Laws, Initial Conditions and Physical Modality: Lessons from Cosmology

Abstract. Certain considerations from cosmology (Ellis 2006, 2014) and other areas of physics (Sklar 1990; Frisch 2004) pose challenges to the traditional distinction between laws and initial conditions, indicating the need for a more nuanced understanding of physical modality. A solution to these challenges is provided by presenting a conceptual framework according to which laws and fundamental lawlike assumptions within a theory's nomic structure determine what is physically necessary and what is physically contingent from a physical theory's point of view. Initial conditions are defined within this framework in terms of the possible configurations of a physical system allowed by the laws and other lawlike assumptions of a theory. The proposed deflationary framework of physical modality offers an alternative way of understanding the distinction between laws and initial conditions and allows the question of the modal status of the initial conditions of the Universe to be asked in a meaningful way.

Contents

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1. Introduction

Cosmology is often portrayed as a distinctive branch of physics featuring some peculiar aspects that set it apart from other conventional branches of the field. Two notable examples of these distinct characteristics are the uniqueness of its primary subject of examination, i.e. the Universe, and the fact that there seems to be a form of necessity in the determination of the initial conditions during the universe's nascent stages. These peculiarities pose a challenge to the standard traditional understanding of physical modality and the distinction between laws and initial conditions.

According to this view, scientific laws are necessarily true in that they typically express mathematical relations between physical properties that must always hold, while initial conditions are contingent in that they express certain combinations of the physical properties of a system at an initial time t_0 that need not always hold. The designation of initial conditions is a purely contingent and empirical matter which is independent of theories and should not be constrained by laws since this would infringe their 'free assignability' and their contingent nature (Wigner 1964). Moreover, this free variation of initial conditions determines physical possibility by virtue of picking out the different possible states in which a physical system can be found. Once these conditions are fixed, the laws of nature determine the evolution and mutual changes of the physical properties of the system, delineating what is physically necessary.

This view, although quite intuitive and often sufficient for philosophical discussions of physical modality, has been successfully challenged by Sklar (1990) and Frisch (2004). Based on examples from the general theory of relativity and classical electrodynamics respectively, Sklar and Frisch showed that the traditional distinction between laws and initial conditions in terms of their modal status is obscured. Their conclusion is that the 'free assignability' of initial conditions and their overall contingent nature is undermined by the constraints posed on them by laws, in order to preserve the self-consistency of the theory and avoid the violation of fundamental physical principles. In a different context, Ellis (2006, 2014) has also shown that contemplation of certain issues pertaining to the initial conditions of the Universe undermine the status of scientific laws as necessarily true relationships that must always hold due to the possibility of them being constrained by certain initial conditions of the Universe. All three authors concur in concluding that the distinction between initial conditions and laws in terms of their modal status is suspicious, with

Sklar and Frisch further stating that these examples indicate the requirement for a more deflationary account of physical modality in which necessary generalizations are only distinguished by 'mere' generalizations by virtue of being part of scientific theories.

The main goal of this article is to undertake the task of constructing this conceptual framework of physical modality with the aim of providing clear definitions of physical necessity and contingency while preserving the crucial distinction between laws and initial conditions. Within the presented framework, physical necessity is determined by the nomic structure of a scientific theory, which contains the laws of a theory along with every other fundamental lawlike assumption that holds in all the models of the theory. Such an assumption can be a brute fact about nature (e.g. the Past Hypothesis) or every other fundamental assumption in physics such as Lorentz invariance and conservation of energy. In turn, physical contingency is defined in terms of all the possible configurations of physical system in the models of a theory, allowed by its laws and other lawlike assumptions in order to retain consistency. As a result, initial conditions need not be 'entirely free'; rather, their contingent nature emerges from the fact that there is a range of possible configurations that are equally consistent with the nomic structure of a theory. The presented framework thus resolves the various challenges raised by Sklar (1990), Frisch (2004) and Ellis (2006, 2014), and allows the question of the modal status of the initial conditions of the Universe to be asked in a meaningful way by offering an alternative way to understand contingency without appealing to a physical process of preparation before the initial time.

The presented account is 'deflationary' in that it removes the governing power of scientific laws from the actual world and places it into the models of a theory, thus making physical modality a purely theory-relative concept which is strictly defined by the nomic structure of a theory. As a result, necessary generalizations in nature are only distinguished by 'accidental' generalizations merely because they appear in the models of our theories by virtue of being derivable by the laws and lawlike assumptions of a physical theory. This is not to say that what necessarily happens in nature depends on what kind of theories we can construct, but rather that the concept of physical necessity can only be meaningfully determined with respect to a physical theory.

The structure of the article is as follows. In Section 2, a review of physical modality is presented with some working definitions of physical necessity and physical contingency, followed by an overview of Sklar's and Frisch's arguments. Section

3 follows with a critical analysis of Ellis' discussion on the initial conditions of the Universe, and its implications on the traditional understanding of laws and initial conditions. In Section 4, the proposed account of physical modality is presented in detail, resulting in new definitions of physical necessity and physical contingency in terms of the nomic structure and the dynamically possible models of theories. In the last section (Section 5) the proposed framework is applied using Friedmann cosmology as a case study. A plausible (although perhaps unsatisfactory to some) answer to the intriguing question of whether the initial conditions of the Universe are necessary or contingent is also given.

2. Physical modality

Let us begin this section by specifying some working definitions of concepts relevant to physical modality. First, physical modality is to be distinguished from logical modality and metaphysical modality. Logical modality concerns the truth conditions of modal claims according to the laws of logic and mathematics. For instance, it is necessarily true – from a logical point of view – that the sum of the angles of a triangle is 180 degrees, and it is contingently true that a certain triangle is, say, equilateral. Metaphysical modality is notoriously more difficult to define, but a standard way to understand it is in terms of possible worlds. That is, a statement is metaphysically possible iff it is true in at least one possible world, whereas it is metaphysically necessary iff it is true in all possible worlds (cf. Malozzi et al. (2024)). Alternatively, one can express metaphysical modality in terms of the laws of metaphysics. That is, a statement is metaphysically possible iff it is consistent with the laws of metaphysics, and metaphysically necessary iff it follows from the laws of metaphysics (cf. Kment (2021)) – whatever those laws happen to be.

Similarly, physical modality is typically defined in terms of the laws of nature. We shall therefore begin with the following two working definitions:

- *Physical necessity*: An event or state of affairs e is physically necessary if and only if it follows from the laws of nature and could therefore not have been otherwise. Consequently, a true proposition p, is necessarily true (from a physical point of view) if and only if it expresses a necessary event.
- *Physical contingency*: An event or state of affairs e is physically contingent if and only if it is consistent with the laws of nature and could have been otherwise. Consequently, a true proposition p, is contingently true (from a physical point of view) if and only if it expresses a contingent event.

In what follows, the terms 'necessity' and 'contingency' will refer to 'physical necessity' and 'physical contingency' unless stated otherwise. By means of examples, the proposition 'a physical body always travels on a constant velocity in a straight line, unless acted upon by an external force' is necessarily true since it expresses a necessary state of affairs that follows from Newton's first law. The proposition 'the weight of the book I have in front of me now is 2kg' is contingently true since it expresses a contingent sate of affairs which is consistent with the laws of nature, but could nonetheless have been different.[1] The above definitions and examples are usually more than sufficient for fruitful discussions of physical modality, however, as we shall see in what follows, upon further scrutinization of certain examples things start to become a bit more complicated.

