

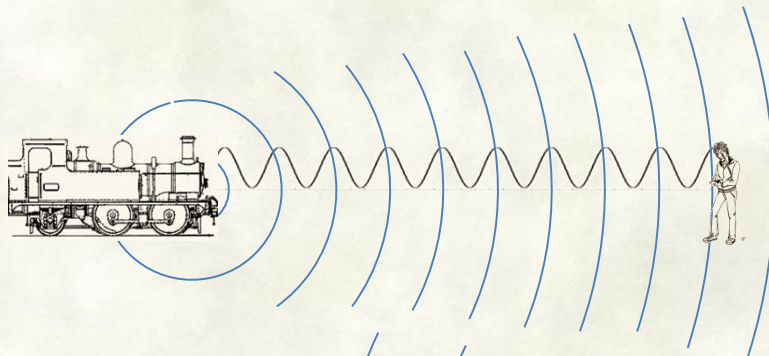
# The Nature of Light and Matter: 3

Doppler Effect, Mater and Energy

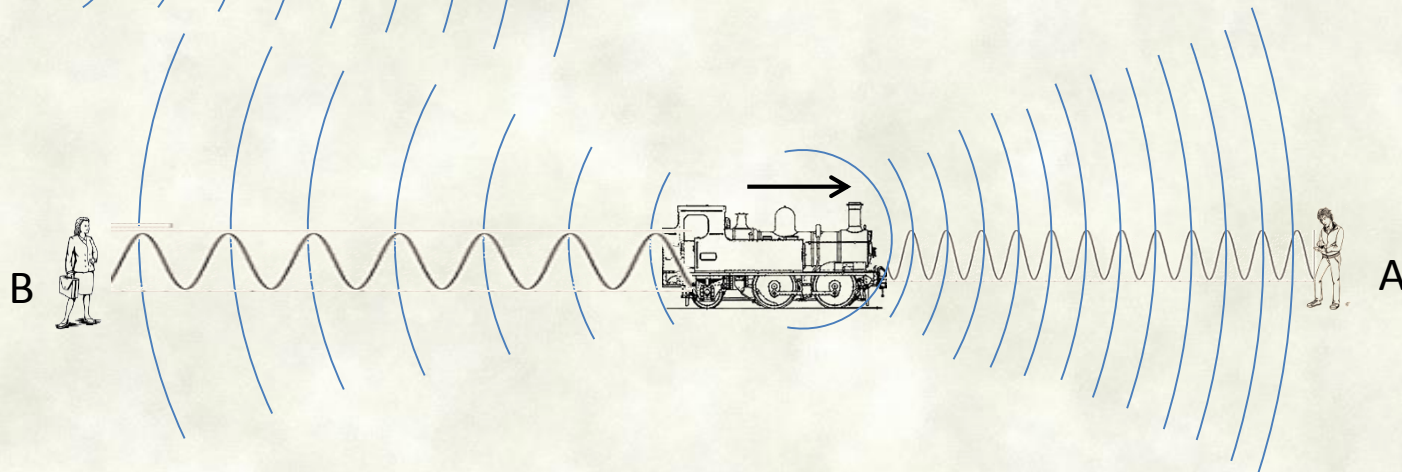
ASTR 101  
10/31//2017

# Light from Moving objects: Doppler effect

- When there is a relative motion between the source and the observer, it affects the received frequency of the wave.
  - First pointed out by the Austrian physicist **Christian Doppler** in 1842.
- A well known example is the rising pitch of a train horn as a train approaches at a rail crossing and drop in pitch as it moves away.



When the source not moving, wave crests pass the observer at time intervals equal to the transmitted period of the wave.



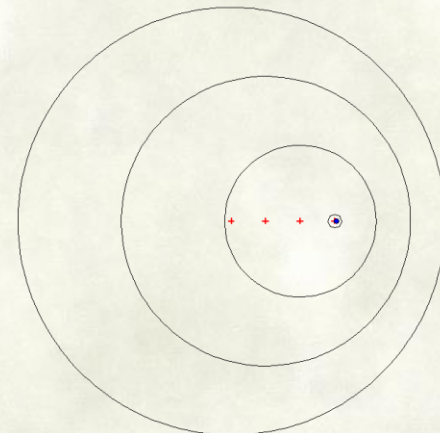
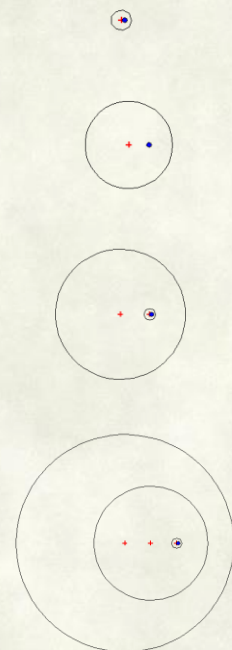
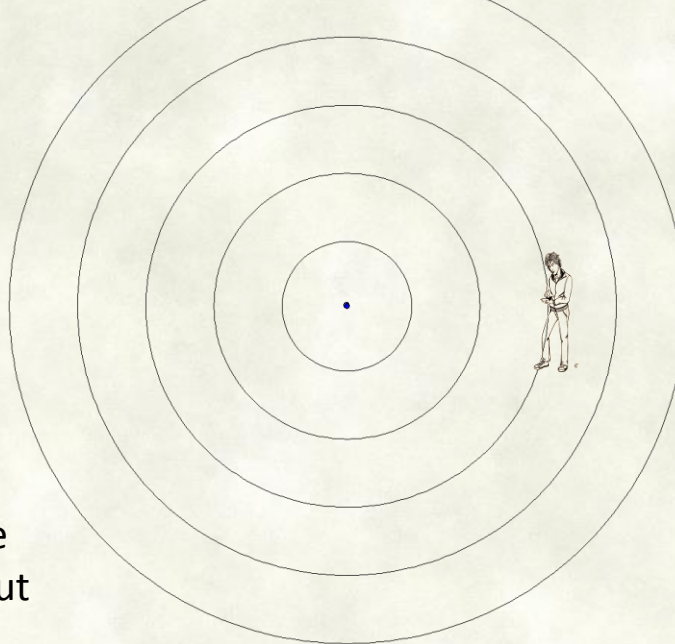
If the source is moving, wave crests in the direction of motion are 'bunched together' (shorter wavelength) and in the opposite direction are spread out (longer wavelength)





