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**SPECIAL**

## *In the beginning...*
## *The* ORIGIN *of the* UNIVERSE

AN AUSTRALIAN GEOGRAPHIC PUBLICATION

Newton **special**

*In the beginning...*

# THE ORIGIN OF THE UNIVERSE

by Charles Lineweaver

In the beginning, about 13 billion years ago, existence came into existence. Time began. Space came into being. The Universe was more than a billion, trillion times hotter than the centre of the Sun.

From then till now the Universe has expanded and cooled. Galaxies and stars have formed. Life on Earth has evolved and here we are. It's the biggest thing science has ever attempted to explain – the story of everything.

Thousands of detailed observations have given us this general picture. However until recently, the very beginning, the first fraction of a second, was beyond the limits of science. Heedless of such limits, a new group of scientists is exploring the very beginning. These pioneers have combined our knowledge of the smallest objects in the Universe (quantum theory) with our knowledge of the largest (cosmology) and are building the new science of quantum cosmology.

Quantum cosmology is producing a scientific scenario that answers the biggest question of all: how did the Universe begin?

It is a scenario in which the Universe comes into existence by pinching off from a timeless quantum nothing. Some of the story is easy to follow but much of it is simply mind-boggling.

If we could do the impossible and see the origin of the Universe from the outside, it might resemble what you see when you scuba dive at night. In the black ocean of a quantum dreamtime from which the Universe began, you look up at the surface and see dark ripples in the timeless quantum vacuum. These ripples are the quantum fluctuations that exist outside time and space, created by the wave function of the Universe as it hovers over the surface like a mist. We do not know the true nature of this state where the laws of the Universe live like spirits without bodies. But this quantum dreamtime brings universes into existence. Under one of the larger ripples a bubble has pinched off from the surface. It glows with colours that represent all the future planets, stars and galaxies that will evolve in our Universe. The blue spotlight could be your mind looking at, able to think about, the origin of our Universe.

# PART ONE: Life of the Universe

## An abbreviated history

There are stages in a human life: conception, birth, babyhood, childhood, puberty and adulthood. The life of the Universe can be similarly divided into stages, for it too was born and has grown up.

Here in a single page is a summary of the creation and evolution of the entire Universe – a 13-billion-year panorama of the major events in the history of the Universe.

Time and space begin with the Big Bang. The Universe was born, inflated rapidly, filled with hot energetic particles and then cooled. (What happened before the Big Bang? The question doesn't make sense, as we'll see later.)

First it was opaque (you couldn't see through it), but as it cooled it became transparent. The yellow surface is the boundary between the opaque, early Universe and the current, transparent Universe.

It is at this surface that it was cool enough for the first atoms to appear, forming a wispy network of filaments and great walls of hydrogen gas clouds.

Over the next 13 billion years, the gravitational collapse of this wispy network created all the structures in the Universe.

A billion years after the Big Bang, the first generation of massive stars may have formed. About a billion years later galaxies began to form. Four and a half billion years ago our Sun ignited, and the Solar System and our planet were formed.

Many of the terms on these pages will be explained in the rest of this story.

*A note on numbers*

*1 billion = 1000 million. Many other numbers in this story are presented as powers of 10 because they are so large or so small that it is not practical or meaningful to spell them out. A billion = $10^{9}$; or 1 with nine zeroes after it (1,000,000,000). A billionth = $10^{-9}$; or 1 with nine zeroes in front of it (0.000 000 001). On this page you'll see numbers like $10^{-43}$ – 10 to the minus 43. That's one billion, trillion, trillion, trillionth of a second.*

**Birth of galaxies**

Our Galaxy, like billions of others, was born about 10 billion years ago. Huge hydrogen clouds, more than 100,000 light years across, gravitationally collapsed. In each of these galaxies, cloud fragments collapsed further to form stars.

**Birth of our Solar System**

Four and a half billion years ago, one late-forming fragment collapsed to form a yellow star, our Sun. In a disc around the star, gas, ice and rock fell together into clumps. In less than 100 million years these clumps formed planets. Over the next billion years the gravity of these planets swept up debris and grew in size to become the planets of our Solar System.

**Now**

13 billion years after the Big Bang, in one of 100 billion galaxies in the observable Universe, orbiting a modest yellow star among more than 200 billion stars in our Galaxy, the Milky Way, the cloud-covered watery planet called Earth shelters us and spins.

# Our changing Universe

When we look out at the Universe beyond the stars of our own Galaxy we see billions of other galaxies shining and drifting in the darkness. They seem stable and unchanging, as if they have been and will remain that way forever. This timeless appearance is deceiving.

Most humans live for less than 100 years. But if we could live for 10 billion years, we could have watched the Universe unfold like a time-lapse film of a flower opening.

We could have watched as the galaxies, one after another, burst into existence. Today their fading glow is punctuated by an occasional burst of light as galaxies collide.

One of the lasting legacies of astronomy is the knowledge that the Sun was born 4.6 billion years ago and that it will die after another 4 or 5 billion years. It is not infinitely old and will not always be here. The Sun and other stars cannot be infinitely old because their fuel supplies are not infinite.

Stars burn hydrogen into helium and they shine as long as their hydrogen lasts; like a tank of petrol, eventually it runs out.

The Universe does not come with a birth certificate, but there are dozens of ways to measure its age. For example, the ages of stars and meteors can be determined by measuring the amounts of radioactive material in them. Until recently there was a wide spread in the age calculations. Depending on the technique used, the Universe was somewhere between 10 and 20 billion years old. After much hard work and improved precision we now know that it is between 12 and 15 billion years old.

Independent of the ages of objects in the Universe, Einstein's theory of general relativity allows us to calculate the age of the Universe by how fast it is expanding (see next page). The result is again between 12 and 15 billion years.

These and other independent methods of ageing the Universe all suggest it's around 13 billion years old.

The discovery that the Universe is changing and that it had a starting point (which we can roughly measure) could be the most important intellectual achievement of the 20th century, if not of all time.

