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On anthropic solutions of the cosmological constant problem

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Abstract: Motivated by recent work of Bousso and Polchinski (BP), we study theories which explain the small value of the cosmological constant using the anthropic principle. We argue that simultaneous solution of the gauge hierarchy problem is a strong constraint on any such theory. We exhibit three classes of models which satisfy these constraints. The first is a version of the BP model with precisely two large dimensions. The second involves 6-branes and antibranes wrapped on supersymmetric 3-cycles of Calabi-Yau manifolds, and the third is a version of the irrational axion model. All of them have possible problems in explaining the size of microwave background fluctuations. We also find that most models of this type predict that all constants in the low energy lagrangian, as well as the gauge groups and representation content, are chosen from an ensemble and cannot be uniquely determined from the fundamental theory. In our opinion, this significantly reduces the appeal of this kind of solution of the cosmological constant problem. On the other hand, we argue that the vacuum selection problem of string theory might plausibly have an anthropic, cosmological solution.

Keywords: M-Theory, p-branes, Superstring Vacua, Cosmology of Theories beyond the SM.

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Contents

1. Introduction

In a recent paper [1], Bousso and Polchinski (BP) have revisited and improved some old ideas for explaining the value of the cosmological constant. They focused on the membrane creation scenario of Brown and Teitelboim [2, 3] and found what they claim to be a consistent anthropic solution of the cosmological constant problem. They exhibited models which potentially have a large number of discrete vacuum states, a small fraction of which have a small cosmological constant. They then invoke Weinberg's bound on values of the cosmological constant consistent with galaxy formation [4] and/or recent improvements on that bound [5, 6] (see however [7]) to argue that only those states with cosmological constant consistent with observation will have living organisms in them to observe the value of the cosmological constant. Finally, they argue that their models solve the empty universe problem encountered in several previous attempts to find an anthropic resolution of the cosmological constant problem.

The anthropic determination of the constants of nature is very controversial.[1] The present paper may be read as a critique of anthropic arguments in general; it was

[1] Weinberg has remarked that a physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you're against it, some people will think you're a little too interested.

directly inspired by the work of Bousso and Polchinski, which is, in our view, one of the more successful efforts to date to give a framework for such an anthropic discussion. We begin with a statement of principle about the anthropic principle, and argue that within a certain context one might imagine a scientifically defensible anthropic determination of the cosmological constant, but that with the current state of scientific knowledge, it does not make sense to discuss anthropic arguments for other physical parameters. Bousso and Polchinski proposed various scenarios to obtain a small cosmological constant. All require utilizing the strong version [5] of Weinberg's galaxy formation bound. In one, in which the compactification scale does not differ significantly from the fundamental scale, we find that the gauge hierarchy problem of the standard model is not resolved. Since, within our groundrules, one cannot explain this fine tuning anthropically, the model fails to be a consistent theory of our universe, but rather predicts that among those points in the BP discretuum which might contain intelligent organisms, the typical point does not contain a low energy spontaneously broken gauge theory.

In scenarios with d large compact dimensions, different issues arise. One cannot consistently ignore the flux dependence of the potential for moduli. As a consequence, if $d \neq 2$, cancellation of the cosmological constant still requires significant fine tuning. For $d = 2$ [8], however, it appears possible, in principle, to cancel the cosmological constant and to obtain a suitable hierarchy. This picture is much like that of the large dimension picture of [8], where the logarithmic behavior of massless propagators in two dimensions can give rise to hierarchies.

We have found another mechanism, which employs six-branes wrapped on CY three-cycles, which does not require large internal dimensions and achieves results similar to those of the two-dimensional BP models, in what appears to be a more generic region of moduli space.

We then describe a rational version of the irrational axion model [9] which might be derivable from string theory. This model can solve both the hierarchy problem (using SUSY) and the cosmological constant problem (anthropically).

The empty universe problem often arises in discussions of solutions of the cosmological constant [10, 2]. We believe that this is an artifact of constructing one's theory out of noninteracting modules. In a realistic theory, the potential for any inflaton field can have a dependence on the discrete vacuum labels. As a consequence, as long as the inflaton potential does not have a large flux independent piece, after the final tunneling event, the inflaton begins its classical motion at a point far removed from its vacuum value. It can thus reheat the universe in the standard manner.[2] However, in models of inflation with only very small fine tuning of parameters, this proposal leads, as a consequence of the low scale of the inflaton potential, to too

[2] The idea that the excitation of an inflaton away from its vacuum value could be a consequence of tunneling, was first employed in [13, 14].

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small an amplitude for density perturbations. Thus, all of the models which solve both the gauge hierarchy and cosmological constant problems, either have an empty universe problem, or predict too small an amplitude for density perturbations, or require finely tuned models of inflation.

We find this disturbing in the context of models based on a large discretuum, because all of the low energy parameters are random variables. Indeed, there are generically many solutions to the anthropic constraint on the cosmological constant, all of which have very different low energy physics. Since we discount the possibility of explaining the values of other parameters anthropically, we are left in an uncomfortable situation if we find that generic models in the class do not give correct predictions for low energy physics.

We should mention a very recent proposal to solve the cosmological constant problem using four-form fluxes which invokes, at most, much more mild applications of the anthropic principle. This idea involves tunneling through a large set of metastable states, a tunneling which finally ends when the cosmological constant is very small. If successfully realized, such a proposal would not suffer from many of the problems to be discussed here [11] (though some of the cosmological difficulties might persist). We will not explore this proposal here.

Finally, we propose a rather different, and much more modest, application of anthropic arguments. We imagine that generic SUSY violating vacua of M-theory are unstable and/or do not lead to any sort of large spacetime. There might be only a few special points which are dynamically stable once SUSY is violated. Even if one of them resembles our world, we must still understand why Nature did not choose one of the stable SUSY vacuum states. We suggest that anthropic arguments may provide part of the answer to this question, and give a broadbrush description of how such an argument might work.

As we were completing this paper, the paper [12] appeared, which has some overlap with our considerations.

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2. A principled approach to the anthropic principle

In our opinion, at the present time, any scientifically defensible use of the anthropic principle must conform to the following two guidelines:

- It must be embedded in an explicit mathematical model which truly has an enormous number of ground states, including some with the observed values of low energy coupling constants.
- It must not make arbitrary assumptions about the necessary conditions for intelligent life.

