Saturday Morning Physics 2021 Lecture Notes

Fermilab

1/23/2021 - 4/03/2021

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Day 1 Lecture - Intro to Fermilab

Saturday, January 23, 2021 9:11 AM

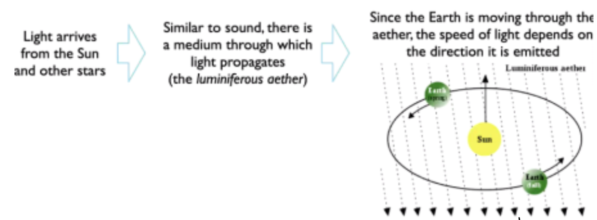
The presence of dark matter = structure

- structure = galaxies
- galaxies = pressure
- SN explosion (accelerate debris [nuclei]) and when they reach earth like cosmic rays

Scientific Method

Observation → Hypothesis → Prediction → Experiment

Ex.



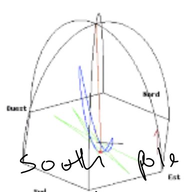
(tested by Michelson - Morley experiment)

⇒ Hypothesis rejected

[experiments only reject hypothesis]

Ex. Foucault's Pendulum (1851)

- floor rotates but pendulum continues swinging in same direction



South pole is opposite of north pull (earth spins in a linear fashion)

Equator – no rotation

(north pole → rotates counter clockwise)

→ Hypothesis is neither rejected or proved, as experiments can only reject.

Quantum mechanics

- physics of small scales
- observable quantities are quantized
- things are both particles and waves
- intrinsic limited

Relativity

- physics of fast objects
- independent of reference frame

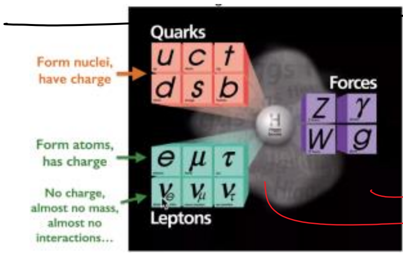
- things are both particles and waves
m- easurements have intrinsic limited precision

- independent of of reference frame
- speed of light (c) is the limit

What is studied at Fermilab

~~the~~ standard model of particle physics

(flavors = types, tau neutrinos, etc)

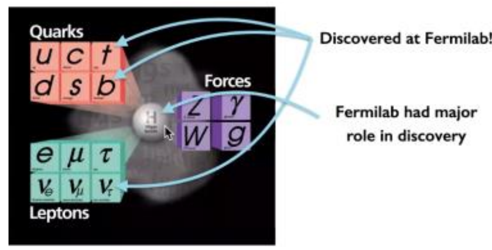


(periodic table of periodic table)

Strong force is mediated by gluons

Explains mass of all elementary particles

Ex. Emmission of neutrinos cool down the sun
→ sun does not cool down by emmission of light.



c t
s b } heavier copies
N τ
ν ν

gluon g responsible for glueing particles together

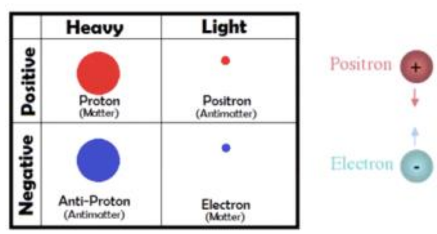
Z and W → radioactive decays

- Forces are manifestation of symmetries
(forces of the standard model)
Ex. Z, γ, W, g

- Standard model is extremely succesful so far
+ the standard model
goal is to further does it break down?
- How

? color ≠ red, blue, green, etc

color = quantum number



antimatter is

Sub-atomic particles identical to matter but with opposite electric charge and color
Charge-Parity conjugates of fermion field multiplets of the standard model gauge group

→ basic
→ Specialist

dark matter — does not emmit light, only interacts with gravity dark energy – related to universe expansion

anything regarding nuclear decay ⇒ neutrinos

more light = more neutrinos

Open questions:

How did matter (and not antimatter) survived in the big bang?

What is the mass of the neutrinos?

What is dark matter and dark energy?

Why is the universe expanding?

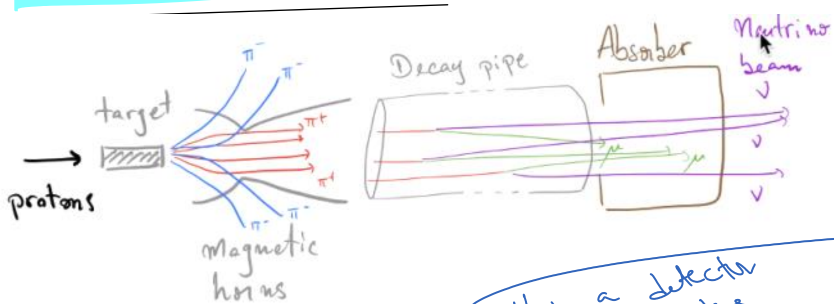
Any reason behind the 3 families?

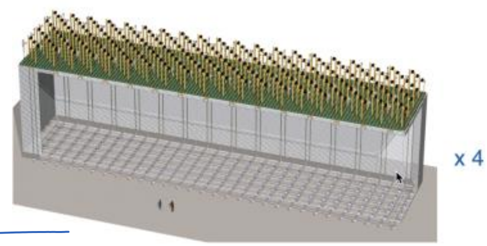
What is the mechanism of neutrino masses? → Higgs boson does not describe neutrino mass due to low interactions between muons and neutrinos

any particle that carries gravitational force?

The DUNE Experiment

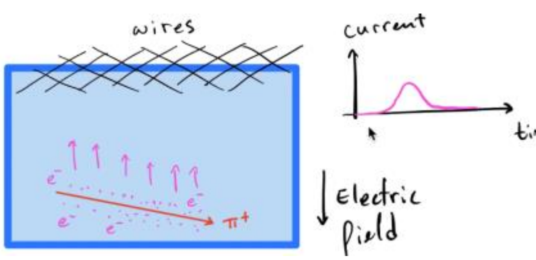
How to create neutrinos



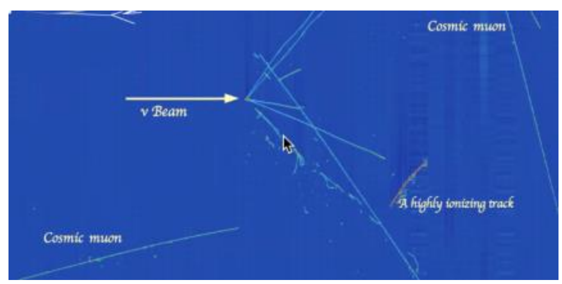


How a detector works

when charged particles go through liquid, they ionize, (lose charge)



Example of detection sequence



top quark mass ≈ 1

electron mass $\approx 10^{-6}$ → why does every other mass $\neq 1$ like top quark

annihilation → breaking a proton into muons, tau quarks, tau neutrinos, etc.

Day 2 Pre-Lecture - Relativity

Saturday, January 30, 2021 2:30 PM

Light always moves at the speed of light through a vacuum.

Special Relativity - only applies to situations when the different frames of reference are not accelerating

→ inertial reference frame

2 postulates of Special Relativity

1) Laws of Physics are both the same in all inertial reference frames

2) speed of light is same for all observers when traveling through vacuum

Speed of Light, c, is always constant

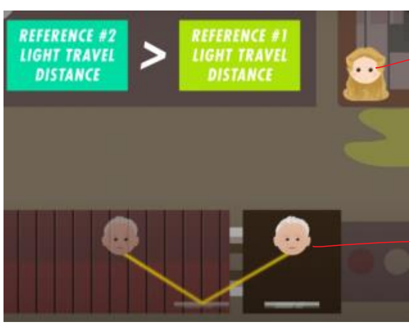
$$\underbrace{\text{speed}}_{\text{constant}} \cdot \text{time} = \text{distance}$$

time → Δ time = time dialation

distance → Δdistance = length contraction

Time Dialation

When another reference frame moves relative to you, so time in that frame slows down relative to the time you measure



ref frame 2

— in your observation, light traveled a greater distance at c, so it must have been traveling for a longer period of time

ref frame 1

t = time in moving reference frame

t_0 = time in stationary reference frame

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

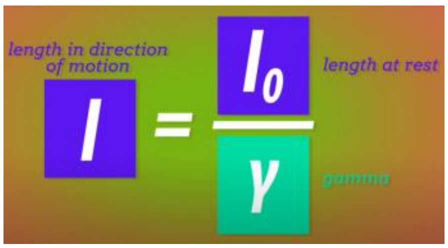
then $t = \dfrac{t_0}{\sqrt{1-\frac{v^2}{c^2}}} = \gamma t_0$ } γ always > 1

Simultaneity - some events simultaneous from one reference frame may not be simultaneous in another

Length Contraction

- if something moves relative to you, its length in the direction that it's moving will seem shorter than it would be if it was stationary

in general, if object moves relative to your reference frame



→ happens at regular speeds too!
(just very little)

- light slows down in mediums

Ex. Shooting electrically charged particles like muons, electrons, etc.

→ Charged particle moves faster than light in that medium

→ Charged particle emmits blue light, called Cherenkov light

Cherenkov light here is formed when radioactive material emmitting highly energetic particles is immersed in water.

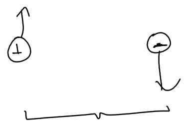
$\underbrace{\hspace{10em}}$
light gets slower

Brief into (Quantum entanglement)

Ex.

Basically states information in quantum mechanics

Ex.



2 particles with opposite spins are entangled if knowing one helps you determine other spin

Basically states information in quantum mechanics travels faster than light

Expansion of the Universe

- a galaxy a megaparsec (million parsecs / 3.26 million lightyears) away moves away from earth 70 km/second
  - → 70 km/sec / mega parsec
    - → a galaxy 3 megaparsecs away moves away at $3 \cdot 70 = 210$ km/sec

Then approximately 4,296 megaparsecs away, or 14 billion light years, a galaxy moves away from earth at the speed of light

not because galaxy is moving away, but rather space is expanding

Galilean transform equations

$$x' = x + vt$$

$$t' = t$$

Core Assumptions for Einstein's Equations

1) laws of physics are same for both observers
2) Speed of light is constant for all observers

⇒ Einstein's transform equations / Lorentz transforms

$$x' = \gamma(x + vt)$$

$$t' = \gamma\left(t + \frac{v}{c^2}x\right)$$

2 core equations of relativity

γ = lorentz factor

→ tell you how to convert from point of view of

one person to point of view of the other frame
[primed vs unprimed]

Day 2 Lecture - Special and General Relativity

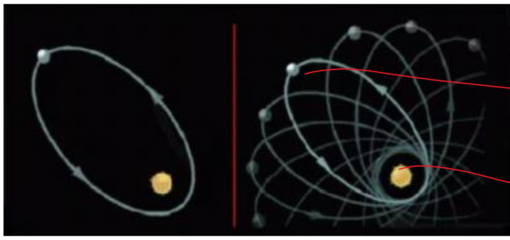
Saturday, January 30, 2021 9:03 AM

1) Gravitational Mass : $F_G = \frac{G m_1 m_2}{r^2}$

Gravitational mass = inertial mass

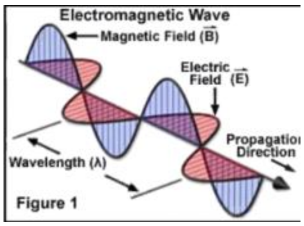
} everything with ↑ gravitational mass = ↑ inertial mass

2)



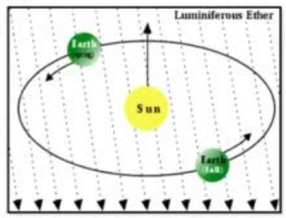
→ Mercury's orbit followed an ellipse for some reason

3)



→ for every wave, sound → air, water wave → ocean so light moves through 'luminiferous ether'

If this were true, then light should move at a fixed speed in the rest frame of the aether, and as the Earth moves around the Sun, we should experience a "wind" of aether, causing the speed of the light reaching Earth to vary seasonally



Michelson-Morley Experiments found light always moved at the same speed

4) Where does the Sun get the energy?

Galilean transformations only work for low velocity speeds, due to Michelson-Morley

Under a Lorentz Transforms, the usually constant quantities (length, time), can change in reference frame

1) Length Contraction:

According to Einstein, an object of length L_0 at rest will be measured to have a length L_0/γ by a moving observer, where γ is the "Lorentz factor" (or "gamma factor") related to velocity by:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

Ex. Q: How long is a meter stick to someone moving at 10 km/s?

$$\gamma = \frac{1}{\sqrt{1-\frac{10^2}{c^2}}}$$ } no change

Ex. 2 Q: How long is a meter stick to someone moving at 99.9% c ?

$$\gamma = \frac{1}{\sqrt{1-(0.99)^2}}$$ so $\frac{100}{\gamma} \approx \boxed{0.045 \text{ meters}}$

$$\gamma = \frac{1}{\sqrt{1-\frac{(0.99c)^2}{c^2}}} \quad \text{so} \quad \frac{100}{\gamma} \approx \boxed{0.045 \text{ meters}}$$

2) Time Dialation

According to Einstein, two events that are separated by a duration t_0 at rest, will be measured to separated by a time ($t_0 \times \gamma$) by a moving observer, where γ is the same Lorentz factor

Ex. Q: Imagine a radioactive atom with a half-life of 1 hour.
How long does it take to someone moving at 10 km/s?
A: γ=1.0000000006, so t=1.0000000006 hours, or 1 hour + 2 microsec.

Ex 2 Q: Imagine a radioactive atom with a half-life of 1 hour.
How long does it take to someone moving at 99.9%?
A: γ=22.4, so t=22.4 hours, or almost an entire day

Twin Paradox

-Consider two twins – one becomes an astronaut and travels at 99.9% of the speed of light to a distant solar system 50 light years away and back, while the other stays home

-To those of us on Earth, the astronaut's 100 light year (round trip) journey takes almost 100 years (0.999x100=99.9 years) , however $\gamma = \frac{1}{\sqrt{1-\frac{(0.99c)^2}{c^2}}} = 22.4$

so for her $\rightarrow$ $\frac{100 \text{ years}}{22.4} = 4.5$ years for her!

in a 100 year span for us, she only experienced 4.5 years

Basically: 1) moving objects shrink
2) moving clocks run slow

Big Idea: Space and Time are not separate things, but are instead parts of 4-dimensional spacetime.
What is time to one observer is space to another, and vice versa.

Atmospheric muon decay:

-At rest, muons decay with a half-life of 2.2×10^{-6} seconds
-Without relativity, muons created by cosmic rays in the top of the atmosphere should never reach the Earth's surface ($c \times 2.2 \times 10^{-6}$ sec = 0.6 km)
-But we observe muons coming from the atmosphere all of the time

Solution: Since they are moving at nearly the speed of light, the muons are time dilated, and time passes more slowly in their frame of reference (γ of roughly 50 or more is required for them to reach the surface before they decay)

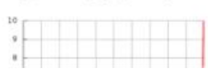
Hafele-Keating Experiment

-In 1971 (for the first time), scientists took atomic (cesium) clocks onboard commercial airliners and flew around the world twice
-The velocity of the plane was enough to make a small but measurable degree of time dilation (~100 nanoseconds)
-The results agreed almost perfectly with the predictions of relativity

Implications of Einstein's Theory

1) Nothing is faster than light:

-The kinetic energy carried by an object is KE=$(\gamma-1)mc^2$
(does this agree with KE=$mv^2/2$ for v<<c?) ✓
-By adding energy, you can always speed up something, making γ (and v) larger and larger
-But even as γ goes to infinity, v only gets closer and closer to c, never exceeding it

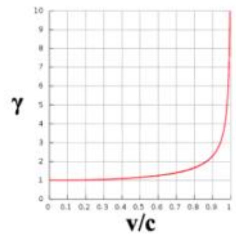


$\rightarrow$ asymptotic to the speed of light

-Anything traveling faster than c in one frame of reference is traveling

-By adding energy, you can always speed up something, making γ (and v) larger and larger

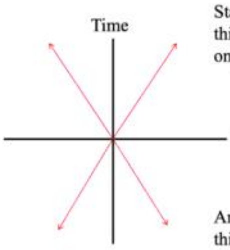
-But even as γ goes to infinity, v only gets closer and closer to c, never exceeding it



right

-Anything traveling faster than c in one frame of reference is traveling backwards in time for observers in some other frame of reference

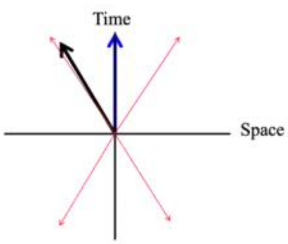
-Traveling backwards through time violates causality and creates general logical havoc



Starting from the center of this diagram, things can only move within this cone

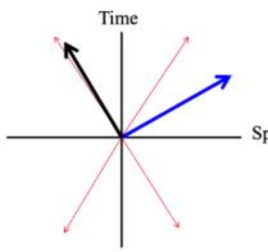
And only things within this past cone can affect things at the center

Twin paradox on spacetime diagram

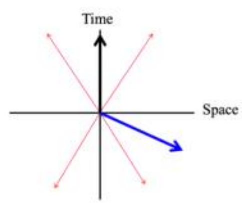


The blue arrow represents a spaceship moving at almost the speed of light, while the black arrow is an observer who stays on Earth

From the perspective of the spaceship, it is stationary, while the Earth is moving away from it at almost the speed of light



Now imagine something that is moving faster than the speed of light (blue) while something else is moving in the opposite direction at almost the speed of light (black)



Now imagine something that is moving faster than the speed of light (blue) while something else is moving in the opposite direction at almost the speed of light (black)

In the rest frame of the black arrow, the blue arrow is moving backward in time

Fast objects have more mass by $e = mc^2$

If mass and energy can be converted at the rate of **$E=mc^2$**, even very small amounts of mass could provide huge amounts of energy

1 gram of mass is equivalent to 9×10^{13} joules of energy, or 21,500 tons of TNT (more than the atomic bombs detonated at Hiroshima or Nagasaki)

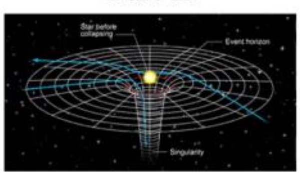
→ by $E=mc^2$,

Remember the problem of where the Sun gets its energy from? Well, the mass of the Sun is equivalent to 1.8×10^{49} joules; enough to power the Sun for about 10^{15} years

Fusion, which converts a small fraction (about 0.7%) of the mass in the Sun's core into energy, is able to power the Sun's light for about ten billion years

From Special to General Relativity

Part II



General Relativity

→ really just a geometrical theory

→ space-time is curved

Equivalence Principle

$$F_G = -\frac{Gm_1m_2}{r^2}$$?

} Why are these equal?

$$F_G = -\frac{Gm_1m_2}{r^2}$$

?

$$\mathbf{F}_{net} = m\mathbf{a}$$

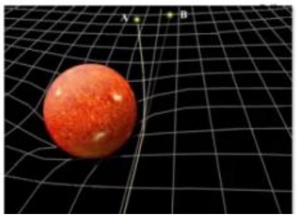
Why are these equal?

Central Idea of General Relativity

- special relativity can be only used in 'flat' spacetime

Spacetime, however, is "curved" "warped" whenever there is forms of energy nearby

This curvature of spacetime is what we experience as gravity

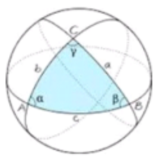


$$R_{ij} - \frac{1}{2}g_{ij}R = -\frac{8\pi G}{c^4}T_{ij}$$

Curved Spacetime

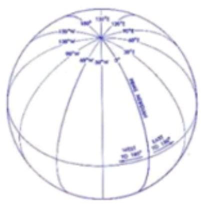
- rules in Euclidean geometry do not apply in curved geometry

Ex. The angles of a triangle inscribed on the surface of a sphere always add up to more than 180 degrees



Ex 2.

And lines of longitude are parallel at equator and cross at the poles



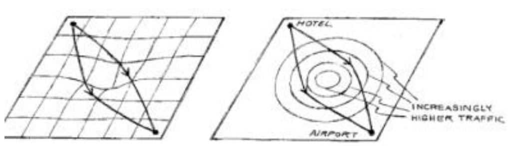
According to Newtonian physics, an object moves through shortest route in space

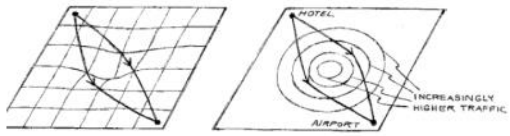
However, In general relativity, objects move along the shortest path through spacetime; The geometry of spacetime can alter which route is shortest, and thus alter the trajectories of objects moving through space

Example :

Newtonian rules = 'as the crow flies'

Space time curvature : I-55 faster, traffic, speed limit

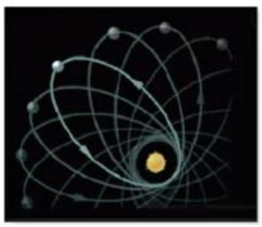




-Objects move along the shortest paths through spacetime
-The presence of mass and energy curves spacetime
-The effect of this curvature is the change in trajectories that we call gravity

Newtonian gravity works when space is flat, but breaks down when space is non-euclidean space

Ex.



→ mercury is effected by spacetime curvature & gravity

Imagine a compact object with a mass equal to the mass of the Sun

At a distance 700,000 km away from the mass (the radius of the Sun), spacetime is only modestly curved (by a factor of about 1.000004)

As you move closer and closer to the massive object the curvature gets more and more pronounced, warped by a factor of:

-1.003 at a distance of 1000 km
-1.031 at 100 km
-1.43 at 10 km
-4.0 at 4 km
-31 at 3.1 km
-301 at 3.01 km
-Infinity at about 3 km ← **Schwarzschild Radius (or event horizon)**

Black Holes!

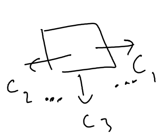
No infinite curvature regions are found in our experience, because the densities needed are not easily reached (1 solar mass within a 3 km radius is awfully dense, 10^{15} times denser than lead!)

However, when stars (massive stars), collapse, they form black holes

Once something is inside the Schwarzchild Radius, it can never get out

→ No interactions ever, in principle
→ so does the inside of a black hole exist?

Tidal Forces in a black hole



→ centripetal forces tear anything from atom to atom to subatomic particles

The event horizon of a black hole emmits Hawking Radiation
(as a result of Hawking evaporation, the event horizon shrinks)

Information Paradox

Black holes erase information

→ Ex. Black hole made from collapse of hydrogen or helium stars looks exactly the same, so information is lost and laws of relativity cannot reconstruct it

→ to explain, we need a theory of quantum gravity

General Relativity and Cosmology

Cosmology as a science was born out of relativity

- general relativity shows space-time is curved, and not static, but rather expanding/contracting

$$R_{ij} - \frac{1}{2}g_{ij}R = -\frac{8\pi G}{c^4}T_{ij}$$

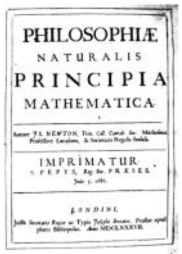
- 13.8 bya, universe was small and hot, and now is expanding and accelerating extremely fast, due to dark energy

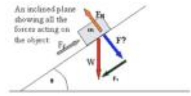
Day 3 Lecture - Quantum Mechanics

Saturday, February 6, 2021 9:01 AM

The beginning and end of classical physics

- Explains all physics up to ~1990
  - Newton, Gallileo, Maxwell
- Deterministic

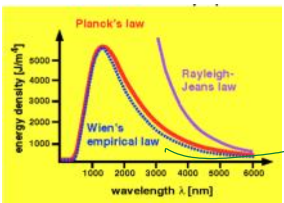




$$\oint \mathbf{E}\cdot d\mathbf{A} = q/\varepsilon_0$$
$$\oint \mathbf{B}\cdot d\mathbf{A} = 0$$
$$\oint \mathbf{E}\cdot d\mathbf{S} = -d\Phi_B/dt$$
$$\oint \mathbf{B}\cdot d\mathbf{S} = \mu_0 i + \mu_0\varepsilon_0 d\Phi_E/dt$$

Black Body

- a body/object that only emmits of absorbs light



→ area under curve = amount of energy

- Light can only be emitted and absorbed in discrete units of energy, quanta

Example of black body ←

Max Planck assumed that light only comes in integer quantities, that is, light is only emitted/absorbed in integer amounts (quanta)

[4, 5, 6, ~~6.5~~, ~~7.25~~]

Planck's constant

Light of frequency ν can only be emitted and absorbed in units (quanta) of $h\nu$

$$E = h\nu$$

$h = 6.626068 \times 10^{-34} m^2 kg/s = 6.626068 \times 10^{-34} Js$

→ Given frequency, Planck determined a constant that E can be predicted

How many photons in light in our room?

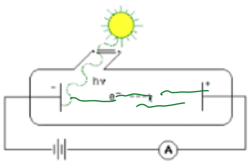
$$\nu = \frac{c}{\lambda} = \frac{3 \times 10^8 \ m/s}{600 \ nm} = 5 \times 10^{14} \ Hz$$

$$\Rightarrow E_q = (6.6 \times 10^{-34} Js)(5 \times 10^{14}) Hz = 3.3 \times 10^{-19} J$$

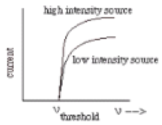
$$\text{so } N = \frac{100 \ J/s}{E_q} = \frac{100 \ J/s}{3.3 \times 10^{-19} J} = 3 \times 10^{20} \text{ photons per second}$$

[Assuming light efficiency is 100%]

Photoelectric Effect



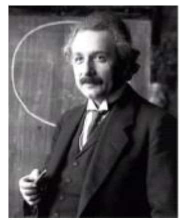
→ Current should not run, but when light is shined on metal, metal emmits electrons

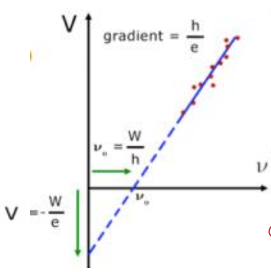


1. Metals emit electrons when irradiated
2. Threshold, depends on frequency
3. Current ∝ intensity
4. Energy ∝ frequency

Photons as waves can't explain this

Light behaves as if it is discrete bundles of energy (photons) of energy of $h\nu$.



