INTRODUCTION TO STANDARD MODEL OF PARTICLE PHYSICS

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Web resources

- http://particleadventure.org/index.html
  - Especially designed for a very wide audience
  - A lot of links from this web page –please try as many as you can
- http://quarknet.fnal.gov/
  - Again, a lot of links from this web page – to modern experiments, and to more practical materials
- http://eddata.fnal.gov/lasso/quarknet_g_activities/detail.lasso?ID=18
  - This is specific link from the previous web page that I consider as a most important for implementation of an information about particle physics into your curriculum

What is particle physics or HEP?

- Particle physics is a branch of physics that studies the elementary constituents of matter and radiation, and the interactions between them. It is also called "high energy physics", because many elementary particles do not occur under normal circumstances in nature, but can be created and detected during energetic collisions of other particles, as is done in particle accelerators
- Particle physics is a journey into the heart of matter.
- Everything in the universe, from stars and planets, to us is made from the same basic building blocks - particles of matter. Some particles were last seen only billionths of a second after the Big Bang. Others form most of the matter around us today.
- Particle physics studies these very small building block particles and works out how they interact to make the universe look and behave the way it does

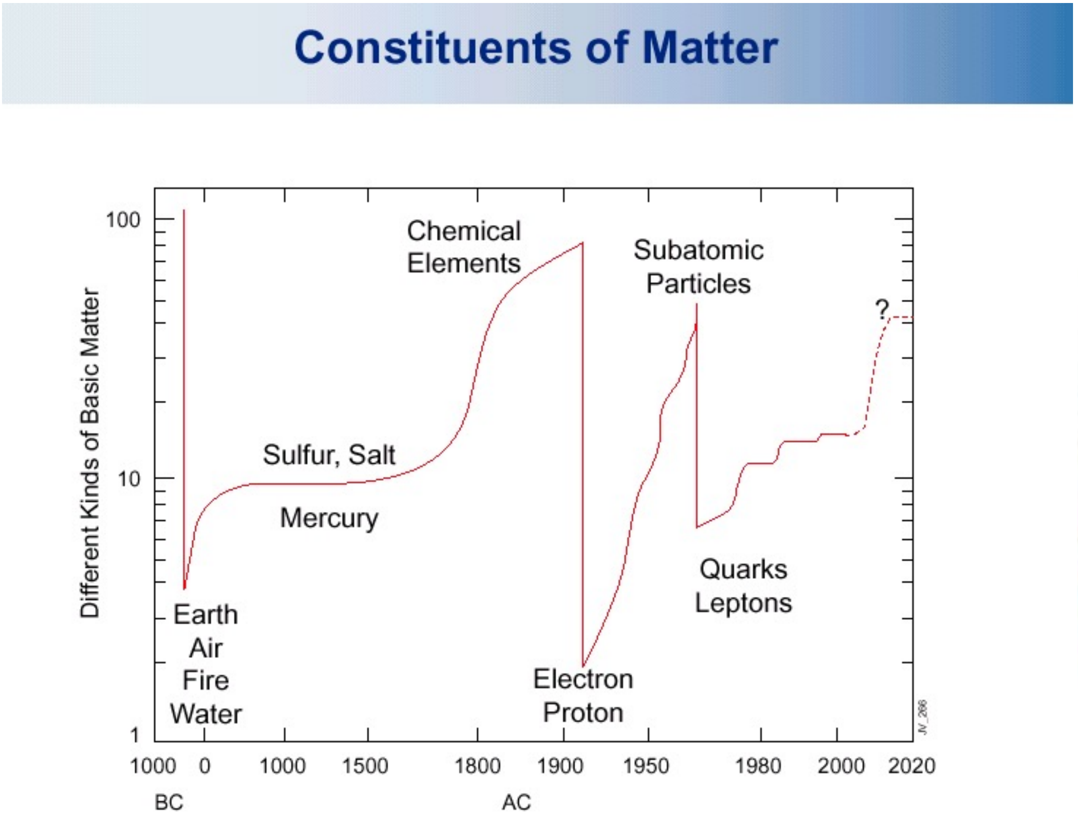
What is the universe made of?

- A very old question, and one that has been approached in many ways
- The only reliable way to answer this question is by directly enquiring of nature, through experiments
  - not necessarily a “natural human activity”, but perhaps the greatest human invention
- While it is often claimed that humans display a natural curiosity, this does not always seem to translate into a natural affinity for an experimental approach
  - Despite hundreds of years of experience, science is not understood, and not particularly liked, by many people
  - often tolerated mainly because it is useful
  - Something to think about, especially when we are trying to explain scientific projects that do not, a priori, seem to be useful

Experiment has taught us:

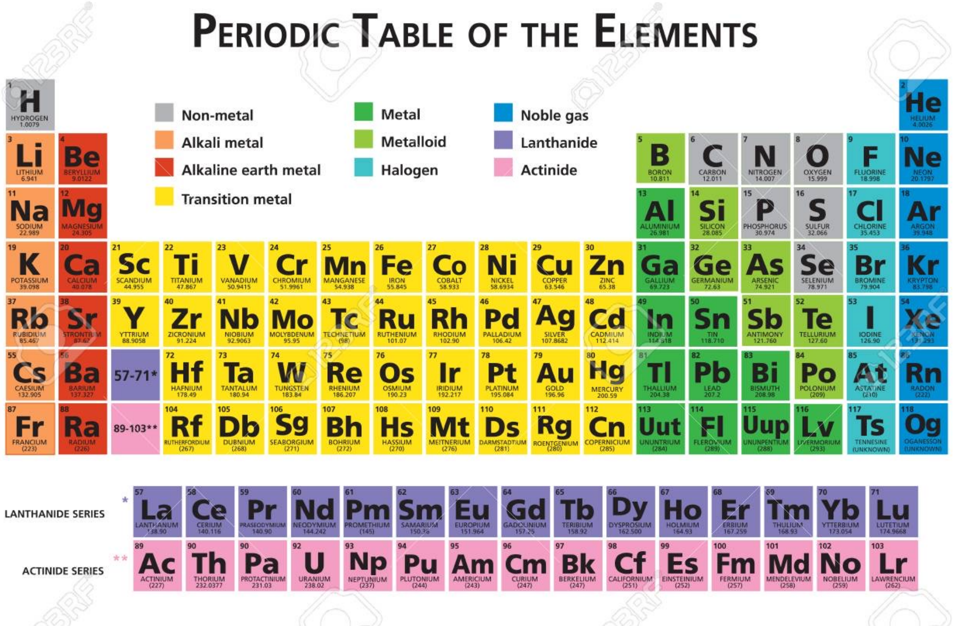
- Complex structures in the universe are made by combining simple objects in different ways
  - Periodic Table
- Apparently diverse phenomena are often different manifestations of the same underlying physics
  - Orbits of planets and apples falling from trees
- Almost everything is made of small objects that like to stick together
  - Particles and Forces
- Quantum mechanics taught us that everyday intuition is not necessarily a good guide

History of constituents of matter



The Periodic Table of Chemical Elements

- Atoms are grouped in families which present similar properties.
- This symmetry suggests a structure with simpler constituents.

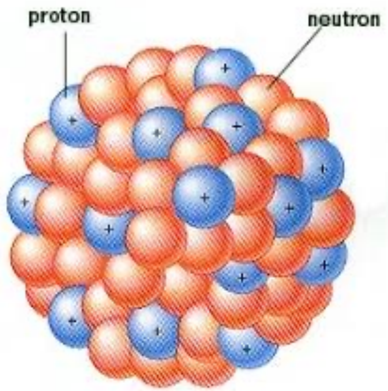


- Atoms reacts through chemical reaction
- More than 100 atoms known (H, He, Fe ..
- The internal structure is not well known

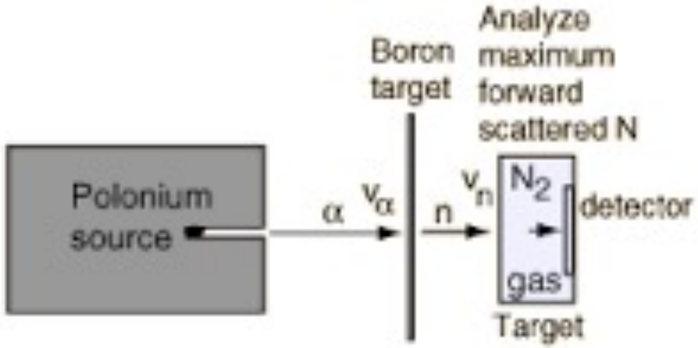
A work a century in the making

From the discovery of the electron in 1886,

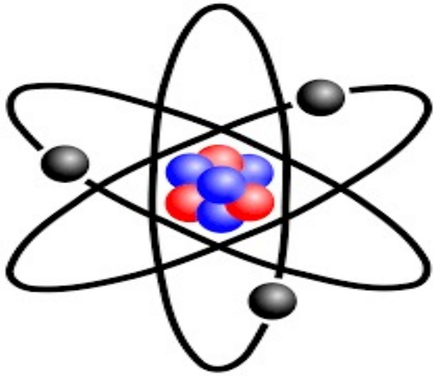
the nucleus in 1911 to



the neutron in 1932

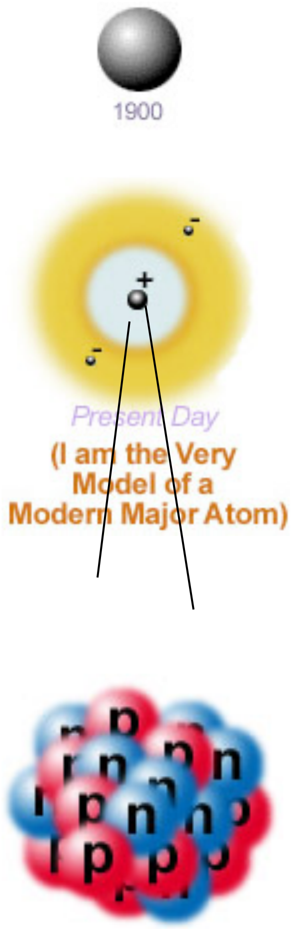


the particles that compose an atom



History of the particle physics

- Modern particle physics began in the early 20th century as an exploration into the structure of the atom. The discovery of the atomic nucleus in the gold foil experiment of Geiger, Marsden, and Rutherford was the foundation of the field. The components of the nucleus were subsequently discovered in 1919 (the proton) and 1932 (the neutron). In the 1920s the field of quantum physics was developed to explain the structure of the atom. The binding of the nucleus could not be understood by the physical laws known at the time. Based on electromagnetism alone, one would expect the protons to repel each other. In the mid-1930s, Yukawa proposed a new force to hold the nucleus together, which would eventually become known as the strong nuclear force. He speculated that this force was mediated by a new particle called a meson.



