ASTROPHYSICS AND THE EVOLUTION OF THE UNIVERSE–FIVE SESSIONS

Leonard S Kisslinger, Physics Department, Carnegie Mellon University

1. OUTLINE OF ASTROPHYSICS AND EVOLUTION OF THE UNIVERSE

SOME BASIC PHYSICS CONCEPTS

TIME, DISTANCE, SPEED, ACCELERATION ENERGY AND TEMPERTURE UNITS

REVIEW OF ELEMENTARY PARTICLES

HUBBLES LAW: THE UNIVERSE EXPANDS THE BIG BANG

2. STARS, GALAXIES, ETC

EVOLUTION OF OUR SOLAR SYSTEM

GALAXIES, GALAXY CLUSTERS, QUASARS AND DARK MATTER

MASSIVE STAR COLLAPSE, SUPERNOVAE, PULSARS, AND BLACK HOLES

3. THE RADIUS OF THE UNIVERSE, R(t), AND TEMPERATURE, T(t) (t= time)

HORIZON PROBLEM, INFLATION and OUR UNIFORM UNIVERSE: DARK ENERGY

4. COSMIC MICROWAVE BACKGROUND RADIATION (CMBR) AND WHAT IT TEACHES US ABOUT THE UNIVERSE

5. EWPT (ELECTROWEAK PHASE TRANSITION) AT t $\simeq$ 10 trillionth sec. HOW PARTICLES GOT MASSES. BARYOGENESIS (WHY WE HAVE MORE PROTONS THAN ANTI-PROTONS)

QCD (QUANTUM CHROMODYNAMICS) PHASE TRANSITION at t $\simeq$ 10 millionth sec AND HOW QUARKS CLUSTERED TO FORM PROTONS, OUR UNIVERSE

SEARCH FOR QUARK-GLUON PHASE

BIG BANG NUCLEOSYNTHESIS-
LIGHT NUCLEI PRODUCED

MORE ON DARK ENERGY-
EXPANSION ACCELERATING

STUDY OF DARK ENERGY-MASS OF DARK MATTER VIA EPWT
if time permits

OTHER TOPICS THAT YOU MIGHT SUGGEST

SOME BASIC PHYSICS CONCEPTS

TIME, POSITION, DISTANCE, VELOCITY, ACCELERATION, MASS, FORCE

At time t_1 I am at position r_1. At time t_2 I am at position r_2, $r_2 - r_1$=difference between positions
DISTANCE= $D = r_2 - r_1$

VELOCITY, v=distance/(time difference), or
$v = (r_2 - r_1)/(t_2 - t_1)$

If v_1, v_2 are velocities at t_1, t_2
ACCELERATION = $a = (v_2 - v_1)/(t_2 - t_1)$ **or**
ACCELERATION CHANGE IN VELOCITY/TIME

NEWTON'S LAW OF MOTION:
If a mass m has acceleration a, then
F=ma or
FORCE = MASS X ACCELERATION

EXAMPLE: NEWTON'S FORCE OF GRAVITY

Masses m_1 and m_2 are separated by distance R
F(gravity)=G m_1 **x** $m_2/(R$**x**$R)$
G=Newton's constant

Example, g=acceleration of gravity on earth
M_e**=mass of earth,** R_e**=radius of earth**
F(gravity) on mass m = G m **x** $M_e/(R_e$**x**$R_e)$**=mg**
g=G $M_e/(R_e$**x**$R_e)$**=acceleration of gravity on earth**

TIME, DISTANCE, SPEED, ACCELERATION, ENERGY AND TEMPERATURE UNITS

TIME: 1s=1sec = 1second 1 minute = 60 s

1 hour =60 x 60 s= 3,600 s = 3.6 x 10^3 s

1year = 365 days=365 x 24 x 3,600 s=31,536,000 s = 3.1536 x 10^7 s $\simeq$ 3.15 x 10^7 s

DISTANCE: 1 m = 100 cm 1 km = 1000 m

SPEED (magnitude of VELOCITY) = distance/time

Speed of light = c =300,000 km/s

ACCELERATION OF GRAVITY=g=9.80 m/s^2

ASTRONOMICAL UNITS OF DISTANCE

1 lightyear =1 ly= distance light travels in 1 year

1 ly = 300,000 km/s x 3.15 x 10^7 s=9.46$\times 10^{15}$ m

1 pc = 1 parsec = 3.25 light years = 3$\times 10^{18}$ cm

ENERGY: 1 ev =potential energy an electron gets when raised through a one volt potential difference

1 MeV = 1,000,000 ev = 10^6 ev; 1 GeV = 10^9 ev

kinetic energy = energy of motion = mass x speed^2/2

electron mass energy: 1 $m_e c^2$ = 0.511 MeV

proton mass energy: 1 $m_p c^2 \simeq$ 1.O GeV

T=TEMPERATURE: ONE FORM OF ENERGY

Units of T: ^{o}C(Celcius)=273^{o}K. 1^{o}C= 1.8^{o}F

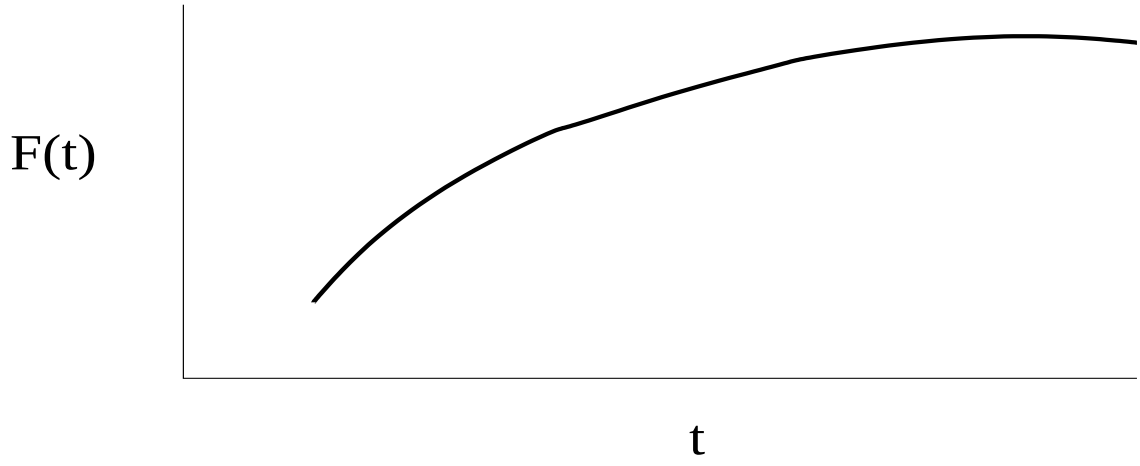
Energy = kT, k = Boltzman's constant.

1 ev = 11,604 k^{o}K.

