Out of Sight, Not Out of Mind: Scientific Progress in (quasi) de Sitter Cosmology

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Abstract

Our best cosmological model, the ΛCDM model, predicts that in a finite time all unbound systems will cross a cosmic event horizon, meaning that no new empirical data can ever be gathered. The Universe has already entered this phase, in which cosmological sources of information are progressively disappearing. This prospect shows that the dependence of Bird's epistemic and Dellsen's noetic accounts of scientific progress on continuing empirical input is not merely a definitional feature of *conditional* accounts, but a boundary that cosmology itself guarantees will be reached. This paper is not revisionary: it does not alter these accounts, but clarifies their scope by situating them within this cosmologically mandated regime. As an outlook, I sketch a *general* account of scientific progress grounded in *structural understanding*, which could preserve a notion of progress even once observation is no longer possible—while leaving open the further question of whether progress ought in fact to continue under such conditions.

Contents

1 Introduction

The observational discovery of cosmic acceleration at the close of the twentieth century deeply transformed cosmology (Riess et al., 1998; Perlmutter et al., 1999). Drawing on measurements of distant Type Ia supernovae, along with precision data from the Cosmic Microwave Background (CMB) and large-scale structure, astrophysicists have demonstrated that the expansion of space is accelerating under the influence of a mysterious dark-energy component, well described by a positive *cosmological constant*, Λ (Planck Collaboration, 2020a).[1]

Within the ΛCDM paradigm—the prevailing *concordance model* (Merritt, 2017)—this dark-energy component becomes ever more dominant, eventually overwhelming the content of matter and radiation Weinberg (1972).[2] The resulting evolution is *exponential* and the geometry asymptotically approaches that of a *pure* de Sitter spacetime, in which Λ fully governs the dynamics. The evolution of the Universe towards such an asymptotic phase characterises what I term the *quasi de Sitter phase*, which is the phase we are *currently* in.

One implication of this cosmological destiny is the formation of a cosmic event horizon. Within a finite proper time, all structures not gravitationally bound to an observer—those following the *Hubble flow*—will recede beyond this horizon. The Hubble flow describes large-scale motion driven by the expansion of spacetime, and is to be distinguished from local peculiar velocities due to local gravitational interactions (see Bamonti and Thébault, 2025). Although unbound objects remain physically present in the Universe, they become permanently causally disconnected: no signal they emit can *ever* again reach observers within the horizon. Inside the horizon, the Universe becomes observationally 'barren'. For observers in the Milky Way, only gravitationally bound structures such as the Local Group remain accessible. Such residual access sustains local astrophysics, but not *cosmology* understood as the inquiry into the Universe on large scales. In such a 'barren Universe', the empirical bedrock on which the entire cosmological enterprise traditionally rests is progressively and irreversibly eroded. This erosion is not speculative or anthropocentric: it is a demonstrable consequence of the dynamical structure of spacetime as described by general relativity and encoded in the ΛCDM model.

The epistemological significance of event horizons has long been recognised in the foundations of general relativity. As early as Schrödinger (1956)'s treatment of de Sitter spacetime, and through the influential work of Hawking and Ellis (1973), it became clear that global causal structures impose fundamental constraints on what can be observed, raising foundational questions about determinism and information. Philosophers such as Earman (1995) subsequently deepened these insights, elaborating on how horizons sever the empirical tether between theory and world. The present paper continues this line of inquiry, but reframes horizons in terms of their implications for two leading accounts of scientific progress.

In particular, I examine Alexander Bird's knowledge-based and Finnur Dellsén's understanding-based accounts.

Bird's *epistemic account* of progress defines scientific progress as the accumulation of scientific knowledge about

[1] I do not address here the physical, historical, or philosophical problems associated with the cosmological constant. For further discussion, see Weinberg (1989); Merritt (2017); Belot (2023).

[2] The term 'CDM' refers to 'Cold Dark Matter' The interpretation of CDM as consisting of material particles beyond the Standard Model remains contested. For an in-depth analysis, see, e.g., Turner (2000).

the world (Bird, 2007, 2022). Knowledge, as *factive*, requires both truth and empirical justification; by definition, if empirical input vanishes, epistemic progress stalls or even regresses.

Dellsén's *noetic account* identifies progress with increases in scientific understanding, understood as the scientist's grasp of how to correctly explain or predict real natural phenomena (Dellsén, 2016). Although understanding, in Dellsén's formulation, is only *quasi-factive*, its connection to the real world is maintained by the demand for correctness of explanations and predictions, which need to be tested against observations.

Both accounts are, by construction, tethered to empirical input. That fact is not in dispute. What the barren-universe case uniquely shows is that ΛCDM cosmology guarantees a regime where such input is permanently foreclosed. The contribution of this paper is therefore to situate current epistemologies of progress against this cosmologically mandated horizon, without attempting any reclassification or prescriptive revision.

In what follows I use the distinction between *conditional criteria*, which track progress only under specific background conditions—here, the availability of suitable empirical input, and *general criteria*, which are advanced as principled frameworks intended to characterise scientific progress as such, irrespective of contingent state of background conditions, e.g. data availability. They are valid as methodological or philosophical principles in principle, not only 'when data are available'.[3]

Classical accounts of progress such as those of Popper, Lakatos, Kuhn and others (see §2) were advanced as principled criteria intended to hold *generally*: they aimed to characterise how scientific progress should work as a matter of principle, rather than being explicitly restricted to contexts where new empirical input happens to be available.[4]

By contrast, Bird's and Dellsén's accounts are *conditional*: they deliver criteria of progress if and only if empirical input is available. Their restricted validity in empirically accessible regimes does not point to any flaw in the criteria themselves, which remain valuable for characterising scientific progress in the standard sense, namely, in relation to *empirical* science. The point is not that these accounts rely on empirical input and hence are conditional—a fact already built into their design— but that their *inapplicability as general criteria* is physically mandated. Accordingly, my aim is not to supplant these criteria, but is more modest and diagnostic: namely to show, via the barren-universe regime, that their conditionality is not simply a feature of their definition, but physically mandated by the causal structure of our Universe. Cosmology itself guarantees such a regime, making their conditionality a matter of physical inevitability. Therefore, the two accounts are not 'valid only in the presence of empirical data,' but are 'valid *as long as* empirical data are available.'

