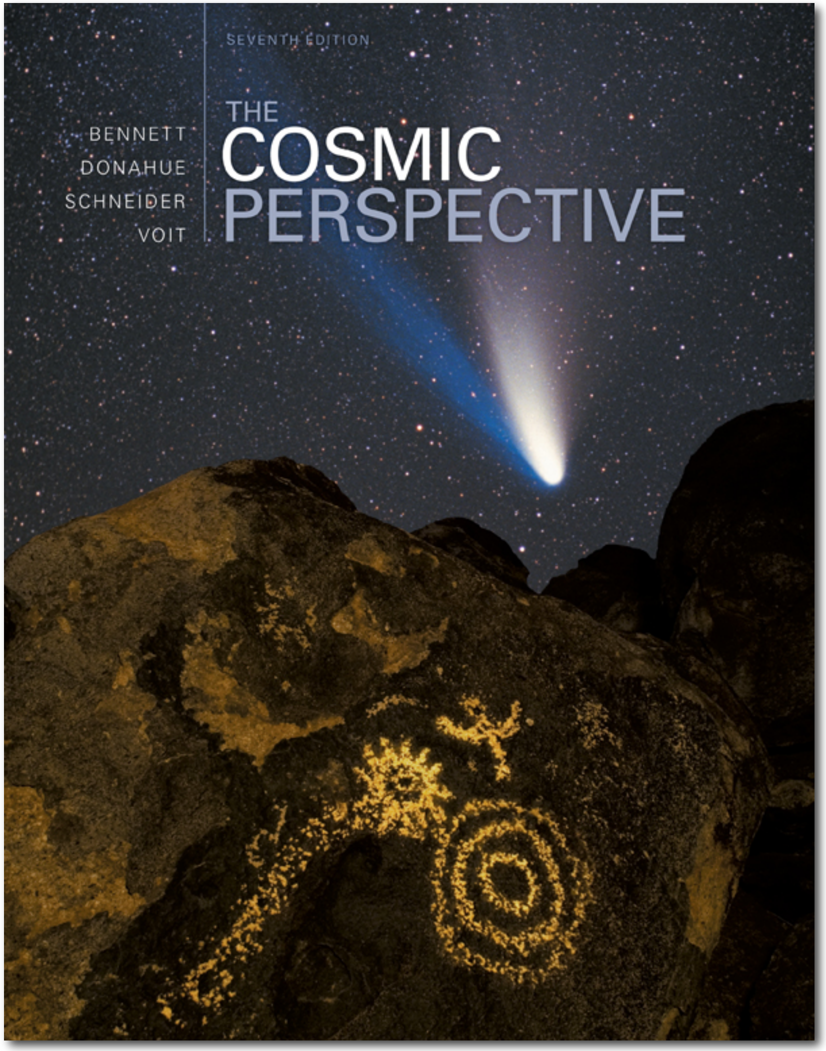
The Cosmic Perspective

Seventh Edition



The Birth of the Universe

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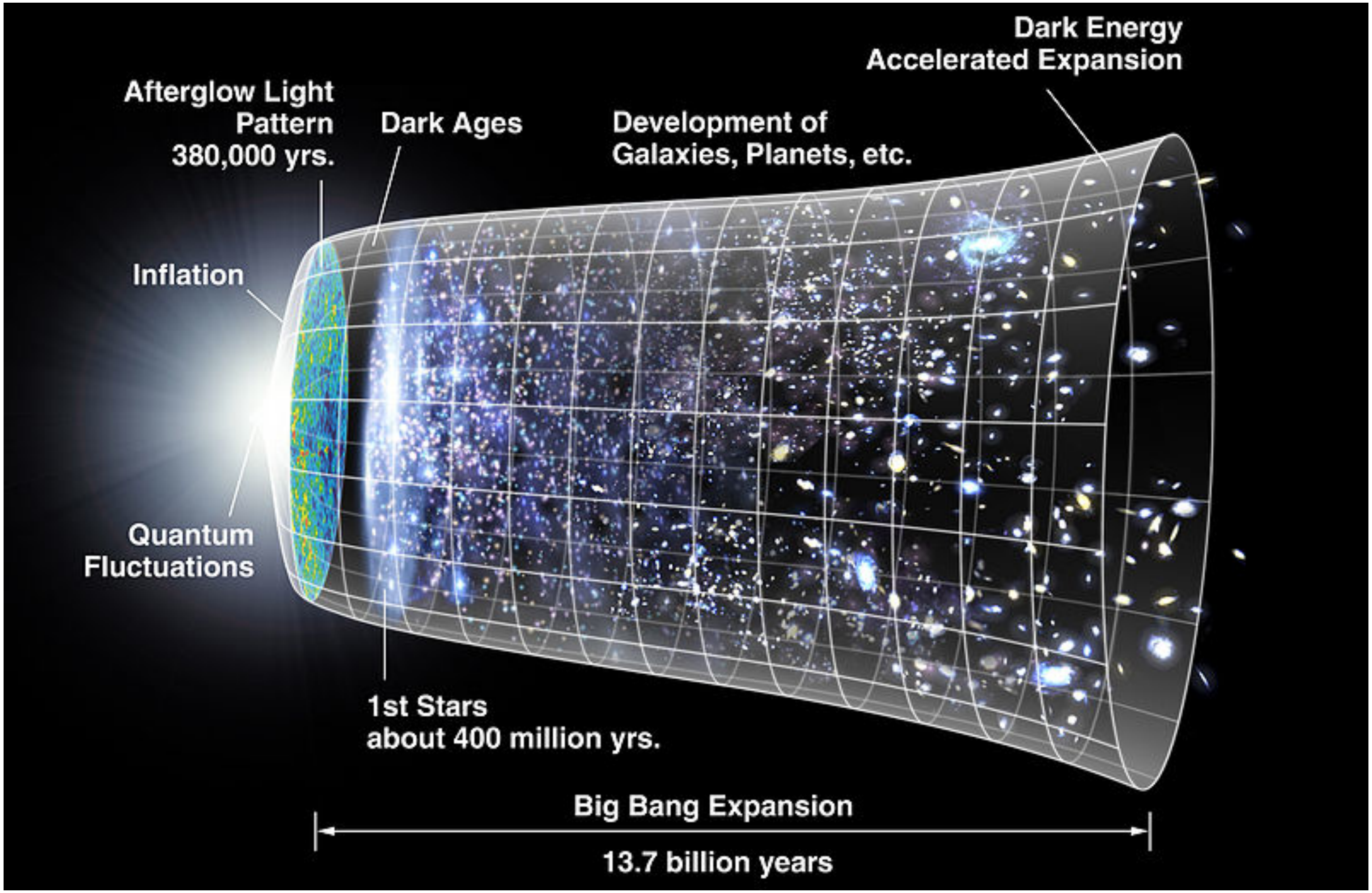
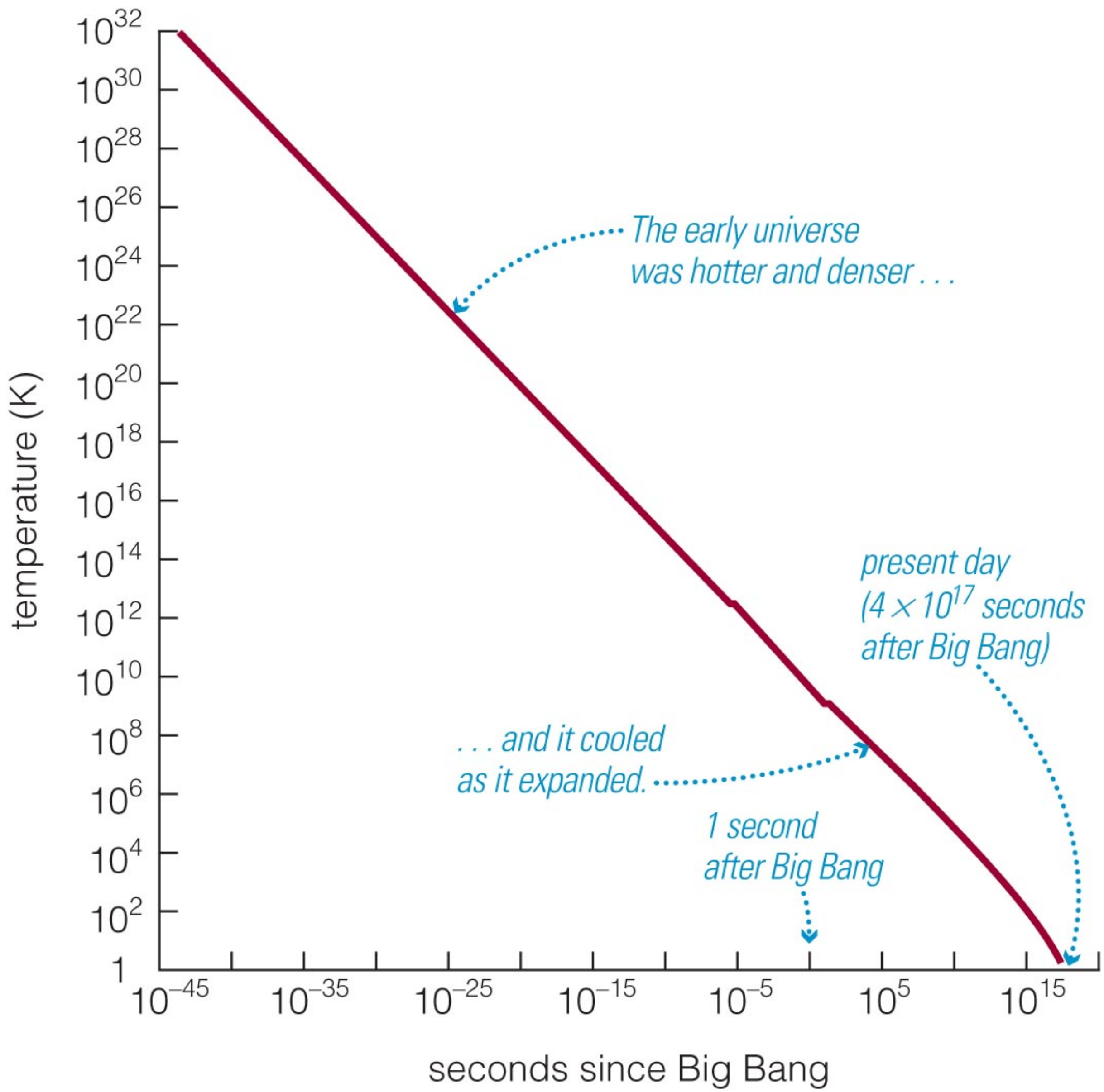


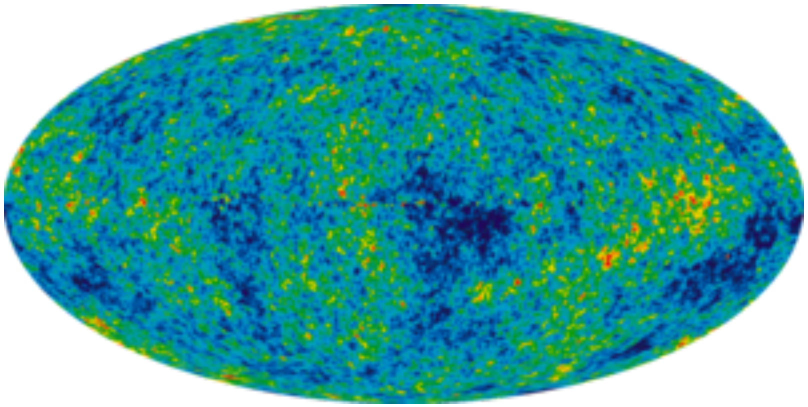
22.1 The Big Bang Theory

- Our goals for learning:
  - **What were conditions like in the early universe?**
  - **How did the early universe change with time?**



- The early universe must have been extremely hot and dense.

Cosmic Microwave Background (CMB)



When H atoms first formed 380,000 years after the Big Bang light was able to freely travel through the Universe.