ICE-WATER TRANSITION: T=0.0 ^{o}C =32 ^{o}F

WATER-STEAM TRANSITION: T=100 ^{o}C =212 ^{o}F

FUNCTION: F(t) gives the value of F at time=t



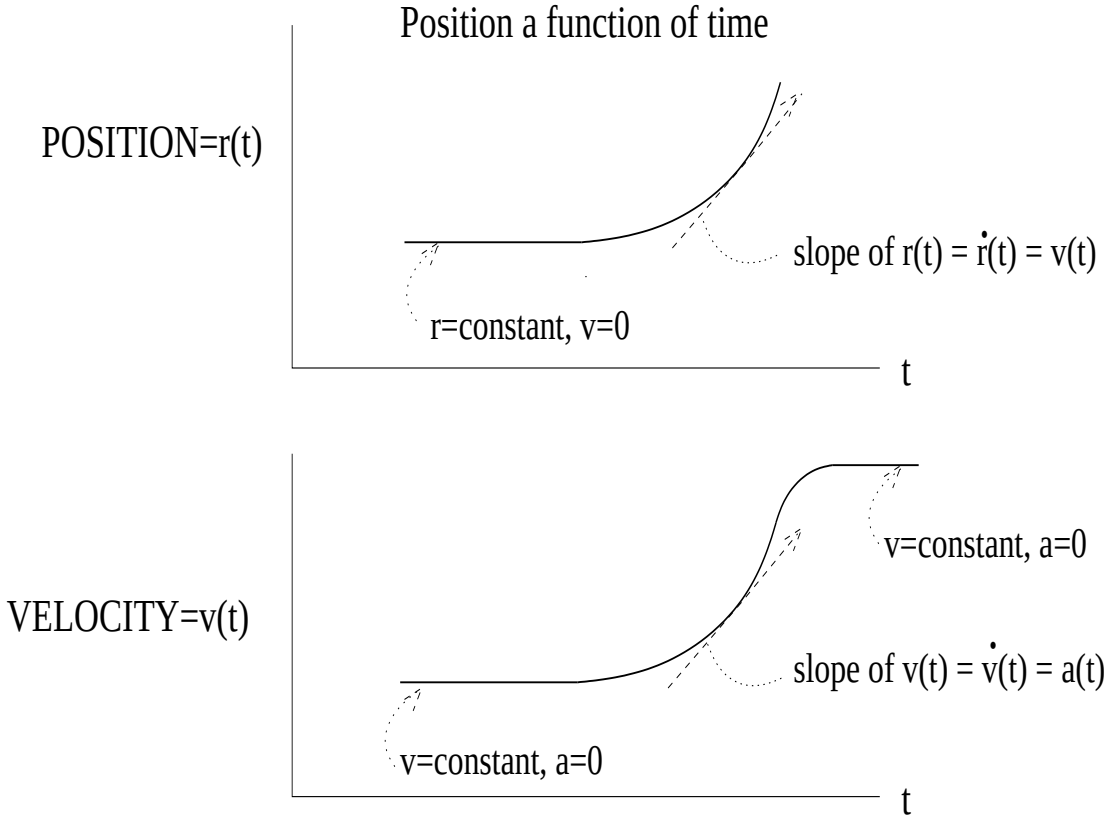
VECTOR FUNCTION: $\vec{F}$**(t)**
$\vec{F}$**(t) has MAGNITUDE F(t) AND DIRECTION** $\vec{}$

EXAMPLE: VELOCITY = $\vec{v}$**(t) (AT SOME TIME t)**

$\vec{v}$**(t) can be 100 km/s east, or 100 km/s west**

To go from 100 km/s east to 100 km/s west needs acceleration, even though the magnitude v (speed) is the same.

POSITION, VELOCITY, AND ACCELERATION OF A PARTICLE or A POINT IN SPACE-TIME ONLY MAGNITUDES OF FUNCTION CONSIDERED



VELOCITY=TIME RATE OF CHANGE OF POSITION: $v(t) = \dot{r}(t)$

ACCELERATION = TIME RATE OF CHANGE OF VELOCITY:

$a(t) = \dot{v}(t) = \ddot{r}(t)$

Examples: r=constant. v=a=0

r=3 (cm/s) x t, v=3 cm/s, a=0 where t is in units of sec

v=5 (cm/s)x t/s, a=5 cm/s ^{2}

ELEMENTARY PARTICLES AND FORCES

Elamentary Particles: No components, e.g., electrons
Elementary Forces: Particles Interact Via Fields

CLASSICAL: A particle emits a field
Another particle in the field feels a force

QUANTUM: A particle emits a quantum of an elementary field.
Another particle absorbs the quantum.

1) FORCE OF GRAVITY: Our most familiar force. It drops an apple on Newton's head, and keeps the earth going around the sun. F(G)= G $m_1 m_2/(R^2)$-as above.

QUANTUM FIELD THEORY DOES NOT WORK FOR THE GRAVITATIONAL FORCE.

2) ELECTROMAGNETIC FORCE: The force that holds atoms together. This is the force mainly involved in Chemistry, Biology, Material science.

3) STRONG INTERACTION: This force holds quarks (elementary particles) together to make protons and neutrons (NOT elementary, as we shall discuss).

4) WEAK INTERACTION: This force causes neutrons to decay into protons. Neutrinos, partners of electrons, as we shall see, interact only with the weak interaction. Important for astrophysics, such as supernovae.

BRIEF HISTORY OF PARTICLES

Atoms discovered in nineteenth century

1911 Rutherford experiment, scattering of a beam of particles by atoms, showed that atoms have most mass at the center, the atomic nucleus, and at a great distance are electrons. At that time it was known that the electric charge of the nucleus was Ze, with Z the number of electrons, each having electric charge -e. Z is also called the atomic number.

Atomic spectra had been observed. Using a spectrograph or even a prism it was seen that the light emitted from hydrogen was a series of lines, with colors red, blue, violet, etc. This required an new theory, as by classical physics the electrons spinning around the nucleus would emit the entire rainbow of colors.

1913 Niels Bohr's model of special orbits, which was the start of quantum theory.

1930-32 Atomic nuclei with atomic number Z were shown to have Z protons, each with electric charge +e and neutrons, which have no electric charge.

1935-40 Yukawa postulated a theory of the nuclear force between neutrons and protons: the force comes from the exchange of mesons, like the electric force arises from the exchange of photons–discussed below.

1947 The lightest meson the pion (π) was discovered in cosmic rays

1952 With new cyclotrons pion beams were produced. The Delta, with a mass of 1232 MeV was discovered in pion scattering on protons. The delta is an excited state of the proton. This proved that the proton is not an elementary particle, as elementary particles have no composite structure (like elecrons and protons in hydrogen).

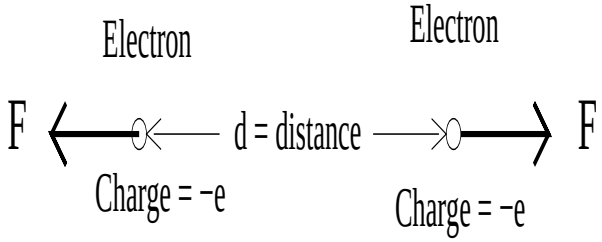
1953 Strange particles were discovered. The Lambda, with mass of 1116 MeV lives about 10 trillion (10^{13}) times longer than expected from the decay produced by the nuclear foce. Its lifetime is about 10^{-10} s compared with the Deltas lifetime of about 10^{-23} s. There was no explanation: it was called a strange particle.

Over the next two decades the discovery of many strange, as well as "charm, bottom, top" particles led to the quark model, with three "generations". Quarks are elementary particles. The strong force does not change strangness while the weak force does, explaining the long lifetimes of strange particles. Similarly with charm, bottom, and top.

