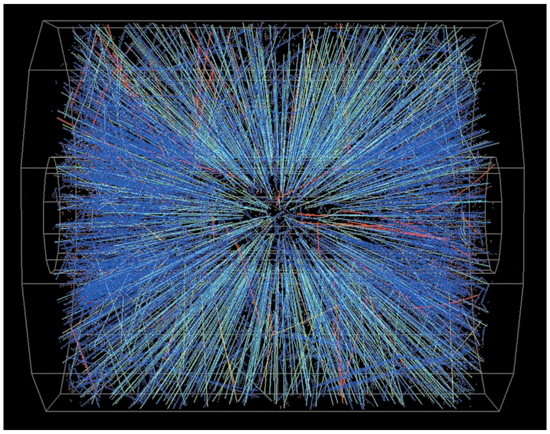
THE EARLY UNIVERSE



Big Bang Standard Model

Cosmic Singularity “exploded” into existence.

Expansion has been in all directions at equal speeds.

Observable Universe is the entire Universe.

Is the Big Bang Model Perfect?

NO

Flatness Problem

Isotropy Problem

Anti-Matter Problem

What is the Flatness Problem?

Observations show that the Universe is close to the “marginally bound” case.

The Universe is now ~15 billion years old, so at the time of the Big Bang, the matter density (ρ_m) must have been equal to the critical density (ρ_{crit}) out at least 50 significant digits.

1.0000000000000000000000000000000000000000000000000

If we had deviated a little **too low**, the Universe should have been **so open no matter coalesced to form stars**.

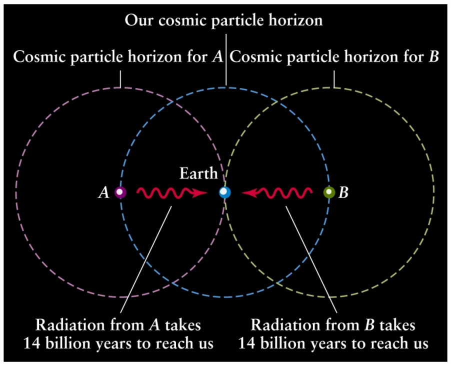
If we had had **too high** a density, the Universe should have **collapsed upon itself** by now.

What is the Isotropy Problem?

The Cosmic Microwave Background Radiation (CMB) shows that the Universe is **extremely uniform in all directions**.

But with the Big Bang Standard Model, the different parts of the Universe were never in contact, so they should not have the same temperature.

Apparently, the Universe must have been well mixed almost from the start.



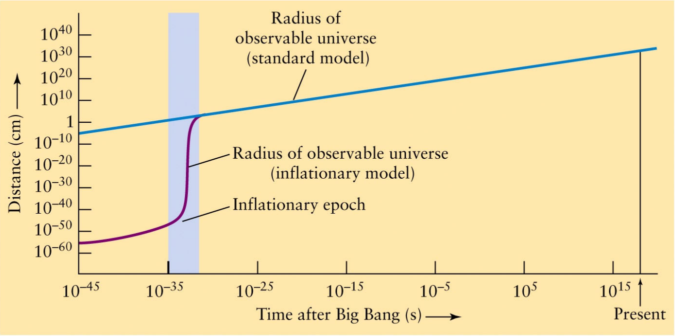
What is the Anti-Matter Problem?

Quantum mechanical models indicate that there should be equal amounts of matter and antimatter. But we live in a matter Universe.

Inflationary Universe Theory

Theory: The Universe rapidly expanded at $\tau = 10^{-35}$ s but for only 10^{-24} s.

During this time, *Space* – but not Matter – ballooned out by a factor of 10^{50}. This does not violate Einstein's dictate of $v < c$, because *matter* did not travel through space faster than *c*.



