Scientific Progress and Modern Cosmology

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Abstract:
The paper examines the nature of scientific progress through the lens of the history of modern cosmology (i.e. from Einstein's 1917 static universe to the present-day Standard (ΛCDM) model of cosmology). We distil three novel lessons, germane to the debate between the two main accounts of scientific progress (the noetic and the epistemic one, respectively). First, it's difficult to sharply locate—to precisely pinpoint the locus of—the epistemic content of scientific knowledge. Cosmology displays stark epistemic holism: epistemic content and evidence are typically inextricably distributed over a wider "web of beliefs". Secondly, cosmologists employ a variety of justificatory practices and modes of reasoning. More often than not, they fall short of the fastidious standards of traditional epistemology. Thirdly, cosmological claims typically defy easy and unambiguous characterisation in terms of truth. These three lessons are shown to pose grave challenges to the epistemic account of scientific progress (on which progress consists in the accumulation of knowledge). By contrast, the rivalling noetic account (which characterises progress in terms of improved understanding) can naturally accommodate those lessons.

Key words: *progress, cosmology, understanding, knowledge, models*

I. Introduction

What is the nature of scientific progress? That is, how should we characterise the cognitive improvements in scientific developments we tend to hail as progressive? After a period of relative tranquillity following the heyday of philosophical work on this question in the 1970s (e.g. Lakatos & Mulgrave, 1970; Laudan, 1977; Radnitzky & Andersson, 1978; Rescher, 1978), the question re-emerged recently as a key topic in philosophy of science (see, e.g., Rowbottom, 2023; Shan, 2023). Accounts of scientific progress are often motivated by various historical episodes in which scientific progress is presumed to have occurred (or not). These episodes are then argued to fit one account of progress—to the exclusion of others. To date, these discussions haven't touched on modern cosmology, i.e. the development of cosmology from 1917 onwards.

This lacuna is a missed opportunity, for the history of modern cosmology has much to offer for reflections on progress. In particular, as we shall see, it forcefully illustrates some general facets of science easily overlooked (but nonetheless present) in other disciplines, which directly bear on the nature of scientific progress (see, e.g., also Rowbottom, 2019, esp. Ch.3; or Currie, 2019 for paleontology). Moreover, whereas the extant literature is confined to quite specific, usually brief, episodes, there are methodological advantages to surveying a wider range of research over a longer time span. As a major period in the history of an entire discipline, the development of modern cosmology serves as a more robust test case for accounts of scientific progress.

Historically, the most prominent accounts of scientific progress were *the truthlikeness account*, initially proposed by Popper (1972) and developed by Niiniluoto (1980, 2014), and the *problem-solving account*, initially suggested by Kuhn (1970) and developed by Laudan (1977, 1981). According to the former, scientific progress consists in increasing the truth-likeness of accepted theories: as science progresses, they get closer to the truth about their subject matter. This is designed to capture a realist hunch: it concedes that accepted scientific theories are rarely (if ever) fully true; yet, it allows science to deliver ever "truer" theories. By contrast, friends of the problem-solving account eschew defining scientific progress in terms of truth (or suitably watered-down surrogates thereof). Instead, they aver that science progresses when, by the lights of those working within a particular research tradition, some scientific problem is solved (or dissolved/explained away).

In recent years, two new types of accounts of scientific progress have joined the fray and become the centre of much philosophical debate.[1] One is Bird's (2007, 2008, 2019, 2022) *epistemic account*: according to it, scientific progress consists in the accumulation of knowledge. The acceptance of a new theory, for instance, or the replacement of a previous theory with a new one, is scientifically progressive only if scientists come to know the new theory. Here, "knowing a proposition P" is taken to minimally require that P be (i) true, (ii) believed, and (iii) epistemically justified.[2] The other newcomer, and now main contender, is the *noetic account,* most influentially developed by Dellsén (2016, 2021, 2022). It puts enhanced understanding at the heart of progress: according to the noetic account, scientific progress on an object of inquiry consists in increasing our ability to understand it—that is, roughly, when our representations of how things hang together improve (see also, e.g., Elgin, 2006, 2017, Ch.3).[3] We'll further elucidate these accounts, and the differences between them, below.

In what follows, we'll first examine the development of modern cosmology in some detail, focusing on the advances in the field that are generally considered most significant (**§II**). Based on this historical overview, we then spell out three main lessons about the nature of scientific progress in cosmology. They concern the holistic evaluation of cosmological theories

[1] These two accounts are presently the most vigorously developed and debated options. Our discussion will therefore focus on them. But our analysis has implications for less prominent accounts as well.
[2] These are standardly taken as necessary but not sufficient conditions, and are occasionally taken to provide part of an analysis of the concept of knowledge (see fn.25 below).
[3] See also Rowbottom (2019) for a somewhat different kind of understanding-based account of scientific progress.

(**§III.1**), their often speculative nature (**§III.2**), and the frequent use of idealisations and approximations (**§III.3**). We go on to trace the implications of these lessons for the epistemic and noetic accounts of progress in particular (**§III.4)**. These lessons, we maintain, undermine the epistemic account's commitment to progressive theories being true, believed, and epistemically justified in the senses required for knowledge (**§III.4.1**), while supporting the noetic account's contention that a certain form of understanding lies at the heat of scientific progress (**§III.4.2**).[4]

II. The evolution of modern cosmology

After preliminary remarks motivating the choice of our case study (**§II.1**), this section reviews the major developments in the history of modern cosmology (**§II.2**).

II.1. Merits of the chosen case study

Philosophers of science are acutely aware of the problems associated with using case studies as evidence for philosophical theories (see, e.g., Pitt 2001; Currie 2015a; McAllister 2018; Dimitrakos, 2020). To ameliorate such problems, case studies must be chosen judiciously and be accompanied by rigorous philosophical arguments. In our view, modern cosmology serves as a particularly pertinent case for a number of different reasons.

First, modern cosmology is certainly "a mature physical science" (Peebles, 1993, p.xxv; cf. also Kragh, 2007), an "important part of mainstream science, with a well-established standard model confirmed by various strands of evidence" (Ellis, 2006, p.2). Indeed, cosmology is widely flaunted as one of the proudest achievements of modern science, fulfilling some of the highest scientific ambitions, and is well-integrated into other major branches of physics (and vice versa). This plausibly suggests that developments in cosmology paradigmatically instantiate *scientific* progress.

Secondly, cosmologists themselves frequently extol the "tremendous progress in recent decades" (Ellis, 1991, p.553; see also Longair, 2020, p.1.21; see also Fereira et al., 2025). Even professional historians of cosmology (wont to be leery of appeals to progress) unabashedly acknowledge cosmology's "remarkable progress since Einstein's pioneering work of 1917" (Kragh, 2008, p.538). By contrast, practitioners of other sciences, such as economics and psychology, not seldom express doubts about genuine progress in their fields

[4] As we'll discuss in detail below, the epistemic account has been criticised in the extant literature on grounds similar to those we adduce below. Perhaps most prominently, Rowbottom (2008; 2010; 2019) and Dellsén (2016; 2021; 2023) have both forcefully argued that the epistemic account's commitment to justification and (strict) truth are problematic. Both Dellsén (2016; 2021) and Rowbottom (2019) have proposed understanding-based accounts of scientific progress.

(e.g., Solow 1982; Khemlani and Johnson-Laird 2012, p.2). The evolution of cosmology thus plausibly exemplifies a paradigmatic case of scientific *progress*. (Of course, it's incumbent on philosophers to explicate the apposite sense of progress.)

Thirdly, our case study encompasses a comparatively long phase of an entire discipline, as opposed to being limited to an isolated and brief episode of research on a single topic, such as the alleged discovery of "N-rays" (Bird 2007, 2008; Rowbottom, 2008) or Einstein's explanation for Brownian motion (Dellsén 2016; Emmerson 2022). Our material will cover—albeit perforce in broad brush strokes—the major stages in the history of cosmology since 1917. We thereby hope to go some way towards meeting Pitt's (2001, p. 374) demand that the case studies examined by philosophers of science be sufficiently detailed and extended to bolster the lessons they want to draw.

Fourthly and finally, as will become apparent below (**§III**), the development of modern cosmology poignantly illustrates a number of features from which philosophical lessons for the debate on scientific progress can be drawn.[5] These features relate especially to the multidisciplinary nature of modern cosmology, with the confluence of multiple physical subdisciplines (such as nuclear, high-energy and gravitational physics, and thermodynamics), as well as to its distinctive epistemological challenges (difficulties in testing cosmological theories, in particular).

II.2. Five paradigms of modern cosmology

Following Ellis (1988, 1990), we can divide the history of modern cosmology roughly into five major stages, or "paradigms".[6] They are more or less coherently circumscribed by preoccupation with certain questions, and adoption of ideas or theoretical frameworks for tackling them. We'll group the five paradigms, in chronological order, under the following headers:

1. *The unchanging universe* (1917-ca.1930), during which, primarily mathematically, the application of general relativity to a static or stationary universe was studied (**§II.2.1**).

