The First Three Minutes: Cosmology, Astrophysics, and Particle Physics[1]

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Abstract: At the commencement of the universe and in the deep past of the observable realm, the first three minutes is a topic both scientifically challenging and philosophically intriguing. While the universe is believed to have undergone drastic changes over this short period, scientists seem to have essential difficulties with gaining observational evidence and conceiving physics in high-energy conditions. This essay delves into philosophical issues concerning evidence, inference, methodology, and the standard for legitimate scientific knowledge about the early universe. Focusing on three central scientific topics, the Big Bang nucleosynthesis, cosmic inflation, and multiverse, I analyze how scientists employ various forms of evidence, methods, and inferences to achieve remarkable success in obtaining detailed knowledge. It also turns out that those topics face different epistemic challenges and deserve different degrees of credibility. A feature of the early universe is the philosophical root of debates in science. I exemplify this by showing that debates about inflation and the multiverse stem from philosophical disagreements about standards for scientific explanation and the significance of hypothesis testing. I conclude by situating the philosophy of the early universe in the context of big history and pinpointing how it shapes our picture of "the beginning of everything".

Keywords: philosophy of cosmology, early universe, inference, evidence, scientific explanation

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I. **Introduction**

People have always wondered about the beginning of everything. What started space and time? How does matter come into being from nothing? How was the universe born, what did it look like in its infancy, and how did it evolve to its current stage? Over the last century, cosmology, astrophysics, and particle physics have obtained unprecedented observational and experimental data. They developed delicate theoretical frameworks to begin to answer these questions about the early universe and proposed quantitative models for many of its aspects. These scientific developments raise new philosophical questions about the nature of knowledge. How do scientists manage to know the early universe? Is this knowledge credible? What are the limits of this knowledge?

By the early universe, I am referring to the period between the start of time retrodicted from the standard model of the Big Bang (aka. ΛCDM cosmological model) and the first few minutes after it, climaxing with the Big Bang nucleosynthesis, the genesis of the first atomic nuclei. The scientific investigation into this early universe is unique in multiple respects. It faces two intrinsic limitations: It is impossible to directly observe or manipulate the early universe and we cannot securely extrapolate our currently established physical laws to that high-energy era. The study of the period thus involves interdisciplinary intellectual input. As the Nobel Laureate Steven Weinberg writes in his famous book *The First Three Minutes: A Modern View of the Origin of the Universe* ([1977]2022), this period has been especially intriguing for the ouroboric meeting between cosmology, the study of the grandest, and particle physics, the investigation into the tiniest. philosophy is useful for considering the criteria for evaluation and comparison of competing theories or models and for analyzing competing or different methodologies or metaphysical assumptions. (Ellis 2006).

This entry discusses both the lights and shadows of our scientific knowledge about the early universe, stretching from the acquisition and justification of knowledge to its uncertainties, open questions, and controversies. In section II I provide an overview of the key events in the early universe, then I introduce the difficulties in knowing the early universe and the present scientific endeavors. I focus on three major scientific topics that pose epistemic challenges: the Big Bang nucleosynthesis, cosmic inflation, and what is possible outside the present universe. Scientists investigate these topics by combining different sources of evidence and types of inference. A philosophical perspective considers the varied degrees of credibility of these inquiries. In section IV, I discuss two open scientific debates and show how philosophy plays a central role in shaping them. In the first debate between inflationary and non-inflationary scenarios, there are philosophical disagreements about the standards for the best explanation of observational evidence. In the second debate about the existence of the multiverse, the philosophical question is whether a hypothesis counts as scientific if it cannot be tested by experience. I conclude by situating the knowledge of the early universe in the general philosophical discussion about knowing the past and constructing big history.

II. What roughly happened in the early universe?

The "timeline" of the early universe is written in the grids of energy or temperature changes. The energy of the universe provides the conditions for certain physical laws to hold and for some crucial phenomena to happen. Phase transitions, like when the cooling of seawater triggers the crystallization of solved minerals and subsequently the formation of ice, also happen in the early universe. As the very hot and high-energy universe expanded and cooled, corresponding changes happen to its geometry, the types and amounts of matter within it, and the interactions between its components.

