DK

FOREWORD BY **DAVID CHRISTIAN**

MACQUARIE UNIVERSITY
BIG HISTORY
INSTITUTE | SYDNEY · AUSTRALIA

TIME
BEGINS
STARS FORM
ELEMENTS EVOLVE
PLANETS APPEAR
LIFE DEVELOPS
KNOWLEDGE BUILDS
AGRICULTURE STARTS
INDUSTRY EMERGES

BIG HISTORY

OUR INCREDIBLE JOURNEY, FROM BIG BANG TO NOW

"**BIG HISTORY** PROVIDES A FRAMEWORK FOR UNDERSTANDING LITERALLY ALL OF HISTORY, EVER..."

BILL GATES

BIG HISTORY

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A WORLD OF IDEAS: SEE ALL THERE IS TO KNOW
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Big History Institute

MACQUARIE UNIVERSITY BIG HISTORY INSTITUTE | SYDNEY · AUSTRALIA

Macquarie University was founded with a unique purpose: to bring minds together unhindered by tradition. Created to challenge the education establishment, Macquarie has a rich track record of innovation – Big History is such an innovation. The Big History Institute builds upon the pioneering role that Macquarie University has played in the evolution of the new field of Big History. It brings together a community of scholars and students from both the sciences and the humanities who pursue research questions across disciplinary boundaries and discover new ways of thinking. The Big History Institute is also a global hub for educators, members of the public, and partners from the research, government, non-profit, and business sectors.

Consultants

David Christian, Director, Big History Institute
Professor David Christian (DPhil Oxford) is the founder of Big History. David is a Distinguished Professor at Macquarie University, co-founder with Bill Gates of the Big History Project, presenter of one of the 11 classic TED Talks with over 6 million views, and instructor in the world's first Big History MOOC on COURSERA®. David has given hundreds of presentations internationally, including Davos World Economic Forum in 2012, 2014, and 2015. He is a member of the Australian Academy of the Humanities and the Royal Holland Society of Sciences and Humanities, and a member of the editorial boards of the Journal of Global History and The Cambridge World History.

Andrew McKenna, Executive Director, Big History Institute
Andrew McKenna (BCom LLB UNSW, MIntRel Macquarie) coordinates Big History as an integrated initiative encompassing research, teaching, and outreach. Andrew leads the strategic growth and development of the Big History Institute globally.

Tracy Sullivan, Education Leader, Big History Institute
Tracy Sullivan (BA GradDipEd UWS, MA Macquarie) was on the curriculum development team for Big History Project, and oversees implementation in Australian schools. Tracy coordinates educational initiatives to support the growth and development of Big History globally.

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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 England. 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 England and 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 chemistry, and on to a cosmos that contained 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

FOUNDER OF BIG HISTORY

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 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

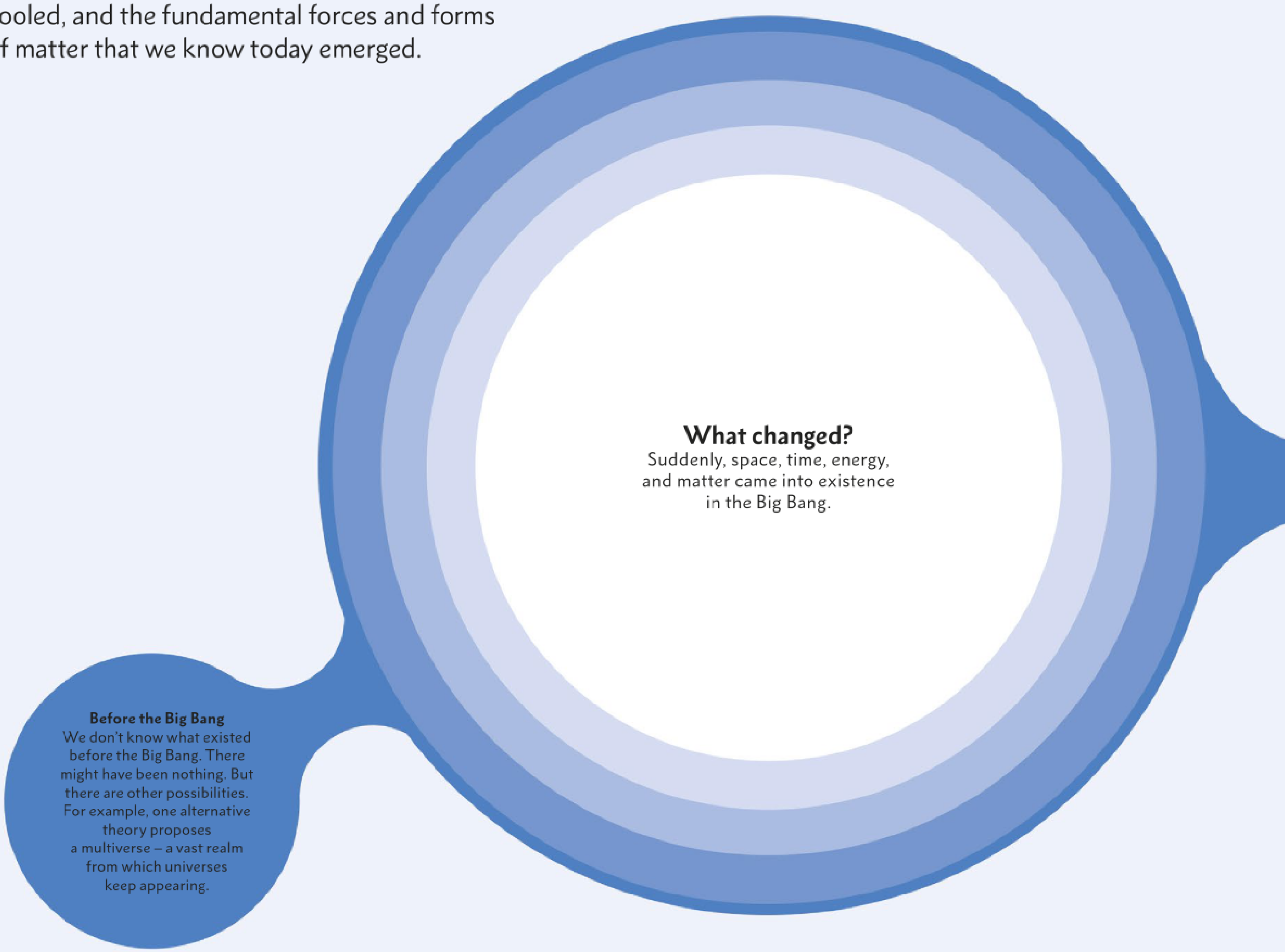
1

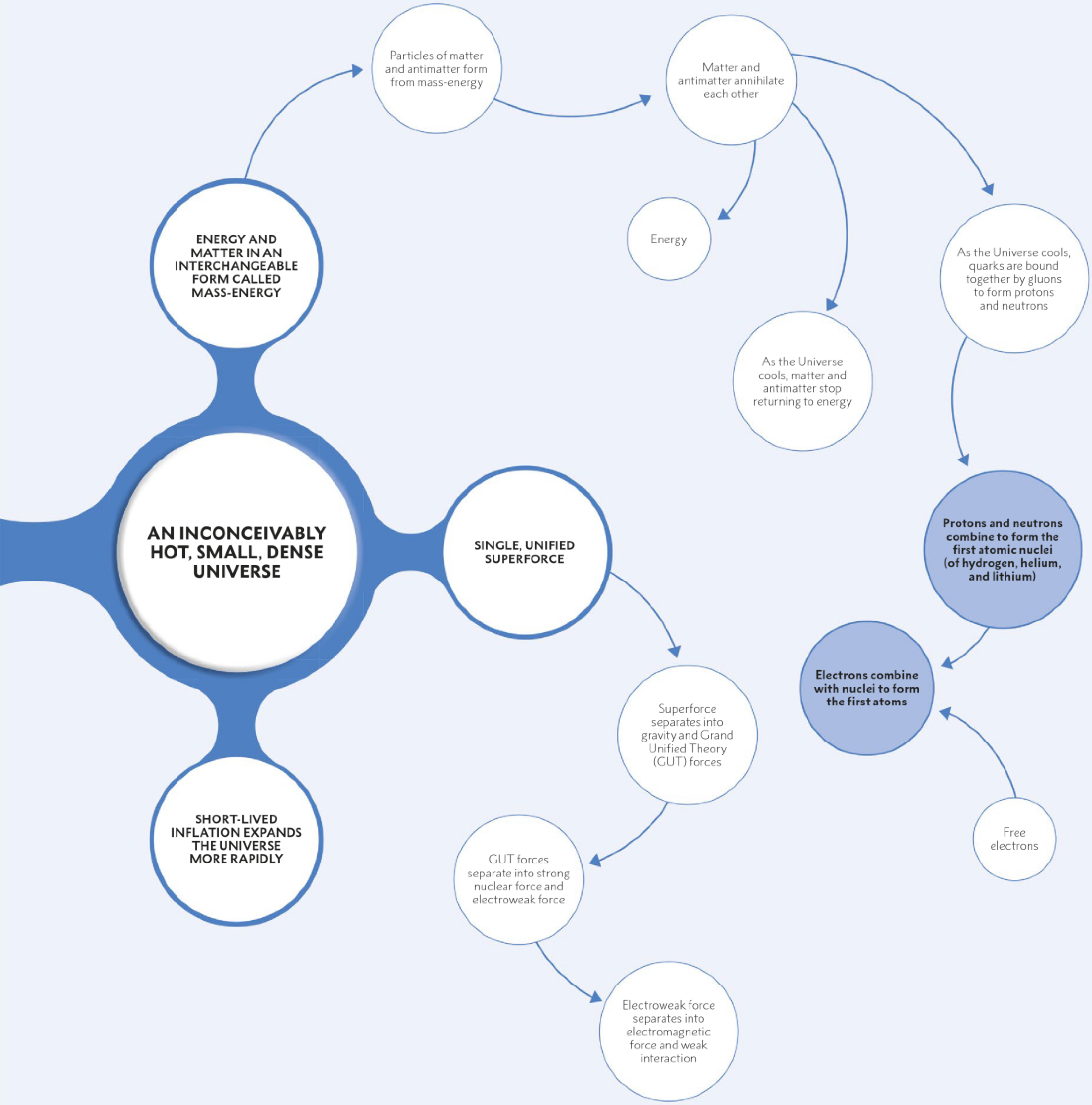
THE BIG **BANG**

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

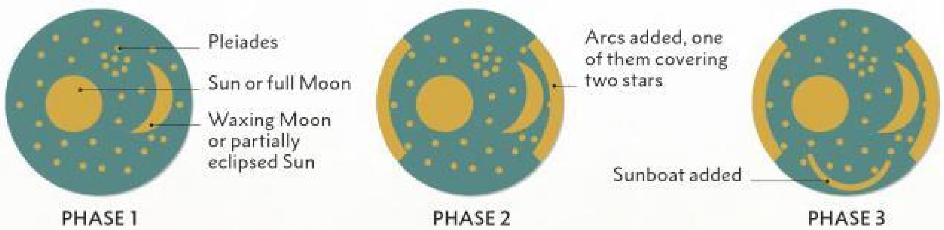
THE NEBRA **SKY DISC**

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.



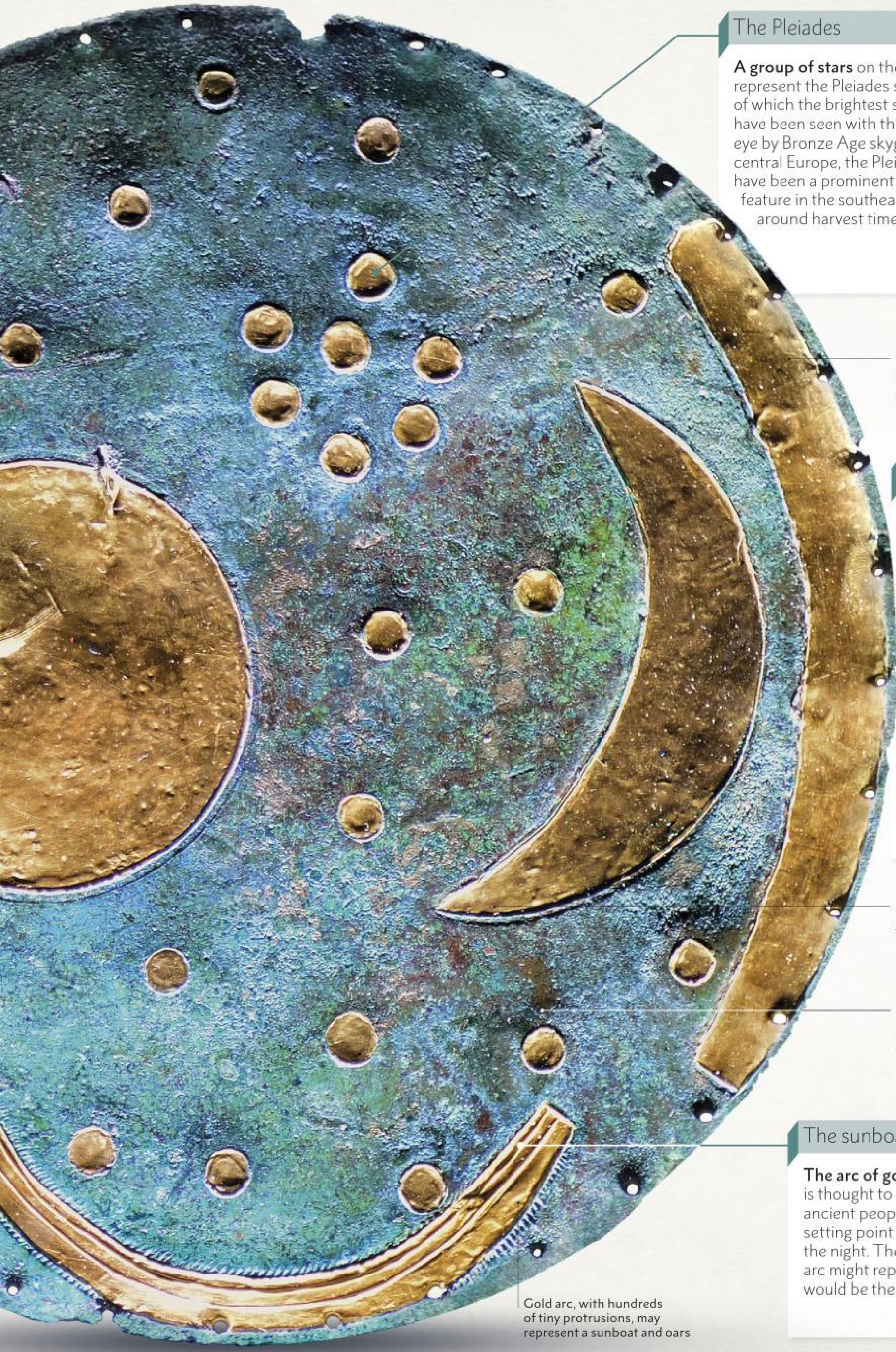
▲ **Phases in construction** The disc was made in three phases, significantly separated in time, suggesting it underwent some repurposing. The addition of the sunboat indicates that it may have taken on religious significance.

► **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

Golden arcs span the angle between the setting (or rising) points of the Sun at summer and winter solstices

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

Gold crescent may signify either a crescent Moon or the Sun during a solar eclipse

Blue-green patina, caused by oxidation of disc's copper content, was probably an intentional decorative feature

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.