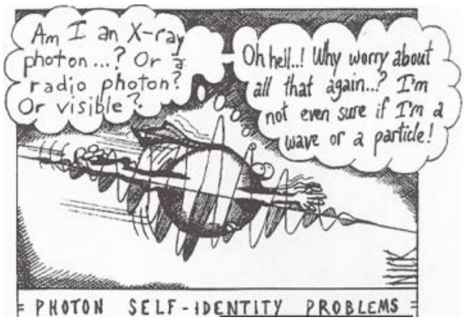


$$\frac{1}{2}mv^2 = h\nu - W$$

Explains photoelectric effect

Light is a particle!

and a wave [from before]



Wave-particle Duality

If a wave can be a particle, can a particle be a wave?

Louis de Broglie

For light:

$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda}$$

→ Stated every particle must have a wavelength associated with it.

Example:

What is your de Broglie wavelength?

$\approx 10^{-36}$ m

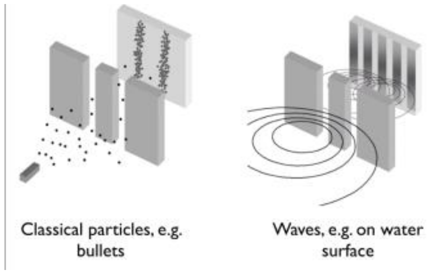
super small wave length

For comparison: proton is about 10^{-15} m

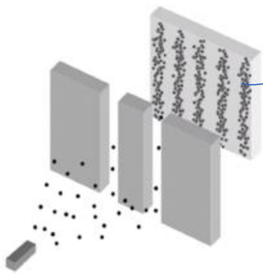
Experiments to convince of

Double Slit Experiments

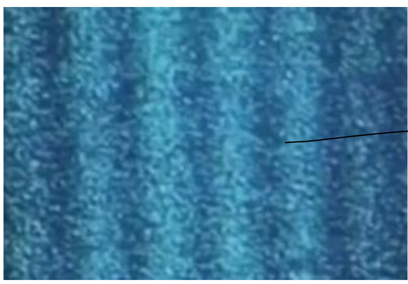
Experiments to convince of wave-particle duality:



Repeat this with electrons [as electrons are 'particles']



Interference pattern has multiple slits, looks like a wavelength behavior!



real version of repetition of experiment

there are fringes!

de Broglie wavelength for electron ≈ 60 km/s !
so comparable to atomic spacing in a metal

During electron period of transit, it changes from particles to waves, so they inteference with themself!

The quantum mechanics wave function

$\Psi(x,t)$

- the probability for a particle to be at point (x,t) is
  $|\Psi(x,t)|^2$
- Quantum mechanics is a probabilistic theory [not to say

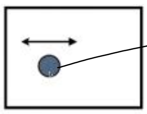
it is not deterministic, but only measure the wave function!

Schrödinger Equation

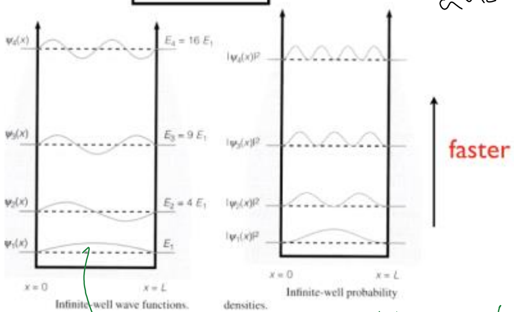
- there is an equation that governs the evolution of the wave-function

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi(x,t)}{\partial x^2} + V(x)\psi(x,t)$$

Particle trapped in a box



particle only moves backwards and forwards

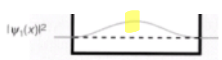


→ Wave-function = 0 outside the box

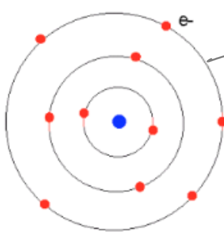
→ Try to find waves that 'sit' inside the box

→ integer multiples of waves in the box

Ex.



If $\Psi_1(x) =$ ↓, then most likely will be in middle of box $[|\Psi_1(x)|^2]$



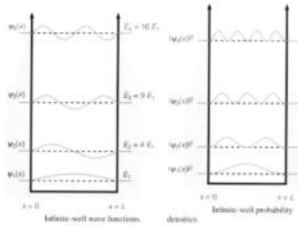
moving in circle means constant acceleration

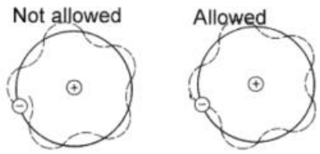
The Bohr Atom, with stable quantum mechanics

accelerating charges particle emmit radiation/energy

→ thus, orbits must shrink moving closer to the center of atom

⇒ the atom disappears in a fraction of a second!?

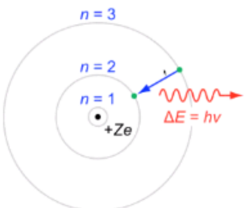




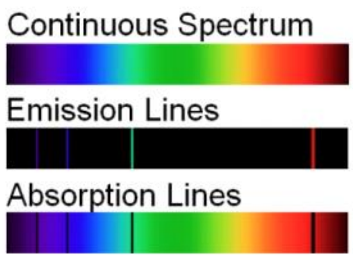
→ there is a lowest possible energy

Lowest orbital has L=1, no where to decay to

Angular momentum is quantized



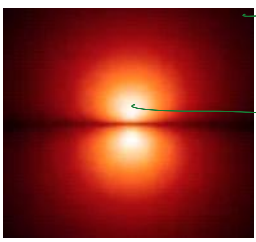
Light emitted/absorbed at fixed frequencies



By shining light on atoms, electrons 'jump' creating emission or absorption lines, which every material (element) has.

$$\nu \sim \frac{1}{n_1^2} - \frac{1}{n_2^2}$$

→ in reality, quantum mechanics is probability, so the Bohr atom is actually like



→ less likely for electrons to be in dark areas

→ more likely for electrons to be in lighter areas

Heisenberg Uncertainty relation

$$\Delta p = \frac{h}{a}$$

"The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa."

$$\Delta x \, \Delta p \geq \frac{h}{2}$$

as 'the act of trying to measure something disturbs the system'

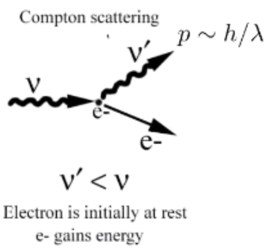
→ don't often get to find where something is AND where it is moving

'Measuring' a particle's position

- using a 'microscope' - shining light on electron
- shorter wavelength means better precision

$\rightarrow \Delta x \sim \lambda$

But shorter wavelength = higher momentum



In the process of measuring position, the 'where' and 'how fast' it is moving changes

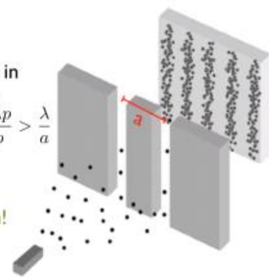
Example of this phenomena where → measuring the electron is in the double slit experiment

Monitor two slits, need $\Delta x < \frac{a}{2}$

But then $\Delta p > \frac{\hbar}{a}$

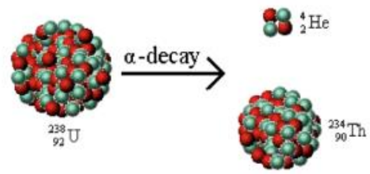
The fractional change in electrons momentum parallel to screen is $\frac{\Delta p}{p} > \frac{\lambda}{a}$

Smears out interference pattern!



In Quantum Mechanics, the classically impossible is now just very unlikely.

Example : radioactive decay



Superpositions

$$\Psi = \sum_i \psi_i$$

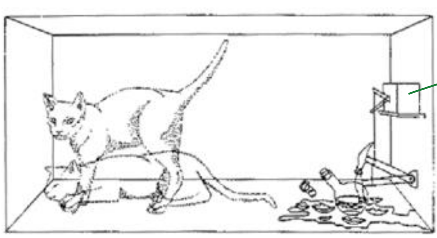
Wavefunction is a superposition of all possibilities

QM predicts outcomes if expt. is repeated many times

→ Measurement "collapses" the wave function

[Copenhagen Interpretation of quantum mechanics]

Ex. Schödinger's cat



→ radioactive element has 50-50 chance of killing cat

So

$|cat\rangle = \alpha\,|$  $\rangle + \beta\,|$  $\rangle$

→ cat is the superposition of [alive, dead]

QM Interpretations

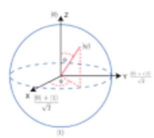
What collapses the wave function?
Why is an observer classical but the thing being observed is quantum?

Many alternatives:
Many Worlds (Everett)
Spontaneous Collapse
Hidden variable
Pilot wave

To bypass the Copenhagen Interpretation, but all predict the same outcomes

Quantum Computers and other devices [using superposition theory]

Bits — Qubits



00, 01, 10, 11

$\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$

Leads to quantum etangement to speed up computations

Day 4 Pre-Lecture - The Standard Model of Particle Physics

Friday, February 12, 2021 1:00 AM

From the 1940s - 1960s, literally hundreds of subatomic particles were discovered through particle accelerators.

Protons and Neutrons were discovered to be made out of

Quarks → there are 6 types of quarks

u c t
d s b

up, down, charm, strange, top, bottom

Up and down quarks are found inside protons/neutrons, while others explain more discoveries with the particle accelerator

In addition to Quarks, there are also

Leptons

e μ τ → top 3 Leptons have electrical charge

ν_e ν_μ ν_τ

electron, muon, tau

bottom 3 are neutrinos, which are electrically neutral

These Quarks and Leptons form every particle that we know of.

However, it is important to note forces, as the particles would randomly move through cosmos.

If something didn't connect quarks and leptons together, there would be no atoms.

there are 4 different forces:

Gravity - a weak force, and we don't know how it works in the quantum realm

Electromagnetic force - responsible for binding electrons to nuclei to create structures (atoms)

Strong Nuclear Force - ties quarks together inside protons and neutrons

Weak Force - responsible for different types of radioactivity

These forces have very different properties:

Gravity and Electromagnetic forces have a very long range

Strong Nuclear and Weak forces only have an appreciable effect over distances smaller than a proton

Nuclear forces don't exist over distances $>$ size of an atom

---

The strength of the forces also greatly differ:

If we say strength of Strong force = 1 unit:

Electromagnetic Force: $1/10^2$

Weak Force: $1/10^5$

Gravity Force: $1/10^{40}$

We don't understand why gravity is so weak compared to the other forces. It is not currently part of the standard model.

All the subatomic forces work by 'exchanging' particles

Forces

Z

W

$\gamma \rightarrow$ photon (electromagnetic force)

$g \rightarrow$ gluon (strong nuclear force)

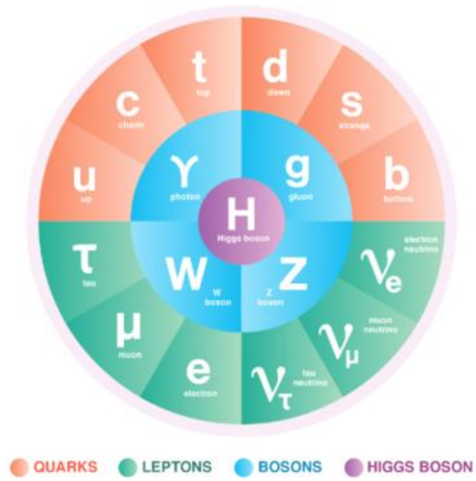
Z and W boson (weak force)

→ Scientists speculate there is a 'graviton' for the gravity force, but this has not been demonstrated

The **Higgs boson** is thought to give mass to other particles

we still don't know the origin of mass

The standard model is the best description of the subatomic world, but it only incorporates 3/4 fundamental forces (omitting gravity)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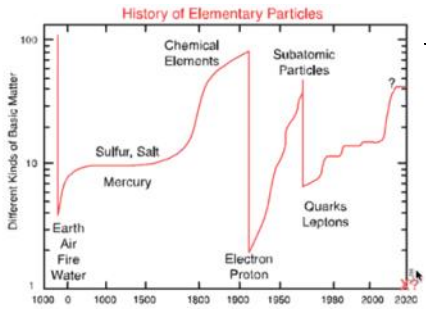
d
c
s
u
b
γ
photon
g
gluon
H
Higgs boson
W
boson
Z
boson
τ
μ
muon
e
electron
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
QUARKS
LEPTONS
BOSONS
HIGGS BOSON

Day 4 Lecture - The Standard Model of Particle Physics

Saturday, February 13, 2021 9:05 AM



→ What we thought were the fundamental building blocks (subatomic particles) of the universe.

Physics at turn of century ~1900

common belief: Everything could be explained by Newtonoian Mechanics and Maxwell's equations

Discovery of Electron

J.J. Thompson: explored cathode rays in evacuated glass tube

Hypothesis for beam'

massless electromagnetic vibrations in the aether?

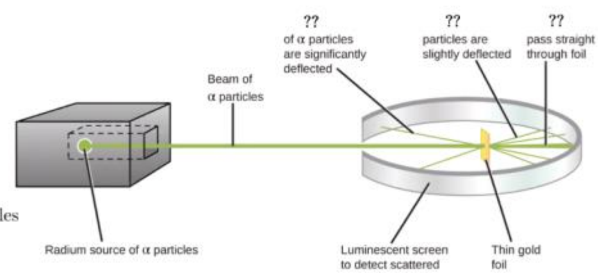
- affected by electricity

gas molecule?

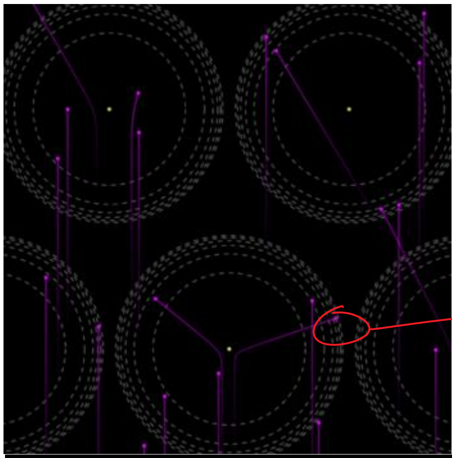
- same e/m ratio!

Rutherford Scattering experiment

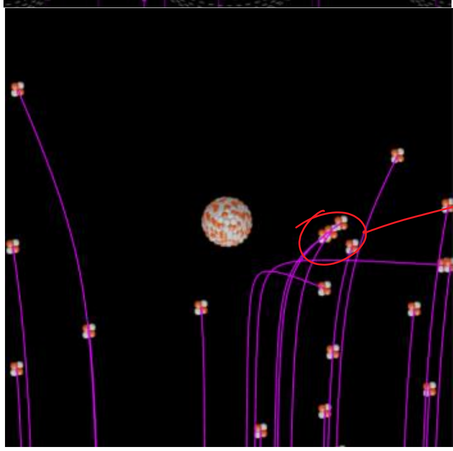
- Ernest Rutherford: wanted to study structure of nucleus



Alpha (α) particles are ^4_2He ions (+2 charge)



α particle gets deflected from protons in the center of nucleus
→ more protons ⇒ more deflection



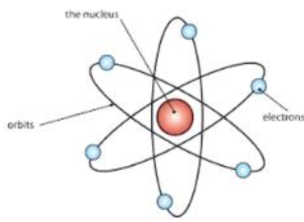
same phenomenae as above

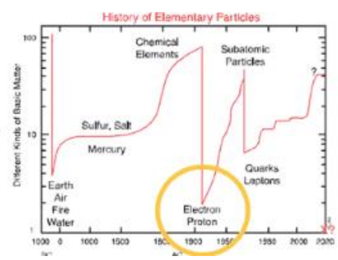
a higher energy α particle means less harder to deflect

"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.

- Conclusion: positive mass had to incredibly compacted

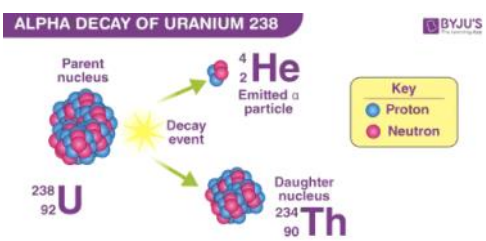
- Atoms are made up of a central positive charge surrounded by a cloud of orbiting electrons
  - As you heard last week, this model isn't quite right either and fails to account for quantum mechanics
- 1917: Rutherford proved that the nucleus of all atoms includes protons
- 1932: Neutrons discovered by James Chadwick





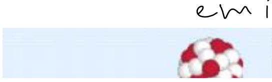
The Neutrino

- α decay → when original nucleus breaks into a smaller nucleus and an alpha particle



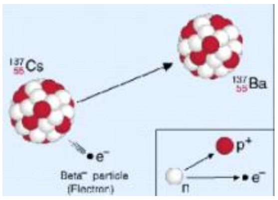
- Two equations and two unknowns:
  - Energy conservation: energy from mass difference ($E = mc^2$) gets converted into kinetic energy of Th and α
  - Momentum conservation: $\vec{p}_\alpha$ must balance $\vec{p}_{Th}$
  - → Energy of α particle is uniquely determined

- β decay → when neutron converts to proton and electron is emitted



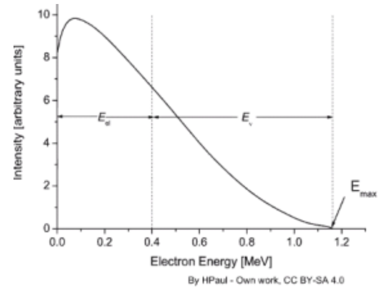
- As expected, α particles from a decay always have the same energy

emitted



- As expected, α particles from a decay always have the same energy
- But for β decay, a **range of energies** is observed!
  - First observed by Lise Meitner, Jean Danysz in 1913

Is energy conserved?



Pauli's proposition

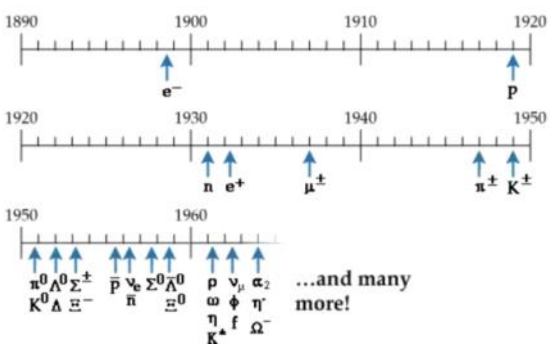
- 1930: "desperate remedy" by Pauli
  - Maybe there is an undetectable third particle involved in the decay – the **neutrino**
  - Then there are 2 equations and >3 unknowns; energy is not uniquely determined

→ Neutrinos only interact through the weak force

How to make neutrino experiment

1. Use an intense neutrino source to produce neutrinos to study
2. Build the biggest detector possible to increase chances of interacting
3. Minimize backgrounds from other sources (go underground)
4. Collect data over a long period and analyze results

The Particle Zoo



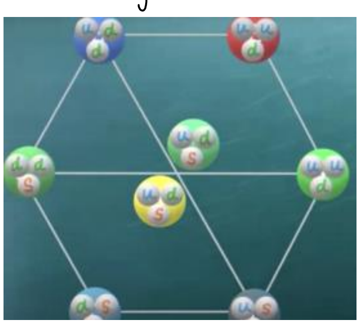
- Charged Pion (1947)
- Charged Kaon (1947)
- Neutral Pion (1950)
- Neutral Kaon (1950)
- Lambda (1950)
- Charged Sigma (1950)
- Delta (1952)
- Charged Xi (1953)

Called 'hadrons'

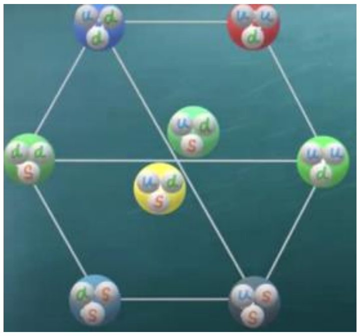
The Eightfold way

Proposed by Gell-Mann and Ne'eman (1961)

- organized hadrons by charge and 'strangeness'



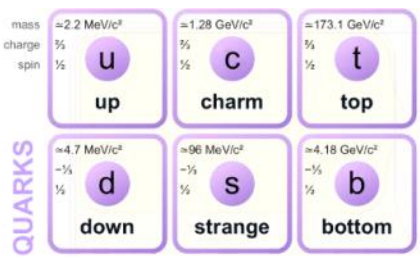
These 'quarks' have fractional experiments

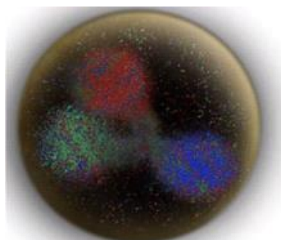


These 'quarks' have fractional experiments

Quarks

- Mathematical framework or the way the world actually works?
  - Direct evidence for quarks within proton came from experiments at SLAC in 1968
- Discovery of the J/ψ particle at SLAC and Brookhaven in 1974 showed there was a 4th quark: **charm** quark
  - Bottom quark discovered in 1977
  - Top quark discovered in 1995

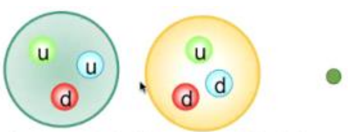




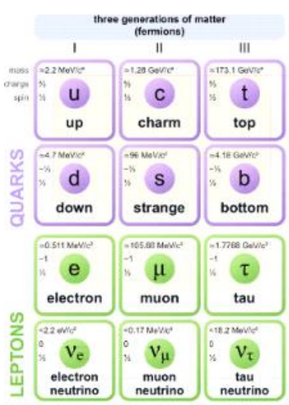
DOE Pulse

all ordinary matter is formed with up/down quarks + electrons

there are 3 generations however



Proton (+) Neutron (0) Electron (-)



→ all of these 'matter' particles are fermions
→ their spin is 1/2

Antimatter

- 1927: Dirac derived equations to describe relativistic electron
- corresponded with +1 or −1 charge
- 1932: Carl Anderson recorded a positron in cloud chamber

How do we make antimatter

Radioactive Decay
Positrons from Potassium - 40
→ your body constantly produces positrons [180 /hr]

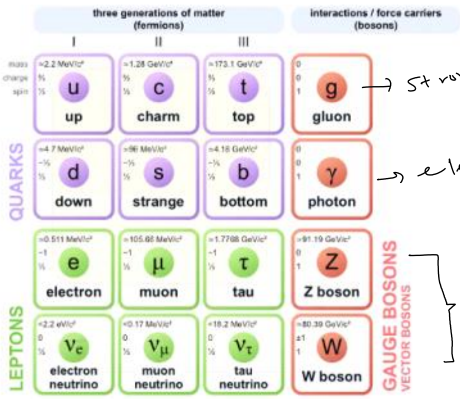
Antiprotons from high energy collisions of proton beam of fixed target metal

$$p + p \rightarrow \overline{p} + p + p + p$$

Force Carriers

- The other group of particles in the Standard Model are bosons: particles with **integer spin**
- These are the force carriers

- All interactions which affect matter particles are due to the exchange of force carrier particles
- Forces are the effects of the force carrier particles (bosons) on matter particles (fermions)



→ strong force

→ electromagnetic

the weak force

Color Charge

- quarks and gluons are color-charged particles

- Color-charged particles cannot be found individually; Quarks are confined in groups with other quarks. These composites are color neutral.
  - Baryons: 3 quarks (red+green+blue = color neutral)
  - Meson: 2 quarks (red + anti-red = color neutral)

"Color charge" has nothing to do with the visible colors, it is just a convenient naming convention for a mathematical system

Referred to as Quantum Chromodynamics (QCD)

Last missing piece : Higgs boson
→ developed in 1960's to explain how other particles have mass

1. **Higgs field** permeates the universe
   - Massive particles interact a lot with the field

(top quark → very slow by higg's field)
(photon moves very fast)

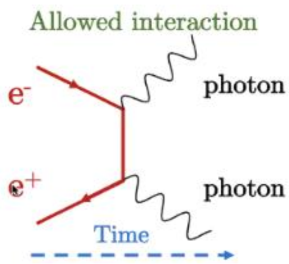
2. New particle predicted: **Higgs boson**
   - Discovered at the LHC in 2012
   - Only fundamental spin-0 particle (so far)

-

Feynman Diagrams

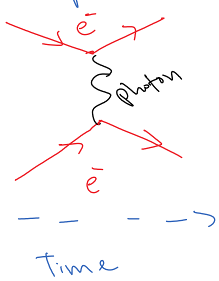
- essential tool in Quantum Field Theory → the math
- visual rep of underlying math

Ex. electron positron annihilation



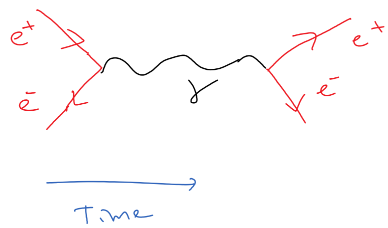
→ y axis = space
→ x axis = time

Example 2 : electron scattering (start with 2 electrons, end with 2 electrons)

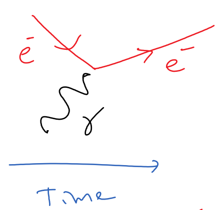


electrons interact through exchanging photons

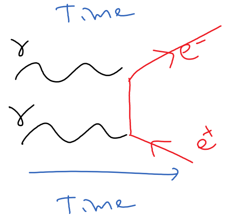
1. Start with one electron and one positron; end with one electron and one positron →



2. Start with one electron and one photon; end with one electron and one photon →



3. Start with two photons; end with one electron and one positron →



What is particle accelerators?

- machine to add energy to subatomic particles by accelerating them

Beam - we consider how a whole bunch of particles move

- the 'ultimate microscope'

• $\lambda = \frac{h}{p}$ ⇒ if we want to see small things, we need high energy

Play an important role in the experimental confirmation of standard model

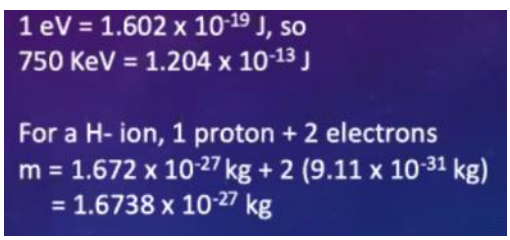
Building a Particle accelerator

• $\vec{F} = m \cdot \vec{a}$, $\underbrace{W = Fd}_{\text{dot product (as work is a scalar)}} = F \Delta x$

• Energy is conserved → potential energy ⇔ kinetic energy

Using Gravity as force

what distance should we drop H-ion for gravity to accelerate to 750 keV?



