PHY100 — The Nature of the Physical World

Lecture 17
More Particle Physics

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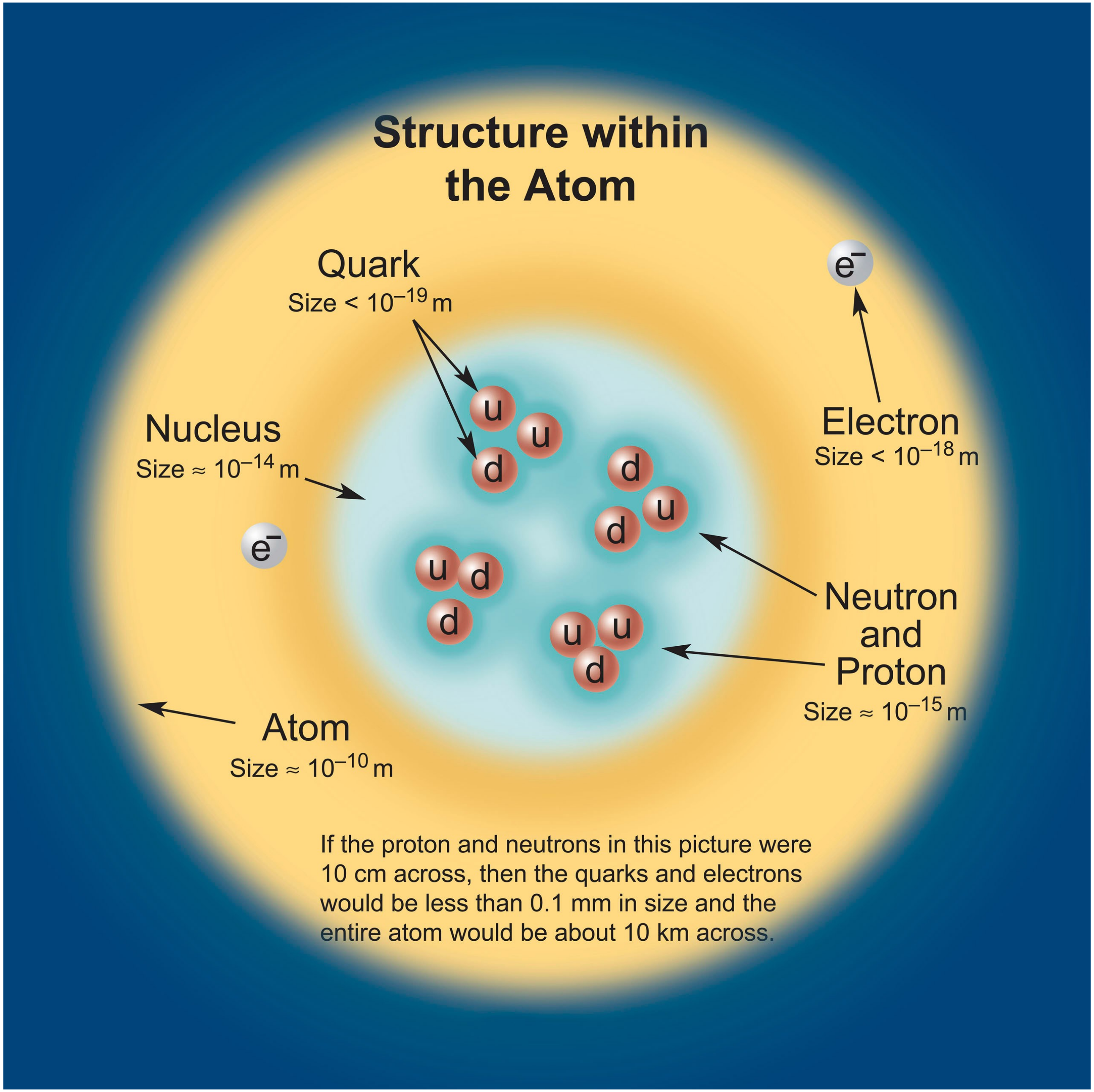
News

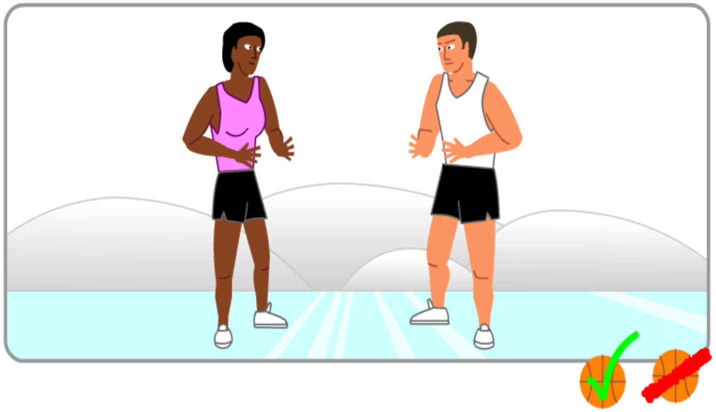
- Exam 2: Wednesday March 31 (next week!)
  - Hoyt at 2-3.15 pm, instead of class
  - Bring a **calculator**
  - I will provide a formula sheet
  - Material: lectures 8 – 15 (up to nuclear physics, life of a star), recitations 5-7
- I'll be available in my office Monday-Wednesday
  - Come see me if you have questions!
- No recitations or problems next week

