Establishing a Theory of Inflationary Cosmology

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Abstract

Inflation remains a promising, yet speculative, account of structure formation in the early universe. In this paper, we provide a general account of what is needed to establish a speculative theory, and apply the account to inflation. Particular challenges for inflation are its flexibility as a phenomenological framework, and the lack of empirical access to test seemingly independent features of specific realizations of inflation. This makes it difficult to leverage initial empirical successes to learn further physical details about the inflationary epoch. One *prima facie* appealing response is to treat phenomenological accounts of inflation as effective field theories (EFTs), screening off details of higher-energy physics. We argue that inflation is a poor fit into the EFT framework due to its sensitivity to high-energy physics. We close by stating specific recommendations to take steps towards establishing inflation as part of a theory of the early universe that follow from our approach.

Acknowledgements

We thank James Owen Weatherall, Feraz Azhar, William Wolf, and Robert Brandenberger for helpful discussions and / or comments on earlier drafts of this paper. We are also grateful to audiences at the Cosmology and Quantum Gravity Beyond Spacetime 2023 workshop at Western University and the History and Philosophy of Cosmology Conference 2024 at the University of Milan, and two anonymous referees, for their helpful feedback.

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1 Introduction

The integration of particle physics and cosmology has spurred an ambitious research agenda. Cosmologists now aspire to fulfill a rationalist's dream: to show *why* the universe must be as it as, rather than to merely describe it. A successful account of baryogenesis, for example, would show why the universe has to have a striking matter-antimatter asymmetry as a consequence of early universe dynamics, alleviating the need to treat the asymmetry as a contingent, and intuitively improbable, feature of the "initial state." Inflationary cosmology is by far the most influential proposal that serves such ambitious explanatory aims. It treats the universe's flatness and remarkable uniformity, properties revealed by the cosmic microwave background (CMB) radiation, as consequences of an early phase of exponential expansion, at $t \approx 10^{-35}$s and an energy scale of $\approx 10^{15} - 10^{16}$ GeV. Cosmologists now routinely interpret early universe observations in light of inflation. Almost any popular illustration of cosmic history includes an inflationary stage, reflecting its secure status according to many cosmologists. One goal of this paper is to provide a philosophical assessment of the empirical warrant for inflation. Despite its popular status, we argue that inflation has not yet earned its place as part of an established theory of the early universe.

Even within physics, inflationary cosmology continues to spur debates, which touch on several central questions in philosophy of science. In a recent episode, Ijjas, Steinhardt, and Loeb (2013; 2017) argued that inflation does not even qualify as scientific, prompting a strident defense co-signed by 33 leading cosmologists (Guth, Kaiser, Linde, et al. 2017). Although not always couched in such provocative language, earlier critics have challenged inflation for similar reasons. How much does inflation's phenomenological success lend credibility to the theory? Posed more generally, to what extent does compatibility with observations support the claim that the theory correctly describes the dynamics in a particular regime, as opposed to reflecting the theory's flexibility and ability to accommodate *any* data? Weinberg (2008) characterized inflation as a plausible speculation, noting that (p. 507):

> This [the consistency of observations with a large class of inflationary models] is encouraging, because it supports the general idea of slow-roll inflation, but also disappointing, because it shows that these observations so far do not really tell us anything specific about the details of inflation. With further improvements in experimental precision, we can look forward to a more decisive test of theories of the early universe.

In other cases in physics, resolving further details has countered the skeptic's worry that a theory matches observations through merely fitting the data. Ijjas, Steinhardt, and Loeb (2013) argued that despite the increase in precision, Planck observations failed to provide the more decisive test Weinberg (and others) have long sought.

Recently, philosophers have analyzed these debates using different approaches to understanding theory construction and the relationship between theory and evidence. For example, cosmologists's preference for a theory that offers dynamical explanations of the initial state—that "solves fine-tuning problems"—has been analyzed in terms of explanatory depth (Azhar and Loeb 2021; Wolf and Thébault 2023). If one can show that deeper explanations are more likely to be true, or conducive to discovering the truth, then assessing the explanatory depth of inflation (and any competing theories) would be an essential evaluative question. Others take the scope of epistemic questions that are appropriate at a given stage of inquiry to be limited: at early stages we should determine whether a proposal is worthy of further pursuit, rather than trying to assess whether it is true (Wolf and Duerr 2023). The goal is then to identify several markers of pursuit-worthiness and see whether inflationary theory exhibits them. Still others have extended the scope of epistemic questions, suggesting that we should evaluate the controversy regarding inflation by appealing to "data" about the research field—such as the lack of competing proposals—that does not directly concern how inflation applies to the early universe (Dawid and McCoy 2023).[1]

Despite their differences, we take these approaches as directed at clarifying, assessing, or providing more explicit justification for the confidence that cosmologists have in inflation. Our approach differs in two main respects. To start, we agree that a narrow view of confirmation neglects evaluative questions regarding the role theory can play in guiding inquiry. However, we first take it as a criteria of adequacy for an account of empirical support that it is able to distinguish among theories that "save the phenomena" (in a narrow sense) but nonetheless offer very different possibilities for further inquiry.[2] Furthermore, we hold that most appeals to pragmatic virtues, explanatory depth, and the like should in fact be treated as integral parts of a richer account of empirical support, which in particular considers whether a proposed theory makes it possible for evidence to be brought to bear on the theory's fundamental assumptions through iterative applications, with increasing demands on precision and scope, to a specific domain. Several of the considerations highlighted in these other philosophical discussions feature in our account as well, albeit subsumed within an evaluation of the prospects for further empirically-driven refinement rather than being treated as "extra-empirical" considerations. Second, our evaluation of the methodology of inflation is more critical (cf. Earman and Mosterin 1999), and we focus on questions in the foundations of physics relevant to determining whether it can provide a secure basis for further inquiry that have been focal points for discussion within cosmology.

We start by clarifying what is meant by the "theory of inflation." As we review in §2, inflation is often now treated as a broad phenomenological framework spanning an enormous variety

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[1] Although see Wolf (2024) for a critical rejoinder.

[2] We do not have the space to defend this view here; for a more detailed critical assessment of the other approaches, see Smeenk (2017) and Smeenk (2019).

of physical models. The fact that there are inflationary models compatible with observations is a significant success. But how much this success lends credence to inflation depends on a variety of factors, including the flexibility of the framework. How can we bring observations to bear on claims at different levels—to evaluate the general principles used to define the phenomenological framework, or the claim that a specific Lagrangian characterizes the dynamics driving an inflationary phase? Critics have raised doubts about the prospects for physically implementing inflation, and have argued that its phenomenological success does not actually support the theory due to flaws in its logical structure. We will evaluate this line of criticism. In doing so we will not address all of the foundational issues raised by inflation: for example, inflation's account of the origin of structure treats classical density perturbations as emerging from vacuum fluctuations of an initial quantum state—tacitly assuming a solution to the measurement problem. We will instead focus on methodological questions regarding the features that make it fit to serve as a basis for further inquiry, and epistemological questions regarding the evidential status of inflation. We provide a historical example (§3) exemplifying the kind of arguments that have been used to establish a hypothesis as the basis for further inquiry. Even prior to the development of quantum theory, physicists had made a compelling case for the molecular hypothesis by leveraging specific results and measurements to discover further physical details regarding molecular structure. By contrast, the lack of similarly stable, specific empirical results leaves open the possibility that inflation has succeeded only in curve-fitting as a phenomenological framework. This undermines its usefulness as a basis for further inquiry into the details of the early universe. We are therefore left with the question: how can we understand inflation as a piece of a more comprehensive theory of the early universe?

