The Landscape, Supersymmetry and Naturalness

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The LHC: Will it Find Anything?

It will almost surely find a Higgs particle.

But we all hope for more. These hopes are based on the notion of naturalness.

Puzzles:

- Cosmological constant
- M_{higgs}/M_p
- θ_{qcd}
- Fermion mass hierarchy
- ...

Recently, in light of the landscape, naturalness has been declared (almost) dead by Douglas Susskind, Arkani-Hamed, Dimopoulos and others.

Claims today:

1. The landscape actually makes the question of naturalness sharp. Low energy effective theories selected from distributions. Observed couplings, scales, may be much more common in some regions of the landscape than in others.

2. It is questions of naturalness which one has best hope to address in landscape context. Precisely questions of what is generic, of correlations, statistics, as opposed to hunting for particulars.

3. If you are an advocate of naturalness, the landscape [right or wrong, anthropic or not] is currently the best (theoretical) framework in which to test your ideas. (supersymmetry, warping, technicolor).

Aspects of Naturalness

Usual notion: Quantity x naturally small if theory becomes more symmetric in the limit that $x \to 0$.

Large ratios of scales from small couplings: $e^{\frac{-8\pi^2}{g^2}}$ small for g of order 1.

Prior to string theory, with its original aura of uniqueness, this notion of naturalness had almost a mystical quality. As if one was worried a supreme being should not have to work to hard to make the universe more or less like it is (*strongly anthropic*).

If the underlying theory is unique, not clear why these ideas should be relevant. This, indeed, has been (and remains) the view of many string theorists: somehow miraculously the observed universe will simply emerge.
An alternative view: parameters of low energy effective field theory (gauge groups, matter content, couplings) are chosen from distributions.

Symmetries, dimensional transmutation might work as we have long imagined. Whether symmetries are favored might depend on questions such as relative numbers of symmetric, non-symmetric states, and whether cosmology favors symmetric states.

String Theory and the Landscape

String Theory Prior to 2002: Lot's of string vacua, but only those with (unbroken) supersymmetry and exact moduli (massless fields) were known, understood. It was always conceivable that there were good vacua without supersymmetry in regions of strong coupling, but no means to access them. Cosmological constant: no reason it should be zero or small.

As a result, no program for making predictions from string theory, testing the theory, or in any sharp way comparing with nature.

This changed with the appearance of the flux landscape, esp. through the work of KKLT. 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$\Rightarrow$ LHC; Cosmology/Astrophysics

Caveat: the very existence of the string landscape is not well established. Banks (also Banks, Dine, Gorbatov): serious objections. Only serious response: Susskind. But most string theorists (e.g. poll Toronto 2005): abhor idea of environmental selection, *but accept that string theory has some vast number, e.g.* 10^{500} *or more, metastable states.*

Today we will assume string landscape exists, and ask where this might lead.

What of our list of problems:

- Cosmological constant – enough states to implement Weinberg's solution. Only plausible solution we know now; successful prediction of dark energy density.

- M_{higgs}/M_p – the landscape has states with low energy supersymmetry, and with warping (technicolor).

- θ_{qcd} – Here, illustration of possibility of failure. States explored to date in landscape don't have light axions. Even if there are such states, not clear if they should be generic. Hard to give a selection mechanism which would favor very light axions, small θ (dark matter?).

- Fermion mass hierarchy – discrete symmetries? Some examples and issues later.

- ...

If the landscape exists, we have no choice but to confront these questions.

Naturalness and the Landscape

The landscape provides a realization of the idea that the parameters of low energy physics arise from distributions.

Example: IIB compactifications on Calabi-Yau with fluxes, the distribution of couplings is known to be roughly flat as a function of coupling,

$$\int dg^2$$

(Douglas). Consistent with SL(2,Z) symmetry of the underlying string theory;

$$\tau = \theta + \frac{i}{g_s}$$

Invariant measure is:

$$\int \frac{d^2\tau}{\tau_2^2} = dg^2$$

Other distributions also consistent with simpleminded notions and symmetries. E.g. in supersymmetric compactifications:

- Distribution of $W_o = \langle W \rangle$ is flat as $\int d^2 W_o$

- Distribution of susy-breaking scales follows from simple-minded effective lagrangian arguments.

What about symmetries. Symmetries might account for features of the low energy effective theory, but this begs the question: How common are they? Could it be that there are simply overwhelmingly more states with

- Large hierarchy, no supersymmetry

- Quarks and leptons light simply by accident (no symmetry explanation)

than with these features due to (approximate) symmetries?

Naturalness irrelevant?

Explore here SUSY, discrete symmetries.

Supersymmetry

The usual notion: supersymmetry could explain hierarchy. As $M_{susy} \to 0$, theory more symmetric.