Inflationary Universe Theory

Diameter 1: 1 fm = 10^{-15} m diameter of a proton

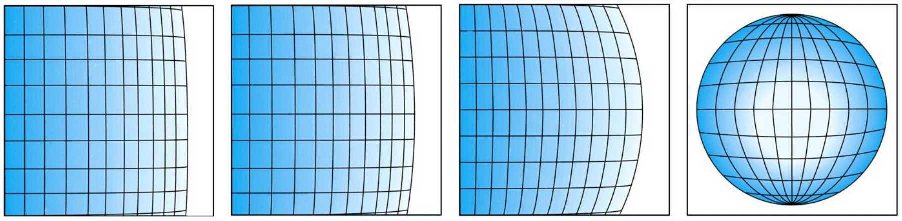
Diameter 2: 10^{50} fm = 10^{35} m = 10^{27} AU = 10^{21} pc = 10^{15} Mpc

16.3 billion light years

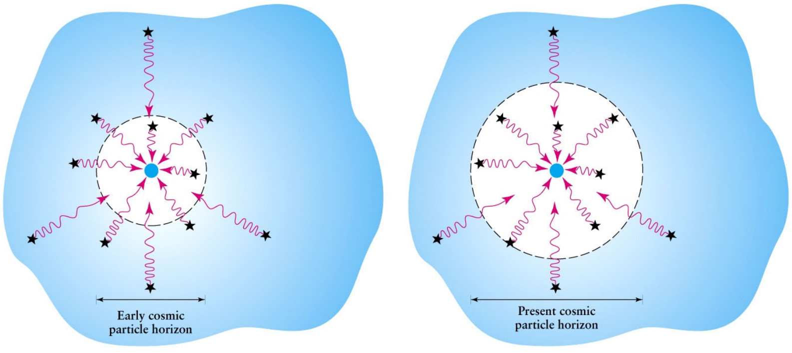
(about half the size of today's Observable Universe)

Removes Flatness Problem

When we only see a small part of the curved Earth, it appears flat to us. Likewise, the Universe appears flat because we only see a very small part of it.



The Observable Universe

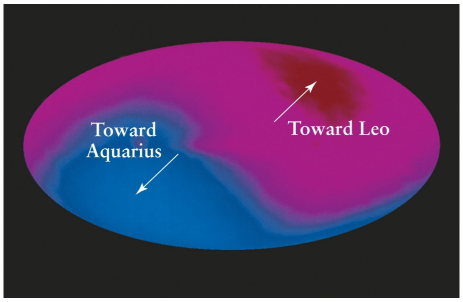


The part of the Universe that we can observe lies within a sphere centered on the Earth called the **Cosmic Particle Horizon**. Its radius is equal to the distance that light has traveled since the start of the expansion.

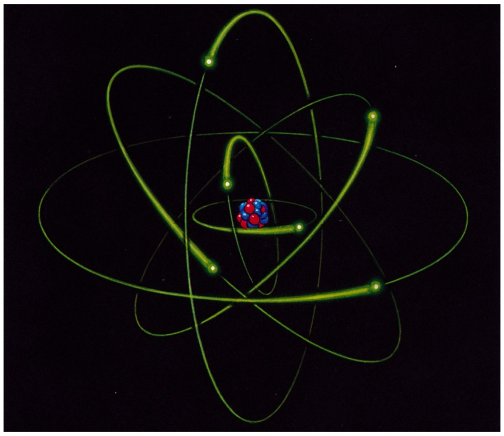
Removes Isotropy Problem

The small part of the Universe we observe was previously very close together (i.e., intimate, mixed, thermalized) – close enough that it had mixed prior to the Inflationary event.

So the Cosmic Microwave Background Radiation we see in all directions comes from a very small region of the early Universe.

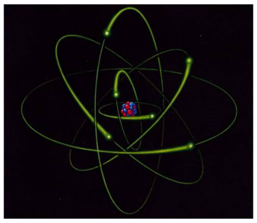


Need to Learn a Little
Quantum Mechanics



Quantum Mechanics

Quantum Mechanics is the branch of physics that explains the behavior of nature on the atomic scale and smaller. The sub-microscopic world of quantum mechanics is significantly different from the ordinary world around us. A certain amount of fuzziness, or uncertainty, enters into the description of reality.



