Thirteen point eight billion years ago, the universe began. In one moment there was nothing, and the next, there was
everything. Just how this is possible is perhaps the biggest question in all of science, crossing the boundaries between
theory and experiment, physics and philosophy. Everything we know about our universe hinges on mechanism, process, and
causality. We strive to understand the reasons things are the way they are. And yet, at the most fundamental level, we
do not know how or why the entire universe came to be. But this lack of explanation is not for want of searching.
Perhaps, as famed cosmologist Stephen Hawking once supposed, there really was nothing before. Considering space and time
as inherent, conjoined properties of the universe we inhabit, the beginning of that universe marked the beginning of
time. Before time, there could be no space, and therefore no universe. Considering the geometry of spacetime back
through the ages, he saw it contract, and curve around and eventually round out. Searching for something beyond that
would be as meaningless as searching for something that was north of the Earth’s North Pole. Or perhaps there was no
actual beginning, but rather a limit to our powers of observation. Scientists believe that it was a split-second period
of exponential expansion, known as inflation, that put the bang in the Big Bang, and which set the stage for everything
that was to follow. Our inflation stopped after a tiny fraction of a second, but some physicists have argued that this
is not the ONLY period of inflation in the cosmos as a whole. Rather, inflation continues elsewhere, eternally,
producing bubble universes distributed through a potent, everlasting multiverse. Or perhaps our current universe is
merely the latest in a long and potentially infinite series of expanding and contracting cosmos, a theory known as the
Big Bounce. In this, instead of starting from nothing and inflating exponentially to produce the structure we see today,
contemporary physicists like Paul Steinhardt suggest a cyclical growth and contraction of everything within the
universe. Or perhaps our understanding of scale is fundamentally incomplete. Physicist Roger Penrose considered the
properties of shapes, regardless of their size, and believes we can do the same with the cosmos. In this idea, the
universe loses a sense of time and scale at the infinitely small and the infinitely big and becomes, to all intents and
purposes, equivalent. The game of chess is played the same weather on a board that fits in your pocket or spans an
entire courtyard. Or perhaps our cosmos came about as a transient collision of dimensions. Superstring theory attempts
to explain the fundamentals of reality as tiny vibrating strings within an eleven-dimensional reality of hyperspace. The
three dimensions of space and one dimension of time that we experience within our cosmos are merely a single ‘brane’ in
the overall bulk, with the beginning and growth of our universe coming about as higher order branes collide. Or perhaps
there is something else. Some corner of mathematics or physics that we have yet to shine a light into and which, for the
time being, eludes our understanding. For now, our universe’s origin story remains a mystery, a multiple-choice,
choose-your own adventure. Nevertheless, thirteen point eight billion years ago, the universe DID begin. This is the
story of what happened next. Thank you to BetterHelp for sponsoring this video. This is proxima centauri. Even if we
traveled at more than 50,000 km an hour it would still take more than 80,000 years to arrive there - and it is our
closest star - it is estimated there are 100,000 million more distant stars in the Milky Way. Indeed, sometimes it can
be overwhelming to square our own lives with the vastness of everything else - and to work

these things through its nice
to have some help. BetterHelp is the world's largest therapy service, and it's 100% online. With BetterHelp, you can tap
into a network of over 30,000 licensed and experienced therapists who can help you with a wide range of issues.

You can then talk to your therapist however you feel comfortable, whether it's via text, chat, phone or video call. You
can message your therapist at any time, and schedule live sessions when it's convenient for you and if your therapist
isn't the right fit for any reason, you can switch to a new therapist at no additional charge. With BetterHelp, you get
the same professionalism and quality you expect from in-office therapy, but with a therapist who is custom-picked for
you, with more scheduling flexibility, and at a more affordable price. Get 10% off your first month at betterhelp.
com/HOTU - and I've also linked them below in the description. Thanks to Betterhelp for supporting educational content
on youtube. Where is the hottest place in the universe? You might expect to find it in the natural fusion reactor at the
centre of a star. But even as you incinerate in the plunge through its fiery depths, your journey would be in vain.
Temperatures at the core reach a 'mere' 15 million degrees Celsius. You may look to even more violent phenomena in the
cosmos, like explosive supernovae. Here, during the dramatic death of a star, superheated shells of gas are ejected many
light years in every direction, leaving a gravitationally compactified neutron star at their centre. Temperatures here
far exceed normal stellar furnaces, reaching 100 billion degrees Celsius - but this still isn't the hottest temperature
to be found. In fact, the highest temperature that has ever been recorded anywhere in our vast cosmos, was 100 meters
beneath the snow-covered ground near the shores of Lake Leman, in Switzerland. And it didn't come about from a natural
process but rather the concerted efforts of hundreds of scientists, and billions of Euros' worth of research and
development. In CERN's Large Hadron Collider, where individual particles are routinely smashed into one another at
velocities approaching the speed of light, the collision of two lead atoms in 2012 briefly produced a temperature of
around 5. 5 TRILLION degrees Celsius - 50 times hotter than a supernova. But this still isn't even close to the highest
possible temperature. Temperature is little more than a manifestation of a particle's energy, its motion, or how fast it
is vibrating. Absolute zero, marking zero Kelvin, equivalent to -273. 15 degrees Celsius, is the lowermost limit, where
particles hypothetically would come to a complete, shuddering stop - were it possible to reach. But there is also an
upper limit too, an 'absolute hot' that marks the highest temperature before the particles themselves are torn apart by
their own energy. It's known as the Planck temperature, and it is around 1. 4 times ten to the 32 Kelvin. Max Planck,
who gave his name to this impossibly blistering temperature, was a dedicated German theoretical physicist who found his
academic stride around the beginning of the 20th Century. His ideas are seen as the founding blocks of quantum physics,
and led to the quantisation of light into discrete chunks of energy called photons. But they also led him to consider
the fundamental quanta of other natural phenomena. Using such universal qualities as the speed of light and the force of
gravity in combination with his eponymous Planck constant that he derived from his work on electromagnetic radiation, he
defined the Planck length, the smallest quantum of distance, as around 1. 6 times ten to the minus thirty five metres -

around 100 quintillion times smaller than a proton. The time it takes for light to travel this minuscule distance
through a vacuum is the Planck time, amounting to 5. 39 times ten to the minus 44 seconds. And the Planck temperature,
that practical measure of absolute heat, is the temperature at which the wavelength of thermal radiation reaches the
Planck diameter - it can go no smaller. It is no fair reflection on the human brain to say that these numbers are beyond
our true comprehension. We are evolutionarily attuned to scales that are relevant to us. And so it may seem that these
Planck units are too small, or in the case of temperature, too large, to be of any practical use.

But it is when contemplating the immeasurably tiny moment at the beginning of our immeasurably vast cosmos, that these
units really come into their own. Because our universe is expanding, becoming less dense - and has been for all of its
history. Scientists don't know if our universe is infinite or not, but if it is then it always has been. So rather than
starting as a single point, it would also have begun infinitely large - and rather than grow over time, it would simply
have become less dense. Our observable universe however, is different. It is the only part of the universe we could ever
see or interact with or could ever see and interact with us, and is limited by the speed of light, and the distance it
has been able to travel since the universe´s birth 13. 8 billion years ago. But as we travel back in time, that
observable part of the universe shrinks and becomes more compact - until eventually we get to a time when everything
within it was only a single Planck unit of time old, a single Planck length in diameter - and with all of our observable
universe compacted into such a tiny space, the temperature of the whole cosmos sat squarely at Planck temperatures. It
may come as little surprise to learn that this moment, one hundred million trillion trillion trillionths of a second
after the beginning of time and space, is known as the Planck Era. And it is a very strange time. In the cosmos today,
everything we experience is governed by certain immutable laws of nature, which are ultimately controlled by the
interaction of four major forces - the strong force holding atoms together, the weak force governing certain types of
radioactivity, the electromagnetic force distributing energy over great distances, and gravity. As Max Planck predicted
at the end of the 19th Century, the strong, weak, and electromagnetic forces can be quantised, represented and thought
of as tiny and indivisible parcels of interaction - kind of like particles of matter. These so-called messenger
particles are known respectively as gluons, W and Z bosons, and photons. But gravity is different. With his general
theory of relativity, Albert Einstein was responsible for overthrowing the classical mechanical definition of gravity.
Instead, he conceptualized it as the curvature of spacetime, a warping in the very fabric of reality. Through various
large-scale experiments general relativity has been verified time and time again, and the gravity-induced curvature of
spacetime is now recognised as a property inherent to the universe, which affects all matter and energy within it.
Therefore, during the Planck era, long before any of the conventional laws of nature held sway, it was gravity that was
first to manifest. But there is a problem. Everything we know about the workings of gravity today are based on
Einstein’s successful theory, but that theory is only really tested and verified on larger scales. During the Planck era
however, our entire observable universe was condensed into an area many trillion times

smaller than a proton, and
general relativity simply does not help. Instead, the dynamics of the extremely tiny are governed by quantum mechanics.
At scales small enough that we can consider the individual subatomic particles of matter, or the quantised messenger
particles of force and energy, an entirely different set of rules holds sway, where nothing is ever where you expect it
to be, and the very act of observing changes the outcome. Instead of dealing in absolutes, quantum physicists consider
probabilities, and nothing ever stays the same for long. Fortunately for us, this lawless quantum world only reigns on
nanoscopic scales, and by the time we reach magnitudes that we're more familiar with, the probabilistic weirdness
averages out. But during the universally nanoscopic Planck Era, there is no escaping the quantum. And herein lies the
problem for understanding how things actually worked in that moment. General relativity and quantum mechanics are
fundamentally incompatible with one another. So researchers are still searching for a solution - a so-called 'quantum
gravity' that is able to reconcile two of the most important theories in modern physics, and properly describe how the
Planck era universe behaved.

Unfortunately, it is a question that can not reasonably be tackled by experimental means. Considering the vast energies
needed to produce and study the other force messenger particles inside collider facilities, AND the elevated plane that
gravity occupies in defining all of spacetime, it would take a particle accelerator roughly the diameter of our entire
solar system to generate enough power to truly probe gravity during the extremes of the Planck Era. But this doesn't
stand in the way of theoretical speculation and extrapolation. One idea suggests that, like the other fundamental forces
of nature, gravity also is communicated by a messenger particle, a quantum unity of gravity that has come to be known as
a graviton. But gravity as a force is so much weaker than the others, that its meager messenger would be practically
impossible to detect. Another theory, known as loop quantum gravity, is very different. In this, physicists imagine the
smooth and ever-changing geometry of spacetime to be ultimately pixelated on the very smallest scales, and by rewriting
Einstein's equations of general relativity in terms of lines, or loops, instead of points, the calculations for gravity
on a quantum scale become much more manageable. And perhaps the leading possible quantum gravity solution continues to
rumble away in the background of theoretical physics. String theory imagines the pointlike particles of traditional
physics as one-dimensional, vibrating strings, and it is the vibrational state of the strings that defines what a
particle is, as well as the elusive force of gravity. And yet in order to make the mathematics of string theory work, it
becomes necessary to involve no fewer than ten or eleven dimensions, many of which are folded in on themselves within
the strings themselves, or are partitioned into two- or five-dimensional structures known as 'branes' - the fundamental
objects of an even more elusive overarching theory with the simple moniker "M". Each of these hypotheses for how quantum
gravity may actually work is more mind-bending than the last, rooted in the abstractions of mathematics, almost
impossible to visualize. And yet, that is just what we are trying to do, when we cast our minds back, to imagine the
first fraction of a second of our universe during the Planck Era. Ironically, it was in the 1950s, when the science of
quantum mechanics was still in its infancy, that American theoretical physicist John

Archibald Wheeler provided us with
a tangible description of conditions in that turbulent and confusing time. He imagined the early universe to be composed
of a bubbling and dynamic quantum foam. This quantum foam, as Wheeler described it, comes about because of the dynamical
and unpredictable nature of interactions on the quantum scale. Heisenberg’s uncertainty principle seriously compromises
our ability to define length, time, or energy at any one point within the Planck-sized universe, and so the continuous
and coherent spacetime that we are familiar with today is replaced by an inherently unpredictable and varying foam-like
texture that shifts and changes randomly. Quantum micro-black holes and wormholes spring spontaneously into existence
and then disappear without a trace without any apparent cause and effect. In this highly energetic, super-compact, and
miniaturized cosmos, for the briefest of moments, anything goes. But after only 100 million trillion trillion
trillionths of a second, the widespread unpredictability of the Planck Era comes to an end, as the gradual and minuscule
growth and cooling of the universe heralds a new epoch. The universe won't look or behave anything like it does today
for a while - but from here on out our current theories do at least stand a chance of describing what is going on.
Everything in our universe is controlled and defined by the four fundamental forces of nature. Imagine turning on your
television. Gravity keeps you pinned firmly to the seat of your chair, holds the Earth’s atmosphere close to the
surface, and holds the Earth in orbit around our nearest star, providing a habitable environment for your continued
existence.

