The string landscape and low energy supersymmetry

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Abstract

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Outline

String theory, considered as a fundamental theory of nature, should someday make a prediction for such a basic question as low energy supersymmetry – meaning, will a given experiment (say LHC at 14 TeV) see superpartners. Let us refer to this type of prediction as "susy."

In our present state of understanding it seems fair to say that string theory fits well with susy, but does not require it. Compactifications have been constructed which agree with the data so far and predict susy, to the extent that we can check them – this includes superpartner masses in a reasonable approximation and even patterns of Yukawa couplings. On the other hand, there is no clear obstacle to constructing very similar compactifications with higher supersymmetry breaking scales, and with tuning to get a small Higgs. We will sketch these arguments in the talk.

Thus, if our definition of a prediction requires that falsifying the prediction should falsify the theory without any additional assumptions, string theory appears to make no prediction about susy.

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In this talk we will explain a – somewhat long range – program for making stronger predictions, and at least sketch a way that the prediction could go. This requires making additional assumptions.

Ours are the framework of the string landscape:

- Our general framework for compactification is a good guide to the possibilities, and what we think are vacua (choice of extra dimensions, branes, fluxes, metastable scalar field values) are each candidates to describe our universe.

- Metastability of these vacua can be determined by looking at the effective potential.

- There is a phase of very early cosmology in which all of the different vacua are created with different probabilities. Some of these undergo inflation and exit it in a way which is described by our usual slow-roll models, and which can reproduce cosmological observations.

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- There is a phase of very early cosmology in which all of the different vacua are created with different probabilities. Some of these undergo inflation and exit it in a way which is described by our usual slow-roll models, and which can reproduce cosmological observations.

- There are many hidden choices, particularly of flux, which can be varied to turn more or less "any" vacuum into one whose cosmological constant is of the observed small magnitude. Anthropic selection then explains why the cosmological constant is small.

- Similarly, other observables need not come out right in all vacua, but they should come out right in the most probable anthropically selected vacua.

Thus, to make predictions, we need to

1. Understand the measure factor produced by very early cosmology.

2. Understand the set of string vacua which might have significant probabilities to be produced, and work out their observable predictions.

3. Take some position on what "anthropically allowed" means.

There is a candidate answer for (1), steady progress on (2), and a great deal has been written about (3) - see for example Bert Schellekens' recent review.

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Although the problem of the measure factor is by no means solved (see Freivogel's 1105.0244), there is a candidate answer which is not obviously wrong, the "dominant" or "master" vacuum ansatz:

The measure factor is overwhelmingly dominated by the "master vacuum," which is the longest lived metastable de Sitter vacuum. For other vacua, it is given by the tunnelling rate from the master vacuum, which to a good approximation is that of the single fastest chain of tunnelling events.

This was argued in various works, starting with Schwarz-Perlov and Vilenkin hep-th/0601162, from the more general framework of eternal inflation. The idea is that the dynamics of eternal inflation is described by a Markov chain, and given enough time such a chain will find the largest eigenvector of the matrix of tunnelling rates. The dominant factor in this eigenvector is the inverse tunnelling rate; it turns out that the others cancel out.

To find the master vacuum, we need some general picture of the string vacua with positive vacuum energy. Hopefully this is familiar, at least in outline, to this audience. There is no evidence that such vacua exist in dimensions greater than four, and in $D = 4$ there is some reason (stability) to think that the metastable vacua have spontaneously broken $N = 1$ supersymmetry at scales somewhat below the string/Planck/KK scales. We thus need to look at heterotic string and type II with branes on Calabi-Yau, M theory on G_2, and F theory on fourfolds. We can then use much developed technology to compute the nonperturbative effective potential.

KKLT argued that, if a local minimum has any barrier to tunneling to large volume, this decay rate will be negligible. Furthermore, it is not hard to arrange a barrier, by adding two or three nonperturbative effects.