This prospect might seem to admit an obvious upshot: without empirical data, science cannot progress. That position is perfectly coherent and I do not dispute its legitimacy. This paper does *not* argue that progress should

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[3] A more pertinent term would be 'structural', but I want to avoid confusion with my proposal in §4 of *structural understanding*, so I will use the broader term 'general'.

[4] Of course, none of these accounts is free from empirical contingencies: their practical operation still involves empirical engagement. The point is only that they were advanced as general criteria for progress, not as criteria conditional on the presence of new data.

or must continue without data and therefore any account of empirically-based scientific progress must be rejected. Whether one sees this as a problem or as an acceptable limitation is another question.[5]

When later I consider analogue experiments, it is only to ask whether what counts as *empirical input* for these *conditional* accounts could be broadened (without suggesting that their core accounts require such broadening) to include indirect, surrogate forms of access; the conclusion is negative.

The structure of the paper is as follows.

In §2 I introduce Bird's and Dellsén's accounts within the broader landscape of competing accounts of scientific progress in epistemology and explains how the barren Universe illustrates, in physical terms, the limits of their conditional scope. I then briefly asses, whether *indirect* empirical input via analogue experiments could count, even in principle, as the sort of empirical access these *conditional* accounts require (§2.1.1).

§3 presents the physics of cosmic event horizon formation in ΛCDM cosmology, detailing the conditions under which the event horizon forms, and computing the characteristic timescales over which all unbound objects become causally disconnected, leaving behind a barren Universe. Technical details are left in §A.

The paper concludes by raising a further question: if empirically grounded accounts fall silent in our Universe's future, does this invite a rethinking of what scientific progress means in principle? I sketch, without presupposing its necessity, a non-factive, structurally oriented conception as one optional path that remains applicable even in observationally barren domains (§4).

2 The Epistemology of Scientific Progress

The question of what constitutes scientific progress remains a central concern in epistemology. Competing accounts have sought to capture its essence under different assumptions about the aims and structure of science (Niiniluoto, 2024). Before turning to the two conditional accounts that form the focus of my analysis, I briefly survey (without claiming to be exhaustive) some influential approaches to situate the discussion.

In the early to mid-twentieth century, Karl Popper proposed that scientific progress should be measured by a theory's capacity to make bold, *falsifiable* predictions and to survive stringent empirical tests (Popper and Weiss, 1959). On this view, a theory progresses to the extent that it exposes itself to the risk of being proven wrong and survives such scrutiny, thus eliminating error. Crucially, Popper was well aware of what later came to be called the *Duhem–Quine problem*: since no theory is tested as a whole, empirical evidence cannot decisively falsify a theory (Duhem, 1906; Quine, 1951). Empirical anomalies can always be ascribed to auxiliary assumptions or background theories rather than to the core theory itself (Popper, 1962).

[5] The consensus that scientific progress simply ceases without empirical inputs is anything but unanimous as it carries a potential cost: it would imply that current work in domains such as quantum gravity or string theory—fields lacking in achievable data—cannot count as genuine scientific progress. Whether one accepts that consequence or prefers to recognise some form of non-empirical progress is a substantive further question that I do not resolve here.

To accommodate this methodological insight, Imre Lakatos developed a methodology of scientific research programmes that evaluated progress by comparing the heuristic power of competing programmes, particularly their ability to generate novel predictions and accommodate anomalies without ad hoc adjustments (Lakatos, 1969; Leplin, 1975; Grünbaum, 1976).

Later, Thomas Kuhn offered a paradigmatic view, contending that science proceeds through cycles of 'normal science' governed by dominant paradigms, followed by revolutionary 'paradigm shifts' when anomalies accumulate and a new paradigm supplants the old (Kuhn, 1962). On this view, progress is not linear or cumulative but episodic and, to some extent, incommensurable across paradigms. This view introduced the idea that progress may be internally coherent within paradigms but does not necessarily imply convergence on a single objective truth.

Larry Laudan reacted to both Popper and Kuhn by advocating a problem-solving model (Laudan, 1977). He argued that scientific progress is best understood in terms of a theory's capacity to solve more empirical and conceptual problems than their rivals. His account preserved a commitment to rationality and empirical adequacy, while shifting the focus to pragmatic success.

Finally, the notion of verisimilitude, or *truthlikeness*, firstly introduced by Popper (1962), also gained traction, particularly in the work of Niiniluoto (1987). Verisimilitude seeks to formalise the intuition that newer theories can be 'closer to the truth' than their predecessors, even if the absolute truth remains out of reach. Yet defining a non-circular 'metric' for closeness to truth—without presupposing a standard of truth itself—remains a central technical challenge in this approach.

