"The Standard Model" of Elementary Particles:
What is it?
Where did it come from?
What is it good for?

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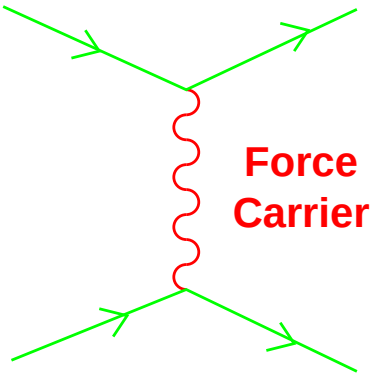
"The Standard Model"

This is the last slide on which you will hear me voluntarily use that phrase. . .

- I don't like the implication that we understand it all! We don't!
- So what does the phrase usually refer to?
  - ↪ A description of the weak, strong and electromagnetic forces caused by exchanges of fundmental particles
  - ↪ Unification of weak and electromagnetic forces
  - ↪ Proton, neutron, etc. modeled by strongly bound quarks
- What else might be out there?
  - ↪ New forces, particles, "symmetries"?
  - ↪ Explanation for heavy generations?
  - ↪ Unification of strong and electro-weak forces
  - ↪ Gravity?

Four Fundamental Forces

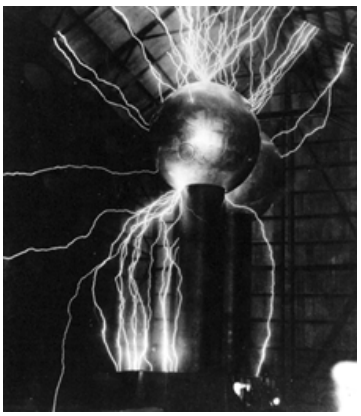
Gravity, Electromagnetism, Strong and Weak Nuclear Forces
Mediated by Force Carriers



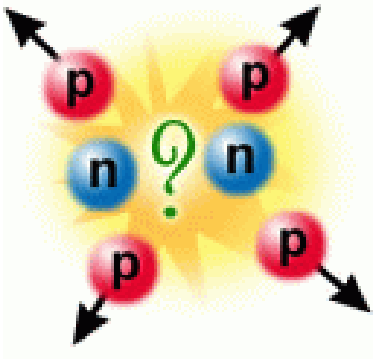
- Gravity
  - ↪ Attractive force between particles with mass or energy
  - ↪ Long range, macroscopic
  - ↪ Holds planets, solar systems, galaxies together


Gravity at Work

- Electromagnetism
  - ↪ Attractive or repulsive force between particles with electric charge
  - ↪ Long range, macroscopic
  - ↪ Holds atoms together, keeps matter from collapsing under gravity

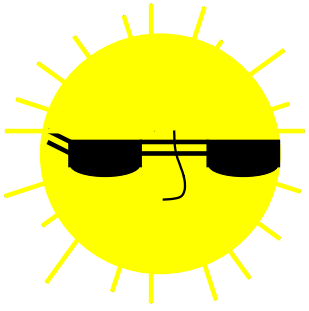

Shockingly Electromagnetic

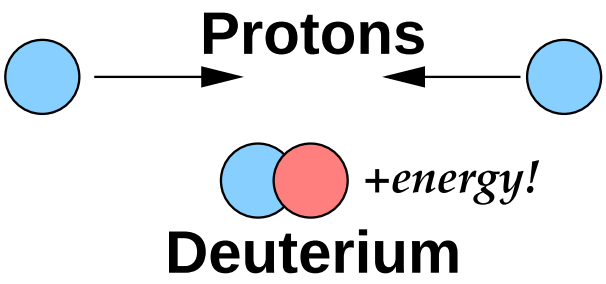
Four Fundamental Forces



- Strong Nuclear Force
  - ↪ The nucleus of an atom contains lots of protons that repel each other electromagnetically
  - ↪ Strong force binds them
  - ↪ Microscopic *because* it is strong!

- Weak Nuclear Force
  - ↪ Responsible for β decay. . . of nuclei
  - ↪ So who cares?





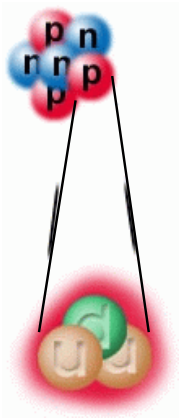
  - ↪ Fusion requires that a proton change into a neutron
  - ↪ This is the inverse process of β decay!

Anti-Matter

Not just for Star Trek anymore. . .

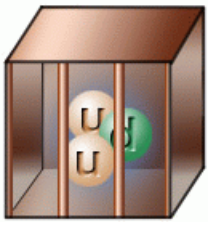
- Every particle we know about has a corresponding anti-particle
  - ↪ Proton has an anti-proton; electron has positron
  - ↪ Photon is its own anti-particle!
- Anti-particle has all the same properties, include same mass, but opposite electric charge
- Matter and anti-matter can be combined to make "pure energy"
  - ↪ Meaning force carriers for a particle physicist
  - ↪ And energy can make pairs of matter and anti-matter particles

Building Protons: Quarks



- Protons (and neutrons) are made up of three quarks
  - ↪ "Up" quarks have charge +2/3
  - ↪ "Down" quarks have charge -1/3
  - ↪ Proton = uud
  - ↪ Neutron = udd

- How can charged "u" be bound to "ud" combination?
  - ↪ Strong force is strong as glue!
  - ↪ So strong, that free quarks cannot be found