$g = 9.8 \ m/s^2$

⇒ $h \approx 73$ million km to yield a 750 keV kinetic energy

≈ half the distance from earth to Sun

So ~~Gravity~~, as gravity does accelerate particles, but is not practical for results we want to achieve.

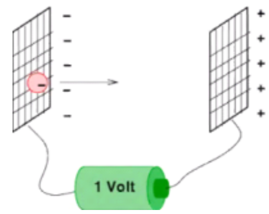
Electromagnetic Force?

Fields - electric fields, magnetic field, gravitational fields

- Charged particles produce electric fields

Fields

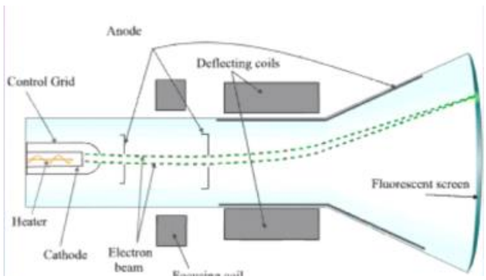
- Charged particles produce electric fields



- $\vec{F} = q\vec{E}$
  - q = electric charge
  - E = electric field

eV = amount of energy gained by accelerating one electron by 1 volt

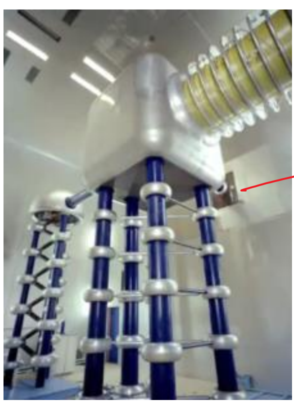
Crooke's tube



(used in CRT screen)

Cockcroft - Walton

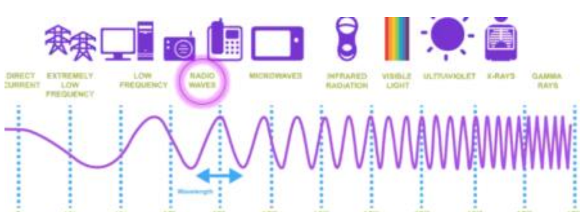
- clever design, high voltages possible
- Limitations: breakdown voltage, sparking



everything in room has rounded corners

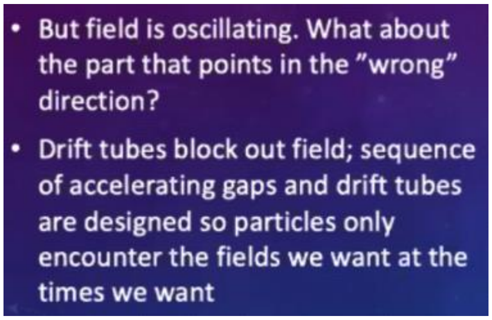
Higher energy ⇒ Electrostatic → Electrodynamic

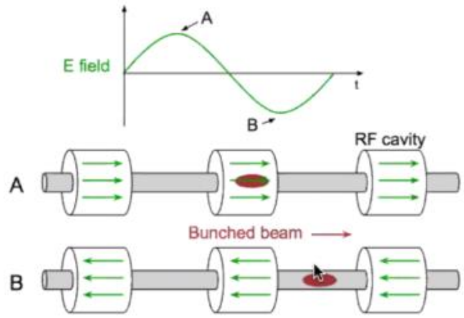
- RF cavities (radio frequency waves)

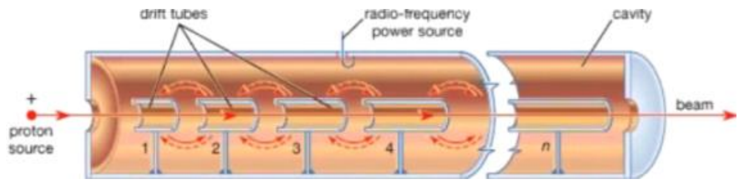


  - metallic structure in which produces/controls occilating electric fields

- $\vec{F} = q\vec{E}$: when particle encounters electric fields, it gets 'pushed' and since the field oscilates, it goes back and forth $\Rightarrow$ P

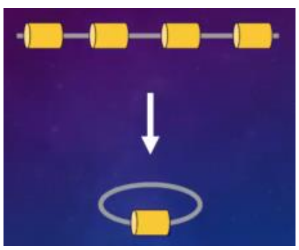






this works! → how about ↑ energies

SLAC accelerates electrons up to 50 GeV in 2.0 miles



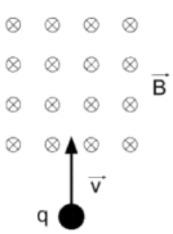
Bending Charged Particles (Magnetic fields)

- moving charged particles ⇒ magnetic fields

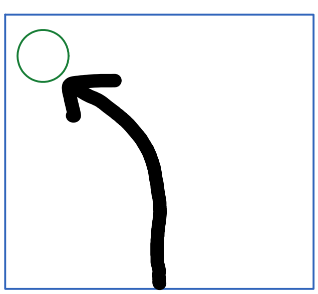
$\underbrace{\vec{F} = q\vec{v} \times \vec{B}}_{\text{Lorentz force}}$ where $\vec{B}$ = magnetic field

$\vec{F}$ is perpendicular to $\vec{v}$ and $\vec{B}$ → Right Hand Rule

- $\vec{F}$ changes direction based on charge of particle

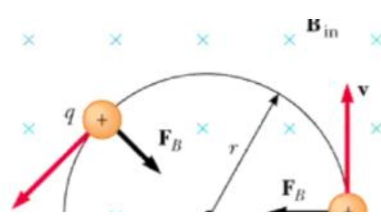


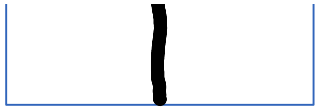
Trace the path of particle :

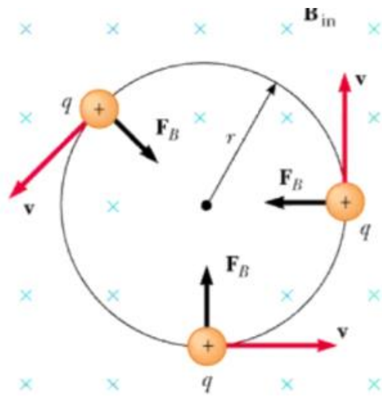


→ perpendicular to direction of $\vec{v}$ and $\vec{B}$

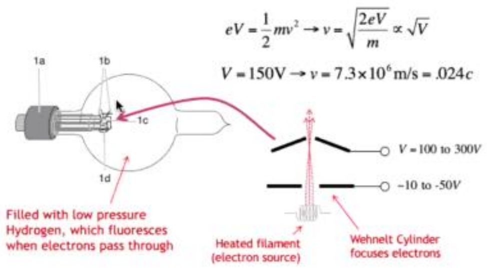
→ results in a circular motion

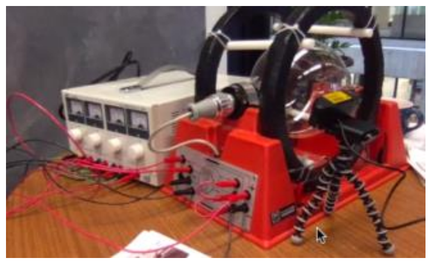


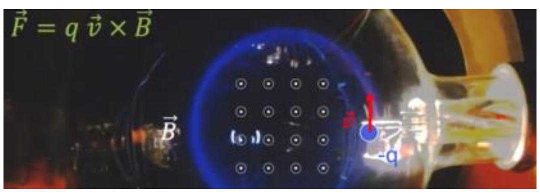


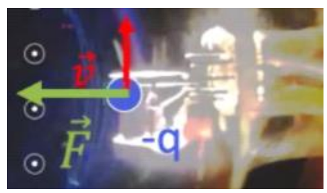


Fine beam tube / Helmholtz coils



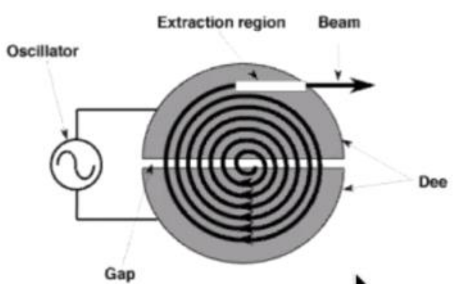






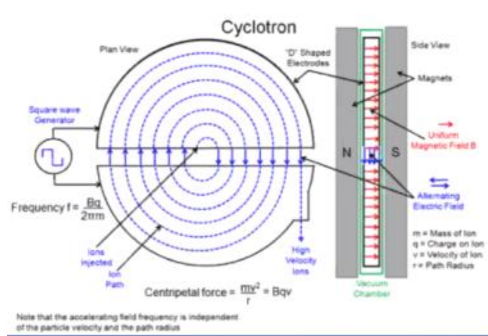
if velocity ↑ but $\vec{B}$ is same, radius ↑

⇒ Cyclotrons



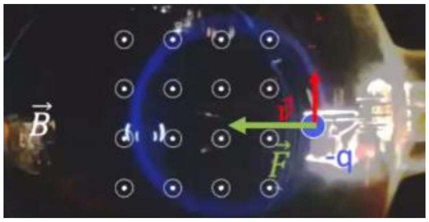
→ uses RF cavities (Dees)

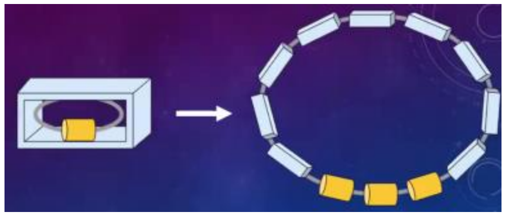
→ large uniform magnetic field



TRIUMF → largest cyclotron in Canada (radius = 310 inches)

What if $\vec{B}$ ↑ and $\vec{v}$ stays the same?



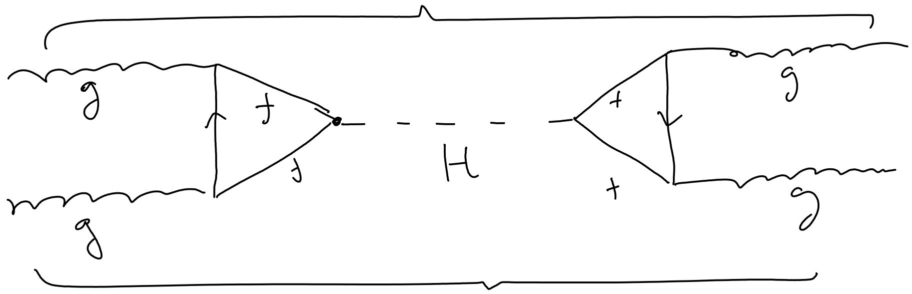


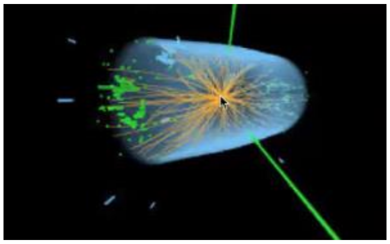
Cyclotron → Synchrotron

- increase $\vec{B}$ as particles $\vec{v}$ increases

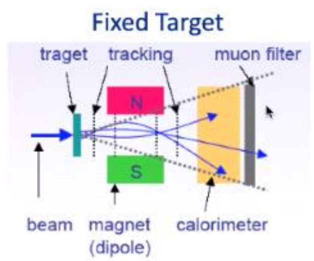
Not nessacarily that Synchrotrons are best, each machine has their PROS / CONS

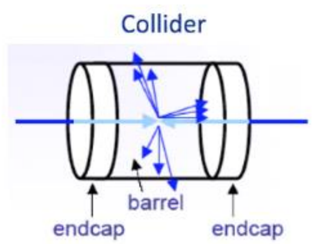
Feynman diagram for Higgs Boson



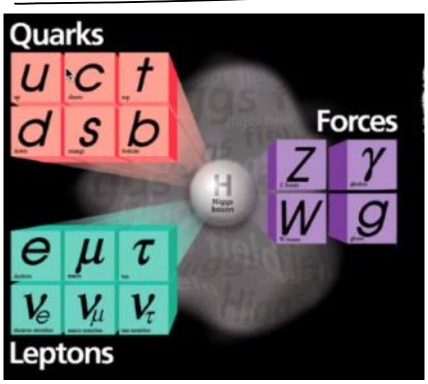


Detector Geometries





The Usual Suspects



The Unusual Suspects

- Dark Matter
- SUSY particles
- Sterile Neutrinos
- Magnetic Monopoles
- Etc

Distinguishing a Particle

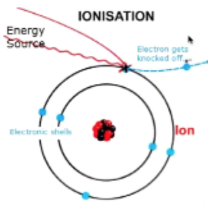
- mass, charge, spin, etc.
- Conservation (energy, momentum, Charge/Parity/Time)
- particle lifetime

Tools for Particle detection

- particle lif...

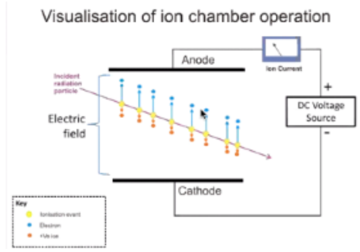
Tools for particle detection

Ionization



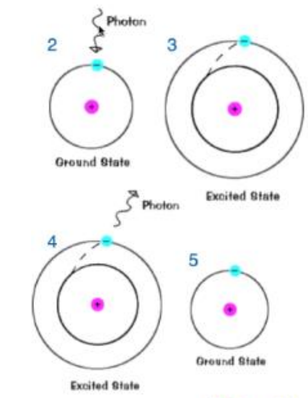
→ 'deposits' energy to knock of electrons

can apply an electric field to collect ionization beams



- only works for charged particles

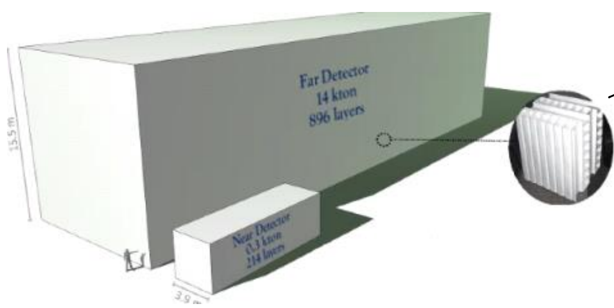
Scintillation Light

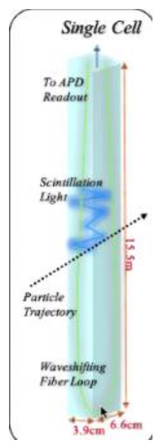


→ materials: organic, inorganic

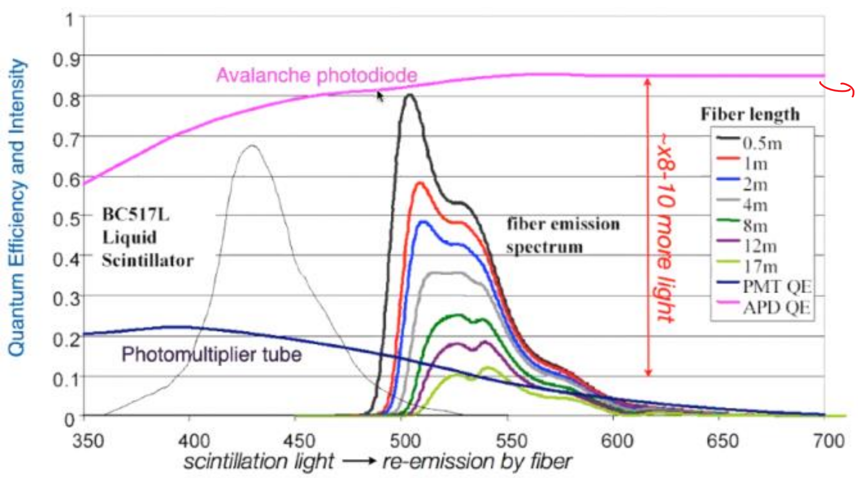
→ devices: avalanche photodiodes, photomultiplier tubes

NOvA





- Grid of long cells filled with a scintillating material
- Optical fiber to collect light coupled to a readout device

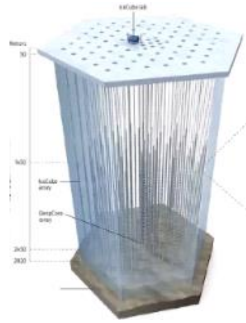


↪ 8-10 x more efficient than photomultiplier at particular wavelengths

Tracking Charged Particles

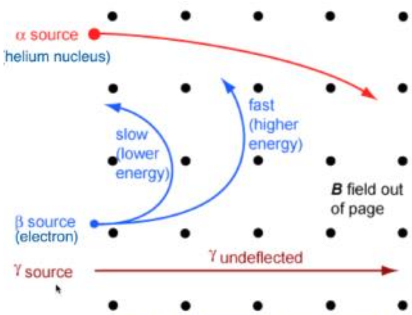
- We can use ionization and scintillation to track particles in discrete steps
- We want the best tracking resolution required to make the physics measurement
  - Minimize dead material which degrades energy resolution
  - More channels -> higher cost
  - More channels -> larger data rates, processing times

→ CMS



→ Ice cube

Tracking Charged Particles in Magnetic field



Effect of a magnetic field on alpha, beta and gamma radiation

→ opposite charges

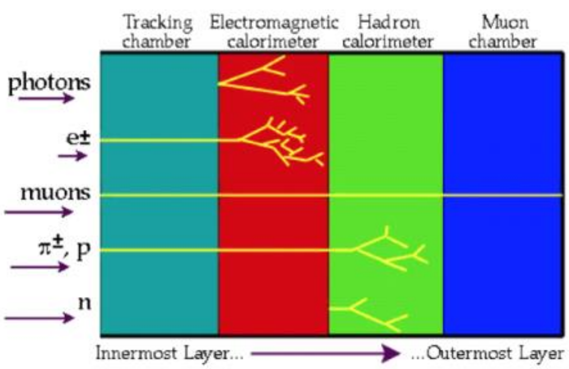
→ opposite direction

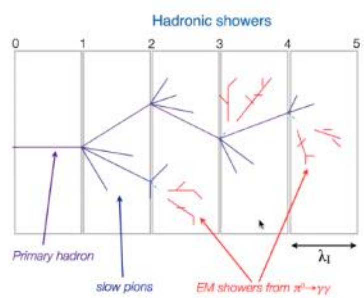
Eg. Proton vs electron

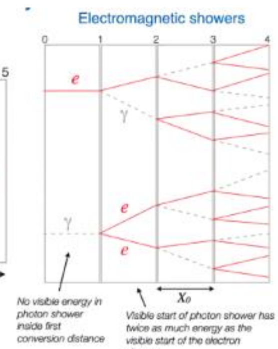
Calorimetry

Different types (electromagnetic vs hadronic)

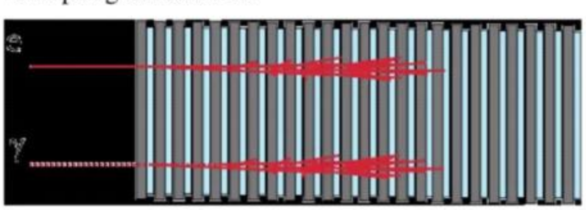
Calorimetry is the science or act of measuring changes in state variables of a body for the purpose of deriving the heat transfer associated with changes of its state due, for example, to chemical reactions, physical changes, or phase transitions under specified constraints. Wikipedia







Sampling Calorimeter



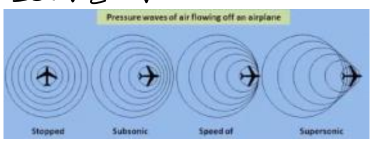
→ planes of simulating material for stopping/slowing down particles

Homogeneus Calorimeter

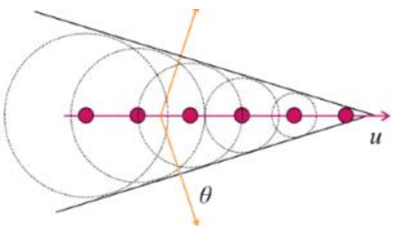
→ one cell { only gives amount of energy, not dispersion / distribution

Cherenkov Radiation

- sound barrier



- light barrier

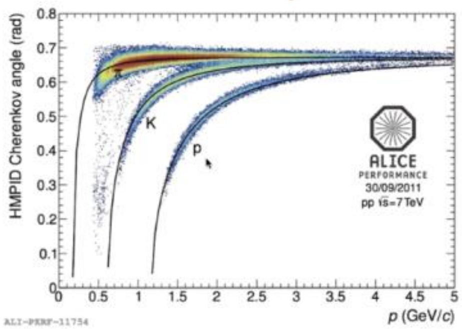


c : speed of light in vacuum

n : index of medium

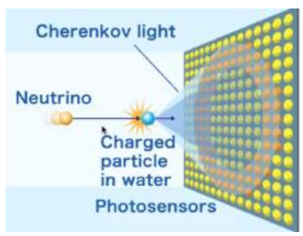
β : velocity of particle → • Cherenkov radiation requires $c/n < \beta < c$

$$\cos\theta_c = \frac{1}{n\beta}$$

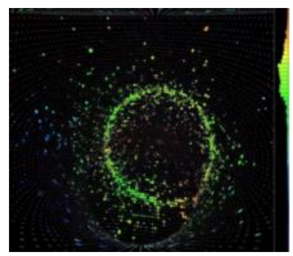


θ depends on $\vec{v}$, m, and material

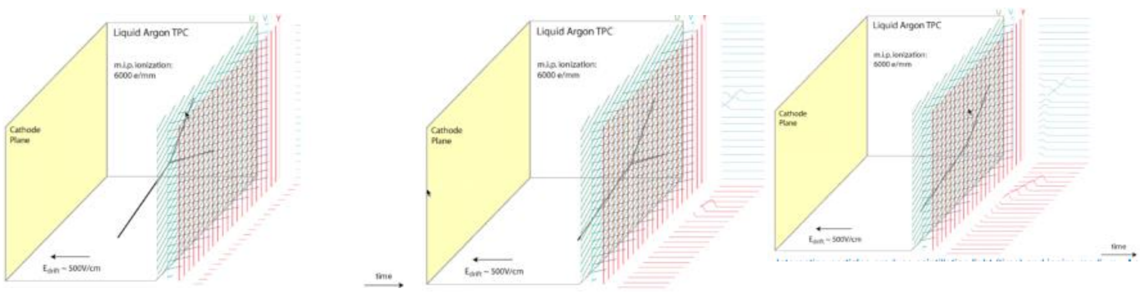
Water Cherenkov detector



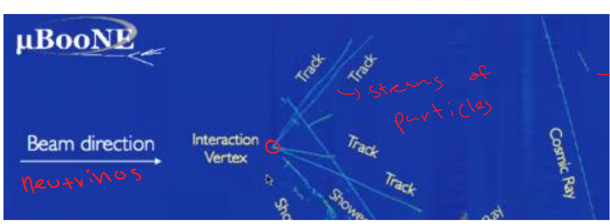
Simulated Electron-Neutrino Interaction



Liquid Argon Time Projection Chamber (TPC)

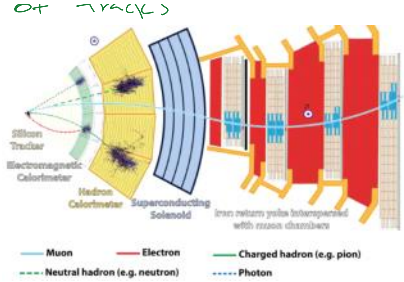


- What advantages would liquid argon have as a detector medium?
  - Nobel element so little interaction with electrons resulting from ionization as they drift.
  - Produce scintillation light in addition to ionization, gives you event time.
  - Relatively inexpensive -> large volume
  - High density -> more interactions
- Provide tracking, calorimetry, particle ID all in one.



→ color of track tells us amount of energy of tracks

of tracks

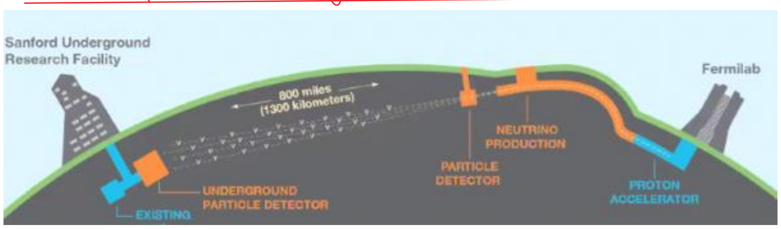


Neutrino Experiments

- interactions are very rare, due to mass, and due to neutrinos only interact through weak nuclear force

- Build a detector as large as possible in target mass
- Use an intense source of neutrinos
- Run the experiment as long as possible
- Minimize background sources
- Good energy resolution, fully contain the event

DUNE (Deep Underground Neutrino Experiment)

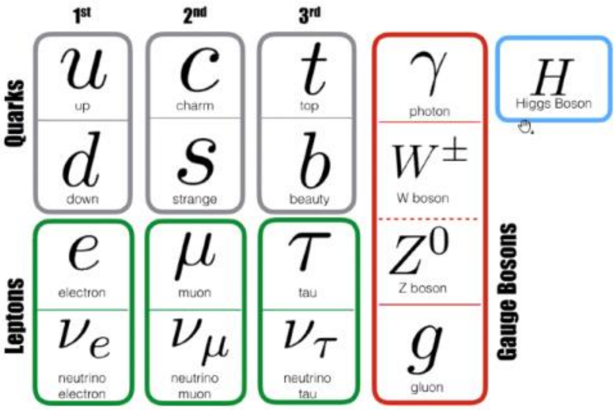


Summary :

- Many tools for identifying particles inside a detector (far more than covered today!).
- Optimize detector design to satisfy a set of physics goals, there is no one way to build an experiment.
- We have a lot of tools we can use to detect particles: ionization, scintillation, magnetic fields, calorimetry
- As much effort or more can go into designing and building a detector as collecting and analyzing the data. Many detector concepts require technological innovations to become reality.

