Testability and Viability: Is Inflationary Cosmology "Scientific"?

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Abstract

We provide a philosophical reconstruction and analysis of the debate on the scientific status of cosmic inflation that has played out in recent years. In a series of critical papers, Ijjas, Steinhardt, and Loeb have questioned the scientificality of current views on cosmic inflation. Proponents of cosmic inflation, such as Guth and Linde, have in turn defended the scientific credentials of their approach. We argue that, while this defense, narrowly construed, is successful against Ijjas, Steinhardt, and Loeb, the latters' reasoning does point to a significant epistemic issue that arises with respect to inflationary theory. We claim that a broadening of the concept of theory assessment to include meta-empirical considerations is needed to address that issue in an adequate way.

1 Introduction

String theory, variations of the multiverse idea, and inflationary cosmology have become influential, even dominant paradigms in central areas of theoretical physics over the last few decades. While the specific scientific character of these individual paradigms vary in a number of respects,[1] they nevertheless share some basic characteristics. Though the ideas behind each of them are speculative (albeit to different degrees), their supporters maintain that there are nevertheless good reasons not only to pursue them further in their research but to regard them as genuinely well-supported and evidentially justified paradigms. Of course, not all of the promise of these ideas has been realized over the years, and so it is that they have found their (often very vocal) critics. Many of these critics debate these ideas on their scientific merit; some, however, have elevated their objections beyond the level of normal scientific disagreement, inveighing against the supporters of these paradigms for violating "the scientific method," by maintaining empirically invalidated, unscientific, or otherwise defective ideas.

The controversy which is our primary interest in this paper concerns the status of inflationary cosmology. According to inflationary cosmology, the early universe underwent

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[1] The main one being that individual inflationary models are currently empirically testable, whereas models of the others are scarcely so, if at all.

a brief stage of accelerated expansion, "cosmic inflation," which contributes to explaining the near spatial flatness and homogeneity of the present day universe,[2] as well as the perturbations in the early universe which gave rise to structure formation in the universe. In a series of articles, Ijjas et al. (2013, 2014, 2017) claim that recent observational results from the Planck satellite have put significant pressure on the inflationary paradigm, particularly the models which they call the "classic" inflationary paradigm. Among the responses from supporters of the inflationary paradigm, Guth et al. (2014, 2017) notably defend a wider, more flexible theoretical framework than that presupposed by Ijjas et al. in their initial paper. In a subsequent response paper, the latter pejoratively name Guth et al.'s framework the "postmodern" inflationary paradigm and claim that it is "a construct that lies outside of normal science" (Ijjas et al., 2014, 145). They argue that the only way it will achieve any empirical success "is by delicately designing all the test criteria and data" (Ijjas et al., 2013, 264) into its models—that is, by simply evading any potential falsifying data by ad hoc accommodation. They conclude that it is time to begin seriously considering adopting an alternative approach to early universe cosmology.

Although this has so far been a debate among scientists, the philosophical tenor of the discussions is unmissable. For example, Ijjas et al. explicitly advocate a likelihoodist standard for the empirical validity of a scientific paradigm and reject ad hoc accommodations whose sole purpose is to adjust likelihoods to favor an empirically invalidated paradigm, while Guth et al. explicitly defend an empiricist criterion of empirical validity and advocate the inflationary paradigm on the basis of theoretical virtues like fruitfulness, explanatory power, and accuracy. This championing of significantly different philosophical ideas about scientific methodology leads them for the most part to talk past one another, and the debate in the main appears to end in a stalemate.

As philosophers, our aim in this paper is neither to adjudicate nor to resolve the debate but rather to use it as a stepping stone to articulate a view on scientific methodology that does better justice to the epistemology of assessing scientific paradigms like those mentioned at the beginning of the paper: string theory, the multiverse, and inflationary cosmology. Our first task is to reconstruct the arguments of this debate carefully (§2). We do so because that reconstruction will reveal a significant problem for inflationary cosmology that can be extracted from the arguments of Ijjas et al, one to which Guth et al. do not provide an adequate response. While the arguments made explicitly by Ijjas et al. are convincingly rebutted, as we show, by Guth et al.'s (and others') defense of inflationary cosmology, when those arguments are refined and re-situated in standard formal likelihoodist and Bayesian confirmation frameworks (§3), it is clear that there is currently no basis for generating significant empirical confirmation of the inflationary paradigm (due to, e.g., its flexibility in generating models).

While Guth et al. are surely right in their claims that individual inflationary models are empirically *testable* and some are indeed empirically adequate (thereby insuring the empirical validity of the paradigm), the inability to generate significant empirical confirmation of the paradigm itself undermines the standard scientific mechanism for generating trust in the paradigm. We argue, however, that significant justified credence in inflationary cosmology can nevertheless be secured by *indirect* means, namely, by what has been called "non-" or "meta-empirical" considerations by Dawid (2013, 2022).[3] We

[2] At least this is the standard view; see (McCoy, 2015) for a critique.

[3] Theoretical physicists who support paradigms like string theory, the multiverse, and inflationary cosmology have in many cases deployed these distinctive indirect means to justify their support, though only implicitly and intuitively, lacking any well-articulated doctrine (like "falsificationism") to which to

show (§4) how the combination of both meta-empirical evidence and standard empirical evidence can contribute to the confirmation of a paradigm, even when the empirical confirmation of individual models of the paradigm alone cannot secure confirmation for the paradigm (e.g., because of the problem for inflationary theory which we extract from Ijjas et al.'s arguments). Again, this is not to claim that the inflationary paradigm *is* so confirmed, for in our view that is an assessment that physicists should make based on the (empirical and meta-empirical) evidence which they have available. Our aim is a philosophical one: to show how the status of scientific paradigms like inflationary cosmology can and should be assessed. While Dawid (2013) has contributed to this aim in the related case of string theory, the case of inflationary cosmology is important to consider in an independent way, since it, unlike string theory, has significant empirical data with which to carry out standard assessments of empirical confirmation. What we show by our reconstruction and analysis is that, even in cases where there is such empirical evidence available, meta-empirical evidence and assessment can, and in some cases should, play a crucial role in theory assessment. We sum up our argument in the conclusion (§5).

2 Analysis: Inflationary Paradigm in Trouble?

In this section, we analyze Ijjas et al.'s and Guth et al.'s arguments which were written in the aftermath of the then new results from the Planck satellite's observations of the cosmic microwave background (CMB) radiation. We focus specifically on the former authors' two critical papers (Ijjas et al., 2013, 2014) on the inflationary paradigm and the response by the latter group (Guth et al., 2014). Although a number of other authors have contributed to the recent discussion, for example (Linde, 2015; Chowdhury et al., 2019), including many who have responded directly to the scientific issues, we choose to focus only on the contributions by Ijjas et al. and Guth et al., as they serve best our aim to extract the essential philosophical points that underlie the debate.

2.1 Act I: Planck 2013

In their first critical paper, Ijjas et al. (2013) offer three principal arguments challenging the inflationary paradigm, each of which is intended to undermine the explanation for the precise spectrum of inhomogeneities detected in the CMB made available by inflationary expansion.[4]

- The first is that "natural" initial conditions for the posited scalar field driving inflation, the inflaton, make it such that inflationary expansion consistent with the Planck data is unlikely to occur.
- The second is that the paradigm in general is not predictive, insofar as the inflationary mechanism generically leads not to a single universe but to a multiverse of "bubble universes." This argument is related to the well-known "measure problem" in multiverse theories (Freivogel, 2011), which is the problem of supplying a

make appeal.

[4]In the following, we use the terms "paradigm" and "theory" interchangeably, as the authors we discuss do. These will, however, be distinguished from "models," which are concrete exemplars of the theory/paradigm to which they belong. For simplicity, we will often treat a theory/paradigm as a collection of models.

probability measure that can be used to make concrete predictions within the multiverse. Without an appropriate and justified measure, one cannot make predictions of observations across the bubble universes that make up the multiverse.

- The third concludes with the claim that "plateau-like" inflaton potentials favored by the Planck data are "exponentially unlikely according to the inner logic of the inflationary paradigm itself" (Ijjas et al., 2013, 263). The argument for this claim, and its significance, requires some elaboration, so it will be explained below.

Each of these arguments is probabilistic in character, specifically depending on likelihoods that Ijjas et al. maintain are essential for assessing the validity of any scientific paradigm, including the inflationary paradigm:

> In testing the validity of any scientific paradigm, the key criterion is whether measurements agree with what is expected given the paradigm. In the case of inflationary cosmology, this test can be divided into two questions: (A) *are the observations what is expected, given the inflaton potential X?*, here the analysis assumes classical slow-roll, no multiverse, and ideal initial conditions; and (B) *is the inflaton potential X that fits the data what is expected according to the internal logic of the paradigm?*. In order to pass, *both* questions must be answered in the affirmative. (Ijjas et al., 2013, 265, emphasis in original)

Qualitatively speaking, it follows that if a model is expected (that is, likely) according to the paradigm but the data are surprising (unlikely) given the predictions of that model, then the paradigm is not supported by the data via that model; it is also not supported if the data are expected given a model's predictions but that model is surprising according to the paradigm. Ijjas et al.'s first and second arguments dispute the likelihood of the Planck data to occur in a model with the (allegedly) empirically-favored "plateau-like" potential given, respectively, natural initial conditions (which they regard as a basic assumption of the paradigm) and an eternally inflating multiverse (which they believe the "plateau-like" potential entails); their third argument disputes the likelihood of "plateau-like" potentials within the inflationary paradigm itself.[5]

The epistemological view that Ijjas et al. endorse in the quoted passage above, namely, that probabilistic likelihoods are crucial for assessing scientific paradigms, theories, or models, is sometimes advocated in the philosophy of science. One inducement to this so-called "likelihoodism" is a desire to make "explanatory power" relevant to the assessment of (rival) theories, while still remaining broadly empiricist in orientation (Sober, 1990).[6] The fundamental principle advocated by likelihoodists is the "Law of Likelihood" (LOL):

[5]Before advancing further, it is important to draw attention to a significant problem with Ijjas et al.'s presentation pointed out by Chowdhury et al. (2019). This problem is a confusion between "plateau-like" potentials and "hilltop-like" potentials. As Chowdhury et al. explain, the potentials discussed by Ijjas et al. are actually of the "hilltop-like" kind, which includes the well-known "Mexican hat" potential. These potentials are disfavored by the Planck data (except for some special cases, which, however, do not suffer from the fine-tuning problems pointed out by Ijjas et al.). The *genuine* "plateau-like" potentials, which *are* favored by the data, do not actually suffer from the fine-tuning problems alleged by Ijjas et al. Although this error seriously undercuts the specific arguments given by Ijjas et al., it will not have much bearing on the philosophical issues with which we are concerned, so we will continue to follow their argument as it is given and simply ask the reader to keep in mind the unfortunate conflation of these kinds of models in their presentation.

