What is the evidence that Big Bang really occurred

- Hubble expansion of galaxies
- Microwave Background
- Abundance of light elements

- but perhaps most fundamentally...
  - Darkness of the night sky!!
The very darkness of the night sky is evidence for the Big Bang!
Olbers’ Paradox

If universe were

1) infinite

2) unchanging

3) everywhere the same

then stars would cover the night sky.
The night sky is dark because the universe changes with time. As we look out in space, we can look back to a time when there were no stars.
What have we learned?

- Why is the darkness of the night sky evidence for the Big Bang?
  - If the universe were eternal, unchanging, and everywhere the same, the entire night sky would be covered with stars.
  - The night sky is dark because we can see back to a time when there were no stars.
23.1 The Big Bang

Our goals for learning:

• What were conditions like in the early universe?
• What is the history of the universe according to the Big Bang theory?
What were conditions like in the early universe?
The universe must have been much hotter and denser early in time.
The early universe must have been extremely hot and dense.
Photons converted into particle–antiparticle pairs and vice versa.

\[ E = mc^2 \]

The early universe was full of particles and radiation because of its high temperature.
Four known forces in universe:

**Strong force**

**Electromagnetism**

**Weak force**

**Gravity**
Thought Question

Which of the four forces keeps you from sinking to the center of Earth?

A. gravity
B. electromagnetism
C. strong force
D. weak force
Thought Question

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Do forces unify at high temperatures?

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(Yes! (Electroweak))
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Yes! (Electroweak)

Maybe (GUT)
Do forces unify at high temperatures?

Four known forces in universe:

- **Strong force**
- **Electromagnetism**
- **Weak force**
- **Gravity**

<table>
<thead>
<tr>
<th>Relative strength of force</th>
<th>Temperature (K)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>strong force</td>
<td>$10^{32}$</td>
<td>$10^{-43}$</td>
</tr>
<tr>
<td>electromagnetism</td>
<td>$10^{29}$</td>
<td>$10^{-38}$</td>
</tr>
<tr>
<td>weak force</td>
<td>$10^{15}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>gravity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Yes! (Electroweak)    |    |    |
Maybe (GUT)            |    |    |
Who knows? (String Theory) |    |    |
What is the history of the universe according to the Big Bang theory?
What have we learned?

• What were conditions like in the early universe?
  – The early universe was so hot and so dense that radiation was constantly producing particle–antiparticle pairs and vice versa.

• What is the history of the universe according to the Big Bang theory?
  – As the universe cooled, particle production stopped, leaving matter instead of antimatter.
  – Fusion turned remaining neutrons into helium.
  – Radiation traveled freely after formation of atoms.
23.2 Evidence for the Big Bang

Our goals for learning:

- How do we observe the radiation left over from the Big Bang?
- How do the abundances of elements support the Big Bang theory?
Primary Evidence

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.
How do we observe the radiation left over from the Big Bang?
The *cosmic microwave background*—the radiation left over from the Big Bang—was detected by Penzias and Wilson in 1965.
Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature $\sim 3000$ K: visible/IR.
Background has perfect thermal radiation spectrum at temperature 2.73 K.

Expansion of universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: microwaves.
WMAP gives us detailed baby pictures of structure in the universe.
How do the abundances of elements support the Big Bang theory?
Protons and neutrons combined to make long-lasting helium nuclei when universe was ~ 3 minutes old.
Big Bang theory prediction: 75% H, 25% He (by mass). This prediction matches observations of primordial gases.
Abundances of other light elements agree with Big Bang model having 4.4% normal matter—more evidence for WIMPs!
Thought Question

Which of these abundance patterns is an unrealistic chemical composition for a star?

A. 70% H, 28% He, 2% other
B. 95% H, 5% He, less than 0.02% other
C. 75% H, 25% He, less than 0.02% other
D. 72% H, 27% He, 1% other
Thought Question

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D. 72% H, 27% He, 1% other
What have we learned?

• 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.
23.3 The Big Bang and Inflation

Our goals for learning:

• What aspects of the universe were originally unexplained with the Big Bang theory?
• How does inflation explain these features of the universe?
• How can we test the idea of inflation?
What aspects of the universe were originally unexplained with the Big Bang theory?
Mysteries Needing Explanation

1) Where does structure come from?

2) Why is the overall distribution of matter so uniform?

3) Why is the density of the universe so close to the critical density?
Mysteries Needing Explanation

1) Where does structure come from?

2) Why is the overall distribution of matter so uniform?

3) Why is the density of the universe so close to the critical density?

An early episode of rapid inflation can solve all three mysteries!
How does inflation explain these features of the universe?
Inflation can make all the structure by stretching tiny quantum ripples to enormous size.

These ripples in density then become the seeds for all structures in the universe.
How can microwave temperature be nearly identical on opposite sides of the sky?
Regions now on opposite sides of the sky were close together before inflation pushed them far apart.
Overall geometry of the universe is closely related to total density of matter and energy.

Density = Critical

Density > Critical

Density < Critical
Inflation of the universe flattens its overall geometry like the inflation of a balloon, causing the overall density of matter plus energy to be very close to the critical density.
How can we test the idea of inflation?
Patterns observed by WMAP show us the “seeds” of structure in the universe.
Observed patterns of structure in universe agree (so far) with the “seeds” that inflation would produce.
“Seeds” Inferred from CMB

• Overall geometry is flat.
  – Total mass + energy has critical density.
• Ordinary matter is ~ 4.4% of total.
• Total matter is ~ 27% of total.
  – Dark matter is ~ 23% of total.
  – Dark energy is ~ 73% of total.
• Age is 13.7 billion years.
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_in excellent agreement with observations of present-day universe and models involving inflation and WIMPs!_
What have we learned?

• What aspects of the universe were originally unexplained with the Big Bang theory?
  – The origin of structure, the smoothness of the universe on large scales, the nearly critical density of the universe

• How does inflation explain these features of the universe?
  – Structure comes from inflated quantum ripples.
  – Observable universe became smooth before inflation, when it was very tiny.
  – Inflation flattened the curvature of space, bringing expansion rate into balance with the overall density of mass-energy.
What have we learned?

• **How can we test the idea of inflation?**
  – We can compare the structures we see in detailed observations of the microwave background with predictions for the “seeds” that should have been planted by inflation.
  – So far, our observations of the universe agree well with models in which inflation planted the “seeds.”