Session 6

Cosmology

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S. Shenker As I was writing up the program of the cosmology session of today, I had one of these epiphanies that are such a nice part of our subject. I realized in describing the structure of our little session that phenomena which are familiar from biology seem to be taking place: there is this remarkable phenomenon called "ontology recapitulates phylogeny" where the structure of the embryo when it is growing seems to reproduce the entire history of the species that is developing. And here in our little session we see the whole history of the Universe being recreated. We are likely to start with a Big Bang. Then there will be a rapid period of high temperature in our discussion, probably optically opaque. I do not know what this coffee break is, maybe you can help me with that. Then we return to a prolonged period of inflation which will exit into a period of reheating, again probably optically opaque, and then we will basically return to the period of structure formation. Now, any good analysis like this, you test by trying to apply it outside the domain of its validity. And although it is not written on this schedule, after this discussion what takes place is that David Gross will give some closing remarks. So I tried to place Davis Gross' presentation in this framework and it could be that this presentation will be a Big Crunch. But thinking more carefully, it seems more likely that it will be one of those phases in the evolution of the Universe that seems to go on almost forever.

Laughter.

Alright, I have had my fun. I turn things over to Polchinski.

6.1 Rapporteur talk: The cosmological constant and the string landscape, by Joseph Polchinski

6.1.1 *The cosmological constant*

I would like to start by drawing a parallel to an earlier meeting — not a Solvay Conference, but the 1947 Shelter Island conference. In both cases a constant of nature was at the center of discussions. In each case theory gave an unreasonably large or infinite value for the constant, which had therefore been assumed to vanish for reasons not yet understood, but in each case experiment or observation had recently found a nonzero value. At Shelter Island that constant was the Lamb shift, and here it is the cosmological constant. But there the parallel ends: at Shelter Island, the famous reaction was "the Lamb shift is nonzero, therefore we can calculate it," while today we hear "the cosmological constant is nonzero, therefore we can calculate *nothing*." Of course this is an overstatement, but it is clear that the observation of an apparent cosmological constant has catalyzed a crisis, a new discussion of the extent to which fundamental physics is predictable. This is the main subject of this report.

In the first half of my talk I will review why the cosmological constant problem is so hard. Of course this is something that we have all thought about, and there are major reviews.[1] However, given the central importance of the question, and the flow of new ideas largely stimulated by the observation of a nonzero value, we should revisit this. One of my main points is that, while the number of proposed solutions is large, there is a rather small number of principles and litmus tests that rule out the great majority of them.

In recent years the cosmological constant has become three problems:

(1) Why the cosmological constant is not large.
(2) Why it is not zero.
(3) Why it is comparable to the matter energy density *now* (cosmic coincidence).

I will focus primarily on the first question — this is hard enough! — and so the question of whether the dark energy might be something other than a cosmological constant will not be central.

In trying to understand why the vacuum does not gravitate, it is useful to distinguish two kinds of theory:

(1) Those in which the energy density of the vacuum is more-or-less uniquely determined by the underlying theory.
(2) Those in which it is not uniquely determined but is adjustable in some way.

[1]For a classic review see [1]. For more recent reviews that include the observational situation and some theoretical ideas see [2, 3]. A recent review of theoretical ideas is [4]. My report is not intended as a comprehensive review of either the cosmological problem or of the landscape, either of which would be a large undertaking, but a discussion of a few key issues in each case.

I will discuss these in turn.

6.1.1.1 *Fixed-Λ theories*

The basic problem here is that we know that our vacuum is a rather nontrivial state, and we can identify several contributions to its energy density that are of the order of particle physics scales. It is sufficient to focus on one of them; let us choose the electron zero point energy, since we know a lot about electrons. In particular, they are weakly coupled and pointlike up to an energy scale M of at least 100 GeV. Thus we can calculate the electron zero point energy up to this scale from the graphs of Fig. 1 [5],

$$\rho_V = O(M^4) + O(M^2 m_e^2) + O(m_e^4 \ln M/m_e) \; , \tag{1}$$

which is at least 55 orders of magnitude too large.

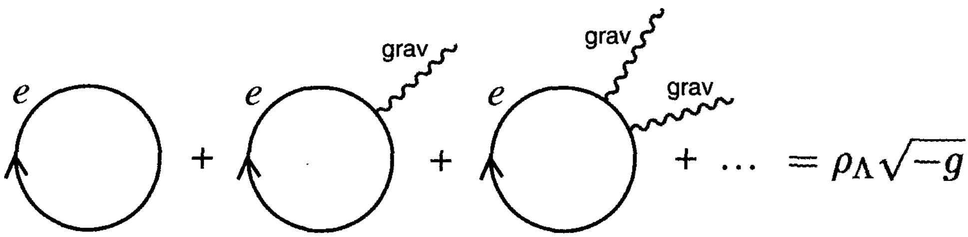

Fig. 6.1 An electron vacuum loop and its coupling to external gravitons generate an effective cosmological constant.

So we must understand why this contribution actually vanishes, or is cancelled. To sharpen the issue, we know that electron vacuum energy does gravitate in some situations. Fig. 2a shows the famous Lamb shift, now coupled to an external gravi-

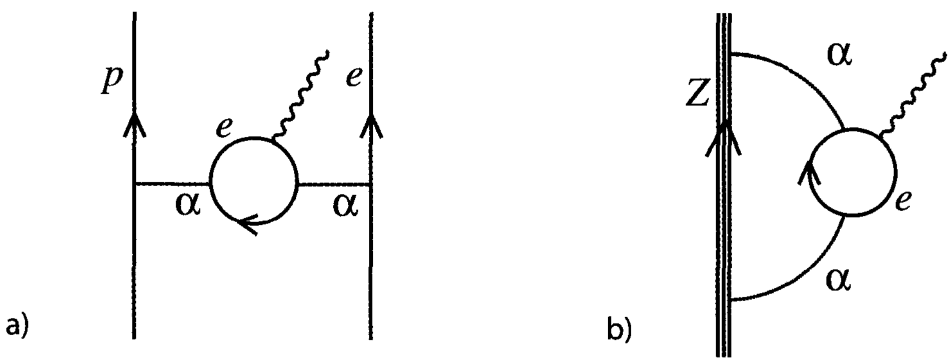

Fig. 6.2 a) The Lamb shift, coupled to an external graviton. b) A loop correction to the electrostatic energy of a nucleus, coupled to an external graviton.

ton. Since this is known to give a nonzero contribution to the energy of the atom, the equivalence principle requires that it couples to gravity. The Lamb shift is very small so one might entertain the possibility of a violation of the equivalence principle, but this is a red herring, as there are many larger effects of the same type.

One of these is shown in Fig. 2b, a loop correction to the electrostatic energy of the nucleus. Aluminum and platinum have the same ratio of gravitational to inertial mass to one part in 10^{12} [6, 7]. The nuclear electrostatic energy is roughly 10^{-3} of the rest energy in aluminum and 3×10^{-3} in platinum. Thus we can say that this energy satisfies the equivalence principle to one part in 10^9. The loop graph shifts the electrostatic energy by an amount of relative order $\alpha \ln(m_e R_{\rm nuc})/4\pi \sim 10^{-3}$ due to the running of the electromagnetic coupling. Thus we know to a precision of one part in 10^6 that the effect shown in Fig. 2b actually exists. In fact, the effect becomes much larger if we consider quark loops rather than electrons, and we do not need precision experiments to show that virtual quarks gravitate, but we stick with electrons because they are cleaner [8].

We can think of Fig. 2 to good approximation as representing the shift of the electron zero point energy in the environment of the atom or the nucleus. Thus we must understand why the zero point energy gravitates in these environments and not in vacuum, again given that our vacuum is a rather complicated state in terms of the underlying fields. Further, if one thinks one has an answer to this, there is another challenge: why does this cancellation occur in our particular vacuum state, and not, say, in the more symmetric $SU(2) \times U(1)$ invariant state of the weak interaction? It cannot vanish in both because the electron mass is zero in the symmetric state and not in ours, and the subleading terms in the vacuum energy (1) — which are still much larger than the observed ρ_V — depend on this mass. Indeed, this dependence is a major contribution to the Higgs potential (though it is the top quark loop rather than the electron that dominates), and they play an important role in Higgs phenomenology.

I am not going to prove that there is no mechanism that can pass these tests. Indeed, it would be counterproductive to do so, because the most precise no-go theorems often have the most interesting and unexpected failure modes. Rather, I am going to illustrate their application to one interesting class of ideas.

Attempts to resolve the Higgs naturalness problem have centered on two mechanisms, supersymmetry and compositeness (technicolor). In the case of the cosmological constant much attention has been given to the effects of supersymmetry, but what about compositeness, technigravity? If the graviton were composite at a scale right around the limit of Cavendish experiments, roughly 100 microns, would this not cut off the zero point energy and leave a remainder of order $(100\ \mu)^{-4}$, just the observed value [9, 10]? Further this makes a strong prediction, that deviations from the inverse square law will soon be seen.

In fact, it can't be that simple. When we measure the gravitational force in Cavendish experiments, the graviton wavelength is around $100\,\mu$. When we measure the cosmological constant, the graviton wavelength is around the Hubble scale, so there is no direct connection between the two. Moreover, we already know, from the discussion of Fig. 2, that the coupling of gravity to off-shell electrons is unsuppressed over a range of scales in between $100\,\mu$ and the Hubble scale, so whatever is affecting the short-distance behavior of gravity is not affecting longer scales. We can also think about this as follows: even if the graviton were composite one would not expect the graphs of Fig. 1 to be affected, because all external fields are much softer than $100\,\mu$. In order to be sensitive to the internal structure of a particle we need a hard scattering process, in which there is a large momentum transfer to the particle [11]. Further, the large compact dimension models provide an example where gravity is modified at short distance, but the electron zero point loop is not cut off. Thus there is no reason, aside from numerology, to expect a connection between the observed vacuum energy and modifications of the gravitational force law.

Ref. [12] tries to push the idea further, defining an effective theory of 'fat gravity' that would pass the necessary tests. This is a worthwhile exercise, but it shows just how hard it is. In order that the vacuum does not gravitate but the Lamb shift and nuclear loops do, fat gravity imposes special rule for vacuum graphs. The matter path integral, at fixed metric, is doubly nonlocal: there is a UV cutoff around $100\,\mu$, and in order to know how to treat a given momentum integral we have to look at the topology of the whole graph in which it is contained. Since the cosmological constant problem really arises only because we know that some aspects of physics are indeed local to a much shorter scale, it is necessary to derive the rules of fat gravity from a more local starting point, which seems like a tall order. To put this another way, let us apply our first litmus test: what in fat gravity distinguishes the environment of the nucleus from the environment of our vacuum? The distinction is by fiat. But locality tells us that that the laws of physics are simple when written in terms of local Standard Model fields. Our vacuum has a very complicated expression in terms of such fields, so the rules of fat gravity do not satisfy the local simplicity principle.

The nonlocality becomes sharper when we look at the second question, that is, for which vacuum is the cosmological constant small? The rule given is that it is the one of lowest energy. This sounds simple enough, but consider a potential with two widely separated local minima. In order to know how strongly to couple to vacuum A, the graviton must also calculate the energy of vacuum B (and of every other point in field space), and if it is smaller take the difference. Field theory, even in some quasilocal form, can't do this — there are not enough degrees of freedom to do the calculation. If the system is in state A, the dynamics at some distant point in field space is irrelevant. Effectively we would need a computer sitting at every spacetime point, simulating all possible vacua of the theory. Later we will mention a context in which this actually happens, but it is explicitly nonlocal in a strong way.

The failure of short-distant modifications of gravity suggests another strategy: modify gravity at very long distances, comparable to the current Hubble scale, so that it does not couple to vacuum energy at that scale. There is of course a large literature on long-distance modifications of gravity; here I will just point out one problem. If we have zero point energy up to a cutoff of $M \sim 100$ GeV, the radius of curvature of spacetime will be of order $M_{\rm P}/M^2$, roughly a meter. So modifications of gravity at much longer distances do not solve the problem, the universe curls up long before it knows about the modification. It is possible that the spacetime curvature decays away on a timescale set by the long-distance modifications, but this would imply a large and uncanceled cosmological constant until quite recently.[2] These problems have already been discussed in Ref. [13], which argues that long distance modifications of gravity can account for the cosmological constant only in combination with acausality.

In another direction, it is tempting to look for some sort of feedback mechanism, where the energies from different scales add up in a way that causes the sum to evolve toward zero. The problem is that only gravity can measure the cosmological constant — this term in the action depends only on the metric — so that the contribution from a scale M is only observed at a much lower scale $M^2/M_{\rm P}$, and we cannot cancel $O(M^4)$ against $O(M^8/M_{\rm P}^4)$. In another language, the cosmological constant has scaling dimension zero and we want to increase it to dimension greater than four; but gravity is clearly classical over a wide range of scales so there is no possibility of this.

Again, there is no proof that some fixed-Λ solution does not exist; perhaps our discussion will spur some reader into looking at the problem in a new way. In fact there is at least one idea that is consistent with our tests: a symmetry *energy* $\rightarrow$ *−energy*. This requires a doubling of degrees of freedom, so the electron loop is cancelled by a mirror loop of negative energy. This idea is discussed as an exact symmetry in ref. [14] and as an approximate symmetry not applying to gravity in ref. [15]; the two cases are rather different because the coordinate invariance is doubled in the first. It might be that either can be made to work at a technical level, and the reader is invited to explore them further, but I will take this as a cue to move on to the next set of ideas.