Before we delve into these intriguing examples however, let as add some clarificatory remarks. In the spirit of similar discussions by Sklar (1984), Earman (2004), and Woodward (2020), throughout this article we shall understand the *laws of physics* as mathematical propositions within physical theories that constrain the evolution and the behaviour of physical systems in the models of the theory. As will become evident in Section 4, any such statement within the nomic structure of a given physical theory is a scientific law even if it turns out to be 'false' or only applicable within a very limited domain (i.e. an effective law). Consequently, the honorific title of a 'law of nature' is merely reserved for those laws that turn out to be empirically successful within an appropriately large domain. Whether such statements correspond to something else in nature which is independent of human theorising and 'governs' the behaviour of physical systems is largely tangential to the present discussion. It is acknowledged however, that a different – more realist – understanding of laws may lead to a different framework of physical modality and the modal status of the initial conditions of the Universe.

Finally, it is taken for granted that one of the main aims of physical theories is to provide models that represent actual physical systems in order to explain, predict, and understand their behaviour. The exact nature of this representational relationship has been the subject of a long-standing and ongoing debate (cf. Frigg and Nguyen 2017). However, regardless of the specifics of how physical systems are represented by scientific models, a crucial aspect of this relationship is that certain

[1] Here we sidestep the thorny question of what makes a proposition true and focus on the distinction between *necessarily true* propositions and *contingently true* propositions. Whatever theory of truth one holds, and whatever the truth conditions for a certain proposition, p, are, the proposition can be regarded—from a physical point of view—either as a necessarily true proposition or as a contingently true proposition as indicated above.

properties of the physical systems are encoded in the models as variables. The *initial conditions* of a physical system then refer to those variables that describe the configuration of a physical system at a certain time t_0 that marks the beginning of an analysis.

Based on the above definitions, a standard and rather intuitive way to understand the distinction between laws and initial conditions is in virtue of their modal status. That is, laws are typically understood as propositions expressing generic relations between physical properties that must always hold – i.e. propositions that are necessarily true – whereas initial conditions express certain combinations of the properties of physical systems at t_0 that need not always hold – i.e. contingent states of affairs which could nonetheless have been different. This idea is often attributed to Wigner (1964, 1967), but only because he was perhaps the first to highlight the importance of a clear separation between laws and initial conditions in physics. For Wigner, this distinction is based on the different constraints posed by initial conditions and laws, and essentially determines what is physically possible and what is physically necessary according to a theory. In other words, initial conditions must be 'freely assignable' and solely determined by empirical facts; they must be 'as random as the externally imposed, gross constraints allow' (Wigner 1964, p.996). Laws, on the other hand, should only constrain the possible evolution of physical systems and the subsequent changes of the initial conditions, without imposing any constraints on the possible combinations of initial conditions, as this would undermine their 'free assignability' and consequently their contingent character. In other words, for Wigner, the 'free assignability' of initial conditions also guarantees their 'pure contingency', i.e. the possibility to be assigned *any* possible value allowed by the externally imposed gross constraints.

Despite its simplicity and strong intuitiveness, Wigner's idea has been challenged, rather successfully, by Lawrence Sklar who argued that the initial conditions of the world at a given time 'are not as "freely choosable" as one might think', and hence they are not purely contingent (Sklar 1990, 553). Sklar's main argument is that in order to preserve self-consistency in some models of general relativity with closed timelike curves, various restrictions must be imposed on the initial conditions of these models, which means that the latter are not entirely free as implied by Wigner. Spacetimes with closed timelike curves are hypothetical solutions to Einstein's field equations in general relativity that allow for the existence of closed loops in the fabric of spacetime along which objects can travel back in time. Their presence in spacetime models raises a number of paradoxes and logical inconsistencies, and violates many commonly accepted principles of physics such as causality and the conservation of energy. In order to avoid these paradoxes and retain the self-consistency of these models, certain restrictions must be placed in the assignment of initial conditions, thus undermining their assumed 'free assignability'.

A characteristic example given by Sklar is Gödel's world model. This solution to the Einstein field equations comprises a smoothed out mass distribution, but also has the notorious feature of containing closed timelike curves. However, once such closed causal loops are tolerated as possibilities for the world, the paradoxical nature of this model can only be eliminated by stipulating that all states of the world at a given time are self-consistent, which further implies that some specifications of the initial conditions – i.e. those that generate events that lead to closed causal loops – are impossible. Sklar then rightly concludes that 'there is much that is obscure in the notion of the "physically necessary"' (1990, p.551) and that 'there seem to be some aspects of physics that cast doubt on claims that the stipulation of initial states is a purely "contingent" matter...' (*ibid.*,p.563).

Similarly, Frisch (2004) provides further examples from classical electrodynamics 'challenging the distinction between laws that delineate physically possible worlds and initial conditions' (p.696). Frisch's main idea is that there are certain cases in which the laws of classical electromagnetism, i.e. the Maxwell-Lorentz equations, place constraints on certain initial conditions, and that 'some [initial] conditions used in constructing mathematical models of electromagnetic phenomena do not seem to fit the contingent-necessary dichotomy very well' (Frisch 2004, 705). He then proceeds to suggest that 'we can make sense of both these features of scientific theorizing, if instead of thinking of laws as delineating the class of possible worlds allowed by a theory, we think of laws as tools for model-building' (*ibid.*). This idea is put in practice in Section 4 where laws are understood as constraints on models within the nomic structure of a theory.

In summary, both Sklar's and Frisch's arguments suggest that initial conditions in physics cannot always be entirely 'free', as certain constraints must be imposed to ensure the self-consistency of models and theories. This challenges Wigner's claim that initial conditions must be 'freely assignable' and therefore purely contingent, making the standard distinction between laws and initial conditions in terms of their modal status rather obscure. It should be noted however, that while Wigner does not explicitly assert that free assignability is a necessary condition for contingency, Sklar and Frisch's interpretation implies this reading of his view. For them, the undermining of the free assignability of initial conditions also undermines their supposed contingency. As a result, the distinction between laws and initial conditions becomes blurred, making the broader notion of physical modality suspicious.[2]

In the following section, we shall see that in addition to these complications, certain considerations regarding the initial conditions of the Universe provide further grounds for challenging this traditional distinction, highlighting the need for a more nuanced framework of physical modality. The ultimate aim is to provide a conceptual framework in which the contingency of initial conditions and their distinction with laws can be preserved, without the unfeasible requirement of free assignability. This will be shown in Section 4.

3. The Initial Conditions of the Universe

As defined above, the initial conditions of a physical system refer to the (values of the) variables representing its physical properties at t_0, i.e. its configuration at a certain point in time that marks the beginning of the study of the system from a physical theory's point of view. by the same token, the initial conditions of the universe refer to the value of its properties at t_0, where t_0 is usually taken to mark the birth of the Universe at the time of the Big Bang, approximately 13.8 billion years ago. The crucial question is whether these initial conditions are a necessary or a contingent fact. In other words, should the properties of the Universe at an infinitesimal period of time after the Big Bang have taken the specific values they did, or could they have been different?

