(Excerpt)
How we know what we know about the universe

Luke Keller

First words

This book is about understanding the universe. We have learned about the structure of the universe, its origin, and its evolution by doing science. In writing a book about science and scientific work there are several things I assume are true:

- ✓ Our universe, which I somewhat presumptuously call *the* universe throughout this book, consists of all matter, energy, space, and time. In other words everything we can physically observe and measure is in our universe.

- ✓ The universe is physically self-consistent and understandable by making and interpreting observations and measurements.

- ✓ The properties of nature, for example how energy and matter interact, are the same in all frames of reference. In a given time and place during the evolution of our universe, nature works the same in any state of motion.

Knowing the physical nature of our universe through the scientific process would be difficult, if not impossible, if these are not true. I have organized the narrative so that it will work in multiple modes of reading. I anticipate that as you read this book you might:

- ✓ Read from cover to cover. It's a relatively short book, given the subject, and I have taken great care to present it as a clear and continuous narrative.

- ✓ Read the chapters out of order. I actually call them episodes. Most of them stand on their own despite being elements of a larger narrative.

- ✓ Read only the episodes that interest you at the moment. If you really want to know about dark energy right now, just flip to the 'Dark Energy' episode.

I'll start with a detailed, but brief summary of what we know in the year 2020 about the origin, structure, and evolution of the universe. This is the longest episode in the book. Science, at its pinnacle, is good story telling so I present the universe narrative as just that: a real page turner. I recommend reading the universe story from start to finish, but I realize that questions will arise that may be distracting. Not to worry. We'll return to details of the story throughout the rest of the book. Each episode explores a particular element of the universe story: a process or fact, what observations we made to learn about it, what questions we still have, and what alternative explanations we are considering. A labeled galaxy symbol, like the one here in the righthand margin, indicates the episode in which I have elaborated the concept on that line.

Episode
marker

Misunderstandings left unexamined are missed opportunities to communicate and learn. So in writing this book I have made an effort to describe concepts in a narrative that is understandable to anyone who is interested, regardless of their familiarity or level of expertise in the subject, *without oversimplifying to the point of inaccuracy*. So precise and consistent language is really important. To avoid confusion, I have been deliberate in my use of a few words and concepts that have multiple meanings in contexts outside of natural science: 'Evolution' is simply the change of physical characteristics with time. In this context anything that changes is evolving. 'Radiation' is any process that emits matter or energy in multiple directions. Physicists and astronomers often refer to light as electromagnetic radiation. A 'natural process' describes interactions of matter and energy that change a physical system. I have chosen to describe distances in miles until they get so large that light years make more sense. Despite the name, light years measure distance not time. One light year is six trillion miles, the distance light waves travel in a time period of one Earth year. Mainly as a narrative choice, I give temperatures in degrees, just degrees, because in most astrophysical environments temperatures are so hot—sometimes so cold—that the difference between the Fahrenheit, Celsius, and Kelvin scales is negligible.

Episode:
Light &
other Waves

Episode:
Observations &
Measurements

Science is often described as an awe-inspiring, even spiritual, activity because it allows us to tell our own story as part of a vast universe that we can understand and describe through systematic observation. Like many other inspirations, this can be revelatory, transformative, profoundly empowering, and also crushingly disturbing. As we contemplate the universe and seek to understand it, we can feel both significant and insignificant, sometimes simultaneously. Either way, my goal is to encourage a deep appreciation for the scientific process as a way to know about nature, all of nature, and to have confidence in what we know. I hope that this book will inspire you to think about the universe and our cosmic origins carefully and seriously and then ask: *How do we know that? Where is the evidence?* I expect that this book will provide convincing answers to these questions, but ultimately that assessment is yours to make.

What we know about the universe has developed from asking questions like: How old is it? What are its size and shape? What is it made of? How did it form and from what? How has it changed with time? What will happen to it in the future? And where are we in this universe? How do we answer these questions? How do we get from what we can observe and measure—simple things like apparent brightness and color, apparent size and shape, and position in the sky—to a detailed physical understanding of what we really want to know about the universe? And how do we know how well we know it?

