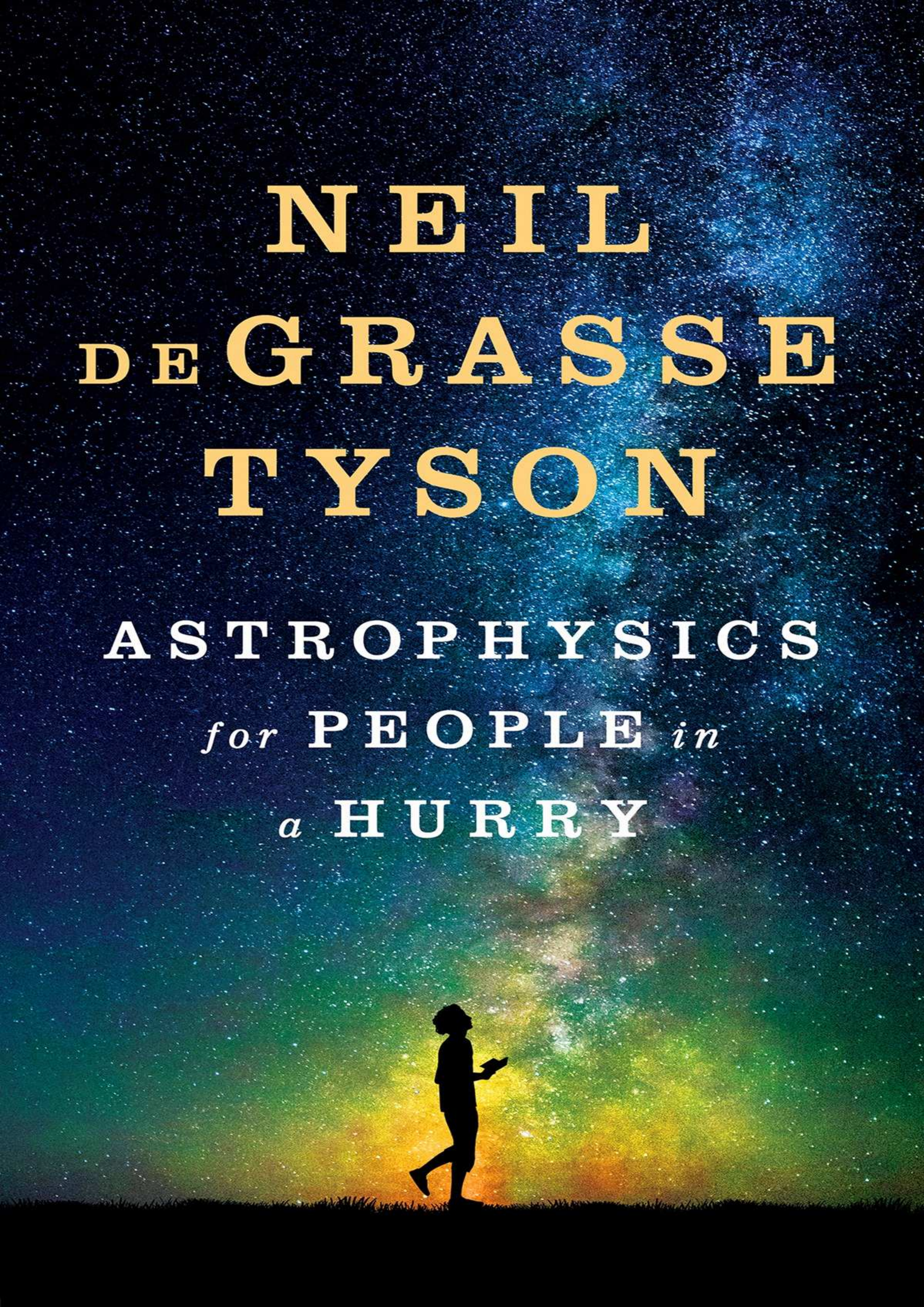
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