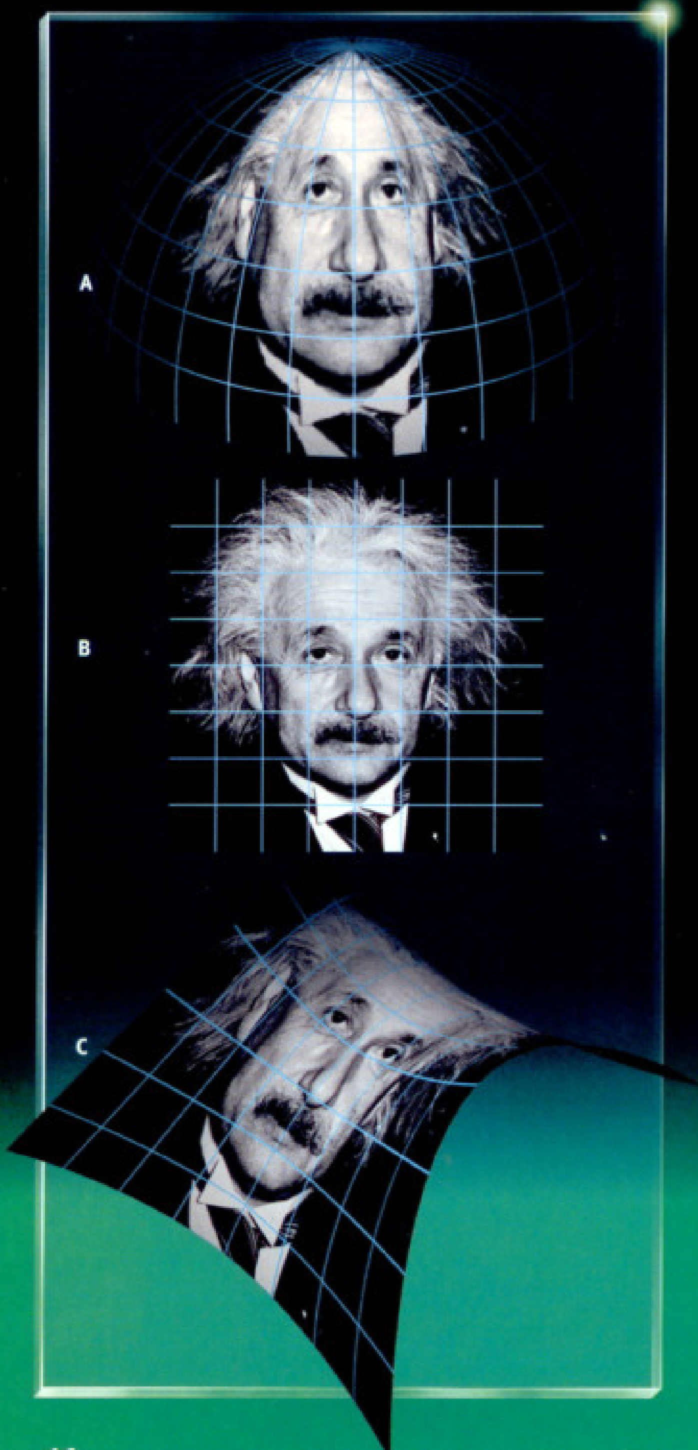
There does not seem to be a centre of the Universe or even an edge. In every direction, galaxies are sprinkled through space. They are not sprinkled perfectly randomly like raindrops on a footpath. Rather, there are walls of galaxies as well as empty regions where fewer galaxies live. The large-scale distribution of galaxies resembles a honeycomb that has been put into a blender. Where did this large-scale structure come from? What determined this distribution of galaxies in the Universe? The answer, it seems, is from quantum fluctuations – the dance of fundamental particles – on the smallest scales imaginable.

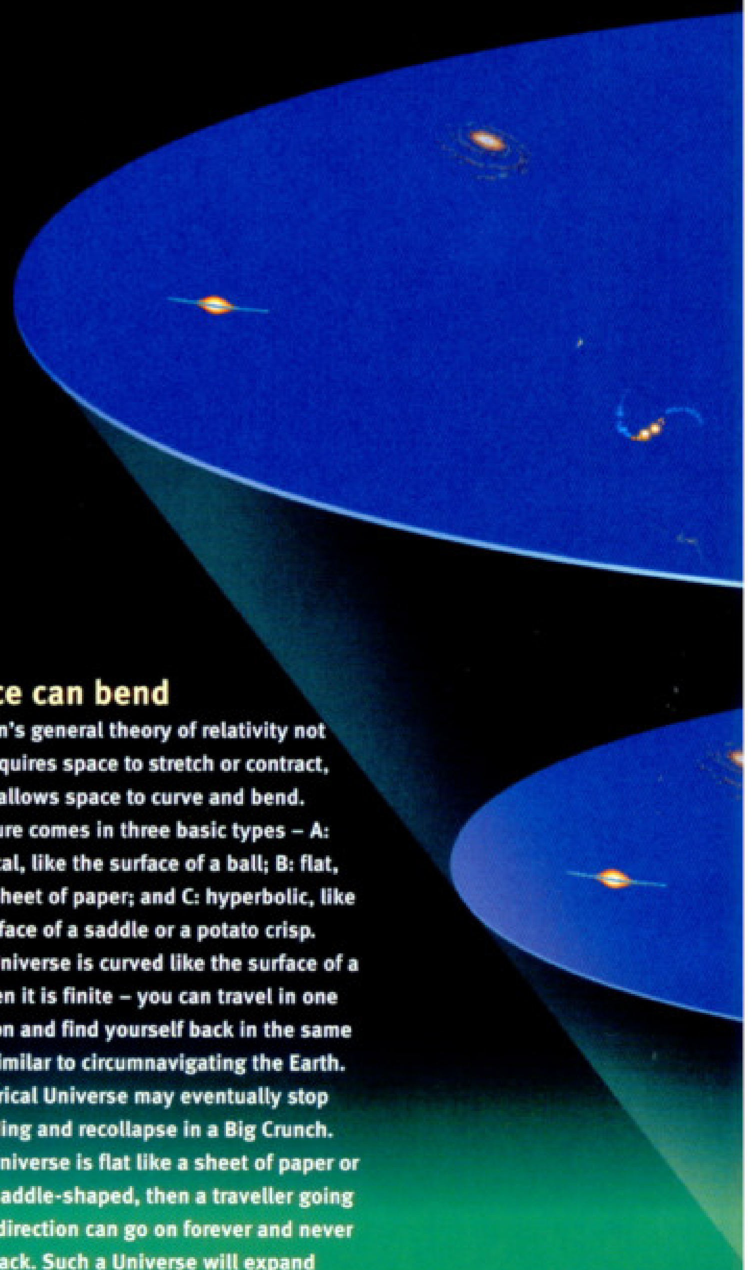
# Why do we think there was a beginning?

