# Branches of the Landscape

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Strings 2005
Toronto

The landscape poses challenges for our understanding of string theory, but also, for the first time, provides a framework which might allow us to connect string theory to nature⇒ LHC; Cosmology/Astrophysics

What is the Landscape? String theory vacua:

1. SUSY Flat Space, $N_{susy} > 4$ Continuous Infinity

2. SUSY ADS $N_{susy} > 4$ Continuous, Discrete Infinity

3. SUSY AdS $N_{susy} = 4$ (IIA Theories*): Discrete infinities (in IIA theories with fluxes)

*DeWolfe, Giryavets,Kachru; Villadoro and Zwirner; Derendinger Kounnas, Marios Fabio Zwirner; Camara, Font, Ibanez

But the source of current interest is Non SUSY AdS, DS.

Challenges:

- Finite, infinite? [Douglas talk]

- Utility of effective field theory in a theory of gravity (Banks, Gorbatov,MD; Banks; Freivogal, Susskind); IIA improves situation (Kachru et al).

- Assuming landscape exists, need to formulate a sensible cosmology; determine how to weight different states.

- Selection effects? Anthropics? (If necessary, hold your nose) – how to implement?

- Even granted some anthropic selection, it is hard to understand how the landscape picture can reproduce many features of the laws of nature at low energies, e.g. $\theta_{qcd}$. (Witten's talk – why not axions? Perhaps, but, e.g., KKLT: approximate susy, all moduli fixed $\Rightarrow$ no axions).

## Paths to Prediction in the Landscape

Today, I won't approach these hard questions. Rather narrow focus to a subset of vacua for which Kachru et al, Douglas et al have done some analysis and statistics, as a prototype for understanding how predictions might emerge from the landscape [Denef review].

- Can we hope to make predictions? Most promising are questions related to traditional issues of naturalness. After all, *the problem of naturalness is precisely the issue that some features of the Standard Model seem improbable*. These are precisely the sorts of questions for which statistics might be useful.

- While some sort of anthropic selection may be required to understand features of nature, like the value of the cosmological constant, this does not mean that prediction is impossible. Question is one of correlations. E.g. $\Lambda, G_F \Rightarrow$ Supersymmetry? $RS$? Technicolor? Or not?

- Identify three branches of the landscape, distinguished by the statistics of susy breaking on each. Within each branch, statistics are generic (e.g. result of Douglas/Denef for SUSY breaking branch). Relative numbers on each branch require microphysical understanding. Within particular branches, more detailed phenomenological predictions may be possible.

- It is probably not true that, e.g., all metastable dS vacua in the landscape are equally probable. *But* the success of Weinberg's argument suggestions that there is some reasonably democratic sampling of states. We will proceed on the assumption that the more states with a given property, the more likely that property.

- It is well known (e.g. Aguirre) that, even if one accepts some role for anthropic selection, it is difficult – perhaps impossible – to decide a priori what set of parameters anthropic considerations select. At best, we can hope to say that if some parameter changes by $\Delta$, with all others fixed, life is impossible. If imposing this as a prior on the distribution leads to an interesting prediction, I will take this as a success. Other parameters should either be random, or explained as features of the underlying distribution. Today mainly $\Lambda$, $G_F$

A Faustian Bargain? If we can do statistics well enough, and are willing to impose priors using such rules, the first predictive framework for string theory.

## The KKLT Construction

IIB on orientifold of Calabi Yau Space with D-branes, fluxes. Two types of moduli: complex structure moduli and dilaton, $z_i$. Complex structure moduli, $\rho_a$. In presence of RR and NS-NS three form fluxes, superpotential (GVW) for dilaton, complex structure moduli. Fixes this set of moduli.

Integrate out these moduli. KKLT Superpotential:

$$W = W_o + e^{ic\rho} \tag{1}$$

Leads to fixing of $\rho$ as well, $\rho \sim -\frac{1}{c} \ln(W_o)$. *So All Moduli Fixed*. Valid(?) approximation for $W_o \ll 1$, large fluxes $(g \sim \frac{1}{N})$.

KKLT also suggested a mechanism to obtain SUSY breaking: adding $\overline{D3}$ branes to these configurations. In a warped geometry, could even give hierarchically small susy breaking (and again, a roughly controlled approximation).

