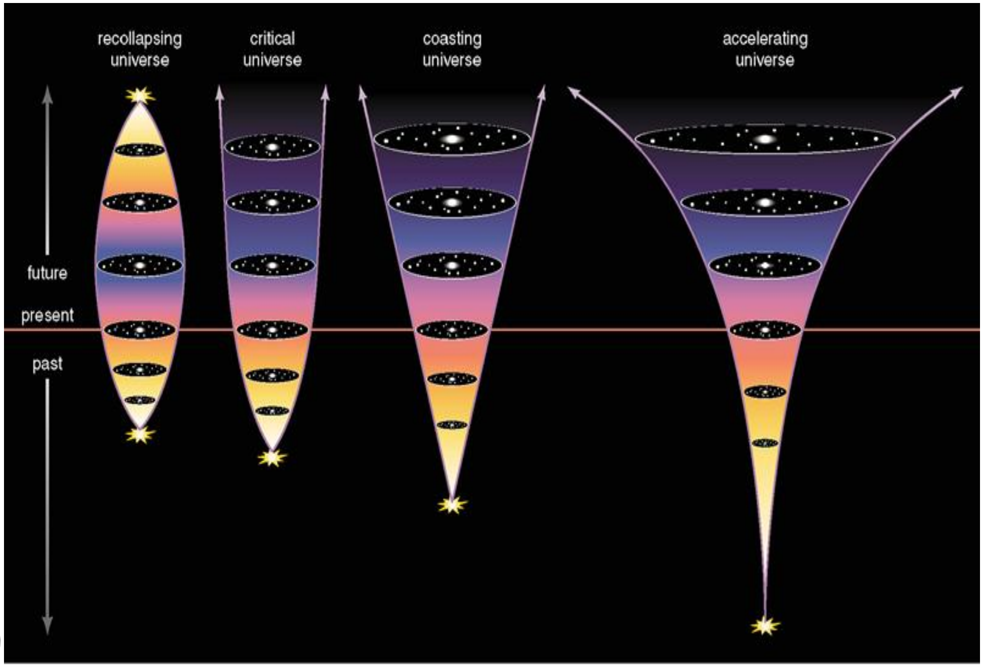
Possible Fate of the Universe

We already know that the universe is expanding. Only the pull of the gravitational force can slow it down. So, similar to the fate of the stars, ***how the universe evolves depends on how much matter we have in the universe***…

- **Recollapsing (or closed) universe**
  If the mass density is greater than the critical density, the gravitation pull will eventually pull all the matter back.
- **critical (or *flat*) universe**
  If we have just the right amount of mass per unit volume (the **critical density**), the universal expansion will eventually stops.
- **coasting (or *open*) universe**
  If the mass density is less than the critical density, then universe will expand forever
- **accelerating universe**
  Some new observations seem to suggest that the expansion is *not* slowing down, but instead is accelerating



Chapter 16, Dark Matter, Dark Energy, and the Fate of the Universe

- ***I****f we know how much matter we have in the universe, then we can predict how the universe is going to evolve in the future…*

- In our effort to measure the total mass of the universe and trying to determine how the universe is going to evolve, we have come to some surprising conclusions, that is, most of the mass of the universe are in the form of ***dark matter***, and that there is an unknown force pushing the expansion of the universe in an ever-increasing rate. This unknown force is what

Dark Matter and Dark Energy

- **D**efinitions…

Dark Matter

– Dark matter is the name given to mass that we infer to exist through its gravitational effects but that ***emits no detectable radiation***.

Dark Energy

– Dark energy is the name given to an unseen influence that may be ***causing the expansion of the universe to accelerate with time.*** .