Episode:
Scientific
Process

The scientific process, that's how. We know about the universe by observing objects and events in the sky and connecting patterns of structure—what things look like and where things are relative to one another—and patterns of time—how their physical characteristics change—to create a detailed, complete, and increasingly accurate description. So if I've answered the question in a single sentence, what's in the rest of this book? Details. Essential details like how we observe the universe and what tools we use to make observations, what we mean by 'accurate,' and the process we use to conduct, record, analyze, and synthesize our observations. We know how well we know about the universe by comparing predictions of past descriptions to current observations. If observations match predictions we have higher confidence in our knowledge. If not, we have lower confidence and more work to do refining our observation techniques or our descriptions, or both. We also assess our knowledge of the universe by discussing our findings with other people.

In 1948 Albert Einstein wrote about the importance of communicating science and scientific work in his foreword to *The Universe and Dr. Einstein*, by Lincoln Barnet:

> *It is of great importance that the general public be given an opportunity to experience—consciously and intelligently—the efforts and results of scientific research. It is not sufficient that each result be taken up, elaborated, and applied by a few specialists in the field.*

> *Restricting a body of knowledge to a small group deadens the philosophical spirit of a people and leads to spiritual poverty.*

Einstein was making a crucial point: in many ways the most important step in the scientific process, one that is often left out of the version taught in introductory science at the high school and college levels, is communication of the research process to a larger audience. The audience must include other scientists who can scrutinize the work since peer review is part of the scientific process. Crucially, though, the audience must include anyone who is interested, regardless of their level of expertise in the particular field of science. That is my aim with this book.

Have a look again at the first sentence of Einstein's commentary: "It is of great importance that the general public be given an opportunity to experience—consciously and intelligently—the *efforts* [my emphasis] and results of scientific research." Descriptions of the universe in print, video, and other media often focus primarily on the amazing results of scientific research, describing *what* we know. The efforts of scientists carrying out the research show *how* we know: how we transform systematic measurements into insight and understanding in which we can have high confidence. A detailed appreciation of that transformation does not require familiarity with complicated instrumentation or mathematical formulations. It does require paying attention to detail and asking questions, something we all can do.

Most of us can recite, or at least could at one time, the Scientific Method—what I am calling the scientific process—but we may not directly associate it with the science results and commentary we encounter in news media. Our culture values the results, the answers, the scientists themselves and where they work, the possible practical applications, but rarely the often lengthy and laborious process of science. These are all essential elements of the story of our learning about nature. In science, though, it is the process that matters, period. Science is not defined by who does the study, by what we study, or even by what we learn. Science is defined by what we do; it's more like a verb and less like a noun. People do science.

And doing science, we have learned a lot about the universe. There are planets orbiting most stars. Stars and planets form after the gravitational collapse of interstellar gas clouds. Black holes exist and they are not necessarily black, nor are they holes. We know what objects in space, like stars and galaxies, are made of, how old they are, how they formed, and how distant they are. We know that the atoms, molecules, and physical environment necessary for the formation of life on Earth are very common in the universe, especially in regions where stars and planets are forming. We know that the universe was once smaller than a proton and is now so large that we cannot observe its edge or if it even has an edge.

What we have learned about the universe is amazing, at times perplexing and even a bit ridiculous, at other times a little scary, and it routinely inspires our imaginations. The story of how we learned all of this is just as amazing, ridiculous, scary, and inspiring. This has not changed in millennia of astronomical observing. What has changed are the tools we use to observe, record, and analyze our observations—chiefly telescopes, light detectors, and computers—and our fundamental understanding of how nature works. These are essential parts of this amazing story, too.

So here we go. Once upon a time…

Episode 1
The Universe Story

The universe began as a singularity, a point of vanishingly small size, much smaller than an atom. In fact it was so small that our most developed language for describing things smaller than atoms—quantum theory—doesn't really help. Nor does our most developed language for describing things much larger than atoms—the theory of general relativity. Really? Stop for a moment. It's important to let that sink in because it is a ridiculous thing to ask anyone to believe. The singularity contained the potential—in the form of pure energy—for all matter, space, and time and was so small that we cannot yet fully describe it. Since we have no external vantage point from which to observe and describe the universe, the word 'size' really has no simple meaning. Space, which now contains everything that exists and outside of which we cannot go or even observe, simply did not exist in the singularity.