This question has been thoroughly studied by cosmologist G. F. R. Ellis (2006; 2014), who, like Sklar and Frisch, argues that the distinction between laws (generic conditions that must always be true) and initial conditions (contingent conditions that need not be true) in terms of their modal status is unclear. In his earlier article, Ellis begins his analysis by highlighting the fact that even though the initial conditions of the Universe are intuitively understood as contingent rather than necessary, they are in fact given to us as being absolute and unchangeable (Ellis 2006, p.19). That is, the unique initial conditions that led to the particular state of

[2]Another prominent rejection of the standard distinction between laws and initial conditions, albeit in a different spirit, is due to Ruetsche (2011). For Ruetsche, the distinction between laws and initial conditions is essential to what she calls the 'pristine interpretation' of theories, and depends on a clear concept of a common shared structure across the physically possible worlds according to a theory. She then argues that in the case of quantum theories with infinitely many degrees of freedom the ideal of pristine interpretation fails for various reasons, and therefore the distinction becomes blurred. For further discussion and application of these ideas to the past hypothesis see also Jacobs (2023).

the Universe we observe today were somehow fixed by the time physical laws started governing its evolution after the Big Bang and there is no conceivable way in which they could be altered. However, if these initial conditions are indeed contingent, the puzzling issue is to explain in what sense they could have been different at t_0 and assign well-defined probabilities to the different possible combinations of initial conditions that are equally consistent with the current laws of physics.

This issue is further elaborated by Ellis in his later work (Ellis 2014, p.12) where he points out that the problem of the demarcation between initial conditions and laws arises from the facts that (a) we do not know what aspects of those initial conditions had to be that way and what could have been different, and (b) some relationships between physical properties that appear to us to be fundamental physical laws may rather be the outcome of specific initial conditions in the universe, and they could therefore have worked out differently.

Regarding the second fact, the two examples used by Ellis come from the second law of thermodynamics and the constants of nature. As Ellis notes, there seems to be a growing consensus today that the arrow of time embodied in the second law of thermodynamics is not a fundamental physical law, but rather, the outcome of the special initial condition of low entropy at the beginning of the Universe (e.g. Carroll 2010; Penrose 2013).[3] As for the constants of nature, Ellis draws on existing arguments from physics suggesting that it is possible that they vary with position in the Universe (e.g. Rees 2008; Susskind 2008; Uzan 2011) and therefore, local laws of physics featuring these constants may be variable and context dependent too. Hence, while Sklar's and Frisch's arguments challenge the contingent status of initial conditions compared to laws, the two examples presented by Ellis in effect challenge the status of laws as necessary relationships that must always hold by showing that they too might be constrained by initial conditions, similar to the way the laws constrain initial conditions in the aforementioned examples. In other words, if the initial conditions of the Universe could have been different but at the same time determine some laws (e.g. the second law of thermodynamics) then these laws also have been different. Same with laws featuring constants. If it is possible

[3]This issue is closely related to the problem of explaining the initial condition of low entropy, which has been at the centre of a debate between Price (1996, 2002, 2004) and Callender (1998, 2004). In essence, Price and Callender disagree on whether the so-called Past State requires explanation or should be taken as a brute fact, and on whether there is a clear and widely accepted criterion based on which certain facts require explanation or not. Interestingly, the dialectic leads Callender to the conclusion that the Past Hypothesis is a fundamental law because it is physically impossible for entropy not to be low in the past (2004, p.209). We will return to this issue in Section 4. For further arguments on why the Past Hypothesis is law-like see also Farr (2022) and Chen (2023).

that these constants vary with position in the universe, then the corresponding laws also vary with position and therefore, such laws are not necessarily always true. Thus, the arguments from Sklar and Frisch indicate that initial conditions may not be purely contingent, and the arguments from Ellis indicate that laws may not be purely necessary.

Regarding the first issue, it should be stressed that the impossibility to understand whether the initial conditions of the universe could have been different is not merely an epistemological problem. It is not only a matter of limited knowledge or lack of access to the physical processes occurring near the Big Bang. Rather, it is the combined result of the lack of appropriate cognitive, linguistic and scientific tools to understand and define the ways in which certain physical properties of the universe – such as the curvature of spacetime – could have taken a different initial value than what our current scientific theories and observations say they have. Ellis' formulation of this puzzling situation is particularly vivid: 'Prior to the start (if there was a start) physics as we know it is not applicable and our ordinary language fails us because time did not exist, so our natural tendency to contemplate what existed or happened "before the beginning" is highly misleading – there was no "before" then, indeed there was no "then" then!' (2006, p.30).

To put it differently, unless additional clarifications are given, the question 'could the initial conditions of the Universe have been different?' is not well-defined. And the root of the problem can be found in the lack of a clear definition of the precise meaning of the term 'could' in the claim 'could have been different'. Within the traditional understanding of physical contingency this term has an ambiguous meaning in that it can both mean 'consistent with physical laws' *and* 'manipulable / amenable to preparation'. So when one says that the initial conditions of, say, a simple Newtonian model are contingent, this usually means that different values of its properties at t_0 are consistent with Newton's laws, and that the corresponding physical system can, in principle, be prepared (not necessarily by a human agent) so as to have these values. The problem is that while for ordinary physical systems these two meanings of 'could' are compatible, in the case of the Universe as a physical system they are not. On the one hand, there are multiple sets of initial conditions of the Universe that are consistent with the laws of physics, but on the other hand, there is no conceivable way in which the Universe could have been prepared to have different initial conditions since time itself begins at the Big Bang and no current physical theory is able to provide a meaningful explanation of what underlies the particular choice of initial conditions that indeed occurred.

Ellis' underlying point is that, as opposed to ordinary physical systems, the alleged contingency of the initial conditions of the Universe cannot be understood in terms of preparation since this would presuppose the occurring of a mechanism taking place prior to t_0. But the problem is that t_0 not only marks the beginning of the Universe but also the beginning of time itself and therefore it is not clear what the claim 'could have been different' means in this case. Hence, this realisation forces us to adopt an understanding of the contingency of initial conditions of the Universe only in terms of consistency with laws, and not in terms of manipulability and preparation.

Moreover, given that there is no time prior to the beginning of the universe at t_0, the time symmetric nature of the laws of physics dictates that the specific conditions that led to the universe's current state follow directly from these laws and therefore, according to the definition of physical necessity in Section 2 they seem to be necessary rather than contingent. In other words, if the current form of the Universe is determined by its initial conditions and the laws of physics, then running the laws of physics 'backwards' leads to a unique set of initial conditions, which could simply not have been different. And this is precisely what Ellis seems to have in mind when he says that '[b]ecause we cannot vary the initial conditions in any way, as far as we are concerned they are necessary rather than contingent – so the essential distinction between initial conditions and laws is missing' (2006, p.31).

Prima facie, appealing to the theory of cosmic inflation that leads to certain initial conditions seems to be a promising route out of this conundrum, however, this move cannot solve the problem for two reasons. First, cosmic inflation – if true – is believed to have happened from 10^{-36} to approximately 10^{-32} seconds after the Big Bang and so the same questions about the initial conditions of the universe before this inflationary epoch can still be asked. Second, there is currently no consensus in the various proposed mechanisms that generate a cosmic inflation and no possible testable way of determining which of these mechanisms is ultimately responsible for the inflationary period of the universe we live in. Even if this turns out to be the case in future physics however, the same questions would still apply regarding the initial conditions that generated the responsible mechanism.[4]

Similar worries arise if one attempts to provide a possible explanation for the contingency of the initial conditions of the universe by avoiding the notion of a 'true beginning' of the universe altogether, as is the case in various proposals of bouncing

[4] For a comprehensive review on cosmic inflation see Liddle (1998) .

cosmologies. Bouncing cosmology theories suggest that an initial singularity can be avoided by replacing it with a 'Big Bounce', i.e. a form of eternal cycle of contraction and expansion in which the universe contracts until it collapses in on itself, and 'bounces' back to an expanding phase.[5] However, even in these scenarios, the problem of explaining the initial conditions of the universe remains the same, since it is still not clear how the specific initial conditions at a time t_0 right after a 'Big Bounce' are fixed. As Ellis (2006, p.60) notes, these attempts do not solve the problem; rather, they merely postpone facing it, since one can simply ask the same questions of the origins and the 'fixing' of the initial conditions on the supposed initial state prior to the hot Big Bang expansion phase. In any case, regardless of any inflation and bouncing scenarios, the ultimate questions regarding the contingency of the initial conditions of the universe persist: Why has one specific state occurred rather than another which is compatible with current physical laws? And what underlies the choice of the instantiated combination of initial conditions of the universe?