Day 7 Lecture - The Neutrino

Saturday, March 6, 2021 8:55 AM

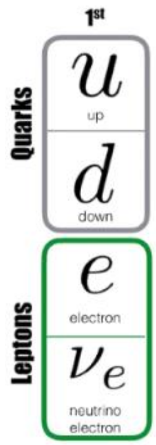


Quarks
- fractionally charged
- never seen by themselves
- Combinations of Quarks are called Hadrons
  - Ex. protons neutrons

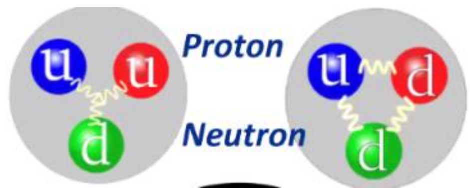
force carriers
- Gauge bosons are force carriers
- W bosons ⇒ ±1 charge
- rest are neutral charge

Gluons come in different colors!

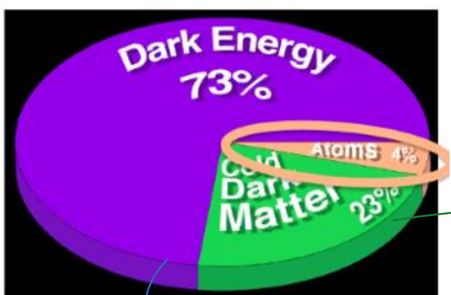
- Higgs Boson produces a field by which particles gain mass



- almost all particles are made with 1st generation particles



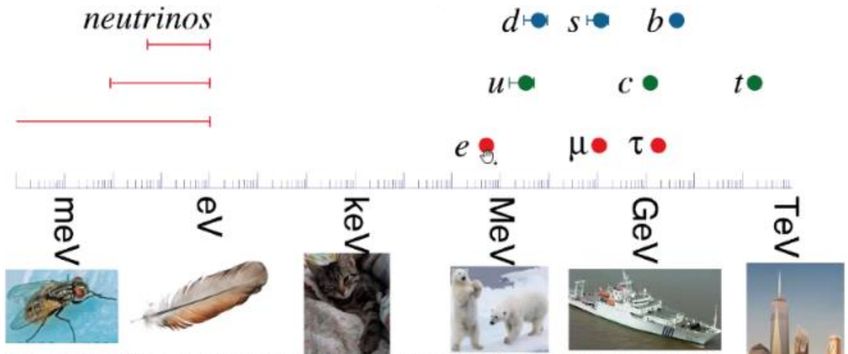
Standard Model Problems



→ only predicts about 4% of energy content of universe

→ Holds galaxies together
- If it weren't for this they would fly apart at millions of miles per hour!

→ Dark Energy appears to cause the universe to expand faster and faster
- Counteracting the force of ***Gravity***

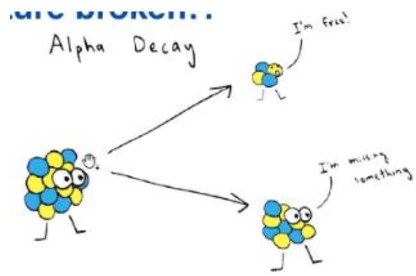


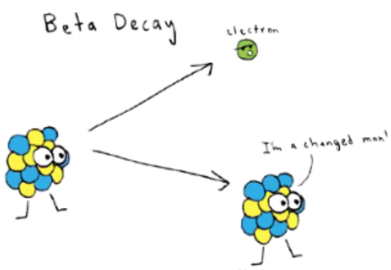
- It handles everything on the right hand side of this table quite well.
  - Accurately explains the masses and mass differences.
- However, it really struggles to explain neutrino masses.

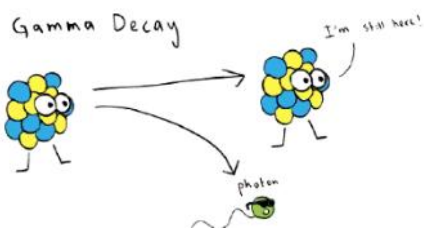
Something about neutrinos are fundamentally different to all other particles. Neutrinos are fundamentally neutrally charged.

Radioactivity

- unstable nucleus loses energy by emitting a particle







Beta-Decay

- N-14 is more stable than C-14 because it has protons = neutrons

=) carbon → nitrogen + electron

$$ {}^{14}_{6}\mathrm{C} \quad = \quad {}^{14}_{7}\mathrm{N} \quad + \quad e^- $$

13,043.**94** MeV   13,043.**27** MeV   0.**511** MeV

However, 159 keV was never found → peaked at 30 or 40 keV) so not just one particle emitted.

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. Unfortunately I will not be able to appear in Tubingen personally, because I am indispensible here due to a ball which will take place in Zurich during the night from December 6 to 7...

Your humble servant,
W. Pauli

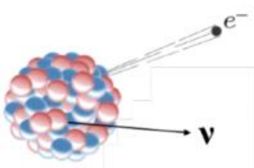
The neutron was discovered shortly after this letter, at which point Fermi proposed calling the above hypothesised particle the neutrino, or the "little neutral one."

(1930) Pauli postulated an additional particle (neutral and very small) in beta decays.

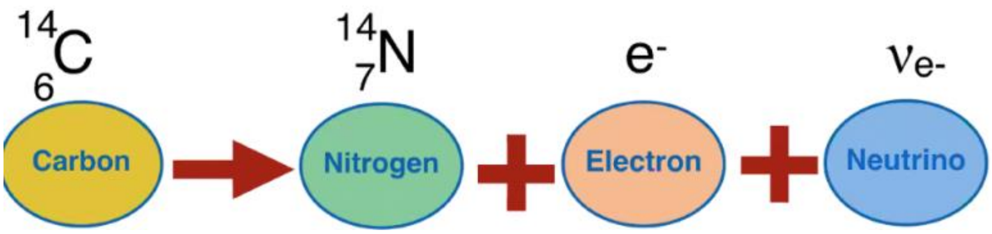
(1933) Fermi formulated the theory the weak force to explain the process.

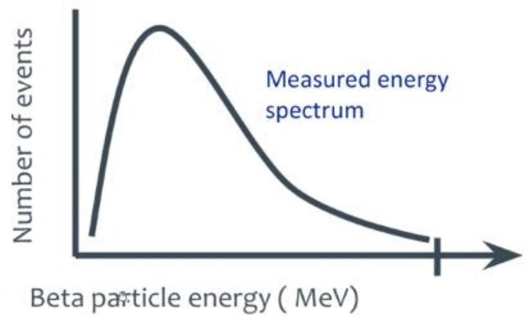
(1936) Yukawa proposed W boson as a carrier of the weak force.

What actually happens in beta decay then?



- A neutrino is emitted from the nucleus in addition to the electron.
- Energy is still conserved, but now the 0.159 MeV is split semi-randomly between the electron and neutrino.
  - Therefore we measure a continuum of electron energies.





Measuring Neutrinos

- a bubble chamber event from high energy chamber
- can calculate electrical / magnetic charge

- None of this works for neutrinos.
  - They're neutral and so don't feel E/B fields.
  - They also barely interact, and could easily travel through 200 Earths before interacting!

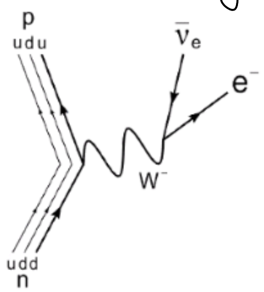
Producing Neutrinos

- produced by radioactive decay → beta decay

p
udu

$\bar{\nu}_e$ → but impractical

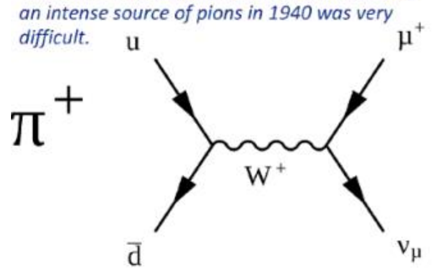
- produced by radioactive decay → beta decay



→ but impractical

- Decay of pions (combinations of Up / Down Quarks)

This is how we produce them now, but making an intense source of pions in 1940 was very difficult.

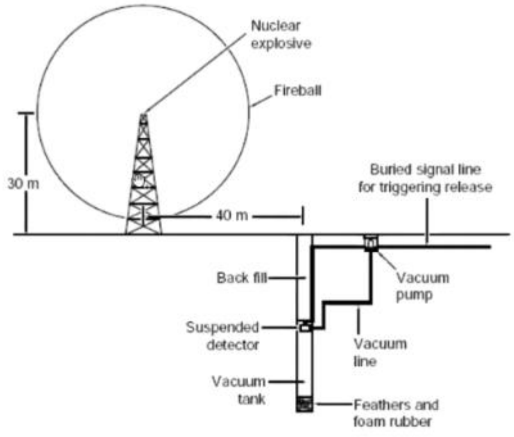


- Neutrinos are produced by the sun as it fuses Hydrogen to make Helium (fusion)

→ but what is the sun but a huge nuclear reactor...

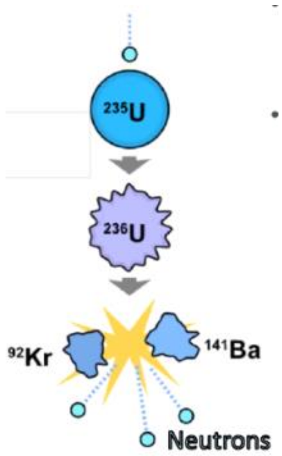
→ but what is the sun but a huge nuclear bomb...

Project Poltergeist #1



- Step 1. Explode nuclear bomb
- Step 2. Let the detector drop down the mine shaft at the same time.
- Step 3. Detect the neutrinos.

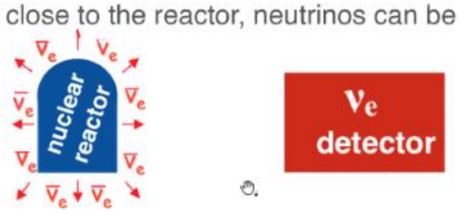
Project Poltergeist #2



Neutrinos are produced when the neutrons produced by fission decay.

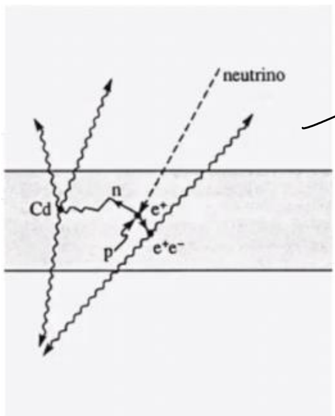
$$n \to p + e + \nu_e$$

By placing a detector close to the reactor, neutrinos can be measured.



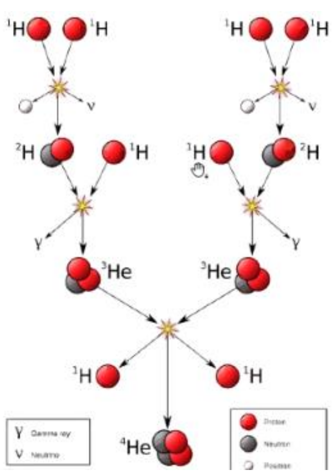
In 1956 the neutrino was measured for the first time, by placing a Cadmium filled detector next to a reactor.

- A rate of 0.56 neutrino interactions per hour was measured.

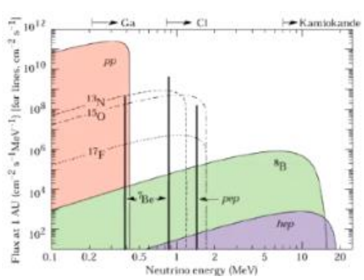


→ schematic of neutrino interaction

The Homestake experiment

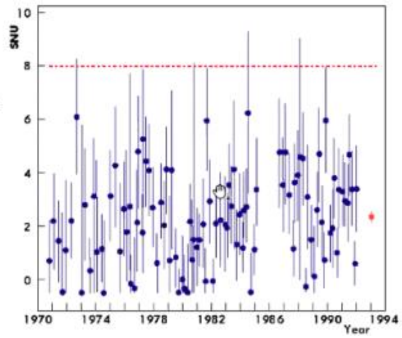


→ Helps us understand the structure of the Sun



- 1961 – Ray Davis proposed an experiment to measure solar flux

- 615 tonnes of C_2Cl_4, 1 mile underground in an active gold mine.
  - More on this location later!
- Measured inverse beta decay on the Chlorine atoms
- *It was therefore only sensitive to electron neutrinos.*



- Ran for 25 years, and consistently saw a rate roughly 1/3 of the expected solar flux.
  - They expected to see about 1 interaction per day, but they saw 1 interaction every 3 days.

→ Solar Neutrino Problem
→ only measuring 1/3 of expected solar flux meant something was wrong

Day 8 Lecture - LHC Physics

Saturday, March 13, 2021 9:00 AM

Ordinary matter is made of quarks/leptons

atoms: protons, neutrons + electrons → proton = 2 up + 1 down

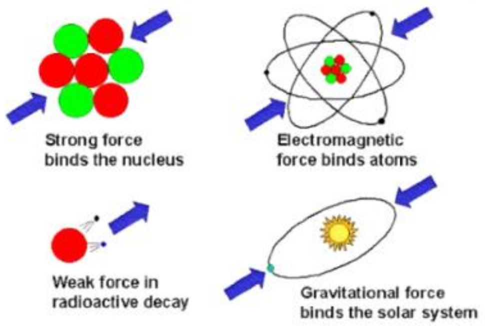
neutron = 1 up + 2 down

→ every matter particle has antimatter particles

3 generations of particles → same particle but more mass

→ muons are just heavier electrons

Force	Carrier
Strong	g gluon
Electro-magnetic	γ photon
Weak	W W boson, Z Z boson
Gravity	graviton?

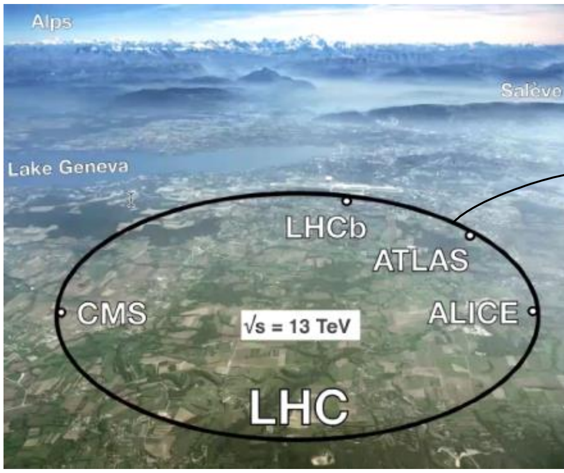


fundamental forces

Sources of Particles

Source	Unique Features	Caveat
Ordinary Matter	rare processes can probe highest energies - 10^{15}-10^{16} GeV eg. proton decay	theory assumptions
The Universe	high energy cosmic rays - 10^{10} GeV dark matter - 10^{-20} - 10^{3} GeV	background assumptions
Colliders	only place to study heavy Standard Model Particles, eg. Higgs, top also look for new particles up to ~10^{3} GeV	requires powerful accelerators

Large Hadron Collider



27 km circumference

protons travel at 99.99999999 %
of speed of light

⇒ Making Heavier Particles

⇒ $E = \sqrt{m^2 + p^2}$

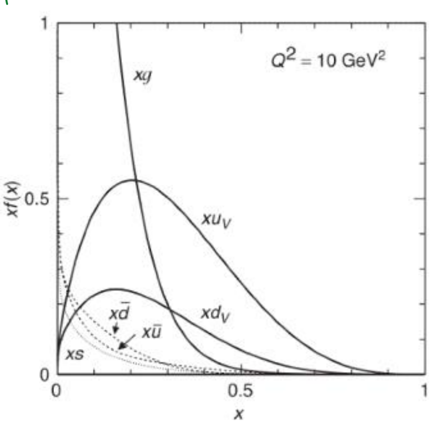
proton
$m = 1$ GeV
$E = 6500$ GeV

Higgs (125 GeV)
Top (173 GeV)
Exotic particles?

proton

So LHC is a gluon collider

Proton Distribution Function



Only a fraction of that energy goes into the proton constituents (quarks+gluons)

→ only a fraction of that energy goes into the proton constituents (quarks + gluons)

Particle Colliders as microscopes

- High-energy collisions access small distances

Visible light ~ 5×10^{-7} m LHC collision ~ 2×10^{-20} m

- Quantum Mechanics ⇒ particles ~ waves

A particle with energy E has wavelength $\lambda = hc/E$

where c = speed of light, h = Plank intrinstic angular momentum

Proton mass = 10^{-24} grams, or 1 Giga electron-volt (GeV)

$\Rightarrow$ proton wavelength = 0.2 femto-meters (10^{-15})

Atomic Nuclei

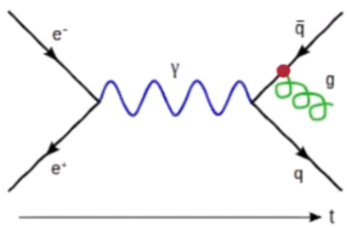
- Elements can in turn be replaced by protons, neutrons, electrons
- curiously $m_{proton} = 0.9383$ GeV

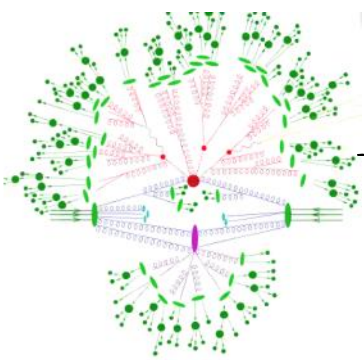
  $m_{neutron} = 0.9396$ GeV

$\rightarrow$ So similar structure! $\rightarrow$ symmetry at play

$\Rightarrow$ Simplicity = Predictiveness

- Strong Force: interaction structure + a single coupling $\rightarrow$ strength of an interactions
- Predicts a vast amount of phenomena:
  - Protons, neutrons, electrons
  - excited states
  - gluon force carrier

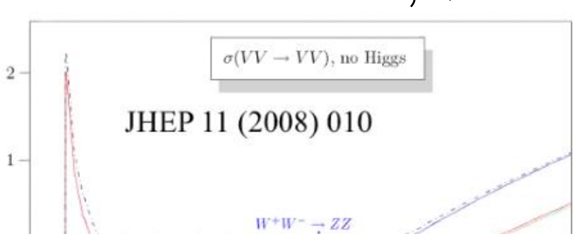




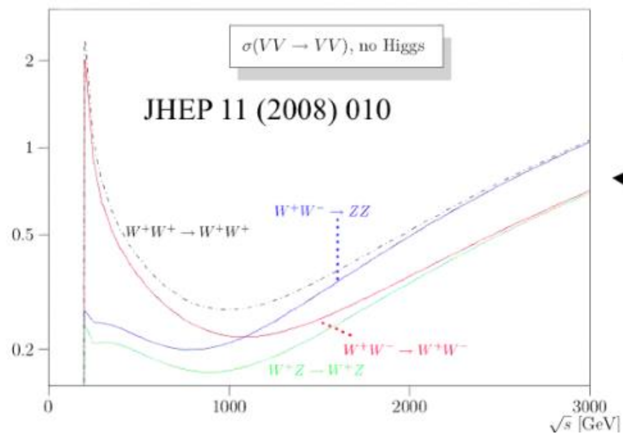
$\rightarrow$ production of the Higgs Boson

- Similar applies to Weak Force (eg muon decay in cosmic rays)

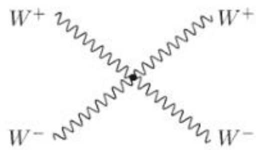
At small distances, the theory breaks $\rightarrow$ hole in the theory



- Predict probabilities > 1 !!!

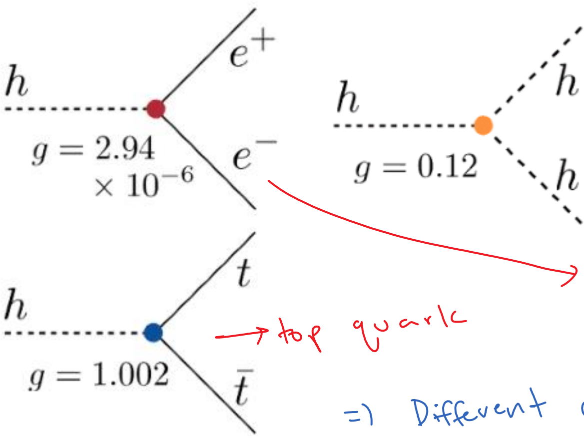


- Predict probabilities > 1 !!!



The Higgs Field

- couples to ALL massive coupling (electron has small mass)



→ Higgs to Higgs

electron

→ top quark

⇒ Different coupling for every particles

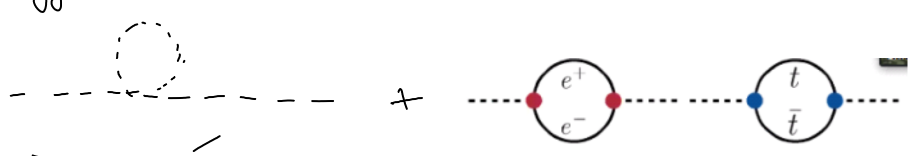
Beyond the Higgs ...

- Many questions revolve around the Higgs — the newest and least-understood component of the 'Standard Model'
  1. Why are there so many different masses/couplings, and with such different sizes?
  2. Is there only one Higgs boson?
  3. Is the Higgs a fundamental particle or a composite, like the proton?
  4. Is the Higgs also responsible for neutrino masses?
  5. Does the Higgs respect the known symmetries of nature?
  6. How does dark matter fit into this picture??
  7. …
- Higgs is a fundamentally unique particle within the SM!

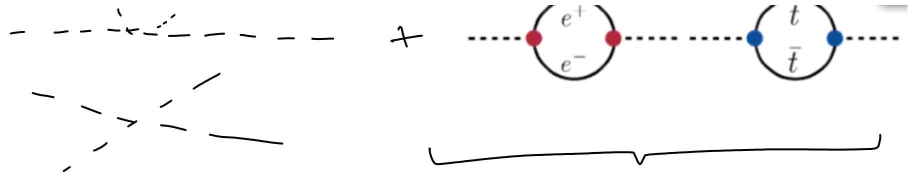
The Hierarchy Problem

- can calculate Higgs mass

Higgs Mass =



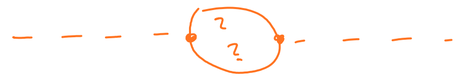
Higgs Mass =



Measured! (125 GeV)

a few models ~ 100 GeV

Contributions from each massive particles

or with undiscovered particles too ⇒ 

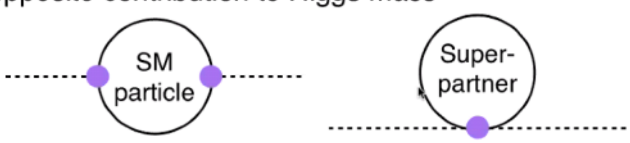
New Heavy particles ⇒ heavy higgs boson, but higgs is light

- E.g. a 10^{16} GeV graviton wants to "pull up" the Higgs mass to 10^{16} GeV, but we observe it as 125 GeV. Why??

A new symmetry?

- suggests a mechanism to keep Higgs light

- Supersymmetry is one possible answer
  - Idea: every SM particle gets a copy, with equal and opposite contribution to Higgs mass

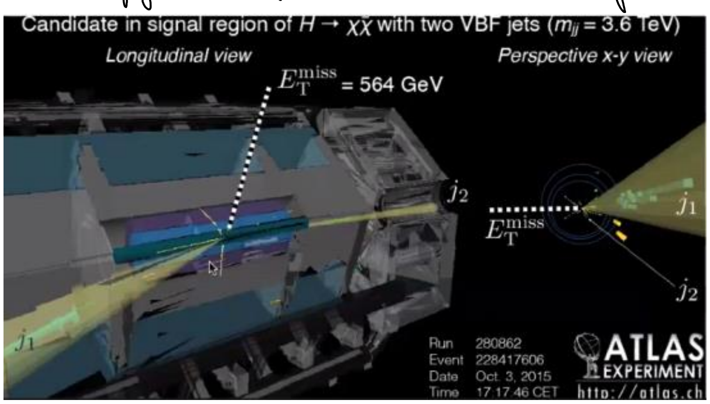


› but where are the supersymmetric-partners?

- Expected to be near Higgs mass

Dark Matter

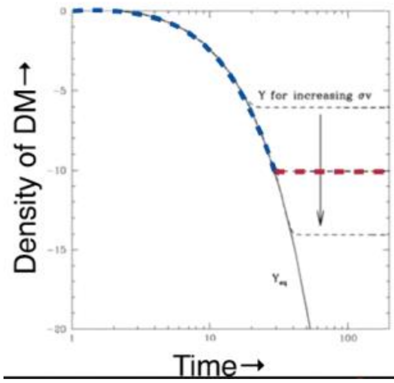
- If Higgs couples to all SM particles, why not Dark Matter?



Weakly-interacting massive particles (WIMP)

Weakly-interacting massive particles (WIMP)

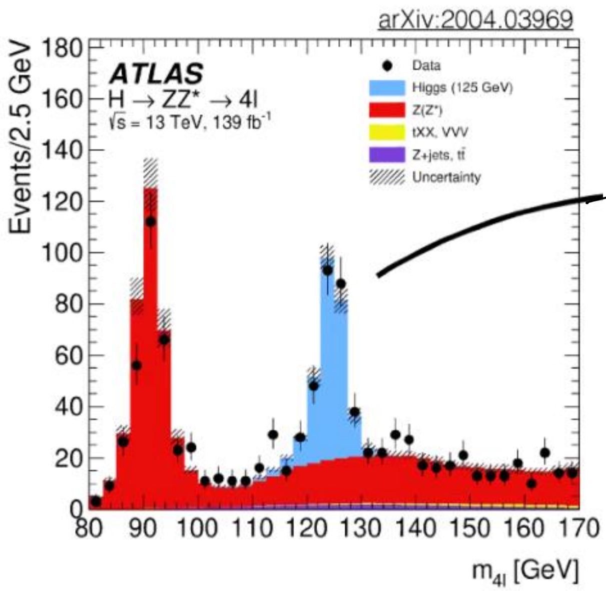
- New particles near the Higgs make excellent dark matter
  - WIMPs: weakly-interacting massive particles



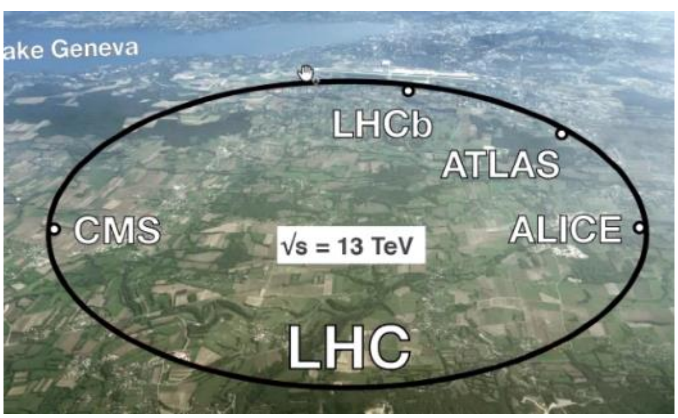
After early equilibrium, DM particles ~stop interacting with SM and "freeze out"

DM —— visible
DM —— visible

Hint of a common solution for Higgs mass problem and dark matter ?



