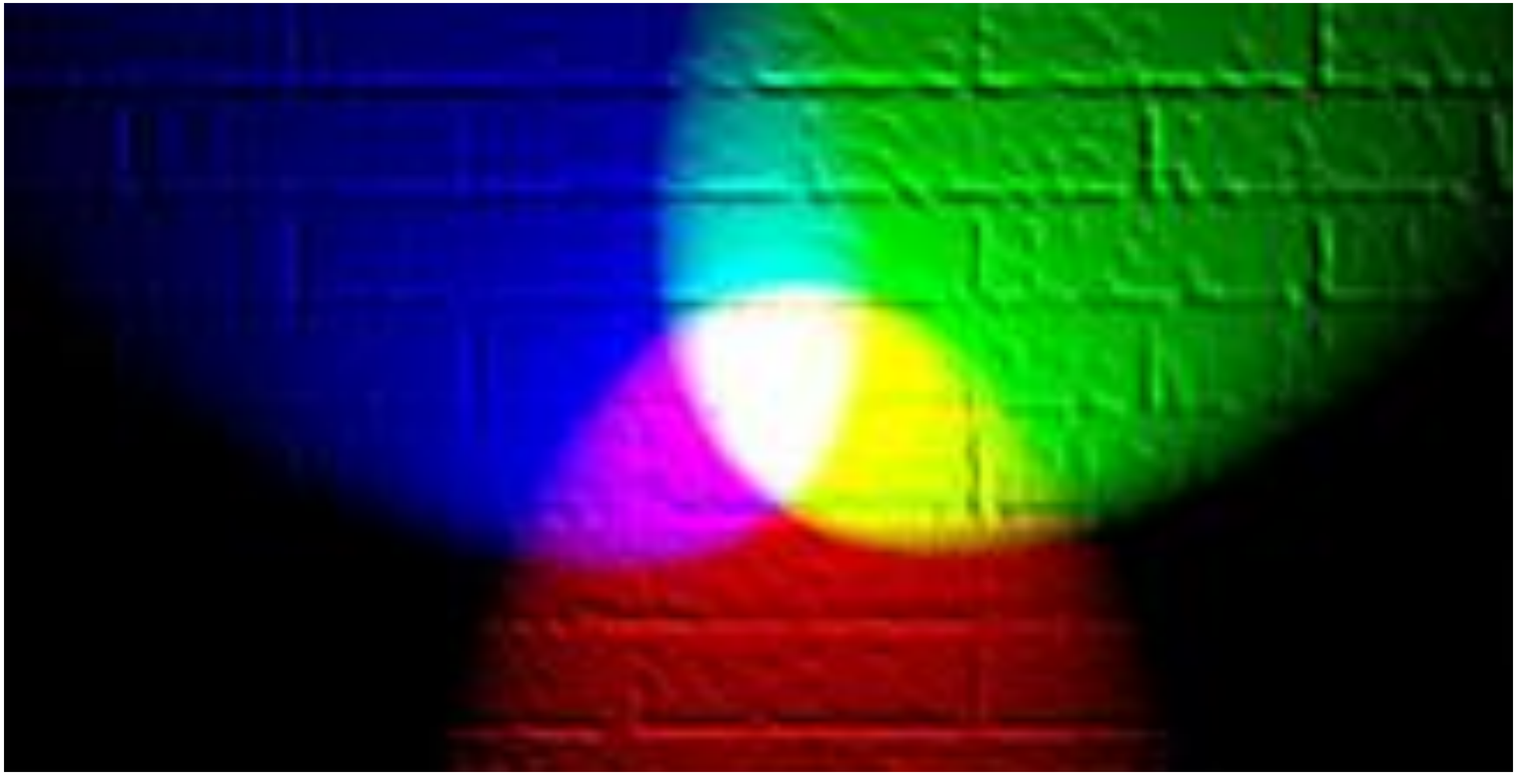



… in such a way that the color (-charge) is conserved (i.e. the overall does not change!)

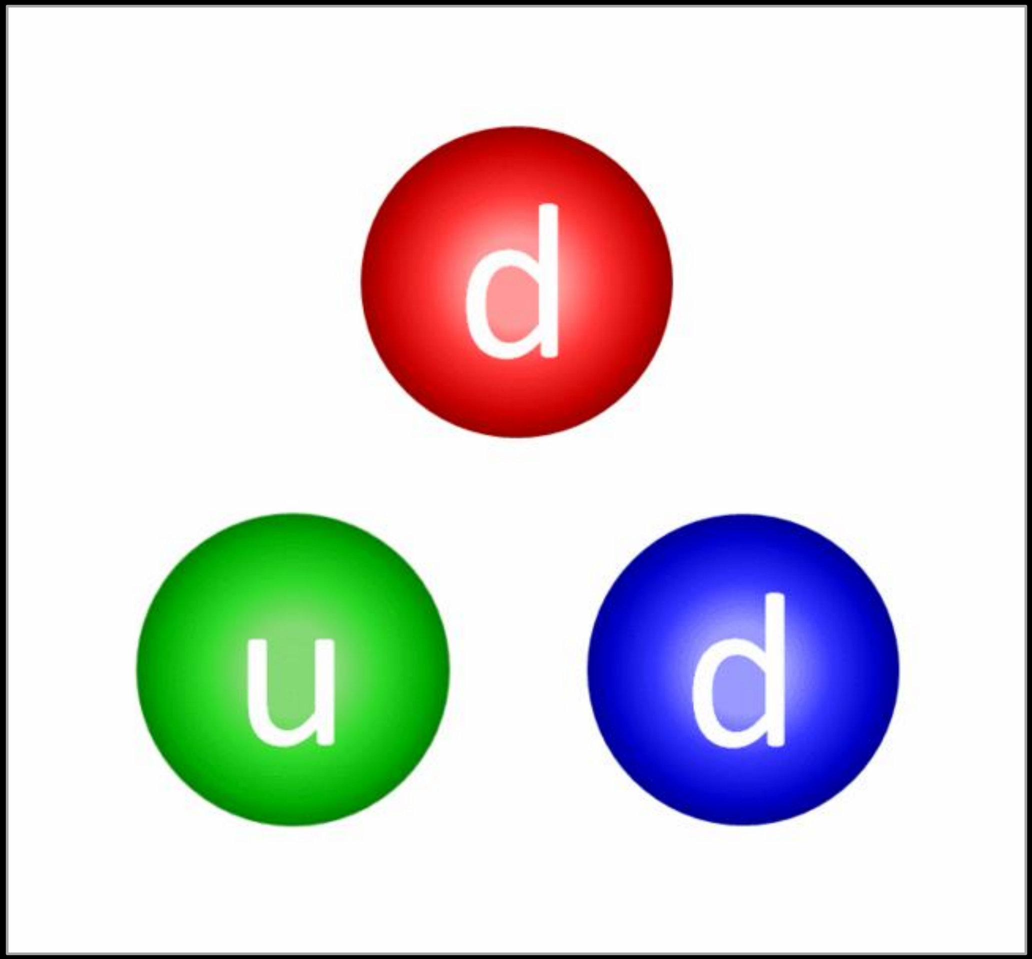

Strong Interaction (8 Gluons)