The upshot is that while the contingency of the initial conditions of ordinary physical systems can be explained by stating that they can be prepared in various ways that are consistent with the laws of physics, the initial conditions of the universe are not as easily understood. It is simply not clear how the initial conditions of the universe *could have been different* from what our current observations and laws indicate. The presented arguments by Ellis (2006, 2014) therefore supplement the arguments by Sklar (1990) and Frisch (2004) suggesting that a distinction between laws and initial conditions in terms of their modal status is not feasible within our current understanding. This further implies that the related notions of physical necessity and physical contingency require a more nuanced and 'deflationary' framework in which they can be clearly defined and distinguished, allowing the question of the modal status of the initial conditions of the universe to be asked meaningfully. This framework is presented in detail in the next section.

4. Nomic structure and Physical modality

The proposed account of physical modality draws inspiration from Friedman's (2001) seminal work on the structure of laws and physical theories as well as from relevant contemporary discussions, especially by Caulton (2015), Curiel (2016), Woodward (2018, 2020) and Gryb and Thébault (2023), albeit with important modifications to suit the purposes of this article. The main idea is that

[5] For a comprehensive review of bouncing cosmologies see Brandenberger and Peter (2017).

physical theories consist of a *constitutive structure* which, roughly speaking, defines the types of physical systems to which a theory is applicable and consequently its kinematically possible models (KPMs), and a *nomic structure* which contains the theory's laws and other fundamental lawlike assumptions, which jointly constrain and determine the behaviour of physical systems in the dynamically possible models (DPMs) of the theory.[6] Physical modality is then defined in terms of the nomic structure and the dynamically possible models of a theory, whereas the distinction between initial conditions and laws is defined in terms of the role of the former in defining the allowed configurations of a system.

To elaborate, the constitutive structure of a scientific theory encompasses all the necessary ingredients required to (a) specify the types of physical systems to which the theory can meaningfully apply and (b) articulate the laws that *constrain* their behaviour. In the framework of Gryb and Thébault (2023), this structure consists of: (i) a manifold structure which is used to characterize physical events, (ii) the geometric structures which characterize relations of ordering, distance and orientation between the events, and (iii) various matter structures which characterise the non-geometric content of the theory. To these, one may add (iv) the specification of a set of quantities $Q = \{q_1, ..., q_n\}$ corresponding to all the quantitative properties of the physical systems described by the theory and the various constants of nature that appear in the nomic structure of the theory as parameters in its laws and fundamental assumptions. A KPM is a trivial model of the theory based on the constitutive structure where the initial values of the parameters and their subsequent evolution are not constrained by any laws and other lawlike assumptions.

Clearly determining the constitutive structure of a particular theory is not an easy task and is something that goes beyond the scope of this article. For our purposes, it suffices to say that the constitutive structure can be understood as comprising the *minimum necessary* pre-existing structure in order to specify the physical systems to which the theory applies and express its laws and fundamental assumptions in a coherent and meaningful way.[7] For instance, the constitutive

[6]The deployment of the concepts of constitutive and nomic structure builds upon the analysis of Gryb and Thébault (2023, Ch.5), which is further rooted on Friedman's distinction between the mathematical, the mechanical and the physical/empirical part of a theory (Friedman 2001, pp.79-83).

[7]cf. Gryb and Thébault (2023, p.77): 'Constitutive structure is structure that is necessary and sufficient to represent a kinematical universe of structured events within the theory', and Curiel (2016, p.3): 'it is satisfaction of the kinematical constraints that renders meaning to those terms representing a system's physical quantities in the first place, even before one can ask whether or not the system satisfies the theory's equations of motion'.

structure of Newtonian mechanics would include a Euclidean geometry of flat and absolute space, matter composed of point particles that interact only via the force of gravity, a specification of all the fundamental quantities needed to formulate the theory (mass, length, gravitational force, velocity, acceleration, momentum etc.), a one-dimensional infinite and continuous time which is independent of space, facts and definitions such that velocity is the first derivative of position and that momentum is the product of an object's mass and velocity and so on. To construct a kinematically possible model of Newtonian mechanics, is then to construct a physical system whose configuration $\mathbb{C} = \{q_1, q_2, ..., q_n\}$ is a set of n related quantities according to the constitutive structure of the theory, but which are nonetheless not constrained by any laws.[8] Constraints on the behaviour and time evolution of such physical systems come from the nomic structure.

The nomic structure of a theory contains all the necessary information to *control* the behaviour of a physical system in the KPMs of a theory by *constraining* its possible configurations and thus generating the DPMs. This structure comprises the laws of the theory and their respective symmetries, as well as any other lawlike fundamental assumptions in the theory that are shared by all the models of the theory and place some sort of constraint in the possible configurations of a physical system within the DPMs of the theory. Laws are typically mathematical propositions expressing relations between certain parameters of the theory, and they can be dynamical, scaling (Suppe 1977; van Fraassen 1989), or conservation laws (Lange 2007; Maudlin et al. 2020). Dynamical laws are typically expressed in the form of differential equations and constrain the dynamical evolution of certain parameters. That is, they determine how certain quantities characterizing the state of a physical system in a model change their values as time passes. Scaling laws (or laws of coexistence) determine which instantaneous configurations of parameters are allowed within the dynamically possible models of a theory by specifying various mathematical relationships between certain physical quantities of the theory. Thus, while dynamical laws constrain how certain parameters of a system change in time, scaling laws place constraints on the possible combinations of these parameters at any given time. Finally, the conservation laws of a theory place constraints on certain

[8]The term 'configuration' has been deliberately selected here over the more common term 'state' of a physical system to denote something more general than the state of a system in classical mechanics which is specified by a point (x, p) in the position-momentum state space at time t. In this context, the configuration of a system does not necessarily refer to position and momentum. Rather, it includes a more general set of related physical properties from a certain theory's point of view.

physical quantities within a physical system by stating that a certain physical property, q, does not change in the course of time within an isolated physical system, i.e. by stating that dq/dt=0.[9]

Lawlike fundamental assumptions comprise every other assertion of the theory which is introduced *by fiat* and imposes, directly or indirectly, a constraint in the possible configurations of a physical system. Like laws, lawlike assumptions must always be respected and are therefore *always present across all the dynamically possible models of the theory.* A clear example of such an assumption in Newtonian mechanics is the specification of the value of the universal gravitational constant G which indirectly constrains the evolution of physical systems via Newton's universal law of gravity. Another example is the principle of locality and the related second postulate of the theory of relativity according to which light always propagates in vacuum with a definite velocity c in all frames of reference. Depending on the theory in hand, such lawlike assumptions can also include the free parameters of the theory, brute facts about the world such as the past hypothesis and Penrose's Weyl curvature hypothesis, as well as any other metaphysical or mathematical principle incorporated in the theory, insofar as it imposes a constraint in all DPMs of the theory. As will become evident in the next section, as long as one operates within the scope of Friedmann cosmology, the cosmological principle – i.e. the assumption of homogeneous and isotropic distribution of matter in spacetime – can be seen as a lawlike assumption which places certain constraints on the structure of spacetime, even though from the broader scope of view of general relativity, the cosmological principle is merely an idealization.[10]

[9]For further views of physical laws as constraints see also Adlam (2022) and Ross (2023).

