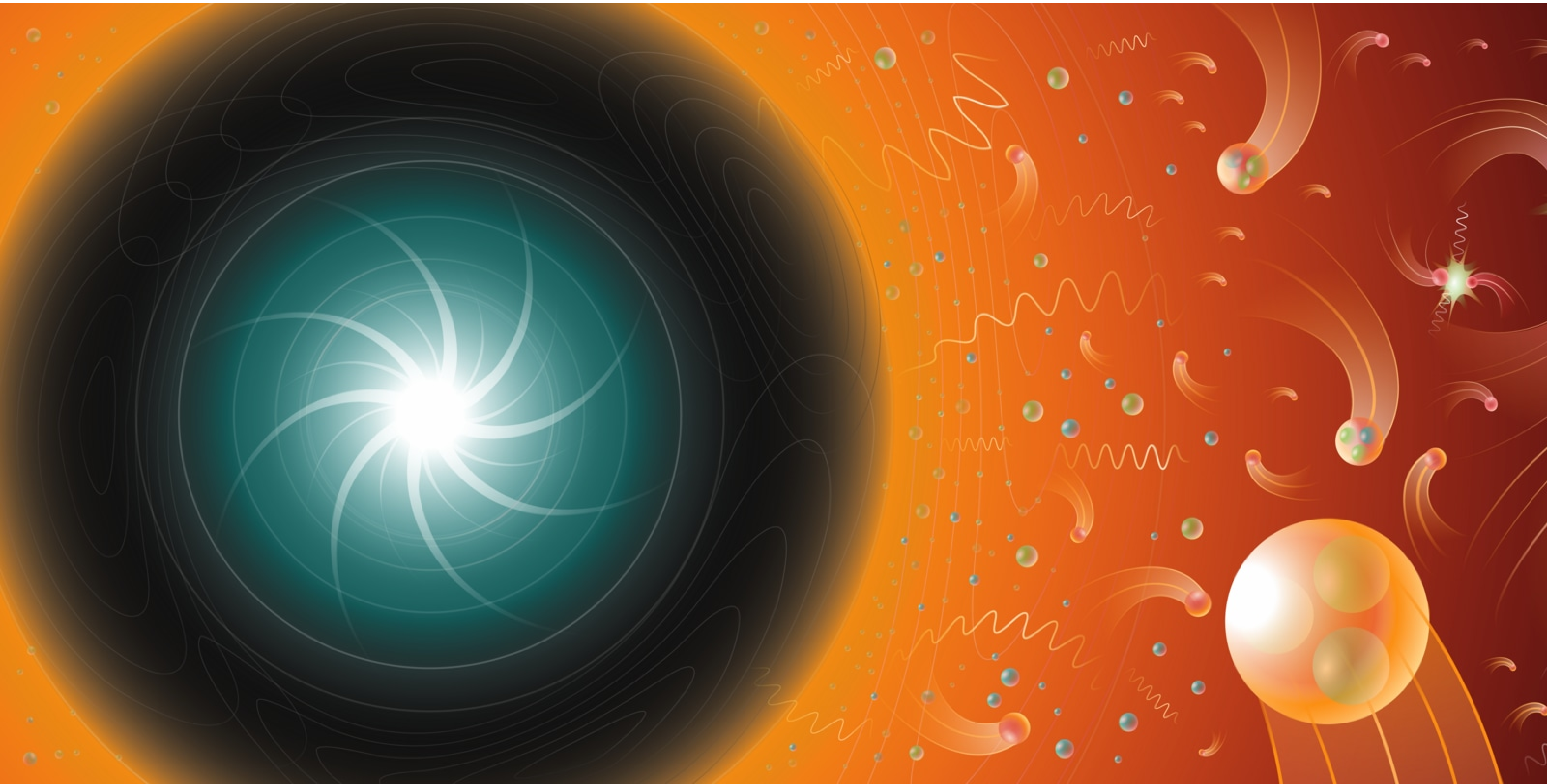
Theory of Inflation

13,813 ± 58 Ma



During its earliest moments the Universe was filled with a special type of matter: a uniform field, like a magnet's, with unusual properties. Space containing this field looked empty, but it had an enormous energy that forced the Universe to expand—like a balloon—at an ever-quickening pace. This time period is called *inflation*. Inevitably, inflation ended when the field decayed and its energy transformed into an incredibly hot, energetic mix of elementary particles: matter, antimatter, and radiation. That transformation of energy into particles was the "bang" of the commonly known *Big Bang*.

Relevance

Inflation set the stage for a hot Big Bang and explains why the Universe is so gigantic. This scientific theory also offers insights into how tiny quantum fluctuations produced during inflation resulted in galaxies.

A superhot cloud of hydrogen, helium, and trace amounts of lithium was produced within Time's first four minutes; no great amounts of other elements would have survived the early Universe. Later, gigantic glomerations of those elements ignited into stars.

Knowledge

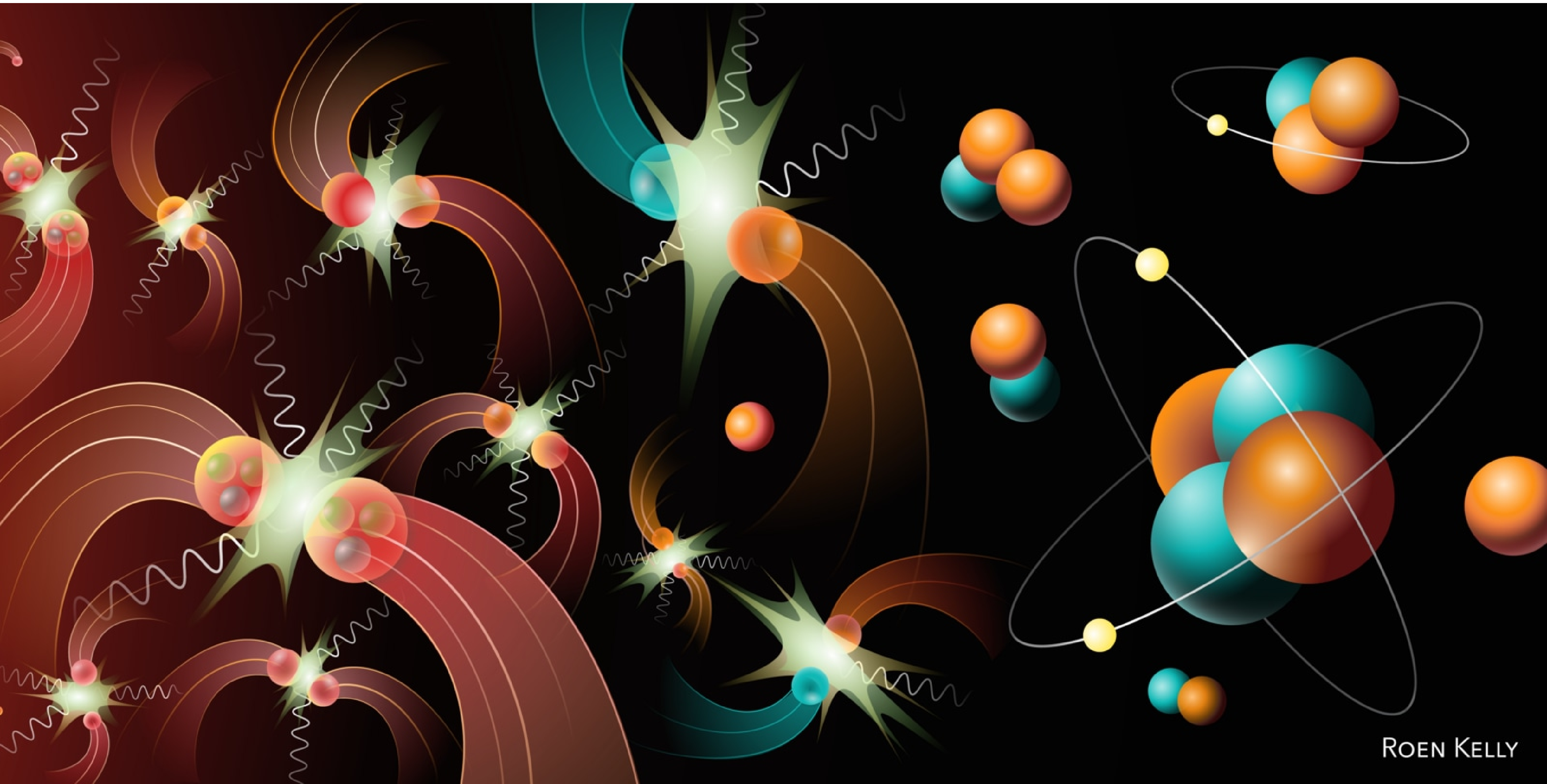
Knowledge is gained by applying the scientific method: a tool to learn about our surroundings. Although imperfect, and sometimes abused, it is the most critical, adaptive, self-correcting, and widely applicable empirical tool we have ever devised. Scientific theories are valuable because they help us predict the past, present, and future. Constantly refining tests for those predictions gives us confidence in whether a theory remains a good description of reality.

Evidence for the hot Big Bang comes from equations and observations. Using solutions to key equations, Russian cosmologist Alexander Friedmann predicted an expanding Universe. After his prediction, observations confirmed that galaxies are moving away from each other at speeds proportional to their distances.

The Universe is expanding faster and faster.

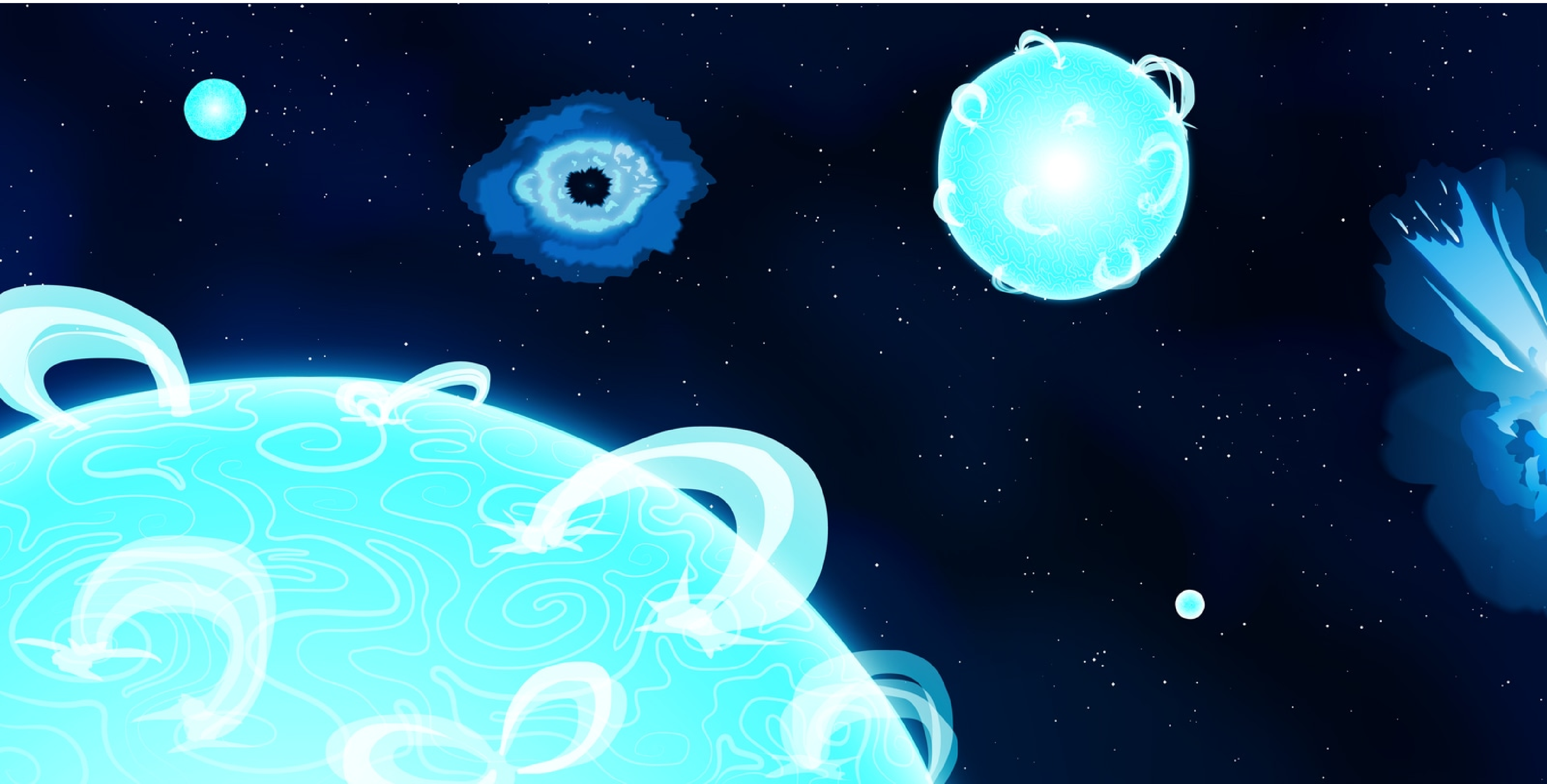
Long before stars formed, the Universe was hotter, denser, and filled with a uniform glow from white-hot plasma. That plasma cooled as the Universe expanded. Now, only a faint glow from that time fills the Universe, like sunshine on an overcast day. This glow is the remaining heat from the hot Big Bang and can be detected in every direction. Called the *cosmic microwave background radiation*, it provides substantial evidence that favours a hot Big Bang.

What happened immediately before the hot Big Bang remains mysterious. Refined, highly precise measurements of tiny changes in the cosmic microwave background temperature have solved parts of that mystery, in strong support of the Theory of Inflation.



Stars

13,633 ± 40 Ma



Nearly 400,000 years following the hot Big Bang, the white-hot plasma that filled the Universe had cooled enough for hydrogen and helium to attract electrons, leading to a period of transparency. The hot Big Bang's residual glow faded; the Universe cooled while it expanded; darkness took hold until stars started to shine. The very first stars formed when dense clumps of gas—primarily hydrogen—began to contract under gravity. Perhaps hundreds of times more massive than the Sun and millions of times more luminous, the appearance of these primordial stars is called *Cosmic Dawn*—or *first light*.

Cosmologists have indirect evidence that stars came into existence around 180 million years after the Universe was born.

The earliest stars to have existed—*Population III stars*—would have burned bright blue from hydrogen, helium, some lithium, and little else. Inside their nuclear furnaces, stars fused atoms together to create heavier elements up to and including iron. Even within the heart of the very first and largest stars ever thought to have existed, elements heavier than iron were not easily forged.

Heavier elements fuse together when atoms capture electrically neutral particles known as neutrons. Neutron captures can occur when neutron stars collide or colossal stars explode. After a few million years, the stellar cores of those first stars became so laden with iron that their fusion energy could no longer withstand the immense gravitational forces. Their cores collapsed, leading to the death throes of stars in events known as *supernovae*.

Relevance

Supernovae scattered elements throughout the expanse of space. Such acts were instrumental in forming stars that burn for billions of years, solar systems, and rocky planets like Earth.

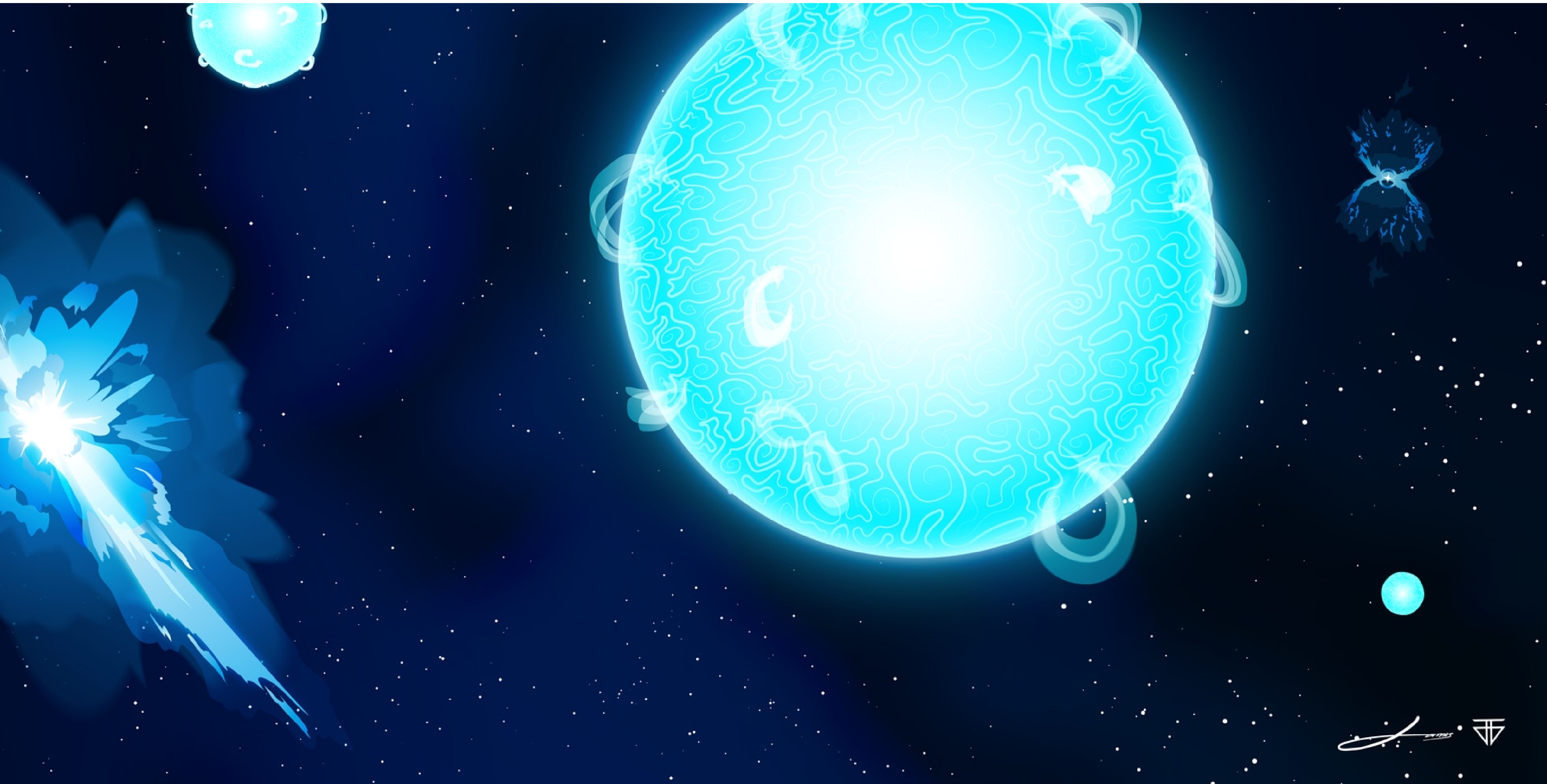
Knowledge

Imagine a pitch-black night sky overcast with impenetrably thick storm clouds. When those clouds flicker and flash, momentarily lit from behind, we would surmise that lightning was the cause, without needing to see a bolt.

