



The landscape and the multiverse: What's the problem?

James Read¹ · Baptiste Le Bihan²

Received: 19 August 2020 / Accepted: 24 March 2021
© The Author(s) 2021

Abstract

As a candidate theory of quantum gravity, the popularity of string theory has waxed and waned over the past four decades. One current source of scepticism is that the theory can be used to derive, depending upon the input geometrical assumptions that one makes, a vast range of different quantum field theories, giving rise to the so-called landscape problem. One apparent way to address the landscape problem is to posit the existence of a multiverse; this, however, has in turn drawn heightened attention to questions regarding the empirical testability and predictivity of string theory. We argue first that the landscape problem relies on dubious assumptions and does not motivate a multiverse hypothesis. Nevertheless, we then show that the multiverse hypothesis is scientifically legitimate and could be coupled to string theory for other empirical reasons. Looking at various cosmological approaches, we offer an empirical criterion to assess the scientific status of multiverse hypotheses.

Contents

1	Introduction	.....
2	String theory and the landscape	.....
3	Prediction and explanation	.....
4	From the landscape to a multiverse	.....
5	Empiricist and rationalist motivations for the multiverse	.....
6	Smolin's rationalist motivations	.....
7	Other multiverses and their scientific credentials	.....
7.1	Eternal inflation	.....
7.2	Cyclic multiverses	.....
7.3	Loop quantum cosmology	.....

✉ Baptiste Le Bihan
baptiste.lebihan@unige.ch

James Read
james.read@philosophy.ox.ac.uk

¹ Faculty of Philosophy, University of Oxford, Radcliffe Humanities, Woodstock Road, Oxford OX2 6GG, UK

² Département de philosophie, Université de Genève, Rue De-Candolle 2, 1205 Genève, Switzerland

7.4 Modal realism and pythagoreanism	
8 Conclusions	
References	

1 Introduction

As a candidate theory of quantum gravity, the popularity of string theory has waxed and waned over the past four decades. Recently, the endorsement of the approach has again faced a downturn, in light of issues such as the so-called *landscape problem*. Roughly, the idea of this alleged problem is the following: while physicists originally held out hope that string theory would allow for the derivation of the standard model of particle physics *uniquely*, in fact the theory can be used to derive, depending upon the input geometrical assumptions that one makes, a vast range of *different* quantum field theories (often, the number 10^{500} is floated). Early hopes by string theorists for a unique ground state hinged on the possibility that vacuum stabilisation worked only in special cases of the wide range of possible Calabi-Yau manifolds. In fact, however, modern analysis of vacuum stabilisation (following e.g. Kachru et al. 2003) suggests a very broad class of possible vacua. In light of this, critics claim that the predictive and explanatory power of string theory is lost. In response, some scholars have suggested answering the landscape problem by positing the existence of a multiverse comprised of different universes corresponding to the various string theory solutions.¹

The purpose of this paper is to argue first that, all things considered, the landscape problem is *not* a damning issue for string theory (indeed, stronger: there is no genuine landscape problem at all), and second that, even if one were motivated to move to a multiverse hypothesis in light of the landscape problem, the concept of a multiverse can nevertheless be a perfectly scientific one.² Auxiliary aims of this paper are twofold: first, to add to the nascent philosophical literature on the landscape problem;³ second,

¹ Note that the landscape problem is often associated with another distinct issue: *the fine-tuning problem*. The fine-tuning problem raises the question of why the values of the parameters involved in the laws of nature, or the background geometry in the string setting, seem to be fine-tuned for life. The multiverse hypothesis is often advanced as a way to solve the fine-tuning problem. The fine-tuning problem and the landscape problem should be kept separate, as while the former starts by appealing the contingency of parameters or background geometry involved in the theory under consideration, the latter points out the tremendous size of the space of solutions of that theory. In the present article we focus on the landscape problem only.

² Throughout this paper, we understand a ‘scientific’ hypothesis or concept to be one which is amenable to empirical test. This standard usage does not commit us to a Popperian falsificationist methodology (on which more to follow).

³ Philosophical papers which address the landscape problem are Smolin (2013a), Camilleri and Ritson (2015), Ritson and Camilleri (2015), Matsubara (2018) and Alonso-Serrano and Jannes (2019); works discussing multiverse hypotheses more generally include Ellis (2007, 2011, 2012), Ellis and Silk (2014), and Carroll (2019). Although we will have some critical comments to make on Smolin below, in our view he, more than any other author, has advanced philosophical discussion of the landscape problem. With respect to the majority of the other above papers: we take the present work, broadly speaking, to be complementary—although this paper, as will become clear, seeks (a) a more thoroughgoing analysis of the predictive/explanatory content of multiverse hypotheses (with particular focus on the landscape problem of string theory), and (b) a novel distinction between empiricist/rationalist motivations for multiverse hypotheses.

to bring out important general issues in the philosophy of science regarding multiverse hypotheses, via the lens of the landscape problem. We argue that the landscape problem is not a genuine problem as it relies on question-begging metaphysical assumptions and hence does not in itself suffice to motivate a multiverse hypothesis. Nevertheless, we elucidate the existence of two very different possible sorts of motivations in favour of multiverse hypotheses and review more convincing reasons for defending such hypotheses.

We focus first on the landscape as defined by Susskind (2005, p. 574)—that is, the space of dynamically possible models of string theory (we will elaborate upon this in more detail in Sects. 2 and 3). We then consider the idea of a landscape in a second sense—namely, a landscape associated with a *single* solution, describing a reality in which ‘bubble universes’ or ‘pocket universes’ of some kind are embedded in a multiverse (Sect. 4), and discuss the various motivations behind such hypotheses (Sect. 5). We then focus on motivations offered specifically by Smolin in favor of the multiverse hypothesis, showing that they are too philosophical to establish anything beyond doubt—however, we show that they are perfectly legitimate as guiding principles in theory construction (Sect. 6). We then analyse different popular notions of the multiverse to be found both in contemporary physics and philosophy, with a focus on eternal inflation, examining their relations with empirical testability (Sect. 7).

2 String theory and the landscape

String theory is one of the best-known and most-studied candidate quantum theories of gravity—i.e., theories which attempt to unify quantum mechanics and general relativity. In brief, the picture that string theory presents is the following. Begin with a background ‘target space’ of some topology and geometry. On this target space, consider a one-dimensional string. Quantise this string, and study its spectrum; one finds certain excited states with the same quantum numbers as certain quantum fields—notably, for the closed string, one finds an excited state corresponding to the graviton (i.e., a massless spin-2 field). Now consider strings in a particular such excited state, distributed across target space—in the non-stringy, non-quantum limit, such strings behave as classical fields on the target space—so-called ‘coherent states’.⁴ Returning to the dynamics of the string, consistency constraints on the string worldsheet mandate that the background fields obey certain equations: if the original target space is Minkowskian, then one finds that these background fields must satisfy (generalisations of) the Einstein field equations of general relativity, plus dynamical equations for matter fields.⁵

Again for reasons of consistency, the target space of a fermionic string theory (so-called ‘superstring theories’, due to their inclusion of supersymmetry) must be ten-dimensional. In order to recover the phenomenology of our four-dimensional world, it

⁴ There are particular subtleties involved in making this precise, which warrant the urgent attention of the philosophical community. For further discussion, see Huggett and Wüthrich (forthcoming). We set these matters aside in the remainder of this paper.

⁵ See e.g. Huggett and Vistarini (2015) for a philosophical presentation.

is typical⁶ to ‘compactify’ six of the dimensions of the target space—that is, to associate such dimensions with some compact manifold. Still for reasons of consistency, this compactification must be effected on a so-called ‘Calabi-Yau threefold’: certain six-real-dimensional compact manifolds. There is a huge number of such manifolds; different choices will lead to different four-dimensional matter fields.⁷ To add to this, for each such choice of target space, one can introduce extra objects, e.g. D-branes, which in turn lead to further possible configurations for the four-dimensional matter fields. The result is that string theory is consistent with *a vast range of solutions*. Thus, the string landscape is born (see Susskind 2005, 2007).

Note that, at this point, the landscape merely represents the *space of solutions* (sometimes: space of ‘dynamically possible models’) of a particular physical theory. That a theory has many solutions is not particularly new, and we will investigate later why the situation is taken to be particularly problematic in the case of string theory. At this stage, what matters is that physicists were initially expecting string theory to have only one solution, an ‘old hope’ (as Matsubara 2018, p. 45 puts it), which has now been supplanted by the landscape view that string theory will probably end up having a huge number of solutions. Now, the nostalgia of the old hope of getting one solution only from string theory might be taken to motivate theorists to reify the landscape into a multiverse.⁸ This amounts to turning a situation of one theory having many solutions into an extended theory taking all the solutions of the former theory to describe parts of a multiverse, thereby gluing together what seemed to be distinct possible worlds (i.e. possible solutions to the original theory) into a multiverse. However, before examining in detail the concept of the multiverse and its scientific status, let us turn first to the landscape problem, in order to examine whether this is genuinely a problem, and if so, the nature of this problem.