[10]A few further clarificatory remarks might be helpful here. Given that the DPMs of a theory are a subset of its KPMs, whatever shared principle holds in the KPMs, also holds in all the DPMs of the theory, but the converse is of course not true. So, for example, what determines that locality is part of the nomic and not the constitutive structure of general relativity is the fact that one can construct different non-local versions of general relativity by introducing non-local terms in the Einstein-Hilbert action. The constitutive structure would then be the shared structure in these local and non-local versions of general relativity. One might reasonably worry that there appears to be an element of arbitrariness in deciding whether a principle belongs to the constitutive structure or the nomic structure of a theory—and this concern is valid. Whether a principle is considered part of the constitutive structure depends on whether it is regarded as "essential" to the theory, such that abandoning the principle would result in a fundamentally different theory operating within a distinct conceptual framework (e.g. a quantum theory of gravity). This is not necessarily problematic for physical modality though. Regardless of whether a principle is part of the constitutive structure or the nomic structure, physical necessity is defined by the principles shared across the DPMs of a theory. In other words, what matters is that these principles hold consistently within the DPMs, whether or not they also extend to the totality of the KPMs of the theory.

To some extent, whether one choses to label these fundamental assumptions in theories as 'laws'—as Callender (2004) does with the past hypothesis—is simply a matter of preference in terminology. What matters is that such lawlike assumptions serve the same purpose as 'traditional laws' in constraining and determining the behaviour of physical systems. They *must* hold across all models of the theory, just as conventional laws do, in order to generate the class of DPMs from the broader class of KPMs.[11] In other words, the set of DPMs is the proper subset of the KPMs of the theory whose configuration and evolution is constrained by the nomic structure of the theory, i.e. by the laws of the theory and its fundamental lawlike assumptions. Hence, for instance, a KPM of Newtonian mechanics may contain planetary systems in which gravitational attraction is characterised by a different value of G than the standard one ($G \approx 6.674 \cdot 10^{-11} N \cdot m^2/kg^2$) and/or a different gravitational law, e.g. an inverse cube law. However, insofar as Newton's laws are respected and the value of G is fixed in the model according to the nomic structure of the theory, the model becomes a DPM, provided that it is also consistent with every other constrain in the nomic structure of the theory.[12]

In sum, the constitutive and nomic structure of a theory allows the meaningful specification of kinematically and dynamically possible models with the aim of representing actual physical systems. The behaviour of these physical systems is captured by a set of related quantities corresponding to constants of motion, i.e. quantities representing physical properties whose values remain constant in time within the model, and state variables, i.e. quantities Q corresponding to physical properties whose values change in time within a model. Constants of motion and state variables jointly determine the configuration $\mathbb{C}$ of a given physical system as a set in which different combinations of elements correspond to the different states in which a physical system can be found according to the theory. Changes in the values of at least one constant of motion or state variable correspond to changes in the configuration of a system. In the dynamically possible models of the theory, the initial combinations and the subsequent changes of these values are jointly constrained by the nomic structure of the theory via the dynamical, scaling and

[11]On a plausible reading, the fact that the past hypothesis determines the second law of thermodynamics which in turn constrains the configuration of physical systems in thermodynamics, is precisely what drives Callender and others (Loewer 2020; Chen 2023) to claim that the past hypothesis is a fundamental law of nature or acts like one.

[12]Another way to illustrate this picture is by understanding Milgrom's (2014) Modified Newtonian Dynamics (MOND) as having the same constitutive structure with Newtonian mechanics, but a different nomic structure since Newton's second law is modified in low accelerations. As a result, the two theories share the same set of KPMs, but their DPMs are different.

conservation laws as well as by every other fundamental lawlike assumption of the theory, including the fixed values of the constants of nature appearing in laws and the free parameters of a theory.

Initial conditions are defined in this framework as surjective functions f from the set of quantities Q of a DPM specified in a theory's constitutive structure to the set of real numbers $\mathbb{R}$. That is, they are functions $f : Q \to \mathbb{R}$ that may map one or more elements of Q to an element of $\mathbb{R}$ (i.e. different physical properties can have the same value). In less formal language, initial conditions correspond to all possible values that can be attributed to the physical quantities in a dynamically possible model at t_0 which marks the starting point for the dynamical laws of the theory to take effect in determining the dynamical evolution of the system within the model. Thus, in any given physical system represented by a DPM, the initial conditions assign values to the quantities characterising the system as constants of motion and state variables, creating a class of configurations with an, in principle, infinite number of set-elements, each configuration corresponding to a specific initial combination of values for the quantities characterizing the system. Once the values are fixed, the subsequent mutual changes of these values are then determined by the relevant dynamical laws of the theory. The crucial point here is that amongst this, in principle, infinite number of combinations of initial configurations of physical systems there is a special subset of configurations $\mathbb{C}_P$ for which the laws of the theory remain *consistent with every other lawlike assumption* in the nomic structure. This subset of configurations and their possible subsequent changes according to the dynamical laws determine what is physically possible with respect to a theory.

From this conception of laws and initial conditions, a more nuanced and at the same time deflationary account of physical modality can be constructed. In addition to the clear and robust definitions of physical necessity and contingency, this framework provides a clear distinction between laws and initial conditions and allows the determination of the modal status of the initial conditions of the Universe. The new definitions are as follows:

- *Physical necessity*: An event or state of affairs e is physically necessary from a physical theory's point of view if and only if it is explicitly defined as a fundamental lawlike assumption in the nomic structure of the theory, or is a deductive consequence of one or more laws and lawlike assumptions and therefore holds in all DPMs of a theory. A true proposition p is necessarily true if and only if it expresses a necessary event or it is a proposition within the nomic structure of a theory expressed as a law or a fundamental lawlike assumption.

- *Physical contingency*: An event or state of affairs e is physically contingent from a physical theory's point of view if and only if it satisfies the following three conditions: (i) it is consistent with the laws and fundamental lawlike assumptions of the theory, (ii) it corresponds to a full or partial configuration of at least one DPM allowed by these laws and lawlike assumptions, and (iii) it is violated in at least one other DPM of the theory. A true proposition p is contingently true if and only if it expresses a contingent event.

