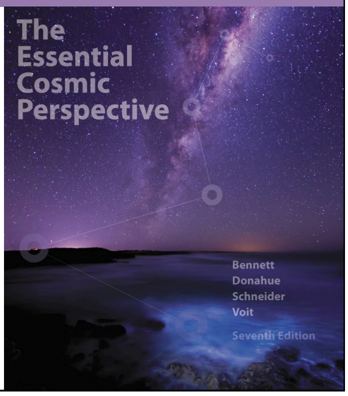
Lecture Outline

Chapter 17: The Birth of the Universe

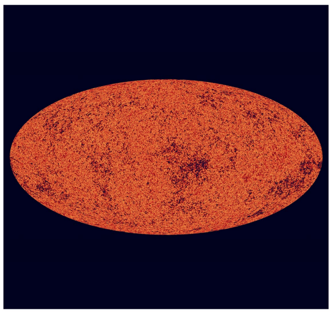


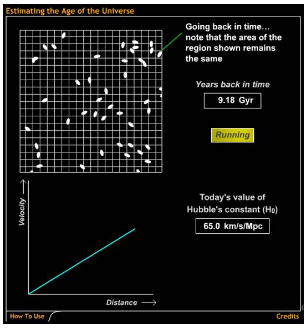
17.1 The Big Bang Theory

Our goals for learning:

- What were conditions like in the early universe?
- How did the early universe change with time?

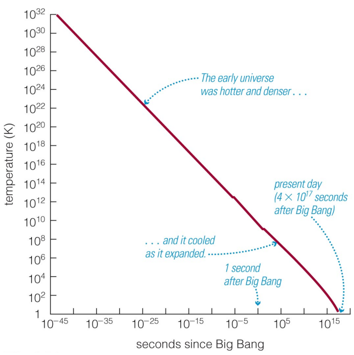
What were conditions like in the early universe?



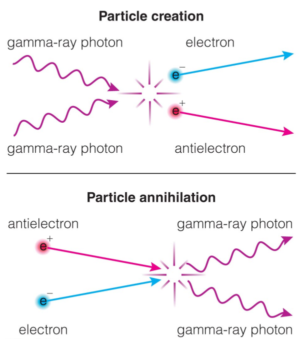


The universe must have been much hotter and denser early in time.

PLAY Estimating the Age of the Universe



The early universe must have been extremely hot and dense.

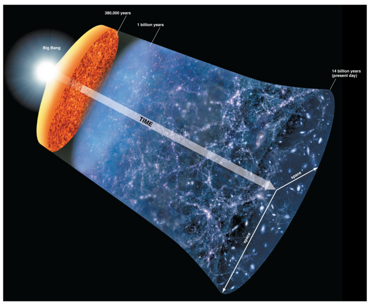


Photons converted into particle–antiparticle pairs and vice versa.

$$E = mc^2$$

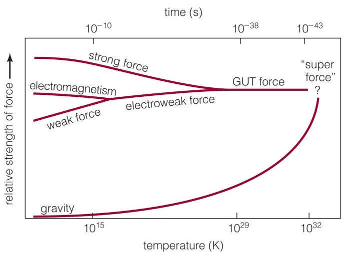
The early universe was full of particles and radiation because of its high temperature.

How did the early universe change with time?



Defining Eras of the Universe

- The earliest eras are defined by the kinds of forces present in the universe.
- Later eras are defined by the kinds of particles present in the universe.



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

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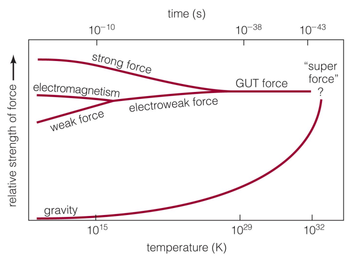
Do forces unify at high temperatures?



