

The Road to Precision Cosmology

Michael S. Turner^{1,2}

¹Kavli Institute for Cosmological Physics, University of Chicago, Chicago, Illinois, USA;
email: mturner@uchicago.edu

²The Kavli Foundation, Los Angeles, California

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Annu. Rev. Nucl. Part. Sci. 2022. 72:1–35

First published as a Review in Advance on
June 9, 2022

The *Annual Review of Nuclear and Particle Science*
is online at nucl.annualreviews.org

<https://doi.org/10.1146/annurev-nucl-111119-041046>

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Keywords

cosmic microwave background, cosmology, dark energy, dark matter, early Universe, inflation, particle cosmology, Lambda CDM

Abstract

In the past 50 years, cosmology has gone from a field known for the errors being in the exponents to a precision science. The transformation—powered by ideas, technology, a paradigm shift, and culture change—has revolutionized our understanding of the Universe, with the Lambda cold dark matter (ΛCDM) paradigm as its crowning achievement. I chronicle the journey of precision cosmology and finish with thoughts about the next cosmological paradigm.

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1. OVERVIEW

Only a half century ago, cosmology was the province of West Coast astronomers, the total number of redshifts measured was a few hundred, and high redshift meant $z \sim 0.1$. A “standard model”—the hot big bang model—had just emerged. Named and described in detail by physicist Steven Weinberg, it took the Universe from an early hot soup of hadrons to galaxies expanding away from one another. I call this the first cosmological paradigm.

Today, cosmology is mainstream, “industrial” science with a mix of more than a thousand astronomers and physicists around the world working to both understand the birth and evolution of the Universe and learn about the fundamental nature of matter, energy, space, and time. It used to be said about cosmology that the errors are in the exponents; true or not, the field was certainly data starved. Today, the term precision cosmology is a reality, and cosmology is an exemplar of big-data science.

The current—and second—paradigm, Lambda cold dark matter (Λ CDM), describes the Universe from a fraction of a second after the big bang—when the seeds for all the structure we see today were quantum fluctuations on subatomic scales—to the present, 13.80 ± 0.023 Gyr later. The Λ CDM paradigm is supported by a wealth of cosmological data, from tens of millions of redshifts extending to $z = 10$ to nanokelvin measurements of the cosmic microwave background (CMB) on angular scales down to arcminutes.

The progress over the past 50 years has been remarkable, driven by ideas, technology, big discoveries, a paradigm shift, and culture change. My review is not comprehensive (that would require a book), and it both benefits and suffers from being the perspective of an active participant. I hope that the reader also “hears” the story of the grand adventure that the past half century has been and the stunning opportunities ahead.

Section 2 is devoted to beginnings: the development of the hot big bang model, the explosion of technology, and the entrance of particle physicists into cosmology. Section 3 chronicles the development of the Λ CDM paradigm: the dark matter paradigm shift; the CMB discoveries that mark the birth of precision cosmology; the two big ideas—inflation and CDM—that underpin it; and last, but not least, the discovery of cosmic acceleration and dark energy, which completed

Λ CDM. Section 4 sings the praises of Λ CDM, highlights some of the grand opportunities ahead, and ends with some personal reflections.

2. BEGINNINGS

2.1. The First Paradigm: The Hot Big Bang Model

The Universe is big in both space and time, and for much of human history it has been largely beyond the reach of our boldest ideas and most powerful instruments. I mark the birth of modern cosmology at roughly 100 years ago. Albert Einstein had introduced General Relativity, the first theory of gravity and space-time capable of describing the entire Universe, and the first cosmological solutions had been found (e.g., the de Sitter, Friedmann, and Lemaître solutions as well as Einstein’s static model). At about the same time, George Ellery Hale and George Willis Ritchey invented the (modern) reflecting telescope, and Hale moved astronomy to the mountaintops of California—first Mount Wilson and, later, Palomar Mountain. With bold ideas and new instruments, astronomers were ready to explore the Universe beyond our own Milky Way galaxy and began to discover and understand the larger picture.

Hale’s second big reflector, the 100-inch Hooker telescope, enabled Edwin Hubble to discover that galaxies are the building blocks of the Universe today and that it is expanding—the signature of its big bang beginning. While it took a few years to connect the solutions of General Relativity to the observational data, the basics of the big bang model were in place.

The “hot” in the hot big bang model came with Penzias & Wilson’s (1) discovery of the CMB in 1964. While the idea of a hot beginning was introduced by Gamow and colleagues (2) in 1948 to explain the nonequilibrium origin of the chemical elements, the 1964 discovery was accidental—an interesting and oft-told story.¹

In 1972, years before Standard Model referred to the remarkable theory that describes quarks and leptons, Weinberg coined the term “standard model” for the hot big bang model and described it in his classic textbook (4). This standard model traces the Universe from a hot soup of hadrons at around 10^{-5} s through the synthesis of the light elements (largely ^4He with trace amounts of D, ^3He , and ^7Li) at a few seconds to the formation of neutral atoms and the last scattering of CMB photons at around 400,000 years after the big bang, and finally to the formation of stars and galaxies.

The first paradigm embodied the basic cosmological picture—expansion from a hot big bang beginning to a Universe filled with galaxies moving away from one another today. General Relativity, nuclear physics [for big bang nucleosynthesis (BBN)], and atomic physics (for the interpretation of the CMB) provided a strong theoretical foundation. The triad of the expansion, the light-element abundances, and the blackbody spectrum of the CMB provided an equally strong observational foundation.

In 1970, Sandage (5) summed up cosmology as the search for two numbers, H_0 and q_0 . The expansion rate of the Universe, H_0 , also sets the age of the Universe, $t_0 = aH_0^{-1}$, with the deceleration parameter q_0 determining the constant a . And for a universe made up only of matter, q_0 , the ratio of the matter density to the critical density (Ω_0), and the curvature radius of the universe are related: $q_0 = \Omega_0/2$ and $R_c = H_0^{-1}/|\Omega_0 - 1|^{1/2}$.

It would take until 2000 and the Hubble Space Telescope (HST) Key Project to pin down H_0 with a reliable error estimate: $H_0 = 72 \pm 2 \pm 6 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (statistical and systematic) (6). As I

¹ Both the CMB story and a more detailed history of the discovery and interpretation of the expansion can be found in Reference 3.

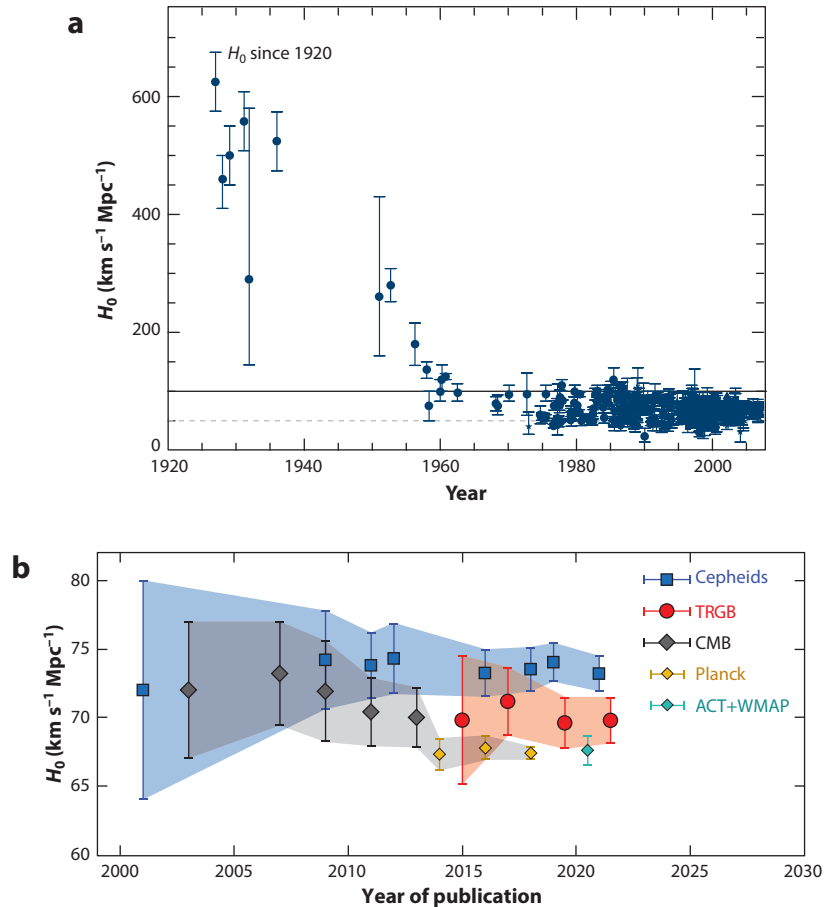


Figure 1

“Low-precision” and “high-precision” cosmology. (a) H_0 measurements from 1920 to 2000. By 1970, most measurements were between 50 and 100 $\text{km s}^{-1} \text{Mpc}^{-1}$ but with unrealistically small error bars. The Hubble Space Telescope Key Project changed that with its 2000 determination, $H_0 = 72 \pm 2 \pm 6 \text{ km s}^{-1} \text{Mpc}^{-1}$. Plot created by John Huchra, Harvard-Smithsonian Center for Astrophysics. (b) H_0 measurements since 2000. The Cepheid and TRGB data are from direct measurements of H_0 , and the CMB data use CMB measurements and the assumption of the Λ CDM to determine H_0 . The discrepancy between the CMB determinations and the methods that determine the current expansion rate is known as the Hubble tension and is discussed in Section 4.2.2. Panel adapted from Reference 189 (CC BY 4.0). Abbreviations: ACT, Atacama Cosmology Telescope; CMB, cosmic microwave background; Λ CDM, Lambda cold dark matter; TRGB, Tip of the Red Giant Branch; WMAP, Wilkinson Microwave Anisotropy Probe.

discuss in Section 4.2.2, H_0 remains a lively topic and continues to live up to its reputation as the most important number in cosmology (see **Figure 1**).

As for the deceleration parameter, the Universe is actually accelerating, and q_0 cannot be measured with both precision and accuracy.² While its value can be inferred ($q_0 = -0.55 \pm 0.05$), q_0

²The reason is simple: q_0 is the second term in a Taylor expansion relating distance to redshift z ; at large enough redshifts to determine q_0 , the Taylor expansion is not accurate. There are many better parameterizations for cosmic distance (see Reference 7).

has been replaced by other cosmological parameters that better capture the physics and that can be measured with accuracy and precision.

Two big questions loomed: How did structure form, and what happened during the first microsecond when the soup of hot hadrons would have been strongly interacting and overlapping? Gott's (8) review of galaxy formation in 1977 described the unsettled state of affairs for the gravitational instability picture, and Weinberg's (4) text described the difficulty of the early Universe—the hadron wall—and a glimmer of hope that an “elementary particle” description might eliminate this barrier to discussing the earliest history of the Universe.

2.1.1. Cosmo-sociology. During this period, cosmology was largely the province of astronomers and a few physicists (certainly fewer than 30 full-time cosmologists worldwide). The discovery of the CMB began to bring in physicists: Penzias and Wilson (radio astronomy physicists), Wagoner and Fowler [who with Hoyle carried out the first modern calculation of BBN (9)], and the Princeton group who interpreted the Penzias–Wilson discovery, Dicke et al. (10). This foreshadowed the large number of physicist–cosmologists we see today, who would begin entering the field soon.

The observational side of cosmology was dominated by the Californians with their big glass on Mount Wilson (2.5 m), Palomar Mountain (5 m), and Mount Hamilton (3 m). Until 1973, the rest of the world did not have an optical telescope on a mountaintop with aperture larger than 3 m.³ The situation today is very different, with 19 optical telescopes of aperture larger than 6 m around the globe, none in California.

2.1.2. Other activities. I have focused on US astronomers and the influence of Weinberg's (4) text, leaving out other cosmological activities. Peebles wrote his first book, *Physical Cosmology* (11), around the same time that Weinberg wrote his, but it was much less influential among physicists, in part because Weinberg's text was so complete, beginning with a full development of General Relativity.⁴ Peebles's second book, *The Large-Scale Structure of the Universe* (13), spurred the study of cosmic structure and was very influential among astronomers.

The controversy between the steady-state theory and the big bang model was brief because the nonevolving steady-state model was quickly ruled out by radio counts, quasars, and finally the CMB (14). Relativists, including George F.R. Ellis, Charles W. Misner, Stephen Hawking, Roger Penrose, and members of the Russian school led by Yakov B. Zel'dovich and Igor Dmitriyevich Novikov, were looking for important applications of General Relativity, and much of their work was on the nature of the initial singularity.

Zel'dovich wrote two interesting reviews of cosmology itself—one just before the discovery of the CMB (15) and one just after (16). The former argued against a high-entropy beginning because it predicted a background radiation of temperature 20 K, which was inconsistent with observations.⁵ The latter exuberantly described all the new avenues of research that the discovery had opened up as well as big questions that needed to be addressed.