As a racing car approaches you, you hear the high pitch of the engine. As it zooms past you and moves away, the high pitch becomes a low pitch. The high pitch is from the sound waves being compressed as they are emitted by the approaching car. The low pitch is caused by the sound waves getting stretched as they are emitted by the receding car. This is known as the Doppler Effect.

Just before World War I, astronomers had found that light from certain cloudy patches far away in space (which we now know to be distant galaxies) was stretched. That is, the measured wavelengths of the light were longer than expected – as if these light sources were receding from us.

In 1929, American astronomer Edwin Hubble discovered that the more distant the galaxy, the longer the wavelength. That is, a galaxy's red shift (the amount the wavelength of the light is stretched) is proportional to its distance. This is now known as Hubble's Law. It can perhaps be most simply explained if distant



## Space can bend

**Einstein's general theory of relativity not only requires space to stretch or contract, it also allows space to curve and bend. Curvature comes in three basic types – A: spherical, like the surface of a ball; B: flat, like a sheet of paper; and C: hyperbolic, like the surface of a saddle or a potato crisp. If the Universe is curved like the surface of a ball then it is finite – you can travel in one direction and find yourself back in the same spot, similar to circumnavigating the Earth. A spherical Universe may eventually stop expanding and recollapse in a Big Crunch. If the Universe is flat like a sheet of paper or if it is saddle-shaped, then a traveller going in one direction can go on forever and never come back. Such a Universe will expand forever. Cosmologists are trying to determine whether our Universe is like A, B or C. Most current observations favour B or C: an infinite Universe.**

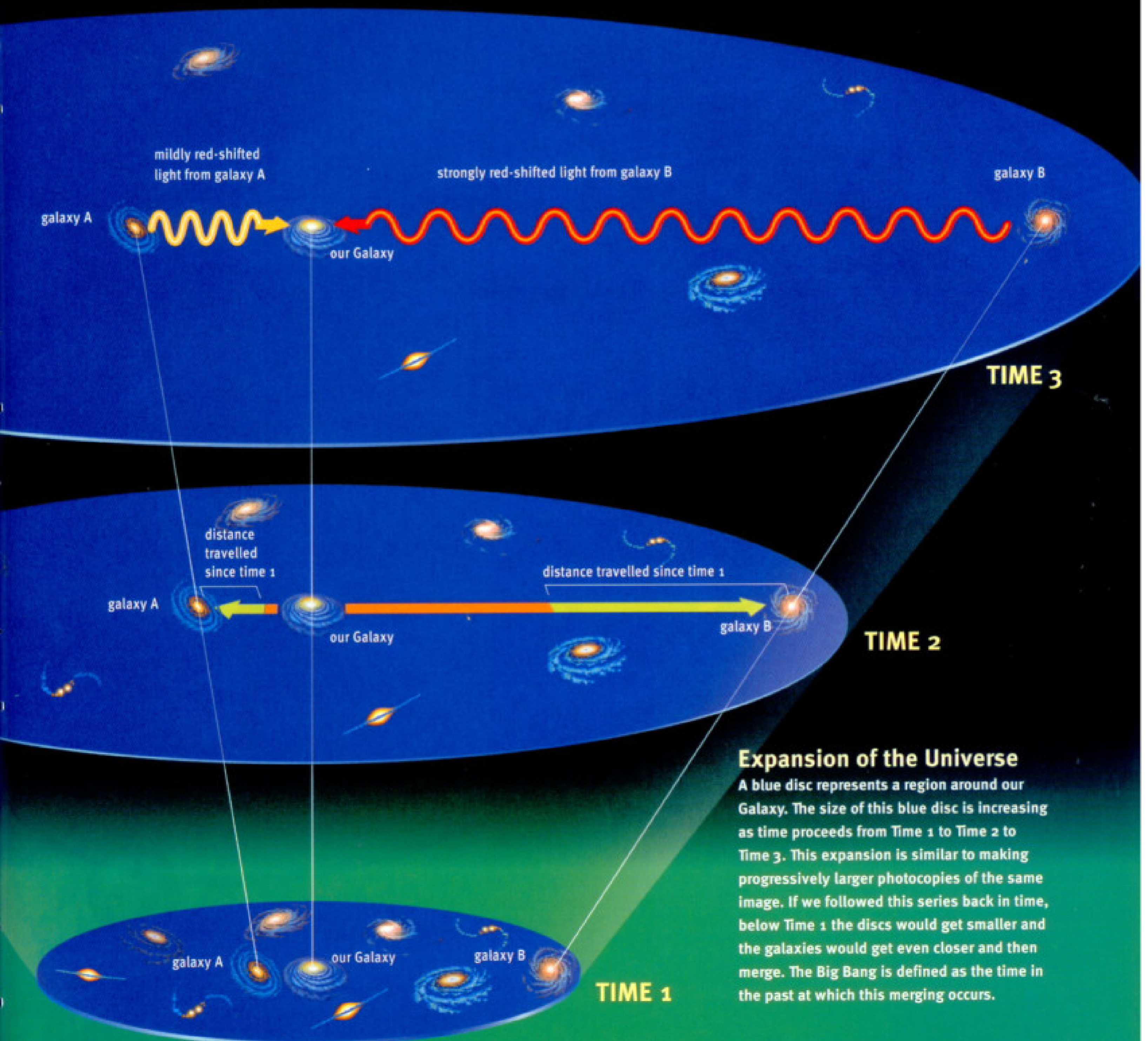
galaxies are receding from us more quickly than galaxies that are closer to our neighbourhood.

