Announcements

- Exam 3 on Thursday
  - Covers Chapters 19–23
- Assignment on Chaps 22–23, due next week, is optional and will count as extra credit
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- Dark Matter & Dark Energy
  - What is dark matter & dark energy?
  - What is the evidence for dark matter?
  - Does dark matter really exist?

- Early Universe
  - The implied history of the universe Bang theory?
  - Evidence for the Big Bang theory?

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Read: Chaps 22–23
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Early Universe
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Questions?

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Read: Chaps 22–23
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.
**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 the Universe**

<table>
<thead>
<tr>
<th>Component</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Matter</td>
<td>4.4%</td>
</tr>
<tr>
<td>Normal Matter inside stars:</td>
<td>0.6%</td>
</tr>
<tr>
<td>Normal Matter outside stars:</td>
<td>3.8%</td>
</tr>
<tr>
<td>Dark Matter:</td>
<td>23%</td>
</tr>
<tr>
<td>Dark Energy:</td>
<td>73%</td>
</tr>
</tbody>
</table>

**Read:** Chaps 22–23
Evidence for dark matter in galaxies

Rotation Curve

- We measure the mass of the solar system using the orbits of planets
  - Orbital period, $P$
  - Average distance, $a$
  - $a^3 = P^2 \Rightarrow P = a^{3/2}$
  - Orbital velocity: $v = \frac{2\pi a}{P} \propto \frac{a}{P} \propto \frac{1}{\sqrt{a}}$

![Graph showing the relationship between average velocity and semi-major axis.]

Read: Chaps 22–23

12/04/12 – slide 4
Evidence for dark matter in galaxies

Rotation Curve

- We measure the mass of the solar system using the orbits of planets
- Solar systems rotation curve declines because Sun has almost all the mass
Evidence for dark matter in galaxies

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- Rotation curve of galaxies stay flat with distance

1. Mass must be more spread out than in solar system
Evidence for dark matter in galaxies

Rotation Curve

- We measure the mass of the solar system using the orbits of planets
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  1. Mass must be more spread out than in solar system
  2. Mass in galaxies is spread out over a larger region than the stars

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Rotation Curve

- We measure the mass of the solar system using the orbits of planets
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- Rotation curve of galaxies stay flat with distance
  1. Mass must be more spread out than in solar system
  2. Mass in galaxies is spread out over a larger region than the stars
  3. Most of a galaxy’s mass seems to be dark matter!

Read: Chaps 22–23
The visible portion of a galaxy lies deep in the heart of a large halo of dark matter.
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.

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

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>85%</td>
<td>dark matter</td>
</tr>
<tr>
<td>13%</td>
<td>hot gas</td>
</tr>
<tr>
<td>2%</td>
<td>stars</td>
</tr>
</tbody>
</table>
Dark matter in clusters

Gravitational lensing, the bending of light rays by gravity, can also tell us a cluster’s mass
All three methods of measuring cluster mass indicate similar amounts of dark matter
Does dark matter really exist?

The 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

Read: Chaps 22–23
Does dark matter really exist?

The 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

Some observations of the Universe are very difficult to explain without dark matter

Read: Chaps 22–23
What is dark matter?

Two Basic Options

1. Ordinary Dark Matter (MACHOS)
   - Massive Compact Halo Objects: dead or failed stars in halos of galaxies

2. Extraordinary Dark Matter (WIMPS)
   - Weakly Interacting Massive Particles: mysterious neutrino-like particles

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Two Basic Options

1. Ordinary Dark Matter (MACHOS)
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Best bet!

Read: Chaps 22–23
Why believe in WIMPS?

1. There is not enough ordinary matter
2. WIMPs could be left over from Big Bang
3. Models involving WIMPs explain how galaxy formation works
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.
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
Will the Universe continue expanding forever?

Does the Universe have enough kinetic energy to escape its own gravitational pull?
Will the Universe continue expanding forever?

- Does the Universe have enough kinetic energy to escape its own gravitational pull?
- Fate of Universe depends on the amount of dark matter
The Fate of the Universe

Fate of Universe depends on the amount of dark matter

Read: Chaps 22–23
Amount of dark matter is $\approx 25\%$ of the critical density suggesting fate is eternal expansion.
But expansion appears to be speeding up!

Dark energy??
Estimated age depends on both dark matter and dark energy.
Accelerating Universe is best fit to supernova data
Will the Universe continue expanding forever?

- Current measurements indicate that there is not enough dark matter to prevent the Universe from expanding forever.

Is the expansion of the Universe accelerating?

- An accelerating Universe is the best explanation for the distances we measure when using white dwarf supernovae as standard candles.
The Universe is current expanding. Imagine reversing the arrow of time so that the Universe is then contracting.

What happens?
The Universe is currently expanding. Imagine reversing the arrow of time so that the Universe is then contracting.

**What happens?**

- The density increases.
- The temperature increases.
Extrapolate the expansion back in time

The Universe is current expanding. Imagine reversing the arrow of time so that the Universe is then contracting.

What happens?

