Summer Particle Astrophysics Workshop
Introduction to Particle Physics

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Particle Physics

The study of stuff that makes up the Universe

Two types of particle physics...

Collider Physics:

- Create weird particles by smashing boring ones together
- Good for creating heavy particles
- eg. CERN

Particle Astrophyiscs:

- Letting weird particles from space smash into you
- Good for seeing rare stuff we can't make with colliders yet
- eg. SNOLAB

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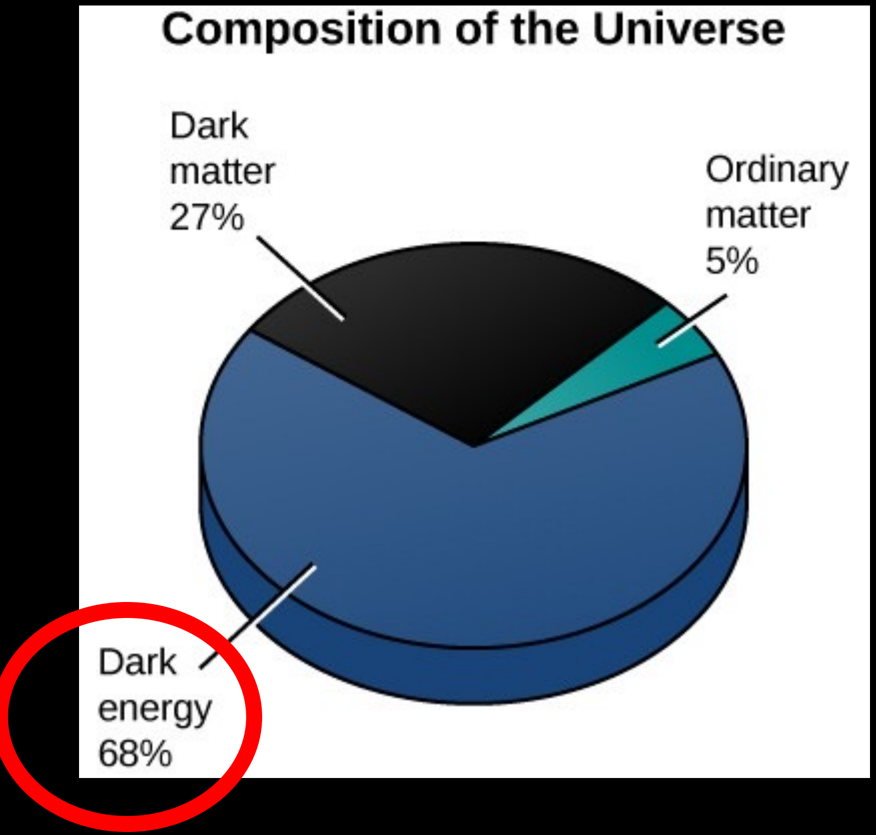
What do we know about the Universe?

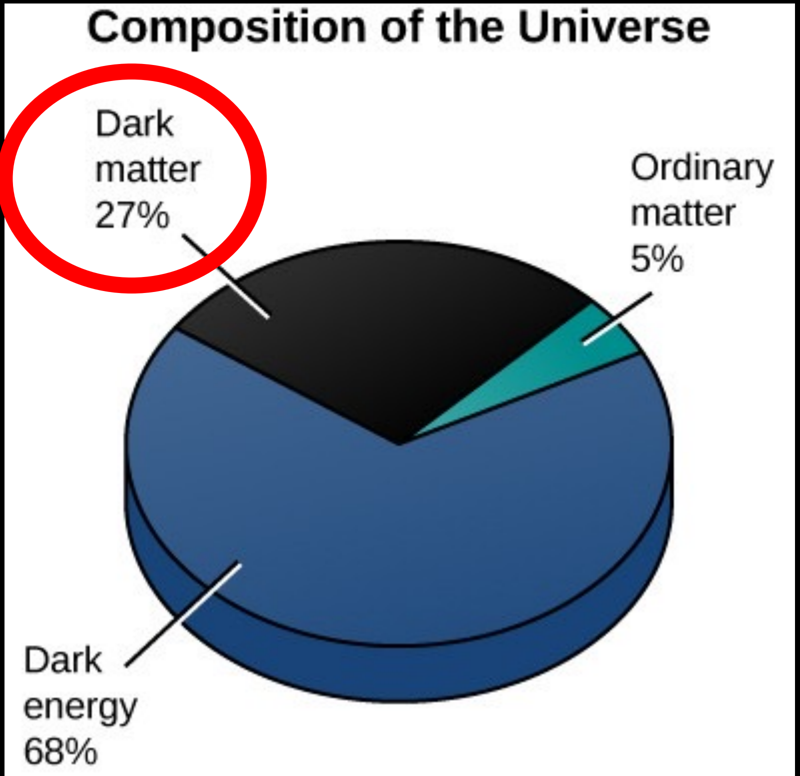


Dark Energy (~68%)

- Universe is expanding at an increasing rate
- The "Energy" responsible for this expansion is called Dark Energy (2011 Nobel Prize)
- We don't now anything about it.

...yep that's about it.

What do we know about the Universe?

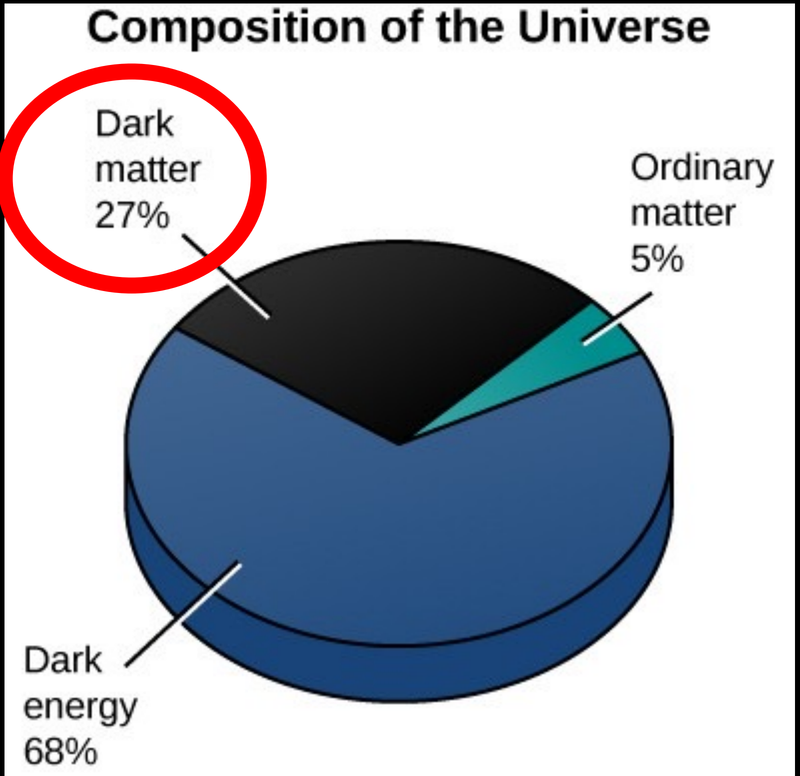


Dark Matter (~27%)

- A majority of the galaxy has gravity we can't account for by regular matter (eg stars, etc)

It ought to be here but it isn't.
Gravity is pulling all the stars around it to this spot.

What do we know about the Universe?