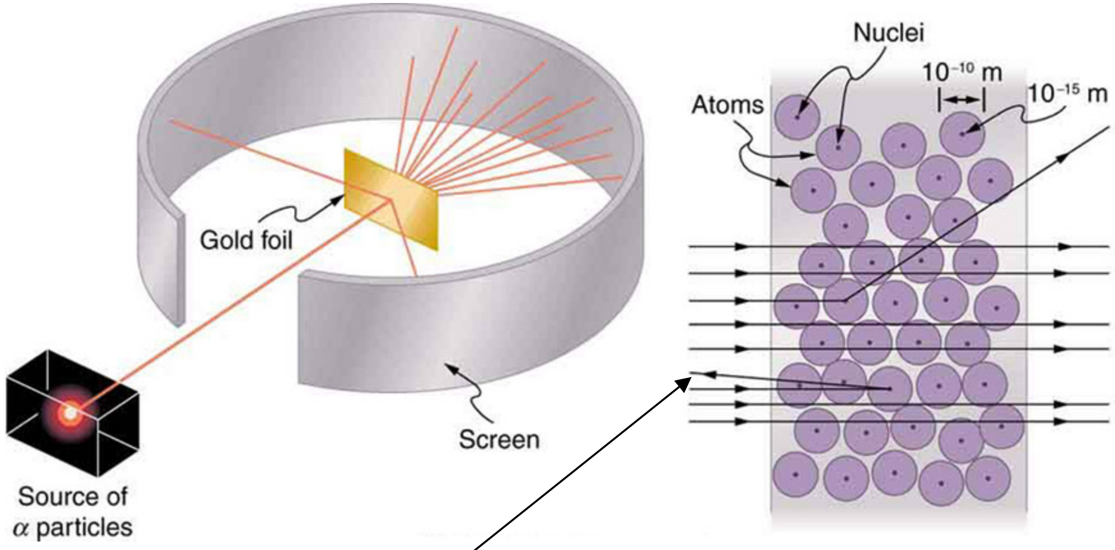
Search for fundamental particles

- Also in the 1930s, Fermi postulated the neutrino as an explanation for the observed energy spectrum of β-decay, and proposed an effective theory of the weak force. Separately, the positron and the muon were discovered by Anderson. Yukawa's meson was discovered in the form of the pion in 1947. Over time, the focus of the field shifted from understanding the nucleus to the more fundamental particles and their interactions, and particle physics became a distinct field from nuclear physics.
- Throughout the 1950-1960's, a huge variety of additional particles was found in scattering experiments. This was referred to as the "particle zoo".

Are protons and neutrons fundamental?

- To escape the "Particle Zoo," the next logical step was to investigate whether these patterns could be explained by postulating that all composite particles are made of other particles. These particles were named Quarks
- As far as we know, quarks are like points in geometry They're not made up of anything else.
- After extensively testing this theory, scientists now suspect that quarks and the electron (and a few othe things we'll see in a minute) are fundamental.
- An elementary particle or *fundamental particle* is a particle not known to have substructure; that is, it is not known to be made up of smaller particles. If an elementary particle truly has no substructure, then it is one of the basic particles of the universe from which all larger particles are made.

Rutherford Scattering Experiments



Hard central core!

Like firing a cannon ball at a paper towel and having the ball bounce back

Most of the atom is empty space.

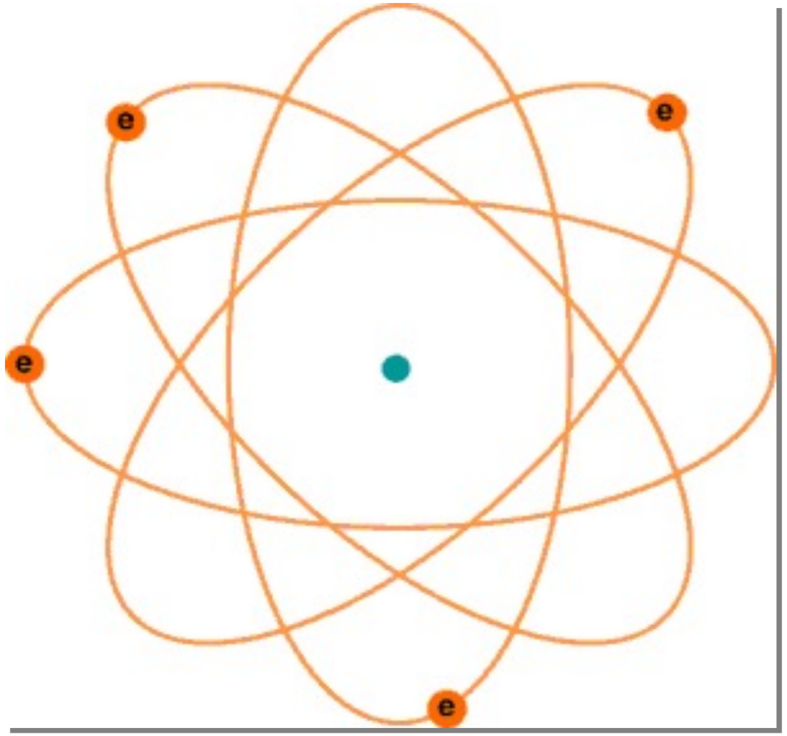
The alpha particle is probing the structure of the gold in the foil. This basic idea has been repeated many times over the last hundred years to further probe the structure of matter.

The atom has a rich structure

- Eventually, it was realized that the atom is **not** elementary:
  - it consists of a positively charged nucleus and negatively charged electrons.

- The properties of outermost electrons in atoms give rise to chemistry and biochemistry, with all of its complexity!

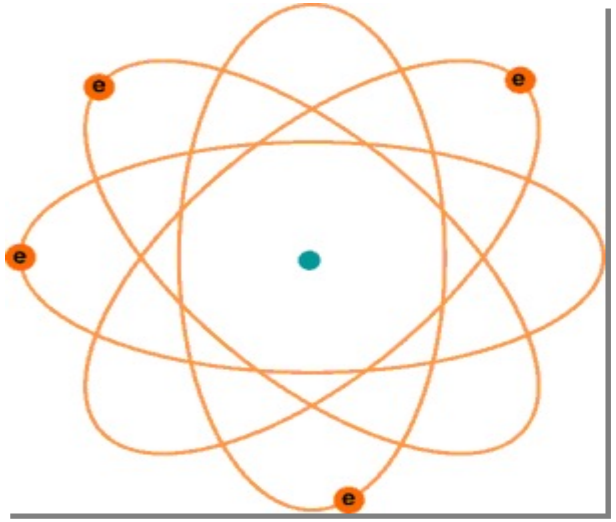
- The electron, as far as we know, is elementary

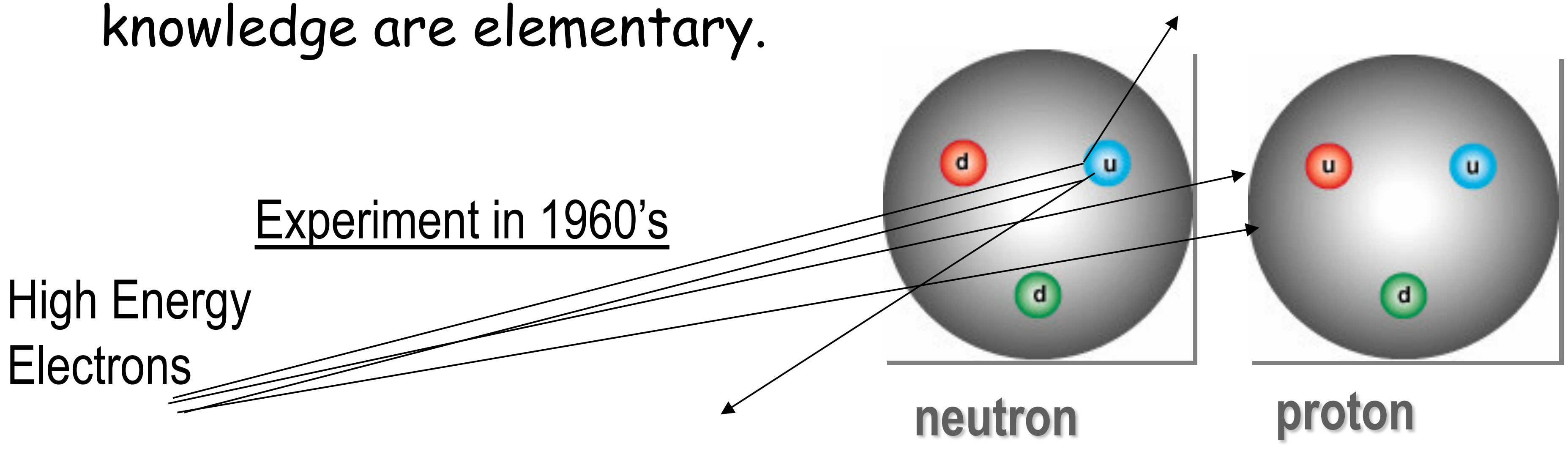


If the nucleus were as big as a baseball, then the entire atom's diameter would be greater than the length of **thirty** soccer fields!

Is the nucleus elementary, too?