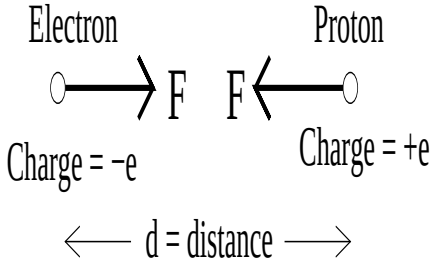
ELECTRIC FORCE: two charges separated by a distance = d, like charges repel, unlike charges attract

$$Force(electric) \; = \; \frac{electric\ charge\ 1 \times electric\ charge\ 2}{d \times d}$$

LIKE CHARGES REPEL : ELECTRIC FORCE = F= $\frac{(e)^2}{d^2}$ OUTWARD



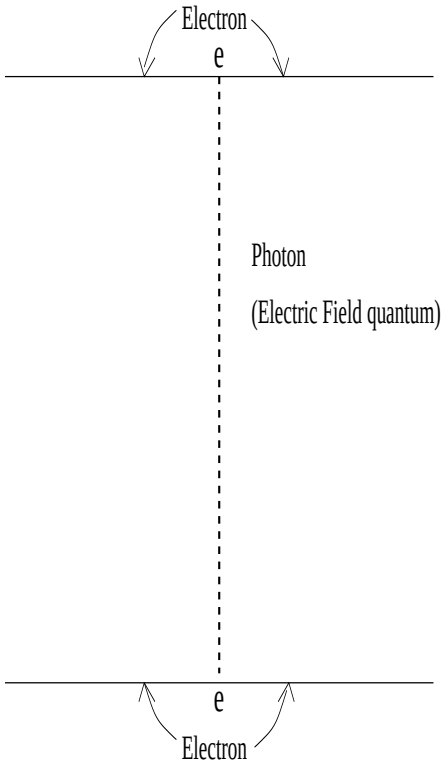
UNLIKE CHARGES ATTRACT: ELECTRIC FORCE = F= $\frac{(e)^2}{d^2}$ INWARD



QUANTUM ELECTRODYNAMICS (Quantum Field Theory of Electromagnetism-QED):

Electric force caused by exchange of PHOTONS, quanta of em field.

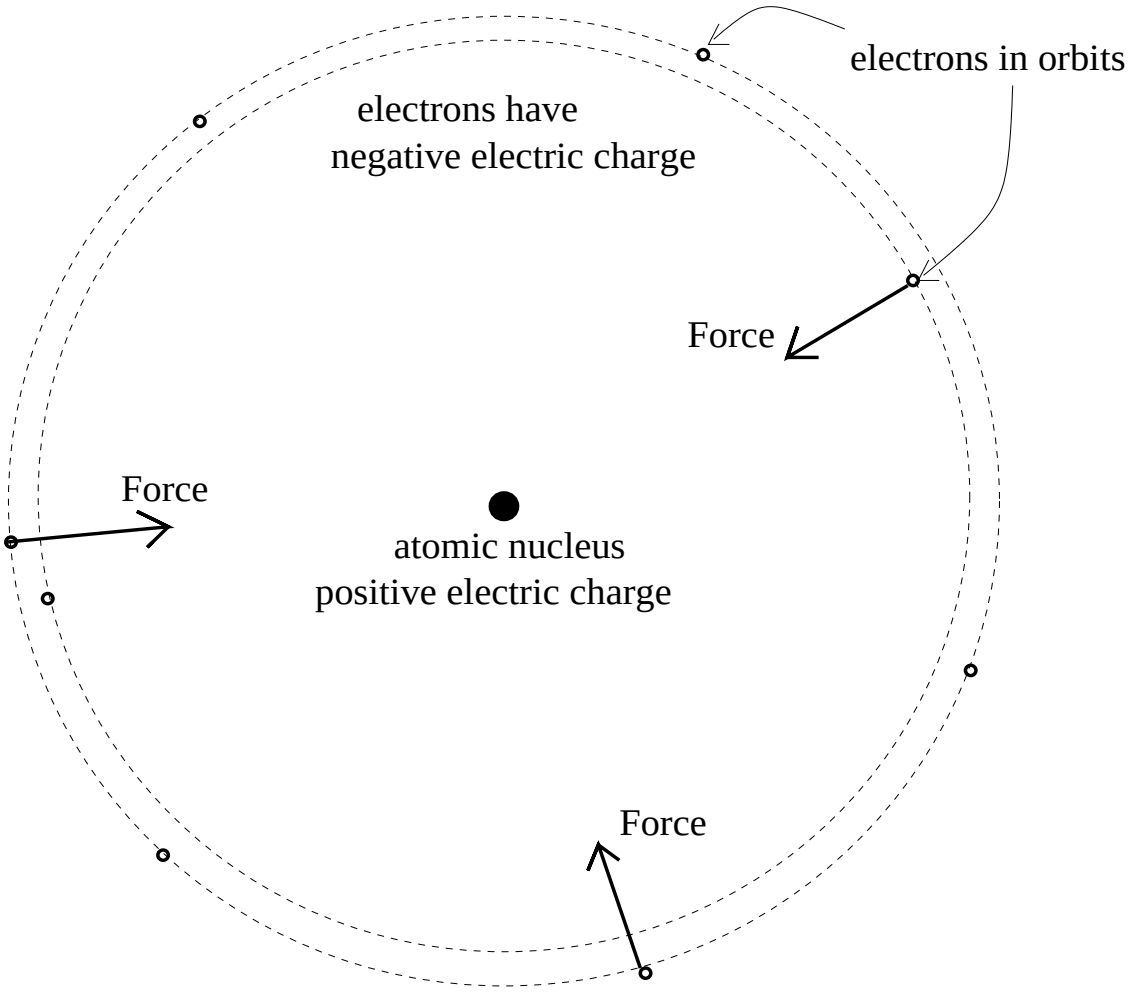
Coupling of photon to particle given by electric charge of particle. Feynman Diagram (lowest order):



