30 The landscape: a challenge to the naturalness principle

We have focused in this text on several questions of naturalness, and have used them to motivate searches for possible new physics. It is fair to say that most physicists find this principle compelling and are reluctant to accept extreme (or even modest!) fine tunings in theories of natural phenomena. But, during the past decade, a plausible, if highly speculative, alternative picture has gained currency, known as the *landscape*. If correct it provides a picture for the emergence of the laws of nature in which fine tunings are not surprising and provide few or no clues as to new degrees of freedom that might lie at higher energy scales.

We will divide our discussion into two parts. First we will explain, in very general terms, what is meant by a landscape and how it might address some naturalness problems in our current understanding of particle physics. Then we consider models for how a landscape might arise in string theory. These models are at best plausible; the existence of any non-supersymmetric states in string theory (apart, possibly, from certain special AdS vacua), much less vast numbers of them, is hardly established.

30.1 The cosmological constant revisited

We have stressed that the cosmological constant (i.e. the dark energy) presents potentially the most striking failure of naturalness. One might hope to solve this problem by introducing new degrees of freedom. Supersymmetry helps to some extent. In global supersymmetry the ground state energy is well defined and of order the scale of supersymmetry breaking raised to the fourth power. In local supersymmetry there is also the term $-3|W|^2$ in the potential. The problem is that this last term must very nearly cancel the positive contributions from supersymmetry breaking. The superpotential W can naturally be small as a result of R symmetries, but no one has proposed a mechanism, based on either dynamics or symmetries, which would lock W onto its required value. Many physicists have searched for an analog of the axion solution of the strong CP problem, in which some light field would adjust in such a way as to cancel the c.c. Without reviewing the various proposals, one might expect that the basic obstacle is in fact illustrated by the Peccei–Quinn mechanism. The axion solution to the strong CP problem relies critically on the existence of an approximate CP symmetry of QCD at $\theta = 0$; small θ is singled out within the Standard Model. There is no clear analog of this (approximate) enhanced symmetry for the cosmological constant. More strikingly, the *measured* value of the dark energy is itself quite peculiar, being nearly coincident with the density of dark matter (and baryonic matter), *at this moment in the history of the universe*.

Weinberg, following suggestions of Banks and Linde, put forward a very different sort of proposal to understand why there could be a small cosmological constant value. At the time he made this proposal, the dark energy had not been observed and there was a prejudice among many theorists that the cosmological constant was rendered exactly zero by some mechanism. Weinberg asked how, in the presence of a cosmological constant, the universe would differ from what we observe. He assumed that other important cosmological quantities, and particularly the spectrum of the initial density perturbations remained unchanged and that matter–radiation equality is obtained at a time of order 10^5 years as in the standard big bang theory. He noted that in that case galaxy formation began when these fluctuations became non-linear, about 10^9 years after the big bang. If the universe was dominated by a cosmological constant at that time, the galaxies would not have formed. This limits the cosmological constant to be less than about 100 times its observed value.

By itself this is an interesting observation, a statement that certain facts about the universe and the underlying laws are consistent. But Weinberg went further. As had been stressed by Linde, in a universe which has undergone inflation, our observable universe is typically only a small part of some larger *metaverse*. Suppose that in different regions of this metaverse, the constants of nature and in particular the cosmological constant, differ: in most regions the cosmological constant is large, but there are observers only in that fraction in which the cosmological constant is extremely small. This is much like the situation of fish and water. Only a very tiny fraction of the universe contains water, but fish inevitably find themselves in that tiny fraction. He dubbed this principle the *weak anthropic principle*.

Now, the most likely value of the cosmological constant would then, be expected to be that value which was most common in a landscape consistent with this anthropic constraint. More precisely, we might imagine that there is a distribution function $f(\Lambda)$, for cosmological constants and a function $\mathcal{E}(\Lambda)$ which describes the likelihood of there being observers in a particular environment and that the probability of a given value of Λ would be obtained by integrating over the product of these. Weinberg reasoned that since a small value of Λ is not favored by any symmetry, one would expect $f(\Lambda)$ to be roughly flat; as a crude model one might then take $\mathcal{E}(\Lambda)$ to be a step function. Then one could predict that the most common value of Λ is close to the maximum allowed by the anthropic constraint.

This argument can be viewed as a *prediction* of the dark energy. The result is somewhat large compared with observation but not too bad on a log scale. One could contemplate refinements which would do better. In particular, $\mathcal{E}$ might well not be a θ function. One could also consider the consequences of allowing other parameters to vary, or “scan”, significantly complicating the question of prediction.

There has been much discussion about the use of the arthropic principle and whether it has scientific validity. On the one hand, it is the only explanation so far offered which is at all compelling. On the other hand, to be really persuasive one should have, at the very least, some sort of underlying theory which gives rise to a landscape.