Episode:
Space

The universe began at the beginning of time, or at least time as we can currently measure it. What is time, anyway? Most people know what time is intuitively, but find a satisfying definition difficult to pin down. We can easily describe time with examples: time is what my clock measures; time is the past, present, and future; time lets us know we're moving; time is… well…time *just is*. Time progresses from the past to the present and then into the future, never from the future to the past. This so-called arrow of time is an important observable characteristic of our universe. The past is fixed, we cannot change it, but we can describe it in precise detail. The future is not fixed, physical processes in the present can change the future, but we can't know exactly how it will play out.

Episode:
Time

What came before the singularity and how did it form? We don't know. We have no information, or at least do not yet know how to gather information, from before the singularity existed because everything we can observe exists in space and time after the singularity. We can speculate, though. Perhaps nothing existed, not even the vacuum of space. A vacuum, though void of matter, can contain energy so it is something, not nothing! Perhaps the universe, and therefore time, existed before the singularity. Maybe singularities are common phases of evolution for universes. Perhaps a different universe preceded this one. Or maybe many universes exist or have existed, in which case we really should say *our* universe instead of *the* universe. Trying to develop a physical description of what existed before the singularity is kind of like

Episode:
Multiverse

trying to write a poem without a fully developed language or even a full alphabet of letters. The universe was ridiculously small in the past. That much we can say with confidence.

We'll have an easier time describing the structure of the universe if we avoid saying 'space and time.' Sometimes it makes more sense to use one or the other, but it's much more informative and accurate to regard our descriptions of where and when as 'space *with* time'. Despite our perception to the contrary, time is not independent of space. You cannot be somewhere without also being somewhen; your location in space must be accompanied by your location in time. We live in a four-dimensional spacetime; the familiar three dimensions of space and the familiar dimension of time inseparably woven together. There may be more dimensions of space and time, but they are not detectable with any observations or measurements that we can make currently.

Episode:
Spacetime

Spacetime unfolded from the singularity and has continued expanding throughout the evolution of the universe. Since it began with the singularity, the initial moment of expansion happened everywhere at the same time. This germinal event is known as the Big Bang, though that name can be problematic. The universe in its first moments was neither big (its scale was infinitesimally small) nor a bang (it was pure energy, intensely luminous). So I suggest a new, more accurately descriptive name: the universe began with the *Small Flash*. The expansion from that moment is happening everywhere. Every location in spacetime is the center of expansion, therefore every point in the universe is the center of the universe! You are the center of the universe (and so am I).

What caused the singularity to start expanding? We don't know. What we do know is that the universe must have expanded from the singularity rapidly at first. We cannot yet fully characterize the energy source for this expansion so we call it 'dark energy.' I think this name is unfortunate, too, because it conjures images of magic and fantasy as if some dark sorcerer's spell causes the expansion of the universe. The universe story is much more interesting. Some cosmologists call it 'vacuum energy;' I think I'd have called it 'hidden energy' since we observe its effect on the universe and it appears to be evenly distributed throughout spacetime, but we are still looking for its precise nature. Once we know what it is and precisely how it works we can give it a properly descriptive name.

Episode:
Dark Energy

What does the universe expand into? The universe expands into nothing. And I do mean nothing, not even empty spacetime. The expansion is not an explosion in the sense of an object blowing up, sending pieces flying in all directions into air or empty space. It's more

Episode:
Expansion

accurate to think of the expansion of the universe as the expansion of spacetime that matter and energy occupy. The matter that forms observable structures in the universe—atoms, stars, galaxies—is not moving through spacetime as a result of cosmic expansion. Matter has been along for the ride as spacetime expanded over the past 13.8 billion years. The expansion shows no sign of stopping. In fact it may be speeding up.

We humans like to organize expanses of time into named eras and epochs on a timeline. Like a story board for a picture book or film, this can help us organize a complex and lengthy process. And names are important; they help us make connections. In keeping with this tradition: the universe began in the primordial era, a fitting name don't you think? As the universe continued its expansion during the 380 thousand years of the primordial era, sometimes called the very early universe or the energy-dominated era, things went from almost unfathomable and weird to downright boring.

