

# A brief history of the multiverse

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## Abstract

The theory of the inflationary multiverse changes the way we think about our place in the world. According to its most popular version, our world may consist of infinitely many exponentially large parts, exhibiting different sets of low-energy laws of physics. Since these parts are extremely large, the interior of each of them behaves as if it were a separate universe, practically unaffected by the rest of the world. This picture, combined with the theory of eternal inflation and anthropic considerations, may help to solve many difficult problems of modern physics, including the cosmological constant problem. In this article I will briefly describe this theory and provide links to the some hard to find papers written during the first few years of the development of the inflationary multiverse scenario.

# 1 Introduction

The theory of inflationary multiverse is based on unification of inflationary cosmology, anthropic considerations, and particle physics. Its most advanced versions include a combination of eternal inflation and string theory into what is now called “string theory landscape.” This theory is still ‘work in progress,’ and the pendulum of public opinion with respect to it swings with a very large amplitude. Some people love this theory, others hate it and write papers defending the integrity of physics. It does not help much that the word “multiverse” is used differently by different people. In this situation it may be useful to remember what exactly we are talking about and why this theory was invented.

This is not an easy task. Until the mid-90’s the cosmological anthropic principle pioneered by Dicke, Carter, Rees, Barrow, Rozental and others remained very unpopular. For example, we know that the proton mass is almost exactly equal to the neutron mass. If the proton were 1% heavier or lighter, life as we know it would be impossible. Similarly, one cannot significantly change the electron charge and its mass without making the universe unsuitable for life. But if physical parameters are just constants in the Lagrangian, nothing can change them. Therefore the standard lore was that one should avoid using anthropic arguments for explaining fundamental properties of our world.

As a result, some of the key ideas relating to each other inflation and anthropic considerations originally were expressed in a rather cryptic form and scattered among preprints, conference proceedings and old journals which are hard to find. In this paper I will briefly describe the history of the evolution of these ideas and provide links to some of the original publications which are especially difficult to find.

Historically, there were many different versions of the theory of the multiverse based on the many-world interpretation of quantum mechanics [1] and quantum cosmology [2], on the theory of creation of the universe ‘from nothing’ [3], and on the investigation of the Hartle-Hawking wave function [4]. These ideas are most powerful, but their consistent implementation requires deep understanding of difficult conceptual issues of quantum cosmology. Moreover, quantum cosmology by itself does not allow us to change fundamental constants.

Therefore the main progress in the development of the theory of the inflationary multiverse was achieved in a different, conceptually simpler context. To explain it, let us remember that one of the starting points of the pre-inflationary cosmology was that the universe is globally uniform. This was the so-called ‘cosmological principle’, which was invoked by many people, from Newton to Einstein, to account for the observed large-scale homogeneity of the universe. The physical mechanism explaining the homogeneity of our part of the world was provided by inflationary theory. Surprisingly enough, this theory made the cosmological principle obsolete.

Indeed, the main idea of inflationary cosmology is to make our part of the universe homogeneous by stretching any pre-existing inhomogeneities and by placing all possible ‘defects,’ such as domain walls and monopoles, far away from us, thus rendering them unobservable. If the universe consists of different parts, each of these parts after inflation may become locally homogeneous and so large that its inhabitants will not see other parts of the universe, so they may conclude, incorrectly, that the universe looks the same everywhere. However, properties of different parts of the universe may be dramatically different. In this sense, the universe effectively becomes a multiverse consisting of different exponentially large locally homogeneous parts with different properties. To distinguish these exponentially large parts of our world

from more speculative ‘other universes’ entirely disconnected from each other, I called these parts ‘mini-universes,’ others call them ‘pocket universes’. Eventually, we started using the word ‘multiverse’, or ‘inflationary multiverse’ to describe the world consisting of many different ‘mini-universes’, or ‘pocket universes’.

An advanced version of this scenario describes our world as an eternally growing self-reproducing fractal consisting of many locally homogeneous parts (mini-universes). If the fundamental theory of all interactions has many different vacuum states, or allows different types of compactification, the laws of the low-energy physics and even the dimensionality of space in each of these mini-universes may be different. This provided, for the first time, a simple scientific interpretation of the anthropic principle, which did not rely on the possible existence of ‘other universes’: We can live only in those parts of the world which can support life as we know it, so there is a correlation between our own properties, and the properties of the part of the world that we can observe.

