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1

Our Universe

In this first chapter, I outline our universe's history as we currently understand it, and describe the main observations and measurements that we have used to deduce and support these conclusions. I also provide a brief description of some of the open questions and puzzles which motivate much of the research in modern cosmology. Readers with a strong background in both cosmology and particle physics can feel free to skip this chapter.

A little over a century ago, there was nothing that one could call a science of cosmology. On the observational side, it was being actively debated until the 1920s whether the collection of stars known as the Milky Way constituted the entirety of our universe, or was instead just one of many "island universes," or what we would now call galaxies [1]. In terms of theory, physicists had developed a framework to describe how objects move through space, but those theories were fundamentally incapable of asking how space itself might change or evolve with time. To begin to meaningfully ask questions such as these, one had to wait until November of 1915, when Einstein completed and presented his general theory of relativity [2].

I would argue that observational cosmology really began with the work of Henrietta Leavitt [3], Vesto Slipher [4], Edwin Hubble, and Milton Humason [5], whose observations collectively demonstrated not only that many long-observed nebulae are in fact galaxies, independent of the Milky Way, but also that nearly all of these objects are moving away from our location in the universe. Furthermore, these galaxies are each receding with velocities that are approximately proportional to their distance from us, thus demonstrating that our universe is expanding with time.

Taken at face value, the fact that our universe is expanding also implies that it must be changing and evolving. Although some astronomers attempted to accommodate the expansion of space within the context of steady state cosmological models [6, 7], such efforts became only more contrived as the evidence accumulated. As early as the 1950s, observations had begun to support the fact that our universe was hotter and denser in the past than it is today. With the discovery of the cosmic microwave background in 1964, the so-called "Hot Big Bang" theory became the leading paradigm for our universe's history and evolution. In the decades that followed, the fact that our universe evolved from a hot and dense state gradually became a matter of scientific consensus.

To understand the earliest eras of our universe's history, it is essential to know how matter and energy behave under extremely hot and dense conditions. The first few hundred

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thousand years after the Big Bang played out in large part according to the principles of atomic physics, while the first few seconds and minutes were dictated by the laws that govern the interactions of atomic nuclei. Modern particle accelerators allow us to study the behavior of particles at temperatures as high as roughly a TeV, probing times as early as a trillionth of a second after the Big Bang.

In these first moments, the seeds of what would become our universe were planted. The particles that make up the dark matter were created during this primordial era, along with the neutrinos, electrons, and nuclei that occupy our universe today. During this earliest period of time, significant quantities of matter somehow survived, while antimatter did not. By the end of inflation, density perturbations were already in place that would ultimately lead to the formation of our universe's large-scale structure. We cannot claim to understand our universe without understanding this brief but critically formative moment of time.

1.1 A brief history of our universe

As with many historical timelines, the farther cosmologists look into the past, the less certain they are about the events that unfolded then. Without any way to observe the earliest moments, or to study the conditions under which they existed, we are forced to blindly extrapolate beyond the regimes that are currently observationally or experimentally accessible to us. This has led many to speculate about a variety of possible events that may have taken place in the very early universe, including the following:

- **The Big Bang singularity** ($t = 0$, $T = \infty$): Perhaps our universe began as a spacetime singularity of infinite temperature and density, prior to which neither space nor time existed.
- **The Planck era** ($t \sim 10^{-43}$ s, $T \sim 10^{19}$ GeV): At temperatures near the Planck scale, the effects of quantum gravity are expected to have been in full effect, perhaps involving radical departures from the laws of physics as we currently understand them.
- **The era of grand unification** ($t \lesssim 10^{-36}$ s, $T \gtrsim 10^{15}$ GeV): In grand unified theories (GUTs), the three forces of the Standard Model are each part of a singular force (and symmetry group) that was broken as the universe cooled. During the grand unified era, this symmetry remained unbroken, blurring the distinction between these three forces, and between quarks and leptons.
- **The inflationary era** ($t = ?$, $T = ?$): The flatness and uniformity of our universe suggest that our universe may have undergone a period of exponential expansion during its very early history. While there now exists significant evidence for inflation, much remains unknown about this era and the physics behind it.

