Did the Laws of Physics Emerge at $t = 10^{-34}$ s? Inflation, Reheating and Particle Creation in the Very Early Universe

Abstract

According to the leading hypothesis in primordial cosmology, the very early universe underwent a rapid phase of accelerated expansion known as *cosmological inflation*. Inflation ended approximately 10^{-34} s after the expansion began, through a process called *reheating*, during which the inflaton field decayed into the particles of the Standard Model.

In this paper, we do not address questions concerning the empirical adequacy of this cosmological scenario. Instead, we focus on two following questions:

1. According to inflationary cosmology, can we argue that the particles of the Standard Model *emerged* from the inflaton field, and in what sense?
2. If we claim that the interaction carriers of the Standard Model (e.g., gluons) emerged during reheating, does this imply that the laws governing these interactions (e.g., the strong nuclear force) emerged at the same time?

We argue that current models of reheating already provide a clear answer to the first question when interpreted through a diachronic account of emergence. However, the second question may not have a definitive answer, as it depends on one's metaphysical conception of physical laws. We propose that a *powers ontology*, according to which laws are based on the causal profile of fundamental dispositional properties, could elegantly accommodate the claim that physical laws emerged in the wake of inflation.

Keywords: emergence, cosmology, metaphysics of science, laws of nature, inflation, dispositions

1 Introduction

A common idea is that the elementary particles composing all matter in the universe are as old as the universe itself. According to this view, the universe's history is merely one of combinations and reorganizations of these building blocks into various compounds.

However, the answer to the question, *"Where do the particles in our observable universe come from, and when did they appear?"* depends on our interpretation of a cosmological theory developed in the late 1970s: *inflation theory.* This theory encompasses a family of models that propose the universe underwent a brief but dramatic phase of accelerated expansion, during which its size increased by a factor of approximately 10^{22}. Inflation ended roughly $10^{-34}\,$s after the universe began to expand.

In section 2, we briefly discuss the motivations for inflation theory, its underlying physics, and its empirical support. However, this paper does not focus on inflation *per se*. Instead, we are interested in the physical process known as *reheating*, which marks the end of the inflationary period. During reheating, "the coupling of the inflaton field to other particles leads to a decay of the inflaton energy" and "eventually, the inflationary density is converted into standard model degrees of freedom and the hot Big Bang commences" (Baumann 2009, 35). From the perspective of Quantum Field Theory (QFT), these particles are excitations of the fields described by the Standard

Model. The reheating process can thus be viewed as a transfer of energy from the inflaton field to these fundamental fields.

How should we interpret the creation of new particles during reheating if we regard inflation as more than just a model but as a true depiction of events in the very early universe? In section 3, we argue that this event is a clear case of what some philosophers have called *diachronic emergence* Guay and Sartenaer (2016); Humphreys (2016); Sartenaer (2018), i.e., a temporal process enriching the ontology of the world by producing something fundamentally new on the basis of something already existing.

Moreover, among the particles of the Standard Model are not only fermions (quarks and leptons) but also bosons, which act as the physical carriers of fundamental interactions (e.g., gluons, photons, Z^0, W^+, W^-). A boson is an excitation of a force field that mediates interactions between elementary particles in accordance with fundamental physical laws, such as the strong nuclear force or the electroweak force.[1] This raises an intriguing question: Does the emergence of bosons during reheating also signify the emergence of the fundamental interactions they mediate? For instance, did the strong nuclear force exist *before* gluons were created during inflation? In section 4, we explore this question and argue that the answer depends on our metaphysical understanding of fundamental interactions. As noted by Jessica Wilson, this remains ”an underdeveloped area of research” (Wilson 2021, 132). To address this issue, we introduce a metaphysical framework called *powers ontology*, which provides an elegant way to reconcile the idea that physical laws emerged alongside their physical carriers.

2 Defrosting the universe

In this section, we present the main features of the inflation theory needed to understand the creation of the particles of the Standard Model during reheating.

---

[1] The gluon is the boson associated with the strong nuclear force, while photons, Z^0, W^+, and W^- are bosons of the electroweak force (a unification of electromagnetism and the weak nuclear interaction). The Higgs boson is an excitation of the Higgs field, which gives mass to fundamental particles. The graviton, although hypothetical, is the proposed boson carrying gravity.

2.1 The original motivations of inflation: killing three birds with one stone

For reasons examined below, there are many models of inflation – i.e., different parameterizations of the theory according to which a scalar field drove an accelerated expansion of the very early universe[2]. However, for our purposes, it is not necessary to delve into the many differences between these models. We will focus here on the common core hypotheses of the most standard models of inflation.

First and foremost, inflation is a period during which the expansion rate of the universe $H(t)$ is constant:

$$H(t) \equiv \frac{\dot{a}}{a} = \text{const.} \tag{1}$$

where $a(t)$ is the scale factor of the universe[3] at time t, and $\dot{a}$ its time derivative. Hence, during inflation, the scale factor of the universe grows exponentially with time:

$$a(t) \propto e^{Ht}. \tag{2}$$

As we see, inflation can thus be defined as a period of exponential expansion. This exponential growth characterizes the inflationary era as a (quasi) ”de Sitter phase”[4] and is what originally motivated the theory of inflation.

Historically, the first models of inflation were developed to solve four different problems related to cosmology and particle physics Smeenk (2005, 2012):

1. **The singularity problem**: The first model of inflation was proposed by Alexei Starobinsky as an alternative to models with a singularity Starobinsky (1980). In

---

[2] Between 74 and 193 models, depending on what counts as an individual model Martin et al. (2014b,a). It is important to note that some of these models use more than one field to account for the inflationary phase (see appendix). But as we argue below, this does not change our philosophical analysis of the reheating process.

[3] The scale factor at time t can be seen as the size of the universe at this time: ”the scale factor characterizes the relative size of spacelike hypersurfaces Σ at different times” (Baumann 2009, 15).

[4] While de Sitter's model of the universe was initially proposed as a static and zero-density universe de Sitter (1917), it is now understood as a universe in which a constant (such as Λ, the cosmological constant) is the dominant contribution to its expansion rate, resulting in accelerated expansion.

standard Big Bang cosmology, singularity theorems Hawking and Ellis (1968) prove that if matter satisfies the strong energy condition $\rho + 3p > 0$, then there exists a singularity – i.e., $a(t \equiv 0) = 0$ (see appendix). This singularity can be seen either as a breakdown of General Relativity or as a temporal origin of the universe – both of which some cosmologists would like to avoid.

2. **The horizon problem**: Independently of Starobinsky, Alan Guth introduced another model of inflation to address three "puzzles." The first of these is the *horizon puzzle*. The oldest detectable light in the universe is the Cosmic Microwave Background (CMB), emitted at the time of photon decoupling (before which light was coupled with matter, rendering the universe opaque). The CMB shows a highly isotropic universe (see figure 1). This isotropy is surprising because, as Guth noted in his seminal paper, "the initial universe is assumed to be homogeneous, yet it consists of at least $\sim 10^{83}$ separate regions which are causally disconnected (i.e., these regions have not yet had time to communicate with each other via light signals)" (Guth 1981, 347). In other words, standard Big Bang cosmology provides insufficient time before photon decoupling for a process of thermal equilibration to produce the observed isotropy of the CMB. Therefore, the initial temperature and density conditions of the universe at $t = 0$ must have been extremely fine-tuned (see appendix).

3. **The flatness problem**: The second puzzle noted by Guth is the *flatness problem*. In standard Big Bang cosmology, a Euclidean geometry (i.e., global spatial curvature $k = 0$) is unstable: the universe's expansion drives its geometry exponentially away from flatness. Yet, today's observed geometry of the universe is very close to Euclidean. This observation also requires a significant fine-tuning of the universe's initial conditions (see appendix).

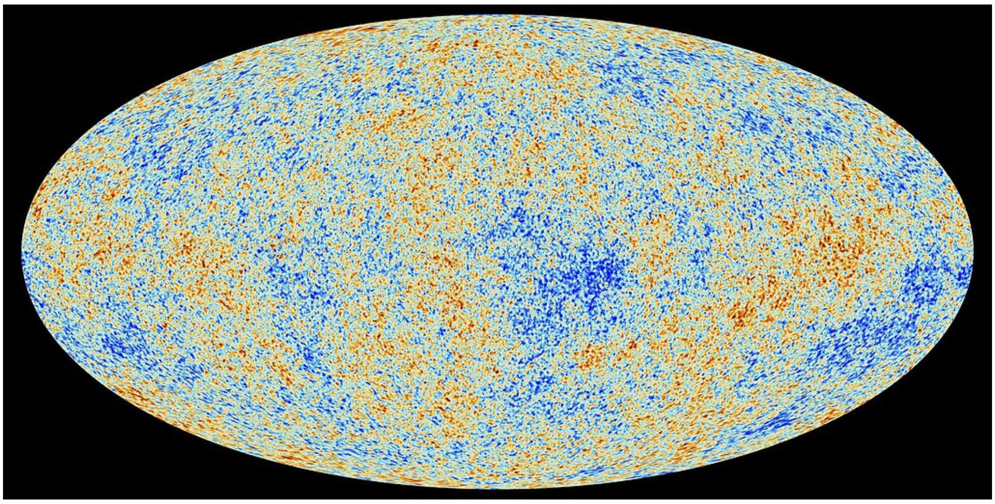
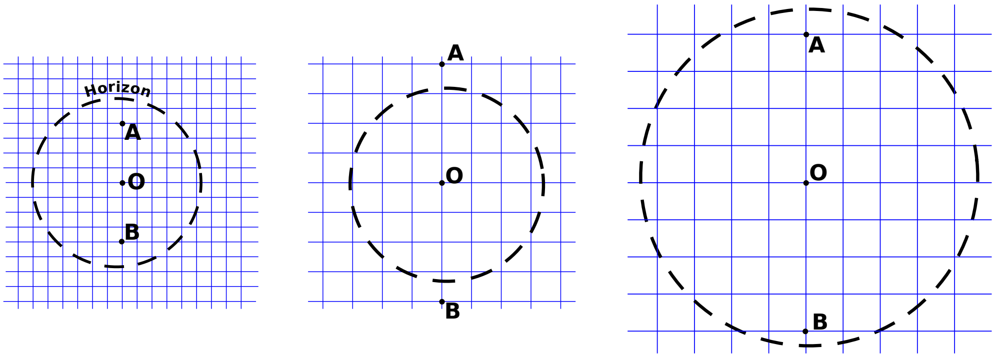


Fig. 1 This map of the Cosmic Microwave Background radiation, imprinted on the sky when the universe was 370,000 years old, shows tiny temperature fluctuations corresponding to regions of slightly different densities. The temperature of this blackbody radiation is ~ 2.7 K, and the anisotropies are on the order of 10^{-4} K. Although small, these density contrasts grow through gravitational collapse to form the first structures (stars and galaxies). Predicting the size and amplitude of the CMB anisotropies is one of the most striking successes of current inflation theory. Source: ESA and the Planck Collaboration, image licensed under CC BY 4.0.

4. **The monopole problem**[5]: This issue is not a problem of standard Big Bang cosmology per se and is thus often overlooked. However, as the physicist Andreas Albrecht emphasized, it poses a significant challenge for Grand Unified Theories, which unify the strong nuclear force and the electroweak interaction. ”In 1974, Preskill showed how, quite generally, a significant number of magnetic monopoles would be produced during the cosmic phase transition required by Grand Unification. Being non-relativistic ($\rho \propto a^{-3}$), they would rapidly come to dominate over ordinary matter” (Albrecht 2001, 19). Therefore, any theory proposing unification of the electroweak force and strong nuclear force in the very early universe must explain why we have never observed any monopoles, even though they are predicted to be as common as electrons and protons.

---

[5] Magnetic monopoles are hypothetical elementary particles predicted by Grand Unified Theories (GUTs). They are isolated magnets, i.e., they possess only one magnetic pole.



before inflation   during inflation   after inflation

Fig. 2 *Left:* Before inflation, A and B are within the causally connected region around O. *Middle:* During inflation, space expands faster than the growth of the causally connected region, pushing A and B outside this region. *Right:* After inflation ends, the region of causal connection grows faster than space expands, bringing A and B back into the observable universe. This process, described as the shrinking of the comoving Hubble radius $\frac{c}{aH}$, solves the puzzles of standard Big Bang cosmology (see appendix).

