

Epistemic Justification and Methodological Luck in Inflationary Cosmology

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Abstract

I present a recent historical case from cosmology—the story of inflationary cosmology—and on its basis argue that solving explanatory problems is a reliable method for making progress in science. In particular, I claim that the success of inflationary theory at solving its predecessor’s explanatory problems justified the theory epistemically, even in advance of the development of novel predictions from the theory and the later confirmation of those predictions.

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1 Introduction

Much discussion over the relevance of explanatory considerations to scientific methodology and epistemology has centred on general philosophical concerns, often at some remove from scientific practice and the analysis of historical cases. Especially prominent in the literature, due to their applicability to the scientific realism debate, are ‘in principle’ underdetermination arguments and whether inference to the best explanation (IBE) is a generally valid form of reasoning. As the well-worn story goes, the underdetermination of theory by empirical evidence leads the realist to posit various theoretical virtues, such as explanatory power, to break this

underdetermination, or else to argue that an inference to the best explanation of the evidence suffices to infer the truth of the most explanatory of the lot of theories she considers. Her opponent rejoins the argument by insisting that theoretical virtues are merely pragmatic (and hence non-epistemic), and that inference to the best explanation is insufficient to secure the truth of the most explanatory theory (if he grants that ‘most explanatory theory’ even makes sense).

Attending to the roles that explanation actually plays and has played in scientific practice, such as the way it structures discourse in a discipline and coordinates exemplars (Woody [2015]), suggests that explanation is epistemically relevant in various respects and contexts independently of the considerations raised in the well-worn philosophical debate over realism. Explanationism, as I understand it, acknowledges this suggestion: it is the position which holds that explanation is epistemically relevant in science. By epistemically relevant I mean that explanatory considerations can reliably justify (in an epistemic sense) trust in the viability of a theory, if not fully justifying it and its contents as knowledge.

In my view explanationism is thus comfortable with a variety of epistemological views concerning science. While I do believe that science has an epistemic aim, I do not presuppose that this aim is, for example, the mere acquisition of knowledge (Bird [2007]) or approaching the truth (Niiniluoto [2014]), for it may well be that the epistemic aim of science is better characterized in a different way, such as the achievement of understanding (Elgin, Elgin [2007, forthcoming]). Even if it is best characterized as knowledge, one does not have to suppose that knowledge depends on any particular metaphysical account of truth, such as that favored by scientific realists. To allow for consistency with different views on the epistemology of science, I will therefore prefer locutions like ‘trust in the viability of a theory’ in this paper over ‘belief in the truth of a theory’ or similarly strong and presumptive epistemic attitudes, while still allowing that these presumptions may ultimately be correct.¹

Explanationism understood in this way therefore does not depend on the general validity of IBE, nor does it obviously depend on the acceptance of any version of scientific realism and its attendant metaphysics—yet it is certainly compatible with both of these. The explanationist will, however, reject the common anti-realist claim that explanatory considerations are merely of pragmatic or heuristic value, maintaining instead that they can play a genuinely epistemic role in science. She is, as it were, a methodologist, not a metaphysician.

Is there conclusive aid to be found for the explanationist cause from scientific practice and historical cases? I argue in this paper that there is. The case of inflationary cosmology, I claim, compellingly offers a concrete example of the crucial methodological role that explanatory considerations can and do play in science. Indeed, it makes a strong case that explanatory considerations in some cases provide an epistemological warrant for our scientific theories.

Opposition to any form of explanationism in science is typically rooted in a strongly empiricist stance towards science. Accordingly, my strategy will be to show that empiricist interpretations of the case of inflationary cosmology are implausible, for the empiricist relies on evidential resources that are too limited to make rational sense of the success of the theory. Explanationism, by contrast, avails itself of broader evidential resources by allowing explanatory considerations to justify the pursuit or acceptance of theories. By making use of these resources, the explanationist is able to supply an acceptable interpretation of this historical episode—and may be able to shed light on many other scientific episodes as well.

¹One useful way to think about viability (which a referee suggests and which I endorse as relevant) is degree of epistemic support or confirmation (for example, in the Bayesian sense) of a theory, although I will not defend this particular interpretation.

2 A Portrait of the Argument as a Short Précis

A few words about empiricism and explanation are first in order. Dedicated as it is to the epistemological rather than metaphysical, this paper brackets the anti-realism of the empiricist in order to focus on his epistemology. Certainly there is a variety of views having some empiricist element in their epistemic outlook. Nevertheless, I take it that a fundamental epistemic tenet of the empiricist view of science is this: scientific knowledge is at bottom empirical knowledge. Thus, for the full-blooded empiricist the epistemic justification of scientific theories can only rest on the agreement of theory with observation and experiment. The empiricist believes, in other words, that empirical evidence alone grounds the acceptance of a theory.

Of course there are many philosophers who consider themselves empiricists but would reject this strict characterization of the epistemology of empiricism. However, if all it takes to be an empiricist is accepting that empirical considerations are epistemically relevant, then almost no philosopher of science fails to be an empiricist. Empiricism in this wider sense would not be an epistemological position worth discussing.

Given this characterization of empiricist epistemology, it is important to recognize that explanatory considerations derive from theory rather than empirical evidence alone. If a theory explains some observation and that explanatory relation is taken to warrant the theory, then something other than empirical evidence must be involved in the justification, a justification which the scrupulous empiricist would reject as extra-empirical. Explanationist epistemology is therefore fully at odds with empiricist epistemology.

These preliminaries related, we may now, in a preliminary way, visit the historical case at the heart of the argument (it is described in further detail in the following section). According to the empiricist characterized above, inflationary cosmology was epistemically no better initially (if not much less justified) than the accepted standard model of cosmology, the hot big bang (HBB) model, since it lacked distinctive observational support, made no novel predictions, and resolved no real empirical inadequacies with the HBB model (Earman and Mosterín [1999]). Nevertheless, it was quickly accepted in the cosmological community on the basis of its putative solution to certain explanatory problems with the HBB model. According to empiricist epistemology solving such explanatory problems at best provides a non-epistemic justification for inflationary theory (a pragmatic reason for pursuing the theory, for example, but no reason to expect its later empirical success). According to explanationist epistemology, however, solving such explanatory problems can provide an epistemic warrant for scientific theories.

Since the introduction of inflationary theory in the early 1980s, a wealth of precise cosmological data has been acquired, particularly in the last 15 years by the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck space observatory. Cosmologists routinely claim that these data empirically support cosmological models that incorporate an inflationary stage—and strikingly so in terms of accuracy. See, for example, (Guth and Kaiser [2005], p. 888); the chart found there (the same is found in many books, papers, and presentations) depicts observational data from cosmic microwave background (CMB) anisotropies following the curve predicted by simple inflationary models almost exactly. This is the kind of correlation that cosmologists often have in mind when they claim that the data support inflationary theory. If this claim of confirmation is correct—and it surely is taken as such by most contemporary cosmologists—then inflationary theory should reasonably be considered an empirically successful theory whose predictive successes go beyond the HBB model.

Yet it is important to note that these precise predictions were not clearly foreseen at the time of inflation's proposal and initial acceptance by the community of theoretical cosmologists. How, then, can this widespread adoption of inflationary theory and its later empirical vindica-

tion be explained? While there are surely sociological, psychological, and other non-epistemic factors relevant for a complete historical account of this episode, I take it that the philosopher of science should be greatly interested in the question of whether there is a salient methodological, epistemic account as well. I argue that the empiricist must reject that there is such an account; the explanationist can argue that there is.