Let us unpack these definitions. First, note that prima facie it seems that the definition of physically contingent events also includes physically necessary events, since the latter are of course also consistent with laws. Consistency with the nomic structure is not the only criterion for contingency however. A physically contingent event is one that also corresponds to the configuration of at least one DPM of a theory but at the same time it is also violated in at least one other. Hence, for instance, the value of matter density of the universe with respect to other related quantities at a given time is contingent insofar as the theory within which it is expressed allows this value (under certain conditions) in at least one DPM *and* there is at least one other DPM in which this quantity takes a different value. By the same token, a given configuration of a model of a pendulum with certain values of its variables (i.e. with mass m_1, period T_1 etc.) is a contingent state of affairs insofar as this configuration can be found in at least one DPM, but at the same time the theory also allows different configurations of these quantities (with mass m_2, period T_2, and so on) in at least one other DPM. On the contrary, as will be shown in more detail in the next section, the Cosmological Principle which is taken as a lawlike assumption within Friedmann cosmology (understood as a narrow version of general relativity) is not contingent, since it is not violated in any DPM of the theory (i.e. it does not satisfy condition (iii)). From the point of view of the broader theory of general relativity however, the cosmological principle is contingent, since it satisfies all three conditions. That is, it is consistent with the fundamental laws of the theory and the theory includes both DPMs in which the principle is satisfied and DPMs in which it is not.

Physically necessary states of affairs however, do not correspond to such configurations. Rather, they correspond to more general states of affairs that follow deductively from the laws and lawlike assumptions of the theory and could therefore not have been different according to the theory. For instance, a physically necessary state of affairs would be the general fact that a dropped object in a vacuum falls towards the ground due to gravity, since this is a deductive consequence of the laws and lawlike assumptions of Newtonian gravity and no DPMs can be found in the theory in which this proposition does not hold. Note also that a certain state of affairs expressed within a model may *follow necessarily* given specific initial conditions, however, insofar as it corresponds to one of the many allowed configurations it is not a physically necessary state of affairs. For instance, that the period of a pendulum takes a certain value, T_1, given a particular length, L_1, follows necessarily from Newton's laws, but it is a contingent state of affairs since it only corresponds to one of the many values allowed by the theory. The necessary state of affairs in this case would be the more general fact that the period is proportional to the length of the pendulum since no DPM exist in the theory in which this claim is false.

Finally, note that within this view, claims about what is physically necessary or contingent are strictly theory-dependent and their truth conditions are determined by the nomic structure of the theory in hand. Hence, from the point of view of Newtonian mechanics, the universal law of gravitation is a necessarily true proposition qua its status as a law of the theory, and the equations of motion of a two body system, for instance, are necessarily true qua deductive consequences of the laws and lawlike assumptions of the theory. Moreover, from the point of view of Newtonian mechanics it is physically possible to violate locality and from the point of view of general relativity it is physically possible to have spacetimes with close timelike curves, since these two states of affairs correspond to allowed DPMs of the two theories respectively. Similarly, it is physically necessary that a constantly accelerating body will gradually develop an infinite velocity according to Newtonian mechanics, and it is physically necessary that a homogeneous and isotropic universe with a positive curvature will eventually collapse on itself according to general relativity (under certain conditions).

This is to be expected since what we – as limited human agents – can meaningfully assert is physically necessary or not depends on what the laws and lawlike assumptions of our physical theories say. In practice, the way to avoid the absurdity of claiming that it is physically necessary that accelerating bodies will eventually reach an infinite velocity for instance, is to distinguish between *genuine physical possibilities* and *theoretical physical possibilities*. The latter are the ones we have described so far based on the DPMs of a theory, and the former are a subset of theoretical physical possibilities in which certain fundamental logical and philosophical principles, empirical facts, as well as scientific principles that lie outside these theories and are considered to be more fundamental are also taken into consideration. For instance, this is the case when Earman (1995) argues that the (dynamically possible) models of general relativity with closed timelike curves violating various consistency conditions do not represent genuine physical possibilities.[13] This is a fair and plausible intuition, however it should be stressed that from the point of view of the theory of general relativity there is no fundamental distinction between Gödel's solution that admits closed timelike curves and, say, a de Sitter solution that does not. Rather, what this teaches us is that not all the DPMs of our current theories correspond to what we consider to be genuine physical possibilities – i.e. physical states of affairs that could actually occur regardless of what our theories say – and that the criteria for distinguishing between models that capture genuine possibilities and models that do not are ultimately found in other scientific theories, in empirically confirmed facts and in our logical and philosophical intuitions which may vary with personal preference and with time.

Nevertheless, this does not change the fact that our assertions about what is physically possible depend on the laws and other lawlike assumptions of our physical theories and can therefore change as our theories evolve. It is perfectly reasonable to imagine a possible scenario where general relativity appears as a limit of a more fundamental (and probably quantum) theory of gravity, in which the Einstein field equations emerge as an effective description in the appropriate limit where quantum gravitational effects are negligible, in the same way that Newton's laws appear as a limit of general relativity in low accelerations. In this case, and from the point of view of the new theory, the field equations will lose their status as necessarily true mathematical statements, since they will no longer be 'always true'. In other words, given that the Einstein field equations will not be expected to hold in the quantum regime, they will not hold in all DPMs of this new theory of gravity, and therefore they will not be included in the nomic structure of the theory as universal statements that are true across the entire regime of the theory. [14]

[13] Pooley (2001) puts forward a similar argument about vacuum solutions in general relativity, based on the fact that there can be no spacetime in the absence of matter.

[14] This view is close in spirit with a similar idea found in the recent work of Baron et al. (2024) in which the authors argue that what corresponds to physical possibilities are the models of effective theories. One of the motivations for their proposal is that the laws of our physical theories are not universally true and are best understood as effective laws within an appropriate domain. The main advantage of this view is that it does not require that the laws of physical theories are universal and always true, and can therefore explain why the laws of Newtonian gravity, for instance, can capture physical necessity despite not being 'necessarily true'. The authors conclude that their proposed principle in terms of the models of effective theories provides the foundation for future

Returning to the definition of physical contingency, this is determined purely in terms of the configurations of physical systems allowed by the laws and lawlike assumptions, without reference to any physical process of *preparation* before the initial time t_0. Hence, as will be made clear in the next section, from the point of view of Friedmann cosmology—which is understood as a narrower version of general relativity—the initial conditions of the Universe are indeed contingent, in that they correspond to one of the many initial configurations of the Universe allowed by the laws and the fundamental lawlike assumptions of the theory. The claim 'they could have been different' only corresponds to the fact that there is more than one configuration of initial conditions to which the laws and lawlike assumptions of the theory remain invariant, and does not require the occurring of a physical process prior to the Big Bang.

This understanding also clarifies the relationship between 'free assignability' and 'contingency' discussed in Section 2. As opposed to Wigner's view, initial conditions need not be entirely free in order to be contingent, since as shown by Sklar and Frisch this demand is unattainable. Here, the contingency of initial conditions amounts to the fact that there is no unique possible combination of these conditions but rather, there is a set of several combinations that are compatible with the nomic content of the theory in question. Contingency is therefore understood not in terms of preparation and free assignability, but in terms of allowed variability with respect to the nomic structure. In other words, within the presented framework, free assignability (in Wigner's strict sense) is not a necessary condition for contingency.

Finally, the complications raised by Sklar (1990), Frisch (2004), and Ellis (2006, 2014) are overcome since the distinction between laws and initial conditions is achieved without reference to their modal status as necessary or contingent. For instance, Sklar's observations about the required restrictions on the initial conditions of spacetimes with closed timelike curves can be understood in this context as a different way of saying that certain configurations of systems $\mathbb{C}_i$ in which the laws and fundamental lawlike assumptions lose their consistency lie outside the subset $\mathbb{C}_P$ of physically possible configurations, since they are in tension with the self-consistency of the nomic structure of the theory. Hence, while contingent, initial conditions need not be 'entirely free'. Rather, what gives them their contingent nature is the fact that there is room for variability in their values insofar as the content of the nomic structure of the theory is respected. Correspondingly, laws

work, and the ideas presented in this article, although stemming from different motivations, are largely in line with this view.

and lawlike assumptions are associated with necessity by virtue of remaining fixed and unchangeable in all the models of the theory.