3 Prediction and explanation

The landscape, understood as the existence of a plurality of solutions of string theory, is often viewed as being problematic for string theory by undermining its predictive power, its explanatory power, or both.⁹ Let us first have a look at predictive power, before turning to explanatory power. What does it mean for a given scientific theory to

⁶ Though not essential, as demonstrated by brane cosmology: an approach in which our familiar four-dimensional spacetime is regarded as being located on a hypersurface of certain codimension within a higher-dimensional space. See Sect. 7 below.

⁷ An ongoing task for string theorists is to identify the appropriate choice of Calabi-Yau compactification such that the standard model of particle physics is recovered on the four-dimensional space. One interesting approach to this problem has deployed the tools of machine learning: see He (2017).

⁸ It is worth stressing that what we are countenancing here is a possible theoretical move—we are not claiming that any theorists actually endorse this move; moreover, it is distinct from a cosmologically-populated multiverse (more on which below). In particular, in the language which we will introduce in later sections, the above ‘old hope’ is a *rationalist* motivation for a multiverse; considerations from e.g. eternal inflation are *empiricist* motivations. Many early proponents of the multiverse in string theory held the latter motivations, but it is not obvious that they ever held the former.

⁹ In applying this (fairly standard) distinction to the landscape problem, we follow in this section the prior work of Matsubara (2018).

have predictive power? One plausible answer here is the following: given the empirical data observed thus far, we are able to identify at least one solution of the theory in question compatible with that empirical data; such solutions can then be used to make new predictions that could turn out (but do not have) to be correct. Note that if *no* solutions of the theory under consideration were compatible with the empirical data thus far gathered, then the theory would have no predictive power, for it would be empirically inadequate;¹⁰ if *multiple* solutions of the theory under consideration were compatible with the available empirical data, then, within the context of that theory, one would face an issue of *weak underdetermination*.¹¹

On this understanding, the *total* number of solutions of the theory under consideration is irrelevant to the predictive capacities of that theory—what is relevant is the number of solutions of the theory which are *compatible* with the empirical data gathered thus far. It is worth noting that we are setting aside here questions regarding whether the predictive capacities of a theory (and its associated class of models) are a function of how that theory was constructed: in particular, whether it was constructed to accommodate certain empirical data, or, rather, whether its saving certain empirical phenomena was ‘novel’.¹² Note also that our approach to predictivity is clearly couched in the terms of the semantic approach to scientific theories; for earlier approaches to predictivity which proceed in terms of the syntactic approach to scientific theories, see Barrett and Stanford (2004) and references therein.

To illustrate with an example our point, and this notion of predictivity, consider two theories, \mathcal{T}_1 and \mathcal{T}_2 . If \mathcal{T}_1 has one solution compatible with the empirical data gathered thus far and no others, and \mathcal{T}_2 has one solution compatible with the empirical data gathered thus far but 99 others which are not, then we claim that the theories are equally predictive: the other 99 solutions of \mathcal{T}_2 are irrelevant to its predictive capacities. On the other hand, if \mathcal{T}_2 has 100 solutions, all of which are compatible with the empirical data gathered thus far, but it remains the case that \mathcal{T}_1 has only one solution (which is compatible with the empirical data gathered thus far), then we claim that, in a certain sense, \mathcal{T}_1 can be regarded as being more predictive, for it does not face an issue of underdetermination (cf. our discussion below of predictivity *tout court* versus decision-theoretic predictivity).

Now consider the landscape problem of string theory. Essentially, the problem here is the charge that string theory loses its predictive power, in light of the great many solutions of the theory—one for each compactification and

¹⁰ There are subtle issues here. A theory might be inadequate to the entire stock of empirical data, yet remain empirically adequate in a certain domain—think, for example, of Newtonian mechanics, or of non-normalisable quantum field theories (we thank a reviewer for the second suggestion). Given this, such a theory may nevertheless still have predictive power, within that domain of applicability. With this in mind, all of the foregoing can be relativised to a particular domain of applicability.

¹¹ By ‘weak underdetermination’, sometimes also called ‘transient underdetermination’, we mean, following Ladyman (2002, Sect. 6.1), having to hand multiple distinct models, each *prima facie* representing physically distinct states of affairs, and all of which being compatible with the empirical data thus far gathered. By contrast, ‘strong underdetermination’ consists in having to hand multiple distinct models, each *prima facie* representing physically distinct states of affairs, and all of which being compatible with *all* empirical data—regardless of whether it has been gathered thus far.

¹² See e.g. Barnes (2018) for further discussion of prediction versus accommodation.

choice of non-perturbative effects (e.g., configuration of branes—see above). In light of the above considerations, it would be reasonable to be puzzled by claims to the effect that, because of this plethora of solutions, string theory loses its predictive power—for what is truly *relevant* here is whether string theory has *at least one* solution compatible with the empirical data of the actual world, and whether that theory can be used to make further predictions *in the actual world* (we shall return to this latter issue in a moment). In this regard, we share the puzzlement of the string theorist Michael Green, when he says:

This supposed problem with a theory having many solutions has never been a problem before in science. There is a ‘landscape’ of solutions to general relativity, yet nobody says the theory is nonsense because only a few of them describe the physics we observe while the rest appear to be irrelevant. (Chalmers 2007, p. 44)

So, why is the existence of many solutions taken to be a particular issue in the context of string theory? The difference in the reaction of several physicists to the existence of many solutions might find its roots in the largely-accepted view that our current most fundamental theories in physics are not absolutely fundamental.¹³ For instance, Smolin voices this point of view about general relativity when he writes:

Why does general relativity so extravagantly overperform its job, giving not just predictions for the actual universe but also predictions for an infinite number of universes that never exist? The only conclusion to draw is that general relativity is not the correct cosmological theory. It is—at the very least—to be supplemented, either by a theory of initial conditions or by an historical explanation which explains why such special initial conditions were picked out for realization in the one real world. (Smolin 2013a, Sect. 2.1)

This shows a point that will become important later in this article: string theory is sometimes regarded not only as a theory of quantum gravity, but also as a *final theory of everything*. What exactly a theory of ‘everything’ should explain is of course a contentious matter; but, interestingly, it has been claimed that it could account for the values of the parameters involved in our fundamental equations and the values of cosmological initial conditions (see e.g. Greene 1999; Smolin 2013a). As we shall see, the finality claim, understood as the capacity to explain absolutely everything about the natural world including its initial conditions and the parameters involved in the fundamental equations, plays a central role in the difference of treatment between string theory and (e.g.) general relativity to be found in the literature.

As we see it, much of the confusion and concern over the predictive status of string theory is explicable with reference to a certain kind of Popperian dogma. Recall that, for Popper, the mark of a scientific theory is that it is *falsifiable* (see Popper 1959)—that is, that it is possible that empirical data be gathered which contradict the theory,

¹³ By ‘fundamentality’, we mean here the degree of accuracy and generality of a theory. In this terminological convention, an ‘absolutely fundamental theory’ would be a final theory of everything; relative fundamentality allows for the classification of theories as more or less accurate and general. There are many other notions of fundamentality in physics, science, and philosophy that we do not discuss here—see e.g. Ladyman et al. (2007), Le Bihan (2018) and Crowther (2019).

and which thereby lead us to reject that theory. Naïvely, one might maintain that the landscape renders string theory unfalsifiable—and therefore unscientific. But it should be clear from the above that such is *not* the case—what is relevant to these concerns is the *number* of models of the theory in question compatible with the empirical data gathered thus far. The landscape does not *per se* speak against this problem—and given the dearth of models of string theory compatible with the standard model (we have yet to find a single one¹⁴), if anything there may be better grounds to claim that string theory is *already falsified*, rather than being *unfalsifiable*.¹⁵

There is one final complication which deserves to be mentioned here. Suppose that a theory has an infinite number of solutions which are compatible with the empirical data gathered thus far.¹⁶ Then, it is reasonable to say that the theory makes an infinite number of predictions, assuming that these solutions are taken to represent distinct states of affairs. However, there is a further problem: how is an agent in the world to weigh these different solutions in his or her own subjective deliberations about the future? Without some well-defined measure on the relevant class of solutions, it is not clear what this agent's subjective future expectations should be. This issue is often dubbed the *measure problem*, which afflicts both theories with landscapes in the sense of an infinity of solutions (as considered here), and theories with multiverses within a given model (as considered below).¹⁷

Although we agree that the measure problem is, indeed, a genuine problem, we suggest that clarity can be gained here by distinguishing two different senses of predictivity: what we dub (i) predictivity *tout court*, and (ii) decision-theoretic predictivity. The former is the sense of predictivity discussed above: a theory is predictive *tout court* just in case it has at least one solution compatible with the empirical data gathered thus far. This is true even for theories (or multiverse models—see below) with infinitely many solutions compatible with such data. Such models need not, however, be decision-theoretically predictive: we will say that a theory is decision-theoretically predictive just in case, when multiple (potentially—although not necessarily—infinite) solutions of that theory are compatible with the empirical data gathered thus far, there is a well-defined measure over those solutions, allowing an agent in such a world to adjudicate on the data they expect to observe in the future. Given the measure problem, there is no such way for an agent to weigh these different predictions from the theory under consideration in their own deliberations about the future. Thus, we suggest that the measure problem does not hamper predictivity *tout court*, but that it does hamper decision-theoretic predictivity. Note also that, at present, the measure problem is *not* a problem for string theory, for the theory does not have a large number of (known)

¹⁴ Though cf. footnote 7.

