Chapter 9
Before the Big Bang

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Abstract The Big Bang has been typically identified as the beginning of the Universe: $t = 0$ if you extrapolate back our expanding Universe to a state of arbitrarily high temperatures and densities. While you can naively do exactly that in an expanding Universe under the rules of General Relativity, those conditions lead to observable effects that run contrary to what we see. Instead, the Universe is better described by cutting off the matter-and-radiation dominated Universe at some early time, patching on an inflationary epoch where space is expanding exponentially and dominated by some sort of vacuum energy. This is not mere theory nearly 40 years on, but is supported by a vast suite of observable evidence. The case for this conclusion, even in the absence of B-mode polarization in the CMB, is laid out here.

9.1 Introduction

There is, perhaps, no greater question in all of cosmology than the one concerning the origin of the Universe. When Albert Einstein first put forth his General Theory of Relativity, it was quickly recognized that the only static solutions containing matter required an inordinate amount of fine tuning and were inherently unstable. One of the earliest sets of solutions discovered were of isotropic, homogeneous Universes filled either with a cosmological constant or with a mix of matter, radiation, and spatial curvature. In both cases, it was found that the Universe cannot be static, but, depending on the initial conditions, will either expand or contract over time.

The revelation that, unlike in Newtonian physics, Einstein's equations admitted an evolving Universe solution, meant that spacetime was not necessarily static over time. In fact, the Universe could be full of many different types of matter and energy and still expand or contract. This was a big deal, because not only was our Universe full of stars, but galaxies as well. Making use of Leavitt's Law, Edwin Hubble became the first to measure the distance to a galaxy other than our own, by discovering Cepheid variables in the great Andromeda nebula, M31. Leavitt's Law

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provides a period/luminosity relationship between Cepheid variable stars, allowing an inference of the intrinsic brightness—and hence the distance—to any such star observed. Since Hubble could measure the apparent brightness and then the period of these Cepheids, a distance could be calculated.

By continuing on to measure Cepheids in a slew of spiral nebulae, Hubble and his assistant, Humason, derived the distance to a large number of galaxies. Complementary to that data set was Vesto Slipher's work, which noted the large redshifts of the spectral lines in a myriad of spiral and elliptical nebulae, corresponding to large recession velocities. These two data sets were first combined by Georges Lemaître to derive a redshift-distance relation, and then more robustly and independently by Hubble himself. This relationship is now known as Hubble's Law and has an astounding implication in the context of Einstein's relativity: that the fabric of space itself is expanding over time. The reason light gets redshifted is because the space between the emitting source and us, the observer, is stretching.

The rate of expansion is determined, on the observational side, by the measured Hubble constant, while on the theoretical side, it's a combination of the Universe's initial conditions along with the ratio of the various energy components present in the Universe. Although there are many possible cosmologies that admit expanding space like this, one of the most straightforward was put forth by George Gamow in what would grow into the idea of the Big Bang. If space was expanding and stretching, that implied that any gravitationally bound objects within it, like individual, isolated galaxies, would be expanding away from one another. Similarly, any radiation within this space would be stretched as is traveled through the Universe, causing its wavelength to lengthen and its energy to decrease. As you moved farther and farther forward in time, the Universe would become more dilute, and the temperature of the Universe would become cooler.

But as you extrapolated in the opposite direction—backwards in time—you'd move towards a hotter, denser, more uniform state. If the Universe becomes cooler, sparser, and gravitationally clumpier as we move forward in time, then the converse would be true as we moved backwards. Since the volume of our three-dimensional space scales is a^3, where a is the scale factor of the Universe, and the energy of an individual photon scales is a^{-1}, this implies that the matter density will shrink as a^{-3}, while the radiation density will shrink as a^{-4}. If we define the scale factor today, a_0, to equal 1, then we can extrapolate back to earlier times where the Universe was denser, hotter, and more uniform, and we can do this in a quantitative fashion, noting the cosmological implications along the way.

