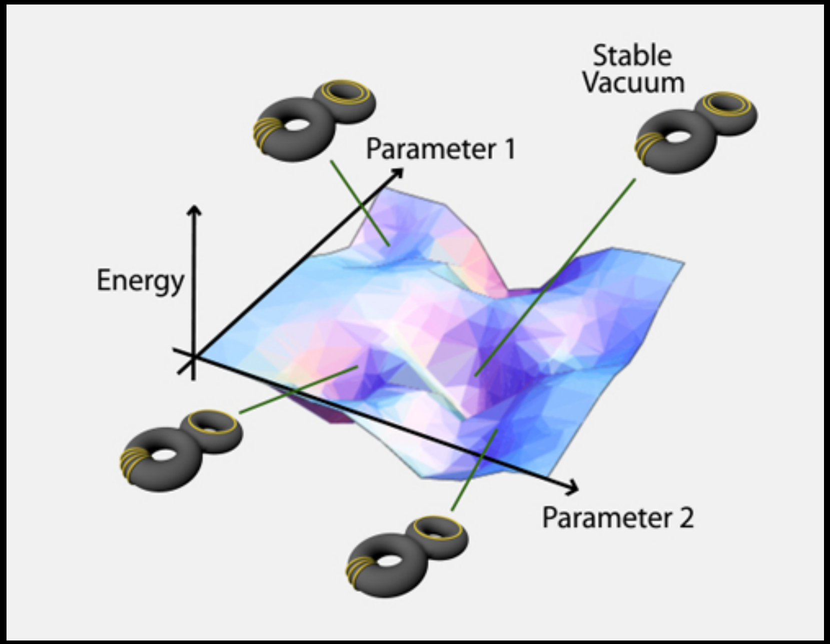
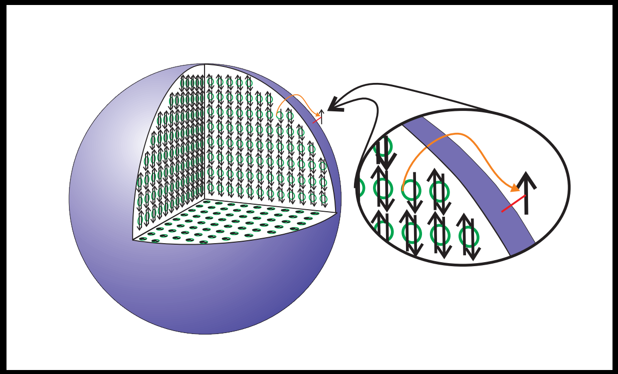
Joe and the large scale structure of space-time

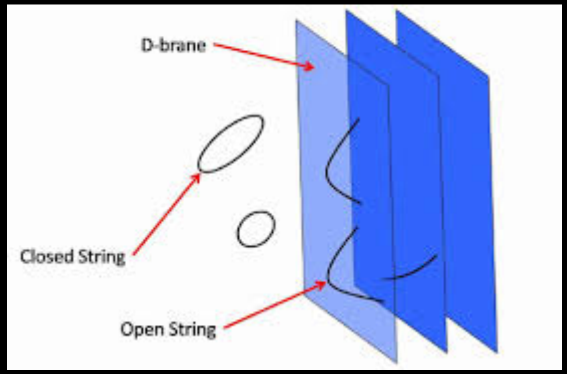


Shamit Kachru
(Stanford)

1. Introduction

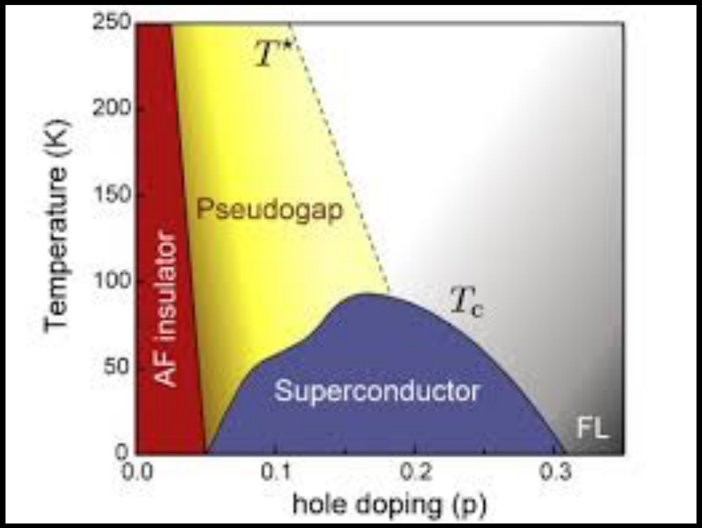
Today, I am going to talk about some of Joe's profound contributions to our thinking about string theory vacua, and some recent work I've done on that subject.





