Low Energy Supersymmetry From the Landscape

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Beyond the Standard Model in the late 20th Century:

- Model Builders: Explored a large space of possible field theories. (A very large infinity if allow extra dimensions, non-renormalizability...)

  A few rules: phenomenological constraints, *naturalness, simplicity.*

- String Theorists: Lots of classical solutions; no quantum solutions with $N < 2$ supersymmetry. In any controlled approximation, moduli, no stable vacuum. General argument says it will be difficult to find stable, non-susy (broken susy) vacua in any controlled approximation. No (persuasive) clue to understanding the small value of the cosmological constant.

  Approaches:

  a. Look for realistic models at weak coupling. Assume selected, features survive at strong coupling (or couplings accidentally weak).

  b. Look at generic features of string models (susy, axions, large dimensions); hope somehow general. Hope reflect properties of some stable quantum system(s).

A New Element: The Flux Landscape, or Discretuum

- Metastable points: Kachru, Kallosh, Linde and Trivedi (KKLT) have exhibited metastable points in the moduli effective potential, in (nearly?) controlled approximations. Strongly indicates existence of a vast number with all moduli stabilized.

- In this vast “landscape”, can’t hope to find “the state” which describes our universe. Interest is in statistics of these states (Douglas).

- Possibility for predictions: *Correlations* or lack thereof. The vast majority of states with some set of properties consistent with experiment have some other property.

- Possibility of falsification: typical states in the landscape inconsistent with experiment.

There are reasons to be skeptical about theses constructions (Banks, Gorbatov, MD) but today, will assume OK. If true, *a fundamental change in our view of string theory/"fundamental physics."*

We don't yet know all we need to know to make predictions. But we can do some prototype calculations, and can pose sharp questions, which can plausibly be answered.

The most obvious and quite possibly the easiest question: does this framework predict low energy supersymmetry? If so, does it suggest a particular scale for the breaking?

This talk:

- Possibility that cosmological constant + weak scale → low energy supersymmetry.
- Problem that θ_{qcd} might be a uniformly distributed random variable (BDG,Donoghue).

Review of the KKLT Construction

Particular case: Orientifold of IIB theory on a Calabi-Yau space.

Moduli: Complex structure (z_a), Kahler moduli (ρ_i), $\tau = \frac{1}{g_s} + ia$

IIB theory has two types of three-index antisymmetric tensor fields, F, H. Solutions of string equations exist on CY spaces with non-trivial, quantized fluxes, characterized by integers:

$$\int_{\Sigma_i} H = M_i \qquad \int_{\Sigma_i} F = K_i$$

In general, many possible cycles, possible values of K, M.

z_a's are fixed in these solutions. Low energy explanation:

With (quantized) flux, non-trivial superpotential: $W(z,\tau)$, at the leading order in the α' (large radius) expansion.

Example (Giddings, Kachru, Polchinski):

z: measures distance from conifold point.

Fluxes on collapsing three cycles. Both stabilization and warping.

$$W = (2\pi)^3\alpha'(M\mathcal{G}(z) - K\tau z) \tag{1}$$

where M, K: fluxes.

$$\mathcal{G}(z) = \frac{z}{2\pi i}\ln(z) + \text{ holomorphic.} \tag{2}$$

This has a supersymmetric minimum where

$$D_zW = \frac{\partial W}{\partial z} + \frac{\partial K}{\partial z}W = 0 \tag{3}$$

Solved by:

$$z \sim \exp(-\frac{2\pi K}{Mg_s}) \tag{4}$$

If the ratio N/M is large, then z is very small. The corresponding space can be shown to be highly warped (i.e. Randall-Sundrum).

$$W_o = < W > \tag{5}$$

exponentially small.

Including additional fluxes, it is possible to fix other complex structure moduli, including τ.

$$W = (2\pi)^3\alpha'[M\mathcal{G}(z) - \tau(Kz + K'f(z))] \tag{6}$$

$$D_\tau W = \frac{\partial W}{\partial \tau} + \frac{\partial K}{\partial \tau} W = 0$$

for

$$\bar{\tau} = \frac{M\mathcal{G}(0)}{K'f(0)} \qquad W_o = 2(2\pi)^3\alpha' M\mathcal{G}(0)$$

z is still exponentially small, and the space is highly warped, but W_o is no longer exponentially small.

More generally, many possible choices of fluxes. Huge number of states.

W_o a random variable. Small W_o: approximate $N = 1$ supersymmetry. Can describe by a supersymmetric effective lagrangian.

Features:

- The radii (Kahler moduli) are not fixed. For large R, discrete shift symmetries guarantee that any dependence in W on the $\rho_i (\sim R^3)$ is exponentially small, $e^{-c\rho}$.

- KKLT: Exponentially small corrections, $W = W_o + e^{-c\rho}$ may arise from various sources (gluino condensation, membrane instantons...) The resulting potential has supersymmetric (AdS) solutions with
$$D_\rho W = \frac{\partial W}{\partial \rho} + \frac{\partial K}{\partial \rho} W = 0.$$
$$\rho \approx -\frac{1}{c} \ln(W_o).$$

So far, supersymmetric.