Three branches of landscape, distinguished by distributions.

1. Badly broken supersymmetry.

$$P(m_{susy} < M; \Lambda < \Lambda_o) = C_1 \Lambda_o M^{12}$$

   Almost all states have susy broken at Planck scale [IIB: Broken SUSY at tree level]

2. $$P(m_{susy} < M) = C_2 \Lambda_o \ln(M^2)$$

   Phenomenology like gravity mediation. [IIB: Unbroken SUSY, $W \neq 0$ at tree level]

3. $$P(m_{susy} < M) = C_3 \Lambda_o / M^2$$

   Phenomenology like gauge mediation [IIB Unbroken SUSY, $W = 0$ at tree level due to R symmetries – we will see may be suppressed]

There is a widespread prejudice that supersymmetric states are far more numerous than non-supersymmetric states. This is based on the statistics of the first branch above. But the relative numbers of metastable states on the branches not known. Later, an argument that the non-susy branch might be rather sparse.

If the conventional wisdom is correct, it is hard to see how our ideas about low energy supersymmetry could be correct. Something like technicolor, or warping, would be more plausible; large hierarchies a few percent of the time.

What then solves the usual problems (flavor; precision electroweak?) Perhaps just more states with light Higgs by accident; no low energy explanation.

Phenomenology of the Non-Supersymmetric States

Very difficult to see how one might say anything at all. On this branch, no obvious small parameters, not clear how even to do statistics. A Bleak Prospect (no more SUSY meetings?)

Proposal (Arkani-Hamed et al): SPLIT SUPERSYMMETRY

Rationale:

1. Gives as good (better?) unification of couplings than susy
2. Dark matter candidate selection? or just a fact?
3. Supersymmetry badly broken;
4. R symmetry can protect gaugino masses naturally

A Rich and Interesting Phenomenology

But even with our limited understanding, puzzles with this proposal:

First, discussion of gauginos presumes at least an approximate susy. In this case, there is much that we know.

- We will see that R symmetries are costly in landscape

- We will see that in the presence of R symmetries, supersymmetry and R symmetry are likely to be *unbroken*

- Badly broken susy $+ \Lambda = 0 \Rightarrow$ badly broken R symmetry.

In supergravity,

$$V = e^K \left[D_i W g^{i\bar{i}} D_{\bar{i}} W^* - 3|W|^2 \right]$$

where

$$F_i = D_i W = \partial_i W + \partial_i K W$$

Broken susy: $D_i W = M_s^2$; Vanishing Λ: $W \approx M_p D_i W$

W transforms under any R symmetry like $\lambda\lambda$.

By itself, $\langle W \rangle$ does not lead to a gaugino mass at tree level. But at one loop expect an anomaly-mediated contribution. While sometimes cancellations (Arkani-Hamed et al discussed such models), in the classes of states which have been studied in the landscape (KKLT, Douglas-Denef), generically no cancellation.

An alternative possibility is that there is no approximate supersymmetry at all. Symmetries *can* give rise to light octets and triplets of fermions, perhaps additional doublets – the split susy spectrum (unification). Not difficult to construct models of this type in field theory and string theory (John Mason, M.D.).

Given observations about symmetries in the landscape, this seems a far less likely outcome of string theory/landscape than supersymmetry.

Problems on the Non-Supersymmetric Branch

Why do we need a cutoff? One reason: stability against (*rapid* tunneling)

Suppose all fluxes of order N, N large. Then:

1. Energies of order N^2
2. Splitting of nearby vacua ($N \to N+1$) of order N; barrier heights of order N.
3. Moduli of order 1; change by $1/N$ in transitions.

How large is tunneling amplitude? For tunneling between small Λ and negative Λ, Coleman (Coleman-Deluccia):

$$\ddot{\phi} + \frac{1}{r}\dot{\phi} = NV'(\phi)$$

Bounce action: e.g. if thin wall, $\epsilon \propto N$, $S_o \sim 1$, so

$$S_{bounce} \sim \frac{S_o^4}{\epsilon^3} \sim \frac{1}{N^3}.$$

So tunneling amplitude of order one. Each state has *many* neighbors, so these are typically not states at all.

States which are nearly supersymmetric are stable or extremely long lived. So this *might* favor supersymmetric branch.

The third branch is in some ways the most interesting. It has a phenomenology similar to that of gauge mediation. The statistics favors the lowest possible scale of supersymmetry breaking (the only theoretical argument I know for a low scale of supersymmetry breaking in gauge mediation). But we will see shortly that R symmetries are likely to be rare in the landscape. So we will turn to the second, intermediate branch.

