The Multiverse and Particle Physics

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Abstract

The possibility of fundamental theories with very many ground states, each with different physical parameters, changes the way that we approach the major questions of particle physics. Most importantly, it raises the possibility that these different parameters could be realized in different domains in the larger universe. In this review, I survey the motivations for the multiverse and the impact of the idea of the multiverse on the search for new physics beyond the Standard Model.

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1. THE MULTIVERSE

1.1. Sociology

One of the key science questions concerning the fundamental interactions is whether the underlying theory of nature has a unique ground state, a few possible ground states, or very many ground states. This simple question leads to the idea of the multiverse—multiple domains in the universe with different properties—as well as anthropic reasoning.

We may as well confront the issue that the multiverse and anthropics engender strong opinions among individual scientists as well as difficult questions about the process of doing science in a multiverse. A common attitude is that research on mulitverse and anthropic considerations is distasteful and not even scientific. However, at the other extreme one has to recognize that not everything that relates to the multiverse is really good science. The community is gradually trying to understand the implications of the possibility of a multiverse.

The point of view taken in this review is that it would be unscientific not to take the idea of a multiverse seriously, as it is a real physical possibility. Exploration of multiverse ideas provides new insights into the primary puzzles of fundamental physics and often changes our approach to searches for new physics. So in this regard, it is a valuable motivator of fundamental theories.

However, although we may eventually be able to test some predictions of a concrete multiverse theory, it is also true that the job of testing many aspects of such a theory is likely out of reach. We may run into a fundamental barrier to what we can know. However, the possible existence of multiverse theories is exciting and deserves more investigation.

Let us start with a situation in which reasoning similar to that of multiverse theories is accepted without controversy.

1.2. Analogy: The Earth–Sun Distance

In trying to understand the nature of the Solar System, it is natural to ask about the laws that govern the distance of the Earth and other planets from the Sun. In his *Mysterium Cosmographicum*, Kepler (1) proposed an elegant geometric explanation—that the then-known planetary orbital radii correspond to the size of the five platonic solids, inscribed in spheres and nested inside each other. The Earth would correspond to the dodecahedron, outside of the icosahedron, itself outside of the octahedron. Initial evidence was consistent with this structure, although eventually it became clear that the model does not work in detail. Despite its elegance, the model was incorrect. Should we continue to look for a fundamental law that predicts the Earth–Sun distance?

This science question can also take a personal turn. Given our understanding of chemistry and biology, we realize that life as we know it would not be possible on Earth if its distance to the Sun were significantly different. Many of the other planets appear to have physical properties that are not conducive to life. What placed the Earth at just the right distance from the Sun to sustain life?

Of course, we now understand that the Earth's distance from the Sun, and many other properties of the Solar System, cannot be directly predicted from fundamental laws. They occur as an accident of the past history of the matter that collapsed gravitationally to form the Sun and planets. There are other stars with different luminosities and other solar systems with planets that have other distances from their stars. And out of the multiplicity of all these solar systems and planets, we should not be surprised to find that we find ourselves on a viable planet. Given the conditions for the existence of life as we know it, only a subset of the many planets would be suitable, and we could only find ourselves on one of these.

In this setting, it is not a useful scientific endeavor to search for a fundamental law uniquely predicting the Earth–Sun distance. There is no such law of physics that we know of—we are not that special. However, there could be a valid scientific attempt to predict the distribution of distances of planets from their stars, based on primordial matter distributions and gravitational force laws. There will exist a more fundamental theory that describes the mechanism of planet formation, and this theory could make predictions for this distribution or "measure" in a statistical sense, given the primordial matter distribution. From our own Solar System we could obtain some constraints on this measure, although the statistics would be weak because we have only a small number of examples. If we explore other solar systems, we could potentially test the fundamental theory with more precision.

Kepler's quest to understand the planets mirrors our own attempt to understand the parameters of the Standard Model, such as quark and lepton masses and couplings. We would like a fundamental theory that rigidly predicts these parameters, preferably from some elegant construction. We also have a personal connection in that the parameters that we measure appear remarkably fine-tuned for atoms, nuclei, and life. There have been many attempts to create predictive theories for all the masses and couplings, but they have not yet been successful in detail. Should we continue to search for such a theory, one that applies universally everywhere in space-time? This is the standard assumption of particle physics and, of course, continues to be worthwhile. But perhaps the more fundamental theory allows these parameters to take on different values, and perhaps these different values can be realized differently in various domains of the universe. This would be the multiverse solution. The analogy with Kepler's quest indicates that we at least need to explore this possibility.

1.3. Conditions for a Multiverse

The Standard Model (2–5), with measured values for the parameters named above, has a unique ground state. It is found by looking for the minimum energy state of the Higgs potential. Somewhat more generally, the structure of the Standard Model could allow two ground states if the $\mu^2 H^\dagger H$ term in the Higgs potential were allowed to take on different signs. These ground states, one with an unbroken symmetry and the other with spontaneous symmetry breaking, have vastly different properties (6, 7). If one considers Grand Unified Theories with more complicated scalar potentials (8), such theories most often contain multiple ground states, again with vastly different properties. Although this consideration was enough to start multiverse thinking (9), it is not sufficient for most present discussions of the multiverse.

For the purposes of this review, I take the term multiverse to imply that there are multiple domains within the larger universe, each with different properties such as different values of the physical parameters, and perhaps even different gauge structures. These domains are contiguous, although generally domain walls would exist between them. I do not consider alternate uses of the phrase, for example, as variations of the many-worlds interpretation of quantum mechanics, which is quite a different beast. (Other reviews with a similar focus can be found in References 9–14.)

How many ground states are needed for a functioning multiverse? There must be enough states that the parameter space is populated so densely that it is likely that one or more of the states look similar to our own. As discussed in the next section, this is a reasonably tight constraint, so the original theory must possess very, very many ground states. If we include the cosmological constant (Λ) in the constraints and the parameter distribution is relatively flat, then there are at least 10^{60} ground states, perhaps more than 10^{120}. This is not for the faint of heart. It requires a qualitative change from the theories that we normally study, with at most a few ground states. However, it is a physical possibility. We most often assume that the parameter space is discrete, although it is possible for it to be continuous.