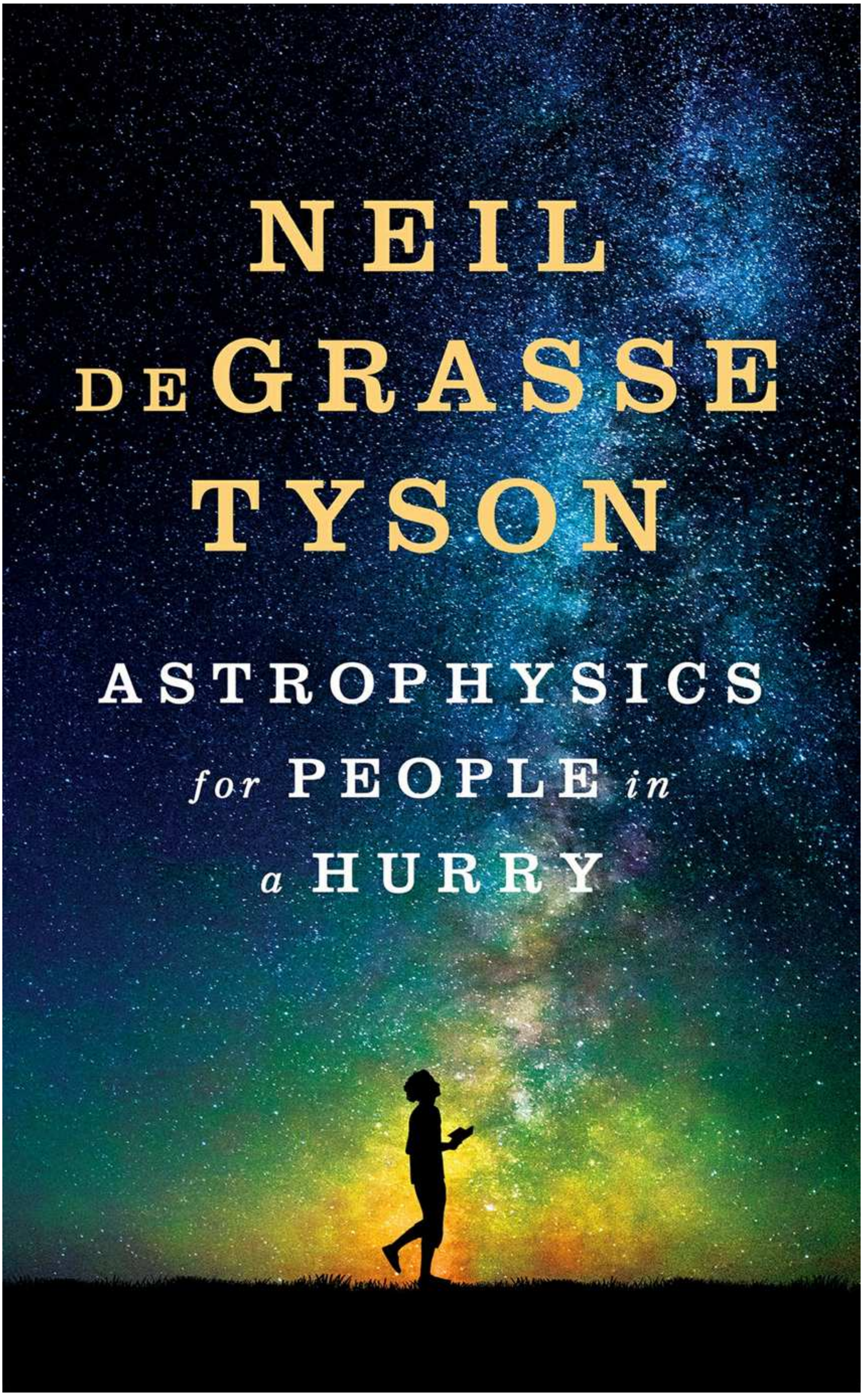
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Astrophysics for People in a Hurry