[6]A very strict empiricist, of course, only requires logical compatibility between theory and data.

data (E) favors one theory (T_1) over another (T_2) just when the likelihood of the data given T_1 is greater than the likelihood of the data given T_2, that is, $P(E|T_1) > P(E|T_2)$.

Ijjas et al., however, venture one step beyond the typical likelihoodist (and, it would seem, empiricism) by not only assessing the favorability of a model on the basis of the data's expectability but also by assessing the favorability of the paradigm via an assessment of the likelihoods of *models* of that paradigm. The "Law of Likelihood" that they in effect endorse would read something like this: data (E) favor the paradigm (T_1) over the paradigm (T_2) just when the likelihood of the data given the paradigm's models ($M_1, M_2, M_3, \dots$) and the likelihood of those models with respect to one paradigm is higher than the other. For this Law of Likelihood, when we express the condition as $P(E|T_1) > P(E|T_2)$, we understand that $P(E|T_i) = \sum_j [P(E|M^i_j) \times P(M^i_j|T_i)]$,[7] since the likelihood of the data with respect to the paradigm factors into the two likelihoods just mentioned (and mentioned in the quoted passage of Ijjas et al.'s above).[8] Thus, one must be able to attribute likelihoods not only to the data given the models but also to the models of a paradigm given the paradigm in order to assess the validity of that paradigm—and the latter is plainly a non-empirical assessment.

Although advocacy of this general likelihoodist perspective on hypothesis assessment may not be especially common among philosophers of science, many cosmologists do in fact accept reasoning along these lines in practice.[9] Indeed, the principal response (Guth et al., 2014) to Ijjas et al.'s arguments does not explicitly reject their likelihoodist standard of validity for a paradigm (although it does emerge that they have a significantly different methodological perspective from Ijjas et al.); instead, their response focuses on offering direct rebuttals to the three arguments listed above.

Guth et al. observe that the first problem, the "initial conditions problem," is only a problem if one makes the precise assumptions that Ijjas et al. describe as "natural." While these assumptions were indeed seen as reasonable in the past, Guth et al. point out that they entail that the inflaton's potential is "essentially featureless between ... the Planck era and the era of observable inflation" (Guth et al., 2014, 114). Given the large separation in scale between the Planck era and the inflationary one, this is clearly quite a strong assumption to make (albeit a very simple one). This is particularly so given how little we know about physics over this range of energies. Guth et al. argue that fine-tuning issues with respect to initial conditions can be avoided in what they take to be a much more plausible scenario: an inflaton with a complicated potential, with various

[7]The index i, $i \in \{1, 2\}$ distinguishes between the two paradigms under comparison and M^i_j a model (with index j) of paradigm T_i. Here, for simplicity, we express the set of models as countable, but the expression can easily be adapted to any mathematically conceivable scenario with an appropriate indexing set for j. Naturally, the indexing set can be uncountable, made up of n-tuples to account for models with multiple parameters, etc.

[8]Why does the likelihood factorize in this way? Given our simple assumption in this paper that a theory determines its models (the models partition the theory), each model entails the theory of which it is part, so the models screen off their theory in the conditional probabilities, i.e., $p(E|M^i_j \wedge T) = p(E|M^i_j)$. Here is a short proof (where the penultimate equality follows by an application of the law of total probability):

$$\sum_j [P(E|M^i_j \wedge T_i) \times P(M^i_j|T_i)] = \sum_j \left[\frac{P(E \wedge M^i_j \wedge T_i)}{P(M^i_j \wedge T_i)} \times \frac{P(M^i_j \wedge T_i)}{P(T_i)} \right] = \frac{P(E \wedge T_i)}{P(T_i)} = P(E|T_i).$$

[9]Although we would be inclined to reject likelihoodism on general grounds—for some relevant criticism, see (Fitelson, 2007, 2011)—our objections to Ijjas et al.'s arguments are tied to details emerging from the specific case at hand, not their likelihoodism.

slopes, maxima, minima, etc. With such a potential, it is likely that somewhere in the multiverse the field will tunnel to a point on the potential where slow-roll inflation can occur. Guth et al. claim that "anthropic selection effects can then make it plausible that we live in a pocket universe that evolved in this way" (Guth et al., 2014, 115). Put simply, their rebuttal of Ijjas et al.'s first problem is that mandating certain "natural" initial conditions is not a fundamental assumption of the inflationary paradigm, just a convenient one which should be discarded when it is no longer convenient (or plausible).

The second problem, the failure of predictability in the multiverse, is acknowledged by Guth et al. as a real problem, insofar as they agree that the multiverse measure problem exists and needs to be solved.[10] They hold that inflation is generically eternal and therefore entails a multiverse, which demands a measure so that probabilistic predictions can be made across its array of bubble universes. The current level of understanding of inflation and the multiverse does not unequivocally enforce a specific choice of the measure on physical grounds. Nevertheless, Guth et al. insist that the measure problem does not affect the narrowly predictive use of inflationary models. What they say earlier about the choice of potential goes for the choice of measure as well: "one need not know how our observable universe came to undergo its final phase of inflation in order to make specific, quantitative predictions for observable quantities today" (Guth et al., 2014, 115) (i.e., one needs to know neither the entire history of a bubble universe nor how bubble universes are probabilistically generated in order to make quantitative predictions from specific models of inflation, so long as it is plausible that a period of slow-roll inflation occurs somewhere in the multiverse).

Surely Guth et al. are correct about this much, for if the measure problem precluded the predictive use of inflationary models, then the Planck Collaboration could not describe their data as supporting certain inflationary models (as they do). Their response to the second problem, however, defends only the validity of inflationary *models* against the measure problem, a point which Ijjas et al. could grant. Ijjas et al.'s specific concern is more general, namely, with the inability to specify the likelihoods of observations given the inflationary paradigm, which they claim undermines the validity of the *paradigm* itself (and not the mere predictive use of individual models). They maintain that the fact that some concrete models (of a paradigm) are predictively verified should not validate the paradigm by that fact alone (which, incidentally, is a point with which we agree, although for different reasons, as will be seen).

Guth et al. counter Ijjas et al.'s likelihoodism here by insisting on a strict empiricist criterion of paradigm validation: a scientific paradigm is observationally validated if at least one (well-motivated) model makes predictions that agree with observations (Guth et al., 2014, 112, 115). Since all parties agree that there are such models for the inflationary paradigm given the Planck results, they should conclude that the inflationary paradigm is indeed observationally validated. Furthermore, Guth et al. are unmoved by Ijjas et al.'s more general worry, for they interpret it merely as Ijjas et al.'s admission of a low prior credence in eternal inflation's multiverse cosmology, in contrast to their own comparatively high credence in it.[11] They conclude that, "since the measure problem

[10] Not all supporters of inflationary cosmology accept that inflationary cosmology entails a multiverse, as Guth et al. do. There are, for example, "plateau-like" models of inflation that do not generically lead to a multiverse (Mukhanov, 2015). Thus, this second problem only exists for those who believe an inflationary multiverse is either inevitable or the most plausible view.

[11] Thus, Guth et al. here advocate what looks like a conventional Bayesian perspective on hypothesis assessment, which we will be making use of below.

is not fully solved, [Ijjas et al.] are certainly justified in using their intuition to decide that eternal inflation seems unlikely to them. To us, the measure problem is simply an important problem that remains to be solved" (Guth et al., 2014, 115).

Ijjas et al.'s third argument, as said, requires some elaboration. Its conclusion is that the "plateau-like" models favored by the Planck results are unlikely with respect to the inflationary paradigm itself. In fact, the particular models which they present as "plateau-like" are instead "hilltop-like" models (see fn. 4), which have potentials with two symmetric minima (at some field strength), are roughly "hill-shaped" in between the minima, and increase from the minima in a roughly power-law fashion on the side of the minima away from the "hill." Ijjas et al. make the following two points in support of their conclusion:

- First, they argue that slow-roll inflation down the "sides" of the "hill" (the field "slides" down the potential to the minima, thereby causing inflation) is unlikely since the "width" of the field values which make up the "hill" is small compared to the range of field values where inflation is possible along the power-law slopes to either side of the "hill." To illustrate, imagine that a field value that leads to inflation is picked at random (with the tacit assumption of a uniform probability along the field values); since the width of the power-law part of the potential is much larger than the "hill" part, one can infer that it is unlikely that inflation occurred by a slow-roll down the "hill" (which, however, Ijjas et al. claim must happen if the Planck results support such the model).[12]
- Second, they argue that much more inflationary expansion occurs along the power-law part of the potential; that is, the number of times the universe doubles in size while inflating is much larger when the field rolls down the power-law part of the potential as compared to the number when the field rolls down the "hill" part. Ijjas et al. assume a similar uniform measure of probability in the context of this second claim too, supposing that larger bubble universes (associated with appropriate initial conditions and potentials for greater growth) in the multiverse are more probable by such a "volume-weighting" measure.