If we accept the hypothesis that a period of inflation expanded the universe by a factor of around e^{60} (implying that the scale factor of the universe was multiplied 60 times by $e = 2.71828$) in a very short time (before $t = 10^{-34}$ seconds), all these problems can be solved at once (see figure 2 and the appendix). The existence of a de Sitter phase in the very early universe resolves the horizon problem because the exponential expansion implies that our entire observable universe originated from a small, causally connected region. Simultaneously, inflation solves the flatness problem by driving global curvature toward zero as the universe expands faster than the growth of the observable universe. Finally, because monopoles would have formed prior to inflation, inflation dilutes their density to near zero in the observable universe. Yet, regarding the singularity problem, although it was initially thought that a de Sitter phase could replace the singularity, it was later shown that inflationary universes have incomplete geodesics in the past direction Borde and Vilenkin (1996); Borde et al. (2003).

We call here each model which solve these three problems a "standard model of inflation", and we are here interested only in the common core of hypotheses of these models, that we dub the "minimal standard model of inflation" (MSMI).

The fact that this MSMI solves multiple problems simultaneously may appear to be a remarkable scientific success, but this success has been (and continues to be) the subject of intense debate. The idea that inflation solves genuine scientific problems has been debated since the 1980s. The singularity problem, for instance, is only a problem if one assumes singularities are undesirable. Yet, some see them as hints of new physics or a genuine temporal origin of the universe. Similarly, the horizon and flatness problems arise from the need to impose fine-tuned initial conditions on the standard Big Bang model. But neither observations nor theory independently suggest these initial conditions are improbable. As Ellis and Rothman noted, absent a measure of initial condition probabilities, one could simply assert, as Zel'dovich did: "I chose to believe that the universe started isotropic!" (Ellis and Rothman 1987, 13). The monopole problem is only pressing for those endorsing versions of Grand Unified Theories (GUT) that predict abundant magnetic monopoles. Their non-detection could equally count as a refutation of such GUTs. Overall, it is unclear that these supposed problems necessitate inflation[6].

Compounding this, the physical nature of inflation remains speculative. Most models postulate an inflaton field φ, treated phenomenologically due to the proliferation of possible models:

> Scalar fields abound, at least in the imagination of particle theorists [...]. This situation has caused the world of cosmology to regard the "inflaton" in a phenomenological way, simply investigating the behaviors of different

---

[6] Though it can be argued that inflation has greater *explanatory depth* than the standard Big Bang by avoiding fine-tuning; see Wolf and Thebault (2023).

> inflaton potentials, and leaving the question of foundations to a time when the particle physics situation becomes clearer. (Albrecht 2001, 28)

This flexibility has sparked ongoing debates about inflation's testability, how it compares to alternatives like bouncing models, and how to discriminate among inflationary scenarios Barrow and Liddle (1997); Smeenk (2017); Ijjas et al. (2017); Dawid and McCoy (2023); Azhar and Loeb (2021); Wolf (2024). Despite this, inflation has notable successes. Chief among them is providing the first explanation for the origin of primordial density fluctuations and predicting CMB anisotropies. As Liddle and Lyth observe, while the flatness and horizon problems are no longer the strongest motivations, inflation's account of structure formation is ”powerfully predictive” (Liddle and Lyth 2000, 5).

However, our aim here is not to settle these debates about the empirical status of inflation but to interpret the MSMI realistically. The main object of our paper is that all standard models of inflation end with a phase known as the *reheating* during which the inflaton decays into particles of the Standard Model.

2.2 How inflation ends

The process of reheating is indispensable in all models of inflation because, at the end of inflation, the universe is in a supercooled state. Indeed, the massive increase in volume that the universe experienced during inflation led to a sudden drop in its temperature[7]. Hence, ”any successful theory of inflation must also explain how the cosmos was reheated – or perhaps defrosted – to the high temperatures we require for the standard hot Big Bang picture” (Bassett et al. 2006, 28). Therefore, a reheating process must be part of our MSMI, which would otherwise be in contradiction with the rest of Big Bang cosmology.

---

[7] It is not even certain that the classical concept of temperature can be applied here. See (Mambrini 2024, 132-133).

How is the cosmos defrosted according to the standard models of inflation? As we have seen, the accelerated expansion of inflation is explained by the existence of a scalar field (or multiple fields): the inflaton, usually noted φ. The dynamics of this field, and therefore of inflation, is determined by the potential $V(\varphi)$. Depending on the model of the inflaton, the shape of this potential changes (see appendix). For example, the potential of the inflaton in the most standard models of inflation (*slow-roll* inflation) has the shape of a hill with a gentle slope (see figure 3). While the inflaton rolls down this slope, the expansion of the universe is exponential, and inflation occurs. When the inflaton reaches the potential minimum, it starts oscillating and decaying into the particles of the Standard Model. The energy released by the creation and interaction of these particles is the cause of the reheating of the universe. Thus, in inflationary cosmology, the "hot Big Bang", i.e., the creation of a hot plasma of elementary particles, begins with this process of reheating. It is therefore necessary for the MSMI to follow the steps described by Andrei Linde:

> At the stage of inflation all energy is concentrated in a classical slowly moving inflaton field φ. Soon after the end of inflation, this field begins to oscillate near the minimum of its effective potential. Eventually it produces many elementary particles, they interact with each other and come to a state of thermal equilibrium with some temperature T_r. (Linde 2005, 15)

How can the inflaton decay into these particles? This process has been studied early in the history of the theory of inflation Abbott et al. (1982). The first mechanism that was proposed was to treat the inflaton field as a collection of homogeneously distributed particles with a probability of decay into the particles of the Standard Model, just as the particles of the Standard Model can decay into each other (for instance, β^- decay is the decay of a neutron into a proton, an electron, and an anti-neutrino). For

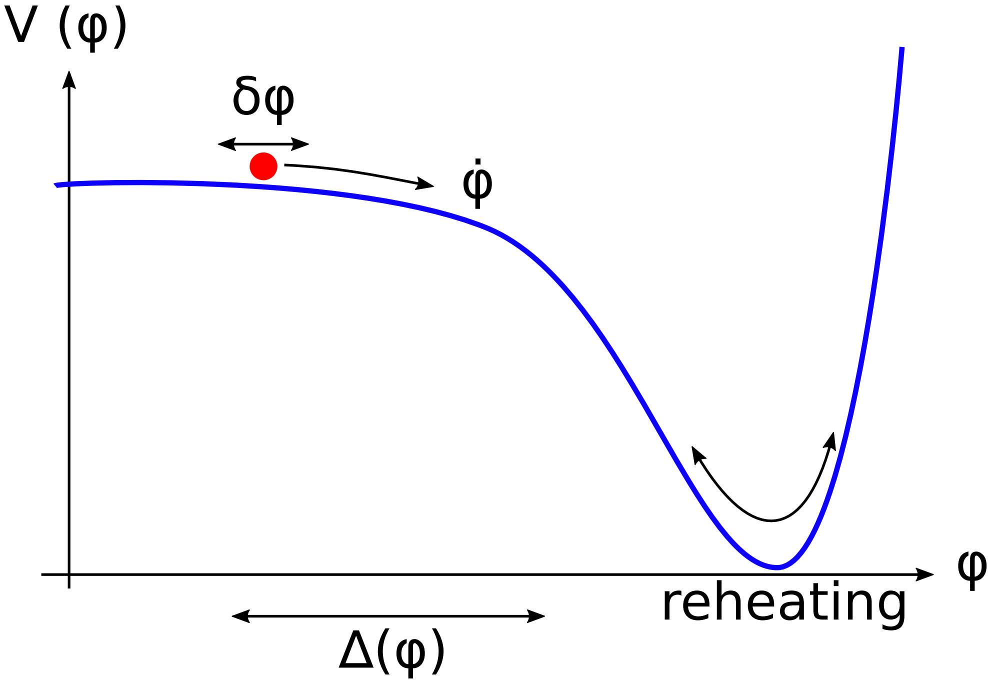


Fig. 3 *Example of slow roll inflation.* When $V(\varphi) > \frac{1}{2}\dot{\varphi}^2$, i.e. when the potential energy dominates the kinetic energy of the field, the expansion of the universe is accelerated. At the beginning of inflation, the inflaton field is impacted by quantum fluctuations $\delta\varphi$ that will grow into the anisotropies detectable in the CMB. Reheating begins when $V(\varphi) \approx \frac{1}{2}\dot{\varphi}^2$. During reheating, the inflaton oscillates around its minimum potential value and its energy density is converted into the particles of the Standard Model.

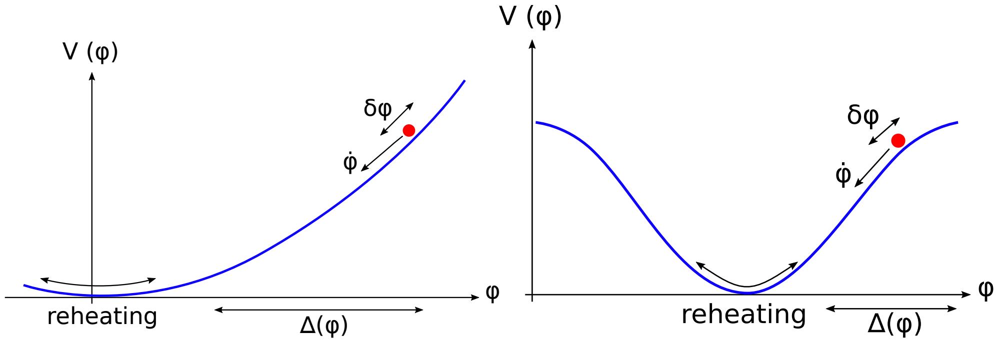


Fig. 4 Depending on the nature of the inflaton, the shape of its potential can vary, but a phase of reheating always follows inflation. *On the left*: large-field potential. *On the right*: natural inflation (see the appendix).

these decays to take place and to calculate their rate, one has to introduce couplings of the inflaton φ with bosons χ and/or fermions ψ (Bassett et al. 2006, 28). Formally, these couplings are treated through interaction terms in the Lagrangian such as $\sigma\varphi^2\chi^2$ or $\mu\varphi\chi^2$ for bosons, and $y\varphi\bar{\psi}\psi$ for fermions – where σ and y are small dimensionless coupling constants and where μ has the dimension of a mass (see appendix). In QFT, these interaction terms indicate how strongly different fields interact with each other. This means that we have to postulate that the inflaton was coupled with the fields of the Standard Model in order to explain how the inflaton decayed and created particles during reheating[8], and thus that the fields of the Standard Model had some sort of existence before the inflation era, just as the gravitational field was coupled to the inflaton and existed before the inflation started. These couplings ensure that the energy of the inflaton causes the excitations of the fields of the Standard Model, i.e., produces the particles of the Standard Model.

The mechanism of reheating was considerably refined during the 1990s and 2000s. A phase of *preheating*, during which the inflaton decays into massive exotic bosons (themselves decaying afterwards into the particles of the Standard Model), is often added to the classical scenario (see appendix)[9]. During this phase, the fields coupled with the inflaton behave as a parametric oscillator, and *"as a result, the number of particles grows exponentially within just a few oscillations of the field φ"* (Kofman et al. 1994, 3)[10].

The details of the mechanism of reheating (and preheating) are still intensively studied today (Baumann 2022, 154), (Mambrini 2024, 127), but all reheating models have in common the assumption that, when the inflaton reaches its minimum potential value, it decays into particles and becomes quickly negligible. The universe is filled with radiation, and the radiation-dominated era of the universe begins. In conclusion, we

---

[8] Note that this coupling can be indirect: some models of inflation postulate that the inflaton is coupled via gravity to the fields of the Standard Model.

[9] Here, the term "exotic" refers to any particle which is not described by the Standard Model of particle physics.