[5] Similar lessons have been pointed out for scientific models (see, e.g., Bailer-Jones, 2009; Gelfert, 2016). Given the prevalence of models in all walks of scientific life, such lessons therefore have wide-reaching relevance for science more generally. It's one of our paper's goals to highlight them specifically for the debate on scientific progress. Instructive studies on scientific progress with conclusions sympathetic to ours are found in Shan's (2023, part II). The analyses therein, however, tend not to bring the material to bear upon the dispute between the epistemic and the noetic account.

[6] We use the notion loosely—*not* in the Kuhnian sense, with its more specific (and controversial) meaning(s). In particular, our paradigms (apart from the second vis-à-vis the first) don't compete with each other (let alone display incommensurability).

2. *The evolving universe* (ca. 1930-late 1950s/early 1960s), characterised via its *geometric* properties, with redshift/distance relation, the so-called Hubble-Lemaître Law (**§II.2.2**).
3. *The Hot Big Bang model* (ca. early 1960s-early 1980s), describing a hot initial phase, and increasing incorporation of, and links with, microphysics (nuclear and particle physics (**§II.2.3**).
4. *Primordial cosmology* (since early 1980s), which posits an extremely early phase of the universe with *hyper-accelerated* cosmic expansion and proposes solutions for baryogenesis (**§II.2.4**).
5. The *Standard (*or: *ΛCDM) Model of Cosmology* (since mid/late 1990s), which postulates, and elaborates the consequences of, the predominance of Dark Matter and Dark Energy in the universe's energy-mass budget (**§II.2.5**).

II.2.1. The static universe

Modern cosmology is generally considered to have been born in 1917, when Einstein applied his recently formulated theory of General Relativity (GR) to the universe as a whole. Its matter content he modelled as uniformly distributed, collisionless, and non-clumping dust; the universe at large he further assumed to be static (i.e. not subject to temporal change). To allow for staticity, Einstein had to minimally modify his original (1915) field equations—by introducing the so-called *cosmological constant*, Λ, an additional term in the equations. While evidently a rough approximation at best, Einstein's static universe qualifies as the first consistent cosmological theory (i.e. model of the cosmos).[7]

Two peculiarities are salient to this first paradigm. Both pertain to the kind of *reasoning* involved. First, Einstein's motivation was primarily *philosophical*. He didn't attempt to confront his model with empirical reality. Instead, Einstein's objective was to demonstrate that his fledgling theory of gravity conformed to his Machian intuitions (Smeenk, 2014). Ironically, GR's physics and mathematics themselves soon forced Einstein to jettison these intuitions. As mentioned, Einstein's cosmological model was static: it described an unchanging universe—in line with the time-honoured doctrine of the immutable and eternal heavens. The observational basis at which Einstein (1917, p.148) gestures—the alleged fact that the

[7] The reasons for this restriction are twofold (cf. e.g. Kragh, 2004; 2007, Ch.1&2 for historical details). First, prior to 1917, consistent cosmological theorising wasn't possible for both theoretical reasons and effective absence of relevant data. Cosmological speculations were essentially theological or philosophical. Our paper's goal, by contrast, is to study *scientific* progress. A second, more sociological consideration seconds this (together with the premise that science is an essentially communal enterprise, see e.g. Longino, 1990; Solomon, 2001): cosmological speculations were rare. Very few serious scientists were engaged in cosmological work; it would be anachronistic to speak of a cosmological research tradition beyond isolated contributions.

velocities of stars are negligibly small—is flimsy, and false (and, even for his time, arguably not au courant); as an *empirical* argument it would seem perfunctory.

Secondly, at this stage of its development, extrapolating GR to cosmological scales was iffy. In no way could GR be said to have been well-tested at the time. While in 1916 Einstein had proposed GR's three classical tests—the perihelion shift of Mercury, light deflection, and gravitational redshift—only the first two would be confirmed within the next four decades (see e.g. Eisenstaedt, 2015). We stress that they don't qualify as *strict* tests: they effectively test GR's empirical adequacy for the *same* physical scenario in a very limited regime (viz. a static, spherically symmetric weak gravitational field, such as that surrounding the Sun).

A rivalling cosmological model—likewise an application of GR—was proposed the same year by de Sitter. In contrast to Einstein's model, it described a matter-free universe. It too was regarded as a static universe—erroneously so.[8] It was seriously contemplated because it predicted redshift, i.e. the stretching of wavelengths of light from far-away galaxies, evidence of which was gradually piling up. These redshift data were puzzling. De Sitter's model offered a promising explanation—despite its manifest counterfactual, unphysical character. Indeed, it was this redshift phenomenon, once it had crystallised into a more robust and precise observational relation by the late 1920s, especially with Hubble's (1929) and Hubble and Humason's (1931) measurements, that ushered in the second paradigm, the transition to a changing—*expanding*—universe.

II.2.2. The expanding universe: dynamical-geometrical models of the universe

Despite their blatant shortcomings, the static universe—in its Einsteinian and de Sitterian incarnations—reigned supreme. As the 1920s were drawing to their close, it dawned on scientists that limiting themselves to static universes had landed them in a cul-de-sac. Eddington's (1930) realisation that Einstein's static universe was physically unstable—a mathematical discovery about GR's structure—catalysed the transition to dynamical universes. Soon, Lemaître's (1927) idea of an expanding universe would supersede the earlier paradigm: dropping the assumption of a static universe, GR *generically* implied a universe in which space itself changes (expands or contracts, depending on the density of matter in the universe). Not only was this an insight about GR's mathematical structure (pointed out already by Friedman in 1922), i.e. its typical cosmological solutions. Rather, and more importantly,

[8] At bottom, GR's mathematical formalism wasn't well-understood. Confusion over the physical status of certain features and mathematical techniques are a recurrent theme in the history of General Relativity (dramatically illustrated by the case of gravitational waves and singularities, see e.g. Kennefick, 2007).

Lemaître discerned clearly that GR allowed an elegant and natural *explanation* of Hubble's redshift-distance relation: GR predicts it, explaining the phenomenon in terms of the manifestation of an *expanding* universe. By 1933, the majority of astronomers accepted the idea of an expanding universe (Kragh, 2007, p.148).

The variant of the expanding universe that became one of the standard models cosmologists worked with for much of the 20th century was the 1932 Einstein-de Sitter model (see O'Raifeartaigh et al., 2021). The primary reason for its popularity was the model's simplicity. It fixed, by fiat, two major unknowns: the curvature of space, and the cosmological constant. Physically/mathematically, it was a special case of earlier cosmological models. The Einstein-de Sitter model *sets* the so-called cosmological constant (a free parameter in GR) to zero, and *postulates* that three-dimensional space remains geometrically flat. The spatial geometry, however, was simply unknown.[9]

These simplifying assumptions rested on two fairly weak arguments. First, the cosmological constant had previously been introduced as a minimal modification of Einstein's original version of GR for the purpose of allowing for a static universe—a hope that in turn hinged on his Machian penchants. After relinquishing the notion of a static universe by the early 1930s, Einstein's reasons to retain the constant became obsolete. Secondly, to justify the assumption of zero spatial curvature, Einstein and de Sitter cite the expressly tentative absence of "direct evidence" to the contrary. They stress, however, that "the spatial curvature may not in fact be zero, and suggest that an increase in the precision of observational data will allow for the determination of its sign and value" (O'Raifeartaigh et al., 2021, p.4).

Despite these tenuous arguments, the model, which "was probably intended as a rough sketch of the expanding cosmos" (op.cit., p.8), was adopted primarily for two reasons. First, it allowed an estimate of the mean density of matter in the cosmos. It turned out to roughly tally with observational estimates at the time. The second reason was pragmatic: the *prospect* of an observational way forward. More generally, the Einstein-de Sitter model marked an important benchmark.[10] It allowed a description of the cosmos via just two parameters, the cosmic expansion rate (i.e. the Hubble parameter) and the mean matter density. Astronomers could, in principle, determine the value of each of these parameters through various methods available at the time (ibid.).

[9] For (ipso facto controversial) *philosophical* reasons, a few high-profile physicists have contrariwise plumped for a spatially *closed* geometry (see de Swart, 2020, pp. 17; Antoniou & Fay, 2025).
[10] It postulated a mean cosmic matter density that matched the so-called critical density. From the late 60s onwards, it became increasingly apparent that the *observed* density fell far below that.

A pragmatic rationale for pursuing the Einstein-de Sitter model—*anything* conducive to a way forward—was in dire need. Cosmology from 1940 until the mid-1950s was in a sorry state. Due to difficulties in observationally determining the cosmic parameters, it was stagnating. “To those scientists interested in the field, there seemed little prospect in discriminating between the large variety of cosmological models proposed the previous decade on the basis of empirical observation [...]. Indeed, it could be said that cosmology did not truly constitute a test for general relativity in these years. Worse, the one cosmic parameter that could be determined with reasonable accuracy—the rate of expansion” (O’Raifeartaigh, 2022, p.13) implied an *impossibly* young age of the universe. The roots of this so-called Age Problem lay in the observationally determined value of one of the two parameters, characteristic of mainstream relativistic cosmological models, the Hubble constant (i.e. the universe’s expansion rate). Its value was off by no less than an order of magnitude, for almost 40 years—until its painstaking revisions in the 1950s by Baade and Sandage (see Kragh, 2007, p. 191, Fig.4.3 which plots the values of the Hubble constant from 1927 to the 1970s—hammering home the *huge* systematic errors). In fact, “(i)t would take until 2000 and the completion of the Hubble Space Telescope Key Project to pin down to 10% with a reliable error estimate […]” (Turner, 2021, p.2).