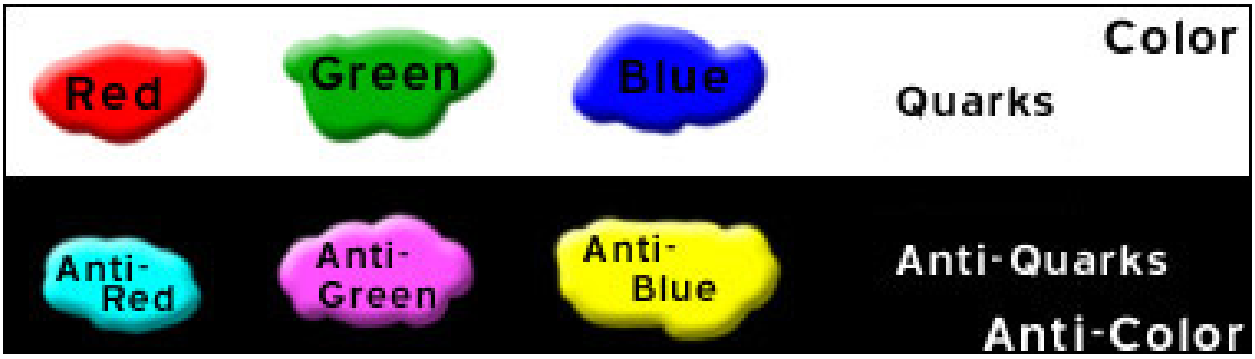


- What quark combinations are found?
  - ↪ The key is making it "color neutral"
  - ↪ Three colors (red, blue, green) combine like light

Building with Quarks

- Red+green+blue ⇒ colorless
- These three quark combinations are called "hadrons"
- Quark+antiquark combinations ("mesons") are also allowed

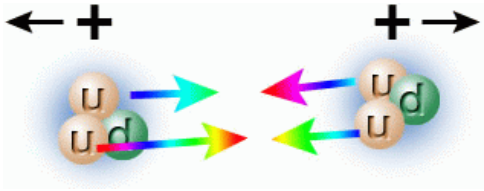
  ↪ Color+anticolor ⇒ colorless



- What holds a nucleus together?
  (protons and neutrons are colorless)

  ↪ Residual strong forces

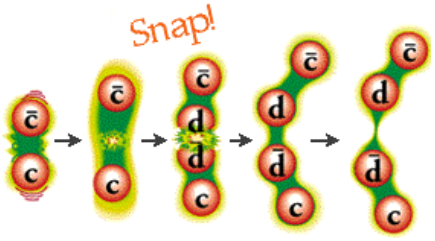
  ↪ This is why nucleus is not so much bigger than proton



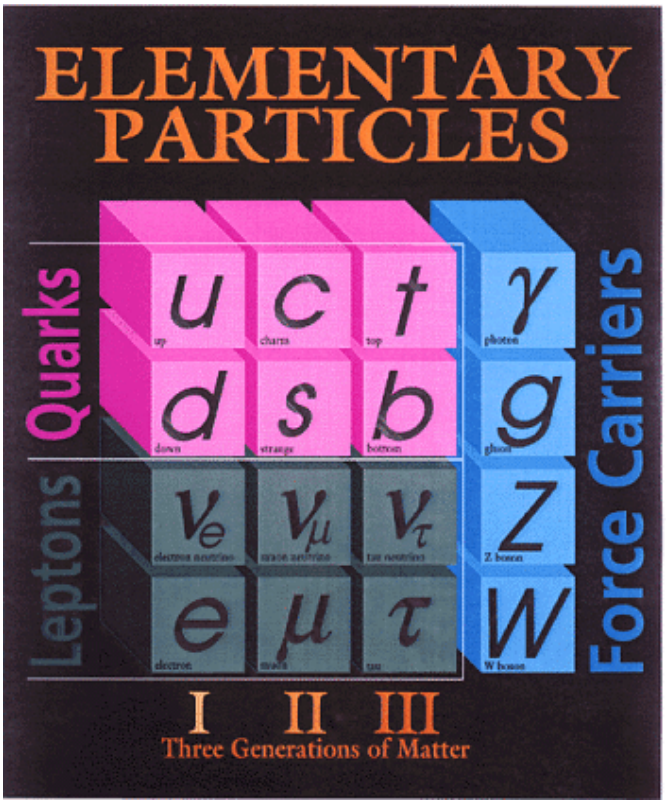
- What happens if you try to defeat confinement?

  ↪ Convert energy into matter

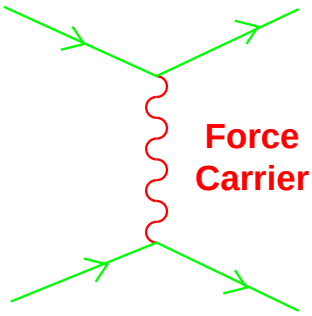
  ↪ Like snapping a spring!



Elementary Particles



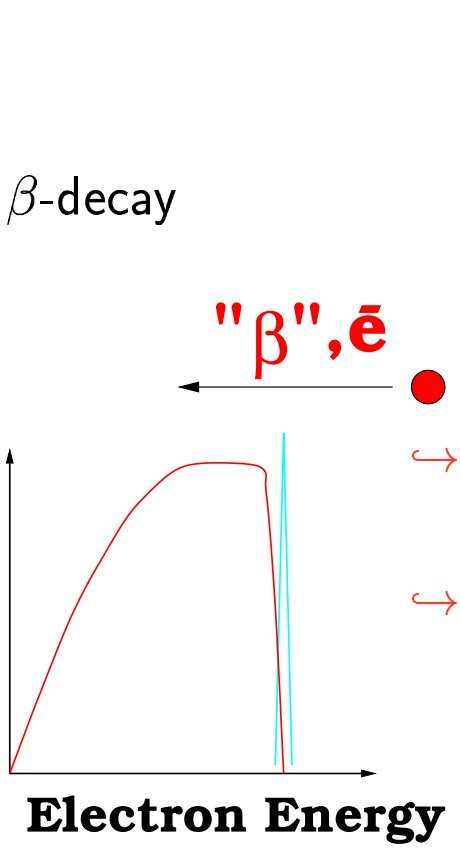
What are these things?



- "Force Carriers" are the particles responsible for creating the four forces
- "Quarks" are the things that make up protons and neutrons and are bound together inside a nucleus
- "Leptons" include the electron and the neutrino

What's a Neutrino?