Indeed, a central claim of the argument I make in this paper is that views of science rooted in an empiricist epistemology must admit that inflationary theory's empirical success was achieved by extraordinary methodological luck—roughly, epistemic success achieved through a method no more effective than guessing. Yet this degree of luck is implausible in the case at hand, for it seems evident that cosmologists were not guessing; rather, it appears as if they knew the theory was viable from the beginning (much like the similar case of the Higgs mechanism in particle physics). The alternative to the methodological skepticism that comes from attributing extraordinary luck to a scientific success is to consider that inflation's rapid and early acceptance among cosmologists was somehow epistemically justified prior to any observational support or provision of novel predictions.

I propose that the explanationist can provide such an alternative by showing that a favorable epistemic status of inflationary theory in cosmology can be traced to explanatory considerations which arise from its approach to solving explanatory problems with the HBB model, namely the fine-tuning problems known as the horizon and flatness problems. These problems center on explanations of certain presently observed cosmological conditions: the universe's spatial uniformity and flat spatial geometry. Inflationary theory's putative solution of these fine-tuning problems was largely responsible for the widespread acceptance of the theory, principally because inflation provided a better explanation for the uniformity and flatness of space than the HBB model's. I argue, making use of the notions of problem-solving and progress from Laudan ([1977]), Nickles, and others, that there is thus a salient and significant methodological story linking inflationary theory's putative success at solving the HBB model's fine-tuning problems with the later confirmation of its observational predictions. Although there is certainly no guarantee that its predictions would be borne out, cosmologists' confidence in the theory's viability is, I claim, reasonably justified by its past problem-solving success. Depending on one's predilections in epistemology, this justification may also be sufficient to consider inflationary theory or parts thereof as genuine items of scientific knowledge.

It must be acknowledged that, as my argument is based on a specific case, it is sensitive to the details of the case. For example, the success of my explanationist account of the case depends on whether inflation does in fact solve the HBB model's fine-tuning problems, which, despite cosmologists' sanguinity on the matter, is disputable. Indeed, I have recently argued myself that at present it cannot be said that inflationary theory solves them (McCoy [2015]). The basic issue is that it is not very clear how to interpret the problems, since whether inflationary theory solves them or not depends on what precisely the problems are. Conventional interpretations, where fine-tuning is characterized in terms of likelihood or probability, fail for both philosophical and technical reasons as pointed out in (Schiffrin and Wald [2012]) and (McCoy [forthcoming]). I do believe that there are promising alternative interpretations deserving of investigation, such as characterizing fine-tuning as a case of over-idealization or a lack of robustness, which would ground the cosmologists' claim. Some solution, along these lines or otherwise, is clearly required to sustain the argument of this paper. I will proceed on the plausible assumption that an appropriate account of fine-tuning can be given.

I begin the main body of the paper with a brief history of recent cosmology and inflationary theory in particular (§3). It is to this history that I will subsequently apply empiricist (§4) and explanationist (§6) interpretations. In between I argue for the central claim mentioned

above, concluding that the empiricist interpretations are inadequate (§5). §7 offers concluding remarks.

3 A Brief History of Inflationary Theory

Cosmology is the science of the universe. From our limited spatiotemporal perspective on it, the universe appears to be remarkably similar in every direction that we look—the universe is nearly isotropic about us. At cosmological distance scales where one averages out smaller scale features (such as galaxies, stars, planets, and so on) one observes a very close to uniform universe. Much of modern cosmology is based on the supposition that perspectives on the universe from elsewhere look much as ours does here and now in our own cosmological neighbourhood. This supposition is enshrined in a basic theoretical principle of cosmology, the cosmological principle (CP) (Beisbart and Jung [2006], [2009]; Butterfield [2014]). The CP holds that space is not only locally isotropic (roughly, the same in every direction from here) but also homogeneous (roughly, the same in every place or, equivalently, isotropic about every point in space). Thus the universe as a whole is (nearly) spatially uniform according to the CP.

The assumption of the CP determines a subset of relativistic spacetimes permitted by the general theory of relativity (GTR), the theory of gravitation relevant for cosmological modeling. The spacetimes that respect the CP are known as Friedman-Robertson-Walker (FRW) spacetimes. In the early decades of the 20th century Slipher’s spectral observations of galaxies, Hubble’s analysis of their distances, and Lemâitre’s theoretical investigations established the idea that space is expanding; thus the appropriate FRW models for modeling our universe is the set of FRW spacetimes that have an initial stage of expansion. These are the FRW spacetimes that may serve as possible hot big bang universes. In an HBB universe, the universe begins in a hot, dense state and then expands (at a decelerated rate) and cools, so that localized observers like ourselves observe every part of the universe (galaxies, for example) moving away from them (in what is known as the Hubble expansion). More accurately, an observer observes the wavelengths of light emitted or absorbed from distant objects shifted relative to what one would expect in local experiments (which lengthening of wavelengths is known as redshifting).²

The HBB model was remarkably successful as the standard cosmological model of the latter half of the 20th century (Kragh [1996]; Longair [2006]). Two theoretical problems, however, eventually led to its modification by the introduction of inflation (Earman [1995]; Earman and Mosterín [1999]; Smeenk [2005], [2013]). These problems are generally known as the horizon problem and the flatness problem. Both problems arise from the kind of explanation that the HBB model gives of certain cosmological conditions. The HBB explanation of these observationally-inferred cosmological conditions depends on the universe beginning with very special initial conditions, for which reason these are often called fine-tuning problems.

The horizon problem begins with the observation of the aforementioned (near) spatial isotropy of the universe. One infers (on the basis of the CP) its (near) spatial homogeneity as well. Because of the dynamics of general relativity, in order for the HBB universe to be as spatially uniform as it is now, it had to be extraordinarily uniform near in time to the big bang itself. If it had been the slightest bit less uniform initially, the universe would be nowhere near as uniform as it is now. This fine-tuning of initial conditions required to yield the presently ob-

²Further details on HBB cosmology can be found in standard cosmology textbooks, for example (Dodelson [2003]; Mukhanov [2005]; Weinberg [2008]), and in some work aimed at philosophers (Smeenk [2003]; Ellis [2007]; McCoy [2016]). Precise mathematical details can be found in (McCabe [2004]; Malament [2012]).

served uniformity is therefore perhaps better described as the ‘uniformity problem’ (Earman and Mosterín [1999], p. 18). A more robust explanation of uniformity than the HBB model’s (which depends on special initial conditions) is, however, precluded by the presence of particle horizons in the model (this being the origin of the usual name of the problem). Particle horizons separate the cosmic microwave background (at the time of its creation) into a large number of causally disconnected regions, that is, regions of the universe that could never have physically interacted (in such a way so as to ensure uniformity). These horizons thus represent an obstacle to devising a physical scenario to explain flatness and uniformity which would be less dependent on special initial conditions.