More generally, GR was relegated to the backwaters of physics—largely isolated from the rest of physics (Eisenstaedt, 1989). Its epistemic credentials were severely curtailed. We already commented on the absence of persuasive tests. In two regards, the situation was worse still. First, the available observational data was precarious. Still in 1963, there were “only 2.5 facts in cosmology” (Longair, 1993, p.160). The first was the darkness of the night sky (effectively irrelevant for the developments in cosmology); the second Hubble’s empirical redshift-distance relation, the so-called Hubble-Lemaître “Law” (cf. Duerr & Mills, 2024). The alluded to half-fact, in the twilight since the first reliable source counts in the mid-1950s, concerned the universe’s evolution, i.e. the idea that “the contents of the universe have probably changed as the universe grows older” (ibid.)—at the time “a matter of considerable controversy” (ibid.). Secondly, alternatives to GR—that is, rivalling theories of gravity—were proposed early on (see Whitrow & Morduch, 1965 for several options). For instance, Milne’s (1935) “kinematic relativity”, a *special*-relativistic theory, could explain the cosmological redshift data without invoking the expansion of the universe.[11] Even if loath to depart from GR as a gravitational theory, one can also muster alternative explanations of the Hubble-Lemaître Law. The most famous of them was the tired light hypothesis (see e.g. Kragh, 2017), espoused

[11] In fact without invoking a dynamical spacetime geometry at all, distinctive of GR (for details see e.g. Kragh, 2007, sect. 3.4.4).

by none other than Hubble himself. It postulated that light on its path across the universe would "fatigue" (e.g. due to scattering).

II.2.3. The Hot Big Bang model

Against the backdrop of the relativistic models of the expanding universe, Gamow and collaborators, in the late 1940s, developed further Lemaître's earlier (1931) idea of a cosmos with a compact, dense *beginning*. The 1948 *αβγ paper* (after the authors' initials: Alpher, Bethe, Gamow) propounded the first modern Hot Big Bang mode. The authors sought to tackle the problem of nucleosynthesis: to explain the relative abundance of the lightest chemical elements in the universe, viz. He, De, and Li.

Working semi-quantitatively, and "through some combination of good luck and good management" (Peebles, 2022, p.109) Gamow et al. obtained reasonable fits with measured abundances. A second key result concerned the prediction of a faint background microwave radiation as a fossil record of the universe's early Hot Big Bang phase. Estimating the expected present radiation temperature, Alpher and Hermann (in a 1948 paper) "reported that the temperature 'is found to be about 5°K.' This is remarkably close to the measurements obtained a decade and a half later" (op.cit., p.111)—measurements that would enthrone the Hot Big Bang Model as the ruling paradigm from the mid 1960s onwards.

In the early 1950s, Gamow's research programme was small but thriving (Kragh, 1996, p.137). Despite being well-known, and despite making those predictions that would later be nigh-universally hailed as triumphs of modern cosmology, it was, bafflingly, aborted in 1953. Its predictions were effectively forgotten. In 1965, however, the programme was resurrected in more or less the form as it had been left abandoned 12 years earlier—but independently re-invented by a new generation of cosmologists (see e.g. Peebles, 2022, Ch.5).

In the intervening 1950s, cosmology was a small research field. Worse, "it was still a matter of some debate whether physical cosmology could be counted as a proper science at all [...], primarily because of its unsettled theoretical foundation and the lack of connection to solid astronomical data" (Kragh, 2007, p.196). Heterodox ideas prospered. They included the most important alternative to the general-relativistic Big Bang model, the Steady-State theory (see e.g. Kragh, 1996, esp. Ch. 4). "The problem [during the 1950s] was the embarrassing paucity of observations that realistically could distinguish between the steady-state theory and the class of relativistic evolution models." (Kragh, 2019, pp.192). But this predicament produced a salubrious effect on cosmology. It led to extensive debates that clarified the conceptual and methodological foundations of cosmology, and concerted efforts to devise tests to adjudicate between evolutionary models of the cosmos models based on GR and the Steady-State theory.

After an intriguing back-and-forth between the two rivalling approaches (which included the presentation of counter-evidence against the Steady-State theory, the refutation of that counter-evidence, and its subsequent re-affirmation) the early 1960s saw an increasing pressure on the Steady-State theory. The first solid evidence for a Hot Big Bang theory came in 1961, with the first reliable estimates of the primordial abundance of He. The serendipitous 1964 discovery of the Cosmic Microwave Background (CMB), the fossil remnant radiation from an earlier, hot phase of the universe, is usually seen as a watershed: it unambiguously tipped the scales in favour of the Big Bang model over the Steady-State alternative (Kragh, 1996, Ch.7).

The discovery of the CMB flung open the gates to cosmology's golden age. More and better observational data fastened cosmology's empirical moorings (de Swart et al., 2017; de Swart, 2020. The perplexing discovery of quasars and pulsars in particular considerably sparked interest in cosmology: its relevance for other areas seemed to grow. Cosmology, with its Hot Big Bang Model, "was increasingly integrated into the interests of astronomers and astrophysicists" (op.cit., p.12). An especially momentous development was the establishment of Dark Matter in the 1970s: the realisation—on the basis of both astrophysical data, as well as cosmological, but non-empirical, philosophical reasons—that only a fraction of the universe's total matter content is given by the visible mass in galaxies and galaxy clusters. We'll resume this thread in **§II.2.5**, devoted to the fifth paradigm. Beforehand, let's expound another line of research, the fourth paradigm, initially independent but quickly incorporated into mainstream cosmology.

II.2.4. Primordial cosmology: inflation and baryogenesis

The 1980s saw the opening up of a new paradigm. It extends the Hot Big Bang Model to fractions of a second after the Big Bang, a domain of extremely high temperatures/energies. Here, we'll focus on the most important development in early-universe cosmology: cosmic inflation. Its key idea is to postulate an ultra-brief period during which the universe underwent a stupendous (quasi-exponential) growth spurt, blowing up its size, before smoothly segueing into the more sedate expansion dynamics of the Big Bang model.

In part, this postulate was motivated by certain speculative theories in high-energy physics, so-called Grand Unified Theories, which aim to unify the strong, weak, and electromagnetic forces. These theories provided the blueprint for the types of fields supposed to produce the inflationary dynamics. Soon, however, they would have to be discarded, as the Grand Unified Theories in question turned out not to be empirically viable. Nonetheless, the cosmological effect for which they had been invoked—the short period of exponential expansion—was retained. Suitable dynamics were stipulated, without relying on the original motivation. The surge of interest in inflation lay in the *explanatory* benefits that it afforded (McCoy, 2015, 2019; Wolf & Duerr, 2023). Inter alia, it explained in one fell swoop—and in an especially elegant and epistemologically gratifying manner—three otherwise puzzling coincidences of the Hot Big Bang model: the near-perfect flatness of the observable universe, its uniformity on large scales, and the existence of seemingly acausal correlations. Cosmic inflation traces these facts back to a common origin. In the same vein, cosmic inflation provided an explanatory mechanism for the formation of cosmic structure by providing the "seeds" of matter density fluctuations that would later develop into galaxies and galaxy structures.

Impressive as these achievements are, they aren't knock-down arguments in favour of cosmic inflation. The Hot Big Bang model *was* capable of accommodating these facts—albeit at the cost of having to posit circumspectly chosen, prima facie extraordinary, initial conditions. This was perceived by many as a blemish—smacking of fine-tuning.

More compelling empirical arguments for cosmic inflation would still have to wait for two decades. Not even *now* in fact do they qualify as conclusive evidence: it would be more appropriate to say that cosmic inflation passed some *generic* tests with novel predictions which inflation had successfully made (e.g. spatial flatness to sub-percentage levels and certain statistical features of primordial density perturbations). In spite of such skimpy empirical-evidential credentials, inflation was adopted as the mainstream paradigm in theoretical cosmology by the late 80s; vast research efforts were, and continue to be, invested in its further exploration. The key for inflation's ascendent was its tantalising allure—as a (speculative) mechanism promising a slew of enticing explanations, a connection with particle physics, and a powerful and fertile heuristic for various problems in cosmology (Wolf & Duerr, 2023).

