PART TWO: The quantum world

Science of the tiny

Our goal is to understand the creation of the Universe. The size of the observable Universe (the part of the Universe we can see today) is more than a trillion, trillion kilometres. This is not small. This is the distance light has travelled during the 13 billion years since the Big Bang.

However, as we go back in time closer to the Big Bang, closer to the cosmic traffic jam, what is now the observable Universe was smaller and smaller. At 10^{-33} seconds after the Big Bang (a trillionth of a trillionth of a billionth of a second) it was about as big as a basketball. Go back further in time and the currently observable Universe was smaller than an atom. In order to understand how the Universe behaved in these first moments and where it may have come from, we need to think in different ways. Studying the way electrons behave will help.

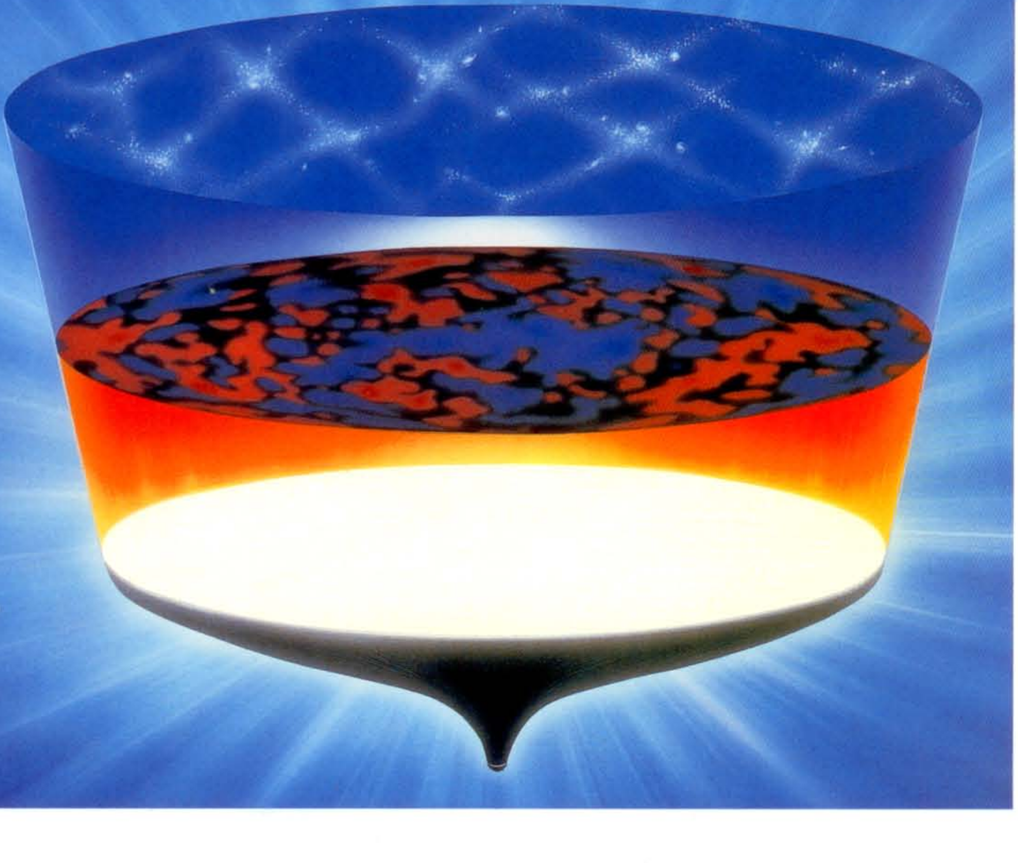
Small things (like electrons, photons and the early Universe) behave so differently from large things that we need a radical, weird, counter-intuitive approach called quantum theory to understand them. Quantum theory became necessary because the more we learned about the microworld, the weirder it became.

The difference between the classical macroworld and the quantum microworld is so great that universities teach separate courses on each subject. It's as if the Universe could be divided into two types of objects: big things and small things. General relativity describes big things while quantum theory looks after small things.

In the following pages we will look at what makes quantum theory so weird:

1. **atoms do not collapse**
2. **electrons behave like particles and like waves**
3. **tiny objects can tunnel through walls**
4. **tiny particles don't have precise positions**
5. **some events don't have a cause**
6. **empty space is not empty**
7. **there are two types of empty space**

These weird ideas are the tools we need to understand the quantum creation of the Universe. Before we put the ideas together, let's explain them one by one.



Here, in the centre, is a map of the cosmic microwave background as part of a time sequence. It's a different version of the map shown opposite but displays the same idea. Above the map is the Universe as we see it today – a fractured honeycomb of galaxies. The bright knots of galaxy clusters have emerged from the cool blue areas on the COBE map. Below the map is the beginning of the Universe. To explain the patterns of the COBE map (and, consequently, explain the patterns we see in today's Universe), we need to understand the behaviour of the Universe when it was very young and very small.

Electrons are not orbiting satellites

Quantum weirdness 1: atoms do not collapse

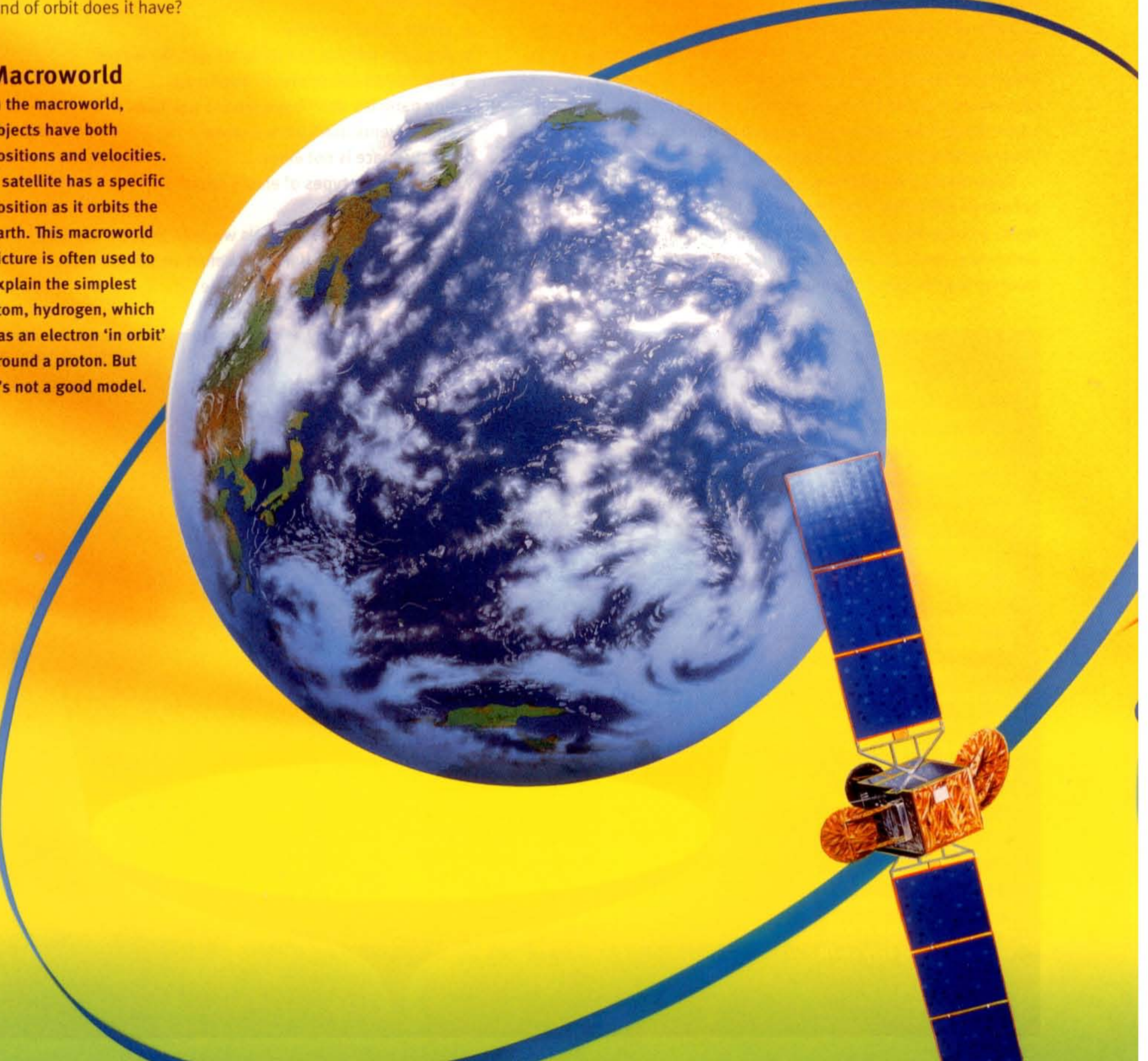
Many people envisage an electron orbiting a nucleus as a satellite orbiting the Earth. The centrifugal force balances the gravitational force and the satellite moves around the Earth in a circle. If an electron were accelerated like this around a nucleus, it would radiate away its energy and spiral into the nucleus in a fraction of a second. Every atom in our bodies would collapse and we wouldn't be around to wonder about it. In fact atoms don't collapse. Why not? Why is their behaviour so different from large objects? If the electron does not have an orbit like a satellite, what kind of orbit does it have?

Quantum theory answers these questions by describing the electron as a smeared-out cloud of probability with discrete (fixed) energy levels (see page 54). The early Universe may have been similar to an electron.

Just as quantum theory can explain why the electron does not collapse into the nucleus, quantum cosmology may be able to explain why the Universe could not have been completely collapsed and did not originate from a point of infinite density and temperature.

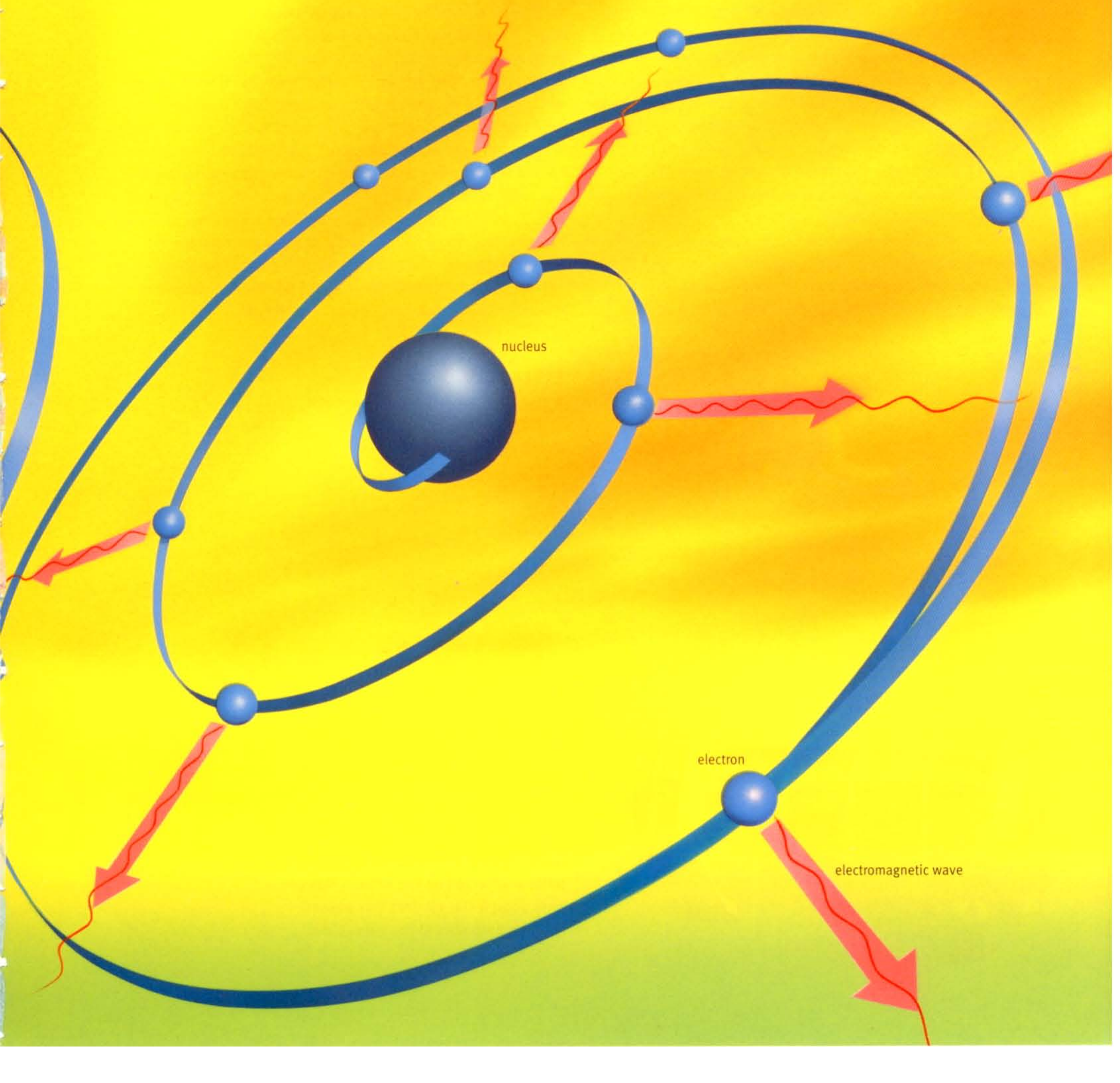
Macroworld

In the macroworld, objects have both positions and velocities. A satellite has a specific position as it orbits the Earth. This macroworld picture is often used to explain the simplest atom, hydrogen, which has an electron 'in orbit' around a proton. But it's not a good model.