As our universe expanded, it eventually cooled to temperatures that we can study using particle accelerators. From the data collected at the Large Hadron Collider (LHC), the Tevatron, the Large Electron-Positron (LEP) collider, and other such experiments, we can deduce much about our universe's likely state during its first trillionth of a second, including the following:

- **The quark-gluon plasma** ($t \lesssim 10^{-5}$ s, $T \gtrsim 0.3$ GeV): During this era, our universe was filled with a dense plasma of quarks and gluons, containing all of the known species of particles.

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- **The electroweak phase transition** ($t \sim 10^{-11}$ s, $T \sim 200$ GeV): Prior to this time, electroweak symmetry remained unbroken, and the known gauge bosons, quarks, and leptons were each massless. During this transition, these particles acquired masses through the Higgs mechanism, and the electromagnetic and weak forces took on their familiar forms.
- **The QCD phase transition** ($t \sim 10^{-5}$ s, $T \sim 0.3$ GeV): During this transition, the quarks and gluons became bound together into mesons and hadrons, resulting from the evolving strength of the strong force.

Although particle accelerators and other laboratory experiments allow us to speculate about our universe's first $\sim 10^{-12}$ seconds in a way that is reasonably well informed, significant events may have taken place during this period that accelerators are not yet capable of revealing to us. In particular, particles that are only feebly coupled to the Standard Model may have been very consequential during this period of time, while also being very difficult to produce and study in accelerators. Similarly, particles that were produced at temperatures greater than those probed by the Large Hadron Collider could have been present during this period of time, substantially impacting how our early universe evolved.

Moving forward in time, we find ourselves on much firmer ground. Beginning roughly a second after the Big Bang, we have both laboratory data and cosmological observations to inform our understanding of cosmic history. Through measurements of the primordial light element abundances, we can be quite confident that the following events took place in the early universe:

- **Neutrino decoupling** ($t \sim 1$ s, $T \sim 1$ MeV): Before our universe had become even one second old, its density had become low enough to allow it to become transparent to neutrinos. These particles have been traveling unimpeded ever since, and now constitute what is known as the cosmic neutrino background.
- **Proton-neutron freeze out** ($t \sim 1$ s, $T \sim 1$ MeV): Prior to this transition, protons could be converted into neutrons and vice versa through weak interactions. As our universe expanded, these processes became inefficient, and the abundances of protons and neutrons each became fixed (until the neutrons began to decay).
- **Deuterium and helium fusion** ($t \sim 1$–300 s, $T \sim 1$–0.07 MeV): During this era of Big Bang nucleosynthesis, free protons and neutrons fused together to form deuterons, followed by ^{3}He, ^{3}H, and ^{4}He. Within only a few minutes, approximately a quarter of all nucleons were bound within helium nuclei. A much smaller proportion of the nucleons were fused into the nuclei of lithium and beryllium.
- **The decay of the free neutrons** ($t \sim 880$ s, $T \sim 30$ keV): As the age of the universe became comparable to the neutron's lifetime, these particles gradually disappeared from our universe. Eventually, unstable nuclei such as ^{7}Be and ^{3}H followed suit.
- **Matter domination begins** ($t \sim 51{,}000$ yr, $T \sim 0.8$ eV): As photons and neutrinos lost their energy to the expansion of space, matter (including both baryons and dark matter) came to make up an increasingly large fraction of our universe's energy density, ultimately constituting the majority of the total energy.

It would greatly surprise me to learn that these events did not take place as described above. Our observational handles on this era are strong enough to give us considerable confidence in this overall picture. As we move further forward in time, this becomes only more true. From the era of photon decoupling onward, we have vast quantities of diverse

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observational information to rely on. We can be approximately as certain about this period of our universe's history as the scientific method allows us to be about anything.