¹⁵ Of course, this is not to deny that we might still find such a solution in the future—our point is that, the longer it is that our investigations do not yield such a solution, the less confident we might become in its existence. It is also worth pointing out that we are setting aside here the interesting possibility of non-empirical theory confirmation: see Dawid (2013) for the *locus classicus*, and Smolin (2014); Chall (2018); Menon (2019); Dawid (2020) for discussion.

¹⁶ Is it the case that such an infinity of solutions renders the theory unfalsifiable? Not obviously—for an infinity of solutions might be ruled out by future empirical data. Cf. our discussion in Sect. 7.1.

¹⁷ For in-depth philosophical discussion in the latter context, see Smeenk (2014).

models compatible with the empirical data thus far gathered—quite to the contrary, and as already discussed above, we have yet to find a single solution of this kind.

To close this subsection, turn now to the distinct claim that the landscape renders string theory *non-explanatory*. In order to make progress in assessing this claim, one must be precise about the notion of explanation at play. Focus first on the idea of *explanation as theoretical unification*—that is, a ‘bottom level’ theory T_b is explanatory with respect to some ‘top level’ theory T_t just in case what was a coincidence in T_t is offered some explanation in T_b . For example, it is common to find the claim that while the proportionality of gravitational and inertial masses is a coincidence in Newtonian mechanics, it admits of some explanation in general relativity—the reason being that, while the latter of these two theories does not contain, in its articulation, these notions, consideration of the limiting relation between general relativity and Newtonian mechanics is sufficient to *derive* the coincidence of gravitational and inertial masses (see Weatherall 2011).¹⁸ In the context of string theory, there does appear to be room to offer explanations of this kind. For example, one might ask: why do the standard model coupling parameters, or masses, take the values that they do? One explanation that can be offered via string theory would proceed by appeal to the geometry of the target space, and choice of compactifications, which gave rise to those masses and couplings.¹⁹

Now, if one demands an explanation in the sense of: *the situation could not have been otherwise*, then it is clear that string theory cannot offer explanations of this kind—for the above explanations are themselves based upon contingent properties in string theory.²⁰ That is to say: one can explain (e.g.) why certain standard model coupling parameters take the values they do by appeal to certain string theory compactifications, but why those particular compactifications obtain itself remains unaccounted for—and said compactifications could have been otherwise. It is clear that authors such as Smolin are seeking explanations of the fundamental, ultimate variety, rather than of the contingent kind. But one should distinguish: features in T_t being explained by features of T_b , versus those latter explanations being *ultimate* explanations. One can recognise that the former is true while understanding that the latter is lacking. In his search for the latter here (on which more below), Smolin, as we read him, effaces this distinction.²¹

¹⁸ Weatherall in fact argues that the mode of explanation at play here does not align exactly with e.g. Friedman’s unificatory model of explanation (Friedman 1974). For further discussion, see Moiraghi (2020).

¹⁹ See Read (2019) for more on this kind of explanation. Note that it is plausible that such reasoning could also be deployed in the context of effective field theory (see Franklin 2020), in which it is claimed that the ultimate explanation as to why certain effective field theories can be constructed is that the coupling parameters in the associated more fundamental theories scale in the right way. Given the foregoing, it is clear that this need not be the ultimate explanation—for one may, in turn, appeal to certain string-theoretic geometrical properties in order to account for such field theories.

²⁰ Further, one might be sceptical of ‘ultimate explanations’ (in the sense of ‘the situation could not have been otherwise’) in general, for well-rehearsed reasons, e.g.: (i) What is the envisaged contrast class? (ii) What are the background assumptions that one holds fixed for the counterfactual variations one performs to evaluate the situation ‘otherwise’? (iii) Is it even coherent to demand an ultimate explanation which dispenses with any contingent input? We will return to some of these matters in our discussion of Smolin below; our thanks to Patrick Dürr for discussion on this point.

²¹ Popper himself recognised (see e.g. Popper 1959) that even unscientific theories (in his sense—i.e., unfalsifiable theories) may be explanatory: famously, he cited psychoanalysis as a case in point. In light of this, even a Popperian who maintains (incorrectly, in our view—see above) that string theory is not predictive, and so is unscientific, need not conclude that the theory has no explanatory virtues.

4 From the landscape to a multiverse

Following Wallace (2012, ch. 2), we take in this article a multiverse to be a multiplicity of classical or quasi-classical worlds.²² In this section, we discuss the move from the landscape problem to the existence of a (particular kind of) multiverse. The idea behind this move is to trade multiple dynamically possible solutions for one broader solution encompassing each of the original solutions.²³ Is the positing of the existence of a multiverse any more problematic than the original landscape problem when it comes to predictive and explanatory power? Arguably, no—for all we have done is push the class of models to *within* a particular broader model. Insofar as string theory itself can be predictive, so too can string theory embedded in this multiverse (for note that if the first model is empirically adequate, then so too is the second); insofar as the first model can offer an explanation of certain coincidences in our less-fundamental theories of physics, so too can the latter (indeed, there is a sense in which the latter offers in turn a deeper explanation of these coincidences—for some *origin* of the different string-theoretic solutions, and associated geometries, might now be postulated); insofar as the former theory is falsifiable (because only certain subclass of the solutions of the former class of solutions is adequate to the empirical data gathered thus far), so too is the latter. In addition: the measure problem looms just as large in this context as in the context discussed above. Thus, this latter multiverse does not pose a special problem when it comes to these issues of underdetermination, and of falsifiability.

The only extra issues of underdetermination which arise after positing a landscape of this kind occur when one compares the new multiverse solution of the original theory, and the many possible solutions of the original theory. In this case, a new issue of underdetermination arises, for one's given empirical data are now compatible with *both* theories. Thus, the construction of such a multiverse solution does not generate further issues of *intra*-theoretic underdetermination (i.e., underdetermination regarding which of a theory's models correctly represents reality), but does generate further issues of *inter*-theoretic underdetermination—for one now has no means of ascertaining empirically which of the two theories (i.e., the original theory, or the associated multiverse theory) is correct. (Note that, at this point, we are assuming that the multiverse under consideration does not have distinct empirical signatures of its own; the above issues of underdetermination would be resolved if the multiverse model were to have *distinct* empirical signatures. Though we discuss this in more detail below, it is worth noting that, in order to construct a multiverse model with

²² Here, the 'quasi-' is used to indicate that these worlds may be approximate and emergent entities: see Wallace (2012, ch. 2) for discussion.

²³ Note that capturing this move at the level of mathematics may require relaxing certain kinematical constraints: for example, that the manifolds of the models under consideration be connected. (For more on kinematical constraints, see Curiel (2016).) Of course, this is at the level of mathematics—what it would take to *represent* such a multiverse in a mathematical model—rather than at the level of metaphysics. The fact that one cannot represent such a multiverse without relaxing such kinematical constraints has no bearing on the metaphysical possibility of a multiverse. (Cf. the response to Weatherall (2018) offered by Pooley and Read (2021) in the context of the hole argument: even granting that one cannot use Lorentzian manifolds to capture merely haecceitistic differences between worlds, this does nothing to speak against the metaphysical possibility of such worlds; moreover, in this case one *could* represent mathematically such worlds by relaxing the kinematical constraint that spacetime models be specified by Lorentzian manifolds.)

distinct empirical signatures, more would need to be done than simply ‘bundling together’ distinct models of one theory into one model of some new theory—which is the proposal we are contemplating here.)

