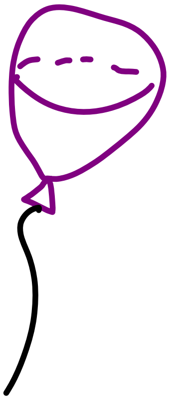
Toward 4d quantum gravity in string theory

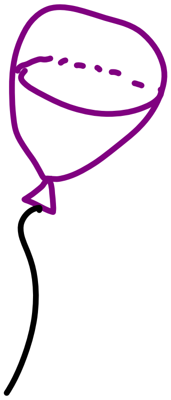
Work in Progress with Joe Polchinski

Banks/Fischler fest UCSC 6/15/09



Happy

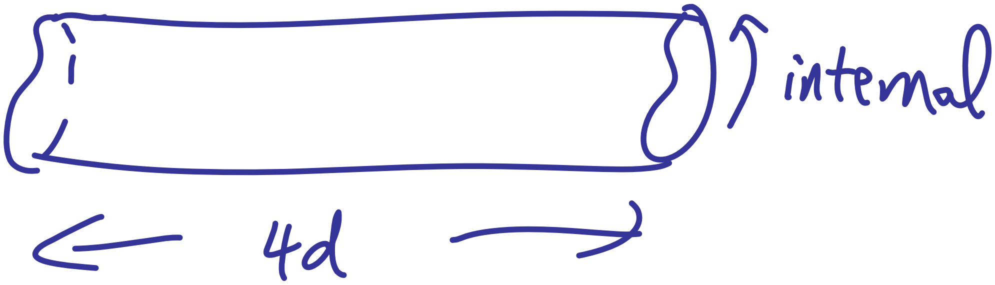
$\mathrm{Log}_{10}\left(\frac{M_p^2}{\Lambda}\right)$ 'th



Birthday, Tom + Willy!

Don't worry! With TeV-scale SUSY, $\mathrm{Log}_{10}\left(\frac{M_p^2}{\Lambda}\right)$ is the new $\mathrm{Log}_{10}\left(\frac{M_{SUSY}^2}{\Lambda}\right)$!

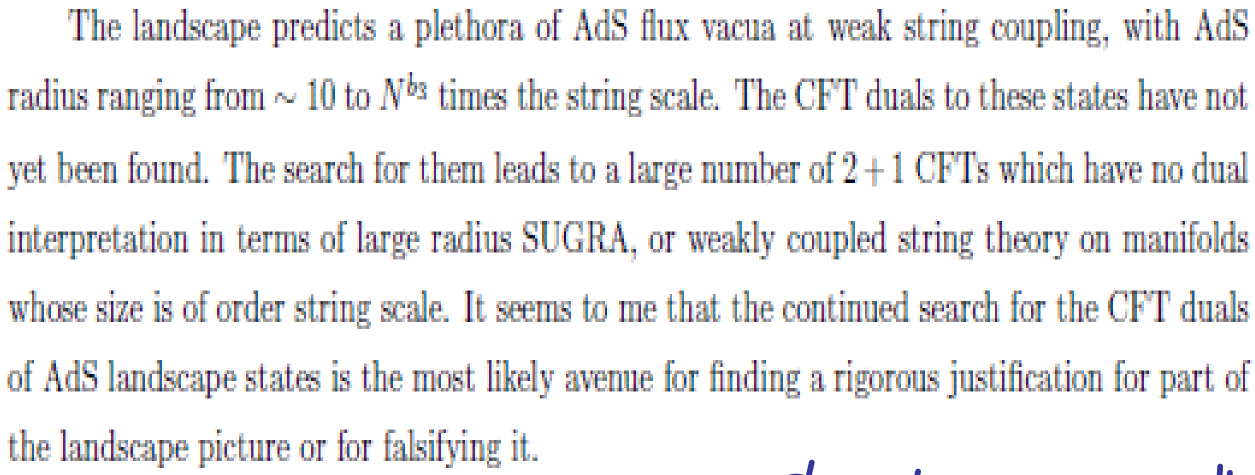
We'd like a non-perturbative formulation of 4d physics:



with a hierarchy of energy scales

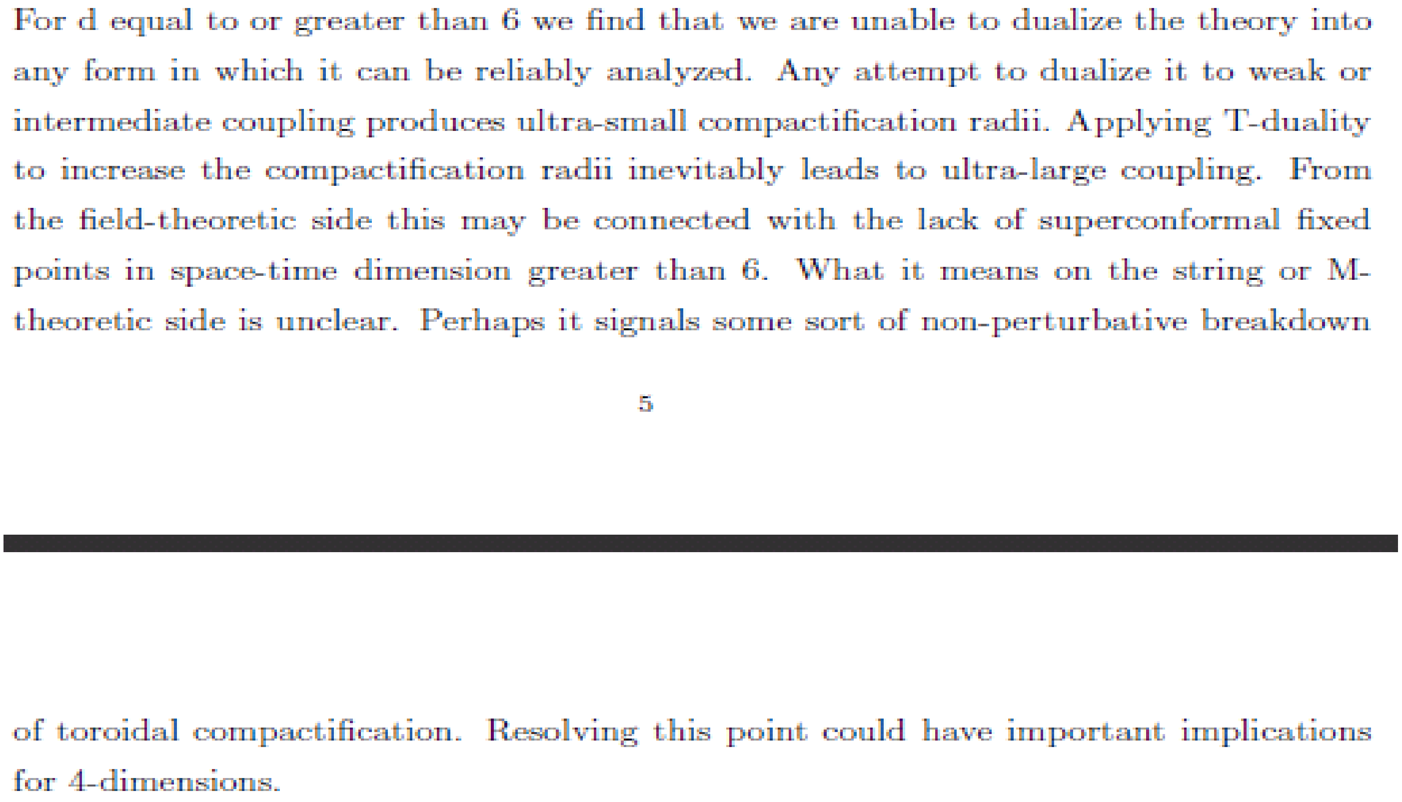
$$m_{\left\{\begin{smallmatrix}KK\\ \text{string}\\ D\end{smallmatrix}\right.} \gg \frac{1}{L_{4d}}$$

From "Landskepticism" (Banks)



The landscape predicts a plethora of AdS flux vacua at weak string coupling, with AdS radius ranging from ~ 10 to N^{b_3} times the string scale. The CFT duals to these states have not yet been found. The search for them leads to a large number of 2 + 1 CFTs which have no dual interpretation in terms of large radius SUGRA, or weakly coupled string theory on manifolds whose size is of order string scale. It seems to me that the continued search for the CFT duals of AdS landscape states is the most likely avenue for finding a rigorous justification for part of the landscape picture or for falsifying it.

From "the Incredible Shrinking Torus" (Fischler, Halyo, Rajaraman, Susskind)



For d equal to or greater than 6 we find that we are unable to dualize the theory into any form in which it can be reliably analyzed. Any attempt to dualize it to weak or intermediate coupling produces ultra-small compactification radii. Applying T-duality to increase the compactification radii inevitably leads to ultra-large coupling. From the field-theoretic side this may be connected with the lack of superconformal fixed points in space-time dimension greater than 6. What it means on the string or M-theoretic side is unclear. Perhaps it signals some sort of non-perturbative breakdown

of toroidal compactification. Resolving this point could have important implications for 4-dimensions.

Outline

- The problem & previous attempts
- Our strategy
- Consistency conditions (cf singularities)
- Candidate Examples

$$AdS_{\substack{5\\4}} \times \text{Small}_{\substack{5\\6}} \Leftrightarrow CFT_{\substack{4\\3}}$$

stabilized compactifications ⇔ IR limit of concrete brane systems (w/ SUSY)

- Generalizations toward dS

AdS/CFT (and previously, BFSS matrix theory) formulate some backgrounds non-perturbatively, but did not (yet) get down to 4d :

BFSS : 11d ↔ N D0-brane Q.M.

4d (max susy) ↔ $\underbrace{\text{D7-branes}}$ on T^7

↳ codim 2 → log potential → $N \le 24$

<u>AdS/CFT:</u> ① $\underbrace{AdS_2 \times S^2}_{\text{want } L_{AdS} \to \infty} \times \underbrace{CY}_{\text{small } \checkmark}$

↳ IR divergences in AdS_2

AdS/CFT ②

$$AdS_4 \times \underbrace{\left\{\begin{array}{ll} S^7 & (M) \\ S^7/\Gamma & \\ \mathbb{CP}^3 & (IIA) \end{array}\right.}_{L_{internal} \sim L_{AdS}}$$

No hierarchy of scales in Freund-Rubin compactifications.

Basic reason: In 11/10 d Einstein equations

$$\underbrace{R_{MN} - \tfrac{1}{2} R G_{MN}}_{\text{Internal} + 4d} = 8\pi G \underbrace{T_{MN}}_{\text{flux}}$$

all three contributions are of the same order in the solution

For future reference, let us reproduce this in the language of the 4d effective potential energy:

$$S = \int d^{10}x \frac{\sqrt{G}}{\alpha'^4}\left(\frac{R}{g_s^2} + F_p^2 + \cdots\right)$$

→ 4d potential energy

$$U_4 = \frac{1}{\alpha'^2}\left\{-\int d^6x \frac{\sqrt{G_6}\, R^{(6)}}{\alpha'^2 g_s^2} + \int d^6x \frac{\sqrt{G_6}\, F_p^2 + \cdots}{\alpha'^2}\right\}$$

$$\sim \frac{R^6}{\alpha'^2 g_s^2}\left(-\frac{1}{R^2} + \frac{g_s^2 Q^2}{R^{2p}} + \cdots\right)$$

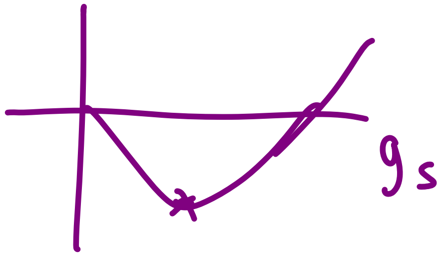
where $R \equiv$ size in string units.