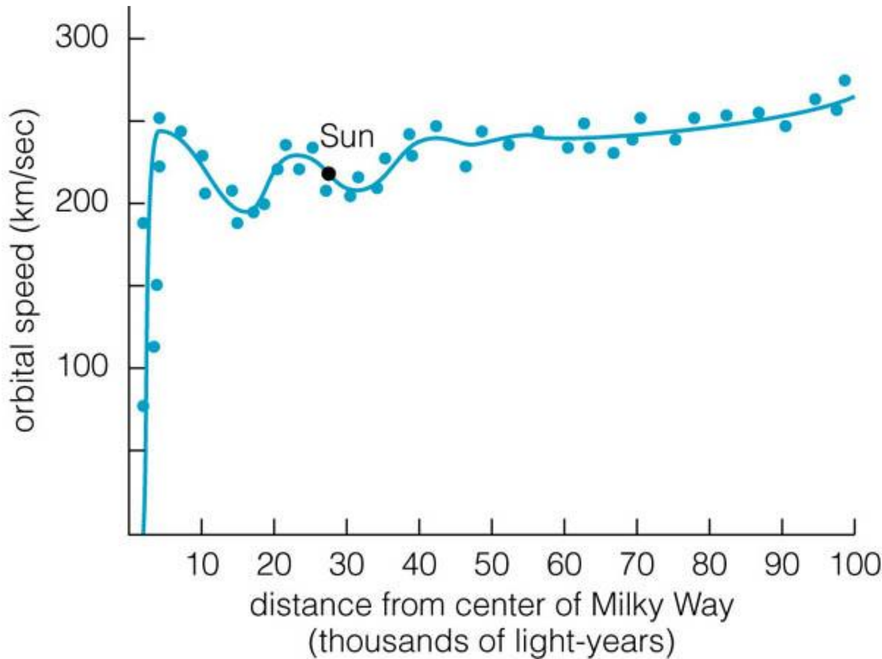
- ***How do we measure the mass of Milky Way, or other galaxies?***

The Rotation Curve of the Milky Way Galaxy

Like our measurement of the mass of solar system objects, or the mass of stars in binary systems, we can estimate the mass of a object from the rotation period of another object around it, using ***Newton's version of Kepler's third law of planet motion…***

- By observing the ***orbital motion of stars*** at different distance from the galactic center, we can estimate the mass contained by the Milky Way galaxy as a function of distance from the galactic center….
- *Note that this method assumes that the stars are in* ***stable bound orbits!***

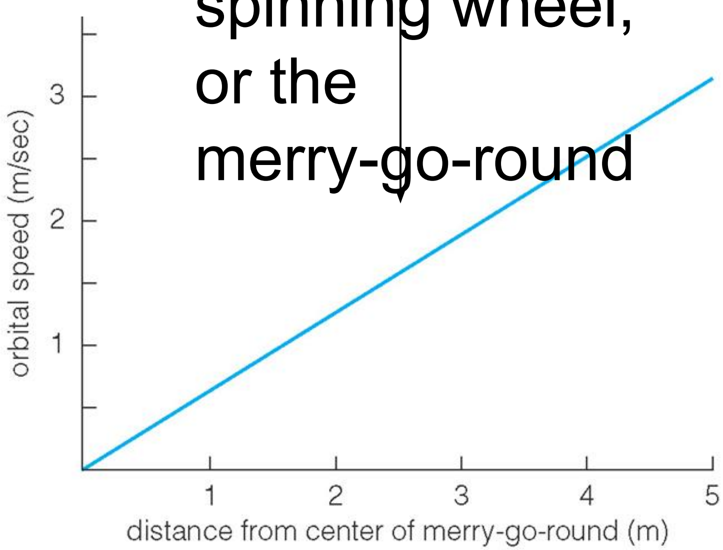
Observed *rotation curve* of the Milky Way Galaxy…



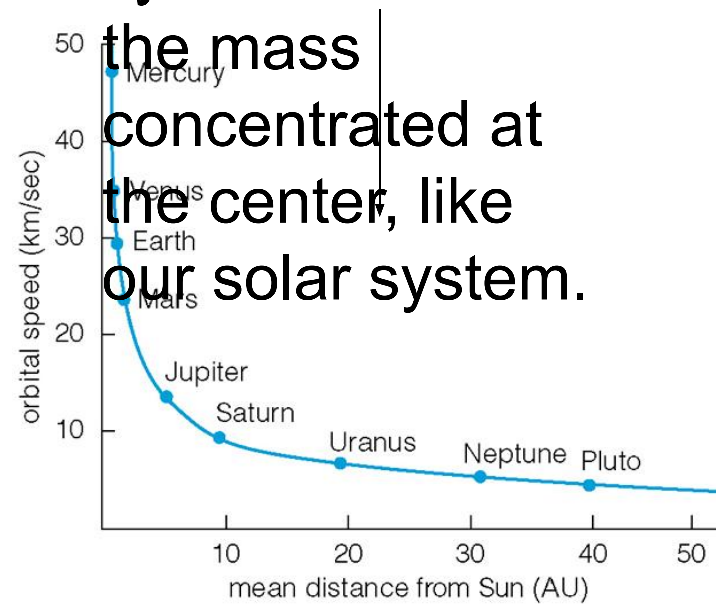
What Does the Flat Rotation Curve of the Milky Way Tell Us?