The flatness problem starts from the recognition that the universe’s spatial geometry is very close to flat (or Euclidean). To be as nearly flat as we observe it to be today, the universe’s spatial curvature had to be extraordinarily flat near in time to the big bang. If it had been any more curved, the universe would have never produced stars and galaxies or else would have quickly contracted back into a big crunch (Guth and Kaiser [2005]). The fine-tuning of initial conditions required for this degree of flatness is known as the flatness problem.³

The HBB model’s fine-tuning problems are not problems concerning the model’s consistency or empirical adequacy, since the model is certainly capable of explaining the present flatness and uniformity of the universe. Why does the universe have a nearly flat geometry? Why is the universe so nearly uniform? According to the HBB model it is because the universe was initially very uniform and close to flat; it then evolved (according the dynamical laws of general relativity) to the present degree of uniformity and flatness. This is clearly an explanation of the kind that is paradigmatic of physics. Instead the problems raise concerns over the kind of explanation given by the model (Earman and Mosterín [1999]). The essence of the problems is that only the explanatorily-deficient special initial conditions of flatness and uniformity can give rise to certain currently-observed conditions within the context of the standard HBB model. The special initial conditions of the HBB model are explanatorily deficient because they are not robust (McCoy [2015]). They make the explanations of which they are part fragile: if the conditions had been ever so slightly different, the explanation no longer would hold.

Inflation theory promises a solution to both problems. It is a cosmological scenario that was first proposed by Guth ([1981]).⁴ Inflationary theory is based on the supposition that the very early universe underwent a brief period of accelerated and exponential spatial expansion. This expansion greatly increases the size of particle horizons—indeed, to such a degree that the entire observable universe fits within a single causally-connected region. Note that this accelerated expansion is in contrast to the decelerated Hubble expansion that figures in the radiation-

³A referee emphasizes the point that the presence of dark energy can affect the eventual fate of the universe. Indeed, a universe with positive spatial curvature may not contract into a big crunch if it becomes dark energy-dominated (as our universe presently is). However, what is relevant for the flatness problem is the fine-tuning of our universe’s initial conditions (when it was not dark energy-dominated). At early times very slight changes in the curvature of space would result in a universe very unlike ours—this is why the flatness problem is a fine-tuning problem.

⁴Guth (as well as other early adopters of inflation (Linde [1982]; Albrecht and Steinhardt [1982]) was also somewhat concerned to solve a cosmological problem that arises in grand unified theories (GUTs) in particle physics. This problem, the monopole problem, is that in certain GUTs magnetic monopoles are created in sufficient numbers that they should be observable, but in fact no magnetic monopoles have ever been observed. As it is an external problem (Penrose [1989]) in the context of HBB cosmology (it only concerns speculative theories in particle physics), it will not be discussed here.

and matter-dominated epochs of the HBB model (which must occur after the end of inflation in order to maintain consistency with the empirically confirmed aspects of the HBB model). Proponents of the theory claim that the effect of inflation is to flatten the spatial geometry of the universe and make its contents more uniform. (One may usefully—if in some important respects disanalogously—picture the inflation of a balloon, which decreases the curvature of the balloon’s surface and smooths small irregularities on the surface.) This mechanism is thought to operate for a brief period in the very early universe, giving rise to the conditions that eventuate in the presently observed spatial flatness and uniformity.⁵

Since uniformity and flatness are supposed to be natural outcomes of inflation, cosmologists maintain that the previous paradigm’s fine-tuning problems are solved by inflationary theory. Inflationary models explain our observations better than the HBB model, because inflationary theory is able to give more robust explanations of uniformity and flatness. The universe could have begun with a range of initial conditions which would eventuate in a present universe as flat and uniform as we observe it. This is certainly not to say that inflationary theory suffers from no fine-tuning of its own, despite many proponents’ hopes and claims to the contrary. It is just to say that the inflationary explanation is better than the HBB one: it does not depend on special initial conditions to the degree that the HBB one does (McCoy [2015]), hence it is capable of furnishing solutions to the HBB fine-tuning problems.

It is important to emphasize that at the time of its introduction inflationary theory could not be said to differ in its observable consequences from the HBB model. As already noted, this is because the inflationary stage must ‘smoothly splice’ into some early stage of the hot big bang universe so that the latter’s observationally confirmed content (the existence of the cosmic microwave background (CMB), light element abundances in accord with big bang nucleosynthesis, and the Hubble expansion) are not lost. The CMB is particularly important in cosmological research, for it provides the best observational evidence of the earliest times currently available to us. It is a remnant of the decoupling of light from matter; this light has since traveled freely throughout the universe with an imprint of the primordial perturbations from uniformity at the time of decoupling. Since inflation occurs well before the decoupling of light from matter responsible for the CMB, inflation’s direct effects may well be observationally inaccessible.⁶

Since inflationary theory had no clear observational consequences which would differentiate it from the standard HBB model, cosmological theory in the early 80s is an actual case of transient underdetermination (Sklar [1975], [1981]; Stanford [2001], [2006]) of theory by evidence. This kind of underdetermination is distinct from ‘in principle’ underdetermination given all possible evidence and is the kind which is relevant to the decisions of actual scientists, who want to know whether theories can be distinguished on the basis of presently available or expected future empirical tests. The only clear difference between the HBB model and the inflationary modification thereof, then, is in how they explain observed cosmological conditions like uniformity and flatness. This circumstance is precisely what makes the case an important one for understanding scientific methodology, for it isolates the impact of explanatory considerations. In most familiar historical cases, by contrast, differences in explanatory considerations are accompanied by empirical differences, such that epistemological differences can always be

⁵See (Smeenk [2003], [2005], [forthcoming]; McCoy [2015]) for philosophical criticism and historical details concerning inflationary theory.

⁶As a referee points out, the ability to detect primordial gravitational waves would allow us to probe times much earlier than decoupling. Although there is some hope that this may become possible, for now cosmologists’ attention remains focused on the CMB for clues about the early universe (particularly how primordial gravitational waves affect it).

easily attributed to the empirical ones.

In any case, cosmologists were evidently not bothered by this lack of distinguishing empirical evidence and quickly adopted the inflationary framework for theorizing (Earman and Mosterín [1999]; Smeenk [forthcoming]). The usual reason given then (and to a significant extent even to this day) was that inflationary theory solved the HBB fine-tuning problems (see, for example, the interviews in (Lightman and Brawer [1990])). Although inflation was quickly accepted during inflationary theory's early history, at present the generally acknowledged best argument for inflationary theory is not that it solves these problems however; instead it rests on the striking observational confirmation of predictions later developed out of the inflationary framework, specifically of a very precise spectrum of small anisotropies in the cosmic microwave background.

It was soon realized after the introduction of inflation that quantum fluctuations in a hypothesized scalar field (the 'inflaton') driving inflation could seed the primordial density perturbations of the hot big bang (Mukhanov and Chibisov [1981]; Guth and Pi [1982]; Hawking [1982]; Bardeen *et al.* [1983]), which density perturbations are then later imprinted in the CMB (and eventually give rise to structure formation—galaxies, stars, and so on—in the universe as a whole). This development came quickly on the heels of the general acceptance of inflation (within one to two years). Nevertheless, it is clear from the cited papers that the motivation for this work was to build on the accepted success of inflationary theory at solving the HBB model's fine-tuning problems, not merely the realization that inflationary theory was capable of generating predictions of CMB anisotropies.⁷

The existence of these anisotropies in the CMB was observed by NASA's Cosmic Background Explorer (COBE) in the early 90s, although the precision of the observations was limited. The inflationary predictions of a precise spectrum of anisotropies that are adiabatic, gaussian, and nearly scale-invariant were confirmed in the early 2000s by WMAP (Mukhanov [2005]; Linde [2007]; Baumann [2009]). More recently they were confirmed with even greater precision by the Planck satellite (Linde [2014]; Guth *et al.* [2014]).