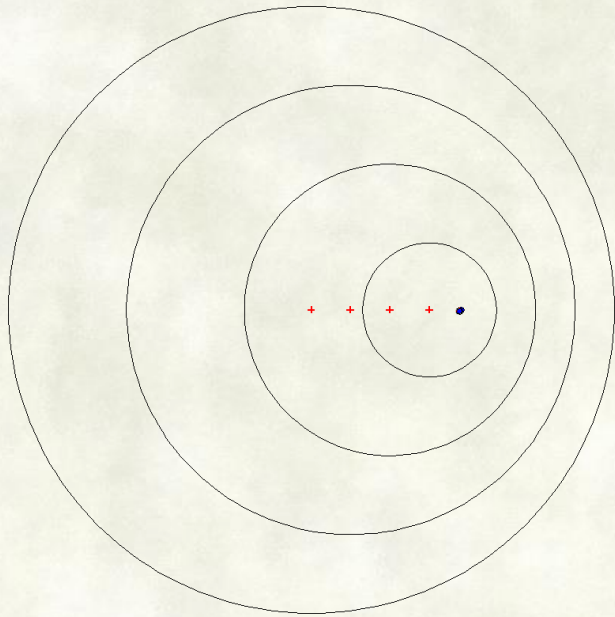


when the source is not moving, all the wave crests are emitted and move out from the same point



If the source is moving towards the Observer:

- Each successive wave crest is emitted from a position closer to the observer than the previous wave.
- Therefore, each wave takes slightly less time to reach the observer than the previous wave.
- The distance between successive wave fronts is reduced in the direction of motion,
  - waves are "bunch together", shortening the wavelength (and increasing in the frequency).



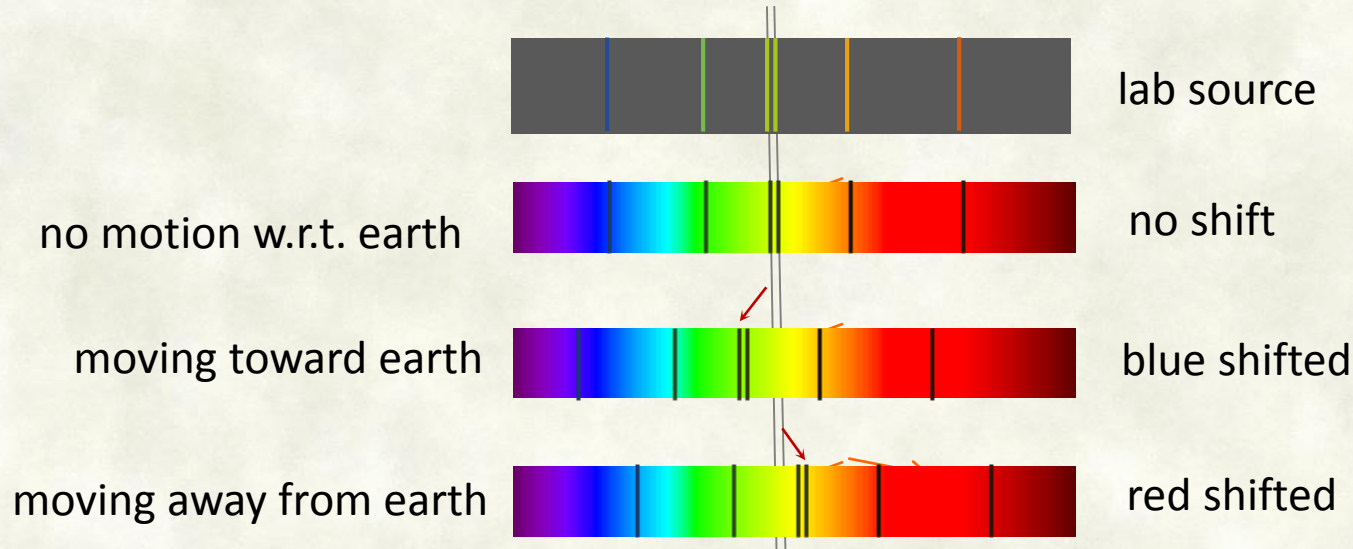
Wave crests emerging from a moving source



