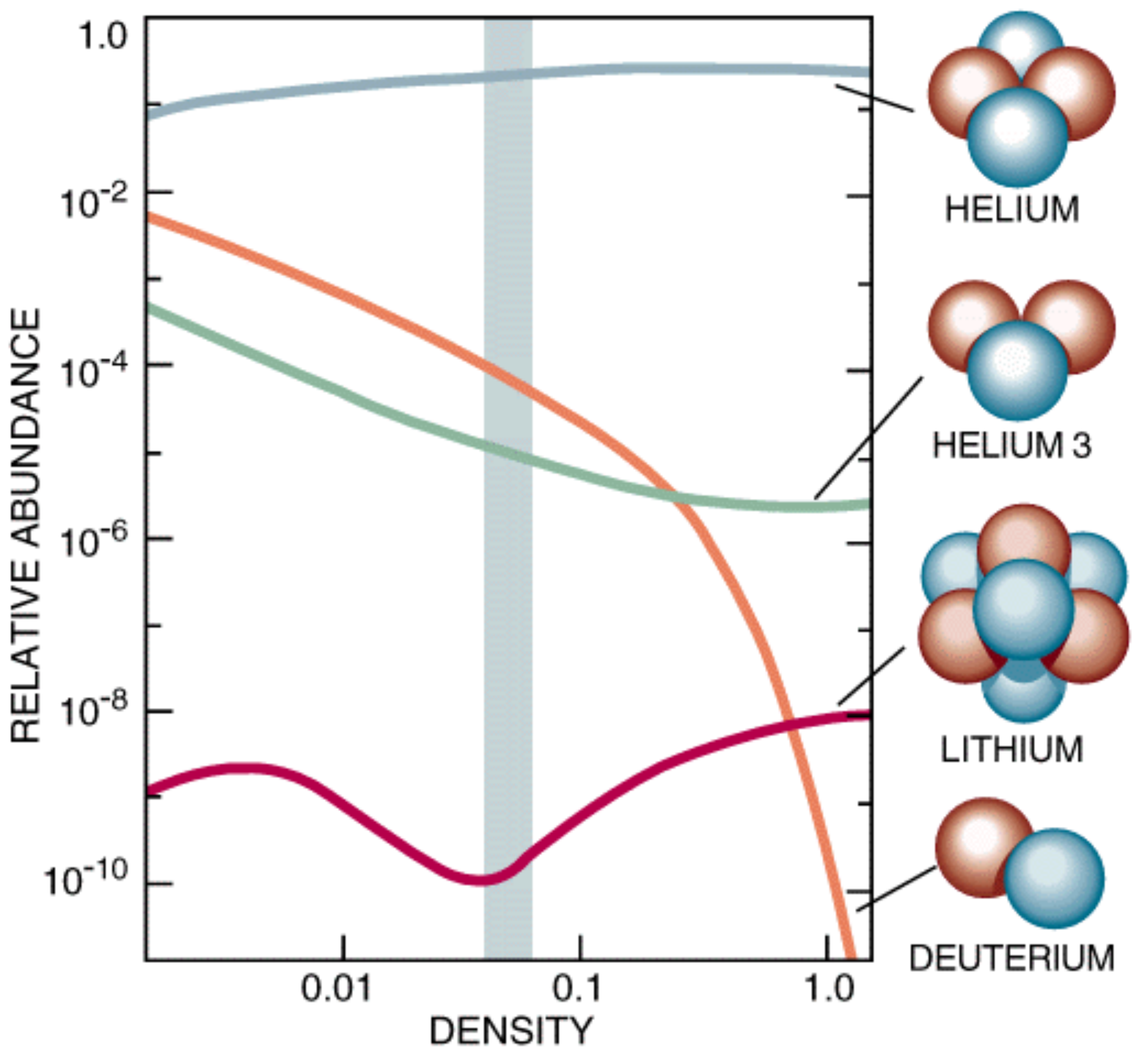
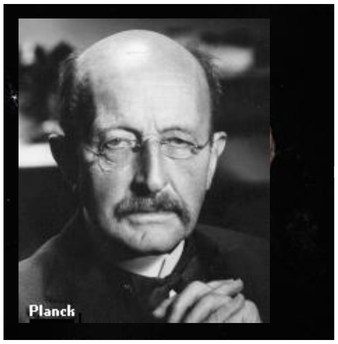
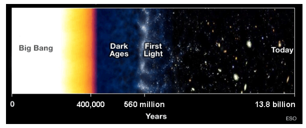
Chapter 5