To what degree inflationary theory is actually confirmed by these observations remains a matter of debate (Ijjas *et al.* [2013], [2014]). Moreover, a common complaint raised against inflationary theory's predictions is that the range of inflationary models is such that one can be found to adapt to any observational result whatsoever.⁸ Although these are significant issues, they are nevertheless not so much to the point for the argument I make here. As I argue below, it is appropriate to characterize the theory's predictions at least as novel (as opposed to accommodations, since they were made in advance of any relevant observation), which is all that I require. One should also make a distinction between the basic theory of inflation, which entails a stage of accelerated, exponential expansion and which addresses the fine-tuning problems, and specific models that implement it, for example as a quantum scalar field with some potential.⁹ Initial models of inflation were empirically inadequate, such that new models had to be devised and adjusted. Yet my argument does not concern the individual models of inflation. Indeed, I do agree with critics that there are problems to be found here, in the particular realization

⁷To be sure this work did not come out of a vacuum. The relevant pre-history to inflation, particularly the many contributions by Soviet physicists like Starobinsky, is presented in detail in (Smeenk [2003]).

⁸I thank various referees for stressing these issues with inflationary theory.

⁹An analogy with the Higgs is relevant here: what was long expected in particle physics was the Higgs mechanism, not necessarily the simple Higgs boson actually discovered at CERN. This latter was something of a surprise to many theorists, since there were several other (more) plausible realizations of the Higgs mechanism available in theory.

of inflation. These problems do not, however, imperil the methodological and epistemological claims that I advance, since they concern the general theory, not its specific implementation.

In my view it is a matter of considerable philosophical interest that a research program motivated by and widely accepted on the basis of its solution of mere explanatory problems should then lead to specific predictions that are then confirmed much later. It is a case from modern physics where it seems like theoretical physicists were right about a theory well in advance of its confirmation—and apparently knew they were on the right track. I mention, again, the suggestively analogous case of the Higgs mechanism in high energy physics (Dawid [2013]; Friederich *et al.* [2014]). I take it that it is a task for the philosophy of science to make some methodological sense of such episodes, so to this task I now turn.

4 Empiricist Interpretations of Inflationary Case

In this section I consider how the preceding historical episode would be understood from the empiricist point of view on scientific epistemology. There are perhaps various precise empiricist positions one could take that differ on how empirical knowledge justifies the acceptance of scientific theories. I consider two—what I will call simple empiricism and predictivism—which illustrate the most salient empirically grounded features of scientific theories—empirical adequacy and empirical confirmation.

The simplest empiricist conception of epistemic justification of scientific theories requires only that a scientific theory is empirically adequate.¹⁰ A theory is empirically adequate, I will say, if the theory's observable consequences correctly describe the known phenomena within its purview.¹¹ The standard of warrant is therefore consistency between empirical knowledge and theory. This is obviously an empiricist conception of epistemic justification, since theory acceptance is licensed solely by empirical knowledge. If a theory is empirically adequate, then it is epistemically justified to accept the theory.¹²

Empirical adequacy is a fairly weak standard on epistemic justification—it is permissive with respect to theory acceptance. Note that on the simple empiricist view no empirically adequate theory is better justified than its empirically adequate competitors. It therefore follows that theory choice (or acceptance) is, for the simple empiricist, necessarily based on non-empirical grounds when empirical evidence transiently underdetermines theory. These grounds may provide merely a pragmatic warrant to accept a theory (van Fraassen [1980]) or may be driven by social or contextual values (Longino [2002]). The strict kind of empiricist which I am describing here does not, however, allow for these grounds to epistemically justify the choice. Less strict 'empiricists' may of course allow that some of these theoretical virtues or social values do so and continue to call themselves empiricists, but this is strictly speaking a significant departure from empiricism, in particular the fundamental epistemological tenet of empiricism:

¹⁰van Fraassen ([1980]) holds something very much like this conception, although there are various particularities of his view, which, because they are not relevant to my overall argument, I will not discuss here.

¹¹To avoid any confusion, I should emphasize again that I restrict 'observable' to a time contemporary to the assessment of adequacy, for this is the standard relevant to the decision making of actual scientists. It matters not for methodology what in principle could be or could have been observed by hypothetical, all-knowing scientists concerning the past and future.

¹²A referee points out that this condition by itself would license accepting two incompatible theories which are both empirically adequate. Just as it is reasonable to accept a doxastic norm requiring logical consistency of beliefs, it is reasonable to suppose that theory acceptance demands a similar norm, which I will assume in the following.

empirical evidence alone grounds the acceptance of theory.

Predictivism, the second empiricist position I introduce, maintains the doctrine that empirical knowledge is the ground for the epistemic justification of scientific theory, but also holds that the empirical confirmation of novel predictions confers greater credibility to the hypothesis that makes them than a hypothesis which merely accommodates the same empirical facts. Whether predictivism is correct has been vigorously debated in the past few decades (Douglas and Magnus [2013]). Regardless of whether the doctrine is defensible, we can at least state an appropriate conception of epistemic justification on the behalf of the predictivist: a scientific theory is epistemically justified to the extent that its novel predictions are empirically confirmed. A theory that does not offer novel predictions or whose predictions remain untested is accordingly unjustified.

Predictivism is especially noteworthy in the present context since there is a predictivist analysis of the case of inflationary theory (Earman and Mosterín [1999]). Earman and Mosterín's principal claim is that inflationary theory is epistemically unjustified. They are therefore clearly not simple empiricists (in the sense defined above), since the HBB model and the inflationary modification thereof were at the time of the latter's devising up until the 2000s equally empirically adequate to known observations. By the simple empiricist standard of epistemic justification the two theories were thus equally epistemically justified. According to the predictivist the HBB model was epistemically justified because it made novel predictions (the existence of the CMB and light element abundances in accord with big bang nucleosynthesis) which were observationally confirmed (Earman and Mosterín [1999], p. 19); inflationary theory, however, merely accommodates these predictive successes after the fact. Thus the HBB model was better justified by the lights of the predictivist than inflationary theory at the time of the latter's proposal and acceptance in the community.

According to the predictivist standard of epistemic justification, the post-2000 observation of a precise spectrum of anisotropies by the WMAP and Planck satellites which confirm novel predictions of inflationary theory should reverse the judgments of Earman and Mosterín's 1999 assessment, for at that time only the imprecise detection of some degree of CMB anisotropy had been obtained by the COBE satellite. The HBB model by itself suggests no particular predictions of the spectrum of inhomogeneities in the matter distribution of the universe, since it is by assumption spatially homogeneous. Lacking any account for the origin of a particular primordial spectrum of inhomogeneities, the HBB model should become disfavored with respect to inflationary theory. For the predictivist this is entirely due to the successful confirmation of inflationary theory's predictions.

Of course, the basic HBB model can be easily modified to accommodate the CMB data by introducing by fiat an appropriate primordial spectrum of spatial inhomogeneities that accounts for the observed anisotropies.¹³ Thus, on a simple empiricist assessment the empirical adequacy (and justification) of both the HBB model and inflationary theory remains equivalent (although naturally the pragmatic assessment of these two theories by cosmologists may change).

At this juncture it is worth mentioning some further historical details which were left out of the account given above.¹⁴ That is that the detection of some degree of anisotropy in the CMB was in fact long expected by cosmologists, since if there were no inhomogeneities in the early universe, then it would be a complete mystery how galaxies formed. Indeed, a scale free spectrum was proposed by several cosmologists well before inflation (Harrison [1970]; Peebles and Yu [1970]; Zeldovich [1972]) as a way of accounting for structure formation.

¹³As a referee puts it, the output spectrum of inhomogeneities of any early universe theory, like inflationary theory, can be taken as an initial condition of the HBB model.