KKLT suggested a further subset of all states would have supersymmetry broken: small susy breaking through $\overline{D3}$ branes located at the ends of throats. Metastable DS spaces possible (numerous).

How many? Flux lattice, dimensionality K: $\vec{n}$. $\vec{n}^2 \leq L$.

$$N \sim \frac{L^{K/2}}{\Gamma(K/2)}.$$

$$L \sim 1000's \qquad K \sim 100's.$$

For low energy observers, physics is different in these states. Gauge groups, coupling constants. *The cosmological constant*, in particular, is a random variable in these 10^{1000}(?!) states.

Problem is not to find "the state" which describes our universe (hopeless). Instead, need to study statistics of these states: gauge groups, matter content, couplings, cosmological constant, etc.

First striking observation: If the landscape is correct, string theory can accommodate, if not explain, the small value of the cosmological constant.

Experimental Predictions from the Landscape

What data should we use (Priors)?

One approach: take all measured parameters of Standard Model, Cosmology. Ask what values of other quantities are typical, given these priors

In practice, this is very difficult and perhaps not the most interesting. Need a more limited set.

One particularly striking quantity is the value of the cosmological constant. Within the landscape, M_p^4 is the most natural value. On this scale, if we simply view the cosmological constant as a piece of data, we would say that this quantity is measured with extraordinary accuracy. This is clearly not a reasonable way to describe the situation. There is some sense in which zero is special. But it is certainly not typical of the landscape. So a reasonable approach would be to discard the landscape.

The Anthropic Principle

An (the?) alternative is, following Weinberg, to consider (weak) anthropic explanations. Indeed, KKLT have provided the most plausible framework to date which might realize the weak anthropic explanation of the cosmological constant.

Usually, mention of the anthropic principle brings hand-wringing about the end of science, etc. To quote Weinberg:

“A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you’re against it, some people will think you are a little too interested.”

But, for better or worse, the anthropic explanation is arguably the most plausible proposal we have to understand the small value of Λ.

I will argue that we confront a Faustian bargain here. If we adopt the anthropic viewpoint, we are lead to the first predictive framework for string theory.

That said, it is nearly impossible to say: the weak anthropic principle (the requirement that we find ourselves in an environment or neighborhood which can support life) requires the cosmological constant to be..., the fine structure constant to be... the strength of inflationary fluctuations to be...

Instead, for the moment, adopt a more pragmatic view: we are willing to impose, as priors, any quantity which might plausibly be anthropic – but not those which cannot be.

1. Perhaps anthropic: The gauge group, Λ, α, Λ_{qcd}, m_e, m_u, m_d, the dark energy density...

2. Probably not anthropic: the value of θ_{qcd}, heavy quark masses and mixings...

These rules leave open very real possibilities for failure (falsification)

With mild [in my view] assumptions about the distribution of states and two anthropically motivated priors, the observed small cosmological constant and Higgs mass leads to a prediction of low energy supersymmetry.

These assumptions are true of a small piece of the landscape which as already been studied, but may not be true more generally; *what is important is that they can be checked.*

θ_{qcd}: no plausible anthropic explanation. In the flux discretuum, appears to be a random variable with a roughly uniform distribution. Some rational explanation (axions? $m_u = 0$) required. The mechanism must be typical of the states which satisfy other selection criteria in the landscape, or landscape idea is false.

Path to Prediction

There are some distributions which we do know, thanks to the work of Douglas and collaborators. Two are relevant to the question of low energy supersymmetry.

1. W_o. The distribution of W_o, as a complex variable, is known at least in some cases to be roughly uniform. KKLT gave a crude argument for this, which is supported by the results of Douglas and Denef. Might imagine roughly $W_o = \sum a_i n_i = \vec{a} \cdot \vec{n}$. This gives, at small W_o, a uniform distribution of both Re W_o and Im W_o. So
$$\int d^2 W_o P(W_o)$$
with $P(W_o)$ approximately uniform.

2. $\tau = \frac{1}{g} + ia$. Since the IIB theory has an $SL(2Z)$ symmetry, might expect
$$P(\tau)\frac{d^2\tau}{(\text{Im }\tau)^2}$$
with $P(\tau)$ roughly constant. Indeed, this is what Douglas and Denef find. Corresponds (roughly) to gauge coupling constants uniform with g^2.

Supersymmetry: Three branches of the flux landscape

1. Broken supersymmetry at level of supergravity analysis: If vastly more non-susy than susy states, this can overwhelm the usual naturalness arguments for susy (Douglas, Susskind). But to date, no evidence for this; *in fact, usually find more supersymmetric than non-supersymmetric states*.

2. Unbroken supersymmetry, $W_o \neq 0$.

3. Unbroken susy, $W_o = 0$.

Non-susy branch: might dominate. Would be disappointing. Hard to see how any prediction should emerge (e.g. in generic states, all would-be R symmetries which could realize the Arkani-Hamed-Dimopoulos scenario *are broken!*).