Above, I use the concept of a parameter space. The idea is that if the parameters of the theory are not uniquely determined, they will have a range of possible values. For example, the Yukawa couplings of the Standard Model range at least[1] from that of the electron with a coupling of 3×10^{-6} up to the top quark's coupling of essentially 1. Therefore, one would expect the range of each of the Yukawa couplings to be about a spread of unity on a linear scale. The gauge coupling constants in the Standard Model, at the weak scale, range at least from the QED coupling, $\alpha(M_Z) = 1/128$, up to the strong interactions, $\alpha_s(M_Z) = 0.11$. The union of all these ranges is the overall multidimensional parameter space. The total size is rather fuzzy in the absence of a specific fundamental theory. More importantly, the shape/distribution/measure of the parameter space is unknown. Are the parameters arranged evenly on a linear scale, or perhaps on a logarithmic scale, or something else? Presumably, different multiverse theories would have different measures. This is relevant for the discussion of the number of states needed. However, in order to address this question realistically we need a specific underlying theory. We are not there yet.

The other physical requirement for the multiverse is a mechanism to populate the different ground states to form a multiverse of different domains with at least a reason why our domain

[1]The observed range could be larger if the small neutrino masses come from small Yukawa couplings.

looks roughly uniform and isotropic. At present, this actually seems like the easier requirement, as long as inflation or something like it is at work in our domain. Inflation takes a small patch of the very early universe and spreads it out to a larger spatial extent than the limits of our observable universe. Inflation also allows quantum fluctuations, and potentially tunnelling events, that can populate different values of the fields.

Indeed, it was in the theory of inflation that the idea of a multiverse first arose (9). Inflation driven by a scalar field will have a multiverse character of sorts, in that some other regions of the universe will still be inflating and will inflate in different amounts. Our domain will have stopped inflating and gone through reheating, whereas others are not there yet. However, the earliest inflationary descriptions did not contain a key ingredient of what we now consider a crucial part of the multiverse—the very large number of ground states needed for the low-energy theory. Even if inflation is still taking place elsewhere in the universe, there is a separate question of whether those domains that have stopped inflating will settle down into a unique ground state or into very many possibilities. However, if the multiple ground states do exist in the fundamental theory, then inflation becomes a useful ingredient because it can easily be invoked to populate these states in different domains of the greater universe. Theorists can use inflation to create initial conditions that populate different ground states in different locations, yet allow our domain to appear smooth. For the particle physics discussion below, we simply assume that this has happened in the early universe.

2. FINE-TUNING: MOTIVATION FROM THE BOTTOM UP

After decades of hard work, we finally have a theory that describes the world around us—the Standard Model—and we understand how to use the fundamental parameters of that theory to describe the structure of that world. The Standard Model itself is a beautiful structure based on gauge symmetries. However, it has a not-so-beautiful aspect as well. To fully specify the theory, one needs to provide the values of 26 parameters—masses, mixing angles, coupling constants. These have no known symmetry and do not display any apparent logic. We expect that a more fundamental theory will give us insights into these parameters.

Given the success of the theory, we should also be able to understand what the world would look like if these parameters were modestly different. Regarding their physical values, we should be able to understand what happens under variation in the parameters.

Performing this exercise leads us to the remarkable conclusion that the modest variation of a few parameters would drastically change the world as we know it. In some cases, atoms and nuclei would no longer exist, and the universe would be sterile. Various aspects of this conclusion are discussed elsewhere (6, 7, 15–24). Cosmology provides another constraint, with the well-known argument that if Λ were much different, matter would not clump into stars and planets (25–34). We can refer to these as anthropic constraints (35). Although the word anthropic has its roots in the Greek word for human, these constraints do not refer to humanity specifically but instead to rather general physical properties of the world that we see. It takes careful science to delineate these physical constraints.

The anthropically allowed portion of parameter space appears to be a very small portion of what we would expect for the overall size of the parameter space. The world appears to be fine-tuned for atoms, nuclei, stars, complexity, and so on. What do we make of this fact? The ultimate fundamental theory could have a unique ground state that just happens to have all the right values for these parameters (i.e., good luck indeed!). Or perhaps there are many ground states with different parameters, and the universe realizes domains with these different parameters (i.e., the multiverse). In the latter case, we should not be surprised that we find ourselves in a domain with the right properties. This reasoning provides a bottom-up motivation for multiverse theories.

Here come the caveats: Perhaps there are other islands in parameter space where enough complexity is found to lead to an interesting world, perhaps even with a form of life.[2] Certainly, if the parameters were wildly different from ours, an exploration of such a situation would be much more difficult and much less reliable, and we cannot rule out the possibility of other islands of viable parameters. However, such situations do not appear to dominate the overall parameter space. This leaves the fundamental motivation unchanged. Even if some other possibilities exist, the viable neighborhood of our parameters appears to be puzzlingly small.

In addition, the structure of the world is not sensitive to all of the parameters of the Standard Model. If the top quark were modestly different, the structure of atoms and nuclei would be essentially unchanged. But for a handful of parameters (or, more realistically, combinations of parameters), it appears that the anthropic constraints apply.

Finally, it is possible to be too extreme and attempt to claim that anthropic selection is the determining factor for most of the features of our world. Given how little we understand potential theories with many ground states, the utility of this claim is not clear at present. There can also be a debate about exactly where the boundaries of the viable parameters are. This is a valid scientific discussion about the reliability of our present techniques, but in the big picture it is beside the point. In this review, I allow the estimates of the precise constraints to be somewhat rough. The important points are that such boundaries in parameter space exist and that the viable region constitutes a very small part of the overall parameter space.

2.1. Atoms and Nuclei

The complexity that we see in the world arises because we have many elements, which can be arranged in various ways. If we dig deeper into the fundamental theory, we see that having several elements relies on the fact that the up quark, the down quark, and the electron have masses that are small compared with the QCD scale, and they have a particular ordering. That the fermion masses satisfy these properties is rather strange, because the quark masses actually arise from the weak interaction, which is completely independent of QCD. They are the product of a Yukawa coupling and the Higgs vacuum expectation value (vev), and the vev is much larger than the QCD scale, $v = 246$ GeV. Roughly stated, the weak interactions must overlap with the strong interactions in order to have atomic structure.

In addition to the strong and weak interactions, electromagnetic effects play a role in determining the spectrum. A subtle dance of many features is needed in order to have the elements. Below, I discuss individual masses or couplings, initially treating them as independent variables and later recognizing that this independence may not be correct. However, this separate treatment allows us to gain at least a preliminary understanding of the constraints on the parameter space.