6.1.1.2 *Adjustable-Λ theories*

Many different mechanisms have been put forward that would avert the problems of the previous section by allowing the cosmological constant to adjust in some way; that is, the vacuum energy seen in the low energy theory is not uniquely determined by the underlying dynamics. A partial list of ideas includes

- Unimodular gravity (see Ref. [1] for a discussion of the history of this idea,

[2] One might consider models where this decay occurs in an epoch before the normal Big Bang, but this runs into the empty universe problem to be discussed in Sec. 1.2.

which in one form goes back to Einstein).

- Nonpropagating four-form field strengths [16, 17].
- Scalar potentials with many minima [19, 18, 20].
- A rolling scalar with a nearly flat potential [21]; the potential must be very flat in order that the vacuum energy be constant on shorter than cosmological times, and it must have a very long range to span the necessary range of energies.
- Spacetime wormholes [22–25].
- The metastable vacua of string theory [26–32].
- Self-tuning (an undetermined boundary condition at a singularity in the compact dimensions) [33, 34].
- Explicit tuning (i.e. an underlying theory with at least one free parameter not determined by any principle).

The possible values of ρ_V must either be continuous, or form a sufficiently dense discretuum that at least one value is as small as observed. It is important to note that *zero* cannot be a minimum, or otherwise special, in the range of allowed values. The point is that the electron zero point energy, among other things, gives an additive shift to the vacuum energy; if the minimum value for ρ_V were zero we would have to revert to the previous section and ask what it is cancels the energy in this true vacuum.

In this adjustable scenario, the question is, what is the mechanism by which the actual small value seen in nature is selected? In fact, one can identify a number of superficially promising ideas:

- The Hartle-Hawking wavefunction [35]
$$|\Psi_{\rm HH}|^2 = e^{3/8G^2\rho_V} \tag{2}$$
strongly favors the smallest positive value of the cosmological constant [36, 37].
- The de Sitter entropy [38]
$$e^S = e^{3/8G^2\rho_V} = |\Psi_{\rm HH}|^2 \tag{3}$$
would have the same effect, and suggests that the Hartle-Hawking wavefunction has some statistical interpretation in terms of the sytem exploring all possible states.
- The Coleman-de Lucchia amplitude [39] for tunneling from positive to negative cosmological constant vanishes for some parameter range, so the universe would be stuck in the state of smallest positive energy density [18, 40].

These ideas are all tantalizing — they are tantalizing in the same way that supersymmetry is tantalizing as a solution to the cosmological constant problem. That is, they are elegant explanations for why the cosmological constant might be small or zero under some conditions, but not in our particular rather messy universe. Supersymmetry would explain a vanishing cosmological constant in a sufficiently supersymmetric universe, and these mechanisms would explain why it vanishes in an *empty* universe.

To see the problem, note first that the above mechanisms all involve gravitational dynamics in some way, the response of the metric to the vacuum energy. This is as it must be, because again only gravity can measure the cosmological constant. The problem is that in our universe the cosmological constant became dynamically important only recently. At a redshift of a few the cosmological constant was much smaller than the matter density, and so unmeasurable by gravity; at the time of nucleosynthesis (which is probably the latest that a tunneling could have taken place) today's cosmological constant would have been totally swamped by the matter and radiation densities, and there is no way that these gravitational mechanisms could have selected for it.[3] This is the basic problem with dynamical selection mechanisms: only gravity can measure ρ_V, and it became possible for it to do so only in very recent cosmological times. These mechanisms can act on the cosmological constant only if matter is essentially absent.

Another selection principle sometimes put forward is 'existence of a static solution;' this comes up especially in the context of the self-tuning solutions. As a toy illustration, one might imagine that some symmetry acting on a scalar ϕ forced ρ_V to appear only in the form $\rho_V \phi^4$.[4] If we require the existence of a static solution for ϕ then we must have $\rho_V = 0$. Of course this seems like cheating; indeed, if we can require a static solution then why not just require a flat solution, and get $\rho_V = 0$ in one step? In fact these are cheating because they suffer from the same kind of flaw as the dynamical ideas. In order to know that our solution is static on a scale of say 10^{10} years, we must watch the universe for this period of time! The dynamics in the very early universe, at which time the selection was presumably made, have no way to select for such a solution: the early universe was in a highly nonstatic state full of matter and energy.

Of course these arguments are not conclusive, and indeed Steinhardt's talk presents a nonstandard cyclic cosmological history that evades the above no-go argument. If one accepts its various dynamical assumptions, this may be a technically natural solution to the cosmological constant problem. Essentially one needs a mechanism to fill the empty vacuum with energy after its cosmological constant has relaxed to near zero; it is not clear that this is in fact possible.

In the course of trying to find selection mechanisms, one is struck by the fact that, while it is difficult to select for a single vacuum of small cosmological constant, it is extremely easy to identify mechanisms that will populate *all* possible vacua — either sequentially in time, as branches of the wavefunction of the universe, or as

[3]This might appear to leave open the possibility that the vacuum energy is at all times of the same order as the matter/radiation density. Leaving aside the question of how this would appear phenomenologically as a cosmological constant, the simplest way to see that this does not really address the problem is to note that as the matter energy goes to zero at late times then so will the vacuum energy: this violates the principal that zero is not a special value. By contrast, the dynamical mechanisms above all operate for a ρ_V-spectrum that extends to negative values.

[4]For example, such a form arises at string tree level, though it is not protected against loop corrections. An exact but spontaneously broken scale invariance might appear to give this form, but in that case a Weyl transform removes ϕ from both the gravitational action and the potential.

different patches in an enormous spatial volume. Indeed, this last mechanism is difficult to evade, if the many vacua are metastable: inflation and tunneling, two robust physical processes, will inevitably populate them all [41–43, 28].

But this is all that is needed! Any observer in such a theory will see a cosmological constant that is unnaturally small; that is, it must be much smaller than the matter and energy densities over an extended period of the history of the universe. The existence of any complex structures requires that there be many 'cycles' and many 'bits': the lifetime of the universe must be large in units of the fundamental time scale, and there must be many degrees of freedom in interaction. A large negative cosmological constant forces the universe to collapse to too soon; a large positive cosmological constant causes all matter to disperse. This is of course the argument made precise by Weinberg [44], here in a rather minimal and prior-free form.[5]

Thus we meet the anthropic principle. Of course, the anthropic principle is in some sense a tautology: we must live where we can live.[6] There is no avoiding the fact that anthropic selection must operate. The real question is, is there any scientific reason to expect that some additional selection mechanism is operating?

Staying for now with the cosmological constant (other parameters will be discussed later), *the obvious puzzle is the fact that the cosmological constant is an* order of magnitude smaller than the most likely anthropic value. This is an important issue, but to overly dwell on it reminds me of Galileo's reaction to criticism of his ideas because a heavier ball landed slightly before a lighter one (whereas Aristotle's theory predicted a much larger discrepancy):

> Behind those two inches you want to hide Aristotle's ninety-nine *braccia* [arm lengths] and, speaking only of my tiny error, remain silent about his enormous mistake.

The order of magnitude here is the two inches of wind resistance, the ninety-nine *braccia* are the 60 or 120 orders of magnitude by which most or all other proposals miss. This order of magnitude may simply be a 1.5-sigma fluctuation, or it may reflect our current ignorance of the measure on the space of vacua.

If there is a selection mechanism, it must be rather special. It must evade the general difficulties outlined above, and it must select a value that is *almost exactly the same* as that selected by the anthropic principle, differing by one order of magnitude out of 120. Occam's razor would suggest that two such mechanisms be replaced by one — the unavoidable, tautological, one. Thus, we should seriously consider the possibility that there is no other selection mechanism significantly constraining the cosmological constant. Equally, we should not stop searching for such a further principle, but I think one must admit that the strongest reason for

[5] For further reviews see Refs. [1, 45, 46].

[6] Natural selection is a tautology in much the same sense: survivors survive. But in combination with a mechanism of populating a spectrum of universes or genotypes, these 'tautologies' acquire great power.

expecting to find it is not a scientific argument but a psychological one:[7] we wish fundamental theory to be as predictive as we have long assumed it would be.

The anthropic argument is not without predictive power. We can identify a list of post- or pre-dictions, circa 1987:

(1) The cosmological constant is not large.
(2) The cosmological constant is not zero.
(3) The cosmological constant is similar in order of magnitude to the matter density.
(4) As the theory of quantum gravity is better understood, it will provide a microphysics in which the cosmological constant is not fixed but environmental; if this takes discrete values these must be extremely dense in Planck units.
(5) Other constants of nature may show evidence of anthropic constraints.

Items 2 and 3 are the second and third parts of the cosmological constant problem; we did not set out to solve them, but in fact they were solved before they were known to be problems — they are predictions. Item 4 will be discussed in the second half of the talk, in the context of string theory. Item 5 is difficult to evaluate, but serious arguments to this effect have long been made, and they should not be dismissed out of hand.

Let us close this half of the talk with one other perspective. The cosmological constant problem appears to require some form of UV/IR feedback, because the cosmological constant can only be measured at long distances or late times, yet this must act back on the Lagrangian determined at short distance or early times. We can list a few candidates for such a mechanism:

- String theory contains many examples of UV/IR mixing, such as the world-sheet duality relating IR poles in one channel of an amplitude to the sum over massive states in another channel, and the radius-energy relation of AdS/CFT = duality. Thus far however, this is yet one more tantalizing idea but with no known implications for the vacuum energy.
- Bilocal interactions. The exact *energy* $\to$ *−energy* symmetry [14] and the wormhole solution [24, 25] put every point of our universe in contact with every point of another. This ties in with our earlier remarks about the computational power of quantum field theory: here the calculation of the true vacuum energy is done in the entire volume of the second spacetime.
- The anthropic principle. Life, an IR phenomenon, constrains the coupling constants, which are UV quantities.
- A final state condition. At several points — in the long distance modification of gravity, and in the dynamical mechanisms — things would have gone better if we supposed that there were boundary conditions imposed in the future and not just initially. Later we will encounter one context in which this might occur.

[7] Again, the Darwinian analogy is notable.

To conclude, we have identified one robust framework for understanding the vacuum energy: (1) Stuff gravitates, and the vacuum is full of stuff. (2) Therefore the vacuum energy must have some way to adjust. (3) It is difficult for the adjustment to select a definite small value for the vacuum energy, but it is easy to access all values, and this, within an order of magnitude, accounts for what we see in nature. We have also identified a number of other possible hints and openings, which may lead the reader in other directions.

6.1.2 *The string landscape*

6.1.2.1 *Constructions*

Now let us ask where string theory fits into the previous discussion. In ten dimensions the theory has no free parameters, but once we compactify, each nonsupersymmetric vacuum will have a different ρ_V. It seems clear that the cosmological constant cannot vary continuously. Proposed mechanisms for such variation have included nondynamical form fields and a boundary condition at a singularity, but the former are constrained by a Dirac quantization condition, and the latter will undoubtedly become discrete once the internal dynamics of the 'singularity' are taken into account. (A rolling scalar with a rather flat potential might provide some effective continuous variation, but the range of such a scalar is very limited in string theory).

Given a discrete spectrum, is there a dense enough set of states to account for the cosmological constant that we see, at least 10^{60} with TeV scale supersymmetry breaking or 10^{120} with Planck scale breaking?[8] The current understanding, in particular the work of KKLT [31], suggests the existence of a large number of metastable states giving rise to a dense discretuum near $\rho_V = 0$. A very large degree of metastability is not surprising in complicated dynamical systems — consider the enormous number of metastable compounds found in nature. As a related example, given 500 protons, 500 neutrons, and 500 electrons, how many very long-lived bound states are there? A rough estimate would be the number of partitions of 500, separating the protons into groups and then assigning the same number of neutrons and electrons to each group; there is some overcounting and some undercounting here, but the estimate should be roughly correct,

$$P(n) \sim \frac{1}{4n\sqrt{3}} e^{\pi\sqrt{2n/3}}\,, \quad P(500) \sim 10^{22}\,. \tag{1}$$

The number of metastable states grows rapidly with the number of degrees of freedom.

In string theory, replace *protons*, *neutrons*, and *electrons* with *handles*, *fluxes*, and *branes*. There are processes by which each of these elements can form or decay, so it seems likely that most or all of the nonsupersymmetric vacua are unstable,

[8]These numbers would have to be larger if the probability distribution has significant fluctuations as recently argued in Ref. [47].

and the space of vacua is largely or completely connected. Thus all states will be populated by eternal inflation, if any of the de Sitter states is. The states of positive ρ_V would also be populated by any sort of tunneling from nothing (if this is really a distinct process), since one can take the product of an S^4 Euclidean instanton with any compact space.

The number 500 has become a sort of a code for the landscape, because this is the number of handles on a large Calabi-Yau manifold, but for now it is an arbitary guess. It is still not certain whether the number of vacua in string theory is dense enough to account for the smallness of the cosmological constant, or even whether it is finite (it probably becomes finite with some bound on the size of the compact dimensions: compact systems in general have discrete spectra[9]).

