The Big Picture…

The Big Picture… of Physics 100

- What did we learn about?
  - We took the theory of gravity from the surface of the earth and showed it applied to the solar system
  - Then we looked at relativity
    - And the implications for the whole Universe
  - Then we got introspective…
    - Quantum theory explained the atom
    - Nucleus needed the addition of a “new force”

Two Major Goals for studying the smallest things…

- Want to understand the “dynamics” of a theory, and not just “kinematics”
  - “How” as opposed to “what”
- Want to understand the structure of matter at the smallest scales
  - Are there more “nucleus” like surprises?
  - What holds them together into larger structures of matter (protons, electrons, etc.)

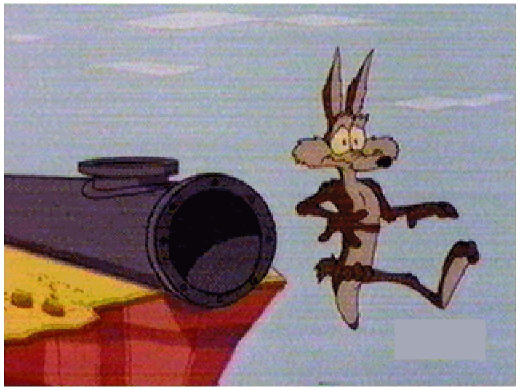
Dynamical Forces

Dynamics vs. Kinematics

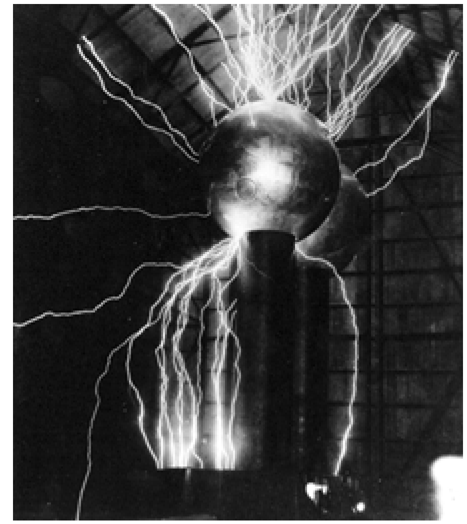
- "Kinematic analysis" of Newton's gravity
  - Gravity exerts a force on my tennis ball
  - The tennis ball accelerates down
- But a "dynamic" theory would tell us…
  - Why does the earth pull the tennis ball down?
  - Einstein's general relativity, remember, is actually a dynamical picture!

What are the forces we need to explain "dynamically"?

- Gravity
  - attractive force between particles with mass or energy
  - long range but very weak
  - holds planets, galaxies, etc. together
  - makes road runner happy…



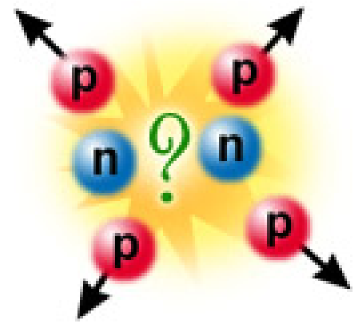
What are the forces we need to explain "dynamically"?

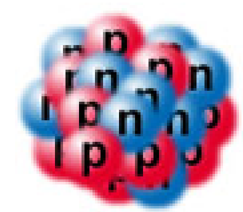


- Electromagnetism
  - attractive or replusive force between particles with charge
  - long range
  - holds atoms together
  - keeps matter from collapsing under the force of gravity
    - shockingly important!

What are the forces we need to explain "dynamically"?

- Strong Nuclear Force
  - the nucleus of an atom contains lots of protons that all repel each other electromagnetically
  - the strong force binds them
  - it's a force that is short-range because it is so strong!

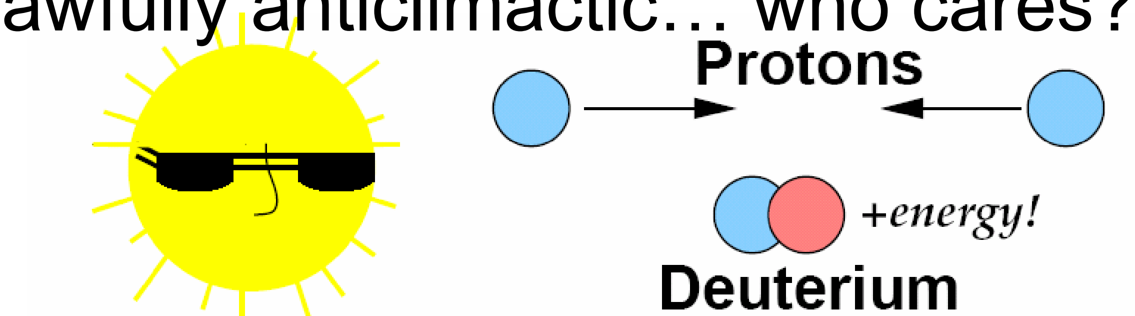




Miracle of all these different forces is that they operate on complete different scales!

What are the forces we need to explain "dynamically"?

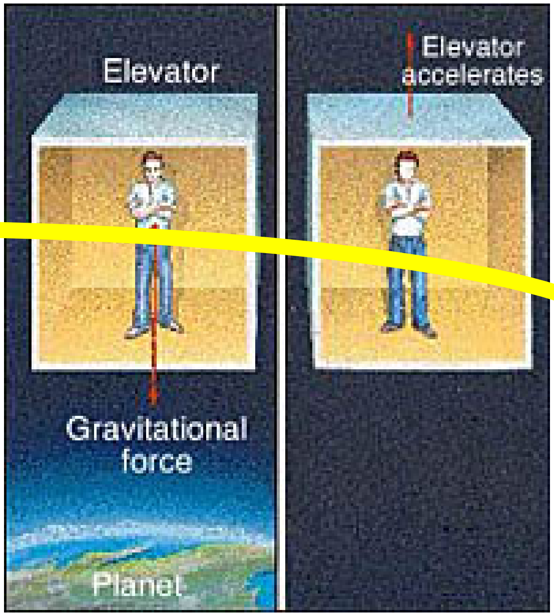
- Weak Nuclear Force
  - its exciting role is to, well, make β-decays
  - that sounds awfully anticlimactic… who cares?
    - actually, you do. A lot.



  - Fusion in the sun requires that a proton turn into a neutron. Inverse of β-decay!
  - Without β-decay, we are stuck where the sun don't shine…

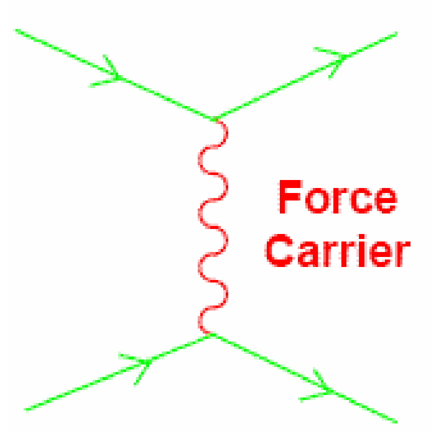
"Dynamical" Gravity from Einstein

- Einstein's General Relativity is Dynamical
  - tells us, for example, that the "why" is because space is curved and the ball is taking an "inertial" path
  - Remember our elevators!
  - "Inertial path, to either accelerating observer, is not a straight line!



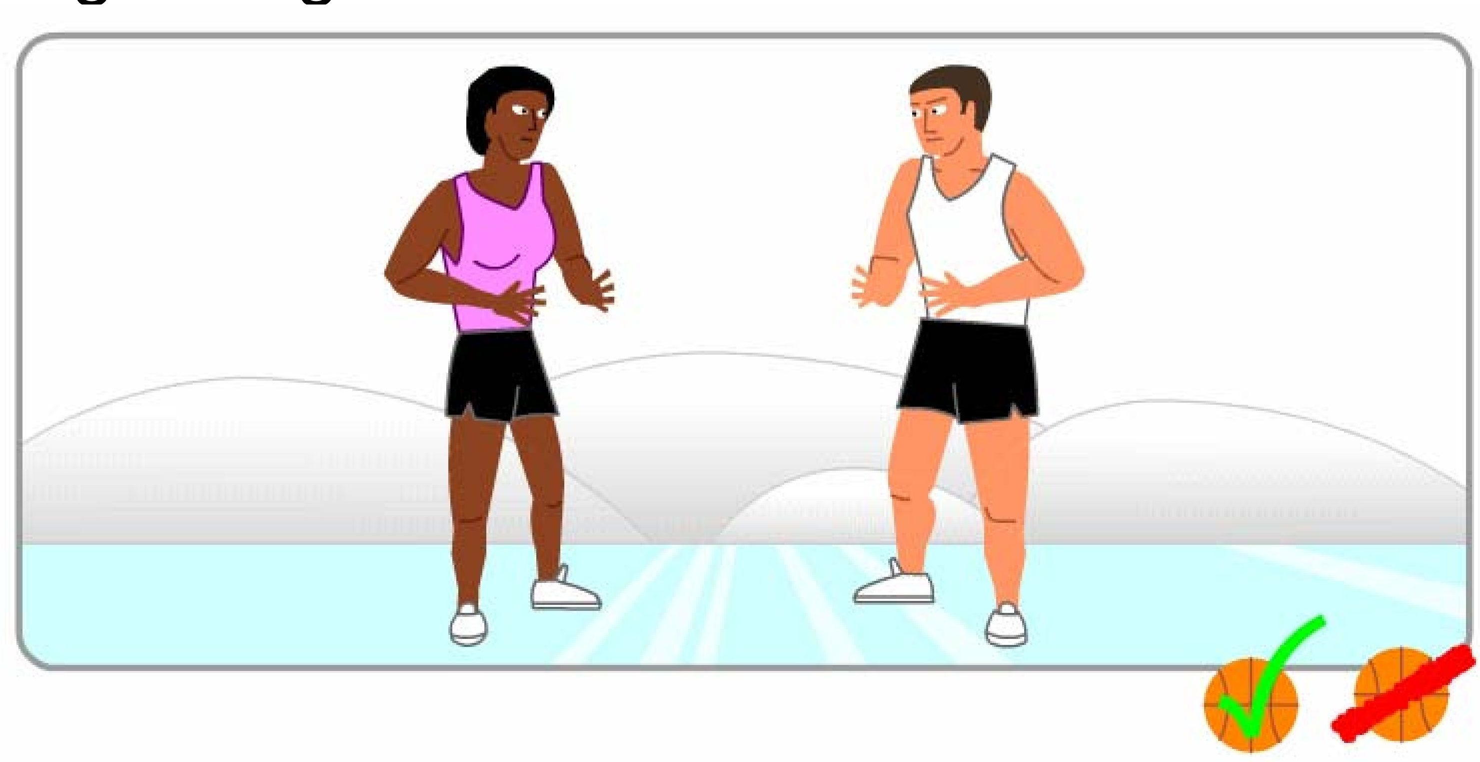
What is our dynamical Quantum Theory of the atom?

- It's a theory of force carriers
  - The strong, weak, electromagnetic and gravitational forces are all "mediated" by an exchange of force carrying particles
- Symbolically…
  "Feynman diagram"



How does this work?

