22. Dark Matter and the Fate of the Universe

It is difficult beyond description to conceive that space can have no end; but it is more difficult to conceive an end. It is difficult beyond the power of man to conceive an eternal duration of what we call time; but it is more impossible to conceive a time when there shall be no time.

Thomas Paine (1737 – 1809)
American patriot, from The Age of Reason

Agenda

- Announce:
  - Part 2 of projects due
  - Observations Wed & Thurs 8pm if weather nice (can check web)
  - Lab 2 *Solar Altitude* Lab Due 4/18 (ask questions Thursday)
- Ch. 22—Dark Matter
- Let out early for “Religion and Science” at 3:30pm

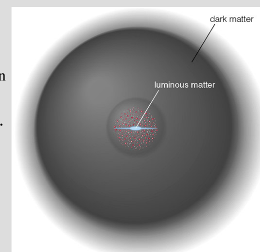
22.1 The Mystery of Dark Matter

Our goals for learning:

- Does dark matter really exist?
- How does the distribution of dark matter compare to the distribution of luminous matter in spiral galaxies?

What is Dark Matter?

- Recall the rotation curve of the Milky Way Galaxy.
  - atomic H clouds beyond our Sun orbit faster than predicted by Kepler’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



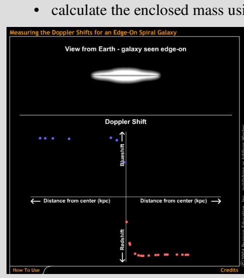
22.2 Dark Matter in Galaxies

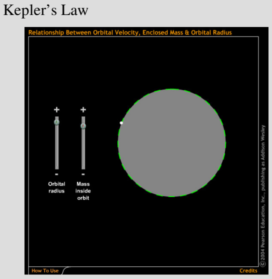
Our goals for learning:

- How do we determine the distribution of mass in distant galaxies?
- How does a galaxy’s mass-to-light ratio tell us how much dark matter it contains?
- What have we learned about galaxies from their mass-to-light ratios?

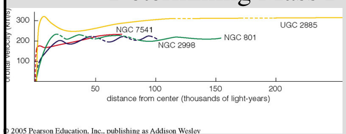
Determining Mass Distribution

- 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 Kepler’s Law

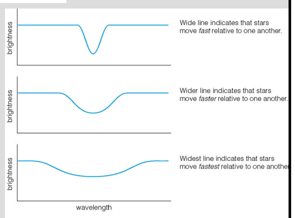




Determining Mass Distribution



- 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

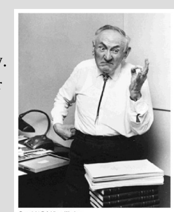
22.3 Dark Matter in Clusters

Our goals for learning:

- Describe three independent ways to measure the total mass of a cluster of galaxies.
- What have we learned about dark matter in galaxy clusters?

Measuring the Mass of a Cluster

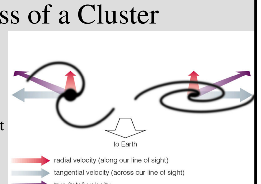
- There are three independent ways to measure galaxy cluster mass:
  1. measure the speeds and positions of the galaxies within the cluster
  2. measure the temperature and distribution of the hot gas between the galaxies
  3. observe how clusters bend light as gravitational lenses
- Orbiting Galaxies
- 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 Kepler'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

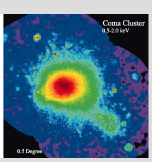


Fritz Zwicky

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



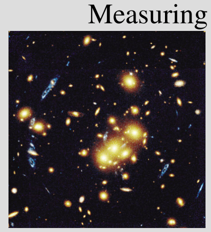


Coma cluster of galaxies
(optical) (X-ray)

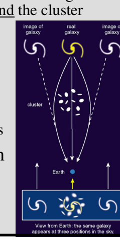
Intracluster Medium

- 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



- This is a **gravitational lens**.
- Einstein's Theory of Relativity states that massive objects distort spacetime.
  - a massive cluster will bend the path of light which approaches it (like a lens)
  - the blue arcs are the lensed images of a galaxy which is behind the cluster
- The angle at which the light is bent depends on the mass of the cluster.
  - by analyzing lensed images, we can calculate cluster mass
- All previous methods for finding mass depended on Newton's Law of Gravity.
  - this method uses a different theory of gravity