Yet, even nowadays cosmic inflation remains controversial for three principal reasons. First, it's best characterised not as a specific theory, but as a *framework* (and is typically referred to as such). Put differently, cosmic inflation is a research programme which itself comprises a huge number of more specific theories. Accordingly, its flexibility is sometimes excoriated as lack of specificity and testability (e.g. Dawid & McCoy, 2023): inflation is thus reprimanded as methodologically flawed. Secondly (and relatedly), its foundations are far from clear (to the extent that general doubts have been cast on its testability and even scientific status, see e.g. Smeenk, 2019; Koberinski & Smeenk, 2023). Inflation bursts the confines of the Standard Model of particle physics. To-date, it has not been possible to identify the nature of the field responsible for inflation, i.e. its “particle physical realisation”. The mainstream candidates for this field rely on speculative physics which hitherto haven’t been corroborated. Thirdly, alternatives to inflation exist—even though they are heterodox, and somewhat controversial, minority programmes (see e.g. Wolf & Thébault, 2023).

II.2.5. The ΛCDM model

The present-day standard model of cosmology, the ΛCDM model, established itself in two main phases. The first phase, which began around 1980, consisted in the acceptance of (Cold) Dark Matter (hence the “CDM” in the standard/ΛCDM model’s appellation) as the lion’s share of matter in the universe. The *existence* of Dark Matter is inferred via its gravitational effects from sundry observations. It explains a multitude of independent phenomena, such as rotation curves of galaxies, gravitational lensing, the stability of galaxies, or the so-called power spectrum of the CMB radiation. Apart from its non-luminous appearance, little else is known about Dark Matter—other than that it *can’t* be composed of matter vouchsafed by verified particle physics.[12] Several proposals for more specific models of Dark Matter exist (see e.g. Bauer & Tilmann, 2019).

The second phase of the ΛCDM model’s establishment, reference to which is encoded in the “Λ”, concerns Dark Energy. Around the mid-to-late 1990s, ever-stronger empirical evidence was mounting for the universe’s accelerated expansion: its expansion—as ascertained through data points reaching us from the far-away cosmic past—is speeding up. To account for this, one must postulate that around 70% of the universe’s energy budget is made up of an unknown form of energy, “Dark Energy”. Again, all we know about it are its phenomenological properties—its manifestations on large cosmic distances. Any details about what kinds of matter/fields generate this Dark Energy remain entirely elusive thus far (see, e.g., Durrer, 2011).

A number of proposals have been mooted for the nature of Dark Energy. They span modifications of GR, exotic types of matter, a so-called cosmological constant Λ as a new constant of nature, effects from quantum field theories or artefacts of specious assumptions about the distribution of matter in the universe. None of these approaches can currently claim to enjoy convincing epistemic credentials; they don’t even admit of independent tests at present. Indeed, the prospects of any laboratory experiments seem exceedingly dim. Worse

[12] Also its spatial distribution can only be *inferred* (*retrofitted)*, from observed gravitational effects.

still, it has been argued that the evidential underdetermination amongst the options is plausibly permanent (Wolf & Pereira, 2023). Nor does any of them appear to be much more promising, or likely to be true, than its competitors (Wolf & Duerr, 2024b). The choice amongst them seems staked on "bets on future physics" (Schneider, 2020, 2023).

The ΛCDM model is chiefly pursued in the hopes of hitting on phenomena that unambiguously pin down its empirical limits: its ramifications are explored in order to "test it to destruction" (Efstathiou, 2023). The model is "consistent with a wealth of high-precision data, both laboratory measurements and astronomical observations. However, the foundation of ΛCDM involves physics beyond the standard model of particle physics: particle dark matter, dark energy, and cosmic inflation." (Turner, 2018, p.1).

The ΛCDM model is "at best incomplete, and at worst a phenomenological construct that accommodates the data" (ibid.). Its phenomenological—non-fundamental—nature is further underlined, first, by the nigh-universal expectation that GR, on which it is based, will be replaced by a future quantum theory of gravity, and that at sufficiently early times, temperatures are reached beyond the warranted validity of established high-energy physics. Secondly, the ΛCDM model is haunted by well-known anomalies intimating, at best, gaps in our comprehension of details, and at worst, mistakes in basic assumptions. Of special relevance here are the so-called Hubble tension, i.e. the empirical discrepancy between two ways of determining the universe's expansion rate (see, e.g., Smeenk, 2023), and puzzling galactic phenomena in the low-acceleration regime that *might* hint at the need for modified theory of gravity (see, e.g. Duerr & Wolf, 2023).

III. Philosophical lessons for scientific progress

Vis-à-vis the evolution of modern cosmology, we now draw three lessons, germane to debates on scientific progress. The first is that cosmology often exhibits a grave form of holism (**§III.1**). The second concerns the speculative nature of cosmology: its epistemic practices frequently fail to deliver the sort of epistemic justification that is traditionally taken to be necessary for knowledge (**§III.2**). Our third lesson is that indispensable reliance on idealisations blocks neat cleaving of cosmological claims into true and false chunks; claims to (approximate) truth and falsehoods delicately mix (**§III.3**). Having drawn these lessons, we then home in on the debate between the noetic and the epistemic account of progress. The three lessons, we suggest, are better accounted for by the former than by the latter (**§III.4**).

III.1. First lesson: *holistic* progress

Zooming in on the individual scientific achievements, it often proves difficult to precisely locate the more robustly supported content of the theories and models of each cosmological paradigm. It remained unclear *which* specific claims—which hypotheses, posits, and implications of these theories and models—were firmly supported by the evidence. Instead, the support provided by the relatively meagre empirical evidence available at each stage tended to be smeared out over a vast web of assumptions, individually not amenable to independent appraisal. As a result, unambiguous judgements of a particular hypothesis' corroboration or falsification remained elusive (cf. McMullin 1981, p. 180).[13] In other words, the evidential warrant for cosmological paradigms didn't admit of univocal distribution amongst its constituent assumptions. This epistemic holism has two closely related principal sources.

First, cosmological modelling involves a large number of interlocked assumptions which cannot be independently tested. The assumptions straddle sundry levels of model-building: non-trivial intricacies of calculational and numerical codes, the tricky effects of approximations and idealisations, educated guesses about plausible initial and boundary conditions, astrophysical inputs about star and galaxy formations, the physical assumptions as far as *gravity* is concerned (where we have to adopt a gravitational theory—with General Relativity as the standard, but by no means unique, choice), as well as those that concern *matter* (where the theoretical resources of hydrodynamics, particle/high-energy physics, nuclear physics or equilibrium, as well as non-equilibrium, thermodynamics are employed). The resulting complexity makes it practically impossible to unambiguously distribute confirmatory/evidential credentials over the "web of cosmological beliefs" relied on in (empirically) successful modelling.[14]

Secondly, not only is epistemic access to individual hypotheses in cosmology hampered by their typical intertwinement in a larger nexus; many of these hypotheses are also inherently untested, or even untestable, *in isolation*. That is, hopes for testing these hypotheses come from testing other hypotheses with which these hypotheses are entangled.

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[13] Our argument *doesn't* hinge on subscription to Quine's (1953) radical holism, encompassing the *total* web of scientific belief (including mathematics and logic). Instead, the *Duhemian* holism our argument presupposes is more moderate—and, to our minds, fairly uncontroversial (cf. Ariew, 1984; Ivanova, 2021): one type of tests assays a *conjunction* of hypotheses, with neither logic nor obvious rules telling us which of the conjuncts to blame/praise for a favourable/unfavourable outcome.

[14] Matters are further confounded by significant uncertainties, including downright nescience. One tries to tame them with (more or less) educated guesses (about e.g. initial/boundary conditions, and especially distributions of Dark Matter). Certain galactic phenomena testify to the challenges for conclusively assessing such persistent anomalies (see Peebles, 2022b). Indeed, a complex web of assumptions arises, and entails epistemic holism, not only in *theoretical* model-building: also the interpretation of *observational* data and *empirical* testing of theoretical claims itself requires it (see e.g. Goenner, 2010, sect. 3.1.3; cf. Boyd, 2018, 2021). Such uncertainties make claims to truth—in the sense that traditional epistemologists have in mind—extraordinarily challenging to evaluate (**§III.2-3**).

Consider, in particular, cosmology's core theories after 1960, namely (classical) GR and the standard model of particle physics. As Smeenk and Ellis (2017, p. X; see also Ellis 2006) note, "[…] cosmologists have explored speculative ideas in physics that can only be tested through their implications for cosmology; the energies involved are too high to be tested by any accelerator on Earth." In this way, the core physical theories on which cosmological models draw are also being simultaneously tested via these cosmological models. This is especially true of cosmological theorising that goes beyond what Ellis (2007, sect. 5C) evocatively dubs the "physics horizon". It "delimits the physical regime accessible to terrestrial experiments and observations". Cosmological adventures beyond the physics horizon—common as they are during the fourth and fifth paradigm—lack independent lines of relevant evidence.

In sum, an epistemologically disquieting form of epistemic holism vexes cosmology. It flows both from the number of interwoven assumptions, theories and posits within each paradigm, as well as from the inherent difficulties in testing these claims independently of one another. As a result, the available empirical support—though by no means insignificant as such—tends not to be concentrated on a small number of highly confirmed claims that can be identified as such. Rather, this empirical support tends to be smeared out over a large number of such claims.