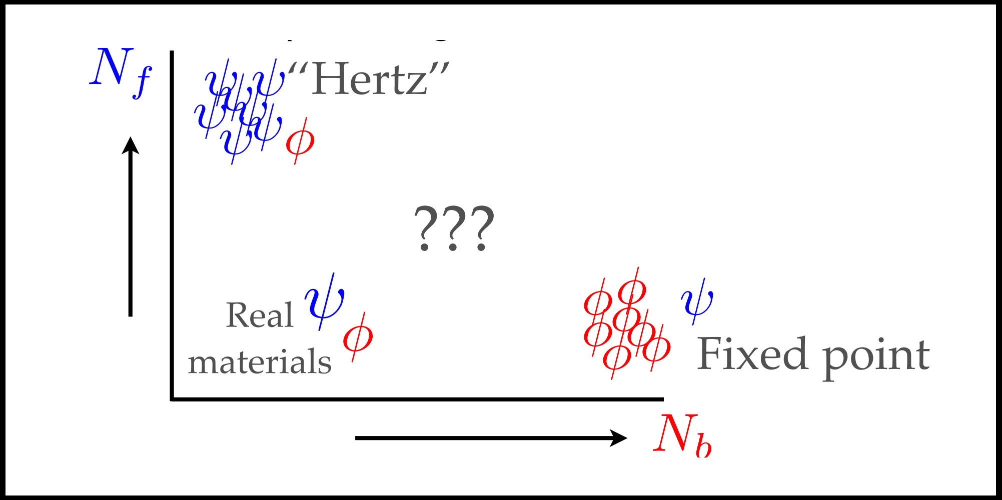
But I'd like to begin by briefly describing Joe's impact on my thinking about physics more generally.

The first work of Joe's that I encountered was at TASI 1992. 2d gravity was all the rage then, and Joe had done central work on the subject.



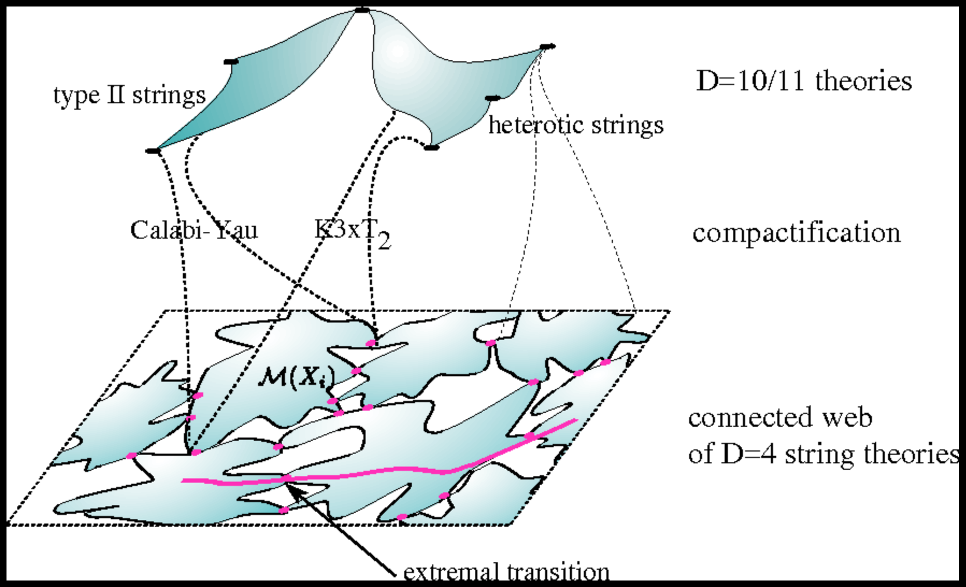
But he talked instead about non-Fermi liquids. He joked that if he could solve high Tc, he would get a fancy chair (like Weinberg's).

High Tc remained unsolved, but Joe did get his well deserved fancy chair, and more.



Years later, by about 2013, I was mature enough to start appreciating this subject, and did some work of my own on non-Fermi liquids. Joe's thinking was a central guide. (By then, he had moved on to the paradoxes of black hole physics).

As for all of us, another guiding piece of Polchinski-ology was the discovery of D-branes.



These first changed my work and life in 1995, and have played a starring role since.

I could go on and on (his take on the RG, on singularities, on holography, on …).

But let me transition at this point to my talk proper, and discuss Joe's work on string compactification.

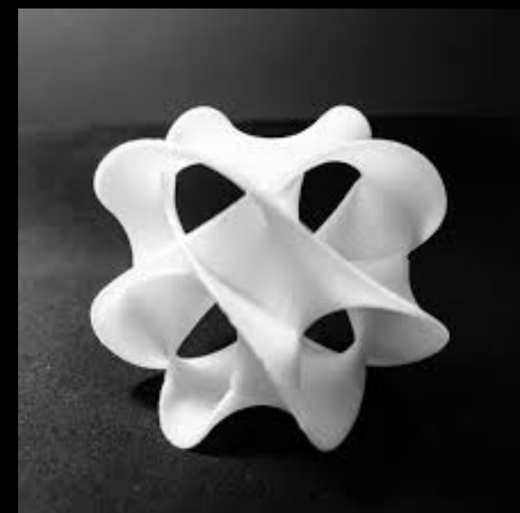
II. The string landscape

Joe wrote many technical papers on string compactification.

