New Phenomena

in

Compactifications with Flux

Based on:

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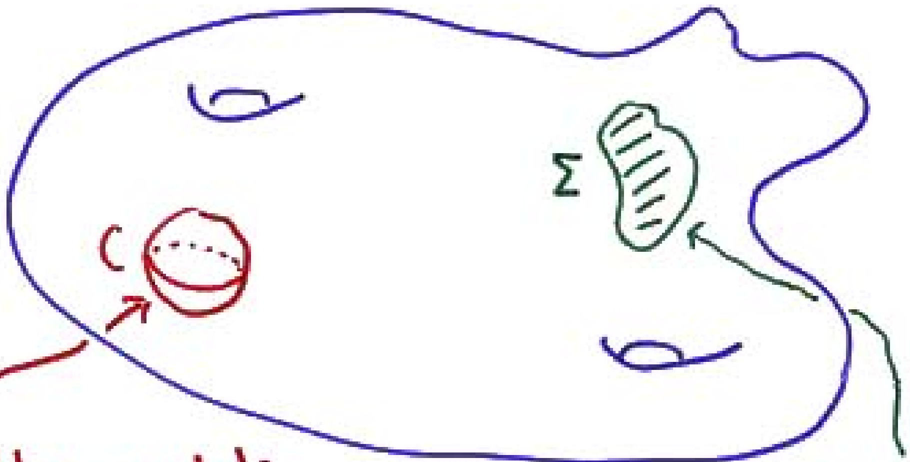
Introduction

The usual starting point for string model building involves a choice of Calabi-Yau manifold M. (In type II theories, one should consider an orientifold of M if one wants minimal 4d SUSY).

PROBLEM : M comes with moduli



$h^{1,1}(M)$ kähler moduli: control volumes of even dim. cycles

$h^{2,1}(M)$ complex structure moduli control 3-cycles

This is a problem since:

- 4d $\mathcal{L}_{eff}$ depends on moduli VEVs → loss of predictivity
- Gravitationally coupled TeV mass fields → cosmological problems (ruin BBN)

Banks, Kaplan, Nelson

There is a <u>generic</u> and <u>calculable</u> effect that helps to improve this situation.

For concreteness, consider IIB string theory.