One appealing possibility is that inflation can be formulated and assessed independently of proposals for quantum gravity. If inflation acts as a dynamical attractor, a large range of pre-inflationary states converge on the same post-inflationary state, washing away the details of the earlier quantum gravity epoch. Furthermore, if we can construct consistent inflationary models in quantum field theory (QFT), based on minimal extensions beyond the Standard Model that are insensitive to higher-energy physics, the dynamics driving inflation will also be screened off from quantum gravity effects. On this view, inflation can be treated as an effective field theory (EFT), applying an approach ubiquitous in other areas of physics. This addresses the questions mentioned above by formulating the most generic Lagrangian possible for describing inflationary dynamics, compatible with background symmetry assumptions. Within the EFT approach, observations are then used to directly constrain the coupling coefficients in this expansion, and the effects of higher energy physics explicitly decouple. The EFT framework seems to provide the justification that inflationary dynamics are stable and secure due to the insensitivity to high-energy physics. We should then treat inflation as having a similar status as other EFTs employed throughout physics.

We argue that there are several distinctive challenges to treating inflation as an EFT, however, and that these undermine the appealing idea that inflation decouples from earlier phases of cosmic history and high-energy physics. The simplest models of inflation have a light scalar field with an extremely flat effective potential. Both features are unnatural and unstable within an EFT framework unless further symmetries are stipulated to hold. Simple inflationary models are also based on QFT in curved spacetimes. Inflation requires definite answers to several of the most pressing questions regarding the consistency of this approach, including the nature of the vacuum state and vacuum energy. Even granting these assumptions, the EFT framework applies only to sufficiently well-behaved spacetimes; rapid expansion due to inflation falls outside of this domain. Mode crossing and the trans-Planckian problem indicate that decoupling is likely to fail. Unless special conditions are met by the high-energy theory, one should generically expect inflation to couple sensitively to currently unknown physics.

This leaves us with the conclusion that the way forward for early universe cosmology requires linking inflation to a more complete high-energy theory. The arguments against decoupling also serve as a basis for optimism about the prospects of using inflation as a window into the early universe: the sensitivity to high-energy physics means that we should be able to leverage features of inflation to see some imprint of high-energy physics in precision observations of, e.g., the CMB. Though we conclude that inflation is currently not as secure a part of early universe cosmology as is commonly assumed, the perspective we adopt is methodologically optimistic. By working to fill out a broader theory of which inflation is a part, we take a stance that early universe cosmology is capable of generating stable, secure knowledge by iterative refinement, as done in other areas of physics.

The remainder of the paper is structured as follows. After a brief overview of inflation in §2, we introduce in §3 the idea of a distinct epistemic status articulated by Smith (2014): that evidence can warrant presupposing a theory as the starting point for further inquiry. Using the theory to leverage initial evidence to discover new physical details of the system at hand provides a particularly compelling form of confirmation. Although we do not have space to defend this account in detail, we use a comparison to the historical evaluation of the molecular-kinetic theory (Smith and Seth 2020) to highlight the relevant implications for inflation. We argue that inflation needs (1) a more compelling evidential case; (2) to be fit into a more comprehensive theory of the early universe; or (3) to be cast as an EFT. In §4 we argue that the EFT framework cannot provide the principled basis from which to construct a systematic guide to inquiry, since inflationary spacetimes violate several assumptions needed to construct an EFT. We further argue that one should expect inflation to couple sensitively to high-energy physics. In §5 we describe some of the most pressing current foundational problems for inflation, given this sensitivity. Solving these will provide the first steps towards options (1) and (2), thereby beginning to establish a theory of inflationary cosmology.

2 Inflation: Paradigm without a Theory

Inflation sets the stage for ΛCDM cosmology, in the sense that the end state of a phase of exponential expansion—a uniform, flat universe with nearly scale-invariant scalar density perturbations to seed structure formation—matches the "initial" state obtained by evolving backwards from later observations. Textbooks often echo Guth (1981)'s influential argument that inflation thereby solves "fine-tuning problems" of big bang cosmology. Critics have noted that the treatment of these features of the early universe as "problems" reflects the view, arguably incompatible with the application of thermodynamics, that the initial state should be chaotic rather than highly ordered (see, e.g., Penrose 2004; Albrecht 2004; Holman 2018; McCoy 2015). Although we find these critiques compelling, here we set aside such foundational questions and consider two distinct questions. First, how much credence should inflation have in light of current evidence? Second, what prospects do we have for leveraging the empirical successes of inflation to learn further details about the early universe?

We immediately encounter a challenge: what is "inflationary cosmology"? One answer characterizes inflation purely phenomenologically: as a temporary phase of accelerating expansion in the early universe, $\ddot{a} > 0$ (where a is the scale factor in an FLRW cosmological model). A phase of accelerated expansion changes the causal structure of the early universe, such that the entire observed universe traces back to a single causally-connected region (provided it lasts long enough); rapidly drives the geometry towards the flat FLRW model; and generates scalar density perturbations. The account of structure formation depends on the interplay between the evolution of fluctuation modes and the Hubble radius during the inflationary phase, which makes an account of the origin of coherent oscillations on super-Hubble scales in terms of local physics possible.[3] Finally, the transition back to the standard cosmological model requires a phase called "re-heating," to populate the universe with matter and radiation at appropriate densities after they have been diluted during the inflationary phase (see, e.g., Baumann 2022, for a recent overview).

This characterization does not specify the physical source of the inflationary phase, and cosmologists have produced a bewildering variety of different implementations—a "paradigm without a theory," as Michael Turner aptly put it. One particularly simple class of models introduces a scalar field ϕ, the "inflaton," temporarily trapped in a false vacuum state, as the cause of inflation. The duration of the inflationary phase and its implications for primordial perturbations depend on the shape of the effective potential for this field, $V(\phi)$. In a further subset, the potential satisfies "slow-roll" conditions, which constrain the potential to be extremely flat. The Lagrangian for ϕ must include couplings to Standard Model fields, such that ϕ decays into particles of different

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[3] The Hubble radius is given by $H^{-1} = \frac{a}{\dot{a}}$, and it characterizes the length over which causal interactions could take place during a particular phase of cosmic history. Local physics can only generate coherent fluctuations on scales smaller than the Hubble radius. See Smeenk (2014) for an historical overview.

types and repopulates the universe during reheating. The similarity of physical conditions throughout the observed universe traces back to the synchronized decay of the inflaton field throughout that same portion of the universe at the time inflation ends

The lack of a canonical theory has not been an obstacle to steady improvements in observations of the CMB and large-scale structure. One active line of work clarifies how these rich data sets can constrain features of inflationary models, and potentially select the best models from among the extremely large model space. Even with focus restricted to single-field slow-roll models, there are well over 100 distinct classes of models—so many that theorists sometimes complain of the difficulty of finding a name for a new model. There are several approaches to setting up this model selection problem. Martin, Ringeval, and Vennin (2014), for example, adopt a Bayesian approach: weighing the closeness of fit to the data a given model achieves against the complexity of the model, in order to avoid overfitting the data. The method relies on statistical tools optimized for determining the best model given the inherent noise and uncertainty of observational data. Other approaches aim to reconstruct the inflationary effective potential $V(\phi)$ directly from CMB data (Akrami et al. 2020), given different modelling assumptions.

There are three types of questions that such a model selection approach, considered in isolation, is ill-equipped to address. First, does success in finding models consistent with the data reflect the accuracy of the background assumptions, or merely the flexibility of the framework? This first challenge has been raised repeatedly by critics of inflation, who have pressed the point that introducing the inflaton in isolation leads to an under-constrained modelling problem, by adding a free scalar field and free function $V(\phi)$. Ellis and Madsen (1991) clarify how much freedom this really introduces: they prove that if there are *no* constraints on the effective potential, then *any* specified behaviour of the scale factor in the early universe can be obtained with an inflationary model with a single scalar field. It should come as no surprise, according to the critics, that we have succeeded in finding models of inflation compatible with the data by treating the effective potential as a free function. Ijjas, Steinhardt, and Loeb (2013), for example, contrast this sense of "success" with the early promise of inflation, namely to deliver specific, robust predictions from a particular inflaton candidate from particle physics applied to the early universe.