The following is a list of possible key events in the early universe; many of which are uncertain.

- The very early universe had extremely high temperature and energy, so the known physical laws could not be applied to it. Some theoretical physicists hypothesize two eras governed by different untested new physics:
- First, in the Planck era ($t<10^{-43}$s), the size of the universe was so small that quantum effects should be considered. Like a photon or an electron, depicted in basic quantum physics, the universe then could have been in a superposition state and have uncertain properties. Many physicists strive to develop a quantum theory of gravity for this era.
- Then, the grand unification epoch refers to the time ($t<10^{-36}$s) when the temperature was higher than 10^{27} K. This epoch is hypothesized to be governed by the "grand unification theory (GUT)". GUT suggests that strong, weak, and electromagnetic forces were unified into one. The universe was thus dominated by a hot dense plasma of unknown particles corresponding to this unified field.
- At the end of the grand unification epoch, there was a hypothetical stage called cosmic inflation. During inflation, the universe expanded exponentially. Its dimension increased drastically (10^{20}-10^{60} times) in an extremely short time (10^{-36}-10^{-32}s).
- By the end of inflation (10^{-5}-10^{-2}s), Standard Model particles gradually emerged from the unknown plasma. These particles included baryons, mesons, leptons, photons, and their antiparticles. This soup of particles is often called the primordial plasma.

- Before the temperature fell to 10^{12}K, particles were created and destroyed continuously. The presence of large numbers of strongly interacting particles makes the behavior of matter hard to calculate. The dominating energy and geometry during this era are uncertain.
- Between 10^{-2} to 1 s, the temperature dropped to 10^{10} K. Neutrinos stopped interacting with other particles in the "soup" and traveled freely. From this time, the dominating energy for the expansion of the universe became radiation.
- With temperatures between 10^9 to 10^{10} K, the energy of photons was not enough to produce electron-positron pairs. Positrons and electrons then annihilated each other through collisions, making positrons disappear from the primordial plasma and leaving a small number of electrons present.
- As the temperature reached 10^9 K, in a stage called the nucleosynthesis era, protons and neutrons combined to form the first atomic nuclei.

In a distant epilogue, 360,000 years later, when the temperature fell to 3,000 K, electrons combined with atomic nuclei to form neutral atoms. Since photons are less likely to scatter on neutral atoms than charged particles, they decoupled from matter. These photons are the presently observed cosmic microwave background (CMB). CMB offers one of the most precise and informative evidence for the theories of the early universe.

III. Accessing the first three minutes: uncertainties, evidence, and inference

Many presentations of the early universe, like I just introduced, provide a sequence of events. However, they remain unobservable. Instead, knowledge is inferred by "winding back the clock" from what can be currently observed. In this sense, the study of the early universe is very much like excavating a historical site, where a plausible story is reconstructed by identifying and analyzing present relics. Next, I review the uncertainties, available observational evidence, and inferential processes in three scientific topics: the Big Bang nucleosynthesis, the cosmic inflation, and what is outside the present universe.

3.1. Horizon

These three topics face a common overarching limitation, the horizon. In everyday life, when we gaze afar, our gaze terminates at the horizon, where the sky appears to meet the surface. Likewise, when detecting faraway objects in the universe, there is also a sense of a “horizon,” not caused by the roundness of the earth, but by the finite speed of light that limits any information signal. If the universe has a finite age, then we can only detect objects that lie within the distance that light can travel over this time. Astrophysicists and cosmologists call this distance “horizon”. The portion of spacetime beyond the horizon is in principle unobservable to us. Moreover, the earliest observable universe depends on when photons could decouple from matter to propagate freely in the very early universe. As a result, we cannot observe the state of the universe before CMB (Cosmic Microwave Background Radiation) was released. This limitation is called the “visual horizon”.