III.2. Second lesson: *speculative* progress

Another notable feature of cosmology is the speculative nature of its theorising and arguments. The foregoing lesson already touched on evidential infirmities plaguing cosmology due to holist considerations. Here, we'll inspect a related aspect: cosmological theories and arguments are frequently subject to *contrastive underdetermination* at several levels. Moreover they are often based on substantive—and controversial—*philosophical* ideas and criteria.[15]

In **§III.1**, we diagnosed a form of *holist* underdetermination. However, a different, and epistemologically no less unsettling, form of underdetermination also afflicts cosmology: what has been called "*contrastive* underdetermination" (see, e.g., Stanford 2023). It occurs whenever the evidence taken to support a theory does (or might) provide similar or even better support for another theory—perhaps one that is yet to be conceived of by the theorists of the day. Contrastive underdetermination thus "questions the ability of the evidence to confirm any given hypothesis *against alternatives"* (op.cit., sect. 3.1).

[15] Both points are closely related, since philosophical ideas and criteria are invariably brought in to arbitrate in situations where empirical evidence underdetermines theory choice.

Contrastive underdetermination looms largest when the strength of the evidence in favour of a given theory is disproportionate to the logical strength of the theory it's supposed to support—when the theory significantly outstrips the evidence. Stanford (2001, 2006; see also Sklar 1981; Salmon, 1990) has forcefully argued that "even such a transient underdetermination predicament undermines our justification for believing present theories in general, so long as we have some reason to think that it is also recurrent: that is, that there is (probably) at least one such alternative available (and thus this transient predicament rearises) whenever we must decide whether to believe a given theory on the strength of a given body of evidence" (Stanford, 2006, p.17). Plausibly, such a reason can, for instance, be gleaned from the historical record in a given field, whenever viable theoretical alternatives, consistent with the available evidence at the time, are repeatedly shown to exist.[16] Also (some of) our current or future theories may then be expected to have such alternatives.

Our historical survey buttresses a diagnosis of sizable contrastive underdetermination in the development of modern cosmology. In particular, recall that the situation during the first two paradigms was only superficially anchored in empirical warrant.[17] GR itself wasn't well-tested—insufficiently on solar-system scales, and not at all cosmic ones; indeed, it had "practically no applications before the 1960s" (Eisenstaedt, 2015, p.345). A plethora of rivals to both GR and GR-based cosmology was flourishing (with the Steady State Cosmology being the most famous one). To be sure, the empirical situation with respect to GR improved with the third paradigm. It falls within the period of GR's consolidation, and the vindication and elaboration of the Hot Big Bang picture of the universe by incorporating well-tested nuclear physics and non-equilibrium thermodynamics; testable predictions were derived from it, and triumphantly corroborated. Nonetheless, rivalling theories—indubitably minority proposals, and unpersuasive *today* for various methodological reasons—have regularly been considered (e.g. López-Corredoira & Marmet, 2022; Ćirković & Perović, 2024).

As adumbrated earlier (**§II.2.4**), primordial and ΛCDM cosmology abound in proliferation of underdetermined theories and proposals (see e.g. Famaey & Mcgaugh, 2012; Merritt, 2020; Duerr & Wolf, 2024 for the case of Dark Matter; Wolf & Read, 2025 for inflation and Dark Energy). As Ellis (2006, p.16, see also Azhar & Butterfield, 2017) points out, "(w)hile a great many possibilities have been proposed […], at the present time the identity of the proposed inflationary field [...] has not been established or linked to any known particle or

[16] For this argument, it's immaterial whether at the time scientists (say, Newtonian corpuscularians about light) failed to conceive of those alternatives (such as quantum electrodynamics), whose existence is disclosed later, or whether historically such alternatives were *actually* entertained.

[17] The poor epistemic credentials of cosmology until the third paradigm are aggravated by two social factors: the lack of a strong consensus within the *cosmology* community, and cosmology's marginal status within the *physics* community. Both, on common views in social epistemology, erode justification.

field." Inflation, many detractors complain, is in several regards even *untestable* (see Smeenk 2017, 2019; Koberinski & Smeenk, 2023 for details). Similar problems occur for Dark Energy and Dark Matter.

In short, cosmology across the five paradigms exhibits contrastive as well as holistic underdetermination. In this way, cosmological theorising can be said to be unusually speculative for a mature science.

Pressure on it is further increased from a different angle: cosmological hypotheses and arguments are often based on non-empirical ideas and criteria. In particular, due to the absence or dearth of empirical arguments and severe restrictions on observational data, *philosophical* considerations frequently play a pivotal role in cosmology (Ellis 1991, sect. 1.2; 2007, sect. F). They enter cosmology in two main forms (cf. McMullin, 1981, sect. III): as constitutive assumptions in concrete model-building, and as criteria for the selection and assessment of theories and hypotheses. Let's briefly discuss each in turn.

The use of philosophical considerations as constitutive assumptions in model building is best illustrated by the example of the Cosmological Principle (asserting the homogeneous and isotropic distribution of matter), a cornerstone of cosmology since Einstein (see also Beisbart, 2009).[18] Regarding the geometry of the standard cosmological model, according to Ellis (2006, p.24), "(e)stablishing a Robertson-Walker geometry for the universe relies on plausible philosophical assumptions. The deduction of spatial homogeneity follows not directly from astronomical data, but because we add to the observations a philosophical principle that is plausible but untestable." The principle Ellis alludes to is the so-called *Copernican* Principle, the assumption that as observers the data available to us is representative, or typical, of other conceivable observers (see Beisbart & Jung, 2006 for attempts to justify this principle).[19] The Copernican Principle in effect precludes that we occupy a privileged position in the universe.[20]

Secondly, the role of super-empirical considerations is widely acknowledged—first and foremost in the guise of so-called theory virtues, such as simplicity, explanatory power,

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[18] It's worth pointing out Beisbart's conclusion that "a convincing justification [for the Cosmological Principle] […] has not yet been established" (op.cit., p.175).

[19] The Copernican Principle itself opens a can of philosophical worms: how to construe "typical"/ "representative"? If cashing it out in terms of probabilities (or a formal typicality measure over an ensemble of universes), one instantly gets bogged down in deep conundrums. Given the universe's uniqueness, "(t)he concept of probability is problematic [...]. Problems arise in applying the idea of probability to cosmology as a whole — it is not clear that this makes much sense in the context of the existence of a single object which cannot be compared with any other existing object. But a concept of probability underlies much of modern argumentation in cosmology" (Ellis, 2007, p.20).

[20] It also exemplifies (contrastive) underdetermination: "(o)ne should note here that alternative explanations of the observations are possible, for they can be exactly reproduced by a spherically symmetric *inhomogeneous* universe model where we are near the centre" (Ellis, 2007, p.10).

unificatory power, coherence, and scope (see, e.g., Kuhn, 1981; McMullin, 1982; Longino, 1990; Keas, 2017; Schindler, 2018). In the absence of a "mature approach to uncertainty and the limits of verification of the geometry and distribution of matter in cosmology" (Ellis, 1991, p.567) these super-empirical considerations play an outsized role in cosmology (see Peebles, 2020 for examples).[21] Correlatively, Ellis (2006, 6F) stresses cosmology's inevitable "explicit philosophical basis". Occasionally, the freedom in this regard is harnessed to an extreme; in those cases, e.g. in multiverse speculations (see Vaas, 2010; Carroll, 2019), more traditionally minded insistence on empirical evidence and testability is brushed aside in favour of non-empirical considerations.[22]In sum, *bona fide* philosophical assumptions and arguments figure at crucial junctures of cosmological research. Their non-empirical character renders the models and theories they are meant to support quite speculative. They are also speculative in frequently outstripping available empirical evidence; thereby the door is opened, in a particularly striking way, to contrastive underdetermination. It's thus far from obvious that they confer higher probability or greater likelihood to be true (see e.g. Ellis, 1991, p.564).

III.3. Third lesson: true enough for cosmology

Cosmology poses challenges to philosophical views of progress that tie achievements of progressive science too fastidiously to truth.[23] The indispensable, pervasive reliance on approximations and idealisations obstructs claims to truth *tout court*.

Approximations and *idealisations* are omnipresent in cosmology. Following Norton (2012), we take the former to be inaccurate representations of a target system. The latter, by contrast, are (typically also inaccurate) representations of surrogate systems, distinct from the

[21] "Cosmology between 1932-48 provides an excellent example of how explicitly philosophical considerations directed the evolution of a modern science during a crucial period of its development" (Gale, 2023).

[22] How suffused questions in cosmology are with substantive philosophical issues is also driven home through appeals to statistical methods, commonplace in other sciences. Whatever their (seeming) innocuity there, in cosmology "(e)ven applying statistical arguments to the constituents of the universe (clusters, of galaxies, etc.) is valid only insofar as initial conditions in the universe allow them to be valid […]; if these conditions vary too much, the statistics that apply in one part of the universe will cease to be valid in another. [...] In the case of the universe itself, is not the contingent approach [which takes the initial/boundary conditions of the universe as brute facts we've got to swallow; our addition] the *only* logically correct one, because there is no other member of the class? […] We wish to use generic arguments, but logically can only use specific ones, unless we base our arguments on an imagined ensemble of unobserved universes […]. Despite these problems, probabilistic arguments are often applied in cosmology" (Ellis, 1991, p.583; see also Smeenk & Ellis, 2017, sect. 2.5).
Methodological questions regarding statistical arguments become especially thorny for cosmological/astrophysical simulations (see e.g. Ruphy, 2011; Anderl, 2016, 2021; Jacquart, 2018; Guegen, 2020).