water waves around a moving duck

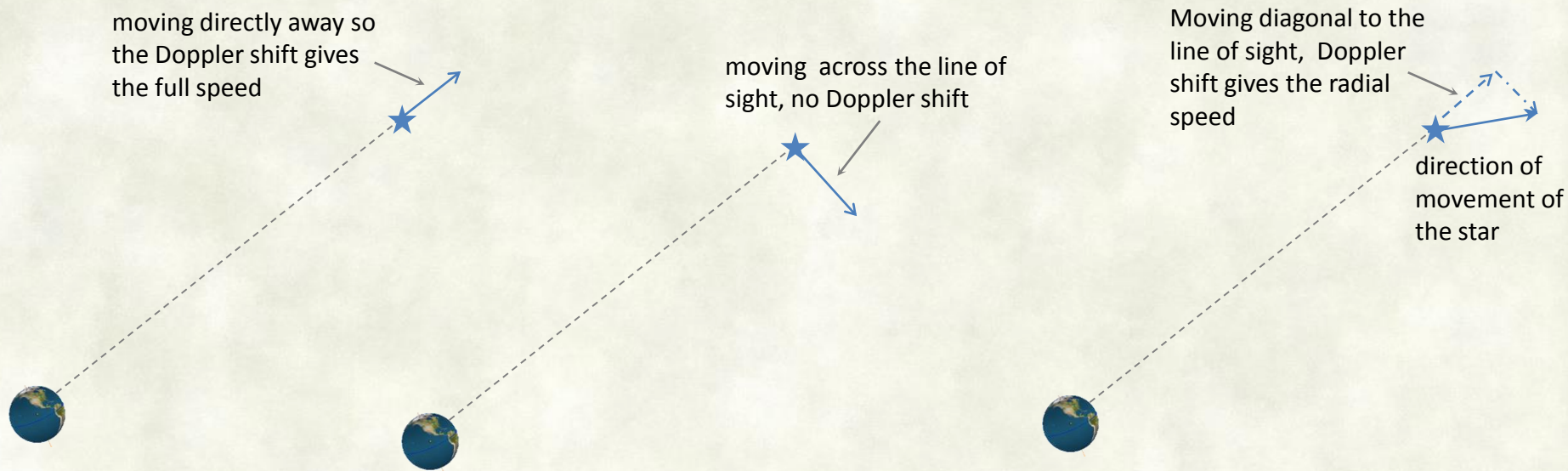
- Doppler shift can be observed for any type of wave - water wave, sound wave, light wave....

# Doppler shift in Astronomy



- Due to the Doppler effect, wavelength of emission and absorption lines from celestial objects shifts:
  - **blue shift:** wavelength gets shorter when moving towards the Earth
  - **red shift:** wavelength gets longer when moving away from the Earth
- Measuring the Doppler shift of spectral lines can be used to estimate the relative velocity between the Earth and celestial objects.
- A powerful tool in astronomy





Only the radial velocity contribute to the Doppler shift. (ie. component of velocity in the direction of line of sight).

The change in wavelength is  $= \frac{v}{c} \lambda_0$

$\lambda_0$  : original wavelength,  $c$ : speed of the wave

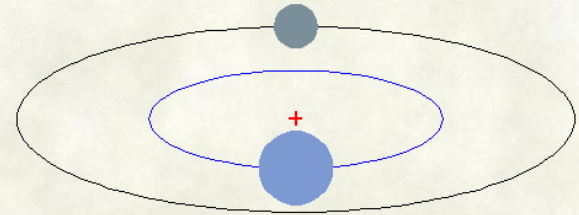
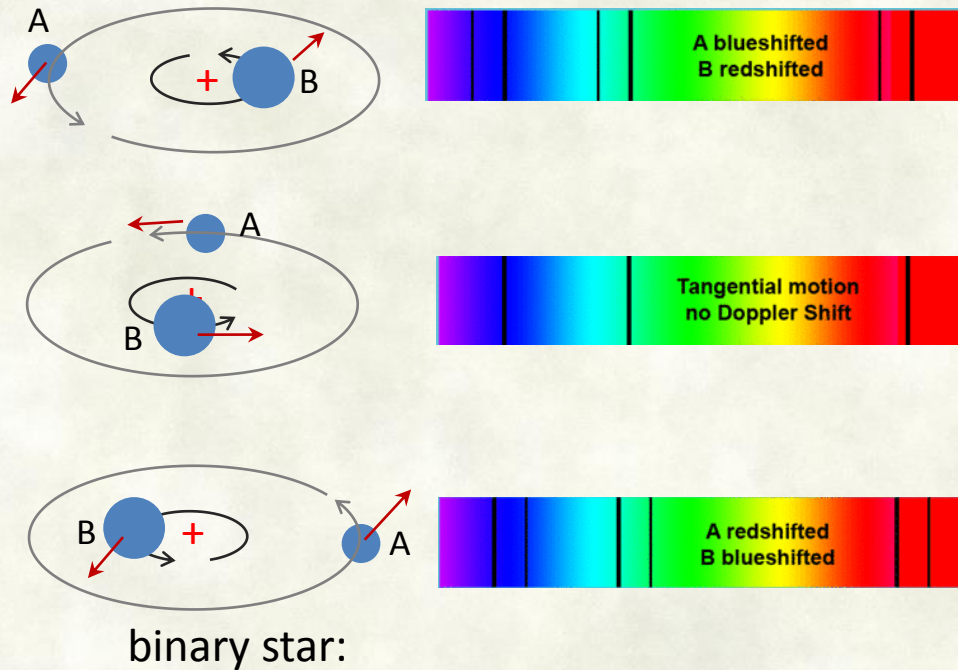
$v$ : radial speed between the source and the observer

e.g. For a star moving directly towards us at 100 km/s,

$c$  = speed of light =  $3 \times 10^5$  km/s

For  $\lambda_0$  500nm, shift in wavelength  $= \frac{100}{3 \times 10^5} \times 500 = 0.2 \text{ nm}$