The most important tunneling processes are probably to nearby vacua, meaning to those which were nearby on the moduli space (before supersymmetry breaking), and those connected by changing one flux or making one extremal transition. In any case, tunnelling from almost supersymmetric vacua is highly suppressed, see Dine, Festuccia and Morisse 0901.1169. Generically one expects

$$\Gamma \sim \exp -\beta \frac{M_{Pl}^2}{M_{3/2}^2}. \tag{1}$$

Furthermore, given many fluxes, one expects to be able to tune Λ to a far better accuracy than $M_{3/2}$. This suggests that

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Because supersymmetry breaking is additive,

$$M_{susy}^4 = \sum |F|^2 + \sum |D|^2, \tag{2}$$

finding the vacuum with the smallest M_{susy} is a relatively tractable problem. Both in nonperturbatively generated effective potentials, and in their duals as flux vacua, the general behavior is $V \sim \exp{-\frac{1}{g^2 N}}$. Thus one is trying to find gauge theories with a small stabilized gauge coupling. In IIb flux vacua, and on general grounds, gauge couplings will be fixed)in some approximation) to ratios of fluxes:

$$V \sim \exp{-\frac{L}{g_s^2 M}}. \tag{3}$$

Thus, one expects to find the smallest supersymmetry breaking in the compactifications which allow the largest flux values L, M.

Now, the number of flux vacua (putting a bound on the KK scale) is finite, and the sizes of the fluxes are bounded by topological conditions. In IIb with flux and F theory, one has

$$N_{NS} \cdot N_{RR} + N_{D3} = \frac{\chi}{24} \tag{4}$$

where χ is the Euler number of the fourfold. Thus, one wants manifolds with large Euler number.

In fact there is a fourfold with largest known Euler number $\chi = 24 \cdot 75852$, which can be realized as a hypersurface in weighted projective space. This manifold might realize hierarchies and supersymmetry breaking scales 10^{-1000} or even 10^{-10000}. In any case there should be a minimum, somewhere on the moduli space of these manifolds, with some branes and fluxes.

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Presumably this vacuum is not anthropically allowed, so we are looking for some anthropically allowed vacuum with a reasonable tunnelling rate from this one. Actually, the potential barriers on the pseudomoduli space of the master vacuum CY are so small that we might need to think about dynamics on this space. We might have some probability distribution on this space, and the final measure factor would be a product of this distribution with the subsequent tunnelling rates.

Now, although the master vacuum itself is not anthropically allowed, it is plausible that it contains matter sectors which look a lot like the Standard Model. It is known (Candelas *et al* hep-th/9704097) that this CY admits an F theory vacuum with a gauge group of rank 60740, including 1276 E_8 factors. These gauge factors come from intersecting groups of D7-branes (in IIb language) or intersecting divisors (in F theory langauge) and are grouped together into "clusters" of intersecting cycles.

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As shown by Donagi and Wijnholt, Beasley Heckman and Vafa, and others, such clusters can lead to local models with Standard Model matter content and unified gauge couplings. Later work, particularly by the Munich group, showed that these are generic and not hard to embed in fourfolds.

Supersymmetry breaking would be driven by a single cluster, with no relation to the SM cluster.

The allowed clusters include the local models based on del Pezzo surfaces used in the existing F theory work, and probably others based on Fano and other threefolds. Although the list is not known in $D = 4$, it was recently worked out in $D = 6$ in Morrison and Taylor 1201.1943. The basic clusters are gauge theories with matter which cannot be Higgsed, for example $SU(2) \times SO(7) \times SU(2)$ with half-hypermultiplets in the $(2, 8, 1) \oplus (1, 8, 2)$, or E_8 with no matter. There should be a similar finite list of fibration singularities which cannot be resolved in $D = 4$ (D. Morrison, private communication).

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What kind of dynamics would lead from a configuration with a very small supersymmetry breaking scale and a matter content with sectors "somewhat like" the Standard Model, to a realistic supersymmetric Standard Model ?