- ∃ NS and RR 3-forms H_3, F_3

axio-dilaton

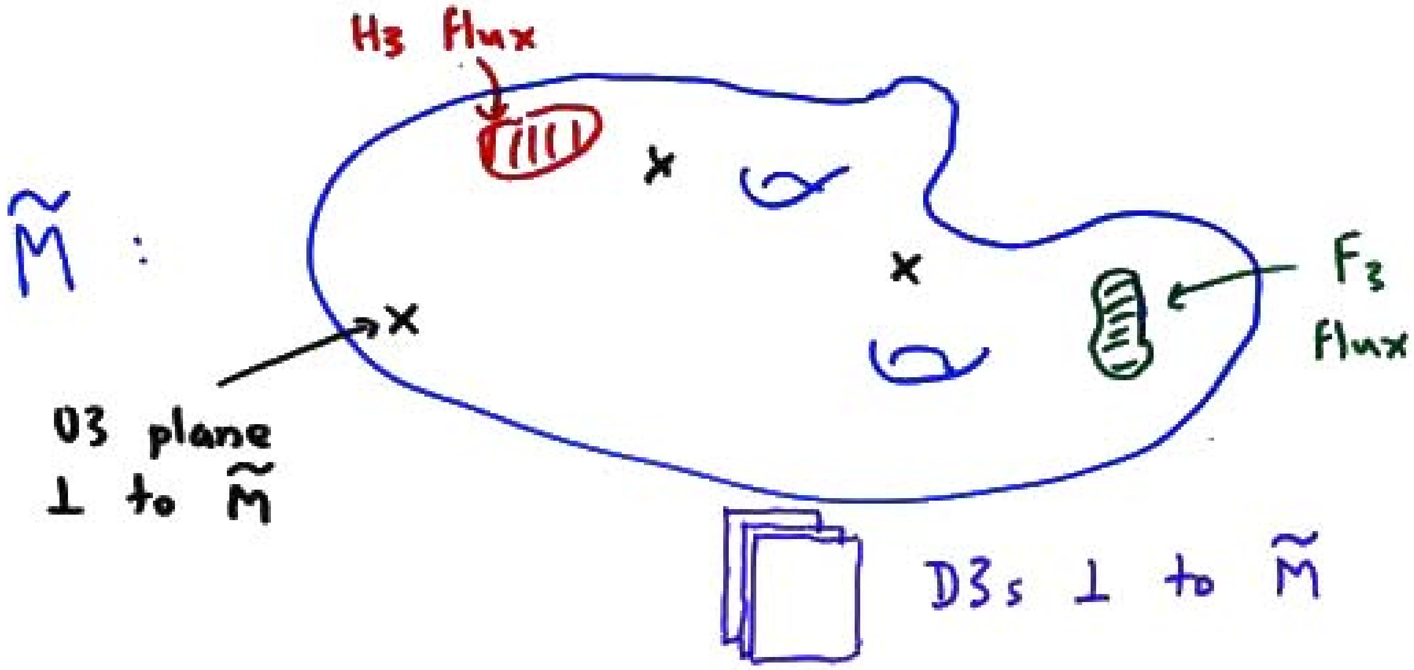
$$G_3 = F_3 - \phi H_3$$

- So one should "generically" consider

$$\int_{\Sigma_3^i} H_3 \ , \ \int_{\Sigma_3^i} F_3 \neq 0$$

(Σ_3^i runs over 3-cycles in the CY)

So our full model is:



$\tilde{M}$ = orientifold of M $\left(M / \sigma \cdot \Omega \right)$

σ : Appropriate $\mathbb{Z}_2$ symmetry of M

Ω : Worldsheet parity

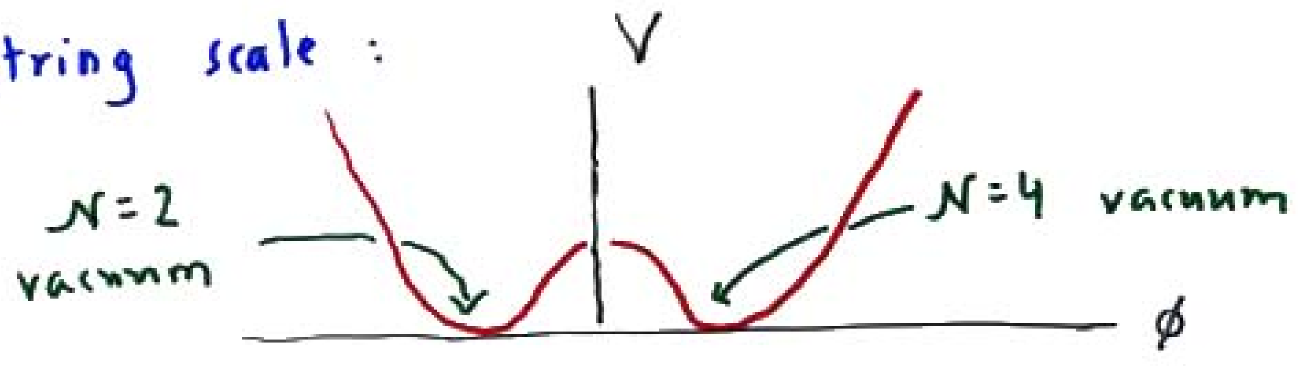
(Alternative language: "F-theory on fourfolds...")

Today I want to briefly discuss three aspects of such models.

I. Fluxes $\to$ calculable potential which can fix many moduli, at a high scale, without completely breaking SUSY.

We'll discuss the simplest case $M = T^6$.

II. Models with different amounts of unbroken Minkowski SUSY appear as part of a larger configuration space, separated by a pot. barrier << string scale:



III. Many such models include D3 branes for tadpole cancellation. The dynamics on such a brane as it rolls around on $\tilde{M}$ can yield interesting 'mirage' cosmologies, including some with bouncing $k=0$ FRW metrics.