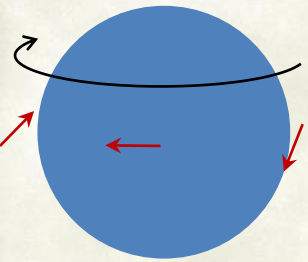
# Spectroscopic binary Stars



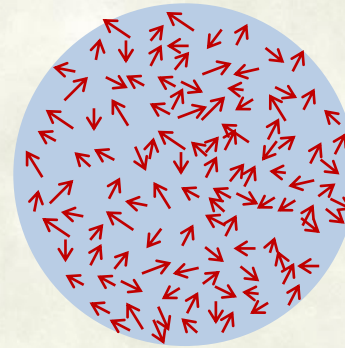
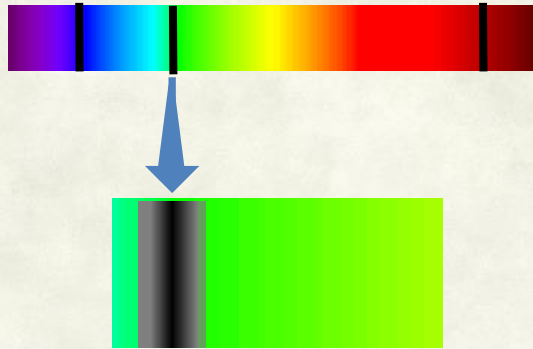
Doppler shift from binary stars:

- each star is alternatively moving toward and away.
- spectral lines are periodically blue shifted and redshifted
- Most binary stars cannot be separated visually, but can be identified from their periodical spectral line shifts.( called **Spectroscopic binaries**)
- Same technique can be used to identify planets orbiting stars (extra solar planets).





Rotation



Thermal motion: In a gas, particles are moving in random directions. Their velocities are depend on the gas temperature

### Rotation:

- Different areas of the stellar surface move in different directions with respect the observer.
  - Towards and away at the edge near equator - red or blue shifted
  - Tangential in the central region - no Doppler shift.
  - No motion near poles. - no Doppler shift.
  - Spectral line will appear smeared out, center of the line darker than edges.

### Other factors:

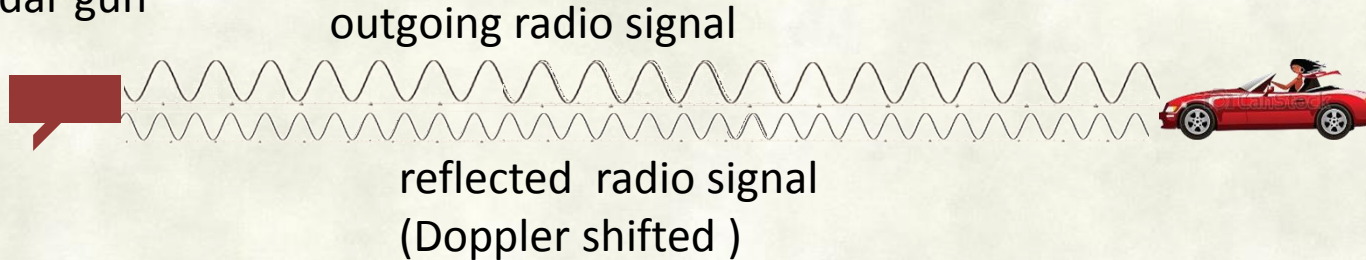
- Temperature, turbulences, (and pressure, magnetic field) all affect the spectral line shape

Analyzing the spectrum is a powerful technique to probe many properties of celestial objects.

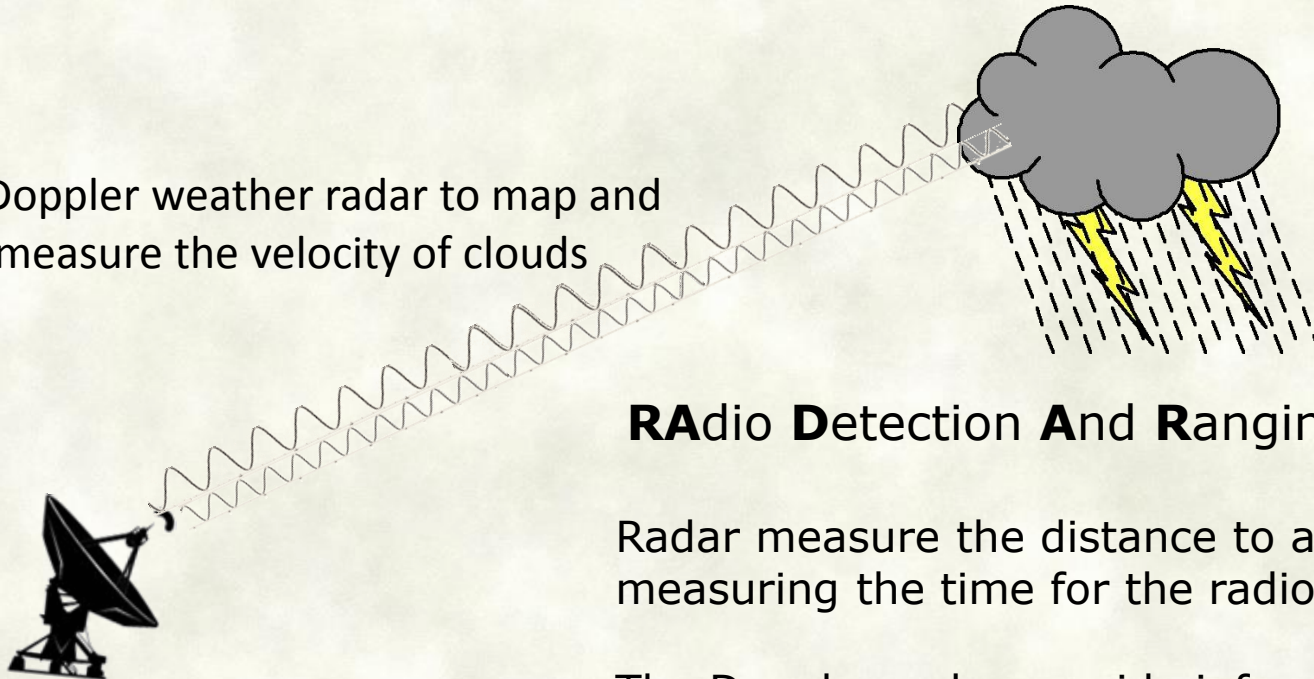
# Terrestrial Applications of the Doppler effect