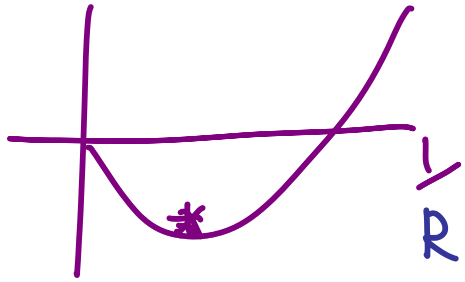
$$U_4 \sim M_p^4\left(\frac{g_s^2}{R^6}\right)\left(-\underset{\substack{\uparrow \\ U_R}}{\frac{1}{R^2}} + g_s^2 \underset{\substack{\uparrow \\ U_{F_p}}}{\frac{Q^2}{R^{2p}}} + \cdots\right)$$

in Einstein frame

e.g. IIA on $\mathbb{CP}^3$ w/ F_6 & F_2 :

$$\frac{U_4}{M_p^4} \sim -\frac{g_s^2}{R^8} + \frac{g_s^4 Q_2^2}{R^{10}} + \frac{g_s^4 Q_6^2}{R^{18}}$$





Equivalently

$$U_4 \sim M_p^2\left(\underbrace{-\frac{1}{R^2\alpha'} + \frac{g_s^2 Q^2}{R^{2p}\alpha'} + \cdots}_{``\Lambda \sim \frac{1}{R_{AdS}^2\alpha'}}\right)$$

i.e. $\Lambda_{\min} \sim \Lambda_{gR}$ in Freund-Rubin

- n.b. CFT_3 dual to IIA/$\mathbb{CP}^3$ is $\left\{\right.$ • IR limit of D2, D6, KK • strongly coupled CS
  or M thy / S^7/Γ

  Schwarz, BL, ABJM, et seq.

In fact there is a large class of 3d CFTs obtained via RG flow from gauge theory with flavors

Appelquist/Heinz HET
Sachdev.. CMT

$$\frac{1}{g^2} = \underbrace{\frac{1}{g_0^2}}_{\text{classical}} + \underbrace{\frac{\Delta N}{E}}_{\text{1-loop screening}} + \cdots$$

(In 3d $\mathcal{N}=4$, $\Delta N = N_f - 2N_c$
and this is exact)

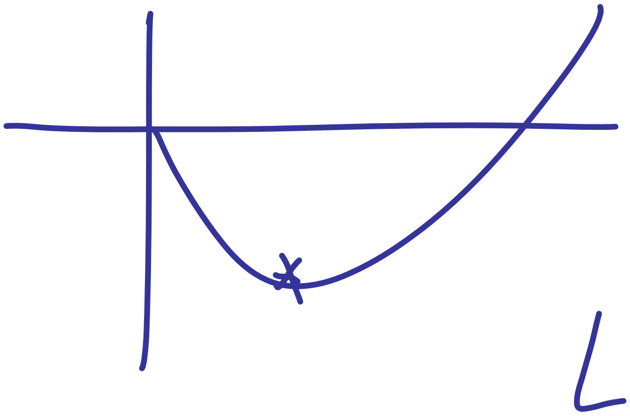
→ dimensionless coupling has fixed point

$$\frac{1}{\bar{g}^2} = \left.\frac{E}{g^2}\right|_{E\to 0} = \Delta N \underbrace{+ \cdots}_{}$$

controlled at large N_f independently of SUSY.

e.g. D2-D6, D2-D6-orbifold ; Hanany-Witten
... examples : still Freund-Rubin (or stringy)

Similarly, compactification on S^5 w/ F_5 → $AdS_5 \times S^5$



fixed line

$\Updownarrow$

$N=4$ SYM

$L_{AdS} \sim L_{S^5}$

In general, the negative term(s) in the potential are key

e.g. $\left\{ \begin{array}{l} \text{positive curvature} \\ \text{O-planes} \\ -3|W|^2 \end{array} \right.$

Coming from the other direction, we can construct

$$(A)dS_4 \times X_{small}$$

in an apparently large number of ways B^2s DRS BP MSS GKP+KKLT...

suggesting a rich set of dual CFT_3 s.

- Not a priori realized as near-horizon limit of brane system
- Can read off interesting properties:

$$N_{d.o.f.} \sim L^2_{(A)dS} M_p^2 \leq N^{b}$$

b ← betti #

← flux #

ES
BvdB
AAB

Plan: Start from known,
Freund-Rubin dual pair:

$$\underbrace{AdS \times S}_{} \leftrightarrow QFT$$

(at least brane construction)

add ingredients which cancel or nearly cancel U_R ⟷ additional field content, couplings of QFT

$$\overbrace{\text{stabilize the moduli} \rightarrow AdS_4} \leftrightarrow \overbrace{CFT_3}$$

$\underline{\underline{\text{7-branes}}}$ contribute to $\mathcal{U}$ naively as

$$\mathcal{U}_7 \sim M_p^4 \left(\frac{g_s^2}{R^6}\right)^2 \cdot \left(\underbrace{\tau_7}_{\text{tension in string units}} \cdot R^4 \right)$$

compare to curvature energy

$$\mathcal{U}_R \sim M_p^4 \left(\frac{g_s^2}{R^6}\right)^2 \cdot R^6 \cdot \left(-\frac{1}{R^2 g_s^2} \right)$$

$\Rightarrow$ for $\tau_7 \sim \frac{1}{g_s^2}$, i.e. (p,q) 7Bs,

cf Aharony Fayyazuddin Maldacena

they compete.

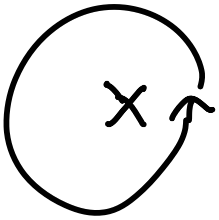
Of course 7Bs, being codimension 2, have large IR back reaction...