Yet despite this, gravity is relatively weak, and you can overcome it with the muscles of a single arm to lift the
remote. In response to your button press, invisible infrared light, electromagnetic radiation, beams across the living
room from the front of the remote. The picture comes to life in front of you, through millions of tiny pixels emitting
visible light, another form of electromagnetic radiation, which travels back across the room and into your eyes. Your
eyeballs themselves are marvels of evolutionary innovation, but they ultimately rely on the properties and behaviors of
the atoms within - electrons and nuclei held together by the electromagnetic force. The atomic nuclei themselves are
held together by the strong nuclear force - protons and neutrons forced together in the centre of the atom. Not only
that, these protons and neutrons are really a combination of three smaller subatomic particles, called quarks, which are
also bonded by the same pull. Every atom in your body, in the television, in existence itself, relies upon this force.
As your eyes focus and you engage with the pictures moving on the screen in front of you, each of the nerves inside your
brain fire at up to 200 times per second. All of that coordinated electrical potential relies on a proper balance of
potassium in the body. Like the other elements, potassium is held together by the strong nuclear force, but there is
something else at play as well. Because potassium is very slightly radioactive, and around 5000 potassium atoms
radioactively decay every second - a decay driven by the weak nuclear force. And one hundred and fifty million
kilometres away, the core of our sun burns with the heat of a stellar furnace, powered by the fusion of hydrogen into
helium. This incredibly powerful reaction is responsible for the heat that keeps the earth habitable, and on a galactic
scale, the very elements that make up the planet, the television, and you. And all of this is

also reliant on the weak
nuclear force. It may be weak in name, but it is mighty in its reach. Each of these four fundamental forces - gravity,
electromagnetism, and the strong and weak nuclear forces, act together to shape our experiences of the universe. And so
it has been for the majority of our cosmos's multi-billion year history. But in the very first moments of time,
conditions conspired to craft a very different set of rules, derived from the same basic physical ingredients. During
the Grand Unification Epoch, which followed the Planck era - there were only two forces. But how could this be the case?
The key to visualizing this lies in a coin toss. Flip a coin to decide between two equally weighted choices. Heads for
one team, tails for the other. The decision is only reached when the coin settles AFTER the flip, when the energy
provided by the flexing of thumb and forefinger is completely spent, and the disk comes to rest. Before that point, when
the coin is still imbued with energy, and it is spinning through the air or across the table, it is nigh on impossible
to even distinguish its two faces, the two choices available to you. There is just a single spinning orb, with
characteristics all of its own. This is what we encounter when we examine the behaviors of the fundamental forces at
higher energies - the energies that were present in the nascent universe. Increase the temperature dramatically, and the
individual properties of the weak nuclear force and the electromagnetic force begin to weaken and blur into one another.
We no longer see the distinct 'heads' of electromagnetism and the 'tails' of the weak force, but rather the spinning,
faceless force of the two united - the so-called 'electroweak' force. Increase that energy even further, and the
spinning coin concept again applies to the strong force and the electroweak. With high enough temperatures, these too
blur into a single unified whole, in a process known as Grand Unification. This ultimate unification of three of the
major fundamental forces gives rise to what is known as the electrostrong force - though this tidy spinning coin theory
of grand unification has yet to be definitively proven experimentally.

Even though the energetic collisions inside particle accelerators can point us towards the joining of electromagnetism
and the weak force, it would take energies some million million times greater for the strong force to lose its identity
in the same way. Even the most energetic phenomena in the universe today, like supernovas and the jets emitted from the
poles of black holes, are still a million times too feeble. And as for whether gravity, the fourth fundamental force, is
ever accepted into the unified fold? That is a question for the mysterious and unpredictable Planck era, and yet another
problem for contending theories of quantum gravity to address. Still, the Grand Unification Theory, as it is known, is a
strong contender for explaining the workings of the universe just after the Planck Era. For a period of time some ten
million times longer than than the entire Planck Era, the universe expanded and cooled. But it is testament to just how
small everything started out, that even by the end of this time, the entire cosmos was still smaller than a single quark
- the smallest particle of matter known today. With the latent energy of that cosmos compressed into such a tiny space,
the temperature reached 100,000 trillion trillion Kelvin, some trillion times higher than the Large Hadron Collider has
ever managed. These were the conditions for the Grand Unification Epoch, ruled by the chimeric electrostrong force, and
the bizarre interactions that it brings about. The minuscule cosmos is filled with particles

undergoing an extreme
identity crisis. Photons transform spontaneously into matter-antimatter pairs, creating quarks and leptons. But these
nascent particles are desperately short-lived, decaying rapidly back into photons scarcely as soon as they have formed.
Electrostrong messenger bosons only serve to complicate the picture, helping quarks to transform into leptons, leptons
into quarks, matter into antimatter, and vice versa. Under the chaotic rule of Grand Unification, it is a free-for-all
of energy and matter, of particles both virtual and real. Until, a trillion trillion trillionth of a second after it
began, the penny drops. Temperatures drop to a mere 1000 trillion trillion degrees, rendering it cool enough for the
strong force to break free, for two forces to become three - and everything changes once again. And yet, there is a
problem with this picture. While these theories may adequately describe the behavior of particles within the earliest
moments after the Big Bang, they fall short of explaining the large-scale cosmos that will eventually come to exist.
When comparing the starting conditions with the universal end result, the Big Bang appears to be broken. By July 2022,
the iconic James Webb Space Telescope was well established in orbit around the sun, one and a half million kilometres
out in space. Following a nail-biting month-long journey and a phase of deployment and calibration that lasted almost a
year, it was finally ready to begin its scientific operations in earnest. But when it focused its eighteen golden
mirrors into some of the deepest reaches of the observable universe, scientists were shocked. After seeing the images
returned from the revolutionary telescope, American astrophysicist Allison Kirkpatrick wrote in the scientific journal
Nature, that she found herself lying awake at three in the morning, wondering if everything she had ever done was wrong.
Within a month, these images and Kirkpatrick's comments had grown a life of their own. The fixed speed of light means
that the deeper we peer into space, the farther back in time we are looking - and at distances corresponding to just 200
million years after the beginning of everything, the James Webb telescope had seen galaxies. Not only that, but these
galaxies were ordered with much more structure than anyone had thought possible. Theories of star and galaxy formation
had no way to explain it - and it was this that Kirkpatrick had been so concerned about. Unfortunately, soon her
concerns had been extrapolated to cast doubt on the Big Bang, with some media outlets claiming that the next generation
telescope had DISPROVED the landmark theory with its very first images.

Thankfully, those concerns were misplaced. Kirkpatrick had only been concerned about existing theories on GALAXY
formation, not entire COSMOS creation. The inexplicable structuring of early galaxies meant that there was a piece
missing from our understanding, NOT that everything we knew was wrong - little more than a storm in a comic teacup. And
so the Big Bang is safe from that quarter, for now at least. But as a complete explanation of how our modern universe
came to be, it has been under far more severe threat for much longer. When we look at the large-scale structure of the
universe as it is today, there are a number of phenomena that don't quite add up. To begin with, the average
temperature. Even though stars burn at several million degrees Celsius and empty space shivers at just a few degrees
above absolute zero, the AVERAGE temperature that we observe in one direction is remarkably similar to any other. 2. 7
kelvin - everywhere in the universe. All 93 billion light years in diameter of it. But how?

If the universe has been
gradually expanding for nearly 14 billion years, then how can two points further than 14 billion light years apart have
averaged out without breaking the speed of light? The fact that we see such thermal homogeneity now implies that there
was thermal homogeneity back in the universe's earliest moment - a fact that seems wildly improbable given the nature of
quantum fluctuations in the compactified early cosmos. This is known as the homogeneity problem, or the Horizon problem.
But there is more. Einsteins general theory of relativity describes how massive objects create curves in spacetime,
which then govern the movement and evolution of matter within that space time. Stars, galaxies and black holes leave
pinches and pockmarks in the local-scale structure of space-time, but when we zoom out to a larger scale, those
imperfections even-out to leave a smoother structure which, like the average temperature of the cosmos, seems to vary
very little. The universe, on the largest scales, seems flat. If the overall density of matter in the universe is
sufficiently great, spacetime will be what's known as 'positively curved', bending back on itself like the surface of a
sphere. This means that eventually, the gravity exerted by all the matter in the universe will be enough to slow down
and eventually reverse the trend of expansion, collapsing the universe back in on itself in a so-called Big Crunch. In
contrast, if the overall density is much lower, it will result in a 'negative curvature' of spacetime, bending out in an
open fashion like the surface of a saddle. With this geometry, gravity will never overcome expansion, and the cosmos
will continue to grow for eternity. Which of these overall geometries holds true has big implications for the future
evolution of our universe, and so it has been the preoccupation of astronomers to try to measure the overall curvature
of the cosmos that we can see. And counterintuitively, it appears to be completely flat. Just like the horizon problem,
the likelihood of this being the case is incredibly small, tantamount to tossing a coin and having it land perfectly on
its edge. For obvious reasons, this has become known as the Flatness problem. And there is one additional problem that
blights our theories of the cosmos in the first trillionth of a second. There seem to be no magnetic MONOPOLES at all.
All through the universe, electrical charges exist in positive and negative pairs, canceling one another out to result
in a stable, neutrally charged whole. In a similar way, magnets are found with both north and south poles, with magnetic
field lines flowing between them to produce a stable and balanced whole. However, while it is possible for both positive
and negative charges to be found alone, like in isolated protons or electrons, respectively, no such isolated poles
exist for magnets. No matter where we look in the cosmos, we have yet to find a lone monopole without its opposite
pairing. So it was on a December night in 1979, while puzzling over the mystery of the missing monopoles, that
theoretical physicist Alan Guth struck on a remarkable solution.

One that not only addressed his own problem, but also tackled the Horizon and Flatness Problems as well. Instead of
expanding gradually over billions of years, from a point-like state to the vastness we see today, Guth found a mechanism
by which the universe could have suddenly and almost instantaneously INFLATED to many, many times its original size,
before slowing down and continuing its more linear expansion. The inflationary period that Guth proposed would see the
universe double in size around 90 times in less than a trillionth of a second, resulting in

an exponential expansion
that would fundamentally change the face of the cosmos. Because when exponential expansion is at play, things get very
large, very quickly. Consider folding a gigantic piece of paper in half time and time again. If it starts out one tenth
of a millimetre in thickness, then the first fold will double that, to two tenths, and the next brings it to just under
half a millimetre. A third fold doubles it again, and now it is about the thickness of a fingernail. So far so
unremarkable, but by the time you reach seven folds, the single sheet has now reached the thickness of an entire
notebook, ten folds and it will be as thick as your hand is wide. The world record for actually doing this experiment
sits at just 12 folds, when in 2002 an American schoolgirl folded a piece of tissue paper more than 1. 2 kilometers in
length into a bundle over half a meter thick. But if it were possible to make and handle an even bigger sheet, further
folds would increase the thickness astronomically. Twenty three folds will make the paper around one kilometre thick,
and thirty folds will be enough to get you to space, rising 100 kilometres from the surface of the Earth. Forty two
folds will get you to the moon, and 51 will make it to the sun. Eighty one folds will make the paper as wide as the
Andromeda galaxy, at around 141,000 light years across. And ninety folds, equivalent to the 90 doublings that Guth
proposed for the inflationary period, will transform that single colossal piece of paper to a folded pile bigger than
the entire Virgo supercluster, 130 million light years across. This incredible inflation is what Alan Guth proposed for
the entire universe. In less than a trillionth of a second, after the confusing turbulence of the Planck Era and the
Grand Unification Era, the hot, hyperdense cosmos blew up to more than an octillion times its original size. It was
this, if anything, that put the BANG, in the Big Bang. The universe which one moment had seemed so hot, energetic and
full, is now left vast, vacuous, and cold. It seems drastic, but it is indeed an elegant solution for the three problems
vexing the Big Bang theory. Because this inflation allows us to entertain the possibility that the immense universe we
see isn’t actually all there is. It is merely a bubble of observable universe whose size is defined by the speed of
light, the amount of time that has passed, and the expansion that has taken place since the beginning of time. Thanks to
inflation and subsequent expansion, our observable bubble is some 93 billion light years in diameter, but it is still
merely a fraction of the universe as a whole And it is in this unseeable extent that the answers to our problems can be
found. The Horizon Problem of thermal homogeneity is only a problem if the homogeneity we see applies to the entire
universe. But inflation ALLOWS the compact early universe to contain extreme thermal variations, which are then flung
far apart from one another during exponential expansion. Our local patch of observable universe merely represents one
small part of the whole, which WAS in thermal equilibrium with itself before inflation happened, and may be wildly
different from other parts that we cannot see. Similarly, the Flatness problem of spacetime curvature is only a puzzling
coincidence if the flatness we see applies to the entire universe. But if we are only seeing a tiny fraction of the
whole, then it is impossible to say whether it does or not. It could be a matter of perspective.