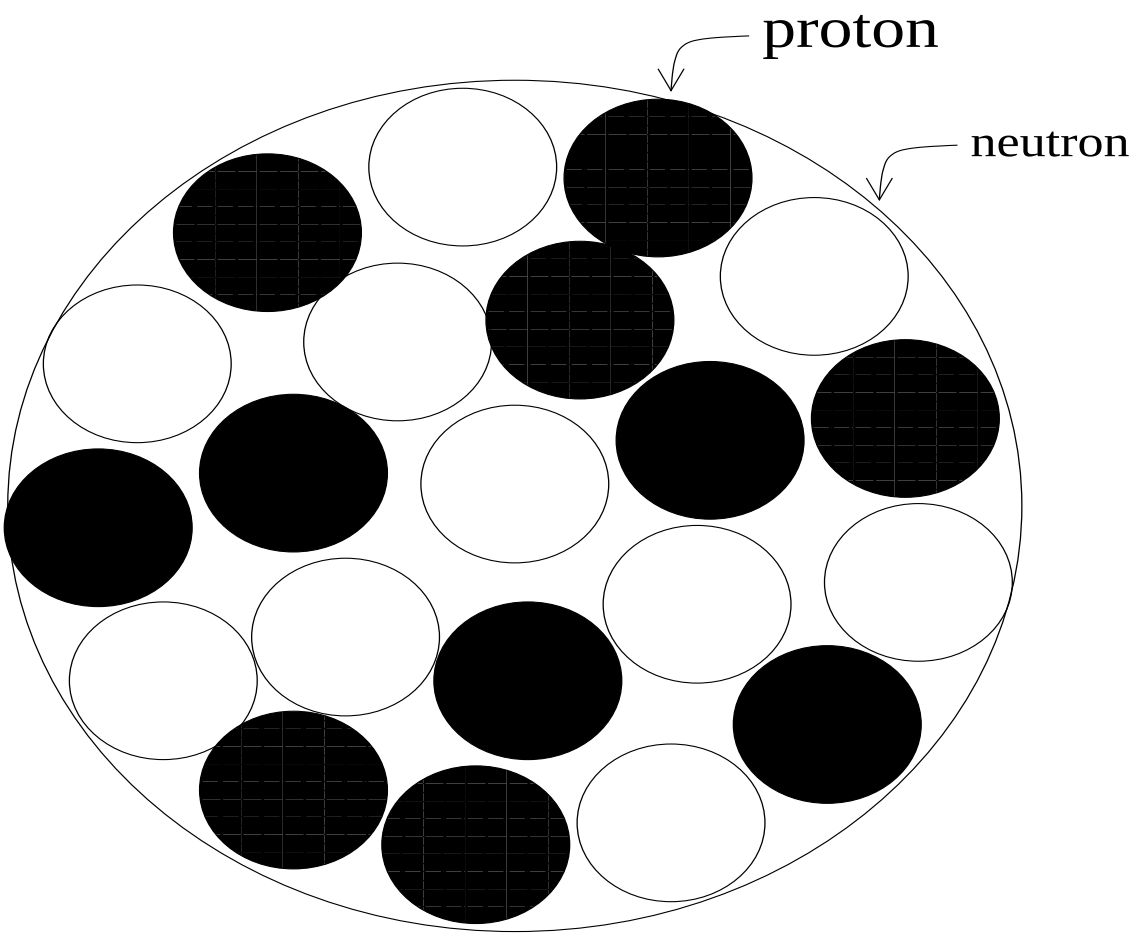
Electric Force Produced By Photon exchange

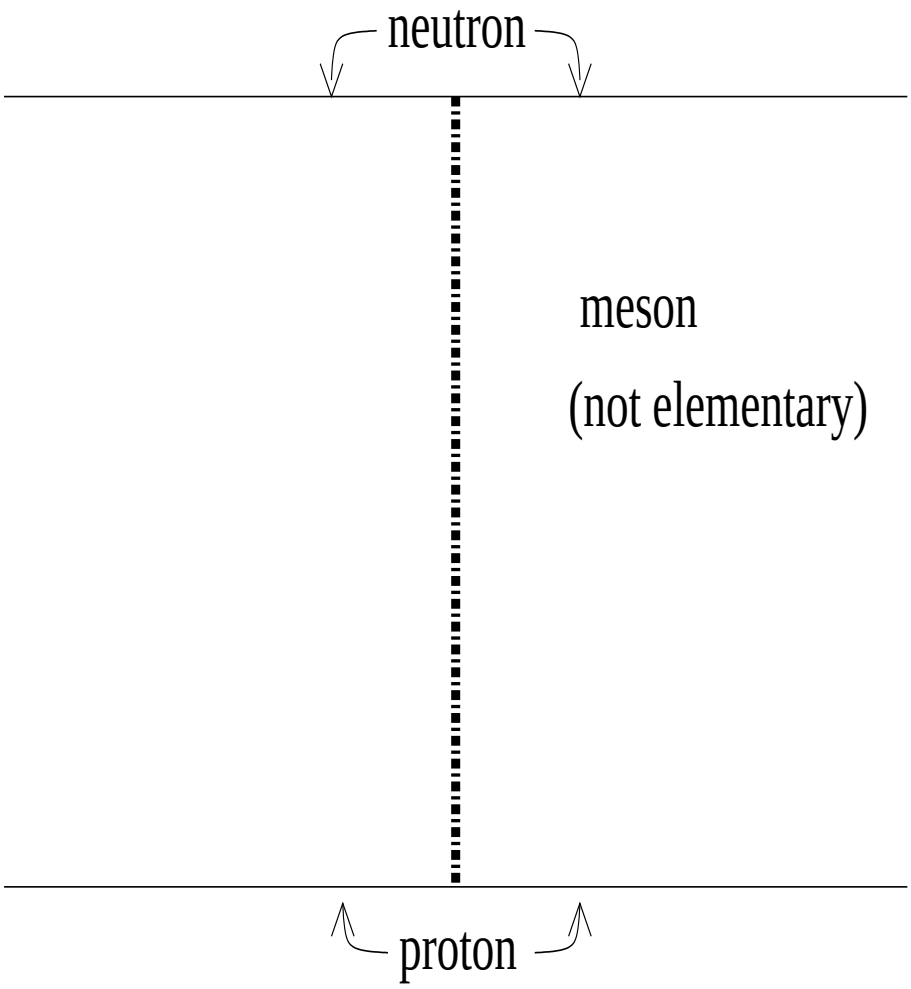
Note $e^2 \sim 1/137$ Therefore higher order diagrams are small

ATOMS: Electrons and Atomic Nucleus Bound by Electric Force, Opposite Charges Attract