The First Million Years

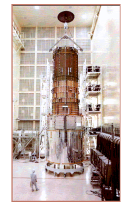


Introduction









Left to right: Max Planck, (top) Timeline of the early Universe, (bottom) Einstein with Yukawa (pioneer of the Strong Force) and Wheeler (coined the term "Black Hole", Newton (of the Law of Gravity), The Hubble Space Telescope

For a million years, the Universe was filled with hot gas, like one infinitely big star that filled all of space. It was bright, hot, smooth, inimical to life. Yet during this period, the building blocks of matter, the seeds of galaxies, and the very forces of nature took the forms that led to the Universe we live in today.

The Beginning

The fundamental premise of the Big Bang Theory is that the Universe began in a phenomenally hot, dense state, hotter than any place in the Universe today. Space was either infinitely small or infinitely large. If it was inifinitely small, then the entire Universe we see today was squeezed into a space the size of an atom. If space was infinitely big, then all of space was filled with gamma ray photons. Matter as we know it did not exist yet. In its simplest form, the Big Bang Theory assumes that in the beginning, the Universe was *infinitely hot* and *infinitely dense.* In this extreme state, called a **singularity,** the known laws of nature broke down. Even space and time as we know them did not exist. This bizarre situation lasted until the Universe was about 10^{-43} seconds old. At that moment, space and time as we know them came to be. Physicists called this moment the **Planck Time.** It marks the earliest time when we can calculated what's going on in the Universe.

Exactly how the Universe got started in the first place nobody knows. Some say it was an act of volition on the part of a divine Creator. Some say it was just a random fluctuation in space and time. Some say that Universes are popping into existence all the time, but we are only aware of the one we happen to live in. But in fact no one can say for sure whether there was a Universe before ours. It is probably the wrong thing to imagine that space was empty for a long, long time until matter and energy suddenly appeared. The current thinking is that space and time themselves came into existence along with the matter and energy, so that it doesn't make any sense to ask what happened *before* the Big Bang, any more than it makes any sense to ask what is south of the South Pole.

The truth of the matter is that the close we get to the beginning, the shakier the ground we are on (if we can use that metaphor). We understand well what was going on when the Universes was a minute old. What was going on in the Universe during the first microsecond, however, brings us the the frontier of knowledge as well as the frontier of time. Perhaps the Universe wasn't *infinitely hot and dense* when the expansion of the Universe started. But if the Universe was not infinitely hot and dense, you have to explain why it started out with the temperature and density it had. The simplest assumption, then, is that it started out infinitely hot and dense. But no one really knows.

At the moment, the situation is that no one can describe the universe as it existed prior to the Planck time. For practical purposes, then, the Big Bang Theory takes up the story of the Universe when the Universe was already 10^{-43} seconds old. You have to admit though, that wasn't very old. The Universe today is only 10^{17} seconds old. That is to say, 26 more powers of ten went by before the Universe was 1 second old than have passed since the Universe was 1 second old. Looked at that way, most of the Universe took place in the first tiny fraction of a second of time.

THE FOUR FORCES

In our era of time there are four fundamental forces of nature:

Gravity
The Electromagnetic Force
The Strong Force
The Weak Force

These four forces appeared in the first second of time.

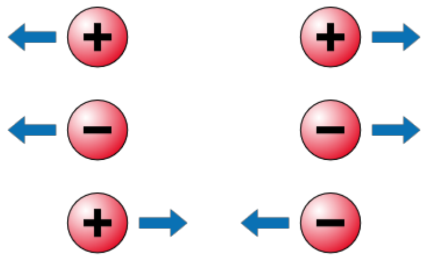
Gravity

Gravity and the electromagnetic force are the only forces that we experience in our daily lives. Gravity we are all aware of. Since our remote ancestors lived in trees, the fear of falling is wired into our brains; gravity is something we are intimately familiar with. Not only does gravity cause things to fall, it causes the Moon to orbit the Earth, moon to orbit other planets, the planets to orbit the Sun, and the Sun to orbit the center of the Galaxy. Gravity holds together the Earth and prevents the atmosphere from dissipating into space. Gravity holds the Sun and the stars together as well.