Temperature of CMB Then ~ 3,000K
Temperature of CMB NOW ~ 2.725 K

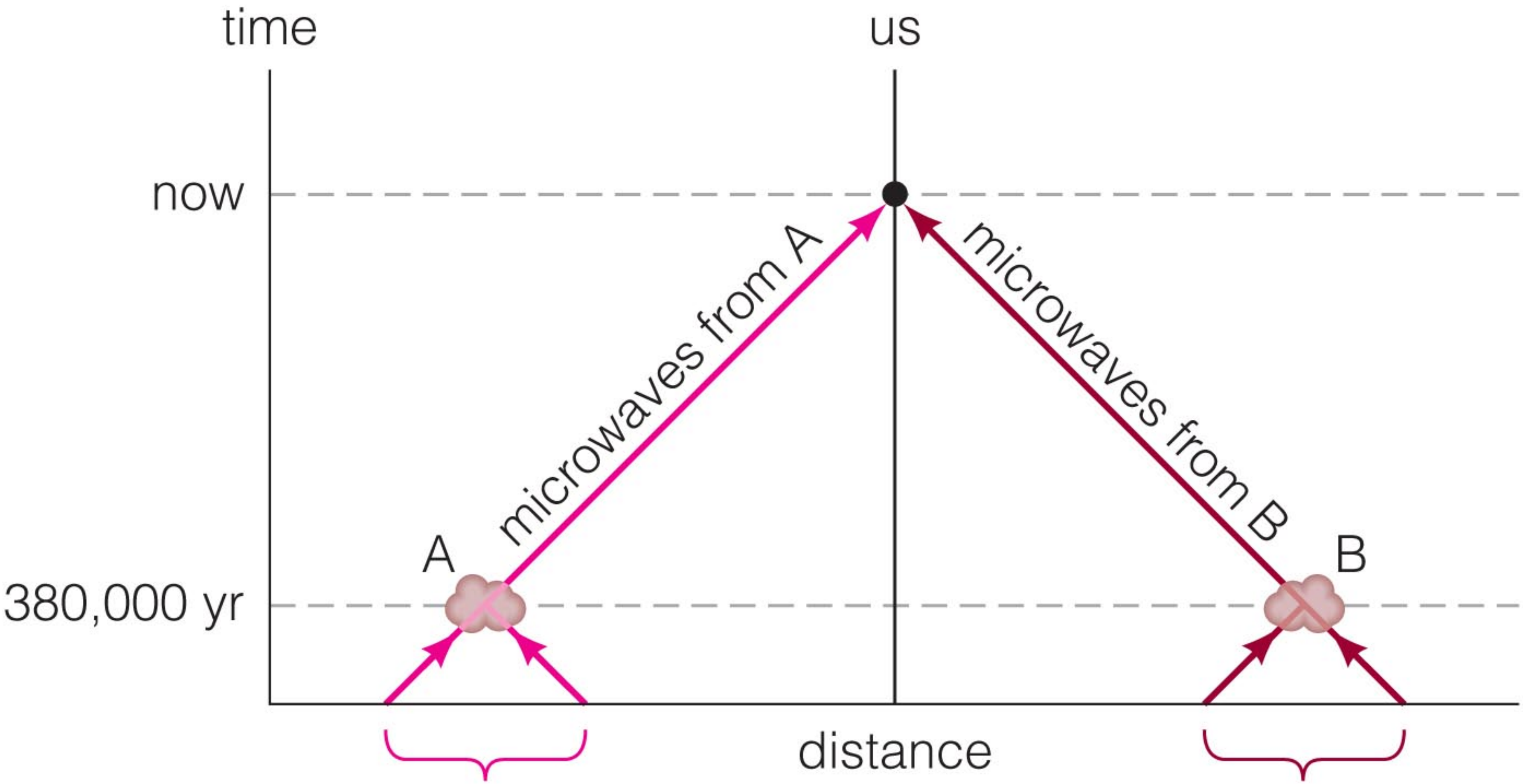
A great discovery that confirmed the big bang theory was the detection of the **cosmic microwave background** (CMB).

A careful analysis of the CMB revealed two strange results:

1. It's too uniform (or isotropic).

2. The curvature of space of the Universe is near zero today.

(1) Universe is uniform over large scales



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

(2) Curvature of space is near zero today

What do we mean by curvature of space?

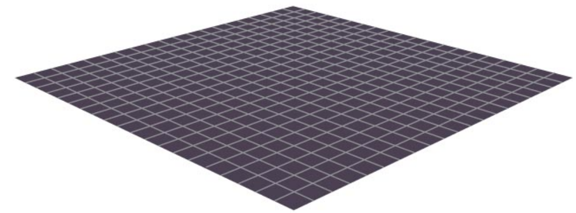
According to Einstein's theory of General Relativity space is curved by mass and energy.

The curvature of the Universe depends on the total density of the Universe.

Density of Universe: $\rho_0 = \frac{Mass}{Volume}$

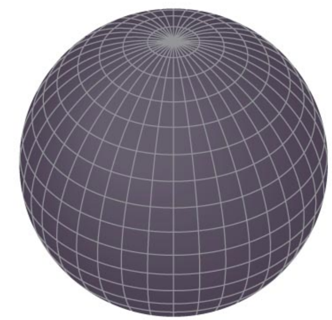
- Density = Critical Density

  $\rho_0 = \rho_{crit}$ (zero curvature)


flat (critical) geometry

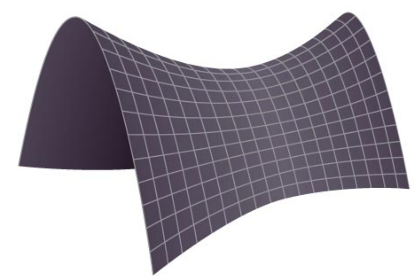
- Density > Critical Density

  $\rho_0 > \rho_{crit}$


spherical (closed) geometry

- Density < Critical Density

  $\rho_0 < \rho_{crit}$


saddle-shaped (open) geometry

Overall **geometry of the universe is closely related to total density** of matter and energy. The density of our Universe is equal to the critical density resulting in zero curvature (flat geometry).

The Early Universe: The Flatness Problem

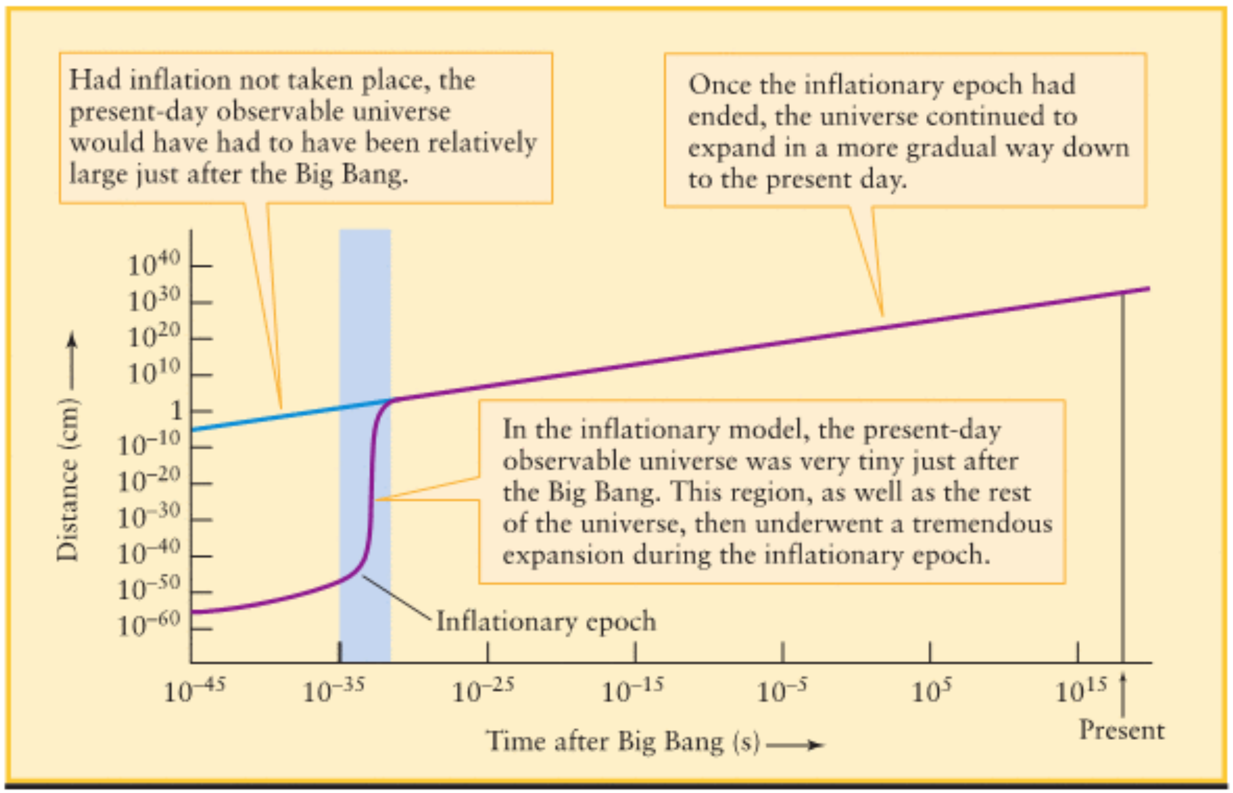
The **geometry of our universe depends on the density parameter** Ω_0, which is the ratio of the combined mass density in the universe (ρ_0) to the critical density (ρ_c)

$$\Omega_0 = \rho_0/\rho_c$$

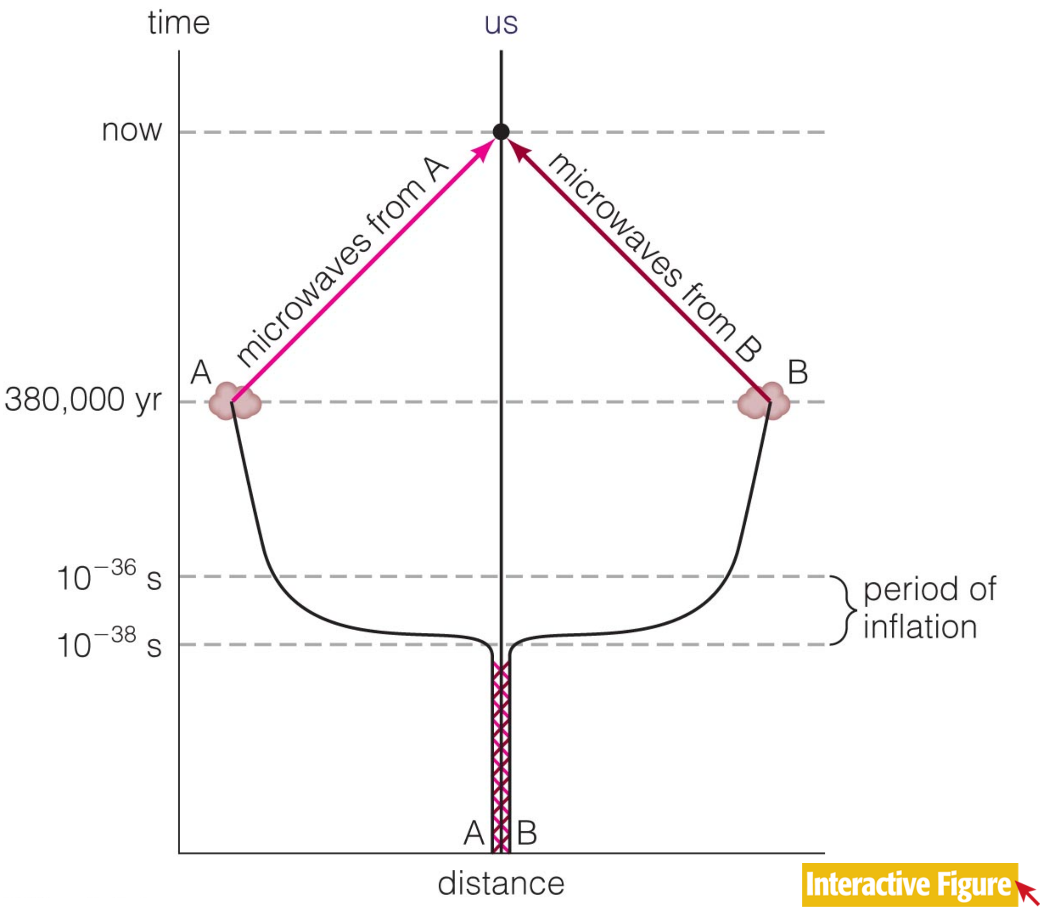
We now know that the density of the Universe is exactly equal to the critical density: Ω_0=1 (flat Universe).

Inflation model explains uniformity and flatness

Independently Alexei Starobinsky and Alan Guth suggested that the universe might have experienced a brief period of inflation, expanded by a factor of 10^{50}, shortly after the big bang.