2.2. The Up Quark Mass

The up quark and down quark masses are some of the more obscure parameters of the Standard Model. They are small on the scale of QCD, with the Particle Data Group (36) quoting values of 2.1 MeV and 4.7 MeV, respectively, when defined at the running scale of 2 GeV. Yet they play an oversized role in the structure of our world. The near equality of the neutron and proton masses is not a fundamental symmetry of the Standard Model. Rather, it appears to be an accidental near symmetry that occurs because both of these quark masses are so small that they are a small

[2] An example of this phenomenon, with nearly degenerate Δ baryons and the proton, is given in Reference 7.

correction to the overall nucleon mass.[3] Moreover, the proton is stable because the up quark is slightly less massive than the down quark.

If the up quark and down quark masses were equal, then the proton would be heavier than the neutron and hydrogen would not be stable. The down quark is required to be heavier in order to stabilize the proton. Recent lattice calculations (37) placed the electromagnetic effect at 1.0 MeV in favor of the proton and the effect of $m_d - m_u$ at 2.4 MeV in favor of the neutron. Accepting these values implies that if the up quark mass were increased by only 1 MeV, the proton would be unstable.

If the up quark mass were even slightly larger, other changes in the elements would appear. Eventually, even bound protons would be unstable, decaying to a free neutron through electron capture. It would be a neutron world, and no atoms would exist. Using the average binding energy per nucleon of 10 MeV, and the effect of $m_d - m_u$ mentioned in the previous paragraph, one can estimate that this change would occur if the up quark were 12 MeV heavier, with all other parameters held fixed. Because quark masses run up to $m_t = 1.7 \times 10^5$ MeV, it is clear that the allowed up quark window is a tiny proportion of this range.

2.3. The Electron Mass

The atomic physics of the previous section can be adapted without much change to also constrain the electron mass. The neutron–proton mass difference is 1.29 MeV, and the electron mass is 0.511 MeV. If the electron were heavier than this 1.29 MeV, then the hydrogen atom would not be stable but instead would decay into a neutron and a neutrino. Likewise, if the mass were to increase much beyond 10 MeV, all the bound protons would combine with electrons to decay to neutral matter. Leptons have masses up to 3,500 times the electron mass. Atoms would exist only if the electron mass fell into a small part of this range.

2.4. The Fine-Structure Constant

Of the parameters of the Standard Model, the one that most likely has a good dynamical explanation is the fine-structure constant. Within Grand Unified Theories (8), if one postulates that the three gauge couplings of the Standard Model are subsets of a unified gauge coupling at high energy, then the fine-structure constant naturally comes close to the observed value. Yet within the Standard Model itself, this idea does not work exactly in practice. To make it work, new physics of a particular form[4] at relatively low energies is required in order to modify the running couplings. However, we do not have evidence for Grand Unified theories, nor (yet) of the needed low-energy physics. Therefore, we should at least consider the possibility that, like Kepler's platonic solid construction, this elegant construction is not what nature has chosen.

Electromagnetic effects by themselves would tend to make the proton heavier than the neutron. The simplest estimate would involve the energy contained in the electromagnetic field external to a charge distribution of a size $R \sim 1$ fm: $U = \frac{1}{2}\int d^3x E^2 \sim 3\alpha/5R \sim 0.88$ MeV. The electromagnetic interactions of the quark interior with the neutron and proton are more complicated but, again, favor the proton.[5] If the fundamental electric charge e were twice as large, with other

[3]The overall nucleon mass arises from the scale of QCD and is mostly independent of the quark masses.

[4]Supersymmetry at the weak scale appears to work.

[5]The electromagnetic self-energies of the quarks themselves are somewhat ill defined but also favor the up quark—and hence the proton—and are considered small.

parameters held fixed, the proton would be approximately 1.6 MeV heavier than the neutron. This estimate, again, comes from the lattice calculation referred to above (37), which sets a rough bound on the viable range, according to which the electric charge should not be more than 33% larger than its physical value if hydrogen is to be stable.

2.5. The Down Quark Mass

The considerations of the previous sections can also apply to the down quark mass. If m_d became slightly larger, by a few MeV, then deuterium would no longer be bound, as the element has a binding energy of only 2.2 MeV. This becomes a problem for nucleosynthesis (see Section 2.7, below) because the deuteron is a key step in the synthesis of the light elements. If the down quark mass became even larger, then bound neutrons would decay into free protons plus an electron and an antineutrino. The world would be one of hydrogen, with very little chance for complexity, which occurs when the down quark mass is increased by perhaps 10 MeV.

This same set of constraints arises if we try to rescale all quark masses by a common factor, for example, by increasing the value of the Higgs vev, keeping all their ratios fixed. Because $m_d/m_u > 1$, the neutron–proton mass difference eventually becomes great enough to produce this transition, which has been estimated (6, 7, 15) to occur if all the masses are increased uniformly by approximately 65%.

2.6. The Average of the Light Quark Masses

The above discussion of the neutron–proton mass difference yields constraints that apply mainly to $m_d - m_u$, so one might expect that if one held $m_d - m_u$ fixed there would be a large range for their sum. However, different physics enters to constrain the sum or average of these masses. The average $\hat{m} = (m_u + m_d)/2$ enters physics most importantly in the pion mass. Chiral physics predicts that the square of the pion mass is proportional to this quantity $m_\pi^2 \sim \hat{m}$. The vanishing of the pion mass at $\hat{m} = 0$ is a consequence of Goldstone's theorem for broken chiral symmetry in QCD. The dependence of the mass and couplings of other hadrons on $\hat{m}$ is quite small, but for the pion mass the dependence is dramatic.

The pion is the lightest hadron, and its mass most directly influences everyday physics through nuclear binding. The long-range forces in the nuclei most responsible for binding depend on pion exchange. Note that nuclear binding itself is a delicate balance. The average binding energy of 10 MeV per nucleon is very small on the typical scales of QCD, which typically are hundreds of MeV. The short-range component of the mean field interaction appears to be largely repulsive. In the central nuclear potential, the long-range attractive portion occurs in the two-pion channel. It is often modeled by the exchange of a sigma meson, and we now know that the sigma is a strongly coupled resonance of two pions. When modeled by meson exchange, both the attractive and repulsive components have a large value closer to the typical QCD scale, but the sum produces a shallow potential with a much-reduced binding energy. Single-pion exchange is relevant for the light elements, but much less so for heavy elements because it is proportional to spin and isospin quantum numbers that average closer to zero in heavy nuclei.