¹⁴The importance of including these details was particularly emphasized to me by a referee.

The existence of observable structure in the universe plainly places an empirical constraint on the primordial spectrum of inhomogeneities. Yet there are two issues that need to be stressed. One is that the so-called Harrison-Zeldovich spectrum, the scale free spectrum, was proposed in an exploratory spirit and on the basis of many simplifications in a context where much about our universe remained unknown, both theoretically and observationally. Two is that the spectrum proposed is assumed essentially by fiat, with either a very speculative account of its origin or none at all. As Peebles and Yu ([1970], p. 834) say, ‘it is well to bear in mind that in this calculation the initial density fluctuations are invoked in an ad hoc manner because we do not have a believable theory of how they may have originated’. Thus it is fair to say that the perturbed HBB model which incorporates a primordial spectrum does so either by accommodation or on an ad hoc basis and that inflationary theory’s prediction of the CMB’s spectrum should indeed be considered novel. While consistent with theoretical expectations of a scale free spectrum, inflationary theory’s prediction was not accommodated or included by construction.

As said above, inflation has been widely accepted by theoretical cosmologists since shortly after its introduction and continues to be widely accepted at present as a core component of the contemporary standard model of cosmology (the so-called Λ CDM model). Since there was no epistemic reason for the initial acceptance according to the predictivist, he must explain the sociological fact of inflation’s adoption by the community of theoretical cosmologists by non-epistemic factors. From the common empirical point of view of simple empiricism and predictivism such facts about theory choice can only be accounted for by pragmatic, sociological, or other contingent historical factors, since there is no rationally compelling epistemic reason to favor (for the simple empiricist) one empirically adequate theory over another or (for the predictivist) to adopt an untested speculative proposal. Indeed, Earman and Mosterín ([1999], p. 6 ff.) offer precisely these kinds of factors to explain the quick adoption of inflationary theory in the early 80s.

Summing up this section, I have provided two interpretations of this scientific episode based on standards of epistemic justification motivated by prominent empiricist doctrines found in the philosophical literature. The simple empiricist account offers the following claims and explanations:

1. (<1980) The HBB model is epistemically justified because it is empirically adequate to all observed cosmological phenomena.
2. (1980) Inflationary theory is equally epistemically justified because it is empirically adequate to all observed cosmological phenomena.
3. (early 1980s) Inflationary theory’s adoption by cosmologists is understood to be for pragmatic, social, or other non-epistemic reasons.
4. (2000s) Inflationary theory is epistemically justified because it is empirically adequate to WMAP observations, as is an ad hoc HBB model appropriately modified.

The predictivist account offers these:

1. (<1980) The HBB model is epistemically justified because of the successful confirmation of its novel predictions.
2. (1980) Inflationary theory is epistemically unjustified because it does not offer any novel predictions.

3. (early 1980s) Inflationary theory remains epistemically unjustified because its novel predictions are unconfirmed.
4. (early 1980s) Inflationary theory's adoption by cosmologists is understood to be for pragmatic, social, or other non-epistemic reasons.
5. (2000s) Inflationary theory is epistemically justified because of the successful confirmation of its novel predictions.

5 A Confutation of Empiricist Interpretations

Is the empiricist epistemology adequate to interpreting this historical episode? I argue in this section that it is not. The central claim of my argument is that empiricist explanations of inflationary theory's epistemic success must accept an implausible degree of luck in its attainment. A methodological view that attributes such luck to scientific successes evinces some degree of skepticism toward the idea that the methodology of science is a reliable means of securing scientific knowledge. If such skepticism is severe in degree, then it should, like any philosophical skepticism, be held in abeyance where there are viable philosophical alternatives. I maintain that there is an alternative and propose in the next section that explanationism fits the bill well.

To begin, it is worth remarking that luck of various kinds certainly does play an ineliminable role in the sciences. It is surely the case that Guth, for example, was quite lucky to hit on the idea of inflation and its solution to the HBB model's fine-tuning problems. With respect to scientific methodology accepting some degree of luck is just to recognize that the methods of science offer no infallible means to scientific knowledge. There is, after all, no general logic of discovery (Nickles [1990]; Schickore [2014]).

The kind of luck that is relevant to my argument is what might be called 'methodological' luck. By methodological luck (admittedly something of an oxymoron) I mean a case where epistemic success is achieved by means of a method no better (epistemically) than random guessing (Nickles [1987]).¹⁵

Attributing a sufficiently high degree of luck to scientific successes threatens the acceptability of any epistemology that demands it. Either the methods of science are sufficiently reliable, economical means to epistemically justified theories, or, with Popper, we conclude that 'the success of science is not based upon rules of induction, but depends upon luck, ingenuity, and the purely deductive rules of critical argument' (Popper [2002 [1963]], p. 70). A preponderance of clear cases of luck of this sort would either indicate that the methodology of science is unreliable (if methodological at all) and hence could not account for clear cases of progress, or else it would suggest that some economical methods have so far been overlooked within that conception of scientific methodology. In the latter case, examples thought to be matters of luck may in fact be rather sensible applications of legitimate methodology (Jantzen [2016]).

Even a single case of significant putative methodological luck, however, may put pressure on the acceptability of a conception of scientific methodology that allows it, particularly if the case is a central development within some science. I claim that the successes of inflationary

¹⁵It is difficult to provide a precise rendering of the concept, since it depends on being able to specify a relevant set of possible theories over which one may guess. This depends on making assessments of transient underdetermination with respect to several things, such as the relevant criteria of epistemic appraisal and scientificity conditions (Dawid [2013]). Due to such difficulties, the overcoming of which would contribute little to the present argument, the intuitive characterization I have given must suffice.

theory represent just such a case. It demonstrates that empiricism does lead to an inappropriate methodological skepticism, for empiricist methods and standards of justification are inadequate to account for these successes.

To illustrate the point, it is helpful to explain, following Nickles ([1985]), how discovery and progress (epistemic success) are connected to epistemic justification. For methodology to be epistemically relevant to the progress of science, standards of epistemic justification should be appropriately related to rational methods of theory discovery. That is, 'there must be some degree of coupling between the modes of generating theories and criteria of epistemic appraisal (Nickles [2000], p. 92). Standards of epistemic justification tell us what marks a theory must have to be a good theory and what defects in a theory should be remedied through the generation of new theories which address these defects. Conversely, successful modes of generating theories (that is, successful by already accepted standards of justification) can lead to the revision or introduction of standards of epistemic justification. Methods of discovery—the modes of generating theories in Nickles' terminology (or positive heuristics in Lakatos's)—furnish candidate theories which are subsequently subject to the relevant criteria of epistemic appraisal (for example, the empiricist criteria of epistemic justification). Unless the modes of generating theories furnish candidates in a way that lends sufficient credence to their future viability (with respect to the appropriate criteria of epistemic appraisal), then there is no reason to expect methods of discovery to be epistemically relevant and no reason to think that there are standards of justification related to those modes.