Before stars started to shine, the Universe was a cold, dark place awash with hydrogen gas and cosmic background radiation. By analogy, hydrogen would be like the clouds and stars the lightning. Without seeing the first stars, astronomers can measure the influence that stars had on the surrounding matter.

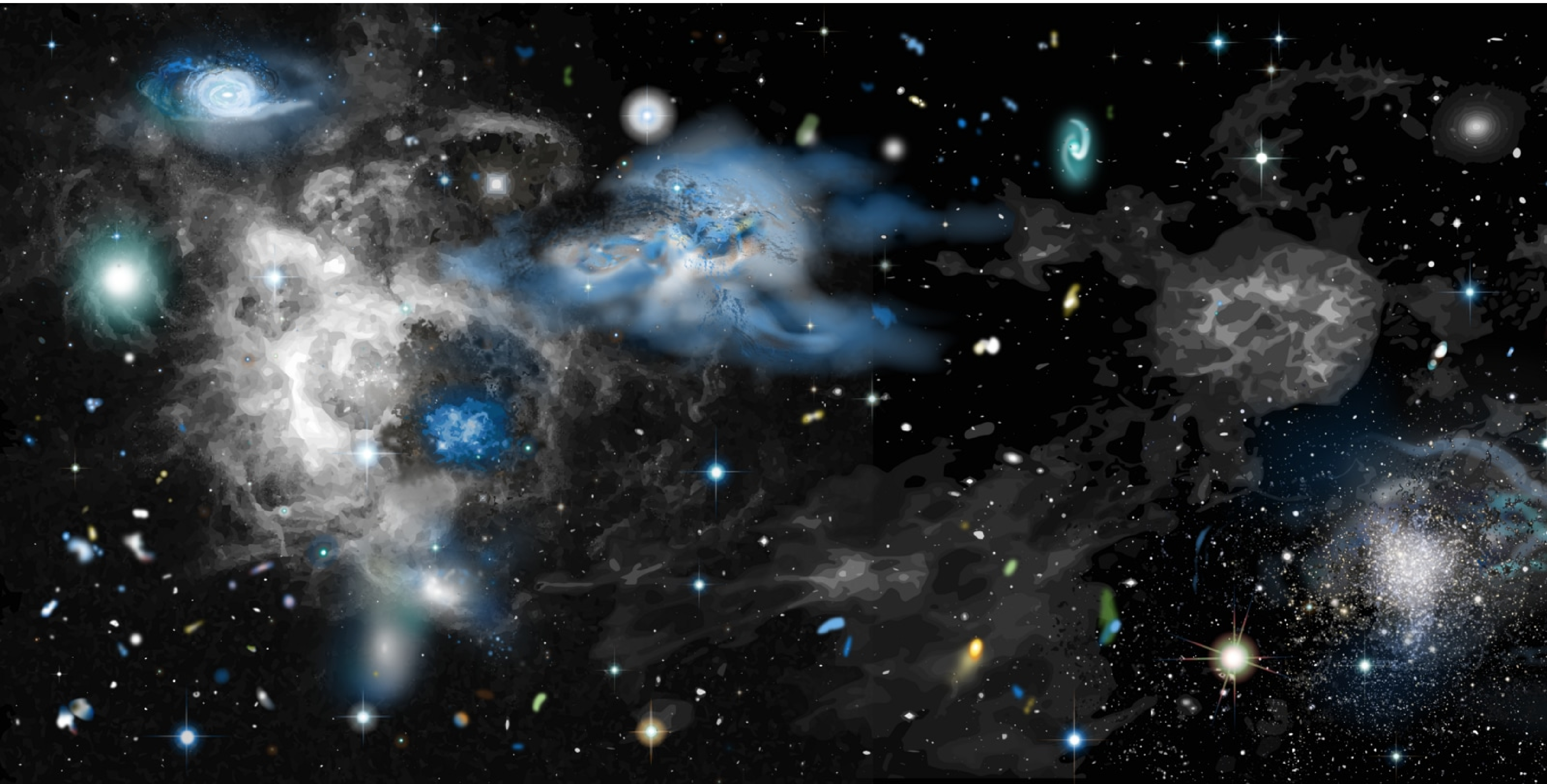
Deep in the Australian outback, far from any machine-made radio signals, a small team of scientists set up sensitive radio antennas—a bit bigger than coffee tables—to search for changes in those early hydrogen gas clouds.

Eventually they detected signals that stars had begun to slow the cooling of hydrogen gas, warming the Universe with first light.



Galaxies

13,403 ± 21 Ma



Galaxies are massive collections of stars, star clusters, gas clouds, and something called *dark matter*. Although not yet seen, astronomers think that the first galaxies were: without rocky planets, blue in colour, small in comparison to later galaxies, home to the largest stars of all time, not often spiral-shaped, and where black holes started to amass.

Relevance

Before the first stars went supernova, primal galaxies were pristine: too few element types existed for complex nuclear reactions to take place. Stellar explosions enriched space with new elements. Clumped within galaxies, star clusters forged heavier elements at higher rates than would have been possible by lone stars.

Elements produced by supernovae are found in blood (iron), teeth and bones (calcium), hair (carbon), nerves (potassium), plant cells (boron), and everything around us.

Knowledge

Driving down a country road, roadside fences pass by quickly, far away trees shift slowly, and remote hills hardly move. This behaviour can help measure distances. By taking a picture of a given tree, driving a known length, then taking another picture, the tree's distance to the road can be computed. Likewise, by imaging stars six months apart, astronomers use Earth's travels around the Sun (a known length) to measure out to neighbouring stars.

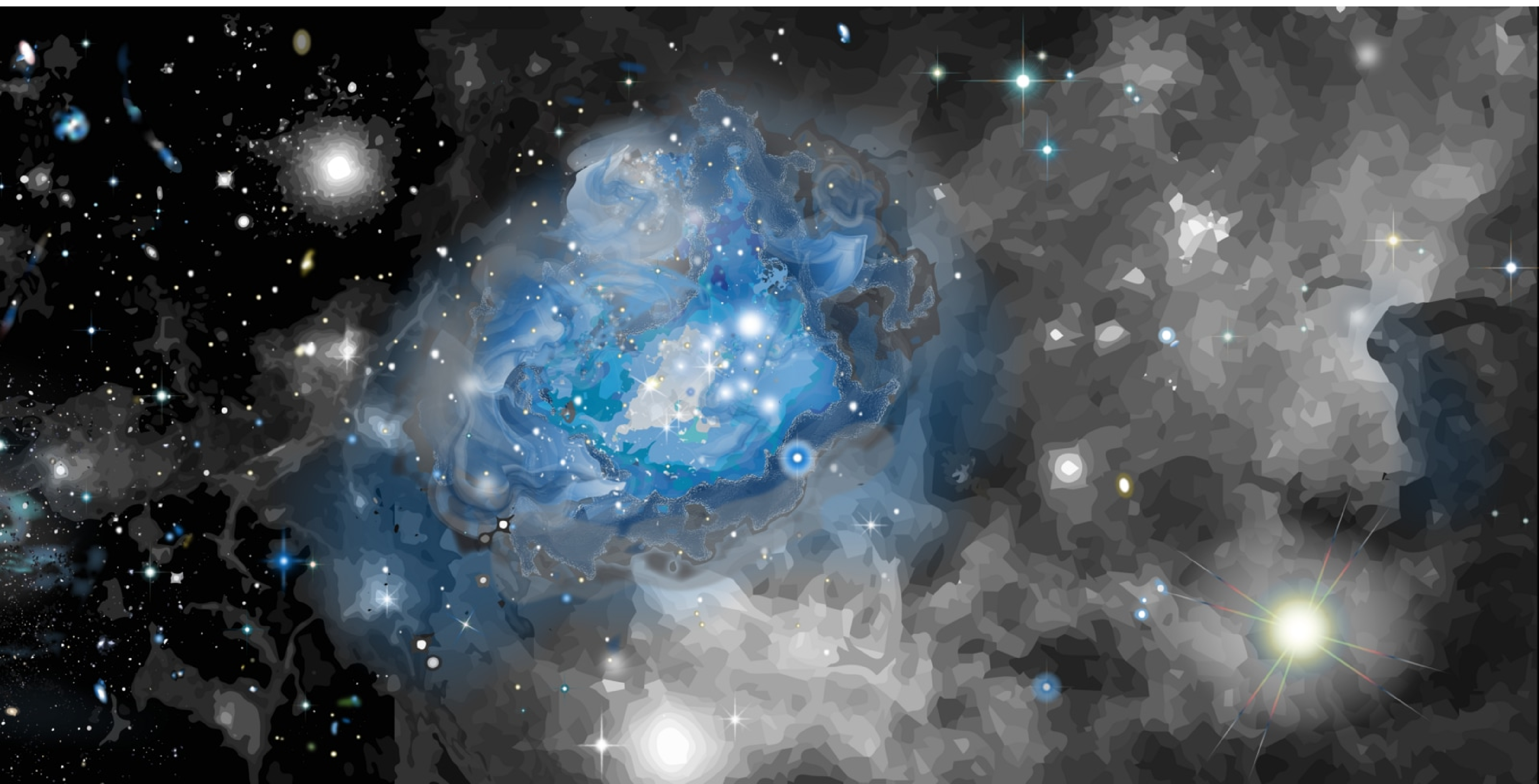
While walking at night, street lamps near by appear brighter than those far away. A lamp's distance relates to its brightness and the energy it radiates (its *luminosity*). Various lamps emit different amounts of energy, so only lights of known luminosity can be used to measure distance. Such lights are named *standard candles*.

Many celestial objects can act as standard candles. Cepheid Variable stars brighten and dim at regular intervals, which allows their luminosity to be calculated, giving an estimated distance to their host galaxy.

When a fire engine approaches, high-pitched sound waves from its siren lower in pitch as the vehicle drives past. The same effect affects light waves. Fast-moving galaxies headed towards Earth appear bluish because the light is compressed; whereas, receding galaxies appear red due to stretched light. Blueshifts and redshifts reveal the motions of celestial objects.

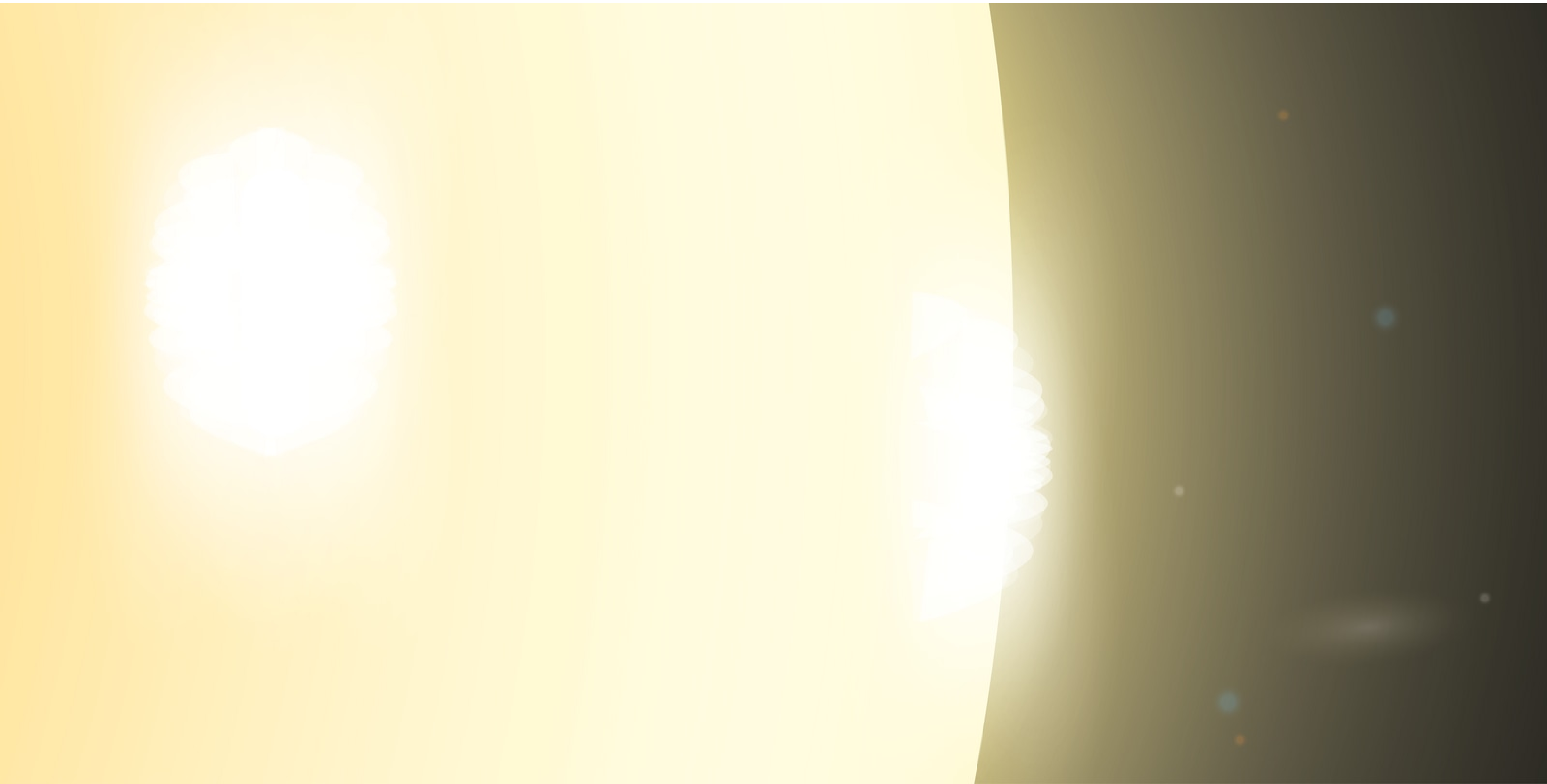
A standard candle to measure the farthest galaxies is a *Type IA Supernova*: it is a type of star that explodes at a known luminosity.

Astronomers who studied galaxies having standard candles learned that galactic light is redshifted because the Universe is expanding. Farther galaxies appear to move away faster because there is more space in between that is expanding. Distant galaxies have greater redshifts, so measuring redshift allows computing the Universe's age when the light was emitted.



Exoplanets

13,365 ± 50 Ma



Planets are celestial bodies that orbit the Sun, are spherical from self-gravity, and not significantly affected by the gravity from other objects. An *exoplanet* is similar to a planet, but orbits a star that is not the Sun.

In astronomy, *metals* are elements other than hydrogen and helium. Huge, metal-free stars enriched space with heavier elements during supernovae events. Ejecta from those stellar explosions included surprisingly large amounts of carbon. From such ashes were born *carbon-enhanced metal-poor stars*: the earliest known type of second-generation stars.

Elements heavier than hydrogen and helium are needed to create dust grains, the building blocks of all known planet types. In theory, any exoplanets that formed around early second-generation stars could have been very dark *carbon exoplanets*. Their existence is unproven.

Temperature would have influenced other characteristics. Hot carbon exoplanets might have had atmospheres made mostly of carbon monoxide; cool carbon exoplanets could have supported complex chemistry in the form of reddish organic compounds called *tholins*.

Exoplanet sizes may be linked to metallicity. Metal-poor stars may make small planets while gas giants probably need metal-rich regions.

Relevance

If exoplanets can occur around ancient metal-poor stars, it greatly expands where life could gain a foothold across space and time.

Typically, galaxies have higher abundances of metals towards their center, thinning out with distance. If planet building does not need metal-rich regions, it means more of the galaxy could host habitable exoplanets.

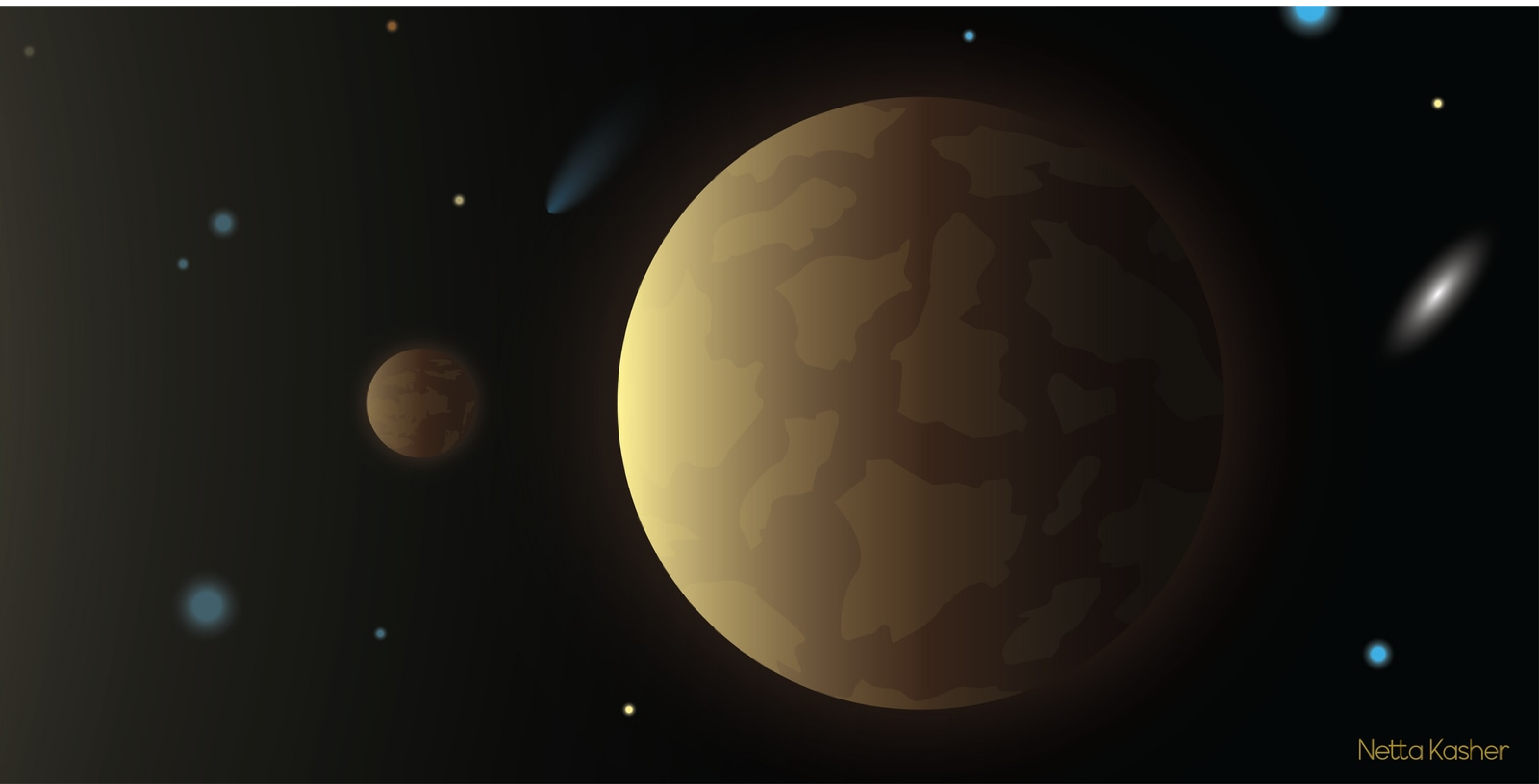
Knowledge

In 1925, Cecilia Payne published her thesis on the composition of stars. She discovered that stars are made almost entirely of hydrogen and helium, much like the Universe itself.