- The mysterious extra particle in beta decay



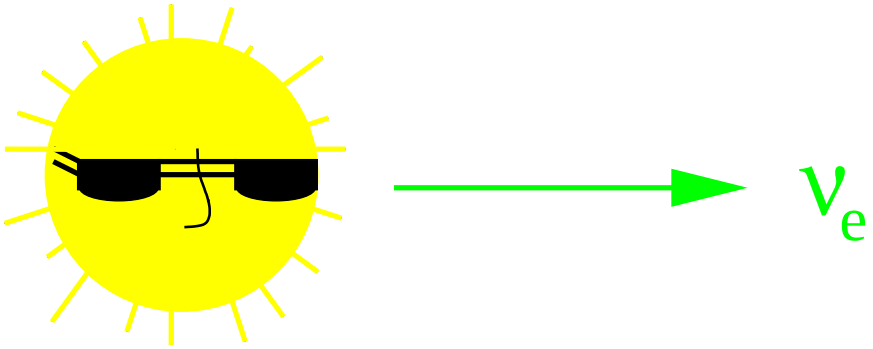
↪ Two-body reaction, electron energy should be fixed

↪ Where did the other energy go?
into a neutrino!

- Has no electric or "color" charge; interacts weakly!

Where do we find neutrinos?

- The Early Universe
  - ↪ Decays of the heavy generations leave ~ 100/cc of each type of neutrino behind
  - ↪ These are, by now, very cold (slow) and hard to detect
  - ↪ But, if the neutrino has significant mass (10 eV), they would make up most of the mass in the Universe!
- The Sun

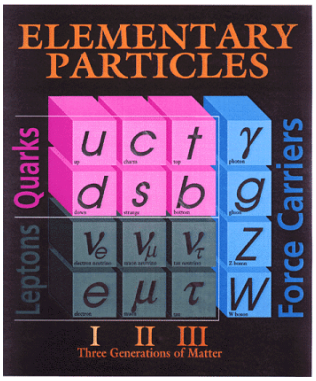


  - ↪ If the sun shines from fusion, energy flux on earth from light and neutrinos are similar
  - ↪ About 100 billion neutrinos per cm^2 per second rain down on the earth
- Natural Radioactivity
  - ↪ We contain about 20 mg of ^{40}K, which is a radioactive β emitter
    - ⋆ Each of us emits about 0.3 billion ν/sec
  - ↪ At the earth's surface, the natural radioactivity in the earth results in 10 milliion $\nu/\text{cm}^2/\text{sec}$

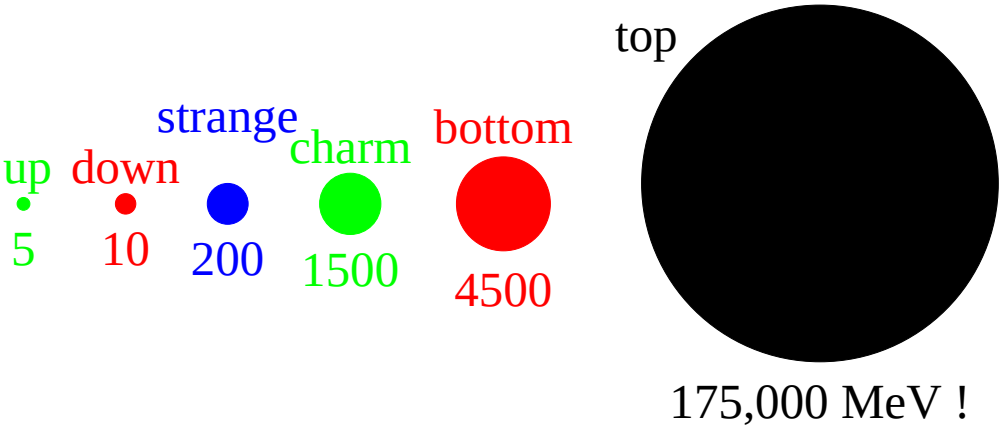
Generations

If ordinary matter around us is made of up and down quarks and electrons. . .

. . . what are all those other particles doing there?



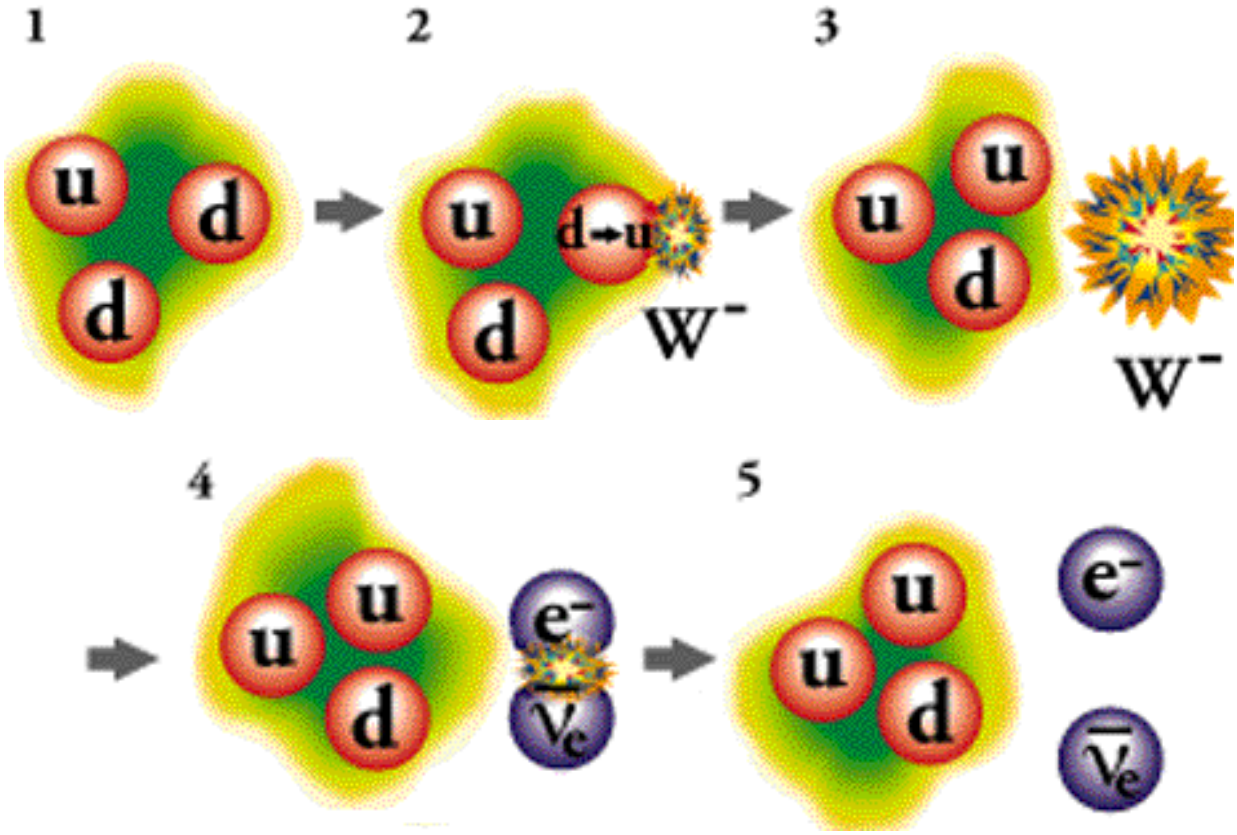
- Good question!
- There appear to be three copies of each of the "light" particles that make up ordinary matter
- Particle physicists call these "generations"
- The only property that seems to separate them is mass