30.2 Candidates for an underlying landscape

Weinberg's argument is interesting, but how might a *metaverse* or *landscape* of this type arise? One proposal was put forth by Bousso and Polchinski. They noted that, as we have seen, string theories possess different types of flux. These can sometimes be thought of as electric, sometimes as magnetic. They are typically quantized, by Dirac's argument. In particular, on compact spaces, fluxes with indices in the compact space will take discrete values and can be labeled by integers n_i, in some units appropriate. Here $i = 1, \dots, N$ runs over the different types of flux; n_i is often itself constrained by various consistency conditions, e.g.

$$\sum_{i=1}^{N} n_i^2 \le \chi . \tag{30.1}$$

If N is large and χ is a large integer then the number of possible flux choices will be very large, of order the volume of a sphere in N dimensions (a computation familiar from dimensional regularization in quantum field theory) of radius $\sqrt{\chi}$:

$$\chi^{N/2} \frac{2\pi^{N/2}}{\Gamma(N/2)} . \tag{30.2}$$

Bousso and Polchinski wrote down toy models involving four-form flux, but it was subsequently recognized that other types of flux might dominate, such as three-form fluxes in the case of Type II string theories compactified on Calabi–Yau manifolds.

It turns out also that fluxes can stabilize, even classically, many moduli of the Type II theories, and furthermore there exist scenarios for how the remaining moduli might be stabilized. These are, at the moment, merely scenarios but they provide models for how Weinberg's proposal might be implemented in a microscopic theory.

30.3 The nature of physical law in a landscape

In flux landscapes the features of whatever low-energy theories emerge depend on which vacuum, or ground state, the system occupies. This includes the low-energy degrees of freedom (the light fields) and the parameters of the underlying Lagrangian. For the cosmological constant, in particular, one might expect more or less random values to emerge, at least if there are no symmetry considerations such as supersymmetry. The resulting distribution of parameters was dubbed a *discretuum* by Bousso and Polchinski. In order to obtain the value of the cosmological constant, in a theory where the typical energy scale is the Planck scale, one would need more than 10^{120} such states, so one should certainly be able to think of the distribution as approximately continuous. If random, with zero not a special value, one will inevitably obtain Weinberg's flat distribution.

But, having opened up this possibility, that the parameters in a landscape could be scanned for the cosmological constant, there is no obvious reason why other parameters might not scan as well. Among the parameters of the Standard Model, we would include the Higgs mass and quartic coupling, the gauge couplings and the quark and lepton Yukawa couplings as well as the QCD scale and the θ parameter.

We could well imagine that on the one hand there is some anthropic selection for some of these parameters. If we hold the others fixed, the rates for important stellar processes, relevant to the creation of heavy elements, depend on the value of the weak scale. The proton–neutron mass difference, and thus the values of the u and d quark masses, might also be importance for the existence of observers. On the other hand our existence is not contingent, at least in any obvious way, on the masses of the heavier quarks and leptons or on the mixing angles, and so one might expect them to be random numbers, picked from some underlying distribution. These distributions might not be uniform; the theory *is* found to be more symmetric as these couplings become small, for example. Various possibilities have been considered.

Particularly puzzling from this viewpoint is the θ parameter. While we have seen that experimentally θ must be extremely small, for quantities such as nuclear reaction rates θ has the potential to play only a minor role. It is hard to imagine an anthropic constraint which would require θ even as small as 0.01, much less 10^{-10}. So, something more is required if the anthropic principle is to be viable. Conceivably axion dark matter is important for the formation of structure in the universe, and this somehow leads to a small θ. But it is probably fair to say that no convincing case for this has yet been made.

30.4 Physics beyond the Standard Model in a landscape

One might argue that that if one adopts an anthropic viewpoint then there is no need for physics beyond the Standard Model, at least until one reaches scales such as those associated with the right-handed neutrino mass. In particular, there need not be new phenomena associated with electroweak symmetry breaking. This viewpoint might be correct, and the experimental situation at the LHC in late 2015 might give some limited support for this possibility, but there are reasons to question it.

For definiteness, let us focus on supersymmetry. In a landscape one would expect that there are states with no supersymmetry, with some approximate supersymmetry and with unbroken supersymmetry. The class of states with approximate supersymmetry might well provide a realization of conventional notions of naturalness. One might expect that, among these, states with a low value of the weak scale (compared with M_{p}) typically have a low value of the supersymmetry breaking scale. So, if the supersymmetric states are somehow more numerous, or otherwise favored, one would predict low-scale supersymmetry breaking. It could be, however, that the non-supersymmetric states are far more numerous than the supersymmetric ones and that low-energy supersymmetry is extremely rare. One might then obtain a low-energy theory which appears extremely tuned. Detailed studies of model landscapes lead to refinements of these considerations.

Flux models with and without supersymmetry have been extensively studied. In these studies, “without supersymmetry” typically means that one starts with a locally supersymmetric action and studies the stationary points of an effective action computed in a crude (i.e. not systematic) approximation. At some of these stationary points the supersymmetry is badly broken but at others it is not. These models lead, in many cases, to distributions of low-energy parameters which appear potentially robust. For example, superpotential parameters are often uniformly distributed, for small values of the parameters, as complex numbers. From these sorts of studies, at least three branches of the landscapes are suggested:

1. a non-supersymmetric branch;
2. a supersymmetric branch with spontaneous (non-dynamical) supersymmetry breaking;
3. a supersymmetric branch with dynamical supersymmetry breaking.