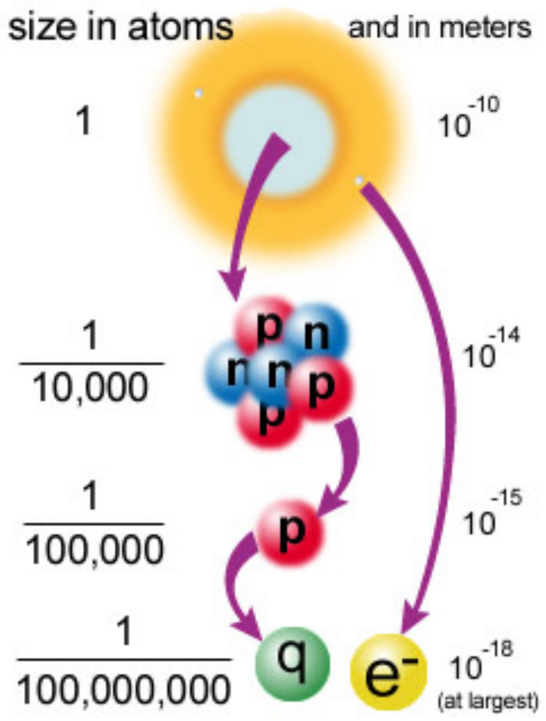
- Unlike the electron, the nucleus is not structureless! It consists of protons and neutrons.
- But protons and neutrons are **not** elementary, either!
- They consist of **quarks**, which to the best of our knowledge are elementary.





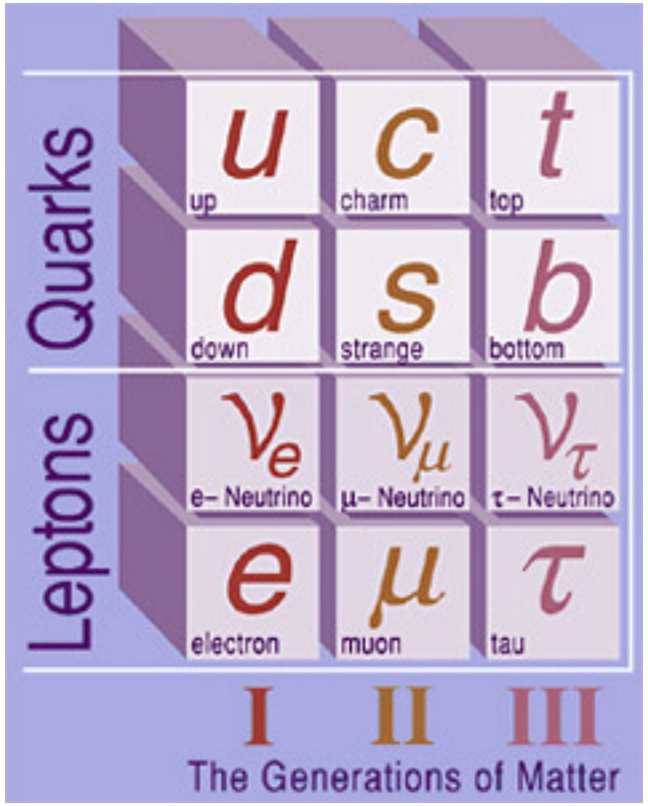
Scale of the atom

- While an atom is tiny, the nucleus is ten thousand times smaller than the atom and the quarks and electrons are at least ten thousand times smaller than that. We don't know exactly how small quarks and electrons are; they are definitely smaller than 10^{-18} meters, and they might literally be points, but we do not know.
- It is also possible that quarks and electrons are not fundamental after all, and will turn out to be made up of other, more fundamental particles.



Fundamental blocks

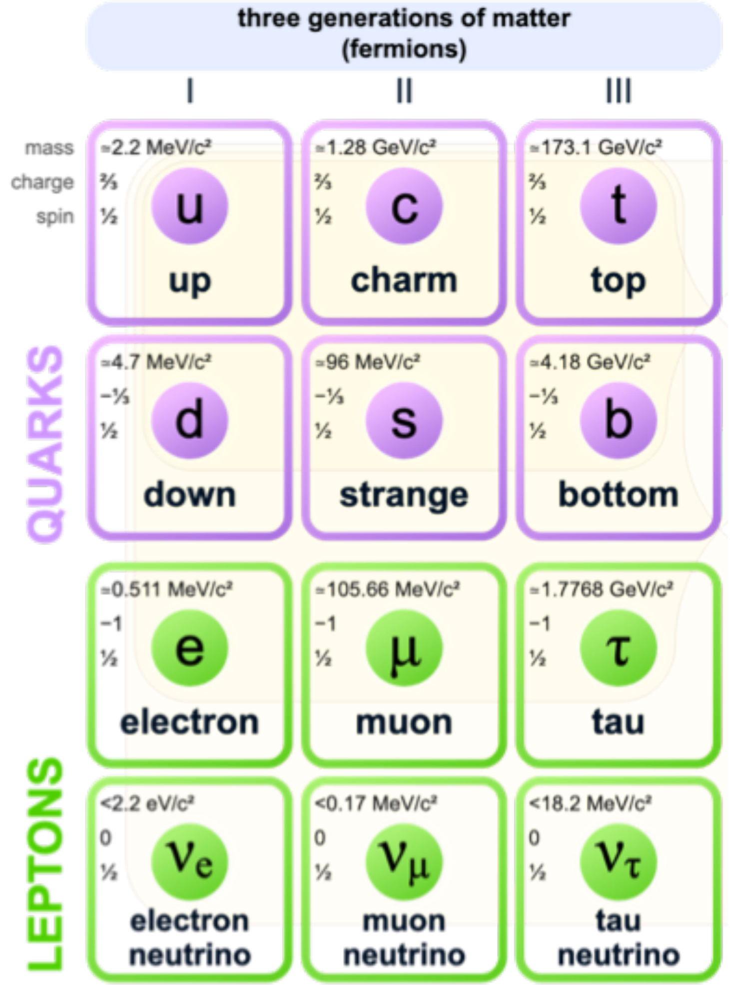
- Two types of point like constituents



- Plus force carriers (will come to them later)
- For every type of matter particle we've found, there also exists a corresponding antimatter particle, or antiparticle.
- Antiparticles look and behave just like their corresponding matter particles, except they have opposite charges.

Generations of quarks and leptons

- Note that both quarks and leptons exist in three distinct sets. Each set of quark and lepton charge types is called a generation of matter (charges +2/3, -1/3, -1, and 0 as you go down each generation). The generations are organized by increasing mass.
- All visible matter in the universe is made from the first generation of matter particles -- up quarks, down quarks, and electrons. This is because all second and third generation particles are unstable and quickly decay into stable first generation particles.
- Spin is a value of angular momentum assigned to all particles
- Classification of particles according to spin:
  - **Fermions: have spin ½**
  - **Bosons: : have spin 1**
  - **Scalar particles: have spin = 0**



Quarks

- Most of the matter we see around us is made from protons and neutrons, which are composed of up and down quarks.
- There are six quarks, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.)
- Quarks have the unusual characteristic of having a fractional electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called color charge, which we will discuss later.

Quantum numbers of quarks

Type of quark	Charge	Spin
u (up)	+2/3	1/2
d (down)	-1/3	1/2
s (strange), S = 1	-1/3	1/2
c (charm), C =1	+2/3	1/2
b (bottom), B = 1	-1/3	1/2
t (top)	+2/3	1/2

Fractional charges and unseen quarks

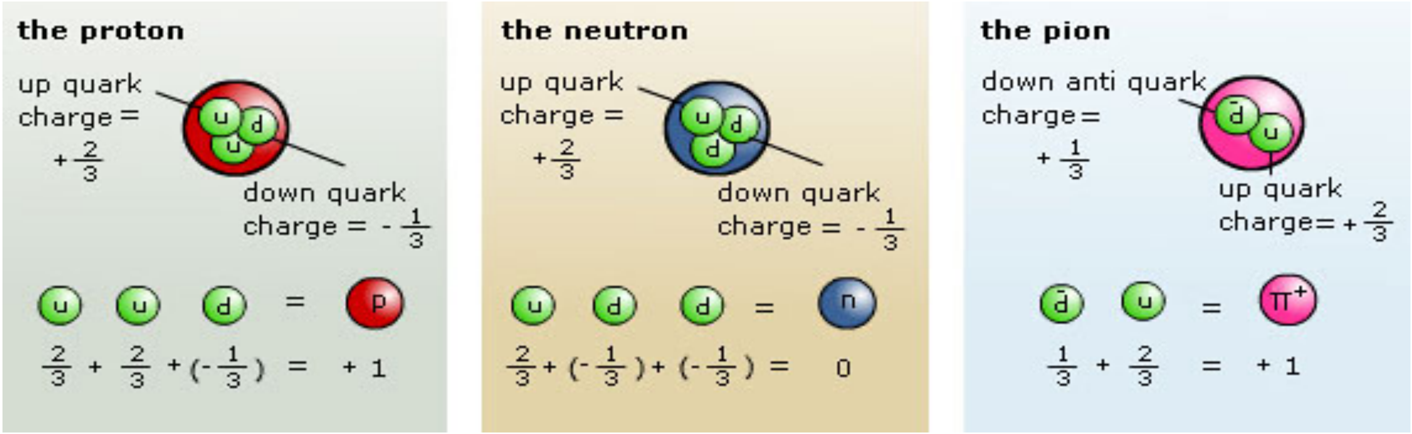
- Murray Gell-Mann and George Zweig proposed the idea of the quarks to find some order in the chaos of particles:
  - baryons are particles consisting of three quarks (qqq),
  - mesons are particles consisting of a quark and anti-quark (q q-bar).

qqq	Q	S	Bar.
uuu	2	0	Δ^{++}
uud	1	0	Δ^{+}
udd	0	0	Δ^{0}
ddd	-1	0	Δ^{-}
uus	1	-1	Σ^{*+}
uds	0	-1	Σ^{*0}
dds	-1	-1	Σ^{*-}
uss	0	-2	Ξ^{*0}
dss	-1	-2	Ξ^{*0}
sss	-1	-3	Ω^{-}

qqbar	Q	S	Mes.
uubar	0	0	π^{0}
udbar	1	0	π^{+}
ubar d	-1	0	π^{-}
ddbar	0	0	η
uus	1	-1	K^{+}
uds	0	-1	K^{0}
dds	-1	-1	K^{-}
uss	0	-2	K^{0}
dss	-1	-2	η'