³Because of its poor performance, I am not including the Russian 6-m BTA-6 telescope. The US National Science Foundation built 4-m telescopes for public use on Kitt Peak (1973) and Cerro Tololo (1976); the 3.9-m Anglo-Australian Telescope on Siding Spring Mountain (Australia) was built in 1974, and the European Southern Observatory (ESO) built a 3.6-m telescope at La Silla (Chile) in 1977.

⁴Further, Weinberg's popular book *The First Three Minutes* (12), published in 1977, had equations and was widely read by physicists.

⁵While the details of his prediction were scant, the physics appears to be correct, in contrast to the many predictions of Gamow and his collaborators (17).

2.2. Technology

Around 1970, astronomy was largely done with ground-based optical telescopes using photographic plates, which captured only 1% of the incident light. Radio and microwave astronomy were still young, though both played crucial roles in falsifying the steady-state theory. Computing did not yet play a decisive role in astronomy, though it was beginning to do so in other fields, notably high-energy physics.

The next 50 years would see epic changes in how astronomy is done: the introduction of electronic detectors in the 1960s and 1970s (photoelectric devices), followed by charge-coupled devices (CCDs) in the 1980s and the opening of new windows on the Universe: ultraviolet and infrared in the 1970s, x-rays and γ -rays in the 1970s and 1980s, neutrinos in the 2000s, and gravitational waves in 2016.

The transformational role of NASA's Explorer program and its four "Great Observatories" (Chandra, Compton, Hubble, and Spitzer) cannot be overstated. In particular, the HST pinned down H_0 and opened our eyes to the high-redshift Universe, from supernovae to the birth of galaxies. Its excellent, well-calibrated, reproducible observing conditions were necessary for and enabled precision cosmology.

Today, gigapixel CCD cameras collect almost 100% of the incident light and enable photometry with 1% precision, adaptive optics makes possible aperture-limited resolution on ground-based telescopes, and space-based observatories (US, European, and Japanese) view the sky from the far infrared to γ -rays. Global facilities like ALMA provide unprecedented resolution and sensitivity for imaging distant galaxies. And much more is ahead: JWST, Euclid, and the Roman Space Telescope in space, and the Rubin Observatory and two or three Extremely Large Telescopes with adaptive optics on the ground.

Amassing and analyzing the large, complex data sets that are being created is possible only because of the advances in computing and storage driven by Moore's Law. Taking advantage of the larger data sets and achieving precision cosmology requires complex simulations that connect the theoretical models with the raw data, taking account of how they are collected, from instrumental acceptance to astronomical seeing and foregrounds. Astronomers were among the first to adopt the use of powerful Bayesian techniques that allow theories to be tested and compared and multiple cosmological parameters to be extracted. Things have come a long way from χ^2 model testing!

Advances elsewhere were crucial. The search for dark matter particles and proton decay led to the development of new instrumentation and the birth of underground astronomy. Large ultra-sensitive, low-energy, low-background detectors are now deployed to detect dark matter particles and neutrinos in deep underground laboratories shielded from cosmic rays and other backgrounds. Today, underground science crosses multiple disciplines, from astronomy and physics to biology and geophysics.⁶

Martin Harwit's claim that progress in astronomy is driven by technological developments (19) is supported by cosmology. CMB discoveries were enabled by ever-increasing detector capability. Photoelectric imagers enabled the discovery of the existence of dark matter in galaxies. Wide-field CCD cameras and powerful computing made survey science and batch supernova discovery possible, which led to the discovery of cosmic acceleration.

Finally, with technology came culture change. Fifty years ago, an astronomer built the instrument, went to the mountaintop to observe, did the necessary theory, analyzed the data, and published the results, sending out a few hard-copy preprints after the paper was accepted. Today, there

⁶Underground science was pioneered in 1965 by Ray Davis and his solar neutrino experiment in the Homestake mine (18).

are instrumentalists, theorists, observers, phenomenologists, and data specialists. Queue observing and open access archives (pioneered by HST) have redefined observing; collaborations have grown to thousands, knit together by the web. And even astronomers post their preprints on the arXiv before journal submission. Without all of this change, many of the advances in cosmology would not have been possible.

2.3. Origins of Particle Cosmology

The roots of particle cosmology trace back to Gamow and his famous 1948 $\alpha\beta\gamma$ paper, written with Alpher and Bethe, which introduced the idea of BBN to explain the origin of the chemical elements (2). Gamow among others realized that equilibrium nucleosynthesis in stars could not explain the abundance pattern of the chemical elements, and, in grand style, Gamow turned to the big bang for a wildly nonequilibrium event.

2.3.1. $\alpha\beta\gamma$. Gamow and colleagues got much wrong, made several conceptually flawed predictions for the temperature of the relic radiation (the CMB), and inadvertently invented the r-process (what their model basically was) (20). Nonetheless, they got the big idea right: Nuclear physics in the radiation-dominated early phase of the Universe is important. A year before the CMB was discovered, Hoyle & Tayler (21) pointed out that BBN could explain the large primordial abundance of ^4He . A year after the discovery, Peebles (22) calculated how much ^4He would be produced. The first complete calculation of BBN, and the forerunner of all modern calculations, was that of Wagoner et al. (9) in 1967.

The landmark 1957 paper by Burbidge et al. (23), which outlined the complex astrophysical story of how the elements in the periodic table are produced,⁷ launched the field of nuclear astrophysics. This vibrant field today encompasses astrophysical neutrinos, supernovae, and compact objects and has much overlap with cosmology.

In the 1970s, particle physics entered the picture with the Universe being deployed as a “heavenly laboratory.” Three pioneering papers (25–27) used the relic abundance of neutrinos (about 113 cm^{-3} per species) and an estimate for the current mass density of the Universe to derive an upper bound to the neutrino mass. Steigman et al. (28) used the BBN production of ^4He to derive an upper limit to the number of light (mass $\ll \text{MeV}$) neutrino species (the presence of more light species leads to more ^4He production), and Lee & Weinberg (29) used the mass density of the Universe to place a lower limit to the mass of a hypothetical heavy neutrino species (about 2 GeV) (30).

The hot big bang cosmology was being taken seriously enough to use the Universe to constrain particle physics. This was a significant turnaround for the field, for which it had been said that the errors were in the exponents.

I trace the actual birth of particle cosmology to 1979 and a series of papers that addressed another cosmological puzzle: namely, how the prevalence of matter over antimatter could have arisen in the early Universe (31–33). This idea is now known as baryogenesis, and its essential elements go back to a prescient paper written by Sakharov (34) in 1967.

2.3.2. Baryogenesis. The concept of baryogenesis is simple: In the early Universe ($t \ll 1\text{ s}$), nonequilibrium interactions that violate B , C , and CP allow the Universe to evolve a small, net

⁷I have often heard that Hoyle initiated this program to keep pace with Gamow’s model for the origin of the elements. Others have reported that Hoyle disputed that claim (24).

baryon number. When the temperature was much greater than the mass of the lightest baryon-number-carrying particle species, baryons and antibaryons were as abundant as thermal photons, and the net baryon number corresponded to a slight excess of baryons over antibaryons. When the temperature fell below the mass of the lightest baryon, essentially all of the antibaryons and most of the baryons annihilated, leaving the few baryons we see today for every 10 billion or so photons.⁸

Sakharov's idea seemed far out in 1967.⁹ While *CP* violation had recently been discovered, there was no reason to believe that baryon number was not conserved, and cosmological issues were not front and center for physicists. By 1979, things had changed dramatically. The discovery of asymptotic freedom (38, 39) had broken down Weinberg's hadron wall: During the first microsecond, the Universe was a soup of weakly interacting, point-like quarks, leptons, gauge and Higgs bosons of the Standard Model, and probably other elementary particles.

Further, the convergence of the three coupling constants of $SU(3) \otimes SU(2) \otimes U(1)$ at an energy scale of 10^{15} GeV or so led to grand unified theories (GUTs). Baryon-number violation was now mandatory, not crazy, and it had a laboratory signature: proton decay. In the early 1980s, the race was on to detect proton decay (40). Other cosmological consequences of GUTs followed: magnetic monopoles, phase transitions, inflation, and particle dark matter. The early Universe was open for business, and the frontiers of particle physics and cosmology were converging.

2.3.3. Inner space and outer space meet at Fermilab. My mentor, the late David Schramm, was a powerful advocate, through his scientific contributions and leadership, for the convergence of the very small and the very big (41). In 1982, he and Leon Lederman challenged NASA to fund an astrophysics group at Fermilab to explore the then-hypothetical deep connections between particle physics and cosmology & astrophysics. NASA did, through their innovative research program.

Lederman brought Edward “Rocky” Kolb and me to Fermilab to lead the new group. In May 1984, Fermilab hosted the new field's coming out party, Inner Space/Outer Space. More than 220 astronomers and physicists attended, and Weinberg gave the summary talk. The timing could not have been better, as the two big ideas—inflation and CDM—that were to underpin cosmology had just emerged. To convince the scholarly University of Chicago Press to publish a mere proceedings volume, we boasted that it would mark the birth of a new discipline; readers can judge for themselves (42).

The NASA Fermilab Astrophysics Center (NFAC) became the “mother church” for this exciting interdisciplinary science and created the iconic poster that linked the two fields and would be seen on walls around the world (Figure 2). With a unique style (e.g., primordial pizza on Monday nights in my basement, topical workshops on cosmic strings, wormholes, and dark energy—all with Kolb- and Turner-designed conference T-shirts), NFAC trained many of the field's future researchers and leaders and sent them around the globe to spread the word.

The existence of NFAC paved the way for Fermilab to play a leading role in the Sloan Digital Sky Survey (SDSS), bringing in many particle physicists, especially experimentalists, looking for a new challenge. SDSS achieved its primary scientific goal of determining the large-scale structure

⁸For many, until baryogenesis, the puzzle was, how was the large entropy per baryon created (16, 35, 36)? Even at the center of a newly born neutron star, the entropy per baryon is only a few. Some, notably Penrose (37), viewed an entropy of a few billion per baryon as very small compared with what gravity could have created and sought an explanation for a low-entropy universe.

⁹I have been told that when he first presented it in an April 1 seminar, his colleagues thought it was meant to be a joke.

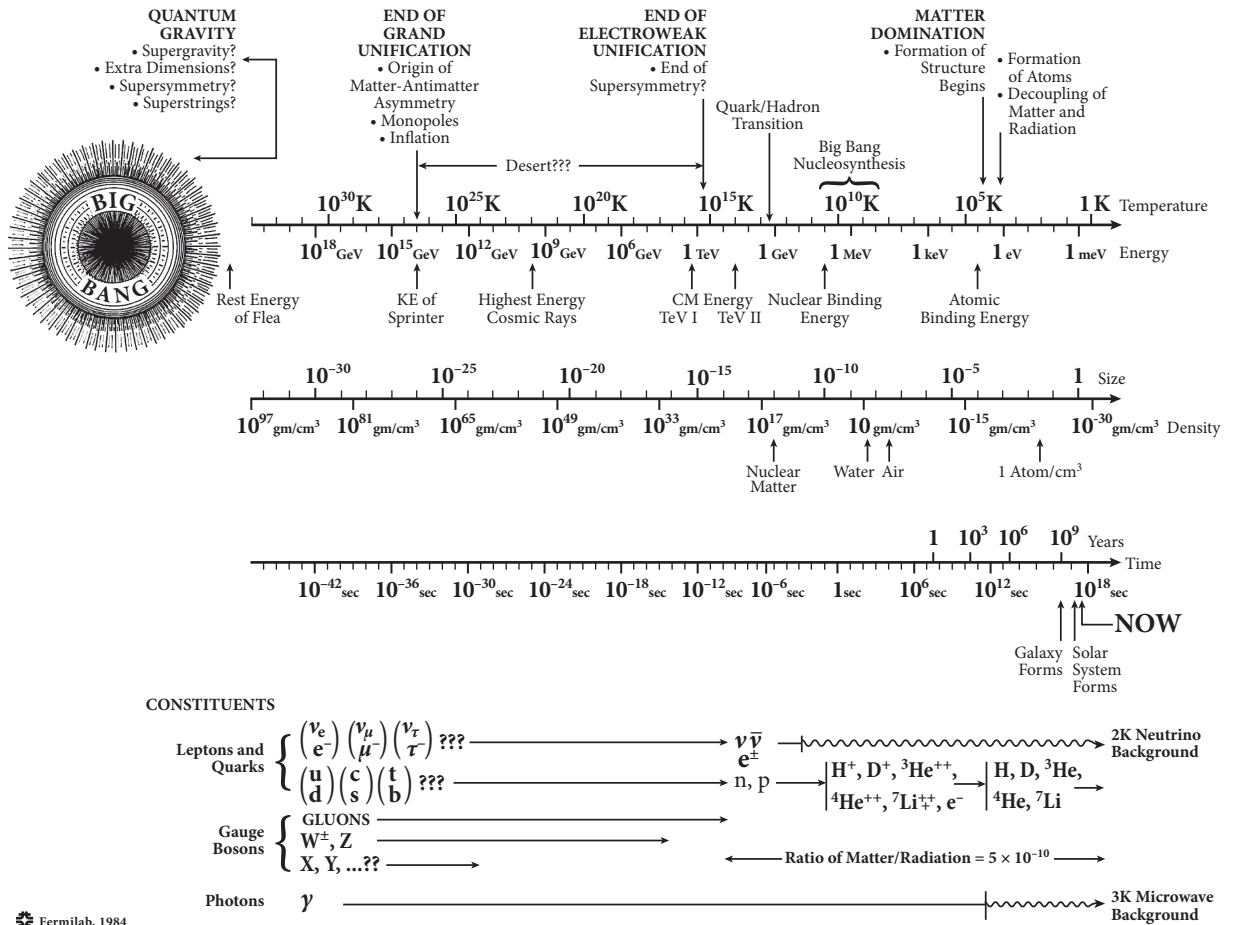


Figure 2

Complete history of the Universe (a collaboration of Angela Gonzales of Fermilab and the author, circa 1984). This poster, which illustrates the inner space–outer space connection, became ubiquitous, gracing the walls of physics departments, US Department of Energy labs, and even Department of Energy headquarters.

of the Universe to test inflation + CDM, but its larger legacy is the birth of survey science in astronomy.¹⁰

Other big surveys followed in the footsteps of SDSS (and its sequels), including the Dark Energy Survey (DES), the Baryon Oscillation Spectroscopic Survey (BOSS), the Dark Energy Spectroscopic Instrument (DESI), the Legacy Survey of Space and Time (LSST) at the Rubin Observatory, and soon the Nancy Grace Roman Space Telescope. This mega-object approach to astronomy dramatically changed the kind of science that could be done, the tools and skill sets needed to do it, and even the astronomy culture, including the size and composition of the collaborations.