The Electro-magnetic Force

All the other forces of nature that we see and feel are some aspect of the **electro-magnetic force**. The electric force is one aspect. Static electricity, lightning, and electrical currents are the electric force in action. The electric force is carried by electric *charge*. There are two kinds of charge, positive and negative.

<u>The rules of electric charges</u>
Positive charges are attracted to negative charges.
Like charges repel each other.

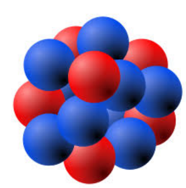


The electric force holds together the atom, since the positively-charged nucleus attracts the negatively-charged electrons. The magnetic force is another aspect of the electromagnetic force. It is generated whenever electric charges are put in motion. The strength and properties of materials is due to the electric and magnetic fields of their atoms. Light is yet another aspect of the electromagnetic force. Light, you may recall, is nothing more than travelling waves of electric and magnetic fields.

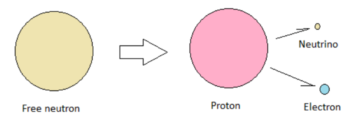
The Strong Force and the Weak Force

The other two forces are the nuclear forces, the strong and the weak. These are extremely short-range forces, felt only over distances the size of an atomic nucleus—that is to say, distances much smaller than an atom. Consequently, these forces are completely invisible to us and in fact weren't discovered until the 20th century. Nevertheless, both the strong force and the weak force are important and we would not be here without them.

The **strong force** holds together the nucleus of the atom. The nucleus contains protons, which have positive electric charge, and neutrons, which have no charge. The elcctric force is constantly pushing the protons apart. Only a very powerful attractive force can hold the protons and neutrons together—the strong force. The strong force is the source of the energy from nuclear power reactors, from nuclear bombs, and from the Sun.



The **weak force** doesn't hold anything together. What it does do that no other force can do is turn a proton into a neutron and vice versa. This little trick turns out to be essential to the proper functioning of the Universe. A characteristic of the weak force is that it produces a particle called a **neutrino** as a byproduct. The neutrino is a chargeless, nearly massless particle that is immune to both the electromagnetic force and the strong force. As such, the neutrino doesn't interact much with ordinary matter. In fact, neutrinos left over from the Big Bang are streaming through your body even as you read this.



Force particles

Each of the four forces is carried by subatomic particle. The electromagnetic force is carried by the **photon.** The force of gravity is carried by the **graviton.** The strong force is carried by particles called **gluons,** of which there are eight. The weak force is carried by three other force particles (**W^+**, **W^-,** and **Z**). In the modern view, forces work by exchanging these particles. For example, if an electron comes near a proton, they will exchange photons with each other, changing their paths in the process. In the 1930s, the Japanese physicist Hideki Yukawa proposed that the strong force works by exchanging force particles.

The Origin of the Four Forces

In the beginning there was only one force. It is thought that at extraordinarily high temperatures—temperatures that existed only before the Planck time—all the four forces were combined into one. There is no name for this force, but there is a name for the theory that describes it: the **Theory of Everything**. Unfortunately, the Theory of Everything has yet to be discovered.

For the next 10^{-35} seconds after the Planck time, there were two forces: gravity and the **GUT** force. GUT is short for Grand Unified Theory, the theory (if it exists) that combines the strong force, the weak force, and the electromagnetic force. However, no one has yet discovered the Grand Unified Theory.

When the Universe was 10^{-35} seconds old, the GUT force split into the strong force and the **electroweak** force. Here at last we come into the domain of the known, as a successful theory of the electroweak force exists. The electroweak force was a combination of the electromagnetic force and the weak force.

The electroweak force lasted for about a nanosecond (a billion of a second). As the Universe expanded and its temperature continued to drop. When it reached a quadrillion degrees above absolute zero (10^{15} Kelvin), the electroweak force split into the electromagnetic force and the weak force. Since that time, there have been four forces behaving in four different ways.