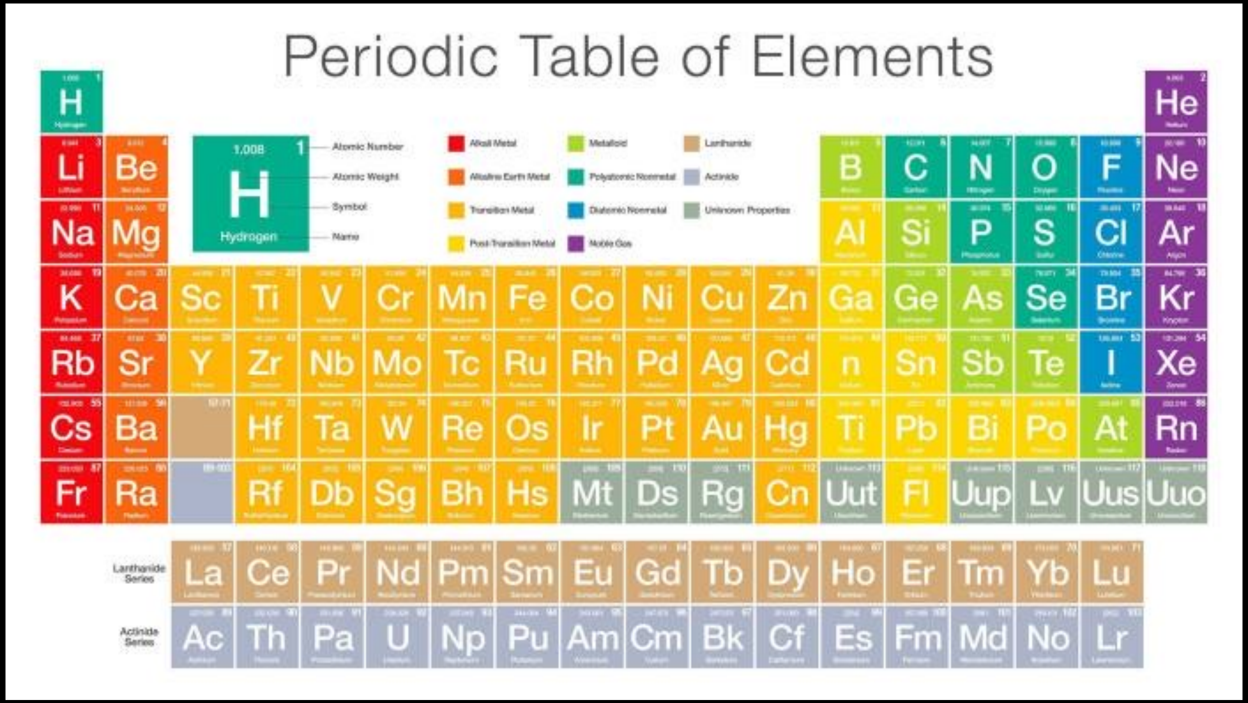


Dark Matter (~27%)

- A majority of the galaxy has gravity we can't account for by regular matter (eg stars, etc)
- idk probably a particle lmao
- On the cusp of figuring this one out (including what some of you will be working on)
- The race is on to find it first...

Ordinary Matter

The most important component because it’s what you’re made of <3
Has been puzzling everybody for millennia



Modern Atomic Theory: The Atom

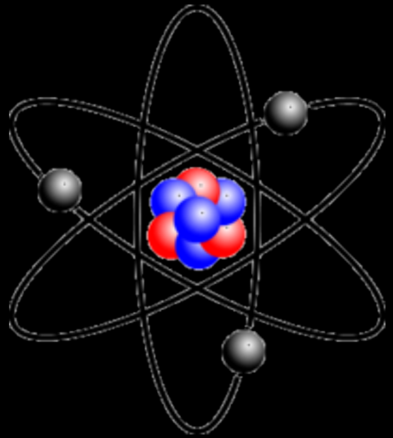
The Elements are made up of atoms.

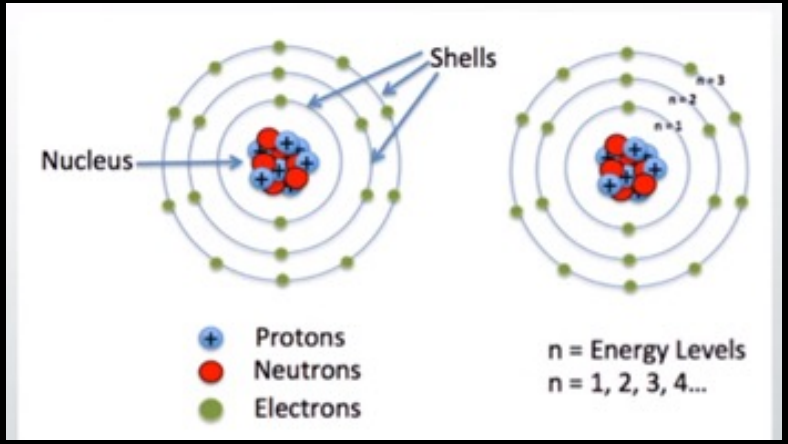
Each atom has a nucleus made up of protons and neutrons and has 3 distinctive numbers:

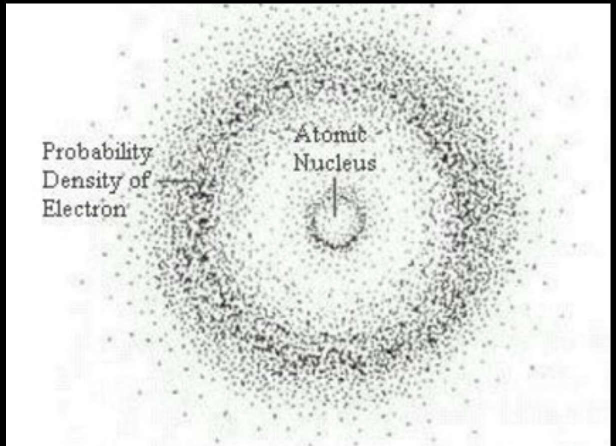
- Z = # protons. Unique to each element.
- N = # neutrons.
- A = Z + N = The Atomic Mass Number

Each element has a unique Z, but may have different Ns (resulting in different As). These differences in mass numbers are the atomic Isotopes. (e.g. 6p/6n is ^{12}C and 6p/8n is ^{14}C, but 8p/6n is ^{14}O)

The nucleus is surrounded by a cloud of electrons that can be imagined as shells







Modern Atomic Theory: Special Relativity

Special Relativity Crash Course:

- The speed of light $c = 3 \times 10^8$ m/s is the universal speed limit. When things move near the speed of light, spacetime itself grows to make sure the object doesn't exceed it.

- If you are stationary on a train moving at 0.9 m/s and throw a baseball at 0.9 m/s...
  - You see the ball moving at 0.9 m/s
  - An outside observer sees the baseball travelling at 1.8 m/s.

- If you're stationary on a (very fast) train moving at 0.9c and throw a baseball (very hard) at 0.9c...
  - You see the ball moving at 0.9c
  - An outside observer *does not* see the ball moving at 1.8c.
  - Space and time actually expand such that in every reference frame, the ball is moving at less than 1c.

The math to figure out how space (length) and time change is not challenging – it's just a factor (The Lorentz Factor) you slap to adjust for the different speeds.

Modern Atomic Theory: Special Relativity

Special Relativity Crash Course:

- Takeaway: when things move near the speed of light, their properties change based on your reference frame.

- Since particles are very light relative to every day objects, they are relativistic – they travel near the speed of light, which warps their properties. Therefore, frames of reference are very important.

- Something neat: the speed of light in a vacuum is *always exactly* c, regardless of the frame of reference.

- The Rest Mass of a particle is $E = mc^2$. This is the mass in a frame of reference that the particle is stationary.

- $E=mc^2$ implies that Mass and Energy are interchangeable! Also, it makes math a lot cleaner if you "re-cast" all of the units such that the speed of light $c = 1$.

Modern Atomic Theory: The Electron Volt

- Masses of elementary particles are small AF compared to every day objects. SI units (kg, J, etc) just don't cut it.
- Makes more sense to talk about energies in units of electron-volts (eV). 1 eV is the energy an electron gains by travelling across an electric potential of 1V. 1eV = 1.602×10^{-19} J

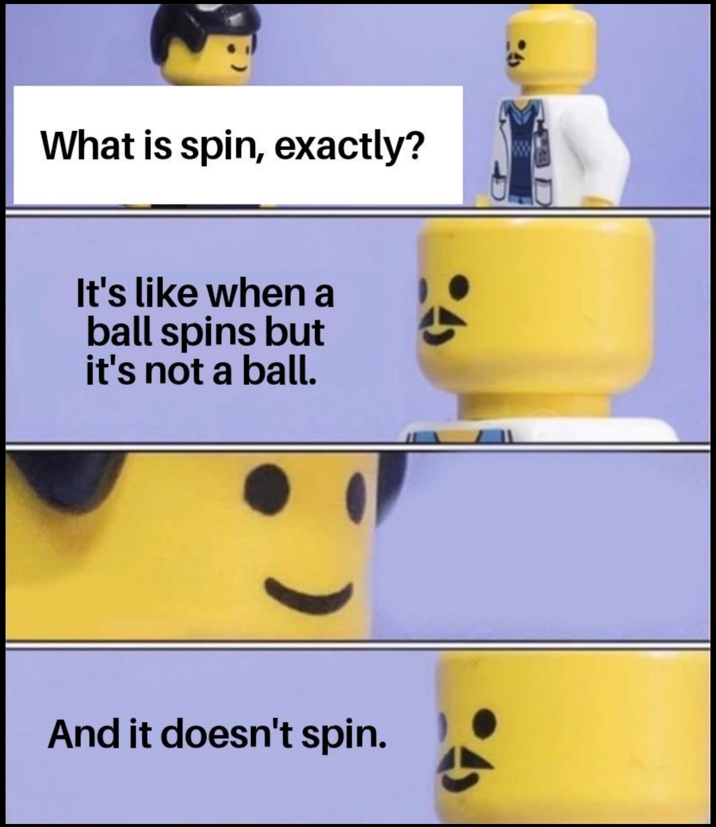
eg. The proton has a rest mass of 1.67×10^{-27} kg = 938×10^{6} eV/c^2 = 938 MeV/c^2 = 938 MeV (c =1)
1 eV = super duper light
511 keV = rest mass of electron
0.8 MeV = The lightest particles the SNO+ detector can reliably see
938 MeV = Rest mass of the proton
1-100 GeV = Mass range we think dark matter might be
173 GeV = Rest mass of the heaviest fundamental particle
10^{12} eV = Most energetic particle ever created by humans (Large Hadron Collider)
10^{20} eV = Most energetic particle ever detected. (Rest mass + kinetic energy)

