Symmetries and Naturalness in String Theory

Talk at Harvard Workshop *Stringy Reflections on the LHC*

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October, 2008

Supersymmetry

Almost all of the talks at this meeting have involved supersymmetry in an essential way.
Motivations:

1. Hierarchy
2. Unification
3. Dark Matter

Worry: Little Hierarchy, 1% Fine tuning (or worse).
Also, much about gauge mediation.
Motivations:

1. Flavor
2. Rich dynamical possibilities, esp. with metastable supersymmetry breaking
3. Improved tuning if scale of messengers low (e.g. with GGM, 10% or worse (Carpenter)).

Supersymmetry in String Theory

Most of what we understand in string theory is supersymmetric, but perhaps a crutch. Any reason of principle that we might think low energy susy an outcome?
In models we understand, problems:

1. Moduli
2. Susy breaking
3. c.c.
4. Unification – in what sense generic?

If susy discovered, or not, will tell us something about string theory. But at present, any reason of principle to expect low energy susy?

The Landscape

Biggest reason not to like: the Landscape is the Damocles sword hanging our heads. If explanation of hierarchy like that of c.c., *no* low energy consequence. Bleak scenario for LHC. But at least the landscape addresses the basic limitations which have frustrated us in string theory. Still, frustrating:

- No way to find *the* state which describes our universe
- We lack any complete classification of states, much less some sort of (statistical) catalog.

But I'll argue that there are principled reasons to think SUSY is an outcome of such a picture. Perhaps even low energy gauge mediation. Hardly a proof – I don't expect to convince most of you today. But I hope this might be the kernel of an argument, and that, at the least, within this structure, the discovery or not of supersymmetry might help us pose useful questions in string theory.

The Landscape Framework

Whether or not a *landscape* underlies the ultimate quantum theory of gravity, it is arguably the only model we have at present for how the laws of nature we observe at ordinary energies [including absence of susy., absence of massless particles, c.c.] might emerge from the sort of quantum gravities we understand.
Claim: first should study questions of naturalness.
The obvious place to begin is asking whether states which exhibit symmetries are in any sense singled out [contrast c.c.].

IIB Landscape

IIB landscape as a model. Orientifold on a Calabi-Yau manifold. RR, NS-NS fluxes, N_i, $i = 1, \dots I$.
Exponentially large number of states possible because large number of different fluxes, taking large number of possible values.
Tree level: superpotential for complex structure moduli, z_i; independent of Kahler moduli, ρ.

$$W = \sum_i N_i f(z_i) \tag{1}$$

Kahler potential known; no-scale structure for potential.

At best can study systematically only small fraction of states. E.g. KKLT: SUSY stationary points of effective action for z; low energy effective theory for ρ

$$W = W_0 + e^{-a\rho} \tag{2}$$

Many possible states; W_0 sometimes small $\Rightarrow \rho$ large. α', g_s expansions perhaps not misleading.
SUSY breaking: $\overline{D3}$ branes, breaking in low energy effective theory (Seiberg's talk). Sometimes small, positive c.c.

Expect many non-susy stationary points of the effective action. Neighborhood of KKLT point typically small ρ, might include many stationary points with positive, negative c.c. Most not accessible to any sort of weak coupling or α' analysis.
One might think that non-susy solutions more common (Douglas, Susskind). SUSY exceptional? Unlikely?
Here ask about stability. A putative low c.c. state typically surrounded by a large number of negative c.c. states. Tunneling to *every one* must be suppressed.

What might account for stability?

Known features of string states with a generic character:

- Small Coupling
- Large volume
- Warping
- Supersymmetry

General scaling of tunneling amplitudes (IIB case):

1. Energies scale like N^2/V^2, so $\Delta E \sim N/V^2$ if volume is same in neighboring states (we have seen volume changes in KKLT case)
2. Tensions scale like $1/V$.
3. Assuming scaling as in thin wall (scaling laws below are valid more generally), amplitude

$$A \sim e^{-T^4/\Delta E^3}$$

$$e^{-V^2/N^3}$$

So for large N, need large volume.

So it appears that (without other sources of suppression) one needs volume scaling like $N^{2/3}$ in both the initial and final state to suppress tunneling. Won't detail here, but warping, small coupling don't suppress tunneling.

