

# Scientific alternatives to the anthropic principle

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## Abstract

It is explained in detail why the Anthropic Principle (AP) cannot yield any falsifiable predictions, and therefore cannot be a part of science. Cases which have been claimed as successful predictions from the AP are shown to be not that. Either they are uncontroversial applications of selection principles in one universe (as in Dicke's argument), or the predictions made do not actually logically depend on any assumption about life or intelligence, but instead depend only on arguments from observed facts (as in the case of arguments by Hoyle and Weinberg). The Principle of Mediocrity is also examined and shown to be unreliable, as arguments for factually true conclusions can easily be modified to lead to false conclusions by reasonable changes in the specification of the ensemble in which we are assumed to be typical.

We show however that it is still possible to make falsifiable predictions from theories of multiverses, if the ensemble predicted has certain properties specified here. An example of such a falsifiable multiverse theory is cosmological natural selection. It is reviewed here and it is argued that the theory remains unfalsified. But it is very vulnerable to falsification by current observations, which shows that it is a scientific theory.

The consequences for recent discussions of the AP in the context of string theory are discussed.

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# 1 Introduction

I have chosen a deliberately provocative title, in order to communicate a sense of frustration I've felt for many years about how otherwise sensible people, some of whom are among the scientists I most respect and admire, espouse an approach to cosmological problems that is easily seen to be unscientific. I am referring of course to the anthropic principle. By calling it unscientific I mean something very specific, which is that it fails to have a necessary property to be considered a scientific hypothesis. This is that it be *falsifiable*. According to Popper[1], a theory is falsifiable if one can derive from it unambiguous predictions for doable experiments such that, were contrary results seen, at least one premise of the theory would have been proven not to apply to nature.

Having started boldly, I will put the outlines of my argument on the table in a few paragraphs here. The purpose of this essay is then to develop the points in detail.

While the notion of falsifiability has been challenged and qualified by philosophers since Popper, such as Kuhn, Feyerabend and others<sup>1</sup>, it remains the case that few philosophers of science, and few working scientists, would be able to take seriously a proposal for a fundamental theory of physics that had no possibility of being disproved by a doable experiment.

This point is so basic to how science works that it is perhaps worthwhile taking a moment to review the rationale for it. Few working scientists will disagree that an approach can be considered "scientific" only to the extent that it requires experts who are initially in disagreement about the status of a theory to resolve their disagreements-to the fullest extent possible- by rational argument from common evidence. As Popper emphasizes, science is the only approach to knowledge whose historical record shows over and over again that consensus was reached among well trained people as a result of rational argument from the evidence. But-and this is Popper's key point- this has only been possible because proposed theories have been required to be falsifiable. The reason is that the situation is asymmetric: confirmation of a prediction of theory does not show that the theory is true, but falsification of a prediction can show it is false.

If a theory is not falsifiable, there is the very real possibility that experts may find themselves in permanent disagreement about it, with no possibility that they may resolve their disagreement rationally by consideration of evidence. The point is that to be part of science, *X*-theorists have to do more than convince other *X*-theorists that *X*-theory is true. They have to convince all the other well trained scientists who up till now have been skeptical. If they don't aspire to do this, by rational arguments from the evidence, then by Popper's definition, they are not doing science. Hence, to prevent the progress of science from grounding to a halt, which is to say to preserve what makes science generally successful, scientists have an ethical imperative to consider only falsifiable theories as possible explanations of natural phenomena.

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<sup>1</sup>I will not discuss here the history and present status of the notion of falsifiability, my own views on the methodology of science are discussed elsewhere[5].

There are several versions of the anthropic principle[2, 3, 4]<sup>2</sup>. There is of course the explicitly theological version, which is by definition outside of science. I have no reason to quarrel with that here. I also have no argument against straightforward consideration of selection effects, so long as the conditions invoked are known independently and not part of a speculative theory that is otherwise unsupported by any evidence. I will discuss this in some detail below, but the short version is that there simply is a vast logical difference between taking into account a known fact, such as the fact that most of the galaxy is empty space, and arguing from a speculative and unproven premise, such as that there is a large ensemble of unseen universes.

In recent discussions, the version of the anthropic principle that is usually put forward by its proponents as a scientific idea is based on two premises.

- **A** There exists (in the same sense that our chairs, tables and our universe exists) a very large ensemble of “universes”,  $\mathcal{M}$  which are completely or almost completely causally disjoint regions of spacetime, within which the parameters of the standard models of physics and cosmology differ. To the extent that they are causally disjoint, we have no ability to make observations in other universe than our own. The parameters of the standard models of particle physics and cosmology vary over the ensemble of universes.
- **B** The distribution of parameters in  $\mathcal{M}$  is random (in some measure) and the parameters that govern our universe are rare.

This is the form of the Anthropic Principle most invoked in discussions related to inflationary cosmology and string theory, and it is the one I will critique here.

Here is the basic argument why a theory based on **A** and **B** is not falsifiable. If it at all applies to nature, it follows that our universe is a member of the ensemble  $\mathcal{M}$ . Thus, we can assume that *whatever properties our universe is known to have, or is discovered to have in the future, it remains true that there is at least one member of  $\mathcal{M}$  that has those properties. Therefore, no experiment, present or future, could contradict **A** and **B**.* Moreover, since, by **B**, we already assume that there are properties of our universe that are improbable in  $\mathcal{M}$ , it is impossible to make even a statistical prediction that, were it not borne out, would contradict **A** and **B**.

There are a number of claims in the literature of predictions made from **A** and **B**. By the logic just outlined, these must all be spurious. In section 5 below I will examine the major claims of this kind and demonstrate that they are fallacious. This does not mean that the conclusions are wrong. As we shall see, there are cases in which the part of the argument that is logically related to the conclusion has nothing to do with **A** and **B** but instead relies only on observed facts about the universe. In these cases, the only parts of the argument that are wrong are the parts that fallaciously attribute the conclusion to a version of the Anthropic Principle.

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<sup>2</sup>My understanding of the logical status of the different versions of the Anthropic Principle was much improved by [6].

But what if **A** is true? Will it be possible to do science in such a universe? Given what was just said, it is easy to see how a theory could be constructed so as to still be falsifiable. To do this **B** must be replaced by

- **B'** It is possible nevertheless, to posit a mechanism,  $\mathcal{X}$  by which the ensemble  $\mathcal{M}$  was constructed, on the basis of which one can show that almost every universe in  $\mathcal{M}$  has a property  $\mathcal{W}$ , which has the following characteristics<sup>3</sup>:
  1.  $\mathcal{W}$  does not follow from any known law of nature or observation, so it is consistent with everything we know that  $\mathcal{W}$  could be false in our universe.
  2.  $\mathcal{P}$  There is a doable experiment that could show that  $\mathcal{W}$  is not true in our universe.

If these conditions are satisfied then an observation that  $\mathcal{W}$  is false in our universe disproves **A** and **B'**. Since, by assumption, the experiment is doable, the theory based on these postulates is falsifiable.

Note that what would be falsified is only the specific **B'** dependent on a particular mechanism  $\mathcal{X}$ . Since  $\mathcal{X}$  by generating the ensemble, will imply **A**, what is falsifiable is in fact the postulate that the mechanism  $\mathcal{X}$  acts in nature. Conversely, a mechanism that generates a random ensemble, as described by **B** rather than **B'** cannot be falsified, as I will demonstrate in some detail below.

Someone might argue that it is logically possible that **A** and **B** are true and that, if so, this would be bad only for those of us who insist on doing science the old fashion way. If an otherwise attractive theory points in a direction of **A** and **B** then we should simply accept this and abandon what may be outmoded ideas about "how science works".

If this is the case then it will always be true that basic questions about the universe cannot be answered by any scientific theory (that is by a theory that could be rationally argued, based on shared evidence to be true). But the fact that is a possibility does not mean we should worry unduly about it turning out to be true. This is not the only hypothesis about the world that, if true, means that science must remain forever incomplete.

Similarly, there are those who argue that it is sufficient to do science with one way predictions, of the form,

"Our theory has many solutions,  $S_i$ . One of them,  $S_1$  gives rise to a prediction  $X$ . If  $X$  is found that will confirm the combination of our theory and the particular solution  $S_1$ . But if  $X$  is not found belief in the theory is not diminished, for there are a large number of solutions that don't predict  $X$ ."

One problem with this is that it can easily lead to a situation in which the scientific community is indefinitely split into groups that disagree on the likelihood that the theory is true, with no possibility for resolution by rational argument. It is indeed plausible that this is already the case with string theory, which appears so far unfalsifiable, but can

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<sup>3</sup>As I discuss in section 5 because of the issue of selection effects connected with the existence of life, this can be weakened to *almost every universe in  $\mathcal{E}$  that contains life also has property  $\mathcal{W}$ ...*

make some claims of this form. A second problem is that even if  $X$  were found, it is easy to imagine in this situation another theory could be invented that also had a solution that predicted  $X$ . If neither are falsifiable, there would be no possibility to resolve rationally which were true.

Thus, so long as we prefer a science based on what can be rationally argued from shared evidence, there is an ethical imperative to examine only hypothesis that lead to falsifiable theories. If none are available, our job must be to invent some. So long as there are falsifiable-and not yet- falsified-theories that account for the phenomena in question, the history of science teaches us to prefer them to their non-falsifiable rivals. The simple reason is that once a non-falsifiable theory is preferred to falsifiable alternatives, the process of science stops and further increases in knowledge are ruled out. There are many occasions in the history of science when this might have happened; we know more than people who espoused Ptolemaic astronomy, or Lysenko's biology, or Mach and others who dismissed atoms as forever unobservable, because at least some scientists preferred to go on examining falsifiable theories.

Thus, to deflate the temptation to proceed with non-falsifiable theories, it is sufficient to demonstrate that falsifiable alternatives exist. In this paper I review one falsifiable alternative to the Anthropic Principle which is cosmological natural selection (CNS)[7, 8, 9]. As it is falsifiable it may very well be wrong.

In the last sections of this paper I will review cosmological natural selection in light of developments since it was first proposed. I will show that, in spite of several claims to the contrary, the theory has yet to be falsified. However, it remains falsifiable as it makes at least one prediction for a property  $\mathcal{W}$  of the kind described in  $\mathbf{B}'$ . But whether it is right or wrong, the fact that a falsifiable theory exists is sufficient to show that the problems that motivate the Anthropic Principle might be genuinely solved by a falsifiable theory.

But if the anthropic principle cannot provide a scientific explanation, what are we to make of the claim that the universe is friendly to life? It is essential here to distinguish the different versions of the anthropic principle from what I would like to call the *anthropic observation*. This observation states:

- **The anthropic observation:** *Our universe is much more complex than most universes with the same laws but different values of the parameters of those laws. In particular, it has a complex astrophysics, including galaxies and long lived stars, and a complex chemistry, including carbon chemistry. These necessary conditions for life are present in our universe as a consequence of the complexity which is made possible by the special values of the parameters.*

I will describe this more specifically below. There is good evidence that the anthropic observation is true[2, 3, 4, 9]. Why it is true is a puzzle that science must solve. To solve it, it does not suffice just to restate what is to be explained as a principle, especially if the resulting theory that follows from that principle is not falsifiable. One must discover a reason why it is true that has nothing to do with our own existence. Cosmological natural selection may be right or it may be wrong, but it does provide a genuine explanation

for the anthropic observation. This is that the conditions life requires, such as carbon chemistry and long lived stars, serve another purpose, in that they contribute to the reproduction of the universe itself.

