DK

NEW EDITION

BIG

HISTORY

THE GREATEST EVENTS OF ALL TIME
FROM THE BIG BANG TO BINARY CODE

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FOREWORD

I vividly remember a globe map of the world sitting in a classroom when I was a child. I also remember a geography class, taught in a school in Somerset in England, where we learnt how to draw sections through the earth, showing the various layers of soil beneath our feet, and how they connected to other parts of Britain. For me, the most exciting thing in school was always the sudden connections, realizing that layers of chalk beneath our feet were made from the remains of billions of tiny organisms – called coccolithophores – that had lived millions of years ago, and that the same remains could also be found in layers of chalk in other parts of Britain and in other countries much further away. What was Somerset like when the coccolithophores were alive? For that matter, where was Somerset back then? That's a question I couldn't even ask when I was at school because at that time scientists didn't know for sure that the continents moved around the surface of the earth.

For me, the globe in the corner of my classroom was a key to all this knowledge. It helped me see the place of Somerset in Britain, of Britain in Europe – so *that's* where the Vikings came from! – and of Europe in the world. Big History is like the globe, but it's much bigger: it includes all the observable universe and all observable time, so it reaches back in time for 13.8 billion years to the astonishing moment of the Big Bang, when an entire Universe was smaller than an atom. Big History includes the story of stars and galaxies, of new elements from carbon – the magical molecule that made life possible – to uranium, whose radioactivity enabled us not just to make bombs, but also to figure out when our earth was formed. It is like a map of all of space and time. And once you start exploring that map, you will be able, eventually, to say: "So that's what I'm a tiny part of! That's my place in the grand scheme of things! So what's next?"

Today, more and more schools and universities are teaching Big History, and it's a story we all need to know. In the book you are holding in your hands, you will find a beautifully illustrated account of this story, a sort of globe in words and pictures that links knowledge from many different disciplines. *Big History* shows how our world developed, threshold by threshold, from a very simple early Universe, to the emergence of stars and new chemical elements, and on to a cosmos that contained chemically rich places like our earth on which life itself could emerge.

And you'll also see the strange role played by our own species, humans, in this huge story. We appear at the very end of the story, but our impact has been so colossal that we are beginning to change the planet. We have done something else that is perhaps even more astonishing: from our tiny vantage point in the vast Universe, we have figured out how that universe was created, how it evolved, and how it became as it is today. That is an amazing achievement, and in this book you will explore the discoveries that allowed us to piece together this story. This is the world globe that we need today, early in the 21st century, as we try to manage the huge challenges of maintaining our beautiful planet and keeping it in good condition for those who will come after us.

DAVID CHRISTIAN
PROFESSOR EMERITUS, MACQUARIE UNIVERSITY
A FOUNDER OF BIG HISTORY
FORMER DIRECTOR, BIG HISTORY INSTITUTE
CO-FOUNDER OF THE BIG HISTORY PROJECT

“Big History provides a framework for understanding literally all of history, ever, from the Big Bang to the present day. So often subjects in science and history are taught one at a time – physics in one class, the rise of civilization in another – but Big History breaks down those barriers. Today, whenever I learn something new about biology or history or just about any other subject, I try to fit it into the framework I got from Big History. No other course has had as big an impact on how I think about the world.”

BILL GATES, WWW.GATESNOTES.COM
CO-FOUNDER OF THE BIG HISTORY PROJECT

WHAT IS **BIG HISTORY?**

BIG HISTORY IS THE STORY OF HOW YOU AND I CAME TO BE.

It is a modern origin story for a modern age. This grand evolutionary epic rouses our curiosity, confronts our ingrained intuitions, and marries science, reason and empiricism with vivid and dynamic storytelling. Best of all, Big History provides the scope and scientific foundations to help us ponder some of the most exciting and enduring questions about life, the Universe, and everything.

These universally compelling questions include: How did life on Earth evolve? What makes humans unique? Are we alone in the Universe? Why do we look and think and behave the way we do? And what does the future hold for our species, our planet and the cosmos? Throw a dart at any point in the history of the Universe and it will land on a page of the Big History story. No matter how obscure this page, or how far removed it may seem from the world we know, it will invariably describe a fragment of this grand scientific narrative, in which all events and all chapters are connected.

In this volume we traverse the stars, the galaxies, the cells inside your body, and the complex interactions between all living and non-living things. We stretch our minds to the limits of human understanding in order to see reality from many angles, and on many scales. What is truly remarkable about looking at the world from such an expansive perspective is that we begin to engage with many facets of the natural world that we often miss, or take for granted.

How often do we think about the fact that every atom inside each of our

HOW OFTEN DO WE THINK ABOUT THE FACT THAT EVERY ATOM INSIDE EACH OF OUR BODIES WAS MADE INSIDE A DYING STAR?

bodies was made inside a dying star? Or that ancient celestial implosions gave rise to the kinds of chemistry that makes life possible? How frequently do we zoom out far enough in our historical musings to see connections that transcend the actions of kings, armies, politicians, and peasants?

Our minds do not instinctively follow the threads of our evolutionary history to the point where all national, tribal, and species boundaries fall away. But when we allow ourselves to explore beyond these domains we come face to face with a single family tree, which shows that every one of us shares a common ancestor with every living organism on the planet: from worms, to fish, to reptiles, to chimpanzees, to a bird singing on the other side of the world, and the strangers who sleep through its refrain.

naked eye. It is also important to remember that Big History is not a static tale that proclaims how things are and will be for all time. It is a provisional narrative that is constantly being updated as our knowledge about the natural world grows, and as our needs as a species evolve.

From a cosmic perspective, we see that humans are a novel species that appear on the scene very late in this evolutionary history. We were not there at the beginning, and we are almost certainly not the species with whom the evolutionary buck stops. Yet Big History is still very much a human story, written by humans, for humans. At a certain point in this tale we choose to focus on our species and our corner of the galaxy, because from our point of view, this is where the action and the meaning is.

In the grand scheme of space and time, humanity may seem like little more than a cosmic footnote. But when we look closely at our blue planet we see that our species is responsible for some very remarkable things, which no other species has achieved in the 3–4 billion years that life has existed on Earth. As far as we know, *Homo sapiens* is the first and only species to represent the Universe becoming self-aware. Humans are now the dominant force altering the planetary biosphere, and we have kicked the pace of terrestrial evolution into a dramatic new gear.

BIG HISTORY HELPS US TO QUESTION EVERYTHING WE SEE, AND EVERYTHING WE THINK WE KNOW.

Big History helps us question everything we see, and everything we think we know. In the process, we discover that the Universe is far stranger than we often imagine, and that the shape of history is moulded by forces that are often surprising, and hard to see with the

As you explore this remarkable narrative, you will discover that our species has been so successful in expanding and colonising the globe, in large part because of our capacity for what big historians call collective learning. Although we cannot impart our accumulated knowledge and experiences to new generations via DNA, we have developed the means to transmit this information culturally. Such a radical innovation in information sharing was made possible by the human invention of symbolic language.

At first this meant sharing ideas through the oral tradition. But eventually we developed writing, which reduced the error rate in the transmission of information and left humans in possession of a tool resembling a crude external hard drive. For the first time we could store large bodies of information without having to use the limited memory capacity of our brains.

WITH THE ABILITY TO BUILD UPON EXISTING INFORMATION OVER MANY GENERATIONS, HUMANS LEARNED EVER FASTER, AND KNOWLEDGE AND INNOVATION PROLIFERATED.

With the ability to build upon existing information over many generations, humans learned ever faster, and knowledge and innovation proliferated. While many civilizations collapsed and some discoveries were lost for centuries, the overall trend was a feedback loop of accelerating cultural change: the invention of ever faster and more accurate methods of information sharing generated rapid bursts of innovation, and vice versa.

While the oral tradition persisted for tens of thousands of years, it only took a few hundred years for humans to transition from the age of the printing press to the digital world of today. If the pace of cultural evolution continues at such a rate we may see the emergence of a new evolutionary paradigm in mere decades.

Because of our astounding capacity for collective learning and cultural development, humans have made a giant evolutionary leap in a relatively short period of time. We have transitioned from our initial role as one of evolution's many simple players, to a fledgling director engaged in the task of consciously shaping the trajectory of evolution on Earth. While this is a very exciting role, it also presents immense challenges.

It is sobering to look back at our extensive family tree and recall that 99 per cent of species that have ever lived are now extinct. In light of this, it is natural and beneficial to consider whether our species will be able to live sustainably and prosperously for many years into the future. And if we can achieve this, how might it be possible?

Will we reduce our consumption of energy and live more simply? Or will we harness our immense collective brainpower to engineer more sophisticated ways of producing clean energy and sustainable products and services? Will our modern technological arms race leave us liberated or enslaved? And how long will most of us continue to exist as fully biological beings, unenhanced by technological modifications?

These are the kinds of questions that the Big History story prompts us to consider. There is no doubt that in terms of its scope, content, and method, Big History is a truly modern story, fit for the needs of a modern age.

Like all origin stories of previous ages, this narrative is designed to help orient us with where we come from, what we are, and where we might be going. But unlike ancient origin stories that were built upon myth and intuition, this evolutionary epic relies on the theories of modern science to help us get to grips with the world around us.

For most of us, thinking about things that are very big, very small, and very old does not come naturally. But pursuing big ideas and chasing the answers to profound universal questions

BIG HISTORY IS A TRULY MODERN ORIGIN STORY, FIT FOR THE NEEDS OF A MODERN AGE.

does! We cannot help wanting to know what else is out there: whether it be among the stars, inside black holes, or in the mysterious workings of our brains, our DNA, or the remarkable bacterial ecosystems that live on, around, and inside us.

The Big History story helps to facilitate our exploration of these and other exciting domains. It allows us to focus on an array of subjects and historical moments and encourages us to ponder the nature of reality on many different scales. We learn to relate the details to the big picture, and observe how broad trends can contextualise local phenomena and events. By exploring the viewpoints of both the generalist and the specialist, we are able to think more carefully and creatively about cause and effect, and devise more innovative responses and solutions to the many challenges we face in the world today.

Big History's unified perspective also helps us to see the present in dynamic terms, and shows us that we are not only the successors of previous evolutionary thresholds, but also the possible progenitors of those to come.

Our story is divided into eight thresholds of increasing complexity, which highlight some of the key transitionary phases in this cosmic evolutionary history. As we move from threshold to threshold you will see how profoundly each stage is connected, and how matter and information in the Universe grow denser and more complex in various pockets of cosmic order. This story helps us to see that our planet and our species emerged among a rare set of goldilocks conditions, where the balance and stability of elements was "just right" to sustain life.

Once you explore this book and get a feel for the big picture it presents, we hope you will be left pondering many new and rousing questions. As you sit, poised to embark on this journey of discovery, there is one question in particular that we hope you will consider.

What role will you play in determining how events unfold in the next threshold of the this great cosmic drama?

"BENEATH THE AWESOME DIVERSITY AND COMPLEXITY OF MODERN KNOWLEDGE, THERE IS AN UNDERLYING UNITY AND COHERENCE, ENSURING THAT DIFFERENT TIMESCALES REALLY DO HAVE SOMETHING TO SAY TO EACH OTHER."

