Title: Building chiral flux vacua

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Abstract:

Building Chiral Flux Vacua

Fernando Marchesano

University of Wisconsin-Madison

String Theory Seminars
Perimeter Institute, March 8, 2004

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Outline

- **Motivation**
  - Why Fluxes?
  - Why D-branes?
- **Model Building**
  - Magnetized D-branes
  - $\mathcal{N} = 1$ and $\mathcal{N} = 0$ models
- **MSSM-like vacua**
  - Higgsing as D-brane recombination
  - μ-term and Yukawas

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$D = 4$ 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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$\rightarrow$ Generates a superpotential W which freezes the complex structure moduli and dilaton

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

$\rightarrow$ Induces soft terms in gauge theories living on D-branes

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

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

$\longrightarrow$ 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]

D-branes & chirality

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

- In order to get a realistic vacuum, however, we need these gauge theories to be chiral.

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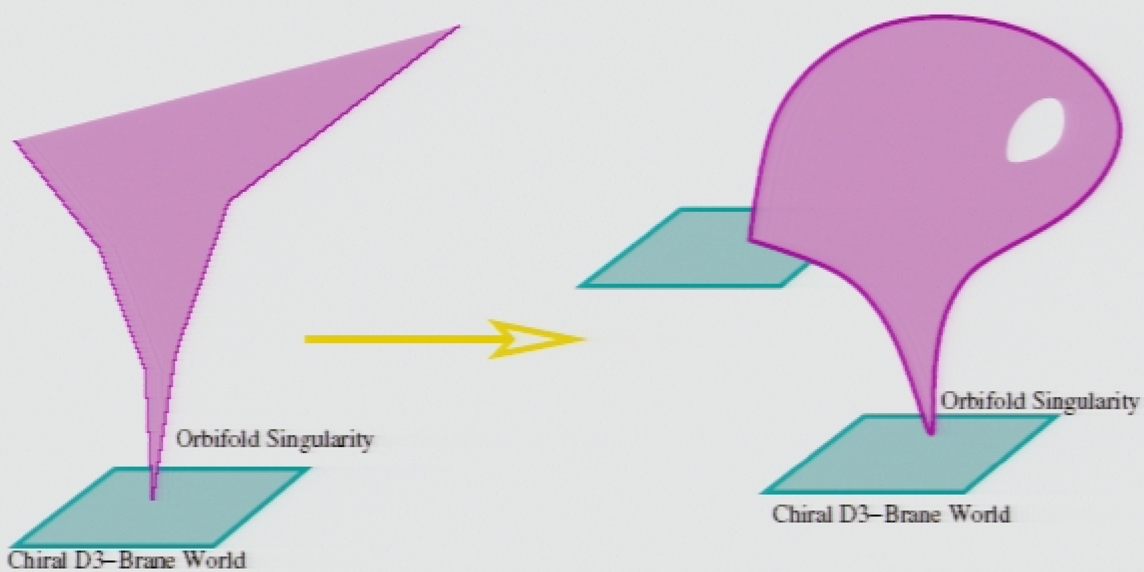
- Two known ways to achieve chirality in type IIB flux compactification
  - D-branes at singularities [Cascales, García del Moral, Quevedo, Uranga]



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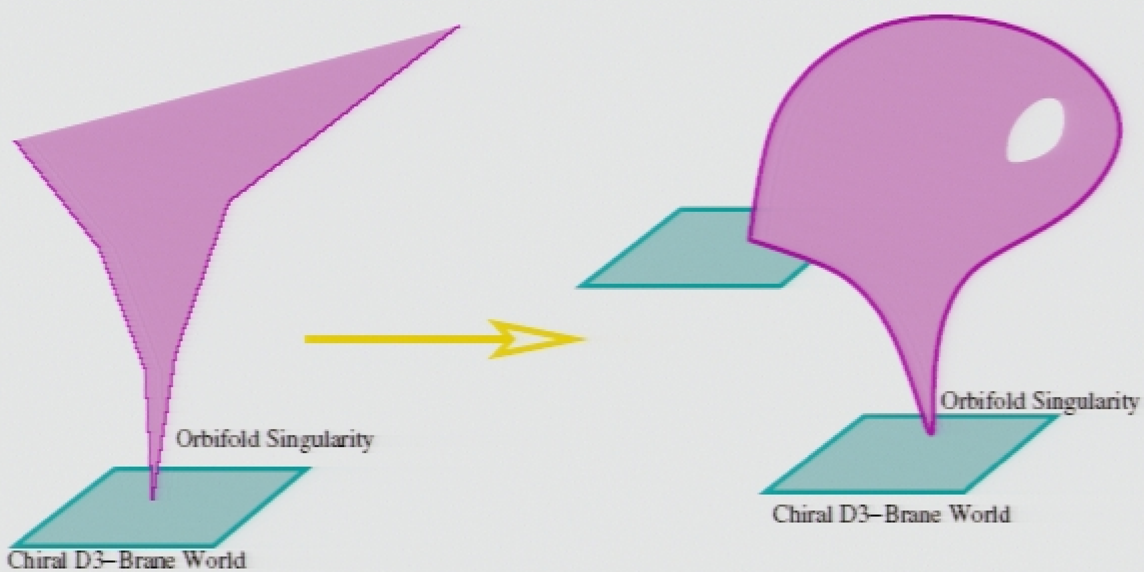