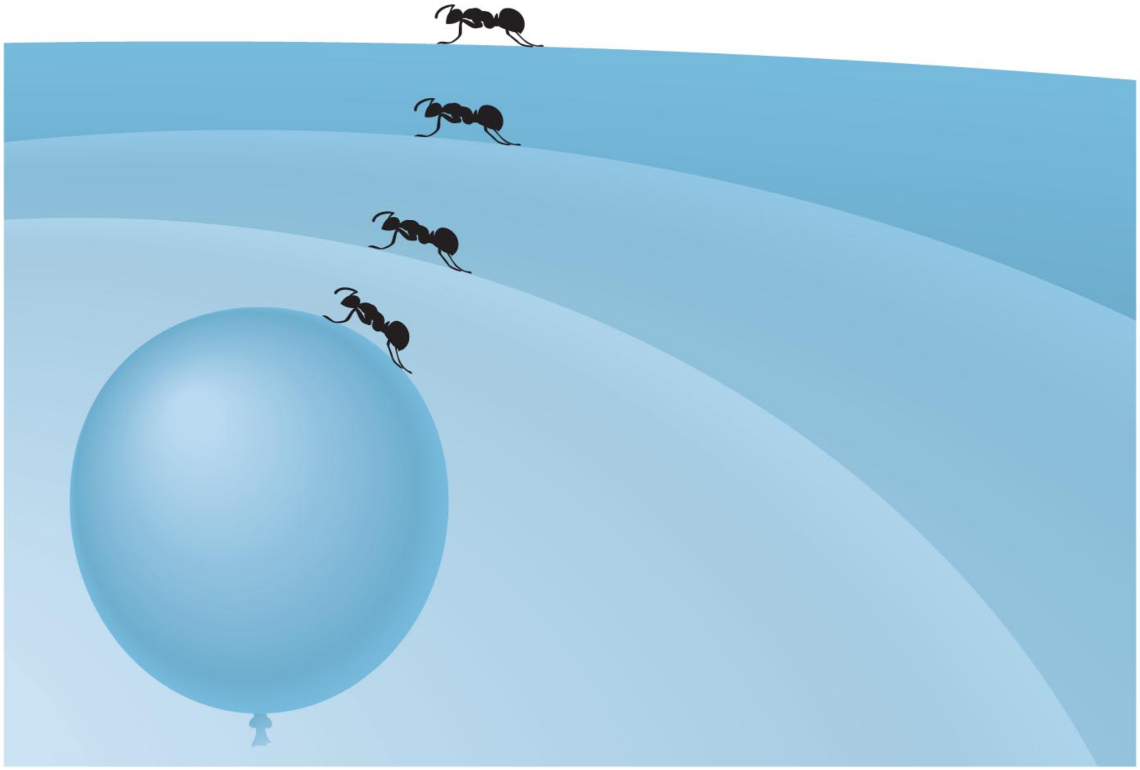


Inflation explains uniformity of Universe



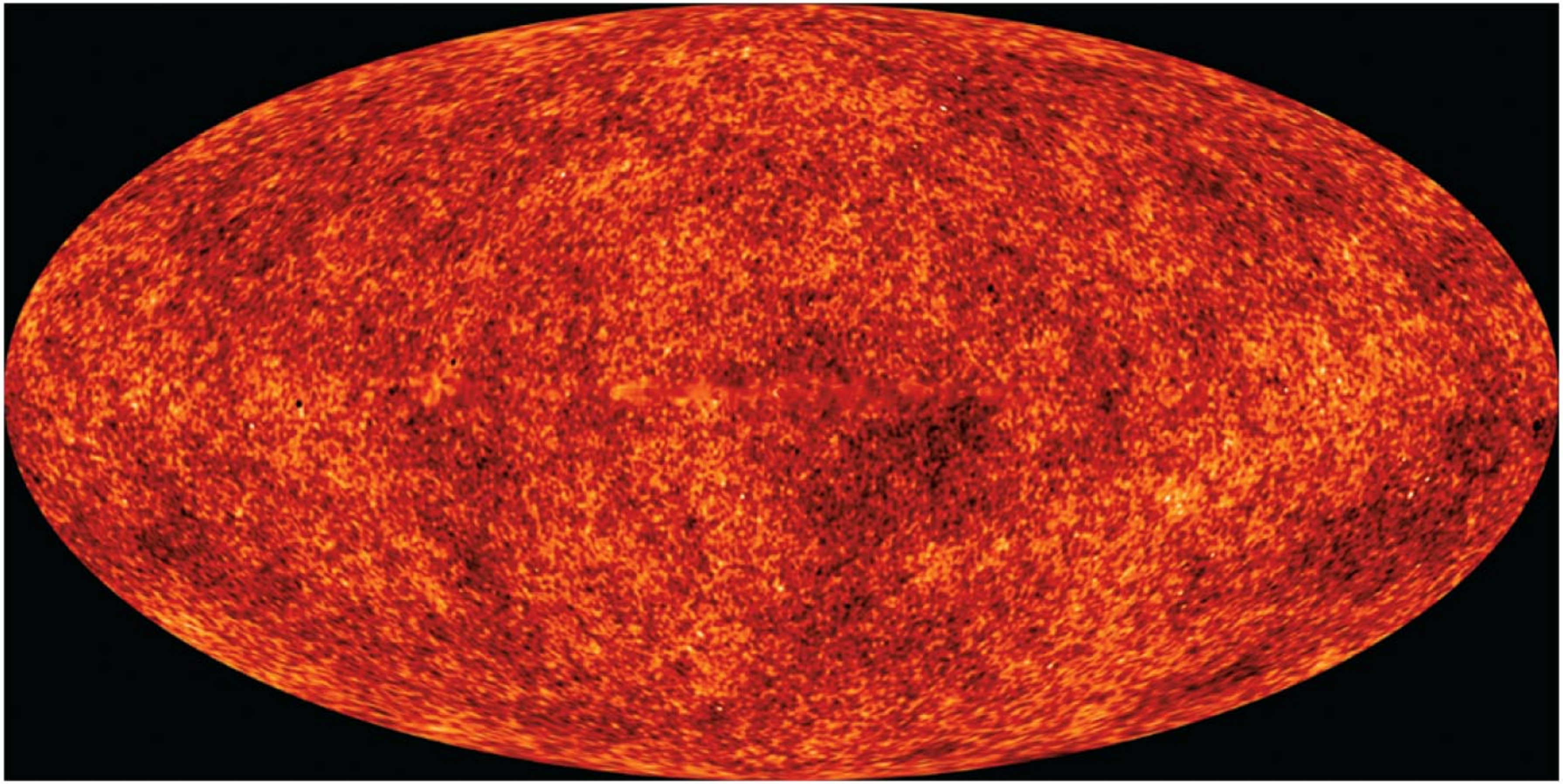
- Regions now on opposite sides of the sky were close together before inflation pushed them far apart.

Inflation explains flatness of Universe

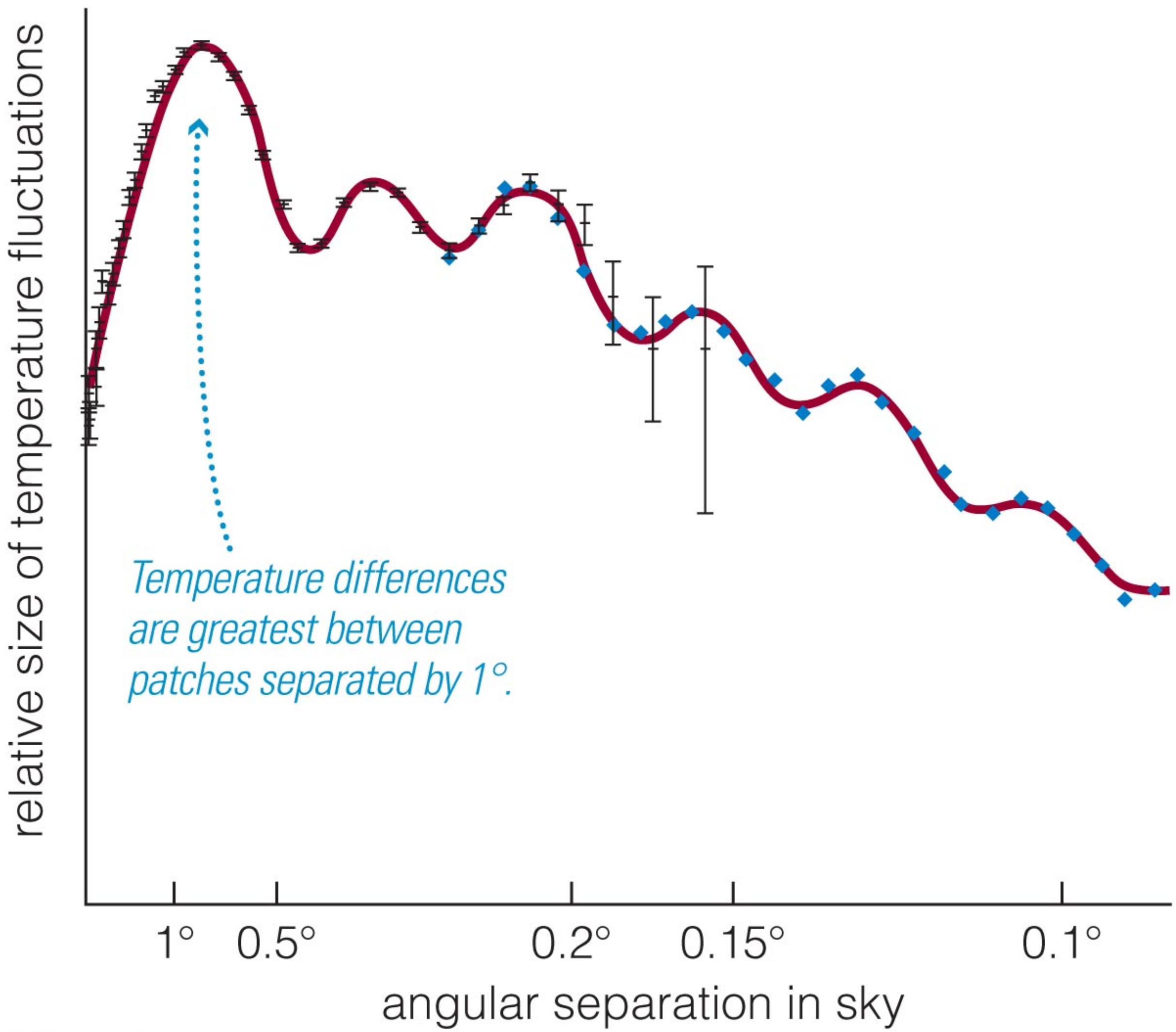


- Inflation of the universe flattens its overall geometry like the inflation of a balloon, causing the overall density of matter plus energy to be very close to the critical density.

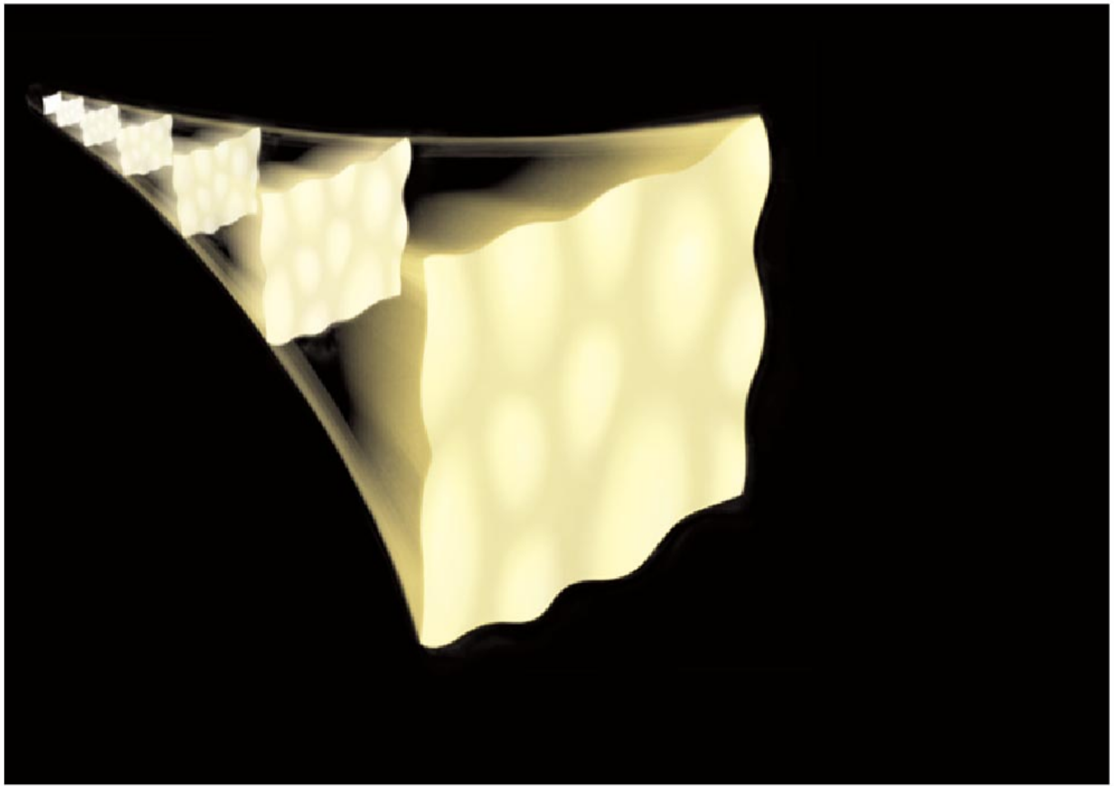
Did inflation really occur?



- 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.



- **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.

"Seeds" Inferred from CMB

- Ordinary matter density is ~ 5% of total density.

- Total matter density is ~ 31% of total density.
  - Dark matter density is ~ 26% of total density.
  - Dark energy density is ~ 69% of total density.

$$\varrho_0 = \varrho_{matter} + \varrho_{dark\ matter} + \varrho_{dark\ energy}$$

5% 26% 69%

The Early Universe: Fundamental Forces

To understand what happened in the early universe we need to understand how particles interact at high energies.