Since both the "hilltop-like" potentials and the initial conditions of the field associated with slow-roll down the "hill" are unlikely according to these measures, they should not be expected with respect to the inflationary paradigm, which, according to Ijjas et al.'s likelihoodist criterion, invalidates the inflationary paradigm. Guth et al.'s rejoinder to the first of these two points is simply that "there is no way of knowing whether we should expect [inflation] to have occurred on the plateau [i.e, the hill] or on the power-law part of the potential" (Guth et al., 2014, 116). That is, the paradigm gives us no theory of initial conditions with which we could assess where inflation is likely to begin. Their response to the second is similar. They admit that Ijjas et al.'s preferred volume-weighting measure is one possible proposal to solve the multiverse measure problem, but they claim that it is one that has since been found to provide an inadequate solution. Guth et al. thus argue that there is no good reason to follow Ijjas et al. in their preferred assumptions for computing likelihoods. Although simplicity might be taken to favor a uniform measure for the initial field value and the volume weighting measure, these are nothing more than

[12] A simplified, illustrated version of this argument can be found in their *Scientific American* article (Ijjas et al., 2017).

plausible assumptions which can be (and have been) discarded in the course of further investigations. They are not fundamental assumptions of the inflationary paradigm.[13]

2.2 Act II: Inflationary Schism?

In their first paper, Ijjas et al. attempt to show that the likelihood of the Planck data given the inflationary paradigm as a whole invalidates the paradigm (or at least substantially disconfirms it). Guth et al. respond that in each case Ijjas et al.'s assessments are based on faulty assumptions which should be rejected: what Ijjas et al. call "natural initial conditions" and the probability measures assumed by them in their "unlikeliness problem" are overly simplistic, and the lack of a solution to the measure problem does not entail that it cannot be solved, nor does it automatically invalidate the inflationary paradigm. Ijjas et al. respond to these rebuttals in (Ijjas et al., 2014) by shifting their argument to the claim that a "schism" has emerged between what they describe as the "old" inflationary scenario ("classic inflation," as Ijjas et al. call it), which was their intended target in (Ijjas et al., 2013), and the inflationary scenario ("postmodern inflation," as Ijjas et al. call it) that Guth et al. use to rebut their arguments in (Guth et al., 2014). Ijjas et al. insist that their arguments against classic inflation (i.e., that classic inflation is invalidated by the Planck data) are unaffected by Guth et al.'s response, and then press further arguments against "postmodern inflation," claiming that it dispenses with well-accepted canons of scientific methodology. Thus, they insist that inflationary cosmologists face an uncomfortable dilemma between classic inflation and postmodern inflation, between a refuted theory and an unscientific one. Ijjas et al. take this to suggest the need for an alternative paradigm to inflation:

> The scientific question we may be facing in the near future is: If classic inflation is outdated and a failure, are we willing to accept postmodern inflation, a construct that lies outside normal science? Or is it time to seek an alternative cosmological paradigm? (Ijjas et al., 2014, 145)

The vast majority of inflationary cosmologists, however, would surely reject the idea that there is a "schism" between different kinds of inflation, maintaining instead that there is a clear historical and conceptual continuity between the inflationary cosmology of the past and present: inflationary cosmology is just a single paradigm. Granted, like most theoretical paradigms in science, it is composed of many specific models (of which Ijjas et al.'s "classic inflation" is one subset), as a group of 33 physicists, including Guth et al., point out in their letter responding to Ijjas et al.'s *Scientific American* article (echoing as well the argument for inflationary theory's empirical validity from (Guth et al., 2014)):

[13]Before moving to the next round of the dispute, it is worth mentioning that, while their paper is primarily focused on rebutting Ijjas et al.'s criticisms of the inflationary paradigm, Guth et al. do provide positive arguments in support of the inflationary paradigm, that is, over and above the mere validation of certain models of the paradigm by the Planck results. Indeed, they insist that "inflationary cosmology rests on very firm foundations" (Guth et al., 2014, 118), emphasizing that it is self-consistent, well-motivated by building on well-understood theories (like quantum field theory in curved spacetime), has passed every single empirical test of its predictions (whereas competitors, like the topological defects theory, have not), offers explanations for puzzling features of our universe, and has the resources with which to address important questions about the very early universe (Guth et al., 2014, 112–3, 118). These comments suggest, at minimum, a cautious hypothetico-deductivist or Bayesian empiricism supplemented with the pragmatic consideration of "theoretical virtues" (in contrast to the extra-empirical likelihoodism of Ijjas et al.).

> Inflation is not a unique theory but rather a class of models based on similar principles. Of course, nobody believes that all these models are correct, so the relevant question is whether there exists at least one model of inflation that seems well motivated, in terms of the underlying particle physics assumptions, and that correctly describes the measurable properties of our universe. (Guth et al., 2017, 5)

In their letter, these scientists are primarily concerned to defend the scientificality of present day work on inflationary cosmology against Ijjas et al.'s complaints. They therefore focus on the testability of inflationary models, especially the consistency of some inflationary models with observation, emphasizing in particular "the desirable process of using observation to thin out the set of viable models" (Guth et al., 2017, 5). As individual inflationary models make specific predictions for testable parameters, it is these models that are confirmed or disconfirmed by observations, such as those made by the Planck satellite.[14]

In their brief reply appended to this letter, Ijjas et al. claim that the authors miss their key point, which concerns "the differences between the inflationary theory once thought to be possible and the theory as understood today" (Guth et al., 2017, 7). They insist that what Guth et al. describe as "standard inflationary models," those whose predictions Guth et al. (2017, 5) claim have been confirmed in the past (Guth et al., 2014, 112), are the models that have now been strongly disconfirmed by recent observations with the Planck satellite.[15] Because of this, Ijjas et al. insist that the "highly flexible framework" (Ijjas et al., 2017) which has emerged as contemporary inflationary theory cannot benefit from the fact that some predictions of the old version were confirmed. To allow this would be, as they say, to conflate "two very different paradigms" (Ijjas et al., 2014, 145).

Why do Ijjas et al. take there to be two different paradigms, where inflationary cosmologists only see one? They appear to base the division on how predictions are generated from a theory. In their view, three pieces are required to make predictions within an inflationary "scenario": a potential for the inflation field, initial conditions for the field, and a likelihood measure on the space of possible "bubble" universes created by the inflationary process. They assert that "classic inflation" (1) has a simple potential, (2) is understood to be insensitive to initial conditions, since inflation is supposed to transform generic initial conditions into a flat, smooth universe, and (3) relies on a common-sense "volume"-based measure. In their view this is a promising setup, because (1) the simple potential allows a single, continuous stage of inflation and has few degrees of freedom and few parameters; (2) insensitivity to initial conditions means little fine-tuning; (3) the measure makes it likely that we inhabit an inflated region, as these tend to be larger than uninflated regions. And when it became possible to make observations of the cos-

[14] It is worth mentioning that one may also take a more "model-independent" approach here, by identifying conditions that specify entire classes of models, and testing such "effective theories" against observation, as opposed to focusing on an analyzing sets of proposed models. See, e.g., (Cheung et al., 2008; Azhar, 2020) for the former approach and (Martin et al., 2014a,b) for the latter. Although there may be some heuristic value in following a model-independent approach in an eliminative observational program, it makes no difference to the general epistemology of eliminative reasoning (McCoy, 2021), nor to the points discussed in this paper.

[15] Again, Ijjas et al.'s claims here are mistaken, as pointed out in (Chowdhury et al., 2019). While the "hilltop-like" models that they describe are strongly disconfirmed by the Planck observations, some of the genuine "plateau-like" models which are confirmed by the Planck observations were among the first models proposed in the early 1980s by Soviet physicists, e.g., by Starobinsky and Linde (Smeenk, 2005; Linde, 2008).

mic microwave background, these promises of classic inflation were made good on, with the famous confirmed predictions of a slight red tilt in the spectrum of inhomogeneities, near-spatial flatness, negligible non-Gaussianity, etc.

Nevertheless, despite its successes, there are long-standing conceptual problems with this "classic" inflationary scenario: (1) even simple potentials end up requiring considerable fine-tuning; (2) initial conditions required for inflation are not actually generic; (3) since inflation leads to a multiverse, one has to face the measure problem. The sum total of these problems implies, Ijjas et al. claim, that classic inflation cannot in fact make any generic predictions at all, including the ones that allegedly confirmed it. These long-standing conceptual problems are exacerbated by the Planck satellite's observations, which is what they take their main point to be in (Ijjas et al., 2013) (with the caveats noted previously about the confusion between "hilltop-like" and "plateau-like models"): (1) the simple inflaton potentials are empirically disconfirmed, (2) the favored "plateau-like" potentials require special initial conditions, and (3) these "plateau-like" models naturally lead to a multiverse, hence the multiverse measure problem. Thus, they claim, the classic inflationary paradigm for generating predictions must be rejected as not only conceptually fraught but empirically falsified.

Ijjas et al. argue that Guth et al.'s response depends on a very different set of inputs that they believe clearly distinguishes their contemporary inflationary scenario from "classic" inflation. Instead of a simple potential, the contemporary inflationary paradigm has it that the most plausible potentials are complex, leading to many phases of inflation (since this is more plausible than an "essentially featureless" potential up to the Planck scale). Instead of supposing that inflationary theory is insensitive to initial conditions, the present inflationary paradigm removes initial conditions from consideration, the idea being that the appearance of any special initial conditions can be compensated for by adjustments to the measure. Finally, instead of supposing that the measure is a "naturally given one" (like the volume-weighted measure they mention), the present inflationary paradigm takes it to be something that must be determined by theoretical or empirical considerations.

Ijjas et al. find this scenario highly problematic—indeed, unscientific. According to them, predictions in such a scenario are impossible, since there is no paradigm-sanctioned measure across the bubble universes of the multiverse (needed for making probabilistic predictions). Therefore, predictions can only be presently attributed to specific models (or a classes of models). While models admit of predictive testing, predictive testing of the inflationary paradigm itself is precluded. Hence, all that inflationary cosmologists can offer is a promissory note that predictions will generically be in agreement with observations once the right potential and measure are identified. Moreover, complex potentials make a huge variety of behaviors possible in different parts of the potential (slow-roll inflation but also tunneling); leaving the initial conditions unspecified thus makes it impossible to say what will happen in a particular instance. Adding this to the measure problem, which they maintain has no obvious means of solution, leaves inflationary cosmologists the task of merely adjusting the pieces (the potential, the initial conditions, and the measure) in light of observations—in other words, of accommodating the data. Since inflationary models are highly flexible in accommodating data, they conclude that the "postmodern" inflationary paradigm is not truly empirically testable; there can be no possible falsification (and no possible confirmation either) of the paradigm, which ultimately makes the contemporary paradigm unscientific.

Given that Guth et al. emphasize the testability of inflationary *models* in their letter, it may be easy to read into their response that they accept the basic terms of Ijjas et al.'s dilemma: they accept that the "classic" inflationary models are disfavored by observation, and therefore have simply chosen the second horn of "postmodern inflation." Yet, according to Ijjas et al., the problem with choosing this horn is that it forces one to "[discard] one of [science's] defining properties: empirical testability" (Ijjas et al., 2017, 39). This, of course, is the claim that Guth et al. are most at pains to dispute. Nevertheless, one might understand their defense of the empirical testability of inflation as succeeding only at the level of inflationary *models*, which fails to do justice to Ijjas et al.'s critique, which is at the level of the inflationary *paradigm*.

