

Cosmological Origins

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1. INTRODUCTION

They are some of the oldest questions that human beings have ever asked—renewed again and again by every child who looks up in wonder at the sun, the moon, the stars, and the planets: What *are* they? Why do they move and change the way they do? Where do they all come from? And where do *we* come from?

These questions are so fundamental that every culture and every religion provides answers, often in the form of origin stories that illuminate equally fundamental questions about the group’s identity, worldview, values, and purpose. Who are we? How should we live our lives? What is our role in the cosmos (Leeming and Leeming 1996, vii)?

Those origin stories are a fascinating study in themselves, from the Acoma Indians’ tale of humankind’s birth from the womb of the Earth, to the Hebrews’ story of God creating the cosmos *ex nihilo*, to the Zulu tale of a hero who created mountains, cattle, people, and everything else from the reeds (Leeming 2010). Science doesn’t tackle such cultural questions, but confines itself to puzzles that can be addressed by reason, experiment, and observation. Yet as we will see, that discipline has guided scientists to a cosmic story that is far stranger than our ancestors could have imagined—a centuries-long journey that has required (at least) four radical shifts in perspective.

The planets are other worlds, and the stars are other suns. A massive upheaval in Western thought began in 1543 when Nicolaus Copernicus published a sun-centered model of the universe (Kuhn 1957). Prior to that, most scholars had assumed that the universe revolved around Earth. Copernicus’ motivation was mathematical beauty: he realized that the complex, looping movements of the celestial lights known as “planets” (from the Greek word for “wanderer”) would make far more sense if they were actually just circular motions seen from the moving platform of an Earth that also orbited the sun.

Yet this mathematical exercise upended everything that scholars of the day thought they knew about physics (Kuhn 1957), which may be why Copernicus published his theory only when near death, and only after much persuasion. Although the heliocentric model was initially accepted by the Catholic Church—it was only mathematics, after all—the Church’s views shifted later in the century, and Copernicus’ book was banned in 1616 (Heilbron 2010). Yet the evidence for the heliocentric model continued to accumulate. Famously, Galileo Galilei built one of the first telescopes and pointed it at the heavens. What he saw—including mountains on our moon, and four previously unknown moons orbiting Jupiter—proved that these points of light were far more like our world than ever imagined (Galilei 1957).

The heavens and the Earth are one, and operate according to natural law. For most of human history it was assumed that the celestial realm is profoundly different from the base matter here on the ground. It wasn’t until after the findings of Copernicus, Galileo, and Johannes Kepler, who identified the laws of planetary motion, that philosophers began to think in terms of natural law: fixed rules that apply everywhere, to everything, at all times. In the 1600s, this notion was made mathematically rigorous by Isaac Newton; his laws of motion and gravity governed both the orbit of the moon and the fall of an apple.

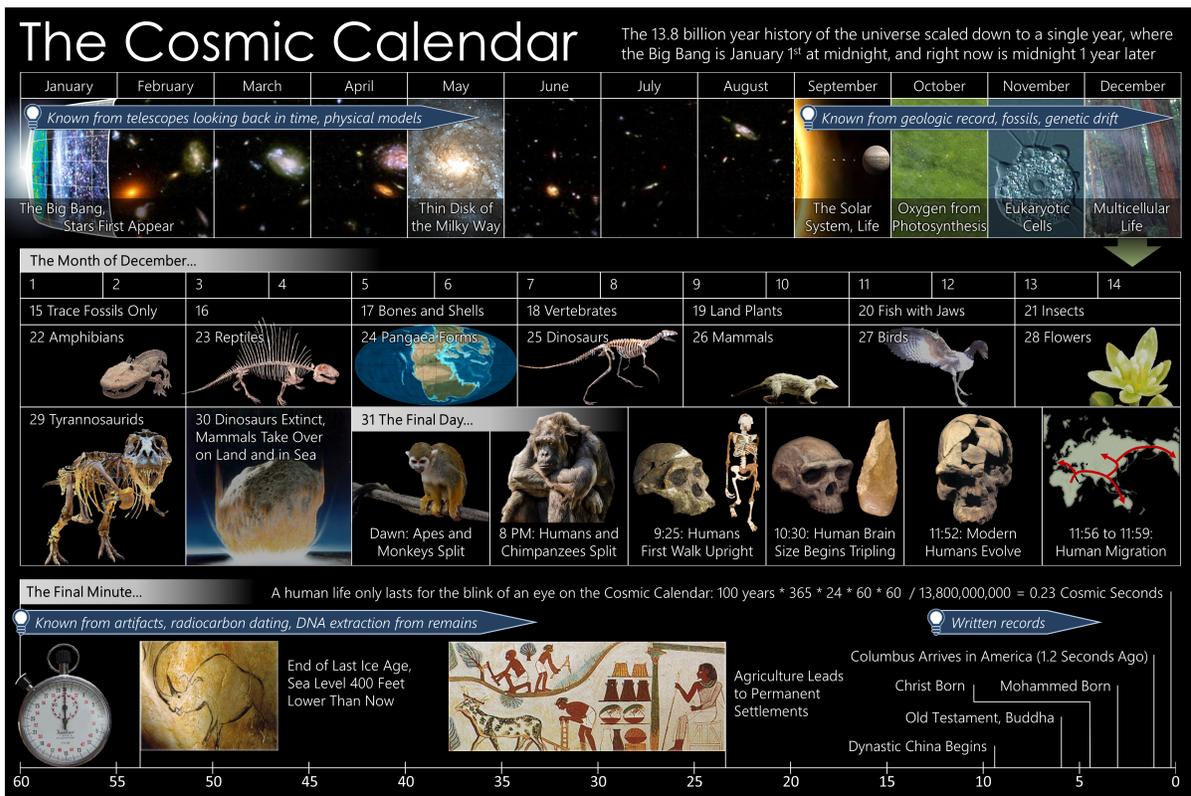
The universe is very large and very old. The immense size of the universe was already implied by Copernicus’ heliocentric theory in the 1500s: If you were willing to believe that a tiny, reddish dot like Mars was in fact a world like our own, then you also had to believe that it was ridiculously far away. (The modern figure is 55 million to 400 million kilometers, depending on where Earth and Mars are in their orbits.) And the fixed stars had to be much further still. Otherwise, the closer stars would visibly

shift position relative to the more distant stars as the Earth moved around the sun. But it was only in the late 1700s that the equally immense scale of time became apparent, as pioneering geologists began to understand that the ancient rocks they saw in cliffs, quarries, and road cuts had been formed by erosion, sedimentation, volcanic activity, and the like, over the course of millions of years. Scientists henceforth had to deal with the dizzying reality of what one 19th century thinker called “the abyss of time” (Playfair 1805). The modern figure for the age of the Earth is 4.6 billion years and 13.8 billion years for the entire universe (Figure 1).

The universe started small and grew. According to tradition, the world around us was formed pretty much as we see it now, with plants, animals, mountains, and oceans, all brought forth in a single act of creation (Leonard and McClure 2004). But according to the story that’s been uncovered by science over the past 150 years or so, cosmic history is a long process of becoming: everything we see took shape according to natural law from much simpler beginnings.

The quest to understand how that happened—and what those cosmic beginnings might be—has defined much of 20th- and 21st-century astronomy and physics, and is the subject of this review. The final answer is familiar enough: our universe began with the “Big Bang,” an event some 13.8 billion years ago in which space, time, matter, energy, light, and everything else came into being as an infinitesimal point of near-infinite temperature and density.¹ And the universe has been expanding ever since, allowing the superhot energy of that initial point to cool and condense into electrons, protons, atoms, galaxies, stars, planets—and eventually, us.

Figure 1: The 13.8 billion-year lifetime of the universe mapped onto a single year. The scale was popularized by Carl Sagan. (Image credit: Efbrazil, shared under the creative common license CC BY-SA 3.0.)



¹ It’s worth noting that the phrase “Big Bang” is used in different ways. Some apply it only to the initial singularity that’s conjectured to occur at the very first instant of the universe, when the cosmos is compacted to a point of infinite temperature and density. But many others use the phrase as a shorthand for some or all of the expansion and condensation process leading up to the formation of the cosmic microwave background (see Chapter 3). In this review, we will generally follow the second convention, but will always try to make the meaning clear in context.

As we'll see, however, getting to this answer was anything but easy. Again and again, what are now considered to be foundational discoveries were met with indifference, incomprehension, or even hostility—and achieved widespread acceptance only after accumulating evidence made the new ideas impossible to ignore.

In Chapter 2, **The Expanding Universe**, we review how this dynamic played out in the discovery of the first key piece of evidence for the Big Bang: the realization that just about all the galaxies in the universe are flying apart from one another, like sparks from some titanic explosion. Our story begins with Albert Einstein and his two theories of relativity. The 1905 version, now known as the special theory of relativity, showed that the three dimensions of space and the time dimension are connected and malleable. The 1915 version, known as the general theory of relativity, showed that this spacetime can bend, ripple, and curve—and that its curvature is the origin of the force we call gravity.

Meanwhile, in the 1910s, observers training ever more powerful telescopes on the sky discovered that the stars that are bright enough to see with the naked eye comprised only a tiny fraction of our Milky Way galaxy, which in turn proved to be an immense flattened disk many tens of thousands of light years across. Then in the 1920s, astronomers found that even this huge structure is just a dust mote on the cosmic scale—that the sky is full of star-filled galaxies just like ours, located at distances measured in millions of light years. And finally, in the 1930s, astronomers realized that this already vast cosmos is getting bigger. The universe—in keeping with Einstein's equations—is expanding.

In Chapter 3, **The Discovery of the Big Bang**, we trace how astronomers and physicists confirmed that the universe began in a cosmic fireball. This conclusion did not come quickly or easily; few astronomers in the 1930s were comfortable with the idea of a cosmic beginning. Attitudes began to change only in the 1940s, when a handful of scientists used the new field of nuclear physics to calculate how thermonuclear reactions would have unfolded during the first few minutes of the universe. They found that the suite of chemical elements produced in those reactions would form a kind of fossil record of the event. The abundances they calculated for hydrogen and helium matched the observed values very closely.

This key piece of evidence was not yet enough to rule out an alternative model to the Big Bang, the popular “steady-state” model of cosmology. But then, in 1964, radio astronomers discovered a bath of microwave radiation filling the sky—the Big Bang's afterglow, comprising particles of light, or photons, that were emitted some 380,000 years after the universe's birth. This cosmic microwave background radiation not only made the Big Bang idea almost inescapable, but it has proved to be the richest source of information for astronomers studying the very early universe.

Chapter 4, **Before the Beginning**, recounts how most cosmologists came to believe that the early universe underwent an incomprehensibly brief interval of incomprehensibly rapid expansion that stretched cosmic spacetime as taut as a hyper-inflated balloon. Only after that period of “inflation” would a multi-billion-light-year patch of spacetime slow down and begin the comparatively tame expansion seen today.

Cosmic inflation explains some otherwise hard-to-understand features of our present-day universe, such as the fact that it's big, old, and looks pretty much the same in every direction. But things became exceedingly weird and controversial when physicists realized that an inflating cosmos might not produce just one bubble of normal, non-inflating spacetime—our universe. In theory, it could just as easily produce a multitude of others. Each would be a universe in its own right, perhaps with its own laws of physics; collectively, they would comprise a kind of cosmic foam known as the “multiverse,” without a beginning at all.

Thus the controversy: despite the popularity of inflation, its proponents have yet to explain when and how inflation itself got started. We conclude Chapter 4 with a sketch of some prominent alternative frameworks to the inflationary multiverse including models in which the speed of light in the early universe was faster, and “rainbow cosmologies” in which different colors of light follow different trajectories in the presence of extreme gravity; such models suggest there was no initial Big-Bang moment, but rather our (lone) universe extends infinitely to the past. We shall also discuss frameworks in which the past universe contracted down to a small size and then rebounded outwards following a Big Bounce, and those suggesting a mirror universe was birthed alongside our own, with a reversed arrow of time.

In Chapter 5, **The Dark Universe**, we look at how astronomers discovered an astonishing fact, which is that most of our universe is utterly invisible. One component of this invisible sector is a haze of “dark matter” that is about five times as massive as all the visible stars and galaxies put together. No one yet knows what dark matter is—but it has an overwhelming gravitational influence on the visible stars. A second, even more mysterious component of the invisible sector is “dark energy.” Discovered only in the 1990s, dark energy seems to be some kind of universal cosmic repulsion that is causing the expansion of our universe to slowly speed up.

The discovery of the dark universe has helped scientists to home in on a standard model of cosmology—our best description for our cosmic origins. Or maybe not. Chapter 6 describes **The Crisis Over the Age of the Universe**, which has unfolded over the past decade. As our observations have become increasingly accurate, measurements of the cosmic expansion rates obtained from examining the cosmic microwave background radiation have consistently shown a small, but worrisome, difference from the rates obtained by measurements on the most distant stars and galaxies. This has led to a billion-year discrepancy in our estimates of the time since the Big Bang. The question is whether this is the result of some calibration error, or is revealing something new and profound about our understanding of the universe.

The final chapter, **Concordance and Beyond**, summarizes what we know and the three, or possibly four, fundamental mysteries in cosmology: inflation, dark matter, dark energy, and (maybe) the expansion-rate discrepancy. Over the coming decade or so, high-precision measurements made by a new generation of space- and ground-based telescopes could help cosmologists understand what these mysterious phenomena are, how (or whether) they relate to one another, and what they can tell us about cosmic origins.

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2. THE EXPANDING UNIVERSE

The discovery of cosmic expansion unfolded along two parallel tracks, as theorists and observers found themselves coming to the same conclusion only after working in near-total ignorance of one another. The theoretical track involved Albert Einstein’s discovery of relativity, from which followed a set of equations that suggested that the universe is not a static entity. Later, observations by Edwin Hubble and others showed that the cosmos is growing.

I. SPACE AND TIME: EINSTEIN’S THEORIES OF RELATIVITY

In 1905, Einstein, then just 25 years old and working at the Swiss Patent Office in Bern, found himself puzzling over the behavior of light. He was deeply influenced by the work of James Clerk Maxwell (Mahon 2004), who in the 1860s had mathematically demonstrated that electricity, magnetism, and light are three different aspects of the same thing. Maxwell’s theory of “electromagnetism” could be

summarized in just a handful of equations (Maxwell 1861). These equations showed that oscillating electric and magnetic fields could reinforce each other and go rippling across the universe in the form of a wave—which was predicted to move at roughly 300,000 kilometers per second, which was also the measured speed of a light beam (Maxwell 1865, pt. VI).

It was already known that light was a wave of some kind; Thomas Young had demonstrated that fact in 1803 (Young 1804). Maxwell’s finding suggested that light is this predicted electromagnetic ripple. Two decades later, Heinrich Hertz proved this by generating electromagnetic waves with a radio transmitter (Hertz 1887b; 1887a; 1888b; 1888a). The full electromagnetic spectrum includes radio, microwaves, infrared, visible, ultraviolet, X-rays, and gamma rays (Figure 2).

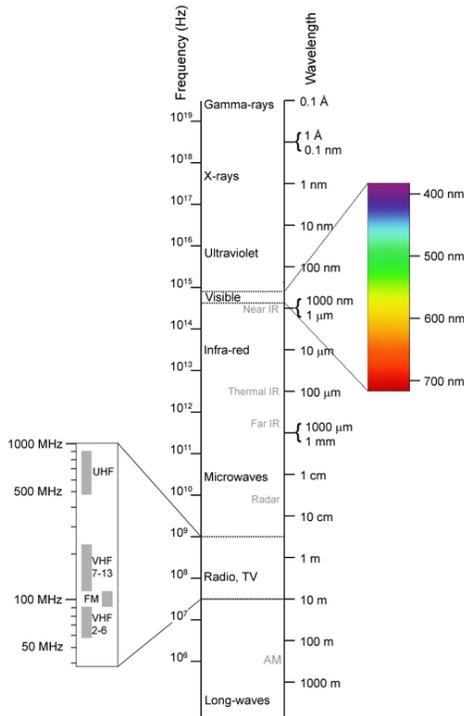


Figure 2: Electromagnetic spectrum. (Image credit: Penbag, shared under the creative commons license CC BY-SA 3.0.)

What Einstein found puzzling was Maxwell’s prediction about the wave’s speed. The velocity of light didn’t seem to work like speeds do in everyday life. If you run after a bus, for example, the bus will seem to be moving slower relative to you, simply because you are catching up with it. And if you run alongside at the same speed, the bus will seem stationary and you can hop on board. But even as a schoolboy in the 1890s, Einstein later wrote, he realized that things would get weird if he tried that same trick with a light beam. If he ran alongside at exactly the speed of light, then presumably he could look over and see the beam just hanging in mid-air—a set of oscillating electric and magnetic fields going nowhere. Yet a stationary light wave was something that Maxwell’s equations did not allow for at all.

Einstein published his resolution to this conundrum, now known as the special theory of relativity, in 1905 (A. Einstein 1905). Central to the theory was a profoundly radical assertion: the speed of a light beam in a vacuum is the same for every observer, no matter how its source is moving. That meant that no matter how fast he ran after a light beam, he couldn’t catch up: he would still see it passing him at 300,000 kilometers per second. And forget about running at the speed of light itself. Einstein also proved that accelerating a person or any other massive object to light speed would require an infinite amount of energy. (This turns out to be a consequence of $E = mc^2$ —easily the most famous equation ever written (Albert Einstein 1905). It states that mass, m , and energy, E , are two aspects of the same thing; with the constant c being shorthand for the speed of light.)

What Einstein *would* notice as he chased the light beam was a change in its wavelength: if he were running away from the source—or if the source were moving away from him—the wave would appear to be stretched out and shifted toward the red end of the spectrum. This means that the wave would look redder to him—or be more ‘redshifted’—the faster it was moving away. Conversely, if he were running toward the source, the waves would appear to compress and become blueshifted. As discussed in section II.3, this redshift effect would prove pivotal in establishing that our universe is expanding.

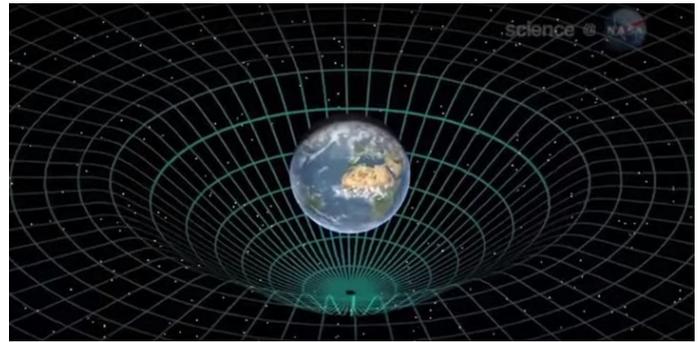
To make this constant speed-of-light assumption work mathematically, Einstein derived the famously weird consequences of relativity, including length contraction and time dilation. If I see your rocket ship moving past me at some velocity, for example, then I will see you, your ship, and everything in it

appear to contract in the direction of motion. (You would see me contract by the same amount.) Likewise, we would each see a slowdown of every clock in the other's ship: time would appear to be flowing at different rates, including our respective heartbeats and brain rhythms. And if you perceived two events as happening simultaneously, I might very well see them as happening at different times—and vice versa. (The implications of relativity on the nature of the past, present, and future are discussed further in [JTF's Time review](#).)

These strange effects boil down to one deceptively simple fact: space and time are two aspects of an underlying unity—spacetime—that are perceived differently by observers in relative motion. Spacetime became the centerpiece of his quest to find a more general version of his relativity theory that would encompass gravity, published in 1915 (Albert Einstein 1915b).

With general relativity, Einstein discovered that spacetime isn't just a rigid framework that exists only as a kind of stage for matter to do its thing. Spacetime is dynamic. It can curve and ripple, expand and contract. It can even guide how particles move. In fact, said Einstein, that's what gravity *is*—not a force as we usually understand it, but a warping of spacetime that's produced by a star or a planet's very presence. The standard analogy is that the sun bends spacetime like a bowling ball resting on a rubber sheet, while the planets that orbit the sun are just following the contours of the warped sheet (Figure 3).

Figure 3: Massive objects like planets curve spacetime, as shown in this artist's illustration of Einstein's conception. (Image credit: Science@NASA.)



Testing this theory was tricky. The differences between general relativity and Newton's law of gravity would be negligible for masses that are small on some cosmic scale, and for objects moving much, much slower than the speed of light. Still, Einstein came up with three observations in which the tiny differences might be detectable. One, an infinitesimal slowdown in the vibration of atoms located deep in a gravitational field, was too subtle for instruments of the day. But another, a tiny, but steady shift in the orbit of the fastest-moving planet, Mercury, had been known (and defied explanation) since the 19th century; general relativity fit the anomalous data almost exactly (Albert Einstein 1915a). And the third, a slight deflection of starlight passing close to the sun, was confirmed in spectacular fashion when astronomers observed the total solar eclipse of May 29, 1919 (Dyson, Eddington, and Davidson 1920; Catchpole and Dolan 2020).

Einstein also predicted that spacetime could sustain ripples—or gravitational waves—but these seemed beyond experimental reach (Albert Einstein 1916). However, a century later, the Laser Interferometer Gravitational-Wave Observatory, LIGO, famously reported detecting ripples generated when two black holes merged, some 1.3 billion light years from Earth (Abbott et al. 2016).