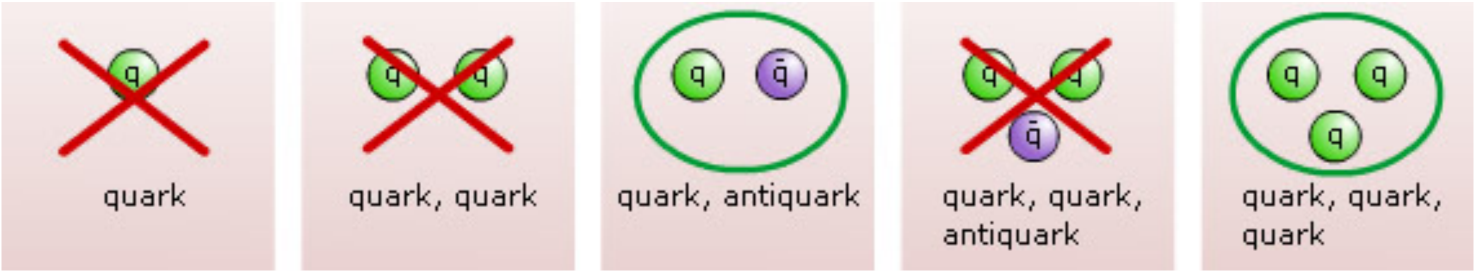
Fractional charges and unseen quarks

- Problems arose with introducing quarks:
  - Fractional charge – never seen before
  - Quarks are not observable
  - Not all quark combinations exist in nature
- It appears to violate the Pauli exclusion principle
  - Originally was formulated for two electrons.
  - Later realized that the same rule applies to all particles with spin ½.
  - Consider Δ^{++}(uuu): is supposed to consist of three u quarks in the same state – inconsistent with Pauli principle!



Color charge of quarks (1)

- So one had to explain why one saw only those combinations of quarks and antiquarks that had integer charge, and why no one ever saw a q, qq, qqqbar, or countless other combinations.



- Gell-Mann and others thought that the answer had to lie in the nature of forces between quarks. This force is the so-called "strong" force, and the new charges that feel the force are called "color" charges, even though they have nothing to do with ordinary colors.

Color charge of quarks (2)

- They proposed that quarks can have three color charges. This type of charge was called "color" because certain combinations of quark colors would be "neutral" in the sense that three ordinary colors can yield white, a neutral color.
- Only particles that are color neutral can exist, which is why only qqq and q q-bar are seen.
- This also resolve a problem with Pauli principle

Just like the combination of red and blue gives purple, the combination of certain colors give white. One example is the combination of red, green and blue.

Summary so far

- There are 6 quarks and 6 leptons which we believe are fundamental blocks of nature
- They have antiparticles, i.e. the same quantum numbers except electric charge
- Quarks have fractional electric charges
- A new charge for quarks has been introduced: this charge is color

Forces

Although there are apparently many types of forces in the Universe, they are all based on four fundamental forces: Gravity, Electromagnetic force, Weak force and Strong force.

The strong and weak forces only act at very short distances and are responsible for holding nuclei together.

The electromagnetic force acts between electric charges.
The gravitational force acts between masses.

Pauli's exclusion principle is responsible for the tendency of atoms not to overlap each other, and is thus responsible for the "stiffness" or "rigidness" of matter, but this also depends on the electromagnetic force which binds the constituents of every atom.

Forces

All other forces are based on these four. For example, friction is a manifestation of the electromagnetic force acting between the atoms of two surfaces, and the Pauli exclusion principle, which does not allow atoms to pass through each other.

The forces in springs modeled by Hooke’s law are also the result of electromagnetic forces and the exclusion principle acting together to return the object to its equilibrium position.

Centrifugal forces are acceleration forces which arise simply from the acceleration of rotating frames of reference

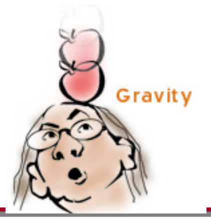
Forces at the fundamental level

- The particles (quarks and leptons) interact through different "forces", which we understand as due to the exchange of "field quanta" known as "gauge bosons".

Electromagnetism (QED)	**Photon (γ) exchange**
Strong interactions (QCD)	**Gluon (g) exchange**
Weak interactions	**W and Z bosons exchange**
Gravitational interactions	**Graviton (G) exchange ?**

Four fundamental interactions

- There are four fundamental interactions between particles:

	Interaction	Mediating particle	Who feels this force
	Strong	Gluon (g)	Quarks and gluons
	Electromagnetic	Photon (γ)	Everything electrically charged
	Weak	W and Z	Quarks, leptons, photons, W, Z
	Gravity	Graviton (?)	Everything!

Exchange forces

- You can think about forces as being analogous to the following situation:
  - **Two people are standing in boats. One person moves their arm and is pushed backwards; a moment later the other person grabs at an invisible object and is driven backwards. Even though you cannot see a basketball, you can assume that one person threw a basketball to the other person because you see its effect on the people.**

- It turns out that all interactions which affect matter particles are due to an exchange of force carrier particles, a different type of particle altogether. These particles are like basketballs tossed between matter particles (which are like the basketball players). What we normally think of as "forces" are actually the effects of force carrier particles on matter particles.

Exchange forces

- We see examples of attractive forces in everyday life (such as magnets and gravity), and so we generally take it for granted that an object's presence can just affect another object. It is when we approach the deeper question, "How can two objects affect one another without touching?" that we propose that the invisible force could be an exchange of force carrier particles. Particle physicists have found that we can explain the force of one particle acting on another to INCREDIBLE precision by the exchange of these force carrier particles.
- One important thing to know about force carriers is that a particular force carrier particle can only be absorbed or produced by a matter particle which is affected by that particular force. For instance, electrons and protons have electric charge, so they can produce and absorb the electromagnetic force carrier, the photon. Neutrinos, on the other hand, have no electric charge, so they cannot absorb or produce photons.

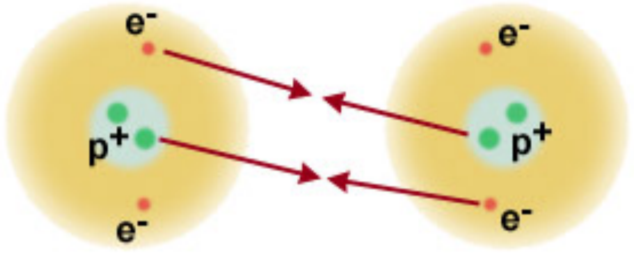
Electromagnetism

- The electromagnetic force causes like-charged things to repel and oppositely-charged things to attract. Many everyday forces, such as friction, are caused by the electromagnetic, or E-M force. For instance, the force that keeps us from falling through the floor is the electromagnetic force which causes the atoms making up the matter in our feet and the floor to resist being displaced.

- Photons of different energies span the electromagnetic spectrum of x rays, visible light, radio waves, and so forth.

Residual EM force

- Atoms usually have the same numbers of protons and electrons. They are electrically neutral, because the positive protons cancel out the negative electrons. Since they are neutral, what causes them to stick together to form stable molecules?
- The answer is a bit strange: we've discovered that the charged parts of one atom can interact with the charged parts of another atom. This allows different atoms to bind together, an effect called the residual electromagnetic force.
- So the electromagnetic force is what allows atoms to bond and form molecules, allowing the world to stay together and create the matter. All the structures of the world exist simply because protons and electrons have opposite charges!



Residual E-M force in action: the atoms are electrically neutral, but the electrons in one are attracted to the protons in another, and vice versa!

What about nucleus?

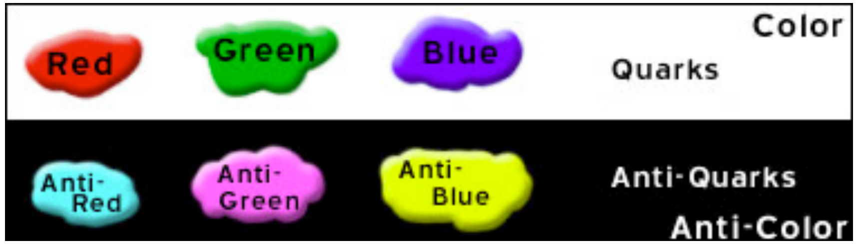
- We have another problem with atoms, though. What binds the nucleus together?
- The nucleus of an atom consists of a bunch of protons and neutrons crammed together. Since neutrons have no charge and the positively-charged protons repel one another, why doesn't the nucleus blow apart?
- We cannot account for the nucleus staying together with just electromagnetic force. What else could there be?

Strong interactions

- To understand what is happening inside the nucleus, we need to understand more about the quarks that make up the protons and neutrons in the nucleus.   Quarks have electromagnetic charge, and they also have an altogether different kind of charge called color charge. The force between color-charged particles is very strong, so this force is "creatively" called strong.
- The strong force holds quarks together to form hadrons, so its carrier particles are called gluons because they so tightly "glue" quarks together.
- Color charge behaves differently than electromagnetic charge. Gluons, themselves, have color charge, which is weird and not at all like photons which do not have electromagnetic charge. And while quarks have color charge, composite particles made out of quarks have no net color charge (they are color neutral). For this reason, the strong force only takes place on the really small level of quark interactions.

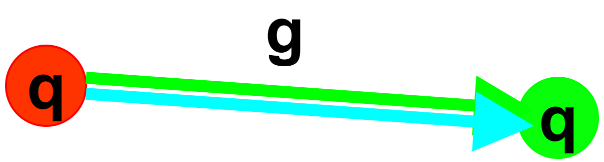
Color charge

- There are three color charges and three corresponding anticolor (complementary color) charges. Each quark has one of the three color charges and each antiquark has one of the three anticolor charges. Just as a mix of red, green, and blue light yields white light, in a baryon a combination of "red," "green," and "blue" color charges is color neutral, and in an antibaryon "antired," "antigreen," and "antiblue" is also color neutral. Mesons are color neutral because they carry combinations such as "red" and "antired.“
- Because gluon-emission and -absorption always changes color, and -in addition - color is a conserved quantity - *gluons can be thought of as carrying a color and an anticolor charge*. Since there are nine possible color-anticolor combinations we might expect nine different gluon charges, but the mathematics works out such that there are only *eight combinations*. Unfortunately, there is no intuitive explanation for this result.