Particles interact through **four fundamental forces of nature.**

1. **Gravity** (force between everything including massless objects like photons, infinite range)

2. **Electromagnetism** (force between charged particles, infinite range)

3. **Strong Force** (force between quarks that make up neutrons and protons, short-range force ~ 10^{-15}m)

4. **Weak Force** (force acts on quarks, electrons, neutrinos and involved in certain radioactive decays, short-range force ~10^{-16}m)

The Early Universe: Fundamental Forces

What do we mean by a force between particles :

Particles interact by exchanging particles. Each force has its own exchange particles. The exchange particles cannot be directly observed and are called virtual particles.

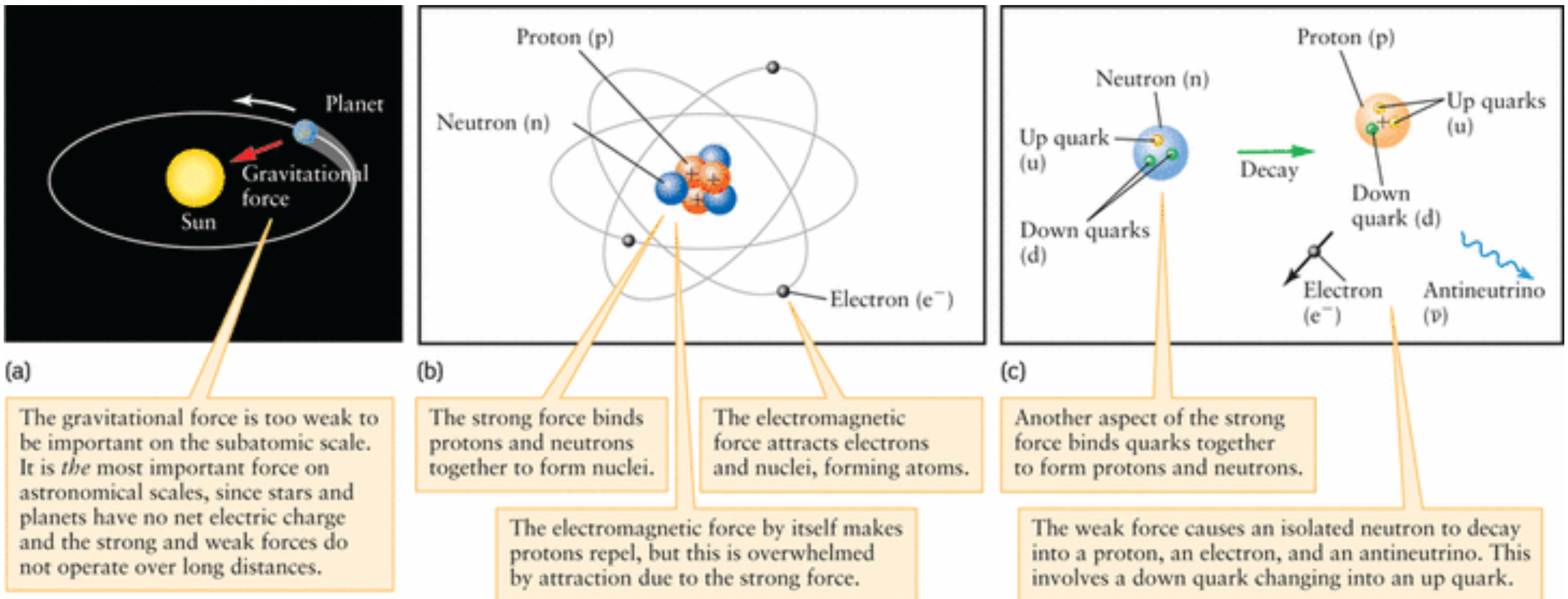
1. **Gravity** (exchange particle=graviton)

2. **Electromagnetism** (exchange particle=photon)

3. **Strong Force** (exchange particle=gluon)

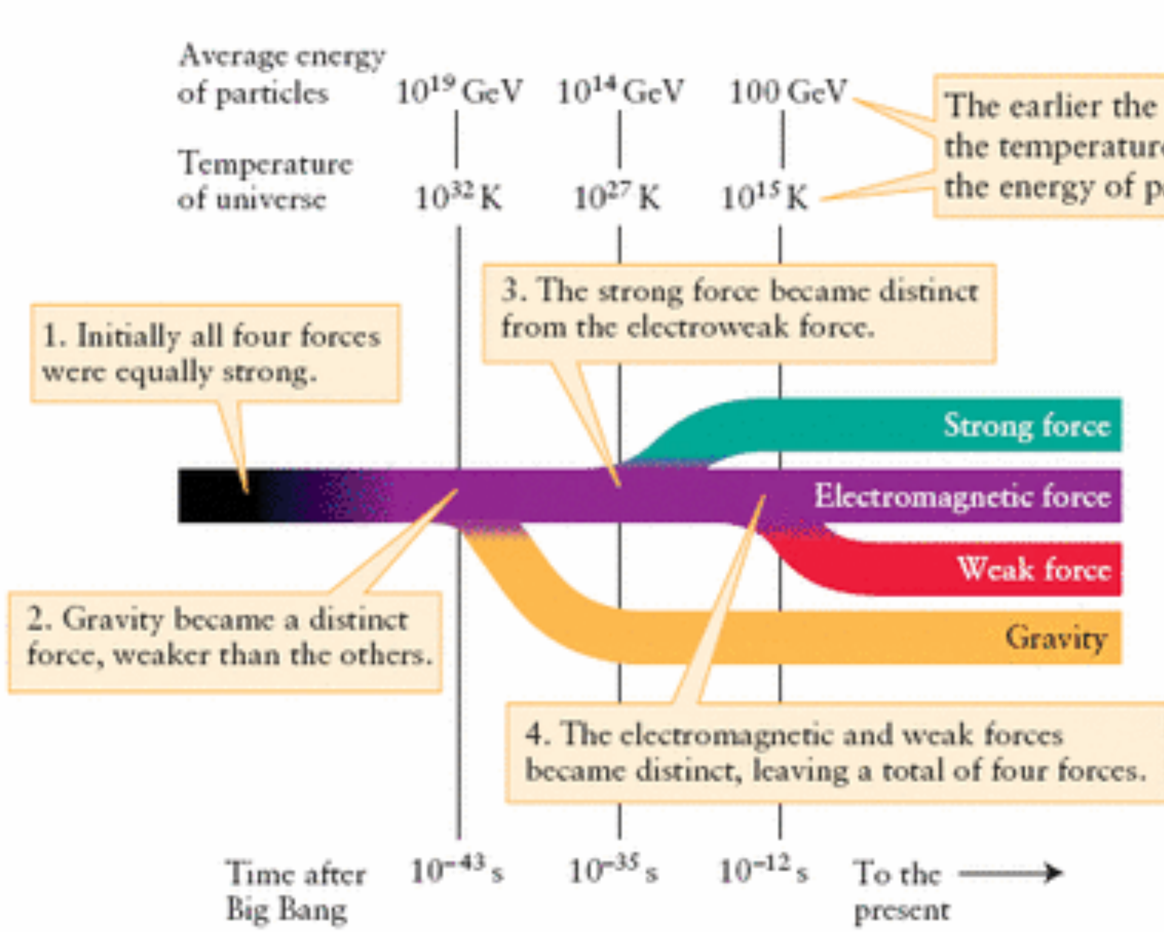
4. **Weak Force** (exchange particles=intermediate vector W^+, W^- and Z bozons)

The Early Universe: Fundamental Forces

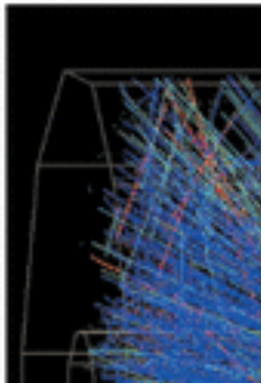


Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	10^{-15} m	holding protons, neutrons, and nuclei together
Electromagnetic	1/137	photons	charged particles	infinite	holding atoms together
Weak	10^{-4}	intermediate vector bosons	quarks, electrons, neutrinos	10^{-16} m	radioactive decay
Gravitational	6×10^{-39}	gravitons	everything	infinite	holding the solar system together

One Force in the Beginning?



(a) How the four forces behave at different energies and temperatures



Matter and Radiation Created During Inflation

To understand how radiation and matter were created we need to discuss the **uncertainty principle**.

According to Heisenberg's uncertainty principle the more precisely you try to measure the position *x* of a particle, the more unsure you become of the particle's momentum *p* (*p* = mass × velocity).

The uncertainty principle between position and momentum states :

$$\Delta x \Delta p \geq \frac{\hbar}{2} \rightarrow \Delta x \geq \frac{1}{2}\left(\frac{\hbar}{mc}\right), \hbar = 1.054 \times 10^{-34} Js$$

Where Δx is the uncertainty in the position of the particle and Δp is the uncertainty in its momentum.

Matter and Radiation Created During Inflation

The uncertainty principle between mass and time states :

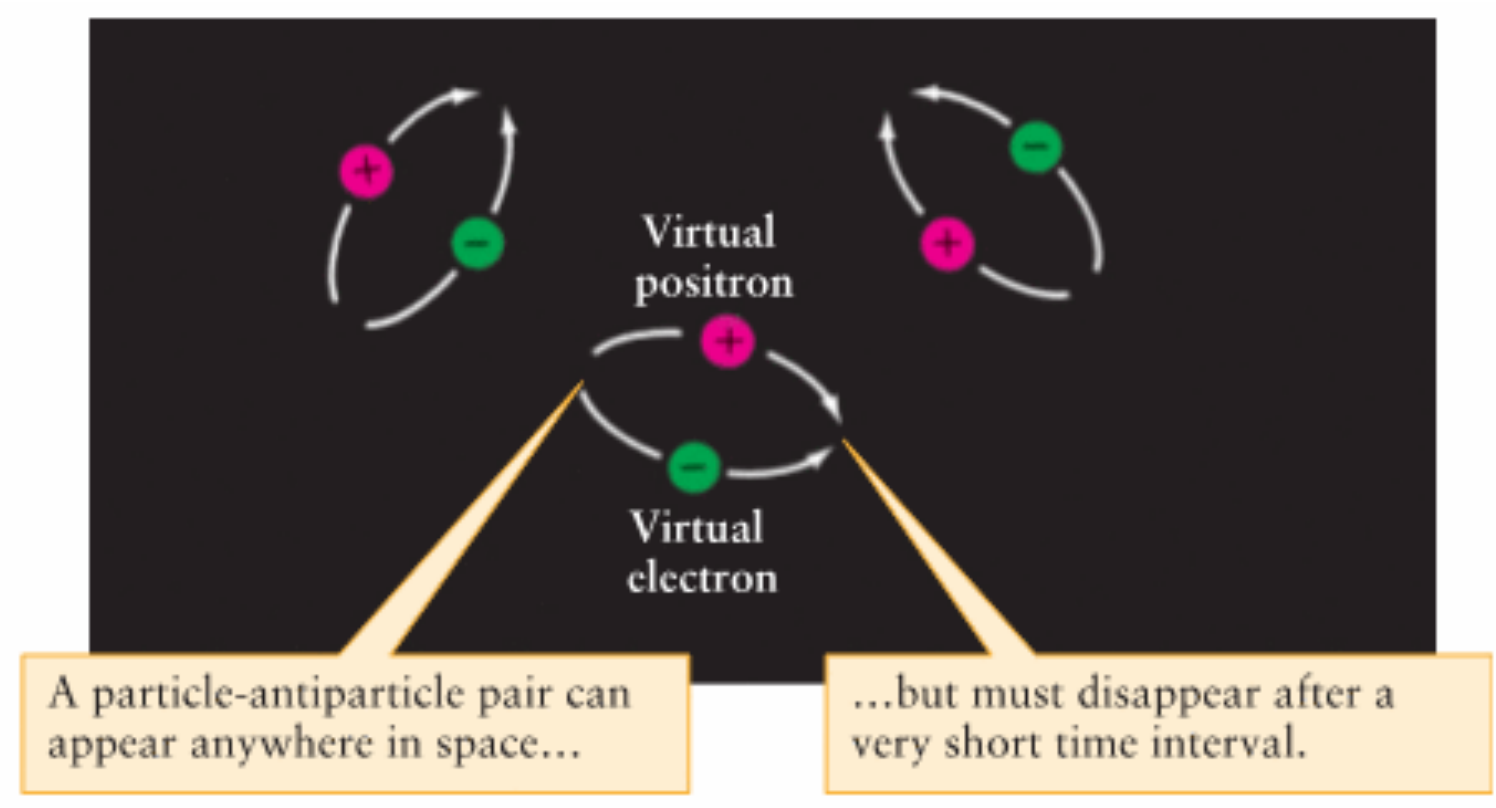
$$\Delta m \Delta t \geq \frac{\hbar}{2c^2} \quad \text{where } \hbar = 1.054 \times 10^{-34} \text{ Js}$$

Δm is the uncertainty in the mass of the particle and Δt is the uncertainty in the time interval over which the energy is measured.

For very small time intervals large uncertainties in mass are allowed by nature! This means than over a very short time interval matter can just appear and then disappear even in empty space!

No particle can appear by itself but has to be created with an antiparticle.