But that is jumping ahead. Back in 1917, Einstein was laying the foundations for modern cosmology with a paper that would have immense implications for our understanding of spacetime's origins—and that made Einstein himself quite uncomfortable (Einstein 1917). Einstein started by asking what relativity could tell us about the universe as a whole. To find out, he applied his equations to what seemed like a common-sense approximation of the universe: an immense sphere filled with a uniform distribution of stars. He assumed it was stable and unchanging in size. But the universe that Einstein found in his equations was anything but stable. No matter how his cosmic sphere started out—expanding, stationary, contracting—general relativity decreed that it would end up collapsing to a

point. The gravitational attraction between all those stars would eventually win out and pull everything inwards.

To Einstein, this was unacceptable. He felt so strongly, in fact, that he ended up modifying general relativity itself, by adding a tiny constant to the equations. Such a “cosmological constant,” as it came to be known, would be too small to detect on the scale of the solar system, which explained why nobody had noticed it earlier. But over cosmological distances it would produce a tiny, but steady repulsion—just enough to counteract the mutual gravitation of the stars and prevent a cosmic collapse.

But there was mounting theoretical evidence that this stable picture was wrong. In the early 1920s, for example, Alexander Friedmann showed that a spherical universe was just one possibility among many others allowed by general relativity (Friedman 1922; Friedmann 1924; 1999). Friedmann’s solutions encompassed both expanding and contracting universes, and allowed for curvatures that were positive (Einstein’s sphere), zero (infinite flat space), or negative (an infinite space shaped something like a saddle). At the time, Einstein just assumed that Friedmann had made a mathematical error. Even after Einstein was convinced that the equations were correct, he dismissed the non-static results as “unphysical.”

Einstein wouldn’t change his mind about cosmic stability until 1931—after he realized that all the observational evidence astronomers were accumulating was against him: the universe was indeed expanding.

II. VELOCITY AND DISTANCE: SLIPHER, HUBBLE, LEMAÎTRE, AND COSMIC EXPANSION

Among the most vexing mysteries that astronomers faced at the beginning of the 20th century was the puzzle of spiral nebulae: faint, fuzzy pinwheels of light found by the thousands all over the sky. The

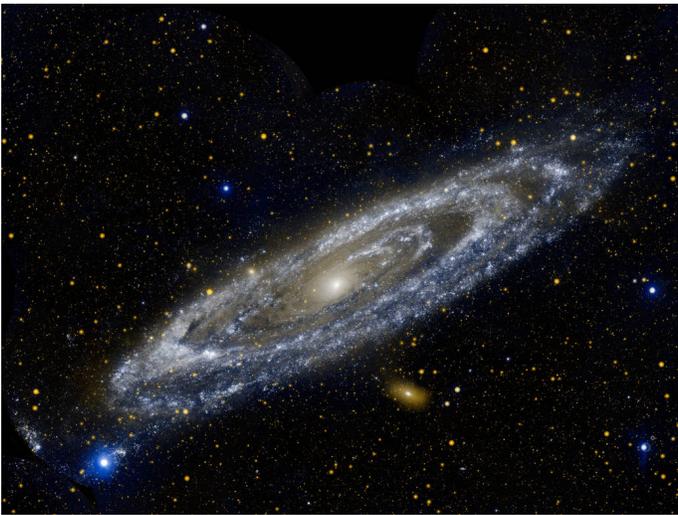


Figure 4: The Andromeda Galaxy, M31, is about 2.5 million light years away. (Image credit: NASA/JPL-Caltech.)

most famous (and one of the few visible to the naked eye) was a gossamer patch of light in the constellation of Andromeda (Figure 4). The debate over what these objects were raged well into the 1920s. Most astronomers believed the spirals were comparatively nearby objects—abnormal stars that had somehow become shrouded within whirlpools of gas, perhaps, or brand-new solar systems caught in the act of forming. A minority argued that spiral nebulae were other “island universes”—what today we would refer to as “galaxies.” Bolstering this notion were observations dating back to 1785, when William Herschel counted the number of stars he could see in each direction with his telescope and concluded that they formed a vast flattened disk aligned with the pale river of light known as the Milky Way (Herschel 1785).

Indeed, the Milky Way was just the disk seen edge-on from the perspective of the solar system.

The most compelling argument against the idea of other island universes (or other galaxies in today’s parlance) was that such large entities would have to be millions of light years away to explain why they looked so small from Earth. Most astronomers found this utterly implausible.

To resolve this dispute, astronomers sorely needed data. Fortunately, they were making rapid progress on two tools that could give it to them. The first, “spectroscopy,” enabled them to measure what distant cosmic objects are made of and how fast they are moving, by looking at the light they emit. The second used a special kind of star with very well understood properties as a “standard candle” to measure the distance to other galaxies. These techniques are described in some detail below. It is worth understanding how they work because, as we shall see, they underpin many of the modern observations to be discussed in Chapter 5 and lie at the heart of the current controversy over estimates of the age of the universe, as described in Chapter 6.

1. Spectroscopy

Spectroscopy is based on the 19th-century discovery that atoms and molecules will emit or absorb light only at certain characteristic wavelengths. These wavelengths are generally called “lines” because that’s what they looked like in 1814, when Joseph von Fraunhofer peered at the sun with a new instrument he called a spectroscope and saw a thin sliver of sunlight spread sideways into a rainbow. It was a rainbow interrupted by hundreds of vertical black lines, each representing a wavelength where the light was missing (Figure 5). Fraunhofer detected similar lines in the light from prominent stars, as well as bright lines in candle flames and the like.

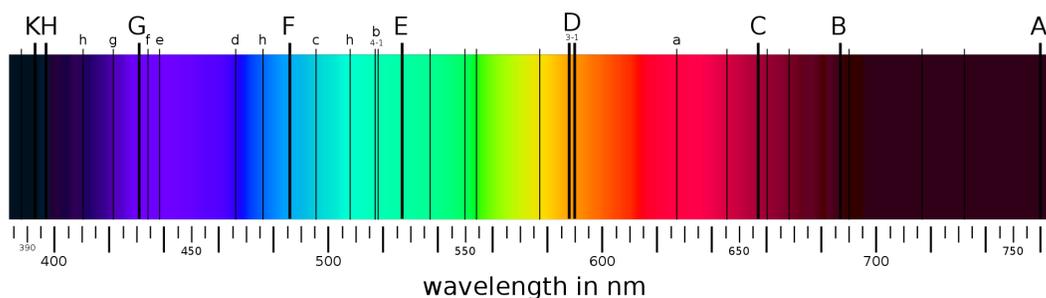


Figure 5: Fraunhofer lines from the sun.

Fraunhofer’s work was cut short by toxic fumes from his glassmaking; he died in 1826, at age 39. More than three decades later, however, Gustav Kirchhoff and Robert Bunsen discovered that the bright and dark lines produced by any given substance were like photographic negatives of one another. If you heated a sample of that atom or molecule in a flame—using a “burner” of Bunsen’s own design—it would emit a pattern of bright lines. If you placed a gaseous form of the sample in front of a brighter source, it would absorb light at those same wavelengths and form an identical pattern of dark lines. Indeed, this pattern could identify the substance as reliably as a fingerprint.

For astronomers, this meant that they could compare the lines that they saw in a star or nebula with emission patterns seen in the laboratory and determine the object’s chemical composition. Finer details, such as the width and intensity of the lines, determined the object’s temperature and how fast it was rotating. And by measuring how far the lines were shifted toward the blue or red end of the spectrum, they could get an accurate measure of how fast the object was moving toward or away from us. In 1912, using a state-of-the-art instrument at the Lowell Observatory in Arizona, Vesto Slipher observed the Andromeda nebula—and was astonished to find its lines strongly blueshifted, meaning that this spiral was moving toward us at roughly 300 kilometers per second (Slipher 1913; O’Raifeartaigh 2013; Nussbaumer 2013). For comparison, this was roughly 600 times the speed of a rifle bullet, and so much faster than the motion of any known star that Slipher had to wonder if he’d made a mistake.

He hadn't; other astronomers soon confirmed Slipher's result (although the modern figure for Andromeda's approach speed is 110 kilometers per second). But as Slipher collected spectra from dozens of additional spiral nebulae, he did find that Andromeda's blueshift was the exception rather than the rule. Most were redshifted—meaning they were moving away from us, at immense speeds (Slipher 1917). The data brought Slipher into the island-universe camp. He reasoned the spirals must be far, far away, because any nearby object that was moving that fast would have escaped the Milky Way long ago.

To nail down the island-universe hypothesis beyond a doubt, however, somebody would have to measure the spirals' actual distances. And distance measurement, happily, was the other astronomical tool that was progressing rapidly.

2. Standard Candles and Distance Measurements

Until just a few years earlier, the only known way to find celestial distances was with parallax, which is a geometric effect that's easy to see: just hold up a finger in front of your face, and then alternately close your right and left eyes. Notice how your finger seems to jump back and forth relative to objects on the far side of the room, by an amount that increases as you move your finger in, and decreases as you move it out. Much the same thing would happen if you made simultaneous observations of the moon from the opposite sides of the Earth: the two views would show the moon shifted relative to the distant stars. From there, it would just be a matter of elementary geometry to calculate the moon's distance, which is about 234,000 kilometers.

By the 18th century, observers had used variations on this idea to fill in most of the distances within the solar system. And they kept trying to do the same thing with stars, although the stars are so distant, the effect was miniscule. The first compelling evidence for stellar parallaxes had to wait for the advent of bigger and better instruments in the 19th century (Webb 1999, 71–72). Even into the 20th century, however, the inevitable uncertainties in the measurements made parallax essentially useless for determining distances beyond a few hundred light years—not nearly far enough to settle the spiral nebula question.

What finally shattered that limit was the Harvard College Observatory's 1908 publication of a meticulous survey of 1,777 variable stars in the Large and Small Magellanic Clouds—irregular swarms of stars shining in the southern sky like detached pieces of the Milky Way (Leavitt 1908). Variable stars are those that repeatedly brighten and dim on a more or less set schedule, and had been known for centuries. But the survey's author, Henrietta Swan Leavitt, realized that the brighter stars in her catalog tended to vary over longer periods. Since all the stars in a given Cloud were essentially the same, albeit unknown, distance from Earth, a difference in their brightness seen on Earth must correspond to a difference in their intrinsic brightness—a quantity known as a star's luminosity.

Leavitt followed up in 1912 with a detailed study of 25 variables in the Small Magellanic Cloud (Leavitt and Pickering 1912). These variables were a type known as Cepheids, which wax and wane over the course of days or weeks. Leavitt found a clear relation between each variable's period and its average brightness: measure one, and you would know the other. That meant, in Leavitt's phrase, that the Cepheids could serve as “standard candles” for cosmic distances: Anywhere you found one, you just had to time its dimming and brightening to measure its period, then use Leavitt's relation to find its true luminosity. From there, finding the Cepheid's distance would be a simple matter of comparing how bright it looks to how luminous it truly is. (Any star's apparent brightness will follow an inverse square law: when it's twice as far away it will look one fourth as bright, and so on.)

Or rather, the calculation would have been simple if anyone could determine the true luminosity of Leavitt's variables, which she herself couldn't do because the actual distance to the Small Magellanic Cloud was unknown. But others soon filled that gap by measuring the distance to nearby Cepheids using parallax (Hertzsprung 1913; Shapley 1918a). Once that had been done, Leavitt's relation could be used to determine the distance to Cepheids located further away. As soon as 1918, in fact, Harlow Shapley had used Leavitt's relation to make an astonishing discovery about the Milky Way star system (Shapley 1918a; 1918b).

It was *big*.

Using what was then the world's largest telescope, a 100-inch (2.5 meter) reflector at the Mount Wilson Observatory above Pasadena, California, Shapley found that the Milky Way, the clusters, and the Magellanic Clouds together encompass a volume some 100,000 times larger than anyone had imagined. Shapley's best guess located our solar system roughly 60,000 light years out from the center. (The modern figure is about 26,500 light years.)

In his papers, Shapley referred to this Brobdingnagian structure as "the galaxy," an old word for the Milky Way as seen with the naked eye. (It comes from *galaxias*, the Greek term for "milky.") He assumed that this galaxy comprised the entire universe. But it was soon to be joined by others. In 1925, Edwin Hubble described his observations of the Andromeda nebula and several other spirals using the Mount Wilson 100-inch (E. P. Hubble 1925). They turned out to be made not of gas, but of stars. Andromeda, said Hubble, lay some 930,000 light years from Earth—far beyond the Milky Way structure found by Shapley. (Hubble's distance was an underestimate. The modern figure is 2.5 million light years.) It was a galaxy in its own right.

In the 1920s, Hubble continued to gather galaxy distance data with Milton Humason (Webb 1999, 239–45). And somewhere along the way, he took 18 galaxies for which he had decent data and plotted his distances versus the mysterious redshifts measured a decade earlier by Slipher.

The plot showed a clear trend: the further away a galaxy was, the faster it was receding from us (E. Hubble 1929) (Figure 6).

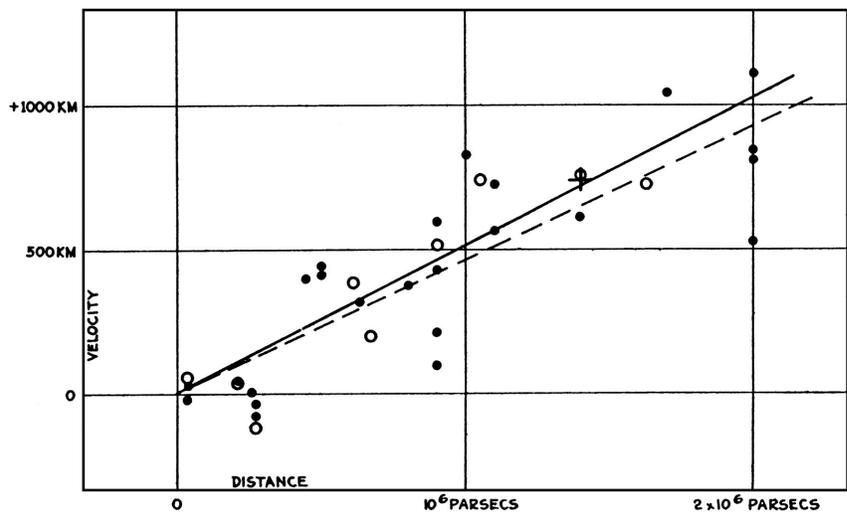


Figure 6: Hubble's original plot of the velocity-distance relation among extra-galactic nebulae. (Image credit: *PNAS* March 15, 1929 15 (3) 168-173, © (1929) National Academy of Sciences.)

3. Hubble's Law and the Age of the Universe

Hubble's result is now hailed as one of the most transformational discoveries in cosmology. Yet, at the time, almost no one, including Hubble, knew quite what to make of it. One physicist who did know what Hubble's data implied was Georges Lemaître, who had a grounding in both observational astronomy and general relativity theory. (He also happened to be a Catholic priest.) In 1927, Lemaître had independently reached much the same conclusion that Friedmann had in 1924—that the universe is almost certainly not static. Unless the universe is very precisely balanced, à la Einstein, it will either

be expanding or contracting—with or without a cosmological constant. Unlike Friedmann, however, Lemaître had pointed out a striking observational consequence of that fact: if the universe is expanding, then the cosmic sphere will get bigger and bigger over time and take the galaxies along for the ride. So from the vantage point of any one galaxy, every other galaxy will appear to be receding with a velocity proportional to its distance (G Lemaître 1927; (English) Georges Lemaître 1927).

Unfortunately, Lemaître had written his paper in French, and published it in a small Belgian journal that few astronomers saw. When Lemaître told Einstein about his work at a conference later in 1927, Einstein praised the younger man’s mathematics—but went on to say, “from the physical point of view, that [result] appeared completely abominable” (Luminet 2011).

Lemaître’s paper didn’t come to wider attention until January 1930, after he read about the confusion that Hubble’s findings had caused at a meeting of the Royal Astronomical Society and sent a copy to the renowned astronomer Arthur Eddington, with whom he had studied. Eddington immediately became the young priest’s ardent champion. In 1930, he published a commentary in which he raved about Lemaître’s results and pointed out that Einstein’s static-universe model of 1917 was about as stable as a pencil balanced on its point. The slightest perturbation would send it toppling one way or another, into expansion or contraction (A. S. Eddington 1930).

Meanwhile, Hubble and Humason had extended their observations out to galaxies lying many times farther away than the 18 in their original sample and found that the straight-line relation between distance and redshift continued unabated (E. Hubble and Humason 1931). Writing v for the speed at which a galaxy is moving away and D for its distance from Earth, and using the modern notation H_0 for the constant of proportionality (today known as the Hubble parameter), this became “Hubble’s Law,” $v = H_0 D$ —the relationship between velocity and distance that Lemaître had said would govern the motion of galaxies in an expanding universe.

This relation continues to be of fundamental importance to cosmology—not least because measuring H_0 automatically yields an estimate for the age of the universe; the bigger it is, the smaller the universe’s age, and vice versa. This was a bit awkward for Hubble and Humason in 1931, however: their value for H_0 was 558 kilometers/second per million parsecs, which required the universe to be only one or two billion years old. That was tough to reconcile with the apparent age of the Earth and sun. Only later would a recalibration of the Cepheid distance scale move estimates for H_0 down into the modern range of roughly 70 kilometers/second per million parsecs, corresponding to a cosmic age estimate of 13.8 billion years. That said, however, we shall see in Chapter 6 that getting the value of H_0 much more precise than that continues to be a matter of intense controversy, calling into question our estimates of the age of the universe, and perhaps suggesting we need to rethink our models of the early universe.

In the meantime, Einstein’s belief in a static universe was crumbling. In 1931, Einstein wrote in a report to the Berlin Academy of Sciences that he had been wrong, that the work of Hubble had changed everything, and that “the assumption of a static nature of space is no longer justified” (Harry Nussbaumer 2014).

The universe was indeed expanding.

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3. THE DISCOVERY OF THE BIG BANG

Even after the expansion of the universe was discovered in the 1930s, the notion that it implies a cosmic beginning was far from clear. For most astronomers of the day, the question of where the universe came from was a non-issue—a fine topic for philosophers, theologians, and late-night dorm debates, maybe, but much too nebulous a subject for serious researchers (H. Kragh 2008).

Perhaps astronomers shared Einstein’s deep-seated belief in a static universe. Or perhaps they just didn’t want to face the inevitable follow-up question: if there was a “beginning,” then where did that beginning itself come from? This seemed to be a mystery that was unanswerable by any known physical law (but one that we will return to in Chapter 4, when we discuss how scientists are now addressing this puzzle). In 1931, for example, Arthur Eddington gave a talk admitting that while it was logically possible for time to have a beginning, philosophically “the notion of a beginning of the present order of Nature is repugnant to me” (Arthur S. Eddington 1931).

Indeed, this reluctance to contemplate cosmic origins was so entrenched that what we now call the Big Bang had to be rediscovered three times, in different ways, before the idea finally took hold.

I. THE PRIMORDIAL ATOM

The first discovery was triggered when the British journal *Nature* published Eddington’s 1931 address. Georges Lemaître saw the “repugnant” comment and quickly wrote a rebuttal (G. Lemaître 1931). Although Lemaître was a Catholic priest as well as a physicist, his objections had nothing to do with the Biblical creation account. Rather, it had everything to do with the newly revealed physics of the quantum realm, where small particles behave in ways alien to our everyday experience. Lemaître wrote, “I would rather be inclined to think that the present state of quantum theory suggests a beginning of the world very different from the present order of Nature.”

After all, Lemaître explained, as time passes, the total energy of the universe must inevitably get subdivided among more and more “quanta”—what we’d now call elementary particles. So if we imagine the clock running backwards toward the beginning, said Lemaître, “we must find fewer and fewer quanta, until we find all the energy of the universe packed in a few or even in a unique quantum”—a single small entity whose decay would give rise to the universe as we see it today.

And what came before the first quantum? The question is meaningless, Lemaître suggested, because it’s likely that space, time, and matter came into being together, emerging as collective phenomena from the behavior of groups of quanta. In this, Lemaître anticipated the thinking of 21st-century quantum-gravity theorists, who are today investigating how spacetime may emerge from something more fundamental (see [JTF’s Emergence review](#)).

Lemaître was wrong about the specifics of this process. His guess was that the first quantum was some kind of primordial atom: a titanic atomic nucleus that contained the entire mass of the universe. It wasn’t, as we’ll discuss below. But that mistake doesn’t change the fact that Lemaître had given the first recognizable description of a Big-Bang origin for the cosmos.

Lemaître elaborated on this idea just a few months later with the publication of another *Nature* essay, which included another prescient suggestion: The initial expansion of the universe, he said, must have been very fast, and the matter it contained must have been very hot. These initial fireworks at the beginning of the universe would produce a kind of afterglow: radiation that would still be streaming down from the sky (A. G. Lemaître 1931, 705). Here too, Lemaître was wrong on the specifics; he believed that this afterglow is the source of the celestial particles known as cosmic rays, which are now

thought to originate much later in cosmic evolution. But, as we will see in section III, there *is* a Big-Bang afterglow—although it wouldn't be detected for another three decades.

In the meantime, however, Lemaître's concept of cosmic origins drew little attention. It was only in the late 1940s that another group of researchers would reason that the universe must have originated in a tiny fireball, in order to explain how the chemical elements came to be.

