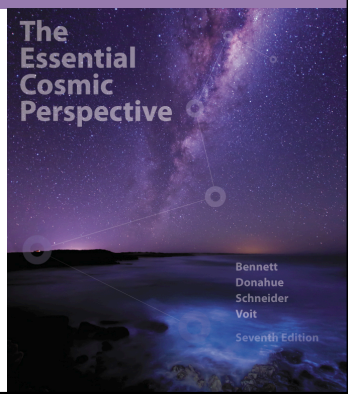
Lecture Outline

## Chapter 18: Dark Matter, Dark Energy, and the Fate of the Universe






## 18.1 Unseen Influences in the Cosmos

Our goals for learning:

- What do we mean by dark matter and dark energy?



## What do we mean by dark matter and dark energy?



## Unseen Influences

- ***Dark matter:*** An undetected form of mass that emits little or no light but whose existence we infer from its gravitational influence
- ***Dark energy:*** An unknown form of energy that seems to be the source of a repulsive force causing the expansion of the universe to accelerate



## Contents of Universe

- Normal matter: ~ 5%
  - Normal matter inside stars: ~ 0.5%
  - Normal matter outside stars: ~ 4.5%
- Dark matter: ~ 27%
- Dark energy: ~ 68%



## What have we learned?

- What do we mean by dark matter and dark energy?
  - Dark matter is the name given to the unseen mass whose gravity governs the observed motions of stars and gas clouds.
  - Dark energy is the name given to whatever might be causing the expansion of the universe to accelerate.

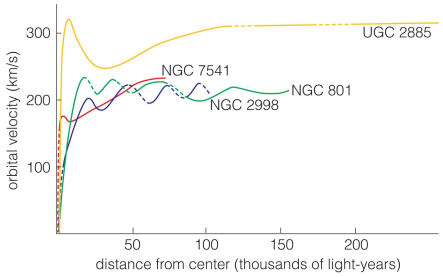
## 18.2 Evidence for Dark Matter

Our goals for learning:

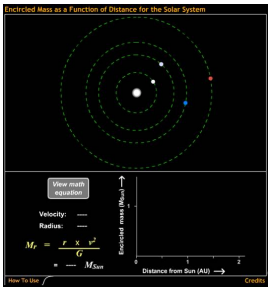
- What is the evidence for dark matter in galaxies?
- What is the evidence for dark matter in clusters of galaxies?
- Does dark matter really exist?
- What might dark matter be made of?



## What is the evidence for dark matter in galaxies?






We measure the mass of the solar system using the orbits of planets.

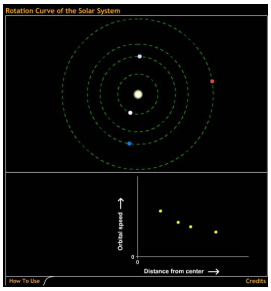
- Orbital period
- Average distance

Or for circles:

- Orbital velocity
- Orbital radius

PLAY Encircled Mass as a Function of Distance for the Solar System






***Rotation curve***

A plot of orbital speed versus orbital radius

Solar system's rotation curve declines because Sun has almost all the mass.

PLAY Rotation Curve of the Solar System




Who has the largest orbital speed?
A, B, or C?

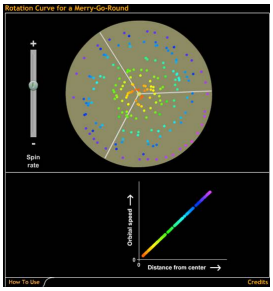
PLAY Motion on a Merry-Go-Round




Who has the largest orbital speed?
A, B, or C?

**Answer: C**

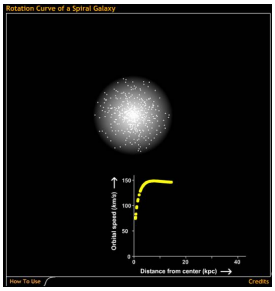
PLAY Motion on a Merry-Go-Round




Rotation curve of merry-go-round rises with radius.