The remainder of these proceedings is laid out as follows. Section 9.2 focuses on the classical steps that take place as we move through time in the standard hot Big Bang. Section 9.3 focuses on the puzzles that arise if we extrapolate back to arbitrarily high temperatures, energies, and densities in such a model. Section 9.4 presents the solution to these puzzles in the form of cosmological inflation and includes the novel, generic predictions that arise from inflation and the status of where, whether, and how well they've been measured and tested. Finally, Sect. 9.5 presents an in-depth discussion of the implications for what occurred in our Universe before the Big Bang.

9.2 The Big Bang

If we begin at the present day, we can measure a whole slew of properties of the Universe as it is right now. There are specific temperature fluctuations that exist in the cold (2.725 K) cosmic microwave background (Planck Collaboration et al. 2015a), there are patterns to the clustering of galaxies on the largest scales in the Universe (Alam et al. 2017), and there are measurements of the expansion rate of the Universe out to many billions of light years (Suzuki et al. 2012). Combined, this gives us a concordance picture of the Universe, teaching us that it's composed of a specific mix of dark energy (68%), dark matter (27%), baryons (4.9%), neutrinos (0.1%), and photons (~0.01%), where these and other various methods of inquiry all produce measurements which point to the same, consistent cosmic picture (Freese 2017).

We also, when we look at the Universe nearby, find galaxies that are—on average—intrinsically redder in color, with high levels of metallicity (heavy element content), that are quite tightly clustered together, and that display relatively large masses and an advanced, evolved morphology (Baillard et al. 2011). The Universe shouldn't have always been this way, however. Gravitational attraction is a runaway process, pulling matter into structures slowly but increasingly when overdense regions are only slightly greater than the mean density (Mészáros 1974), and growing non-linearly once a certain density threshold is reached (Peacock and Dodds 1994). Applying this to the Universe, where looking back to great distances equates to looking back large amounts in time, we can reconstruct how more distant galaxies ought to be different in the past. Specifically, they should appear less clustered, with less power on large scales. For individual galaxies, they should be intrinsically bluer in color, less evolved in morphology, smaller in size and mass, with lower metallicities, and with different luminosity functions for their constituent stellar populations (Kawamata et al. 2018).

This should progress more and more severely as we go back in time, culminating in pristine populations of gas which have never yet formed any stars. This prediction of the Big Bang dates back 70 years (Alpher et al. 1948) and was at last verified just a few years ago (Fumagalli et al. 2011). As we continue to go back in time, we should reach an epoch where there was so little starlight that the atoms in intergalactic space remained neutral, since there was no ultraviolet radiation to ionize them (Gunn and Peterson 1965). This light-blocking matter was detected in high-redshift quasars; the Gunn-Peterson trough is now a solid part of observational cosmology (Becker et al. 2001). Prior even to this, there must be a time where no stars at all had formed, and the Universe was entirely dark, save for the leftover radiation from even earlier times. These cosmic "dark ages" are consistent with the timescale for reionization measured in the optical depth of the cosmic microwave background (Bennett et al. 2013).

But we can go back even farther, to when the Universe was more uniform, less clumped, and even smaller in size. Any radiation that existed would have its wavelength severely compressed in comparison to what exists today, implying a much hotter temperature under these early conditions. At some sufficiently early time, the wavelength of the most energetic photons would be short enough to enable the spontaneous ionization of neutral atoms: the photoelectric effect of this ultraviolet radiation would have prevented the stable formation of bound states of electrons and nuclei. In the face of an ionized plasma, this radiation would experience rapid Thomson scattering off of the free electrons, while after sufficient stretching and cooling, neutral atoms will form and the radiation will free-stream, creating a leftover radiation bath—a primeval fireball—whose remnants should exist with a low temperature and blackbody spectrum today (Dicke et al. 1965). The detection of this radiation (Penzias and Wilson 1965) and the subsequent measurement of its spectral properties (Fixsen et al. 1996) have thoroughly verified this cornerstone of the Big Bang. We've even come so far as to measure the minuscule temperature fluctuations in the spectrum of this radiation (Planck Collaboration et al. 2015a), corresponding to the density fluctuations that gave rise to the large-scale structure of the Universe today in great detail (Alam et al. 2017).

