Title: Towards Realistic Flux Vacua

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Abstract:

Towards Realistic Flux Vacua

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Outline

- **Motivation**
  - Why Fluxes?
  - D-branes and chirality
- **Model Building**
  - Magnetized D-branes
  - An MSSM-like example
- **Some Phenomenology**
  - Higgsing as D-brane recombination
  - Moduli lifting and soft terms

Why Fluxes?

$D = 4$ Compactifications:

- Standard $\mathcal{N} = 1$ Calabi-Yau string compactifications suffer from two well-known problems of string phenomenology
  - Moduli stabilization
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- Generalizations to compactifications with background fluxes may help solving both since
  - Most moduli get lifted by an effective potential
  - SUSY can be broken in a controlled way

Fluxes in Type IIB

- Type IIB flux compactifications provide an interesting framework for realizing these ideas. Introducing a non-trivial 3-form flux

$$G_3 = F_3 - \tau H_3 \qquad \begin{cases} F_3 & \text{RR flux} \\ H_3 & \text{NSNS flux} \\ \tau & \text{complex dilaton} \end{cases}$$

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→ Generates a superpotential W which freezes the complex structure moduli and dilaton

[Gukov, Vafa, Witten]
[Dasgupta, Rajesh, Sethi]

→ Induces soft terms in gauge theories living on D-branes

[Cámara, Ibáñez, Uranga]
[Graña, Grimm, Jockers, Louis]
[Lüst, Reffert, Stieberger]

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→ Generates a superpotential W which freezes the complex structure moduli and dilaton [GVW,DRS]

→ Induces soft terms in gauge theories living on D-branes [CIU,GGJL,LRS]

- In addition, this class of supergravity backgrounds
  - Embed the Randall-Sundrum scenario by means of a warped metric [Giddings, Kachru, Polchinski]
  - Admit the construction of de Sitter vacua [Kachru, Kallosh, Linde, Trivedi]

Good. But... where is the SM?

- Type IIB flux compactifications naturally involve D-branes, which yield $U(N)$ gauge theories at low energies.

- However, most of the flux literature is based on $\mathcal{N} = 1$ vacua whose gauge theories are too simple: no chiral fermions arise.

Good. But... where is the SM?

- Type IIB flux compactifications naturally involve D-branes, which yield $U(N)$ gauge theories at low energies.
- However, most of the flux literature is based on $\mathcal{N} = 1$ vacua whose gauge theories are too simple: no chiral fermions arise.
- We know how to achieve chiral vacua in Calabi-Yau compactifications so...

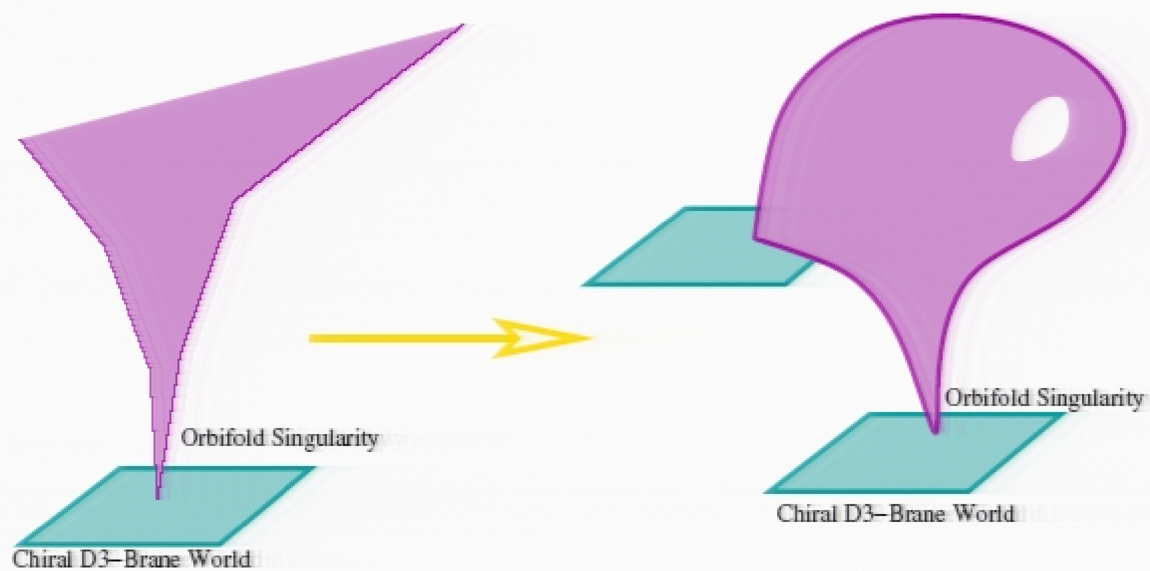
$$\Downarrow$$

IDEA

Implement the mechanisms for obtaining D=4 chiral vacua within flux compactification

D-branes & chirality

- Two known ways to achieve chirality in type IIB flux compactification
  - D-branes at singularities [Cascales, García del Moral, Quevedo, Uranga]



