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 et al. have questioned the scientificality of the current views on cosmic inflation. Proponents of cosmic inflation have in turn defended the scientific credentials of their approach. We argue that, while this defense, narrowly construed, is successful against Ijjas et al., the latters' reasoning does point to a significant epistemic issue that arises with respect to inflation. A broadening of the concept of theory assessment is needed to address that issue in an adequate way.

1 Introduction

String theory, variations of the multiverse idea, and inflationary cosmology have become dominant, influential paradigms in various parts of theoretical physics over the last few decades. While the ideas behind these paradigms are to some extent speculative, 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. Of course, not all of the promise of these ideas has been realized over the years. So it is that they have found their (often very vocal) critics, who inveigh against these supporters for violating "the scientific method," by maintaining empirically invalidated, unscientific, or otherwise defective ideas.

The cosmic controversy which is our interest in this paper concerns the status of inflationary cosmology, according to which the early universe underwent a brief stage of accelerated expansion, "cosmic inflation," which contributes to explaining the near spatial flatness and homogeneity of the present day universe, at least in the standard view, and the perturbations in the early universe which gave rise to structure formation in the universe (McCoy, 2015). In a series of articles, Ijjas et al. (2013, 2014, 2017) argue, however, that observational results from the Planck satellite put significant pressure on the inflationary paradigm, particularly the models disfavored by the data which they call the "classic" inflationary paradigm. In a response, Guth et al. (2014, 2017) defend a wider, more flexible framework that Ijjas et al. pejoratively call

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the "postmodern" inflationary paradigm. Ijjas et al. claim that this approach to inflation is "a construct that lies outside of normal science" (Ijjas et al., 2014, 145), arguing that the only way it will work "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 is first and foremost a debate among scientists, the philosophical tenor of the discussions is unmissable: Ijjas et al. explicitly advocate a likelihoodist standard for the empirical validity of a scientific paradigm and reject ad hoc accommodation in order to adjust likelihoods to favor an invalidated paradigm; Guth et al. explicitly defend an empiricist criterion of empirical validity, while advocating the inflationary paradigm on the basic of theoretical virtues like fruitfulness, explanatory power, and accuracy. Nevertheless, they champion various different philosophical ideas in a way that only leads them to talk past one another, and the debate appears to end in a stalemate.

Our first task in this paper 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. The actual, literal arguments made by Ijjas et al., as we show, are convincingly rebutted by Guth et al.'s defense of inflationary cosmology. However, when those arguments are refined by situating them in formal likelihoodist and Bayesian confirmation frameworks (§3), it is clear that, in theories like inflation, there is no basis for generating significant confirmation of the paradigm (due to, e.g., its flexibility in generating models).

While Guth et al. are right that individual inflationary models are empirically *testable* and some are indeed empirically adequate, thereby insuring the empirical validity of the paradigm, this point threatens the scientific mechanism of generating credence in the *viability* of the paradigm.[1] In other words, the reasoning underlying Ijjas et al.'s critique raises doubts as to whether inflationary cosmology can provide any grounds to believe that it is on the right track. We argue, however, that the viability of inflationary cosmology can nevertheless be secured by indirect means. Theoretical physicists who support paradigms like string theory, the multiverse, and inflationary cosmology have deployed these distinctive indirect means (albeit unsystematically) by appealing to what have been called "non-" or "meta-empirical" considerations (Dawid, 2013). We show (§4) how the combination of both meta-empirical evidence and observational data can contribute to the confirmation of a paradigm, even when individual models, like those falling within the inflationary paradigm, cannot admit of confirmation due to the problem we extract from Ijjas et al.'s arguments. We sum up our argument in the conclusion (§5).

2 Analysis: Inflationary Paradigm in Trouble?

In this section, we analyze Ijjas et al.'s arguments in their two critical papers on the inflationary paradigm, which they wrote in light of the then new results of analyzing the Planck satellite's observations of the cosmic microwave background (CMB) radiation, as well as the responses by Guth et al. Our aim is to clearly extract the essential philosophical points that are raised by the two parties in their disagreements.

[1] A paradigm is viable on our account if there are grounds to trust that it has the resources to account for all empirical data that can possibly be collected with a given empirical "horizon."