# Lecture 4 – **Particles** – Force Carriers

The **strong force** (interaction) only allows **bound systems** that don´t have color (-charge); they are **color-neutral** (“white”):

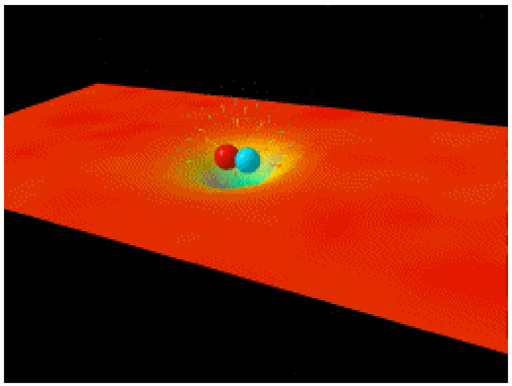


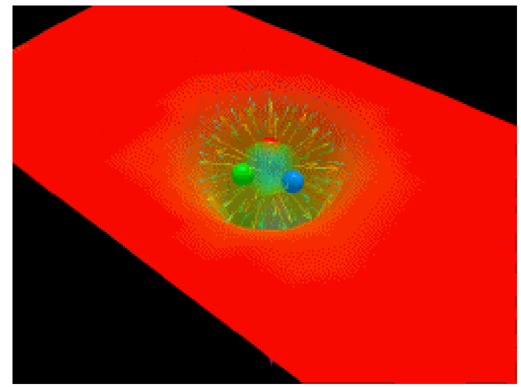
→ quark-antiquarks **(“mesons”);** 3 quarks **(“baryons”),** …

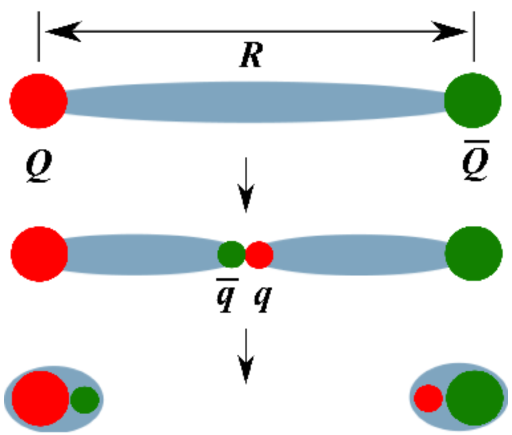


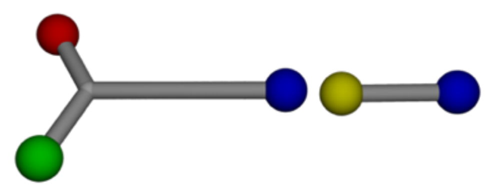

Bound System (e.g. Neutron)

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:



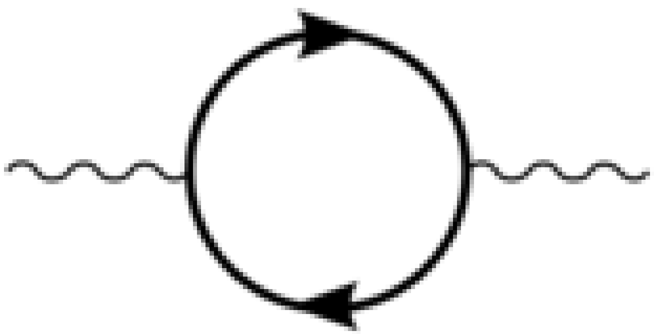




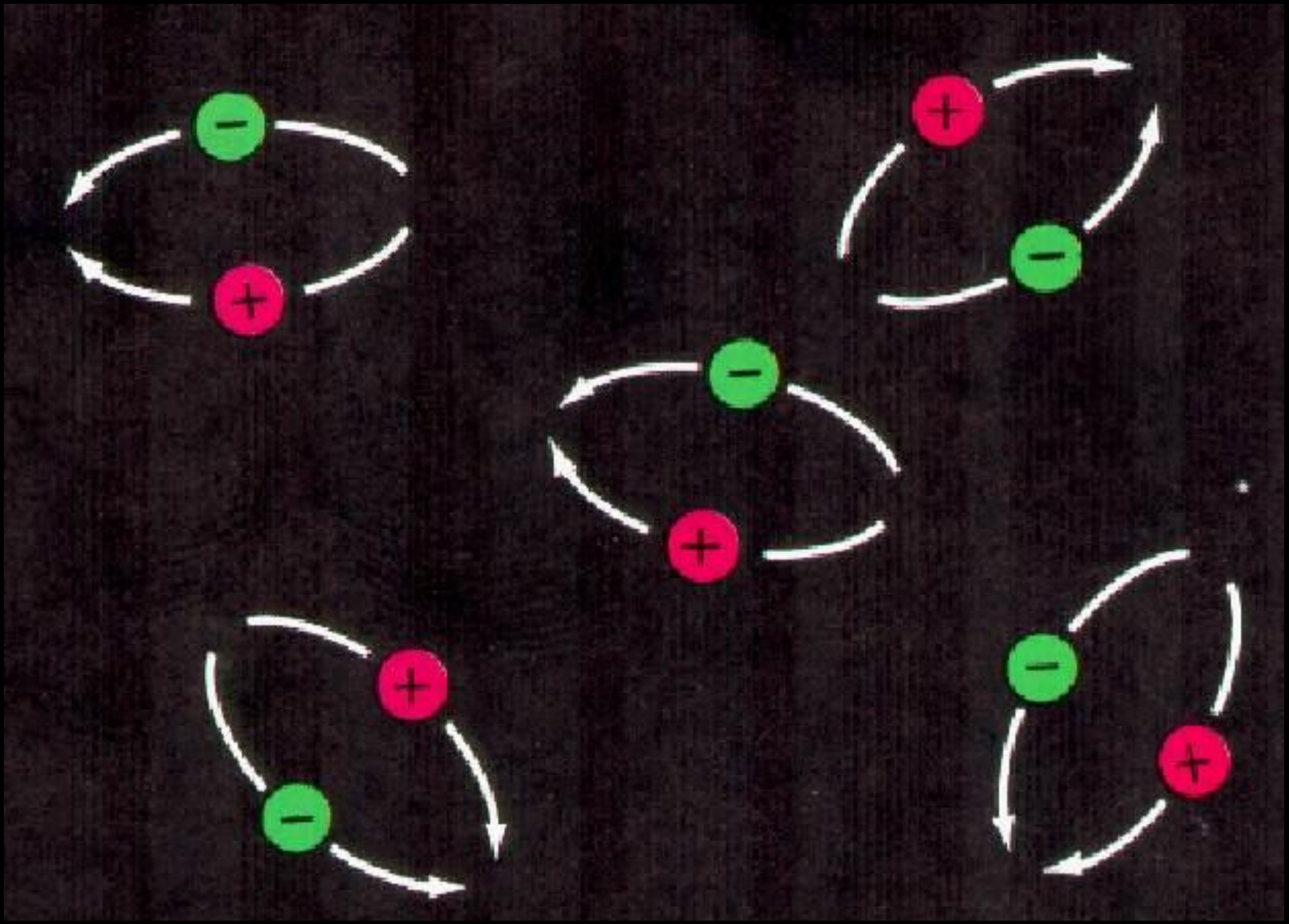



# Lecture 4 – **Particles** – Virtual Particles

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:

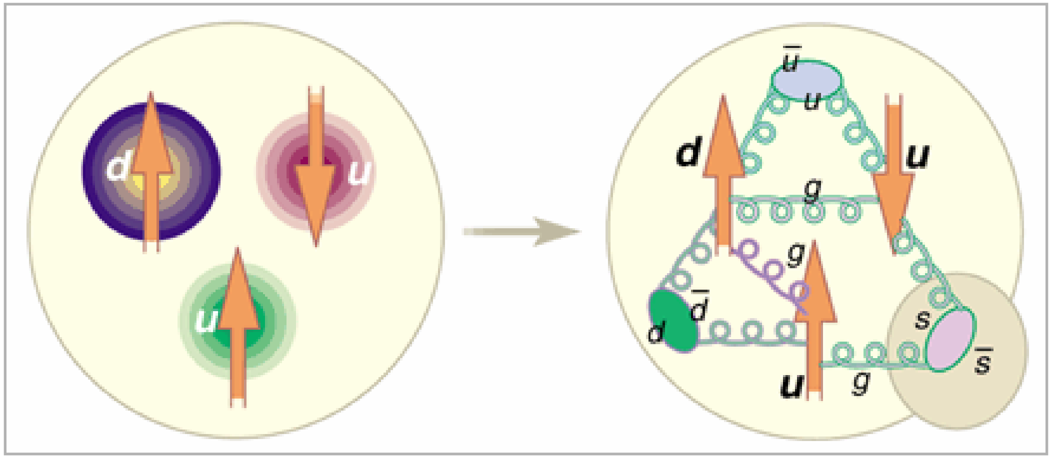


While the virtual particles are briefly part of our world they can interact with other particles, and that leads to a number of tests of the quantum-mechanical predictions about virtual particles: one example is the **Lamb-shift** in hydrogen (see: "atoms").

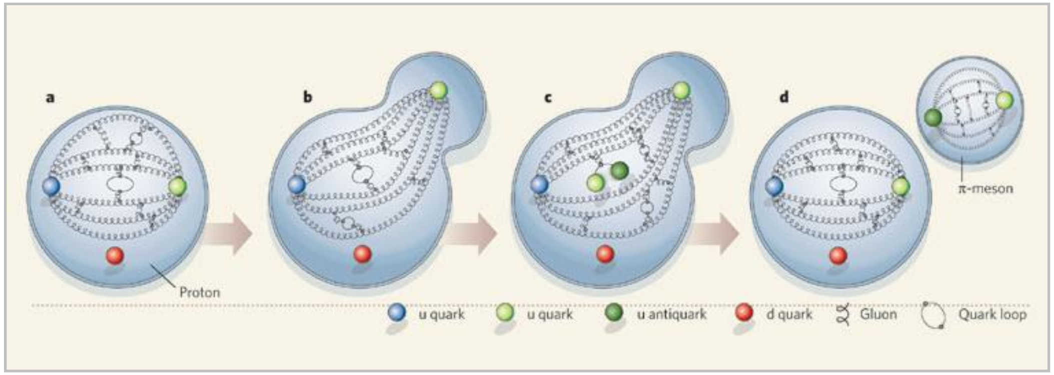


Vacuum Fluctuations

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




… and **meson production** can be "more realistically" pictured as:



# Lecture 4 – Particles – Bottomline

| Force | Electromagnetism | Weak Nuclear | Strong Nuclear | Gravity |
|---|---|---|---|---|
| Number of Bosons | 1 | 3 | 8 | 1 |
| Bosons | Photon | $W^+$, $W^-$, $Z^0$ | Gluon | Graviton** |
| Boson Mass* | 0 | 80 | 0 | 0 |
| Boson Charge | 0 | ±1, 0 | 0 | 0 |
| Acts on | Anything With Charge | Left Handed particle or Right Handed anti-particle with Flavour | Anything With Colour | Anything With Mass |