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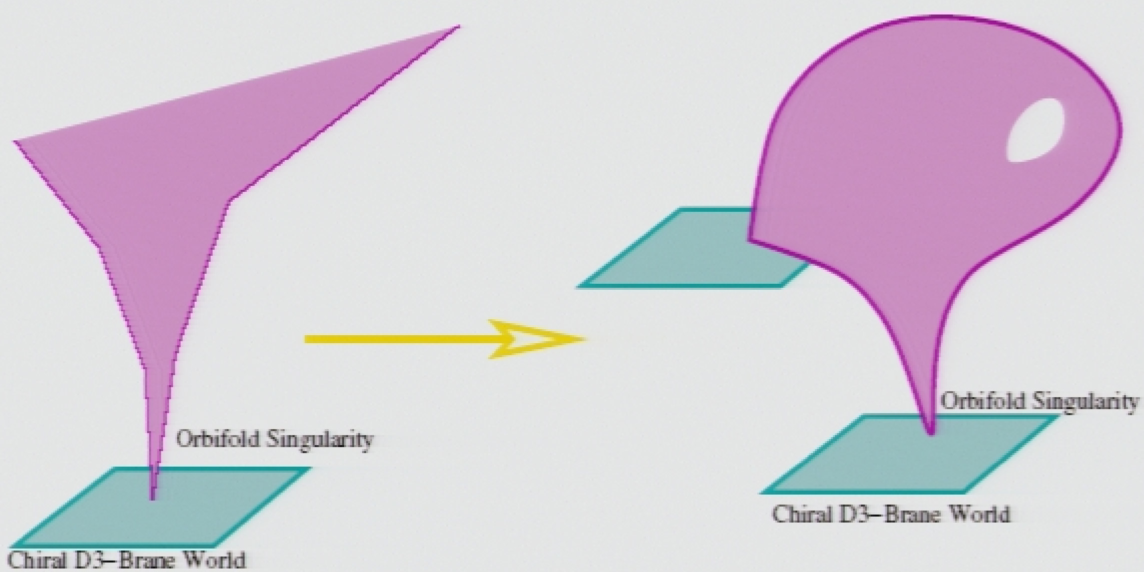

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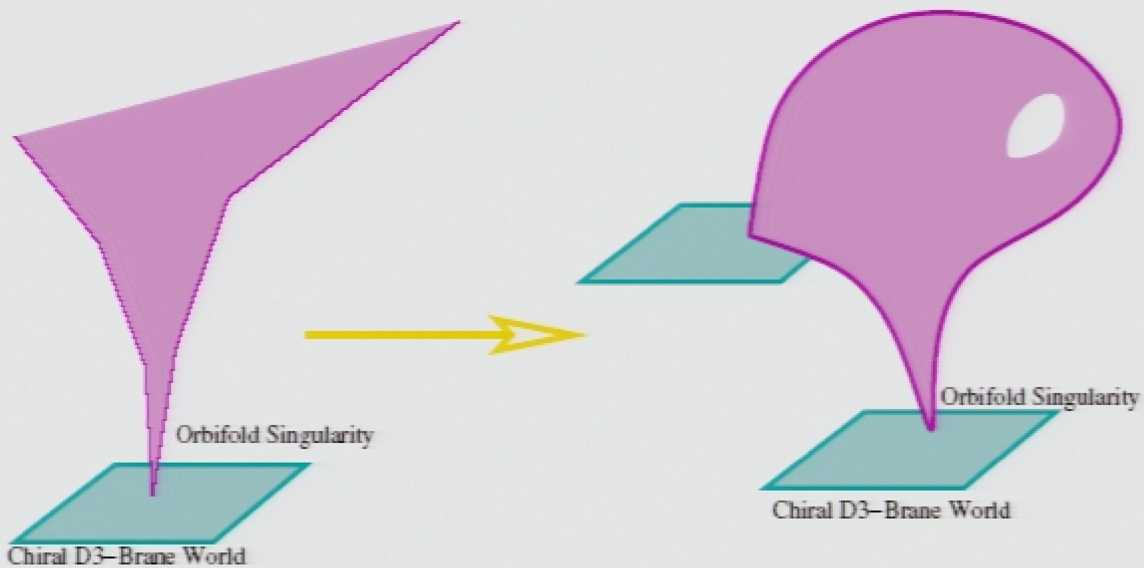