There is one further subtlety which deserves to be mentioned. It may be that not *all* string theory solutions are realisable within the context of the multiverse cosmology under consideration, if that cosmology is more than a mere ‘bundle of solutions’, and has its own empirical signatures. If this is so, and the allowed class includes *fewer* solutions adequate to the empirical data gathered thus far, then this latter theory would be *more* predictive (if it still includes at least one ‘bubble’ adequate to the empirical data gathered thus far), and *more* falsifiable.²⁴

In brief, a multiverse has no more trouble than a landscape of solutions to account for empirical data, when it comes to predictive and explanatory power. However, and quite obviously, the ontological costs of a multiverse hypothesis are substantial!²⁵ Consequently, in order to be justified in moving from the landscape to the existence of a multiverse, one must have good—and unrelated with predictive and explanatory power, as we just saw²⁶—motivations to do so.²⁷ What could those motivations be?

5 Empiricist and rationalist motivations for the multiverse

There is an interesting interplay between the motivations that one might have for believing in a given multiverse theory, the empirical content of that theory, and one’s prior philosophical convictions. To see this, consider first Everettian quantum mechanics (EQM), according to which the fundamental ontology of the physical world is exhausted by the quantum state $|\psi\rangle$,²⁸ different non-interacting branches of this quantum state (as picked out by the process of dynamical decoherence) represent different (quasi-)classical worlds. (For the canonical contemporary elaboration and defence of EQM, see Wallace 2012.) Since quantum mechanics is a theory of striking empirical success, and since EQM purports to take quantum mechanics ‘at face value’ and interpret it realistically, an advocate of this approach may argue that we have good *indirect* evidence for the existence of such a quantum mechanical multiverse. This one might understand as an empiricist argument: this belief in the Everett interpretation

²⁴ Cf. Carroll (2019).

²⁵ At least if one is more concerned by what Lewis calls ‘quantitative parsimony’ (i.e., the sheer number of elements in one’s ontology) than ‘qualitative parsimony’ (i.e., the number of *kinds* of elements in one’s ontology). See Lewis (1986) for further discussion.

²⁶ At least for the ‘bundle of solutions’ multiverses considered up to this point.

²⁷ Indeed, one could even say that one must presuppose certain rationalist motivations (in the sense of the following section) if one is to take there to be a landscape problem to begin with—as, clearly, Smolin (2013a) does. Our thanks to an anonymous referee for this point.

²⁸ Crucially, Everettians such as Wallace maintain that, in addition to the fundamental ontology of the physical world (given by $|\psi\rangle$), there exists also an *emergent* or *derivative* ontology, given by a certain functionalist strategy—see Wallace (2012, ch. 2)—or grounding strategy (Wilson 2020).

is, ultimately, grounded in the empirical data, combined with a fairly straightforward scientific realist methodology.^{29,30}

One might reject the Everettian picture, based upon prior philosophical convictions. Consider, for example, the pilot wave theory, according to which, in addition to the quantum state, there exist at the fundamental level point particles ('corpuscles'), with determinate positions at all times. If one imposes *ab initio* the requirement that one's physics manifest certain aspects—for example in this case, that it have a primitive ontology of point particles—then it is clear that these requirements will be satisfied by the pilot wave theory, but not by EQM.³¹ In this paper, we dub such super-empirical requirements—i.e. requirements not motivated solely by the empirical data—*rationalist motivations*.

Thus, while advocates of EQM are guided by the empiricist motivation that one's ontological picture should be given by one's best theory of science, advocates of the pilot wave theory, while not rejecting such a view, embrace in addition certain rationalist tendencies to impose *extra* requirements on one's physics—to make that physics ontologically perspicuous, or palatable.

Let's be crystal clear on what we mean here by empiricist and rationalist motivations. By 'empiricist motivations', we mean to the attitude of sticking as closely as possible to our best physics in our attempts to understand the ontology of the world. We can then commit ourselves to the existence of the theoretical entities posited by these theories, and be justified in said commitment on empirical grounds.³² By 'rationalist motivations', we mean the attitude of taking it that other *a priori* principles, such as unifying principles, principles of ontological clarity (cf. again the above example of Bohmian mechanics), or the quest for a final theory of everything, should guide and constrain our understanding of the ontology of the world. Note that rationalist motivations are question-begging in a very literal sense: it is hard to justify them on grounds which go beyond mere intuitions. This is not to say that rationalist motivations are not intrinsically valuable as guiding principles. They can be used to guide and constrain theory construction. However, in our view, to take rationalist motivations as anything more than guiding principles is problematic, as we articulate below.

The relevance of this discussion of rationalist versus empiricist motivations manifests itself in the context of cosmological multiverse scenarios. Suppose that (a) one has a cosmological theory which predicts a multiverse (e.g., an eternal inflation multiverse, discussed in further depth in Sect. 7.1); (b) such a theory (unlike the case considered in

²⁹ For an approach seeking to make this issue of theory confirmation precise in the Everettian context, see Greaves (2007), Greaves and Myrvold (2010).

³⁰ Of course, there is a small dose of rationalism here, insofar as the Everettian must assume that the simplest, most straightforward, literal ontological interpretation (consistent with one's other metaphysical commitments, if any) of a given theory is indeed the correct interpretation. It's widely acknowledged that this transcends straightforward empiricism (see e.g. van Fraassen 1980)—but we take this to be a rationalist principle necessary for a scientific realist outlook, and thus regard it as being endorsed by all parties to the debate considered in this section. We take the wider moral here to be that all scientific realists will be motivated by some combination of empiricist and rationalist factors; only the most committed (and, likely, implausible) empiricist position would embrace only the former.

³¹ For a pointed critique of EQM in this regard, and corresponding endorsement of the pilot wave theory, see Maudlin (2014).

³² Although cf. footnote 30.

the previous section) *does* have empirical signatures; and (c) such empirical signatures have been detected—so that the theory is empirically confirmed.³³ In that case, the situation would be analogous to the quantum mechanical case described above: one would have *empiricist* motivations for believing in the existence of such a multiverse. In response to this, one could make the claim that such a theory is unpalatable, and that one must construct an alternative theory subject to certain *ab initio* requirements—with this theory turning out to be a one-world (i.e., non-multiverse) theory. In this case, the latter theorist would again be guided, in our terminology, by rationalist motivations.

Suppose, on the other hand, that a multiverse theory (as in the case of the examples discussed in the previous section) has *no* empirical consequences, and is taken to be true only on the basis of super-empirical considerations—for example, the willingness to formulate a final theory with only one solution, or the desire to account for the otherwise unaccounted-for, and sometimes apparently fine-tuned, free parameters in one's theories of physics.³⁴ In this case, the tables turn, and one is motivated to construct the *multiverse* theory on the basis of rationalist principles—in this particular example, the principle that free parameters should be explained further. By appealing to an anthropic principle in a multiverse cosmology,³⁵ one might then offer an explanation of why we observe a particular fine-tuning of the free parameters: intelligent beings can only develop in particular universes 'correctly tuned' in the multiverse. In this case, in contrast to the above, it is the single-world theorist who manifests the empiricist motivation, and the multiverse proponent who is driven by a rationalist motivation.

The crucial factor underlying the difference in these two cases is whether the multiverse theory under consideration has empirical content—whether that theory contributes to empirical predictions in the actual world. If it does, an empiricist can be motivated to accept it—in spite of its apparent ontological profligacy. Indeed, the only reason to reject such a theory would be rationalist in nature—compare again advocacy of the pilot wave theory. On the other hand, if the multiverse theory in question does *not* contribute to any empirical predictions, then the only reason to introduce that theory would itself be rationalist in nature, whereas the empiricist will remain sceptical about that theory in this case. Thus, the tables turn *vis-à-vis* rationalist versus empiricist motivations, depending upon whether the theory under question contributes to the making of empirical predictions about the world.

Now for our own take on these matters. Although we take empiricist motivations for positing the existence of a multiverse to be perfectly legitimate, we find, on the contrary, rationalist motivations to be question-begging, in the literal sense: rationalist motivations, for us, cannot be more than methodological guiding principles in theory

³³ We use in this paper the Bayesian notion of confirmation, of augmenting significantly the probability of an hypothesis of being true, which does not amount to conclusive confirmation. On the two notions of confirmation, see e.g. Dawid (2019, Sect. 6). For further discussion of Bayesianism in the context of multiverse scenarios, see Carroll (2019).

³⁴ The fine-tuning of the Higgs field in the standard model of particle physics offers such an example. On the one hand, the Higgs boson's mass cannot be too heavy in order to give the right mass to the other fields. On the other hand, quantum fluctuations contribute to the Higgs too, requiring the so-called Higgs bare mass to be finely-tuned in order to yield the right mass for the Higgs.