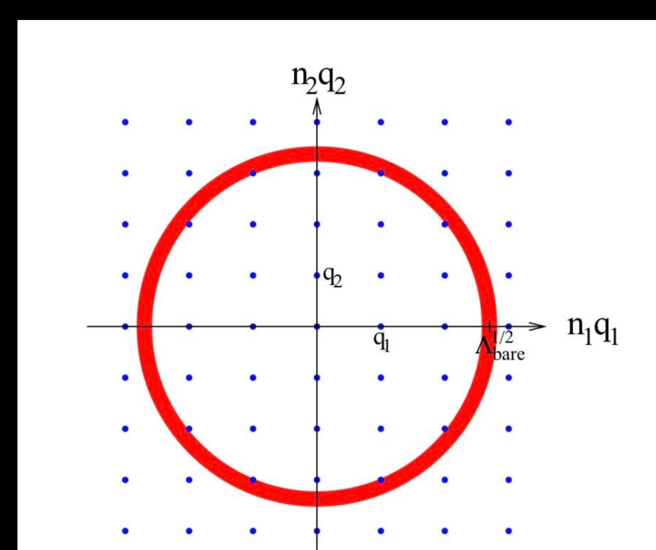
$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2\kappa_4^2} R - \lambda_{\rm bare} - \frac{Z}{48} F_4^2 \right) + S_{\rm branes}$$

His crucial insight with Bousso is very simple.

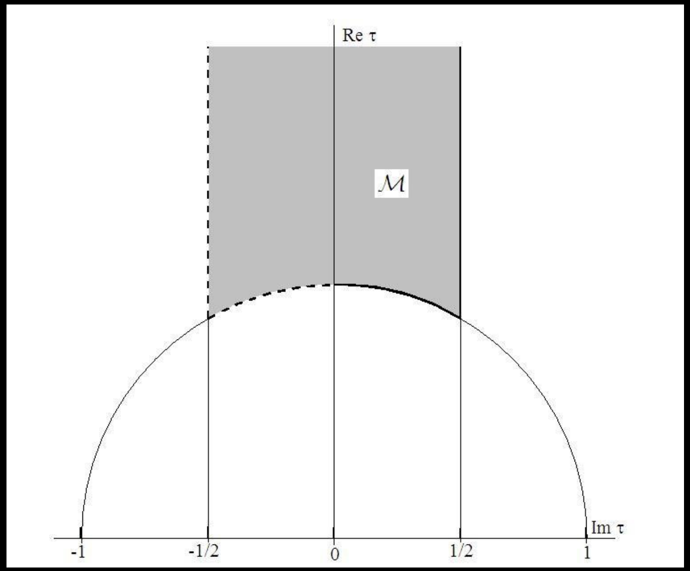
The extra dimensions are a complicated place:



With fluxes contributing incommensurately to the energy, one can tune the cosmological constant.

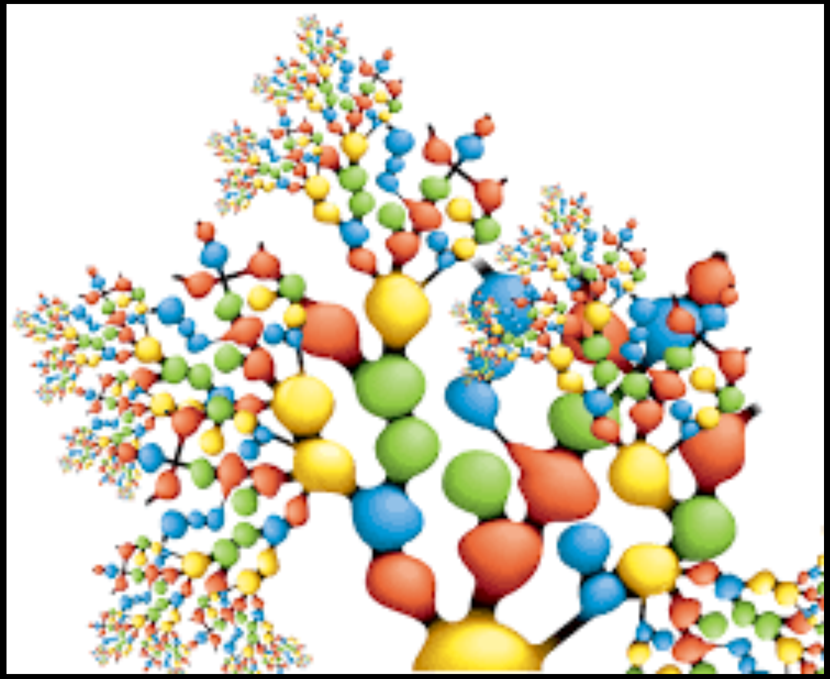


Under mild assumptions, Bousso-Polchinski argued that starting with a bare negative c.c. and considering a model with ~100s of distinct cycles threaded by flux, one could fine tune the vacuum energy to attain very small positive values. In their toy model.



Their toy model neglected the problem of treating the moduli.

Putting that aside for a moment, their work gave us a qualitative picture of the Universe on large scales governed by eternal inflation + bubble nucleation….



…in keeping with the same (admittedly, imprecise) pictures coming out of studies of inflationary theory.

But: turning on fluxes in string theory backreacts on moduli, and unless one is careful, one either:

— decompactifies
— ends up in AdS

Many of us focused on this in the KITP workshop “Avatars of M theory” in 2001.