For an example, consider how this sketch of methodology functions in the context of empiricist epistemology. The empiricist view of science can certainly provide an acceptable account of those cases, so familiar from the history of science, where recalcitrant empirical data motivated the development of theories to save the phenomena responsible for them. There is in empiricist epistemology a strong coupling between the standard of justification and the heuristics or methods of theory generation that guide discovery based on it, a simple economy between the standard of empirical adequacy and the heuristic of saving recalcitrant phenomena. Recall that empirical adequacy is the most basic empiricist conditions on epistemic justification; recalcitrant data represent an empirical problem for extant theories because a theory that cannot account for the associated phenomena is epistemically unjustified according to this basic condition. Such empirical problems obviously rationally motivate the discovery of—in a sense, generate—theories which can account for the unaccounted for phenomena. Obviously the mode of generating theories focused on solving empirical problems provides no sure recipe for success, but it is equally clear that eschewing the mandate to generate theories in accord with this mode would generally lead to failure. However, success in this endeavor—judged according to the basic empiricist condition on epistemic justification—represents progress over previous theories which could not. In this way scientific problems of empirical adequacy and their potential solutions are harmoniously coupled with the empiricist standards of epistemic justification. This harmony might sound 'pre-established' and hence the account described might seem trivial, but one should not forget that establishing the pre-eminence of an empirical standard of justification emerged only after a long, gradual historical process.

For a second example, consider for contrast a methodology that privileges simple theories. There is evidently no coupling between a mode which privileges the generation of simple theories and the empiricist criteria of epistemic appraisal, since empiricism would only sanction simplicity as epistemically relevant when observations are in fact appropriately simple. A methodological norm that mandates generating simple theories would only eventuate in success, then, as a matter of luck by the methodological lights of strict empiricism. Such a norm is therefore not epistemically relevant unless there is also an additional epistemic criterion based

on simplicity. There could seemingly only be such a criterion, however, if the world is in fact appropriately simple, which it is evidently not in any articulable and substantive sense. Therefore one is left to regard simplicity as at best only a pragmatic factor in science and not at all a matter of genuine epistemology.

Returning now to the case of inflation, it is crucial, in my view, to recognize that inflationary theory is generated by the explanatory problems of the HBB model, not by empirical problems or its provision of novel predictions.¹⁶ In other words, inflationary theory cannot be understood as coming about by the generative methods related to empiricist-sanctioned conditions on epistemic justification. Its acceptance in the community too was neither based on its solution of an outstanding empirical problem nor on its promise of novel predictions. Thus its later epistemic success through the confirmation of its novel predictions cannot be wholly attributed to the empiricist's epistemologically-approved methodology.

From a methodological point of view, empiricists are therefore forced to attribute inflationary theory's adoption and later empirical success to luck. Of course some degree of methodological luck is surely acceptable, and the empiricist is happy to concede that there is much luck in science in order to preserve his epistemology. Still, there must be a point where the degree of luck becomes implausible. As I argued above, when the luck involved is significant enough, that is, preponderant or acutely severe, the empiricist position must countenance a corresponding degree of methodological skepticism. I claim that attributing inflation's success to methodological luck is indeed implausible for the luck involved is acutely severe. I provide two supporting arguments for this claim.

First, several factors point to the significance of this historical episode in cosmology: the inclusion of inflation as one of the central pillars of the present standard model of cosmology; the fact that COBE, WMAP, and Planck, the primary missions of which were to measure anisotropies in the CMB, were among the most important experiments in cosmology in the past few decades; the centrality of inflationary model-building to contemporary theoretical practice. If one of the most significant episodes in the history of scientific cosmology can only be methodologically explained by luck, this alone casts some serious doubt on the efficacy of scientific methodology in cosmology. Such a conclusion, however, would fly in the face of the many astounding empirical successes of cosmology over the past century.

Second, when one looks at the precise predictions from inflationary theory and compares them to the spectrum of CMB temperature anisotropies, one finds a precise agreement in essentially all respects (Guth and Kaiser [2005], p. 888). Practically speaking, one could not have intuited this exact spectrum of spatial inhomogeneities responsible for these anisotropies from the theoretical point of view of the unperturbed HBB model, which makes no assumptions at all about possible divergences from perfect homogeneity, whereas the observed spectrum is (ostensibly) a natural prediction of inflationary theory.¹⁷ If cosmologists were merely guessing

¹⁶Although, as a referee points out, it should be noted that the HBB model in concert with certain grand unified theories is inconsistent with the absence of magnetic monopoles. This is indeed an empirical problem, but it is not one of the primary motivations for inflation, and definitely not a motivation in the context of cosmology (rather it is a motivation for certain speculative theories of high energy physics).

¹⁷An important consideration when intuitively assessing underdetermination in this case is whether there are alternative theories of the early universe that could seed the initial perturbations which lead to the empirically confirmed spectrum of anisotropies in the CMB. If the nearly scale-free (flat) spectrum of perturbations is not really a distinctive prediction of inflation, then inflationary theory's success might not seem quite so lucky from an empiricist point of view.

at possible spectra or theories that predict them, they likely would have been wrong given all the overwhelming number of alternative possible spectra of inhomogeneities.

The existence of structure in the universe represents an empirical problem for this unperturbed HBB model; as noted in the previous section, cosmologists have long understood that a primordial spectrum of inhomogeneities is required to account for structure formation and favored a scale-free spectrum like that proposed by Harrison, Peebles, and Zeldovich. Empirical constraints from the existence of structure indeed make it more likely to guess the actual spectrum than it would be without them, but there is still a very significant degree of luck involved in guessing that the simple Harrison-Zeldovich spectrum is correct. As pointed out above, simplicity is not epistemically relevant and hence confirmation of their proposals would have to be seen ultimately as having been a matter of methodological luck.

I conclude that the methodological luck involved in empiricist interpretations of the inflationary case is therefore serious. It follows, then, that empiricist epistemology is committed to a degree of methodological skepticism. It is far more plausible, however, to suppose that cosmologists' acceptance of inflationary theory was epistemologically motivated—in other words, that their confidence in inflation's viability for future empirical test was epistemologically justified. It follows that epistemic justification should be more than empirical adequacy or a high degree of empirical confirmation, at least if one is to avoid a pronounced and implausible skepticism in the methodology of science.

6 Explanationist Interpretation of Inflationary Case

If there were no reasonable alternative interpretation of the inflationary case according to which inflationary theory was epistemically justified, then perhaps one should be willing to accept the methodological skepticism attendant to empiricist epistemology. There is, I suggest, a reasonable alternative, one manifestly suggested by the case itself: inflationary theory was epistemically justified well in advance of its empirical confirmation because of its solutions to the HBB model's explanatory problems. Indeed, cosmologists standardly argue in favor of inflation—even in contemporary textbooks, papers, and reviews—for exactly this reason. If its acceptance were only for non-epistemic reasons, then its later empirical success would be, as I argued in the previous section, a matter of luck—methodological skepticism would then be nigh. So we should well consider the possibility that (at least in some cases or contexts) a method of discovery based on solving explanatory problems is epistemically economical, that is, reliably leads to success by a novel explanationist standard of epistemic appraisal. The prominence of this case in the history of cosmology and the striking confirmation of inflationary predictions should, I think, lend this thought at least some plausibility.

One way to argue for such a standard is to give an account of why solving explanatory problems is epistemically relevant.¹⁸ I do not have such an account and, in any case, am doubtful whether explanationism can bootstrap its way into epistemology. Another way, the one I take here, is to use the empiricist standards of justification to argue for the epistemic relevance of solving explanatory problems, since we already accept that these empiricist standards are reliable.