Microworld

If an electron really did have a circular orbit (like a miniature satellite) around a proton, it would quickly emit energy in the form of photons. Its orbit would decay in a fraction of a second and the electron would fall into the proton as shown in the illustration. All atoms would collapse and we wouldn't be here. No chemistry or life would be possible. Before quantum theory, no one could explain why atoms did not collapse like this.



The mystery of the double slit

Quantum weirdness 2: electrons behave like waves and particles

Throw a ball at a wall with two slits in it. Mark the positions on a screen behind the wall where the ball has hit. As you do this hundreds of times, the pattern of positions where the ball hit starts to look like the two slits.

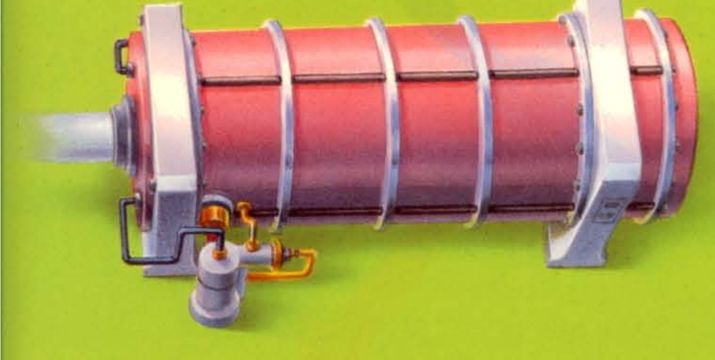
Now try the same thing with an electron (throwing electrons at a screen is what your television set does). The result is not an image of two slits but an image of many slits. Why do microballs (electrons) act so differently from macroballs? The electron results are identical to that made by a wave (see box). A wave goes through both slits simultaneously and then is able to interfere with itself. A tiny electron should pass through one slit or the other. It doesn't. Like a wave, it goes through both. The electron is not just a particle in a precise location with a precise trajectory. It is some kind of weird hybrid of a wave and a particle. The double-slit experiment brings out its double nature.

A wave cannot deposit all its energy in a precise spot on the screen. It can't produce one bright image without producing all the bright images simultaneously. Waves cannot be localised. However, the multiple slits of the electron image are made of hundreds of individual, well-localised hits where you can say the electron hit here, here, and here – just as you can with a ball. So a microball, an electron, acts a bit like a macroball, depositing its energy in one spot on the screen. But it also acts a bit like a wave, interfering with itself when it goes through both slits at once.

A single electron acts like many electrons. It simultaneously takes all possible paths between its source and its detection. Nobody expected an electron to behave this way. Nobody wants electrons to behave this way. It doesn't make sense. How can an electron be a point particle when we detect it in a particular very precise spot and yet, when we don't detect it, it behaves as a wave that is spread out all over the place? This weird behaviour is not limited to electrons – all small things behave this way – including perhaps the small early Universe. Can the Universe interfere with itself the way an electron can? Can the presence of other universes be revealed in some way analogous to the way the double-slit experiment reveals the multiple paths the electron has taken before hitting the screen? These are the new types of questions that quantum cosmology is beginning to answer.

Macroworld

A macroball passes through one slit or the other and hits the screen directly behind that slit.

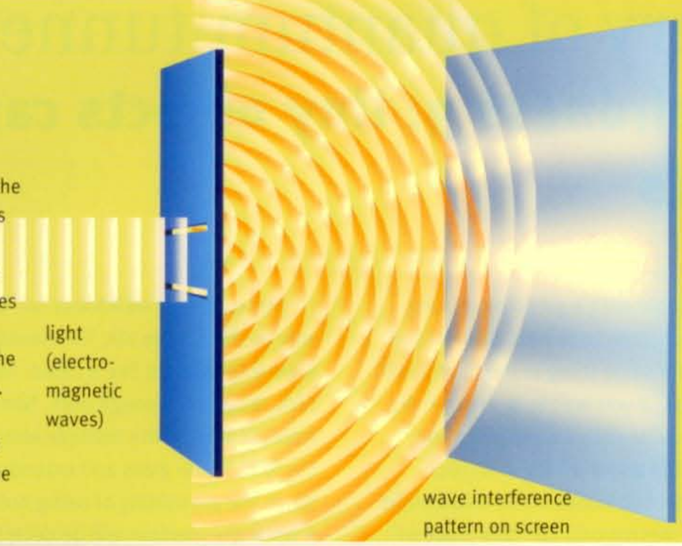


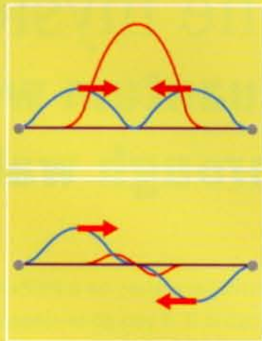
Microworld

Like a macroball, an electron hits the screen at a single spot, but that spot will not be right behind a slit. If we repeat the same experiment many times, the well-known wave interference pattern emerges on the screen. This can only occur if the electron has passed through both slits at the same time.

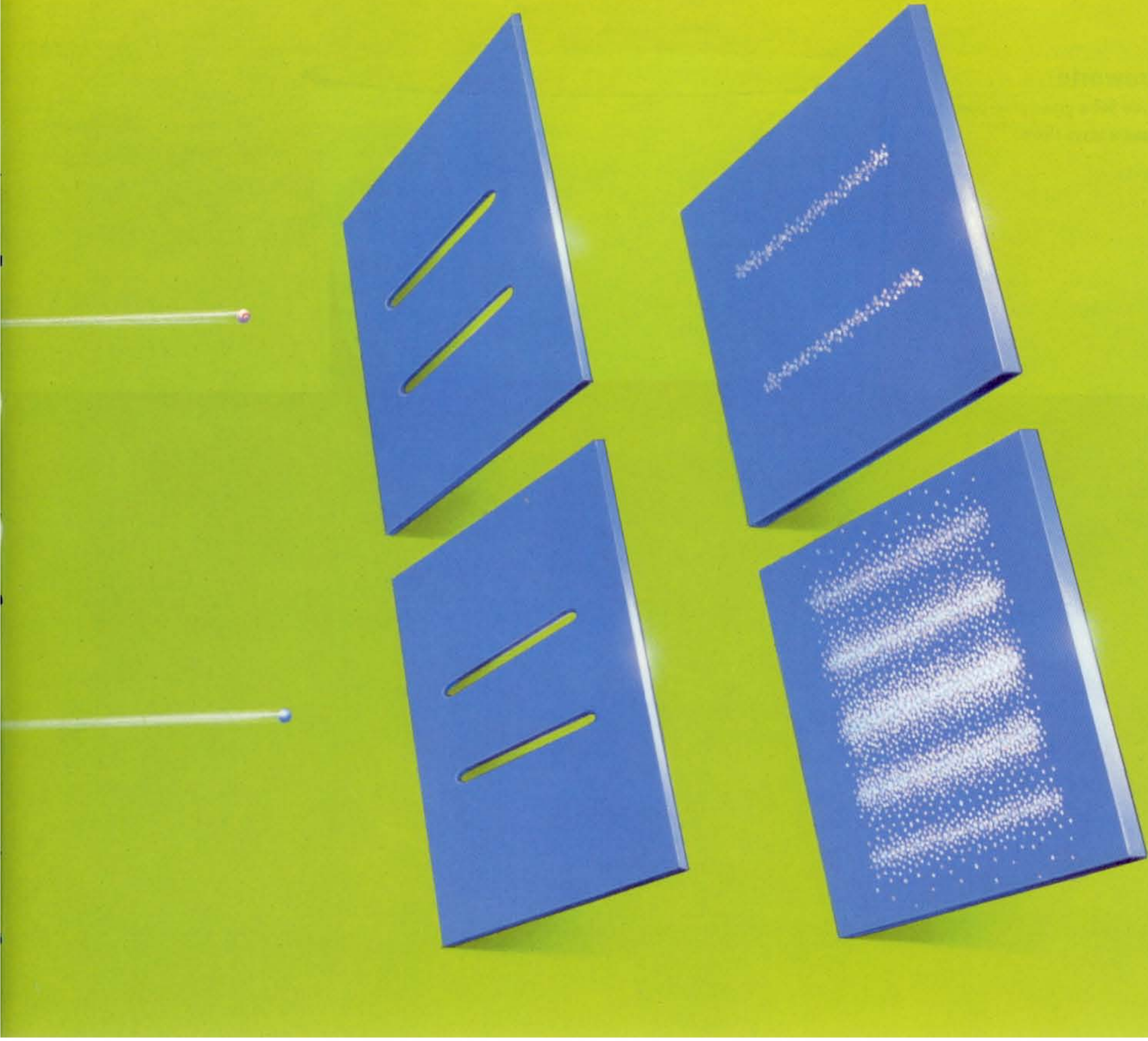
Wave interference

A wave goes through both slits simultaneously and becomes effectively two point sources. It is then able to interfere with itself. Constructive interference produces the bright stripes. Between these stripes destructive interference (where the waves cancel each other out) leaves the screen blank. This series of stripes is an interference pattern. Sound waves and water waves behave in the same way as the light waves shown. Notice that, unlike the macro and microballs, a wave does not deposit all its energy in one point spot on the screen. Waves cannot be localised.





Top: constructive interference, in which the crests of two waves overlap. Above: a crest and a trough overlap in destructive interference.



The mystery of quantum-tunnelling

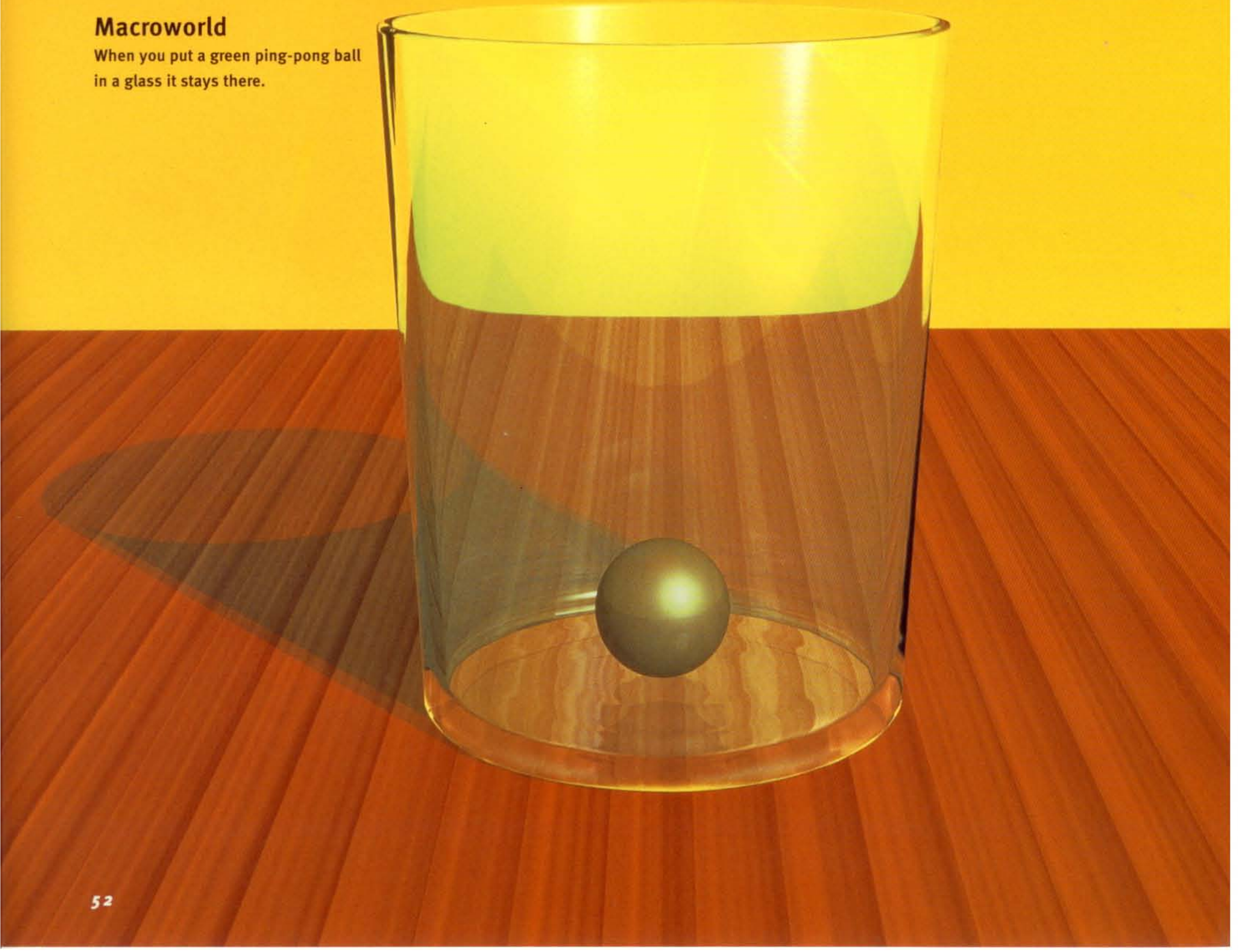
Quantum weirdness 3: tiny objects can tunnel through walls

Consider a glass on a kitchen table with a green ping-pong ball in it. If you go to sleep and come back next day, the ball will still be in the glass. Now do the same thing in the microworld. Put an electron in a miniature glass. If you wait long enough the electron will be gone (how long you have to wait depends on how small the glass is and how high and thick its walls are). Such quantum-tunnelling is normal behaviour in the microworld. Events that are impossible in the macroworld can take place in the microworld.