II. THE FIREBALL'S FOSSILS

This second discovery of the Big Bang began with a seemingly unrelated question: what makes the stars shine?

It had been obvious since the 19th century that neither the sun nor any other star could be burning like candle flames. There is no oxygen in space to support combustion and, even if there were, the stars would have exhausted any available fuel and burned out long ago. In 1920, though, Eddington suggested a new possibility based on two empirical facts. First, physicists had recently established that every atom in the universe consists of a tiny, dense, positively-charged nucleus surrounded by a fluffy cloud of negatively-charged electrons. And second, the lightest element, hydrogen, had a nucleus that was one quarter of the mass of the second lightest element, helium.

This led Eddington to wonder—what if the hot, dense conditions inside the sun somehow allowed those four hydrogens to fuse into a single helium nucleus? He knew that the latest high-precision laboratory measurements showed that the mass of four hydrogen nuclei taken together was actually a bit larger than the mass of one helium. And since that was the case, he realized, Einstein's celebrated equation $E = mc^2$ (see Chapter 2.I) implied that the excess mass would be transformed into a huge burst of energy—enough to be the power source of stars (A. S. Eddington 1920, 354).

Eddington was right: today this process is called thermonuclear fusion, and it does indeed power the stars. But proving it would take a while. Astronomers were initially skeptical because they thought stars did not contain enough hydrogen to keep such reactions going. In fact, that confusion wasn't cleared up until 1925, when Cecilia Payne showed that those hydrogen estimates were based on an incorrect reading of spectral lines—features in the light of a star that reveal how much of each chemical element it contains (see Chapter 2.II.1). In fact, hydrogen is actually by far the most abundant element in any star, followed by helium (Cecilia Helena Payne 1925; Cecilia H. Payne 1925). The modern figures are 75% hydrogen, 23% helium, and about 2% heavier elements (Dayah 2017).

But that insight just forced astronomers to confront new questions. Why, for example, does virtually every star have that same three-to-one ratio of hydrogen to helium? Why do the heavier elements form such a tiny fraction of the cosmic total? And why are some of the elements in that fraction, such as carbon or oxygen, so much more abundant than elements such as lithium or boron?

1. Nucleosynthesis

The 1930s were a good time to be asking such questions, since physicists were finally getting somewhere in their efforts to understand the atomic nucleus. One of their major achievements was discovering that each atomic nucleus contains two types of particles: positively charged protons that determine which element it is—one proton for hydrogen, two for helium, six for carbon, and so on—plus a roughly equal, but variable, number of electrically neutral neutrons that determine which isotope it is. The six protons in carbon, say, can be joined by six, seven, or eight neutrons to make carbon-12 (the most common isotope), carbon-13 (rare), or carbon-14 (which is unstable and radioactive).

Holding these particles together is a “strong” force that only the protons and neutrons can feel; the much lighter, negatively charged electrons that orbit the nucleus are impervious to it. This force is far stronger than gravity or electromagnetism—and it has to be, to keep the electrostatic repulsion between the positively charged protons from tearing the nucleus apart. Yet it’s extremely short-range: the protons and neutrons in the nucleus practically have to be touching for the strong nuclear force to have any effect at all.

Taken together, these properties explained how new elements can form from existing nuclei via a “nucleosynthesis” process, which boils down to smashing things together and letting the protons and neutrons reshuffle themselves. This can happen only in the most extreme environments, however. Thanks to electrostatic repulsion between the positively charged protons, nuclei can get close enough to fuse only if they are raised to temperatures measured in millions or even billions of degrees. And scientists soon realized that there are only two places where conditions like that can occur in nature. The first is the interior of stars; by the late 1930s, physicists had begun to work out precisely how thermonuclear fusion generates the energy to keep stars shining—and in the process, creates the heavy elements that make up the Earth and all of us who live on it (Bethe 1939).

A prime catalyst for this work on stars was George Gamow; but by 1946, Gamow had turned his attention to the second possibility for nucleosynthesis (Gamow 1946): could at least some of the chemical elements have been born in the very early universe? Gamow tackled this question with two young colleagues, Ralph Alpher and Robert Herman. And, in an extraordinary burst of creativity, the trio separately and together produced 11 publications on early-universe nucleosynthesis in 1948 alone (Peebles 2014; Chernin 1995; Gamow 1948).²

The picture they arrived at is very close to modern thinking, starting with their realization that the initial state of the universe was a superheated soup of protons and neutrons at around 10 or 20 seconds after its birth. They made no attempt to push back any closer to that initial instant, $t = 0$: the cosmological equations of Einstein’s general relativity showed that if they had tried to they would have been faced with a universe compressed into a single point—a singularity of infinite density, infinite temperature, and zero size, where no known laws of physics could possibly apply. (Two decades later, Roger Penrose and Stephen Hawking would show that such singularities are inevitable in Einstein’s theory (Penrose 1965; Hawking 1966).)

So instead, Gamow, Alpher, and Herman simply took the soup of protons and neutrons as a given—we will return to its origins in Chapter 4—and traced how it would have evolved as the universe expanded. Their calculations showed that within just a few minutes after $t = 0$, the rapidly cooling brew would have condensed into nearly pure hydrogen and helium, with element- and isotope ratios close to those we see today (Helge Kragh 2001, 166).

Almost as an afterthought, moreover, Alpher and Herman reached an additional conclusion: the radiation emitted from that primordial fireball would still be around, just cooled and redshifted by billions of years of cosmic expansion (Ralph A. Alpher and Herman 1948). This was similar to what Lemaître had suggested in 1931, except that Alpher and Herman’s more sophisticated calculations suggested that today we would see that radiation not as cosmic rays, but as photons with a temperature just a few degrees above absolute zero—a frigid value that would put the photons’ wavelengths in the microwave region of the spectrum.

² The first of the 1948 papers, written by Alpher and Gamow, is also famous for a non-physics reason: Gamow jokingly added physicist Hans Bethe as the second author, although Bethe had not contributed to the research, so that when the list was read out loud it would rhyme with the *alpha-beta-gamma* start of the Greek alphabet (R. A. Alpher, Bethe, and Gamow 1948).

In hindsight, that prediction would come to look very prescient indeed. But at the time, like Lemaître before them, Gamow, Alpher, and Herman soon saw their work sink into obscurity—not least because the tiny community of cosmologists became caught up in controversies over a rival cosmological theory from 1948.

2. The Steady-State Universe v The Big Bang

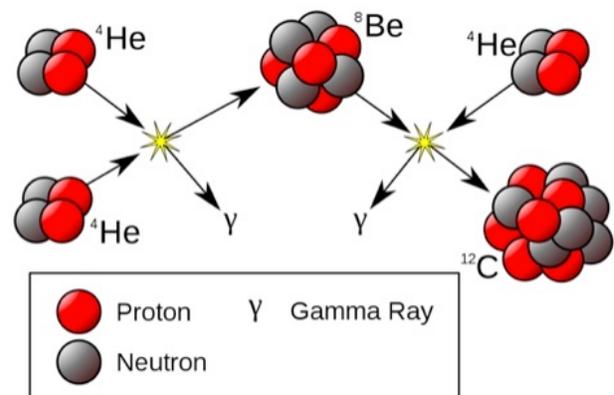
As they later recalled it, the three young physicists Hermann Bondi, Thomas Gold, and Fred Hoyle were motivated by a profound distaste for the very idea of a creation event (Helge Kragh 1996, 162). Their problem, of course, was that if the universe was expanding, then a cosmic beginning seemed unavoidable.

It was Gold who first thought of a resolution: What if empty space wasn't quite empty? What if the vacuum were somehow generating new matter—neutrons, possibly—at some low rate? If so, then as the universe grew and galaxies moved apart, this newly generated matter would pop up out of empty space to fill in behind them and keep the average cosmic mass density a constant. A quick calculation showed that the continuous creation process would only need to generate a mass equivalent to a few new hydrogen atoms per cubic meter per million years—a rate that would be completely unobservable. Such a universe would be always expanding yet never changing—and would not require an origin (Bondi and Gold 1948; Hoyle 1948).

The model did not attract much notice until the BBC invited Hoyle to discuss his ideas in a radio lecture aimed at the general public (“Fred Hoyle: An Online Exhibition” n.d.; Helge Kragh 1996, 191). The BBC broadcast is remembered today mainly because Hoyle coined the term “Big Bang” while trying to disparage the main rival to his steady-state model. But at the time, Hoyle’s high-profile advocacy for the steady-state idea also ignited intense controversy among his fellow scientists. Some embraced it as an elegant way to get around the cosmic-origin problem. Others despised it, on the grounds that continuous creation was an utterly ad-hoc assumption that violated some of the most fundamental principles of physics—not the least being the conservation of energy.

A particularly urgent question for the steady-state advocates was to understand where the heavier chemical elements came from and why they have the abundances seen today. Because the steady-state model didn't allow for a primordial fireball, they had to prove that all the elements could have been made in the only alternative site: the stars (Hoyle 1946; 1954; Hoyle et al. 1956). An apparent breakthrough for that effort came in 1952, when Edwin Salpeter showed that, under the hot, dense conditions that prevail at the core of certain red giant stars, it was possible for three helium nuclei to merge simultaneously. The result would be a very stable carbon-12 nucleus, which has six protons and six neutrons (Figure 7). And from there, the way would be open for thermonuclear reactions in the stars to produce all the other heavy elements (Salpeter 1952). Crucially, these conditions would not have occurred during the Big Bang—and so the paper was widely viewed as indirect support for the steady-state model.

Figure 7: The Triple-Alpha Process. Three helium atoms, He, combine to form a stable carbon atom, C, with beryllium, Be, formed as an intermediate step. Gamma rays—a type of electromagnetic radiation—are also released. (Image credit: Borb, shared under the creative commons license CC BY-SA 3.0.)



There was still a hitch, however. Salpeter’s calculation predicted heavy-element ratios that didn’t match the observed values, and a rate of carbon formation that seemed way too low. But that discrepancy inspired Hoyle to make an audacious proposal: the ratios could be brought into line and carbon production increased a thousand-fold if carbon-12 had a “resonance”—a spike of enhanced reaction probability at a certain energy. Experimental nuclear physicists looked—and the resonance was right where Hoyle predicted (Dunbar et al. 1953; Hoyle 1954). (This is one of the first examples of using what scientists call ‘anthropic reasoning’—discussed further in Chapter 4—to make a testable prediction. That is, Hoyle’s arguments hinged on the assumption that some such process must be at play, or there would not be enough carbon to account for the existence of humans. [JTF’s Fine-Tuning review](#) describes this, and other examples, in more detail.)

Buoyed by this success, Hoyle, along with Geoffrey Burbidge, Margaret Burbidge, and William Fowler, went on to show that stellar nucleosynthesis could plausibly account for all the heavy elements (Burbidge et al. 1957). For steady-state believers, this conclusion was a triumph.

Yet ironically, the paper would also ultimately come to be seen as support for the Big-Bang model. That’s because, as impressive as the calculations were, the numbers never quite worked for the light elements. For instance, helium does indeed get made by hydrogen fusion in stars, but that process couldn’t begin to account for the helium abundances that astronomers were seeing. In 1961, for example, an influential survey found that the three-to-one hydrogen-to-helium ratio was pretty much the same in old stars, young stars, glowing nebulae, interstellar space, distant galaxies—everywhere (Osterbrock and Rogerson 1961). This was exactly what you’d expect to see if the hydrogen-helium ratio was primordial—that is, forged in the Big Bang—but not at all what you’d expect if the helium had been produced in individual stars with lots of local variation.

These wrinkles would, in turn, fuel the common-sense compromise that is still the consensus view today: at least when it came to element creation, both sides were right. The light nuclei—hydrogen, deuterium, helium, and a tiny bit of lithium-7—were virtually all made in the Big Bang, as advocated by Gamow, Alpher, and Herman. But every other element was made much later in stars.

Meanwhile, an even more serious challenge to the steady-state idea had been brewing since 1955, when Martin Ryle and Peter Scheuer published the first reliable survey of “radio stars”—very distant, point-like sources that emitted copious energy at radio wavelengths (Ryle and Scheuer 1955). In every direction Ryle and Scheuer looked, the dimmer, far-away sources substantially outnumbered the brighter, comparatively nearby sources—which was another way of saying that radio stars used to be a lot more common billions of years ago, when those far-away sources had emitted the radio waves that were just now reaching us. This was a serious problem for steady-state believers, since their model held that the average distribution of radio stars, galaxies, and whatever else was out there, had to be constant over time. Subsequent surveys only made the data stronger (Helge Kragh 2012). By the early 1960s, most astronomers felt that the steady-state model was on life-support.

All of which set the stage for the third and final rediscovery of Big-Bang cosmology—a chance observation that effectively killed the steady-state idea forever.

III. THE COSMIC MICROWAVE BACKGROUND

In the summer of 1964, Robert Dicke set out to find relic radiation from the Big Bang in the microwave region of the spectrum. During World War II, Dicke had been part of the MIT team that had developed radar, and had invented a microwave detector known as the “Dicke radiometer,” which is still widely used today (Dicke 1946). Now at Princeton, he had two of his students, Peter Roll and David Wilkinson, build an advanced version of his radiometer. Roll and Wilkinson would also build a

horn-shaped antenna to capture and concentrate the incoming radiation and a refrigeration system that would maximize the detector's sensitivity by bathing it in liquid helium at 4 Kelvin (4° Celsius above absolute zero).

Meanwhile, another of Dicke's students, James Peebles, who knew nothing of Gamow, Alpher and Herman's earlier work, calculated that billions of years of cosmic expansion would have cooled the Big-Bang emissions down to a few degrees Kelvin. By early 1965, the theoretical calculations were done and work on the detector was proceeding nicely. Then, during a team meeting one Tuesday lunchtime in February 1965, Dicke got a disturbing phone call. "Well boys," Dicke told his trio of students when he finally hung up, "we've been scooped" (Peebles, Page, and Partridge 2009, 191).

They had been—and totally by accident. Just 40 kilometers due east of Princeton, at the Bell Labs campus in Holmdel, New Jersey, Arno Penzias and Robert Wilson had spent the previous year trying to make an astronomical instrument out of an old horn antenna originally built for satellite communications (Figure 8). To achieve the extreme sensitivity they were after, Penzias and Wilson had doggedly eliminated every source of interference they could find—radar signals, radio broadcasts, pigeon droppings, everything. But try as they might, there remained a faint microwave hiss that just would not go away. It was the same, day or night. It was the same anywhere in the sky they looked.

It was an utter mystery—until they read a draft of one of Peebles' papers on cosmic radiation, and the meaning of their mysterious hiss began to snap into focus. They had accidentally discovered the afterglow of the Big Bang.

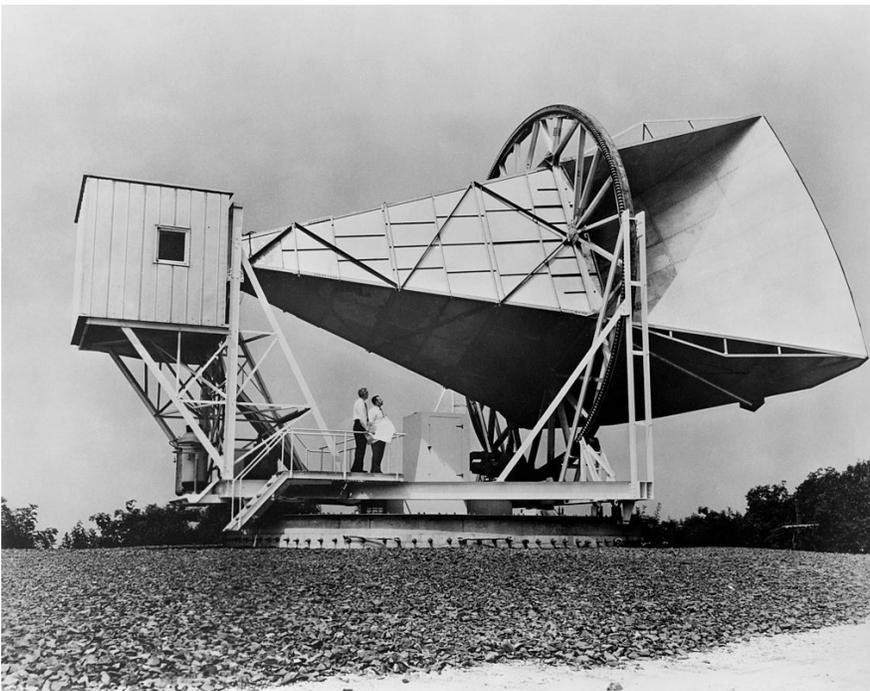


Figure 8: Penzias and Wilson stand at the 15-meter Holmdel Horn Antenna that brought their most notable discovery. (Image credit: NASA, restored by Bammesk.)

The two groups published back-to-back papers in *The Astrophysical Journal*: one from the Princeton team describing the theory and one from the Bell Labs duo describing their data (Dicke et al. 1965; Penzias and Wilson 1965). The papers met with...incomprehension, mostly. And scoffing. Wilkinson later recalled that the steady-staters hated it and the big-bangers didn't believe it (Peebles, Page, and Partridge 2009, 205).

Still, observational data has a persuasive power. Roll and Wilkinson confirmed Penzias and Wilson's find later that same year (Roll and Wilkinson 1966). And so did a very different, but equally

compelling measurement: When astronomers searched interstellar space for free-floating molecules of the famously poisonous compound cyanide, which was known to behave like a tiny antenna tuned to 0.26-centimeter microwaves, they found that the molecules were absorbing and re-emitting photons from the cosmic microwave background radiation (Field, Herbig, and Hitchcock 1966; Thaddeus and Clauser 1966).

Over time, both the reality of the cosmic microwave background and its Big-Bang interpretation would become almost universally accepted.

Hoyle, for his part, would reject the Big-Bang idea until the day he died in 2001. Gamow, by contrast, felt vindicated by the discovery—if perhaps a little miffed that others were getting all the attention. As he was heard to declaim at one meeting in 1967, he had lost a penny. Penzias and Wilson had found a penny. Was it his penny? (Peebles, Page, and Partridge 2009, 374)

Lemaître was both gratified and gracious. News of the discovery reached him in June 1966, as the 71-year-old president of the Pontifical Academy of Sciences lay dying of leukemia. Gravely ill though he was, “Lemaître lucidly praised this news, which confirmed the explosive genesis of our universe” (Mitton 2016).

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4. BEFORE THE BIG BANG

It’s a fundamental fact found in every astronomy textbook: the further out we look into space, the further back we’re looking into time.

Granted, this usually doesn’t matter too much. We see the moon as it was about 1½ seconds ago—the time it takes for sunlight to bounce off its surface and cross the 384,400 kilometers to our eyes. That’s rarely long enough for things to change significantly. The same is true with the sun, which we’re seeing as it was about 8 minutes and 20 seconds ago. The delay isn’t even too important for the Andromeda galaxy, which we’re seeing by the light it emitted some 2.5 million years ago—about the time that a new species named *homo habilis* started wandering the plains of Africa. Astronomical objects tend to be big, and to change very slowly on any human timescale.

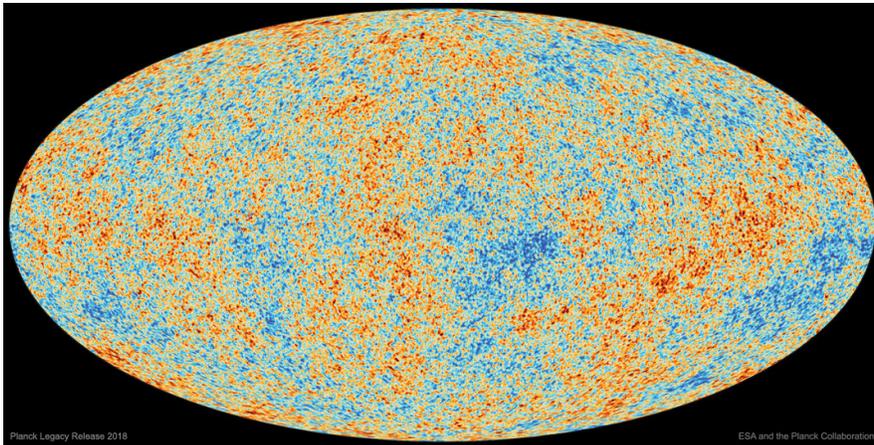


Figure 9: The Cosmic Microwave Background. Maps of the CMB reveal slight temperature variations in the relic radiation of the Big Bang, in exquisite detail. (Image credit: ESA and the Planck Collaboration.)

Eventually, though, this time-machine aspect of astronomy does start to matter. The furthest galaxies detected by the Hubble Space Telescope look noticeably different from their descendants today because astronomers are seeing them in their infancy, when they were just beginning to form less than a billion years after the Big Bang. And the faint hiss of the cosmic microwave background (CMB), introduced in Chapter 3, gives astronomers a view of the 380,000-year-old universe

back when it contained nothing but rapidly cooling hydrogen and helium gas (Figure 9).

This is as far as astronomy’s time machine can go, however. Before the CMB, the universe was a haze of ionized matter that scattered any light that tried to pass through it; looking further back is like trying to look beneath the surface of the sun. So astronomers are left with two options. They can learn an enormous amount by studying the cosmos on this side of the CMB surface—investigations that have revealed much about the hidden contents of the universe and provided many clues about cosmic

origins; this work will be the subject of Chapter 5. Or cosmologists can try to infer what went on behind the veil through a combination of theory and extrapolation from lab experiments.