DAVID CHRISTIAN, BIG HISTORIAN

THRESHOLD

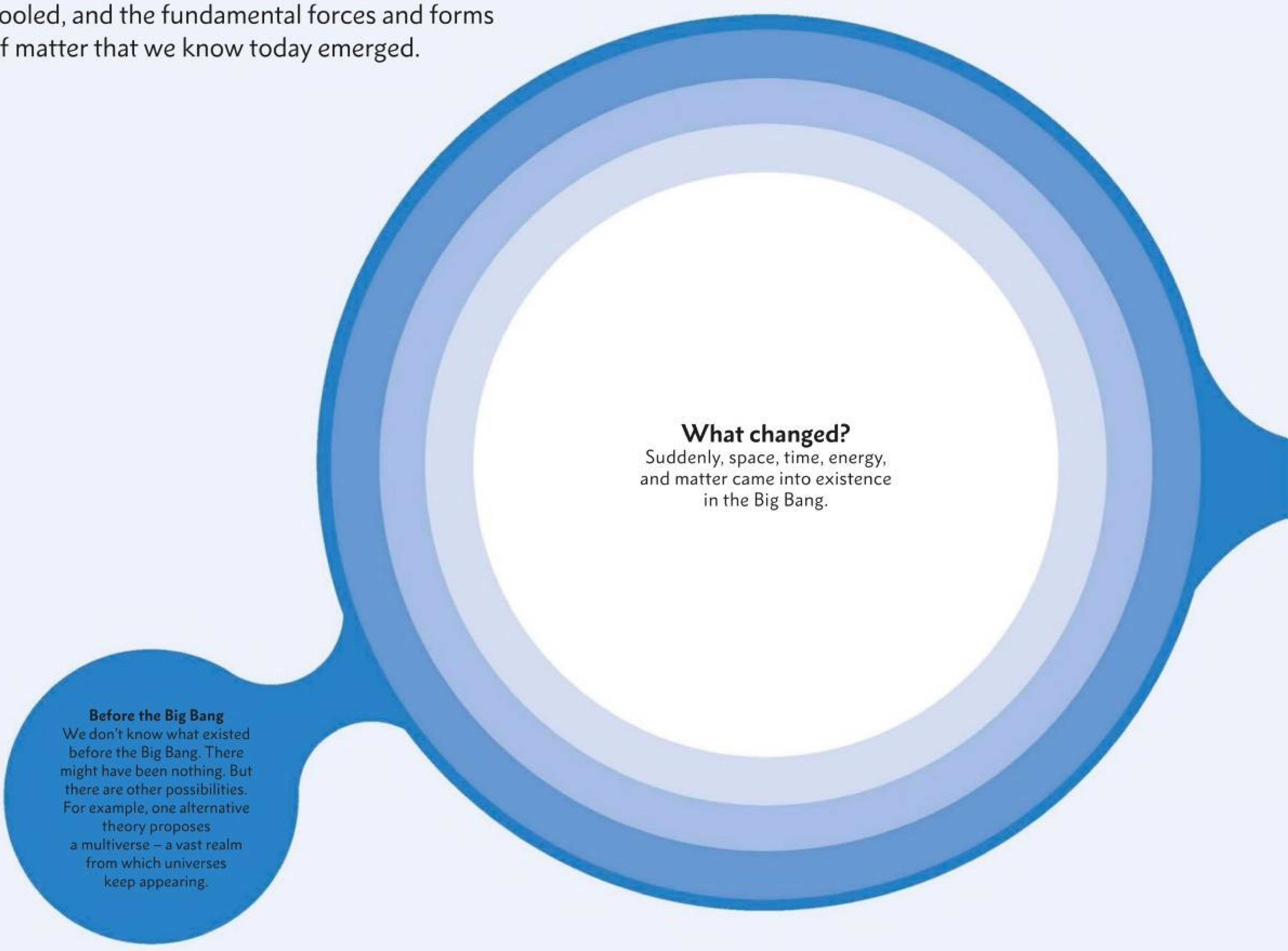
1

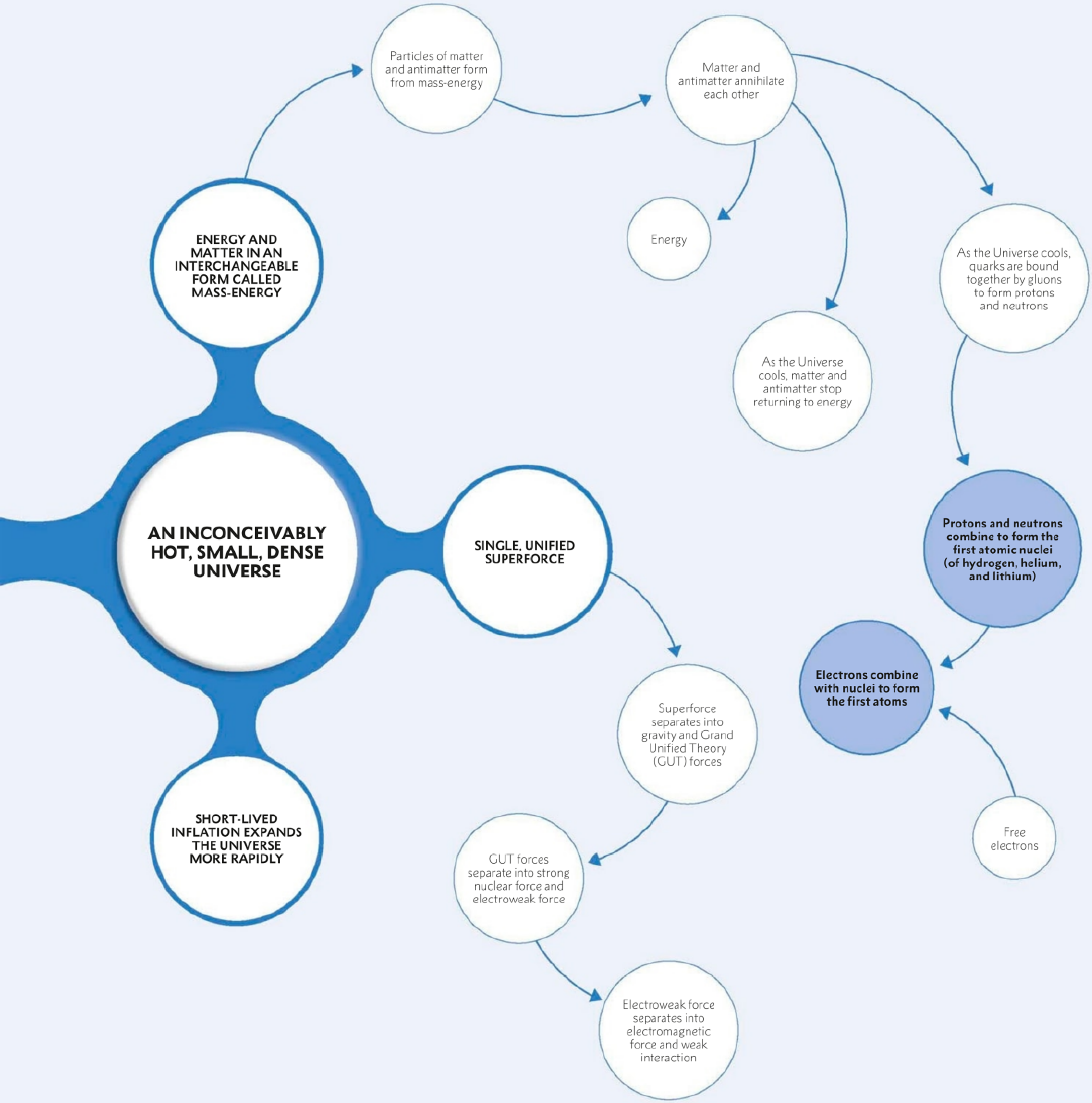
THE BIG **BANG**

What are the origins of our Universe? It is a question that has captivated humans probably since we emerged as a species and began trying to make sense of our place in nature. Centuries of observation, investigation, and scientific endeavour have led us to the Big Bang theory – but that too leaves questions unanswered, and our quest for further explanation continues.

GOLDILOCKS CONDITIONS

The Universe formed in the Big Bang. We do not know if anything existed before it, and we only have a glimpse of what happened in the fraction of a second immediately afterwards. But over the next 380,000 years, the Universe expanded and cooled, and the fundamental forces and forms of matter that we know today emerged.





AN INCONCEIVABLY HOT, SMALL, DENSE UNIVERSE
ENERGY AND MATTER IN AN INTERCHANGEABLE FORM CALLED MASS-ENERGY
Particles of matter and antimatter form from mass-energy
Matter and antimatter annihilate each other
Energy
As the Universe cools, matter and antimatter stop returning to energy
As the Universe cools, quarks are bound together by gluons to form protons and neutrons
Protons and neutrons combine to form the first atomic nuclei (of hydrogen, helium, and lithium)
Electrons combine with nuclei to form the first atoms
Free electrons
SINGLE, UNIFIED SUPERFORCE
Superforce separates into gravity and Grand Unified Theory (GUT) forces
GUT forces separate into strong nuclear force and electroweak force
Electroweak force separates into electromagnetic force and weak interaction
SHORT-LIVED INFLATION EXPANDS THE UNIVERSE MORE RAPIDLY

ORIGIN **STORIES**

Nearly all human cultures and religious traditions have nurtured origin stories – symbolic accounts that describe how the world came about. These stories or narratives were most often passed from one generation to the next in the form of folk tales or ballads and sometimes through writing or pictures.

Origin stories are extremely varied in detail, but they tend to include some common themes. Often they tell how the Universe acquired order from an original state of either darkness or deep chaos. In several versions, including the Old Testament's *Book of Genesis*, this order is imposed by a supreme being or deity. In some stories, creation is a cyclical process. For example, in Hindu thought, order is generated only to be destroyed and then regenerated. Many stories begin with Earth. In some, people and gods emerge from the Earth. In others, an animal dives into a boundless primeval ocean and retrieves a portion of Earth from which the cosmos is created.

ORIGINS OF THE SKY, SUN, AND MOON

Many origin stories describe how the sky was created along with Earth, often by splitting off from another primeval object. In a common form of the Māori creation myth, the Universe is created from nothing by a supreme being, Io. He also creates Ranginui (Rangi) and Papatuanuku (Papa), the Sky Father and Earth Mother. Rangi and Papa remain physically cleaved together until pushed apart by their six offspring to create the separate realms of Earth and sky. Many stories also account for the creation of celestial bodies such as the Sun and Moon. For example, in a story from China, the first living being, Pangu, hatches from a cosmic egg. Half the shell lies under him as the Earth; the rest arcs above him as the sky. Each day for thousands of years he grows, gradually pushing Earth and sky apart until they reach their correct places. But then Pangu disintegrates. His arms and legs become mountains, his breath the wind, his eyes turn into the Sun and Moon. Often celestial objects originate as physical representations of gods. For example, an origin story from ancient Egypt begins with Nun, the primeval ocean, from which the god Amen rises. He takes the alternative name Re and breeds more gods. While his tears become mankind, Amen-Re retires to the heavens, to reign eternally as the Sun.

Origin stories such as these developed because early humans needed to find an explanation for their own existence and for everything that they saw around them. The cultures that fostered these stories regarded them as true, and for their adherents they usually carried great importance and emotional power. But such perceptions were based on faith and not on accurate observations or scientific reasoning.

> “WE HAVE INHERITED FROM OUR FOREFATHERS THE KEEN LONGING FOR **UNIFIED, ALL-EMBRACING KNOWLEDGE**.”
>
> **Erwin Schrödinger**, Austrian theoretical physicist, 1887–1961

MORE THAN **100 DISTINCT ORIGIN STORIES** HAVE BEEN IDENTIFIED FROM VARIOUS PEOPLES AND CULTURES ACROSS THE WORLD

THE EARLIEST ASTRONOMERS

At points in history that vary according to the culture, but typically from about 4000 BCE in Europe and the Middle East, it seems that humans began to tire of merely gazing at, and devising stories about, objects such as the stars, Sun, and Moon. Instead some individuals began making detailed recordings of celestial phenomena. These investigations were carried out for a variety of mostly practical reasons. An ability to identify a few stars, and to understand sky movements, proved useful for navigation. It was also realized that the sky is a sort of clock that could be used, for example, to tell farmers when to sow crops or to give warning of important natural events. In ancient Egypt, for example, the rising of the bright star Sirius around the same time as the Sun heralded the annual flooding of the Nile. A final reason for studying the heavens was to predict solar eclipses. Chinese astronomers are thought to have attempted this as long ago as 2500 BCE, but it was not until the 1st century BCE that the ancient Greeks reached the level of astronomical sophistication needed to do it accurately. Successful eclipse prediction had little specific practical use but it did confer on the predictor very significant mystical powers and, as a result, considerable peer respect.

ASTRONOMERS IN CHINA RECORDED OBSERVATIONS OF **MORE THAN 1,600 SOLAR ECLIPSES** FROM 750 BCE ONWARDS

In some early cultures, accurate observation not only had practical uses but was also intertwined with religion. Some of the most sophisticated observations before the invention of the telescope were made by the Maya, who colonized parts of Central America between 250 and 900 CE. They made accurate calculations of the length of the solar year, compiled precise tables of the positions of Venus and the Moon, and were able to predict eclipses. They used their calendar to time the sowing and harvesting of crops. But they also saw a link between the cycles they observed and the place of their gods in the natural order. Specific events in the night sky were seen as representing particular deities. The Maya also practised a form of astrology, drawing a connection between cycles in the sky and the everyday life and concerns of the individual.

A MODERN NARRATIVE

Big History is a modern-day origin story. Part of this story is an account of how the Universe formed provided by the Big Bang theory of cosmology. The theory describes the formation of a Universe with a beginning and a structure. Modern cosmology as a whole also contains an account of a Universe that changes over time, as matter and energy take on different forms, new particles come into existence, space itself expands, and structures such as stars and galaxies emerge. The Big Bang theory, as part of the Big History narrative, shares some other features with traditional origin stories. For example, in common with several of the stories, it proposes that everything – all matter, energy, space, and time – originated from nothing. Big Bang theory and the traditional stories also set out to answer many of the same questions – including how did the Universe begin? The theory does not give a complete account of how the Universe came to be the way it is now. For example, it does not explain the origin of life or the evolution of humans. But it does form part of the larger framework of Big History that attempts to answer these and other questions.

However, in one crucial respect, Big Bang theory, like Big History in general, differs from traditional origin stories in that it seeks to provide a literal and accurate account of the Universe's origins. It represents the current state of scientific thinking, arrived at after many centuries of both gradual change and sudden leaps forward. Like other scientific theories in Big History, the theory also makes predictions that can be tested against evidence, allowing it to be refined or even disproved and overturned. Some questions remain unanswered by Big Bang theory. But, at least for now, it offers the most convincing account of when and how the Universe began.

► **Brahma the creator**
According to some older forms of Hinduism, the god Brahma, who is usually depicted with four heads, was born from a golden egg and created Earth and everything in it.

> THERE WAS NEITHER **NON-EXISTENCE NOR EXISTENCE** THEN; THERE WAS NEITHER THE REALM OF **SPACE NOR THE SKY** WHICH IS BEYOND.
>
> **The Rig Veda**, a collection of Sanskrit hymns, 2nd millenium BCE

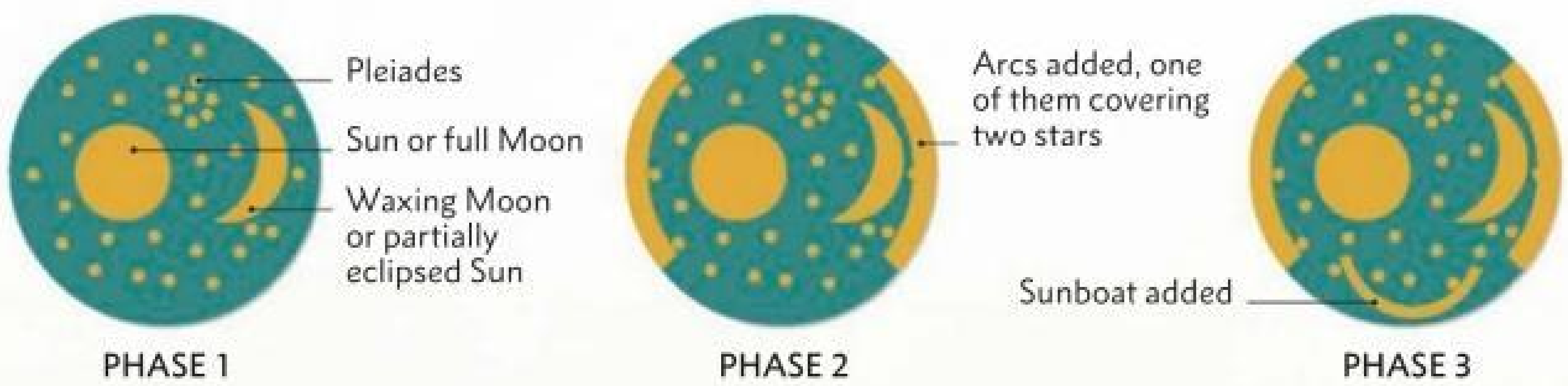
THE NEBRA **SKY DISC**

During the European Bronze Age, people developed their knowledge of astronomy and put it to practical uses. The Nebra Sky Disc is a key piece of evidence for observation of the sky at this time. Analysis of the disc's materials also reveals information about metalworking and trade.

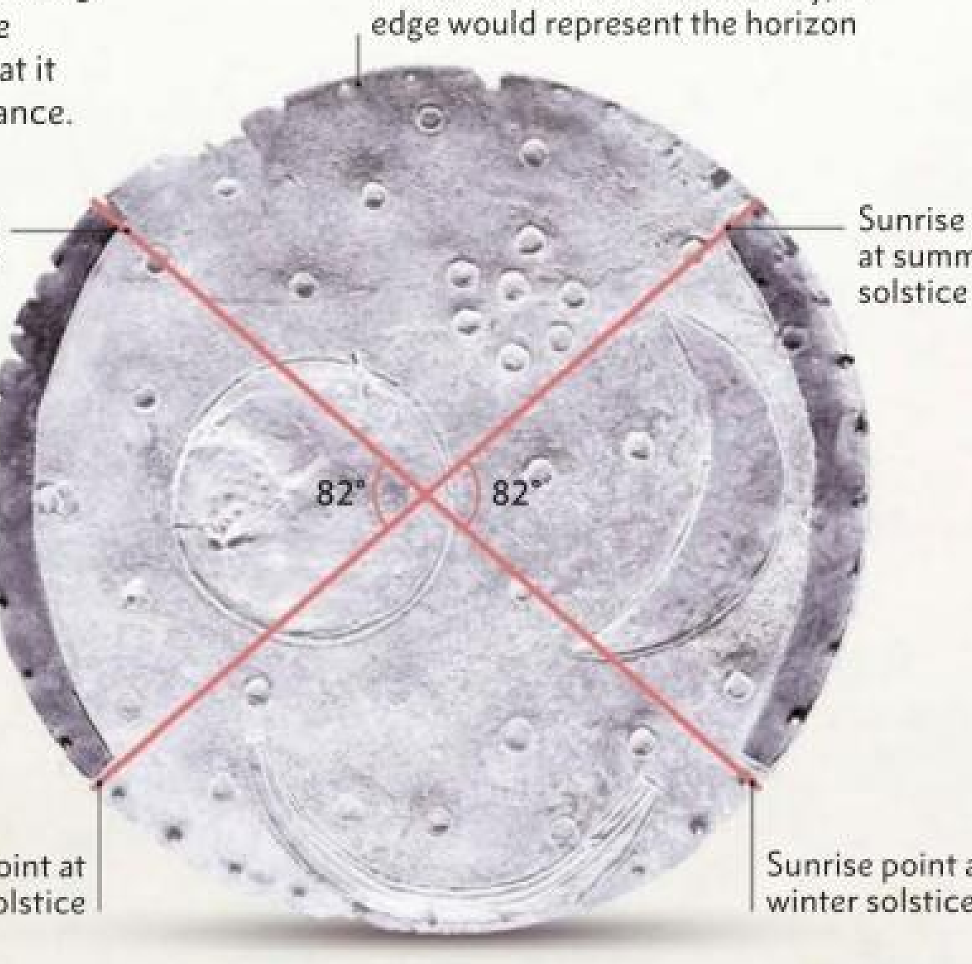
The Bronze Age in Europe began around 3200 BCE. Dug up near Nebra in central Germany in 1999, the 3,600-year-old Nebra Sky Disc depicts the Sun, Moon, and 32 stars, including possibly the Pleiades star cluster. It is the oldest known portrayal of such a variety of sky objects. The disc also reveals that its owners had measured the angle between the rising and setting points of the Sun at the summer and winter solstices – the days of greatest and least daylight each year.