- Intermediate branch:
  1. Includes original KKLT proposal.
  2. Selecting for Λ & G_F: implies intermediate scale $M_{int}^2 = m_{3/2} M_p$ supersymmetry breaking (as in conventional "SUGRA" model– but also different, as below).
  3. Two "scenarios" for susy breaking. KKLT antibranes, and Dynamical Supersymmetry Breaking in low energy theory. *Both have same statistics*. Latter is simpler to analyze, since can use conventional field theory, e.g., to understand structure of $\mathcal{L}_{eff}$.
  4. Features of phenomenology can be worked out (consequence of [3]), and they are distinctive.
     – Hierarchy between scale of moduli and scale of soft scalar masses. (Solution of moduli problem, interesting possibilities for dark matter).
     – Hierarchy (of order $\sqrt{\alpha}$) between scalars and gauginos. Ameliorates (somewhat) problems of flavor in susy.

More on KKLT Phenomenology

Focus on modulus ρ (R^3) and a hidden sector field, Z.

$$K = -3\ln(\rho + \rho^*) + Z^* Z$$

$$W = e^{-c\rho} + W_o + \mu^2 Z$$

For small W_o, ρ is large:

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

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

Integrating out ρ leaves Polonyi model for Z. ρ is heavy, $m_\rho = \rho m_{3/2}$. Squark and slepton masses of order $m_{3/2}$; gaugino masses generated by loops (anomaly mediation) so further suppressed.

Significant mass hierarchy

But to be consistent with current limits, scalars *very* massive, so Higgs somewhat tuned.

One could speculate that this is a result of environmental selection. If formation of suitable structure restricts the dark energy density to be close to its observed value, this might fix the masses of the lightest neutralino.

The ρ field, in this case, would be a very massive modulus (as contemplated by Banks, Kaplan and Nelson). The dark matter would be produced in its decays, or in decays of approximate moduli in the hidden sector.

One issue raised recently (by Endo et al, Yamuguchi et al): may overproduce gravitinos. Earlier argued by Moroi and Randall that in such decays, gravitino production is suppressed. If correct, this particular scenario for the landscape is ruled out.

What actually happens depends on details of the hidden sector (Kitano, Morisse, Shirman, M.D.).

We will see that the third, very low energy branch seems to be disfavored. This is progress! To make further progress, would like answers to questions like:

- Are there vastly more non-supersymmetric than supersymmetric states in the landscape? We gave some stability arguments which might favor supersymmetric states.

- How common is dynamical supersymmetry breaking in the landscape? (Berenstein et al, Kachru et al, Volansky and Antebi)

Discrete symmetries

In weakly coupled string theories, a theorem that there are no continuous global symmetries; expect general. Discrete symmetries arise in many string constructions. How do discrete symmetries arise in the landscape? Focus on IIB. Calabi-Yau manifolds, at particular points in their moduli spaces, often admit large discrete symmetries. The quintic in CP^4 is a famous example.

$$P = \sum_{i=1}^{5} Z_i^5 = 0$$

Symmetries

$$Z_i \to \alpha Z_i; \alpha = e^{\frac{2\pi i}{5}}$$

Permutations of Z_i

i.e. $Z_5^4 \times S_5$. In general, these are R symmetries.

When are symmetries R symmetries?

In Calabi-Yau compactifications, basic object is covariantly constant spinor, η,

$$\eta = \begin{pmatrix} 0 \\ 0 \\ 0 \\ \eta \end{pmatrix}$$

From this one can build a covariantly constant three form, $\Omega^{ijk} = \bar{\eta}\Gamma^{ijk}\eta$. Transforms under symmetries like the *superpotential*.

$$\Omega = dx_1 \wedge dx_2 \wedge dx_3 \left(\frac{\partial P}{\partial x_4}\right)^{-1}.$$

So under $\alpha \to \alpha Z_1$, $W \to \alpha W$, similarly for other symmetries.

This model has 101 "complex structure moduli" and one "Kahler modulus". Complex structure moduli: in 1-1 correspondence with deformations of the polynomial. Transformation properties immediate. E.g. under $Z_1 \to \alpha Z_1$, $\alpha = e^{2\pi i/5}$

$$Z_1 Z_2^2 Z_3^2 \to \alpha Z_1 Z_2^2 Z_3^2 \quad Z_1 Z_2 Z_3 Z_4 Z_5 \to \alpha Z_1 Z_2 Z_3 Z_4 Z_5$$

Symmetries in Flux Vacua

What happens when compactify IIB on an orientifold of CY with fluxes. Fluxes are in 1-1 correspondence to complex structure moduli.