Color charge (2)

- When two quarks are close to one another, they exchange gluons and create a very strong color force field that binds the quarks together. The force field gets stronger as the quarks get further apart. Quarks constantly change their color charges as they exchange gluons with other quarks.



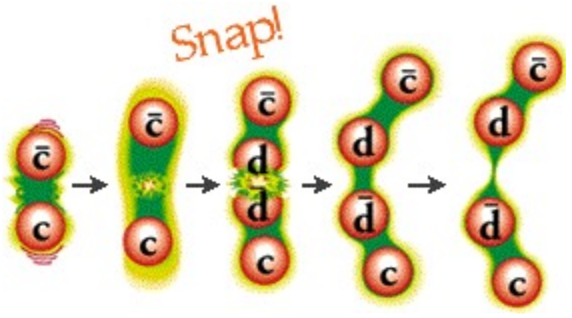
Anti-red-green gluon transforms the red quark into the green quark

Quark Confinement

- Color confinement is the physics phenomenon that color charged particles like quarks cannot be isolated. Quarks are confined with other quarks by the strong interaction to form pairs of triplets so the net color is neutral. The force between quarks increases as the distance between them increases, so no quarks can be found individually.
  - As any of two electrically-charged particles separate, the electric fields between them diminish quickly, allowing electrons to become unbound from nuclei.
  - However, as two *quarks* separate, the gluon fields form narrow tubes (or strings) of color charge) – quite different from EM!
  - Because of this behavior, the color *force* experienced by the quarks in the direction to hold them together, remains constant, regardless of their distance from each other.
  - Since energy is calculated as force times distance, ***the total energy increases linearly with distance***.

Quark Confinement (2)

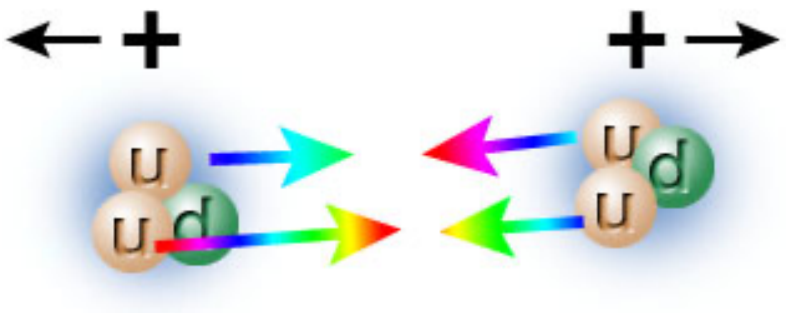
- When two quarks become separated, as happens in accelerator collisions, at some point it is more energetically favorable for a new quark/anti-quark pair to "pop" out of the vacuum.



- In so doing, energy is conserved because the energy of the color-force field is converted into the mass of the new quarks, and the color-force field can "relax" back to an unstretched state.

Residual strong force

- So now we know that the strong force binds quarks together because quarks have color charge. But that still does not explain what holds the nucleus together, since positive protons repel each other with electromagnetic force, and protons and neutrons are color-neutral.
- The answer is that, in short, they don't call it the strong force for nothing. The strong force between the quarks in one proton and the quarks in another proton is strong enough to overwhelm the repulsive electromagnetic force



- This is called the residual strong interaction, and it is what "glues" the nucleus

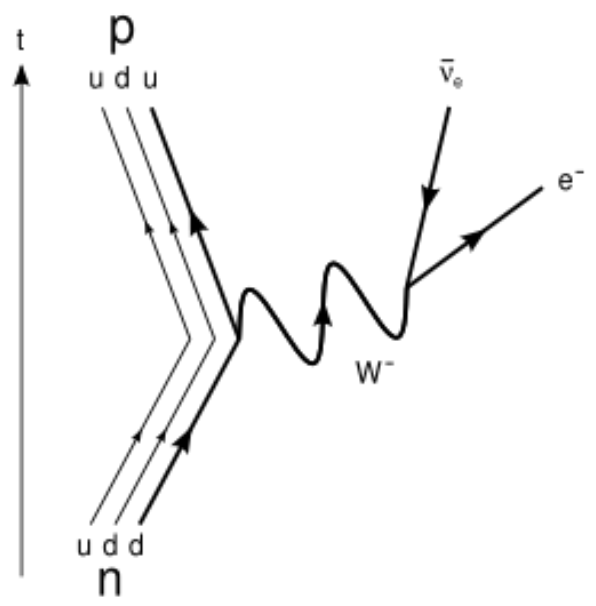
Weak interactions

- There are six kinds of quarks and six kinds of leptons. But all the stable matter of the universe appears to be made of just the two least-massive quarks (up quark and down quark), the least-massive charged lepton (the electron), and the neutrinos.
- It is the only interaction capable of changing flavor.
- It is mediated by *heavy* gauge bosons W and Z.
  - Due to the large mass of the weak interaction's carrier particles (about 90 GeV/c2), their mean life is limited to $3x10^{-25}$ s by the Uncertainty principle. This effectively limits the range of weak interaction to 10^{-18} m (1000 times smaller than the diameter of an atomic nucleus)
- It is the only force affecting neutrinos.

Weak interactions (2)

- Since the weak interaction is both very weak and very short range, its most noticeable effect is due to its other unique feature: flavor changing.

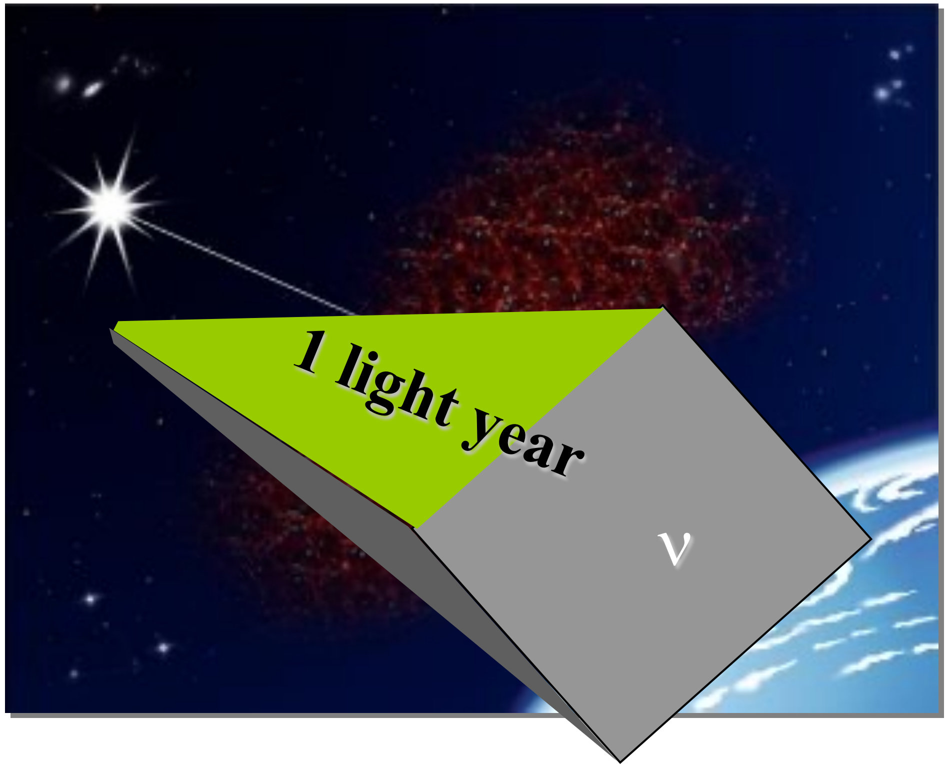
- Consider a neutron **n(udd) β-decay.** Although the neutron is heavier than its sister proton **p(uud)**, it cannot decay to proton without changing the flavor of one of its **down quarks d.**
- Neither EM nor strong interactions allow to change the flavor changing, so that must proceed through weak interaction.
- Here $d \rightarrow u + W \rightarrow u + e + \bar{\nu}_e$



$$n \rightarrow p + e + \bar{\nu}_e$$

The weak interaction

- Weak interactions are indeed weak:
  - Neutrinos can only interact with matter via weak interactions -- and so they can go through a light year of lead without experiencing one interaction!



- Weak interactions are also responsible for the decay of the heavier quarks and leptons.
- So the Universe appears to be made out of the lightest quarks (**u** and **d**), the least-massive charged lepton (electron), and neutrinos.

Gravity

- Gravitons are postulated because of the great success of the quantum field theory at modeling the behavior of all other forces of nature with similar particles: EM with the photon, the strong interaction with the gluons, and the weak interaction with the W and Z bosons. In this framework, the gravitational interaction is mediated by gravitons, instead of being described in terms of curved spacetime like in general relativity.
- Gravitons should be massless since the gravitational force acts on infinite distances.
- Gravitons should have spin 2 (because gravity is a second-rank tensor field)
- Gravitons have not been observed so far.
- For particle physics, it is very weak interaction to worry about.

Kinematics

- One of the most striking general properties of elementary particles is their tendency to disintegrate.
- Universal principle: Every particle decays into lighter particles, unless prevented from doing so by some conservation law.
- Obvious conservation laws:
  - **Momentum conservation**
  - **Energy conservation**
  - **Charge conservation**
- Stable particles: neutrinos, photon, electron and proton.
  - **Neutrinos and photon are massless, there is nothing to decay for them into**
  - **The electron is lightest charged particle, so conservation of charge prevents its decay.**
  - **Why proton is stable?**

Baryon number

- Baryon number: $B=(n_q - n_{\bar{q}})/3$
  - **all baryons have baryon number +1, and antibaryons have baryon number -1. The baryon number is conserved in all interactions, i.e. the sum of the baryon number of all incoming particles is the same as the sum of the baryon numbers of all particles resulting from the reaction.**
- For example, the process $p \rightarrow e^{+} + \gamma$ does not violate the conservation laws of charge, energy, linear momentum, or angular momentum. However, it does not occur because it violates the conservation of baryon number, i.e., B = 1 on the left and 0 on the right. It is fortunate that this process "never" happens, since otherwise all protons in the universe would gradually change into positrons! The apparent stability of the proton, and the lack of many other processes that might otherwise occur, are thus correctly described by introducing the baryon number B together with a law of conservation of baryon number.
- However, having stated that protons do not decay, it must also be noted that supersymmetric theories predict that protons actually do decay, although with a half-life of at least 10^{32} years, which is longer than the age of the universe. All attempts to detect the decay of protons have thus far been unsuccessful.