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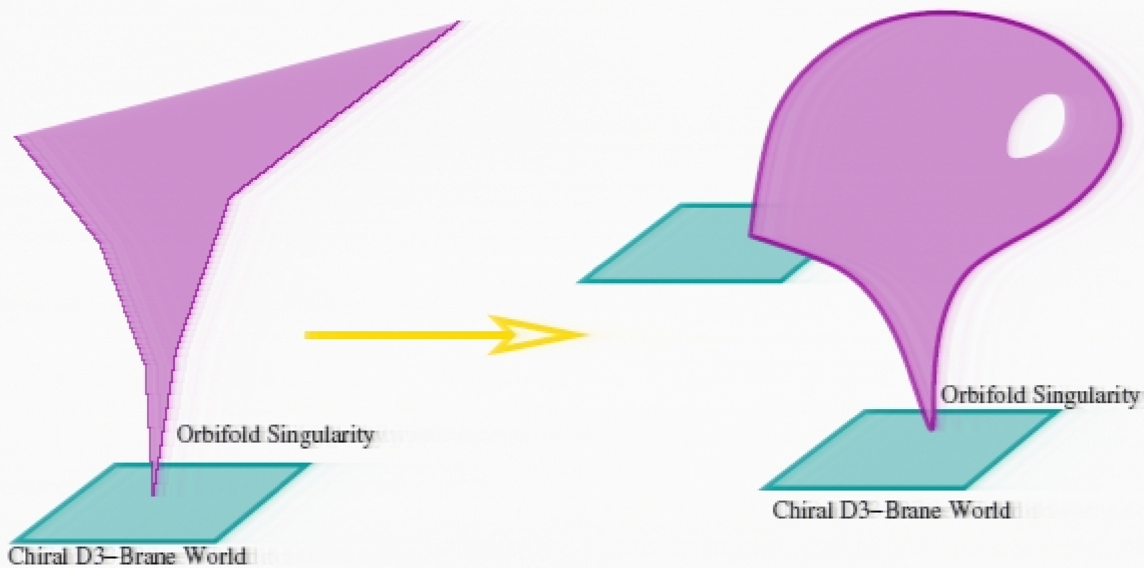
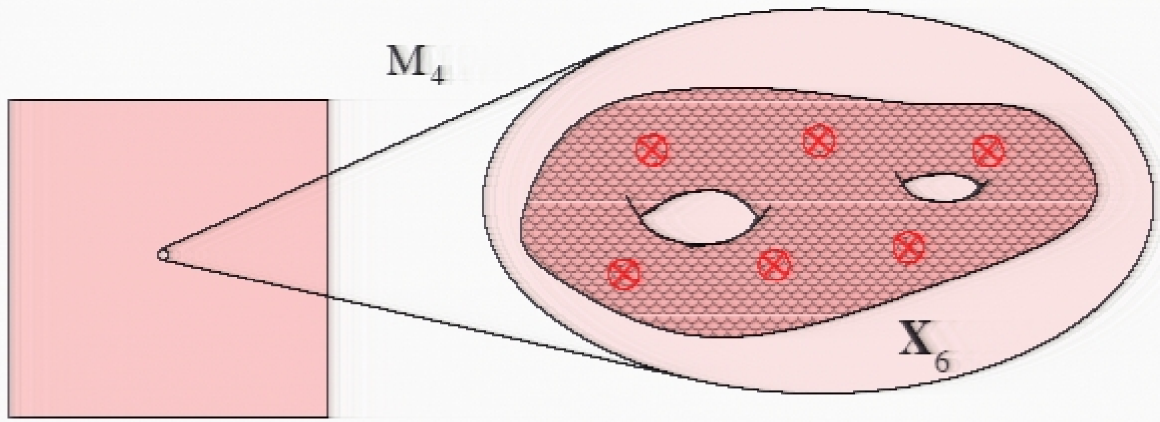


J. Cascales' talk

  - Easier to embed in a warped throat, in a bottom-up fashion
  - Good understanding of the holographic gauge dual
  - Simple soft term pattern

D-branes & chirality

- Two known ways to achieve chirality in type IIB flux compactification
  - Magnetized D-branes [Blumenhagen, Lüst, Taylor], [Cascales, Uranga]



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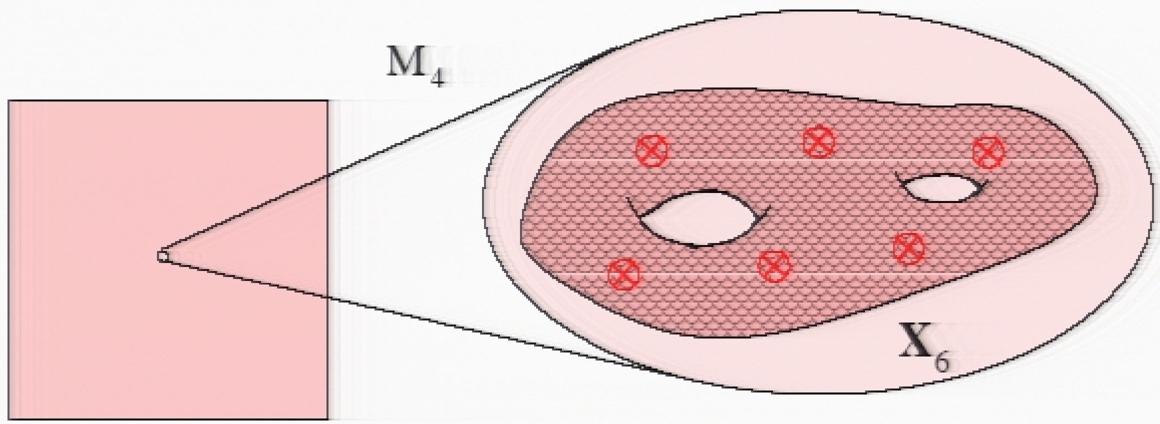

  - First examples of type IIB $\mathcal{N} = 1$ chiral flux compactifications [F.M., Shiu]
  - They also admit chiral $\mathcal{N} = 0$ D=4 Minkowski vacua, with a $D = 10$ supergravity description
  - SUSY softly broken in the D-brane sector, with a richer and very interesting soft-term pattern [Ibáñez]

What are magnetized D-branes?