The nuclear example has a hidden cheat, in that a small parameter has been put in by hand: the action for tunnelling of a nucleus through the Coulomb barrier is of order $Z_1 Z_2 (m_\mathrm{p}/m_\mathrm{e})^{1/2}$, and this stabilizes all the decays. String theory has no such small parameter. One of the key results of KKLT is that in some regions of moduli space there are a few small parameters that stabilize all decays (see also Ref. [48]). Incidentally, the stability of our vacuum is one reason to believe that we live near some boundary of moduli space, rather than right in the middle where it is particularly hard to calculate: most likely, states right in the middle of moduli space decay at a rate of order one in Planck units.

How trustworthy are the approximations in KKLT? A skeptic could argue that there are no examples where they are fully under control. Indeed, this is likely to inevitable in the construction of our vacuum in string theory. Unlike supersymmetric vacua, ours has no continuous moduli that we can vary to make higher-order corrections parametrically small, and the underlying string theory has no free parameters. It could be that our vacuum is one of an infinite discrete series, indexed by an integer which can be made arbitrarily large, and in this way the approximations made parametrically accurate, but in the KKLT construction this appears not to be the case: the flux integers and Euler number are bounded. For future reference we therefore distinguish *series* and *sporadic* vacua, by analogy to finite groups and Lie algebras; perhaps other constructions give series of metastable nonsupersymmetric vacua.

The KKLT construction has something close to a control parameter, the supersymmetry breaking parameter w_0. In an effective field theory description we are free to vary this continuously and then the approximations do become parametrically precise; in this sense one is quite close to a controlled approximation. In specific models the value of w_0 is fixed by fluxes, and it is a hard problem (in a sense made precise in Ref. [49]) to find vacua in which it is small. Thus, for now the fourth prediction from the previous section, that string theory has enough vacua to solve the cosmological constant problem, is undecided and still might falsify the whole idea.

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[9]See the talk by Douglas for further discussion of this and related issues.

Underlying the above discussion is the fact that we still have no nonperturbative construction of string theory in any de Sitter vacua, as emphasized in particular in Refs. [50, 51]. As an intermediate step one can study first supersymmetric AdS vacua, where we do understand the framework for a nonperturbative construction, via a dual CFT. The KKLT vacua are built on such AdS vacua by exciting the system to a nonsupersymmetric state. The KKLT AdS vacua are sporadic, but there are also series examples with all moduli fixed, the most notable being simply $AdS_5 \times S^5$, indexed by the five-form flux. Thus far we have explicit duals for many of the series vacua, via quiver gauge theories, but we do not yet have the tools to describe the duals of the sporadic vacua [52]. The KKLT construction makes the prediction that there are $10^{O(100)}$ such sporadic CFTs — a surprising number in comparison to the number of sporadic finite groups and Lie algebras, but indeed 2+1 dimensional CFTs appear to be much less constrained. It may be possible to count these CFTs, even before an explicit construction, through some index; see Ref. [53] for a review of various aspects of the counting of vacua.

Beyond the above technical issues, there are questions of principle: are the tools that KKLT use, in particular the effective Lagrangian, valid? In many instances these objections seem puzzling: the KKLT construction is little more than gluino condensation, where effective Lagrangian methods have long been used, combined with supersymmetry breaking, which can also be studied in a controlled way. It is true that the KKLT construction, in combination with eternal inflation, is time-dependent. However, over much of the landscape the scale of the time-dependence is well below the Planck scale, because the vacuum energy arises from a red-shifted throat, and so the landscape is populated in the regime where effective field theory is valid.

A more principled criticism of the use of effective Lagrangians appears in Refs. [50, 51]; I will try to paraphrase this here. It is not precisely true that the nonsupersymmetric KKLT states (or any eternally inflating states) are excitations of AdS vacua. That is, it is true locally, but the global boundary conditions are completely different. Normally one's intuition is that the effective Lagrangian is a local object and does not depend on the boundary conditions imposed on the system, but arguments are given that this situation is different. In particular one cannot tunnel among inflating states, flat spacetimes, and AdS states in any direction (for example, tunneling from eternal inflation to negative cosmological constant leads to a crunch); thus these are in a sense different theories. This is also true from a holographic point of view: the dual Hamiltonians that describe inflating, flat, and AdS spaces will inevitably be completely different (as one can see by studying the high energy spectrum). Is there then any reason to expect that constructions of an effective action, obtained from a flat spacetime S-matrix, have any relevance to an eternally inflating system?

I believe that there is. The entire point of holography and AdS/CFT duality is that the bulk physics is emergent: we obtain the same bulk physics from many different Hamiltonians. We can already see this in the AdS/CFT context, where many different quiver gauge theories, even in different dimensions, give the same IIB bulk string theory, and local experiments in a large AdS spacetime are expected to give the same results as the same experiments in flat spacetime. Thus there is no argument in principle that these do not extend to the inflating case. Also, while holography does imply some breakdown of local field theory, it does so in a rather subtle way, as in phase correlations in Hawking radiation. By contrast, the expectation value of the energy-momentum tensor in the neighborhood of a black hole (i.e. the total flux of Hawking radiation) appears to be robust, and the quantities that enter into to construction of string vacua are similar to this.

However, for completeness we mention the possible alternate point of view [54]: that the landscape of metastable dS vacua has no nonperturbative completion, or it does have one but is experimentally ruled out by considerations such as those we will discuss. Instead there is a completely separate sector, consisting of theories with finite numbers of states, and if these lead to emergent gravity it must be in a stable dS spacetime.

6.1.2.2 *Phenomenological issues*

Thus far we have dwelt on the cosmological constant, but the string landscape implies that other constants of nature will be environmental to greater or lesser extents as well. In this section we discuss a few such parameters, especially those which appear to be problematic for one reason or another.

$\boldsymbol{\theta_{\mathrm{QCD}}}$ Why is θ_{QCD} of order 10^{-9} or less? This strong CP problem has been around for a long time in gauge theory, and several explanations have been proposed — an axion, a massless up quark, and models based on spontaneous CP violation. However, it has been argued that none of these are common in the string landscape; for example, the first two require continuous symmetries with very tiny explicit breakings, and this appears to require fine tuning. Further, it is very hard to see any anthropic argument for small θ_{QCD}; a larger value would make very little difference in most of physics. Thus we would conclude that the multiverse is full of bubbles containing observers who see gauge theories with large CP-violating angles, and ours is a one-in-a-billion coincidence [50].

Of course, this is a problem that is to some extent independent of string theory: the axion, for example, has always been fishy, in that one needed a global symmetry that is exact *except for* QCD instantons. The string landscape is just making sharper an issue that was always there.

String theory does come with a large number of potential axions. In order that one of these solve the strong CP problem it is necessary that the potential energy from QCD instantons be the dominant contribution to the axion potential; any non-QCD contribution to the axion mass must be of order $10^{-18}\,\mathrm{eV} \times (10^{16}\,\mathrm{GeV}/f_{\mathrm{a}})$ or less. This is far below the expected scale of the moduli masses, so appears to imply a substantial fine tuning (even greater than the direct tuning of θ_{QCD}) and so rarity in the landscape.

However, the landscape picture also suggests a particular solution to this problem. In order to obtain a dense enough set of vacua, the compact dimensions must be topologically complex, again with something around 500 cycles. Each cycle gives rise to a potential axion, whose mass comes from instantons wrapping the cycle (we must exclude would-be axions which also get mass from other sources, such as their classical coupling to fluxes). Generically one would expect some of these cycles to be somewhat large in string units; for example, one might expect the whole compact space to have a volume that grows as some power of the number of handles. The axions, whose masses go as minus the exponential of the volume, would be correspondingly light. Thus, compactifications of large topological complexity may be the one setting in which the QCD axion *is* natural, the smallness of θ_{QCD} being an indirect side effect of the need for a small cosmological constant. More generally, it will be interesting to look for characteristic properties of such topologically complex compactifications.

This example shows that even with anthropic selection playing a role, mechanism will surely also be important.

The baryon lifetime This is a similar story to θ_{QCD} [50]: as far as we understand at present, the baryon lifetime is longer than either anthropic argument or mechanism can account for, so that bubbles with such long-lived baryons would be rare in the multiverse. This problem is lessened if supersymmetry is broken at high energy. This is an significant challenge to the landscape picture: it is good to have such challenges, eventually to sharpen, or to falsify, our current understanding.

The dark energy parameter w A naive interpretation of the anthropic principle would treat the dark energy equation of state parameter w as arbitrary, and look for anthropic constraints. However, in the string landscape a simple cosmological constant, $w = -1$, is certainly favored. With supersymmetry broken, the scalar potential generically has isolated minima, with all scalars massive. In order to obtain a nontrivial equation of state for the dark energy we would need a scalar with a mass of order the current Hubble scale. Our discussion of axions indicates a mechanism for producing such small masses, but it would be rather contrived, for no evident reason, that the mass would be of just the right scale as to produce a nontrivial variation in the current epoch.

Three generations Three generation models appear to be difficult to find in string theory. A recent paper quantifies this [55]: in one construction they are one in a billion, even after taking into account the anthropic constraint that there be an asymptotically free group so that the long distance physics is nontrivial. It is then a puzzle to understand how we happen to live in such a vacuum. One conjecture is that all constructions thus far are too special, and in the full landscape three generations is not rare. Again, explaining three generations is equally a problem for any hypothetical alternate selection mechanism — another challenge to sharpen our understanding.

Q I am not going to try to discuss this parameter in detail; I am only going to use it to make one rhetorical point. The anthropic bound on Q, which is the normalization of the primordial temperature fluctuations, has been quoted as [56]

$$10^{-6} < Q < 10^{-4} \,, \tag{2}$$

and it is interesting that the observed value is in the middle, not at either end. What would we expect from the landscape?

A string theorist would note that the anthropic bound is on $\rho_V Q^{-3}$ [44], and so by making Q a factor of 10 larger we can multiply ρ_V by 1000, and there will be many more vacua with this larger value of Q. A cosmologist would note that a smaller Q would imply a flatter potential and so more inflation, and therefore much more volume and many more galaxies. Thus the cosmologist and the string theorist agree that we should be on the end of the anthropic range, but they disagree on which end.

This is a caricature, of course — there are other considerations, and model-dependencies [50, 57–60]. I use it to make two points: first, it is a puzzle that we are in the middle of the anthropic range, yet another thing to understand. Second, the string theorist and the cosmologist each look at part of the measure, but it is clear that we are far short of the whole picture. (For reviews of the counting and the volume factors see Refs. [53] and [61] respectively.)

$\boldsymbol{\rho_V}$ Can we understand understand the number 283, as in

$$\rho_V = e^{-283.2} M_{\rm P}^4 \; ? \tag{3}$$

I quote it in this way, as a natural log, to emphasize that we are to think about it completely free of all priors (such as the fact that we have ten fingers). Thus, there may be an anthropic relation between $\rho_V/M_{\rm P}^4$ and $M_{\rm weak}/M_{\rm P}$, for example, but we should not make any assumption about the latter. It should be possible to calculate the number 283, at least to some accuracy. We know that it has to be big, to get enough bits and cycles, but why is 100 not big enough, and why is 1000 not better?

One possibility, the best from the point of view of string theory, is that $\rho_V/M_{\rm P}^4$ has its original purely in microphysics; that it, that it is close to the smallest attainable value, set by the density of the discretuum. The other extreme is that it is almost purely anthropic — that 283, plus or minus some uncertainty, really gives the best of all attainable worlds, and any attempt to vary parameters to give a larger or smaller value inevitably makes things worse. Certainly, knowing where we sit between these two extremes is something that we must eventually understand in a convincing way.

Other questions An obvious question is whether we can understand the supersymmetry-breaking scale (see [63] and references therein). Is low energy supersymmetry, or some alternative [64, 65], favored? Will we figure this out before the LHC tells us?

Another potentially telling question [66]: are there more coincidences like the cosmic coincidence of ρ_V, such as the existence of two different kinds of dark matter with significant densities?

6.1.2.3 *What is string theory?*

Of course, this is still the big question. We have learned in recent years that the nonperturbative construction of a holographic theory is very sensitive to the global structure of spacetime. Thus, the current point of view, the chaotically inflating multiverse, casts this question in a new light. It is also another example of how the landscape represents productive science: if we ignore this lesson, ignore chaotic inflation, we may be trying to answer the wrong question.

Before addressing the title question directly, let us discuss one way in which it bears upon the previous discussion. We touched briefly on the issue of the measure. This has always been a difficult question in inflationary cosmology. Intuitively one would think that the volume must be included in the weighting, since this will be one factor determining the total number of galaxies of a given type. However, this leads to gauge dependence [67] and the youngness paradox [68]. Further, this would imply that the vacuum of highest density plays a dominant role, whereas the de Sitter entropy would suggest almost the opposite, that when the system is in a state of high vacuum energy it has simply wandered into a subsector of relatively few states. Further, the idea of counting separately regions that are out of causal contact is contrary to the spirit of the holographic principle.

There have been attempts to modify the volume weighting to deal with some of the paradoxes (for a recent review see Ref. [61]), but as far as I know none as yet take full advantage of the holographic point of view, and none is widely regarded as convincing. Providing a compelling understanding of the measure is certainly a goal for string theory. It is possible that this can be done by some form of holographic reasoning, even without a complete nonperturbative construction. It is perhaps useful to recall Susskind's suggestion, that the many worlds of chaotic inflation are the same as the many worlds of quantum mechanics. This can be read in two directions: first, that chaotic inflation is the origin of quantum mechanics — this seems very ambitious; second, that the many causal volumes in the chaotic universe should just be seen as different states within the wavefunction of a single patch — this is very much in keeping with holography. It is also interesting to note that the stochastic picture presented in Ref. [67] has a volume-weighted probability that seems to have a youngness paradox, and an unweighted one that seems to connect with the Hartle-Hawking and tunneling wavefunctions, and possibly with a thermodynamic picture.