From the sea shore, an ocean horizon appears flat, but it is only when we fly far above the surface, perceiving more of

the Earth, that we see it is in fact curved. In reality, the wider cosmos may be positively curved, negatively curved,
or a twisted combination of both, but we are unable to see past our own cosmic shore. And finally, the absence of
magnetic monopoles is only a problem if we assume they are missing from the universe as a whole. But they need not be.
If they existed in the early universe in the quantity predicted by our current models, then exponential inflation would
have seen them spread apart from one another until they were distributed to roughly one per observable universe. When we
are looking for a singular monopole within a sphere 93 billion light years across, it’s little wonder we haven’t found
it yet. Inflation is now securely a part of our understanding of the earliest moments of the universe, and cosmologists
have spent the forty years since Alan Guth’s revelation figuring out the mechanism by which a universe can so suddenly
and so drastically blow up. The timing of this dramatic phase coincides with the energy drop and cooling that saw the
end of the grand unification of fundamental forces, and the emergence of the strong nuclear force. It is theorized by
some scientists that the decay of the X boson messenger particles that carried the electrostrong force created a strong
inflation field, carried by a new messenger called the inflaton. This overwhelming new inflation energy drove universal
exponential expansion, which saw quantum scale irregularities instantaneously scaled up to large scale structure.
Transient quantum fluctuations became huge regions of overdensity and energy that would provide the seeds for galactic
clusters and superclusters in the modern universe. All of this expansion inevitably cooled and emptied the cosmos,
leading to a 100,000-fold drop in average energy levels. Scientists are as yet unsure of why exactly inflation stopped,
but when it did, the inflaton field and particle decayed away, pouring much of that energy back into the universe, in a
phase known as ‘reheating’. It’s this that allows for the decisive creation of matter, and now, in a larger and roomier
cosmos, the laws of nature are approaching something that we can finally understand and model. This is the electroweak
epoch, which lasts until around a trillionth of a second after the Big Bang. There are quarks and leptons, matter and
antimatter, all ruled by gravity, the strong nuclear force, and the chimeric electroweak force. But temperatures and
energies are still far too high for the strong force to have any real effect on the supercharged particles in this
post-inflationary maelstrom. Similarly, the electroweak force has little hold on the matter-energy interactions. And
while gravity may have pervaded the universe since its beginning, there is one major component still missing, which
renders it all but powerless. Until the newly formed particles are granted MASS, they remain unruly and ungoverned.
It’ll take another energy drop and another cosmological transformation before we reach a universe we begin to recognise
as our own. Symmetry is everywhere. Anywhere we look in nature, we find balance, regularity and geometric harmony, be it
in our own bodies, or the bodies of all animals, great and small. We are bilaterally symmetric, mirrored down the
centre, and perceive the greatest beauty in those whose symmetry is most perfect. Many creatures share our bilateral
symmetry too, from the greatest whale, to the lowliest worm. And if not mirrored twofold, other animals like starfish
and sea urchins favour five spokes of radial symmetry. And we can find both bilateral and radial symmetry in all other
kingdoms of life, too, among the plants, fungi, even bacteria. Scientists have found that evolution has a clear
preference for these balanced, symmetric forms, not least because they can be constructed from much more simplistic

instructions than other, more complex and non-repeating geometries. And it is mathematical, algorithmic simplicity that underlies the symmetries found throughout the natural, non-living world.

In science, symmetry has a much wider meaning than its day to day use - it means that something is the same, something does not change - whatever happens. From the laws of physics to the conservation of energy and momentum, the universe is inherently symmetrical. Positive charges are balanced with negative ones, some particles spin clockwise, others spin counterclockwise, and if you measure the strength of gravity on Alpha Centauri you will get the same result as in our solar system. And yet, the universe is not PERFECTLY symmetric. Just like the human body, when examined more closely, has the heart shifted to one side, there are also flaws in the perfect balance of the cosmos. There are some particles that never spin clockwise, and others that never spin counterclockwise. There is an imbalance in the amount of matter and antimatter, there are things that electric fields can do that magnetic fields cannot, despite the two being notionally equivalent. And many of these imbalances are key to the functioning of reality. But it did not start this way. Indeed, for the first trillionth of a second or so, cosmologists believe that everything WAS perfectly symmetric. There was balance. But that all changed with the final separation of the forces, and the emergence of something that would come to influence much of existence - mass. Just as dropping temperatures herald phase changes in water, from vapour, to liquid, to solid ice, fundamentally changing its properties at each transition and reducing its symmetry, so the dropping temperature in the young cosmos brings about phase changes in the energy and matter that fill it. As the four fundamental forces finally fully split and crystallize as separate entities, we see the birth of a new era - the Quark Era - defined for the first time by the interactions of MATTER. The biggest single object yet discovered in our universe is probably the hypergiant star UY Scitu. With a diameter some 1700 times larger than our sun, if it sat at the centre of our solar system its outer edge would sit just beyond the orbit of Jupiter. And yet this, like all stars, is composed almost entirely of some of the SMALLEST things to be found in the universe - individual atoms of the lightweight elements hydrogen and helium. Hydrogen is the smallest of all the atoms, which themselves were once considered THE smallest thing possible. Their very name derives from the Greek word for ‘unsplittable’. But we now know, thanks to revolutions in atomic theory throughout the early 20th Century, that atoms ARE eminently splittable, a fact which has given rise to some of the most devastating weapons in human history. Hydrogen and helium, for all their simplicity, are composite particles of protons, neutrons, and electrons, which can be isolated and manipulated with relative ease. But even these are not the smallest fundamental particles there are. Protons and neutrons are THEMSELVES composites of even smaller units, called quarks, whose various properties, alongside those of electrons, ultimately govern the characteristics and behavior of everything, including the largest object in the universe, UY Scuti. The search for the fundamental particles of matter has been a guiding quest for physicists for some 200 years. Experiments to crack open smaller and smaller particles, to reveal what lies inside, require vast amounts of energy, which can only be obtained by accelerating those particles to blinding speeds and then smashing them into one another in particle

colliders. Examining the wreckage of such collisions, we can piece together a full picture of the building blocks of our
universe. This picture, which has come to be known as the Standard Model of particle physics, is theoretically all we
need to explain why everything looks the way it does in the cosmos today. Normal matter, as we have seen, is composed of
protons and neutrons, which are collectively known as hadrons. But they are themselves composed of a combination of
quarks, each with distinct characteristics such as mass, charge, spin, as well as another property called colour, an
arbitrary name which has no relation to colour, but helps to explain how they bind together in groups.

A positively charged proton is made from two ‘up’ quarks and one ‘down’ quark, while an uncharged neutron is two ‘downs’
and an ‘up’. But there are other flavours of quark out there, with esoteric names like ‘strange’, ‘charm’, ‘top’, and
‘bottom’, which combine to form more exotic composite hadron particles, which are scarcely ever seen outside of physics
experiments. Despite smashing hadrons together in these experiments with ever-increasing force, physicists have found no
hint that quarks are made of anything smaller - they are the bottom of the rabbit hole. Meanwhile, the electrons that
orbit atomic nuclei appear similarly indivisible. They are a kind of particle known as a lepton, and while all normal
matter makes do with the negatively charged electron, there are exotic varieties to be found inside our colliders.
Muons, tau leptons, and several varieties of neutrino can all be found in the wreckage of particle collision. And so our
standard model consists of twelve fundamental, unsplittable particles of matter - six types of quark, and six types of
lepton, in addition to antimatter counterparts of each of these, and the messenger particles of the fundamental forces -
photons for the electromagnetic force, gluons for the strong nuclear force, and W and Z bosons for the weak nuclear
force. If a virtual particle exists to communicate gravity through spacetime, then it still evades detection. So for
now, the four gauge bosons join the particles of matter to describe everything within the universe today. At least,
almost everything. There is one, crucial missing piece to our model so far. And that is mass. Every element in the
universe, from hydrogen to plutonium, has its own characteristic mass, corresponding mainly to the number of protons and
neutrons within its nucleus. So it follows that the majority of an atom’s mass comes from those protons and neutrons.
But when we peer down smaller and smaller to find the ultimate source of that mass, that is not what we see. It turns
out that a proton weighs in at considerably more than the sum of its parts. The fundamental particles at the heart of a
proton are the three quarks, but the masses of these amount to just 9% of the proton’s overall mass. The rest comes from
energy stored up inside that nucleus, from the intrinsic relationship between energy and mass that Einstein identified
with his famed E=mc^2 equation, and from the bizarre quantum interactions of gluons, the mediators of the strong nuclear
force. So when we reconsider the masses of every piece of normal matter in the universe, more than 90% of it doesn’t
actually come from the ‘stuff’ of matter at all, but from the latent energy and empty space within. But quarks do still
have mass - something separate, something different to this energy. And the reason for this was a mystery for a long
time. Photons and gluons get by just fine without mass at all, electrons and neutrinos have even less than the smallest
quark, while the W boson carrier of the weak force weighs in at some 40,000 times heavier

than an up quark - heavier
than an entire iron atom. What causes this incredible disparity in mass, and why do particles have mass at all? This was
the question that plagued British theoretical physicist Peter Higgs in the 1960s while teaching and researching at the
University of Edinburgh. As a solution to the problem, he suggested that all particles first came into existence in the
universe without ANY mass at all, and that at some point within the first split-second, a new kind of energy field
emerged and permeated all of space time, gifting the various particles the property of mass. This Higgs field, as it
became known, would be communicated by its own quantised messenger particle, called the Higgs Boson, which would sit
alongside the other sixteen particles of the Standard Model, and play a major role in describing the behaviors and
interactions of matter in the universe. And yet, even though Higgs' theory was sound, it would take nearly 50 years to
finally FIND the elusive Higgs boson. In the meantime, in order to bolster support for this expensive and seemingly
esoteric search, the UK minister for science promised in 1993 to buy a bottle of champagne for the best analogy to
explain the action and importance of the Higgs field to the general public.

