Announcement

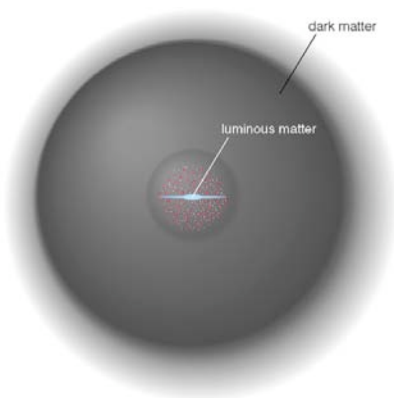
- Mid-term graded
  - Your scores can be seen on-line at CLIP.
  - Average was about 85%
- Quiz#5 on Nov 9
  - Announced at the end of this lecture.

Lecture 19
Dark Matter and Dark Energy

Reading: Chapter 22

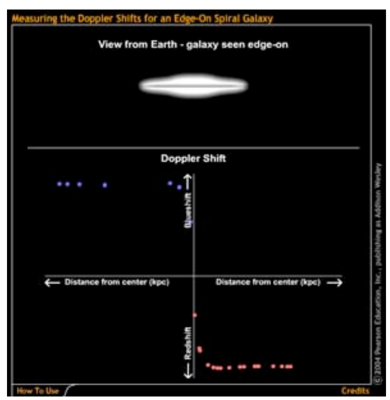
What is Dark Matter?

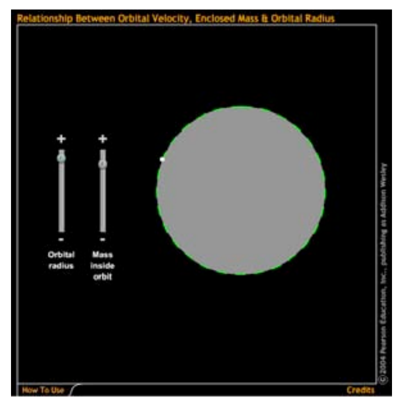
- Recall the rotation curve of the Milky Way Galaxy.
  - atomic H clouds beyond our Sun orbit faster than predicted by Newton's Law
  - most of the Galaxy's light comes from stars closer to the center than the Sun
- There are only two possible explanations for this:
  - we do not understand gravity on galaxy-size scales
  - the H gas velocities are caused by the gravitational attraction of unseen matter…called **dark matter**
- If we trust our theory of gravity...
  - there may be 10 times more dark than luminous matter in our Galaxy
  - luminous matter is confined to the disk
  - dark matter is found in the halo and far beyond the luminous disk



Determining Mass Distribution

- In Spiral Galaxies
  - measure the Doppler shift of the 21-cm radio line at various radial distances
  - construct a rotation curve of the atomic Hydrogen gas (beyond visible disk)
  - calculate the enclosed mass using Newton's Law

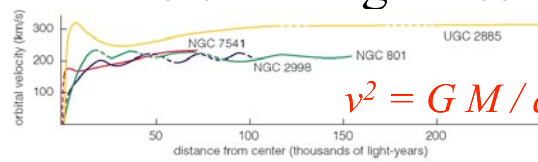




The Key Equation

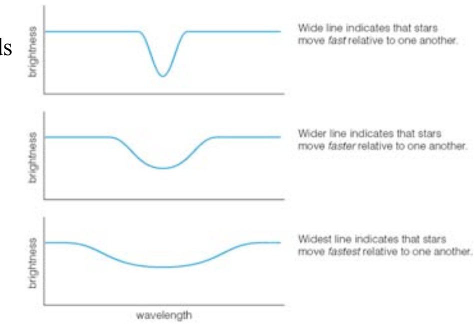
- Newton's Force Law
  - $F_{gravity} = G\,m\,M / d^2$
- Centrifugal Force
  - $F_{centrifugal} = m\,v^2 / d$
- When they equate, an object with mass m can orbit around an object with mass M. The rotation velocity then becomes
  - $v^2 = G\,M / d$
- **Rotation velocity measures mass!**

Determining Mass Distribution



$v^2 = G\,M / d$

- Rotation curves of spirals…
  - are flat at large distances from their centers
  - indicates that (dark) matter is distributed far beyond disk
- In Elliptical Galaxies
  - there is no gas
  - measure the average orbital speeds of stars at various distances
  - use broadened absorption lines
- Results indicate that dark matter lies beyond the visible galaxy.
  - we can not measure the total amount of dark matter, since we can see only the motions of stars