Gold arc, with hundreds of tiny protrusions, may represent a sunboat and oars

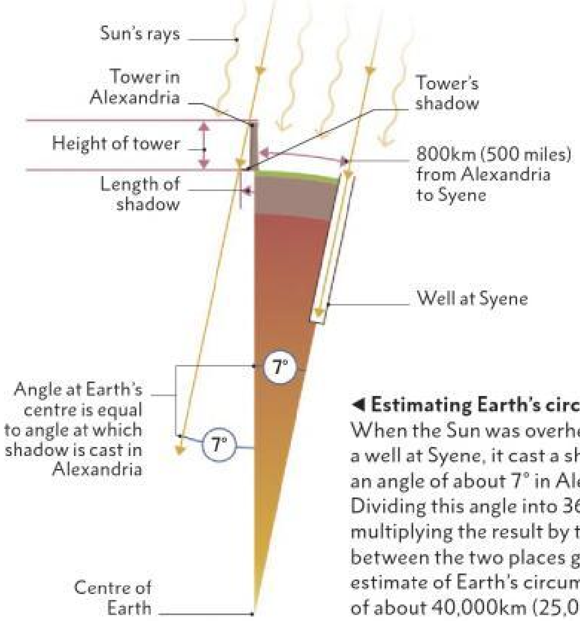
ASTRONOMY BEGINS

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.



◀ 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'S SHAPE AND SIZE

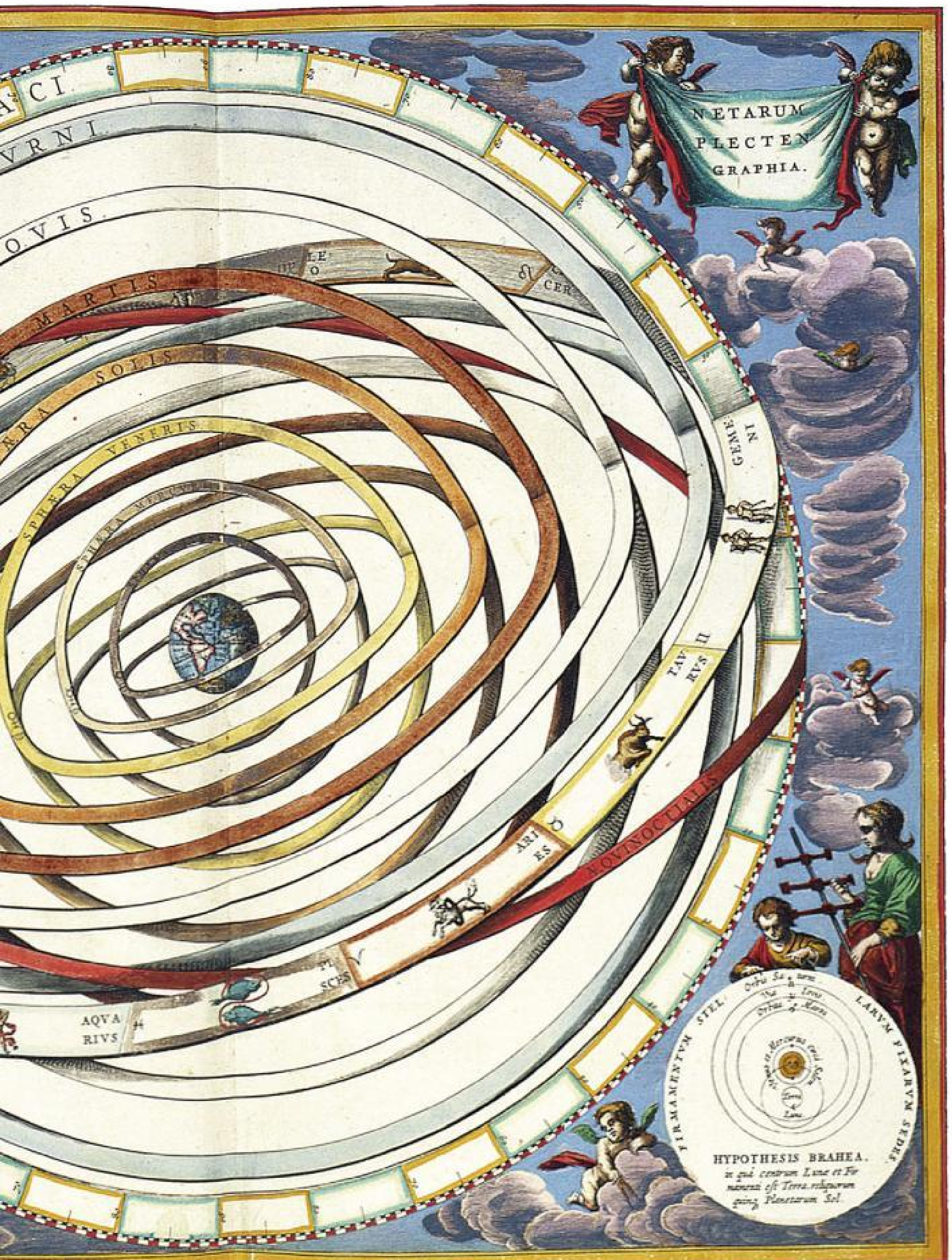
Among many other ideas that Aristotle gave his views on was the concept that Earth is a sphere. Earlier Greek scholars, such as Pythagoras, had already argued this, but Aristotle was the first to summarize the main points of evidence. Chief among them was that travellers to southern lands could see stars 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**

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

BIG IDEAS

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.

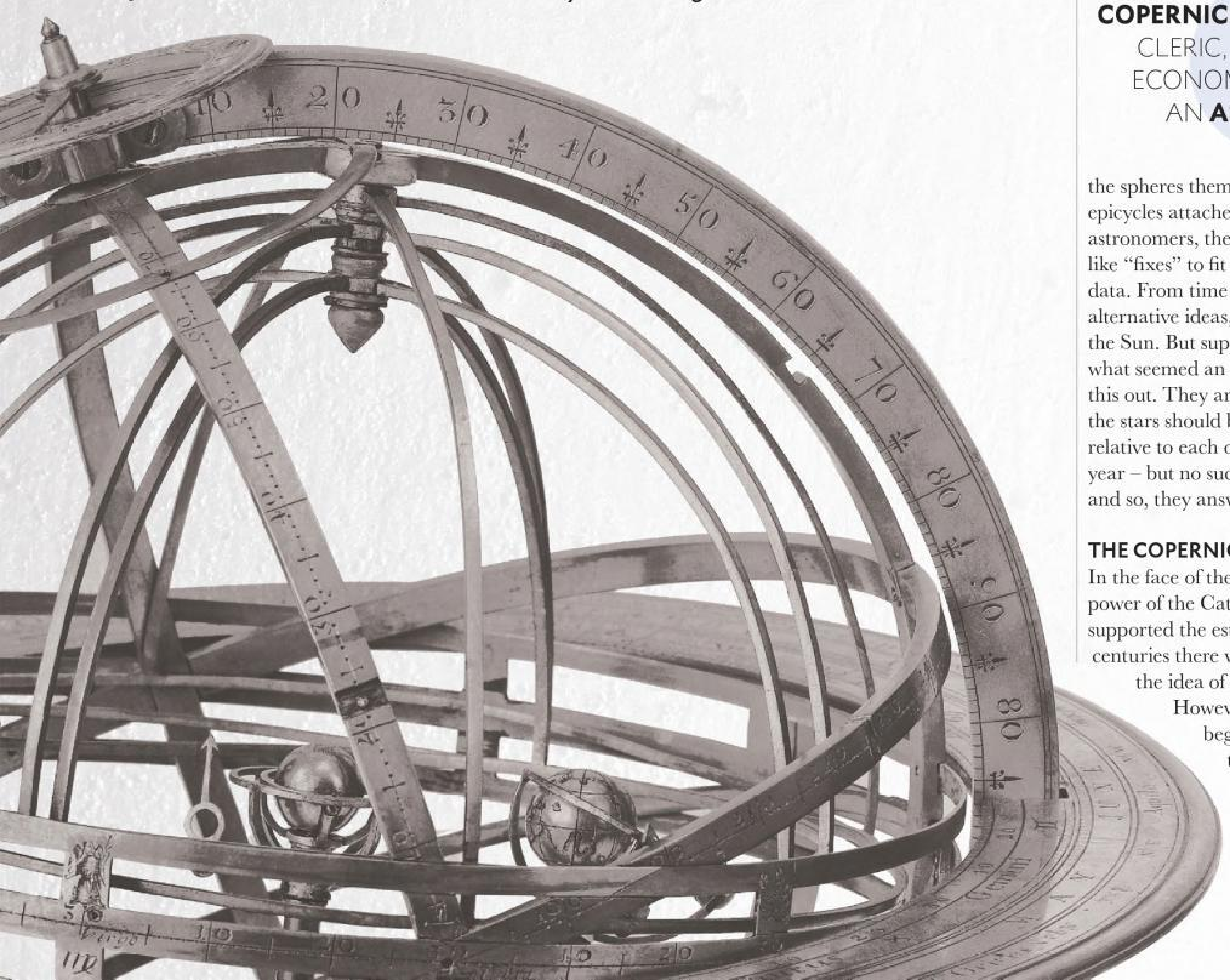
DOUBTS ABOUT GEOCENTRISM

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.

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.

James Webb Space Telescope is due to launch, 2018.

2000

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.

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

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

SPACE TELESCOPES

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

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

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.

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

BEYOND VISIBLE LIGHT

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

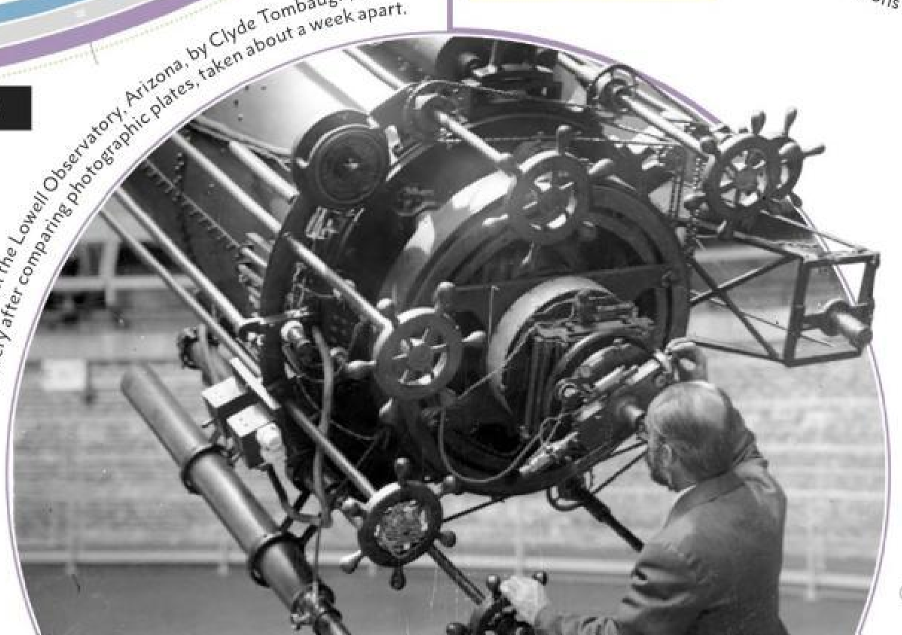
First photograph of a star's spectrum taken by Henry Draper, 1872. The star is Vega, and the photograph shows its absorption lines.

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

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.

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



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.

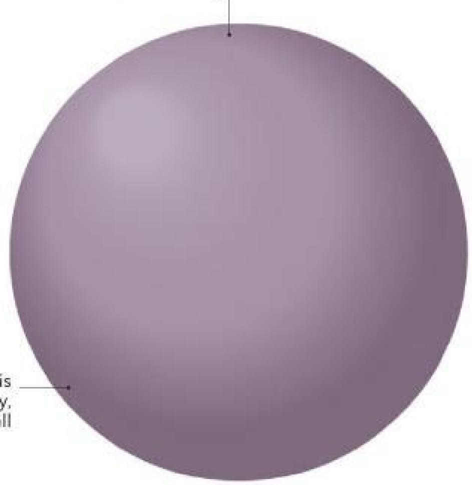
These discoveries paved the way for the advances of the 1930s to the 1950s, from the realization that the Universe is expanding to the development of ideas on how energy and matter interact at the subatomic level. Through the coming together of ideas in cosmology and particle physics, these breakthroughs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

PROBING MATTER AND ENERGY

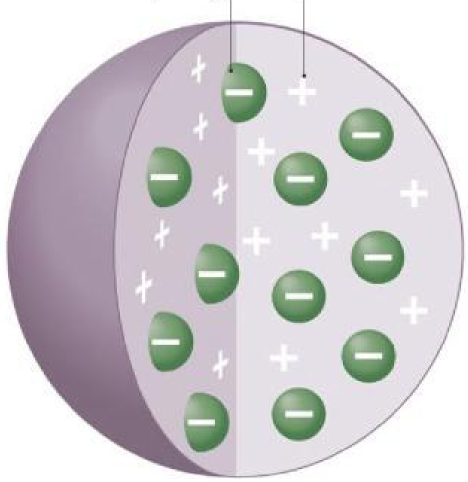
The idea that matter consists of atoms was first suggested by the ancient Greek, Democritus (see p.22). In the early 1800s, an Englishman, John Dalton, revived the idea. Dalton regarded atoms as indivisible, but around the turn of the 20th century experiments by scientists such as the New Zealander Ernest 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

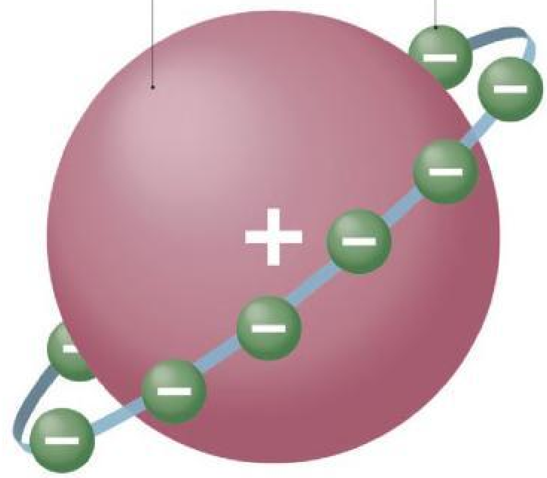
▶ **Understanding the atom** From around 1800 until the mid-1920s, a step-by-step evolution occurred in the understanding of atomic structure. Later, from the late 1920s, physicists found that atomic nuclei have a substructure.



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

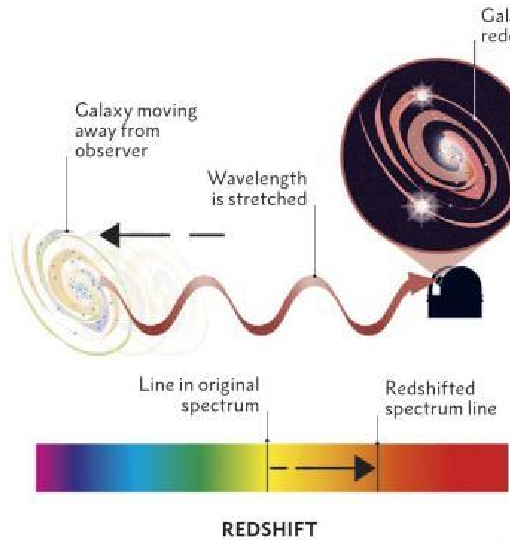
During roughly the same period, great advances were made in understanding the true scale of the cosmos. In 1838, the German astronomer Friedrich Bessell made the first reliable measurement of the distance to a star other than the Sun, using a method called stellar parallax. The star, although one of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

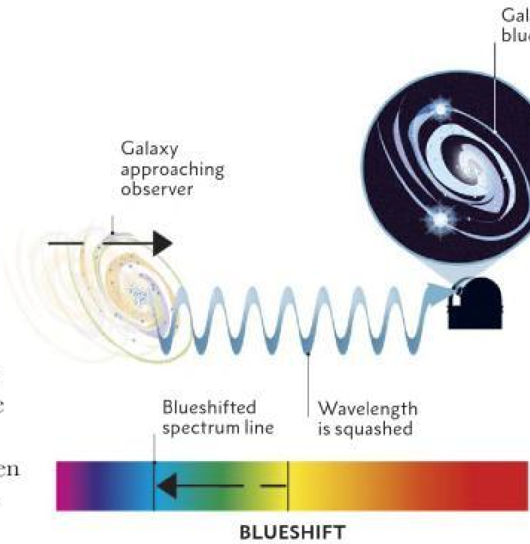
time almost unimaginably far-off – what would now be called 10.3 light-years away. It was 1912 before a system was discovered for estimating the distance to many more remote stars. The discoverer was an American called Henrietta Leavitt. Her breakthrough concerned a class of star called Cepheid variables, 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

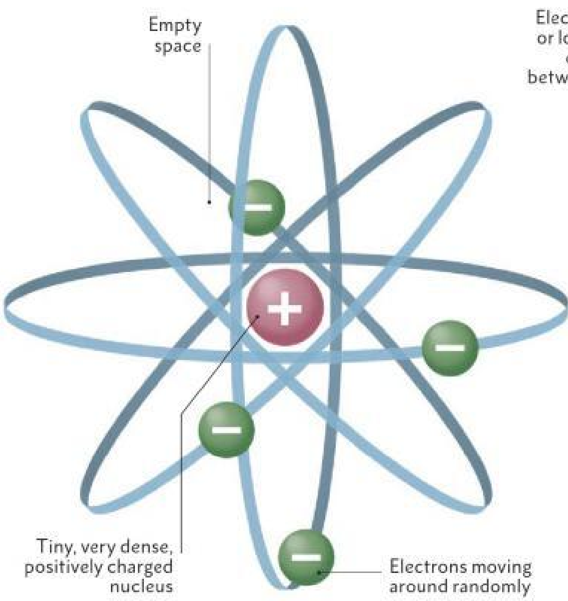
Between 1912 and 1917, the American astronomer Vesto Slipher studied several "spiral nebulae" and realized that many were moving away from Earth at high speed, while a few were approaching Earth. He found this out by measuring a property of the light from the nebulae called redshift or blueshift. It 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).