When sunlight enters different media (such as water), some colours bend more than others upon exiting. This bending separates light into a colourful rainbow, called a *spectrum*. Closely observing the Sun's spectrum reveals that some colours are missing; starlight passed through a prism also shows absent colours, like this:

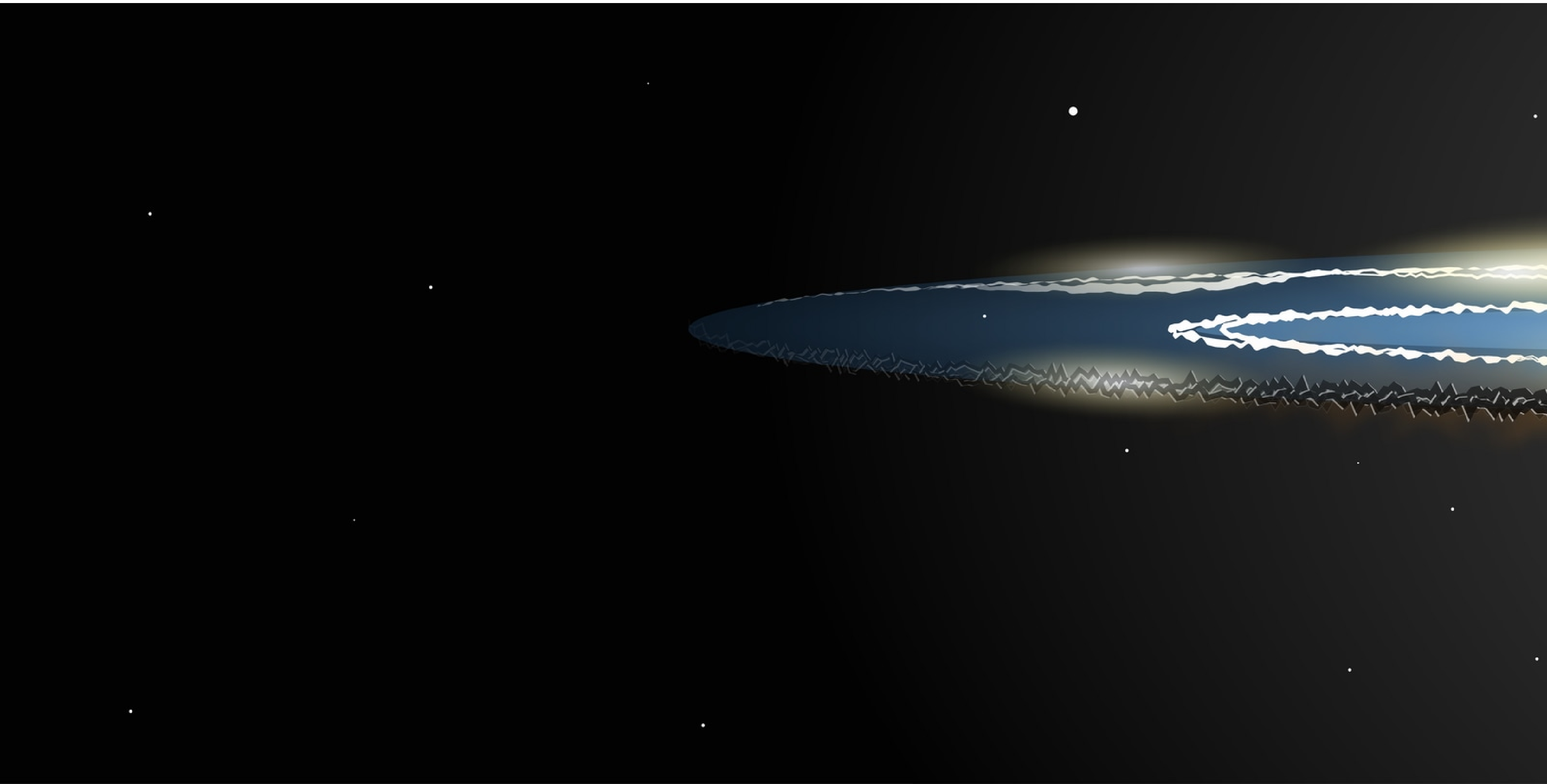
With enough heat, all atoms emit distinct light patterns. Hydrogen looks like this:

Note how absent starlight colours compare to the colours hydrogen gives off when heated. By comparing starlight spectra to light patterns of known elements, any star's chemical make-up can be deduced. Carbon-enhanced stars imply that carbon exoplanets might have existed.



Thin Galactic Disc

8,400 ± 500 Ma



Beyond brightly lit cities, a wide band of twinkling stars is easily viewed by anyone who can see the sky on clear, moonless nights. While only a few thousand stars are visible to the unaided eye, that band contains billions of stars clustered together in a vast structure: the Milky Way Galaxy.

It is our home galaxy.

Among the oldest galaxies known, the Milky Way is a *barred spiral galaxy* that has a halo, central bulge, galactic centre, and a thick disc that enwraps a thin disc. All the stars that our eyes can see at night, except for those in the central bulge, are part of the thin disc.

Viewed edge on, most of the galaxy's mass lies midway between the top and bottom, along what's called the *Galactic plane*. Closer to the Galactic plane, metal-rich stars outnumber metal-poor ones. Moving farther away from the plane, the trend gradually reverses until metal-poor stars dominate the thick disc.

About halfway out from the galactic centre, situated well within the thin disc and not far from the Galactic plane, our Sun is located in a relatively calm and metal-rich neighbourhood.

Relevance

Frequent events can annihilate life closer to the galactic centre: exploding stars, sterilizing gamma radiation emissions, forces of gravity strong enough to shred exoplanets, excessive collisions by comets and other celestial objects, and rogue black holes so powerful they engulf entire stars.

Yet the inner galaxy hosts far more stars and exoplanets than the outer regions. Despite the dangers, the sheer number of stars near the galactic centre may afford life more chances to rise should a suitable star present itself.

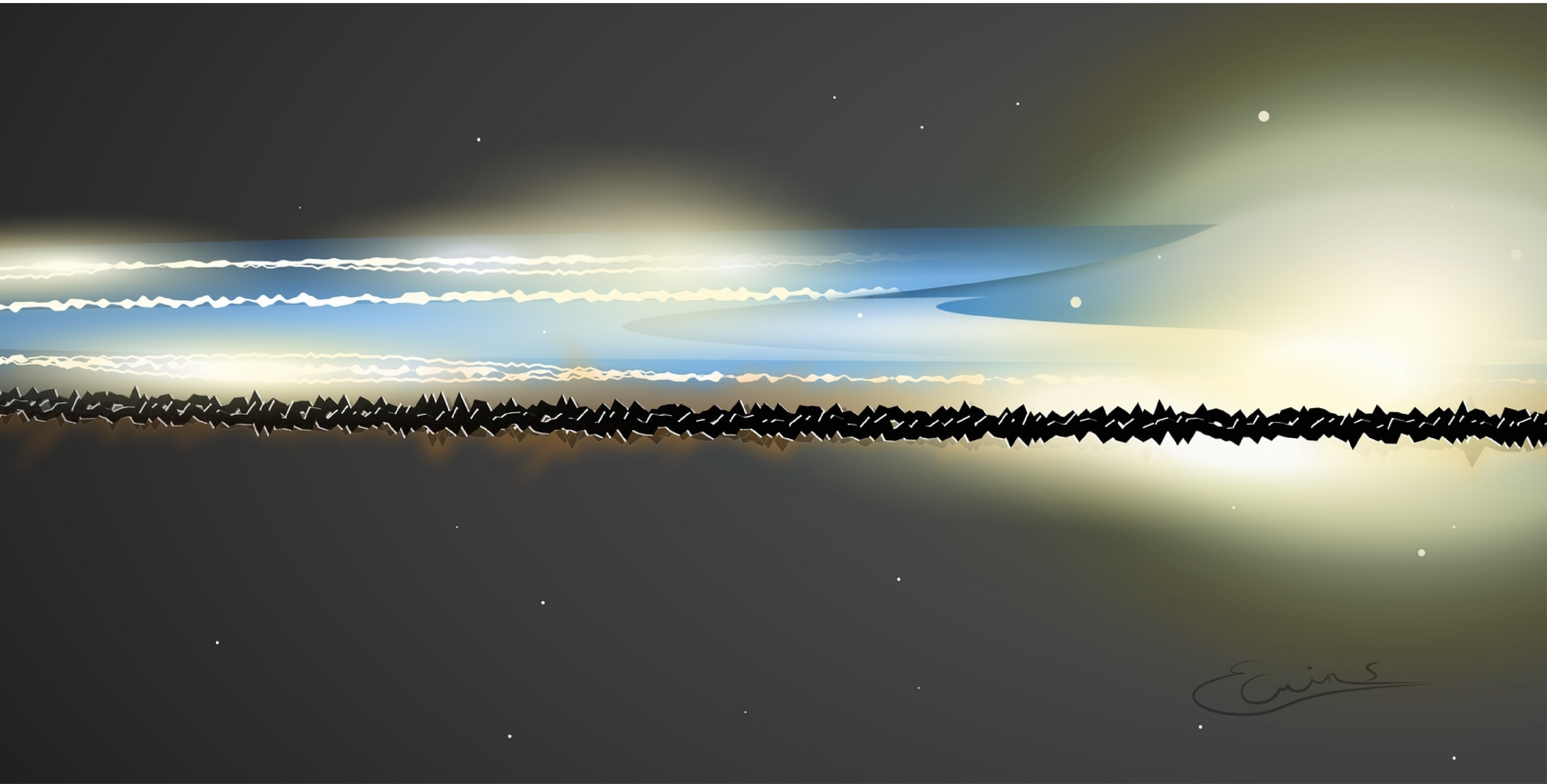
A *galactic habitable zone* is a region within a galaxy thought to favour exoplanets capable of sustaining life. Earth is in such a zone.

Knowledge

When stars similar to the Sun burn through their nuclear fuel, they shrink into dead husks called *white dwarfs*. White dwarfs are usually Earth-sized and contain an enormous amount of matter. Just one teaspoon of matter from an average white dwarf would weigh a little less than an elephant on Earth.

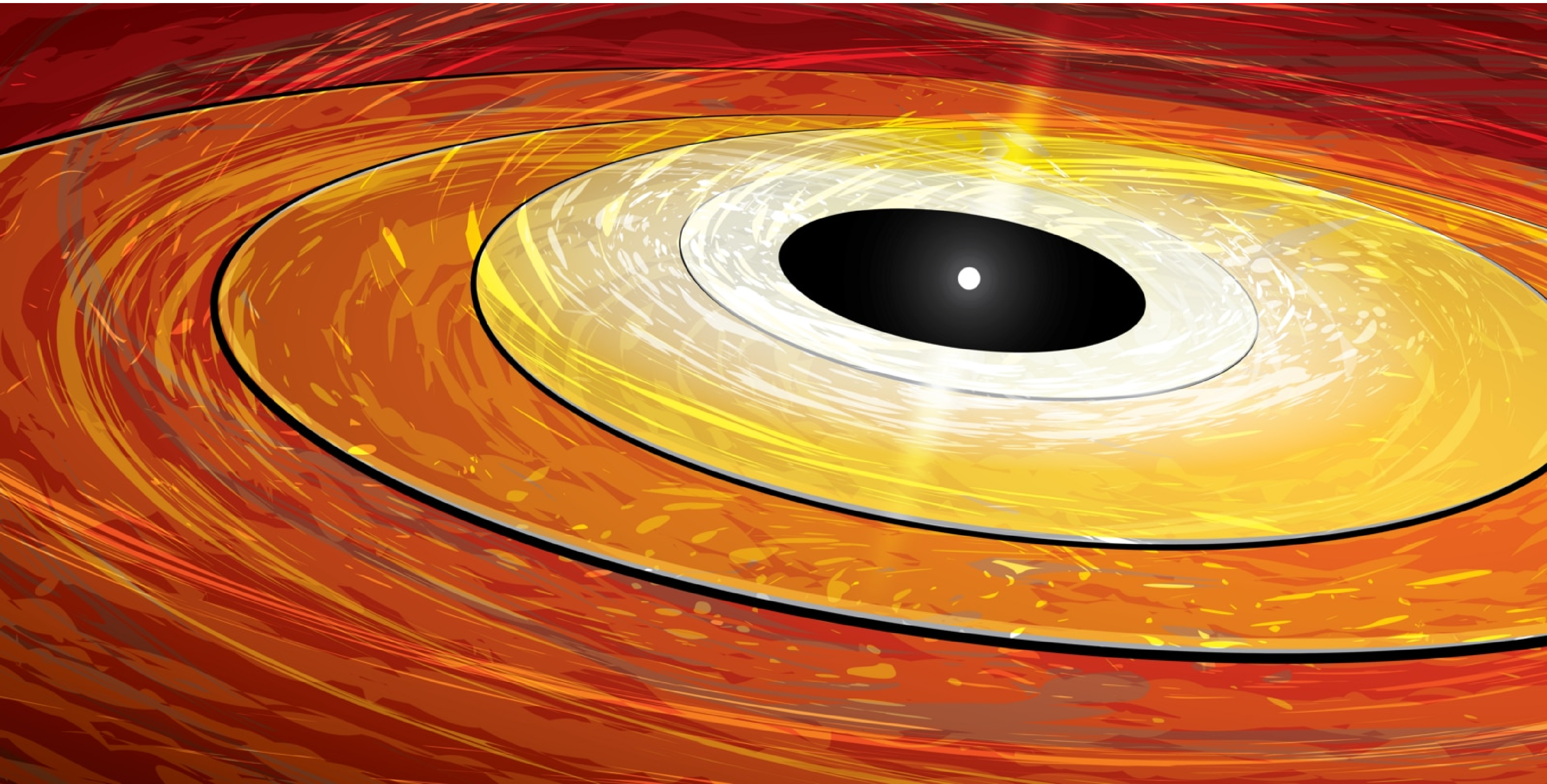
Without a fusion furnace, white dwarfs cool down into black dwarfs: the fading embers of a dying fire. Like how an ember's reddish glow indicates that it is quite hot, a white dwarf's luminosity relates to its temperature. Realizing that white dwarfs cool at predictable rates, astrophysicists can use a white dwarf's mass and brightness to determine its age—known as *white dwarf cosmochronology*.

By applying white dwarf cosmochronology to well over 100 white dwarfs observed in the Milky Way's thin disc, scientists estimated the thin disc's age, approximately.



Protoplanetary Disc

4,572 ± 2 Ma



Vast molecular clouds of gases (and dust) are referred to as *nebulae*. The Sun, along with all eight planets, was seeded from a nebula laced with the remains of ancient supernovae. Hydrogen, helium, carbon dioxide, ice, and debris drifted through space within the nebula. After a while, a nearby star might have exploded, injecting the nebula with freshly made iron. The stellar shock wave could have triggered compression of the nebula, leading to a runaway collapsing cloud.

As the cloud collapsed under its own gravity, its rotation sped up, like figure skaters who spin faster by pulling in their arms. Gradually, the centre of the rotating nebula transformed into a concentrated mass balled up at the middle of a flattened structure called a *protoplanetary disc*.

The gravitational pull of the central mass was converted into thermal energy as the nebula's gas was compressed. The protoplanetary disc's centre heated sufficiently to become a glowing hot protostar that shone with the brilliance of a mature star. As the nebula's remaining gas and debris that orbited the protostar flowed inward, the central mass increased; however, the disc continued to gather new material from the cloud. Eventually, the protostar's mass and temperature increased until its thermal energy became so high that atomic nuclei began to fuse, which triggered a cascade of nuclear fusion reactions.

Over time, the contracting protostar became so hot and dense in its centre that its richest resource—hydrogen—began to fuse, producing abundant energy. Astronomers regard the time of this event (the *solar zero age main sequence*) the Sun's birth date. The protoplanetary disc would have dissipated some time earlier.

Relevance

All known life is based on chemical substances containing carbon, called organic compounds. When a planet forms, it gathers gas molecules from the surrounding nebula.

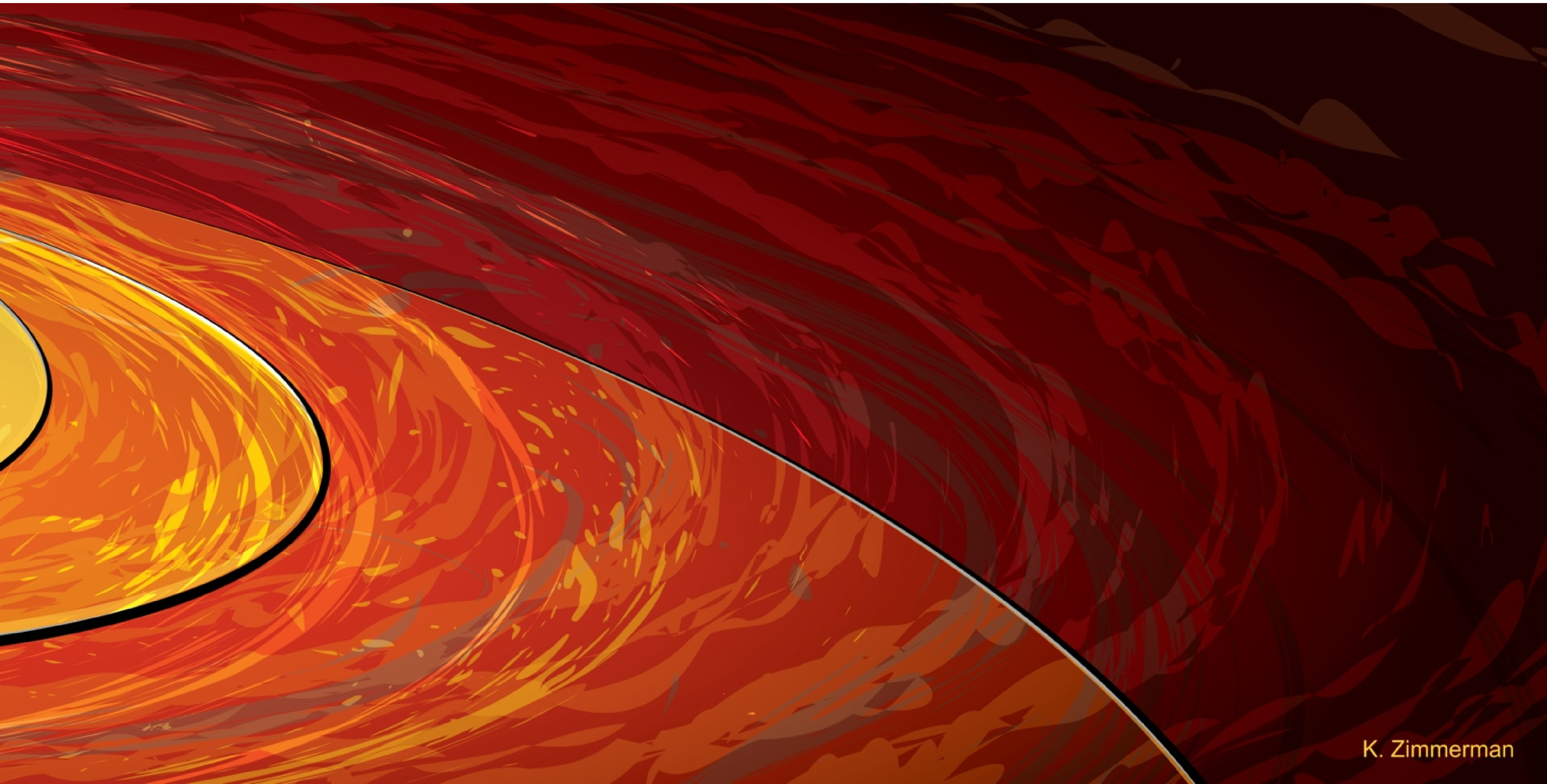
Using *astronomical spectroscopy* researchers have detected organic compounds in distant protoplanetary discs. Some of these finds, such as methanol, are vital to the building blocks needed for life.