Phenomena within the horizon are the only relics of the unobservable early universe. Many astrophysicists and cosmologists compare their work to an archaeological excavation: they examine stars, galaxies, or large-scale radiation, trying to identify information signals from the deeper past of the early universe. Philosophers have pointed out that historical sciences, such as archaeology and paleobiology, similarly have limited ability to make reliable and unequivocal inferences about their object of study (Cleland 2002; Turner 2007). They also cannot manipulate objects in the past to test hypotheses against each other. Traces of the past decay, distort, or disappear, so it can be hard to identify and interpret them. The existence of horizon in cosmology can be considered a special case of these general epistemic and methodological problems.

Despite the general acknowledgment of these challenges, philosophers disagree about the extent to which they impede genuine scientific knowledge about the unobservable past. While some argue that such knowledge of the past is naturally limited (Turner 2007), optimists propose that scientists can often apply various epistemic strategies to mitigate these challenges and enhance inferences (Currie 2018). In cosmology, for example, many philosophers believe that the limitations of horizons do not impede the choice of an optimal cosmological model (ΛCDM) that depicts the evolution of the universe through 13.7 billion years (Smeenk 2019b) because cosmologists can employ multiple well-tested physical laws and sound theoretical assumptions when building those models and find empirical support from observational evidence in astrophysics. These tightly constrain the model despite the inaccessibility of observations beyond the horizon. Let us examine next three major examples where horizon limits scientific knowledge to different extents:

3.2. Big Bang Nucleosynthesis

No horizon impedes the relatively successful construction of models of the Big Bang Nucleosynthesis (BBN). The reconstruction of how the first nuclei were formed demonstrates the success of many inferential strategies often employed in the historical sciences. Nucleosynthesis explains the abundance of light elements in stars and globular clusters, which has been accurately measured in astrophysics. A BBN model serves as a good *common cause explanation* of the universal observed abundances of light elements, and there are no alternative models that explain them with comparable consistency. Such common cause explanations are prevalent in the historical sciences by inferring common causes from correlated and independent effects. (Cleland 2002, 2011). Further, nucleosynthesis is based on well-established physical theories, including nuclear reaction equations that describe what particles can combine to produce others, and the Boltzmann equation that describes the dynamical evolution of those reactions in the expanding universe. Using *theories* that are independently tested in other situations guarantees a reliable link between traces and the processes that produced them (Jeffares 2008). Moreover, models of BBN generate predictions about certain physical quantities that can be tested with other independent sources of evidence. For example, their predictions of the density of baryons (protons and neutrons) relative to all gravitating matter in the universe can be compared with that calculated from CMB data (Ratra and Vogeley 2008). As has been stressed by many philosophers, *diverse and multiple sources of evidence* can serve to test the coherence of methods that use different data or theoretical assumptions as well as offer stronger support for the theories they test (Bokulich 2022), impose strict constraints on model parameters (Currie 2018), and weave a web of models of past events and their evidence, whose overall consistency justifies the models and undermines alternatives (Wylie 2011; Yao 2023). Still, there are some lingering discrepancies between predictions of the present BBN model with observation, especially regarding the abundance of the element Lithium, which indicates possible systematic errors in measurement or the need for new physics in BBN.

3.3. The Cosmic Inflation

In contrast to the relative success of ΛCDM and BBN models, the horizon poses a challenge to many models that are specifically about phenomena in the unobservable early universe, such as inflation and the initial condition of the universe. These models are not a part of general cosmological models that govern the entire evolution of the universe, and therefore cannot share in the rich theoretical and empirical resources of other branches of physics. The only way to study them is through the traces they left on some very early observable parts of the universe. Therefore, cosmologists often have to speculate about untested new physics.

The historical hypothesis of cosmic inflation suggests a period of drastic exponential expansion of space before the universe entered the radiation-dominated era of slower expansion, characterized by the ΛCDM model. This scenario initially attempted to solve puzzles generated by the ΛCDM model (Guth 1991, 2007; Ratra and Vogeley 2008; Longair and Smeenk 2019; Baumann 2022):

1. The horizon problem: the observed CMB is largely isotropic--its different regions have almost the same temperature. However, any two points separated by more than 2° degrees on the CMB have never been in causal contact. It is puzzling that all those causally isolated regions happen to have the same temperature independently, unless they share a common cause.
2. The flatness problem: The universe is observed to be geometrically flat. This imposes a strict constraint on the initial condition of the universe: according to ΛCDM, had the geometry of the early universe deviated slightly from flatness, it would have diverged rapidly as the universe evolved. What makes the early universe strictly flat?
3. The baryon-asymmetry problem: in the early universe, baryons, i.e. heavy subatomic particles including protons and neutrons, and their antiparticles are produced in pairs from photons. However, current observations suggest that there is a slight asymmetry between them. What can be the mechanism for this unequal production?