Modern Atomic Theory: Quantum Mechanics

Crash course on Quantum Mechanics:

- Classical (Newtonian) physics is good enough for our size scales, but doesn't explain a things at the small scale.
- Quantum Mechanics explains nature at both the small and every-day scale.
- Basically, everything is made up of discrete, indivisible units.
    - ie. they're quantitatively countable
    - ie. they're quantized.
    - The units are the elementary particles.

- Interactions are governed by exact, never-violated conservation laws.
    - Conservation of mass-energy
    - Conservation of matter
    - Conservation of linear momentum
    - Conservation of angular momentum
    - Conservation of electric charge
    - A few others we'll worry about later.



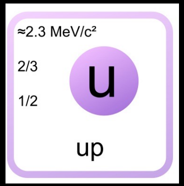
Elementary Particles also have a "spin" - their intrinsic angular momentum.

Modern Atomic Theory: Elemental Constituents

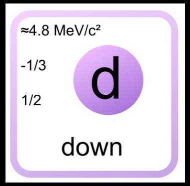
Elements are made of Atoms:

- Protons: Spin = ½, Charge = +1
- Neutrons: Spin = ½, Charge = 0
- Electrons: Spin = ½, Charge = -1

Turns out the Proton and Neutron isn't actually fundamental, but made up of even smaller subatomic particles called Up and Down.

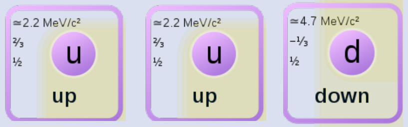


- Up: Spin = ½, Charge = +2/3

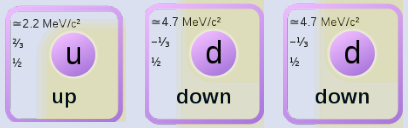


- Down: Spin = ½, Charge = -1/3

Proton



Neutron



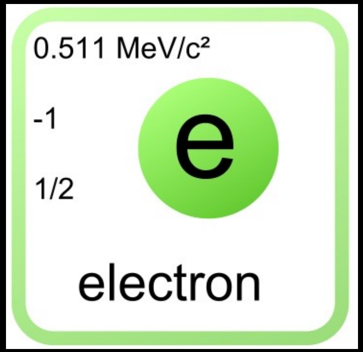
Charge conservation:

2/3 + 2/3 – 1/3 = +1

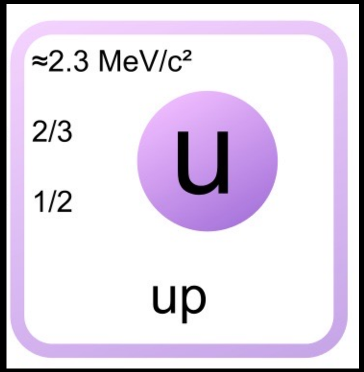
2/3 – 1/3 – 1/3 = 0

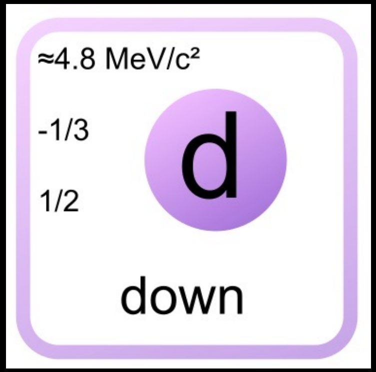
The Elementary Particles

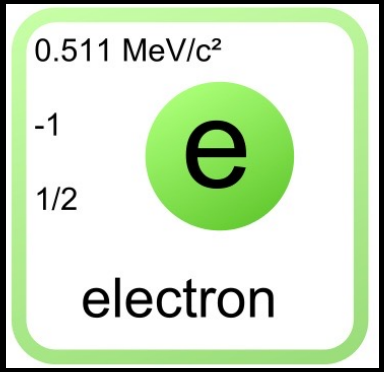
Turns out Electrons are fundamental…



So we have the 3 elementary particles that make up the periodic table of the elements!








MISSION ACCOMPLISHED

Example particle interaction: Beta Decay

Let’s turn a neutron into a proton. Since a neutron has a higher mass than the proton, this is a **Spontaneous Decay** – that is, it is energetically allowed.

$$n \rightarrow p$$
$$0 \quad\quad 1$$

Due to **Charge Conservation**, it also has to release an electron

$$n \rightarrow p + e-$$
$$0 \quad\quad 1 \quad -1$$

Electrons used to be called beta particles, hence the name “beta decay”.

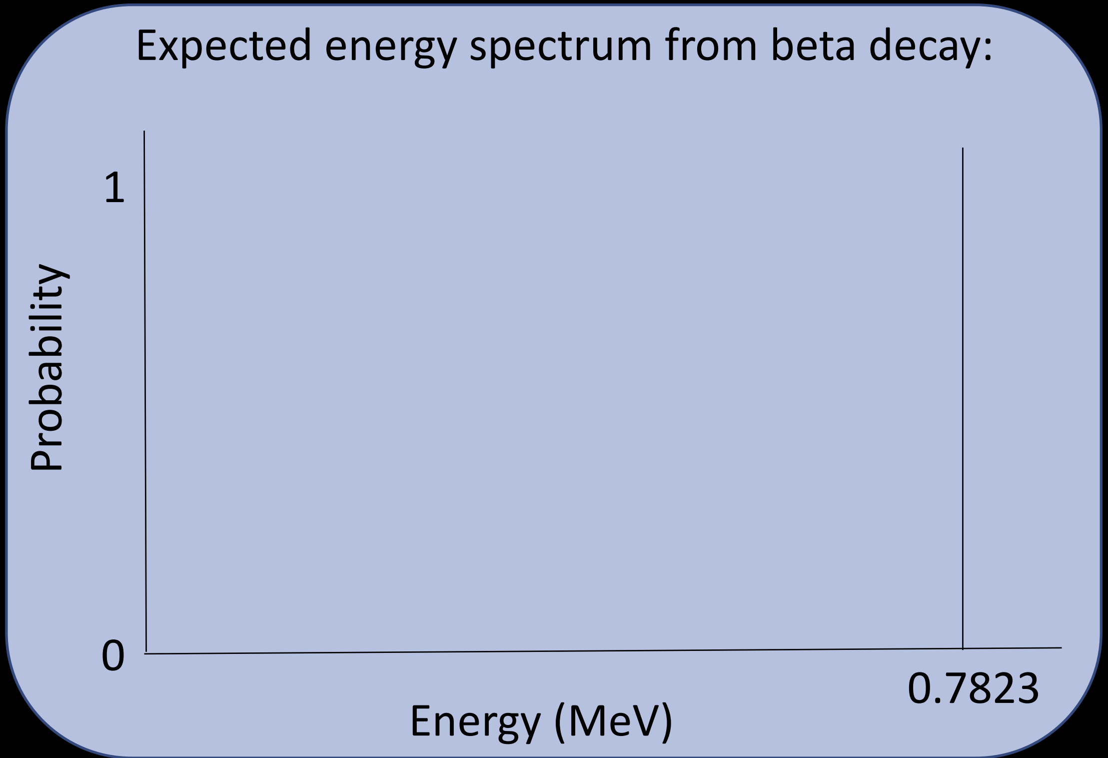
We also need to take into account **mass-energy conservation**, where the before and after mass+energy has to be equivalent.

$$n \rightarrow p + e^{-} + 0.7823 \text{ MeV}$$

The excess energy is the Q-value – each type of decay has a signature Q-value.