Heisenberg Uncertainty Principle

This principle states that there is a reciprocal uncertainty between **position** and **momentum** (equal to the mass of the particle times its velocity).

$$\Delta x \cdot \Delta p = h / 2\pi$$

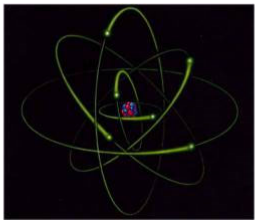
The more precisely you try to measure the position of a particle, the more unsure you become of how the particle is moving (i.e., its velocity).

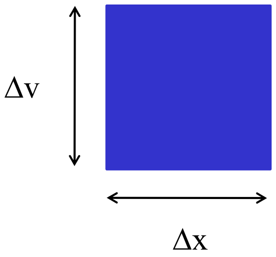
Conversely, the more accurately you determine the momentum/velocity of the particle, the less sure you are of its location.

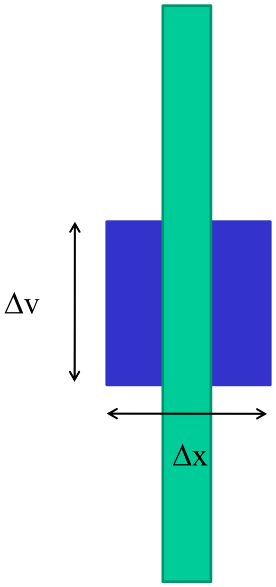
These restrictions are not a result of errors in making measurements; they are fundamental limitations imposed by the nature of the Universe.

Quantum Mechanics

To appreciate the reasons for this uncertainty, image trying to measure the position of a single electron. To find out where it is located, you must observe it. And to observe it, you must shine a light on it. However, the electron is so tiny and has such a small mass that the photons possess enough energy to give the electron a mighty kick. The electron recoils in some unpredictable direction.

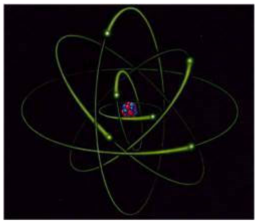


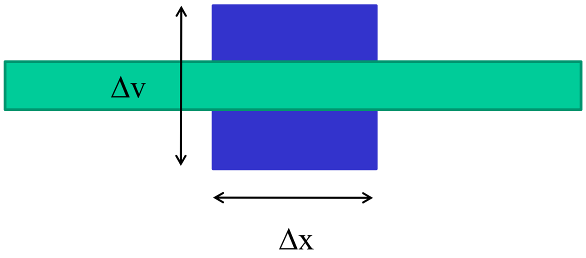

Δv
Δx


Δv
Δx

Quantum Mechanics

If one tries to carefully measure the precise location of an electron, one "sees" it with photons. But these photons hit the electron, impart energy, and cause it to change direction and change speed. Trying to improve on one of these parameters, causes the other to become less certain.





Heisenberg Uncertainty Principle

There is an analogous uncertainty involving **Energy** and **Time**.

$$\Delta E \cdot \Delta t = h / 2\pi$$

One cannot know the energy of a system with infinite precision at every moment in time. Over short time intervals, there can be great uncertainty about the amounts of energy in the subatomic world.

Heisenberg Uncertainty Principle

$$\Delta E \cdot \Delta t = h / 2\pi$$

$E = m c^2$ so $\Delta E = \Delta m c^2$

$$\Delta m \cdot \Delta t = h / 2 \pi c^2$$

For an electron-positron pair:

$$\Delta t = (1 / \Delta m) (h / 2 \pi c^2) = 6.44 \times 10^{-22} \text{ s}$$

Spontaneous Production

During this brief moment of 6.44×10^{-22} s, an electron and positron can spontaneously appear and then disappear.

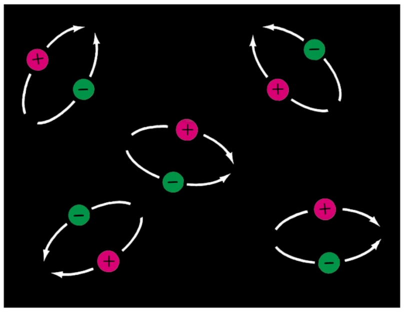
The greater the amount of matter that appears spontaneously, the shorter the time interval it can exist before it disappears into nothingness.