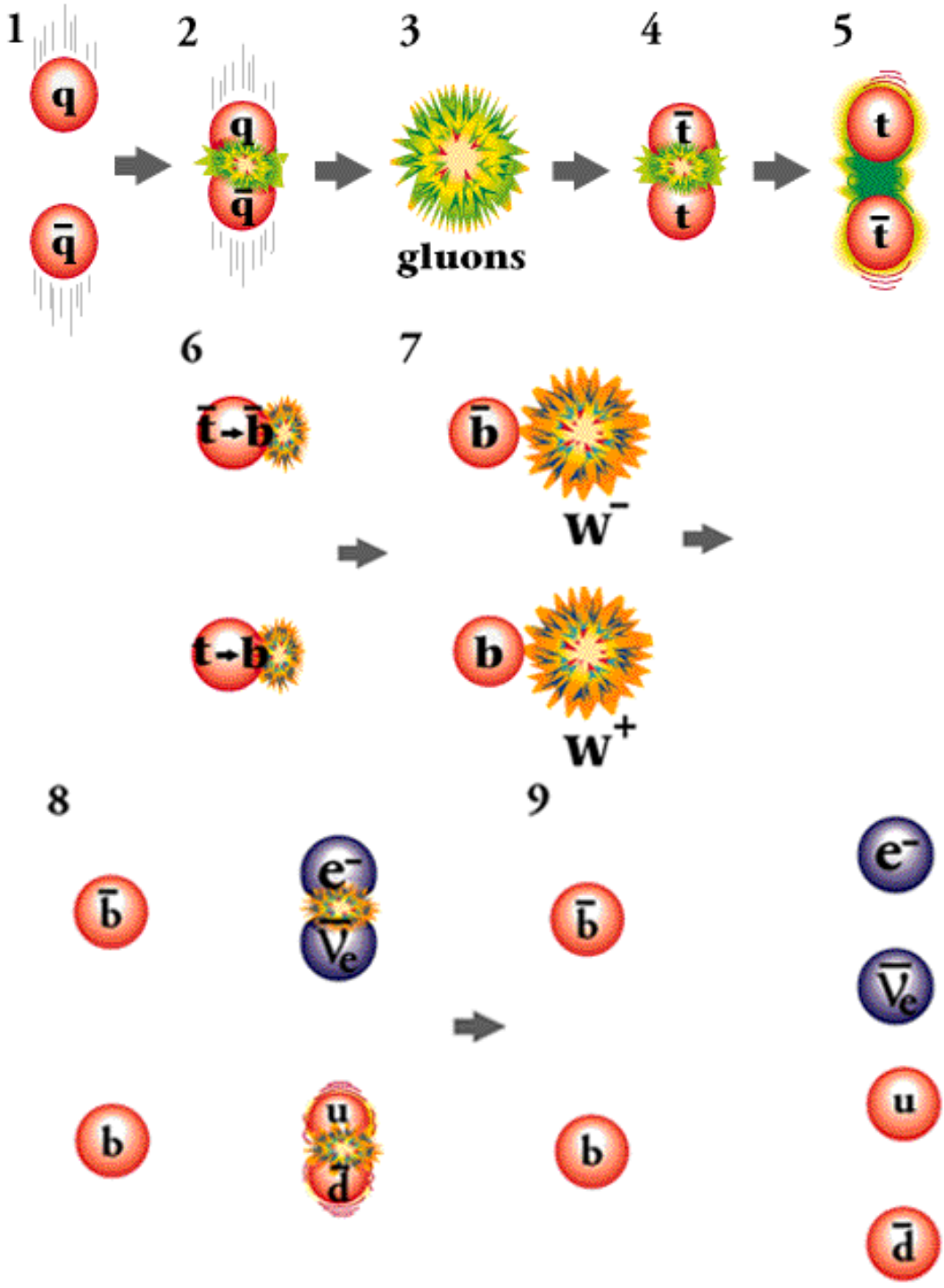
- And the only way for particles of one generation to change into another is. . .

the weak interaction ("β-decay")