The Q-Value

- The Q Value is unique for each decay. Again, it's the E difference between parent and daughter products.
- The larger the Q value, the more likely the decay is to happen.
- The daughter products of each decay must have exactly the Q value.
- **Beta decay** has a Q Value of 0.7823 MeV. The proton has 2000x the mass of the electron, so virtually all of the energy is carried away by the electron due to **Conservation of Momentum.**
- If we look at many beta decays, we can measure the energy of the electron and build a histogram called the energy distribution of the decay. It should look like this.



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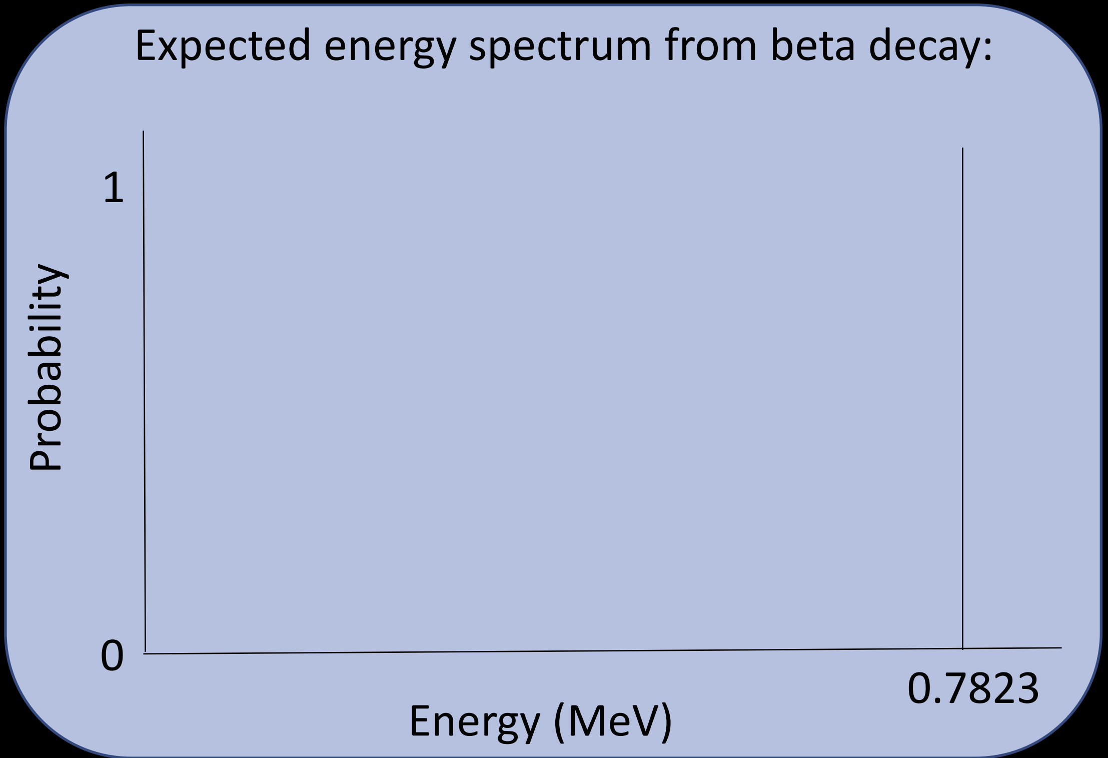
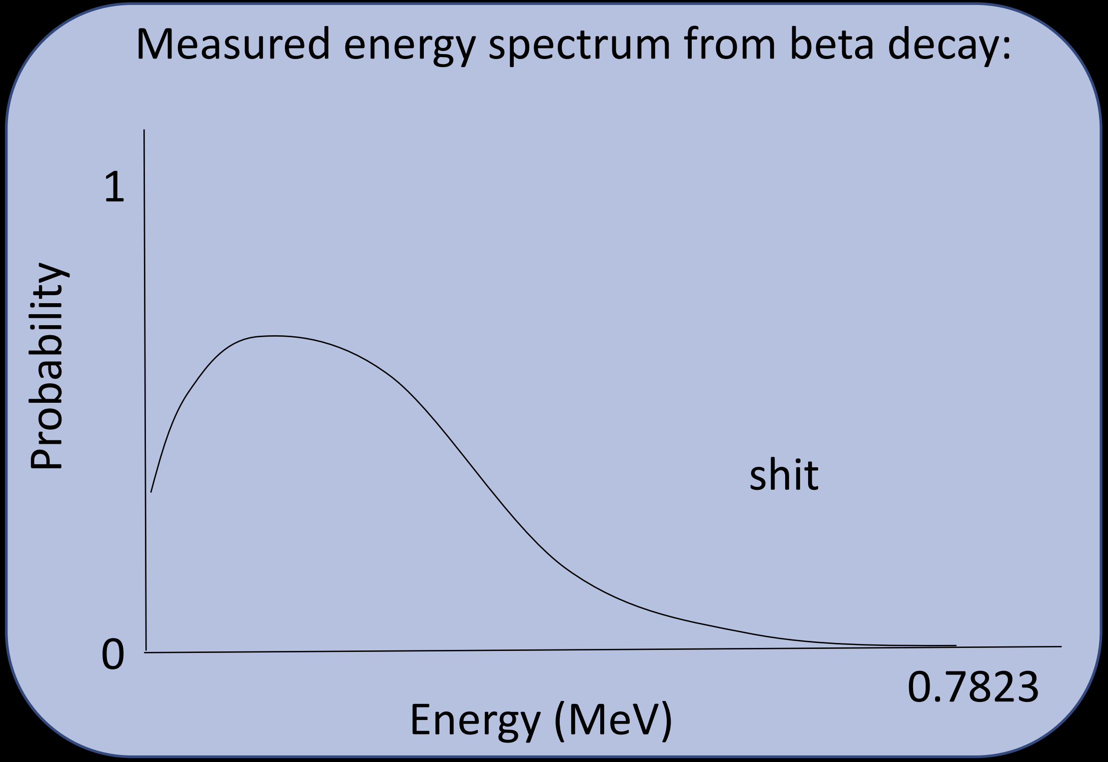




Continuous Energy Distribution???

Solution: Remember our training.

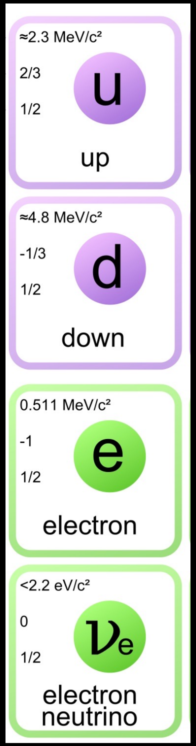
When the math doesn’t work out, make up fake stuff to fill in the gaps.
In this case, we make up a particle that is neutral and invisible…
We can say it’s a nu particle because it’s new.

Beta Decay is therefore
$n \rightarrow p + e^- + \nu + 0.7823$ MeV

The made-up particle is also very light, and carries away a random amount of energy in each decay. The electron carries away the rest. Hence why if you measure many beta decays, the electron can take on many energies.

The Elementary Particles (Final)

So we have the ~~three~~ four fundamental elementary particles.

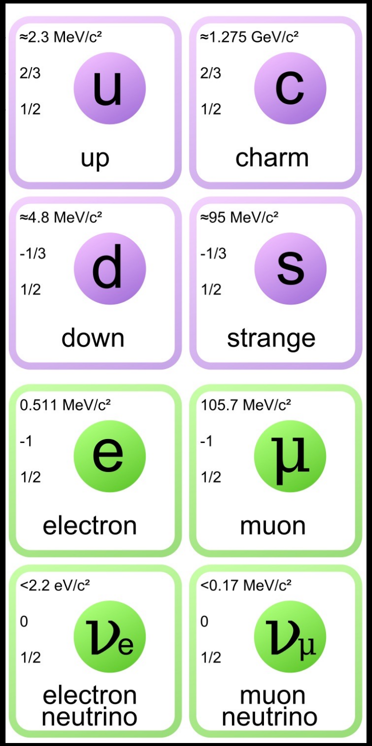


"The Gang discovers more elementary particles"

The Elementary Particles (Final_Final)

- Each particle has a heavier version.
- This "second generation" is heavier and spontaneously decays to the first generation

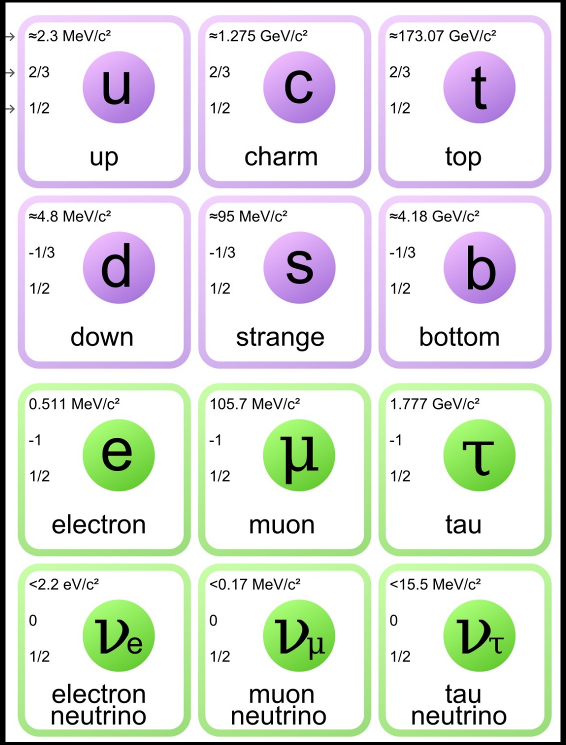
So we have the ~~three~~ ~~four~~ eight fundamental elementary particles.