Measuring the Mass of a Cluster

- 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

22.4 Dark Matter: Ordinary or Extraordinary?

Our goals for learning:

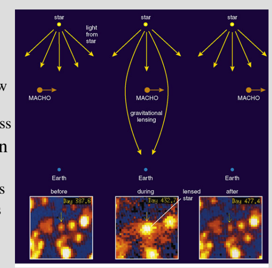
- What do we mean when we ask whether dark matter is ordinary or extraordinary matter?
- What are MACHOs, and can they account for dark matter?
- What are WIMPs, and can they account for dark matter?
- Why can't neutrinos account for dark matter in galaxies?

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 "MAssive Compact Halo Objects" 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

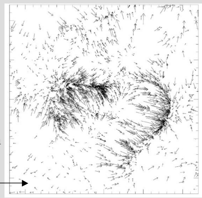
- We have already studied a nonbaryonic form of matter:
  - the **neutrino**…detected coming from the Sun
  - neutrinos interact with other particles through only two of the natural forces:
    - gravity
    - weak force (hence we say they are "weakly interacting")
  - their masses are so low & speeds 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 "Weakly Interacting Massive Particles" 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

22.5 Structure Formation

Our goals for learning:

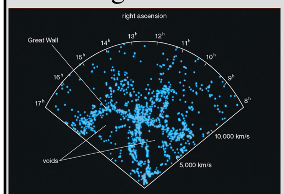
- How does structure appear to be growing in the Universe?
- What does the Universe look like on very large scales?

The Growth of Structure

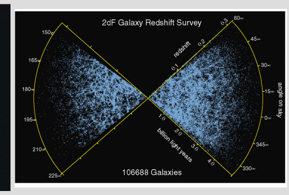


- At close range, gravitational attraction overcomes the Hubble expansion.
  - we see this in a galaxy's **peculiar velocity**
  - although the Universe as a whole expands, individual galaxies attract one another
  - peculiar velocity is a galaxy's deviation from the Hubble Law
  - can measure it for galaxies out to 3 x 10^8 ly ⟶
- We project that Universal structure began with slight enhancements in the density of matter in the early Universe.
  - these regions collapsed into protogalactic clouds to form *galaxies*
  - individual *galaxies* fell in towards one another to form *clusters*
  - individual *clusters* are now congregating to form *superclusters*
- These "collapses" against Universal expansion are facilitated by dark matter.

Large Scale Structure of the Universe



slice of the Universe out to 7 x 10^8 ly

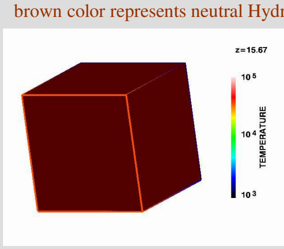


slice of the Universe out to 4 x 10^9 ly

- On scales of 10^8 ly, galaxies are distributed in gigantic chains and sheets surrounding great voids.
  - the chains come from the initial regions of density enhancement
  - the voids come from the initial regions of density depletion
- On scales of several x 10^9 ly, galaxies appear evenly distributed.

Computer Simulation of Structure Formation

brown color represents neutral Hydrogen



$$z = \frac{\Delta\lambda}{\lambda} = redshift$$

simulation courtesy of Prof. Nickolay Gnedin, University of Colorado

22.6 The Universe's Fate

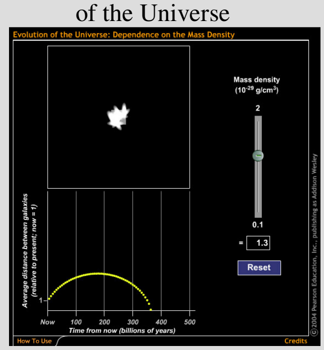
Our goals for learning:

- What is the critical density?
- What are the four general models for the future expansion of the Universe? Which model is currently favored?
- Do we know what might be causing the universe to accelerate?