³⁵ See Weinstein (2006) for a philosophical discussion of anthropic principles in relation to string theory and multiverse cosmologies.

construction, whose truth cannot be known with certainty.³⁶ In the next section, we examine Smolin's arguments in favor of the existence of a landscape problem and emphasize their rationalist—and thereby contentious—grounds.

6 Smolin's rationalist motivations

Smolin does not defend the existence of a multiverse; on the contrary, he argues for the claim that we live in a *singular universe* (see especially Unger and Smolin 2015). He defends a view according to which the universe proceeds through successive stages, described by theories with different laws.³⁷ Furthermore, he claims that only the present stage—thus the present universe—is real, his view thereby being that there is only one universe.³⁸ These claims are motivated by the idea that *the existence of a landscape of solutions triggers a need for explanation*. In this section, we discuss one of Smolin's rationalist motivations that leads him to recognize the existence of a landscape problem. In addition, we argue that the cosmological selection principle to which Smolin appeals is similar to the anthropic reasoning used to motivate the multiverse view.

Smolin presents three criteria for what would constitute an acceptable solution to the landscape problem. A solution, according to Smolin, must give an explanation of the effective laws of nature (i.e., those of general relativity and quantum mechanics) and of their parameters as we observe them in our own actual universe. In addition, the explanation in question should explain the improbable features of the standard model of particle physics, which include (e.g.) the large hierarchies in scales and dimensionless parameters and the fact that they seem to be finely-tuned to create a universe that has highly improbable complex structures over a wide range of scales from clusters of galaxies down to molecular biology. Finally, the hypothesis should explain the very special initial conditions of the universe.

It is worth dwelling on this last point. Smolin takes this demand that even initial conditions be explained to be a contemporary manifestation of Leibniz's Principle of Sufficient Reason (PSR):

I bring up Leibniz's principle of sufficient reason because I believe it helps greatly to clarify the issues that we confront in seeking a solution to the landscape problem. In particular, the principle of sufficient reason [...] tells us that laws

³⁶ That we regard rationalist motivations as being question-begging in a literal sense does not necessarily mean that we invariably regard them as being question-begging in a pejorative sense, as long as they are taken to be guiding principles.

³⁷ See also Smolin (2013b).

³⁸ See, for example: 'There is only one universe at a time, with the qualifications that we discuss. ... This idea contradicts the notion of a multiverse—of a plurality of simultaneously existing universes—which has sometimes been used to disguise certain explanatory failures of contemporary physics as explanatory successes' (Unger and Smolin 2015, xi). Even endorsing (what one might dub) Smolin's 'cosmic presentism', it is hard to understand why there should not be other universes also co-existing with the actual universe, given Smolin's further doctrine of 'cosmic natural selection': that one universe can 'seed' multiple others, with different laws. To our minds, the idea of cosmological natural selection would fit better with an eternalist ontology that does not restrict the content of reality to one universe only.

must evolve to be explained and that there must be a dynamical explanation for the initial conditions of the universe. (Smolin 2013a, p. 26)

Smolin proposes that a string-theoretic multiverse—i.e., the packaging of all string theory solutions into *one* multiverse solution of some deeper theory—does indeed address these three matters; the rationalist motivations thereby justify endorsing a multiverse scenario, in order to explain (a) the form of the effective laws of nature (one set of laws per ‘bubble universe’ in the multiverse represented by some deeper theory); (b) the parameter values in those effective theories (by appeal to certain e.g. string theory geometries associated with each ‘bubble universe’); (c) various possible initial conditions (by embedding each model of one theory, with its own initial conditions, into one model of a multiverse theory). Clearly, all of these motivations are rationalist in nature: they are reasons to embrace a multiverse in response to a landscape problem that *appears only if one subscribes to dubitable assumptions*, which are not directly related to the need to account for the empirical data in the actual world.

The central issue here is that although it is certainly true that the PSR acts as a useful abstract principle, these successes do not establish beyond any doubt that the PSR applies universally to the world. Trying to explain as many things as can be is of course an essential aspect of scientific investigation, and as such the PSR is a perfectly legitimate *guiding principle* in theory construction. Nonetheless, making the further (metaphysically driven) claim that *everything must have a reason* exceeds the scope of scientific practice and cannot be inferred from previous successes in the history of physics.³⁹

It should be clear from the foregoing, however, that appeal to a string-theoretic multiverse is in fact *not* Smolin’s own preferred approach to the construction of a PSR-satisfying physics; rather, the centrepiece of his outlook lies in the claim that laws ‘must evolve in order to be explained’. Such a view has its own problems. For one: the claim seems to disregard much of the extant literature on the ontology of laws of nature. Indeed, laws of nature could be afforded a different kind of explanation which need not have anything to do with causal/historical explanations.⁴⁰ But more generally, even if we do not focus on laws, it is important to note that many explanations in science are not causal explanations. In general relativity, for instance, the relation between the metric field and the matter fields can hardly be accounted for in terms of dynamical processes unfolding in time—see Vassallo (2020). Even subscribing to the PSR, one might take non-causal explanations to be as valuable as causal explanations

³⁹ Here, we take ‘reason’ to mean ‘explanation’, rather than (e.g.) ‘cause’. Note also that irreducibly chancy theories would seem to be in tension with this version of the PSR; our thanks to Patrick Dürr for this observation.

⁴⁰ Think, for instance, of the four main views of scientific laws discussed in the philosophical literature: (1) *primitivism*, namely the view that laws of nature are primitive entities in a liberal sense of ‘entity’ that cannot be explained further (see e.g. Maudlin 2007); (2) the *neo-Humean view* advocated by Lewis (1986, ix) that ‘all there is in the world is a vast mosaic of local matters of particular fact, just one little thing and then another’, the laws being the simplest and strongest codifications of those empirical regularities; (3) the *dispositionalist view* that identifies laws of nature with dispositional properties of objects and/or other non-nomological categories of entities (Ellis 2001; Bird 2005); and (4) the *DTA view* that identifies laws of nature to second-order relations of necessitation existing between first-order universals, see Dretske (1977), Tooley (1977) and Armstrong (1978, 1983). Those approaches, except for primitivism, give ahistorical explanations for the existence of scientific laws.

(see e.g. Reutlinger 2017; Reutlinger and Saatsi 2018; Wilson 2018). In that case, one need not posit a dynamical origin for the laws of nature in order to offer some explanation as to why those laws take the form that they do.⁴¹

In sum: one might object to Smolin's argument by maintaining that there is no reason to believe that laws of nature/parameter values/initial conditions *must* be explained in the first place (although it is certainly *desirable* that this be the case); moreover, even if one wants to explain the existence of these laws/values/conditions, there is no reason to believe that this explanation *must* be a dynamical/causal/historical explanation. Therefore, *there is no landscape problem per se*; there is, rather, a rationalist motivation for exploring further intellectual ideas (that there could be a dynamical explanation for the laws and the initial conditions of the universe), without any guarantee that those ideas must inevitably lead us somewhere.

7 Other multiverses and their scientific credentials

As we have seen, the landscape problem is an heuristic issue which could—but which certainly need not—teach us something about reality. As we have also seen, one possible response to the landscape problem is that we do live in a multiverse. As should now be clear, we take this possibility to be scientific as long as the considered multiverse scenarios lead, or could potentially lead, to an empirical signature.⁴² In this section, we review briefly the prospects of popular multiverse views in order to assess their status with respect to the making of novel empirical predictions.⁴³

In physics, multiverses are to be found in quantum mechanics with the Everettian approach already mentioned, in string theory with the multiverse, and in cosmology

⁴¹ Furthermore, Smolin takes for granted that time must be fundamental to the physical world—however, many physicists and philosophers of physics working in quantum gravity believe that time might turn out not to be fundamental. For philosophical discussion of the fundamentality of spacetime in general and time in particular in quantum gravity, see e.g. Huggett and Wüthrich (2013); Huggett et al. (2013); Le Bihan (2018); Le Bihan and Linnemann (2019); Huggett et al. (2020); Huggett and Wüthrich (forthcoming) and Wüthrich et al. (forthcoming).

⁴² Cf. footnote 2. Note that this does not mean that all multiverse scenarios discussed below are taken equally seriously by practicing physicists. In particular, multiverse scenarios which require novel physical mechanisms are often set aside in mainstream theoretical physics. For example, although Penrose's conformal cyclic cosmology (discussed in Sect. 7.2 below) does have empirical signatures, it requires postulating that all massive particles eventually decay to massless particles, so that only conformal structure matters in the identification of past infinity with the future infinity of a previous epoch. Since, however, there is no independent evidence to support this hypothesis, the scenario is set aside by many cosmologists. (Our thanks to an anonymous referee for pressing us to make this point.)