Douglas: Important to Study Statistics

Many distributions are known (esp. Douglas and Denef (DD)):

- Number of susy states of order

$$\mathcal{N}_{susy} = \sum_{\vec{N}} \int d\mathcal{M}\delta(D_i W) \approx L^{b_3} \int d\mathcal{M}\sqrt{g} f(\mathcal{M}) \quad (2)$$

  The prefactor is potentially quite large ($b_3 \sim 100$, $L \sim 1000$).

- Distribution of $W_o$ in Susy states: $\int d^2 W_o$ at small $W_o$. [Not a surprise; $\int d^2 W_o f(W_o) = \int d^2 W_o f(0)$. Just need dense, non-singular at $W_o = 0$.]

- Distribution of couplings: $\int d^2 g$ (DD: uniform in $SL(2, Z)$ of IIB).

- Distribution of warping scales:

$$\int \frac{d^2 M_{warp}}{M_{warp}^2 \ln(M_{warp})}$$

  – as would be expected from dynamical symmetry breaking, $e^{-\frac{8\pi^2}{g^2}}$.

- Distribution of states with broken susy, small $\Lambda$

$$\mathcal{N}(\Lambda < \Lambda_o, |F| < F^*) = \mathcal{N}_{susy} F^{*6}. \quad (3)$$

  Will give a simple explanation of this shortly.

# Branches of the flux landscape

Among the states of the landscape studied in IIB compactifications, three types can be distinguished:

1. Unbroken supersymmetry at tree level, $W_o \neq 0$.

2. Unbroken susy, $W_o = 0$.

3. Broken supersymmetry at tree level

These distinctions are not, by themselves, sharp – in field theory, we know that non-perturbative effects can break supersymmetry and give rise to non-vanishing $W$. But we will see that there is a sharp distinction – there are three distinct branches in the distribution of supersymmetry breaking scales.

# SUSY Breaking on the $W \neq 0$ Branch

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. Both suggest a similar distribution of breaking scales.

KKLT: $\overline{D3}$ branes explicitly break supersymmetry. In a warped geometry (Klebanov-Strassler), suppression of breaking by $M^2_{warp}$. So SUSY breaking distribution:

$$\int \frac{d^2 M^2_{3/2}}{M^2_{3/2} \ln(M^2_{susy})}. \tag{4}$$

Low energy dynamical breaking similar. Calling $\mu$ 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 $g^2 \to \frac{dm^2_{3/2}}{m^2_{3/2}(-\ln(m^2_{3/2}))}$.

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:

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

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

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

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

Imposing the value of the weak scale as an additional requirement can favor supersymmetry breaking at the weak scale. *This is a realization of conventional naturalness.*

## Weak Scale and Naturalness

Require $m_H < TeV$:

$$m_H^2 = \mu^2 - |W|^2. \quad (5)$$

If $\int d^2\mu$ (Susskind, Thomas): still a log distribution of susy breaking scales.

$$\int \frac{d^2 m_{3/2} \text{TeV}^2}{m_{3/2}^2}$$

If $\int \frac{d^2\mu}{\mu^2}$:

$$\int \frac{d^2 m_{3/2} \text{TeV}^2}{m_{3/2}^4}$$

## The W=0 Branch: Supersymmetry Breaking at Very Low Energies

There are a class of states with $W_o = 0$. So a $\delta$-function distribution.

One might expect that $W_o$ generated dynamically (as in gaugino condensation). Distribution smeared out:

$$\int d^2 W_o f(W_o) \sim \int \frac{d^2 W_o}{W_o^2} \tag{6}$$

What happened to our earlier argument for smoothness?

$W = 0$ can be a symmetry point – unbroken $R$ symmetry. If so, a special point in the moduli space.

$$\int d^2 W_o f(W_o)$$

$f$ singular at the origin, no Taylor expansion. It is the singular behavior of the distribution function which distinguishes this branch of the moduli space.

## The scale of supersymmetry breaking on the $W = 0$ branch

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

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

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

## LHC

## Counting States with $W = 0$ and Discrete R Symmetries Sun,MD;DeWolfe

Suppose that at some point in moduli space, in the absence of fluxes, there is an (discrete) $R$ symmetry. Under the symmetry, $W$ transforms by a phase $\alpha$. Suppose that there are some number of fields, $Z_i$, which also transform by $\alpha$, and some number, $\phi_i$, which are neutral. Then the superpotential has the form:

$$W = \sum_i Z_i f_i(\phi_j); i = 1, n; j = 1, m. \tag{7}$$

$W = 0$ is $Z_i = 0$; $\frac{dW}{dZ_i} = 0$ if $f_i(\phi_j) = 0$. Then provided $m > n$, and that $f_i$ is a reasonably generic function, there will be supersymmetric solutions with $W = 0$. There will not be supersymmetric solutions if $m < n$. In the former case, not all moduli are fixed.