2.1 Act I: Planck 2013

In their first critical paper, Ijjas et al. (2013) offer three principal arguments to challenge 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.[2]

- 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 to a multiverse of "bubble universes." This argument depends on the well-known "measure problem" in multiverse theories (Freivogel, 2011), which is the problem of supplying a probability measure that can be used to make concrete predictions within the multiverse. Without an appropriate and justified measure, one cannot make predictions of what one expects to observe 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, and will be explained below.

Each of these arguments is evidently 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)

It follows that if a model is expected (that is, likely) according to the paradigm but the data is 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 is expected given a model's predictions but that model is surprising according to the paradigm. Ijjas et al.'s first argument disputes the likelihood of inflation to occur in a model with the empirically-favored plateau-like potential given natural initial conditions (which they regard as a basic assumption of the paradigm); their second and third arguments dispute the likelihood of plateau-like potentials within the inflationary paradigm.

The epistemological view that Ijjas et al. endorse in the quoted passage, 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

[2] 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.

desire to make "explanatory power" relevant to the assessment of (rival) hypotheses, while still remaining broadly empiricist in orientation (Sober, 1990).[3] The fundamental principle advocated by likelihoodists is the "Law of Likelihood": data (E) favors one hypothesis (H_1) over another (H_2) just when the likelihood of the data according to H_1 is greater than the likelihood of the data according to H_2, that is, $P(E|H_1) > P(E|H_2)$.

Ijjas et al. 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 non-comparative "Law of Likelihood" that they in effect endorse would read something like this: data (E) favor the paradigm (T) just when the likelihood of the data according to the paradigm's models (M) and the likelihood of those models according to the paradigm is sufficiently high (c): $P(E|T) = \sum_i [P(E|M_i) \times P(M_i|T)] > c$. The likelihood of the data (with respect to the paradigm) factors into the two likelihoods mentioned in the quoted passage above. Thus, one must be able not only to attribute likelihoods to the data with respect to the models but also to attribute likelihoods to models of a paradigm in order to assess the validity of that paradigm—the latter is plainly a non-empirical assessment.

Although explicit advocacy of this general perspective on hypothesis assessment may not be especially common among philosophers of science, many cosmologists do in fact reason along these lines in practice.[4] The principal response (Guth et al., 2014) to Ijjas et al.'s arguments, however, does not explicitly reject the likelihoodist standard of validity for a paradigm; instead, it focuses on offering direct rebuttals to their three arguments. Nevertheless, one can glean a significantly different methodological perspective from Guth et al.'s comments.

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 vis-à-vis initial conditions can be avoided in what they take to be a much more plausible scenario: an inflaton with a complicated potential, with various 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 but a convenient one.

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. 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, however, 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 predic-

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

[4] Although we would be inclined to reject likelihoodism on general grounds—for some relevant criticism, see (Fitelson, 2007, 2011)—our objection to Ijjas et al.'s arguments is tied to details emerging from the specific case at hand.

tive use of inflationary models, for "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 need not know how bubble universes are probabilistically generated in order to make quantitative predictions from specific models of inflation).

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. would certainly grant. Ijjas et al.'s concern is more general, namely, with the inability to specify the likelihoods of models of inflation given the inflationary paradigm, which they claim undermines the validity of the *paradigm*, *not* the predictive use of individual models. They maintain that the fact that some 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, they conclude that the inflationary paradigm is indeed observationally validated. Hence, 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.[5] They conclude that, "since the measure problem 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. These particular models have potentials with two symmetric minima (at some field strength), are plateau-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 plateau. 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 plateau (the field "slides" down the potential to the minima, thereby causing inflation) is unlikely since the "width" of the plateau field values is small compared to the range of field values where inflation is possible along the power-law slope. 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 plateau part, one infers that it is unlikely that inflation occurred by a slow-roll down the plateau (this, however, being precisely what observations suggest happens).[6]

- 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 plateau part. Ijjas et al. assume a

[5] Thus, Guth et al. here advocate what looks like a conventional Bayesian perspective on hypothesis assessment.

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

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 plateau-like potentials and the initial conditions of the field associated with slow-roll down the plateau 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 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 perhaps favors a uniform measure for the initial field value and the volume weighting measure, these are nothing more than plausible assumptions which can be (and have been) discarded in the course of further investigations. They are not fundamental assumptions of the inflationary paradigm.

Before moving to act two, 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.).