The Elementary Particles (Final_Final_Actually)

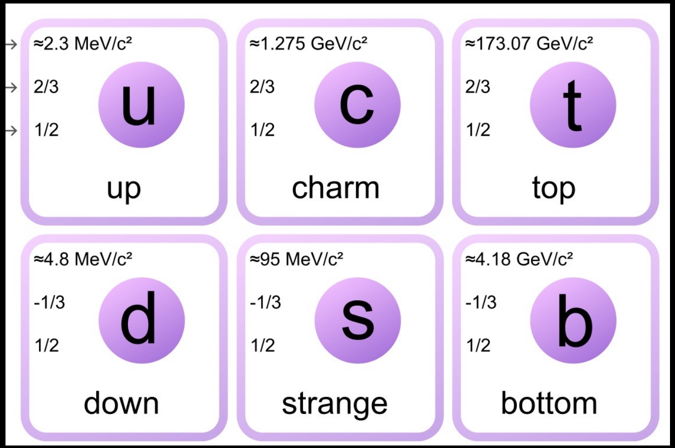
Aaaaand there's also a third generation.

So we have the ~~three~~ ~~four~~ ~~eight~~ twelve fundamental elementary particles.



The Quarks

- The particles that make up composite particles (ie proton, neutron) are called Quarks
- The composite particles themselves are called Hadrons
- There are two types of Hadrons.

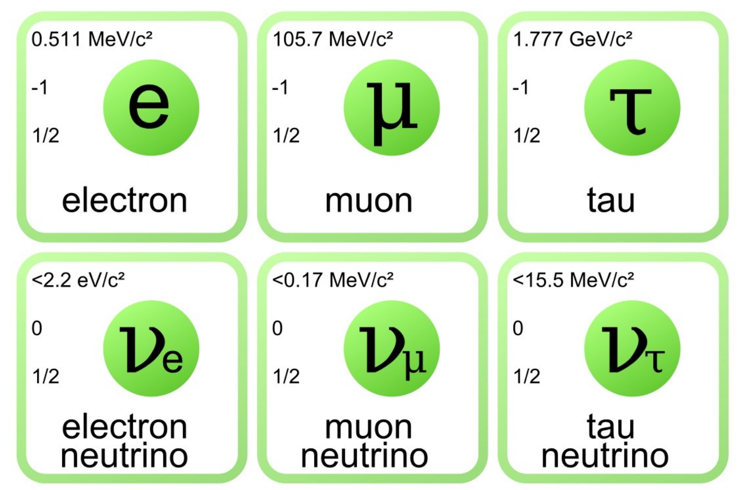


- 3 Quarks = "Baryons"
- 2 Quarks = "Mesons"

- Quarks stick together even if they have like electromagnetic charges
  - This is due to some strong force in the nucleus.
  - It's called the **nuclear strong force**.

The Leptons

- The other elementary particles can’t interact through the Strong Nuclear Force
- They can’t make composite particles and are lept behind.
  - That’s definitely why they’re called Leptons.



- They interact through a nuclear force that is weaker than the Strong Nuclear Force
- It’s called the **Weak Nuclear Force**

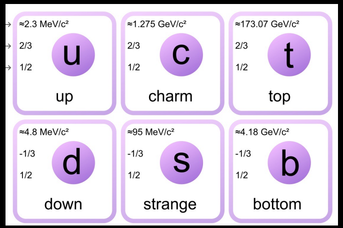
Anti-matter

- Each of the 12 particles have an anti-version of itself
- The anti-version is the exact same in every way except with an opposite electric charge

- When a particle and anti-particle interact, they destroy itself (pair annihilation)
- When a particle is created, its antiparticle is also created.

- An antiparticle is symbolized using an overhead dash:

Up Quark:	Particle	u
Anti-Up Quark	Anti-Particle	$\bar{u}$



Baryon Number Conservation

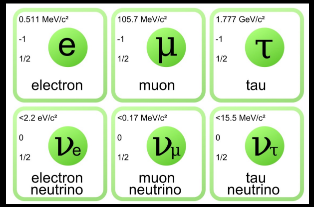
- Baryons (3-quark composites) are assigned a value per particle.

Baryon = 1
Anti-baryons = -1

This is the Baryonic Number. The Baryon number is conserved.

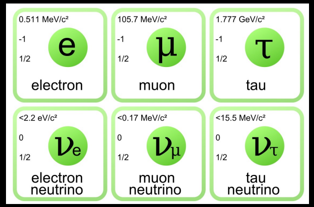
“Baryon Number Conservation”

Third Grader: Matter cannot be created or destroyed
Big Brain You: Uhm acktually, Net Baryonic matter cannot be created or destroyed.



Lepton Number Conservation

- Here’s an interesting thought: if neutrinos have 0 charge, what’s the difference between neutrinos and anti-neutrinos?



Lepton Number Conservation

- Here's an interesting thought: if neutrinos have 0 charge, what's the difference between neutrinos and anti-neutrinos?

- Uhm uhhh ummmm okay if baryon number is conserved, lepton number is probably also conserved.
- All leptons have a lepton number of 1, anti-leptons have a lepton number of -1
- This totally legitimate and 100% believable line of logic gives us

"Lepton Number Conservation"

So back to beta decay:

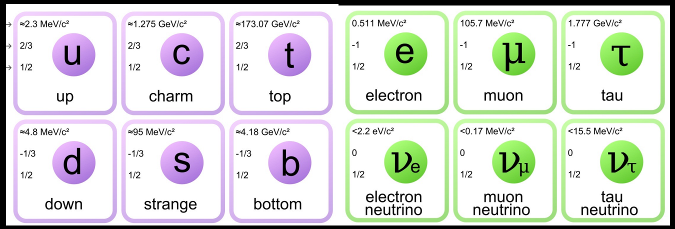
$$n \rightarrow p + e^- + \nu_e + 0.7823\ \text{MeV}$$

0 0 1 1

Should really be

$$n \rightarrow p + e^- + \overline{\nu}_e + 0.7823\ \text{MeV}$$

0 0 1 -1



The Fermions

- The fundamental particles obey Fermi-Dirac Statistics because they have half-integer spins
- You can picture spin as its inherent angular momentum.
- Quarks and Leptons collectively called the Fermions (lol Dirac got shafted)

$$F(E) = \frac{1}{e^{(E-E_f)/kT} + 1}$$

Quantum Properties described by the Dirac Equation

$$i\partial\psi - m\psi = 0$$

It’s math mumbo jumbo, let’s move on (sorry theorists)

The Fundamental Forces

The Fermions interact with each other through the fundamental forces...

