The string theory landscape

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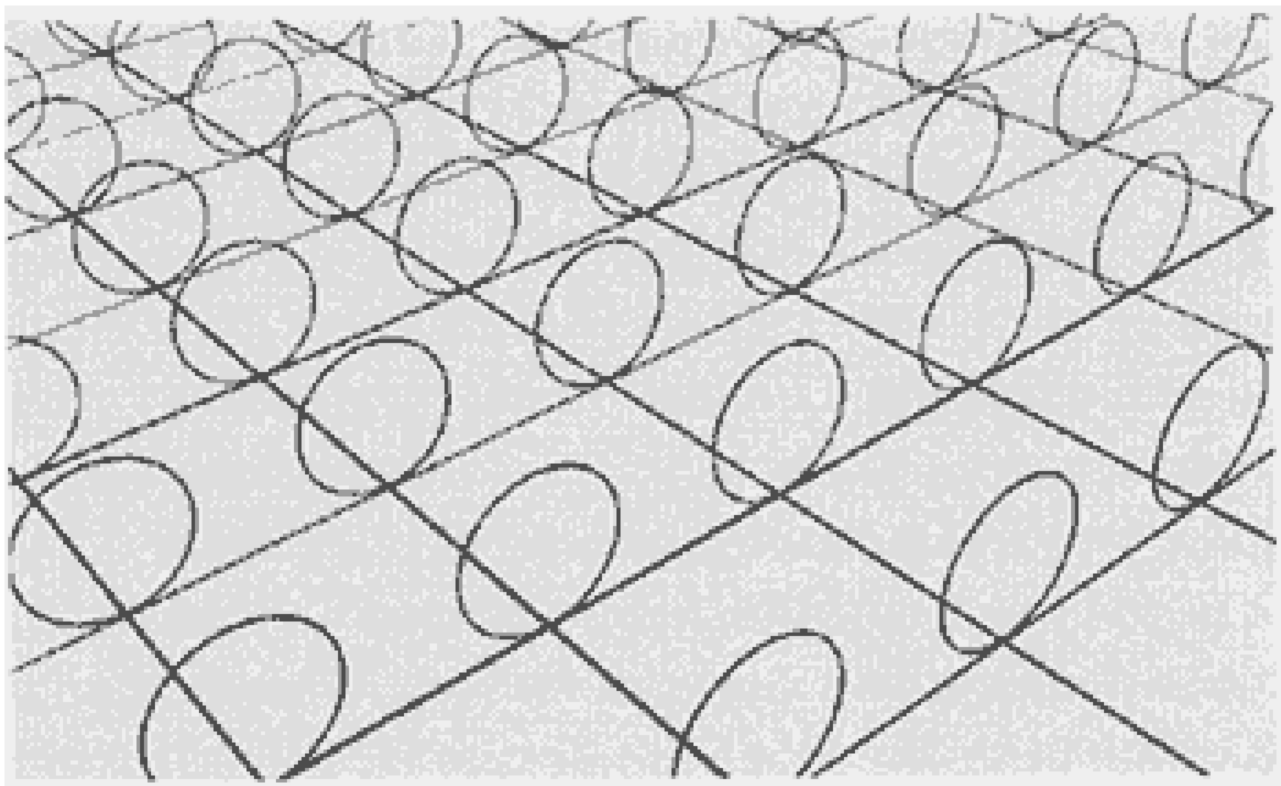
It is an old idea that extra space-time dimensions may be tied in an important way to a unified description of the fundamental forces. Already in the 1920s, Kaluza and Klein developed a theory based on a geometrical picture where, above each point in our 3+1 dimensional (approximately) Minkowski spacetime, there is an extra 5th dimension: a circle of some radius R.



