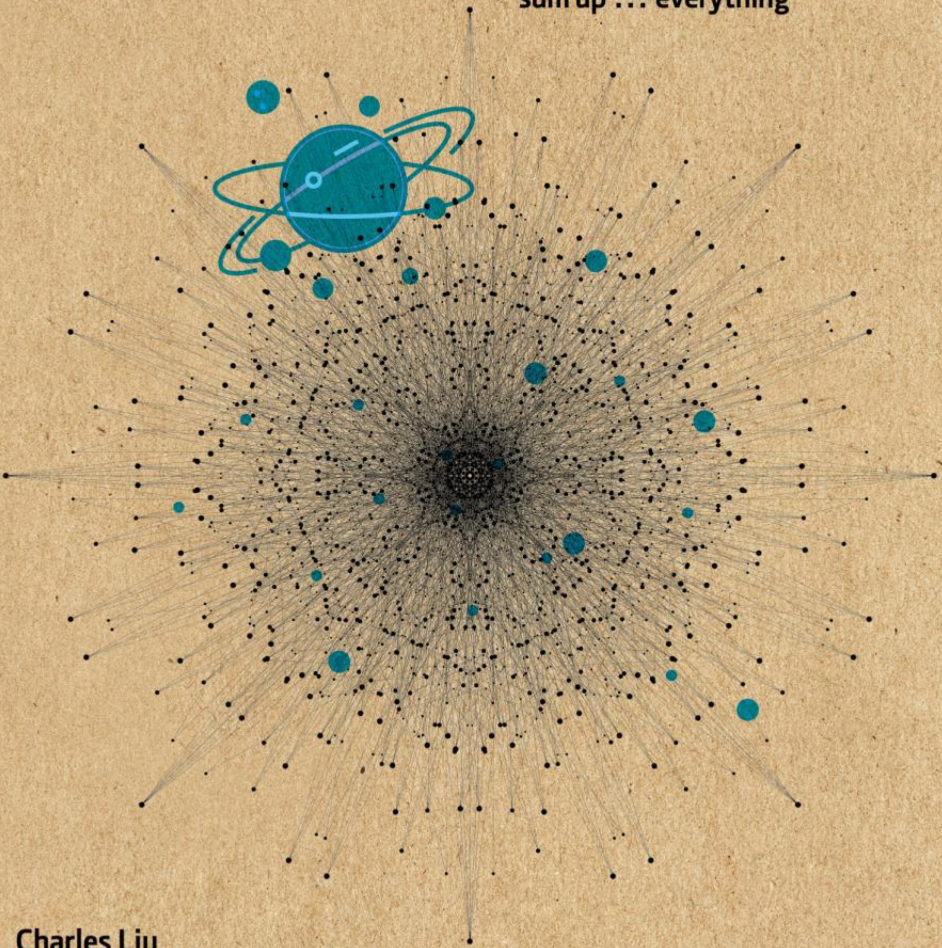
30-SECOND UNIVERSE

The 50 most significant ideas, theories and events that sum up . . . everything



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INTRODUCTION

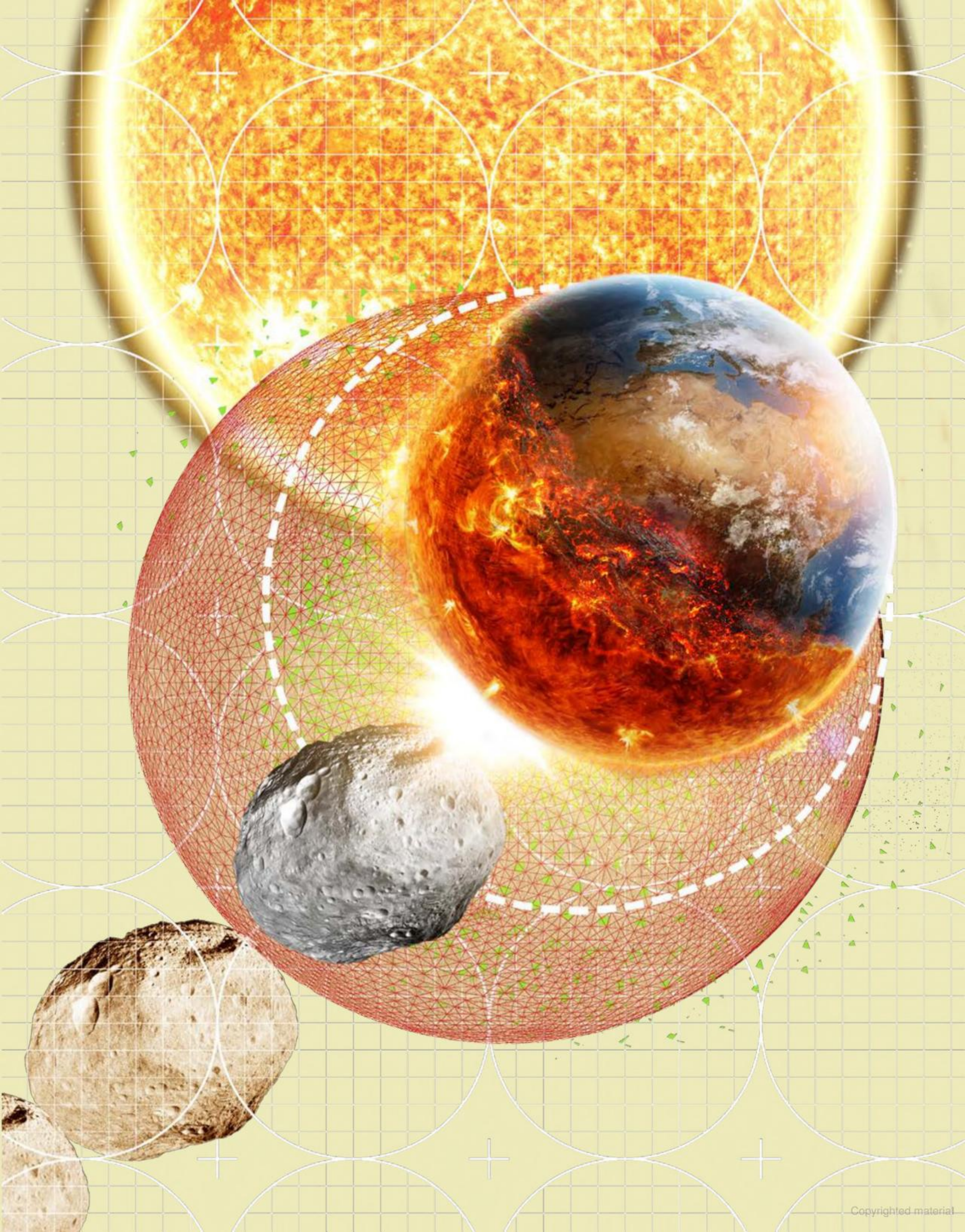
Charles Liu

Universe. Most of us connect that word with the heavens above – the planets, stars, nebulae and galaxies that we gaze upon with wonder in the darkness of the night. We are absolutely justified in doing so, for the story of humanity is inextricably linked with our collective realization, gradually over the millennia, that our species occupies only a tiny volume within a vast and possibly limitless expanse of space that extends far beyond our world's firm earth and flowing water.

Awesome and amazing as all that 'out there' may be, however, that vision of the cosmos is incomplete. The universe comprises all of space, time, matter and energy in existence. It includes everything that has emerged from the interaction of all its constituents – including all that is physical, chemical, biological, psychological, intellectual and societal. The universe would not be whole without every particle, every wave, every creature and every idea that has ever appeared or ever will appear, whether it has vanished or persisted, whether we perceive it or not, and whether it affects us or not.

Only by contemplating all of this staggering content and complexity can we even begin to grasp the enormity that is the universe. And through that contemplation, we realize that the greatest, deepest and profoundest questions we ask are reserved for the universe itself. How did it all begin? How has everything become what it is today? What is out there, beyond our ken, and how much? What are the smallest and most basic building blocks of everything? Will the universe go on forever? What exists beyond the limits of infinity? And, perhaps most self-servingly and most frustratingly, why are we here?

Piece by painstaking piece, over hundreds of generations we humans have been trying to put together the vast and nearly unknowable cosmic puzzle – and, remarkably, we have been making real progress. As Albert Einstein famously observed, 'The most incomprehensible thing about the Universe is that it is at all comprehensible.' Today, we know how long ago our universe started to exist – 13.8 billion years ago, when time began.