¹⁰While astronomers had carried out surveys of the optical and radio skies before, the SDSS was the first survey designed to produce a high-quality, digital data set that would allow a broad range of science to be done by the larger astronomy community.

The bold agenda of particle cosmology was laid out in the 2002 US National Research Council report *Connecting Quarks with the Cosmos* (43), and its 11 big questions were featured on the cover of *Discover Magazine* (44) as “the 11 greatest unanswered questions of physics.” Today, particle cosmology is front and center not only in most physics and astronomy departments but also in all of the US Department of Energy’s high-energy physics labs.¹¹

The particle cosmology agenda is featured in the priority-setting documents of both astronomy and particle physics. The annual April meeting of the American Physical Society (APC) is now known as the Q2C meeting, for Quarks to Cosmos, and brings together 1,500 or so astronomers, particle physicists, nuclear physicists, and relativists.

While I have focused on Fermilab’s role in jump-starting the field, important activities also took place elsewhere, including workshops at the Institute for Theoretical Physics (ITP) at the University of California, Santa Barbara (including one of the very first ITP programs), and many summer and winter workshops at the Aspen Center for Physics.

3. THE SECOND PARADIGM

3.1. Dark Matter: A Kuhnian Shift

Today, dark matter is a central issue in cosmology and astrophysics. It was not always that way; astronomy used to be the study of a Universe composed of stars. Dark matter fits the Kuhnian paradigm shift: There is an anomaly that is not paid attention to, evidence grows in significance, and finally a shift to a new paradigm occurs.

As Roberts (45) recounted in his short history, the evidence for something beyond stars began with Zwicky and the Coma cluster when Zwicky (46) described the need for dark matter to hold the Coma galaxies together.¹² Smith (48) showed that the same was true for the Virgo cluster. Babcock (49) measured a rising rotation curve for M31 (Andromeda) and described it in terms of a rising mass-to-light ratio. Even earlier, Lundmark (50) had found more mass than stars could account for in M31 and a few other spirals.

Soon after neutral hydrogen (HI) gas clouds in the Milky Way were first detected with the 21-cm spin-flip transition (51), radio astronomers began using 21 cm to trace galactic rotation curves, probing them farther out than optical measurements could at the time (52, 53). By 1975, they had established that the rotation curve of M31 was not Keplerian (54), but a connection to dark matter was not made.

The use of electronic detectors in place of photographic plates allowed Vera Rubin and Kent Ford to probe galactic rotation curves farther out than ever before, and in 1978 they published results from 10 high-luminosity spiral galaxies (55). All showed flat or rising rotation curves with enclosed masses that grew linearly with galactocentric distance. To quote from their concluding section, “The observations presented here are thus a necessary but not sufficient condition for massive halos” (55, p. L111). They also wrote, “Roberts and his collaborators deserve credit for first calling attention to flat rotation curves” (55, p. L111).

In the early 1970s, theorists began to weigh in. Ostriker & Peebles (56) asserted that spiral galaxies need massive halos to stabilize their disks, and with Yahil (57), they made the case that

¹¹Given all the pushback they received from the Department of Energy and the other lab directors about their venture, both Lederman and Schramm must be smiling somewhere.

¹²Dark matter was a small part of the paper, which was more concerned with his tired-light explanation of redshifts. Oort (47), the year before, used the term dark matter to refer to the nearby disk matter that he inferred was there from stellar dynamics but that was not seen. Oort’s dark matter is composed of nearby faint stars, dust, and gas clouds and is not the dark matter that holds galaxies together.

with larger halo masses the estimates for Ω_0 should rise as well—possibly to 0.2.¹³ Einasto et al. (58) made the case for massive galactic halos connecting them to cluster dark matter as well. Reeves et al. (59) argued that big bang deuterium production, which falls rapidly with increasing baryon density, puts an upper limit on Ω_0 of about 0.2.

Around 1980, all the pieces were put together—flat rotation curves, dark matter halos, rising mass-to-light ratios, and cluster dark matter. In my opinion, two papers mark the paradigm shift: an influential review by Faber & Gallagher titled “Masses and Mass-To-Light Ratios of Galaxies,” whose Coda section’s first sentence was “After reviewing all the evidence, it is our opinion that the case for invisible mass in the Universe is very strong and getting stronger” (60, p. 182), and Rubin’s *Science* article summarizing her work on galactic rotation curves, whose abstract included the following statement: “There is accumulating evidence that as much as 90 percent of the mass of the universe is nonluminous and is clumped, halo-like, around individual galaxies. . . . At present, the form of the dark matter is unknown” (61, p. 1339).

In 1985, the International Astronomical Union held its first symposium on the subject, Dark Matter in the Universe, bringing together 190 researchers (62).¹⁴ Dark matter was now officially a big deal. However, there was still one big piece to come: Dark matter is not made of atoms.

3.1.1. Particle dark matter. BBN deuterium production places an upper limit on the baryonic mass density, $\Omega_B < 0.2$. In 1983–1984, the use of all four light-element abundances identified a best-bet range, $0.015 \leq \Omega_B h^2 \leq 0.026$ (63). This means if the Hubble constant is greater than $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, baryons can at most contribute 10% of the critical density no matter what form they take. This fact, the growing evidence for large amounts of dark matter (perhaps even approaching the critical density), the absence of a viable baryonic dark matter candidate, and the attractive candidates provided by particle physics opened the door for nonbaryonic, particle dark matter.

First through the door were light neutrinos, where $\Omega_\nu h^2 = m_\nu / 93 \text{ eV}$ (per species). A neutrino mass of around 25 eV and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ would give the critical-density Universe predicted by inflation. In 1980, Schramm & Steigman’s (64) paper “A Neutrino-Dominated Universe” won the Gravity Research Foundation’s annual essay competition. Adding wind to their sails, particle theorists had proposed the seesaw mechanism that predicted eV neutrino masses (65), and, in 1980, a Russian experiment reported an electron neutrino mass of $14 \text{ eV} \leq m_\nu \leq 46 \text{ eV}$ at 95% confidence (66).

This idea was short-lived. The Russian experiment was a false alarm, and a neutrino-dominated universe was ruled out because of disagreement between numerical simulations of how structure would form with the Universe we actually see (67).

More candidates came from particle physics. Pagels & Primack (68) boldly proposed the first supersymmetric (SUSY) dark matter candidate, a keV gravitino. The axion followed (69, 70), and it ushered in the CDM scenario (71). Next came the neutralino (72), which has attracted the most attention since.

3.1.1.1. Neutralino. In most SUSY extensions of the Standard Model, the lightest SUSY particle is neutral, is stable, and has an expected mass between 100 GeV and a few TeV. Called the

¹³ Ω_0 is the mean mass density divided by the critical mass density, equal to 1 for a spatially flat universe. Once the Universe was something other than just stars, the different components—stars, dark matter, baryons, and finally dark energy—each got their own subscript: $\Omega_0 = \Sigma_i \Omega_i$.

¹⁴In the proceedings from this symposium (62), my 46-page contribution explains and ranks the particle dark matter candidates (top three: neutrinos, axions, and photinos), puzzles about the ratio of particle dark matter to baryons, and mentions the possibility of Λ .

neutralino, it is a linear combination of the zino, photino, and higgsino—the SUSY partners of the Z boson, the photon, and the Higgs boson. Further, its interactions with ordinary matter are weak, which means that neutralinos can be produced at an accelerator and that halo neutralinos can potentially be detected, and it behaves like CDM. It is an excellent dark matter candidate, but its path to front-runner was complicated.

It began with a false start, the gravitino: the SUSY partner of the graviton (68). In the Pagels–Primack model, the lightest SUSY particle is the gravitino, not the neutralino. Further, the gravitino behaves like warm dark matter, not CDM (73). When the neutralino arrived, theorists were at first timid, writing “limit-setting” papers, not neutralino dark matter papers (74–76). By 1984, it was all sorted out and the inflation + CDM paradigm was in place, with the neutralino as the leading CDM candidate.

The neutralino’s attractiveness as a dark matter candidate goes beyond the appeal of SUSY in particle physics and its detectability. There is another pull, often referred to as the WIMP miracle, a term I hate (I would prefer “the WIMP hint”).

The neutralino’s presence today as dark matter owes to the freezing out of its annihilations in the early Universe and the subsequent freezing in of its abundance. When the temperature of the Universe was much greater than its mass, neutralinos were in thermal equilibrium with an abundance comparable to that of photons; as the temperature fell below its mass, neutralinos *should* have annihilated to exponentially small numbers. However, as they became less abundant, they ceased annihilating, leading to a freeze-in of their relic abundance.

Calculations show that the relic mass density scales inversely with the annihilation cross section and is comparable to the critical density for a weak-interaction annihilation cross section, $\sigma \sim 10^{-36} \text{ cm}^2$ (77), like that of a neutralino or any particle whose annihilation cross section is weak. [WIMP, for weakly interacting massive particle, is the term I coined for such particles (78).] Whether this fact is a hint or a misleading coincidence remains to be seen.¹⁵

3.1.1.2. Desperately seeking dark matter. Today, the 100σ discrepancy between $\Omega_M b^2$ and $\Omega_B b^2$ (see Section 4.1) makes an airtight case for nonbaryonic dark matter. Namely, there is much more matter than can be explained by baryons alone. But a 100σ discrepancy does not make particle dark matter a fact; it could just be evidence for a coming paradigm shift. Seeking additional, independent evidence and identifying the dark matter particle has become a holy grail of cosmology, particle physics, and astrophysics.

Neutralinos interact weakly with ordinary matter, opening three avenues for additional evidence: detection of the kinetic energy halo neutralino deposit by scattering off nuclei in a detector (79), their creation at particle accelerators, and detection of annihilation products from halo neutralinos or those captured by and annihilating in Earth or the sun. All three methods now have the sensitivity to probe interesting regions—but not all—of the neutralino parameter space; none has produced a definitive signal (80). These searches also apply to other WIMPs because the key is weak interactions with ordinary matter.

Much effort has gone into searching for axions, based upon a proposal by Sikivie (81): the conversion of halo axions traversing a very strong magnetic field into microwave photons. The

¹⁵Shortly after the discovery of the CMB, Hoyle and colleagues (9) pointed out that the energy released by an early generation of stars that made the large primordial ^4He abundance would be comparable to that in the CMB and could explain the CMB if it could be thermalized. It cannot be thermalized, and so this hint was just misdirection.

field has to be very strong, and a high-Q cavity is needed to collect and detect the photons. The necessary sensitivity has been achieved, but only a small fraction of the most promising mass range (10^{-6} to 10^{-3} eV) has been probed, and without success (82).

Finding independent evidence for the dark matter particle would not only complete the dark matter story but also open a new window on early Universe cosmology, akin to BBN. However, all we know for certain is that dark matter particles have gravitational interactions, move slowly (i.e., are cold), and do not interact like baryons. They could have no interactions with baryons, or they might have very, very weak interactions with them that make dark matter particles undetectable despite their great abundance and impact.