→ Collecting Data on Higgs Boson

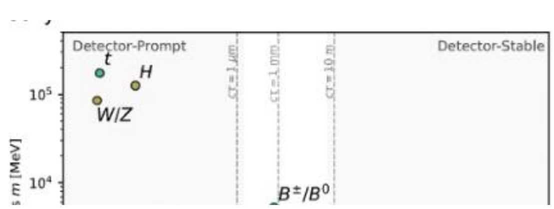


→ p-p collisions at 4 points to produce Higgs Boson

Particle Decay

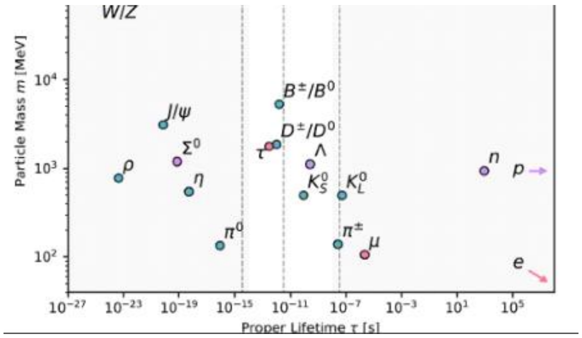
- each particle decays into smaller particles

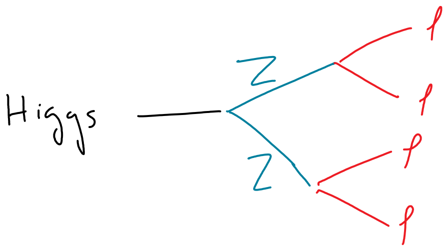
- Three categories of particles
  - Stable - live long enough we can "see" them interact with our detector

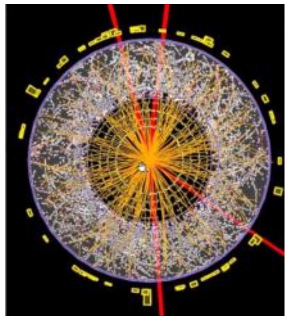


each particle decays into smaller particles

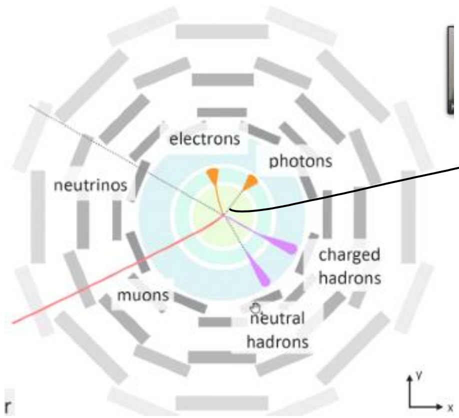
- Three categories of particles
  - Stable - live long enough we can "see" them interact with our detector
    - truly stable: electron, proton, photons, neutrinos
  - Intermediate - decay slightly displaced from point of pp-collision (can form a vertex)
  - Prompt - decay too quickly to detect directly





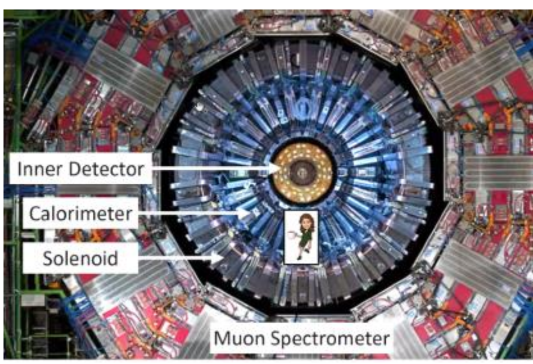


General purpose detectors



→ cylindrical geometry

→ Inner Detector, electromagnetic calorimeter, hadronic calorimeter, muon Spectrometer

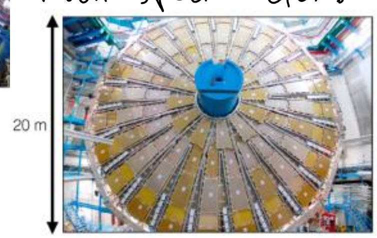


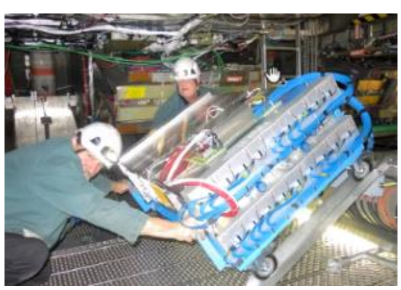
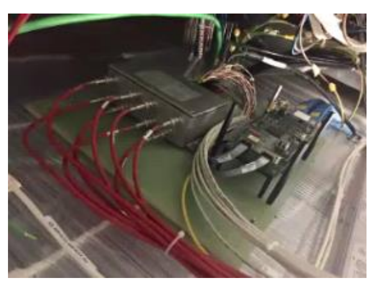
→ A real detector: CMS

~ complete design (1997)

~ installation (2008)

Muon Spectrometer:



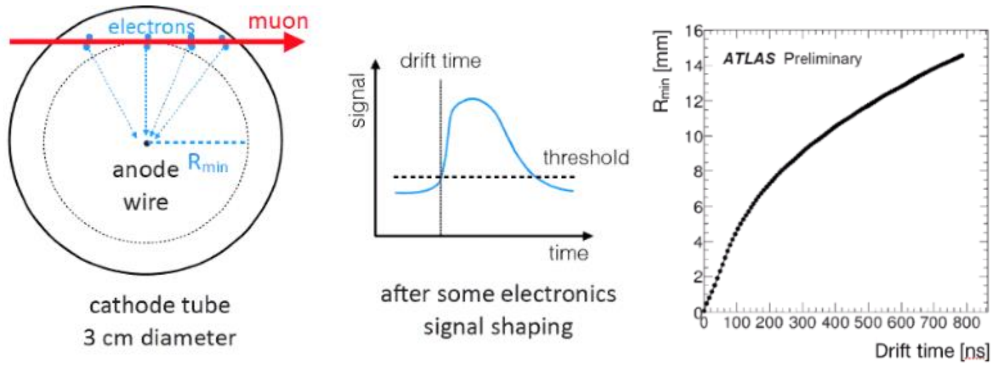
 →  → 

takes 2 weeks per chamber (if nothing breaks)

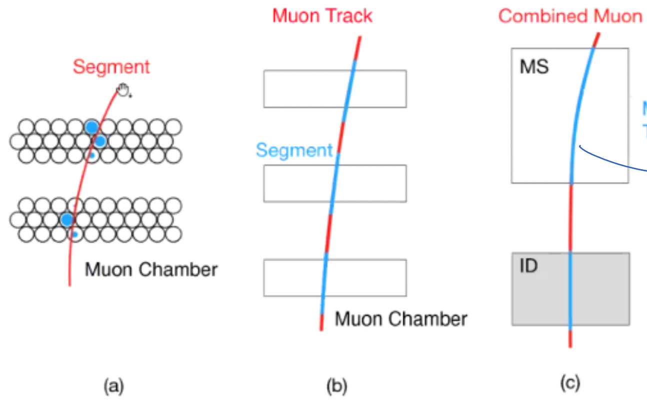
and the muon spectrometer has 2000+ chambers!

How a muon chamber works:

muon chambers made up of drift tubes



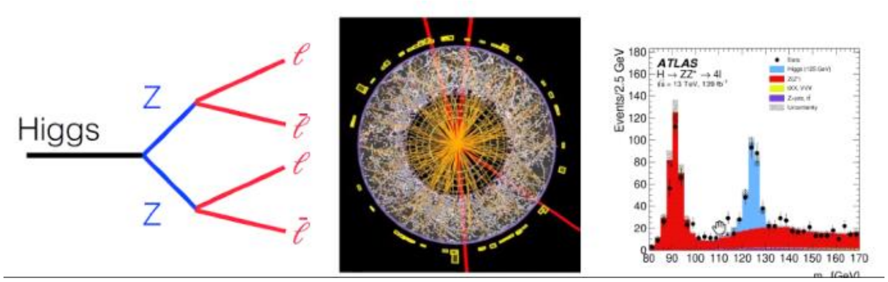
all the signals make drift radii, and can track signals into muons

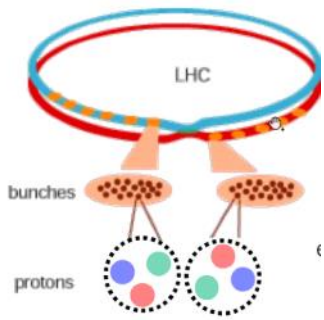


Bending tells us the momentum of muon at instantaneous time frames

To make a Higgs...

events with 4 muons, indentify pairs of muons with Z bosons, compute the Higgs mass, fill the histogram to find 'bumps'





~ 3200 bunches of protons in LHC ring

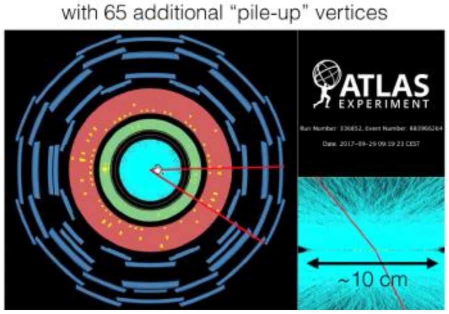
bunches cross 25 ns

⇒ 40 million per second

and 50 pp collisions per crossing ⇒ 2 billion pp collisions per second!

→ 1/2,000,000,000 of interactions is Higgs

A 2017 Z→μμ candidate,
with 65 additional "pile-up" vertices



→ the trigger challenge

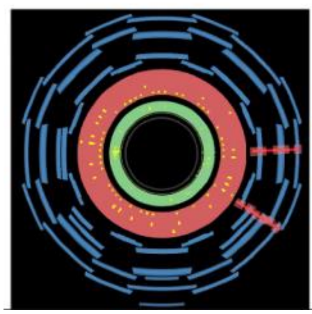
No room for error!

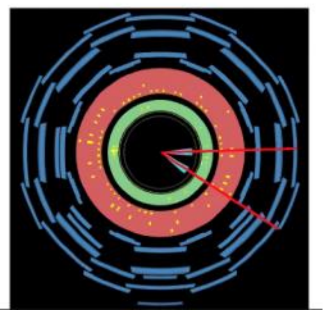
if trigger throws event away, it's lost for ever

⇒ ATLAS takes data 24/7

Step 1.
coarse muon and
calorimeter information
decision time: 3.2 μs
keeps 1/400 crossings

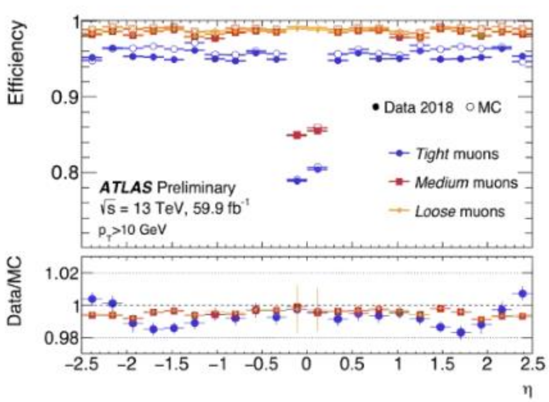
Step 2.
nearly full detector in
region of interest
decision time: 200 ms
keeps 1/100 crossings





Quantifying Detector Performance

After data-taking, make projections to ensure detectors still works



Finally, our data is ready for physics

measure top quark mass

Finally, our data is ready for physics

$\Rightarrow$ measure top quark mass
study properties of W/Z bosons
look for new exotic particles!

Life-cycle of accelerator/detector

Operate $\rightarrow$ Design $\rightarrow$ Construct $\rightarrow$ Commision $\rightarrow$ Operate

LHC |

- Limits of accelerator lifetime
  - damaged
  - scientific mission is accomplished

  cost/benefit too high

LHC / HL-LHC physics goals

$\rightarrow$ currently in blue phase

- **Discovery of the Higgs boson**
- Searches for new physics (Nope!)
- Observation of **rare processes**, such as $B_s \rightarrow \mu\mu$
- Precision measurements of SM processes
- ...

- Searches for new physics
- Improved measurements of **Higgs boson couplings**
- Observation of the Higgs boson in new decay modes
- Measurements of **rare SM processes**

- Precision measurement of the **Higgs boson couplings**
- Observation of very rare Higgs boson decays
- Ultra precise SM measurements, even for **rare processes**
- New physics searches as high mass
-

- Need to collect a much data in least time

$$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{N}}$$

$\sigma \rightarrow$ SD

$\sqrt{N} \rightarrow$ # of observations

$\sigma_{\bar{x}} \rightarrow$ standard error

Unit	Symbol	m^2	cm^2
megabarn	Mb	10^{-22}	10^{-18}
kilobarn	kb	10^{-25}	10^{-21}
barn	b	10^{-28}	10^{-24}
millibarn	mb	10^{-31}	10^{-27}
microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}

Relevant for

$\rightarrow$ cross sections - probability of a given process

$\rightarrow$ luminosity - rate of collisions

microbarn	μb	10^{-34}	10^{-30}
nanobarn	nb	10^{-37}	10^{-33}
picobarn	pb	10^{-40}	10^{-36}
femtobarn	fb	10^{-43}	10^{-39}
attobarn	ab	10^{-46}	10^{-42}
zeptobarn	zb	10^{-49}	10^{-45}
yoctobarn	yb	10^{-52}	10^{-48}

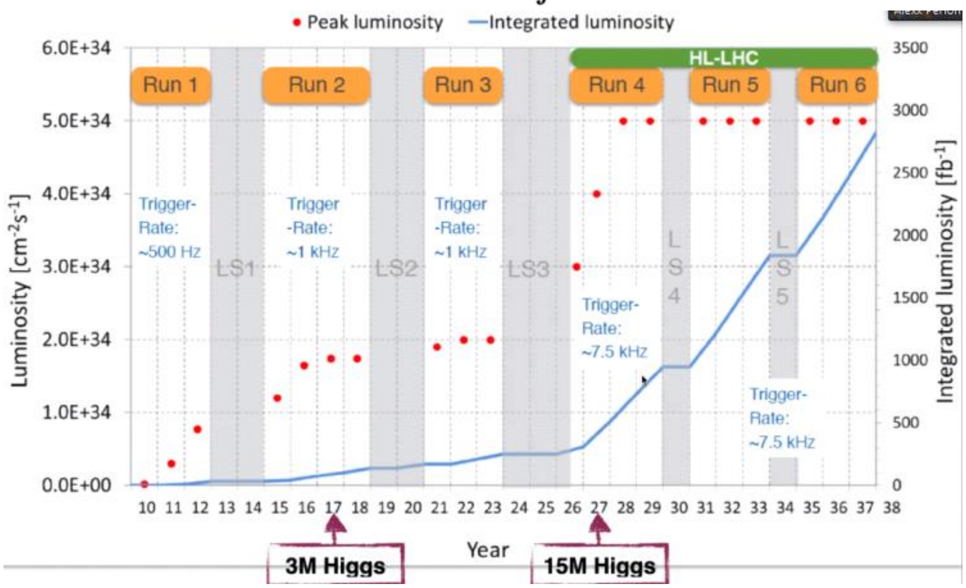
Relevant for Higgs physics

→ luminosity – rate of collisions

Luminosity →
$$\mathscr{L} = \frac{1}{\sigma_{exp}} \frac{dN_{exp}}{dt}$$

$$\mathscr{L}_{int} = \int \mathscr{L}\, dt$$

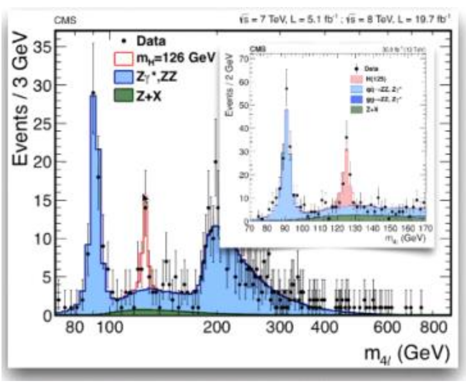
$$N_{exp} = \sigma_{exp} \times \int \mathscr{L}(t)\, dt$$

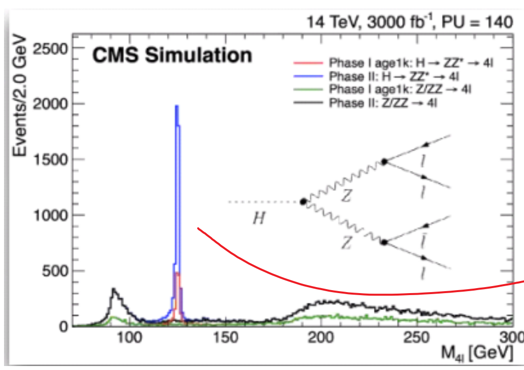


increasing the amount of data saved over time

→ High Luminosity LHC

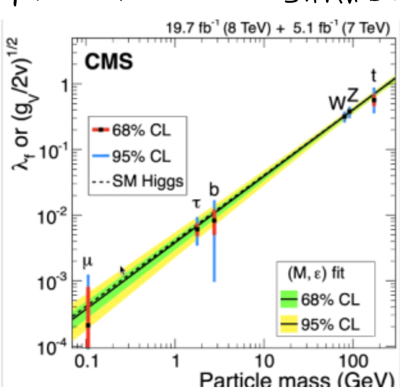
Higgs boson mass measurements:

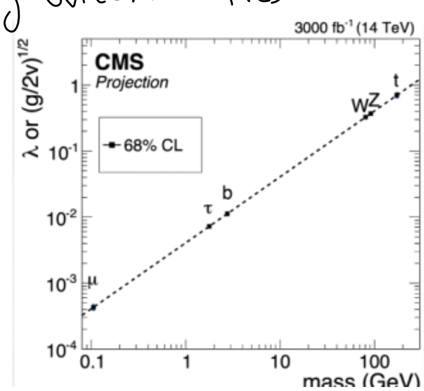




→ more information means it is very obvious where the particles are

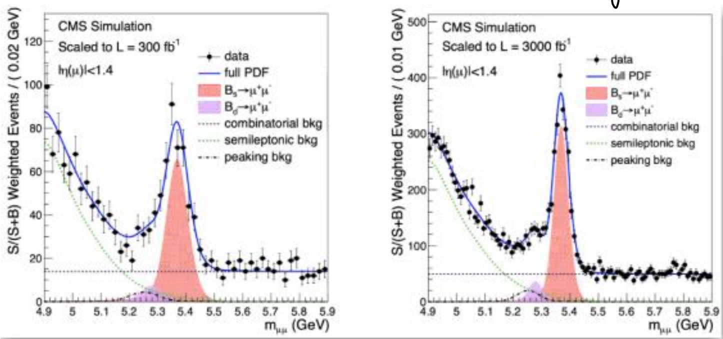
More Data → shrinking uncertainties



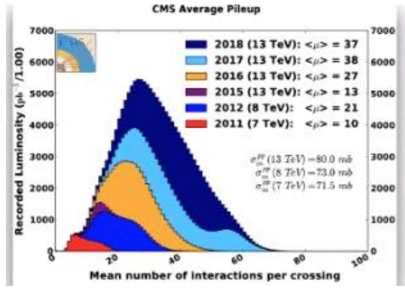


But not only about Higgs Boson:

also detections of rare decays



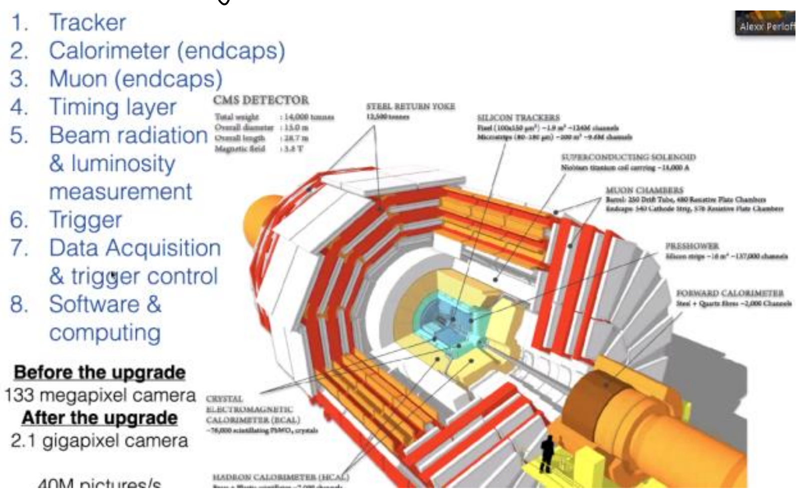
but there are also many simultaneous collisions! :(



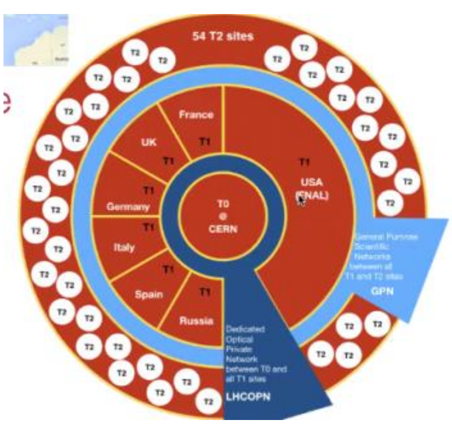
~ 80 ish collisions per event

and HL-LHC has ~ 200 collisions per event

CMS Upgrades toward HL-LHC



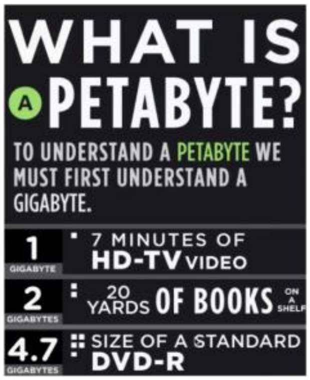
The GRID

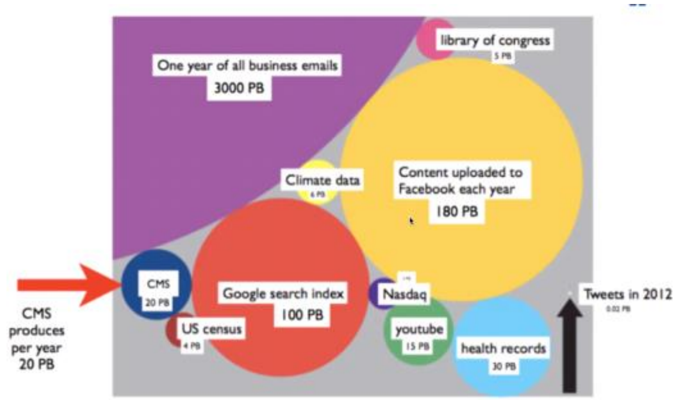


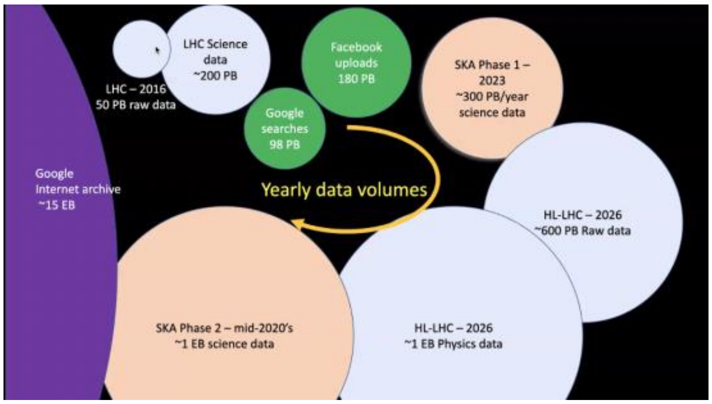
World wide network of centers

• > 60 centers

~ 120,000 cores!



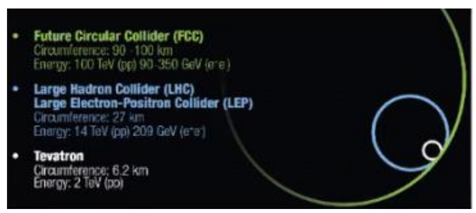




(extreme jump in raw data, up to 1000 petabytes, or 1 exobytes, 1/15 th of google internet archives)

Future Experiments

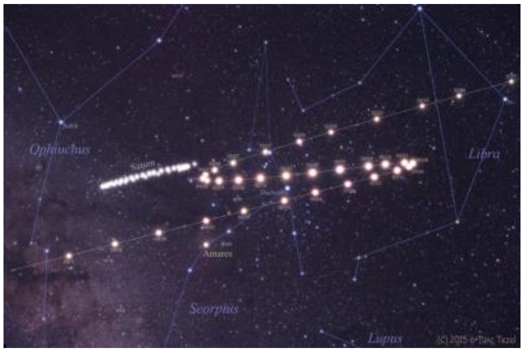
- Future Circular Colliders (FCC)
- Future Linear Colliders (FLC)
- New types of accelerators
  - muon collider
  - plasma wakefield accelerators
    - → i.e. Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE - CERN, Switzerland) or the FACET facility at SLAC

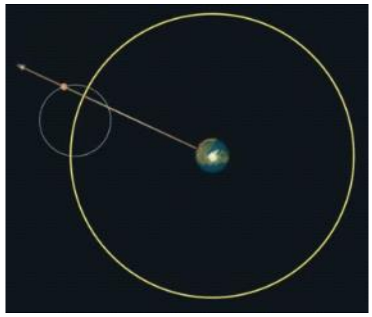


Day 9 Lecture - Galactic Astrophysics and Cosmology

Saturday, March 20, 2021 9:00 AM

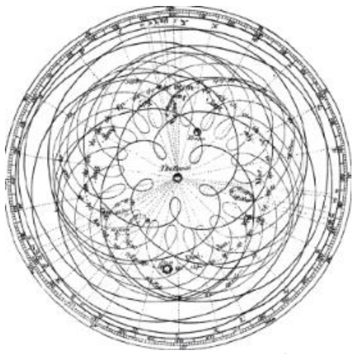
Some planents move linearly (Saturn) and others move in a retrograde motion.