## 2 The problem of the undetermined parameters of physics and cosmology

The second half of the twentieth century saw a great deal of progress in our understanding of elementary particle physics and cosmology. In both areas, standard models were established, which passed numerous experimental tests. In elementary particle physics the standard model, described in the mid 1970's is based on two key insights. The first is about unification of the fundamental forces. The second is about why that unification does not prevent the different particles and forces from have different properties. The unifying principle is that all forces are described in terms of gauge fields, based on making symmetries local. The second principle is about how the symmetries between particles and among forces can be broken naturally when those gauge fields are coupled to matter fields. The standard model of cosmology took longer to establish, but is based also on the behavior of matter fields when the symmetry breaks. In particular, this leads generally to the existence of a non-zero vacuum energy, which can both drive an early inflation of the universe and act today, accelerating the expansion.

In each case, however there is a catch. The interactions of the gauge fields with each other and with gravity is determined completely by basic symmetries, whose description allows a very small number of parameters. However, the dynamics of the matter fields needed to realize the idea of the symmetry breaking spontaneously and dynamically is arbitrary and requires a large number of parameters to describe. This is because the easiest matter fields to work with are scalar fields, and no transformation properties constrain the form of their interactions.

The result is that the standard model of elementary particle physics has more than 20 adjustable parameters. These include the masses of all the basic stable elementary particles: proton, neutron, electron, muon, neutrinos etc, as well as the basic coupling constants and mixing angles of the various interactions. These are not determined by any principle or mechanism we know; they must be specified by hand to bring the theory into agreement with experiment. The standard model of cosmology has similarly about fifteen parameters.

Two of the biggest mysteries of modern science are then how these 35 or so parameters are determined.

There are two especially puzzling aspects to these problems

The first is the *naturality problem*. Many of these parameters, when expressed in terms of dimensionless ratios, are extremely tiny or extremely large numbers. In Planck units, the proton and neutron masses are around  $10^{-19}$ , the cosmological constant is  $10^{-120}$ ,

the coupling constant for self-interactions of the field responsible for inflation cannot be larger than  $10^{-11}$  and so on.

The second is the *complexity problem*. Our universe has an array of complex and non-equilibrium structures spread out over a huge range of scales from clusters of galaxies to living cells. It is not too hard to see that this remarkable circumstance depends on the parameters being fine tuned into narrow windows. Were the neutron heavier by only one percent, the proton light by the same amount, the electron twice as massive, its electric charge twenty percent stronger, the neutrino as massive as the electron etc. there would be no stable nuclei at all. There would be no stars, no chemistry. The universe would be just hydrogen gas. The anthropic observation stated in the introduction is one way to state the complexity problem.

Despite all the progress in gauge theories, quantum gravity, string theory etc. not one of these problems have been solved. Not one mass or coupling constant of any particle considered now to be elementary has ever been explained by fundamental theory.

### 3 The failure of unification to solve the problem

For many decades there has been a consensus on how to solve the problems of the undetermined parameters: *unify the different forces and particles by increasing the symmetry of the theory and the number of parameters will decrease*. The expectation that unification reduces the number of parameters in a theory is due both to historical experience and to a philosophical argument. The former is easy to understand: It worked when Newton unified the theory of the planetary orbits. It worked when Maxwell showed that light was a consequence of the unification of electricity and magnetism and so on. In several cases, unification was accomplished by the discovery of a symmetry principle, and by relating things heretofore unrelated, a new symmetry principle can sometimes reduce the number of parameters. The philosophical argument is along the lines of the following: reductionism will lead to a fundamental theory, a fundamental theory will answer all possible questions and so can't have free parameters, and unification operates in the service of greater reductionism. Or perhaps: the theory that unifies everything should be able to answer all questions. So it had better be unique, otherwise there would be unanswerable questions, having to do with choosing which unified theory corresponds to nature.

Whatever the arguments for it, the correlation between unification and reduction in the number of parameters has not worked recently. Indeed, the last few times it was tried, it went the other way. One can reduce by a few the number of parameters by unifying all of elementary particle physics in one Grand Unified Theory. One does not eliminate most of the freedom, because the masses of all the observed fundamental parameters are traded for the values of Higgs vacuum expectation values, which are not determined by any symmetry and remain free parameters.

The grand unified theories had two problems. The first is that the simplest version

of them, based on the group  $SU(5)$ , was falsified. It predicted that protons would decay, with at least a certain rate. The experiment was done, and protons were seen not to decay at that rate. This is the last time there was a significant experimental test of a new theoretical idea about the elementary particles.

One can consider more complicated grand unified models in which protons don't decay, or the decay rate is much smaller. But all such models suffer from the second problem. This is the problem of naturalness. They require two Higgs scales, one at around  $1\text{TeV}$  and one at about  $10^{15}\text{TeV}$ 's. But quantum corrections tend to pull the two scales closer to each other, To keep their ratio so large requires fine tuning of the coupling constants of the theory to roughly a part in the ratio or  $10^{-15}$ .

To solve this problem, it has been proposed to supersymmetrize the model. Supersymmetry relates bosons to fermions, and one might think it reduces the number of free parameters, but it goes the other way. The *simplest* supersymmetric extension of the standard model has more than 100 parameters.

Supersymmetry is a beautiful idea, and it was hard not to get very excited about it when it was first introduced. But so far it has to be counted as a disappointment. Had the addition of supersymmetry to what we know led to unique predictions, for example for what will be seen at the *LHC*, that would have been very compelling. The reality has turned out to be quite different. The problem is that, while supersymmetry is not precisely unfalsifiable, it is difficult to falsify, as many negative results can be-and have been- dealt with by changing the parameters of the theory. Supersymmetry would be completely convincing if there were even one pair, out of all the observed fundamental particles, that could be made into superpartners. Unfortunately, this is not the case and one has to invent superpartners for each one of the presently observed particles.

This turns out to introduce a huge amount of arbitrariness. The current situation is that the minimal super symmetric standard model has so much freedom, coming from its 105 dimensional parameter space, that, depending on which region of the parameters space one chooses, there are at least a dozen scenarios for what could be seen by the upcoming *LHC* experiments[10]. It is not too much of an exaggeration to say that almost any results that could be seen by the *LHC* could be-and probably will be-promoted as evidence for supersymmetry, whether or not it actually is. To actually test whether or not particle physics is supersymmetric will take much longer as it will require measuring enough amplitudes to see if they are related by supersymmetry.

Another possible solution is to further unify the theory, by coupling to gravity. However, this seems either to not help, or to make things much worse. There are two well developed approaches to quantum gravity, one non-perturbative, which means it makes no use of a background classical spacetime and one perturbative, which describes small excitations of a classical spacetime, The non-perturbative approach, called *loop quantum gravity*, readily incorporates coupling to the standard model of elementary particle physics and also readily incorporates supersymmetry. It does not seem that, from a non-perturbative point of view, coupling to quantum gravity constrains the parameters of particle physics.

The perturbative approach, which is string theory, makes very strong assumptions

about how the string is to be quantized<sup>4</sup> and it also makes two physical assumptions: 1) that no matter how small one looks, spacetime looks classical, with small quantum excitations 2) Lorentz invariance is a good symmetry out to infinite energies and boosts. It is not certain that all these assumptions can be realized consistently, as after many years there are only proofs of consistency and finiteness of perturbative string theory to second non-trivial order in perturbation theory, and attempts to go further have not so far succeeded<sup>5</sup>. But these results indicate that the assumptions just mentioned do put some constraints on particle physics. Supersymmetry is required and the dimension of spacetime must be ten.

To the order of perturbation theory it is known to be consistent, string theory unifies all the interactions, including gravity. It was therefore originally hoped that it would be unique. These hopes were quickly bashed, and indeed, the number of string theories for which there is some evidence for has been growing exponentially as string theorists developed better techniques to construct them. Originally there were five consistent supersymmetric string theories in ten dimensions. But, of course, the number of observed dimensions is four. This led to the hypothesis that the extra six dimensions are curled up in small spaces, or otherwise hidden from large scale observations. Unfortunately, the number of ways to do this is quite large, at least  $10^5$ . In recent years evidence has been found for many more string theories, which incorporate non-perturbative structures of various dimensions, called branes.

A key problem has been constructing string theories that agree with the astronomical evidence that the vacuum energy (or cosmological constant) is positive. The problem is that a positive cosmological constant is not consistent with supersymmetry. But supersymmetry appears to be necessary to cancel dramatic instabilities having to do with the existence of tachyons in the spectrum of string theories.

A year ago dramatic progress was made on this problem by Kachru[13] and collaborators<sup>6</sup>. They found a way to sneak up on the problem by wrapping branes around cycles of the compactified six manifold. They discovered evidence for the existence of string theories with positive vacuum energy. This evidence is very weak—they are unable for example to construct propagation amplitudes even for the free, non-interacting strings. What they are able to do is to argue that if there are consistent string theories with the desired characteristics, their low energy behavior should be captured by solutions to classical supergravity, coupled to the patterns of branes in question. Then they construct the low energy, classical, supergravity description.

Of course the logic here is backwards. Had they been able to show that the required supergravity solutions don't exist, they would have ruled out the corresponding string theories. But the existence of a good low energy limit is a necessary but not sufficient

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<sup>4</sup>A recent paper by Thiemann[11] suggests that with different technical assumptions there are consistent string theories in any dimension, without supersymmetry.

<sup>5</sup>For details of precisely what has and has not been proven regarding string theory, loop quantum gravity and other approaches to quantum gravity see[12]

<sup>6</sup>building on earlier work by Giddings et al, [14], Bousso and Polchinski[15] and others.

condition for a theory to be shown to exist. So on logical grounds, the evidence for string theories with positive cosmological constant is very weak.

However, if one takes the possibility of the existence of these theories seriously, there is a disturbing consequence. For the number of distinct theories that the evidence points to is vast, estimates have been made on the order of  $10^{100}$  to  $10^{500}$  [16, 17]. Each of these theories is consistent with the macroscopic world being four dimensional, and the existence of a positive and small vacuum energy. But they disagree about everything else, in particular, they imply different versions of elementary particle physics, with different gauge groups, spectra of fermions and scalars and different parameters.

That is, if the string theorists are right, there are on the order of  $10^{100}$  or more different ways to consistently unify gauge fields, fermions and gravity. *This makes it likely<sup>7</sup> that string theory will never make any new, testable predictions concerning the elementary particles<sup>8</sup>.*

Of course, a very small proportion of the theories will be consistent with the data we have, to date, about particle physics. Suppose this is only one in  $10^{50}$ . There will still be  $10^{50}$  different theories, which will differ on what we will see in future experiments at higher energy. This number is so vast, it appears likely that whatever is found, there will be many versions of string theory that agrees with it.

## 4 Mechanisms of production of universes

Whatever the fate of the positive vacuum energy solutions of string theory, one thing is clear. At least up till now, the hope that unification would lead to a unique theory has failed, and it has failed dramatically. So it seems unlikely that the problem of accounting for the values of the parameters of the standard models of particle physics and cosmology will be solved by restrictions coming from the consistency of a unified theory.