- Let's first look at the rotation curves of
  1. a **rigid body** and
  2. a system with **concentrated mass**…

- Rotation curve of a rigid body…like spinning wheel, or the merry-go-round



- Rotation curve of a gravitational system with all the mass concentrated at the center, like our solar system.



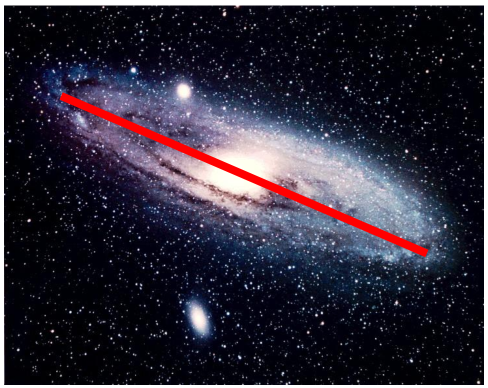
What Does the Flat Rotation Curve of the Milky Way Tell Us?

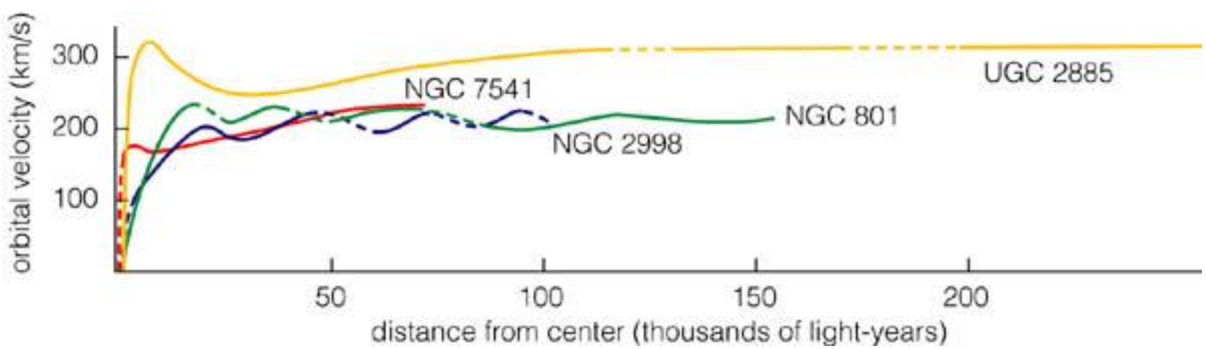
- The flat rotation curve of the Milky Way Galaxy implies that…
  - The mass of the Milky Way is not concentrated at the center of the galaxy..
  - The mass enclosed in a sphere increases as we increase the radius of the sphere…
    - The mass in a sphere inside the Sun's orbit contains about 100 billion times the mass of the Sun.
    - The mass in a sphere twice the size of the Sun's orbit contains twice as much mass (200 billion M_{sun}).
  - ***Most of our galaxy's mass lies well beyond our Sun, tens of thousands of light-years from***

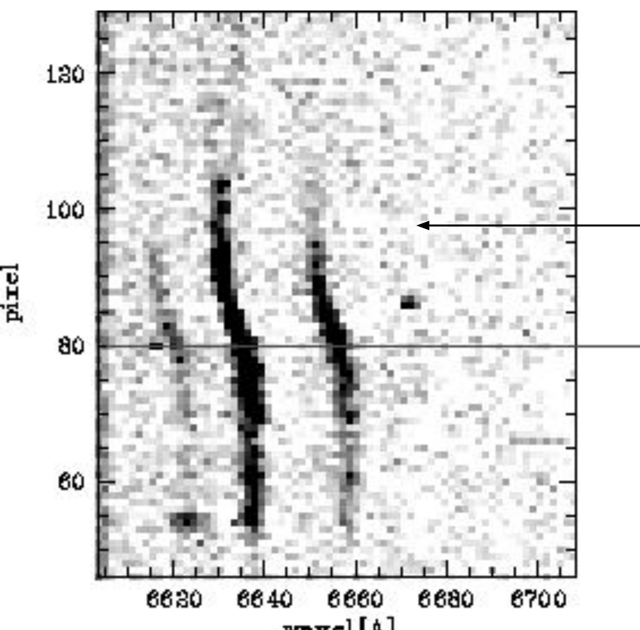
The Rotation Curve of the Spiral Galaxies