My suggestion is that solving explanatory problems, such as the HBB model's fine-tuning problems, is economical, in the first place, as judged by empiricist standards of appraisal (for

¹⁸A referee points out that a natural story to tell is that explanatory considerations are truth-tropic. However, in keeping with my remarks in the introduction, I do not wish to take a stand one way or the other on the realism question, particularly matters of truth.

example, empirical adequacy). To the extent that solving explanatory problems is economical according to these standards one is licensed to introduce an independent explanationist standard of appraisal, harmonizing standards of epistemic appraisal and modes of generating theories. In this way we ground an economy between a method of discovery based on solving explanatory problems and the assessment of solutions on the basis of an explanationist standard of appraisal—without having to moot an account of why it works.¹⁹

The explanationist interpretation of the inflationary case then provides the following assessments:

1. (<1980) The HBB model is empirically justified because it meets the empiricist conditions but explanatorily unjustified because it suffers from various salient fine-tuning problems.
2. (1980) Inflationary theory is explanatorily justified because it solves the HBB model's fine-tuning problems.
3. (early 1980s) Inflationary theory is partially empirically justified by its empirical adequacy, although its novel empirical predictions remain unconfirmed.
4. (early 1980s) Inflationary theory is adopted by cosmologists because it is sufficiently epistemically justified.
5. (2000s) Inflationary theory is epistemically justified because of its empirical adequacy (and the successful confirmation of its novel predictions).

Solving explanatory problems is surely not as reliable as empiricist-sanctioned methods. So long as explanationist methods are better than guessing, though, they will be sufficiently reliable to count as methodological. The inflationary case strongly suggests that at least in some contexts solving explanatory problems is economical. The importance of such a method will be particularly salient, it seems, in contexts, like cosmology and high-energy physics, where the more reliable standards of epistemic appraisal are inapplicable or unreliable due to experimental and observational limitations. Indeed, such situations have become increasingly common in the physics of the last century, although I suspect they may be found elsewhere in science, especially in other historical sciences besides cosmology. I have offered only one case here (although I do think it is a strong case); the epistemological significance of explanationism ultimately depends, however, on the degree to which explanatory considerations play an important role in science as a whole.

¹⁹A referee suggests that my continued discussion of methods of discovery is a red herring, and that the argument I make is independent of any consideration of how theories are generated. Perhaps this is so and the argument could be purged of such notions, which in the past were considered merely 'psychological'. I suppose the argument would then go as follows: the empirical confirmation of inflationary theory lends credence to the idea that the explanatory merits of inflationary theory over the HBB model are truth-conducive or epistemically relevant, whereas empiricist epistemology remains committed to the theory's success being a matter of luck. I have several concerns with this rendering of the argument however, of which I mention a few: (1) it strikes me that it is far more vulnerable to charges of weak induction; (2) it provides no methodological guidance beyond theory choice, whereas my version suggests that solving explanatory problems is methodologically sound; (3) it ignores the salient role that problem solving played in motivating theory development and assessment.

7 Concluding Remarks

I have argued that solving explanatory problems can reliably lead to scientific progress and that explanatory considerations can epistemically justify theories on the basis of the case of inflationary cosmology. Inflationary theory was proposed and accepted in the cosmological community because of its solution of the hot big bang model's fine-tuning problems. These problems are explanatory problems, for the HBB model's explanations of certain cosmological conditions are fragile in a way compared to which inflationary theory's explanations are more robust. I claim that at this point inflationary theory was already adequately justified, such that the later observational confirmation of the theory only reinforced the epistemic justification that the theory already enjoyed.

Although my proposal is an explanationist one, I emphasize once again that it does not necessarily presuppose that explanatory considerations can justify inferences to truth like inference to the best explanation purports to do. It is therefore not committed to scientific realism—although it is certainly compatible with it.²⁰ For this reason my argument advances reasons to take seriously the methodological role of explanation independently of the considerations raised in the scientific realism debate. These reasons are based not on general philosophical arguments but rather on attention to scientific practice in an actual historical case.

I argued against broadly empiricist interpretations of this case in order to show that standards of epistemic justification that go beyond empiricist standards are required to account for the successes of inflationary theory. Empiricist interpretations cannot adequately account for the success of inflationary theory, which I illustrated by showing how the acceptance of the theory cannot be attributed to methods of theory generation sanctioned by empiricist standards of justification. This circumstance becomes problematic when one considers the likelihood of this success. I argued that the degree of luck involved (which the empiricist necessarily must accept) is serious in this case, such that the empiricist interpretation must countenance a significant and undesirable degree of methodological skepticism in science. To avoid this skepticism some 'extra-empirical' standard of justification is required; the one that is naturally suggested by the case of inflation is the explanationist one I propose.

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²⁰For the status of scientific realism in cosmology, see the recent assessment by Azhar and Butterfield ([2017]).

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References

- Albrecht, A. and Steinhardt, P. [1982]: ‘Cosmology for Grand Unified Theories with Radiatively Induced Symmetry Breaking’, *Physical Review Letters*, **48**, pp. 1220–1223.
- Azhar, F. and Butterfield, J. [2017]: ‘Scientific Realism and Primordial Cosmology’, in J. Saatsi (ed.), *The Routledge Handbook of Scientific Realism*, London and New York: Routledge.
- Bardeen, J., Steinhardt, P. and Turner, M. [1983]: ‘Spontaneous creation of almost scale-free density perturbations in an inflationary universe’, *Physical Review D*, **28**, pp. 679–693.
- Baumann, D. [2009]: ‘TASI Lectures on Inflation’, ArXiv Eprint.
<<http://arxiv.org/abs/0907.5424>>
- Beisbart, C. [2009]: ‘Can We Justifiably Assume the Cosmological Principle in Order to Break Model Underdetermination in Cosmology?’, *Journal for General Philosophy of Science*, **40**, pp. 175–205.
- Beisbart, C. and Jung, T. [2006]: ‘Privileged, Typical, or Not Even That?—Our Place in the World According to the Copernican and the Cosmological Principles’, *Journal for General Philosophy of Science*, **37**, pp. 225–256.
- Bird, A. [2007]: ‘What Is Scientific Progress?’, *Noûs*, **41**, pp. 64–89.
- Butterfield, J. [2014]: ‘On Under-determination in Cosmology’, *Studies in History and Philosophy of Modern Physics*, **46**, pp. 57–69.
- Dawid, R. [2013]: *String Theory and the Scientific Method*, Cambridge: Cambridge University Press.
- Dodelson, S. [2003]: *Modern Cosmology*, San Diego, CA: Academic Press.
- Douglas, H. and Magnus, P. D. [2013]: ‘State of the Field: Why novel prediction matters’, *Studies in History and Philosophy of Science Part A*, **44**, pp. 580–589.
- Earman, J. [1995]: *Bangs, Crunches, Whimpers, and Shrieks*, Oxford: Oxford University Press.
- Earman, J. and Mosterín, J. [1999]: ‘A Critical Look at Inflationary Cosmology’, *Philosophy of Science*, **66**, pp. 1–49.