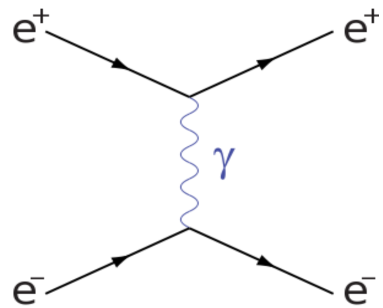
Last layer in the onion? 10^{-18}m



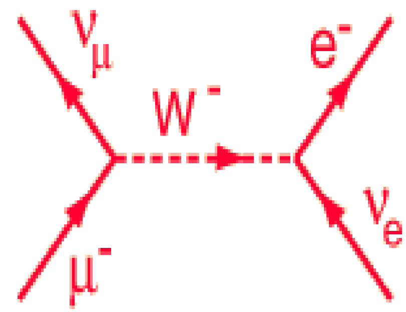
Quantum field theory

- Forces are “carried” or “mediated” by particles: exchange force

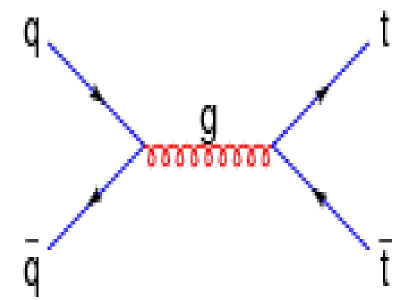




Electromagnetic



Weak



Strong

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Matter and forces

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

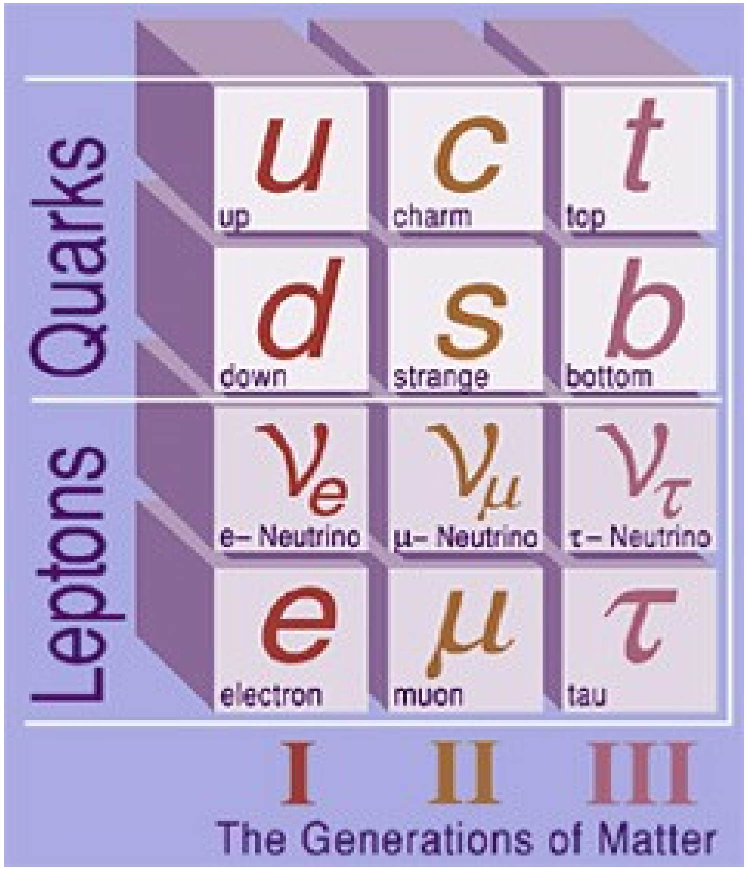
Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

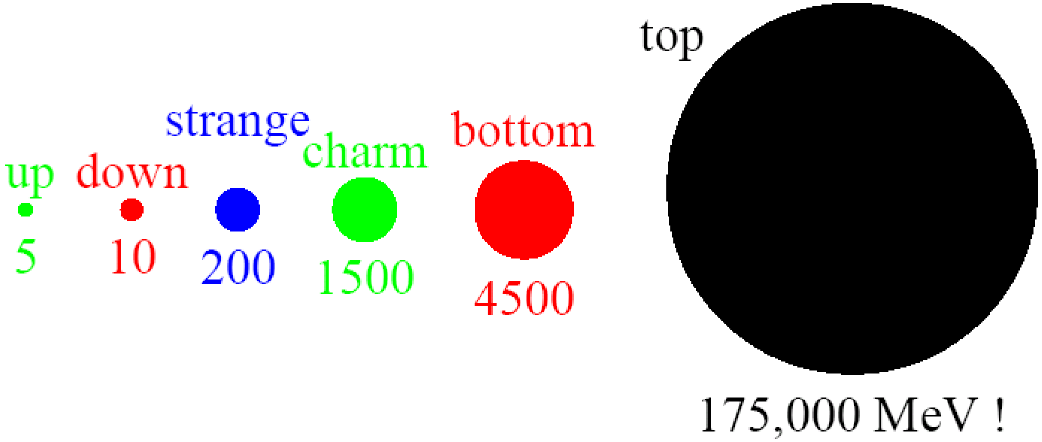
Quarks spin =1/2

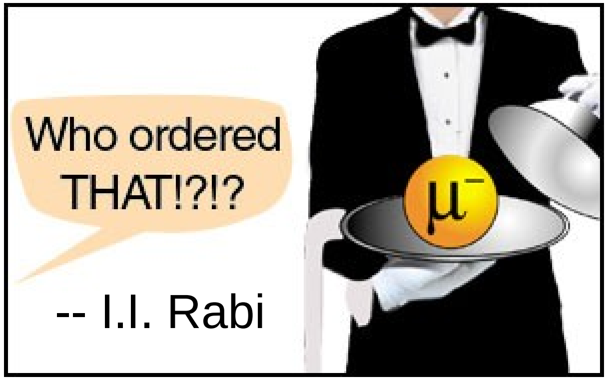
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Three families

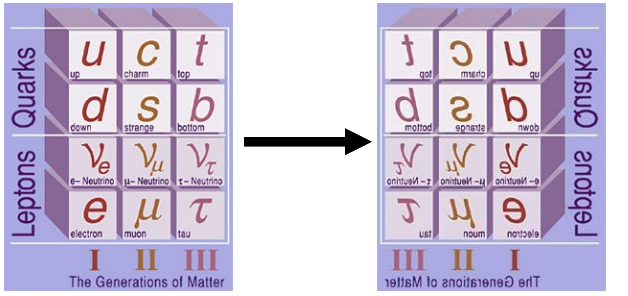
- Look at the particle "periodic table"
- It has up and down quarks which make protons and neutrons…
- Which bind with electrons to make atoms…
- *And a neutrino, partner with electron…*
- So what's all the stuff to the right?
- There just appear to be three copies of all the matter that really matters…
- All that distinguishes the "generations" is their mass