The Critical Density

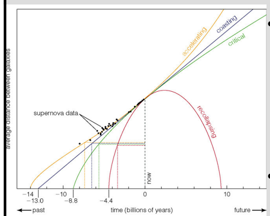
- We have seen that gravitational attraction between galaxies can overcome the expansion of the Universe in localized regions.
  - how strong must gravity be to stop the entire Universe from expanding?
  - it depends on the total mass density of the Universe
- We refer to the mass density required for 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



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

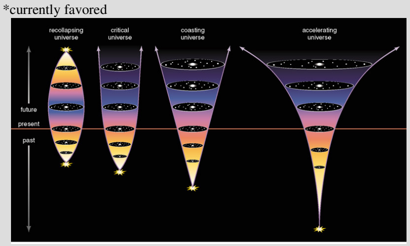


- At a given cosmological redshift
  - galaxies should be closer to us…
    i.e. shorter lookback time
    …for greater Universal mass densities
  - these supernova are farther back in time than even the models for an ever-expanding (coasting) Universe predict
- This implies that the Universal expansion 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



What have we learned?

- Does dark matter really exist?
  - We infer the existence of dark matter from its gravitational effects on visible matter. The evidence for its existence is overwhelming — if we correctly understand the theory of gravity. Although the success of our theory of gravity in so many other cases makes it unlikely that we could be misinterpreting the evidence for dark matter, we cannot completely rule out this possibility.
- How does the distribution of dark matter compare to the distribution of luminous matter in spiral galaxies?
  - The luminous matter is concentrated in the disk, while the dark matter is distributed throughout the spherical halo and far beyond the visible light from the disk.

What have we learned?

- How do we determine the distribution of mass in distant galaxies?
  - For a spiral galaxy, we can determine its mass distribution from its rotation curve. A rotation curve that is flat at large distances from the galactic center tells us that mass is widely distributed in the galactic halo. We can determine the mass distribution of an elliptical galaxy from the average orbital speeds of its stars at different distances from the center, as measured from the broadening of the galaxy's spectral lines.
- How does a galaxy's mass-to-light ratio tell us how much dark matter it contains?
  - The mass-to-light ratio tells us how many solar masses of matter the galaxy contains for each solar luminosity of light output. Because we can estimate the mass-to-light ratio the galaxy would have if it were made only of stars, we know that any excess mass must be dark matter.

What have we learned?

- What have we learned about galaxies from their mass-to-light ratios?
  - The mass-to-light ratios in the outer reaches of galaxies are particularly high, telling us that stars alone cannot account for the mass. Thus, we conclude that galaxies contain large amounts of dark matter.

What have we learned?

- Describe three independent ways to measure the total mass of a cluster of galaxies.
  - (1) We can use the orbital speeds and positions of the galaxies to estimate the cluster's mass. (2) We can estimate the cluster's mass from the temperature and distribution of its hot, intracluster medium, which we can measure with X-ray observations. (3) We can measure a cluster's mass, and sometimes the distribution of its mass, by observing how it affects the appearance of more distant galaxies distorted by the gravitational lensing of the cluster.
- What have we learned about dark matter in galaxy clusters?
  - All three methods of measuring cluster masses agree and imply large amounts of dark matter in clusters.

What have we learned?

- What do we mean when we ask whether dark matter is ordinary or extraordinary matter?
  - Ordinary matter is made from protons, neutrons, and electrons; we refer to it as baryonic matter because protons and neutrons are both classified as baryons. However, the baryonic matter we have found does not account for all the dark matter. It is possible that much of the dark matter is made of nonbaryonic particles that have yet to be discovered. This form of matter would be very different from that which we encounter in daily life, and hence is considered extraordinary.

What have we learned?

- What are MACHOs, and can they account for dark matter?
  - MACHO is short for massive compact halo object and refers to ordinary objects that might populate the galactic halo without being visible to our telescopes — such as dim stars, brown dwarfs, and planet-size bodies. Attempts to detect MACHOs through gravitational lensing show that they do indeed exist, but probably not in large enough numbers to account for all the dark matter inferred from gravitational effects.
- What are WIMPs, and can they account for dark matter?
  - WIMP is short for weakly interacting massive particle, and refers to undiscovered particles of extraordinary (nonbaryonic) matter that do not interact with light (instead interacting only through the weak force and gravity). WIMPs are the leading candidate for dark matter, even though we have not yet discovered such particles.

What have we learned?

