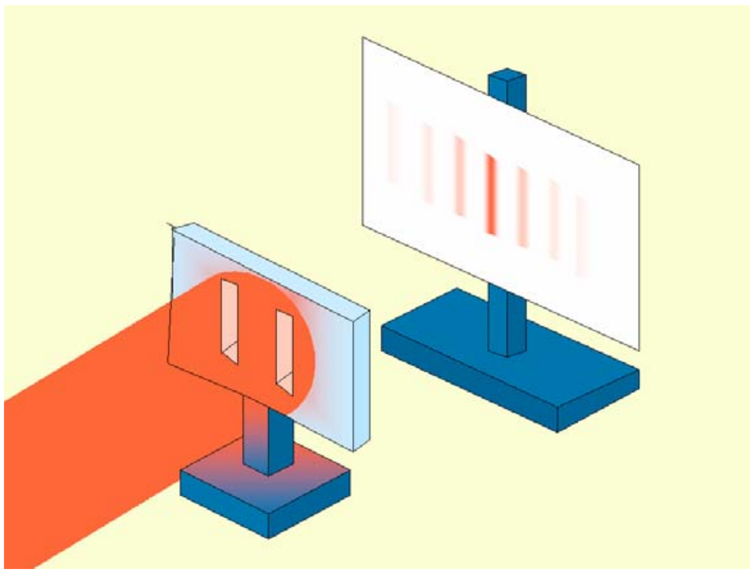
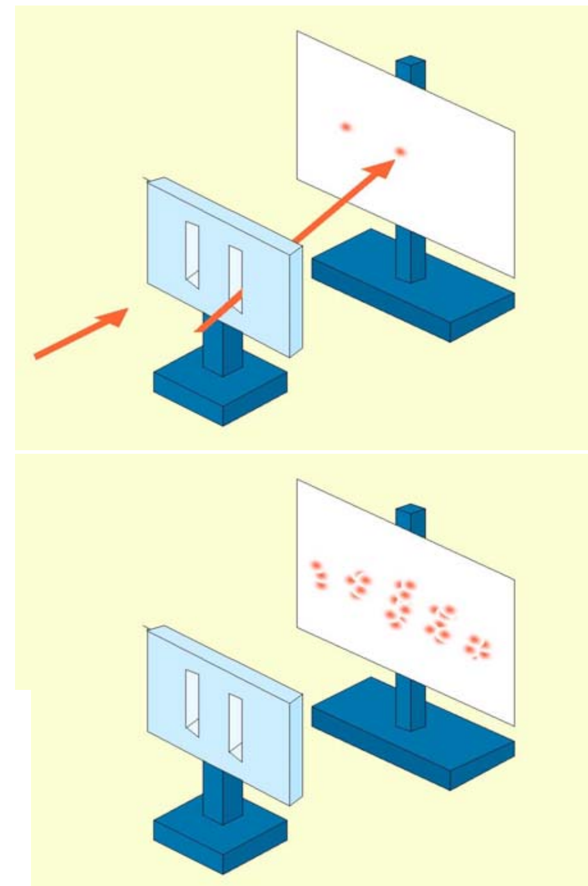
Today

- Announcements:
  - HW#7 is due by 8:00 am Wednesday March 12th.
  - The fourth extra credit problem (Spring Break Story) is due March 19 at 8:00am
  - Exam #2 Review Sheet is available on-line
- Quantum Mechanics
- Weak Force
- Strong Force

Two-slit interference of electrons or photons

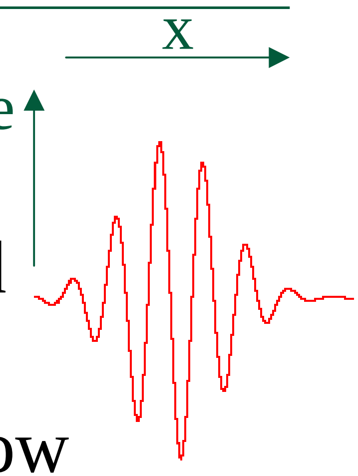


If we cover one slit we get just one spot. This means that somehow, the photons sample all possible paths.



How can a particle interfere with itself? This implies the particle, somehow, takes more than one path at the same time. The particle goes through both slits!