Taken together, these accounts reflect diverse and sometimes conflicting intuitions about progress: whether it is cumulative, revolutionary, instrumental, or truth-directed. Each has its own criteria and underlying assumptions and aims to capture progress in principle, not merely under specific empirical conditions. They form the conceptual backdrop for two recent proposals that have dominated current debate: Bird's epistemic account and Dellsén's noetic account. Unlike their predecessors, these are explicitly conditional on continued empirical access—a feature that becomes especially relevant once viewed in light of the horizon-enforced regime mentioned earlier.

2.1 Epistemic vs. Noetic Account: The Challenge of The Barren Universe

Accounts of scientific progress are numerous, but two have dominated recent debate: Alexander Bird's epistemic view and Finnur Dellsén's noetic view.[6] These are particularly relevant in the considered barren universe regime imposed by cosmology because they inherently tie progress to empirical access.

The distinction between conditional criteria and general, principled criteria of scientific progress frames the analysis.

Bird's *epistemic account* argues that progress is synonymous with the net increase of scientific knowledge. As Bird (2007, p.64) puts it: ''a [cognitive] episode in science is progressive when at the end of the episode there is more knowledge than at the beginning.'' On this view, scientific progress is not mere accumulation of justified true belief or successful problem-solving, but the growth of *scientific knowledge*—that is, beliefs which are (i) *factive*

[6]For other significant contributions, see Shan (2019); Rowbottom (2023).

(they must be true) and (ii) *Gettier-proof* (they must be supported by sufficiently robust justification so as to rule out cases of epistemic luck) (Gettier, 1963; Goldman, 1979).[7] Accordingly, Bird holds that, in order to count as scientific knowledge—and thus to contribute to genuine scientific progress— justification must go beyond the standard 'justified true belief' (JTB) model and instead be supplied by a *reliable* source of Gettier-proof justification. Empirical justification, when grounded in robust experimental design and rigorous data-processing, provides precisely this kind of reliability. In the absence of such rigorous empirical grounding, belief may be accidentally true or methodologically suspect, rather than genuine knowledge and therefore cannot contribute to scientific progress. Crucially, Bird (2022) distinguishes between mere raw data gathering and observations. Only after data have been processed by reliable statistical and methodological protocols—thereby attaining the epistemic status of *observations*—do they satisfy the Gettier-proof requirements for knowledge. It is through this process of disciplined scientific analysis that empirical data are rendered epistemically justificatory. For example, the raw strain data from LIGO's gravitational-wave detectors are not by themselves evidence of gravitational waves (Abbott et al., 2016). It is only after data analysis meets stringent reliability criteria (eliminating false positives or instrumental artefacts) that they secure the proper empirical justification and contribute to knowledge.[8] On Bird's view, then, empirical validation is not merely one way to track progress; it is constitutive of scientific progress *within his account*.

By contrast, Dellsén's *noetic account* (referring to the Greek word 'νοῦς', often translated as 'understanding') offers a more flexible alternative. In a sustained critique of the epistemic model, Dellsén argues that scientific progress is better captured by gains in *scientific understanding* rather than in knowledge (Dellsén, 2016). Central to this account is the notion of *grasping*, which Dellsén takes to involve a cognitive ability not only to infer how things are, but also to *counterfactually anticipate* how certain elements of the system would behave if other elements were different (see also Grimm, 2011; Wilkenfeld, 2011). In particular his focus is on what he terms *objectual understanding* (or 'understanding-what'), referring to grasping phenomena as wholes.[9] In detail, Dellsén defines scientific understanding in terms of an agent's cognitive capacity to *grasp how* to correctly explain or predict aspects of a target phenomenon: ''An agent has (partial) scientific understanding of a given target just in case she grasps how to correctly explain and(/or) predict some aspects of the target in the right sort of circumstances.'' (ibid., 75). Importantly, Dellsén includes *both* the ability to explain *and* the ability to predict, departing from some views that associate understanding

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[7]A further innovation of Bird's account is its treatment of *approximate* truth, which is supported, in part, by *pessimistic meta-induction* (Laudan, 1981). Schematically, Bird's argument goes as follows: If p is approximately true, then the proposition q, that 'p is approximately true', is itself true. Bird concludes that the epistemic account remains sound in the face of the objection that it is not possible to combine knowledge and the theoretical structure of science itself.

[8]Bird's focus is not on defining 'observation' *per se*, but on distinguishing between unprocessed data (the collection of which is not progress) and data that has been epistemically validated (which contribute to scientific progress). The knowledge of the existence of a gravitational wave, inferred from the processed LIGO data, is of the latter type. It is not 'mere data gathering'.

[9]This is contrasted with the more common notion of explanatory understanding or 'understanding-why'.For discussion on these two versions of understanding see Khalifa (2011).

exclusively with explanation (see e.g. Strevens (2013)'s view of understanding).[10] Unlike knowledge, understanding does not require full justification, nor even belief in the relevant theory. Dellsén's account is therefore *quasi-factive* : it does not require the truth of the full theoretical framework, but it does require that the explanatorily or predictively relevant elements be *correct*.[11] Quasi-factivity also allows the use of *minimalist idealisations*—simplifications or even deliberate falsehoods that do not undermine understanding because they are irrelevant to the *explanandum* and (/or) *predictandum*.[12]

To sum up, despite Bird and Dellsén's consensus that cognitive accomplishment is a component of scientific progress, they hold differing views on its essential virtues. Bird insists on the necessity of both truth and justification, rooted in empirical evidence. In contrast, Dellsén relaxes the requirement for justification (one may grasp *how* to correctly explain or predict a phenomenon even in the absence of justification or belief in the relevant theory), but maintains a substantive connection to truth via the requirement of *correctness*, thus emphasising a form of empirical grounding.[13]

Although understanding may appear more resilient than knowledge when empirical access is lost, this resilience proves illusory. Both Bird's epistemic account of scientific progress and Dellsén's noetic account, despite their differences, rely fundamentally on a sustained empirical connection to the world. That shared dependence becomes fatal once this connection is structurally severed by the formation of a cosmological event horizon.