- Magnetized D-branes are type IIB D($2n + 3$)-branes, filling M_4 and wrapping $2n$-cycles in the compact space X_6.

- They can carry a non-trivial gauge connection A_μ in their worldvolume, such that $F = dA \neq 0$ in the internal coordinates.

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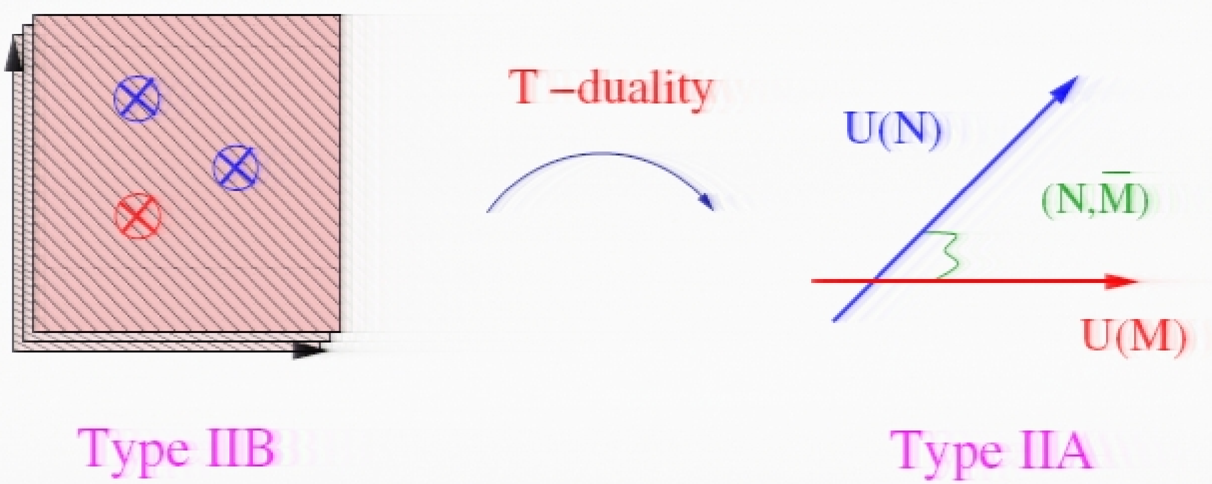
- Just as in the Heterotic string, a non-trivial $F_{\mu\nu}$ allows to obtain a $D = 4$ chiral theory at low energies. [Bachas,BGKL,AADS]

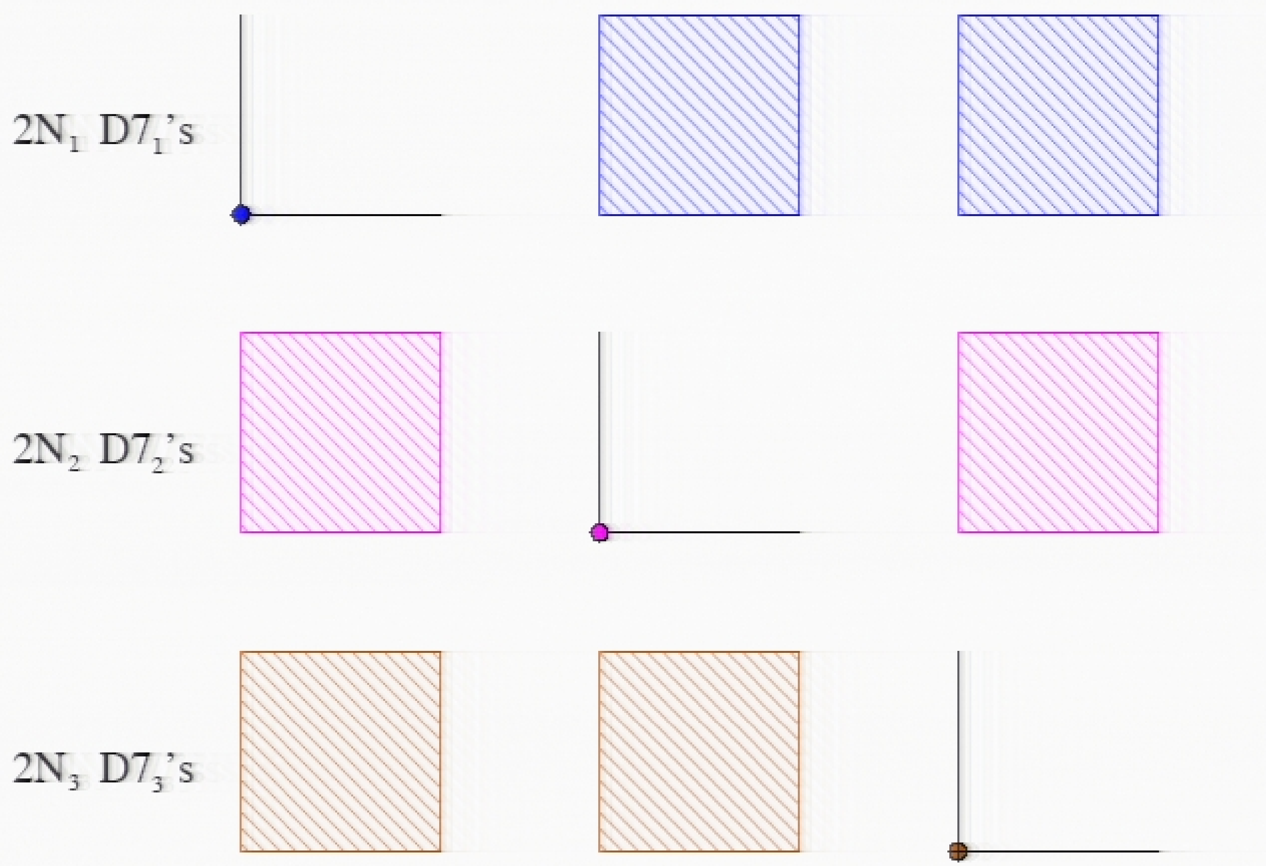
- These constructions are T-dual to type IIA Intersecting D6-branes. [Berkooz, Douglas, Leigh]