PLAY Rotation Curve for a Merry-Go-Round



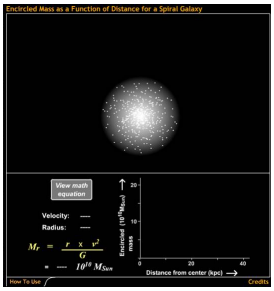



The rotation curve of the Milky Way stays flat with distance.

Mass must be more spread out than in the solar system.

PLAY Rotation Curve of a Spiral Galaxy






The mass in the Milky Way is spread out over a larger region than the stars.

Most of the Milky Way's mass seems to be ***dark matter!***

PLAY Encircled Mass as a Function of Distance for a Spiral Galaxy

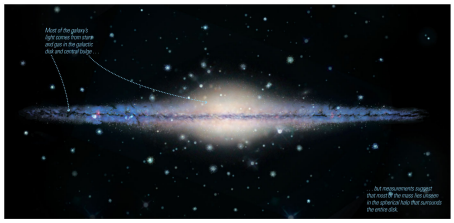


Mass within Sun's orbit:

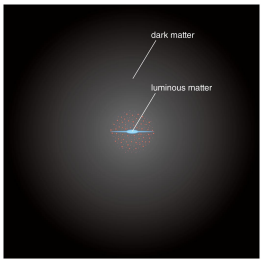
$1.0 \times 10^{11} M_{Sun}$

Totalmass:

$\sim 10^{12} M_{Sun}$

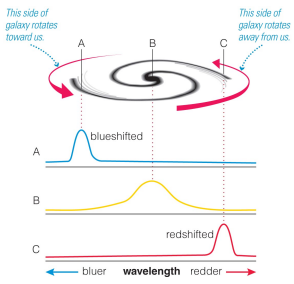




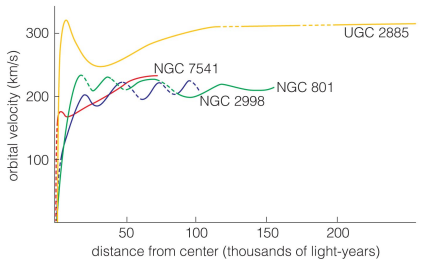



The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.



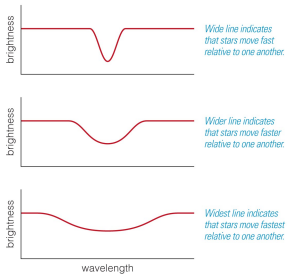



We can measure orbital velocities in other spiral galaxies using the Doppler shift of the 21-cm line of atomic H.




Spiral galaxies all tend to have orbital velocities that remain constant at large radii, indicating large amounts of dark matter.






The broadening of spectral lines in elliptical galaxies tells us how fast the stars are orbiting.

These galaxies also have dark matter.



## Thought Question

What would you conclude about a galaxy in which orbital velocities rise steadily with distance beyond the visible part of its disk?

A. Its mass is concentrated at the center.
B. It rotates like the solar system.
C. It is especially rich in dark matter.
D. It's just like the Milky Way.



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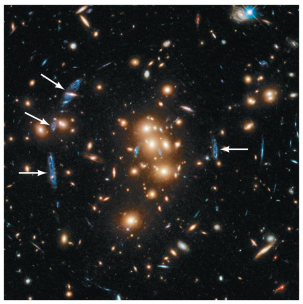
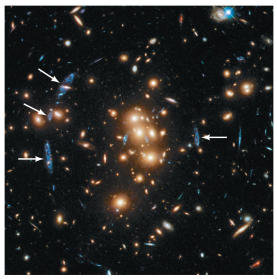
## What is the evidence for dark matter in clusters of galaxies?