In the mid 1980s, Green and Schwarz (building on work of many others as well) found that superstring theories are a very promising candidate for such a higher-dimensional unified theory. These theories were found to have two remarkable properties:

1) While in naive quantization of general relativity, one gets a non-normalizable theory whose scattering amplitudes diverge as powers of

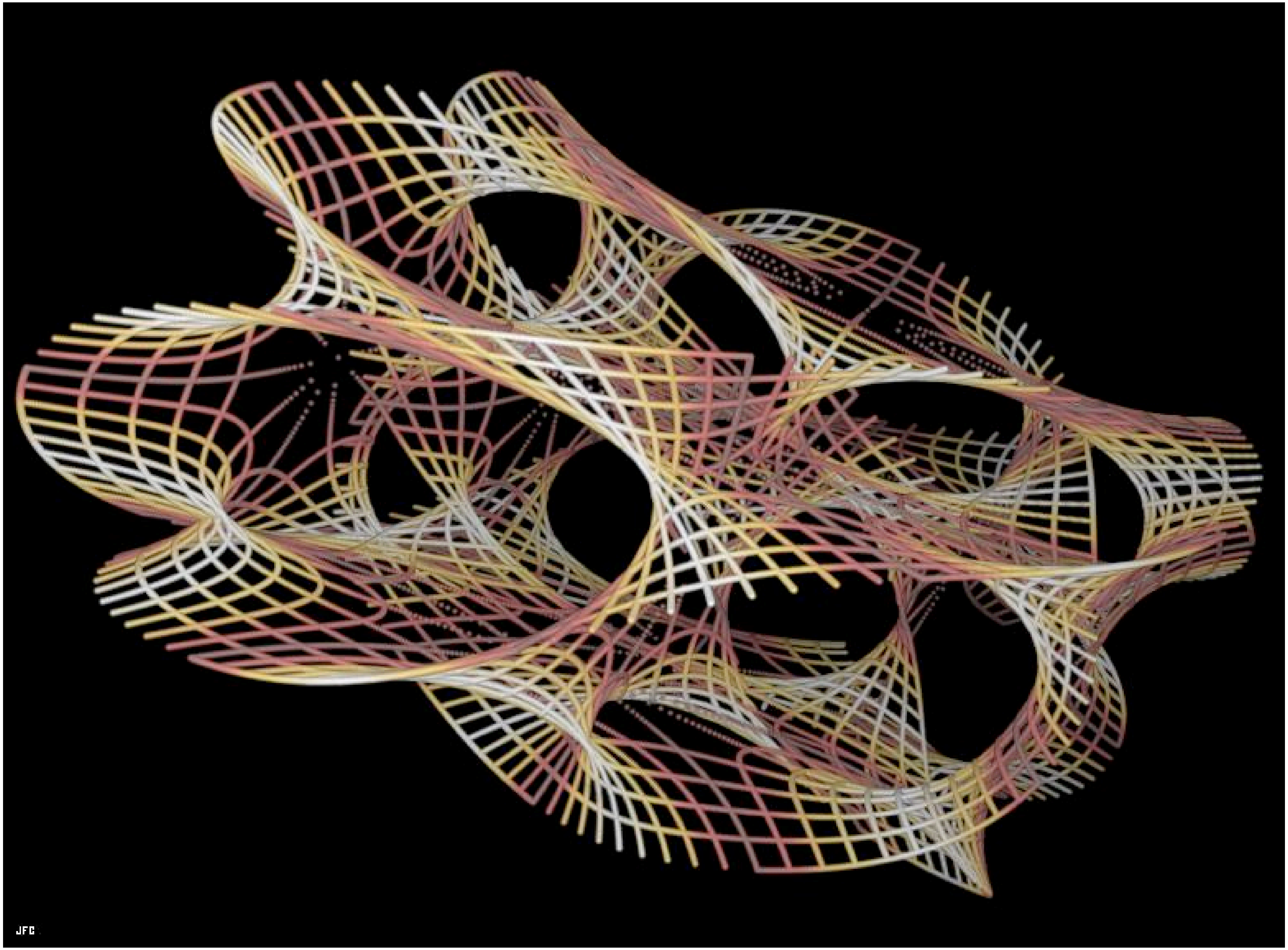
$$G_N E^2$$

at high energy, in string theory the extended nature of the string softens the high energy scattering, yielding a theory with good ultraviolet behavior.

2) Simple versions of the theory have naturally massless (or very light, compared to Planck scale) Yang-Mills fields. Simple string models can accommodate the observed SU(3) x SU(2) x U(1) of the Standard Model.

The theories which were studied intensively in this period naturally live in 9+1 dimensions, and are closely related to the maximally supersymmetric supergravities in 10 dimensions. However, it was found by Candelas, Horowitz, Strominger and Witten that compactifications of these theories to four dimensions, e.g. on Calabi-Yau manifolds (Ricci flat 6d spaces which preserve 1/4 of the 10d supersymmetry), could also easily give rise to generations of chiral fermions in the appropriate Standard Model representations.