Think about that. If galaxies are moving apart today, in the past they were closer together. In the more distant past they were even closer and at some time they must have been right on top of each other – a hot galactic traffic jam of cosmic proportions. We call this traffic jam the Big Bang or the origin of the Universe. We can say it took place 13 billion years ago by tracing the paths of the galaxies into the past. So we think there was a beginning because today we see all the galaxies in the Universe moving away from each other.

Hubble's law is most simply explained by the idea that the Universe is expanding. This deceptively simple concept is easily misunderstood. One might imagine that expansion means every galaxy in the Universe is going away from a single point, from some centre. However, galaxies are scattered almost uniformly and there is no point that can be regarded as the centre of the Universe. The Big Bang did not have a centre.

The Big Bang was not like an explosion of a bomb in a pre-existing space. It was more like an explosion of space itself. The observed galactic red shifts cannot be explained by galaxies moving through space, but rather by the expansion of space itself.

Space is expanding but we are not, even though we are part of it. Our Galaxy, just like our planet and our bodies, is held together by atomic or gravitational forces.




**Expansion of the Universe**

**A blue disc represents a region around our Galaxy. The size of this blue disc is increasing as time proceeds from Time 1 to Time 2 to Time 3. This expansion is similar to making progressively larger photocopies of the same image. If we followed this series back in time, below Time 1 the discs would get smaller and the galaxies would get even closer and then merge. The Big Bang is defined as the time in the past at which this merging occurs.**

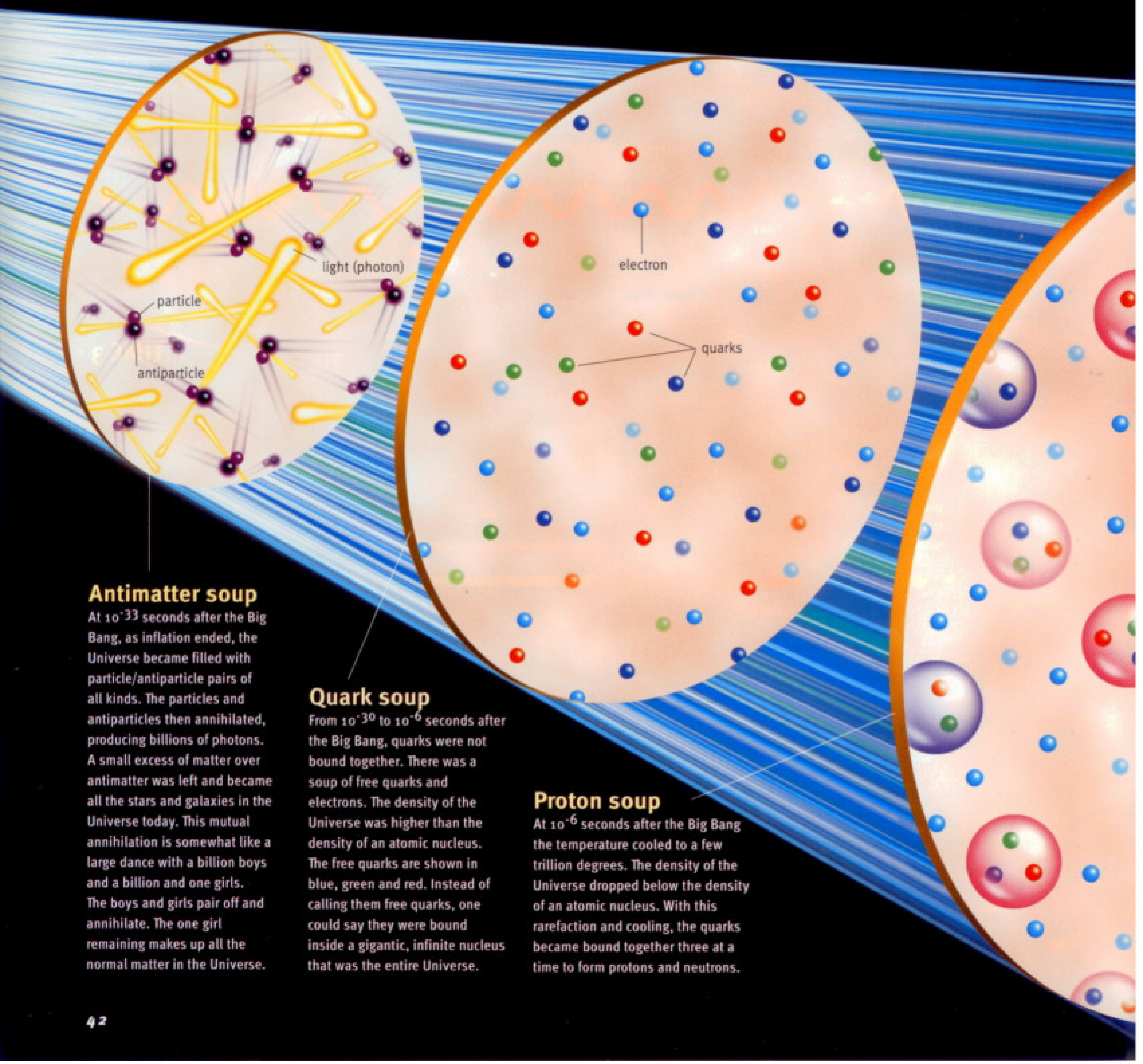
# Atoms: frozen relics from the hot Big Bang

When things cool down they change. For example, as it cools, liquid lava becomes solid rock, steam condenses into liquid water and liquid water freezes into ice.

Many features of the current Universe can be understood as the frozen relics of a hotter past. The young Universe was very hot and dense. As it expanded it cooled and changed. This thermal trip went from trillions of degrees to a few thousand degrees and then further to today's frozen −270°C.