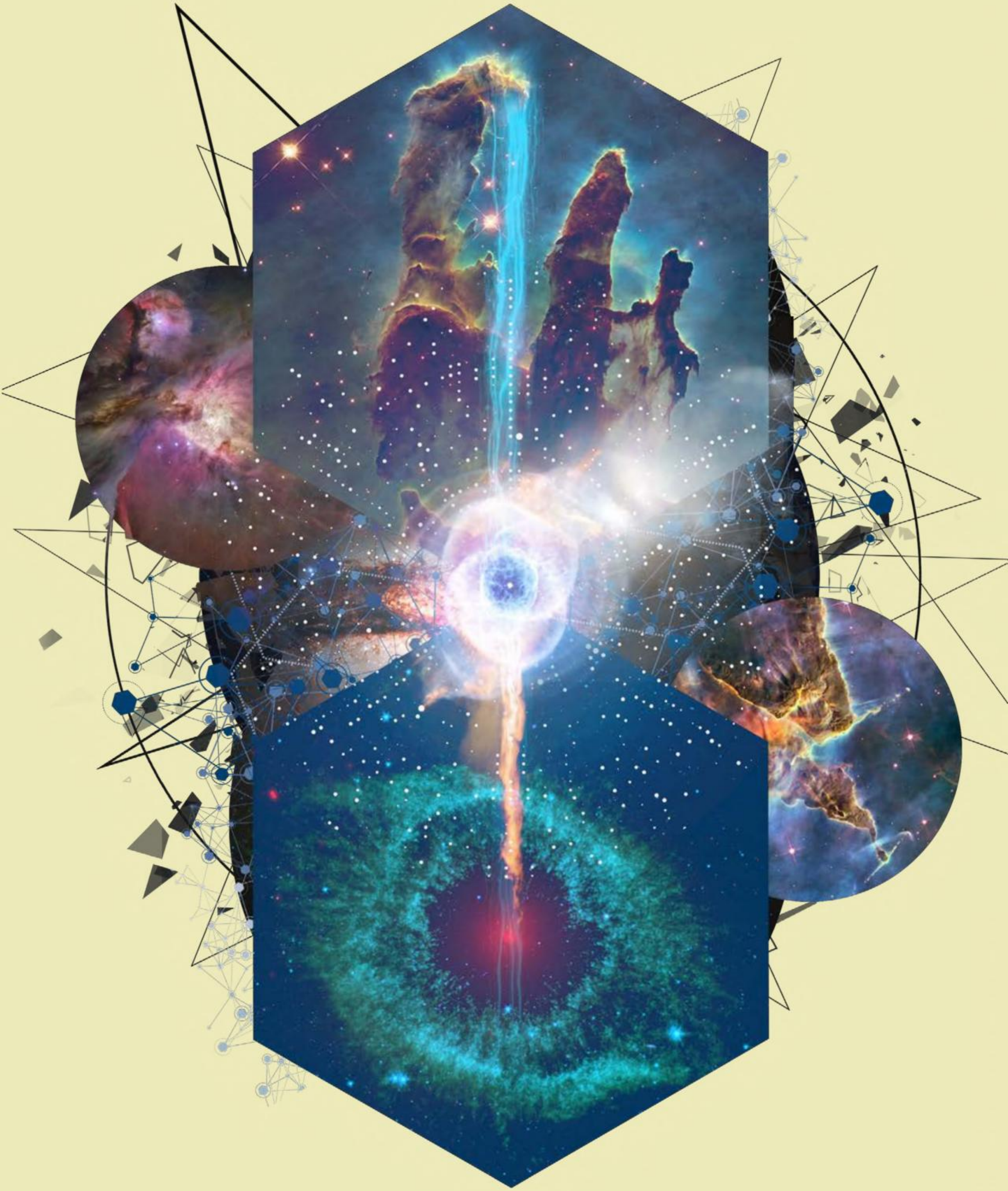


We know what the universe was like at that time, and how it reflects the microscopic underpinnings of all matter and energy today. We know how planets spin, how stars shine, and how galaxies can crash and combine even as space itself expands ever faster, spreading matter ever more thinly throughout the cosmos.