What do we expect? In the Calabi-Yau case, there is a pairing of complex structure moduli and fluxes. The pairing is such that if the flux is neutral, *the corresponding modulus transforms like the superpotential*. Can only turn on neutral fluxes if the low energy lagrangian is to preserve the symmetry. In order to have a large number of states, and a small number of vanishing fluxes, we must have a large number of fields which transform under the symmetry. So we are in the limit $n > m$, above. So if there is not a big suppression of the number of states, the low energy lagrangian will leading to breaking of supersymmetry and/or $R$ symmetry.

## The Price of Discrete Symmetries

These ideas are illustrated by IIB orientifold on the CY defined by:

$$WCP^4_{1,1,1,6,9}[18]$$

$$P = z_1^{18} + z_2^{18} + z_3^{18} + z_4^3 + z_5^2 = 0. \quad (8)$$

$h_{2,1} = 272$ independent deformations of the polynomial. Rich set of discrete symmetries:

$$Z_{18}^3 \times Z_3 \times Z_2 \times S_3. \quad (9)$$

Under $z_1 \rightarrow e^{\frac{2\pi i}{18}} z_1$, $\Omega$ (holomorphic three form) transforms as:

$$\Omega \rightarrow e^{\frac{2\pi i}{18}} \Omega, \quad (10)$$

and similarly for the other coordinates. Orientifold projector includes, e.g., $z_5 \rightarrow -z_5$, under which $\Omega \rightarrow -\Omega$ All of the polynomial deformations are invariant under the $Z_2$. Any polynomial linear in $z_5$ can be absorbed into a redefinition of $z_5$ So all of the fluxes are odd and survive the projection.

Now we want to ask: what fraction of the fluxes preserve a discrete symmetry of the orientifold theory. Consider, for example, $z_4 \rightarrow e^{\frac{2\pi i}{3}} z_4$. Invariant fluxes are paired with polynomial deformations linear in $z_4$. There are 55 such polynomials. I.e. only about 1/3 of the fluxes are invariant under the symmetry.

In this example, the dimensionality of the flux space is reduced by more than half. This is typical of models in weighted projective spaces. While this is a dramatic reduction, there may be other selection effects which favor such states.

A similar analysis: $Z_2$ R-parities (which do not rotate the superpotential, and which might be important to understanding the stability of the proton), are very common in the landscape.

## Broken SUSY Branch

Here one has distinctly less control than on the SUSY branches.

At the Level of the lowest order supergravity analysis, the number of non-susy stationary points of the effective action is infinite( Douglas and Denef (DD)). It is likely that only a finite subset of these states in fact exist and are metastable. DD argue that one needs to impose a cutoff on the supersymmetry breaking scale. The need for such a cutoff complicates the relative counting of susy and nonsusy states.

## Douglas and Denef and the Number of States with Cutoff $F^*$

With a cutoff, DD have done a counting of states.

Want to evaluate:

$$\mathcal{N} = \sum_{\vec{N}} \int d^{2m} z \delta(V') \det(V'') \tag{11}$$

Treating the fluxes as continuous, imposing the tadpole constraints, allows conversion of this expression to a manageable form.

$$\mathcal{N}_{ns} = \frac{(2\pi L_*)^{2m}}{(2m)!} \int_{\mathcal{M}} d^{2m} z \det g \rho(z) \tag{12}$$

where

$$\rho(z) = \pi^{-2m} \int d^2 X d^2 Z d^2 m Z F e^{-|x|^2 + |F|^2 - |Z|^2} f(X, F, Z) \tag{13}$$

Note the sign of $|F|$ in the exponent. In this form, it is again clear that a cutoff is necessary. Douglas and Denef performed careful analysis of the object $f$. The final result: with cutoff $F^*$,

$$\mathcal{N}(\Lambda < \Lambda_o, |F| < F^*) = \mathcal{N}_{susy} F^{*6}. \tag{14}$$

We can obtain this result by thinking about features of the low energy effective lagrangian (O'Neil,Sun,MD). If scale of susy breaking is small, and cosmological constant is small, there must be a light chiral multiplet in the effective lagrangian. Surely it is more probably to have only one chiral multiplet, $z$, than several. We can take the superpotential to have the form:

$$W = W_o + \alpha z + \beta z^2 + \gamma z^3 + \dots \qquad (15)$$

and the Kahler potential:

$$K = a + bz + b^* z^* + cz^2 + c^* z^{*2} + dz^* z + \dots \qquad (16)$$

In perturbation theory, $a, ...d \sim 1$, and we will assume that this is general.