## Doppler radar:

Radar gun



Doppler weather radar to map and measure the velocity of clouds

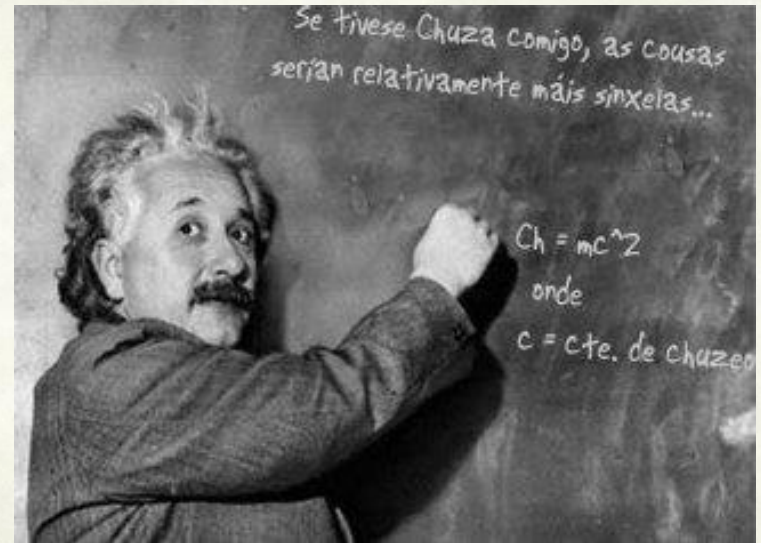
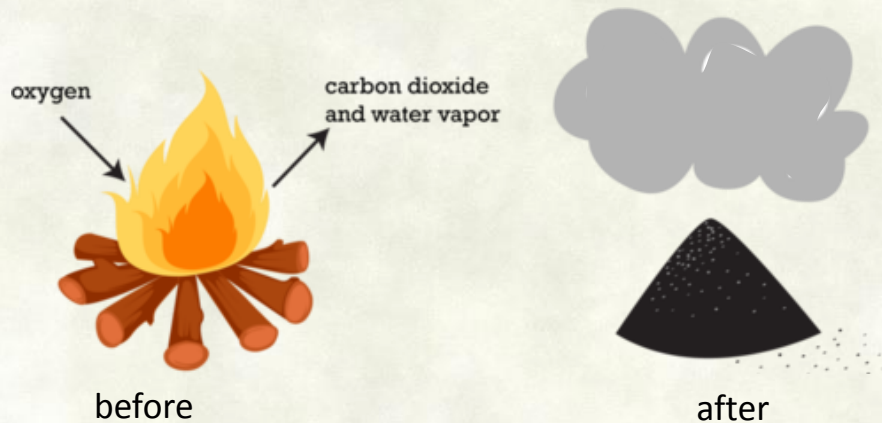


## **Radio Detection And Ranging**

Radar measure the distance to an object by measuring the time for the radio echo.

The Doppler radar provide information about the object's speed in addition to distance.

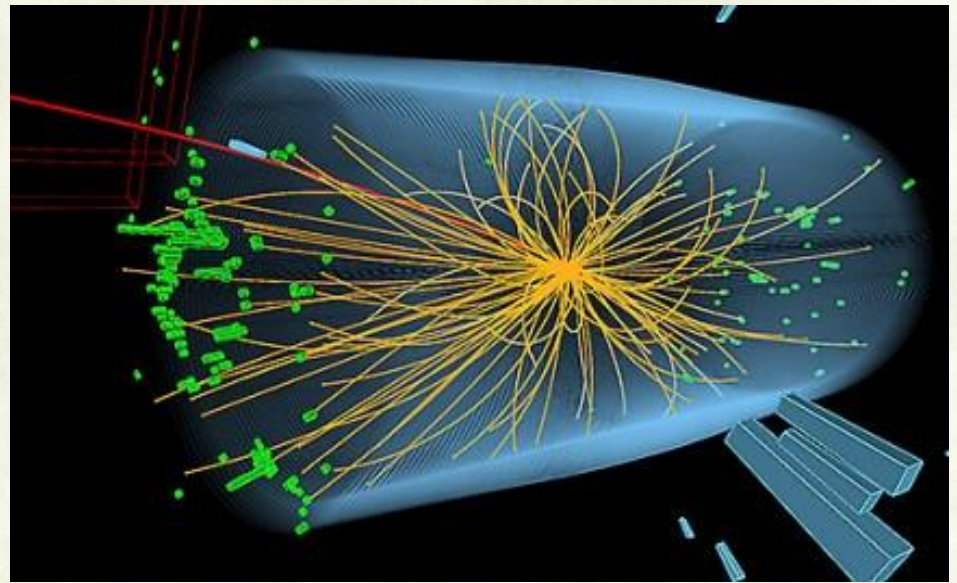
# Equivalence of Matter and Energy : $E = mc^2$



- Long held view was that matter was conserved
  - Only change form one form to other in reactions
  - cannot be created or destroyed.
- In the early 20<sup>th</sup> century, Albert Einstein showed that matter and energy are interchangeable.
  - Matter can be converter to energy, and energy can be used to create matter.
- Relationship between them are given by the formula  **$E = mc^2$** 

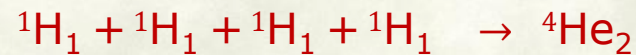
E: amount of energy produced when a mass m is converted to energy and *vice versa* . (c: speed of light)





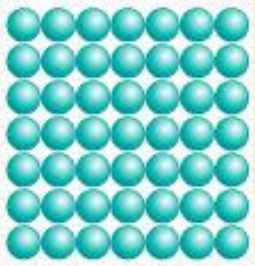
Tracks of particles created by energy in the CMS particle detector

- 1 gram of mass converted to energy:
  - equal to the energy of burning 70 million gallons of gasoline.
  - same amount of matter converted to energy in the nuclear bomb dropped at Nagasaki.