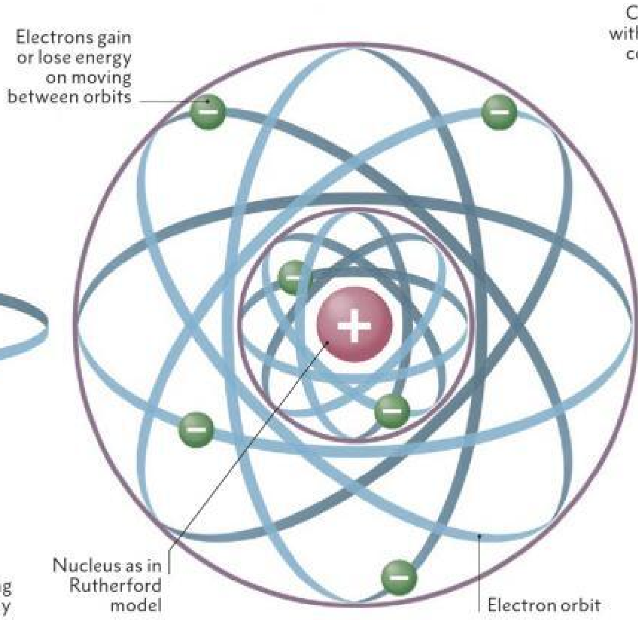
◀ Redshift When an object such as a galaxy is receding at high speed, light waves from it appear stretched. This causes features in the galaxy's spectrum, such as prominent lines, to shift towards the red (long wavelength) end. This is a redshift.



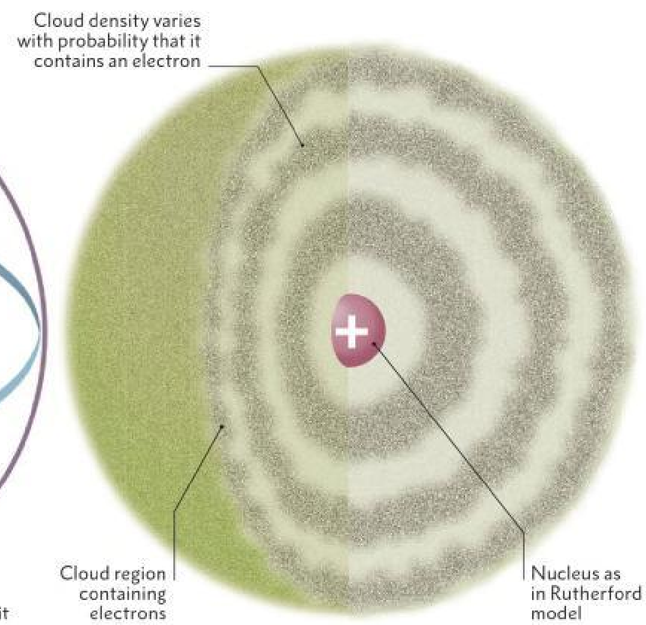
◀ Blueshift Light waves from a rapidly approaching object appear squashed, shifting features in the spectrum towards the blue (short wavelength) end. This is a blueshift.



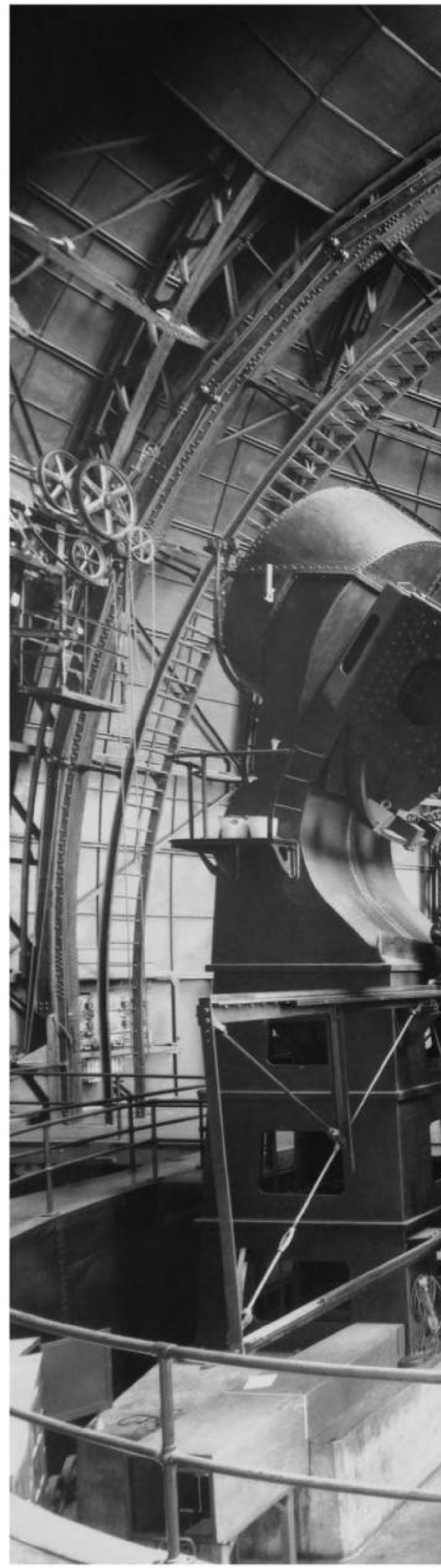
Rutherford and the nucleus (1911) Rutherford proves experimentally that an atom's nucleus is much smaller and denser than previously thought – and that much of an atom is empty space.



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.



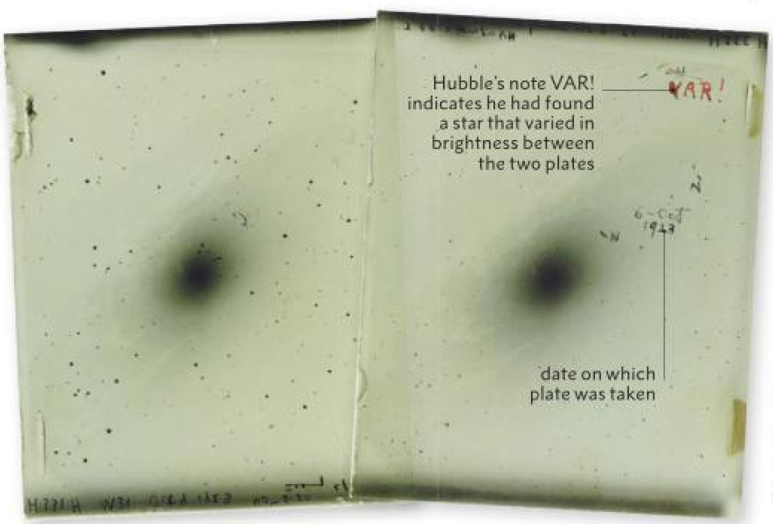
THE UNIVERSE **GETS BIGGER**

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.



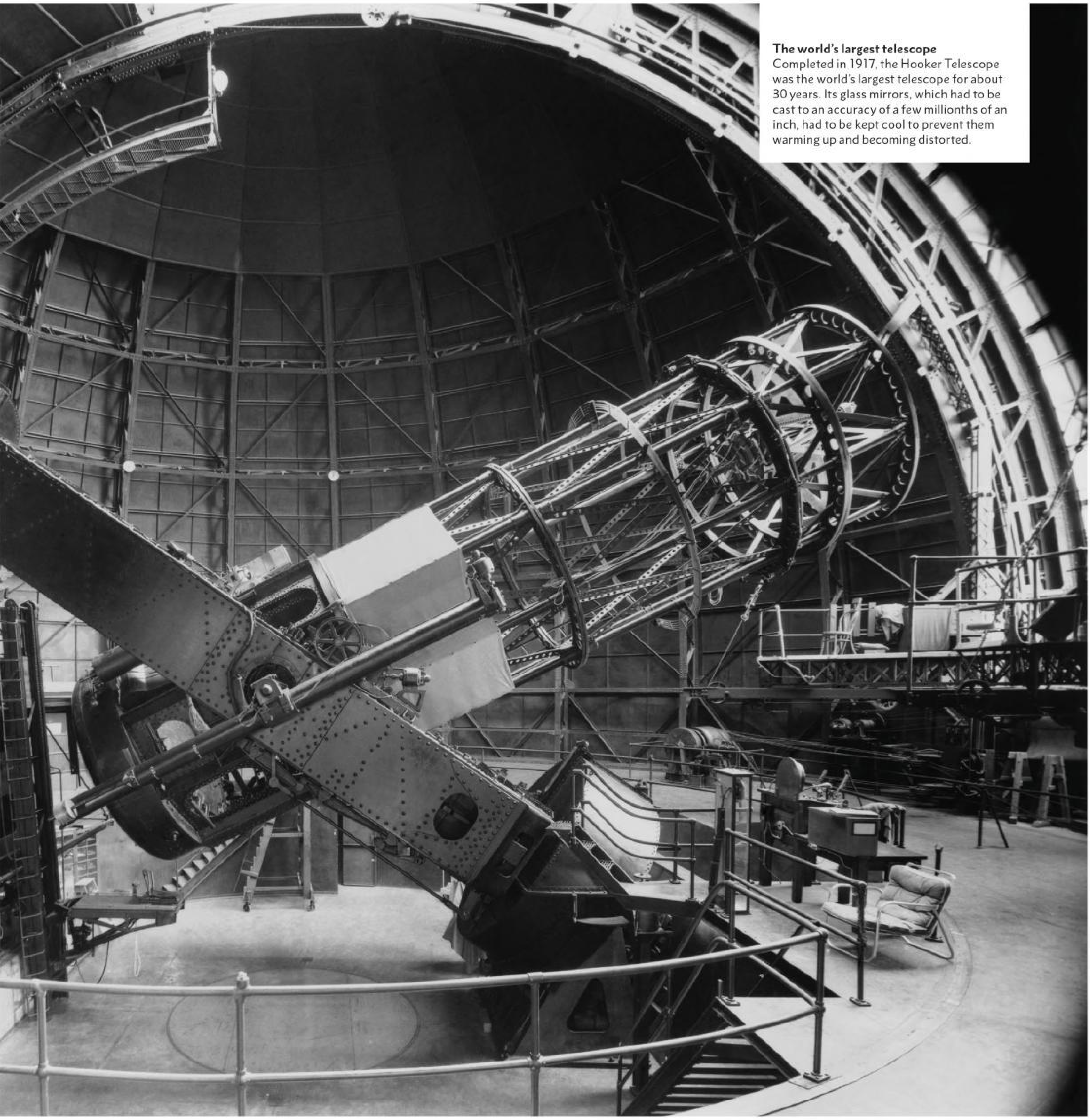
▼ Photographic evidence
These two (negative) photographic plates were used by Hubble to identify a specific Cepheid variable star in the Andromeda Galaxy. Studies on this star were crucial in confirming that the Andromeda Galaxy is outside the Milky Way.

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!

> 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.

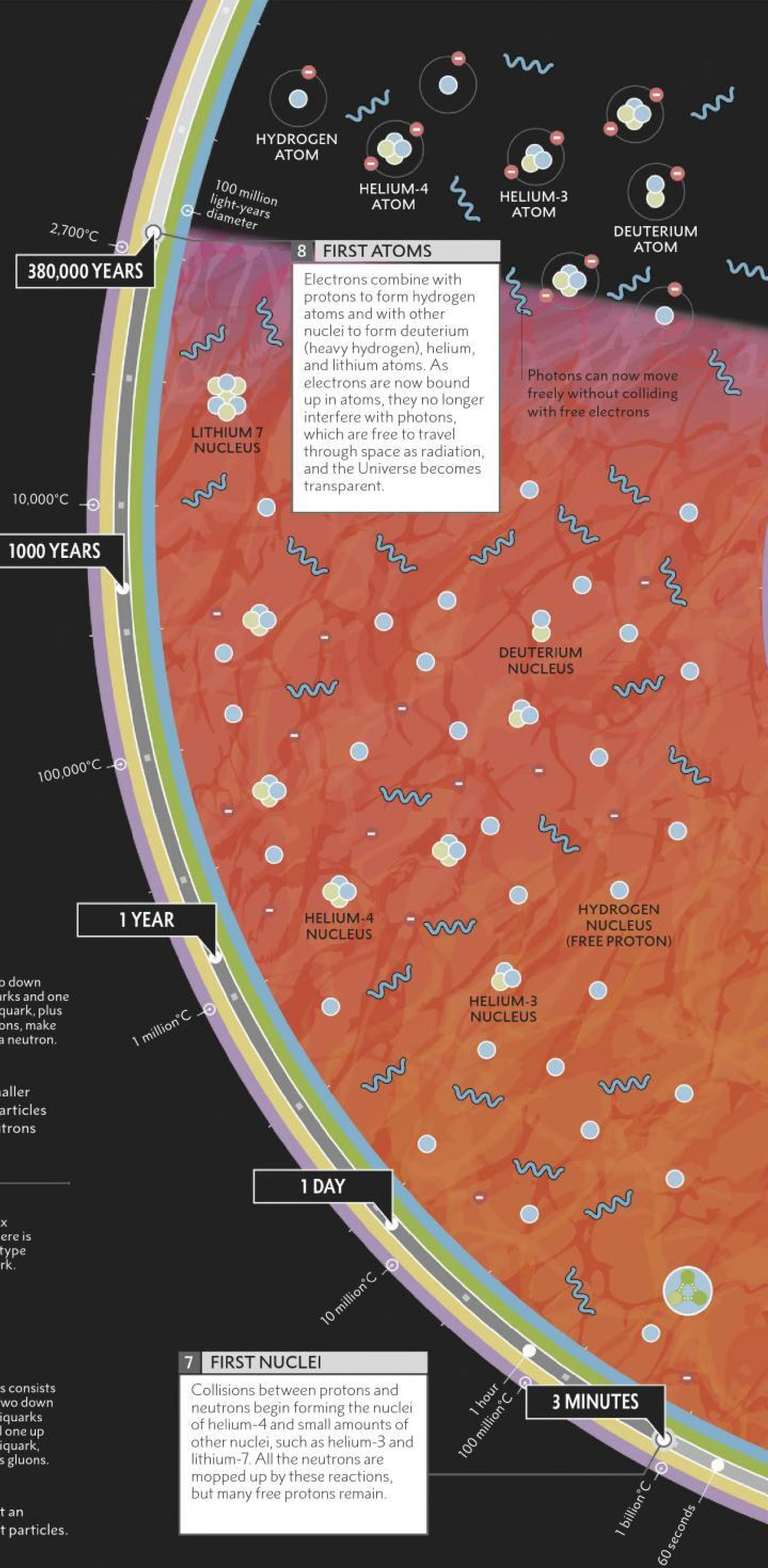
Up antiquark **Down antiquark** For each of the six types of quark there is a corresponding type called an antiquark.