This combination of eternal inflation and the anthropic principle, which we will concentrate upon in this paper, was first proposed in 1982 in my preprint written during the famous Nuffield Symposium on inflationary cosmology [5]. It was argued there that an eternally inflating universe “contains an infinite number of mini-universes (bubbles) of different size, and in each of these universes the masses of particles, coupling constants, etc. may be different due to the possibility of different symmetry breaking patterns inside different bubbles. This may give us a possible basis for some kind of Weak Anthropic Principle: There is an infinite number of causally unconnected mini-universes inside our universe, and life exists only in sufficiently suitable ones.” A full text of the preprint can be found at <http://www.stanford.edu/~alinde/1982.pdf>.

This idea, which plays the central role in the theory of inflationary multiverse, was further extended in my contribution to the proceedings of the Nuffield Symposium [6]. In addition to the discussion of various types of symmetry breaking in different parts of the multiverse, I also revisited there an old observation by Paul Ehrenfest that life as we know it may exist only in a four-dimensional space-time, because planetary and atomic systems would be unstable for  $d \neq 4$  [7]. I argued in [6] that this idea finally acquires a well defined physical meaning in inflationary theory combined with the idea of spontaneous compactification: “In the context of this scenario it would be sufficient that the compactification to the space  $d = 4$  is *possible*, but there is no need for the four-dimensional space to be the *the only* possible space after the compactification. Indeed, if the compactification to the space  $d = 4$  is possible, there will be infinitely many mini-universes with  $d = 4$  in which intelligent life can exist.”

Being impressed by free lunches provided to the participants of the Nuffield Symposium, I summarized the main consequence of this scenario as follows: “As was claimed by Guth (1982), the inflationary universe is the only example of a free lunch (all matter in this scenario is created from the unstable vacuum). Now we can add that the inflationary universe is the only lunch at which all possible dishes are available” [6], see <http://www.stanford.edu/~alinde/LindeNuffield.pdf>.

Ref. [5] described eternal inflation in a particular version of the new inflationary scenario [8] where the inflaton potential has a shallow minimum at the top. The regime of eternal inflation occurs in the old inflationary theory as well, but there it was considered a major obstacle precluding a consistent realization of inflationary cosmology [9, 10]. A possible existence of this regime in new inflation was first mentioned by Steinhardt in his talk at the Nuffield symposium. A brief discussion of this idea, as well as of my paper [5], is contained in his contribution to

the Proceedings of the Nuffield Symposium [11]. However, he did not discuss the use of the anthropic principle; in fact he opposes the theory of inflationary multiverse in strongest possible terms [12]. A more general approach to the theory of eternal inflation in the new inflationary scenario was developed in 1983 by Vilenkin [13]. He explained that inflationary quantum fluctuations may keep the field at the top of the potential in some parts of the universe even if the potential does not have a local minimum at the top.

The first practical application of the anthropic principle in the context of inflationary cosmology was found in [14]. It was shown there that inflationary fluctuations can induce transitions between different vacua in supersymmetric grand unified theories. These transitions divide the universe into exponentially large parts with different types of symmetry breaking, and therefore with different laws of low-energy physics. If not for this mechanism, the hot universe would stay forever in the  $SU(5)$  symmetric vacuum, unsuitable for life as we know it.

None of these developments attracted much attention at that time, in part because the anthropic principle was very unpopular, and in part because the new inflationary scenario did not work and was replaced by the chaotic inflation scenario [15]. The simplest versions of the chaotic inflation scenario describe inflation far away from any extrema of the inflaton potential, so the previous results obtained in [5, 11, 13] did not apply to it. In addition, the energy scale of eternal inflation in the new inflation scenario was extremely small as compared to the Planck scale. Therefore it was not clear whether inflationary fluctuations could be powerful enough to probe the inner structure of space and divide the universe into different parts with different types of compactification, as proposed in [6]. This problem was solved in 1986 with the discovery of the regime of eternal inflation in the chaotic inflation scenario [16, 17], which we will discuss later, but back in 1983-1985 this solution was not known to us, so we were exploring alternative possibilities.