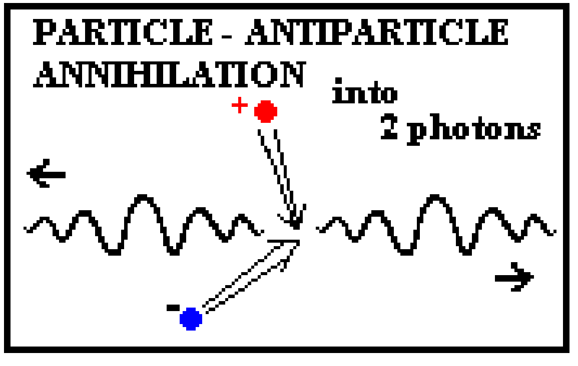


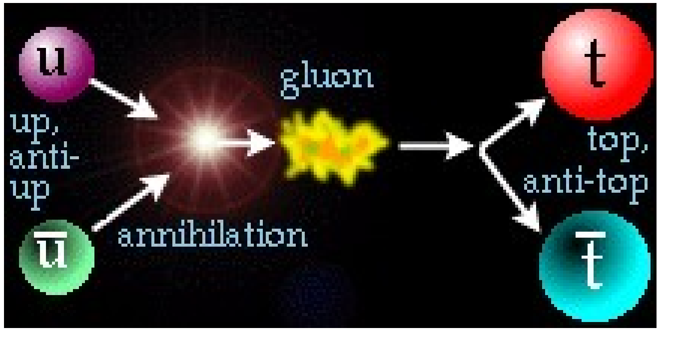


Antimatter… is really weird



- All particles have antiparticles!
- Antimatter has the same properties as matter
  - Same mass, same spin, 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. $E=mc^2$



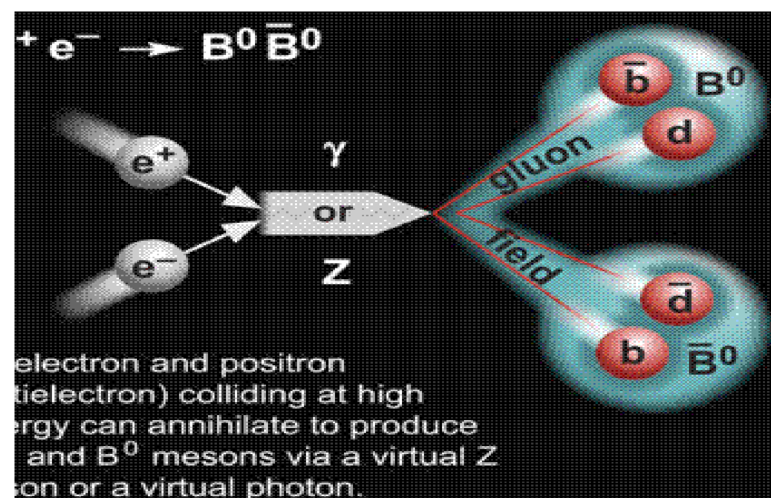


- So you might ask: The early Universe had a lot of energy…. where is the antimatter in the Universe?

Why is the Universe made of matter?

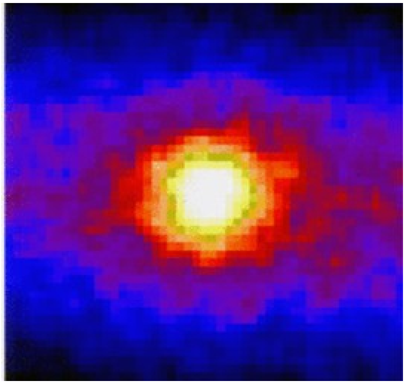
- Good question: if the Universe started with same amount of matter and antimatter, where is the antimatter?
  - Look for annihilations
  - As far away as we can tell, today there aren't big matter and antimatter collisions

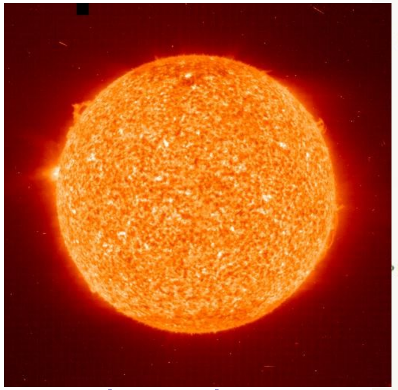
- We don't know why this is true yet!
- Active field of research
- There must be a basic matter-antimatter asymmetry in one of the forces of Nature



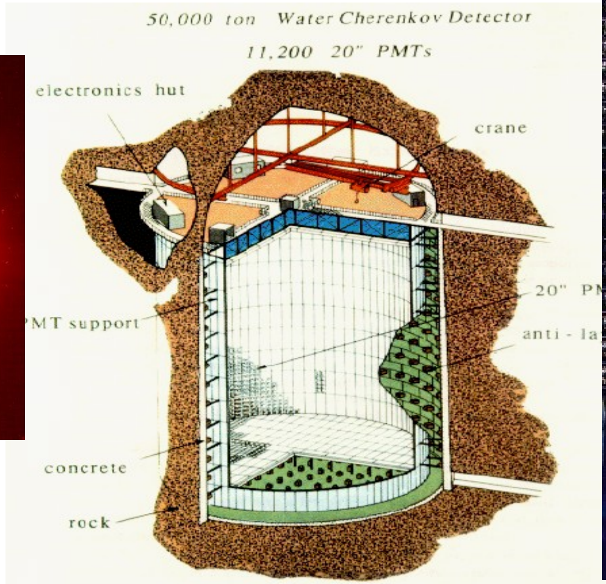
How weak are Weak Interactions?