As mentioned above, Guth et al. hold that the modern inflationary paradigm satisfies what they regard as the canonical criterion of scientificality already, due to the uncontested fact that it provides the basis for developing models that can be tested empirically. They also reject Ijjas et al.'s methodological stricture that prohibits accommodation. In their view, that selecting certain empirically adequate models is currently a matter of accommodating data (even within a highly flexible framework for model building) is not a threat to the basic scientificality of the approach. From their point of view, one might suggest that it rather represents a fairly standard characteristic of a research field at a stage where contingencies of model building are not yet highly constrained by empirical data; indeed, once stronger constraints can be put on model building by more advanced and fine-grained empirical data, a stronger element of novel prediction may even be expected to re-emerge.[16]

Accordingly, with respect to the measure problem specifically, Guth et al. accept that some disagreements between data and predictions of inflation may be legitimately interpreted as consequences of a false measure choice, one which can be corrected by accommodation. In their view, this does not pose a problem for scientificality—as long as the right measure can be expected to be implied by the theory when the latter is fully understood. Ruling out measures on an empirical basis is thus simply part of the process of testing a theory by data, even though, given the present insufficient understanding of the theory, data that are at variance with a given prediction may simply indicate an incorrect understanding of the theory's proper empirical implications (e.g. a false measure choice) rather than the invalidation of the theory itself.

Therefore, from Guth et al.'s point of view, Ijjas et al.'s "classic inflation" is an inadequate construal of inflationary theory. While the Planck observations do disfavor certain specific classes of inflationary models, they do not disfavor the inflationary paradigm itself, for there is nothing in the basic concepts of inflationary theory mandating the "simple" modeling assumptions that select the disfavored classes of models. Some of these specific modeling assumptions were taken, quite naturally, for merely practical reasons in the earlier development of the paradigm, such as for reasons of simplicity. But as Guth et al. emphasize, "simplicity is subjective, and we see no reason to restrict attention to a narrow subclass" (Guth et al., 2017, 5) of inflationary models—and this is especially so from the present theoretical understanding, where many of the assumptions of classic inflation now appear limited and inadequate.

It is certainly fair to say, though, that inflationary theory exists in a state where there is relatively little theoretical guidance available for the further development of the theory. One important sign of this state of affairs is the extensive model-building efforts of infla-

[16] One may also expect that a better conceptual understanding of various mechanisms of inflation in conjunction with improved data may make arguments based on generic predictions more reliable than they are at the current stage.

tionary cosmologists: there exists a vast spectrum of possible models in inflation, in some cases with dramatically different consequences and deploying very different mechanisms for generating inflation. The existence of so many varied possibilities shows that there is little indication that the paradigm itself, as it is understood currently, entails strong constraints on the field of possible inflationary models. Undoubtedly, there are many presently unconceived models waiting to be identified as well. Therefore, cosmologists seem to have little basis for extracting criteria on what should count as a generic inflationary prediction from the currently available field of inflationary models. What looks generic now may not look generic based on a more extensive knowledge of the field of possible models of inflation (and vice versa).

It is therefore natural, even necessary, to look to observation for additional guidance on how to develop the paradigm. As Guth et al. say, "inflation does not determine the shape of the potential ... but this only means that (given current theoretical technology) the details of inflation will need to be determined by observation" (Guth et al., 2014, 114). Putting the point in methodological terms, this amounts to saying that eliminative reasoning (McCoy, 2021) will have to play an important role in developing the inflationary paradigm further (given the present epistemic situation), as theoretically there are too many possibilities licensed by the paradigm—more constraints are needed from observation.

Given this elaboration of Guth et al.'s point of view, Ijjas et al.'s complaints about "postmodern inflation," for example, that it is merely accommodating observations and cannot yield novel predictions, misunderstand the current phase of research in inflationary cosmology: they misread a constructive phase of *eliminative reasoning* as mere ad hoc *accommodation*. While theoretical cosmologists will, of course, continue to seek solutions of theoretical problems by theoretical means (especially in the hopes of obtaining novel predictions), present epistemic circumstances suggest that empirical input is valuable, if not essential, at this stage in order to make further progress in understanding inflationary theory.

We caution against an inviting misreading of the role of eliminative reasoning in this process however. The aim of eliminative reasoning in a context like this is not to simply winnow down the possible inflationary models by observation in order to select the "right" model of inflation. That would indeed be mere accommodation. Rather, given the existence of a variety of uncertainties attached to the paradigm (due to its internal problems, etc.), the use of eliminative reasoning is a means to the further development of an improved theoretical understanding of inflation and its foundations—in particular to aid in the attainment of the ultimate aim of inflationary cosmology: to make a firm connection to fundamental physics, the sine qua non of a successful account of the evolution of the universe. To achieve this aim, theory must develop. By identifying new constraints on the physical possibilities empirically, eliminative reasoning can make a crucial contribution to the process of developing an improved understanding of inflationary theory (or, if inflationary theory proves to be unviable, then whatever might develop out of it).

Before moving on to further developing Ijjas et al.'s line of criticism and responding to it, it may be helpful to sum up the contrasting viewpoints of Ijjas et al. and Guth et al. as given in the articles discussed in this section. We see the basic difference between the two sides as boiling down to different views on the process of theory testing. Ijjas et al. endorse a "rigid," conservative view of theory testing which assumes that a theory's empirical implications need to be unequivocally spelled out before empirical testing related to those implications can begin. This requirement is, on their view, essential for safeguarding the falsifiability of the theory. Conceptual flexibility that keeps a theory empirically unfalsifiable for a considerable amount of time would, on that view, be detrimental to scientific progress. Guth et al., on the contrary, hold that it would be detrimental to the scientific process to reject a scientific theory based on such a strict application of a falsifiability criterion, one that fails to account for the complex interaction between empirical testing and theory evolution. They assume that empirical tests of a theory can be productive even in contexts where the conceptual understanding of the theory is in flux. While data, under such circumstances, have only reduced potential to confirm or disconfirm the paradigm, they can nonetheless contribute to a better understanding of its prospects and provide guidelines for further conceptual analysis. In short, empirical results may be taken to indicate something about the paradigm's theoretical content rather than solely about its empirical acceptability.[17]

The empiricist response to Ijjas et al. provides a convincing rebuttal of Ijjas et al.'s charge that "postmodern inflation" does not satisfy principles of scientific reasoning. However, the analysis offered so far has not yet fully reached the bottom of the disagreement between the two sides. In our view, Ijjas et al. still have a point to contend if they object to the *degree* to which inflationary cosmologists accept a potentially long term phase of accommodation/eliminative reasoning, along with its attendant eschewal of rigid, critical testing criteria (for the purpose of falsification). This feature distinguishes the field from most earlier contexts of empirical theory testing in physics. Questions such as the following become acute: Under what conditions is it legitimate to weaken the stringency of conditions on empirical testability in light of prospects of future, more unequivocal predictive success? How long should cosmologists wait before they take the lack of such testability of inflationary theory to be a threat to scientificality?[18]

One might conclude from this that the issue reduces to nothing more than a matter of different camps placing "the bets that count on which avenues of research will prove to be fruitful" (Earman and Mosterín, 1999, 46), as Guth et al. themselves suggest when they interpret Ijjas et al. as simply "using their intuition to decide that eternal inflation seems unlikely to them" (Guth et al., 2014, 115). We propose that a deeper look into the case of inflationary cosmology reveals that this conclusion is too hasty and too limited however. It overlooks a dimension of theoretical assessment that is crucial for understanding the confirmation of scientific theories in circumstances like that in which inflationary cosmology finds itself. In our view, the reasonableness of persisting with the inflationary paradigm should be wholly based on the epistemic, evidential justification of the inflationary paradigm itself. If there is no epistemic basis for trust in the paradigm (as Ijjas et al. allege), then using inflationary theory to guide an eliminative observational program might be wholly ineffective in achieving any meaningful scientific progress, and it may indeed be better for theorists to concentrate their efforts instead on developing alternative paradigms, such as those favored by Ijjas et al. On the contrary, if there is a sufficient basis for trust in the paradigm, then prolonged periods where theory testing is used as an input into theory development are licensed and legitimate.

[17]In this respect, Ijjas et al.'s methodological view is broadly in line with Popper's "bold conjectures" and "refutations" method of trial and error, whereas Guth et al.'s methodological view is more in line with the post-Popperian methodological views of Kuhn, Lakatos, and Laudan, who all highlight the *productive* resistance of "meta-theoretical" units (paradigms, research programs, etc.) to change.

[18]These questions, of course, were left unanswered by the likes of Kuhn and Lakatos, who saw no prospect for extending their historical perspective on scientific theorizing and experiment to future developments of a given paradigm. For related discussion on these questions in the context of dark matter cosmology, see (De Baerdemaeker and Boyd, 2020; De Baerdemaeker and Dawid, 2022).

3 Taking Credence into Account

In this section, we elaborate on a serious confirmational issue for the inflationary paradigm which we believe is implicitly present in Ijjas et al.'s argument, one that we find becomes more conspicuous when theory assessment is viewed from a different perspective than the one they adopt. The legitimate worry hinted at by Ijjas et al. does not reveal itself in terms of the empirical falsifiability of the paradigm of inflation; rather, it revolves around the issue of generating credence in the paradigm.

A likelihoodist view on theory testing, like that adopted by Ijjas et al., avoids any direct question of overall trust in a theory's truth or viability, since the evaluation is carried out merely in terms of likelihoods of theories and not in terms of probabilities of theories. Other views on theory assessment, like Bayesianism, take credence in a theory to be at the very core of theory assessment. These views assume that the successful empirical testing of a theory provides epistemic justification for endorsing that theory, not just in comparison with empirically rejected competitors but in more absolute terms. This understanding may or may not be linked to a realist commitment to the theory in question. Since we are not interested in the philosophical question of scientific realism in this paper, we prefer to use the term "viability" rather than couch the discussion in terms of the realist notion of truth. We call a theory viable in a given empirical domain if its predictions are consistent with all data that could be collected in that domain. Note that a theory's viability is by no means easy to establish. It takes strong empirical confirmation to imply that a theory is most probably viable within a given domain of empirical testing.

The importance of regarding credence in a paradigm is not just a philosophical nicety. It is a natural part of discussions surrounding the scientific status of theories, including cosmic inflation, even within science. Indeed, trust in the theory of cosmic inflation is expressed quite forcefully by many of its proponents. While we have seen that Guth et al.'s principal defense of the scientificality of inflation from Ijjas et al.'s arguments focuses on the point that inflationary models can be empirically tested and falsified, they do point out the legitimacy of having trust in the theory as well:

> During the more than 35 years of its existence, inflationary theory has gradually become the main cosmological paradigm describing the early stages of the evolution of the universe and the formation of its large-scale structure. No one claims that inflation has become certain; scientific theories don't get proved the way mathematical theorems do, but as time passes, the successful ones become better and better established by improved experimental tests and theoretical advances. This has happened with inflation. (Guth et al., 2017, 6)

The degree of trust expressed in this quote and other statements by leading proponents of inflation clearly amounts to a strong commitment to the theory's truth or viability.[19]

[19] Cf. (Linde, 2008, 46): "Twenty five years ago, the inflationary theory looked like an exotic product of vivid scientific imagination. Some of us believed that it possessed such a great explanatory potential that it had to be correct; some others thought that it was too good to be true. Not many expected that it would be possible to verify any of its predictions in our lifetime. Thanks to the enthusiastic work of many scientists, the inflationary theory is gradually becoming a widely accepted cosmological paradigm, with many of its predictions being confirmed by observational data. . . . the basic principles of inflationary cosmology are rather well established."