This quantum weirdness can be understood in much the same way as the double slit. The electron passed through both slits as if it were spread out like a cloud. Too big to fit through just one of the slits, it passes through both. Similarly, this probability cloud (represented by the multiple images in the illustration) is too big to fit in the glass and extends beyond the walls of the glass. Since the probability of being outside the glass is not zero, once in a while the electron will be detected outside it. The electron does not move to the outside, it just appears there instantaneously.

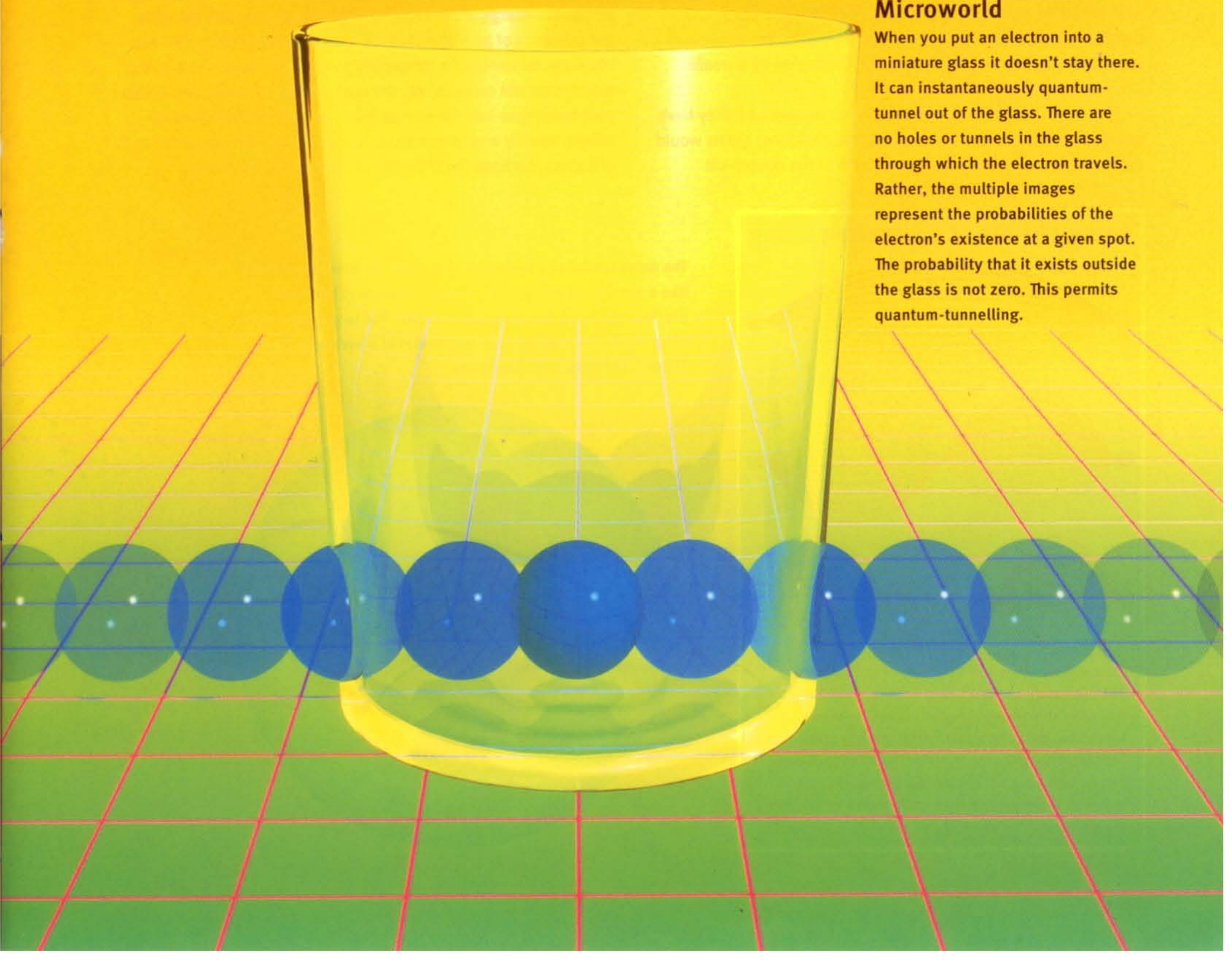
Macroworld

When you put a green ping-pong ball in a glass it stays there.



Although there are no holes or tunnels in the wall of glass, this appearance on the other side of a barrier is called quantum-tunnelling. When the electron is detected outside the glass, it is detected in a specific, very precise location and all the cloud of probability surrounding the glass disappears instantaneously. The smaller the glass, the more likely the cloud is to extend out of it, and thus the easier it is for the electron to appear on the outside or 'quantum-tunnel' through the barrier.

The inability to confine an electron to a glass may be related to an inability for the Universe to shrink beyond a certain limit as we go back in time towards the Big Bang. Just as the electron quantum-tunnelled instantaneously (and causelessly) from a stable state inside the glass to the outside of the glass, the quantum Universe may have quantum-tunnelled into existence from a stable timeless state.



Microworld

When you put an electron into a miniature glass it doesn't stay there. It can instantaneously quantum-tunnel out of the glass. There are no holes or tunnels in the glass through which the electron travels. Rather, the multiple images represent the probabilities of the electron's existence at a given spot. The probability that it exists outside the glass is not zero. This permits quantum-tunnelling.

A smeared-out existence

Quantum weirdness 4: tiny particles don't have a precise position

A good image for the hydrogen atom is illustrated opposite. Smeared-out around the black nucleus is a cloud of blue dots representing the probability of a *single* electron being at that point. The more blue dots there are in a given area, the more likely the electron is to show up there when a position measurement is made. There are more dots near the nucleus and fewer further away. This means that when we make measurements we're more likely to find the electron near the nucleus. When we aren't directly detecting the electron, the blue cloud of probability is the electron. It is everywhere at once. We must accept the idea that, in the absence of a position measurement, the electron has no position.

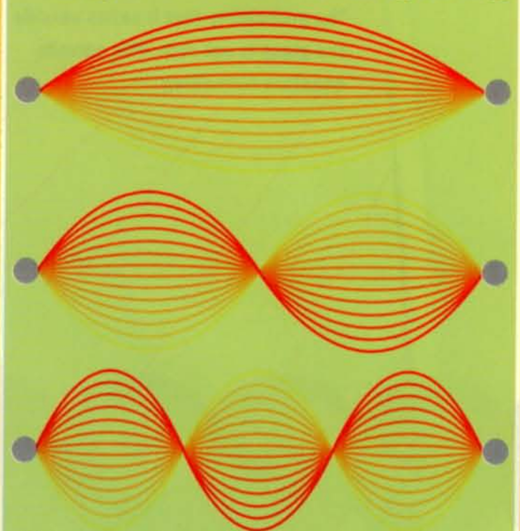
When a position detection is made, the probabilities of the electron existing in other positions immediately become zero. After a horse race, all bets are off. Although we have been concentrating on the electron, the nucleus is also spread out over space and should be represented in the illustration by a smaller cloud of black dots.

Electrons and other small things do not behave as if they have precise positions. If electrons had precise positions, atoms would collapse, there would be only two images in the double-slit experiment and electrons would stay in miniature glasses. Electrons behave like smeared-out clouds of probability able to maintain a stable existence around a nucleus without emitting radiation, able to pass through both slits at the same time in the double-slit experiment and able to exist outside the walls of a glass even though it was originally put inside the glass.

Another feature of this smeared-out existence is that particular patterns of smearing correspond to particular energy levels, in much the same way as the vibrations of a guitar string (see box). There is a minimum energy level which prevents the electron from collapsing into the nucleus.

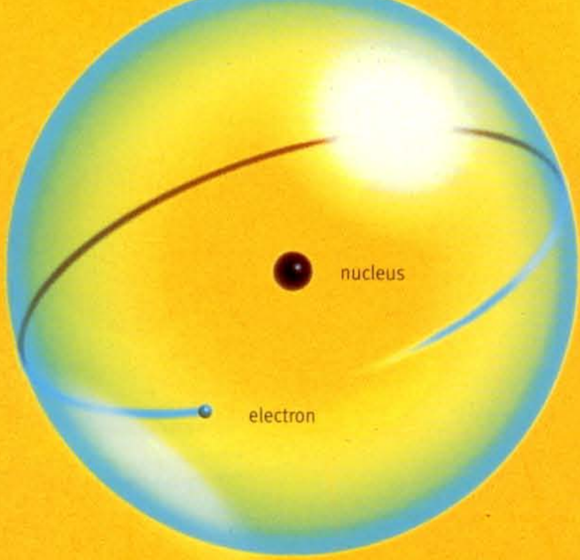
Near the Big Bang we may need to describe the Universe with a cloud of probability similar to the one used to describe an electron. Just as the energy of the electron is quantised and does not allow the existence of a collapsed atom, a similar quantisation may not allow the existence of a completely collapsed Universe. Just as the electron cannot collapse into the nucleus, the Universe may not be able to collapse into (or emerge from) an indescribable point of infinite density and temperature. Just as an electron can tunnel out of a glass, perhaps the Universe can tunnel into existence.

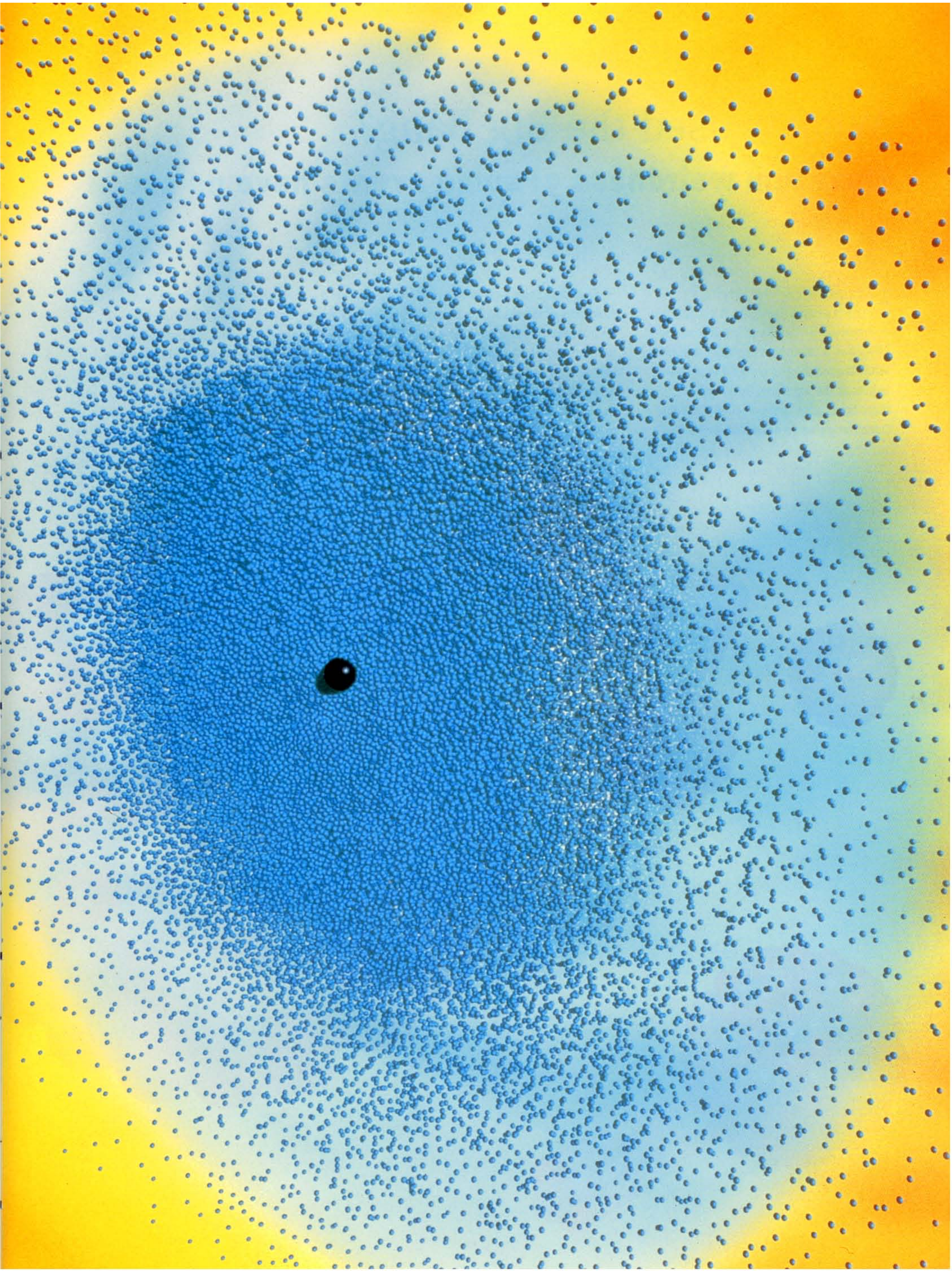
Energy levels of a vibrating string



Pluck a guitar string and it vibrates as shown in the top panel at its longest wavelength (lowest pitch). The string can also vibrate at higher pitches, as shown, which have their own wavelengths, much as an electron in an atom has fixed energy levels. Both can take certain values, both have a minimum energy level (like the longest wavelength of the string). At its lowest energy the electron can't lose energy, so atoms do not collapse.

The naive model of a hydrogen atom with the electron orbiting like a satellite is popular but wrong. If electrons had such precise positions, atoms would collapse. The larger illustration to the right is a more appropriate model of a hydrogen atom. The single electron is spread out.