We can estimate the mass contained in other spiral galaxies from Doppler shift of the spectrum…

- *The rotation curves of spiral galaxies are very similar to that of the Milky Way Galaxy…*







If we measure the Doppler shift of the galaxy along the red line, we would see a spectra like this…

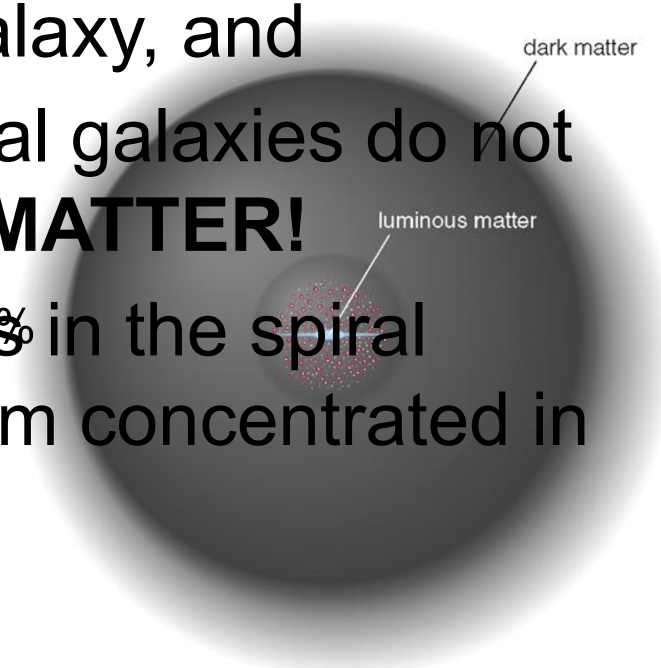
Dark Matter in Spiral Galaxies

- **A**ll observations of the mass in spiral galaxies suggest that
  - The majority of the masses in spiral galaxies are contained in a ***spherical halo*** that surrounds the disk of our galaxy, and
  - 90% of the mass of the spiral galaxies do not emi

e **DARK MATTER!**

10%

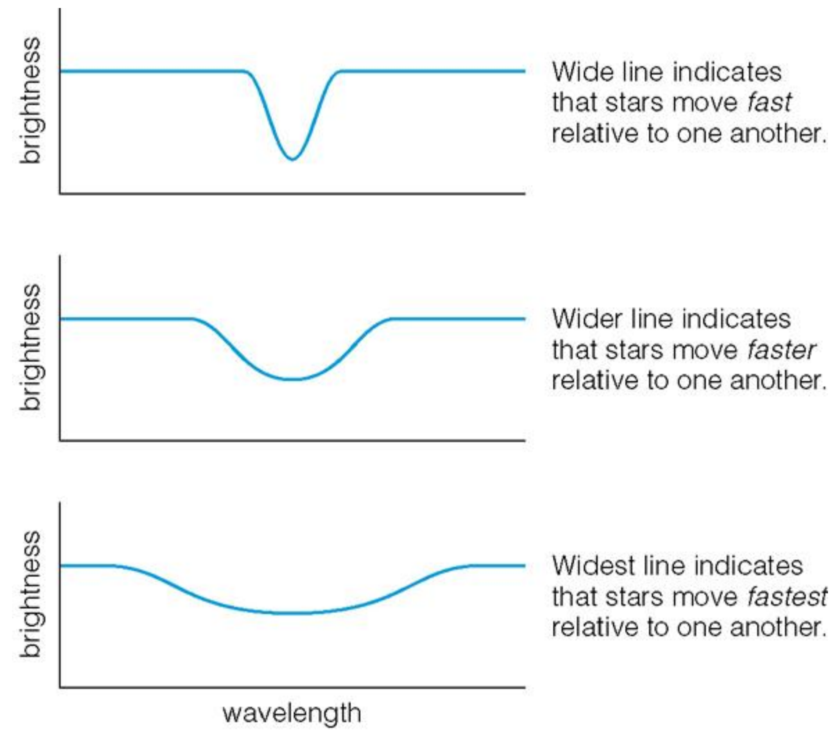
– Onl f the mass 90% in the spiral gala ninous form concentrated in the alaxies…