THE FOUR PARTICLES

The word *particle* refers to subatomic particles, tiny point-like objects smaller than an atom. The most familiar particles are the proton, neutron, and electron. The photon is also a particle. And there are hundreds more known, most of which are unstable and live less than a fraction of a second. Most of these particles are combinations of other particles. Only a few particles are *fundamental particles,* particles *not* made of anything smaller. The electron is a fundamental particle. The neutrino, mentioned above, as also fundamental. The proton and the neutron, however, are not. They are made of smaller particles called **quarks.**

The Universe today—all the stars, all the planets, and indeed all the people—are made of just four fundamental particles: the **up quark,** the **down quark**, the electron and the neutrino. The electron and the neutrino belong to a group of particles called **leptons.**

Quarks	Leptons
up quark	electron
down quark	neutrino

Antimatter

Possibly you've heard of antimatter. It's often used in science fiction because it is the highest-energy fuel source. It's very dangerous, however. If you touch it, you will go *poof!*

Antimatter is matter made of antiparticles. Every particle (except the photon) has a corresponding antiparticle. Antiparticles have the following properties:

1. If the particle has a + charge, the antiparticle has a - charge, and vice versa.
2. The particle and antiparticle have exactly the same mass or energy.
3. If the particle and antiparticle come together, they both turn into photons.

The antiparticle of the electron has a special name: the **positron.** It has a positive charge. If an electron and a positron collide, they will **annihilate** each other and turn into two gamma-ray photons. This is *not* a good thing if it's one of your electrons!

The antiparticle of the proton is the **antiproton.** It has a negative charge. The antiparticle of the neutron is the **antineutron.** Like the neutron, the antineutron has no electric charge, but it's nevertheless quite a different particle. If a neutron and an antineutron (or a proton and an antiproton) collide, they will annihilate each other. Quarks also have corresponding antiquarks.

Leptons

Leptons are fundamental particles (they are not thought to be made of anything smaller). Leptons feel the weak force, not the strong force. As far as the strong force is concerned, they are invisible. Because of this, leptons don't stick together to form larger particles. The long-lived leptons are:

Lepton	Charge
electron	-1
positron	+1
neutrino	0
antineutrino	0

Quarks

Quarks are fundamental particles. Quarks feel both the weak force and the strong force (as well as the electro-magnetic force). The strong force combines quarks into groups of two or three quarks called **hadrons.** Oddly, the quarks have fractional electric charges. The most important quarks are:

Quark	Charge
up quark	+2/3

anti-up quark	-2/3
down quark	-1/3
anti-down quark	+1/3

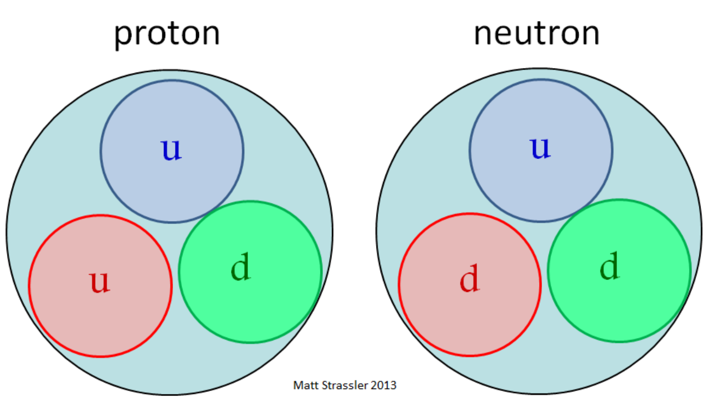
It is a peculiar feature of the strong force that *isolated quarks are never seen*. What we see are hadrons, which always have a charge of +1, -1, or 0 (occasionally +2 or -2).

There are two kinds of hadrons: **baryons,** which are made of 3 quarks, and **mesons,** which are made of 2 quarks (a quark and an antiquark). If you think about it, you will realize that although quarks have a fractional charge, baryons and mesons always have interger charge (usually +1, =1, or 0). Mesons will not be discussed in this course, because stars and planets are made of baryons. You are made mostly of baryons.

Protons and neutrons are baryons. They are constructed as follows:

proton		neutron	
up quark	+2/3	up quark	+2/3
up quark	+2/3	down quark	-1/3
down quark	-1/3	down quark	-1/3
net charge:	+1	net charge:	0

Can you figure out what an antiproton and an antineutron are made of?



The Law of Conservation of Charge

The *net charge* of a particle or group of particles is the difference between the number of + charges and the number of - charges. A fundamental law of nature says that:

In any particle reaction, the net charge cannot change.