That's what we discuss in this chapter. We'll find that scientists still can't answer the most fundamental origins question: where did the universe come from? But they have given us a radically new way to think about it.

The key insight grew out of the discoveries recounted in Chapters 2 and 3, which told how astronomers and physicists established that the universe was born billions of years ago in an explosive Big Bang, and has been expanding outward ever since, from a point of near-infinite temperature and density. But, as we'll see in the next section, the Big-Bang model left cosmologists with three major puzzles about the shape, fate, and contents of the universe. And in the 1980s, their struggle to solve these puzzles led them to an audacious notion—that in the Big Bang's first, infinitesimal fraction of a second, the cosmos must have gone through a period of “inflationary” expansion so fast that it briefly exceeded the speed of light.

This idea about cosmic inflation turned out to be such a beautiful solution to the three puzzles that it's become conventional wisdom in the field. But the implications didn't end there: physicists quickly realized that if inflation happened once, at the beginning of our universe, there was no reason it couldn't occur repeatedly at different places and times. If true, this means that our cosmos might be one of many inflating patches that exist inside a vastly larger ‘multiverse.’

Or maybe not. The multiverse theory remains highly controversial, for reasons that we will detail. So we will end this chapter with a look at some of the many alternatives that researchers are exploring—and what, if anything, these possibilities imply about the universe before the Big Bang.

I. INFLATION THEORY

1. Three Cosmic Conundrums

(i) The Flatness Problem

In the previous chapter, we described the 1965 discovery of the cosmic microwave background (CMB), which convinced almost everyone in the field that our cosmos was born several billion years ago in a Big Bang; the microwave radiation that bathes the universe is simply a relic of that original explosion. But researchers had to wonder: If the universe had a beginning, might it also have an end? And if so, what was it? Would the universe expand forever? Or would it eventually halt its expansion and crash back down to a Big Bang in reverse—the Big Crunch?

The answer came down to one number: the average density of matter in the universe. The significance of this number had become apparent in the 1920s and 1930s, when (as described in Chapter 2), the cosmologists Alexander Friedmann and independently Georges Lemaître (and also Howard P. Robertson and Arthur Geoffrey Walker) had found exact solutions to Einstein's equations that described how the universe might evolve. If the average matter density was below a certain critical value, equivalent to a few hydrogen atoms per cubic meter, the equations said that the collective gravitational pull of all those galaxies would not be enough to reverse the expansion, and the universe would indeed go on forever. It would be described as ‘open’ and also be infinite in extent. But if the average density was greater than that critical value, said the equations, the universe would be pulled back inwards by gravity. It would be ‘closed,’ spherical and finite—albeit very big—and it would one day contract back in on itself in the Big Crunch.

There was also a solution balanced on the knife edge between these two possibilities: if the cosmic density exactly matched the critical density, the cosmos would be infinite but ‘flat’—meaning that it would expand forever at a decelerating rate, with the gravity between the stars and galaxies slowing the expansion down but never quite able to stop it.

And herein lay the flatness problem: If the cosmic density had been even slightly too high soon after the universe’s birth, then the closed universe would have experienced more of a Big Burp than a Big Bang. It would have expanded and then contracted again almost instantly. Conversely, if the cosmic density had been even slightly too low, the open, infinite universe would have expanded too fast for stars or galaxies to form. Yet here we are more than 10 billion years later, with stars and galaxies everywhere and an average matter density that’s no more than a factor of ten away from the critical density (thought to be about six hydrogen atoms per cubic meter). For that to be true today, cosmologists realized, then the cosmic density soon after the universe was born would need to match the critical density to one part in 10^{55} (10 with 55 zeroes after it)—a precision that makes balancing a pencil on its point look easy. ([JTF’s Fine-Tuning review](#) discusses the scientific and philosophical debates surrounding this apparent cosmic coincidence and other physical phenomena that seem fortuitously fixed to just the right value to have enabled the evolution of human life in the universe.)

This was a precision that cried out for explanation. But in the late 1970s, standard cosmology could not provide one.

(ii) The Horizon Problem

The next puzzle was that the universe looked pretty much the same in every direction. As cosmologists studied the CMB in more detail, for example, they discovered that its temperature is 2.73 K (2.73 degrees Celsius above absolute zero) in every part of the sky. (Figure 9 depicts tiny variations that have been mapped across the CMB around this average temperature.) Likewise, astronomers found the same statistical distribution of galaxies in the northern sky as in the south. But why?

As Wolfgang Rindler and others had been pointing out since the 1950s, this cosmic uniformity is actually very strange (Rindler 1956; Misner 1968; Weinberg 1972). The early universe wasn’t like soup that’s simmering on the stove, where there is plenty of time for heat to flow, for ingredients to blend, and for temperature and taste to equalize throughout the pot. The early universe was expanding so fast that particles generally couldn’t make it from one region to another. (Imagine an ant crawling on the surface of a balloon that’s being blown up faster than the creature can move: its destination just keeps getting farther and farther away.) So most of what we see when we look at the distant, early universe should be regions that had no time to communicate with one another, much less time to mix and come to a common temperature. And yet they all ended up in sync, looking the same. How?

In technical terms, any region of the universe that can’t get signals to you, even at the speed of light, is said to be beyond your horizon. So this became known as the horizon problem.

(iii) The Monopole Problem

The third puzzle was tied to developments in particle physics—the study of elementary particles and the forces between them—and concerned a particle that was posited to exist, but has never been found. This was the magnetic monopole. We’re used to the idea of elementary particles carrying a single electrical charge (or no charge); electrons, for example, have a single negative charge while the protons found inside atomic nuclei have a single positive charge. But physicists have never found a particle with a single magnetic charge. Break a real bar magnet, and you just get two short bar magnets, each with its own north and south pole. There seems to be no way to isolate the north and south poles.

Yet theories coming from particle physics suggested that magnetic monopoles should exist (see “The Standard Model of Particle Physics and Beyond”). Of course, it was always possible that magnetic

The Standard Model of Particle Physics and Beyond

In the same decade that cosmologists were coalescing around the Big Bang as their “standard model” of cosmic origins, particle physicists were developing their own standard model that used quantum rules to unify all the known forces except gravity. There are three of them: electromagnetism; the weak nuclear force, which is a subtle interaction responsible for certain forms of radioactivity; and the strong nuclear force, which binds subatomic particles known as “quarks” together inside protons, neutrons, and certain other particles. The first success in this unification program was the development of the “electroweak theory,” which combined electromagnetism and the weak force (Yang and Mills 1954; Glashow 1961; Weinberg 1967; Salam 1968). Then the strong nuclear force was brought into the fold, in a theory that came to be known as Quantum Chromodynamics (Fritzsch, Gell-Mann, and Leutwyler 1973).

The Standard Model now comprises 17 elementary particles (Figure 10). Matter is made up of fermions, while bosons are associated with the three forces: electromagnetism is carried by photons; the electroweak interaction is mediated by W and Z bosons; and gluons carry the strong force that holds quarks together. The Higgs boson is involved in giving elementary particles their mass.

Standard Model of Elementary Particles

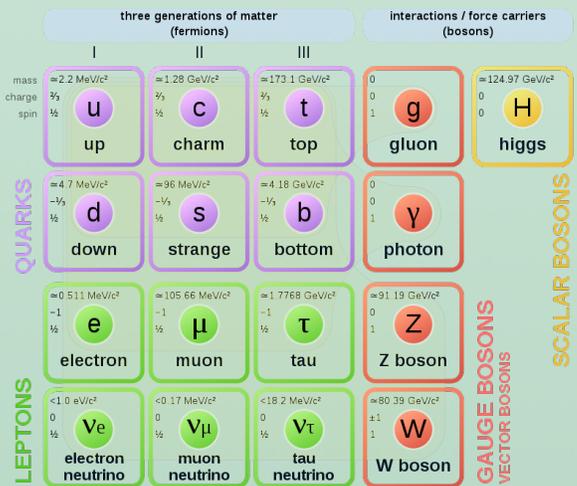


Figure 10: The Standard Model of Particle Physics. (Image credit: MissMJ, shared under creative commons attribution 3.0 unported license.)

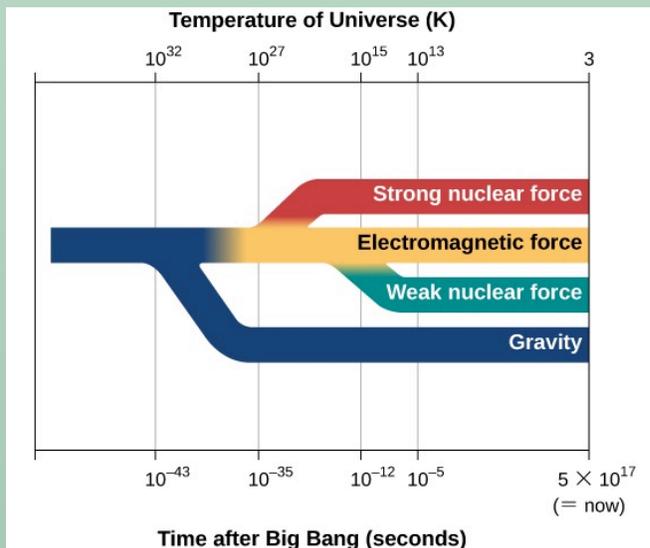


Figure 11: As the temperature of the universe cooled, the four forces separate. (Image credit: openstax.org/details/books/astronomy, Rice University, shared under a creative commons 4.0 international license.)

Physicists have come up with several ways to embed these particles and forces into a Grand Unified Theory, or GUT, that encompasses them all in a natural way. But they have had considerably less success with their efforts to unify the first three forces with the fourth known force, gravity. None of the ideas put forward to date has been completely satisfactory. Still, physicists are confident that in the very early universe, all four forces were (somehow) unified. As the temperature cooled, one by one, the individual forces we recognize condensed out, while some initially massless particles would acquire mass (Figure 11). If such theories were correct then, as a byproduct, new objects such as magnetic monopoles should also appear, as the universe went through this series of transitions (Zel’dovich and Khlopov 1978).

monopoles do exist somewhere in the universe, and scientists had just never noticed them. The trouble was that calculations also showed that these things would have a mass of about 10 million billion times the mass of a proton and that the Big Bang should have made *lots* of them. They would have been really hard to miss (Preskill 1979).

So where were they hiding?

This monopole conundrum left some of the best theorists in the world scratching their heads—until one young physicist named Alan Guth had an idea that solved all three puzzles in one fell swoop, and completely changed our conception of the early universe.

2. A Spectacular Realization

Guth knows exactly when the idea hit him, because it's right there in his notebook: late in the evening of Friday, December 7, 1979.

The physicist had just recently arrived in California for a temporary post-doctoral appointment at the Stanford Linear Accelerator Center, after a stint at Cornell University in New York (Guth 2015a; 2015b). He and Henry Tye, another young Cornell physicist, were just finishing up a paper suggesting that monopole production might have been suppressed if the early universe had “super-cooled” in much the same way that water sometimes does in clouds, when it manages to remain fluid even below its freezing point (Guth and Tye 1980).

This scenario worked, sort of, and seemed to explain why there were few, if any, monopoles around today. But now, with his co-author getting ready for an extended visit to his native China, Guth was taking a fresh look. In the earlier paper, he and Tye had just assumed that the universe would continue to expand in the same way despite the super-cooling effect. But was that really true? If not, and super-cooling caused the cosmos to behave in some strange way that does not fit with observations, then their solution to the monopole problem would not work.

To Guth's disappointment, he realized that he and Tye had been wrong. Super-cooling would have altered the universe's behavior dramatically, causing it to expand outwards at faster-than-light speeds that would have dwarfed the already mind-boggling expansion speeds predicted in standard cosmologies. (Einstein's relativistic speed limit that we met in Chapter 2 applies only to individual particles. Space, as it turns out, can expand as fast as it wants to.) It would be an exponential expansion, doubling the size of the universe in an infinitesimal slice of time—then doubling it again, and again, and again, at least 90 to 100 times. In considerably less than a nano-nano-nanosecond, such an exponential expansion could have inflated the universe by a factor of 10^{28} or more. To put that number in perspective, it was like growing today's observable universe, now roughly 28 billion light-years wide, from a patch of space the size of a basketball (Siegel 2017).

But Guth also realized that inflation offered its own solution to the monopole problem. Even if the pre-inflation baby universe had been riddled with monopoles, such extreme expansion would have diluted them to the point of invisibility. There would be maybe one left in our entire observable universe, so of course we'd never notice it.

But there was more. Guth recalled listening to a talk about the flatness problem given a year before by Robert Dicke, one of the physicists who predicted the existence of the CMB. Dicke had explained that the early universe must have somehow been perfectly tuned to exactly the critical density, to explain how stars, galaxies, and planets, later formed. If the density had been slightly higher or lower, no such structure (let alone physicists to mull it over) would now exist.

Standard cosmology offered no reason why the universe would be born in this very particular—and from a human perspective, very useful—state. But that, as Guth realized with growing excitement, was because those models didn't take inflation into account. Once you did, the flatness problem went away as easily as the monopole problem had: no matter how the universe started out, inflation's exponential expansion would have stretched it as taut and as flat as the surface of a balloon that's been blown up to the scale of light years or more.

Guth was so thrilled with this insight that he wrote it down in his notebook and drew a double box around the whole paragraph: “SPECTACULAR REALIZATION: This kind of supercooling can explain why the universe today is so incredibly flat—and therefore resolve the fine-tuning paradox pointed out by Bob Dicke in his Einstein Day lectures.”

Spectacular though it was, however, there was still more. Just a few weeks later, Guth learned about the horizon problem—the one that ponders why, on average, the universe looks the same in every direction—and he immediately realized that inflation held the answer for this mystery, as well. Once you took into account that the cosmos would swell by a factor of at least 10^{28} during inflation, then you could calculate that everything that would grow into today's observable universe must once have been unimaginably close, packed into a space considerably smaller than a proton. Or to turn that around, inflation would have taken an infinitesimal patch of the universe so small that it did have time to mix and equilibrate, and expanded it to cosmic dimensions. Thus the universe should look more or less the same wherever we looked.

Guth considered this to be yet another compelling argument for the inflation idea. And yet, he was also acutely aware that inflation theory itself had a big problem—once inflation was triggered in the universe, his theory struggled to explain how it would end.

3. Stopping Inflation

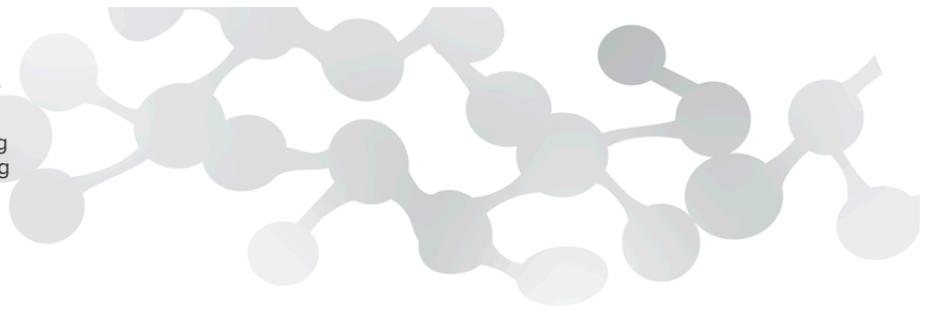
Inflation obviously did end, since the universe is not inflating now. (Or at least, it's not inflating at that same prodigious pace; as we will see in the next chapter, the universe seems to be undergoing a kind of micro-inflation that's slowly increasing the cosmic expansion rate.) The mystery was, *how* did it end?

Mathematically speaking, Guth knew, inflation occurred when the vacuum that pervades the empty universe was a “false vacuum,” meaning that it contained an unusually large amount of energy (Figure 12). So inflation would have ended when the vacuum dropped to its lowest possible energy—the “true vacuum.” Intuitively, though, the equations were very much like those of a ball rolling across a rugged energy landscape. The ball could either sit at the top of a hill representing the higher-energy false vacuum, where it would force the universe to inflate. Or it could roll down to the true low-energy vacuum at the bottom, causing inflation to cease. In particular, Guth imagined that the cosmic ball would be caught for a while in a depression at the top of the hill, giving the universe enough time to inflate sufficiently (Figure 12a). The trouble was that Guth couldn't fathom how the cosmic ball could ever get itself out of that high-altitude hollow, so that it could roll down to the true vacuum and bring inflation to an end. He tried a few tricks to get the universe to drop from the false to the true vacuum, when required, but he could not make it work.

Still, inflation solved so many problems that Guth felt there had to be something right about it. So when he finally published his paper in January 1981, he frankly admitted that he couldn't solve the “graceful exit” problem and appealed to his fellow physicists for help: “I am publishing this paper in the hope that it will ... encourage others to find some way to avoid the undesirable features of the inflationary scenario” (Guth 1981).

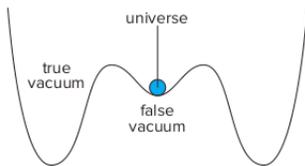
The Inflationary Multiverse

Inflation may start and end at different times and places, creating a multiverse of parallel neighboring cosmoses. String theory suggests these universes may have different properties, laws and even dimensions.



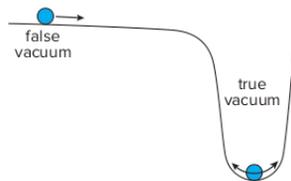
Old Inflation

(a) While the universe is nestled in the higher-energy 'false vacuum' state, it inflates, expanding at an exponential rate. Inflation only ends when the universe is in the true vacuum. But how can it reach there?



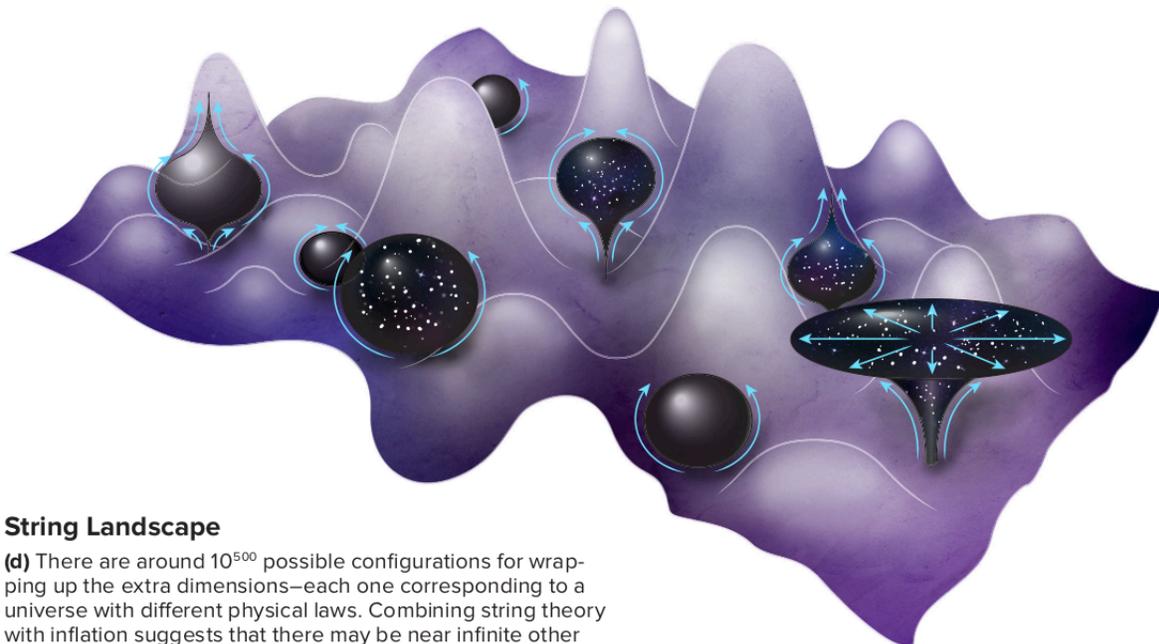
New 'Slow-Roll' Inflation

(b) The false vacuum is represented by a shallow incline. As the universe slowly rolls down, it continues to inflate. Inflation ends when it hits the true vacuum, rolling back and forth in the valley, releasing energy to create new particles.



Extra Dimensions

(c) String theory predicts there are a number of extra dimensions, hidden from us because they are small and curled up in complex ways. The image shows a 2-dimensional slice of one such proposed 6-dimensional folding pattern.



String Landscape

(d) There are around 10^{500} possible configurations for wrapping up the extra dimensions—each one corresponding to a universe with different physical laws. Combining string theory with inflation suggests that there may be near infinite other universes, generated by inflation, and populated with different parameters, forces and dimensions by string theory. Only very rarely will one be produced that has the right parameters for stars, galaxies, planets and people to evolve.



Created by Maayan Harel for FQXi, the Foundational Questions Institute
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Figure 12: The Inflationary Multiverse. (Image created by Maayan Harel. Image in (c) adapted from work by Andrew J. Hanson, under a creative commons license.)