This bizarre state of affairs is a natural consequence of quantum mechanics.

Virtual Pairs

Spontaneous creation happens anywhere and at any time. Quantum mechanics says that **if a process is not strictly forbidden**, **then it must occur**.

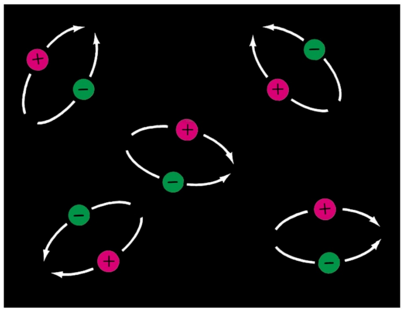
Pairs of every type of particle and anti-particle are constantly being created and destroyed at every location across the Universe.



Virtual Pairs

We have no way of observing these pairs directly without violating the Uncertainty Principle.

These are called **virtual pairs**. They do not "really" exist – they "virtually" exist.



Antiparticles

No particle can appear spontaneously by itself, however. For each particle created there is a second, almost identical antiparticle made. Equal amounts of matter and antimatter come into existence and then disappear.

A particle and antiparticle are identical in almost every respect except that they carry **opposite electric charges**. Because particles and antiparticles come and go in pairs, the total electric charge in the Universe remains constant.

This kind of balance between matter and antimatter is known as **symmetry**.

Pair Production

In some circumstances, virtual pairs can become **real pairs** of particles and antiparticles, which is known as **Pair Production**. Two gamma rays can convert their energy into pairs of particles and antiparticles.

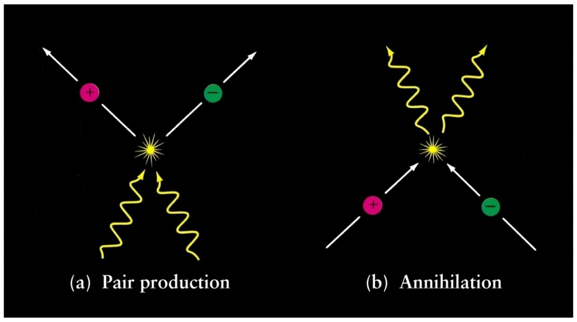
To create a particle and an antiparticle having a total mass M, the gamma-ray photons must possess an amount of energy E that is greater than or equal to Mc^2. The gamma rays disappear upon colliding, and a particle and an antiparticle appear in its place.

These particles and antiparticles come from nature's ample supply of virtual pairs. The gamma rays provide a virtual pair with so much energy that the virtual particles can appear as real particles.

Annihilation

The inverse process, in which a particle and antiparticle collide with each other and are converted into high-energy gamma rays, is known as **Annihilation**.

particle + **anti-particle** ↔ $\gamma + \gamma$



During the Inflationary Epoch

During the Inflationary Epoch, space was expanding with explosive vigor. All space was seething with virtual pairs of particles and antiparticles.

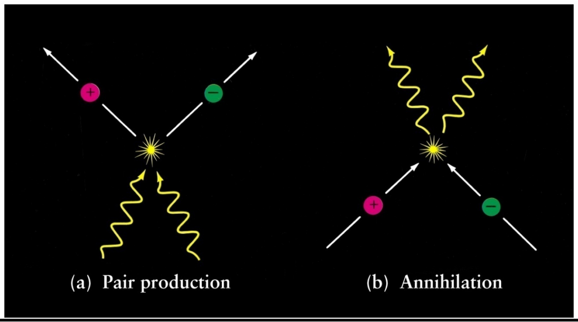
Normally, a particle and an antiparticle have no trouble getting back together in a time interval (Δt) short enough to be in compliance with the uncertainty principle.

During Inflation, however, the Universe expanded so fast that particles were rapidly separated from their corresponding antiparticles. **These virtual particles became real particles.** The Universe was flooded with particles and antiparticles.