The Calabi-Yau spaces are topologically complicated objects:



The number of generations of chiral fermions was tied to the topology of the Calabi-Yau space M. For instance

$$N_{gen} = \frac{1}{2}|\chi(M)|$$

More generally, in string compactification from 10d to 4d on a space M, physical observables in 4d are tied to the topological and geometrical properties of M.

These earliest string models enjoyed exact 4d N=1 supersymmetry, and exactly vanishing vacuum energy. They also typically came with dozens or hundreds of scalar moduli fields.

In recent years, there has been significant progress in improving on the realism of similar string compactifications. Much of the recent work has been driven by:

1) The quest to make realistic string models which incorporate supersymmetry breaking.
2) The desire to incorporate realistic models of inflation into string theory.
3) The need for finding to what extent string theory can accomodate or explain the tiny but non-vanishing and positive dark energy which is dominating the energy density of the Universe today.

I'll give a (undoubtedly personal and idiosyncratic) description of some of the work on 1) and 3).

Fixing the moduli fields of string compactification

To understand the nature and existence of moduli fields, we can return to the old Kaluza-Klein model. If spacetime has an additional circle of radius R, then the metric takes the form:

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + R^2 dx_5^2$$

In addition to the spacetime metric of general relativity, $g_{\mu\nu}$ there are also metric components $g_{\mu 5}$ and g_{55} which appear in the 4d physics as a vector field (the photon!) and an additional massless scalar field (the "radion"). The radion is basically the scalar degree of freedom that allows the radius of the extra circle R to vary as a nontrivial function R(x) over the Minkowski dimensions.

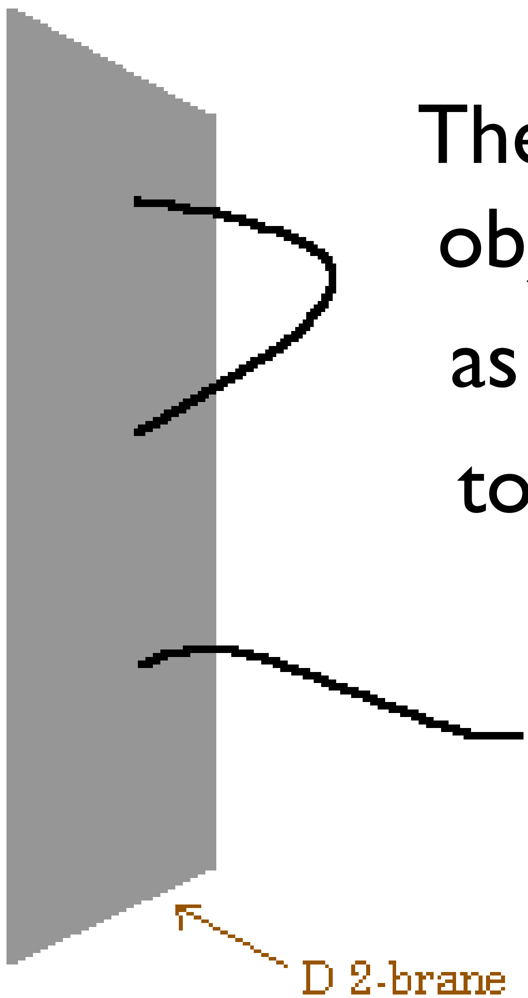
Any constant R solves the equations of motion. Therefore, there is a massless and spinless long distance excitation, a scalar field, whose long wavelength modes cost very little energy to excite.

In the Calabi-Yau spaces I mentioned before, the metric comes not with one modulus but with a multidimensional "moduli space" of Ricci-flat metrics. In typical examples, this is a space with dozens or hundreds of dimensions. Needless to say, physical models which predict the existence of dozens or hundreds of light scalar fields are in gross contradiction with a variety of experiments (fifth force, equivalence principle tests, etc.).