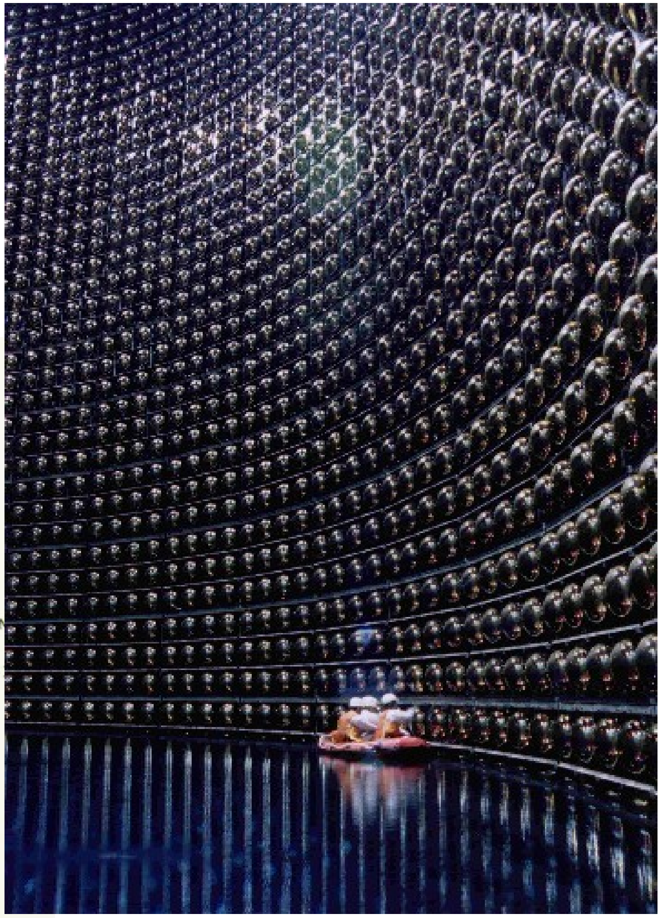
- Weak is, in fact, way weak
- A 3 MeV neutrino produced in fusion from the sun will travel through water, on average **53 light years**, before interacting
  - The 3 MeV positron (anti-matter electron) produced in the same fusion process will travel 3 cm, on average
- Moral: to find neutrinos, you need a lot of neutrinos and a lot of detector!
- Super-Kamiokande: confirms the existence of the sun in neutrino image!
  - Masatoshi Koshiba, UR PhD 1955, Nobel 2002





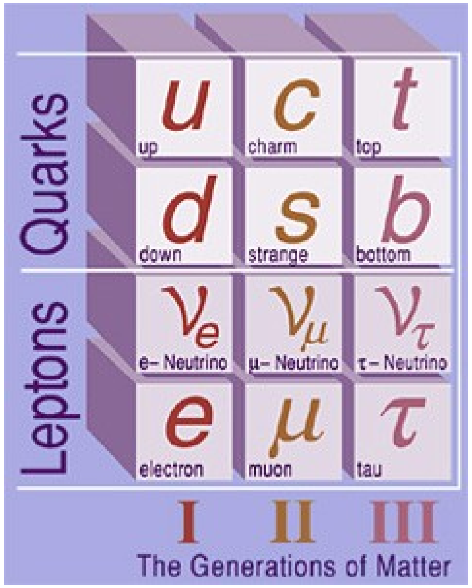
The Sun, imaged in neutrinos, by Super-Kamiokande, and optical



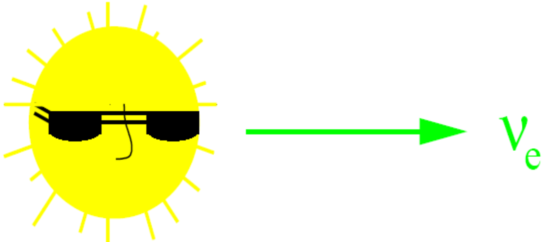


Where are neutrinos found?

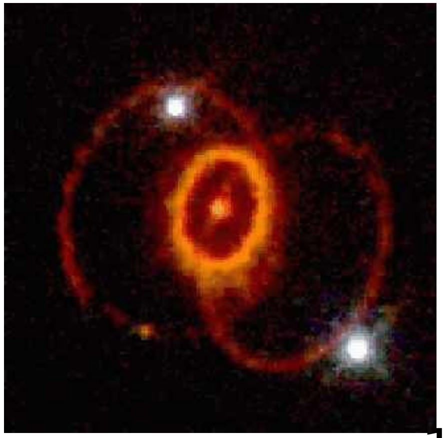
- **Anywhere there are weak interactions!**
- **The early Universe**



  - 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
- **In the sun**

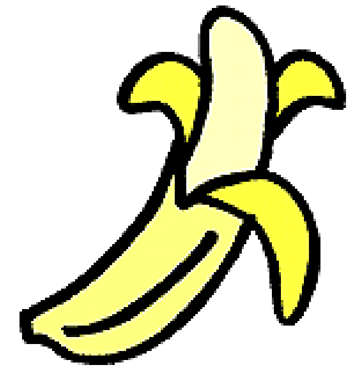


  - Sun shines by fusion, energy reaching Earth in light and in neutrinos is similar
  - 100 billion neutrinos per cm^2 per second rain on us
- **Supernova 1987A** (150,000 light years away)
  - When it exploded, it released 100 times the neutrinos the sun will emit in its whole lifetime
  - We observed 11 neutrinos in detectors on Earth!