Heisenberg’s Uncertainty Principle

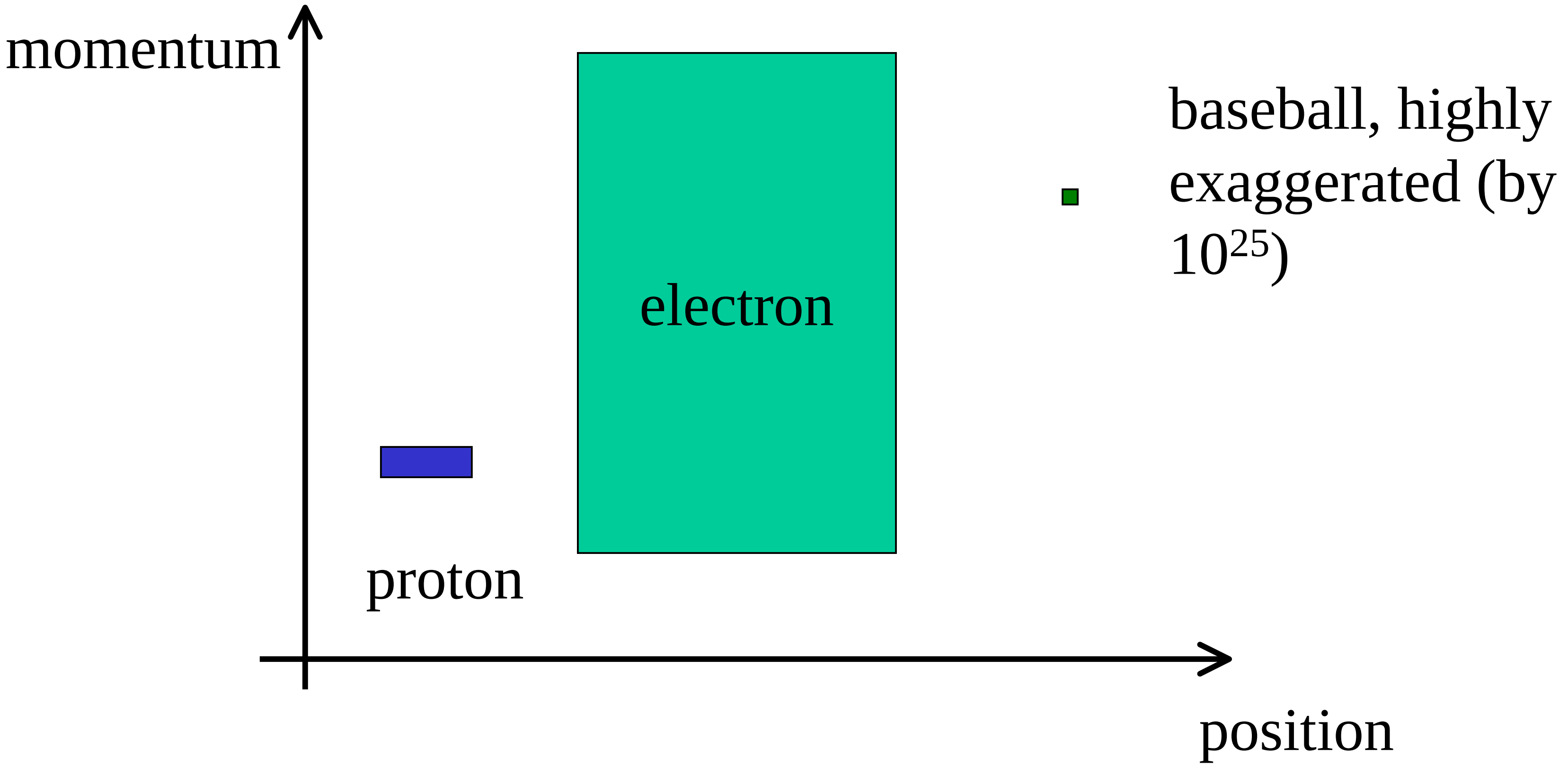


- If a particle has a wavelength, its position and speed are not perfectly defined.
- Uncertainty Principle: It is not possible to know exactly the position and momentum of a particle at the same time.

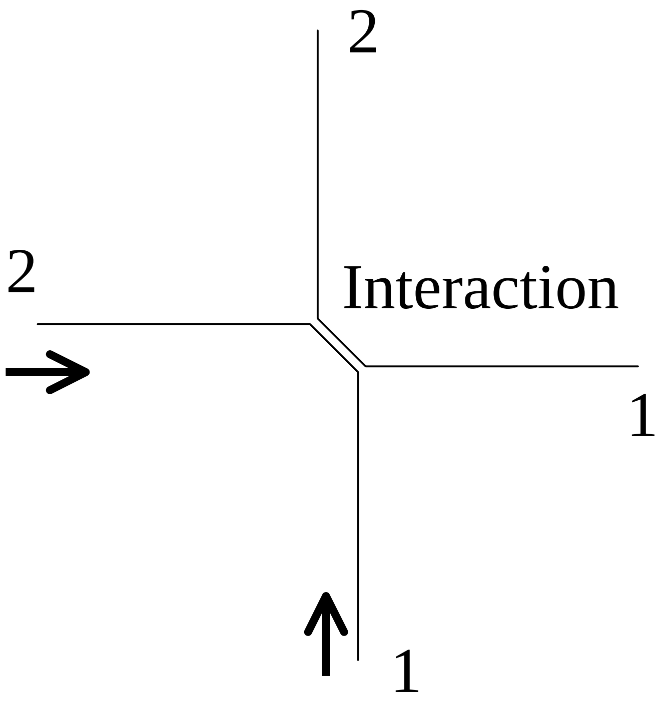
$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

- There is no absolute knowledge. The Newtonian view of the world (if everything were known, everything could be predicted) in not attainable.