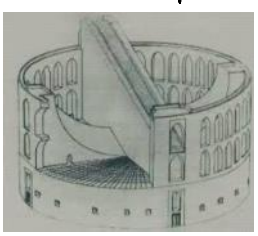


Ptolemaic Epicycles

- Ptolemaic Universe
  - all motion is circular
  - complex retrograde motion



- Intervening Years (2nd to 16th century)



→ observatory (Samarkand) over 1000 stars

Kepler and Newton

- Kepler (1609) measures distances in 3 dimensions of ellipses

- Newton (1687) circular motion /elliptical motion;

$$\frac{T^2}{a^3} = \frac{4\pi^2}{G(M_1+M_2)}$$

force; if the strength of that force is proportional to the mass of the attractor, that leads to an inverse-square law force

$$F/m = a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2} = \frac{4\pi^2}{r^2 C_{sun}}$$

→ gives us an actual scale of the solar system

Enlightenment Universe

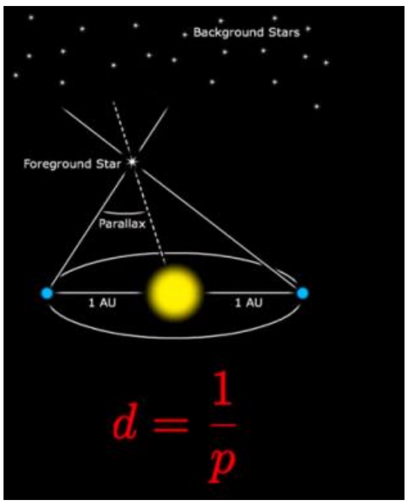
- Explanation of periodicities of comets due to orbits

- Comet hunters also start to observe stars and other 'nebulae'
- Messier catalogs 110 bright nebulae (1781)
- Bessel infers that many stars exist in binary systems due to odd motion on the sky (1844)
- Parsons notes that some of Messier's objects appear to be rotating clouds (1845)

Mapping Stellar Distributions

- Kant and Wright – If solar system is gravitationally supported, it is a disk
- Hershel – density of stars is constant

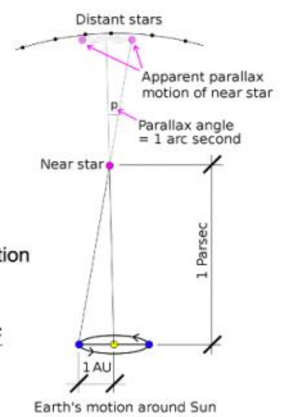
Parallax



$$\frac{1AU}{d} = \tan(p)$$
$$\approx p + \frac{1}{3}p^3 + O(p^5)$$
$$\rightarrow d = \frac{1AU}{p}$$

If angle is less than ~10 degrees, we can make a 'small angle' approximation and get this simple relationship

$$1AU * 1.58 * 10^{-5}\,\frac{\text{ly}}{\text{AU}} * 206265\,\frac{\text{arcsec}}{\text{rad}}$$
$$= 3.25\,\frac{\text{ly}}{\text{arcsec}} = 1\,\frac{\text{pc}}{\text{arcsec}}$$



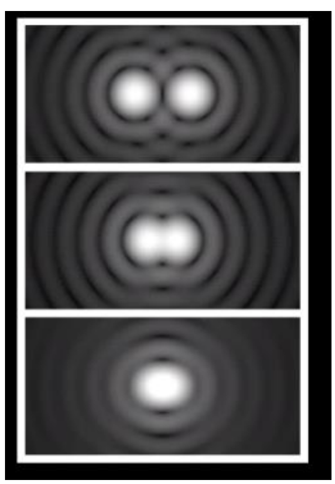
How far does this work? [Essentially an Optics Problem]

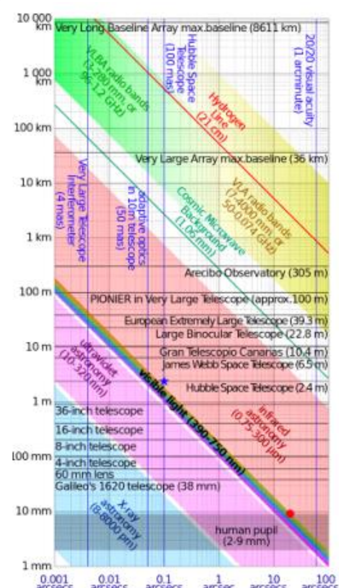
Parallax is limited

- Angular resolution

$$\theta = 1.220\frac{\lambda}{D}$$

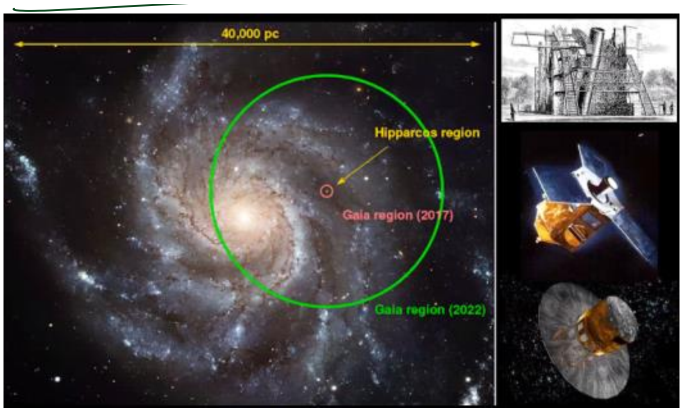
- Atmospheric distortion
- Collection Area
- Sensor sensitivity





Space Telescope

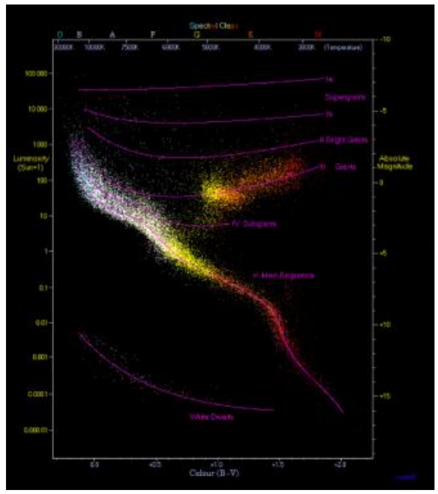
–Uses the Earth-Sun distance as an apparature for a



- Uses the Earth-Sun distance as an apparature for a telescope
- Very technically challenging

Stellar Physics

- We have distances, and we plot absolute brightness
  - Brightness comes from color correction



Physics of Stars

- self sustaining explosions
- convective heat transfer
- hydrogen based

Star Formation

a protostar

forms density pockets from gas

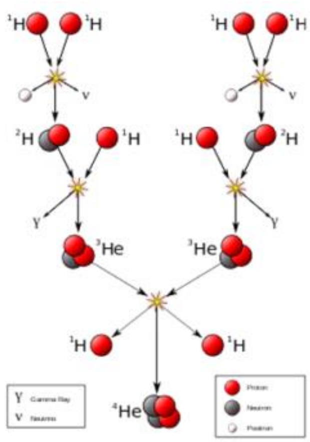
2 stars

(orbiting bodies usually are not stars because of centrifugal force and outward pressure of graphs - brown dwarfs)

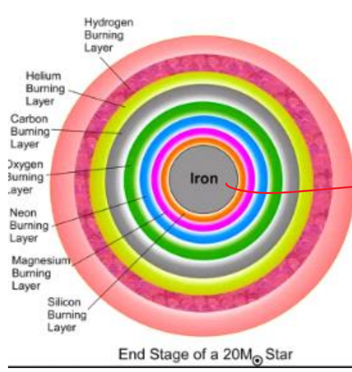
Each frame ~ 100,000 years

Fusion Processes

- Hydrogen Burning
  - PP Chain - turning hydrogen into Deuterium and Helium
    - 4H -> 1 He



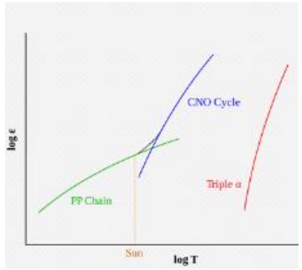
- I, II, III cycle (using brilium and lithium)
- CNO cycle, once enough carbon, it is a catylist to generate nitrogen, oxygen, and helium
- Helium burning
  - Triple Alpha Process
- Heavy Element Fusion [more heavy = less efficient]



End Stage of a 20M$_\odot$ Star

Iron = 'star poison'

- Rate of fusion goes as the core temperature of the star
- Larger stars require more outward pressure to balance gravity, and their cores heat up to get higher fusion rates
  - Higher fusion rates burn fuel much faster
- Rates of fusion are exponentially related to core temperature, so high mass stars are incredibly unstable!
- If a gas cloud collapses but can't heat its core enough, it won't become a main sequence star
  - These are called brown dwarves, but if they orbit a star, they're often called 'super jupiters'
  - Jupiter is actually more massive than some of the smallest brown dwarf stars



HR diagram gives us a Mass-Luminosity relation:

$$L \propto M^{\beta}, \beta \in [3,5]$$

Stars support themselves through radiation, which is sustained through fusion. Lifetime related to amount of fuel:

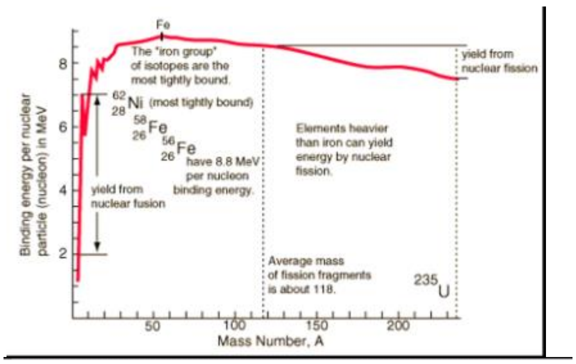
$$T_{MS} \propto \frac{M_H}{L} \propto \frac{M}{L} = M^{1-\beta}$$

Luminosity is related to temp

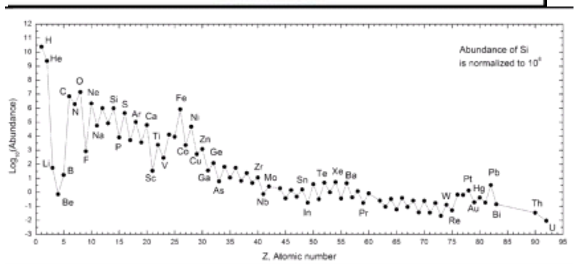
Mass is related to lifetime

Star Death

- If we go right to iron, stars lose energy
- Heavier elements are made in super novae

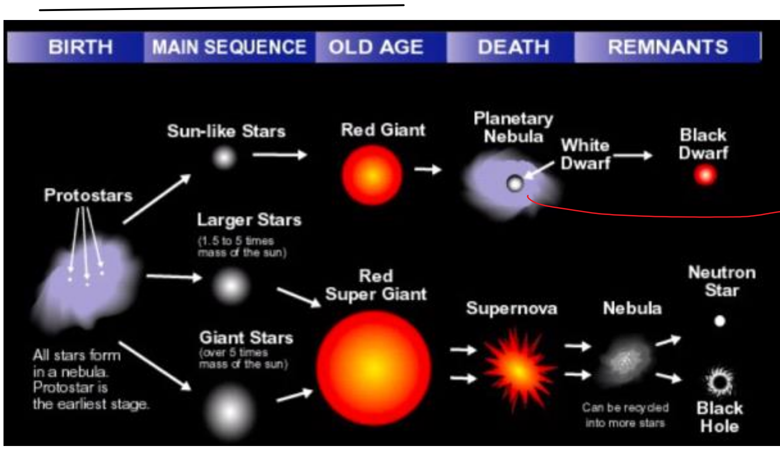


- We can see the effects of fusion cycles and supernova nucleosynthesis in atomic abundance data; multiples of 4 much more common due to alpha ladder processes.



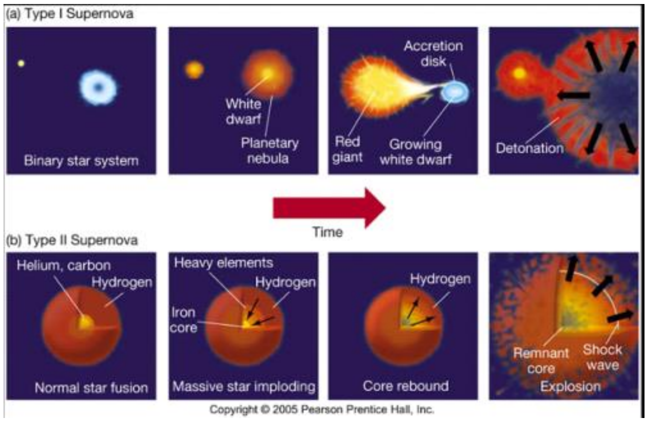
- However, lithium, being light is very rare.

Stellar Evolution



a chunk of highly dense oxygen/carbon (called 'celestial diamonds')

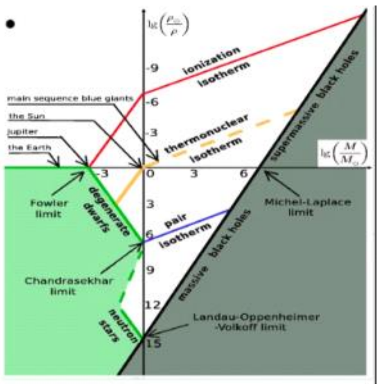
Supernovae



→ white dwarf accretes gas, causing the star to detonate

→ star implodes; generates a shockwave that destroys the star

Stellar End Stages

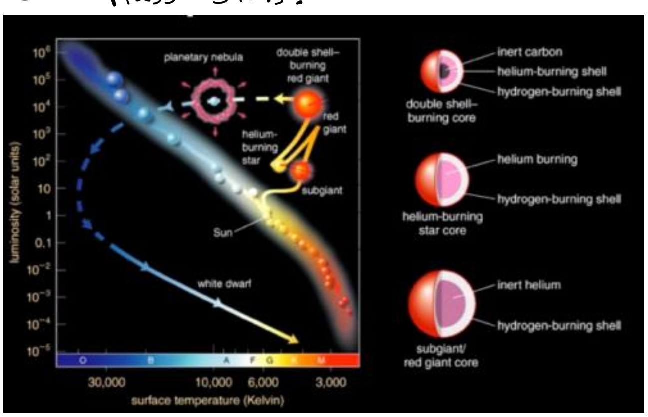


- Mass determines how a star will end its life
- White dwarf stars are supported by electron repulsion (electron-degeneracy pressure)
  - Chandrasekhar mass is the maximum mass that this pressure can support
- Neutron stars occur when electrons and protons combine above the Chandrasekhar mass, supported by neutron degeneracy pressure
  - Landau-Oppenheimer limit is the larger mass supportable by neutron pressure
- Black holes have no minimum or maximum mass; if mass is compressed within the event horizon, a black hole will result.

Schwarzchild radius → $r_s = \frac{2GM}{c^2}$

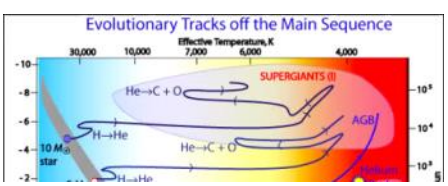
Main Sequence Evolution

Low Mass Stars:



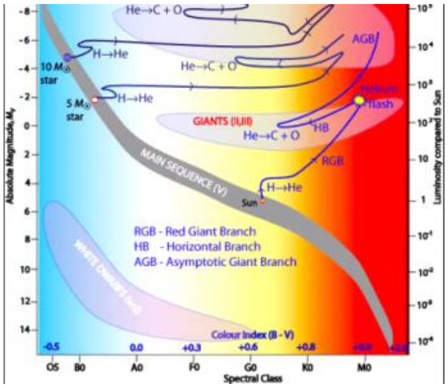
Higher Mass Stars

- More fusion phases, shorter lifetime, more active life cycle.
- End stage not on HR diagram because neither



active life cycle.

- End stage not on HR diagram because neither neutron stars nor black holes are luminous
- As you go further up the main sequence, it becomes less stable; lifetime of stars is almost too short for them to settle to the main sequence



- most likely explodes into supernovae or collapses into neutron stars

Cepheids Variable Stars

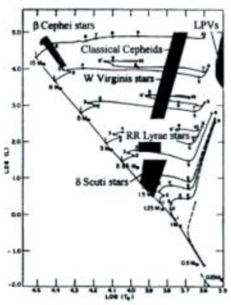
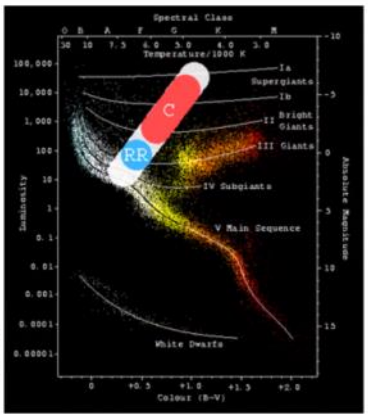
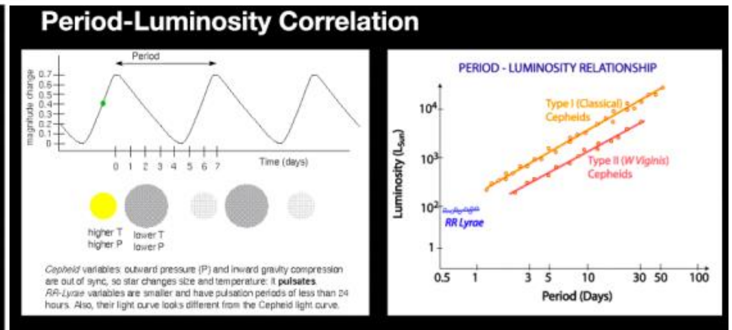
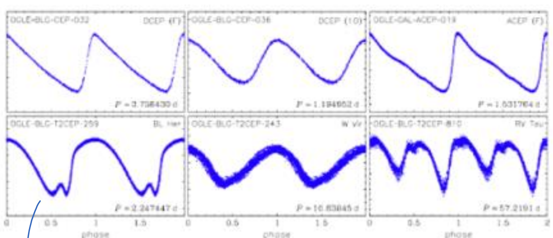


Figure 14.6 Pulsating stars on the H–R diagram. The evolutionary tracks are incomplete, and those of the lower-mass stars extend into the LPV (long-period variable) region. (The evolutionary tracks are from Iben, *Annu. Rev. Astron. Astrophys.*, *5*, 571, 1967. Reproduced with permission from the *Annual Review of Astronomy and Astrophysics*, Volume 5, ©1967 by Annual Reviews Inc.)





- High mass are unstable, they overheat and cool off in a deterministic way



→ Now can actually measure absolute luminosity

→ can tell distance by actual luminosity vs observed

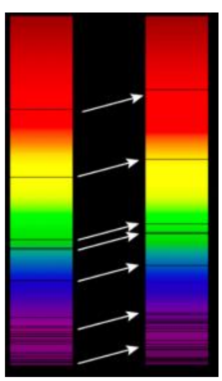
2 different fusion cycles

Redshift

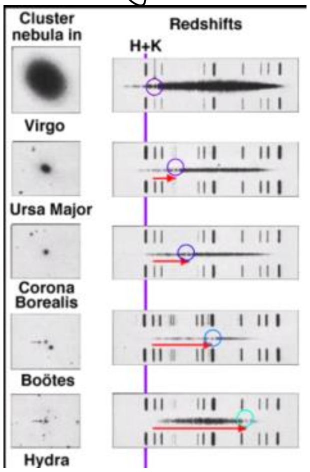
Measuring radial velocity

- Relative shifts in an entire spectrum as used to measure radial velocity of objects

$$1 + z = \frac{\lambda_r}{\lambda_s} = \sqrt{\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}}} \approx \frac{v}{c} (v << c)$$



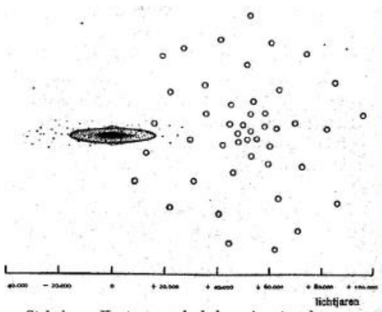
Galaxy Rotation Curves



- Vesto Slipher (1914) uses this new observational tool to show that the 'nebulae' seen in earlier star catalogs have very peculiar properties
- The nebulae seem all to be receding at a high radial velocity from the solar system
- The majority of them can also be shown to be rotating. The magnitude of the rotation implies that, if they're bound by gravity, they must be very large.
- More evidence, including observation of faint novas in these objects, suggests an extragalactic origin.

Curtis Vs. Shapely

- Meanwhile, Harlow Shapley used cepheid variable stars to measure the distance to 93 globular clusters, finding that they were centered on a distant point 15 kpc from the sun (1915-1919).
- These measurements, among others led to the 'Great Debate' in 1920 between Shapley, who argued that there was only one galaxy, and those studying nebulae, led by Heber Curtis, who advocated for Kapteyn's galaxy model and a multi-galaxy universe.
- Both were right and wrong; Shapley was right about the scale of the galaxy, and Curtis was right about the fact that the many observed nebulae are extragalactic objects.



Stelsel van Kapteyn en de bolvormige sterrehoopen

- Both were wrong about Sun being center of universe

Hubble Expansion

- For a group of nebulae, hubble measured both redshift *and* distance, using variable stars.
- He showed that the proper motion was correlated with distance, and that all of the nebulae in his sample were much further away than Shapley's globular clusters
- Hubble's primary finding implies that the universe is expanding; this is one of the main empirical observations that gave birth to the field of cosmology, the study of the evolution of the universe
  - Only a few years earlier, Einstein had introduced a 'cosmological constant' to general relativity to enforce a static universe…so this was a novel idea

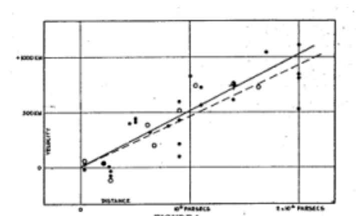
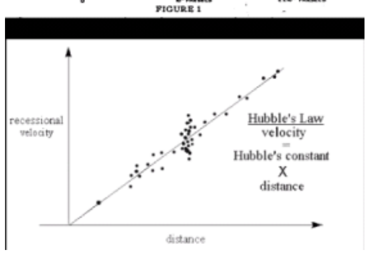
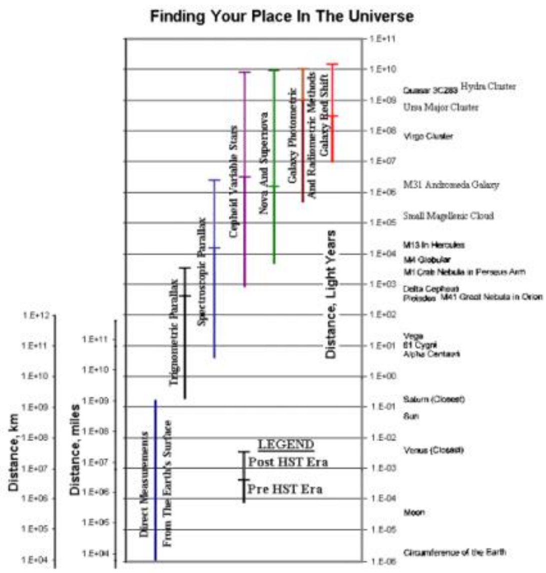
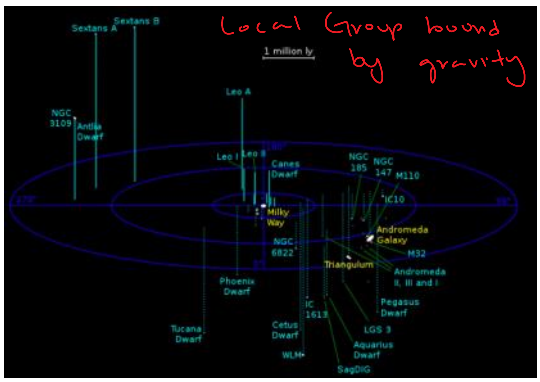
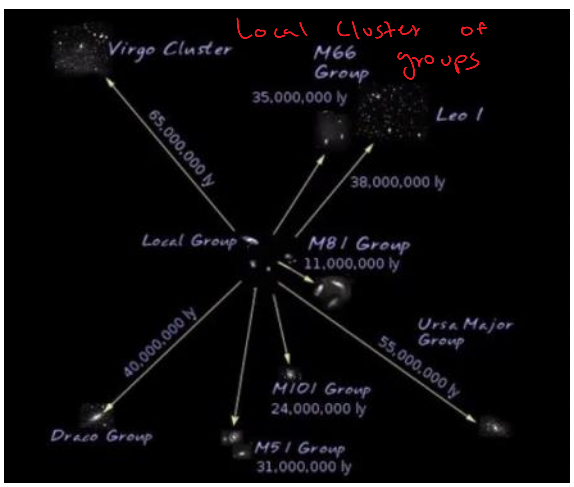


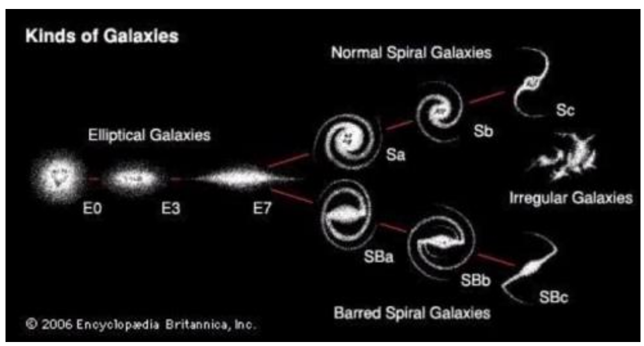
FIGURE 1











Dark Matter / Cosmology

The Virial Theorem

Mapping out Gravitational Potential

- The Virial theorem is a very general result, which relates the average kinetic energy to the potential which governs a closed system.
- For a *dispersion* supported system (highly elliptical orbits), velocity isn't constant. Mass can be inferred from the variance of the measured velocities.
- Some variability depending on degree of ellipticity but good to O(1) factors.

$$\langle KE\rangle = -\frac{1}{2}\sum\langle F\cdot r\rangle$$

$$2\langle KE\rangle = -\langle V\rangle$$

$$\langle V\rangle \approx -\alpha\frac{GM_{tot}m_p}{R}$$

$$KE = \frac{3}{2}m_p\sigma_v^2$$

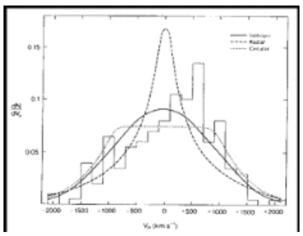
$$\sigma_v^2 = \frac{\alpha}{3}\frac{GM_{tot}}{R}$$

→ relate dispersion and velocity to mass and R

→ If we plug in planetary bodies, we get Kepler's Laws

Coma Cluster (1938)

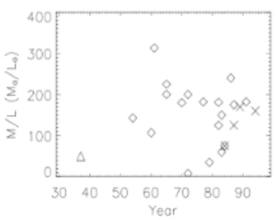
- If we use the virial theorem as Zwicky did, and compare to the absolute luminosity using the redshift measurements from Hubble, we find masses way heavier than you would expect from stars alone.