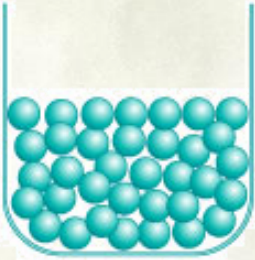


- In the Sun 600 million tons of hydrogen is converted into 596 million tons of helium every second.
  - 4 million tons of matter into energy (100 billion H bombs each second)

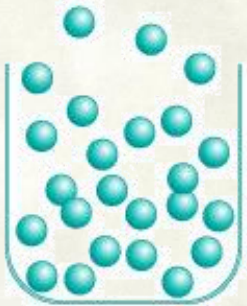
# States of Matter



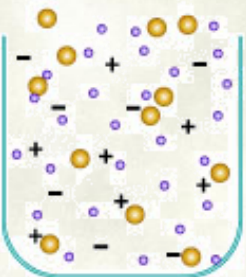
**Solid:** Atoms are held in a regular pattern by inter atomic forces. Atoms cannot move, but vibrate at an amplitude determined by the temperature.



**Liquid:** At higher temperatures atoms vibrate faster. When the temperature is high enough atomic bonds break and atoms move around, still kept from flying apart by attractive forces between them. Liquids take the shape of the container



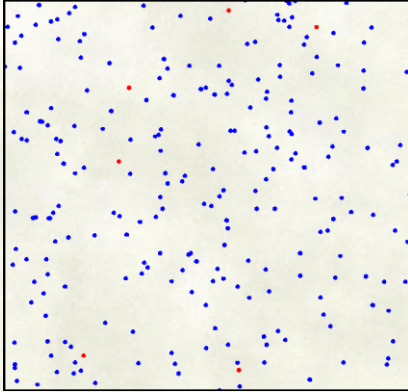
**Gas:** As the temperature increased further, atoms moves at speeds fast enough to get over inter atomic attractive forces and fly apart. They move in all directions, at speeds that increase with the temperature. Gases fills up its container.



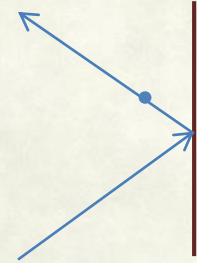
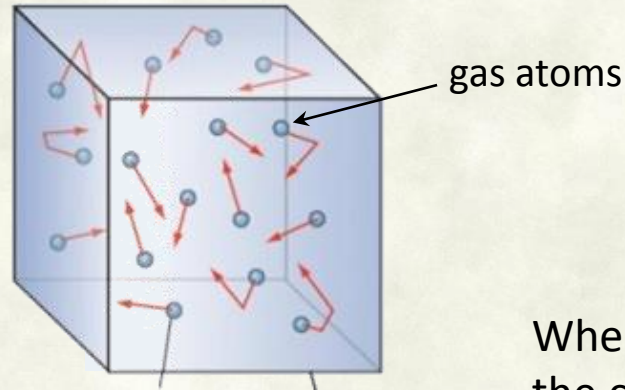
**Plasma:** Ionized gas. At very high temperatures (few thousands K) some electrons break free from atoms, making a mix of ionized (electrically charged) atoms and electrons. They are subjected to electrical and magnetic forces. Plasma is the most common state of matter in the universe.



## Temperature and pressure.



In a gas, atoms are always moving at random velocities.



When an atom bounces off the container wall, it imparts a force on the wall.

- In a gas, particles (molecules, atoms) are always moving at random velocities.
- Velocity of a gas particle increases with the temperature,
  - Temperature is a measure of how fast particles are moving.
- The pressure of a gas in a container is the result of continuous collisions of gas molecules on the container wall.
- Since the velocity of the gas particles goes up with the temperature, the pressure of a gas in a container increases when its temperature is increased.



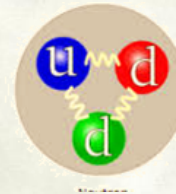
# Elementary particles and forces

## Subatomic particles:

- According to our current understanding, all matter in the universe is made of few basic constituents, called **elementary particles**.
  - Electron is an elementary particle, as far as we can probe, it can not be divided further.
  - Neutrons and protons are not elementary particles, they have a structure, they are made of even smaller constituents called quarks.
- There are six known types of quarks.
  - Most important are u (up) and d (down) quarks which protons and neutrons made of .



Proton uud



neutron udd

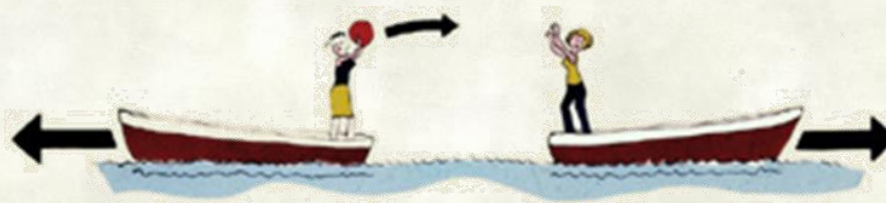
- They are held together by nuclear interaction forces.