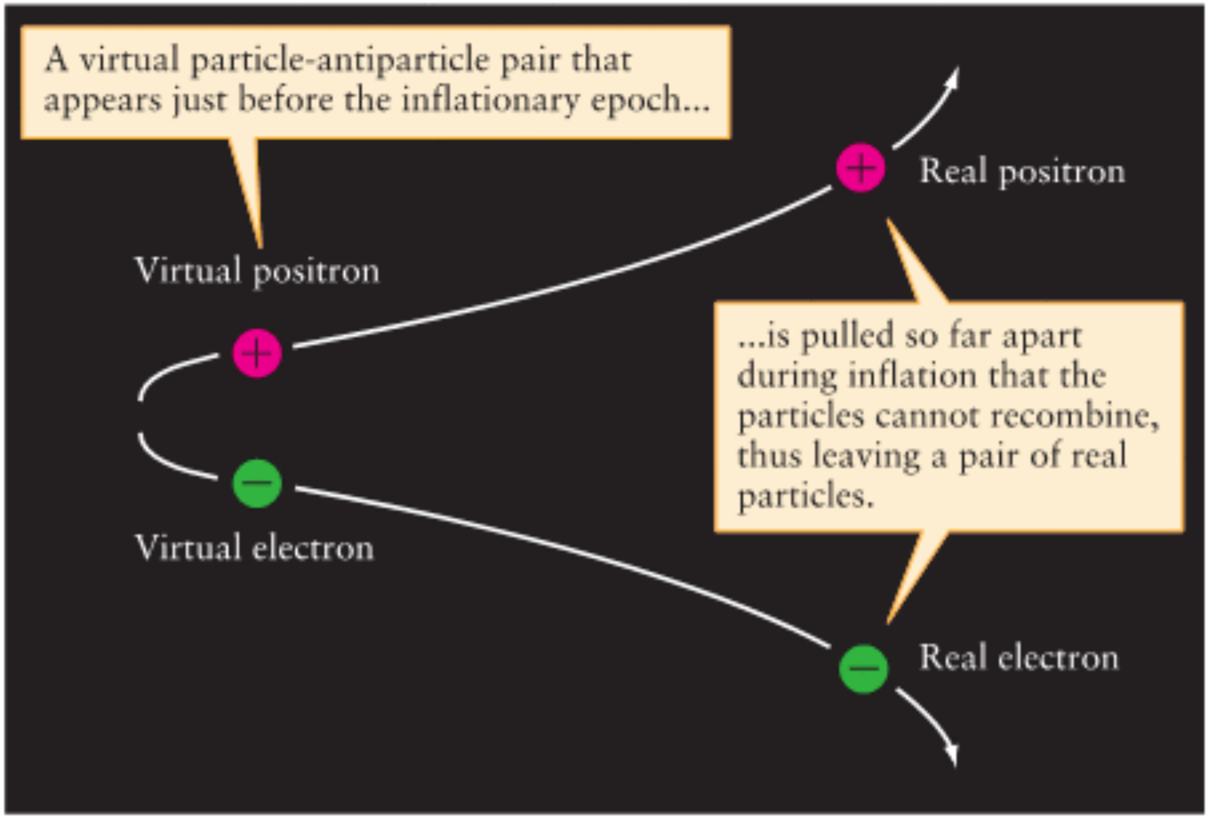
Matter and Radiation Created During Inflation



Virtual Pairs of particles and antiparticles can appear and then disappear in space provided that each pair exists only for a very short time interval, as dictated by the uncertainty principle.

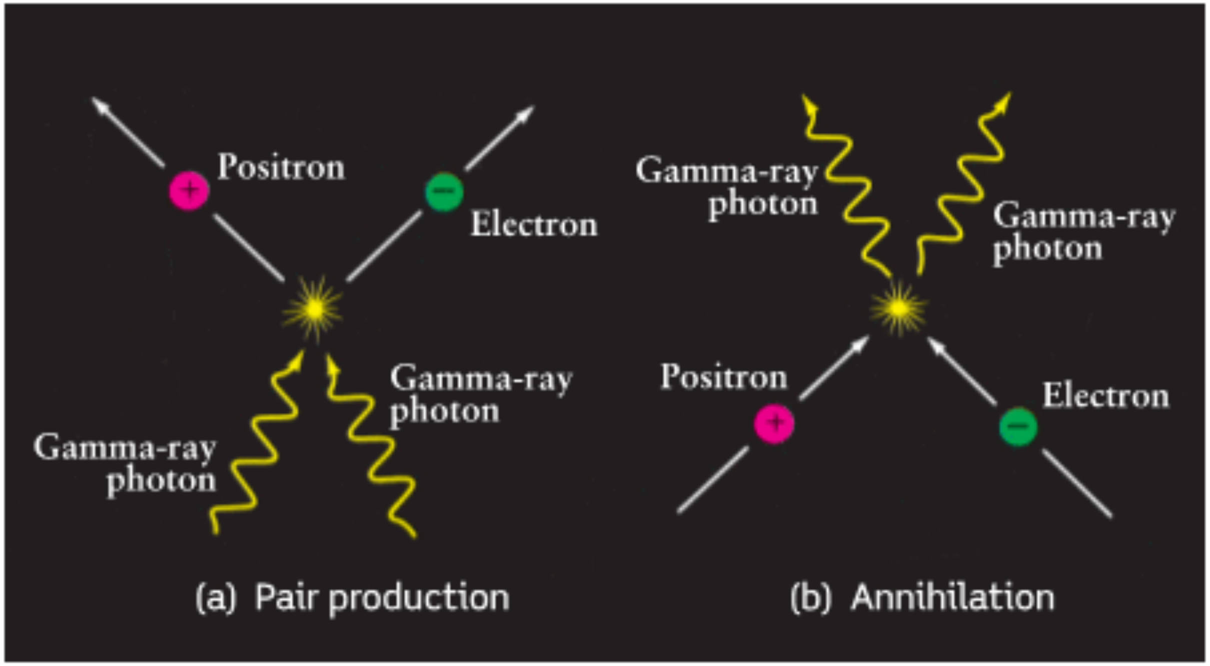
For example, an electron positron pair can be created out of vacuum and will exist for about 3×10^{-22} sec without violating the uncertainty principle.

Matter and Radiation Created During Inflation



Matter is created during Inflation: Virtual Pairs turn into real particles during inflation.

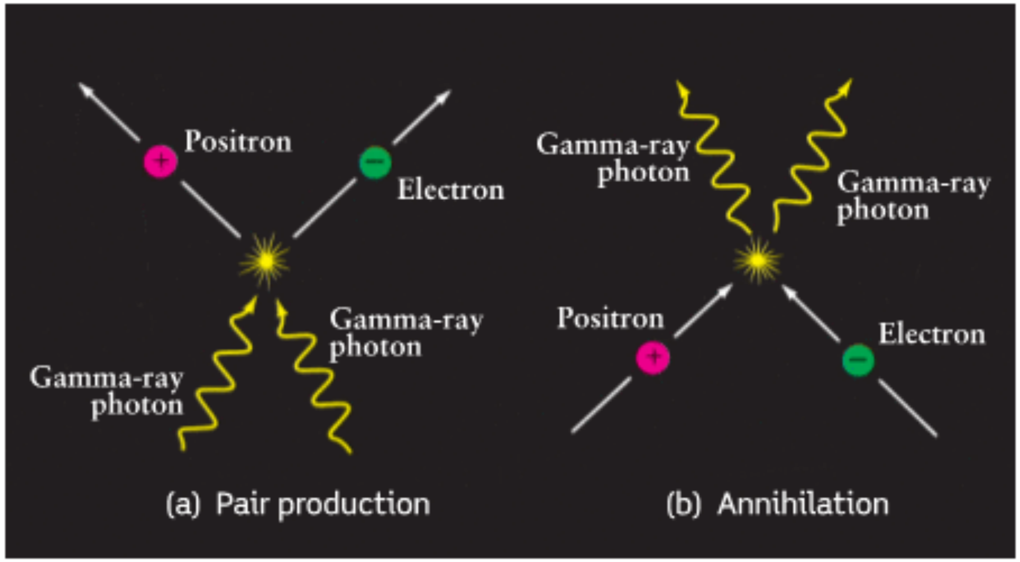
Matter and Radiation Created During Inflation



Pair production can take place only if the combined energy of the two photons is greater than *Mc^2, where M is the total mass of the electron and positron*

In the Early Universe the rate of pair production was equal to the rate of annihilation but as the Universe expanded and the temperature dropped…

Matter and Radiation Created During Inflation

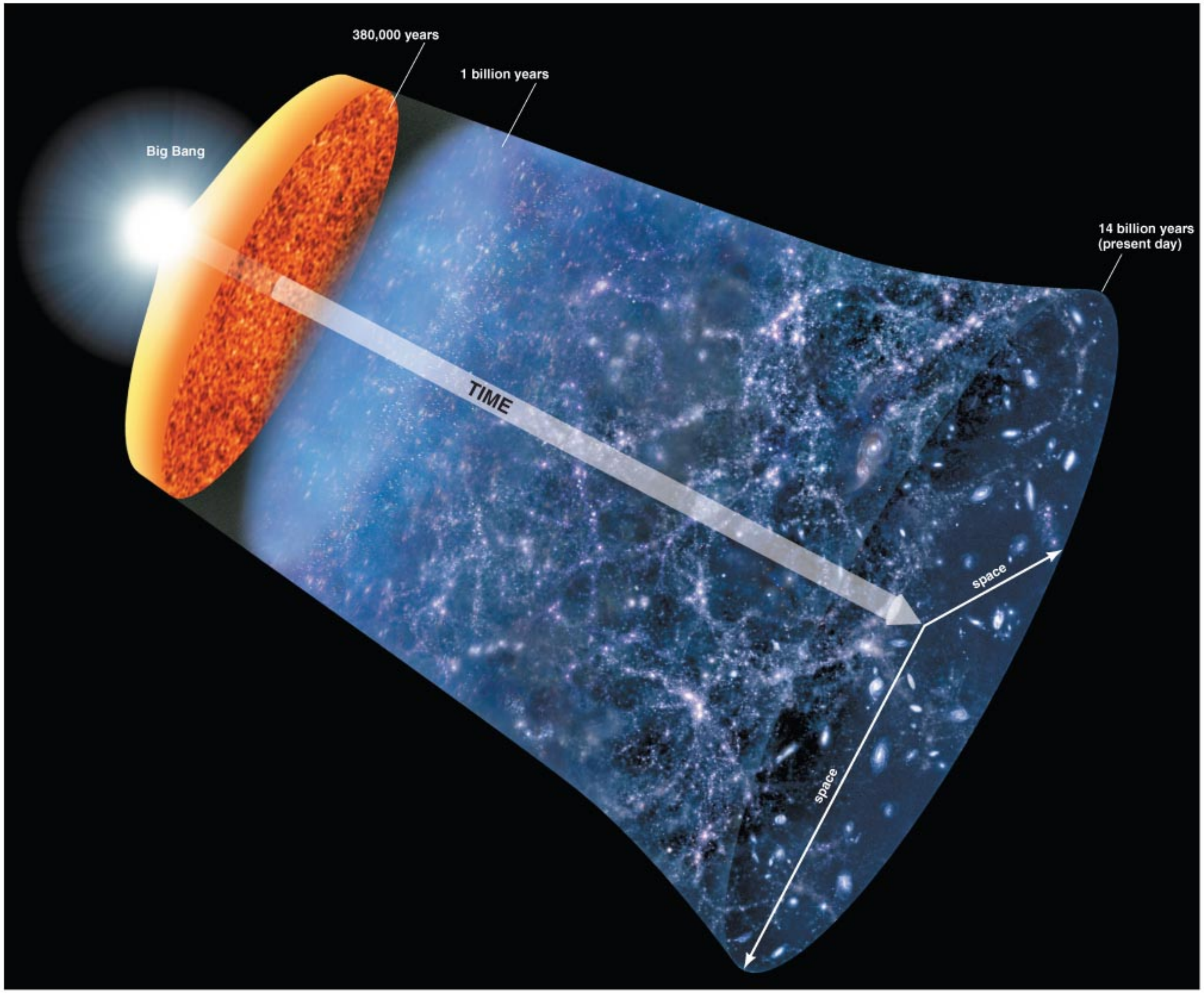


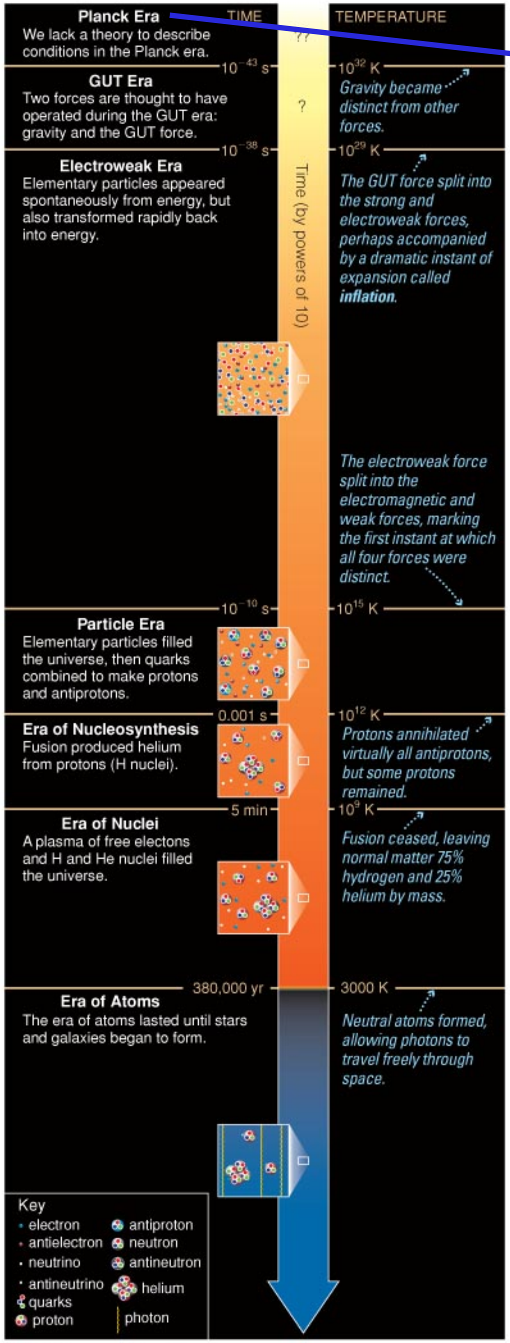
The rate of pair production decreased as the Universe expanded but annihilation continued.

