Title: Landscape Architecture

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Abstract:

Landscape Architecture

Based on work with :

Denef, Douglas, Florea, Grassi 0503124

Arkani-Hamed, Dimopoulos 0501082

Kashani-Poor 0411279

DeWolfe, Giryavets, Taylor 0411061

⋮

Kallosh, Linde, Trivedi 0301240

Introduction

There is by now significant evidence that string theory gives rise to a vast "landscape" of metastable vacua, manifesting various possibilities for the gauge group, matter content, Λ_{4d}, and other quantities of physical interest.

Practically speaking, the techniques that go into proving this assertion, are identical to the techniques which we use to produce string compactifications with

Whatever one's philosophical feelings about the landscape are, the latter problem is very concrete & must be dealt with :

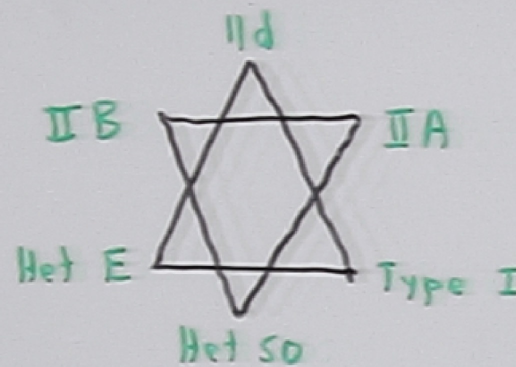
- Existence of moduli is highly constrained by experiments : 5^{th} forces, equivalence principle, BBN, ...
- In absence of moduli stabilization, inflation cannot occur ; so any string scenario for early Universe cosmology must address this issue.

What do we know about producing

It is natural to divide models into <u>three</u> classes:

- Those with $M_{\cancel{susy}} \equiv M \ll$ KK scale M_{KK}. Such models have a 4d $\mathcal{N}=1$ effective description; they'll be my focus.
- Models with $M = M_{KK}$ — Saltman, Silverstein
- Models with $M = M_{string}$ — Maloney, Silverstein, Strominger

Within the SUSY class, we still need to pick a corner of the M-theory star to make concrete



I will split my time between IIB (where the most well developed picture exists) and IIA (where a simple picture is developing now).

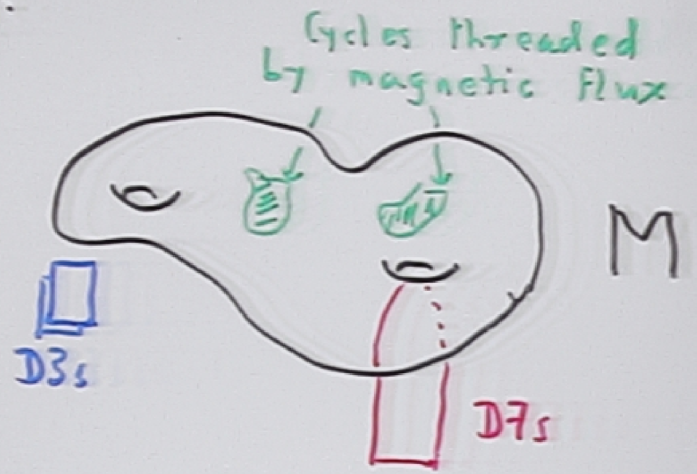
Type IIB Vacua

Setting: F-theory on CY 4-fold

$\Updownarrow$

IIB on orientifold of

Picture:



Moduli:

- Complex str of M $\quad z_\alpha \quad \alpha = 1 \dots h^{2,1}$
- Dilaton $\quad \phi$
- Kähler str of M $\quad \rho_i \quad i = 1 \dots h^{1,1}$
- D-brane moduli

$\exists$ two three-forms H_3, F_3 $\to$ can pick quantized fluxes

$$\int H_3 = h_a \; ; \; \int F_3 = f_a$$

subject to constraint :

$$\int H \wedge F + N_{D3} = N_{D3} \leftarrow \frac{\chi}{24} \text{ in F-theory}$$

Given a choice of $\{h_a, f_a\}$, you get a 4d $\mathcal{N}=1$ sugra of the no-scale type at leading order, with

$$W = W_{flux} = \int (F - \phi H) \wedge \Omega \qquad \text{GVW}$$

- W_{flux} "fixes" z_a, ϕ generically
- # of flux vacua, including Σ over choices of h_a & f_a, is <u>very</u> <u>large</u>

$$N_{vac} \sim (N_{D3})^{b_3(M)}$$

BP; Ashok

· Known non-perturbative effects can

$\Rightarrow \quad \delta W = W_{np}(\rho_i)$

- Euclidean D3 instantons (→ M5s in M-theory dual)

Witten; GKTT; Saulina; KKT

- Gauge dynamics on D7s whose $g_{YM}^{-2} \sim \rho$

If W_{flux} fixes z_α, Φ with

· g_s small

· $W_{flux}|_{vacuum} = W_0$ small

(really $e^K |W|^2$)

statistically expect this to be possible

$\Rightarrow$ these effects can produce a vacuum at large enough ρ that

⑧

This KKLT construction → a very concrete proposal for constructing a landscape $\in$ string theory.