# Fundamental Interactions (forces)

Matter (particles) interact with each other due to forces in between them. There are four types of such fundamental forces:

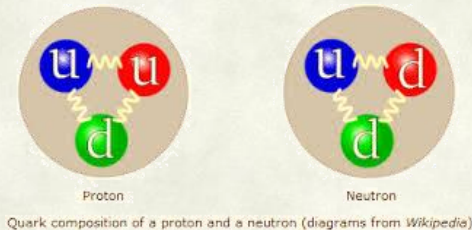
interaction	range	mediator
– Gravitation	long range ( $1/r^2$ )	graviton
– Electromagnetic force	long range ( $1/r^2$ )	photon (light)
– Strong force	short range ( $10^{-14}$ )	gluon
– Weak force	short range ( $10^{-16}$ )	W,Z

- Forces are mediated by another category of particles called gauge bosons.
- When gauge bosons exchanged between particles they are subjected to forces.



If a ball is exchanged between two boats, each time the ball is thrown it pushes the boat away (Newton's 3<sup>rd</sup> law). So as the ball is exchanged, boats would move away from each other as if there is a repulsive force between them.

# Anti particles



Proton and neutron

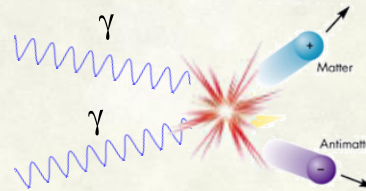
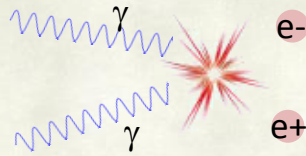
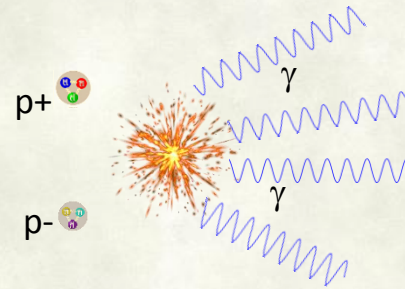
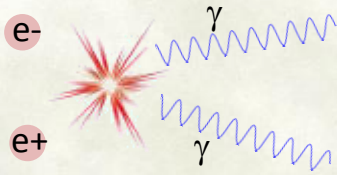


anti-proton and anti-neutron  
made of anti-quarks

- Each particle has an anti-particle:
  - a particle which has the same mass and other properties, but opposite electric charge.
  - Electron's antiparticle is the positron, its existence by predicted by Paul Dirac in 1929 and discovered by Carl Anderson in 1932.
  - Anti particles (anti-quarks) of u and d quarks are denoted by  $\bar{u}, \bar{d}$ , anti u and d quarks can form anti protons and anti neutrons.

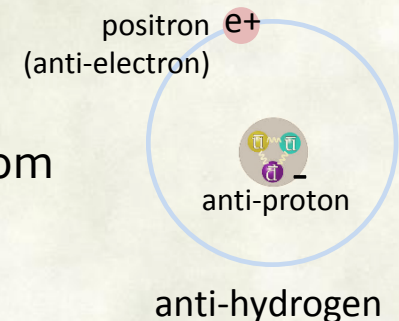
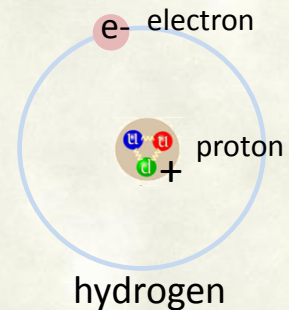


# Anti-matter



Tracks of an electron-positron pair produced from a  $\gamma$  ray inside a particle detector

- When particles and anti-particles interact they annihilate each other releasing energy in the form of photons.
- Also particle, anti-particle pairs can be produced from energy.
- In principle it is possible have things (worlds) entirely made of anti-matter.
- But the universe seems to be entirely made of matter
  - One of the major astrophysics puzzles today.
    - At the beginning, universe was filled with energy
    - Elementary particles and anti particles were produced from that energy
    - What happened to anti-matter?





- High energy physics: Branch of physics studying the fundamental particles and forces .
- In high energy accelerators, particles (electrons, protons and their anti-particles) are accelerated to extremely high energies, and make them to collide with each other to produce new particles and study their interactions.
- Conditions similar to very early stages of the universe, fraction of a second after the Big Bang.



Accelerator complex at the Fermilab, near Chicago (accelerator ring diameter: 2 km)

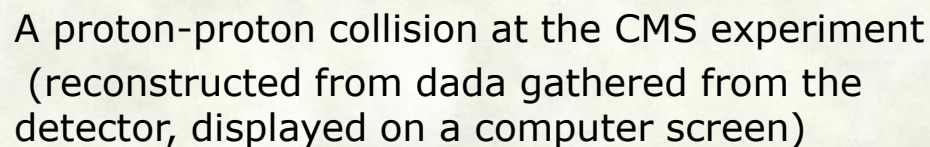
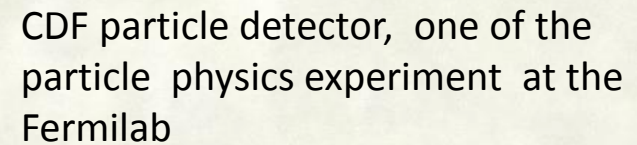
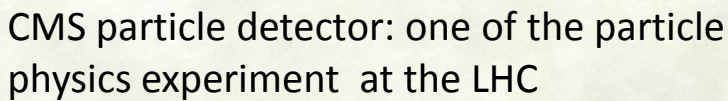


Inside the Fermilab accelerator tunnel.