1. The Electromagnetic Force
2. The Strong Nuclear Force -> Quarks Only
3. The Weak Nuclear Force -> Leptons Only

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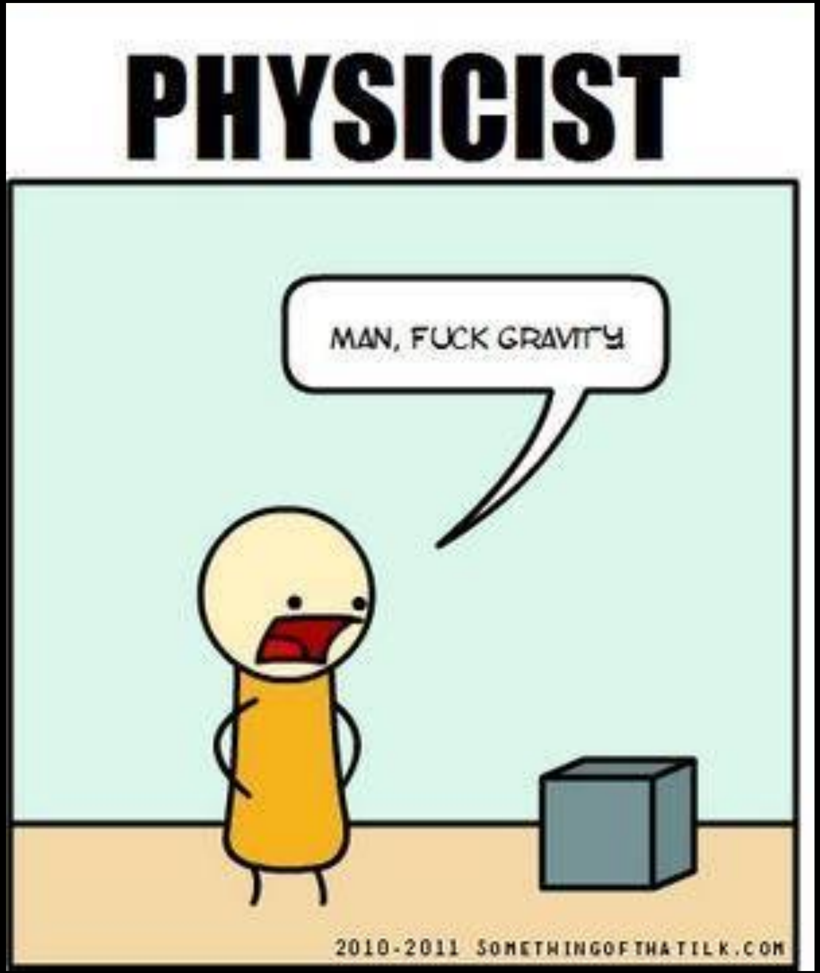


But they were all of them deceived, for a 4^{th} force exists

4. Gravity

We have no idea how Gravity works.

The Bosons

Forces are transfers of information. This information is carried through messenger “mediator” particles.

- The Electromagnetic Force mediator is the **Photon**
- The Strong Force mediator is the **Gluon**
- The Weak Force has 3 mediators, since they can affect the charges of particles
  - The **Z** (neutral)
  - The **W+** (Charge = +1)
  - The **W-** (Charge = -1)

These particles have whole-integer spins and obey Bose-Einstein statistics
Called the **Bosons** because Einstein has enough time in the spotlight already.

Other Bosons

The Higgs Boson mediates mass Interactions between particles

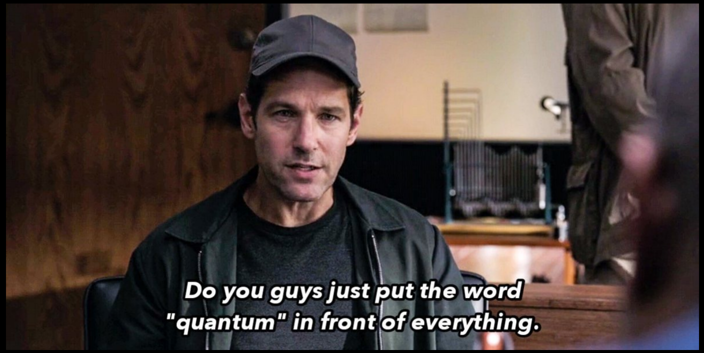
It’s very heavy and therefore decays very quickly, making it hard to find

The Graviton: Probably what we’d call the mediator for Gravity. If it exists it’ll probably be massless since gravity exchanges information at the speed of light.

Jedi Business

Three fields of study investigate the fundamental Forces...

- Quantum Electrodynamics (QED)is the study of the EM Force
- Quantum Chromodynamics (QCD) is the study of the gluon
- Quantum Flavourdynamics (QFD) is the study of the weak force



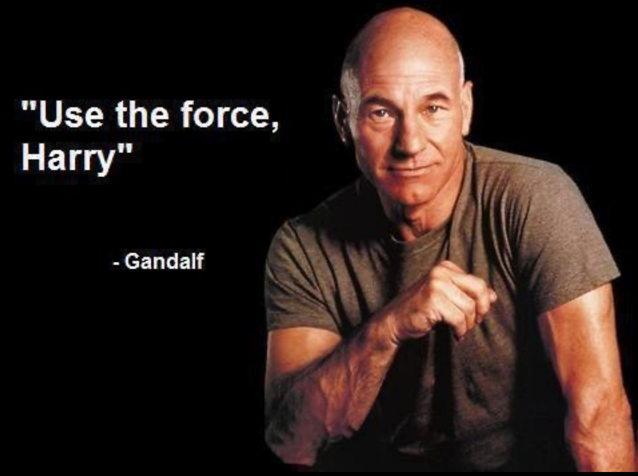
At certain energy levels, the forces merge into one.

- The EM and Weak forces merge into the Electroweak force at about 250 GeV
- The EM, Weak, and Strong force hopefully merge at (probably) around 10^{25} eV

“Grand Unification”

...This is a work in progress.

Jedi Business



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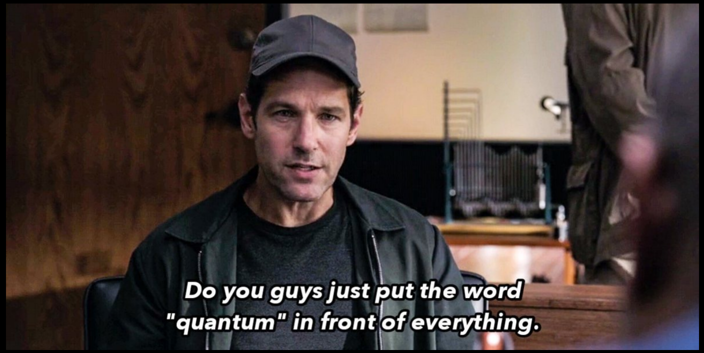

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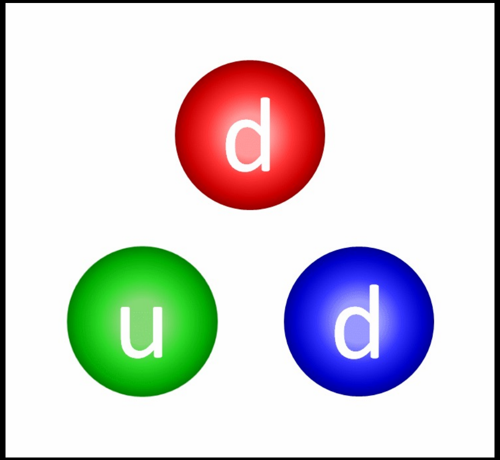
Quantum Chromodynamics

The Gluon comes in 3 varieties (and anti-varieties), named after the 3 primary colours

- Red (anti-red)
- Green (anti-green)
- Blue (happiness)



The colour of each gluon is the "Colour Charge"
Particles with a net colour charge of 0 (equal red, green, blue) are stable
Colour is conserved in the **Conservation of Colour**.

The Great Symmetries

Symmetries are physical features that are unchanged when a system undergoes some operation or transformation.
Symmetries are assigned a property of “1”. If the symmetry is reversed (‘flipped’), the symmetry property goes from 1 to -1.

Particle Physics has three great symmetries: CPT

- **C**harge Conjugation: When a particle flips to their antiparticle, their charge must also flip
- **P**arity: When a particle is reflected, their positions are also flipped
- **T**ime Reversal: Regardless if a particle goes forwards or backwards in time, it stays the same.

Symmetry Violations

The Weak Nuclear Force violates C and P

Products of symmetries may also be considered...

CP is not conserved: Quarks can change from one flavour (aka type) to another.
They “mix” – governed by a matrix called the CKM matrix.