We now know, 2 years later, that:

- Based on statistical theory of IIB flux vacua:

Ashok, Denef, Douglas

$$[\text{Fraction w/ } g_s \leq g^*] \sim g^*$$

- $$[\text{Fraction w/ } |W|^2 \leq \varepsilon^2] \sim \varepsilon$$

In examples with $N_{vac} \sim 10^{300}$, requiring $g_s < \frac{1}{10}$ and small W_0 (c.f. 10^{-4} in KKLT)

- The fraction of CY 4-folds that are amenable to Kähler moduli fixing is not particularly small ; c.f. "29 of 92 4-folds with Fano base" DDF
- This is a lower bound because it appears that the strongest "$\chi = 1$" condition on instantons may be relaxed in various cases

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So the statistical considerations → very strong evidence that many models exist. Can we exhibit them

Its very hard work!

Even finding integral basis for $H^3(M)$ + computing periods is tough (cf mirror symmetry literature, only models with very small b_3 were done).

A simple example: DDFGK

F-theory on $T^8/(\mathbb{Z}_2)^3$

($\equiv$ IIB on $T^6/(\mathbb{Z}_2)^2$)

See also:
Blumenhagen...
Cascales...
Cvetic...
Lüst...
Marchesano...

Model introduced by Gopakumar + Mukhi (1996):

· $SO(8)^{12}$ gauge group from 12 D7

Model has 3 complex moduli (inherited from $(T^2)^3$), 3 untwisted kähler moduli, and 48 blow-up modes.

- Each blow-up comes with its own divisor of $\chi=1$ $\rightarrow$ instanton superpot.
- Each untwisted kähler mode appears in g_{YM} of 4 D7 stacks $\rightarrow$ gaugino condensate

Flux vacua:

$$\int H \wedge F + N_{D3} = 28$$

Flux vacua 'easy' to study in this

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- We look for some at

$$\int H \wedge F = 28$$

→ no wandering D3s.

Note that while

$$N_{vac} \left(\int H \wedge F \leq L \right) \sim L^{b_3}$$

at a <u>given</u>

$$\int H \wedge F = \tilde{L}$$

# of vacua can fluctuate wildly with $\tilde{L}$ (summing over $\tilde{L} \leq L$ smooths result). <u>See picture</u>

<u>Upshot</u>: We found explicit vacua

at $\int H \wedge F = 28$ ...

the integers, which can be encoded in functions like $\sigma(k)$. In this model, we found that both approximation methods lead to the same asymptotic formula for the number of vacua, (3.13). An important question is how large the fluxes must be for these approximations to be valid. Some discussion of this issue was given in [25,26]. For the rigid CY model discussed here, it is easy to put the exact discrete equations on a computer and demonstrate that the approximations are already valid at quite small values of the fluxes.

It is important to note, however, that in general the discreteness of the fluxes will strongly affect any equations involving quantities which are not summed over all integers below some bound L, but rather involve specific properties of a particular integer N. For example, as discussed above the total number of flux vacua in the rigid CY model at a particular value of $N_{\rm flux}$ is given by

$$N_{\rm vacua}(N_{\rm flux}) = \sigma(N_{\rm flux}) = \sum_{k|N_{\rm flux}} k. \tag{3.16}$$

This function of $N_{\rm flux}$ is not smooth and depends on the number theoretic properties of the argument. Both this function and its fluctuations are of order $N_{\rm flux}$ – this is clearly illustrated in the figure below. On the other hand, the total number of vacua with $N_{\rm flux} \leq L$ is much better behaved–this function, as described above, scales as L^2, with fluctuations which decrease in relative scale as $L \to \infty$. Thus, in comparing precise analytic or numerical calculations to asymptotic estimates, we will be much better off when we compare to quantities like the total number of vacua with $N_{\rm flux} \leq L$, involving inequalities, rather than quantities like $N_{\rm vacua}(N_{\rm flux})$, which are much more dependent on factorization properties of their arguments.