⁴³ We take inspiration from a classification proposed by Greene (1999), but we do not consider all the options he does. In particular, he considers two types of multiverse which we will set aside in the present discussion: the 'simulated multiverse' and the 'holographic multiverse'. The simulated multiverse hypothesis states that a plurality of distinct universes are simulated on a computer—existing somewhere outside of what we regard to be the actual world—and running what we take to be the actual world as a simulation. Insofar as this multiverse is very peculiar in nature and would presumably require us to branch into computer science, we choose not to discuss it in the present paper. The holographic multiverse rests on a specific interpretation of the AdS/CFT correspondence, a mathematical duality obtaining between different mathematical models that describe worlds with different ontological structures. However, interpreting the AdS/CFT correspondence as entailing the existence of a multiverse is quite unorthodox in the literature. For discussions of the ontological interpretation of duality in general, see e.g. Le Bihan and Read (2018) and Butterfield (forthcoming).

with *eternal inflation*, *conformal cyclic cosmology*, and *loop quantum cosmology*, to name a few popular approaches. In philosophy, Lewis' *modal realism* and Tegmark's *Pythagoreanism* offer two options. In what follows, we comment on the physical connections/interactions obtaining between the different universes within each multiverse approach—the stronger these connections/interactions, the more realistic the possibility of the empirical detection of one universe from within another (cf. Wallace 2012, pp. 100–101).

7.1 Eternal inflation

String theory, as we saw, admits of many solutions, corresponding to different input geometrical choices, as well as choices of non-perturbative effects. Sometimes, string theory solutions are taken to represent parts of a cosmological multiverse scenario known as 'eternal inflation', which today remains the leading hypothesis among cosmologists.⁴⁴

Eternal inflation proposes the existence an infinity of 'bubble universes' emerging from the inflation of a primordial scalar field called the 'inflaton' (see e.g. Freivogel et al. 2006; Aguirre 2007; Nomura 2012). Unlike in the 'bundle' multiverse scenarios considered previously, cosmologists have made several proposals for the empirical testing of eternal inflation hypotheses (see e.g. Guth and Nomura 2012). Carroll summarises the situation as follows:

In this kind of scenario, bubbles of lower-energy configurations appear via quantum tunneling within a region of space undergoing inflation; these bubbles grow at nearly the speed of light, and can contain within them distinct "universes" with potentially different local laws of physics. The distribution of bubbles depends on details of physics at high energies—details about which we currently have next to no firm ideas. But we can parameterize our ignorance in terms the nucleation rate of such bubbles and the energy density within them. If the rate is sufficiently high, this model makes a falsifiable prediction: the existence of circular features in the anisotropy of the cosmic microwave background, remnants of when other bubbles literally bumped into our own. Cosmologists have searched for such a signature, allowing us to put quantitative limits on the parameters of false-vacuum eternal inflation models ...

This particular version of the multiverse, in other words, is indubitably falsifiable for certain parameter values. (Carroll 2019, p. 6)

⁴⁴ Historically, eternal inflation and string theory were developed hand-in-hand (see e.g. Kachru et al. 2003). However, there is nothing in principle to preclude a scenario like eternal inflation being realised in other approaches to quantum gravity. Although this has not been worked out in detail for any other particular approach, at least some cosmologists have countenanced it:

[The eternal inflation] picture is obtained by just [using] general relativity. And all this energy scale associated with this process is much smaller than the Planck scale, where we believe that the theory is correct.

The only aspect you need for this particular purpose, from string theory, is a lot of different vacua, a lot of different universes, where the vacuum energy is different. As long as that aspect stays in whatever theory of quantum gravity, then that's enough to keep this picture (Nomura 2016).

However, it has also been claimed that eternal inflation does not have, at the moment, any independent and empirical line of justification (McCoy 2015; Smeenk 2017). As Smeenk explains, this is due not only to the difficult observational access to the early universe, but also to the high flexibility of the inflation framework:

There are no analogs, as far as I am aware, of adding a new physical feature as part of the model that can, like the existence of Neptune, be easily checked by other means. This is in part due to the observational inaccessibility of the early universe, but also to the lack of a canonical choice of the inflaton field. Given a fixed choice for the inflaton field, discrepancies with observations would force theorists to elaborate the model, possibly identifying new features of the early universe in the process. At present the choice of inflationary models is too flexible to support this kind of approach. (Smeenk 2017, p. 222)

The point, then, is that while, *given a choice of inflaton field*, eternal inflation may be falsifiable, the hypothesis is not falsifiable *tout court*, given the great flexibility in said choice of inflaton field. The fact that (coarsely speaking), for each choice of empirical data, there is one eternal inflation model compatible with it (with a particular choice of inflaton), means that the hypothesis is not straightforwardly falsifiable in its entirety; it also gives rise to concerns regarding underdetermination: if the empirical data gathered thus far is compatible with many choices of inflaton field, which is the correct one? However, the lack of present falsifiability of eternal inflation does not amount, to our minds, to a defect in the scientific status of the hypothesis, so long as the research programme relies on empirical data to develop a framework consistent with it, which could potentially in the future be more constrained by further empirical data (for a similar line of reasoning, see Carroll 2019).⁴⁵

7.2 Cyclic multiverses

Eternal inflation is not the only string-theoretic cosmological view entailing the existence of a multiverse. The *brane multiverse*, although also linked to the string program, relies on a different ontology involving ‘large extra dimensions’ (the model was proposed by Arkani-Hamed et al. 1998; see Shifman 2010 for a more recent presentation). This approach takes the whole cosmos to be ten- or eleven-dimensional, with specific smaller spacetimes being certain physical hypersurfaces—‘branes’—within this larger cosmos. Our familiar four-dimensional spacetime would be a particular brane within this overall cosmological structure. In this approach, it is sometimes further speculated that the big bang resulted from a collision between two different branes: this is the *cyclic brane multiverse view*. Given the possibility of such collisions, the cyclic brane multiverse entails the existence of causal connections between the pocket universes. In turn, this model has the potential to give rise to experimental consequences, suggesting that the brane multiverse is a testable hypothesis.

⁴⁵ It is worth re-emphasising that eternal inflation scenarios face the cosmological measure problem—but we have already discussed such matters in Sect. 3. See Smeenk (2014) for further discussion of the measure problem.

Another cyclic scenario suggested by Penrose is *conformal cyclic cosmology*—see Penrose (2010) and Gurzadyan and Penrose (2013).⁴⁶ This scenario does not rely on string theory. In a nutshell, the idea behind this approach is that successive universes (called ‘aeons’) may be connected through a conformal transformation. In more detail: the past conformal boundary of one copy of an FLRW spacetime is glued to the future conformal boundary of another FLRW spacetime, after an appropriate conformal rescaling. According to Penrose, this scenario should give rise to particular fluctuations in the CMB (due to the different behaviours of bosons versus fermions under conformal rescalings), thereby establishing the empirical status of this cyclic multiverse approach.

7.3 Loop quantum cosmology

Loop quantum cosmology (LQC) is a cosmological model based on a simplification of the canonical approach to loop quantum gravity (LQG) (see Bojowald and Brahma 2016; Brahma forthcoming, and, for philosophical discussion, Huggett and Wüthrich 2018). In this approach, our universe has a twin sibling universe localised on ‘the other side’ of the big bang. Since LQC is a cosmological model based on LQG, LQC’s epistemological destiny is likely to be tied to LQG: if LQG were to fail some future empirical tests, these tests would speak also against LQC.⁴⁷ But the opposite is not true, insofar as the success of LQG would not entail the truth of LQC, and empirical tests may also tell against the latter, but not the former.

As far as we know at present, the ‘multiverse’—perhaps the expression ‘*dualverse*’ would be more accurate to describe situations of mirror universes—posited by LQC might well turn out to have an empirical signature. In brief, it might well be that: (i): LQC turn out to be the right approach to quantum gravity, (ii) the mirror universe is not an artefact of the LQC mathematical idealisations, (iii) LQC has an empirical signature.⁴⁸ As long as these conditions can be met, the existence of the LQC dualverse should remain a legitimate possibility amenable to empirical test.

7.4 Modal realism and pythagoreanism

According to Lewis’ *modal realism* (Lewis 1986), modal statements should be analysed in the framework of possible world semantics, and this semantics’ most natural interpretation is that possible worlds are real entities that exist in the same way as the actual world. The very notion of actuality then becomes a purely indexical notion, similar to the indexical ‘here’. Possible worlds are distinct, and neatly separated in a

⁴⁶ We recognise that there is a danger in presenting (relatively) mainstream multiverse hypotheses (such as eternal inflation) alongside much less mainstream multiverse hypotheses (such as conformal cyclic cosmology). We do not wish to make any implication that these approaches are equally credible; rather, we lay them out side-by-side in this manner in order to explore their conceptual parallels. Cf. footnote 42.