In Bird's case, the breakdown is immediate: justification must be tethered to empirical evidence. If no new observations are possible, no new knowledge can be generated. Worse still, even *past* knowledge—acquired during earlier, data-rich epochs—becomes vulnerable to what I call *epistemic regression*: without the ability to reassess and 're-justify' earlier beliefs in light of new data or emerging doubts, knowledge may gradually lose its epistemic status and may degrade into mere belief.

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[10] According to Dellsén, scientific understanding is 'clearly a matter of degree' (ibid., 74): a *complete* understanding of a given objective would require grasping how to correctly explain *and* predict every aspect of that objective. A *partial* understanding of a given goal occurs when one grasps how to correctly explain *or* predict such aspects. Here, I do not need to prefer one or the other for my argument.

[11] I note that the author does not explain *how* to identify these 'relevant elements'.

[12] While not universally adopted, I suggest that *predictandum* may function as a conceptual counterpart to *explanandum* in discussions about the logical structure of scientific prediction.

[13] For the sake of completeness, I point out that Dellsén recently updated his proposal in terms of *dependency models*. According to the new proposed account ''an agent *S understands X* if and only if *S* grasps a sufficiently accurate and comprehensive dependency model of *X* ; and *S*'s *degree of understanding* of *X* is proportional to the accuracy and comprehensiveness of their dependency model of *X*'' (Dellsén, 2021, p.11256) (see also Dellsén, 2020). Here, dependency models are 'information formal structure' representing dependency relations between natural phenomena (e.g. causal relationships). However, this update in no way affects my arguments and the relationship between noetic account and observational void. In particular, the central role of correctness (here *accuracy*) remains intact. Understanding is still anchored in empirical reality. It is *this* that renders his account defenceless against the lack of empirical data in an empirically barren Universe.

At first glance, Dellsén's noetic account appears more resilient, since understanding does not require justifications, but only correctness. But this resilience is superficial. As Dellsén himself insists, scientific understanding is anchored in the *correctness* of explanations and predictions of *actual natural phenomena*.[14] And correctness, like justification, must be empirically assessable. If empirical access is no longer possible, then the criterion of correctness loses its grounding. In such a scenario, the quasi-factivity of understanding risks collapsing into mere speculation.

These are not incidental inconveniences but direct consequences of how the accounts are defined. Empirical access is not just helpful but constitutive for both. The barren Universe case matters here not because it is needed to infer the truism that 'without data, Bird's and Dellsén's accounts are inapplicable', but because it supplies a *physically guaranteed* regime in which their lack of generality is enforced. Their inapplicability as general criteria is thus not only definitional, but cosmologically inevitable. In fact, far from being exotic or hypothetical, the barren regime follows necessarily from our best current cosmological theory.

What remains true is that scientific progress, *if defined exclusively in epistemic or noetic terms*, cannot survive the de Sitter future. However, this does not by itself recommend any alternative account. It only motivates the option of *complementing* conditional criteria with a more general one, not in order to displace them in standard empirical science, but in case one wish to retain a notion of progress if (or, more appropriately, *when*) empirical access is foreclosed. I will tentatively sketch one such possibility in the conclusion (§4): a non-factive conception of progress grounded not in truth or observation, but in the internal coherence, structural integration, and synoptic power.

2.1.1 A natural line of resistance: analogue experiments

Since Bird's and Dellsén's accounts are conditional by design they lose applicability once empirical access is foreclosed. A natural objection, however, is that *indirect* empirical traction might still preserve their scope, *even in a barren regime*. The question, then, is not whether analogue methods could reclassify conditional criteria as general ones, but only whether they, in principle, broaden what counts as *empirical input* for those very criteria.

Analogue experiments are strategies in which a laboratory *source* system S is engineered and measured, and its behaviour is used to support claims about an *inaccessible target* T (Thébault, 2016; Dardashti et al., 2017, 2019; Crowther et al., 2019; Field, 2025). Proponents generally appeal to three requirements: (i) an argument for *external validity*: under suitable conditions, empirical results about S can be legitimately projected onto T;[15] (ii) a formal correspondence—often a *syntactic isomorphism*—between the *modelling frameworks* $\mathbf{M}_S$ and $\mathbf{M}_T$, allowing analogical transfer despite differing physical realisers (Bartha, 2010, 2024); and (iii) *universality*: the phenomenon $\mathscr{P}$ of interest must be insensitive to microphysical details and *multiply realisable* across a class of systems (Batterman, 2000). Acoustic dumb holes are canonical examples: they aim to establish that Hawking radiation effects depend on horizon

[14] ''The kind of understanding that I will argue increases as science makes progress is concerned with understanding natural phenomena as opposed to theoretical concepts[. . .]'' (Dellsén, 2016, fn.8).

[15] ''If arguments for external validation can be found and justified in cases of analogue experimentation then we *can* legitimately think about analogue experiments as providing evidence of the same epistemic type as conventional experiments'' (Thébault, 2016, p. 8).

kinematics rather than on fine microphysical structure, thereby supporting universality (Hawking, 1975; Unruh, 1981; Unruh and Schützhold, 2005; Steinhauer, 2016).[16]

Despite these promising features, several authors raised significant methodological concerns that, if recognised as well-founded,[17] would render analogue methods immaterial for my diagnosis of conditional accounts. Two main concerns are relevant here:

1. **Question-begging.** To infer from S that $\mathscr{P}$ obtains in T, one must already *presuppose* that the target modelling framework $\mathbf{M}_T$ (e.g. QFT in curved spacetime for black holes) applies to T. But that presumption is exactly what analogue confirmation purports to secure (Crowther et al., 2019).