Dark Matter in Elliptical Galaxies

- **W**e cannot measure the rotation rate of stars in Elliptical galaxies like we do with the spirals, because *stars in elliptical galaxies do not rotate around the center in any organized way*…However,
  - At any particular location, some stars will be moving toward us, some will be moving away from us, while some will be moving

Rotation curves of ellipticals measured from the broadening of the absorption lines yielded the same results – that ***ellipticals also contain large amount of dark matter, about the same like the spirals***!



Measuring the Mass of Galaxy Clusters

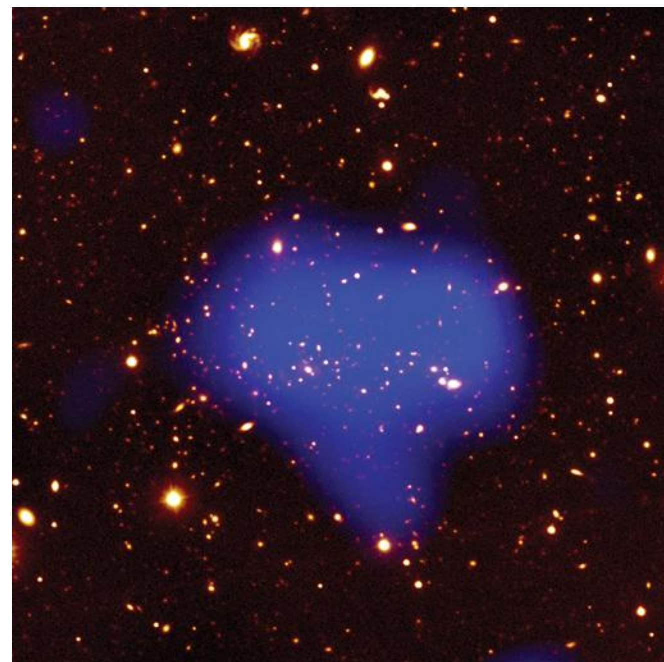
- The mass of cluster of galaxies can be measured by three different methods…
  - Orbits of Galaxies in Cluster
  - ***Hot Gas in Clusters***
  - ***Gravitational Lensing Effect***
- The first method is obviously the application of the Newtonian dynamics methods (Kepler's Third Law of Planet Motion)…

X-ray Observation of Intercluster Medium

Assuming that the thermal pressure of the hot intercluster medium is in equilibrium with the gravitation pull (like the gas in a star), we can estimate the amount of matter in the cluster by measuring the **pressure (temperature)** of the intercluster medium.

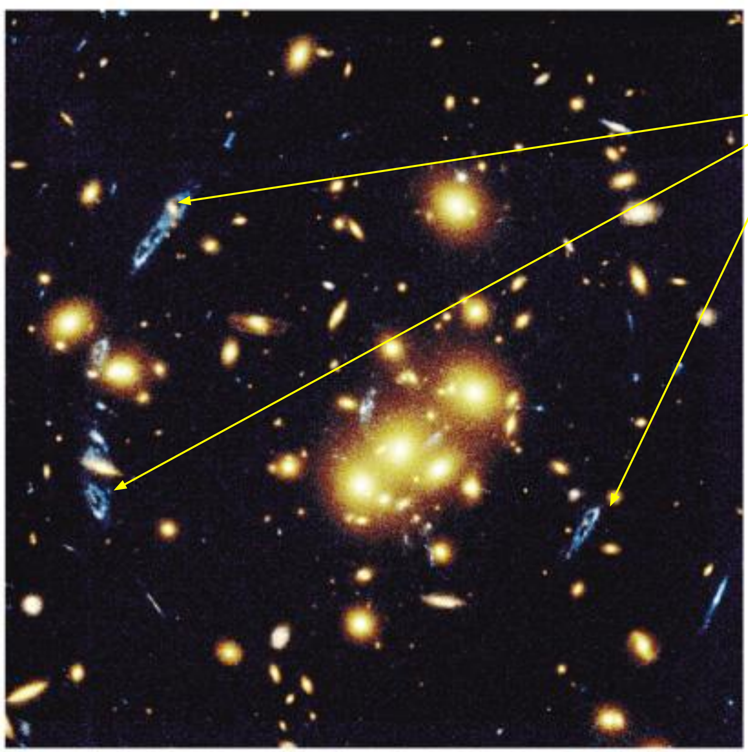
- The estimated mass of the Intercluster medium in the space between the galaxies in a cluster is about ***50 times that mass of the visible mass*** of the cluster.