The second question regards the physical plausibility of the observationally preferred models. Perhaps success by itself is not sufficient to inspire confidence, given the lack of constraints, but can it be bolstered by considering the detailed implementation of specific models? Such assessments typically focus on compatibility of the model with proposals in high-energy particle physics, and whether there is a need for "finely-tuned" features of the model or pre-inflationary initial conditions. Consider the exchange between Ijjas, Steinhardt, and Loeb (2013) and Guth, Kaiser, and Nomura (2014), for example. Ijjas, Steinhardt, and Loeb (2013) argued that the Planck data actually disfavour the simplest models of inflation. The plateau potential models favoured by the data, they claim, exacerbate conceptual issues with inflation and introduce further problems, such as requiring a finely-tuned pre-inflationary state, a plateau-like potential that is difficult to generate, and leading to eternal inflation. The fact that observations single out models with such unappealing features undermines confidence in the inflationary paradigm, on their view. Guth, Kaiser, and Nomura (2014) respond by arguing that the data simply favour such eternal inflation scenarios. Just as we learned a great deal about the early universe given ΛCDM, on this view we learn something about the very early universe by using the Planck data in conjunction with the inflationary paradigm.[4] Rather than creating problems for the inflationary paradigm, on this view the observations have helped cosmologists to narrow in on a particular class of models.

Finally, a third question concerns how to compare inflation with alternative accounts of the early universe. Success in finding an inflationary model compatible with observational data does not by itself rule out alternative scenarios, and there are in fact competing accounts that apparently fit the CMB data (Brandenberger 2014).[5]

Answers to these questions all require going beyond inflation as a phenomenological framework, and are intimately linked to philosophical issues of theory acceptance and the relationship between theory and evidence. We take these as a starting point for an account of what is needed to bolster the status of inflation beyond speculation. Our aim is to provide a prospective philosophical assessment of what is needed to establish inflation as part of a theory of early universe cosmology.

3 Generating stable, specific knowledge from inflation

A majority of cosmologists clearly take inflation seriously in at least two senses: as a plausible explanation of structure formation and other features of the early universe, and as a general framework guiding interpretation of precision observations. Here we assess whether inflation should be given a stronger epistemic status, elucidated by George Smith in his reflections on Newtonian methodology and other historical episodes. Some hypotheses have undergone an epistemic phase transition, on this view, changing their status from heuristic and explanatory to providing an inviolable foundation for subsequent research. Smith and Seth (2020) reconstruct how this transition unfolded for the molecular hypothesis ca. 1913. Their analysis of the evidential reasoning that triggered this transition contains several general insights, which we use for an assessment of inflation in a similar spirit.

Smith's approach reflects the insight that, as also recognized by Stein (1995; 2004), what is

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[4] Here we have isolated one point from a broader exchange between Guth, Kaiser, and Nomura (2014) and Ijjas, Steinhardt, and Loeb (2013). Despite profound disagreement on the status of inflation, both sides agree that plateau-like potentials and eternal inflation are favoured by the observational data.

[5] These alternatives have not been subjected to the same level of detailed analysis as the inflationary paradigm.

epistemically distinctive about science can be more clearly discerned in how a line of research develops over extended time periods rather than in the debates that accompany the introduction of new ideas. Taking the long view makes concerns about the risks and rewards of particular investigative strategies more salient. There is a trade-off between the potential risk and reward in basing future research on the presumed truth of a theory. The risk is that, if the initial results are not sufficiently stable, then all research presupposing the theory will have to be abandoned if the initial claims turn out to be false. The reward comes from the ability to leverage early successes to learn further physically relevant details about the world. This requires that the initial results are not only secure, but that they must have a degree of specificity that allows one to derive further consequences by assuming their truth. A claim that is presupposed in Smith's sense serves as a necessary premise for further lines of investigation, and, furthermore, it is subjected to testing and evaluation through its role in this subsequent work.

In the case of inflation we cannot adopt a historical perspective like that in Smith's treatments of celestial mechanics and the molecular-kinetic theory. But the clear identification of patterns of reasoning through historical reconstructions can help to identify similar evidential strategies prospectively. The long view prompts a different set of evaluative questions than those that are relevant to initial acceptance, or evaluation of whether a proposal is worthy of further pursuit (Wolf and Duerr 2023). In particular, we can assess the ongoing work in inflationary cosmology in terms of the risk of predicating future work on the truth of inflation. Should we think of the ability to find regions of theory space compatible with observations as more than curve-fitting? Can we leverage the initial successes of inflation to begin an iterative process of closing the loop, learning further physical details about the early universe? One major obstacle for establishing that an inflationary stage occurred is that we still do not know much about the specific dynamical details of inflation. Due to this lack of specificity, cosmologists have not been able to leverage the inflationary hypothesis to go beyond the initial step of interpreting various features of the early universe as the consequences of an inflationary stage, and using observations to place constraints on model parameters.

The contrast between the status of molecular-kinetic theory in the 1890s and the 1910s (following Smith and Seth 2020) illustrates the significance of stability and specificity in grounding a fruitful line of further inquiry. By 1900, several major results amply demonstrated the heuristic value of the molecular hypothesis in understanding a wide range of phenomena. However, attempts to determine molecular parameters such as Avogadro's number (N_0) before 1908 required several implausible assumptions, including taking molecules to be spherical, to connect coefficients of viscosity, diffusion, and other measurable properties to the molecular scale. By contrast, after 1908 physicists discovered a number of methods that depended on weaker, sharply formulated assumptions. Perrin's famous experiments, for example, inferred N_0 from the motion of granules in

Brownian motion based on the assumption that their mean translational kinetic energy equals that of the molecules of the substrate. This suffices to directly link observable properties of the granules to the molecular scale; hypotheses about molecular shape play no role. Perrin's contemporaries discovered several other independent methods to determine N_0 and other parameters, including the electric charge quantum and Faraday's constant. These alternative methods each employed minimal, quantitatively precise assumptions linking observable features and the molecular parameters. Furthermore, mutual constraints from these independent experiments led to converging, consistent values of the three constants.

These results triggered the shift from an initial phase, in which theorists used admittedly speculative hypothetical accounts of the nature of molecules as the basis for qualitative explanations of an increasingly wide range of phenomena, to a later phase in which the values of the molecular parameters were employed constitutively in ongoing research, such as Bohr's atomic model and the Braggs' treatment of diffraction. These equations provided the stable foundation for further research into molecular structure, which proceeded by using discrepancies between precisely formulated quantitative models and observations to determine further detailed features of atomic and molecular structure. Smith (2014) calls this process of turning data into evidence "closing the loop": an initial discrepancy is used to identify further details, which can then be incorporated into a more sophisticated model; and the process of comparisons with observations continues. This view treats success not in terms of successful predictions, but rather in terms of the ability to consistently develop more refined models with ever increasing demands on precision and scope, while retaining the initial core features as a foundation. Success in identifying further details that can then be checked independently confirms the accuracy of the calculations performed at earlier stages. In this way, the initial claims play a constitutive role and undergo ongoing evaluation that is more revealing than mere compatibility with the initial data as the line of inquiry proceeds.

This account requires the stability and specificity of results available at a given stage. By specificity we mean the ability to quantiatively state what the theory implies in circumstances that can be exactly specified. Specificity is needed to identify discrepancies and evaluate their implications. Interim conclusions reached at a particular stage of inquiry are stable to the extent that they remain (nearly) fixed as inquiry proceeds. For example, since around 1916 the value of N_0 has maintained a consistent value (within error estimates), with increasing precision, through profound theoretical changes. The linking of important empirical parameters via the theory must also be stable: the particular relationship between N_0 and Faraday's constant, for example, has also remained stable. But these should be confused with a requirement of completeness. The values of N_0 and the other constants, and the mathematical equations in which they appear, proved to be stable despite a profound lack of knowledge about the structure of atoms and molecules, such as the nature of the vibratory degrees of freedom revealed by specific heats. To accept the results supporting the measurements of N_0 and the other constants as the constitutive basis for further inquiry does not require that all open questions have been answered. A few specific, stable results can be leveraged to begin the cycle of closing the loop and pursuing these further questions. As with the modern EFT approach we return to below, on this view it is possible to achieve secure, detailed knowledge of a domain without already possessing a comprehensive theory.