Even before that, the wavelength of photons would have been so short that atomic nuclei themselves would have been blasted apart. High-energy radiation can dissociate protons and neutrons from one another, creating a sea of unbound particles. The first step towards binding protons and neutrons together towards the formation of heavier nuclei is to create deuterium: a heavy isotope of hydrogen with a binding energy of just 2.2 MeV. When there are sufficient densities of photons in excess of those energies, no nucleosynthesis of heavier elements can proceed; the "deuterium bottleneck" delays those interactions due to the fragility of the products of this first, necessary step (Peacock 1999). Only when photons cool below this critical threshold can the synthesis of the first elements proceed. In this framework of the Big Bang, the only parameter that determines the relative element abundances is the baryon-to-photon ratio (Steigman 2006). The direct measurement of that ratio (Bennett et al. 2013) aligns spectacularly with the observations of the abundances of helium-4, helium-3, deuterium, and lithium-7, many of which are seen in distant quasar absorption lines (Riemer-Sørensen and Jennsen 2017).

So far, all of these predictions of the Big Bang have been spectacularly verified, but we can continue to extrapolate even farther back, to early times and high temperatures where no verifiable signatures remain. Before nucleosynthesis, particles should have high enough energies to spontaneously produce matter-antimatter pairs. Electrons and positrons remain the longest, but at even earlier times, any-and-all standard model particles and antiparticles are produced in great abundance, as defined by their fermionic or bosonic statistics. After the Universe cools and the particle/antiparticle pairs annihilate away, a tiny fraction of leftover matter remains: this baryon asymmetry is one of the greatest unsolved mysteries in all of physics.

When temperatures are high enough and the density of the Universe exceeds certain limits, protons, neutrons, and any type of baryon cease to exist, as they become replaced with a quark-gluon plasma. At even higher temperatures, exotic physics is expected to exist, particularly as we approach the theorized grand unification (GUT) scales. Particles mediating proton decay may appear; leptoquarks may exist; the couplings of the fundamental forces may run, and possibly run together; a slew of relic particles may be created at this time, including heavy Dirac neutrinos, potential dark matter candidates, and t'Hooft-Polyakov monopoles (t'Hooft 1974; Polakov 1974) may all exist under these extraordinary conditions. At the limit of our extrapolations, we exceed the Planck energy, achieve infinite (or arbitrarily high) densities, and run into the limits of our fundamental physics theories. We achieve a singularity, from where space and time themselves are believed to emerge.

9.3 Consequences

A singular beginning to the Universe, and its steady evolution from a set of hot, dense, uniform, expanding initial conditions, has tremendous implications for what we'd observe today. If the Universe began with arbitrarily high temperatures and energies, it would immediately create all the particles, antiparticles, and quanta of radiation that the quantum laws of nature—and energy constraints given by Einstein's $E = mc^2$—admitted. Beginning from the birth of the Universe, at a time $t = 0$, we would only be able to evolve the Universe forward, even in our imaginations. The first day in the Universe after the Big Bang occurred, as cosmologists sometimes put it, would be "a day without a yesterday."

After the first major verification of the predictions of the Big Bang came in, with the discovery of the cosmic microwave background radiation, the extrapolation back to a singularity seemed an inevitability. The singular beginning of the Universe would lead to a hot, dense state full of matter and energy, which would then evolve through the early stages in the Universe as outlined in Sect. 9.2. It's true that many of the stages we've passed through in the aftermath of the Big Bang have extraordinary amounts of evidence supporting them. But extrapolating back to arbitrarily high temperatures and energies not only lacks that evidence and remained a speculative extrapolation, but brought with it a significant number of unexplained puzzles (Siegel 2015) that the assumption of an initial singularity provided no answers for.