3.1.2. False starts. In 1983, Milgrom (83) noticed that the need for dark matter in galaxies occurs not at a particular distance from the center of a galaxy but rather at an acceleration, $a_0 \simeq 10^{-8}$ cm s $^{-2}$, and proposed MOND (modified Newtonian dynamics). MOND posits that $F \simeq ma^2/(a + a_0)$, so that for $a \ll a_0$, $F \propto a^2$. This one-parameter model fits all the rotation-curve data, but it cannot account for cluster dark matter and makes no other predictions. In short, it cannot be falsified. Nonetheless, the fact that the need for dark matter in galaxies occurs at an acceleration a_0 must be explained (84).

Before the argument against baryonic dark matter was airtight, dark baryons in the form of optically faint objects (e.g., brown dwarfs, white dwarfs, black holes, Jupiters) were still a possibility but hard to test. In 1986, Paczynski (85) proposed using gravitational microlensing, the brightening of a star as an object passes along its line of sight to us, to detect halo dark matter in the form of massive astrophysical compact halo objects (MACHOs).¹⁶ In 1993, the first microlensing events were announced (86, 87), and for a while, as more events were seen, it looked as if the Milky Way might have a MACHO halo. However, many of the events turned out to be other brightenings (e.g., a star whose light is blended with a distant supernova), and the current consensus is that MACHOs do not make up our halo (88).

Quark nuggets were the most intriguing suggestion. Witten (89) pointed out that if the quark-hadron transition were first order and if objects with large baryon numbers were more stable than nucleonic matter, a majority of the baryons could end up in quark nuggets rather than nucleons after the quark-hadron transition. This could explain the 5:1 dark matter:baryonic matter ratio and get around the BBN bound without the need for a new form of matter. However, a better understanding of QCD has ruled this out.

I close this subsection by mentioning two comprehensive reviews of the dark matter story—the first from a particle physicist’s perspective (90), the second from an astronomer’s perspective (91)—and by pointing out that dark matter has become such a cultural touchstone that even biologists have borrowed it, using it as an informal term for poorly understood genetic material, unclassified microorganisms, and junk DNA in the genome.

3.2. The Cosmic Microwave Background and the Birth of Precision Cosmology

It would be hard to overstate the role of the CMB in ushering in precision cosmology, and it is still its best exemplar. Why? First, the underlying physics is simple: atomic and gravitational physics and linear perturbations of the homogeneous and isotropic background cosmological model. Next, the relationship between temperature variations and the underlying density perturbations that

¹⁶The acronym MACHO was coined by Kim Griest in response to WIMPs.

create them is straightforward: the response of the baryon–photon fluid to the dark matter inhomogeneities, which depends upon the baryon and dark matter densities, the expansion rate, the atomic composition, and the geometry of the Universe. This means that the anisotropy of the CMB can be used to reveal much about the Universe. Finally, the individuals involved in making CMB measurements were (and still are) largely physicists, who brought their rigorous laboratory approach.

Because CMB anisotropy and its polarization have yielded so much precision information about the Universe, I mark the Cosmic Background Explorer (COBE) satellite’s detection of CMB anisotropy in 1992 (92) as the official beginning of precision cosmology.

3.2.1. The long road to COBE. In their discovery paper, Penzias & Wilson (1) noted that the CMB was isotropic at the 10% level. Peebles and others realized that if structure was formed by gravitational amplification of small density inhomogeneities (93), those inhomogeneities should leave their imprint in the anisotropy (94, 95). Anisotropic expansion or the rotation of the Universe would give rise to a quadrupole anisotropy. Rees (96) showed that the CMB anisotropy should be polarized at the few-percent level. And Sunyaev and Zel’dovich (97) pointed out that spectral distortions would arise in the CMB if the line of sight passed through clusters and scattered off the hot gas in them on the way to us.

While CMB anisotropy had to be present and was clearly important, well-founded predictions for its level were lacking. Nonetheless, a generation of talented experimentalists continued to search and to place more and more stringent limits on CMB anisotropy at various angular scales, from the dipole and quadrupole to arcminutes.

In 1977, a definitive detection of the dipole anisotropy was made from data collected by a reconfigured U2 spy plane (98). The bulk of the dipole results from Earth’s motion today with respect to the cosmic rest frame and not the underlying density perturbations at the last scattering. The magnitude and direction of the kinematic dipole are known with great precision. The Solar System moves at a speed of $369.82 \pm 0.11 \text{ km s}^{-1}$ in the general direction of the constellation Leo ($l = 264.021 \pm 0.011^\circ$ and $b = 48.253 \pm 0.005^\circ$) (99).

By the early 1980s, limits to the CMB anisotropy on various angular scales were $\delta T/T < 10^{-4}$ (100). Theorists were getting more serious about their predictions—for instance, including non-baryonic dark matter (101). In 1984 the first calculations of CMB anisotropy in CDM models were done (102, 103), and today’s ubiquitous angular power spectrum was introduced (104). The CDM prediction, $\delta T/T \simeq 10^{-5}$, was a factor of ten below the limits.

3.2.2. COBE. In 1976, NASA approved the COBE mission, a merger of three concepts (DMR, FIRAS, and DIRBE). It was designed to fly on the Space Shuttle, but the Challenger disaster changed that, and COBE was launched on November 18, 1989, from Vandenberg Air Force Base on a Delta launch vehicle.

Less than 2 months later, John Mather showed the first spectrum of the CMB produced by his FIRAS (Far Infrared Absolute Spectrophotometer) instrument on the last day of the January 1990 American Astronomical Society meeting in Washington, DC (105). It was a perfect blackbody over the range of 60 to 640 GHz (see **Figure 3**), and he received a standing ovation. Ultimately, FIRAS pinned down the CMB temperature to four significant figures, $T = 2.72548 \pm 0.00057 \text{ K}$ (106)—precision cosmology indeed.

The DMR (Differential Microwave Radiometer) team would make its big announcement 2 years later at the April 1992 APS meeting (also in Washington, DC, and also on the final day). They announced the first detection of CMB anisotropy beyond the dipole, at a level of

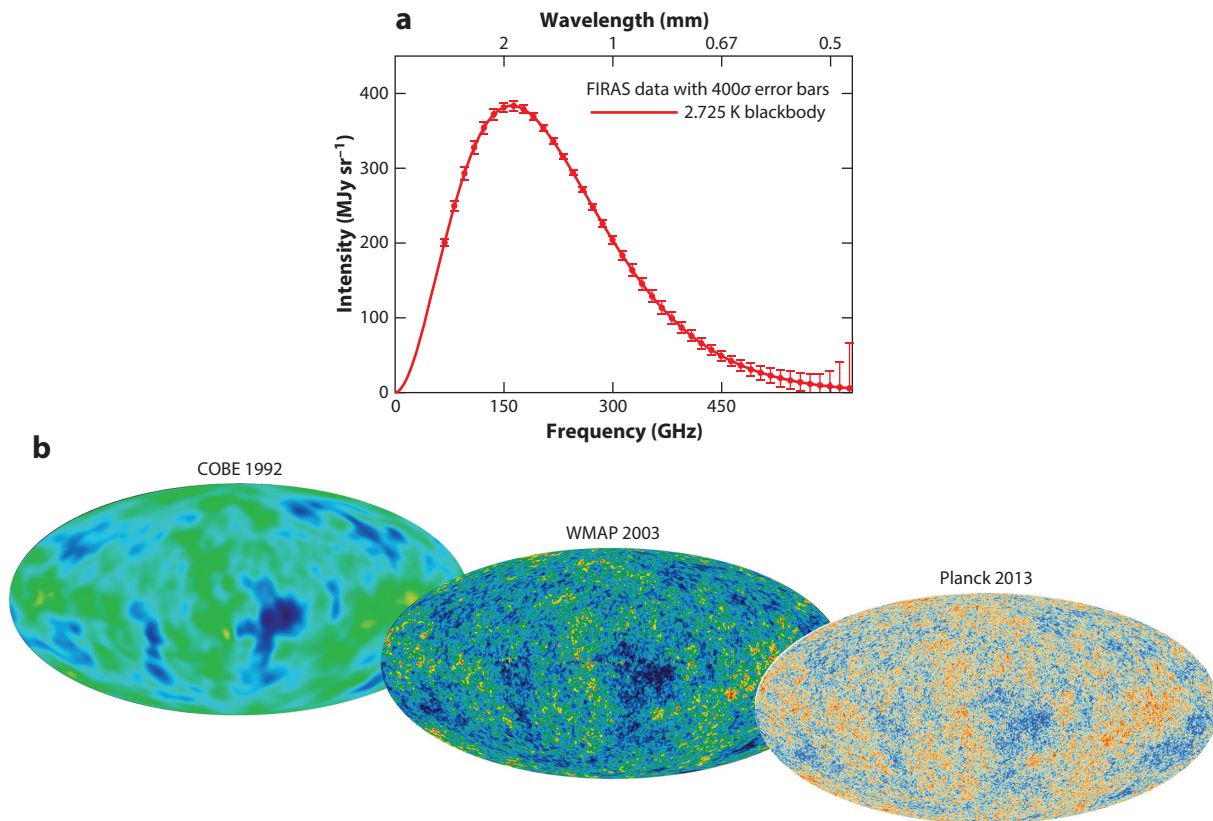


Figure 3

Birth of precision cosmology. (a) The perfect blackbody spectrum measured by the FIRAS instrument on COBE. Plot created by Ned Wright; adapted with permission. (b) The cosmic microwave background anisotropy progression, with increasing sensitivity and resolution, from COBE to WMAP to Planck. Images from NASA (public domain). Abbreviations: COBE, Cosmic Background Explorer; FIRAS, Far Infrared Absolute Spectrophotometer; WMAP, Wilkinson Microwave Anisotropy Probe.

$\delta T/T \simeq 10^{-5}$ on the angular scale of 10° (92).¹⁷ Stephen Hawking called it the greatest discovery of all time (an overstatement to be sure, but COBE had opened the era of precision cosmology).

Inflation set the shape of the spectrum of density inhomogeneities (scale-invariant), and so COBE could be used to set the overall amplitude. In turn, this allowed comparison with measurements of the inhomogeneity today from the distribution of galaxies.

With its 10° beam, COBE had probed only the Sachs–Wolfe plateau (94) and not the acoustic peaks, where all the information about cosmological parameters lies. In 1992, the race was on to design and build experiments with greater angular resolution and sensitivity to read cosmology’s Rosetta Stone (108).

¹⁷The DMR did not have much margin to spare: The year 1 data had an S/N of about 1 per pixel (roughly a 100-square-degree patch), which increased to about 2 in the final 4-year data set. The detection of anisotropy on the 10° scale was highly significant, but the features in the map were much less so (107).

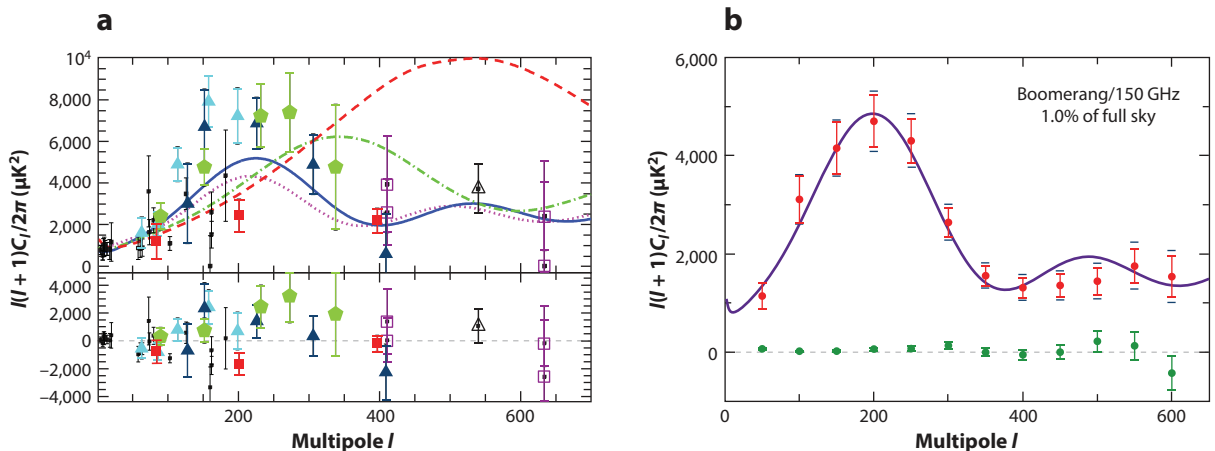


Figure 4

The first peak in the angular power spectrum reveals the geometry of the Universe. Here, $C_\ell = \langle a_{\ell m} a_{\ell m}^* \rangle$. (a) Circa 2000, emerging from COBE (black) and ground-based experiments (colored symbols); the solid curve is for a flat Universe, and the dashed and dotted curves are for open models. Panel adapted with permission from Reference 115; copyright 2000 by the American Physical Society. (b) The Boomerang experiment's angular power spectrum clearly shows the first peak at $l = 200$, as expected for a flat Universe with $\Omega_B = 0.05$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $b = 0.70$ (curve). Panel adapted with permission from Reference 114; copyright 2000 Springer Nature. Abbreviation: COBE, Cosmic Background Explorer.