2. **Model/target gap.** Even granting isomorphism and persuasive universality arguments, analogue experiments establish only that $\mathscr{P}$ occurs in the *model of* T, not in T itself. As Crowther et al. (2019, p. 3720) emphasise: multiply realisable radiation follows for whatever is accurately described by the current theory of black holes; it is a further question whether *actual* black holes instantiate the effect. Assumptions about the trans-Planckian regime, stationarity, asymptotic structure, or the validity of the effective-field-theory domain all erode the semantic adequacy of $\mathbf{M}_T$ for *actual* targets (cf. Thébault, 2016, §4). The analogue method confirms a phenomenon in S or in $\mathbf{M}_T$, not in T.

For conditional accounts, what matters is observational access to the *target* domain. In a horizon-foreclosed cosmos, no amount of laboratory analogy supplies observation of T or restores answerability to facts about T. Accordingly, while analogue experiments retain heuristic and modelling value, they do not broaden the empirical input on which these conditional accounts depend; the barren regime remains outside their domain of applicability.

3 Event Horizon in (quasi) de Sitter Cosmology: The Barren Universe

Having clarified the conditional scope of Bird's and Dellsén's accounts, I now specify what the *barren Universe* amounts to in physical terms. The aim here is to summarise, in a self-contained way, the standard causal structure and timescales of a ΛCDM universe approaching de Sitter, thereby making the epistemological stakes explicit. I do not claim any novel cosmological result; full derivations and numerics are deferred to Appendix A.

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[16] perturbations in fluids or Bose–Einstein condensates (BECs) propagate on an effective metric with a sonic horizon mirroring an event horizon; thermal phonon flux and entanglement can then be measured in the dumb hole S as surrogates for Hawking radiation-type behaviour in T. In Bose–Einstein condensates (BECs), perturbations propagate on an effective metric with a sonic horizon mirroring an event horizon; thermal phonon flux and entanglement can then be measured in the dumb hole S as surrogates for Hawking radiation-type behaviour in T. The detection of entanglement between partner phonon modes across the sonic horizon is considered a 'witness' to Hawking radiation (Page, 1993).

[17] The philosophical debate between supporters and detractors is still ongoing.

In the ΛCDM paradigm, the present Universe is already in a *quasi de Sitter phase*, defined by the dominance of the cosmological constant Λ over all other energy components. Standard analyses (both analytical and numerical) show that this evolution leads toward what I term the *barren epoch*, preceding the asymptotic *pure* de Sitter phase.

In a Λ–dominated (quasi de Sitter) regime, accelerated expansion leads to the formation of a *cosmic event horizon* (Faraoni, 2015). Its proper radius at cosmic time t is given by

$$r_{\rm ev}(t) = a(t) \int_t^\infty \frac{dt'}{a(t')}, \tag{1}$$

where $a(t)$ is the so-called *scale factor*, governing the dynamics of spacetime in a homogeneous and isotropic Universe. This quantity gives the proper distance that marks the boundary separating regions of spacetime at each time t that can causally influence an observer, from those that cannot *and never will* (but in the past $t_p < t$ they could). Unlike the static event horizon of a black hole event, which arises from gravitational collapse, the cosmological event horizon emerges from the expansion of the Universe.

In the *pure* de Sitter limit (with scale factor $a(t) = e^{H_\Lambda t}$, $H_\Lambda = \sqrt{\Lambda/3}$) one obtains the familiar constant value

$$r_{\rm ev}^{dS} = H_\Lambda^{-1} \approx 15.9 \text{ Gly}. \tag{2}$$

Using Planck data (Planck Collaboration, 2020a), the *present* event horizon is $r_{\rm ev}(t_0) \approx 13.8$ Gly and increases only slightly thereafter, asymptoting to (2).[18] By contrast, the proper distance of any unbound source comoving with the Hubble flow grows as $D(t) = D_0\, a(t)/a_0$ and, in the Λ–dominated regime, effectively as $D(t) \propto e^{H_\Lambda (t-t_0)}$. The difference in rate of expansion is therefore clear: a slowly saturating horizon versus exponentially receding sources. For every unbound system there exists a crossing time $t_{\rm cross}$ at which $D(t_{\rm cross}) = r_{\rm ev}(t_{\rm cross})$; beyond that epoch, no future light from that system can ever reach us.

Crucially, this process is *already underway*. *Even today*, in a Universe not yet fully dominated by Λ, the expansion is sufficient to push distant sources toward disconnection. Because the event horizon asymptotes to a fixed value while the recession of sources accelerates, we are witnessing the gradual erosion of causal access. Each time a galaxy crosses the event horizon, its future light becomes permanently inaccessible. Although such sources continue to exist and emit radiation, their signals are increasingly redshifted, weakened, and dispersed.

Agreed: no observer ever sees an object *crossing* the horizon: its redshift diverges asymptotically and signal-to-noise ratio collapses (Serjeant, 2010). However, as redshift increases, the photon energies fall, arrival rates slow, and brightness drops steeply. Eventually, these signals become observationally indistinguishable from instrumental noise and for all practical purposes, they vanish from the observational domain.