As the Universe cooled, structures such as protons, atoms and molecules froze into existence. The first atoms formed only after the temperature of the Universe had dropped below 3000°C, some 300,000 years after the Big Bang.

Understanding the formation of structures in a cooling Universe might be easiest if we run time backwards. If we were to heat the molecules of our bodies and the Earth they would break up into their parts, atoms.




## Antimatter soup

At $10^{-33}$ seconds after the Big Bang, as inflation ended, the Universe became filled with particle/antiparticle pairs of all kinds. The particles and antiparticles then annihilated, producing billions of photons. A small excess of matter over antimatter was left and became all the stars and galaxies in the Universe today. This mutual annihilation is somewhat like a large dance with a billion boys and a billion and one girls. The boys and girls pair off and annihilate. The one girl remaining makes up all the normal matter in the Universe.

## Quark soup

From $10^{-30}$ to $10^{-6}$ seconds after the Big Bang, quarks were not bound together. There was a soup of free quarks and electrons. The density of the Universe was higher than the density of an atomic nucleus. The free quarks are shown in blue, green and red. Instead of calling them free quarks, one could say they were bound inside a gigantic, infinite nucleus that was the entire Universe.

## Proton soup

At $10^{-6}$ seconds after the Big Bang the temperature cooled to a few trillion degrees. The density of the Universe dropped below the density of an atomic nucleus. With this rarefaction and cooling, the quarks became bound together three at a time to form protons and neutrons.

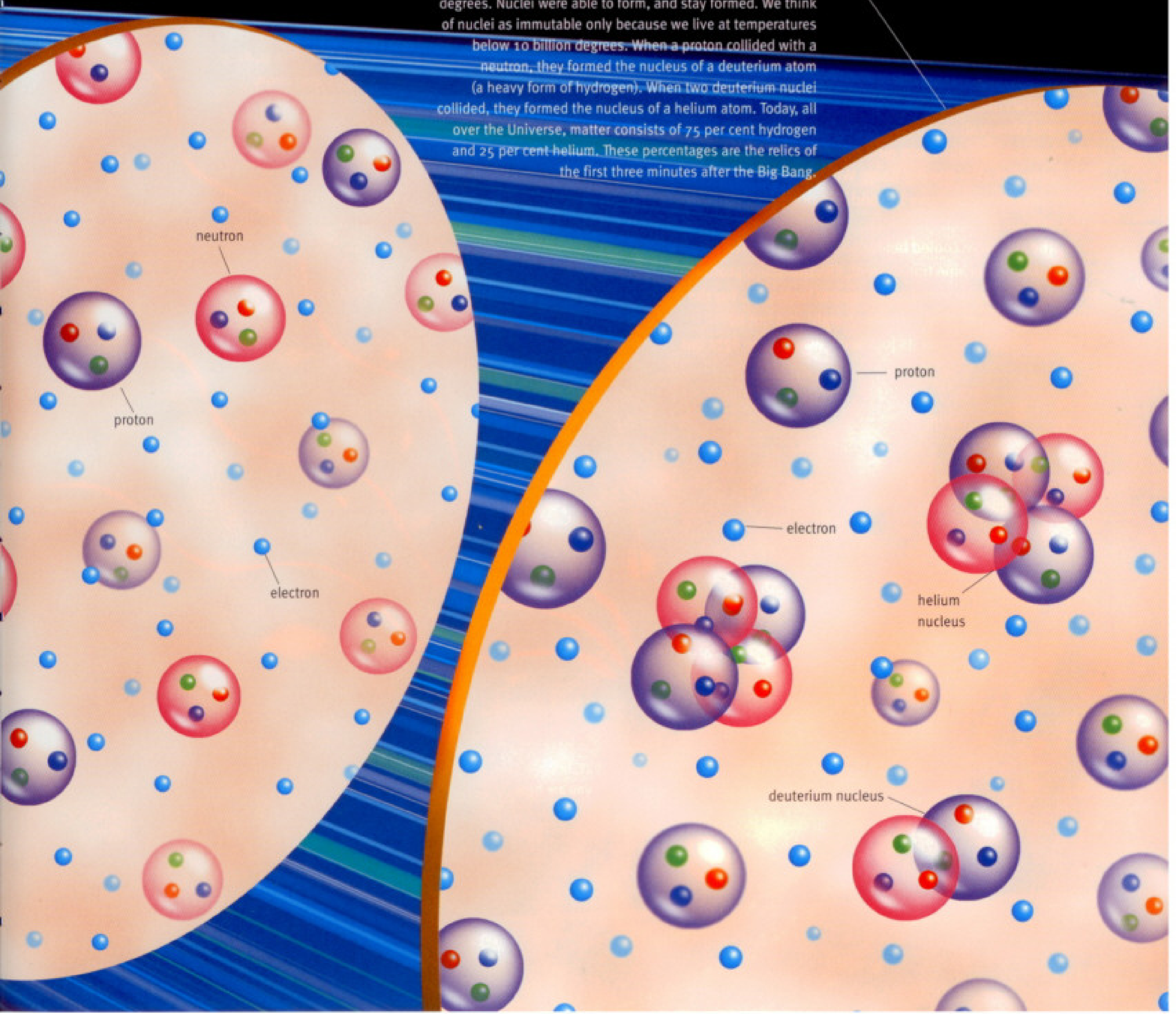
Heat atoms and they will change from solid to liquid to gas. Then the atoms themselves start to break up. The electrons begin to fly off from around nuclei. With more heat all the electrons depart, leaving only the nuclei. Heat these nuclei and they break into their component parts: protons and neutrons. Heat these and they break into fundamental particles called quarks. The Universe becomes a hot, dense soup filled with quarks and energetic photons (a photon is a particle of light).

Heat this soup further and you have so much energy that antiparticles and particles form in equal numbers from the photons. Heat the Universe further and the true vacuum becomes a false vacuum (see page 60). All the energy and matter in the Universe is used up in this transition, making the Universe collapse by at least $10^{26}$ in size. Heat this collapsed false vacuum and spacetime itself begins to froth and boil. Time loses its meaning and there the heating stops.