Our insights about the universe have often been gained with amazing machines built for discovery: the Hubble Space Telescope for finding dark matter and dark energy; the Large Hadron Collider for revealing the Higgs particle and quark-gluon plasma; and LIGO for detecting the gravitational waves released by colliding black holes rippling through the fabric of space-time. Building on these and other scientific results, we have furthered theories that, despite their solid scientific foundation, sometimes feel almost unrealistically fantastical: the Big Bang, cosmic inflation, string theory, supersymmetry and even a multiverse where our universe is just one among possibly infinitely many others.

Alas, deciphering the cosmos can be an achingly slow process – and humanity is not a particularly patient lot. So even when the data have not been available, we have, throughout history, reached beyond the tangible with our minds alone. This, too, is part of the universe – the realm of metaphysics, where we wonder what lies beyond even the most distant cosmic horizons. What, if anything, supersedes all there is? Does thought, consciousness or even existence have any larger meaning? Can we *really* know everything – or, for that matter, anything at all?

This book sets forth a seven-step path along humanity's quest of cosmic enquiry. Beginning with the **Origins of the Universe**, we travel from the very first moment of existence to the time when stars and galaxies illuminate the vastness of space. We next examine the properties of our curving, ageing and expanding **Observable Universe**, then peer into the **Quantum Universe** of submicroscopic particles and strangely predictable uncertainty that govern the cosmos at its most fundamental levels. We zoom out again to view the stars, galaxies and other cosmic objects that populate the **Physical Universe**; and mindful of that grand perspective, we contemplate what may extend beyond it all, into the **Metaphysical Universe**. We face the **Fate of the Universe** as our lives, our world and all the nestled pieces of the cosmos refuse to go gently into that good night; and, finally, we look beyond all there is – to the **Multiverse** that just might be – and perhaps glimpse the edges of an unbounded reality where there will never be the dying of the light.



ORIGINS OF THE UNIVERSE

angular size A term that refers to how large an object appears to be in your field of view. The closer an object the larger it appears to be: if a coin a metre from your eye has an angular size of about 1 degree; at 0.5 metre it is 2 degrees; at 2.5 centimetres away, it is about 40 degrees.

black body In physics, an object that is emitting light because it is glowing hot. Black bodies emit a characteristic spectrum of light – with the peak moving to shorter wavelengths as they get hotter. Most people are familiar with the idea of lumps of metal glowing red hot or white hot: this glow is the black body radiation from the heated metal, and the white (or blue) light has shorter wavelength than the red.

cosmic horizon The distance from which light has had time to travel to us since the beginning of the universe. Any part of the universe more distant is not possible for us to have observational knowledge of.

cosmological constant See dark energy.

cosmic rays High-energy particles moving through the solar system that hit Earth's upper atmosphere and produce showers of other particles, which can be detected.

dark energy A mysterious energy source in the universe, with negative pressure, that can speed up cosmic expansion. No one knows what it is but all constraints suggest it is constant with time and space (the 'cosmological constant').

fusion/fission The processes by which atomic nuclei either join together (fusion) or break apart (fission), regulated by the strong force. Atomic nuclei up to about the mass of iron release energy by fusion. Those more massive than iron release energy by fission.

ion An atom with an electric charge. Usually atoms have as many electrons as protons, and therefore are electrically neutral. In a process known as ionization – electrons can be removed from atoms, making them positively charged, or added to make them negatively charged.

light year The distance light travels (in a vacuum) in a year (365.25 days). Equal to 9.46 trillion kilometres, or 5.88 trillion miles. Often misinterpreted as a unit of time – but it is not time, it is distance.