- **The formation of atoms** ($t \sim 380{,}000$ yr, $T \sim 0.3$ eV): As our universe cooled to temperatures well below the binding energies of hydrogen and helium, the overwhelming majority of the electrons became bound to these nuclei, forming the first electrically neutral atoms.
- **Photon decoupling** ($t \sim 380{,}000$ yr, $T \sim 0.3$ eV): As the plasma of charged particles that filled our universe transformed into a gas of neutral atoms, space became transparent to light for the first time. The photons that decoupled from the plasma during this era have been traveling through our universe ever since, and make up today's cosmic microwave background.
- **First stars and galaxies** ($t \sim 50$–200 Myr, $T \sim 0.01$–0.005 eV): Star formation began during this era, followed shortly thereafter by the formation of our universe's first galaxies.
- **Reionization** ($t \sim 0.5$ Gyr, $T \sim 0.002$ eV): Within half a billion years or so, energetic photons produced by the first stars and galaxies began to disassociate electrons from nuclei, returning our universe to a nearly fully ionized state.
- **Dark energy domination begins** ($t \sim 10$ Gyr, $T \sim 0.0003$ eV): For the past few billion years, the density of dark energy has exceeded that of matter, propelling our universe toward a state of exponential expansion.
- **Today** ($t \simeq 13.8$ Gyr, $T \simeq 0.000235$ eV): All of human history and culture plays out.

1.2 The empirical pillars of modern cosmology

On the opening page of Kolb and Turner's classic text, *The Early Universe*, the authors write, "Astronomy is a data-starved science. Cosmology is even more so." While this was a fair assessment at the time (circa 1990), it is certainly not the case today. Over the past few decades, cosmology has grown into an observationally rich science, with the ability to draw upon a huge body of diverse and precise data. In my view, it is this data that has made the present era of modern cosmology so exciting and vibrant. In this section, I'll summarize some of the most important portions of this data and what they tell us about our universe and its evolution.

1.2.1 The expansion rate

Although astronomers have been measuring the expansion rate of our universe since the time of Hubble and Humason, modern cosmology has dramatically improved such measurements in terms of both precision and the range of time (and redshift) across which such measurements can be made. When I took an undergraduate cosmology course in the late 1990s, my textbook reported that the current rate of Hubble expansion was probably somewhere in the range of $H_0 \sim 50$–100 km/s/Mpc. Today, measurements of the cosmic microwave background indicate that $H_0 \simeq 67.4 \pm 0.5$ km/s/Mpc [8]. Even taking into account the fact that other measurement techniques currently seem to prefer values in the range of $H_0 \sim 72$–76 km/s/Mpc [9, 10, 11], it is clear that enormous progress has been made over the past two decades. Furthermore, while a variety of techniques have long been used to measure the local rate of Hubble expansion, cosmologists have over the past few decades begun to use objects such as Type Ia supernovae to measure how this

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rate has evolved over most of our universe's history (i.e., out to redshifts of $z \gtrsim 2$). These measurements have had a great impact on our understanding of the composition of our universe, in particular, in revealing the presence of a significant density of dark energy.

1.2.2 The cosmic microwave background

Since its discovery in 1964, the cosmic microwave background (CMB) has been central to the field of observational cosmology. This collection of photons provides us with a detailed description of the state of our universe at the time of recombination, when electrons and nuclei formed the first electrically neutral atoms 380,000 years after the Big Bang. As a result of this transition from a plasma of charged particles to a gas of electrically neutral atoms, the photons decoupled from the matter, and have been more or less freely propagating through our universe ever since. The measured temperature anisotropies of the CMB tell us about how matter and energy were distributed throughout our universe at the time of recombination, as well as about the distribution of intervening matter. By scrutinizing the detailed properties of the CMB, cosmologists have been able to precisely determine the abundances of baryons, dark matter, and neutrinos in our universe, as well as the geometry of our universe itself.