Knowledge

Meteorites are objects from space that impact Earth, such as small asteroids. Between Mars and Jupiter is an asteroid belt with millions of asteroids. Material from the belt is thought to have existed when planets were first forming.

On occasion, a rock that was ejected from the belt lands on Earth, bringing with it primordial material. Determining the rock's age, scientists effectively date the Solar System's origin.

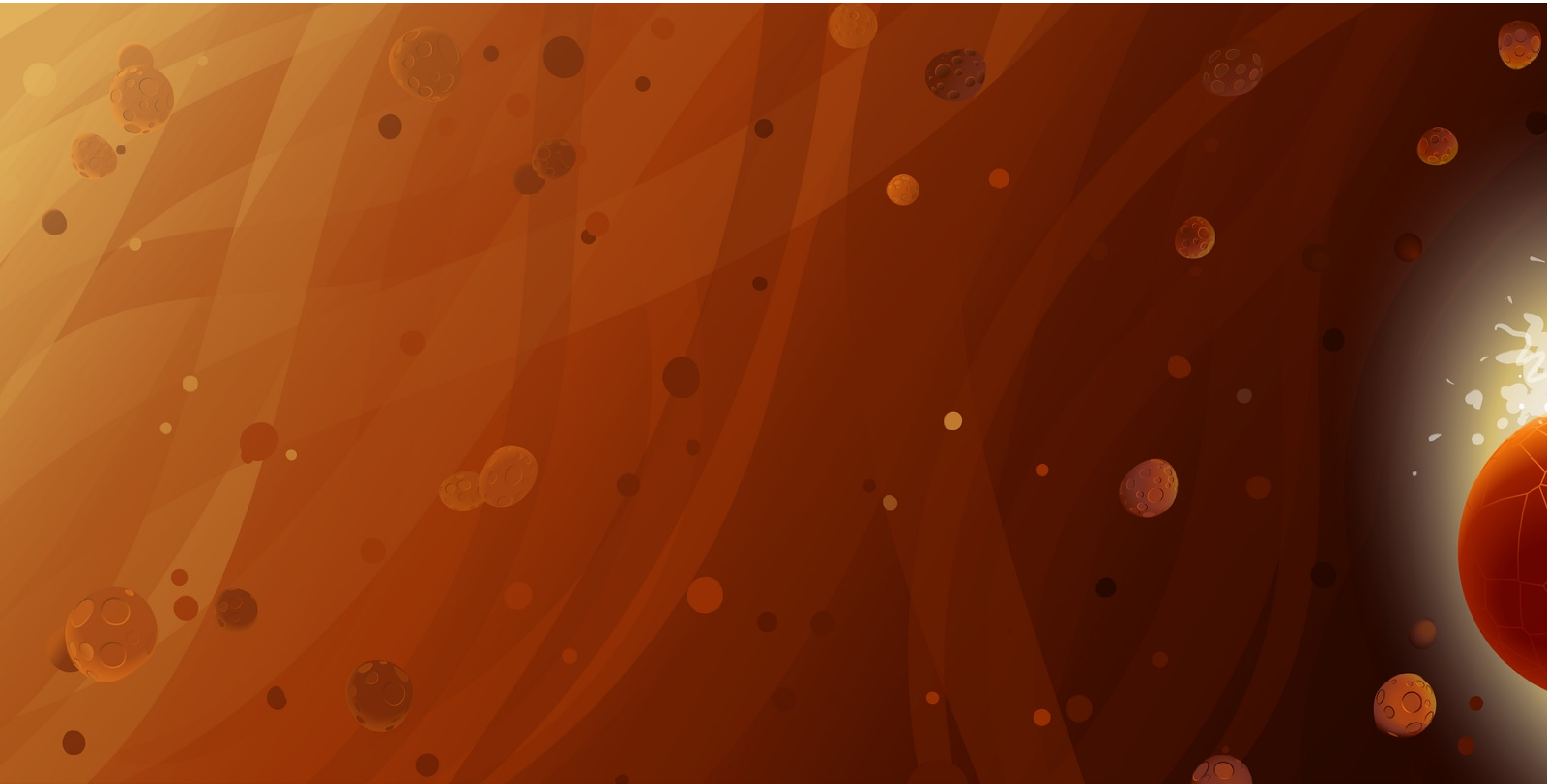
Besides studying local rocks, scientists can capture images by telescope of protoplanetary discs that are deep in space.



K. Zimmerman

Earth Accretion

4,568 ± 1 Ma



Whatever nebular, protoplanetary disc debris that was not engulfed by the protosun, amassed to form Earth, the planets, moons, and other Solar System objects.

Astronomers suspect that tiny grains stuck together to make pebble-sized objects. Groups of them collected in swirling eddies, likely with ice layers for glue. Those collections then collapsed into objects hundreds of metres wide, which crashed into each other, forming *planetesimals*. Strike upon strike, the planetesimals grew through further collisions, accumulating centimetres per year over a few million years.

Near the end of its main accretion phase, the proto-Earth (*Tellus*) further enlarged as comets, asteroids, and Moon-sized bodies hailing from the inner Solar System smashed into it.

According to the *Giant Impact Hypothesis*, a Mars-sized object named *Theia* slammed into Tellus. Scientists consider Theia's impact to be the end of Tellus and the beginning of Earth.

That glancing blow is believed to have had significant outcomes: vaporised rock shot into orbit, providing enough material to make the Moon; Earth's axis of rotation tilted; massive amounts of iron infused into Earth's mantle; a day's length increased over time; and it might have brought water-rich material to Earth from elsewhere in the Solar System.

Earth's first atmosphere is thought to have been primarily water vapour, hydrogen, and helium. Being the lightest elements, hydrogen and helium escaped into space, leaving water vapour to condense as rain.

Relevance

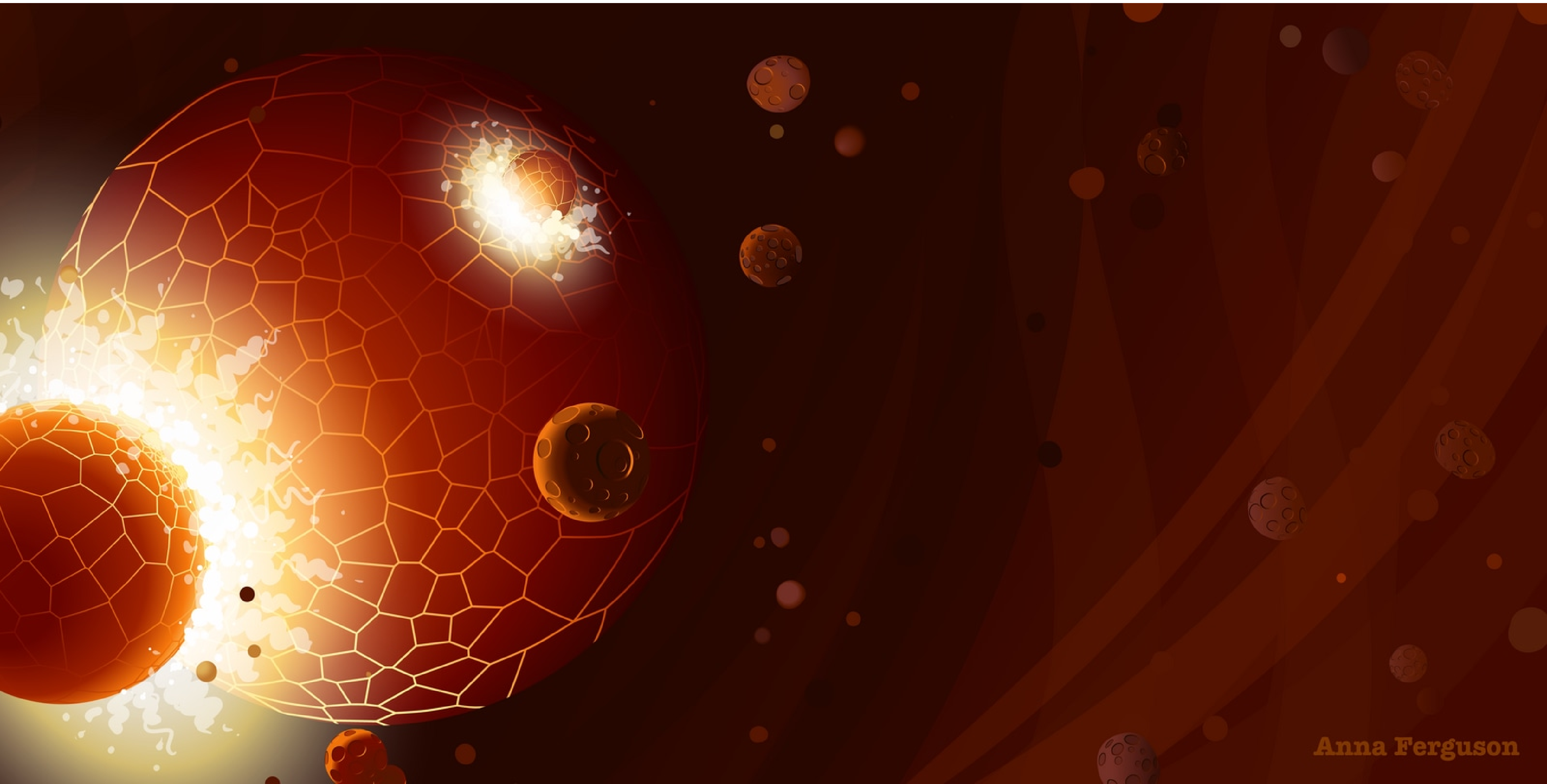
Earth's iron transfusion from Theia's impact generated a durable magnetic field that greatly improved life's chances to take root. Without a magnetic field to divert matter ejected from the Sun, solar winds would strip away Earth's atmosphere like a gust upon dandelion seeds.

Extended exposure to cosmic radiation can overwhelm an organism's repair mechanisms, resulting in death. Earth's protective magnetic field shields life from many effects thought to hinder life. Theia's glancing impact resulted in periodic seasons that might have encouraged evolutionary adaptations.

Magnetic fields as strong as Earth's could be rare for otherwise habitable rocky exoplanets, which may restrict where life can emerge from non-living matter naturally.

Knowledge

Evidence for the nebula theory of Solar System formation includes: direct observation through telescopes; simulation of large gas clouds using computers; the Sun's predominant hydrogen composition; all planets orbit the Sun in the same direction; and the inner planets have little hydrogen because the inner disc would have been too hot for hydrogen gas to condense.



Prolonged Bombardment

4,500 to 3,500 Ma

After Earth had nearly fully formed, the planet was hotter than iron's melting point. Heavy metals, like iron and nickel, sank freely towards Earth's centre to make a distinct core. Core formation is such a pivotal event it is named the Great Iron Catastrophe. From this event, Earth separated into layers: a light crust, a medium-density mantle, and a liquid metal core as hot as the Sun's surface.

Near the end of its accretion phase, Earth was bombarded by impacts from comets, asteroids, and planetesimals. During this turbulent time period—the *Hadean Eon*—large bodies of water began to pool on the surface, which had also started to solidify into a hard crust.

Over timescales of 100 to 200 million years, Earth's crust was recycled from continental plate collisions and erosion; geological records hold little evidence of Hadean Eon events. But two competing ideas have surfaced to explain the cannonade of comets and asteroids.

For the first scenario, Earth experienced a sudden surge of impacts 3,900 million years ago, lasting some 150 million years. The second scenario asserts that the impacts were the tail-end of a bombardment that waned in intensity over time.

Relevance

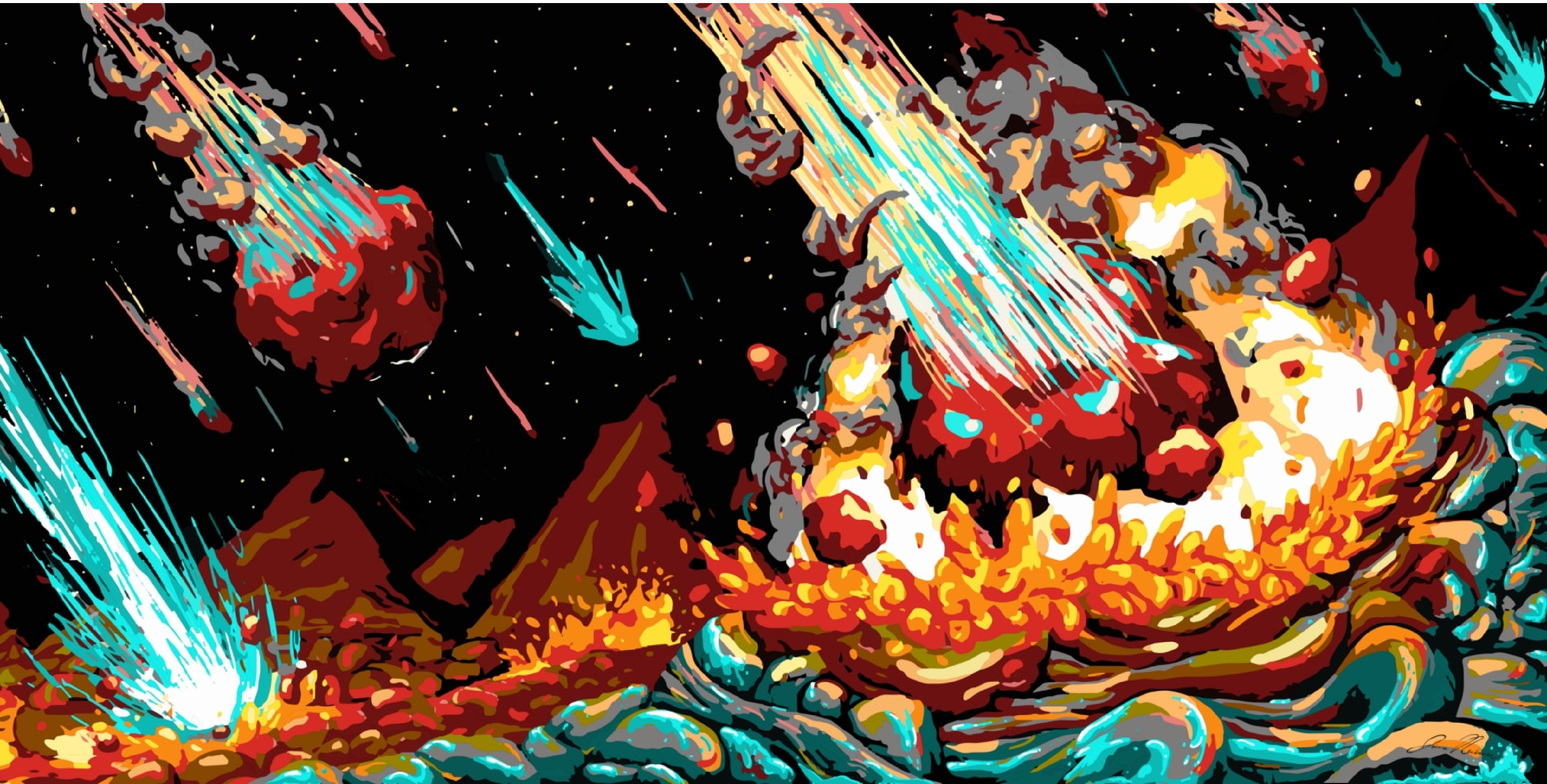
Knowing whether Earth sustained a sudden spike in strikes or experienced a waning bombardment of celestial bodies affects our understanding of life's timeline. Did life start in warm little ponds as Charles Darwin once thought? Did life begin near hot, ocean floor vents? Or perhaps it emerged some other way? Studying these ancient rocks may tell us of life's origins.

Knowledge

Although when the planet's first crust cooled is not known, Slave Craton in Canada's Northwest Territories retains what many geologists consider to be the oldest rocks on the planet. The rocks suggest the presence of stable continents, liquid water, and surface temperatures no hotter than boiling water soon after Earth had fully formed.

Three of the Apollo Moon landing sites were chosen for their closeness to large lunar craters, called *basins*. Astronauts gathered rocks from four different basins, which were analysed to determine when the craters were formed. The samples, though, were not diverse enough to conclude what scenario most likely happened during the Hadean Eon.

Besides analysing moon rocks, scientists can also learn about the bombardment by studying Mars, Mercury, and asteroids. These celestial objects have no significant geological movement or crustal recycling, which makes them time capsules that reveal how the Solar System's innermost planets were battered by an eruptive past.



Microbial Mats

3,496 ± 3 Ma

Imagine Earth having an orange sky, green oceans, and black land. Heat-trapping gases such as water vapour, methane, and others likely filled the air. Methane, if plentiful, would have created a smog, colouring the sky an alien orange; iron permeated the ocean, giving it pale green hues; and volcanoes burst with lava, cooling into giant, black continental crusts.

Biofilms are microorganism groups that stick together collaboratively and quite often to a surface (such as the ocean's floor). *Microbial mats* are biofilm communities—usually visible to the unaided eye—and are considered one of the earliest ecosystems on Earth.

Stromatolites (meaning *layered stone*) are microbial mats that ingest carbon and store it as minerals in a variety of distinct shapes. Called microbially-induced sedimentary structures, they are produced by one of the oldest known life forms on the planet, having dominated the fossil record for most of Earth's history.