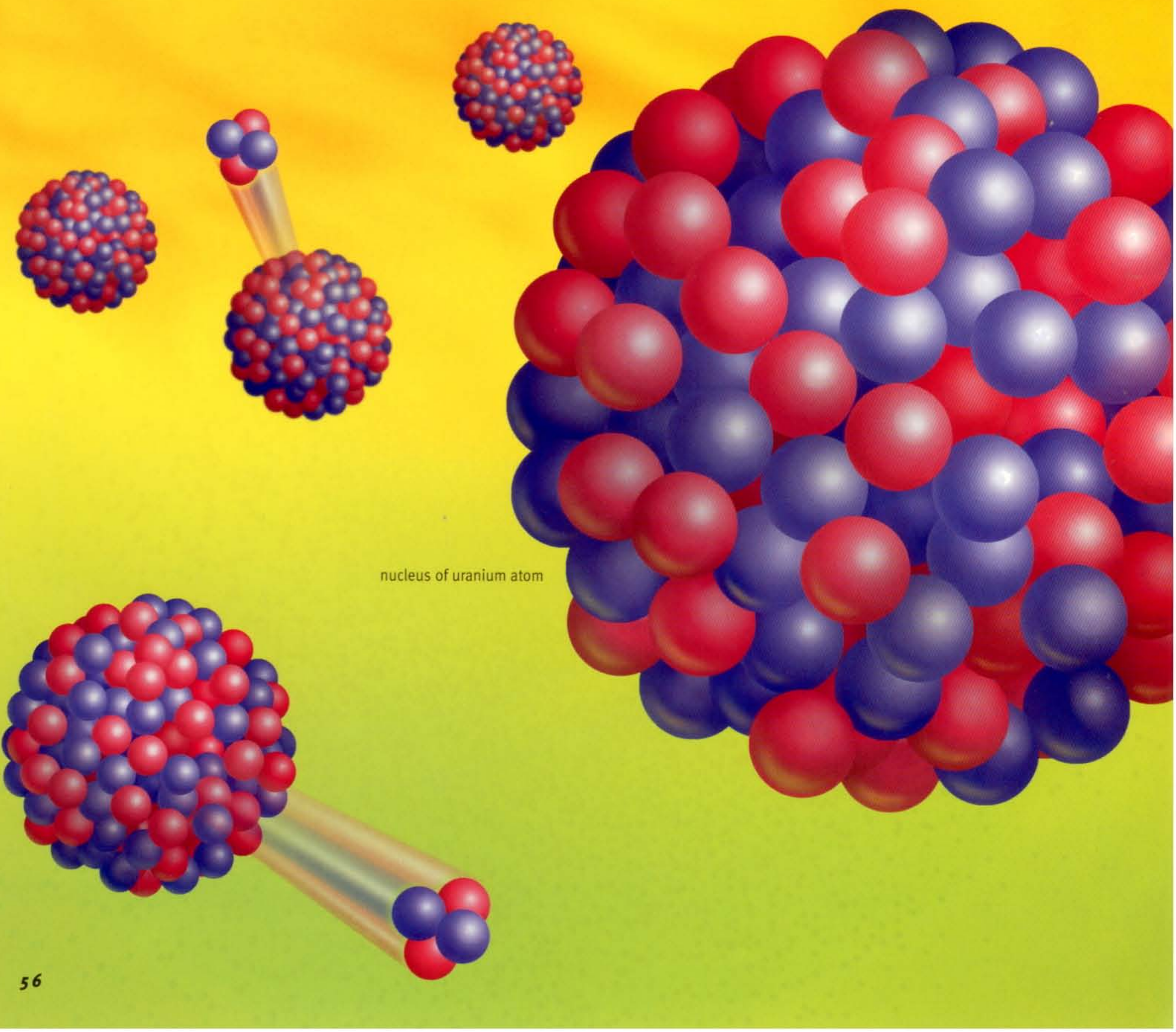


What caused the Big Bang?

Quantum weirdness 5: some events have no cause

Fires generate smoke. Flipping a switch causes the lights to come on. Common sense seems to insist that every effect has a cause that precedes it in time. What caused the Big Bang? If time itself begins at the Big Bang, how can there be a cause that precedes it in time? Does the Universe need a cause?

Quantum theory gives us many examples of events without causes. Radioactive decay is one. Take two uranium atoms and wait. After a while one will emit an alpha particle (two protons and two neutrons). The other will not. According to our best understanding of the Universe, there is absolutely no way to predict which of the uranium atoms will decay first. We know the half-life of uranium from which we can calculate the probability of the decay but this probability is the same for both atoms. There is no activity inside the nucleus, no gears, no details, no hidden variables which, if we knew them, would allow us to predict the time of the



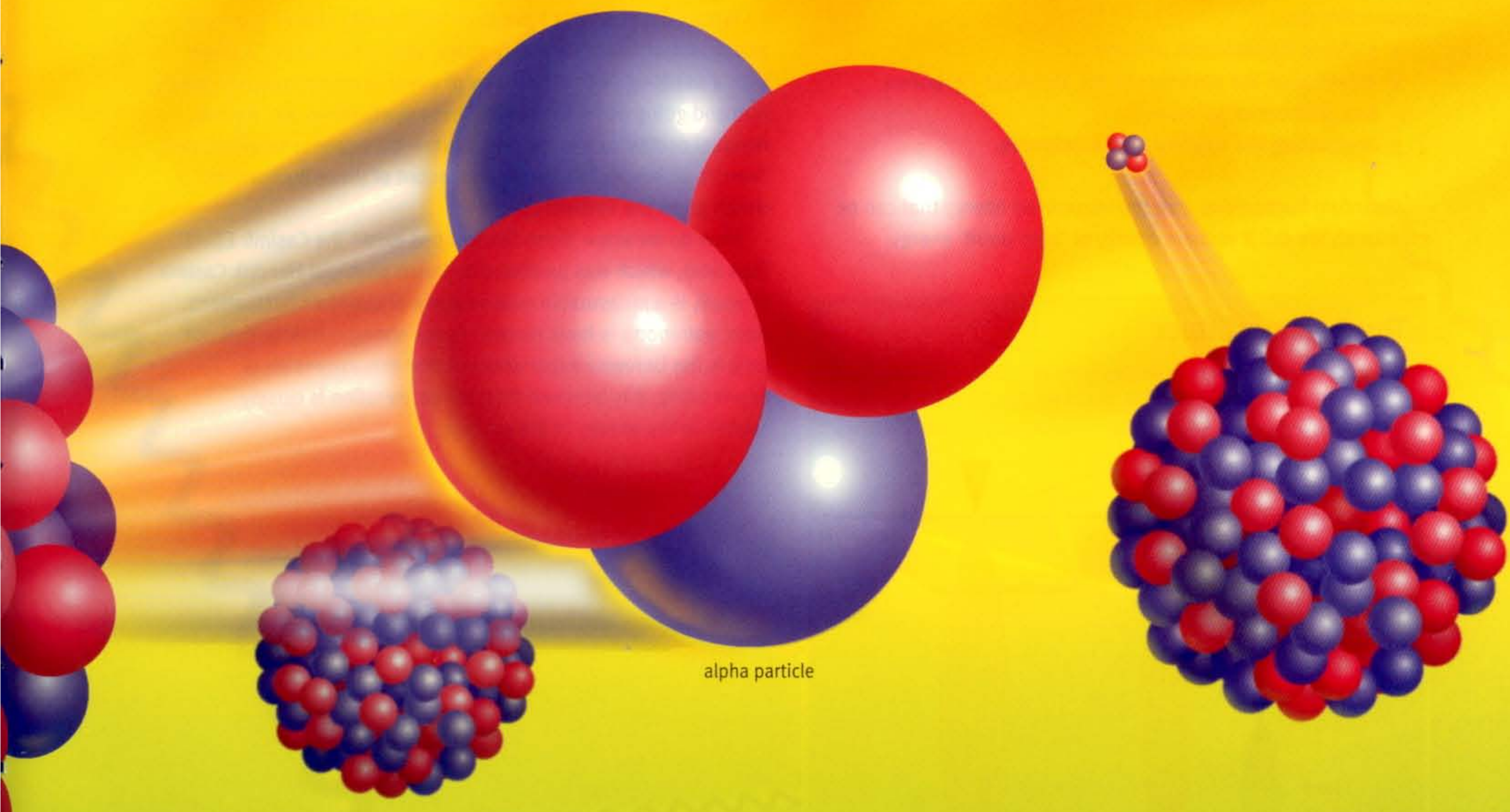
radioactive decay. The time of the decay is unknown and by all indications unknowable. Uranium atoms decay by chance, with a certain probability, but without a cause. Radioactive decay is an event without a cause.

When we put the electron into the miniature glass and then detect it in a precise position outside the glass, there is nothing about the electron before detection that causes it to be where it is found. There is no way to know when it will appear outside the glass. We can calculate a probability for quantum-tunnelling to happen, but there is no cause.

The cloud of probability describing the alpha particle in a uranium nucleus is spread out, and some of it is outside the nucleus. That means that once in a while the alpha particle will tunnel out.

This is bad news for common sense which seems to insist that all events have causes. If common sense is wrong and quantum theory is right, our quest for the cause of the Universe may be ill-conceived. Maybe the Universe doesn't have a cause. It could have come into existence in a particular state by chance, with a certain probability but without a cause.

Since we know we need quantum theory to describe the early Universe and we know quantum events have no causes, it seems plausible that the creation of the Universe can be best understood as an uncaused quantum event analogous to the quantum-tunnelling of the alpha particle in the decay of a uranium atom. The Universe may not need a cause to come into existence.



Before radioactivity was understood, the mysterious rays emitted by uranium were called alpha particles. We now know that alpha particles are made up of two protons and two neutrons. Alpha particles tunnel out of uranium nuclei. In nuclear power plants around the world, tunnelling alpha particles heat water to steam that turns a turbine and makes 20 per cent of the world's electricity.

Space, the final frontier

Quantum weirdness 6: empty space is not empty

Consider the space between this page and your head. Remove all the air and light from it so there is nothing there. You're left with boring empty vacuum – nothing. So what's to talk about?

Lots. What we call empty space is filled with quantum fluctuations that cannot be eliminated. You can't see them because they are too small. Quantum fluctuations seem to make up the very fabric of space. Just as it is silly to try to separate a shirt from the cloth it is made of, it is silly to try to separate the idea of vacuum from the quantum fluctuations that give the vacuum its structure.

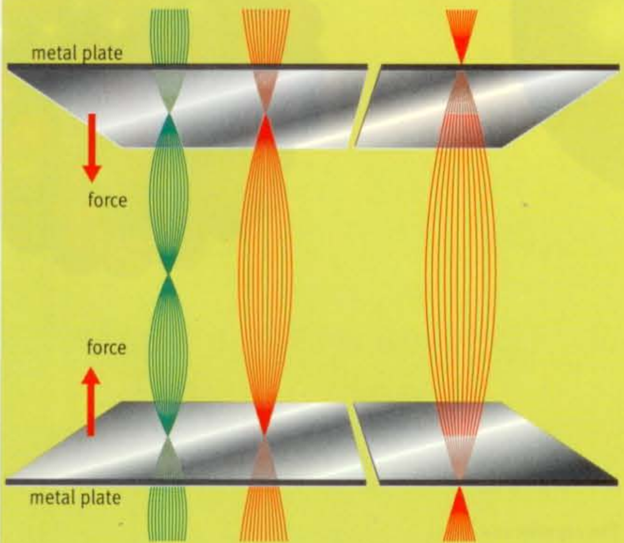
The study of the vacuum is one of the most important areas of current research. The latest evidence indicates that these quantum fluctuations are vital parts of any cosmology since they are responsible for:

1. **making the Universe expand**
2. **creating all the structure in the Universe (galaxies and clusters of galaxies)**
3. **controlling the destiny of the Universe**

Quantum fluctuations give the vacuum an energy that can be measured. We call it vacuum energy or 'zero-point' energy.