We can measure the velocities of galaxies in a cluster from their Doppler shifts.



The mass we find from galaxy motions in a cluster is about

***50 times*** larger than the mass in stars!

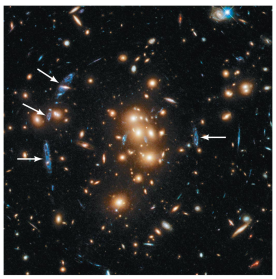


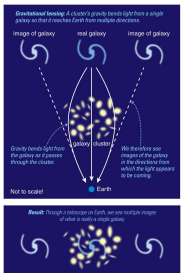
Clusters contain large amounts of X-ray–emitting hot gas.

The temperature of hot gas (particle motions) tells us cluster mass:

85% dark matter
13% hot gas
2% stars

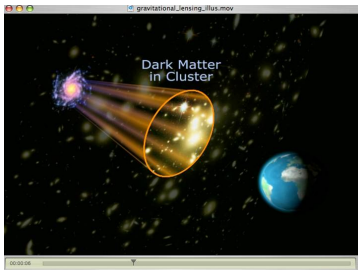







***Gravitational lensing***, the bending of light rays by gravity, can also tell us a cluster's mass.






A gravitational lens distorts our view of things behind it.

PLAY Gravitational Lensing Illustrated



All three methods of measuring cluster mass indicate similar amounts of dark matter.



## Thought Question

What kind of measurement does not tell us the 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

## Thought Question

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

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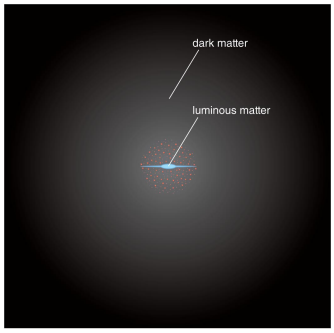
D. Measuring distorted images of background galaxies



## Does dark matter really exist?






## Our Options

1. Dark matter really exists, and we are observing the effects of its gravitational attraction.
2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter.

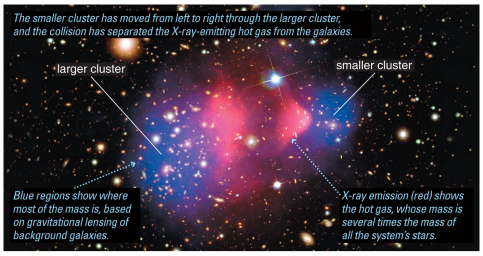


## Our Options

1. Dark matter really exists, and we are observing the effects of its gravitational attraction.
2. Something is wrong with our understanding of gravity, causing us to mistakenly infer the existence of dark matter.

***Because gravity is so well tested, most astronomers prefer option #1.***






The Bullet Cluster, the collision of two smaller clusters, provides strong evidence for the existence of dark matter. Here the blue represents the bulk of the cluster mass, while the pink represents the gas (visible matter.)



## What might dark matter be made of?

## How dark is it?



## How dark is it?

… not as bright as a star.



## Two Basic Options

- Ordinary Matter (MACHOs)
  - Massive Compact Halo Objects: dead or failed stars in halos of galaxies
- Exotic Particles (WIMPs)
  - Weakly Interacting Massive Particles: mysterious neutrino-like particles



## Two Basic Options

- Ordinary Matter (MACHOs)
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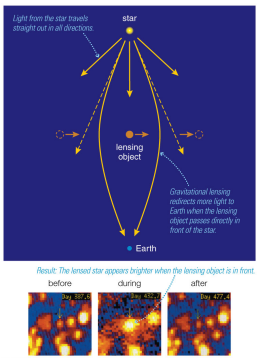
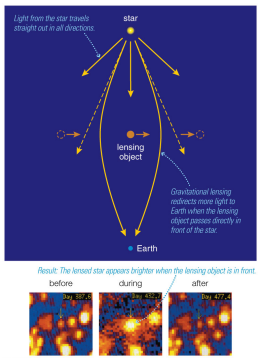
The Best Bet






Compact starlike objects occasionally make other stars appear brighter through lensing…






Compact starlike objects occasionally make other stars appear brighter through lensing…

… but there are not enough lensing events to explain all the dark matter.