[10] In later models of preheating, a similar resonance effect produces Higgs bosons or other bosons of the Standard Model because they acquire an effective mass due to their coupling with the inflaton.

can thus describe the MSMIR as follows: whatever model of inflation is your favorite, as long as you subscribe to the basic idea of the theory of inflation, i.e., exponential expansion, you are obliged to accept a subsequent process of reheating that can be described as the transformation of the inflaton into particles of the Standard Model (and eventually some exotic particles if one adds couplings with non-standard fields). The question is now to propose a realist interpretation of the MSMIR: what really changed at the end of inflation? Can we say that the particles of the Standard Model emerged from the inflaton field and that new ontological categories emerged with them? Does it also mean that new laws of physics appeared alongside their physical carriers?

3 An enriching inflation

In this section, we argue that, contrary to economic inflation, cosmological inflation can be considered as enriching because it ends with the production of something ontologically new. This claim aligns with the accounts of diachronic emergence developed over the past decade by several philosophers of science. First, we examine why the philosophical concept of (ontological) diachronic emergence aptly describes what happens in the universe at the end of inflation when interpreting the MSMIR as a true depiction of the universe's evolution. Then, we show what is genuinely novel about reheating and argue that this process adds new powers to the world's ontology.

3.1 Emergentism in the very early universe

The MSMIR described in the previous section, particularly the phase of reheating, exhibits a paradoxical nature. On the one hand, it uses only well-established physical theories and phenomena, such as the quantum theory of particle creation via decay. This theory explains how fundamental particles transform into each other, provided conservation laws are respected. Reheating, from this perspective, appears as a mere transfer of energy from one field (the inflaton) to another (the fields of the Standard Model). On the other hand, reheating marks a pivotal moment in the universe's history. For instance, Delia Perlov and Alex Vilenkin describe reheating as the onset of the hot Big Bang, when the universe transitioned into a plasma of elementary particles that allowed baryogenesis (formation of baryons) and nucleosynthesis (formation of nuclei):

> The false vacuum [φ] eventually decays, producing a hot fireball, marking the end of inflation. The fireball continues to expand by inertia and evolves along the lines of hot big bang cosmology. Decay of the false vacuum plays the role of the big bang in this scenario. (Perlov and Vilenkin 2017, 337-338)

In inflationary cosmology, reheating is nothing less than the instant the building blocks of the universe appeared for the first time.

Now, if we take models of reheating as true – describing the actual course of events in the universe – how should we characterize the transition from the inflationary era to the hot Big Bang? We argue that the paradoxical nature of reheating makes it an excellent candidate for emergence, as philosophers use the term to describe how something new arises on the basis of something else. Specifically, we adopt the broad, non-controversial definition of emergence provided by Alexandre Guay and Olivier Sartenaer:

> Emergence is an empirical relation between two *relata*, namely an emergent E and its emergence basis B, such that the following theses simultaneously hold:
>
> - (DEP) E is dependent on, or determined by, B; and yet
> - (NOV) E is novel with regard to, or autonomous from, B.
>
> (Guay and Sartenaer 2016, 298)

There are various relations satisfying these conditions. Guay and Sartenaer point out that (NOV) "can be construed either epistemologically or ontologically, depending on whether the autonomy or novelty in question is to be found in our representations of the natural world or in the natural world itself" (Guay & Sartenaer 2016, 299). Here, we assume the theory of inflation and reheating is literally true, meaning that the universe behaved as this theory describes. Thus, we treat reheating as a case of *ontological* rather than *epistemological* emergence (as we will see below, this does not mean that we cannot look for the epistemological traces of this ontological process in the scientific models)[11].

The most important distinction for our purpose here is between *synchronic* and *diachronic* emergence. Synchronic emergence frames (DEP) and (NOV) in terms of a co-temporal relation between a hierarchy of levels: E belongs to a "higher-level" than the underlying and co-existing B. Diachronic emergence frames (DEP) and (NOV) in terms of a diachronical process between two events: E is temporally determined by B (B is antecedent to E) and historically novel because it exhibits different features than B (Guay and Sartenaer 2016, 299)[12]. In the case of reheating, diachronic emergence is more appropriate because the concept of "levels" does not straightforwardly apply to the early universe. If one were to claim that the particles of the Standard Model synchronically emerged on the inflaton φ, they would have to argue that the inflaton φ and the particles of the Standard Model belong to different "levels" of reality in order to satisfy (NOV). But nothing in the MSMI or in any model of reheating supports such a claim. On the contrary, the inflaton and the particles of the Standard Model are considered in those models as "fundamental", in the sense that they are not

---

[11] It is also usual to distinguish *weak* and *strong* cases of emergence. But this distinction is somehow vague and debated, because it can be construed in several ways. Wilson's account of emergence, for example, considers that strong emergence is characterized by E having a *new power* absent in B, while weak emergence is characterized by E having strictly *fewer* powers than B (Wilson 2021, chapter 2). What Wilson characterizes as a new power reflects the coming-into-play of a novel fundamental interaction. But this distinction is also meant to capture more or less anti-reductionistic commitments, strong emergentism being a form a anti-reductionism while weak emergentism is reputed to be compatible with physicalism. We will argue here that reheating is indeed a case of emergence where the emergent exhibits new powers, but that it is obviously compatible with physicalism – because it involves nothing more than physically fundamental entities.

[12] Note that diachronic emergence is agnostic toward levels: E and B can belong to different levels or not.

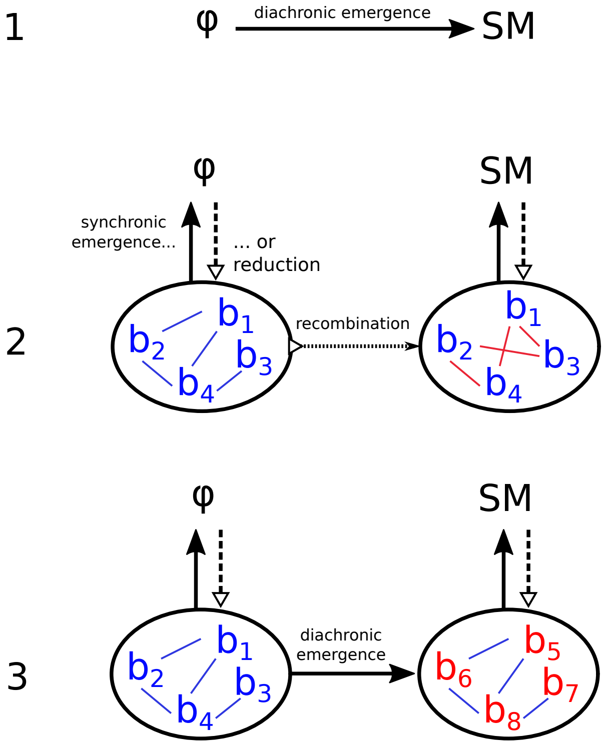


Fig. 5 (1) According to our present theory of reheating, the inflaton φ decayed into the particles of the Standard Model. We suggest to understand this decay as a case of diachronic emergence. (2) One could argue that in a future theory, only synchronic emergence or reductionism will be needed to explain how the inflaton gave birth to Standard Model particles, because we will have found the lower-level constituents of these entities. (3) But one could argue that, even if a future theory describe the constituents of the inflaton and of the Standard Model particles, it is equally possible that reheating will be understood as a diachronic emergence because the constituents of the inflaton $(b_1, ..., b_4)$ will not the same as the constituents of the Standard Model particles $(b_5, ..., b_8)$. The appeal to a future theory can go both way and in the absence of any empirical evidence to what this future theory may look like, this appeal is not relevant for our discussion.

composed of anything else – they do not depend on any other more fundamental entities. Moreover, to satisfy (DEP), a synchronic account of reheating would have to argue that B (the inflaton) is underlying E and co-existing with E. But as we have seen in the previous section, in all models of reheating, the inflaton φ decays – and therefore disappears – into a mix of quarks, gluons and photons at the end of reheating[13].

---

[13] This does not mean that all of the inflaton disappears, only that the energy lost by the inflaton goes into the excitation of the fields of the Standard Model

A first objection against using a diachronic account of emergence to represent the transition from inflation to reheating would be to argue that, since the inflaton is a phenomenological field (see previous section), it is not impossible that the inflaton is composed of lower-levels entities which rearrange themselves during reheating to give birth to the particles of the Standard Model. This perspective suggests that what appears as a transformation of fundamental entities today might, in the future, be understood as transitions between different cases of synchronic emergence. Similarly, a reductionist could argue that what appears as a case of diachronic emergence will, in a future theory, be explained as a transition between two states of lower-level constituents. While possible, such an appeal to future theories is speculative. First, the candidates that are currently considered for the inflaton are all fundamental particles (standard or exotic) such as the Higgs field or the axion (see appendix). So, if we limit ourselves to current research, there is no reason to think that reheating involves different levels of reality. Second, even if a future physical theory reveals that the inflation field is composed of lower-level entities, e.g. loops or strings, it is perfectly possible that these entities would have to transform into entities of a different kind before combining into the Standard Model particles (see figure 5). Diachronic emergence would then still be necessary to understand the process transforming the inflaton field into the particles of the Standard Model. Hence, this case illustrates what we could call the "no future condition": any appeal to unknown lower-levels in a possible future physics to argue in favor of synchronic emergence or of reductionnism is a purely *ad hoc* move. Therefore, only arguments grounded in the present state of physics can have any weight when discussing what happens at an ontological level.

A second objection against a diachronic account of reheating would be the claim that the particles of the Standard Model must interact with each other to thermalize the universe, i.e., to defrost it. These interactions are typical of what happens in synchronic emergence: the temperature T_r of the universe at a global level would synchronically emerge from the particles of the Standard Model at the micro-level. This is a perfectly legitimate interpretation of what occurs during reheating if one endorses synchronic accounts of emergence. However, this is not the focus of our analysis. Before the particles of the Standard Model interact, they must first be created, and it is this process of creation that we examine here as a case of diachronic emergence. It is true that, in our present understanding of the physical history of the universe, the creation and the interaction of the particles of the Standard Model are simultaneous events. Nevertheless, these processes can still be distinguished: one involves the inflaton decaying (and thus a transformation), while the other does not. A synchronic account of thermalization must first presuppose a diachronic account of the inflaton decay – and this is what is under scrutiny here.

A final objection against a diachronic account is that one might wonder why the particles of the Standard Model have to be considered as diachronically emergent from inflation, and not simply *caused* by it. However, there is a difference between causation and diachronic emergence; there are cases in which the diachronic, determinative relation between two objects (or events, processes, state-of-affairs, etc.) is different from garden-variety causation, giving rise to novel phenomena in a different sense: making them emerge, rather than merely causing them. An emergent entity is not simply caused, it is not the effect of garden-variety causation, because even if it is dependent on its emergence basis, it is also fundamental – while caused effects can never be. Causation is a recombination of present elements; diachronic emergence is different because what emerges is fundamental, therefore it is not a recombination of elements that were present. The ontology of the world has changed. Following the example made by Paul Humphreys, when muons transform into electrons, electron neutrinos and muon neutrinos, the new particles are "fundamental" in the sense that they are not composite, but not in the sense that they existed at the temporal origin of the transformation. In other words: they are part of the list of the fundamental components of reality, even if they were not there *ab initio* (Humphreys 2016, ch.2). Wilson argues that producing other fundamental goings-on is something that anti-emergentists could accept:

> Humphreys offers certain empirically confirmed cases of fundamental physical particle transformation (muon decay, tau decay) as illustrative of transformation emergence. As with the case of fusion emergence, however, it is unclear why the phenomena at issue should be seen as involving emergence [...] one might wonder if Humphreys could maintain that transformation emergence corresponds at least to a distinctive form of intra-level causation – here, one which produces a new type of entity, which difference in type is reflected in the new entity's having properties or dispositions that are different from those had by its cause(s). But garden variety intra-level causation also frequently produces new types of entities – after all, causes and effects are typically (as Hume was fond of pointing out) entirely distinct. (Wilson forthcoming, 15)

Here Wilson misses the point: if the result of a determinative chain leading from object A to object B is a fundamental object, there actually is a difference with respect to garden-variety cases of causation. Causation operates the existing building blocks of reality, putting them together and apart, but the transformations involved are always at the non-fundamental level. Causation remains inside the boundaries of what there is, it deals with the ontology of the world. Diachronic emergence adds pieces to this list, while others go out of existence: when a transformation like the one described by Humphreys happens, it is not merely a transitive determinative relation like causation, but it must be different, as it is a determinative relation that puts new fundamental objects in play. This metaphysical fact explains how cosmologists have to add the coupling of the inflation field with fields of the Standard Model: "To avoid that the universe ends up completely empty, the inflaton has to couple to Standard Model fields. The energy stored in the inflaton field will then be transferred to ordinary particles" (Baumann 2022, 153). In other word, without prior knowledge of the Standard Model, cosmologists could not have been able to predict that the inflaton would have decayed into particles of the Standard Model. This prediction can only be made *a posteriori*, because from the vantage point of the present, we know that the inflaton decayed into something else.