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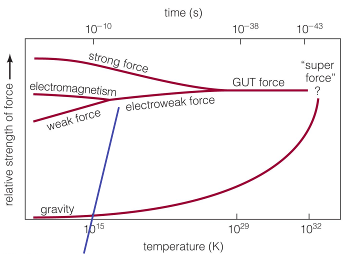

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Yes!
(Electroweak)

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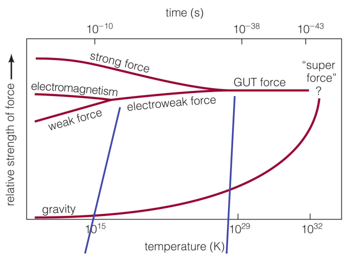

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Yes!
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Maybe
(GUT)

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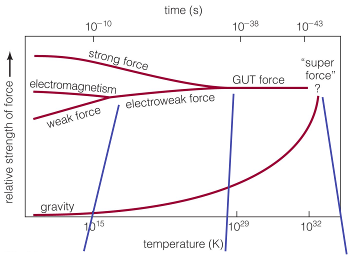


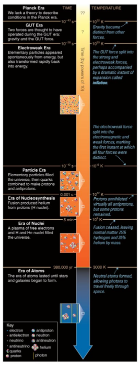
Four known forces in universe:

Strong Force
Electromagnetism
Weak Force
Gravity

Yes!
(Electroweak)

Maybe
(GUT)

Who knows?
(String Theory)

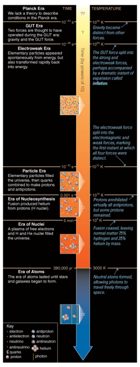


Planck Era

Time: < 10^{-43} s
Temp: > 10^{32} K

No theory of quantum gravity

All forces may have been unified

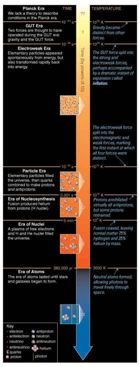


GUT Era

Time: 10^{-43}–10^{-38} s
Temp: $10^{3}2$–10^{29} K

GUT era began when gravity became distinct from other forces.

GUT era ended when strong force became distinct from electroweak force.

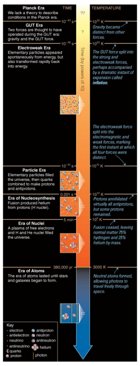


Electroweak Era

Time: 10^{-10}–10^{-10} s
Temp: 10^{29}–10^{15} K

Gravity became distinct from other forces.

Strong, weak, and electromagnetic forces may have been unified into GUT force.



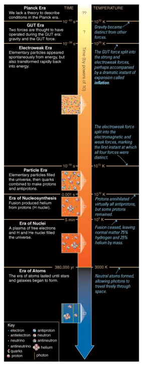
Particle Era

Time: 10^{-10}–0.001 s

Temp: 10^{15}–10^{12} K

Amounts of matter and antimatter are nearly equal.

(Roughly one extra proton for every 10^9 proton–antiproton pairs!)



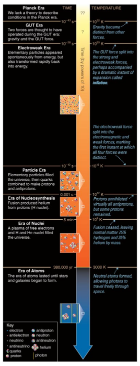
Era of Nucleosynthesis

Time: 0.001 s–5 min

Temp: 10^{12}–10^9 K

Began when matter annihilates remaining antimatter at ~ 0.001 s.

Nuclei began to fuse.



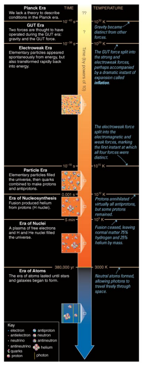
Era of Nuclei

Time: 5 min–380,000 yrs

Temp: 10^9–3000 K

Helium nuclei formed at age ~3 minutes.

The universe became too cool to blast helium apart.



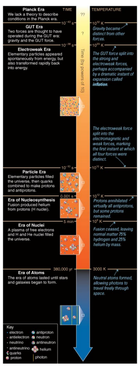
Era of Atoms

Time: 380,000 years–1 billion years

Temp: 3000–20 K

Atoms formed at age ~380,000 years.

Background radiation is released.



Era of Galaxies

Time: ~1 billion years–present

Temp: 20–3 K

The first stars and galaxies formed by ~1 billion years after the Big Bang.

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.
- How did the early universe change with time?
  - As the universe cooled, particle production stopped, leaving matter instead of antimatter.
  - Fusion turned the remaining neutrons into helium.
  - Radiation traveled freely after the formation of atoms.