Lepton Number

- Lepton number: $L = n_{\ell} - n_{\bar{\ell}}$
  - leptons have assigned a value of +1, antileptons −1, and non-leptonic particles 0. Lepton number (sometimes also called lepton charge) is an additive quantum number.
  - **The lepton number is conserved in all interactions, i.e. the sum of the lepton number of all incoming particles is the same as the sum of the lepton numbers of all particles resulting from the reaction.**

Other quantum numbers

- Strangeness: $S = N_{\bar{s}} - N_s$ is a property of particles, expressed as a quantum number for describing decay of particles. Strangeness of anti-particles is referred to as +1, and particles as -1 as per the original definition.
  - Strangeness is conserved in strong and electromagnetic interactions but not during weak interactions.
  - ΔS=1 in weak interactions. ΔS>1 are forbidden.
- Charm: $C = N_c - N_{\bar{c}}$
  - Charm is conserved in strong and electromagnetic interactions, but not in weak interactions. ΔC=1 in weak interactions.
  - Examples of charm particles: D meson contains charm quark and D_s meson contains c and s quarks, J/ψ is (cc) combination, charmonium; Baryon (but not the only one): Λ_c contains both s and c quarks

What governs the particle decay? (1)

- Each unstable particle has a characteristic mean lifetime. Lifetime τ is related to the half-life $t_{1/2}$ by the formula $t_{1/2}=(\ln 2)\tau = 0.693\tau$. The half-life is the time it takes for half the particles in a large sample to disintegrate.
- For muons μ it's 2.2×10^{-6} sec, for the π^+ it's 2.6×10^{-8} sec; for π^0 it's 8.3×10^{-17} sec.
- Most of the particles exhibit several different decay modes
  - **Example: 63.4% of K^+'s decay into $\mu^+ + \nu_\mu$, but 21% go to $\pi^+ + \pi^0$, 5.6% to $\pi^+ + \pi^+ + \pi^-$ and so on.**
- One of the goals of the elementary particle physics is to calculate these lifetimes and branching ratios
- A given decay is governed by one of the 3 fundamental forces:
  - **Strong decay: $\Delta^{++} \rightarrow p^+ + \pi^+$**
  - **EM decay: $\pi^0 \rightarrow \gamma + \gamma$**
  - **Weak decay: $\Sigma^- \rightarrow n + e + \nu_e$**

What governs the particle decay? (2)

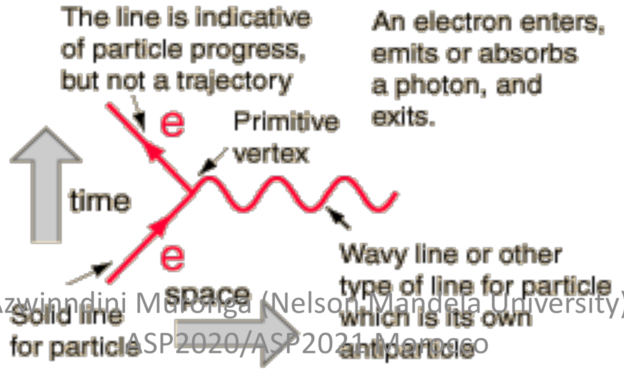
- Momentum/energy conservation law in particle physics. Example: is decay $\Lambda^0(uds) \rightarrow \pi^- + p^+$ allowed?
  - m_Λ = 1116 MeV ; m_p = 938 MeV ; m_π = 140 MeV, so $m_\Lambda > m_p + m_\pi$ and decay is allowed. $Q = m_\Lambda - m_p - m_\pi = 38$ MeV, so the total kinetic energy of the decay products must be $K_p + K_\pi = 38$ MeV. Using relativistic formula for kinetic energy, we can write this as

$$K_p + K_\pi = \sqrt{p_p^2 + m_p^2} - m_p + \sqrt{p_\pi^2 + m_\pi^2} - m_\pi = 38 MeV$$

  - Conservation of of momentum requires $p_p = p_\pi$.
  - The kinetic energies can be found: K_p = 33 MeV, K_π = 5 MeV

Feynman diagrams

- Feynman diagrams are graphical ways to represent exchange forces. Each point at which lines come together is called a vertex, and at each vertex one may examine the conservation laws which govern particle interactions. Each vertex must conserve charge, baryon number and lepton number.
- Developed by Feynman to describe the interactions in quantum electrodynamics (QED), the diagrams have found use in describing a variety of particle interactions. They are spacetime diagrams, ct vs x. The time axis points upward and the space axis to the right. Particles are represented by lines with arrows to denote the direction of their travel, with antiparticles having their arrows reversed. Virtual particles are represented by wavy or broken lines and have no arrows. All electromagnetic interactions can be described with combinations of primitive diagrams like this one.



Which decays are allowed?

- $\Sigma^0 \rightarrow \Lambda + \pi^0$
  - Σ^0(uds), Λ(uds), π^0(u ubar). M(Σ) = 1197.45 MeV, M(Λ) = 1115.68 MeV, M(π^0) = 134.98 MeV;
- $\Sigma^- \rightarrow$ n + π^-
  - Σ^-(dds), n(udd), π^-(ubar d). M(Σ) = 1197.45 MeV, M(n) = 939.56 MeV, M(π-) = 139.57 MeV ;
- $\Xi^0 \rightarrow \pi^-$ +p
  - uss, ubar d, uud correspondingly. M(Ξ^0) =1314.83 MeV , M(p) = 938.27 MeV
- $\Xi^- \rightarrow \pi^- + \Lambda$
  - dss, ubar d, uds correspondingly. M(Ξ^-) =1321.31 MeV
- N $\rightarrow$ e + π^-
  - M(e) = 0.511 MeV

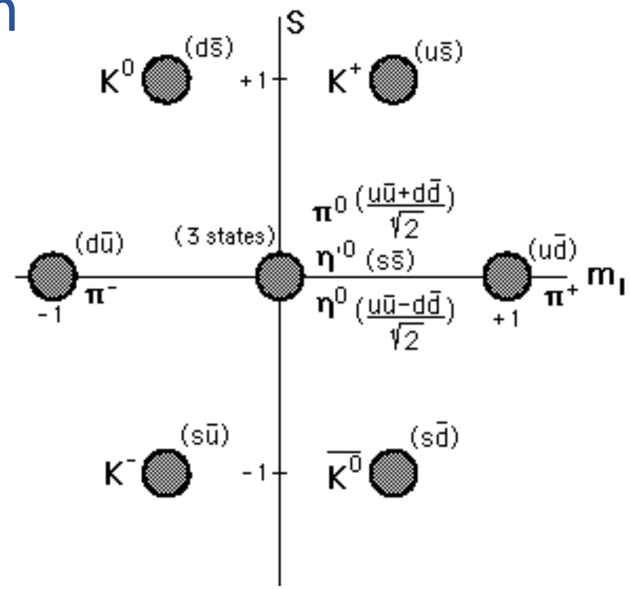
Parity

- One of the conservation laws which applies to particle interactions is associated with parity.
- Quarks have an intrinsic parity which is defined to be +1 and for an antiquark parity = -1. Nucleons are defined to have intrinsic parity +1. For a meson with quark and antiquark with antiparallel spins (s=0), then the parity is given by $P = P_q P_{\bar{q}} (-1)^{\ell}$, where l = orbital angular momentum.
- The meson parity is given by $P = -(-1)^{\ell} = (-1)^{\ell+1}$
- The lowest energy states for quark-antiquark pairs (mesons) will have zero spin and negative parity and are called pseudoscalar mesons. The nine pseudoscalar mesons can be shown on a meson diagram. One kind of notation for these states indicates their angular momentum and parity

$$J^P = 0^{-1}$$

Parity (2)

- Excited states of the mesons occur in which the quark spins are aligned, which with zero orbital angular momentum gives j=1. Such states are called vector mesons, $J^P = 1^{-1}$
- The vector mesons have the same spin and parity as photons.
- All neutrinos are found to be "left-handed", with an intrinsic parity of -1 while antineutrinos are right-handed, parity =+1.
- Parity conserves in strong and EM interactions, but not in weak interactions.