Branes, fluxes and moduli potentials

It was realized in the mid 1990s that string theory contains extended objects other than strings, whose dynamics can be be tremendously important:

Polchinski



These are the Dp-branes, p dimensional objects on which strings can end. Just as an electron is stable due to its coupling to the electromagnetic field

$$\int_{worldline} A_\mu \frac{dx^\mu}{dt}$$

a Dp-brane is stabilized by its coupling to a generalized gauge field with p+1 indices:

$$\int_{worldvolume} A_{\mu_1 \ldots \mu_{p+1}}$$

And just as the vector potential of electromagnetism has a field strength F = dA, these generalized gauge fields come with generalized gauge field strengths:

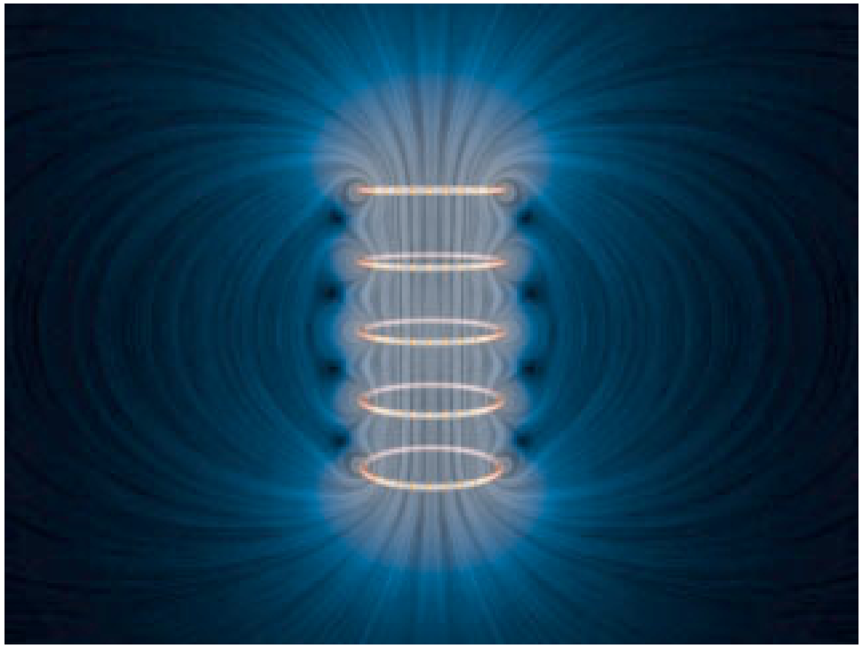
$$F_{p+2} = dA_{p+1}$$

In addition, there is a two-index gauge field B with field strength H, that explains stability of closed strings themselves.

Given these field strengths, one can easily imagine threading cycles in the compactification manifold M by magnetic gauge fluxes. It was realized in the late 1990s that in generic classes of models, one is even required to introduce such fluxes, to satisfy Gauss' law on the compact space:

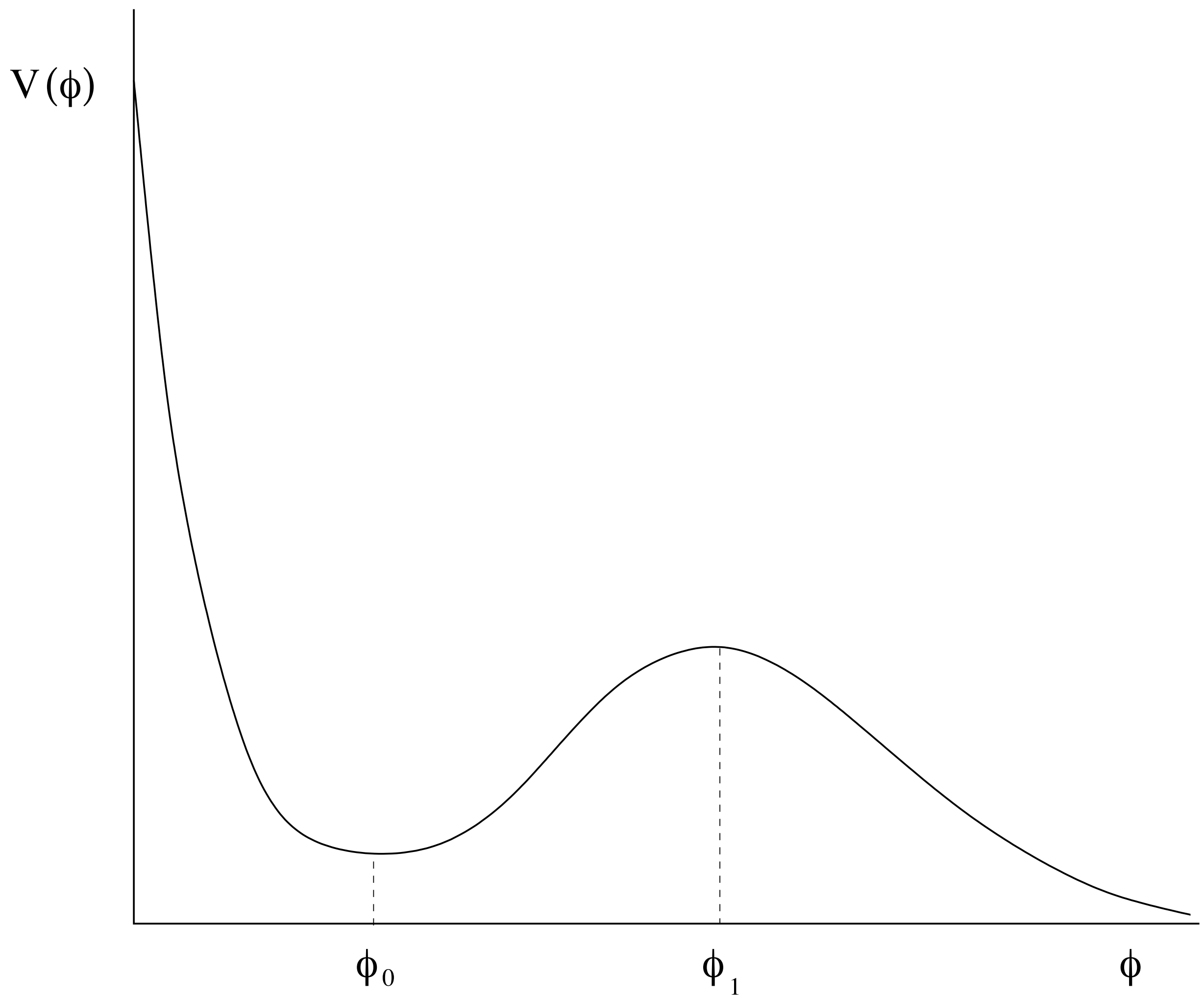
Becker, Becker; Sethi, Vafa, Witten

$$\int_M dF_5 = N_{D3} + \int_M H_3 \wedge F_3 - \chi(X_4) = 0$$



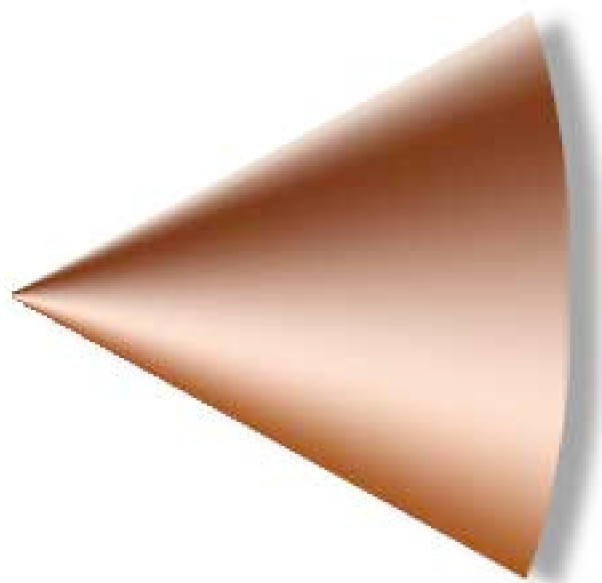
The backreaction of fluxes generates potentials on "moduli space"

Gukov, Vafa, Witten



In many simple cases, one can explicitly see what the flux backreaction does to the geometry of the extra dimensions. For instance, in the simplest nontrivial noncompact Calabi-Yau space, the conifold:

$$x^2 + y^2 + z^2 + w^2 = 0$$



turning on garden variety three-form fluxes produces a space-time with a highly warped metric:

$$ds^2 = (\frac{r^2}{R^2})\eta_{\mu\nu}dx^\mu dx^\nu + (\frac{R^2}{r^2})(dr^2 + r^2 dS^2_{T^{1,1}})$$