- Elgin, C. [2007]: ‘Understanding and the facts’, *Philosophical Studies*, **132**, pp. 33–42.
- Elgin, C. [forthcoming]: ‘Nominalism, realism and objectivity’, *Synthese*, **0**, pp. 1–16.
- Ellis, G. [2007]: ‘Issues in the Philosophy of Cosmology’, in J. Earman and J. Butterfield (eds), *Philosophy of Physics*, vol. B of *Handbook of the Philosophy of Science*, Amsterdam: Elsevier, pp. 1183–1285.
- Friederich, S., Harlander, R. and Karaca, K. [2014]: ‘Philosophical perspectives on ad hoc hypotheses and the Higgs mechanism’, *Synthese*, **191**, pp. 3897–3917.
- Guth, A. [1981]: ‘Inflationary universe: A possible solution to the horizon and flatness problems’, *Physical Review D*, **23**(2), pp. 347–356.
- Guth, A. and Kaiser, D. [2005]: ‘Inflationary Cosmology: Exploring the Universe from the Smallest to the Largest Scales’, *Science*, **307**, pp. 884–890.
- Guth, A., Kaiser, D. and Nomura, Y. [2014]: ‘Inflationary paradigm after Planck 2013’, *Physics Letters B*, **733**, pp. 112–119.
- Guth, A. and Pi, S.-Y. [1982]: ‘Fluctuations in the New Inflationary Universe’, *Physical Review Letters*, **49**, pp. 1110–1113.
- Harrison, E. [1970]: ‘Fluctuations at the threshold of classical cosmology’, *Physical Review D*, **1**, pp. 2726–2730.
- Hawking, S. [1982]: ‘The development of irregularities in a single bubble inflationary universe’, *Physics Letters B*, **115**, pp. 295–297.
- Ijjas, A., Steinhardt, P. and Loeb, A. [2013]: ‘Inflationary paradigm in trouble after Planck2013’, *Physics Letters B*, **723**, pp. 261–266.
- Ijjas, A., Steinhardt, P. and Loeb, A. [2014]: ‘Inflationary schism’, *Physics Letters B*, **736**, pp. 142–146.
- Jantzen, B. [2016]: ‘Discovery without a ‘Logic’ Would Be a Miracle’, *Synthese*, **193**, pp. 3209–3238.
- Kragh, H. [1996]: *Cosmology and Controversy*, Princeton: Princeton University Press.
- Laudan, L. [1977]: *Progress and Its Problems: Towards a Theory of Scientific Growth*, Berkeley: University of California Press.
- Lightman, A. and Brawer, R. [1990]: *Origins: The Lives and Worlds of Modern Cosmologists*, Cambridge, MA: Harvard University Press.
- Linde, A. [1982]: ‘A New Inflationary Universe Scenario: A Possible Solution of the Horizon, Flatness, Homogeneity, Isotropy, and Primordial Monopole Problems’, *Physics Letters B*, **108**, pp. 389–393.
- Linde, A. [2007]: ‘Inflationary Cosmology’, in M. Lemoine, J. Martin and P. Peter (eds), *Inflationary Cosmology*, vol. 738 of *Lecture Notes in Physics*, Berlin: Springer Verlag, pp. 1–54.

- Linde, A. [2014]: ‘Inflationary Cosmology after Planck 2013’, .
<<http://arxiv.org/pdf/1402.0526v2.pdf>>
- Longair, M. [2006]: *The Cosmic Century*, Cambridge: Cambridge University Press.
- Longino, H. [2002]: *The Fate of Knowledge*, Princeton, NJ: Princeton University Press.
- Malament, D. [2012]: *Topics in the Foundations of General Relativity and Newtonian Gravity Theory*, Chicago: University of Chicago Press.
- McCabe, G. [2004]: ‘The structure and interpretation of cosmology: Part I—general relativistic cosmology’, *Studies in History and Philosophy of Modern Physics*, **35**, pp. 549–595.
- McCoy, C. [2015]: ‘Does inflation solve the hot big bang model’s fine-tuning problems?’, *Studies in History and Philosophy of Modern Physics*, **51**, pp. 23–36.
- McCoy, C. [2016]: *Philosophical Implications of Inflationary Cosmology*, Ph.D. thesis.
- McCoy, C. [forthcoming]: ‘The implementation, interpretation, and justification of likelihoods in cosmology’, *Studies in History and Philosophy of Modern Physics*, **0**, pp. 1–17.
- Mukhanov, V. [2005]: *Physical Foundations of Cosmology*, Cambridge: Cambridge University Press.
- Mukhanov, V. and Chibisov, G. [1981]: ‘Quantum fluctuations and a nonsingular universe’, *JETP Letters*, **33**, pp. 532–535.
- Nickles, T. [1985]: ‘Beyond Divorce: Current Status of the Discovery Debate’, *Philosophy of Science*, **52**, pp. 177–206.
- Nickles, T. [1987]: ‘Lakatosian Heuristics and Epistemic Support’, *British Journal for the Philosophy of Science*, **38**, pp. 181–205.
- Nickles, T. [1990]: ‘Discovery Logics’, *Philosophica*, **45**, pp. 7–32.
- Nickles, T. [2000]: ‘Discovery’, in *A Companion to the Philosophy of Science*, Oxford: Blackwell, pp. 85–96.
- Niiniluoto, I. [2014]: ‘Scientific progress as increasing verisimilitude’, *Studies in History and Philosophy of Science Part A*, **46**, pp. 73–77.
- Peebles, P. and Yu, J. [1970]: ‘Primeval adiabatic perturbation in an expanding universe’, *Astrophysical Journal*, **162**, pp. 815–836.
- Penrose, R. [1989]: ‘Difficulties with Inflationary Cosmology’, *Annals of the New York Academy of Science*, **571**, pp. 249–264.
- Popper, K. [1963/2002]: *Conjectures and Refutations*, London and New York: Routledge, 2nd edition.
- Schickore, J. [2014]: ‘Scientific Discovery’, in E. Zalta (ed.), *The Stanford Encyclopedia of Philosophy*, spring 2014 edition.
<<http://plato.stanford.edu/archives/spr2014/entries/scientific-discovery/>>

- Schiffrin, J. and Wald, R. [2012]: ‘Measure and probability in cosmology’, *Physical Review D*, **86**, pp. 1–20.
- Sklar, L. [1975]: ‘Methodological Conservatism’, *Philosophical Review*, **84**(3), pp. 374–400.
- Sklar, L. [1981]: ‘Do Unborn Hypotheses Have Rights?’, *Pacific Philosophical Quarterly*, **62**, pp. 17–29.
- Smeenk, C. [2003]: *Approaching the Absolute Zero of Time: Theory Development in Early Universe Cosmology*, Ph.D. thesis, University of Pittsburgh, Pittsburgh, PA.
- Smeenk, C. [2005]: ‘False Vacuum: Early Universe Cosmology and the Development of Inflation’, in A. J. Kox and J. Eisenstaedt (eds), *The Universe of General Relativity*, Boston: Birkhäuser, chap. 13, pp. 223–257.
- Smeenk, C. [2013]: ‘Philosophy of Cosmology’, in R. Batterman (ed.), *The Oxford Handbook of Philosophy of Physics*, Oxford: Oxford University Press, chap. 17, pp. 607–652.
- Smeenk, C. [forthcoming]: ‘Inflation and the Origins of Structure’, in D. Rowe (ed.), *Beyond Einstein*, Einstein Studies, Boston: Birkhäuser.
- Stanford, K. [2001]: ‘Refusing the Devil’s Bargain: What Kind of Underdetermination Should We Take Seriously?’, *Philosophy of Science*, **68**, pp. S1–S12.
- Stanford, K. [2006]: *Exceeding Our Grasp*, Oxford: Oxford University Press.
- van Fraassen, B. [1980]: *The Scientific Image*, Oxford: Oxford University Press.
- Weinberg, S. [2008]: *Cosmology*, Oxford: Oxford University Press.
- Woody, A. [2015]: ‘Re-orienting discussions of scientific explanation: A functional perspective’, *Studies in History and Philosophy of Science Part A*, **52**, pp. 79–87.
- Zeldovich, Y. [1972]: ‘A hypothesis, unifying the structure and the entropy of the universe’, *Monthly Notices of the Royal Astronomical Society*, **160**, pp. 1–3.