2.2 Act II: Inflationary Schism?

In their first paper, Ijjas et al. attempt to show that the likelihood of the Planck data with respect to the inflationary paradigm as a whole is such as to invalidate the paradigm (or at least substantially disconfirm 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), where they shift their argument to the claim that a "schism" has emerged between what they describe as the "old" inflationary scenario ("classical 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 classical inflation are unaffected by Guth et al.'s response (i.e., classical inflation is invalidated by Planck's data), 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, one with unpalatable consequences on both horns. Ijjas et al. take this to suggest the need for an alternative paradigm:

> 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)

Inflationary cosmologists, however, would certainly reject the idea that there is a "schism" between different kinds of inflation, maintaining 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 "classical 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:

> 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.

In their brief reply appended to this letter, Ijjas et al. claim that the authors miss their key point, however, 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. 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) relies on 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; (3) 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 tending to be larger than uninflated regions. And when it became possible to make observations of the cosmic microwave background, these promises of classical inflation were made good on, with the famous confirmed predictions of a slight red tilt in the spectrum of inhomogeneities, a large tensor-to-scalar ratio, negligible non-Gaussianity, etc.

Nevertheless, according to Ijjas et al., despite its successes, there are long-standing conceptual problems with this “classical” 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, they 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 later exacerbated by the Planck satellite’s observations, which is their main point in (Ijjas et al., 2013): (1) the simple inflaton potentials are empirically disconfirmed, (2) the favored plateau potentials require special initial conditions, and (3) these plateau models naturally lead to a multiverse, hence the multiverse measure problem. Thus 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, supposing that the appearance of any special initial conditions can be compensated for by adjusting 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 and empirical considerations.

Ijjas et al. find this scenario highly problematic—indeed, even 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 attributed to specific models (or a classes of models) presently. 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 be generically 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 merely the task of 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, it seems that this “postmodern” inflationary paradigm is not truly empirically testable; there can be no possible falsification (and no possible confirmation either) of the paradigm. This is what makes the contemporary paradigm unscientific in Ijjas et al.’s view. As they say already in their earlier paper, "if the only way the inflationary paradigm will work is by delicately designing all the test criteria and data into the potential, this is trouble for the paradigm" (Ijjas et al., 2013, 264).

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 "classical" 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 at pains to dispute. [7] 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, the mere fact that selecting certain empirically adequate models is currently a matter of accommodating data (even within a highly flexible framework for model building) does not threaten the basic scientificality of the approach. For them, 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. Guth et al. suggest that once stronger constraints can be put on model building by more advanced and fine-grained empirical data, a stronger element of novel prediction should be expected to re-emerge.[8]

Thus, 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 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 "classical inflation" is an excessively narrow construal of inflationary theory. While the Planck observations certainly do disfavor the specific models characterized by this class of inflationary models, they do not necessarily disfavor the inflationary paradigm itself, for there is nothing in the basic concepts of inflationary theory mandating the "simple" modeling assumptions that select this class of models. 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 the assumptions of classical inflation now appear limited and inadequate.

[7] In their response, they do note that their disagreement is broader than just this. Indeed, as they say, "we disagree with a number of statements in their article, but in this letter, we will focus on our categorical disagreement with these statements about the testability of inflation" (Guth et al., 2017, 5).

[8] 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.

It is certainly fair to say, however, 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 inflationary cosmologists: there exists a vast landscape 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 particularly 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 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 necessary (McCoy, forthcoming).

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* for mere *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 at this stage in order to make further progress.

We caution, however, against an inviting misreading of the role of eliminative reasoning in this process. 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 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 whatever might develop out of it).

To sum up the contrasting viewpoints of Ijjas et al. and Guth et al. we believe the essential difference between the two sides boils 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 can begin. Failing to reject an empirically invalidated theory or holding an empirically untestable theory would consequently 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 viability.[9]

The analysis of this section evidently recapitulates some familiar issues in the philosophy of science. Nevertheless, the analysis offered so far has not yet gotten fully to 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, along with its attendant eschewal of rigid testing criteria. This feature distinguishes the field from most earlier contexts of empirical theory testing in physics. Questions such as the following become more acute: Under what conditions is it legitimate to weaken 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 solid testability of inflationary theory to be a threat to scientificality?[10] In our terms, the reasonableness of persisting with the inflationary paradigm depends on having credence in the *viability* of the inflationary paradigm itself. If there is no basis for having this credence in the paradigm (as Ijjas et al. allege), then using inflationary theory to guide an eliminative observational program might be relatively ineffective in achieving any meaningful scientific progress in comparison to instead developing alternative paradigms, such as those favored by Ijjas et al. One might conclude 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). We propose that a deeper look into the case of inflationary cosmology will reveal that this conclusion is too hasty and too limited, for it overlooks a dimension of theoretical assessment that is crucial for understanding the confirmation of scientific theories.