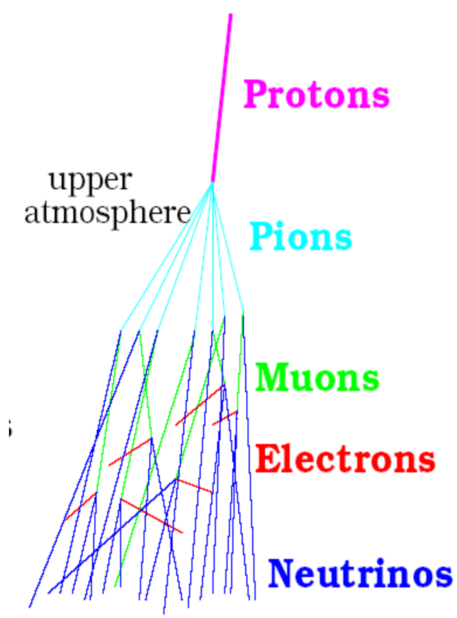
More neutrinos!

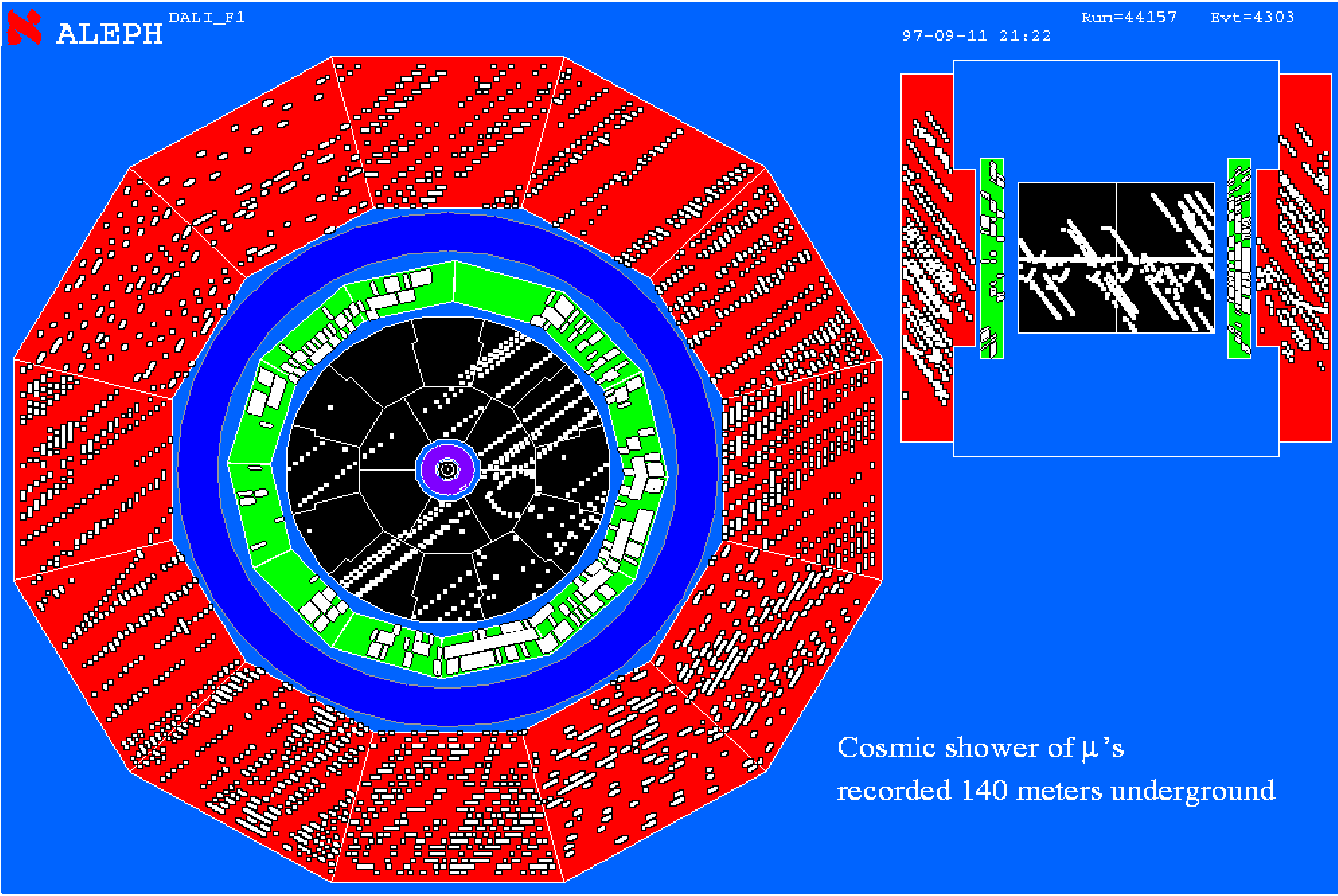
- **Bananas?**
  - We each contain about 20mg of ^{40}K which is unstable and undergoes β decay
  - So each of us emits 0.3 billion neutrinos/sec



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

- **Nuclear reactors** (6% of energy is anti-neutrinos)
  - Average plant produces 10^{20} anti-neutrinos/sec
- **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

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DALI_F1
Run=44157
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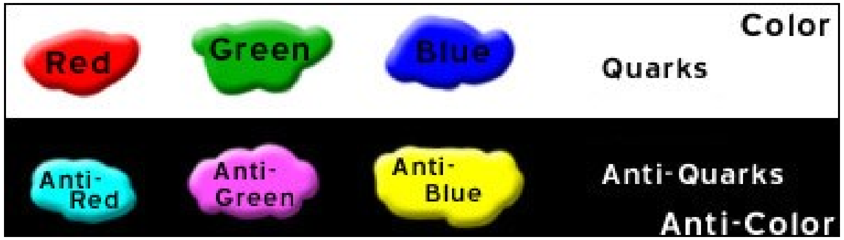
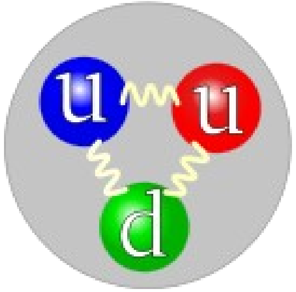
Cosmic shower of μ's
recorded 140 meters underground

The Strong Force…

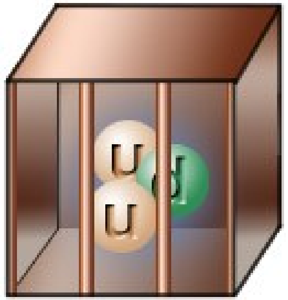
- This force is so strong that it can effectively be thought of as glue
  - Force carrier is named the "gluon"
  - Gluons connect to "color"
  - Can think of these colors as combining like light
  - "White" (colorless) things don't feel the strong force

- 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



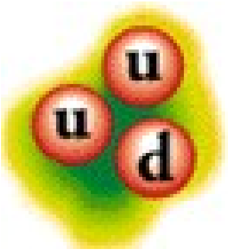


- So two questions follow from this picture
  - What happens if you try to pull things apart?
  - How do protons stick to each other?