The Casimir Effect

When two metal plates are placed parallel to each other a small distance apart, a force pushes them together. This is the Casimir Effect. The plates act like the fixed ends of a guitar string, allowing only certain vibrations



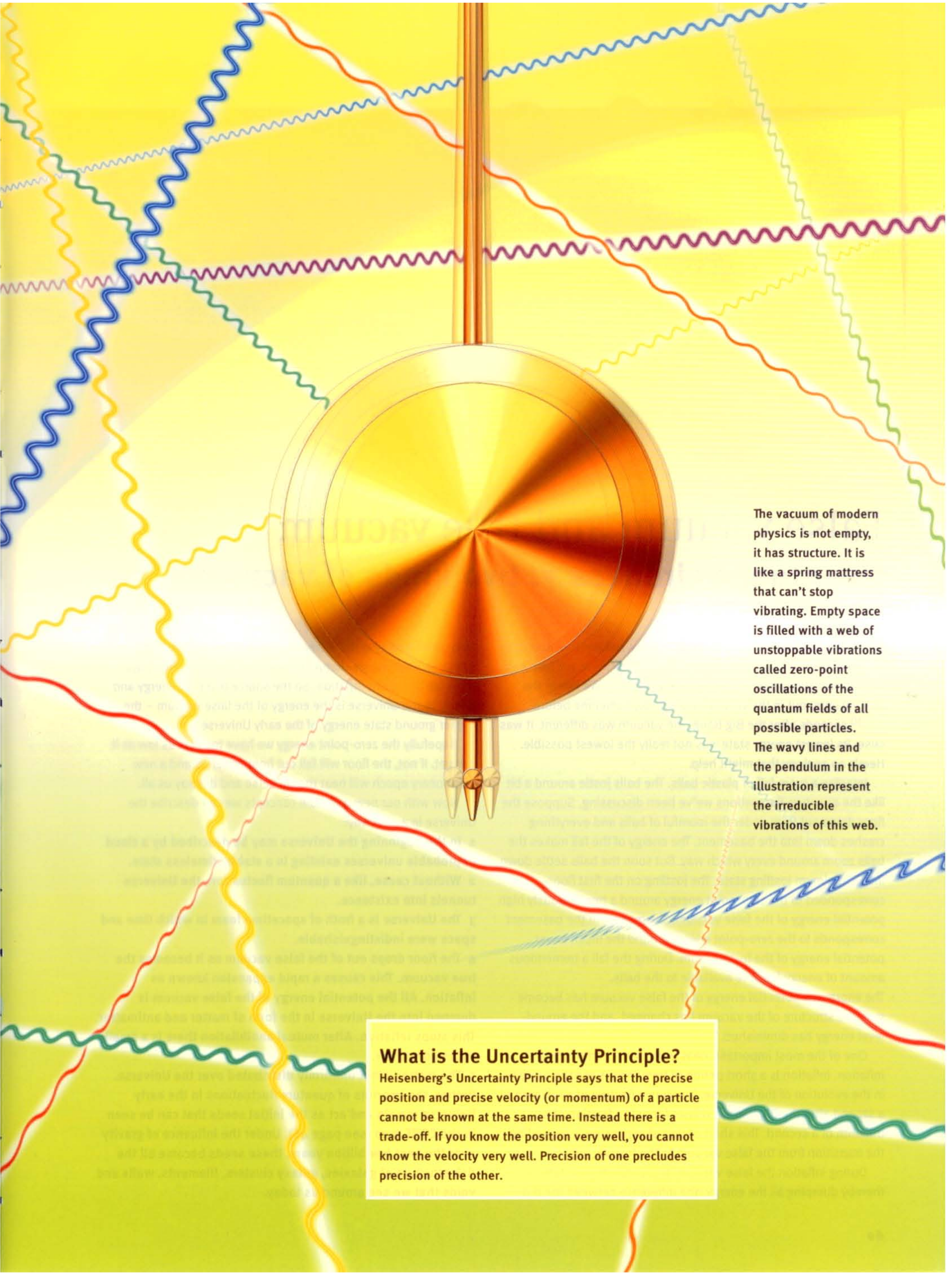
or zero-point oscillations (quantum fluctuations of particles coming into and going out of existence) to occur. In this diagram the two vibrations shown at left can occur between the plates. The vibration at right, however, is too long to occur inside the plates (but still occurs outside the plates). The net effect is a greater pressure on the outside of the plates (because there are fewer vibrations between the plates).

It is much like the lowest energy level of an electron in an atom. But vacuum energy exists in the absence of atoms and everything else. Empty space is not empty. It is filled with vacuum energy.

Consider a microscopic pendulum like that shown on the opposite page. When it is swinging it has energy. When it is still it has no energy. However, the uncertainty principle tells us that it can never be perfectly still (see box). If it were, we would know its position and its velocity exactly – which the uncertainty principle forbids. If we look at its small, sharp tip very carefully we will see that it is not perfectly still. So there is a tiny amount of uncertainty in its position (hence the multiple images) and this is equivalent to a tiny amount of energy, a minimum amount of energy that cannot be eliminated – zero-point energy.

What do pendulums have to do with empty space? Our most accurate description of empty space tells us that space is filled with a seething froth of particles of every kind continuously coming into and going out of existence. These fluctuations are like the residual oscillations of the pendulum – they cannot be eliminated. There is an irreducible minimum amount of these fluctuations which gives the vacuum an energy.

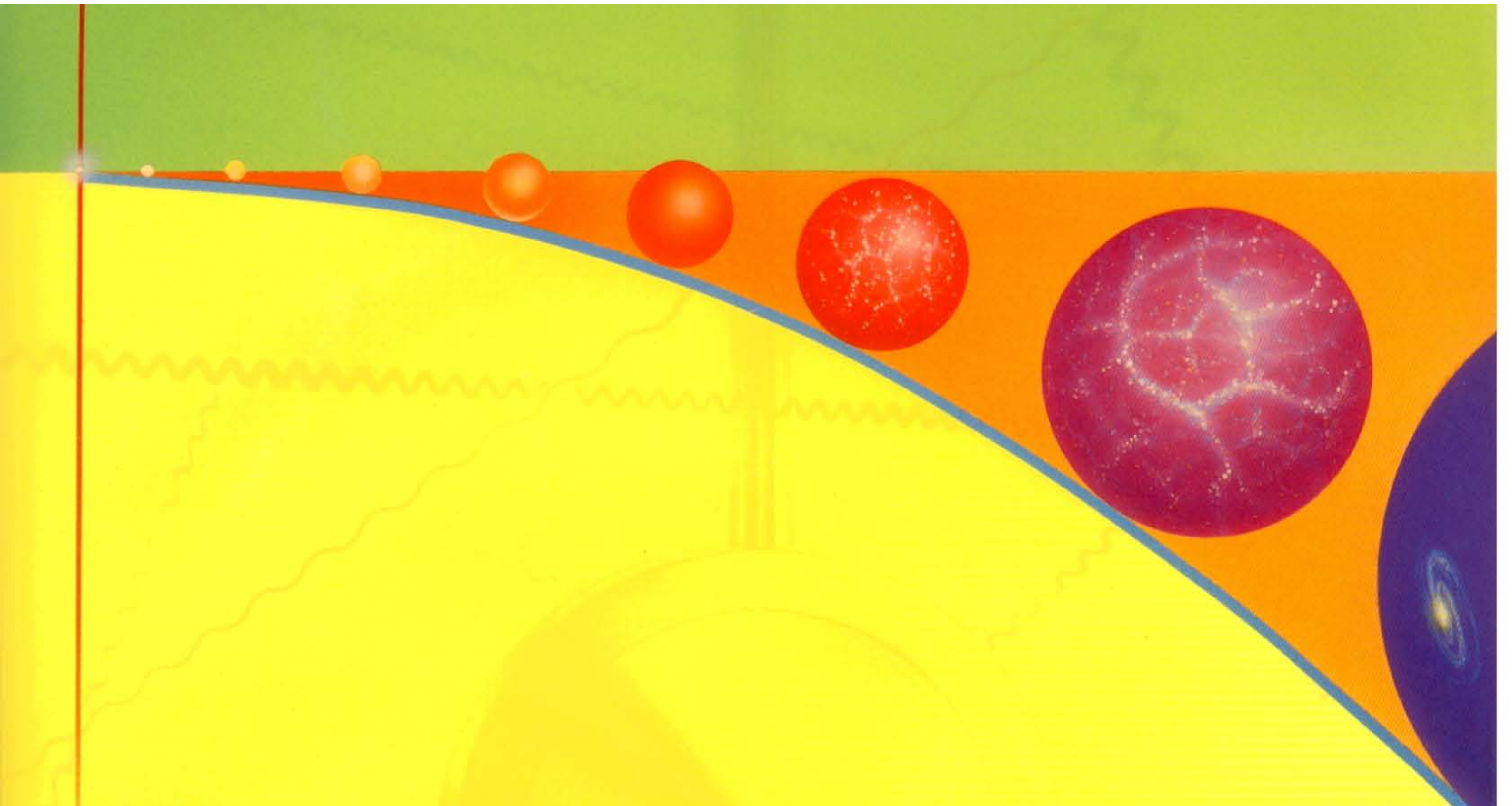
How do we know these fluctuations exist? The Casimir Effect (see box), which was predicted by Dutch physicist Hendrik Casimir in 1948, is a measurable consequence of quantum fluctuations. Also, astronomers have recently found strong evidence that not only is the Universe expanding but that this expansion is accelerating. It is believed that this acceleration is closely related to the energy of the vacuum.



The vacuum of modern physics is not empty, it has structure. It is like a spring mattress that can't stop vibrating. Empty space is filled with a web of unstoppable vibrations called zero-point oscillations of the quantum fields of all possible particles. The wavy lines and the pendulum in the illustration represent the irreducible vibrations of this web.

What is the Uncertainty Principle?

Heisenberg's Uncertainty Principle says that the precise position and precise velocity (or momentum) of a particle cannot be known at the same time. Instead there is a trade-off. If you know the position very well, you cannot know the velocity very well. Precision of one precludes precision of the other.



False vacuum and true vacuum

Quantum weirdness 7: two kinds of vacuum

Empty space has a fixed amount of energy, but another quantum weirdness complicates the story. Apparently there are two kinds of vacuum: false vacuum and true vacuum. We live in the true vacuum, but in the very early Universe, sometime before 10^{-30} seconds after the Big Bang, the vacuum was different. It was false. Its lowest energy state was not really the lowest possible. Here's an analogy that might help.

Imagine a room full of plastic balls. The balls jostle around a bit like the quantum fluctuations we've been discussing. Suppose the floor drops out from under the roomful of balls and everything crashes down into the basement. The energy of the fall makes the balls zoom around every which way. But soon the balls settle down into a minimum jostling state. The jostling on the first floor corresponded to the zero-point energy around a tremendously high potential energy of the false vacuum. The jostling in the basement corresponds to the zero-point energy around the much lower potential energy of the true vacuum. During the fall a tremendous amount of energy became available to the balls.

The enormous potential energy of the false vacuum has become real. The structure of the vacuum has changed, and the ground-level energy has diminished.

One of the most important ideas in modern cosmology is inflation. Inflation is a short period of tremendous expansion early in the evolution of the Universe. It occurs a fraction of a trillionth of a second after the Big Bang and lasts for only a fraction of a trillionth of a second. This short period of expansion is caused by the transition from the false vacuum to the true vacuum.

During inflation the false vacuum decays to a lower state, thereby dumping all the energy (the difference between the old zero-point energy and the new zero-point energy) into the Universe. This energy-dump heats up the Universe, fills it with particles and stops inflation. So the source of all the energy and matter in the Universe is the energy of the false vacuum – the higher ground state energy of the early Universe.

Hopefully the zero-point energy we have today is as low as it can get. If not, the floor will fall out from under us and a new inflationary epoch will heat the Universe and destroy us all.

Now with our new quantum concepts we can describe the Universe in a new way:

1 In the beginning the Universe may be described by a cloud of probable universes existing in a stable, timeless state.

2 Without cause, like a quantum fluctuation, the Universe tunnels into existence.

3 The Universe is a froth of spacetime foam in which time and space were indistinguishable.

4 The floor drops out of the false vacuum as it becomes the true vacuum. This causes a rapid expansion known as inflation. All the potential energy of the false vacuum is dumped into the Universe in the form of matter and antimatter. This stops inflation. After mutual annihilation there is a small excess of matter.

5 The matter is not uniformly distributed over the Universe. Rather, the imprints of quantum fluctuations in the early Universe remain and act as the initial seeds that can be seen in the COBE map (see page 46). Under the influence of gravity over the next few billion years, these seeds become all the rich structure of galaxies, galaxy clusters, filaments, walls and voids that we see around us today.

We represent the inflating Universe (during the first trillionth of a second after the Big Bang) as a ball rolling down a hill. The energy of the false vacuum is the hill. As the Universe rolls down, it inflates and picks up energy that gets converted into the matter and energy in the Universe today. At this early time, galaxies have not had time to form so the pretty images on the ball should not be taken too literally.

The beginning of time

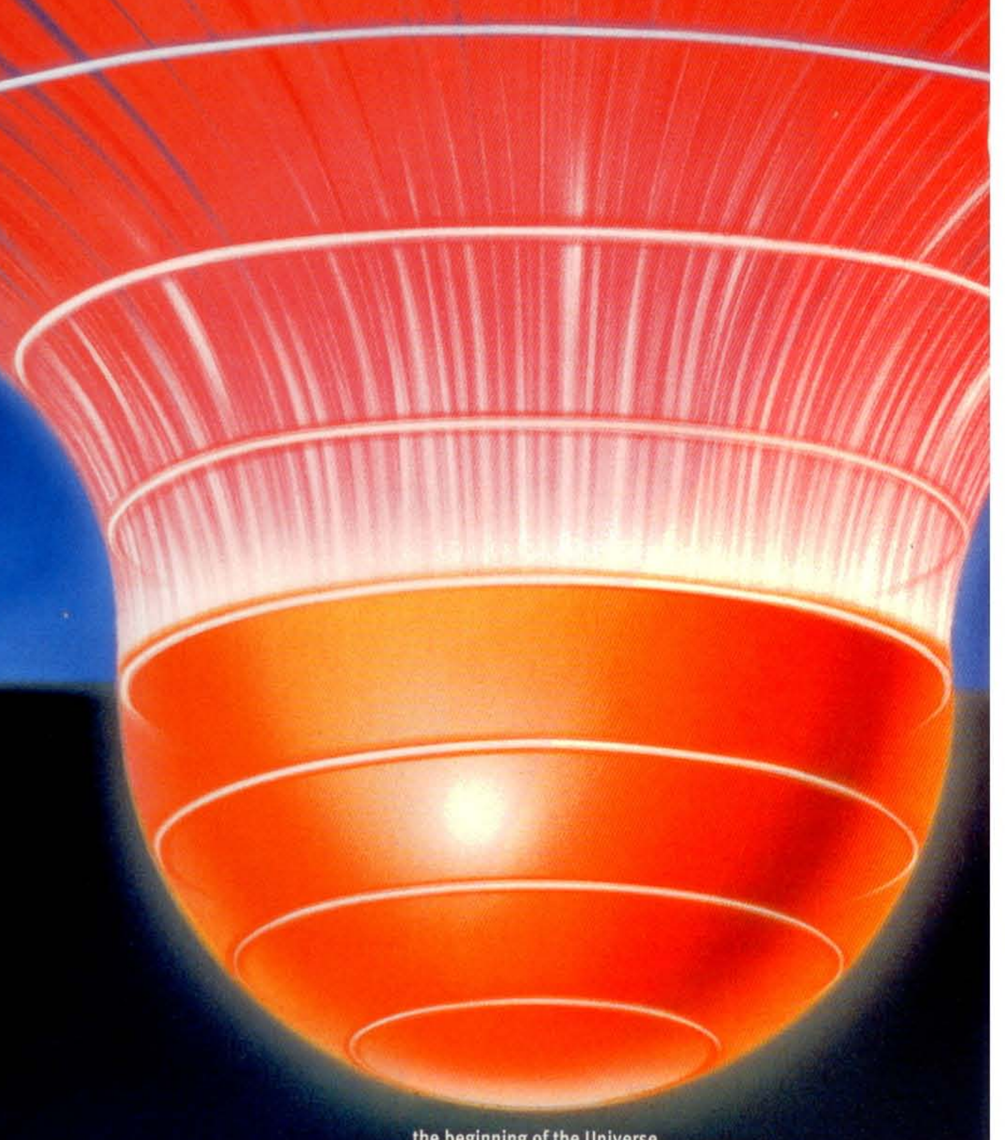
In quantum theory, sometimes the more precise one tries to be, the more confused one becomes. The things we are trying to measure (exact positions and trajectories) do not exist in the way we have conceived them. A beginning of time may be one of those misconceptions.