Accurately representing the views of inflationary cosmologists thus requires a conceptual framework that allows for addressing the issue of credence in a theory. It turns out that addressing the issue of credences is helpful for understanding Ijjas et al.'s position as well. Although Ijjas et al. do not explicitly consider credences in their argument, relying as they do only on likelihoods, we maintain that their core criticism of inflation, namely that it is too flexible to be admissible in the context of theory assessment, does not get off the ground as long as credence in the theory is not considered part of the basic question of the scientificality of inflationary cosmology. When it is considered, then it is possible to see how a flexible theory like inflationary cosmology faces a serious confirmational issue with respect to empirical evidence.[20]

The leading formal approach that is capable of representing the described view on theory assessment is Bayesian confirmation theory, so we will now turn to reconstruing Ijjas et al.'s reasoning within this framework.

3.1 A Bayesian Reconstrual of Ijjas et al.'s Reasoning

Incorporating the concept of credences into the analysis, we should first recognize that a confrontation between empirical data and inflationary models is only be profitable in two distinct scenarios:

- Generic Predictions. In the first scenario, the paradigm itself unequivocally predicts certain quantitative characteristics of the precision data. This scenario does not generate substantial credence in individual models but in the theory of inflation itself. Notably, inflationary cosmologists do indeed often claim that significant and successful generic predictions of inflation exist (see, e.g., (Guth et al., 2017)).
- Model Selection. In the second scenario, eliminative reasoning has a clear prospect of radically narrowing down the spectrum of models that are in agreement with the data. If successful, this process would eventually, in the foreseeable future, increase the credence significantly in one or a few models that survive testing. (Those models may not be the last word, to be sure, but they could be expected to eventually play the role of effective models of a more fundamental theory.) This is roughly the scenario that was realized in the case of the standard model of particle physics. Inflationary cosmology at the present stage, however, does not seem to be anywhere near finding itself in this scenario. The vast spectrum of possible models and the complex relation between models and empirical data render the empirical survival of just a small number of models implausible, surely for many years to come.

For the first scenario, Ijjas et al.'s reasoning (on our Bayesian reading of it) raises the question whether the generic predictions of inflation are sufficiently rigid to generate significant credence in the theory. These doubts play out at two levels. First, the fact that generic models of inflation predict observed characteristics of the CMB, such as near Gaussianity or adiabaticity, leaves open the question as to how deviations of the data from those predictions would be or would have been handled. The flexibility of inflationary model building would presumably allow one to account for such deviations.

[20]Without consideration of credences, Ijjas et al.'s complaint can only carry weight by taking a very strong position on the acceptability of accommodation, a position that Guth et al. can, philosophically speaking, resist without embarrassment (as discussed in the final parts of the previous section.

But then on what basis should one decide whether those deviations speak against inflation per se or just indicate that more intricate models of inflation are instantiated in nature? Second, Guth et al.'s approach to solving the measure problem, namely, that it should be guided by empirical data, renders the question of what is or is not "generic" in an inflationary context even more complicated. In light of these specific doubts, a Bayesian representation of Ijjas et al.'s reasoning would imply that the agreement between collected data and generic predictions of inflation does not generate significant credence in the theory of inflation at the current stage.

With respect to the second scenario, then, criticism of the kind formulated by Ijjas et al. could be construed in terms of credences in two different ways. The more radical variation, which seems neither plausible nor in line with Ijjas et al.'s reasoning, would be that "postmodern" inflation just amounts to an idiosyncratic parametrization of data: for any possible set of cosmological data, an inflationary model can be developed consistent with any theory of high energy physics that may be established in light of (non-cosmological) empirical evidence. Credence in the viability of inflation in such a scenario would have value one a priori, because we know a priori that inflation could consistently account for all possible empirical data. To even raise the question whether inflation is viable in light of empirical evidence would be a category mistake.

The described view stands in tension both with the unclear prospects of future cosmological precision measurements and with the understanding that inflationary model building, once fully spelled out, will be constrained significantly by the viable theory of high energy physics on which it is based. The view thus could not be based on an analysis of the current situation of inflationary model building alone but would need to rely on the prediction that no amount of future empirical data could in principle be in conflict with inflation's arsenal of model building as seen from a far more advanced future perspective. In other words, the view would require an unreasonable element of clairvoyance. At no point do Ijjas et al. indicate that this is what they have in mind.

The more measured understanding, which we would take Ijjas et al. to endorse (if they were to adopt the Bayesian point of view), amounts to the claim that at the *current* historical stage of confrontation between empirical data and inflationary model building, there are no substantial limits on the flexibility of model building, which makes this confrontation epistemically inert. In principle, on this understanding an improved understanding of the links between model building and the high energy physics on which they are based, in conjunction with new (maybe de facto unreachable) experimental technologies, may be expected to reach a level of analysis at which one could decide whether the viable theory of the early dynamics of the universe is inflationary or not. Accordingly, it does make sense to ask whether inflation is a viable theory in principle. From this point of view, though, prior credence in the viability of inflation should be low in the absence of strong empirical data or argumentation in favor of the theory.

A Bayesian view based on this latter understanding fully recovers Ijjas et al.'s reasoning discussed in Section 2.1.: Ijjas et al. claim that, in order to seriously test a theory (paradigm)—that is, in Bayesian terms, to allow for significant posterior credence in it—the observations need to be in line with what is expected according to the "internal logic of the paradigm." On a Bayesian account, if there is an uncontrolled abundance of competitor models, no significant credence in an individual model or model group is generated by the the agreement of that model or model group's predictions with observation. But if significant credence is not generated for models, no significant credence in the paradigm from which the models are built is generated either. Only if the "internal logic of the paradigm" substantially favors the group of models that make the given predictions (i.e., provides the basis for generating significant credence in that group of models), significant credence can also be generated in the paradigm from which the group of models was built (since there is only so much credence to go around).

An assessment of inflation parallel to Ijjas et al.'s reasoning would thus suggest that neither of the two scenarios, generic prediction and model selection, apply, such that there is no way to generate substantial credence in inflation, nor can such be expected in the foreseeable future. This verdict, for sure, does not render the process strictly speaking *unscientific* from a Bayesian perspective (*pace* Ijjas et al.), for the formal conditions for Bayesian confirmation are fulfilled even if confirmation is just incremental and insignificant. However, it raises the question (discussed already above at the end of sec. 2) how long one should feel content with a state of the research process where the crucial role of empirical testing, which is to significantly increase or decrease the credence in a theory or model, is not being fulfilled. If credence in the theory is not supported by anything beyond a subjective choice of priors, on what basis can physicists be confident that inflation is the correct paradigm? And if they are in no position to answer that question, how confident can they be that generic predictions or eliminative reasoning within the framework of inflation is helpful at all? For a brief period, working on a theory without confidence may be pragmatically fine. But for how long could physicists justify spending so many intellectual resources on a hypothesis without legitimate reasons to assume that they are working on a viable theory?

As mentioned, inflationary cosmologists, in stark disagreement with Ijjas et al., do have a lot of trust in their theoretical paradigm however. Is their trust unjustified? We believe that it can in fact be justified by considering different evidential scenarios than the ones considered at the beginning of this subsection. Thus, to make our point, we need to show on what grounds they can discard the legitimate and important worry just stated about the flexibility of inflationary model building.

3.2 Bayesian Analysis in Epistemology and in Data Analysis

Our analysis will play out within the framework of Bayesian epistemology, which, as argued above, is the natural framework for addressing the epistemic issues raised by Ijjas et al. It is appealing to introduce Bayesian epistemology in the given context by contrasting it with the use of Bayesian methods for analyzing cosmological data. Explaining the difference between these two uses of Bayesian methods restates the problem we have identified in the previous section in an instructive way and, at the same time, demonstrates why Bayesian epistemology is a promising framework for addressing it.

In cosmology, Bayesian statistics has increasingly acquired an important role as a method of data analysis and model selection. Bayesian methods are considered helpful and potentially superior to frequentist data analysis in physical contexts where (1) constraints enforced by well-established background theories need to be accounted for in data analysis or (2) highly complex data sets need to be fitted by models whose degree of complexity is not a priori determined. Bayesian methods are employed in these contexts to understand the ways in which the available data favors or disfavors specific models based on well-established physical background theories. The guiding principle of Bayesian analysis in such contexts is to insert into the priors all well-established physical background knowledge but keep the priors as uninformative as possible otherwise. The goal of Bayesian data analysis is to extract explicit numbers which can be presented as quantitative scientific results. To achieve that goal, Bayesian data analysis is often set up as model comparison: Bayesian analysis implies that one model or class of models should be preferred by the extracted probability margin over another.

Let us, in the simplest terms, sketch the logic of Bayesian reasoning in these cases. Bayes' theorem gives the posterior probability of hypothesis H given empirical data E as

$$P(\mathrm{H}|\mathrm{E}) = \frac{P(\mathrm{E}|\mathrm{H})\,P(\mathrm{H})}{P(\mathrm{E})}. \tag{1}$$

In order to extract this probability, one needs to specify, apart from the prior probability $P(\mathrm{H})$, also the probability of the evidence $P(\mathrm{E})$, which can be written as the total probability

$$P(\mathrm{E}) = P(\mathrm{E}|\mathrm{H})P(\mathrm{H}) + P(\mathrm{E}|\neg\mathrm{H})P(\neg\mathrm{H}). \tag{2}$$

A Bayesian approach can be helpful because physical background information or information on model complexity can be encoded in the specifications of the priors of each hypothesis H. It is obvious, however, that neither the assessment of $P(\neg\mathrm{H})$ nor $P(\mathrm{E}|\neg\mathrm{H})$ can be part of data analysis. The point of data analysis is to specify the relation between a hypothesis H and data E. It is not to discuss the prior probabilities and physical implications of possible alternative hypotheses to H that may not even have been formulated. Model comparison thus gets rid of contributions that involve $\neg$H.