## Why WIMPs?

- There's not enough ordinary matter.
- WIMPs could be left over from the Big Bang.
- Models involving WIMPs explain how galaxy formation works.



## What have we learned?

- What is the evidence for dark matter in galaxies?
  - Orbital velocities within galaxies remain nearly constant at large radii, indicating that most of the matter lies outside the visible regions.
- What is the evidence for dark matter in clusters of galaxies?
  - Masses measured from galaxy motions, temperature of hot gas, and gravitational lensing all indicate that the vast majority of matter in clusters is dark.



## What have we learned?

- Does dark matter really exist?
  - Either dark matter exists or our understanding of our gravity must be revised.
- What might dark matter be made of?
  - There does not seem to be enough normal (baryonic) matter to account for all the dark matter, so most astronomers suspect that dark matter is made of (nonbaryonic) particles that have not yet been discovered.



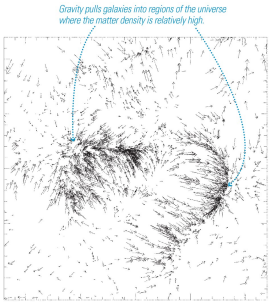
## 18.3 Structure Formation

Our goals for learning:

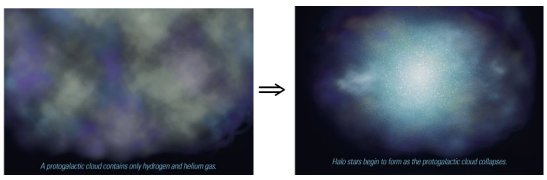
- What is the role of dark matter in galaxy formation?
- What are the largest structures in the universe?



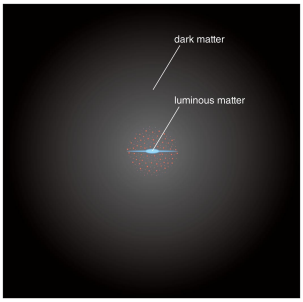
## What is the role of dark matter in galaxy formation?





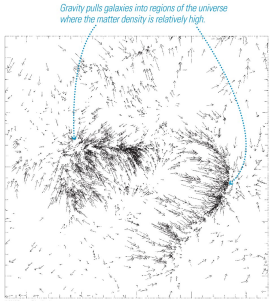




Gravity of dark matter is what caused protogalactic clouds to contract early in time.




WIMPs can't contract to the center because they don't radiate away their orbital energy.



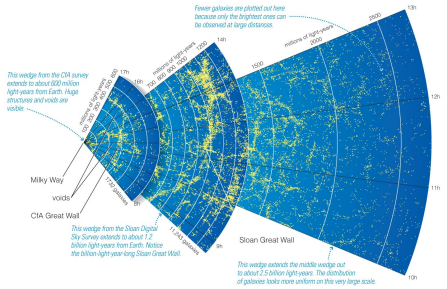



Dark matter is still pulling things together.

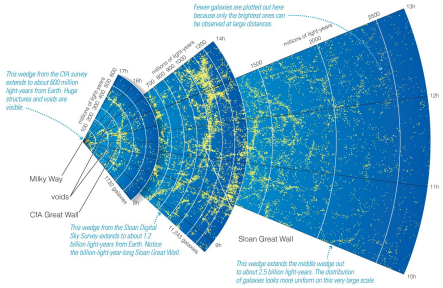
After correcting for Hubble's law, we can see that galaxies are flowing toward the densest regions of space.