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[18] The fact that the present-day event horizon is at 13.8 Gly is merely a numerical coincidence with the fact that the age of the Universe is 13.8 Gyr . In fact, over those 13.8 billion years, space itself has been expanding, so even though light has only been travelling for 13.8 Gyr, the expansion of the intervening space carries its sources far beyond 13.8 Gly. For details on these standard concepts in cosmology, see e.g. Misner et al. (2017); Carroll and Ostlie (2017); Kolb (2018).

This marks the onset of what I term the *barren epoch*, in which empirical access to unbound structures is irreversibly and progressively lost. Cosmology is already entering the first stages of disconnection. This is not a theoretical extrapolation to infinity, but a gradual process currently unfolding. This fact grounds the present focus on its epistemological implications.

Crucially, it is not even necessary to wait an infinite amount of time for us to consider the universe as genuinely observationally barren. Given that we are already in a quasi de Sitter phase, one can compute a *finite time* (t_{barren}) after which an observer will inhabit an effectively'informationless' universe, thus entering the barren epoch.

Calculations (details in Appendix A) yield:

$$t_{\text{barren}} - t_0 \approx 61.6 \text{ Gyr}, \tag{3}$$

By t_{barren}, photons from all unbound structures will have been redshifted into observational oblivion. Supernovae, large-scale structure, and the cosmic web *beyond* the Local Group will no longer provide empirical input. At this stage, cosmology as the science of large-scale structure will have lost the capacity for data-driven testing and, with it, its empirical foundation. What remains is an observational domain bounded and impoverished—a *barren Universe*. The relevant 'information vacuum' occurs well short of any $t \to \infty$ idealisation: by t_{barren} the cosmic horizon has essentially saturated to its de Sitter value whereas the scale factor has grown by $e^{H_\Lambda(t-t_0)}$, so recession overwhelms causal contact long before asymptotia.

This physical picture bears directly on the epistemology of scientific progress and on the conditions of applicability for the two contemporary accounts under consideration. Bird's epistemic account, which requires new justified observations, falls outside its scope once the evidential pipeline is structurally foreclosed. Dellsén's noetic account, which requires empirically assessable correctness, likewise loses its footing once large-scale structures become inaccessible. Agreed: astrophysics of bound systems may continue, but *cosmology qua science of the Universe* enters the barren regime.

One might object that the barren Universe lies too far in the future to matter for present-day epistemology. This misses the point. Although the epoch t_{barren} lies far beyond any plausible *human* future, its epistemological impact is not diminished. The point is not merely whether *we*, as human beings, will be present to witness this empirical silence. The relevance of the scenario is not its temporal proximity but its status as a guaranteed regime, given our best cosmology, that shows that the limits of the accounts under consideration are guaranteed by physics itself. The proposed cosmological case study therefore matters *now*, because it shows that conditionality of Bird's and Dellsén's accounts is not just a rhetorical or counterfactual issue, but has an inevitable physical horizon that makes it conceptually relevant, even today.

4 Conclusion and Outlook

This paper has offered a diagnosis of the scope of Bird's epistemic account and Dellsén's noetic account of scientific progress by situating them against an empirically barren regime mandated by our best cosmological theory. The relevance of this diagnosis is not the self-evident statement that these accounts presuppose empirical data—a fact already built into their design—but that their conditional scope and inapplicability as general criteria are physically mandated by the causal structure of our Universe. Accordingly, the conclusion is not the collapse of the epistemology of progress *tout court*. This analysis does not demand that progress must continue beyond empirical contact, nor that these accounts require revision. I also showed that analogue experiments, while often heralded as a way to probe otherwise inaccessible regimes, do not alter this diagnosis, since they do not extend the domain of applicability of conditional accounts into a genuinely barren universe.

This scenario can also be situated within broader debates in the epistemology of historical science. Currie (2018) characterises 'unlucky epistemic situations' where trace-evidence is degraded and distorted, rather than entirely absent. In such situations, Currie argues for *epistemic optimism*, grounded in *methodological omnivory*—the practice of drawing on diverse, often heterogeneous methods that include 'non-trace' sources of historical knowledge (modelling, simulation, experimental analogy, narrative reconstruction, etc.)—to overcome evidential gaps. Crucially, optimism in the historical sciences ultimately depends on at least minimal empirical contact, however indirect. By contrast, in a permanently barren universe the causal structure of spacetime forecloses even this minimal contact. Since analogue surrogates also fail to extend empirical reach (§2.1.1), the situation here is uniquely severe: evidential absence is not contingent but physically mandated. The present analysis therefore points toward *epistemic pessimism*—though without prescriptive intent.

What, then, of a more general criteria of scientific progress? I do not attempt to resolve this question here, but I tentatively sketch one possible direction: a radical, *structural account of scientific understanding*. For present purposes, its most crucial feature is *non-factivity*: it does not depend on truth or empirical feedback, but on the development coherent and robust theoretical frameworks. On this account, science does not progress by coming to know or understand the empirical world. Science, in this sense, flourishes structurally: it deepens and *interconnects* both distinct theories and the internal architecture of individual theories, generating new conceptual resources and novel cross-domain insights. This is precisely what allows structural understanding to remain a viable conception of progress even in a barren universe, where empirical input is irreversibly absent. Its epistemological value is measured by *synoptic power*: scientific progress is indexed by the integration of disparate theoretical domains within a coherent structure, thereby enhancing the *overview* of science. As such, it is indexed not by its increasing representational fidelity to empirical phenomena, but by the expansion and networking of our *theoretical repertoire*. Crucially, the radical non-factivity advocated here is not to be confused with milder forms of non-factivity found in accounts such as those of Doyle et al. (2019) and Chirimuuta (2022), which emphasise how strategic falsehoods (e.g. idealisations) provide no less understanding than more accurate representations, but still support that understanding somehow answers to facts. By contrast, the proposal here is more radical: to sever the notion of understanding entirely from the world.[19] Its ambition would be to provide the *generality* lacking in conditional epistemic and noetic criteria. The suggestion here is illustrative rather than prescriptive: it indicates one way of extending the concept of progress, should one wish

[19]For a critique of the complete disconnection of understanding from the world, even within a structuralist framework, see Kosso (2006) .

to retain a notion of progress in empirically barren regimes. In this sense, it does not replace conditional accounts in ordinary contexts, but rather *complements* them.