As to the first point, we will see that the Bousso-Polchinski analysis is the first plausible demonstration that the required dense set of metastable states might exist in string theory, but it is certainly far from convincing. As to the second, we will, for most of our discussion, adopt the viewpoint that the anthropic principle requires only that it be possible for complex forms of life to develop. We will only briefly touch on scenarios in which it might make sense to restrict one's attention to carbon based life. Then, given the current state of physics and biology, we claim that the second guideline rules out, for the forseeable future, the possibility of an anthropic explanation of any parameter besides the cosmological constant. The current state of biology is that we do not have an explanation of our own carbon/oxygen based form of life. The best expert scientific estimates of the probability for finding another intelligent species in our galaxy differ among themselves by many orders of magnitude. The current state of physics is that we do not have any fundamental explanation for what the low energy gauge group and its matter representations are. A consistent anthropic argument for e.g. the fine structure constant would have to show not only that the value of the fine structure constant was necessary to the existence of a large number of intelligent civilizations composed of carbon/oxygen people, but also that there were no other chemical compositions of life or different low energy gauge theories whose life forms differed from our own by virtue of having different low energy physics, which gave rise to comparable or larger numbers of civilizations. Thus, an anthropic argument which explains the value of some parameter makes sense if vacuum states with different values of this parameter suffer catastrophes so universal and cataclysmic that we can be absolutely sure (on the basis of current physics) that they can contain no intelligent life forms. The only parameters for which this seems conceivable are the cosmological constant, and (perhaps) the dimension of spacetime. They affect the universal dynamics of gravity and may thus lead to highly generic phenomena. We emphasize that within particular scenarios in particular vacuum states one may find that other parameters can affect the history of the universe in what appear to be catastrophic ways. For example, in states whose physics is close to what we observe, various parameters may affect the baryon asymmetry by many orders of magnitude. However, choosing the value of such a parameter anthropically would violate our principles unless we could show conclusively that no other states of the theory exist which have radically different low energy physics, but a reasonable probability of having some form of life.[3]

Our first guideline forces us to work within the context of a real theory with many ground states. The only candidate we have for such a theory at present is M-theory, and the candidate ground states in this theory include some with low energy physics wildly different from the Standard Model. Once we have accepted the anthropic principle we must, within M-theory, show not only that the most probable ground

[3]We emphasize that it is conceivable that with a more sophisticated understanding of physics and biology than we possess today, we might eventually find that the explanation of the value of some of the constants of nature would depend on the details of e.g., carbon based chemistry. However, for the forseeable future, this is not likely to be a question we can address scientifically.

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states with life resembling our own must have a certain parameter tuned to get the right baryon asymmetry, but also that this vacuum does not have a much lower probability for producing life forms than any other M-theory vacuum (or that it is dynamically chosen by minimizing the potential). Again, this is a task far beyond our current abilities. The only acceptable context for an anthropic determination of the sort of parameter under discussion, would be a theory with a large number of ground states which all had standard model low energy physics and differed only in the value of certain parameters. Prior to the work of BP, we would have found this possibility totally implausible. In the context of the BP approach, the question of whether there are many vacua with standard model low energy physics depends on how the moduli are affected by the fluxes.

In a geometrical picture, nonabelian gauge groups arise from singularities on moduli space. If the moduli which control the singularity have nothing to do with the cycles which bear the BP fluxes then it is perhaps plausible that we could have the same low energy gauge groups for many BP vacua. The parameters in the low energy gauge theory would be vacuum dependent.[4]In this context, we might imagine determining some other parameters anthropically. For example, it is plausible (though certainly not proven) that, within the standard model, the existence of life depends on the existence of a baryon asymmetry. Given a unique and verified theory of how the asymmetry is generated (which we do not yet have, and which probably depends on the existence of degrees of freedom outside the standard model) one could then get an anthropic constraint on the standard model parameters by insisting that a baryon asymmetry of some reasonable size was generated. This is likely to constrain the parameters to lie within a (not terribly small) distance from a submanifold of low codimension.

Although we have now identified a set of hypotheses under which anthropic determination of some other parameters would be valid, the price to be paid is high: in such a model, none of the parameters of low energy physics is determined by anything other than these very weak anthropic constraints. An honest evaluation of such a model would require us to determine the properties of all the vacuum states within the anthropic range and see whether the values of parameters which fit our observations are not highly improbable members of the distribution. If they are, one would have a fine tuning problem. There are many parameters in the standard model (masses and mixings of fermions in the heavier generations)which appear somewhat fine tuned but are unlikely to significantly affect the question of whether there is a baryon asymmetry, so it seems likely to us that even with the hypothesis that all BP vacua within the anthropic range of the cosmological constant have standard model physics with varying parameters one is unlikely to get a satisfactory anthropic

[4]In the large dimension scenario discussed below, it is possible that the low energy parameters depend only weakly on the fluxes.

explanation of the world. This is disturbing, because we will find that there are typically many BP vacua which satisfy the anthropic bound on Λ, so that this sort of model forces one to find anthropic explanations for the other constants of nature.

There is a second approach to the sort of anthropic argument described by BP, whose existence we feel we must acknowledge. One can imagine a vast multiverse in which all of the metastable vacua are realized at different "places". Then the much more restrictive anthropic arguments based on our own biochemistry could be used to explain why we were in a particular place. One would need only to show the existence of vacuum states with low energy parameters in the right range and would not have to take into account questions of how typical these were among all vacuum states which could support some kind of life.

It seems to us that this scenario amounts to abandoning the basic goal of fundamental physics, which is to find the principles which regulate the behavior of the world we observe. That quest, in the kind of theory envisaged in the previous paragraph, would stop at the standard model. All further explanation of the world we see would have a contingent nature, like the explanations of history and geography. The fundamental theory of physics would mostly be about things we can never in principle observe. In addition to our evident distaste for such a state of affairs, we have serious doubts about whether it is compatible with the holographic ideas which seem to play a central role in M-theory. The different "places in the multiverse" are outside each other's event horizons and we are ascribing independent degrees of freedom to each of them. Though we cannot rule it out at present, we suspect that such a scenario is incompatible with the holographic principle.

One other disturbing feature of such a picture should be noted. In such a model, all of the constants of nature relevant to low energy physics are random variables of this sort. As we have remarked above, it seems highly unlikely that they are all fixed by anthropic considerations. Thus, for example, one might imagine that the mass of the u quark or the value of the fine structure constant is fixed by anthropic reasoning, but it seems unlikely that, say, all of the values of neutrino masses, or all of the elements of the KM matrix and the heavier quark masses, can be fixed in this way. Thus, even the strong anthropic principle implied by the multiverse picture will, in the end, leave us with fine tuning puzzles that cannot be resolved.