Increasing the pion mass reduces the long-range attractive component of the central nuclear potential. Because of the delicate balance described above, this increase can destroy nuclear binding of most elements relatively easily for even a modest mass increase. Estimates (15) using modern understanding of two-pion scattering, following earlier estimates (6, 7), indicate that if the pion mass increases even by 30% the binding of heavy nuclei disappears. Estimates made using fundamental sigma fields are somewhat weaker, but that may be because of the lack of modeling of the quark mass dependence of the fundamental sigma properties. It will be interesting to compare the parameter dependence of the analytic potential in Reference 15 with the emerging numerical calculations using lattice methods in Reference 21. Preliminary comparisons are encouraging. Overall, one can conclude that the average mass of the light quarks is also tightly constrained.

2.7. Nucleosynthesis

The above constraints have focused on the existence of atoms and nuclei. One could also consider whether the elements get synthesized in the universe. This is potentially quite a difficult study because, although we have mapped out the standard path of nucleosynthesis quite well, there could be alternate paths that also lead to a state with a sufficiently complex set of elements. However, there is no point in going overboard in this exercise. For our motivational purposes, it is again sufficient to note that fairly simple considerations of the neighborhood of our parameters indicate that our standard mechanisms for nucleosynthesis fall apart under quite modest variation in the parameters, reinforcing the sense of fine-tuning for our point in parameter space.

The most sensitive measure is the stability of the deuteron. Both the pathways of primordial nucleosynthesis and further synthesis in stars rely on deuterium as the initial step. Removing it would require alternate pathways with quite different outcomes. This idea is interesting because the deuteron is just barely bound, by 2.2 MeV, which is tiny on the QCD scale. Small changes in the quark masses readily unbind it. This is a variation of the nuclear/atomic considerations described above and simply provides a tighter constraint (6, 7, 15, 17). Even more stringent constraints can be obtained if one considers the triple-alpha process, used in the generation of the heavier elements, to be essential (19, 21).

The relative numbers of neutrons and protons produced primordially provide a constraint that differs in character from those described above. These relative numbers, which lead to relative amounts of hydrogen and helium, are determined by the strength of the weak interactions. The strength is determined mainly by the mass of the W boson or, equivalently, by the Higgs vev. If the W boson mass is too light, then neutron decay occurs rapidly and all the neutrons decay as they are falling out of thermal equilibrium, leading to a world of hydrogen only. At the other, more interesting extreme, if the W boson mass is much heavier, then the neutron and proton amounts get locked in earlier at a high temperature, where their mass difference is irrelevant. This scenario leads to an almost equal ratio of neutrons and protons, which are then processed dominantly into helium. The need for surviving hydrogen has been converted into a constraint that the W boson mass (or Higgs vev) is not more than five times the observed value (23).

2.8. Correlated Constraints

Considering the viable range of a single parameter clearly understates the available parameter space. For example, if we raise the up quark, down quark, and electron masses and keep the mass differences $m_n - m_p$ and $m_n - m_p - m_e$ unchanged, then some of the constraints listed above no longer apply, so the available parameter space is enlarged. However, eventually we would run into a boundary due to the average of the up and down quark masses. In addition, we do not even know which parameter to vary. Is the Higgs vev, which changes the quark and lepton masses and the W boson mass in parallel, the most important variable? Or should all the fundamental parameters of the Standard Model vary independently? One can try looking for extreme situations that leave the essential physics unchanged (38, 39). These are some of the caveats for the exercise described above.

However, the generic conclusions remain unchanged. There are relatively tight constraints on certain combinations of parameters, and small changes in these combinations lead to major changes in the structure of the world. Briefly, the weak interactions must overlap with the strong interactions. The light quarks and the electron masses are the product of the Higgs sector of the Standard Model and are constrained to be in a small window far below the QCD scale. By contrast, the W boson mass is larger than the QCD scale, which is relevant for nucleosynthesis. The allowed parameter space appears to be very small, and the world as we know it seems highly fine-tuned for the existence of atoms and nuclei.

I have devoted this much space to describing the atomic constraints because they provide a unique form of motivation for multiverse theories. One has to see the many constraints in order to appreciate just how little parameter space is available that leads to atomic structure. Moreover, there seems to be no possibility of a dynamical mechanism to generate parameters in this small window. Unlike Λ or the Higgs vev, for which dynamical mechanisms are at least sought to explain their small values, even theories attempting to describe the Yukawa couplings would simply have to be lucky to have the outcome fall in exactly the right window to explain atoms and nuclei.

2.9. The Universe and the Cosmological Constant

The best-known anthropic constraint is that of the cosmological constant, Λ (25–27, 35). Here the physical constraint is on the gravitational clumping of matter into stars and planets. If Λ is positive and too large, the universe expands so fast that clumping does not occur. If it is negative and too large, the universe will have collapsed before clumping occurs. Although, again, the boundaries of the allowed region are not exceptionally precise, it appears that Λ should be within two orders of magnitude of its observed value[6]—and perhaps is even more tightly constrained.

This constraint is exceptionally tight. Λ is the energy density of the ground state of the theory. The observed value is $\Lambda_0 = 2.4 \times 10^{-47}\ \mathrm{GeV}^4 = (2 \times 10^{-3}\ \mathrm{eV})^4$. There are very many contributions to the vacuum energy. However, all are expected to carry energy scales that are much larger than $(10^{-3}\ \mathrm{eV})^4$. Zero-point energies of quantized fields are formally divergent but hopefully either cancel or are made finite at some high energy. The Higgs potential carries energy densities of order $10^{51}\Lambda_0$. The strong interactions bring in contributions of order $10^{47}\Lambda_0$. Many of these contributions are difficult to calculate precisely, but their order of magnitude should be correct. One needs to have all such contributions cancel to at least 50 or so orders of magnitude.

I would like to explain in some detail one contribution to Λ that can be calculated with great reliability. It has not been described in the literature before to the best of my knowledge.[7] It is also a good illustration of how difficult it would be to adjust the parameters of the Standard Model to bring Λ in line. We need to specify the forty-first digit of the up quark mass if we are trying to adjust the parameters to provide the correct Λ.