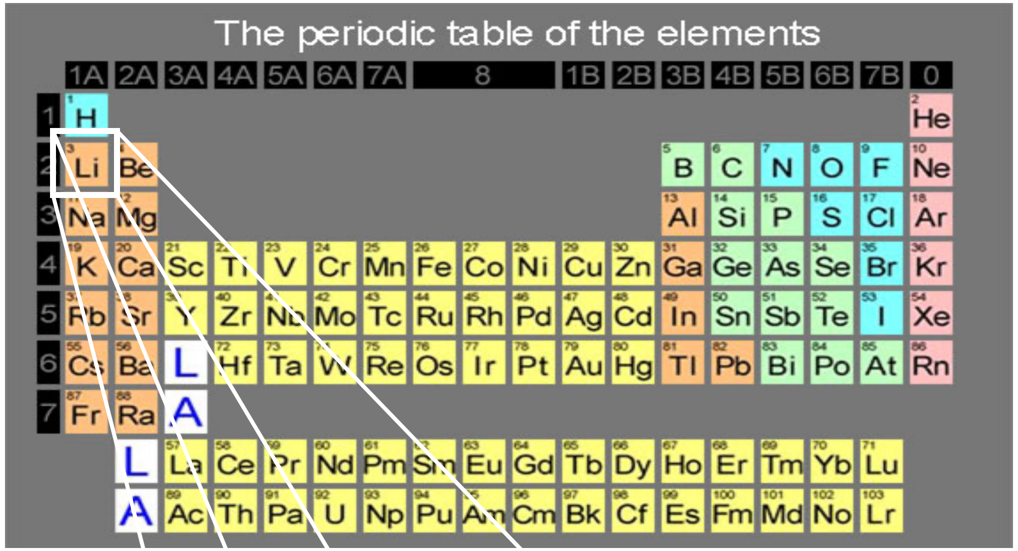


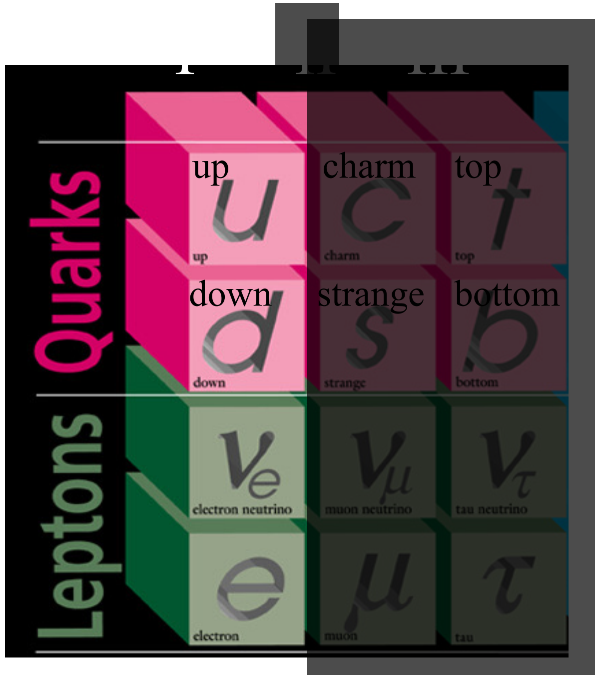
Take home message

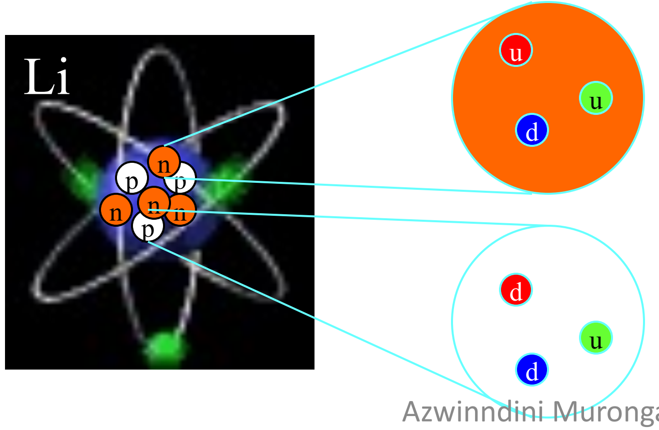
The Standard Model

What have we learned by experiments that collide particles at high energy?

- ❑ A “new” periodic table.
- ❑ Total of 12 **fundamental** particles







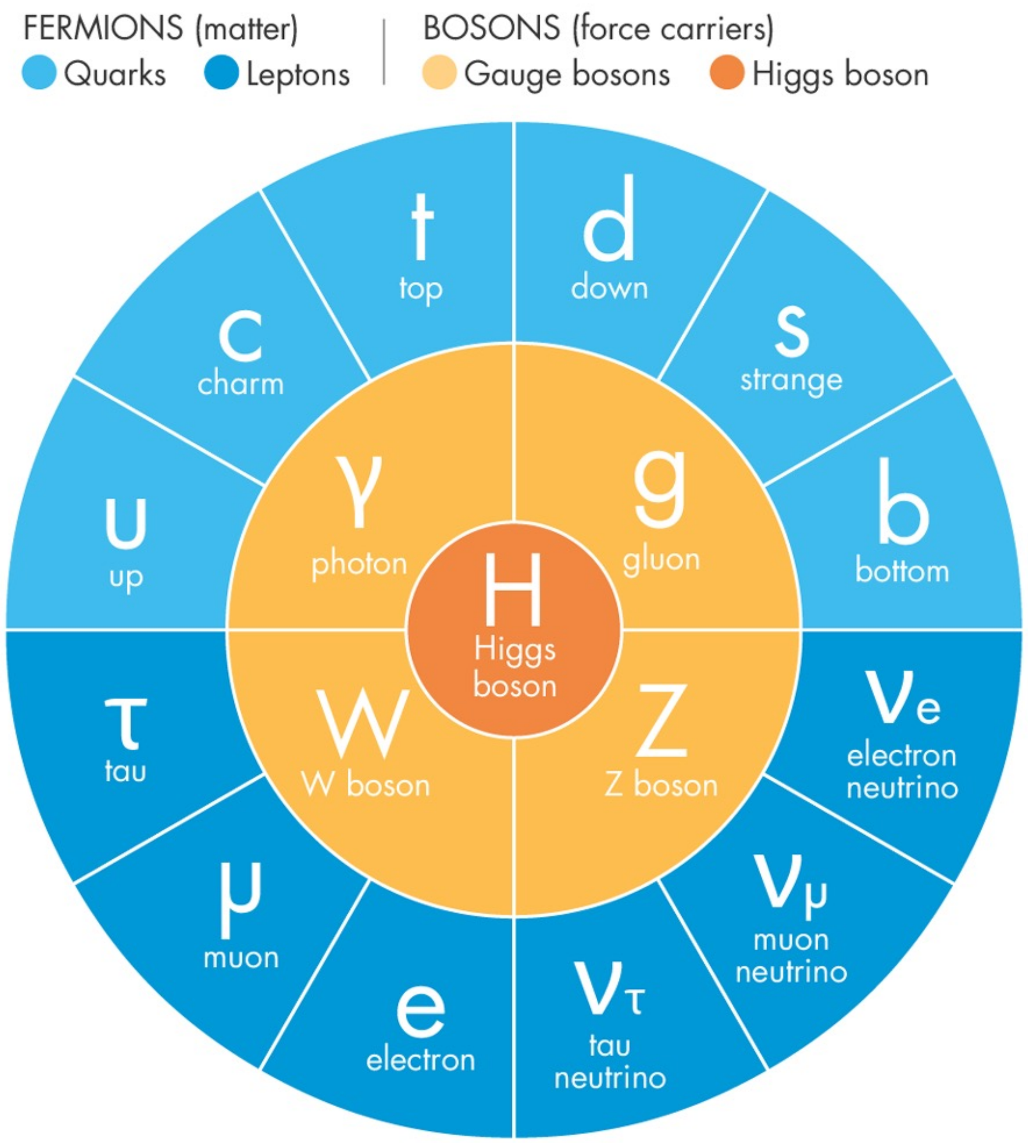
Protons and neutrons are made of quarks

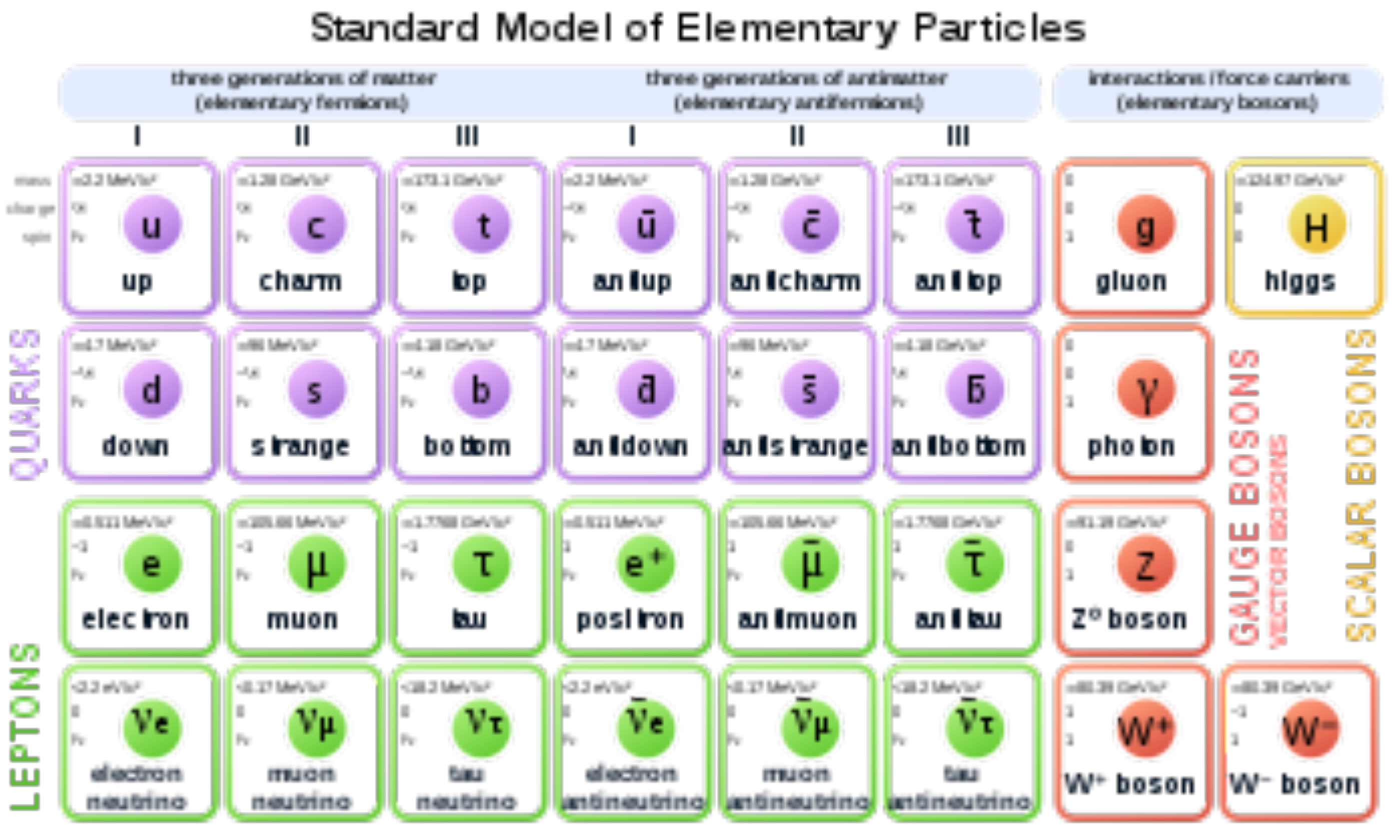
- ❑ Proton (uud)
- ❑ Neutron (udd)