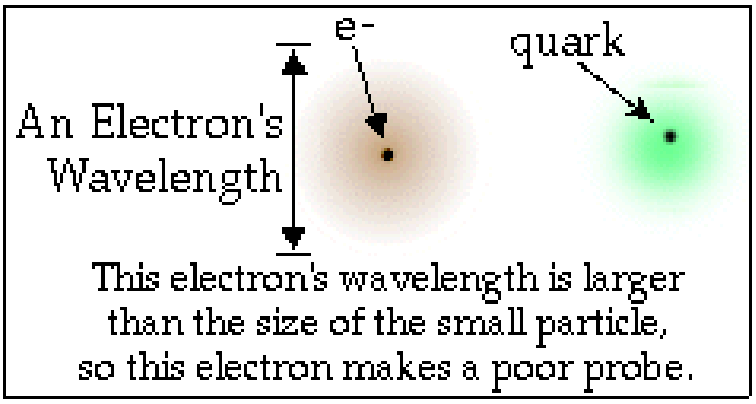
Radioactive Beta Decay

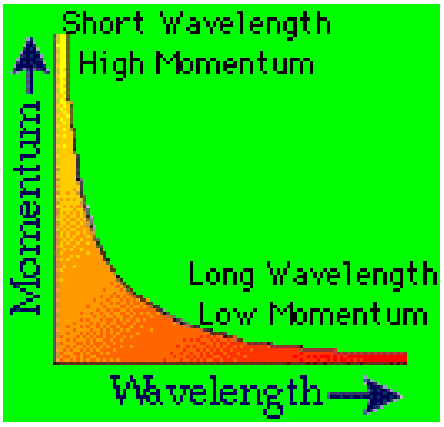


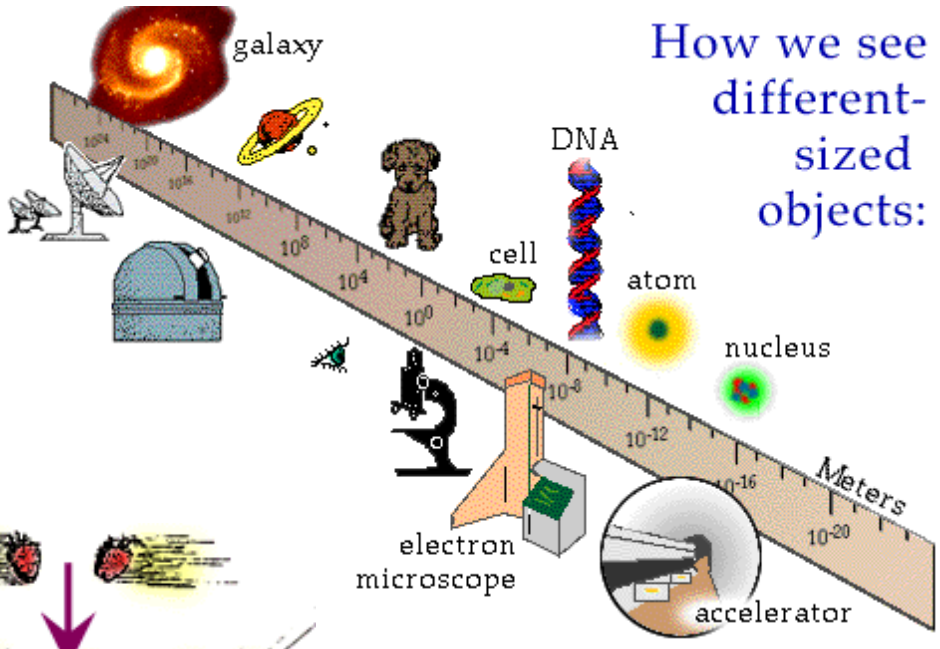
Producing Top Quarks

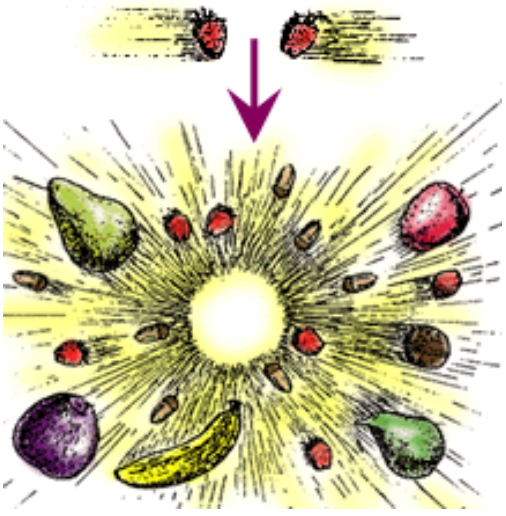


What Are Particle Accelerators For?





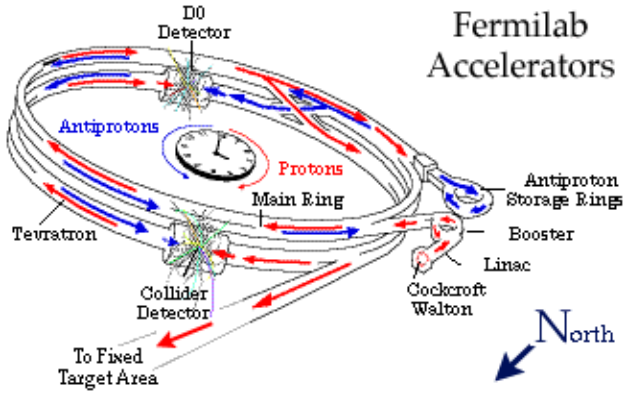


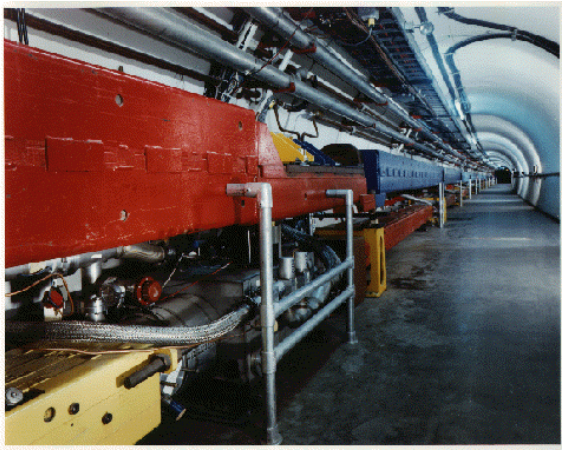


Can also use the energy contained in the beams to produce matter that was not originally there!