On our view inflation has a status quite similar to that of molecular-kinetic theory around 1900. It provides speculative explanations of a variety of otherwise puzzling features of the early universe. This is a significant achievement in its own right. But it is important to make a further assessment, namely whether the field has made a transition comparable to that triggered by the development of converging, independent measurements of molecular parameters. Furthermore, this shift can precede—and drive—the development of more comprehensive theory. The account of how primordial fluctuations form during an inflationary stage promises to provide a causal explanation of their amplitude and super-horizon coherence. This is arguably inflation's most important success and leads to the richest link with observations. Yet even this amounts to re-interpreting features of the primordial fluctuations that were expected for other reasons, and has not generated iterative refinements. Peebles and Yu (1970) and Sunyaev and Zel'dovich (1970) argued that a nearly scale-invariant spectrum of density fluctuations in the early universe was needed to seed structure formation as observed in the late universe. The work mentioned in the previous section uses observations as input to constrain parameters in inflationary models based on the account of structure formation. The flexibility of inflationary model-building undermines the prospects for using inflation as the starting point for further inquiry. Even if there are many models compatible with the data, what is lacking is a collection of specific, precise, mutually consistent but independent determinations of the parameters for specific models, or a canonical model giving specific predictions as output. As a result, theorists have not been able to leverage inflation to discover novel features of the early universe that can be independently evaluated, to initiate the process of closing the loop.[6]

Enhancing the specificity of inflationary models by re-instating a close fit with other areas of physics is one way to potentially address this objection. We will discuss these further in §5; for now, it suffices to say that the prospect of substantive constraints from high-energy physics or quantum gravity are much less plausible than in the early days of inflation. A quite different response is to treat inflation as an effective field theory (EFT). As Koberinski and Smeenk (2020) argue in the context of quantum electrodynamics, the EFT framework provides a rich enough structure to guide inquiry by closing the loop, while further providing a systematic means to decouple a given EFT from physics at higher energy scales.

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[6] This concern with iterative applications is absent from Dawid and McCoy (2023)'s analysis of the implications of flexibility of inflationary model-building within the context of meta-empirical confirmation.

Treating inflation as an EFT along the same lines would mitigate concerns about how inflation relates to a comprehensive account of high-energy physics. If the background conditions for treating inflation as an EFT are met, then one could screen off the details of high-energy physics, yet still provide a structured explanatory framework with sufficient stability and specificity to support further inquiry. Such a move would minimize the epistemic risk of wedding inflation to a particular, even more speculative high-energy theory, and possibly limit the impact of our ignorance of pre-inflationary conditions. As we argue next, however, inflation is not compatible with standard assumptions made in constructing EFTs.

4 The Limitations of Effective Field Theories

In this section, we provide a brief overview of standard EFT ideas and barriers to treating inflation as an EFT. In most cases, physicists justify using an EFT for a given domain with a mix of top-down and bottom-up reasoning (Koberinski and Fraser 2023).[7] In the former, the justification derives from confidence in a more complete theory that the EFT is built to approximate, whereas in the latter, justification stems from the plausibility of the assumptions used to construct it. The successor theory for inflation is unknown, so justification comes primarily from the bottom-up. We find that the assumptions needed to construct an EFT *prima facie* fail, in ways that are essential to the physics of inflation.

The barriers are of two kinds: first, the EFT framework itself is ill-suited to the rapidly expanding, quasi-de Sitter spacetime background that emerges during inflation. EFTs usually assume that a well-defined, near constant separation of high- and low-energy degrees of freedom can be maintained. In a rapidly expanding spacetime, this separation breaks down. There are related concerns regarding a realistic onset of inflation within the EFT framework. Second, particular issues arise regarding the plausibility and stability of effective scalar fields with plateau-like potentials in an EFT, undermining the idea that high- and low-energy physics is appropriately separable. We focus here on elucidating these barriers to standard EFT techniques, with minimal technical detail for readability. Ongoing debates within cosmology concern whether and how to extend EFT techniques to apply to the early universe in light of these problems.[8]

EFT generalizes from the QFT framework by dropping the requirement of perturbative renormalizability. Instead of only allowing renormalizable terms in the Lagrangian defining a QFT an

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[7] The terminology comes from taking an energy scale as the reference; higher-energy theories (typically taken as more comprehensive or more fundamental) are up top, while lower energy (less fundamental, effective) theories are below. Note the contrast to the typical philosophical metaphor of more fundamental theories being lower.

[8] We will treat these questions in greater detail in a companion paper. For overviews of the EFT approach, which we draw on here, see for example Manohar (2020), Donoghue (2012), and Burgess (2020); see Brandenberger (2022) for a critical assessment of EFTs in cosmology.

EFT includes all possible interaction terms of the chosen fields consistent with specified symmetries. Central to the definition of an EFT is an upper limit energy scale Λ, which places bounds on the domain of applicability of the theory. For energies E much less than Λ, the EFT captures the salient physics in terms of its fields, their symmetries and leading interaction terms. All of the other terms are suppressed by positive powers of E/Λ. As one approaches Λ, more and more terms in the Lagrangian contribute appreciably to the theory's predictions, and the theory becomes computationally intractable. At $E = \Lambda$, these factors become one, and all of the infinitely many possible terms contribute to any predictions. The theory therefore becomes mathematically undefined, and yields only infinities as predictions. Thus, a given EFT delivers reliable results in domains where the characteristic energy of interactions is much less than Λ.

But what guarantees that a given EFT will be an accurate model of physics below Λ, when one consciously ignores any physics at scales higher than Λ in its construction? The use of EFTs depends crucially on scale separation: we can only construct an EFT to model physics when low-energy effects are largely insensitive to the specific details of high-energy physics (Williams 2015). In cases where a more comprehensive high-energy theory is known, one can compare the low-energy predictions of the EFT and more comprehensive theory, and find matching conditions to ensure that they agree. When the construction is successful, the effects of high-energy physics are confined to determining the exact form of interaction coupling constants in the EFT; since one can take these as empirical inputs, one need not know any details about the successor theory to construct a relatively autonomous EFT.[9] More generally, decoupling theorems have been proven to guarantee that, when the successor theory is a renormalizable QFT without scalar fields, any low-energy EFT will decouple appropriately from the high-energy regime of the successor (e.g., Appelquist and Carazzone 1975). Even more broadly, this decoupling is expected to hold whenever one is dealing with local physics and small perturbations to a stable background state. In several applications, one can use the renormalization group equations to show that various EFTs differing in their high-energy behaviour all converge to a fixed surface of low-energy behaviour in theory space (e.g., Polchinski 1984), which further bolsters the idea that low-energy physics is insensitive to differences in high-energy physics. Such proofs, however, assume the applicability of the EFT framework, and that the high-energy physics can be appropriately modelled within it.

At a more basic level, there are important physical conditions that need to apply in order for the concepts of the EFT framework to make sense. First, an EFT requires that there is a well-defined notion of energy in the spacetime region in which it applies. Second, this notion of energy

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[9] This also relates to the breakdown of an EFT at energies near Λ. as $E/\Lambda \lesssim 1$, more and more terms from the EFT expansion are needed to make accurate predictions. For each term that can't be neglected, an additional coupling constant must be measured to set the exact magnitude of that term. Theories that require a large number of empirical inputs to fix free parameters can make fewer predictions; even before one reaches $E = \Lambda$ the EFT becomes practically useless, if not undefined.

must remain relatively stable in order to enforce a separation of low-energy modes included in the EFT, and high-energy modes excluded from the EFT. This means that the spacetime setting for the EFT must be approximately locally static for the timescales relevant to using it (cf. Burgess 2017). When the spacetime or the Hamiltonian is not sufficiently static for the problem of interest, one has to worry about the possibility of mode crossing: high-energy degrees of freedom initially excluded from the EFT becoming important for the low-energy dynamics. This signals a failure of decoupling, and requires the creation of new degrees of freedom within the EFT to account for the crossing modes. The latter leads to a breakdown of unitarity for the EFT as well. Even when the background conditions are met, and an EFT can be created, it is limited to treating small perturbations around a background state determined self-consistently by its dynamics. The state need not be a vacuum state, but it must be a state in which high-energy degrees of freedom are not overly excited, since this will generically spoil the predictive power of the EFT. Global changes to the state or dynamics, as well as high-energy and nonperturbative effects, are typically outside the scope of an EFT.