Now, what is the nonperturbative construction of these eternally inflating states? The lesson from AdS/CFT is that the dual variables that give this construction live at the boundary of spacetime. In the context of eternal inflation, the only natural boundaries lie to the future, in open FRW universes (and possibly also in time-reversed universes to the past) [32, 69, 70].

This is much like AdS/CFT with timelike infinity replacing spatial infinity, and so it suggests that time will be emergent. Let us interpose here one remark about emergent time (see also the presentations by Seiberg and by Maldacena at this meeting). Of course in canonical general relativity there is no time variable at the start, it emerges in the form of correlations once the Hamiltonian constraint is imposed. This sounds like emergent time, but on the other hand it is just a rewriting of the covariant theory, and one would expect emergent time to be something deeper.

To see the distinction between emergent time in these two senses let us first review emergent gauge symmetry. In some condensed matter systems in which the starting point has only electrons with short-ranged interactions, there are phases where the electron separates into a new fermion and boson [71, 72],

$$e(x) = b(x) f^{\dagger}(x) \ . \tag{4}$$

However, the new fields are redundant: there is a gauge transformation

$$b(x,t) \rightarrow e^{i\lambda(x,t)} b(x,t) \ , \quad f(x,t) \rightarrow e^{i\lambda(x,t)} f(x,t) \ , \tag{5}$$

which leaves the physical electron field invariant. This new gauge invariance is clearly emergent: it is completely invisible in terms of the electron field appearing in the original description of the theory (this "statistical" gauge invariance is not to be confused with the ordinary electromagnetic gauge invariance, which does act on the electron.) Similarly, the gauge theory variables of AdS/CFT are trivially invariant under the bulk diffeomorphisms, which are entirely invisible in the gauge theory (the gauge theory fields do transform under the asymptotic symmetries of $AdS_5 \times S^5$, but these are ADM symmetries, not gauge redundancies).

Thus, in the case of emergent time we look for a description of the theory in which time reparameterization invariance is invisible, in which the initial variables are trivially invariant. It is not a matter of solving the Hamiltonian constraint but of finding a description in which the Hamiltonian constraint is empty. Of course we can always in general relativity introduce a set of gauge-invariant observables by setting up effectively a system of rods and clocks, so to this extent the notion of emergence is imprecise, but it carries the connotation that the dynamics can be expressed in a simple way in terms of the invariant variables. The AdS/CFT duality solves this problem by locating the variables at spatial infinity, and in the present context the natural solution would be to locate them at future infinity. That is, there some dual system within which one calculates directly the outgoing state in the FRW patches, some version of the Hartle-Hawking wavefunction perhaps. To access our physics in a nonsupersymmetric and accelerating bubble would then require some holographic reconstruction as in the bulk of AdS/CFT. Certainly such a picture would cast a very different light on many of the questions that we have discussed; it does suggest a possible mechanism for 'post-selection' of the cosmological constant.

It would be useful to have a toy model of emergent time. The problem with the string landscape is that all states mix, and one has to deal with the full problem; is there any isolated sector to explore?

6.1.3 *Conclusions*

A few closing remarks:

- The extent to which first principles uniquely determine what we see in nature is itself a question that science has to answer. Einstein asked how much choice God had, he did not presume to know the answer.
- That the universe is vastly larger than what we see, with different laws of physics in different patches, is without doubt a logical possibility. One might argue that even true this is forever outside the domain of science, but I do not think it is up to us to put a priori bounds on this domain. Indeed, we now have five separate lines of argument (the predictions near the end of Sec. 1) that point in this direction. Our current understanding is not frozen in time, and I expect that if this idea is true (or if it is not) we will one day know.
- A claim that science is less predictive should be subjected to a correspondingly higher level of theoretical skepticism. Our current picture should certainly be treated as tentative, certainly until we have a nonperturbative formulation of string theory.
- The landscape opens up a difficult but rich spectrum of new questions, e.g. [73].
- There are undoubtedly many surprises in the future.

Let me close with a quotation from Dirac:

> One must be prepared to follow up the consequences of theory, and feel that one just has to accept the consequences no matter where they lead.

and a paraphrase:

> One should take seriously all solutions of one's equations.

Of course, his issue was a factor of two, and ours is a factor of 10^{500}.

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6.2 Discussion

E. Silverstein You have said that you think that dimensionality is conserved and that the supercritical string theories do not mix with the rest. I do not understand that comment because we know of such transitions.

J. Polchinski I think they might mix in one direction, so if you go back in time the dimension rises and you do not mix with the low-dimension stuff. That was what I was sort of hoping. I was hoping that there is some kind of scaling in the large D limit.

J. Maldacena The supercritical strings have a tachyon, so this is not a well-defined boundary condition in the future.

E. Silverstein It is not true that every supercritical strings have a tachyon. Some models do, and some models do not, just like with other string theories. It is possible to project out tachyons in supercritical strings.

A. Strominger A question to Polchinski: Why do you think it is possible to decide how predictive science is? Are you asserting that, if you have an anthropic explanation for something, it is possible to rule out that there is another explanation that we have missed? Of course, if you were able to predict everything, you would know that science was totally predictive. But if you fail to do that, how can you even imagine ruling out some clever bleb field method of understanding things that we just had not thought about?

J. Polchinski I think it is fair to say that we do not need to be skeptical until we answer the question "what is string theory?", a question which has a very long future.

A. Strominger What is string theory and whether string theory is related to our world? Fair enough.

J. Polchinski There is structure and correlations that you could not anticipate. The cosmological constant is a smoking gun, there may be others. There is still room for skepticism. It's a Goedel thing. There are undecidable questions. We should not assume a priori how predictive science is, it is not something we can know.

A. Strominger Right, but we can try as hard as we can to predict everything that we are able to.

J. Polchinski We can try relaxing different prejudices and see where each of them leads.

B. Greene Is it not important to draw a distinction between correlations and explanations? I agree that one can find interesting correlations between various features of the theory, but is that an explanation? No, it is just an interesting correlation.

J. Polchinski It is true, but it may be the way nature is. You cannot exclude that this is the way nature is.

D. Gross I just wanted to ask about the many worlds equals many bubbles. You went over that very rapidly, and since I spoke for Hartle, and one of the things on one of the slides was "many worlds not equal to many bubbles", so I am asking his question: why is that?

J. Polchinski I put that in there partly because Hartle did, but also because Susskind said it at "Strings" and other people said it in other language. You can read that in two directions. The more ambitious direction is to say that eternal inflation explains quantum mechanics. I do not think anybody believes that. The less ambitious way to read it is simply that holography tells you that you do not talk about things that are out of causal contact, they are folded back into your own wave function, and so in that sense the many worlds of eternal inflation really are the many worlds of quantum mechanics.

M. Gell-Mann In Everett's work of the late 1950's when he was a graduate student of Wheeler, he formulated the ideas that were ancestrial to a lot of things that we do today. Bryce De Witt called them — or somebody else, not Everett — called them "many worlds". What they are, and what they continue to be today, is a set of ideas about multiple alternative histories of a Universe. If you want to believe that for every such history there is a universe somewhere, then if the universes do not communicate with one another, it does not change anything. But the many-worlds idea is not in any way important for this idea of many histories of the Universe. The other idea having to do with the budding off of new universes in a multi-verse is completely different. That might have some actual consequences for the individual universe we study. If it used to be part of a bigger system which broke up, the state vector would become a density matrix of a certain kind, for example. There might be some consequences. But referring to the other theory, the many-histories idea, as many worlds is just misleading, I think.

N. Seiberg I really enjoyed your nuclear physics analogy. I would like to pursue it a little bit further. If at the time people faced nuclear physics with all its resonances, they had adopted the anthropic principle, you could have repeated your talk with minor changes at that time and it would have had a very negative effect on the development of science. The standard model would not have been discovered. Returning to our time, there could be all sorts of rich physics that we should understand, and adapting the anthropic principle will prevent us from finding it. I think it is premature to declare defeat.

M. Douglas May I answer this? This is sort of a standard answer. There are different metaphors that I like, such as the one that says that we live in a big crystal and we have to figure out which one it is. The situation here is sort of historically reverse. Back then you could have said that the real interesting thing is to identify the protons and quarks and so forth, while here we are actually working backwards. We really believe in the fundamental nature of the supersymmetric pieces, and now we are trying to assemble this into the complicated mishmash that looks more like our world. From that point of view we have already answered the prettiest part of the problem, and now we have this more difficult, chemical, condensed matter problem of reproducing the nature of the world we see. I am not saying this is necessarily the case, but it would be an equally valid analogy to the one that you are suggesting.

E. Rabinovici I want to point out that in field theories that are scale-invariant and finite, the vacuum energy is the same if scale invariance is spontaneously broken or not, and in particular it can be zero. I appreciate that you view this spontaneous breaking of the scale invariance as fine-tuning, therefore it is not on your list, but I beg to differ.

J. Polchinski I think that your selection principle is what I call the static solution principle where you insist that the Lagrangian be such as to give you a static solution. I think that is not a selection principle, and in particular, if you think about it, it is like the dynamical solutions where to know that you would have a static solution you would have to look at your system for all of time. It is not something that can constrain what state the system is at the beginning of time. So it really is the same problem as in other dynamical ideas. That also applies to self-tuning which uses the same strategy.

V. Rubakov I wanted to make a comment on your argument against the dynamical relaxation mechanisms. Actually the fact that the cosmological constant is so small might tell us that the cosmological evolution is quite different from what we think. This was called by Graham Ross "déjà-vu Universe", meaning that there could be a state of the Universe some time in the past which was very similar to the Universe we are now living in, and at that time one or another relaxation mechanism worked. Or, even more, maybe there is strong non-locality and some relaxation mechanism works at very large length scales, while beyond our small part of the Universe, the Universe is just empty. Then all this criticism will not work.

A. Polyakov A couple of comments, nothing to do with philosophy. There are two mechanisms which are probably worth having in mind. They may work eventually. First, as far as the strong CP problem is concerned, there is at least one model in which the solution of the problem comes from the infrared corrections and is completely analogous to the behavior of the theta-angle in the quantum Hall effect. Namely, the behavior is that you take an arbitrary bare θ of the order of 1 and, as you go to the infrared, it tends to zero. Which means that it actually predicts that if you go back to higher energy, the renormalization group flow enhances the CP violation. I certainly do not have any realistic model of field theory with this feature, but some highly non-trivial Yang-Mills theories have it, so it is worth keeping in mind. Although it actually plays for the anthropic principle, which I do not want.

The second thing is that there is also another model, I think, in which we can at least see a tendency of the cosmological constant to be screened by the renormalization group flow also. And it is very natural, because the cosmological term is the only term in the Lagrangian which does not have derivatives, so it is important in the infrared. There could be a phenomenon similar to the Landau zero charge picture when it is screened out as you go to large distances. So that is another possibility, but I admit it does not solve the coincidence problem. But it is still interesting to keep in mind.

N. Arkani-Hamed I just want to make some general comments about the angst of predictivity in this picture. I think that part of the problem is that we continue to confuse prediction of parameters with the more traditional accomplishment of physics which is to predict and understand new dynamics. I do not think you can even start talking about environmental or anthropic or whatever constraints on parameters until you understand the dynamics well enough even to be able to figure out what the relevant parameters are and how they vary. No one would have been tempted to try to explain the phenomena of nuclear physics anthropically. There is clearly major dynamics that was not understood, and there was not even a question of talking about parameters to be tuned or not tuned. Similarly, if we could go up to the string scale or the Planck scale we would experimentally see what is going on, we would see weakly coupled strings if we happened to be in the weakly coupled sector of the theory, and all of that would be absolutely wonderful. It is only because of the practical difficulty of not being able to do that, that we have psychologically replaced it with being able to predict all of the parameters, which of course was never promised. While in the history of physics, understanding dynamics always has pushed us forward, focusing on parameters has some times pushed us forward, and sometimes has not been the right question. The classic example of Kepler trying to predict the distance of the planets from the Sun, is an example of something that was just the wrong question.

I feel that what is different about our situation today is that, at least in our understanding of long distance theories in terms of effective Lagrangians, we are finally at a point where with a finite small number of parameters, we can imagine in a controlled way what happens to physics as those parameters are changed. Our questions are questions about those parameters. That dynamics, at least at large distances, is basically governed by special relativity and quantum mechanics, so that dynamics is under control in the infrared. Now, in that context some parameters can be environmental, but not all of them. So the kind of response that anything that you do not understand, there is an anthropic explanation for it, is simply not true. There is no anthropic explanation for V_{cb}, there is no anthropic explanation for bottom quark mass, there is no anthropic explanation for θ_{QCD} or why there are three generations. And no one would even attempt to come up with them, there are some things that are clearly irrelevant to infrared physics. There are few other parameters, the relevant operators and perhaps some other parameters, which are of great importance for infrared physics and may have an environmental explanation, or not. I want to remind, as Galison very nicely talked about in the first talk in this conference, and Polchinski was mentioning as well, that the issue of how much we get to predict is really not up to us. The angst over not having one world or maybe 10^{500} worlds pales in comparison to the angst that the Laplacian determinists must have felt when they were told that they could not predict the position and velocity of every particle deep into the future from measuring the positions and velocities of every particle now. We are talking about a far less drastic reduction in the degree of predictivity than was already suffered in this transition from classical to quantum mechanics.