In the jargon of physics, we say that the net charge is *conserved.* This is just one of many such **conservation laws.**

We can see the Law of Conservation of Charge at work when an electron and a positron annihilate each other:

electron + positron —> photon + photon

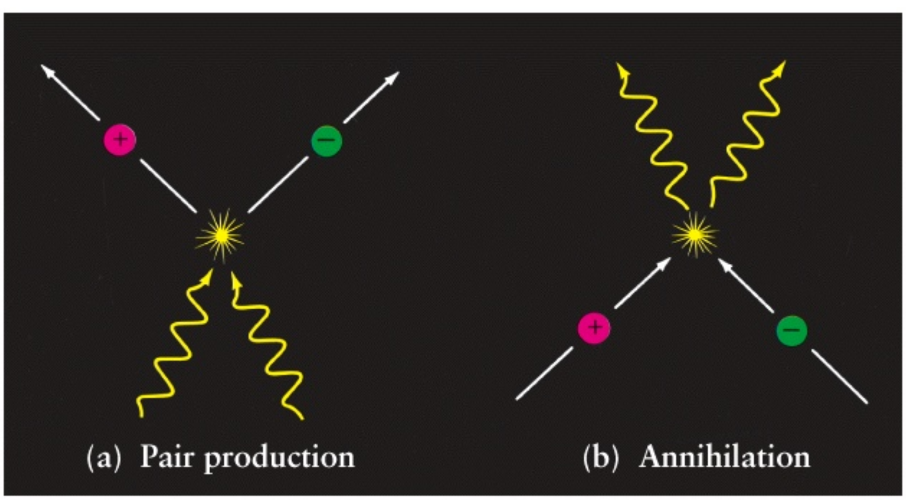
The net charge of the electron and positron is -1 + 1 = 0. Photons are chargeless, so the net charge of the two photons is also 0.

Pair Production

We are now is a position to talk about the creation of matter—that is, hadrons and leptons. Matter was created the the Big Bang by the process of **pair production.** Pair production is the opposite of annihilation. For example, if the annihilation reaction shown above is reversed, you get:

photon + photon—> electron + positron

Not just any photon will do, otherwise electrons and positrons would be popping into existence all the time. The photons have to have enough energy to make electrons and protons. They must be *gamma ray photons.* In the current Universe, gamma ray photons are rare (that's a good thing!). But in the first second of the Big Bang, they were common, and electrons and protons were made continuously by this process. Quarks are much more massive than electrons, so even higher energy photons were needed to make quarks and hadrons, including the proton and the neutron.



For the first nanosecond, quarks and antiquarks, protons and antiprotons, neutrons and antineutrons, electrons and antiprotons and many other particle-antiparticle pairs were continually being created. Just as they were created, they would annihilate each other. Particles and antiparticles existed in nearly equal numbers. As the Universe cooled, there came a time when there were no more photons energetic enough to make quarks; later on, even the production of electrons ceased. All the surviving particles were annihilated by the remaining antiparticles. There should have been no particles left at all—only photons.

Yet somehow, some particles survived. No one understands why, but there was a slight excess of particles over antiparticles: 1 billion and one particles for every billion antiparticles. The end result is that one particle in a billion survived: one out of a billion protons, one out of a billion neutrons, and one out of a billion electrons. That is why the stars are made of matter, not antimatter. It is fortunate for us that there was this slight imbalanace in the numbers of particles and antiparticles, otherwise we wouldn't be here today. The reason for it, however, awaits the successful formulation of the Grand Unified Theory, if not the Theory of Everything.