There are two schools of thought as to what the disc was used for or represents. Some archaeologists think that it was an astronomical clock, which could have been used to indicate times for sowing and harvesting crops and to coordinate the solar and lunar calendars. Alternatively, the objects on the disc may illustrate a significant astronomical event – a solar eclipse on 16 April 1699 BCE. On that date, the Sun, as it was eclipsed by the Moon, was close in the sky both to the Pleiades and to a tight grouping of three planets – Mercury, Venus, and Mars.

Whatever its exact use, the Nebra Sky Disc provides clear evidence that some Bronze Age people had made detailed sky observations and also developed tools to help them mark the passage of time and the seasons.



▲ Phases in construction
The disc was made in three phases, significantly separated in time, suggesting it underwent some repurposing. The addition of the sunboat indicates that it may have taken on religious significance.



► The golden arcs
The two arcs on the disc span 82°, the angle between the points on the horizon where the Sun sets (or rises) at the summer and winter solstices for the location where the disc was found.

Metal sources

The disc's copper came from the Austrian Alps. Its tin – used with copper to make bronze – and its original gold were from Cornwall, England. The gold in the arcs and sunboat came from the Carpathian Mountains in eastern Europe. Evidently there were well-established trade routes across Europe at the time.


Gold nugget

The Pleiades

A group of stars on the disc may represent the Pleiades star cluster, of which the brightest stars could have been seen with the naked eye by Bronze Age skygazers. In central Europe, the Pleiades would have been a prominent evening feature in the southeastern sky around harvest time.

Stars and dust in the Pleiades

The Nebra hoard

The disc was buried with other objects, including two swords made of bronze with copper and gold inlays, a chisel, two axeheads, and two armbands, collectively called the Nebra hoard. It is not known why the disc was placed with these objects. The hoard was buried in around 1600 BCE, but the disc could be older. When first examined by archaeologists, it was suspected to be an elaborate fake, but corrosion tests, excavation of the burial site, and examination of the other artefacts pointed to its authenticity.

Bronze Age sword from the Nebra hoard

The sunboat

The arc of gold at the bottom of the Nebra sky disc is thought to be a sunboat – the means by which some ancient people imagined the Sun was conveyed from its setting point in the west to its rising point in the east during the night. The hairlike protrusions around the edge of the arc might represent oars. If the arc is indeed a sunboat, it would be the earliest known representation of one.

ASTRONOMY BEGINS

For most of human history, people were too busy surviving to spend much time thinking about the world's underlying nature and origins. But from around 1000 BCE, a few began to try answering key questions about the Universe without recourse to supernatural explanations.

These thinkers – initially concentrated in Mediterranean lands, especially Greece – realized that to understand the world it is necessary to know its nature, and that natural phenomena should have logical explanations. Although they did not always find the correct answers, this leap marked the start of a 3,000-year journey that has led in the modern world to such key theories as the Big Bang model of the Universe.

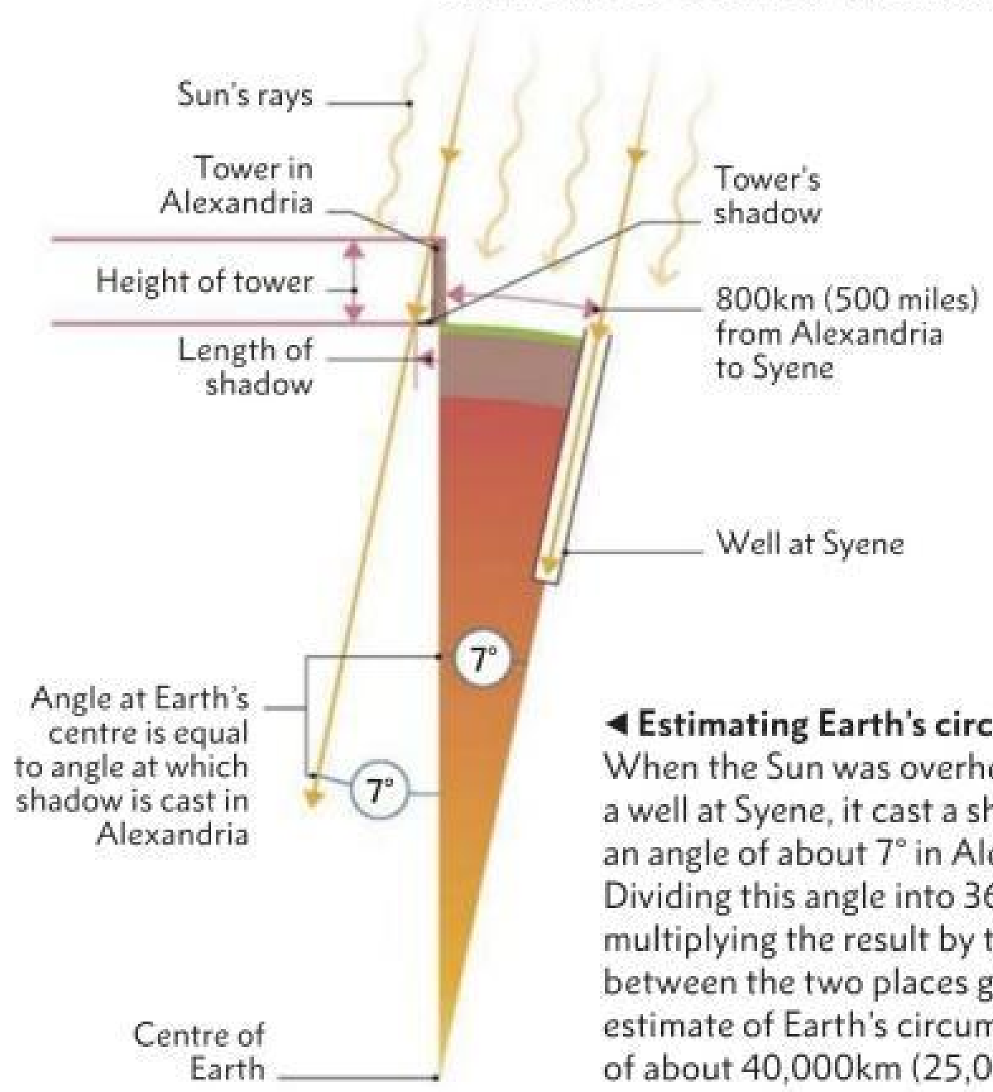
THE NATURE OF MATTER

The fundamental questions of what the world is made of, and where matter came from, are some of the oldest. In the 6th century BCE, Greek philosophers such as Thales and Anaximenes proposed that all substances were modifications of more intrinsic substances, the main candidates being water, air, earth, and fire. In the 5th century BCE, Empedocles claimed that everything was a mixture of all four of these substances, or elements. His near-contemporary Democritus developed the idea that the Universe is made of an infinite number of indivisible particles called atoms. Finally, in the 4th century BCE the influential scholar Aristotle added a fifth element, aether, to Empedocles' four. Although Aristotle was sceptical of the idea of atoms, it is remarkable that the concepts of both atoms and elements had been proposed more than 2,000 years before either was proved to exist.

EARTH'S SHAPE AND SIZE

Among many other ideas that Aristotle gave his views on was the concept that Earth is a sphere. Earlier Greek scholars, such as Pythagoras, had already argued this, but Aristotle was the first to summarize the main points of evidence. Chief among them was that travellers to southern lands could see stars that could not be seen by those living further north – explainable only if Earth's surface is curved. In 240 BCE, by comparing how the Sun's rays reach Earth at Syene and Alexandria, the mathematician Eratosthenes was able to estimate Earth's circumference. He came up with a figure of about 40,000km (25,000 miles) – close to the true value known today.

THE IDEA THAT **EARTH IS FLAT** WAS STILL THE PREVAILING VIEW IN **CHINA UP TO THE EARLY 17TH CENTURY**



◀ Estimating Earth's circumference
When the Sun was overhead above a well at Syene, it cast a shadow at an angle of about 7° in Alexandria. Dividing this angle into 360°, then multiplying the result by the distance between the two places gave an estimate of Earth's circumference of about 40,000km (25,000 miles).

EARTH AND THE SUN

Aristotle thought that Earth was at the centre of the Universe and that the Sun, planets, and stars move around it. This seemed like common sense given that every night various celestial objects (and during the day, the Sun) could be seen moving across the sky from east to west, whereas Earth itself did not seem to move. An alternative view, put forward by the astronomer Aristarchus, was that the Sun is at the centre and that Earth orbits it, but this idea did not gain much credence. In 150 CE, Claudius Ptolemy – an eminent Greek scholar living in Alexandria – published a book called the *Almagest*, which

▲ Earth-centred Universe
This 17th-century illustration by Andreas Cellarius depicts Aristotle and Ptolemy's model. Working out from the centre, the Moon, Mercury, Venus, the Sun, Mars, Jupiter, Saturn, and the stars move in circular orbits around Earth.

affirmed the prevailing view that Earth is at the centre. Ptolemy's detailed model fitted with all known observations but in order to do so contained complex modifications to Aristotle's original ideas. For about the next 14 centuries, the Earth-centred view of Aristotle and Ptolemy totally dominated astronomical theory, and it was adopted throughout Europe by medieval Christianity. During this time, Islamic astronomers such as Ulugh Beg (who worked from a great observatory in Samarkand, in what is now Uzbekistan, during the 15th century) made major contributions to knowledge of the Solar System and in particular to cataloguing star positions.

A STATIONARY OR A SPINNING EARTH?

Linked to the issue of what is at the centre of the Universe, the question of whether or not Earth rotates was debated for around 2,000 years up to the 17th century CE. The prevailing view was that Earth does not spin, as this fitted best with the idea of an Earth-centred Universe. However, there were opponents to this view, including Greek philosopher and astronomer Heraclides Ponticus in the 4th century BCE, as well as an Indian astronomer, Aryabhata, and Persian astronomers (Al-Sijzi and Al-Biruni) between the 5th and 15th centuries CE. Each proposed that Earth rotates and that the stars' apparent movement is just a relative motion caused by Earth's spin. But it was not until the Copernican Revolution (see pp.24–25) that Earth's rotation became accepted as fact, and it was not until the 19th century that it was categorically proved.

▲ **Ulugh Beg**
Working at his observatory at Samarkand, Ulugh Beg and other astronomers determined matters such as the tilt of Earth's spin axis and an accurate value for the length of the year.

THE SIZE AND AGE OF THE UNIVERSE

A final popular subject for speculation among early philosophers was the question of whether the Universe is finite (limited) or infinite, both in extent and in time. Aristotle proposed that the Universe is infinite in time (so it has always existed) but finite in extent – he believed that all the stars were at a fixed distance, embedded in a crystal sphere, beyond which was nothing. The mathematician Archimedes made a reasoned estimate of the distance to the fixed stars and realized it was vast (at least what we would now call 2 light years) but stopped short of claiming it to be infinite. In the 6th century CE, Egyptian philosopher John Philoponus opposed the prevailing Aristotelian view by arguing that the Universe is finite in time. It was not until the 20th century that scientists began to find answers to these questions.

> “IN POSITION **EARTH LIES IN THE MIDDLE OF THE HEAVENS** VERY MUCH LIKE ITS CENTRE.”
>
> **Claudius Ptolemy**, astronomer and geographer, 90–168 CE

EARTH **ORBITS THE SUN**

In the 16th and early 17th centuries, the prevailing view of an Earth-centred, or geocentric, Universe, as first put forward by the Greek scholars Aristotle and Ptolemy, was challenged by a simpler Sun-centred, heliocentric, model. This single idea eventually led to the scientific revolution, a whole new way of thinking about the Universe.

To the people of medieval Europe up to the mid-16th century, the question of how the Universe is organized had been answered centuries before by Ptolemy, in his modifications to ideas first asserted by Aristotle (see pp.22–23). According to Ptolemy, Earth stood still at the centre of the Universe. Stars were "fixed" or embedded in an invisible, distant sphere that rotated rapidly, approximately daily, around Earth. The Sun, Moon, and planets also revolved around Earth, attached to other invisible spheres. For most people, this explanation seemed reasonable – after all, looking up at the sky at night, it did seem that Earth was quite still, while all other objects in the sky, including the Sun and stars, rose up in the east, moved across the sky, and then set below the western horizon.