- Imagine a game of basketball on ice…



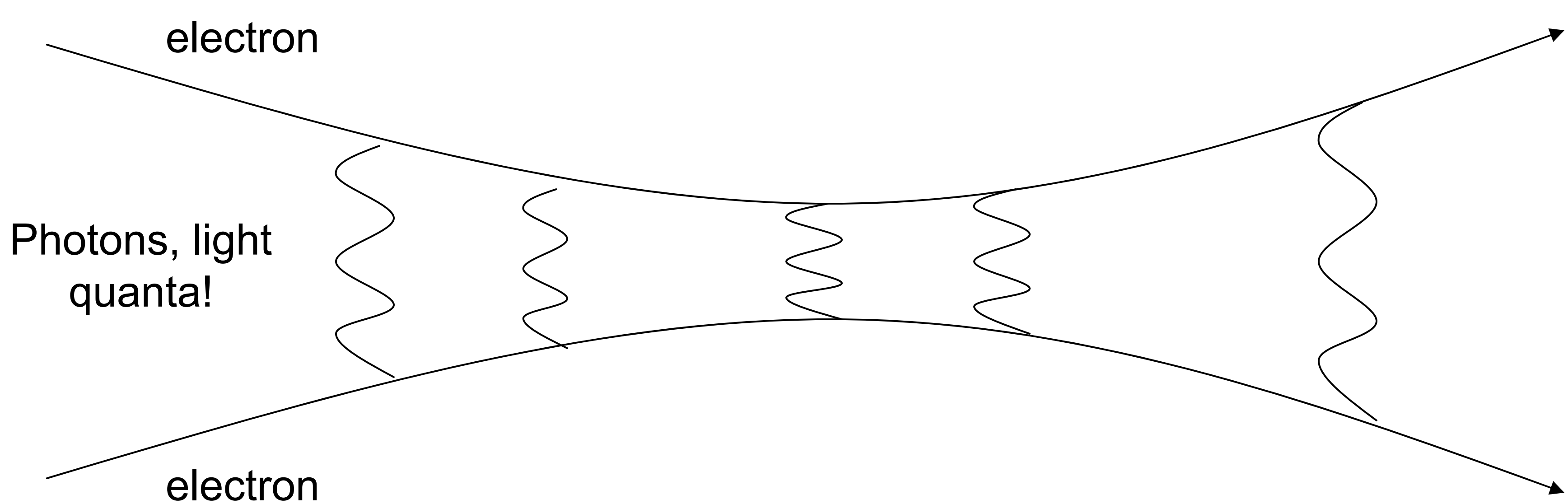
- By exchanging basketballs, players also exchange momentum. Definition of a force!

This is Quantum Electrodynamics!

- Yicky name…
- But all it means is a quantum…
  - Think uncertainty principle, wave/particle duality
- … electro…
  - Electricity and magnetism. Like charges repel, etc.
- …dynamical theory
  - Finally an explanation for WHY!
- Developed by Richard Feynman and Julian Schwinger in late 1940’s

So the electrostatic repulsion of two electrons looks like…

- Now might exchange many photons (far apart)
- The photons are a "quantum fluctuation" allowed by the uncertainty principle…



“Correspondence” Principle

- Here’s an interesting “who cares” question
  - If two particles exchanging a force are far apart (force is weak) then do you need this fancy quantum fluctuation dynamics?
- Nope…
  - If many particles are being exchanged, the whole Maxwell picture of forces in empty space still holds
- “Corresponds” to “classical” theory

Uncertainty principle and quantum dynamics

- But imagine the other limit… very short distance
  - Short range force, implies photon doesn't travel long $t = \frac{D}{c}$
  - So Heisenberg says… $(\Delta E)(\Delta t) \sim h$
  - So minimum energy $E_\gamma \sim \frac{hc}{D} \sim \frac{2 \times 10^{-25}\, Joule \bullet meter}{D}$
  - So if D is size of nucleus (10^{-15} m), E~10^{-10} Joules
    - This is the mass of a proton! Coincidence? No…

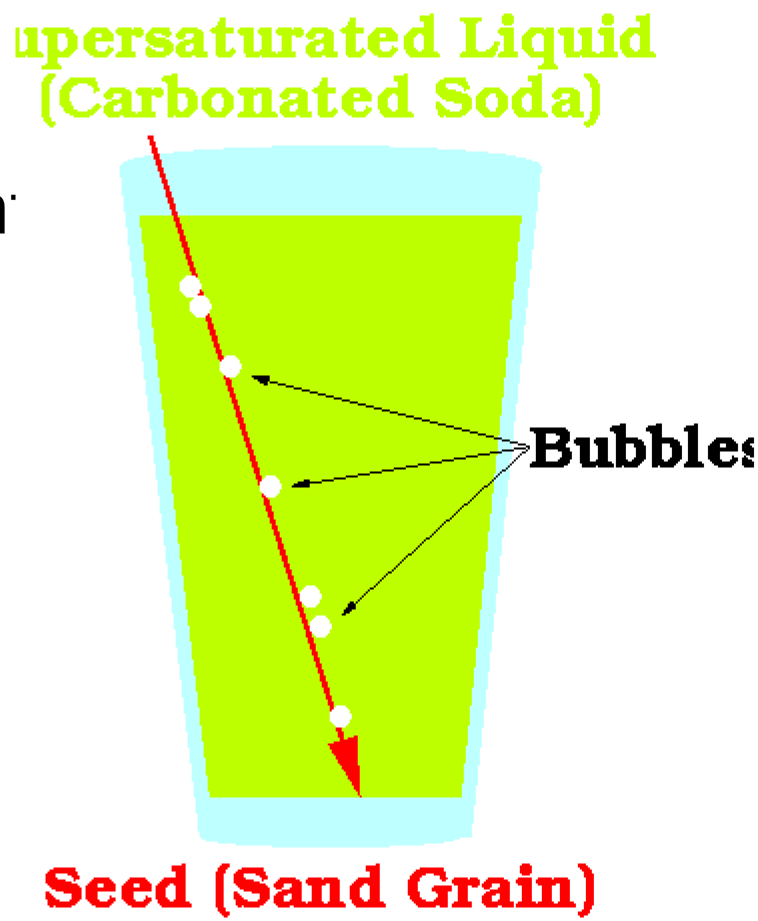
Detecting Particles

Detecting tiny particles…

- Seeing very small single particles is important in this business…
- We saw one important tool (Geiger counter)
  - But I didn’t give you a dynamic theory of the Geiger counter…
- Let’s develop a dynamic theory of another kind of detector, the cloud chamber, to understand how to see the sub-atomic…

Cloud Chamber…

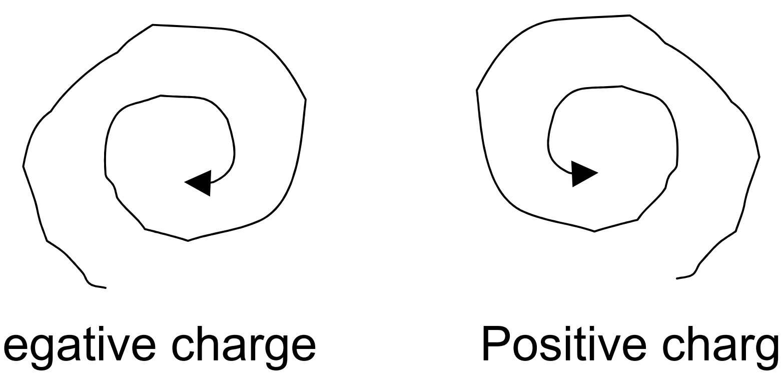
- Works on principle of supersaturated environmen
  - The particle ionizes atoms as it goes through material
  - Ionizing acts as a “seed” for a cloud



Matter and Anti-Matter:
It’s not just for Star Trek Anymore

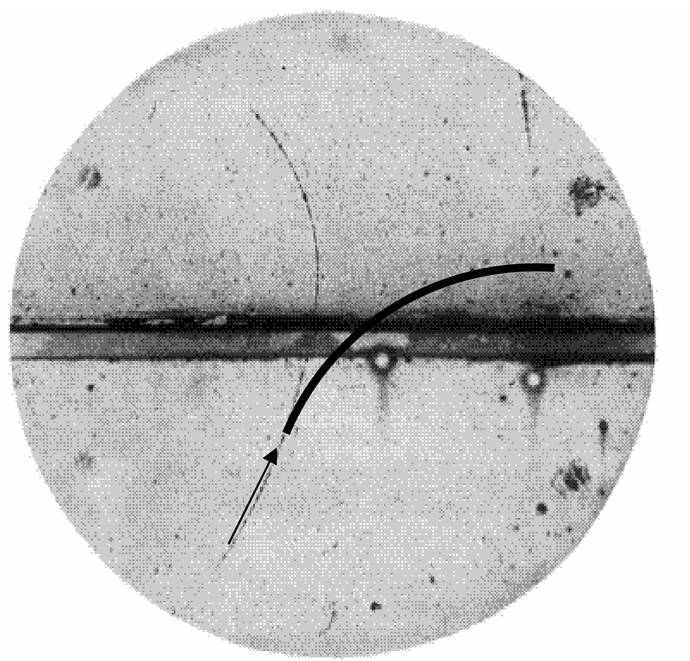
Particles in Cloud Chamber

- Remember that particles bend in magnetic field
  - "cathode rays" of J. J. Thomson
- Electric charge of particle determines the direction of the bend…
  - Curling up is because of losing energy ("friction")



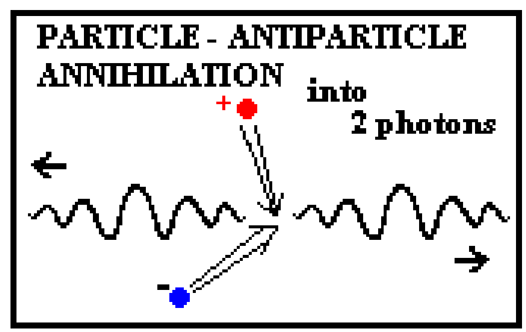
Discovery of Antimatter…

- Carl Anderson (1932) slowed down electrons from cosmic rays by lead and found that some of the
  - Bent the wrong way!
  - Electron should have done this…
  - Could not be a proton (would not have slowed down)

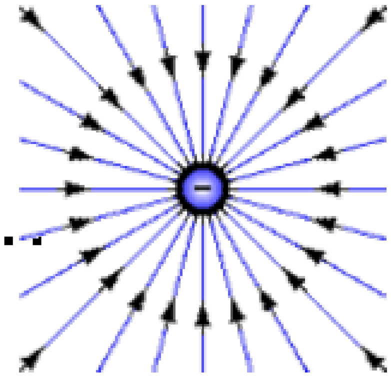


Antimatter… is really weird

- It has all the same properties as matter
  - Same mass
  - Same interactions
  - But opposite electric charge
- Has another weird property…
  - It can annihilate with matter to create pure energy!
  - Or, conversely, energy can create matter and antimatter pairs. $E=mc^2$



But anti-matter had better be there…



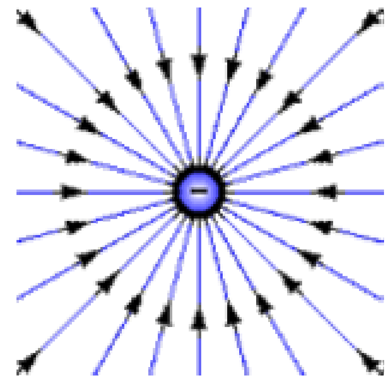
- The Coulomb force of an electron…

$$F \propto \frac{1}{(\text{distance})^2}$$

- …actually means there is energy around the electron. It is just as real as "rest mass"
  - How much energy?

$$\Delta E \propto \int_0^\infty 4\pi r^2 E^2 dr = \int_0^\infty 4\pi r^2 \frac{k^2 e^2}{r^4} dr \rightarrow \infty$$