Hence, the transformation involved is not merely a recombination of objects already present in the ontology, but it is a transformation that results in the rewriting itself of said ontology. This is why, when diachronic emergence happens, we find an ontological gap in the determinative chain leading from an object at time t_1 to a transformed emergent object at t_2. The distinction between causation and diachronic emergence maps this difference: the fact that the standard "explanatory path" is not epistemically accessible is actually an ontological fact, about the underlying physical process involved. Diachronic emergence is then a stronger type of determinative relation than causation[14], one in which new fundamental building blocks are added (while others go out of existence) to the ontological puzzle of the world. Diachronic emergence is thus a good choice to understand what is happening when the reheating process produces new particles that did not exist before.

For all these reasons, the physical process of reheating seems best described by an ontological and diachronic approach of emergence. One of the advantages of this approach is that it provides a precise interpretation of the conditions (DEP) and (NOV). It is therefore possible to test whether this account genuinely applies to the case of reheating by examining the traces left by these conditions in our cosmological models of the primordial universe.

---

[14] Because there is no unified account of causation, one may also claim that diachronic emergence is merely a specific case of causation. But as long as this specificity involves new fundamental entities or properties coming into being, our argument still holds.

3.2 Operationalizing the reheating

We follow the account of diachronic emergence provided by Guay and Sartenaer, termed "transformational emergence," which builds on the work of Humphreys (2016).

> Let us consider a natural system S at two successive times t_1 and t_2 of its evolution. [...] The given system at t_2 (S_2) transformationally emerges from the same system at t_1 (S_1) if and only if there exists a transformation **[Tr]** such that:
>
> - (DEP$_d$) S_2 is the product of a spatiotemporally continuous process going from S_1 (for example causal, and possibly fully deterministic). In particular, the "realm" R to which S_1 and S_2 commonly belong (e.g. the physical realm) is closed, to the effect that nothing outside of R participates in S_1 bringing about S_2. And yet:
> - (NOV$_d$) S_2 exhibits new entities, properties or powers that do not exist in S_1, and that are furthermore *forbidden* to exist in S_1 according to the laws $\{L_1^i\}_{i=1}^n$ governing S_1. Accordingly, different laws $\{L_2^i\}_{i=1}^m$ govern S_2. (Guay and Sartenaer 2016, 305)

The system S under consideration in our case is the whole universe. S_1 is the state of the universe during inflation (i.e.,dominated by the scalar field φ), S_2 is the state of the universe during reheating, after the decay of this scalar field into particles of the Standard Model.

Let us first address the dependence condition (DEP$_d$). In our case, this condition is clearly satisfied. First, S_1 and S_2 belong to the same physical realm. Second, by definition, nothing outside the universe can intervene in bringing about S_2 because it would necessarily belong to the universe itself.

Satisfying the novelty condition (NOV_d) is more intricate. At first glance, it might seem that the novelty of S_2 lies in the presence of entities that were forbidden to exist in S_1 (during inflation). However, this explanation requires further refinement. As discussed in the previous section, the creation of Standard Model particles depends on the inflaton's coupling to boson and fermion fields. These fields, in turn, must have existed before the end of inflation and are implicitly assumed to have been present from the very beginning of the universe. Thus, as particles are excitations of fields in QFT, it seems nomologically possible for particles to exist during inflation. Additionally, bosons of the Standard Model can exist as *virtual* particles, mediating interactions even under conditions unsuitable for the formation of "material" particles. Virtual particles possess the same properties and, despite their name, are no less "real" than their material counterparts Weingard (1982); Jaeger (2019). In other words, if one wants to have a reheating, it seems that one must accept the coupling of the inflation field to the fields of the Standard Model, and therefore that the Standard Model particles were already possible during inflation. But then, what is the novelty of S_2 ? How can one prove that the laws of S_1 forbade the existence of the particles of the Standard Model?

To solve this conundrum, it is necessary to see how the novelty of **[Tr]** manifests itself in our effort to theorize it. This is precisely what Guay and Sartenaer offer when they consider "an operationalization of transformational emergence, a translation of its underlying metaphysical intuitions into formal requirements that can enter into dialogue with the sciences" (Guay and Sartenaer 2016, 304). This operationalization expresses conditions (DEP_d) and (NOV_d) as claims about the traces that **[Tr]** leaves in our models of S_1 and S_2 (see figure 6:

- (C_1) M_1 and M_2, which both describe the same system at two successive stages S_1 and S_2 of its evolution, are models of one and the same non-trivial theory T. And yet:

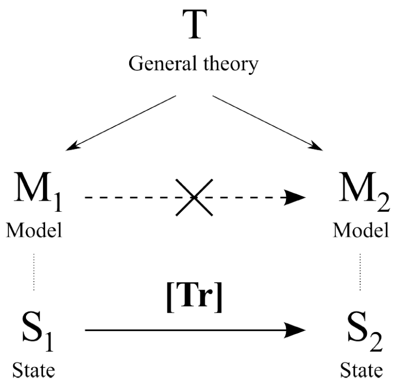


Fig. 6 ”The traces that **[Tr]** leaves in our way of investigating S” (Guay and Sartenaer 2016, 305).

- (C$_2$) M_2 is not derivable from M_1 as a matter of principle, for M_2 contains features that are forbidden in M_1 according to theory T. More precisely, S_2's dynamics as described by M_2 is not continuously deformable into S_1's dynamics as described by M_1.

Condition (C$_1$) is satisfied because M_2 and M_1 are formulated with the same theoretical terms drawn from General Relativity and QFT. Condition (C$_2$) tells us to go look for the novelty of S_2 in the features, and especially in the dynamics, of M_2 forbidden in M_1. As we have seen in the previous section with equation (2), during inflation (S_1), the dynamic of the universe is characterized by exponential behavior: the scale factor of the universe grows exponentially with time. After inflation, as the inflaton decays into a plasma of particles of the Standard Model, the universe becomes radiation-dominated and its dynamic shifts to $a(t) \propto t^{1/2}$. This significant change in the expansion rate serves as the sought-after trace: such a slow rate of expansion was impossible in the inflationary universe, where the dynamics were governed by a scalar field designed for accelerated expansion.[15]

---

[15] The scale factor is proportional to $t^{2/3(w+1)}$, where w is the equation of state parameter. For a radiation-dominated universe, $w = 1/3$, giving $a \propto t^{1/2}$.

One might argue that this change of dynamics does not fully satisfies condition (C_2), because e^{Ht} and $t^{1/2}$ can be seen as continuously deformable (at least for $t > 0$). But the condition (C_2) is here to ensure that there is a novelty in M_2's depiction of S, and that is clearly the case if we compare the dynamics of the universe during and after inflation. As Humphreys notes, radically different mathematical expressions for laws (e.g., linear versus non-linear) justify treating them as distinct laws (Humphreys 2021, 2753). Similarly, exponential and square-root behavior are too different to be considered the same dynamic with altered parameters. Furthermore, inflation models violate the strong energy condition, while models of a radiation-dominated universe do not[16]. And finally, these differences impact the metric of the model. As we have seen in the previous section, the inflation era is a quasi de Sitter phase. We can use de Sitter's metric to measure distance in it – and it is often done by cosmologists to study the dynamics of the inflation. But this metric is not suited to the radiation era which is described by a classical Friedmann-Lemaître-Robertson-Walker model (see equations (3) and (6) in the appendix). Therefore, there is a trace of the novelty of S_2 in the model M_2: what is impossible is M_2 is not a topological equivalence – as in the Fractional Quantum Hall Effect studied by Guay and Sartenaer (Guay and Sartenaer 2016, 308) – but a metrical equivalence.

Now that we have identified the trace left by the transformation **[Tr]** in our models, we can come back to the ontological level of analysis and ask: what was novel in S_2 which was forbidden in S_1? The answer lies in the radiation that defines (and gives its name) to the post-inflationary era. During inflation, even if excitation of the fields of the Standard Model were nomologically possible, the rapid exponential expansion stretched any fluctuation of these fields : no fluctuations could coalesce into

---

[16] See section 1. "If you believe in cosmological inflation, the [strong energy condition] must be violated during the inflationary epoch, and the need for this [strong energy condition] violation is why inflationary models are typically driven by scalar inflaton fields" (Visser and Barcelo 2000, 99). This violation implies that all the theorems that can be derived from General Relativity in conjunction with the strong energy condition are not valid in the MSMIR.

localized particles with a relativistic speed (i.e. radiations). Moreover, particle formation required the Standard Model fields to exchange energy, a process hindered in the supercooled state of the inflationary universe. Hence, radiations of the Standard Model particles were indeed *nomologically* impossible during inflation, even in the presence of Standard Model fields. Only when the excitation of the fields of the Standard Model were individuated that the content of the universe can be described as a high-energy plasma. Therefore, it is only after the expansion rate of the universe dropped and when the decay of the inflaton produced enough Standard Model particles that these particles had the possibility to thermalize the universe.

In summary, the novelty of S_2 in our case is not that new fields popped into existence, but rather than a new properties for those fields and new relations between those fields were made possible. This mode of interaction manifests as particles, which became the primary agents of the universe's evolution post-inflation[17]. The trace of this novelty in our models is the marked change in the universe's dynamics. This is how reheating changed the rules of the game and enriched the fundamental furniture of reality: this process opened the possibility of new entities (radiations) and powers (interactions between Standard Model fields). The next question is whether the emergence of new fundamental interactions in S_2 also signifies the emergence of new physical laws. Did the laws governing the strong nuclear and electroweak forces emerge during reheating, or did they preexist in a dormant state, awaiting suitable conditions to govern the universe? We address this question in the next section.

---

[17] Note that we do not advocate here for a "particle" interpretation over a "field" interpretation of QFT. See (Kuhlmann 2023, §5) for an account of the different ontological interpretations of QFT. From a cosmological perspective, the question of whether particles or fields are primary is not relevant because what matters is the contribution of some entities to the dynamics and evolution of the universe. We claim that no *individuated* radiation of the Standard Model could exist during inflation, but each reader is free to view this claim through the lens of their preferred ontology: as a prohibition of relativistic particles or of specific excitations of the Standard Model fields. In the next section, regarding the emergence of physical laws, we argue in favor of a powers ontology, which could be seen as compatible with Meinard Kuhlmann's dispositional trope ontology Kuhlmann (2013). However, a detailed comparison between his ontology and our powers ontology exceeds the scope of our present paper and is left for future work.

4 Emergence of the physical laws

Laws of nature are the paradigm of immutability in the common imaginary: the intuition behind it is that at the very beginning of our universe, the fundamental elements of reality were already there; the evolution in time of the universe is just a transformation of what was already there: the building blocks of the universe, and the rules they follow when they act and combine. However, there have been philosophers and scientists who have put into question this somehow popular understanding of the nature of the external reality: Dirac (1937) famously questioned the nature and the alleged immutability of the laws of nature; more recently, Shimony (1999), Lange (2008), Tahko (2015) and Smolin (2015) developed further this idea. Quite obviously, the nature of the claim that laws of nature can change in time depends crucially on what laws of nature are taken to be to start with. Given the number of ways in which the concept of laws of nature has been articulated by philosophers over the last decades, it is not easy to give a unitary account of what it means for a law of nature to change over time.