Below, I propose a significant example of how structural understanding works in the cosmological case under consideration, although further details will need to be developed in future work. Substantial progress could be achieved by integrating models of late-time dark energy and primordial inflation into a single coherent framework.[20] Such integration would count as progress not because it approaches empirical truth through new data, but because of its synoptic power: how effectively it systematises existing theoretical resources, reveals structural connections across domains and expands our theoretical repertoire. This provides a brief insight into how a structural explanation of understanding can support cosmological progress even in the absence of empirical data characterising the barren Universe.

A few further features of structural understanding, though not directly relevant for the present argument, are worth noting for completeness.[21] It is *non-doxastic*, *compatible with epistemic luck*, and *insular to sceptical doubt* (e.g. in Descartes' *genius malignus* scenario (Newman, 2023), structural relations remain understandable even if the external world were an illusion). Together, these properties underscore the character of structural understanding as an alternative epistemological basis for scientific progress.

A further question for future work is whether, and in what sense, structural understanding–driven progress still counts as *scientific*. At the very least, the present analysis has clarified the conceptual terrain: empirically-based accounts must be qualified as conditional, while structural understanding aspires to generality. Future work will need to develop this proposal in detail, assessing both its philosophical coherence and its practical relevance for cosmology and beyond.

A Appendix A: Technical Derivations and Numerical Details

FLRW Cosmology. The standard spatially flat Friedmann–Lemaître–Robertson–Walker (FLRW) metric, written in natural units where the velocity of light $c = 1$ reads:

$$ds^2 = -dt^2 + a^2(t)(dr^2 + r^2 d\omega^2),$$

The dynamics of $a(t)$ is governed by the *first Friedmann equation*, which for a Universe composed of pressureless matter (both baryonic and cold dark matter), radiation (relativistic particles and CMB photons), and a cosmological constant Λ, reads:

[20] For the *locus classicus* on the physics-side for unifying inflation and dark energy see Peebles and Vilenkin (1999); for a philosophy-side overview of inflation and dark energy, see Smeenk (2013); Ferreira et al. (2025).

[21] This list does not claim to be exhaustive. A study dedicated exclusively to fully characterising the structural understanding proposed here, with a more in-depth analysis of all its properties, is to be carried out in the future.

$$H^2(t) = \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left(\Omega_{m,0}a^{-3} + \Omega_{r,0}a^{-4} + \Omega_{\Lambda,0}\right). \tag{4}$$

Here the parameters $\Omega_i(t) := \frac{\rho_i(t)}{\rho_{\text{crit}}(t)}$ are called *density parameters* for the i-th component (radiation, matter and Λ) at cosmic time t and are defined as the ratio of the energy density $\rho_i(t)$ of that component to the *critical density* $\rho_{\text{crit}}(t) = \frac{3H(t)^2}{8\pi G}$, with G Newton's gravitational constant. Their present-day values, according to Planck CMB data (Planck Collaboration, 2020a), are: $\Omega_{m,0} = 0.31$, $\Omega_{r,0} = 10^{-4}$, and $\Omega_{\Lambda,0} = 0.69$, while the *Hubble constant* is $H_0 = 67.4$ km/s/Mpc.[22]

Cosmic time and Redshift. Cosmic time of a certain epoch characterised by a certain value of the scale factor is given by:

$$t(a) - t_0 = H_0^{-1}\int_1^a \frac{da'}{a'\sqrt{\Omega_{m,0}a'^{-3} + \Omega_{r,0}a'^{-4} + \Omega_{\Lambda,0}}}, \tag{5}$$

where t_0 (such that $a(t_0) = 1$) corresponds to 'today'.

In an expanding universe, the cosmological redshift is defined by $1+z = \lambda_0/\lambda_e = a(t_0)/a(t_e)$, so that $a(t_e) = 1/(1+z)$, and corresponds to a *lookback time*:

$$t_0 - t(z_e) \ = \ \int_0^{z_e} \frac{dz'}{(1+z')H(z')} \ = \ H_0^{-1}\int_0^{z_e} \frac{dz'}{(1+z')\ \sqrt{\Omega_{m,0}(1+z')^3 + \Omega_{r,0}(1+z)^4 + \Omega_{\Lambda,0}}},$$

where $t(z_e) = t_e$ is the past cosmic time when the source emitted the light we observe today.

Quasi-de Sitter Phase. Once $\Omega_\Lambda(t) > \Omega_m(t)$ and $a(t) > a(t_{\text{equivalence}}) := a_{\text{equivalence}} \approx (\Omega_{m,0}/\Omega_{\Lambda,0})^{1/3} \approx 0.77$, that is, roughly 4 Gyr ago ($z \approx 0.3$), cosmological constant began to dominate the dynamics, triggering accelerated expansion. This phase, here described as *quasi de Sitter phase*.