Relevance

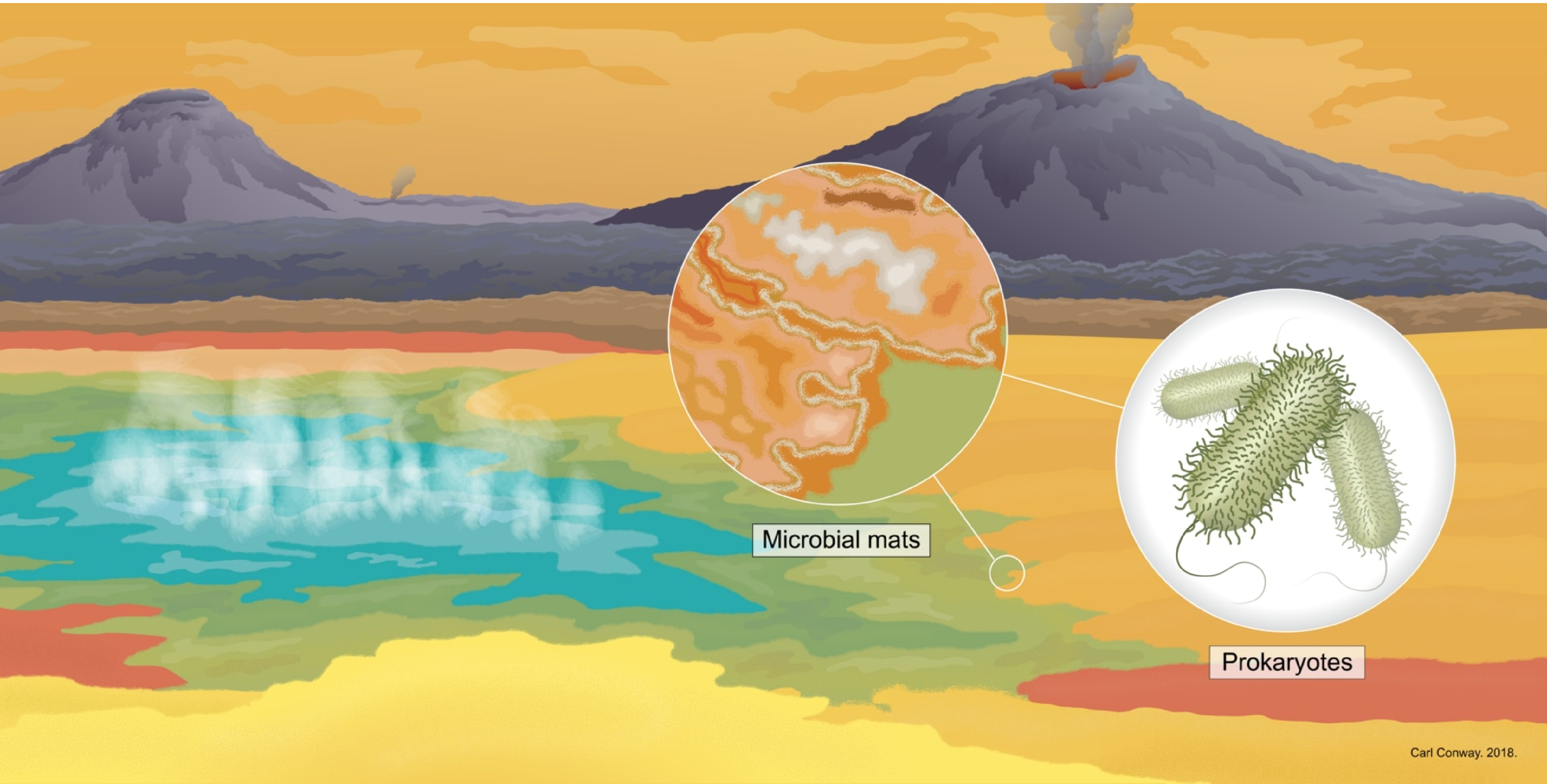
Microbial mats are linked with advancements including: solar-powered cells that convert light energy, water, carbon dioxide, and other elements into food (chemical energy stored as sugars); oxygen-producing cyanobacteria; and the earliest known complex multicellular organisms. In time, microbial mats themselves became a food source for higher life.

Stromatolites provide valuable insights into the early stages of life. Studying them reveals the evolutionary role that microbes played and valuable insights into paleoenvironments.

Knowledge

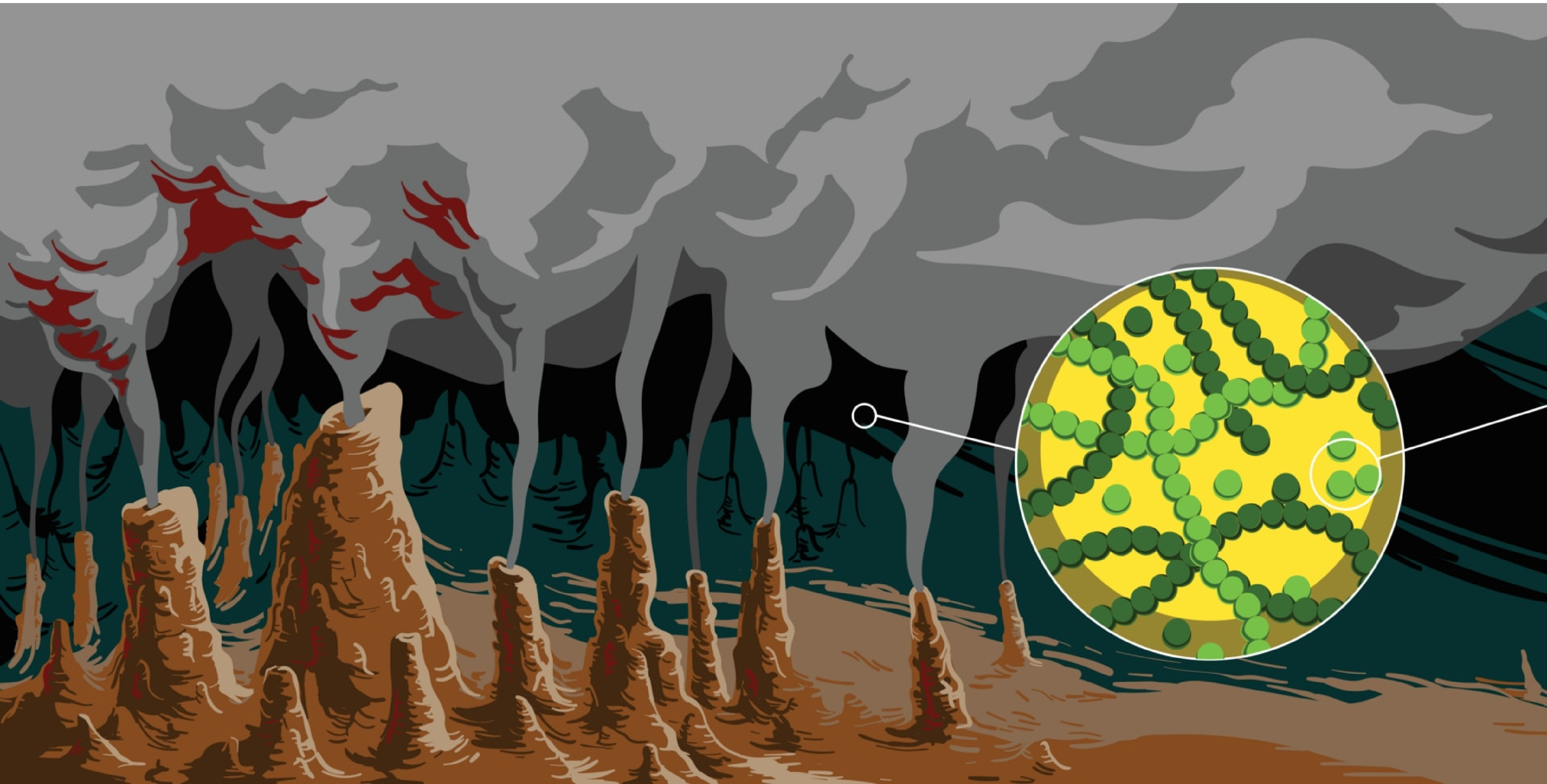
Geologists use *radiometric dating* techniques to probe the ages of ancient stromatolites, such as those found in Pilbara, Western Australia. First, geologists collect a sample rock from the area. The rock is washed, crushed, and then pulverised into a powder of loose minerals. Machines sift the powder, like flour, to separate select minerals. Minerals are then sorted by density in specially prepared liquids such that the heavy ones sink and light ones float to the top. Next, the heavier minerals are separated magnetically to extract a few grams of *zircon*. Geologists hand-pick several dozen zircon crystals to analyse in an electron microscope. From this batch, crystals with the fewest imperfections are dissolved into a solution that is poured into a particular resin. That resin isolates uranium and lead from all other elements.

Through a natural *radioactive decay process*, uranium becomes lead over long periods of time. A *mass spectrometer* analyses the masses of elements. By substituting the mass ratios of uranium to lead into a formula known as the *age equation*, geologists can determine when the zircon formed. By subjecting zircon in rock layers above and below stromatolite fossils to this process, the fossils' ages can be estimated.



Great Oxygenation Event

2,326 ± 7 Ma



Cells (meaning *small room*) are the basic structural parts of organisms; a *nucleus* is a cell's command centre, but not all cells have a nucleus. Many *bacteria* are single-celled organisms that lack a nucleus. Named after their colour, *Cyanobacteria* are bacteria that make their own food using carbon dioxide, sunlight, and water. Producing food this way is called *oxygenic photosynthesis* and it releases oxygen into the surrounding environment.

Cyanobacteria live just about everywhere on Earth that sunlight reaches: cold arctic tundra, dry sandy deserts, and most aquatic habitats.

Relevance

Despite their tiny size, immense collections of cyanobacteria that bloomed across the oceans contributed to planet-wide ecological changes over time. These impacts include: oxygenating the atmosphere, originating plants, producing oil deposits, and energy efficient metabolisms.

Oxygen made by cyanobacteria at first would have been overwhelmed by volcanic release of noxious gases that stripped oxygen from the atmosphere; as volcanism waned, oxygen production came to exceed volcanic consumption, and atmospheric oxygen levels rose. This shift to a highly oxygenated atmosphere is referred to as the *Great Oxygenation Event* (GOE).

Organelles are parts of cells that have specific functions, analogous to organs. Plant cells have an organelle called a *chloroplast*, which can be traced back to cyanobacteria, genetically.

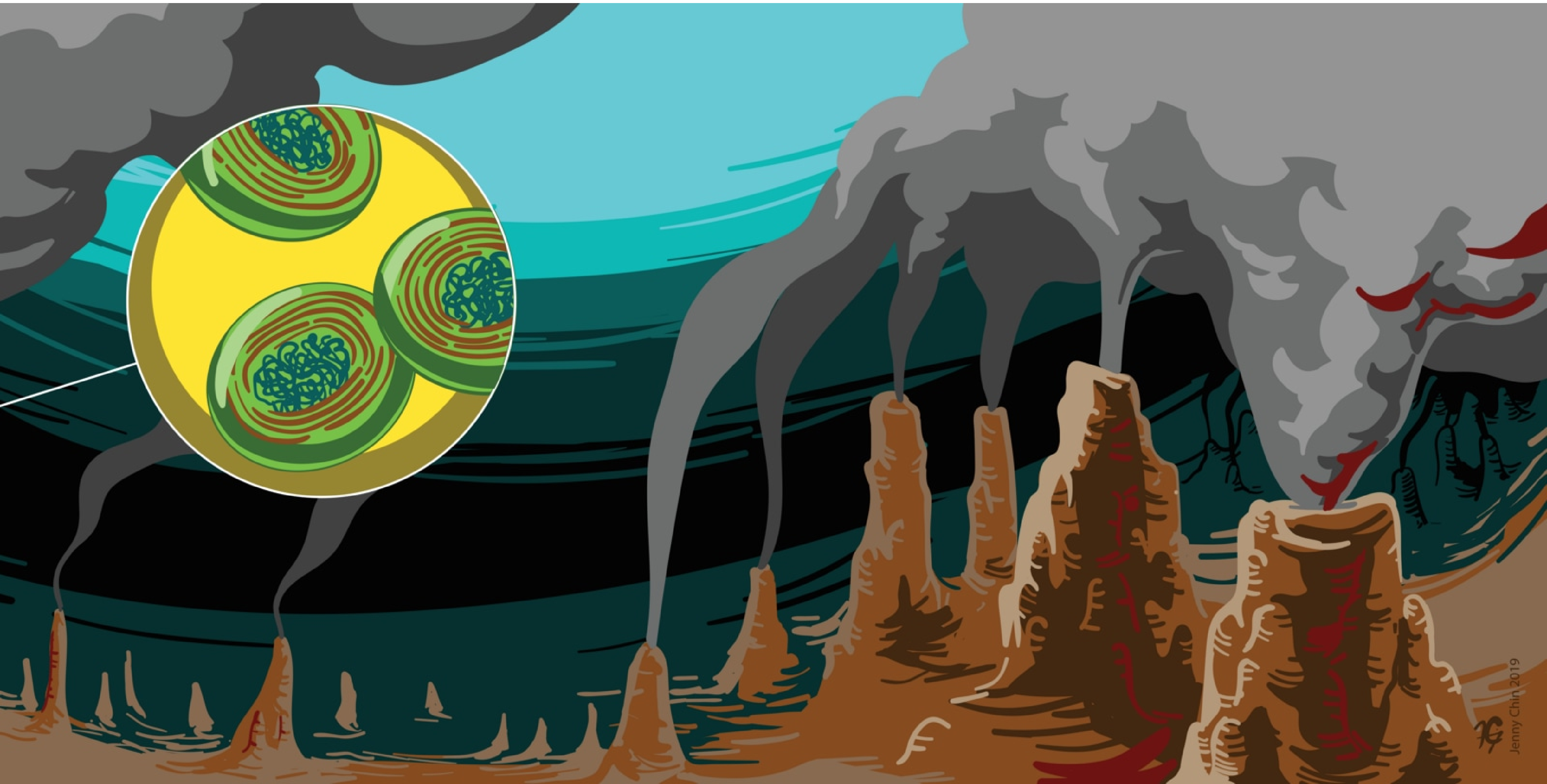
Oil deposits from after the GOE have been linked to cyanobacteria activity, pointing to their role in creation of petroleum.

Cyanobacteria were so successful at taking in carbon dioxide that they narrowly caused their own extinction event. Many other microbes perished, too; however, life that had adapted to use oxygen flourished. Oxygen releases a lot of energy when combined with food molecules. Every organism having cells that used oxygen could grow and reproduce faster.

Knowledge

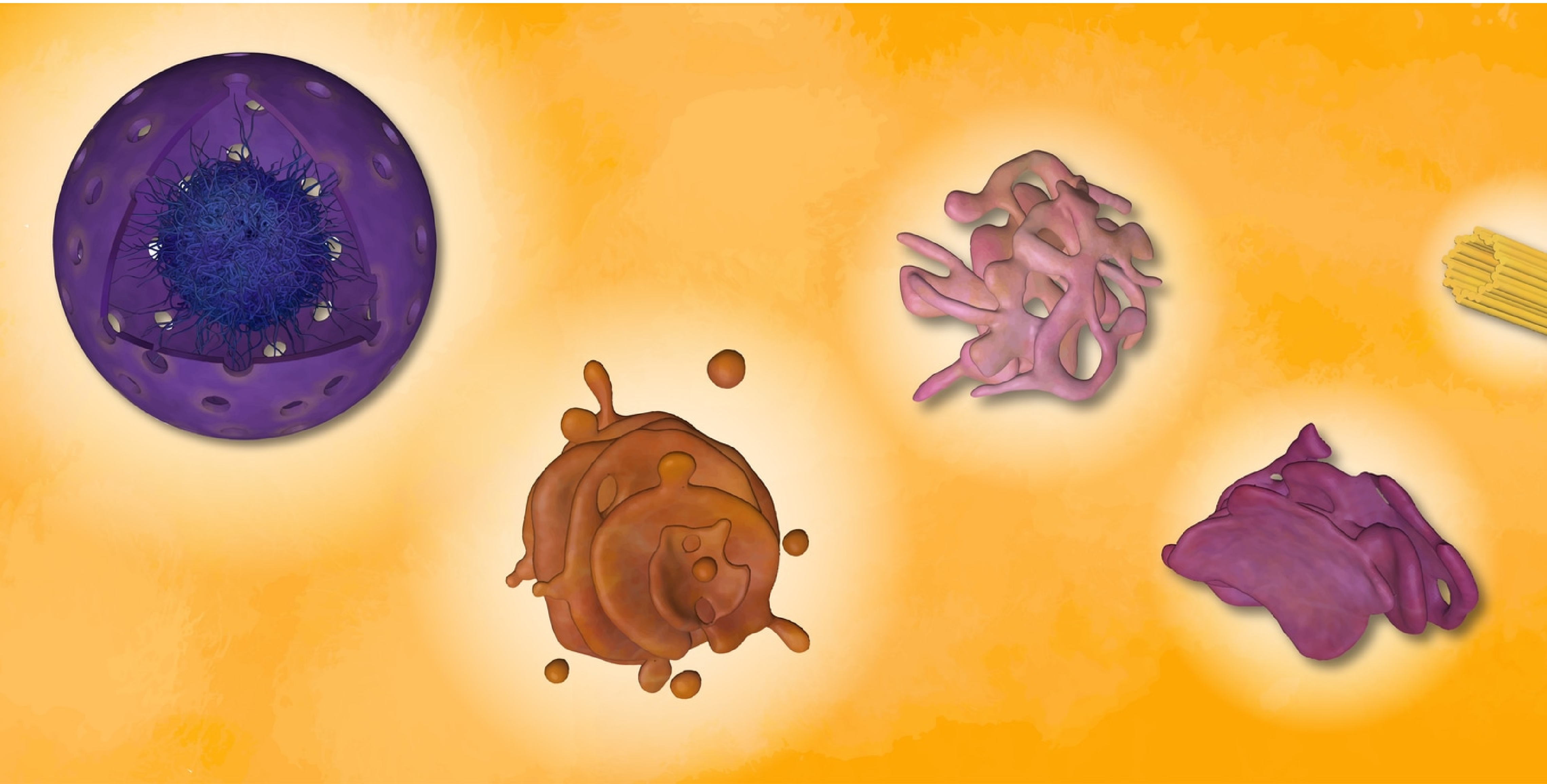
Although the precise timeline is uncertain, oxygenic photosynthesizing abilities probably arose about three billion years ago, possibly earlier, in a distant ancestor of cyanobacteria. Scientists debate whether life emerged near hydrothermal vents or under the selective pressures of the Sun's ultraviolet radiation. If the latter, then the first cyanobacteria might have formed in shallow, warm-water bodies.

Molybdenum, a silvery metal and a key ingredient for life, dissolves better in oxygenated water than oxygen-poor water. Molybdenum levels in rocks echo oxygen changes over time. Samples from South Africa's Griqualand West Basin, once an ancient marine environment, were dated to just before the GOE. They show the metal's rising trend, implying oxygen's rise.



Complex Cells

2,312 ± 11 Ma



Eukaryotes are organisms of one or more cells that have genetic material—details that instruct a cell how to replicate, grow, and more—inside a nucleus.