Result for me: work with Giddings, Polchinski; Pearson, Verlinde; + initiation of collaboration with Trivedi

III. String compactifications with flux

One starting point was IIb string theory compactification on orientifold of a Calabi-Yau manifold.

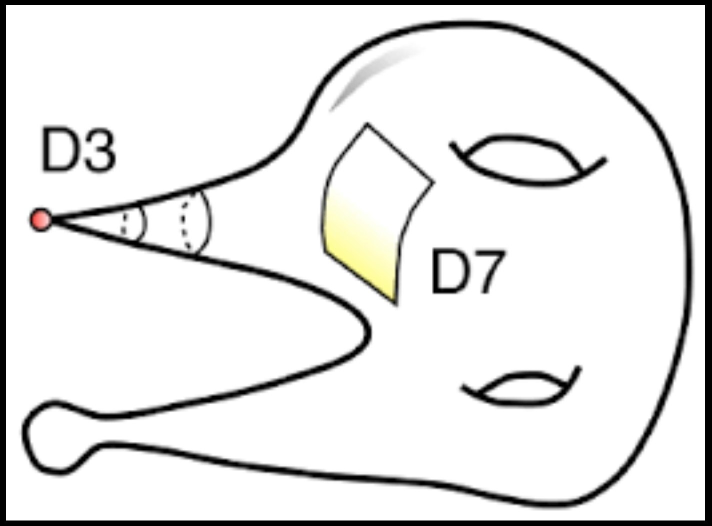
$$W = \int G_3 \wedge \Omega$$

$$\Omega = F_3 - \tau H_3$$

$$K = -3\log(-i(\rho - \bar{\rho})) + \log(-i\int \Omega \wedge \bar{\Omega})$$

Tree level supergravity: “no-scale structure” (includes O-planes; crucial!)

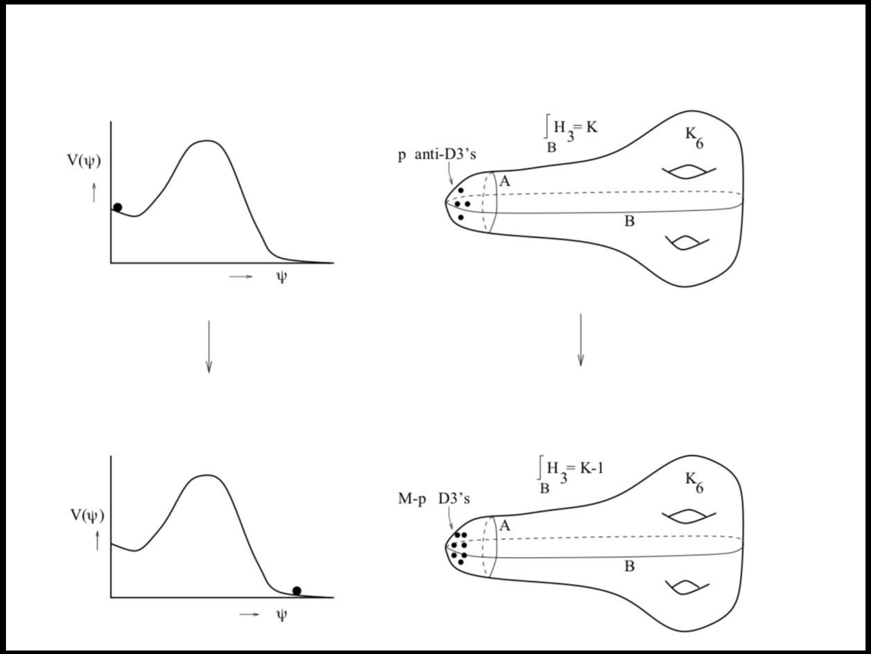
result: (highly) warped flux vacua, V = 0



The picture after GKP was a low-energy effective theory of the volume modulus.

Dynamics on branes could lead to further interesting dynamics.

One very interesting variant:



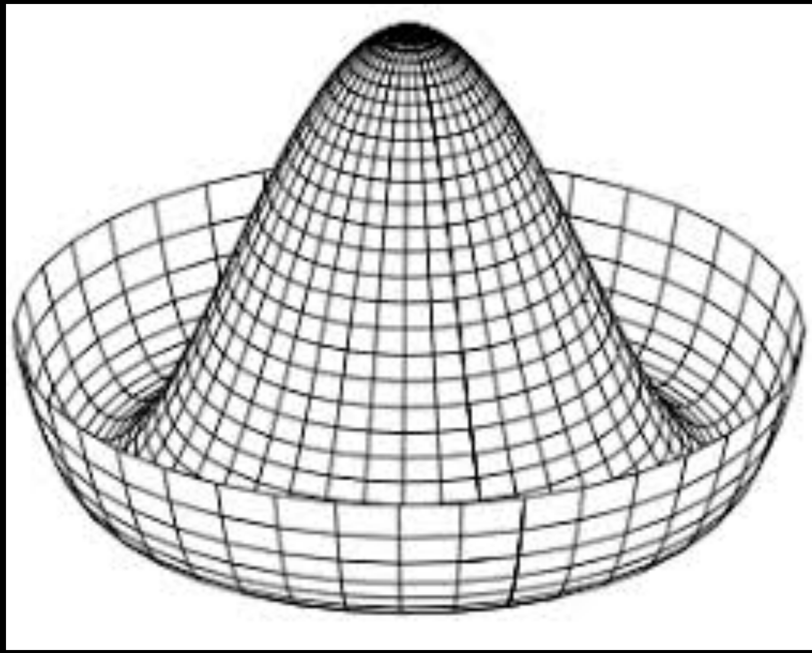
theory including anti-D3 branes

$(g_s p \ll 1)$

— in non-compact confining throat of Klebanov, Strassler:

Probe approximation justified. Metastable SUSY breaking with a compact moduli space of Goldstones!