Lyman-alpha forest A collection of absorption lines in the spectra of many distant galaxies or quasars. The lines are caused by the Lyman-alpha transition of electrons in a hydrogen atom along the line of sight to a galaxy or quasar. The expansion of the universe makes them appear at different observed wavelengths – the 'forest'.

megaparsec A unit of distance used in extragalactic astrophysics. It is 1 million parsecs, or about 3.3 million light years.

multiverse The idea that our universe is one of many, which might have different fundamental properties

photon A particle of light. The energy of a photon is proportional to its frequency, so high frequency (short wavelength) photons like X-rays carry a lot of energy, while low frequency photons carry very little.

proton One of the types of particle that make up an atomic nucleus; this is the kind with a positive charge. The simplest atomic nucleus – hydrogen is simply a single proton, whereas uranium, the heaviest known naturally occurring atomic nucleus, has 92 protons.

quantum fluctuation The uncertainty principle puts a limit on how well you can know the energy of a point in time and space. A quantum fluctuation is a temporary increase in the energy at a point in space caused by this uncertainty. This allows for the formation of particle-antiparticle pairs, particularly important in the early universe.

quasar or quasi-stellar object A point of light created by the accretion disc around a supermassive black hole in a very distant galaxy. As material spirals into a black hole it forms a doughnut-shaped accretion disc that gets very hot due to friction between particles and makes a lot of light. Because the galaxy is so distant you see only a point, and often cannot see the host galaxy as it is too dim.

radioactive decay The process by which massive atomic nuclei spontaneously fall apart (but not through fission) into other smaller atomic nuclei, releasing energy.

recombination The point in the history of the universe at which electrons and protons first combined to create hydrogen atoms, releasing the first light that could travel across the entire universe.

redshift The stretching of wavelengths of light caused by the expansion of the universe.

space-time The idea that the three dimensions of space and the time dimension can be expressed as a single, four-dimensional 'space-time'. A three-dimensional surface in this is called a 'cosmic hypersurface'. Often diagrams collapse the space dimensions into a plane, and there is one, the 'cosmic space hypersurface', which is a representation of all of space as it moves through time.

4 July 1868
Born in Lancaster, Massachusetts, the eldest of seven children born to George Roswell Leavitt and Henrietta Swan Kendrick

1886–88
Attends Oberlin College Ohio when her family moved to the vicinity

1888–92
Attends the Society for the Collegiate Instruction of Women – nicknamed the 'Harvard Annex' – in Cambridge, Massachusetts (later becomes Radcliffe College); takes her first lessons in astronomy

1893–96
Works as a volunteer assistant at Harvard College Observatory financially supported by her parents

1896–98
Travels in Europe and contracts a disease that leaves her partially deaf. She was to experience poor health for most of her life

1898–1902
Works as an arts assistant at Beloit College in Wisconsin where her family had relocated

1903
Returns to Cambridge, having been invited to work at Harvard College Observatory as a permanent staff member

1904
Begins to discover many variable stars in images of the southern skies, including in the Large and Small Magellanic Clouds; this triggers her interest in the subject

1908
Publishes a paper on the brightness of stars, '1777 Variables in the Magellanic Clouds'

1912
Discovers the relationship between the period of variation and absolute brightness of Cepheid variable stars

21 December 1921
Dies in Cambridge, Massachusetts. Subsequently, asteroid 5383 and the crater Leavitt on the Moon were named in her honour

HENRIETTA SWAN LEAVITT

Henrietta Swan Leavitt was the daughter of a church minister, George Roswell Leavitt, and Henrietta Swan Kendrick. Her father's work meant the family moved regularly, and in Henrietta's late teens they relocated to Cambridge, Massachusetts, home of Harvard University. As the nineteenth century drew to a close, educational opportunities for women were growing, particularly in the USA, and Leavitt was able to attend the Society for the Collegiate Instruction of Women. She graduated with a certificate which stated that 'had she been a man' she would have been granted a bachelor's degree from Harvard. Her credits included mathematics and astronomy.

This was also a time when astronomy was making increased use of photography, with glass plates being exposed nightly in the larger observatories. This made it possible to examine the results in greater detail than ever before. Charles Pickering, then director of the Harvard College Observatory, realized he could hire women to do this job for far less money than men, and Leavitt became one of more than 80 women (called the 'women computers') who undertook this role during Pickering's tenure. The job involved recording the position, colour and brightness of all the observable stars captured by the photographic plates. It was exacting work that required meticulous attention to detail as well as careful mathematical analysis.