Now we want to impose the following conditions:

1. $F$ is small at the minimum, i.e.

$$\alpha + bW_o = F \qquad |F| < F^*. \tag{17}$$

2. The potential is zero at the minimum. Since $F$ is small, this means that $W_o \sim F$.

3. The potential has its minimum at $z = 0$. DD:

$$\partial_z V = e^K (D_z D_z W \bar{D}^{\bar{z}} \bar{W} - 2 D_z W \bar{W}). \tag{18}$$

4. The minimum is metastable.

$$\partial_z^2 V = e^K (D_z D_z D_z W \bar{D}^{\bar{z}} \bar{W} - D_z D_z W \bar{W}) \tag{19}$$

If we assume that the Kahler potential is bounded, $b$ cannot become arbitrarily large. So from the first two conditions we learn that $\alpha \sim F$. Then the third condition gives that $\beta \sim F$. Finally, if $\gamma$ is large, examining the second derivative terms, we see that the masses cannot be positive; so once more, $\gamma \sim F$.

To obtain the number of states with $|F| < F^*$, we need to know the distribution of the parameters $\alpha$, $\beta$, etc. But again, provided there are states, we can obtain these distributions by Taylor series expansion about the origin. The origin is not a special point, so there is no reason these should be singular. So we have:

$$\int d^2\alpha d^2\beta d^2\gamma d^2 W_o \theta(\Lambda_o - V)\theta(F^* - |\alpha|)\theta(F^* - |\beta|) \quad (20)$$

$$\theta(F^* - |\gamma|) \sim \Lambda_o F^{*6}.$$

This illustrates that the result of Douglas and Denef is robust, and does not depend on details of the microscopic theory. Follows from general expectations of low energy field theory, and very mild assumptions about the distributions.

Pile up of states at the high scale means that most states cannot be studied in any approximation scheme; statistics hard.

Features of these phenomenologies:

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

2) Intermediate scale breaking: e.g. if take KKLT scheme literally, assume matter on $D7$ branes, gauginos much lighter than squarks, sleptons. Dark matter likely to be wino. This might select for a relatively large value of the gravitino mass; perhaps could explain why susy higgs not yet seen (i.e. fine tuning of susy). Possible solution of the usual cosmological moduli problem. Significantly ameliorates flavor problems. Spectrum of "split supersymmetry" with 100 TeV scale for scalars.[MD]

3) High scale breaking – perhaps provides additional motivation for exploring the phenomenology of technicolor/RS.[Douglas et al] Challenging to relate to any microphysical understanding.

## Split Supersymmetry and Related Ideas

So far, discussion has been: can one use statistics (esp. correlations) to make predictions for low energy physics from the landscape.

Is there an alternative, "bottom up" approach? Esp. a rationale for tunings in model building?

Split susy: motivation is observation that squarks, sleptons are irrelevant to unification.

Argue: fermions naturally light due to R symmetries, scalars, heavy.

But:

- Large susy breaking, small $\Lambda \Rightarrow W$ very large, $R$ symmetry badly broken. Detailed models required to suppress the masses of gauginos; not clear that generic.

- We have seen, $R$ symmetries plus landscape $\Rightarrow$ unbroken susy.

But, who knows?

## Lessons

- Statistics of classes of vacua follow from simple considerations:
  1. Assumption of dense set of states
  2. smoothness of distribution functions
  3. Wilsonian effective lagrangian reasoning.

- Within different branches, can make phenomenological statements. Much more detailed microscopic understanding required to choose among different branches (Douglas). At present, can only hypothesize nature lies on one or another branch, but we gave some tentative evidence that the low energy branch might be suppressed.

## Conclusions: What to do now?

- Statistics of gauge symmetries. E.g. is dynamical susy breaking at low energies common?
- More on statistics of ranks, etc. might give insight into more detailed phenomenology. Blumhagen et al; Kumar, Wells
- Question of unification in the landscape.
- Hard questions: cosmology, stability, etc. E.g. perhaps non-susy vacua disfavored by stability considerations?
- We have just over two years!