In 1983, Stephen Hawking and James Hartle proposed a new solution to the problem of the creation of the Universe. Their proposal uses a 'no-boundary condition' in which time does not have an abrupt edge. The beginning of time is rounded off like the end of a shuttlecock, as shown below.

Imagine you're an explorer travelling to the South Pole. You head south, always south. When you get to the pole, you find you can't get any further south. There is no edge or boundary preventing you from going further south. It's just that further south does not exist. If you go further south you start heading north. The direction south becomes meaningless at the South Pole.

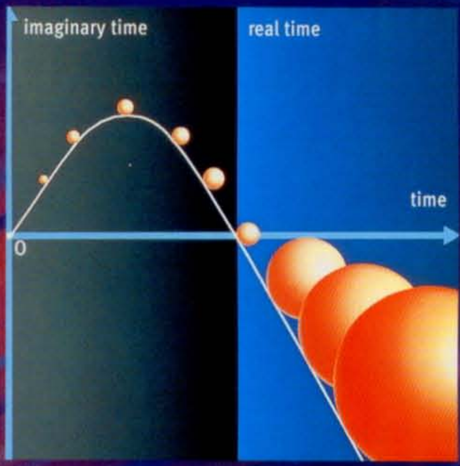
In Hawking and Hartle's model, if you could time-travel back to the Big Bang you would see no boundary on the rounded orange surface. But every direction you travelled would be into the future. Near the Big Bang the past does not exist because the nature of time changes.

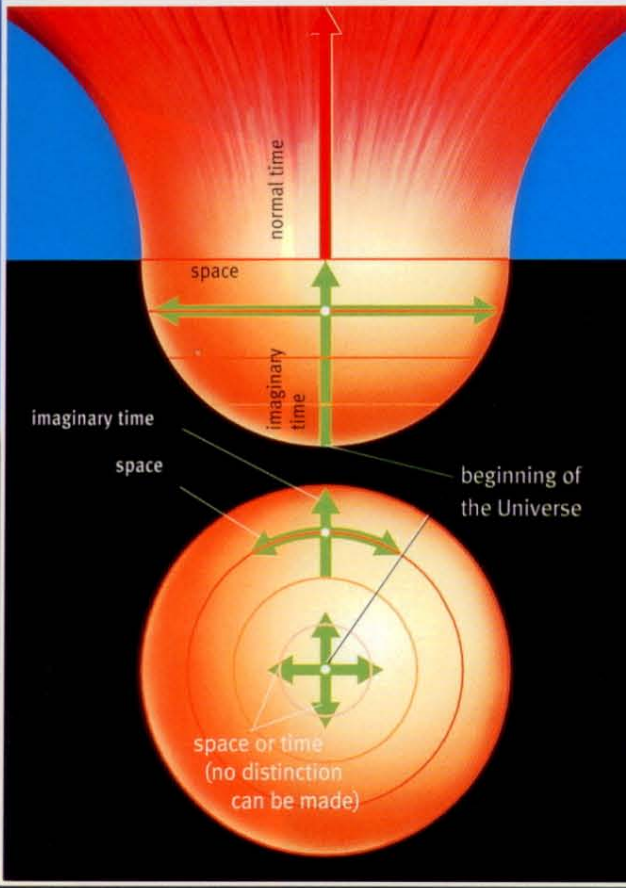
Not only is there no time before the Big Bang, in the Hawking–Hartle model there is no precise, one-dimensional time at the Big Bang. That's because it was at this point that time began. The beginning of time may be 'rounded off', like the South Pole. And because of this rounding off, you can't get south of the South Pole or earlier than the Big Bang. Hawking's interpretation of this rounding off is: "Instead of talking about the Universe being created ... one should just say: the Universe is."



In Hawking and Hartle's model, the usual distinction between time and space does not exist. In the very earliest Universe, time resembles another spatial dimension with no boundary or edge. In the illustration, this corresponds to the rounded off end of the 'shuttlecock'. Only later does time adopt the conventional characteristics which make it distinct from space. The pink feathers of the shuttlecock correspond to the inflationary epoch in which the Universe rapidly expanded.

Tunnelling is another way to conceive of the transition of the Universe from a state where time and space are indistinguishable to a state in which they are separate. The time axis is imaginary at first (black) and then becomes real (blue). At O, the Universe is in a stationary state. It is not waiting (time is not passing because there is no time), it just is, trapped by a potential hill. Then, for no reason, with no cause, and in no time at all, it tunnels through the barrier. On the other side, time is real (normal) rather than imaginary. Shortly thereafter inflation occurs as the Universe expands tremendously.





In the beginning time and space are indistinguishable

In Einstein's special relativity, time and space are distinct. When spacetime distances are computed, space and time contribute in different ways. In Hawking and Hartle's proposal, the Big Bang has the nice property of being 'rounded off' because space and time are indistinguishable dimensions and contribute in the same way to spacetime distances. Mathematically and physically time becomes another dimension of space. The three-dimensional space and one-dimensional time we are all accustomed to becomes a four-dimensional space with no boundary in time. There is no first moment worth speaking about. It's as if the spacetime of special relativity has become spacespace and the beginning of the Universe has become a place with no time.

Welcome to the multiverse

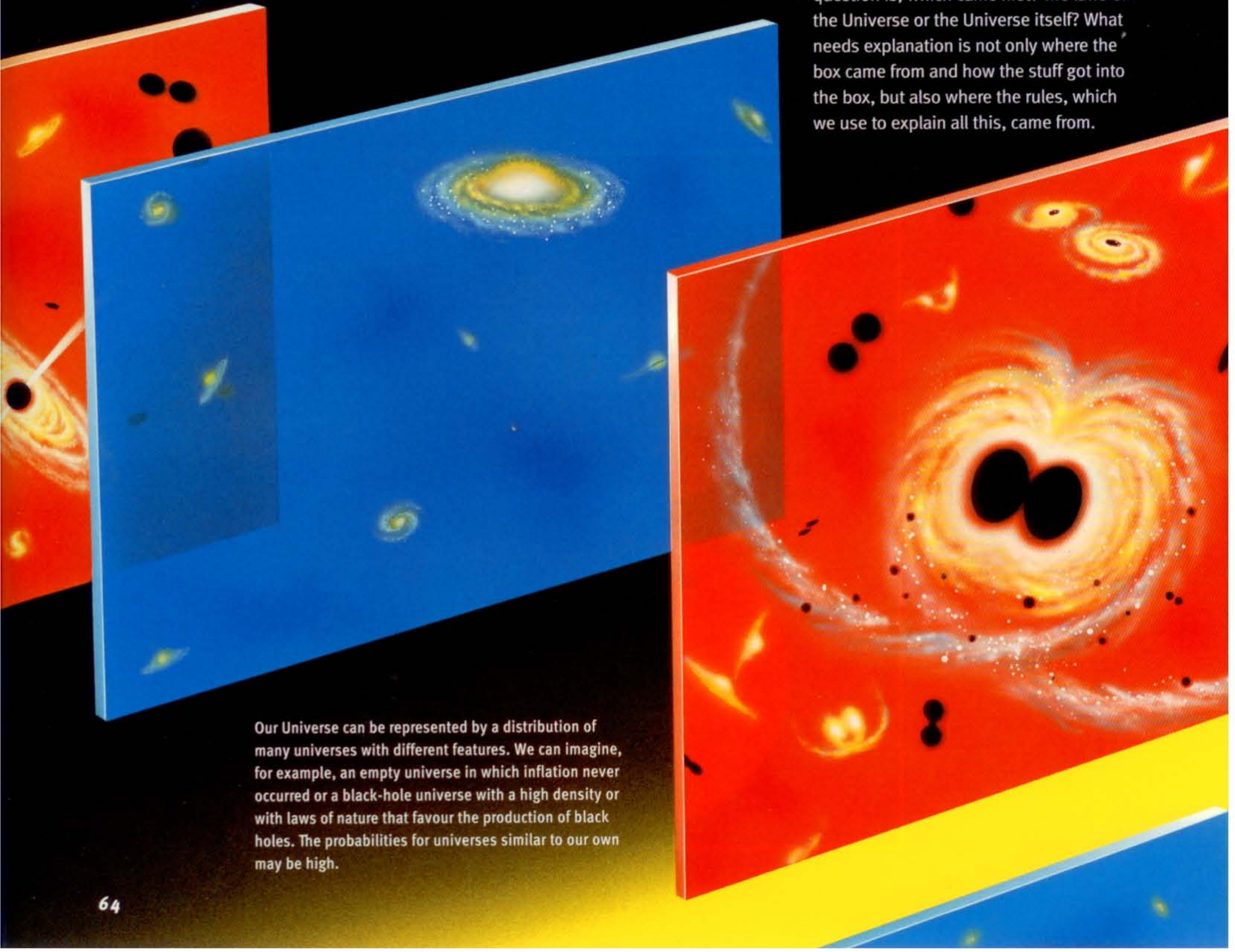
Are there other universes?

In quantum theory, the cloud of probability describing the electron is defined at all possible positions in space. But in quantum cosmology, the cloud of probability describing the Universe needs to be defined at all positions in the abstract space of all possible universes. Hawking and Hartle define 'all possible universes' as all universes that have the beginning of time rounded off (see page 62). That's one possibility.

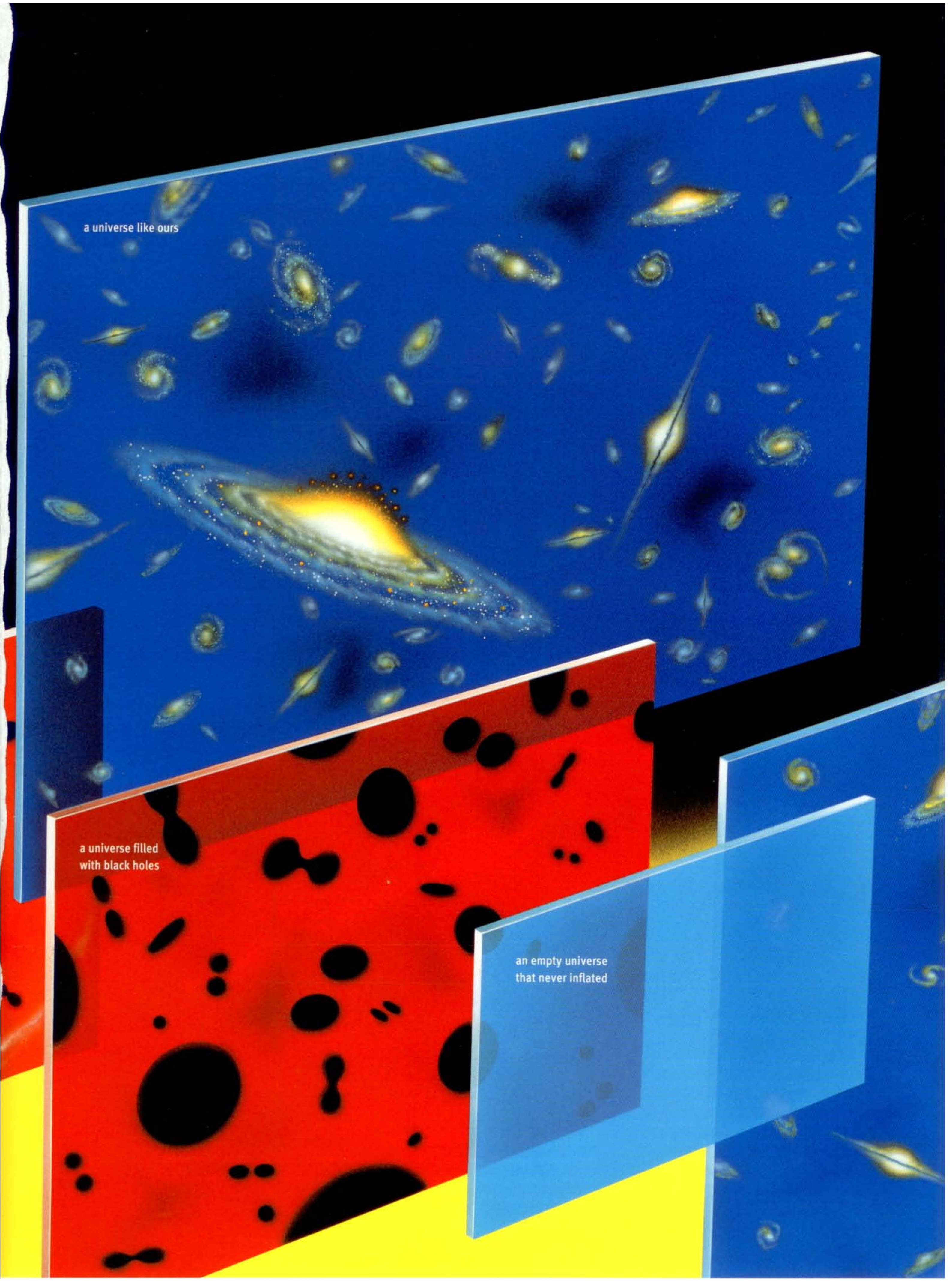
Another is that a multiplicity of universes can be found in the chaotic inflation models of Russian physicist André Linde. In his models, our entire Universe is one small blob-like protrusion from a network of similar universes. This infinite network of universes is called the multiverse. In the multiverse, 'before the Big Bang' does have a meaning; it refers to the existence of the multiverse before the Big Bang when our particular Universe protruded from it. The multiverse from which it came may or may not have had a beginning.