Leavitt was particularly interested in the variable stars she noticed, points of light that get periodically brighter and dimmer over periods of days or weeks. She saw that many of these were in the Large and Small Magellanic Clouds (a pair of satellite galaxies of the Milky Way) and realized, crucially, that as the stars were in these small galaxies they were all equal distance from Earth. This leap in understanding allowed her to uncover a relationship between how quickly the brightness varies and the absolute brightness of these stars. This type of star is a Cepheid variable, a large evolved star, which is physically pulsating in and out and, in so doing, its brightness varies. The period of the variation is proportional to the star's brightness, and Leavitt provided the first calibration of this relationship, even before it was understood why it occurred. 'Leavitt's Law' became one of the most important ways to measure distances from the Milky Way to other galaxies, and Edwin Hubble later cited it his paper in which he used distances to galaxies to reveal the expansion of the universe itself.

In 1921 Leavitt was appointed head of stellar photometry at the Harvard College Observatory, but this was cut short by illness. and she died of cancer aged 53. After her death Hubble is said to have acknowledged her work as having been worthy of a Nobel Prize in Physics – although too late, sadly, as Nobels are not awarded posthumously.

BIG BANG

the 30-second blast

The universe is expanding. As measured by astronomers, every point in the universe not otherwise bound to its local environs by forces of some kind is moving away from every other point in space-time. The rate is roughly 70 kilometres (43.5 miles) per second per megaparsec – about one-ten-billionth of a kilometre per hour if we were unaffected by gravity and standing on opposite sides of planet Earth. On terrestrial scales its effect is almost immeasurable; on scales of distant galaxies millions or billions of light years away, however, the expansion is clearly observed. Although there are measured and important variations in the expansion rate of the universe over the aeons, the current rate appears not to have been too different in the past from what it is today. Even though astronomers still don't know whether the universe has a finite size, by running the clock backwards we do know that the universe was smaller yesterday than it is today and smaller still last week, last month, last year and so on. Taking the reciprocal of the expansion rate, astronomers calculate that around 13.8 billion years ago the universe was a tiny dot – far smaller, hotter and denser than it is today. The moment that tiny spot began to grow, turning into the universe we inhabit today, is known as the Big Bang.

3-SECOND FLASH
The universe began as a tiny point of incredibly high density, which suddenly began to expand about 13.8 billion years ago.

3-MINUTE EXPANSION
Although it is not yet known if the universe was infinitely small when the Big Bang occurred, it is possible to estimate the maximum size of the universe at the moment expansion began: about 10^{-35} metres. The ratio of that diameter to a grain of sand is 100 million trillion times smaller than the ratio of that sand grain to the entire planet Earth.