However, a fairly comprehensive way to shape the debate might be to consider the metaphysical source of change in the world: according to governism, the metaphysical source of change is external to the entities that are changing – and it is therefore possible to have a world with the same natural properties but different laws; there are, then, positions according to which the metaphysical source of change in the world is internal, it takes place inside the elements populating the world – such as dispositionalism; finally, there are philosophical positions which envisage no necessary connections at all – such as Humeanism. A thorough discussion of the merits of each possible stance is beyond the scope of the actual paper: we merely aim to show how, once given some general coordinates of the metaphysical debate surrounding the nature of the laws, a certain framework is able to elegantly accommodate what has been said above about the emergence of new fundamental entities after cosmic inflation[18]. After a brief survey of the most discussed models of lawhood, we will claim that a powers ontology can deliver the best account for the emergence of new entities and laws at the same time.

4.1 What does it mean that laws change

The most popular and intuitive view of lawhood is probably governism (sometimes called in the literature ”necessitarianism”), which relies on the idea that the nomological source of change in the world is external to the entities populating that world. There are objects, and there are laws of nature which govern them: the laws dictate how to act, how to interact, etc. This view describes laws of nature as necessity relations between universals. In such a framework, it is not entirely clear how and why would laws change in time: it seems much more natural to think that the rules of the game, so to speak, are given *ab initio*. In this sense, considering what said above, a governist would say that the nuclear strong force was already there, before gluons and quarks appeared; it was ”waiting behind the scene” (Humphreys 2021, 2749). The claim here might be, then, that the laws of nature did not emerge at $t = 10^{-34}$ s; they were already present, just not applicable.

The coupling of the inflaton field with the fields of the Standard Model seems to argue in favor of this conclusion. As we have seen, this coupling imply that the fields of the Standard Model already existed during inflation – and since the beginning of the universe. If one is inclined towards a reductionist view of QFT according to which everything that happens in the universe happens to fields, then this approach can be appealing: every field that physics needs to describe the universe at any time of its evolution already existed since the first moment of the universe and, consequently, the laws governing those fields were already there. But the downside of this approach

---

[18] For an analysis of the metaphysical possibility of changing laws of nature in each of these stances, see Sartenaer et al. (2021). As the authors themsleves claim: ”In this paper, we show that it is not a conceptual truth about laws of nature that they are immutable (though we are happy to leave it as an open empirical question whether they do actually change once in a while)” (Sartenaer et al. 2021, 1). Our goal here is precisely to tackle this empirical question and to discuss which option is best suited to describe the case of particle creation in cosmology.

is that it means that we have to imagine that fields were governed by physical interactions even when they did not interact with each other. This seems to be a very counterintuitive way to think about interactions. If we imagine a Newtonian world without any matter (or just one body) but with gravitons (the hypothetical carrier of the gravitational interaction), it seems strange to say the law of gravity exists in this system, even with the presence of physical carriers Black (1952). Whatever new element or interaction comes about in the history of the universe, a governist would seem to be forced to commit to the idea that the rules governing it were already present at the beginning of the universe; but this looks more like a presupposition than a philosophical position: we are just supposing that literally any rule can now be ”dormant”, only to show its effects at a later stage[19].

This is, to many philosophers, not very satisfying, for it implies an ontology which is not sparse enough to be acceptable. A metaphysical model should not only be able to accommodate the elements observed at present, but should also give some guidance as to how to shape the categorization of future observation, at least in principle: a monist ontology is considered ontologically parsimonious not only because it says that the elements we know now are made of one fundamental substance, but first and foremost because it states that, in principle, everything that we will observe in the future is made of that very fundamental substance as well. If the governist stance, then, is simply that ”whatever rule we find, I posit that it was already present at the beginning of the universe”, the statement is certainly possible, but rather metaphysically shallow.

But what about the other horn of the dilemma? What if, in other words, the governist bit the bullet and claimed that the laws of nature can actually change in time, or the list of said rules can change[20]? Both cases seem unpalatable to the governist intuition as, in fact, either there is a sort of meta-rule that governs the change of the

---

[19] Another possibility is to describe the coupling of the inflaton with standard fields as a physical law. This is not a problem for our claim, since we only argue that new laws appeared after inflation, and not that no law was present during inflation and reheating.

[20] See (Sartenaer et al. 2021, 2-6) for a metaphysical account of how governist laws can change with time in a framework where universals are indexical.

laws of nature, or there is no rule governing these changes. In the first case, not only the ontological status of such a meta-rule is unclear, and not only the solution looks prone to a vicious regress; first and foremost, the reasoning applied above about the emptiness of the governist stance seem to be even more powerful here: this mysterious, primitive "meta-rule" would be doing all the metaphysical heavy lifting, without any predictive or restrictive power over the ontology of the world. In the second case, if there is no rule governing these changes, it is not clear how the changing laws of nature are actually "laws" and not merely regularities; in other words, in such a case the distinction between changing laws changed becomes so blurred to question the whole account: where exactly does one law end, and where does the other law begin?

A different possibility consists in denying that there are necessary laws at all. This 'Humean' attitude has been revived in contemporary philosophy by David Lewis (see e.g. 1994), who developed a Humean regularity theory that eschew any commitment to (natural) necessity, and claimed that the laws of nature simply supervene on the distribution of intrinsic qualities over the entire reach of spacetime. In this sense, the world just is an arrangement of local, particular facts (typically space-time points having intrinsic qualities and related to one another by spatio-temporal relations). Everything that is not itself an arrangement of qualities only exists in virtue of some arrangements of qualities. Given its rejection of necessary connections, Humeanism is very hospitable to regularity accounts of laws, according to which laws are those worldly regularities that are captured by the axioms and theorems of the true deductive system that best systematizes the world. Laws are then nothing over and above statements of regularities that are included in our best science. Turning to the case in point, this account would allow us to say that the strong nuclear force appeared at the end of inflation, because the strong nuclear force is the regularity of the interactions between quarks – even if, as pointed out by Humphreys (Humphreys 2021, 2749), right after inflation this interaction was not a regularity, as it was happening for the first time. Discussing the pros and cons of this Humeanist attitude towards the laws of nature is clearly beyond the scope of the present purposes; it will suffice to say that such a minimalist theory might not be satisfying for those who wish to look for something deeper than just "a thing after another".

A third possibility, that have been gaining popularity in contemporary philosophy, is to consider the source of change in the world as internal to the entities themselves. In a sense, we might say that, according to this "dispositionalist" stance, the fundamental elements of reality are atoms of laws of nature; it is not the case that there are objects and rules which these objects follow but, rather, these objects carry with them their own rules. Even more: in a sense, they are the rules. Prima facie, this option might seem best fitted to account for the emergence of new elements of reality and, at the same time, the laws of nature managing them. In what follows, we will present some interesting features of this powers ontology and show how this metaphysical option can elegantly accommodate the emergence of the particles of the Standard Model from the inflation field along with the laws governing these interactions.

4.2 The emergence of bosons in a powers ontology

In recent years, fundamentality have come to occupy a central place in both metaphysics and the philosophy of science. Many metaphysicians now think that, in giving a complete account of reality, saying what exists is only part of the story – we also need to say how everything "hangs together". Meanwhile, philosophers of science have begun to appreciate that much of physics – including theories in so-called "fundamental physics" – may depend on the metaphysical framework chosen. The philosophical view called 'powers ontology', we contend, can elegantly fit with the inflationary model of the cosmos: in particular, the fact that when the inflation field decayed into the particles of the Standard Model, new entities and laws of nature were born. This view consists in considering the fundamental constituents of reality as bundle of properties;

properties, however, of a peculiar kind: instead of being 'categorical' – such as 'being square', 'having two arms', etc. – these properties are essentially dispositional, which it is typically taken to mean that what such properties are is defined in terms of the changes that they are disposed to bring about in the world. In a slogan, we could say that the fundamental elements, in a metaphysics of powers, are defined in terms of what they do, instead of what are their shape, size, etc. This, prima facie, may seem odd: macroscopic objects are what they are, and what they do changes from situation to situation. A chair can be used to sit on, to smash a glass wall, or to reach the highest shelf of the kitchen: but what has this to do with what the chair is? That is a reasonable question, and if we were concerned only with macroscopic objects, a categorical description of the chair (what is the chair made of, its shape, its colour, etc.) would probably be best suited to tell us what fundamentally is a chair; however, when it comes to describe the fundamental constituents of reality, the situation is radically different: what is the shape, size, and colour of an electron? It is not even clear that an electron could have such 'categorical' qualities: it seems that, in order to describe what an electron is, we need to spell out what an electron does; already Heisenberg was convinced that "we should abandon all attempts to construct perceptual models of atomic processes" (Heisenberg 1971, 76).

Of course, according to powers ontologists not every real, dispositional property is a power. Neo-Humean ontologies envisage dispositional properties, which are however reducible to a categorical base. In order for a dispositional property to be a power, its dispositionality needs to be a non-reducible, ineliminable part of what that property is. A nice and direct way to understand what powers are, then, would be to say that powers are properties which are essentially dispositional;[21] powers are fundamental, in the sense that they are irreducible, or 'ungrounded': their dispositionality is not

---

[21] As in e.g. Shoemaker (1998), Ellis (2001), Heil (2003), Bird (2007), Martin (2008), Yates (2013). This might however be controversial, as some power ontologists prefer to avoid the reference to 'essences', which they think might turn out to be tricky; Molnar (2003), Mumford (2004), Engelhard (2010) prefer to say that the dispositionality of powers is what fixes their identity, instead of representing their essence. This latter option, however, can be viable only if we refer to fundamental properties: non-fundamental properties can acquire their identity thanks to more fundamental properties.

imposed upon them by something else (e.g. the laws of nature) and, more in general, there is not a way to reduce their dispositionality to simple conditionals or counterfactuals that hold in virtue of something that is not, itself, a power. Powers ontologists aim at describing the way reality is at the most fundamental level (granting there is one), usually following the path of a physics-informed metaphysics which looks closely at our best science. Neo-humeans claim that fragility can be explained away in terms of counterfactual conditionals, that rely on categorical properties, posited at a more fundamental level.[22] It could well be made the case that when we think of what are the properties of macro-objects, we have in mind the specific type of material that it is composed of; we think of colour, size, shape; this seems the most scientific and objective way to describe an object. However, the situation is radically different when it comes to describe the fundamental constituents of physics: arguably, our best physics spells out the constituents of its ontology in dispositional terms: charge is defined in terms of the potentiality of producing electromagnetic fields, spin in terms of the potentiality of contributing to the angular momentum of a system, etc. (Williams 2019, 14)

The picture contemporary physics depicts is one in which what is actually fundamental are not inert properties, but dispositions; and it is only from this essentially dispositional ground level that we can recover second-class, categorical properties of large objects – such as shape, size, etc. But this is not something new: already Heisenberg believed that ”the atoms or elementary particles [...] form a world of potentialities or possibilities rather than one of things or facts” (1955, 18), and suggested explicitly that quantum entities could be understood as a form of Aristotle’s ’potentia’: he claimed that ’potentiae’ were not merely statistical approximations of determined facts, but full-fledged ontologically fundamental constituents of nature, things ”standing in the middle between the idea of an event and the actual event” (Heisenberg 1958,

---

[22] Typical examples of basic, ’more fundamental’ properties are geometrical or structural properties, like the shape and size of an object.

41), a ”new kind of ’objective’ physical reality [...] closely related to the concept of natural philosophy of the ancients such as Aristotle” (Heisenberg 1955, 12)[23].

But how can we individuate powers in the world? What fixes a power’s identity? Answering these questions straightforwardly, while taking into account the contemporary relevant literature[24], is simply not possible; the reason is that the notion is cashed out by different philosophers in many (related, but) different ways. To fully understand what are powers, we need to think of what fixes their identity; the dispositionality of powers is what fixes their identity. But what does that actually mean? According to the most common and shared understanding of powers, their dispositionality is their ability to bring about certain manifestations given certain stimuli (as counterfactually stated in the ’simple conditional analysis’[25]). According to this reading, then, there are at least two components fixing the identity of powers – telling us what powers are: manifestation conditions and stimulus conditions. To these two components, most contemporary powers ontologists add a third one: a ceteris paribus clause, to prevent finking[26], masking[27] and mimicking[28] situations. This means, to use the usual example of fragility, that a glass is fragile because it has a property that (1) make it liable to break (2) under certain circumstances (e.g. when struck) unless (3) some external disturbances (e.g. packing material).