The Holy Grail of physics is to combine quantum ideas with gravity: to create the so-called 'Theory of Everything'. Superstring models may be the best candidates for such a theory. According to superstring models, our four-dimensional spacetime is part of the real but much larger universe which has 10, 11 or more dimensions. Our familiar three dimensions are special – they have unrolled into an existence we can perceive, while the other hidden dimensions are curled up. But long ago, closer to the Big Bang, all dimensions, including ours, were curled up.

Most quantum cosmologists deal with the creation of the Universe within a pre-existing framework of laws. But the big question is, which came first? The laws of the Universe or the Universe itself? What needs explanation is not only where the box came from and how the stuff got into the box, but also where the rules, which we use to explain all this, came from.



Our Universe can be represented by a distribution of many universes with different features. We can imagine, for example, an empty universe in which inflation never occurred or a black-hole universe with a high density or with laws of nature that favour the production of black holes. The probabilities for universes similar to our own may be high.


a universe like ours
a universe filled
with black holes
an empty universe
that never inflated

PART THREE: Behind the theory

Extraordinary evidence

Without a theory that can describe the large (the world of galaxies) and the small (the world of electrons), without a theory that ties it all together, without a Theory of Everything – we are making only informed guesses about the origin of the Universe. We are aiming as best we can. However, if the current candidates for a Theory of Everything are any indication, the solution will be at least as wild as those discussed here.

Ideas like changing time into space, or of clouds of probability hovering over all possible universes, may sound far-fetched. They are extraordinary concepts that require extraordinary evidence to back them up. What evidence is there and what instruments were used to obtain it?

Our picture of the Universe needs to be consistent with our increasingly large set of detailed observations. An arsenal of instruments is probing deeper and deeper into the Universe, giving us a more detailed look at the Universe. Pictured on these pages are some of these devices.

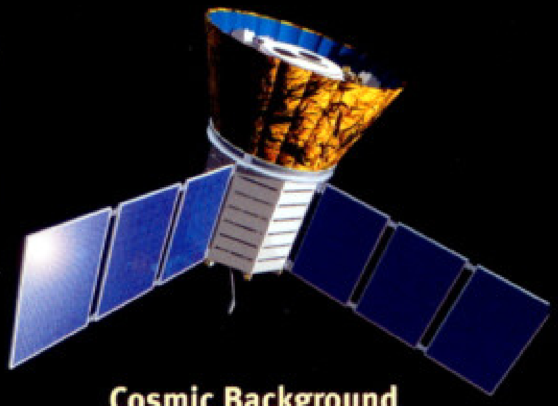
One of the most important discoveries in observational cosmology in the past 10 years was the measurement of variations in the cosmic microwave background radiation. This 'fossil' radiation is the most direct evidence we have for the existence of a hot Big Bang. It shows us what the Universe looked like 13 billion years ago.

In 1992, tiny fluctuations were discovered in this background radiation by special sensors on the COBE (Cosmic Background Explorer) satellite. Detailed measurements of these fluctuations support the inflationary version of the Big-Bang model. The tiny fluctuations (hot and cold spots on the COBE map) are also of the right size to provide the seeds that grow, by gravitational collapse, into galaxies and the other large-scale structures we see around us.

Several dozen ground-based instruments and two satellites are following in COBE's footsteps. This decade they will be able to measure many of the most fundamental parameters of cosmology and give more precise answers to such questions as: how old is the Universe? What is it made of? How did it begin?

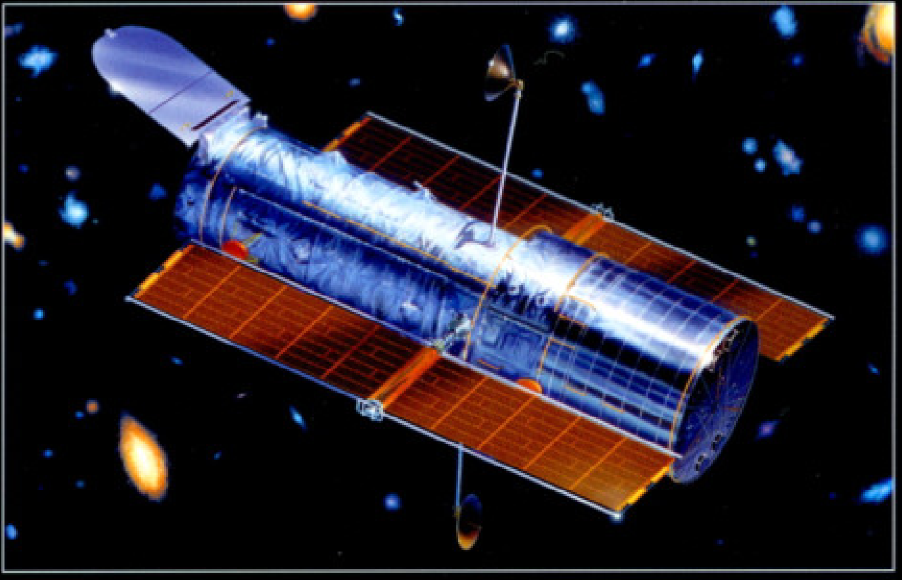
The Hubble Space Telescope continues to unravel mysteries. Its high resolution reveals details of nearby stellar objects and it has peered further into the past than any other optical instrument. The formation of galaxies is still poorly understood. Data from Hubble is allowing us to piece together the origin and growth of galaxies, and how galaxies formed from the density fluctuations discovered by COBE.

The COBE satellite has allowed us to look back further than ever before. Hubble has allowed us to see with unprecedented precision. Now three X-ray satellites are being launched that will search for black holes. The entire electromagnetic spectrum – from radio to light to gamma rays – is being explored for clues to answer the question: where did it all come from?



Cosmic Background Explorer

In 1992, the NASA satellite, COBE, was used to measure variations in the cosmic microwave background radiation. The resultant full-sky map (see page 46) reveals red and blue spots that are only 100 millionths of a degree hotter and colder than the average temperature of the background.



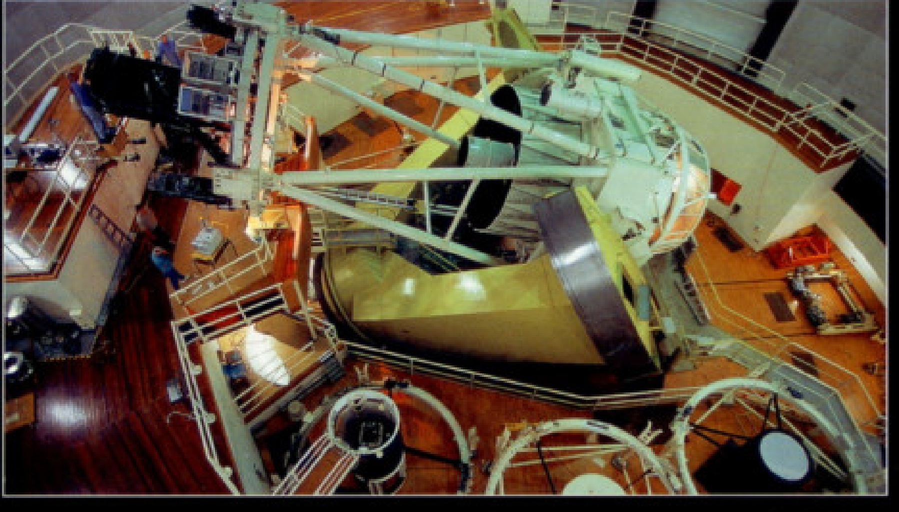
Hubble Space Telescope

The Hubble Space Telescope is an optical observatory in orbit around the Earth. One of its main goals is to measure the expansion rate of the Universe by taking detailed pictures of distant stars.

CSIRO ATNF

Australia Telescope

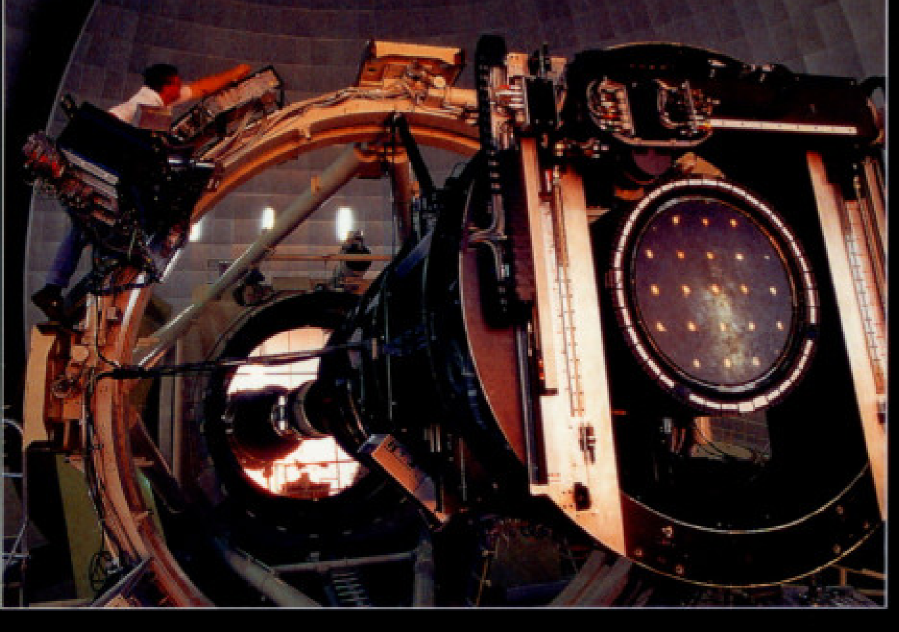
Australia is a world leader in radioastronomy. Pictured left is part of Australia's most advanced radiotelescope array, the Australia Telescope, located near Narrabri in New South Wales. Radiotelescopes pick up radio waves (instead of light) being emitted by distant objects. Many objects, like pulsars, do not radiate light but do emit radio waves. Other objects that do radiate light cannot be seen by optical telescopes because they are obscured by interstellar dust. For example, the Australia Telescope has provided exciting new views of the centre of our Galaxy, the Milky Way.



GRAHAME McCONNELL

Anglo-Australian Telescope

The Anglo-Australian Telescope, on Siding Spring Mountain near Coonabarabran, New South Wales, is the largest optical telescope in Australia with a diameter of 4 metres. Instruments attached to the telescope can measure temperature, chemical composition, velocity and distance of stars and galaxies – keys to understanding how they formed.



GRAHAME McCONNELL

2-degree field instrument

To improve the ability of the Anglo-Australian Telescope to measure the Universe, scientists have incorporated into it an ingenious device called the 2-degree field instrument (2DF, left). The 2DF sits on the end of the Anglo-Australian Telescope and can analyse light from 400 astronomical objects simultaneously (where previously light from only one star or galaxy at a time could be analysed). The map on page 46, which reveals the honeycomb structure of galaxies, was made with this instrument. This photo shows the 2DF (the black disc with white spots) sitting above the primary mirror of the Anglo-Australian Telescope. It's called the 2-degree field instrument because it collects information from a 2-degree segment of the night sky.

1900 Quantum hypothesis
Max Planck hypothesised that energy comes in indivisible packets called quanta.

1905 Hypothesis of light quantum
Albert Einstein explained that although light has many wave-like properties, its energy is quantised and it comes in particles called photons.

1911 Model of atom
Niels Bohr describes how electrons orbit in atoms.

1911 Radioactivity
Marie Curie wins Nobel Prize for discovery of polonium and radium, and for showing that atoms can decompose through radioactive decay.

1916 General relativity
Albert Einstein publishes his theory about the nature of gravity.

1919 Discovery of the proton
Ernest Rutherford discovered that an atom is made up of a nucleus that contains the vast bulk of its mass, with tiny electrons moving around it.

1922 Expansion cosmology
Alexander Friedmann, applying Einstein's equations of general relativity, shows that the Universe could either expand or contract.

1923 Matter waves
Louis de Broglie showed that some of the behaviour of electrons and other particles can be better understood by regarding them as waves.

1926 Wave equation of particles
Erwin Schroedinger works out an equation describing a particle's behaviour based on its wave function.

1927 Uncertainty principle
Werner Heisenberg shows that a particle's exact position and velocity cannot be described at the same time.

1928 Prediction of antiparticles
Paul Dirac, while working on the wave function of particles, demonstrates that electrons and other particles have antiparticles of the opposite sign.