1.2.3 The light element abundances

Although the nuclei of the heavier atomic species originated in stars, those of the lightest few elements (hydrogen, deuterium, helium, and lithium) were forged largely through nuclear fusion in the first seconds and minutes after the Big Bang. During this period of Big Bang nucleosynthesis (BBN), the temperature of our universe was hot enough to facilitate rapid fusion, $T \sim 1-0.01$ MeV, binding many of the free protons and neutrons together through the strong force. Measurements of the primordial helium-to-hydrogen and deuterium-to-hydrogen ratios each agree with the predictions of the Big Bang theory, and provide us with a measurement of the energy density and expansion rate of our universe as early as ~ 1 second after the Big Bang.

1.2.4 Large-scale structure

Over time, gravity causes regions that contain a greater than average density to collapse, forming increasingly dense structures. By studying the distribution of galaxies and galaxy clusters in our universe, we can infer facts about the expansion history of our universe, and the nature of dark matter. In particular, since the 1980s, observations of large-scale structure have made it clear that our universe contains large quantities of cold (or warm) dark matter. Such observations also provide us with evidence that dark energy has come to dominate our universe's energy density at late times.

1.2.5 Laboratory measurements

To reliably understand and interpret a given set of astronomical observations, one generally must possess knowledge of the laws of physics that are involved. For example, if physicists and chemists had not discovered and measured the spectral lines associated with various atomic species, cosmologists would not have been able to use redshift as a measure of distance. Similarly, if scientists had not performed laboratory experiments to study the interactions of nuclei at high temperatures, it is unlikely that astronomers would have learned much from their measurements of the primordial element abundances. In the current era, particle accelerators provide us with a foundation to understand our universe's first fraction of a second. In particular, by colliding pairs of protons together with 13.6 TeV

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of energy, the Large Hadron Collider allows us to study the forms of matter and energy that populated our universe as early as a trillionth of a second after the Big Bang.

1.3 Cosmic concordance

It is remarkable how well the standard Big Bang theory has held up to observational scrutiny over the past several decades. Forty years ago, no large-scale galaxy survey had been completed, and no anisotropies had been detected in the CMB. And yet, as the avalanche of modern cosmological data subsequently accumulated, the same underlying cosmological model remained in place and continued to be supported by the data. The many precise measurements that were carried out during these decades certainly allowed us to determine the values of many of the parameters of the standard Big Bang theory, but they did not force us to discard or alter this model in any substantial way. With only a handful of free parameters, this long-standing model remains to this day capable of describing the vast collection of data that has been accumulated over this period of time. This standard theory, including the presence of dark energy and cold dark matter, has become known as the ΛCDM model.

Many of the facts pertaining to our universe and its history have now been independently determined using multiple probes. The density of matter, for example, has been determined with measurements of galaxies and galaxy clusters, as well as using the temperature anisotropies of the CMB. Furthermore, starting with the distribution of cold dark matter at the time of recombination as inferred from the CMB, we can calculate how this matter should be distributed in our universe today, and this prediction agrees well with the observed large-scale structure of our universe. On similar grounds, we have determined the density of dark energy by measuring the evolution of our universe's expansion rate, by measuring the evolution of large-scale structure, and by studying the CMB's temperature anisotropies.

The most restrictive constraints on our universe's evolution prior to the time of recombination come from measurements of the light element abundances. These data confirm that our universe expanded at approximately the predicted rate from $\sim$1 second after the Big Bang (corresponding to $T \sim$ MeV) onward, which in turn implies that it did not contain any large abundances of matter or energy beyond those described by the standard ΛCDM model.

As for understanding the era prior to BBN, we have essentially no direct observational probes to rely on. Instead, we use what we have learned from particle accelerators to deduce as much as we can about how this era likely played out. There are many ways, however, that such inferences could be unreliable. First of all, there could exist particle species that interact too feebly with the particles of the Standard Model to be detected at existing particle accelerators, while still being produced in significant abundances in the early universe. Second, even the Large Hadron Collider cannot probe the kinds of interactions that took place during our universe's first $\sim 10^{-12}$ seconds (corresponding to $T \gtrsim$ TeV). Any attempt we might make to describe this first trillionth of a second must, therefore, rely on significant extrapolations, leaving us with little reason to be confident in the predictions of our existing theories.