But anti-matter had better be there…



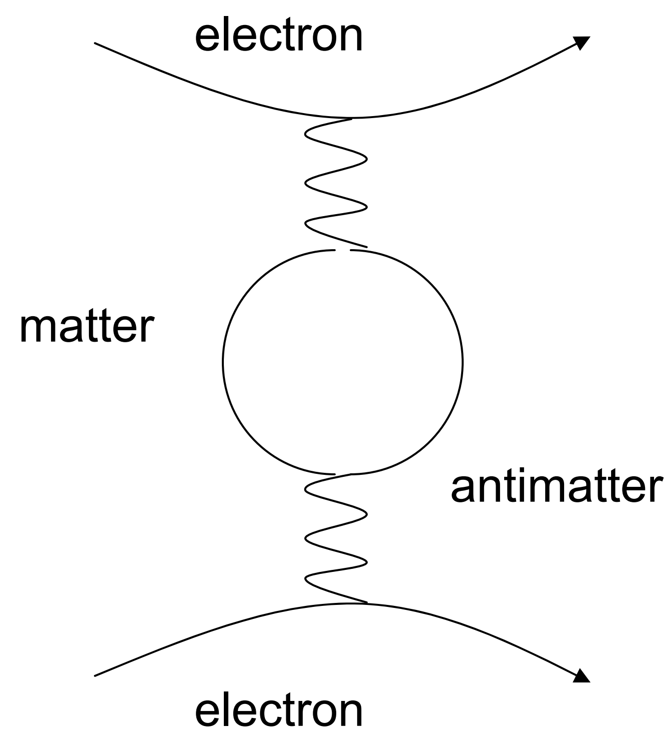
- Oops… well, that's OK, the electron has a "size" that off the infinity
- Size of electron is now known to be $<10^{-18}$m, so we conclude

$$\Delta E \sim 10^{-9} \text{ Joules}$$

- But that's nuts! $E=mc^2$ of electron is only $\sim 10^{-13}$ Joules so where did the factor of 10000 go?
  - What's the solution to the dilemma?

What antimatter does to the Coulomb force…

- Quantum mechanics and anti-matter save the day!
  - Quantum fluctuations to matter and anti-matter!



- These processes tame the infinite energy by screening the field with "quantum bubbles"
- These bubbles act to shield the Coulomb force, but only at very small distances where force is huge

Seeing Structure

First glance at studying the structure of matter…

- Study structure by peeling layers from an onion. See the next layer for its own sake!

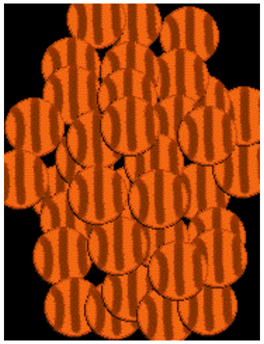
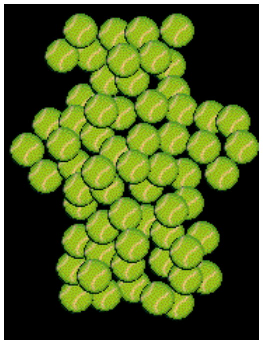
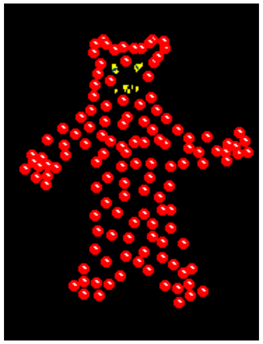
- In my view, this is only a part of the goal

How to probe the very small…

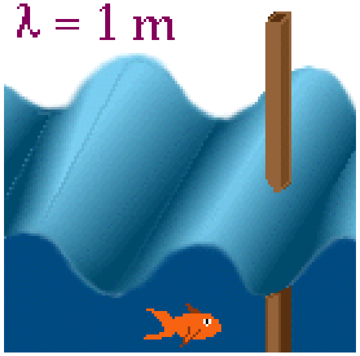
- This part of the goal requires a very expensive and rare tool, an accelerator.
- Why? Imagine you fell into a dark cave and you hear ominous snorting noises. Is it a bear?

So we have learned…

- Easier to see a bear with marble-sized probes than basketball-sized probes

- Use wave-particle duality to think of the “size” as the wavelength. Long wavelength waves can’t be scattered by small things…



What is wavelength is small compared to what you want to see?

- Ocean waves scatter over large sized rocks!

- Breakwaters stop waves

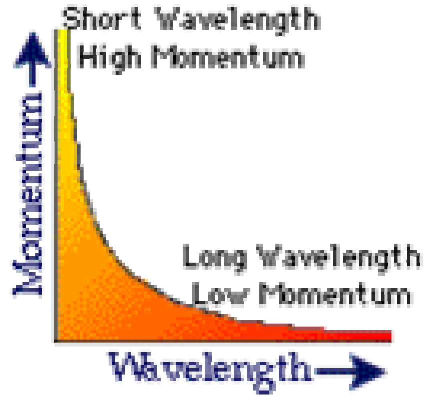
Calm waters

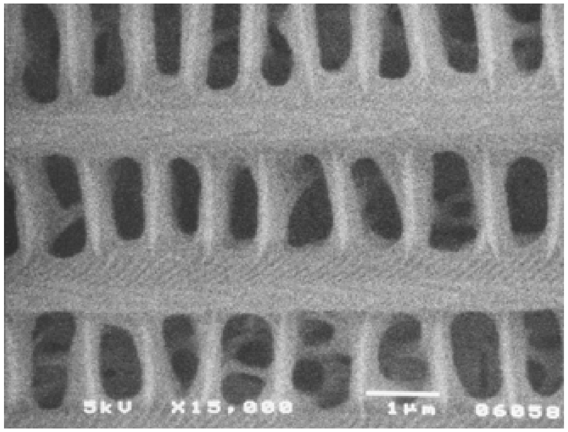
Waves

You could determine shape of breakwater from wave pattern!

How to see the very small…

- So probes must be small if we want to see small structures.
  - deBroglie says $\lambda = \dfrac{h}{mv}$
  - Visible light limits microscopes. λ is 3×10^{-7}m
  - Electron microscope can have smaller wavelength



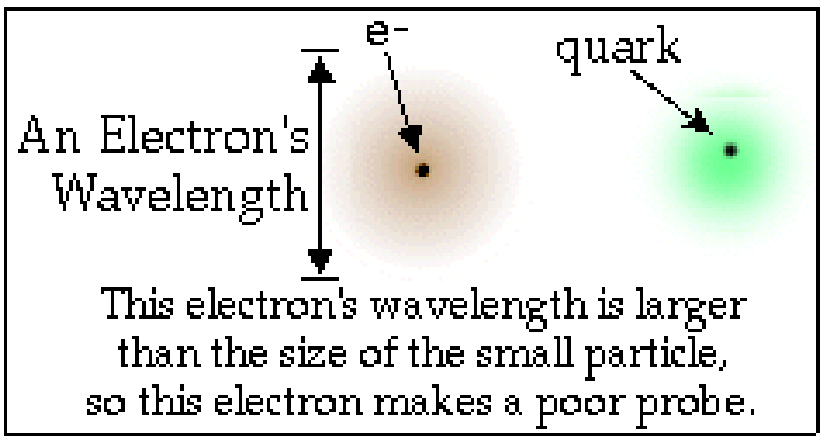


Cecropia Moth scales

How to see the very small…

- But electron microscopy doesn’t work for subatomic structure!