Uncertainty depends on mass



Quantum Nonlocality



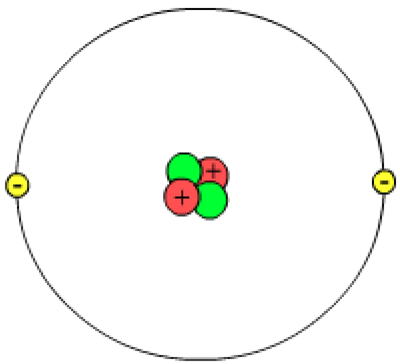
After interaction the wave functions are **entangled**.

If we measure 1 and 2 at the same time the difference in position forms an interference pattern.

If we measure 2 before 1, the measurement of 2 defines where 1 must hit. This information travels faster than the speed of light.
This has been confirmed experimentally.

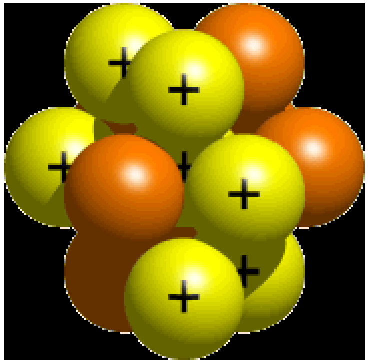
From large to small

Atoms



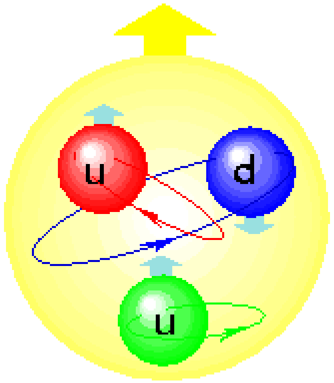
Made of nuclei and electrons. Size: 10^{-9}m

Atomic Nucleus



Made of neutrons and proton. Size 10^{-14} m

A proton (uud)



Made of quarks: Size 10^{-15} m
A neutron has ddu

There are two more forces in nature – Strong Force

Strong force

- A force that exists between quarks, which have a property called color charge.
- The carrier of the force is the gluon (the gluon also has color charge)
- No isolated quarks are found in nature
- The force between protons-proton, protons-neutrons, and neutrons-neutrons is the result of the exchange of pairs of quarks. Pairs of quarks are called mesons (the pion is the lightest meson)
- The Strong force is responsible for binding atomic nuclei.