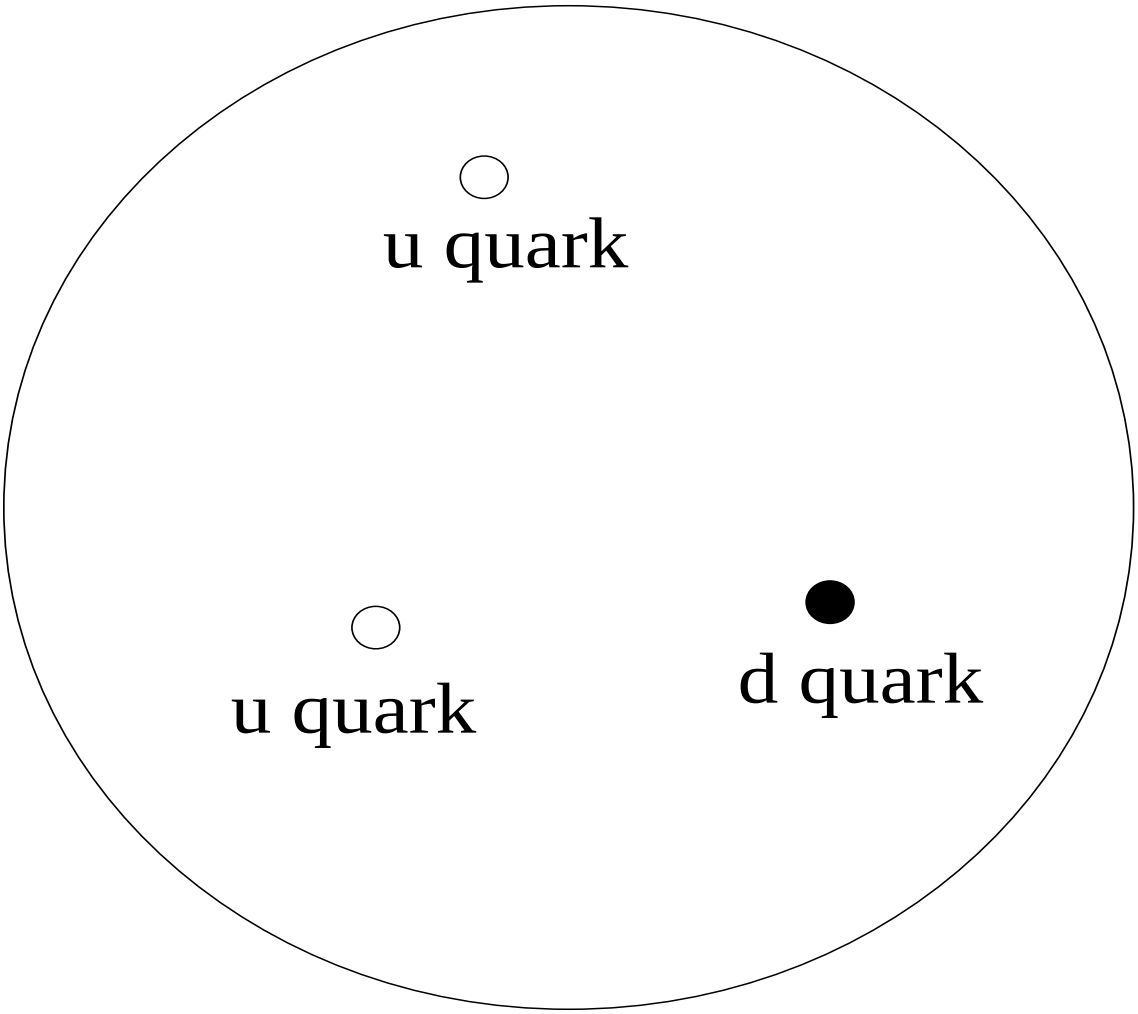
ATOMIC NUCLEUS



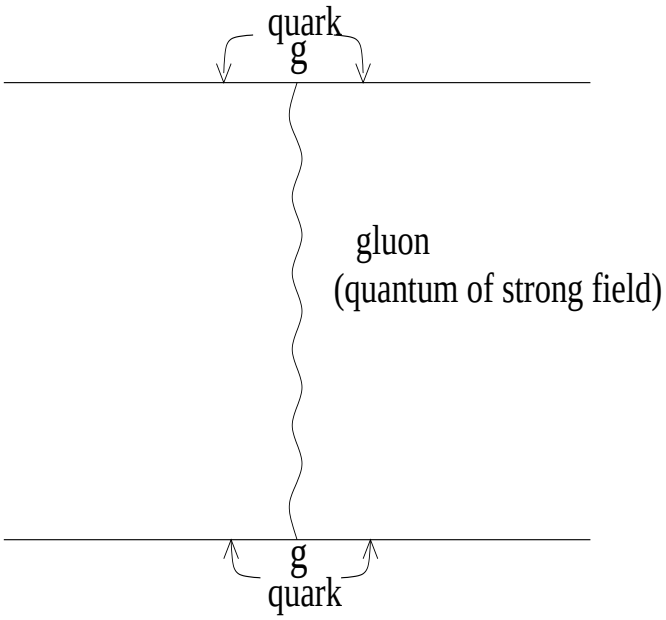


Nuclear force via meson exchange:not elementary

Protons Are composed of Quarks (Elementary Particles)



Proton



QCD (Quantum Chromodynamics):Quark force via gluon exchange

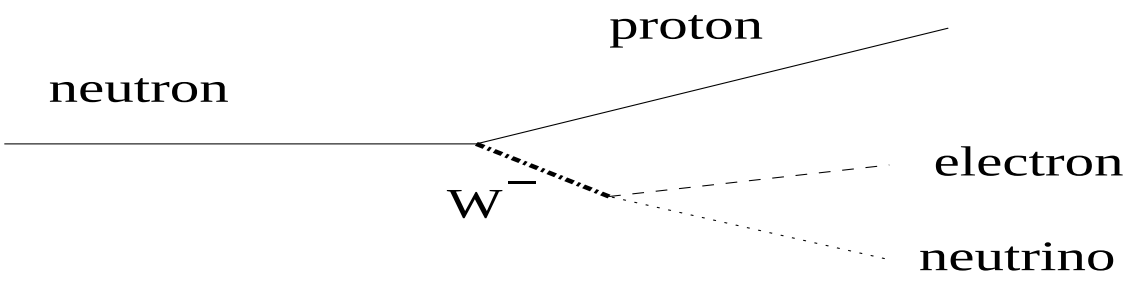
STRONG FORCE

$g^2 \sim 1 \sim 100 \times e^2$

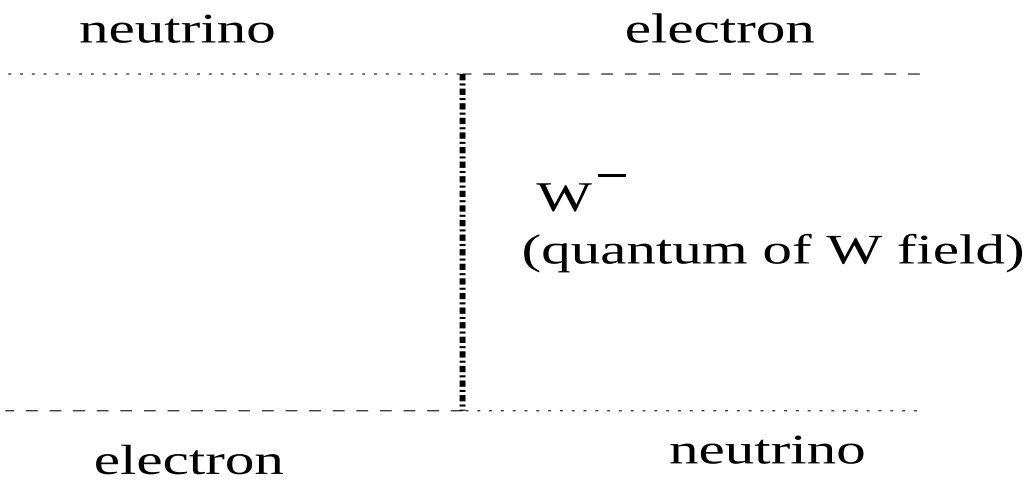
Strong force ~ 100 x electromagnetic force

For QCD "color" replaces "electric charge" of QED

Nonperturbative. Feynman diagrams do not converge (no good!)



Neutron Beta Decay



WEAK FORCE

ANTIPARTICLES

Every particle has an antiparticle: opposite charge and color

Electron (charge = −e). Positron (antielectron) (charge =+e)

Antiquark vs quark: Opposite electric charge and color

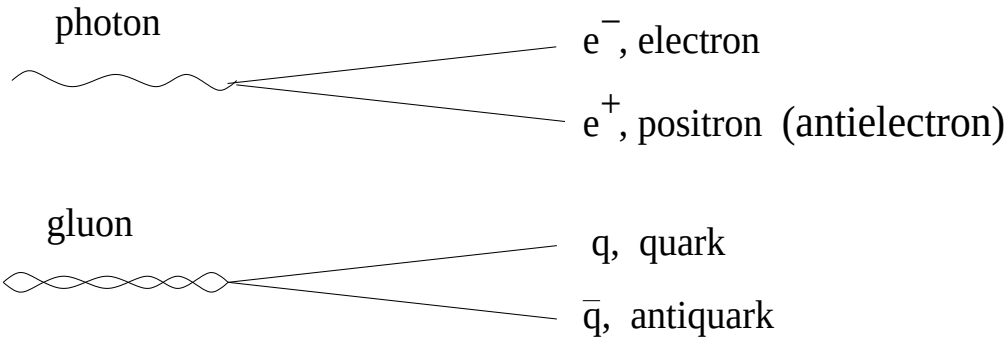
Lepton number (electron, electron number = 1)

Baryon number (a quark has baryon number = 1/3}

ANTIPARTICLES HAVE OPPOSITE CHARGE, COLOR, LEPTON NUMBER, BARYON NUMBER

ELECTRIC CHARGE, COLOR, LEPTON NUMBER, BARYON NUMBER ARE CONSERVED

Particles and antiparticles can be produced together



Homework Question: just after the B.B., the lepton number and baryon number were zero−−same number of particles as antiparticles must be produced (conservation laws). How can the universe have more electrons and protons (antiquarks make antiprotons) than positrons and antiprotons, which would annihilate giving us a very boring universe (without us).