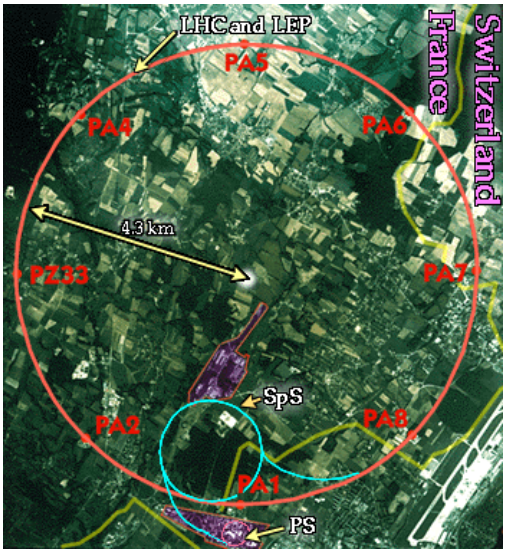
$p\overline{p} \rightarrow$ FRUIT

Some Accelerators in the World

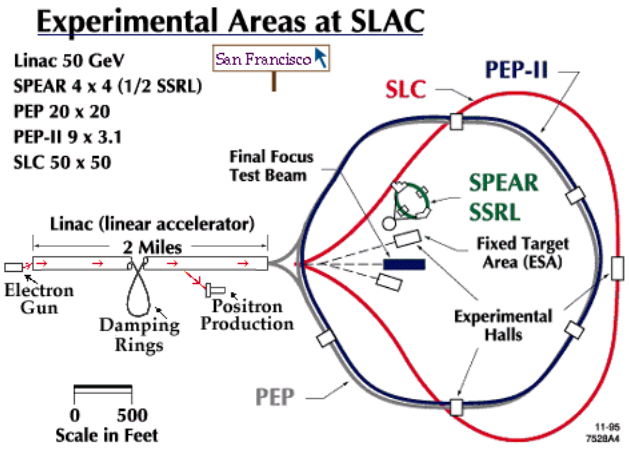


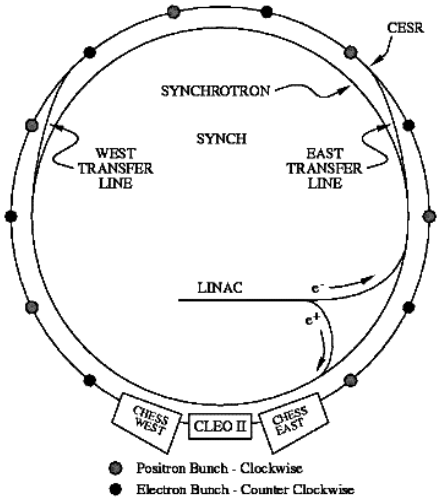


FNAL $p\overline{p}$ $\sqrt{s} = 2$ TeV



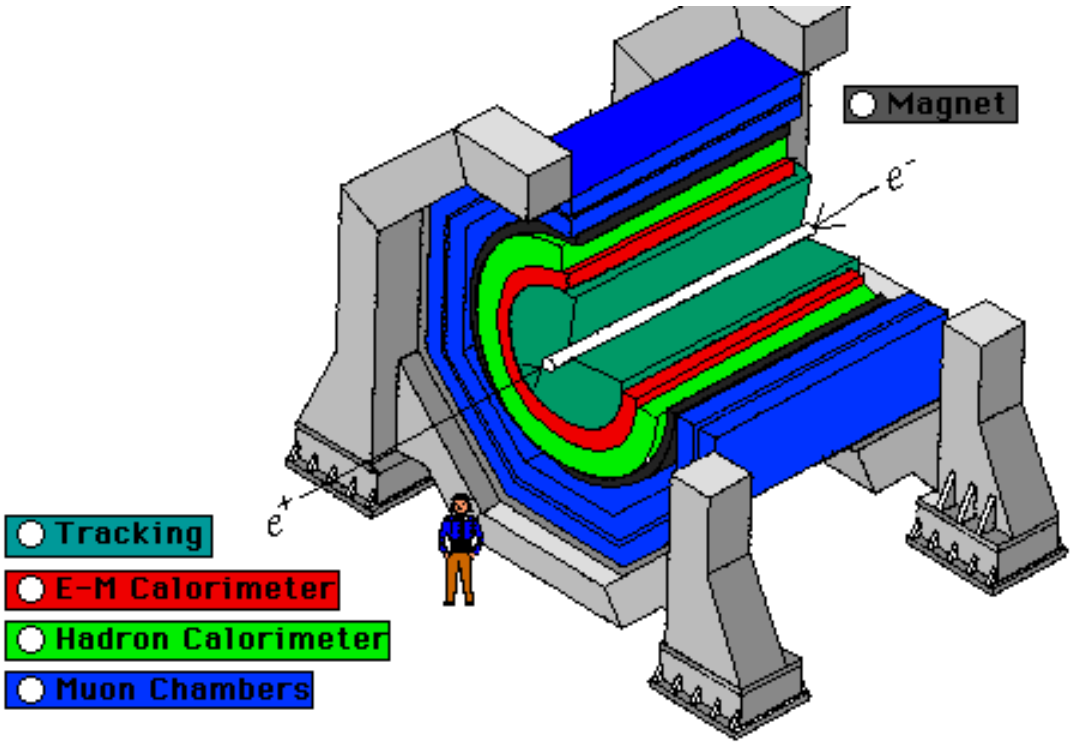
LHC pp
$\sqrt{s} = 14$ TeV

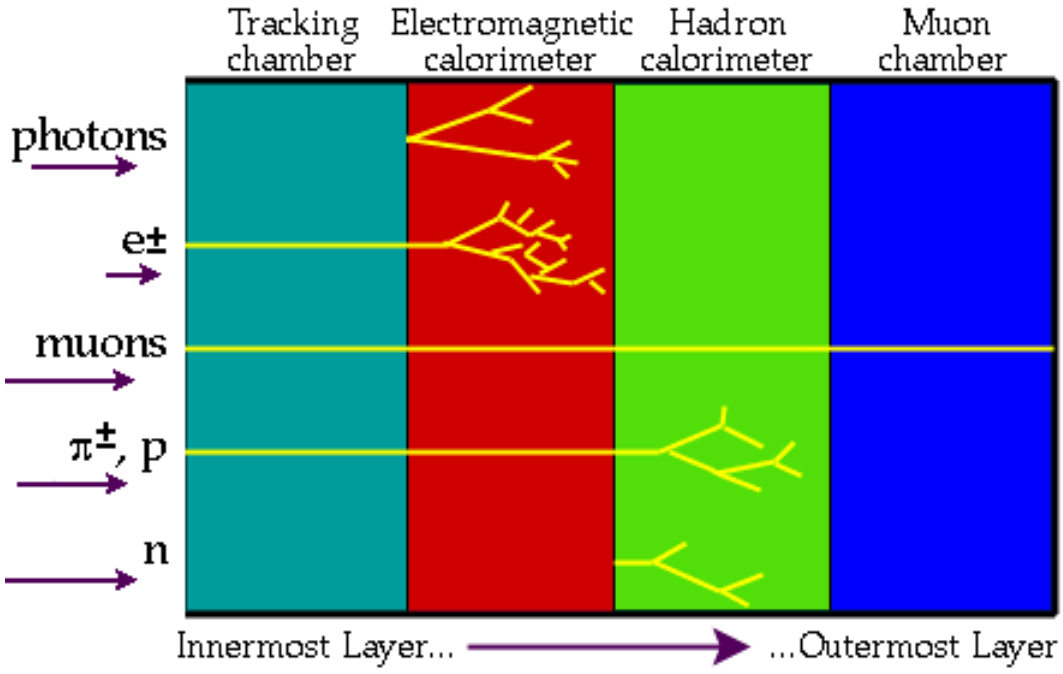




Particle Detectors

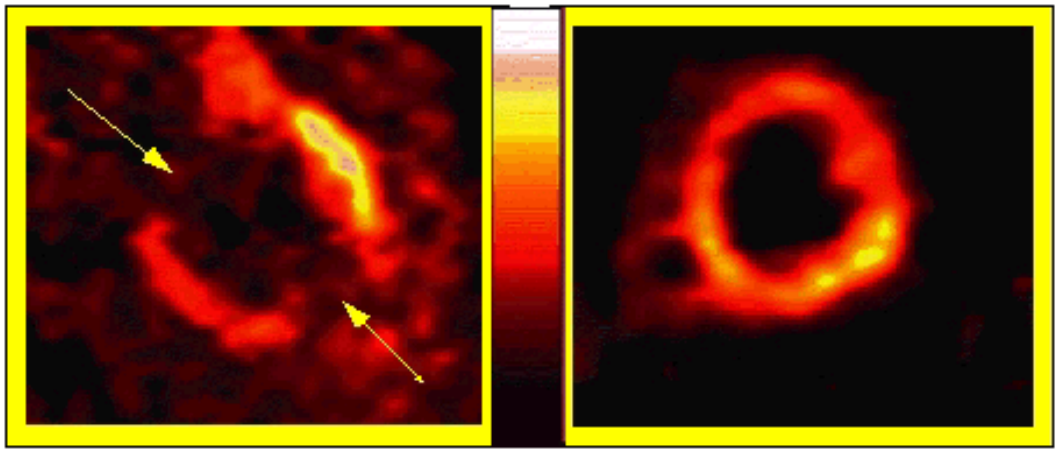
Collider Detectors: Surround the Interaction





Of What Use is all this Techology?