To our knowledge, the first attempt to make an anthropic determination of the cosmological constant incorporating our first guideline was [13, 14].This model combined a scalar field called a *relaxon* with an extremely flat potential (which could be justified using a variety of symmetries) with a (then) conventional tunneling inflaton field. The inflaton was supposed to tunnel out of a false DeSitter vacuum and reheat single bubbles. As a consequence of the exponential expansion, the bubbles never coalesced and each was a potential universe. This process continued eternally. The low energy cosmological constant in each bubble was determined by the position of the relaxon field at the time the bubble was nucleated. This gave rise to an ensemble of universes with various values of the cosmological constant. It was conjectured that only those with a cosmological constant within a few orders of magnitude of what was then the observational upper bound would be able to support life. This would have been an adequate explanation of the observations if the distribution for Λ had been flat. But in fact, according to the logic of the model, the number of possible universes grows exponentially with time, as Λ decreases and so there is a prediction that Λ take on the largest possible negative value compatible with the existence of life. It was later argued [4] that this might actually be zero within the observational errors. However, today the model is surely ruled out.

Abbott [10] attempted to rescue this model by adding a rapidly oscillating potential for the scalar field, which had many minima and in particular, one near the origin. The universe was then argued to sequentially tunnel, rather than slowly roll, down to the last positive minimum. This minimum is stable because of the Coleman-DeLuccia suppression of tunneling into Anti DeSitter spaces. The problem is that in the penultimate metastable state, the universe inflates away all of its energy density and finds itself in a state with very small positive cosmological constant, but no matter or radiation. This is the *empty universe problem*.

Weinberg attempted to constrain models of this type by doing the first honest calculation of the anthropic bound on the cosmological constant. He pointed out that once galaxies form, there can be no further bound. Given a single galaxy one will inevitably have stars and planets, and physics inside this gravitationally bound system will be insensitive to the exponential expansion of the universe on time scales much longer than the age of our universe. Weinberg's original estimate was a bound of $10^2 - 10^3$ times the critical density. Recent work has attempted to argue that the *typical* value of the cosmological constant in an ensemble satisfying Weinberg's bound is actually of order the critical density [5]. The arguments which go into this bound depend only on the physics of gravity and the equations of state of matter and radiation. Thus, it has the insensitivity to our ignorance required by our second guideline.[5] In the next section we will see whether the models of Bousso and Polchinski are similarly insensitive.

3. Flux redux

The work of BT was based on the observation that screening of 4-form flux by membrane antimembrane creation provided a mechanism for dynamically changing

[5]Weinberg's bound does implicitly assume that galaxies are necessary for life. The eminent astronomer F. Hoyle once suggested [15] (albeit in a work of speculative fiction) that the typical lifeforms in the universe were vast interstellar gas clouds who were very surprised to find that life could exist on planets. It is clear to us neither that Weinberg's bound would apply in such a hypothetical situation, nor that we know enough about complex systems to rule out Hoyle's Conjecture. Such are the travails of anyone foolish enough to think seriously about the anthropic principle.

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the cosmological constant in a four dimensional universe. This is a precise analog of screening of electric fields by charged particle creation in the Schwinger model. BP generalize this idea by observing that M-theory compactifications on a 7-manifold with many 3-cycles (we will generally think of a Calabi-Yau 3-fold fibered over a circle or an interval), will have many four-form fluxes in the four dimensional effective field theory. The corresponding membranes are the original membrane of M-theory and five-branes wrapped around the three-cycles. If there are N such fluxes, the low energy effective energy has an energy density, in the case of a torus

$$\frac{M^6}{M_P^2}\sum_1^N q_i^2 n_i^2 - \Lambda_b\,, \tag{3.1}$$

where q_i^2 (in a slight change of notation from BP) is the volume of the i-th 3-cycle in fundamental units ($V_i M^3$) and Λ_b a bare cosmological constant independent of the fluxes. M_P is the four-dimensional Planck mass, given by the equation $M_P^2 = M^2(M^7 V_7)$. In the simplest scenario. While this equation looks rather general, this is deceptive. It is valid for the seven torus, but not for manifolds in which some cycles can shrink to zero at fixed volume, with the volume of Poincaré dual cycles also fixed. BP argue that if the q_i are incommensurable, and if either the unit of energy density involved in the change of a single flux is small compared to Λ_b or the number of fluxes is large, then there will always be points in the *discretuum* of allowed values of n_i, for which the cosmological constant is consistent with observation. These vacua are then chosen by the anthropic principle.

There are a large number of assumptions involved in writing the energy equation in the simple form above (most of these are mentioned by BP). First and foremost, we are using low energy effective field theory. Thus, all energy densities should be much smaller than the fundamental scale, and fluxes should not be so large that higher order terms in the effective action are important. As an example of what is involved, note that in 11D SUGRA, the BP fluxes give tree level masses to many components of the gravitino. The one loop Coleman-Weinberg formula for the dependence of the vacuum energy density on the fluxes contains terms quartic in the flux. Thus to trust the BP analysis one must be in a regime where these and other terms are negligible. BP achieve this by insisting that some of the internal dimensions are larger than the fundamental scale. We can distinguish two cases: the dimensions are slightly larger than the fundamental scale, or they are much larger.

Consider, first, the case that they are slightly larger. Note that low energy supersymmetry, in the conventional sense, is not likely to be relevant in this case, since the energy associated with the fluxes will be far larger than the would-be scale of supersymmetry breaking, and the fluxes themselves break SUSY. If the dimensions are only slightly larger (up to a few orders of magnitude), then the parameters of the standard model, such as the Higgs mass and the value of the QCD scale, as well as

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gauge and Yukawa couplings, will be sensitive to the values of the fluxes. Moreover, there is likely to be a huge number of states which satisfy the anthropic bound on the cosmological constant. For example, if there are, as in the discussion of BP, of order 120 fluxes, than changing the values of the charges (q_i) by a factor of 2 changes the number of acceptable states by a factor of order 10^{60}. So all of the parameters of the standard model — and in particular the gauge hierarchy — will be, unpredictable, simply determined by anthropic considerations. The Higgs mass, for example, will receive contributions from couplings to the four-form flux, such as

$$\int d^d y d^4 x \sqrt{g} F^2_{MNOP} |\phi|^2 \,. \tag{3.2}$$

Corrections to the gauge couplings, from operators such as $F^2_{MNOP} F^2_{\mu\nu}$, will be nominally of order one ($\int d^d y \sqrt{g} F^2_{MNOP}$ is, by assumption, of order the fundamental scale); similar remarks apply to the Yukawa couplings.