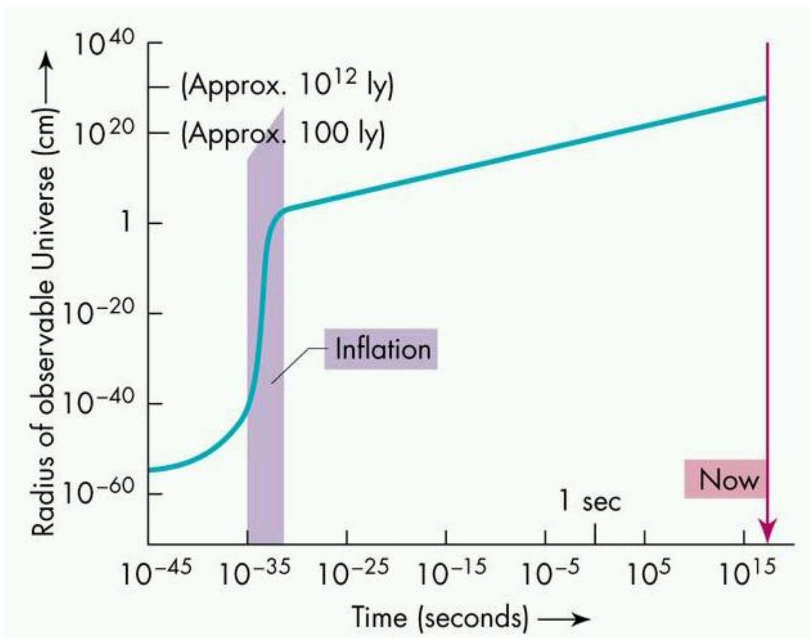
THE FIRST MINUTE OF THE UNIVERSE

The idea of the Big Bang is that the Universe started out in a hot, dense state and then rapidly expanded. As it expanded, the temperature dropped rapidly and the density decreased. (**Density** is the mass per unit volume.)

Cosmic Inflation

When the Universe was about 10^{-35} seconds old (if you can call that old), the strong force separated from the electroweak force. Physicists believe that this event triggered a rapid speeding of of the expansion of the Universe — a process called **cosmic inflation.** This hypothesis explains otherwise mysterious characteristics of the Universe we see today. For example, although Einstein showed that space can be curved, the Universe today is perfectly flat — too flat to be just a coincidence. The cosmic inflation explains this **flatness problem**: if the Universe started out curved, the rapid expansion would smooth out the curvature. An analogy is the comparison of a basketball with the Earth. The basketball and the Earth are both curved, but because the Earth is so much larger, we don't notice its curvature: the sea is flat for all practical purposes.

Following the cosmic inflation, the Universe continued to expand at a much slower rate. At the age of 1 nanosecond (1 billionth of a second), the electroweak force split into the electromagnetic force and the weak force. During the next second, the Universe went through several major transformations as it cooled.



The Quark Epoch

For the next 100 microseconds (millionths of a second), the temperature was so hot that high-energy gamma rays existed that could form quarks and antiquarks via pair production. At the same time, the quarks continually annihilated the antiquarks. The Universe was a hot soup of quarks, protons, neutrons, other hadrons, electrons, positrons, and other particles.

At the age of 100 microseconds, the temperature dropped to a point where there were no more gamma ray photons energetic enough to make quarks, protons, neutrons, or other hadrons. Most of the protons collided with antiprotons and were annihilated. The same was true of the neutrons and other hadrons. It would seem that they all should have destroyed each other and no hadrons should have survived. Yet somehow, there must have been a slight excess of protons over antiprotons, because about 1 out of a billion protons survived. Likewise, 1 out of a billion neutrons survived. Physicists aren't sure of the reason — it's one of the big mysteries in physics today. But it''s a good thing the protons and neutrons survived, otherwise there would be no atoms today.

The Lepton Epoch

For the next minute, the Universe consisted of protons, neutrons, electrons, positrons, neutrinos, and antineutrinos. The electrons and positrons existed in equal numbers, as did the neutrinos and antineutrinos. They were being continually created by pair production and continually destroyed by annihilation. There were roughly a billion electrons for every proton; most particles were leptons.

When the Universe was a minute old, it went through another transformation. The temperature was no longer hot enough to produce gamma ray photons energetic enough to create electron-positron pairs. The electrons and positrons all annihilated each other — except for one lousy electron out of a billion. Again, no one knows why, but that is why the Universe is made of matter today and not antimatter (or no matter).