NEIL DEGRASSE TYSON

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New York | London

For all those who are too busy to read fat books Yet nonetheless seek a conduit to the cosmos

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PREFACE

In recent years, no more than a week goes by without news of a cosmic discovery worthy of banner headlines. While media gatekeepers may have developed an interest in the universe, this rise in coverage likely comes from a genuine increase in the public's appetite for science. Evidence for this abounds, from hit television shows inspired or informed by science, to the success of science fiction films starring marquee actors, and brought to the screen by celebrated producers and directors. And lately, theatrical release biopics featuring important scientists have become a genre unto itself. There's also widespread interest around the world in science festivals, science fiction conventions, and science documentaries for television.

The highest grossing film of all time is by a famous director who set his story on a planet orbiting a distant star. And it features a famous actress who plays an astrobiologist. While most branches of science have ascended in this era, the field of astrophysics persistently rises to the top. I think I know why. At one time or another every one of us has looked up at the night sky and wondered: What does it all mean? How does it all work? And, what is my place in the universe?

If you're too busy to absorb the cosmos via classes, textbooks, or documentaries, and you nonetheless seek a brief but meaningful introduction to the field, I offer you *Astrophysics for People in a Hurry*. In this slim volume, you will earn a foundational fluency in all the major ideas and discoveries that drive our modern understanding of the universe. If I've succeeded, you'll be culturally conversant in my field of expertise, and you just may be hungry for more.

The universe is under no obligation to make sense to you.

—NDT

Astrophysics for People in a Hurry

1.

The Greatest Story Ever Told

> The world has persisted many a long year, having once been set going in the appropriate motions. From these everything else follows.
>
> LUCRETIUS, C. 50 BC

In the beginning, nearly fourteen billion years ago, all the space and all the matter and all the energy of the known universe was contained in a volume less than one-trillionth the size of the period that ends this sentence.

Conditions were so hot, the basic forces of nature that collectively describe the universe were unified. Though still unknown how it came into existence, this sub-pinpoint-size cosmos could only expand. Rapidly. In what today we call the big bang.

Einstein's general theory of relativity, put forth in 1916, gives us our modern understanding of gravity, in which the presence of matter and energy curves the fabric of space and time surrounding it. In the 1920s, quantum mechanics would be discovered, providing our modern account of all that is small: molecules, atoms, and subatomic particles. But these two understandings of nature are formally incompatible with one another, which set physicists off on a race to blend the theory of the small with the theory of the large into a single coherent theory of quantum gravity. Although we haven't yet reached the finish line, we know exactly where the high hurdles are. One of them is during the "Planck era" of the early universe. That's the interval of time from $t = 0$ up to $t = 10^{-43}$ seconds (one ten-million-trillion-trillion-trillionths of a second) after the beginning, and before the universe grew to 10^{-35} meters (one hundred billion trillion-

trillionths of a meter) across. The German physicist Max Planck, after whom these unimaginably small quantities are named, introduced the idea of quantized energy in 1900 and is generally credited as the father of quantum mechanics.

The clash between gravity and quantum mechanics poses no practical problem for the contemporary universe. Astrophysicists apply the tenets and tools of general relativity and quantum mechanics to very different classes of problems. But in the beginning, during the Planck era, the large was small, and we suspect there must have been a kind of shotgun wedding between the two. Alas, the vows exchanged during that ceremony continue to elude us, and so no (known) laws of physics describe with any confidence the behavior of the universe over that time.

We nonetheless expect that by the end of the Planck era, gravity wriggled loose from the other, still unified forces of nature, achieving an independent identity nicely described by our current theories. As the universe aged through 10^{-35} seconds it continued to expand, diluting all concentrations of energy, and what remained of the unified forces split into the "electroweak" and the "strong nuclear" forces. Later still, the electroweak force split into the electromagnetic and the "weak nuclear" forces, laying bare the four distinct forces we have come to know and love: with the weak force controlling radioactive decay, the strong force binding the atomic nucleus, the electromagnetic force binding molecules, and gravity binding bulk matter.

✷

A trillionth of a second has passed since the beginning.

✷

All the while, the interplay of matter in the form of subatomic particles, and energy in the form of photons (massless vessels of light energy that are as much waves as they are particles) was incessant. The universe was hot enough for these photons to spontaneously convert their energy into matter-antimatter particle pairs, which immediately thereafter annihilate, returning their energy back to photons. Yes, antimatter is real. And we discovered it, not science fiction writers. These transmogrifications are entirely prescribed by Einstein's most famous equation: $E = mc^2$, which is a two-way recipe for how much matter your energy is worth, and how much energy your matter is worth. The c^2 is the speed of light squared—a huge number which, when multiplied by the mass, reminds us how much energy you actually get in this exercise.

Shortly before, during, and after the strong and electroweak forces parted company, the universe was a seething soup of quarks, leptons, and their antimatter siblings, along with bosons, the particles that enable their interactions. None of these particle families is thought to be divisible into anything smaller or more basic, though each comes in several varieties. The ordinary photon is a member of the boson family. The leptons most familiar to the non-physicist are the electron and perhaps the neutrino; and the most familiar quarks are . . . well, there are no familiar quarks. Each of their six subspecies has been assigned an abstract name that serves no real philological, philosophical, or pedagogical purpose, except to distinguish it from the others: *up* and *down*, *strange* and *charmed*, and *top* and *bottom*.