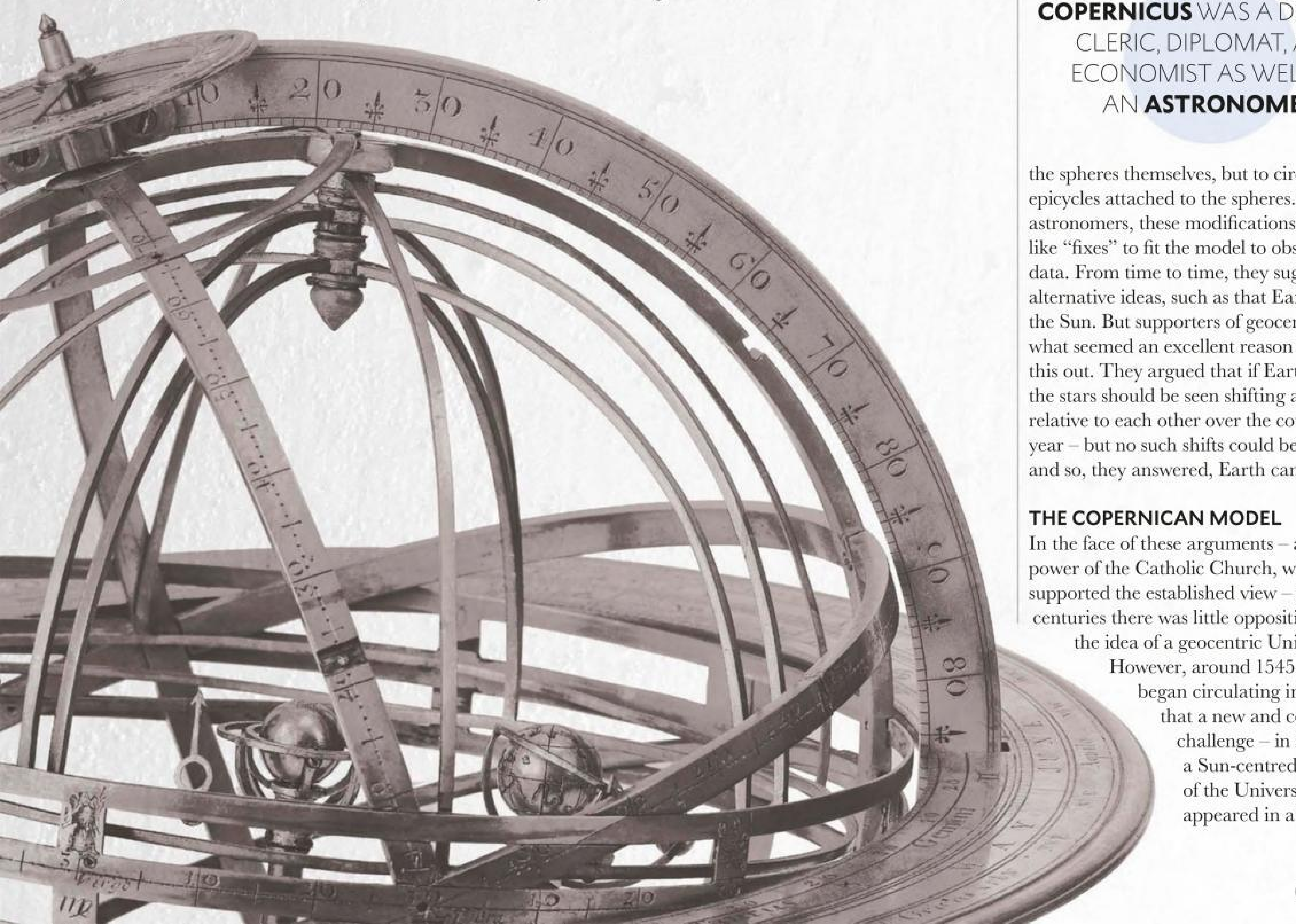
DOUBTS ABOUT GEOCENTRISM

The geocentric model of the Universe did not satisfy everyone, however. A serious doubt focused on what it predicted about the planets. According to the original Aristotelian version of geocentrism, the planets rotated around Earth in perfect circles, each at its own steady speed. But if this was true, the planets should move across the sky with unvarying speed and brightness because they were always the same distance from Earth – and this wasn't what was observed. Some planets, such as Mars, varied hugely in brightness over time, and when their movements were compared with those of the outer sphere of fixed stars, the planets sometimes reversed direction – a behaviour called retrograde motion. To deal with these problems, Ptolemy had modified the Aristotelian model. For example, he had planets attached not to the spheres themselves, but to circles called epicycles attached to the spheres. To some astronomers, these modifications looked like "fixes" to fit the model to observational data. From time to time, they suggested alternative ideas, such as that Earth orbits the Sun. But supporters of geocentrism had what seemed an excellent reason for ruling this out. They argued that if Earth moves, the stars should be seen shifting a little relative to each other over the course of a year – but no such shifts could be detected and so, they answered, Earth cannot move.

COPERNICUS WAS A DOCTOR, CLERIC, DIPLOMAT, AND ECONOMIST AS WELL AS AN **ASTRONOMER**

THE COPERNICAN MODEL

In the face of these arguments – and the power of the Catholic Church, which supported the established view – for centuries there was little opposition to the idea of a geocentric Universe. However, around 1545, rumours began circulating in Europe that a new and convincing challenge – in the form of a Sun-centred theory of the Universe – had appeared in a book,



▼ The Solar System in miniature
This model of the Solar System, called an armillary sphere, is a Copernican version, showing the Sun at the centre and the planets revolving around it.

Spectra of nebulae, stars, and galaxies are studied by William and Margaret Huggins, 1860s. They measure the redshifts of stars, showing how fast they are moving.

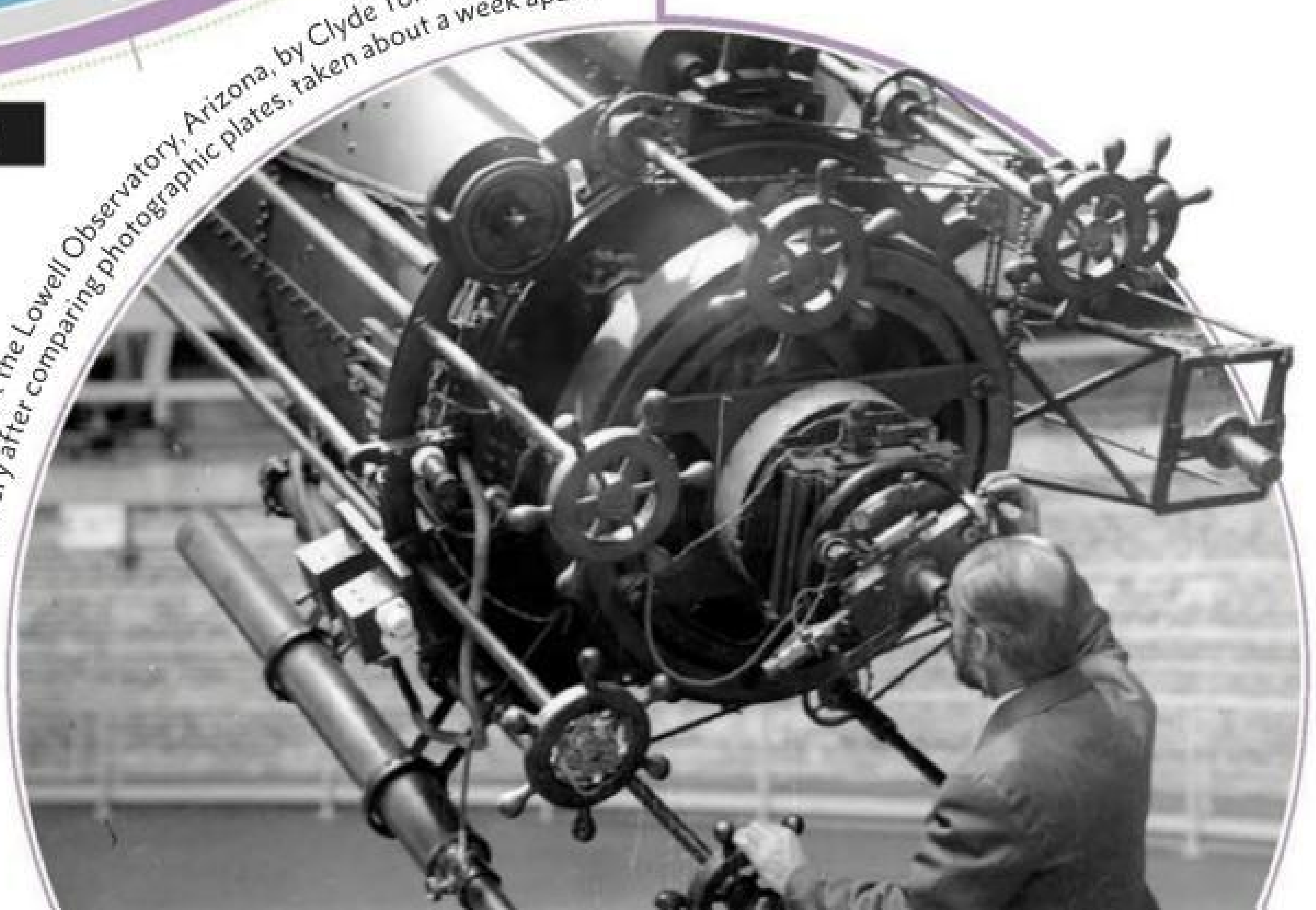
Elements in the Sun's atmosphere identified by Gustav Kirchoff, 1861. He notices dark lines in its spectrum match wavelengths of light emitted by elements burned in a flame.

First photograph of a star's spectrum taken by Henry Draper, 1872. The star is Vega, and the photograph shows its absorption lines.

Yerkes Refractor is completed in Wisconsin, 1895. The largest refractor ever used for research, it is involved in discoveries such as the spiral nature of the Milky Way.

1900

Edwin Hubble uses the Hooker Telescope in the 1920s to show there are galaxies outside our own and to relate the distances and recessional velocities of galaxies – leading to the discovery that the Universe is expanding.



Pluto discovered, 1930, at the Lowell Observatory, Arizona, by Clyde Tombaugh, who makes his discovery after comparing photographic plates, taken about a week apart.

BEYOND VISIBLE LIGHT

First parabolic dish radio telescope, built by Grote Reber in Wheaton, Illinois, 1937. Reber then makes an all-sky map of radio emissions from space.

Cosmic microwave background radiation detected, 1964, by Arno Penzias and Robert Wilson using a radio telescope at Bell Telephone Laboratories, New Jersey. It helps to confirm the Big Bang theory.

First pulsar discovered, 1967, by Jocelyn Bell and Antony Hewish using a radio telescope at the University of Cambridge.

The Very Large Array (VLA), a group of 27 radio telescopes that work together to form images, begins operations in New Mexico, 1980.

Hipparcos Satellite makes its first observations, 1989. Hipparcos makes highly accurate measurements of the positions of stars.

SPACE TELESCOPES

The Hubble Space Telescope placed in orbit, 1990. It has peered deep into space and time, providing astonishing images of objects in our galaxy and beyond, and improved measurements of the Universe's age.

Cosmic microwave background radiation mapped from space, 1993. This first map is made by the Cosmic Background Explorer (COBE).

First Keck Telescope begins operation in Hawaii, 1993. The telescope, and its twin, has a 10m (33ft) wide mirror made of 36 segments and uses a technology called adaptive optics to adjust for atmospheric turbulence by altering the mirror's shape.

2000

James Webb Space Telescope is due to launch, 2021.

THE **ATOM** AND THE **UNIVERSE**

From the early 19th century to the late 1920s, a series of breakthroughs occurred in the physical sciences. They transformed our understanding of the workings and structure of the world at both infinitesimally small scales and at the very largest, raising the possibility of an infinite cosmos.

◀ **Henrietta Leavitt** Over 20 years, Leavitt studied 1,777 variable stars at the Harvard College Observatory before stumbling upon her key discovery.

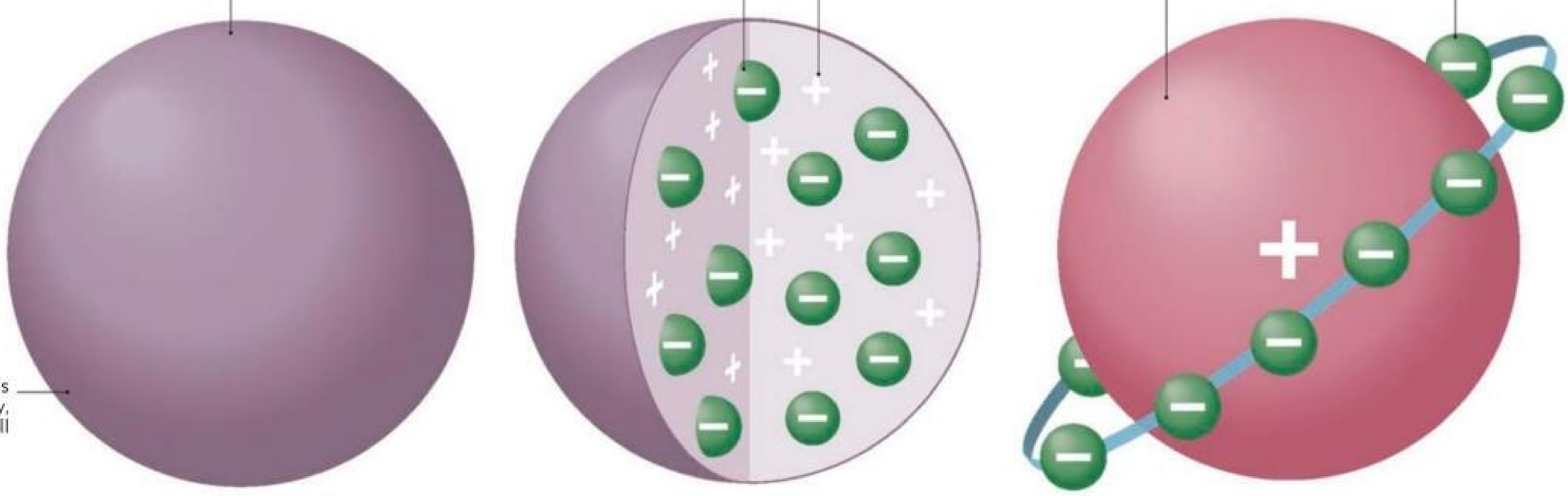
These discoveries paved the way for the advances of the 1930s to the 1950s, from the realization that the Universe is expanding to the development of ideas on how energy and matter interact at the subatomic level. Through the coming together of ideas in cosmology and particle physics, these breakthroughs eventually led to the development of the Big Bang theory.

PROBING MATTER AND ENERGY

The idea that matter consists of atoms was first suggested by the ancient Greek, Democritus (see p.22). In the early 1800s, an Englishman, John Dalton, revived the idea. Dalton regarded atoms as indivisible, but around the turn of the 20th century experiments by scientists such as the New Zealander Ernest Rutherford proved that they have a substructure. Around the same time, the German theoretical physicist Albert Einstein showed that matter and energy have an equivalence. Simultaneously, a new field of physics, quantum theory, was proposing (among other things) that light can behave either as a wave or as a stream of particles. By the late 1920s, it was known

> WHAT WE OBSERVE AS **MATERIAL BODIES AND FORCES** ARE NOTHING BUT **SHAPES AND VARIATIONS IN THE STRUCTURE OF SPACE**.
>
> **Erwin Schrödinger**, Austrian theoretical physicist, 1887–1961

▶ **Understanding the atom** From around 1800 until the mid-1920s, a step-by-step evolution occurred in the understanding of atomic structure. Later, from the late 1920s, physicists found that atomic nuclei have a substructure.



Dalton's atom (1803) English chemist John Dalton pictures atoms as extremely small spheres, like tiny billiard balls, that have no internal structure and cannot be subdivided, created, or destroyed.

Thomson's plum pudding (1904) The discoverer of the electron, British physicist J.J. Thomson, suggests a "plum-pudding" model, with negatively charged electrons embedded in a positively charged sphere.

Nagaoka's Saturnian model (1904) Japanese physicist Hantaro Nagaoka proposes an atom has a central nucleus, around which the electrons orbit in one or more rings, like the rings of Saturn.

that atomic nuclei consist of protons and neutrons and are held together by a newly detected force, the strong force. Also discovered at this time was antimatter – subatomic particles that are identical to their matter equivalents except for opposite electrical change – and that the coming together of matter and antimatter can annihilate both, producing pure energy.