SUMMARY OF ELEMENTARY PARTICLES AND FORCES IN THE STANDARD MODEL

	leptons	quarks
First Generation	$\begin{pmatrix} e^- \\ \nu^e \end{pmatrix}$	$\begin{pmatrix} u \\ d \end{pmatrix}$
Second Generation	$\begin{pmatrix} \mu^- \\ \nu^\mu \end{pmatrix}$	$\begin{pmatrix} c \\ s \end{pmatrix}$
Third Generation	$\begin{pmatrix} \tau^- \\ \nu^\tau \end{pmatrix}$	$\begin{pmatrix} t \\ b \end{pmatrix}$

STANDARD MODEL FORCES (QUANTA=PARTICLES)

STRONG (GLUON−STRONG FIELD)
ELECTROMAGNETIC (PHOTON−EM FIELD)
WEAK (W^+, W^-, Z^o−WEAK FIELDS)

[GRAVITY (GRAVITON−STANDARD MODEL USING FIELD THEORY DOES NOT WORK)]

HIGGS (EWPT−to be studied later)

Note that the three generations of leptons are called FLAVOR leptons, electron, muon, tau flavors.
A lepton with good flavor does NOT have a definite mass. This causes a neutrino of one flavor at time t to convert partly to the other flavors at later time: NEUTRINO OSCILLATION.

This is discussed below.

BEYOND THE STANDARD MODEL:

SUPERSYMMETRY: EVERY PARTICLE HAS A SUPERSYMMETRIC PARTNER, PREDICTED IN PARTICLE PHYSICS MODELS

STERILE NEUTRINOS: BEYOND 3-GENERATIONS, MORE NEUTRINOS. SOME EXPERIMENTS INDICATE THAT THERE ARE STERILE NEUTRINOS. COULD EXPLAIN DARK MATTER AND PULSAR KICKS

FOR THE ELECTROWEAK PHASE TRANSITION, THE EXISTENCE OF SUPERSYMMETRY IS ESSENTIAL FOR MASS GENERATION AND BARYOGENESIS TO WORK–AS WE SHALL SEE

HUBBLES LAW: EXPANSION OF THE UNIVERSE

History of Hubbles Law:

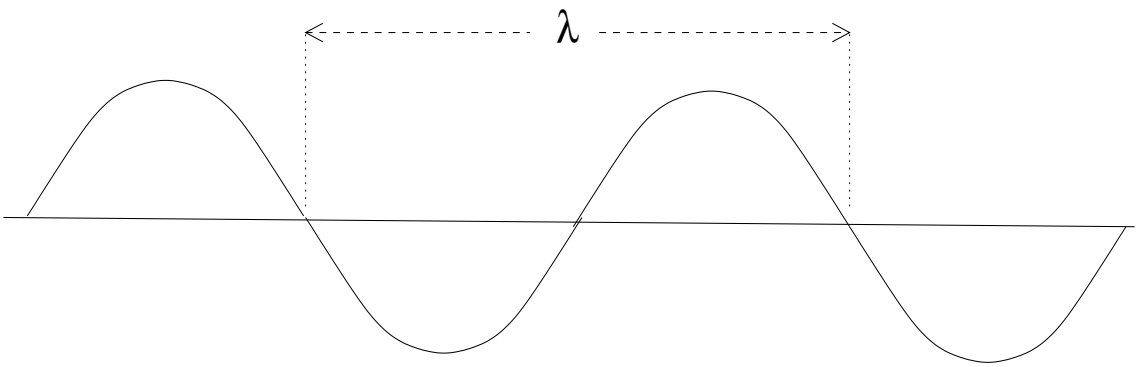
In 1912 Vesto M. Slipher, working under the direction of Percival Lowell, carried out the spectroscopy of radiation from distant galaxies. He found that the atomic lines were not at the same wavelengths as the lines from the same atoms when measured on earth. They were REDSHIFTED.

In THE 1920's Edwin Hubble gathered information from many galaxies. From the amount of redshift he could find the velocity of each galaxy with respect to the earth. By using information on the distance of each galaxy from us, he was able to plot the velocity as a function of distance. Velocity only depends on distance, not direction.

The result is HUBBLES LAW, ONE OF THE GREATEST DISCOVERIES IN ASTROPHYSICS, which we now review.

PROPERTIES OF AN ELECTROMAGNETIC WAVE

LIGHT WAVE



λ = wavelength of light wave

c = speed = 300,000 km/s

ν = frequency = c/ λ

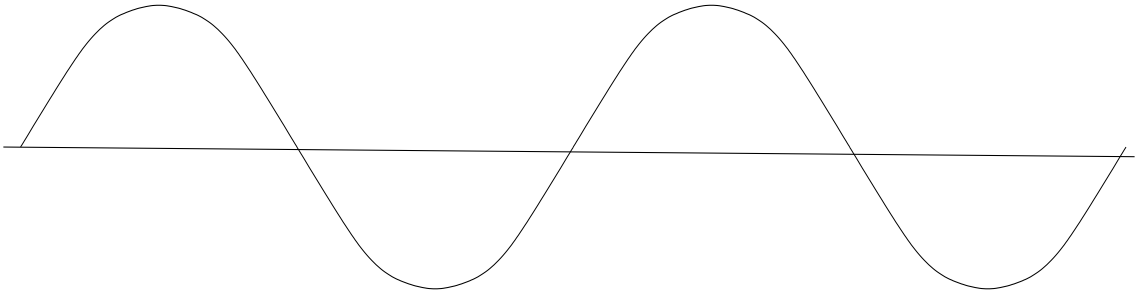
The speed of the light wave is the same in any system,

but the wavelength & frequency depends on the system:

THE DOPPLER SHIFT

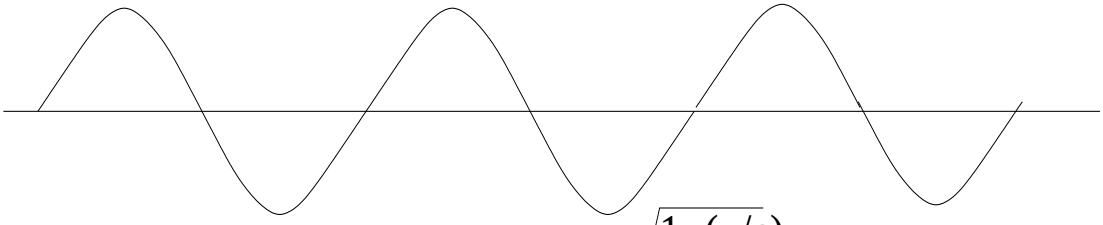
DOPPLER SHIFT

System of light source (rest system)