- Main sequence from part 1 gives us the relation

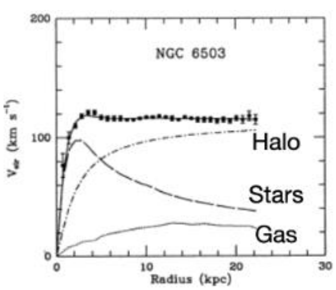
$$\frac{M_{star}}{L_{star}} = \frac{M_{sun}}{L_{sun}}\left(\frac{M_{sun}}{M_{star}}\right)^{2.5} = \frac{M_{sun}}{L_{sun}}\left(\frac{L_{sun}}{L_{star}}\right)^{5/7}$$

- To get such large M/L ratios, you can't use stars!
- M/L has only gone up with improved observation techniques



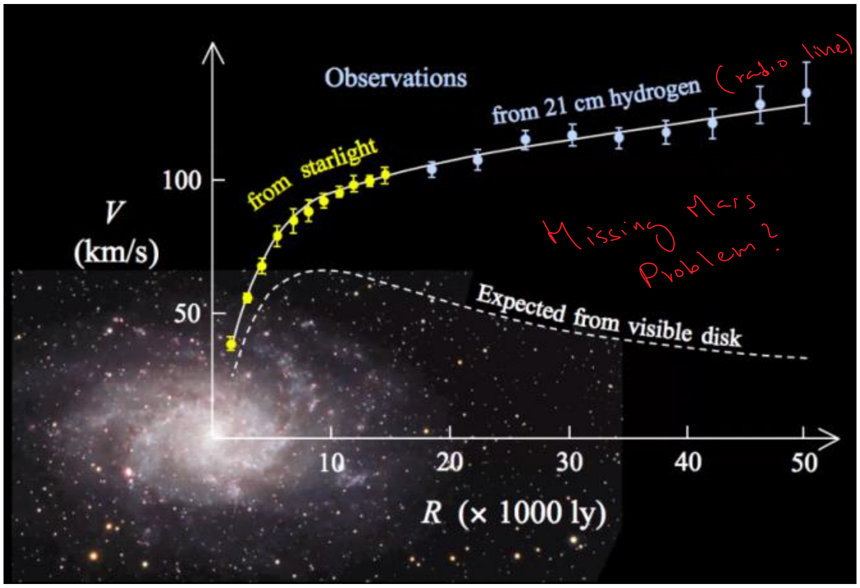
M/L ratio of stars should be roughly 1 → 6

But Coma Cluster has 50:1 (modern estimation is 200:1)



$$M(R) = \frac{v_{flat}^2}{\alpha G}R \approx \frac{3v_{flat}^2 R}{2G}$$

- Higher quality rotation curves showed that there is a strong radial dependence to the orbits of spiral galaxies
- Again using a virial theorem argument, we can see that this implies a total mass component that increases at high radius, while the star light decreases.
- Using radio emission from gas allows us to also account for the gaseous component; that does extend further, but is not sufficient to explain the mass discrepancy

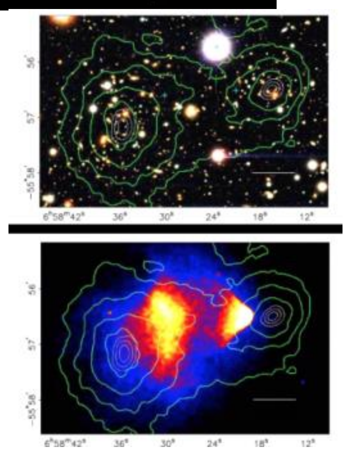


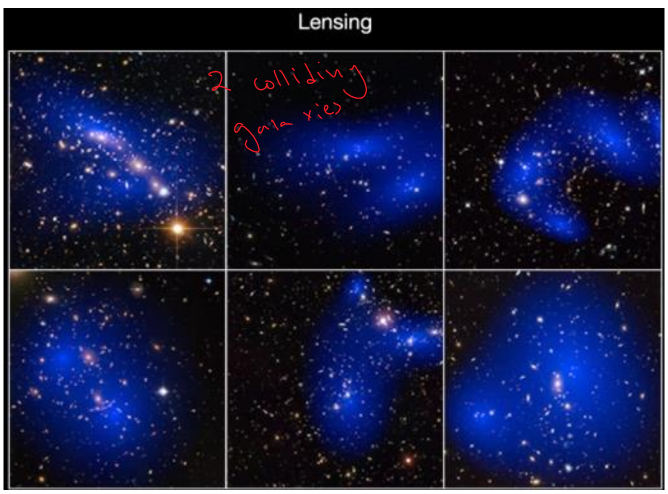
Summary of Dark Matter:

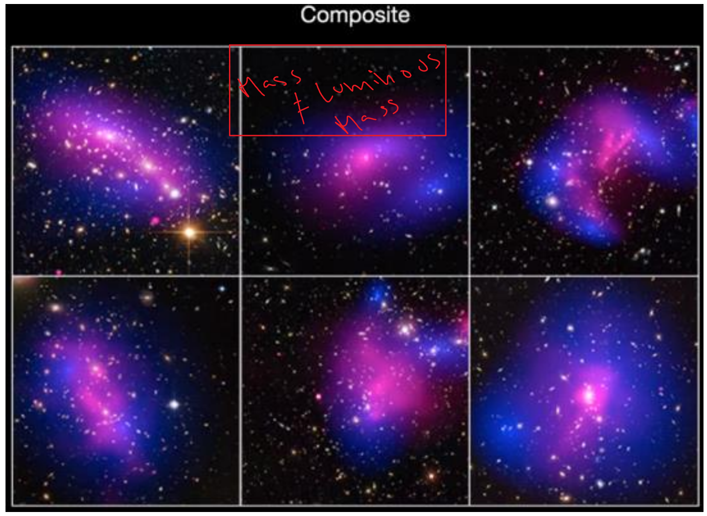
- Galaxy clusters have M/L ratios far in excess of stellar populations, which can't be accouted for by gas or known compact objects; known since ~1930
- Galaxies have a missing mass problem that is worse further from the galactic center, and is anti correlated with stellar population; known since ~1970
- All of the evidence so far might be explained by a misunderstanding of gravity:
  - Virial arguments assume a Newtonian potential for gravity that follows a 1/R^2 force law.
  - At high enough radii, the inferred mass density becomes very small, and galaxies aren't gravitationally bound
  - At small radii (solar systems and local galactic scales) we know gravity works pretty well
- For a decade or two, Modified Newtonian Dynamics (MOND), or alternative gravitational theories, were considered seriously by the scientific community
  - It is hard to swallow these theories, since they violate energy conservation, and are non-local theories…that's a discussion for another day, because…

$$M_{lens} = \frac{c^2 d \tan(\theta_{obs})\,(\pi - 2\theta_{obs})}{4G}$$

→ looking at map of mass density, the missing mass is far from the luminous mass







Estimation of DM (Locally)

$$4\pi G\rho = \nabla^2\Phi = \frac{\partial^2\Phi}{\partial z^2} + \frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial\Phi}{\partial R}\right)$$

$$\rho(R,z) \approx \rho(R_{sun})\exp(-z/z_0),$$

$$4\pi G\rho \approx \frac{\partial^2\Phi}{\partial z^2}$$

$$4\pi G\Sigma(z_{max}) \approx \frac{d\Phi}{dz} = -F_z(z_{max})$$

$$\rho_{dm}(z_{max}) = \frac{\Sigma(z_{max}) - \Sigma_b(z_{max})}{2z_{max}}$$

→ can actually infer local DM density by measuring stellar motion

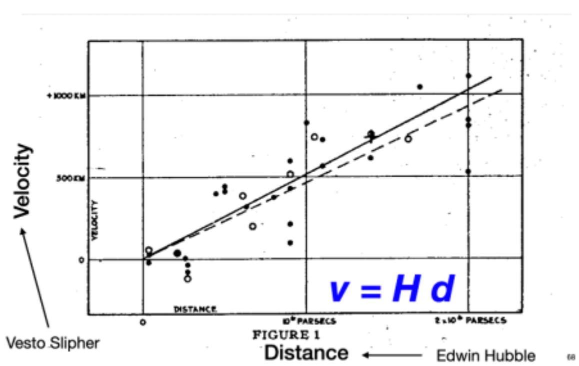
- We have a poisson equation for gravity (similar to Maxwell's equations for E&M) that tells us how the gravitational potential relates to the mass density

→ tracked by as a function of time

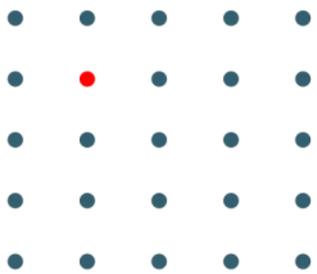
Estimation of DM ≈ 0.3 GeV per cm^3, constant everywhere as DM does not interact

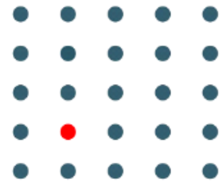
Big Bang Cosmology

Hubble's Law



Thought Experiment





→ No real sense of center!

$$ds^2 = -c^2dt^2 + a^2(t)(dx^2 + dy^2 + dz^2)$$

scale factor: "length" of grid line
(1 = today, 0 = beginning)

Friedman Equation

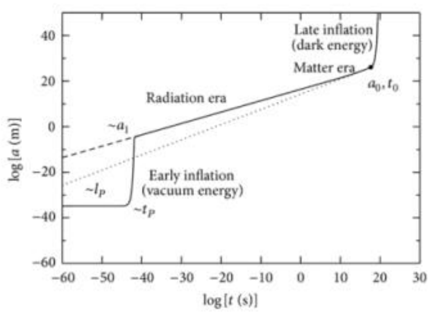
$$\left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi G}{3}\rho$$

energy density

rate of change in scale factor

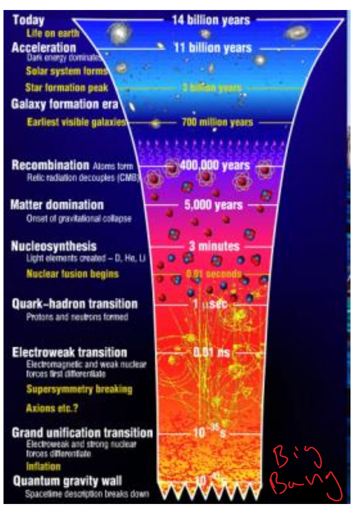
Solutions to Friedman Equation

- Matter-dominated universe:
  $\rho_{\text{mat}} \propto a^{-3}$ $\quad a \propto t^{2/3}$
- Radiation-dominated universe:
  $\rho_{\text{rad}} \propto a^{-4}$ $\quad a \propto t^{1/2}$
- Dark-energy-dominated universe:
  $\rho_{\text{DE}} \propto \text{constant}$ $\quad a \propto \exp Ht$



↳ DM and DE ↑ as DM is constant per cm^3

- Keep rewinding, and universe must have started out at a poin — Big Bang
- At early times, universe must have been much hotter and denser
- **Idea 1:** Use our knowledge of high-energy physics + observation to learn about history
- **Idea 2:** Use observations to learn about new fundamental physics



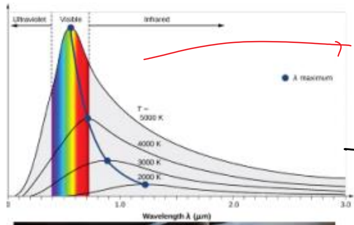
Cosmic Microwave Background

- At early times, nearly all

→ should be . red

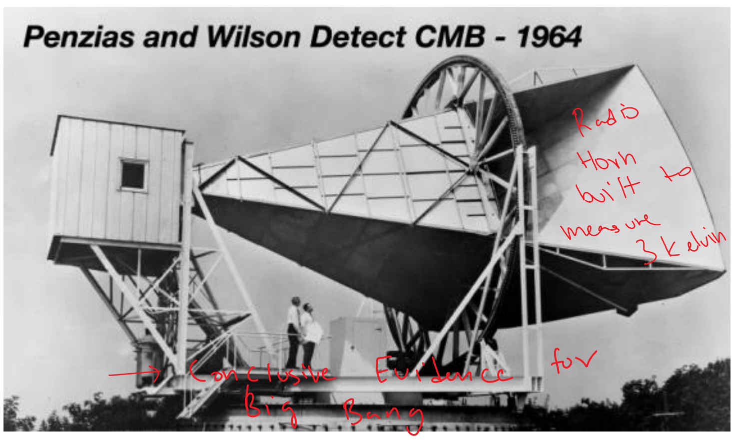
Cosmic Microwave Background

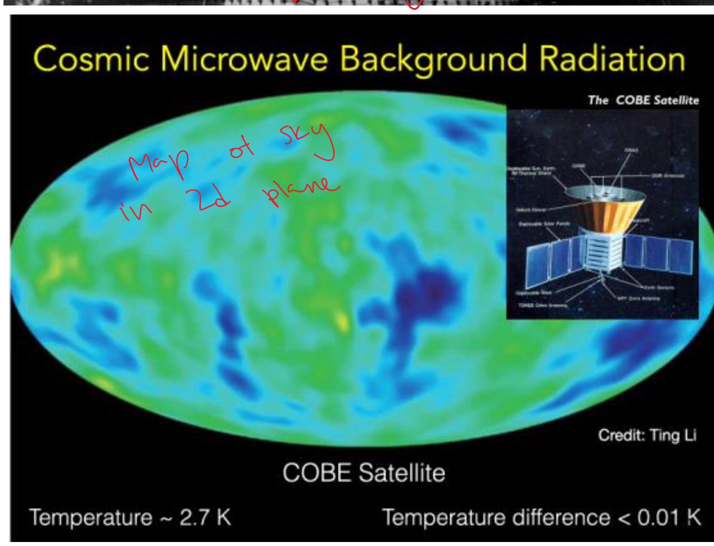
- At early times, nearly all matter is a plasma of free protons, electrons, and photons
- Universe should be filled with CMB "light" left over from recombination
- Because of expansion of universe, light (aka "radiation") is redshifted to ~3K or 160 GHz = microwaves
- Look for irreducible background of microwave radiation
- "Blackbody" radiation

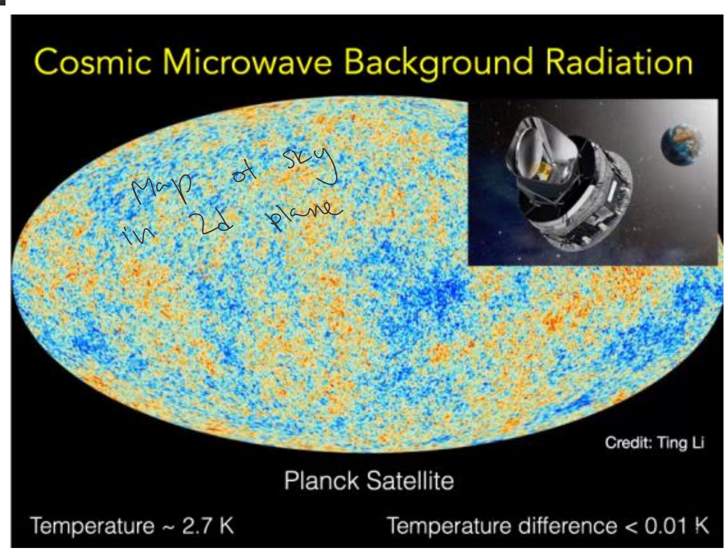


→ should be highly redshifted

→ all radio waves

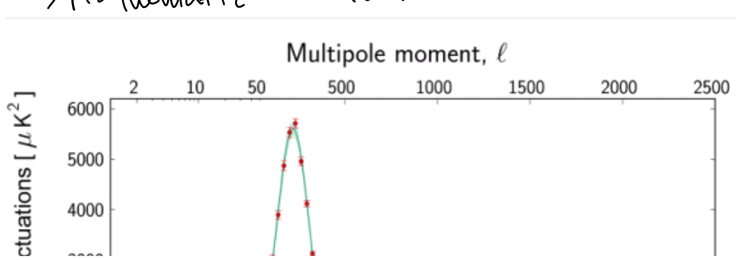






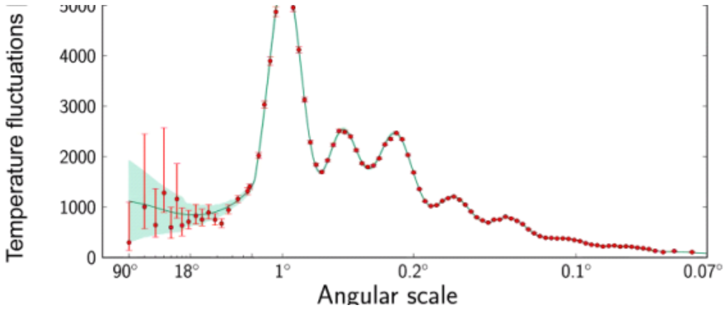
- Fluctuations are the beginnings of structure, galaxies, stars
- ***Typical*** *Angular size* (how "wide") and *amplitude* (how red or blue) determined by matter and energy content of the universe

→ Mathematical Convolution

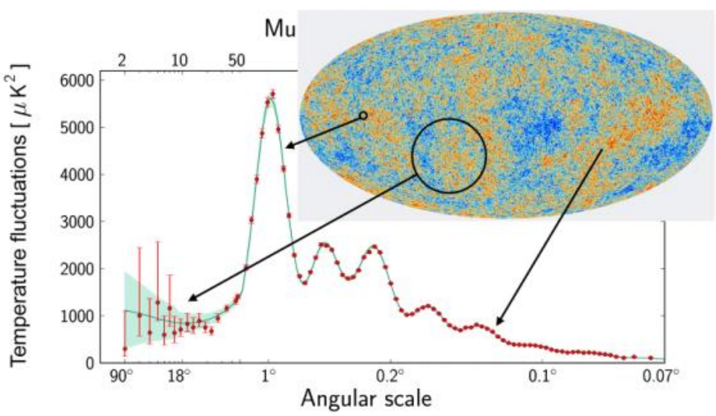


and energy content of the universe

- Exact pattern of fluctuations is ***random***
- ***How do we compare with theory?***

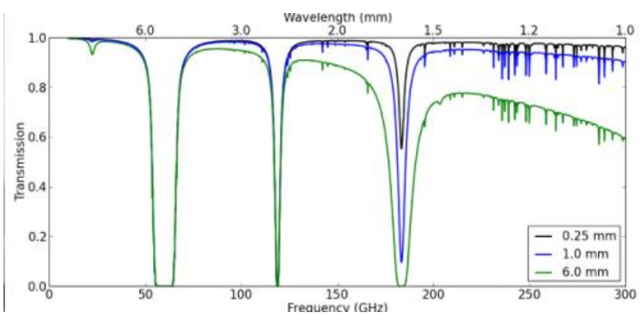


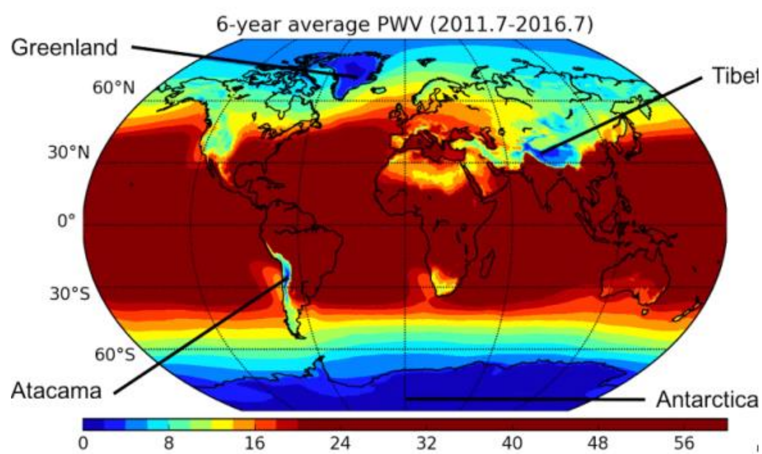
→ so changing varionic matter can change scale factor to form power spectrum



Model fit to data is perfect to estimitations

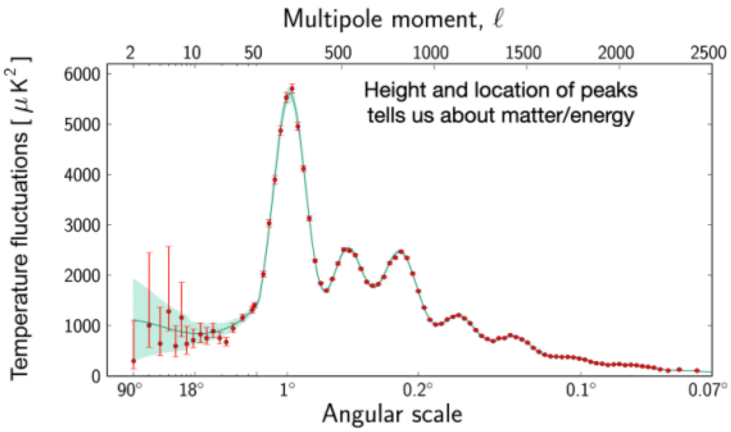
Water absorbs Radiation, so dry places are best

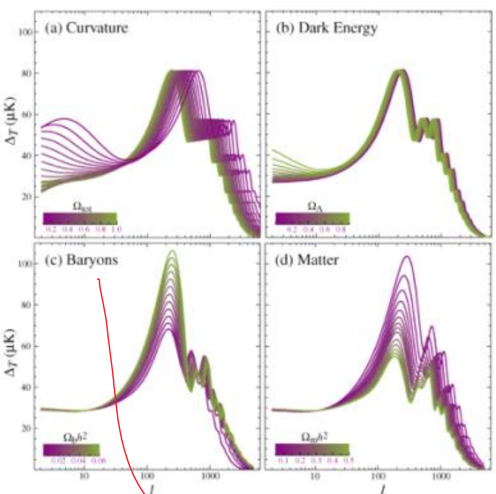




Telescopes

- Large mirror = high resolution, but expensive
- Small refractor = low resolution, but cheap

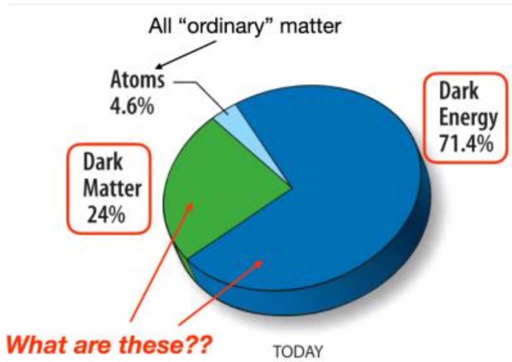




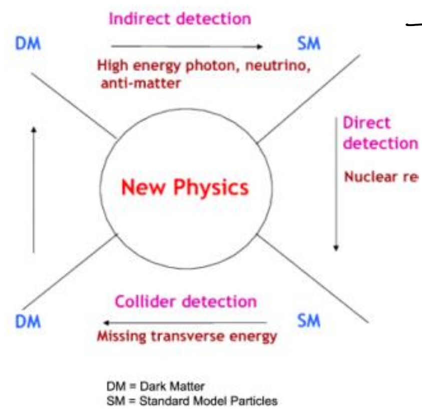
these power structures come from fluid dynamics

Dark matter = Matter - Baryons

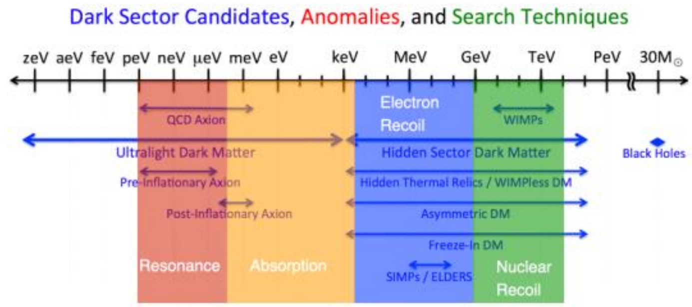
Modern Standard Cosmological Model



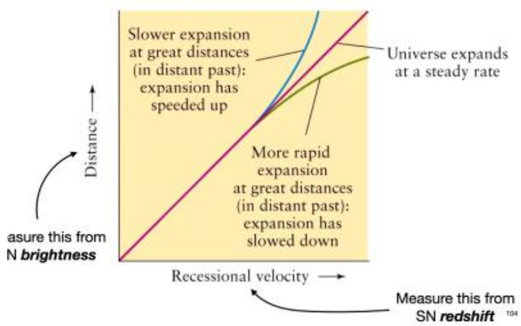
→ mostly DM is very large as space expands and DM is constant at k GeV per cm^3

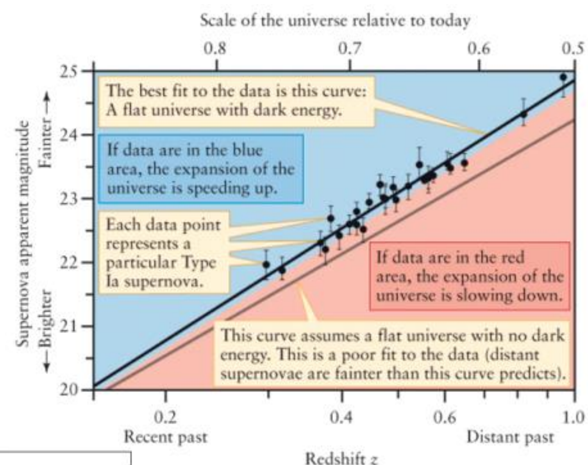


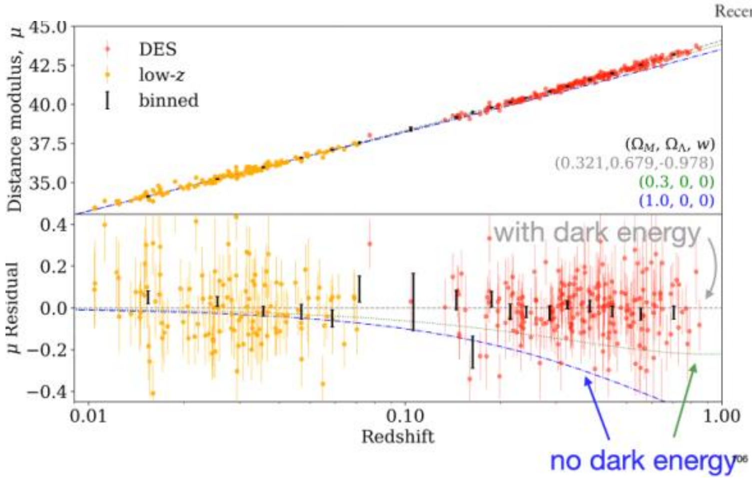
→ if we assume DM is a particle, then particle physics can be used to annihilate multiple particles



Measuring Acceleration of Hubble Expansion







Parametizing Dark Matter as

Ω_Λ

Dark Energy?