THE DISTANCES TO STARS

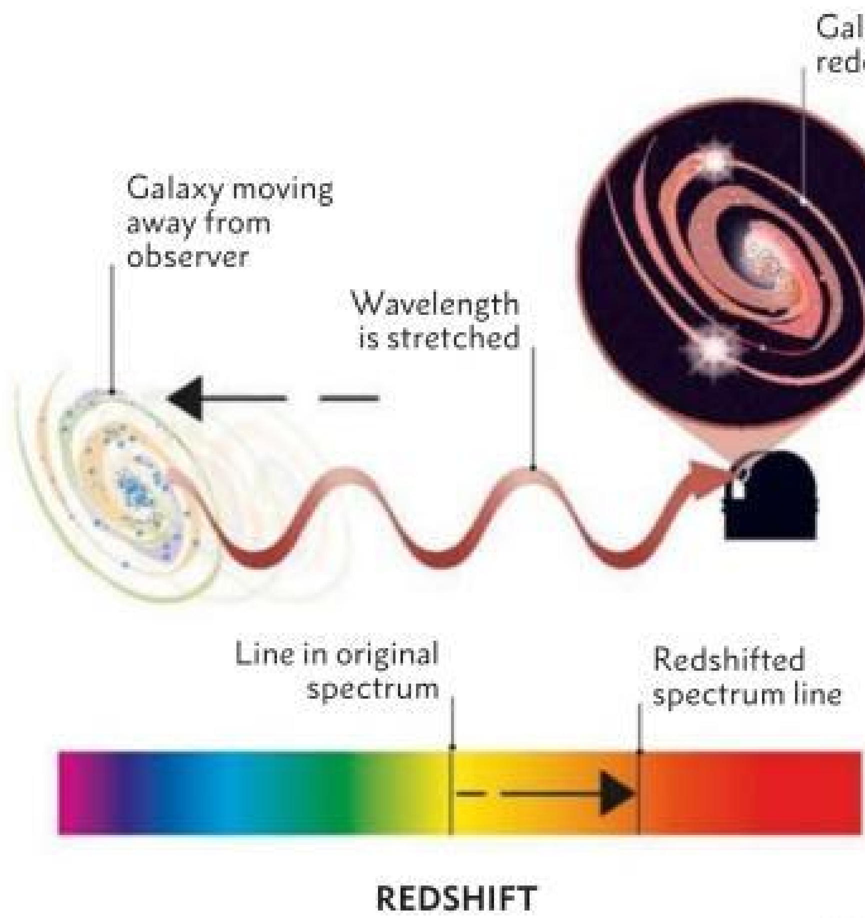
During roughly the same period, great advances were made in understanding the true scale of the cosmos. In 1838, the German astronomer Friedrich Bessell made the first reliable measurement of the distance to a star other than the Sun, using a method called stellar parallax. The star, although one of the closest to the Sun, seemed at the

A LIGHT-YEAR – THE DISTANCE LIGHT TRAVELS THROUGH SPACE IN A YEAR – IS ABOUT **9.5 TRILLION KILOMETRES (6 TRILLION MILES)**

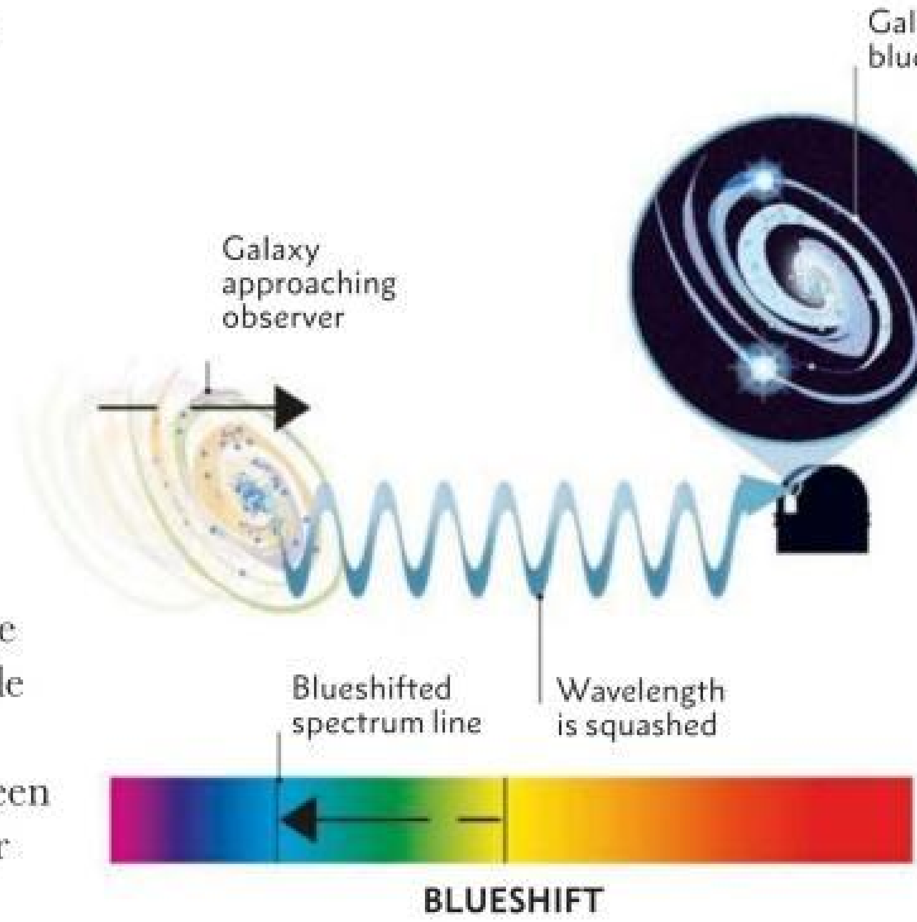
time almost unimaginably far-off – what would now be called 10.3 light-years away. It was 1912 before a system was discovered for estimating the distance to many more remote stars. The discoverer was an American called Henrietta Leavitt. Her breakthrough concerned a class of star called Cepheid variables, which cyclically vary in brightness. Leavitt found a link between the cycle period and brightness of these stars, meaning that if both could be measured a good estimate could be made of their distance from Earth. Within a few years, it became apparent that some stars are tens of thousands of light-years away, while some vaguely spiral-shaped nebulous patches in the sky, known at the time as "spiral nebulae", seemed to be millions of light-years away.

SHIFTING NEBULAE

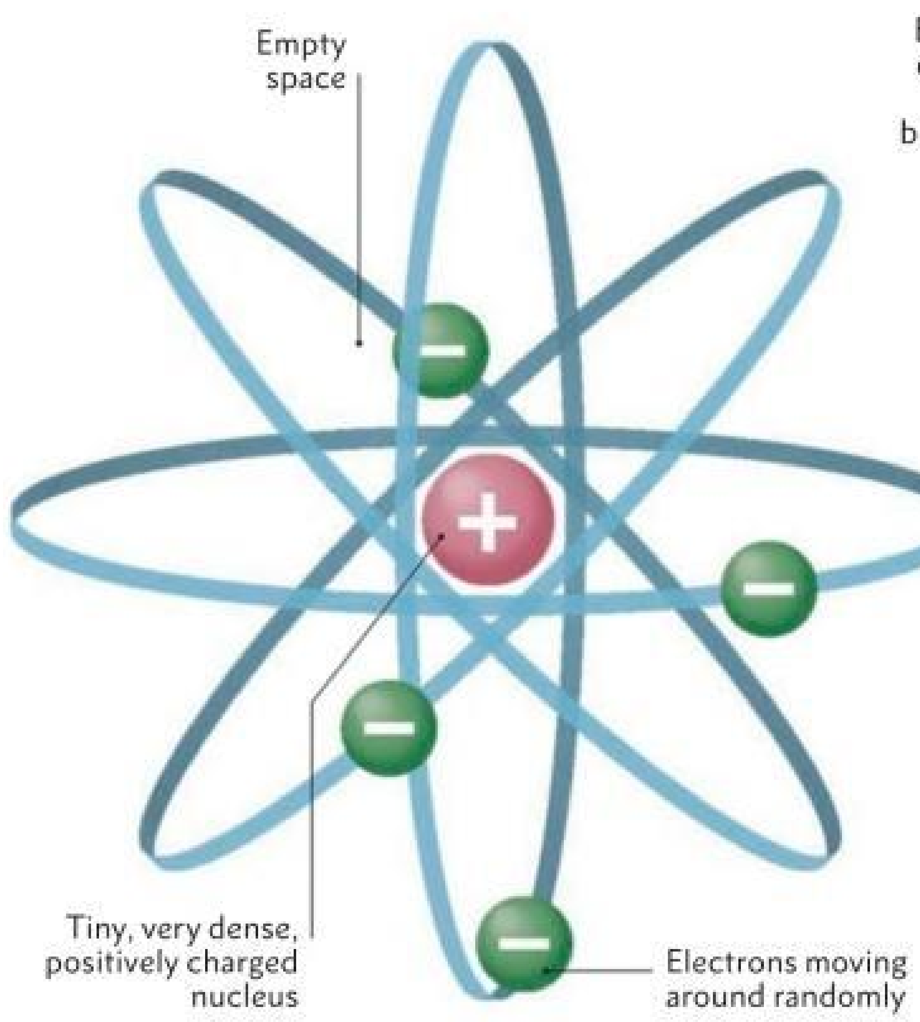
Between 1912 and 1917, the American astronomer Vesto Slipher studied several "spiral nebulae" and realized that many were moving away from Earth at high speed, while a few were approaching Earth. He found this out by measuring a property of the light from the nebulae called redshift or blueshift. It seemed odd that the nebulae were moving at such speed relative to the rest of the galaxy. Partly prompted by Slipher's findings, in 1920 a formal debate was held in Washington, DC on whether these nebulae might be separate galaxies outside our own. The debate was inconclusive. But within a few years, the answer had been found – by another American astronomer called Edwin Hubble (see pp.30–31).



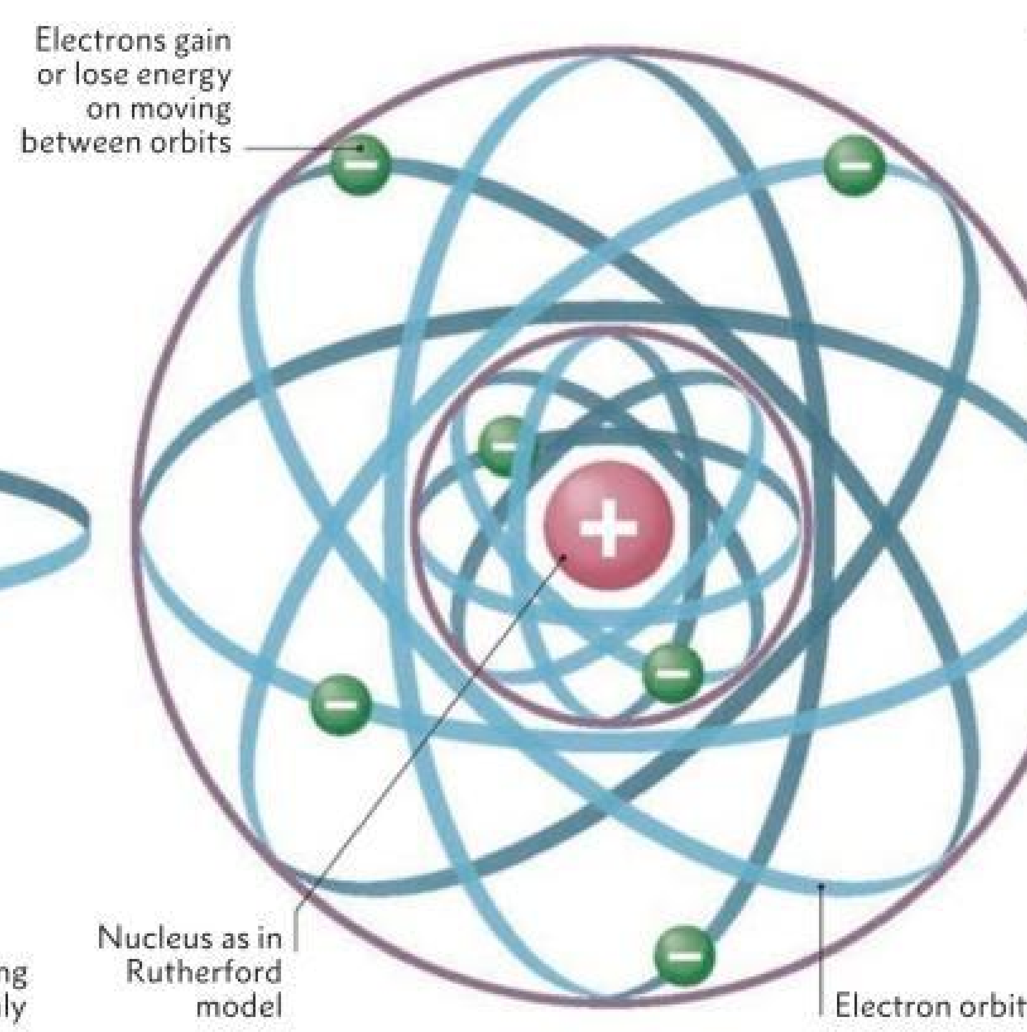
◀ Redshift
When an object such as a galaxy is receding at high speed, light waves from it appear stretched. This causes features in the galaxy's spectrum, such as prominent lines, to shift towards the red (long wavelength) end. This is a redshift.



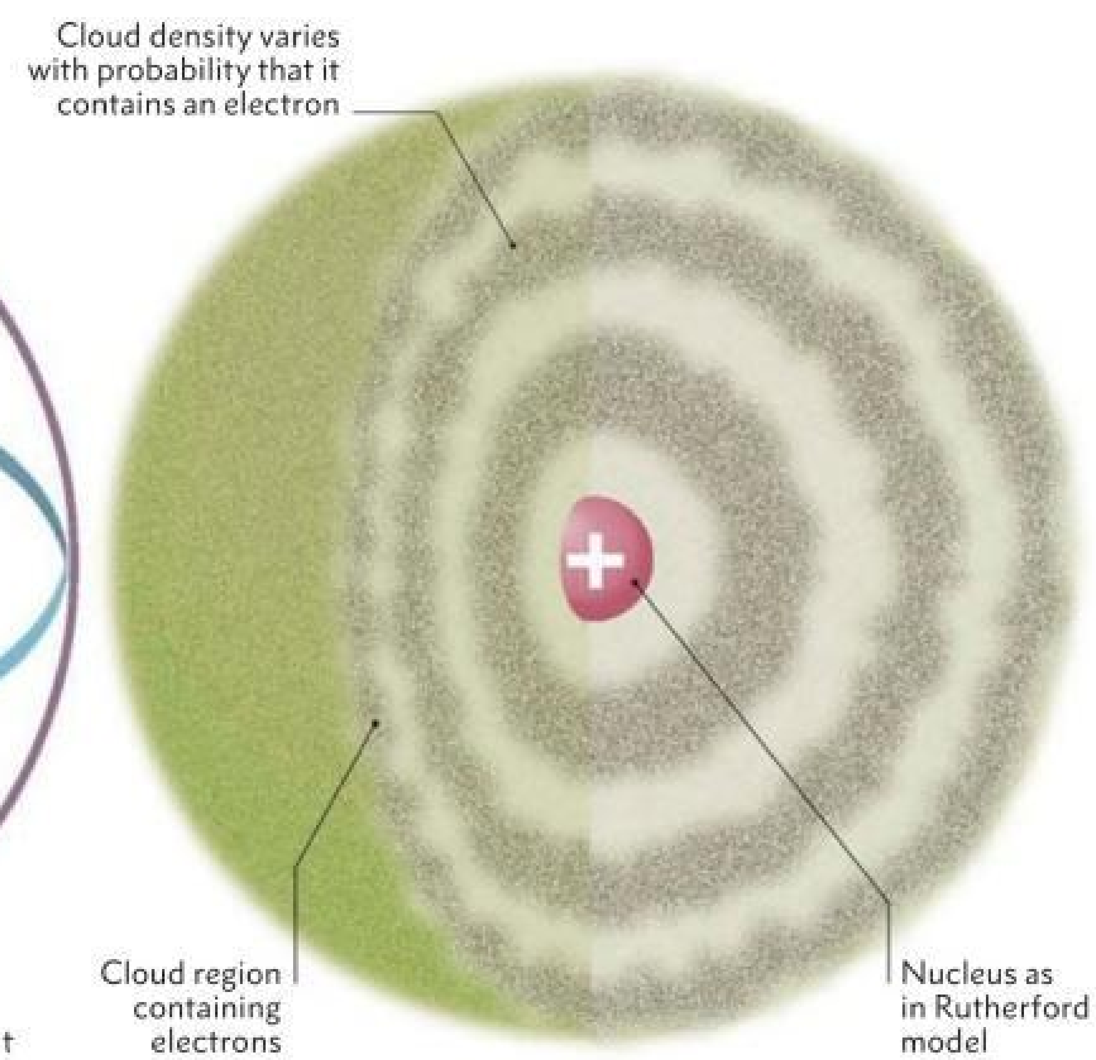
◀ Blueshift
Light waves from a rapidly approaching object appear squashed, shifting features in the spectrum towards the blue (short wavelength) end. This is a blueshift.