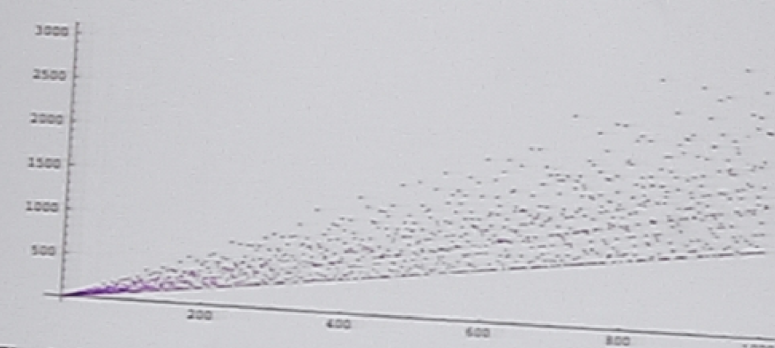

Fig. 1: Plot of $N_{\rm vacua}(N_{\rm flux})$ up to $N_{\rm flux} = 1000$.

- We look for some at

$$\int H \wedge F = 28$$

$\rightarrow$ no wandering D3s.

Note that while

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# of vacua can fluctuate wildly with $\tilde{L}$ (summing over $\tilde{L} \leq L$ smooths result). <u>See</u> <u>picture</u>

<u>Upshot</u>: We found explicit vacua at $\int H \wedge F = 28$, computed stabilized values of all moduli, correction

- It would be interesting to carry this through in models with larger b_3 (but probably becomes computationally intractable rather quickly).
- By using e.g. warped models as in GKP, or by using IASD fluxes as in Saltman/Silverstein, also expect dS vacua in general.

$\#$ vac with given $\sim F^6$ Dine et al, Denef, Douglas
SUSY $\langle F \rangle$

$\Rightarrow$ again in models with large # of flux vacua, expect very controlled

So in IIB limit, we seem to have an increasingly precise (but still crude) picture of a large set of metastable vacua, based both on explicit proposals + constructions, and on statistical arguments that allow us to intelligently discuss how rare or common a given model-building requirement may be.

Crucial feature: in flux vacua in IIB

moduli fixed = b_3 (real)

fluxes (H_3, F_3 on cycles) = $2\, b_3$

Consider more abstractly a case with N moduli fixed by K fluxes (so here $K = 2N$ in IIB). Say you want moduli fixed at $\phi_i = \phi_i^*$.

- $\left.\frac{\partial V}{\partial \phi_i}\right|_{\phi_i^*} = 0 \Rightarrow N$ equations

In "continuous flux" approx. of statistical theories, can solve for N of the fluxes. Then:

$$\boxed{\text{K-N fluxes left to "tune physics" } (\Lambda_{4d}, \ldots) \text{ at } \phi_i^*}$$

- This is why all values of CC, g_s, W_0 are "easy" to get.

Can easily imagine systems where # vacua $\gg 1$ but $\frac{K}{N}$ is smaller; should expect distributions to be more peaked.

This shows up in simple QFT examples of landscapes ($\to$ concept of 'friendly neighborhood' where the natural values of some couplings are consistent w/ a beautiful explanation

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This shows up in simple QFT examples of landscapes (→ concept of 'friendly neighborhood' where the natural values of some couplings are consistent w/ a beautiful explanation despite large N_{vac} ; they don't

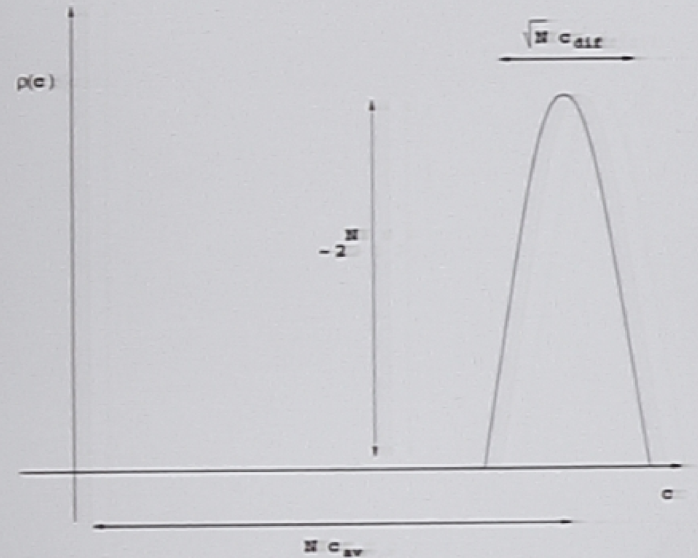

Figure 4: Generic scanning of couplings on our landscape. Note that the region of the scanned couplings is small, $\delta c/c \lesssim 1/\sqrt{N}$, since the mean value of the coupling grows as N while the width only grows as $\sqrt{N}$

⑬

In such a landscape, even scanning Λ well enough to find

$$\Lambda \sim 10^{-120} M_p^4$$

can require a symmetry (e.g. R-symmetry in SUSY), that makes $V = 0$ special.