The rest of this essay is then devoted to alternative explanations of the choice of parameters. All alternatives I am aware of involve the postulate **A**. They also require

- **C** There are many different possible consistent phenomenological descriptions of physics, relevant for the possible description of elementary particle physics at scales much less than Planck energies. These may correspond to different phases of the vacuum, or different theories altogether.

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<sup>7</sup>It should be noted that while some string theorists have argued that this situation calls for some version of the Anthropic Principle[16], other have sought ways to still pull falsifiable predictions from the theory[17].

<sup>8</sup>Of course, it may be correctly claimed that string theory makes a small number of correct *postdictions*, for example that there are fermions, gauge fields and gravitational fields in nature, and that there are no more than 10 spacetime dimensions. But this does not by itself give a strong argument for the truth of string theory as there are other approaches to unifying gravity with quantum theory and the standard model about which non-trivial properties have also been proven[12]. So there is no evidence that string theory is the unique theory that unifies gravity with the standard model.

As a result, fundamental physics is assumed to give us, not a single theory, but a space of theories,  $\mathcal{L}$ , which has been called the *landscape* [8, 9]<sup>9</sup>. As in biology, we distinguish the space of genotypes from the space of phenotypes will have to distinguish  $\mathcal{L}$  from the space of the parameters of the standard model, which we will call  $\mathcal{P}$ .

All multiverse theories then make some version of the

- **Multiverse hypothesis.** Assuming **A** and **C**, the whole of reality-which we call the multiverse- consists of many different regions of spacetime, within which phenomena are governed by different of these phenomenological descriptions. For simplicity, we call these *universes*.

The multiverse is then described by probability distributions  $\rho_L$  in  $\mathcal{L}$  and  $\rho_P$  in  $\mathcal{P}$ . These describe the population of universes within the multiverse. Multiverse theories can be classified by the answers to three questions.

1. How is the ensemble of universes generated?
2. What is the mechanism that produces the probability distribution  $\rho_P$ ?
3. What methodology is used to produce predictions for our universe from the ensemble of universes?

We will be interested here only in those multiverse theories that make falsifiable predictions. To do this the ensemble of universes cannot be arbitrarily specified, otherwise it could be arbitrarily adjusted to agree with any observations for example by making a typical universe agree with whatever is observed about ours. To have empirical content, the ensemble of universes must be generated by some dynamical mechanism and that mechanism, in turn, must be one that is a consequence of general laws. That way, the properties of the ensemble are determined by laws that have other consequences, and, at least in principle, can be checked, independently.

Two mechanisms for generation of universes have been studied, eternal inflation and bouncing black hole singularities. We describe each of them, after which we will contrast their properties.

## 4.1 Eternal inflation

The hypothesis of early universe inflation gives a plausible explanation of several observed features of our universe, such as its homogeneity and uniformity[18, 19]. The basic idea is that at very early times the energy density is dominated by a large vacuum energy, possibly coming from the vacuum expectation value of a scalar field. As the universe expands exponentially, driven by the vacuum energy, the vacuum expectation value also

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<sup>9</sup>It is perhaps worth mentioning that the word “landscape” was chosen in [8, 9] to make the transition to the concept of *fitness landscape*, well known in evolutionary theory, more transparent.

evolves in its potential. Inflation comes to an end when a local minimum of the potential is reached, converting vacuum energy into thermal energy that is presumed to provide the thermal energy that becomes the observed cosmic microwave background.

The model appears to be consistent, assuming all scales involved are less than the Planck scale, and has made predictions which were confirmed<sup>10</sup>. But there are some open problems. One set has to do with the initial conditions necessary for inflation to happen. It has been shown that a region of spacetime will begin to inflate if the vacuum energy dominates other sources over its extent and, the matter and gravitational fields are constant to good approximation over that region. Of course, we do not know the initial conditions for the universe, and we observe nothing so far about the conditions prior to inflation. But on several plausible hypotheses about the initial state, the conditions required for a region of spacetime to begin inflating are improbable. For example, the existence of inflation, together with the smallness of  $\delta\rho/\rho$ , requires that the self-coupling of the inflaton be small.

However, once the conditions necessary for inflation are met, it appears to be, in some models, likely that inflation does not happen just once. The reason is that because of quantum fluctuations, the scalar field will sometimes fluctuate “up” in the potential. The result is that even after inflation has ended in one region, it will continue in other regions. This can lead to the scenario known as *eternal inflation*[20, 21] in which there are always regions which continue to inflate. There is then a competition between the classical force from the potential, causing the expectation value to decrease or “roll” towards a local minimum, and the quantum fluctuations which can lead it to locally increase. Given plausible, but not necessary assumptions[20, 21], this can result in the creation of a large, or even infinite, number of regions which locally resemble ordinary *FRW* universes.

## 4.2 Bouncing black hole singularities

A second mechanism for generating new universes is through the formation of black holes. It is known that a collapsing star, such as a remnant of a supernova, will form either a neutron star or a black hole, depending on the mass. There is an upper mass limit (UML) for a stable neutron star, remnants of supernovae over this mass have nothing to restrain them and will collapse to the point that a horizon is formed. We have rough estimates for the value of the upper mass limit, between 1.5 and 2.5 solar masses.

According to the singularity theorem of Penrose, proved on general assumptions, classical general relativity predicts that a singularity will necessarily form, at which the curvature of spacetime becomes infinite and spacetime ends. No trajectory of a particle or photon can be continued passed the singularity to the future.

However, this result may be modified by quantum effects. Before the singularity is reached, densities and curvatures become Planck scale and the right dynamics will be

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<sup>10</sup>But it should be noted that other theories make predictions so far indistinguishable from those of inflation[22, 23].

those of the quantum theory of gravity. As early as the 1960's pioneers of the field of quantum gravity such as John Wheeler and Bryce deWitt conjectured that the effects of quantum gravity would reverse the collapse, removing the singularity and causing the matter that was collapsing to now expand[24]. Time then does not end, and there is a region of spacetime to the future of where the singularity would have been. The result is the creation of a new expanding region of spacetime, which may grow and become for all practical purposes a new universe. This region is inaccessible from the region where the black hole originally formed. The horizon is still there, which means that no light can escape from the new region to the previous universe. From the point of view of causal structure, unless the black hole evaporates, every event in the new region is to the future of every event in the region of spacetime where the black hole formed.

The transition by which a collapse to a singularity is replaced by a new expanding region of spacetime is called a bounce. One can then hypothesize that our own big bang is the outcome of a collapse in a previous universe and that every black hole in our universe is giving rise to a new universe.

The conjecture that singularities in classical general relativity are replaced by bounces has been investigated and confirmed in many semiclassical calculations[25]. It is also suggested by some calculations in string theory[26]. In recent years the quantum theory of gravity has been developed to the point where the conjecture can be investigated exactly. It has been shown that cosmological singularities do bounce[27]. This means that, assuming that the quantum theory of gravity is correct, the big bang in our past could not have been the first moment of time, there must have been something before that. Results of the same reliability have yet to be published for black hole singularities, but they are in progress[28].

### 4.3 Comparison of universe generation mechanisms

It is useful to compare the two mechanisms of reproduction of universes.

- *How reliably is the evidence for the mode of production of universes?*

We know that our universe contains black holes. There is observational evidence that many galaxies have large black holes in their centers. Black holes are also believed to form from supernova remnants, and there is believed to be around  $10^{18}$  such black holes. A number of candidates for such stellar-mass black holes have been found, and the evidence so far, for example that coming from studies of X-rays from their accretion disks, supports their identification as black holes.

There have been speculations that many black holes may have been created by strong inhomogeneities in the early universe. However, theories of inflation predict that inhomogeneities were not strong enough to create many such primordial black holes. In any case, were they there, one would expect to see signals of their final evaporation, and no such signals have been detected. Thus, it is likely that the population of black holes is dominated, numerically, by supernova remnants.

We also have reasonable, if not yet compelling, theoretical evidence that black holes bounce[25, 26]. And we have exact results that show that quantum effects remove the singularity to our past, implying that there was something to the past of our big bang[27].

Thus, there is plausible evidence that our universe is creating new universes through the mechanism of black hole production, and that our own universe was created by such a process.

By contrast, the process for formation of new universe in eternal inflation cannot be observed, for it takes place outside of our past horizon. The existence of the process depends entirely on believing in particular inflationary models that lead also to eternal inflation. While many do, it is also possible to invent inflationary models that do not lead to eternal inflation. While there is evidence for inflation in general, as several predictions of inflation have been confirmed by observations, the observations do not distinguish so far between different versions of inflationary models, and so cannot distinguish between models that do and do not predict eternal inflation.

It is also the case that some, but not all, of the calculations backing up the eternal inflation scenario are done using very rough methods, based on imprecise theories employing semiclassical estimates for “the wavefunction of the universe”. This is a speculative extension of quantum theory to cosmology which has not been put on firm ground, conceptually or mathematically. Very recently, progress has been made in quantum cosmology which does allow precise predictions to be made from a rigorous framework[27]. However, while inflation has been studied with these methods, so far the results do not address the conjectures that underlie eternal inflation.

Other approaches to eternal inflation[20] rely only on quantum field theory in curved spacetime. This is better understood, but there are still open questions about its applicability for cosmological questions.

As a consequence, eternal inflation can be considered an interesting speculation, but it is supported neither by observation nor by firm mathematical results within a well defined theory of quantum gravity.

- *What physics is involved in the mechanism of reproduction of universes? How well do we understand the processes that govern the numbers of universes which are created?*

The physical scale governing the birth of universes in eternal inflation is the scale of the inflaton potential in the regime where nucleation of new inflating regions take place. This is at least the grand unified scale, ( $\sim 10^{15} Gev$ ) and could be up at the Planck scale. We have theories about the physics at this scale, but so far no predictions made by these theories, have been confirmed experimentally. In fact, the only experimental evidence we have concerning this scale, coming from proton decay experiments, falsified the simplest grand unified theories.

By contrast, the physical scale that governs black hole production is that of ordinary physics and chemistry. How many stars massive enough to supernova is determined by ordinary chemical processes that govern the formation and cooling of giant molecular clouds. We know the physics of stars and supernovas reasonably well, and knowledge is improving all the time due to progress in theory, observation and experiment.

Thus, the answer is that we understand well the physics that controls how many universes are created through black hole formation, while we have speculations, but no confirmed or detailed understanding of the processes that govern the creation of new universes in eternal inflation.

- *What is the structure of the multiverse predicted by each theory?*

A multiverse formed by black holes bouncing looks like a family tree. Each universe has an ancestor, which is another universe. Our universe has at least  $10^{18}$  children, if they are like ours they have each roughly the same number of their own.

By contrast, the structure of a multiverse formed by eternal inflation is much simpler. Each universe has the same ancestor, which is the primordial vacuum. Universes themselves have no descendents.

## 5 How do multiverse theories make predictions?

Just as there are two modes of production of universes, there are two modes of explanation by which people have tried to draw physical predictions from multiverse models. These are the Anthropic Principle (AP) and Cosmological Natural Selection (CNS).