The Weak Force

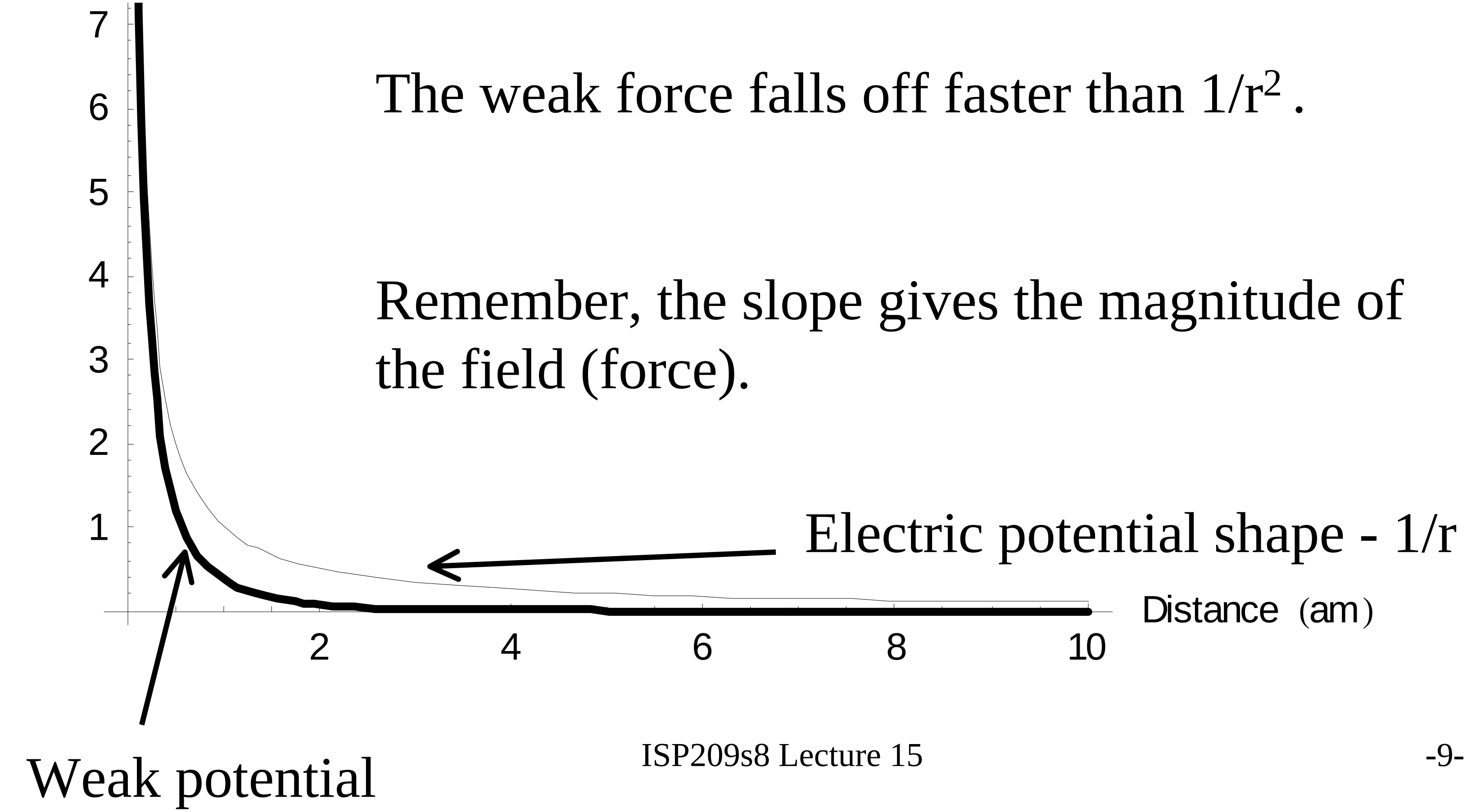
Weak force

- A force between electrons, neutrinos and protons (or neutrons), due to a property of matter called weak charge.
- The carrier of the force are called weak vector bosons W+ or W-, Z. The + or – tells the electric charge of the boson.
- This force allows a neutron to change into a proton and is responsible for most radioactive decays.

Weak Potential

The weak force falls off faster than $1/r^2$.

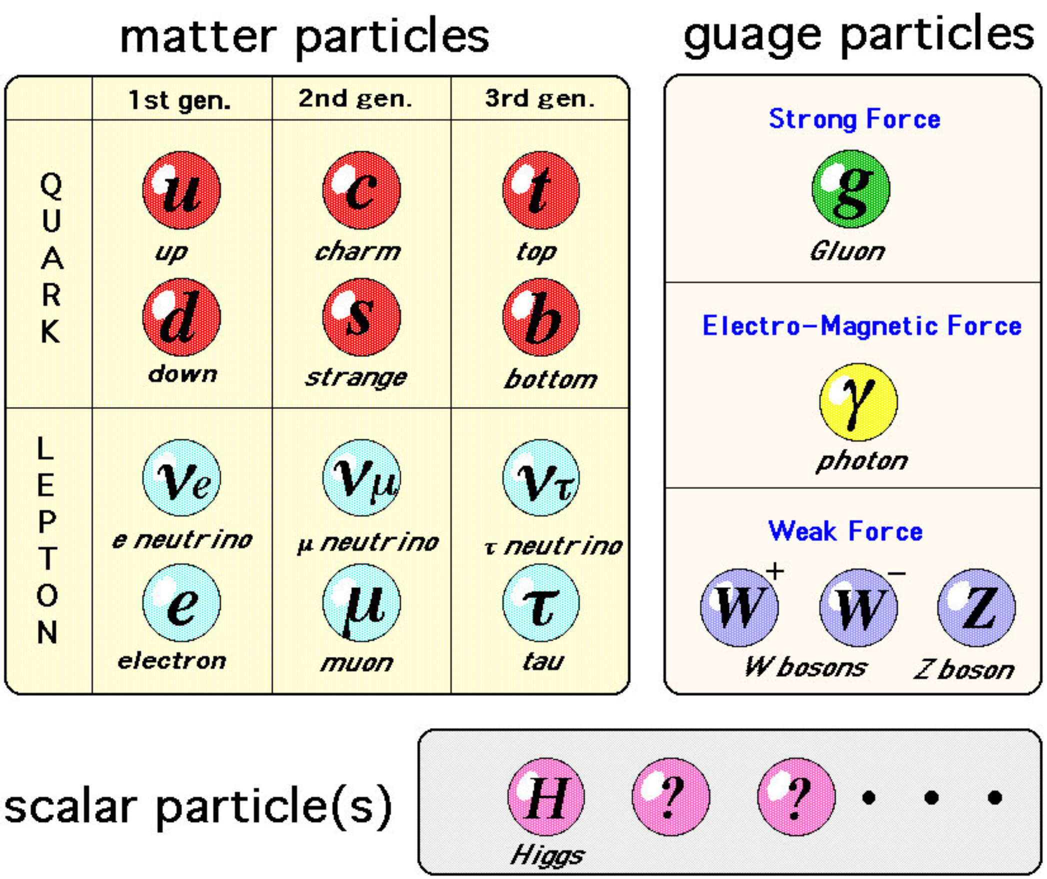
Remember, the slope gives the magnitude of the field (force).