We are now in a position to assess whether inflation can be treated within the EFT framework. In one sense the answer is clearly positive: there are several influential EFT treatments of inflation (Cheung et al. 2008; Weinberg 2008). But this has to be immediately qualified, as these provide treatments of the evolution of *fluctuations* in later stages of inflation and do not aim to describe the onset of inflation and the emergence of a quasi-de Sitter background.[10] These treatments do not directly address the degree to which inflation is sensitive to higher-energy physics or pre-inflationary conditions. There are several obstacles to doing so using EFT techniques, as we will see, which lead us to the conclusion that a theory of inflation requires input from high-energy physics.

First, several proposed models of inflation fall outside the scope of a possible EFT treatment due to the energy scales at the onset of inflation. Inflation may start immediately after the Planck epoch—10^{-43}s after the big bang, or after some delay. A delayed onset requires more finely-tuned initial conditions, as an initially small homogeneous patch of spacetime is likely to be enveloped by nearby inhomogeneities the longer such a delay goes on (Liddle and Lyth 2000, Sec. 3.4.4). Models of inflation that deliver on the promise of ensuring flatness from "generic" initial conditions thus require an early onset of inflation, and many eternal inflation models presuppose an early onset from chaotic initial conditions. Early onset inflation is, however, incompatible with treating inflation as an EFT. By definition, an EFT treatment of inflation neglects Planck-scale physics, so treating inflation as an EFT requires that it begin at energy scales orders of magnitude lower than

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[10] Azhar and Kaiser (2018) use EFT methods with more ambitious aims, to study cosmic no-hair theorems (roughly, that a "generic" initial state flows to a quasi-de Sitter spacetime), although there is still a gap between a fully general treatment and what is mathematically tractable (linearized perturbations around a Bianchi model).

the Planck scale.[11] Azhar (2020) has argued that an EFT treatment of inflation is able to address what he calls the "initial conditions problem", namely whether inflation requires finely-tuned initial conditions to get going. However, on our view, stating this problem in the EFT setting misses a large class of possible initial conditions—those leading to early onset inflation. By using the EFT framework, one automatically restricts oneself to classes of "initial conditions" for inflation that follow a time-delay from the Planck epoch. So, not only does an EFT treatment rule out classes of models that are taken as leading candidates, but it also undercuts inflation's solution to the flatness problem.

Setting this issue aside, there are still further conceptual issues with an inflationary EFT. Even within the class of EFT models (i.e., those with a late onset of inflation), inflation stretches the boundaries of applicability of the EFT framework. One issue is the plausibility of the Bunch-Davies vacuum state as the self-consistent quantum state for the duration of inflation. The Bunch-Davies vacuum state is a vacuum state for de Sitter spacetime, which is the appropriate spacetime setting for inflation. It is the unique vacuum state that satisfies the Hadamard condition, and is interpreted as the vacuum state for a geodesic reference frame in de Sitter spacetime (Bunch and Davies 1978). Inflation's account of structure formation gets the (near) scale-invariance of the CMB power spectrum by considering fluctuations about the Bunch-Davies vacuum. But why can we assume a vacuum state at the onset of inflation, at extremely high energy? What justifies the choice of the Bunch-Davies vacuum as the correct state around which to build an EFT? Dynamically, it is plausible that inflation generically drives field states towards the Bunch-Davies vacuum with the exponential expansion of space. An inflating spacetime region also plausibly approaches de Sitter spacetime as the expansion continues. So once inflation gets going, the Bunch-Davies vacuum seems, at least at face value, like a plausible candidate. But even this qualitative plausibility has been challenged. While Kaloper and Scargill (2019) argue that the Bunch-Davies state is an attractor through an inflationary phase, Armendariz-Picon (2007) argues that any departures from vacuum prior to inflation must rapidly decay towards their ground state in order to justify the choice of Bunch-Davies vacuum, or else rely on a pure stipulation that, prior to inflation, all modes were sufficiently unexcited to remain near the vacuum state. He finds that, within an EFT treatment of inflation, excited modes do not decay as required, and there is therefore no internal justification for this particular state. There is thus still some controversy over the bottom-up justification of the Bunch-Davies vacuum, introducing worries that it therefore requires some appeal to possible high-energy physics outside the EFT's domain. This once again illustrates that inflation displays a degree of UV-sensitivity that sets it apart from other EFTs.

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[11] In early onset models, the scalar field evolves over a range of energies greater than the Planck mass, and as a result the inflaton potential will be sensitive to higher-energy couplings. These can be controlled by stipulating that a symmetry holds for the higher-energy theory, reflecting the UV-sensitivity of the theory.

This closely relates to a further problem with an EFT treatment of inflation. Unlike many standard uses of the EFT framework, the spacetime setting for inflation is not approximately static, and a split of high- and low-energy modes does not hold over the duration of inflation. As space rapidly expands, quantum fluctuations have a rapidly increasing physical wavelength, and thus decreasing energy. An upper limit on the applicability of the EFT is therefore not stable: as inflation progresses, modes that were initially excluded from the EFT will become low-energy and thus must be included. Mode crossing is essential to inflation's account of structure formation: perturbations start out as quantum fluctuations, with wavelength smaller than the Hubble radius. Rapidly accelerated expansion then redshifts the wavelength past the Hubble radius, where the amplitude of that mode is squeezed, growing proportionally to the scale factor. It is this squeezing that "freezes out" the fluctuation, allowing for decoherence and semiclassicalization (Polarski and Starobinsky 1996).[12] Without modes crossing the Hubble radius, the inflationary account of structure formation cannot get off the ground. So we cannot simply ignore the time-dependence of the background spacetime in an inflationary EFT: the time-dependence is essential to the account of structure formation. Mode crossing at the Hubble radius is innocuous; we understand the relevant physics on both sides of the Hubble radius, so crossing from one side to the other leads to no theoretical difficulties. However, the related crossing at the Planck length—or some other cutoff scale—leads to problems for an EFT treatment of inflation. From the perspective of the EFT, new modes must be continuously created, violating unitarity and potentially leading to a failure of decoupling.

Martin and Brandenberger (2001) argue that this is a major problem for treating inflation as an EFT. Even if we take the cutoff scale to be the Planck scale, mode crossing leads to modes that are initially Planck-scale entering the EFT, and potentially seeding structure formation. Thus, it seems like the details of an inflationary model will depend sensitively on physics at super-Planck scales, leading to a trans-Planckian problem.[13] Orthodoxy holds that this is not a problem if modes cross the cutoff scale adiabatically—that is, if they cross in their ground state, the Bunch-Davies vacuum (cf. Burgess 2017). As Burgess, Alwis, and Quevedo (2020) argue, the adiabatic assumption ensures that mode crossing does not spoil the decoupling of high- and low-energy physics necessary to set up the EFT. But the adiabatic assumption is equivalent to the assumption that the Bunch-Davies vacuum is applicable to modes as they cross, which we have seen cannot be established

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[12] Short of solving the measurement problem, this is the best argument that can be made for classicalization of gravitational fluctuations, which is needed for structure formation. The orthodox view in cosmology is that squeezing and decoherence provide a means for turning quantum fluctuations into a stochastic mixture of classical possibilities. A full solution to the measurement problem is needed for a complete picture of the quantum to classical transition. See Sudarsky (2011) for a criticism of the decoherence orthodoxy.