The first of these is the *horizon problem*. Even in an expanding Universe, there's a physical limit to how far, in a given amount of time, information (and temperature) can be exchanged between two disparate locations. Since the discovery of the cosmic microwave background, we've seen that the Universe has the same temperature in all directions in space, yet there's no physical mechanism that would have caused this to be the case. In the absence of such a cause, this simply needs to be an initial condition that the Universe was born with in order for it to be the case in the standard Big Bang, if it arises from a singular beginning. Without such conditions, we would expect the temperature (and density) to vary in different directions by roughly the order of the temperature itself.

The second is the related *isotropy problem*. When we look out at the Universe in all directions, today, we see the same types of large-scale structure everywhere. The types, sizes, populations, and clustering patterns of galaxies are direction-independent, illustrating the tremendous isotropy of the Universe. This also implies that the seed fluctuations from which today's large-scale structure arose were the same in all directions. But why should this be the case? Unless there were a mechanism in place to create these seed fluctuations, and unless that mechanism created fluctuations with the same properties in causally disconnected locations, this is simply another initial condition that arises without motivation.

The third is the *monopole problem*. In practically all grand unified theories, as well as many other extensions to the standard model, as the Universe cools through certain temperatures and conditions, it undergoes a phase transition. These transitions can create ultra-heavy relic particles, such as magnetic monopoles. In most scenarios of beyond-the-standard-model physics, these relics should not only be created, but they ought to be stable, persisting to the present day. Motivated by these calculations, there were a series of dedicated searches for isolated magnetic monopoles traveling through the Universe. Although there was a famously controversial detection of one monopole candidate (Cabrera 1982), follow-up experiments failed to confirm the existence of these particles. Their absence is a mystery that the hot Big Bang, if it were to have reached arbitrarily high temperatures and energies, has no explanation for.

The fourth puzzle is the *flatness problem*. Today, via a number of methods, we can measure the spatial curvature of the Universe. Particularly by looking at the patterns of fluctuations in the cosmic microwave background radiation (Planck Collaboration 2015a), we have determined that the Universe is spatially flat to approximately 1%. But flatness, rather than positive or negative curvature, which would imply a closed (sphere-like) or open (saddle-like) Universe, tells us that the balance between the expansion rate and the amount of matter and energy in the Universe must have been tremendously precise. If we extrapolate back to a time where the Universe was filled with a quark-gluon plasma, the energy density and expansion rate must have been balanced to better than one part in 10^{25}. If the Universe were just the tiniest bit denser, it would have already recollapsed; if it were the tiniest bit less dense, it would be more than double its present size. Without a mechanism to explain why these independent quantities are balanced, this too must be an initial condition that the Universe is simply born with.

Finally, the fifth puzzle can be called the *small fluctuation problem*. There are tiny imperfections in temperature (and therefore, in density) in the cosmic microwave background: on the order of $\pm 0.003\%$, compared to the mean value. This is an independent problem from the horizon problem, which offers no explanation for why the mean temperature value is the same everywhere. Even if you allow for that, there's no mechanism to generate temperature fluctuations that are not only the same magnitude everywhere, but merely one-part-in-30,000 times the average value. Why would these temperature fluctuations be so small, given that other out-of-equilibrium thermal systems where causal contact between disparate regions is disallowed display fluctuations that are thousands of times greater than what we seen in the cosmic microwave background? Again, this must be an initial condition that's added without any driving motivation, other than it's what we see when we examine the Universe in detail.

In theory, there's no reason why these puzzles couldn't simply be resolved by putting in the initial conditions we require. But if we solve these puzzles in that fashion, we give up on the very idea that physics is important for our Universe! We seek to apply laws, rules, and dynamical solutions to the phenomena we observe and measure; that's the key to scientifically examining and understanding the world and Universe around us. Given that these puzzles all suffer from the same problem—a set of initial conditions must be put in by an ad hoc method—it makes sense to attempt to concoct a physically well-motivated explanation for these initial conditions. Ideally, whatever scenario you cook up will not only explain these puzzles, but will make novel, additional predictions that can then be sought out and put to the test.