Bosons, by the way, are named for the Indian scientist Satyendra Nath Bose. The word “lepton” derives from the Greek *leptos*, meaning “light” or “small.” “Quark,” however, has a literary and far more imaginative origin. The physicist Murray Gell-Mann, who in 1964 proposed the existence of quarks as the internal constituents of neutrons and protons, and who at the time thought the quark family had only three members, drew the name from a characteristically elusive line in James Joyce’s *Finnegans Wake*: “Three quarks for Muster Mark!” One thing quarks do have going for them: all their names are simple—something chemists, biologists, and especially geologists seem incapable of achieving when naming their own stuff.

Quarks are quirky beasts. Unlike protons, each with an electric charge of +1, and electrons, with a charge of –1, quarks have fractional charges that come in thirds. And you’ll never catch a quark all by itself; it will always be clutching other quarks nearby. In fact, the force that keeps two (or more) of them together actually grows stronger the more you separate them—as if they were attached by some sort of subnuclear rubber band. Separate the quarks enough, the rubber band snaps and the stored energy summons $E = mc^2$ to create a new quark at each end, leaving you back where you started.

During the quark–lepton era the universe was dense enough for the average separation between unattached quarks to rival the separation between attached quarks. Under those conditions, allegiance between adjacent quarks could not be unambiguously established, and they moved freely among themselves, in spite of being collectively bound to one another. The discovery of this state of matter, a kind of quark cauldron, was reported for the first time in 2002 by a team of physicists at the Brookhaven National Laboratories, Long Island, New York.

Strong theoretical evidence suggests that an episode in the very early universe, perhaps during one of the force splits, endowed the universe with a remarkable asymmetry, in which particles of matter barely outnumbered particles of antimatter: by a billion-and-one to a billion. That small difference in population would hardly get noticed by anybody amid the continuous creation, annihilation, and re-creation of quarks and antiquarks, electrons and antielectrons (better known as positrons), and neutrinos and antineutrinos. The odd man out had oodles of opportunities to find somebody to annihilate with, and so did everybody else.

But not for much longer. As the cosmos continued to expand and cool, growing larger than the size of our solar system, the temperature dropped rapidly below a trillion degrees Kelvin.

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A millionth of a second has passed since the beginning.

⁕

This tepid universe was no longer hot enough or dense enough to cook quarks, and so they all grabbed dance partners, creating a permanent new family of heavy particles called hadrons (from the Greek *hadros*, meaning “thick”). That quark-to-hadron transition soon resulted in the emergence of protons and neutrons as well as other, less familiar heavy particles, all composed of various combinations of quark species. In Switzerland (back on Earth) the European particle physics collaboration[†] uses a large accelerator to collide beams of hadrons in an attempt to re-create these very conditions. This largest machine in the world is sensibly called the Large Hadron Collider.

The slight matter–antimatter asymmetry afflicting the quark–lepton soup now passed to the hadrons, but with extraordinary consequences.

As the universe continued to cool, the amount of energy available for the spontaneous creation of basic particles dropped. During the hadron era, ambient photons could no longer invoke $E = mc^2$ to manufacture quark–antiquark pairs. Not only that, the photons that emerged from all the remaining annihilations lost energy to the ever-expanding universe, dropping below the threshold required to create hadron–antihadron pairs. For every billion annihilations—leaving a billion photons in their wake—a single hadron survived. Those loners would ultimately get to have all the fun: serving as the ultimate source of matter to create galaxies, stars, planets, and petunias.

Without the billion-and-one to a billion imbalance between matter and antimatter, all mass in the universe would have self-annihilated, leaving a cosmos made of photons *and nothing else*—the ultimate let-there-be-light scenario.

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By now, one second of time has passed.

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The universe has grown to a few light-years across,[††] about the distance from the Sun to its closest neighboring stars. At a billion degrees, it's still plenty hot—and still able to cook electrons, which, along with their positron counterparts, continue to pop in and out of existence. But in the ever-expanding, ever-cooling universe, their days (seconds, really) are numbered. What was true for quarks, and true for hadrons, had become true for electrons: eventually only one electron in a billion survives. The rest annihilate with positrons, their antimatter sidekicks, in a sea of photons.