The cooling Universe can be described as a hot soup which, as it cools, goes through the four formative stages illustrated below. Note that the first three stages all occur in a microsecond. Within that blink of an eye, the large-scale structure of the whole Universe was established.

## Nuclei soup

From 1 second to 3 minutes after the Big Bang, the Universe cooled below the binding energy of atomic nuclei, 10 billion degrees. Nuclei were able to form, and stay formed. We think of nuclei as immutable only because we live at temperatures below 10 billion degrees. When a proton collided with a neutron, they formed the nucleus of a deuterium atom (a heavy form of hydrogen). When two deuterium nuclei collided, they formed the nucleus of a helium atom. Today, all over the Universe, matter consists of 75 per cent hydrogen and 25 per cent helium. These percentages are the relics of the first three minutes after the Big Bang.



# Looking at the Big Bang

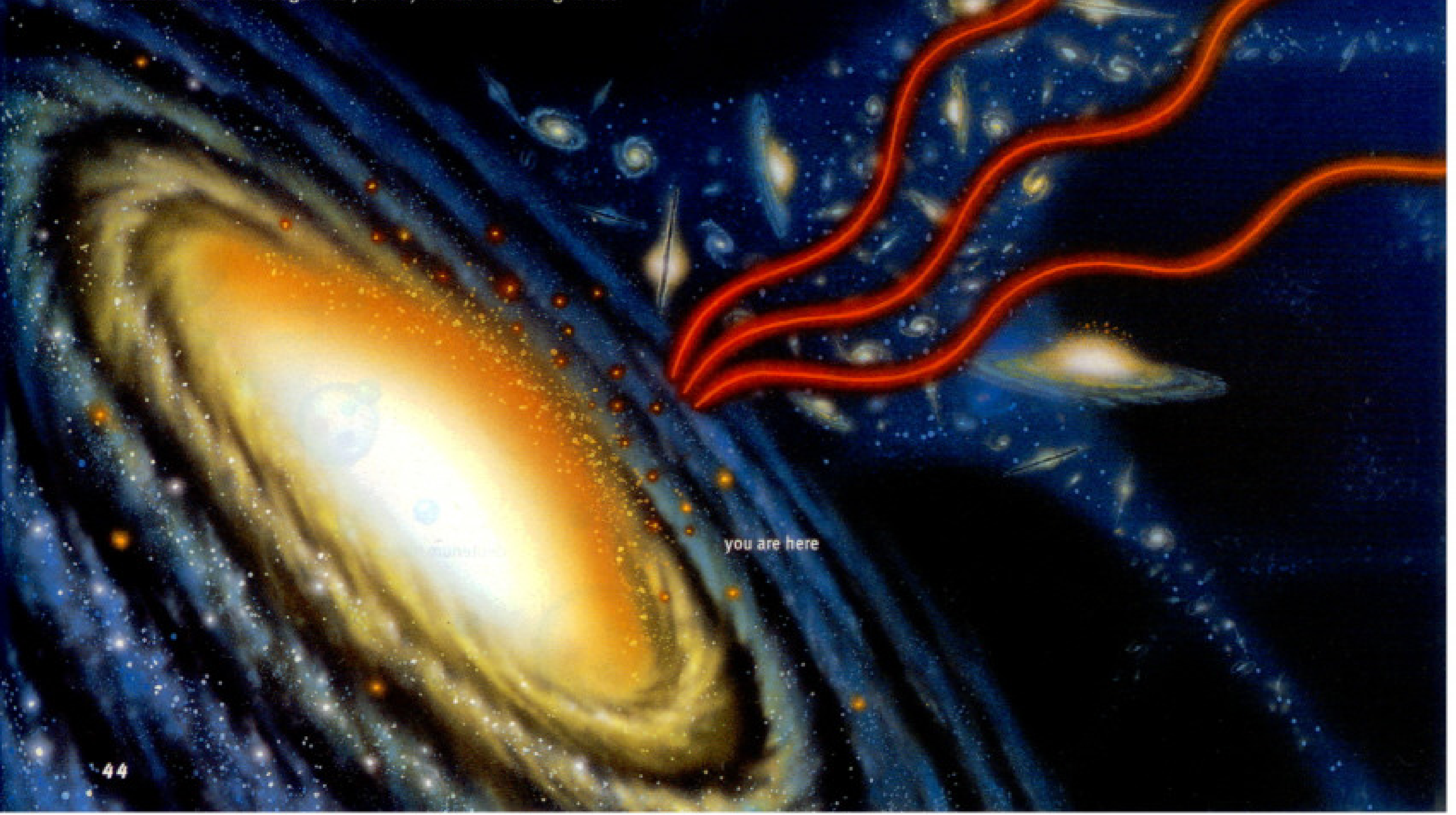
*We know there was a Big Bang because we can see its glow.*