17.2 Evidence for the Big Bang

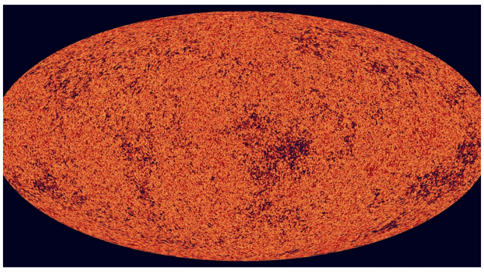
Our goals for learning:

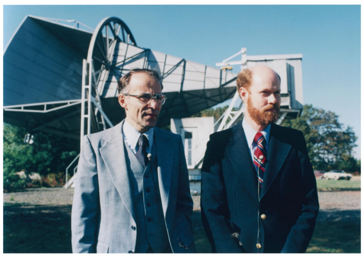
- How do observations of the cosmic microwave background support the Big Bang theory?
- How do the abundances of elements support the Big Bang theory?

Primary Evidence for the Big Bang

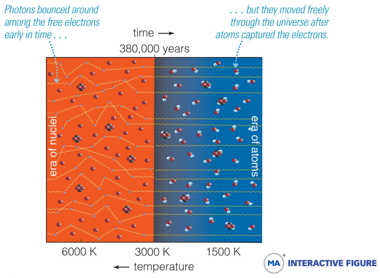
1. We have detected the leftover radiation from the Big Bang.
2. The Big Bang theory correctly predicts the abundance of helium and other light elements in the universe.

How do observations of the cosmic microwave background support the big bang theory?

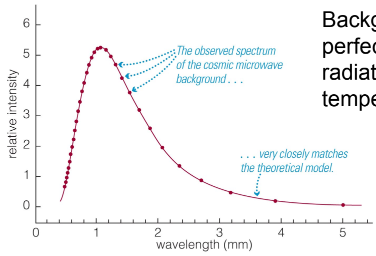




The ***cosmic microwave background***—the radiation left over from the Big Bang—was detected by Penzias and Wilson in 1965.

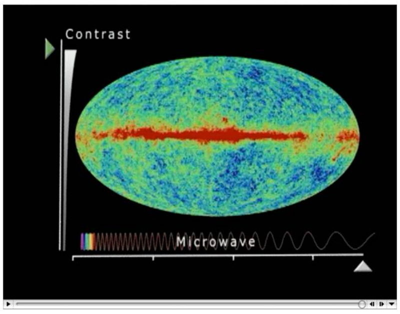


Background radiation from the Big Bang has been freely streaming across the universe since atoms formed at temperature ~3000 K: *visible/IR.*

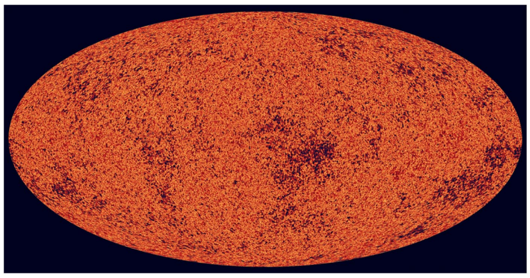


Background has perfect thermal radiation spectrum at temperature 2.73 K.

Expansion of the universe has redshifted thermal radiation from that time to ~1000 times longer wavelength: *microwaves*.