Clearly this is a complicated problem, and we need simplified pictures to think about it. One simplified picture is to think of clusters of cycles moving in the extra dimensions, undergoing internal transitions (change of flux and moduli) and possibly joining and splitting with each other (by gaining massless vector-like matter and vevs). The picture is somewhat like "molecules" moving in the extra dimensions and thus one might call this "hyperchemistry."

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In such a picture, it seems likely that the transition from the master vacuum to a realistic vacuum would involve two steps. First, internal transitions in the supersymmetry breaking cluster would change the supersymmetry breaking scale. Second, it would move "close to" (*i.e.* with large coupling to) the SM cluster.

In the master vacuum, supersymmetry breaking originates in a hidden sector, and is communicated elsewhere gravitationally. In the vacua we obtain by tunnelling, it is possible for other clusters to move to intersect the SSB cluster, leading to light vector-like mediating matter, *i.e.* gauge mediation.

However, this is continuously connected to the original gravitational mediation. In this sense, it is tuned. Unless it comes with some major advantage over gravity mediation, it is disfavored for this reason.

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In gravity mediated models coming from string theory, the cosmological moduli problem is essentially universal. All known constructions have moduli and cosmological considerations force these to have mass $M \gtrsim 30$ TeV.

Furthermore, very generally a model with broken $N = 1$ supersymmetry will have a scalar at $M \lesssim M_{3/2}$. This is a simple calculation in supergravity – the only loophole is that there is an additional contribution from a quartic term in the Kähler potential which geometrically has to do with the sectional curvature on moduli space. For actual moduli this will have a string scale coefficient and be small.

Certainly, all such arguments (that I know about) have loopholes and admit exceptions. But, in the landscape, that does not make the exceptions preferred. One must compare the measure of the different possibilities. Doing this requires a qualitative picture of the measure factor.

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- Positive predictions from string theory will come from learning about **naturalness on theory space**. We are used to naturalness in parameter space and string theory will probably not change this much. But we do not know which matter contents and discrete symmetries are natural. String theory should tell us.

- To make predictions in the landscape we need both vacuum distribution and a measure factor. Both problems have little or no direct relation to the dynamics at the electroweak scale, and thus naturalness in theory space does not follow from bottom-up thinking.

- A very simplified picture leads to the natural theories being preferred "clusters" which include the known local models in F theory and probably a few more models.

- There are many hidden sectors for supersymmetry breaking. Gravitational mediation and gauge mediation by vectorlike matter are continuously connected. In this sense, gauge mediation is tuned. Unless it comes with some compensating advantage, one expects gravity mediation.

- String vacua generically have moduli. Indeed, any broken $N = 1$ theory is expected to have scalars at the scale $M_{3/2}$, partner to the goldstino. In gravity mediated models these are necessarily moduli.

- Thus, the cosmological moduli problem is a very serious constraint. Solving it and the related problems of cosmology and stability in models with many scalars seem difficult.

- The easy solution is to push the scalar masses up – thus we are led to split supersymmetry and related models in which supersymmetry solves the large hierarchy problem, giving us a natural mass scale of $30 - 100$ TeV, and then a relatively small tuning makes the Higgs light.

The upshot is that the scenario with $30 - 100$ TeV supersymmetry is not very tuned, of order 10^{-5} or so, and all the alternatives seem to require postulating compicated matter content and other structures. Thus, we need to quantify the naturalness of such postulates, to judge what string theory favors. This is what we have referred to as "naturalness on theory space" and it is the main output we want from a picture of the string landscape.

Granting this scenario, the most pressing question for phenomenology is whether the gauginos are light. This is more model dependent and one also wants to know more about naturalness on theory space. The overall conclusion is that with many assumptions, we can make qualitative pictures of the landscape which lead to tentative predictions, and hope to justify and improve them in subsequent work.

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