One possibility was to return to the full quantum mechanical description of the universe formation. The first results obtained by the euclidean approach to creation of the universe [3, 4] suggested that the probability of creation of a closed inflationary universe with the inflaton energy density  $V(\phi)$  is given by  $e^{24\pi^2/V(\phi)}$ . This implied that the probability of quantum creation of an inflationary universe is exponentially small, suggesting that it is much easier to create a huge empty universe of a present size, with a tiny value of the cosmological constant. However, the subsequent investigation indicated that the probability of the universe creation is in fact given by  $e^{-24\pi^2/V(\phi)}$  [18–20]. This provided an ideal framework for realization of initial conditions for chaotic inflation, where  $V$  can be large [18, 19]. There could be a problem for those models where inflation is possible only for  $V \ll 1$  and the term  $e^{-24\pi^2/V(\phi)}$  is exponentially small, but one could alleviate this problem using anthropic considerations [20]. Moreover, an investigation of quantum creation of compact open or flat universes with nontrivial topology indicated that this process is not exponentially suppressed even for  $V \ll 1$  [21–23]. And once inflation starts, the nontrivial topology becomes practically irrelevant: The universe becomes locally uniform and isotropic.

If this is the case, one may consider a possibility of quantum creation of different universes corresponding to different values of the potential  $V$  and study the cosmological constant problem in this context. The anthropic bound on the positive cosmological constant was derived by Weinberg in his famous paper of 1987 [24], and further strengthened in [25] and several subsequent publications. The existence of this bound, in a less precise form, was conjectured and used even earlier [19, 26–30]. The main problem was that it was very difficult to find any

physical mechanism that would allow to make this constant small. Until [31], the cosmological constant was considered by many to be just a constant in the gravitational action, so it was not quite clear whether it makes any sense to consider universes with different values of  $\Lambda$ . In what follows I will describe three different ideas proposed in 1984-1986, which found their way to modern discussions of the cosmological constant problem.

In [19] I suggested to consider a combined contribution of scalar fields  $\phi$  and fluxes (anti-symmetric tensor fields  $F_{\mu\nu\lambda\sigma}$ ) to vacuum energy. At the classical level the fields  $F_{\mu\nu\lambda\sigma}$  take constant values all over the universe and contribute to the cosmological constant [32]. At that time it was not known that these fields may change their values due to tunneling with bubble formation [33]. Therefore one could expect that the cosmological constant is just a constant which cannot change. However, in quantum cosmology this is not necessarily an obstacle. One may study the probability of creation of different universes with different values of  $\phi$  and  $F_{\mu\nu\lambda\sigma}$ . If one uses the expression for the probability  $e^{24\pi^2/V}$  [3, 4], one could conclude that  $\Lambda$  must vanish [32], which is not the case according to the observational data. However, if one uses the expression  $e^{-24\pi^2/V}$  [18–20], where  $V = V(\phi) + V(F)$ , one finds that the probability to live in a universe with a given value of  $\Lambda$  has a flat distribution as a function of  $\Lambda$ , which is exactly what we need for the anthropic solution of the cosmological constant problem [19], see the very end of <http://www.stanford.edu/~alinde/1984.pdf>.

The second mechanism was proposed by Sakharov [27]. He mentioned, following [6], that the universe may consist of many different parts with different types of compactification. Then he argued that if the number of compactified dimensions is sufficiently large, the number of different types of compactifications can be exponentially large. He emphasized that if this number is large enough, the typical energy gap between different levels can be extremely small, which may allow to explain the smallness of the cosmological constant by using anthropic considerations, see Section 4 in <http://www.stanford.edu/~alinde/Sakharov1984.pdf>.

The third mechanism was proposed in [30]. It was based on a combination of eternal inflation driven by the inflaton field  $\phi$  and a subsequent slow roll of what was later called ‘quintessence’ field  $\Phi$ . The role of eternal inflation was to generate perturbations of the field  $\Phi$ , which then give this field different values in different exponentially large parts of the universe. As a result, the universe becomes divided into different parts with a flat probability distribution for different values of the effective cosmological constant. Once again, this provided a possibility to use anthropic considerations for solving the cosmological constant problem, see <http://www.stanford.edu/~alinde/1986300yrsgrav.pdf>.

