Dark Matter, Dark Energy, and the Fate of the Universe
23.1 Unseen Influences in the Cosmos

- Our goals for learning:
  - What do we mean by dark matter and dark energy?
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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

- "Ordinary" matter: ~ 4.4%
  - Ordinary matter inside stars: ~ 0.6%
  - Ordinary matter outside stars: ~ 3.8%
- Dark matter: ~ 23%
- Dark energy: ~ 73%
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.
23.2 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

For circles:

- orbital velocity
- orbital radius
Rotation curve

- A plot of orbital velocity versus orbital radius
- The solar system's rotation curve declines because the Sun has almost all the mass.
Who has the largest orbital velocity?

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

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Answer: C
The rotation curve of a merry-go-round rises with radius.
The rotation curve of the Milky Way stays flat with distance.

Mass must be more spread out than in the solar system.
Mass in the Milky Way is spread out over a larger region than its stars.

Most of the Milky Way’s mass seems to be dark matter!
• Mass within the Sun's orbit:

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

Total mass:

$\sim 10^{12} M_{\text{Sun}}$
The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.
We can measure the rotation curves of other spiral galaxies using the Doppler shift of the 21-cm line of atomic hydrogen.
Spiral galaxies all tend to have flat rotation curves, indicating large amounts of dark matter.
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 whose rotational velocity rises 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’s especially rich in dark matter.
D. It’s just like the Milky Way.
Thought Question

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What is the evidence for dark matter in clusters of galaxies?
Method #1: Cluster Velocities

- We can measure the velocities of galaxies in a cluster from their Doppler shifts.
Method #1: Cluster Velocities

- The mass we find from galaxy motions in a cluster is about 50 times larger than the mass in stars!
Method #1: Gas Temperatures

- Clusters contain large amounts of X-ray-emitting hot gas.
- Temperature of hot gas (particle motions) tells us cluster mass:
  - 85% dark matter
  - 13% hot gas
  - 2% stars
Method #3: Gravitational Lensing
All three methods of measuring cluster mass indicate similar amounts of dark matter in galaxy clusters.
What kind of measurement does not tell us the mass of a cluster of galaxies?

A. measuring velocities of cluster galaxies
B. measuring the total mass of cluster's stars
C. measuring the temperature of its hot gas
D. measuring distorted images of background galaxies
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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.
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Because gravity is so well tested, most astronomers prefer option #1.
Some observations of the universe are very difficult to explain without dark matter.
What might dark matter be made of?

Measurements of deuterium match model predictions only for this narrow range in the density of ordinary matter.
Two Basic Options

- Ordinary Dark Matter (MACHOs)
  - Matter made of protons, neutrons, electrons, but too dark to detect with current instruments

- Extraordinary Dark Matter (WIMPs)
  - Weakly Interacting Massive Particles: mysterious neutrino-like particles
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The best bet
Measurements of light element abundances indicate that ordinary matter cannot account for all of the dark matter.
Why Believe in WIMPs?

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

- What is the evidence for dark matter in galaxies?
  - Rotation curves of galaxies are flat, indicating that most of their matter lies outside their 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 (non-baryonic) particles that have not yet been discovered.