The contribution comes from the shift in the vacuum energy caused by the explicit breaking of chiral symmetry, and the reliability of the calculation comes from the use of symmetry in chiral perturbation theory (2, 40). Consider two-flavor QCD without the up and down quark masses, but with external scalar and pseudoscalar currents $s(x)$ and $p(x)$:

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \bar{\psi} i \not{D}\psi - \psi_L(s + ip)\psi_R - \bar{\psi}_R(s - ip)\psi_L, \qquad 1.$$

where ψ is an $SU(2)$ doublet field of the up and down quarks. This system has an exact $SU(2)_L \times SU(2)_R$ chiral symmetry,

$$\psi_L \to L\psi_L \qquad \psi_R \to R\psi_R \qquad (s + ip) \to L(s + ip)R^\dagger, \qquad 2.$$

[6]The constraints on Λ are also correlated with the amplitude of cosmological density fluctuations (28).

[7]However, it does appear as an exercise in Reference 2.

where L is an element of $SU(2)_L$ and R is an element of $SU(2)_R$. This version of massless QCD undergoes dynamical symmetry breaking, with pions being the Goldstone bosons. The resulting low-energy effective Lagrangian for the pion manifests the $SU(2)_L \times SU(2)_R$ symmetry and can be expanded in an energy expansion. At lowest order, the result is the effective Lagrangian [in conventional notation (40)]

$$\mathcal{L}_2 = \frac{F_\pi^2}{4}\left[\mathrm{Tr}\left(\partial_\mu U\, \partial^\mu U^\dagger\right) + \mathrm{Tr}\left(\chi U^\dagger + U\chi^\dagger\right)\right], \tag{3}$$

where the 2×2 matrix U contains the pion fields π^i (with $i = 1, 2,$ or 3):

$$U = \exp i\,\frac{\tau \cdot \pi(x)}{F_\pi}. \tag{4}$$

Here τ^i are Pauli matrices, and the external sources are contained in $\chi = 2B_0(s + ip)$, where B_0 is a constant of dimension (mass)^1 and F_π is the pion decay constant (92 MeV). This Lagrangian displays the exact chiral symmetry

$$U \to LUR^\dagger \qquad (s + ip) \to L(s + ip)R^\dagger. \tag{5}$$

For more on the construction of effective chiral Lagrangians, see Reference 2.

Real QCD, including quark masses, is obtained by replacing the external fields by the quark mass matrix,

$$s = \begin{bmatrix} m_u & 0 \\ 0 & m_d \end{bmatrix}, \qquad p = 0.$$

In this case, the pions pick up a small mass,

$$m_\pi^2 = B_0(m_u + m_d), \tag{6}$$

which is found by expanding the Lagrangian to second order in the pion field. However, for our purposes the effective Lagrangian also yields a contribution to the vacuum energy of the form

$$\Lambda_m = -\langle 0|\mathcal{L}_2|0\rangle = -F_\pi^2 B_0(m_u + m_d) = -F_\pi^2 m_\pi^2. \tag{7}$$

This relation can also be obtained without the construction of the effective Lagrangian by using first-order perturbation theory and the soft pion theorem (2):

$$\Lambda_m = \langle 0|m_u\bar{\psi}_u\psi_u + m_d\bar{\psi}_d\psi_d|0\rangle = -F_\pi^2\langle \pi|m_u\bar{\psi}_u\psi_u + m_d\bar{\psi}_d\psi_d|\pi\rangle = -F_\pi^2 m_\pi^2. \tag{8}$$

However, I have used the effective Lagrangian approach because it makes clear that there is no possible compensating term that is linear in the the quark masses.[8]

This contribution to the vacuum energy is precisely known:

$$\Lambda_m = 1.5 \times 10^8\,\mathrm{MeV}^4 = 0.63 \times 10^{43}\,\Lambda_0. \tag{9}$$

If we consider a situation where the quark mass parameters are slightly different, this contribution would be expressed as

$$\Lambda_m = 0.63 \times 10^{43}\,\Lambda_0 \frac{(m_u + m_d)}{(m_u + m_d)_{\mathrm{phys}}}. \tag{10}$$

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[8]The first unknown contribution comes at second order with a Lagrangian of the form $\mathrm{Tr}(\chi\chi^\dagger)$, which contributes to the vacuum energy but not to the phenomenology of pions (40). However, second-order contributions are much smaller and have a different functional dependence on the masses.

Because of the large multiplier, if one holds all the other parameters of the Standard Model fixed, a change of the up quark mass in its forty-first digit would produce a change in Λ outside the anthropically allowed range. Of course, this should not be treated as a real bound on the up quark mass variation, because small changes in other parameters could compensate for this shift in Λ. There are too many parameters that also contribute enormously to Λ that could have potentially correlated variations keeping Λ fixed. However, because the calculation is so well controlled, it illustrates the degree of fine-tuning required as well as the futility of thinking that some feature of the Standard Model could lead to a vanishing contribution to Λ.

Space considerations preclude a full discussion of other ties between physical properties and anthropic constraints, including neutrinos (41), dark matter (42–45), and even the dimension of space-time (46). Unlike most of the discussion above, where a well-defined theory—the Standard Model—underlies the discussion of the variation of parameters, the fundamental theory for these latter considerations is not known, so the usefulness of these constraints is less clear.

3. NATURALNESS VERSUS THE MULTIVERSE AND THE FINE-TUNING PROBLEMS OF PARTICLE PHYSICS

In particle physics, the term fine-tuning generally has a different meaning from that used in the previous section, where I note that only a small range of parameter space is compatible with atoms, nuclei, stars, and so on. This is fine-tuning of parameters in order to allow a set of physical properties. However, in particle physics, fine-tuning is more commonly used to describe the situation where a parameter is observed to be much smaller than its expected "natural" size (47, 48). The three fine-tuning problems in this sense are the Λ problem, the Higgs vev problem, and the strong-*CP* problem. Of course, the two meanings of fine-tuning can overlap, as they do in the first and second of these problems. That overlap is the source of much interest in the multiverse.

The conventional response to perceived fine-tuning is to look for a physical mechanism to make this occurrence technically natural. Naturalness implies that the various contributions to a parameter, both classical and through quantum radiative corrections, are of the same order of magnitude so that no delicate cancellations are present. For example, a classical contribution to Λ comes from the minimum energy of the Higgs potential being treated as a bare parameter, and quantum effects could be zero-point energies or radiative corrections, among other effects. Although logarithmic divergences in radiative corrections are technically infinite, these are not viewed as barriers to naturalness because, with any reasonable cutoff, the logarithm is not very large.