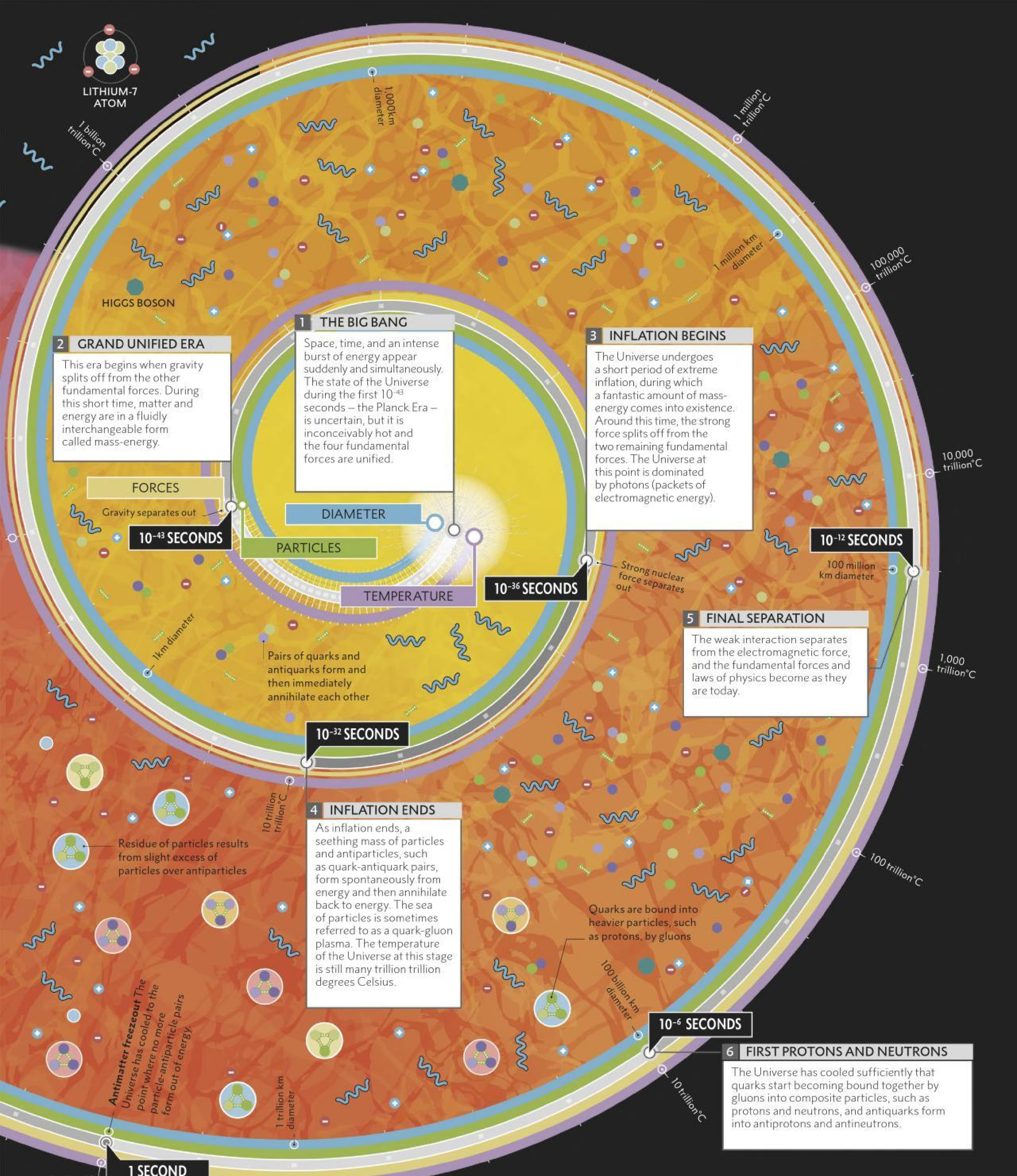
Positron A positron is the positively charged equivalent of the electron.

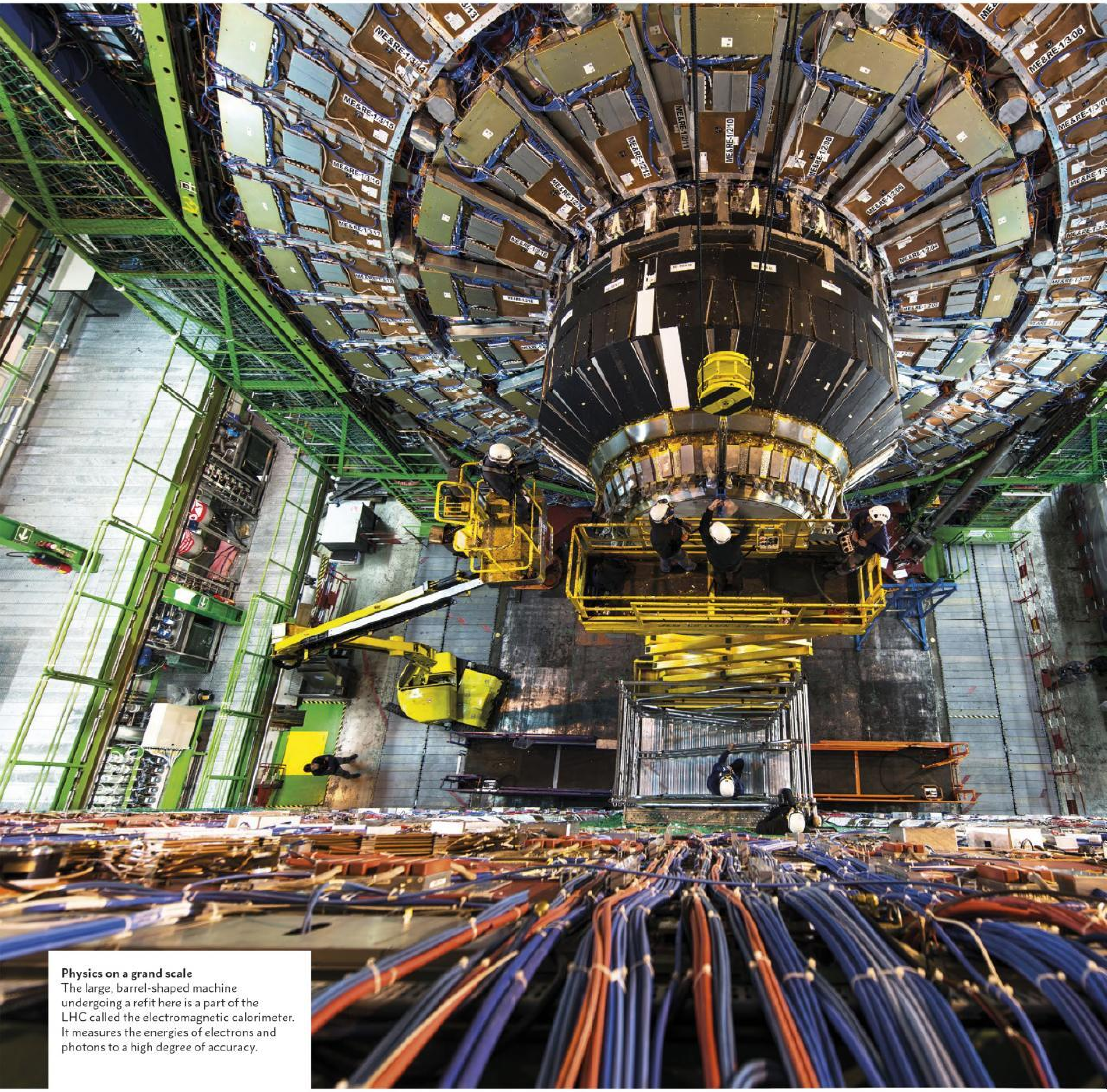
Anti-proton Two up antiquarks and one down antiquark, plus gluons, form an anti-proton.

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

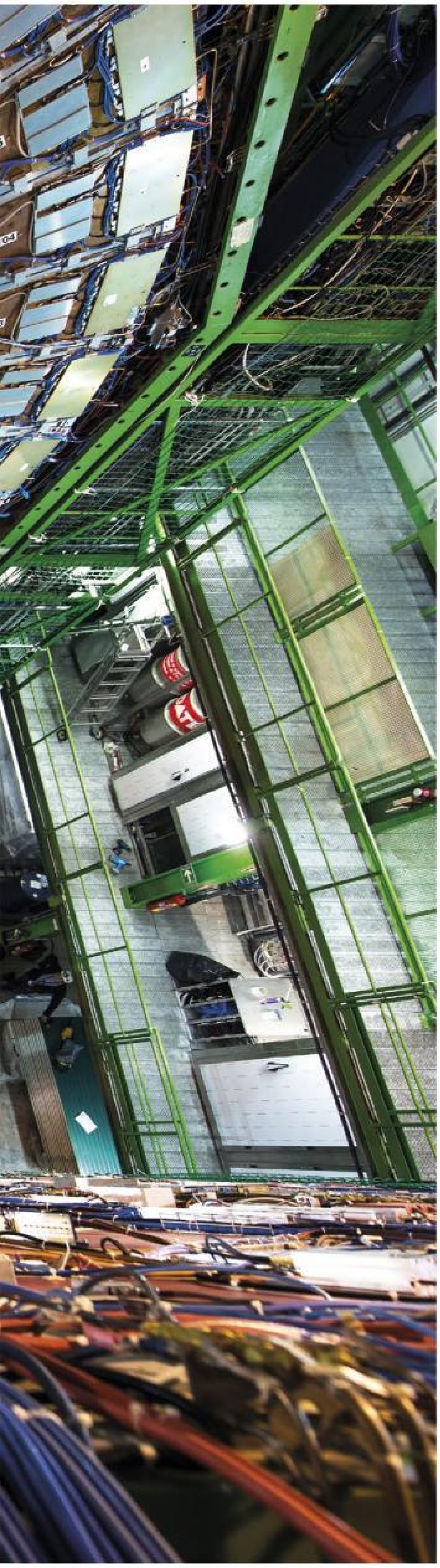
▲ Antiparticles
These are particles with the same mass but an opposite electric charge to their equivalent particles.




LITHIUM-7 ATOM
1 billion trillion°C
1,000km diameter
1 million trillion°C
1 million km diameter
100,000 trillion°C
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).
10,000 trillion°C
FORCES
Gravity separates out
DIAMETER
10^{-43} SECONDS
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.
1,000 trillion°C
1km diameter
Pairs of quarks and antiquarks form and then immediately annihilate each other
10^{-32} SECONDS
10 trillion trillion°C
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
100 trillion°C
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.
10 trillion°C
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
10 billion°C



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.



RE-CREATING THE **BIG BANG**

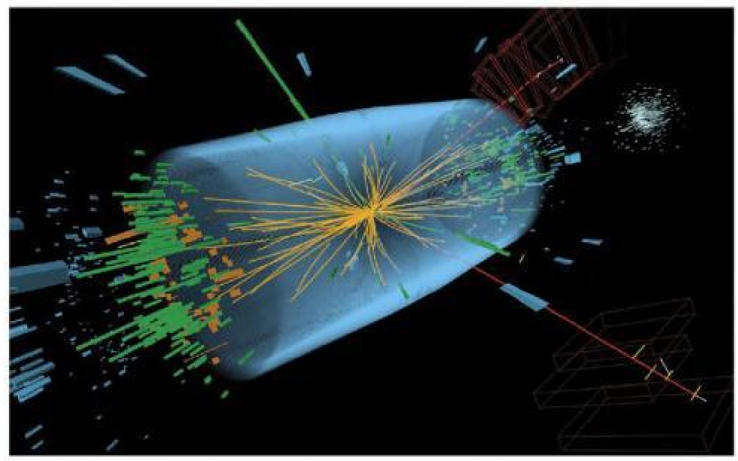
For years, researchers at the European Organization for Nuclear Research (CERN) have used the world's largest particle accelerator – the Large Hadron Collider (LHC) – to smash particles together at extreme speeds to re-create conditions that existed shortly after the Big Bang.

The LHC is the largest, most sophisticated scientific instrument ever built. Located underground on the French-Swiss border, it accelerates two beams of high-energy particles, moving in opposite directions, through pipes connected in a ring with a circumference of almost 27km (17 miles). From time to time, the beams are made to collide, and the results – which typically include the appearance of short-lived, exotic particles – are recorded by detectors around the ring. The purpose of the LHC is to study the range of subatomic particles that can exist and the laws governing their interactions.

Physicists hope these experiments will refine their ideas about what happened in the Big Bang and help them to investigate some poorly understood cosmic phenomena. The Big Bang-type conditions are re-created only in miniature – so there is no chance the experiments could trigger a new Big Bang and the appearance of a new Universe.

NEW DISCOVERIES

One success of the LHC has been to create a quark-gluon plasma, a maelstrom of free quarks and gluons (see p.34) that is thought to have existed for up to a microsecond (a millionth of a second) after the start of the Big Bang. This was achieved in 2015 by colliding protons with lead nuclei, creating minuscule fireballs in which everything broke down momentarily into quarks and gluons.



▲ **Seeking the Higgs boson**
This computer graphic shows a particle collision recorded during the search for the Higgs boson. It displays features that could be expected from the decay of a Higgs boson into two other bosons. One of these decays to a pair of electrons (green lines) and the other to a pair of particles called muons (red lines).

In 2012, a long sought-after, high-mass, extremely short-lived particle called the Higgs boson was detected. Its existence confirmed the presence of an energy field, the Higgs field, that imparts mass to particles passing through it. The significance of this for the Big Bang is that it explains how in the first moments of the Universe particles such as quarks acquired mass, causing them to slow down and combine to form composite particles, such as protons and neutrons.

Other notable successes include the detection in 2014 of a pentaquark (consisting of four quarks and an antiquark). This discovery may allow scientists to study in more detail the strong force that holds quarks together.

> “WE HAVE MADE THE DISCOVERY OF **A NEW PARTICLE** – A **COMPLETELY NEW PARTICLE** – WHICH IS MOST PROBABLY VERY DIFFERENT FROM ALL THE OTHER PARTICLES.”

Rolf-Dieter Heuer, Director of CERN, 1948–, on the discovery of the Higgs boson

BEYOND THE **BIG BANG**

Although the Big Bang model is now accepted by the vast majority of astronomers, additional evidence is continually being sought to support it. There are also some problems with the theory that need to be addressed and some aspects that have yet to be understood.

A general point in favour of the Big Bang model is that an important assumption on which it is based, the cosmological principle (see opposite page), has so far held true. The model also works within the framework of general relativity (see p.32), which is today considered a pillar of cosmology. However, these facts do not necessarily mean the Big Bang theory is correct. To be sure of its validity, specific positive evidence is needed – but there is no shortage of this.

SPECIFIC EVIDENCE

The most important positive evidence for the Big Bang is an extremely faint but uniform thermal radiation coming from the sky called the cosmic microwave background (CMB). Early supporters of the Big Bang theory predicted that this radiation should exist, and in 1964 it was detected by two American radio astronomers. The CMB arose soon after the Big Bang, when photons (small packets of radiant energy) were freed from interacting with matter and began to travel unhindered through space.

Further strong evidence comes from observations of deep space, looking back billions of years in time. Such observations have revealed objects called quasars (the highly energetic centres of galaxies) that no longer seem to exist today. Furthermore, the most distant galaxies – that is, galaxies as they existed 10–13 billion years ago – look different from closer, modern galaxies. These observations suggest the Universe is of a finite age and has evolved over time rather than been static and unchanging.

