Today:
Dark Matter

Dark Matter?

- Dark Matter is matter than we cannot see (but it is 25% of the Universe)
- Dark Matter does not emit/absorb/reflect any light
- How do we know they exist?
- Astronomers measure the amount of dark matter indirectly by observing its gravitational effect
- Dark matter is one of the major unsolved mysteries in science

Evidence of Dark Matter

- How do we know they exist?
  The rotation of galaxies --- they rotate as if there is more mass than those observable

  The behavior of galaxy clusters --- they behave as if there is more mass out there

  The appearance of distant galaxies --- sometimes distorted too much

- Dark Matter is a solution that can explain these puzzles
The rotation of galaxies

Recall: In Our Solar System...

• The inner planets rotate faster compared to outer planets as a result of Kepler's 3rd law:

\[
\frac{R_1^3}{R_2^3} = \frac{T_1^2}{T_2^2}
\]

• Galaxies are collections of billions of stars and most of the light comes from galactic center
• This indicates that most of galaxy's stars and its mass are concentrated at its center (like our solar system..)
• Under this scenario, we should expect the stars in the outer part of the galaxy to rotate about the center
• How do they rotate?

Class Action!
Which of the rotation curves below most closely represents that of the planets orbiting a star?

(A) velocity vs distance (B) velocity vs distance

(C) velocity vs distance (D) velocity vs distance
How do we measure the rotation curve of our Milky Way galaxy?

1. Measure the distance
2. Measure the spectrum of our Milky Way galaxy
3. Measure the Doppler Shift of the spectrum
4. Use Kepler's Laws to measure the mass of the galaxy

Doppler Shift

Observer 1 Car traveling toward the right Observer 2
Doppler Shift

blue = high frequency    red = low frequency

Doppler Shift

UNSHIFTED

REDSHIFTED

BLUESHIFTED

Class Action!

The spectrum of a typical star shows absorption lines at different wavelengths than their laboratory values. If the wavelength of the H-alpha absorption line is greater than its laboratory value of 656.3 nm, one can conclude that ...

A) the separation between Earth and the star is decreasing.
B) the separation between Earth and the star is increasing.
C) the separation between Earth and the star is unchanged.
D) no conclusion is possible.
Class Action!

The spectra for four hydrogen sources are shown below. (The top spectrum is a reference spectrum.) Which source's light is most redshifted?

- Reference spectrum
- (A)
- (B)
- (C)
- (D)

Class Action!

The spectra for four hydrogen sources are shown below. (The top spectrum is a reference spectrum.) Which source's light is most blueshifted?

- Reference spectrum
- (A)
- (B)
- (C)
- (D)

The rotation of galaxies

Recall: In Our Solar System...
The rotation of galaxies

There are more mass than we expected in our Milky Way galaxy!!
Almost all other galaxies have rotation curves like the Milky Way (flat). Individual mass distributions cause the differing shapes.

By measuring the velocity of galaxies in the galaxy cluster, we can estimate how much mass there are in the cluster.

In 1930s, Fritz Zwicky realized that the orbital velocity of galaxies in the cluster cannot be explained with the galaxy light we see.

The mass we find from galaxy motions in a cluster is about 50 times larger than the mass in stars.

Galaxy clusters contain large amounts of hot gas.

These hot gas can reach such high temperature (very high speed) due to enormous gravitational potential in the cluster.

By measuring the temperature of these hot gas, we can estimate how much mass there are in the cluster.

Again, the 85% of derived mass can not be explained only by the observed mass in stars and hot gas.
Evidence of Dark Matter in galaxy cluster

- Einstein predicted that gravitational field due to the mass can not only deflect the trajectory of particle but also the light!
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Evidence of Dark Matter in galaxy cluster
Form the distorted images of background galaxies (galaxies located behind the galaxy cluster), we can estimate how much mass there are in the cluster.

Again.. the matter we can see cannot account for the derived cluster mass..

Evidence of Dark Matter in galaxy cluster

Class Action!

What kind of measurement does not tell us the total mass of a cluster of galaxies?

(A) Measuring velocity of a cluster galaxy
(B) Measuring total mass of the cluster's stars
(C) Measuring temperature of its hot gas
(D) Measuring distorted images of background galaxies

What might dark matter be made of?

A few guesses..

• Ordinary Matter (MACHOs)
  --- Massive Compact Halo Objects (white dwarfs, black holes..) current observations suggest that there are not enough of them to explain all dark matter

• Exotic Particles (WIMPs)
  --- Weakly Interacting Massive Particles (new type of particle not discovered yet..)

Dark Matter -- still a mystery..
Dark Matter Group Exercise

- Divide into groups of 2 or 3 (no more than 3)
- Complete the Dark Matter Exercise
  
  Discuss your answers! Don’t be silent!
- I will be roaming around if you need help.

Appendix

Can our idea of galaxies be

In order for gravity to cause this type of rotation, each galaxy must be surrounded by a super-massive halo of matter. No such halos, however, can be seen. So we conclude that they are made of dark matter.
What is Dark Matter?

Many exotic particles have been proposed as candidates for dark matter:

- massive neutrinos
- weakly interacting massive particles (WIMPs)
- massive compact halo objects (MACHOs)
- black holes
- brown dwarfs

When looking at galaxy rotation, it appears that dark matter occurs in halos around galaxies.

But when looking at gravitational lensing and clusters, most of the dark matter appears to be smeared out in between galaxies!

Hot or Cold Dark Matter?

If the particles that make up dark matter are small, then dark matter is said to be hot.

If the particles are large, then it is called cold.

Theories with cold dark matter have more success explaining how galaxies formed.

Theories with hot dark matter do a better job explaining the origins of clusters and superclusters.

Recent experiments suggest that dark matter is cold, but some researchers believe that the universe contains a mix of both hot and cold dark matter.