The blue patch represent the X-ray emission from extremely hot gas in the cluster.



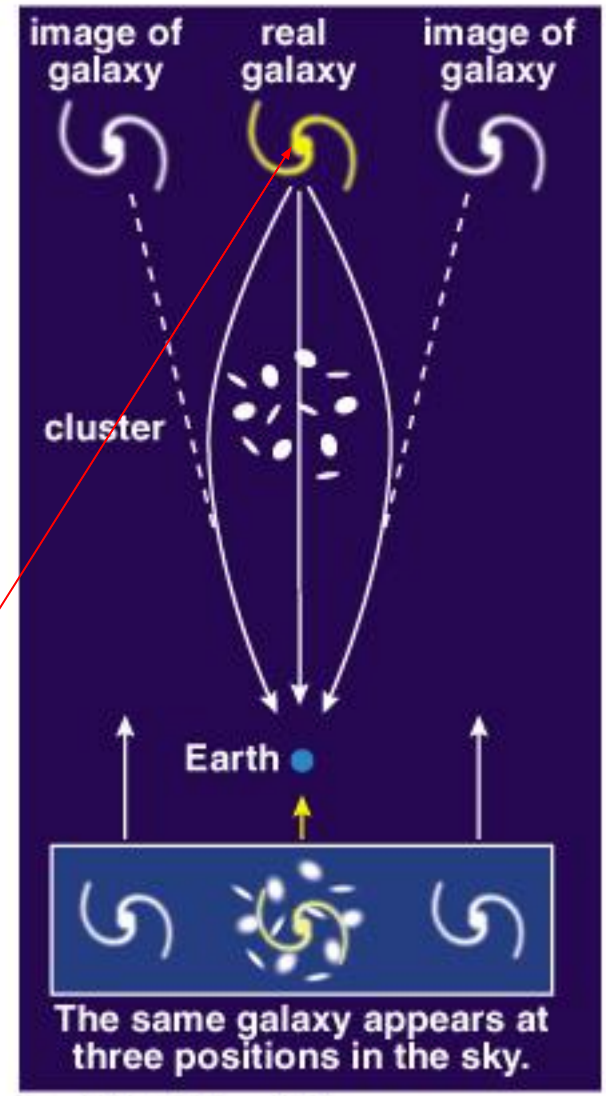
Gravitational Lensing Effect

In general relativity, gravity causes the distortion of spacetime. Light travels along these distorted path. Thus, a large gravitational object sometime behave like a lens. It can form image or images of distant objects behind it for us to see if the alignment happens to be right.



This galaxy is directly behind the cluster. Gravitational lensing produces the multiple copies of the same galaxy we see here.

If we know the distance to the galaxy being imaged, then we can calculate the mass of the cluster.



Results of Mass Measurements

All observations consistently tell us that

- *There are more mass then we can see!*
  - The mass-to-light ratio (M/L) of galaxies and galaxy clusters are
    Solar Neighborhood: ~6
    Galaxies: ~10
    Galaxy clusters: ~50
  - The higher the mass-to-light ratio, the more dark matter there is…

    *These results imply that the universe is full of **dark matter!***

- *The total mass density (including dark matter) of the universe is only about 20% of the **critical mass density**…*

  Critical Mass Density
  The precise average density for the entire universe that marks the dividing line between a recollapsing universe and one that will expand forever.