The ideas of both naturalness and the multiverse do not constitute theories in themselves but rather serve as motivations for new theories. Using naturalness as a motivation, one requires new particles and interactions beyond the Standard Model that make the full theory technically natural. Although Λ is the greatest problem for naturalness, the focus at present is on the Higgs vev problem because naturalness predicts that new physics will be discovered at the LHC. In contrast, using the multiverse as a motivation, one requires the development of models with a great number of ground states in order to allow the fine-tuning to be understood as a selection effect. If one has enough ground states, neither Λ nor the Higgs vev is considered a problem, although the strong-*CP* problem remains.

3.1. The Cosmological Constant

The idea of naturalness appears to fail for Λ. Applied to Λ, naturalness would imply new particles and interactions at the scale of 10^{-3} eV. Although such a model has been proposed (49), to the best of our knowledge nature does not take this path, and technical naturalness fails. In the opinion of many, the multiverse remains the best available explanation for the Λ problem.

3.2. The Higgs Vacuum Expectation Value

As yet there is no consensus on natural theories for the Higgs vev. There are potentially two naturalness problems for the weak scale. One focuses on the quadratic divergences in the Higgs vev that occur when the Standard Model is treated in isolation. When quadratic divergences are treated with a cutoff, they quickly become very large as the cutoff is raised, and one requires large fine-tuning to compensate. This requirement has been used to argue against theories with quadratic divergences, such as the Standard Model, as fundamental theories in isolation.[9] This naturalness problem requires new physics at the TeV scale so that the known cutoff dependence does not become too large.

The second version of the naturalness problem (or the fine-tuning problem) arises when the Standard Model particles also participate in other interactions with a larger fundamental scale, for example, Grand Unified Theories. In this case, radiative corrections with the new interactions tend to bring that larger scale into the Higgs potential, raising the Higgs vev to a larger scale. It is not only divergent effects that are at issue here; even finite quantum corrections could require large fine-tuning. Again, some forms of new physics at the TeV scale could solve this problem. As of early 2016, the LHC has not found evidence of such new physics, even though it has pushed significantly into the energy range where it should occur. However, further experiments continue to push deeper into the realm of possible new physics, and we eagerly await the results.

Agrawal et al. (6, 7) were the first to point out that the multiverse and anthropic selection of atoms could account for the Higgs vev. In these papers (6, 7), for simplicity all parameters except the vev were held fixed, so the quark mass ratios were treated as constants, yielding a particular slice through the atomic constraints. Clearly, this assumption can be relaxed, and subsequent research has done so (15, 54, 55). Anthropic selection of the overall weak scale remains a possibility. As with the Λ problem, this option will undoubtedly attract further interest if more conventionally natural solutions are not uncovered.

3.3. The Strong-*CP* Problem

The multiverse idea fails to resolve the strong-*CP* problem (56–58). Stated more positively, it implies that this is the only one of the three big naturalness problems for which a dynamical explanation is required. The strong-*CP* problem refers to the *CP*- and *T*-violating term proportional to $\theta\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}$ that can be included in the QCD action. Because *CP* is violated in the Standard Model, there is no good reason to set θ to zero, and the effect of θ has an additive contribution, expected to be of order unity, from the phases in the Yukawa couplings that generate other forms of *CP* violation. Yet experiments on the neutron's electric dipole moment require the coefficient of this effect to be smaller than 10^{-10}. If θ were many orders of magnitude larger, there would not be any significant change in the structure of the world. Thus, the multiverse cannot be used to invoke anthropic selection, and leaves this problem for a dynamical explanation. There is in fact a good dynamical explanation involving the Peccei–Quinn symmetry (59) and the axion (60, 61). Both naturalness and the multiverse serve as motivations for searches for the axion.

3.4. An Axion Multiverse

It is worth noting that if the axion is indeed the solution to the strong-*CP* problem, the multiverse idea may enter quite naturally in a slightly different way (62–64). In the standard picture of the early

[9]This version of fine-tuning has been challenged (50–53) as being incorrect, and there may be some merit to these arguments.

universe, the initial value of the axion field is not fixed but rather would be randomized by quantum and/or thermal fluctuations. In the presence of inflation, the regions of different initial values would be inflated such that different initial patches would become causally disconnected domains at late times. We would live in one of these places, but other places in the greater multiverse would have different initial axion values. Because the initial value of the axion determines the extent to which the axion contributes to dark matter, the different domains would also have different amounts of dark matter. This realization also plays a role in axion phenomenology. Naturalness has been used to rule out axion theories with a large value of the axion decay constant because, in this case, a random initial value of the axion would lead to too much dark matter. However, because too much dark matter can also have a negative effect on the evolution of the universe, there is an anthropic selection of the possible domains that allows an anthropic window with a large decay constant (62–64).

The axion multiverse shows that multiverse behavior can occur even with completely conventional physics. Here we are not talking about hypothetical string vacua, but rather a very standard new particle. If axions with the right properties are the source of dark matter, then the amount of dark matter is an accident of the history of our particular patch of the universe, and attempts to predict this quantity are no more useful than attempts to predict the radius of the Earth's orbit. The axion is also an interesting example of how the multiverse could arise from a continuous variation in the properties of the universe.

4. PHYSICAL MECHANISMS: MODELS FROM THE TOP DOWN

The multiverse idea would have little relevance unless there were physical theories that potentially lead to it. As mentioned in Section 1, the most challenging ingredient is the requirement of multiple ground states. Sociologically, the multiverse idea got a major boost when string theory was argued to have this property. However, even string theory cannot yet be counted as a complete model, because we do not have enough control over the theory to make even statistical predictions.

4.1. Many States

It was originally argued that string theory would have a unique ground state and that this would be the signal that it was the correct theory. It would indeed be impressive if such a unique state were identified and all of the masses of the up quark, the down quark, and so on agreed with experiment. However, it is looking less likely that this will occur. The number of string ground states seems enormous (65–69)—some counts estimate 10^{500}—and we do not have a principle to select a unique one out of the multitude. The string ground states are described not only by the way that the extra dimensions are compactified in order to leave our four dimensions, but also by the way that the field components are arranged within these internal spaces. Spaces with different amounts of flux wrapped around the internal dimensions have different low-energy properties.