In the very beginning, during the grand unification epoch of the primordial era, the fundamental forces that we know and love (strong nuclear, weak nuclear, electromagnetic, and gravitational) were indistinguishable. The matter-energy interactions—attractions, repulsions, and transformations—that those four forces characterize in the present time were not yet possible because the early universe was intensely bright and hot, more than a hundred million trillion trillion degrees.

Episode:
Particles
and forces

Episode:
How much?

Like the primordial singularity, these early high-energy conditions are not completely describable with our current language for characterizing the physical world using quantum theory, which accurately describes physical interactions at the scale of atoms and molecules, or general relativity theory, which accurately describes gravitational interactions at larger scales. A complete physical description of this epoch requires a quantum theory of gravity, sometimes called a Grand Unified Theory or Theory of Everything, the precise details of which have so far eluded us. But onward! It wasn't long before the expansion resulted in a cooler, less dense universe that we can describe in great detail despite our on-going search for a Grand Unified Theory.

Episode:
Energy &
Matter

A hundredth of a billionth of a trillionth of a trillionth of a second after the Small Flash, the inflationary epoch of the primordial era began and then ended. Whether it began before, during, or after the grand unification epoch is still uncertain. During this short period of time the matter-energy balance was dominated by dark energy so the universe expanded in scale by a factor of about a hundred trillion trillion. Take another deep breath. I can't visualize quantities that small or that large. No one can, really. We just don't consciously encounter scales like that in our every day existence. Here's something easier to picture: after the inflationary epoch the universe had grown from smaller than a proton to the size of a tennis ball and the universe was still much less than one second old.

Episode:
How much?

The size of a tennis ball? Just a few paragraphs ago I argued that it is not helpful to describe the universe as having a size since it is not a thing we can observe and measure from an external viewpoint. I'm breaking my own rule. Not size, then, length scale. Here's how we quantify the scale of the universe: in this early epoch the distance from a particular location in spacetime to the most distant point in spacetime observable from that location was roughly half the diameter of a tennis ball. Another way to put it is that just after the inflationary epoch the part of the universe that has since expanded to become the present *observable universe*, the part we can see directly, was the size of a tennis ball.

Episode:
Observing
the Past

Inflation was a fortunate development for us because it enabled the intensely hot, dense, and almost perfectly homogeneous and smooth universe—containing intense light and energy, but no matter—to become a much larger, cooler, less dense, and very slightly inhomogeneous and clumpy universe containing energy, light, *and* matter. The gravitational forces within regions of slightly higher density of matter in the early universe caused those regions to condense. The formation of galaxies, stars, planets, and life has depended upon the resulting clumpy structure. All of us are regions of higher density in the universe.

Next came the quark epoch, during which the four fundamental forces in the universe were finally distinguishable and the universe was cool enough that matter in the form of quarks, particles smaller than a proton, could survive. The subatomic particles that we know and love, protons and neutrons, are combinations of quarks glued together by the strong nuclear force during the hadron (heavy particle) epoch. The much lighter electrons emerged during the lepton (light particle) epoch. The universe was now a few seconds old and contained the building blocks of hydrogen atoms: one proton and one electron each. In the next few minutes the nucleosynthesis (atom building) epoch saw the synthesis of atomic nuclei including deuterium (hydrogen with an added neutron), helium (fusion of two protons and two neutrons each), and traces of lithium (three protons and four neutrons). But matter wasn't just in the form of atomic nuclei and electrons.

Episode:
Particles
and forces

We observe two forms of matter: luminous and dark. Luminous matter is made of atoms—also the subatomic particles of which atoms are composed—and it interacts strongly with the electromagnetic force, which means that it emits and reflects light and can have electric charge. We are so familiar with luminous matter that we call it ‘normal matter’ or just plain ‘matter.’

Episode:
Dark matter

Particles of dark matter—we assume dark matter is made of particles—do not interact with the electromagnetic force. This means that they do not emit or reflect light and have no electric charge. It also means that they do not interact with each other or with luminous matter very often, if at all. Most particle interactions, like collisions, require the push of a repulsive force during the encounter, which dark matter lacks. We do not yet know what dark matter is made of, but we do know it has at least one important property in common with luminous matter: dark matter has a mutual gravitational attraction with all other matter and must therefore have mass. The universe would be a very different place today without dark matter and its mass.