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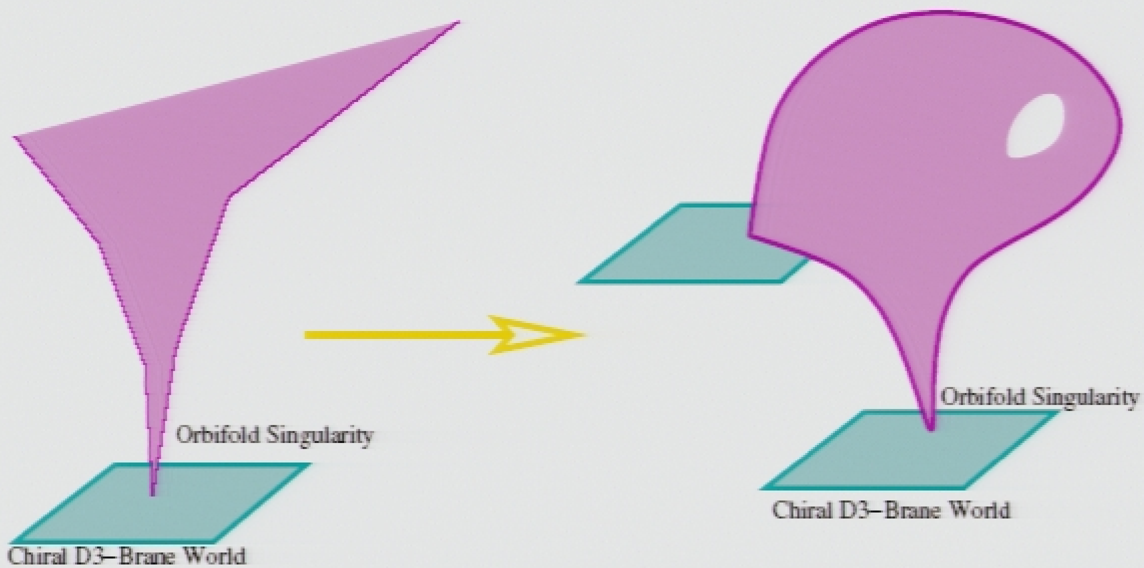

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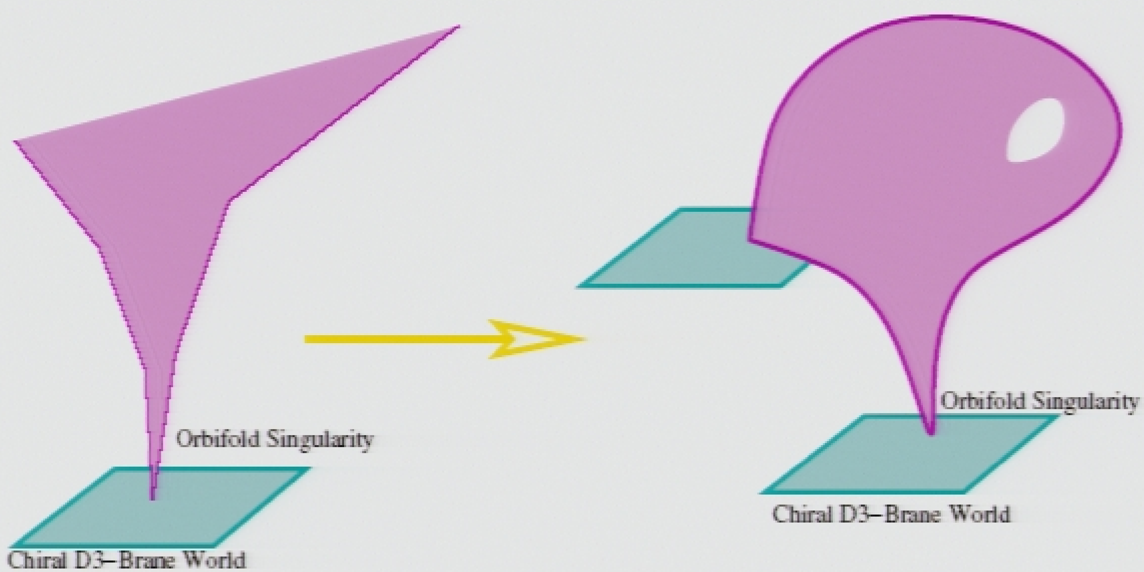