Tunneling in Nearly Supersymmetric Theories

Supersymmetry is well-known to suppress tunneling (Witten, Hull, Deser and Teitelboim, Weinberg)
In flat space case, can understand by noting that there exist global supercharges, energy-momentum, obeying the usual susy algebra:

$$\{Q_\alpha, Q_\beta\} = P^\mu \gamma_\mu.$$

So no negative energy configurations (no bubbles can form, grow).
Small susy breaking?

Tunneling near the Supersymmetric Limit

Limit of small $m_{3/2}$. Suppose that the cosmological constant of the "false vacuum" is essentially zero. Then can distinguish three cases:

1. Lower energy AdS state is non-supersymmetric. In this case, the zero c.c. state is stable.
2. Lower energy AdS state is supersymmetric or approximately so, with $\langle W \rangle \gg m_{3/2} M_p^2$. In this case, the zero c.c. state is stable, or it is unstable, with decay amplitude given by a universal formula: $\mathcal{A} = e^{-2\pi^2 \left(\frac{M_p}{\mathrm{Re}\ m_{3/2}} \right)^2}$. (For special cases, this expression has been derived by Ceserole, Dall'Agata, Giryavets, Kallosh and Linde).
3. Lower energy AdS state is supersymmetric or approximately so, with $\langle W \rangle \sim m_{3/2} M_p^2$. This is the case of *metastable susy breaking*. Tunneling suppressed, but not as strongly; depends on details.

Derivation of tunneling amplitudes

Without Gravity:
Action for $O(4)$ symmetric thin wall configuration:

$$B(\rho) = 2\pi^2 S_1 \rho^3 - \frac{1}{2}\pi^2 \epsilon \rho^4. \tag{3}$$

This action has a stationary point (actually a maximum) for

$$\rho = 3S_1/\epsilon. \tag{4}$$

With gravity: true vacuum is AdS; volume grows like surface. As Coleman-DeLuccia showed:

$$B(\bar{\rho}) = 2\pi^2(S_1 - \frac{2}{\sqrt{3}}\sqrt{\frac{\epsilon}{\kappa}})\bar{\rho}^3 + \frac{6\pi^2\bar{\rho}^2}{\kappa} + \mathcal{O}(\bar{\rho}). \tag{5}$$

There is a critical value of the parameters for which the tunneling amplitude vanishes:

$$\sqrt{\epsilon/S_1} = \sqrt{3}\kappa/2. \tag{6}$$

Near critical parameters, thin wall analysis always valid. As one approaches the critical point, the radius becomes large. Writing

$$\epsilon = \frac{3}{4}\kappa S_1^2(1+\delta) \tag{7}$$

one has

$$B(\rho) = -\pi^2\bar{\rho}^3 S_1\delta + \frac{\epsilon\pi^2\bar{\rho}^2}{\kappa}. \tag{8}$$

So, for small δ

$$\bar{\rho} = \frac{4}{\kappa S_1\delta} \tag{9}$$

For tunneling between supersymmetric states,

$$S_1 = 2\Delta W \quad \epsilon = 3\frac{|W|}{M_p^2}$$

so the critical condition is satisfied.

Moving slightly away from the critical point:

$$\epsilon = \frac{3}{4} \kappa S_1^2 (1 + \delta) \tag{10}$$

one has

$$B(\rho) = -\pi^2 \bar{\rho}^3 S_1 \delta + \frac{\epsilon \pi^2 \bar{\rho}^2}{\kappa}. \tag{11}$$

So, for small δ

$$\bar{\rho} = \frac{4}{\kappa S_1 \delta} \tag{12}$$

which agrees with the result of CDL in this limit. Note that for negative δ, there is no stationary point, and correspondingly no bounce.

Tunneling with SUSY breaking

Can describe the nearly susy situation quite generally, if the AdS state is deep. Necessarily a light field in the Minkowski vacuum, z. Can take

$$W(z) = \mu^2 z + W_0$$

define z so that $\langle z \rangle = 0$. $W_0 = \frac{1}{\sqrt{3}} e^{i\alpha} \mu^2 M_p$.
In the deep vacuum $\langle W \rangle = \tilde{W}_0$, $\tilde{W}_0 \gg W_0$. So

$$\epsilon \approx \frac{3}{M_p^2} \left(|\tilde{W}_0|^2 + 3(W_0 \tilde{W}_0 + \mathrm{c.c.}) \right). \tag{13}$$

The change in S_1 is of order μ^4 / M_p. Taking $\tilde{W}_0$ to be positive, if $\mathrm{Re}\ W_0 < 0$, there is no tunneling. If $\mathrm{Re}\ W_0 > 0$, we arrive at

$$\mathcal{A} = e^{-2\pi^2 \left(\frac{M_p}{\mathrm{Re}\ m_{3/2}} \right)^2}. \tag{14}$$

If $\tilde{W}_0 \sim W_0$, all the terms are of order μ^4. In general, the transition is faster:

$$\mathcal{A} \sim e^{-\left(\frac{M_p}{m_{3/2}}\right)^a} \tag{15}$$

where $1 < a < 2$.