3.2.3. After COBE. Two satellite missions were approved in 1996, NASA's Wilkinson Microwave Anisotropy Probe (WMAP),¹⁸ which launched in 2001 and announced its first results in 2003, and ESA's Planck, which launched in 2009 and announced its first results in 2013. In the meantime, a host of ground-based and balloon-borne experiments were mounted, employing new technology (e.g., bolometers) and new techniques (e.g., use of the angular power spectra).

Theorists were busy too, emphasizing the treasure trove of information contained in the acoustic peaks and forecasting how well they could be measured, often influencing the designs of the experiments (109, 110). The big prize was the curvature of the Universe, encoded in the position of the first peak, with the flat-Universe prediction of inflation corresponding to $l \simeq 200$ or about 1° .

They also pointed out that by analyzing the polarization of the CMB anisotropy in terms of the even (E) and odd (B) parity modes, one could hunt for the signature of the gravitational waves produced by inflation: Only the gravitational waves excite the B-mode (111, 112). [The story is of course more complicated as gravitational lensing by intervening large-scale structure distorts the CMB anisotropy and can transmute the E-mode polarization produced by density perturbations into B-mode polarization (113).]

There was steady progress with results from a number of different experiments filling in the angular power spectrum. The first acoustic peak was beginning to appear in combined data at $l \sim 200$ as expected for a flat Universe (107) (see **Figure 4**). However, the shot heard 'round the world came in April 2000 with the announcement of results from Boomerang, an Antarctic balloon experiment led by Andrew Lange¹⁹ (114).

¹⁸David Wilkinson, who played a leading role in the design of the Microwave Anisotropy Probe (MAP), died in September 2002, and in February 2003, MAP became WMAP in his honor.

¹⁹Lange died tragically in 2010; his CMB legacy continued with bolometric detectors his group had designed being deployed on Planck and the Keck/BICEP array.

Boomerang's power spectra (see **Figure 4**), from $l = 50$ to $l = 600$ and at four frequencies, revealed a clear peak at $l = 200$ and a good fit to today's consensus Λ CDM model. At 95% confidence, Ω_0 was between 0.88 and 1.12. The Boomerang result firmly established Λ CDM.

Much more would follow: the first detection of CMB polarization by the Degree Angular Scale Interferometer (DASI) in 2002 (116), the definitive detection of the SZ effect (117) and discovery of clusters using the SZ signal alone (118), the TE and EE angular power spectra, the detection of B-mode polarization from both dust emission and gravitational lensing, and limits to the portion of the B-mode signal due to inflation-produced gravitational waves (119).

Today, WMAP, Planck, and two ground-based CMB experiments [South Pole Telescope (SPT) and Atacama Cosmology Telescope (ACT)] have measured the anisotropy of the CMB with cosmic-variance precision from $l = 2$ to $l = 2,500$, and the hunt is on for the B-mode polarization produced by inflationary gravitational waves.

For 10 years, the Keck/BICEP experiment at the South Pole has led that hunt; it has the best upper limit, $r < 0.04$ at 95% confidence (119). That is, gravitational-wave-produced anisotropy is at most 4% of that produced by density inhomogeneities. The CMB Stage IV (CMB-S4) experiment, which is being developed and involves 21 telescopes at the South Pole and in the Chilean Atacama Desert, aims for a sensitivity of $r = 10^{-3}$ (<https://cmb-s4.org/>).

There is no consensus prediction for r ; some theorists argue that it must be larger than 0.01 (120), others say that it must be much smaller than 10^{-3} (121), and various models of inflation predict all numbers in between. All that can be said with certainty is that detecting the signature of these gravitational waves would be a major milestone, revealing when inflation took place and teaching us about the underlying physics (122).

3.3. Big Ideas: Inflation + CDM

While 1980 marked the birth of particle cosmology, it was not until 1984 that inflation + CDM arrived and became a guiding light for cosmology. It built upon and dramatically expanded the very successful hot big bang model. Its bold and falsifiable predictions caught the attention of those in the field and attracted both theorists and experimentalists from outside the field, many from particle physics.

3.3.1. Inflation. The story begins with superheavy magnetic monopoles, which, in addition to baryon-number violation and neutrino mass, are predicted by GUTs (123). Moreover, they should be produced in the early Universe during the phase transition in which the GUT symmetry is spontaneously broken to that of the Standard Model. And further, a Stanford low-temperature physicist had detected a signal consistent with a magnetic monopole traversing a superconducting loop in his lab (124).

There was only one problem: A calculation by Harvard graduate student John Preskill (125) clearly showed that magnetic monopoles should have been produced in numbers far too large to be consistent with the hot big bang cosmology.

There was a possible out: dilution of the monopoles by the entropy produced in a first-order GUT phase transition. In the absence of entropy production, the number of photons in the Universe is conserved.²⁰ The number of monopoles here today is simply the monopole-to-photon ratio produced in the early Universe times the number density of photons today (about 411 cm^{-3}). Thus, the monopole problem can be solved by the creation of additional photons, which reduces the initial monopole-to-photon ratio.

²⁰More precisely, the number of relativistic particles is conserved (see 77, chapter 3.4).

Many pursued this fix. In a paper that stood out for its expansiveness and clarity, Guth (126) showed that not only does a strongly first-order phase transition produce entropy but also, when the Universe is stuck in the old phase, false vacuum energy behaves like a cosmological constant and the Universe expands exponentially. Moreover, the exponential growth and entropy production could solve two other cosmological problems, the horizon and flatness problems, which were less well appreciated, especially by particle physicists. And finally, a phase transition that takes long enough to solve all three problems never finishes and leaves a Universe that is a mess—that is, no graceful exit (got it: a good idea that doesn't work).

Regarding the horizon and flatness problems (127), while the Universe was much smaller earlier on, it was also expanding rapidly, and the distance that a photon could have traveled since the beginning until a given time (the distance to the horizon) is not infinite; rather, it is a factor of order unity times the age of the Universe at that time. The CMB is very smooth; unless the Universe began smooth, causal interactions could smooth it up only to scales of about 1° , the size of the horizon at the last scattering as seen on the CMB sky today. The horizon problem also prevents any causal process from creating the small amount of lumpiness needed to seed structure in a smooth Universe. The flatness problem involves the fact that with time, the deviation of Ω from 1 grows; unless Ω were initially very, very close to 1, the Universe would have long ago collapsed or gone into free expansion, leading to $\Omega_0 \ll 1$, in conflict with measurements.

The horizon and flatness problems were part of the larger issue of the special initial conditions required to achieve a Universe similar to ours—long-lived, smooth, and flat, which relativists (36, 128) had been worrying about long before Dicke & Peebles (127). To address these issues, Penrose was advocating for rules about the kind of initial singularities permitted, and he proposed his Weyl curvature hypothesis as an alternative to inflation (37).

Back to the main story: Guth made his case for inflation well. People paid attention, and within about a year, a solution to the graceful exit problem was put forward by Linde (129) and by Albrecht & Steinhardt (130) and Albrecht et al. (131): slow-roll inflation.

3.3.2. Nuffield. All the pieces came together at the Nuffield Workshop on the Very Early Universe, organized by Stephen Hawking and Gary Gibbons at Cambridge University, in the summer of 1982 (see **Figure 5**). The details of slow-roll inflation and the quantum origin of density fluctuations were thrashed out in real time (132–136). Without a doubt, Nuffield was the most exciting meeting of my scientific career.

While the original Linde–Albrecht–Steinhardt model did not work because it resulted in density perturbations that were too large, by the end of the workshop there was a prescription for successful inflation (137), and new models began springing up. Today, there is no shortage of viable models of inflation, but there is also no standard model.

The same basic idea still underlies almost all models of inflation today. A scalar field rolls slowly down a very flat potential having started far from the potential's minimum. While it slowly rolls, its potential energy behaves like a cosmological constant and drives a nearly exponential expansion, taking a tiny bit of the Universe that could have been smooth and blowing it up to enormous size. The wavelengths of quantum fluctuations in both the scalar field and in the space-time metric are similarly blown up, to astrophysical size.

Inflation ends when the scalar field reaches the bottom of its potential, and its potential energy is converted into particles, thereby reheating the Universe and creating an enormous amount of entropy. The quantum fluctuations become density perturbations and gravitational waves, respectively, and the Universe begins its usual hot big bang phase.

By 1983, inflation had become the driving force in cosmology because of the power of its three big predictions: (a) a flat Universe ($\Omega_0 = 1$), (b) an almost scale-invariant spectrum of

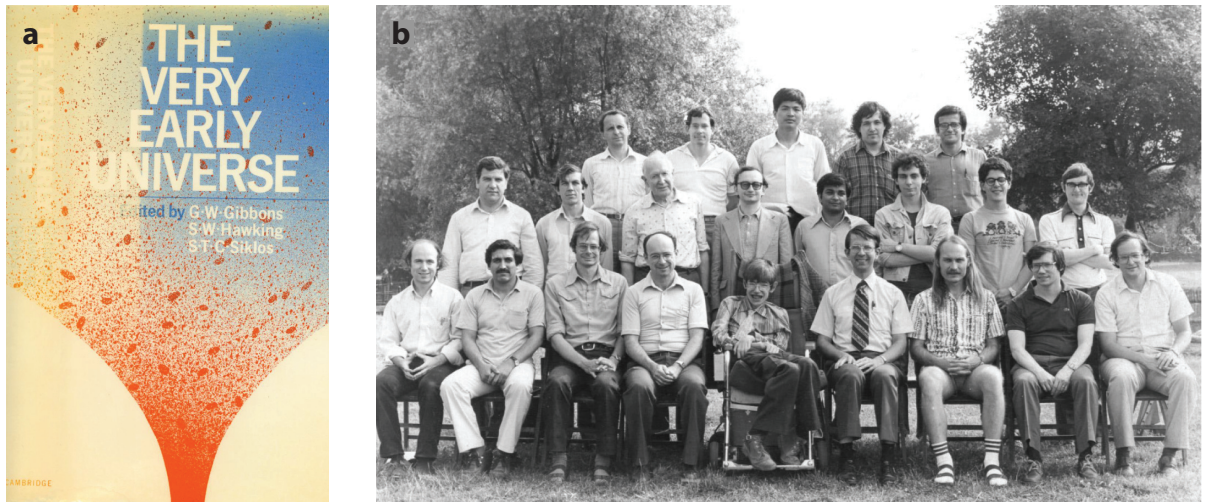


Figure 5

Images from the 1982 Nuffield Workshop on the Very Early Universe. (a) The cover of the proceedings. (b) A group photo including Frank Wilczek (front row, far left); Stephen Hawking (front row, center); James Bardeen (left of Hawking); Michael Turner, Alan Guth, and Paul Steinhardt (front row, far right); Alexei A. Starobinsky (behind Hawking); and John Preskill (behind and to the left of Starobinsky). Andrei Linde is not in the photo.

nearly Gaussian density (curvature) perturbations,²¹ and (c) an almost scale-invariant spectrum of gravitational waves (139).

The first prediction made inflation both bold and falsifiable: The best observational evidence at the time was $\Omega_0 \sim 0.1$, about what baryons could account for. If the Universe were flat, there must be something in it in addition to baryons. The second prediction fixed the shape of the spectrum of density perturbations, which could then be normalized by using the level of inhomogeneity on the scale of $8 h^{-1}$ Mpc today (about unity). This set the overall amplitude at the level of $\delta\rho/\rho \sim 10^{-5}$. This is the hardest constraint for inflation model builders and necessitates a very flat scalar field potential.

Together, the first two predictions provide the initial conditions for the formation of structure, and growing computing power made possible more and more realistic simulations of structure formation. The results could then be compared with the growing body of data about the large-scale structure of the Universe, leading to a renaissance in the study of structure formation as well as a key test of inflation.

The third prediction is the most intriguing. While the amplitude of density perturbations needed to explain cosmic structure was known, there was no such prediction for gravitational waves. Gravitational waves of any kind had yet to be detected, and the challenge of doing so was daunting.²²

²¹The scale-invariant spectrum of perturbations was first proposed by Harrison (138); its special feature is that, unlike any other spectrum, it does not diverge on either small or large scales and does not need to be cut off. This virtue was well appreciated by cosmologists.

²²The decay of the orbit of the binary pulsar provided strong indirect evidence for their existence (140), but the Laser Interferometer Gravitational-Wave Observatory (LIGO) experiment, which would detect them in 2016, would not begin for 10 years.

Detection of these gravitational waves would reveal when inflation took place: Their dimensionless strain amplitude is simply the expansion rate during inflation divided by the Planck mass, $h \sim H/m_{\text{Pl}}$. A few years later, a consistency relationship between their amplitude and the deviation of their spectrum from scale invariance was discovered (141), and some ideas were proposed about how to reconstruct the scalar field potential (142).