[23] Following Elgin (2004, p.114), we "do not deny that (unqualified) truth is an intelligible concept or a realizable ideal." Our point is merely, again concurring with Elgin, that *wholesale*, *strict* fidelity to facts and truths is "unduly limiting": "(i)t prevents epistemology from accounting for the full range of our cognitive achievements" (op.cit., o.115)—including those of cosmology (see **§III.4.2**).

target system. Insofar as cosmological modelling draws on approximations or idealisations, it seems patently compromised when it comes to truth: approximations *mis*represent it, whereas idealisations deal with something *other* than the purported subject matter. Cosmological research *essentially* relies on both. Neither kind of misrepresentation can be dispensed with, or winnowed out until eventual elimination. They remain permanent traits of cosmological model-building and reasoning.

Simplifications, the most common type of approximations, permeate cosmology (as well as all of astrophysics (e.g. Anderl, 2018)—or, in fact, applied physics). Else, the complexity of any realistic system would mar tractability. Simplifications aren't limited to omitting factual details ("abstractions"). They also concern calculational techniques (for instance, cosmological perturbation theory, with its inevitable truncations), or even ("effective") physical laws. The complexity of cosmological objects and modelling typically forestalls firm cognitive control over estimated deviations from the "real" or "true" description. Due to the ubiquitous nonlinearity in the physics involved in cosmology, small variations (e.g. deviations in initial/boundary conditions) can entail dramatic differences. Such instability makes it difficult to control how far, even as a matter of principle, a successful model, with its inevitable error margins, strays from the "correct" model—e*ven if*, per impossibile, we knew that "correct"/"true" model (see Tavakol & Ellis 1988; Tavakol, 1991).

The already-remarked upon Cosmological Principle epitomises a *counterfactual* idealisation. A uniform spatial distribution of matter manifestly doesn't correspond to the cosmos we inhabit: not at the level of the Sun's galactic neighbour, not at the level of galaxy distributions, not even at the level of galaxy cluster distributions. At best (see, however, Aluri et al., 2023 for waxing scepticism), it's a rough description for scales above galaxy clusters: it results when one coarse-grains (statistically[24] averages) scales at the level of galaxy-clusters and beyond, smoothing over known non-uniformities (given by the filament-like structure of matter at those scales, with huge voids in-between).

In sum, the ineliminable—historical and continuing—distortions through approximations and idealisations contained in cosmology impede straightforward truth claims in cosmology. Holism aggravates the challenges: with cosmological results involving large webs of hypotheses, deviations from truth rapidly spread. Insistence on wholesale and unvarnished truth is too restrictive for cosmology. Cosmology flouts the demand that "*each separate* bit of knowledge (answer) to the facts" (Elgin, 2007, p.33, our emphasis).

[24] Such averaging is far from *mathematically/conceptually* innocuous. It's an open problem, at the heart of a protracted debate surrounding so-called inhomogeneous cosmologies (e.g. Ellis, 2011).

III.4. Implications for the epistemic and noetic accounts

What does the foregoing imply for the contemporary debate on progress? In particular, what do they imply for the two most recently prominent accounts of scientific progress, the epistemic account and the noetic account? With respect to the epistemic account, we'll argue that each of the three lessons either strengthens existing arguments against the epistemic account, or presents a novel problem for it. By contrast, the noetic account faces no similar problem from any of the three lessons. In sum, we suggest that the three lessons militate against the epistemic account, and speaks in favour of the noetic one.

III.4.1 The epistemic account and progress in cosmology

As noted, the epistemic account of progress in science holds that progress occurs when and only when there is accumulation of *knowledge*. The notion of knowledge to which proponents of the epistemic account, such as Bird (2007, 2022), appeal is one that has been hotly debated in contemporary epistemology—and for which there no generally accepted definition exists. That said, Bird and other proponents of the epistemic account all take knowledge to be a state that requires quite stringent conditions to be satisfied. In particular, knowing a proposition P is taken to minimally require that P be (i) *true*, (ii) *believed*, and (iii) *epistemically justified*.[25]

We won't embroil ourselves in the intricacies of the notion of truth (cf. fn.23). The other two requirements, however, merit comments. Note first that the second requirement, concerning belief, is generally considered to be quite demanding. While conceptions of "belief" differ widely, the type of belief required for knowledge is standardly taken to involve a high degree of confidence that P is in fact true (see e.g. Foley, 1992). Secondly, "epistemic justification" refers roughly to the having of good enough reasons to believe P, a sort of warrant that renders it right or fitting to hold P as true. Standardly, this is also taken to be quite demanding: the "good reasons" required for knowledge that P are generally taken to make it highly probable that P is true (Reed, 2002)—perhaps even absolutely certain (Climenhaga, 2023). Bird (2022, p.41) himself avers that "true beliefs that might easily have been false are not knowledge"; a belief arrived at by a "procedure [that] is imperfectly reliable" would not be knowledge (op.cit., p.114); and that "to know that a hypothesis is true, our evidence must rule

[25] In traditional epistemology, these conditions are generally viewed as necessary but—due to so-called Gettier-cases—not quite sufficient for knowledge. Bird himself endorses a "knowledge-first epistemology". It takes knowledge to be explanatorily fundamental and conceptually primitive (see, e.g., Bird 2024). On this view, (i)-(iii) should not be seen as constituent parts of knowledge, or and the concept of knowledge should not be analysed in their terms. Nevertheless, (i)-(iii) are *implications* of someone's knowing that *P*.

out *all but one* hypothesis" (op.cit., p.176, our emphasis). Paradigmatic examples of the intended sense of knowledge include claims about one's immediate observable surroundings and other propositions that might seem to be on similarly firm footing (see e.g., Brown 2018).

Now, what are the implications, for the epistemic account, of the three lessons for scientific progress that we distilled from the history of cosmology (**§III.1-§III.3**)? Let us consider, in turn, the three requirements for knowledge–truth, belief, and epistemic justification in view of these lessons.

Start with the *truth* condition. Our third lesson (**§III.3**) bodes ill for it.[26] The omnipresence of ineliminable "pervasively distorting" (Rice, 2018) idealisations and approximations scotch claims to truth of individual propositions (save, perhaps, some low-level phenomenological regularities). Due to the holistic entanglement (both logical and conceptual-interpretative) of numerous other hypotheses, such falsehoods bleed into vast swaths of cosmology more widely. Claims of substantive cosmological import consequently clash with traditional epistemology's requirement of strict truth (shared by advocates of the epistemic account). For illustration, note an especially disturbing casualty: "one of the major milestones in the development of the science of astronomy during the last 100 years, [...] one of the founding pillars of modern cosmology" (IAU, 2018)—the expansion of the universe. The observational redshift/distance correlation, the Hubble-Lemaître "law", receives this interpretation only within standard cosmology (**§II.2.2**); without the latter's highly idealising assumptions, the very notion of cosmic expansion loses its natural meaning.

Our historical survey, and our first and second lessons **(§III.1-2)** conflict with the *justification* condition at three levels (for similar arguments, see, e.g., Rowbottom 2008; Cevolani and Tombolo 2013; Dellsén 2016).[27] First, the substantive revisions of measured values for key cosmological parameters, and the inherent uncertainty engendered by the universe's uniqueness ("cosmic variance", see Ellis, 2006, esp. sect.3) scorn pretensions to the kind of epistemic justification that is required for progress on the epistemic account.[28] For

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[26] Several authors have argued against a truth requirement on scientific progress (e.g., Laudan 1977; Rowbottom 2010; Stegenga 2024). Our argument here is compatible with, and perhaps complementary to, these arguments, but ours is more modest in so far as it is compatible with requiring progressive theories to be "true enough" (see **§III.3**).

[27] Proponents of the epistemic account might consider lowering the evidential threshold for epistemic justification. However, by lowering the standards for "knowledge", one would undermine the motivations usually adduced in favour of the epistemic account: its advocates (e.g. Bird, 2007, 2022; see also Park 2017; Emmerson 2022) expressly insist on strict epistemic requirements on progress to preclude specious progress through unreliable methods.