He didn't have long to wait. Guth's inflation idea soon drew the attention of Andrei Linde, whose colleague Alexei Starobinsky had (unknown to Guth) suggested a somewhat similar inflationary scenario (Starobinskiĭ 1979). The early universe was already familiar terrain to Linde, who had worked on similar ideas for years (Linde 1974). And now Linde was quick to come up with an alternative graceful-exit scenario, dubbed slow-roll inflation. In effect, he imagined a differently-shaped energy landscape, in which the universe was perched not in a mountaintop depression, but instead on the mathematical equivalent of a broad, flat dome similar to Ayers Rock in Australia, or Stone Mountain in Georgia (Figure 12b). Like an ordinary marble placed on such a dome, Linde argued, the universe would roll down from the false vacuum very slowly at first—inflating furiously every instant that it was up there. But when it finally did plunge toward the true vacuum at the bottom, it would convert its energy into swarms of particles (as would also happen in Guth's model). The result would be a bubble of normal space more than big enough to accommodate our entire observable universe.

Linde published this result in 1982—and so did Andreas Albrecht and Paul Steinhardt, who had independently arrived at the same idea (Linde 1982a; A. Albrecht and Steinhardt 1982; A. Albrecht et al. 1982).

These “new inflation” models together put the idea on a much more solid footing. And, as we describe in the next section, they also gave astronomers a way that they could look at the sky and actually test all this theorizing.

4. Wrinkles in the Universe

The test started from the observation that (new) inflation was *too* successful. By itself, it would have produced a cosmos stretched so flat that there would be nothing in it but a uniform haze of hydrogen and helium gas, with no discernible lumps. So where did the universe get all those lumps that we now call galaxies and clusters?

The answer went back to 1966, when Andrei Sakharov noted that, according to quantum physics, the energy of the vacuum is constantly shimmering around its average value. In effect, the energy is undergoing tiny, very rapid fluctuations that vary at random from one point to the next. So in the very first instants of the universe, Sakharov argued, these quantum fluctuations would have caused subtle variations in the density of the primordial plasma—variations that would have expanded along with the rest of the universe. And over the billions of years since, Sakharov suggested, the inexorable pull of gravity would have caused the denser regions to contract and grow denser still, until they condensed into galaxies, clusters, and other massive structures—among them our own Milky Way galaxy (Sakharov 1966).

If Sakharov was right, in other words, we owed our existence to a quantum fluctuation that occurred billions of years ago.

Sakharov's idea was revived in 1981, and applied to the version of inflation developed by Starobinsky (Mukhanov and Chibisov 1981; 1982). Then a year later, multiple teams of physicists rushed to do the same for the recently invented theory of new inflation; they published their work in four separate papers that grew out of a two-week workshop held in Cambridge, UK, during the summer of 1982 (Starobinsky 1982; Guth and Pi 1982; Hawking 1982b; Bardeen, Steinhardt, and Turner 1983). The physicists agreed that these variations might one day be detectable, showing up as subtle shifts in the temperature of the CMB at different points on the sky.

In Chapter 5 we'll see that in 1992, researchers working with NASA's Cosmic Background Explorer (COBE) satellite would announce that they had indeed found CMB temperature variations with exactly the statistical distribution expected from quantum fluctuations (Smoot et al. 1992). Moreover, these

findings would continue to hold up when later satellites mapped the CMB in much finer detail. And in the meantime, a multitude of detailed computer simulations would confirm that gravity could indeed have taken these density perturbations and produced the observed distribution of galaxies.

Such results have led to inflation theory becoming part of the cosmological paradigm. But in the next section we'll see that over the coming decades, at least some of inflation's authors would become convinced that the framework implies an even more radical (and controversial) possibility—that our cosmos is just one universe in a multiverse of parallel universes.

II. THE MULTIVERSE

1. Eternal Inflation

By the early 1980s, Guth's spectacular realization had proved to be a spectacular success, providing a unified explanation for a variety of otherwise disconnected observations (Guth 2007). But theorists didn't stop there. At the same Cambridge workshop where Guth and others were calculating the quantum fluctuations produced during new inflation, Steinhardt pointed out one of the theory's more radical implications (P. J. Steinhardt 1983). Just for fun, he said, let's imagine that you have a cosmos that's inflating away. Now, zoom out and look at this (infinite) cosmos on a really big scale—say, 10^{30} times the size of our observable universe. Then you might find that what we naïvely call *the* universe is just an isolated bubble of normal space surrounded by an endless expanse of space that's still inflating. After all, there was no reason why inflation had to occur in lockstep everywhere; our bubble could just be a region where it ended earlier than some places, and later than others. In fact, noted Steinhardt, our über-cosmos could be as full of holes as a fractal swiss cheese, even as inflation kept opening up room for more.

But wouldn't we have noticed such a thing? Not necessarily. The walls of any given cosmic bubble would expand at essentially the speed of light, which would make the walls impossible to see for observers in the interior—as we are. Nor were we likely to see another bubble universe colliding with ours; inflation in the larger cosmos would drive the bubbles apart much faster than light.

In fact, this scenario seemed to have no observational consequences at all—which is why Steinhardt whimsically gave this whole field of inquiry the name “metaphysical cosmology.”

Meta or not, however, the idea was compelling. Alexander Vilenkin, for example, showed that the fractal Swiss-cheese picture held true for any form of new inflation (Vilenkin 1983). Cosmologists, meanwhile, found that it was possible to come up with other energy landscapes that would give rise to inflation, not just the Stone Mountain shape that gave rise to new inflation. And Linde himself soon realized that any kind of inflation would create a cosmos of interlocking bubbles that looked less like Swiss cheese and more like an ever-expanding, fractal Christmas tree. Linde called this “the eternally existing, self-reproducing, chaotic inflationary universe” (Linde 1983a; 1986; 1994)—or in today's parlance, a multiverse.

By “eternal,” Linde meant that in a cosmos that's infinite in spatial extent, there's no reason that this web of endlessly proliferating bubble universes couldn't also extend infinitely far into the past and future. Each bubble would have its own beginning of time: the point where its local inflation ceased and gave way to a standard Big Bang. (Indeed, that's what the Big Bang *is* in this picture: the end of inflation and the beginning of normal expansion.) But the whole “multiverse” (to use the modern term) might very well have no beginning and no end—and no need for a $t = 0$ singularity. We might mark the beginning of time in *our* universe with *our* Big Bang, but time in the multiverse would have stretched back before that eternally. In fact, the multiverse would exist as a kind of steady-state cosmos—albeit

on a much larger scale than the ones imagined by Arthur Eddington or Fred Hoyle, as described in Chapter 3.

2. The Anthropic Principle

As Linde continued to think about the implications of this parallel-universe idea, he found himself asking an even more unsettling question: What if these other creations weren't just physically separated from ours? What if the various bubbles wound up with different particle masses, different values for the electric charge and other physical constants—maybe even a different number of dimensions? What if they had different physical laws entirely? (Linde 1982b; 1983a; 1983b)

That question then led to another: what if only a few of the bubble universes had laws conducive to life? If that were the case, reasoned Linde, then our universe must obviously belong to that set. And that, in turn, might go a long way toward explaining some odd coincidences in cosmology that scientists had been puzzling over for decades. In 1917, for example, Paul Ehrenfest had asked why our universe has only three spatial dimensions (plus the one dimension of time), even though it's mathematically possible to have any number (Ehrenfest 1918).

In 1974, Brandon Carter provided many more examples (Carter 1974). One concerned the strength of gravity. Carter pointed out that if we lived in a universe where gravity were very much smaller or larger than it is, then planets could not have coalesced from interstellar gas, we wouldn't have evolved and we thus wouldn't be here to worry about it. Likewise with the strong force that holds protons and neutrons together in the nucleus. If it had been even a little bit weaker than it is, said Carter, then helium wouldn't have formed in the early universe, and hydrogen would have been the only element. If the force had been a little stronger, though, then the universe would have become nothing *but* helium. Either way, no planets, and no people.

Carter coined the term “anthropic principle” to describe this line of reasoning: we shouldn't be surprised to find ourselves in a universe with exactly the forces and parameters needed to give rise to intelligent life, since if it didn't have these features, there would be no one here to wonder about their values. Other physicists soon suggested that the anthropic principle could also account for the electric charge of an electron, or its mass, or any number of other physical constants (Carr and Rees 1979; Rosental 1980; Davies and Unwin 1981; Hawking 1982a; Weinberg 1987). (See [JTF's Fine-Tuning review](#) for a more detailed discussion of such coincidences—and how multiverse theory and other alternative approaches address their origins.)

Traditionally the anthropic principle was not hugely popular, since it appeared to discourage scientists from searching for deeper explanations for the values of physical parameters. However, the inflationary multiverse idea breaks us out of the idea that the universe around us is *the* universe. Instead, it provides a plausible mechanism for the cosmos to try out myriad different (bubble) universes with myriad variations in physical law—which in turn makes it much more plausible that the laws we see around us are a selection effect. We live in one of the many neighboring cosmoses that happens to have the perfect parameters for human life to evolve. But there's no longer a mystery about why it took that fortuitous form. It's not that our universe was finely tuned to take on those parameters; they are just an accident. Most of our neighboring universes are not suited to life (at least not as we know it).

Still, to most researchers in the 1990s, the notion of unobservable other universes sounded like just so much metaphysics, not to mention comic-book science fiction—until, that is, the idea received a boost from string theory, one of the most popular candidate frameworks proposed to unify all the laws of physics.

3. The String Landscape

String theory is a mathematical framework that had become very popular in the 1980s and 1990s and that is widely considered to be about as close as anyone has ever come to a fully unified account of particle physics and gravity (Polchinski 2005). The basic idea is that particles are actually infinitesimal threads of energy—superstrings—and that these threads have to move around and vibrate in 10 dimensions: 9 directions of space plus one of time. Indeed, that number 10 is actually a prediction of the theory: if you try to formulate the equations in a lower or higher number of dimensions, they become mathematically inconsistent. So, since we obviously live in a universe with just three space dimensions, the others must be “compactified,” or curled up so tightly that we can’t see them (Figure 12c). (Think of rolling a 2-D sheet of paper into a thin straw; from a distance, the straw looks like a 1-D line.)

String theorists had always known that there are many ways to carry out such a compactification, with each yielding different physical laws and particles. But it was only in the early 2000s that they began to understand how this might play out in a cosmological context—and just how *many* compactifications there could be (Bousso and Polchinski 2000; Douglas 2003; Susskind 2003; Kachru et al. 2003). Researchers in the field were soon talking about an undulating string theory “landscape” with something like 10^{500} valleys that corresponded to stable compactifications (Figure 12d). In other words the theory’s equations could lead to 10^{500} different types of universe, with different forces, particles, and even dimensions.

That’s a number so large as to defy all metaphor. And, since there was no obvious reason for nature to prefer one compactification over another, it’s a number that did a lot to boost the anthropic principle’s reputation. After all, it wasn’t hand-wavy anymore: physicists now had a rigorous example of how one underlying theory could produce an inconceivable multitude of universes with different-seeming physical laws. And that made it much more plausible that the particular universe we see around us is the result of anthropic selection (Susskind 2005). In short, as Guth described in a 2007 review of inflation’s first quarter-century (Guth 2007), anthropic reasoning became downright respectable thanks to the confluence of the string-theory landscape and the eternally-inflating multiverse. (Guth also noted that it was helped by the astonishing discovery in the late 1990s that the expansion of the universe is accelerating, which will be described in depth in Chapter 5.) Linde, in his own review a decade later (Linde 2017), described how the resulting influx of researchers “transformed this field into a vibrant and rapidly developing branch of theoretical physics.”

It must be said, however, that to many other researchers this whole line of reasoning is anathema—not to mention intellectually lazy: anything you don’t understand, just wave your hand and say, “anthropic” (D. J. Gross 2005; D. Gross 2005). From their perspective, wrote Guth in his 2007 review, “anthropic reasoning means the end of the hope that precise and unique predictions can be made on the basis of logical deduction”—a hope that is not to be given up lightly. In fact, Steinhardt—one of the first physicists to work on the multiverse idea—eventually rejected the multiverse saying, “a theory that predicts everything predicts nothing” (Paul J. Steinhardt 2011).

Multiverse theory has also been criticized because it is difficult to conceive of ways to ever directly confirm the existence of parallel universes—which, by definition, are completely disconnected from our own. (Or maybe not; this issue is contentious, and methods to find direct evidence of ancient collisions between our universe and a neighboring bubble universe have been proposed (Feeney et al. 2011; Aguirre and Johnson 2011; Kleban 2011). [JTF’s Fine-Tuning review](#) discusses this criticism, and describes attempts to bolster the multiverse theory with both direct and indirect evidence.) As described in the next section, this criticism has led at least some physicists to explore a host of alternatives to the multiverse—and, in some cases, to inflation itself.

III. ALTERNATIVES TO THE MULTIVERSE

1. Varying Speed of Light, Rainbow Gravity—and a Universe Without Origin

Several investigators have suggested that the horizon problem, the flatness problem, and all the rest, could be solved without inflation if the fundamental constants of physics weren't really constants—that is, if parameters such as the speed of light took on very different values during the earliest instants of the universe.

The idea of time-varying constants is not a new one. Paul Dirac, one of the founders of quantum mechanics, raised the possibility as early as 1937 (Dirac 1937; 1938), and Dicke explored the notion further in the 1960s (Dicke 1961). But no one saw the idea as an alternative to inflation until 1993, when John Moffat realized that the horizon problem would go away if the speed of light had been much, much faster in the early universe (Moffat 1993b; 1993a). The higher speed limit would have allowed the cosmic patch that is now our observable universe to have mixed completely before it expanded, thereby ensuring that today's universe would still look the same on average in every direction. A similar analysis allowed Moffat to conclude that a dramatically faster speed of light would also make the flatness and monopole problems disappear.

In 1999, Albrecht and João Magueijo independently rediscovered this idea and reached much the same conclusions (Andreas Albrecht and Magueijo 1999). Magueijo would go on to become one of the most ardent champions of the variable-constant approach (Magueijo 2003). In 2004, for example, he and Lee Smolin introduced “rainbow gravity”: a variant of general relativity in which different frequencies, or colors, of light experience a slightly different level of gravity, causing them to split and take different paths (Magueijo and Smolin 2004). This effect would not be detectable on Earth, but could become important in regions where the curvature of spacetime is extremely high, such as near a black hole. Magueijo and Smolin argued that rainbow gravity could solve the horizon problem. It has also been shown that such models could do away with the initial cosmic singularity; if you trace the path of matter and light back 13.8 billion years within this framework, not all the light rays would trace back to the same place at the same time. So there would be no infinitely small point of origin; instead, the cosmos would have an infinitely long tail as you went backwards, shrinking toward zero at an exponentially slower rate, but never reaching it (Awad, Farag Ali, and Majumder 2013).

In more recent work, Magueijo and his collaborators have explored other possibilities. Perhaps gravity didn't even exist in the early universe, for example, and turned on only after the expanding cosmos had cooled to a certain point. That would eliminate the need to reconcile quantum theory and gravity, and thereby get rid of one of the biggest headaches in theoretical physics (Alexander, Barrow, and Magueijo 2016). Or perhaps gravity did exist in the early universe, but moved at a speed different from light (Magueijo 2009). Making this second assumption mathematically consistent requires that the speed of light vary over time in a particular way, and predicts primordial density fluctuations that turn out to be very close to the ones we observe—without the need for inflation (Afshordi and Magueijo 2016).

2. The Big Bounce—Loop Quantum Gravity and Cyclic Universe Models

Although string theory is easily the most popular approach for physicists hoping to unify gravity with quantum physics, a strong runner-up is “Loop Quantum Gravity”: a framework proposed in the 1980s by Abhay Ashtekar (Ashtekar 1986), and further developed in the 1990s by Ashtekar, Smolin, Carlo Rovelli, and others (Rovelli and Smolin 1988; 1990; 1995a; 1995b; Ashtekar, Rovelli, and Smolin 1992). This model, described in more detail in [JTF's Emergence review](#), posits that space emerges from a network of tiny geometrical loops (not to be confused with superstrings). It also imposes a fundamental minimum size limit, suggesting that the universe could never have been squashed down

into an infinitely small point at the Big Bang. Indeed, this suggestion was made explicit in the early 2000s with the development of Loop Quantum Cosmology: a family of models that are roughly analogous to the classical cosmological equations that Friedmann, Lemaître, Robertson, and Walker derived from Einstein’s general relativity (Bojowald 2000a; 2000b; 2001a; 2001b; 2001c; 2008; Ashtekar and Singh 2011).

As the name suggests, Loop Quantum Cosmology allows for a fully quantum-mechanical analysis of the early universe, and leads to a picture in which the universe was once large and contracting, shrinking down to a minimum size around 13 billion years ago before growing again. There was thus no Big Bang in this picture, but a Big Bounce—and we live in the expanding post-bounce phase (Bojowald 2007). In some versions of the model, in fact, the universe cycles through a series of such bounces, expanding and then contracting repeatedly. Either way, this picture does not invoke an inflationary multiverse—but it is compatible with an inflationary phase occurring post-bounce, with predictions that fit with the observed patterns in the CMB (Ashtekar and Gupta 2017).

A different cyclic-universe model was proposed as an alternative to inflation by Steinhardt and Neil Turok in 2005 (Paul J. Steinhardt and Turok 2005). Indeed, their model contains no inflationary phase at all. Instead, Steinhardt and Turok propose that the universe is smoothed to the requisite flatness and homogeneity as it contracts. Their approach is controversial, however, and there is some debate over whether it has been ruled out (Planck Collaboration et al. 2014b) by CMB observations made by the European Space Agency’s Planck satellite, or remains viable (Ijjas and Steinhardt 2016).

3. Mirror Universes and Backwards Time

Time’s arrow has perplexed scholars for centuries: why can we only travel in one direction, from the past to the future, and never in reverse. Physics brings the problem into even sharper relief because equations governing the motion of particles are time-symmetric—they are equally valid whether they run forwards or backwards. In 2014, Julian Barbour and colleagues proposed an audacious cosmological model that preserves overall time symmetry, while providing our universe with a twin—a mirror cosmos created alongside ours during the Big Bang. This twin evolves identically to our own, but with time’s arrow reversed (Barbour 2014).

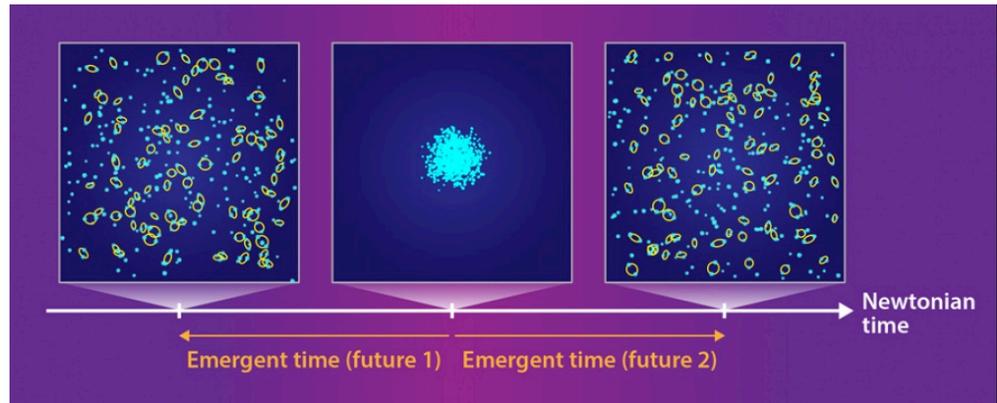


Figure 13: According to the shape dynamics framework, the Big Bang birthed two universes, with opposing arrows of time. (Image credit: APS/Alan Stonebraker.)

The novel cosmology stems from Barbour’s alternative approach to general relativity, called “shape dynamics,” in which the evolution of objects is defined in terms of their relation to each other, rather than against a spacetime backdrop. Such a framework has been shown to reproduce the equations of general relativity (Gomes 2011). Computer simulations to track the evolution of matter backwards in time revealed a mirror universe that may have been spawned along with ours (Figure 13). (It’s worth noting that Sean Carroll and Jennifer Chen have also invoked the idea of universes with opposing

arrows of time, but within the multiverse scenario (Carroll 2004.) [JTF's Time review](#) discusses the puzzle regarding time's arrow in more depth.

It's not clear how viable any of these less-conventional cosmological models are. But then, there's not likely to be a final resolution until physicists come up with a fully satisfactory merger of quantum theory and general relativity—a merger that, as discussed in the [JTF review of Emergence](#), is widely expected to encompass not just the origin of the universe, but the origin of space and time themselves.

It's fair to say, however, that no rival models have anything like the widespread acceptance enjoyed by inflationary cosmologies. As mentioned briefly above, confidence in inflation was boosted in part by the discovery in the late 1990s that the expansion of the universe is accelerating, a phenomenon attributed to some unknown source dubbed “dark energy.” The next chapter describes the series of independent observations made over the course of decades that suggest that the bulk of the universe is a mystery, made up of invisible and unidentified “dark matter” and dark energy—and attempts by physicists to work out what these entities may be.

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5. THE DARK UNIVERSE

In Chapter 4, we saw how the cosmic microwave background (CMB) draws a veil across the early universe. And we looked at how scientists have tried to peer past that barrier by extrapolating known physics back as far as it will go—only to end up with a radically new picture of what the Big Bang *was*, and what cosmic origins might really entail.