Finally I just want to make a concrete point when we talk about the cosmological constant as the "central engine" that is motivating us to think about all of these issues. It is really true that throughout particle physics, and other parts of cosmology, there are, at a much smaller and less dramatic level, but certainly present, many little tunings like this on which the existence of interesting atoms, more complex structures, stars etc., really critically depend. And if you really believe that there is a unique theory, and a unique vacuum, then you really believe that there is a formula involving pure numbers that sets each and every one of those constants. And in such a situation it would really be shocking that so many of them ended up having just the right values that they had to have in order to allow us to exist.

I can just make one last comment. The situation is a lot like in biology. Not everything is selected for. Some things are the way they are because they are selected for, some things are the way they are because they cannot be any other way. It is the analog of environmental selection versus symmetries and dynamics, and one of the characteristics of biological creatures is that somethings are exquisitely designed, and other things are just sort of random, and the standard model looks a lot like that. There are some things that are exquisitely adjusted like the vacuum energy, there are all these irrelevant things like the third generation, V_{cb}, and the bottom quark mass which may just be incidental things that came along for the ride, correlated with other things that happened to be selected for. I think we would all agree that if this was not the picture of the world, we would have an easier job. But it does not strike me as a particularly awkward thing, and certainly not worse than the classical to quantum transition, at least as the issue of predictivity is concerned.

6.3 Prepared Comments

6.3.1 *Steven Weinberg*

Well, I was asked to talk for ten minutes and I don't have any positive new ideas to offer; so I am going to make some remarks of the opposite sign.

First of all, this is a small addendum to Joe's talk. I have a worry about the anthropic prediction or argument about the vacuum energy: that anthropic considerations may not really explain quite why it is as small as it is. If you fix the fluctuations at early times and suppose they don't scan and then calculate what is the average vacuum energy density that would be seen by an astronomer, in any part of the multiverse, weighting, and here Alan's point on how to weight things comes in, but if you do something for want of anything better, you weight the different subuniverses according to the fraction of baryons that find themselves in galaxies that are large enough to hold on to heavy elements after the first generation of stars, then you find that the average density that will be seen by all these astronomers throughout the multiverse, the vacuum energy density, is about 13 times the energy density of matter in our universe at the present time, not that that's a fundamental unit, but it just happens to be a convenient unit. In fact, experimentally, the number is not 13, it is 2.3 and you can ask what is the probability of getting a vacuum energy that small. The answer is: it is about 13%, 13% of all astronomers weighted the way I described will see a vacuum energy as small as we see it. Well, that's not so bad: I mean, 13% I could live with, those are the breaks. But this hinges on an assumption that, in order to hold on to heavy elements, the size of a fluctuation in the co-moving radius projected to the present has to be 2 Mpc's or greater and the answer is quite sensitive to that: if you reduce it to 1 Mpc, then the probability goes from 13% down to 7%. This is a difficult astrophysical question which is beyond my pay grade but, it really is important for astrophysicists to settle the question of how large fluctuations have to be to hold on to their heavy elements. And I just wanted to give you that to worry about a little bit.

Now, Alan has talked about the wonderful agreement of theory and observation for the microwave anisotropy, I could not agree more, it's wonderful, while we have been ringing our hands, the real cosmologists have been in hog heaven and, as Alan pointed out, everything, all the agreement that we see, not only for the microwave background but also for large scale structure, which continues the curve up to larger and larger values of L, large than can be reached by studying the microwave background, all this agreement flows from the assumption that the perturbations before they reenter the horizon are adiabatic, Gaussian and scale invariant. With that and just adjusting the overall scale, you fit these curves. So the wonderful shape of the curves does not really tell you very much about the early universe, it tells you the perturbations, when they are outside the horizon, are adiabatic, Gaussian and scale invariant. Now, that's usually interpreted in terms of a single scalar field rolling down a potential and the first caution I would like to offer is that this outcome is actually much more robust than that and much more generic and so that there isn't that much reason to believe in this very simple picture.

First of all, that the perturbations are adiabatic. By the way, in practice, as far as the microwave background is concerned, that means that $\delta\rho/(\rho+p)$ (ρ being the energy density and p being the pressure) is the same for the cold dark matter and the photon-baryon plasma, and that is verified to a fair degree of accuracy, although is is not very accurate right now. Well, that is extremely easy to achieve: it's automatic if you have a single scalar field rolling slowly down a potential; it's not automatic if you have many scalar fields, as you might expect, but if after inflation all these scalar fields dump their energy into a heat bath and if at that time, because baryon-number has not yet been generated, there were no non zero conserved quantum numbers, then of course automatically the perturbations must be adiabatic; that's almost trivial. What is a little bit less trivial is that later on, when the cold dark matter and then the neutrinos decouple from the photon-baryon plasma, the perturbations remain adiabatic. So that, it is by no means true that if you have many scalar fields you expect non adiabatic perturbations to be observed at the present time. Now, it is possible that you can get non adiabatic perturbations, there are the so called curvaton models, where you carefully arrange that some of the scalar fields that were present during inflation do not dump their energy into the heat bath but survive for some reason and these provide a model for non adiabatic perturbations. *I think that the generic case is that you get adiabatic* perturbations. That is true even if you have things much weirder than scalar fields: as long as after inflation you have a heat bath with no non zero conserved quantum numbers, then, even later when you no longer have local thermal equilibrium, you still have purely adiabatic perturbations.

That they are Gaussian, well, that follows from the fact that the perturbations are small, we know that experimentally, and that there was a time (this is true of a lot of theories although not all theories) in the very very early universe, when the physical wave number was large compared to the expansion rate, that the fields behaved like free fields. It's easy to arrange theories of many kinds including multiple scalar field theories in which that is true and if it is true, then you get Gaussian perturbations.

Scale invariance? Well, there are lots of theories that give you scale invariance. I made that remark at a meeting in Santa Barbara and Andrei Linde challenged me to thing of others. Of course, one example is multiple scalar fields all rolling slowly down a potential, but I could not really come up with any alternative but, Neal Turok here, just the other day, pointed out that in the oscillating or bouncing cosmology that he was suggesting you do get scale invariant perturbations. And scale invariance after all, scale invariant perturbations are pretty ubiquitous in nature, communications engineers call them $1/f$ noise and they are used to $1/f$ noise, even though it has nothing to do with inflation.

So, I would say that what you really need in order to settle these questions and to really get a handle on what was happening during inflation, which I don't think we have now, is to observe the effect of the tensor modes, the gravitational waves. Many people have said this, it's hardly an original observation. Fortunately, the Europeans are going ahead with the Planck satellite which may be able to detect the effect of tensor modes on the polarization of the microwave background because they are not wasting their money on manned space flight the way America and Russia are.

Now, I have talked about what are the necessary conditions for what we see: adiabatic, scale invariant, Gaussian perturbations. What about sufficient? The question here comes from the quantum corrections. We normally say that the quantum corrections are small. Why do we say they are small? Because the measure of smallness, the factor that you get every time you add a loop to a diagram, is something like $G\,H^2$, where G is Newton's constant and H is the Hubble constant, at the time the perturbation left the horizon. Experimentally, we know $G\,H^2 \simeq 10^{-12}$ so that is why quantum corrections are small and you don't have to worry about them. But, is it really true that the quantum corrections only depend on what was happening at the time the perturbations left the horizon? The calculations that have generally been done have been purely classical, for instance Maldacena calculated corrections, non Gaussian terms, that were corrections to the usual results, but that corresponded to a tree graph in which you have 3 lines coming into a vertex: that was not really a specifically quantum effect. When you include quantum effects, you begin to worry because the Lagrangian, after all, contains terms with positive powers of the Robertson-Walker scale factor a. For example, for a scalar field with a potential, you get an a^3 just from the square root of the determinant and even without a potential, just from the $(\bar{\nabla}\phi)^2$-term you get a factor of a. Now, there are lots of complicated cancellations which deal with this and, in fact, you can show that there are lots of theories in which the same result applies: the quantum corrections depend only on what was happening at the time of horizon exit and therefore they are small and therefore we don't worry about them.

It is clear though that there are other theories where that is not true. In particular... A kind of theory where it is true is a minimally coupled massless scalar field which has zero vacuum expectation value (not the inflaton but an additional scalar field with zero vev). If it does not have any potential, then the quantum effects caused by loops of that particle, to any order, do not produce any effects that grow with a as you go to late times in inflation. But, if you add a potential for the scalar, $V(\phi)$, then you get terms that do.

Last week I thought I was going to come here and show you a theory in which you get positive powers of a so that all bets are off and that the corrections become very large at late time. And just last week I was able to prove a theorem that, in fact, in every theory that I am able to think of, the corrections, when they are there, grow only like $\log a$. So, I am afraid, I don't have anything exciting to announce. Although there are quantum effects which do not depend only on what is happening at the time of horizon exit, they do not grow any faster than $\log a$. Which is a pity but that seems to be the way it is.

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6.3.2 *Renata Kallosh: Inflationary models as a test of string theory*

Our Universe is an Ultimate Test of the Fundamental Physics. High-energy accelerators will probe the scale of energies way below GUT scales. Cosmology and astrophysics are the only known sources of data in the gravitational sector of the fundamental physics (above GUT, near Planck scale). After the supernovae obser-

Early Universe Inflation	Late-time Acceleration
Near de Sitter space	Near de Sitter space
13.7 billion years ago	Now
During 10^{-35} sec	During few billion years
$V \sim H^2 M_P^2$	$V \sim H^2 M_P^2$
$H_{\text{infl}} \leq 10^{-5} M_P$	$H_{\text{accel}} \leq 10^{-60} M_P$

$$\frac{\dot{a}}{a} = H \approx \text{const}$$

$$\frac{\ddot{a}}{a} > 0\,, \qquad a(t) \sim e^{Ht}$$

vations and particularly after the release of the 1st year WMAP data on CMB in 2003 it become clear that any fundamental theory which includes gravity as well as particle physics has to address these data. The theory is expected to explain the origin of the near de Sitter space both during inflation as well as during the current acceleration. The most recent new observations from the Boomerang [1] are in agreement with the so-called *standard cosmological model* supported by the first set of WMAP data. This is ΛCDM model, in which the universe is spatially flat, it has a mysterious combination of matter we know it ($\sim 5\%$), cold dark matter ($\sim 25\%$) and dark energy ($\sim 70\%$). The model is using just few parameters to explain the large amount of cosmological observations. These parameters are suggested by the inflationary cosmology [2] which plays a significant role in ΛCDM standard model. The model also incorporates the current acceleration of the universe, see Table I.

String theory is the best candidate for the unified theory of all fundamental interactions. It has been realized over the last few years that the long standing difficulties in explaining cosmological observations may be resolved due to the current progress in string theory.

Quite a few models of inflation were derived since 2003 within compactified string theory with stabilized moduli. The inflaton field, whose evolution drives inflation is the only field which is not stabilized before the exit from inflation. Each of these models relies on particular assumptions. Some of these models have clear predictions for observables and therefore are FALSIFIABLE by the future observations. We will shortly comment here on few recently constructed models of inflation where, under clearly specified assumptions, one can predict three important observables.

(1) Tilt of the primordial spectrum of fluctuations, n_s
(2) The tensor to scalar ratio, $r = \frac{T}{S}$
(3) Light cosmic strings produced by the end of inflation

One can approximate the spectrum of the scalar and tensor perturbations of the metric by a power-law, writing

$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_*)\left[\frac{k}{k_*}\right]^{n_s-1}, \qquad \Delta^2_h(k) = \Delta^2_h(k_*)\left[\frac{k}{k_*}\right]^{n_t}, \qquad r = \frac{\Delta^2_h(k_*)}{\Delta^2_{\mathcal{R}}(k_*)}$$

where n_s, n_t are known as the scalar spectral index and the gravitational spectral index, respectively, and k_* is a normalization point, r is the tensor/scalar ration , the relative amplitude of the tensor to scalars modes. The observations require n_s close to one, which corresponds to the perturbations in the curvature being independent of scale. The deviation of the spectral index from one, $n_s - 1$, is a measure of the violation of the scale invariance of the spectrum of primordial fluctuations.

The only known at present viable mechanism for generating the observed perturbations is the inflationary cosmology, which posits a period of accelerated expansion in the Universe's early stages. In the simplest class of inflationary model the dynamics are equivalent to that of a single scalar field ϕ slowly rolling on an effective potential $V(\phi)$. Inflation generates perturbations through the amplification of quantum fluctuations, which are stretched to astrophysical scales by the rapid expansion. The simplest models generate two types of density perturbations which come from fluctuations in the scalar field and its corresponding scalar metric perturbation, and gravitational waves which are tensor metric fluctuations. Defining slow-roll parameters, with primes indicating derivatives with respect to the scalar field, as

$$\epsilon = \frac{m^2_{\rm Pl}}{16\pi}\left(\frac{V'}{V}\right)^2 \quad ; \quad \eta = \frac{m^2_{\rm Pl}}{8\pi}\frac{V''}{V},$$

the spectra can be computed using the slow-roll approximation (ϵ, $|\eta| \ll 1$). In each case, the expressions on the right-hand side are to be evaluated when the scale k is equal to the Hubble radius during inflation. The spectral indices and tensor to scalar ratio follow

$$n_s \simeq 1 - 6\epsilon + 2\eta \quad ; \quad n_t \simeq -2\epsilon\,, \qquad r \simeq 16\epsilon \simeq -8n_t\,,$$

The last relation is known as the consistency equation for the single field inflation models, it becomes an inequality for multi-field inflationary models.