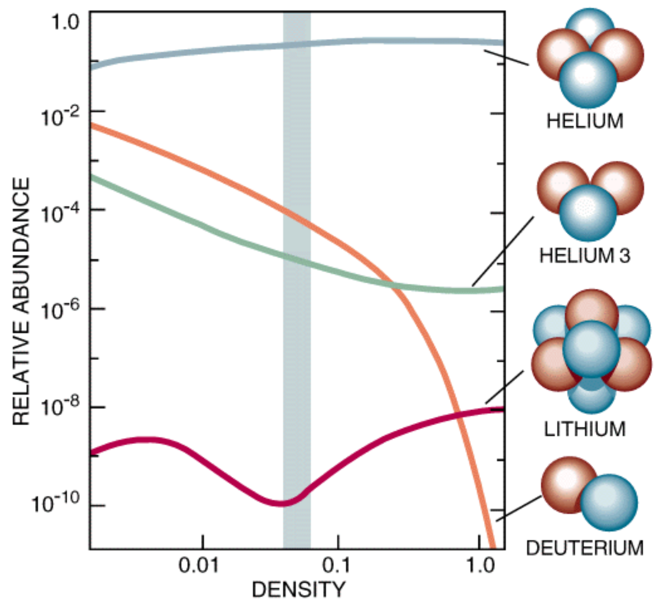
The Nuclear Epoch

During the next few minutes, the neutrons decayed into protons. As discussed in the last chapter, conditions were favorable for **nuclear fusion** reactions that combined protons and neutrons into atomic nuclei. Before this time, it was too hot — nuclei would have been quickly destroyed. After a few minutes, there were no more free neutrons and fusion ceased. This was the only period when nuclei could be created.

Protons and neutrons combined to make several small nuclei, but by far the most abundant was helium-4, consisting of two protons and two neutrons. In addition, small quantities of these other nuclei were created:

Deuterium	1 proton, 1 neutron
Helium-3	2 protons, 1 neutron
Lithium-7	3 protons, 4 neutrons

The amount of each kind of nucleus produced depends on how dense the Universe was at that time. The diagram shows the results of calculations of the expected amounts produced of each kind. The horizontal axis shows the density, the vertical axis the amount of each nucleus produced at that density. The vertical grey bar shows the density at which all four curves match the abundances observed in the Universe today.



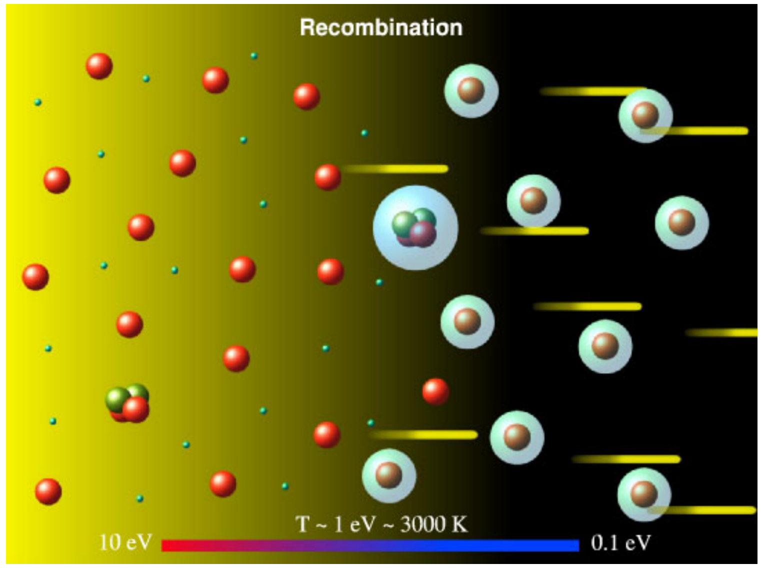
The fact that these four different calculations agree is dramatic evidence in favor of the Big Bang Theory.

THE NEXT MILLION YEARS

By the time the Universe was one hour old, nucleosynthesis of helium had ceased. In its first hour of existence, the Universe had transformed itself many times, made of different particles in each stage. But now the Universe settled down and no transformations took place for the next half a million years. During this period, the Universe was mainly made of protons, Helium-4 nuclei, electrons, and neutrinos (plus the dark matter — about which more later). During this period there were no atoms — it was too hot for atoms to form. Atoms form when electrons combine with protons and nuclei. But it was so hot that any atom that formed would be broken up by high-energy collisions. This is what happens in stars. During this period, the whole Universe was in essence one big star filling all of space. Like a star, it was filled with light.