4. The primordial fluctuation problem: density fluctuations can be found in CMB and serve as the seed for the growth of all cosmic structures. What mechanism generates the fluctuation with this observed amplitude and scale?
5. The magnetic monopole problem: the Grand Unification Theory (GUT) in particle physics predicts that phase transitions in the early universe should create numerous magnetic monopoles, which are effectively magnets with only one pole. However, no monopole has been observed.

Physicists conceived the scenario of inflation not by inferring it from observed phenomena with known physical laws. Instead, inflation was inferred through abduction. It is constructed as the best explanation for the above puzzles. By being the best explanation, it is justified as plausible. Inflation resolves the problems of horizon and flatness. With exponential expansion, a very small region where particles were initially in close causal interaction can expand quickly over a very large distance. This allows prior causal interaction within regions that appear to be causally disconnected, solving the horizon problem. The exponential expansion can also straighten out the geometry toward a flat space, so that the universe did not have to be in a special initial state to have the presently observed flatness.

The theory of inflation also appeared promising when it was introduced three decades ago because it proposed a mechanism that can be realized by Grand Unification Theory (GUT), then trending in particle physics. Inflation is assumed to be driven by a “false vacuum.” A vacuum is a space that has as little energy as possible, but still contains a quantum field. A false vacuum is a vacuum whose quantum field does not lie in the lowest energy state. By transiting to its lowest energy state, it can release energy and drive inflation. Some early theories of inflation hypothesized the nature of this quantum field and envisaged observational evidence from particle accelerators (Guth 1991). The combination of inflation and GUT was thus favored due to its unifying promise and hypothetical mechanisms that anticipated observational evidence.

Combining inflation and GUT provides potential explanations for the three remaining puzzles. GUT alone offers a solution to the baryon-asymmetry problem but generates the magnetic monopole problem (Longair and Smeenk 2019). Parameters of the inflationary model can be tuned to eliminate magnetic monopoles: if inflation happened after the production of monopoles, the monopole density can be diluted to a negligible level (Guth 2007). Finally, the primordial fluctuation can be explained as stemming from quantum fluctuations of the quantum field at the end of inflation. Models of this inflationary field thus make predictions about the patterns of its fluctuation, which can fit empirical data from CMB and large-scale structures (Guth 2007). Despite this promising unification and explanation, it should be noted that solving these three puzzles does not constitute direct evidence for inflation. The magnetic monopole puzzle arises from GUT, so solving it is only a viability check for GUT rather than support for inflation (Ratra and Vogeley 2008), and primordial fluctuation is explained only when inflation is coupled with GUT.

The inflation hypothesis in general has explanatory virtues, but a detailed model of it is far from settled. Inflation is consistent with diverse scenarios that assume different physical mechanisms. However, the hypothesized new physics in these scenarios elude laboratory tests due to the unattainable high energy density required to reproduce the conditions of the early universe. Without testability, physicists have not agreed on one best scenario. The early explosion of interest in GUT as the theoretical framework for inflation has cooled down. GUT has been theoretically and observationally stagnant for years. Consequentially, recent studies of inflation have entered a stage of “paradigm without a theory”: under the umbrella of exponential expansion, “cosmologists developed a wide variety of models bearing a loose family resemblance”, that disagree on the nature of the field and the form of the potential driving inflation (Longair and Smeenk 2019: 447).

Scenarios and models of inflation are thus in a state of *underdetermination*. This term refers to the existence of multiple theories or models for the same phenomenon and the lack of theoretical resources or empirical evidence to adjudicate between them (Stanford 2023). The choice of a model often requires ruling out its underdetermined alternatives.