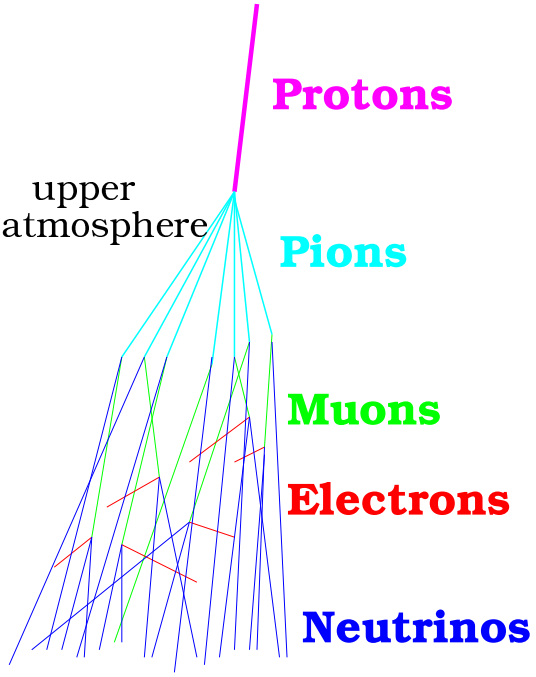
- Particle physics technology is the backbone of medical imaging!
  - ↪ X-rays, MRI, PET, etc.
- Example: Positron Emission Tomography (PET)
  - ↪ Doctors inject patient with a radioactive material that decays and emits anti-matter electrons (positrons)
  - ↪ Positrons combine with electrons in body to emit pure energy (photons)
  - ↪ Doctor detects photons (gamma rays)
  - ↪ Radioactive material embedded in *biologically active compounds!*
    - ⋆ E.g., into sugar to feed healthy tissue