Historically, every new scientific idea has had to meet three criteria in order to be universally accepted as superior to the previously prevailing idea:

- It must reproduce the full suite of successes of the prevailing theory, meaning any replacement for the hot Big Bang with a singular beginning must successfully give the light element abundances, the cosmic microwave background, the large-scale structure of the Universe, and match the observed Hubble expansion.
- It must succeed where the prevailing theory has failed, which means it needs to provide an explanation for these five puzzles that the Big Bang cannot provide on its own.
- And it must make new, testable predictions for phenomena and properties that can be measured within this Universe. These predictions must be fundamentally, veritably, and quantifiably different from the predictions made by the alternative theory it's seeking to supplant.

If a scenario could be concocted that would satisfy all of those conditions, perhaps it could either replace or augment the hot Big Bang scenario, as it was originally formulated, to better explain the cosmic origins of our Universe.

9.4 The Inflationary Universe

By the late 1970s, many physicists and cosmologists were thinking about these problems, with a special emphasis on the horizon and flatness problems, owing to the robustness of the data indicating a uniform temperature and spatial flatness to the Universe as a whole. On December 7, 1979, a young postdoc named Alan Guth wrote the following in his notebook:

9.4.1 Spectacular Realization

This kind of supercooling can explain why the universe today is so incredibly flat—and therefore resolve the fine-tuning paradox pointed out by Bob Dicke in his Einstein day lectures.

This spectacular realization would very quickly lead to one of the most important papers in the history of modern cosmology, which detailed a new scenario for the Universe's origin: cosmic inflation (Guth 1981).

Unlike the standard hot Big Bang, where arbitrarily high temperatures, energies, and densities are achieved at a time $t = 0$ when you extrapolate backwards from today, cosmic inflation provided a cutoff to how hot, dense, and energetic the Universe was in the earliest stages. Rather than continuing back to a singularity, inflation postulated that there was a time period prior to the hot, dense, expanding state that the Big Bang describes. In the inflationary scenario, this prior phase contained no matter, antimatter, or radiation, but rather the Universe existed in a de Sitter-like state, dominated by energy in the inflaton field, which behaves similarly to vacuum energy or a cosmological constant.

During this inflationary phase, space expands exponentially, obeying the relation that $a(t) = a_0\, e^{Ht}$, where the value of H is determined by the energy scale of inflation. This exponential expansion doesn't necessarily need to occur at a rapid rate, but the exponential property is special because of how relentless it is. For inflation occurring at the hypothesized GUT scale, for example, it can turn a Planck-scale region (~10^{-35} m) into the size of the observable Universe today (~10^{27} m) in a timespan that's merely 10^{-33} s in duration.

This type of exponential expansion has a number of physical effects that are vital for both setting up the initial conditions of the Big Bang and ameliorating a number of cosmic puzzles. The inflationary phase, for example, stretches the Universe flat, by taking whatever amount and type of spatial curvature that may have pre-existed and expanding it so thoroughly that, to an observer that can only see the extent of the Universe that's accessible to us, it's indistinguishable from flat. It takes whatever properties existed in a tiny, causally connected region of space, and stretches that region across a volume far bigger than that of our observable Universe, giving it the same properties everywhere. Given that whatever field causes inflation is likely to be quantum in nature, the field ought to exhibit quantum fluctuations at all times; hence, these fluctuations should be stretched by the expansion of space to exist, with practically the same magnitude and spectrum, across all scales and in all locations in space.

Finally, when inflation ends, the energy that's inherent to the inflaton field—and hence, that's behaving as vacuum energy during the inflationary phase—gets converted into matter, antimatter, and radiation (Linde 1982; Albrecht and Steinhardt 1982). Inflation goes on so long as the field that drives it remains out of the ground state (such as at the top of a potential "hill"), but comes to an end when it reaches the lowest-energy, most stable state (such as rolling down into a potential "valley"). The temperature that the Universe reaches, post-inflation, is bounded from above by the energy scale of inflation, and may be lower depending on the particulars of the reheating process. In the aftermath of this conversion of energy, from the inflaton field to the matter, antimatter, and radiation permeating all of space, the conditions at the end of inflation are imprinted on the forms of energy that fill the Universe as it enters the familiar hot, dense, expanding-and-cooling state. Finally, given the size of our observable Universe, it's only the last few dozen *e*-foldings of inflation that have any observable impact on our Universe today.