This proposal was initiated by the discovery of the regime of eternal inflation in the chaotic inflation scenario [16,17]. (In fact, the name “eternal inflation” was first introduced in these two papers.) It was shown there that eternal inflation is a generic regime which is possible in any theory with a sufficiently flat potential. This included not only new inflation, but any chaotic inflation model with polynomial potentials. More generally, eternal inflation occurs in any inflationary regime where the amplitude of density perturbations becomes  $O(1)$  for some values of the fields. One of the most important features of this regime was the possibility of eternal inflation at arbitrary values of energy density, up to the Planck energy density. This implied that inflationary perturbations of all other fields produced at that epoch could be large enough to bring us from one vacuum state to another, and even from one type of compactification to another, practically irrespectively of the size of the barrier separating different vacua. This opened the possibility to implement the anthropic principle in its strongest form, using the

analogy with mutations of the laws of physics and the Darwinian approach [34]. The main idea was illustrated in [30, 34] by an image of a multicolored self-reproducing universe, which gradually became the standard symbol of the inflationary multiverse. Fig. 1 shows its version published in [34], with the original figure caption.

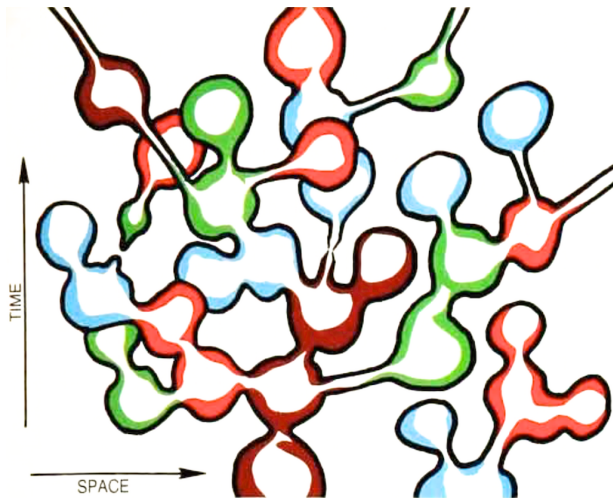


Figure 1: Global structure of a chaotic, self-reproducing inflationary universe. Locally (out to the  $10^{10}$  light-year horizon) the universe looks quite homogeneous, but its global structure is complex. Mini-universes at the Planck energy density are “mutants” that may forget completely the “genetic code” (color) of their parent universe. They may even have a different space-time dimensionality. The typical thickness of a tube connecting two mini-universes after inflation is exponentially large, but if it corresponds to a compactified inflationary universe it can be as thin as the Planck length ( $\sim 10^{-33}$  cm). If the tube then evaporates by Hawking radiation, the parent and offspring mini-universes have lost their umbilical space-time connection.

By looking at this figure, one can instantly realize that eternal inflation transforms the universe into a huge eternally growing fractal. These are not just words: In 1987 Aryal and Vilenkin calculated fractal dimension of the universe in the new inflation scenario [35], and then, few years later, a similar calculation was performed for the eternal chaotic inflation [36].

I anticipated that the most interesting consequences of this scenario will be achieved in string theory and suggested that “an enormously large number of possible types of compactification which exist e.g. in the theories of superstrings should be considered not as a difficulty but as a virtue of these theories, since it increases the probability of the existence of mini-universes in which life of our type may appear” [17]. But time was not yet ripe for eternal inflation in string theory because we did not know how to stabilize multiple string theory vacua discussed e.g. in [37]. The emphasis shifted to other aspects of the inflationary multiverse scenario. In particular, in order to make the anthropic selection viable, it was necessary to find physical mechanisms that would allow physical parameters to take different values in the context of the same physical theory. And here inflation helped to reveal many new possibilities.

For example, it was found that in certain mechanisms of baryogenesis, the ratio  $n_b/n_\gamma$  was controlled by a light scalar field which experienced quantum fluctuations during inflation [38]. As a result, the parameter  $n_b/n_\gamma$  in this scenario may take different values in different parts of the universe [39]. But why do we live in the part of the universe where  $n_b/n_\gamma$  is extremely small? A possible answer was that the large scale structure of the universe in its parts with relatively large ratio  $n_b/n_\gamma$  would be very different, which would make emergence of life as we know it much less likely. A similar argument was used in [40] to remove the standard constraints on the

axion mass and explain the large ratio of dark matter to normal matter. Recently these ideas were revived and developed by several authors, see e.g. [41–43]. Investigation of inflationary perturbations in the Brans-Dicke theory has shown that the effective gravitational constant and the amplitude of perturbations of metric can take different values in different part of the post-inflationary universe [44]. Ref. [45] contained an explicit realization of the possibility that our world may consist of different parts with different number of large (uncompactified) dimensions. Thus it was realized that many features of our world may indeed have anthropic origin. Most of these results were summarized in 1990 in my books “Particle physics and inflationary cosmology” [46] and “Inflation and quantum cosmology” [47].