Rutherford and the nucleus (1911) Rutherford proves experimentally that an atom's nucleus is much smaller and denser than previously thought – and that much of an atom is empty space.



Bohr's electron orbits (1913) Danish physicist Niels Bohr proposes that electrons can move in spherical orbits, at fixed distances from the nucleus, and can "jump" between orbits.



Schrödinger's electron cloud model (1926) According to Austrian physicist Erwin Schrödinger's model, the locations of electrons in an atom are never certain and can be stated only in terms of probabilities.

THE UNIVERSE **GETS BIGGER**

During the 1920s, two key breakthroughs led to a revolution in understanding of the size and nature of the Universe. Both were the result of discoveries made by the astronomer Edwin Hubble.

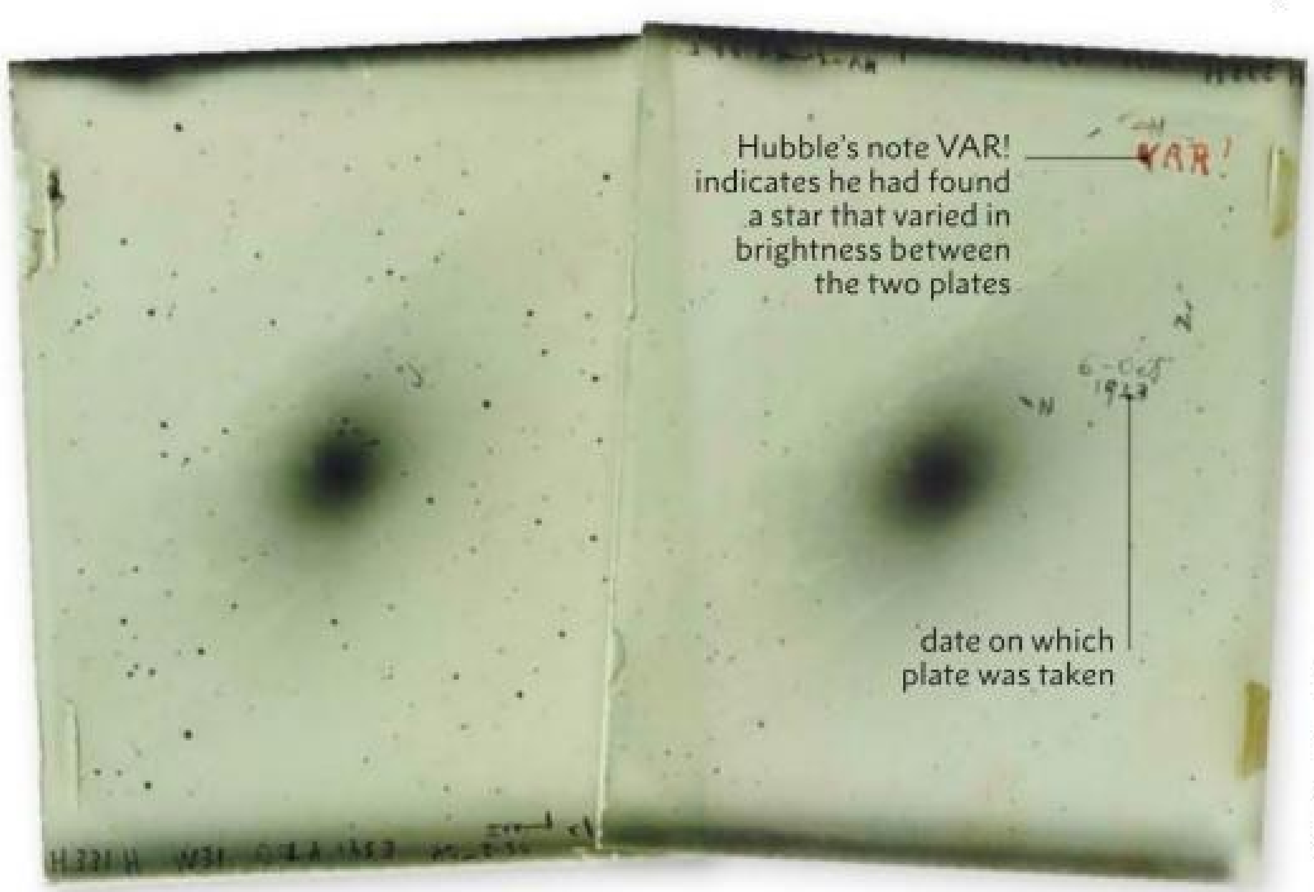
In 1919, Hubble arrived at Mount Wilson Observatory in California, aged 30. His arrival coincided with the completion of what was then the largest telescope in the world, a reflector with a 2.5m (100in) wide mirror, called the Hooker Telescope.

ENDING THE GALAXY DEBATE

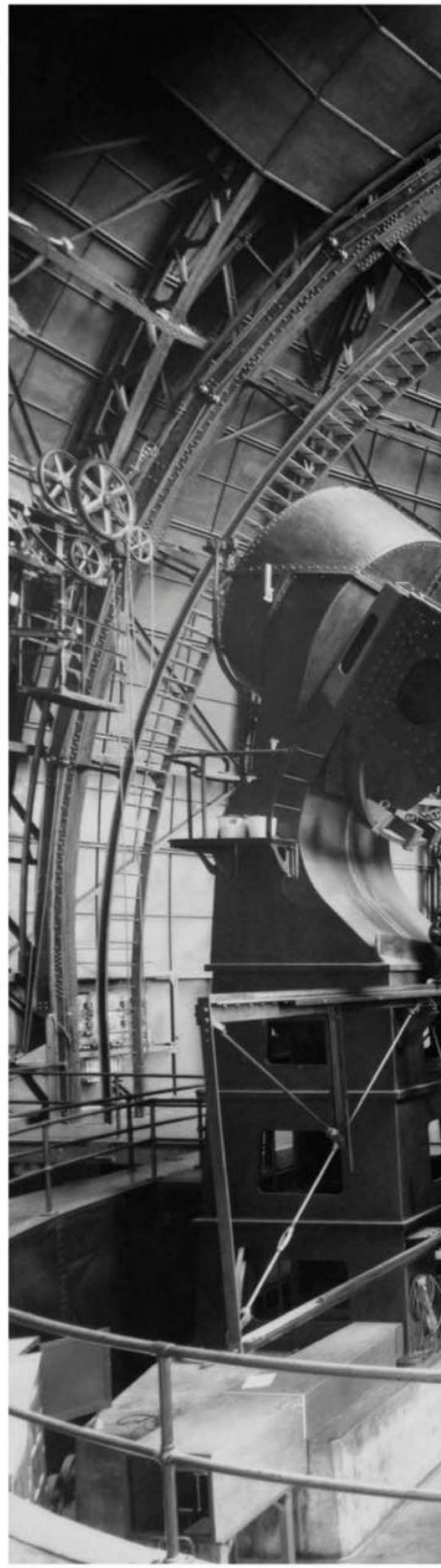
At that time, the prevailing view was that the Universe consisted of just the Milky Way Galaxy, although in 1920 a famous debate (see p.29) had considered whether or not some vaguely spiral-shaped nebulae – fuzzy, star-containing objects – in the night sky might be collections of stars outside our own galaxy. Hubble, who had been studying these nebulae, already strongly suspected that they were outside our galaxy. In 1922–23, he used the Hooker Telescope to observe a class of stars called Cepheid variables in some of the nebulae, including what today is called the Andromeda Galaxy. Cepheid variables stars whose distances can be estimated by measuring their average brightness and the lengths of their cycles of brightness variation. As a result of his observations, in 1924 Hubble was able to announce that the Andromeda nebula and other spiral nebulae were far too distant to be part of the Milky Way and so must be galaxies outside our own. Almost overnight, the Universe had become a much bigger place than anyone had previously imagined.

RECEDING GALAXIES

Hubble next studied a phenomenon that had already been noted by an astronomer called Vesto Slipher: many of the spiral galaxies had large "redshifts" in their spectra, meaning that they were moving away from Earth at high speed (see p.29). Again by observing Cepheid variables, Hubble began measuring the distances to these galaxies and compared the distances to their redshifts. He noticed something remarkable: the more distant a galaxy was, the greater was its recessional velocity – a relationship that became known as Hubble's Law. Hubble published his results in 1929. Although he himself was initially sceptical, to other astronomers it was clear that only one conclusion could be drawn – the whole Universe must be expanding!

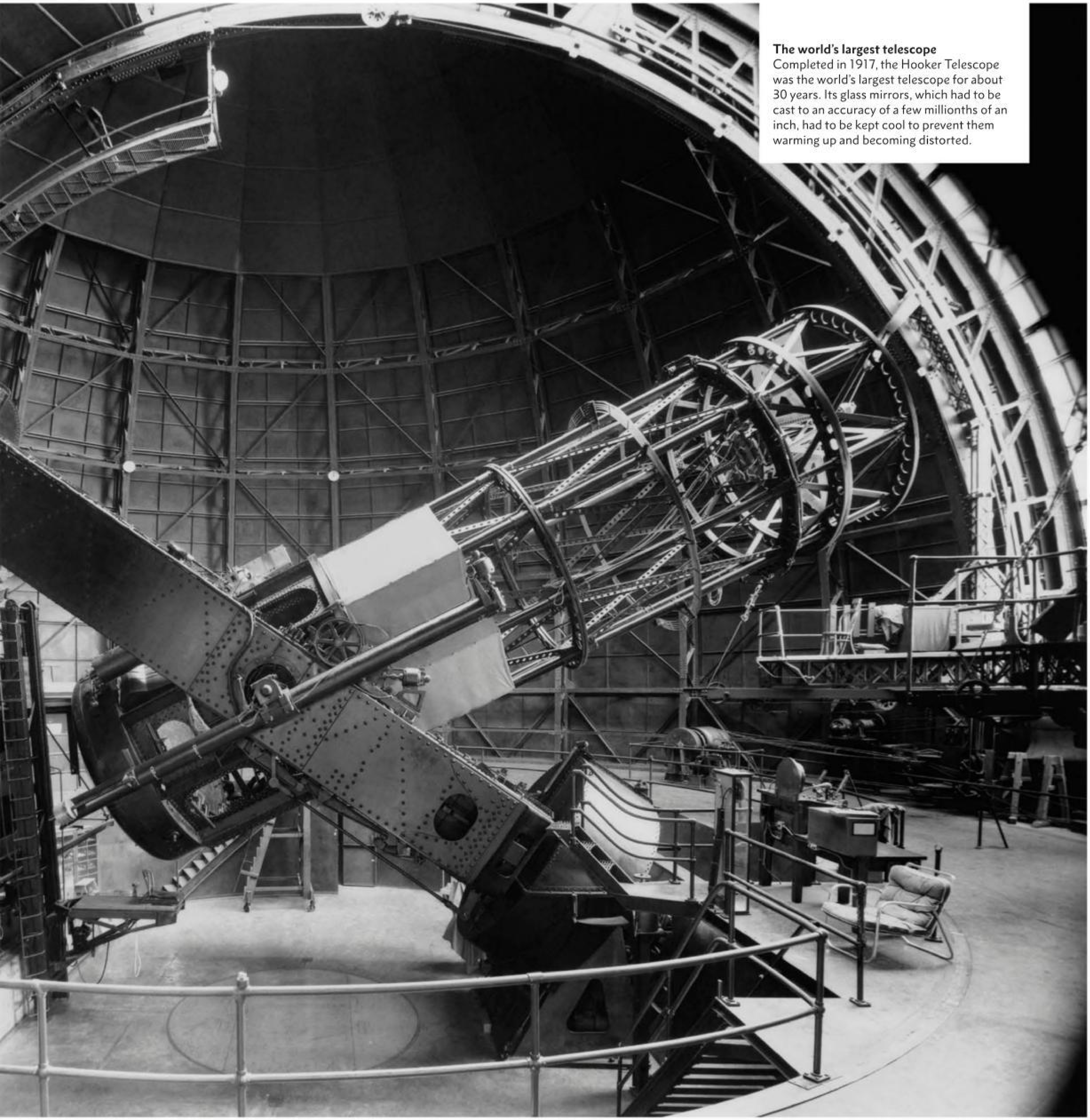


▼ Photographic evidence
These two (negative) photographic plates were used by Hubble to identify a specific Cepheid variable star in the Andromeda Galaxy. Studies on this star were crucial in confirming that the Andromeda Galaxy is outside the Milky Way.



> THE **HISTORY OF ASTRONOMY** IS A **HISTORY OF RECEDING HORIZONS**.

Edwin Hubble, American astronomer, 1889–1953



The world's largest telescope
Completed in 1917, the Hooker Telescope was the world's largest telescope for about 30 years. Its glass mirrors, which had to be cast to an accuracy of a few millionths of an inch, had to be kept cool to prevent them warming up and becoming distorted.

THE **BIG BANG**

Since the 1930s, when the Big Bang theory was first proposed, physicists and cosmologists have been testing and developing the theory and filling in the details of the first moments of the Universe.

Part of the work to improve Big Bang theory has been carried out by experiments in which high-energy particles are collided to re-create Big Bang-like conditions (see pp.36–37), and part has been purely theoretical, involving the formulation of equations and models. During the experimental side of this journey, many new subatomic particles have been discovered. Another focus of research has been the fundamental forces that govern particle interactions. It has been known since the 1930s that there are four of these forces: gravity, the electromagnetic force, the strong force, and the weak interaction. During the Big Bang, it is theorized that these forces were initially unified. Then, as the Universe cooled, they split off, possibly triggering new phases of the Big Bang. Gradually, physicists have fitted all the known particles and the forces into a scheme called the Standard Model of particle physics.

One important change to the original theory was made in the 1980s by the American physicist Alan Guth. He proposed that at a very early stage a part of the Universe underwent an extremely fast expansion called cosmic inflation. Guth's idea helped explain some aspects of the Universe today, including why at the largest scales matter and energy seem to be distributed very smoothly. The reality of cosmic inflation is now widely accepted.

Up quark, Down quark — There are six types of quark. Up and down quarks are the most stable and common.

Electron — This tiny subatomic particle has a negative electrical charge.

Gluon — By carrying the strong nuclear force, gluons hold quarks together.

Photon — A photon is a tiny packet of light or other electromagnetic radiation.

Higgs boson — This particle is associated with a field that gives mass to other particles.