This violates the principles we laid out earlier. Note also that one is also making the assumption, here, that any moduli of the compactification (e.g. those associated with the relatively large size of the compact dimensions) have stable minima for all values of the fluxes. This seems a quite strong assumption, given that the flux contributions to the potential are not likely to be much smaller than other contributions.

We have spoken of the Higgs particle, in this small extra dimension case, but one could also imagine that technicolor plays some role. However, in the anthropic context, technicolor scenarios are highly suspect, if not ruled out altogether. Even the most ardent enthusiast would admit that the generic technicolor model is inconsistent with experiment. To promote an anthropic technicolor scenario consistent with our rules, advocates would have to show that these models not only arose among those BP vacua with reasonable values of the cosmological constant, but also that technicolor models consistent with experiment were generic in these vacua. Otherwise, and this is the most likely conclusion, the BP prediction for a universe with relatively small internal dimensions is that the universe does not contain a spontaneously broken gauge symmetry at the electroweak scale, or at best that it does contain one but that the model is inconsistent with observation.

The alternative, is to consider the possibility that some dimensions are very large, as in the large dimension proposal of [8]. In this case, the assumption that the values of the moduli are independent of the fluxes is almost certainly not correct, and it is most natural to imagine that the fluxes play a role in fixing the moduli. We will first assume that there are $d \geq 3$ dimensions with $RM \gg 1$ and, for the moment, that the cycles which define the fluxes have linear scale of order R. Most other assumptions about the number of large dimensions and the flux bearing cycles lead to similar conclusions. We will explore some possible exceptional cases individually below. We further assume that the standard model lives on a brane, that the bulk is supersymmetric and that SUSY breaking comes from a brane, not necessarily the standard model brane. In particular, the leading order in RM bulk geometry will be assumed Ricci-flat.

Contributions to the four-dimensional cosmological constant can now be classified by their dependence on RM. A brane cosmological constant is of order one. A bulk curvature squared term is of order $(RM)^{(d-4)}$ and there are various bulk contributions to the energy which scale like $(RM)^{(d-6)}$. The flux terms scale like $(RM)^{(d-6)}$. They are thus subdominant at large RM but we can make them arbitrarily large and positive by increasing the value of the quantized flux (though we should stop before violating the rules of effective field theory). Finally, we can imagine some independent flux which (perhaps unrealistically) we assume cannot be changed by dynamical tunneling processes. This will give a positive term in the energy, with a coefficient that we allow to be large. We will call it the *flux ex machina*.

Assume first that $d > 4$. Then the energy is dominated by the curvature squared term, $a(RM)^{(d-4)}$. In order for the potential to be bounded below at large RM, a must be positive[6]. The radius can be stabilized at a large value by balancing the contribution of a large BP flux against this curvature squared term. However, both terms give positive contributions to the cosmological constant and the BP cancellation is not operative. The situation is not improved by introducing the *flux ex machina* since it too gives a positive contribution to the cosmological constant. Note that it does not make sense to stabilize the radius by balancing the positive curvature squared term against, e.g. a curvature cubed term. These can balance at large RM only if we fine tune dimensionless coefficients. One would have to find a theory which had a variety of vacuum states for each value of the BP flux, in which the short distance physics induced many different values for the coefficients in the effective lagrangian, including finely tuned ones, in order to find an anthropic explanation of this tuning.

We thus assume $d \leq 4$, in which case the brane cosmological constant dominates the energy density in the absence of large fluxes. This can be assumed negative. The BP flux term must be of the same order of magnitude as this term at the anthropic value of the BP fluxes. Since this term depends on R, it must be one of the important terms in the radial stabilization equation. For the same reason, it is also much larger than the curvature cubed term (which scales the same way as a function of RM). For four large dimensions this means that we must rely on a *flux ex machina* whose contribution to the energy grows like $(RM)^p$ with $p > 0$ in order to stabilize the radius. But there are no such fluxes in four dimensions, so we conclude that while the BP mechanism can work, the radius cannot be stabilized at a large value and the

[6] We note that a metastable minimum for RM would be incompatible with the BP idea. In the BP scenario the universe is imagined to tunnel around the flux lattice many times before finding the anthropic vacuum with small cosmological constant. No metastable vacuum for the moduli could have a long enough lifetime to "wait for the BP process to be completed".

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model is inconsistent. If there are three large dimensions, we can stabilize the radius by balancing the curvature squared term against the BP flux.[7] The required coefficient of the curvature squared term is however negative (since both terms decrease with RM) and we are again stuck with a metastable minimum for the radius.

We now relax our assumptions and turn to the case of two large dimensions. The seven-form flux of M-theory is integrated over one small and two large dimensions in order to get the BP fluxes in the noncompact dimensions. The energy of a BP flux now scales like $(RM)^{(-2)}$. The dominant term in the energy is no longer the brane cosmological constant, but a term scaling like $a\ln(RM)$ coming from the infrared behavior of two-dimensional massless propagators. We will however include the brane cosmological constant as well because logarithms are not that large even when $RM \sim 10^{15}$. Stabilization now requires $\sum n_i^2 \sim a(RM)^2$ and that the coefficient of the logarithm is positive. The requirement that the cosmological constant cancel is now $\ln(\sum n_i^2) \sim \Lambda_b$. The bare cosmological constant must of course be negative.

In order to solve the gauge hierarchy problem, we follow [8] and ask that $M \sim 1\,\mathrm{TeV}$, which,[8] given $M_P \sim 2 \times 10^{18}\,\mathrm{GeV}$, means $RM \sim 10^{15}$. This requires Λ_b to be an order of magnitude or two higher than we might have expected it to be but still much smaller that one would have obtained in a similar theory with no bulk SUSY. We can also estimate the contributions to the vacuum energy due to loops of particles which obtain SUSY violating masses from the BP fluxes. These are smaller than or equal to the flux energies themselves, so the model appears self consistent.