Despite various suggestions featuring pools of syrup, prisms, and electric fields, it was physicist David Miller from
University College London who ultimately claimed the prize with a description that focused on a busy cocktail party. At
a party, he said, everyone is happily chatting amongst themselves, and a normal person is able to move through the room
with relative ease. But when a more popular figure - a notable scientist in Miller's example - enters the room, they
attract attention from the partygoers and are overwhelmed with attention. Everyone wants to talk to them, and their
progress through the room is slowed. In this, the room full of partygoers represent the Higgs field, and the popular
figure is a particle that has been imbued with mass. For those too far away to see the influential person, a rumour
passes around the room as people come together to discuss their arrival. This physical rippling through the crowd can be
thought of as the messenger Higgs Boson. While the analogy isn't perfect, it HAS stood the test of time. And time was
what was needed in what ultimately proved to be a frustrating search for something akin to a needle in a haystack. Two
of the most powerful particle accelerators - the Tevatron at Fermilab in America, and the Large Hadron Collider at CERN
in Europe, smashed particles and searched wreckage for years. The problem was, although Peter Higgs had theorised the
field and boson EXISTED, his theories said nothing about what energies would be needed to manifest them, or the
properties of the particles once they were found. So, like searching for a needle in a haystack when you had no idea
what a needle even looked like. Eventually though, in 2012, experiments at the Large Hadron Collider achieved this
seemingly impossible task. Scientists confirmed they had in fact found the Higgs boson, and in doing so proved the
existence and action of the Higgs field, once and for all. The particle has earned its place in the standard model, and
the field its role in the evolution of the early universe. A trillionth of a second after the Big Bang, the electroweak
force splits catastrophically in two, ending the perfect symmetry of the universe as the W and B bosons that carried it
decay into the photons of the electromagnetic force and the W and Z bosons of the weak nuclear force. But this is only
the beginning of the symmetry breaking. The emergence of the Higgs field around this time

imbues the real and virtual
particles that were created spontaneously during inflation and electroweak splitting with mass. The W and Z bosons
become heavyweights, the quarks and leptons get their masses according to their flavour and type, while the photon and
gluon continue as massless and unbounded by the Higgs as they did before. As the Quark Era becomes fully realised by a
billionth of a second after the Big Bang, the universe is finally filled with all of the ingredients - the
characteristic particles and the characteristic forces - needed to make stars, planets, and us. The quark-gluon plasma
that permeates the inflated cosmos is the primordial soup from which all structures in the universe will be made. Our
universe is full of incredible variety and diversity. There are stars that burn hot and fast, exploding catastrophically
after scarcely a million years, and others that sizzle away slowly, unchanged for trillions of years. There are
multitudes of planets: giant gas worlds, scorched and barren rocky worlds, and occasionally green, watery, life-ready
worlds. And on those worlds that do host life, like Earth, there is every kind of lifeform you can imagine, from tiny
bacteria which breathe sulphur, or methane, to self-aware and cognisant apes that build structures and telescopes, and
wonder about their place in the universe. In the potentially infinite extent of the cosmos, there is almost infinite
scope for variety. But there are also certain facets of reality that are immutable and constant, regardless of where you
are in the cosmos or how you observe them. These so-called constants of nature have been revealed one by one, as
scientists expand our understanding of HOW the universe behaves, and WHY it behaves as it does.

Time and time again we stumble across seemingly magical numbers, unrelated to any other physical law or phenomenon. Like
the speed of light through a vacuum, often considered the absolute speed limit for anything travelling through the
universe. It is 2. 99792 times ten to the eight metres per second. Or the universal constant of gravitation, which
describes how strongly two objects will be attracted to one another due to gravity. It is 6. 67384 times ten to the
minus eleven metres per second squared per kilogram. And the list goes on - there are precise and definable constants
relating the energy of particles to their temperature, or temperature to the amount of radiation that’s given off, for
the strength of magnetic fields produced by electric currents, and for the strength of an electric field that forms in
response to electric charges. Less obviously, but still importantly, the masses of the fundamental particles are also
set at constant, but seemingly arbitrary amounts - a fact that even the Higgs mechanism is unable to account for. Why
should these natural relationships have these precise values? It is a problem that vexed even the great physicist
Richard Feynman when he considered what is known as the Fine Structure Constant, that essentially describes the strength
of electromagnetic forces between particles, defining the chances that an electron will absorb a photon. Its value is a
little over 137, but there is no link between it and any other physical law, no reason for it not to be 12, or 135, or
3015. But the fact that it IS 137 rather than any other number is crucially important for the overall state of the
universe. If it were much larger, or smaller, then it would seriously affect the stability of protons throughout the
cosmos, meaning that matter would have a hard time staying together. And the same goes for most of the other natural

constants. If gravitation were weaker than it is, the universe would be filled with just an ever-thinning soup of hydrogen gas. If it were stronger, then all matter would be drawn into black holes or violent short-lived stars, leaving no room for planets and life to form. The many constants of nature may seem arbitrary, but they are also finely-tuned to allow for the diverse and varied universe we find ourselves within. But why? We still don't know. Is it just a lucky coincidence? The hallmark of a creator with their hands on the dials? Or, as many scientists suppose, is it that our universe is merely one of a multitude, all created with different starting conditions, and different values for these fundamental constants - the vast majority having resulted in failed, barren universes, and only those in which the values are just right able to culture cosmological variety, longevity, and, consequently, us? Whatever the reason, this fine tuning is already hugely important in the opening seconds of existence. By the time a billionth of a second has passed since the Big Bang, the universe has been filled with an astonishing abundance of quarks, leptons, and virtual particles. But temperatures and energies were still too high for any of these fundamental particles to interact meaningfully with one another. Temperatures drop, and by a millionth of a second after the Big Bang, the universe is a mere one trillion degrees Celsius. Gluons and quarks finally slow down their frantic vibration, allowing them to interact with one another for the very first time. As we have seen, protons and neutrons are composite particles, each made from three quarks. But the component parts of a proton, two up quarks and a down quark, are not natural bedfellows. The up quarks both have positive charge, and like charges repel. The closer the like charges get, the more strongly they reject one another, so it takes the assembled might of the strongest force of all, the strong nuclear force mediated by gluons, to hold them together into a stable hadron particle. But it turns out, the internal anatomy of a proton is even stranger than we might imagine. Not only is the majority of the mass made up of energy and quantum dynamics, but the composition of the matter isn’t as constant as we might imagine.

Sometimes, one of the typical quarks inside a proton can spontaneously shape-shift into a charm quark and its antimatter counterpart. The transformation is extremely short-lived, however, and the charm quarks quickly recombine. But it means that protons are ultimately a constantly changing blur of the normal quarks, known as valence quarks, as well as gluons and charm quarks. Since both the gluons and the transient charms can be considered virtual particles, that means that the vast majority of a proton, as much as 99%, is actually made up of particles that don’t really exist. The internal workings of protons and neutrons may be truly bizarre, but in the first millionth of a second of the universe, they are becoming an ever more prominent part of the universe’s make up. However, thanks to the effect of the weak force in this hot, dense plasma, newly formed protons can easily change identity to become neutrons, and vice versa. It’s only as the temperature drops even further, as the universe is approaching one second old, that this particular quirk of the weak force becomes ineffective and the protons and neutrons eventually slow their switching. During this so-called freeze-out, the hadrons choose an identity once and for all. And it is when this happens, that the seemingly arbitrary fine-tuned constants of nature, in this case the masses of up and down quarks, have their first real opportunity to

shape the future of our cosmos. Because down quarks are heavier than their up cousins, and neutrons contain two downs,
the mass of a neutron is very slightly greater than the two-up-containing proton. So as the final identity switches take
place in an ever-cooling cosmos, the downhill energy slope from heavy neutron to lighter proton is favored over the
energy-intensive haul in the opposite direction. It is this very slight mass difference that ultimately results in an
imbalance in the number of protons to neutrons in the universe from that point on, with roughly seven protons to every
neutron. And this, it transpires, has been an important ratio for the formation of the universe as we know it. Protons
are the basis for hydrogen and helium, the fuel for stars and the building blocks for all other, heavier elements in the
universe. The abundance of these charged particles over the uncharged neutrons is what allows for elemental
interactions, leading to chemistry and biology. If things had started out differently, if the down quark had been
allocated a slightly lower mass during the fine tuning of our reality, then the universe we see today would be very
different. If neutrons weighed less than protons, then it would have been these that were favored during freeze out.
With more uncharged neutrons than protons, there is a limit to what chemistry could reasonably be accomplished.
Hydrogen, consisting of only a proton with NO neutrons in attendance, wouldn’t be stable for long periods of time. Some
of the heavier protons could have been saved, by binding to neutrons before decaying away, creating atoms of helium. But
helium is often considered the most inert of all of the elements. It is inherently stable, and unwilling to react.
Between this and an overabundance of generally unreactive neutrons, it would be hard to imagine how nuclear fusion could
work. We would be left with a cold, dark universe with no stars, no galaxies, no planets, and certainly no us. We can
therefore be thankful for the universe’s inexplicable leaning toward protons over neutrons. But this isn’t the only
imbalance that becomes baked into the cosmos around this point of its evolution. There is also a mysterious but
fortuitous lack of ANTIMATTER. One day in the future, as we peer into the sky, we may be looking in the right direction
at the right time, to see an alien civilisation destroy itself. Scarcely more dramatic than the subtle brightening of
one of the fainter stars in the black, but representing an energetic explosion from a weapon powerful enough to level an
entire world. History tells us that disagreement, territoriality, and discord is a common theme among Earth
civilisations - and there’s no reason to believe this wouldn’t be the case elsewhere in the galaxy.

On a warring alien world, as on Earth, efforts to prevail over the enemy lead to an arms race. From sharpened points to
explosive projectiles, nanomachinery to atomic bombs, the struggle for the most destructive weaponry goes on. But these
advanced extraterrestrials are still not satisfied, and soon turn their attention to an even more powerful source of
latent energy. With greater technological prowess than humanity, they have learned to produce and isolate particles of
antimatter, holding them in a vacuum, suspended by electromagnetic forces, until it is time for them to be deployed. But
they do not need vast quantities of fuel, or any sort of trigger. For the moment antimatter comes into contact with the
‘normal’ matter that prevails on their homeworld, the particles will annihilate together, destroying themselves and
releasing vast amounts of energy. Just one gram of antimatter will release as much energy as

a traditional nuclear
weapon with some 90 KILOGRAMS of fuel. And as this arms race goes on, the stockpiles grow. Whether it is used in anger,
confusion, or simply by accident, the detonation of this antimatter weaponry occurs. Night turns to day in an instant,
scorching winds raze entire cities, destroying both warring factions and all other life on the planet. The entire world
is transformed for centuries to come. Such is the devastating possibility of antimatter coming into contact with matter.
And yet, we are surrounded by it. Every day. It was the English physicist Paul Dirac who, in 1928, first predicted the
existence of antimatter. Working to integrate Einstein's theory of special relativity with the relatively new science of
quantum mechanics, he realised his equations applied not only to negatively charged electrons, but also to positively
charged equivalents, thereby predicting a particle that was entirely new to science - an antielectron, or positron. Four
years later, an independent American physicist, Carl Anderson, actually detected this elusive particle, in a rudimentary
instrument called a cloud chamber, built to study incoming cosmic waves. With the existence of antimatter now proven,
physicists turned their attention to OTHER antimatter particles. In the 1950s, the Bevatron Accelerator in California
succeeded in detecting the first antiproton and the first antineutron - and in 1995 scientists finally assembled an
anti-hydrogen atom. Now, we recognise antimatter in a wide variety of settings. From supernovas and black hole jets, to
the radioactive decay of potassium in a banana producing a positron roughly every 75 minutes. So antimatter may not be
confined to futuristic sci-fi settings, but it is still hugely outweighed by normal matter in the universe. Based on the
notable absence of annihilation signatures, physicists believe that there can be no more than one antimatter particle
for every quadrillion matter particles within the Milky Way. And this is just as well, because if there were equal
quantities of both, then annihilation would have resulted in the ultimate destruction of ALL particles, leaving nothing
with which to build stars and planets. But the question of how this lucky imbalance came about is one that still
troubles physicists. Could it be another quirk of fine-tuning? In the beginning, antimatter would have formed in tandem
with matter, with pairs of particles forming from spontaneous energy transformations within the universe's first
billionth of a second. But in such a dense environment, they wouldn't have lasted long before encountering their
opposite, annihilating together, and transforming back into energy. This process of spontaneous creation and destruction
continues until the temperature of the universe drops, and no new quark-antiquark or lepton-antilepton pairs are made.
But gluons are not discerning on what kinds of matter they assemble, and as protons and neutrons are being made for the
first time, they are accompanied by an equal number of antiprotons and antineutrons. Everything should be in balance -
at this point there should be no difference in the quantity of matter and antimatter, and since the two kinds of
particles behave identically, and are only destroyed in pairs as well, there should continue to be equal amounts of
each.