Last but not least, it could be—and was—said that a flat Universe and scale-invariant perturbations were the attributes of any sensible cosmological paradigm, and thus not a strong test of inflation. The same could not be said of gravitational waves or the slight deviation of both density perturbations (and gravitational waves) from scale invariance. While not appreciated early on, the prediction of not-quite-scale-invariant density perturbations has become a key test of inflation, which it passes with flying colors (see Section 4.1.1). And as described in Section 3.2.2, the most powerful way of detecting gravitational waves is through the B-mode imprint they leave on the CMB polarization. The detection of inflation-produced gravitational waves is an important test of inflation and has become the holy grail of cosmology.

3.3.3. Cold dark matter. Inflation needed something beyond baryons to reach the prediction of $\Omega_0 = 1$. Particle dark matter provided the most compelling possibility. There are two limiting cases: hot dark matter (HDM), where the DM particles move fast and stream out of the small perturbations that make galaxies and clusters; and CDM, where the DM particles move slowly and cannot stream out.²³

With HDM, structure forms from the top down: Very large structures form first and fragment to form smaller objects; HDM was ruled out almost immediately (67). CDM, where structure forms from the bottom up (galaxies, followed by clusters and superclusters), looked much better. Its broad-brush predictions were fleshed out very quickly (143, 144), and by the time of the Inner Space/Outer Space meeting in mid-1984, inflation + CDM was firmly in place (see Reference 42).

3.3.4. Defective defects. Revolutions are not linear, even in cosmology. There was another worthy idea that aspired to lead cosmology forward, a network of one-dimensional topological defects produced in a GUT-scale phase transition: cosmic strings (145). Such a network should evolve as strings collide and intercommute to produce a self-similar distribution of string loops that act as seeds for structure formation. Further, the oscillation of string loops produces a spectrum of gravitational waves that might be detected, and long strands of string leave a unique signature in the CMB.

For a time, strings were Pepsi to inflation's Coke. The end for cosmic strings came when the first acoustic peak was detected (114) because they predicted no acoustic peaks (146). Like a strong competitor often does, cosmic strings made inflation's triumph look all the more impressive. Topological defects are so attractive that there is continued interest in them, with the hope that some remain from early on and can be detected (see, e.g., 147, 148).

3.4. Cosmic Acceleration, Dark Energy, and the Emergence of Λ CDM

It all came together in 1998. The two supernova teams announced their discovery of cosmic acceleration early in the year (149, 150), by midyear Λ CDM was the new cosmological paradigm, and the year ended with *Science* magazine naming cosmic acceleration the breakthrough discovery of 1998 (151). Cosmic acceleration was called one of the biggest surprises of all time; in fact, the long lead up to it may have made it the most anticipated one.

²³There is an intermediate case, warm dark matter, where the streaming scale is the size of galaxies (73).

3.4.1. Troubles with CDM. The story begins in 1984. Numerical simulations had quickly dispensed with HDM, and similar simulations of CDM reproduced the large-scale structure revealed by the CfA1 survey (152), making inflation + CDM look like a winner. However, there were dark clouds on the horizon.

First, the observational data suggested that Ω_0 was around 0.1, and not close to 1 (60); second, CDM predicted a highly evolving Universe for which there was no evidence (and conventional wisdom, loudly espoused by Peebles, held that galaxies were in place at redshift $z \gg 10$); and third, to get the large-scale structure just right, one needed $\Omega_M b \sim 0.2\text{--}0.3$.

None of these problems was a show stopper (yet). After all, the full extent of galactic halos was not yet known, and estimates of Ω_M were still increasing as the scale of the region probed increased (60). Further, few observations probed the Universe beyond redshifts of a few tenths, and lots of evolution at modest redshifts could not be ruled out. In fact, there was evidence for such evolution, the so-called Butcher–Oemler effect, where more blue (star-forming) galaxies were observed in clusters at redshifts $z \sim 0.3$ than at lower redshift (153).

The third problem could be dismissed by pointing out that numerical simulations were not yet very sophisticated and that the CfA1 galaxy survey had only 2,400 galaxies. Shifting $\Omega_M b = 0.2\text{--}0.3$ to 0.5 or so might be just fine since the age of a flat Universe, $2H_0^{-1}/3 \simeq 7 b^{-1}$ Gyr, needed a small Hubble constant to accommodate the oldest stars whose ages were estimated to be 10–15 Gyr.

3.4.2. Λ again. The Ω problem seemed the most challenging—namely, how to make a flat Universe consistent with data that indicated $\Omega_0 \sim 0.1$ (154). Remedies were suggested (154–156), including the possibility of a cosmological constant.

Λ had much to recommend it: It was a smooth component of energy density that would escape detection and did not impede the growth of structure significantly. It “lengthened” the age of the Universe (for $\Omega_M \sim 0.3$, the age $t_0 \sim H_0^{-1}$), and it was highly testable.

But Λ had a checkered history too, having been invoked for every crisis du jour in cosmology (157, 158): by Einstein to get a static Universe, by Arthur Eddington to resolve the age crisis that arose due to Hubble’s very large “Hubble constant” ($H_0 \sim 500 \text{ km s}^{-1} \text{ Mpc}^{-1}$), by Hoyle, Hermann Bondi, and Thomas Gold in their steady-state model (159, 160), and in the 1960s to explain the preponderance of quasars at redshifts $z \sim 2$ (as it turns out, a real effect due to galactic evolution).

Further, in 1968 Zel’dovich (161) pointed out that the energy of the quantum vacuum was mathematically equivalent to a cosmological constant and that it should be enormous—more than 50 orders of magnitude greater than the critical density.²⁴ In 1989, Weinberg reviewed the problems of the cosmological constant and suggested an anthropic solution (162). I believe that many had the feeling that ignoring Λ and making progress elsewhere was the best strategy.

The COBE detection of CMB anisotropy in 1992 (92) added urgency. It provided a second normalization of the power spectrum of density inhomogeneities and a consistency check since the shape of the spectrum was fixed to be close to scale-invariant.²⁵ To fit both, $\Omega_M b \sim 0.3$ was required. Beyond a small Hubble constant ($b \sim 0.3$) or a cosmological constant with $\Omega_\Lambda \sim 0.7$, there were other ways to fix the problem, including adding a bit of HDM or extra radiation (163).

²⁴Wolfgang Pauli and others had realized this even earlier, but they did not formalize their concerns; cosmology was not mainstream science yet (158).

²⁵While the inflation-predicted spectrum of density perturbations is scale-invariant in the gravitational potential, the transition from the early radiation-dominated era to the matter-dominated era imprints a feature on the spectrum of density perturbations. That feature (see **Figure 7**), which depends upon when that transition took place, scales with $\Omega_M b$.

The final nail in the coffin of $\Omega_M = 1$ was the cluster inventory determination of the total matter density (164). Assuming that clusters provide a fair sample of matter in the Universe,²⁶ the BBN-determined baryon density and the ratio of baryons to total mass measured in clusters determine Ω_M . The result, $\Omega_M(b/0.7)^{1/2} \sim 0.3$, is convincingly less than 1, unless the Hubble constant is very small.

In March 1995, Krauss and I boldly proposed that “the cosmological constant is back,” showing that it solved all the problems of inflation + CDM for $\Omega_\Lambda \sim 0.6$ and $b \sim 0.6$ (165). We were surprised at how little outcry there was from the particle physics community about invoking Λ . There was one piece of evidence against our proposal, a 95% confidence upper limit of $\Omega_\Lambda < 0.66$, based upon the statistics of gravitational lenses (166).

At the 1996 Critical Dialogues in Cosmology meeting at Princeton University, I was asked to make the case for Λ CDM in a session devoted to the different versions of inflation + CDM. I noted that the definitive test of Λ CDM was its prediction of $q_0 \sim -0.5$ rather than $q_0 \sim 0.5$ for the other versions of CDM + inflation. In a strange twist of fate, at the same meeting, Perlmutter presented results from the Supernova Cosmology Project’s (SCP’s) first seven high-redshift ($z = 0.35\text{--}0.46$) supernovae: $\Omega_\Lambda < 0.51$ at 95% confidence (167).

3.4.3. It’s Λ CDM. A lot happened in the next 2 years. The SCP, largely a team of physicists, and their rival, the High- z Team, a group of astronomers led by Brian Schmidt, were amassing more type Ia supernovae to study the expansion history of the Universe. In early 1998, they announced their results: The Universe is accelerating, consistent with $\Omega_\Lambda \sim 0.7$ and $\Omega_M \sim 0.3$.

Remarkably, there was rapid acceptance of their extraordinary claim. I believe there were two reasons for that: First, the two very competitive and independent teams came to the same conclusion, each with a very thorough analysis. And second, Λ was the final piece of the puzzle, the one that made everything work.

The acceptance was swift, as the following story illustrates. My mentor David Schramm was scheduled to debate Jim Peebles in April 1998 on the question of whether the Universe was flat or not; he had flat. All fall, Schramm was hoping for last-minute results to make his case viable. After he died tragically in December 1997, I was asked to fill in. Peebles was no longer willing to debate flat or not, and we debated “Cosmology solved?” The debate took place in October 1998, and I took “yes” (168).

3.4.4. Dark energy. In 1997, White and I (169) generalized the idea of a smooth component with large negative pressure by introducing the equation-of-state parameter $w \equiv p/\rho = -1$ for Λ , and in August 1998 I introduced the term dark energy to describe the smooth component that was causing the Universe to accelerate (170). I did so mindful of the fact that while Λ was the simplest example of dark energy and that the data were (and continue to be) consistent with it [$w = -1.026 \pm 0.041$ (171)], there was no compelling reason to believe that Λ was the actual cause. I remain convinced that cosmic acceleration is the most profound mystery in all of science and that the question should remain open to challenge both theorists and observers.

Carl Sagan wisely advised that extraordinary claims require extraordinary evidence. That the Universe is accelerating is certainly an extraordinary claim. The extraordinary evidence was not in place in 1998; however, it is today. I mark the tipping point as April 2000, when Lange’s Boomerang team provided their evidence for a flat Universe from the CMB (114). Two-thirds of the critical

²⁶In clusters, most of the baryons are in the hot, x-ray-emitting gas, whose mass is determined by the x-ray emission; the total mass comes from virial theorem or weak lensing estimates.

density was missing, and dark energy in the form of Λ was the perfect fit. This was additional strong evidence from a very different direction.

4. TRIUMPHS AND CHALLENGES

I began using the term precision cosmology in the 1990s to announce with some fanfare that in cosmology, the errors are no longer in the exponents and the field is no longer data starved. While the title of this review suggests that precision cosmology is a destination, it is really a milestone for a field challenged by the vastness of its undertaking. What enabled precision cosmology? Powerful tools, bold ideas, and great people (and a bit of luck). In what follows, I discuss its accomplishments and provide a brief look forward.

4.1. Triumphs of Λ CDM

The emergence of Λ CDM as the second cosmological paradigm marks a triumph of precision cosmology. This new paradigm illustrates how far cosmology has come from its early days: first, in the depth of understanding that it provides about the origin and evolution of the Universe; next, in the impressive body of evidence—both precision measurements and cross-checks—upon which it rests; and finally, in the profound set of questions that it poses. Here is a brief summary of our current understanding:

- **Inflation:** A very early ($\ll 10^{-5}$ s) period of accelerated expansion is driven by the potential energy of a weakly coupled scalar field and results in a small, smooth patch of the Universe growing exponentially in size to easily encompass all that we see today. Quantum fluctuations in the scalar field grow in size and become an almost scale-invariant spectrum of nearly Gaussian density perturbations that seed all the structure currently seen. Quantum fluctuations in the metric of space-time grow in size and become an almost scale-invariant spectrum of gravitational waves. Inflation ends when the scalar field potential energy is converted into particles that thermalize and initiate the hot quark soup phase.
- **Quark soup:** During this phase of mostly thermal-equilibrium, which lasts from the end of inflation ($t \ll 10^{-5}$ s) until quarks form into hadrons ($t \sim 10^{-5}$ s), two nonequilibrium events occur: Baryogenesis leads to a small excess of baryons over antibaryons, and dark matter particles are created. Other nonequilibrium processes may have occurred and left relics yet to be discovered.
- **BBN:** Nuclear reactions take place from 10^{-2} to 200 s; these lead to the synthesis of a significant amount of ^4He and trace amounts of D, ^3He , and ^7Li , which are still with us today as the oldest relics of the early Universe—at least currently.
- **Gravity builds cosmic structure:** As the Universe became matter-dominated ($t \sim 64,000$ years), baryons fell into the gravitational potential wells of the CDM particles and, owing to the resisting pressure provided by photons, underwent acoustic oscillations until the formation of neutral atoms ($t \simeq 380,000$ years); thereafter, photons streamed freely, becoming the CMB and structure formed in a hierarchical manner—from galaxies to clusters of the galaxies to superclusters. The CMB provides a snapshot of the Universe around the last scattering, and a wealth of information is encoded in the acoustic peaks and other features.
- **Cosmic acceleration:** About 5 Gyr ago, the repulsive gravity of dark energy—consistent with a cosmological constant—overtook the attractive gravity of dark matter, leading to the current epoch of accelerated expansion and inhibiting the formation of larger structures.