Right about now, one electron for every proton has been "frozen" into existence. As the cosmos continues to cool—dropping below a hundred million degrees—protons fuse with protons as well as with neutrons, forming atomic nuclei and hatching a universe in which ninety percent of these nuclei are hydrogen and ten percent are helium, along with trace amounts of deuterium ("heavy" hydrogen), tritium (even heavier hydrogen), and lithium.

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Two minutes have now passed since the beginning.

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For another 380,000 years not much will happen to our particle soup. Throughout these millennia the temperature remains hot enough for electrons to roam free among the photons, batting them to and fro as they interact with one another.

But this freedom comes to an abrupt end when the temperature of the universe falls below 3,000 degrees Kelvin (about half the temperature of the Sun's surface), and all the free electrons combine with nuclei. The marriage leaves behind a ubiquitous bath of visible light, forever imprinting the sky with a record of where all the matter was in that moment, and completing the formation of particles and atoms in the primordial universe.

☀

For the first billion years, the universe continued to expand and cool as matter gravitated into the massive concentrations we call galaxies. Nearly a hundred billion of them formed, each containing hundreds of billions of stars that undergo thermonuclear fusion in their cores. Those stars with more than about ten times the mass of the Sun achieve sufficient pressure and temperature in their cores to manufacture dozens of elements heavier than hydrogen, including those that compose planets and whatever life may thrive upon them.

These elements would be stunningly useless were they to remain where they formed. But high-mass stars fortuitously explode, scattering their chemically enriched guts throughout the galaxy. After nine billion years of such enrichment, in an undistinguished part of the universe (the outskirts of the Virgo Supercluster) in an undistinguished galaxy (the Milky Way) in an undistinguished region (the Orion Arm), an undistinguished star (the Sun) was born.

The gas cloud from which the Sun formed contained a sufficient supply of heavy elements to coalesce and spawn a complex inventory of orbiting objects that includes several rocky and gaseous planets, hundreds of thousands of asteroids, and billions of comets. For the first several hundred million years, large quantities of leftover debris in wayward orbits would accrete onto larger bodies. This occurred in the form of high-speed, high-energy impacts, which rendered molten the surfaces of the rocky planets, preventing the formation of complex molecules.

As less and less accretable matter remained in the solar system, planet surfaces began to cool. The one we call Earth formed in a kind of Goldilocks zone around the Sun, where oceans remain largely in liquid form. Had Earth been much closer to the Sun, the oceans would have evaporated. Had Earth been much farther away, the oceans would have frozen. In either case, life as we know it would not have evolved.

Within the chemically rich liquid oceans, by a mechanism yet to be discovered, organic molecules transitioned to self-replicating life. Dominant in this primordial soup were simple anaerobic bacteria—life that thrives in oxygen-empty environments but excretes chemically potent oxygen as one of its by-products. These early, single-celled organisms unwittingly transformed Earth’s carbon dioxide-rich atmosphere into one with sufficient oxygen to allow aerobic organisms to emerge and dominate the oceans and land. These same oxygen atoms, normally found in pairs (O_2), also combined in threes to form ozone (O_3) in the upper atmosphere, which serves as a shield that protects Earth's surface from most of the Sun's molecule-hostile ultraviolet photons.

We owe the remarkable diversity of life on Earth, and we presume elsewhere in the universe, to the cosmic abundance of carbon and the countless number of simple and complex molecules that contain it. There's no doubt about it: more varieties of carbon-based molecules exist than all other kinds of molecules combined.

But life is fragile. Earth's occasional encounters with large, wayward comets and asteroids, a formerly common event, wreaks intermittent havoc upon our ecosystem. A mere sixty-five million years ago (less than two percent of Earth's past), a ten-trillion-ton asteroid hit what is now the Yucatan Peninsula and obliterated more than seventy percent of Earth's flora and fauna—including all the famous outsized dinosaurs. Extinction. This ecological catastrophe enabled our mammal ancestors to fill freshly vacant niches, rather than continue to serve as hors d'oeuvres for *T. rex*. One big-brained branch of these mammals, that which we call primates, evolved a genus and species (*Homo sapiens*) with sufficient intelligence to invent methods and tools of science—and to deduce the origin and evolution of the universe.

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What happened before all this? What happened before the beginning?