Branches of the landscape: Varying Degrees of Supersymmetry

Supersymmetry has been widely studied in string theory and the landscape (it is the basis of most of the talks at this meeting). Thinking about the LHC, we are particularly interested in low energy supersymmetry.

1. Is supersymmetry an outcome of string theory/quantum gravity/landscape?
2. Are there qualitative features of supersymmetry and its breaking which might emerge in a generic fashion?

Landscape Branches

Within the landscape, three branches identified:

1. Non-supersymmetric branch.
2. Supersymmetric branch: expect $m_{3/2}$ distributed uniformly on a log scale (roughly susy breaking by non-perturbative effects as in KKLT, W_0 a uniformly distributed random number).
3. "R Symmetric" branch: W_0 dynamically determined. Very low energy susy (gauge mediation?).

Conclusion of part 1

While hardly proving low energy supersymmetry, the problem of stability suggests why branches II and III of the landscape might be favored. Note that to provide an adequate degree of stability, a hierarchy between $m_{3/2}$ and M_p would be more than adequate. The additional feature of at least a uniform distribution of $\ln(m_{3/2})$ makes the possibility of low energy susy breaking plausible.
What about the difference between Branch II and III?

Discrete Symmetries in the Landscape

Viewpoint: the large number of states in the landscape arise because of a large number of possible fluxes, each ranging over a large number of possible values.
Symmetric states are inevitably rare. In order to obtain a state with symmetries, it is necessary that

- All fluxes which transform under the symmetry vanish
- With vanishing of the asymmetric fluxes, minima of the potential for the moduli preserve the symmetry.

For interesting symmetries, one typically finds that 2/3 or more of the fluxes must be set to zero $\Rightarrow$ an exponential suppression.
So symmetries uninteresting.

Cosmological Questions

Perhaps this is too naive. We are accustomed to the idea that finite temperature favors symmetries. Perhaps other cosmological considerations might be relevant.

Might symmetric states be attractors? To address this question, we need both a model for states and a model for cosmology.

The Bousso Polchinski Model

E.g., Bousso-Polchinski model.

$$E_0 = \frac{1}{2} N_i^2 q_i^2 - \Lambda_0. \tag{16}$$

The q_i's are constants, independent of N_i. They are assumed to be small enough that all tunneling amplitudes are small. This requires that the internal manifold be large, with volume scaling as a positive power of the flux. This model is extremely useful, first, for illustrating the idea of a discretuum: the model exhibits a nearly continuous distribution of energies for large fluxes. It also provides a model for eternal inflation.

A Cosmological Model

Goal: establish whether there is any reason to think that the rare states in a landscape exhibiting symmetries are somehow favored. Burden (for now) not to establish conclusively that this is the case in an underlying, complete theory of gravity, but simply to establish some general conditions under which symmetries might plausibly be favored.

- Postulate a landscape with a large number of (very) metastable de Sitter states,
- Take as “initial condition" universe starts in one such state. Ask whether, for a non-negligible fraction of possible starting points, the system finds its way to the symmetric state.
- Suppose that the antecedents of the symmetric state are short lived and do not experience long periods of exponential growth.

The Neighborhood of the Symmetric States

As part of our *model*, we adopt (Douglas; Kachru) *continuous flux approximation*.
Consider a state which is symmetric or approximately symmetric under an ordinary discrete symmetry. Some subset of fluxes, N_i, $i = 1, \ldots, B$, respect the symmetry (they are neutral under the symmetry), and there are minima of the resulting potential in which only fields neutral under the symmetry have expectation values. The rest, n_a, $a = 1, \ldots, A$, break the symmetry. Putative, low cosmological constant, symmetric state, $\vec{N}^o$.

$$|n_a| < |N_i - N_i^0| \tag{17}$$

defines the neighborhood of the symmetric point.

States exhibiting discrete symmetries are rare in the flux landscape. But the fraction of states lying nearby such symmetric points need not be small.