Episode:
Observations &
Measurements

At the end of the nucleosynthesis epoch the universe was less than half an hour old, its temperature had cooled to a few million degrees, and its scale had expanded to several hundred light years. For some local perspective: the closest star to the sun is four light years away and the faintest individual stars we see, looking up into in the night sky, are a few hundred light years from the sun.

Episode:
Energy &
Matter

Over the next 50,000 years the expansion, continuing much more slowly than during the earlier inflation epoch, resulted in more cooling so that a game-changing transformation occurred. The high density of energy in the universe, mostly electromagnetic radiation (light), gave way to a predominance of matter. Think of energy and matter as fluid in two partially-filled buckets: one labeled ‘energy’ and the other labeled `matter.’ You can poor the contents from one bucket to the other, but the total volume of matter-energy, also called mass-energy, remains constant unless some process adds to or drains the buckets. Physical processes can transform matter to energy and back again. The temperature and density of the universe eventually lowered to the point that more of the mass-energy could remain in the form of slow-moving matter (atomic nuclei and dark matter) and slight differences in luminous matter density from place to place could persist instead of being smoothed out by interactions with the intense electromagnetic radiation.

The first molecules could form after about 100,000 years when the universe had cooled so that atoms of hydrogen and helium could combine to produce helium hydride without collisions immediately knocking them apart again. This is an exciting time for anyone with an appreciation for chemistry. Although the periodic table still only contained three elements, at least one chemical reaction was now possible. And apparently helium, under the right conditions, isn't such a noble gas after all.

The luminous matter in the universe was still in the form of plasma, positively charged atomic nuclei and a few helium hydride molecules together with a very hot and hyperactive cloud of negatively charged electrons swarming around and between them. This state of things continued until 380,000 years after the Small Flash, at which time the temperature had cooled to a few thousand degrees. Electrons could finally settle down, combining with positively-charged atomic nuclei. This event is known as the time of recombination, another unfortunate name because it was the first time electrons had ever combined with protons and neutrons to form stable atoms so I would have called it the time of combination. No one asked me. With the electrons now bound to atomic nuclei by the electric force (opposite charges attract) the universe became transparent, nearly instantly, and the intense light—it was bright red by the way—from its hot and dense beginnings permeated spacetime, its waves getting longer and fainter with the on-going expansion of spacetime. By the time of (re)combination the scale of the universe had reached almost 100 million light years.

And thus the primordial era came to a close. Luminous and dark matter filled the universe, which was still very nearly uniform in distribution. The difference between the most dense and least dense regions was only 1 part in 100,000. If the surface of the Earth were that smooth the summit of our highest mountain would be just over 3 *inches* above sea level. During the first hundred million years or so after the time of (re)combination the universe was a very boring place: the periodic table still only contained three elements, there were no solid objects larger than a helium hydride molecule, and everything was cooling off and getting fainter. These were the cosmic dark ages; there wasn't much to see. But the boring dark ages would not last for long.

Episode:
How much?

In the first few million years after the Small Flash, the universe was still homogeneous on very large scales, slightly clumpy on smaller scales, and getting more clumpy thanks to the force of gravity. Since gravity is stronger between objects that are closer together, bits of dark matter and luminous gas already in clumps collapsed even further. The structures that formed in the early universe were therefore enhanced by the segregation of matter into what we would now call wispy tendrils and clouds. Dark matter clumped first since its particles could not be scattered by collisions; luminous matter was scattered and therefore could not clump as easily. As the clouds of luminous matter cooled and settled down, though, the dark matter clumps attracted them and together they increasingly dominated the mass-energy balance.

We call these first clouds proto (almost) galaxies. Some cosmologists call them minihalos because they were less massive than galaxies are today, only a few 100,000 times the mass of the sun, and they would have appeared more like fuzzy halos than the complex galaxy shapes we observe in the present era. The definition of a galaxy suffers from something of a chicken-and-egg problem since most descriptions involve hundreds of billions of stars gravitationally bound to one another. But what came first, the galaxies or the stars?