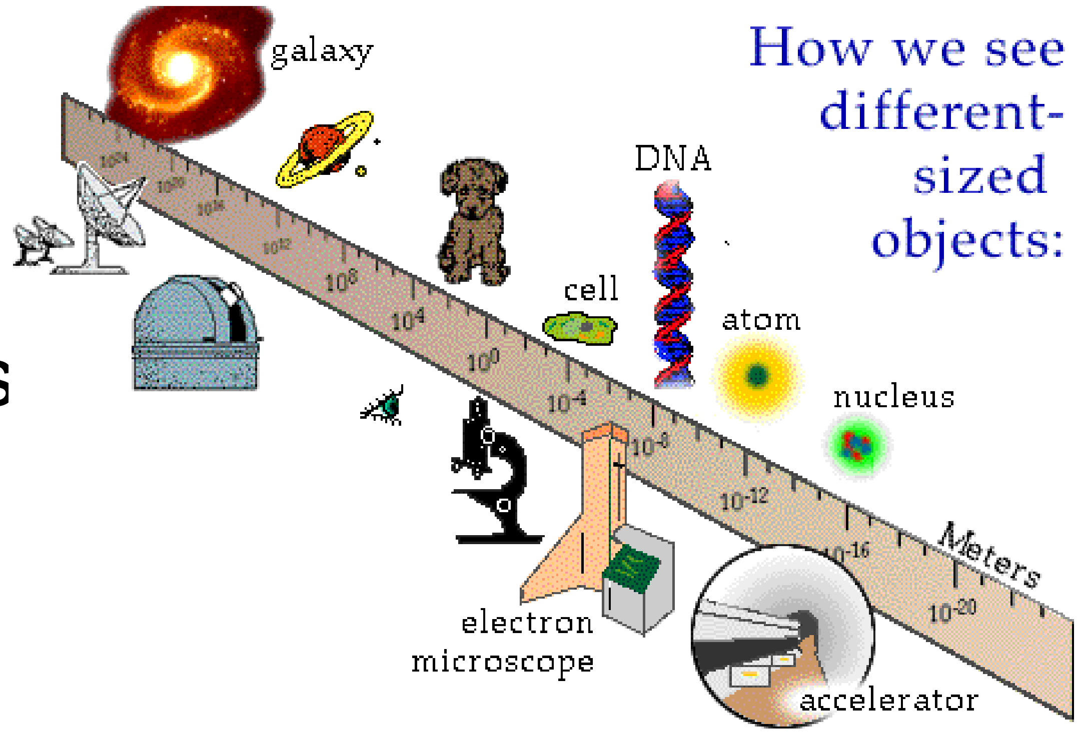
$$\lambda = \frac{h}{mv}$$



- Need smaller electron wavelength
- Which implies higher speed or momentum

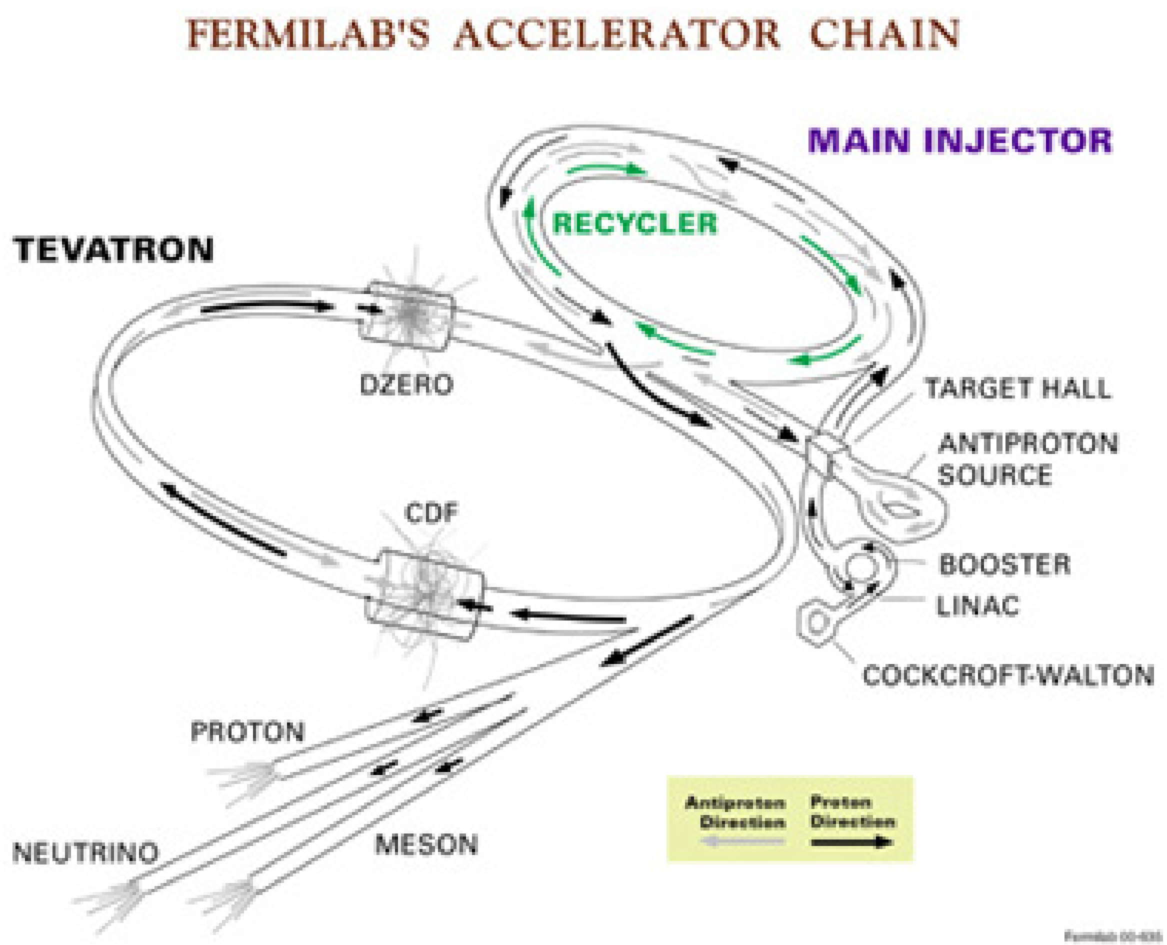
How to see the very small…

- And therefore different technology for different scales

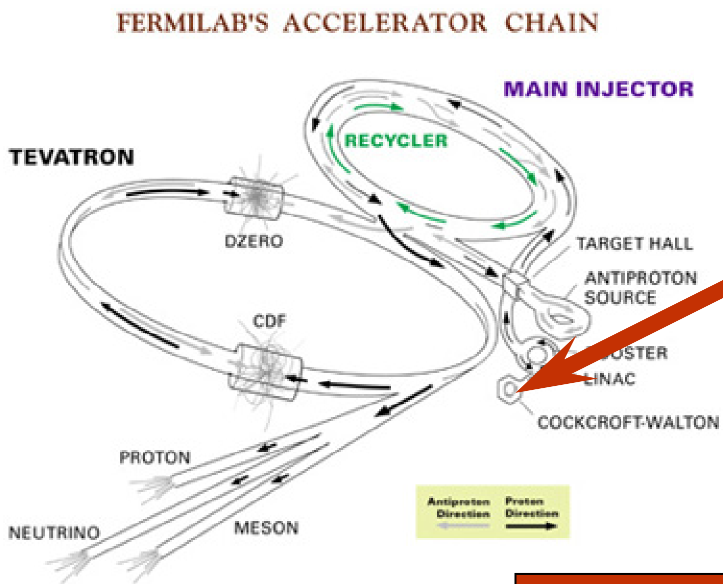


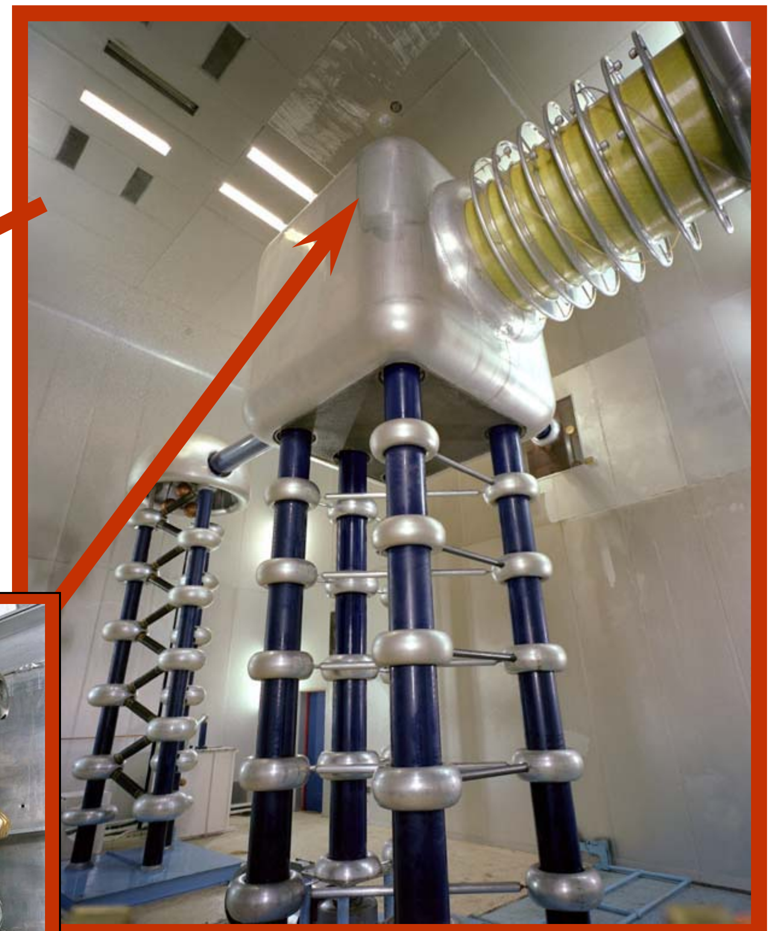
- And modern particle physics is stuck using these cumbersome accelerators!

How Cumbersome?



How Cumbersome?

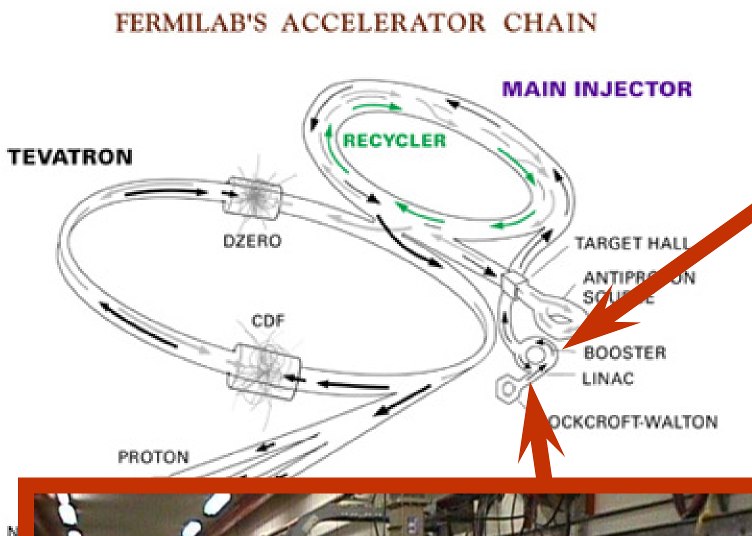




A small bottle of hydrogen is the source of protons to be accelerated.

Ions leaving here have 750 keV of kinetic energy.

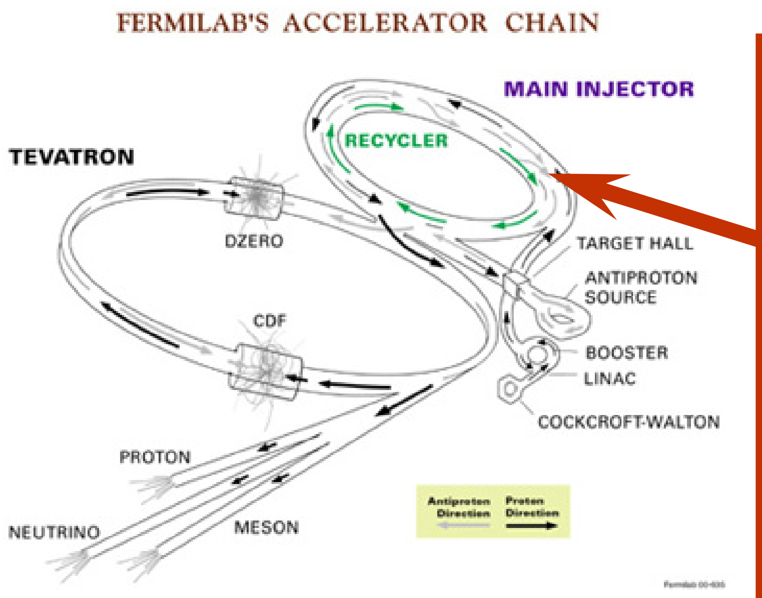
How Cumbersome?



…and 8 GeV here

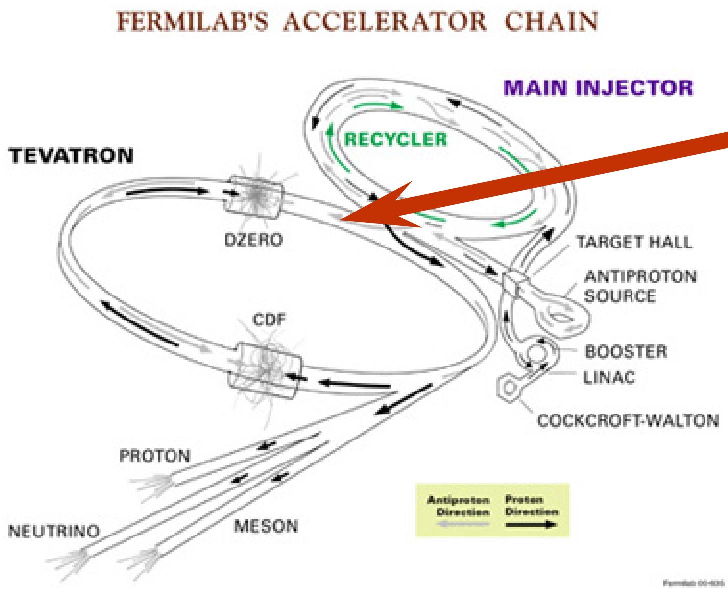
protons leaving here have
400 MeV of kinetic energy…

How Cumbersome?



protons leaving here have 120 GeV of kinetic energy

How Cumbersome?