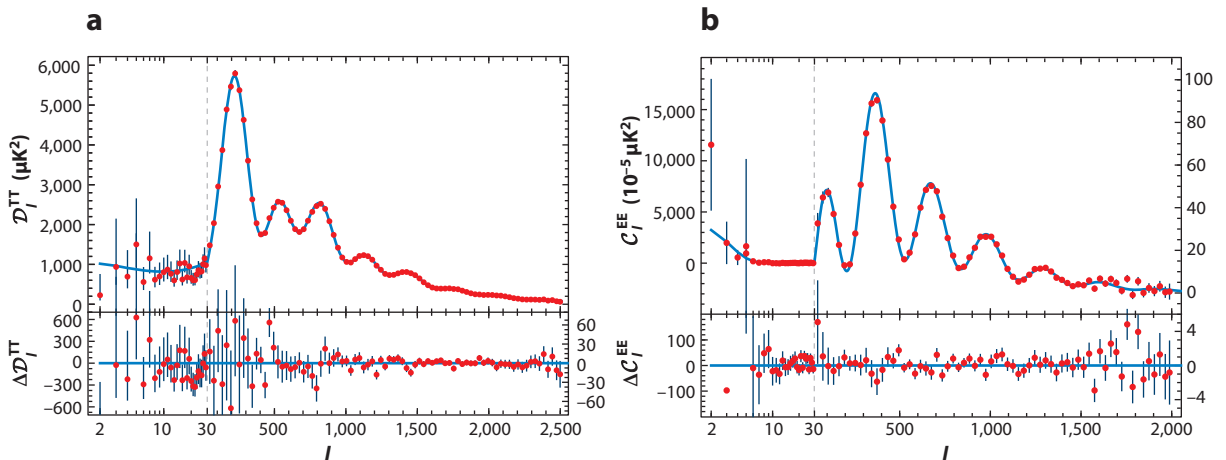


Figure 6

Just six numbers describe the Universe. Here, $\mathcal{D}_\ell^{TT} \equiv \ell(\ell+1)C_\ell^{TT}/2\pi$. The figure shows (a) the Planck TT angular power spectrum and residuals from the best fit six-parameter model and (b) the EE power spectrum. Figure adapted with permission from Reference 172; copyright 2020 ESO.

The body of evidence that supports Λ CDM includes CMB anisotropy and polarization on angular scales from 90° to arcminutes; large-scale structure as quantified by galaxy redshift surveys, weak lensing, and baryon acoustic oscillations (BAOs); the expansion history as probed by type 1a supernovae and BAOs; the light-element abundances; cluster abundances; and observations of galaxy properties and evolution. Two figures cannot summarize the impressively vast amount of data; however, see **Figures 6** and **7**.

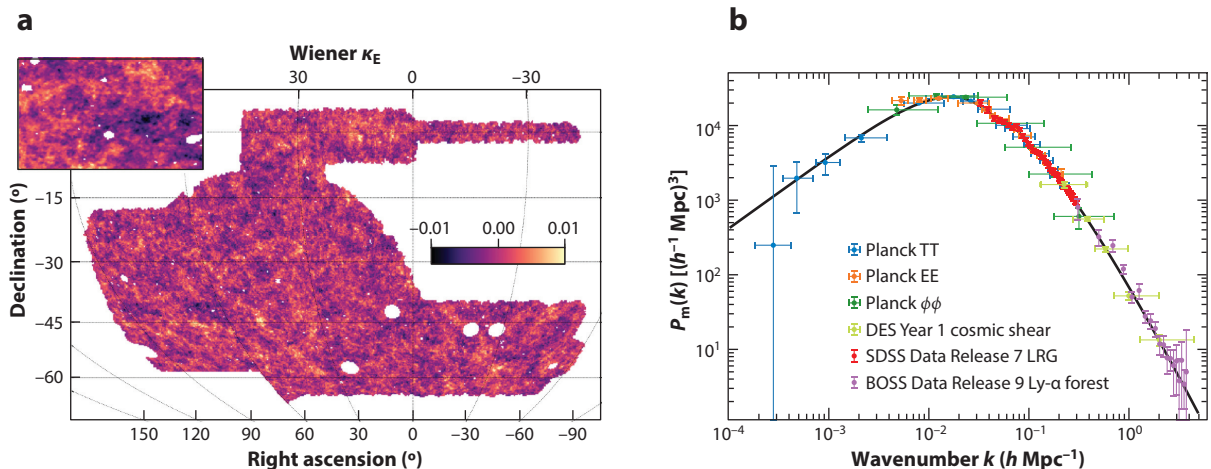


Figure 7

Large-scale structure measurements. (a) DES weak-lensing map of 5,000 square degrees of the sky. The color scale is convergence, which is proportional to the projected mass over density. Panel adapted from Reference 173, figure 5. (b) Planck compilation of the power spectrum of inhomogeneities; the curve shows the predictions of the Λ CDM model. Panel adapted with permission from Reference 99; copyright 2020 ESO. Abbreviations: BOSS, Baryon Oscillation Spectroscopic Survey; DES, Dark Energy Survey; Λ CDM, Lambda cold dark matter; LRG, Luminous Red Galaxies; SDSS, Sloan Digital Sky Survey.

4.1.1. Planck speaks. Consider just a small subset of cosmological parameters from the final Planck results, almost all measured with subpercent precision (99):

1. $\Omega_0 = 0.999 \pm 0.002$
2. $n_s = 0.9649 \pm 0.0042$
3. $\Omega_B b^2 = 0.02237 \pm 0.00015$
4. $\Omega_M b^2 = 0.143 \pm 0.0011$
5. $t_0 = 13.80 \pm 0.023$ Gyr
6. $H_0 = 67.4 \pm 0.54$ km s⁻¹ Mpc⁻¹
7. $\sigma_8 = 0.8111 \pm 0.0060$

The first two numbers, together with the Planck upper limits to any non-Gaussianity (174), provide strong evidence for the basic inflationary predictions of a flat Universe with almost scale-invariant, Gaussian curvature perturbations. The power-law index of density inhomogeneity $n_s = 1$ corresponds to scale invariance; the expectation of a small deviation (175) shows up at almost 10σ .

Next comes the almost 100σ difference between the baryon density and the matter density. It anchors the case for nonbaryonic dark matter, unless something is wrong with the whole framework. Planck also limits the amount of HDM, $\Omega_\nu b^2 < 0.0013$, adding to the large-scale structure measurements that scream out for CDM.

The last three cosmological parameters in my list are derived from CMB anisotropy measurements and the assumption of Λ CDM. Having an age determination with an error estimate of 23 million years is a far cry from the 1990s when age estimates ranged from 10 to 20 Gyr. Further, the CMB measurements of H_0 and σ_8 (the level of inhomogeneity on the cluster scale of $8 h^{-1}$ Mpc) allow for end-to-end consistency tests of Λ CDM by comparison with direct measurements of both quantities today (discussed further in Section 4.2.2).

4.1.2. Deuterium. BBN played a crucial role in establishing the hot big bang model with its successful explanation of the large primordial abundance of ^4He ; in the precision era, deuterium takes center stage. Deuterium is the “baryometer” (176) because its abundance depends strongly upon the baryon density (see **Figure 8**).

In 1996 the primordial abundance of deuterium was finally determined by measuring the absorption of quasi-stellar object light by intervening gas clouds of pristine material (177). Clouds with just the right properties are few and far between, and it took the high-resolution spectrograph on the 10-m Keck telescopes to identify the deuterium feature. With a dozen detections, the precision is approaching 1%: $\text{D}/\text{H} = 2.527 \pm 0.03 \times 10^{-5}$ (178).

This abundance implies a baryon density of $\Omega_B b^2 = 0.02166 \pm 0.00015 \pm 0.00011$ ²⁷ with precision better than 1% and consistency with the Planck determination (178). The predicted mass fraction of ^4He that follows from this is $Y_p = 0.2469 \pm 0.0002$, which is consistent with astrophysical measurements, $Y_p = 0.245 \pm 0.0034$ (181). Further, both are consistent with the less precise Planck-determined ^4He abundance, $Y_p = 0.242 \pm 0.024$ (99), based upon the structure of the acoustic peaks.

The baryon density is a poster child for precision cosmology: two different percent-level determinations of a fundamental quantity that agree. One derives from gravity-driven acoustic oscillations when the Universe was 380,000 years old, while the other involves nuclear reactions that took place when the Universe was seconds old.

²⁷The second uncertainty is the theoretical uncertainty that arises from input nuclear data, primarily the cross section for $d(p, \gamma)^3\text{He}$ (see 180).

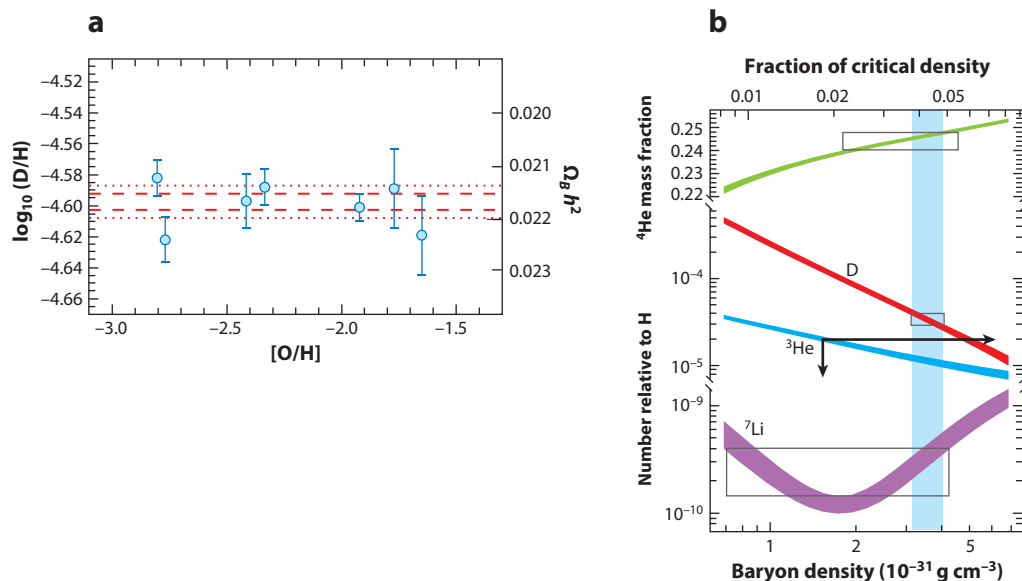


Figure 8

Big bang nucleosynthesis. (a) D/H determinations. Panel adapted with permission from Reference 178; copyright 2018 AAS. (b) The vertical band is the deuterium-determined baryon density, and the other bands are the 1σ predictions. The heights of the black boxes indicate the measured abundances with error estimates. The upper density scale assumes $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Panel adapted from Reference 179.

4.1.3. Loose ends. With precision comes controversy. The biggest one involves ${}^7\text{Li}$, whose predicted abundance is a factor of two larger than the abundance seen in the lowest-metallicity stars—a blemish on an otherwise stellar record for BBN. There is a growing consensus that the putative primordial abundance, which traces back to the 1980s, was a mirage and actually reflected stellar depletion of the primordial value (181). Consensus doesn't mean an evidence-supported fact, and there could still be a surprise ahead.

From the beginning, CDM has been under attack—as any attractive and expansive theory should be (182). Mostly, the problems involve small scales (e.g., predicted shapes of the central rotation curves of dwarf galaxies, or the underabundance of dwarf galaxies as compared with observations), where the influence of baryons can be significant and can possibly explain the discrepancy. I would be more concerned if the problems involved larger scales, where baryonic hydrodynamics cannot be important. Having witnessed CDM survive many crises and near-death experiences, I am convinced that it contains most of the truth about structure formation, and if a replacement is needed, it will look very similar to CDM.

4.1.4. Cosmic limits. Cosmology is not laboratory science. We are constrained to observe rather than set up experiments, and we cannot recreate the big bang or try alternative cosmologies or scenarios. We are also creatures of our own limited time and space horizons in a vast Universe. The standard of proof in cosmology must also be different. I—along, I think, with most other cosmologists—am convinced that BBN really happened, because we use physics well established in the laboratory to make detailed predictions that agree with observations. What will we require in order to say the same for dark matter or inflation?

4.1.5. The heavenly lab. The other big triumph of the coming together of the very big and the very small is the ability to make precision measurements in the heavenly laboratory. It has opened the door to a new way of making discoveries and testing theories.