Mass-to-Light Ratio…

- …is the mass of a galaxy divided by its luminosity.
  - we measure both mass [$M_\odot$] and luminosity [$L_\odot$] in Solar units
- Within the orbit of the Sun, $M/L = 6\ M_\odot / L_\odot$ for the Milky Way
  - this is typical for the inner regions of most spiral galaxies
  - for inner regions of elliptical galaxies, $M/L = 10\ M_\odot / L_\odot$
    - not surprising since ellipticals contain dimmer stars
- However, when we include the outer regions of galaxies…
  - M/L increases dramatically
  - for entire spirals, M/L can be as high as $50\ M_\odot / L_\odot$
  - dwarf galaxies can have even higher M/L
- Thus we conclude that most matter in galaxies are not stars.
  - the amount of M/L over $6\ M_\odot / L_\odot$ is the amount of dark matter

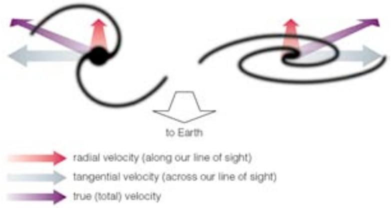
Measuring the Mass of a Cluster

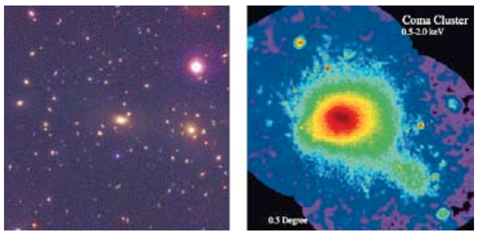
- There are three independent ways to measure galaxy cluster mass:
  1. measure the speeds and positions of the galaxies within the cluster
  2. measure the temperature and distribution of the hot gas between the galaxies
  3. observe how clusters bend light as gravitational lenses
- Orbiting Galaxies
- This method was pioneered by Fritz Zwicky.
  - assume the galaxies orbit about the cluster center
  - measure the orbital velocities of the galaxies
  - measure each galaxy's distance from the center
  - apply Newton's Law to calculate mass of cluster
- Zwicky found huge M/L ratios for clusters.
  - his proposals of dark matter were met with skepticism in the 1930s

Fritz Zwicky

Measuring the Mass of a Cluster

- Measuring galaxy orbits is not straightforward.
  - we can only measure radial velocity
  - must average all radial velocities to get the cosmological redshift (CR)
  - subtract CR from each velocity





Coma cluster of galaxies

(optical) (X-ray)

Intracluster Medium

- is the hot (10^7–10^8 K) gas between the cluster galaxies
  - this gas emits X-rays
  - from the X-ray spectrum, we can calculate the temperature
  - this tells us the average speed of the gas particles
  - again, we can estimate mass

Measuring the Mass of a Cluster

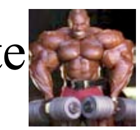
- Three methods
  - Kinematics of galaxies inside clusters
  - Temperature of ICM
  - Gravitational lensing

- The cluster masses which are measured by all three of these independent methods agree:
  - M/L for most galaxy clusters is greater than 100 $M_{\odot}/L_{\odot}$
  - galaxy clusters contain far more mass in dark matter than in stars

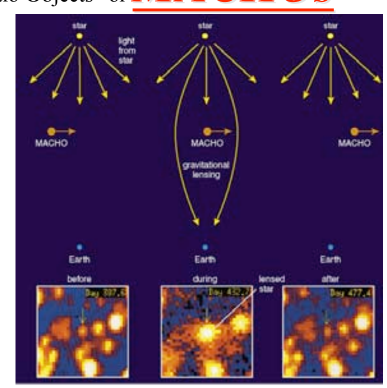
What is Dark Matter Made Of?

- Dark matter could be made out of protons, neutrons, & electrons.
  - so-called "ordinary" matter, the same matter we are made up of
  - if this is so, then the only thing unusual about dark matter is that it is dim
- However, some or all of dark matter could be made of particles which we have yet to discover.
  - this would find this to be "extraordinary" matter
- Physicists like to call ordinary matter **baryonic matter**.
  - protons & neutrons are called baryons
- They call extraordinary matter **nonbaryonic matter**.

An Ordinary Matter Candidate



- Our Galactic halo should contain baryonic matter which is dark:
  - low-mass M dwarfs, brown dwarfs, and Jovian-sized planets
  - they are too faint to be seen at large distances
  - they have been called "**MA**ssive **C**ompact **H**alo **O**bjects" or ***MACHOs***
- We detect them if they pass in front of a star where they…
  - gravitationally lens the star's light
  - the star gets much brighter for a few days to weeks
  - we can measure the MACHO's mass
- These events occur to only one in a million stars per year.
  - must monitor huge numbers of stars
  - # of MACHOs detected so far does not account for the Milky Way's dark matter