## What are the largest structures in the universe?

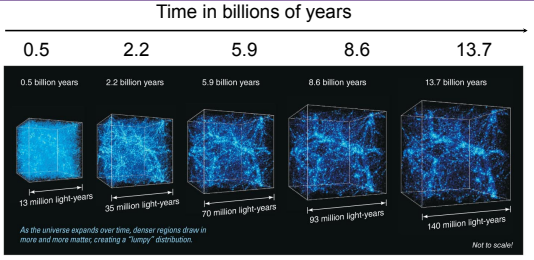




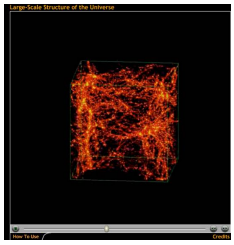

Maps of galaxy positions reveal extremely large structures: ***superclusters*** and ***voids.***





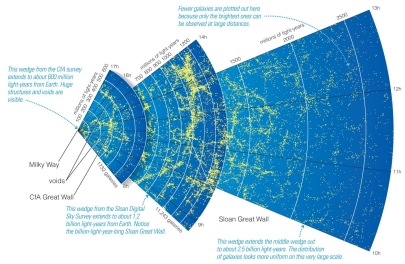

Models show that the gravity of dark matter pulls mass into denser regions—the universe grows lumpier with time.






Models show that gravity of dark matter pulls mass into denser regions—the universe grows lumpier with time.

PLAY Large-Scale Structure of the Universe




Structures in galaxy maps look very similar to the ones found in models in which dark matter is WIMPs.



## What have we learned?

- What is the role of dark matter in galaxy formation?
  - The gravity of dark matter seems to be what draws gas together into protogalactic clouds, initiating the process of galaxy formation.
- What are the largest structures in the universe?
  - Galaxies appear to be distributed in gigantic chains and sheets that surround great voids.



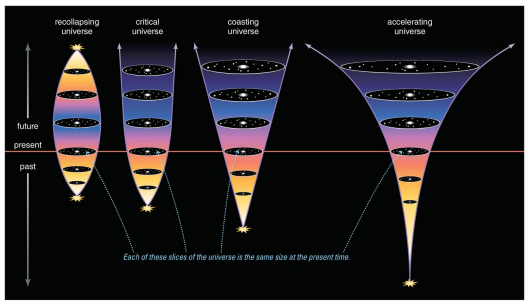
## 18.4 Dark Energy and the Fate of the Universe

Our goals for learning:

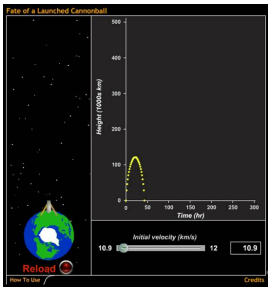
- What is the evidence for an accelerating expansion?
- Why is flat geometry evidence for dark energy?
- What is the fate of the universe?



## What is the evidence for an accelerating universe?



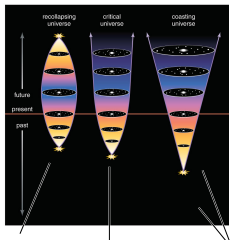



Does the universe have enough kinetic energy to escape its own gravitational pull?

PLAY Fate of a Launched Cannonball





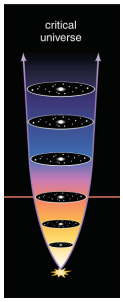

Fate of universe depends on the amount of dark matter.

Lots of dark matter

Critical density of matter

Not enough dark matter

Amount of matter is ~25% of the critical density, suggesting fate is eternal expansion.