- Why can't neutrinos account for dark matter in galaxies?
  - Although neutrinos are weakly interacting particles and thus are form of dark matter, they travel too fast to be gravitationally bound in galaxies. They could potentially account for some dark matter outside galaxies, but the dark matter within galaxies must be made from more massive particles, such as WIMPs.

What have we learned?

- How does structure appear to be growing in the universe?
  - All the structure we see today probably grew from regions of slightly enhanced density in the early universe. Gravity in these higher density regions drew matter together to form galaxies and later drew those galaxies together to form clusters. Some clusters of galaxies appear to be still in the process of formation, suggesting that gravity continues to matter into large-scale structures. Likewise, clusters of galaxies appear to be part of even larger structures called superclusters, which are just beginning to form.
- What does the universe look like on very large scales?
  - Galaxies appear to be distributed in gigantic chains and sheets that surround great voids. These giant structures trace their origin directly back to regions of slightly enhanced density early in time.

What have we learned?

- What is the critical density?
  - The critical density is the average matter density the universe must have in order for the strength of gravity to be enough to someday halt the expansion of the universe (assuming today's expansion rate). Although there may yet be dark matter unaccounted for, it appears that the overall matter density of the universe is only about 30% of the critical density.

What have we learned?

- Describe the four general models for the future expansion of the universe. Which model is currently favored?
  - (1) Recollapsing universe: the expansion will someday halt and reverse. (2) Critical universe: the universe will never collapse but will expand more and more slowly with time. (3) Coasting universe: the universe will continue to expand forever, with little change in the rate of expansion. (4) Accelerating universe: the expansion of the universe will accelerate with time. Recent observations favor the accelerating universe.
- Do we know what might be causing the universe to accelerate?
  - No. Although people give names to the mysterious force that could be causing acceleration — such as dark energy, quintessence, or cosmological constant — no one really knows what it is.

Astronomers now believe that most of any galaxy's mass lies beyond the portions of the galaxy that we can see.

a. Yes, because the orbital velocity of gas and stars remains fairly constant as we look farther from the galactic center, even beyond where most stars are found.
b. Yes, because dark matter telescopes show massive halos well beyond where stars are found.
c. Yes, because the mass-to-light ratio of galaxies is much less than the value for the Sun.
d. Yes, because the mass-to-light ratio of galaxies is much greater than the value for the Sun.
e. No, once we take into consideration the gas in a galaxy as well as the stars, we can account for all its mass.

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If our galaxy had less dark matter, its mass-to-light ratio would be lower.

a. Yes, because the galaxy would have less mass but higher luminosity.
b. Yes, because the amount of mass divided by the amount of starlight would be lower.
c. No, because the amount of mass divided by the amount of starlight would be higher.
d. No, if there was less dark matter, there would be less light so the mass-to-light ratio would stay the same.
e. No, if there was less dark matter, there would be less light so the mass-to-light ratio would be higher.

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A cluster of galaxies is held together by the mutual gravitational attraction of all the stars in the cluster's galaxies.

a. Yes, in the same way that the mutual gravitational attraction of all the stars in the Milky Way holds it together.
b. Yes, a large cluster can contain many billions of stars, sufficient to hold the cluster together.
c. No, the amount of mass in a cluster's stars is much lower than the amount needed to hold the cluster together.
d. No, X-ray observations show that the hot gas between the clusters has enough mass to hold clusters together.
e. No, the focusing effect of gravitational lensing prevents individual galaxies from leaving a cluster.

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So far, clusters of galaxies are the largest structures that have been detected in the universe.

a. Yes, some clusters have been found to contain thousands of galaxies.
b. Yes, the largest clusters stretch halfway across the sky.
c. No, there are several nearby galaxies that have a much larger angular size than distant galaxy clusters.
d. No, clusters are themselves parts of even larger superclusters.
e. No, quasars are the largest objects in the universe.

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The primary evidence for an accelerating universe comes from observations of young stars in the Milky Way.

a. Yes, observations show that there were many more young, massive stars in the early universe.
b. Yes, the supernova that results at the end of a massive star allows us to measure the expansion rate of the universe.
c. No, in order to measure accelerating expansion, we need to measure the distances of objects billions of light-years away.
d. No, evidence for an accelerating universe comes from observations of the oldest stars in the Milky Way, white dwarfs.
e. No, we have to look at young stars in other galaxies beyond the Milky Way to measure the acceleration of the universe.

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