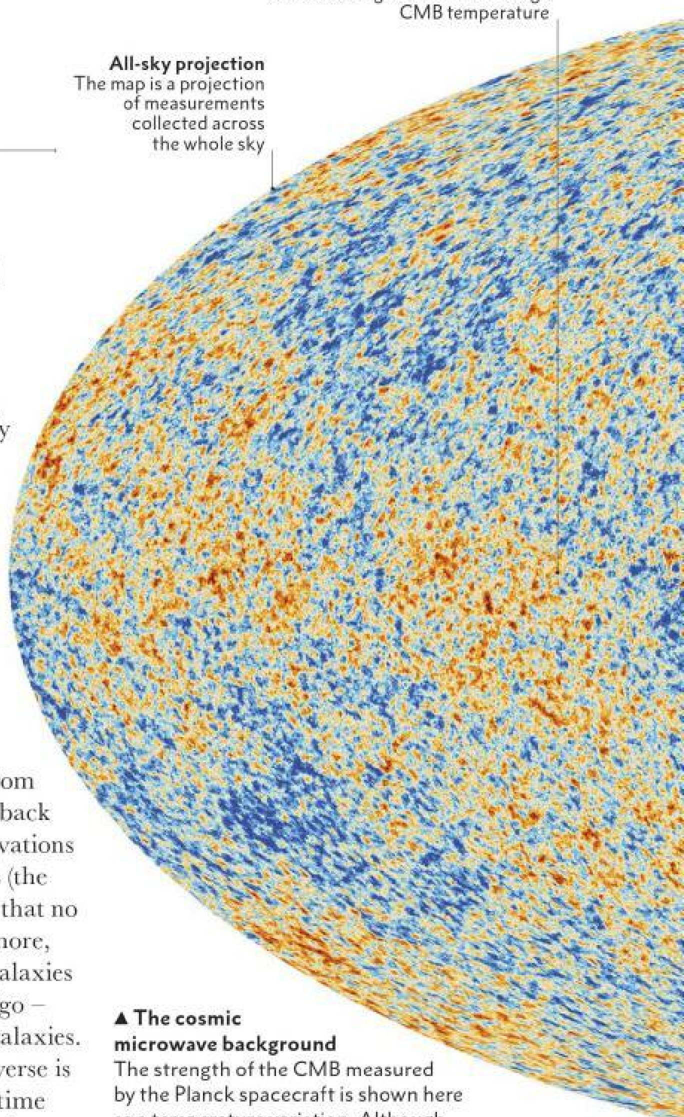
One other important piece of evidence comes from the predominance and proportions of the chemical elements hydrogen and helium in the Universe. The ratios of these two elements in their different forms (called isotopes) agree very closely with what is predicted by the Big Bang theory.

▼ Dark matter
In this image of a galaxy cluster over 7 billion light-years from Earth, called El Gordo ("The Fat One"), the blue haze indicates the distribution of dark matter – hard-to-detect matter that appears to bind galaxy clusters together gravitationally. The pink haze indicates X-ray emissions.

> WE CAN TRACE THINGS BACK TO **THE EARLIER STAGES OF THE BIG BANG**, BUT WE STILL DON'T KNOW **WHAT BANGED** AND **WHY IT BANGED**. THAT'S A CHALLENGE FOR **21ST-CENTURY SCIENCE**.
>
> **Martin Rees**, British cosmologist, 1942–

Red-orange spots
These have a temperature just 0.0002°C higher than the average CMB temperature

All-sky projection
The map is a projection of measurements collected across the whole sky



▲ The cosmic microwave background
The strength of the CMB measured by the Planck spacecraft is shown here as a temperature variation. Although the CMB is uniform across the sky, a finely graded scale has been used to show tiny variations as coloured spots.

UNANSWERED QUESTIONS

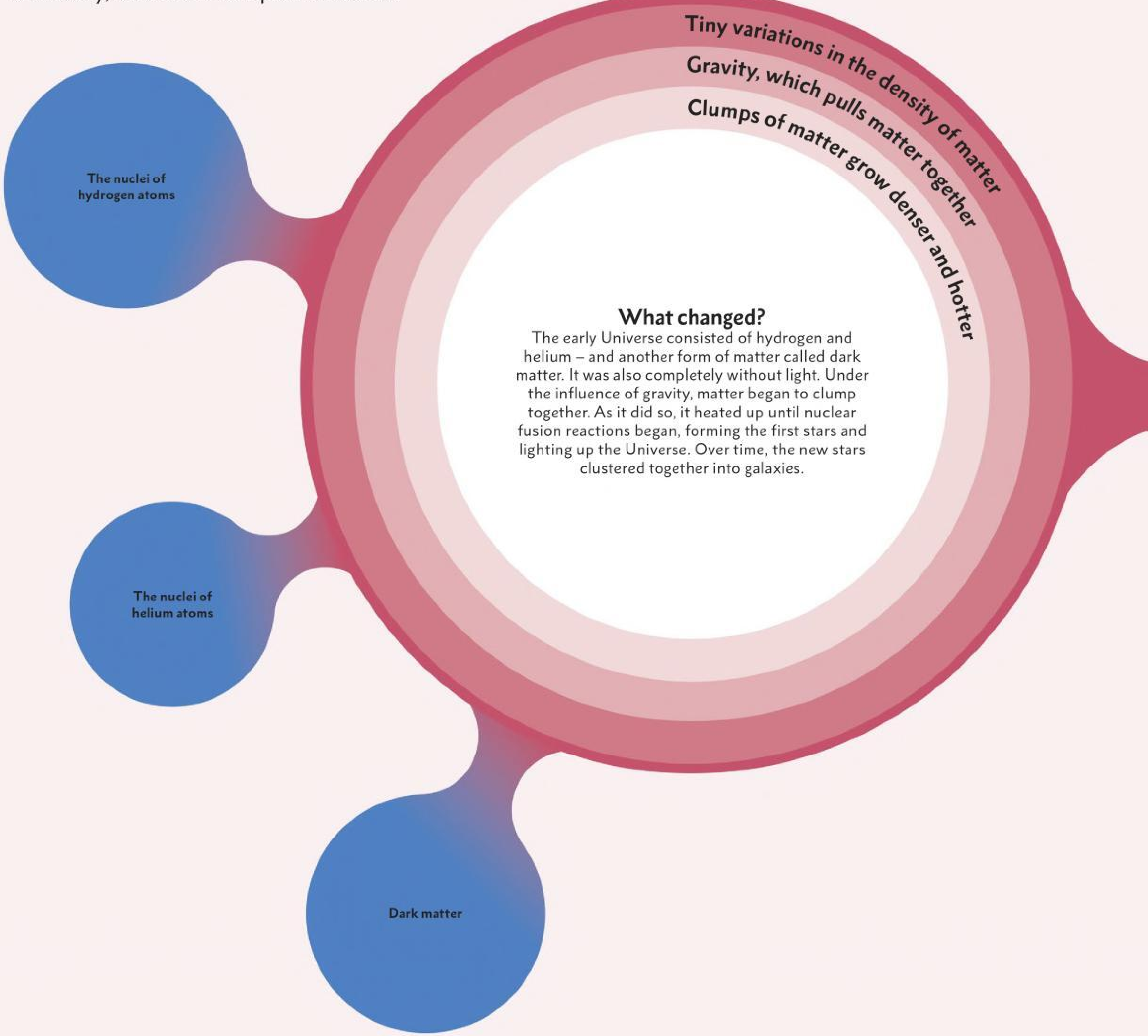
One major problem in cosmology in general is to shed light on the nature of "dark matter" and how it may have arisen in the Big Bang. Dark matter is an unknown substance that emits no light, heat, radio waves, nor any other kind of radiation – making it extremely hard to detect – but it does interact with other matter. Another challenge is to understand "dark energy". In 1998, it was discovered that the expansion of the Universe has been accelerating over the past 6 billion years. The reason for the acceleration is not known, but the mysterious phenomenon of dark energy has been proposed as the cause. Very little is known about it at present, but if dark energy exists, it must permeate the whole Universe.

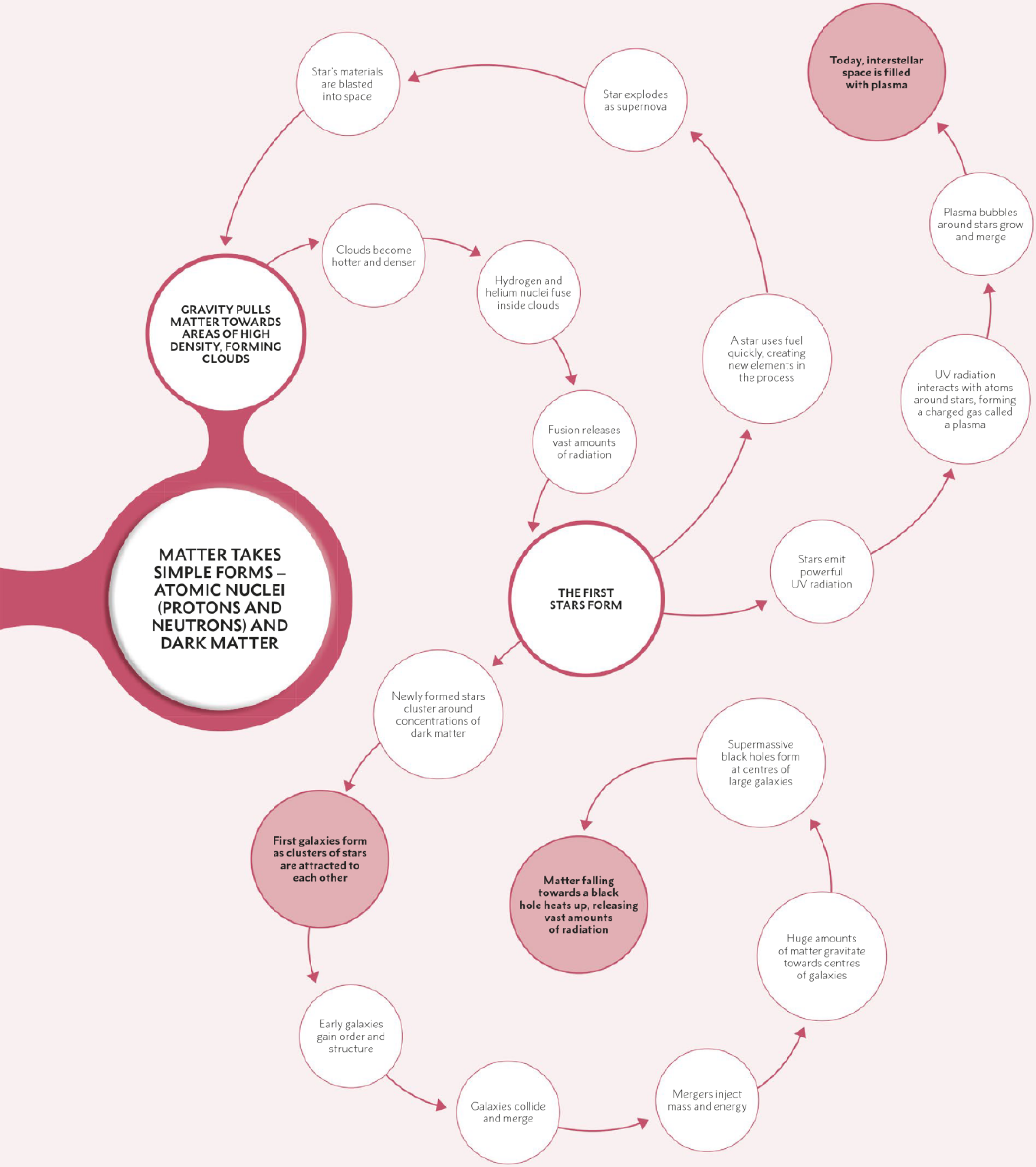
STARS ARE **BORN**

With space, time, matter, and energy in place after the Big Bang, new powerhouses start to appear – stars. These form as matter is packed tighter and tighter together under the influence of gravity. The extremely high temperatures that result cause atoms to fuse together, releasing a huge amount of energy and opening the door to a new level of complexity in the Universe.

GOLDILOCKS CONDITIONS

The early Universe was shaped by two ingredients, both of which emerged while it was less than a second old. Gravity acted on tiny variations in the density of matter, setting in train processes that led to the formation of the first stars and galaxies and, ultimately, a far more complex Universe.




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

THE **FIRST STARS**

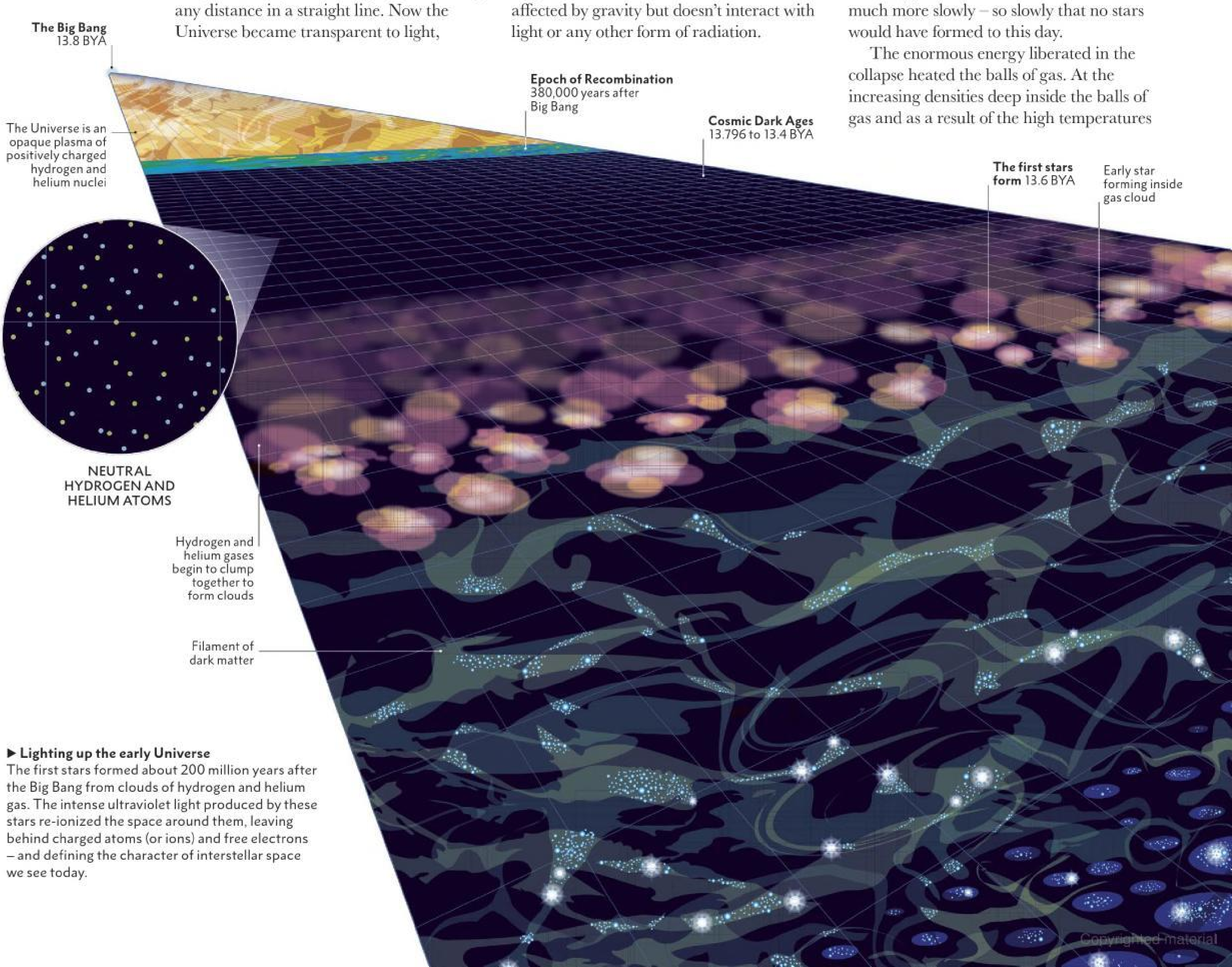
For its first 200 million years, the Universe was a dark place. But things changed dramatically when clouds of gas collapsed to form the first stars. Inside, new chemical elements formed, and at the ends of their short lives the stars exploded, dispersing the elements into space.