Recombination

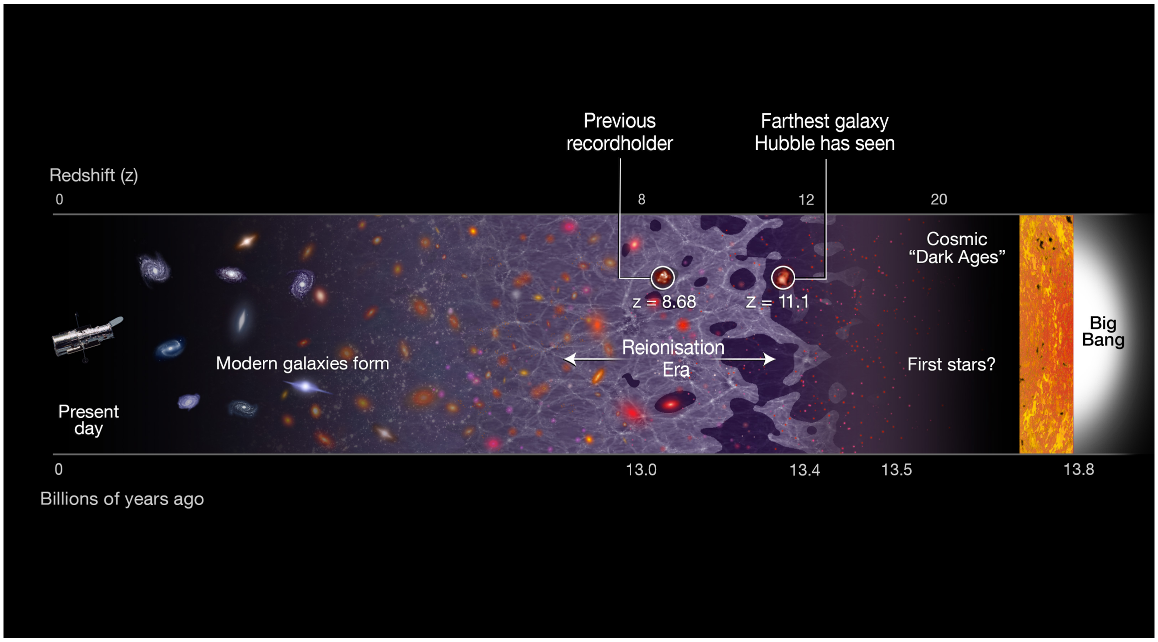
For the next 400,000 years, the Universe continued to expand. As it did so, its temperature and density steadily decreased, until it became cool enough for atoms to form. That is to say, electrons could attach themselves to protons to form hydrogen atoms, while other electrons attached themselves to helium nuclei to form helium atoms. This happened when the temperature of the Universe fell to about 3000 Kelvin (3000 degrees Celsius above absolute zero). This event is called **recombination.** The term is illogical, when you think about it, because the atoms had never been combined before!



After recombination, the Universe was made of atoms of hydrogen and helium. This event was a major event. Light interacts continually with protons and electrons, but not very much with atoms. Consequently, light was at the same temperature as the matter before recombination, but cooled at a different rate than matter after recombination. In the case of light, "cooling" means its energy became less and its wavelength became longer. The light, which was visible light at the time of recombination, became first infrared light, then microwaves. That light is still here around us. It is the **cosmic microwave background.**

The Dark Ages

For millions of years, the Universe was dark. The cosmic background had weakened from visible light to infrared light, invisible to the human eye. Warm hydrogen and helium gas filled the Universe. Not a whole lot was going on. Astronomers call this period the **Dark Ages.**



Nevertheless, tremendous events were beginning to take shape. The gas that filled space was uniform and smooth, but not perfectly smooth. There were slight density variations from place to place, variations left over from the Big Bang. These slight density variations were the "seeds" that would give rise to galaxies and stars. The slightly density spots exerted a slight gravitational tug on the surrounding gas, drawing in more gas and making the dense spot denser still. It was an example of the rich getting richer. Eventually, the gas ended up with dense clumps separated by empty regions.

At some point, the dense clumps collapsed under the force of gravity to form the first galaxies and stars. This occurred, astronomers think, when the Universe was a few hundred million years old. The first stars were big and bright, giving off massive amounts of ultraviolet and visible light. The dark ages were at an end. The ultaviolet light broke up the hydrogen and helium gas — that is, they **ionized** the gas. When that happened, light could no longer travel freely through space.

This brings our story to the limits of observation. Big telescopes and the Hubble Space Telescope can see galaxies that are a few hundred million years old. A top research priority in the 2020s is to detect the first generation of stars. (This is possible because as we look out in space, we look back in time.) The search for the first stars and galaxies is the main reason for the next big space telescope, the **Webb Space Telescope.**