[28] One might retort that cosmology can't be expected to get *everything* right; gaps and domains where reliability crumbles inexorably remain. Couldn't one then try to "insulate" said shortcomings (cf. Lawler, 2023), and hope thus to defang them?

vivid illustration, recall, for instance, the Age Problem (II.2.2), overshadowing the second and third paradigm, or the radical corrections of the universe's energy density and assumed value of the cosmological constant during the fifth paradigm (**§II.2.5**). Secondly, contemporary and historical empirical-evidential underdetermination, and a plausible case for contrastive underdetermination, rebut epistemic justification in its traditional demanding form for cosmology. Moreover, recall our first lesson (**§III.1**): it suggests that empirical-evidential warrant for individual propositions scuppers on confirmational holism. Warrant is smeared out over large webs of assumptions. Even on a sanguine, more empiricist stance on justification—countenancing that empirical-evidential considerations can confer epistemic justification—epistemic justification is short-circuited: on the one hand, owing to holism, cosmologically substantive propositions in isolation lack justification; on the other hand, for *larger* clusters, their epistemic security ipso facto plummets, undercutting the (epistemologist's sense of) justification for those clusters. Thirdly, and finally, the centrality of philosophical arguments in cosmological reasoning (as per the second lesson, **§III.2**)—a parsec's cry from bestowing the security that epistemologists hanker after—stymy epistemic justification at a general level.[29]

Such an extraction stratagem doesn't sit well with standard epistemology's sense of justification, however. One may, for instance, attack the ad-hocness and messiness of the quarantining. It's commonly observed in the literature on models (e.g. Cartwright, 1983, esp. Ch. 3&8; Morgan and Morrison, 1999; Bailer-Jones, 2009) that their proper use and assessment—their epistemic content—are inadequately characterised as knowledge in the traditional epistemologist's sense. Which parts of a cosmological model are workable, reliable, promising, etc. can't be reduced to propositional knowledge but rooted in practical experience, art-like skills and implicit knowledge of (experimental and theoretical) scientists (see Stein, 1995; Curiel, 2022, 2023). Analogously to the prohibition to use illegally gathered evidence in court, one may repudiate such an extraction strategy as an illegitimate move for advocates of the epistemic account: given their commitment to traditional epistemological standards, it involves *shady* practices. The burden of proof would then lie on adherents of the epistemic account to sketch more concretely how "knowledge" is supposed to be extracted from models, in accordance with their own epistemological standards.

But it's doubtful that, even in principle, one *can* neatly quarantine all troublesome aspects. In part, this carries over from the practical dimensions of science, just commented on. They prevent a cut-and-dry segregation from the epistemic content of science. The point is further enforced by the inseparable entanglement of many different hypotheses, assumptions and theories that one encounters in cosmology. It's not possible to cleanly sever the (ostensibly) accurate and the inaccurate parts in cosmological reasoning and hypotheses. Like most models in science (Rice, 2018; see also Rice 2019 for details), cosmological claims, with their strong theory-ladenness, and epistemic holism in the sense of **§III.1**, are "*holistically […] distorted* representations of their target systems" (Rice, 2019, p.180). They arise "from the complex interaction of various modelling assumptions and idealizations that produce a *pervasive* misrepresentation of most of the features of their target system(s)" (ibid.).The idealisations in questions are indispensable. Moreover, some idealisations, for standard cosmology, are even constitutive for the conceptual framework itself (see e.g. op.cit., p.192)—conditions for its applicability: without them, calculations and interpretations become literally *meaningless*.

[29] Proponents of the epistemic account might demur that non-empirical considerations *can* serve to pare down plausible alternatives, thereby restoring epistemic justification. This faces two grave problems. First, the notorious quarrels amongst philosophers/scientists over them suggest that such non-empirical considerations don't confer upon theories the epistemic security that traditional epistemologists solicit for knowledge. Moreover, these non-empirical considerations are at face value more pragmatic rather than epistemic: they have to do with what sorts of features we *would like or need*, rather than what is *likely* to be true. Secondly, even if non-empirical considerations reduce the range of

Lastly, consider *belief*. Should we really impute to cosmologists "high credence in the truth of cosmological claims"? On the face of it, this seems implausible. It's widely recognised that cosmological theorising is holistic and speculative, and often blighted by various, historical and contemporary epistemic shortcomings. Believing or disbelieving (regarding a claim to be true or not) aren't the only cognitive attitudes available to scientists. Alternately, they may for instance, *entertain* them, *utilise* them, or *accept them as working hypotheses* (see, e.g., Laudan 1977, p.111, 1996, p.108; McKaughan, 2007). Given these cognitive attitudes, why think *belief* is required for progress to occur in cosmology, as per the epistemic account?

More plausible to ascribe to scientists than the cocksure certainty that would be required for progress on the epistemic account seems a more (self-)critical/undogmatic attitude. A perusal of philosophically reflective cosmology texts evinces healthy scepticism amongst cosmologists. They alert, for instance, to "major physical *uncertainties* concerning this [the LCDM] model" (Ellis et al., 2011, p.555). Ellis (2006, p.50) explicitly champions a "thesis of uncertainty": "(u)ltimate uncertainty is a key aspect of cosmology. Scientific exploration can tell us much about the universe [...]. Some of this uncertainty may be resolved, but much will remain."[30] Peebles (2022, Ch.1; 2024, see also Hogg, 2009) in fact opines that physicists' practice best tallies with pragmatism: hypotheses in science are adopted as "working assumptions" (see also Elgin, 2017, Chs.1-2); they "need not be justified by anything other than the fact that they are found to be useful"—for predictions or explanations (Peebles, 2022, p.43). His stance is upbeat fallibilism: "many aspects of physics have become plausible enough to inspire confidence, though never absolute belief" (Peebles, 2024, p.13).

In sum, cosmological claims violate necessary conditions for traditional epistemologists' understanding of knowledge.[31] On the epistemic account, there has hence been little to no progress in cosmology: whatever its intellectual fascination, due in particular to its speculative nature, cosmology doesn't deliver the good whose accrual, on the epistemic account, constitutes progress—propositional content that qualifies as knowledge.

What to make of such a verdict? We don't contest its coherence. At first blush, it doesn't even appear entirely devoid of plausibility: a relatively young discipline, cosmology entered its

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alternatives equally or better supported by empirical evidence, it *wouldn't* follow that they leave us with a single such theory—contrary to what, presumably, traditional epistemologists implicitly presuppose. Indeed, the philosophical criteria and principles employed in cosmology generally leave a multitude of alternatives on the table (cf. Kuhn, 1981; Laudan, 1984, Ch.1).

[30] This epistemological modesty is arguably no accident: falsificationism—with its attendant fallibilism—has been extraordinarily influential in cosmology (Kragh, 2012, 2013).

[31] This mismatch between traditional epistemologists' standards and what scientists regard as knowledge applies to almost all scientific findings (Bueno, 2019). It reflects the fundamentally different approaches of those parties to making sense of knowledge, "with very little interaction between the two fields" (op.cit., p.233) .

stage of unimpeachably empirical maturity only in the 1960s, with protracted debates over its scientific status (e.g. Kragh, 2007). Speculation gone wild isn't an uncommon repudiation of some more extravagant theorising by members of the scientific community itself (see e.g. Ellis & Silk, 2014).

Nonetheless, arguably, the epistemic account's conclusion throws out the baby with the bathwater. For two reasons, we view it rather as a reductio. One is its inordinate pessimism: should we really gainsay that cosmology has achieved sturdy progress? This jars with the respect that cosmology is enjoying: amongst scientists (e.g. Nobel prizes) and interested layfolk alike, its status in physics curricula, the astronomical sums of funding invested in it, etc. As mentioned in **§II.1**, it also jars with the verdicts by various historians and cosmologists. Secondly, cosmology's features responsible for the epistemic account's damning verdict are shared with many other disciplines: for instance, climate scientists, or palaeontologists likewise heavily rely on arguments and reasoning that fall short of justification in the traditional epistemologist's sense. It would strike us as preposterous to deny that these disciplines, like cosmology, cannot be (or aren't) progressive.[32]

III.4.2 The noetic account and progress in cosmology

This brings us to the noetic account. It doesn't define progress in terms of knowledge (or what are traditionally understood as its constituent parts: truth, belief and justification). Hence, the noetic account circumvents the foregoing attack on the epistemic account.

Instead, it requires progressive science to purvey *understanding*. While philosophical conceptions of understanding differ, understanding has generally been argued to encompass a cluster of cognitive achievements revolving around the idea of grasping how things hang together, e.g. how one thing explains another. Relatedly, understanding enables us to engage in further fruitful work with the topic (e.g. competent counterfactual, i.e. "what-if-things-had-been-different" reasoning, Baumberger, 2014, pp.74), or effective or reliable model-building (de Regt, 2017). For the sake of concreteness, we'll follow Dellsén (2020, 2021) in defining understanding in terms of *dependence relations* (cf. Elgin, 2017 for a similar proposal). They hold either amongst the intended targets of our understanding themselves (predominantly, but

[32] A different line of criticism would reject the epistemological ideal *underlying* the epistemic account on independent grounds (e.g. Albert, 1991). In particular, insofar as science relies on models, the inadequacy of such an epistemological ideal has been amply belaboured in the literature on models. Alternative epistemological conceptions exist (e.g. Chang, 2022; Anderson & Mitchell, 2023; or Elgin, 1996, 2017).

not exclusively, empirical phenomena), or between those targets and other elements of our wider intellectual horizon (other phenomena, background assumptions, etc.). Such dependence relations include causal ones, but also a broader array, such as reduction, limit and synthesis operations,[33] and metaphysical dependence relations, such as grounding (for others, see e.g. Tahko & Lowe, 2020). The representation of such dependence relations equip us with the ability for explanations, predictions, and (cognitive or practical) interventions on the phenomena that interest us (see e.g. Woodward 2003).