A big picture

- Forces come about because of some property of matter (charge, mass, weak charge, color charge)
- The force is due to the exchange of “force carrier” particles (photon, graviton, vector boson, gluon)

The particles of nature



Quantum Numbers

Type	Charge (e)	Lepton number	Baryon number
e	-1	1	0
ν	0	1	0
u	+2/3	0	1/3
d	-1/3	0	1/3
W^-	-1	0	0

T. Kondo

Antiparticles

Every particle has a corresponding antiparticle. When a particle and an anti particle meet they annihilate giving off energy. The fraction of mass converted to energy in a matter anti-matter annihilation is 1, that is, all the mass is converted to energy.

- A particle and its antiparticle have opposite values for all quantum numbers except spin and mass.
- Example: The antiparticle of an electron is a positron. In all other cases, the name of the antiparticle is anti- in front of the name of the particle, such as proton and anti-proton.
- Antiparticles are written with a line over the top: p vs $\overline{p}$ (the antiproton)

Antimatter

- Antimatter (matter made of anti-particles) is very difficult to make. It can artificially be produced only at large particle accelerators ("atom smashers").
- Matter and anti-matter are created naturally in pairs
- So far the total amount of antimatter ever produced by humankind is a few grams, and that almost immediately annihilated with matter.
- The total energy in 1 g of anti-matter is:

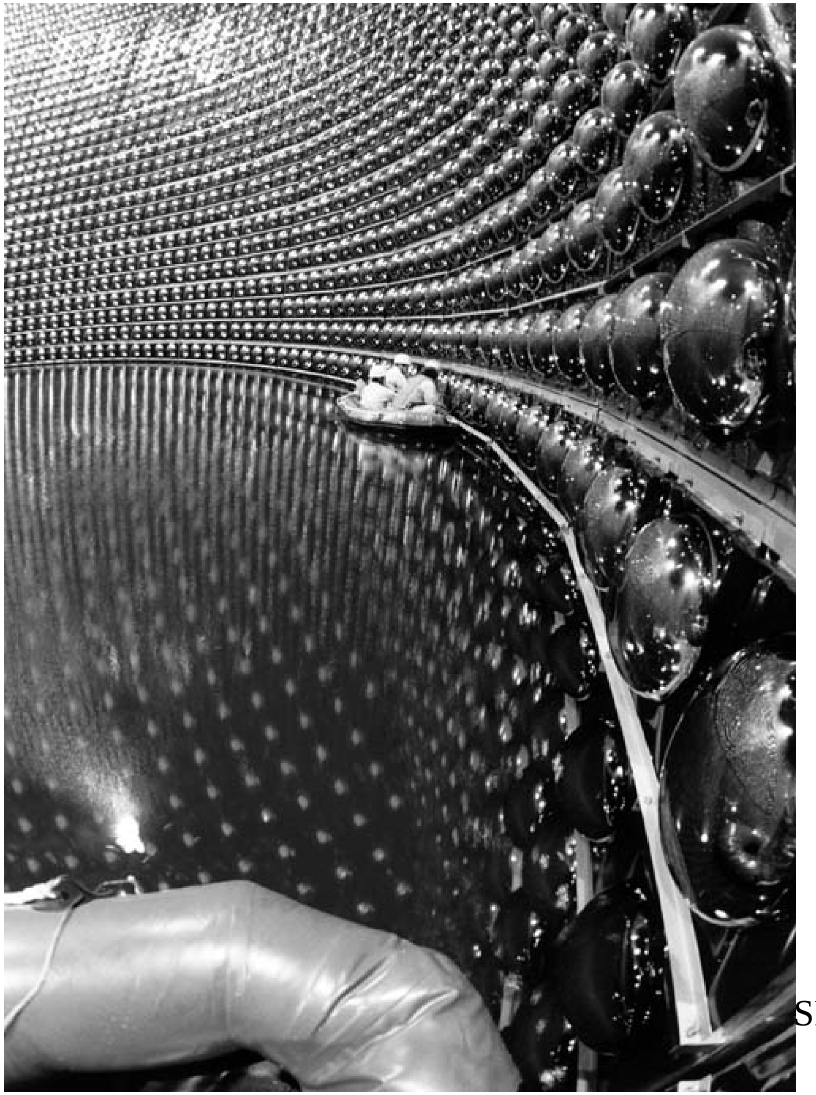
$E=mc^2 = 0.001\text{kg}\ (3E8)^2 = 9E14\ \text{J} = 9E5\ \text{GJ}$