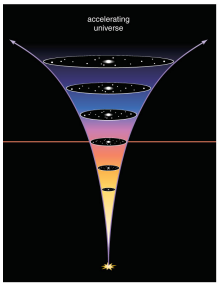



Not enough dark matter



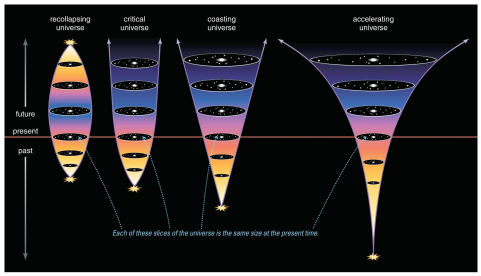
But expansion appears to be speeding up!

Dark energy?




Not enough dark matter






old older oldest

Estimated age depends on both dark matter and dark energy.



## Thought Question

Suppose that the universe has more dark matter than we think there is today. How would that change the age we estimate from the expansion rate?

A. Estimated age would be older
B. Estimated age would be the same
C. Estimated age would be younger



## Thought Question

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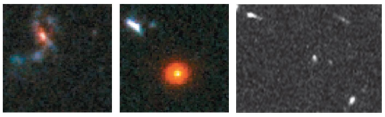
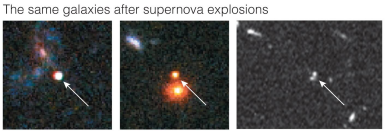
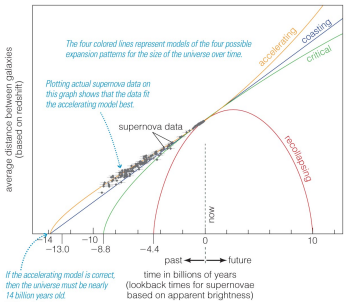
Distant galaxies before supernova explosions



The same galaxies after supernova explosions



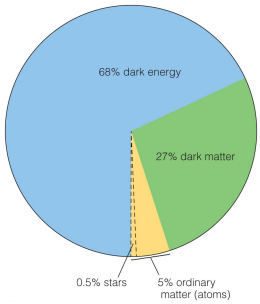
The brightness of distant white dwarf supernovae tells us how much the universe has expanded since they exploded.



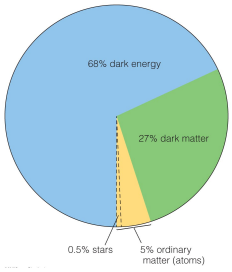

An accelerating universe is the best fit to supernova data.



## Why is flat geometry evidence for dark energy?



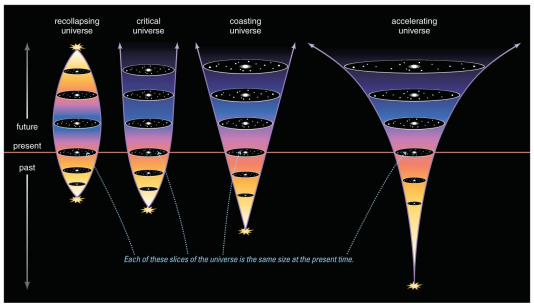


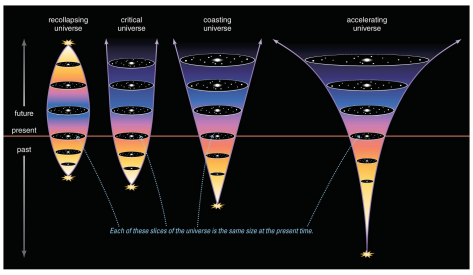

Observations tell us that the density of the universe is equal to the critical density, but we can only account for 30% of that with matter!



## What is the fate of the universe?






We expect that the universe will continue expanding forever, as dark energy continues to accelerate the expansion!



## What have we learned?

- What is the evidence for an accelerating expansion?
  - An accelerating universe is the best explanation for the distances we measure when using white dwarf supernovae as standard candles.
- Why is flat geometry evidence for dark energy?
  - If the overall geometry of the universe is flat, and matter makes up only 30% of the energy required to make it so, then we need dark energy to make up the remaining energy.

## What have we learned?

- What is the fate of the universe?
  - Seemingly, the universe will forever expand.