There are several attractive features of this model. The BP mechanism gives a rationale for the stabilization by large flux postulated in [16]. Using anthropic logic, the large flux vacua are the only ones we are likely to see. The two ideas interact synergistically, for the large flux also facilitates the cancellation of the cosmological constant. In this picture, the parameters of the SM are not very sensitive to the values of the fluxes, since the fluxes are of order $1/\sqrt{V}$. Finally, the problem of the small radius picture, that there are likely to be vast numbers of states with suitable values of the cosmological constant, is significantly ameliorated here. If the volume is large, only a small number of fluxes are required in order to implement the BP cancellation of the cosmological term. So rather than, say, 10^{60} states, one might easily imagine that there are only 100's or 1000's of states compatible with the bound.

4. Brane-antibrane separation

We would like to present another scenario realizing the basic philosophy proposed by

[7] In order for this mechanism to work, the brane cosmological term must be of order $1/R$. This can be explained by SUSY if the SUSY breaking scale is no bigger than the flux terms.

[8] Of course the phenomenological constraints on models with two large dimensions tell us that M must be greater than about $50\,\mathrm{TeV}$. One must presume that this is still consistent with solving the hierarchy problem.

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BP. We will also generate a large number of metastable states among which we find some vacua with a small value of the cosmological constant, but the way we obtain the large number of metastable states will be different.

Let us imagine a compact space (e.g. a Calabi-Yau space) with a p-cycle of a small volume (imagine S^3 which shrinks to zero at the conifold point of the moduli space). Let us furthermore assume that there are two different places where this p-cycle shrinks to a small size: we therefore deal with submanifolds X, Y which are topologically equivalent. Now we can wrap N $(p+3)$-branes on X and N $(p+3)$-antibranes on Y. Those branes and antibranes are extended in the large dimensions, all the transverse dimensions are compact and therefore the total brane charge must vanish. There can be several pairs of cycles X_i, Y_i, $i = 1, \ldots, n_{\text{cycles}}$ in the same way as BP use many different types of fluxes. The number N_i of the branes wrapped on X_i plays the role of the flux in the BP picture. An easy toy model for visualizing this configuration is a torus $\mathbb{T}^2$ whose a cycle shrinks to zero at two opposite points along the b cycle. We see that although conservation of the charge does not prevent the branes from annihilating, there is an energy barrier that makes such an event unlikely. The brane (or antibrane) must move through the "thick" region where its tension is necessarily large.

Otherwise the physics is similar to that of the picture of BP. There is a negative "bare" cosmological constant which is compensated by a large number of branes and antibranes wrapped on the shrunk cycles X_i, Y_i, each of which contributes a positive amount to the vacuum energy. Sometimes — after a cosmologically long period of time — a brane tunnels through the "thick" region of the Calabi-Yau space and annihilates with its antipartner, reducing the number N_i by one. The relevant instanton consists of a bubble in three space in which the compact dimensions of the branes and antibranes move together and annihilate. If there are enough types of six-brane, and/or if the energy densities associated with them are sufficiently small, it is possible to cancel off the negative cosmological constant to the desired degree of accuracy.

There are several reasons why we consider this picture to be more flexible than the picture of BP. First of all, the tensions of the wrapped branes can contribute small amounts to the 4-dimensional effective vacuum energy The natural small number can be obtained from the size of the shrunk cycle. Furthermore in the previous sections we showed that it is hard to ensure both stabilization of the moduli *and* the cancellation of the vacuum energy in the BP picture.

In the case of the wrapped branes, the contribution to the vacuum energy from the wrapped branes depends mostly on the geometry near X_i, Y_i and not much on the overall size of the manifold. Therefore we effectively decouple the problems of the stabilization and the vacuum energy: the branes on X_i, Y_i are responsible for the cancellation of the cosmological constant, while a different dynamics solves the stabilization of the overall size of the manifold.

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As far as stabilizing the moduli of the shrinking cycle is concerned, it appears sufficient to put a three-form flux onto the shrinking cycles on which the branes are wrapped. The size of the cycle is then determined by the ratio of this flux and the 6-brane charge, and is naturally small if the ratio is small. Of course, this discussion is too glib. We are trying to discuss nonsupersymmetric compactifications of 11D SUGRA on a complicated manifold with fluxes and branes, and the real dynamics is highly nontrivial. Our discussion here is merely suggestive of the existence of a stable solution. One point in favor of this view is that by making the manifold large, we can control the scale of SUSY breaking and study configurations that are close to supersymmetric ones.

This might also have phenomenological implications. If the manifold is large, and the standard model lives in the bulk, far from the small cycles, SUSY breaking in the standard model will be suppressed. Thus, this kind of model can support hidden sector SUSY breaking, perhaps with the conventional intermediate scale.

5. Rationalizing the Irrational Axion

Some time ago, Seiberg and two of the present authors described another class of models with a discretuum of vacua [9]. Although the main thrust of that paper was an explanation of the strong CP problem, it was noted that the same model also might provide an anthropic resolution of the cosmological constant problem. We would now like to present an updated version of that model which is at least superficially compatible with M-theory.

It is well known that the F-theory region of M-theory moduli space [17, 18, 19] can give rise to vacua with a direct product gauge group with large numbers of relatively large factors. Let us assume such a compactification, with 4 conserved supercharges (up to low energy gauge theory effects, which will break SUSY) and a product $G \otimes G_1 \otimes \cdots \otimes G_N$. G will be asymptotically free and have SUSY breaking dynamics at a scale $M_{\rm SUSY}$. The G_i are taken to be $\mathrm{SU}(N_i)$ groups with a sufficient number of matter fields to make them infrared stable at the fundamental scale. However, we imagine that their β functions are relatively small because e.g. the number of flavors of fundamental chiral fields is near the critical value. Furthermore, we imagine that there are low energy couplings between the fields in G and those in the G_i. That is, we have low energy SUSY breaking in the G_i rather than gravity mediated effects. The SUSY breaking removes some G_i matter fields, making the infrared running of the G_i couplings unstable. Since the N_i are large, all of the G_i gauge couplings will become strong at scales not too far below $M_{\rm SUSY}$. We will approximate this situation by saying that all the scales are approximately the same, and call the single scale m.

Finally, we imagine that all but one of the moduli of the theory have been frozen, either by a high energy SUSY and R preserving superpotential, or by the effects of

SUSY breaking. The single axion field is a periodic field which originates as a component of some higher dimensional p-form gauge field. If a is the canonically normalized four-dimensional axion, then a/f_a is a periodic variable with period 2π, and this defines the axion decay constant f_a. a has couplings to the gauge fields of the form $(a/f_a)\sum Q_i$, where Q_i the topological charge density of the gauge group G_i. Instanton effects in the gauge groups will give rise to an axion potential with period 2π. However, if the process of SUSY breaking leaves some unbroken chiral symmetries, and a corresponding set of massless nonsinglet fermions, then spontaneous breaking of these symmetries will give us a discretuum of vacua. For simplicity, suppose that all fermions besides the gauginos are lifted by SUSY breaking. Then each SU(N_i) gauge theory will have N_i vacua due to gaugino condensation.