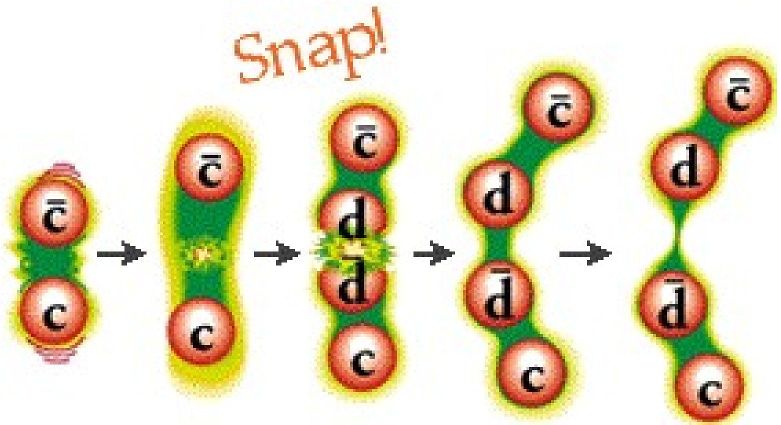


Fighting the strong force

- 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 or bare quarks have never been observed
- 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

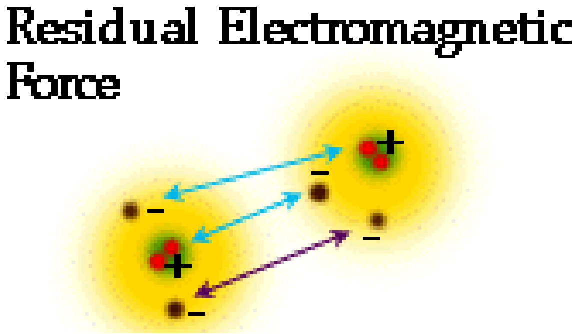


- Most of the mass of a proton is actually energy exchanges carried by gluons
  - Most of your mass is strong force dynamics

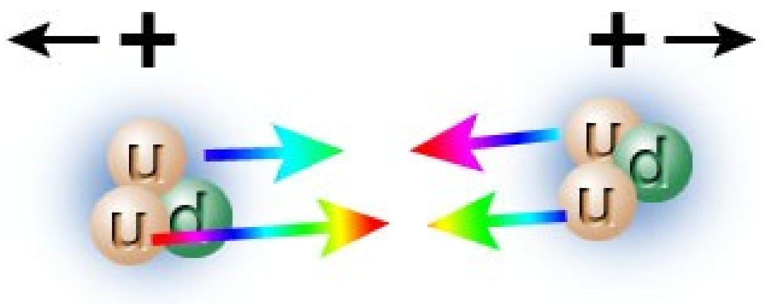
Quantum Chromodynamics (QCD)

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…



Unification of Forces

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

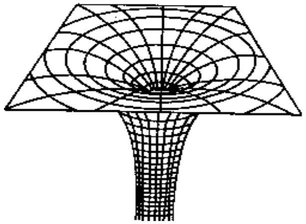
$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

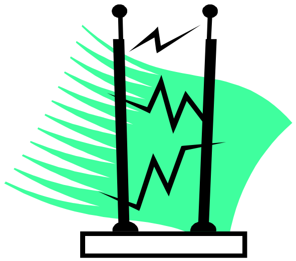
$$\nabla \bullet \vec{D} = \rho$$

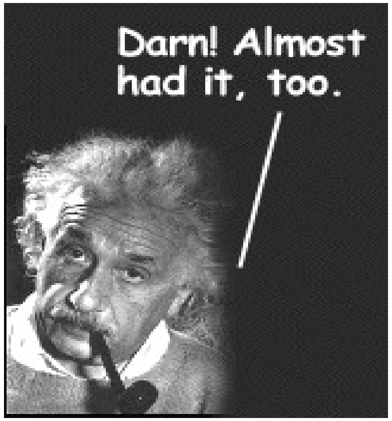
$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

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

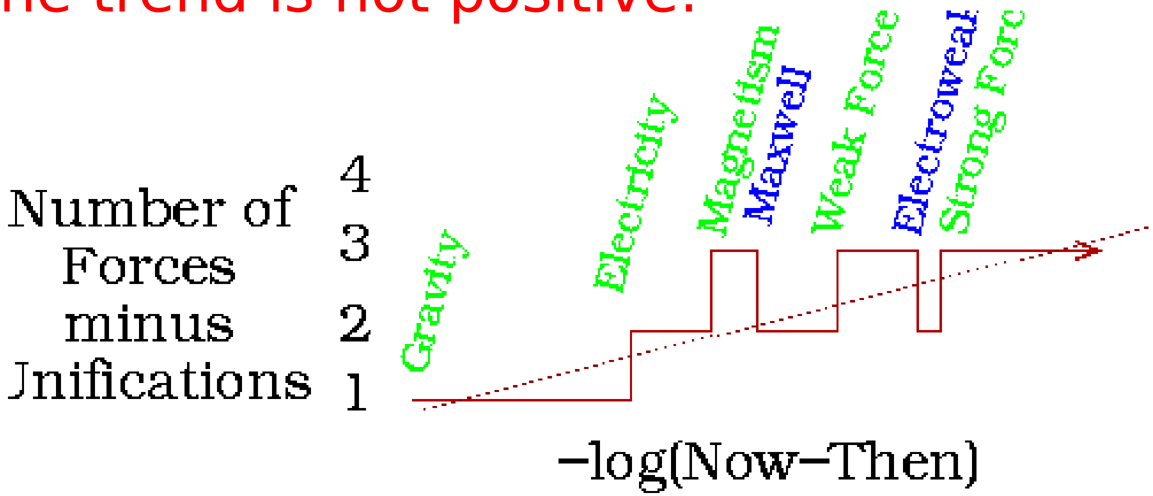
- Unfortunately, the history is not encouraging...
- Einstein spent most of his late career attempting to unify gravity and electromagnetism…