Episode:
Galaxies

Within a hundred million years after the Small Flash, gas in the minihalos collapsed (gravity again!) to form the very first stars and heralded the stelliferous era, my favorite. The cosmic dark ages were over. If your definition of a galaxy requires stars in the mix, you will now agree that the universe had its first galaxies. The first stars were, of course, made primarily of hydrogen and helium and most were very massive and short lived, some of them hundreds of times the mass of the sun and lasting a few million years. There was no dust surrounding the first stars, as there often is today, because dust grains are made of carbon, oxygen, and silicon and those elements did not yet exist in the universe. Stars would soon fix that.

Episode:
Stars

The source of energy keeping stars hot and luminous is nuclear fusion, in their dense and hot cores, that synthesizes heavier elements from the nuclei of lighter elements. We call this stellar nucleosynthesis. When the first generation of stars died, most did it with another kind of flash: a really *big* flash that we call a supernova explosion. Supernovae spread an abundance of newly synthesized heavy elements—everything up to iron—into the space around them along with even heavier elements synthesized in the tremendously hot explosions. Gravity pulls on all matter so those remnants of exploded stars, now clouds of gas with a much richer variety of chemical elements, eventually re-collapsed to form the next generation of stars about a billion years after the Small Flash. We see many of these stars when we look into the night sky. They are the oldest stars we currently observe in our Milky Way and other galaxies.

The deaths of the first massive stars left another spectacular type of remnant. The dense centers of the more massive stars survived their supernova explosions and, now lacking internal thermal pressure from nuclear fusion, collapsed to higher and higher density. The resulting objects have the mass of many suns, but no size so the spacetime near them resembles the primordial singularity; light cannot escape their gravity. We call them black holes. Most are neither black, nor are they holes, but the name seems to have stuck. No one ever asks me about these names!

Episode:
Black holes

Black holes are some of the most fascinating and provocative objects in the universe. Most galaxies have black holes in their centers. These are much larger than the black holes formed in collapsing stellar cores; some of them are millions or even billions of times the mass of the sun. These super-massive black holes formed early in the formation and evolution of their host galaxies by attracting mass from dense matter in their immediate surroundings. Some black holes may even have formed in the intensely hot and dense environment in the early universe right before the nucleosynthesis epoch. These primordial black holes may have played a role in the condensation of galaxies from mini halos of dark and luminous matter.

Episode:
Galaxies

After a few billion years larger galaxies formed, some with flattened disk-like structure resulting from the fact that dark matter only interacts with the gravitational force, but compressed gas made of luminous matter looses energy by radiating light. The luminous gas began to flatten as it collapsed, spinning ever faster, to form the galactic disks. Dark matter, still free to roam, remained more widely distributed in a haze—albeit an invisible haze—surrounding each galaxy and also stretched like a web between galaxies. Stars and gas orbiting in the disks of galaxies interact to form waves of density giving some disk galaxies a spiral structure. Our home galaxy, the Milky Way, is one of these with spiral arms illuminated by young stars and contrasting lanes of dust, an extended halo of older stars, and an even larger halo of dark matter. The Milky Way and its spiral arms formed about three billion years after the Small Flash.

The youngest stars in the universe—you are orbiting one of them right now—formed when the second generation of stars began to explode and mix gas even richer in heavy elements into their surroundings. These third-generation stars began forming about four billion years after the Small Flash at a time when galaxies that formed in close proximity had begun interacting gravitationally, falling into and through one-another.

These interactions and mergers are on-going and are responsible for the largest and most massive galaxies that we currently observe.

Episode: Stars

There are stars forming in the Milky Way galaxy and other galaxies as you read these words. The Sun formed about 9 billion years after the Small Flash. The cold protosolar cloud probably had the mass of at least five hundred suns, an average temperature considerably *below* the freezing point of water, and was several light years in diameter. Not particularly special, typical in fact, as protostellar clouds go in the present epoch.

The star formation process pits the gravitational force against the electromagnetic force. The mutual gravitational attraction between individual hydrogen molecules in the denser regions of a protostellar gas cloud causes a collapse of the cloud core. As the molecules get closer together the gas density increases. Collisions—enabled by the repulsive electric force between electrons surrounding each atom—accelerate the increasingly crowded molecules so the gas temperature increases. Outward pressure within the hot stellar core opposes and slows the gravitational collapse. Eventually the inward gravitational force comes into equilibrium with the outward gas pressure, halting the collapse entirely. The protostar, now spherical, is opaque and luminous with a surface temperature ranging form a few thousand degrees to a few tens of thousands of degrees depending on its mass. Gravitational potential energy of a cloud core originally light years across has transformed into thermal energy in a star now only a few million miles in diameter.

