## Today

- Announcements:
  - HW#7 is due tomorrow October 26th.
- The last lecture covered the strong and the weak forces in nature.
- There are 4 known forces: gravity (mass), electromagnetic (charge), weak (weak charge), strong (color charge)
- Gravity is different (besides being much weaker)





## The Elegant Universe

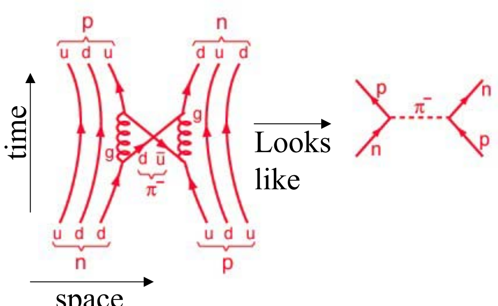
- PBS show written and hosted by Brian Green.
- A sample…
- Describes most of the things we have been talking about
- Should we watch the whole series? This will take two lectures.





## Quantum Chromo Dynamics - QCD

Feynman Diagram for the Strong force



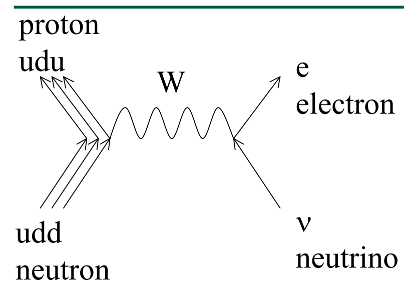

This is called an exchange force. The probability of an interaction decreases exponentially with the mass of the exchanges particle. Exponentially means, twice the mass is $e^2$=7.3 times less

$$\Delta E \Delta t = mc^2 \Delta t \geq \frac{h}{4\pi} \rightarrow range = c\Delta t = \frac{h}{4\pi cm}$$

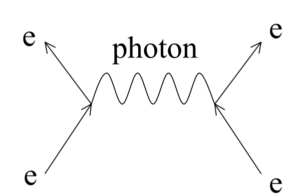




## Back to the weak and electromagnetic forces




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: $\alpha = \dfrac{1}{137.03599941(56)}$ theory

$$\alpha = \frac{1}{137.03599979(32)} \text{ experiment}$$

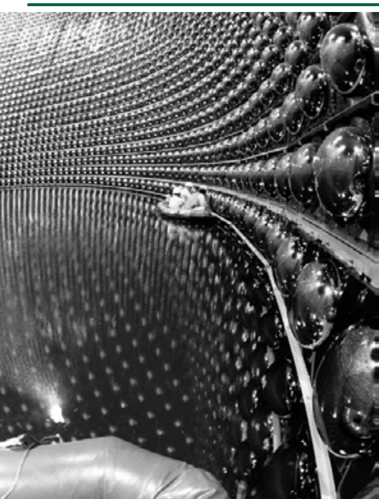


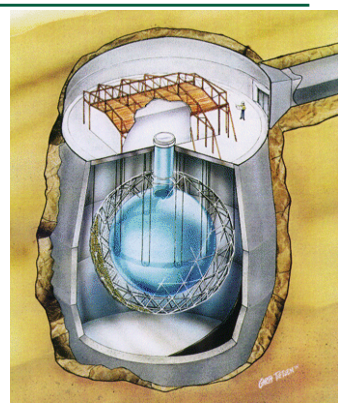
## Neutrinos

- 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. The 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



## The particles in nature

- Atoms – electron, neutron, and proton
- Strong Force – pairs of quarks called mesons (pions, rho meson, kaon, and many more)
- Weak force – neutrinos (electrons, muons, tau)
- Particles are characterized by numbers called quantum numbers. The charge in units of the charge on a proton is one quantum number. Each particle also has an intrinsic spin. Spin comes in units of h (Planks constant).
- When a N-13 nucleus decays it emits a particle with the mass of the electron, but a + charge. This is called a positron (anti-electron)

# 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.

• Every fermion carries charge quantum numbers, and each has a distinct antiparticle partner with opposite values for those labels.

• 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 p vs $\bar{p}$ (the antiproton)





# Antimatter

- Antimatter is very difficult to make. It can artificially only 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 is a few grams.
- 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.





# The Standard Model

The Standard Model is the name given to the current theory of fundamental particles and how they interact. This theory includes:

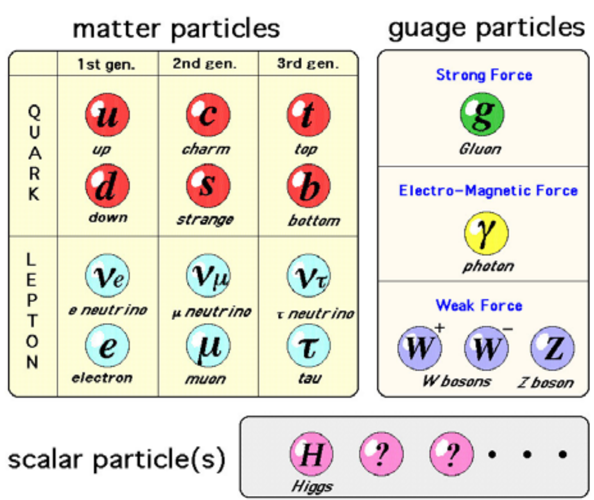
- Strong interactions due to the color charges of quarks and gluons.
- A combined theory of weak and electromagnetic interaction, known as electroweak theory.