An interesting feature to keep in mind is that changing one of the fluxes by one unit can be a large change in the properties. There can be a near continuum of values of the parameters not because each of the flux quanta is each individually small, but rather because there are so many ways to combine the fluxes that one saturates almost every possible result (68).

It is not only in string theory that one can obtain multiple ground states. For example, an old suggestion related to Λ (70, 71) invokes the possibility of three-form potentials $A_{\alpha\beta\gamma}$ with four-form field strengths $F_{\alpha\beta\gamma\delta}$. In four dimensions, the four-form Lagrangian $F_{\alpha\beta\gamma\delta}F^{\alpha\beta\gamma\delta}$ leads to equations of motion that fix the field strength to be a constant but can take on different quantized values (and tunnel between such values) if coupled to a charge. The four-form action, then, is an extra positive contribution to Λ that, in principle, can take on arbitrary values. The use of higher-dimensional operators with the four-form coupled to other fields can also change other particle properties and couplings.

In addition, for the case in which there are large numbers of fields, Dvali & Vilenkin (72, 73) have identified field theoretic ways to have large number of vacua. These mechanisms, put forward both in References 70 and 71 and in References 72 and 73, also illustrate a caveat to theories with many vacua. Both also have dynamical mechanisms at work that populate preferentially some states over others, depending either on the past history of our domain or on the density of states of the vacua.

The axion example described above also illustrates the possibility of a continuous variation of the parameters across the universe. In the axion case, the initial value of the axion is really a continuous field variation in the early universe. Our patch of the universe is then taken from a very small segment of this field and inflated so much that it looks uniform across the sky today. Because the initial axion field value determines the amount of dark matter that we see, other elements of the greater universe outside of our local patch would see a continuous variation of the abundance of dark matter. If desired, this mechanism could be applied to other properties as well. However, the axion example also illustrates an extra feature of models with continuous variation of the parameters—a light field will be associated with such variation. If a parameter has spatial or temporal variation, then it is a field. For the spatial variation to span a large region of space, that field must be light. However, such light fields can potentially evade present attempts at detection, as indeed the axion has done so far.

Therefore, there is considerable room for model building of theories with multiple ground states. This has not been a priority for the community, which has probably been a wise choice. However, it is useful to recognize that multiple ground states are a physical possibility and that landscapes can exist outside of string theory.

4.2. Populating the Multiverse

We also need to know that there is a mechanism for populating the different vacua in different regions of the universe. Because this process would occur in the very early universe—before or during inflation—we can let our imaginations run wild and be confident that some such mechanism can always be found. Nevertheless, some mechanisms are already known (56, 68, 70, 71, 74–77). At high temperatures, all states would get populated, and causally disconnected regions would settle in different ground states. Tunneling between different discrete ground states has been explored using the four-form field strengths (70, 71), which can be adapted to string vacua (56, 68). In the initial four-form problem, the step size for the changes in Λ are treated as very small by taking the associated charge to be very tiny. However, in the string vacua case, the step sizes for any changes would be expected to be large, as one is breaking a flux factor in a highly compact internal dimension. With enough inflation (generically eternal), however, all the different ground states will be sampled.

5. TESTING THE MULTIVERSE

Now comes the weakest part of this review. There are several problems. We do not have a concrete multiverse theory with which we can make predictions. The existence of distant spatially separated domains is likely not directly testable, because they are likely causally disconnected from us. The general nature of a multiverse theory makes it hard to make specific predictions because the parameters of the theory are by definition not uniquely fixed.

In general, we do not have to test every prediction of a given theory. For example, in the Standard Model, it is unlikely that we will ever be able to test the dramatic prediction that the baryon anomaly predicts that the proton is not stable, because the predicted lifetime is approximately 10^{130} years. Nevertheless, for a given theory there must be sufficient predictions that are tested so that we can trust it in its expected range of validity. The Standard Model has passed such tests. The multiverse will have difficulty here.

It is possible that the parameters of the Standard Model could still provide a test of an underlying theory, although that test would likely be statistical in nature. For example, we have six quark masses, three charged lepton masses, two neutrino mass differences, and the weak mixing angles of the quarks and leptons. All of these come from the Yukawa couplings of the theory. In a multiverse theory, we should not expect these couplings to be uniquely predicted. However, the underlying theory would presumably tell us how they are distributed—that is, their measure. Are the masses in the theory uniformly distributed on a linear scale, or perhaps on a logarithmic scale? The distribution of Yukawa couplings would also influence the size of the weak mixing angles, which arise from diagonalizing the original Yukawa matrices.

The experimental measure of the quark and charged lepton masses turns out to be rather striking (54, 78, 79). If we treat all masses as independent, they appear to have a scale-invariant distribution. That is, they are randomly distributed on a logarithmic scale. Quantitatively, if we propose that the weighting of the distribution is dm/m^{δ}, then the fit value of the exponent is $\delta = 1.02 \pm 0.08$, where $\delta = 1$ corresponds to a scale-invariant measure. The exponent is relatively well determined despite the small number of masses, and the quality of the fit is excellent. The scale-invariant distribution also naturally leads to a hierarchy of the quark mixing angles. The neutrino masses are considerably lighter and would not fit this pattern well if they were generated in an identical fashion. However, even in more standard settings the light masses are generally treated as evidence of other mechanisms of mass generation at work, such as the seesaw mechanism (80). Explorations of this possibility indicate that, even in the neutrinos, it is plausible that randomness generates the masses and mixing angles (79, 81).

Of course, there are caveats. The complete independence of the Yukawa couplings would not naturally account for the generation structure of the weak doublets. In addition, the anthropic constraints on the up quark, down quark, and electron are not accounted for.[10] To fully address these and other caveats, one needs a complete controllable underlying multiverse theory with multiple ground states. This theory would allow one to address, from the top down, the correlations between the parameters that appear in the solutions.

Nevertheless, it is clear from the preliminary investigation of the measure for masses that there will be a statistical test of an underlying theory. It may have a somewhat different form than that of the independent mass hypothesis above, but the statistical power is present to allow a discrimination of theories. If that theory predicted a flat distribution of masses on a linear scale, it would clearly be incorrect. Thus, at least in this statistical sense, it would be possible to falsify a given multiverse theory.

In a particular variant of string phenomenology, it is possible to connect the observed Yukawa couplings back to aspects of string theory. In brane-world realizations (82–84), the Yukawa couplings (y) arise from nonperturbative effects that contain an exponential dependence on the area (A) of overlap of different branes:

$$y \sim e^{-cA}. \qquad 11.$$

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[10]However, simply removing the up quark, down quark, and electron from the fit still leaves the scale-invariant form preferred, although with a larger uncertainty.