In the present Universe we mostly find matter and not antimatter. But why did not all matter and antimatter annihilate?

Theories of elementary particles predict an excess of matter over antimatter immediately after the Big Bang, so that the particles outnumbered the antiparticles.

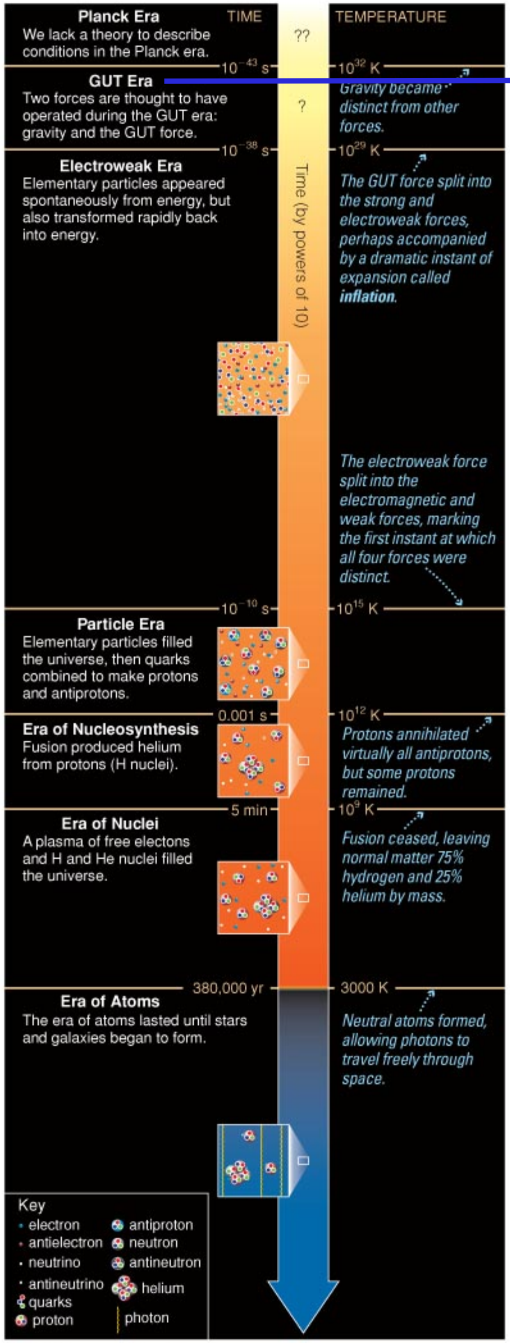
How did the early universe change with time?





Planck era

- Before Planck time (~10^{-43} second)
- No theory of quantum gravity



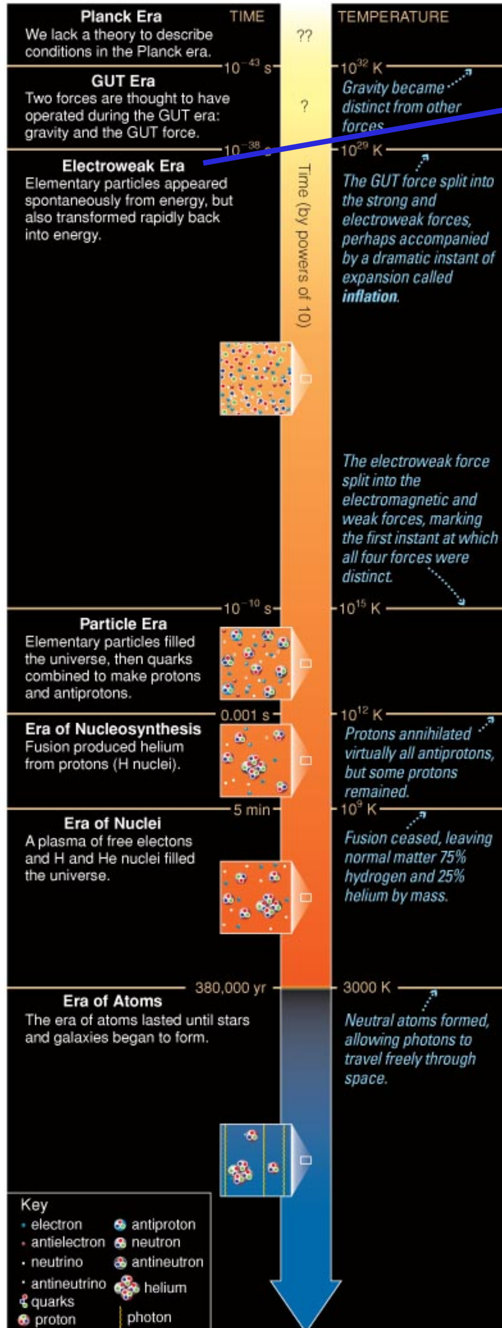
GUT era

- Gravity and the GUT force operated during this era.
- Lasts from Planck time (~$10^{–43}$ second) to end of GUT force (~$10^{–38}$ second)

Electroweak era

The beginning of the electroweak era is thought to coincide with **inflation.**

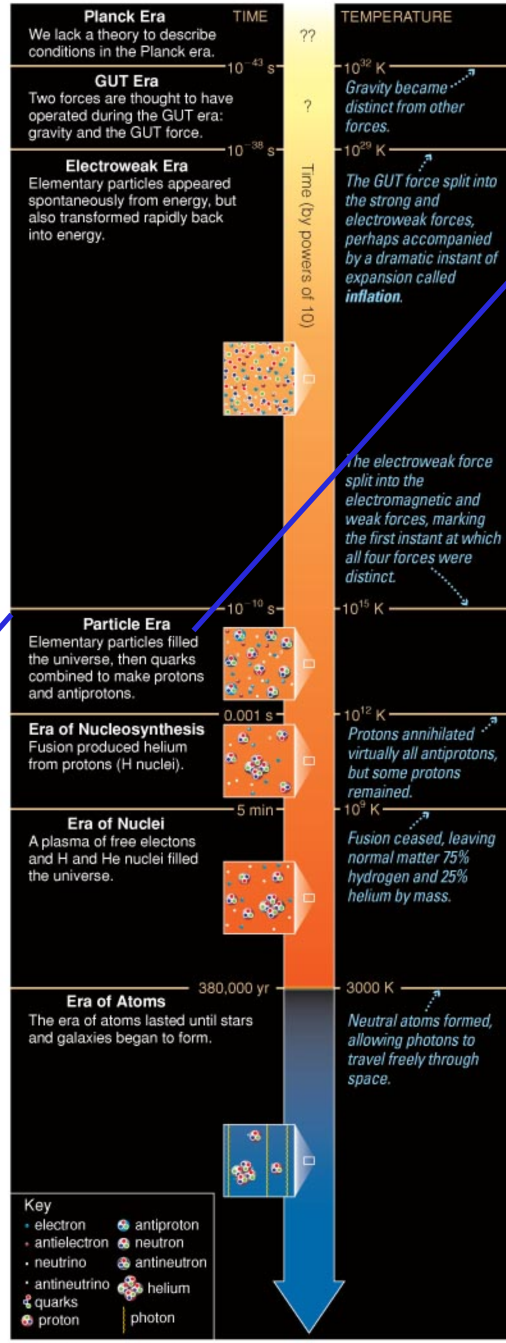
Matter is created during Inflation: Virtual Pairs turn into real particles during inflation.



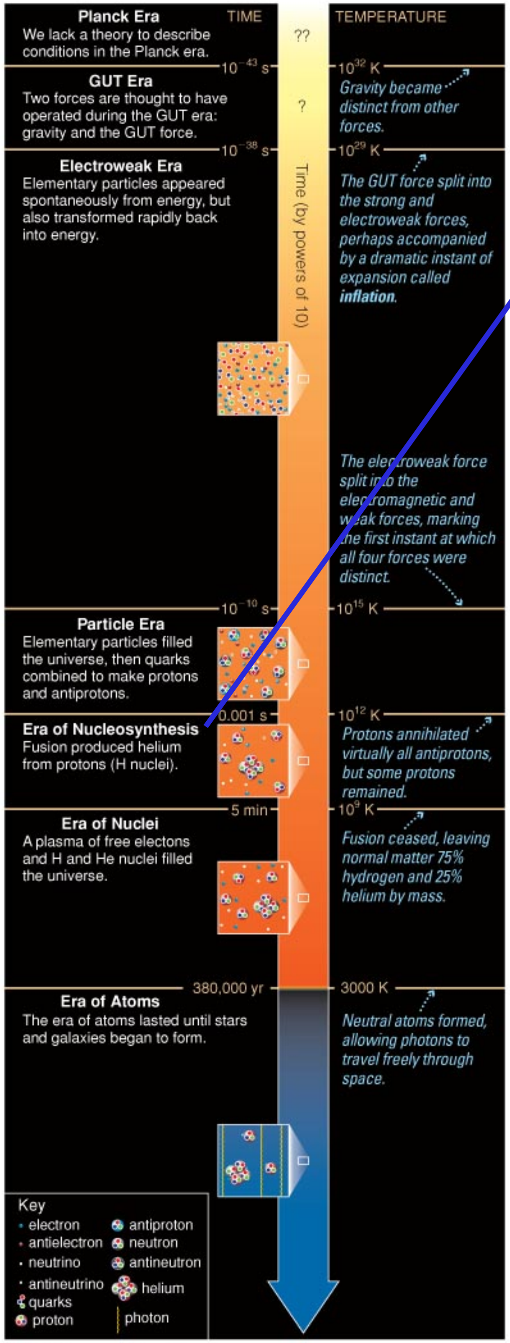
- Gravity, strong and electroweak force operated.
- Lasts from end of GUT force (~10^{-38} second) to end of electroweak force (~10^{-10} second).

Particle era

- Quarks combine to make **protons and antiprotons**
- Amounts of matter and antimatter nearly equal (roughly 1 extra proton for every 10^9 proton– antiproton pairs!)



During the particle era the Universe cooled to the point where spontaneous pair production of particles ceased.

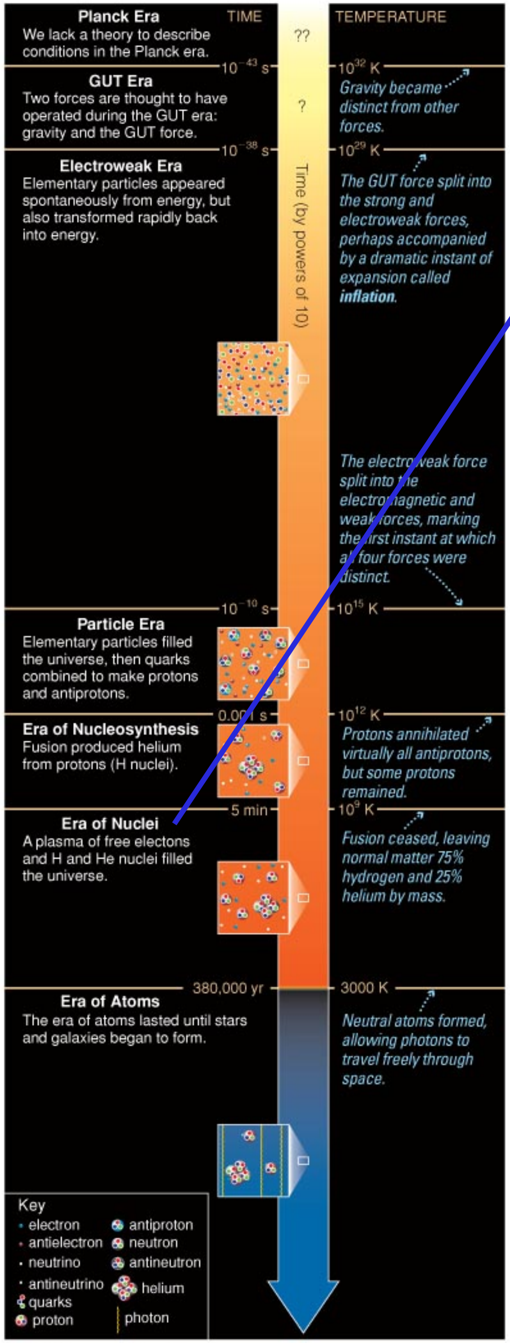


Era of nucleosynthesis

- Begins when protons **annihilate remaining antiprotons** at ~ 0.001 second but some protons remain.