It has been recognized recently that cosmic strings give a potentially large window into the string theory [3]. CMB observations put a stringent constraint on cosmic strings produced at the end of inflation: only very light cosmic strings with the tension $(G\mu)_{obs} < 5 \cdot 10^{-7}$ are consistent with the data. The KKLMMT model [4] of stringy inflation is based on the throat geometry with the highly warped region and therefore can easily explain the existence of light cosmic strings. At present, however, no evidence is available for such cosmic strings, see [5] for the recent Hubble Space Telescope observation which proved that the object CSL-1 is not a lensing of a galaxy by a cosmic strings, contrary to previous expectations.

Inflationary models in string theory have few clear predictions for the primordial spectral index and for the tensor to scalar ratio. A significant amount of gravitational waves is expected to take place in chaotic models of inflation [6]. However, most models of modular and brane inflation in string theory known at present do not predict any significant amount of gravitational waves. Still there are models, like [7] where in the context of string theory there is a possibility to explain the primordial gravitational waves in case they will be actually detected.

With regard to the spectral index n_s the situation is developing in a rather interesting way. The 1st year WMAP data alone suggest

$$n_s = 0.99 \pm 0.04 \ ,$$

the combination of the data from WMAP+CBI+ACBAR+2dFGRS gives

$$n_s = 0.97 \pm 0.03 \ .$$

Moreover, there is an indication from the most recent release of the Boomerang data [1] that the central value of n_s may be moving downwards towards

$$n_s \approx 0.96$$

and it will most interesting to know what emerges from the new WMAP data[10].

The inflationary models in string theory in some cases have a clear computable prediction for n_s. For example, a racetrack model of modular inflation [8] predicts $n_s = 0.95$. This is a model with one Kähler modulus where the system has a saddle point and inflates due to axion-inflaton into a stabilized KKLT string flux vacua with de Sitter minimum [9] to account of the current acceleration of the universe. Another model of hybrid inflation, the so-called D3/D7 brane inflation [10], predicts $n_s = 0.98$ under a condition of the softly broken shift symmetry protecting the near-flat inflationary potential in this model.

Planck satellite (2008?) is expected to provide the precision data on spectral index n_s at the level of 0.5% ! This will help to focus on those models of inflation

[10]On March 16 2006, the WMAP three year data release took place at

http://lambda.gsfc.nasa.gov/.

The new data strongly support the standard cosmological model and favor an inflationary model $\lambda\phi^2$ of [6]. The new value of the spectral index is $n_s = 0.95 \pm 0.02$ in agreement with [1]. From all known at present models of stringy inflation with a clear prediction for the spectral index, the racetrack model [8] seems to give the best fit to the data.

in string theory which will support the data from Planck and other sets of future observations.

- If the inflationary models are derived in string theory by reliable methods and assumptions stated clearly
- If the models have unambiguous prediction for observables
- When the precision data will come in we will be able to test the string theory assumptions underlying the derivation of the corresponding "best fit data" inflationary models.

New cosmological data will be coming during the next 10-20 years "fast and furious"!

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6.3.3 *Andrei Linde: Eternal inflation in stringy landscape and the anthropic principle*

In the beginning of the 80's, when the inflationary theory was first proposed, one of its main goals was to explain the amazing uniformity of our universe. Observations told us that the universe looks the same everywhere and that the physical laws in all of its parts are the same as in the vicinity of the solar system. We were looking for a unique and beautiful theory that would unambiguously predict all properties of our universe, including the observed values of all parameters of all elementary particles, not leaving any room for pure chance.

However, most of the parameters of elementary particles look more like a collection of random numbers than a unique manifestation of some hidden harmony of Nature. But there was one important property shared by many of these parameters: Changing them in any substantial way would lead to the universe where we could not exist. This fact is the foundation of the cosmological anthropic principle [1]. This principle is based on a simple fact: We can observe the universe with a given set of properties only if these properties are compatible with our very existence.

Whereas this fact is certainly correct, many scientists are still ashamed of using the anthropic principle. It is often associated with the idea that the universe was created many times until the final success. It was not clear who did it and why was it necessary to make the universe suitable for our existence. There were some attempts to relate the anthropic principle to the many-world interpretation of quantum mechanics, or to quantum cosmology, but these attempts looked esoteric, and they did not explain why all parts of the universe have similar properties. Indeed, it seemed to be much simpler to have conditions required for our existence in a small vicinity of the solar system rather than in the whole universe.

Fortunately, most of the problems associated with the anthropic principle were resolved more than 20 years ago with the invention of inflationary cosmology. First of all, in the context of inflationary cosmology, nice conditions in a small vicinity of the solar system imply similar conditions in the observable part of the universe, thus removing the most difficult objection against the anthropic principle. Also, in the context of chaotic inflation [2] there is no need to assume that initial conditions were the same in all parts of the universe. If initial conditions were different in different parts of the universe (or in different universes), then a generic inflationary universe should consist of many exponentially large regions containing matter in all of its possible states, with scalar fields rolled down to all possible minima of their energy density, and with space with all of its possible types of compactification. This observation provided the first scientific justification of the anthropic principle [3, 4].

The situation becomes even more interesting when one takes into account quantum fluctuations produced during inflation. It was shown in [5] that even if the universe started with the same initial conditions everywhere, e.g. in the $SU(5)$-symmetric minimum of the $SU(5)$ SUSY, inflationary fluctuations lead to jumps of the scalar fields from one minimum of its potential to another, which divides the universe into exponentially large domains with matter in all possible states corresponding to all minima of the $SU(5)$ SUSY, including our $SU(3) \times SU(2) \times U(1)$ minimum.

These observations merged into one coherent picture after the discovery of eternal inflation in the context of chaotic inflation scenario [6].[11] According to this scenario, some parts of the universe continue eternally jumping at density which may be as high as the Planck density. Inflationary fluctuations produced in this regime are powerful enough to jump over any barrier, and divide the universe into exponentially large domains in which not only the scalar fields but even the type of compactification and the effective dimension of our space-time may change [10].

A similar regime may exist in the theories with many different local de Sitter minima even if inflation near these minima is not of the slow-roll type [11]: The field may tunnel from an upper minimum to the lower minimum and back. A combination of this effect and the effect discovered in [8, 3, 9, 6] provided a necessary background for the string landscape scenario [12].

This scenario is based on the recent discovery of the mechanism of moduli stabilization in string theory [13], which allowed to describe inflation and the present stage of acceleration of the universe. Once this mechanism was found, it was realized that the total number of possible metastable de Sitter vacua in string theory is enormously large, perhaps 10^{100} or 10^{1000} [14]. During inflation our universe becomes divided into exponentially large domains of 10^{1000} different types, which is a perfect setup for the anthropic principle.

The large set of stringy vacua introduces an incredibly large set of *discrete* parameters. However, some of the parameters of our universe are determined not by the final values of the fields in the minima of their potential related to the string theory landscape, but by the dynamical, time-dependent values which they were taking at different stages of the evolution of the universe. This introduces a large set of *continuous* parameters which may take different values in different parts of the universe.

One example of a continuous parameter is the ratio n_γ/n_B. Its observed values is about 10^{-10}. In some cases, the reason why this number is so small is pretty obvious, but in the original version of the Affleck-Dine scenario a typical value of this parameter was $O(1)$ [15]. The ratio n_γ/n_B in this scenario is determined by the angle between two scalar fields soon after inflation. This angle is a free parameter which may take different values in different parts of the universe due to inflationary fluctuations of these fields [16]. It was argued in [16] that the process of galaxy formation strongly depends on the ratio n_γ/n_B. Therefore even if though the total volume of the parts of the universe with $n_\gamma/n_B = O(1)$ is 10^{10} times greater than

[11] The regime of eternal inflation was known to exist in old inflation [7] and in new inflation [8, 3, 9], but none of these papers except [3] mentioned the relation of this regime to the anthropic principle.

the total volume of the parts with $n_\gamma/n_B = 10^{-10}$, we can live only in the parts with $n_\gamma/n_B \sim 10^{-10}$ [16].

The second such example, which is in fact very similar, is the ratio of the baryonic matter density to the cold dark matter density, $\zeta = \rho_{CDM}/\rho_B \sim 5$. In the theory with light axions, $m_a \ll 10^{-5}$ eV, the natural value of this ratio would be much smaller than 0.2, which was considered as a strong evidence that the axions do in fact have mass $m_a \sim 10^{-4} - 10^{-5}$ eV [17]. The resolution of the problem was very similar to the one mentioned above: In inflationary cosmology with $m_a \ll 10^{-5}$ eV the universe consists of many different exponentially large regions with different values of ζ. The prior probability of formation of the region with different $\sqrt{\zeta}$ after a period of inflation does not depend on ζ. However, the existence of galaxies and stars of our type would be much less probable for $\sqrt{\zeta}$ one or two orders of magnitude greater than its present value. This provides an anthropic explanation of the presently observed value of ρ_{CDM}/ρ_B [18, 19].

One of the most spectacular applications of the anthropic principle is the cosmological constant problem. Naively, one could expect vacuum energy to be equal to the Planck density, $\rho_\Lambda \sim 10^{94} g/cm^3$, whereas the recent observational data show that $\rho_\Lambda \sim 10^{-29} g/cm^3$, which is about 0.7 of the total energy density of the universe ρ_0. Why is it so small but nonzero? Why ρ_Λ nearly coincides with ρ_0?

The first anthropic solution to the cosmological constant problem in the context of inflationary cosmology was proposed in 1984 in [20]. The vacuum energy density can be a sum of the scalar field potential $V(\phi)$ plus the energy of fluxes $V(F)$. I argued that quantum creation of the universe is not suppressed if it is created at the Planck energy density, $V(\phi) + V(F) = 1$, in Planck units. Eventually the field ϕ rolls to its minimum at some value ϕ_0, and the vacuum energy becomes $\rho_\Lambda = V(\phi_0) + V(F)$. Since initially $V(\phi)$ and $V(F)$ with equal probability could take any values with $V(\phi) + V(F) = 1$, we get a flat probability distribution to find a universe with a given value of the cosmological constant $\rho_\Lambda = V(\phi_0) + V(F)$. Finally, I argued that life would be possible only for $-\rho_0 \lesssim \rho_\Lambda \lesssim \rho_0$. This fact, in combination with inflation, which makes such universes exponentially large, provides a possible solution to the cosmological constant problem.

In the next couple of years after my work, several other anthropic solutions to the cosmological constant problem were proposed [21]. All of them took for granted that life is possible only for $-\rho_0 \lesssim \rho_\Lambda \lesssim \rho_0$. The fact that ρ_Λ could not be much smaller than $-\rho_0$ was indeed quite obvious, since such a universe would rapidly collapse. Meanwhile the constraint $\rho_\Lambda \lesssim \rho_0$ was much less trivial; it was fully justified only few years later, in a series of papers starting from the famous paper by Weinberg [22].

I would be able to continue this discussion, describing the constraints on the amplitude of density perturbations, on the dimensionality of the universe, on the electron and proton masses, on the expectation value of the Higgs field, etc. What we see here is that many properties of our universe become less mysterious if one try to relate them to the fact of our own existence. We still have to learn how to calculate the probabilities in the eternally inflating universe. We still need to find a full string theory description of particle phenomenology and estimate the total number of vacua which can describe our world. But it will be very difficult to turn back and unlearn what we just learned. Now that we have found that there exist simple anthropic solutions to many problems of modern physics, one would need either to find an alternative solution to all of these problems, or to learn how to live in the democratic world where the freedom of choice applies even to our universe.

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6.4 Discussion

G. 't Hooft I would like to have an answer to the question: Is this notion of the landscape the same as we have heard earlier today? Because here it seems that you can travel on a spacelike orbit. Let us imagine that we can move in this universe on a spacelike orbit, just to watch around us. The question is: would we be able (even in principle) then to enter into another part of the universe where the standard model is a different one and, if so, what would that transition look like? Would we pass through a membrane, or would we pass through the horizon of a black hole? What is it that separates these different kinds of universes? In a picture Linde had these bubbles connected by little throats, and I wonder if you would travel through such a throat what would the transition be like? Is there a moment when you would say "Hey, now we have 4 generations!", or 25 generations, or something that changes?

A. Linde Let me answer the first question, "What I am going to see at the boundary?" That depends on the boundary. Usually, you have boundaries as follows: you have one minimum and another minimum and between the minima you know that you must go up the hill. Typically then, these two minima are divided by domain walls. The sizes of two sides are exponentially large. If these domains are both de Sitter, you are in a hopeless situation, because if you will be traveling here this part will be running away from you because of de Sitter expansion. If you are sitting in Minkowski space, which is just by chance, then you will have a possibility to travel here for some time, and after that you would see the wall and if you are young and stupid still at that time, then you will go through the wall and die because your particles will not exist in that part of the universe.

G. 't Hooft The question was not really whether one could travel there on a time-like geodesic, but suppose — in our imagination — one goes over a space-like geodesic, or a space-like orbit, or even back in time. At some point you should see a transition when you go from one universe to the next. So if you go back in time or on a space-like orbit, then, as you say, you would go through some membrane or something. I want to know what that thing is like.