Orientifold projection:

$$\mathcal{O} = (-1)^{F_L}\Omega_p\sigma^* \qquad \sigma^*\Omega = -\Omega.$$

For the quintic, a suitable σ (Z_2):

$$z_2 \to z_3 \quad z_3 \to z_4 \quad z_4 \to z_5 \quad z_5 \to z_2.$$

Flips sign of Ω since an odd permutation. There are 27 polynomials invariant under this symmetry, so $h_{2,1}$ is reduced from 101 to 27. The number of fluxes which are invariant under the symmetry is reduced to 27. This is only 1/3 of the total. So not a huge number of states.

Better examples: weighted projective spaces (Z_i's identified under $Z_i \to e^{\beta_i} Z_i$).

A case in which there is a large number of fluxes even after the orientifold projection is provided by $WCP^4_{1,1,1,6,9}[18]$. Take the polynomial to be:

$$P = z_1^{18} + z_2^{18} + z_3^{18} + z_4^3 + z_5^2 = 0. \quad (1)$$

One can construct Ω as before;

$$\Omega = dx_1 \wedge dx_2 \wedge dx_3 \left(\frac{\partial P}{\partial x_4}\right)^{-1}.$$

P admits a large discrete symmetry

$$Z_1 \to e^{\frac{2\pi i}{18}} Z_1 \quad Z_2 \to e^{\frac{2\pi i}{18}} Z_2 \quad Z_3 \to e^{\frac{2\pi i}{18}} Z_3 \quad Z_4 \to e^{\frac{2\pi i}{3}} Z_4$$

Then there are $h_{2,1} = 272$ independent deformations of the polynomial.

$$Z_{18}^3 \times Z_3 \times Z_2 \times S_3. \quad (2)$$

To construct the orientifold, take σ to be under the transformation $z_5 \rightarrow -z_5$ (Ω odd). Now all of the polynomials are invariant under the Z_5. Any polynomial linear in z_5 can be absorbed into a redefinition of z_5 (just as the $z_i^4 z_j$ type polynomials to not correspond to physical deformations in the case of the quintic). All of the complex structure moduli and fluxes survive the projection (moduli are even; fluxes are odd).

Under $z_1 \rightarrow e^{\frac{2\pi i}{18}} z_1$, Ω transforms as:

$$\Omega \rightarrow e^{\frac{2\pi i}{18}} \Omega, \tag{3}$$

and similarly for the other coordinates.

The Price of Symmetries

In order that the low energy theory exhibit a symmetry, it is necessary that any non-vanishing fluxes be invariant under the symmetry. Since the large population of the landscape arises from the many possible values of many fluxes, there is potentially a large price to be paid for symmetries.

A symmetry of the orientifold theory is $z_4 \to e^{\frac{2\pi i}{3}} z_4$. Invariant fluxes are paired with polynomial deformations linear in z_4. There are 55 such polynomials, i.e. about 1/3.

Surveying numerous models and many symmetries, we have found no examples in which 1/2 or more of the fluxes are invariant. The model $WCP^4_{1,1,1,6,9}[18]$ is particularly interesting, since it has the largest $h_{2,1}$ in this class.

Breaking R Symmetries

Call X_i, $i = 1, \dots N$, those moduli which transform like the superpotential under R symmetries. Denoting the other fields by ϕ_α $\alpha = 1, \dots P$, The superpotential has the form:

$$W = \sum_{i=1}^{N} X_i f_i(\phi_\alpha) \tag{4}$$

If $N \leq P$, then provided that the f_i's are reasonably generic functions, the equations $f_i = 0$ have solutions, so there are vacua with $X_i = f_i = 0$, and supersymmetry and the R symmetry are unbroken. For $WCP^4_{1,1,1,6,9}$[18] N=55. $P = 217$.

If one does find vacua with N close to $h_{2,1}$, so that there might not be a huge suppression, *supersymmetry typically will be broken; R symmetry may or may not be broken*. Unbroken R symmetry requires that all X_i's have positive curvature near the origin ($1/2^N$?) This situation, if it occurs, might be relevant to the ideas of split supersymmetry, which we discuss further below.

Lessons

- Symmetries can be found in the landscape

- Symmetries are costly; these examples suggest that typically L^{b_o} states $\to L^{b_o/3}$ states ($10^{300} \to 10^{100}$).

- In the presence of R symmetries, at the level of semiclassical analysis, there are typically continuous sets of states with unbroken supersymmetry and R symmetry.

Conclusions

Naturalness may well play a role in the landscape.

- Cosmological constant

- M_{higgs}/M_p – need to know if vastly more non-susy than susy states. Some evidence here that answer might be no. Intermediate scale branch seems most plausible based on what we now know.

- θ_{qcd} – a problem which may have a solution, but against which the landscape may fail.

- Fermion mass hierarchy – there are discrete symmetries, but they are expensive. The pattern of quark and lepton masses is again an area where the landscape might fail.

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