SUSY, $W \neq 0$ Branch:

While susy is unbroken to all orders in ρ, there is no reason to expect that this is exact. Low energy dynamics, the $\overline{D}3$ effects of KKLT, etc. may break it. Focus on low energy dynamics ($\overline{D}3$ may be dual). Calling μ the scale of susy breaking ($m_{3/2} = \frac{\mu^2}{M_p}$

$$\mu^4 = e^{-c\frac{8\pi^2}{g^2}} \qquad (M_p = 1)$$

Uniform distribution in $g^2 \rightarrow \frac{dm_{3/2}^2}{m_{3/2}^2(-\ln(m_{3/2}^2))}$. Roughly uniform with log of energy scale.

On this branch, small cosmological constant and the facts just mentioned do not predict low energy supersymmetry. We can ask, how many states have cosmological constant smaller than a give value.

Simplified model:

$$\Lambda = \mu^4 - 3|W_o|^2$$

$$F_1(\Lambda < \Lambda_o) = \int_0^{W_{\max}} d^2 W_o \int_{\ln(|W_o|^2)}^{\ln(|W_o|^2+\Lambda_o)} d(g^{-2}) g^4$$
$$\approx \int_0^{W_{\max}} d^2 W_o \frac{\Lambda_o}{|W_o|^2} (-1/\ln(W_o))^2$$

Distribution of $m_{3/2}$ flat on a log scale

Imposing the value of the weak scale as an additional requirement then favors supersymmetry breaking at the weak scale. This is just conventional naturalness. (μ may be an issue).

The W=0 Branch: A very low energy breaking scenario

Now expect both W_o and M_{susy} generated dynamically. Repeating our earlier counting,

$$F_1 \propto \int \frac{d^2 m_{3/2}}{m_{3/2}^4}$$

Very low energy breaking significantly favored (gauge mediation).

Note: in past phenomenological approaches to gauge mediation, no particular scale for susy breaking favored by theoretical (naturalness) considerations. Now, lowest scale consistent with other constraints (cosmological constant, weak scale) favored.

Example of an added input to model building

Possible Phenomenologies

Each of these branches has a very different phenomenology.

- Discrete symmetries cheap – the third branch: Then low energy breaking favored. Can give crude estimates, but more detailed analysis needed.

- If discrete symmetries costly– the second branch: Higher energy breaking, as in gravity mediation likely. A natural scenario (proposed already in 1992): susy broken dynamically in a hidden sector. Gaugino masses generated through anomaly mediation. [Similar to one of the scenarios discussed by Arkani-Hamed and Dimopoulos]

- Third branch – overwhelmingly more non-susy than susy states: quite disappointing, hard to see how to make connection with nature (discrete symmetries and dark matter? neutrino masses a clue?)

Features of these phenomenologies:

1) Low scale breaking: gauge mediation, with multi-TeV scale (but serious cosmological moduli problem)

2) Intermediate scale breaking: possible solution of the usual cosmological moduli problem. Still problems (though not so severe) with flavor.

If the following questions were answered, one could establish that supersymmetry is or is not a likely outcome of the landscape:

- Are there, in the leading tree-level approximation, exponentially more non-supersymmetric than supersymmetric vacua? We have indicated that the answer to this question is likely to be no, but we certainly cannot claim to have proven such a statement. This would favor low energy supersymmetry.

- What is the price of discrete symmetries? In particular, we need to compare the cost of suppressing proton decay and (if necessary) obtaining a small μ term with the price of light Higgs without supersymmetry (10^{-36} or so), times the price of obtaining a stable, light dark matter particle (unknown, but probably not less than 10^{-36}), times the other tunings required to obtain an acceptable cosmology.

- Is there a huge price for obtaining theories with low energy dynamical supersymmetry breaking? Given the presumption that one can obtain a landscape of models with complicated gauge groups and chiral matter, it is hard to imagine that the price is enormous (in landscape terms). A part in a billion, for example, would likely lead to a prediction of low energy supersymmetry.

- Are unbroken discrete R-*symmetries* at the high scale common? If so, $\langle W \rangle$ must be generated dynamically at low energies in such vacua. In this case, we have seen that SUSY breaking at the lowest possible scale may be favored.

- Within the present knowledge of the landscape, non-supersymmetric conifolds appear to be the most promising alternative to low energy supersymmetry. What is the relative abundance of such states compared to supersymmetric states?

Conclusions

- It seems likely that the landscape exists. If so, at the very least, it is a very large elephant in the closet. What are we to make of it? Clearly we need to explore it. *The claim today is that for the first time, we have a candidate predictive framework for string theory.*

- The study of the statistics of these states has begun. Many of the important questions seem accessible.

- The proposed set of rules seem likely to lead to predictions. The rules are subject to debate, but a sensible set of rules can probably be formulated.

- Low energy supersymmetry may well be one output. It is possible that we will be able to predict a more specific phenomenology (not covered at length here, but in progress).

- We have about three years!