What is Dark Matter?

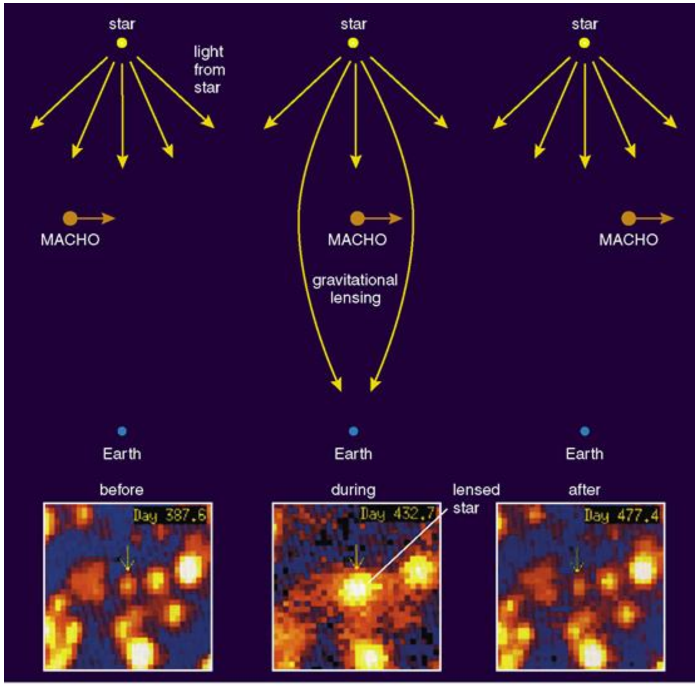
Possible Dark Matter Candidates:

- **Ordinary Dark Matter**:
  MACHOs (Massive Compact Halo Objects) – left over ordinary materials from the formation of the Milky Way still in the halo?
  - ⇒ Brown dwarfs
  - ⇒ White dwarfs,
  - ⇒ Jupiter-sized planets,
  - ⇒ Stellar-size black holes,

  Observations using gravitational lensing effects showed that there are not enough MACHOs to account for the mass of the dark matter…
- **Extraordinary Dark Mater:**
  WIMPs (Weakly interacting *massive* particles) – ***hypothetical*** heavy subatomic particles
  - ⇒ Neutrinos?
  - ⇒ Massive only in atomic particles sense…more massive than the neutrinos…

  This is still in a speculative stage…we don't know what they are or if they even exist…

Gravitational lensing effect of MACHO



Is Dark Matter Real?

- **D**o we really need dark matter to explain the observed rotation curves in galaxies?

- Remember ***Ether***? This is our historical dark matter that was proven to be not in existence.
  - In 19th century, physicists hypothesized on the existence of a omnipresence medium called ***Ether*** to carry the propagation of light!

- Recall that measurement of galactic mass are based on the assumptions that
  - The strength of gravity is given by Newton's Law of Gravity.
  - The stars and gases used to measure the rotation