Forces

# Lecture 4 – Particles – Bottomline

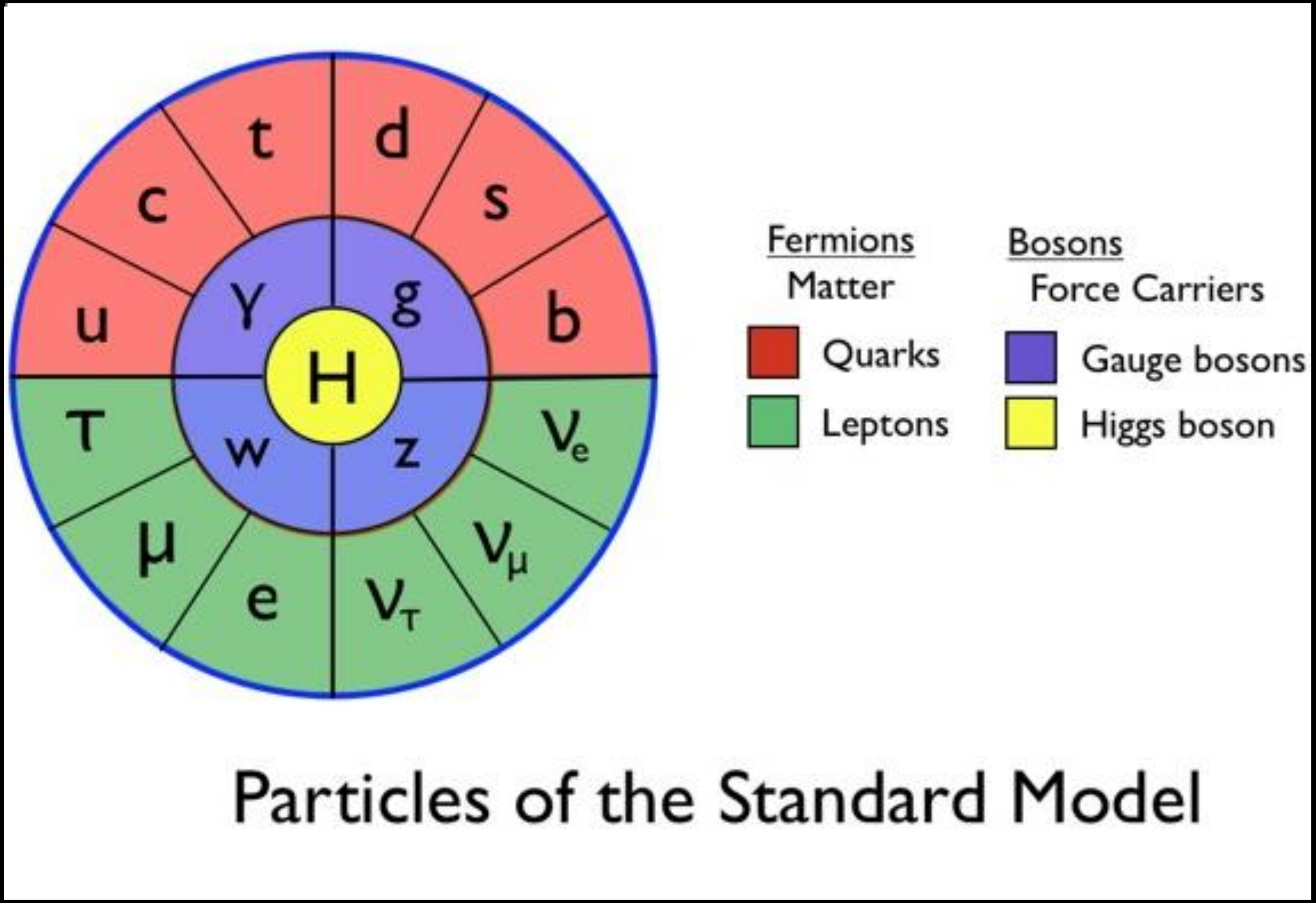
**Table S4.2 The Four Forces**

| 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

# Lecture 4 – Particles – Bottomline




Standard Model

# Lecture 4 – Particles – Bottomline

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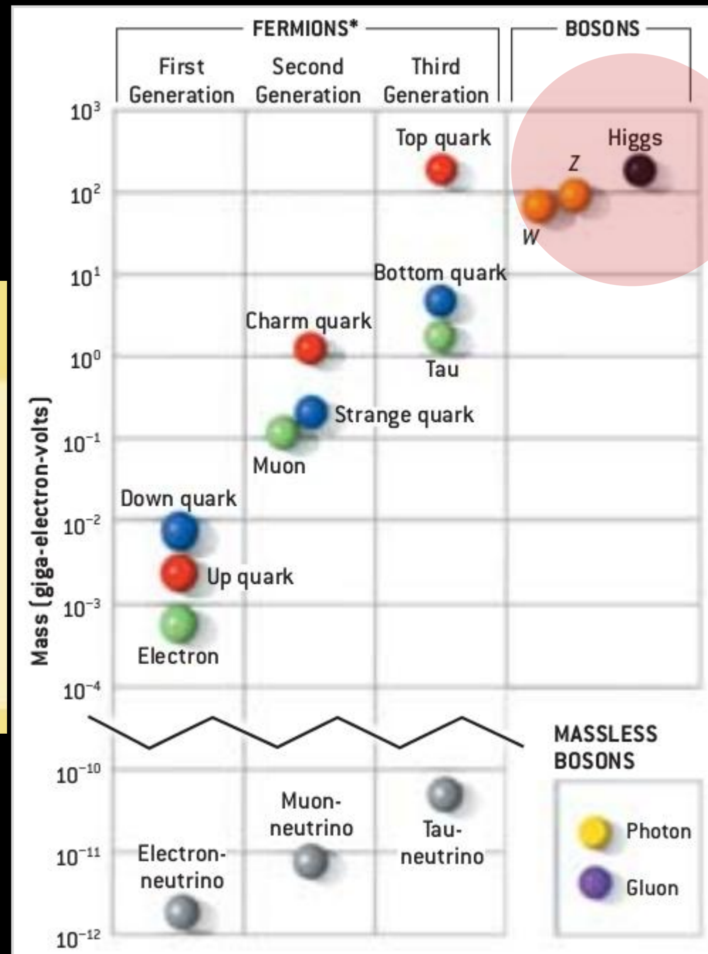
**Fermions**

| | |
|---|---|
| Leptons and Quarks | Spin = $\frac{1}{2}$ |
| Baryons (qqq) | Spin = $\frac{1}{2}, \frac{3}{2}, \frac{5}{2} \ldots$ |



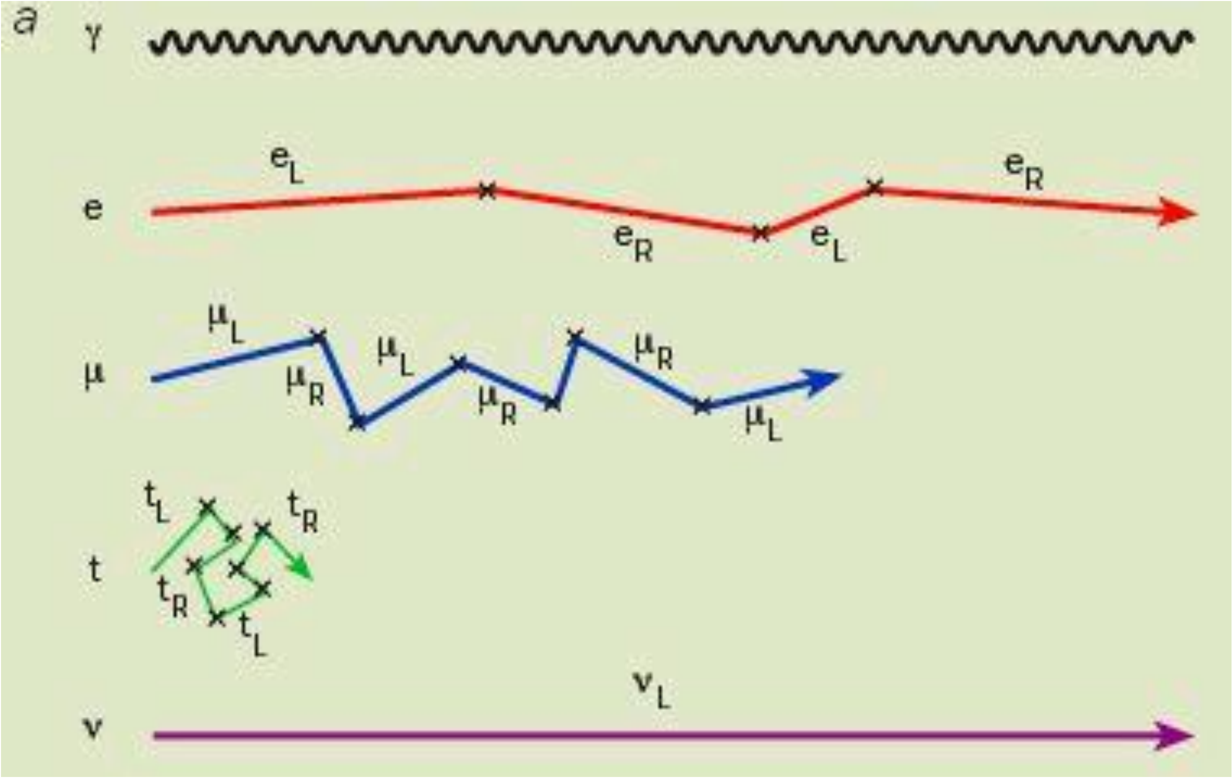

**Bosons**

| | |
|---|---|
| Spin = 1* | Force Carrier Particles |
| Spin = 0, 1, 2… | Mesons ($q\bar{q}$) |