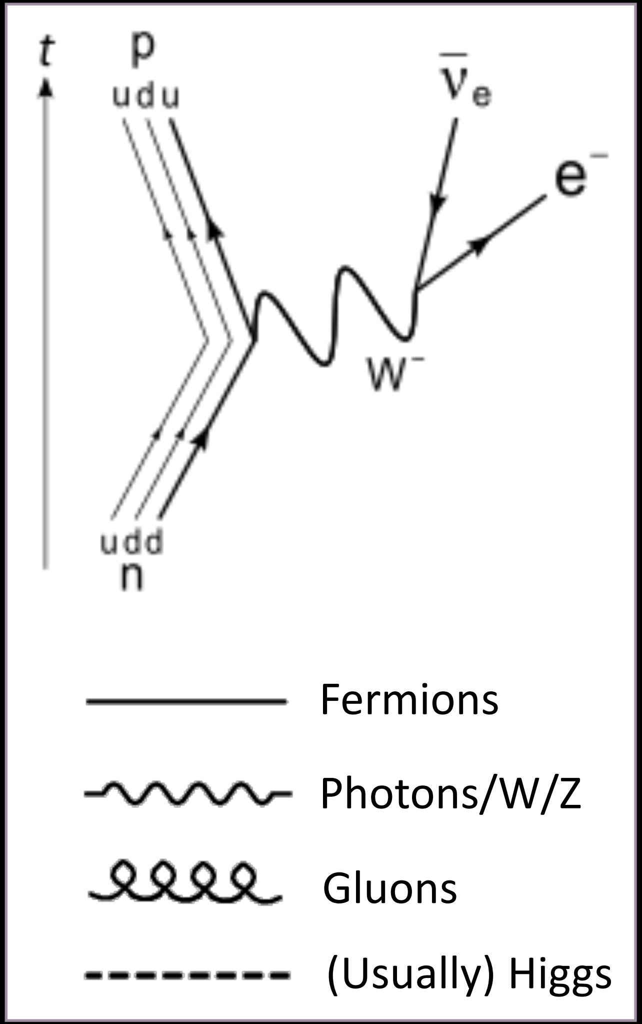
The only exact conservation law is CPT Conservation

Feynman Diagrams

Feynman Diagrams are the standard way to illustrate particle interactions
It shows the point of interactions, the original/final products, the boson that mediates the interaction, and visibly demonstrates preservation of conservation laws.

eg Back to Beta Decay: $n \rightarrow p + e^- + \bar{\nu}_e + 0.7823$ MeV

- Every vertex preserves charge, colour, lepton/baryon number, etc
- Typically time goes from bottom to top, or from left to right
- Antiparticles go backwards in time
- Bosons are squiggly lines (different squiggles based on boson)
- Good form: draw diagrams with maximum 3 lines per vertex.



e.g. Pair Annihilation

$e^- + e^+ \rightarrow 2\gamma$

Note: e^+ is a positron (aka anti-electron)

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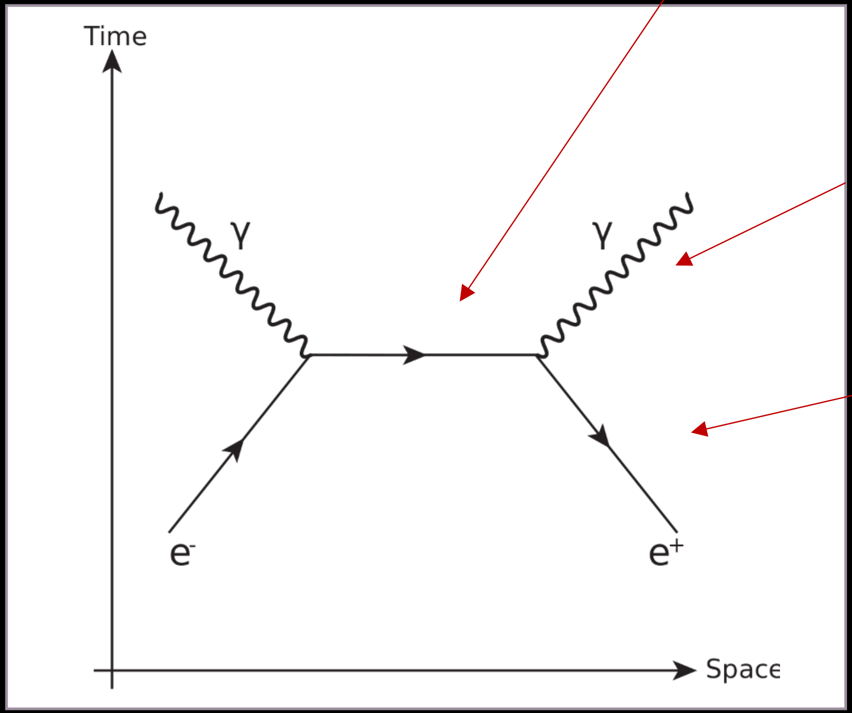
Note: e^+ is a positron (aka anti-electron)

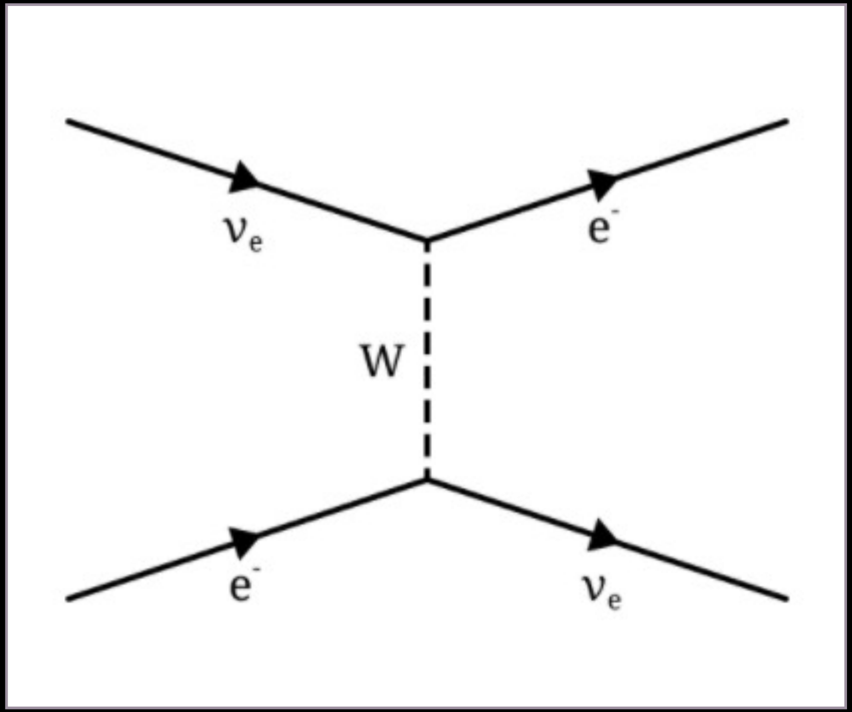
This is a virtual particle – it only exists as a 'ripple' during the interaction



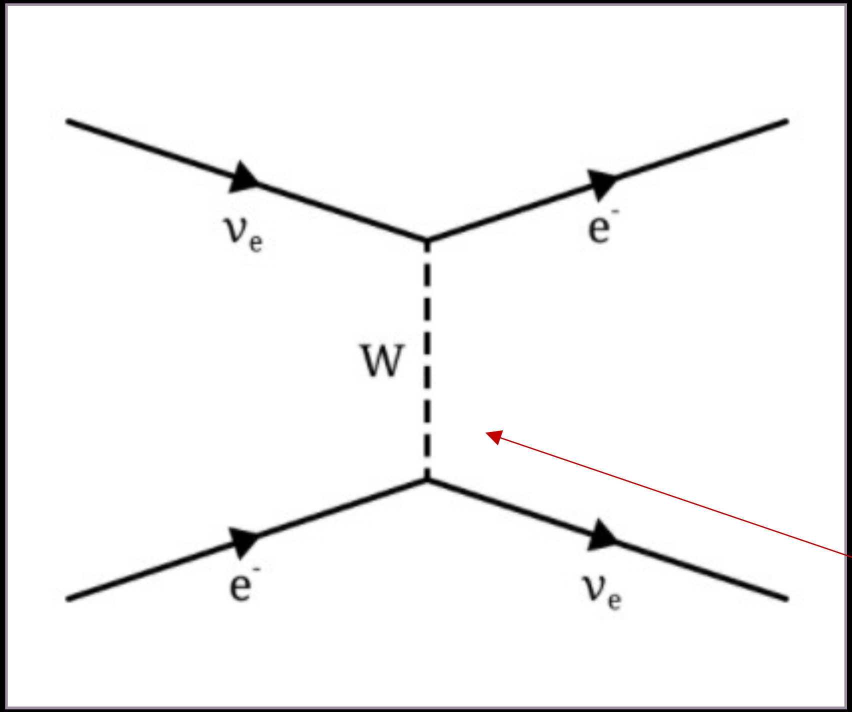
Photons (aka EM radiation aka light) released in this interaction

Antielectron goes backwards in time

e.g. What's going on here?



e.g. What's going on here?



$e^- + \nu_e \rightarrow e^- + \nu_e$

This is Elastic Scattering!