As Sklar (1990, p.552) notes, such a deflationary approach to the concept of physical modality may leave 'those who want to think of physical necessity as something much "deeper" than this, [...] unsatisfied'. It is however, the only viable way to meaningfully talk about the 'contingency' of the initial conditions of the universe and evade the aforementioned challenges on the distinction between laws and initial conditions in terms of their modal status. Understandably, one may object that while our ability to assert what is physically necessary depends on the nomic structure of our best theories, there is still a sense in which 'genuine physical necessity and contingency' are theory-independent. That is, physically necessary events are those events that follow from the 'real' fundamental laws of nature – whatever those laws happen to be – and an event is genuinely physically necessary only if it follows from these laws. Hence, whether an event is physically necessary depends only on those fundamental laws regardless of whether we will ever construct a physical theory containing these laws.

This is a plausible objection, however, on this matter we align with Ruetsche (2023)'s anti-fundamentalist view that even if one accepts that there is a yet unconceived final scientific theory that completely and adequately captures the way the world really is, it is nowhere to be found in the near future and it is very unlikely that future science will ever be able to fully comprehend such a theory. Hence, if one accepts the plausible claim that we will never be in a position to know whether a physical theory is truly fundamental and applies to all scales and contexts, our assertions about whether certain events are physically necessary or contingent will always be theory dependent. That is, answers to such questions will always have the implicit form 'Event e is physically necessary according to theory T, since it is a deductive consequence of one or more lawlike assumptions in the nomic structure of the theory'. And as already noted, assertions about which DPMs of a theory correspond to genuine possibilities necessarily involve various logical and philosophical intuitions which are, to a certain extent, a matter of personal preference and might change in time as we acquire more knowledge.[15]

[15] Baron et al. (2024) express a similar view by noting that 'we should believe that all models of an effective theory approximate physical possibilities, in the absence of countervailing philosophical principles or evidence from a more fundamental theory. Which philosophical principles one endorses is, of course, a matter of choice.' (p.15).

5. The example of Friedmann cosmology

In this last section the presented framework will be put to practice by illustrating how the concepts of physical necessity and physical contingency can be expressed from the point of view of the theory of Friedmann cosmology, and how the contingency of the initial conditions of the universe can be understood within this framework. Friedmann cosmology is taken here as a narrower version of the general theory of relativity in which the cosmological principle is incorporated in the nomic structure of the theory and is deductively related to the two Friedmann equations which play the role of the dynamical laws of the theory. Friedmann cosmology has been deliberately selected here as the background theory for expressing necessity and contingency for two reasons. First, it is widely regarded as the most appropriate theoretical framework to study the evolution of the Universe, and it is therefore the best way to illustrate how questions about the modal status of the initial conditions of the Universe can be meaningfully asked. Second, the fact that Friedmann cosmology is understood as a narrower version of a known and more general theory – the general theory of relativity – provides a clear illustration of how our assertions of physical necessity are theory-dependent and thus open to revision from a more fundamental physical theory's point of view.

The Friedmann equations are considered to be the most fundamental equations in modern cosmology for the understanding of our Universe. They consist of two differential equations that describe the evolution of a scale factor $a(t)$ and its acceleration $\dot{a}(t)$ in an expanding universe. These equations are derived from a specific solution to Einstein's field equations when applied to a homogeneous and isotropic universe. This type of universe is described by the Friedmann-Lemaître-Robertson-Walker (FLRW) metric, which can be thought of as a mathematical representation of a universe where matter and energy are evenly distributed on a large scale. Such a universe is said to be homogeneous – i.e. the spatial distribution of matter is equally distributed – and isotropic – i.e. there is no geometrically preferred spatial direction and the universe appears the same in all directions. These two assumptions are typically expressed as the Cosmological Principle, which states that the properties of the universe are the same for all observers when viewed on a sufficiently large scale.

The first Friedmann equation is given by:

$$H^2 = \left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G}{3}\rho(t) - \frac{kc^2}{a^2(t)} + \frac{\Lambda c^2}{3}$$

where H is the Hubble parameter representing the rate of expansion of the universe, $a(t)$ is the scale factor as a function of cosmic time relating the size of the universe at different times, $\dot{a}(t)$ is the time derivative of the scale factor, G is the gravitational constant, $\rho(t)$ is the energy density of the universe as a function of time, k is the curvature constant representing the spatial curvature of the universe, c is the speed of light, and Λ corresponds to the cosmological constant associated with dark energy. In essence, this equation describes how the scale factor $a(t)$ changes with time based on the matter and energy contents of the universe, and it is often thought of as expressing the law of conservation of energy for the universe as a whole. It captures the interplay between energy density, expansion rate and the overall geometry of the universe by requiring that the expansion of the universe is determined by the balance between (i) the energy density term $\rho(t)$ representing the source of the expansion and (ii) the curvature and cosmological constant terms, k and Λ, which jointly influence the expansion rate. This equation is often employed alongside the second Friedmann equation (also known as the acceleration equation):

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}\left(\rho(t) + \frac{3p(t)}{c^2}\right) + \frac{\Lambda c^2}{3}$$

which contains an additional term p corresponding to pressure, and describes the change in the acceleration of the expansion of the universe $a\ddot{(t)}$ over time.

As already mentioned, the two equations are derived from the Einstein field equations, assuming a homogeneous and isotropic spacetime. These two assumptions provide the FLRW metric and the energy-momentum tensor for a perfect fluid, which can then be plugged in the Einstein equations to derive the two Friedmann equations. In this sense, Friedmann cosmology is understood as a narrower version of the more general theory of relativity, in that it encompasses the cosmological principle (via the FLRW metric) in its nomic structure, thus significantly reducing the number of its DPMs compared to general relativity. To put it differently, the cosmological principle becomes part of the nomic structure of the theory of Friedmann cosmology, in that insofar as one is exploring models whose evolution is constrained by the Friedmann equations (which play the role of the dynamical laws of the theory) the principle necessarily holds across all the models of that theory.[16]

[16]One might argue here that the resulting models in Friedmann cosmology are still models of general relativity with the additional assumption of the cosmological principle. This is true, however, the idea here is that such assumptions give rise to different subversions of the theory, each one with its own nomic structure (cf. Earman (1993, p.415): 'we need to put Carnapian subscripts on [the general theory of relativity], the different subscripts denoting different theories where the differences lie precisely in the postulates (putative laws) being asserted'). In a sense,

Hence, from the point of view of Friedmann cosmology, it is physically necessary that the Universe is homogeneous and isotropic, and that its evolution is described by the Friedmann equations.

However, this does not mean that the actual universe is indeed homogeneous and isotropic; in fact, whether the cosmological principle is valid beyond the observable universe still remains an open issue.[17] Rather, what this means is that the principle is taken as a brute fact which is introduced in the nomic structure of the theory by fiat and therefore, every model universe whose evolution is captured by the Friedmann equation is necessarily homogeneous and isotropic, for if it was not, the Friedmann equations would not hold. Preserving the homogeneity and isotropy of the universe in all DPMs of Friedmann cosmology is therefore necessary for maintaining the self-consistency of the theory.