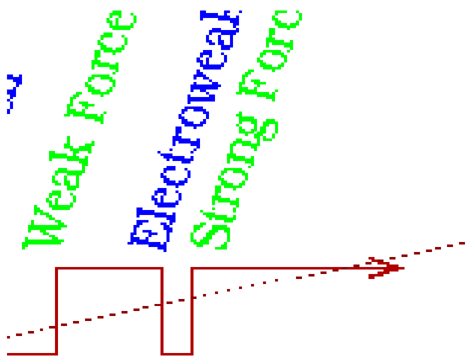


The trend is not positive:

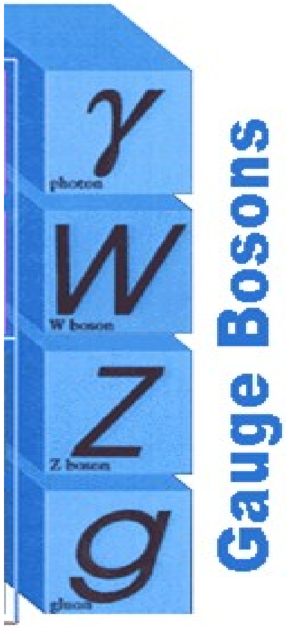


Unification of Forces (cont'd)

- The one exception to this trend is "electroweak" unification
  - Weak and electromagnetic force share a common description
  - Above ~100 GeV they become one force
  - Below that energy, they are distinct

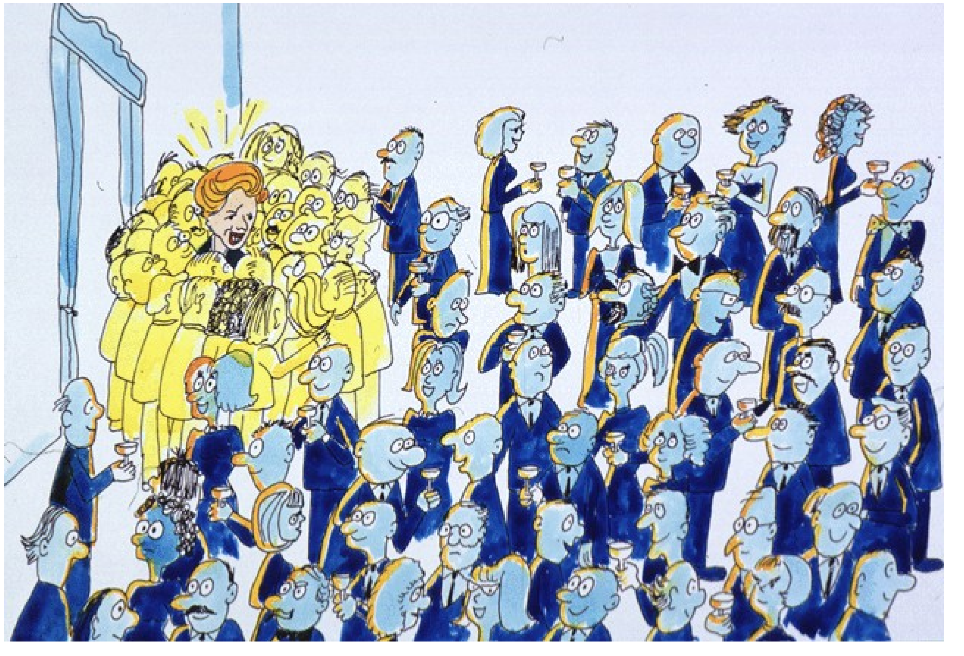


- Weak force and electromagnetism are very different because the carriers of the weak force are very massive bosons (W, Z)
  - Can exchange mass over short ranges by the uncertainty principle
  - "Borrow" the energy for a short time
- How to combine a massless photon and massive W and Z?
  - Answer: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



Higgs mechanism

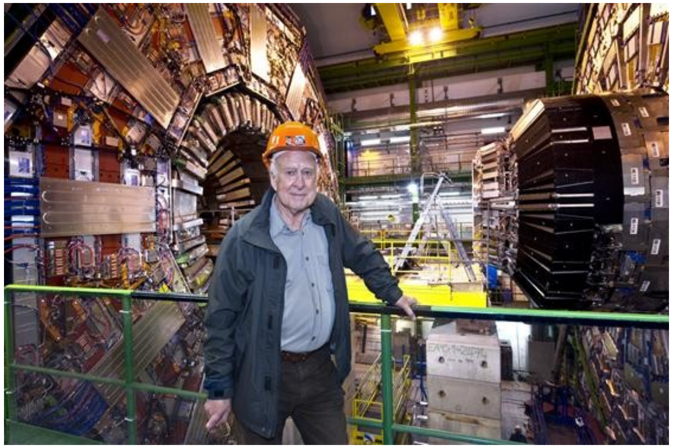
- How does the Higgs work?
- Envisage the motion of people at a party…
  - Outside the party, they are free to walk
  - Inside, limited by crowd



- 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!