1929 Quantum field theory
Werner Heisenberg and Wolfgang Pauli develop Quantum Field Theory, allowing light and electrons to be treated in the same mathematical framework.

1929 Discovery of the expansion of the Universe
Edwin Hubble's observations of distant galaxies indicate that the Universe is expanding, much like Friedmann's 1922 prediction.

1932 Discovery of the neutron
James Chadwick demonstrates that the nucleus of an atom contains neutrons as well as protons.

Milestones of the revolution

In the 20th century, major astronomical discoveries along with the new theories of relativity and quantum mechanics revolutionised our views of the Universe. This timeline illustrates the remarkable progress we have made towards understanding the Universe and its creation and some of the major players.

We have discovered what atoms are and what they are made of. The size of the known Universe has increased by a factor of 100,000 – from the stars around us to the furthest galaxies. Before 1925, we didn't even know what a galaxy was. The importance of each discovery seems to be proportional to how much it turns common sense on its head. As we try to make sense of the Universe from its smallest scale to the very largest, from the electron to the multiverse, our conceptual world has become rich and weird.

This article is based on the firm foundations of physics laid out over the past century, on the most recent observations of the Universe but also on the most speculative ideas of quantum cosmology at the frontiers of current research. This scientific version of genesis is an unfinished story that becomes more complete with each new observation. However, we don't know how or even if it will end.

1948 Big-Bang theory
George Gamow uses a Big-Bang model in which the Universe begins in a hot and dense state, to calculate the relative abundance of different elements produced as the Universe cooled down.

1948 Renormalisation theory
Richard Feynmann, Shinichiro Tomonaga and Julian Schwinger present new ways of defining quantum field theory, making it a useful, practical tool.

1957 Many worlds interpretation
Hugh Everett introduces the idea that all states of the wave function exist simultaneously.

1964 Quark model
Murray Gell-Mann proposes that protons and neutrons are made of smaller particles he calls quarks.

1965 Discovery of the cosmic background radiation
Robert Wilson and Arno Penzias discover microwave radiation coming from all directions in space.

1967 Electroweak unified theory
Steven Weinberg and Abdus Salam unify electricity, magnetism and the force responsible for radioactive decay.

1970 Singularity theorem
Roger Penrose and Stephen Hawking prove that, if we ignore quantum effects, the Universe must have started from an infinitely hot and infinitely dense point called a singularity.

1981 Inflationary scenario
Allan Guth, André Linde and Katsuhiko Sato propose a model in which the Universe goes through a period of rapid expansion during which it becomes filled with matter.

1982 Creation of the Universe from nothing
Alexander Vilenkin proposes that the Universe quantum-tunnelled into existence from nothing.

1983 Imaginary time cosmology
Stephen Hawking and James Hartle introduce imaginary time, which removes the otherwise abrupt nature of the beginning of time.

1986 Discovery of large-scale structure of the Universe
Margaret Geller and collaborators find that some regions in the Universe are dense with galaxies, while other regions are relatively empty.

1990 Launch of Hubble Space Telescope
Wendy Freedman and collaborators used the Hubble Space Telescope to determine the expansion rate of the Universe.

1992 Discovery of fluctuations in the cosmic microwave background radiation
George Smoot and the COBE team (see overleaf).

The Big Bang and me

In 1990, I was in my second year of graduate school at the University of California at Berkeley. My new thesis adviser, George Smoot, was turning out to be not only one of the best scientists I had ever met, but also a slave-driving workaholic.

One senior graduate student kept a hammer prominently displayed on his desk to keep George from pestering him too much. A few years earlier, a graduate student in mathematics at Stanford University had attacked his thesis adviser with a hammer. This had made a lasting, and exploitable, impression on George.

At the office, George worked from 9am to 6pm and then, after dinner, he worked at home. He also came to work on Saturdays and Sundays. After months of being told five times a day to do five different things, I developed the following George Smoot survival kit:

1 Don't do what he tells you unless he says it three times on three different days

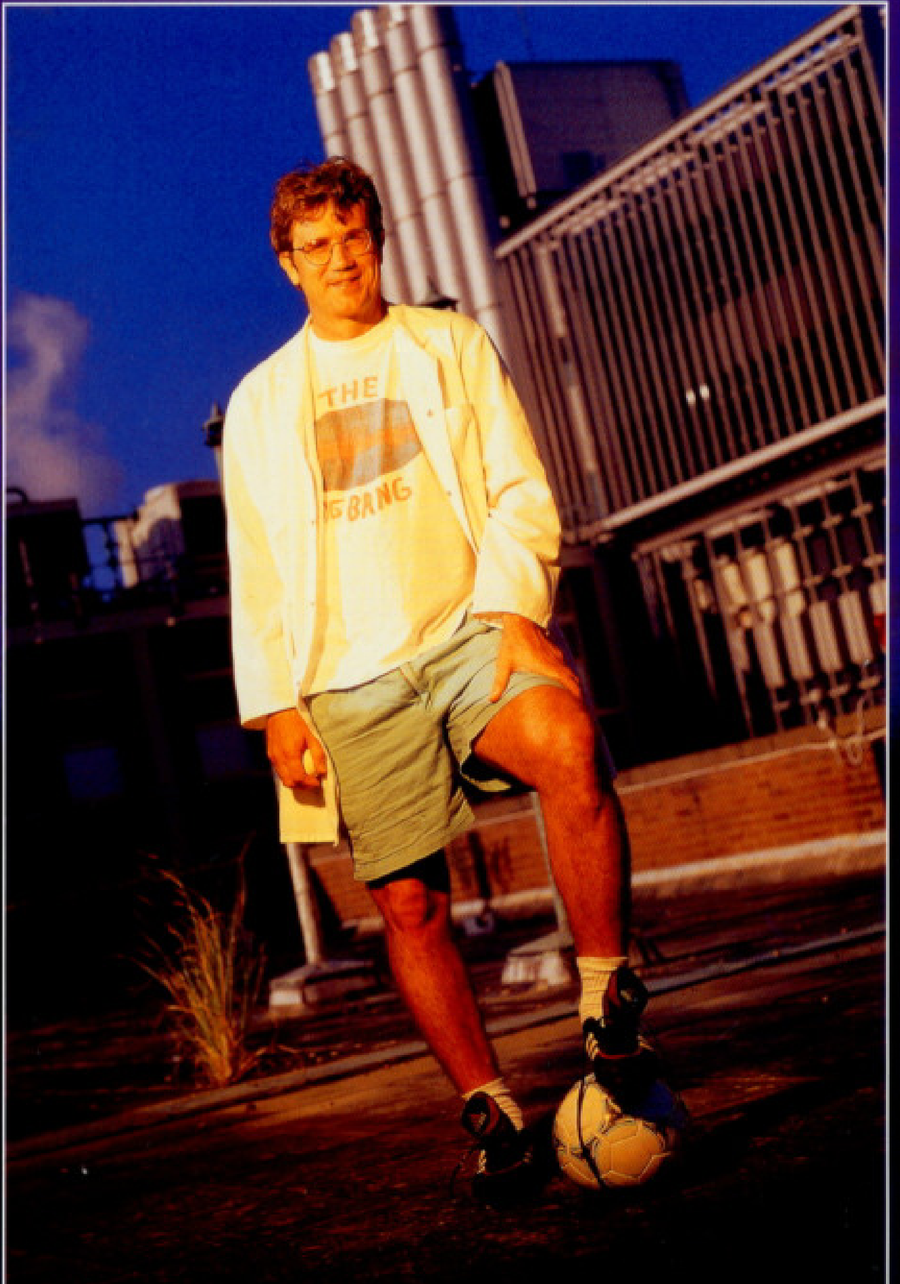
2 Work from noon till 2am to minimise contact with him

3 If he insults you and your work, insult him back (George could dish it out, but he could also take it)

As George's new, and only, graduate student, my job was to help analyse data from one of the instruments aboard the COBE satellite (data that was just about to lead to "the biggest discovery of the century, if not of all time" according to no less a judge than British physicist Stephen Hawking).

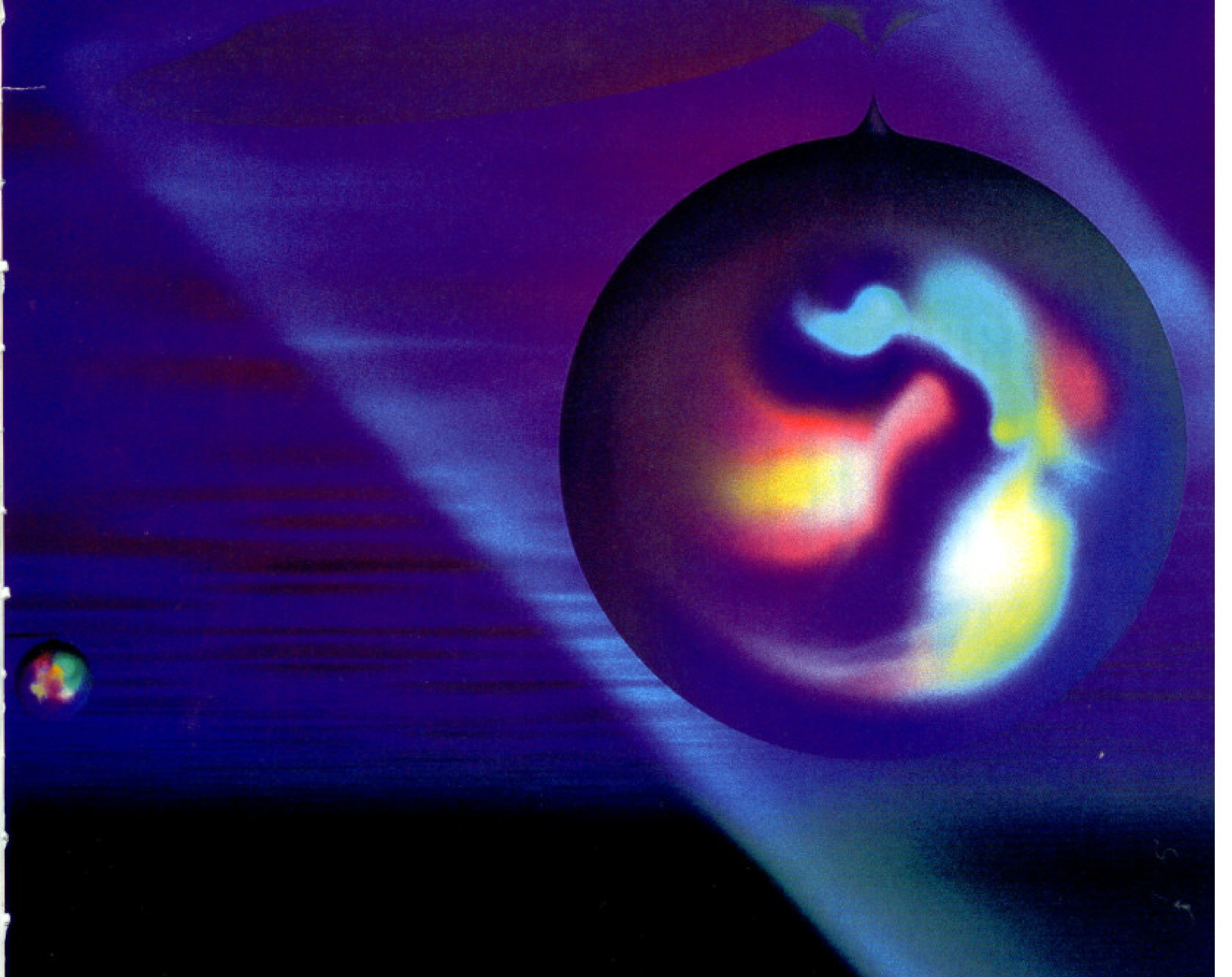
The discovery was not one of those cartoon moments where a light bulb pops on above one's head. Fifteen years earlier, the experiment had been planned, accepted by NASA, then designed. It had been built and was ready for launch in 1986 ... but then the *Challenger* shuttle blew up.

The instruments were redesigned for a Delta rocket, and finally the COBE satellite was launched successfully in 1989. Soon, real data started coming in, and that's when I was recruited. For two years, with the dozen other members of the team, I hunched, pondered and debugged the



Dr Charles Lineweaver is an Australian Research Fellow at the University of New South Wales, in Sydney. He studied physics at Ludwig Maximillian University in Munich, Germany, and at Kyoto University, Japan. He received his PhD in physics from the University of California at Berkeley, and centred his studies on the cosmic microwave background. After a postdoctoral fellowship at Strasbourg, France, he came to University of New South Wales in 1997. Lineweaver also has a degree in history and a master's degree in English. He has travelled widely, speaks four languages and has played semi-professional soccer.

FRANK LINDNER



umpteen computer programs we used to turn the raw data into something understandable.

As we began slowly and systematically to sift the data, we started to see the signal we were looking for. But one of our biggest concerns was whether the signal was being contaminated by stray emissions from our galaxy. Late one afternoon, the team working at Goddard Space Flight Center near Washington DC sent me their best efforts at determining the level at which the galaxy might contaminate the data. That afternoon and well into the night, I analysed, compared and cross-correlated the galaxy maps with the COBE maps. Finally, it became obvious. The galaxy was not causing the signal we were seeing. I printed out the most important plot, scribbled "Eureka?" on it, slid it under George's door and, at 4am, bicycled home to my sleeping wife and one-year-old daughter.

A few weeks later, after many more checks, George announced to the world the discovery of the hot and cold spots in the microwave background. The science journalists of the world descended on all of us. George told this Eureka story to a reporter from *The Wall Street Journal*. The next day, one could read how a young scientist, burning the midnight oil, had contributed to one of the greatest discoveries of all time.