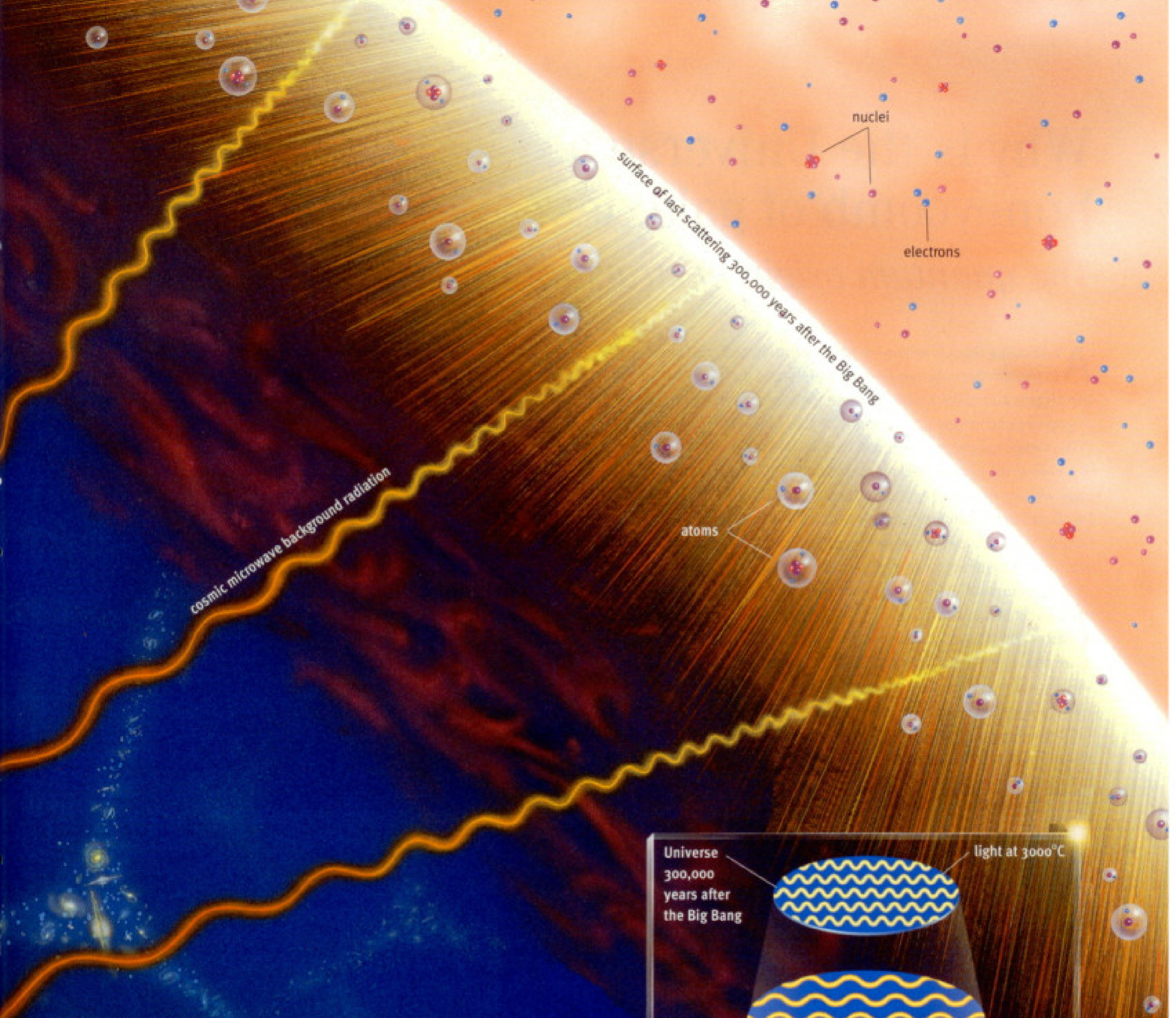
When we look at the Moon, we are seeing it as it was one second ago. We see the Sun as it was eight minutes ago and the light from the nearest stars has taken four years to reach us. We see our neighbouring galaxy Andromeda as it was two million years ago. As we look into the distance, we see into the past because it takes time for light to travel through space. If we look far enough into the past, will we see the Big Bang? Well yes, sort of.

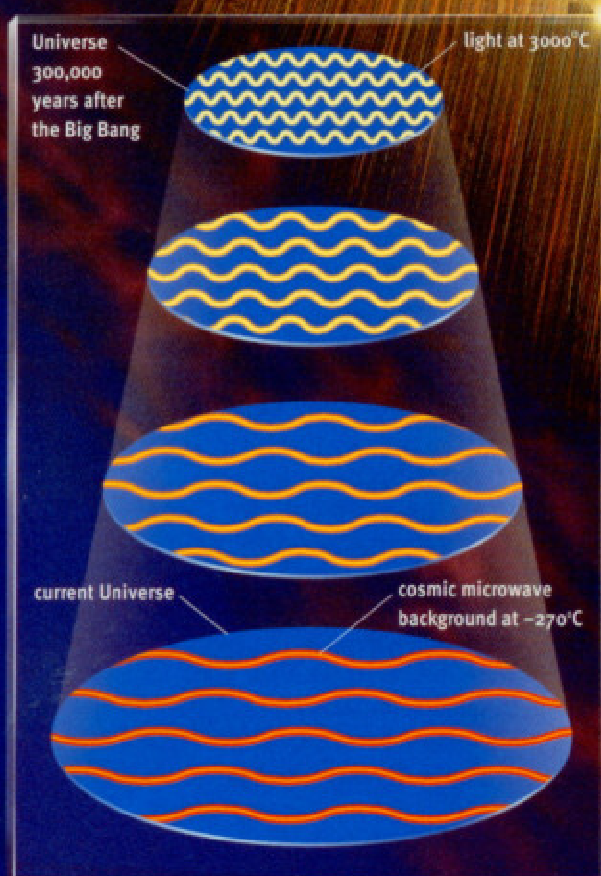
When we look far enough, past all the objects emitting light, we see only one object – the entire Universe glowing. This glow is the cosmic microwave background radiation discovered with a radiotelescope by American physicists Arno Penzias and Robert Wilson in 1964. Its existence is the strongest observational evidence for the Big Bang model of the Universe. This glow was emitted by the entire Universe 300,000 years after the Big Bang. We cannot see any further in time and space because beyond this point the Universe is a hot opaque plasma.

As the Universe cooled below 3000°C, the hot fog of the early Universe became transparent. Electrons and protons fell together to form transparent neutral hydrogen. For the first time, light was able to travel straight and not be scattered. When it began its journey it was visible light but we cannot see it now with our eyes because as it travelled through the expanding Universe, its wavelength got stretched a thousandfold. This red-shifted glow of the Big Bang is the cosmic microwave background radiation.

We are accustomed to light coming from a source in a given direction, such as a light bulb, or the Sun, or the Milky Way. The cosmic microwave background is different. It comes from everywhere since the Big Bang is in the past of everything in the Universe. In the illustration, the hot surface emitting the cosmic microwave background is only in the upper right corner. Don't be fooled. This surface curves around and completely surrounds us and every other observer.