By analogy, if a nucleus is an office then the major eukaryotic organelles are: endoplasmic reticulum (stairs and hallways), mitochondria (electricity), the Golgi apparatus (inter-office mail), and chloroplast (solar panels). The events that led to a eukaryotic cell assembling these different parts from its prokaryotic ancestor(s) is known as *eukaryogenesis*.

How eukaryotes originated is yet unsolved.

Relevance

Eukaryotic cells were evolutionarily pivotal. Complex multicellular organisms need a lot of energy at the cellular level to communicate and signal between cells. Oxygen is used by a cell's power house—mitochondria—to produce sufficient energy for multicellular organisms to thrive. The combination of an oxygenated atmosphere and complex cells led to the ancestors of all modern oxygen-breathing creatures, including humans.

Knowledge

Scientists once thought that a bacteria ancestor (*alpha-proteobacteria*) survived merging with a slightly larger organism, bringing it one step closer to becoming a eukaryote, but physical evidence of this transition was lacking.

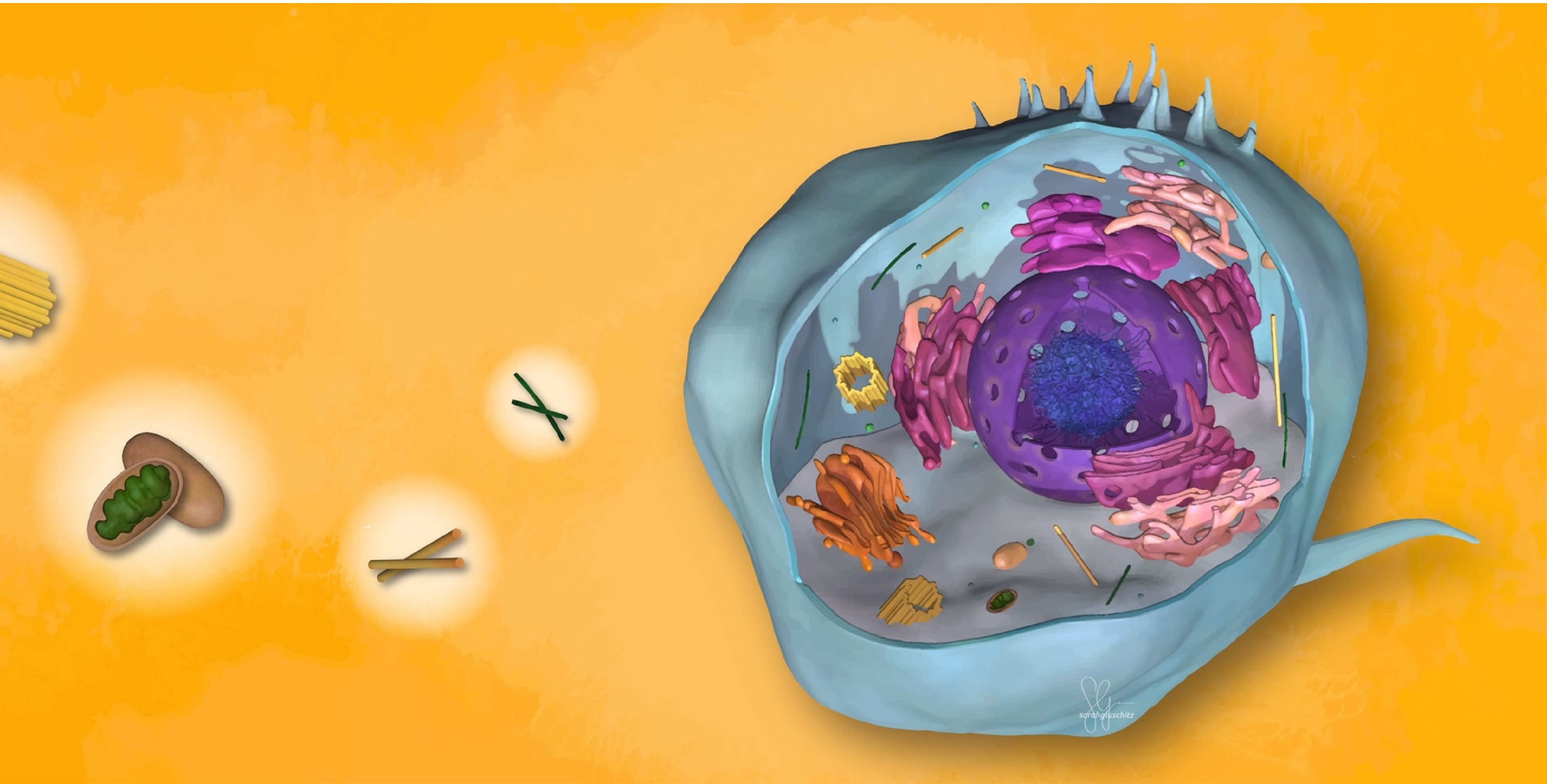
Studies since then revealed that rather than a quick tryst, the evolution from prokaryote to eukaryote happened as an extended, slow dance between kingdoms. Organelles took vast stretches of time to merge.

When continents collide, taking millions of years to do so, underwater mountains rise up. Parts of these mountainous regions are called mid-ocean ridges and are known for producing hydrothermal vents.

Ultra-slow spreading rifts are thought to be evolutionary dead-ends for any simple animals inside because their larvae cannot surmount rifts' crests to disperse. Near Iceland there is an ultra-slow spreading ridge that moves at 16 mm per year, named Mohns Ridge. From a remotely controlled submersible vehicle, researchers found four large, active hydrothermal vents close to Mohns Ridge, which they collectively nicknamed Lokeslottet, or *Loki's Castle*.

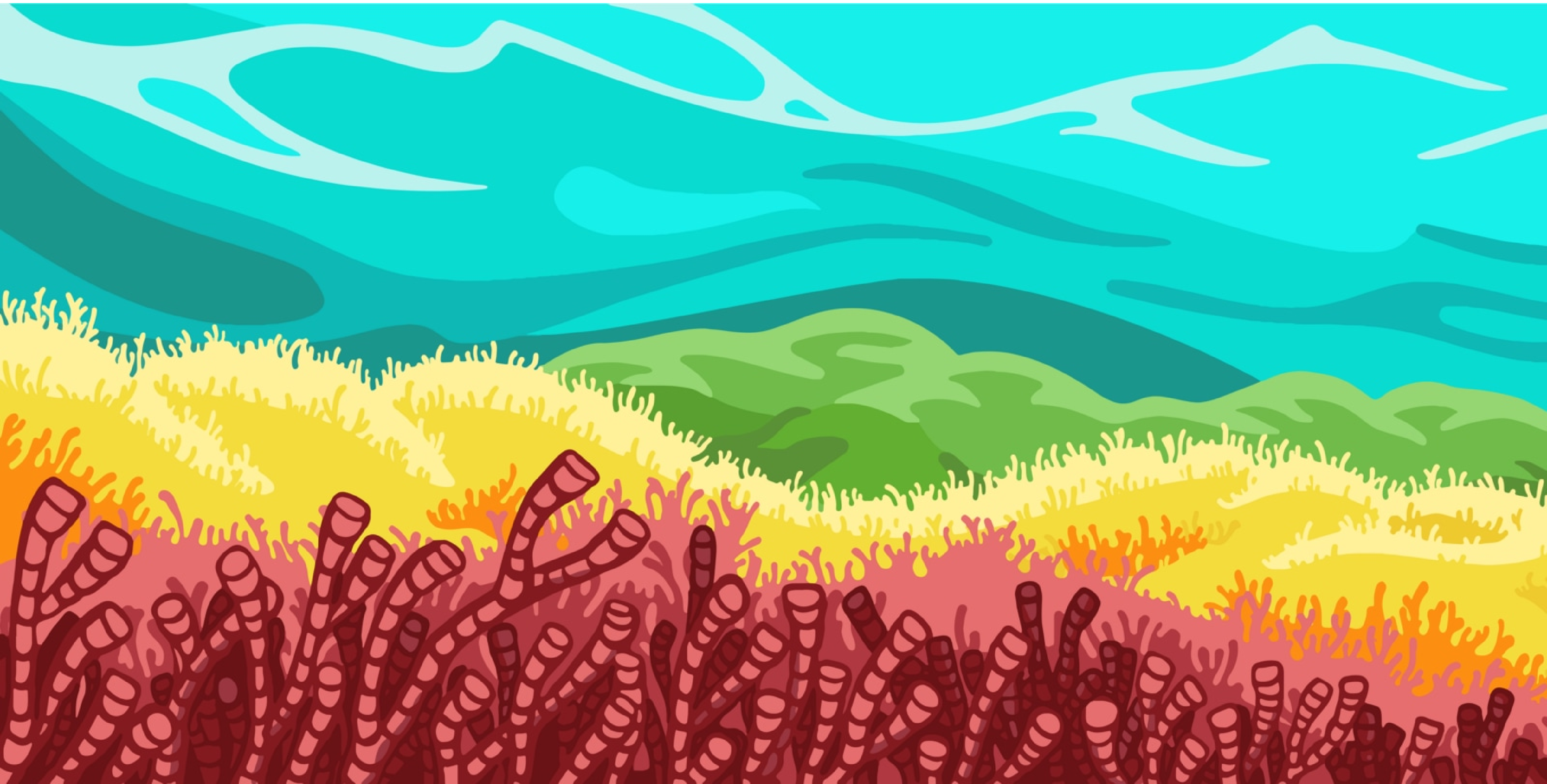
Microbial samples taken 15 km away from Loki's Castle had genetic material from a line of prokaryotes unlike any other known.

Biologists surmise that the ancient cells lacked a nucleus and mitochondria, yet their genes and laboratory observations suggest that it could swallow or entangle other bacteria—a behaviour found in eukaryotes. Discovery of this prokaryotic lineage having eukaryotic features provides strong evidence that supports the theory of eukaryogenesis.



Multicellular Eukaryotes

1,592 ± 32 Ma



Unnamed, elongated fossils found in China measure over 15 mm long and 3 mm wide. They are among the oldest multicellular eukaryotes in the fossil record that have been reliably confirmed.

Transition from single-celled to multicellular life has happened many times, but the process is unclear. (Animals, for example, evolved multicellularity independently sometime before 717 million years ago.) Regardless, two basic traits distinguish multicellular organisms: cells must be stuck together to make a new unit and they must be able to coördinate activity.

A few benefits of multicellularity include: enhancements for gathering resources (such as food), protection from predators, resistance to physical stresses, faster to colonize new areas, greater opportunities to evolve different cell types, and more; some drawbacks include: energy costs for adhesion and communication, plus reduced freedom of movement.

Relevance

Multicellularity made algae (red, brown, and green), fungi, land plants, and animals possible.

Long after multicellular animal life evolved, Earth entered an ice age called the *Sturtian glaciation* that blanketed nearly all the world in thick ice sheets. Gargantuan glaciers most likely crushed and eroded mountains, flushing enormous amounts of inorganic nutrients into slushy oceans. Green algae would have flourished, owing to the abundance of nutrients, leading to an increase of atmospheric oxygen from their photosynthesizing.

When algae blooms die they typically sink to the seafloor, sometimes mixing with clay-like material to create an organic-rich mud. Over time, layers of sediment build up and the oldest layers turn to rock called *organic shale*. If the shale is buried kilometres deep—a process that takes millions of years—then the pressure and heat transforms it into a waxy substance. At temperatures between 90°C and 160°C, the waxy substance turns into oil and natural gas.

Burning these non-renewable fuels reverses the chemical process, releasing carbon dioxide back into the atmosphere.

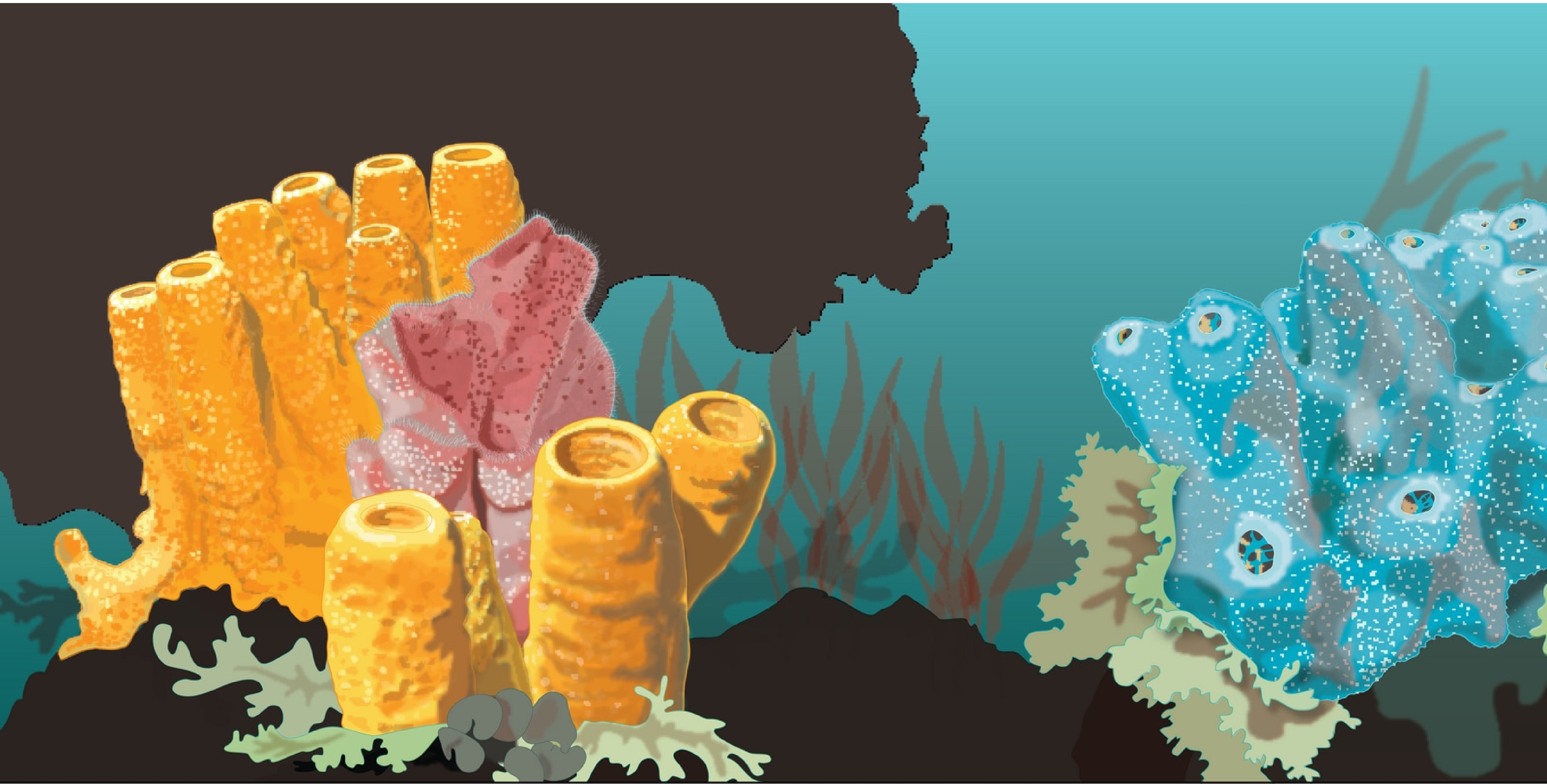
Knowledge

Molecules are atoms joined together by sharing electrons. Every molecule gains or loses energy in fixed amounts; different molecules have distinct fixed amounts that make them change energy levels. Energy received that is not one of the fixed amounts is released immediately and entirely; however, sometimes the energy splits into parts: a fixed amount that changes the energy level and a little bit that's released. Detecting those little energy releases, triggered by lasers, is called *Raman spectroscopy*.

Fossilized mudstone from North China rock formations showed organic fragments with cell structures, viewed via Raman spectroscopy.

Simple Animals

659 ± 6 Ma



Multicellular sponges evolving from eukaryotes was a momentous event. One especially helpful trait that arose (from simpler components) was a thin, whip-like structure called a *flagellum*. An organism or cell possessing at least one flagellum is called a *flagellate*. Biologists assert that all animals stem from a flagellated marine eukaryote, with their closest known living relatives having cell structures similar to those of some sponges.

Single-celled organisms move through water using flagella. In contrast, when water moves through a sponge, flagella are used to filter food particles. The filtered water is then pushed out through a hole at the top, called an *osculum*.

Although they lack a reproductive system, brain, stomach, and mouth, sponges qualify as simplistic animals due to their shared ancestry. Traits and behaviours sponges exhibit include: a skeleton-like structure; a simple immune system that can distinguish between itself and other sponges; individual cells that can react to environmental changes; the ability to act as either female or male; and, amazingly, if broken down to the cell level, the cells can reassemble and resurrect themselves.

When some sponges reproduce, their larvae use external flagella to propel themselves to new locations. After landing, the larvae begin their metamorphosis into adults, anchored to a reef for their entire lives. Being so simple and resilient, certain sponge types can survive for thousands of years.

Relevance

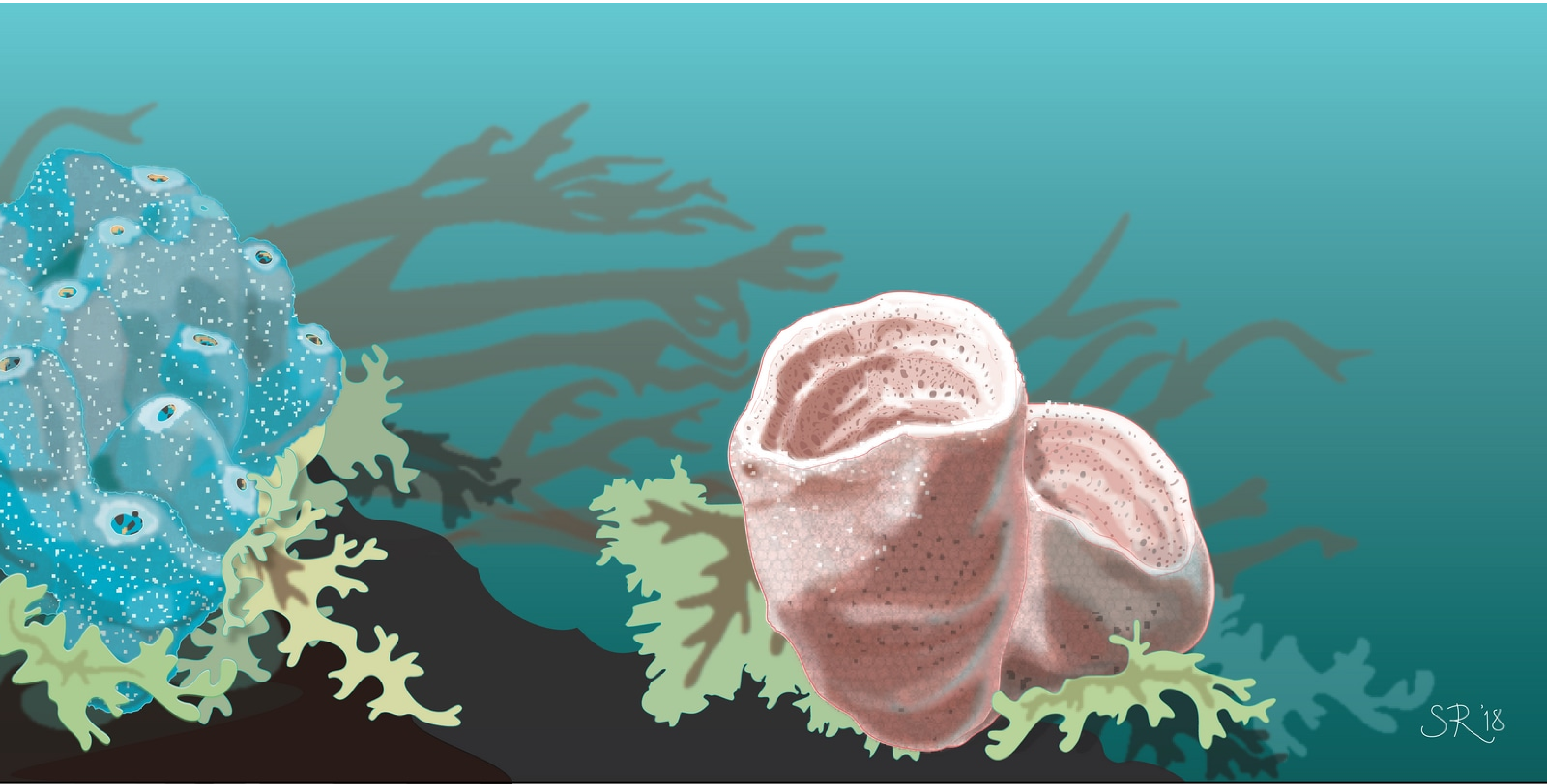
Sponges might have helped to oxygenate deep oceans. The abundance of oxygen would have made a habitable environment that improved the chances for more mobile animals to evolve.