But this isn't what we see. At some point, between a millionth of a second and two minutes into the universe's timeline,
the balance of antimatter and matter changes, until only one antimatter particle in a billion remains. And to this day,
physicists still aren't certain why. It could be partly as a result of the broken symmetry

that came about with the
emergence of the weak force. Experiments by Chien-Shiung Wu in the 1950s showed that quarks and antiquarks ARE in fact
treated slightly differently by the laws of nature - the difference is very small, but it is significant enough for us
to see. Even so, scientists don’t think this is enough to explain the overwhelming triumph of matter over antimatter in
the early universe. Instead, they entertain the possibility that another, as-yet undetected, and potentially extinct
particle has a role to play. The idea comes from another kind of asymmetry that has been found within the standard
model. Every particle and antiparticle we have found exists in both right-handed and left-handed forms, representing a
kind of symmetry in handedness that physicists call parity. But there is an exception, where parity symmetry appears to
be broken. Experimental physicists have only ever been able to find left-handed neutrinos, whereas all the antineutrinos
are right-handed. Where are the right-handed neutrinos and left-handed antineutrinos? Scientists speculate that they may
have existed early on, within the universe’s first millionth of a second, but were unstable and decayed away. If they
decayed preferentially into matter, rather than antimatter, then this could have laid the foundation for matter’s
ultimate triumph. The theory is a tantalising one, but unfortunately there is not much that can be done to prove it,
until we know more about these mysterious missing neutrinos. And it won’t be until the universe is around one second old
that neutrinos have anything to tell us at all. When we peer into the deepest reaches of the night sky, we are greeted
with wonders in almost every wavelength. There are delicately curled galaxies, colorful nebulae, and piercing points of
light known as quasars, far distant supermassive black holes swallowing matter and light at the centres of galaxies. But
these quasars also illuminate another curious feature that permeates deep space, known as the Lyman Alpha Forest. The
constant speed of light through the expanding vacuum of space means that, the more distant an object is, the older it is
as well. So when we see quasars at great distances, we are seeing them as they appeared billions of years ago, and the
light they emit is redshifted - stretched into the red parts of the EM spectrum compared to how they would normally
appear. But when we examine the spectral signatures of such distant and ancient quasars, there is more to see than just
the redshifted light they give off. At shorter wavelengths, there are also sharp dips in the light that we see, and
sometimes so many that they cluster thickly, like a dense thicket of tall pine trees on an alpine mountainside. This is
the Lyman Alpha Forest, and it’s created not by trees, but by low density clouds of hydrogen gas lurking in
intergalactic space. Because when light passes through a cloud of hydrogen, some of it is absorbed, leading to a dip in
the spectrum that we eventually intercept here on Earth. This is what is happening with the light from distant ancient
quasars, with every dip in the spectrum corresponding to an otherwise invisible hydrogen cloud. Visualizing these
tenuous structures is remarkable enough in itself, but there is more we can tell from the structure of this spectral
forest. Astronomers have noticed that the absorption dips cluster most thickly at high redshifts, which correspond to
great age, giving us an insight into the chemistry and composition of the earliest universe. Compared to today, early
space was FULL of these low density hydrogen clouds, such that it became impossible for the quasar’s light to avoid
them. That hydrogen became the nursery for stars and galaxies, and was itself seeded in the first moments of the
universe’s existence.

By the time a single second has passed in the history of the universe, a great deal has happened. It is now a ‘mere’ ten
billion degrees Celsius It is filled with the victors of ruthless particulate battles, along with the energetic photon
shrapnel of countless mutually destructive encounters. Through quirks in the properties of the remaining particles, the
balance between protons and neutrons is set, as the era of impossible, spontaneous particle births and swaps is finally
brought to a close. Those particles that possess mass today are already endowed with it, thanks to the Higgs field, and
the four forces that rule our lives today - the strong nuclear force, electromagnetism, the weak nuclear force, and
gravity, are now in full and comprehensible operation, although their behavior in this hot and energetic firmament is
still somewhat wild. So far, the workings of the one-second-old universe has lain primarily within the realms of
theoretical physics, with our most powerful instruments still struggling to generate the kinds of energies that
prevailed within those first moments. But we are now entering an era of the universe that can be studied more
meaningfully by experimental physicists, and even astronomers. We are finally reaching a part of our cosmological
history that we can hope to observe, and even map. In the icy wastes of Antarctica, for a couple of weeks a year the sun
does not set. And this is when they started. Spraying hot water directly downwards into the ice, in January 2005
scientists working on the cutting edge Ice Cube Neutrino Observatory began the arduous 58 hour long process of creating
the first 2. 5 km hole needed. The first of 80. Indeed, now, the IceCube array´s various holes occupy a square kilometer
of Antarctic ice. But this immense size and improbable location aren’t the only surprising features of this
next-generation telescope. Instead of pointing UP into the night sky, it stares down into and THROUGH the bowels of the
earth. It has no lenses, mirrors or radio dishes, but instead is made up of over 4000 modules dangled on over 80 strings
deep in holes in the ice - hanging like pearls in the cold, dark Antarctic depths. As counterproductive as this may
sound, it is in fact the ideal kind of construction for observing one of the most elusive particles in the entire
universe, and the Icecube Neutrino Observatory is joined by similar projects at the bottom of gold mines, deep beneath
the world's deepest lake, and in the hearts of Japanese mountains, all dedicated to the search for the elusive NEUTRINO.
As a particle, the neutrino was first proposed in the 1930s, when particle physicists were balancing the equations of
nuclear decay. Observing how a neutron would sometimes spontaneously decay into a proton and electron, Wolfgang Pauli
noticed that a tiny amount of energy was missing, which he hypothesized was another kind of particle, too small,
lightweight and ghostly for us to have any hope of detecting it. Indeed, with the frequency of this kind of nuclear
decay, 100 trillion of these ghostly particles must be streaming through our bodies every second, without us having any
notion of their passage. But scientists do not accept defeat that easily, and in 1951, a pair of American physicists,
Clyde Cowan and Frederick Reines, began to search for this ghostly particle, and in what became known as Project
Poltergeist, they turned to powerful nuclear fission reactions to provide the vast quantities of energy needed to detect
neutrinos. Cowan and Reines first proposed detonating a 20 kiloton nuclear payload, and installing an immense detector
just 50 metres away from the blast. This detector, nicknamed El Monstro, was designed to pick

up a flash of light after
a neutrino collision, and if it had been built, would have been 1000 times larger than any previous detector. In the
end, however, this experiment proved too challenging, and the scientists turned to the somewhat more controlled energy
release to be found in nuclear reactors. And so in 1956, Cowan and Reines's experiment succeeded - finally achieving the
seemingly impossible, detecting the ghost particle that had been haunting physics for more than 20 years.

These days, the detection and study of neutrinos has advanced greatly, and scientists are now able to produce and study
them in powerful particle accelerators - though there IS still a place for monstrous detectors like the one in Lake
Baikal - for neutrinos can be used to answer not only questions about our universe today, and it's very first moments.
For neutrinos are produced in such quantity, by such a variety of energetic sources, that scientists are trying to use
them to study some of the most extreme events in the modern universe. 168,000 years ago, a star within the Large
Magellanic Cloud went supernova. The explosion sent atomic shrapnel reeling across intergalactic space at nearly the
speed of light. This shrapnel, including the countless neutrinos that were emitted in the blast, struck the Earth in
1987, and scientists in Japan considered themselves extremely fortunate to be able to detect ELEVEN such neutrinos. And
yet, as insubstantial as this may seem, the fact that astronomers could see the supernova through this neutrino lens,
helped to open up a new era of multi-messenger astronomy. Gravitational waves, telescopes tuned to a variety of
electromagnetic frequencies, AND neutrinos, could all be deployed together to study and understand the most extreme and
mysterious events in the universe. Not only that, but neutrinos give us the opportunity to probe objects that are too
opaque for light to penetrate, since their extreme unwillingness to interact with any matter at all sees them stream
through everything from nebulae, to stars, and even entire planets - this because they only interact with two of the
fundamental forces - the weak force and gravity. But this remarkable penetrative ability also makes them powerful tools
in probing some of the earliest moments of the universe as well. After the decisive formation of matter around one
second after the Big Bang, the sheer density of hot energetic particles and photons rendered the entire universe
completely opaque for hundreds of thousands of years. Our telescopes, which rely on the passage of photons through empty
space, cannot probe this opaque plasma, and so to see further back in time, scientists need a different approach, and
that's where the neutrino comes in. Less than a second after the Big Bang, neutrinos and antineutrinos were just another
part of the hot cosmic soup. They collided and scattered, interacting with other matter because everything in the
still-dense universe was so energetic. But around the one-second mark, temperatures in the universe dropped to 10
billion degrees Celsius, and the particles correspondingly slowed. Eventually, they were moving slowly enough for
neutrinos to escape, and find a way through the snarl of other particles. They no longer collided with matter or light,
and could break free to leave an imprint of their passage on the universe. And so, If we could find that imprint, known
to scientists as the Cosmic Neutrino Background, it would represent an image of the universe at just one second old,
extending our astronomical reach back in time by some 380,000 years. But if these relic neutrinos from the first second

of the universe are out there, they are EVEN MORE elusive than their high energy counterparts. Compared to the 100
billion high energy neutrinos per cubic centimetre of space, there are thought to be just 300 from that earliest time.
To detect them directly, we would need to build our instruments with some billion times the current precision - or
detect the effect they had on the cosmos when they broke free. As the first things to stream through the
otherwise-opaque cosmos, the tiny particles are expected to have left miniature sonic booms in their wake, fundamentally
altering the distribution of matter and energy. Some parts of space would have become slightly hotter, and some parts
slightly cooler, thanks to this disruption and in the intervening 13. 8 billion years, space has expanded, magnifying
these patches into larger scale structure in the universe. If we could decode some of that large-scale structure,
written into the distribution of galaxies today, then we may just be able to tune into the echoes of a universe one
second old.

And this is not the only modern mystery that could have its origins in the one-second old universe. This is TON 618. At
some 18. 2 billion light years away from us, it burns some 140 trillion times brighter than the sun, making it one of
the brightest objects in the known universe. It’s thought to be nearly 11 billion years old, and despite its incredible
luminosity it is actually host to one of the cosmos’s BIGGEST black holes. Understood to be a hyper massive black hole
at the centre of a galaxy, whose trillions of stars it far outshines, TON 618 has a mass that is some 66 billion times
that of our sun, and is more than 15,000 times more massive than Sagittarius A*, the black hole at the centre of the
Milky Way. In fact, this single black hole is heavier than ALL the stars in the Milky Way put together, giving it a
diameter that is 40 times the width of Neptune’s orbit around the sun. Such immense size and mass gives it such an
immense gravitational pull that matter is falling into it at speeds of more than 10,000 kilometres per second, causing
such intense heating that the doomed material in its accretion disc glows brightly, despite the light-swallowing dark
heart at its centre. TON 618 may be the largest we have found, but it is by no means the ONLY such titan lurking at the
hearts of galaxies. Supermassive black holes, with masses more than 100,000 times that of our sun, are a common feature
of large galaxies, and are thought to be a major influence on how those galaxies have formed and evolved over billions
of years. These hot, massive hearts themselves are thought to grow by swallowing stellar matter from their galactic
entourage. But there is something about the TIMING of these supermassives that doesn’t quite add up. When astronomers
survey the sky, they find these gigantic black holes dating to just a few million years after the Big Bang, despite the
fact our models do not allow for the birth and death of enough stars to feed such early giants. Some of the supermassive
black holes we have found grew to a billion times the mass of our sun by less than a billion years after universe
formation, when according to models of star-formation, only around 100,000 solar masses should have been possible. A
potential solution to this conundrum may be found in a theory that was developed many years before we were even aware of
the oversized early supermassives. In 1971, Stephen Hawking proposed that there was another way that black holes could
be formed, WITHOUT any precursor stars at all, but rather from density fluctuations in the very early universe. He

called them Primordial Black Holes. During the radiation-dominated era, when the universe was still an energetic plasma
of photons and matter, major inhomogeneities - essentially lumps of matter - would have resulted from the inflation and
subsequent reheating of quantum irregularities in the nascent universe. Gravity already inherent to the universe would
have acted on these density contrasts, collapsing vast areas of gas down on itself, all over the early universe.
However, there was only around a one-second window after the Big Bang when this could have happened, before the universe
expanded and cooled to such a size that gravity was no longer effective at pulling together matter into these black hole
prisons. After that, the universe would have to wait many millions of years before a new black hole would form though
the death of stars. But these primordial black holes could be the seeds for the otherwise unexplainable black holes we
are detecting today. The problem is, although this theory seems consistent with our understanding of how matter behaved
in the early universe, we have little information on when exactly they did so, and how large they could have grown in
that one-second window. Mathematically, the later a primordial black hole forms, the larger it would be, and estimates
for their size vary spectacularly, ranging from minuscule specks weighing a hundred thousandth the mass of a paperclip,
to mammoths 100,000 times heavier than our sun. How do we find and identify them, if they do exist? One option is to
look for signs of their destruction.