Astrophysicists have no idea. Or, rather, our most creative ideas have little or no grounding in experimental science. In response, some religious people assert, with a tinge of righteousness, that *something* must have started it all: a force greater than all others, a source from which everything issues. A prime mover. In the mind of such a person, that something is, of course, God.

But what if the universe was always there, in a state or condition we have yet to identify—a multiverse, for instance, that continually births universes? Or what if the universe just popped into existence from nothing? Or what if everything we know and love were just a computer simulation rendered for entertainment by a superintelligent alien species?

These philosophically fun ideas usually satisfy nobody. Nonetheless, they remind us that ignorance is the natural state of mind for a research scientist. People who believe they are ignorant of nothing have neither looked for, nor stumbled upon, the boundary between what is known and unknown in the universe.

What we do know, and what we can assert without further hesitation, is that the universe had a beginning. The universe continues to evolve. And yes, every one of our body's atoms is traceable to the big bang and to the thermonuclear furnaces within high-mass stars that exploded more than five billion years ago.

We are stardust brought to life, then empowered by the universe to figure itself out—and we have only just begun.

† The European Center for Nuclear Research, better known by its acronym, CERN.

†† A light-year is the distance light travels in one Earth year—nearly six trillion miles or ten trillion kilometers.

2.

On Earth as in the Heavens

Until Sir Isaac Newton wrote down the universal law of gravitation, nobody had any reason to presume that the laws of physics at home were the same as everywhere else in the universe. Earth had earthly things going on and the heavens had heavenly things going on. According to Christian teachings of the day, God controlled the heavens, rendering them unknowable to our feeble mortal minds. When Newton breached this philosophical barrier by rendering all motion comprehensible and predictable, some theologians criticized him for leaving nothing for the Creator to do. Newton had figured out that the force of gravity pulling ripe apples from their orchards also guides tossed objects along their curved trajectories and directs the Moon in its orbit around Earth. Newton's law of gravity also guides planets, asteroids, and comets in their orbits around the Sun and keeps hundreds of billions of stars in orbit within our Milky Way galaxy.

This universality of physical laws drives scientific discovery like nothing else. And gravity was just the beginning. Imagine the excitement among nineteenth-century astronomers when laboratory prisms, which break light beams into a spectrum of colors, were first turned to the Sun. Spectra are not only beautiful, but contain oodles of information about the light-emitting object, including its temperature and composition. Chemical elements reveal themselves by their unique patterns of light or dark bands that cut across the spectrum. To people's delight and amazement, the chemical signatures on the Sun were identical to those in the laboratory. No longer the exclusive tool of chemists, the prism showed that as different as the Sun is from Earth in size, mass, temperature, location, and appearance, we both contain the same stuff: hydrogen, carbon, oxygen, nitrogen, calcium, iron, and so forth. But more important than our laundry list of shared ingredients was the recognition that the laws of physics prescribing the formation of these spectral signatures on the Sun were the same laws operating on Earth, ninety-three million miles away.

So fertile was this concept of universality that it was successfully applied in reverse. Further analysis of the Sun's spectrum revealed the signature of an element that had no known counterpart on Earth. Being of the Sun, the new substance was given a name derived from the Greek word *helios* ("the Sun"), and was only later discovered in the lab. Thus, helium became the first and only element in the chemist's Periodic Table to be discovered someplace other than Earth.

Okay, the laws of physics work in the solar system, but do they work across the galaxy? Across the universe? Across time itself? Step by step, the laws were tested. Nearby stars also revealed familiar chemicals. Distant binary stars, bound in mutual orbit, seem to know all about Newton's laws of gravity. For the same reason, so do binary galaxies.

And, like the geologist's stratified sediments, which serve as a timeline of earthly events, the farther away we look in space, the further back in time we see. Spectra from the most distant objects in the universe show the same chemical signatures that we see nearby in space and in time. True, heavy elements were less abundant back then—they are manufactured primarily in subsequent generations of exploding stars—but the laws describing the atomic and molecular processes that created these spectral signatures remain intact. In particular, a quantity known as the fine-structure constant, which controls the basic fingerprinting for every element, must have remained unchanged for billions of years.