What sort of credibility should we attribute to inflation then? Inflation can be interpreted as a phenomenalist model as opposed to a theoretical one, that is, not derived from the most fundamental physical principles but constructed to fit approximately the empirical data. Many cosmologists now are happy to take inflation as a phenomenalist model because observations have been successful in narrowing down the scope of remaining alternative possible models. The observation of CMB by the Planck mission, for example, has successfully ruled out several candidate scenarios (Akrami et al. 2020). An upcoming mission in 2024 called SPHEREx promises to detect the large-scale 3D distribution of galaxies with high precision that may possibly adjudicate between two major scenarios, inflation driven by a single field or multiple fields, because their estimations of the density variation in the early universe will become distinguishable by observation (Alibay et al. 2023). One can also expect more evidence in the next-generation CMB probes that will expand observational data and consequently increase constraints on models of inflation, even if their physical foundation is not settled.

The shift of commitment from phenomenalist to theoretical involves a more difficult “leap of faith”. Deriving inflation from fundamental physics would require a coherent system of such new physics, tested by independent evidence that would rule out most theoretical alternatives. These demanding requirements are not likely to be satisfied in the immediate future. Whether inflation can only be the best approximate story about the very early universe or whether it can be further established as “the real story”, and if so, how, remains a lingering question.

Inflation has implications for other puzzles about how the universe started and what may be beyond the spacetime of the observable universe. Inflation suggests that the present universe stems from a tiny causally connected region, but is there anything spatially outside this tiny blob or temporally prior to it? One scenario of inflation, eternal inflation, suggests that the false vacuum state that drove inflation never disappears in the areas beyond our observable universe (Guth 2007). As a result, there are numerous bubbles of universes beyond ours that are undergoing inflation. If eternal inflation is right, it means that our universe is only one of a larger number of universes, also called the “multiverse”. This also suggests a more sophisticated understanding of “the beginning of everything”, as the false vacuum and other bubble universes preceding our universe certainly cannot be considered as “nothing”.

3.4. Multiverse

The idea of the multiverse, the existence of universes spatially or temporally separated from ours, is not new. It stems from the marvel that we, as intelligent creatures, happen to exist in this universe. Had the fundamental physical constants deviated a little from what they are, the universe would have turned out barren, impossible for life to evolve. The values of the constants cannot be derived from fundamental laws but are only measured empirically. How did they come to have their specific values? How can our universe be so special? Philosophers call this puzzling coincidental setting of physical constants “fine-tuning”.

One type of scientific response to the challenge of fine-tuning seeks to find out what may have been prior to the birth of our universe. Misner (1968), for example, proposes a form of attractor dynamics through which a wide range of possible initial states can evolve to a special isotropic state, as a ball rolls into a pit irrespective of its initial position. Penrose (2010) proposed another solution; the universe started in a special state that resulted from the end of an earlier life cycle of the universe. Multiverse, in contrast, admits that “all that can occur, occurs” (Ellis 2006): there are infinitely many universes taking all possible constant values, and we simply dwell in one that enables our existence. Eternal inflation provides one type of physical mechanism for the multiverse to emerge and specifies the possible properties of those universes. The multiverse may offer a plausible explanation for fine-tuning.

However, the inference of the existence of the multiverse is even more tenuous than that of inflation. Theoretically, it is questionable whether the derivation from inflation of eternal inflation, and subsequently the multiverse quite follows (Smeenk and Ellis 2017). Empirically, the multiverse does not leave sufficient detectable imprints. Other universes are in principle unobservable due to the horizon and the general lack of causal interaction between them. Some versions of the multiverse do suggest indirect observational traces of their existence. For example, some models of eternal inflation suggest both proof of possibility and impossibility in CMB data (Ellis 2019). However, none of these “smoking guns” have been identified. Furthermore, even if the multiverse from eternal inflation happens to be supported or disproved in the future, it will still remain open whether other versions of the multiverse are possible. No observational program can unequivocally support or disprove the generic thesis of the multiverse (Ellis 2019). This lack of direct empirical test, detectable information signals from other universes in the multiverse, underdetermines the multiverse and its theoretical alternatives.