If we compare two models H_1 and H_2 of some theory T, we are interested in the following ratio:

$$\frac{P(\mathrm{H}_1|\mathrm{E})}{P(\mathrm{H}_2|\mathrm{E})} = \frac{P(\mathrm{E}|\mathrm{H}_1)\,P(\mathrm{H}_1)}{P(\mathrm{E}|\mathrm{H}_2)\,P(\mathrm{H}_2)}, \tag{3}$$

where $P(\mathrm{E})$ gets canceled out in the ratio. The priors $P(\mathrm{H}_1)$, $P(\mathrm{H}_2)$ are informed by physical knowledge and are kept as generic as possible otherwise. Model assessment carried out on that basis can favor specific models compared to others, with due consideration given to physical background theories.

In the context of inflationary theory, analysis of this kind can be carried out to favor or disfavor specific models of inflation in light of empirical data, where inflationary theory is used as the theoretical framework within which individual models are compared to each other. Here we can see how Ijjas et al.'s point about testing the validity of paradigms (viz., that it involves both the data-model and model-theory levels) can be related to the comparative nature of Bayesian data analysis: while this analysis can favor or disfavor models *within* the framework of inflation, it does not reach all the way towards testing and potentially falsifying the inflationary paradigm itself, since it presumes the framework in its analysis. Thus, comparative assessment of models in an inflationary context is structurally incapable of updating the credence in the theory of inflation itself. Sole reliance on Bayesian data analysis for the purpose of theory assessment would thereby exemplify the issue raised by Ijjas et al.

Let us now contrast the described logic of Bayesian data analysis with Bayesian epistemology. Bayesian epistemology is not a tool generally deployed in the scientific process. It does not aim to extract precise numbers that can be treated as quantitative results of scientific analysis. Rather, Bayesian epistemology is a tool for meta-level modeling of scientific reasoning. It is aimed at representing the process of developing credences of individual agents under the influence of evidence.

Bayesian epistemology therefore needs to pursue a strategy that differs from Bayesian data analysis in two respects. First, it must not be content with specifying generic priors. Non-generic subjective priors are an important element of the way posterior credences are in fact generated. They must be accounted for by an epistemology of science. The scientific considerations that go into the specification of priors therefore are a core object of inquiry in Bayesian epistemology. Second, Bayesian epistemology addresses the issue of absolute credence in a hypothesis. It cannot reduce its analysis to the comparison of two hypotheses as represented in equation (3). This means, however, that it cannot cancel out $P(E)$. $P(E)$ therefore must be specified in terms of the total probability stated in equation (5), which amounts to implicit assessments of credences in conceived *and* unconceived alternatives.

This subsection merely states the conceptual starting point for a meaningful Bayesian epistemology in the given context. In order to amount to a substantial analysis of an agent's credence in a hypothesis like inflation, Bayesian epistemology needs to offer a rationale for the specification of non-generic priors that reaches out beyond the toolbox of Bayesian data analysis. Below, in section 4, we will apply and discuss a concrete strategy for doing so. This strategy, that goes under the name meta-empirical confirmation, remains within the confines of subjective Bayesianism. In other words, it acknowledges an irreducible element of subjectivity in an agent's choice of priors. But, as we will see, it extends the realm of epistemically relevant deliberation on credences beyond the comparison between a hypothesis' predictions and empirical data.

3.3 Collapsing the Distinction Between "Classic" and "Postmodern" Inflation

Before turning to the specifics of meta-empirical confirmation, however, it is important to state a significant result one finds when spelling out the Bayesian representation of Ijjas et al.'s worry in a little more detail, namely, that the Bayesian form of Ijjas et al.'s worry concerns "classic" inflation (as a paradigm) just as much as it does "postmodern" inflation (as a paradigm). On Ijjas et al.'s account, the postmodern paradigm of inflation is not satisfactory because it does not allow for significant testing of the theory based on testing models, whereas the early, "classic" theory of inflation, on the contrary, constrained model building to a sufficient degree to be predictive and therefore scientifically unproblematic. As we will see, this distinction cannot in fact be upheld on a Bayesian rendering of their account.

Let $\mathrm{H_C}$ be the classic inflationary paradigm and $\mathrm{H_I}$ be the full paradigm of inflation (that which Ijjas et al. name "postmodern," understood as inclusive of classic inflation). The two theories differ from each other only in applying different constraints on model building. While $\mathrm{H_C}$ only allows for certain simple potentials, $\mathrm{H_I}$ allows for more complex potentials as well. All models of $\mathrm{H_C}$ are therefore also models of $\mathrm{H_I}$. We can now formally define a third theory $\mathrm{H_+}$ that is complementary to $\mathrm{H_C}$: it differs from $\mathrm{H_I}$ only in disallowing the simple potentials of $\mathrm{H_C}$. We can thus write $\mathrm{H_I} = \mathrm{H_C} \cup \mathrm{H_+}$.

Bayes' theorem gives the posterior probability of theory $\mathrm{H_C}$ given data E as

$$P(\mathrm{H_C}|\mathrm{E}) = \frac{P(\mathrm{E}|\mathrm{H_C})\, P(\mathrm{H_C})}{P(\mathrm{E})}. \tag{4}$$

If we insert the total probability

$$P(\mathrm{E}) = P(\mathrm{E}|\mathrm{H_C})P(\mathrm{H_C}) + P(\mathrm{E}|\mathrm{H_+})P(\mathrm{H_+}) + P(\mathrm{E}|\neg\mathrm{H_I})P(\neg\mathrm{H_I}), \tag{5}$$

we obtain

$$P(\mathrm{H_C}|\mathrm{E}) = \frac{P(\mathrm{E}|\mathrm{H_C})\,P(\mathrm{H_C})}{P(\mathrm{E}|\mathrm{H_C})P(\mathrm{H_C}) + P(\mathrm{E}|\mathrm{H_+})P(\mathrm{H_+}) + P(\mathrm{E}|\neg\mathrm{H_I})P(\neg\mathrm{H_I})}, \tag{6}$$

where $P(\mathrm{H_C}) + P(\mathrm{H_+}) + P(\neg\mathrm{H_I}) = 1$. For $\mathrm{H_I}$ one has

$$P(\mathrm{H_I}|\mathrm{E}) = \frac{P(\mathrm{E}|\mathrm{H_I})\,P(\mathrm{H_I})}{P(\mathrm{E}|\mathrm{H_I})P(\mathrm{H_I}) + P(\mathrm{E}|\neg\mathrm{H_I})P(\neg\mathrm{H_I})} \tag{7}$$

We assume, as a Bayesian proponent of Ijjas et al.-type reasoning would agree, that small priors should be attributed to any (positive) hypothesis in the absence of substantial empirical confirmation. This implies that the prior probability $P(\mathrm{H_I})$ is small. Further, we assume that probability $P(\mathrm{E}|\neg\mathrm{H_I})$ is small, which is a precondition for allowing significant confirmation of $\mathrm{H_I}$ by E at all.[21] In eq.(5), we then find that all three terms on the right side are small, which means that $P(\mathrm{E})$ is small as well.

In Bayesian terms, Ijjas et al.'s claim corresponds to the following assertion. The spectrum of models of $\mathrm{H_I}$ is so wide that it will be consistent with most of the parameter space of future empirical outcomes for a long time, almost regardless of whatever evidence E physicists will collect. $\mathrm{H_I}$, in other words, is not predictive in the foreseeable future. In Bayesian terms, this means that, whatever E we collect, $P(\mathrm{E}|\mathrm{H_I})$ in the foreseeable future will be at most marginally higher than $P(\mathrm{E}|\neg\mathrm{H_I})$ and, consequently, at most marginally higher than $P(\mathrm{E})$. Bayes' theorem then implies that $P(\mathrm{H_I}|\mathrm{E})$ will be at most marginally higher than $P(\mathrm{H_I})$. In short, whatever the evidence E, it will not provide significant confirmation of $\mathrm{H_I}$.[22] Since (as argued in Section 3.1.) the prior $P(\mathrm{H_I})$ should be small at the beginning of the research process, posteriors will remain small as well. In other words, the current mode of developing and testing models of inflation is not capable of generating significant trust in the claim that inflation is the viable theory of the early stages of the evolution of the universe.

This line of reasoning, in its own right, amounts to a coherent empirical argument against endorsing the theory of cosmic inflation $\mathrm{H_I}$. Ijjas et al. make the additional step, however, to contrast the described situation with the case of $\mathrm{H_C}$. They argue that $\mathrm{H_C}$ has a sufficiently constrained set of models to generically predict certain data E. This means that $P(\mathrm{E}|\mathrm{H_C})$ is assumed to be much higher than $P(\mathrm{E}|\neg\mathrm{H_C})$ and, consequently, much higher than $P(\mathrm{E})$. At first glance, one might think that equation (4) now provides a sufficient basis for obtaining a $P(\mathrm{H_C}|\mathrm{E})$ that is much larger than $P(\mathrm{H_C})$, which would amount to significant confirmation of $\mathrm{H_C}$. If so, this would mean that Ijjas et al.'s claim that postmodern inflation is scientifically problematic while classic inflation is fine can be framed consistently in terms of credences.

[21] If $P(\mathrm{E}|\neg\mathrm{H_I})$ were high, the given data would be expected irrespectively of whether $\mathrm{H_I}$ was viable or not. Measuring E then could not significantly increase credence in H_I. Identifying data that is not expected to be measured if the theory to be tested is not viable thus is an obligatory first step in testing a given theory.

[22] "Significant confirmation" is used in the sense that significant credence in the hypothesis is generated. Therefore, the relevant number in our analysis is $P(\mathrm{H}|\mathrm{E}) - P(\mathrm{H})$ rather than $P(\mathrm{H}|\mathrm{E})/P(\mathrm{E})$. This focus on absolute values of credence is essential to our analysis.

A closer look reveals, however, that the credence-based argument in favor of classic inflation fails. The problem is the following. Calling $\mathrm{H_C}$ rather than $\mathrm{H_I}$ the "theory of inflation" does not mean that the models covered by $\mathrm{H_+}$ disappear. The conclusion reached in the previous paragraph was that $P(\mathrm{H_I}|\mathrm{E})$ would always remain small, whatever the evidence. This conclusion can be written as the statement that $P(\mathrm{H_C}|\mathrm{E}) + P(\mathrm{H_+}|\mathrm{E})$ always remains small. This requirement, however, obviously does not allow for large $P(\mathrm{H_C}|\mathrm{E})$. Assuming that significant confirmation for $\mathrm{H_C}$ can be achieved without having significant confirmation of $\mathrm{H_I}$ as well is probabilistically inconsistent.