In this chapter, we'll look at the theorists and observers who've spent those same decades focused on this side of the veil, where they have begun to discover that “known physics” leaves out a lot. Indeed, by pioneering ever more precise and sophisticated versions of their standard tools—spectroscopy, the cosmic distance ladder, and observations of the CMB—these researchers have uncovered at least two major phenomena that are utterly mysterious and absolutely invisible, but that have shaped the evolution of the universe in profound ways. The first is “dark matter,” an unknown substance that is now thought to comprise around 80% of matter in the universe, dwarfing the visible matter we see around us. The second is “dark energy,” a mysterious entity that astronomers believe is causing the cosmic expansion to accelerate. Until astronomers and cosmologists get a better handle on these two factors, they will struggle to understand exactly what happened at our universe's birth, how the cosmos has evolved since, and what its ultimate fate will be.

I. DARK MATTER

1. Missing Mass?

The first inkling of the dark universe's existence came in 1933, when Fritz Zwicky stumbled upon a striking anomaly hidden in the landmark survey of galactic redshifts that Edwin Hubble and Milton Humason had published just two years earlier, relating the velocity of galaxies to their distance from Earth (see Chapter 2.II.3). Zwicky noticed that several galaxies in the sample lay in a dense grouping known as the Coma Cluster (Figure 14), and showed quite a lot of scatter around the straight-line velocity-distance relation (E. Hubble and Humason 1931). Since the Coma galaxies are essentially the same distance from Earth, Zwicky realized, he just had to subtract their average redshift to get their random motions within the cluster. (The technical term is *peculiar* velocity.) And then, since the galaxies' mutual gravitational attraction was presumably what kept them from flying apart, and since the force

of gravity between objects is proportional to their mass, he could use those peculiar velocities to estimate the cluster's total mass.

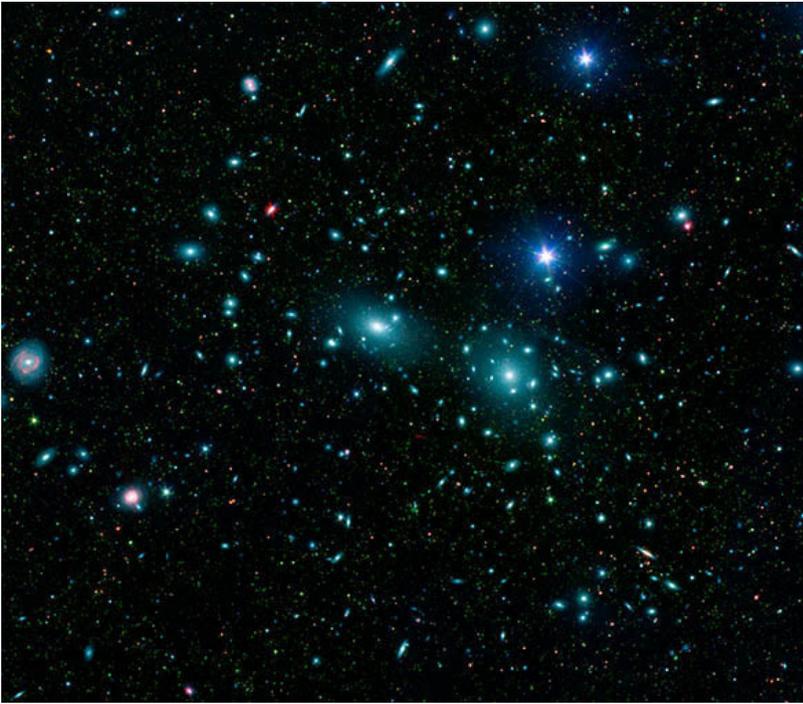


Figure 14: The Coma Cluster. (Image credit: NASA/JPL-Caltech/GSFC/SDSS.)

But therein lay the anomaly: When Zwicky estimated the Coma Cluster's mass from what astronomers could see—roughly 800 galaxies—he concluded that the random speed of a typical Coma galaxy ought to be about 80 kilometers per second. The peculiar velocities that Hubble and Humason actually saw were closer to 1000 kilometers per second. This meant that there was an enormous amount of gravity coming from something astronomers couldn't see—something that Zwicky, writing in German, called *dunkle Materie*: dark matter (Zwicky 1933).

Zwicky didn't think that this matter was invisible in any literal sense. He just thought that it was made of dim or burnt-out stars, or dense clouds of interstellar gas and dust: stuff

that was tough to see through a telescope (Zwicky 1937c). But still—1000 kilometers per second? Most astronomers found these cluster numbers to be so big and so baffling that they figured the analysis had gone wrong somehow—even if the alternatives didn't make much sense either.

Meanwhile, other astronomers had been looking for dark matter in individual spiral galaxies. Their strategy was essentially the same as Zwicky's: use the velocities you *can* see to measure the mass that you (mostly) can't. In the case of spirals, which were known to be rotating like pinwheels, this meant using spectroscopic red- and blueshifts (see Chapter 2.II) to get the rotation speed of stars further and further out in the spiral arms. Then Newton's law of gravity would allow you to relate the speed at any given radius to the mass inside of that radius.

In practice this was tricky, since the outer parts of spiral arms tended to be so faint it was hard to get good spectra. But in 1970, Vera Rubin and Kent Ford described how they had used a new, ultra-sensitive spectrograph developed by Ford to obtain a high-resolution rotation curve for the Andromeda galaxy (Rubin and Ford 1970). Their data encompassed essentially the entire visible disk, and showed that the rotational velocities out in the spiral arms weren't falling as fast with radius as might be expected. In fact, just as the arms were tailing off into invisibility, there were signs that the curve might be flattening out—a possibility that was soon confirmed in Andromeda and other galaxies by radio astronomers studying a strong spectral line emitted by interstellar hydrogen gas at a wavelength of 21 centimeters (Rogstad and Shostak 1972; Whitehurst and Roberts 1972; Roberts and Rots 1973; Roberts 1975). "If [these data] are correct," wrote one of the radio investigators, "then there must be in these galaxies additional matter which is undetected" (Freeman 1970). It was as if each spiral galaxy was embedded in a massive, but transparent, halo that extended far beyond the visible stars.

Although the astronomers who studied individual galaxies didn't often communicate with their colleagues working on clusters, two independent groups finally put their findings together in 1974, and suggested that both might have the same explanation: dark matter. A Princeton collaboration between James Peebles, Jeremiah Ostriker, and Amos Yahil, memorably made the case in their opening sentence: "the masses of ordinary galaxies may have been underestimated by a factor of 10 or more" (Ostriker, Peebles, and Yahil 1974).

This realization had profound cosmological implications. As described in Chapter 4.I.1, the average mass density of the universe is intimately tied to the universe's shape and its ultimate fate. If the density is higher than some critical value, then the cosmos will be 'closed' and eventually gravity will pull the universe back inwards in a crunch; if it is lower than this value, the cosmos will be 'open,' forever growing outwards; and if the average density of the universe is exactly at the critical value, the universe will be 'flat'—forever growing, but at a decelerating rate. Researchers had always assumed that the universe was open, since it appeared to contain relatively little matter. But now, both the Princeton group and a team led by Jaan Einasto calculated that this unknown stuff comprised at least 20% of the mass needed to close the universe, and conceivably might comprise all of it (Ostriker, Peebles, and Yahil 1974; Einasto, Kaasik, and Saar 1974). Or to put it another way, the density of dark matter might just determine the fate of the universe.

As time went on, the evidence for this conclusion would only get stronger; the best figures today show that ordinary matter makes up less than one-fifth the total mass in the universe (Planck Collaboration et al. 2018). But of course, that just leads to another obvious question: if dark matter is ubiquitous yet utterly invisible—what is it?

2. MACHOs or WIMPs?

The answer wasn't (and isn't) quite so obvious. Zwicky and his contemporaries had assumed that dark matter was made up of cold, non-glowing interstellar gas. But on close inspection, that simply wouldn't work. At the scale of clusters, observers looking at radio, optical, and X-ray wavelengths had indeed been able to find a faint haze of ionized hydrogen drifting in the space between galaxies, but it was not nearly enough to explain Zwicky's findings (Penzias 1961; Woolf 1967; Meekins et al. 1971).

Another possibility was that dark matter might be comprised of massive astrophysical compact halo objects, or "MACHOs"—a grab-bag category of objects that shared little except for being dense, dark, and infinitesimally tiny on a galactic scale. Astronomers knew of many candidates, both real and hypothetical. The list included dim red stars; old, burnt-out white-dwarf stars; faintly glowing brown dwarf stars without quite enough mass to ignite thermonuclear fusion; neutron stars formed from the cores of detonating supernovae; free-roaming, Jupiter-sized planets—even primordial black holes left over from the Big Bang. MACHOs remained viable dark-matter candidates well into the 1990s and 2000s, until multiple separate collaborations reported observations showing that there simply are not enough such objects in the universe to account for the missing matter (Irwin et al. 1989; Gould 2000; Alcock et al. 2000; Lasserre et al. 2000; Tisserand et al. 2007).

If not gas, and if not MACHOs that were dim but technically still visible, then maybe dark matter really was invisible. Maybe it was actually a swarm of elementary particles left over from the Big Bang (Feng 2010).

This idea emerged in the 1970s, and by the end of the 1980s had become most physicists' favorite explanation for dark matter. The stuff's otherwise baffling invisibility could be explained quite naturally if the particles were electrically neutral, and thus allowed photons to pass through without getting scattered or absorbed. Likewise with dark matter's ability to flow through stars, planets, and people,

without even slowing down: that would follow if the particles didn't respond to the strong nuclear force. And finally, since the Big Bang should produce the particles in vast numbers, dark matter's immense gravitational pull would follow if the individual particles had even a tiny mass. Thus the hypothetical entities' nickname: WIMPs, or weakly-interacting massive particles (Steigman and Turner 1985).

Adding to the plausibility of the WIMP idea was that real particles existed with each of these properties. And one family of them, the neutrinos, had them all: zero charge, tiny masses, no strong interactions, the works (Gershtein and Zel'dovich 1966; Szalay and Marx 1976; Lee and Weinberg 1977; Gunn et al. 1978; Doroshkevich et al. 1980). Unfortunately, the hope that neutrinos could account for dark matter didn't survive past the mid-1980s. When researchers used computer simulations to model how galaxies and clusters would have evolved over the eons, as explained more fully in section I.4 below, they soon found that the neutrinos-as-dark-matter assumption yielded results that did not match the actual observed distribution of galaxies and clusters in the universe. It's still possible that neutrinos are a small component of dark matter, but physicists are now confident that the main dark-matter particles have to be something else entirely. (JTF's [Fine-Tuning](#) review describes other recent experiments that suggest that new, and as yet unidentified, particles may exist.)

Fortunately, there are lots of other candidate particles—hypothetical, to be sure, but well-motivated by physicists' continued work on unified field theories (Feng 2010). One is the “axion,” which was proposed in the late 1970s as an essential add-on to the theory of quarks, gluons, and the strong interactions—a.k.a. quantum chromodynamics (Peccei and Quinn 1977a; 1977b; Wilczek 1978; Weinberg 1978). If the axion exists, it would have to be very light (10^{-6} to 10^{-4} electron volts, or less than a billionth the mass of an electron), and very feeble in its interactions with other particles. But it would also be stable and copiously produced during the Big Bang (Bertone and Hooper 2018, chap. V). The axion has thus been a prime candidate for the dark-matter particle ever since.

Other dark-matter candidates arose from theories in which our spacetime had more than the usual four dimensions, but with the extras curled up so tight that they were imperceptible. (The best-known example is superstring theory, which calls for 10 dimensions.) The effect of this curling-up would be to give every known particle a series of higher-mass partners, in somewhat the same way that an organ pipe produces a series of higher-pitched harmonics. When researchers worked through the details, several of these partners looked like good dark-matter candidates (Bertone, Hooper, and Silk 2005).

Meanwhile, another large family of dark-matter candidates had turned up as physicists developed “supersymmetry”—a mathematically elegant, but decidedly non-intuitive approach that calls for enlarging Einstein's spacetime with new dimensions that behave a bit like the square root of an ordinary dimension (Gervais and Sakita 1971; Gol'Fand and Likhman 1971; Wess and Zumino 1974). Fortunately, supersymmetry's practical effect was straightforward: each of our familiar particles would get paired with a super-partner. No such super-partners have ever been detected, but if they exist, they might be the missing dark-matter particles.

3. Detecting Dark Matter

Efforts to detect WIMPs follow three major strategies—direct detection, astrophysical annihilation, and new particle production—none of which have proved fruitful so far (Bertone, Hooper, and Silk 2005; Hooper and Baltz 2008; Bertone and Tait 2018; Bertone and Hooper 2018, chap. IX).

(i) Direct Detection

This approach starts from one fact—if dark matter really is made of WIMPs, then zillions of the particles will be streaming through our solar system every second—and one assumption: the particles'

interactions with ordinary matter will be very weak, but not quite zero. So the idea is to take a target made of ordinary matter and put it somewhere deep underground, away from other interference, and just watch and wait for some atom in the target to spontaneously emit an explosive spray of particles as if it had been hit by something that came from nowhere (Gaitskell 2004). That something will be a dark-matter candidate.

Experiments of this type have been underway since the 1980s, and have eliminated many theoretical possibilities for dark-matter particles. Yet not one of them has seen an unambiguous dark matter signal. In 2020, to take the most recent example, the XENON1T team in Italy announced that their 3.3 tonne, liquid-xenon-filled detector in the deep underground Gran Sasso Laboratory had found a signal that was consistent with an axion coming from the sun, or possibly a new kind of neutrino (Aprile et al. 2020) (Figure 15). They could not rule out contamination from radioactive tritium, however;



Figure 15: The heart of the XENON1T apparatus being assembled in the clean room. (Image credit: XENON1T.)

so this detection is currently unconfirmed. Getting a more definitive answer will be a job for one of the next-generation dark-matter experiments now coming on line.³

A number of researchers have also pointed out that most existing detectors assume that dark-matter particles are heavier than the proton—and would have missed them if the particles are actually very light. So instead, these scientists have proposed detectors in which light dark-matter particles passing through a solid-state device could excite a subtle electronic excitation known as a “plasmon” (Kurinsky et al. 2020; Kozaczuk and Lin 2020), or an even more subtle spin excitation known as a “magnon” (Trickle, Zhang, and Zurek 2020).

(ii) Astrophysical Annihilation

Another approach checks to see if dark-matter particles out in interstellar space might occasionally collide and destroy one another, producing either a pair of detectable gamma rays (Gunn et al. 1978; Stecker 1978), or perhaps a proton and antiproton (Silk and Srednicki 1984). Alternatively, dark-matter particles trapped in the core of the sun might accumulate over the eons and annihilate into neutrinos detectable here on Earth (Krauss et al. 1985). Again, however, no one has yet found an unambiguous signal from dark-matter annihilation (Bertone and Hooper 2018, chap. IX; Porter, Johnson, and

³ Next-generation dark-matter detectors include: XENON1T’s successor, the 8-tonne XENONnT in Gran Sasso; the 7-tonne, xenon-filled LUX-ZEPLIN (LZ) experiment located in an former gold mine in South Dakota; the solid-state Super Cryogenic Dark Matter Search (SuperCDMS) at the SNOLab in Ontario; and the second-generation Axion Dark Matter experiment (ADMX G2) at the University of Washington.

Graham 2011). The center of the Milky Way does show a gamma-ray excess consistent with dark-matter annihilation (Goodenough and Hooper 2009; Daylan et al. 2016), but further work is needed to confirm this possibility.

(iii) New Particle Production

Some physicists are trying to make dark-matter particles in a high-energy accelerator such as the Large Hadron Collider (LHC) outside Geneva, Switzerland (Boveia and Doglioni 2018). This is much easier said than done, however. Not only would the collision events that produced a dark-matter particle be exceedingly rare, but the experimenters wouldn't actually see the particle once they'd made it: the thing would fly out of the detector (and the solar system) without interacting with anything else, as utterly invisible as its dark-matter siblings out in space. Instead, physicists would have to infer its existence and properties by looking at the energy and distribution of all the other particles produced in the collision. And even if they managed to pull that off, they would know only that they had discovered an invisible particle, not that it was *the* invisible dark-matter particle.

It's worrisome that neither the LHC nor any other accelerator has yet found the slightest hint of a dark-matter particle, or supersymmetry, or extra dimensions. Of course, that could all change tomorrow—or more precisely, at some point after the spring of 2021, when the LHC is scheduled to finish its current round of upgrades and start generating data again with its beams set to a much higher intensity. This should allow it to do a much more thorough search for rare events. Likewise, events could start appearing at a new-generation dark-matter detector.

In short, the near future is rife with possibilities for dark-matter detection—or not. Stay tuned.

4. The Cosmic Web

Even if astronomers have yet to identify it, evidence has been mounting that dark matter is real. Further strong support comes from looking at the distribution of galaxy clusters across the sky, as observed by a number of huge telescope surveys. Astronomers had known for decades that this large-scale structure is at least somewhat hierarchical: stars form galaxies; galaxies form groups (a prime example being our own local group, which includes the Milky Way, Andromeda, and several others); and groups form clusters like Coma or Virgo. But there was thought to be few if any connections among the largest clusters, which seemed like isolated islands poking up from the Pacific. The first hint of something more came in 1982, when a team at the Harvard-Smithsonian Center for Astrophysics published the first large, 3-D map of the nearby universe constructed from redshift data on 2,200 galaxies (Davis et al. 1982). The authors

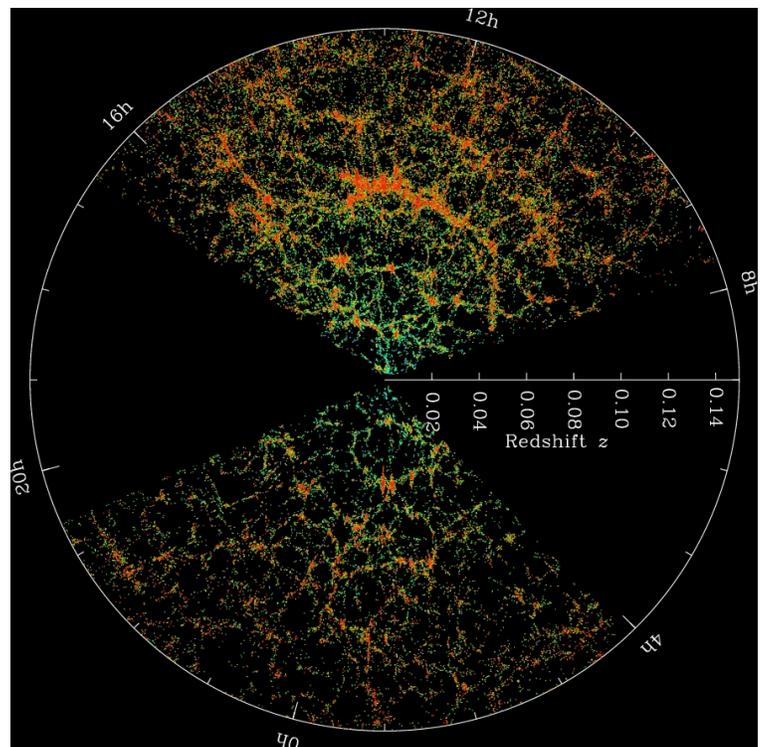


Figure 16: A modern map of the cosmic web, created by the Sloan Digital Sky Survey. Each dot is a galaxy. (Image credit: SDSS.)

described the galaxy distribution they found as “frothy,” as if they were taking a slice through a sea of soap bubbles with walls made of clusters and superclusters, and galaxy-free interiors forming voids more than a hundred million light-years across. Subsequent 3-D maps have pushed out to much greater distances, and have harvested redshifts from many more galaxies. But they show essentially the same frothy structure—the “cosmic web” (Figure 16).

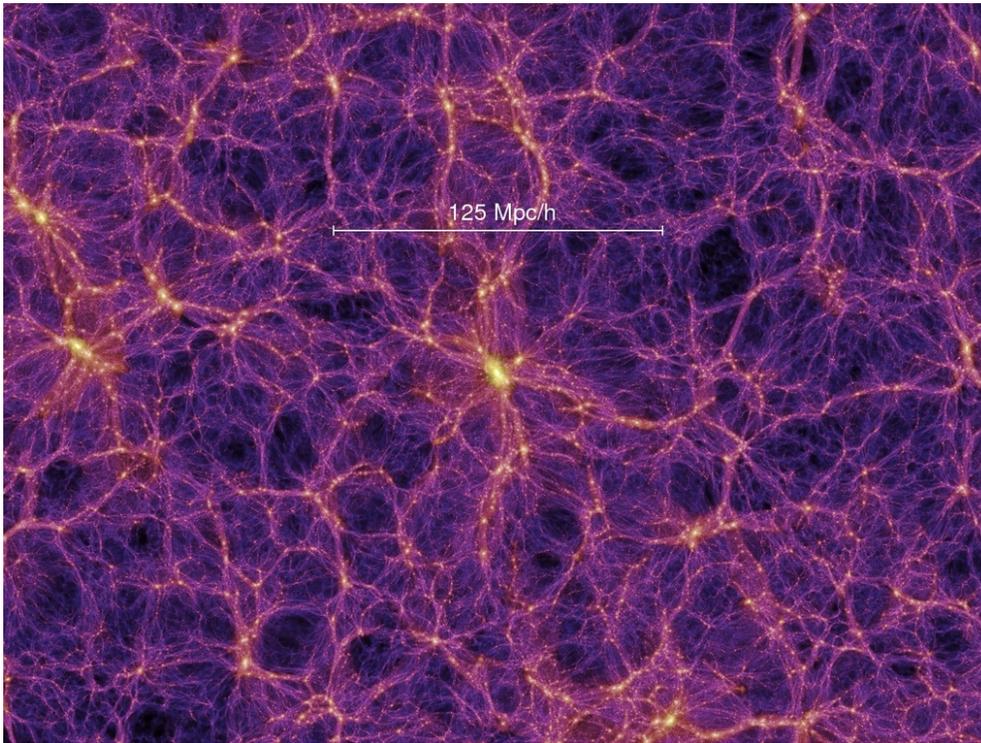


Figure 17: The Max Planck Institute for Astrophysics simulated the evolution of cold dark matter in a cubic region of the universe 2 billion light years on a side. The resulting cosmic web is statistically almost identical to the one seen in galaxy surveys. (Image credit: Springel et al.)