Equal probability W^+ and W^-, so W is sufficient

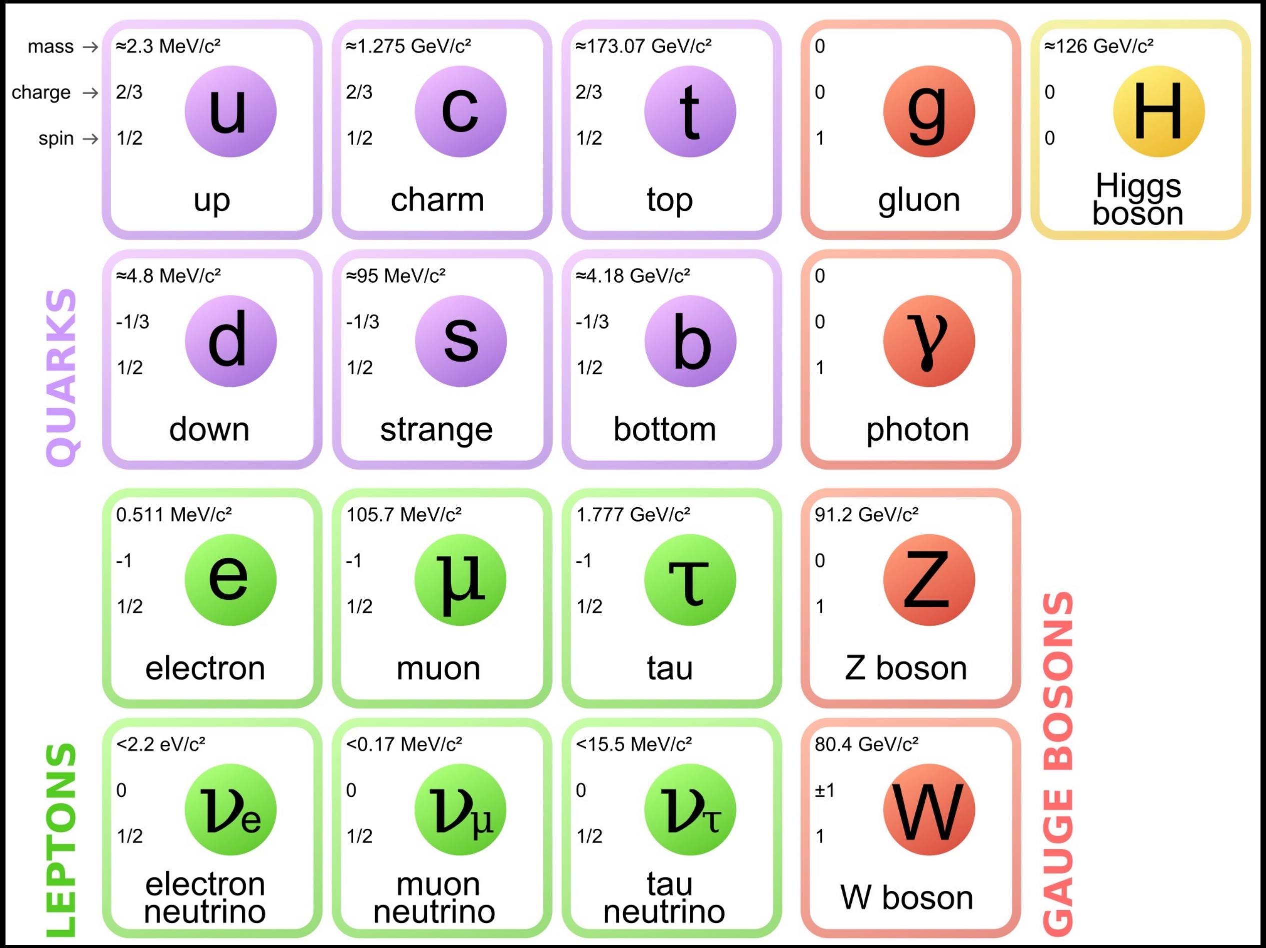
W^+ Case: The boson goes downwards to preserve charge at each vertex
W^- Case: The boson goes upwards

The Standard Model of Particle Physics

- Fermions: Every fundamental constituent of ordinary matter
- Bosons: How the fermions interact with each other
- Conservation Laws
- Works at micro and macro scales
- Speak the language of Quantum Physics
- Relationship between EM, Strong, Weak
- Fuck Gravity

Final "current" form finalized between 50s-70s, experimentally completed in 2012 with discovery of the Higgs Boson

Nearly everything discovered using accelerators



"The Standard Model is the most complete, well-tested, and well-understood framework in all of science"

- Probably People who worked on the Standard Model

The Solar Neutrino Problem...

Few minor outstanding problems with the Standard Model

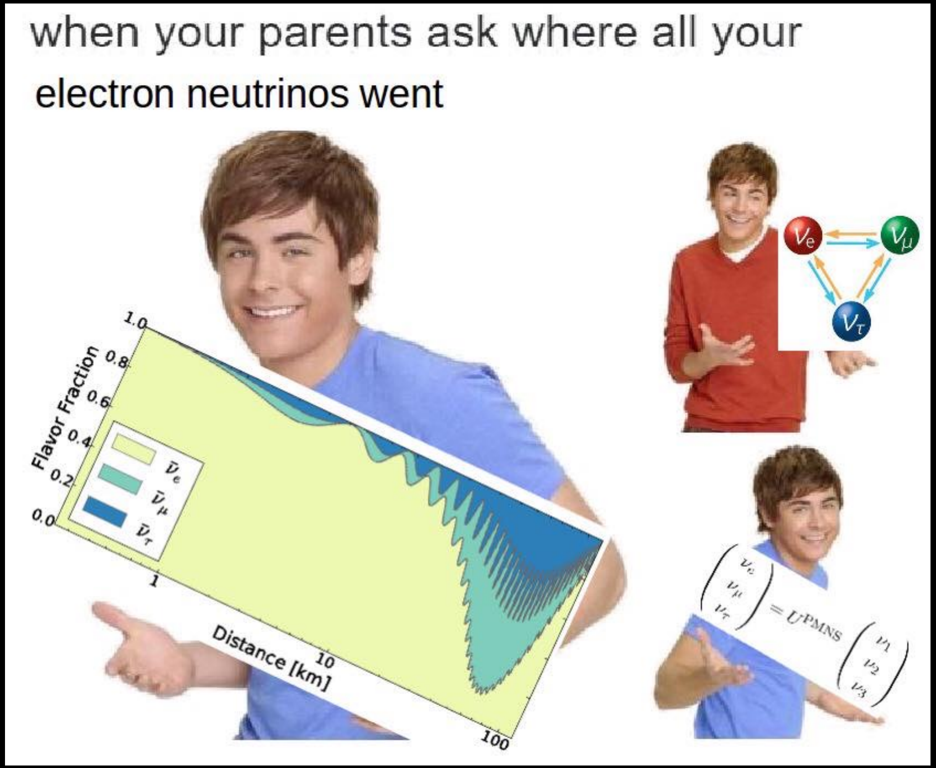
A major one:

- Thermonuclear reactions that power the Sun should only be able to produce electron neutrinos.
- We have a pretty good idea of how many electron neutrinos should be produced.
- When measuring the flux of electron neutrinos from the sun, we found that there were only 1/3 of the amount we predicted...

This is the Solar Neutrino Problem

The Sudbury Neutrino Observatory

- The Japanese Experiment Super-Kamiokande found out that neutrinos in the atmosphere flip between flavours (aka types).
- The first experiment to be sensitive to all types of neutrinos was the Sudbury Neutrino Observatory (SNO).
- SNO showed that neutrinos arriving from the sun came in all 3 flavours with equal quantities.
- Just like Quarks, it seems like Neutrinos can also oscillate between flavours as they propagate through space.
  - Quarks: CKM Matrix
  - Neutrinos: PMNS (MNS) Matrix

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Beyond the Standard Model

- Neutrino Oscillations requires neutrinos to have mass
- Problematic, since the Standard Model predicted neutrinos to have zero mass...

This opens up a whole bunch of problems.

- What are the neutrino masses?
- What order are the neutrino masses? (The Mass Hierarchy Problem)
- Why is there an asymmetry in matter and anti-matter?
- Can neutrinos be their own antiparticles? (The Majorana Paradigm)
- So on so forth

We need bigger, better, broader, bolder neutrino detectors to answer these questions.

The Era of Particle Astrophysics

- SNO and Super-K were among the first megalithic underground particle detectors.
- The implications of Neutrino Oscillations necessitates a new generation of underground experiments: the coming of age of Particle Astrophysics.

- Neutrino Trek: The Next Generation are now maturing.
- These techniques are ushering the golden age of the Dark Matter search
- The reigning scientific world champions – accelerator physics – coming back to defend their championship title
- Particle physics experiments are teaming up with astrophysics to tackle long-standing cross-disciplinary questions
- New particle physics technologies are being developed with scientific and real-world applications

“The World is sailing beyond a new horizon in physics.”
– Cool quote I heard at the opening talk of a conference