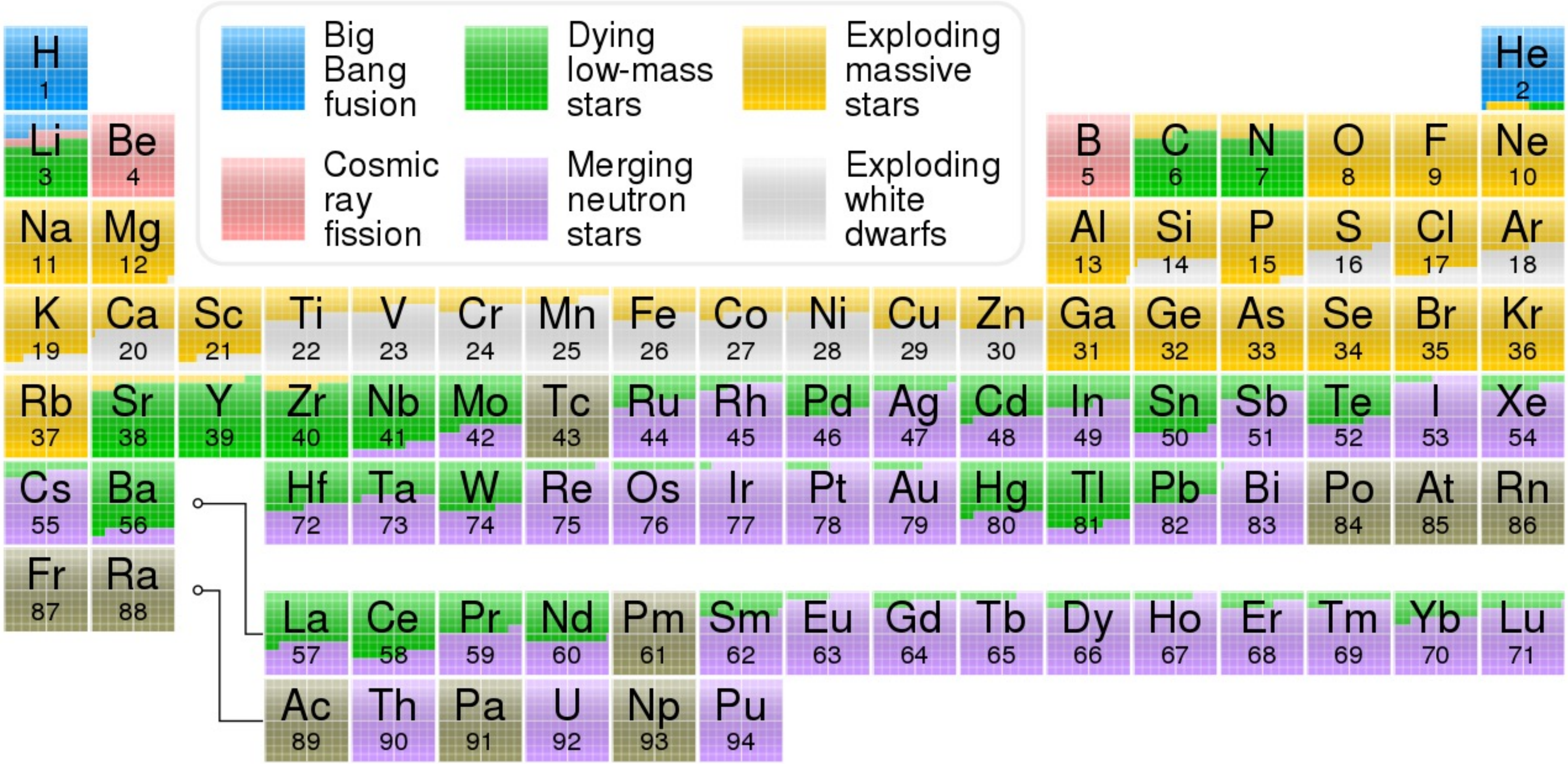
❑ As with Lithium, all atoms are composed of u & d quarks and electrons!

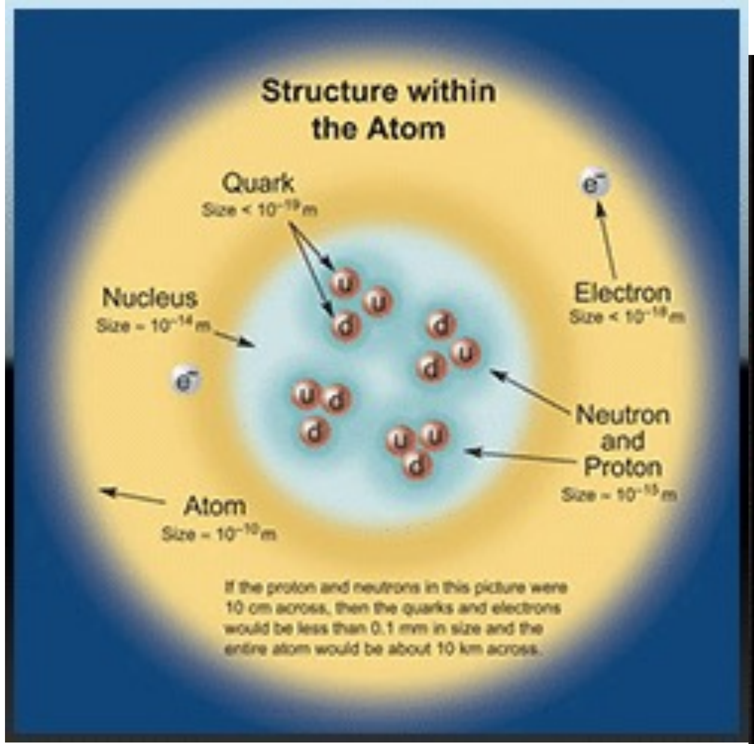
Why do “families II and III exist?

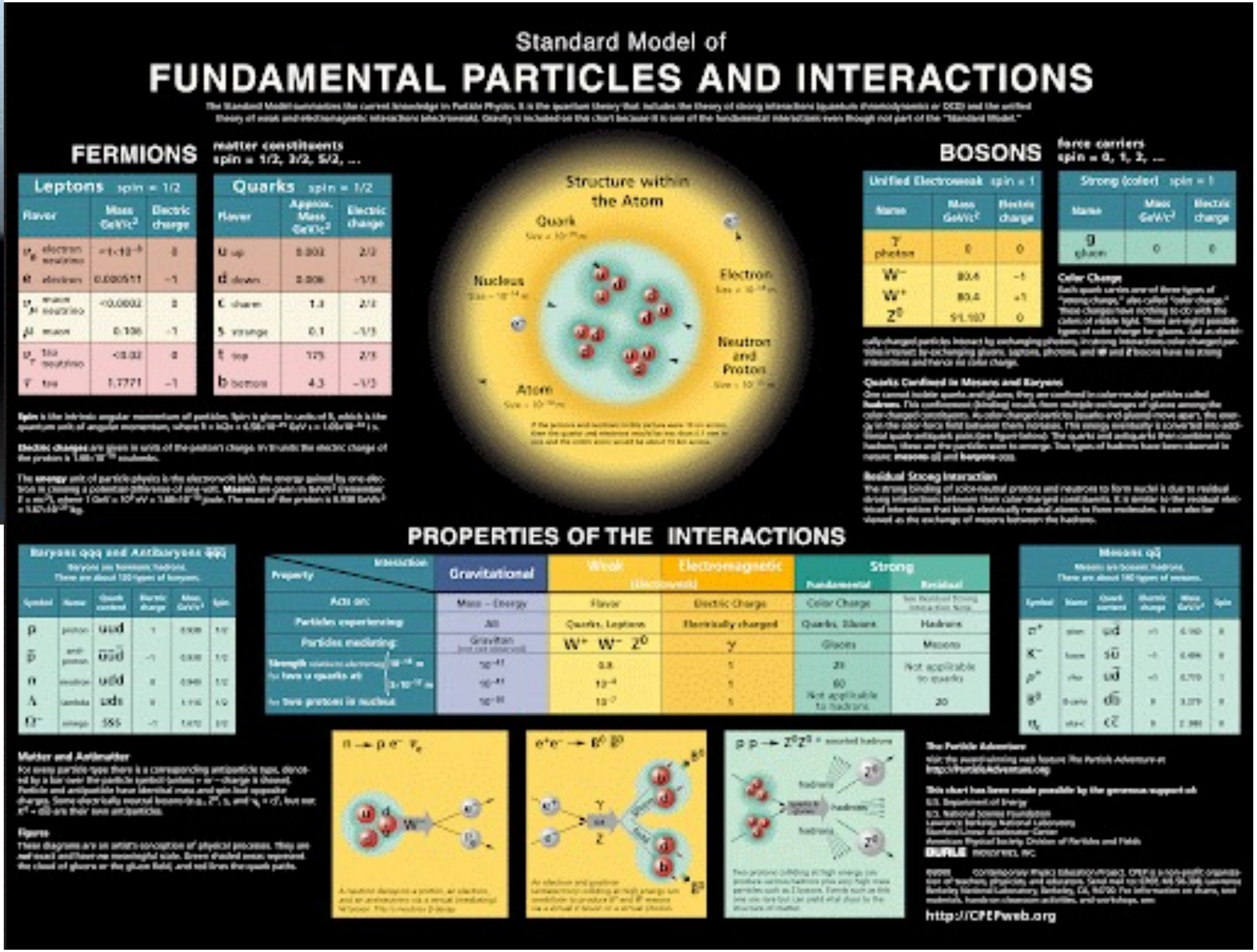
THE STANDARD MODEL






Big Bang fusion
Dying low-mass stars
Exploding massive stars
Cosmic ray fission
Merging neutron stars
Exploding white dwarfs
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94


Structure within the Atom
Quark
Size < 10^{-19} m
Electron
Size < 10^{-18} m
Nucleus
Size ~ 10^{-14} m
Neutron and Proton
Size ~ 10^{-15} m
Atom
Size ~ 10^{-10} m
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.


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
FERMIONS
matter constituents spin = 1/2, 3/2, 5/2, ...
Leptons spin = 1/2
Quarks spin = 1/2
BOSONS
force carriers spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Strong (color) spin = 1
Structure within the Atom
PROPERTIES OF THE INTERACTIONS
Gravitational
Weak
Electromagnetic
Strong
http://CPEPweb.org