▲ Fundamental particles
These particles are not, so far as is known, made of smaller particles. Some, such as quarks, are building blocks of matter. Others, like gluons and photons, are force-carrier particles.

Proton — A proton is made of two up quarks and one down quark plus gluons.

Neutron — Two down quarks and one up quark, plus gluons, make up a neutron.

▲ Composite particles
These particles are composed of other smaller particles. Scores of different composite particles have been identified, but protons and neutrons are the only stable types.

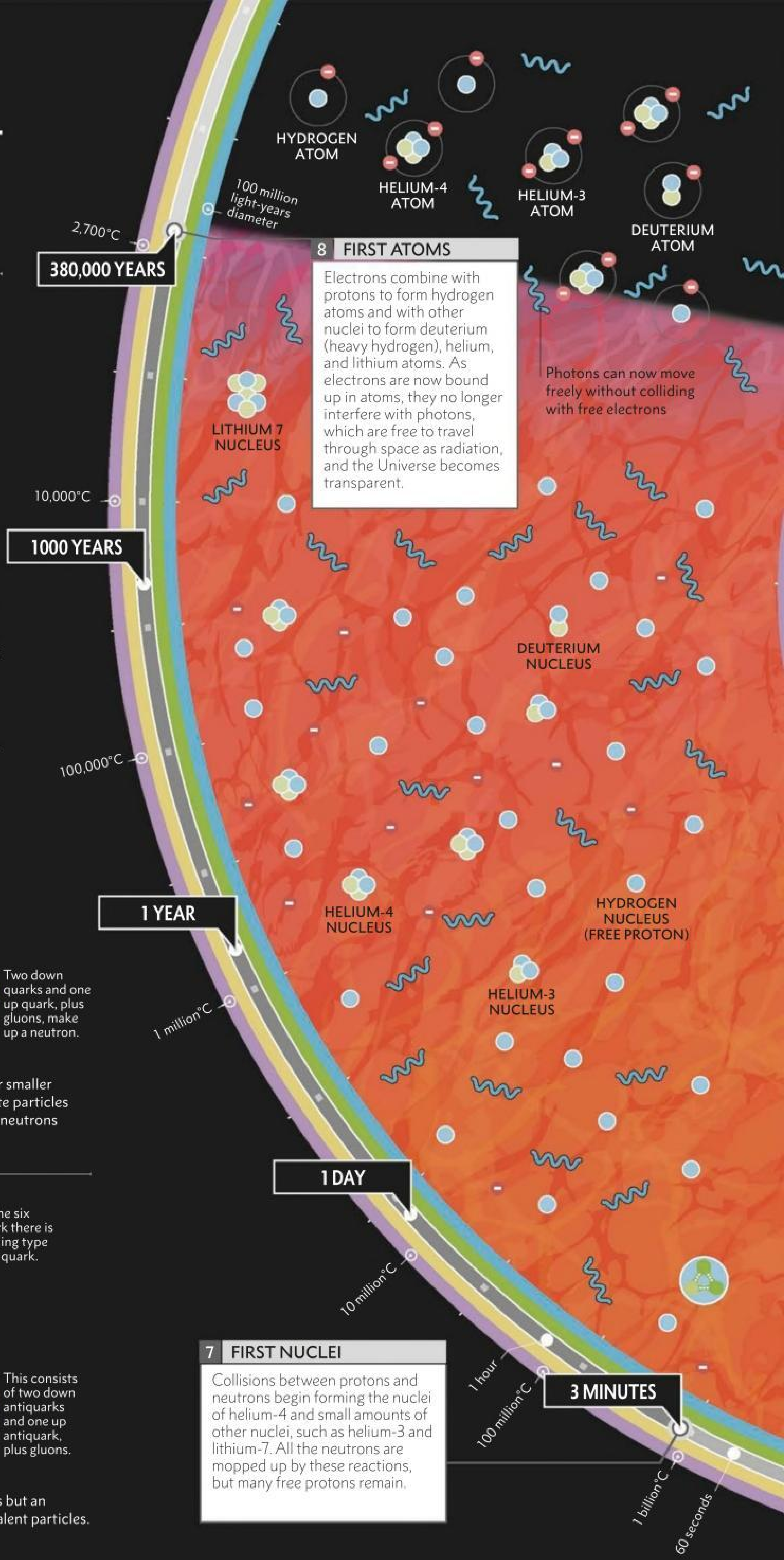
Up antiquark, Down antiquark — For each of the six types of quark there is a corresponding type called an antiquark.

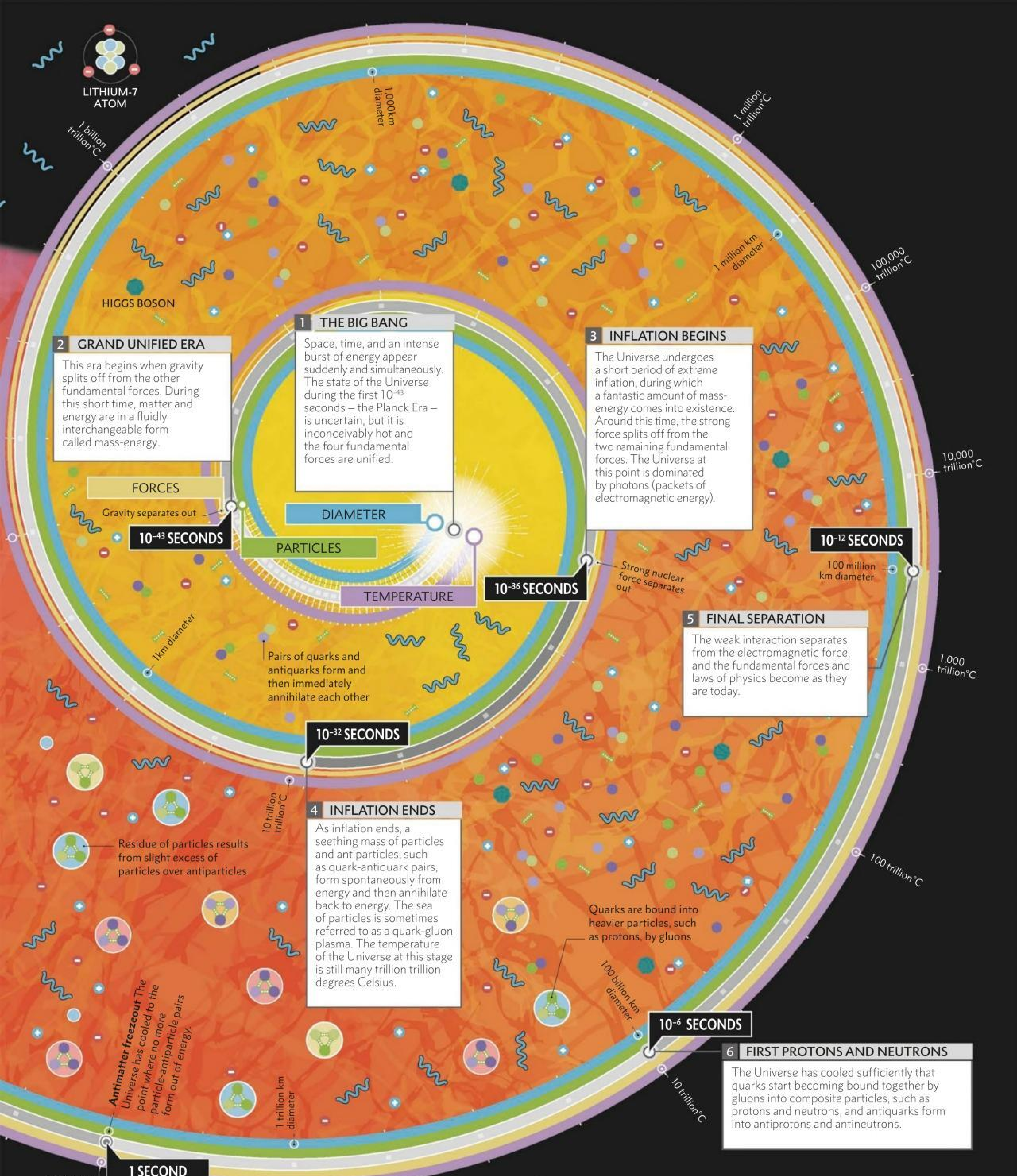
Positron — A positron is the positively charged equivalent of the electron.

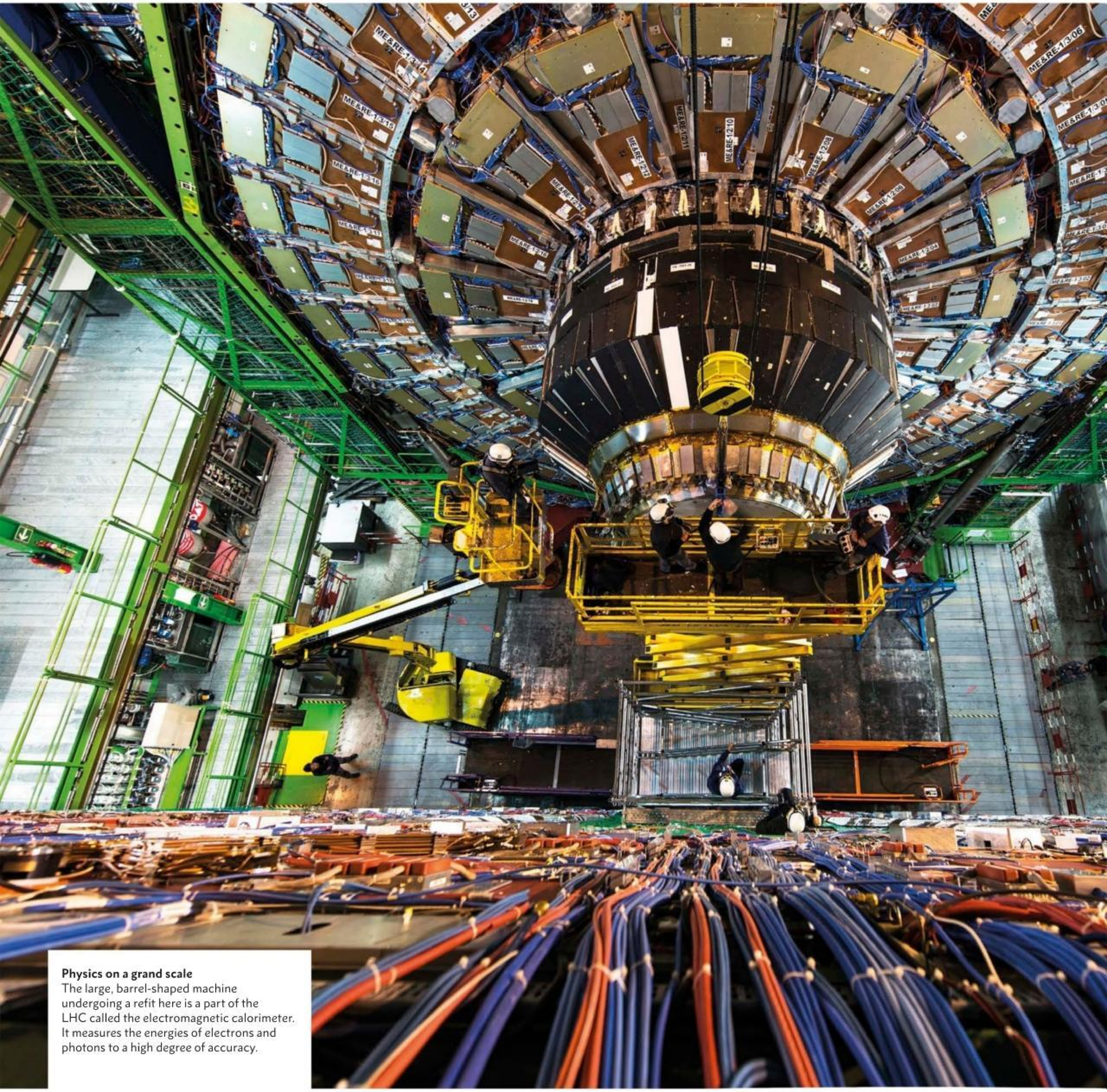
Anti-proton — Two up antiquarks and one down antiquark, plus gluons, form an anti-proton.

Anti-neutron — This consists of two down antiquarks and one up antiquark, plus gluons.

▲ Antiparticles
These are particles with the same mass but an opposite electric charge to their equivalent particles.




LITHIUM-7 ATOM
1 billion trillion°C
1,000km diameter
1 million trillion°C
1 million km diameter
100,000 trillion°C
10,000 trillion°C
1,000 trillion°C
100 trillion°C
10 trillion°C
10 trillion trillion°C
10 billion°C
HIGGS BOSON
1 THE BIG BANG
Space, time, and an intense burst of energy appear suddenly and simultaneously. The state of the Universe during the first 10^{-43} seconds – the Planck Era – is uncertain, but it is inconceivably hot and the four fundamental forces are unified.
2 GRAND UNIFIED ERA
This era begins when gravity splits off from the other fundamental forces. During this short time, matter and energy are in a fluidly interchangeable form called mass-energy.
3 INFLATION BEGINS
The Universe undergoes a short period of extreme inflation, during which a fantastic amount of mass-energy comes into existence. Around this time, the strong force splits off from the two remaining fundamental forces. The Universe at this point is dominated by photons (packets of electromagnetic energy).
FORCES
Gravity separates out
10^{-43} SECONDS
DIAMETER
PARTICLES
TEMPERATURE
10^{-36} SECONDS
Strong nuclear force separates out
10^{-12} SECONDS
100 million km diameter
5 FINAL SEPARATION
The weak interaction separates from the electromagnetic force, and the fundamental forces and laws of physics become as they are today.
1km diameter
Pairs of quarks and antiquarks form and then immediately annihilate each other
10^{-32} SECONDS
4 INFLATION ENDS
As inflation ends, a seething mass of particles and antiparticles, such as quark-antiquark pairs, form spontaneously from energy and then annihilate back to energy. The sea of particles is sometimes referred to as a quark-gluon plasma. The temperature of the Universe at this stage is still many trillion trillion degrees Celsius.
Residue of particles results from slight excess of particles over antiparticles
Quarks are bound into heavier particles, such as protons, by gluons
100 billion km diameter
10^{-6} SECONDS
6 FIRST PROTONS AND NEUTRONS
The Universe has cooled sufficiently that quarks start becoming bound together by gluons into composite particles, such as protons and neutrons, and antiquarks form into antiprotons and antineutrons.
Antimatter freezeout The Universe has cooled to the point where no more particle-antiparticle pairs form out of energy.
1 trillion km diameter
1 SECOND



Physics on a grand scale
The large, barrel-shaped machine undergoing a refit here is a part of the LHC called the electromagnetic calorimeter. It measures the energies of electrons and photons to a high degree of accuracy.