Stephen Hawking also theorised in the 1970s that black holes do more than just swallow matter and grow ever larger. He
suggested they could LOSE some of their weight through what became known as Hawking radiation. This weight loss is
faster, the smaller a black hole is, and the runaway acceleration of radiation would ultimately lead to small the
obliteration of a black hole in an explosion equivalent to one million megaton hydrogen bombs. Any black hole that was
less than 100 billion kilograms in mass could be expected to decay away within the age of the universe, so scientists
have begun searching for these characteristic explosive death throes with instruments like the space-based Fermi Gamma
Ray Telescope. Other potential methods for searching for these elusive primordial seeds involve looking for microlensing
and magnification of stars and galaxies as the black holes pass in front, or trying to detect the destruction of dense
stars caught in the primordials' gravitational wells. But all these studies have accomplished so far is to rule out
certain size ranges, leaving an ever-shrinking envelope of possibility for how big primordial black holes can be, and
when they formed. Though astronomers have not yet given up hope. The next generation of high-tech telescopes will
continue the search, with better reach and precision than ever before. The James Webb Space Telescope is probing the
early universe for some of the first stars and galaxies, and in doing so will be able to search for the primordial black
holes that could have seeded their formation. And the Laser Interferometer Space Antenna, familiarly named LISA, will
launch next decade to continue scanning space for gravitational waves, some of which may come directly from primordial
black holes that have been roaming the universe since they first formed, barely one second after the beginning of time.
On the 5th December 2022, in the bowels of the National Ignition Facility at Lawrence Livermore National Laboratory in
California, humanity achieved something remarkable. Scientists at the lab focused 192 two lasers inside a one-centimetre

long gold cylinder, containing a single fuel pellet the size of a peppercorn, containing two isotopes of hydrogen -
deuterium and tritium. When the laser energy struck the walls of the capsule, it heated them up to around three million
degrees Celsius, a temperature hotter than the surface of the sun, causing them to emit X-rays inside the cylinder.
These powerful X-rays then blasted the surface off the pellet and compressed the fuel at some 400 kilometres per second.
The fuel imploded, reaching 100 billion times atmospheric pressure in less than 10 billionths of a second. The atoms of
deuterium and tritium fused together, transforming them into helium, while also giving off a high energy neutrino and
other energy. In total, 2. 05 megajoules of energy entered the cylinder, and 3. 15 megajoules were produced by the
fusion reaction. In this way, for the first time in nearly 70 years of trying, scientists managed to initiate a
PRODUCTIVE nuclear fusion reaction. The fusion itself was nothing new - humans have been making deadly fusion weapons
since the 1950s, but this reaction in 2022 was the first time we've created fusion that was able to RELEASE more energy
than was put in to get it started. In this small-scale test, the roughly 50% energy gain would have been enough to boil
around 20 kettles, but the success heralded a potential new age of clean, efficient energy generation. And yet, this is
a process that has been going on naturally, in the hearts of every single star in the universe, for billions of years.
Not only that, but the physics of the universe had this fusion figured out within its very first minute. Humans have
long been preoccupied with the seemingly magical act of turning one thing into another. Whether it is producing a bunch
of flowers from thin air, or alchemically transmuting base metals into valuable gold, nothing fascinates us more than
the idea of getting something novel from something mundane. And the very early cosmos was rife with such
transformations, while the unsettled fundamental forces drove chaotic identity swaps, but such transformations continue
all around us even in the modern universe.

Radioactive decay, mediated by the weak force, sees atomic nuclei fracture and break, transforming elements into their
less massive cousins on regular and predictable timescales. This nuclear fission occurs in a wide variety of elements,
from Carbon-14 used for carbon dating, to Technetium-99 used for medical imaging, and Uranium-235 used as fuel for
nuclear reactors. Such radioactive decay occurs as a consequence of unstable atomic nuclei, and will typically happen
spontaneously, under the most ambient conditions. But as the other kind of nuclear transformation - nuclear fusion -
which sees atomic nuclei INCREASE their mass and move UP the periodic table, is much harder to achieve. The identities
of all atoms are determined by the numbers of protons and neutrons within their nuclei. Hydrogen has one proton, with
different varieties or isotopes with different masses possessing different numbers of neutrons. Proteum has only one
proton, deuterium has one additional neutron doubling the relative mass of the atom, and tritium has two neutrons,
bringing the total relative mass to three. Only when another proton is added does the identity of the element change.
Two protons makes a helium nucleus, with Helium 3 possessing one neutron, and the most stable Helium 4 having two
neutrons. The strong nuclear force is the agent responsible for binding all of the hadrons together into stable atomic
nuclei. But with protons sharing a like positive charge, they are pushed apart by another of the four fundamental forces

- the electromagnetic - long before the gluons can hold them together. So it takes intense heat and physical pressure,
such as that found at the heart of stars, or inside an irradiated golden capsule, to push the protons close enough for
the strong nuclear force to overcome its force kin and for the elements to fuse into something new. To make even heavier
elements, combining many tens of protons together, it takes even more extreme cosmic events, like the supernova
destruction or merging of stars. Despite their long efforts to replicate it in the lab, scientists have a good
understanding of how nuclear fusion works inside stellar furnaces to create new elements from simple hydrogen and helium
fuel. They have even witnessed and understood the very beginnings of that process inside so-called ‘failed stars’. Brown
dwarfs are massive orbs of gas, larger than the Jupiter-like gas giants, but smaller than an active star. Inside them,
there isn’t enough heat and pressure for lightweight proteum hydrogen to fuse into helium, but the process is
accomplished by using heavier DEUTERIUM as an intermediate. However, none of these processes help to explain where the
larger atoms of deuterium and helium came from in the first place. For that, we need to look back, to an age before
stars, before stellar fusion, to the universe’s very first minute. When the average temperature of the universe dropped
to around 10 trillion degrees Celsius, about a microsecond after the Big Bang, it was finally cool enough for quarks to
bind into protons and neutrons, making the building blocks for all elements to come. But there is a 100 million-year
gulf of time before we see the first stars begin to shine, powered by the nuclear fusion of atomic nuclei at their
cores. So when, and how, did those nuclei come together? It was in 1948 that the prodigious American PhD student Ralph
Alpher, working with his supervisor George Gamow, proposed a mechanism that would later become known as Big Bang
Nucleosynthesis. It was a bold and inspired theory, but the brilliance of Alpher’s work was somewhat overshadowed by
Gamow’s insistence on including another author on their seminal paper, who had no part in its development. In his words:
“It seemed unfit to the Greek alphabet to have the article signed by Alpher and Gamow only, and so the name of Dr Hans A
Bethe was inserted in preparing the manuscript for print. ” The ‘alpha-beta-gamma’ paper became the authority on
pre-stellar fusion, and to this day provides the foundation for understanding how the high temperatures at the beginning
of the universe could turn hydrogen into helium via deuterium intermediates.

Proteum is the lightest variety of hydrogen, consisting of a single proton. So as soon as quarks bound into protons,
these hydrogen nuclei existed, although it’s important to note that it will still be some time before neutrally charged
hydrogen ATOMS, with both protons and electrons, will form. Around ten seconds after the Big Bang, it was cool enough
for some deuterium nuclei, with one proton and one neutron, to form. But in this hot cosmic soup, temperature and
particle energies were still so high that the deuterium nuclei were unstable. If they were struck by a photon, as was
inevitable under such densities, these first composite nuclei would break apart again. This is known to physicists as
the deuterium bottleneck, and until it was overcome, nucleosynthesis simply couldn’t progress past the fusing of one
proton and one neutron. Only after another three HUNDRED seconds or so, do temperatures drop sufficiently for deuterium
to become more stable, and additional elements to form. First, deuterium, with its one proton and one neutron, is able

to fuse with individual protons, under the intense compressive force of the entire universe. The result is, for the
first time, an entirely new stable element - Helium-3. From this point, the next cosmic creation is the more common
variety of helium, Helium-4, composed of two protons and two neutrons. Helium-4 nuclei represent the most stable atomic
nuclei in existence, and are the hardest of all the elements to break apart. Because of this, and the conditions that
prevailed within those first few hundred seconds, most of the free protons in the early universe became swallowed up
into helium and went no further. Calculations based on the initial balance of protons and neutrons, and the available
energy at this time, predict that this would result in a universe that is around 25% helium by mass. And this is indeed
what we find. Even 13. 8 billion years after this energetic burst of helium creation, even after the lives and deaths of
countless stars, the universe is still around 23% helium. This observation alone is a striking confirmation of Alpher’s
theory. And it is here we see another example of the fortuitous fine tuning of the universe’s initial conditions. We
already know that if the proton to neutron ratio had been different then much of the universe’s ordinary matter would
have decayed away into uncharged and unreactive neutrons and helium. But similarly, even with the proton-neutron ratio
we were dealt, if the matter in the cosmos had been any more compact at the time of big bang nucleosynthesis, then even
more helium would have formed. The unreactivity of a universe made predominantly of helium would have meant little to no
chemistry would have been possible thereafter, again leading to the bleak prospect of a universe with no stars, no
galaxies, and no us. Thankfully, however, this was not the case. Even as so many hadrons settle into their stable helium
nuclei, the universe is still full of latent energy, which COULD be used for further fusion. Now, the race is on to see
how many novel elements can be created before the ambient energy of the universe drops too far. Eventually, after around
1200 seconds of furious cosmic nucleosynthesis, amounting to 20 minutes of universal existence, the nuclear furnace
finally sputters and dies. It is still blisteringly hot by human standards, but it is simply too cold for any further
nuclei to form. At this point, only four elements exist - Hydrogen, Helium, Lithium, and Beryllium. And because of the
short-lived stability of those Beryllium nuclei, only the first three will survive long enough to see the first stars,
and to become the ultimate fuel for creating the other 98 elements that can be found naturally within the modern
universe. At this stage, there are twelve hydrogen nuclei for every helium nucleus, and a billion photons for every
composite matter particle. But with these basic ingredients, the stage is truly set for the formation of everything
else. Even the deuterium and tritium that scientists fused together in California in 2022 was itself first formed in the
heat of a newborn universe, 13.

8 billion years ago. Life in the universe is a miracle of chemistry. And as far as we know, that chemical miracle has
only arisen in one place - on a nondescript wet rocky planet around an average yellow star, sitting on the inner edge of
one of our Milky Way’s smaller spiral arms. But how did living things come to grace the Earth? Despite a healthy fossil
record that extends back through some three billion years of the planet’s history, the moment of biological genesis,
that spark of life, is lost to the mists of time. Biologists agree that living things are composed of ORGANIC molecules,

made from carbon, oxygen and hydrogen. Added to that, they have discovered that all living things share a common
chemical instruction manual in the form of DNA and RNA, which are themselves composed of repeating units called
nucleobases. Cytosine, guanine, adenine, thymine and uracil provide a universal language with which to encode
information on how to grow a leaf, a flipper, or a hair follicle. But where did these molecules come from in the first
place? Some imagine that the warm and potent chemical environment on the newly formed Earth provided the perfect
conditions for assembling organic molecules and nucleobases from scratch. But there is an alternative theory - that the
ingredients for life were not created on Earth, but among the stars, in the depths of space. And indeed, we ARE finding
compelling evidence for the stuff of life far out in the cosmos. In 1969, American astronomers working out of the
National Radio Astronomy Observatory in Green Bank, West Virginia detected the characteristic vibration of formaldehyde
molecules, containing carbon, hydrogen and oxygen - deep in interstellar space - and many others have followed.
Scientists have now identified over 250 complex organic molecules inside interstellar clouds and in the shells of
material surrounding stars. Aldehydes, alcohols, acids and amines, all fundamental building blocks of the larger
molecules of life, lurking out in the lifeless reaches of the universe. Another, even more compelling clue to the
life-bringing potential of outer space arrived on Earth as far back as 1864. Just after 8pm on the 14th May, a meteorite
fell to Earth in around 20 pieces, landing near the town of Orguiel in southern France. The scientist who recovered and
analysed this Orguiel meteorite reported a composition very similar to peat, sparking intense debate over whether this
organic matter could have a biological origin. But the lack of any identifiable biological structures made such a
conclusion unlikely - though when the meteorite was reanalysed almost 100 years later, using more modern instruments and
techniques, chemists were amazed to discover nucleobase molecules of adenine and guanine, identical to those we find in
DNA and RNA today. Subsequent studies of other organic-rich meteorites that have fallen all over the world, including
the Murchison meteorite of Australia, the Murray meteorite of Kentucky, and the Tagish Lake meteorite of Canada, have
found the rest of Earth-life’s nucleobases, as well as several others that aren’t found in our biological makeup. A
definitive answer to this question has yet to be revealed, but the observations so far do at least point to one
certainty - a surprising truth about the cosmos. Without any special provocation or encouragement, the universe itself
has the capacity to build molecules and perform remarkable acts of chemistry. And this space chemistry had its
beginnings right back in the infant universe, less than 100,000 years after the beginning of time. The furious act of
elemental creation during Big Bang nucleosynthesis had ground to a halt after just 20 minutes of universal existence, as
the cosmos expanded and cooled. The ambient energy was no longer high enough to fuel nuclear fusion, but conditions were
still extreme. The entire cosmos was still denser than the air we breathe, and temperatures still too high for
lightweight electrons to slow enough to be captured by the newly formed elemental nuclei. There is still more energy
than matter in the universe, which exists as a hot, dissociated plasma, and it will be tens of thousands of years before
further cooling allows anything to begin to change.