Glass sponges live in deep, cold waters and are found in every ocean. *Monorhaphis chuni* is a glass sponge that forms rods of silica nearly three metres long and one centimetre thick. One specimen is estimated to be between 8,000 and 14,000 years old. Changes in seawater temperature affect the rod, microscopically. Using other methods to determine prehistoric ocean temperatures may be supported by studying glass sponges, independently.

Knowledge

Scientists use advanced technology to discover and describe fossilized sponges.

After collecting rocks containing fossils, the samples are prepared for slicing. When ready, a machine photographs a sample from above then grinds away a layer just a few microns thick. The newly-exposed layer is photographed. The process repeats until no more layers remain. A computer scans each layer for fossils then stacks the photos to produce 3D models of the organisms. The technique can also create models of any small, shelled fossils.



Cambrian Radiation

539 to 521 Ma

Renowned biologist Charles Darwin, in 1859, was bewildered by an apparent lack of fossils prior to the Cambrian Period, about 539 million years ago. Around the Cambrian's dawn, fossils of hard-shelled, oceanic animal groups—including the iconic trilobites—appeared abruptly. Fossils for nearly all major animal groups (*phyla*) that are alive today can be found during the first half of the Cambrian Period.

Fossils before the Cambrian were discovered in the 20th century. Called *Ediacaran* life forms (or *biota*), most fossils from that time resemble frond-shaped, quilted leaves. Other forms were small, tubular, worm-like animals that might be the ancestors of almost all living animals. This suggests that much of life's diversity happened quite quickly, evolutionarily speaking.

When life changes faster than its usual pace, the accelerated timespan is labelled a *radiation*. Theories that help explain the Cambrian radiation include: the newfound ability for animals to swim freely; arms races between predators and prey; animals first burrowing into the sea floor; increased competition for food as algae-covered mats became scarcer; rising oceanic oxygen levels; or melting of global glaciers. All these theories are being tested.

Research shows that organism populations underwent a gradual expansion starting with Ediacaran biota, punctuated by a modest rise in evolutionary rates during the early Cambrian.

Relevance

This noteworthy chapter of life influenced the types of animals that exist on Earth. Humble worms might have been the first animals to have had a mirrored body symmetry (known as *bilaterians*). Bilaterians rose to dominate the animal kingdom while the Ediacaran biota went extinct. With few exceptions, all living animals are bilaterians, including humans.

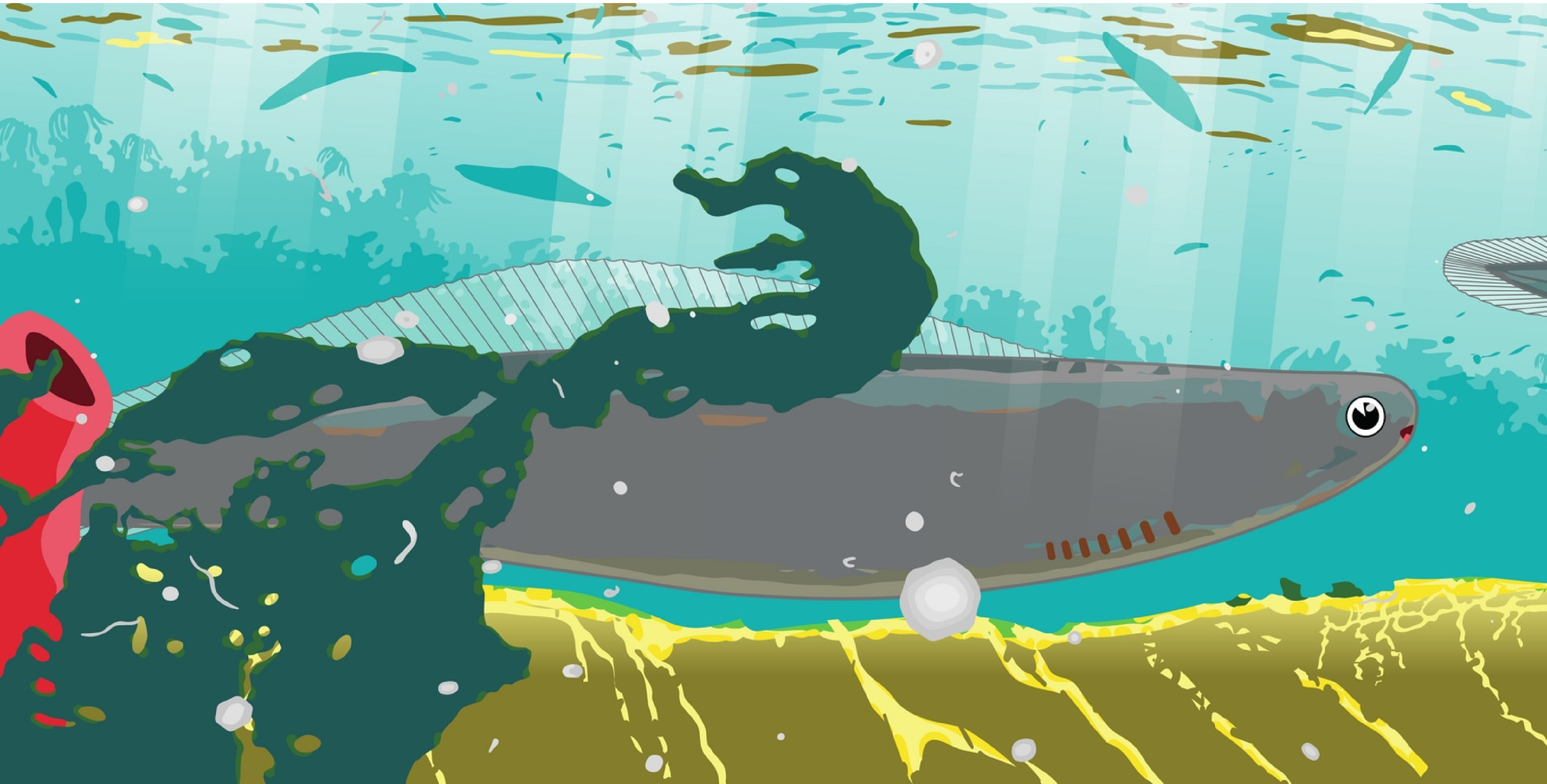
Not many extreme events have occurred in the intervening time periods that rivalled these changes to life on Earth. Humans took 200,000 years to reach 1 billion people, but only 200 years more to make 7 billion. Unlike how the Cambrian radiation produced a wondrous number of new animal types, the impacts of human radiation are causing a significant loss of species. Conservation biologists are working to preserve endangered animal populations facing shrinking habitats.

Knowledge

Organisms grow, survive, and reproduce based on biological instructions called *genetic codes*. A *molecular clock* measures how proteins for the codes have changed between two species or phyla. Given a rate of change, molecular clocks can help pinpoint when two species' diverged from a common ancestor. The clocks show that bilaterian phyla evolved slowly over time.

Vertebrates

518 ± 1 Ma



Jawless fish are among the earliest fishes. Vertebrates are animals that have backbones, also called spines. Vertebrates are a large group that have many aquatic forms and ancestries, including fish and—later—*tetrapods*.

Haikouichthys ercaicunensis (meaning *Haikou fish from Ercaicun*), may be closely related to the ancestor of all fishes. It grew up to two and a half centimetres long, weighed less than an ounce, had a distinct head and tail, a mouth, two eyes, a brain with indications of major divisions believed to help process its sensory inputs, a soft body, and could swim well. Fossil evidence suggests it had a prominent dorsal fin, no pectoral fins, ten or more elements along its back that could be crude separated protovertebrae, and it might have had between six and nine gills. Without any jaws, early fish might have filter-fed close to the sea bed.

At this time, most microbial mats—a rich, easy food source—would have been consumed by grazing animals of all sorts. Bottom filter-feeders like *Haikouichthys* might have travelled long distances to feast on surviving microbial mat patches.

As time passed, fish with jaws evolved. Not long after, bony fish emerged. From them, two notable groups branched: ray-finned fish and lobe-finned fish. Fins of ray-finned fish have thin webs of skin supported by delicate spines; whereas, lobe-finned fish fins are meatier and attached to the body by a limb-like bone.

Though the lobe-finned fish once dominated the oceans, a massive extinction event turned the tables. Fortunately, some lobe-finned fishes had adapted to weedy, shallow waters. Their predecessors never recovered.

Relevance

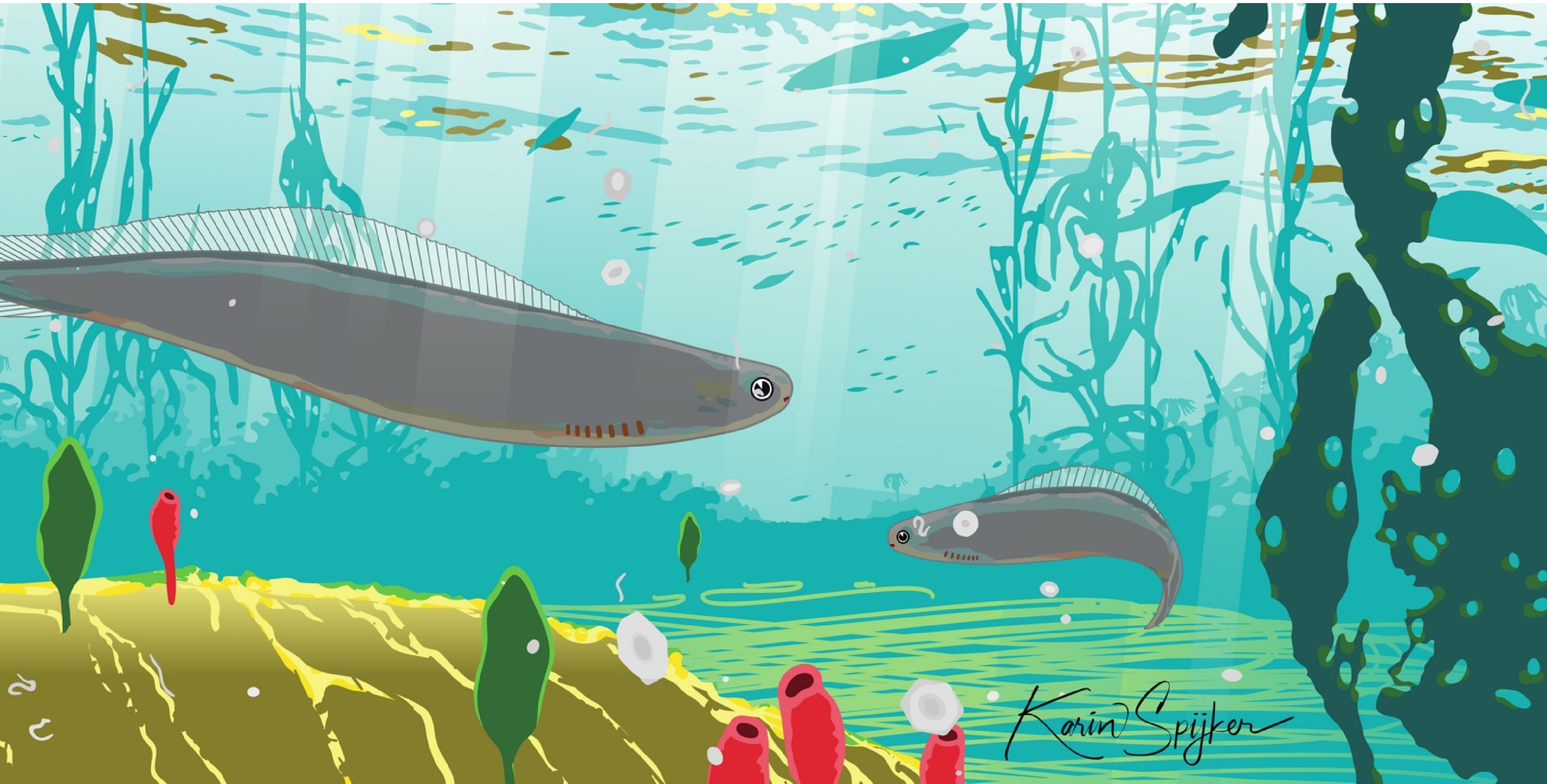
Lobe-finned fish set the basic body plan for all animals that evolved later, such as: amphibians, reptiles (including birds) and mammals.

Climate variability and sea level changes are considered key factors that triggered the die off.

Knowledge

Superbly preserved fossil deposits that retain remains for hundreds of millions of years are known by the scientific community. China's Maotianshan Shales holds *Haikouichthys* while its slightly younger kin, *Metaspriggina*, occurs in Canada's famous Burgess Shale.

Strata are rock layers having features that distinguish them from other layers, similar to sandwich layers. Fossilized organisms follow each other across strata in an order that reliably reflects a consecutive sequence of time periods (like knowing that a bread slice was lain down before its toppings). Dolphin fossils are not in the same strata as a *Haikouichthys* because they lived many millions of years apart. Strata can be dated by their fossils, which is a scientific method known as *biostratigraphy*.



Tetrapods

390 ± 3 Ma

Tetrapods are four-limbed vertebrates. The water to land transition entailed many profound evolutionary "steps." Advances over countless generations led to sturdier limbs, stronger spines, and hearing. As the skull became structurally solid, the jaw's supportive ancestral gill arch was repurposed as a bone to aid hearing.

Tiktaalik roseae (the Inuktitut word meaning *burbot*, a large freshwater fish) has a mixture of traits that record the vertebrate transition onto land. Up to three metres long, it had fish-like scales on its back, a flat crocodile-like head with eyes on top, a physical disconnect between the head and shoulders (a neck), and fins that contained a bone structure echoed in the limbs of mammals, birds, reptiles, and amphibians.

Relevance

Air-breathing most likely evolved before lungs arose. Swim bladders (gas-filled sacs that help bony fish dive or rise in water) evolved from lungs. This meant that most ray-finned fishes lost the connection between lungs and their *trachea* (windpipe); however, some fish, such as catfish, retained their windpipe. Ancestral "air bladders" must have provided both breathing and buoyancy. Most ray-finned fishes lost respiratory ability as air bladders became swim bladders, while tetrapods deemphasized buoyancy as they diversified onto land.

Around the same time, tetrapods developed stronger joints and digits, permitting them first to wade in shallow waters then soon after to walk on land. Tetrapods led to the evolution of all terrestrial vertebrates.

Knowledge

Scientists predicted *Tiktaalik roseae's* location of Ellesmere Island using evolutionary theory.

Fossil trackways are ordered footprints made by ancient animals in soft ground, like swamp bottoms, lagoons, river banks, or seasonal lakes. To escape erosion and be preserved, trackways must be buried by a new sediment soon after they are made.

Paleontologists determined that fossilized sediments from Poland's Zachełmie Quarry had once formed in a shallow, warm, and flat marine environment, quite likely a seasonal lake. There they found trackways resembling a diagonal stride pattern: a clear tell-tale sign of walking tetrapods. The trackways signify the time when animals first trekked across land.

Biozones are strata having fossilized species that are distinct enough to distinguish them from older or younger layers. *Conodonts* are tooth-like structures of tiny, simplistic eel-like predators. Their fossilized "teeth" span many ages and are found across biozones, making them useful as geological timekeepers.

The Zachełmie trackways were dated using conodonts and radiometry, indirectly.

Amniotes

319 ± 4 Ma

Hylonomus (meaning *forest dweller*) was a tetrapod that measured around two decimetres from neck to pelvis. The five-toed lizardesque animal likely ate insects and snails because few other choices existed. Its clawed feet could have been used to grip, hinting at a terrestrial lifestyle. Females laid eggs in moist, sheltered places. Paleontologists reason that *Hylonomus* is one of the first true amniotes (animals that lay eggs on land).

Amniotic eggs have features fish eggs lack. An *amnion*, a fluid-filled sac where the embryo floats, imitates an aquatic setting. Its *albumen* provides water and helps absorb shocks. The *allantois* gives oxygen, removes carbon dioxide, and stores waste. The embryo ingests *yolk*.

Collectively, the features greatly expanded amniote habitats and lifestyles; allowed for larger hatchlings better equipped for survival; and helped eggs tolerate adverse weather and environmental conditions.

Relevance

The shift to laying eggs on land let amniotes abandon their aquatic homes. Amnions meant that embryos could still grow within a watery substance, without the need to be in water while developing. No longer tied to waterways, amniotes ventured inland.

Around this time—the Carboniferous Period, which is known for its vast swamps—dense deposits of decaying vegetation in wetlands, including trees, ferns, mosses, and algae began to accumulate, trapping much carbon.

Dead vegetation that collects in low-oxygen settings can become organic matter called *peat*. If peat is buried under sediment that builds up over millions of years, the vertical pressure changes peat into *lignite*. With added pressure and—in due time—heat, lignite becomes coal.

Electricity from burning coal releases carbon dioxide that ancient plants had removed from the air back into the air. Human activities are reversing a global process that took hundreds of millions of years… in less than two centuries.

Knowledge

Geologists slice time into *eons*. Eons are divided into *eras*, *periods*, *epochs*, and *ages*. Ages span several millions of years. Strata from distant areas having the same fossil content are interpreted to be of the same relative age.