[13] There are two domains where this problem arises: black hole radiation and inflation ('t Hooft 1985; Brout et al. 1995; Martin and Brandenberger 2001). The assumption of mode crossing in the adiabatic vacuum is more plausible in the case of black holes: for the equivalence principle to hold for an infalling observer, modes are physically constrained to be in a well-behaved vacuum state (but see Gryb, Palacios, and Thébault (2021)); the argument does not extend to inflation because there are no "in-falling observers."

from within the EFT. Further, the trans-Planckian problem means that the initial Bunch-Davies vacuum must hold far beyond the regime in which inflation—as weakly coupled-field theory on a semiclassical spacetime background—is thought to apply. Martin and Brandenberger (2001) show that different choices for parameterizing effects of high-energy physics lead to deviations from the usually scale-invariant spectrum, and therefore that "inflationary cosmology depends sensitively on hidden assumptions about super-Planck-scale physics" (p. 2). Without some independent justification for the adiabatic assumption, inflation seems to violate the decoupling needed for a controlled EFT. One can control this issue by imposing a phenomenological limit on the number of e-foldings during inflation such that modes that start out below the Planck length never cross the Hubble radius. This is one way to screen off physics beyond the UV cutoff of an inflationary EFT, though it of course seems ad hoc. Bedroya and Vafa (2020) have recently posited a similar constraint, motivated by compatibility with string theory and the swampland conjectures. They call this posit the trans-Planckian censorship conjecture (TCC). One can think of the TCC as a bottom-up constraint on the consistency of using inflation in absence of a clear understanding of Planck-scale physics, though of course this is an additional stipulation that cannot be tested within the EFT framework. Schneider (2021) has argued that the TCC can be thought of as a bottom-up constraint on acceptable Planck-scale physics: any satisfactory Planck-scale theory should lead to low-energy EFTs that respect the TCC. A similar argument could be made regarding the Bunch-Davies vacuum state. Schneider takes these as commitments to constraints from a future theory of quantum gravity that delimit the regime of applicability of the EFT framework. While it may be true that a future theory of Planck-scale physics naturally gives rise to something like the TCC, we take the bottom-up perspective that the need to posit a TCC undermines a core commitment of the EFT framework: decoupling. Inflation relies essentially on amplifying fluctuations of modes at very small scales to cosmologically relevant scales. This dynamics has to be carefully constrained to avoid revealing trans-Planckian physics. Rather than a restriction on the regime of applicability of the EFT framework, the TCC acknowledges that inflation violates a core commitment of the EFT approach, while also neutralizing by fiat the possible negative consequences of this violation. (See also Wolf and Thébault (2023).)

Finally, inflationary EFTs also face model-specific problems in light of empirical evidence favouring slow-roll models with a plateau-like potential. There are two related problems of this sort. First, plateau-like potentials require a number of parameters to fix the shape of the effective potential — leading to an apparent need for fine-tuning. The second issue regards naturalness of an inflationary EFT that treats the inflaton as a scalar field. Generically, scalar fields are sensitive to physics beyond the cutoff scale, so one should expect corrections to the effective potential that are on the order of the cutoff. For power-law style potentials, this does not have a major qualitative effect on the inflationary dynamics, but plateau potentials are highly sensitive to these

EFT corrections. This is illustrated by the η problem, a hierarchy problem for inflation. Successful inflation requires a slow roll for the inflaton, such that the parameter

$$\eta = M_P^2 \frac{V''}{V} = \frac{m_\phi^2}{3H^2} \ll 1, \tag{1}$$

where M_P is the Planck mass, V the inflaton potential, m_ϕ the inflaton mass, and H the Hubble parameter (primes denote differentiation with respect to ϕ). If η is not small, inflation does not last long enough to give a convincing account of structure formation or solution to the horizon problem. For scalar fields, a large mass hierarchy is unstable, and higher-order corrections to η are generally $\mathcal{O}(1)$. If we treat the inflaton as a quantum field, some symmetry must be assumed to cancel higher-order quantum corrections and ensure that $\eta \ll 1$. Providing a plausible theory within which inflation occurs, and within which η can be kept small due to a symmetry, would help to justify this otherwise unnatural parameter fixing. Azhar and Kaiser (2018) find some classes of potentials for inflationary EFTs that are compatible with the data, but these fall outside the favoured plateau models and still suffer from issues of fine-tuning.

It is not that parameter values for inflationary EFTs can't be made compatible with observational constraints; as we alluded to above, the inflationary framework is quite flexible. The issue is that the parameters are unnatural and dynamically unstable, and therefore hard to justify from within the EFT framework. Williams (2015) has convincingly argued that naturalness is related to a fundamental notion of scale separation. Adding to the concerns about the failure of decoupling and the lack of justification for the vacuum state, it seems that inflation cannot be insulated from higher-energy physics as with other EFTs. A satisfactory account of the dynamics of inflation therefore requires an embedding into a more comprehensive theory of high-energy physics.

5 Justifying the essential features of inflation

We have argued that there is no bottom-up support for the claim that inflation can be effectively screened off from higher-energy physics in a systematic way, such that it can be described using an EFT. A convincing account of inflation must therefore connect to higher-energies in order to explain striking features in the early universe. However, by analogy with our discussion of the atomic hypothesis, we emphasize the value of establishing initial results that can be leveraged to learn about further physical details of inflation. In this section, we consider some ways in which it might be possible to establish stable and specific results that can be leveraged in order to develop a more comprehensive early universe theory. These fall into three major categories: making a stronger empirical case for inflation, solving internal problems to fit the framework better into known physics, and finding model-specific realizations of inflation. Any of these alone would strengthen the case for inflation; all together would make a compelling case indeed. Progress on these issues would contribute to closing the loop for inflation, leading to a theory that guides ongoing inquiry into early universe physics.

Strengthening the empirical case for inflation

As we have discussed above, inflation has shifted from a (small set of) model(s) making direct predictions to a flexible framework with free parameters constrained by observations. But given that such a project assumes the principles that constitute the framework, how do we evaluate the principles themselves? To what degree should we take the success in finding regions of parameter space compatible with observations as evidence that the framework itself is correct, rather than simply flexible? Some approaches, such as the Encyclopædia Inflationaris, use Bayesian measures to quantify the flexibility and complexity of classes of inflationary models (Martin, Ringeval, and Vennin 2014). While such statistical measures can be illuminating, this approach still presupposes the inflationary framework. This issue is especially pressing when the favoured regions of parameter space shift over time. When increasingly precise measurements or observations serve to continually narrow down the same region of parameter space, it is plausible to interpret this as a process of iterative refinement. But, as Ijjas, Steinhardt, and Loeb (2013) emphasize, this has not historically been the case for inflation. The classes of inflationary models initially favoured for internal theoretical reasons were then disfavoured by new data, leading to a shift to a drastically different region of parameter space. A shift to an altogether different region of parameter space in the face of new data indicates (1) that the framework might be too flexible, in that new conflicting observations might always be accommodated within the framework; and (2) that we might therefore be including faulty principles in the setup of the framework.[14] Such shifts undermine claims to stability comparable to that achieved with regard to molecular reality discussed in §3.

Empirical access to details relevant for inflation is currently limited (almost entirely) to high-precision observations of the CMB. These have recently been supplemented with new types of observations—such as observations of large-scale structure via 21 cm radiation from neutral hydrogen—that promise to yield further insights in the years ahead. While we do not have the space to review these prospects, there are two distinct ways that new evidence can be leveraged to make a stronger case for inflation. First, one can devise general tests of the inflationary framework, in order to identify the essential observational consequences of an inflationary stage and sharpen the contrast with competing proposals. Second, one can aim for independent constraints on key parameters of inflationary models, in order to give overdetermination or consilience style arguments for specific

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[14] Other philosophical discussions (Dawid and McCoy 2023; Azhar 2020) of the flexibility of inflationary model-building have not discussed this point.

models (or types of models).