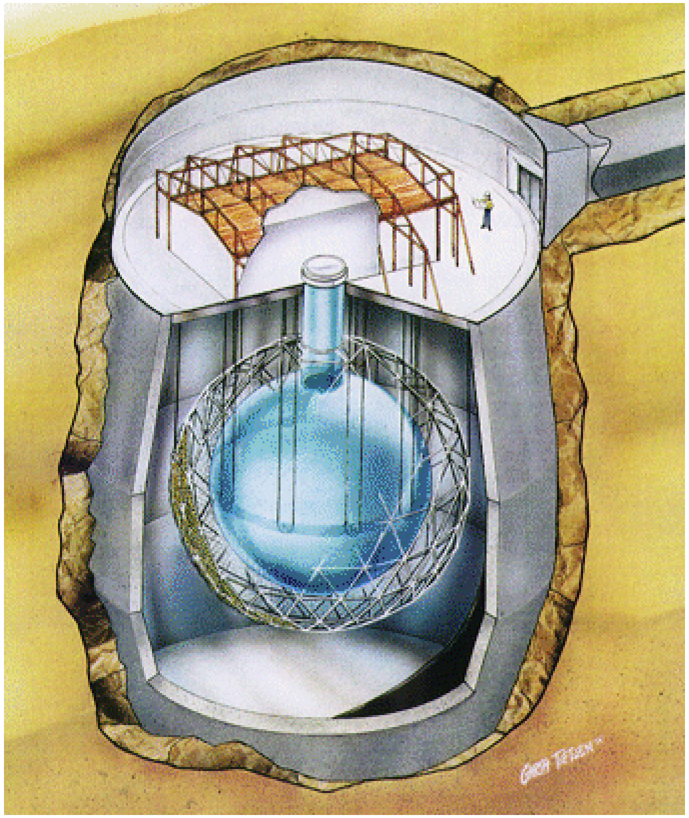
enough to run a normal power plant for 1 day.

Neutrinos

- Subatomic particles that do not have charge, but interact via the weak force.
- These are very unusual particles and we still don't know much about their properties. **They have a mass**, but it is so small we have not been able to measure it.
- They come in three types, but the types mix.
- They account for about 2% of the universe but interact weakly. One light-year of lead would have only a 50% chance of stopping one.

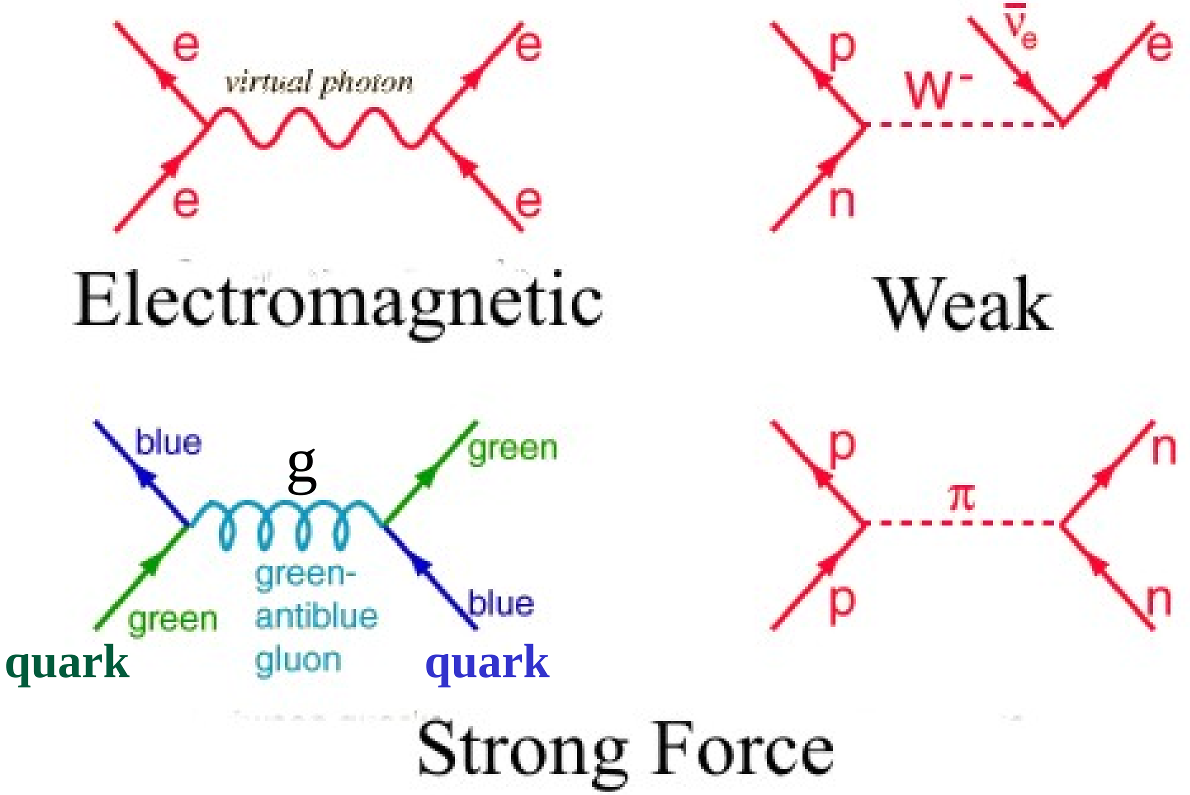
Observatories for neutrinos





Sudbury solar neutrino detector

A way to picture forces – Feynman Diagrams



Alternative version of the uncertainty principle

Time and energy also also related.