### 5.1 Varieties of anthropic reasoning

There are actually several different anthropic principles and several different ways that people reason from them to conclusions. We discuss the major ones here, including the examples that are usually cited as successes of the Anthropic Principle, which are the arguments of Dicke, Hoyle and Weinberg<sup>11</sup>.

#### 5.1.1 The theological anthropic principle

It is not surprising that some theologians and scientists take the *complexity* problem as evidence that our universe was created by a benevolent God. They argue that if the best efforts of science lead to an understanding of laws of nature within which there is choice, and if the choices that lead to a universe with intelligent life are extremely improbable,

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<sup>11</sup>Note that I do not use the traditional nomenclature of weak and strong anthropic principles, as these have been used to refer to different ideas in different books and papers.

the very fact that such an improbable choice was made is evidence for intension. This is of course the old argument from design, recycled from controversies over evolutionary theory. It should be admitted that it does have force: the discovery of a craft as complex as an airbus on a new planet would be good evidence for intelligent life there. But this argument has force only so long as there are no plausible alternative explanations for how the choice might have been made. In the case of biology, natural selection provides a falsifiable and so far successful explanation, which renders unnecessary the argument from design.

We can learn from the long history of the controversy in biology what tests a proposed explanation must satisfy if it is to be more convincing than the argument from design for intentional creation of a life friendly universe.

1. There must be a physical mechanism which converts the improbable to the probable, that is that raises the probability that a universe like ours was chosen from infinitesimal to order unity.
2. That mechanism must be falsifiable. It must be built from processes or components which can be examined empirically and be seen to function as hypothesized, either by being created in a' laboratory or by occurring in nature in our observable universe.

We will see below that these are not satisfied by the different versions of the Anthropic Principle used in physics and cosmology. After this we will see a way to reason about multiuniverses that is not anthropic that does satisfy these two tests.

### 5.1.2 Selection effects within one universe

The first arguments called "anthropic" in cosmology were based on the use of *selection effects* within our observable universe. A selection effect is an effect due to the conditions of observation, which must be applied to a set of observations before they can be interpreted properly. A classical example is the following: Early human beings observed that all around them was land and water, and over them is sky. From this they perhaps deduced that the universe consists of a vast continent of land, surrounded by water, over which is sky. They were wrong, and the reason was that they forgot to take into account that the conditions they observed were necessary for them to exist, as intelligent mammals. We now know that the universe is vastly bigger than they imagined and most of it is filled with nothing but a very dilute gas and radiation. If we picked a point randomly, it would be very unlikely to be on the surface of a planet. But the conditions necessary for our evolution turn the improbable into the probable.

Dicke used this logic to debunk a claim of Dirac, concerning his "law of large numbers". Dirac observed a coincidence between the age of the universe in Planck units and the proton mass in Planck units (the first is roughly the inverse cube of the second). He argued that this required explanation, and proposed one, according to which Planck's constant would change in time. Dicke pointed out that the coincidence could be explained

entirely by our own existence. Intelligent life requires billions of years of evolution on the surface of a planet near a stable long lived star, and he was able to argue that the physics of stars imply that these conditions would only hold at an era in the universe where Dirac's coincidence would hold. Indeed, when checked, Dirac's proposed explanation was falsified.

This argument is, so far as I know, logically sound. But notice as we go along that it is logically quite different than the proposed modes of explanation we are about to discuss. The fact that this argument is sound is not evidence for arguments that have a very different logical structure and empirical grounding.

### 5.1.3 False uses of an anthropic principle

There are other successful arguments, which have been called "anthropic", although they have nothing to do with selection effects or the existence of life. An illustrative example is Hoyle's prediction of a certain resonance in the nuclei of carbon.

Hoyle argued that for life to exist there must be carbon. Indeed, carbon is plentiful in the universe. It must have been made sometime in the history of the universe, either during the big bang, or afterwards, in stars, as these are the only ways the universe synthesizes copious amounts of chemical elements. Detailed studies show it could not have been made in the big bang, hence we know carbon must have been made in stars. Hoyle was able to argue that carbon could only be formed in stars if there were a certain resonant state of carbon nuclei. He communicated this prediction to a group of experimentalists who found it.

The success of Hoyle's prediction is sometimes used as support for the effectiveness of the anthropic principle. But notice that it has nothing whatsoever to do with the existence of life or intelligence. The first line of the last paragraph has no logical relation to the rest of the paragraph. The logic of Hoyle's argument starts with the assertion of the empirically well established fact that the universe is full of carbon. He then reasons correctly from this that there must be a source of carbon. Since calculations show it cannot be made in the big bang, the only plausible site of carbon production is stars. Hoyle analyzed fusion processes in stars and concluded that carbon would not be produced unless that particular resonance existed.

Thus, Hoyle's argument is sound, and led to a successful prediction. But the first line of his argument is unnecessary. The fact that we, or other living things are made of carbon is totally unnecessary to the argument, indeed were there intelligent life forms which evolved without carbon chemistry, they could just as easily make Hoyle's argument.

To be clear about why Hoyle's argument does not employ any version of the Anthropic principle, let us examine its logical schema and then ask which step we would have to question were the prediction falsified.

#### **Hoyle's argument:**

1.  $X$  is necessary for life to exist.

2. In fact  $X$  is true about our universe.
3. Using the laws of physics, as presently understood, together with perhaps other observed facts,  $Y$ , we deduce that if  $X$  is true of our universe so is  $Z$ .
4. We therefore predict that  $Z$  is true.

In Hoyle's case,  $X$  is that the universe is full of carbon,  $Y$  is the claim that it could only be made in stars, and  $Z$  is the existence of a certain resonance in carbon.

We see clearly that the prediction of  $Z$  in no way depends on step 1. The argument has the same force if step 1 is removed. To see this ask what we would do were  $Z$  found not to be true. Our only option would be to question either  $Y$  or the deduction from the presently known laws of physics to  $Z$ . We might conclude that the deduction was wrong, for example if we made a mistake in a calculation. If no such option worked, we might have to conclude that the laws of physics might have to be modified. But we would never question 1, because, while a true fact, it plays no role in the logic of the argument leading to the prediction for  $Z$ .

There are other examples of this kind of mistaken reasoning, in which an argument promoted as "anthropic" actually has nothing to do with the existence of life, but is instead a straightforward deduction from observed facts. We will see below that one famous argument of Weinberg concerning the cosmological constant is of this kind.

#### 5.1.4 Selection effects within a multiverse

More recently, arguments called "anthropic" are made within multi-universe scenarios. It is a bit tricky to pull falsifiable predictions from such a scenario, for the simple reason that we only observe (so far) only one member of the ensemble. But, it is not impossible, as I will shortly show.

First, however, we have to dispose of mistaken uses of multi-universe selection effects. These are arguments in which point 1, in the schema for Hoyle's argument, is replaced by

1' We live in one member of a multiverse in which the laws of physics vary.  $X$  is necessary for life, therefore by a selection effect we must live in a universe in which  $X$  is true.

The full argument is now

##### **Multiverse version of Hoyle's argument:**

1. ' We live in one member of a multiverse in which the laws of physics vary.  $X$  is necessary for life, therefore by a selection effect we must live in a universe in which  $X$  is true.
2. In fact  $X$  is true about our universe.

3. Using the laws of physics, as presently understood, together with perhaps other observed facts,  $Y$ , we deduce that if  $X$  is true of our universe so is  $Z$ .
4. We therefore predict that  $Z$  is true.

We see the substitution of  $1'$  for  $1$  has not changed the logic of the argument.  $1'$  is as irrelevant for the argument as  $1$  was, because  $2$  still does the real logical work. Furthermore, if in this case the prediction  $Z$  were falsified, we would certainly not question  $1'$ . The problem we would then have is in understanding why, *in one universe*,  $X$  is true without  $Z$  being true. The problem must be solved within one universe, it is entirely irrelevant for making the absence of  $Z$  consistent with  $X$  whether or not the universe we live in is the only universe or part of a multiverse.

That is, had the resonance lines of carbon which Hoyle predicted not been found, Hoyle would not have questioned the existence of life. Neither would he have thought the result relevant to the question of how many universes there are. Instead, given that carbon is plentiful, he would have examined all the steps in the argument, looking for a loophole, till he found one. The loophole would have been something like, there are other sources of carbon production, not yet known, for example, in exotic events such as collisions of neutron stars.

Hence, to pull a genuinely falsifiable prediction from a multiverse theory, that genuinely depends logically on the hypothesis that our universe is part of a multiverse, the logic must be different from the schema just given.

Here is one way to do it. Let us fix a multiverse theory, called  $\mathcal{T}$ . This theory gives rise to an ensemble of universes,  $\mathcal{M}$ . We are interested in predictions concerning some properties  $p_i$ , where  $i$  labels a set of possible properties. The theory  $\mathcal{T}$  may give us some *a priori* probability  $\rho_{\mathcal{M}}(i)$  that if a universe is picked randomly from the ensemble,  $\mathcal{M}$ , it will have property  $i$ .

To make the argument below precise, we will need to refer to another ensemble, which is an ensemble of randomly generated universes,  $\mathcal{R}$ . This is produced by taking properties allowed to vary within the theory, and selecting their values randomly, according to some measure on the parameter space of the theory. By random we mean that the measure chosen is unbiased with respect to choice of hypothesis as to the physical mechanism that might have produced the ensemble. For example, if we are interested in the string vacua, we simply pick randomly universes with different string vacua. The difference between  $\mathcal{R}$  and  $\mathcal{M}$  is that the former is picked randomly from the physically possible universes, whereas the latter is generated dynamically, by a mechanism proscribed in the theory,  $\mathcal{T}$ .

But before comparing this with our universe we should take into account that we may not live in a typical member of the ensemble  $\mathcal{M}$ . There will be a sub-ensemble  $\mathcal{LM} \subset \mathcal{M}$  of universes that have the conditions for intelligent life to exist. Depending on the theory, the probability for a random universe in  $\mathcal{M}$  to be also in  $\mathcal{LM}$  may be very small, or it may be close to unity. But we already know that, if the theory is true, we are in a universe in  $\mathcal{LM}$ . So we should compute  $\rho_{\mathcal{L}}(i)$  the property that a universe randomly picked in the sub-ensemble  $\mathcal{L}$  contains property  $p_i$ .

Similarly, there will be a sub-ensemble  $\mathcal{LR} \subset \mathcal{R}$  of those universes within the random ensemble, which contain life.

The theory then can only make a falsifiable prediction if some restrictive conditions are satisfied. It is no good to consider properties that depend on the conditions necessary for life, for they will always be satisfied in a universe where life exists. To find a falsifiable prediction, the following must hold:

I) There must be a property  $\mathcal{B}$  which is logically independent of the existence of life, that is it must be physically and logically possible that universes exist which have life but do not have  $\mathcal{B}$ . To make this meaningful, we must refer to the ensemble  $\mathcal{R}$  of random universes. It must be the case that the probability for a universe in  $\mathcal{LR}$  to have property  $\mathcal{B}$ , is small.

II) It must nevertheless be true that within the ensemble  $\mathcal{M}$  generated by the theory  $\mathcal{T}$  there is strong correlation between universes with life and universes with property  $\mathcal{B}$ .

III) The argument will have force if the property  $\mathcal{B}$  has not yet been looked for, so that the prediction of  $\mathcal{B}$  is a genuine prediction of the theory  $\mathcal{T}$ , one which is vulnerable to falsification at the time the prediction is made.