I. Fixing Moduli

We can turn on H_3, F_3 fluxes in M subject to:

- Quantization:

$$\int_{\Sigma_i} F_3 \,, \quad \int_{\Sigma_i} H_3 \in \mathbb{Z} \quad \forall\, \Sigma_i \subset H_3(M)$$

- Tadpole cancellation

$$\frac{1}{4} N_{O3} = N_{D3} + \int_M H_3 \wedge F_3$$

So for $\tilde{M} = T^6/\mathbb{Z}_2$:

$$\sigma : \ (x^i, y^i) \to -(x^i, y^i) \quad i = 1,2,3$$

$$0 \le x^i, y^i \le 1$$

64 fixed points of $\sigma \Rightarrow$

$$16 = N_{D3} + \int H_3 \wedge F_3$$

- NO flux $\to$ just T-dual of type I, $\mathcal{N}=4$ SUSY.

38 closed string moduli.

What happens when $F_3, H_3 \neq 0$?

Define $G = F_3 - \phi H_3$. Reducing 10d flux kinetic terms $\to$

$$V = \frac{1}{\mathrm{Im}\,\phi} \int_{\mathcal{M}} G^{IASD} \wedge * \bar{G}^{IASD}$$

where

$$* G^{ISD} = i\, G^{ISD}$$

$$* G^{IASD} = -i\, G^{IASD}$$

So $V \geq 0$ and we get Minkowski vacua when $V = 0 \Rightarrow G$ is purely ISD.

SUSY $\to$ stronger conditions : (Becker)^2

- G should be of type $(2,1)$
- G should be primitive $\left(\underset{\text{kähler form}}{J} \wedge G = 0 \right)$

One can derive these conditions from a 4d sugra with :

$$\boxed{\text{Superpotential}: \; W = \int_M G \wedge \Omega_{(3,0)}}$$

Gukov, Vafa, Witten

and primitivity enforced by vanishing of some D auxiliary fields ...

D'Auria, Ferrara, Vaula ; Ferrara, Porrati

So fixing a choice of $H_3, F_3 \subset H^3(M, \mathbb{Z})$ we get equations that fix the kähler, complex and dilaton modulus (though not all of 'em).

EXAMPLE : $M = T^6$

$$F_3 = a^0 \, dx^1 dx^2 dx^3 + a \, (dx^2 dx^3 dy^1 + \text{perms.}) + b \, (-dy^2 dy^3 dx^1 + \text{perms.}) + b_0 \, dy^1 dy^2 dy^3$$

H_3 = Similar with $(a^0, a, b, b_0) \rightarrow (c^0, c, d, d_0)$

The complex structure is specified by a period matrix

$$dz^i = dx^i + \tau^{ij} dy^j$$

With our special choice of fluxes one can quickly convince oneself that SUSY requires

$$\tau^{ij} = \tau\, \delta^{ij}$$

The remaining Eqns to satisfy for a SUSY solution are: $W = \partial_\phi W = \partial_\tau W = 0.$

First two $\rightarrow$

$$P_1(\tau) = a^0 \tau^3 - 3a\tau^2 - 3b\tau - b_0 = 0$$

$$P_2(\tau) = c^0 \tau^3 - 3c\tau^2 - 3d\tau - d_0 = 0$$

For P_1, P_2 to share root with $\mathrm{Im}(\tau) \neq 0$, need them to share a quadratic factor

$$P(\tau) \propto \underbrace{c^0 P_1(\tau) - a^0 P_2(\tau)}_{\text{integer coefs.}}$$

So for those fluxes which do admit a SUSY solution, the resulting τ satisfies a quadratic equation w/ integer coefs. I.e. the torus admits complex multiplication.

c.f. Gukov's talk

(Unfortunately, this does not generalize to the case of fully generic fluxes).

Can then argue, based on explicit form of F_3 and H_3, that

$$J \wedge G = 0 \text{ at codim } 3 \text{ in kähler mod. sp.}$$

Result: In these models, ϕ and τ^{ij} are frozen and J is significantly constrained.