The interplay between curvature & 7-brane energy is accurately captured using the techniques of F-theory :

Vafa '96

$$\begin{tikzcd} T^2 \arrow[r] & X \arrow[d] \\ & B \end{tikzcd}$$

$$\tau_{T^2} = C_0 + \frac{i}{g_s} \quad \text{in IIB}$$



D7-brane: $\tau(u) \sim \frac{1}{2\pi i} \log u$

$\tau \to \tau + 1$ monodromy

(p,q) 7-brane $\tau \to \frac{(1+pq)\tau - p^2}{q^2\tau + (1-pq)}$

Plan: Start from

Freund-Rubin dual pair:

AdS × S ⟷ QFT
(brane construction)

add 7-branes which cancel or nearly cancel U_R ⟷ additional flavors* couplings of QFT

stabilize the moduli → AdS4 ⟷ CFT_3

* in general, both electric & magnetic cf Douglas/Shenker, Argyres/Douglas, Argyres-Plesser-Seiberg-Witten

Probing F-theory With Branes

Tom Banks

Michael R. Douglas

Nathan Seiberg

Department of Physics and Astronomy
Rutgers University
Piscataway, NJ 08855-0849
`banks, mrd, seiberg@physics.rutgers.edu`

Last week, A. Sen found an explicit type I string compactification dual to the eight-dimensional F-theory construction with $SO(8)^4$ nonabelian gauge symmetry. He found that the perturbations around the enhanced symmetry point were described by the mathematics of the solution of $\mathcal{N} = 2$, $d = 4$ $SU(2)$ gauge theory with four flavors, and argued more generally that global symmetry enhancement in $\mathcal{N} = 2$, $d = 4$ gauge theories corresponded to gauge symmetry enhancement in F-theory.

We show that these $\mathcal{N} = 2$, $d = 4$ gauge theories have a physical interpretation in the theory. They are the world-volume theories of 3-branes parallel to the 7-branes. They can be used to probe the structure of the exact quantum F-theory solutions. On the Higgs branch of the moduli space, the objects are equivalent to finite size instantons in the 7-brane gauge theory.

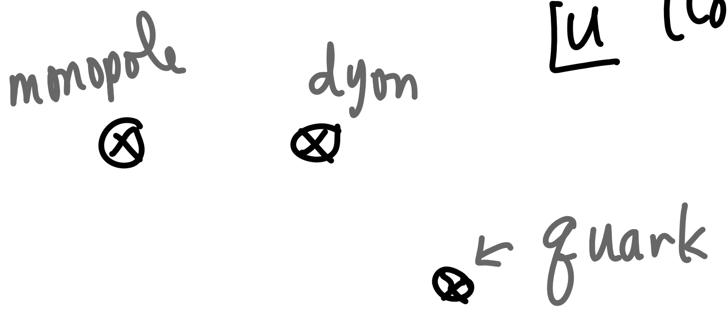
May 1996

D3, D7 and Electric/Magnetic Matter

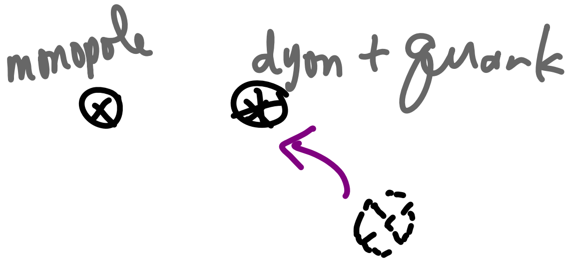
- 4d $\mathcal{N}=2$ SU(2) SYM w/ N_f hypermultiplets

$\lfloor u$ (Coulomb branch)

Seiberg-Witten solution



AD/APSW : can change mass matrix M such that mutually nonlocal matter is light.



- In brane constructions (Sen, Banks Douglas Seiberg ...)

$u \leftrightarrow$ D3 position

$\otimes \leftrightarrow$ 7B position $\qquad \tau_{YM} \leftrightarrow \tau_{IIB}$