The theory does not include the effects of gravitational interactions. These effects are tiny compared to the other forces and can be neglected in describing atoms etc. The Standard Model is a well established theory applicable over a wide range of conditions.



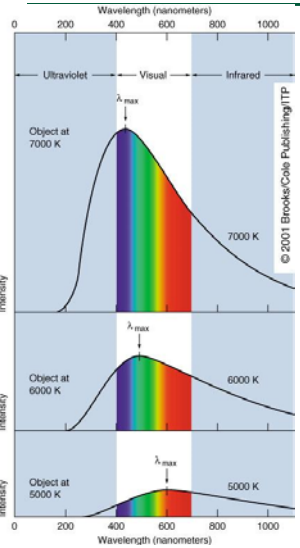


# The particles of the standard model




T. Kondo

## Blackbody Radiation




All objects emit a spectrum of photons. A perfect black body has the spectrum shown at the left.

The emission spectrum depends on temperature. The amount depends on size.

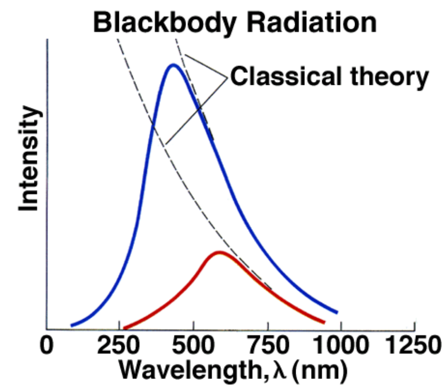
$$L = \sigma A T^4 \; ; \sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$$

$$E_{mean} = 2.705 \cdot kT ; k = 8.617 \times 10^{-5} \frac{eV}{K}$$





## The Ultraviolet catastrophe



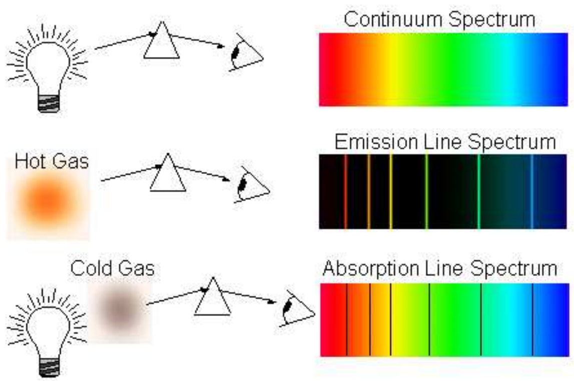

Quantum theory explains why the curves go back to 0 at zero wavelength.

It is because photons comes in packets (of energy hf) called photons





## Spectra come in 3 kinds

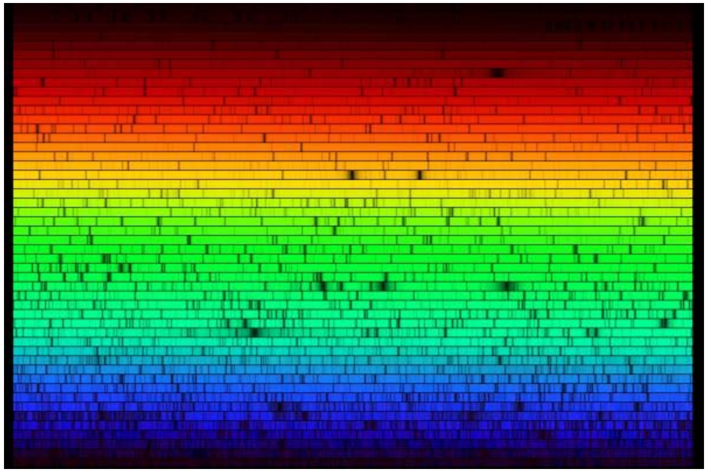



The pattern of lines tells what elements are present.

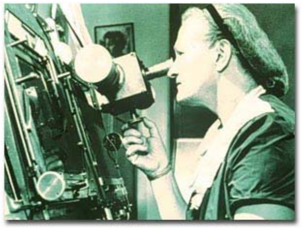




## The spectrum from our Sun



## Cecilia Payne-Gaposchki Story



- Studied astronomy at Oxford
- Came to Havard for graduate study because the only carrier for women in England in astronomy was teaching
- Was the first person to realize that the stars are mostly made of hydrogen and helium
- Here thesis is widely regarded as the best ever in astronomy.





## Problems with the standard model

- Why so many particles?
- Are there more we don’t know about yet?
- What is charge? Why does it come in fixed units?
- Why is the standard model so complicated?
- How is gravity related to the other forces?
- In general the standard model does not answer the WHY question.