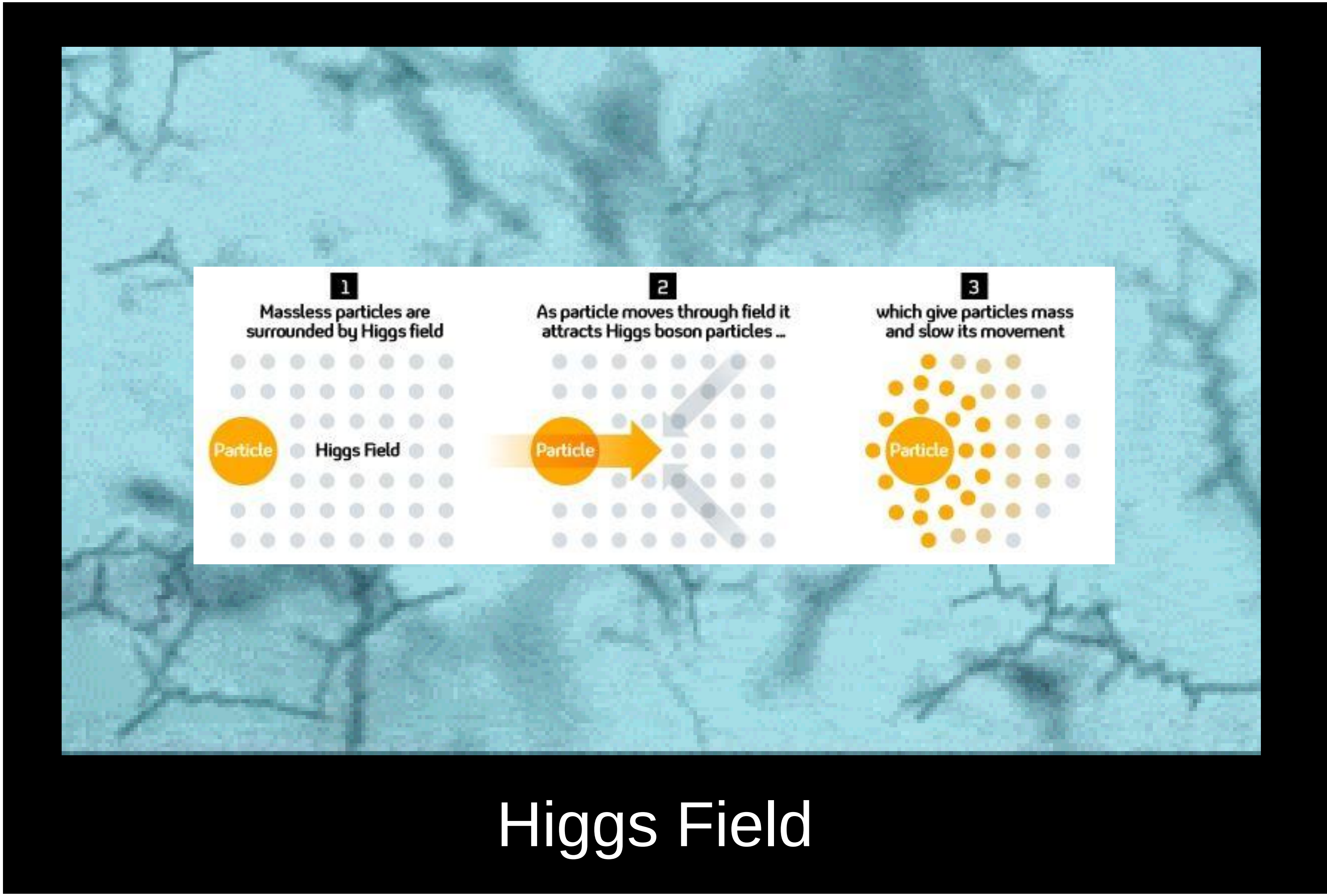
## Masses of Fundamental Particles

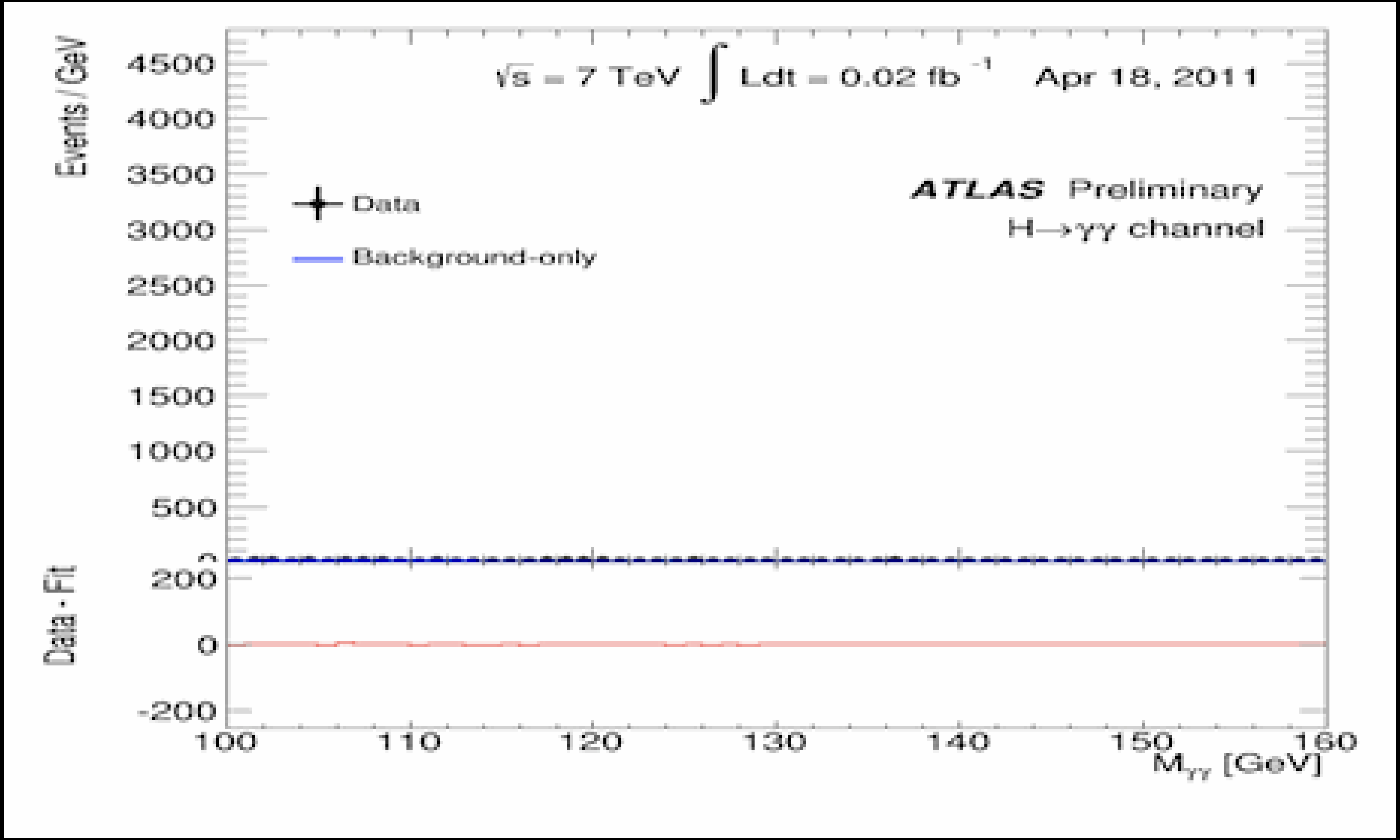
# Lecture 4 – Particles – Higgs Boson

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:



# Lecture 4 – **Particles** – Higgs Boson






# Higgs Discovery at CERN (July 4, 2012)

JÜLICH FORSCHUNGSZENTRUM

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

| | |
|---|---|
| 18 = (6 x 3) | quarks |
| 6 = (2 x 3) | leptons |
| 8 | gluons |