Under these conditions we can now proceed to do real science with a multiverse theory. We make the assumption that our universe is a typical member of the ensemble  $\mathcal{L}$ . We then look for property  $\mathcal{B}$ . The theory is falsifiable because if property  $\mathcal{B}$  is not seen in our universe than we know that theory  $\mathcal{T}$  that gave rise to the ensemble  $\mathcal{L}$  is false. If, however,  $\mathcal{B}$  is found, then the evidence favors the ensemble  $\mathcal{M}$  produced by the theory over the random ensemble  $\mathcal{R}$ .

We can draw a very important conclusion from this. To make a falsifiable prediction, a theory must produce an ensemble  $\mathcal{M}$  that differs from a random ensemble,  $\mathcal{R}$ , generated by choosing physically possible universes randomly. There must be properties that are improbable in  $\mathcal{LR}$  and probable in  $\mathcal{LM}$ . Why is this so? If the two ensembles are identical, then if there is a high probability that a universe with life in  $\mathcal{M}$  has property  $\mathcal{B}$ , this is also true of a universe with life in a randomly generated ensemble. There are two problems with this. First, the particular hypotheses that make up the theory  $\mathcal{T}$  are not being tested, for they are empirically equivalent to a random number generator. Second, and more importantly, without the random ensemble, we cannot give meaning to the necessary condition that  $\mathcal{B}$  is uncorrelated with the conditions necessary for life. For the observation of  $\mathcal{B}$  to have the possibility of falsifying the theory  $\mathcal{T}$ , it must be logically possible that there exist ensembles in which the probability of  $\mathcal{B}$  in universes with life is low. The operational meaning of this is that they are uncorrelated in an ensemble of randomly generated universes.

To put this more strongly, suppose that a theory  $\mathcal{T}'$  generates an ensemble whose living sub-ensemble  $\mathcal{LM}$  is identical to the living sub-ensemble of the random ensemble. Supposing that theory predicts a property  $\mathcal{B}$  because it has probability close to unity in  $\mathcal{LM}$ . If  $\mathcal{B}$  is observed, however, that does not stand as evidence for  $\mathcal{T}$ , because there is already a complete correlation between  $\mathcal{B}$  and life in the ensemble of randomly generated universes.

The conclusion is that no multiverse theory that produces an ensemble identical to  $\mathcal{R}$  can give falsifiable predictions. Genuine falsifiable prediction can only be made by a theory whose ensemble  $\mathcal{M}$  differs from  $\mathcal{R}$ . Further, to give a genuine prediction there must be a property  $\mathcal{B}$ , not yet observed, but observable with present technology, which is probable in  $\mathcal{LM}$  but improbable in  $\mathcal{LR}$ .

A very important consequence of this follows from the following physical observation.

*Properties of the ensemble  $\mathcal{M}$  generated by a mechanism in a theory  $\mathcal{T}$  will be random if that property concerns physics on a scale many orders of magnitude from the scale of the mechanism of production of universes defined by  $\mathcal{T}$ .*

One reason is familiar from statistical mechanics. Ensembles tend to be randomized in observables that are not controlled in their definition. For example, for a gas in a room, the properties of individual atoms are randomized, subject only to their random values being related to the temperature and density in the room.

A second reason has to do with a general property of local field theories, which is decoupling of scales. In renormalizable field theories, including those of the standard model, there is only weak coupling between modes of the field at very different scales.

We can see this applied to eternal inflation models. The mechanism of generation of universes involves quantum fluctuations in the presence of a vacuum condensate with energy between  $10^{15}$  and  $10^{20}$  GeV. Properties of the vacuum that influence physics at those scales will play a role in determining the ensemble of universes created. If we consider the space of possible theories (perhaps string vacua) theories will be preferentially selected by properties that strongly influence the probability for a quantum fluctuation in this environment to be uniform. These will include coupling constants for interactions manifest on that scale and vacuum expectation values for Higgs fields also on that scale. But the exact values of masses or couplings of particles many orders of magnitude lighter are not going to show up. What will matter is the total number of degrees of freedom, but all particles so far observed are many orders of magnitude lighter and may be treated as massless from the point of view of physics at the scale of universe creation. Hence, changes in the proton-neutron mass difference, or the electron-proton mass ratio are not going to have a significant influence on the probability for universe creation. The result is that these properties will be randomized in the ensemble  $\mathcal{M}$  created by eternal inflation.

As a result, it is reasonable to expect that any standard model parameters that govern low energy physics, but do not govern physics at grand unified scales will have the same distribution in  $\mathcal{M}$  as in the random ensemble  $\mathcal{R}$ . These include the masses of the quarks, leptons, and neutrino and the scale of electroweak symmetry breaking (and hence of the weak interactions). *It follows that eternal inflation will not be able to make any falsifiable predictions regarding any of the low energy parameters parameters of the standard model of particle physics. Consequently, no solution to the complexity problem can come from eternal inflation, since that has to do with the values of these parameters.*

Eternal inflation may be able to make some predictions, but only those restricted to parameters that govern physics at grand unified scales.

There are claims that eternal inflation does lead, in conjunction with another principle,

to predictions about the cosmological constant[29, 30, 31, 32, 33]. We next turn to an examination of those claims.

### 5.1.5 The principle of mediocrity

A variant of selection effects applied to a multi-universe is the *the mediocrity principle*. This is defined by Garriga and Vilenkin[29] as requiring that “...our civilization is typical in the ensemble of all civilizations in the universe.”

This means that we weigh the ensemble  $\mathcal{M}$  by the number of civilizations in each universe. It follows that all universes outside of  $\mathcal{LM}$  have zero weight, and universes with more civilizations are weighed more heavily.

Of course, it goes without saying that this principle adds several layers of presently untestable assumptions to the analysis. We know nothing reliable about the conditions that generate civilizations. While we can speculate, our genuine knowledge about this is unlikely to improve in the near future.

We can of course conjecture that the number of civilizations will be proportional to the number of spiral galaxies. So we can provisionally take the principle of mediocrity to mean that we weigh our ensemble with the number of spiral galaxies in each universe. Alternatively, we can postulate that the number of civilizations is proportional to the fraction of baryons that end up in galaxies[34].

Garriga and Vilenkin then argue that certain predictions can be drawn concerning properties of the vacuum energy[29]. We can note that, in conformity with the above argument, no predictions are drawn concerning properties that are 1) have to do with the parameters of low energy physics and 2) are uncorrelated in a random ensemble with the existence of life. Still, it is good that people put predictions on the table and we should take them seriously.

To take them seriously we must ask, what exactly would be falsified if one or more of their predictions is found to disagree with observation? The argument depends on properties of the eternal inflation theory, some rough guesses about the wave function of the universe and how to reason with it, and some reasoning about the effects of vacuum energy on the creation and evolution of galaxies, as well as on their principle of mediocrity.

The principle of mediocrity can only have force if it is more stable than the other parts of the argument leading to the predictions. This must be so, otherwise a falsification of the prediction may teach us only that the principle of mediocrity is unreliable. To be useful, a methodological principle must be reliable enough that it can be taken as firm, and used as part of an argument to disconfirm an hypothesis about physics.

So, is the principle of mediocrity on firmer ground than quantum cosmology or the theory of galaxy formation? What are the independent grounds for believing it?

I know of no *a priori* argument for the principle of mediocrity. It may be the case that, if the multiverse is real, we live in a universe with a maximal number of civilizations. But it could just as easily be false. There is no reason why we may not live in a universe which is untypical, in that it has some civilizations, but many fewer than other members of the

ensemble.

Thus, while we can argue logically for taking into account selection effects coming from the fact that we are in a universe hospitable to living observers, the principle of mediocrity of [29] is on much less firm ground.

The principle of mediocrity is sometimes supported by referring to ensembles within which we as individuals are typical. And indeed, there are many ensembles within which we as individuals are typical. The problem is that there are also many ensembles with respect to which we are untypical. The principle of mediocrity has little force in human affairs, because without further specification it is vacuous, as we are both typical and atypical, depending on what ensembles we are compared against.

To see this, let us ask some questions about how typical we are.

1. Do I live in the universe with the largest number of civilizations?
2. Do I live in the universe with the largest number of intelligent beings?
3. Do I live in the universe with the largest number of conscious minds?
4. Do I live on the planet with the largest number of intelligent beings?
5. Do I live in the most populous city on my planet?
6. Do I live in the most populous country on my planet?
7. Am I a member of the largest ethnic group on my planet?
8. Do I have a typical level of wealth or income on my planet?
9. Do I live at a time when more people are alive than at any other time?

The answers to questions 1-4 are that there is no way of telling, with either present data or future conceivable data. In my particular case the answers to 5-8 are no, but I know people who can answer yes to one or more of them. Question 9 is ambiguous. If the ensemble is all times in the past, the answer is probably yes. If the ensemble is all times, future and past, it is impossible to know.

Given how often any individual fails to be typical in ensembles we know about, it seems to me we are on equally weak ground reasoning from any assertion of answers to 1-4 as any one of us would be reasoning from 5-9.

The conclusion I draw is that the principle of mediocrity is too ambiguous to be useful. It must be supplemented by a specification of the ensemble. When that is done we can test it, but when we do we see that it is unreliable. Thus, it must be even less reliable in situations where it cannot be tested.

Here is an example that illustrates the perils of the use of the principle of mediocrity. This is a well known argument, called the *doomsday argument*[35]. Someone begins it by stating, *I am a typical human being*. They may support that by noting the existence of

some ensembles within which they are typical. Then they introduce a new ensemble,  $\mathcal{H}$  consisting of *all human beings who will ever live*. They then assert that since they are generally typical they should be typical in that ensemble. They then proceed to draw a drastic deduction from this, we will call  $\mathcal{C}$ . This is that *roughly the same number of human beings will live after them as lived before them*.

Given that the population has been growing exponentially for a long time, this leads to the conclusion that the population should begin to fall drastically within their lifetime.

There are more details, but we do not need them to see the ways in which the argument is fallacious<sup>12</sup>. The ensemble  $\mathcal{H}$  contains an unknown number of human beings, who may live in the future. There is no way, given any information we have at present, to determine if we, living now, are in any way typical or untypical members of  $\mathcal{H}$ . There is simply no point in guessing<sup>13</sup>. Whether we who have lived so far constitute most of  $\mathcal{H}$ , an infinitesimal fraction of  $\mathcal{H}$  or something in between depends on events that will take place in the future, most of whom we are unable to control, let alone predict. So it is simply impossible on current knowledge to deduce the truth value of  $\mathcal{C}$ .

However we can do one thing. We can look to the past. The population has been growing exponentially for at least ten thousand years. Any person living in the last ten thousand years would have had exactly as much rational basis to make the argument starting with "*I am a typical human being*" and ending with the conclusion  $\mathcal{C}$  as we have now and no less. Other facts such as the existence of weapons of mass destruction or global warming are irrelevant, as they are not used to support  $\mathcal{C}$ . The whole point of the argument is supposed to be that it is independent of facts such as these.