I note that the potential looks heuristically like:



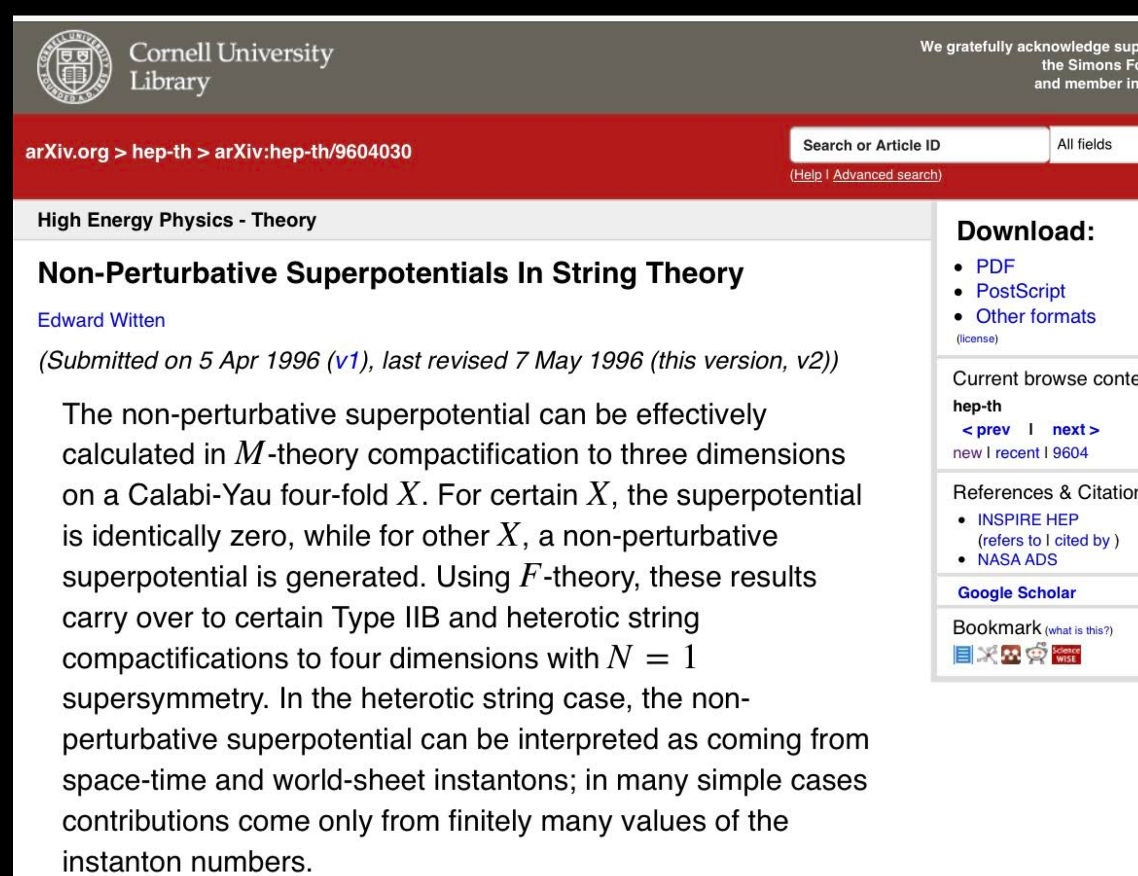
Small corrections (p/M) cannot remove all ground states here; they can tilt the hat selecting one or more at worst.

(This kind of argument goes way back, and is certainly not new in this setting!)

In a compact setting, things change:

In the compact tree-level GKP solutions, the anti-D3 would lead to rapid decompactification!

But of course no-scale structure is not exact.



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High Energy Physics - Theory

Non-Perturbative Superpotentials In String Theory

Edward Witten

(Submitted on 5 Apr 1996 (v1), last revised 7 May 1996 (this version, v2))

The non-perturbative superpotential can be effectively calculated in M-theory compactification to three dimensions on a Calabi-Yau four-fold X. For certain X, the superpotential is identically zero, while for other X, a non-perturbative superpotential is generated. Using F-theory, these results carry over to certain Type IIB and heterotic string compactifications to four dimensions with $N=1$ supersymmetry. In the heterotic string case, the non-perturbative superpotential can be interpreted as coming from space-time and world-sheet instantons; in many simple cases contributions come only from finitely many values of the instanton numbers.