During the Epoch of Recombination, 380,000 years after the Big Bang (see p.34), positively charged hydrogen and helium nuclei combined with negatively charged electrons to form neutral (uncharged) atoms. Until this point, collisions with free electrons had prevented photons of light from moving any distance in a straight line. Now the Universe became transparent to light, although it was also dark, for there were no sources of light. It was a time cosmologists refer to as the Cosmic Dark Ages. Amid the dark soup of neutral gas was even darker stuff: dark matter. Scientists have little idea about the nature of dark matter, although they do know there is lots of it and that it is affected by gravity but doesn't interact with light or any other form of radiation.

HOW STARS FORM

Tiny variations in the density of the dark matter and the hydrogen and helium gases caused vast clouds of gas to collapse under the influence of gravity to form huge spherical clumps of matter. This would have happened without dark matter but much more slowly – so slowly that no stars would have formed to this day.

The enormous energy liberated in the collapse heated the balls of gas. At the increasing densities deep inside the balls of gas and as a result of the high temperatures



▶ **Lighting up the early Universe**
The first stars formed about 200 million years after the Big Bang from clouds of hydrogen and helium gas. The intense ultraviolet light produced by these stars re-ionized the space around them, leaving behind charged atoms (or ions) and free electrons – and defining the character of interstellar space we see today.

▲ The size of early stars
According to astrophysicists' best models, most early stars were much larger than the Sun and hundreds of times as massive.

at their cores, hydrogen and helium nuclei collided, and some of them joined together, or fused. This nuclear fusion resulted in the production of more helium nuclei from the hydrogen nuclei, and new, heavier elements – including boron, carbon, and oxygen – from the helium nuclei (see pp.58–59).

The nuclear fusion inside the collapsing balls of gas released a huge amount of energy, enough to heat the gas to incredibly high temperatures. That made the gas expand, buoying it up against further collapse. The high temperature also made the balls of gas glow brightly – to become the first stars.

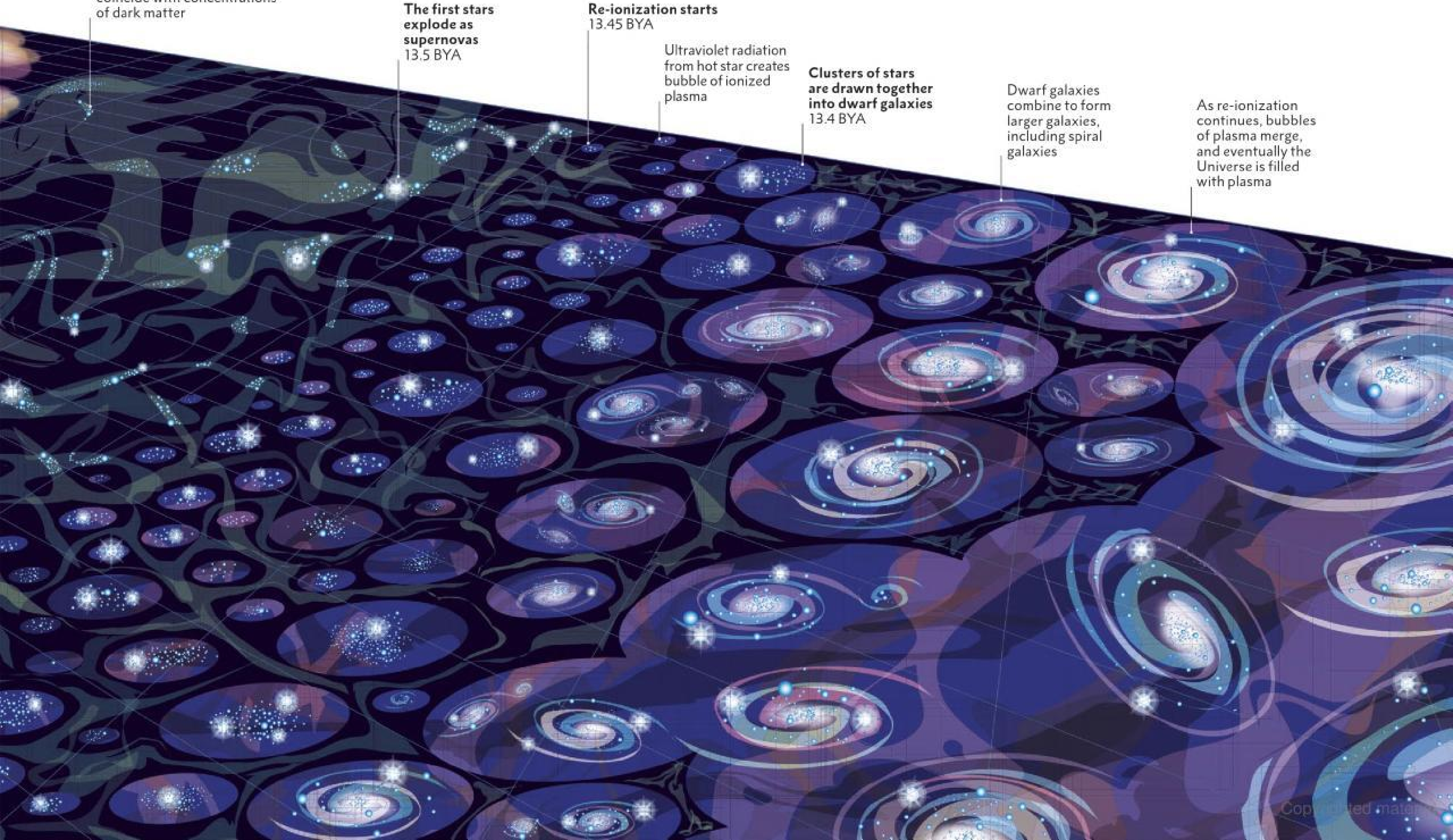
The extremely hot first stars emitted large amounts of powerful ultraviolet radiation that had far-reaching effects. When the intense radiation hit neutral hydrogen and helium atoms still in space, its energy separated the electrons from their nuclei – just as they had been before the Epoch of Recombination. This "re-ionization" created a plasma bubble, of hydrogen ions, helium ions, and free electrons, in the space around each star. Interstellar space today is an extremely tenuous plasma that was created by this re-ionization, and nearly all radiation can pass through it.

SHORT LIVES

The first stars were large and massive: probably dozens of times the diameter of the Sun and with hundreds of times as much mass. Such stars burn out quickly. The first generation of stars probably only lived for a few million years, compared to several billion years for an average star in later generations. As the hydrogen and helium "fuel" began to dwindle at the cores of the stars, they cooled, enabling the collapse to begin again, eventually causing the stars to explode as supernovas (see pp.60–61). The explosions threw a cocktail of new elements and the remaining un-fused hydrogen and helium out into space. This cocktail formed the ingredients of a second generation of stars.

FIRST-GENERATION STARS LIVED ONLY **A FEW MILLION YEARS** BEFORE EXPLODING AS **VIOLENT SUPERNOVAS**

◄ Early light
This is an artist's impression of CR7, a small, bright galaxy. At 12.7 billion light years away, CR7 appears as it was about a billion years after the Big Bang. It represents the best evidence so far of first-generation stars.



THE **FIRST GALAXIES**

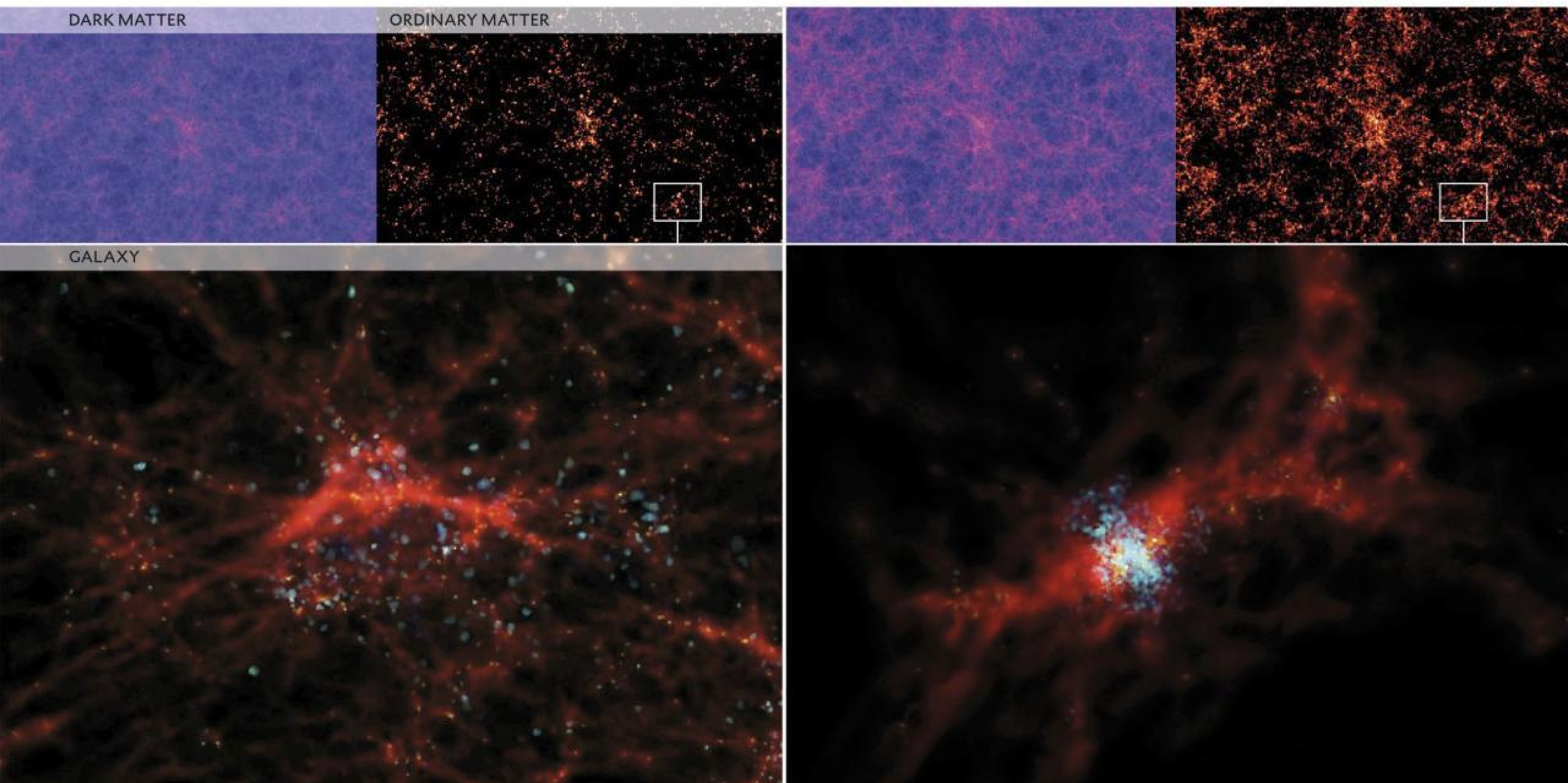
A galaxy is a vast congregation of stars orbiting a common centre. The first galaxies began to form soon after the first stars, around clumps of dark matter. Mutual gravitational attraction caused these small galaxies to merge, each merger sparking new flurries of star birth.

▼ Galaxy evolution In the absence of direct observations, astrophysicists construct simulations to test their theories of how the first galaxies formed. The images below are snapshots from one of those simulations.

Dark matter was crucial in the creation of the first galaxies, just as it was for the formation of the first stars (see pp.44–45). Slight variations in the density of dark matter in the early Universe caused the dark matter and ordinary matter – in the form of hydrogen and helium gas – to clump together. The dark matter formed a network of sinuous filaments and nodes, or haloes, at various scales. The clumping process drove the formation of individual stars as the concentrations of matter began to rotate and heat up, eventually resulting in nuclear fusion (see pp.56–57). At a larger scale, the same process also produced clusters of stars. Each star cluster, plus its surrounding gas, was attracted to neighbouring clusters, and the Universe's first galaxies were born.

GROWING GALAXIES

As matter fell towards matter, the dark matter haloes grew in size, and so did the galaxies. Like water draining down a plug hole, much of the matter began to spin as it fell, so that it went into orbit around the most dense, central part of the halo. As a result, galaxies that began as irregularly shaped masses began to gain order and



0.6 billion years old Dark matter clumps together due to gravity, attracting hydrogen and helium gas (red in the bottom image) into its filaments and nodes. Clusters of stars (blue dots) form where the density is particularly high.

1.0 billion years old The dark matter has further collapsed in on itself, increasing the gravitational attraction on stars and gas. A small, irregularly shaped galaxy forms, its stars orbiting a point at its centre.

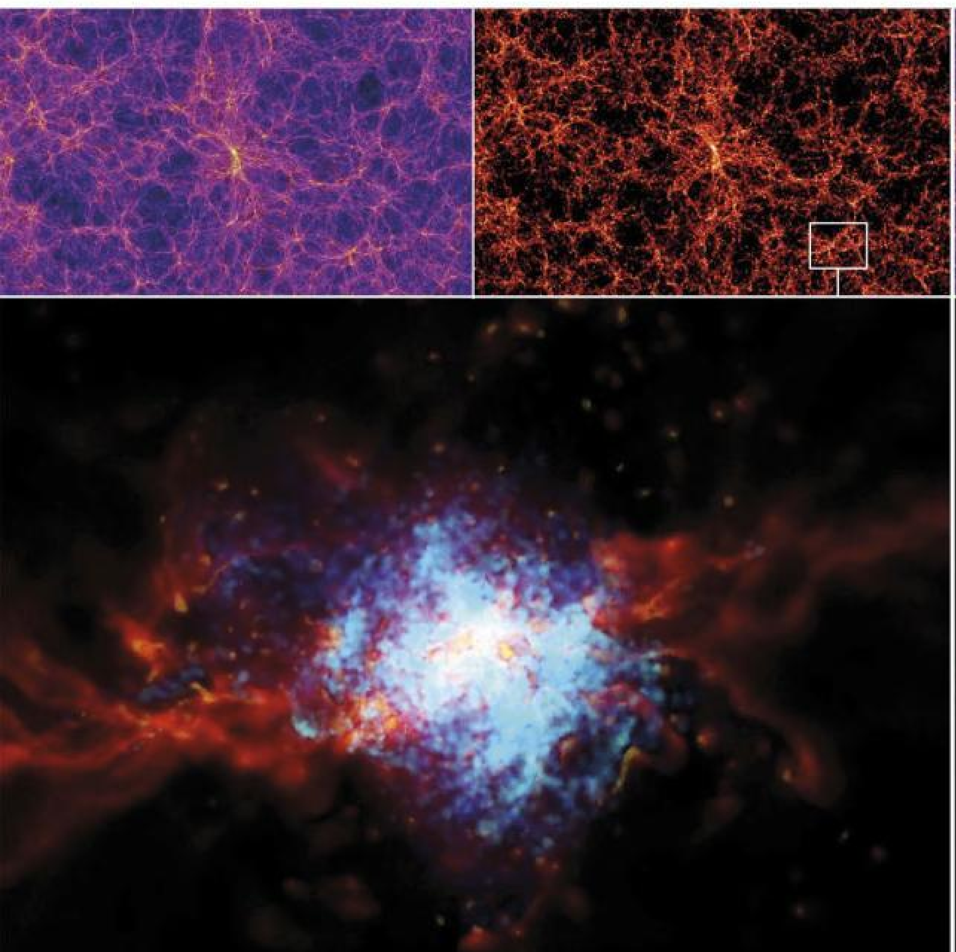
structure. Many formed spinning discs, with spiral arms; others were egg-shaped elliptical galaxies. But with each merger, the structure was disrupted, only to be regained or developed millions or billions of years later. The mergers injected energy and mass, too, and the rate of star formation and star death increased. Each star inside a young galaxy inevitably ended its life in a powerful supernova explosion that filled the galaxy with the elements that would seed the next generation of stars and even planets.