Historically, the first such discovery is that of the element helium through its absorption lines in the sun more than 100 years ago. The list now includes neutrino mass (solar neutrinos and atmospheric neutrinos), three generations of quarks and leptons (BBN ${}^4\text{He}$ production), a new stable particle (dark matter), nonparticulate stress energy with repulsive gravity (dark energy), and the existence of gravitational waves that propagate with the speed of light (LIGO/Virgo detection of gravitational waves).

Today, setting limits to hypothetical particles, objects, events, and so on has become a well-accepted and trusted way to extend the reach of terrestrial laboratories when testing new ideas in fundamental physics.

4.2. Toward a Third Cosmological Paradigm

Two big thinkers—Niels Bohr and Yogi Berra—agreed that prediction, especially about the future, is hard. Furthermore, cosmology is boom-or-bust science with long intervals between big discoveries: 40 years from Hubble to Penzias and Wilson; 27 years to the COBE discovery of anisotropy; 6 years to the discovery of dark energy; and since then, 24 years of quiet, steady progress.

Nevertheless, I cannot resist sharing a few thoughts about the cosmological paradigm²⁸ that may follow Λ CDM. The only clarity I have is in my organization of those thoughts: what we might expect from linear progress, from a Kuhnian-type shift, and from thinking about lofty issues.

4.2.1. Known mysteries. Λ CDM leaves cosmology with three big questions to answer and, by attempting to do so, make linear progress: What is the dark matter particle? What is the nature of dark energy? and What is the physics underlying inflation? And there is an impressive program in place to address these questions, from more than 10 large-scale searches for dark matter particles to precision probes of cosmic acceleration on the ground and in space to CMB experiments to detect the B-mode polarization signature of inflation. Surely, clues or even a big payoff will come from these efforts.

There is another big challenge: a standard model of baryogenesis with consequences that can be tested. That baryogenesis involves Standard Model physics and the electroweak phase transition has all but been ruled out. Viable models now involve physics at scales well beyond those accessible in terrestrial laboratories. I find compelling the idea that the baryon asymmetry arose as a lepton asymmetry among the neutrinos and was transmuted into a baryon asymmetry by Standard Model $(B + L)$ -violating interactions. However, that idea is equally difficult to test (184).

As good as our questions are, they may be the wrong ones. Dark energy could be a mirage with the real explanation for cosmic acceleration being a replacement for General Relativity. The dark matter hunt has focused on a handful of well-motivated particles including the neutralino and axion, but the story could be much more complicated—for instance, with dark matter being a portal to a whole dark sector. In fact, this idea has captured the attention of a large portion of the theoretical particle physics community, leading to a multitude of new dark matter candidates (185).

Inflation in its current form is at best a first approximation to a more fundamental theory. Its loose ends—prediction of a multiverse, uneasy relationship to initial conditions, and the fact that its exponential expansion is the “microscope” that reveals scales that began much smaller than the Planck scale (186)—may help illuminate the path forward.

²⁸In Reference 183, I introduced “the third cosmological paradigm” and opined upon it at length.

Or, inflation could just be way off the mark. Early in my career, I saw the quark model evolve from $SU(3)$ flavor to the $SU(3)$ color gauge theory of QCD; the threes could hardly be more different.

We could be on the wrong track, with dark matter, dark energy, and inflation being the modern equivalents of Ptolemy’s epicycles. Λ CDM is complicated with photons, baryons, neutrinos, CDM, and dark energy, and unexplained ratios between the matter components (187): The ratio of CDM to baryons to neutrinos is 5.4 to 1 to (0.024–0.06). While it seems like too much works for us to be completely off track, there could be an unexpected Kuhnian shift ahead.

4.2.2. Kuhnian shift. If the future is hard to predict, paradigm shifts are even harder. As emphasized by Kuhn, the place to look for signs of such a shift are the “tensions”: 2–3 σ discrepancies of independent measurements of the same quantity within Λ CDM, which could grow in significance and result in a paradigm shift.

The most urgent one today is the Hubble tension: Direct measurements of the current expansion rate yield $H_0 = 74 \pm 1 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and indirect measurements of the expansion rate using CMB anisotropy and the assumption of Λ CDM to extrapolate the early time expansion rate to the present yield $H_0 = 67.5 \pm 0.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (188, 189) (see **Figure 1**).

The resolution could be a systematic error in one (or both) determinations of H_0 , or something important could be missing from Λ CDM. At the moment, there is no compelling modification of Λ CDM that easily accommodates the difference (190). Another lingering tension is the discrepancy between direct measurements of σ_8 and Ω_M with measurements that come from CMB anisotropy, as shown in **Figure 9**.

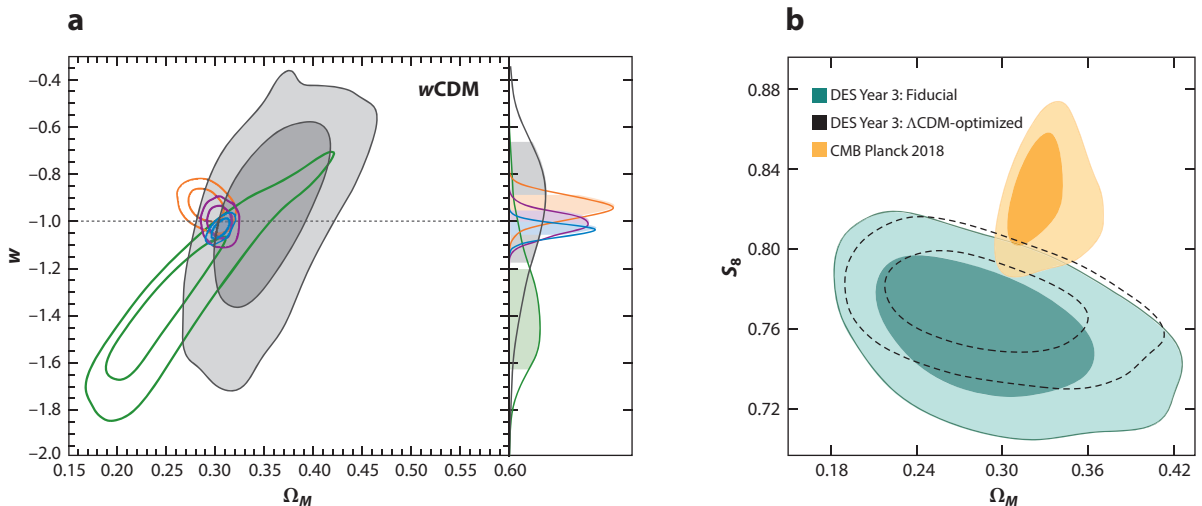


Figure 9

Joint analyses of the cosmological parameters Ω_M , $S_8 \equiv \sigma_8(\Omega_M/0.3)^{0.5}$, and dark energy equation of state w (191). Note the consistency of the Planck and DES precision measurements of (a) w and (b) the slight S_8 tension. In panel a, the contours correspond to various combinations of SNeIa, DES, BAO, and Planck CMB constraints; note the overall consistency of the different methods. Panel a adapted from Reference 192; copyright 2022 by the American Physical Society. Panel b adapted from Reference 191; copyright 2022 by the American Physical Society. Abbreviations: BAO, baryon acoustic oscillation; CMB, cosmic microwave background; DES, Dark Energy Survey; Λ CDM, Lambda cold dark matter.

4.2.3. Two lofty issues. On the one hand, a tiny discrepancy could illuminate the path forward. On the other hand, simply asking the right big question may open the door. Because each brings so much with it, I see two key issues in cosmology: the big bang event and the multiverse.

According to General Relativity, the big bang is the singular beginning of everything: matter, energy, space, and time. It also begs us to ask about initial conditions, that is, whether they are relevant or not; inflation seeks to make them irrelevant in practice, but they are still relevant in principle. And while the big bang is a singularity within General Relativity, it is likely not in the successor to General Relativity. This opens the scientific discussion of what happened before the big bang, and even the origin of space and time. It could be that General Relativity has the right answer but without the supporting mathematical details. Or, what we think of as the big bang might actually be the portal to an earlier phase of a cyclic universe—a decades-old idea that continues to attract attention.

I am not a fan of the multiverse. However, the issues it raises are too important to be ignored. The simplest question we can ask about the Universe—how big is it?—cannot be answered because of the limitations of our past light cone (193). The disconnected pieces of a multiverse raise the stakes: We cannot know how typical the part that we exist in is. Steinhardt and colleagues (194, 195) have argued that the multiverse, which is born of inflation, calls into question whether or not inflation makes firm predictions that can be tested. They conclude not and argue that an alternative to it is needed.

In addition to calling attention to a shortcoming of inflation, the multiverse is at the nexus of string theory and cosmology. It also provides a framework for discussing an anthropic/ensemble view of reality as well as an explanation for the smallness of the cosmological constant and cosmic acceleration (196). While early on string theory and cosmology had the makings of a marriage made in “the heavens,” the search for connections between the two has raised more questions and doubts than answers (197).

4.2.4. Some firm predictions. As I have demonstrated above, theorists, like economists, are famous for “on the one hand, on the other hand”-style predictions. With that low bar, I end with some firm predictions.

1. Cosmology and particle physics will continue to have profound connections.
2. The third cosmological paradigm will look a lot like Λ CDM—and, if we are lucky, there will be a few surprises as well.
3. There is a good chance that we will discover a WIMP-like dark matter particle or dark matter axions. If not, all bets are off; I do not see another compelling candidate.
4. I give two-to-one odds that the Hubble tension can be resolved without adding something new to Λ CDM (take heart: 33% for something new is a really bullish prediction).
5. I am dreaming of the discovery of a gravitational-wave signature in the CMB polarization—what a window to inflation and the earliest moments it would provide. I am enough of a realist to know that I may well have my heart broken.
6. I hope for clues about dark energy, but I believe this is a truly profound problem, and Λ may well be with us as a placeholder for many decades.
7. I am not bullish on progress toward a testable model of baryogenesis or an up-or-out for the multiverse; both will likely be open issues for quite a while.

4.3. Personal Reflections

It is impossible to filter out the effects of one’s own personal lens in viewing the world. And in science, it is easy to think that one’s career coincided with a special time. I do feel that the last half

century or so has seen especially dramatic progress in cosmology. The audacious idea that there might be a connection between the very big and the very small has led to revolutionary advances in our understanding of the Universe, and with it, the field has grown from around 30 astronomers to one that comprises thousands of physicists and astronomers and is front and center on the scientific agendas of both fields. While I used to take joy in understanding everything that was going on and thinking that I could contribute on virtually every topic, that is no longer possible. But so much else is.

In 1970, I suspect few imagined that the big questions would evolve so quickly from determining H_0 and q_0 to identifying the dark matter particle, understanding dark energy, and unraveling how quantum fluctuations become the seeds for all cosmic structure, or that cosmology would attract the interests of particle physicists. It has been my great fortune to be part of this grand adventure and of the quirky group that the tribe of cosmologists is. It would be hard to ask for more, but I hope that even more stunning advances and surprises lie ahead for the next generation of cosmologists.

Here is my advice: Don't pay too much attention to my predictions; make your own future. Find a scientific question you are passionate about and a style of science you are comfortable with, and go at it. There is plenty to do, from thinking about a really big question and trying to imagine how to make progress to getting involved in a large collaboration trying to detect dark matter particles or probing dark energy. And be prepared to be flexible; there will be surprises, discoveries about the Universe, and discoveries about what captures your passion.

Let me finish by saying that cosmology is a science that does not suit everyone: It includes having to observe rather than set up experiments, the daunting challenge of the vastness of the Universe, and the boom-or-bust progress. And more than a little arrogance is required for creatures that evolved from quantum fluctuations and quark soup—that exist only for a short time and are stuck on a small backwater outpost—to think that they might be able to understand everything. Steven Weinberg (12, p. 155) said it more eloquently in the epilogue of the 1993 edition of *The First Three Minutes*: “The effort to understand the universe is one of the very few things which lifts human life a little above the level of farce and gives it some of the grace of tragedy.”

DISCLOSURE STATEMENT

The author is not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

I am most grateful for the comments and illuminating conversations I have had about this review with Andy Albrecht, Barry Barish, John Carlstrom, George Efstathiou, Sandra Faber, Wendy Freedman, Katherine Freese, Josh Frieman, Wick Haxton, Craig Hogan, Dragan Huterer, Marc Kamionkowski, Saul Perlmutter, John Preskill, Martin Rees, Adam Riess, Bernard Sadoulet, Robert Scherrer, Paul Steinhardt, Robert Wagoner, and Larry Widrow. Over the years my research has been generously supported by the US Department of Energy Office of High Energy Physics, Fermilab, the National Science Foundation Physics Frontiers Centers program, NASA's Astrophysics Theory Program and Office for Innovative Research, and the Kavli Foundation. I also had the good fortune to have the support of both the University of Chicago and Fermilab, and most importantly my mentor, David N. Schramm, who brought me to Chicago and introduced me to cosmology.

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