A. Linde Are you are asking about the process, for example, that happens if I am sitting at this point, and quantum fluctuations just push me to some place?

S. Shenker I think that what 't Hooft is asking is the following. Suppose you pick some time variable, does not matter which. Look at a fixed-time space slice and then go along. What happens when you jump from one bubble to the next?

A. Linde That is the thing that I answered, exactly. The image which I showed you is the result of a computer simulation of one particular time slice, a space-like hypersurface.

G. 't Hooft I just want to have you pin down somehow: What would this membrane look like? A membrane separating two different kinds of universes: would that be a running away horizon? I am not quite happy with it, but that could be a conceivable answer. So, is it a horizon which runs away from us or is there really a membrane? Would it be something like in science fiction, a kind of wall at the end of the universe and you just have to go through it to see the other part of the universe, anything like that?

A. Linde As I said, this is a model-dependent issue, and it also depends on the nature of the state. If you are sitting in de Sitter space, you never even come to this part of the Universe. It will run away from you. If you are sitting in Minkowski space, then you would have two possibilities: the one is that the boundary travels away from you with the speed equal to the speed light and then you will never touch it. There is another possibility that this part travels with the speed of light towards you, and then you will never see it because at the moment you see it, how to say, there will be nobody to respond and nobody to report. NSF will not support your further work.

G. 't Hooft Maybe the question to the other people here is the following: is that the same notion of landscape as seen in other talks?

A. Linde We are talking about the same landscape, but this landscape is an "animal with many faces". All of these things are very much different. The parts of the universe which are de Sitter have some properties, parts which are Minkowski are rare animals, and they have some other properties. Parts which we are supposed to associate with anti-de Sitter, they are actually not anti-de Sitter but collapsing Friedman Universes. All of them can be part of this picture.

S. Shenker One of the things about these issues I find the most interesting (that is probably because I just started thinking about them) is this issue that Guth, Linde and others discussed, about putting a measure on the space of "pocket universes". Now that it seems more and more likely that string theory contains some kind of landscape, and it seems that there is a well-defined quantum gravity. For this mysterious bubbling phenomenon, there should be some kind of question about how likely is every kind of bubbling universe. And it is incredibly hard, as Guth mentioned, to figure out what that question means. Now, we think we have a well posed theory. Either this question is, for some reason, completely nonsensical or we should be able to sharpen it up. This problem is one to think about. It has the psychological advantage that you can think about issues of landscape and bubbles and never have to think about anthropics, which I find psychologically appealing.

M. Douglas I agree with the importance of this. There is another version of this question that I have read in the existing literature. It just seems that if at some point of your calculation you get infinity over infinity, or a limit of quantities which is going to become infinity over infinity, then your definition is inherently ambiguous, and at that point you have already lost. Was there any kind of suggestion or hope in the existing works, of a definition that would make at least a denominator finite? I see that the infinity comes in because of the growth of volume. The definition of inflation is this growth of the volume, and any limit would make that infinite, but somehow one has to avoid that.

A. Linde Well, if we would know the answers, we would probably have written about them a long time ago. But I would like just to give some analogies. The first analogy is that there is a question "What is the time of the greatest productivity of a person?" and another question is "What is the time when a typical physicist produces his best work?" The typical time, or age, when the best works are produced by physicists is between 20 and 30. Which would mean that all of us must just retire now in shame because we all are out of maximal productivity. On the other hand, when Ginzburg discussed this question at our seminars (and he was already from my perspective at that time very old — which is my age right now), he said the following: this is a question of statistics. If you are interested in what is the typical age physicists produce their best works, you measure it weighting it with the total number of scientists (which at that time was exponentially growing). That is why you have this youngness paradox. But then, Ginzburg said, I am interested in my own productivity, and that is a different measure. Now, you ask me which of these questions makes sense and I tell you: both make sense from a statistical point of view. What one should learn from this is not which of these measures is better but which of them has any relation with the anthropic principle. That is one possible answer. Another possible answer is that actually we may take a very humble attitude, and the humble attitude would be like that: all my life, I was wondering why I was born in Moscow; when I was a young pioneer, I was wondering why I am so happy to be born in Moscow where the best children in the world live. When I got older I still asked why I was born on Moscow, anyway. Then, right now, I am saying: these questions may have no meaning because there are much more Chinese. So, if I would just measure the total number of people, then by this measure I would be an exception. But if I know that I am born in Moscow, and I see everybody speaking English around, then I would think that this is something surprising, this is something that I must explain.

So, I must ask conditional probability questions: under given experimental results, e.g. under the given result that I know what is $\Delta\rho/\rho$, do I still find the present value of the cosmological constant surprising? No, I do not. But if you let me consider all possible values of Λ and $\Delta\rho/\rho$ and everything else, I will have huge areas of landscapes with infinite volume and I will have nothing to say. So, in a more humble way, that is exactly what experimentalists do: they make new measurements and after these new measurements they evaluate what is the probability of the next outcome of the next experiment. If you use the anthropic principle in this way, there is a better chance that you will not say anything nonsensical.

F. Englert I would like to make a comment, essentially to convey my uneasiness about the way this anthropic principle is used here. It unavoidably makes one think about the principle of natural selection in biology. Now, I do not want to discuss natural selection in biology but I think the transcription of it from biology to physics is a little bit dangerous. I just want to give a simple example. Suppose that we do not know the theory of gravity and suppose that someone asks why do apples fall on the ground (the apple had a historical importance in gravity, that is why I choose apples). The answer is extremely simple: because, if they do not fall on the ground, they do not give rise to trees and therefore those apples that do not fall on the ground have disappeared. You can very easily generalize that statement: not only apples but, of course, everything falls on the ground because what does not fall on the ground is no more there. The morality of this is that, of course, we would like to say that maybe one should not reason too simplistically on this, but one should better look for a theory of gravitation at that moment. Maybe one should look for a decent theory for explaining that particular element which is the cosmological constant.

B. Greene Just a quick remark relevant to the question that was asked about finding the measure on the landscape. I guess I am not still quite convinced that this is a really interesting question. And the reason I am not convinced is the following. If you would ask the same kind of question in the context of ordinary field theories — look at the landscape of all possible field theories and write some measure on that space — you are never going to find the Standard Model as some generic field theory in this space of field theories. It is a very special field theory, and yet it is the one that is right. Although I understand the motivation for having a measure on the space of the landscape from string theory, that is to have a possible anthropic solution to the cosmological constant, but what if you go beyond that and talk about the rest of phenomenology? The basic question is: since we all know that very special theories are sometimes the right theory, why try to have some sense of genericity as a guide to finding the right model?

S. Shenker Now we are going to have the last couple of talks.

6.4.1 *Paul J. Steinhardt: A modest proposal for solving the cosmological constant problem*

Probably all of the participants at the Solvay Conference have dreamed of solving the cosmological constant (Λ) problem. And probably all have, at one time or another, sought the same solution: a dynamical relaxation mechanism that gradually cancels all contributions to Λ, whether due to physics at the Planck scale, the electroweak scale, the QCD scale, *etc.* In this way, the universe could begin with a natural value for Λ of order the Planck scale but have an exponentially small value today. During the last quarter century, though, a serious roadblocks has been placed in the way of this dream due to a combination of inflationary cosmology and dark energy. Inflationary cosmology requires that the relaxation time be long compared to a Hubble time during the first instants after the big bang so that the universe can undergo the cosmic acceleration necessary to resolve the horizon and flatness problems and generate a nearly-scale invariant spectrum of density fluctuations. After inflation, it is essential that the relaxation time become short compared to a Hubble time in order for primordial nucleosynthesis and galaxy formation to proceed in accordance with observations. The discovery of dark energy, though, means that the universe entered a new period of cosmic acceleration 10 billion years later, so the relaxation time must be long compared to a Hubble time today. The situation seems to call for a relaxation mechanism that transforms magically on cue from slow to fast and back to slow again, a cosmological somersault that appears to be anything but simple.

In this comment, I would like to introduce a suggestion by Neil Turok and myself [1] for reviving the concept of a *simple* dynamical relaxation mechanism. Here, rather than seeking a relaxation time that is sometimes shorter and sometimes longer than a Hubble time, we propose a relaxation time that is *always exponentially long compared to a Hubble time.* (Finding ultra-slow relaxation mechanisms turns out not to be difficult; as illustrated below, some have already been identified in the literature.) In our picture, Λ is decreasing excruciatingly slowly throughout cosmic history at a rate too small to be detected even after 14 billion years. Furthermore, the relaxation process slows downs as Λ approaches zero from above. Hence, most of cosmic history is spent with a small, positive cosmological constant, in accordance with what we observe.

Before describing how the concept works, it is instructive to compare our picture of the cosmological constant with the case of the 'Hubble constant,' H. H is about 10^{-42} GeV, exponentially tiny compared to the QCD, electroweak or Planck scale. If it were truly a constant, physicists would find it hard to understand how its value could emerge from fundamental physics. Yet, this small value is essential if galaxies, stars and planets are ever to form. Some might feel driven to introduce an anthropic principle or multiverse to explain the small value. But, as we already know, this is not necessary. We understand that Einstein's theory of general relativity tells us that the 'Hubble constant' is not a constant after all and that gravity incorporates a dynamical relaxation mechanism that naturally causes H to decrease with time. H was once large – so large that galaxies could not form – but after 5 billion years it reached a value small enough for structure to evolve. Furthermore, the Hubble constant decreases more slowly as its value shrinks, so most of cosmic history is spent with a small positive Hubble constant. So, as far as the Hubble constant is concerned, we live at a typical location in space and time. Its small value today is not considered a deep mystery; it is just a sign that the universe is old compared to a Planck time.

Our proposal for Λ is similar. The key difference is a matter of timescale. The Hubble constant changes by a factor of 10^{100} in 14 billion years. For the cosmological constant, we envisage that it relaxes by 10^{100} in $10^{10^{120}}$ years or more. The essential idea is that Λ is small but nearly constant (compared to a Hubble time) today because it has had an exponentially long period (compared to a Hubble time) to relax.

Of course, to implement this idea, the universe must be much older than 14 billion years. For such an old, expanding universe to have a non-negligible H and matter density, it had better be that H and the matter density can be reset to large values at times during the period that Λ slowly decreases. As one reflects further upon the idea, it becomes apparent that a cyclic model of the type described by Neil Turok [2–4] is ideally suited for this purpose – although it is interesting to note that the model was not designed with this idea in mind.

First, the cyclic model provides more time. Each cycle lasts perhaps a trillion years, but there is no known limit to how many cycles there may have been in the past. So, a universe that is $10^{10^{120}}$ years or longer is quite feasible. Second, the cyclic model provides a mechanism, the periodic bounces between branes, for regularly replenishing the universe with matter and radiation at regular intervals and, consequently, regularly restoring H to a large value. Third, the cyclic model does not include a period of high energy inflation, removing the key roadblock discussed in the introduction. Finally, the cyclic model includes matter fields that live on the branes and couple to the brane metric. According to the model, the branes expand from cycle to cycle; the periodic crunches occur because of a contraction along the extra dimension. Hence, fields on the branes are redshifted from cycle to cycle but are not blue shifted during the periods of contraction (of the extra dimension); this turns out to be useful for maintaining the slow relaxation process for reasons that are explained in Ref. [1].

As for the slow relaxation mechanism, there are various possibilities. For simplicity, I focus here on a concrete example first introduced twenty years ago by L. Abbott [5], but in the wrong context. (Another mechanism with similar properties was introduced by J. Brown and C. Teitelboim a few years later [6].) Abbott proposed relaxing the cosmological constant by adding an axion field ϕ with a tilted 'washboard' potential

$$V(\phi) = M^4 \cos\frac{\phi}{f} + \frac{\epsilon}{2\pi f}\phi, \tag{1}$$

where $M \sim 1$ eV, $f \sim 10^{16}$ GeV, and $\epsilon^{1/4} \sim .1$ meV are sample values that serve the purpose. The gauge interaction provides a natural explanation for the small value of M, analogous to the explanation for the QCD scale, Λ_{QCD}. $\Lambda_{QCD} \sim 100$ MeV is generated dynamically and can be expressed in terms of the Planck mass m_p as $\Lambda_{QCD} \sim m_p \exp(-2\pi/\alpha_{QCD})$, where $\alpha_{QCD} = 0.13$ is not so different from unity. Here we imagine that ϕ lives on the hidden brane and is coupled to hidden gauge fields. A modest difference in the the hidden sector coupling constant, $\alpha_{hidden} \sim 0.09$, suffices to obtain the value of M desired for our model. The tilt come from an interaction that softly breaks the periodic shift-symmetry of the axion. The soft breaking scale, $\epsilon^{1/4} \leq 1$ meV, is comparable to but somewhat smaller than M; it sets the scale of the steps in energy density along the washboard: $V_N - V_{N-1} = \epsilon$. The model is technically naturally in that the coefficients are not subject to large quantum corrections.

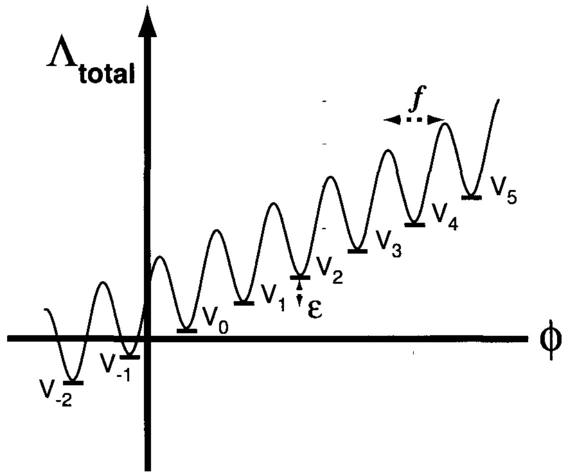

Fig. 6.3 The washboard potential defined in Eq. 2.