Balance of Creation-Distruction

Initially collisions between particles and antiparticles produced numerous high-energy gamma rays. As these gamma rays collided, they turned back into the particles and antiparticles from which they came. So the rate of pair production was equal to the rate of annihilation:

$$p^+ + p^- \leftrightarrow \gamma + \gamma$$



Universe Expansion Effects

As the Universe continued to expand, all of the gamma-ray photons became increasingly **redshifted**, so the photon's energy decreased and the temperature of the radiation field went down.

The temperature (i.e., speed, energy) eventually became so low that the gamma rays no longer had enough energy to create particular kinds of particles and antiparticles.

Collisions of *particles and antiparticles* continued to add photons to the cosmic radiation background, but collisions of *photons* could no longer replenish the supply of particles and antiparticles.

$$p^{+} + p^{-} \rightarrow \gamma + \gamma$$

Protons and Neutrons

When the Universe was about **0.0001 seconds old**, the temperature fell below 10^{13} K. The Universe was now cooler than the threshold temperatures of both protons and neutrons.

No new protons or neutrons appeared, but the

(a) annihilation of protons with antiprotons and

(b) annihilation of neutrons with antineutrons

continued throughout space.

This wholesale annihilation dramatically lowered the matter content of the Universe, while simultaneously increasing the radiation content.

Electrons

A little later, when the Universe was **about 1 second old**, its temperature fell below 6×10^9 K, the threshold temperature for electrons and positrons.

A similar annihilation of pairs of electrons and positrons further decreased the matter content of the Universe while raising its radiation content.

This "radiation field", which fills all space, is the **primordial fireball** that dominates the Universe for the next several hundred thousand years.

Neutrons and Neutrinos

The early Universe must have been populated with vast numbers of neutrinos and antineutrinos.

$$n \rightarrow p + e^- + \overline{\nu} \quad \text{and} \quad p + e^- \rightarrow n + \nu$$

This reaction kept the number of neutrons approximately equal to the number of protons. This balance was maintained only as long as electrons were abundant. By the time the Universe was **about 2 seconds old**, no neutrons were being formed.

Up until this time the neutrinos were contained by the high density, but now they decoupled from matter. They formed a neutrino background, which is estimated to have temperature around 2 K.

Neutrons

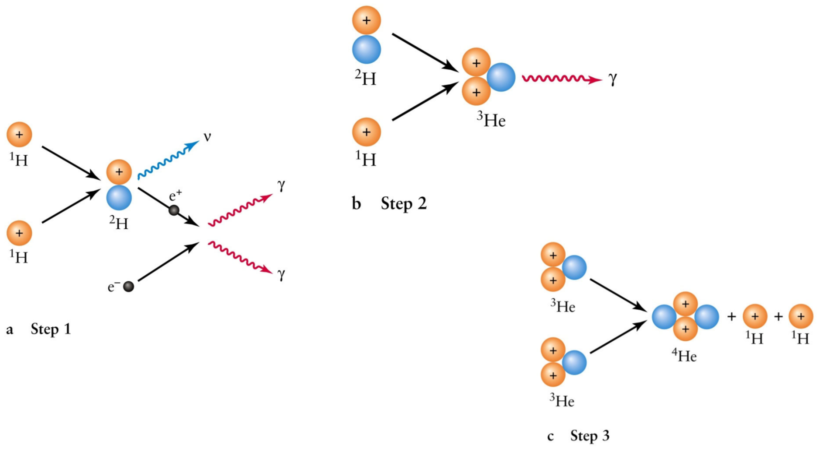
Free neutrons have a half-life of 10.5 minutes – if they do not combine with a proton during this time, they will be gone from the Universe. Before many could decay, they began to combine with protons to form **deuterium**. But remember from the Proton-Proton chain that the production of deuterium is the bottleneck in the chain of creating helium. Deuterium is easily destroyed by photons before the next step in the chain occurs.

$$ {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + e^{+} + \nu $$

$$ {}^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma $$

$$ {}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H} $$

Diagram of PPI



Helium

When the Universe was about **$3^{m}45^{s}$ old**, the background radiation had cooled enough that its photons no longer had enough energy to break up the deuterium. That is, the Universe was able to start making Helium.