And yet, something is happening in the chaos. First created in labs in 1925, Helium hydride is an unstable ion of helium
bonded with hydrogen, very rarely found in nature. And in 1978, Astrochemist John H Black at the University of Minnesota
suggested that it could be found in abundance in space. Specifically, in planetary nebulae, which form from the
energetic explosion of red giant stars late in their lives, he predicted that a thin layer of ionised helium would exist
around a cloud of neutral hydrogen. In this environment, the helium ions' strong need for electrons to neutralise their
charge could drive them to steal one from the only other source around - the hydrogen. The association between these two
in the superheated nebula would ultimately lead to the formation of helium hydride ions. And yet the molecule continued
to prove elusive. A long search ensued, with frustratingly little success. That was, until 2019, when an innovative
telescope managed to achieve the seemingly impossible. These days, most telescopes are either based on the ground,
situated high on mountaintops to avoid the worst of light pollution, weather, and atmospheric distortion - or they're
launched far into space to get rid of these problems altogether as they orbit the Earth or the Sun. But the SOFIA
observatory did something different. It consisted of a 2. 7 meter wide mirrored telescope that was pointed out of the
back door of a specially adapted Boeing 747, flying at over 43,000 feet. At this height, the instruments connected to
the telescope could enjoy many of the benefits of a space telescope, since they would be lifted above the majority of
the water in the Earth's atmosphere, allowing them to probe wavelengths of light that water vapor usually absorbs.
Critically, the telescope connected to the far-infrared receiver known fittingly by its acronym GREAT, which had
sufficient resolution to finally pick out the faint, overlapping signature of helium hydride ions in deep space. In the
end, the detection came from three days of observation of a planetary nebula designated NGC 7027, which sits around 3000
light years away from Earth in the direction of the Cygnus constellation. It is one of the brightest in the sky. In this
hot and energetic interstellar environment, just as John Black predicted 40 years earlier, helium hydride is able to
form, and leave its signature on the nebula's spectrum. Detecting its signal is a triumph for nearly 100 years of
experimental and theoretical chemistry, as well as for astronomical innovation. But the implications of its discovery
here are even greater. The conditions inside this distant nebula are very similar to those that prevailed throughout the
whole universe within its first few tens of thousands of years. Even though THIS helium hydride is not primordial in
origin, proving its formation in such an environment tells us much about its potential in the early cosmos. Big bang
nucleosynthesis was very efficient at creating atomic nuclei, but for hundreds of thousands of years afterwards, cosmic
energies remained too high for hydrogen, deuterium and helium to combine with electrons to make uncharged atoms.
However, when ambient temperatures dropped to around 4000 Kelvin, these wayward nuclei were able to combine with each
other in a specific order, governed by what's known as their ionisation potential. It's because of this that helium is
today considered the MOST noble of all the noble gases. It is the most inert, and the least likely to react because of
the huge amount of energy it takes to strip away one of its electrons and transform it into an ion. But in the early
universe, when all that existed WERE ions, particles with net charge, this supreme grabbing power means that helium was
the first element to attract electrons and hold onto them, forming the very first uncharged atoms. However, this

stability for helium was sadly short-lived. It was still too hot for lone protons to capture electrons to make hydrogen atoms. So the protons turned to the helium and its balancing complement of electrons, seeking an arrangement where they could share.

Eventually, under the crushing burden of these clingy protons, helium relented, forming the very first chemical bonds, and the first molecule in the universe, creating very unstable helium hydride ions in the process. Nevertheless, these short-lived molecules paved the way for the creation of other molecules, and the beginning of space chemistry. Around one hundred thousand years having passed since the Big Bang. Today, the field of astrochemistry is well-developed, as the study of what molecules we can expect to find in space, and how they form. Many atomic structures that are found on Earth are also common throughout the cosmos, including water and ammonia. But others are much more exotic, like dihydrogen monochloride cations, H2Cl+, or hydroperoxyl, HO2. Though many of these are yet to be discovered, whatever they turn out to be, they ultimately owe their existence to helium hydride ions made and unmade in the first 100,000 years of the universe. You may think that you have a good grasp of the world that surrounds you. With specialized organs dedicated to sensing light, sound, the solid touch of matter, and the chemical nuances of molecules, our brains seem well fitted to perceive all the possible stimuli the universe can provide. But this simply isn’t true. There is much, much more to reality than meets the eye, ear, or fingertip. Take light. Most of us are able to see the world in glorious, sharp-focused technicolor. But visible light is just a tiny fraction of a wider electromagnetic spectrum, whose waves are constantly and imperceptibly washing over us every moment of our lives. High energy gamma and x-rays are emitted by the food we eat, the bricks that make up our homes, and even our own bodies. The radiative energy from the sun, which we may think we CAN perceive, contains around 10% ULTRAVIOLET light with the capacity to penetrate and damage our skin and eyes. And at energies lower than the visible light we can see, sunlight is composed of around 50% INFRARED radiation, some of which we experience as heat. In fact all warm objects also glow in infrared light, invisible to our eyes but occasionally perceptible to our touch. But at even lower energies, infrared technologies like motion sensors and television remotes send and receive their signals entirely undetected. Bluetooth, WiFi, cellular mobile and GPS all work by exchanging information through the air via MICROWAVE frequencies of radiation. Meanwhile, our analog radios and televisions use the longest wavelength of EM radiation - RADIO waves. All of these low energy waves wash over us from every direction, every hour of the day. If we could see all of them, we would be blinded. All told, for all our apparent sentience, we are unaware of at least 99% of what is occurring within the universe. Perhaps this is just as well, as it is hard to imagine how our brains could adapt to cope with all of the possible stimuli. The relative calm of a night sky would be a blaze of colour and a riot of sound, with sharp points of light and song from a multitude of sources, a low drone from rippling gravitational waves, and behind it all, everywhere, a faint backlit glow - the lingering glow of the first light in the cosmos. For the first few hundred thousand years of the universe’s existence, it was utterly opaque, despite being full of light. Such a concept is hard for us to imagine today, but since a trillionth of a second after the Big Bang, the photons that carried much of the energy in the universe had become trapped in a maze of their own making. With matter and energy occupying opposite sides of the same coin, the cooling of the newborn cosmos saw pure energy transformed into matter, flooding the universe with subatomic particles - the density and intense vibrational energy of these such that photons simply could not penetrate the swarm. It wouldn’t be until the ultimate formation of ATOMS, that anything would change. In the modern universe, it is uncharged atoms rather than charged ions that are the building blocks for everything around us. Due to their small size, it takes a staggering number of these atoms to build anything.

There are around seven octillion atoms in each human body - that’s a seven followed by 27 zeros. Scale this up to the number of humans and all other living things on Earth, factor in the Earth itself, and multiply by all the planets and stars in the cosmos, and the number of atoms in the entire universe is almost ungraspable. But the real key to making an atom lies in the capture of electrons. First discovered towards the end of the 19th Century, these negatively charged leptons are 2000 times lighter than a proton, and can be thought of as a singular point with no shape or internal structure. At such minute scales, quantum physics governs their behavior, and quantum uncertainty dictates that we cannot know both their speed and position - we would never be able to pinpoint a single electron. Instead, they can be thought of as simultaneously occupying every possible spot that they can, so far as the laws of physics allow. Once positively charged atomic nuclei have been created during Big Bang Nucleosynthesis, the electromagnetic force helps to ensnare negatively charged electrons to create a neutrally charged atom. Hydrogen nuclei capture a single electron, and helium nuclei capture two. But simple as this may sound, it is not a quick process. The electromagnetic force is some 100 times weaker than the strong force that holds hadrons and nuclei together, and so the ambient conditions of the universe must be that much less energetic if electromagnetism hopes to lasso the supercharged electrons and bring them into the corral. In the end, it takes 380,000 years of cosmic expansion for temperatures to drop far enough, to around 3000 Kelvin, for electrons to finally join the herd and make the first stable atoms. And when they do, the entire universe transforms. Electromagnetic attraction sucks electrons into stable orbits around atomic nuclei - where they once roamed freely through the universe, the electrons are now tightly bound to their positively charged counterparts, opening up empty space for the first time since the creation of matter. The photons that have been trapped in a labyrinth for hundreds of thousands of years suddenly find their paths clear. They can escape, traveling in straight lines without instantly striking another particle. They are the first light that truly penetrates the universe. What was one moment opaque now becomes transparent, what was one moment plasma now becomes gas, and what was one moment shattered now becomes whole. For the first time in the entire history of the universe, we finally have a chance of SEEING what was going on. Very few discoveries in science are made by accident, much less the kinds of discoveries that lead to Nobel Prizes. Instead, scientific progress is typically hard-won, through years of commitment, incremental research and investment. But in 1978 the Nobel committee flew in the face of convention, and awarded that year’s prize in physics to

two men whose ground-breaking discovery was something of a fluke. It was in the early 1960s, in the small town of
Holmdel New Jersey, that the stage was set for this most fortuitous of discoveries - for it was there the company Bell
Labs had constructed a 20-foot horn-shaped antenna. Just a few years after the great horn was built, a new satellite
system usurped the original, rendering the instrument obsolete. But Bell Labs didn't let their gigantic hearing aid go
to waste - instead they opened it up to researchers Arno Penzias and Robert Wilson, who planned to tune into and analyse
the radio signals coming from the space BETWEEN galaxies. However, when they began their observations, the two
astronomers struggled to make out the signal above a low but persistent radio hiss. They checked it wasn't coming from
nearby New York City, or from military installations nearby. They confirmed it wasn't coming from any particular part of
the Milky Way or outside of it, but rather, it seemed to be coming from the entire sky. And so, for this noise to appear
so consistent and omnidirectional, the researchers concluded it must be due to some error with the instrument.