Of course, not all things and phenomena in the cosmos have counterparts on Earth. You've probably never walked through a cloud of glowing million-degree plasma, and I'd bet you've never greeted a black hole on the street. What matters is the universality of the physical laws that describe them. When spectral analysis was first applied to the light emitted by interstellar nebulae, a signature was discovered that, once again, had no counterpart on Earth. At the time, the Periodic Table of Elements had no obvious place for a new element to fit. In response, astrophysicists invented the name "nebulium" as a place-holder, until they could figure out what was going on. Turned out that in space, gaseous nebulae are so rarefied that atoms go long stretches without colliding. Under these conditions, electrons can do things within atoms that had never before been seen in Earth labs. Nebulium was simply the signature of ordinary oxygen doing extraordinary things.

This universality of physical laws tells us that if we land on another planet with a thriving alien civilization, they will be running on the same laws that we have discovered and tested here on Earth—even if the aliens harbor different social and political beliefs. Furthermore, if you wanted to talk to the aliens, you can bet they don't speak English or French or even Mandarin. Nor would you know whether shaking their hands—if indeed their outstretched appendage is a hand—would be considered an act of war or of peace. Your best hope is to find a way to communicate using the language of science.

Such an attempt was made in the 1970s with *Pioneer 10* and *11* and *Voyager 1* and *2*. All four spacecraft were endowed with enough energy, after gravity assists from the giant planets, to escape the solar system entirely.

Pioneer wore a golden etched plaque that showed, in scientific pictograms, the layout of our solar system, our location in the Milky Way galaxy, and the structure of the hydrogen atom. *Voyager* went further and also included a gold record album containing diverse sounds from mother Earth, including the human heartbeat, whale "songs," and musical selections from around the world, including the works of Beethoven and Chuck Berry. While this humanized the message, it's not clear whether alien ears would have a clue what they were listening to—assuming they have ears in the first place. My favorite parody of this gesture was a skit on NBC's *Saturday Night Live*, shortly after the *Voyager* launch, in which they showed a written reply from the aliens who recovered the spacecraft. The note simply requested, "Send more Chuck Berry."

Science thrives not only on the universality of physical laws but also on the existence and persistence of physical constants. The constant of gravitation, known by most scientists as "big G," supplies Newton's equation of gravity with the measure of how strong the force will be. This quantity has been implicitly tested for variation over eons. If you do the math, you can determine that a star's luminosity is steeply dependent on big G. In other words, if big G had been even slightly different in the past, then the energy output of the Sun would have been far more variable than anything the biological, climatological, or geological records indicate.

Such is the uniformity of our universe.

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Among all constants, the speed of light is the most famous. No matter how fast you go, you will never overtake a beam of light. Why not? No experiment ever conducted has ever revealed an object of any form reaching the speed of light. Well-tested laws of physics predict and account for that fact. I know these statements sound closed-minded. Some of the most bone-headed, science-based proclamations in the past have underestimated the ingenuity of inventors and engineers: “We will never fly.” “Flying will never be commercially feasible.” “We will never split the atom.” “We will never break the sound barrier.” “We will never go to the Moon.” What they have in common is that no established law of physics stood in the their way.

The claim “We will never outrun a beam of light” is a qualitatively different prediction. It flows from basic, time-tested physical principles. Highway signs for interstellar travelers of the future will justifiably read:

The Speed of Light:
It’s Not Just a Good Idea
It’s the Law.

Unlike getting caught speeding on Earth roads, the good thing about the laws of physics is that they require no law enforcement agencies to maintain them, although I did once own a geeky T-shirt that proclaimed, “OBEY GRAVITY.”

All measurements suggest that the known fundamental constants, and the physical laws that reference them, are neither time-dependent nor location-dependent. They’re truly constant and universal.

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Many natural phenomena manifest multiple physical laws operating at once. This fact often complicates the analysis and, in most cases, requires high-performance computing to calculate what’s going on and to keep track of important parameters. When comet Shoemaker-Levy 9 plunged into Jupiter’s gas-rich atmosphere in July 1994, and then exploded, the most accurate computer model combined the laws of fluid mechanics, thermodynamics, kinematics, and gravitation. Climate and weather represent other leading examples of complicated (and difficult-to-predict) phenomena. But the basic laws governing them are still at work. Jupiter’s Great Red Spot, a raging anticyclone that has been going strong for at least 350 years, is driven by identical physical processes that generate storms on Earth and elsewhere in the solar system.

Another class of universal truths is the conservation laws, where the amount of some measured quantity remains unchanged *no matter what*.