SUPERMASSIVE BLACK HOLES

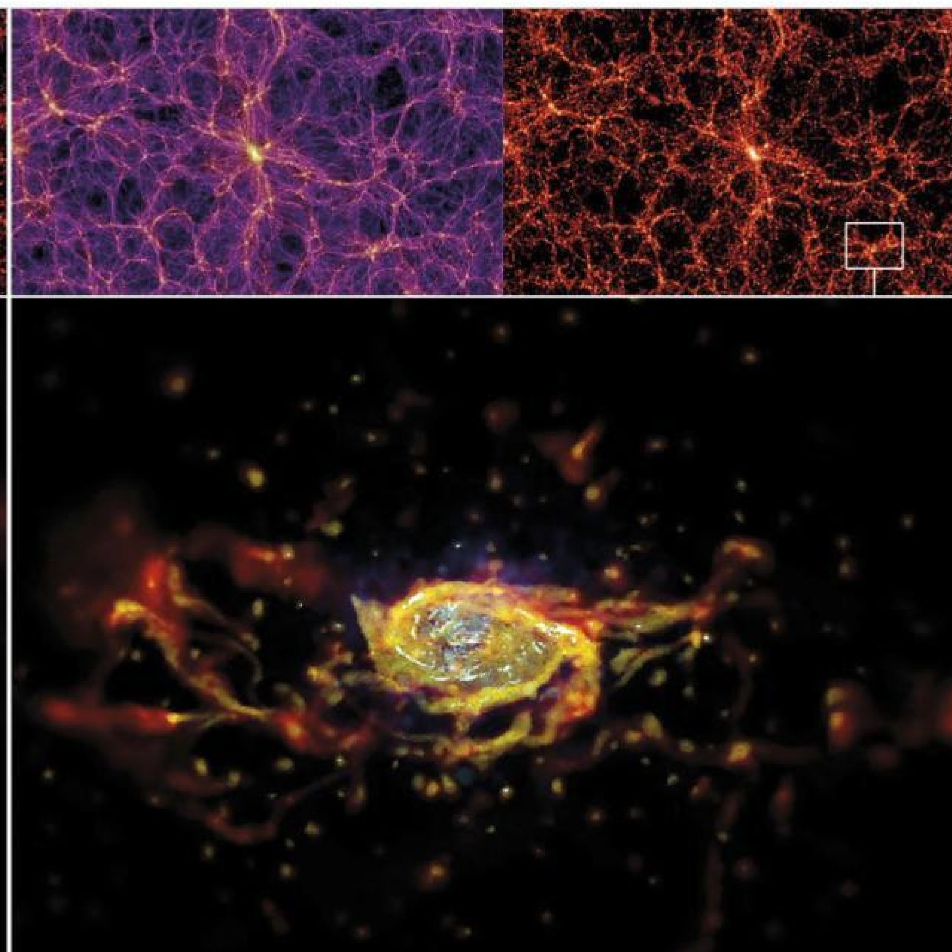
Although much of the gas and many of the stars stayed in orbit around the centre of each galaxy, huge amounts of the matter fell towards the centre. In large galaxies, the density at the centre increased so much that a supermassive black hole (see p.47) formed there. As matter jostled its way in towards the growing black hole, friction heated it to extremely high temperatures, releasing vast amounts of energy as high-energy (short wavelength) X-rays, ultraviolet radiation, and bright visible light. Astronomers first detected these energetic galaxies in the 1950s; they made the discoveries with early radio telescopes, since the short-wavelength radiation has been stretched to such an extent by the expansion of space that it arrives as long-wavelength infrared and radio waves. Most large galaxies in the Universe today, including our own, still have supermassive black holes at their centres.

◀ **Merging galaxies** Astronomers observe many merging galaxies. Shown here is NGC 4676 – also known as the Mice Galaxies – a pair of colliding galaxies around 290 million light-years away.

> “[IN SIMULATIONS] YOU CAN MAKE **STARS AND GALAXIES** THAT LOOK LIKE THE REAL THING. BUT IT IS THE **DARK MATTER** THAT IS **CALLING THE SHOTS**.”
>
> **Professor Carlos Frenk**, cosmologist, 1951–



4.7 billion years old Several galaxies have come together, forming a much larger structure millions of light-years across. Each small galaxy that merges brings new material, and the increasing density leads to a burst of star formation.



13.6 billion years old The galaxy has become stable, merging with others less often. It has a spiral shape, like that of a hurricane, and a supermassive black hole at its core. Fragmented debris of its progenitor galaxies lies around it.

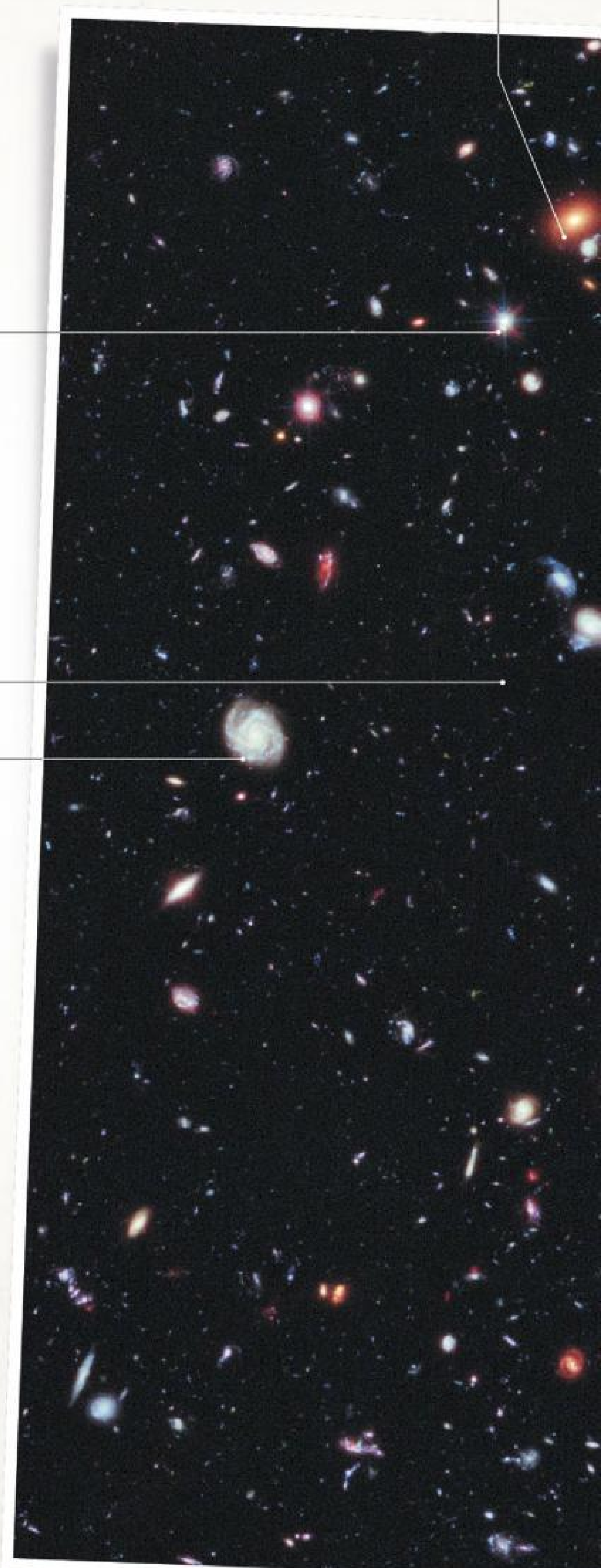
HUBBLE EXTREME **DEEP FIELD**

Taken by the Hubble Space Telescope, the eXtreme Deep Field records faint light from thousands of galaxies in a small area of sky. The deepest view of space ever captured, it provides the best evidence we have about the early Universe's stars and galaxies.

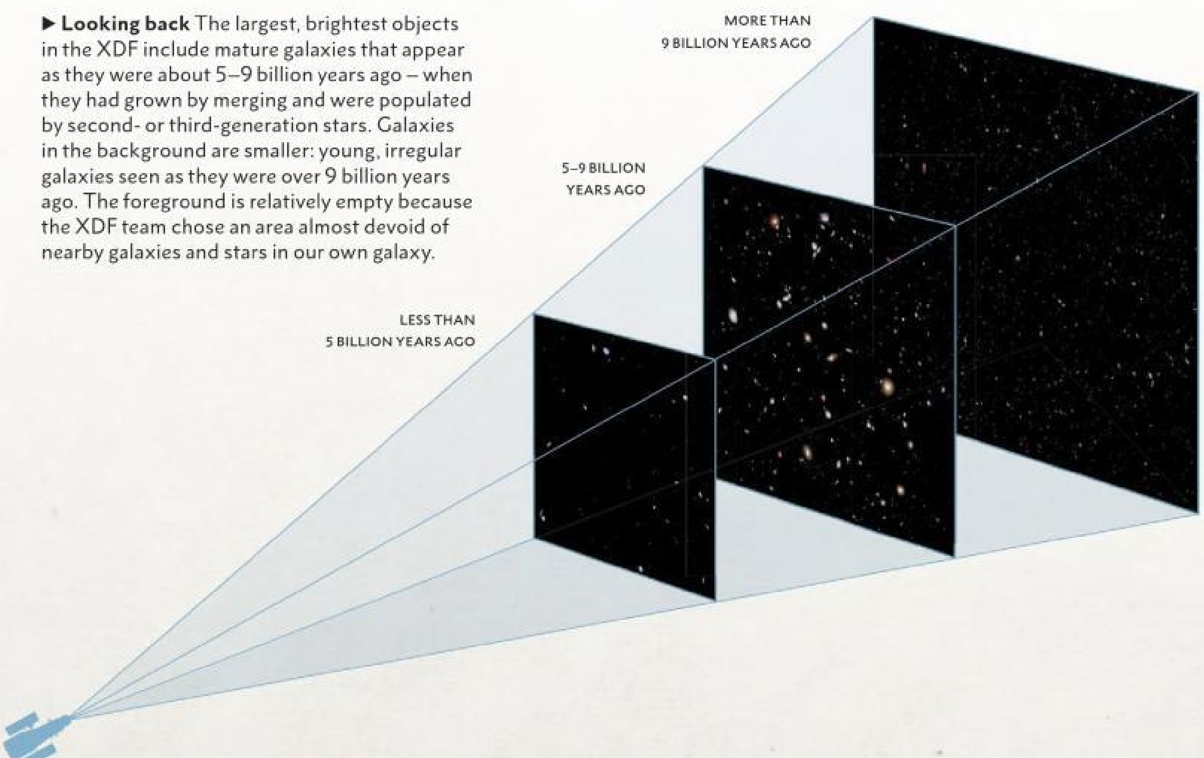
When we look out into space, we are looking back in time, because the light from distant objects left a long time ago. Light that left a galaxy 5 billion years ago will appear extremely faint, however bright the galaxy was at the time. Imaging such a dim object requires a long exposure time – not a fraction of a second, like a typical photograph, but millions of seconds.

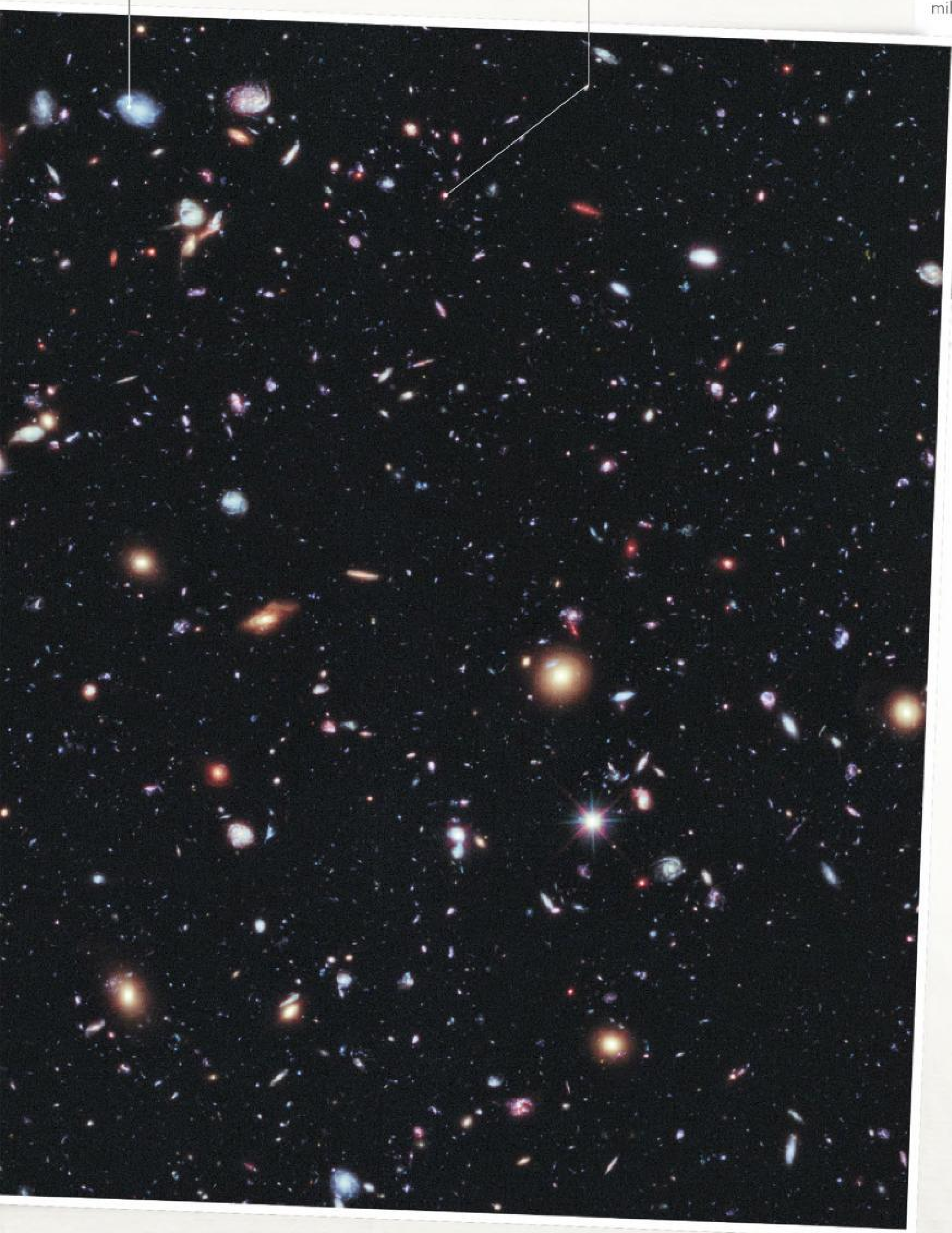
In 1995, astronomers pointed NASA's Hubble Space Telescope at a tiny patch of sky for over 140 hours and combined a total of 342 images into a single, remarkable image called the Hubble Deep Field. In 2004, NASA scientists produced the even more remarkable Hubble Ultra Deep Field – an image with an even longer exposure, on a different patch of sky. Observations on that area continued over the next eight years, and the addition of an infrared camera to the telescope in 2009 meant that objects whose light has been redshifted (see p.29) beyond the visible spectrum and into the infrared could also be seen. The new observations were combined with the Ultra Deep Field, and the result was published in 2012 as the Hubble eXtreme Deep Field (XDF). Light from the most distant galaxies in the XDF took more than 13 billion years to reach us, and they appear one ten-billionth as bright as the dimmest thing visible to the naked eye.

Containing evidence of galaxy mergers (see p.49), extreme redshifting, and gravitational lensing (see p.47), the Hubble XDF is a significant piece of evidence in support of the most convincing theories we have about the evolution of the Universe.