The total vacuum energy density is

$$\Lambda_{total} = \lambda_{other} + V(\phi) \tag{2}$$

where λ_{other} incorporates all other contributions from Planck, electroweak, QCD and other non-axionic physics. The washboard potential (Fig. 6.3) has periodically spaced minima at $\phi = 2\pi f N + \phi_0$ where N is an integer and ϕ_0 is the value of ϕ at $V = V_0$. The minima have vacuum density $V_N = V_0 + N\epsilon$ where V_0 is the vacuum density of the minimum with the smallest non-negative Λ_{total}. The potential also has minima $V_{-1}, V_{-2}, \ldots$ with negative vacuum density.

Suppose the universe begins at some minimum with a large positive potential density V_N. The universe begins to work its way down the potential by quantum tunneling through the energy barriers. That is, growing bubbles of vacuum with $V = V_{N-1}$ form in a background with $V = V_N$. The process continues from one minimum to the next until V approaches V_0 and $\Lambda_{total} \leq \epsilon$. Since the average tunneling rate is $\Gamma \sim M^4 e^{-B}$ where $B \sim M^2 f/V_N$, the relaxation rate decreases exponentially as the field tunnels downhill. Hence, the universe spends exponentially more time at stages when the cosmological constant is small and positive. At the last positive minimum V_0, the tunneling time is roughly $10^{10^{120}}$ years. Eventually, bubbles nucleate with $V = V_{-1}$ in their interior, but these are anti-deSitter minima that undergo gravitational collapse in one Hubble time (about 14 billion years). The collapsed regions probably form black holes. But since most of the universe continues to expand at an accelerating rate, these black holes represent an insignificant fraction of the volume. So, for any patch of space, no matter the value of λ_{other}, ϕ relaxes down to and spends most of cosmic time at the minimum with the smallest positive Λ_{total}.

Abbott's notion was to apply this mechanism in a standard big bang universe where it fails utterly. In the long time it takes to tunnel, the universe expands so much that it is completely vacuous by the time ϕ begins to tunnels down the potential. However, the concept dovetails perfectly with the cyclic model.

If the axion and the gauge fields to which it couples live on the hidden brane, their evolution is independent of the cycling motion of the branes along the extra dimension. Also, because the temperature generated at each big crunch/big bang transition is much less than f [4], the axion is not excited by the periodic reheating of the universe. Therefore, the evolution of the axion and the cycling are completely decoupled. The result is a cosmology with two inherent and disparate time scales: the time for a cycle (about a trillion years) and the tunneling time for the axion (about $10^{10^{120}}$ years in the final stages). The universe spends exponentially many cycles at each step down the washboard potential, with increasingly many cycles as V_N approaches zero. Once a region tunnels to a minimum with negative energy density, the cycling becomes unstable [3] and, with ten billion years, the region collapses into a black hole. Meanwhile, most of the universe continues to cycle.

Although different patches of space work their way downhill at different times, the patches are uniform on scales large compared to the Hubble horizon due to the smoothing caused during each cycle. Furthermore, every patch is locally equivalent: if one measures the Hubble constant to be near 10^{42} GeV and the dark energy density to be near $(1 \text{ meV})^4$ *anywhere in the universe*, the physical conditions and astronomical scene should be similar to what we see today. The situation is the opposite of the scene suggested by anthropic/landscape scenario in which most of the universe never looks like what we see within our horizon and is forever inhospitable to the formation of galaxies, stars, planets and life. All other things being equal, a theory that predicts that life can exist almost everywhere is overwhelmingly preferred by Bayesian analysis (or common sense) over a theory that predicts it can exist almost nowhere.

Remarkably, our modest proposal is subject to experimental refutation. Because it incorporates the cyclic picture for generating perturbations, it shares the cyclic predictions of a purely Gaussian spectrum of energy density perturbations and a gravitational wave spectrum with amplitude too tiny to produce a measurable B-mode polarization [4]. There may be other cosmological conundra that can be resolved by having a relaxation time much longer than a Hubble time, and they may lead to further cosmological tests. At this point, these ideas are new and formative, perhaps to be developed and debated at a future Solvay meeting.

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6.5 Discussion

S. Weinberg This is a trivial remark unless, of course, it is wrong. As I understand it, there is no particular reason in Steinhardt's scenario why the vacuum energy density would be related to the matter density that we see now in the present Universe?

P. Steinhardt No. In the model that I presented, there is nothing that links the total amount of dark matter to the cosmological constant directly. In fact, the ratio decreases from cycle to cycle as the cosmological constant relaxes. However, the universe spends most time when the cosmological constant is small, as we observe it today.

S. Weinberg The anthropic principle (that is the principle that dares not speak its name) does require that the vacuum energy density be of the same order of magnitude, but somewhat larger than the mass energy density that we see now, and in fact even a little larger than we actually are seeing. But yours does not?

P. Steinhardt Right. The amount of dark matter produced at the bounce is presumably the same from cycle to cycle, but the cosmological constant is slowly relaxing away. The ratio of dark matter to dark energy is, therefore, changing with time and we do not have a precise prediction for what the value is for this particular cycle.

A. Linde The equation for the potential which you use for your model contains a cosine term and a linear term. If you remove the cosine term and leave just the linear term, this would be exactly the potential of the model which I used in 1986 to suggest an anthropic solution for the cosmological constant problem, and pretty recently we repeated the discussion of this model in some details with Vilenkin and Garriga, and this model is also extremely similar to the model suggested by Banks at approximately the same time.

G. 't Hooft I wonder whether you are not introducing another kind of unnaturalness in such a system, which is the very small value for the mass term with respect to the kinetic term for such a dilaton-like field. After all you have a variation of the cosmological constant over cosmological scales, so there must be a very small effective mass in that. Is that not an unnatural feature of such a model?

P. Steinhardt It was Abbott's idea that the field be an axion with a mass term generated by the same kinds of instanton effects as the QCD axion. So, the coefficient of the cosine term, for example, would be something of order the Planck scale times $\exp(-2\pi\alpha)$, where α is the strength of the coupling at the Planck scale. For QCD, α is of order 0.1. Here we imagine that, for an axion on the other brane coupled to hidden gauge fields, the coupling might be a bit different. With a value of 0.08, just 20 per cent less, one gets values that work just fine for our scenario. And, because of the axion's special symmetries, the couplings are protected from quantum corrections. So, as Abbott suggested, the potential is technically natural. But, this is a new idea; you could think of lots of different kinds of potentials that may be more appealing; you might consider different kinds of time histories in which you could use the same basic principles of "ultra-slow relaxation" and cyclic evolution. There may be even better ideas out there.

H. Nicolai I have a question to Steinhardt. How do you reconcile the second law of thermodynamics with the cyclic universe?

P. Steinhardt Essentially what happens in this model is that at each stage when you have a collision, you produce a lot of entropy. Then during the subsequent stages of expansion you stretch the branes and you spread the entropy out so that the entropy density becomes exponentially low. And then you have another collision which creates more entropy. So, entropy is actually building up, if you add it up over the entire brane from cycle to cycle. But the entropy density is cycling, and it is the entropy density that is important for cosmology, for an observer like us who can only observe within the horizon. So the entropy is out there, it is just too spread out for us to see it.

F. Wilczek First I would like to say something profound, and then I will illustrate it with something which may or may not be profound. The profound thing I would like to say is that it is sometimes possible to solve some problems without solving all problems. I would like to illustrate that with the case of axion cosmology which was alluded to here. In that case, the assumptions leading to a kind of multi-verse picture, namely what ordinarily might be thought of as universal parameters in fact vary, is much simpler and does not rely on branching universes. All that may or may not be important to determine that measure. It just depends on the fact that the initial misalignment of the axion angle with the QCD angle at the time of the Peccei-Quinn transition carries very little freight in the early Universe, so it is truly random over the multiverse. If inflation intervenes, the measure is absolutely fixed, and there is no question that it does not interfere with any other microphysics. That is a beautiful example when there is no alternative to anthropic reasoning.

T. Banks A question for Steinhardt. In this model, if there is some oscillation of the scalar around its minimum as you approach the crunch, then there is an anti-friction force on this scalar field because the universe is contracting. I would have imagined that if you just run the equations down to the singularity you would find that it wants to jump all over the place around the potential, because the potential becomes irrelevant compared to the anti-friction which is blowing up because $\dot{a}/a$ goes to zero. So, if you could comment on that.

P. Steinhardt The problem you talk about would be a problem if this was a scalar field living in an ordinary bouncing universe like the ideas that people had in the 20s and 30s, because it would have just this problem during the contracting phase: any kinetic energy would be blue-shifted. If you imagine, though, that this field lives on the other brane, in the cyclic model the brane never goes through periods of contraction, it stretches, there is the collision, it stretches more and collides again. So far as that field is concerned, it is essentially seeing an expanding or static background. To say it in a more concrete way, in a 4-dimensional theory what happens is that the field is not just coupled to the scale factor, but also couples to the radion field, and the radion field during the contraction phase exactly compensates for the effect of expansion, so there is no effect, no excitation of the scalar field. Geometrically, this is because these fields are living on the brane which is not contracting.

T. Banks You will have to show me.

P. Steinhardt I wanted to issue a challenge to those pursuing the anthropic principle. We have now measured a number of important parameters about the universe that are important for the existence of life, but we are about to determine more parameters that are important for life: the shape of the power spectrum, for example, which is usually characterized by a spectral index, though it is possible that the spectrum will actually have some bumps and wiggles in it. We are also going to learn something about the reionization epoch. I would like those who are pursuing the anthropic principle to give us a definite prediction before the measurements are made. What are your anthropic expectations? Hopefully, you will converge on a single answer. It does not good if every proponent gives me a different answer. I suspect you do not have an answer at all, but I think it is an appropriate challenge for you to come up with one before the measurements are made so we can see if the anthropic principle has any real utility, and there is a chance for another success story to add to the semi-success of the cosmological constant.

S. Weinberg I think it is an unfair challenge, because we do not know which parameters scan. We do not know which parameters vary from multiverse to multiverse in a smooth way. If you tell us which ones do, we migh tell you what value to expect.

P. Steinhardt Then give me a table of possibilities, depending on your assumptions about which parameters scan.

N. Seiberg I am surprised that I am the only speaker, besides Kallosh, who mentioned the letters "LHC" at this conference. I want to pose the question: how do you think the LHC will change the scene of our field? What fraction of the people will continue studying the kind of physics that we have been discussing here: string theory and cosmology? What fraction will move to more phenomenology-related topics? And also, what kind of impact can we expect from LHC on more fundamental physics, shorter-distance physics?

R. Kallosh My understanding is that if LHC will tell us that there are supersymmetric particles, it would mean that we have this fermionic dimension in space and time, and it will be supergravity instead of gravity. So I would think that we would all tend to consider cosmology in the framework of supergravity and string theory. If they will not see supersymmetry immediately it will not immediately enforce us into it, but we still may do it.

N. Arkani-Hamed I just want to pop onto Seiberg's question. I think it is very interesting that with two years to go until the LHC, the situation is dramatically different from what it was in 1982 with two years to go until the discovery of the W and Z-boson at CERN. I think that 10 years ago, even the phenomenologist among us would have been a lot more confident about what to expect at the LHC than we are now. And as I mentioned in my previous remarks, that is associated with the fact that, quite apart from all the hints from cosmology and the theoretical hints from the string landscape, there is a growing sense of unease with why we have not seen evidence for new physics at the TeV scale. By itself this is not particularly dramatic, but still, something could easily have shown up already. So I think there are three possibilities for what might happen at the LHC and how it might impact the way we think about these questions. One of them is that we see evidence for a really, completely natural theory. And within a natural theory, some nice mechanism built into it would beautifully explain why it is that this expectation we have had for all this time that something would have shown up, was wrong. If that happened I would actually be given some pause and would certainly re-think possible natural solutions to the cosmological constant problem. There is the opposite possibility that the LHC might actually prove that the weak scale is finely tuned. That is a possibility that we have not been contemplating at all, but it is something that may actually happen. And if that happened, there is a variety of models, split supersymmetry being one of the examples but there are others, where you could really be able to prove that the weak scale is very finely tuned. If that happened, while in itself it is not evidence for landscape and anthropic reasoning or anything like that, it would be, I think, another big push in that direction. Now, the most ambiguous thing that can happen, I think, is that we might discover a natural theory and find that it is a little bit tuned. That is possible and basically every attempt to go beyond the Standard Model, when you look at it in detail, the theory is just tuned. Depending on how you talk about it, at the percent level, at five percent, half a percent, it does not matter, but there is something a little bit wrong. It could be that this is just what it is like. In the Standard Model we have several parameters which appear to be a little finely tuned, and that would just be another example. I think that would be the most ambiguous possibility. The natural possibility and the tuned natural possibility would shed no light on the cosmological constant problem, but I think that if we find evidence for tuning of the weak scale at LHC, for me it would be a very powerful evidence that the cosmological constant is also finely tuned. And, whatever the explanation is, we would have to think about it along those lines.

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