# 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. General argument says it will be difficult to find stable, non-susy (broken susy) vacua in any controlled approximation.

  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: possibly a huge number with all moduli stabilized (most persuasively: KKLT; still, not certain that these are good quantum states – Banks, Gorbatov, M.D.; Banks; Susskind)

- If correct, the number of states is *vast.* Can't hope to find "the state" which describes our universe. Interest is in statistics of these states (Douglas).

- Possibility for falsification – no states which agree with facts which we see in nature (Douglas)

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

## Today

- Possibility that cosmological constant + weak scale → low energy supersymmetry.

- Problem that $\theta_{qcd}$ might be a uniformly distributed random variable.

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 system is complicated enough that answers will not simply fall out. Physical insight will be required.

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?

# Review of the KKLT Construction

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

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

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

## Example (GKP):

$z$: 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

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

Solved by:

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

If the ratio $N/M$ is large, then $z$ is very small. The corresponding space can be shown to be highly warped.

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

exponentially small.

Including additional fluxes, it is possible to fix other complex structure moduli, including $\tau$.

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

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

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 solutions with

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

$$\rho \approx -\frac{1}{c} \ln(W_o).$$

KKLT: stabilization of all moduli possible, in principle, in a systematic approximation (small $W_o$, sufficiently large fluxes that string coupling small...)

Proposed: small susy breaking through $\overline{D3}$ branes located at the ends of throats. Metastable DS spaces possible (numerous).

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

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

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

So we are not interested in finding the particular vacuum which describes nature. If this landscape picture is correct, this is a hopeless problem. Also, it is not important that the state in which we find ourselves be weakly coupled. What interests us is the distribution of states with particular properties: gauge groups, matter content, couplings, cosmological constant, etc.

# Prediction/Falsification within the Landscape

Michael Douglas and collaborators have developed most precisely the notion of a statistical distribution of vacua. Ideally, given this distribution, we might take a few measured quantities, and show that the landscape inevitably predicts the correct values of others, and/or the results of experiments to be performed in the future. Alternatively, we might find that the landscape already *does not* predict some quantities correctly.

Fully implementing such a program might be possible in the not too distant future. At the moment, some features of such a program can be outlined.

# Experimental Constraints on 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.

An (the?) alternative is, following Weinberg, to consider anthropic explanations. Indeed, KKLT have provided perhaps the most plausible realization of 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."

In some more recent correspondence (with Lee Smolin) Weinberg writes [apologies to Cliff Burgess, Gordy Kane, Malcolm Perry, Anna Zyktow...]:

" I am very far from being convinced that this is the true explanation of the observed value of the vacuum energy — I only argue that it deserves to be taken seriously. Of one thing I am certain, with almost mathematical rigor; it is, that I don't know of any other explanation."

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

Actually implementing the anthropic principle is probably impossible given our present understanding of astrophysics, cosmology and biology. Instead, we will adopt the point of view that we are willing to impose, as priors, any quantity which might plausibly be anthropic – but not those which cannot be.

What does this tell us about the landscape?

First, there must be a huge number of states if the landscape picture is correct (though as we will see, not necessarily $10^{120}$). *What KKLT, Douglas and others have shown is that there may be enough states in the landscape to accommodate this fact.* We will assume that this is the case; we won't try to explain it, but ask whether it has other consequences.

$\Lambda = 0$ arises in a neighborhood where supersymmetry is restored and the lagrangian has a discrete symmetry. This might be a special place – an oasis – in the landscape (*Landscape Naturalness*).

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

These assumptions may not be true (and we may soon know within the classes of states discussed by Trivedi; Silverstein: we are perhaps looking at the tip of a vast iceberg).

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

The gauge group, $\alpha$, $\Lambda_{qcd}$, $m_e, m_u, m_d$, some cosmological quantities might plausibly be anthropic. Many others are not.

A quantity, like $\Lambda$, "measured" with extraordinary precision: $\theta_{qcd}$.

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.

## Prototype of 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 $g^2$.

## The Distribution of $m_{3/2}$

While susy is unbroken to all orders in $\rho$, there is no reason to expect that this is exact. Low energy dynamics, the $\overline{D3}$ effects of KKLT, etc. may break it. Focus on low energy dynamics ($\overline{D3}$ may be dual):

$$m_{3/2} = e^{-c\frac{8\pi^2}{g^2}} \qquad (M_p = 1)$$

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

## Small Cosmological Constant and Low Energy Supersymmetry

By itself, 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:

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

where $M_p = 1; m_{3/2} \sim |W_o|$

$$F_1(\Lambda < \Lambda_o) = \int_0^{W_{\mathrm{max}}} d^2W_o P_W(W_o) \int_{\ln(|W_o|^2)}^{\ln(|W_o|^2+\Lambda_o)} d(g^2) P_{g^2}(g^2)$$

$$\approx \int_0^{W_{\mathrm{max}}} d^2W_o \frac{\Lambda_o}{|W_o|^2} P_W(W_o) \frac{1}{\ln {W_o}^2} P_W(W_o) P_{g^2}(-1/\ln(W_o))$$

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

Additional constraints can readily predict lower susy breaking scale. Most prominent of these is the Higgs mass (weak scale). Here, the conventional naturalness of low scalar masses in SUSY helps ($\mu$ may be an issue).

# A very low energy breaking scenario:

So far we have considered a flat distribution of $W_o$. But one expects a disjoint distribution at this classical level of analysis. In states with unbroken discrete $R$ symmetries, $W$ classically one can have $W = 0$ and unbroken susy. Now 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

Different branches, depending on facts about the landscape.

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

- Discrete symmetries costly: 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]

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.

## Paths to Prediction/Falsification:

What is striking about the landscape is that, if it is correct, it offers the first context in string theory in which both prediction and falsification are possible.

To really establish that the predictions described here are correct, and which (of any of these scenarios is realized, there are some well-defined questions we can ask – and hope to answer:

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 $\mu$ 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 nothing else, it is a very large elephant in the closet. What are we to make of it? Clearly we need to explore it?
- 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!