On the second branch the distribution of supersymmetry breaking scales, for a fixed value of the weak scale and a small cosmological constant, favors *very high* scales of supersymmetry breaking. This runs counter to the intuition which generates much of the interest in low-energy supersymmetry. It results from very simple considerations, however, such as assuming the uniformity of superpotential parameters. Roughly speaking, if one has a field Z which contains the goldstino (the longitudinal mode of the gravitino), then there are three renormalizable parameters in its superpotenitial, two of which must be small for low-scale breaking; there is also the parameter W_0, the expectation value of the superpotential. One assumes that one pays a price of m_H^2/M_p^2 for the tuning of the Higgs mass. If one also requires a small μ parameter for the Higgs, and this is also uniformly distributed, high scale breaking is even more strongly favored.

On the third branch, things can be better. In this case the supersymmetry-breaking scale is distributed uniformly on a log scale. If W_0 is uniform as a complex variable then supersymmetry breaking is distributed uniformly on a log scale. So, while this does not particularly favor very high scale breaking, it also does not point to TeV breaking scales. To account for scales of order TeV or perhaps slightly higher, one would need to introduce other considerations (perhaps the cosmology of moduli or the density of dark matter). A non-dynamical μ term again pushes towards higher scales.

We returning to the question: are there more or fewer states on the supersymmetric than on the non-supersymmetric branches. One’s first guess would be that supersymmetry is special and that non-supersymmetric states might be far more common. Against this are two arguments, both based on questions of *stability*. The first is perturbative. In landscape models (Type II with fluxes in particular) there are many fields. At the stationary points it is important that the curvature be positive in all directions. For a random potential for N fields, one might expect that only $1/2^N$ of the non-supersymmetric stationary points would be stable; it turns out that the suppression is even larger. But this only addresses the question of perturbative stability. Among the remaining states, only an exponentially small fraction are long lived. Supersymmetric states that have a small cosmological constant, are in fact generically stable in both senses. So this *might* indicate that the supersymmetric branch is more heavily populated than the non-supersymmetric branch.

30.5 ’t Hooft’s naturalness priciple challenged

Finally, we can return to ’t Hooft’s principle of naturalness itself. Why, in fact, would we expect that states with symmetries are favored? One argument has to do, again, with the stationary points of potentials: symmetric points are always stationary. Another argument, in a landscape framework, is the possibility that symmetric points, being special, might be singular points in the distributions of parameters and thus favored.

In a flux landscape one can give a tentative answer: symmetries are *highly disfavored*. Consider, for example, a discrete symmetry. Some fluxes will be invariant under the symmetry, but typically most will not. Since the number of states goes as a power of the number of fluxes, symmetric states will be an exponentially small fraction of the total. It could be that some other model for landscapes would favor symmetric states. It is also possible that adding, for example, cosmological considerations would make the distribution singular at symmetric points. Still, from a landscape perspective, ’t Hooft’s principle is not self evident. We have given arguments why states with greater *supersymmetry* might be favored, but these are at best tentative and it is not clear how they might extend to more conventional bosonic symmetries.

We are left, then, with a great deal of uncertainty. The very existence of a landscape remains purely a matter of conjecture. If it does exist, the manner in which one should enforce anthropic constraints (or even just experimental priors) is not completely clear. Finally, the features of the putative landscape will determine questions such as: is there supersymmetry at scales well below the Planck scale? For the moment, it would seem that we least have to at admit such questions, especially until we have experimental evidence that more traditional notions of naturalness are operative at least for the understanding the scale of weak interactions.

30.6 Small and medium size hierarchies: split supersymmetry

If a landscape picture is operative, it raises the possibility that there are simply large hierarchies. This might be understood anthropically but, whether or not one likes such an approach, the picture raises the possibility that there is no low-energy explanation of these surprising failures of dimensional analysis. But such a picture also raises the possibility of more modest hierarchies. One might imagine that there is some tension between the anthropic requirements for, say, dark matter and the weak scale and that this might account for a somewhat large scale of supersymmetry breaking. Alternatively, simply imposing certain facts – that matter–radiation equality occurs at a temperature of approximately 1 eV, on underlying theories, say, with moduli, implies a supersymmetry-breaking scale of about 30 TeV, compatible with the observed Higgs mass. One proposal is known as “split supersymmetry”. Here it is assumed that the dark matter is a *wino* in an underlying theory with an anomaly-mediated spectrum. To account for the dark matter, the wino mass must be of order several hundred GeV, and the gravitino and squarks and leptons must be more massive by factors of order π/α. In such a picture it is conceivable that we could find gluinos and some other supersymmetric particles in an accelerator with energies somewhat higher than those of the LHC. Alternatively, however, one could imagine that all the new supersymmetric states are rather heavy, with dark matter in, say, the form of axions.

Suggested reading

The cosmological constant problem, and Weinberg's proposal, are discussed in Weinberg's review (1989). A good review of the issues in landscape statistics is provided in Denef *et al.* (2007). Ideas surrounding split supersymmetry are discussed in Arkani-Hamed *et al.* (2005).