Paleopalynology is the study of ancient plant pollens and other organic microfossils, collectively known as *palynomorphs*. Upon burial in sediment, palynomorphs tend to remain intact, even in places where few fossil types can be found. Plant life-cycles can change so swiftly at times that pollen from different plant species mark short geological time periods. A variety of dating methods support these findings.

Scientists dated rocks containing *Hylonomus* fossils to the *Bashkirian age*, around 319 million years ago, using paleopalynology.

Dinosaurs

231 ± 1 Ma

Eoraptor lunensis (meaning *dawn plunderer from the Valley of the Moon*) is among the earliest dinosaurs known. Argentinian fossils give glimpses into its pack-hunter, scavenging lifestyle. Measuring up to one and a half metres long, *Eoraptor* had both herbivorous and carnivorous teeth, making it a *heterodont*. It would have consumed insects, lizards, and other small prey, while tough vegetation rounded out its paleo diet.

Dinosaurs are identified by the circle made where their hip bones connect, which affected how they walked—their gait. Dinosaurs strode upon two legs at first; however, after untold generations, the fossil record reveals that four-footed dinosaurs emerged. Gait sets dinosaurs apart from splayed-limbed reptiles like lizards, turtles, and crocodiles. Crocodilians, dinosaurs, birds, and pterosaurs are all *archosaurs*.

Nyasasaurus is vying for the crown of earliest known dinosaur, but more research is necessary to confirm its ancestry. Dethroning *Eoraptor* would push emergence of dinosaurs back by up to 15 million years.

Relevance

Studying fossils provides insights into Earth's ecosystems over long time periods ages before human influence. Dinosaurs were highly adaptive: they endured for over 160 million years, dominated a variety of ecosystems, and made it through multiple mass extinction events.

Paleontological research has helped identify or confirm various causes of extinctions that are written in the fossil record.

Extinctions can be triggered by huge asteroid impacts, oceans losing oxygen, methane eruptions, continent collisions, massive volcanism, global cooling, or global warming. Learning about what caused previous extinctions can teach us: how to identify great dying events, what preparations are needed to adapt to the future climate, and ways we can change our behaviours to help maintain a habitable planet.

Knowledge

Picture lining up boxes of different weights. If each is kicked with the same force, the lightest box travels farthest. In the same way, an atom's mass can be measured by "kicking" it into one of many detectors using a magnet. Each detector collects and counts atoms having the same mass. Counting them compares how much (the *ratios*) of each element is in the sample. Firing a laser at rocks is one way to begin the process.

If you ate half a pear one day, half of it the next, and so on, anyone could calculate the pear's age knowing only the rate it was eaten and how much is left. Using the ratio of $argon_{40}$ to $argon_{39}$ in a rock and argon's decay rates, chemists can compute a rock's age with respect to a different sample of known age. *Eoraptor* was dated this way.

Mammals

193 ± 4 Ma

Xiao-Chun Wu discovered a shrew-sized fossil that, compared to its body, has a relatively large brain cavity, a common mammalian trait. *Hadrocodium* (meaning *large and full head*) was a *mammaliaform* (mammal-shaped), not a mammal. Given its 12 millimetre-long skull, it might have weighed about two grams. Researchers think it had hair follicles.

Endothermy is the ability for an organism to make its own heat to keep its body warm. Shifting to a more active nightlife might have resulted in early mammal ancestors having better endothermy. Warm-bloodedness likely shaped other traits, such as superior hearing. Ears changed, presumably, because enhanced hearing would have been helpful to survive a nocturnal lifestyle, enabling early mammals to hear high-pitched insect noises. Those changes meant that night-scuttering mammals could avoid day-walking dinosaurs and hide from nighttime carnivores more readily. Mammals could have occupied ecological niches where their reptilian cousins could not compete.

Whiskers became important sensory inputs for navigation and foraging. Improved touch sensation might have helped mammals avoid danger. Typical early mammals had relatively large eyes, thought to aid with seeing without much light. Features associated with smell are considered more pronounced in *Hadrocodium* than its predecessors.

Relevance

Heightened touch and smell sensations might have driven neocortex enhancements, making mammals smarter, and likely helping advance nerve and muscle coordination. Brain growth outpaced skull cavity growth, forcing the brain to ripple into folds to fit inside the skull.

Brain size and sensory capacities diversified greatly as mammals evolved to exploit a variety of environments. Modern mammals have the largest brains relative to body size in the animal kingdom and uniquely possess a neocortex to process sight and sound.

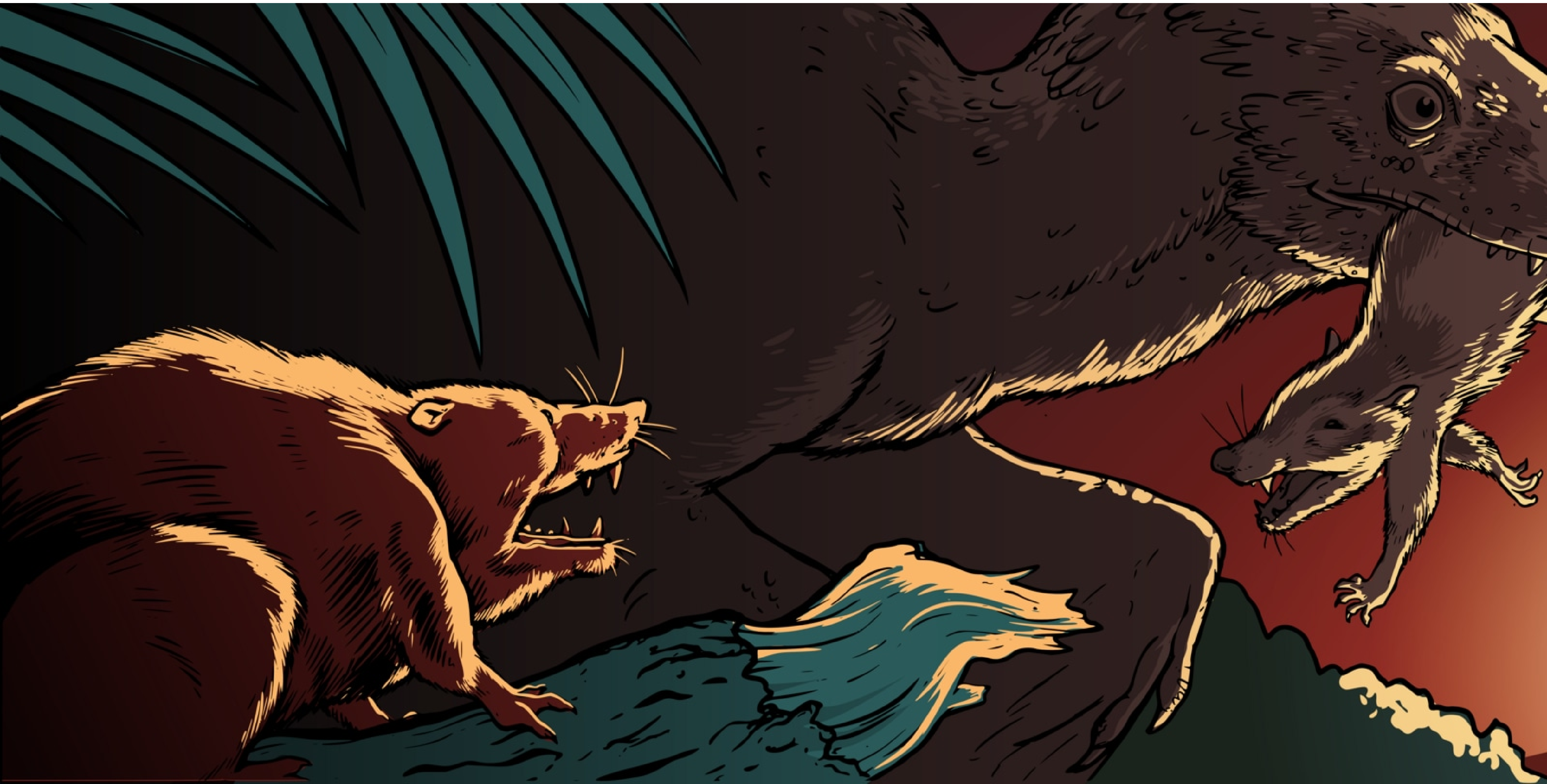
Knowledge

Studying how Earth's position relative to the Sun has altered our planet's past climate is called *cyclostratigraphy*. These climate shifts leave detectable traces in sediment that, when fossilized, remain at regular intervals in strata (layered rocks). Like counting a tree's rings reveals its age, counting climate shifts helps date rock layers to specific time intervals.

England's Blue Lias rock layers were dated to the early Jurassic using many methods, including cyclostratigraphy. Biozones within the Blue Lias strata match those from China's Lufeng Formation in Yunnan Province, the site where *Hadrocodium wui* was found. The fossil was also dated independently using numerous local biostratigraphic findings.

K–Pg Extinction

66.04 ± 0.05 Ma



K–Pg refers to the *Cretaceous–Paleogene* boundary, defined by a global iridium-rich clay layer found in rocks at some 375 sites world wide. The layer was deposited when an asteroid between 11 and 15 kilometres in diameter impacted Earth.

Before it smote the planet, nearly every niche brimmed with life. Paleotemperature studies show equatorial seawater was a sweltering 36 degrees Celsius (°C) and carbon dioxide in the air had surpassed 800 parts per million.

At the time, the impact site—the Gulf of Mexico—stored massive amounts of limestone, sulphur-containing rocks, and organic matter. When the asteroid struck, chaos ensued.

Air blasts levelled forests up to thousands of kilometres away. A Brobdingnagian amount of vaporized rock expanded into space. Building-sized rocks rained down along with trillions of white-hot glass droplets that re-entered the atmosphere. Droplets broiled the air, radiantly igniting fires far afield. An enlarging plume of searing heat sped away from the impact site, travelling up to 1,500 km. Powerful winds tore through the landscape. Earthquakes destroyed coastlines as megatsunami towering hundreds of metres tall submerged them around the Gulf, possibly globally. Clouds emptied acid rain and the ozone layer depleted. It was a bad day.

On the planet's opposite side, volcanoes were pumping carbon dioxide into the atmosphere and acidifying the ocean, stressing marine life.

A combination of fine particulate ejecta, seawater, vaporized rocks, and soot from wildfires enshrouded the planet; Earth's balmy weather tumbled by at least 25°C; the world plunged into a dim winter that lasted over a decade. Without sunshine and heat, land plants all but perished; large herbivores starved to death; and gigantic carnivores fell soon thereafter.

The dominion of nonavian dinosaurs and large marine reptiles had ended.

Relevance

Mammals were safer at night because most dinosaurs hunted by day. But some mammals, such as *Repenomamus giganticus*, had competed with dinosaurs and even ate their young. Still, dinosaurs exerted evolutionary pressures that probably prevented mammals from getting much larger until the calamitous strike.

Most animals weighing more than 25 kg went extinct. Not long after, many ecological niches freed up, which allowed avian dinosaurs (birds) and small mammals to flourish.

Knowledge

Iridium is a dense metal and a rare element in Earth's crust: most of it likely sank during accretion. Asteroids have a higher iridium ratio than Earth's crust. Adjacent strata have been dated radiometrically to the same time period, strongly suggesting that the iridium layer had been lain during one globally destructive event.

Eocene Primates

55 ± 1 Ma

Fossil records from tropical regions where primates probably originated are scarce, especially around the time that primates are thought to have first appeared. Gaps remain to be filled for early primate evolution.

Tarsiers are small, tree-dwelling, leaping, nocturnal primates that sport tails longer than their bodies and see out of large, round eyes. *Haplorhini* are dry-nosed primates that group tarsiers with monkeys and apes, our closest relatives. *Archicebus achilles* means *first long-tailed monkey* and the fossil is named after Achilles, the Greek war hero, owing to its heel bone. The fossil provides insights into when tarsiers and our closest relatives diverged.

Tiny *Archicebus* had beady little eyes; sharp molar teeth; slender limbs; monkey-like feet; a long tail exceeding 13 cm; and weighed around 25 grams. The primate's hind limbs suggest it leaped a lot; yet its hip, shoulder, and foot bones signify that it probably moved through tropical trees by grasping limbs from above, implying an arboreal life. Its large canines and shearing molars led researchers to believe it probably fed on insects, while its relatively small eye sockets indicates that *Archicebus* was active during daytime, unlike tarsiers.

Relevance

Earth had an intense, global warming period during the early Eocene Epoch that was so warm that palm plants flourished in the Arctic. The period's rapid climate changes evoked fast evolutionary responses: a hotter planet led to smaller mammal body sizes, which affected the food chain. Species that did not adapt died out.

Atmospheric carbon dioxide levels around that time have been estimated up to 840 parts per million, spiking higher for short intervals. Without polar ice caps, which had melted, sea levels were close to 60 metres higher than present day. Barring significant reductions in our emission rates, carbon dioxide in the air will surpass 720 parts per million by this century's end. Inland migration costs will be tremendous.

The Eocene's warming period, caused by a relatively sudden release of greenhouse gases, foreshadows how deforestation and burning fossil fuels will affect the planet's future.

Knowledge

Earth's global temperature is maintained when the amount of solar energy absorbed by both the atmosphere and the surface balance the energy returned to space. The Sun's distance, sunspot cycles, Earth's molten core, and other factors negligibly affect the climate.

Sunlight passes through greenhouse gases unimpeded, heating Earth's surface. Heat then radiates as infrared light, which those same gases scatter in all directions, including back to the surface. As greenhouse gases accumulate, more surface heat is trapped, warming Earth.

Ancestral Apes

10 ± 1 Ma

Quips about humans descending from monkeys come from common misunderstandings regarding evolution. Living species are not ancestors of other living species. Humans did not evolve from gorillas, chimpanzees, monkeys, or any species that is alive today; humans evolved from a common ancestor that lived millions of years ago.

Nakalipithecus nakayamai (meaning *Nakali ape* and honouring Katsuhiro Nakayama) was an ape that lived in what is now central Kenya. Researchers reason that *Nakalipithecus* was close to being the last common ancestor of humans, gorillas, and chimpanzees.

Nakalipithecus males weighed nearly 72 kg. The ape is thought to have had a broad torso, lengthy arms, and long chimpanzee-like fingers. As with other apes, it was occasionally bipedal, standing on its legs only as need arose, such as to grab low-hanging fruit or nuts off of branches. Its surrounding paleoenvironment would have been a sparse, thinning evergreen forest forming open areas with plenty of sunlight and limited shade. The roots of bipedalism and a shift towards a less arboreal landscape went seemingly hand-in-hand.

Relevance

One consequence of bipedalism is that it freed our ancestors' hands from walking. Initially, dexterity would have been limited to support an arboreal-terrestrial lifestyle. Yet, as forests thinned over time, the changing climate might have led to selective pressures that favoured full bipedalism, permitting fine-tuned muscle movements to help reshape their environment: a precursor for making and using tools.

Nakalipithecus nakayamai and similar fossils are evidence of when gorillas, chimpanzees, and humans diverged from a common ancestor. The fossils support the theory that humans' closest relatives evolved in Africa, not Asia.

Knowledge

When Romans heated jars in kilns, minerals in the clay spun like compasses, influenced by Earth's magnetic field. As they cooled, minerals locked into place to create permanent, measurable records of the field, like a tape recorder. Royal seals stamped onto the jars provide a chronology of how the field has fluctuated.

Certain minerals in lava flows can also be affected by Earth's magnetic field. As the lava cools, minuscule minerals capture the field's strength and direction, like pottery. Eruptions from the same volcano, but years apart, will solidify into layers having distinct magnetic signatures, similar to Roman jars.

Studying these layered strata is known as *magnetostratigraphy* and can be used to verify radioactive dating methods. Geologists used magnetostratigraphy to cross-check the dates of the Nakali Formation, where *Nakalipithecus nakayamai's* jaw was found.

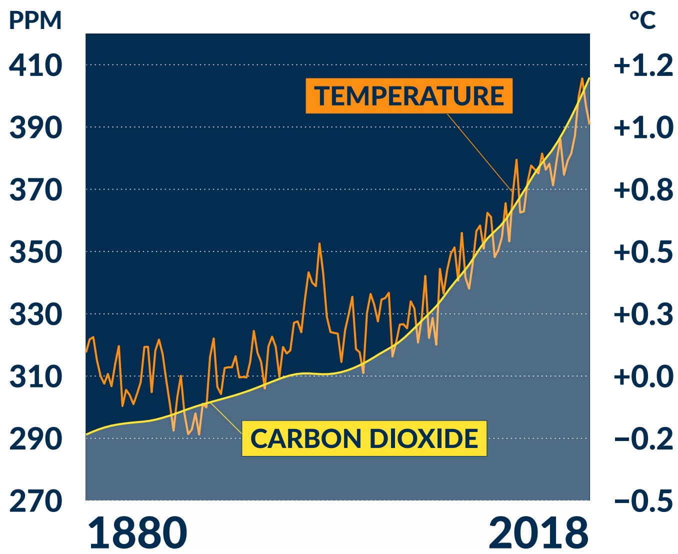
Anthropocene Extinction

0 Ma

Life is experiencing an abrupt, widespread global species extinction event. Humans are destroying intricate webs of animals, plants, and microorganisms. These networks supply our food chain and sustain life on Earth; their annihilation from rapid deforestation and climate change is causing grave consequences: droughts, increased heat waves and wildfires, more frequent severe weather events, coastal flooding, food shortages, and water wars.

Earth's atmosphere was once mostly carbon dioxide. After life took hold, simple organisms (such as bacteria, algae, and plants) converted atmospheric carbon dioxide into oxygen by way of photosynthesis. When those organisms died, natural processes spanning eons changed their remains into carbon-bearing fossil fuels: coal, petroleum, and natural gas.

Burning fossil fuels recombines carbon with oxygen to make carbon dioxide (CO_2). Since the mid-1800s humans have released a stupendous amount of CO_2 into the atmosphere. In the following graph, average annual atmospheric CO_2 measurements in parts per million (PPM) are shown alongside averaged global ocean and surface temperature readings in degrees Celsius (°C), relative to 1881 through 1910:



Both atmospheric CO_2 and temperature are increasing at an exponential rate, in lock-step.

Bubbles in ice cores drilled from polar glaciers provide historic atmospheric gas ratios. Long-term observations reveal an increasing average warming trend that is distinct from natural short-term fluctuations. Temperatures are climbing in proportion to the total amount of atmospheric CO_2 added since the start of the First Industrial Revolution.

Choices

Burning fossil fuels has put life on Earth in peril; our children face an immense carbon dioxide cleanup, devastating climate changes, or both. We can curtail the most catastrophic outcomes, but time to do so grows alarmingly brief.

If we choose air conditioner and refrigerator coolants based on **hydrocarbon refrigerants**; if we urge politicians to invest in **on-shore wind turbines**; if we **reduce food waste**; if we **eat less meat**; and if we support restoration of **tropical forests**… If we take these actions, there is hope.

Acknowledgments

Illustrators

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