Magnetizing D-branes

$$USp(2N_1) \times USp(2N_2) \times USp(2N_3)$$

$$(2N_1, 2N_2, 1) + (2N_1, 1, 2N_3) + (1, 2N_2, 2N_3)$$



Getting a Left-Right MSSM

- The previous example allow us to achieve a semi-realistic spectrum, by using the identity $USp(2) \simeq SU(2)$

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$$g(4,2,1) + g(\bar{4},1,2) + (1,2,2)$$

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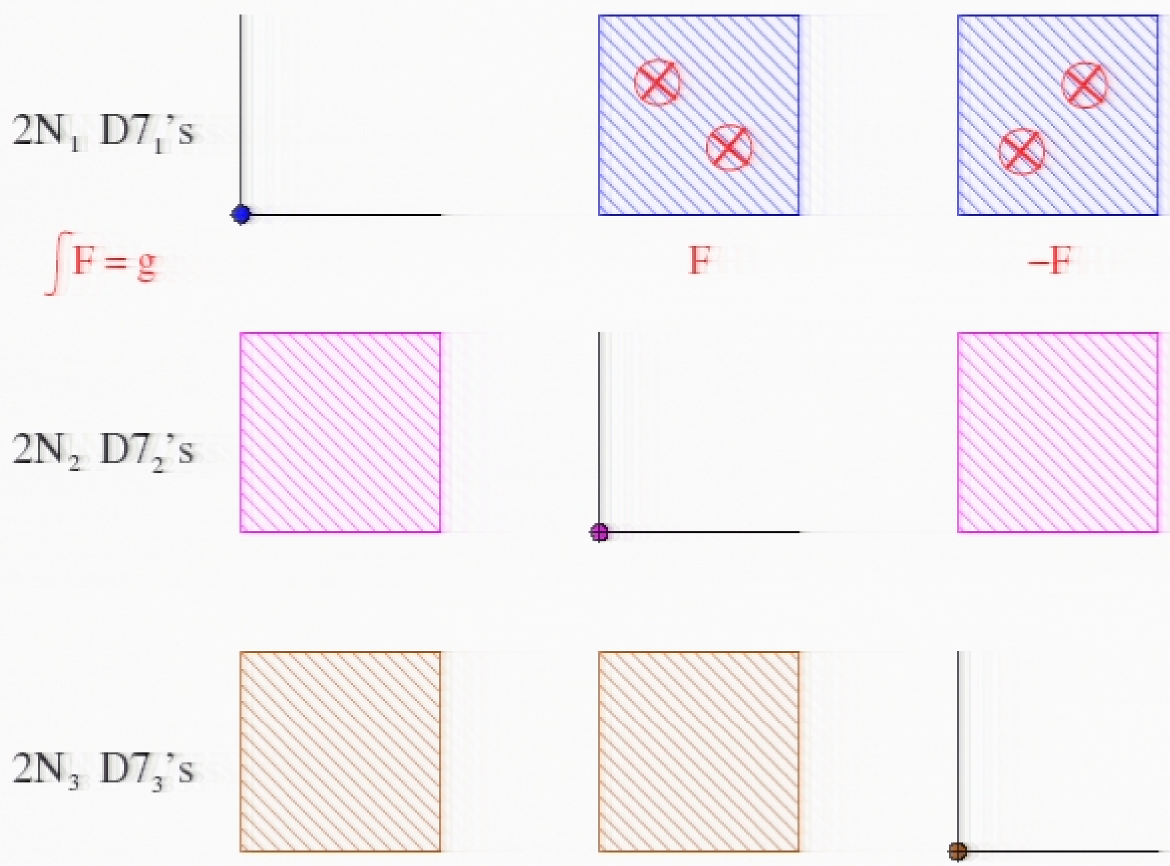

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- By performing an adjoint Higgsing of $U(4)$, we obtain a Left-Right MSSM spectrum with g generations of chiral matter

[Cremades, Ibáñez, F.M.]

$$SU(3) \times SU(2) \times SU(2) \times U(1)_{B-L}$$

$$g(3,2,1)_{1/3} + g(\overline{3},1,2)_{-1/3}$$
$$g(1,2,1)_1 + g(1,1,2)_{-1}$$
$$(1,2,2)$$