λ_o = wavelength of light wave ν_o = frequency = c/λ_o

Move toward the light source with speed u $\xrightarrow{u}$



λ= wavelength of light wave = $\sqrt{\frac{1-(u/c)}{1+(u/c)}}\lambda_o$

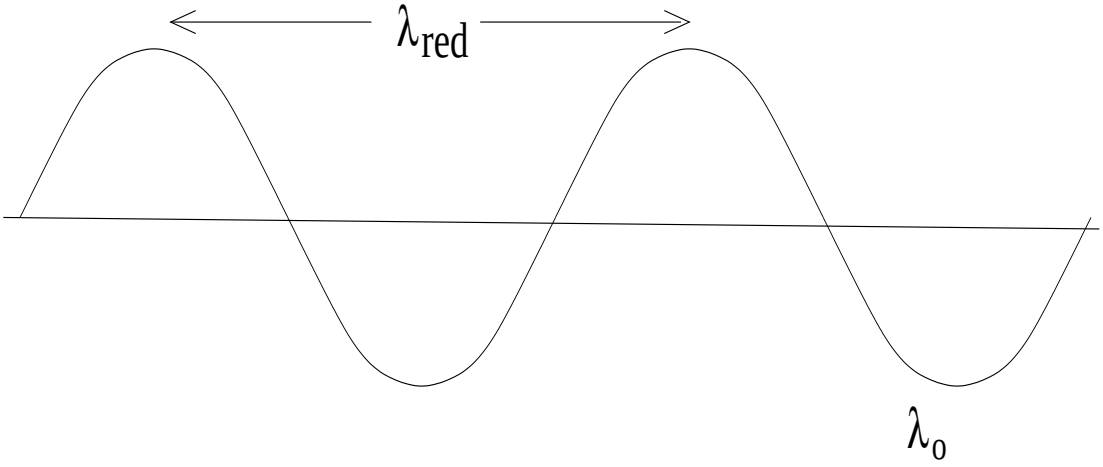
(shorter wavelength)

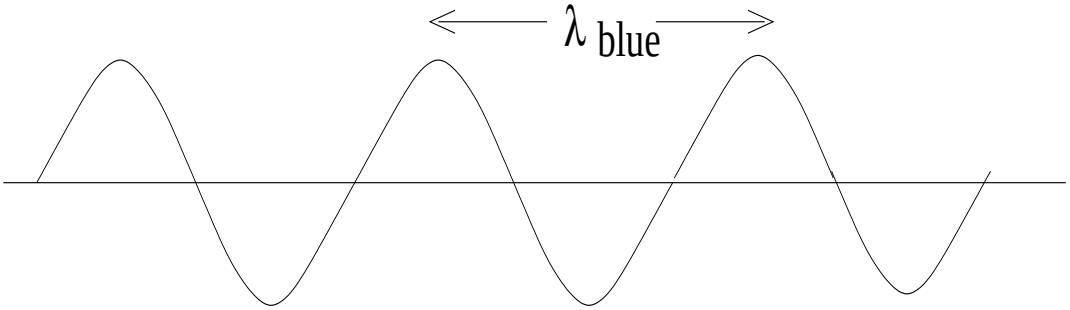
Move away from light source with speed $-u$ $\xleftarrow{-u}$

λ= wavelength of light wave = $\sqrt{\frac{1+(u/c)}{1-(u/c)}}\lambda_o$

(longer wavelength)

REDSHIFT



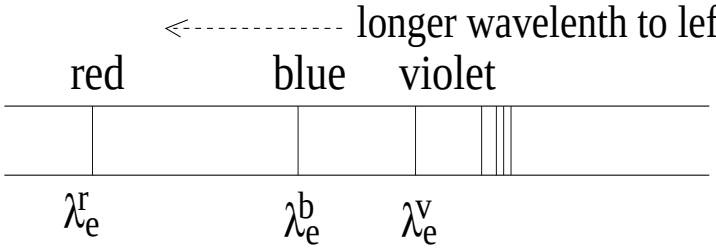


λ_{red} is larger than λ_{blue}

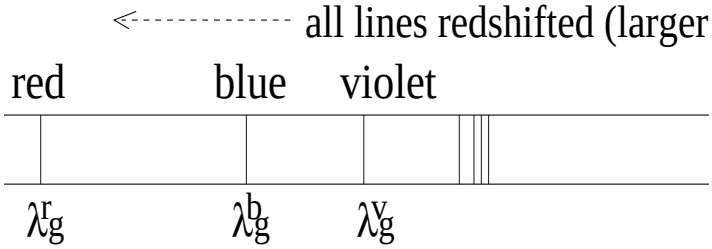
Therefore if a star is moving away from you light from hydrogen or any other atom in the star is REDSHIFTED

HOW HUBBLE MEASURED GALAXY−EARTH VELOCITY

Spectrum of Hydrogen on Earth



λ_e= wavelength measured with Hydrogen on Earth



λ_g= wavelength measured with Hydrogen on Galaxy

Galaxy is moving from Earth with speed v_g,
Doppler shift

$$\lambda_g = \sqrt{\frac{1+(v_g/c)}{1-(v_g/c)}}\lambda_e$$

Therefore

$$\lambda_g^2 = \frac{1+(v_g/c)}{1-(v_g/c)}\lambda_e^2$$

Solve for v_g :

$$v_g = \frac{\lambda_g^2 - \lambda_e^2}{\lambda_g^2 + \lambda_e^2} \text{ x speed of light}$$

That is how Hubble measured v_g using Doppler shift

HUBBLE'S LAW

d_{eg} = distance between earth and galaxy

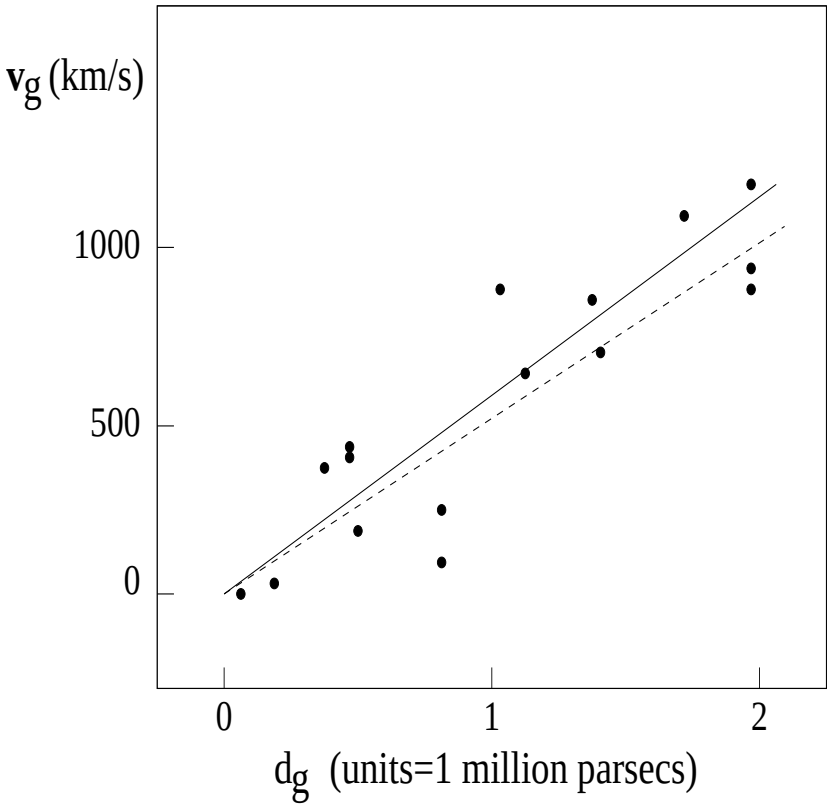
$\mathbf{v}_g$ = velocity of galaxy

HUBBLE'S LAW: $\mathbf{v}_g = H(t)\ d_{eg}$

H(t) = Hubbles parameter−−to be discussed later

Hubble's law means that a galaxy at twice the distance will be moving away at twice the speed.