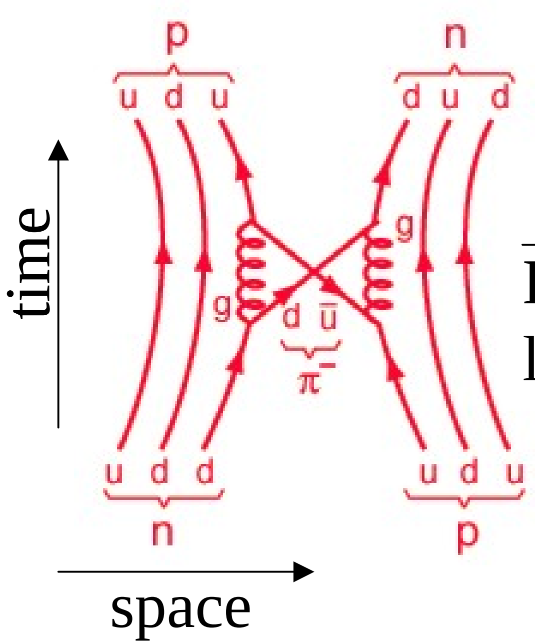
$$\Delta E \Delta t \geq \frac{h}{4\pi} \qquad \Delta x \Delta p \geq \frac{h}{4\pi}$$

It is possible for a short time to get something for nothing. But, it has to be paid back.

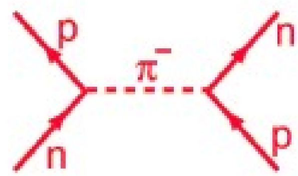
On the very small scale, empty space is alive with “fluctuations”. Particles can pop into and out of existence.

Quantum Chromo Dynamics - QCD

Feynman Diagram for the Strong force



Looks like

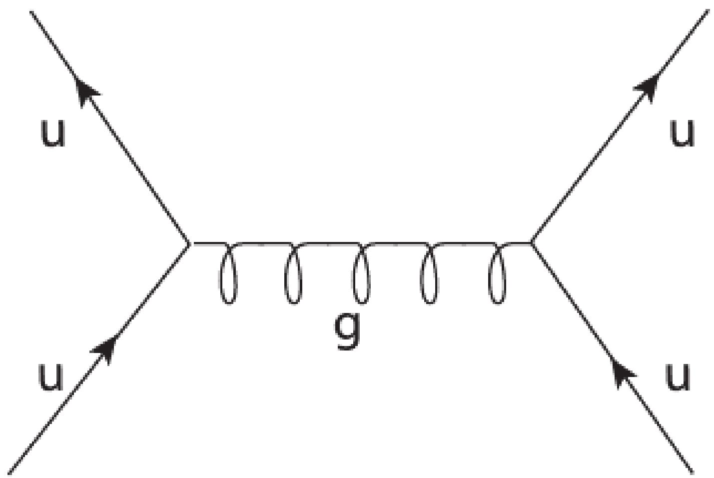


This is called an exchange force. The probability of an interaction decreases exponentially with the mass of the exchanges particle. Exponentially means, twice the mass is e^2=7.3 times less

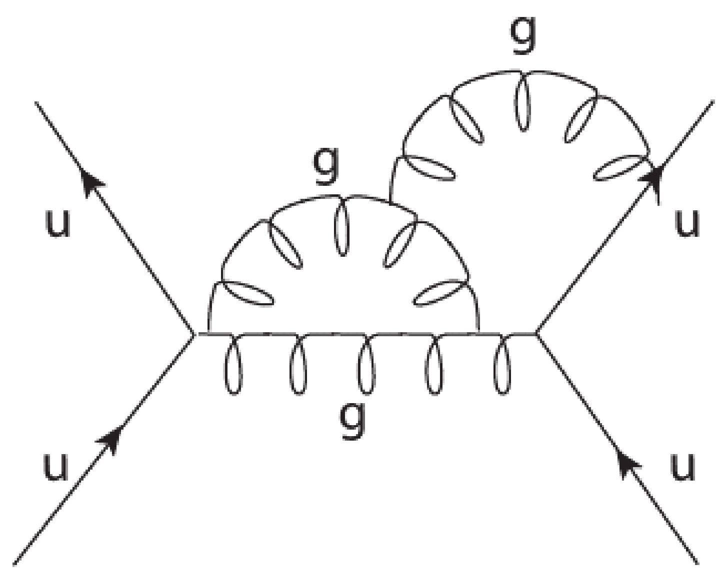
The more massive the particle exchanged, the shorter the range of the force.

The problem with QCD

Gluons themselves have color charge!