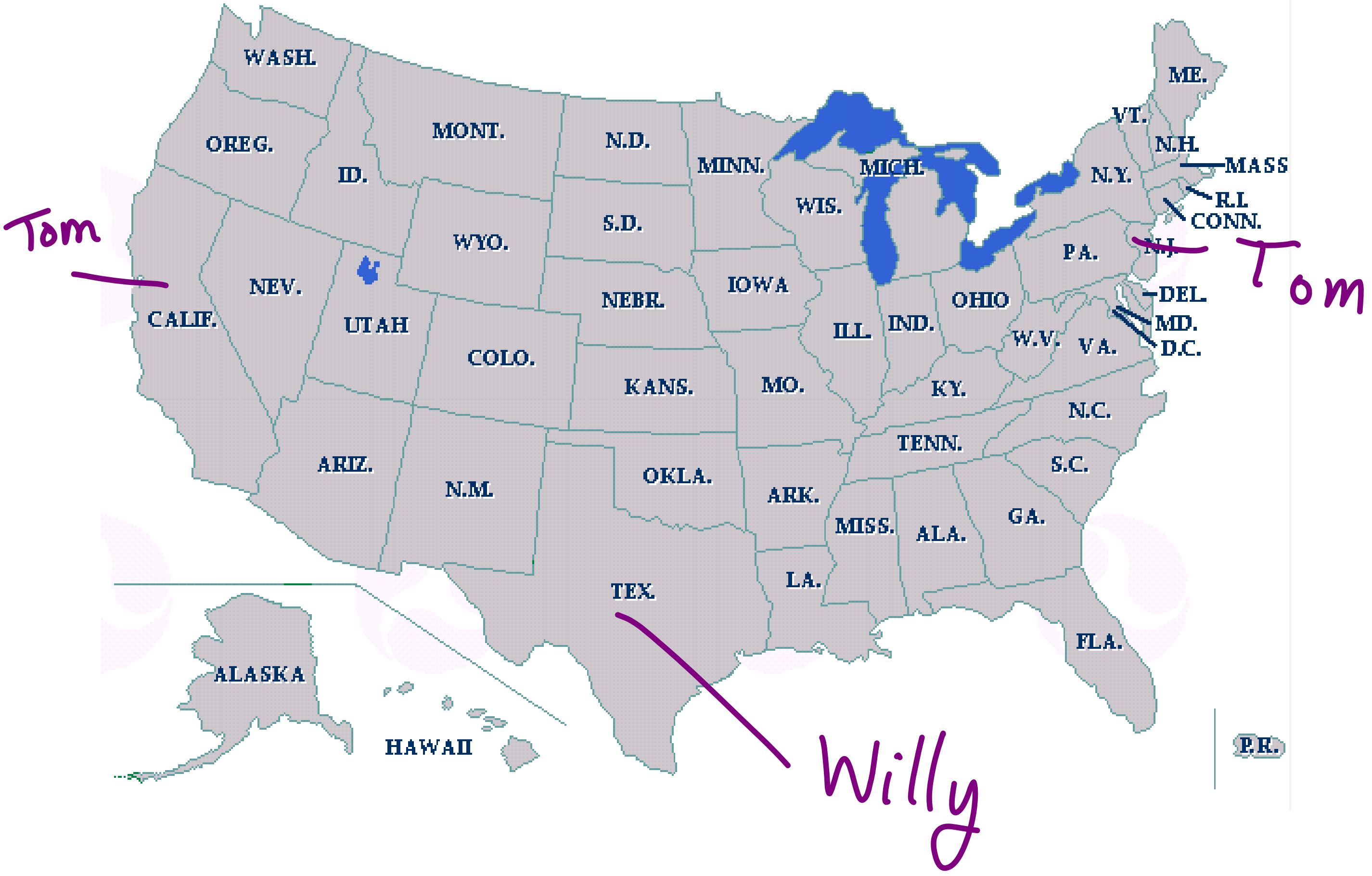
→ Can we unify

"West Coast" & "East Coast" physics?*

Landscape

QFTs from 3-7 systems

Existence proof:



* apologies to rest of world

The T^2 varying over B can be described as

Vafa
Morrison-Vafa
Kachru Intriligator
Morrison Vafa
...

$$y^2 - x^3 - x\underset{\uparrow}{f(u)}\, z^4 - \underset{\nearrow}{g(u)}\, z^6 = 0$$

coordinates on B

i.e. as a degree 6 hypersurface in $WP^2(2,3,1)$.

For a Kähler base B, one can formulate the T^2 fibration

$$\begin{tikzcd} T^2 \arrow[r] & X \arrow[d] \\ & B \end{tikzcd}$$

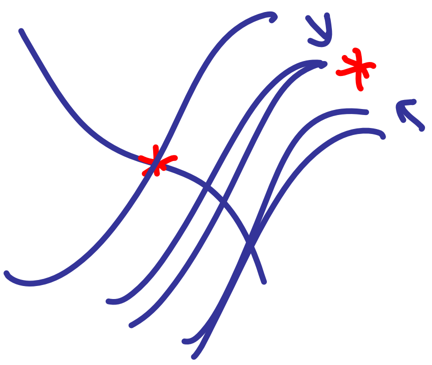
as a hypersurface in $B \times WP^2(2,3,1)$, and as the target space of a (2,2) gauged linear σ-model (GLSM) witten

7-branes live at the locus

$$\Delta = 27g^2 + 4f^3 = 0$$

Singularities

- Some allowed (e.g. enhanced gauge symmetries)

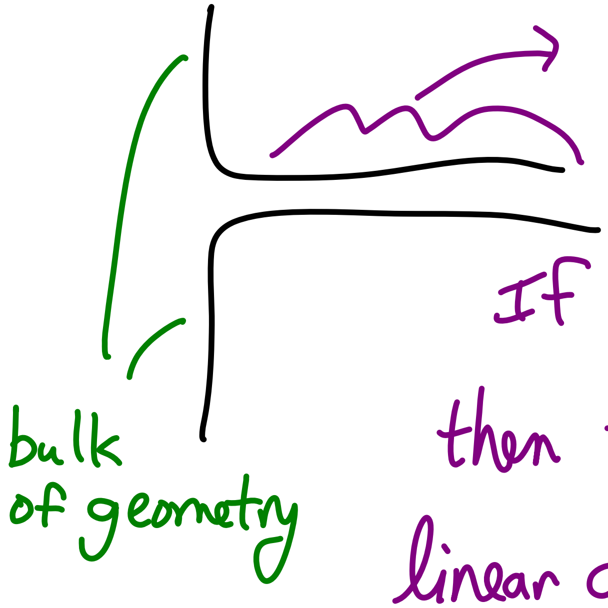


- Some not allowed

A criterion for allowed singularities:

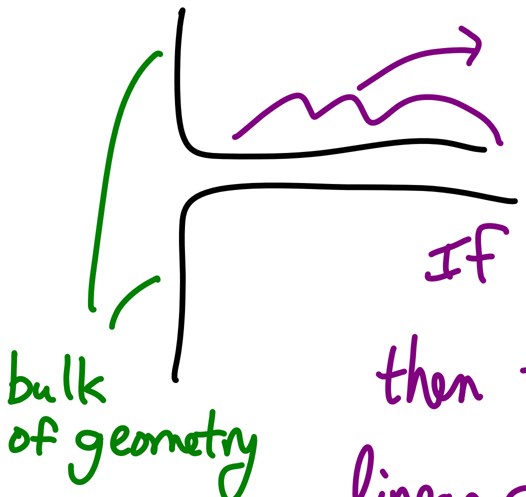
cf W, SW '90s

In the GLSM, singularities arise from extra non-compact branches of scalar field space



Compute (using GLSM) $\hat{c}_{\text{throat}}$:

If $\hat{c}_{\text{throat}} \geq \hat{c}_{\text{bulk}}$ then truly singular. (Otherwise linear dilaton → mass gap in throat)



→ Compute (using GLSM) $\hat{c}_{\text{throat}}$:

If $\hat{c}_{\text{throat}} \geq \hat{c}_{\text{bulk}}$ then truly singular. (Otherwise linear dilaton → mass gap in throat)

This agrees with known cases ...

e.g. $$\int d^2\theta \, P\left(y^2 - X^3 - x \overset{\sim 0}{f(u)} z^4 - \overset{\sim u^n}{g(u)} z^6\right)$$

branch with $\underbrace{\langle p\rangle \overset{(\text{D-term})}{\sim} \langle z\rangle}_{\hat{c}=1}$; $Y = X = 0 = u$

$\hat{c}_Y = 0$ (massive)

$\hat{c}_X = \frac{1}{3}$

$\hat{c}_u = 1 - \frac{2}{n}$

$\Rightarrow$ singular if $n \geq 6$ ✓

... and can be applied widely

Let us start with IIB on

$Y_5 \times S^1$ with $\int_Y F_5 = N_c$

where Y_5 is an S^1 (Hopf) fibration over a Kähler base

(7-branes will be extended along fiber) →

$$\begin{tikzcd} S^1_f \arrow[r] & Y \arrow[d] \\ & B \end{tikzcd}$$

← First study 7-branes on B

Examples: $Y = S^5$, $B = \mathbb{CP}^2$ or $\mathbb{WP}^2$

Topologically $S^2 \times S^3$ $\left\{ \begin{array}{ll} Y = T^{1,1} & B = \mathbb{CP}^1 \times \mathbb{CP}^1 \\ Y = Y^{pq} & B = \ldots \\ Y = L^{abc} & B = \ldots \end{array} \right.$

Klebanov/Tseytlin/Strassler

Gauntlett Martelli Sparks Waldram

Cvetic Liu Pope

can have many 3-cycles $\left\{ \begin{array}{l} \text{base of toric } CY_3 \text{ cones} \\ \text{" " non-toric "} \end{array} \right.$

Hanany...

Martelli/Sparks/Yau

$$\begin{tikzcd} S^1_f \arrow[r] & Y \arrow[d] \\ & B \end{tikzcd}$$

size R_f

size R

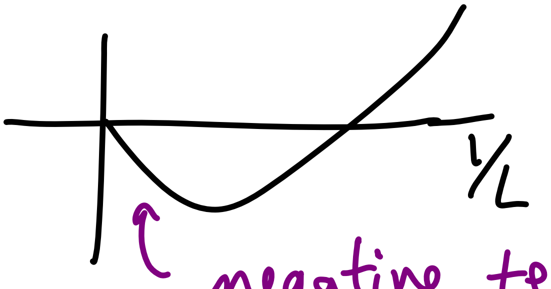
$\cong$ B with "metric flux" $F_{met} = J_B$

(useful description for small fiber)

Two classes of candidate examples:

① 7-branes <u>fully</u> cancel curvature energy: e.g. 36 7-branes on $\mathbb{CP}^2$

$$U_R + U_7 = 0$$ (F-theory on CY)



negative term from O-planes

$$R_{AdS} \gg R \gg R_f$$

② 7-branes <u>nearly</u> cancel $U_R^{(B)}$

$Y \times S^1_\perp \times AdS_4$

$\frac{Q_3^2}{R_\perp^2 R^4}$

$$\mathcal{U}\Big|_{g_s\sim 1} \sim M_p^4 \left(\frac{1}{R^4 R_6 R_f}\right)\left(\frac{R_f^2}{R^4} - \frac{\varepsilon}{R^2} + \frac{N_c^2}{R^8 R_f^2} + \frac{Q_1^2}{R_\perp^2}\right)$$

enforce with e.g. E_n 7-branes

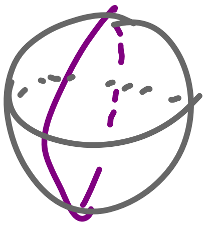
↳ stable minimum with $R_f \ll R \ll R_{AdS}$

Related (simpler) AdS_5 model:

$$\mathcal{U}\Big|_{g_s\sim 1} \sim \frac{M_5^5}{(R^5 R_f)^{2/3}}\left(\frac{R_f^2}{R^4} - \frac{\varepsilon}{R^2} + \frac{N_c^2}{R^8 R_f^2}\right)$$

* Are 7-brane moduli tachyonic?

On S^5



allowed tachyon for $R \sim R_{AdS}$
but what about $R \ll R_{AdS}$?

Note that 7-brane moduli

$$y^2 - x^3 - x\,\overbrace{f(u)}\,z^4 - \overbrace{g(u)}\,z^6 = 0$$

are flat directions in the CY
and nearly flat for $U_R \propto \frac{\varepsilon}{R^2}$

To get started, consider

$$Y = S^5 \quad \text{(topologically)}$$

Start from the $\mathbb{CP}^2$ model:

(2,2) chiral multiplets u_1, u_2, u_3

U(1) Gauge symmetry

$$(u_1, u_2, u_3) \simeq e^{2\pi i \alpha}(u_1, u_2, u_3)$$

$$\Rightarrow D^2 = \left(|u_1|^2 + |u_2|^2 + |u_3|^2 - R^2\right)^2$$

↪ $D = 0$ alone gives S^5

→ α parameterizes S^1_{fiber}

$$\begin{tikzcd} S^1_f \arrow[r] & S^5 \arrow[d] \\ & \mathbb{CP}^2 \end{tikzcd}$$

$$ds^2_{S^5} = d\sigma^2_{\mathbb{CP}^2} + R_f^2(d\alpha + A)^2$$

$$dA = J$$

Gibbons, Pope

To add the 7-branes, want a T^2 fibration over $B = \mathbb{CP}^2$

Gauged Linear σ-model becomes

	u_1	u_2	u_3	x	y	z	P
$T^2 \{ U(1)$	0	0	0	2	3	1	-6
$\times$ $\mathbb{CP}^2 \{ U(1)$	1	1	1	q_x	$\frac{3}{2} q_x$	0	$-3q_x$

$$S_W = \int d^2\sigma \, d^2\theta \; P\left(y^2 - x^3 - f(u)\, x z^4 - g(u)\, z^6\right)$$