Inflation, therefore, can reproduce the successes of the hot Big Bang by giving you the exact state you're seeking, beginning well above the earliest temperatures and energies we're currently capable of probing. In addition to that, cosmic inflation solves all five of the Big Bang's puzzles that we mentioned in Sect. 9.3.

- The horizon problem, that the Universe is the same temperature in causally disconnected regions, is explained by those different regions having been in causal contact in the past. Inflation stretched those regions apart to much larger distant scales, but they originated from the same Planck-scale volume, where they had time to achieve the same properties, like temperature and density.
- The isotropy problem, that the Universe has the same large-scale structure properties in all directions, is solved because the seed overdensities and underdensities that inflation creates, due to the quantum fluctuations that get stretched across the Universe, were created by the same process everywhere within our causal horizon.
- The monopole problem, that the Universe should be filled with these relic particles from a high-energy epoch in the distant past, is solved by a combination of two factors. First, any monopoles that existed during the inflationary phase are inflated away by the exponential expansion of space, meaning that there ought to be, at most, one magnetic monopole in the observable Universe. Second, so long as the maximum temperature we achieve after the end of inflation is below the scale that produces new monopoles, we wouldn't expect our Universe to contain any.
- The flatness problem, which notes that the Universe appears spatially flat, is now explained because no matter what conditions the Universe begins with, inflation will stretch it so that it appears indistinguishable from flat to an observer that can only see tens of billions of light years in any direction.
- And the small fluctuation problem is resolved, so long as inflation occurs well below (by a factor of $\sim 10^3$ or so) the Planck scale.

With these resolutions in place, we can see where inflation has succeeded in the realm where the original formulation of the hot Big Bang could not.

In addition, inflationary theories, including models of new inflation and chaotic inflation (Linde 1983), make six generic predictions that we can look to the Universe for confirmation, validation, or falsification. Inflation predicts a nearly-perfectly scale-invariant set of density fluctuations, parametrized by the scalar spectral index, n_s. Inflation predicts that n_s should be close to but not quite equal to 1; we measure it (Planck Collaboration 2015b) to be approximately 0.97. Inflation also predicts that there should be curvature fluctuations in the Universe, creating a spatial curvature that ought to be somewhere between $10^{-4} \geq \Omega_k \geq 10^{-6}$, consistent with our best constraints that $\Omega_k < 0.003$ (Alam et al. 2017).

In principle, there are two types of density fluctuations that could have existed and imprinted themselves on the Universe: adiabatic and isocurvature fluctuations. Inflation predicts that the fluctuations in our Universe should be 100% adiabatic, at least for all single-field models, both new and chaotic (Linde 1983). Thanks to the results from WMAP, that's exactly what we've observed (Bennett et al. 2013). Inflation also, owing to its stretching of quantum fluctuations across extremely large scales, predicts the existence of superhorizon fluctuations. These, theoretically, would be visible in the TE cross-correlation (temperature/polarization) spectrum of the microwave background, a prediction that has since been verified (Planck Collaboration 2015a). Inflation also predicts that there should be an upper limit to the maximum reheat temperature achieved at the hot Big Bang that follows the end of inflation; from the fluctuations in the cosmic microwave background, we find it's more than 100 times lower than the Planck scale (Bassett et al. 2005).

Finally, inflation also predicts a generic spectrum of tensor fluctuations—gravitational wave fluctuations—that ought to imprint themselves on the B-mode polarization signal in the cosmic microwave background. Although the spectrum is model-independent in inflationary spacetimes, the magnitude and amplitude of the signal is highly model-dependent (de Bernardis et al. 2009). Despite the purported and incorrect claims of detection by the BICEP2 collaboration a few years ago (BICEP2 Collaboration 2014), this remains a promising and active area of research that could further validate or challenge inflation.