Testing $\mathrm{H_C}$ thus faces the same core problem as testing specific models of $\mathrm{H_I}$. Neither $\mathrm{H_C}$ nor $\mathrm{H_I}$ can acquire significant probabilities based on the method of empirical testing. If Ijjas et al. provide substantial reasons to suspect a structural failure of $\mathrm{H_I}$ to allow for significant empirical confirmation, a coherent probabilistic analysis raises the very same problem for classic inflation as well.

Ijjas et al.'s reasoning could be rescued in this setting by adding one element to their assumptions about classic inflation: one would need to assume $P(\mathrm{H_C}) >> P(\mathrm{H_+})$. In other words, one would need to assume that a simple model of inflation of the kind included in $\mathrm{H_C}$ is a priori much more probable than a complex model that resides in $\mathrm{H_+}$. Note that this is a freedom not open to the proponent of a more comprehensive definition of the inflationary paradigm: if the theory $\mathrm{H_I}$ allows for two distinct classes of models, it would seem highly questionable to declare, by fiat, that the empirical implications of one of those classes of models is predicted by the theory. (This is, in effect, the charge Ijjas et al. raise against the claim made by proponents of inflationary theory that inflation is confirmed by the agreement between data and the predictions of generic models). Attributing a very low prior to $\mathrm{H_+}$ as opposed to an *independent* theory $\mathrm{H_C}$, however, would seem feasible. It would suppress the option of complex models and thereby improve the situation for $\mathrm{H_C}$: significant credence in $\mathrm{H_C}$ would in effect be generated by a priori taking more complex models of inflation to be so improbable that they can be ignored as long as there exist simple models that are consistent with the data. Once – as Ijjas et al. claim to be the case – $\mathrm{H_C}$ has been rendered highly improbable by additional empirical data, no significant credence for $\mathrm{H_I}$ can ever be retained.

This solution is unsatisfactory for two reasons however. First, strongly disfavoring complex solutions without reason is arbitrary, and is in any case particularly implausible in the context of high energy physics. To be sure, claims of the epistemic relevance of simplicity criteria have been raised in various contexts in the philosophy of science (see e.g., (Forster and Sober, 2014; Kelly, 2007; Woodward, 2014)). One may also concede that very simple models have led surprisingly far in some contexts in physics and in cosmology in particular. (We are grateful to an undisclosed referee for emphasizing this point.) Nevertheless, it seems clear that preference for the simplest model that was compatible with the data at a given time would have been a thoroughly unreliable predictor of theory development in microphysics and cosmology. The history of particle physics is a history of abandoning simpler models for more complex ones in light of new empirical evidence. It leads from the idea of an indivisible atom to the acceptance of nucleus and electron, protons and neutrons, quarks, a wide spectrum of unstable particles that can be created in deep inelastic scattering, complicated mass spectra, and P- and CP-violation, to name just a few crucial steps. In cosmology, cases where new empirical data established the need for more complex models than what had seemed necessary before include the data indicating dark matter and data in favor of a cosmological constant. Subscribing, in the late 20th and early 21st century, to a high credence in those models that were only so complex as what was enforced by the empirical record at the time would have been exceedingly daring at best.

But even if we assume, for the sake of the argument, that a strong commitment to the simplest models had been justifiable at the early stages of the development of inflationary theory, Ijjas et al.'s distinction between the different degrees of scientificality of "classic" and "postmodern" inflation remains unconvincing. As demonstrated above, that distinction at its core is not about having a narrower definition of inflationary theory in the case of classic inflation but about subscribing to a strong epistemic preference for simple models. Guth et al. (2014) state, however, that they never shared that preference. Bayesian defenders of Ijjas et al. thus would need to suggest that classic inflation may have looked scientifically sound to themselves, to the extent they endorsed a strong preference for simple models, but should always have seemed "outside normal science" to Guth et al., who did not have a strong preference for simple models. Philosophically speaking, the idea that a theory's scientificality hinges on individual commitments to a general preference for simple models is surely not credible. We suspect that this is not the place where Ijjas et al. would want to end up.

4 Applying Meta-Empirical Confirmation to Inflation

Is there a more promising mechanism for generating trust in cosmic inflation? The above analysis points in the right direction already: in order to establish trust in a given theory, it is crucial to make some assumptions about the probabilities of alternatives to the theory under scrutiny. A satisfactory analysis of the status of inflation thus must not limit its reach to whatever one chooses to call the theory of inflation. On the contrary, it needs to take up the formidable task of acquiring some degree of understanding of the probabilities attributed to theories beyond the theory under scrutiny. Ijjas et al.'s inclination to rule out complex models by simplicity is a crude attempt at doing so, but it must fail as a matter of credence due to the lack of scientific motivation (as a merely pragmatic motivation, it is of course acceptable). Thus, what is needed is a less ad hoc way of assessing the array of possibilities that lies beyond the theory under scrutiny, including their probability structure. If successful, a strategy along those lines can provide a basis for generating significant credence in a given theory.

Dawid (2006, 2013, 2022) has developed a method of theory assessment in line with this general idea under the name "meta-empirical confirmation" (MEC).[23] MEC is based on collecting evidence F for the claim that a theory under scrutiny has few or no possible scientific alternatives. The kind of evidence that supports that kind of claim is called *meta-empirical evidence*. Meta-empirical evidence F for a theory H differs from empirical evidence E in lying beyond the theory's intended predictive domain: it is not of the kind that could be predicted or excluded by the theory.

At the core of MEC lies what Dawid calls the no-alternatives argument (NAA), which infers a lack of possible alternatives from the observation F_{NA} that, despite intense and long lasting searches for such alternatives, none were found. As there are salient potential

[23] In (Dawid, 2013), the described method of theory assessment is presented as a specific realization of a wider group of arguments of "non-empirical confirmation." The three specific arguments described below have more recently been given the name "meta-empirical confirmation" in (Dawid, 2022) in order to distinguish them from the wider class of non-empirical arguments.

defeaters to an argument like this (the scientists were simply looking "in the wrong place," for example), in order to be acknowledged as significant support of the given theory's viability, Dawid argues that the typical NAA must be supported by other forms of meta-empirical assessment.

The meta-inductive argument (MIA) is based on the observation F_{MI} that previous cases of theories in the research field that were supported by a NAA tended to be predictively successful when empirically tested. To the extent these previous cases seem comparable to the context of the current theory, this observation is taken to suggest that the NAA deployed in the current case carries some weight as well and does increase the probability that the current theory is viable.

In many cases, an unexpected explanation argument (UEA) is deployed in addition. UEA is based on the observation F_{UE} that the given theory has turned out to explain aspects of physics it was not developed to explain. This observation is best explained by assuming that there are few if any possible alternatives to the theory in question, which, again, strengthens the case for NAA.[24] While none of the described arguments can generate significant credence in a hypothesis on its own, they can, under the right conditions, do so in conjunction.[25]

In the following, we will distinguish genuine MEC, that is, updating credences solely on meta-empirical evidence F, from what we will be calling meta-empirical assessment (MEA). MEA relies on meta-empirical evidence F, just like MEC, but additionally involves updating under new empirical evidence E. As we will see, both modes of reasoning are relevant in the context of inflation.

Given the informal nature of MEA-type reasoning in scientific practice, it is natural to assume that, to the extent it is constitutive of cosmologists' understanding of the current status of inflation, it would be more widespread in private discourse among physicists than in published scientific papers. However, elements of MEA are sometimes deployed in published texts by inflationary cosmologists when they argue for the viability of their theory. A particularly clear example comes from Linde's paper quoted from already in fn. 20. At another point in the same paper, he writes:

> The inflationary scenario is very versatile, and now, after 25 years of persistent attempts of many physicists to propose an alternative to inflation, we still do not know any other way to construct a consistent cosmological theory. ... There were many attempts to propose an alternative to inflation in recent years. In general, this could be a very healthy tendency. If one of these attempts will succeed, it will be of great importance. If none of them are successful, it will be an additional demonstration of the advantages of inflationary cosmology. (Linde, 2008, 21–2)

Linde clearly indicates in this quote that a failure to find alternatives to inflation despite extensive search for such alternatives strengthens the case for inflation itself. If one interprets "demonstration of the advantages of inflationary cosmology" in an epistemic sense, then this is a full-fledged case of an NAA. Other examples of published NAA-type reasoning in support of inflation are (Linde et al., 2010), a critical analysis of the ekpyrotic universe, and the NAA-inspired assessment of the status of the cosmological multiverse in (Polchinski, 2019).

[24] We will pass over a detailed exposition of Dawid's framework, which can be found in the references cited at the head of the second paragraph of this section.

[25] For a formal analysis of how this is achieved, see (Dawid, forthcoming).

As said, an NAA becomes significant only if it is supported by an MIA and possibly also by elements of UEA-type reasoning. Inflationary cosmologists like Linde therefore must base their trust in NAA-type reasoning on the understanding that other theories in recent high energy physics and cosmology that seemed without convincing alternatives showed an eventual tendency of predictive success. Observations that can support MIA type reasoning can be identified both in cosmology as well as in high energy physics. In high energy physics, the predictive success of standard model physics instills trust in the understanding that the techniques used to build scalar potentials within the framework of gauge field theory are the right way to go when aiming at constructing models of inflation. In the context of cosmology, Peebles has emphasized in his recent book the extent to which cosmologists in the 1950s and 1960s had trust in the viability of general relativity over many orders of magnitude, even though empirical support for it was constrained at a fairly narrow range of distance scales at the time. Peebles argues that this degree of trust would not be plausible without reliance on non-empirical theory assessment. In the first chapter of his book, he writes:

> The physical cosmology that is the subject of this history is an empirical science.... But we must pay attention to the role of theory, and intuition, as well, and what Richard Dawid (2013, 2019)) terms "non-empirical theory assessment." The prime example in this history is that during most of the past century of research in cosmology the community majority implicitly accepted Einstein's general theory of relativity. Few pointed out that this is an enormous extrapolation from the few meager tests of general relativity that we had in the 1960s. ...In the first decades of the twenty-first century, the parts of general relativity that are relevant to the standard cosmology have passed an abundance of demanding tests. ...We find that this theory successfully extrapolates to applications on the immense scales of the observable universe. It is a remarkable result. ...The faith in its extrapolation exemplifies the powerful influence and very real success of non-empirical theory assessment. (Peebles, 2020, 3–4)

Although Peebles does not connect his point to an assessment of inflation, proponents of inflationary cosmology can use cases such as the eventual empirical success of general relativity in MIA type reasoning to support a scarcity of options at the fundamental level of cosmological theory building.