## Expanding and cooling

**300,000 years after the Big Bang, the temperature dropped below 3000°C and the Universe became transparent. Because the Universe has remained transparent ever since, we can see back to this time. The surface of the last scattering emitted visible red light, but as the light travelled through the expanding Universe, its wavelength got stretched by a factor of 1000. The temperature of the radiation dropped from 3000°C to −270°C.**

# Why is the Universe a honeycomb of galaxies?

## *The quantum origin of structure*

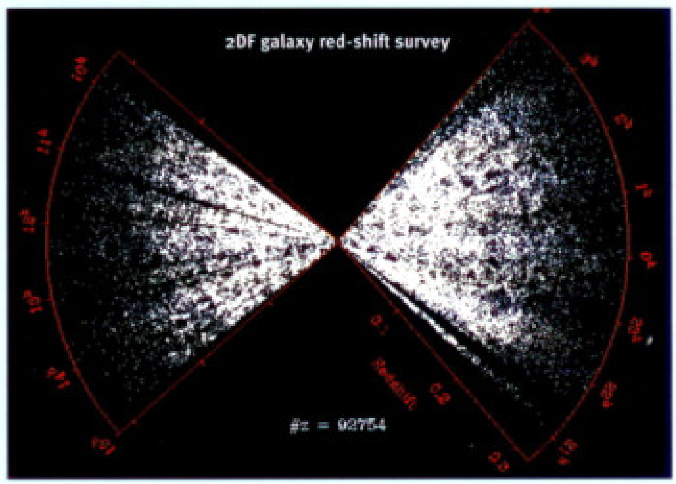
An amazing thing is emerging from our studies of the Universe. To explain the large we need to understand the tiny. The biggest structures in the Universe (dense walls of thousands of galaxies each made up of billions of stars) have their origins in the tiniest quantum structures. Part of the evidence for this lies in a map of the cosmic background radiation. On the previous page we saw how the remnants the Big Bang have been detected. Our instruments can pick up a glow called the cosmic background radiation. It is an icy remnant of the Universe when it was 300,000 years old. So what does this glow look like?

The instrument that has recorded this glow is a satellite called the Cosmic Background Explorer (see page 66), or COBE for short. A map of the glow or cosmic microwave background is shown here as an oval full of red and blue areas. This now-famous image is literally a photo of the Universe 300,000 years after the Big Bang and a couple of billion years before galaxies formed.

There were no galaxies then, but the seeds of galaxies were already in place. The blue spots are the seeds. They are regions of high density which have become regions with a large number of galaxies. The red spots have become voids with a small number of galaxies. What is the origin of these blue and red spots?

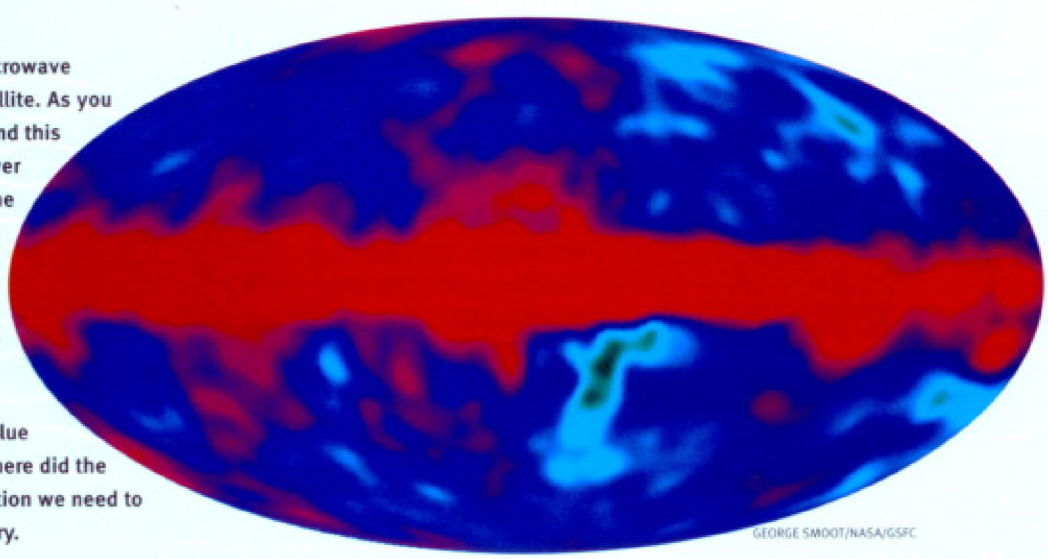
Einstein's theory of general relativity explains how gravity shaped the Universe on the largest scales, but it gives us no clues about what happens on very small scales. When the pattern of galaxies was laid out, the observable Universe was very small. General relativity can't explain the origin of the blue and red spots, but it seems that another science – quantum theory – can.

These spots are the largest structures ever detected, but they may also be the smallest structures known to science. This is because a process called inflation (see page 60) has taken subatomic quantum fluctuations smaller than anyone has ever seen and blown them up to scales as big as the entire Universe. It's as if inflation is a microscope which not only makes a magnified image of small quantum fluctuations, but magically transforms the image into reality.




**The Anglo-Australian Telescope has produced the most detailed map we have of the Universe. Each white dot is a galaxy in a wedge-shaped region of the sky. Our Galaxy is in the centre. The galaxies are not distributed randomly like raindrops on a footpath. Nor are they distributed regularly like squares on a checkerboard. There seem to be empty regions surrounded by walls and clumps of galaxies. The structure is a bit frothy, like a honeycomb put into a blender. This pattern is expected if it formed from the structures which produced the hot and cold spots in the COBE maps. See page 66 for a photo of the 2DF instrument that made this image.**

**This is a full-sky map of the cosmic microwave background captured by the COBE satellite. As you look far away you look into the past, and this is as far into the past as anyone has ever seen. The red horizontal band across the middle is our galaxy but the red and blue spots are hot and cold spots in the early Universe. The blue spots are regions of the Universe that, today, are heavily populated with galaxies. Gigantic clumps of galaxies called superclusters have formed there. The blue spots are the seeds of galaxies, but where did the seeds come from? To answer this question we need to borrow a few ideas from quantum theory.**



GEORGE SMOOT/NASA/GSFC