Now, we can ask, would a person have been correct to use this argument to conclude  $\mathcal{C}$  a thousand years in the past. NO—we know that they would have been wrong, because already many more people have lived since them than lived before them. But  $\mathcal{C}$  is supposed to be a consequence of the mediocrity principle. The conclusion is that there are two cases of individuals to which the principle may be applied. There is a class of individuals to whom the truth value of  $\mathcal{C}$ —and hence of the mediocrity principle—cannot be checked. Then there is a class of individuals about whom the truth value of  $\mathcal{C}$  can be determined. In each and every one of these cases,  $\mathcal{C}$  is false. Thus, in every case in which

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<sup>12</sup>Another criticism of the argument, from F. Markopoulou, is that to even state that a person is typical in the ensemble  $\mathcal{H}$  with respect to a given property, is to assume that there is a normalizable probability distribution for that property in  $\mathcal{H}$ . If the property is birth order, then the normalizability of the probability distribution already implies the population must decrease at some point in the future. Thus, the argument assumes what it claims to demonstrate[60]. The only thing left open is when, but as we see, this cannot in any case be determined by the argument.

<sup>13</sup>It would take us too far afield to analyze why such a fallacious argument is so attractive. It has something to do with the fallacy that every statement that will, at the end of time, have a truth value, has a truth value now. The statement "*I am a typical member of the ensemble  $\mathcal{H}$* " is one that can only be given a truth value by someone in the unhappy situation of knowing they are the last of us, and they would thus judge it false. No one for whom the statement is true could possibly have enough information to ascribe to it a truth value, for the simple reason that to do so would require knowledge of the future. The point can be put simply by saying that the logic of truth values that can be ascribed by humans to questions about themselves is Heyting rather than Boolean[36].

there is an independent check of the consequences of the mediocrity principle, it turns out to be false. Hence, it is either false, or undetermined. Hence there is no evidence for its truth.

### 5.1.6 Weinberg's argument for the cosmological constant

Recently it has been claimed that the Anthropic Principle, and more specifically the Principle of Mediocrity, led to a successful prediction. This was Weinberg's prediction for the value of the cosmological constant, first made in [32], and then elaborated in [33, 34]. It is important to note that Weinberg and collaborators actually make two separate arguments. The first is the following: assuming **A** and **B** then we cannot find ourselves in a universe with too large a positive value of  $\Lambda$ , or galaxies would never have formed. The upper limit for  $\Lambda$ , with all other constants of nature fixed, predicted by this argument is about 200 times the present matter density[34] (baryons plus dark matter) which gives roughly  $\Omega_\Lambda < 100$ . This is about two orders of magnitude larger than the present observed value.

In their second argument, Weinberg and collaborators attempt to improve this estimate by evoking the principle of mediocrity in the form just discussed. They find that the probability to find a cosmological constant giving  $\Omega_\Lambda$  of .7 or less is either 5% or 12% depending on technical assumptions made. Thus, one can conclude that while the actual observed value is a bit low, compared to the mean, it is not at all unreasonable to argue that the present observed value is consistent with the result of the analysis based on the Principle of Mediocrity.

Is there then something wrong with the case I've just presented against the Principle of Mediocrity? Someone might then argue that, given that Weinberg's first paper came before the supernova and other recent CMB measurements giving a value to  $\Lambda$ , his use of the Principle of Mediocrity has to count as a successful prediction. Indeed, this is perhaps the only successful new prediction in fundamental physics for the value of a physical parameter in decades<sup>14</sup>.

To reply, let us first distinguish the two arguments from each other. One can reasonably conclude that Weinberg's first argument is in part correct. Were  $\Omega_\Lambda > 100$  (with all other constants of nature fixed) we would have a problem understanding why we live in a universe filled with galaxies. However, this is an argument of the form we discussed above in section 5.1.3-4: it is a false use of the Anthropic Principle. For the problem has nothing to do with our own existence. Just as Hoyle's argument has nothing to do with life, but is only based on the observed fact that carbon is plentiful, Weinberg's first argument has to do only with the observed fact that galaxies are plentiful. The argument itself can be made by a robot, or by a disembodied spirit. Were  $\Omega_\Lambda > 100$  (with all other constants fixed) there would be a contradiction between present models of structure formation in the universe, which are based on established physical principles, and the observed

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<sup>14</sup>It is sometimes stated that Weinberg made the only correct prediction for the order of magnitude of the cosmological constant. This is not true. A correct prediction was made by Sorkin[37], based on the causal set approach to quantum gravity.

fact that the universe is filled with galaxies.

The first argument of Weinberg is sometimes presented as an example of the success of a selection principle within a multiverse. But it then follows exactly the schema given at the beginning of 5.1.4, with  $X$  now the existence of many galaxies and  $Z$  that  $\Omega_\Lambda < 100$ . Were  $\Omega_\Lambda$  in fact equal to 1000, the problem could not be with the multiverse hypothesis. It would be rather to explain how galaxy formation happened despite such a large  $\Lambda$ , *in a single universe*. Therefore, Weinberg's first argument is partly valid, but the part that is valid is just a rational deduction from an observed fact, that there are galaxies. The mentions of the existence of life and selection effects in a multiverse are completely irrelevant to the actual logical structure of the argument, as they can be removed from the argument without its logical force being in any way diminished.

Before considering the second argument, there is a caveat to deal with, which is the restriction to considering a class of universes in which all the other constants of nature are fixed. As pointed out by Rees[38], Tegmark and Rees[39] and Graesser, Hsu, Jenkins, and Wise[40] it is difficult to justify any claim to make a valid prediction based on this restricted assumption. One should instead consider ensembles in which other cosmological parameters are allowed to vary. When one does this the constraint on  $\Lambda$  from Weinberg's first argument is considerably weakened. They show this by considering the case of the magnitude of the density fluctuations, usually denoted  $Q$ , which is observed to be about  $10^{-5}$ . One can argue that holding  $\Lambda$  fixed,  $Q$  cannot be much more than an order of magnitude larger, for similar reasons. But, as they show, one can have stars and galaxies in a universe in which *both*  $Q$  and  $\Lambda$  are raised several orders of magnitude from their present value (see Figure 2 of [38]).

Thus, to illustrate the point just made, were  $\Omega_\Lambda > 100$ , one option to be considered would be to raise  $Q$ , so as to explain the observed existence of galaxies in our universe.

From the calculations of [38, 39, 40], we have to conclude that, if we make no other assumptions, the pair  $Q, \Lambda$  are each about two orders of magnitude smaller than their most likely values, based only on reasoning from the existence of stars and galaxies. This is non-trivial, after all, they are many orders of magnitude away from their natural values, in Planck units. But it still leaves a great deal to be explained.

Let us now turn to Weinberg's second argument, in which he employs the Principle of Mediocrity. In the last subsection I argued that this Principle provides an unreliable basis for deductions, because the results gotten depend strongly on which ensemble one is considered to be a typical member. Does Weinberg's argument contradict or provide support for this conclusion? It is easy to see that it provides support.

Were Weinberg's second argument reliable, it would be robust under reasonable changes of the ensemble considered. But, as shown by Graesser et al [40], it is not<sup>15</sup>. If the ensemble is taken to be universes in which  $\Lambda$  varies, but all other constants are held fixed, then an application of the Principle of Mediocrity leads to the conclusion that the probability  $\Lambda$  is as small as it is, is around 10%. But, if we consider an ensemble in which  $Q$  as well as

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<sup>15</sup>Related results were found earlier in [30, 31].

$\Lambda$  varies, the probability comes down to order  $10^{-4}$ , with the precise estimate depending on various assumptions made (see Table 1 of [40]).

We draw two conclusions from this. First, the Principle of Mediocrity is, as was argued, unreliable, because the conclusions drawn from it are ambiguous in that they depend strongly on the ensemble considered. Second, if, in spite of this, it is taken seriously, it leads to the conclusion that the probability for the observed value of  $\Lambda$  is on the order of one in ten-thousand. This follows from the fact that, in all modern cosmological theories,  $Q$  depends on the parameters of the inflaton potential, such as its mass and self-coupling. In any fundamental model of particle physics, in which parameters vary, these would certainly be among the parameters expected to vary.

Thus, the example of Weinberg's two arguments illustrates the conclusions we reached earlier.

The Anthropic Principle itself, in the form of **A** and **B** makes no predictions. Arguments that it has led to predictions are fakes: what is actually doing the work in the arguments is never the existence of life or intelligent observers, but only true observed facts about the universe, such as that carbon and galaxies are plentiful.

And we see here in detail that the Principle of Mediocrity cannot help, because it is easily shown to be unreliable. Any argument that it leads to a correct conclusion can be easily turned into an argument for an incorrect conclusion by reasonable changes in the definition of the ensemble in which we are assumed to be typical.

### 5.1.7 Aguirre's argument against the Anthropic Principle

Before moving on to look at an example of a falsifiable theory, we mention one final argument against the Anthropic Principle, given by Aguirre in [41]. He simply points out that intelligent life would be possible in universes with parameters chosen very different from our own. He gives a particular example, which is a cold big bang model. This is a class of examples, which were studied sufficiently to show they disagree with present observations. Yet they still have galaxies, carbon chemistry and long lived stars. This is sufficient, because it follows that any argument that incorporates a version of the Anthropic Principle would have to explain why we don't live in a cold big bang universe. Given that cold big bang universes share the property of our universe of having abundant formation of galaxies and stars, none of the versions of the Anthropic Principle can do this. Thus, either we leave unexplained why we don't live in a cold big bang universe or we have to find another explanation other than the Anthropic Principle for the parameters of our universe.

## 5.2 Natural Selection

I believe I have said enough to demonstrate conclusively that the version of the Anthropic Principle described by **A** and **B** is never going to give falsifiable predictions for the parameters of physics and cosmology. The few times an argument called anthropic has led to a

successful prediction, as in the case of Hoyle’s argument and Weinberg’s first argument, examination shows that the actual logical argument makes no reference to an anthropic principle, but instead rests entirely on a straightforward deduction from an observed fact about our universe.

Thus, if we are to understand the choices of parameters in detail, in the context of a falsifiable theory, we need an alternative approach. One alternative to deriving predictions from a multiverse theories is patterned on the successful model of natural selection in biology. This was originally motivated by asking the question, where in science is there a successful solution to a problem of explaining improbable complexity? To my knowledge, only in biology do we successfully explain why some parameters—in this case the genes of all the species in the biosphere—come to be set to very improbable values, with the consequence that the system is vastly more complex and stable than would be for random values. The intension is then not to indulge in some mysticism about “living universes”, but merely to borrow a successful methodology from the only area of science that has successfully solved a problem similar to the one we face<sup>16</sup>

The methodology of natural selection, applied to multiverse theories, is described by three hypotheses:

1. A physical process produces a multiverse with long chains of descendents.
2. Let  $\mathcal{P}$  be the space of dimensionless parameters of the standard models of physics and cosmology, and let the parameters be denoted by  $p$ . There is a fitness function  $F(p)$  on  $\mathcal{P}$  which is equal to the average number of descendents of a universe with parameters  $p$ .
3. The dimensionless parameters  $p_{new}$  of each new universe differ, on average by a *small* random change from those of its immediate ancestor. Small here means with respect to the change that would be required to significantly change  $F(p)$ .