Some contemporary philosophers hold specifically this tripartite view of the identity conditions of powers, such that every power is properly defined by manifestation conditions, stimulus conditions and ceteris paribus clauses;[29] other philosophers accept

---

[23] See also Kastner, Kauffman & Epperson (2018) for the idea that we should take Heisenberg’s concept of potentia seriously.

[24] To mention some of the ’classics’: Shoemaker (1980), Cartwright (1999), Mumford (1998), Martin and Heil (1999), Ellis (2001, 2002, 2010), Molnar (2003), McKitrick (2003), Heil (2003, 2005), Marmodoro (2009; 2017) Bird (2007), Martin (2008), Lowe (2010), Jacobs (2010, 2011), Mumford and Anjum (2011), Tugby (2012, 2013).

[25] Which states that an object is disposed to manifest in a certain way when certain conditions obtain if and only if it would manifest in that certain way if it were the case that said conditions obtained.

[26] Martin (1994) noted that some dispositions might be ’finkish’, where the conditions for an object’s losing a disposition, for example, are attached to the disposition’s stimulus conditions.

[27] Johnston (1992) and Bird (1998) noted that when a fragile glass is protected by packing material, its fragility is masked – the glass does not break when struck.

[28] Lewis (1997) mentions the possibility of an interfering factor in virtue of which something mimics the manifestation of a disposition even if it does not possess it (a constant correlation for, say, divine intervention).

[29] See e.g. Dumsday (2019) for a recent endorsement of this approach.

this general view but try to simplify the picture by cutting down the number of identity conditions[30]. However, to this already variegated picture, we need to add a lot of other related concepts, which are at times taken to be primary in the identification of powers: directedness[31] (the identity is determined by what a power is directed towards); modality[32] (the fact that powers tell us what something could do); causality[33] (powers are intrinsic causal properties); productivity[34] (powers bring into existence their manifestation); dynamism[35] (powers are intrinsically dynamic properties); modal fixity[36] (powers' causal role is fixed across possible worlds); intrinsicness[37] (powers are properties with intrinsic causal significance). All these concepts are intertwined in many different ways in the definition of the identity of a power in the contemporary literature; many powers theorists have very different notions of what powers are supposed

---

[30] Vetter (2013; 2014; 2015) for example suggests that stimuli do not concur in fixing powers identities, and dispositional sentences are akin to 'can' sentences; Williams (2019), on the other hand, gets rid of ceteris paribus clauses, which might be useful in science but do not help picking out the ontology of powers at the fundamental level.

[31] Molnar (2003, 60): "Powers, or dispositions, are properties for some behaviour, usually of their bearers. These properties have an object towards which they are oriented or directed"; Place (1996a, 105): "a disposition is a state whereby the entity (substance), whose dispositional property it is, is orientated towards the coming about of a possible future state". Other classic works centred on the notion of directedness are Martin & Pfeifer (1986), Place (1996a; 1996b; 1999).

[32] Place (1996c, 60): "Dispositional properties are modal properties, they consist in their possible future and past counterfactual manifestations".

[33] In pandispositionalist ontologies, powers are their causal profile (as argued e.g. in Williams (2019).

[34] As in e.g. Mumford & Anjum (2011) and Groff (2013).

[35] As in e.g. Ellis (2002), Mumford (2009) and Groff (2013). As Groff (2013, 214) puts it, processes are "irreducibly active displays of dispositional properties"; powers dynamism give rise to dynamic processes that are not analysable in terms of sequences of static parts. Mumford (2009, 228) agrees that processes that are the exercise of a certain individual's powers are continuous and constant in the sense that every proper part of a change process undergoes change itself and can hence not be reduced to static parts. Mumford's, Ellis's and Groff's analyses suggest that powers' dynamism conveys the idea that powers produce processes that are irreducibly active.

[36] The idea being that a power could not have a different dispositional character and still be the same power. The fact that the causal role of powers is fixed across possible worlds is what Bird (2007) calls the 'modal fixity' of powers, which contrasts with the primitive identity of categorical properties, whose causal role could change across different possible worlds without affecting their identity (a quiddity). Categorical properties are what they are primitively, while powers are what they are disposed to do. Neo-Humean ontologies posit primitive identity: if we swapped the causal roles of two properties we would be generating a distinct possible world; powers theorists disagree: if we swapped causal roles, we would not be generating a different possible world. It is clear, then, that a powers ontology provides a different account of property identity: what it is to be a particular property is spelled out in terms of the dispositionality of the property, and there is no space for a primitive identity (a mysterious 'quiddity') to be transferred between worlds. In this sense, one might argue, a powers ontology looks simpler and, in a sense, 'ontologically lighter': there is one less thing travelling across worlds.

[37] However, talking of intrinsicality might be tricky. Typically, an intrinsic property is taken to be a property that an object has independently of other things (purely in virtue of what it is), while an extrinsic property depends on a object's relationship with other things (in virtue of the way it interacts). However, when we look more closely at this intuitive distinction, we find reason to suspect that it conflates a few related distinctions, and that each of these distinctions is somewhat resistant to analysis. Using relational as an opposite of intrinsic (as it is typically done), for example, might turn out to be a mistake: some properties seem to be both be relational and intrinsic. Marshall makes the example of most people having the property of having longer legs than arms intrinsically, even though the property consists in a certain relation being satisfied.

to be and how they should be characterised.[38] This is why it is not possible to answer univocally the question 'what are powers in contemporary literature?'.

Beside the differences between the varying dispositionalist accounts, what matters for our present purposes is that powers ontologies in general seem to represent the ideal metaphysical background to answer the puzzles regarding inflationary models, as described in the first sections of this paper. Consider what Humphreys has called "the origin of the universe" problem (Humphreys 2016, 91-93); (Humphreys 2021, 2749): should we believe that laws of physics have been there since the origin of the universe, waiting "behind the scene" to be effective? Or should we believe that laws of physics can appear and/or change during the course of the universe? A powers ontology can give us an elegant way out of this puzzle: the emergence of radiating particles of the Standard Model from the inflation field *just* is the emergence of the laws governing their interactions, in the sense that the fundamental element of reality just *are* their modal/causal profile. If new fundamental element of reality come into play only at a certain time in the life of the universe, we don't need to come up with an *ad hoc* solution for the fact that these elements need also to be, at the same time, governed by certain laws of nature. These elements are dispositional in essence, and are therefore carrying in themselves the very rules that govern their interactions with the other existing elements of reality.

To wrap up what said so far: the common intuition according to which the particles composing all the matter in the universe are as old as the universe itself might be misguided: according to the most accepted cosmological scenario, the particles of the Standard Model of our observable universe appeared during reheating, after a phase of inflation. When inflation ended, the inflation field decayed into particles of the Standard Model. As we have claimed in the previous paragraphs, the particles of the Standard Model diachronically emerged from the inflation field, and the laws describing or governing these interactions (e.g., the strong nuclear force) emerged at

---

[38] In e.g. Bird (2016) some of the most relevant contemporary different strategies are spelt out.

the same time. We have seen how a powers ontology can elegantly accommodate the simultaneity of the coming into play of new entities and the relative laws governing them.

5 Conclusion

In this paper, we have argued that if the basic principles of inflationary cosmology hold true (i.e., if we interpret the MSMI realistically), then the transition from the end of the inflationary era to the reheating period represents a case of ontological diachronic emergence. We have shown that this transition involves the transformation of the inflaton field into radiations of the Standard Model particles, leaving discernible traces in the dynamics of our cosmological models. Furthermore, we have explored whether this diachronic process could also be interpreted as the emergence of new fundamental interactions and new physical laws.

This metaphysical discussion sheds light on the various options scientists and philosophers have to answer the problem of the origin of the physical laws embedded in the strong nuclear and electroweak interactions. From a governist perspective, it is natural to view these laws as governing the fields and their interactions. Consequently, the laws of nature exist atemporally or, at the very least, have existed since $t = 0$. Under this framework, there is no meaningful sense in which fields or laws "emerge."

In contrast, a Humean approach conceptualizes laws as regularities embedded within the best systematization of the world (i.e., the account of regularities that balances simplicity and explanatory power). It is possible, in this approach, to talk about the emergence of new laws Sartenaer (2019). According to this view, physical laws, such as those governing the strong nuclear force, emerged when the particles of the Standard Model interacted frequently enough for these interactions to qualify as regularities. This places the emergence of physical laws sometime after the end of inflation, at $t > 10^{-34}$ s.

Finally, within the dispositionalist framework, physical laws are understood as being embedded in the causal profiles of fundamental entities. Consequently, the laws of physics emerged simultaneously with their physical carriers – the bosons of the Standard Model. This assigns a specific time to the emergence of physical laws: $t = 10^{-34}$ s. One of the advantages of this metaphysical perspective, in addition to those highlighted in the preceding section, is that it provides access to a genuine and precise *ontogeny*: an account of how the various categories of our ontology emerged over time, as revealed through the thermal history of the universe investigated by cosmologists.

Appendix

The problems of the standard Big Bang cosmology and how to solve them with an accelerated expansion of the universe

We follow here the elegant presentation of (Baumann 2022, ch.4) who formulates the problems faced by the standard Big Bang cosmology and their solution by inflation in terms of *the comoving Hubble radius*. The Hubble radius at time t is the sphere of radius $\frac{c}{H(t)}$ surrounding an observer. Following most presentations of cosmology, we use here natural units ($c = 1$) and thus the Hubble radius is equal to the Hubble time $t_H = \frac{1}{H(t)}$. Objects outside the Hubble sphere are receding faster than light from the observer. The comoving Hubble radius is the Hubble radius in a comoving frame, i.e., coordinates that factor out the expansion of the universe [39]. Two observers at rest with each other (and for whom the universe is isotropic) will always be separated by the same distance in the comoving frame. The comoving Hubble radius at time t is thus simply $\frac{1}{a(t)H(t)}$.

---

[39] A comoving distance is defined as $\chi = \int \frac{dt}{a(t)}$.

The singularity problem

In the Standard Big Bang cosmology, the cosmological principle imposes homogeneity and isotropy, i.e., three symmetries of rotation and three symmetries of translation. This assumption gives a generalized form of the metric known as Robertson-Walker metric:

$$\mathrm{d}s^2 = -c^2\mathrm{d}t^2 + a^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2/R_0^2} + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2)\right] \tag{3}$$

If we add the supposition that the content of the universe behaves like a perfect fluid, we obtain Friedmann-Lemaître equations, which describe how the rate of expansion of an isotropic and homogeneous universe depends on the matter-energy density ρ, the pressure p, the global curvature k and the cosmological constant Λ:

$$H^2 = \frac{(\dot{a})^2}{(a)^2} = \frac{8\pi G\rho}{3} - \frac{k}{(a)^2} + \frac{\Lambda}{3} \tag{4}$$

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \tag{5}$$

Λ is often assumed to be zero, which is a good approximation for the early universe[40].

Equation (5) imply that, if the strong energy condition is satisfied ($\rho + 3p > 0$), then $\ddot{a} < 0$. Therefore, there exists a singularity $a(t) = 0$ in the finite time. This conclusion assumes that equation (5) (and therefore General Relativity on which they are based) are applicable through the whole history of the universe, including the very dense and hot phase of the very early universe.

Inflation is a quasi de Sitter phase, which means that the metric can be described with de Sitter metric:

$$\mathrm{d}s^2 = -(1 - r^2\Lambda/3)\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{(1 - r^2\Lambda/3)} + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2) \tag{6}$$

---

[40] See any manual of cosmology for a proof of these equations, e.g. Weinberg (2008); Baumann (2022); Mambrini (2024).

where Λ is a positive cosmological constant.

the expansion is exponential (see equation (2)). Therefore, $\ddot{a} > 0$. Considering equation (5), it requires that:

$$p < -\frac{\rho}{3}$$

This is a violation of the strong energy condition $\rho + 3p > 0$ and the singularity theorems do not apply to inflationary cosmology. Moreover, if we define conformal time (which, in natural units, is the equivalent of the comoving distance in a comoving frame) as

$$\tau = \int \frac{dt}{a(t)} \tag{7}$$

then, during inflation, the scale factor is

$$a(\tau) = -\frac{1}{H\tau}$$

Because H is constant during inflation, it means that the singularity $a = 0$ is pushed to $\tau \to -\infty$, i.e. to the infinite past (Baumann 2009, 29).