"normal"

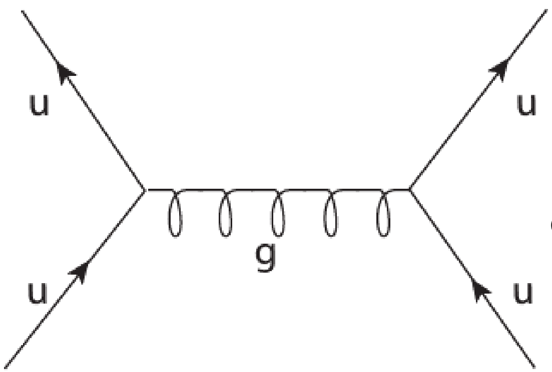


This is also possible.

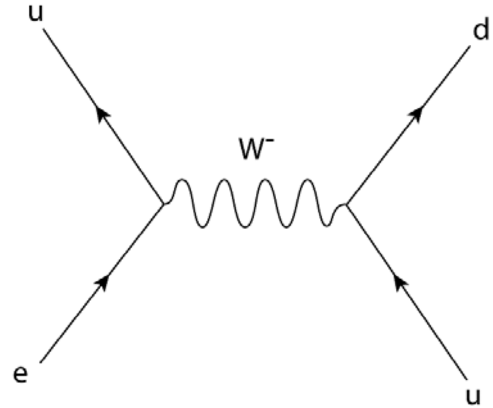
Equations – sort of

Rules for Feynman Diagrams:

1). The number of leptons and baryons must be conserved.



allowed



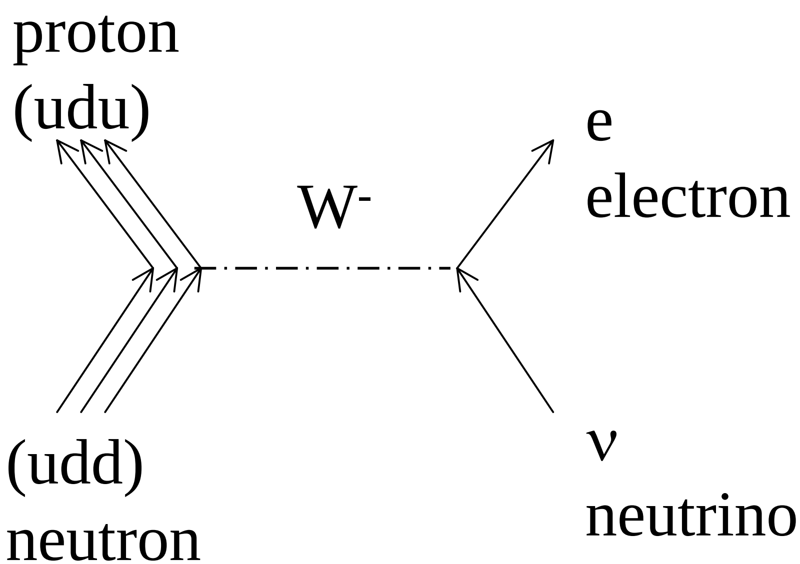
Not allowed since lepton number not conserved

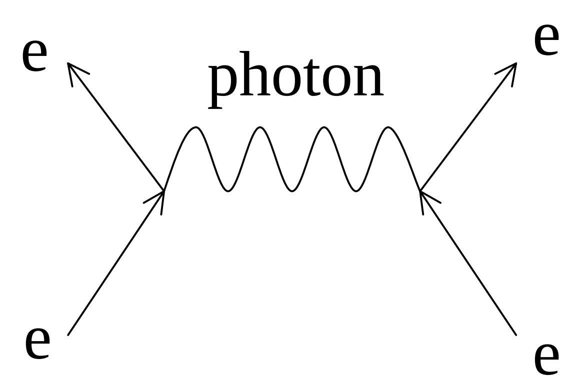
2). Charge must be conserved.

A summary of the forces of nature

Force	Strength	Carrier	Range (m)
Strong	1	Gluon, g, between quarks Mesons-protons/neutrons	10^{-15} size of a proton
Electromagnetic	1/137	photon	infinite
Weak	10^{-6}	Vector Bosons W^{+}, W^{-}, Z^{0}	10^{-18} Only 0.001 width of proton
Gravity	$6x10^{-39}$	Graviton (?)	infinite

Back to the weak and electromagnetic forces





Transformation of a neutron into a proton by an interaction with a neutrino via the Weak force.

Repulsive force between two electrons.

In the process: Energy (including mass); momentum, charge, baryon number, lepton number, are conserved.

Quantum Electrodynamics - QED

- The description of the forces on the previous page is based on a theory called quantum electrodynamics.
- Most successful theory every devised – it has at the moment no known problems and describes all electric, magnetic and weak interactions.
- Strength of the EM force: $$\alpha = \frac{1}{137.03599941(56)} \text{ theory}$$ $$\alpha = \frac{1}{137.03599979(32)} \text{ experiment}$$
- Unification of EM and Weak Forces is called Electroweak theory
- Theory of the strong force is called Quantum Chromodynamics