Here, the notation is as follows. There are two different submanifolds A, B in the conical geometry that can be threaded with a three-form flux. Imagine that

$$\int_A F_3 = M, \quad \int_B H_3 = K$$

Defining N=KM, the radius of curvature of this AdS-like spacetime is

$$R^4 \sim g_s N \ l_s^4$$

The radial coordinate "r" varies over an exponentially large range of values. In a precisely conical geometry it would in fact run down to zero, but the fluxes deform the tip of the cone so it rounds off smoothly:

Klebanov, Strassler

The minimal value of r where the smooth end occurs is naturally exponentially small (for O(1) choices of the flux quanta), and hence the warping of the geometry is naturally exponentially large:

$$r_{min} \sim \mathrm{Exp}(-\frac{2\pi K}{3 g_s M})$$

This gravity solution has a dual interpretation via Maldacena's AdS/CFT duality.

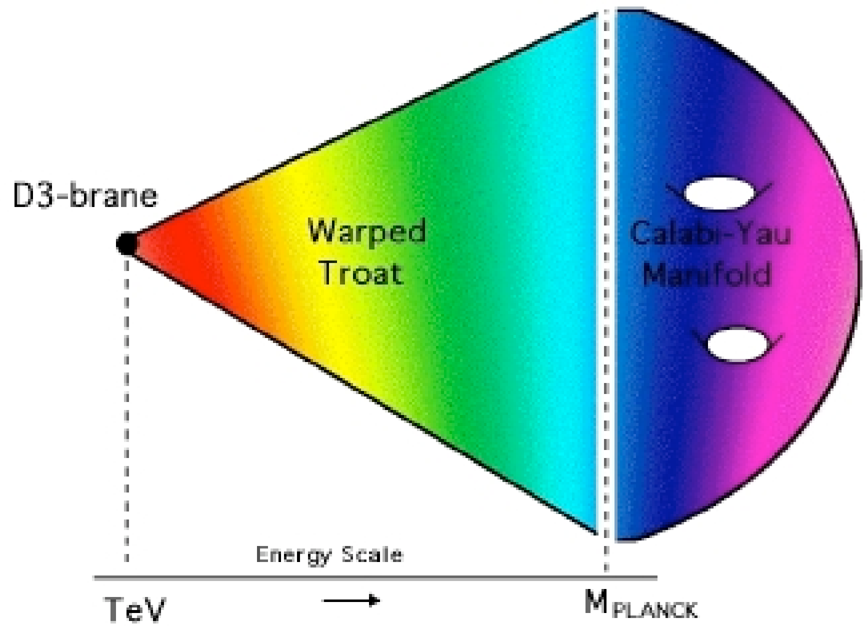
* The gravitational system is dual to a strongly coupled 4d N=1 supersymmetric Yang-Mills theory.

* The long "AdS throat" exists because this field theory is very close to being conformally invariant over a wide range of scales. Different values of the warp factor characterize different energy scales.

* The smooth end with a minimal warp factor, represents the fact that the deep infrared behavior of this field theory has confinement and a mass gap (somewhat similar to real world QCD).

While the precise duality applies to the noncompact Calabi-Yau with flux, one can also construct string solutions where the extra dimensions are compact, but are well modeled in some neighborhood by the noncompact "warped conifold" solution.

Giddings, Kachru, Polchinski



In such models, the flux-generated potential on the moduli space, allows one to give the Calabi-Yau moduli a large mass -- roughly l_s^2/R^3

Such warped compactifications are a rich arena for building models of particle physics and cosmology:

* One can construct the Standard Model on D-branes localized at the region of small warp factor. The warping can then explain the hierarchy between the weak and Planck scales, as suggested by Randall and Sundrum.

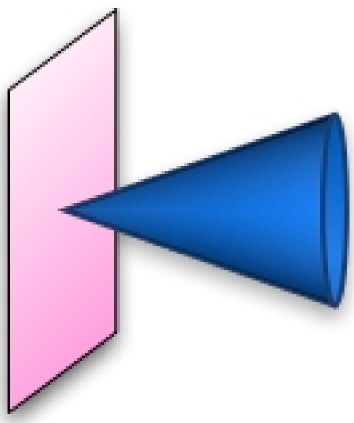
* Alternatively, one can construct novel models of metastable supersymmetry breaking, by considering states with anti-D3 branes at the warped tip of the geometry.