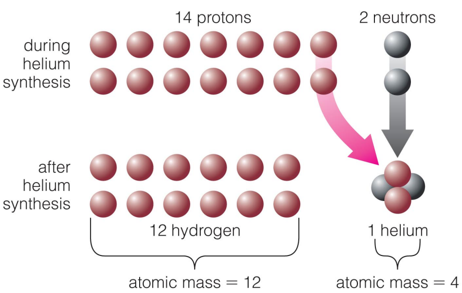


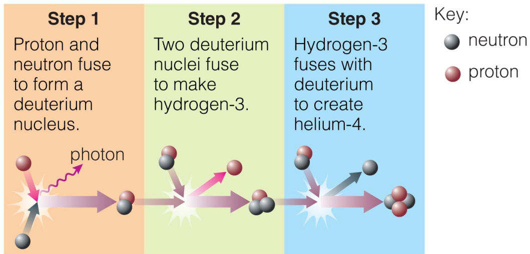
PLAY Full Sky in All Wavelengths



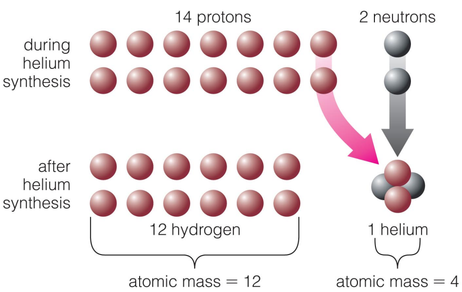
The *Planck* satellite gives us detailed baby pictures of structure in the universe.

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





Protons and neutrons combined to make long-lasting helium nuclei when the universe was ~5 minutes old.



Big Bang theory prediction: 75% H, 25% He (by mass)

Matches observations of nearly primordial gases

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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What have we learned?

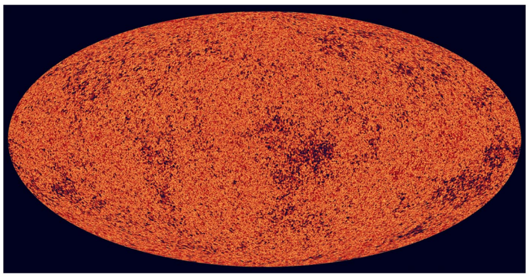
- How do observations of the cosmic microwave background support the Big Bang theory?
  - Radiation left over from the Big Bang is now in the form of microwaves—the cosmic microwave background—which we can observe with a radio telescope.
- How do the abundances of elements support the Big Bang theory?
  - Observations of helium and other light elements agree with the predictions for fusion in the Big Bang theory.

17.3 The Big Bang and Inflation

Our goals for learning:

- What key features of the universe are explained by inflation?
- Did inflation really occur?

What key features of the universe are explained by inflation?



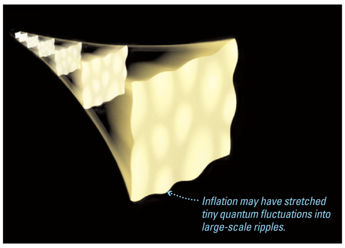
Mysteries Needing Explanation

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

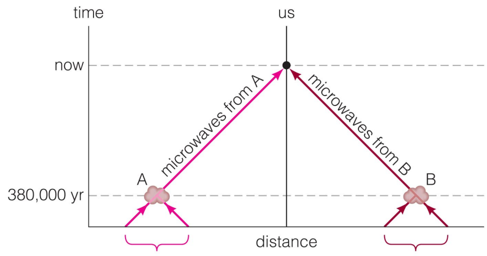
1. **Where does structure come from?**
2. **Why is the overall distribution of matter so uniform?**
3. **Why is the density of the universe so close to the critical density?**

An early episode of rapid inflation can solve all three mysteries!

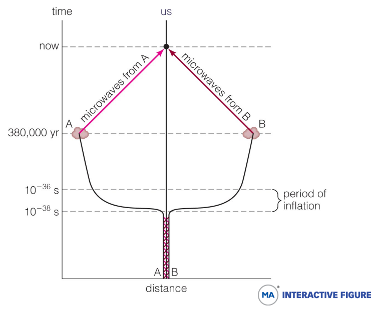


Inflation can make structure by stretching tiny quantum ripples to enormous sizes.

These ripples in density then become the seeds for all structure in the universe.

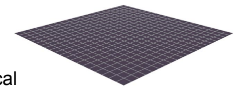


How can microwave temperature be nearly identical on opposite sides of the sky?



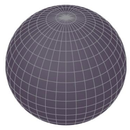
Regions now on opposite sides of the sky were close together before inflation pushed them far apart.