HUBBLES GRAPH



Proc.Nat.Academy Sci. **15** , 158(1929)

parsec = astronomical unit of distance

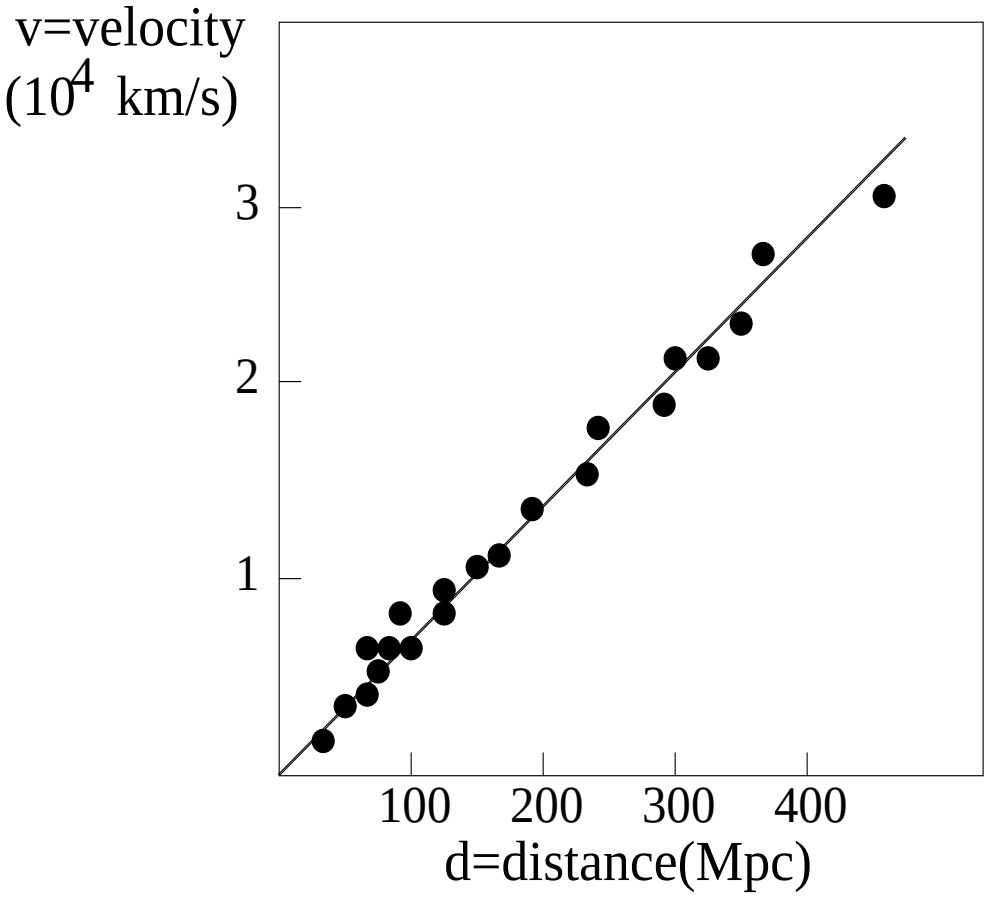
1 parsec = 1pc = 3 X 10^{18} cm = 3.25 light years

1 light year = distance light travels in one year

speed of light =c=300,000 km/sec

Hubble used doppler shift of known spectral lines to find v_g

Modern Hubble Graph
H=Hubbles Constant



v = recessional velocity of galaxy

d= distance to galaxy

H_o =slope= 71 km/s/Mpc

Hubbles Law: $v= H_o \times d$

INTERPRETATIONS OF HUBBLES LAW:

THE INTERPRETATION HAS TO BE THAT THE UNIVERSE IS EXPANDING.

IN THE 1920s AND 1930s MOST DID NOT ACCEPT THE IDEA THAT THE UNIVERSE EXPANDED IN TIME FROM t=0. UNTIL THE CMBR (COSMIC MICROWAVE BACKGROUND RADIATION, WHICH WE'LL DISCUSS LATER), MANY BELIEVED IN A "STEADY-STATE" UNIVERSE, WITH MATTER BEING CREATED TO FILL THE VOID CAUSED BY THE EXPANSION.

AFTER THE STUDY OF THE CMBR THERE WAS NO REASONABLE ALTERNATIVE TO THE "BIG BANG".

FROM THE LATEST CMBR OBSERVATIONS WE FIND THAT THE BIG BANG OCCURED ABOUT 14 BILLION YEARS AGO.

THE EVOLUTION OF THE UNIVERSE
(OVERVIEW)

t = Time	T = Temperature Events
10^{-35}s	10^{14} GeV Big Bang, INFLATION Very early. Current particle theory no good
10^{-11}s	100 GeV Electroweak Phase Transition Particles (Higgs) get masses. Particly theory ok. Baryogenesis? (more particles than antiparticles)
10^{-5} s	100 MeV QCD (quark−hadron) phase transition Quarks(elementary) condense to Protons
1−100 s	Nucleosynthesis: Helium, light nuclei formed 1.0X 10^{9} ^{o}K Superconducting Universe
380,000 years	0.25 ev, 3,000^{o} K Atoms (electrically) neutral Last scattering of light (electromagnetic radiation) from big bang: Cosmic Microwave Background
1 billion years	early galaxies form
14 billion years	2.7^{o} K Now

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SOME QUESTIONS ABOUT THE EARLY UNIVERSE

QUESTION: If time = 0 occured 14 billion years ago, when the universe started with a big bang, what happened before time = 0

ANSWER: I do not know

QUESTION: If different very early expanding universes combined to form our universe, why is it so uniform (except for a few bumps like stars and galaxies)

ANSWER: Inflation

QUESTION: What is a phase transition

ANSWER: If a substance changes its form as temperature changes, like water boiling to form steam, but both water and steam are H_2O, it is called a phase transition.

QUESTION: Why should it take a phase transition for particles to get their masses

ANSWER: In a phase transition (first order) as a substance cools to the critical temperature of the phase transition it gives off energy, called latent heat. Just as heat is energy, so is mass. In the EWPT, the latent heat is the Higgs mass, and all other masses.

QUESTION: When we look for light from the early universe, why can we only go back to when the universe was about 400,000 years old

ANSWER: Before 400,000 years there were so many free electrically charged particles that the light scattered and was trapped. After about 400,000 years there were almost no particles to scatter the light, so we can see it at the present time

QUESTION: What can we learn from the light that was set free about 400,000 years after the Big Bang

ANSWER: A lot! We take this up when we study the Cosmic Microwave Background-CMB