Kachru, Pearson, Verlinde

These states can decay by a tunneling process to supersymmetric states in the same geometry, but the rate is exponentially suppressed when the gravity solution is weakly curved.

Similar metastable states have recently been found in simple supersymmetric quantum field theories (like supersymmetric QCD).

Intriligator, Seiberg, Shih



One can obtain these field theories on the worldvolumes of D-branes at simple Calabi-Yau singularities, providing another source of metastable SUSY breaking in string theory.

Ooguri, Ookouchi; Franco, Uranga; Argurio, Bertolini, Franco, Kachru

One current focus of research is to use such supersymmetry breaking sectors to produce realistic models where SUSY breaking is mediated (via gauge mediation or anomaly mediation) to the MSSM or a simple extension. Constructions of MSSM-like theories on branes have been attained by several groups.

Blumenhagen, Cvetic, Ibanez, Shiu, Uranga, Verlinde, Wijnholt...

The landscape and the cosmological constant

Current understanding (based on constructions of the sort I've described, and many others) suggests that string theory has a large collection of consistent, metastable, non-supersymmetric vacua.

This was anticipated in a remarkable paper of Bousso and Polchinski.

* Consider a compactification with N possible cycles that can be threaded by (Dirac quantized) flux

$$\int_{C_i} F = n_i$$

* We can crudely model the Gauss' law constraint, which restricts possible flux choices, by an equation of the form

$$\sum_i n_i^2 \leq L$$

Then one can estimate the number of local minima in the flux potential (under the assumption that there is O(1) vacuum per flux choice), by just counting the number of integral lattice points inside an N-1 dimensional sphere.

Expected number of vacua:

$$N_{vac} \sim L^{N-1}$$

One furthermore expects a distribution of vacuum energies (since the energy varies with the flux choice). For reasonable numbers in real string models, where

$$L \sim 10^2 - 10^3, \;\; N \sim 20 - 300$$

the large number of vacua combined with the expected spread in vacuum energies, strongly suggests that some of the vacua will have vacuum energy

$$\Lambda << M_{SUSY}^4$$

This is interesting for two reasons:

1) It means that string theory contains metastable vacua with very small positive cosmological constant, though they are rare and hard to find explicitly.

2) It opens up the possibility (failing discovery of a dynamical explanation), of an anthropic interpretation of the observed vacuum energy, along the lines of Weinberg's argument.

Subsequent research has confirmed many of the expectations of the Bousso-Polchinski paper:

* Flux compactifications with stabilized moduli and positive vacuum energy have been constructed. The first constructions (due to Silverstein) were in a supercritical string framework with string scale SUSY breaking. The KKLT paper gave constructions in a low-energy supersymmetric, critical string framework. Since 2003 intense effort has gone into solidifying and generalizing such constructions.

This set of vacua is colloquially known as the string landscape.

Susskind

* Statistical studies of the landscape have been carried out (most notably by Douglas and Denef). They confirm that vacua with small CC should be attainable,but also provide new detailed insights.

* One of the most interesting questions is: do we expect high or low scale of SUSY breaking? Constructions with KK and string scale SUSY breaking exist. It is a priori possible that such high scale breaking is favored, and naive vacuum counting would probably support this idea.

Silverstein; Susskind; Douglas; Dine

* The cosmology of the landscape is governed by eternal inflation. Serious studies of whether and how this can lead to selection among the different vacua are presently under way, though the subject is notoriously confusing.

Bousso, Guth, Linde, Shenker, Susskind, Vilenkin

Most imporantly, the studies of string vacua that culminated in the discovery of the string landscape, have also suggested many new and testable model building ideas. These include:

* split supersymmetry

Arkani-Hamed, Dimopoulos; Giudice, Romanino

* low tension networks of cosmic (super)strings created after exit from D-brane inflation

Sarangi, Tye; Copeland, Myers, Polchinski

* models with strikingly characteristic and measurable CMB bispectrum ("f_{NL}")

Silverstein, Tong

I am optimistic that the data from LHC, Planck, and other near term experiments will give us big hints about which classes of models to focus on!