The potential generated for the axion by G_i now has periodicity $2\pi/N_i$, so we obtain a formula for the total potential

$$V = \sum_i e_i M^4 P_i \left(\frac{a}{f_a N_i} \right), \tag{5.1}$$

where the P_i have period 2π and the e_i are numbers of order one. If the N_i are relatively prime, this function will have $\prod N_i$ minima. If $\prod N_i \sim (M^4/\Lambda)$ then there will typically be at least one minimum with $V \sim \Lambda$. Thus, again we have a discretuum with at least one vacuum which satisfies the observational constraints on the cosmological constant.

We have neglected the contribution to the cosmological constant from the SUSY breaking dynamics itself. We can take this into account by including the coupling of the axion to G. If the G theory has only a few vacua it will generate a potential of the form $M_{\mathrm{SUSY}}^4 P_G(a/f_a)$ where P_G has a short period (a few times 2π). Thus, it will have many zeroes within the period of the potential (5.1). In regions of size $\Delta a/f_a \sim (M/M_{\mathrm{SUSY}})^4$ around these zeroes the problem reduces to the one we solved previously, so if $\prod N_i \sim (M_{\mathrm{SUSY}}^4/\Lambda)$ there will be a minimum with a cosmological constant of order Λ.

6. The empty universe problem and the cosmic microwave background (CMB)

Anthropic models of the cosmological constant often suffer from the empty universe problem [10, 2]. That is, while they explain why there is a vacuum state with small cosmological constant, their mode of accessing that vacuum leaves them with no mechanism for generating the entropy of the cosmos. In broad terms, the problem is that if one achieves the anthropic vacuum by tunneling from a metastable state with positive cosmological constant, one appears to tunnel into an empty vacuum. The model of [13, 14] shows that this is not an inevitable consequence of anthropic ideas.

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BP present three different suggestions for solving the empty universe problem. The first exploits the Hawking temperature of the penultimate metastable DeSitter vacuum to ensure that an inflaton tunnels to a nonvacuum value. This mechanism is unlikely to work in a model in which the gaps in the discretuum are small compared to the Planck scale. We have seen that the latter condition is necessary to a solution of the hierarchy problem. The second suggestion uses properties of a particular class of inflaton potentials. The third (which BP attribute to suggestions of Susskind and Thomas) is, we believe, much more generic. It is simply to recognize that in a model containing a discretuum, $\{n\}$ and an inflaton field ϕ, the effective potential $V(\phi, \{n\})$ is not apt to be a simple sum of a discretuum potential and an inflaton potential. That is, the inflaton potential will depend on which point in the discretuum one is working at. This is essentially the same point that we have made about the $\{n\}$ dependence of the potential for moduli.

It is important that the flatness of the inflaton potential be generic and independent of the discretuum. This is easily achieved if the inflaton is itself a modulus [20].[9] In such a model the tunneling process from the penultimate point in the discretuum to the anthropic vacuum will place the inflaton at some point on the equipotential surface whose energy (including derivative contributions) is equal to that of the false vacuum. The particular point on this surface is determined by minimizing the action of the relevant instanton. This point is in the basin of attraction of the anthropic vacuum but definitely not at it, and in models where the potential is a generic function of discretuum and inflaton there is no reason why we cannot have inflation and reheating.

The real problem is in the details. Models which solve the hierarchy problem have a low value for the gap in the discretuum. In the axion and wrapped brane models we can tolerate a vacuum energy scale of $10^{10.5}$ GeV if SUSY breaking is communicated to the standard model via gravitational effects. In the BP model with two large dimensions and a fundamental scale of a TeV, the vacuum energy scale is 1 TeV. Given a modular inflation model, the generic prediction for the amplitude of CMB fluctuations in such models will be too small to be compatible with observations.

There is a sense in which this problem is more severe than the empty universe problem we claim to have averted. As far as we can see, models of the type we are discussing could easily produce situations in which we would be unable to rule out the possibility of intelligent life. That is, for a broad range of choices of both discrete (gauge groups) and continuous parameters in our models, we would find a matter dominated era of the universe in which galaxies could form and there was a rich and complex low energy physics. Nonetheless, the generic prediction would be that the amplitude of primordial CMB fluctuations was incompatible with observations

[9]Modular inflation models still require two or three orders of magnitude of fine tuning, which is much less than most alternatives. Some ideas for explaining this tuning can be found in [21].

in our universe. We would conclude that within our class of models, a universe that resembled our own was very improbable, among all those which might have life in them.

We would like to acknowledge that many inflation theorists would consider our argument to be a defect of modular inflation models but not of the general anthropic ideas we are exploring here. There are inflationary models with a low vacuum energy scale and adequate amplitudes for density fluctuations. Few of these models satisfy the usual field theoretic criterion of naturalness. They contain small dimensionless parameters whose size is not explained by any symmetries. As in our discussion of technicolor above, we consider this a more serious defect in the anthropic context than otherwise. If one is writing down a phenomenological approximation to a unique theory of the universe, one may hope that violations of naturalness will eventually be explained by explicit calculations in the theory of everything. In the anthropic context, one must view all parameters as being drawn from an ensemble consistent with the very weak anthropic constraint. Violations of naturalness would seem to occur with very low probability.

7. Anthropic vacuum selection in M-theory

So far, we have considered a variety of anthropic proposals for understanding the cosmological constant, and possibly other parameters in the low energy effective action. These suggestions have in common the idea that there are a vast array of stable or metastable ground states of string theory with rather generic properties. We have found all of these ideas troubling in some respect. Not least of all, it is not clear that such a discretuum exists in string theory. In the case where the charges are large, one would require, for example, that there be a stable minimum of the moduli potential for every value of the fluxes. Yet changes in the fluxes are not extremely small perturbations in the theory, and it is not clear whether such a set of stable solutions would exist. Indeed, our experience in M-theory is that it is very hard to stabilize the moduli once SUSY is broken. In the case of large dimensions, we saw that only for the case of two large compact dimensions is it possible to cancel the cosmological constant without fine tuning. Whether or not there exists a discretuum of solutions depends on detailed properties of the theory, which we are not in a position to explore at the present time.