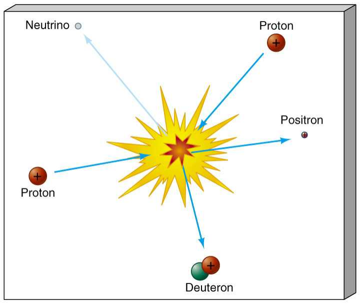
By this time, most of the neutrons had decayed into protons.

The remaining free neutrons combined with protons and rapidly made helium. The result is what we find today − about 1 helium for every 10 hydrogen.

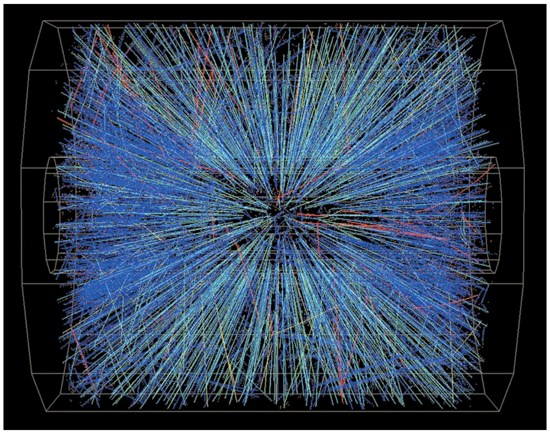
Nucleosynthesis

When the young Universe was about **15 minutes old**, it was now too cool for further nucleosynthesis. Universe stopped making Helium.

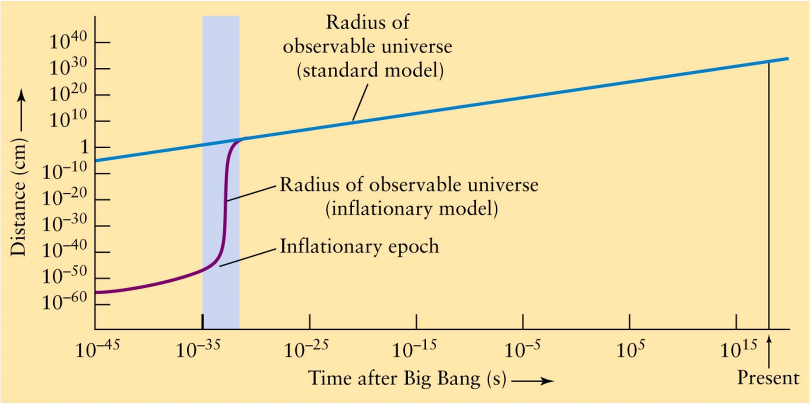
The elements created so far are Hydrogen, Helium, Lithium, and Beryllium. The heavier elements would only be formed much later by nuclear reactions in stars.



THE EARLY UNIVERSE



What Caused the Inflation?



Four Forces of Nature

Gravity
Electromagnetism
Strong Force
Weak Force

Quarks

Protons and Neutrons are composed of quarks. The most common varieties are the "up" (u) quarks and the "down" (d) quarks.

A Proton is composed of two up quarks and one down quark; a Neutron is made of one up quark and two down quarks.

The Strong Force holds quarks together, while the Weak Force is at work whenever a quark changes from one variety to another.

$$d \rightarrow u + e^{-} + \nu$$

Three Forces Explained

EM, Weak, and Strong Forces are explained by **Quantum Mechanics** as interacting by the exchange of various types of virtual particles.

Physicists have not been able to develop a Quantum Mechanical description of Gravity. Einstein's General Theory of Relativity is considered to be a Classical description.

Unified Weak and EM Forces

Current theories state that the Weak and EM forces should be identical to each other for particles with energies greater than 100 GeV. At these energies, Electromagnetic interactions become indistinguishable from Weak interactions.

Above 100 GeV ($T \sim 10^{16}$ K), the EM and the Weak force are "unified" into a single **Electroweak Force**. (Symmetry is restored above 100 GeV − Spontaneous Symmetry Breaking occurs below 100 GeV.)