IV. Philosophy at the crossroads of scientific disagreements

In this section, I survey two major debates in the scientific community that are philosophical as much as scientific: they stem from divergent philosophical views about the standards for scientific knowledge.

4.1. Alternatives to inflation: Are best explanations the best?

The inflationary scenario has accumulated numerous supporters. Many physicists take it as a textbook solution. But alternative scenarios of the early universe have been proposed, together with divergent conceptions of the "beginning of everything".

Inflation is generally considered a supplement to the standard model of cosmology, ΛCDM. It suggests that the evolution of the universe is a unique event. The universe is born, evolves, and then perishes. Inflation is compatible with several types of beginnings of the universe. For example, the universe may have had a definite beginning, an initial singularity when it reached an infinite density and spacetime broke down. The universe may also defy the idea of a beginning as the zero point of time. James Hartle and Stephen Hawking suggest that there may be a special state prior to the Planck era, where time becomes an imaginary dimension with no boundaries or edges (Hawking 1996).

A few alternatives to inflation suggest that the universe is like a phoenix, reborn time after time from its end state. Steinhardt and Turok (2002), for example, propose a cosmology with endless cycles of expansion and contraction. This model solves multiple puzzles, because it accounts for the observed homogeneity, flatness, and density fluctuations. It is also strongly motivated by particle physics and includes the mysterious dark energy in the model's mathematical formalism. It further solves inflation’s remaining questions about the beginning of time. Another model of the cyclic universe proposed by Penrose (2010), “conformal cyclic cosmology,” offers another set of explanatory benefits. It explains the initial low entropy state of the universe, which is left unexplained by inflation. It also provides an explanation for the accelerating expansion without resorting to mysterious dark energy.

A recent theory promoted by Neil Turok suggests the universe is neither alone nor infinite, because it has a mirror twin on the other side of the Big Bang, with all matter replaced by antimatter, and with their positions and momenta reversed. This model not only solves the problems of horizon, flatness, and primordial fluctuation, but also those puzzles beyond the explanatory scope of inflation, such as the nature of dark matter, the absence of primordial gravitational waves, the increase of entropy after the Big Bang, and the CPT symmetry of the universe, the fundamental symmetry according to which physical laws are unchanged when one simultaneously changes particles with antiparticles, reverses time, and flips the sign of a spatial coordinate (Boyle, Teuscher, and Turok 2022).

The above proposals are reasonable alternatives to inflation because of their comparable explanatory powers, and because at present they generate indistinguishable observational predictions. Therefore, in addition to the underdetermination of models within the inflation paradigm, scenarios alternative to inflation are also underdetermined. The existence of underdetermined alternatives can benefit science by eliciting a critical examination of the assumptions that are taken for granted in each scenario.

As competing explanations of the evidence, their competitiveness depends on what exactly are the criteria that decide which explanation is superior to the other explanations. The scope of unification often plays a central role in evaluating explanations in cosmology and other historical sciences. An explanation is considered good if it can unite multiple phenomena. For example, a collision with an asteroid is considered a good explanation for the Cretaceous mass extinction because it serves as the common cause for both the extinction and the geological K-T boundary (Cleland 2002, 2011). The degree of superiority of an explanation depends on the *number* of phenomena it unites: K-T boundary serves as a "smoking gun" for the asteroid explanation over other candidate explanations for the extinction of the dinosaurs that do not also explain this curious geological trace.

Unfortunately, no hypothetical scenario of the early universe by itself explains, or unites, all the puzzles. Each scenario explains only a subset. Consequently, no piece of evidence can serve as the "smoking gun" that prefers one unique explanation. Choosing which theory constitutes the best explanation necessarily involves a trade-off between which phenomena are to be explained. A good explanation may prioritize then the phenomena that are more "surprising" because it is more "urgent" to explain them than others, and they confer a higher posterior value in a Bayesian computation.