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- Both types of constructions are based on B-type branes, so they are essentially the same from an stringy point of view.

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- D3's at singularities are easier to embed in warped throat constructions in a 'bottom-up' fashion, and the soft terms are easier to understand.

- Magnetized D7's have a richer and more interesting soft-term pattern, and SUSY can be broken while still satisfying supergravity equations of motion.

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Towards realistic vacua

- Much of the flux physics in the literature is based on $\mathcal{N} = 1$ vacua, over which we have a better theoretical control.

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no chiral $D = 4$, $\mathcal{N} = 1$ flux compactification as above has been found.

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- The aim of this talk is to describe the **first examples** of such vacua.
- In particular, we find $\mathcal{N}=1$ **and** $\mathcal{N}=0$ **chiral** flux vacua solving the supergravity equations, by means of magnetized D-branes.
- Moreover, these vacua are not only chiral, but also yield gauge theories remarkably close to the **MSSM**.

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Talk based on:

F. M. and Gary Shiu

"Building MSSM Flux Vacua", hep-th/0409132

"MSSM vacua from Flux compactification", hep-th/0408059

General Flux Vacua

- There is a wide class of type IIB flux compactifications yielding $D = 4$ Minkowski vacua.

  [DRS,GKP]

- The necessary ingredients are:
  - A (warped) compact Calabi-Yau background metric X_6
  - O3-planes (and O7-planes) localized in X_6
  - D-branes filling M_4 and not breaking supersymmetry
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- Two possibilities
  - G_3 is a (2,1)-form $\Rightarrow \mathcal{N} = 1$
  - G_3 contains a (0,3) component $\Rightarrow \mathcal{N} = 0$

An orientifold example

- A simple example of CY_3 is given by a $\mathrm{T}^6/(\mathrm{Z}_2 \times \mathrm{Z}_2)$ orbifold

$$T^6 = T^2 \times T^2 \times T^2$$

$$\theta : (z_1, z_2, z_3) \mapsto (-z_1, -z_2, z_3)$$

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- By further quotienting by the orientifold action $\Omega\mathcal{R}$

Ω: World-sheet parity

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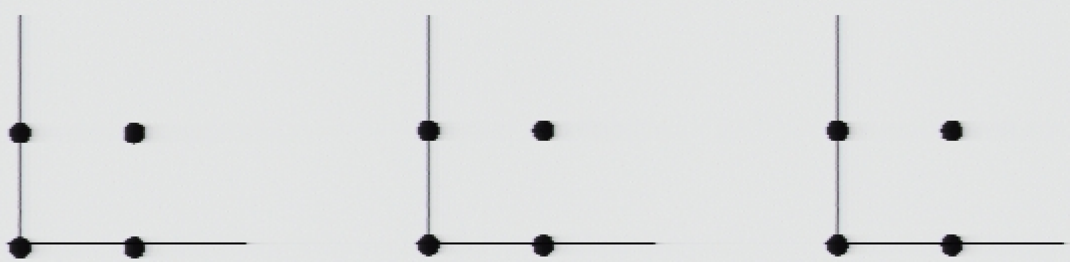
we introduce O3-planes and O7-planes at Z_2 fixed points.