- Get $\mathcal{N}=1$ (or 2,3) preserving masses for moduli at a scale $m \sim \frac{\alpha'}{R^3}$.

Related work by: Frey, Polchinski; Dasgupta, Rajesh, Sethi ... (many)

- The overall radius R is <u>never</u> fixed in this "no-scale" approximation.

- Can hope that { D instantons, in $\mathcal{N}=1$ susy case ; α' corrections in $\mathcal{N}=0$ case ← (Becker)^2, Haack, Louis } will help fix R (but then no-scale $\Lambda_4 = 0$ gone ...)

- Interesting IIA "mirrors" (not CY!) and heterotic analogues of these IIB models exist...

II. "Connecting" $\mathcal{N}=4$ to $\mathcal{N}=2,1$ vacua

We know from many examples that string theory likes its compactifications to be connected, <u>without</u> going to infinite distance in moduli space. E.g.

- conifold transitions between 4d $\mathcal{N}=2$ vacua — Greene, Morrison, Strominger

- transitions with $\Delta n_{tensor} \neq 0$ in 6d $\mathcal{N}=(0,1)$ vacua — Ganor-Hanany, Seiberg-Witten

- "Chirality changing" transitions in 4d $\mathcal{N}=1$ susy models — S.K., Silverstein; Ovrut, Pantev, Park

How about connecting e.g. 4d $\mathcal{N}=4$ Minkowski vacua to 4d $\mathcal{N}=2$ or 1 ? On moduli space:

- Not possible in heterotic theory — Banks-Dixon
- Not possible to have $K_3 \times T^2 \to CY_3$ via conifold transition in type II — Aspinwall

BUT: For many purposes asking for a connection on moduli space is not needed. Can traverse a potential barrier, as long as the scale of $V \ll M_{pl}$.

e.g. in cosmology, at temperatures $\gtrsim V$ but $\ll M_{pl}$ could "sample" between such vacua

SO: Can we show some 4d $\mathcal{N}=4$ models are connected to 4d $\mathcal{N}=2,1$ in this sense?

If this was the case, should be possible to write down spherical domain walls:

$\mathcal{N}=2$ outside

with:

tension: $T \ll M_4^3$

radius: $\rho \gg l_{pl}$

Outside R_{schw}: $\rho \gg T\rho^2 \cdot G_N$

$$\to \rho \ll \frac{(M_{pl})^2}{T}$$

We can do this! As an example:

$\mathcal{N}=4$ vacuum: $H = F = 0$

$\mathcal{N}=2$ vacuum: Solution with

$$\left.\begin{aligned} F &\sim dx^1\, dx^2\, dy^3 + dy^1\, dy^2\, dy^3 \\ H &\sim dx^1\, dx^2\, dx^3 + dy^1\, dy^2\, dx^3 \end{aligned}\right\} \text{At same } \tau^{ij}, \phi, J\ldots$$

How do we make the <u>bubble</u> in string theory?

- NS 5 wraps $\Sigma_3 \subset T^6$ and S^2 of radius ρ in $\mathbb{R}^4 \to H_3$ jumps by one unit (through dual of Σ_3) as one traverses bubble wall.
- Similarly for D5 and F_3.

So its an easy matter to write down a brane config. which jumps fluxes by right amount:

$$\text{Tension} \quad T \sim \frac{R^3}{(\alpha')^3}$$

$$M_{pl} \sim R^3/(\alpha')^2$$

Will have small backreaction + $\rho \gg R_{sch}$ if

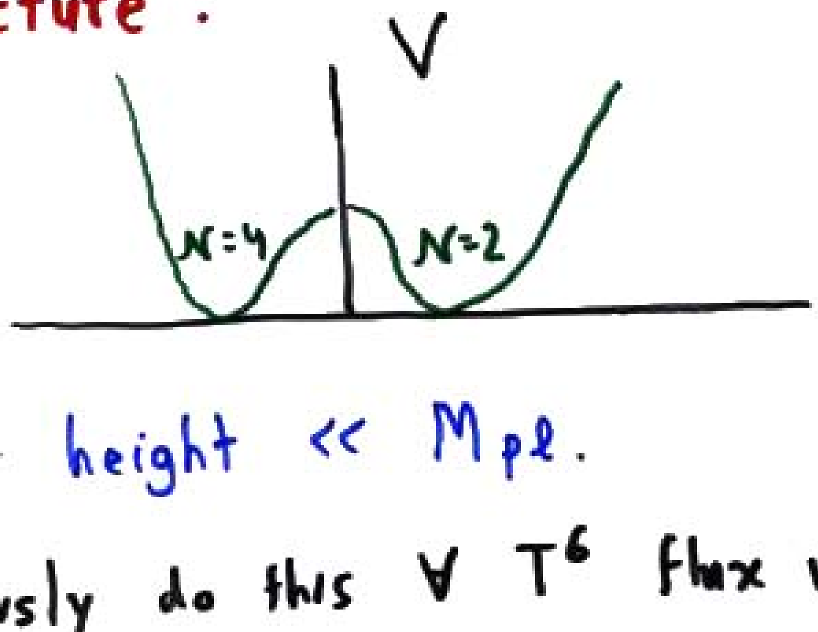
$$\rho < R^3/\alpha'$$

The bubble of NS & D5s <u>will</u> collapse, but in

$$\Delta t \sim R^3/\alpha'$$

So one can make arbitrarily large and long-lived bubbles, with $\frac{T}{M_{pl}^3} = \frac{(\alpha')^3}{R^6}$ as small as desired, by tuning R.

This gives strong evidence that at large R (where one trusts this analysis) there is a picture:

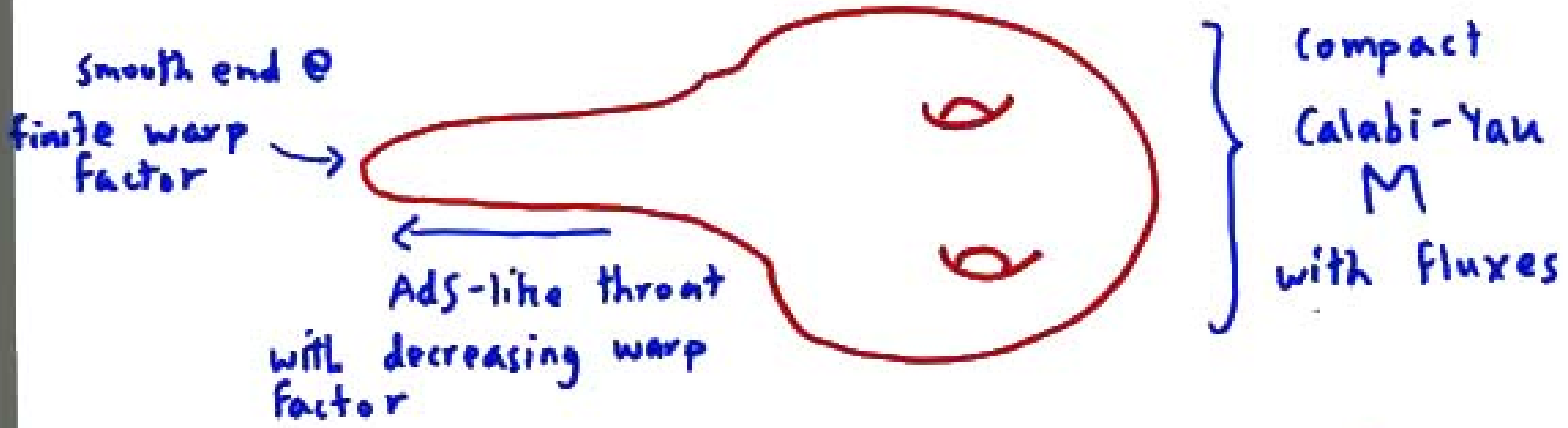


with barrier height $\ll M_{pl}$.

- Can obviously do this $\forall$ T^6 flux vacua
- More careful analysis of bubble dynamics confirms this simple picture
- Vacua are NOT connected in strongest sense described by e.g. Banks ...