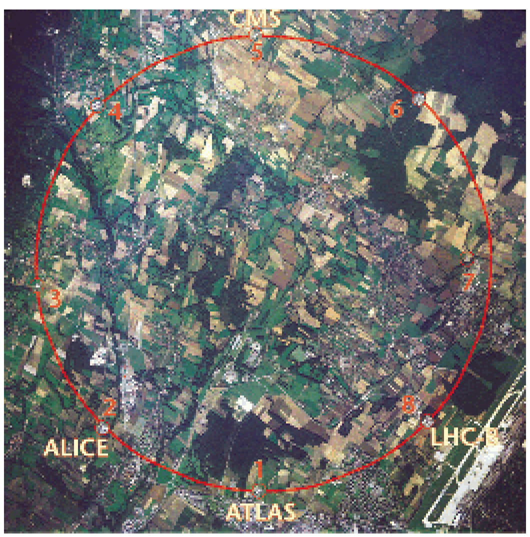
protons accelerated to
~980 GeV of kinetic energy

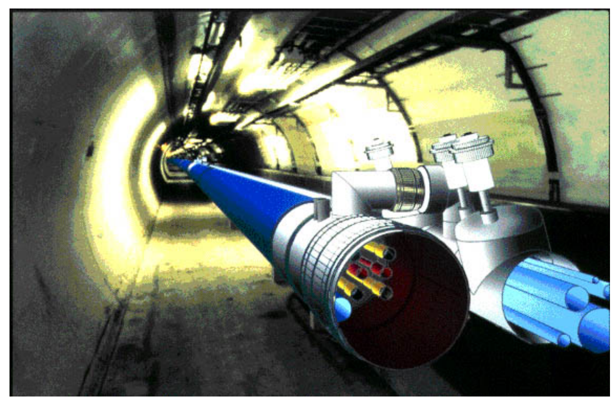
How Cumbersome?

- So the whole thing sits in a site the size of a moderate Chicago suburb… no problem!

But wait, there's bigger and better!

- A fantastic new facility, the Large Hadron Collider (LHC) will come online in ~2008
  - 14 TeV total energy in pp collisions!

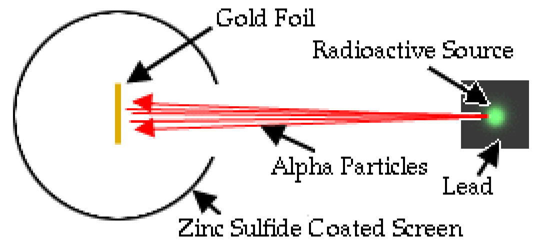




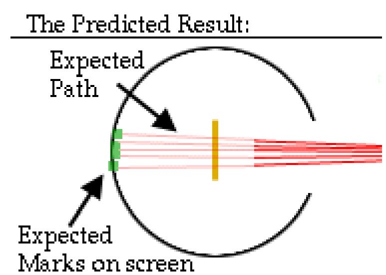
Quarks and the Strong Force…

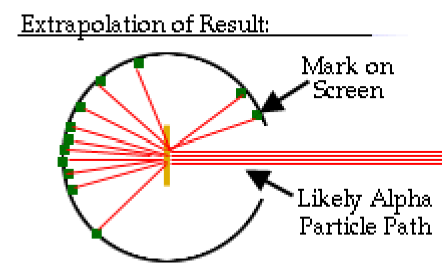
Remembering Rutherford…

- Rutherford found the nucleus by scattering of alpha particles.

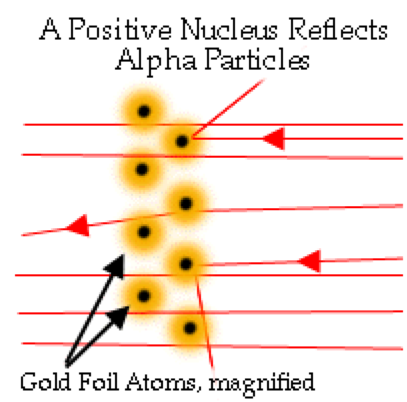


  - Found unexpected large deflections





  - Interpreted these as more structure. “A hard center” to the atom



How could we see structure inside the nucleus?

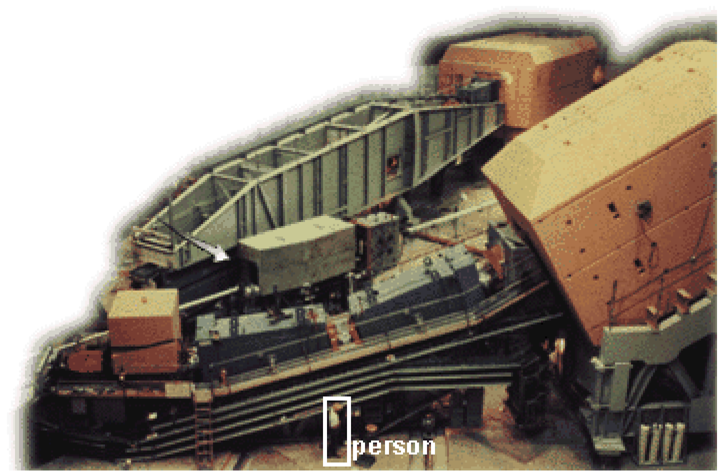
- Rutherford's alpha particle had a mass of 6.7×10^{-27}kg and a speed of about 1×10^{7} m/sec

$$\lambda = \frac{h}{mv}$$

- So the wavelength is about 10^{-14} m
  - Good for resolving structure inside 10^{-10} m atoms
  - Lousy for resolving structure inside 10^{-14} m nucleus
- Need higher momentum (smaller wavelength)

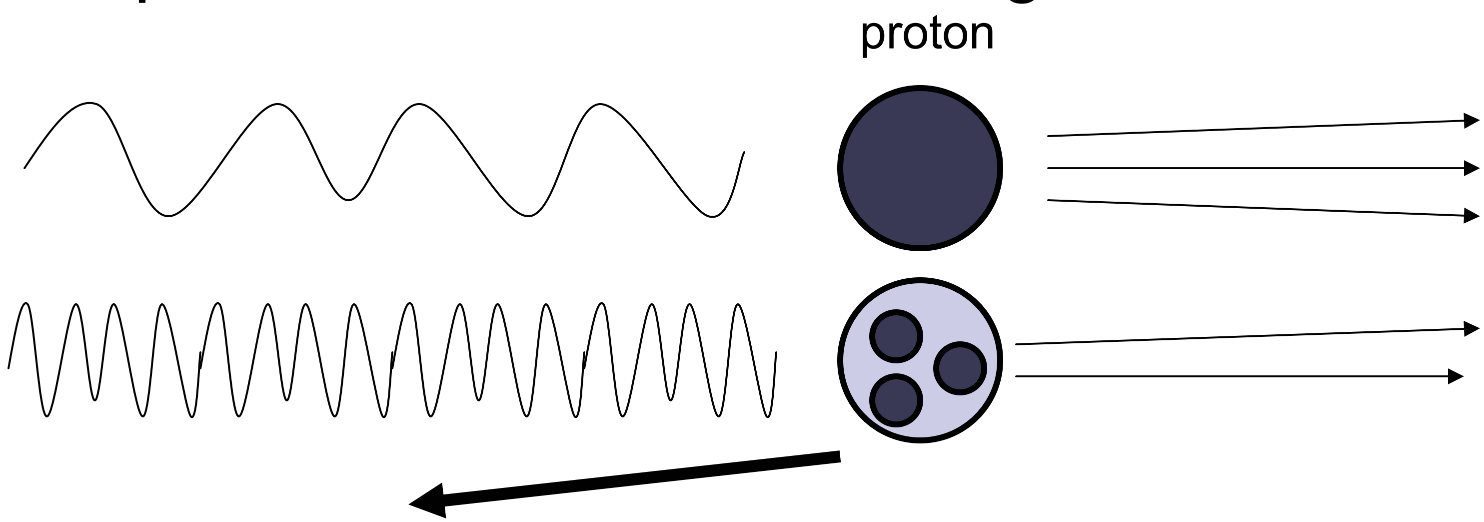
Beam and Detector

- Discovery beyond protons and neutrons using beam at Stanford Linear Accelerator
  - Using massive detectors to find and measure the scattered particles



Result… quarks!

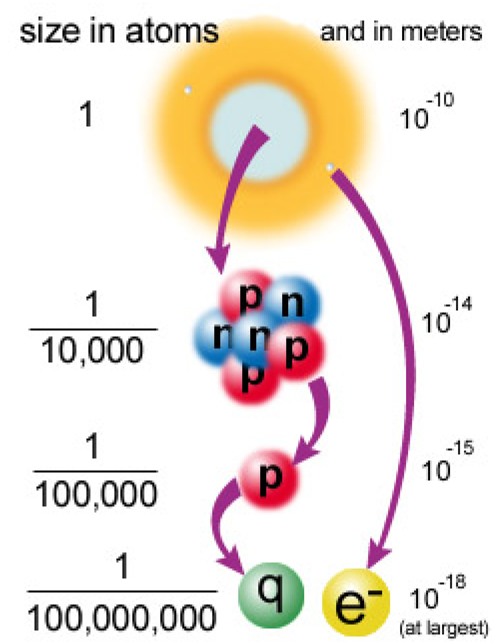
- Just as with Rutherford, essentially found unexpected backward scattering



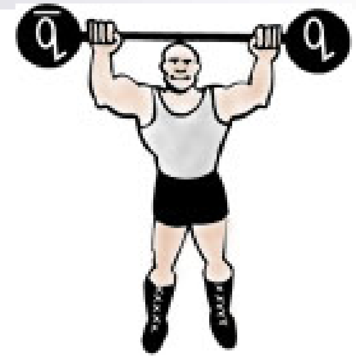
- There are "quarks" inside the proton, bound together by the strong force!

Our new picture of structure…

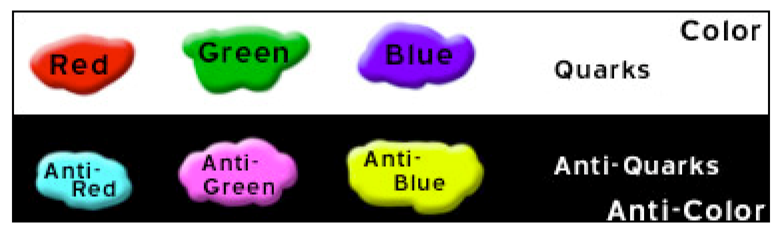
- So now we have a modified picture of the structure of matter
  - Add another layer to the onion
- Question: we saw protons and neutrons before this. Why didn't we see quarks?
  - It's because the strong force is too strong!



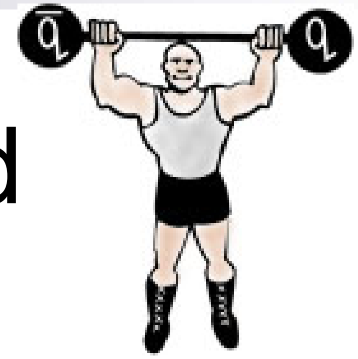
The Strong Force…



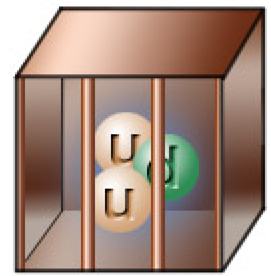
- This force is so strong that it can effectively be thought of as glue
  - Force carrier is named the "gluon"
  - Gluons connect to "color"
  - Can think of these colors as combining like light
  - "White" (colorless) things don't feel the strong force



The Strong Force… cont'd



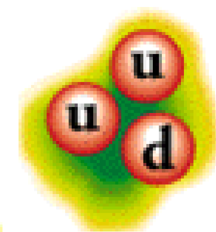
- If you think of this as "glue" then these colorless combinations stick together
  - This is called "confinement"
  - The proton is one such "confined combination of quarks"
    - Red+Green+Blue → Colorless

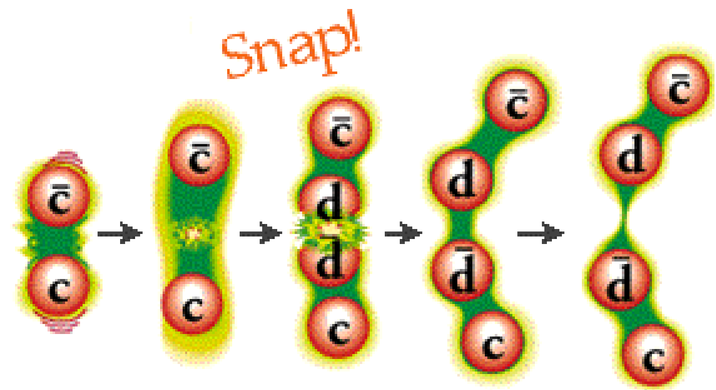


- So two questions follow from this picture
  - What happens if you try to pull things apart?
  - How do protons stick to each other?