| 3 | gauge bosons |
| 1 | photon |
| 1 (at least) | Higgs boson |

+ anti-particles

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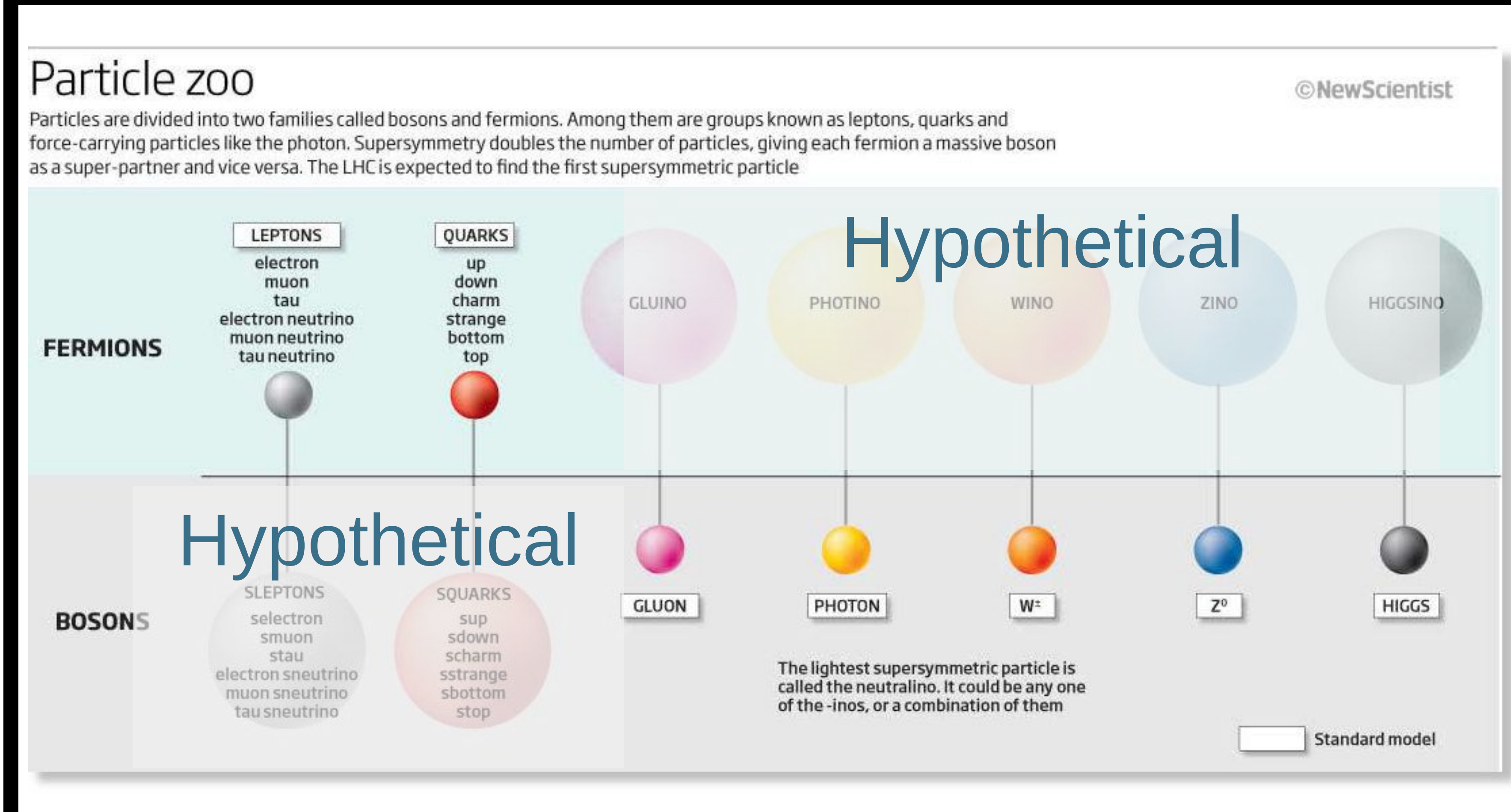
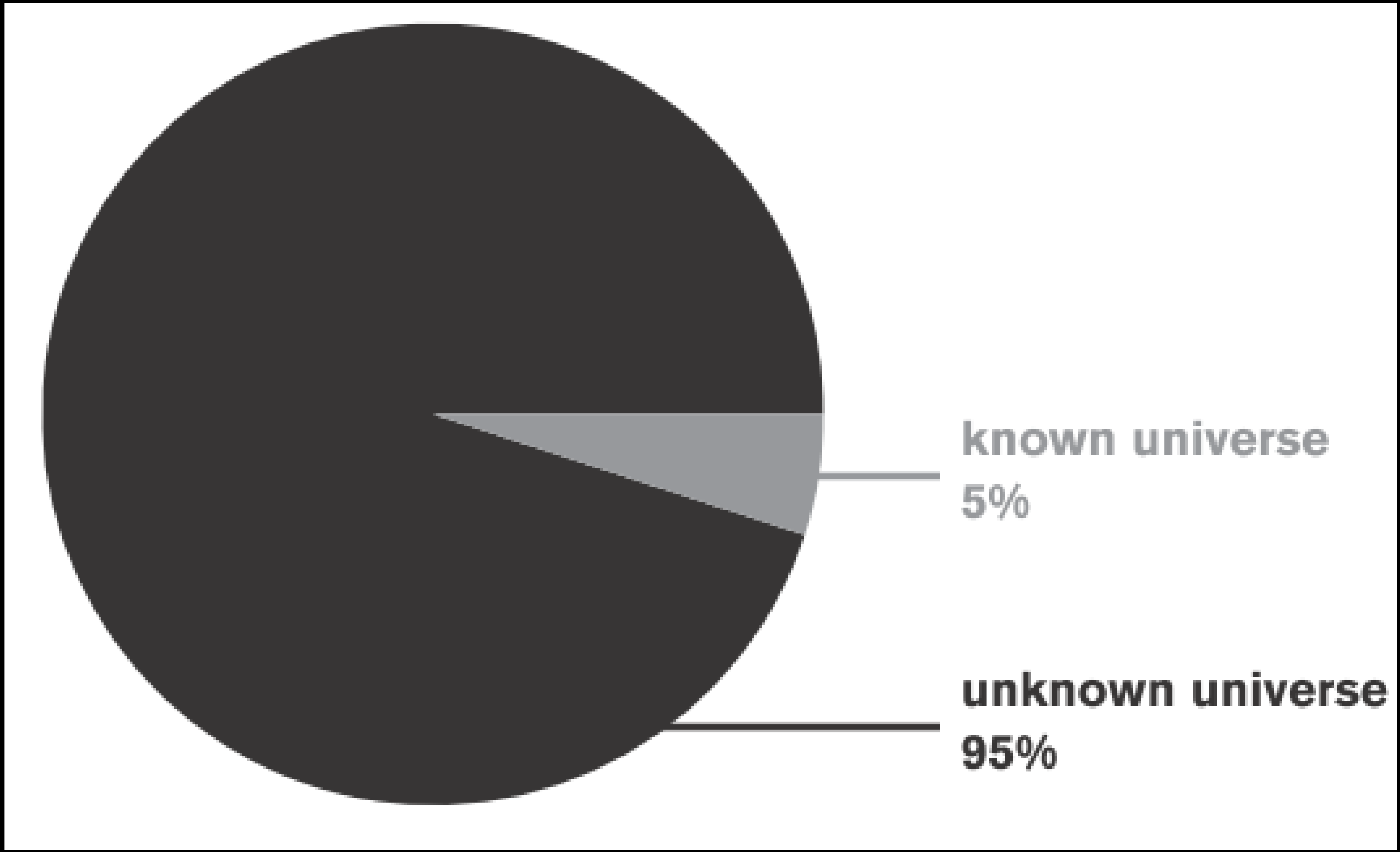
It does not attempt to explain **gravitation**; it needs to be modified in order to accommodate the fact that **neutrinos have mass**, and it cannot explain "**dark matter**" – there must be "**physics beyond the Standard Model**" (BSM) …