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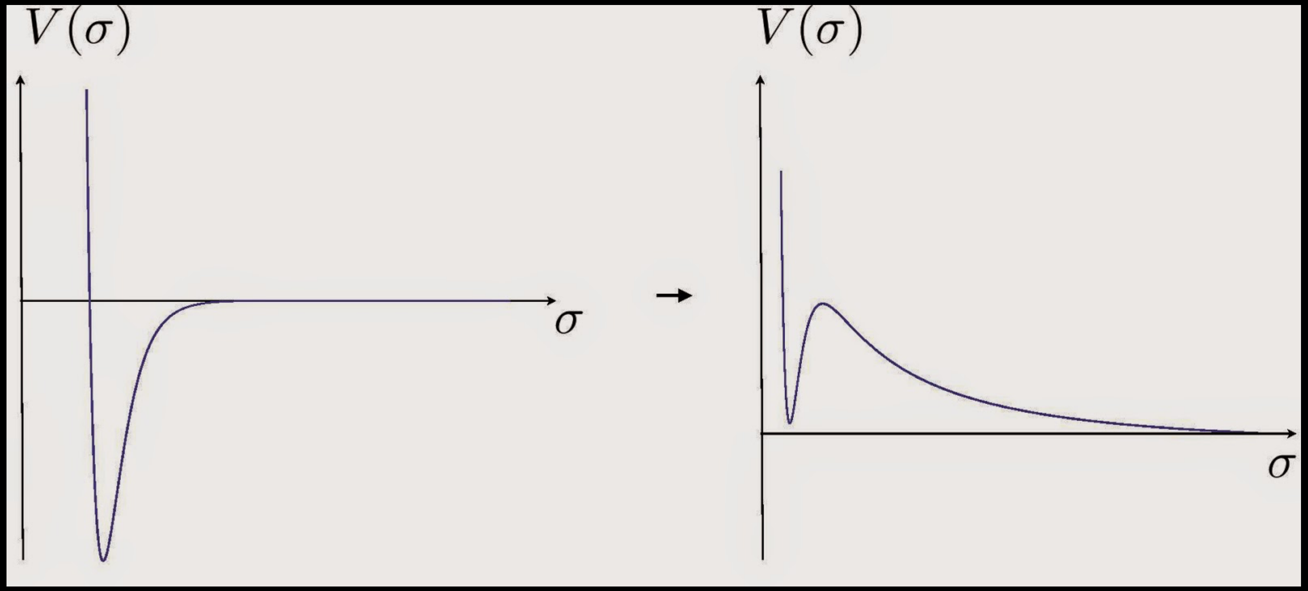
With Kallosh-Linde-Trivedi, we thought to use these effects (or their analogues in strong dynamics) to stabilize the volume.



This work — and work of Silverstein, and of Balasubramanian-Berglund-Conlon-Quevedo, and of Denef-Douglas, and of others — supports the modern picture of the string landscape.

Some comments:

— The details of any of these constructions are historical accidents, and can be varied.

— Criticisms and responses:

i) anti-brane backreaction

"Effective field theory is a powerful tool for analyzing brane back-reaction…In the end, the original KKLT result has stood up well. As far as we can see, none of the putative 10^{500} vacua has been eliminated. Indeed…perhaps there are 10^{501} vacua!"

Joe, arXiv:1509.05710

Most recent analysis of Van Riet et al in a complementary regime $(g_s p > 1)$:

"…we recover the results of KPV."
(arXiv:1812.01067)

ii) …but are you allowed to incorporate non-perturbative effects when you don't know the exact K?

Answer: check shift in results by using ΔK ; small shift @ small values of flux W.

(as stated in 2003 paper; see our note arXiv:1808.08971)

iii) anti-D3 backreaction redux, now on D7s:

(Moritz,Retoaza,Westphal)

Paper in question gives scalings inconsistent with Randall-Sundrum warped scalings, holographic interpretations, and other macroscopic consistency tests. Out of sense of duty, clarifying this now with McAllister + Zimet.

I certainly believe we could improve our understanding of the dS constructions. But quoting Joe:

"There are some objections to the use of effective field theory at all, but it is not clear why it should fail in this particular context. In some cases it simply seems that the result is undesired."

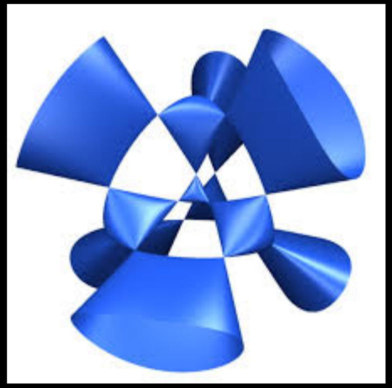
IV. Progress in string compactification

I personally think that to better understand the landscape, we should systematically improve our understanding of the mathematical physics of string vacua. We've taken small steps in this direction in the past couple of years.

A. What is the Calabi-Yau metric?

On M with vanishing first Chern class, there is a Ricci flat Kahler metric for each choice of the Kahler class.

We do not have any idea how to determine the metric on a generic compact Calabi-Yau. But we have recently proposed an analytical technique to get metrics on smooth K3 surfaces.