All evidence is not equally in need of explanation. Some mundane facts simply do not need to be explained, and so explaining them will not make the explanation more plausible. To borrow White's (2005) example, winning a lottery is astonishing to me, but there is no need to explain why it is I who won it ,because this event is bound to happen: someone has to win a fair lottery. Which puzzles relating to the early universe are special or urgent enough to confer higher value on their explanations? Are there some puzzles more important than others? Proponents of different models for the early universe disagree (Longair and Smeenk 2019). Some acknowledge that the universe is "set up" to be flat and isotropic, and hence no further explanation is required. Proponents of inflation believe that there is something special about these properties, but they loosen the explanatory urgency of other puzzles, such as the nature of dark energy or dark matter and the initial condition prior to inflation. Many scientists criticize inflation's explanatory power for this reason. For example, inflation requires the universe to present certain degrees of homogeneity, isotropy, and low entropy as an initial condition, which requires a further explanation (Ellis 2006; Penrose 2010). They point out that inflation does not resolve the puzzle about why the universe appears "special," but just pushes this puzzle to a prior state. Proponents of inflation would retort with a different distribution of "explanatory significance" – inflation is an evolutionary model that is not bound to answer questions about creation (Guth 1991). The debate between scenarios thus boils down to scientists' different takes on the explanatory urgency of the set of possible puzzles.

What then should determine which explanations are more urgent than others? One may envision an objective algorithm to calculate which of the puzzles are more surprising and should be prioritized for explanation. However, here one needs to first assume a model of the probabilistic distribution of all possibilities of our universes. Building such models can be challenging because our universe appears unique, and so there is no obvious way to consider a range of possibilities beyond this universe (Smeenk 2019b). If physical models are used, a vicious circularity may arise if a phenomenon and its urgency are derived from a theory that is expected to explain it. For example, GUT produces the magnetic monopole problem and then uses inflation to explain it. It is questionable whether this explanatory approach really supports the inflationary model: Inflation would not have benefitted from explaining this puzzle if GUT were not the theoretical framework for inflation.

Penrose (2016) pointed out that in the development of new physics, common standards for truth and rigorous scientific knowledge break down. Instead, scientists are often guided by what he called “fashion, faith, and fantasy”. For him, many parts of particle physics belong to fashion, and inflation and the multiverse are forms of fantasy. If trending ephemeral whims, untested dogmas, and entertaining wild thoughts are all unavoidable parts of the new physics, and they play important roles in shaping the standards for a good explanatory theory, then how can the physics of the early universe retain objectivity?

A possible solution can be found in the analogous underdetermination of human historiography, the proliferation of historical narratives about the same historical events. Carr ([1961]1990) argues that it is impossible to have an objective narrative of historical facts independent of the historians’ personal or cultural biases and tastes. However, historiography, as “a continuous process of interaction between the historian and his facts, an unending dialogue between the present and the past” (30), finds its objectivity in this ongoing public process of investigation, when perspectives or underdetermined hypotheses are constantly challenged, surpassed, or revised. Likewise, the way toward objective scientific knowledge of the early universe may lie in the ongoing development of physics, where new generations of physicists question the explanatory standards raised by old ones. Inflation, for example, has gone through the transition from a promising fundamental theory to a phenomenalist “paradigm without a theory”, and it has been continuously questioned by emerging alternatives.

4.2. Approach to the unobservable multiverse: Explanatory power versus testability

Explanatory power and potential are not the only criteria for choosing or justifying a model or theory. In many branches of science, testing a model’s predictions against new empirical observation plays a more decisive role. A good explanation can be contested if it cannot generate new predictions that test it against new evidence, and so may be judged as merely a likely story

(Hempel 1962; Turner 2007). Regarding the early universe, if the parameters of a scenario can be adjusted to fit *any* observation, the scenario simply becomes untestable. A growing trend in cosmology, however, is to loosen requirements for testability and rely more on explanatory power (Smeenk 2019a). This triggers debates about the scientific state of unobservable scenarios of the early universe, especially the multiverse. If in principle we cannot observe the multiverse, can we gain any scientific knowledge about them, or do they become a delicate form of pseudoscience?