The first ten years of the journey through the multiverse were very exciting but rather lonely. Not many people were interested in this theory; almost all of my papers on inflationary multiverse have been written without any collaborators. The editor of my book [46] recommended me to delete the part on the anthropic principle, saying that otherwise I will lose respect of my colleagues. I replied that if I do it, I will lose self-respect, and eventually she agreed to keep it. It appears though that the risk was very minimal anyway, since this part was in the very end of the book, in the chapter on quantum cosmology, which was of little interest to most of the readers at that time.

In the beginning of the 90’s the situation changed dramatically. This change coincided with the all-important invention of the arXiv, which made further developments in this area easily accessible. In 1993 a detailed theory describing two different probability measures in the eternally inflating universe was proposed in a series of papers written in collaboration with Arthur Mezhlumian, Juan Garcia-Bellido and Dimitri Linde [36, 48]. In 1994 Alex Vilenkin resumed his investigation of eternal inflation. His prolific work, as well as the work of his numerous talented collaborators, invigorated the theory of inflationary multiverse, bringing to it new interesting choices of the probability measure and anthropic considerations, see e.g. [49] and his book “Many worlds in one” [50].

Then the discovery of dark energy in 1998 pushed the cosmological constant problem to the forefront of research. For many decades theorists were unsuccessfully trying to find a theory which would explain why the cosmological constant is exactly zero. Now we faced a much more complicated problem: It was necessary to explain why vacuum energy/cosmological constant is not exactly zero but is extremely small, about  $10^{-120}$  in Planck units, and why this constant is of the same order of magnitude as the (time dependent) density of normal matter at the present epoch. The only known way to address this problem without invoking incredible fine-tuning was related to the anthropic principle.

A crucial step was made in 2000 by Bousso and Polchinski [51], who proposed a string theory motivated model explaining a possible reason for an exponentially large number of vacua with different values of the cosmological constant. This could provide an anthropic solution to the cosmological constant problem. The idea was brilliant, preserving some elements of the suggestions made in [19, 27], but going much further. But at that time we still did not know how one could consistently construct any stable or metastable string theory vacua with positive vacuum energy.

Several interesting mechanisms of stabilization have been proposed, see in particular [52]. The most developed one was the so-called KKLT construction [53]. The authors proposed a way to stabilize string theory vacua, but they also found that all dS vacua in string theory are not absolutely stable but metastable, and all barriers separating these vacua can be penetrated with

finite probability. Estimates made in [54] have shown that the total number of such vacua can be as large as  $10^{500}$ . Even if one starts with the universe in one of these vacua, a combination of eternal inflation and the tunneling between these vacua should create a multiverse consisting of parts where all of these dS vacua are represented. Lenny Susskind called this scenario ‘the string theory landscape’ [55]. An incredible richness of this landscape may help us to solve the cosmological constant problem, as well as many other problems which required anthropic explanation. This perfectly matched the earlier expectations expressed in [17].

After these developments, the general attitude towards inflationary multiverse and anthropic considerations changed. Powerful efforts by Vilenkin, Susskind, Bousso, Guth, Shenker, Hall, Nomura and many others rapidly transformed this field into a vibrant and rapidly developing branch of theoretical physics. String theory underpinnings of vacuum stabilization, uplifting, inflation, and other aspects of the multiverse scenario received strong boost from works of Silverstein, Kachru, Polchinski, Kallosh and others. There is a broad agreement between different scientists about the general structure of the inflationary multiverse, and there are even some attempts to expand the concept of the multiverse from physics to mathematics [56]. But much more work is required if we want to use our new knowledge for making unambiguous scientific predictions and explaining our observations. Indeed, if eternal inflation produces infinitely many red universes and infinitely many green universes, then which of these infinite sets of universes will dominate? This is called the measure problem [36].