Inflation is currently the dominant paradigm for explaining patterns observed in temperature and polarization of CMB photons. The strength of the empirical case in favour of inflation based on these observations depends on isolating distinctive signatures of inflationary dynamics, and as often happens in physics, doing so has been driven by comparisons with competing proposals. In the 1990s, cosmologists considered an "active" account of structure formation via topological defects—so-called because the network of defects persist and continue to source gravitational interactions. This account yields a distinctive signature that contrasts with inflation's "passive" account, in which there is no source term, and the fluctuations evolve autonomously. The passive nature of the inflationary account leads to one of its most striking consequences, namely the phase coherence of the density fluctuations (Dodelson 2003). Observations vindicated this aspect of inflation's account, as well as three other key features of density fluctuations produced during an inflationary phase: Gaussianity, near scale invariance, and adiabaticity (Liddle and Lyth 2000; Baumann 2022). There are alternatives (albeit not studied in nearly as much detail as inflation) that recover these features with quite distinctive early universe dynamics (Brandenberger 2020). But ongoing work on inflation has led to a sharper characterization of its observational signature. One clear contrast regards tensor perturbations (gravitational waves): several of the alternative proposals predict a blue tilt for the spectral index of these perturbations, contrasting with the red tilt expected in inflationary models. (In inflation the same dynamics produces both the scalar and tensor perturbations, leading to a consistency relation linking their amplitudes and other features.) Furthermore, the perturbations created through the inflationary phase are expected to exhibit small corrections to Gaussian statistics that reflect non-linear effects due to coupling between modes with extremely short and long wavelengths. Hence measurements of the spectral index and amplitude of tensor perturbations, or of quantities related to non-Gaussianity, would provide new framework-level tests of inflation.

In addition to testing inflation against possible alternatives, one can construct consilience style arguments for the currently favoured classes of inflationary models. Cosmologists routinely employ this kind of argument in other contexts: one starts with a class of models with a number of free parameters, and observations then determine the parameter values. Obtaining consistent parameter values from diverse lines of evidence boosts credence in the model. Taking the choice to model the universe as being nearly FLRW as a pure stipulation, one can then conceive of the ΛCDM model as a complex parameter fit. Many different independent cosmological observations lead to consistent parameter determinations, thereby boosting confidence in the starting assumption that the universe on large scales is well approximated by FLRW spacetimes. And confidence increases with the increasing diversity and amount of evidence that yields consistent parameter values.[15]

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[15] There are further arguments justifying FLRW spacetimes, and ongoing debates regarding consistency (the H_0, σ_8

What are the prospects for similar consilience arguments to establish inflation? Independent lines of evidence overdetermining the parameters of the inflaton potential relevant for structure formation, for example, would boost confidence in this feature of inflationary models. An ideal way to help establish inflation in absence of a high-energy completion is via this form of overdetermination, so it is a worthwhile goal to pursue. Pursuing this style of argument is challenging for two distinct reasons. The first stems from the relative inaccessibility of cosmic domains where inflation is expected to have a measurable impact. The analysis of different cosmological datasets typically relies on a common set of background assumptions, so it is challenging to obtain truly independent lines of evidence. But physics has a long track record of overcoming challenges of this kind, exemplified by the case of molecular reality.

The second hurdle to a consilience style argument supporting inflation is the flexibility of the framework. While we neglected this issue until now, the form of the inflaton potential, the details of reheating, the number of inflationary fields, and other features of inflation vary considerably in the space of inflationary models. It is only when considering "simple" subsets of this space that any systematic relationships between these distinct features can be determined. Suppose, as a worst-case scenario, that the full model space for inflationary model building is saturated, in the sense there is an inflationary model that combines any possible set of specified features. Then a consilience style argument relating these distinct features cannot get off the ground: determinations of any subset of the parameters of inflation would not be informative or constraining for other features—e.g., the parts of the potential related to structure formation and reheating would be independent. The features of inflation would then be modular and disconnected: knowledge of one feature would imply little to nothing about other features. In such a case, one would have to resort only to tests of the principles underlying the framework. One remedy to this worry would be to narrow down the space of possibilities by forming a more constraining set of principles that underwrite the framework of inflation; perhaps tests of the principles might lead to such a narrowing, restoring the viability of consilience arguments.

Fitting inflation with known physics

On the theoretical side, work can be done to advance the plausibility of inflation by solving outstanding conceptual problems. In particular, features that make inflation a poor fit with other theories in physics pose a particular threat to its plausibility. We don't take theories as stand-alone entities; they must be compatible with other relevant theories in order to form a consistent account of the phenomena. Internal problems for inflation come in several forms, and most have to do with treating the inflaton as a scalar quantum field.

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tension) and whether it is legitimate to introduce dark matter and dark energy as part of the modelling framework.

First, and perhaps most foundationally pressing, is the cosmological constant problem.[16] Historically, inflation was one of the driving forces that made it clear that Λ could no longer be ignored.[17] Since the details of structure formation for standard scalar field models of inflation are determined by their potential, and the potential contributes to an effective cosmological constant Λ, one cannot simply ignore the contributions to an effective Λ term from other quantum field sources. A convincing model of inflation must therefore also provide some (dis)solution to the cosmological constant problem, both at the classical and quantum levels.

The problem is amplified if we treat models of inflation as EFTs, as it signals a breakdown of scale separation. EFTs predict large contributions to an effective cosmological constant from the zero-point energies of quantum fields and from the shift in vacuum energies involved in phase transitions. While the latter sources can be tuned away with a judicious choice of a bare Λ_0 term, the former are radiatively unstable, and cannot be perturbatively tuned away. This problem for EFTs is most pressing in the context of combining QFT with gravity, since GR implies that all energy should gravitate. Wallace (2022) classifies the cosmological constant problem as a Kuhnian anomaly for the EFT quantum gravity program. In many contexts it can be safely ignored until a convincing solution arises, but scalar field inflation is not one of those contexts. The very relationship between quantum fields and the cosmological constant that is poorly understood in the EFT framework drives inflationary expansion. As Wilczek noted, "[i]t is surely an act of cosmic *chutzpah* to use this dismal theoretical failure [in understanding the cosmological constant] as a base for erecting theoretical superstructures" (in Hawking, Gibbons, and Siklos 1983, p. 476, original emphasis). We therefore need some grounds for either solving the cosmological constant problem, or else singling out the inflaton potential as relevantly different from all other apparent sources for Λ.

This problem afflicts all scalar field models of inflation. Models of inflation that modify GR in some way or abandon connections to QFT may be able to avoid the direct tension; some EFT approaches to inflation deal with more general setups than a scalar field, and might have further resources to avoid the problem. But the majority of inflationary models must be embedded in a theory of the early universe that solves or dissolves the cosmological constant problem.

Of course, this connection between inflation and the cosmological constant problem can also be viewed as a tantalizing opportunity. A future theory that includes inflation and solves the cosmological constant problem would be seen as a great success. The relationship between the two also constrains possible solutions/interpretations of either individually. If scalar field inflation is an important piece of a theory of the early universe, that theory must also solve the cosmological

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[16] See Schneider (2020), Koberinski (2021a), Koberinski (2021b), Wallace (2022), and Koberinski and Smeenk (2023) for recent philosophical discussions, and Weinberg (1989) for an influential review.

[17] Inflation was discovered following the realization that phase transitions could occur in the early universe, and that these transitions involve shifts in the value of Λ (see Smeenk 2005; Koberinski 2024, for historical overviews).

constant problem in a convincing fashion. This is a high hurdle to clear, but also provides a clear goalpost for future theory construction.

Granting a solution to the cosmological constant problem, there are further issues for a scalar quantum field treatment for inflation. The η problem highlighted above arises for any QFT treatment of a scalar field with an extremely flat effective potential. The most natural way of fixing this problem is to impose new symmetries on the scalar field, constraining the UV features of the theory incorporating an inflaton.

Finally, and in our opinion least pressing: how likely is it for inflation to occur? This issue is a focal point of the Ijjas, Steinhardt, and Loeb (2013) critique of inflation. They claim that the models favoured by inflation are susceptible to what they call the initial conditions problem and the unlikeliness problem, both of which have to do with the probability of plateau models and the appropriate initial conditions to generate long enough periods of inflation. Gibbons and Turok (2008) also argue that the probability for inflation lasting N e-folds in classical general relativity scales as $\exp(-3N)$, indicating that sufficiently long inflation is exceedingly unlikely on this measure. For those who accept the plausibility of measures assumed in these arguments, these are major problems. However, we think that casting the problem in terms of probability is misleading, or at least premature. Probability ascriptions cannot be made without a detailed understanding of the dynamics and state space, which we arguably lack for current models. Defining a measure that supports claims of this kind about probabilities is an achievement that reflects detailed understanding, not something that can simply be stipulated (Myrvold 2021).