Now, $\sum_{\text{fields } I} q_I = 0$ is the Calabi-Yau condition (ensuring anomaly-free $U(1) \times U(1)$ R-symmetries appropriate to (2,2) SCFT)

Witten

The running of R^2 in

$$D^2 = \left(|u_1|^2 + |u_2|^2 + |u_3|^2 + q_x |x|^2 + \frac{3}{2} q_x |y|^2 - |p|^2 - R^2 \right)^2$$

is $\quad M \dfrac{\partial R^2}{\partial M} \sim \sum_I q_I$

Now $\quad \sum q_I = 3 - \frac{1}{2} q_x$

and the degree of $G = y^2 - x^3 - f x z^4 - g z^6$

is $\quad \deg_G = \deg_g = 3 q_x = 18 - 6 \sum q_I$

<u>Fully</u> canceling curvature energy means $\sum q_I = 0 \Rightarrow \deg_g = 18$

$\Rightarrow \deg \Delta = 36 \Rightarrow$ 36 7-branes

(This agrees with naive result from $\mathcal{U}_7 \sim \cdots (Y_7 \times \mathrm{vol})$ ✓)

- The 7Bs are extended along U(1) fiber

As next step, generalize to cases where we do <u>not</u> fully cancel the curvature energy. Consider

T^2 fibration over $B = \underline{\underline{W}}\mathbb{P}^2$

Gauged Linear σ-model

	u_1	u_2	u_3	x	y	z	p
$T^2 \{ U(1)$	0	0	0	2	3	1	-6
$\times$							
$W\mathbb{P}^2 \{ U(1)$	$\underline{\underline{w_1}}$	$\underline{\underline{w_2}}$	$\underline{\underline{w_3}}$	0	0	$w_0 - \Sigma w$	0

$$S_W = \int d^2\sigma\, d^2\theta\; P\left(y^2 - x^3 - f(u)\, x z^4 - g(u)\, z^6 \right)$$

Again $\beta_{R^2, \text{full}} \sim \Sigma q = w_0$

in the full system including the 7Bs.

Again $\beta_{R^2, \text{full}} \sim \sum q = W_0$ in the full system including the 7Bs.

For WP^2 alone,

$$\beta_{R^2, WP^2} = W_1 + W_2 + W_3$$

$\Rightarrow$ If $W_0 << W_1 + W_2 + W_3$

then we almost cancel the curvature.

$$\to \quad \mathcal{U}_{R, \text{full}} \sim M_p^4 \left(\frac{g_s^2}{\text{Vol}}\right)^2 \cdot \text{Vol.} \left(-\frac{\varepsilon}{R^2}\right)$$

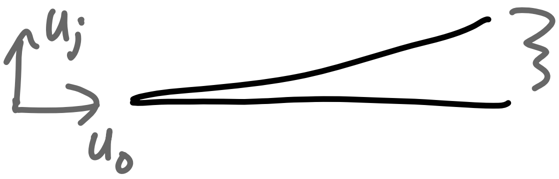
with $\boxed{\varepsilon \sim \frac{W_0}{W_1 + W_2 + W_3}}$

(using the NLSM result $\beta \sim R_{MN}$)

We can describe the full brane system (whose low-energy limit is the QFT) as F-theory on the following noncompact $\underline{\underline{CY_4}}$:

u_0	u_1	u_2	u_3	x	y	z	P
0	0	0	0	2	3	1	-6
$-w_0$	$\underline{\underline{w_1}}$	$\underline{\underline{w_2}}$	$\underline{\underline{w_3}}$	0	0	$w_0-\Sigma w$	0

- $\Sigma w = 0$ overall; cross-section geometry as above



small if $w_0 \ll w_j : w_0 |u_0|^2 \sim w_j |u_j|^2$

- This + N_c D3-branes at tip $(u_0 = u_j = 0)$ is the brane construction.

Altogether preserves 4 supercharges.

* What about the singularities of $WP^2(w_1, w_2, w_3)$?

$$(u_1, u_2, u_3) \simeq (\lambda^{w_1} u_1, \lambda^{w_2} u_2, \lambda^{w_3} u_3)$$

→ for $\lambda = e^{\frac{2\pi i}{w_1}} \in U(1)$

$(u_1, 0, 0)$ is a (generally non-SUSY) $\mathbb{C}^2/\mathbb{Z}_{w_3}$ orbifold fixed point.

By itself*, this has twisted tachyons which condense, smoothing it out

Adams
Polchinski
ES ...
.. Morrison ..

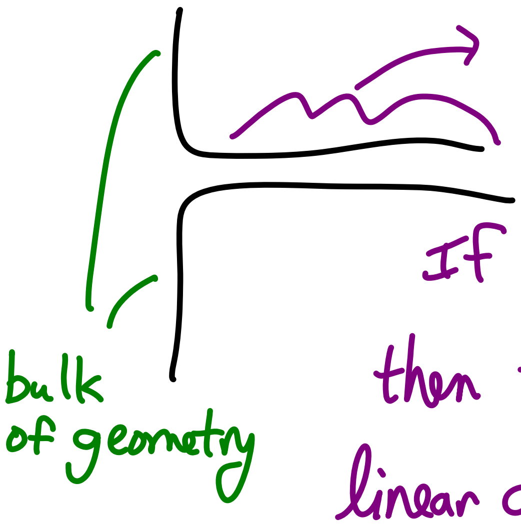
* Don't Panic! • Must include 7-branes

can restore SUSY

• and S^1_{fiber} : Removes $U(1)$ projection entirely

* full brane construction is supersymmetric

* Singularities of 7-branes:



compute (using GLSM) $\hat{c}_{\text{throat}}$:

If $\hat{c}_{\text{throat}} \geq \hat{c}_{\text{bulk}}$ then truly singular. (Otherwise linear dilaton → mass gap in throat)

w_0	W_1	W_2	W_3	z
-1	1	n	n	$-2n$

→ nonsingular but anisotropic

w_0	W_1	W_2	W_3	z
$-w_0$	$w-\delta$	w	$w+\delta$	w_0-3w

isotropic but singular $g \sim \sum_I \underbrace{u_1^{I}\, u_2^{18+\frac{3w_0}{\delta}-2I}}\, u_3^{I-\frac{3w_0}{\delta}}$

high degree → high $\hat{c}$

Generalizations ($\simeq$ isotropic, nonsingular)

$\underbrace{\text{More}}$ fields + more conditions

- e.g.

$$\begin{array}{c|cccc|c|c} u_0 & u_1 & u_2 & u_3 & \overline{u_4} & z & \overline{P_2} \\ -w_0 & w-\delta & w-\delta & w+\delta & w+\delta & w_0-2w & -2w \end{array}$$

with superpotential

$$\int d^2\theta \left\{ P\left(Y^2 - X^3 - \cdots - Z^6 g\right) + P_2\left(\lambda_1 u_1 u_3 + \lambda_2 u_1 u_4 + \lambda_3 u_2 u_3 + \lambda_4 u_2 u_4\right) \right\}$$

lower degree than above

nonsingular, isotropic

-

$$\begin{array}{c|ccc|c} u_0 & u_1 & \cdots & u_D & z \\ -w_0 & w_1 & \cdots & w_D & w_0 - \Sigma w \\ 0 & Q^a_1 & \cdots & Q^a_D & -\Sigma Q^a \end{array}$$

$a = 1 \ldots D-3$ extra $U(1)$ conditions

The string coupling

7-branes corresponding to mutually non-local flavors have $g_s \sim 1$

$\otimes$ e.g. $\tau \sim e^{\frac{i\pi}{3}}$ $f(u) = 0$ branch

Dasgupta/Mukhi

In a (near-) SUSY background, the (approximate-) moduli are

- R^2 (GLSM D-term)
- polynomial coefficients in f, g

(other modes of the metric + dilaton have KK-scale masses $\sim \frac{1}{R\sqrt{\alpha'}}$.)

In the LSM, f + g are superpotential couplings $\Rightarrow$ don't run even at $\mathcal{O}(\varepsilon)$

$\Rightarrow$ expect $|m^2| \leq \mathcal{O}(\varepsilon^2)$

Sen Limit

In F theory, $\exists$ limit (Sen)

$$f = -3h^2 + \epsilon\eta \qquad \varepsilon \to 0$$

$$g = -2h^3 + \varepsilon h\eta - \varepsilon^2\frac{\chi}{12}$$

for which $g_s \to 0$. i.e. all the (p,q) 7-branes boil down to O7-planes + D7-branes

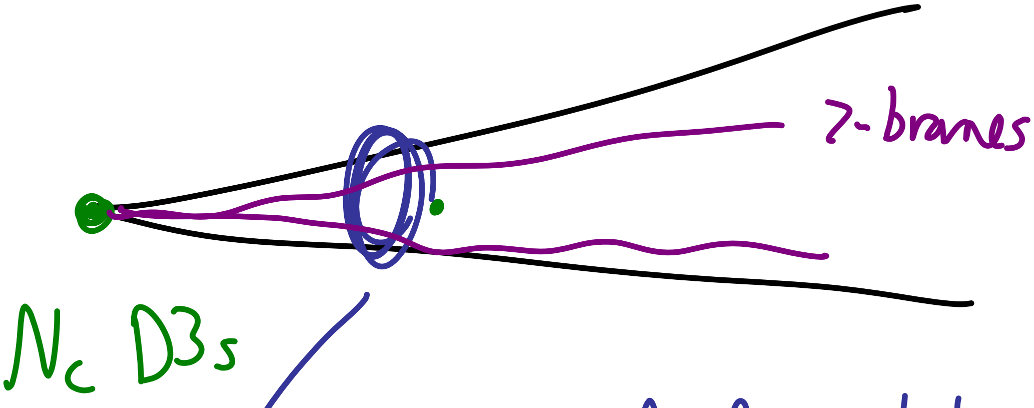
Such examples, if they can also be stabilized (including g_s), would be purely electric on the QFT side.

Number of degrees of freedom:

AdS_5 :

$$N^{(7Bs)}_{d.o.f.} \sim M_5^3 \, R_{AdS}^3 \sim \frac{1}{\varepsilon^3} \cdot N^{(no\ 7Bs)}_{d.o.f.}$$

$$R_f \sim \varepsilon R_{AdS} \,, \quad R^2 \sim \varepsilon \, R_{AdS}^2$$



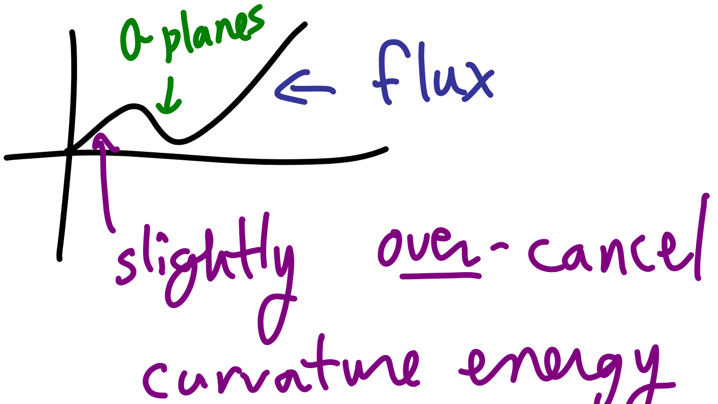
↳ # of light states

$$\sim \frac{1}{(\varepsilon^{\frac{1}{2}})^4} \cdot \frac{1}{\varepsilon} \sim \frac{1}{\varepsilon^3}$$

Future directions

- QFT content & couplings from brane system

- dS$_4$:



→ Now no tachyons are allowed.

- GKP + KKLT use 7-branes (F-theory) and have 5-form flux. Interpret as above?