This problem is not specific to the multiverse, it is just a byproduct of dealing with infinities. Consider for example the usual flat or open Friedmann universe. It is infinite, and therefore it contains infinite number of planets, infinite number of cities, and infinite number of rooms. Since there are infinitely many of them, there are also infinitely many “bad” rooms where all oxygen molecules simultaneously move into a corner of the room, and everybody suffocates. The probability of this process in each particular room is incredibly small, but if one takes into account that the number of “bad” rooms is infinite, the statements about the probabilities become ambiguous. For example, one can take one “bad” room and one “normal” room, then yet another “bad” and “normal” room, continue this counting for indefinitely long time and conclude that 50% of all rooms are “bad.”

This is one of the many paradoxes which appear when one compares infinities. One way to deal with it is to follow the lead of quantum mechanics and make only those predictions that an observer can actually verify, under initial conditions that he/she should know/prepare before making predictions. This makes the subset of accessible rooms finite, and the normal expectations based on the standard laws of thermodynamics prevail.

It is too early to tell which of the proposed solutions of the measure problem will be finally accepted; for some recent reviews and proposals see e.g. [57–60]. It is important that whereas different approaches lead to slightly different constraints on the possible values of the cosmological constant, these differences do not change the main qualitative conclusion: Many parts of inflationary multiverse are expected to be in a state with a very large absolute value of the cosmological constant; we cannot live there. But there are many exponentially large parts of the multiverse with an extremely small value of the cosmological constant, compatible with our existence. That is all that we can say with reasonable certainty, and this is already quite sufficient to make the cosmological problem if not completely and unambiguously solved then at least significantly ameliorated.

Similarly, there is a strong correlation between life as we know it and the values of the

electron charge and its mass, as well as with the ratio between the mass of the proton and the mass of the neutron, and with the number of non-compactified dimensions. Therefore some of the physical parameters describing our part of the world may be environmental, specific to the part of the multiverse where we can live. Meanwhile a discovery of many deep symmetries in the theory of elementary particles suggests that relations between many other parameters may be fundamental rather than environmental. This relates our discussion to the famous statement made by Einstein in this “Autobiographical Notes” [61]:

*I would like to state a theorem which at present can not be based upon anything more than a faith in the simplicity, i.e., intelligibility, of nature: There are no arbitrary constants..., nature is so constituted that it is possible logically to lay down such strongly determined laws that within these laws only rationally completely determined constants occur (not constants, therefore, whose numerical value could be changed without destroying the theory).*

The theory of inflationary multiverse does not challenge this philosophical attitude, which is deeply rooted in the basic principles of science. But what we have found is that the total number of truly fundamental constants may be much smaller than what one could expect by studying the observable part of the universe. Sometimes what we perceive as a fundamental constant may be just an environmental parameter, which seems constant because of the effects of inflation, but which may take entirely different values in other parts of the world.

An often expressed concern about this theory is that we may not see different parts of the multiverse any time soon, and until this happens there will be no experimental evidence supporting this theory. However, I do believe that we already have strong experimental evidence in favor of the theory of the multiverse.

In order to explain it, let us take a step back to the time when the inflationary theory was invented. Its main goal was to address many problems which at that time could seem rather metaphysical: Why is our universe so big? Why is it so uniform? Why is it isotropic, why it does not rotate like our galaxy? Why parallel lines do not intersect? It took some time before we got used to the idea that the large size, flatness, isotropy and uniformity of the universe should not be dismissed as trivial facts of life. Instead of that, they should be considered as *experimental data* requiring an explanation, which was provided with the invention of inflation.

Similarly, the anomalously small value of the cosmological constant, the extreme smallness of the electron mass, the near coincidence between the proton and neutron masses, as well as the fact that we live in a 4-dimensional space, are *experimental data*, and the only presently available plausible explanation of these and many other surprising experimental results has been found within the general framework of the theory of the multiverse. And, talking about coincidences, even though possible roles of inflation and string theory in this construction have been conjectured almost 30 years ago, the way how different parts of the puzzle started falling into proper places within the context of the string theory landscape was nothing short of miraculous.

That was one of the main reasons why I decided to collect and discuss different pieces of hard to find old papers containing some early and often rather naive formulations of the future theory. Hopefully by looking at it one may either find a possibility to deviate from our original path, or understand why many of us take the admittedly incomplete progress towards the theory of the inflationary multiverse so seriously.

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