Their conjunction leads to a predictive theory, because, using standard arguments from population biology, after many iterations from a large set of random starts, the population of universes, given by a distribution  $\rho(p)$ , is peaked around local extrema of  $F(p)$ . With more detailed assumptions more can be deduced, but this is sufficient to lead to observational tests of these hypothesis, because this implies the prediction that:

- *S: If  $p$  is changed from the present value in any direction in  $\mathcal{P}$  the first significant changes in  $F(p)$  encountered must be to decrease  $F(p)$ .*

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<sup>16</sup>Other approaches to cosmology which employ phenomena analogous to biological evolution have been proposed, including Davies[42], Gribbin[43], Kauffman[44], Nambu[46], Schweber, Thirring and Wheeler[24]. We note that Linde sometimes employs the term “Darwinian” to describe eternal inflation[45, 47] However, because each universe in eternal inflation has the same ancestor, there is not inheritance and modification of parameters analogous to the case of biology.

The point is that the process defined by the three hypotheses drives the probability distribution  $\rho(p)$  to the local maxima of the fitness function and keeps it there. This is much more predictive than the anthropic principle, because that principle resulting probability distribution is much more structured, and very far from random. If in addition, the physics that determines the fitness function is well understood, detailed tests of the general prediction  $\mathcal{S}$  become possible, as we will now see.

## 6 Predictions of Cosmological Natural Selection

It is important to emphasize that the process of natural selection is very different from a random sprinkling of universes on the parameter space  $\mathcal{P}$ . This would produce only a uniform distribution  $\rho_{random}(p)$ . To achieve a distribution peaked around the local maxima of a fitness function requires the two conditions specified. The change in each generation must be small so that the distribution can ‘climb the hills’ in  $F(p)$  rather than jump around randomly, and so it can stay in the small volumes of  $\mathcal{P}$  where  $F(p)$  is large, and not diffuse away. This requires many steps to reach local maxima from random starts, which implies that long chains of descendents are needed.

As a result, of the two mechanisms of universe production so far studied, only black hole bouncing fits the conditions necessary for natural selection to be applied. This is also fortunate, because the physics that goes into the fitness function is, in this case, well understood, at least in the neighborhood of the parameters of our universe. The physical processes that strongly influence the number of black holes produced are nucleosynthesis, galaxy formation, star formation, stellar dynamics, supernova explosions, and the formation and stability of neutron stars. All of these stages, except, perhaps, galaxy formation, are understood in some detail, and in several of these cases our theories make precise predictions which have been tested. We are then on reasonably firm grounds asking what happens to each of these processes when we make small changes in the parameters from their present values.

Thus, for the rest of this paper, by cosmological natural selection I will mean the process of reproduction of universes through black hole bounces, supplemented by the hypotheses above.

The hypothesis that the parameters  $p$  change, on average by small random amounts, should be ultimately grounded in fundamental physics. We note that this is compatible with string theory, in the sense that there are a great many string vacua, which likely populate the space of low energy parameters well. It is plausible that when a region of the universe is squeezed to Planck densities and heated to Planck temperatures, phase transitions may occur leading to a transition from one string vacua to another. But there have so far been no detailed studies of these processes which would check the hypothesis that the change in each generation is small.

One study of a bouncing cosmology, in quantum gravity, also lends support to the hypothesis that the parameters change in each bounce[48].

## 6.1 Successes of the theory

Details of tests of cosmological natural selection are described in [7, 8, 9]. I will only here summarize the conclusions here. For details of the arguments, as well as references to the astrophysical literature on which the arguments are founded, see [7, 8, 9].

The crucial conditions necessary for forming many black holes as the result of massive star formation are,

1. There should be at least a few light stable nuclei, up to helium at least, so that gravitational collapse leads to long lived, stable stars.
2. Carbon and oxygen nuclei should be stable, so that giant molecular clouds form and cool efficiently, giving rise to the efficient formation of stars massive enough to give rise to black holes.
3. The number of massive stars is increased by feedback processes by which massive star formation catalyzes more massive star formation. This is called “self-propagated star formation, and there is good evidence that it makes a significant contribution to the number of massive stars produced. This requires a separation of time scales between the time scale required for star formation and the lifetime of the massive stars. This requires, among other things, that nucleosynthesis should not proceed too far, so that the universe is dominated by long lived hydrogen burning stars.
4. Feedback processes involved in star formation also require that supernovas should eject enough energy and material to catalyze formation of massive stars, but not so much that there are not many supernova remnants over the upper mass limit for stable neutron stars.
5. The parameters governing nuclear physics should be tuned, as much as possible consistent with the forgoing, so that the upper mass limit of neutron stars is as low as possible.

The study of conditions 1) to 4) leads to the conclusion that the number of black holes produced in galaxies will be decreased by any of the following changes in the low energy parameters:

- A reversal of the sign of  $\Delta m = m_{neutron} - m_{proton}$ .
- A small increase in  $\Delta m$  (compared to  $m_{neutron}$  will destabilize helium and carbon.
- An increase in  $m_{electron}$  of order  $m_{electron}$  itself, will destabilize helium and carbon.
- An increase in  $m_{neutrino}$  of order  $m_{electron}$  itself, will destabilize helium and carbon.
- A small increase in  $\alpha$  will destabilize all nuclei.

- A small decrease in  $\alpha_{strong}$ , the strong coupling constant, will destabilize all nuclei.
- An increase *or* decrease in  $G_{Fermi}$  of order unity will decrease the energy output of supernovas. One sign will lead to a universe dominated by helium.

Thus, the hypothesis of cosmological natural selection explains the values of all the parameters that determine low energy physics and chemistry: the masses of the proton, neutron, electron and neutrino and the strengths of the strong, weak and electromagnetic interactions.

However, explanation is different from prediction. These cannot be considered independent predictions of the theory, because the existence of carbon and oxygen, plus long lived stars, are also conditions of our own existence. Hence, selection effects prevent us from claiming these as unique predictions of the theory of cosmological natural selection.

If the theory is to make falsifiable tests, it must involve changes of parameters that do not effect the conditions necessary for our own existence. There are such tests, and they will be described shortly.

Before discussing them, however, we should address several criticisms that have been made.

## 6.2 Previous criticisms

Several arguments were made that  $S$  is in fact contradicted by present observation [49, 50, 51]. These were found to depend either on confusions about the hypothesis itself or on too simple assumptions about star formation. For example, it was argued in [49] that star formation would proceed to more massive stars were the universe to consist only of neutrons, because there would be no nuclear processes to impede direct collapse to black holes. This kind of argument ignores the fact that the formation of stars massive enough to become black holes requires efficient cooling of giant molecular clouds. The cooling processes that appear to be dominant require carbon and oxygen, both for formation of  $CO$ , whose vibrational modes are the most efficient mechanism of cooling, and because dust grains, consisting of carbon and ice provide efficient shielding of star forming regions from starlight. But even processes cooling molecular clouds to  $5 - 20^{\circ}$  K are not enough, formation of massive stars appears to require that the cores of the cold clouds are disturbed by shock waves, which come from ionized regions around other massive stars and supernova. For these reasons, our universe appears to produce many more black holes than would a universe consisting of just neutrons<sup>17</sup>.

Vilenkin[53] raised the following issue concerning the cosmological constant,  $\Lambda$ . He notes that were  $\Lambda$  (or vacuum energy) raised from the present value, galaxy formation would not have taken place at all. one can also add that even at a slightly increased value, galaxy formation would have been cut off, leading only to small galaxies, unable

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<sup>17</sup>For details, see the appendix of [9], which addresses the objections published in [49, 51] and elsewhere.

to sustain the process of self-propagated star formation that is apparently necessary for copious formation of massive stars. This of course counts as a success of the theory.

On the other hand, were  $\Lambda$  smaller than its present value, there might be somewhat increased massive star formation, due to the fact that at the present time the large spiral galaxies are continuing to accrete matter through several processes. These include the accretion of intergalactic gas onto the disks of galaxies and the possible flow of gas from large gaseous disks that the visible spiral galaxies may be embedded in. It is of course difficult to estimate exactly how much the mass of spiral galaxies would be increased by this process, but Vilenkin[53] as much as 10 – 20 percent.

However, lowering the cosmological constant would also increase the number of mergers of spiral galaxies, and the number of absorptions of dwarf galaxies by spirals. These mergers and absorptions are believed to convert spiral galaxies to elliptical galaxies, by destroying the stellar disk and heating the gas. The result is to cut off the formation of massive stars, leaving much gas not converted to stars.

There is then a competition between two effects. Raise  $\Lambda$  and galaxies do not form, or do not grow large enough to support disks and hence massive star formation. Decrease  $\Lambda$  and the dominant effect may be to cut off massive star formation, due to increased mergers and absorptions converting spiral to elliptical galaxies. One can conjecture that the present value of  $\Lambda$  maximizes the formation of black holes,

Other claims have been made that with present knowledge  $\mathcal{S}$  is in fact not testable[51, 52]. Below I will show that these claims are also false, by explaining why a single observation of an astrophysical object that very well might exist—a heavy neutron star—would refute  $\mathcal{S}$ . After this I describe two more kinds of observations that may be made in the near future which could lead to refutations of  $\mathcal{S}$ . These have to do with more accurate observations of the spectrum of fluctuations in the cosmic microwave background (*CMB*) and the initial mass function for star formation in the absence of carbon.

### 6.3 Why a single heavy pulsar would refute $\mathcal{S}$ .

Bethe and Brown, in [54] introduced the hypothesis that neutron star cores contain a condensate of  $K^-$  mesons. For the present purposes their work can be expressed in the following way. Calculations show[54] that there is a critical value  $\mu_c$  for the strange quark mass  $\mu$  such that if  $\mu < \mu_c$  then neutron star cores consist of approximately equal numbers of protons and neutrons with the charge balanced by a condensate of  $K^-$  mesons. The reason is that in nuclear matter the effective mass of the  $K^-$  is renormalized downward by an amount depending on the density  $\rho$ . Given a choice of the strange quark mass,  $\mu$ , let  $\rho_0(\mu)$  be the density where the renormalized Kaon mass is less than the electron mass.  $\mu_c$  is the value of  $\mu$  where  $\rho_0(\mu)$  is less than the density  $\rho_e$  at which the electrons react with the protons to form neutrons. In either case one neutrino per electron is produced, leading to a supernova.

Bethe, Brown and collaborators claim that calculations show that  $\mu < \mu_c$  [54]. But their calculations involve approximations such as chiral dynamics and may be sufficiently

inaccurate that in fact  $\mu_c > \mu$ . However, the accuracy of the calculations increases as  $\mu^{-2}$  as  $\mu$  is decreased so, even if we are not sure of the conclusion that  $\mu < \mu_c$ , we can be reasonably sure of the existence of such a critical value  $\mu_c$ . Then we may reason as follows. If  $\mu < \mu_c$  then, as shown by calculations[54] the upper mass limit is low, approximately  $1.5M_\odot$ . If  $\mu > \mu_c$  neutron stars have the conventional equations of state and the upper mass limit is higher, almost certainly above 2 [55]. Therefore a single observation of a neutron star whose mass  $M$  was sufficiently high would show that  $\mu > \mu_c$ , refuting Bethe and Brown's claim for the opposite. Sufficiently high is certainly  $2.5M_\odot$ , although if one is completely confident of Bethe and Brown's upper limit of 1.5 solar masses, any value higher than this would be troubling. Furthermore, this would refute  $\mathcal{S}$  because it would then be the case that a decrease of  $\mu$  would lead to a world with a lower upper mass limit for neutron stars, and therefore more black holes.