The existence of this cosmic web made it clear from the beginning that existing computer simulations of galaxy formation were missing something crucial (Efstathiou and Eastwood 1981). Such simulations had clusters, but no filaments and no web. The missing ingredient, obviously, was dark matter, and modelers rushed to include it. Very quickly, however, they found that their initial assumption—that the dark matter was made of neutrinos—simply would not work. The neutrinos emerging

from the Big Bang would still be moving at virtually the speed of light, making them far too “hot” to condense into the kind of filaments seen in the cosmic web (Frenk, White, and Davis 1983; White, Frenk, and Davis 1983). Much better were “cold” dark-matter particles: axions, WIMPs or anything else that would emerge from the Big Bang moving at speeds much slower than light (Peebles 1982; Bond, Szalay, and Turner 1982; Blumenthal, Pagels, and Primack 1982; Peebles 1984; Blumenthal et al. 1984). When modelers completed the first cosmic simulation using cold dark matter, they found that it would produce a large-scale web very much like the one being revealed in the redshift surveys (Davis et al. 1985). Figure 17 shows an example of such a simulation.

All of which is why the cold dark matter (CDM) paradigm has reigned ever since (Bertone and Hooper 2018, chap. VIII c)—albeit with one other critical caveat. As described in section II below, in the late 1990s, cosmologists would be astonished to discover that the universe is growing at an ever faster rate, forcing them to posit that it is being pushed outwards by another mysterious entity: dark energy. Once this was realized, cosmologists had the final piece of their own standard model.

Is Dark Matter an Illusion? The Case For (and Against) Modified Gravity

While most physicists accept that dark matter exists, a minority of researchers have investigated the possibility that the anomalies found by Zwicky, Rubin, Ford, and others, can be explained without invoking invisible matter. Instead they argue that Newton's law of gravity may need to be modified when applied to galaxies.

In 1963, Arrigo Finzi broached the possibility that the visible galaxies Zwicky noted to be moving surprisingly fast were doing so because gravity just pulls more strongly in these clusters than we expect (Finzi 1963). Two decades later, Mordehai Milgrom introduced a formula for Modified Newtonian Dynamics, or MOND, and gave a dark-matter-free account of galaxy rotation curves and the like (Milgrom 1983c; 1983a; 1983b). He and Jacob Bekenstein would spend the next two decades developing it into a much more sophisticated theory—a variant of Einstein's general relativity that made gravity tug harder than expected in some places (J. Bekenstein and Milgrom 1984; J. D. Bekenstein 1988; 2004; Bertone and Hooper 2018, chap. VII).

MOND struggled, however, when increasingly detailed data about galaxy clusters became available in the early 2000s (Aguirre, Schaye, and Quataert 2001). And in 2004, MOND's prospects went from bad to worse when astronomers got their first close look at the Bullet Cluster: a remote system in which two clusters were just emerging from a violent, 100-million-year-long collision (Tucker et al. 1998). Optical images showed that the visible galaxies had suffered minimal damage—mostly flying right through one another (Figure 18). At the same time, however, the intergalactic gas clouds (shown in pink) had hit hard, slowing them down and creating dramatic shock waves. High-resolution X-ray images captured by NASA's Chandra satellite showed that the two gas clouds are also starting to separate again, but are trailing well behind the visible galaxies.

The real eye-opener, however, was the dark-matter map of the Bullet Cluster derived from "gravitational lensing": an effect predicted by Einstein decades earlier. Lensing is what happens when light from a far-distant object is bent around a star, nebula, or galaxy, lying in between, producing a magnified image for astronomers here on Earth (Albert Einstein 1936). The lensing effect is larger for more massive objects, and can thus be used to estimate their mass (Zwicky 1937a; 1937b; 1937c). Such observations had already verified that clusters in general contain a lot more mass than can be accounted for by visible matter alone (Tyson, Valdes, and Wenk 1990; Kaiser and Squires 1993; Mellier 1999; Massey, Kitching, and Richard 2010). And now, with the Bullet Cluster, the lensing maps showed two lobes of dark stuff (in blue) aligned along the same axis as the gas clouds, but centered much further out—right on top of the two visible clusters. The dark-matter clumps, along with the visible galaxies, had clearly passed right through one another feeling no friction at all—even as the clouds of gas were suffering a trainwreck. The obvious conclusion was that dark matter and visible matter are two separate things that can move independently—a fact that was virtually impossible to square with any form of modified gravity (Markevitch et al. 2004; Clowe et al. 2006). In the years since then, as astronomers study more colliding clusters, that conclusion has only grown stronger (Harvey et al. 2015).

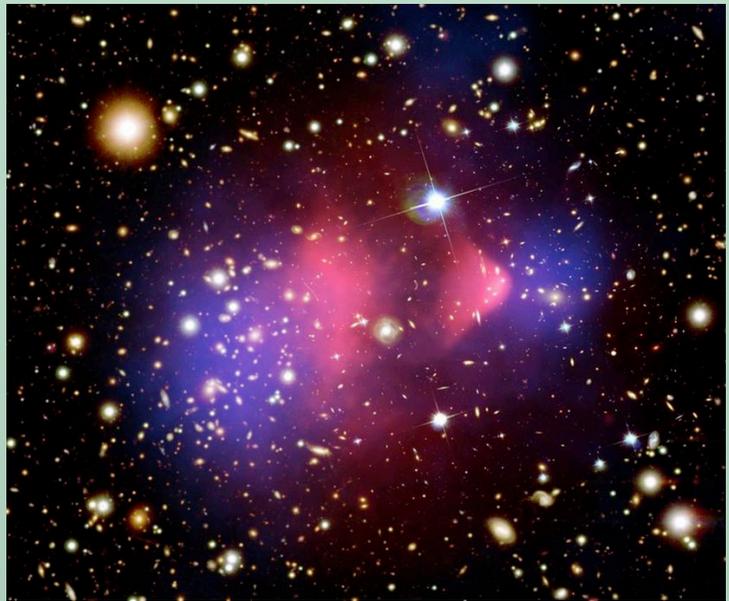


Figure 18: The Bullet Cluster. Hot gas from one cluster (pink) has passed through the hot gas in another. But most mass is found, by gravitational lensing, to reside in the blue clumps. (Image credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)

II. DARK ENERGY

1. The Return of the Cosmological Constant

Cosmology entered the 1990s with the cold dark matter (CDM) model looking like the model to beat (Calder and Lahav 2010). But in a landmark study published in 1990, a team of astronomers scanned 20 years' worth of astronomical imagery from Australia, and compiled a map of some two million galaxies spanning much of the southern hemisphere (Maddox et al. 1990). What they found was that the real universe shows a lot more clustering at the largest scales than any pure CDM simulation could account for, and that only one fix was truly consistent with the data—an idea that Einstein had posited back in the early 20th century and then dismissed.

In Chapter 2, we saw how Einstein had been disturbed to find that his equations of general relativity implied that the universe was unstable; they suggested the cosmos must either be growing or shrinking. To counter this effect, Einstein introduced a cosmological constant into his equations that would push space outwards balancing the inward pull of gravity and keeping his universe static. When Hubble and others showed that the cosmos is in fact expanding, Einstein threw out the cosmological constant as unnecessary. But now, cosmologists were starting to think it might actually exist—not least because computer simulations with a cosmological constant provided the best match with observational data (Efstathiou, Sutherland, and Maddox 1990).

Since Einstein and everyone who came after him had denoted the cosmological constant by the Greek letter lambda (λ , capital form Λ), this scenario soon became known as the Lambda Cold Dark Matter model: Λ CDM. Modelers soon found that they could bring the simulated cosmic web almost perfectly in line with observations if the universe actually contained a cosmological constant that was equivalent to maybe 60% to 70% of the universe's energy and matter budget, with the rest made up of matter (mostly dark matter, plus normal matter) (Martel 1991; Sugimotohara and Suto 1992; Cen, Gnedin, and Ostriker 1993; Cen and Ostriker 1994; Gnedin 1996a; 1996b).

When you put it all together, everything pointed in the same direction—toward a universe best described by the Λ CDM model (Ostriker and Steinhardt 1995; Calder and Lahav 2010).

But such a cosmological constant would create an outward push on the universe, and there was no observational data hinting at such an effect. Not until 1998.

2. Accelerating Expansion

In the 1990s, two rival teams of astronomers had been racing to perfect their observations of type Ia supernovae (Figure 19). This class of exploding stars promised to become a whole new kind of standard candle—which, as we saw in Chapter 2.II.2, are celestial objects whose luminosity can be accurately measured and used to pinpoint their distance from Earth (Kirshner 1999). In 1998, after meticulously refining their distance data, both teams announced the same jaw-dropping result: the universe is not just expanding as Hubble and others had shown. Its growth is accelerating (Riess et al. 1998; Perlmutter et al. 1999; Kirshner 1999).

This acceleration was astonishing because astronomers assumed that, while the universe may have been blasted outwards by the Big Bang, its expansion rate should now be slowing down as the gravity between its contents pulls matter inward. The data from both groups also fit with the picture of a cosmological constant that corresponds to about 70% of the universe's density, with matter (both dark and visible) making up 30%.

It was this dramatic revelation that pushed cosmologists toward a broader acceptance of the Λ CDM idea, although they weren't always happy about it. The model was still asking them to embrace two mysteries instead of one, dark matter and this new thing, Λ . It left everyone wondering what Λ actually was. An honest-to-Einstein constant that affected every point in the universe's vacuum equally, for



Figure 19: G299 is the remnant leftover after a Type Ia supernova—the thermonuclear explosion of a star, involving the fusion of elements that releases vast amounts of energy. (Image credit: NASA/CXC/U. Texas.)

example? Some new kind of quantum field that could vary (very slowly) from place to place and moment to moment (P. J. Steinhardt and Caldwell 1998)? Something even weirder (Caldwell 2004)? No one knew—then or now. The best anyone could do was cover all the possibilities with a catchy new name for Λ : “dark energy” (Turner 1999).

Dark energy raised an additional mystery regarding its measured value. Particle physicists know how to calculate the magnitude of a cosmological constant that takes the form of an energy pervading the vacuum. But their sums suggest that it should be much bigger than observed, by a factor of 10^{120} . If it did take on that immense value, however, the early universe would have barreled outwards so fast that no structure could ever have formed—which is why Steven Weinberg used anthropic arguments (introduced in the previous chapter) back in the 1980s to argue that if any cosmological constant exists, it must have a small value (Weinberg 1987). Any larger, and we wouldn't have evolved.

Following the lines of argument given in Chapter 4, section II.2, multiverse proponents thus cite the strange and fortuitous (for the formation of human life) value of dark energy as another example of a fine-tuning puzzle that can be solved by accepting an inflationary multiverse. If many other universes exist, then it's plausible that at least one would contain a rare small value for the cosmological constant, while larger values are instantiated in other cosmoses. (See JTF's [Fine-Tuning review](#) for more about such anthropic arguments.)

Yet there it was: despite the confusion (and the ongoing contentiousness of anthropic arguments) the dark-energy/ Λ CDM scenario was the only one left that fit *all* the data. And for any remaining doubters, it soon got an even more spectacular confirmation from a completely different source, the cosmic microwave background experiments.

3. Baryon Acoustic Oscillations

Physicists use the term “baryonic,” from a Greek word meaning heavy, for any type of normal matter containing protons, neutrons, or more complex atomic nuclei—a category that includes gas clouds, stars, planets, and us. Back in the 1970s, physicists realized that the hot plasma of baryonic matter in the early universe would be caught in a battle between gravity, which was constantly trying to pull the hot plasma into clumps, and photons, which were constantly trying to push the ions apart again (Sunyaev and Zel'dovich 1970; Peebles and Yu 1970). This push-and-pull would create cosmic sound waves: the plasma would literally have been humming. Later research also showed that the expanding cosmos would have acted on these so-called “baryon acoustic oscillations” something like an organ

pipe, enhancing those wavelengths that resonated while damping those that didn't (Hu, Sugiyama, and Silk 1997).

Astronomers cannot directly measure such oscillations today, because they would have stopped during the cosmic era of 'recombination' when the plasma turned into a bunch of neutral atoms and the photons flew away to become the CMB, as described in Chapter 3.III. But, as we saw in the previous chapter, the CMB contains slight fluctuations in temperature caused by inflation. Astronomers realized that signs of the organ-pipe effect would have lived on in those CMB temperature fluctuations (Tegmark 1997).

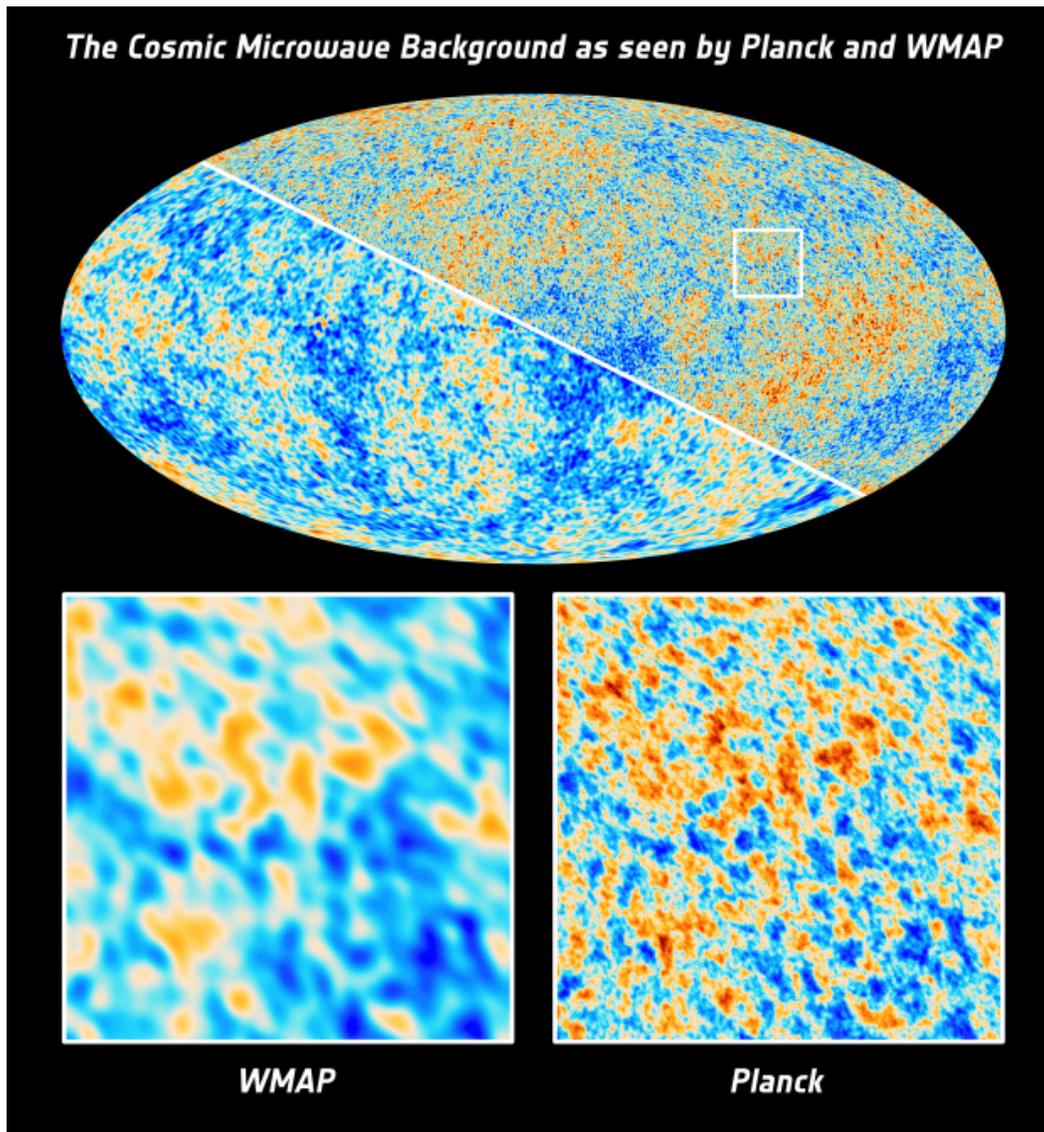


Figure 20: ESA's Planck satellite saw the CMB with three times better resolution than NASA's WMAP satellite that preceded it. (Image credit: © ESA and the Planck collaboration; NASA/WMAP Science Team.)

If, of course, you could get the data. This baryon acoustic oscillation approach was hypothetical until NASA launched its Cosmic Background Explorer satellite (COBE) in 1989. A year later, COBE returned the first really precise measurement of the CMB temperature: 2.735 ± 0.06 K (Mather et al. 1990). And in 1992, it finally detected those elusive temperature variations—or anisotropies, as they are known in the trade (Smoot et al. 1992). The anisotropies turned out to be tiny, only a few parts in 100,000, and unfortunately COBE's microwave vision was much too fuzzy to see any of the baryon

acoustic peaks, which were predicted to start showing up at angular resolutions better than about 1° . But by decade's end, finer-grained microwave data obtained from balloons, sounding rockets, and ground-based observatories in the Andes had begun to show hints of a peak pretty much where the Λ CDM model predicted it would be (Miller et al. 1999, fig. 2). In 2000, two long-duration balloon experiments, BOOMERanG in Antarctica and MAXIMA in Texas, convincingly measured that peak and beyond (de Bernardis et al. 2000; Hanany et al. 2000; Balbi et al. 2000; MacTavish et al. 2006).

Then in 2001, NASA launched the Wilkinson Microwave Anisotropy Probe, or WMAP,⁴ which scanned the entire microwave sky with 33 times the resolution of COBE and 45 times its sensitivity (Bennett et al. 2003) and found peaks fitting beautifully with a Λ CDM universe (Spergel et al. 2003; 2007; Hinshaw et al. 2009; Bennett et al. 2011; Komatsu et al. 2011; Larson et al. 2011; Bennett et al. 2013). WMAP was later superseded by the European Space Agency's Planck spacecraft, which has measured the peaks with even greater accuracy (Planck Collaboration et al. 2018, fig. 1) (Figure 20).

Down on the ground, meanwhile, astronomers were extracting an alternative view of the baryon acoustic oscillations from the large-scale galaxy surveys mentioned above—notably the Sloan Digital Sky Survey. The researchers' thinking was that the cosmic web of galaxies and clusters would still show signs of the peaks and valleys that the oscillations had imposed on the CMB-era density anisotropies. And they were right: they consistently found that the resonance peaks and other cosmological parameters fit very well with the Λ CDM predictions (Percival et al. 2001; 2002; Anderson et al. 2012; Dawson et al. 2013; SDSS 2020; eBOSS Collaboration et al. 2020).

4. The Standard Model of Cosmology

The fundamental conclusion following the discoveries of dark matter and dark energy—and measurements of the subtle temperature variations in the CMB—is that the Λ CDM model describes the universe beautifully; none of the other models come anywhere close. The inferred levels of dark energy and dark matter together imply that the universe is flat, which was a prediction of inflation theory, as noted in the previous chapter, giving that framework another observational boost.

In short, all the pieces of the puzzle seemed to have fallen into place, with numerous independent experiments and observations dovetailing neatly.

Apart from one nagging discrepancy, that is. As described in Chapter 6, there's one parameter that all these different measurement techniques disagree on: the exact value of the Hubble parameter, introduced in Chapter 2, which indicates the universe's growth rate. That means that ironically, as cosmologists get a better handle on the processes that occurred soon after the Big Bang—allowing them to ponder with increasing confidence what might have happened before it—they are becoming less and less certain of *when* the Big Bang happened. Initially, astronomers assumed that as their experiments improved, the tension between their calculations of our universe's age would evaporate. It turns out they were wrong, with additional ever more precise data only exacerbating the confusion. This discrepancy is creating a profound crisis for cosmology, as we shall see in the next chapter.

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⁴ Originally called “MAP,” WMAP was renamed to honor David Wilkinson, one of the first to confirm the existence of the CMB in the 1960s, as described in Chapter 3. Wilkinson had been one of the prime movers behind COBE and this mission, before his 2002 death from cancer.

6. THE CRISIS OVER THE AGE OF THE UNIVERSE

A century ago, astronomers had only the vaguest understanding of our own Milky Way, much less the rest of the universe, and considered speculation about cosmic origins to be a waste of time. Today, after multiple revolutions in perspective, they are routinely measuring cosmological quantities with incredible accuracy, to two and three decimal places, if not more.

But better measurements have a way of raising as many questions as they answer, forcing cosmologists to rethink everything they thought they knew. In this chapter, we turn to one of the biggest mysteries today: What is the age of the universe? The trouble is that depending on which method astronomers use to estimate the universe's age, they can get very different answers—off by about a billion years. This raises the possibility that the standard model of cosmology—and with it the picture of cosmological origins honed over the preceding decades—may be wrong.