An NAA could find further support by cases of unexpected explanation (UEA) that show up in inflationary cosmology. To the extent one acknowledges the near-Gaussianity, near-scale-invariance and adiabaticity of the CMB density fluctuations as generic predictions of inflation, these are clear cases of UEA, since those properties had played no motivational role in the development of inflation. Another case of a UEA does not depend on the issue of the genericity of models of inflation but is controversial in other ways. For adherents of anthropic reasoning within a multiverse framework, the latter provides the only satisfactory explanation of the fine-tuning of the cosmological constant. The scenario where a theory that was developed for explaining the isotropy and flatness of the observed universe also naturally leads to a multiverse scenario which provides the basis for an anthropic explanation of the fine-tuning of the cosmological constant is a pure case of UEA.

We have thus established two significant points. First, inflationary cosmology provides a context for MEA-type reasoning: all three pure MEA modes of reasoning, NAA, MIA, and UEA, can be developed in it. Second, MEA is indeed employed by leading proponents of cosmology (Peebles) and inflationary cosmology in particular (Linde, Mukhanov, Polchinski). Of course, the fact that MEA arguments can be and are being used in cosmology does not tell us how strong these arguments are in the given context. The strength of an NAA in favor of inflation, in particular, will depend on the extent to which proponents of inflation succeed in offering convincing reasons for discarding non-inflationary accounts, such as the ekpyrotic universe (Khoury et al., 2001), string gas cosmology (Brandenberger and Vafa, 1989), or others, as promising alternatives. The strength of an MIA will depend on the plausibility of using examples from earlier cosmology and high energy physics to understand the spectrum of alternatives today. The usefulness of anthropic reasoning in a UEA hinges on the extent to which one acknowledges anthropic arguments as legitimate physical reasoning. In the present paper, we refrain entirely from weighing in on these debates. While some of them, in particular the issue of anthropic reasoning, do have a philosophical aspect, the comparison of merits and problems of competing physical theories, which sits at the core of any NAA argument, obviously must play out largely among the physicists involved in the corresponding research programs. The aim of the present paper can only be to contribute to the clarification of the epistemic argumentative framework within which the debates on physical content can be most profitably carried out.

In this vein, we now need to turn to the question: how do MEA modes of reasoning, to the extent they are successful, play out in the context of inflationary cosmology? The simplest suggestion would be to frame MEA modes of reasoning as full fledged MEC, analogous to the way they are used, for example, in the context of string theory. Confirmation on that account would be fully based on meta-level observations beyond the theory's intended domain. If inflationary cosmologists deem it plausible to endorse an NAA, this would license assuming a very small probability $P(\mathrm{E}|\neg\mathrm{H_I})$. In other words, MEC can license trust in cosmic inflation based solely on the assessment that alternative solutions to the problems inflation aims to solve are unlikely to exist.

Reliance on pure MEC to establish trust in inflationary theory does not account for current practices in cosmology however, as great effort is put into the acquisition of new cosmological data. As discussed in previous sections, proponents of inflation take that data to provide *empirical* support for inflation, while critics such as Ijjas et al. deny it. The current disputes therefore are not about the justification of meta-empirical confirmation but about assessing the relevance of the available empirical data to the confirmational status of inflationary theory.

As we are going to demonstrate now, MEA nevertheless plays a crucial, though slightly different role in the given context. Meta empirical evidence is in fact crucial for turning new empirical evidence E into significant empirical confirmation of a given theory H. In order to understand this mechanism, we need to return to equation (7). According to this equation, a high $P(\mathrm{E}|\mathrm{H_I})$ is not necessary for extracting a high $P(\mathrm{H_I}|\mathrm{E})$ from low priors $P(\mathrm{H_I})$. What is needed is

$$\frac{P(\mathrm{E}|\neg\mathrm{H_I})}{P(\mathrm{E}|\mathrm{H_I})} \lessapprox \frac{P(\mathrm{H_I})}{P(\neg\mathrm{H_I})}. \tag{8}$$

Let us apply equation (8) to the case of inflation. The hypothesis of an inflationary phase (called hypothesis $\mathrm{H_I}$) does have models that are in agreement with the data. Let us, in the spirit of Ijjas et al., concede that inflation, due to its conceptual flexibility, does not strongly predict any specific set of empirical evidence. Let us further assume, in line with the understanding of many proponents of inflation, that there is a strong NAA regarding H_I in light of the collected empirical evidence E: it is very unlikely that there exists any theory other than inflation that is consistent with data E. Relying on these assessments, E looks plausible though not probable when assuming H_I. It looks very improbable when assuming $\neg H_I$. Since there seems to be no reason for an extremely small $P(H_I)$[26], the described scenario generates the condition stated in equation (8).

To be sure, the understanding that E arises *generically* based on H_I and therefore implies a high value for $P(E|H_I)$ would substantially increase the confirmation value of E. But the genericity argument is not strictly necessary. Even for the observer who fully rejects the significance of genericity claims in the given context, an NAA asserting that there probably are no theories other than H_I that can account for data E suppresses $P(E|\neg H_I)$ against $P(E|H_I)$, and on that basis generates significant confirmation of H_I by E.

Thus, our analysis shows that, even if Ijjas et al. were right that H_I is so flexible that it allows for constructing models which can accommodate any precision data that may be collected, this would not block confirmation of H_I by new precision data. Note, once again, that the confirmatory role of MEA plays out entirely at the level of assessing credence in theories rather than models. Since MEA does not increase credence in individual models, new data in light of MEA increases credence in the theory of inflation exclusively based on NAA-type reasoning: if 1) it can be established that inflation explains the observed data, and 2) the probability that an alternative to inflation can provide such an explanation as well decreases based on new data, credence in inflation goes up.

An increase in the precision of the data, as obtained, for example, through new CMB precision measurements, can therefore indeed play a double role. Within the context of inflation, it selects models of inflation that are in agreement with that data and thereby improves the understanding of the way the theory is realized. At the same time, it raises the bar for alternatives to inflation. The more complex and specific the structure of the precision data, the more convincing a no alternatives argument with respect to alternatives to inflation can become.

In the given scenario, it is the NAA rather than the comparison between a model's prediction and the data itself that reaches beyond the level of model testing towards significant confirmation of the inflation paradigm. A high posterior attributed to inflation based on MEA can then provide the basis for confidence in a productive long term evolution of the research field. If MEA-based reasoning suggests that inflation is on the right track, this can also increase trust in the prospect that ruling out models and increasing the conceptual understanding of the theory in the long run will lead towards a more stable and rigorous regime of empirical testing, as indeed is suggested by Guth et al.

[26]Our discussion addresses the prospects for significant empirical confirmation of inflation by future data. The prior $P(H_I)$ therefore denotes the credence in inflation based on all considerations that enter the current assessment of the theory's status. The theory of inflation currently is the by far most popular explanation of flatness and isotropy and is part of the current standard model of cosmology ΛCDM. With very few exceptions, even cosmologists who do not endorse the hypothesis are willing to acknowledge it as a serious contender for explaining those features. Ijjas et al. themselves would do so if the theory were empirically testable on their understanding. (In other words, their worries are a matter of testability rather than low prior credence.) The theory's current status therefore does not seem to be adequately characterized by an extremely small $P(H_I)$.

5 Conclusion: Future Expectations

The dispute between Ijjas et al. and Guth et al. is both philosophically more interesting and conceptually more intricate than the polemical style of the debate would suggest. The fairly complex nature of the debate merits a brief recapitulation of the philosophical reconstruction we have proposed.

The first philosophical disagreement we unearthed concerns the admissible format of theory testing (§2). Ijjas et al. adhere to a rigid, traditional view of theory testing that requires that theories be completed before empirical testing starts, which is necessary in order to spell out their predictions and the conceptual framework of empirical testing. On that basis, the theory can then be empirically tested and validated. Guth et al., by contrast, endorse a more fluid and processual approach to empirical testing: models of theories can be empirically tested before the spectrum of models, the theory's predictions, or even the conceptual framework of empirical testing (cf. the measure problem) has been fully specified. Theory development and theory testing are thereby intertwined. The focus of testing may, at some stage, not be on the falsification of the overall theory but on the exploration of the theory's characteristics.

Although their disagreement is substantially based on their views about testability, the fundamental complaint of Ijjas et al. is that inflationary theory is neither confirmable nor disconfirmable due to its fluidity and flexibility. Guth et al. respond to this criticism with a strictly empiricist argument. They point out that the testing of models is fully sufficient for scientific legitimacy. While this rejoinder works well against the more exaggerated claims of Ijjas et al. concerning scientificality, it is in tension with the strong endorsement of inflation by many of the theory's proponents. Those endorsements, indicate a view on the scientific process that takes the generation of trust in empirically confirmed scientific theories to be an essential element of science—not mere consistency with empirical data.

To capture this element, we find it illuminating to frame the disagreement on the scientific status of inflation in Bayesian terms, which explicitly incorporates credences in theories as a basic aspect of the framework. By framing Ijjas et al.'s arguments in this context, we are led to what emerges as a crucial issue for the status of inflationary cosmology: the nature of confirmation.

As we showed, the Bayesian analysis allows for two different strategies of theory evaluation. On the one hand, a conservative understanding of Bayesian confirmation that constrains confirming data to what lies within the tested theory's intended domain vindicates the underlying worry put forward by Ijjas et al.: no significant empirical confirmation of inflation or any of its models can be generated under the present circumstances. But on this conservative understanding of Bayesian confirmation, *classic* inflation—which Ijjas et al. take to be scientifically unproblematic—cannot be significantly confirmed either. Thus, a narrow understanding of confirmation fails to allow for a meaningful understanding of the way inflationary cosmology can be tested, which renders incoherent the considerable efforts made to empirically test the theory. A more liberal strategy, meta-empirical assessment, which allows confirming data to lie outside the theory's intended domain does, however, provide a coherent epistemological basis for possible significant confirmation of inflation. Once this wider concept of theory confirmation is applied, the worries presented by Ijjas et al. can be countered and the view on inflation expressed by Guth, Linde, and other inflationary cosmologists can be vindicated in principle, if not in fact.

We emphasize, however, that our paper only aims to provide an analysis of the general structure and coherence of the epistemic reasoning deployed in this dispute on the scientific status of inflation. We have not aimed to assess the strengths and weaknesses of the evidential arguments in favor of inflation. To what extent an NAA, an MIA and a UEA are convincing we regard as something which must be decided by a careful, in depth scientific assessment of the given case by knowledgeable practitioners, an assessment which we believe would be substantially aided by carrying it out within the conceptual framework advanced here.

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