3 Taking Credence into Account

In this section, we elaborate the serious confirmational issue for the inflationary paradigm which we believe is essentially 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 the falsifiability of the paradigm of inflation; it rather 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. Other views on theory assessment, by contrast, take credence in a theory to be at the very core of theory assessment. They 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 (for which reason we prefer to use the more general term "viability" rather than couch

[9] In this respect, Ijjas et al.'s methodological view is 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.

[10] These questions, of course, were left unanswered by the likes of Kuhn and Lakatos, who saw no prospect for extending their historical perspective to future developments.

the discussion in terms of the realist notion of truth). In any case, it takes strong empirical confirmation to imply that the theory's predictions within a given domain of empirical testing, a given "empirical horizon," should be taken as probably correct.

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 cosmic inflation even within science. Indeed, trust in the theory is expressed quite forcefully by many proponents of inflation. While we have seen that Guth et al.'s defense of the scientificality of inflation against Ijjas et al. 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 amounts to a strong commitment to the theory's truth or viability.[11]

Representing the views of inflationary cosmologists thus requires a conceptual framework that allows for addressing the issue of credence in a theory. The leading formal approach that is capable of representing the described view on theory assessment is Bayesian confirmation 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, we find that their core criticism of inflation does not get off the ground as long as credence in the theory is not considered part of the basic question of scientificality of inflationary cosmology.

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

If one requires that empirical testing is essentially involved in generating significant credence in a theory or model, then the Ijjas et al. view that the observations need to be in line with what is expected according to the "internal logic of the paradigm" becomes cogent. The mere fact that a given model predicts the data with a high likelihood is insufficient for trust in that model if there are so many competitor models that no significant credence can be attributed to any given model after the empirical test. If the collected data do generate significant credence in the model, however, this means that significant credence is also necessarily generated in the paradigm from which the model was built (after all, there is only so much credence to go around!). Thus, a confirmational link to the paradigm itself thus emerges naturally once significant credence is required.

Once credences become involved, Ijjas et al.'s criticism can be seen to amount to the following account. According to it, the use of eliminative reasoning with respect to models of inflation would only be promising in two distinct scenarios:

[11] 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."

- In the first 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 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.

- In the second 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. Inflationary cosmologists do indeed often claim that significant and successful generic predictions of inflation exist.

For the second scenario, however, 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 easily account for such deviations. 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 really instantiated in nature? This worry gains traction due to the fact that the very simplest class of models has indeed been ruled out by experiment, and this has not been taken to constitute a significant argument against inflation per se. Second, Guth et al.'s approach to solving the measure problem, namely, that it should be guided by empirical data, renders the question what is or is not "generic" in an inflationary context even more complicated. In light of these specific doubts, an Ijjas et al. inspired Bayesian analysis would imply that the agreement between collected data and generic predictions of inflation should not generate significant credence in the theory of inflation at the current stage.

Ijjas et al.'s assessment of inflation thus suggests that neither of the two scenarios apply, so there is no available 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. The formal conditions for Bayesian confirmation are fulfilled even if confirmation is just incremental and insignificant. It raises the question, however, 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 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 eliminative reasoning within the framework of inflation is helpful at all? For a brief period, working on a theory without confidence may be fine. But for how long could physicists justify spending so many intellectual resources on a hypothesis without legitimate reasons to assume that they work on a viable theory?

As mentioned above, inflationary cosmologists, in stark disagreement with Ijjas et al., do have a lot of trust in their theoretical paradigm. Is their trust unjustified? We believe that it is in fact justified, but this requires showing on what grounds they can discard the legitimate and important worry stated above. We will argue in the following that those grounds involve taking meta-empirical theory assessment (MEA) into account.