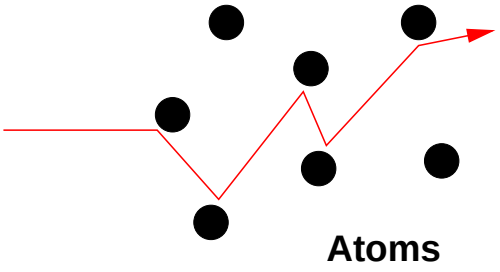
Left: Heart w/ dead Myocardial Tissue; Right: Healthy Heart

Cosmic Rays

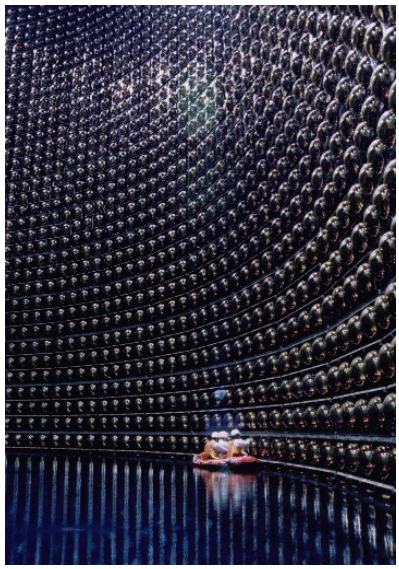
- Cosmic Rays
  - ↪ Cosmic Rays from galaxy interact
  - ↪ Create weakly decaying particles
  - ↪ Muons, Electrons, Neutrinos



Electrons Stop. . .

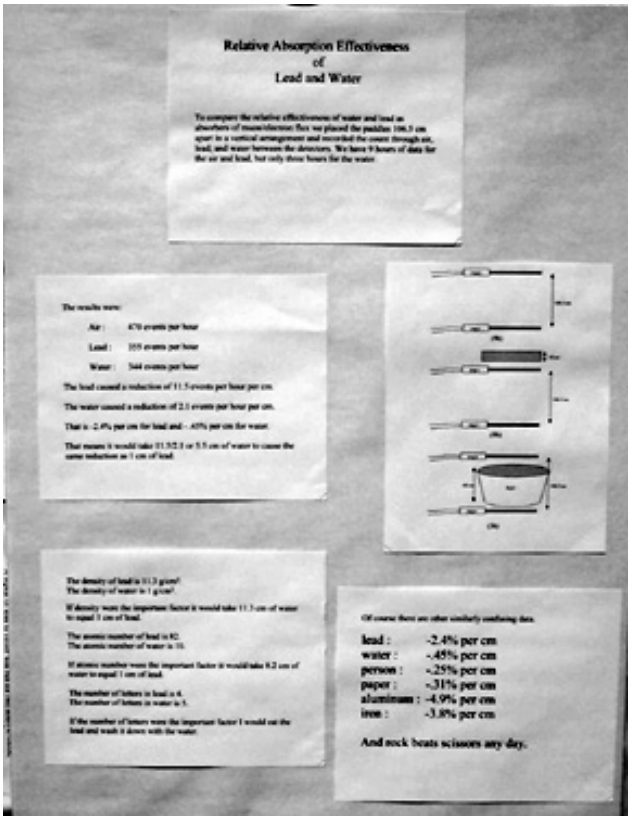


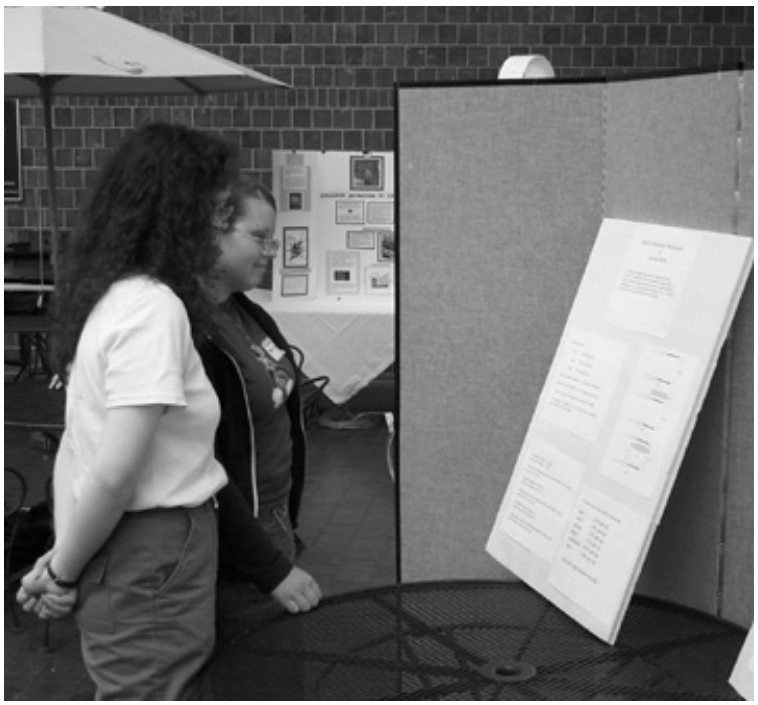
. . . Neutrinos are hard to see



But Muons are just right. . .

Cosmic Rays and the Classroom





Where to go to Learn More?

- On the web

  Particle Adventure `http://particleadventure.org/`

  Fermilab `http://www.fnal.gov/`

  Brookhaven `http://www.bnl.gov/`

  Cornell `http://www.lns.cornell.edu/`

  CERN `http://www.cern.ch/`

  PARTICLE `http://www.pas.rochester.edu/particle/`

- Books

  ↪ "The God Particle" by Leon Lederman

  ↪ "The Charm of Strange Quarks", Barnett, Muehry, Quinn

- To tour

  ↪ Cornell Electron Storage Ring, Cornell University, Ithaca, NY

  ↪ Relativistic Heavy Ion Collider, Brookhaven National Laboratory, Upton, NY

  ↪ TeVatron Collider, Fermilab, Batavia, Illinois