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FINALE DARK & COLD
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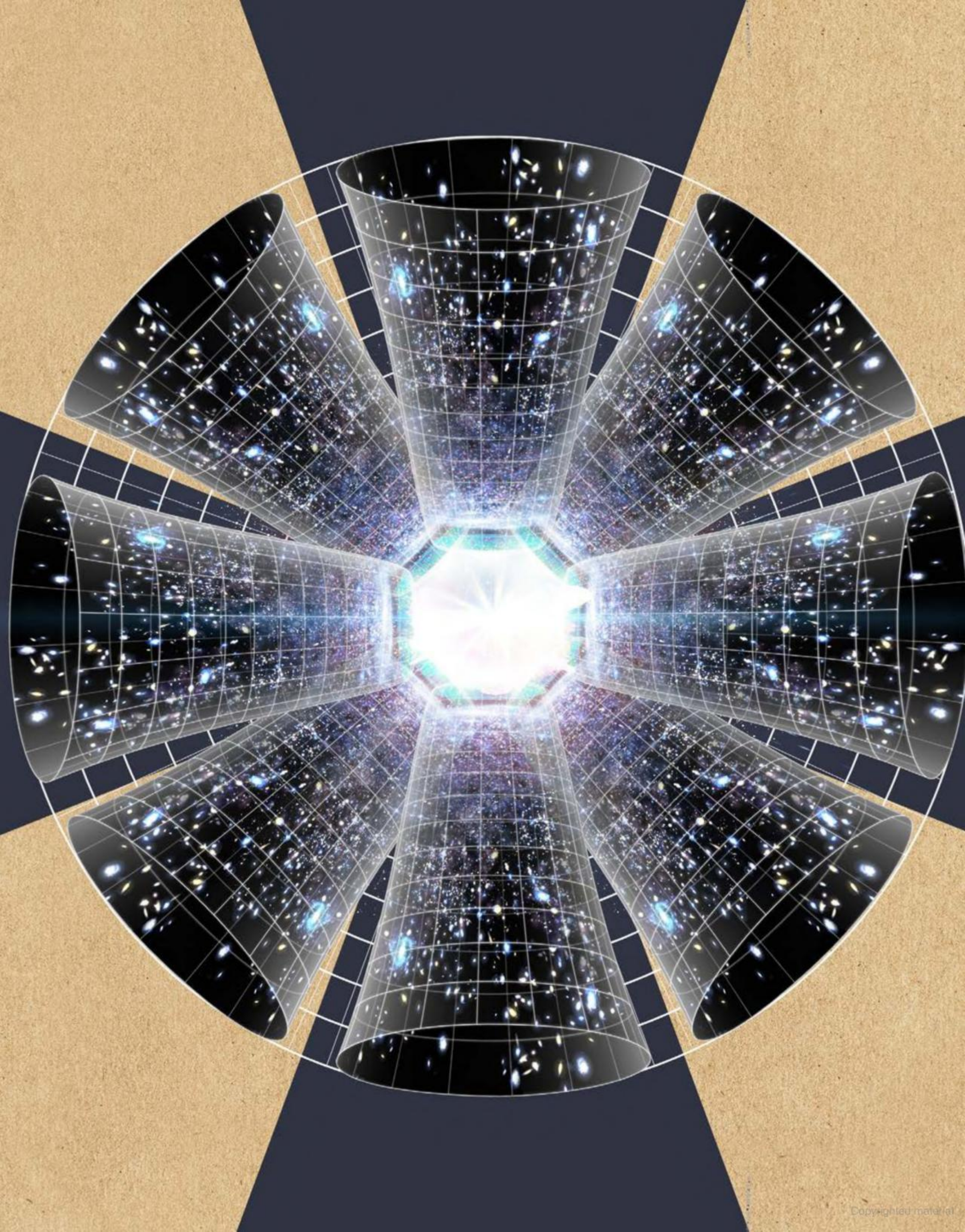
3-SECOND BIOGRAPHY
EDWIN HUBBLE
1889–1953
American astronomer who first showed the universe is expanding by measuring that more distant galaxies consistently move away from the Earth faster than those closer

The Big Bang was an expansion of space, not an explosion in space.



WHERE IT ALL BEGAN

the 30-second blast

The sudden expansion of our universe from one tiny point – the Big Bang – did not happen *at* some location in the cosmos; rather, it happened *to* the entire cosmos simultaneously, as every point in the universe expanded away from every other point at the same time. From any location in the now-expanding universe, it appears as though every other point in the cosmos is moving away from that spot – so everywhere is as much the centre of the universe as everywhere else. The boundary wherein we can observe our portion of the expanding universe is known as the cosmic horizon. To use an analogy, imagine being on a ship in the middle of the ocean. All we can see in every direction is water, because the shape of our planet prevents us from seeing what is over the horizon. We may be able to see two ships – one far to our east, the other far to our west – that could not see one another because their horizons do not intersect. If these were ships not on Earth but rather in space, then each ship would be at the centre of the volume bound by its own cosmic horizon, unable to tell where exactly in the universe it is.

3-SECOND FLASH

The Big Bang occurred everywhere in the universe at the same time, so we are all at the centre of our own cosmic horizon.

3-MINUTE EXPANSION

Astronomers refer to the volume of space within our cosmic horizon as the 'observable universe' – for brevity, the modifier 'observable' is often omitted – after all, according to the laws of physics, there is no way of knowing what is beyond that horizon anyway. Fortunately, there is plenty of space within the cosmic horizon to study – more than 100 billion trillion (10^{23}) kilometres in every direction – and the horizon is continuously growing larger.

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3-SECOND BIOGRAPHY

ALLAN SANDAGE
1926–2010
American astronomer and observational cosmologist who contributed significantly to the measurement of the size of the observable universe and the distance to our cosmic horizon

Each of us is at the centre of the universe, or, more precisely, of our own cosmic horizon.