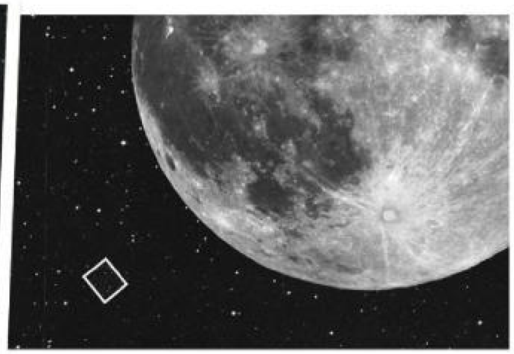
▶ **Looking back** The largest, brightest objects in the XDF include mature galaxies that appear as they were about 5–9 billion years ago – when they had grown by merging and were populated by second- or third-generation stars. Galaxies in the background are smaller: young, irregular galaxies seen as they were over 9 billion years ago. The foreground is relatively empty because the XDF team chose an area almost devoid of nearby galaxies and stars in our own galaxy.





Field of view

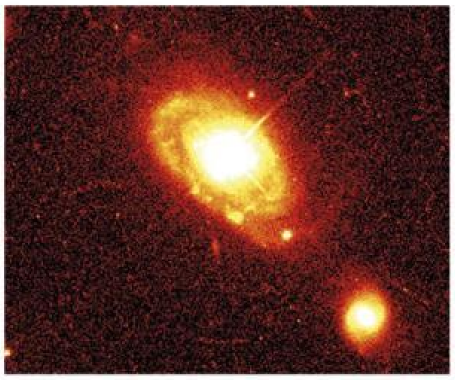
Next to the full Moon, the Hubble eXtreme Deep Field covers a tiny area: less than one twenty-millionth of the area of the whole sky. To see the image at its true size, you would need to hold this page about 300m (1,000ft) away. It is remarkable that more than 7,000 galaxies can be seen in such a small field of view – and to think that each tiny dot in the image is a collection of millions or billions of stars frozen in time.



XDF's field of view, with the Moon for comparison

Early galaxies

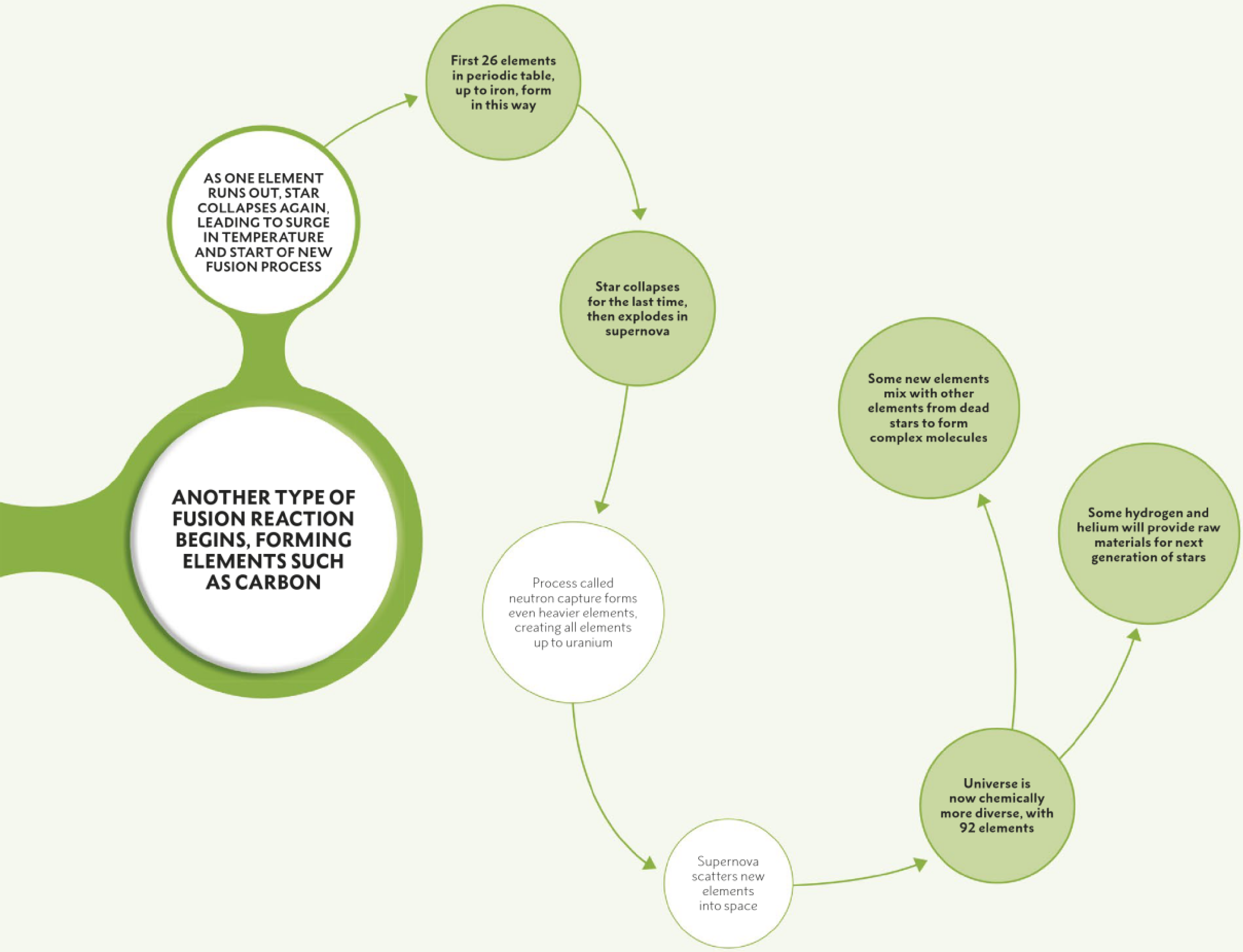
The XDF gives astronomers a unique view of galaxies as they were during the Universe's first few hundred millions of years, when they were relatively small, irregularly shaped groups of stars. As they collided and merged, most became spiral shaped because the collisions resulted in rotation. The Universe was smaller when the light captured in the XDF left the young galaxies. As space has expanded, the light has been "stretched", shifting its frequencies towards or even beyond the red end of the spectrum, which is why so many of the XDF galaxies appear reddish.



Close-up of heavily redshifted galaxy merger

THRESHOLD

3


ANOTHER TYPE OF FUSION REACTION BEGINS, FORMING ELEMENTS SUCH AS CARBON
AS ONE ELEMENT RUNS OUT, STAR COLLAPSES AGAIN, LEADING TO SURGE IN TEMPERATURE AND START OF NEW FUSION PROCESS
First 26 elements in periodic table, up to iron, form in this way
Star collapses for the last time, then explodes in supernova
Process called neutron capture forms even heavier elements, creating all elements up to uranium
Supernova scatters new elements into space
Universe is now chemically more diverse, with 92 elements
Some new elements mix with other elements from dead stars to form complex molecules
Some hydrogen and helium will provide raw materials for next generation of stars

THE **LIFE CYCLE** OF A **STAR**

Just like humans, stars are born, grow old, and die. The way a star ends its days depends on its mass, with the largest stars exploding as supernovas. These detonations furnished, and continue to furnish, the Universe with heavier elements, recycling material ready for it to be turned into new stars.

Consequently, the life cycle of stars also played a crucial role in the emergence of life on Earth. Essential ingredients – including the calcium in your bones and the iron in your blood – were forged inside stars, only for supernovas to spread them far and wide.

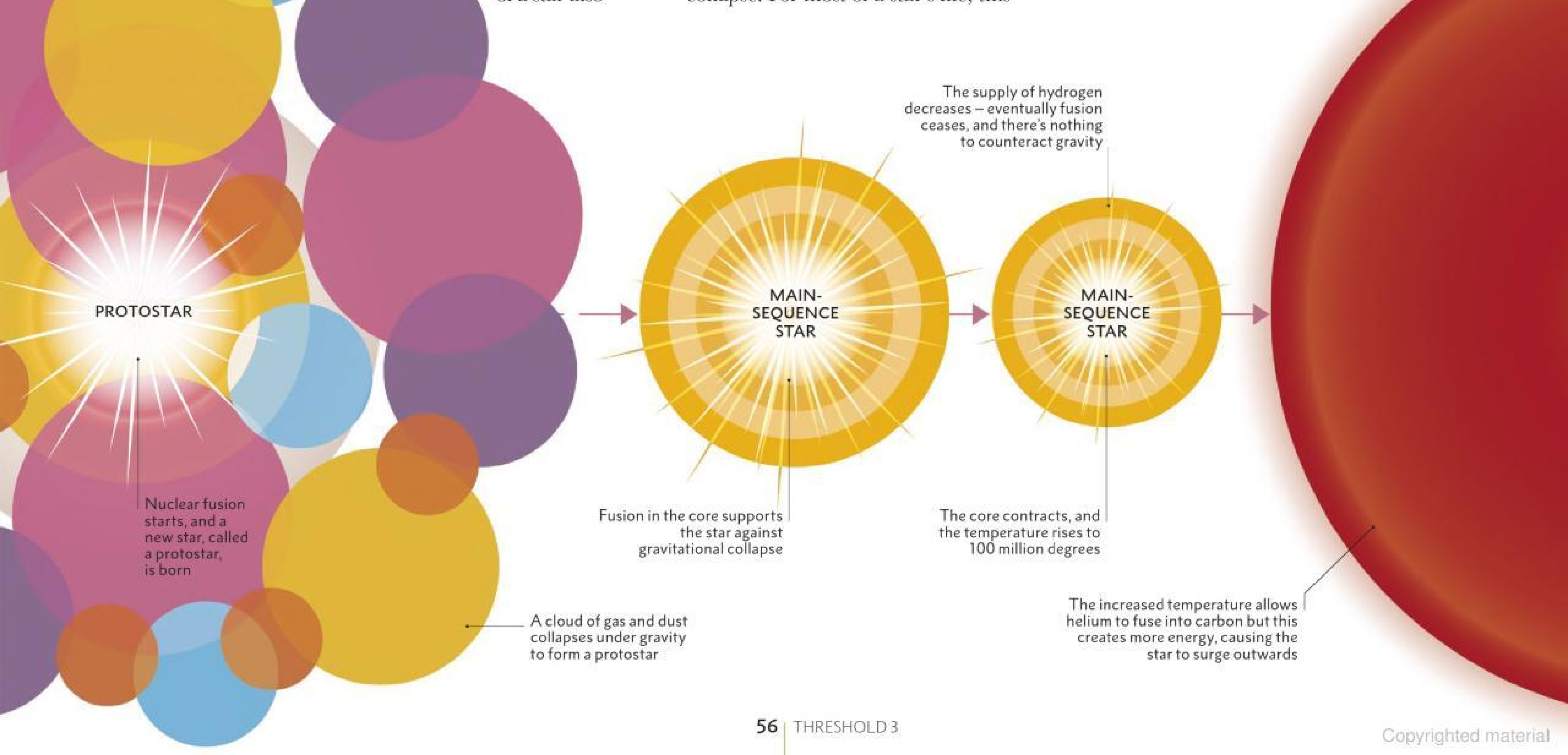
Stars come in a vast array of sizes. Astronomers classify them into seven main groups from largest to smallest denoted by the letters O, B, A, F, G, K, and M. Our Sun is a G star, meaning there are bigger and smaller stars out there than our own. The smallest stars, known as dwarfs, are the most common. M stars, for example, make up more than 75 per cent of all stars. By contrast, O stars account for just 0.00003 per cent. The size of a star also governs how long it will live. The larger the star, the quicker it will consume its nuclear material. O stars live fast and die young, often dying out within just a few million years, whereas the smallest stars can eke out their existence for trillions of years.

A **SUPERGIANT STAR** CAN HAVE A VOLUME **8 BILLION** TIMES THAT OF **THE SUN**

LIFE STAGES

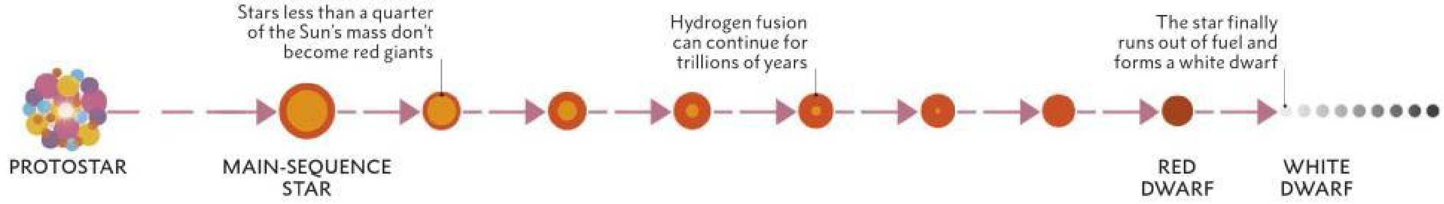
Stars begin their lives as protostars, formed from clouds of interstellar dust (see pp.44–45). Nuclear processes in a star's core then shore it up against gravitational collapse. For most of a star's life, this balance is maintained, but things change when fusion eventually stops. Astronomers refer to a star still fusing hydrogen into helium as a main-sequence star. Once this fusion ceases, the star evolves off the main sequence.

For all but the smallest stars, the core contracts and the temperature rises to around 100 million degrees Celsius. This is hot enough for helium to fuse into carbon, which creates enough energy to upset the balance the other way and the star bloats outwards. Then, depending on size, it will either turn into a planetary nebula with a white dwarf at the centre, or detonate as a supernova, leaving behind a neutron star or black hole.

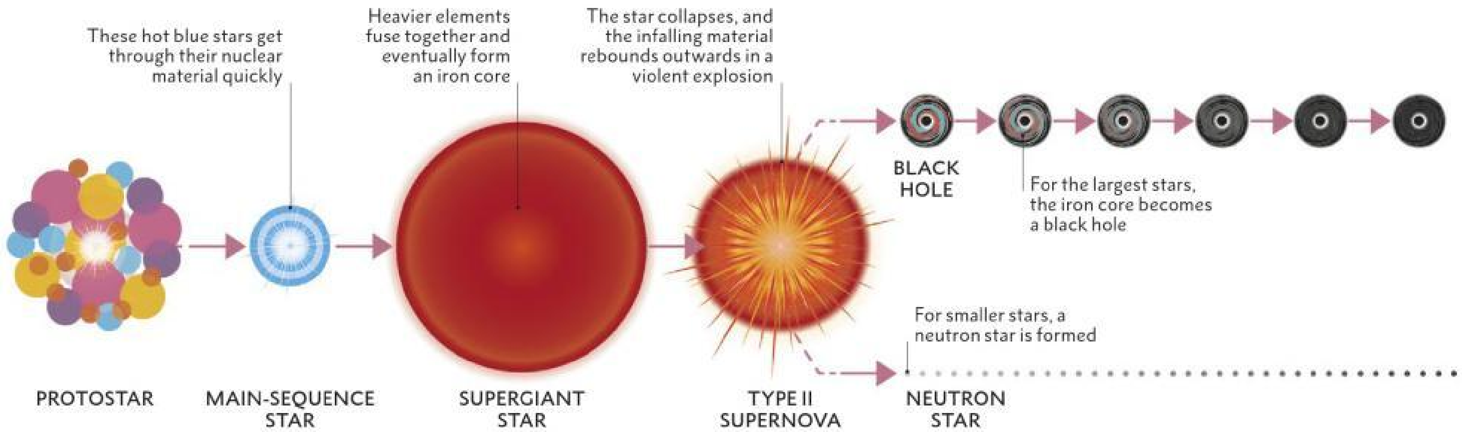


▼ Sun-like star
Stars like the Sun typically live for around 10 billion years. After entering a red giant phase, they form a planetary nebula – and usually do not explode as supernovas.

▶ **Low-mass star**
These smaller stars are able to mix their interiors, meaning that the core's supply of hydrogen gets replenished by the outer layers falling towards the centre – so the core doesn't contract to start helium fusion.



▶ **High-mass star**
The evolution of more massive stars is initially similar to that of Sun-like stars. But they form red supergiants, instead of red giants, and eventually supernovas. The star's ultimate fate depends on its mass.



> STARS ARE **BORN, LIVE** – OFTEN FOR BILLIONS OF YEARS – AND **DIE**… SOMETIMES IN A **SPECTACULAR MANNER**.

Carl Sagan, American astronomer, 1934–1996