III. Bouncing brane cosmology

$\exists$ warped IIB solutions where:



Prototypical eg: embedding Klebanov-Strassler warped deformed conifold $\subset$ compact CY model — Giddings, S.K., Polchinski

What is the cosmology ("mirage") induced on a D3 we kick down the throat? — Kehagias, Kiritsis; Gubser; ...

WARM-UP: Motion in Klebanov-Tseytlin throat

$$ds^2 = h^{-1/2}(r)\, dx_n dx_n + h^{1/2}(r)\left\{ dr^2 + r^2\, ds^2_{T^{1,1}} \right\}$$

$$h(r) \equiv \frac{L^4}{r^4} \ln (r/r_s)$$

What t-dependent physics does D3 observer see?

$$ds^2_{brane} = -dt^2 + h^{-1/2}(r(t))\,(dx_1^2 + dx_2^2 + dx_3^2)$$

t = brane observer proper time

$r = r(t)$ along brane trajectory

→ an FRW cosmology

$$ds^2 = -dt^2 + a^2(t)\,(dx_1^2 + dx_2^2 + dx_3^2)$$

with an $a(t)$ given by

$$a(t) = h^{-1/4}(r(t))$$

There are several important points to make:

1) The graviton wavefunction has r-dependent overlap with the infalling brane. So if by M_{open} we denote a mass scale of a mode there, then

$$G_N\, M^2_{open} \sim a(t)^2$$

One natural interpretation:

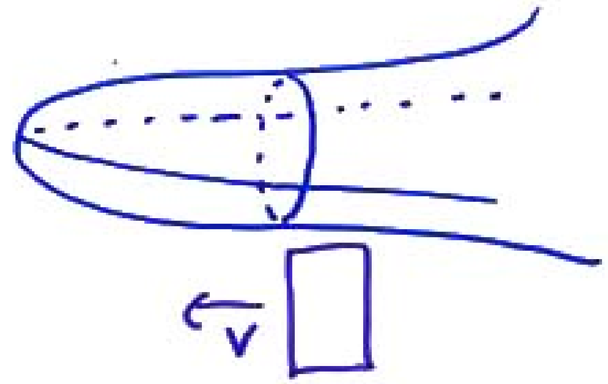
- Elementary particle masses fixed in time
- G_N time varying (and size of Universe in Planck units is fixed)

In units of $(M_{open})^{-1}$, proper distance between galaxies does scale with $a(t)$ as in FRW. As the brane falls, you do see blueshifting of photons.

2) The KT metric has a naked singularity "in the IR." In our warm-up model, the resulting cosmology has a spacelike singularity induced as the brane reaches the KT singularity.

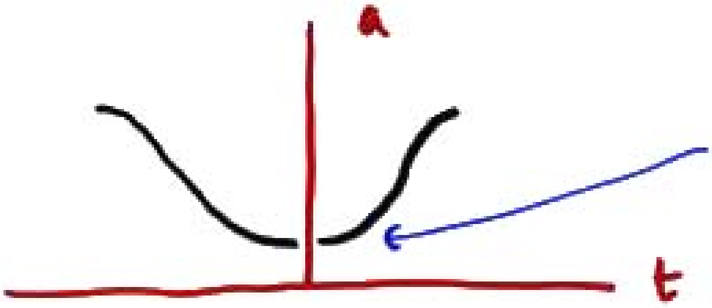
3) The Klebanov-Strassler solution cures the IR naked singularity of the KT sol'n.

The end result is a smooth throat:



When the brane reaches the smooth end where $a(t)$ is minimized, it just starts back up the throat $\rightarrow$ the brane cosmology "bounces."

In the limit of small v the trajectory looks like:



can tune params. to make a_{min} large ...

At least in the transition from KT to KS throats, this mirage cosmology gives an instance of a "resolution" of a spacelike singularity.

CONCLUSION

Compactifications with flux are a good starting point for:

- Producing SUSY (or non-SUSY) models with very few moduli
- Finding new interesting geometries which → SUSY string compactifications < non-CY mirrors / Heterotic duals
- Gaining some insights into string configuration space
- Construction of novel D-brane cosmologies