⁴⁷ We cannot exclude that LQC as a model might still turn out to be a valid approximation in some contexts even if LQG were to fail. However, it seems rather unlikely that the model could teach us a lot about the cosmos if it were based on a false theory.

⁴⁸ For a detailed account of the different possible empirical signatures of LQC, see e.g. Bojowald (2005).

causal way: by definition, different possible worlds are spatiotemporally disconnected and causally non-interacting.

Modal realism posits a multiverse which might seem to be beyond any possible kind of empirical testing. However, it has been argued by Wüthrich (2019) that Lewis' modal realism might be inconsistent with the possible disappearance of spacetime in quantum gravity. Indeed, insofar as spatiotemporal disconnectedness is used as a criterion to identify and distinguish between numerically distinct possible worlds, the claim that spacetime is not fundamental within our actual world threatens modal realism: our own actual world might fail to be part of the collection of possible worlds posited by modal realism. Since at this stage, it cannot be excluded that a theory of quantum gravity denying the fundamentality of spacetime⁴⁹ will be borne out in the future, it follows that *modal realism might turn out to be empirically falsified in the future*. Does it follow from this sheer fact that modal realism is a falsifiable hypothesis? Arguably, yes—in which case, modal realism might be slightly more scientifically respectable than is usually thought to be the case.⁵⁰

The *mathematical universe hypothesis*, endorsed by Tegmark (2008), maintains that the world is a mathematical structure, not a physical structure.⁵¹ Furthermore, all mathematically possible structures exist in the same way as the actual world, i.e. that mathematical structure which we inhabit. This multiverse may sound beyond empirical testing; however, as we just saw, highly abstract metaphysical models of reality sometimes turn out to conflict with scientific theories in unexpected ways. Therefore, this hypothesis should be scrutinised in more detail in order to ensure that, in principle, it could not be empirically tested.⁵²

These approaches cover most sorts of multiverses to be found in the contemporary literature. Except for the two last philosophical multiverses—as posited by modal realism and the mathematical universe hypothesis—they all posit some kind of causal connection obtaining between the various universes, which could, in principle, lead to empirical signatures.⁵³ And even when there are no causal connections between the various bubble worlds as with modal realism, we just saw that empirical science might falsify the position in question. Therefore, we should not be too quick in judging that philosophical multiverses lie out of reach of any empirical testing.

⁴⁹ Note that we use here a notion of fundamentality that has nothing to do with accuracy, but relates instead to levels of descriptions. See Le Bihan (2018).

⁵⁰ Of course, there subtleties here: one might argue, for example, that to say that one of the basic assumptions of a theory (or a metaphysical hypothesis) is falsifiable doesn't necessarily render the theory/metaphysical hypothesis itself falsifiable. For example, the view could shift: a modal realist might assert that, in fact, spatiotemporal disconnectedness was simply the wrong way to think about distinct, causally disconnected possible worlds. We think that this is correct—but then one would not be dealing with *Lewisian* modal realism, which is our focus here. Our thanks to Patrick Dürr for discussions on these matters.

⁵¹ In the interests of charitability, we set aside initial concerns that this is a straightforward category mistake—see Butterfield (2014) for further discussion.

⁵² Cf., though, footnote 50—it may be that similar concerns arise also in this context.

⁵³ Here, we are setting aside 'divergence' models of branching in EQM, one consequence of which is that causal relations do not obtain between branches. For more on these models, see Wallace (2012); Wilson (2020).

8 Conclusions

Positing the existence of a multiverse in order to explain why, of all the possible geometries and matter couplings, we live in a world with *these ones*, amounts to providing a philosophical answer to a philosophical problem. But, as we have seen, one can deny that there is anything to be explained here. Indeed, *the problem only arises if one accepts the question-begging and a priori belief that everything must have a reason in the scientific representation of the world*. This belief might be correct; but this sort of radical rationalism cannot be established on empirical grounds only (if, indeed, it can be established at all!). Moreover, when it comes to the particular predictive or explanatory status of a multiverse model, one must investigate the details of the model itself in order to assess it with respect to these desiderata: it is not the case that multiverse models *invariably* fail in these respects, and, indeed, it does not appear that such is the case when it comes to string-theoretic multiverse models. Thus, there is a clear sense in which the landscape problem of string theory *is no genuine problem at all*.

Acknowledgements Very many thanks to the audience of the Conference on the Foundations of Cosmology and Quantum Gravity in New York Abu Dhabi on January 19–21, 2020, to Richard Dawid, Patrick Dürr, Chris Smeenk and three anonymous reviewers for helpful comments. This work was supported by the Swiss National Science Foundation through BLB's Ambizione grant.

Funding Open Access funding provided by Université de Genève.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Aguirre, A. (2007). Eternal inflation, past and future. *arXiv preprint arXiv:0712.0571*.
- Alonso-Serrano, A., & Jannes, G. (2019). Conceptual challenges on the road to the multiverse. *Universe*, 5(10), 212.
- Arkani-Hamed, N., Dimopoulos, S., & Dvali, G. (1998). The hierarchy problem and new dimensions at a millimeter. *Physics Letters B*, 429(3–4), 263–272.
- Armstrong, D. M. (1978). *A theory of universals* (Vol. 2). Cambridge: Cambridge University Press.
- Armstrong, D. M. (1983). *What is a law of nature?* Cambridge: Cambridge University Press.
- Barnes, E. C. (2018). Prediction versus Accommodation. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy* (Fall 2018 ed.). Metaphysics Research Lab, Stanford University.
- Barrett, J., & Stanford, P. K. (2004). Prediction. In J. Pfeifer & S. Sarkar (Eds.), *The Philosophy of Science: An Encyclopedia*. Springer.
- Bird, A. (2005). The dispositionalist conception of laws. *Foundations of Science*, 10(4), 353–370.
- Bojowald, M. (2005). Loop quantum cosmology. *Living Reviews in Relativity* 8.
- Bojowald, M. & S. Brahma (2016). Signature change in 2-dimensional black-hole models of loop quantum gravity. arXiv preprint [arXiv:1610.08850](https://arxiv.org/abs/1610.08850).

- Brahma, S. (2020). Emergence of time in loop quantum gravity. In N. Huggett, K. Matsubara, & C. Wüthrich (Eds.), *Beyond Spacetime: The Foundations of Quantum Gravity* (pp. 53–78). Cambridge University Press.
- Butterfield, J. (2014). Our mathematical universe? *Plus Magazine arXiv preprint*. (arXiv:1406.4348).
- Butterfield, J. (forthcoming). On dualities and equivalences between physical theories. In C. Wüthrich, B. Le Bihan, & N. Huggett (Eds.), *Philosophy Beyond Spacetime*. Oxford University Press.
- Camilleri, K., & Ritson, S. (2015). The role of heuristic appraisal in conflicting assessments of string theory. *Studies in History and Philosophy of Modern Physics*, 51, 44–56.
- Carroll, S. (2019). Beyond falsifiability: Normal science in a multiverse. In R. Dawid, R. Dardashti, & K. Thébault (Eds.), *Epistemology of Fundamental Physics: Why Trust a Theory?* Cambridge University Press.
- Chall, C. (2018). Doubts for Dawid's non-empirical theory assessment. *Studies in History and Philosophy of Modern Physics*, 63, 128–135.
- Chalmers, M. (2007). Stringscape. *Physics World*, 20(9), 35.
- Crowther, K. (2019). When do we stop digging? Conditions on a fundamental theory of physics. In A. Aguirre, B. Foster, & Z. Merali (Eds.), *What is Fundamental?*, pp. 123–133. Springer.
- Curiel, E. (2016). Kinematics, dynamics, and the structure of physical theory. *arXiv preprint arXiv:1603.02999*.
- Dawid, R. (2013). *String Theory and the Scientific Method*. Cambridge University Press.
- Dawid, R. (2019). The significance of non-empirical confirmation in fundamental physics. In R. Dardashti, R. Dawid, & K. Thébault (Eds.), *Why Trust a Theory? Epistemology of Fundamental Physics*. Cambridge University Press.
- Dawid, R. (2020). Meta-empirical confirmation: Addressing three points of criticism. <http://philsci-archive.pitt.edu/16908/>.
- Dretske, F. (1977). Laws of nature. *Philosophy of Science*, 44(2), 248–268.
- Ellis, B. (2001). *Scientific Essentialism*. Cambridge University Press.
- Ellis, G. (2007). Issues in the philosophy of cosmology. In J. Butterfield & J. Earman (Eds.), *Philosophy of Physics*, pp. 1183–1287. Elsevier.
- Ellis, G. (2011). Does the multiverse really exist? *Scientific American*, 38–43. August.
- Ellis, G. (2012). Multiverses, science, and ultimate causation. In R. D. Holder & S. Mitton (Eds.), *Georges Lemaître: Life, Science and Legacy*, pp. 125–144. Springer.
- Ellis, G., & Silk, J. (2014). Defend the integrity of physics. *Nature*, 516, 321–323.
- Franklin, A. (2020). Whence the effectiveness of effective field theories? *British Journal for the Philosophy of Science*, 71(4).
- Freivogel, B., Kleban, M., Martinez, M. R., & Susskind, L. (2006). Observational consequences of a landscape. *Journal of High Energy Physics*, 2006(03), 039.
- Friedman, M. (1974). Explanation and scientific understanding. *Journal of Philosophy*, 71, 5–19.
- Greaves, H. (2007). On the Everettian epistemic problem. *Studies in History and Philosophy of Modern Physics*, 38(1), 120–152.
- Greaves, H. & W. Myrvold (2010). Everett and evidence. In S. Saunders, J. Barrett, A. Kent, & D. Wallace (Eds.), *Many Worlds? Everett, Quantum Theory, and Reality*, pp. 264–304. Oxford University Press.
- Greene, B. (1999). *The Elegant Universe: Superstrings*. Hidden Dimensions and the Quest for the Ultimate Theory. W. W. Norton and Company
- Gurzadyan, V. G., & Penrose, R. (2013). On ccc-predicted concentric low-variance circles in the cmb sky. *The European Physical Journal Plus*, 128(2), 22.
- Guth, A. H., & Nomura, Y. (2012). What can the observation of nonzero curvature tell us? *Physical Review D*, 86(2).
- He, Y.-H. (2017). Machine-learning the string landscape. *Physics Letters B*, 774, 564–568.
- Huggett, N., Matsubara, K., & Wüthrich, C. (2020). *Beyond Spacetime: The Foundations of Quantum Gravity*. Cambridge University Press.
- Huggett, N., & Vistarini, T. (2015). Deriving general relativity from string theory. *Philosophy of Science*, 82(5), 1163–1174.
- Huggett, N., T. Vistarini, & C. Wüthrich (2013). Time in quantum gravity. In A. Bardon & H. Dyke (Eds.), *A Companion to the Philosophy of Time*, pp. 242–261. Wiley Online Library.
- Huggett, N., & Wüthrich, C. (2013). Emergent spacetime and empirical (in) coherence. *Studies in History and Philosophy of Modern Physics*, 44(3), 276–285.