Nevertheless, there is an important related problem that can be recast with more modest demands on our understanding of the state space and dynamics. Instead of trying to assess the likelihood of inflation to start or continue for a sufficient period, in full generality, one can give a dynamical systems analysis in terms of the stability of inflationary solutions, to assess whether inflation is an attractor within some region of parameter space. These are still open questions, but there is work attempting to address them from within the context of perturbed classical general relativity (Goldwirth and Piran 1992; Brandenberger 2017; Azhar and Kaiser 2018; Azhar and Kaiser 2023). Further work on establishing the robustness of inflation under different realizations would make a stronger case for inflation as a generic consequence of early universe conditions, consistent with known physics.

Constraints on physics underlying inflation

The most important ontological question facing any model of inflation is to identify its physical source. Most models posit the inflaton as a new scalar field designed to account for the inflationary phase. But the underlying physics is often obscure: is it a fundamental field, an emergent field, an effective description of some purely gravitational effects, or something else entirely? If it is a true scalar field dominating the energy content of the universe, how does it couple to other fields and fit into other aspects of high energy physics? If it is an emergent description of some underlying microphysics, then what is it that leads to behaviour well-modelled by a single scalar field? Adequate answers to such questions will embed inflation into a larger theoretical structure, one which provides a coherent account of high-energy physics and makes empirical contact with the world in various other ways. The larger theoretical structure should indicate other possible physical consequences from whatever underlies the inflaton.[18]

Modern accounts of inflation are actually worse off in this respect than their predecessors. Early inflationary models provide a template for what would be minimally required for an acceptable physical source of inflation. Guth's (1981) model, as part of a GUT, treated the inflaton as one of a spectrum of new particles at the GUT scale. The early alternative was the Starobinsky (1980) model, where the Einstein-Hilbert action is modified to an $f(R)$ model due to leading order quantum corrections in the early universe. Note that for these models, the connections with other aspects of physical theory alleviate concerns about curve-fitting a phenomenological model. In the context of a GUT, the inflaton would factor into a number of diverse particle interactions, and should in principle be detected in colliders with a high enough energy threshold. In the context of modified gravity, one would expect to see deviations from GR in black holes or gravitational waves, for example. Such a theory makes bolder, more comprehensive predictions. If these predictions were to be vindicated, the theory as a whole would be confirmed to a greater degree by the coherence of diverse evidence. Unfortunately for early inflationary models like Guth's and simple $f(R)$ models, of course, the connections led to predictions that have not been vindicated.

By contrast, today the basic framework of inflation is assumed, without specifying connections to underlying physical models, and observations are used to constrain the space of possible models. Focusing strictly on the parameterized theory space for the case of inflation has several drawbacks. When constraining the parameter space of inflationary models, the principles that form the core of the framework are only subject to indirect scrutiny. In other cases of constructing theory spaces in physics, there is already good evidence that at least many of the main features of the framework are secure (Koberinski 2023). While it is an important success to find classes of models consistent with the data, a specific realization is needed to establish connections with a broader range of phenomena, as with the early models. Given the current state of research on inflation, the goal of finding a unique theory describing the underlying physics of inflation is at best a long-term goal. In the meantime, however, smaller steps can be taken to discover some details or constraints on the

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[18] Wolf and Thébault (2023) focus on the "explanatory depth" of inflation, which depends in part on the degree of "dynamical fine-tuning." While we agree with some of their analysis, on our view the assessment of dynamical fine-tuning presupposes substantive assumptions about physics at the relevant energy scales.

physics underlying inflation, even in absence of a worked-out theory.

As a contrast, consider the evidence constraining models of dark matter. While we still do not have a theory of dark matter, and therefore do not know what dark matter is, the case in favour of dark matter draws on a wide range of different phenomena in the universe. Lines of evidence range from galactic to cosmic scales, and depend on distinct features of gravitational theory (from Newtonian galactic dynamics to structure formation in general relativity). The inferred properties of dark matter also provide direct evidence for what dark matter isn't; by getting a better handle of the phenomenological effects of dark matter, cosmologists have placed restrictions on the parameter space for dark matter and ruled out certain candidates. But in addition, dark matter has been a crucial component in the iterative refinement of cosmological models in the last several decades, and it is (arguably) increasingly difficult to see how to understand cosmological structures and their dynamics without it. While inflation has similarly ruled out certain candidate models as disfavoured by the evidence, it arguably has not played a similarly essential role in subsequent research. In other words, by assuming inflation occurred, what new information do we learn about the early universe? How does it refine and reinforce the assumption of inflation? Constraints like this would be the first steps toward an answer to the question of the physical source of inflation.

6 Conclusions

Inflation marks the boundary between established theory and speculative physics in modern cosmology. As such, it is fertile ground for philosophy and physics to engage. We have focused on the question of what it would take for inflation to become an established piece of our best cosmological model. Despite its successes, we argued that, as it currently stands, inflation lacks the specificity and stability needed to serve as a constitutive basis for further inquiry. Inflation has become a paradigm without a theory. The advantage of this approach is that it allows one to explore the possibility space of inflation without committing to a specific theory of high-energy physics. The disadvantage is that the space of inflationary models becomes unconstrained. Coupled to the flexibility of inflationary models—almost any possible phenomenology is compatible with some scalar field inflationary model—and their relative modularity—learning details about one aspect of inflation does little to constrain other aspects—we argue that one cannot use the phenomenological framework alone to bootstrap up to a concrete physical realization. While the early universe presents practical challenges of inaccessibility, the issues facing inflation primarily stem from the lack of specificity of the modelling framework.

This apparently leaves two paths forward. The first is to return to the early days of inflation, and look for a highly constrained realization in the context of a more complete theory of high-energy physics. The second is to reduce the epistemic risk of detaching inflation from high-energy physics by appealing to the EFT framework. We reviewed several obstacles to treating inflation as an EFT. In particular, mode-crossing is both essential to inflation in the IR, and problematic in the UV. It is unclear whether the spacetime setting for inflation is an appropriate background for EFT. Further, the justification for late-onset inflation starting from the Bunch-Davies vacuum is questionable on physical grounds. Model-specific obstacles to scalar field inflation include the η problem for generating a stable plateau potential, and the fact that a scalar inflaton is a relevant parameter, and therefore should be highly sensitive to UV physics.

This seems to leave only the first option. However, we have pointed out both general and specific steps toward establishing inflation in the absence of a complete theory answering all open questions. We take contemporary inflation to have a standing similar to that of the molecular hypothesis ca. 1908, and this historical analog suggests a path forward. At the general level, one should seek to leverage empirical evidence to rule out competing theories, and to over-determine mutually constraining physical parameters for the theory. At the specific level, we reviewed suggestions for how to strengthen the empirical case for inflation, fit inflation with known physics, and place constraints on realizations of inflation.

While the tone of this paper may appear pessimistic regarding the current status of inflation, we intend a tone of optimism for the future of early universe cosmology. We see nothing in principle that should hold cosmology back from the high standards of evidential reasoning elsewhere in physics, and see a future where inflation (or some competitor) provides a rich account of causal and functional dependencies that structure our understanding of the early universe. Recent philosophical assessments have taken inflation as a case study for different accounts of the relationship between theory and evidence. Our analysis has focused, by contrast, on whether inflation enables further discoveries through iterative applications to the early universe. On our view, this approach helps to identify the most salient problems and productive avenues for further work, but ultimately progress in physics is required to develop a secure, empirically-grounded theory of the early universe. It is this sort of stable knowledge that has been achieved in other areas of physics, which one should strive for in cosmology as well: knowledge that will both survive theory change and provide hints to where new physics should be expected.

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