Model this by taking the initial state is taken to lie on the "hypersphere"

$$N_i^2 + n_a^2 = R^2 \tag{18}$$

Ask fraction of states with:

$$\alpha^2 N_i^2 > n_a^2. \tag{19}$$

Compare:

$$\int d^I N d^A n \delta(\sqrt{N^2 + n^2} - R^2) \tag{20}$$

with the same integral, restricted by $n^2 < \alpha^2 N^2$.

Suppression is

$$\alpha^A \left(\frac{A}{2}\right)^{\frac{I}{2}}$$

If $\alpha \sim 1$, the suppression with increasing A is quite modest.

If light pseudomoduli in the symmetric vacuum, then energy is not a simple quadratic polynomial in fluxes as in BP. If none,

$$E_0 = \sum_{i,J=1}^{I} f_{IJ} N_I N_J + \sum_{a,b=1}^{A} g_{ab} n_a n_b \tag{21}$$

Two cases:

1. g_{ab} has only positive eigenvalues. Starting in the neighborhood of the symmetric state, those transitions which change the n_a's will tend towards the symmetric state.
2. g_{ab} has some negative eigenvalues. The corresponding n's will tend to grow, and the system will not tend towards the symmetric state.

Non-R Symmetries

Problem: even if all eigenvalues of g positive there is nothing particularly special about $\vec{N}^0$. If eigenvalues of g, f, are all similar, if $n_a \ll N_i$

$$\frac{S_b(\delta n_a = 1)}{S_b(\delta N_i = 1)} \sim \frac{N^3}{n^3} \tag{22}$$

Transitions which change n are much slower than those which change N. Notion of a neighborhood is not relevant to the tunneling process. One may reach a state $(\vec{N}_0, \vec{n}_a)$, but then one will transition to big crunches with negative cc.
If elements of g, in addition to being positive, were far larger that those of f, then some possibility. We will a phenomenon of this sort in the case of R symmetric vacua.

R Symmetric States

Working assumption is that in these states, R symmetry breaking and susy breaking are small, non-perturbative effects (statistics of branch III). Then changes in N, in the symmetric limit, are not associated with changes in energy, so they are potentially highly suppressed.

Features of R symmetric states: Suppose that we have fields, X_I, which transform under the R symmetry like the superpotential, and fields, ϕ_α, which are neutral. There are additional fields, ρ_i, which transform differently than the X's under the R symmetry. Then the superpotential has the form

$$W = X_I F_I(\phi_\alpha, \rho_i) \tag{23}$$

There will be a moduli space of supersymmetric, R symmetric solutions ($X = \rho = 0$) provided there are more ϕ type fields than X type fields (typical of CY compactification)..

For non-zero n_a, the situation is quite different. We can study an effective action for the moduli. Their potential is of order n^2. Correspondingly, the masses-squared of the light moduli are of order n^2. Energy is not a simple polynomial in n^a, but it does scale as n^2.

Study of field theory models indicates that ground states can be dS or AdS. If much of the neighborhood of the symmetric point is AdS, we don't expect a significant probability to reach the symmetric point. So we will assume that the neighbors of the symmetric point are predominantly dS.

Transition rates in the R-symmetric Neighborhood

Crucial difference with the non-R states: the energy in the symmetric state is naturally small..

To compare tunneling rates for processes with changes in N with those with changes in n, we need to understand how the energies of these states depend on n. Expect (examining field theory models) quite weak, n^4/N^2. Dependence of bubble tension also weak, so

$$\frac{S_b(\Delta N = 1)}{S_b(\Delta n = 1)} = \frac{N^9}{n^9}! \tag{24}$$

Transitions towards the symmetric point are likely to be much faster than other transitions.

Lessons

This analysis establishes that in a class of *model* landscapes and *model* cosmologies:

- Non-R symmetries are unlikely to be attractors
- R symmetries may be attractors

The model assumptions are strong; whether they hold in “real" landscapes is an open question. But it is hard to see how things could be much better than this.

Conclusions: Symmetries in a Landscape

It seems plausible that if in (the) quantum theory of gravity, there is an underlying landscape:

- Questions of stability may lead to a preponderance of supersymmetric states, especially among states with hierarchies of mass scales.
- States with R symmetries may be cosmological attractors, favoring low energy supersymmetry.

These questions seem not nearly so hard as asking why the gauge group is what it is, or the specific values of Yukawa couplings. They have immediate importance for the physics of the LHC. Perhaps we can make more definitive statements?

THE END