In other domains of science, it is also sometimes impossible to conduct direct observations: we do not see molecules reacting, nor do we observe T. Rex hunting. Inferences from observable evidence with the help of background knowledge help to gain knowledge about unobservable phenomena. Dawid (2007) and Carroll (2019) argue that many hypotheses about multiverse are no different. According to Dawid (2007), loosening testability is not problematic when competing theories can be reasonably eliminated. Even if a theory cannot generate sufficient empirical predictions for testing, it can be justified if it is the only viable option, due to theoretical constraints. For example, one theoretical constraint cosmologists use to select equally plausible models is parsimony, Ockham's Razor, the preference for models with fewer parameters or simpler assumptions.

Carroll (2019) argues that testability is not significantly loosened in testing the multiverse. The multiverse is not completely unempirical because one can *imagine* empirical tests beyond the visual horizon. Unfortunately, these experiments will never be conducted and will have to remain in the realm of thought and imagination. Further, Carroll claims there is a continuity between the ranges of parameters that are testable and those that are not. "It would be strange, indeed, if the status of an idea as scientific versus unscientific depended on the parameters used.” (305)

Other physicists and philosophers, by contrast, require testability in their criticisms of the multiverse (Ellis 2008, 2019). Empirical testing is needed because the multiverse is not a theoretical necessity, as several inflationary model groups do not imply a multiverse. Further, the explanatory power of the multiverse for fine-tuning is dubious: while the multiverse explains the current cosmological parameters, it would have been able to equally explain any other parameter. Moreover, in contrast to Carroll’s suggestion of continuity, Ellis (2008, 2019) argues that the slippery slope from testable to untestable proposals of multiverse is too tenuous to hold. Unlike in many other sciences, where regularities can be extended to similar unseen situations, one cannot safely extrapolate our known physical laws beyond the edge of our spacetime, nor from testable models to untestable ones. Finally, loosening testability would have a broader impact on other sciences. “Those proposing this weakening in the case of cosmology should be aware of the flood of alternative scientific theories whose advocates will then state that they too can claim the mantle of scientific respectability.” (Ellis 2008: 2.33)

This debate is far from settled, but a philosophical discussion may contribute to navigating through the variety of arguments. Finding the right proportion of testability and explanatory power is a shared theme across many sciences. Philosophers studying historical sciences have initiated rich discussions about it (Cleland 2011; Currie 2018), and cosmology, as another historical science, may learn from their methodological successes and failures. With multiple scientific disciplines as their resources, philosophers are also in a better position to construct a fine-grained framework for distinguishing different types or degrees of testability or explanatory success. One may be able to establish standards for acceptable loosening of testability that do not fall into vicious speculation. Finally, as both proponents and opponents of testability make arguments from the general impact of this debate on other uncertain scientific theories, philosophers can also evaluate whether such broader impacts would actually occur.

V. Conclusion

The early universe challenges our intuitive understanding of basic notions such as space, time, physical regularities, and the beginning of everything. To write a history of the universe means to interpret the physical-mathematical complications and formulate those concepts accordingly. Moreover, studies of the early universe also present distinct patterns of inference and types of uncertainty. Unlike many other sciences, cosmological knowledge here is not acquired by testing predictions with ample empirical data or applying well-tested physical regularities, but new physics is designed to serve the best explanation for sparse observable phenomena. This involves unsettled debates about what is a legitimate inference from limited evidence. Such a special epistemic situation calls philosophy to intervene in science, as its continuation by other means. The study of the early universe is not isolated from other branches of science. Cosmologists conduct methodological exchanges with other historical sciences, and the standards for legitimate inference are shaped by trends in other ongoing physical investigations. Philosophy plays a central role in comparing different domains and providing unifying lessons.

Philosophy is relevant to the debate about knowledge of the early universe and integral to the unification of knowledge from multiple aspects. First, it offers a framework for describing the methods of investigation, evaluating the credibility of knowledge, and analyzing its uncertainties. Second, philosophical considerations are deeply embedded in scientific debates and can also help to navigate through them. Finally, following the multidisciplinary and crossdisciplinary perspective of the history and philosophy of science, philosophy can mediate between disciplines and domains that face similar challenges, adjudicate the broader impacts of methodological commitments, and offer a unifying narrative.

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