3.2 Collapsing the Distinction Between Classical and Post-empirical Inflation

As a first step towards the inclusion of MEA in the analysis, we will spell out the Bayesian representation of Ijjas et al.'s worry in a little more detail. This will lead us to an interesting result: the Bayesian form of Ijjas et al.'s worry concerns classical inflation just as much as "postmodern" inflation.

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. The early theory of inflation, to the contrary, constrained model building to a sufficient degree to be predictive and therefore scientifically unproblematic. As we will see, this distinction cannot be upheld on a Bayesian rendering of their account.

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

Bayes' theorem gives the posterior probability of theory H_C given data E as

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

If we insert the total probability

$$P(E) = P(E|H_C)P(H_C) + P(E|H_+)P(H_+) + P(E|\neg H_I)P(\neg H_I), \tag{2}$$

we obtain

$$P(H_C|E) = \frac{P(E|H_C)\,P(H_C)}{P(E|H_C)P(H_C) + P(E|H_+)P(H_+) + P(E|\neg H_I)P(\neg H_I)}, \tag{3}$$

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

$$P(H_I|E) = \frac{P(E|H_I)\,P(H_I)}{P(E|H_I)P(H_I) + P(E|\neg H_I)P(\neg H_I)} \tag{4}$$

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 (1) that the prior probability $P(H_I)$ is small and (2) that the probability $P(E|\neg H_I)$ is small for any distinctive set of empirical data E that could be used for theory testing in the given context. Therefore, $P(E)$ is small as well.

In Bayesian terms, Ijjas et al.'s claim corresponds to the following assertion. The spectrum of models of H_I is so wide that it will cover most of the parameter space of future empirical outcomes, almost regardless of whatever imaginable evidence E is collected. H_I, in other words, is not predictive. Therefore, whatever E we collect, $P(E|H_I)$ will only be marginally higher than $P(E|\neg H_I)$ and, consequently, only marginally higher than $P(E)$, which ultimately means that

$P(\mathrm{H_I}|\mathrm{E})$ will only be marginally higher than $P(\mathrm{H_I})$. In short, whatever the evidence E, it will not provide significant confirmation of $\mathrm{H_I}$. Thus, we could only have substantial trust in $\mathrm{H_I}$ if we had already assigned a high prior to it. Assigning such high priors would go against the basic assumptions of the Ijjas et al.-inspired Bayesian; indeed, it should be regarded as unscientific per se. Even worse, in the given case it would be impossible to reduce the high probability of $\mathrm{H_I}$ based on empirical testing because most imaginable evidence could be accommodated by $\mathrm{H_I}$.

This line of reasoning, in its own right, amounts to a coherent argument against theories like cosmic inflation. 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 $P(\mathrm{E})$. Thus, according to equation (4), we have a sufficient basis for obtaining a large $P(\mathrm{H_C}|\mathrm{E})$, which amounts to significant confirmation of $\mathrm{H_C}$.

Yet this further step of Ijjas et al. cannot be captured within a Bayesian framework at the same time as the first line of reasoning. 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 substantial confirmation for $\mathrm{H_C}$ can be achieved without having substantial 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 testing $\mathrm{H_I}$ is not sufficient for vindicating the scientific process, neither is testing $\mathrm{H_C}$. In other words, in order to argue that $\mathrm{H_C}$ can find significant empirically confirmation, it is necessary to establish that $\mathrm{H_I}$ can find significant empirical confirmation as well. 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.

One could, in order to rescue Ijjas et al.'s reasoning in this setting, favor classic inflation over "postmodern" inflation by adding one additional element to their assumptions about classic inflation. Namely, one would need to assume $P(\mathrm{H_+}) << P(\mathrm{H_C})$. In 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 $\mathrm{H_C}$: one would have a prediction of $\mathrm{H_C}$ that translates into a high $P(\mathrm{E}|\mathrm{H_C})$, and no preference for E if $\mathrm{H_C}$ is false. This is, of course, the canonical setup for empirical confirmation.

This solution appears to be entirely ad hoc however. What could be the reasons for expecting, a priori, $\mathrm{H_C}$ rather than $\mathrm{H_+}$? No satisfactory answer seems available that reaches beyond a raw and unfounded prejudice in favor of simple solutions. A probabilistic representation of Ijjas et al.'s endorsement of classic inflation thus would have to rely on the physically and conceptually unjustified implicit conviction that viable inflationary models be simple. As soon as that unsupported conviction is abandoned, classic inflation is no more confirmable than "post-modern" inflation.