- Huggett, N., & Wüthrich, C. (2018). The (a) temporal emergence of spacetime. *Philosophy of Science*, 85(5), 1190–1203.
- Huggett, N. & C. Wüthrich (forthcoming). *Out of Nowhere: The Emergence of Spacetime in Quantum Theories of Gravity*. Oxford University Press.
- Kachru, S., R. Kallosh, A. Linde, & S. Trivedi (2003). de sitter vacua in string theory. *Physical Review D* 046005.
- Ladyman, J. (2002). *Understanding Philosophy of Science*. Routledge.
- Ladyman, J., D. Ross, D. Spurrett, J. Collier, D. Spurrett, J. G. Collier, et al. (2007). *Every Thing Must Go: Metaphysics Naturalized*. Oxford University Press.
- Le Bihan, B. (2018). Space emergence in contemporary physics: Why we do not need fundamentality, layers of reality and emergence. *Disputatio*, 10(49), 71–95.
- Le Bihan, B., & Linnemann, N. (2019). Have we lost spacetime on the way? Narrowing the gap between general relativity and quantum gravity. *Studies in History and Philosophy of Modern Physics*, 65, 112–121.
- Le Bihan, B., & Read, J. (2018). Duality and ontology. *Philosophy Compass*, 13(12).
- Lewis, D. (1986). *On the Plurality of Worlds*. Blackwell.
- Matsubara, K. (2018). On predictions and explanations in multiverse scenarios. In A. Christian, D. Hommen, N. Retzlaff, & G. Schurz (Eds.), *Philosophy of Science*, pp. 43–54. Springer.
- Maudlin, T. (2007). *The Metaphysics Within Physics*. Oxford University Press.
- Maudlin, T. (2014). Critical study: David Wallace, the emergent multiverse: Quantum theory according to the Everett interpretation. *Noûs*, 48, 794–808.
- McCoy, C. (2015). Does inflation solve the hot big bang model's fine-tuning problems? *Studies in History and Philosophy of Modern Physics*, 51, 23–36.
- Menon, T. (2019). On the viability of the no alternatives argument. *Studies in History and Philosophy of Science*, 76, 69–75.
- Moiraghi, F. (2020). *Explanation through functionalism*. University of Oxford, B.Phil. thesis.
- Nomura, Y. (2012). Quantum mechanics, gravity, and the multiverse. *Astronomical Review*, 7(2), 36–52.
- Nomura, Y. (2016). Before the big bang 4 : Eternal inflation and the multiverse. *Youtube*. <https://www.youtube.com/watch?v=QqjsZEMR7I>.
- Penrose, R. (2010). *Cycles of Time: An Extraordinary New View of the Universe*. Random House.
- Pooley, O. & J. Read (2021). On the mathematics and metaphysics of the hole argument.
- Popper, K. (1959). *The Logic of Scientific Discovery*. Routledge.
- Read, J. (2019). On miracles and spacetime. *Studies in History and Philosophy of Modern Physics*, 65, 103–111.
- Reutlinger, A. (2017). Explanation beyond causation? New directions in the philosophy of scientific explanation. *Philosophy Compass*, 12(2).
- Reutlinger, A. & J. Saatsi (2018). *Explanation Beyond Causation: Philosophical Perspectives on Non-causal Explanations*. Oxford University Press.
- Ritson, S., & Camilleri, K. (2015). Contested boundaries: The string theory debates and ideologies of science. *Perspectives on Science*, 23(2), 192–227.
- Shifman, M. (2010). Large extra dimensions: Becoming acquainted with an alternative paradigm. *International Journal of Modern Physics A* 25(02n03), 199–225.
- Smeenk, C. (2014). Predictability crisis in early universe cosmology. *Studies in History and Philosophy of Modern Physics*, 46, 122–133.
- Smeenk, C. (2017). Testing inflation. In K. Chamcham, J. Silk, J. D. Barrow, & S. Saunders (Eds.), *The Philosophy of Cosmology* (pp. 206–227). Cambridge University Press.
- Smolin, L. (2013a). A perspective on the landscape problem. *Foundations of Physics*, 43(1), 21–45.
- Smolin, L. (2013b). *Time Reborn: From the Crisis in Physics to the Future of the Universe*. Penguin Books.
- Smolin, L. (2014). Review of 'string theory and the scientific method'. *American Journal of Physics*, 82, 1105–1107.
- Susskind, L. (2005). *The Cosmic Landscape: String Theory and the Illusion of Intelligent Design*. Brown and Company: Little.
- Susskind, L. (2007). The anthropic landscape of string theory. In B. Carr (Ed.), *Universe or Multiverse?* (pp. 247–266). Cambridge University Press.
- Tegmark, M. (2008). The mathematical universe. *Foundations of Physics*, 38(2), 101–150.
- Tooley, M. (1977). The nature of laws. *Canadian Journal of Philosophy*, 7(4), 667–698.

- Unger, R. M., & Smolin, L. (2015). *The Singular Universe and the Reality of Time*. Cambridge University Press.
- van Fraassen, B. (1980). *The Scientific Image*. Clarendon Press.
- Vassallo, A. (2020). Dependence relations in general relativity. *European Journal for Philosophy of Science*, 10, 1–28.
- Wallace, D. (2012). *The Emergent Multiverse: Quantum Theory According to the Everett Interpretation*. Oxford University Press.
- Weatherall, J. O. (2011). On (some) explanations in physics. *Philosophy of Science*, 78(3), 421–447.
- Weatherall, J. O. (2018). Regarding the ‘hole argument’. *British Journal for the Philosophy of Science*, 69, 329–350.
- Weinstein, S. (2006). Anthropic reasoning and typicality in multiverse cosmology and string theory. *Classical and quantum gravity* 23.
- Wilson, A. (2018). Metaphysical causation. *Noûs*, 52, 723–751.
- Wilson, A. (2020). *The Nature of Contingency: Quantum Physics as Modal Realism*. Oxford University Press.
- Wüthrich, C., B. Le Bihan, & N. Huggett (forthcoming). *Philosophy Beyond Spacetime*. Oxford University Press.
- Wüthrich, C. (2019). When the actual world is not even possible. In G. Darby, D. Glick, & A. Marmodoro (Eds.), *The Foundation of Reality: Fundamentality*. Space and Time. Oxford University Press.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.