Large Hadron Collider (LHC)  
Accelerator at CERN, Geneva.  
(accelerator ring diameter: 8.5 km)

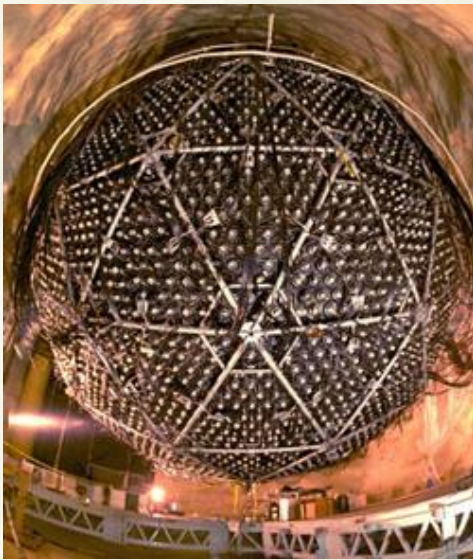




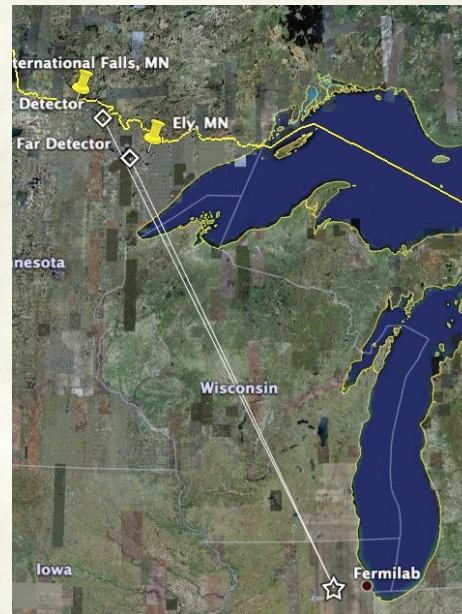


# Neutrinos

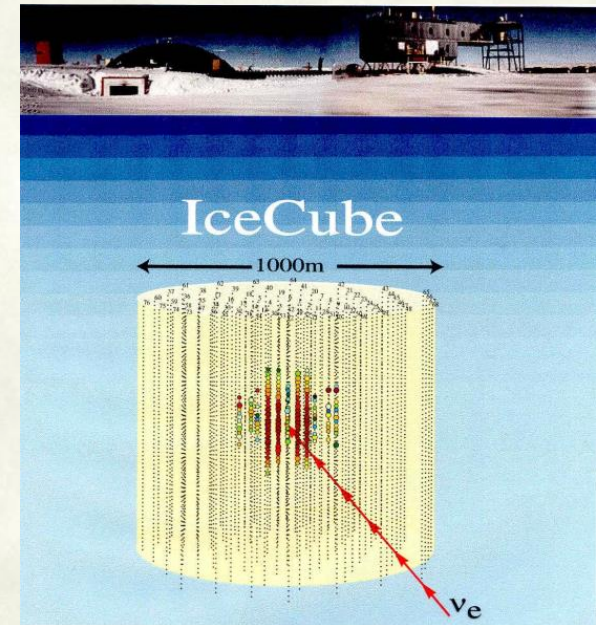
- Among the elementary particles most elusive one is the neutrino.
  - A particle with extremely low mass (almost zero), it has no electric charge. It is not subjected to electromagnetic force, strong nuclear force. So it interacts with matter only weakly, (hardly interact with matter)
  - can travel across the earth without interacting.
- They play an important role in many astrophysical process, like in stars, early stages of the universe...



The Sudbury Neutrino telescope in Canada to detect neutrinos from the Sun. The 12-meter sphere, located 2km underground is filled with heavy water and contains 12,000 light detectors. It looks for the light produced from neutrinos when they interact.



MINOS neutrino experiment sends neutrinos from Fermilab to Minnesota through earth



Ice Cube neutrino detector under the Antarctic ice sheet

# Particle Physics and Astronomy

- Particle physics studies the fundamental nature of matter and the (four) forces governing them.
- Studying the nature at microscopic level has an intimate relation to the study of the universe.
  - What was there before the universe, How did the universe come to be, what led to the formation of space-time, what is the fundamental nature of space time.
  - All such questions are in the domain of questions particle physics tries to answer.
  - It is compelling to think that at earlier times (higher temperature and energies all four forces unify to a single force field in the universe
    - We already know weak interaction and electromagnetism were unified (electroweak force) until about  $10^{-32}$  second after the Big Bang.
    - Expectation is other forces would also unify, eventually to a single interaction.
  - At the beginning universe was filled with energy (radiation) there was no matter. As the universe cooled off energy converted to matter.
    - This is directly in the realm of particle physics
    - We know after few minutes after the Big Bang primordial elements H, He were formed from particle physics.



## Review Questions

- Why is the Doppler shift important in astronomy?
- What type of waves are affected by Doppler shift?
- What is a blue shift and a red shift?
- If you see no Doppler shift in the spectrum of a star is that enough to conclude that the star is not moving with respect to the Earth?
- Why are the spectral lines from galaxies are always redshifted?
- What are the spectral binary stars?
- What are the practical application of the Doppler effect?( other than in astronomy).
- According to Einstein's theory of relativity mass is not really conserved, but can be converted to energy. But until then it was an experimentally proven fact that the mass was conserved. Why?
- At the rate of current consumption how long the Sun can continue produce energy converting hydrogen to helium. (use the rate of H burning and the mass of the sun given in the class)
- Give a simple explanation why solids melts when they are heated.
- What are elementary particles? Why isn't the proton an elementary particle.
- Why is the universe made of only matter (no anti-matter) is such a major puzzle.
- Why is it necessary to use such huge detectors to detect neutrinos.