In this section, we propose an alternative viewpoint. Rather than arguing that there are innumerable string vacua with properties almost compatible with the existence of life, we would like to consider what we view as a far more reasonable possibility: generic string vacua are incompatible with the formation of structure in the universe. This, we would suggest, might be the solution of the vacuum degeneracy problem of string theory — provided that there are at least a small number of vacua compatible with the very weak anthropic principle we have advanced in section 2.

To understand this point, let us divide the known ground states of string theory into categories:

- Supersymmetric vacua in dimension $d \geq 5$, or supersymmetric vacua in dimension $d = 4$ with more than eight supersymmetries.

- Supersymmetric vacua in dimension $d = 4$ with four or eight supersymmetries and exact moduli (as well as some approximate moduli).

- Four-dimensional vacua with SUSY restored only in extreme regions of moduli space where gravity decouples.

- Vacua in $d = 4$ without supersymmetry anywhere in the moduli space — i.e. with Planck scale SUSY breaking. Note that most of the hypothetical BP vacua fall into this category.

- Theories in $d < 4$ with or without supersymmetry.

Our goal will not be to prove that any of these possibilities is incompatible with the development of a large universe with structure on interesting scales, but rather to argue that it is plausible that generic vacua in each of these classes are incompatible with the very weak version of the anthropic principle we have proposed. This is, in our view, the most reasonable possibility, compatible with our present understanding of M-theory, for understanding the problem of vacuum selection. The reasons our arguments must be very tentative are easy to understand. First, if we give up the anthropic explanation of the cosmological constant, we don't know how (or whether) the cosmological constant problem is solved in string theory. We might imagine a gamut of possibilities: that it is only solved in states with some degree of (approximate) supersymmetry, that it is always solved, or that it is never solved. Second, we have no understanding of the degree to which inflation is generic in string theory. Our working assumption is that it is reasonably generic, i.e. that it happens in some finite (if small) fraction of string ground states. For example, if the scale of some modulus potential is lower than the string scale, and if the modulus varies on a scale of order M_p, then the number of e-foldings is of order one; presumably if it is of order $20 - 30$, one has the possibility of structure formation.

With the understanding that our goal is only to provide suggestive, rather than definitive, arguments, let us consider the various cases in turn.

- Theories in $d > 4$, with some degree of supersymmetry, or in 4 dimensions with more than 8 supercharges: in all of these theories, there are exact moduli spaces. The dynamics on the moduli space is highly constrained. Suppose that the universe was at some time hot, and reasonably large. Subsequently, the energy density in the zero modes of the moduli redshifts much more rapidly than T^d. Furthermore, there is an instability [20] which converts modular zero mode energy rapidly into radiation. There are stable massive objects in these models, but they are BPS and in generic regions of M-theory moduli space have mass of order the Planck scale. The only conserved quantum numbers they carry are coupled to long range fields and there cannot be an excess of particles over antiparticles. There are no known metastable neutral particles.

There is no mechanism for producing these particles in the regime where the temperature is well below the Planck mass and semiclassical cosmology makes sense. Thus, their initial density is an input. However, we can conclude that structure formation is unlikely for any initial density. Would be structures are composed of equal mixtures of particles and antiparticles and rapidly annihilate into radiation. It seems that generic models of this type are radiation dominated throughout all of cosmic history, and no structures are formed.

We realize that there are loopholes in these arguments, but suggest that it is likely that they can be closed as our understanding of these states improves.

- Theories in $d = 4$ with approximate $N = 1$ supersymmetry in extreme regions of the moduli space: it is well known that these theories tend to exhibit runaway behavior towards supersymmetric regions of moduli space. No example is known where one can show, reliably, that there is a stable local minimum of the potential in the interior of the moduli space. While in general we do not expect metastable minima in the interior of the moduli space, it is plausible that there are reasonably stable minima in some cases. The question would be how frequently such minima appear. Roughly speaking, we might imagine local minima are metastable when, for example, there is a low energy theory with moderately small gauge couplings. We do not know how to assess this possibility, since we have no examples. It is possible that they are rare. Racetrack models have been proposed as a mechanism to stabilize some moduli [21]. These models involve discrete fine tunings of gauge groups and particle content, and so, by definition, if they occur at all they are rare. We will assume that this is the case; generic string states with asymptotic $N = 1$ SUSY exhibit only cosmological solutions. Can these be compatible with the formation of structure? Quite generally, for the superpotentials that give rise to runaway behavior, the potential is related to the scale of supersymmetry breaking. Generally for these potentials the potential energy drops more rapidly than $1/R^4$, and the temperature always dominates the energy [20].

- Theories where SUSY is broken at the Planck scale and there is no runaway to a supersymmetric region. All examples of this type have negative potentials which draw the system towards apparently catastrophic regions in the interior of moduli space. Since reliable approximations break down before the catastrophe is achieved, we cannot say for certain that these models have no sensible large scale physics, but it appears highly unlikely. Note that once one puts moduli into the picture, the BP vacua are in this category. In the bulk of the text we have imagined, with BP, the possibility that most of the moduli are stabilized by some higher energy dynamics. Here we opine that this is unlikely, and that the BP vacua are not really stable.

- Theories in $d < 4$: here the bizarre nature of long range gravitational interactions makes it unlikely that structure will form. There is no newtonian gravitational potential, no Jeans instability, and no reason to expect galaxies.

- The most likely candidate vacua in which there might be structure formation but obvious disagreement with observation, are those with exact $N = 1, 2$ supersymmetric moduli spaces in $d = 4$. ($N = 1$ theories with exact moduli spaces were discussed in [22].) These vacua can have weakly coupled gauge theories in them which generate a variety of scales well below the Planck scale. As a consequence, it is possible to have approximately conserved quantum numbers like baryon number or exact discrete symmetries which guarantee the existence of long lived massive particles (this was not the case in the examples described in [22], however). Given this possibility, depending on initial conditions and the details of the dynamics, one may develop an asymmetry in the approximate quantum number. Stable structures can now develop via gravitational clumping. Note that the cosmological constant vanishes in such scenarios, so something like galaxy formation may very well occur. For the $N = 2$ case, the region of moduli space where there is strong IR dynamics at scales well below the Planck scale is very tiny, and one may argue that these vacua require fine tuning. However, for $N = 1$ there may be codimension zero moduli spaces with unbroken nonabelian groups. The real question with regard to these vacua is how likely it is that one has weakly coupled gauge theories. This is a question that we do not yet know how to answer. One possibility for $N = 1$ is that the gauge couplings depend on the exact moduli. If the universe is closed, the exact moduli will be time dependent early in cosmological history, but will come to a halt at some point in moduli space. The question of whether gauge couplings are weak would depend on the initial conditions. Thus, the search for an anthropic vacuum selection principle might fail because of our inability to rule out vacua in this category. While it is possible that SUSY is incompatible with life, it seems possible that it is compatible with structure formation.