Star formation takes a few hundred thousand to a few million years, again depending on the initial cloud core mass. The more massive the star the faster it forms and the hotter its interior and surface. Stars shine because the gas on their surfaces is hot. A star's luminosity, proportional to its size and surface temperature, carries thermal energy away in the form of light radiated in all directions. With no energy source to replenish this lost energy the star would cool and dim over just millions of years. We would see far fewer stars in the sky than we observe today.

Fortunately the temperature of gas in the deep interiors of even the coolest stars is in the tens of millions of degrees, similar to the temperature of the early universe during the nucleosynthesis epoch. At these temperatures atomic nuclei are moving so fast that collisions result in nuclear fusion reactions: first helium and then heavier nuclei like carbon, oxygen and silicon. Stars maintain their hot surfaces and the resulting luminosity with nuclear energy from fusion in their hot interiors. With this energy source most stars exist in gravity-pressure equilibrium for billions of years. The sun has been fusing hydrogen into helium, maintaining roughly the same surface temperature and luminosity for the past five billion years and will continue for several billion more years. During the first few million years of their lives most stars do something with their gravity that is every bit as spectacular as nucleosynthesis: they form planets.

Episode:
Planets

Planetary systems condense from gas and dust orbiting newly-formed stars. This protoplanetary material is left over from the star formation process. Its the same stuff, but it did not fall into the protostar in the end stage of the cloud core collapse. Instead, the building materials for planets went into orbit and formed a disk with the star at its center, resembling the planet Saturn with its rings, but much larger and thicker. Protoplanetary material is about 99% gas, mostly hydrogen, and 1% dust, formed from silicon, oxygen, and carbon. Planets form because the protoplanetary disks are unstable. Instead of following smooth orbits, the gas can become turbulent. Protoplanetary material mixes and swirls creating regions of higher density. And we're very familiar with the fate of high density gas: it collapses under its own gravity so that small spheres of gas condense in orbit around the star.

At the same time another planet building process sweeps up grains of dust into ever-growing structures: individual particles of dust stick instead of bouncing after close encounters. First grains like sand form, then rocks, then boulders, then asteroids and even larger bodies called planetesimals. Planetesimals combine to form planets like Earth and they may also form the cores of the larger, ice giant and gas giant planets like Neptune and Jupiter. Rocky planets can attract interplanetary gas to form atmospheres as they orbit their star. Eventually most of the circumstellar gas and dust forms planets and a planetary system remains. Our solar system completed this process about 4.6 billion years ago and nine billion years after the Small Flash. 4.6 billion years is an auspicious figure; it is the age of planet Earth.

We now observe a universe of at least two trillion galaxies, each containing around a hundred billion stars along with gas and dust, and each immersed a halo of dark matter. The expansion rate of spacetime in our universe is increasing again—dark energy has become more dominant since about four billion years after the Small Flash—though the current expansion is still not as rapid as during the inflation epoch. On distance scales the size of groups of galaxies, or smaller, the gravitational force has more influence than dark energy so stars and galaxies do not grow with the cosmic expansion. On larger distance scales dark energy has more influence than the gravitational force so the expansion of the universe, now accelerating, creates space between galaxies faster than they can attract one another and they are carried farther apart. The bright red light that permeated the newly transparent universe at the end of the primordial era has been traveling through expanding spacetime so that its waves have stretched into the radio part of the light spectrum. We call this the cosmic microwave background radiation.

Our cosmological origins story brings us to what we call the present era. We now take for granted a full periodic table of 90 chemical elements synthesized in stars or supernovae, four fundamental forces that govern the interaction of matter and energy, and physical structure on a wide range of size scales. The observable universe currently has a scale of 96 billion light years and contains structures ranging from galaxy groups and clusters, to individual galaxies, to stars and planets, to cells of living organisms, to molecules and the atoms they are built from, to sub-atomic particles like quarks and electrons.

Episode: Life

How do we know all of this? Why is this outlandish story the leading cosmological theory; for decades the most widely accepted scientific description of the universe and its origin? The rest of this book is a detailed exploration of that essential question.