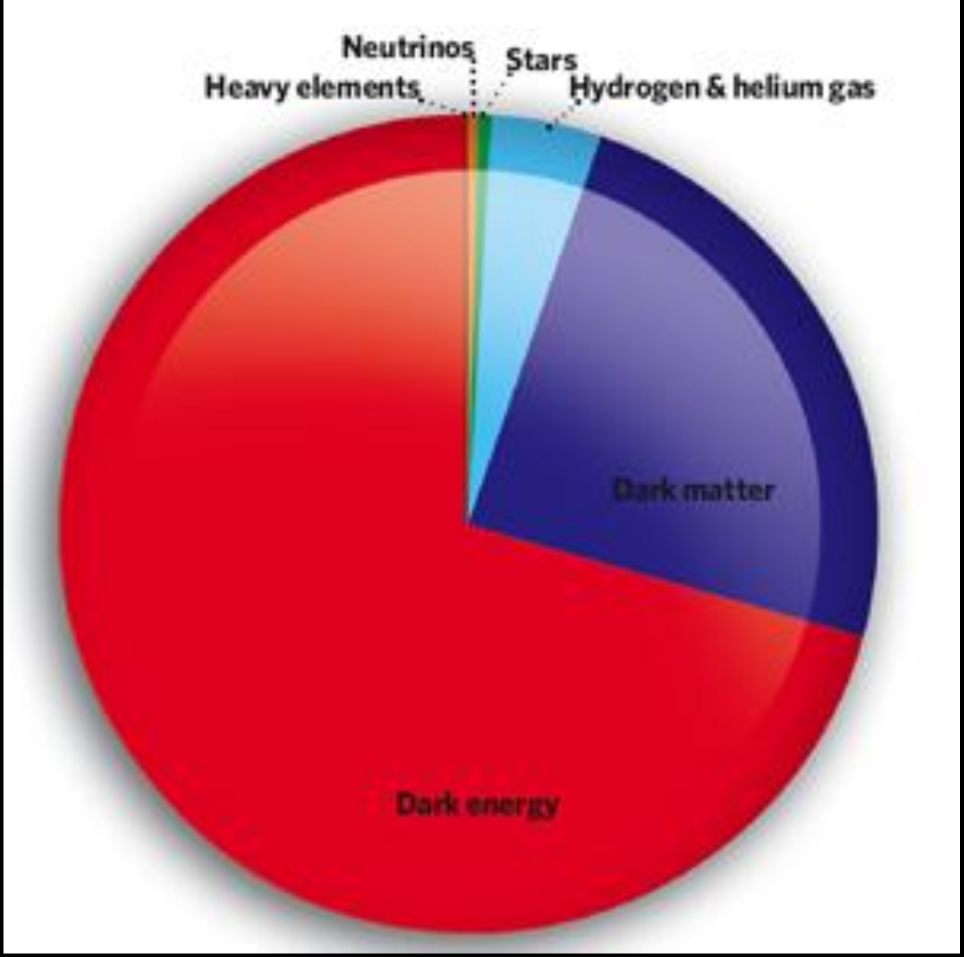

Supersymmetry (SUSY) ?