Our proposed anthropic vacuum selection principle can rule out large classes of string vacua, but vacua with exact $N = 1$ SUSY resemble the real world a little too closely to be eliminated by the very weak form of the anthropic argument that we have advocated. We have however assumed that reasonably weak gauge couplings are easy to come by in M-theory. Perhaps this is not the case. One way of explaining the weakness of gauge couplings utilizes the racetrack mechanism [21]. This requires an intricate pattern of gauge groups and might be realized only rarely among solutions of M-theory. Perhaps, for reasons we do not currently understand, it cannot occur in vacua that are also supersymmetric. Or perhaps exact $N = 1$ moduli spaces with metastable particles are, for some reason, very rare. Otherwise, one would have to hope for a more detailed anthropic argument that could eliminate exact SUSY. At the moment, we do not have one.

8. Conclusions

We have examined anthropic models which explain the value of the cosmological constant in terms of tunneling between a large discrete set of metastable vacua. Within the modern M-theoretic point of view, we emphasized the necessity of considering modular stabilization in conjunction with minimization of the vacuum energy with respect to discrete parameters. Examining the bare minimum in this regard, namely stabilization of the overall breathing mode of the internal manifold, we found strong constraints on such models. In particular, when we incorporate the further requirement of solving the gauge hierarchy problem, we find that the only sensible models have a vacuum energy scale bounded by about 10^{11} GeV. Such models generally lead to a prediction for the amplitude of CMB fluctuations which is orders of magnitude too low.

We presented some ground rules for anthropic models which incorporate a decent respect for our ignorance of the physical basis of intelligent life. These rules imply that in our current state of knowledge, anthropic determination of parameters is acceptable only if the physics involved in the argument is generic and model independent, and if the disaster implied by values of the parameters outside their experimentally determined range was sufficiently terrible for us to conclude that no form of self-organized behavior would be possible. In our view this argument virtually rules out anthropic determination of parameters other than the cosmological constant and (perhaps) the number of large spacetime dimensions. For example, we believe that strong anthropic determination of the vacuum state in M-theory (we must have an $\mathrm{SU}(3, 2, 1)$ gauge theory in order to have conventional chemistry and carbon based life, etc.) would not be scientifically defensible.

We would also like to reiterate a remark about the anthropic models studied in this paper which is perhaps the most disturbing criticism of this circle of ideas. Our initial attitude towards anthropic arguments was that they might be reasonable when restricted to the cosmological constant. However, the central point of models of the BP type is that we can explain an extraordinarily small number in terms of a concatenation of numbers of reasonable magnitude.

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As we have seen, if the internal dimensions in the BP scenario are small, or if one adopts the almost irrational axion models, one finds that there will be *many* metastable vacua with cosmological constants within anthropic bounds. Insisting that there be only one would be an artificial and arbitrary constraint on the model, with not even anthropic justification. The set of vacua within the anthropic window for the cosmological constant will differ from each other in many ways. Thus, all of the details of low energy physics (values of constants in the low energy lagrangian and perhaps even its field content) must be viewed as being chosen from an ensemble. These models thus require anthropic arguments to explain not just the cosmological constant, but also the other parameters of the low energy effective lagrangian. If we are to declare such a model an acceptable explanation of the physical world, we must decide between the two philosophies we have sketched above.

According to the first we would have to show that the vacuum in which the details fit experiment was typical among all those for which we could not rule out the possibility of life. Thus, the work involved in verifying such a model of physics is multiplied many times compared to our usual task of simply calculating all the numerical details of a complicated dynamical system and comparing them with experiment. We must repeat the calculation for all the other vacua (with no guide from experiment) and show that our effective lagrangian was typical. We are more likely to be able to show that it is not, and to rule the model out. And even if we succeeded in this herculean task we would be left with the conclusion that the detailed numerical values of low energy parameters were a statistical accident with no hope of scientific explanation. It is a very bleak picture of the future of physics.

The second philosophy declares that all vacua compatible with the weak anthropic principle are actually realized, in a vast multiverse whose component universes can never communicate with each other. We are just one of many forms of life in the multiverse, and we can use the strong anthropic principle to explain why our particular life form lives in the component of the multiverse where the parameters are *just so*. The fundamental theory has no more to say about all the low energy physics we will ever observe than that it is a possible metastable state of the theory (very likely a very special one). We leave further discussion of this philosophy to its proponents.

We have seen that in the case of two large dimensions, the situation is better. The parameters of the SM are not so sensitive to the values of the fluxes, and, while the number of vacua compatible with formation of structure is probably large, it need not be enormous.

Thus, we believe that it may be possible to overcome the difficulties of the anthropic models that have been discussed so far. Still, we are extremely skeptical of this mode of explanation. This skepticism is scientifically based, but coincides (perhaps suspiciously) with our emotional reaction to the notion of an anthropic resolution of the cosmological constant problem. Puzzles like that of the magnitude of the cosmological constant often lead to revolutionary conceptual changes in the structure of physics. There is a wealth of vague and partial evidence that our notion of how M-theory reduces to local field theory is flawed. This evidence relates to the holographic principle and the idea that M-theory has many fewer degrees of freedom than field theory (exactly the opposite of the naive counting). It is obvious that these ideas have a bearing on the cosmological constant problem and it seems unlikely to us that the problem will be solved by anthropic reasoning in a low energy effective field theory.

Finally, we have advocated the use of anthropic arguments in a rather different context, that of vacuum selection in M-theory. We propose to eliminate dynamically stable but phenomenologically repugnant vacua by showing that they cannot support life. The aim is to use only Weinberg's structure formation criterion in making the decision about whether a given vacuum state is hostile to life. We found that a large class of vacua might be eliminated by such arguments, but that the jury is still out on vacua with exact $N = 1$ SUSY in four dimensions. The issue may hinge on questions about the prevalence of weakly coupled gauge theories and stable particles. What we view as exciting about this possibility is that these are questions which might be amenable to resolution in the not too distant future.

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