Fighting the strong force

- A good model for trying to pull two quarks is like putting energy into a spring
  - When it "breaks" it breaks by creating matter!
  - Separate into two "colorless" objects

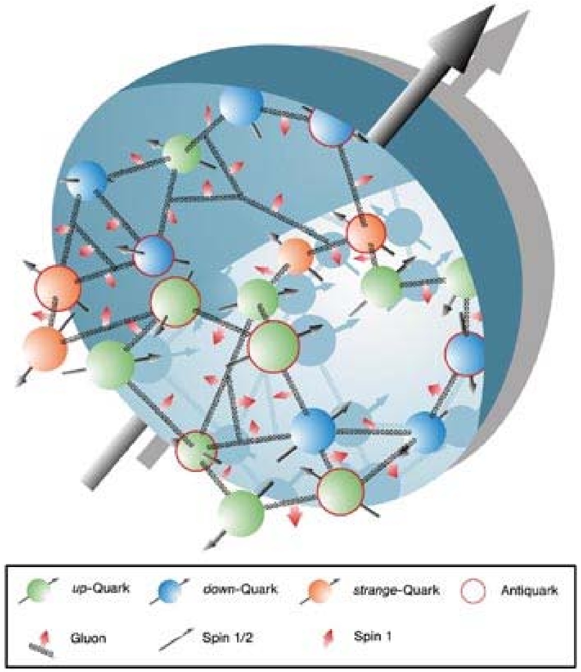




- This is why free quarks were not discovered the way cathode rays were…

Fighting the strong force (cont'd)

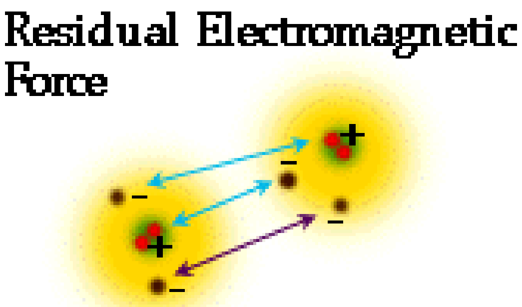
- The further away the strong force binds two quarks, the stronger it is?
  - Why? Because gluons also feel the strong force, so as distance increases, make more and more gluons
  - and quark+antiquark pairs



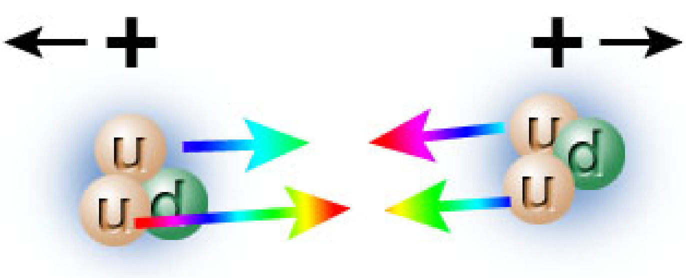
- Most of the mass of a proton is actually energy exchanges carried by gluons
  - Most of your mass is strong force dynamics

Gluing together protons

- Asking why two (colorless) protons are attracted by the strong force is analogous to asking how molecules bind together
  - Answer is basically the residual electric force over the size of the atom. Only works if nearby



- Answer is exactly the same for strong force
  - Residual strong force, but only if nearby…



The Puzzle of the Neutrino and the Question of Flavor

The Birth of the Neutrino

Wolfgang Pauli

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und [illegible] von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie [illegible] mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen [illegible] von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

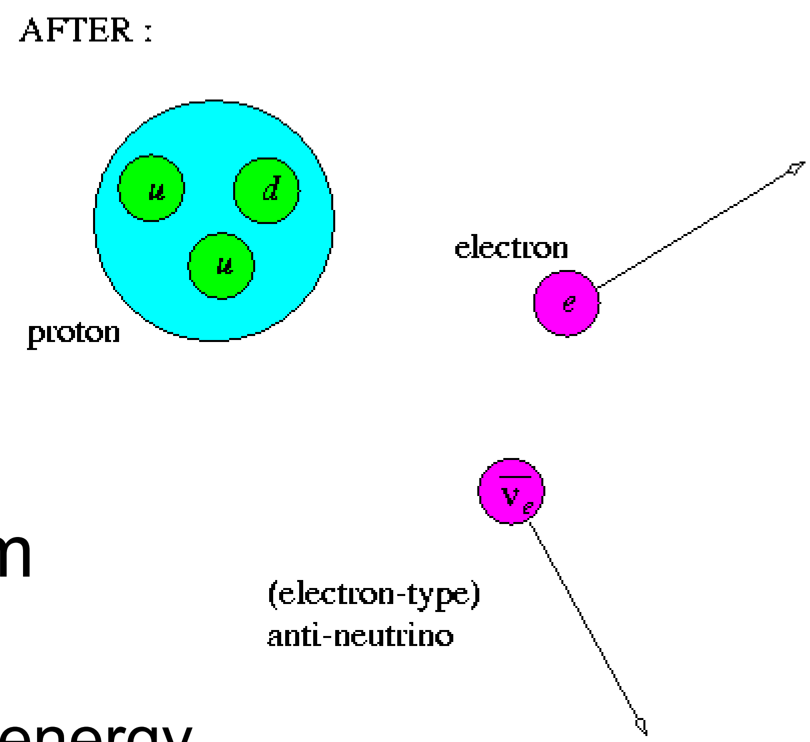
Translation, Please?

4th December 1930
Dear Radioactive Ladies and Gentlemen,
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass (and in any event not larger than 0.01 proton masses). The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.
Your humble servant,
W. Pauli

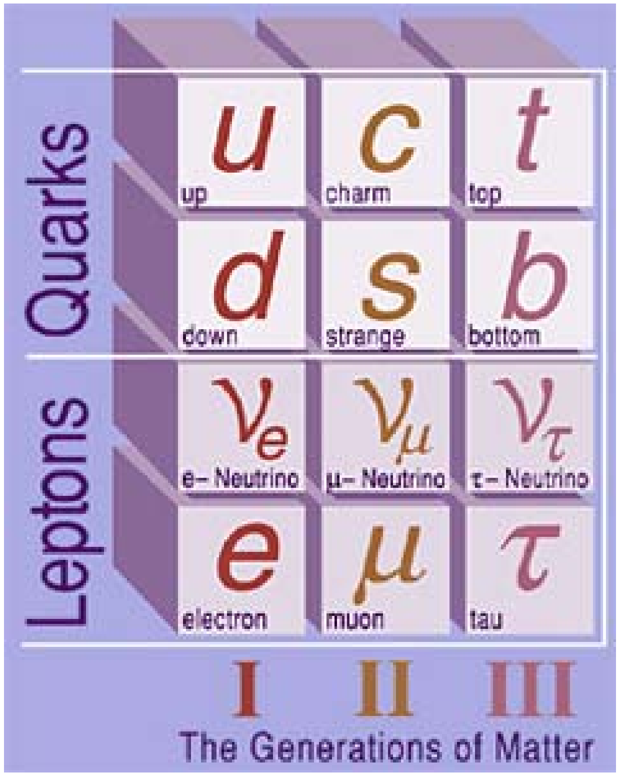
What's this about conservation of energy?

- We talked about beta decay as emission of electron
- But actually, this caused a big puzzle because it didn't seem to conserve energy
  - Pauli's solution: extra energy taken by invisible neutrino



Where do neutrinos fit in to matter?

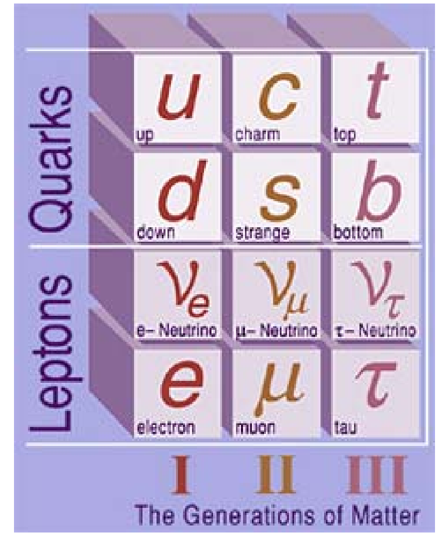
- look at the particle "periodic table"
- it has up and down quarks which make protons and neutrons
- which bind with electrons to make atoms

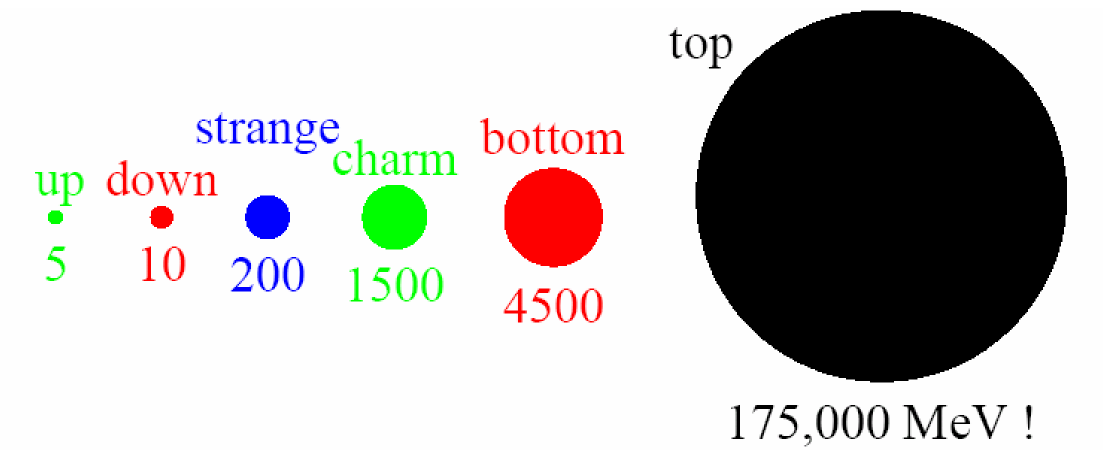


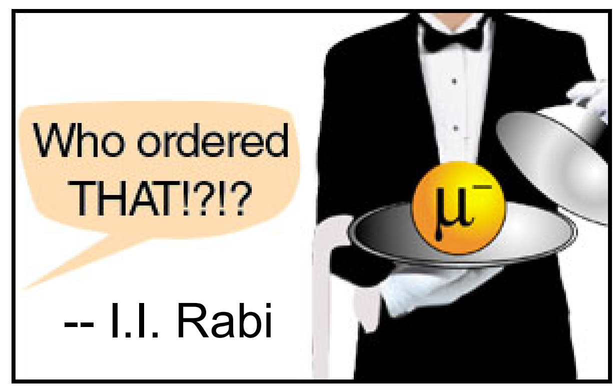
- *and a neutrino, partner with electron*
- so what's all the stuff to the right?