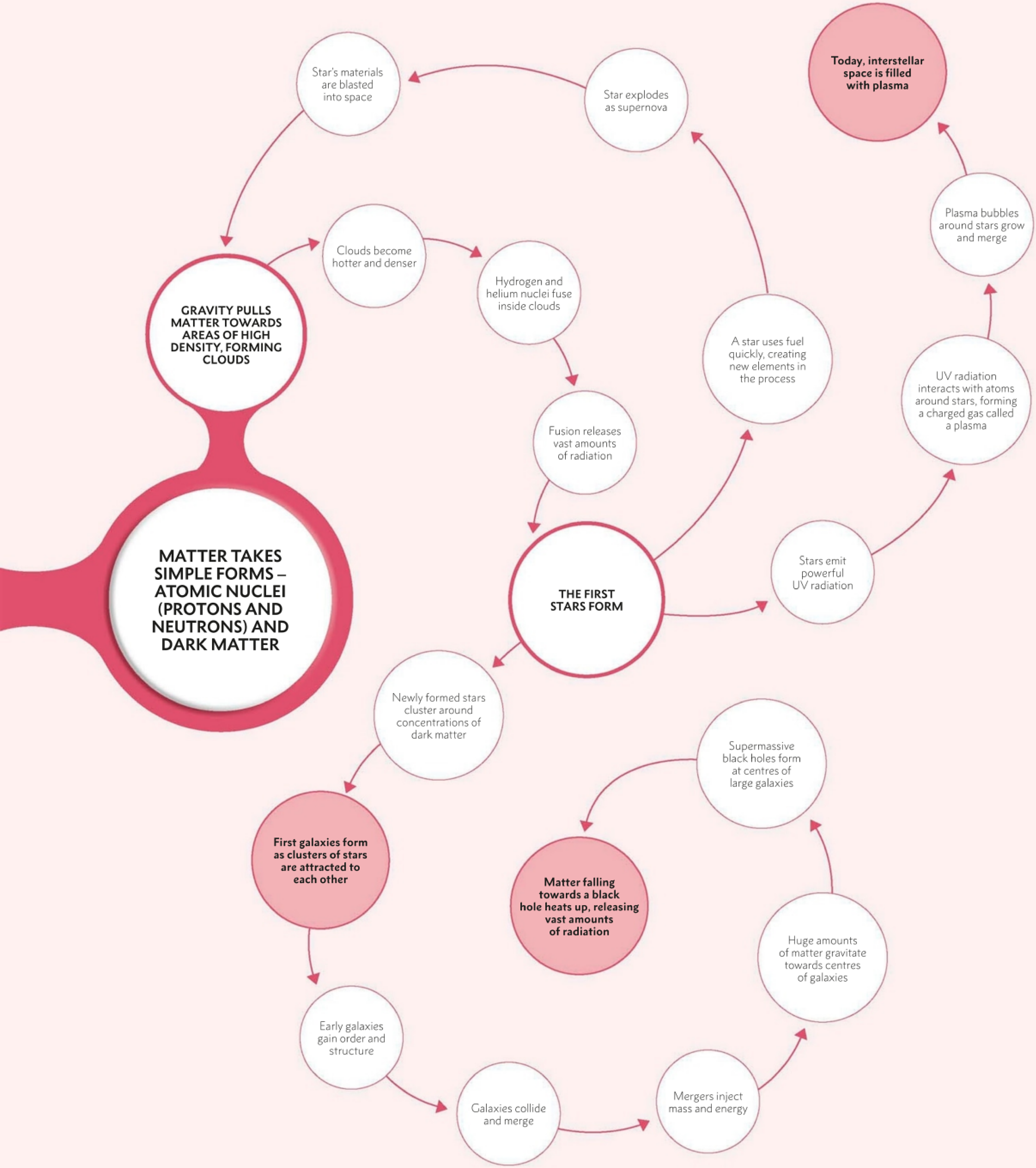

MATTER TAKES SIMPLE FORMS – ATOMIC NUCLEI (PROTONS AND NEUTRONS) AND DARK MATTER
GRAVITY PULLS MATTER TOWARDS AREAS OF HIGH DENSITY, FORMING CLOUDS
Clouds become hotter and denser
Hydrogen and helium nuclei fuse inside clouds
Fusion releases vast amounts of radiation
THE FIRST STARS FORM
A star uses fuel quickly, creating new elements in the process
Star explodes as supernova
Star's materials are blasted into space
Stars emit powerful UV radiation
UV radiation interacts with atoms around stars, forming a charged gas called a plasma
Plasma bubbles around stars grow and merge
Today, interstellar space is filled with plasma
Newly formed stars cluster around concentrations of dark matter
First galaxies form as clusters of stars are attracted to each other
Early galaxies gain order and structure
Galaxies collide and merge
Mergers inject mass and energy
Huge amounts of matter gravitate towards centres of galaxies
Supermassive black holes form at centres of large galaxies
Matter falling towards a black hole heats up, releasing vast amounts of radiation

image
not
available

THE **PUZZLE OF GRAVITY**

Gravity, or gravitation, plays a crucial role in the formation of stars and planets because it causes matter to clump together. The modern theory of gravity, Einstein's general theory of relativity, accurately explains its effects. Nevertheless, the true nature of gravity remains a mystery.

▼ Isaac Newton
In the late 1680s, Newton published both his Universal Law of Gravitation – the first scientific theory of gravity – and his three laws of motion.

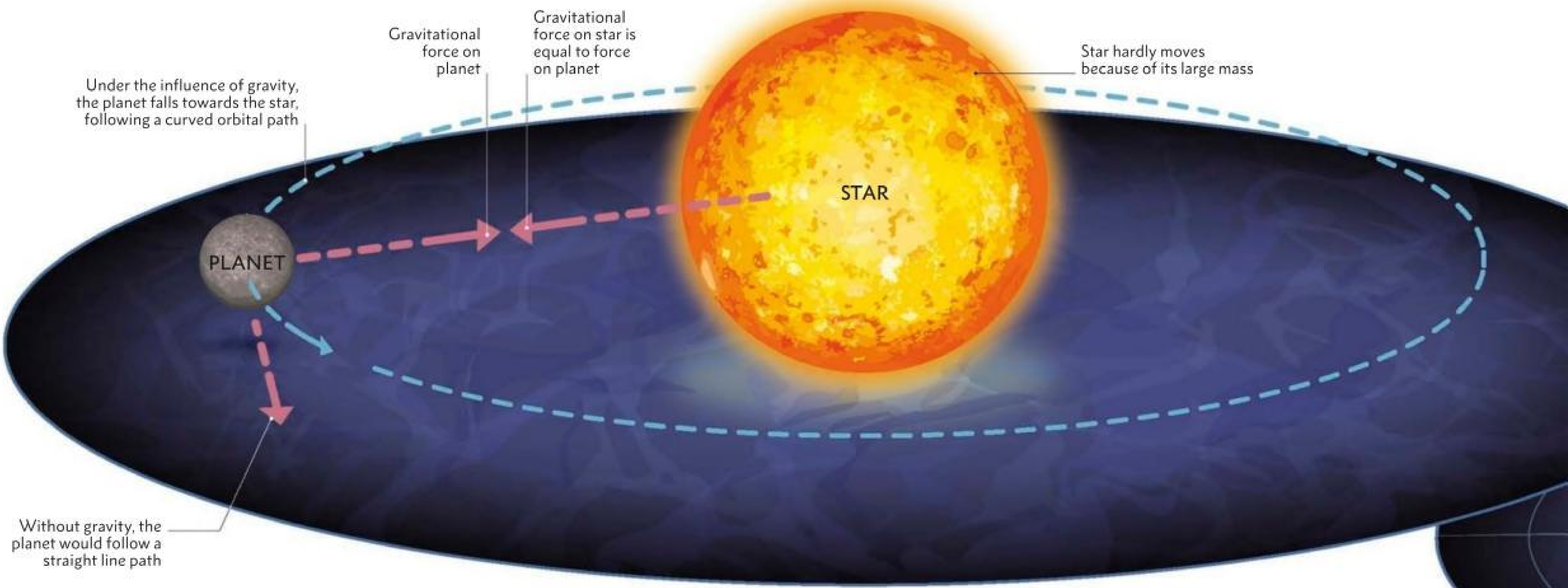
The ancient Greek philosopher Aristotle supposed that Earth is at the centre of the Universe and that everything has a natural tendency to move towards it. According to Aristotle, heavier things have more of this tendency and so fall faster.

Although Aristotle's simple notion was superficially supported by observations, experiments by Italian scientist Galileo Galilei in the 17th century showed that he was wrong. Galileo's experiments led him to predict, correctly, that in the absence of air resistance, all falling objects would accelerate downwards at the same rate. English scientist Isaac Newton made sense of Galileo's prediction with his Universal Law of Gravitation.

NEWTON'S GRAVITY

Newton realised that what makes things fall to the ground here on Earth also keeps the Moon in orbit. He proposed that gravity is a force and derived an equation that could predict the strength of the force between any two objects. According to Newton's law, the force depends on the masses of the objects and the distance between their centres.

By combining his law of gravitation with his laws of motion, Newton was able to account for the motions of any object under the influence of gravity – from projectiles on Earth to planets in space. His theory was accepted for over 200 years – and scientists still use his equation in most situations where they need to calculate the effects of gravity. However, in the 19th century,



▲ Newton's theory
In Newton's theory, a star and planet exert an attractive force on each other. Both are subject to an equal force, but the effect on the planet is more obvious because it has a lower mass.

> **NEWTON** HIMSELF WAS BETTER AWARE OF THE **WEAKNESSES IN HIS INTELLECTUAL EDIFICE** THAN THE GENERATIONS OF LEARNED SCIENTISTS WHICH FOLLOWED HIM.

Albert Einstein, German physicist, 1879–1955 calculations of the orbit of planet Mercury, at odds with observations, showed Newton's theory to be flawed. In 1915, German physicist Albert Einstein proposed a radical new theory of gravitation – the general theory of relativity – that could accurately predict the orbit of Mercury. And according to Einstein's theory, gravity is not a force at all.

EINSTEIN'S GRAVITY

General relativity is an extension of special relativity, a theory Einstein published in 1905. Special relativity was an attempt to reconcile Newton's laws of motion with the theory of electromagnetism, developed in the 1860s. To do that, Einstein had to abandon the idea that space and time are absolute: people in motion relative to each other measure distances and intervals of time differently – the differences only become significant at extremely high relative speeds. One of the direct consequences of special relativity was the realization that time is a dimension, just like the three dimensions of space, and that all four exist in a four-dimensional grid called spacetime; objects therefore move through spacetime, not space.

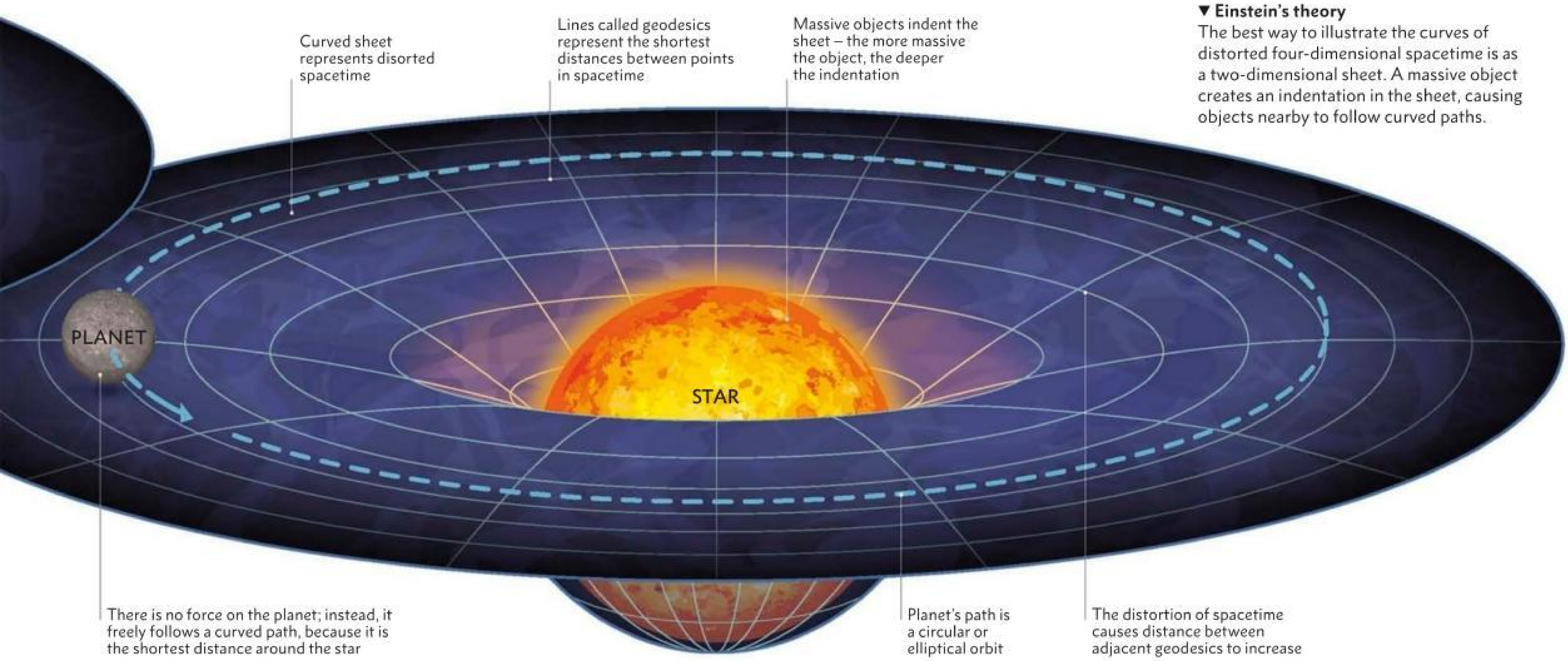
In order to generalize special relativity to include gravity, Einstein realized that objects with mass distort spacetime. The more massive an object, the greater the distortion. Objects travelling freely through distorted spacetime follow curved paths. So projectiles and planets are simply following the equivalent of straight line paths, but in distorted spacetime. A force is needed to change an object's path. For example, the ground pushes upwards on a person's feet, which stops the person from following a path that would take him or her "freefalling" towards the centre of Earth. For a star, the expansion of the hot gas of which it is made provides the force necessary to stop it collapsing – expansion that lasts as long as the star produces heat (see pp.56–57).

EINSTEIN'S PREDICTIONS

The general theory of relativity has been tested many times, to extremely high precision. It has also made several important predictions, such as the idea that light must also follow the curved paths of distorted spacetime. The result is a phenomenon called gravitational lensing, which is evident in the distorted views of distant galaxies whose light has been bent as it passed close to nearby galaxies. Another key prediction is the existence of gravitational waves: ripples in spacetime emanating at the speed of light from any very energetic event. In 2015, scientists detected the first hard evidence of the existence of gravitational waves, produced by the merging of two black holes.

◀ **Gravitational waves** The first gravitational waves ever detected resulted from the merger of two black holes. Here, the waves are represented as ripples in a two-dimensional sheet of spacetime. These ripples were detected by sensitive equipment on Earth.

Despite the success of general relativity, the theory is at odds with quantum mechanics, an equally well-tested cornerstone of modern science. Quantum mechanics accurately describes the behaviour of matter at the atomic and subatomic scales, while gravity accurately describes the behaviour of matter at much larger scales – but the two theories are incompatible. The search for a quantum theory of gravity is a major concern of modern physics, and it is likely that Einstein's theory of gravity will be reinterpreted or superseded as part of a grand theory that can describe the behaviour of matter at all scales. One thing is certain: the puzzle of gravity is not yet solved.



▼ **Einstein's theory** The best way to illustrate the curves of distorted four-dimensional spacetime is as a two-dimensional sheet. A massive object creates an indentation in the sheet, causing objects nearby to follow curved paths.

THRESHOLD

3

INDEX

References in ***italics*** refer to illustrations and photographs, those in **bold** indicate the main information for the topic.

A

B