- **Fusion begins and produces helium nuclei from protons**

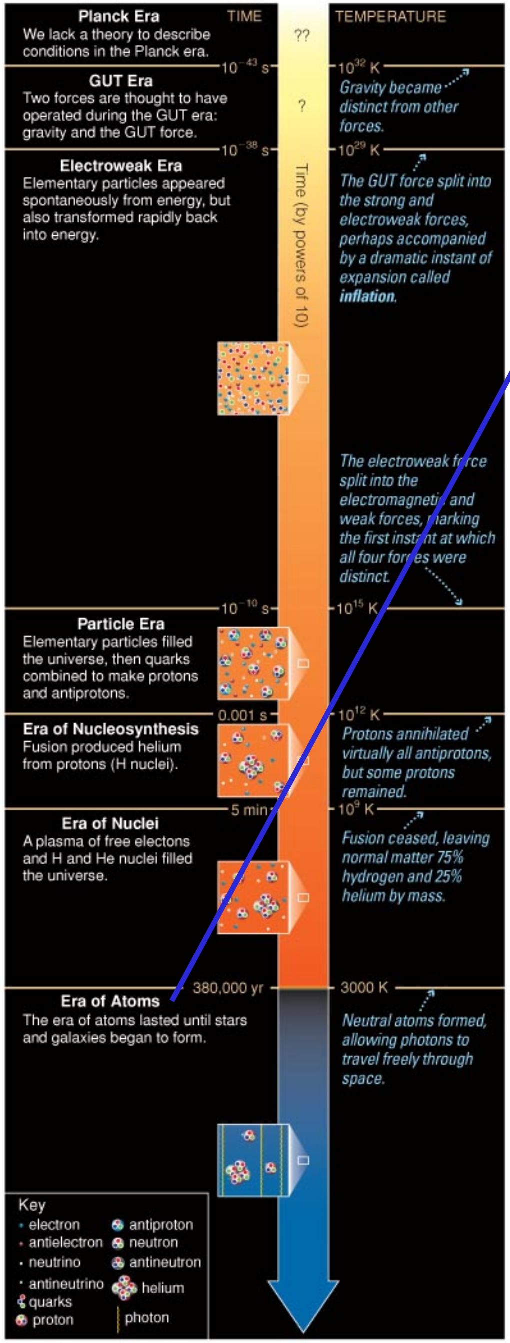
Era of nuclei



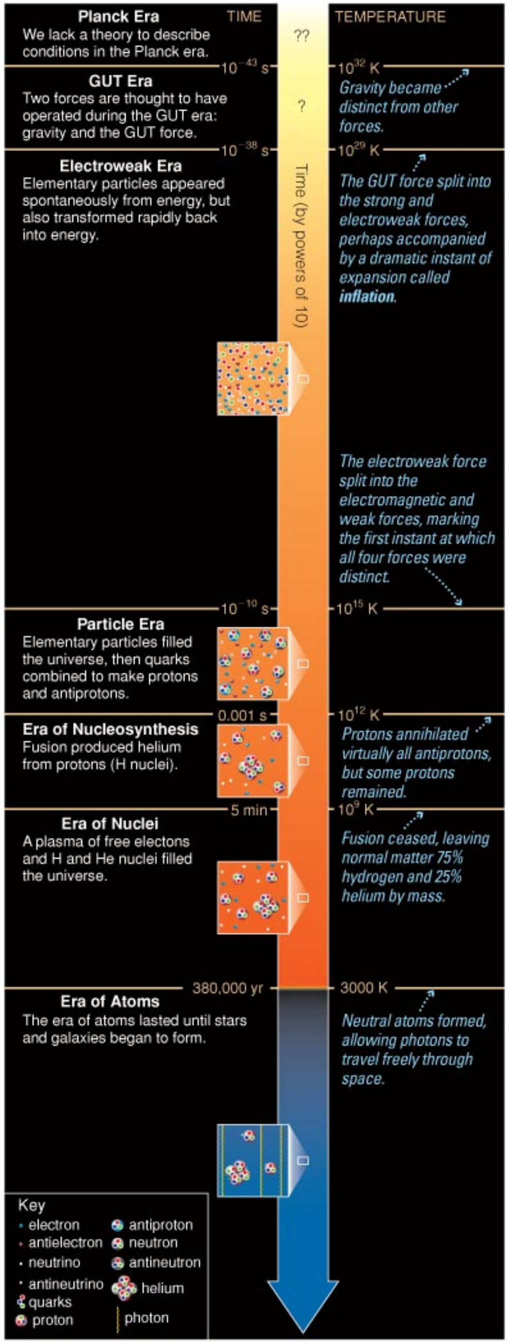
Electrons are not bound to nuclei. Photons do not travel far because of multiple scattering off of electrons.

- A plasma of free electrons and H and He nuclei fill the Universe between ~ 3 minutes – 380,000 years.
- Fusion ceased leaving ~75% H and ~25% He nuclei.

Recombination Era



- Neutral Hydrogen atoms form at age ~ 380,000 years.
- Cosmic Microwave Background radiation released.



Era of galaxies

- Galaxies form at age ~ 1 billion years.

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 protons into helium.
  - Radiation traveled freely after formation of atoms.

22.2 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

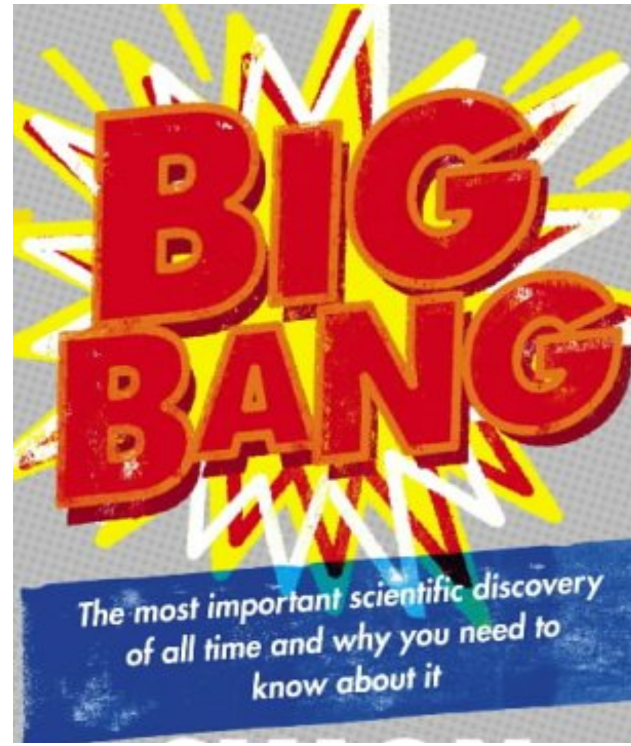
1) We have detected the leftover radiation from the Big Bang.

2) The Big Bang theory correctly predicts the abundance of helium and other light elements.

Evidence for the Big Bang theory

As the universe expanded the plasma of protons and electrons cooled. When it reached T~3000 K the electrons combined with protons to form neutral H.

A prediction of the Big Bang theory is that about 380,000 years after the beginning of our Universe photons were able to escape and travel freely through space.



Evidence for the Big Bang theory

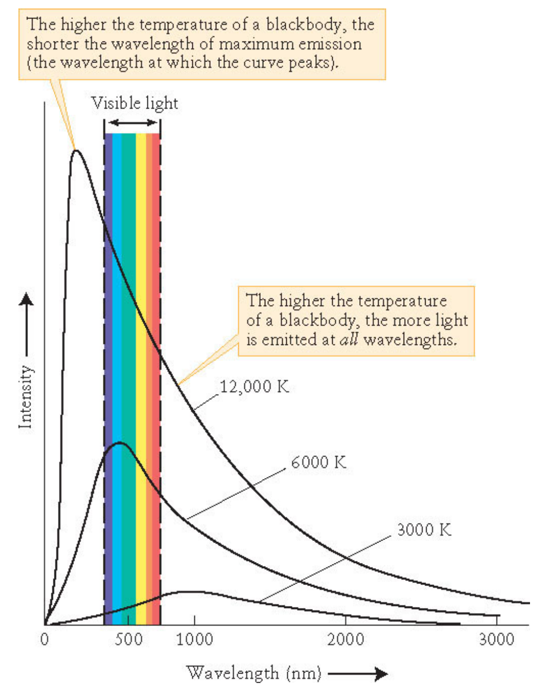
Radiation from the hot plasma produced just after the Big Bang has a blackbody spectrum.

Recall that a Blackbody spectrum is characterized by a peak wavelength and a temperature that follow Wien's Law:

$$\lambda_{\max}(m) = \frac{0.0029\,K\,m}{T(K)}$$

$\lambda_{\max}$ = wavelength of maximum emission in meters

T = temperature of object in kelvins



Evidence for the Big Bang theory

In 1965 Arno Penzias and Robert Wilson while working at Bell Labs on a horn antenna discovered cosmic background radiation left over from the hot Big Bang.

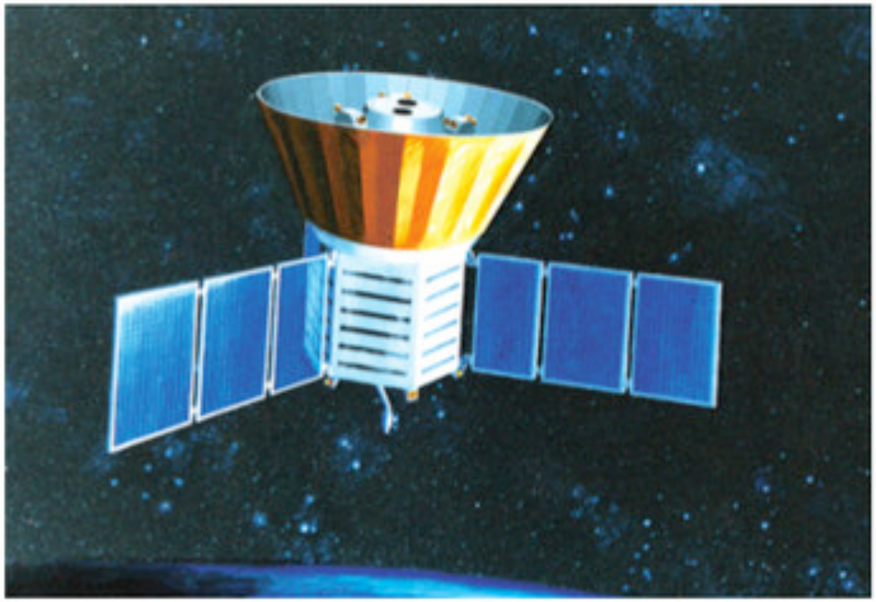
Temperature of the cosmic microwave background (CMB) now T_{obs} = 2.725 K

Because of the cosmological redshift the spectrum of the CMB is redshifted making the observed temperature now much cooler than the original one of 3,000 K!

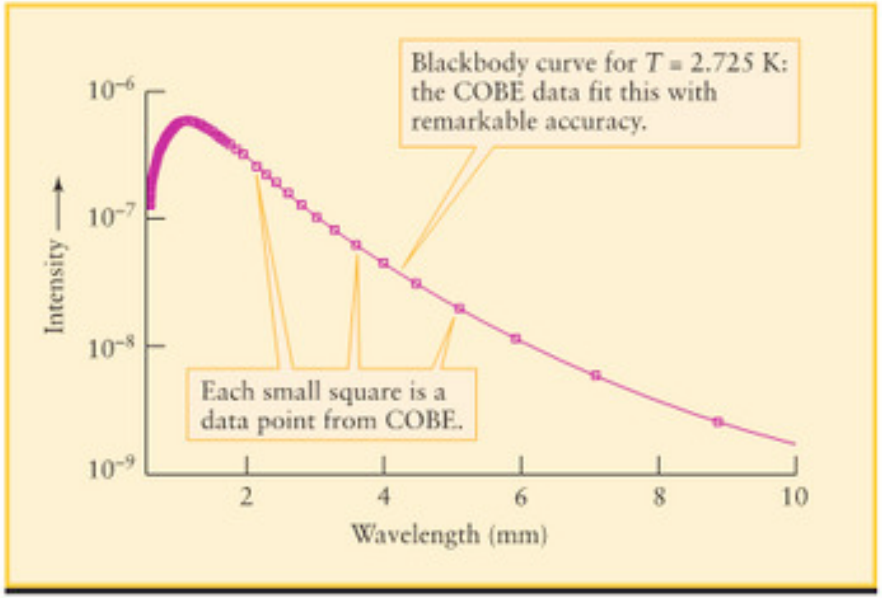
Since the temperature decreased by a factor of 3,000 K / 2.725 K = 1100 the wavelength increased by 1100.

