Turning in Your Moon Project Write-up

- You can hand it in to your TA during normal lab hours
- You can bring it to the Astronomy 1001 TA office hours room:
  - Tate 510-02
  - Follow the signs to the Observatory
- TAs will be there from 11am until 3pm Friday December 1
- For any additional information see your lab syllabus or contact your Astronomy 1001 TA.

Important Stuff (Section 001)

- The Final Exam is Tuesday, December 19, 8:00 – 10:00 am
- The Final Exam will be given in:
  - Tate B20 (last names starting with A-K)
  - Tate B50 (last names starting with L-Z)
  - Bring 2 pencils and a photo-id.
- In accordance with the syllabus (boldface), "You are allowed to bring in one 8.5x11 (inch) page of notes covered on both sides".
- Test consists of 10 True/False and 60 Multiple Choice questions.
- Test will cover chapters 15 - 19 (up to 8 T/F, 48 MC)
- Test will also include questions from the second midterm (at least 2 T/F, 12 MC)
- Special Review session on Thursday, December 14 at 1:30pm in Tate B20 (Bring your questions).

Important Stuff (Section 002)

- The Final Exam is Wednesday, December 20, 10:30 – 12:30
- The Final Exam will be given in:
  - Bruininks 220 (last names starting with A-K)
  - Bruininks 230 (last names starting with L-Z)
  - Bring 2 pencils and a photo-id.
- In accordance with the syllabus (boldface), "You are allowed to bring in one 8.5x11 (inch) page of notes covered on both sides".
- Test consists of 10 True/False and 60 Multiple Choice questions.
- Test will cover chapters 15 - 19 (up to 8 T/F, 48 MC)
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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?
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%

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

Rotation curve

A plot of orbital speed versus orbital radius

Solar system’s rotation curve declines because Sun has almost all the mass.
Who has the largest orbital speed? A, B, or C?

Answer: C

Rotation curve of 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.

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!

Mass within Sun’s orbit: \(1.0 \times 10^{11} M_{\text{Sun}}\) Total mass: \(~10^{12} M_{\text{Sun}}\)
The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.

We can measure 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.

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.
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.
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

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.

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?

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

How dark is it?

… not as bright as a star.

The Best Bet
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.

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.

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.

<table>
<thead>
<tr>
<th>Time in billions of years</th>
<th>Size of expanding box in millions of light-years</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>13</td>
</tr>
<tr>
<td>2.2</td>
<td>35</td>
</tr>
<tr>
<td>5.9</td>
<td>70</td>
</tr>
<tr>
<td>8.6</td>
<td>93</td>
</tr>
<tr>
<td>13.7</td>
<td>140</td>
</tr>
</tbody>
</table>

Models show that gravity of dark matter pulls mass into denser regions—the universe grows lumpier with time.
Structures in galaxy maps look very similar to the ones found in models in which dark matter is WIMPs.

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?

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

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.

But expansion appears to be speeding up!

Dark energy?

Not enough dark matter

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

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

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
An accelerating universe is the best fit to supernova data.

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!

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