1.4 Open questions and outstanding puzzles

If the questions raised by the science of cosmology had all been answered, I would not have bothered to write this book. In fact, the field of particle cosmology is a vibrant one in large part because of the many important and intriguing puzzles that we have, so far,

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failed to resolve. These open questions provide us with motivation to consider new models and theories, and to conduct new experiments and observations. Unanswered questions are the lifeblood of any healthy scientific community.

Below is a list of the questions and puzzles that at this time have not been conclusively addressed by our best current theories (general relativity and the Standard Model of particle physics).

- **Dark matter**: There is a near-consensus among cosmologists that most of the matter in our universe does not consist of atoms, but of something that does not appreciably radiate, reflect, or absorb light. It is not, however, yet known what this dark matter actually is. The existence of dark matter requires physics beyond the Standard Model, and almost certainly originated in the early universe, prior to BBN.
- **The matter-antimatter asymmetry**: The fact that our universe contains a significant abundance of baryonic matter but almost no antimatter also requires physics beyond the Standard Model. To generate this matter-antimatter asymmetry, there must exist exotic forms of matter that were present but were not in equilibrium in the early universe, whose interactions violate the conservation of both baryon number and charge-parity (CP) symmetry.
- **Dark energy**: Although general relativity allows for the possibility of vacuum energy in the form of the cosmological constant, quantum field theory leads us to expect that the density of this energy should be vastly larger than is observed in our universe. This apparent problem has led many cosmologists to explore dynamical mechanisms for dark energy, or to consider scenarios involving anthropic selection effects.
- **The flatness and horizon problems**: In the original form of the Big Bang theory, the degree to which the universe is curved increases as space expands. It thus requires highly fine-tuned initial conditions to explain the fact that our universe is approximately flat today. Furthermore, we observe regions of space that appear to have never been in causal contact, and yet are at nearly identical temperatures. These twin puzzles have motivated cosmologists to propose inflationary scenarios in which space expanded exponentially shortly after the Big Bang, driving the overall curvature toward zero and providing a mechanism to explain how the entire observable universe was once in causal contact.
- **The existence of neutrino masses**: Unlike in the case of other fermions, there is no mechanism in the Standard Model to generate masses for the neutrinos. The empirical fact that these particles have small masses requires new physics.
- **The hierarchy problem**: In the Standard Model, quantum corrections are expected to drive the mass of the Higgs boson to a very high value, well above that measured at the Large Hadron Collider. In lieu of an extreme fine-tuning of parameters, the relatively small value of the Higgs mass would appear to require physics beyond that of the Standard Model, typically involving new particles that are not much heavier than the TeV scale. Supersymmetry is the best known example of new physics that could resolve this problem.
- **The strong CP problem**: Despite the fact that the structure of QCD allows for the combined symmetries of charge and parity (CP) to be violated in the strong interactions, this has never been observed. To explain this without requiring a large degree of fine-tuning, dynamical mechanisms have been proposed that can drive the CP violating interactions to zero. The most well-known example of this is the

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Peccei-Quinn mechanism, which leads to the prediction of a dark matter candidate in the form of the axion.

- **Quantum gravity**: Despite the incredible empirical successes of general relativity, it is a classical theory that must break down on scales shorter than the Planck length, where quantum effects become important. Unlike the three forces described by the Standard Model, gravity is nonrenormalizable and cannot be self-consistently quantized using the same approach. The question of how to reconcile general relativity with quantum field theory is perhaps the single most significant open question in all of contemporary physics.

Additional reading

For readers who are interested in the history of cosmology, I enthusiastically recommend *Cosmology's Century* by Peebles. At the risk of coming across as overly self-promoting, I'll also suggest my own book, *At the Edge of Time*. On the particle physics side, I have particularly enjoyed Weinberg's *The Discovery of Subatomic Particles* and *The Second Creation* by Crease and Mann.

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