However, this solution is true only in conformal time τ. According to cosmic time t, it is still possible to date the end of inflation between t^{-34} s and t^{-32} s. Moreover, Arvind Borde, Alan Guth and Alexander Vilenkin proved that even inflationary universes violating the strong energy condition have incomplete geodesics in the past direction Borde and Vilenkin (1996); Borde et al. (2003).

The horizon problem

We define the comoving horizon τ as the maximum distance a light ray can travel between time 0 and time t in a comoving frame. Using natural units, its mathematical expression is similar to that of conformal time :

$$\tau = \int_0^t \frac{dt}{a(t)} = \int_0^a \frac{da}{Ha^2} = \int_0^a \mathrm{d}\ \ln a \frac{1}{Ha} \tag{8}$$

For a radiation-dominated universe, $\tau \propto a$ and for a matter-dominated universe $\tau \propto a^{1/2}$. This means that the comoving horizon grows monotonically with time in the standard Big Bang cosmology. This comoving horizon represents the fraction of the universe in causal contact. Therefore, regions of the universe that enter in causal contact at time t have not been in causal contact before t. Calculating the size of the comoving horizon of a region from $t = 0$ to $t_{dec} \simeq 370{,}000$ years gives a result of more than 10^{80} regions causally disconnected. Observationally, a separation of two degrees is sufficient to imply no common causal past between two points of the last scattering surface.

Now, if we define inflation as a period during which H is constant, then a grows exponentially (see equation (2)). This means that the comoving Hubble radius $\frac{1}{aH}$ shrinks during inflation and only increases after inflation. Therefore τ can be larger than the comoving Hubble radius, which means that all the regions in our comoving Hubble radius (the observable universe) have been in causal contact in the past.

The flatness problem

The critical density ρ_c is the density of the universe for which $k = 0$. Using (4), we find:

$$\rho_c = \frac{3H^2}{8\pi}$$

We can then defines the dimensionless parameter $\Omega = \frac{\rho}{\rho_c}$. If $\Omega = 1$ then the universe is "flat", i.e., its geometry is Euclidean. We can hence rewrite equation (4) as

$$1 = \frac{8\pi G\rho}{3H^2} - \frac{k}{(aH)^2}$$

$$1 - \frac{\rho}{\rho_c} = -\frac{k}{(aH)^2}$$

$$1 - \Omega = -\frac{k}{(aH)^2} \tag{9}$$

Because in standard Big Bang cosmology, the comoving Hubble radius $\frac{1}{aH}$ is increasing with time, $1 - \Omega$ diverges with time. This implies that, for example, if at $t = 1$ second, $\Omega = 1.08$, then at $t = 10$ seconds $\Omega = 2$. In order to have $\Omega \simeq 1$ today, at $t = 1$ second Ω had to be 1 ± 10^{-16} (Azhar and Butterfield 2016, 24).

But in inflationary cosmology, H is constant and a grows exponentially with time. Therefore $-\frac{k}{(aH)^2}$ in equation (9) quickly converges towards zero, which means that Ω is driven towards 1, i.e. Euclidean space.

Dynamical models of inflation

The dynamics of the scalar field

We define the inflaton as a scalar field φ together with its pressure p_φ and density ρ_φ. From Friedmann-Lemaître equation (5), we know that:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{6}(\rho_\varphi + 3p_\varphi)$$

We can rewrite this as:

$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = H^{^2}(1 - \epsilon) \tag{10}$$

Reformulating this equation, we can relate ϵ to the expansion of the universe:

$$\epsilon = -\frac{\dot{H}}{H^2} \tag{11}$$

Accelerated expansion occurs when $\ddot{a} > 0$. This implies that

$$-\frac{\ddot{a}}{a} < 0$$

$$-\frac{\ddot{a}}{a} - H^2 < H^2$$

$$-\frac{\ddot{a}a - \dot{a}^2}{a^2} < H^2$$

$$-\dot{H} < H^2$$

and therefore that $\epsilon < 1$. By definition,

$$\epsilon \equiv \frac{3}{2}(w_\varphi + 1) \tag{12}$$

where w_φ is the equation of state of the inflaton:

$$w_\varphi \equiv \frac{p_\varphi}{\rho_\varphi} = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)} \tag{13}$$

This equation shows that for ϵ to be inferior to 1, we must have $p_\varphi < \rho_\varphi$. The de Sitter limit corresponds to $p_\varphi \to -\rho_\varphi$ and thus to $\epsilon \to 0$. In this case, $\frac{1}{2}\dot{\varphi}^2 \ll V(\varphi)$, i.e., the kinetic energy of the inflaton is dominated by its potential. Therefore, as long as the kinetic energy is negligible in comparison with the potential, the conditions are satisfied for inflation to occurs (see figure 3). But as soon as these two components are of equal magnitude, inflation stops and reheating begins.

Different models of inflation

The shape of the inflaton potential depends on the nature of the inflaton and of its couplings (see figure 2.2). This can help discriminate among different models of inflation and reheating. Each potential shape defines a $\Delta(\varphi)$ between the value of φ

where quantum fluctuations leading to the CMB anisotropies occur and the value of φ where inflation ends ($V(\varphi) \approx \dot{\varphi}^2$). If $\Delta(\varphi)$ is smaller than M_{Pl}, the reduced Planck mass, the model is called as *small-field inflation*. Otherwise, it is called *Large-field inflation*.

The Coleman-Weinberg potential is one of the most famous example of small-field inflation:

$$V(\varphi) = V_0 \left[\left(\frac{\varphi}{\mu}\right)^4 \left(ln\frac{\varphi}{\mu} - \frac{1}{4} \right) + \frac{1}{4} \right]$$

Chaotic inflation[41] of the type $m^2\varphi^2/2$ is the prototypical case of large-field inflation. It has a potential of the shape:

$$V(\varphi) = \lambda_p \varphi^p$$

If the inflaton is taken to be an axion, an hypothetical boson, then the potential has the shape of *natural inflation* :

$$V(\varphi) = V(0) \left[cos(\frac{\varphi}{f} + 1 \right]$$

If $2\pi f > M_{Pl}$ then natural inflation is a case of large-field inflation.

In addition, some models of inflations imply more than one field and are known as "multi-field" or "hybrid" models.

Mechanisms of reheating

We follow here the review of of the different mechanisms of reheating in Bassett et al. (2006).

Classical reheating

"Reheating" is a process that takes its name from the fact that the universe, at the end of inflation, is very near to zero temperature. Therefore, the decay of the inflaton

---

[41] Chaotic inflation has been ruled out by the observations of the anisotropies of the CMB.

must explain how the temperature of the universe rose back to the high temperatures of the primordial universe, needed to trigger a baryogenesis and a nucleosynthesis.

Reheating was first studied as a case of single-body decay. To do so, we use interaction terms in the Lagrangian to describe how the inflaton field φ is coupled with the fields of the Standard Model:

- $\mu\varphi\chi^2$ or $\sigma\varphi^2\chi^2$ for an interaction with a boson field χ
- $y\varphi\bar{\psi}\psi$ for an interaction with a fermion field ψ

μ has the dimension of a mass, σ and y are dimensionless couplings. When we consider particles of the Standard Model as χ and ψ, their mass is much smaller that the mass of the inflaton m_φ. The decay rate is given by:

$$\Gamma_{\varphi \to \chi\chi} = \frac{\mu^2}{8\pi m_\varphi} \tag{14}$$

$$\Gamma_{\varphi \to \psi\bar{\psi}} = \frac{y^2 m_\varphi}{8\pi} \tag{15}$$

If the expansion rate of the universe H is larger than the decay rate Γ, the particles created cannot interact enough for a thermal distribution to be reached. This implies an upper-limit on the temperature of reheating is given by $\Gamma = H$ (Bassett et al. 2006, 28). Moreover, the temperature of reheating cannot go back to the temperature before inflation (10^{16} GeV) to ensure that there is not another phase of production of magnetic monopoles.

Note that this scenario of reheating depends on the idea that the inflaton decays into radiations. Following (Mambrini 2024, 128-129), we write the law of conservation of energy for a decaying field φ of width Γ_φ and energy density ρ_φ:

$$\frac{\mathrm{d}\rho_\varphi a^3}{\mathrm{d}t} = -\Gamma_\varphi(\rho_\varphi a^3)$$

Developping the derivative, we obtain:

$$\dot{\rho_\varphi} + 3H\rho_\varphi = -\Gamma_\varphi \rho_\varphi$$

If we are concerned with relativistic fields, then we can then use the first law of thermodynamics to find the evolution of the density of radiation. If we consider the decaying inflaton as a system transmitting heat $\mathrm{d}Q = -\mathrm{d}(\rho_\varphi a^3)$ to a system of internal energy $U = \rho_\varphi a^3$, then the amount of internal energy $\mathrm{d}U = \mathrm{d}Q - p_R \mathrm{d}V$ (with $V = a^3$ received by the radiation sector is:

$$\mathrm{d}(\rho_R a^3) = -p_R \mathrm{d}a^3 - \mathrm{d}(\rho_\varphi a^3) = -\frac{\rho_R}{3}\mathrm{d}a^3 - \mathrm{d}(\rho_\varphi a^3)$$

where p_R is the pressure of the relativistic gas such as $p_R = \frac{\rho_R}{3}$. Thus, we obtain:

$$\dot{\rho_R} + 4H\rho_R = -\Gamma_\varphi \rho_\varphi$$

This is how inflationary models describe the decay of the inflaton into radiation like the Standard Model particles. If one introduces new couplings between the inflaton and massive particles, the reheating cannot be summarized by the direct decay of the inflaton into particles of the Standard Model: it involves a previous phase of preheating during which the inflaton decays into exotic particles.

Different models of preheating

Preheating is an intermediary phase between inflation and classical reheating during which the inflaton decays into massive particles, which in turn decay into particles of the Standard Model. There are different models of preheating depending on the different families of inflations described in the previous section:

> In the simplest versions of chaotic inflation, the stage of preheating is generally dominated by parametric resonance, although there are parameter

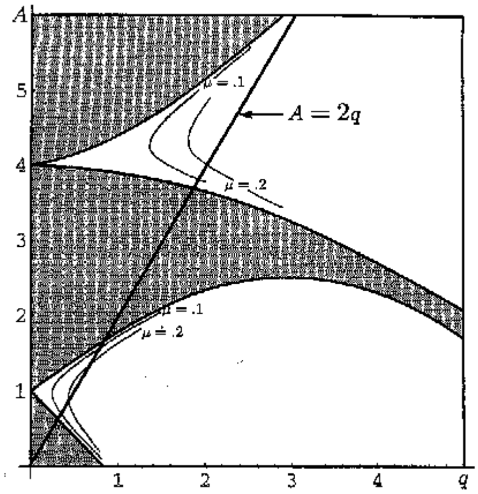


Fig. 7 Sketch of the stability/instability of Mathieu's equation. White regions correspond to the instability (resonance) bands, grey regions to the stability bands. Source: Kofman et al. (1994).