Penzias and Wilson in front of the Horn Antenna.

Evidence for the Big Bang theory



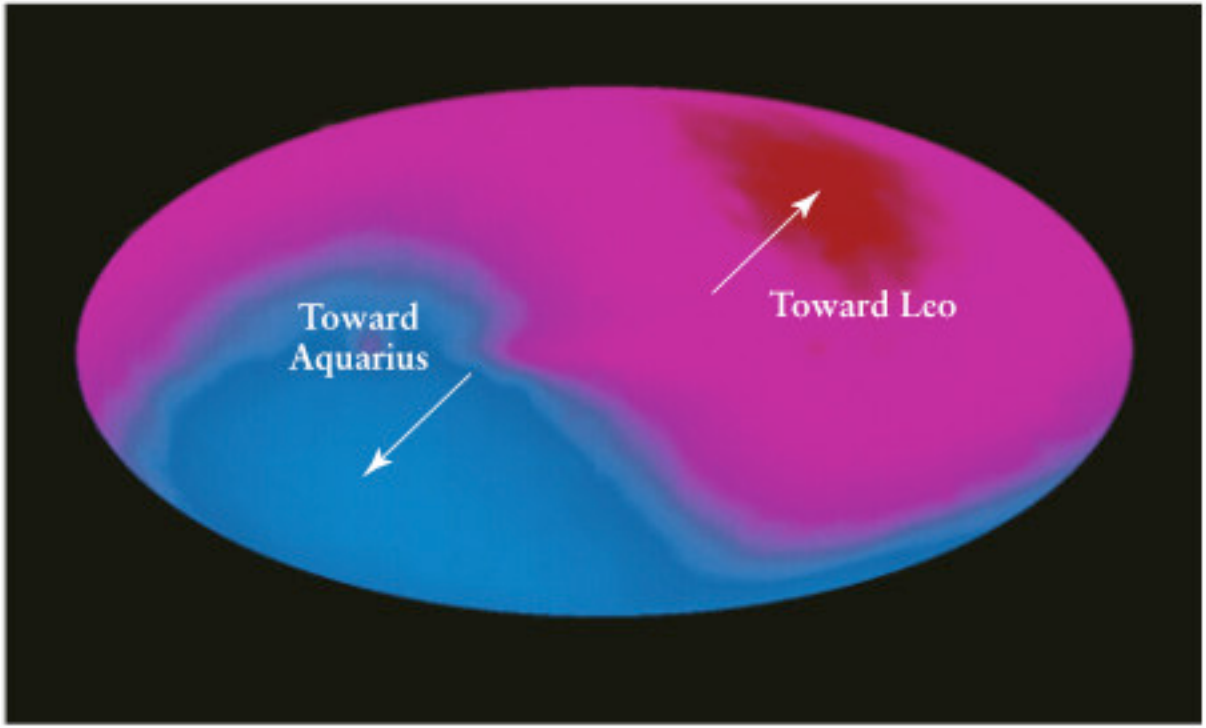
(a) The COBE spacecraft



(b) The spectrum of the cosmic microwave background

The first high-precision measurements of the cosmic microwave background came from the Cosmic Background Explorer (COBE) satellite, which was placed in Earth orbit in 1989. The CMB intensity is almost perfectly isotropic with a slight variation in temperature across the sky.

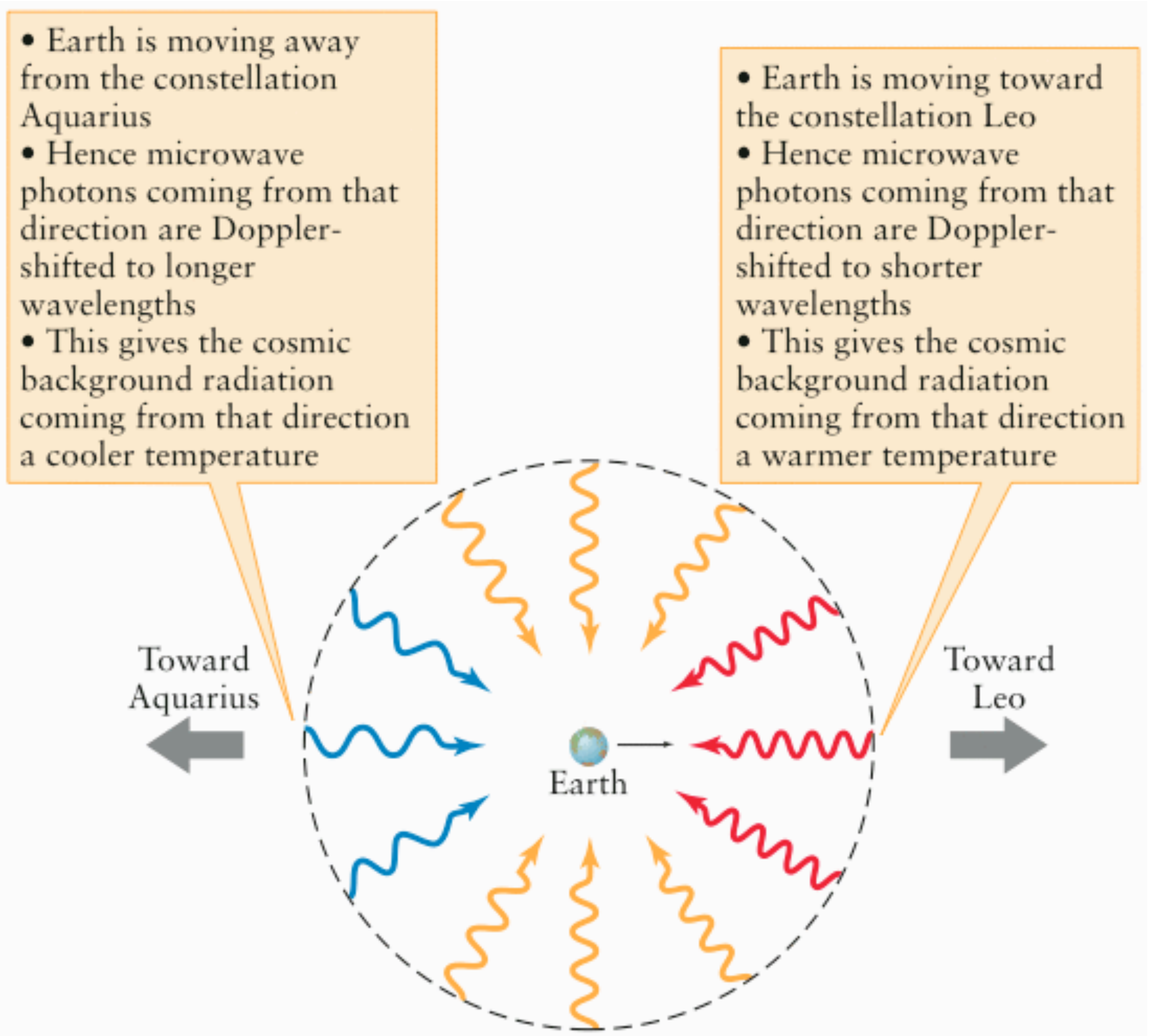
Evidence for the Big Bang theory

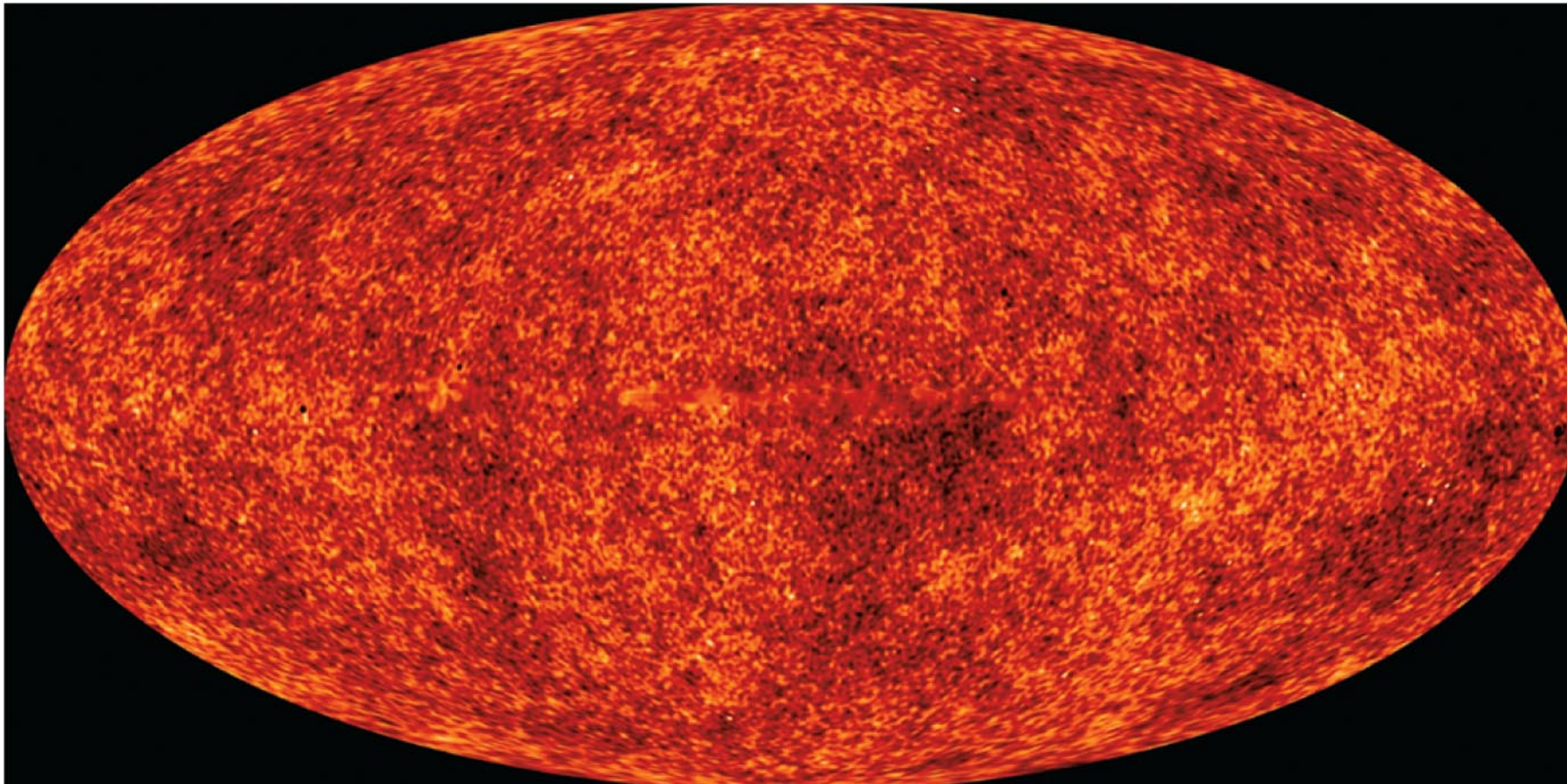


The microwave background appears slightly warmer than average toward the constellation of Leo and slightly cooler than average in the opposite direction toward Aquarius. In this map of the entire sky made from COBE data, the plane of the Milky Way runs horizontally across the map, with the galactic center in the middle. Color indicates temperature—red is warm and blue is cool. The temperature variation across the sky is caused by Earth's motion through the microwave background.

Evidence for the Big Bang theory

Because of the Doppler effect, we detect shorter wavelengths in the microwave background and a higher temperature of radiation in that part of the sky toward which we are moving. This part of the sky is the area shown in red. In the opposite part of the sky, shown in blue the microwave radiation has longer wavelengths and a cooler temperature.





Interactive Figure

- WMAP gives us detailed baby pictures of structure in the universe.

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

Calculations of the amount of Helium expected to have been produced a few minutes just after the Big Bang agrees well with the amounts of He observed in primordial gas (~75% H and ~25% He).

In order for the Universe to have produced those H→He fusion reactions it must have been extremely hot and dense filled with high energy photons.

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.

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.
  - Inflation flattened the curvature of space, bringing expansion rate into balance with the overall density of mass-energy.

Extra Slides

Electroweak Force > 100 GeV?

Steven Weinberg, Sheldon Glashow, and Abdus Salam first proposed that the weak force is mediated by the W^+, W^- and Z bozons.

These three particles were actually discovered in the 1980s, providing strong support for the theory.

They also predicted that the **electromagnetic force and the weak force** between particles **are identical for particles with energies greater than 100 GeV**!

The **W^+, W^- and Z bozons lose their mass at > 100 GeV** and behave like photons.

GUTs > 10^{14} eV?

In the 1970s, scientists proposed **grand unified theories** (or **GUTs**), which predict that the strong force becomes unified with the weak and electromagnetic forces (but not gravity) at energies above 10^{14} GeV.

No supergrand unified theory has been developed yet that can unify all four forces (some theorists think that this happens at 10^{19} eV).

Combining all the forces would require a theory that could combine gravity at the microscopic scales (quantum gravity).