Science progresses, on the noetic account, when we are better positioned to understand: progressive science enables us to more accurately or more comprehensively represent dependence relations. Typical vehicles or loci of progress are scientific models (rather than theories or individual hypotheses, cf. Bailer-Jones, 2009; Gelfert, 2016; de Regt, 2017; Frigg & Hartmann, 2020). We thus apprehend a first relevant consequence of the difference between the noetic and the epistemic account: whereas knowledge is traditionally applicable to individual propositions, understanding is inherently holistic (cf. also Elgin, 2017, esp. Ch.1&4). Understanding is concerned with *connections* within a wider context of information, rather than the piecemeal assessment of individual propositions/hypotheses. Hence, the noetic account ab initio evades friction with the holism in cosmology (**§III.1**) (and endemic to other disciplines with rampant model-use).

Three hallmarks of understanding are widely accepted as such across different explications of "understanding" (including Dellsén's). One is the ability for successful predictions.[34] The Big Bang model's key accomplishment is an especially clear case in point—and the principal reason for its establishment as the leading paradigm: it successfully predicted the CMB, and the relative abundances of the light elements.

A second archetypal way in which noetic progress is achieved is the ability to formulate successful explanations of some target phenomenon.[35] Cosmology's second paradigm illustrates this particularly lucidly. The central achievement that inaugurated the shift to dynamically evolving models of the universe was Lemaître's interpretation of the redshift/distance data as a natural explanation in terms of an expanding universe. By the same

[33] It redounds to our understanding of a theory (and its domain) if we clarify its (partial) reduction to its precursor, such as in the case of quantum and classical physics, see Scheibe (1997).

[34] Here, "success" shall denote a satisfactory fit between the target phenomena and what our inferences, based on theorising, make us expect.

[35] No commitment needs to be made to any particular model of explanation. For concreteness, think of Skow's (2016) broad characterisation of explanation as a principled answer to a why question.

token, the fourth paradigm was instituted, to a large measure, thanks to inflation's ability to provide a common cause explanation of several putative fine-tuning problems.

Thirdly, and finally, understanding can also be paradigmatically achieved through what one might call conceptual integration[36] (cf. Falkenburg, 2014): especially for a nascent area of research, it's a cognitively weighty feat to accommodate target phenomena by successfully embedding them into a wider, coherent network of more abstract or merely phenomenological dependency relations—typically, a theoretical framework (see also Fraser & Koberinski, 2024).[37] Thus systematising and structuring a domain paves the way for further, more detailed and deeper inquiry. Cosmology's first paradigm is a case in point: Einstein's 1917 model allowed—for the first time!—the subsumption of the entire universe (albeit highly idealised) under a coherent, and consistent theoretical framework. By the same token, the fifth paradigm's impressive integrative accomplishments are routinely praised: "(w)ith some simple assumptions, [the ΛCDM] model fits a wide range of data, with just six (or seven) free parameters" (Scott, 2018, p.1).

Two main differences between understanding and knowledge bear reiteration. First, understanding doesn't require that *every* element involved in a noetic achievement be true. As Dellsén (2016, p.74) emphasises, understanding can be—and typically is—partial (rather than complete), and contextual (i.e. dependent on the target phenomenon and its aspects of interest that one wants to investigate, cf. Parker, 2010, 2020). Understanding furthermore admits of degrees. By contrast, knowledge is traditionally conceived of as an absolute—universal, and all-or-nothing—affair. To understand a phenomenon, it suffices if our grasp of it (through, say, a model) is "true enough" (Elgin, 2004) for the epistemic purposes at hand (e.g. explaining or predicting a particular type of phenomena)—if the "divergence from truth, if any, is negligible" (p.119). Understanding succeeds if those purposes are *satisficed*. Hence it allows for "felicitous falsehoods" (Elgin, 2022): idealisations and approximations can further our understanding—even at the expense of deliberate distortions. From this immediately ensues the noetic account's immunity to the queasiness surrounding cosmology's claims to truth (**§III.3**): advocates of the account recognise cosmology's noetic accomplishments, while

[36] This is kindred in spirit to unificatory accounts of explanation (Kitcher, 1981, 1989). Hence, one might view conceptual integration as a cognate of the foregoing noetic achievement.
[37] Such integration often also spawns *further* merits, predictions and explanations in particular. A case in point is Mendeleev's periodic table (see e.g. Schindler, 2018, Ch.3.5) (and also inflation, see **§II.2.4**). What matters for us is that the integration *per se* affords a substantial kind of understanding. Stellar or galaxy classification systems in astronomy (Ruphy, 2013) arguably come close to this .

conceding that the understanding achieved is merely partial and “adequate for purpose” (Parker, 2009, 2020).[38]

Secondly, whereas knowledge requires strict epistemic justification, understanding demands less. Some (e.g. Dellsén 2016, 2017, 2023; see also Rowbottom 2019) have argued that the notion of understanding doesn’t, and shouldn’t, require justification in the epistemologist’s sense. Advocates of the noetic account needn’t renounce *all* forms of justification (cf. Park, 2017; Emmerson, 2022; McCoy 2023; see also McCoy 2019). They may still embrace weaker and more flexible ones, or more heuristic styles of reasoning, shot through with pragmatism and opportunism (see e.g. Nickles, 2006; Currie, 2015b, 2017). The empirical-evidential underdetermination plaguing cosmology (**§III.2**) thus forfeits much of its horror. Understanding is consistent with a plurality of justificatory practices; they needn’t safeguard knowledge in the epistemologist’s sense.[39] Substantive reliance on extra-empirical (and, in particular, philosophical) considerations, and a dash of pragmatism—characteristic of cosmological reasoning, as per our second lesson (**§III.2**)—in particular find a natural home in the noetic account.

To wrap up, let’s juxtapose the noetic and epistemic account with respect to diverging predilections for the kind of cognitive improvements especially valorised in progressive science. The epistemic account places a premium on caution and conservatism (risk-aversion): it singularly prizes epistemic safety and security. Accordingly, one expects progressive science to prioritise the search for additions to a comparatively small corpus of ironclad epistemic achievements. Conversely, speculation and contentious assumptions are disincentivised. The noetic account, by contrast, places a premium on satisfying intellectual curiosity: it applauds innovation and amplification of our understanding, with tolerance for epistemic risks. Accordingly, for the noetic account, one expects—in the main—progressive science to prioritise the quest for expanding the cluster of hypotheses we adopt, our “web of understanding” (i.e. pushing the boundaries of what we understand) and improving the material quality of that web (i.e. increasing its accuracy or comprehensiveness).

[38] Accuracy for understanding isn’t to be confused with *wholesale* truth. Not all aspects of the target must be accurate for substantial understanding, only those of interest and (surmised) relevance. Rather than total truth, we only need “true enough” representations (Elgin 2004; see also de Regt & Gijsbers, 2016; Cornelissen & de Regt, 2022). Not all aspects of the target in fact must matter equally. Accuracy and comprehensiveness (scope) often pull in opposite directions. The trade-off is a context-dependent matter of “adequacy for purpose”. We’ll revert to this theme below.

[39] If at this juncture one were to fret about *too much* leeway, recall that an arguably minimal criterion, coherence (internal, and with other areas of scientific inquiry) is a feature integral to understanding. It imposes demanding constraints (see e.g. Currie, 2017; Currie & Sterelny, 2017; for the more general constraint of reflective equilibrium, see Elgin, 1996).

Advocates of the noetic account may thus join the chorus of scientists who hail the history of modern cosmology as a beautiful story of progress: *each* of the five paradigms augmented our understanding of the universe. This isn't, of course, to revel in triumphalism, or to soft-pedal epistemic defects, lacunae, anomalies, etc. The noetic account merely rightly celebrates and accentuates what makes science intellectually so gratifying and thrilling: the tangible understanding that we have achieved, and that holds encouraging promise for more. Understanding, with its link to potential for further inquiry, spurs scientists on to tackle outstanding shortcomings and continue exciting lines of progress.

IV. Conclusion

In this paper, we have argued that the development of modern cosmology presents a potent case study for the recent debate about scientific progress. With respect to the latter, we focused on the two main rivalling positions: the epistemic account, which defines progress in terms of knowledge, and the noetic one, which defines it in terms of understanding. The holistic and speculative nature of cosmological research in particular discords with key tenets of the epistemic account: modern cosmology, on this view, doesn't qualify as a progressive field. By contrast, the noetic account is not only fully compatible with—in fact, congenial to—those aspects of modern cosmology that proved a challenge for the epistemic account. On the noetic account, modern cosmology exemplifies a progressive discipline with substantial understanding-based accomplishments—in line with widespread verdicts by historians of science, and scientists themselves.

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