What is that Stuff?
(The question of flavor…)

- there just appear to be three copies of all the matter that really matters…
- all that distinguishes the "generations" is their mass



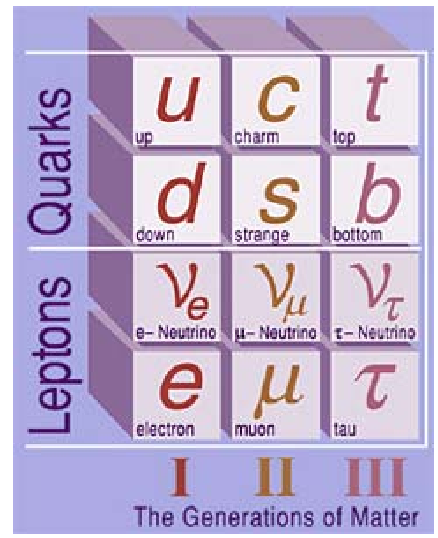




Where are Neutrinos Found?

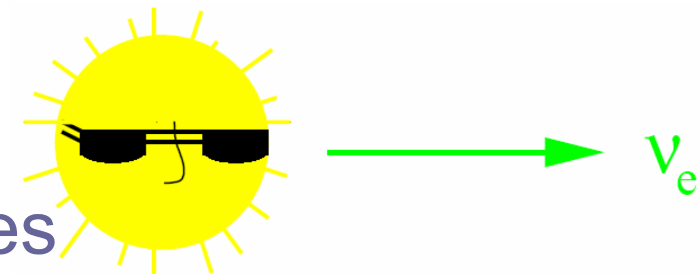
- Anywhere there are weak interactions!

- The early Universe
  - The heavy things to the right decay (weakly), leaving a waste trail of 100/cm^3 of each neutrino species
  - They are (now) very cold and ***slow*** and hard to detect
  - But if they have even a very small mass, they make up much of the weight of the Universe



Where are Neutrinos Found?

- In the sun

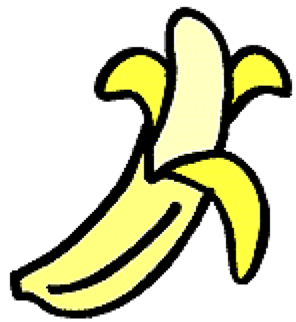


  - If the sun shines by fusion, energy reaching earth in light and in neutrinos is similar
  - 100 billion neutrinos per cm^2 per second rain on us

- Supernova 1987A (150000 light years away) exploded, releasing 100 times the neutrinos the sun will emit in its whole lifetime
  - we observed 11 neutrinos in detectors on earth!

Where are Neutrinos Found?

- Bananas?

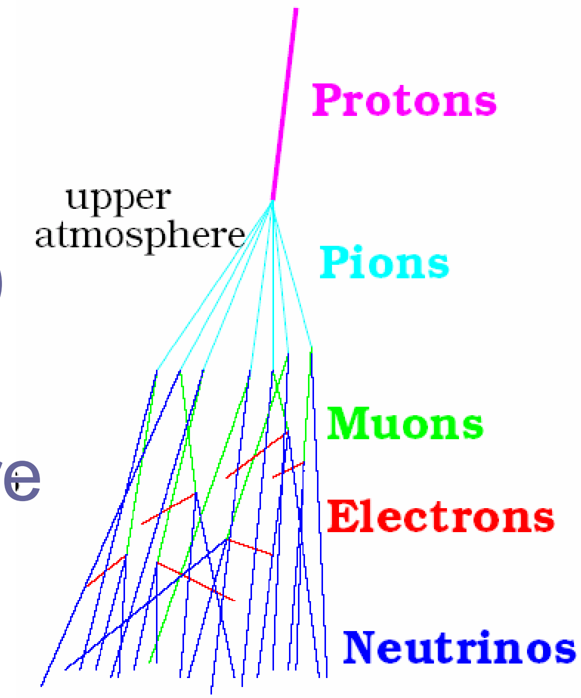


  - We each contain about 20mg of ^{40}K which is unstable and undergoes β decay
  - So each of us emits 0.3 billion neutrinos/sec

- For the same reason, the radioactivity of the earth results in 10 million neutrinos per cm^2 per second here

Where are Neutrinos Found?

- Cosmic Rays
  - Cosmic rays from galaxy
  - Each particle (mostly protons) has many GeV of energy
  - Collisions in upper atmosphere create particles which decay (weakly) to neutrinos



- Can use same technique to produce neutrinos at accelerators

How Weak are Weak Interactions?

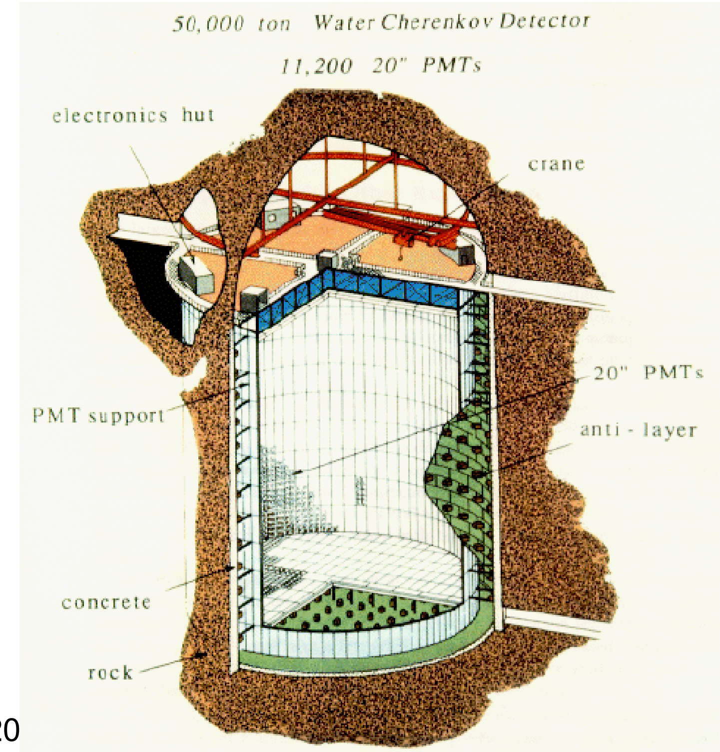
- Weak is, in fact, way weak.
- A 3 MeV neutrino produced in fusion from the sun will travel

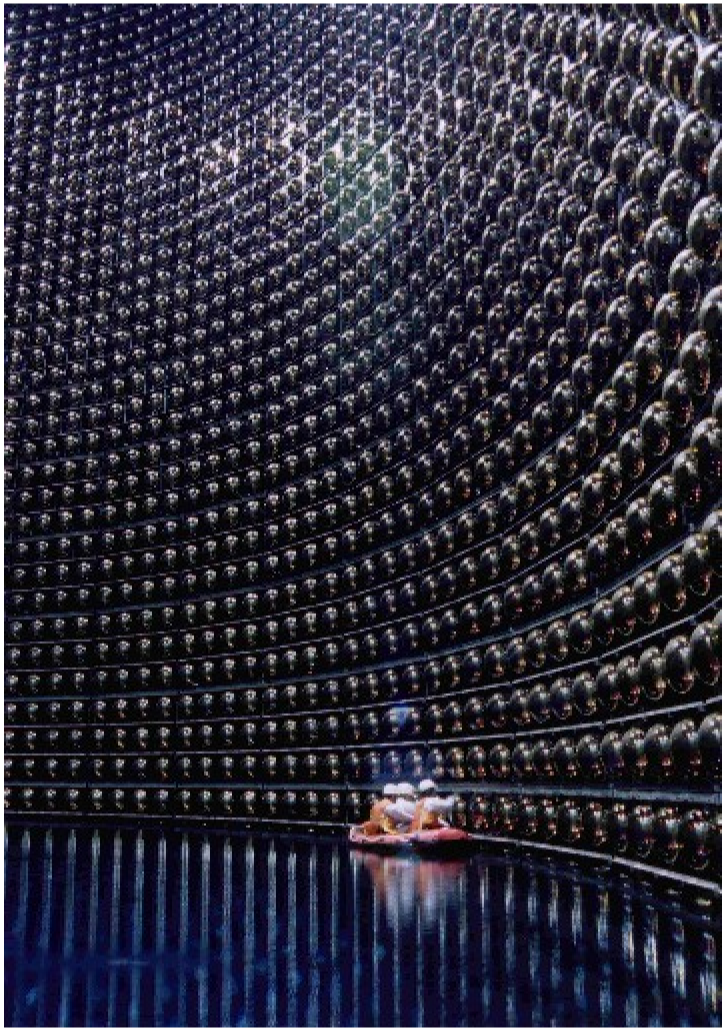
  53 light-years

  through water, on average, before interacting.
  - The 3 MeV positron (anti-matter electron) produced in the same fusion process will travel 3 cm, on average.
- Moral: to find neutrinos, you need a lot of neutrinos and a lot of detector!

Modern Neutrino Hunting

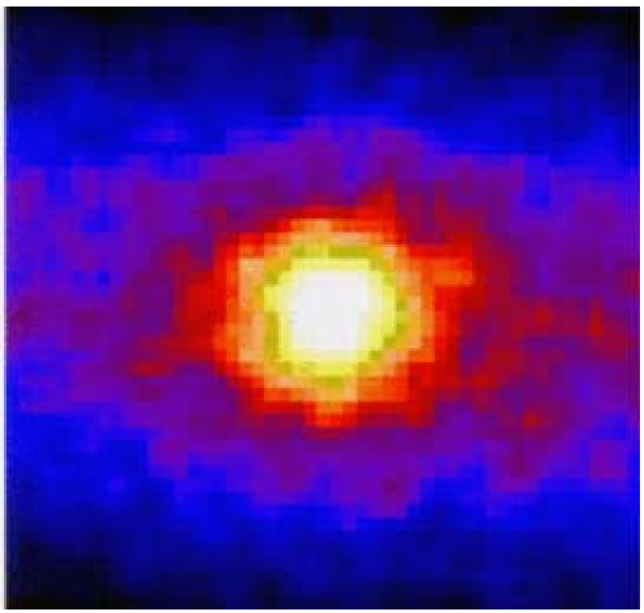
- Super-Kamiokande
  (Masatoshi Koshiba,
  UR PhD 1955, Nobel Laureate 2002)



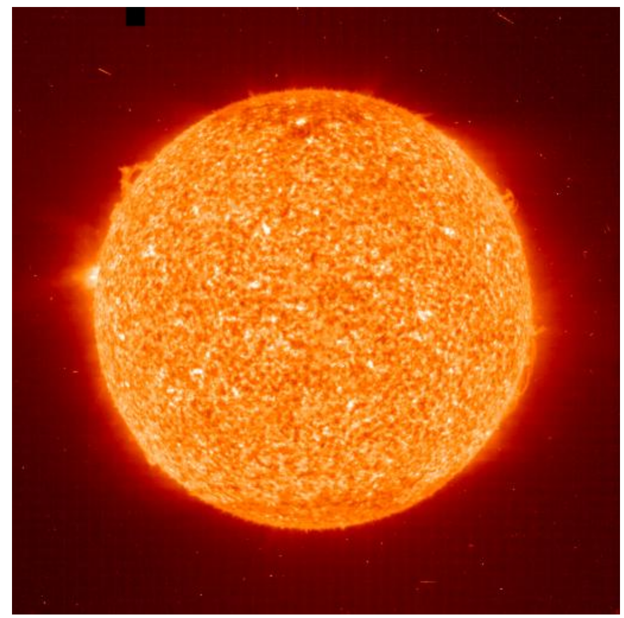


Modern Neutrino Hunting

- The Sun, imaged in neutrinos, by Super-Kamiokande



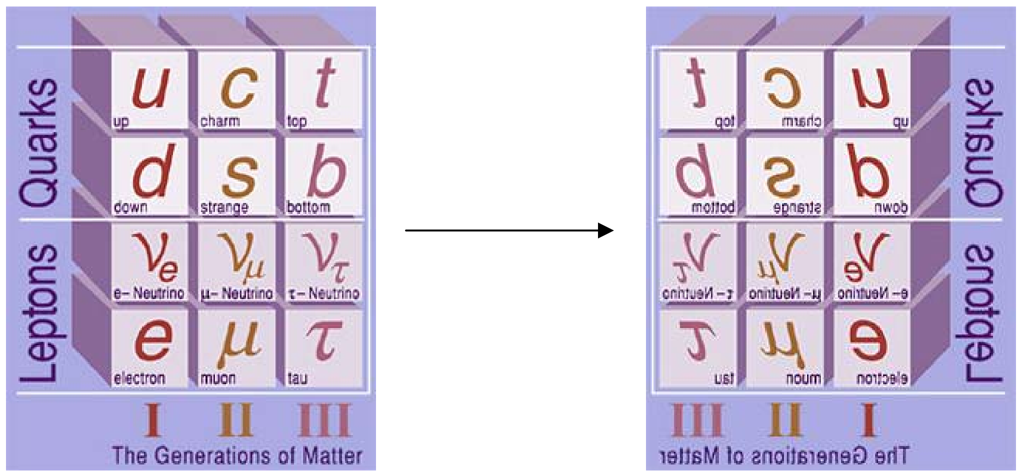
Existence of the sun confirmed by neutrinos!



