The 'Big Bang' The Beginning of Time



What were conditions like in the early universe?





The early universe must have been extremely hot and dense



Photons converted into particle-antiparticle pairs and vice-versa

 $E = mc^2$

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

electron

gamma-ray photon

Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos

(antimatter rare)

Particle Era Elementary particles (antimatter common)

Electroweak Era Elementary particles

> GUT Era Elementary particles?

> > Planck Era



neutron







Timeline and Events Since Big Bang

> 1 billion years: First galaxies form.

 14 billion years (present day): Humans observe the cosmos.

History of the Universe

380,000 years: Atoms form; photons fly free and become microwave background.

3 minutes: Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.

0

0

0

 0.001 second: Matter annihilates antimatter.

10⁻¹⁰ second: Electromagnetic and weak forces become distinct.

10⁻³⁹ second: Strong force becomes distinct, perhaps causing inflation of universe.

10⁻⁴³ second: Gravity becomes distinct from other forces?

Interactive Figure



Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos

(antimatter rare)

Particle Era Elementary particles (antimatter common)

Electroweak Era Elementary particles

> GUT Era Elementary particles?

> > Planck Era



neutron









0

quarks 🔫

No theory of quantum gravity

14 billion years (present day): Humans observe the cosmos. Before Planck

sec)

Timeline and Events

lion years: galaxies form.

380,000 years: Atoms form: photons fly

free and become

matter is 75% hydrogen.

25% helium, by mass.

Matter annihilates antimatter.

Electromagnetic and weak forces

3 minutes: Fusion ceases: normal

0.001 second:

10⁻¹⁰ second:

become distinct.

Gravity becomes distinct from other forces?

Strong force becomes distinct,

perhaps causing inflation of universe.

10-38 second:

10⁻⁴³ second:

microwave background.

Since Big Bang

Planck Era

time (~10⁻⁴³









Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos

(antimatter rare)

Particle Era Elementary particles (antimatter common)

Electroweak Era Elementary particles

> GUT Era Elementary particles?

> > Planck Era













10⁻⁴³ second:

0





GUT Era

Lasts from Planck time $(\sim 10^{-43} \text{ sec})$ to end of GUT force $(\sim 10^{-38} \text{ sec})$

380,000 years: Atoms form; photons fly free and become microwave background.

3 minutes: Fusion ceases; normal

0.001 second:

10⁻¹⁰ second:

become distinct.

Strong force becomes distinct,

perhaps causing inflation of universe.

10-38 second:

matter is 75% hydrogen.

25% helium, by mass.

Matter annihilates antimatter.

Electromagnetic and weak forces

Timeline and Events

14 billion years (present day): Humans observe

ion years:

galaxies form.

Since Big Bang

Inflation - due to energy from force 'symmetry breaking'?

Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos

(antimatter rare)

Particle Era Elementary particles (antimatter common)

Electroweak Era Elementary particles

> GUT Era Elementary particles?

> > Planck Era

Key











quarks <

Timeline and Events

14 billion years (present day):

Humans observe

in years:

galaxies form.

1 bil First

380,000 years: Atoms form: photons fly

free and become

matter is 75% hydrogen.

25% helium, by mass.

Matter annihilates antimatter.

Electromagnetic and weak forces

3 minutes: Fusion ceases: normal

0.001 second:

10⁻¹⁰ second:

become distinct.

Strong force becomes distinct,

Gravity becomes distinct from other forces?

perhaps causing inflation of universe.

10-38 second:

10⁻⁴³ second:

microwave background.

Since Big Bang

Lasts from end of GUT force $(\sim 10^{-38} \text{ sec})$ to end of electroweak force $(\sim 10^{-10} \text{ sec})$

Electroweak

Era

Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos (antimatter rare)

Particle Era Elementary particles (antimatter common)

Electroweak Era Elementary particles

> GUT Era Elementary particles?

> > Planck Era

1



Key

electron-







quarks <

Timeline and Events

14 billion years (present day): Humans observe

> on years: galaxies form.

Fin

380,000 years: Atoms form: photons fly

free and become

matter is 75% hydrogen.

25% helium, by mass.

Matter annihilates antimatter.

Electromagnetic and weak forces

3 minutes: Fusion ceases: normal

0.001 second:

10⁻¹⁰ second:

become distinct.

Strong force becomes distinct,

Gravity becomes distinct from other forces?

perhaps causing inflation of universe.

10-38 second:

10⁻⁴³ second:

microwave background.

Since Big Bang

Amounts of matter and antimatter nearly equal

Particle Era

(Roughly 1 extra proton for every 10⁹ protonantiproton pairs!)

Why?

Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos (antimatter rare)

Particle Era Elementary particles (antimatter common)

Electroweak Era Elementary particles

> GUT Era Elementary particles?

> > Planck Era

Key









antielectrons

10⁻⁴³ second:

0



Begins when matter annihilates remaining antimatter at ~ 0.001 sec

Universe heats up by 35%

Since Big Bang 14 billion years (present day): Humans observe the

> ion years: galaxies form.

380,000 years: Atoms form: photons fly

free and become

matter is 75% hydrogen.

25% helium, by mass.

Matter annihilates antimatter.

Electromagnetic and weak forces

3 minutes: Fusion ceases: normal

0.001 second:

10⁻¹⁰ second:

become distinct.