- The density increases.
- The temperature increases.
- Universe becomes ionized, like the inside of a star.
The Universe is current expanding. Imagine reversing the arrow of time so that the Universe is then contracting.

**What happens?**

- The density increases.
- The temperature increases.
- Universe becomes ionized, like the inside of a star
- As we keep going, fusion may occur.
The Universe is currently expanding. Imagine reversing the arrow of time so that the Universe is then contracting.

**What happens?**

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- Universe becomes ionized, like the inside of a star.
- As we keep going, fusion may occur.
- Still later, the temperatures get so high that the baryons break up into constituent sub-particles (quarks).
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????

**Realm of the Early Universe**
The early universe must have been extremely hot and dense.
Early Universe

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Unseen influences
DM in Clusters
Does it exist?
What is DM?
Why WIMPS?
Summary I
The Fate of the Universe
Accelerating Universe
Summary II
Back in time
Early Universe
Particle physics
Big Bang Theory
Evidence for BBN
CMB prediction
Recombination
CMB discovery
COBE satellite
CMB all sky
Last scattering
Nucleosynthesis
Summary III

- Early universe was full of particles and radiation because of its high temperature.

\[ E = mc^2 \]

- Photons converted into particle-antiparticle pairs and vice-versa.

Read: Chaps 22–23
Four known forces in Universe:

1. Strong Force
2. Electromagnetism
3. Weak Force
4. Gravity
Do the forces unify at high temperatures?

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Electroweak (Yes!)
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Electroweak (Yes!)
GUT (Maybe)
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Four known forces in Universe:

1. Strong Force
2. Electromagnetism
3. Weak Force
4. Gravity

Electroweak (Yes!)
GUT (Maybe)
String theory (???)
Particle colliders attempt to create early-universe conditions
Running the clock forward from the beginning...
1. **Planck Era**
   - Before Planck time ($\approx 10^{-43}$ sec)
   - No theory of quantum gravity

2. **GUT Era**
   - Lasts from Planck time ($\approx 10^{-43}$ sec) to end of GUT force ($\approx 10^{-38}$ sec)

3. **Electroweak Era**
   - Lasts from end of GUT force ($\approx 10^{-38}$ sec) to end of electroweak force ($\approx 10^{-10}$ sec)
4. **Particle Era**

- Matter and antimatter nearly equal
- 1 extra proton for $10^9$ proton-antiproton

5. **Era of Nucleosynthesis**

- Begins when matter annihilates remaining antimatter at $\approx 0.001$ sec
- Nuclei begin to fuse

6. **Era of Nuclei**

- Helium nuclei form at this age
- $\approx 3$ minutes
- Universe too cool to blast helium apart
7. Era of Atoms
   - Atoms form at age $\approx 380,000$ years
   - Background radiation released

8. Era of Galaxies
   - Galaxies form at age $\approx 1$ billion years
Evidence for the Big Bang

1. We have detected the leftover radiation from the Big Bang!

2. The Big Bang theory correctly predicts the abundance of helium and other light elements.
Observed helium abundance too large to be the result of supernovae

Extrapolate backwards in time

- At some point: Universe as hot as star center
- Fuse H to He!

Prediction: Cosmic Microwave Background

- Radiation from this epoch will shift to larger wavelength as Universe expands
- Black body temperature radiation will decrease
Recombination

- Universe now consists of protons and electrons (some He, ...): ionized H
- Universe continues to expand and cool
- At $t = 300,000$ years with $T = 3000$K:
  - Photons no longer sufficiently energetic to keep H ionized
  - Atoms form!
- Universe becomes transparent!
Background radiation from Big Bang has been freely streaming across Universe since atoms formed at temperature $\approx 3,000$ K: visible/IR
CMB = Cosmic Microwave Background

- Engineers designed first microwave satellite uplink
- Signal independent of pointing antenna
- Assumed additional noise in their receivers that they could not understand
- Discovered relic cosmic radiation: T=2.73 K

CMB = Cosmic Microwave Background

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Read: Chaps 22–23
The microwave background is a precise blackbody!

Expansion of universe has redshifted thermal radiation from that time to $\approx 1000$ times longer wavelength: microwaves
Cosmic Background Explorer

- The microwave background is a precise blackbody!
- Temperature profile close to isotropic but not quite
BB temperature on the sky

WMAP gives us detailed baby pictures of structure in the universe
Last scattering

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12/04/12 – slide 39
Protons and neutrons combined to make long-lasting helium nuclei when universe was \( \approx 3 \) minutes old.
Big Bang theory prediction: 75% H, 25% He (by mass)
Matches observations of nearly primordial gases
Abundance of the elements

Abundances of other light elements agree with Big Bang model having 4.4% normal matter—more evidence for WIMPS!
How do we observe the radiation left over from the Big Bang?

- Radiation left over from the Big Bang is now in the form of microwaves—the cosmic microwave background—which we can observe with a radio telescope.

How do the abundances of elements support the Big Bang theory?

- Observations of helium and other light elements agree with the predictions for fusion in the Big Bang theory.