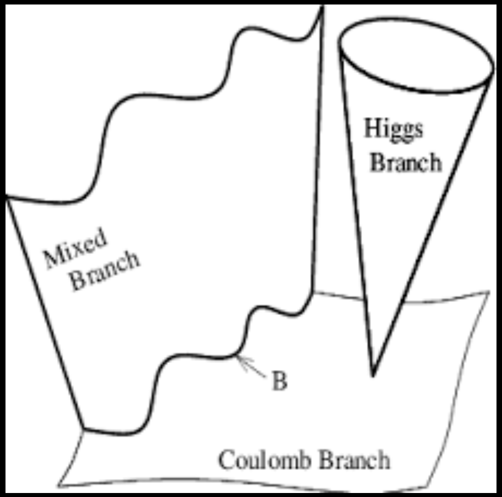
S.K., Arnav Tripathy, Max Zimet

Particularly nice class: elliptic K3s:

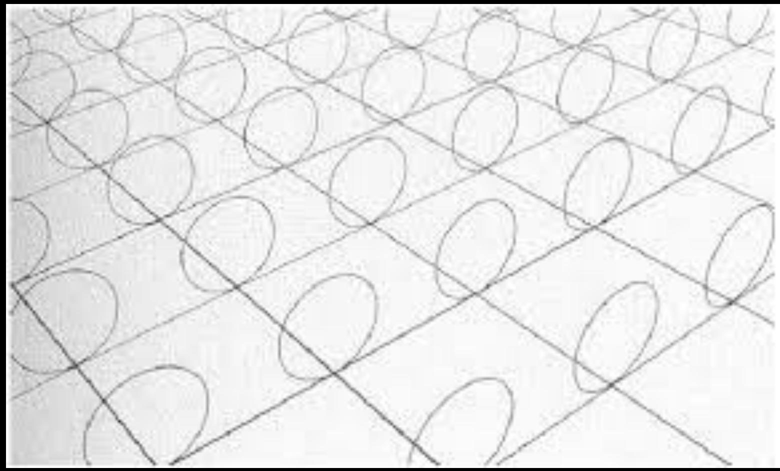
$$y^2 = x^3 + x f_8(z) + g_{12}(z)$$

To describe our idea, we take a detour.

The moduli space of a 4d N=2 theory has Higgs and Coulomb branches.

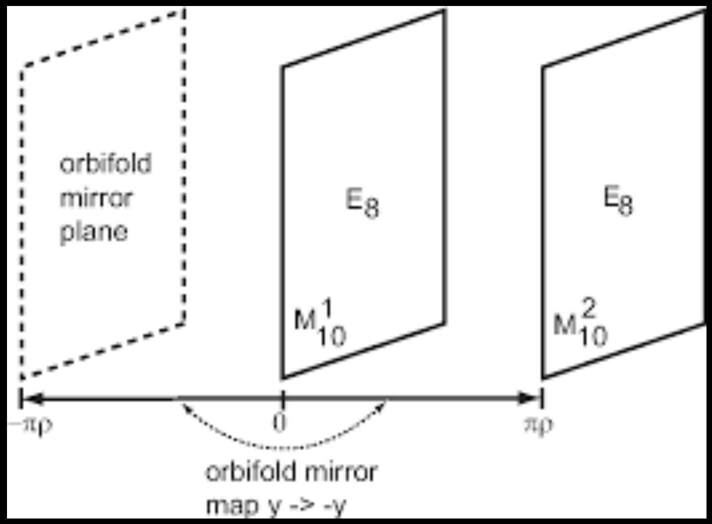


Gaiotto-Moore-Neitzke considered theory on a circle:

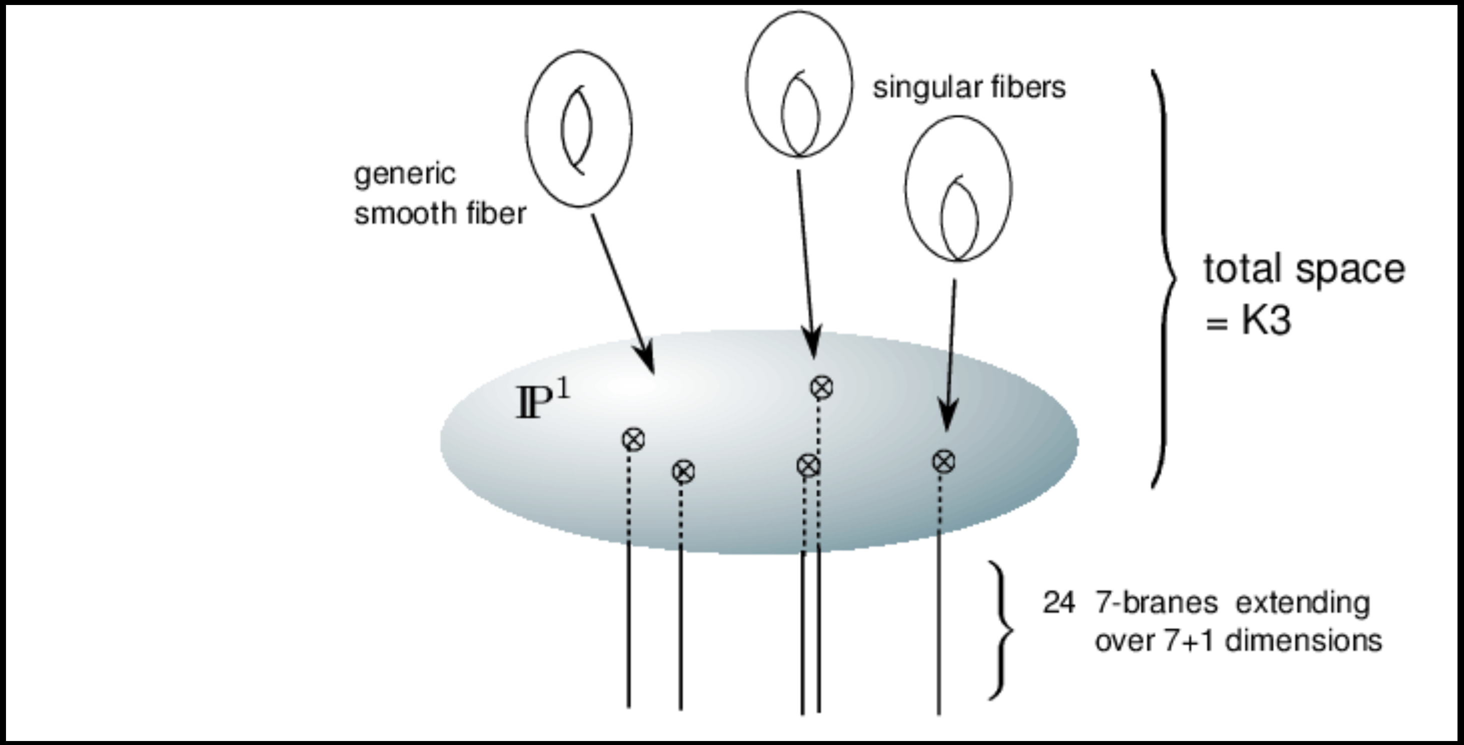


The Coulomb branch becomes a hyperKahler manifold, and GMN are able to determine it. Roughly, their idea is to show that the only corrections to the metric obtained from reduction come from BPS states running around the circle.

A particularly interesting 4d N=2 theory can be obtained as follows. Consider the E8xE8 little string:



Compactifying this on a two-torus yields a 4d N=2 theory with a compact Coulomb branch.



Related by dualities to D3 brane probing F-theory on elliptic K3. Coulomb branch is a sphere with marked points; on circle compactification, get a K3 surface!

The K3 metric in the large complex structure "semi-flat" limit is given by

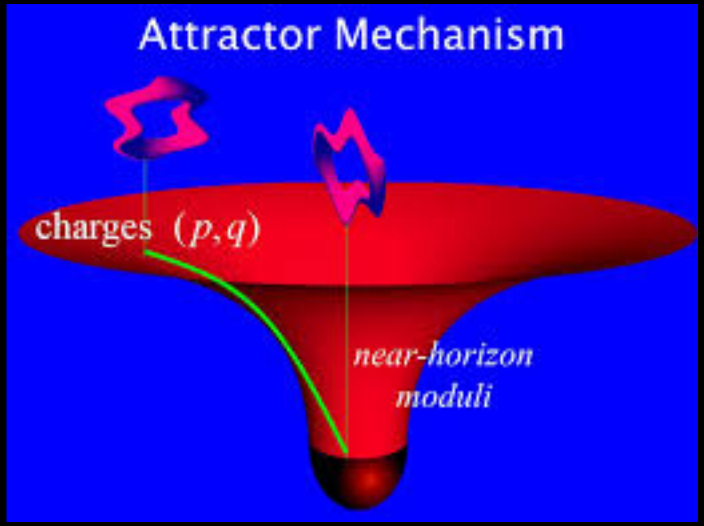
$$ds^2 = e^{\phi} du d\bar{u} + \partial\bar{\partial} K(u, \bar{u}, z, \bar{z})$$

$$e^{\phi} = \tau_2 |\eta^2 \prod_{a=1}^{24} (u - u_a)^{-1/12}|^2$$

$$K = -(z - \bar{z})^2 / 2\tau_2$$

The world-line instantons correct this to give smooth Ricci flat metrics on K3. Approximations keeping the lightest BPS states are analogous to an ansatz of Mark Gross and PMH Wilson; but the BPS states of the little string systematically correct that.

B. Can we learn global facts about flux vacua?



Close relative: can we learn global facts about attractor black holes on a Calabi-Yau

To find attractor points, you extremize:

$$Z = \int Q \wedge \Omega$$

$$Q \in H^3(M, \mathbb{Z})$$

There are some remarkable facts about the solution to this problem for 4d N=4 string vacua.

They follow from Kudla-Millson theory in arithmetic algebraic geometry.

The simplest result I can mention: the attractor black holes on $K3 \times T^2$ are governed by a mock modular form discovered by Zagier.

$$Z(q) = \sum_N H_N \, q^N$$

$$H_N = \text{class numbers}$$

c.f. Moore; S.K., Tripathy; Benjamin, SK, Ono, Rolen

The class numbers count the number of U-duality inequivalent attractor black holes with entropy (squared) given by the discriminant N.

This is a shadow of a deeper result that attractors and flux vacua in N=4 models are automorphic; the loci in moduli space where they live are components of a (homology-valued) automorphic form.

Extensions to Calabi-Yau threefolds, if possible, would give us global information about full sets of (tree level) flux vacua and attractors.