- DE causes universe to expand
- Cosmological constant?
- Modified gravity that introduces vacuum energy?

Day 10 Lecture - Energy and Long Term Hydrodynamical Flows on an Ideal Planet

Saturday, March 27, 2021 9:15 AM

$W = \vec{F} \cdot \vec{d} \rightarrow \underbrace{\text{negative mechanical work}}_{W = -\Delta U} \Rightarrow$ potential energy

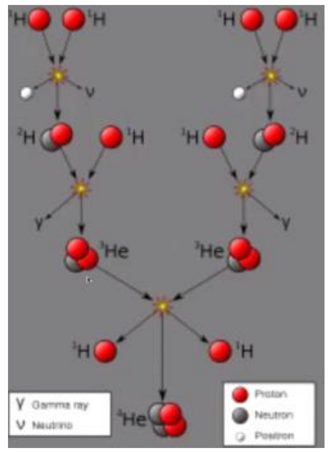
→ There are multiple types of

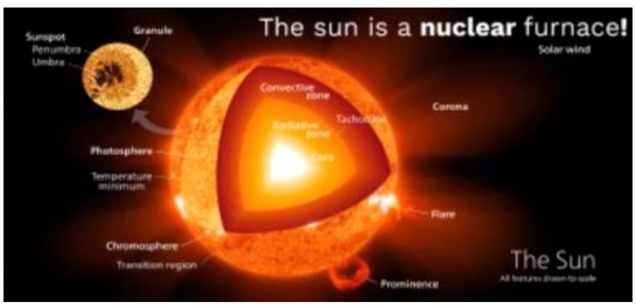
mech
- electric
- gravitational
- chem
- ionization

- thermal
- nuclear
- chromodynamic
- elastic
- radiant
- rest

How does the sun make energy?

- interstellar hydrogen condenses into a star because of gravity
- a nuclear furnace





Gravitational energy converts nuclear energy to thermal energy.

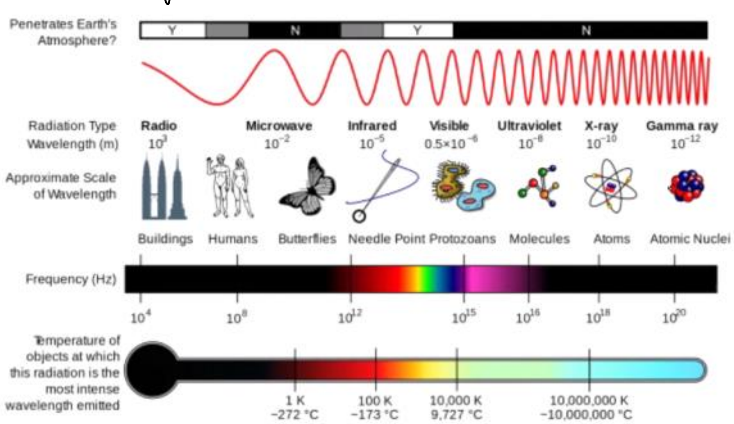
Heat transfer

Conduction - surface to solid fluid

Convection - from a surface to moving fluid

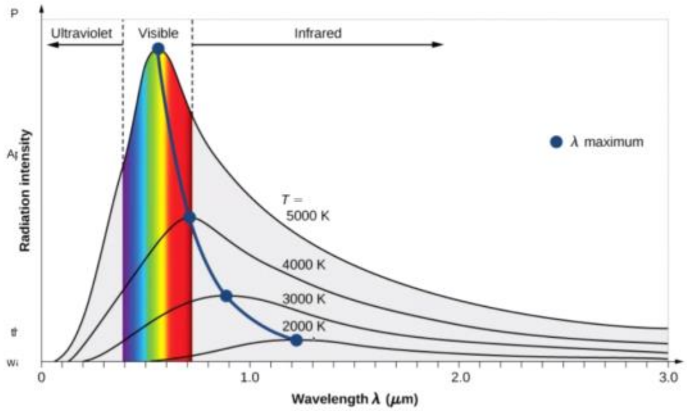
Radiation - heat exchange - majority of radiation is electromagnetic

So Energy, wavelength and wavelength is related in a photon



- once an object is heated enough, it emitts black-body radiation:

- once an object is heated enough, it emitts black-body radiation:



if heat ↑, the energy of photons ↑ and the amount of photons ↑

Amount of light from sun to earth ~ $\frac{1}{4}$ of total ~ 342 Watts per m^2

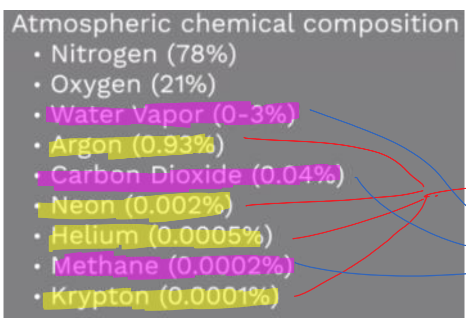
$P = A\sigma T^4$ → temp just from sunlight ≈ -16.417 → which is very cold

But Earth has atmosphere, so earth also acts like a black body object

So Greenhouse effect ⇒ ≈ 14 C / 57 F on average

Atmospheric Composition

- there are 5 different sections with different pressure, temp, and chemical composition

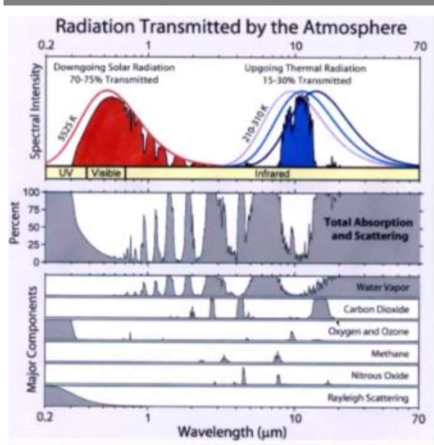


→ How do the trace gasses cause the greenhouse effect?

→ Trace gasses

'Dangerous Gasses'

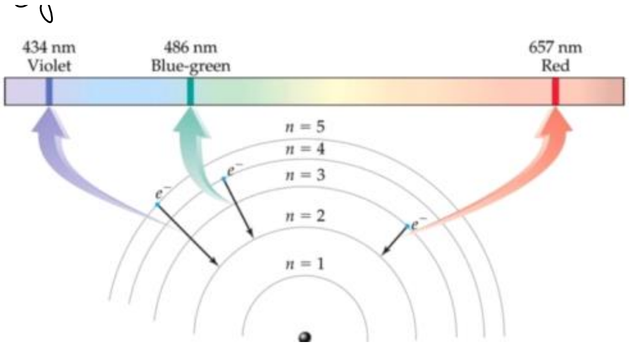
Water Vapor, CO_2, methane



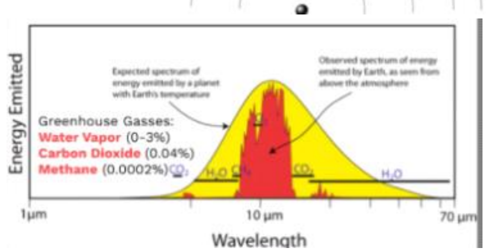
Although WV absorbs more IR radiation, the energy balance already exists with WV levels, but CO_2 ↑ = bad.

Light color corresponds to a certain wavelength.

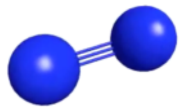
→ Bohr model of ... atom



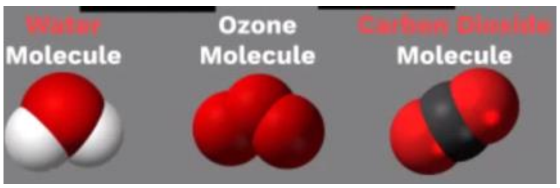
→ Bohr model of a hydrogen atom



→ Greenhouse gasses → atoms connected like a spring → and the vibrational modes absorb light, like hydrogen!

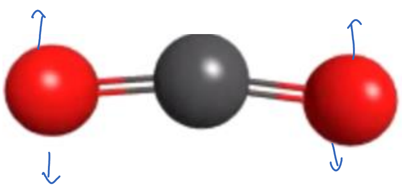


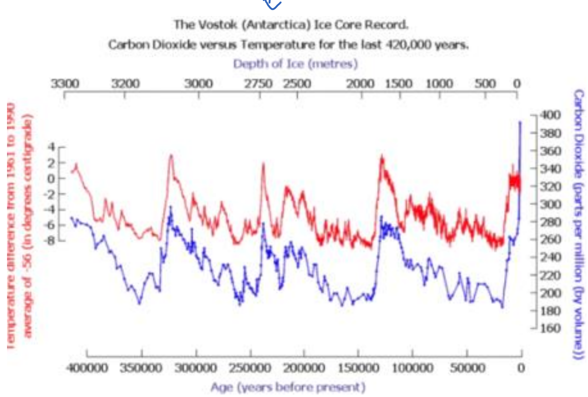
→ O_2, doesn't vibrate 'badly'



→ specific molecular geometries absorb IR

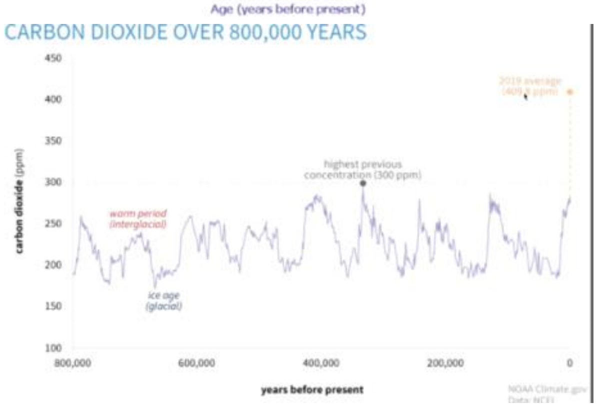
Ex → CO_2 outer planar vibration



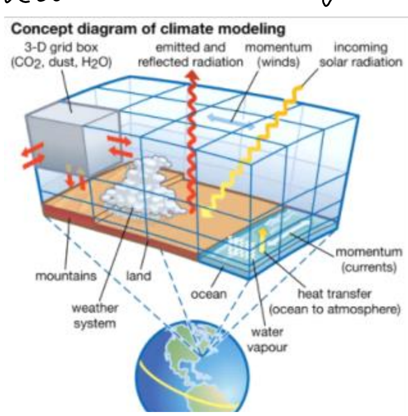


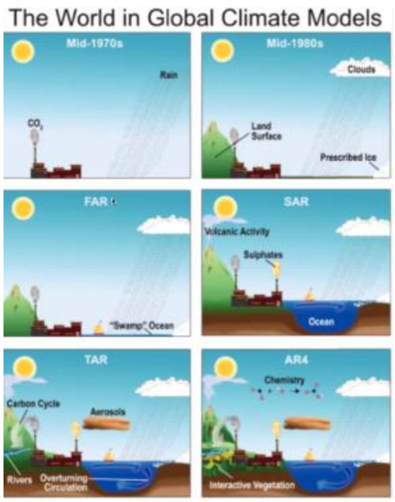
→ Temp graph derived by observing radioactive isotopes of oxygen

Large changes in temperature cannot be explained without carbon dioxide



→ Today's concentration of CO_2 is about 37% higher than ever



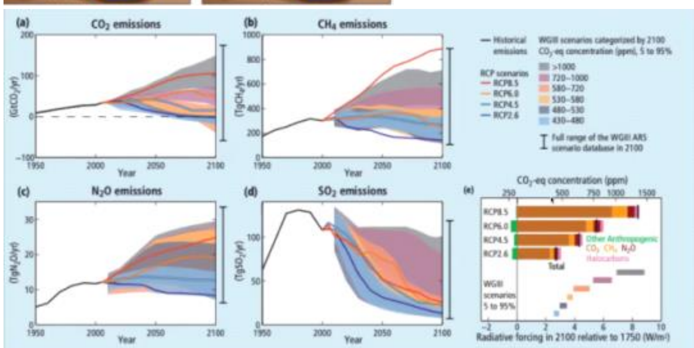


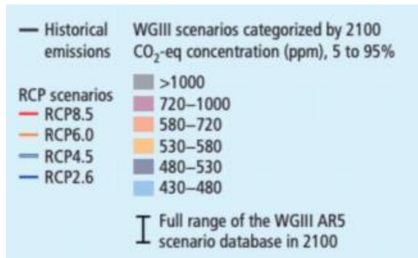
The **radiative forcing** from Carbon dioxide affects more than just the atmosphere!

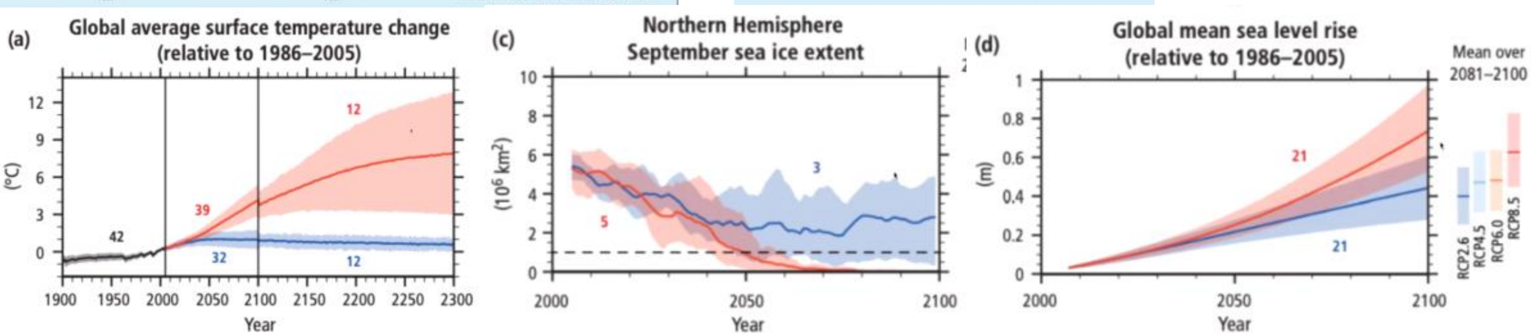
Also important to simulate **atmospheric effects** and **feedbacks** from land, ocean, and ice among a number of different **dynamical** effects!

→ Modeling by RCPs

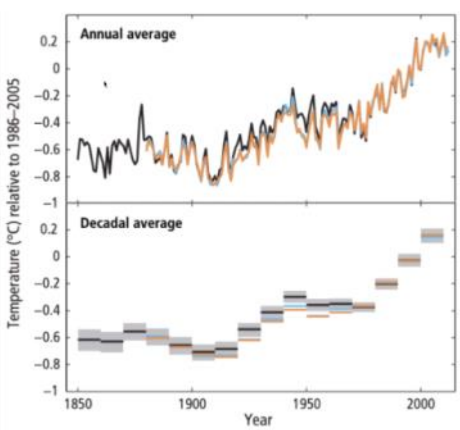
we can simulate different concentrations of GHG and other

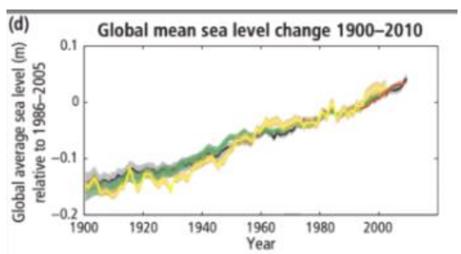






and predictions compared to observations are very accurate





Sea surface changes are driven by a warming ocean

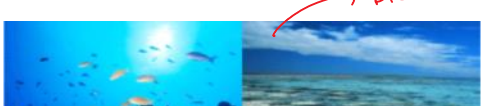
Liquid water expands as it warms

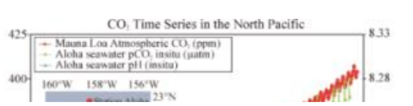
Sea level has already risen about 20 cm since 1900...

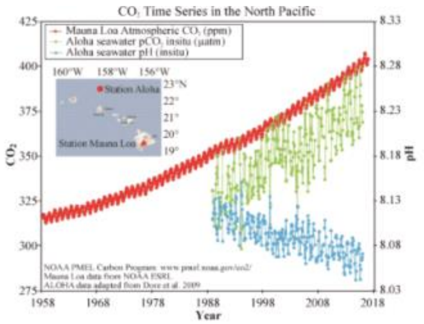
→ sea level rose more in the past 20 yrs than in the last 70 millenia!

warm water also absorbs more CO_2, which leads to ↓ph so more acidity.

→ bleaching Great Barrier Reef

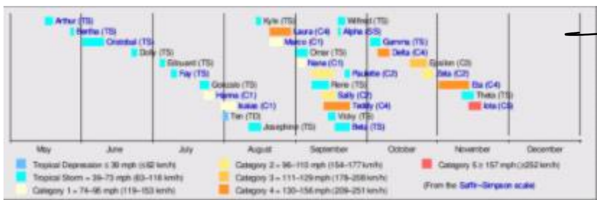




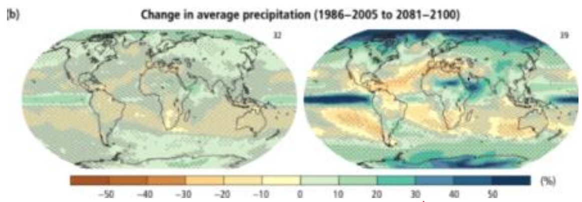


Weather Extremes

In 2005, Katrina cost the US about \$161,000,600,000, and damaged ~ 650,000 homes



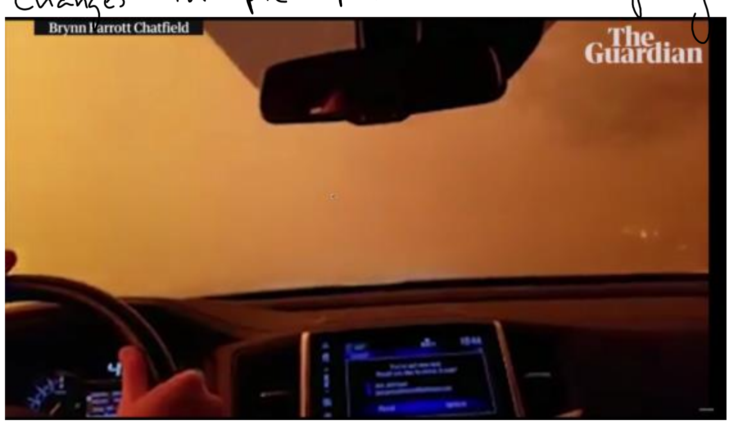
→ 2020 had the most active hurricane season

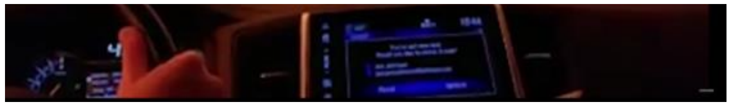


Even without giant storms, precipitation events went up.

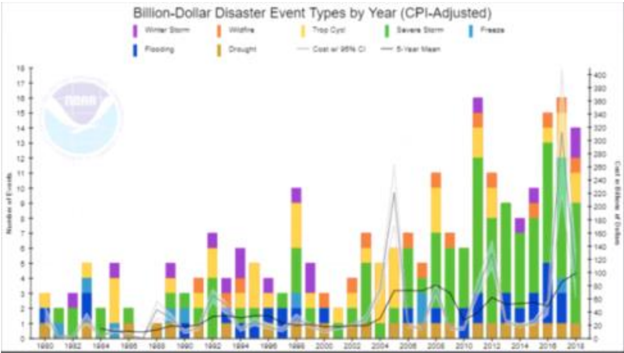
→ Polar Vortex in Chicago 2020! Temps of −22°F sustained for days, weeks on end.

- Changes in precipitation are highly local

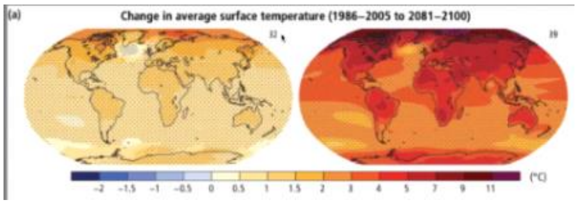




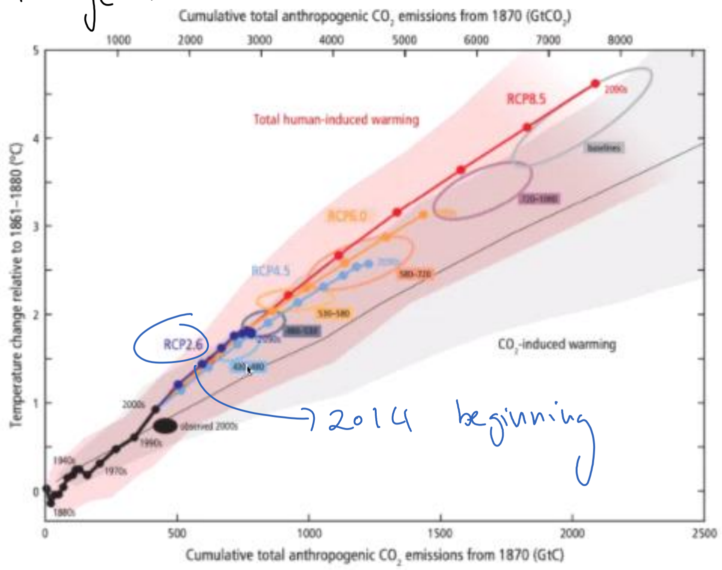
Drought and high temp in California led to longest continuos wildfire in history



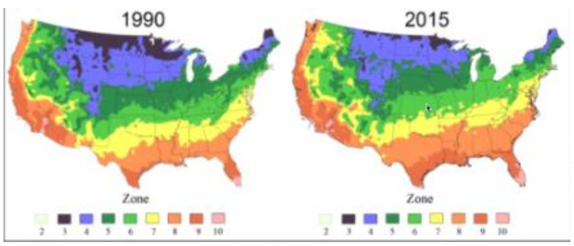
– Weather based disasters have became more frequent and more costly in the last 40 years.



Annual Artic Sea Ice is at a minimum.



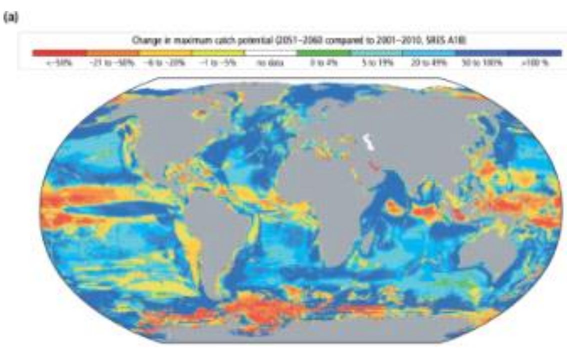
2014 beginning



In the Mid-Latitudes, we can see the effects of a warmer temperatures in plant survivability, which has improved in 25 years.

This effect is overall harmful towards fisheries and crop yields

→ Increased conflict and migrations

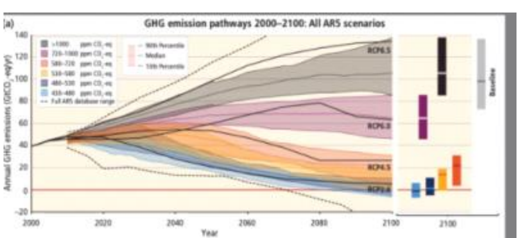


One example is the **Arab Spring**, which started in 2010 and brough about **mass unrest and political revolution**.

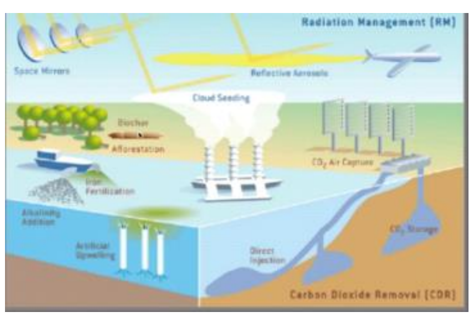
The wave was sparked by the self-immolation of a poor Tunisian fruit vendor, named **Mohamed Bouazizi**. Political tensions had been stoked by high-wheat prices from the drought of the previous year.

The entire middle East is involved in it.

- "an ounce of prevantation is worth a pound of cure!"



This means worldwide adoption of RCP 4.5 or less.



- 2 strategies: reduce emissions or remove after the fact