I. THE HUBBLE TENSION

The age of the universe is intimately related to the value of the Hubble parameter, H_0 , which was first described in Chapter 2.II.3 and serves as a measure of the rate at which the cosmos is expanding. Recall that early in the 20th century, Edwin Hubble and others had established that the universe is growing in size by noting that most other galaxies appear to be receding away from our planet. (In fact, all galaxies are receding away from all other galaxies, on average.) They found that the speed v at which the galaxies are moving away from Earth is directly related to their distance D from us, according to the equation $v = H_0 D$, where H_0 is just a constant that astronomers could estimate by making observations.

The inverse of this parameter, $1/H_0$, is actually a measure of the time since the Big Bang—a larger measured value of H_0 would imply that the universe is relatively young, while a smaller value would suggest that the universe is older. It seemed reasonable to assume that as the decades passed and observations and experiments became more sophisticated, astronomers would get closer to the true value of H_0 and thus have a more precise handle on just how long our universe has been around (or, if you are a proponent of the multiverse view, how long the bubble of the multiverse that we call home has existed).

As described in Chapter 5.II.3, some of the most precise measurements to have been carried out in recent years have been those made of the cosmic microwave background (CMB). In 2013, the Planck science team released their first tranche of data from their CMB observations (Planck Collaboration et al. 2014a). Included was their best estimate for the Hubble parameter: 67.11 kilometers per second per megaparsec. (The current best figure, after further refinement, is 67.44 ± 0.58 in the same units (Planck Collaboration et al. 2018).) The Planck numbers fit with the estimates of the age of the universe made by earlier measurements of the CMB by NASA's Wilkinson Microwave Anisotropy Probe (WMAP), landing at an age of around 13.8 billion years for the universe. But rather than celebrating, astronomers had the sinking feeling that something might be going very wrong.

The problem was that just two years earlier, the Supernovae, H_0 and Equation of State (SHoES) consortium based at the Space Telescope Science Institute in Baltimore had completed its own quest to determine H_0 . They made their estimate using a different technique that involved two types of standard candles. As discussed in Chapter 2.II.2, standard candles are variable stars or supernovae whose distance from Earth can be pinned down extremely accurately when astronomers measure their luminosity. In Chapters 2 and 5, we saw how they were used to prove two shocking revelations about the cosmos—first that it was bigger than thought, and expanding, and then that this growth is mysteriously accelerating. Using the same methods, the SHoES team used the Hubble Space Telescope

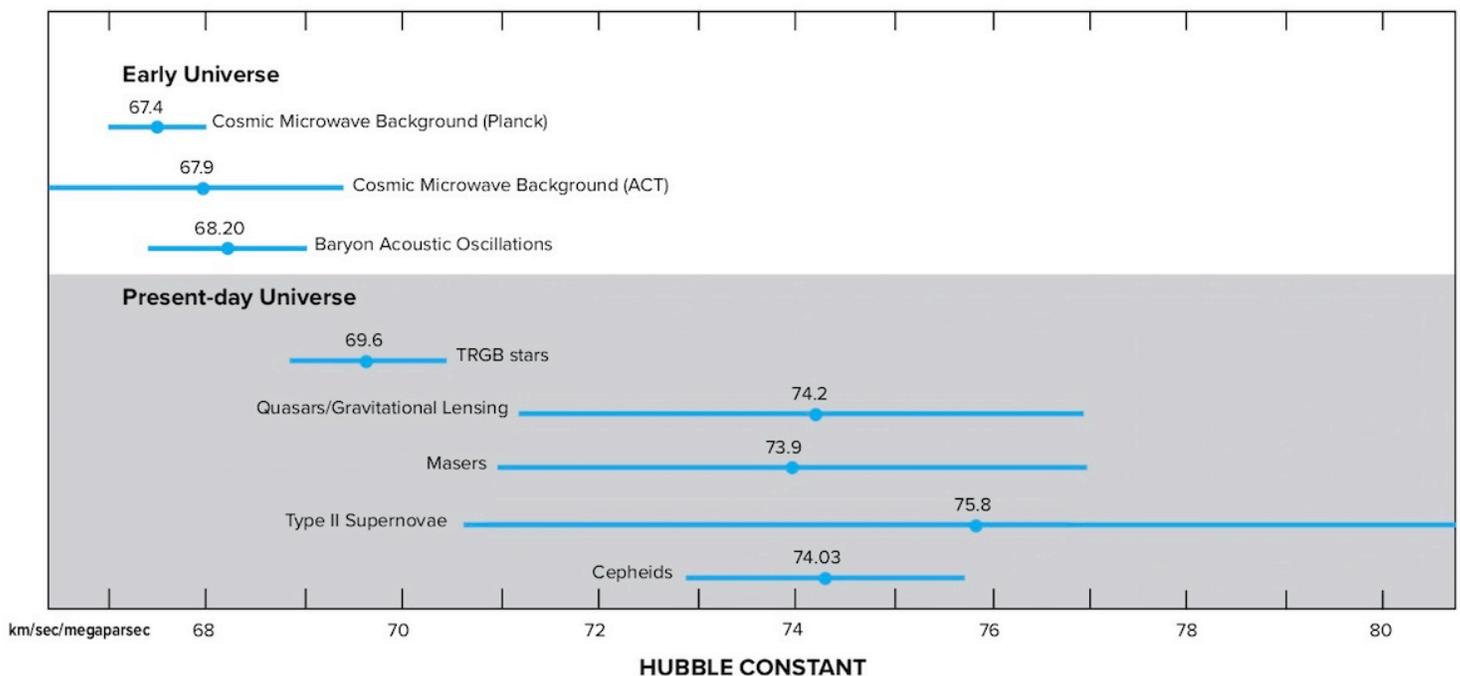
to monitor Cepheid variable stars and Type Ia supernovae in the same galaxies, and calculated that H_0 is 73.8 ± 2.4 kilometers per second per megaparsec—10% higher than the Planck result. (The current best value from the SHoES group is 74.03 ± 1.42 in the same units (Riess et al. 2019).) Even taking into account that there may be some leeway in these numbers due to errors in the measurement techniques, these numbers are way off (Riess et al. 2011). If nothing else, this would correspond to a universe at least a billion years younger than the Planck/WMAP age of 13.8 billion years.

Now, discrepancies crop up all the time in astronomy, especially when it comes to cosmology. But this billion-year mismatch is too huge to shrug off.⁵ It's a testament to how precise these measurements have gotten that this difference was widely seen as a crisis. In an effort to pinpoint where the problem lay, cosmologists turned to every alternative measure of the Hubble parameter that they could think of—and soon concluded that something was *really* wrong (Verde, Treu, and Riess 2019).

When they looked at estimates of H_0 derived from physics in the early universe, at or before the CMB formation at 380,000 years, they always got low numbers consistent with the Planck value of 67.44. A good example was an estimate of about 68 for H_0 derived from a combination of baryon acoustic oscillations (described in Chapter 5.II.3) and an analysis of how nuclei heavier than hydrogen formed in the early universe, primordial nucleosynthesis (Cuceu et al. 2019).

But when they looked at direct measures of H_0 based on recession velocities and distances to objects in the late universe—quasars, galaxies, clusters, and the like, within a few billion light years of our cosmic neighborhood—they always got high numbers consistent with the SHoES result. Examples included Cepheid variables in the Large Magellanic Cloud, a satellite galaxy of the Milky Way (Riess et al. 2019); multi-image gravitational lenses, as described in Chapter 5.I (Shajib et al. 2020); and high-resolution tracking of naturally occurring “masers” (astrophysical objects that emit microwaves) as they orbit around supermassive black holes (Pesce et al. 2020). (Figure 21 compares the values measured by various techniques.)

Figure 21: The Hubble Tension. (Image created by Maayan Harel for FQXi.)



⁵ Technically, it is described as a difference of more than four standard deviations, which means it cannot be ignored.

II. RESOLVING THE TENSION

This “Hubble tension” has caused much consternation in the cosmology community, and has inspired many attempts to resolve it.

1. Changing the Standard Model of Cosmology

One strategy is to note that H_0 can't be determined from the CMB in isolation; it pops out of the data only when you take the standard model of cosmology—the Lambda Cold Dark Matter (Λ CDM) model—as a given. Recall from Chapter 5 that this model assumes that the universe is flat, there is a small cosmological constant (causing the expansion of the universe to accelerate), and the cosmos is filled with cold dark matter. It seems sensible to think that if you change this model, maybe you could adjust the low H_0 number.

But change the model how? Theorists have struggled mightily to come up with a replacement for Λ CDM that could resolve the Hubble tension while preserving its extraordinary successes, including its predictions for the flatness of the universe, the slight temperature fluctuations in the CMB (the anisotropies), or the fluctuations in the density of visible matter (the baryon acoustic oscillations), and all the rest. They've postulated the existence of new kinds of fields, new phases of matter that vanish just before the CMB forms—on and on. So far, however, none of these alternatives have gained wide acceptance (Knox and Millea 2020).

2. The Cosmic Distance Ladder

Another approach to resolve the discrepancy notes that from Hubble's law, H_0 is just the ratio of an object's cosmic expansion velocity, v , to its distance, D , given by: $H_0 = v/D$. Velocity can be measured quite accurately from the object's spectrum. But distance? Well, that can only be obtained through an elaborate series of overlapping measurements known as the “cosmic distance ladder.” First, as discussed in Chapter 2.II, you use parallax to relate the known diameter of Earth's orbit to the distance of objects in our stellar neighborhood. Then you use parallax to calibrate the distance to various standard candles—notably the very bright Cepheid variable stars that can be seen in nearby galaxies. And finally, as mentioned earlier in this chapter, you use Cepheids to calibrate an even brighter standard candle: the Type Ia supernovae that allowed the discovery of cosmic acceleration. Thus the skepticism: when you do a string of overlapping calibrations like this, errors can accumulate. So maybe that was the source of all these late-universe, high- H_0 results: somewhere along the line, someone had made a mistake.

But where? Astronomers have had lots of experience with the distance ladder by this point. The SHoES team, in particular, has done meticulous work, with multiple cross-checks; neither they nor anyone else has found a serious error. Furthermore, the distances obtained from techniques such as maser tracking are independent of the classic distance ladder—but yield a high H_0 anyway (Pesce et al. 2020).

If nothing else, the impasse put an intense focus on an alternative distance-ladder calibration method being explored by Wendy Freedman and her team. Known as the Tip of the Red Giant Branch (TRGB) technique, it called for skipping the Cepheid rung of the ladder entirely, and instead looking at the brightest red-giant stars in any given sample of a galaxy. Red giants represent an extremely luminous, end-of-life transition that happens in stars like our sun as they are running out of fuel, and they provide an excellent standard candle. Red giants can also be identified quite readily, even across

millions of light years. On the near end, the red giants' intrinsic brightness can be calibrated through the use of parallax here in the Milky Way and in neighboring Magellanic Clouds. And on the far end, they can be used to calibrate distances to the Type Ia supernovae.

In short, the red-giant technique promised to eliminate any subtle source of error lurking in the Cepheid calibration, and hopefully say which side of the Hubble tension was correct. But in September 2019, when Freedman and her team announced their new and highly anticipated value for H_0 using the TRGB technique, it came out to 69.6 ± 0.8 —right in between the late-universe high values and the early-universe low values (Freedman et al. 2019; 2020).

Astrophysicist Mike Boylan-Kolchin succinctly summed up the thoughts of most of the cosmology community when they heard the news: “The Universe is just messing with us at this point, right?”⁶

3. Redshift Surveys

In July 2020, two other much-anticipated surveys announced equally confounding results. On July 15, observers with the Atacama Cosmology Telescope in the Chilean Andes released the first ground-based map of CMB anisotropies that could rival the ones obtained by Planck (Aiola et al. 2020). Their H_0 came in at 67.9 ± 1.5 kilometers per second per megaparsec, perfectly consistent with Planck.

Then two days later, on July 17, the Sloan Digital Sky Survey (SDSS) released its most massive compilation of galaxy redshifts ever—a 3D map of the heavens that used quasars and other tracers to fill in the 11 or so billion years between the CMB and the galaxies used in the supernovae studies (eBOSS Collaboration et al. 2020). Among other things, the survey used baryon acoustic oscillations and other data to confirm that the universe is flat to a high precision, and that dark energy has behaved like an unchanging constant over that entire span of time, suggesting that the Λ CDM model is set up fine. And, in an attempt to avoid any uncertainties inherent in the traditional cosmic distance ladder, the SDSS team calibrated the velocity-distance relation with an “inverse distance ladder” that works backward from the CMB. Perhaps not surprisingly, then, their value for H_0 is 68.20 ± 0.81 —again, consistent with Planck.

And so the tension simmers, with no resolution yet. Either there is something wrong with the Λ CDM model (Riess 2019; Knox and Millea 2020), or there is something wrong with the distance ladder (Efstathiou 2020).

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7. CONCLUSION: CONCORDANCE AND BEYOND

As we've described throughout this review, scientific understanding of cosmic origins has advanced over the past century through a series of paradigm shifts: profound realizations that have forced cosmologists to rethink much of what they thought they knew about the universe.

A prime example is how the field has spent the past four decades converging on a *concordance* model of cosmic origins that encompasses virtually all the available data. Essentially it's the Λ CDM model. And as we've seen, it has four key elements:

- **The Big Bang:** The universe we see today has spent the past 13.8 billion years expanding outward from its origins—a hot, dense, explosive event that left an afterglow we now know as

⁶ @MBKplus on Twitter, 16 July 2019, retrieved 12 September 2020: <https://twitter.com/MBKplus/status/1150938134819102721?s=20>.

the cosmic microwave background, and that brewed a primordial mix of hydrogen, deuterium, and helium, in the ratios we still find today (Chapters 2 & 3).

- **Inflation:** The Big Bang itself emerged from a period of exponential expansion that stretched out the universe until it was completely flat in a geometrical sense, but that also left behind a series of density fluctuations that would eventually grow into today's cosmic web of galaxies. It would be too much to say that the concordance model also includes the theory of eternal inflation and the multiverse, which holds that our Big Bang was only one of many; this idea is too hard to prove observationally, and leads to anthropic arguments that too many researchers find distasteful. But if you accept inflation at all, the multiverse is difficult to avoid (Chapter 4).
- **Dark Matter:** The universe is partially filled with a mysterious, utterly invisible substance that outweighs the ordinary, baryonic matter that we are made of by roughly 5 to 1, and that exerts a gravitational pull that dominates the dynamics (and formation) of visible galaxies. No one can be completely sure what dark matter is, but it behaves like a swarm of weakly interacting, massive particles (WIMPs) left over from the Big Bang (Chapter 5).
- **Dark Energy:** The cosmic expansion is slowly being accelerated by an equally invisible, but even more mysterious substance that accounts for roughly 70% of all the mass/energy in the universe. Dark energy doesn't seem to be made of particles; so far as anyone can tell, it's mathematically equivalent to Einstein's cosmological constant, and affects every point of spacetime equally (Chapters 2, 5 & 6).

Of course, no one expects the concordance model to be the end of the story. The fact that we have not yet identified dark matter or dark energy, as outlined in Chapter 5, and that the Hubble tension discussed in Chapter 6 is still ongoing, may already be pointing us toward the next paradigm shift. But even if the dark-matter particles are found in one of the new-generation detectors, and even if the Hubble tension is resolved, there are questions still to be answered. Perhaps most fundamental is the deceptively simple question, “What banged?” Or to put in a slightly more formal way, how did dark energy, dark matter, inflation, and the Big-Bang singularity arise from physical law? And how do they all fit in with the multiverse idea—if indeed they do? Right now, all these components of the concordance model are just ... *there*, with no explanation.

Finding a more satisfying account may well require profoundly new ideas. But the search for them will at least have lots of guidance from new data. In 2021, for example, NASA is expecting to launch Hubble's successor, the James Webb Space Telescope. With more than six times Hubble's light gathering power, the Webb should provide uniquely clear insight into supernovae standard candles, gravitational lensing, and baryon acoustic oscillations in the cosmic web. Following close behind will be the European Space Agency's Euclid spacecraft, due for launch in 2022; and NASA's Nancy Grace Roman Space Telescope, scheduled for launch in 2025. Both will be specialized to carry out highly detailed studies of the dark universe at infrared wavelengths.

On the ground, a consortium of US funding agencies is constructing the Vera Rubin Observatory in the high Andes, with first light expected in 2022. Formerly known as the Large-Scale Synoptic Telescope, the observatory will photograph the entire visible sky in depth and detail—and then do it again, and again, and again every few nights for a decade or more. Among other things, this enormous dataset will catalog billions of galaxies, and will give astronomers an unprecedented view of how dark matter influenced their formation, and how (or if) dark energy has evolved over the lifetime of the universe.

And at microwave wavelengths, finally, a consortium of funding agencies and philanthropic foundations is constructing the Simons Observatory at another site in the Andes—right next to the Atacama Cosmology Telescope, in fact. The Simons site will have several telescopes optimized for studying the

CMB in even more detail than Planck could manage. One particular target will be *B-modes*: an extremely subtle, swirling pattern in the polarization of the CMB radiation (Figure 22). *B-modes* are widely considered to be the smoking gun for inflation. In fact, in 2014, the BICEP2 collaboration at the South Pole wrongly announced it had discovered them, and the ultimate evidence for inflation, before having to retract their result (BICEP2 Collaboration et al. 2014). That hiccup aside, finding *B-modes* would be the first direct proof that inflation actually happened—and would finally allow astronomers to study exactly how it happened.

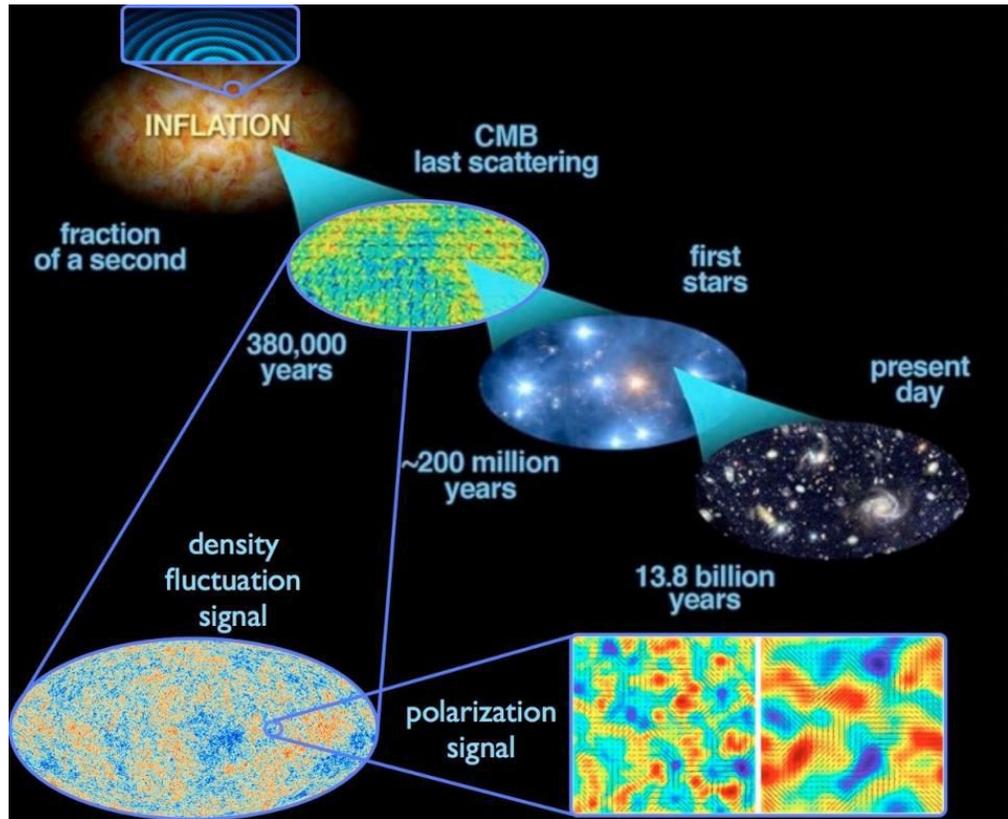


Figure 22: Cosmic History. Tiny fluctuations, amplified by inflation, give rise to everything we see in the universe today. The smoking gun of inflation will be the detection of a subtle polarization signal in the CMB. (Image credit: Ethan Siegel, with images derived from ESA/Planck and the DOE/NASA/NSF Interagency Task Force on CMB Research.)

In sum, then, no one can predict when the new ideas will come. But with all this new data pouring in, no one should be surprised if the coming decade brings yet more revolutionary changes.

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8. ACKNOWLEDGEMENTS

Alexander Vilenkin and Andrei Linde took the time to help me understand some of the subtleties of cosmic inflation theory, and João Magueijo showed me how certain “constants” of physics may actually have varied over time; please accept my deep appreciation. My thanks also go to Anthony Aguirre at FQXi, the Foundational Questions Institute, and to Thomas Burnett from the John Templeton Foundation, who not only conceived of this project, but coordinated the FQXi/JTF reviews. The illustrator Maayan Harel did a beautiful job developing the inflationary multiverse graphic and the Hubble tension diagram; thank you, as well. And of course, there is my editor Zeeya Merali, whom I have known since I was *her* editor back when she was writing mind-blowing cosmology and physics features for *Nature*. In either role, she has been a joy to work with.

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