One might wonder here whether there is a fact of the matter about whether principles such as the cosmological principle are lawlike assumptions or merely initial conditions. Within the presented framework the answer is no. The classification of such principles as lawlike or as initial conditions depends on the theory in question and, in a sense, also reflects the theory's limitations. To see why, consider that within the broader framework of general relativity, the cosmological principle represents a contingent initial condition, since the theory also allows DPMs in which space is not homogeneous and isotropic. In Friedmann cosmology this is not the case. Given that the Friedmann equations act as laws in the nomic structure of the theory, all the DPMs of this theory must be homogeneous and isotropic in order to maintain self-consistency. Hence, the cosmological principle is elevated to the status of a lawlike assumption since it is introduced by fiat to derive the equations, and therefore holds across all DPMs of the theory. The fact that the principle is a fundamental lawlike assumption in this case thus reflects the limitations of the theory in describing models where space is not homogeneous.

Another way to fathom this subtlety, is to consider the fact that the Friedmann equations can also be derived from Newtonian theory—albeit in a mathematically less rigorous way—by making use of the fact that the gravitational effect on a particle within a sphere comes only from the amount of matter inside the sphere. In a hypothetical scenario where general relativity had not been discovered yet, Friedmann cosmology would constitute a theory of the universe's evolution in which the cosmological principle is taken as a brute fact, i.e. a lawlike assumption,

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one may perceive the assumption of cosmological principle within Friedman cosmology as serving a similar purpose as the assumption of Lorentz invariance in general relativity.

[17] See, for instance, Aluri et al. (2023). For a philosophical discussion see Beisbart (2009).

in a similar way to the past hypothesis. Conversely, the eventual discovery of a broader theory that allows DPMs with non-homogeneous and non-isotropic DPMs would relegate the cosmological principle to a contingent initial condition.

Now to see how this framework applies to the initial conditions of the Universe, consider the fact that the equations allow a range of values of the parameters figuring in them, namely the scale factor a and its time derivatives, the energy density ρ, the curvature k, the cosmological constant Λ and the pressure p. Assigning different initial values in these parameters corresponds to creating different possible configurations of the universe $\mathbb{C}_U = \{a, \dot{a}, \ddot{a}, \rho, k, \Lambda, p\}$ whose subsequent changes are constrained by the nomic structure of the theory of Friedmann cosmology. In the special case of the DPM representing the actual universe we live in, the initial value of the scale factor represents the size of the universe at its nascent stages, the initial energy density includes contributions from all forms of matter and energy at that time, and the curvature constant represents the initial spatial geometry of the universe which can be negative, zero, or positive, corresponding to an open universe ($k < 0$), a flat universe ($k = 0$) and a closed universe ($k > 0$) respectively. Hence, from the point of view of Friedmann cosmology, the initial conditions of the Universe are contingent, in that they correspond to one of the many configurations of the Universe in the DPMs of the theory, to which the laws (i.e. the Friedmann equations) remain consistent.

The variability in the different combinations of these initial conditions need not be understood as meaning that the universe *could have been prepared* to have any specific combination of these values at t_0. Rather, the 'contingency' of these initial conditions merely reflects the fact that the Friedmann equations remain consistent under variations in these parameters and constrain the mutual changes of a number of different configurations $\mathbb{C}_P$ specified by different combinations of initial conditions. In other words, fixing the values for some of these parameters and studying how the rest of these quantities are constrained by the Friedmann equations allows us to specify all the dynamically possible models of the theory, each model corresponding to a possible scenario for the evolution of the universe according to the theory of Friedmann cosmology.

For instance, in Einstein's (1917) static universe the scale factor is constant, there is no pressure, and the energy density is positive, corresponding to an initial configuration $\mathbb{C}_{Static} = \{a, \dot{a} = 0, \ddot{a} = 0, \rho > 0, p = 0, k, \Lambda\}$. Proper manipulation of the Friedmann equations then gives two equations of the cosmological constant and of the spatial curvature in terms of the energy density, from which one concludes –

as Einstein did before the Friedmann equations were derived in 1922 – that a static universe with these initial conditions is necessarily closed (i.e. k is positive) and has a positive cosmological constant.[18] Similarly, the special configuration which is believed to represent the actual initial conditions of the universe we live in $\mathbb{C}_{Actual}$, includes an initial value of the scale factor very close to zero ($a \approx 10^{-30} - 10^{-50}$), positive initial energy density and pressure capturing the contributions from all forms of matter and energy, mainly coming from the latter in the early universe, a curvature constant very close to zero resembling a flat universe ($k \approxeq 0$) and a positive cosmological constant ($\Lambda > 0$). In this case, the Friedmann equations constrain the subsequent changes of these parameters in a way that tells us that the universe is necessarily always increasing in size and its acceleration rate is initially determined by energy density and pressure (it is, in fact, decelerating) but as time passes, the acceleration is gradually determined only by the cosmological constant and becomes positive corresponding to a universe that expands in an accelerating rate. In other words, it is physically necessary – according to Friedmann cosmology and standard thermodynamics – that a universe with the aforementioned initial conditions will forever expand at an accelerating rate until it reaches its 'heat death', a state of no thermodynamic free energy where processes that increase entropy can no longer be sustained.

6. Concluding remarks

We began our analysis by showing how certain considerations about the initial conditions of the Universe (Ellis 2006, 2014) and other examples in physics (Sklar 1990; Frisch 2004) provide a challenge for the traditional understanding of the distinction between laws and initial conditions, indicating the need for a more nuanced and deflationary conceptual framework of physical modality. Building on existing views on the structure of scientific theories in philosophy of physics, a new framework was presented as a possible solution to these challenges, where physical necessity is defined in terms of the laws and lawlike assumptions in the nomic structure of a physical theory, and physical contingency is defined in terms of the possible configurations of physical systems in the dynamically possible models of the theory to which the laws and lawlike assumptions remain invariant and self-consistent. We have also distinguished between theoretical physical possibilities – i.e. physical possibilities according to the DPMs of a theory – and genuine physical

[18]The translated version of Einstein's (1917) original paper on cosmology can be found in Einstein (1952) and online at: `https://einsteinpapers.press.princeton.edu/vol6-trans/433`.

possibilities – i.e. physical state of affairs that can indeed occur in nature regardless of what our theories say – by noting that the latter are usually a subset of the former in which additional criteria based on fundamental scientific, logical and philosophical principles outside the theory are enforced. The presented framework was then put to practice via the example of Friedmann cosmology – understood as a narrower version of the general theory of relativity – showing how the initial conditions of the Universe are indeed contingent when seen from the theory's point of view although there is no clear way to understand how – practically speaking – they could have been different.

The presented framework has the advantage of preserving the useful distinction between laws and initial conditions and facilitates the formulation of the question of the modal status of the initial conditions of the Universe in a meaningful way. It also illustrates how the concept of physical possibility with respect to the models of our theories that seem to be in tension with the physical world (e.g. models indicating singularities or leading to logical paradoxes) can still make sense by clarifying the distinction between theoretical physical possibilities and genuine physical possibilities. It is important however, to bear in mind what this framework does not achieve, namely to provide the grounds for answering the rather puzzling question why the universe began with a certain set of initial conditions and not a different one which is equally consistent with the current laws of physics. This is a genuine scientific question, which perhaps reflects the limits of our scientific understanding, and it is very likely that it will forever elude a convincing scientific resolution.

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