4 Applying Meta-Empirical Confirmation to Inflation

Is there a more promising mechanism for generating trust in 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 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.

Dawid (2006, 2013, 2020) has developed a method of theory assessment in line with that general idea under the name "meta-empirical confirmation" (MEC).[12] 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 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 (1) by a meta-inductive argument (MIA) based on the observation F_{MI} that no-alternative assessments in comparable contexts tended to be predictively successful when empirically tested and, in many cases, (2) by an unexpected explanation argument (UEA) that 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.[13]

In the following, we will distinguish genuine MEC, that is, updating 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.

It does not take an intense and long lasting search to establish that patterns of MEA-type reasoning are deployed by inflationary cosmologists when they argue for the viability of the theory of inflation. A particularly clear example is Andrei Linde's paper already quoted (fn. 11). At another point in the same paper, he writes:

[12]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, 2020) in order to distinguish them from the wider class of non-empirical arguments.

[13]We will pass over further details of Dawid's frameworks, which can be found in the references cited at the head of the paragraph.

> 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.

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, James Peebles has emphasized in his recent book (Peebles, 2020) 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. Peebles does not connect his point to an assessment of inflation however. But proponents of inflationary cosmology can use the eventual empirical success of general relativity at distance scales where it was initially trusted (without empirical basis) in MIA type reasoning to support a scarcity of options at the fundamental level of cosmological theory building.

An NAA could also find further support by cases of unexpected explanation (UEA) that show up in inflationary cosmology. We will mention only one possible case of a UEA that is controversial, but interesting. 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, MEA-type reasoning has plausibility in the context of inflationary cosmology: all three pure MEA modes of reasoning, NAA, MIA, and UEA, can be developed in that context. Second, MEA is indeed employed by some of the theory's leading proponents (e.g., Linde, Peebles). Of course, the fact that MEA arguments can be and are used in cosmology does not tell us how strong these arguments are in the given context. The strength of an NAA, in particular, will depend on the extend 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 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 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.

The described view 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.

As we are going to demonstrate now, MEA nevertheless plays a crucial, though slightly different role in the given context: it is 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 (4). 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:

$$P(\mathrm{E}|\neg \mathrm{H_I}) << P(\mathrm{E}|\mathrm{H_I}) \tag{5}$$

Let us now assume a scenario where E is consistent with $\mathrm{H_I}$ but not significantly favored by it. Let us further assume that we have a strong NAA regarding $\mathrm{H_I}$ based on E: we consider it very unlikely that there exists any theory other than $\mathrm{H_I}$ that is consistent with data E. In such a scenario, E looks plausible though not probable based on assuming $\mathrm{H_I}$. It looks very improbable based on assuming $\neg \mathrm{H_I}$. In other words, a strong NAA generates exactly the condition stated in equation (5) based on the mere fact that the hypothesis of an inflationary phase does have models that are in agreement with the data.

To be sure, the understanding that E arises generically based on $\mathrm{H_I}$ and therefore implies a high value for $P(\mathrm{E}|\mathrm{H_I})$ 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 $\mathrm{H_I}$ that can account for data E suppresses $P(\mathrm{E}|\neg \mathrm{H_I})$ against $P(\mathrm{E}|\mathrm{H_I})$, and on that basis generates significant confirmation of $\mathrm{H_I}$ by E.

Thus, our analysis shows that, even if Ijjas et al. were right that $\mathrm{H_I}$ 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 $\mathrm{H_I}$ by new precision data. An increase in the precision of the data, as obtained, for example, through new CMB precision measurements, can 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 no alternatives argument rather than the comparison between a model's prediction and the data itself that reaches beyond the level of model testing towards actual 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.

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 are 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. about 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.

To capture this element, we found it useful 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 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 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. A more liberal strategy (MEA) which allows confirming data to lie outside the theory's intended domain does, however, provide a 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 et al. can be vindicated.

We emphasize 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 factual arguments in favor of inflation. To what extent an NAA, an MIA and a UEA are convincing, we regard that as something which must be decided by a careful, in depth scientific assessment of the given case by knowledgeable practitioners, an assessment which, however, would be aided by the conceptual framework advanced here.

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