Constructing a Flux Compactification

- We need to embed the previous model in a fully-fledged global flux compactification.
- This has been shown to be possible for a simple orientifold background

G. Shiu's talk last week

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  – Metric background $\mathrm{T}^6/(\mathrm{Z}_2 \times \mathrm{Z}_2) \xrightarrow{\Omega\mathcal{R}}$ O3 and O7-planes

  [Berkooz, Leigh]

  – Admits constant ISD fluxes of the form

$$G_3 = G_{\bar{1}23}\, d\bar{z}_1 dz_2 dz_3 + G_{1\bar{2}3}\, dz_1 d\bar{z}_2 dz_3 + G_{12\bar{3}}\, dz_1 dz_2 d\bar{z}_3 + G_{\bar{1}\bar{2}\bar{3}}\, d\bar{z}_1 d\bar{z}_2 d\bar{z}_3$$

SUSY breaking

  – Consistency conditions

$$\left.\begin{array}{l}\text{Usual RR tadpoles} \Leftrightarrow \text{Chiral anomalies} \\ \text{K}-\text{theory torsion charges} \Leftrightarrow \text{SU(2) Witten's anomalies}\end{array}\right\}$$

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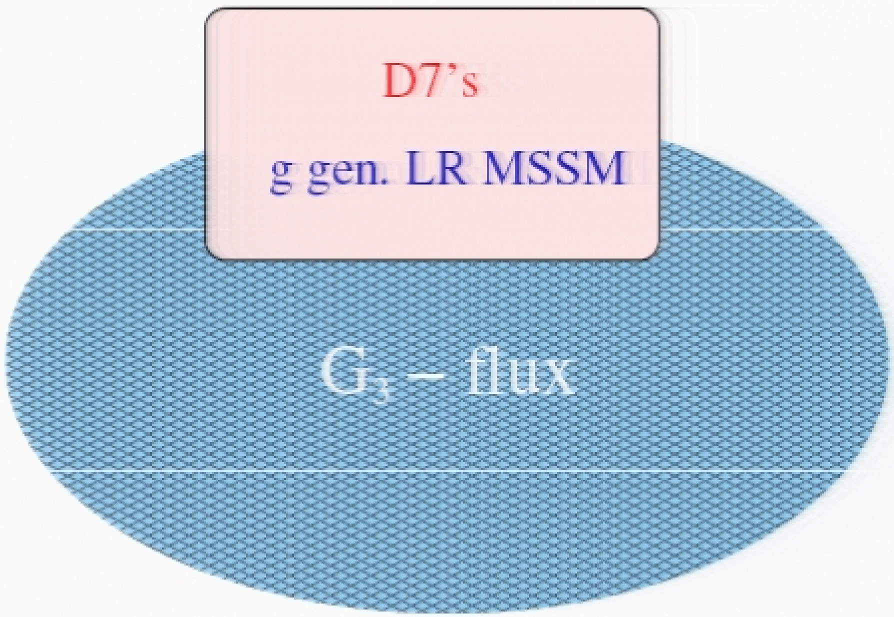
$$\Downarrow$$

$\mathcal{N} = 1$ requires magnetized $D9 - \overline{D9}$ pairs

A Cartoon



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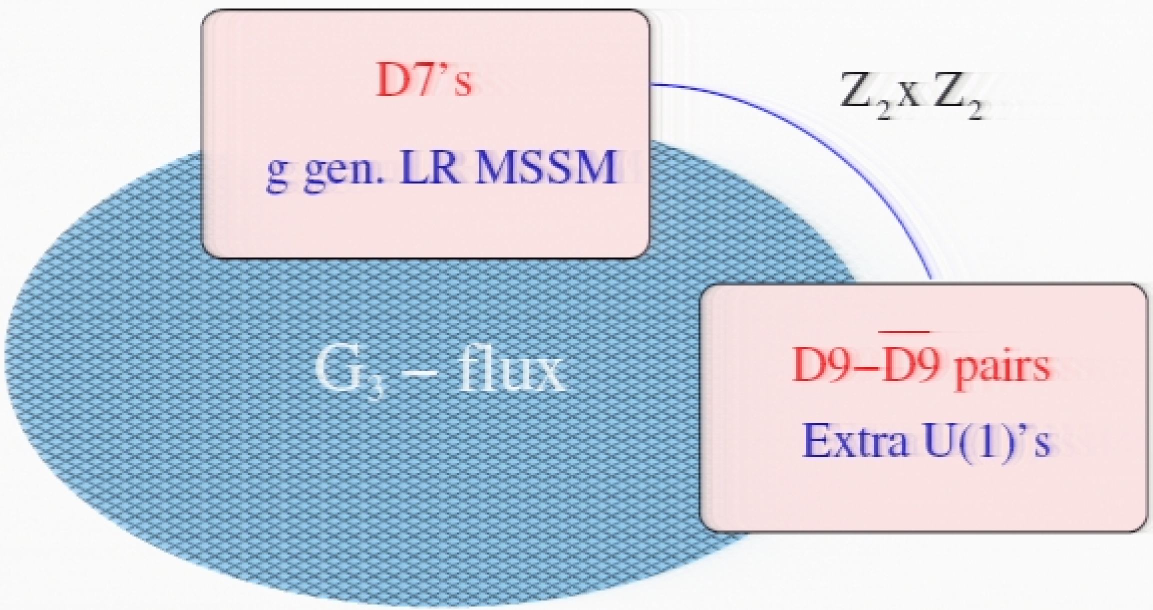
D7's
g gen. LR MSSM
Z_2x Z_2
G_3 – flux
D9–$\overline{\text{D9}}$ pairs
Extra U(1)'s