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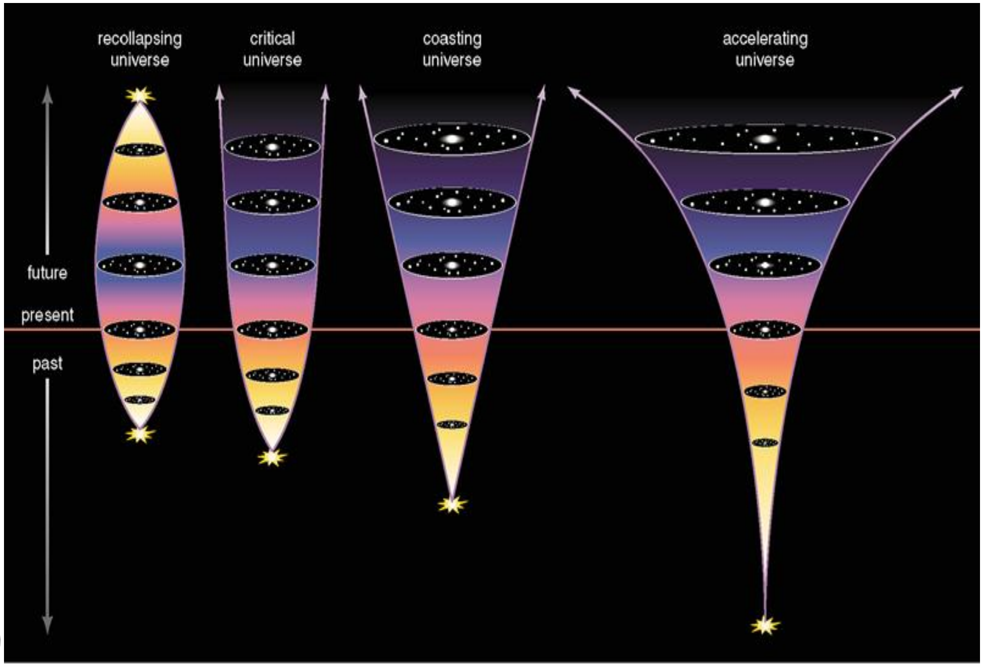
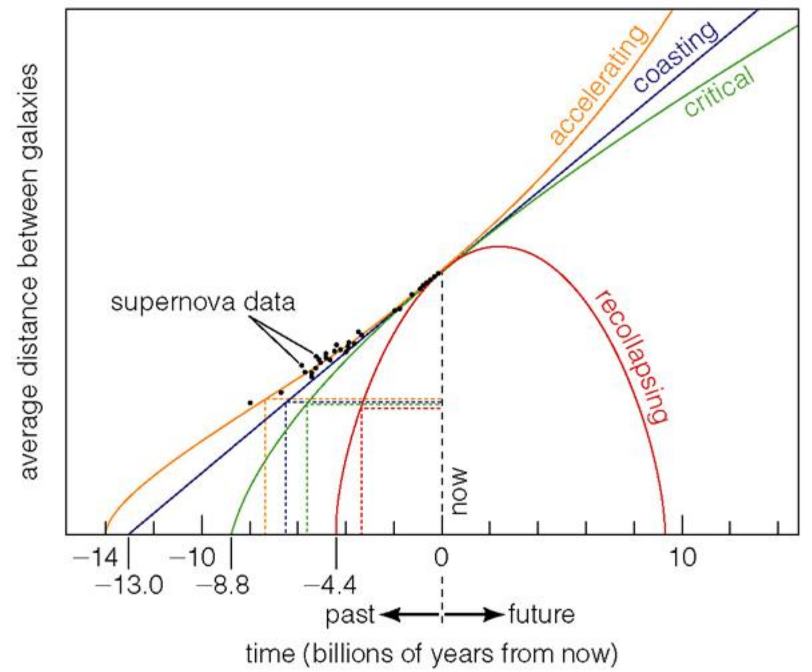


Evidence of the Acceleration of the Galaxies

Latest data suggest that the expansion rate of the universe is not static, nor is it slowing down, but ***is actually accelerating***…

- These observations, if verified, point to an ***accelerating universe*** in which the distances between the galaxies will increase at an ever increasing rate. Eventually, we will not be able to see anything around us, but vast dark, cold, and empty space.
- If the galaxies are accelerating away from each other, then some strange, unseen force must be acting on them (acceleration = force, Isaac Newton)…this is what the astronomers refer to as the ***dark energy*** of the universe.



Supernovae from Distant Galaxies

- **T**hese snapshots, taken by NASA's Hubble Space Telescope, reveal five supernovae, or exploding stars, and their host galaxies.

Dark Energy and the Cosmological Constant

"Greatest Blunder" of Einstein's Career…

Einstein believed that the universe should be standing still. In order to make his General Theory of Relativity predict a **static, flat** universe, Einstein "invented" the **cosmological constant** to act as a ***repulsive force*** to counteract the pull of gravity.

- After Hubble's discovery of the universal expansion of the universe, which contradicts Einstein's idea of static universe, Einstein referred to the addition of the cosmological constant to GR as the "greatest blunder" in his career.
- With the new evidences showing that the expansion of the universe is accelerating, astronomers have proposed that Einstein's cosmological constant may be responsible for the acceleration of the expansion fo the universe. So, maybe Einstein was correct in adding the cosmological constant to his theory…Let's wait and see.
- But while we are waiting, let's also examine if there are other possibilities…