Density = Critical



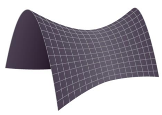
flat (critical) geometry

Density > Critical



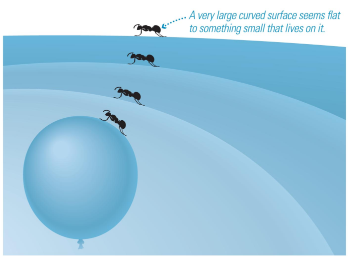
spherical (closed) geometry

Density < Critical



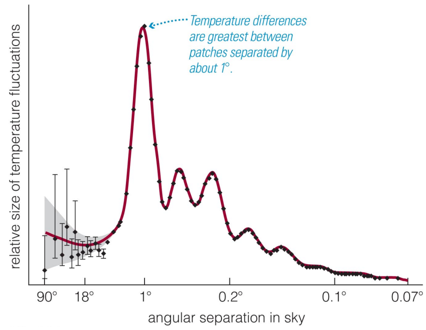
saddle-shaped (open) geometry

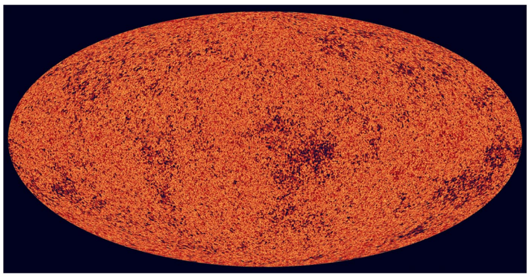
The overall geometry of the universe is closely related to total density of matter and energy.



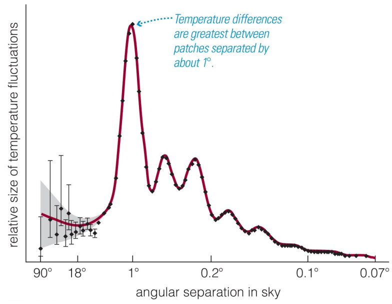
The inflation of the universe flattens the overall geometry like the inflation of a balloon, causing overall density of matter plus energy to be very close to critical density.

Did inflation really occur?





Patterns of structure observed by *Planck* show us the "seeds" of the universe.



Observed patterns of structure in the universe agree (so far) with the "seeds" that inflation would produce.

What have we learned?

- What key features of the universe are explained by inflation?
  - The origin of structure, the smoothness of the universe on large scales, the nearly critical density 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 the expansion rate into balance with the overall density of mass-energy.

What have we learned?

- Did inflation really occur?
  - 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."

17.4 Observing the Big Bang for Yourself

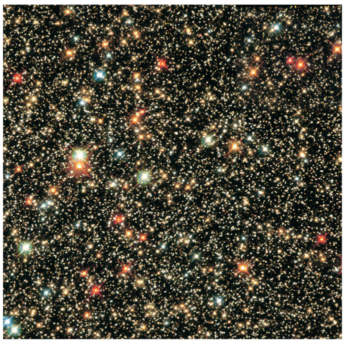
Our goals for learning:

- Why is the darkness of the night sky evidence for the Big Bang?

Why is the darkness of the night sky evidence for the Big Bang?

a In a large forest, a tree will block your view no matter where you look. Similarly, in an unchanging universe with an infinite number of stars, we would expect to see stars in every direction, making the sky bright even at night.

b In a small forest with a smaller number of trees, you can see open spaces beyond the trees. Because the night sky is dark, the universe must similarly have spaces in which we see nothing beyond the stars, which means either that the number of stars is finite or that the universe changes in a way that prevents us from seeing an infinite number of them.



Olbers' Paradox

If the universe were

1. infinite
2. unchanging
3. everywhere the same

then stars would cover the night sky.

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Olbers' Paradox

If the universe were

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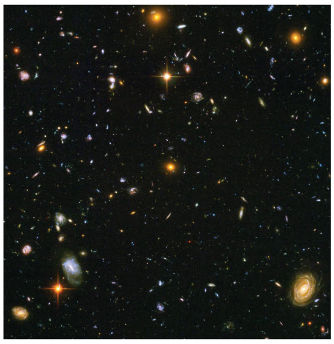
b In a small forest with a smaller number of trees, you can see open spaces beyond the trees. Because the night sky is dark, the universe must similarly have spaces in which we see nothing beyond the stars, which means either that the number of stars is finite or that the universe changes in a way that prevents us from seeing an infinite number of them.

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.



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.