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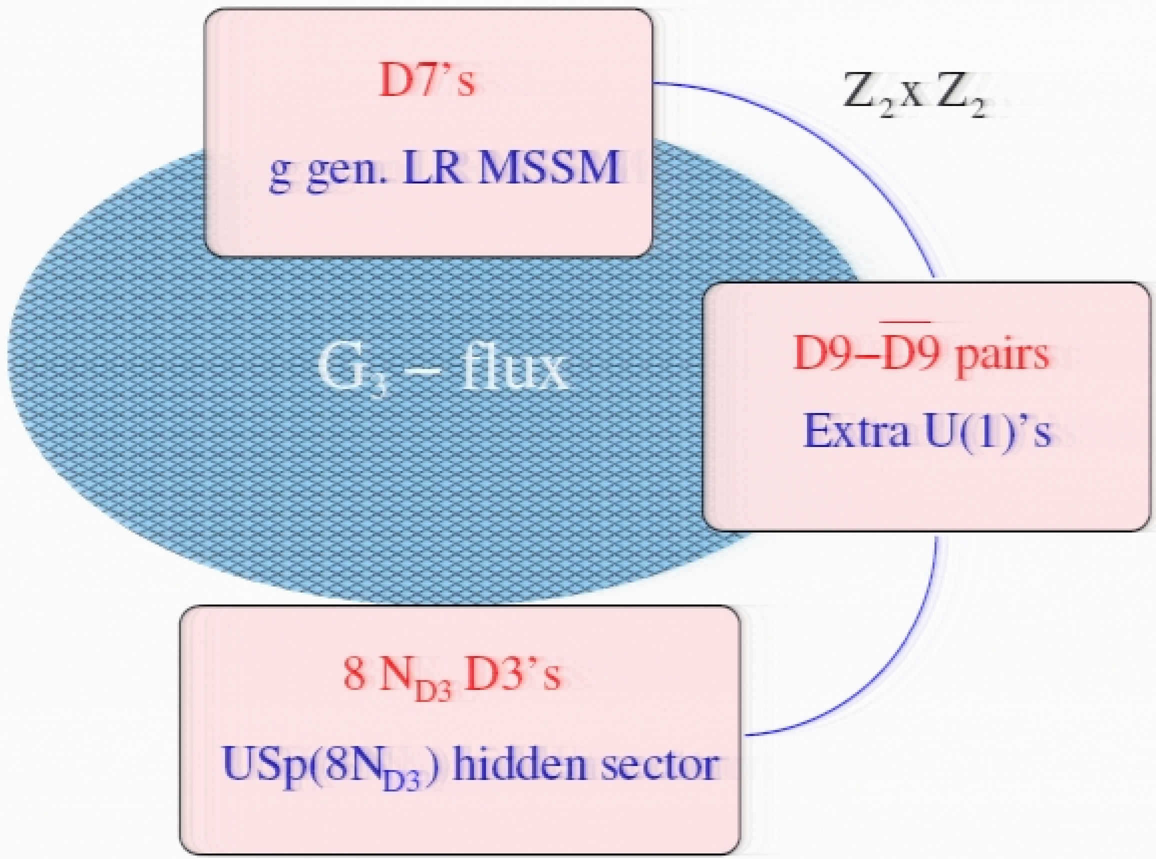
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Extra U(1)'s
8 N_{D3} D3's
USp($8N_{D3}$) hidden sector

Statistics?

- The number of models I'm going to describe is of order 10^0

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  . . . so not much vacua statistics you can do today

- However, the underlying techniques used in this construction are the same as the ones used in, i.e., getting MSSM vacua in Gepner models

  [Dijstra,Huiszoon,Schellekens]

- It is then not unlikely that a landscape of MSSM flux vacua is out there

- Building and studying a simple example may give us the key to access such hypothetical plethora of models

Solutions

- RR tadpoles are satisfied if

$$g^2 + N_{D3} + 4n = 14 \qquad \begin{cases} g & = \text{ \# generations} \\ N_{D3} & \rightarrow \text{ \# D3}-\text{branes} \\ n & \rightarrow \text{ amount of } G_3 \text{ flux} \end{cases}$$

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which admits several solutions

- $n = 3, \quad g = 1, \quad N_{D3} = 1 \quad \Rightarrow \quad \mathcal{N} = 1$ chiral flux compactification
- $n = 2, \quad g = 2, \quad N_{D3} = 2$
- $n = 1, \quad g = 3, \quad N_{D3} = 1$
- $n = 0, \quad g = 3, \quad N_{D3} = 5$

$$G_3 = \frac{8}{\sqrt{3}} e^{-\frac{\pi i}{6}} (d\bar{z}_1 dz_2 dz_3 + dz_1 d\bar{z}_2 dz_3 + dz_1 dz_2 d\bar{z}_3)$$

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- $n = 1, \quad g = 3, \quad N_{D3} = 1 \quad \Rightarrow$ 3-gen. $\mathcal{N} = 0$ flux compactification
- $n = 0, \quad g = 3, \quad N_{D3} = 5$

$$G_3 = 2\,(d\bar{z}_1 dz_2 dz_3 + dz_1 d\bar{z}_2 dz_3 + dz_1 dz_2 d\bar{z}_3 + d\bar{z}_1 d\bar{z}_2 d\bar{z}_3)$$