Pure de Sitter phase. When Λ completely dominates the expansion, the Hubble parameter approaches a constant $H(t) \to H_\Lambda = \sqrt{\frac{\Lambda}{3}}$, and the FLRW metric (**??**) approaches that of a *pure* de Sitter Universe:

$$ds^2 = -dt^2 + e^{2H_\Lambda t}(dr^2 + r^2 d\omega^2), \tag{6}$$

in which we recognise the scale factor to grow *exponentially* as $a(t) = e^{H_\Lambda t}$.[23]

Working in the so-called *static patch*, the de Sitter metric (6) reads:

$$ds^2 = -(1 - H_\Lambda^2 r^2)dt^2 + \frac{dr^2}{1 - H_\Lambda^2 r^2} + r^2 d\Omega^2, \tag{7}$$

exhibiting a physical event horizon at (proper) radius $r_{\text{ev}}^{dS} = H_\Lambda^{-1}$. No signal originating from $r > r_{\text{ev}}^{dS}$ can ever reach a static observer at $r = 0$, since $g_{tt} = 0$ marks an infinite-redshift surface. In detail, in static coordinates the cosmological

[22] The measurement of H_0 suffers from the so-called *Hubble-tension*. For a review see Smeenk (2022).
[23] I have rescaled the coordinates such that $t_0 = 0$.

horizon is the null surface where the time-translation Killing field goes null at $r_{\rm ev}^{dS} = H_\Lambda^{-1}$, enclosing a 'static patch' $0 \le r < H_\Lambda^{-1}$.

de Sitter event horizon. The event horizon in ΛCDM can be written in the usual form:

$$r_{\rm ev}(t) = a(t) \int_t^\infty \frac{dt'}{a(t')} = a(t) \int_{a(t)}^\infty \frac{da'}{a'^2 H(a')} \,. \tag{8}$$

In de Sitter, $a = e^{H_\Lambda t}$ gives $r_{\rm ev}^{dS} = H_\Lambda^{-1} = \sqrt{3/\Lambda} \approx 15.9\,\text{Gly}$. Note that the value coincides with that of the *Hubble length* $L_H(t) = \frac{1}{H(t)}$ which mark the transition between subluminal and superluminal recession at time t.

Barren threshold and timescale. Define the practical threshold by

$$\frac{\Omega_{m,0} a^{-3}}{\Omega_{\Lambda,0}} = 10^{-5} \quad \Rightarrow \quad a_{\rm barren} = \left(\frac{\Omega_{m,0}}{10^{-5}\Omega_{\Lambda,0}} \right)^{1/3} \approx 35.8. \tag{9}$$

This threshold is comparable to the magnitude of small inhomogeneities fluctuations in the CMB (Planck Collaboration, 2020b). Since the Universe is considered practically homogeneous at those scales, despite small inhomogeneities, I believe that it is reasonable to adopt the same threshold to consider a practically perfect de Sitter Universe.

Using the equation (5), we can compute the corresponding time interval from the present:

$$t_{\rm barren} - t_0 = H_0^{-1} \int_1^{a_{\rm barren}} \frac{da'}{a' \sqrt{\Omega_{m,0} a'^{-3} + \Omega_{r,0} a'^{-4} + \Omega_{\Lambda,0}}}, \tag{10}$$

As stressed above, already 'today' ($a = 1$) we are in a phase where the cosmological constant *dominates* the evolution, thus we can safely set $a(t) \propto e^{H_\Lambda t}$ and consider radiation as completely negligible. Thus, the integral (10) approximates to:[24]

$$\begin{aligned}
t_{\rm barren} - t_0 \approx\; & H_0^{-1} \int_1^{a_{\rm barren}} \frac{da'}{a' \sqrt{\Omega_{m,0} a'^{-3} + \Omega_{\Lambda,0}}} \\
& \approx H_0^{-1} \int_1^{a_{\rm barren}} \frac{da'}{a' \sqrt{\Omega_\Lambda} \left(\sqrt{1 + \frac{\Omega_{m,0}}{\Omega_{\Lambda,0}} a'^{-3}} \right)} \\
& \approx H_0^{-1} \int_1^{a_{\rm barren}} \frac{da'}{a' \sqrt{\Omega_\Lambda}}, \quad \text{given that } \frac{\Omega_{m,0}}{\Omega_{\Lambda,0}} < 1 \text{ and } a > 1 \\
& \approx \frac{1}{H_0 \sqrt{\Omega_{\Lambda,0}}} \ln(\mathrm{a_{barren}}) \\
& = \frac{1}{3 H_0 \sqrt{\Omega_{\Lambda,0}}} \ln \left(\frac{\Omega_{m,0}}{10^{-5}\Omega_{\Lambda,0}} \right) \approx 61.6\,\text{Gyr}.
\end{aligned} \tag{11}$$

This result is consistent with earlier estimates in the literature. At $t_{\rm barren}$, the event horizon is practically identical

[24]To the best of my knowledge, these explicit calculations have never been *explicitly* reported before. However, related estimates can be found, for example, in Krauss and Starkman (2000); Krauss and Scherrer (2007).

to its asymptotic pure de Sitter value $r_{\rm ev}(t_{\rm barren}) \approx r_{\rm ev}^{dS} \approx 15.9\,\mathrm{Gly}$. So its present value will have grown only marginally. The fractional difference $\frac{r_{\rm ev}(t_{\rm barren})-r_{\rm ev}(t_0)}{r_{\rm ev}(t_0)} \sim 0.15$, shows precisely that the event horizon only grows in size by a few percent over the interval $(t_{\rm barren} - t_0)$. By contrast, the Universe will have expanded by a factor of approximately $e^{H_\Lambda(t_{\rm barren}-t_0)} \approx 35.8$. The disparity in growth rates illustrates how recession overwhelms causal contact.

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