# Lecture 4 – Particles – BSM

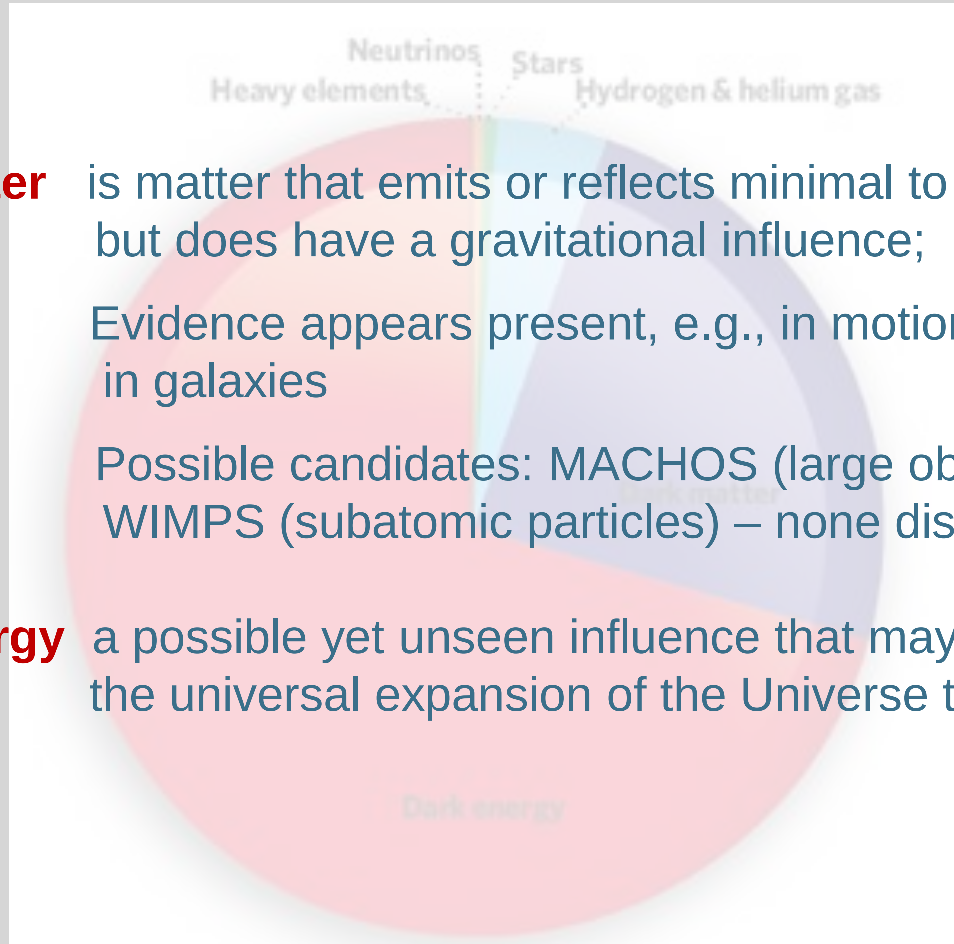



„Dark Universe“

# Lecture 4 – Particles – BSM




„Dark Universe“




**Dark Matter** is matter that emits or reflects minimal to no light, but does have a gravitational influence;

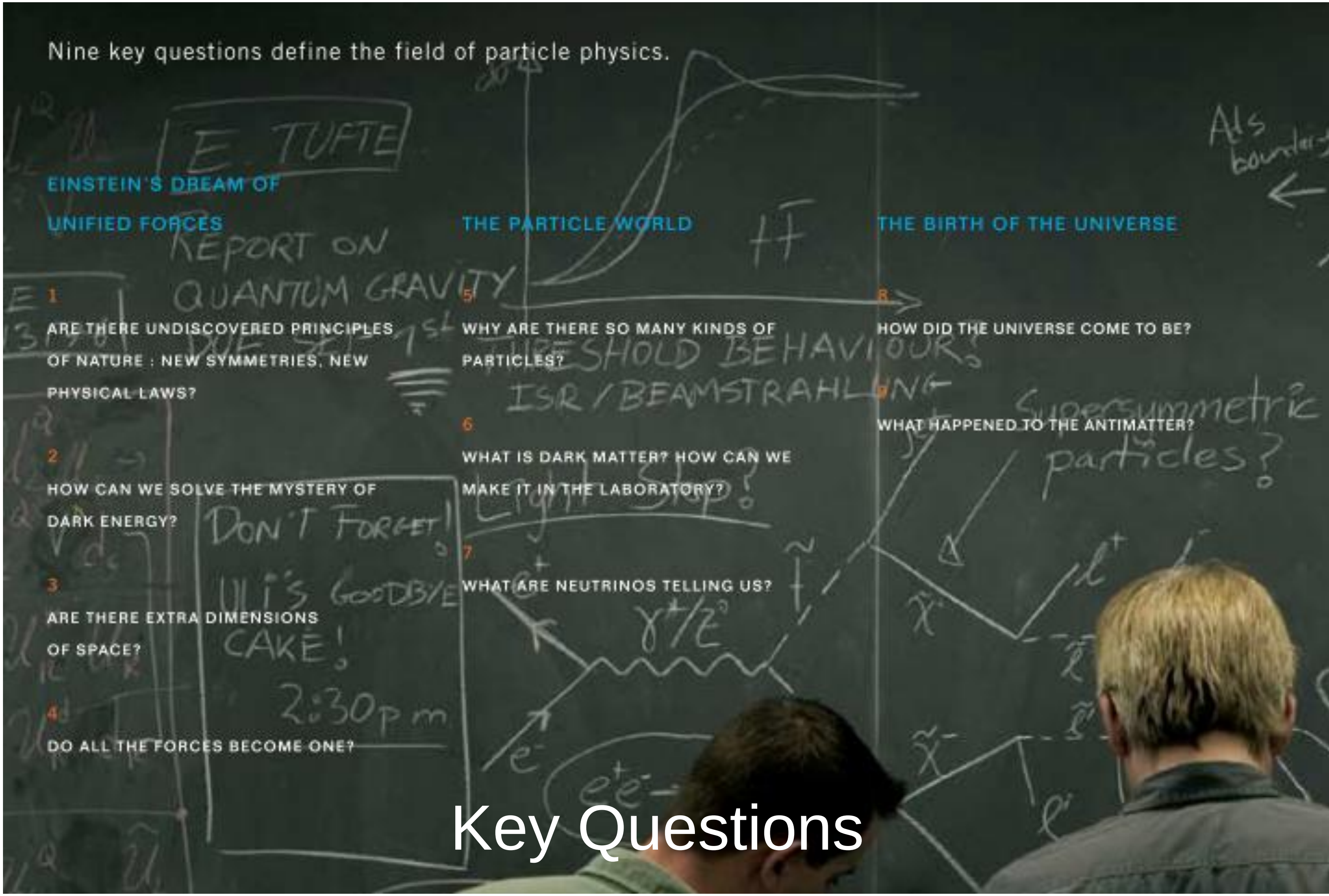
Evidence appears present, e.g., in motion of the stars in galaxies

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“

# Lecture 4 – Particles – BSM



"MAKE EVERYTHING AS SIMPLE AS POSSIBLE, BUT NOT SIMPLER."

Albert Einstein


გმადლობთ