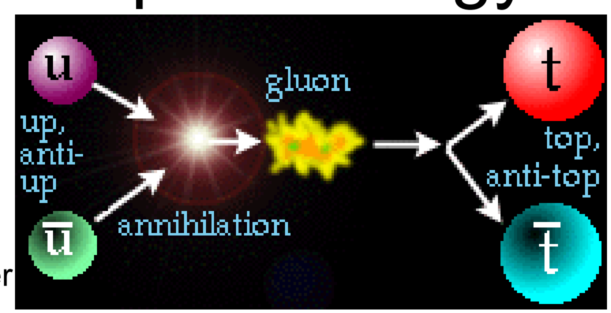
The Sun, optical image

Neutrinos vs. Anti-Neutrinos

- Every fundamental particle has an anti-matter partner (solved electron problem!)



- When the meet, they annihilate into pure energy. Alternatively, energy can become matter plus anti-matter



So you might ask…

- The early Universe had a lot of energy. Where is the anti-matter in the Universe?
- Good question… how do we know it isn't around today?
  - look for annihilations.
  - As far away as we can tell, today there aren't big matter and anti-matter collisions

Emerging Idea!

- Prove or disprove the hypothesis:

  neutrinos cause the matter anti-matter asymmetry in the Universe!

- Use accelerators to make neutrinos to study whether or not neutrino anti-neutrino differences seeded an asymmetry
  - This is a long-term program with many steps, but a clear and worthy "big goal"

Grand Unified Theories, The Higgs Boson and Mass

Unification of Forces

- Ever since Maxwell, physicists have dreamed of becoming famous by unifying descriptions of fundamental forces

Ha! Beat this!

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

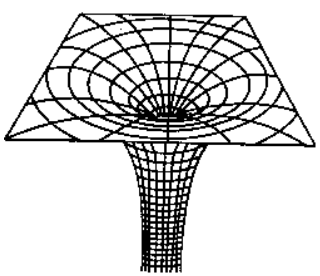
$$\nabla \cdot \vec{D} = \rho$$

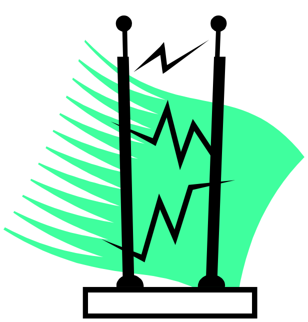
$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

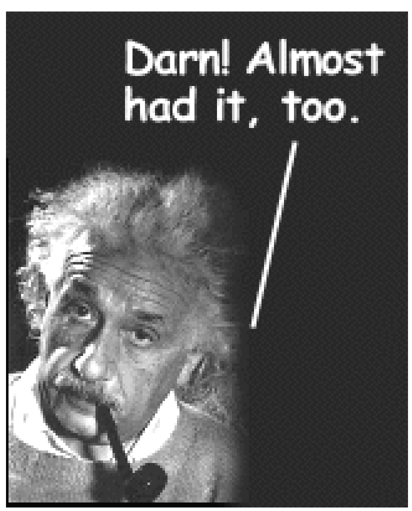
$$\nabla \cdot \vec{B} = 0$$

Unification of Forces (cont'd)

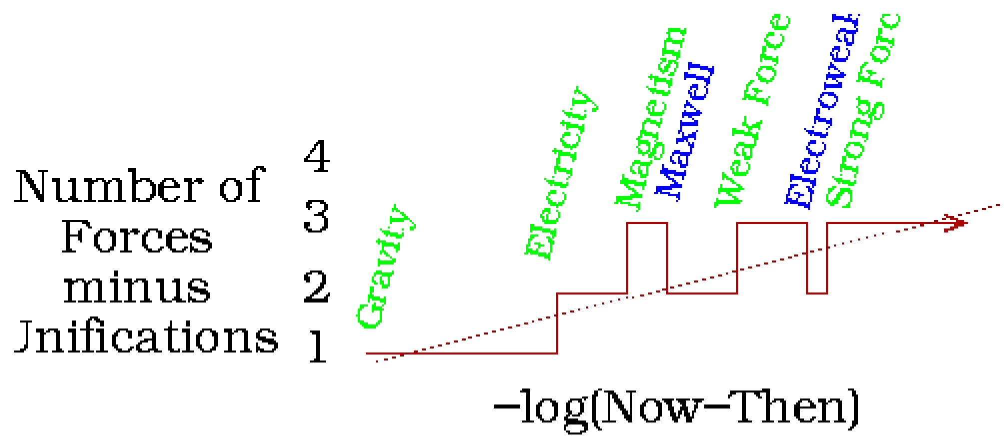
- Unfortunately, the history is not encouraging
- Einstein spent most of his late career attempting to unify gravity and electromagnetism…





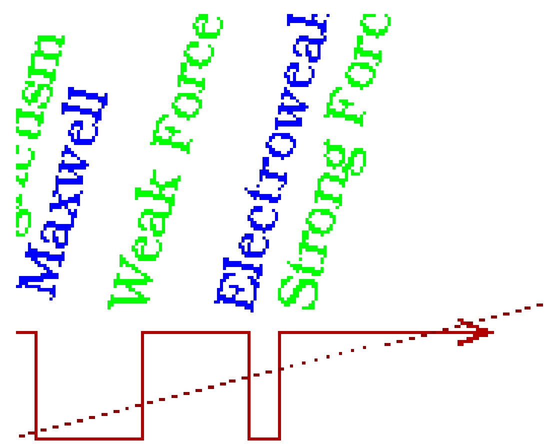


- The trend is not positive…



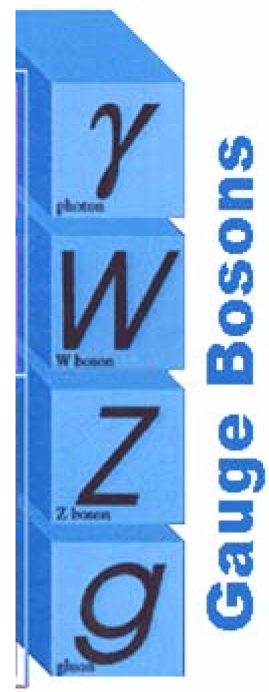
Unification of Forces (cont'd)

- The one exception to this trend is "electroweak" unification
  - Weak and electromagnetic force share a common description
  - But a major challenge is understanding how electricity can explain atomic structure, but weak force has apparently little or no role!



Why is the Weak Force Weak?

- Weak force and electromagnetism are very different because the carriers of the weak force are very massive bosons (W, Z)
  - Can exchange mass over short ranges by the uncertainty principle
  - "Borrow" the energy for a short time
- How to combine these two?
  - Answer: The Higgs Mechanism

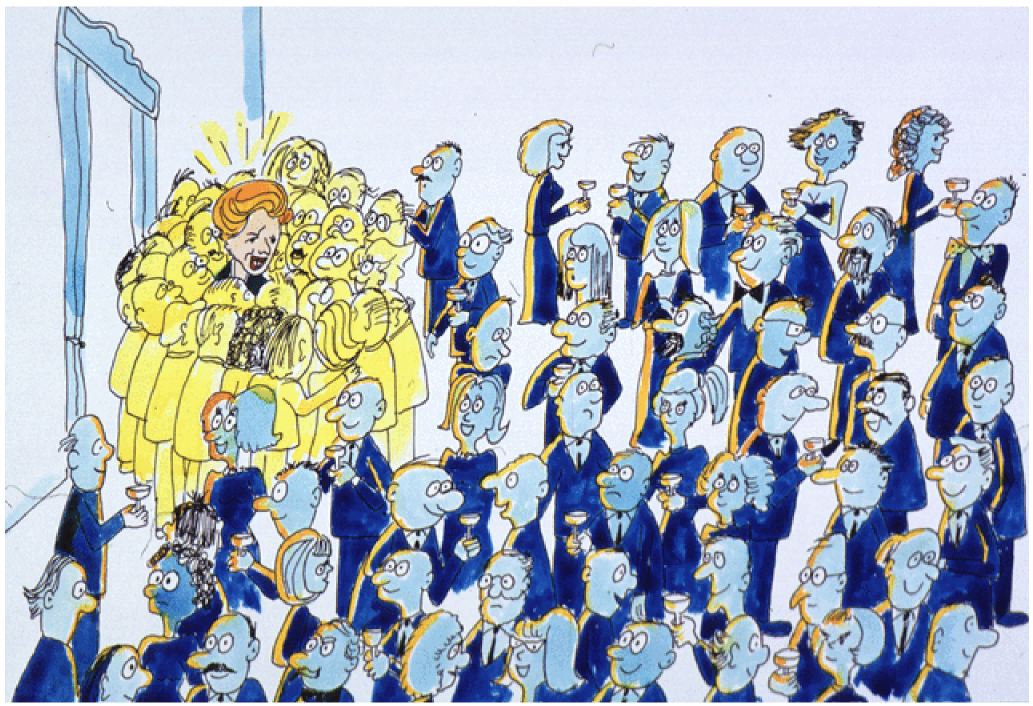


Higgs Mechanism and 1 TeV

- How does the Higgs work?
  - Envisage the motion of people at a party…
  - Outside the party, they are free to walk. Inside, limited by crowd.

Higgs Mechanism and 1 TeV

- Now imagine a VIP enters the room…
  - A cluster of people forms around the VIP
  - Her motion is more restricted. More inertia (mass)
  - This is what happens to W, Z
    - But not to photon!



Higgs Mechanism and 1 TeV

- There are also collective excitations of the medium (imagine a rumor spreading…)
  - The rumor ***causes*** people to cluster.
  - This strong interaction ***is like a mass.***
  - The mechanism itself has mass!
  - A new particle to discover!

What about gravity?

- Unifying gravity with all the other forces is the purview of an effort in physics called "string theory"
  - It's a very beautiful picture, but it shows the unification dynamics happening at very tiny distances
  - Roughly 10^{-35} m! We can't even conceive of how to see something this small!