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The spectrum

- The low energy gauge group of these models is given by

$$[SU(3) \times SU(2) \times SU(2) \times U(1)_{B-L}]_{D7}$$
$$[U(1)']_{D7+D9} \times [USp(8N_{D3})]_{D3}$$

$$U(1)' = \frac{1}{g}\left[U(1)_{D7_a} + U(1)_{D7_d}\right] - 2\left[U(1)_{D9_1} - U(1)_{D9_2}\right]$$

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- The extra pairs of $D9 - \overline{D9}$'s induce extra chiral matter beyond the Left-Right spectrum
- Most of these chiral exotics dissappear after giving a v.e.v. to some scalar fields in the hidden sector
- In terms of D-brane physics, this can be understood as the process of D-brane/gauge bundle recombination

$$D9_1 + \overline{D9}_2 \;\rightarrow\; \tilde{D9}$$

Higgsing away chiral exotics

- Let us consider a Pati-Salam spectrum in the case $g = 3$, $N_{D3} = 5$

Sector	Matter	$SU(4) \times SU(2) \times SU(2) \times [USp(40)]$	Q_a	Q_{h_1}	Q_{h_2}	Q'
$D7_a D7_b$	F_L	$3(4,2,1)$	1	0	0	$1/3$
$D7_a D7_c$	F_R	$3(4,1,2)$	-1	0	0	$-1/3$
$D7_b D7_c$	H	$(1,2,2)$	0	0	0	0
$D7_a \overline{D9}_1$		$6(\bar{4},1,1)$	-1	-1	0	$5/3$
$D7_a D9_2$		$6(4,1,1)$	1	0	-1	$-5/3$
$D7_b D9_1$		$8(1,2,1)$	0	-1	0	2
$D7_b D9_2$		$6(1,2,1)$	0	0	-1	-2
$D7_c D9_1$		$6(1,1,2)$	0	-1	0	2
$D7_c D9_2$		$8(1,1,2)$	0	0	-1	-2
$D9_1 \overline{D9}_1$		$23(1,1,1)$	0	-2	0	4
$D9_2 \overline{D9}_2$		$23(1,1,1)$	0	0	-2	-4
$D9_1 \overline{D9}_2$		$196(1,1,1)$	0	1	1	0
$D3D9_1$		$(1,1,1) \times [40]$	0	-1	0	2
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$D7_bD7_c$	H	$(1,2,2)$	0	0	0
$D7_b\tilde{D9}$		$2(1,2,1)$	0	-1	2
$D7_c\tilde{D9}$		$2(1,1,2)$	0	+1	-2

$$\langle D9_1 \overline{D9}_2 \rangle \quad \simeq \quad D9_1 + \overline{D9}_2 \rightarrow \tilde{D9}$$

- The PS sector does not get affected by this process

From Left-Right to MSSM

- An MSSM-like spectrum can be achieved by additional Higgsing

Sector	Matter	$SU(4) \times SU(2)_L \times SU(2)_R$	Q_a	Q_h	Q'
$D7_a D7_b$	F_L	$3(4,2,1)$	1	0	1/3
$D7_a D7_c$	F_R	$3(\bar{4},1,2)$	-1	0	$-1/3$
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– Step 1: Perform adjoint Higgsing $SU(4)\rightarrow SU(3)\times U(1)$

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Sector	Matter	$SU(3)\times SU(2)_L$	Q_a	Q_j	Q_h	Q_Y	Q'
$D7_a D7_b$	Q_L	3(3,2)	1	0	0	1/6	1/3
$D7_a \tilde{D7}_j$	U_R	3($\bar{3}$,1)	-1	1	0	-2/3	1/3
$D7_a \tilde{D7}'_j$	D_R	3($\bar{3}$,1)	-1	-1	0	1/3	-1/3
$\tilde{D7}_j D7_b$	L	3(1,2)	0	1	0	-1/2	1/3
$\tilde{D7}_j \tilde{D7}'_j$	E_R	3(1,1)	0	-2	0	1	-2/3
$\tilde{D7}_j D7_b + D7_b \tilde{D7}_j$	H_u, H_d	(1,2)	0	$\mp$1	0	$\pm$1/2	$\mp$1/3
$D7_b \tilde{D9}_h$		2(1,2)	0	0	-1	0	2
$\tilde{D7}_j \tilde{D9}_h$		2(1,1)	0	-1	+1	1/2	-2
$\tilde{D7}'_j \tilde{D9}_h$		2(1,1)	0	+1	+1	-1/2	-2

– Step 1: Perform adjoint Higgsing $SU(4) \to SU(3)\times U(1)$

– Step 2: Give a v.e.v. to $\langle L_R \rangle$ $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$

D-brane recombination $D7_c + D7_d \to \tilde{D7}_j$

μ-term and Yukawas

- This Left-Right MSSM model comes equipped with a μ-term.
  The superpotential for two D7-branes with $F_{\mu\nu} = 0$ is [Berkooz, Leigh]

$$W = \mu \cdot \det \mathbf{H} = \left(\langle \Phi^1_{cc} \rangle - \langle \Phi^1_{bb} \rangle \right) \cdot \det \mathbf{H}$$

H: (2,2) Higgs matrix

Φ^1: Wilson lines on the first T^2 factor

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- The Yukawa couplings of the Left-Right sector depend on the compactification moduli.
  They can be computed by field theory or by using Mirror Symmetry.
  One obtains:
  - One heavy generation of quark and leptons
  - Two massless generations

[Cremades, Ibáñez, F.M.]