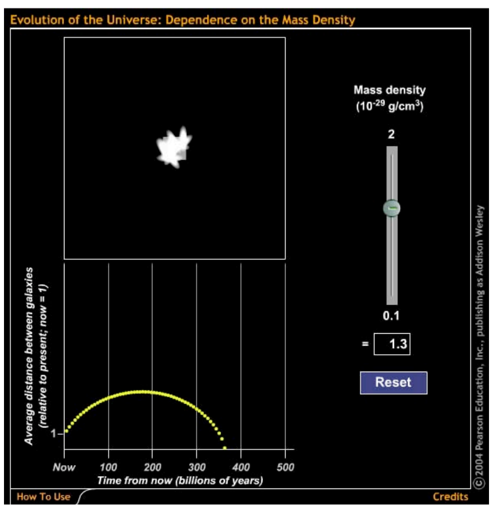
An Extraordinary Matter Candidate

- We have already studied a nonbaryonic form of matter:
  - the **neutrino**…detected coming from the Sun
  - neutrinos interact with other particles through only two of the natural forces:
    - gravity
    - weak force (hence we say they are "weakly interacting")
  - their masses are so low & speeds so high, they will escape the gravitational pull of a galaxy…they can **not** account for the dark matter observed
- But what if there existed a *massive* weakly interacting particle?
  - physicists call them "**W**eakly **I**nteracting **M**assive **P**articles" or ***WIMPs***
  - these particles are theoretical; they have not yet been discovered
  - they would be massive enough to exert gravitational influence
  - they would emit no electromagnetic radiation (light) or be bound to any charged matter which could emit light
  - as weakly interacting particles, they would not collapse with a galaxy's disk
  - yet they would remain gravitationally bound in the galaxy's halo

The Critical Density

- We have seen that gravitational attraction between galaxies can overcome the expansion of the Universe in localized regions.
  - how strong must gravity be to **stop the entire Universe from expanding**?
  - it depends on the total mass density of the Universe
- We refer to the mass density required for this gravitational pull to equal the kinetic energy of the Universe as the **critical density**.
  - if mass < critical density, the Universe will expand forever
  - if mass > critical density, the Universe will stop expanding and then contract
- The value of H_o tells us the current kinetic energy of the Universe.
  - this being known, the critical density is 10^{-29} g / cm^3
  - all the luminous matter that we observe accounts for < 1% of critical density
  - for dark matter to stop Universal expansion, the average M/L of the Universe would have to be 1,000 $M_\odot / L_\odot$ … a few times greater than clusters
- This line of research suggests the Universe will expand forever!

How Mass Density affects the Expansion of the Universe

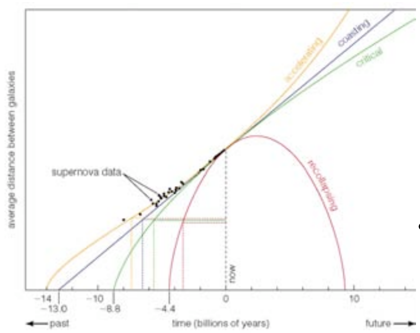


- In 1998, a group of astronomers discovered that supernovae appear to be too faint compared to the usual expectations.
- The universe WAS bigger than expected -- the interpretation is that the universe is accelerating.
- But, what causes accelerations?
  - **DARK ENERGY**

ADAM RIESS

Does Gravity alone Influence the Expansion?

- Recent observations of white dwarf supernovae in very distant galaxies have yielded unexpected results.
  - remember, white dwarf supernovae make very good standard candles: the supernovae are apparently fainter than predicted for their redshifts



- At a given cosmological redshift
  - galaxies should be closer to us…

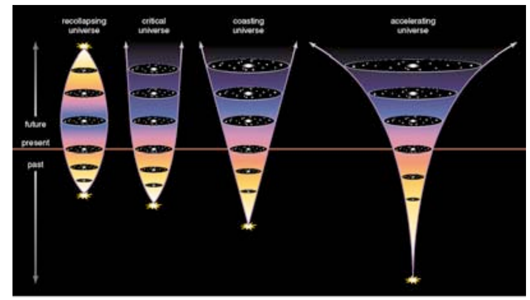
    i.e. shorter lookback time

    …for greater Universal mass densities
  - these supernova are farther back in time than even the models for an ever-expanding (coasting) Universe predict
- This implies that the Universal expansion is *accelerating*!
  - there must be an as yet unknown force which repels the galaxies
  - a **Dark Energy**

Four Models for the Future of the Universe

1. Recollapsing Universe: the expansion will someday halt and reverse
2. Critical Universe: will not collapse, but will expand more slowly with time
3. Coasting Universe: will expand forever with little slowdown
4. Accelerating Universe*: the expansion will accelerate with time

   *currently favored



Next Station: Cosmic History

- Next lecture: An Overview
  - Reading: Chapter 23
- Quiz#5 on Nov 9.
  - 11 Multiple choices from
    - Sensible Statements? Chapter 19, 20
    - True Statements? Chapter 21, 22
  - Short Answer questions about
    - *Rotation curves and dark matter* (Problem 9&15; Chapter 22)