Presently all well measured neutron star masses are from binary pulsar data and are all below  $1.5M_\odot$  [56]<sup>18</sup>. But an observation of a heavy neutron star may be made at any time.

We may note that this argument is independent of any issue of selection effects associated with "anthropic reasoning", because the value of the strange quark mass  $\mu$  may be varied within a large range before it produces a significant effect on the chemistry<sup>19</sup>.

## 6.4 How observations of the CMB could refute $\mathcal{S}$ .

It may be observed that the universe might have had many more primordial black holes than it seems to have were the spectrum of primordial fluctuations,  $f(n)$  tilted to increase the proportion on small scales[51]. Of course, this observation by itself does not refute  $\mathcal{S}$  directly unless it is shown that the standard model has a parameter that can be varied to achieve the tilt in the spectrum. It does not, but it is reasonable to examine whether plausible extensions of the standard model might. One such plausible extension is to add fields that could serve as an inflaton, so that the theory predicts inflation. Given an extension of the standard model,  $\mathcal{E}$ , that predicts inflation, the spectrum of primordial fluctuations is in fact predicted as a function of the parameters of  $\mathcal{E}$ . Thus,  $\mathcal{S}$  is refuted if a) some model  $\mathcal{E}$  of inflation is observationally confirmed and if b) that particular extension of the standard model has some parameter,  $p_{inf}$  that can be modified to *increase the total*

<sup>18</sup>Other methods yield less precise estimates[57].

<sup>19</sup>Skeptics might reply that were  $\mathcal{S}$  so refuted it could be modified to a new  $\mathcal{S}'$ , which was not refuted by the addition of the hypothesis that  $\mu$  is not an independent parameter and cannot be varied without also, say, changing the proton-neutron mass difference, leading to large effects in star formation. It is of course, a standard observation of philosophers of science that most scientific hypotheses can be saved from refutation by the proliferation of ad hoc hypotheses. In spite of this, science proceeds by rejecting hypotheses that are refuted in the absence of special fixes. There are occasions where such a fix is warranted. The present case would only be among them if there were a preferred fundamental theory, such as string theory, which had strong independent experimental support, in which it turned out that  $\mu$  was in fact not an independent parameter, but could not be changed without altering the values of parameters that strongly affect star formation and evolution.

numbers of black holes produced, including primordial black holes. Given the accuracy expected for observations of the *CMB* from MAP and PLANCK, there is a realistic possibility that observations will distinguish between different hypotheses for  $\mathcal{E}$  and measure the values of their parameters.

In the standard “new” inflationary scenario[19] there is no parameter that fulfills the function required of  $p_{inf}$ . There is the inflaton coupling  $\lambda$ , and it is true that the amplitude of the  $f(n)$  is proportional to  $\lambda$  so that the number of primordial black holes can be increased by increasing  $\lambda$ . However, the size of the region that inflates  $R$ , is given by  $R \approx e^{\lambda^{-1/2}}$ . This effect overwhelms the possibility of making primordial black holes. In fact, if the observations confirm that the standard new inflationary scenario is correct, then  $\mathcal{S}$  is refuted if  $\lambda$  is not tuned to the value that results in the largest total production of black holes in the inflated region[7]. Because of the exponential decrease in  $R$  with increasing  $\lambda$ , this is likely close to the *smallest* possible value that leads to a sizable constant density of black holes produced in comoving volumes during the history of the universe. This is likely the smallest  $\lambda$  that still allows prolific formation of galaxies[7].

This seems consistent with the actual situation in which there appears to have been little production of primordial black holes, so that the primary mode of production of black holes seems to be through massive star production, in galaxies that apparently do not form till rather late, given that  $Q = \delta\rho/\rho \approx 10^{-5}$ .

However, there are non-standard models of inflation that have parameters  $p_{inf}$  that can be varied from the present values in a manner that tilts  $f(n)$  so that more primordial black holes are created than in our universe, without at the same time decreasing  $R$ [58]. If future observations of the *CMB* clearly show that the standard new inflation is ruled out, and only models with such a parameter  $p_{inf}$  are allowed, then  $\mathcal{S}$  will be refuted.

This is a weaker argument than the first one, but given the scope for increases in the accuracy of measurements of the *CMB*, and hence of tests of inflationary models, it is a realistic possibility that  $\mathcal{S}$  may be refuted by such an argument.

## 6.5 How early star formation could refute $\mathcal{S}$ .

As shown in [2, 52, 7] there are several directions in  $\mathcal{P}$  which lead to universes that contain no stable nuclear bound states. It is argued in [7, 9] this leads to a strong decrease in  $F(p)$  because the gravitational collapse of objects more massive than the upper mass limit of neutron stars in our universe seems to depend on the cooling mechanisms in giant molecular clouds, which are dominated by radiation from *CO*. In a universe without nuclear bound states the upper mass limit for stable collapsed objects is unlikely to decrease dramatically (as the dominant factor ensuring stability is fermi statistics) while without cooling from *CO* collapsed objects whose ultimate size is above the upper mass limit are likely to be less common.

In the absence of bound states the main cooling mechanism appears to involve molecular hydrogen[59], but there are two reasons to suppose this would not lead to plentiful collapse of massive objects in a world with nuclear bound states. The first is that in such

a world there would be no dust grains which appear to be the primary catalysts for the binding of molecular hydrogen. The second is that in any case molecular hydrogen is a less efficient coolant than  $CO$  [59].

This is also a weaker argument than the first, given present uncertainties in our understanding of star formation processes, but as that understanding is likely to become more precise in the near future let us follow it. Could this argument be refuted by any possible observations? In the present universe the collapse of massive objects is dominated by processes that involve nuclear bound states, but we have available a laboratory for the collapse of objects in the absence of nuclear bound states, which is the universe before enrichment with metals. Indeed, we know that there must have been collapse of massive objects during that period as otherwise carbon, oxygen and other elements would not have been produced in the first place. But given that  $CO$  acts as a catalyst for formation of heavy elements, and that the dust formed from heavy elements produced in stars is also a catalyst for molecular binding, there is an instability whereas any chance formation of massive objects leads in a few million years to both an enrichment of the surrounding medium and the production of significant quantities of dust, and these greatly increase the probability for the formation of additional massive objects. Hence, the initial rate of formation of heavy objects in the absence of enrichment *does not have to be very high* to explain how the universe first became enriched.

This shows that the fact that there was some collapse of heavy objects before enrichment does not refute the argument that the number of black holes produced in a universe without nuclear bound states would be much less than at present. But while it thus doesn't refute  $\mathcal{S}$ , it doesn't establish it either. It is still consistent with present knowledge that the production of massive objects in the absence of heavy elements proceeds efficiently under the right conditions, so that there may have in fact been a great deal of early star formation uncatalyzed by any process involving heavy elements.

This could lead to a refutation of  $\mathcal{S}$  because, in a world without nuclear bound states, many more massive collapsed objects would become black holes than do in our universe, where the collapse is delayed by stellar nucleosynthesis.

The question is then whether a combination of observation and theory could disentangle the strong catalytic effects of heavy elements leading to a strong positive feedback in massive star formation from the initial rate of massive star formation without heavy elements. Although models of star formation with and without heavy elements are not sufficiently developed to distinguish the two contributions to early star formation, it is likely that this will become possible as our ability to model star formation improves. If so then it is also possible that future observations will be able to measure enough information about early star formation to distinguish the two effects. If the conclusion is that the number of black holes formed is greater in world without nuclear bound states than in our own then  $\mathcal{S}$  would be refuted.

## 7 Conclusions

This article has been written with the hope of contributing to a debate about the possible role of the Anthropic Principle in physics and cosmology. Closing it I find myself even more puzzled than when I began as to why the Anthropic Principle has such strong support by so many otherwise good scientists. Having carefully considered the arguments, and engaged several proponents who I deeply respect in conversation and correspondence, I come to the conclusions I have explained here. The logic seems to me incontrovertible, and it leads to the conclusion that not only is the Anthropic Principle not science, its role may be negative. To the extent that the Anthropic Principle is espoused to justify continued interest in unfalsifiable theories, it may play a destructive role in the progress of science.

If I am mistaken about any of this, I hope someone will set me straight. The main points of my argument have been:

- No theory can be a candidate for a physical theory that does not make falsifiable predictions. To violate this maxim is to risk the development of a situation in which the scientific community splits into groups divided by different unverifiable faiths, because there is no possibility of killing popular theories by rational argument from shared evidence.
- The version of the Anthropic Principle described by **A** and **B** cannot lead to falsifiable theories.
- There are successful predictions claimed to have come from anthropic reasoning. Examination shows they all are of two kinds. 1) Uncontroversial use of selection effects within one universe, as in the argument of Dicke. 2) Simple deductions from observed facts, with the mention of life, or ensembles of universes playing no actual role in the argument leading to the successful prediction, as in the arguments of Hoyle and Weinberg. There are no successful predictions claimed to be Anthropic that do not fall into these two classes. Hence all claims for the success of the Anthropic Principle are false.
- The Principle of Mediocrity is ambiguous, because a reasonable change in the definition of the ensemble in which we or our civilization are taken to be typical can often turn an argument for a correct conclusion into an argument for an incorrect conclusion. In specific applications we find it is often unreliable. When the claims made can be tested, as in the doomsday argument applied to our ancestors, it often leads to false conclusions.
- We also find that eternal inflation cannot in any case lead to an explanation of the low energy parameters of the standard model, and thus to a resolution of the problem of why the parameters are chosen so as to allow stars and organic chemistry,

because the values of the low energy parameters play no role in the mechanism that generates the probability distribution for universes created by eternal inflation.

- It is possible to derive falsifiable predictions from a multiverse theory, if the following conditions are satisfied: 1) The ensemble of universes generated must differ strongly from a random ensemble, constructed from an unbiased measure. 2) Almost all members of the ensemble must have a property  $\mathcal{W}$  that is not a consequence of either the known laws of physics or a requirement for the existence of life. 3) It must be possible to establish whether  $\mathcal{W}$  is true or not in our universe by a doable experiment.
- There is at least one example of a falsifiable theory satisfying these conditions, which is cosmological natural selection. Among the properties  $\mathcal{W}$  that make the theory falsifiable is that the upper mass limit of neutron stars is less than 1.6 solar masses. This and other predictions of CNS have yet to be falsified, but they could easily be by observations in progress.

It must then be considered unacceptable for any theory, claimed to be a fundamental theory of physics, to rely on the Anthropic Principle to make contact with observations. When such claims are made, as they have been recently for string theory[16] this can only be considered signs that a theory is in deep trouble, and at great risk of venturing outside the bounds of science.

There are of course alternatives. String theory could possibly be shown to imply the conditions necessary for cosmological natural selection to be applied, in which case it would yield falsifiable predictions. Or another mechanism of selection of parameters could be found that does lead to falsifiable predictions. What is clear is that some falsifiable version of the theory must be found. If not, the theory cannot be considered a scientific theory, because there will be no way to establish its truth or falsity by a means which allows consensus to be established by rational argument from shared evidence.

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