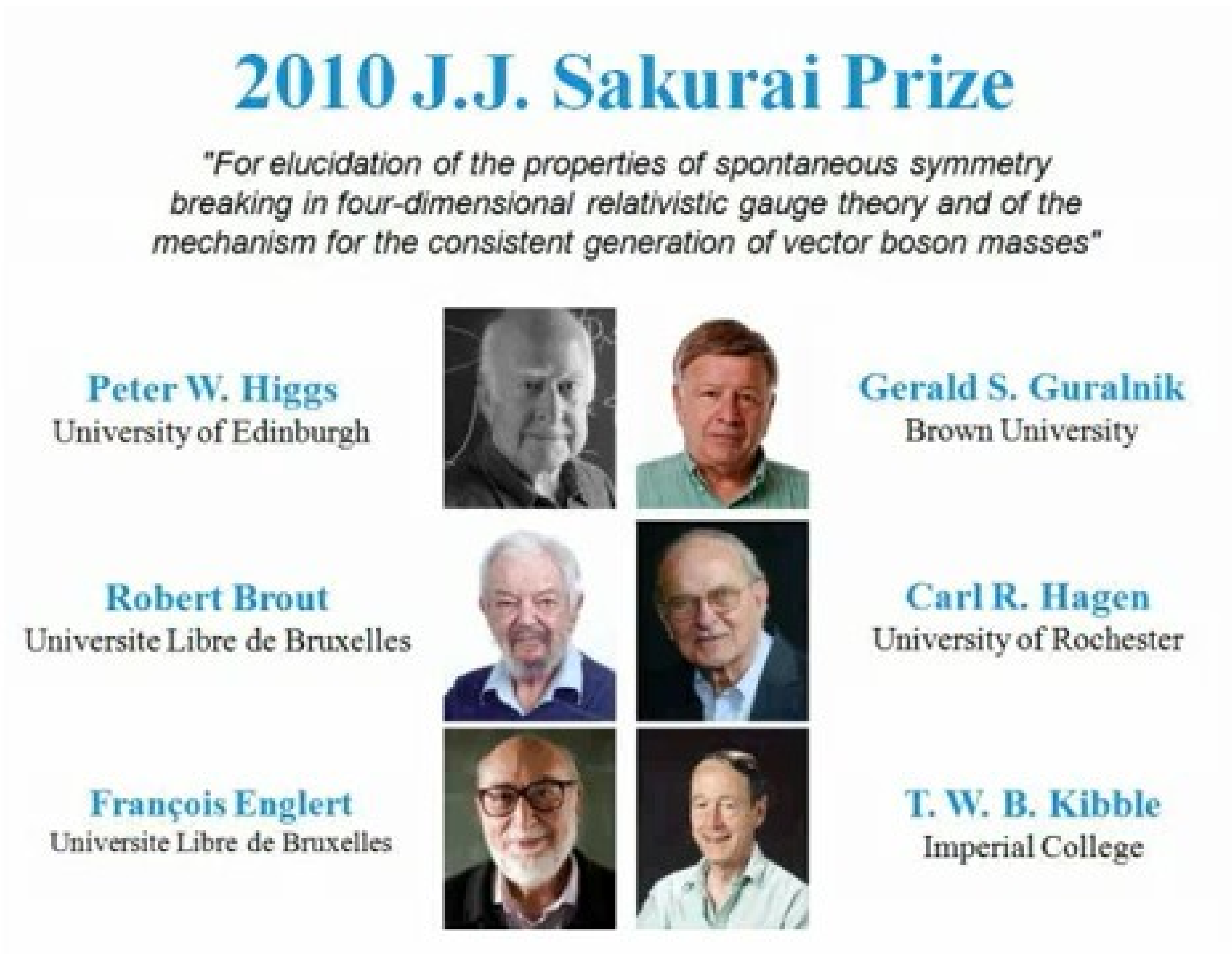
Higgs particles

- Ok, so the Higgs mechanism explains why particles acquire mass
- 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!



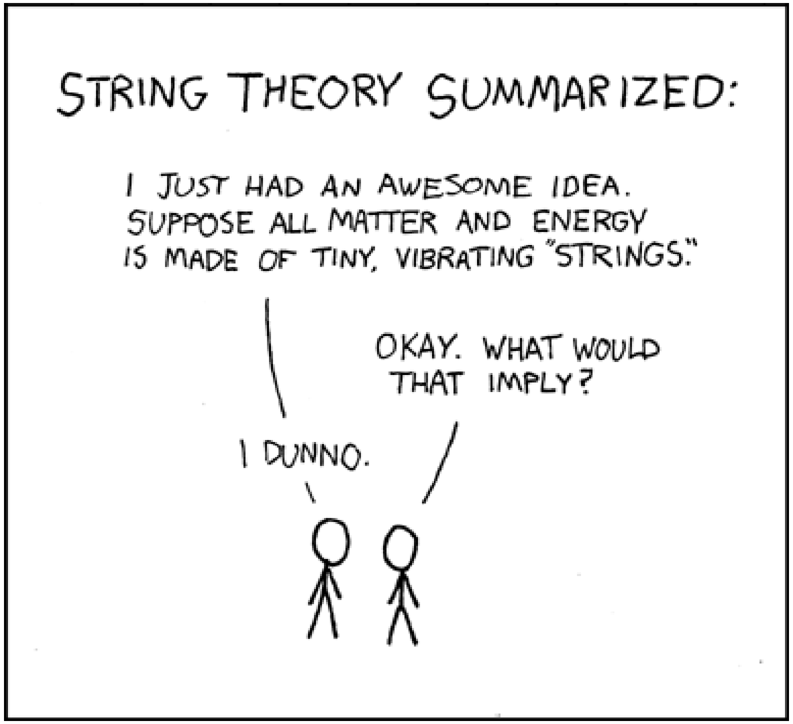
- This particle has not yet been observed
  - So we still don't know why particles have a mass!
  - It could be a mechanism different from the Higgs mechanism
  - But something does what the Higgs does
  - Build LHC to continue our quest for the origin of mass

The Rochester connection



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!



- Supersymmetry may get us closer to including gravity, but it is still not a complete theory
  - Like antiparticles but with spin
  - Fermion ↔ Boson