9.5 Discussion

The Big Bang remains one of the greatest theoretical frameworks and achievements of modern cosmology. Its four cornerstone predictions, of the abundances of the light elements from Big Bang nucleosynthesis, of the existence and spectrum of the cosmic microwave background, of the Universe's expansion rate and its evolution over time, and the formation of large-scale structure, have been validated and verified in glorious detail. However, the inference that you can extrapolate the expanding, cooling Universe all the way back in time to $t = 0$ and the existence of a singularity is problematic at best, leading to the assumption of a slew of ill-motivated initial conditions.

The idea of cosmic inflation, however, removes the singular beginning to the Big Bang and instead replaces the earliest stages with an exponentially expanding phase to the early Universe. During this phase, the energy in the Universe exists in the form of the inflaton field, which drives the de Sitter-like behavior of the Universe during this time. Inflation is not only compatible with the four cornerstones of the Big Bang, but it dynamically sets up the initial conditions required to make the Big Bang compatible with our observations. In addition, cosmic inflation makes a number of generic predictions that are relatively model-independent; of the six presented in Sect. 9.4, four have been verified and two are consistent with inflation's predictions to the limits of our best observations.

Inflation, therefore, occurs before the Big Bang, setting up the initial conditions for what we see in our observable Universe during its final moments. It is only the final $\sim 10^{-33}$ s of inflation that imprint itself on what we can observe; although there are many fascinating predictions that arise from inflation, we have no way of knowing how long inflation lasted, how it arose, or whether it was eternal to the past or had, at some point, a singular beginning of its own. Although there is a theorem that demonstrates inflating spacetimes are past-timelike-incomplete (Borde et al. 2001), this theorem only demonstrates that particle trajectories separated by a finite distance in an inflating spacetime will have a common point-of-origin in the past. This does not necessitate the existence of a singularity, however, as numerous scenarios that avoid a singularity in inflating spacetimes have been found.

One remarkable consequence of inflation, even though it does not lead to any observables, is its prediction of the existence of a multiverse. The inflaton field, while slowly rolling towards the most stable, equilibrium field value, will spread out, being quantum in nature. If the rate of slow-roll is slower than the rate of field-spreading, which it is in practically all models that provide a sufficient amount of inflation, then there will inevitably exist regions of space where inflation continues indefinitely. No matter how many regions see inflation come to an end and give rise to a hot Big Bang, there will be inflating space between these regions to drive them apart from one another, continuing to generate new, inflating space, and—over time—to give rise to new, hot Big Bangs that will forever remain causally separated from the one that created our observable Universe. The generic phenomenon of eternal inflation (Vilenkin 1983) demands that once inflation begins, there are regions of it that continue inflating forever into the future. These regions of spacetime will continuously grow, exit inflation and reheat, creating an ever-increasing number of Universes similar to our own. This is why we expect our Universe to exist as part of a multiverse.

Back when it was first formulated, it was seen as an inevitability that the Big Bang was something you could extrapolate backwards to arbitrary times, energies, and temperatures, eventually reaching a singularity. Although the Big Bang can be accurately described as a hot, dense, expanding initial state, the Big Bang itself can no longer be said to imply a singularity. There may be a singularity at some early stage, but it is not a certainty, and if it does exist, it occurs before cosmic inflation does, which itself precedes and sets up the conditions for the Big Bang. Inflation makes many other predictions that are unique to it, and a great many of those predictions have been observationally confirmed. In addition, it predicts the existence of a multiverse, but sadly, the multiverse, as well as any properties of inflation that existed prior to the final 10^{-33} s (or so) of inflation, have no observable impact on our Universe. The Big Bang still represents an important moment in our cosmic history, but it is no longer the beginning of it all. Our matter-and-radiation-filled Universe started with a bang, but cosmic inflation takes us farther back, and does so more accurately, than the Big Bang on its own ever could.

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