With this relation, the scale-invariant distribution of Yukawa couplings corresponds to a flat distribution of areas (i.e., random on a linear scale). If this flat distribution could be derived in the brane-world scenario, it would pass the Yukawa measure test.

Other suggestions for tests have also been put forth. For example, one could find evidence of different domains by observing the cosmic microwave background (CMB) (85, 86). If the amount of inflation is just small enough to barely separate the domains, then the domain walls could be visible in the temperature fluctuations. If this occurred, it would be a very dramatic and direct piece of evidence of other domains. However, it is not a necessary consequence of a multiverse. Most inflationary pictures produce more inflation that that, and the domain boundaries would be far removed from the CMB surface of last scatter. It would take luck to have just enough inflation to allow this effect to be visible.

If the variation of parameters is continuous rather than discrete, there could potentially be an observation of a spatial variation across the observed universe (87–91). Such variations are being searched for independently of this motivation, but they become even more interesting because of it.

It likely that Λ would be the most sensitive parameter (92) because of the large cancellation that appears to be needed to get the small Λ. As described above, a variation of the up quark mass of one part in 10^{43} would lead to an enormous variation of Λ across the sky. The most sensitive tests appear to be the parameters of the CMB temperature fluctuations, which constitute the longest lever arm for experimental observations of spatial variations. Although an unexpected directional dependence in the power is observed in the data, it does not appear to be due to a dipole in the fit parameters describing the relative contributions of the fundamental parameters (93).

The multiverse also motivates new classes of theories that themselves could be tested more directly. An example is the idea of split supersymmetry (94–96). In a supersymmetric theory with the possibility of variable masses, if one wants to keep the Higgs vev light for atomic selection, it might be advantageous for certain extra supersymmetric particles to be light as well. Other supersymmetric particles could then still be heavy. (An analogy is in the quark masses—there is an anthropic selection for the up and down quarks to be light, but the top and bottom quarks can be heavier because there is no selection for them.) This idea is directly testable at the LHC, as it predicts that some supersymmetric particles would be found there but others not.

This is probably also the appropriate place to mention the contentious issue of developing a measure for the multiverse in the context of inflation (97–101). This is an attempt to assess how likely our patch of the universe could be in a universe that has other patches that continue to inflate. This issue is surprisingly subtle, as the definition of probabilities depends on whether one averages over volumes at one time slice or follows back world-lines to earlier times. From the view of particle physics, a solution is not crucial for discussing what happens in our patch, as long as such patches exist. However, the inflationary measure problem is of conceptual interest for the development of a more complete multiverse theory.

6. SUMMARY

Given the physical possibility of theories with very many ground states, one of the great questions becomes, "Universe or multiverse?"[11] Does the fundamental theory have a single ground state leading to our world, or does it have many possible ground states of which we find ourselves in a domain with favorable parameters?

[11]Note also that a book by this name (10) exists and provides the curious reader with much more to think about.

The existence of fine-tuning for stars, atoms, and nuclei favors the multiverse option. We do not appear to live at a random point in parameter space, but rather at a special one that allows these features. One may judge for oneself how likely this good luck would have to be in order for a theory with a unique ground state to have parameters in the neighborhood of our special point.[12] In particular, the exponential fine-tuning needed for Λ seems to have no technically natural explanation and is a strong motivation for a multiverse explanation.

It does seem that multiple ground states are a physical possibility. However, we have no complete theory that allows us to make even statistical predictions.

The paucity of experimental tests does not mean that multiverse theories are wrong. It would be unscientific to exclude theories with multiple ground states from consideration—they could be correct. However, it does mean that we need to be more modest in what we can expect from the study of the fundamental interactions. There may be questions that we cannot possibly answer about the origin of our theories. In the meantime, there are still great problems to address about the structure of nature, such as the form of dark matter, the mechanism of baryogenesis, and the combination of quantum mechanics with general relativity. Perhaps a satisfying unique theory with all the right properties will emerge, and we will be content to forget about the multiverse. But we have to recognize that we may not be able to construct such a completely satisfying theory.

Even more-conventional theories may have have insurmountable obstacles to complete testing of the theory. Physics is an experimental science, and there are sociological limitations to pushing exploration to ever-higher energies. Full exploration of the Planck scale may never be possible, and the best that we may hope for is an occasional and limited test sensitive to all the rich physics that we expect at that scale. Multiverse theories may have different obstacles. The inherent limitations of testing multiverse theories will prove to be a barrier to full knowledge of the origin of the fundamental interactions if this is the solution that nature has chosen.

However, as always, more research is needed. Our exploration of either conventional theories or multiverse theories is far from complete. It is also possible that a very satisfying multiverse theory will be developed that will explain connections between the different aspects of the world that we presently do not understand. In the meantime, both naturalness and the multiverse can play the role of motivations for new theories. In the case of naturalness, Λ and the Higgs vev are the greatest puzzles. We have developed a large range of theories to solve the naturalness puzzles of the Higgs vev and are actively testing them at the LHC. Using the multiverse as motivation points not toward these but rather to the strong-*CP* problem as the greatest puzzle requiring a dynamical solution. Searches for the axion as the solution to this puzzle are also under way.

In Voltaire's philosophical fable *Candide, ou l'Optimisme* (102), the title character and Pangloss, the professor of "metaphysico-theologo-cosmolonigology," debate the question of whether this is the "best of all possible worlds." After examining the evil in the world, they give a negative assessment, then retire to "cultivate their garden." Perhaps we have the physically equivalent question. We have seen that we are close to the best in terms of atoms, nuclei, and stars, and we have suggested that there could be other worlds. Our evidence is not yet clear. Yet the second part of Voltaire's title—*l'Optimisme*—should still apply. We are in the early days of investigations of such theories, and perhaps if we cultivate them some fruit will come. Although we may run into barriers, it is still time to be optimistic and see where these theories lead.

[12] Browsing the Internet on this topic will also reveal claims that fine-tuning reveals evidence of deistic design, although this is not a scientific response. However, even that would not resolve the issue. Even the theologically inclined would need to question whether the creator designed a rigid structure with only one option or a flexible one where the natural evolution would lead to life somewhere in the multiverse. There is a science question here.

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