Fluxes and Soft Terms

- $\mathcal{N} = 0$ ISD fluxes induce soft SUSY-breaking terms on D7-branes gauge groups, as well as in the chiral spectrum

$$\Downarrow$$

MSSM + soft terms induced by G_3

[Lüst, Reffert, Stieberger]
[Kane, Kumar, Lykken, Wang]
[Ibáñez, Font]

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T-dominance

$m^2_{L_\alpha}$	$\left[\frac{1}{2}-\mathcal{F}_0(\delta,u_2,u_3)\right]m^2_{3/2}$
$m^2_{R_\beta}$	$\left[\frac{1}{2}-\mathcal{F}_0(\delta,u_3,u_2)\right]m^2_{3/2}$
m^2_H	$\frac{1}{2}m^2_{3/2}$
$M_{SU(3+1)}$	$cos^2(\pi\delta)\ m_{3/2}e^{-i\gamma_T}$
$M_{SU(2)_L}$	$m_{3/2}e^{-i\gamma_T}$
$M_{SU(2)_R}$	$m_{3/2}e^{-i\gamma_T}$
$A_{HL_\alpha R_\beta}$	$\left[-\frac{3}{2}+\mathcal{F}_1(\delta)\right]m_{3/2}e^{-i\gamma_T}$
A_{XHH}	$-m_{3/2}e^{-i\gamma_T}$

$\delta=\frac{1}{\pi}tan^{-1}\frac{\alpha' g}{\mathcal{A}_{2,3}}$ gauge bundle curvature, $\mathcal{F}_{0,1}\xrightarrow{\delta\to 0}0$

$m_{3/2}\propto|G_{(0,3)}|/\mathrm{Vol}(\mathrm{T}^6)$, $\mathcal{N}=0$ flux density

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General features:

- Non-universal but flavour independent scalar masses.
- Scalar masses always non-tachyonic.
- Depend on flux densities $m_{3/2}$ and δ, as well as on complex structure moduli u_i.

Fluxes vs. Moduli

Closed String Moduli:

- The superpotential generated by the fluxes naturally fixes complex structure moduli/dilaton.
- In addition, chiral models with $\mathcal{N} = 0$ fluxes may provide a source for Kähler moduli stabilization

Fluxes vs. Moduli

Open String Moduli:

- Chiral fields are stabilized by means of the scalar masses $m^2_{\phi_n}$
- Besides these chiral fields, these models also present non-chiral matter beyond the MSSM, like
  - Adjoints of $SU(3)$, $U(1)$
  - Singlets of $SU(2)$

Are we happy?

The flux compactification that we have constructed contains many appealing features, but we can point out two problematic ones:

* Problem 1

  Soft terms $\propto m_{3/2}$, which is tied-up to the string scale.

  Lowering M_s by Vol $(\mathbf{T}^6) \to \infty$ conflicts with $\alpha_{MSSM} \to 0$.

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→ Solution

  Problem generic of toroidal compactifications, where lowering the string scale is difficult. It need not happen in more general Calabi-Yau geometries.

  In particular, we can achieve hierarchically small $m_{3/2}$ by means of warped throats.

Are we happy?

The flux compactification that we have constructed contains appealing features, but we can point out two problematic ones:

* Problem 2

  Even if we get rid of all open string moduli by means of fluxes, the masses of the MSSM adjoint fields will be of the order of magnitude $m_{soft} \Rightarrow$ spoils Asymptotic Freedom

Conclusions

- We have constructed $\mathcal{N}=1$ and $\mathcal{N}=0$ chiral four-dimensional vacua of flux compactification by means of magnetized D-branes.
- Even in the $\mathcal{N}=0$ case (first order) NSNS tadpoles cancel, so the instabilities associated with them are not present.
- In addition, these models admit a low energy spectrum remarkably close to the MSSM, with 3 generations of chiral matter.
- In the $\mathcal{N}=0$ case, SUSY is broken by the flux, which not only lifts moduli but also induces soft terms in the MSSM sector.
- We can analyze phenomenological features of these models, such as the Higgsing processes, μ-terms and Yukawas in terms of D-brane physics.

What have we learnt?

- $D = 4$ $\mathcal{N} = 1$ chiral Minkowski vacua with fluxes can indeed be constructed. $\mathcal{N} = 0$ chiral models as well, without 1^{st} order NSNS tadpoles.

- Their construction is remarkably simple compared to most chiral string vacua, while still being quite close to realistic physics.

What have we learnt?

- $D = 4$ $\mathcal{N} = 1$ chiral Minkowski vacua with fluxes can indeed be constructed. $\mathcal{N} = 0$ chiral models as well, without 1^{st} order NSNS tadpoles.

- Their construction is remarkably simple compared to most chiral string vacua, while still being quite close to realistic physics.

- This explicit construction allows us to perform explicit computations and, as usual with toroidal compactifications, the scales generated are not hierarchical.

- This poses a problem for generating the MSSM soft term structure, but it can be solved by extending our construction to more involved CY geometries, with
  - Warped throats
  - Rigid cycles

- Until then, the present vacua represent the perfect model to study the interesting subject of Flux-Induced SUSY-breaking.