> ranges where this can not occur. It was shown that tachyonic preheating dominates the preheating phase in hybrid models of inflation. New inflation in this respect occupies an intermediate position between chaotic inflation and hybrid inflation: if spontaneous symmetry breaking in this scenario is very large, reheating occurs due to parametric resonance and perturbative decay. However, for the models with spontaneous symmetry breaking at or below the GUT scale, $\varphi \ll 10^{-2} M_{Pl}$, preheating occurs due to a combination of tachyonic preheating and parametric resonance. The resulting effect is very strong, so that the homogeneous mode of the inflaton field typically decays within few oscillations. (Linde 2005, 16)

The two main mechanisms of preheating are parametric resonance an tachyonic reheating (see (Bassett et al. 2006, 31-37) for more models and details). Parametric resonance in chaotic inflation has been described in Kofman et al. (1994). It occurs because the inflaton interacts with another scalar field χ. The oscillations of the inflaton causes the fluctuations of this field to behave like a parametric oscillator with a variable frequency: ”particle production occurs due to a nonadiabatic change of this frequency” (Kofman et al. 1994, 2). The equation of this fluctuation is similar to Mathieu’s equation that describes parametric oscillators:

$$\ddot{\chi}_k + (A(k) - 2q\cos(2m_\varphi t))\chi_k = 0$$

where $A(k) = \frac{k^2}{m_\varphi^2} + 2q$ and $q = \frac{g^2\varphi^2}{4m_\varphi^2}$. Mathieu’s equation is characterized by the existence, for almost all choice of parameters A and q, of solutions either converging to zero or diverging to infinity. These regions of stability and instability are represented on the Mathieu’s chart (see figure 7).

The instability corresponds to an exponential rate of particle creation and to an ”explosive” decay of the inflaton φ.

Tachyonic reheating was first studied in Felder et al. (2001). In this context, tachyonic means that we consider a scalar field χ with an effective mass $m^2_{\chi,eff}$ $g\varphi^2$ which can be negative. This implies ”tachyonic phases”, an instability of this field because of its coupling with the oscillating inflaton field (Bassett et al. 2006, 33). The decay of φ is even more rapid and can end after only one oscillation.

References

Abbott L, Farhi E, Wise M (1982) Particle production in the new inflationary cosmology. Physics Letters B 117(1-2):29–33

Albrecht A (2001) Cosmic inflation. In: Structure Formation in the Universe: Proceedings of the NATO Advanced Study Institute on Structure Formation in the Universe Cambridge, UK 26 July–6 August 1999. Springer, p 17–42

Azhar F, Butterfield J (2016) Scientific realism and primordial cosmology. arXiv preprint arXiv:160604071

Azhar F, Loeb A (2021) Finely tuned models sacrifice explanatory depth. Foundations of Physics 51:1–36

Barrow J, Liddle A (1997) Can inflation be falsified? General Relativity and Gravitation 29(12):1503–1510

Bassett B, Tsujikawa S, Wands D (2006) Inflation dynamics and reheating. Reviews of Modern Physics 78(2):537–589

Baumann D (2009) Tasi lectures on inflation. arXiv preprint arXiv:09075424

Baumann D (2022) Cosmology. Cambridge University Press

Bird A (1998) Dispositions and antidotes. The Philosophical Quarterly 48(191):227–234

Bird A (2007) Nature's metaphysics: Laws and properties

Bird A (2016) Overpowering: How the powers ontology has overreached itself. Mind 125(498):341–383

Black M (1952) The identity of indiscernibles. Mind 61(242):153–164

Borde A, Vilenkin A (1996) Singularities in inflationary cosmology: A review. International Journal of Modern Physics D 5(06):813–824

Borde A, Guth A, Vilenkin A (2003) Inflationary spacetimes are incomplete in past directions. Physical review letters 90(15):151301

Cartwright N (1999) The Dappled World: A Study of the Boundaries of Science. Cambridge University Press

Dawid R, McCoy C (2023) Testability and viability: is inflationary cosmology "scientific"? European Journal for Philosophy of Science 13(4):51

de Sitter W (1917) On the relativity of inertia. remarks concerning einstein's latest hypothesis. Koninklijke Nederlandse Akademie van Wetenschappen Proceedings 19:1217–1225

Dirac P (1937) The cosmological constants. Nature 139(3512):323–323

Dumsday T (2019) Dispositionalism and the Metaphysics of Science. Cambridge University Press

Ellis B (2001) Scientific Essentialism. Cambridge University Press

Ellis B (2002) The Philosophy of Nature: A Guide to the New Essentialism. Routledge

Ellis B (2010) Causal powers and categorical properties. In: Marmodoro A (ed) The metaphysics of powers. Routledge, p 141–150

Ellis G, Rothman T (1987) Has cosmology become metaphysical? Astronomy 15:6–21

Engelhard K (2010) Categories and the ontology of powers: A vindication of the identity theory of properties. In: Marmodoro A (ed) The metaphysics of powers. Routledge, p 49–65

Felder G, Garcia-Bellido J, Greene P, et al (2001) Dynamics of symmetry breaking and tachyonic preheating. Physical Review Letters 87(1):011601

Groff R (2013) Whose powers? which agency? In: Powers and Capacities in Philosophy. Routledge, p 207–228

Guay A, Sartenaer O (2016) A new look at emergence. or when after is different. European Journal for Philosophy of Science 6:297–322

Guth A (1981) Inflationary universe: A possible solution to the horizon and flatness problems. Physical Review D 23(2):347

Hawking S, Ellis G (1968) The cosmic black-body radiation and the existence of singularities in our universe. The Astrophysical Journal 152:25

Heil J (2003) From an Ontological Point of View. Clarendon Press

Heil J (2005) Dispositions. Synthese 144(3):343–356

Heisenberg W (1955) The development of the interpretation of the quantum theory. In: Pauli W (ed) Niels Bohr and the Development of Physics

Heisenberg W (1958) Physics and Philosophy. Harper & Brothers

Heisenberg W (1971) Physics and Beyond: Encounters and Conversations, World Perspectives, vol 42. Harper & Row, New York

Humphreys P (2016) Emergence: A Philosophical Account. Oxford University Press

Humphreys P (2021) Invariances in transformational emergence. Synthese 199:2745–2756

Ijjas A, Steinhardt P, Loeb A (2017) Pop goes the universe. Scientific American 316(2):32–39

Jacobs JD (2010) A powers theory of modality – or, how i learned to stop worrying and reject possible worlds. Philosophical Studies 151:227–248

Jacobs JD (2011) Powerful qualities, not pure powerful. The Monist 94:81–102

Jaeger G (2019) Are virtual particles less real? Entropy 21(2). https://doi.org/10.3390/e21020141, URL https://www.mdpi.com/1099-4300/21/2/141

Johnston M (1992) How to speak of the colors. Philosophical Studies 68:221–263

Kastner RE, Kauffman S, Epperson M (2018) Taking heisenberg's potentia seriously. International Journal of Quantum Foundations 4(2):158–172

Kofman L, Linde A, Starobinsky AA (1994) Reheating after inflation. Physical Review Letters 73(24):3195

Kuhlmann M (2013) The Ultimate Constituents of the Material World: In Search of an Ontology for Fundamental Physics, vol 37. Walter de Gruyter

Kuhlmann M (2023) Quantum Field Theory. In: Zalta EN, Nodelman U (eds) The Stanford Encyclopedia of Philosophy, Summer 2023 edn. Metaphysics Research Lab, Stanford University

Lange M (2008) Could the laws of nature change? Philosophy of Science 75(1):69–92

Lewis D (1994) Humean supervenience debugged. Mind 103(412):473–490

Lewis D (1997) Finkish dispositions. The Philosophical Quarterly 47:143–158

Liddle A, Lyth D (2000) Cosmological Inflation and Large-scale Structure. Cambridge University Press

Linde A (2005) Inflation and string cosmology. arXiv preprint hep-th/0503195

Lowe EJ (2010) On the individuation of powers. In: Marmodoro A (ed) The Metaphysics of Powers: Their Grounding and Their Manifestations. Routledge, New York, p 8–26

Mambrini Y (2024) Particles in the Dark Universe: A Student's Guide to Particle Physics and Cosmology. Springer

Marmodoro A (2009) Do powers need powers to make them powerful?: From pandispositionalism to aristotle. History of Philosophy Quarterly 26:337–352

Marmodoro A (2017) Aristotelian powers at work: Reciprocity without symmetry in causation. In: Jacobs JD (ed) Causal Powers. Oxford University Press

Martin CB (1994) Dispositions and conditionals. The Philosophical Quarterly 44:1–8

Martin CB (2008) The Mind in Nature. Oxford University Press, Oxford

Martin CB, Heil J (1999) The ontological turn. Midwest Studies in Philosophy 23:34–60

Martin CB, Pfeifer K (1986) Intentionality and the non-psychological. Philosophy and Phenomenological Research 46(4):531–554

Martin J, Ringeval C, Trotta R, et al (2014a) The best inflationary models after planck. Journal of Cosmology and Astroparticle Physics 2014(03):039

Martin J, Ringeval C, Vennin V (2014b) Encyclopædia inflationaris. Physics of the Dark Universe 5:75–235

McKitrick J (2003) A case for extrinsic dispositions. Australasian Journal of Philosophy 81:155–174

Molnar G (2003) Powers: A Study in Metaphysics. Oxford University Press

Mumford S (1998) Dispositions. Oxford University Press, Oxford

Mumford S (2004) Laws in Nature. Routledge, New York

Mumford S (2009) Powers and persistence. de Gruyter Berlin, p 223–236

Mumford S, Anjum RL (2011) Getting Causes from Powers. Oxford University Press

Perlov D, Vilenkin A (2017) Cosmology for the Curious. Springer

Place UT (1996a) Intentionality as the mark of the dispositional. Dialectica 50:91–120

Place UT (1996b) Structural properties: Categorical, dispositional or both? In: Armstrong DM, Martin CB, Place UT, et al (eds) Dispositions: A Debate. Routledge, p 105–125

Place UT (1996c) Mental causation is no different from any other kind. The British Psychological Society, History and Philosophy of Psychology Newsletter 23:15–20

Place UT (1999) Intentionality and the physical: A reply to mumford. The Philosophical Quarterly 49:225–231

Sartenaer O (2018) Flat emergence. Pacific Philosophical Quarterly 99:225–250

Sartenaer O (2019) Humeanism, best system laws, and emergence. Philosophy of Science 86(4):719–738

Sartenaer O, Guay A, Humphreys P (2021) What price changing laws of nature? European Journal for Philosophy of Science 11:1–19

Shimony A (1999) Can the fundamental laws of nature be the results of evolution?, Cambridge University Press, pp 208–233

Shoemaker S (1980) Causality and properties. In: van Inwagen P (ed) Time and Cause: Essays Presented to Richard Taylor. Reidel, Dordrecht, p 109–135

Shoemaker S (1998) Causal and metaphysical necessity. Pacific Philosophical Quarterly 79:59–77

Smeenk C (2005) False vacuum: Early universe cosmology and the development of inflation. In: The universe of general relativity. Springer, p 223–257

Smeenk C (2012) Inflation as a Theory of Structure Formation, Einstein Studies, vol 13, Birhauser, pp 1–31

Smeenk C (2017) Testing inflation. The Philosophy of Cosmology pp 206–227

Smolin L (2015) Temporal naturalism. Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics 52:86–102

Starobinsky A (1980) A new type of isotropic cosmological models without singularity. Physics Letters B 91(1):99–102

Tahko T (2015) The modal status of laws: In defence of a hybrid view. The Philosophical Quarterly 65(260):509–528

Tugby M (2012) Rescuing dispositionalism from the ultimate problem: Reply to barker and smart. Analysis 72(4):723–731

Tugby M (2013) Platonic dispositionalism. Mind 122:451–480

Vetter B (2013) Multi-track dispositions. The Philosophical Quarterly 63:330–352

Vetter B (2014) Dispositions without conditionals. Mind 123:129–156

Vetter B (2015) Potentiality: From Dispositions to Modality. Oxford University Press, Oxford

Visser M, Barcelo C (2000) Energy conditions and their cosmological implications pp 98–112

Weinberg S (2008) Cosmology. OUP Oxford

Weingard R (1982) Do virtual particles exist? In: PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association, Cambridge University Press, pp 235–242

Williams NE (2019) The Powers Metaphysic. Oxford University Press, Oxford

Wilson J (2021) Metaphysical emergence. Oxford University Press

Wilson J (forthcoming) On the notion of diachronic emergence

Wolf WJ (2024) Cosmological inflation and meta-empirical theory assessment. Studies in History and Philosophy of Science 103:146–158

Wolf WJ, Thebault KP (2023) Explanatory depth in primordial cosmology: A comparative study of inflationary and bouncing paradigms. The British Journal for the Philosophy of Science

Yates D (2013) The essence of dispositional essentialism. Philosophy and Phenomenological Research 87(1):93–128