Grand Unified Theory

Above 10^{14} GeV ($T \sim 10^{27}$ K), the Strong force is unified with the Electroweak, in what is known as the **Grand Unified Theory (GUT)**.

Above 10^{19} GeV ($T \sim 10^{32}$ K), Gravity *may* be unified with the GUT, giving a **Supergrand Unified Theory** or a **Theory of Everything (TOE)**.

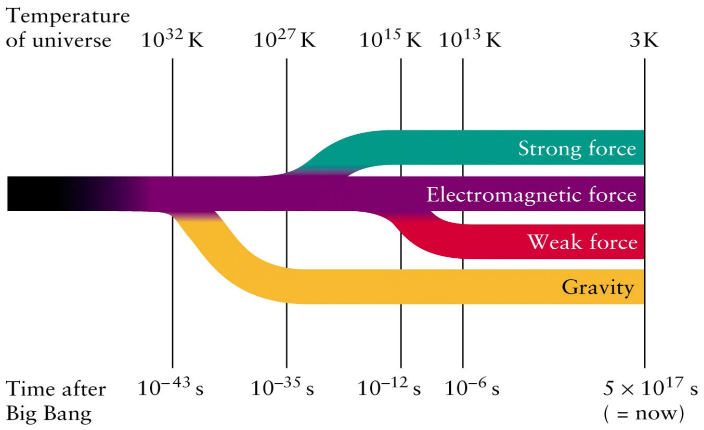
Early Expansion

Because Physicists do not yet have a TOE, we remain ignorant of what was going on during the first 10^{-43} second of the Universe's existence. But by the end of the Planck time, the expansion and cooling of the Universe had caused the energy of particles to fall to 10^{19} GeV.

At $t = 10^{-43}$ sec there was a spontaneous symmetry breaking in which gravity was "frozen out". The temperature was about 10^{32} K.

As the Universe expanded, its temperature decreased and the energy of particles decreased as well. At $t = 10^{-35}$ sec, the energy of particles had fallen to 10^{14} GeV and the temperature was 10^{27} K. **At this time, the Strong force "froze out".**

Forces of Nature



Inflation Occurred

Physicists hypothesize that before the Strong Force decoupled from the Electroweak Force, the Universe was in an unstable state called a False Vacuum.

The Physicists hypothesize that the energy associated with a quantity called the *Inflaton field* had a nonzero value.

At this time, the Universe changed to a True Vacuum, which released the energy.

Timeline of the Early Universe

10^{-43} sec	End of Planck Time – Gravity freezes out
10^{-35} sec	Strong Force freezes out – Inflation occurs
10^{-12} sec	Weak and EM Forces freeze out
10^{-6} sec	Confinement of quarks
10^{-4} sec	Production of protons and neutrons ends
1 sec	Production of electrons ends

Timeline of the Early Universe

2 sec	Universe becomes transparent to neutrinos
	Free neutrons begin to decay: $n \rightarrow p + e^- + \nu$
3^m45^s	Deuterium is formed and then Helium is formed
15 min	Creation of Helium ceases
2500 yr	Universe goes from Radiation to Matter Dominated
300,000 yr	Atomic hydrogen is formed
	Universe becomes transparent to photons (creation of Cosmic Background Radiation)

Today's Universe

How did the Universe go from an initial, extremely smooth state to a very lumpy one of today?

Current Cosmological Model

The current model assumes a flat Universe with a cosmological constant.

$$(\Omega_m = 0.27, \quad \Omega_\Lambda = 0.73, \quad \Omega_O = \Omega_m + \Omega_\Lambda = 1.00)$$

In this model, the cosmological constant (dark energy) has made the expansion speed up over time, so that the expansion was slower in the distant past.

Some of Many Issues

What happened to the anti-matter?

Do we really know what quarks are?

Why is today’s Universe lumpy but during the Big Bang it was not?

Why does something special happen with the emergence of the Strong force by not when the Weak force appears?

From whence comes Dark Energy? [A fifth force?]