Gravity becomes distinct from other forces?

Strong force becomes distinct,

perhaps causing inflation of universe.

10-38 second:

microwave background.

Timeline and Events

Era of Nucleosynthesis

Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos

Elementary particles (antimatter common)

Electroweak Era Elementary particles

> **GUT Era** Elementary particles?

> > Planck Era 7777

Key











quarks.

Timeline and Events Since Big Bang 14 billion years

(present day): Humans observ

billion years: First galaxies form.

380,000 years: Atoms form; photons fly

free and become

matter is 75% hydrogen.

25% helium, by mass.

Matter annihilates antimatter.

Electromagnetic and weak forces

3 minutes: Fusion ceases: normal

0.001 second:

10⁻¹⁰ second:

become distinct.

Strong force becomes distinct,

Gravity becomes distinct from other forces?

perhaps causing inflation of universe.

10-38 second:

10⁻⁴³ second:

microwave background.



Helium nuclei begin to form from age \sim 3 minutes to 30 minutes

Universe has become too cool to blast helium apart

Particle Era

(antimatter rare)



Protons and neutrons combined to make long-lasting helium nuclei.

Question: *Why is Big Bang Nucleosynthesis different from Stellar Nucleosynthesis?*



Question: *Why is Big Bang Nucleosynthesis different from Stellar Nucleosynthesis?*

- 1. There are no free neutrons in stars (all used up in Big Bang)
- 2. Densities are much lower when nuclear fusion occurs in the Big Bang; cannot get Triple- α process - ⁴He + ⁴He + ⁴He \rightarrow ¹²C There is not much fusion beyond He (get a bit of Li, Be, B)



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

Matches observations of nearly primordial gases

Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos (antimatter rare)

Particle Era Elementary particles (antimatter common)

Electroweak Era Elementary particles

> GUT Era Elementary particles?

> > Planck Era 7777

Key











0

0

quarks-

Atoms form at age ~ 380,000 years

380,000 years: Atoms form: photons fly free and become microwave background.

Timeline and Events

14 billion years (present day): Humans obse

1 billion years: First galaxies form.

Since Big Bang

3 minutes: Fusion ceases: normal matter is 75% hydrogen. 25% helium, by mass.

0.001 second: Matter annihilates antimatter.

10⁻¹⁰ second: Electromagnetic and weak forces become distinct. 10-38 second: Strong force becomes distinct,

perhaps causing inflation of universe.

10⁻⁴³ second: Gravity becomes distinct from other forces?

Background radiation 'decouples from matter'

Era of Atoms

Era of Galaxies

Stars, galaxies and clusters of galaxies (made of atoms and plasma)

Era of Atoms Atoms and plasma (stars begin to form)

Era of Nuclei Plasma of hydrogen and helium nuclei plus electrons

Era of Nucleosynthesis Protons, neutrons, electrons, neutrinos

(antimatter rare)

Particle Era Elementary particles (antimatter common)

Electroweak Era Elementary particles

> GUT Era Elementary particles?

> > Planck Era

Key











10⁻⁴³ second:

G

0

0



Timeline and Events Since Big Bang 14 billion years (presenday): Universide Serve the Cosmos. Final Action of Control of Contr

1 billion years: First galaxies form.

380,000 years: Atoms form: photons fly

free and become

matter is 75% hydrogen.

25% helium, by mass.

Matter annihilates antimatter.

Electromagnetic and weak forces

3 minutes: Fusion ceases; normal

0.001 second:

10⁻¹⁰ second:

become distinct.

Gravity becomes distinct from other forces?

Strong force becomes distinct,

perhaps causing inflation of universe.

10-38 second:

microwave background.

Galaxies form at age ~ 1 billion years

Summary

- 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

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





Abundances of other light elements agree with Big Bang model having 4.4% normal matter – more evidence for WIMPS!

Cosmic Background Radiation



The *cosmic microwave background* – the radiation left over from the Big Bang – was detected by Penzias & Wilson in 1965 (Nobel Prize 1978)





Background radiation from Big Bang has been freely streaming across universe since atoms formed at temperature ~ 3,000 K: *visible/IR*





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

Primary Evidence

- 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.

Three Mysteries about the Big Bang

- 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?



size of ripple before inflation = size of atomic nucleus



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

size of ripple after inflation = size of solar system





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 & energy



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

How can we test the idea of inflation?





Patterns of structure observed by WMAP show us the "seeds" of 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 ~ 4.4% of total
- Total matter is $\sim 27\%$ of total
 - Dark matter is $\sim 23\%$ of total
 - Dark energy is $\sim 73\%$ of total
- Age of 13.7 billion years

"Seeds" Inferred from CMB

- Overall geometry is flat
 - Total mass+energy has critical density
- Ordinary matter ~ 4.4% of total
- Total matter is $\sim 27\%$ of total
 - Dark matter is $\sim 23\%$ of total
 - Dark energy is $\sim 73\%$ of total
- Age of 13.7 billion years

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?
 - 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

Why is the darkness of the night sky 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



Olbers' Paradox If universe were 1) infinite 2) unchanging 3) everywhere the same Then, stars would cover the night sky



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



Night sky is dark because the universe changes with time As we look out in space,

As we look out in space, we can look back to a time when there were no stars