Indeed, when they inspected the antenna, they found it to be home to a number of roosting pigeons. Perhaps their
droppings, what they described as a 'white diaelectric material', was giving off heat that was creating the noise. After
several failed attempts to humanely rehome the birds, the researchers resorted to more drastic measures and eventually
cleared the horn of both pigeon and droppings. And yet, the hissing still remained. Penzias and Wilson had eliminated
all possible sources of error in their instrument, and as a last resort began to entertain the notion that this radio
noise COULD in fact be coming from the entire sky. They reached out to a fellow astronomer at Princeton University,
Robert Dicke, for advice. And it was Dicke who solved the mystery, in the grandest way. He had been developing a theory
of atom formation in the early universe - believing the Big Bang to be cyclical, all the atoms of a 'previous' universe
being ripped apart in a scorching fireball of compression and reassembled when the universe expanded and cooled again.
This so-called 'recombination' would turn the cosmos transparent and allow light to be released for the very first time
in this universe's chronology. His theories predicted that such light, originally in the visible part of the spectrum as
a yellow-orange glow, could still be detected at great distances within the universe. Subsequent expansion of the cosmos
would stretch that early spacetime until the glow became redshifted beyond the perception of our eyes, and into
microwave wavelengths. Dicke planned to search for it himself, but Penzias and Wilson had unwittingly beaten him to it.
And a decade later it was the two Bell Labs researchers who were awarded the Nobel Prize for the discovery of the
so-called Cosmic Microwave Background, and not Robert Dicke. Regardless of who was credited for finding or figuring out
the Cosmic Microwave Background, and despite Dicke´s cyclical fireball model being later ruled out - its detection
represented a major turning point for our understanding of the Big Bang. The discovery of this redshifted fireball glow,
now stretched to be just 2. 7 degrees above absolute zero, is conclusive evidence that the universe did in fact start
out in a hot dense state. Even though it dates to a moment some 380,000 years AFTER that moment of cosmological
creation, it is vindication of all theories for how things unfolded in the intervening period - the earliest
observational evidence we have of a hot, energetic, and compact early universe, even

containing within it clues as to
how the universe will unfold. Because, while Penzias and Wilson found the microwave hum to remarkably consistent across
the night sky, later instruments designed to study the CMB discovered very slight variations - places where it was
slightly hotter or cooler by a few hundred thousandths of a degree. Mapping the CMB became a priority for projects like
the Cosmic Background Explorer, the Wilkinson Microwave Anisotropy Probe, and the Planck telescope, giving rise to
increasingly detailed images of energy and density variations in the 380,000 year old universe. Those density variations
provide the seeds for large scale structure today, since they contain more matter, which ATTRACTS more matter, becoming
denser and pulling in even more. Within 100 million years, these overdensities have grown massive enough to trigger the
formation of the first stars and galaxies. And it's the variations in the CMB that help us predict where they will be.
Those variations seem to be largely random, as would be expected - the result of subatomic quantum fluctuations inflated
to massive scale through inflation in the first fraction of a second after the big bang. But closer analysis also
reveals another curious pattern hidden within the CMB - one that is also mirrored in the large-scale structure of the
cosmos today. Prior to the formation of atoms, when the universe was still filled with opaque plasma, it was dense
enough for sound waves to pass through it, just as sound travels through the air today. These waves had their origin in
conflicting forces of attraction and repulsion within the roiling, energetic soup, as gravity pulled matter in toward
the centre of denser patches, but photons trapped within that collapsing maze rebelled and exerted an OUTWARD pressure
upon being packed too tightly.

And so those photons push back out, taking some of the matter with them, spreading out in three-dimensions, creating a
complex pattern of concentric ripples, as from so many raindrops in a pond. In a sense, these compressional waves
through the stuff of the early cosmos ARE sound waves, and are therefore known to cosmologists as baryonic acoustic
oscillations. However the phenomenon did not survive past atomic recombination. Once the universe reached its critical
temperature of 3000 Kelvin, allowing electrons to be captured and atoms to form, the expanding ripples were suddenly
stopped in their tracks, as the photons that were carrying the matter outwards could now escape unhindered. The baryonic
acoustic oscillations were all frozen in place. They could grow no further, and the bunched matter at their spherical
periphery was left stranded just as the photons had left it. Now, some thirteen and a half billion years later, the
universe has expanded, but the pattern left behind by these frozen ripples can still be discerned in the overall
structure of galactic clusters and superclusters. Cosmologists find the baryonic acoustic oscillations in the modern
universe are now roughly 150 megaparsecs, or nearly 500 million light years across, and measurements of their dimensions
at greater distances and times within the observable cosmos provide astronomers with a so-called 'standard ruler' with
which they can measure the expansion of space. With this information, in a universe that is finally rendered visible to
our instruments, we can model how things have unfolded, and predict how things WILL unfold in the future. The imprint of
the universe's first light may have already stretched and dimmed to a shadow of its former self, but it will be
trillions of years yet before it fades completely from our view, giving cosmologists of the

future plenty of time yet to
decode its mysteries. A bright twinkle of light ignites in the blackness of space. First one, then another, then a
cascade of pinpoints light up. A cluster grows, swelling in size and gradually brightening with the light of even more
young stars, and within a few billion years, is large enough and massive enough to begin to spin. Its own angular
momentum is enough to stretch it out at its equator, flattening the cluster into a disk that whirls at more than 200
kilometers per second, completing a full rotation every 250 million years or so. As this young spiral galaxy wheels
through extragalactic space, it captures and absorbs smaller clusters that lie in its path. Head-on collisions with
other spinning galaxies result in mergers, which seed the original spiral with new material for a frantic burst of star
formation. It is some ten billion years ago, and our Milky Way galaxy is in the prime of its life. For a few billion
years, within the rippling spiral arms of the Milky Way, massive stars ignite, burn furiously, and die dramatically,
shedding their spent fusion fuel back into the galactic cloud for recycling. This gas is enriched with the heavier
elements that are formed during stellar nuclear fusion, and provide the foundation for an entirely new generation of
stars and, for the first time, planetary systems. Late to the star-forming party, on a fragmented spiral arm some 25,000
light years from the galactic centre, one such star sputters into existence around 4. 6 billion years ago, and like the
galaxy itself mirrored on a smaller scale, dust and gas whirl around it in a flattened disk. Dust becomes pebbles,
pebbles become boulders, and eventually boulders become entire rocky worlds. Those rocky worlds jostle for a stable
position around the yellow star, and after a few catastrophic collisions, eventually settle into orbits they will occupy
for the next four and half billion years. On the third such rocky world from the sun, as the heat from its violent
formation dissipates, water condenses to make oceans and atmospheres, and plate tectonics begins the slow recycling of
rock at the planetary surface. Somewhere inside the oceans, somehow, a spark of life ignites, finds its feet, and adapts
and evolves, filling this unique world with an entirely new kind of creation.

Chemistry becomes biology, as a multitude of lifeforms swarm the sea, land, and sky. And then, as if from nowhere, a
sentient mind appears to contemplate its place in the universe. Despite knowing the broad sequence of events that led to
the formation of the Milky Way galaxy, the Sun, Earth, life and us, there are still gaps in the cosmological
understanding of our creation. Just how did the lumpy soup of atoms created a few hundred thousand years after the Big
Bang led to all of THIS, several billion years down the line? Was all of it inevitable, or could the universe have
followed a different path? Taking the matter and energy we know existed around the time of atomic recombination and the
formation of the cosmic microwave background, and simulating the subsequent cosmic evolution, we end up with a universe
that is subtly but significantly different to the one in which we find ourselves. There are fewer galaxies, less
vigorous star formation, and delayed planetary formation. It’s possible in these simulations that life may be lagging
behind, or even absent altogether. There is clearly something missing from the picture, one final puzzle piece that
quite literally brings everything together. Unfortunately, that missing piece is a phenomenon that cosmologists simply
cannot see. Three hundred and eighty thousand years after the Big Bang, light has finally

escaped its matter prison.
Photons can travel freely through the expanding cosmos, but lose energy as it grows. The universe may no longer be opaque, but it is DARK. The fierce energy of formation has faded, and it will be millions of years yet before a new process - nuclear fusion - comes to concentrate energy once again. These are the dark ages of the universe - and there may be little to see, but this doesn't mean there is little going on. Indeed, it is during this time, up to and beyond the first million years of cosmological history, that scientists believe DARK MATTER steps up to shape the future of the universe. The existence of dark matter was first considered in 1933, when Swiss astronomer Fritz Zwicky was studying the Coma cluster of galaxies, some 320 million light years away from the Earth. The galaxies seemed to be moving too fast for the cluster to remain a cluster. Estimates of the masses of each galaxy in the cluster, based on the luminous stars that could be seen and counted, gave a number that was some ten times less than what would've been needed to keep the group together, given how fast the galaxies were moving. To explain this apparent discrepancy between the two methods of determining mass, Zwicky proposed that there must actually be a lot of UNSEEN mass lurking out there among the stars, gas, and visible matter. He called it 'dunkle materie', German for dark matter. Though little progress was made in this area for almost fifty years, in the late 1970s pioneering astronomer Vera Rubin was studying the rotation of the Andromeda galaxy, the closest spiral galaxy to our own, when she noticed that something didn't add up in the motions of its stars. At the time, she and her colleagues studied cryptic punchcard readouts from their instruments, but to this seasoned astronomer, the problem was as clear as day. Galaxies were expected to spin fast close into the centre, while stars at the edges would make a more stately progression - but the punchcards were telling a different story. The stars at Andromeda's outer edge seemed to be moving JUST as fast as those in the central bulge, with the tips of its spiral arms whipping around with implausible speed. The only explanation for such a movement, without violating the universe's fundamental laws of motion, was that the stars themselves were only a PART of the overall mass of the galaxy. Rubin calculated that the visible matter must represent just 15% of what was really there, and that the Andromeda galaxy must be cocooned in a much larger halo of invisible, DARK matter. Subsequent observations revealed that MOST galaxies are surrounded in this way, including our own - indeed current estimates suggest that the Milky Way's dark matter halo could be up to fifteen times larger than the visible extent of its stars.

Astronomers are now convinced of dark matter´s significance in shaping the modern universe, despite our continued inability to detect it. Larger scale studies suggest that dark matter outweighs normal matter six to one, and potentially always has. But what exactly it IS, remains a mystery even after several decades of concerted study. One possibility is that the dark matter in the universe consists of ordinary objects made up of normal baryonic matter like quarks and leptons, but which are hard for us to detect with our current technologies. Known as Massive Compact Halo Objects, these are more often referred to as MACHOs. Such objects could be black holes of a wide range of sizes, small but incredibly dense and massive neutron stars created when giant stars collapse at the end of their lives, or an extraordinary number of brown dwarfs, which contain almost enough mass as a star, but not

quite enough to ignite fusion.
However, as our telescopes and instruments improve, and we are able to probe the depths of intergalactic space in
ever-more detail, the chances of such objects in sufficient number continuing to escape our notice grows smaller with
every passing year. Because of this continued lack of observational evidence, an alternative possibility is currently
favoured among cosmologists - that the majority of dark matter exists as a Weakly Interacting Massive Particle,
correspondingly nicknamed WIMPs. These would be a completely new kind of particle, which sits outside the standard model
as we understand it today, but which we have so far failed to detect. They would not interact with normal matter via any
of the known fundamental forces except for gravity, but would nevertheless have a high mass, or be present in sufficient
number to make up for the universe’s 85% missing mass. The search is on in particle accelerators and out in the cosmos,
for any hint of these heavyweight WIMPs, but with so little to go on, we may have a long road ahead of us. Regardless of
whether dark matter is a MACHO or a WIMP, or something else entirely, it’s likely that it has always been around,
sitting in the shadow of tangible matter since its creation in the universe’s first few fractions of a second. And it
was back in the cosmic dark ages, around a million years after the Big Bang, that it began to shape the overall
structure of the universe. The Cosmic Microwave Background suggests that matter and energy were distributed unevenly at
the moment of atomic recombination, and so we can expect that dark matter followed suit. But in these darkened
millennia, all of that mass comes into its own. Gravity pulls the dark matter together, clumping it more quickly and
more thickly than we’d expect the baryonic matter to collapse. The normal matter then has a dark matter template to
follow, and is sucked into invisible gravity wells, creating cosmos-spanning filaments, nodes, and clusters of gas that
will become the nurseries for the first stars and galaxies. From this point on, the evolution of the universe we see
today HAS become inevitable. Everything that has happened up to this point, spanning the first million years of the
cosmic chronology, has set the stage for the next several BILLION years of astrophysical creation. The universe has
cooled to a point where comprehensible physics holds sway. The four forces have settled and become distinct, determining
all fundamental interactions. And the nature and quantities of matter have settled to provide the ingredients for
generations of stars and galaxies, the genesis of chemistry, and the ultimate creation of life. But that is not quite
all. For eight billion years, events in the universe unfold just as we would expect them to with these basic
ingredients. But between five and six billion years ago, not long before the formation of our solar system within the
Milky Way, something changed. And discovering that something made it clear that we still didn't really understand the
balance of the universe. This disturbing change in the evolution of the universe was first recognised some 25 years ago,
when astronomers were studying supernovae at different points in space and time.