Both to see if such "other" values of $\frac{k}{N}$ show up, & to develop more confidence in the landscape idea, it will be useful to develop another corner of M-theory in

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Type IIA Calabi-Yau flux vacua

Consider IIA on a CY $\Rightarrow$ 4d $\mathcal{N}=2$ sugra.

Fluxes ?

RR sector: F_0, F_2, F_4, F_6

NS sector: H_3

Turning on fluxes $\longleftrightarrow$ "gauging" $\mathcal{N}=2$ sugra.

- RR fluxes give dilaton charges under various vectors
- NS fluxes give graviphoton charges to hypers

Louis, Micu

the 4d potential that arises via gauging .. determined by $\mathcal{N}=2$ prepotential + Quaternionic metric (up to $e^{-1/g}$ corrections).

Via $\left\langle \begin{matrix} RR \\ NS \end{matrix} \right.$ fluxes, this V

depends on $\left\langle \begin{matrix} \text{kähler} \\ \\ \text{cplx + dilaton} \end{matrix} \right.$ moduli $\Rightarrow$

the flux generated potential depends on <u>all</u> <u>moduli</u> of CY at tree level (aside from some axions).

<u>Tadpoles</u>? Only

D6 charge $\leftrightarrow$ $-\int F_0 \wedge H_3$

So both at $\mathcal{N}=2$ level (avoiding tadpoles), and $\mathcal{N}=1$ level (allowing tadpoles + adding O-planes to cancel):

IIA on CY + generic flux can have all geometric moduli fixed.

This story was developed with A. Kashani-Poor & we are now (DeWolfe, Giryavets, Taylor + SK) explicitly stabilizing all moduli of the famous "Z-orbifold" $T^6/\mathbb{Z}_3$.

See Oliver's talk.

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See Oliver's talk.

Very related works: Grimm-Louis ;

These IIA models are in fact ("almost") dual to M-theory compactifications on spaces of G_2 holonomy, studied by e.g. Acharya + Denef.

While explicit egs are hard in the G_2 case, they did statistics under reasonable assumptions.

Results: "Friendly" (see picture)

Key point: $\left(\frac{K}{N}\right)_{IIA} < \left(\frac{K}{N}\right)_{IIB}$

in these CY vacua.

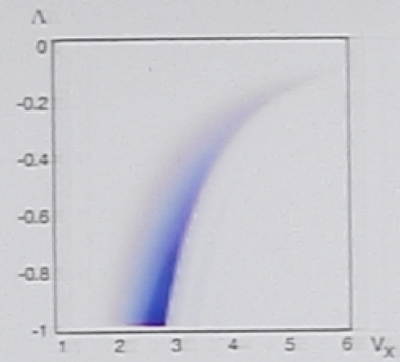

Figure 5: Density plot of the joint distribution of AdS vacua over V_X and Λ, for $c_2 = 100$, $n = 20$.

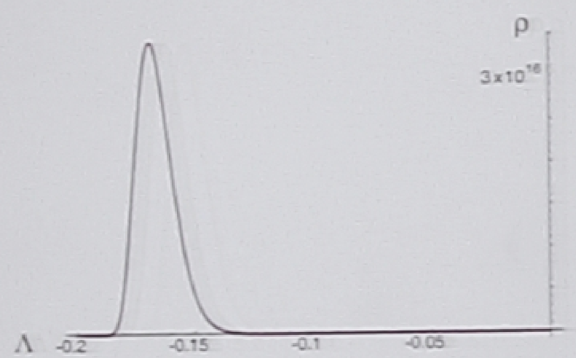

Figure 6: Distribution of cosmological constants $d\mathcal{N} = \rho(\Lambda)\, d\Lambda$. Here we took $a_i = 7/3n$, $n = 50$, $c_2 = 100$, and we restricted to stable vacua with $V_X \geq 5$.

(27)

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• Could well be that including "dJ" (non-kählerity) $\Rightarrow$ broader distributions, ~ IIB (duality hints that this is true)

• But maybe relative "stiffness" of some flux parameters is increased in pockets of landscape, so friendly distributions are relevant?

• We are probably missing 'most' classes of vacua still -- large # of gaugings one can imagine given the $\mathcal{N}=2$ data of a CY,