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- A simple example of CY_3 is given by a $T^6/(Z_2 \times Z_2)$ orbifold

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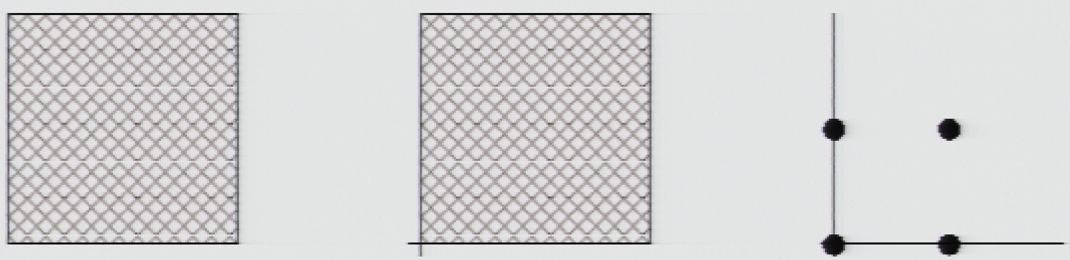

An orientifold example

- A simple example of CY_3 is given by a $\mathrm{T}^6/(\mathrm{Z}_2 \times \mathrm{Z}_2)$ orbifold

$$T^6 = T^2 \times T^2 \times T^2$$

$$\theta : (z_1, z_2, z_3) \mapsto (-z_1, -z_2, z_3)$$

$$\omega : (z_1, z_2, z_3) \mapsto (z_1, -z_2, -z_3)$$

- By further quotienting by the orientifold action $\Omega\mathcal{R}$

Ω: World-sheet parity

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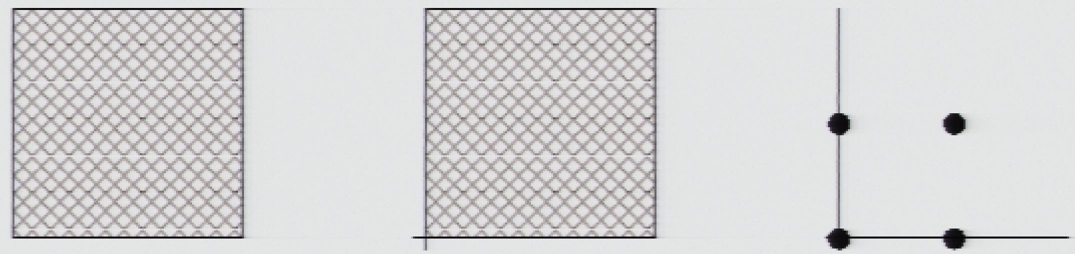

Adding D-branes

- Absence of tadpole divergences requires that we add D-branes in our compactification.
- The simplest way to cancel O-plane charges is to consider D3 and D7-branes parallel to the O3 and O7-planes. [Berkooz and Leigh]

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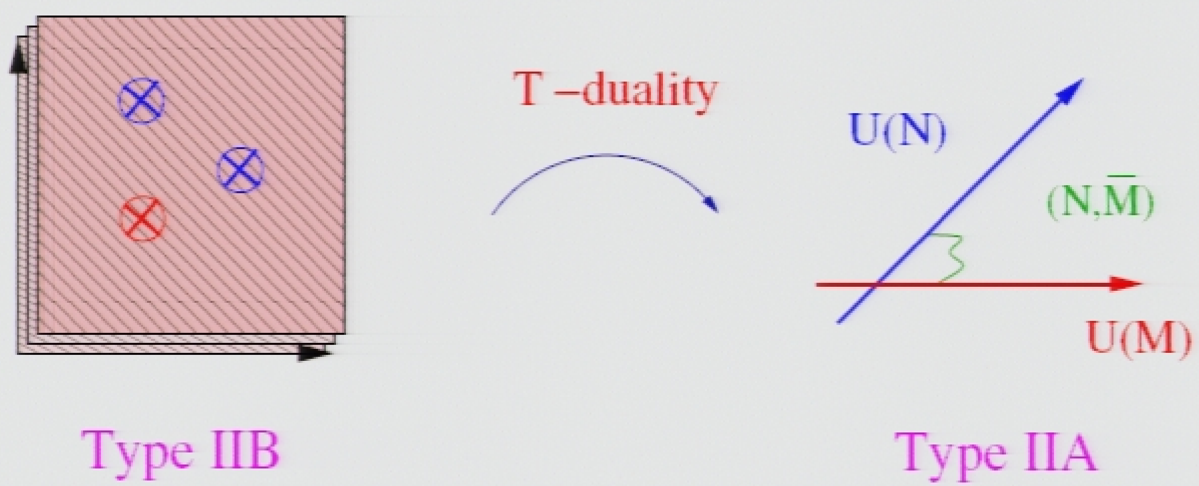
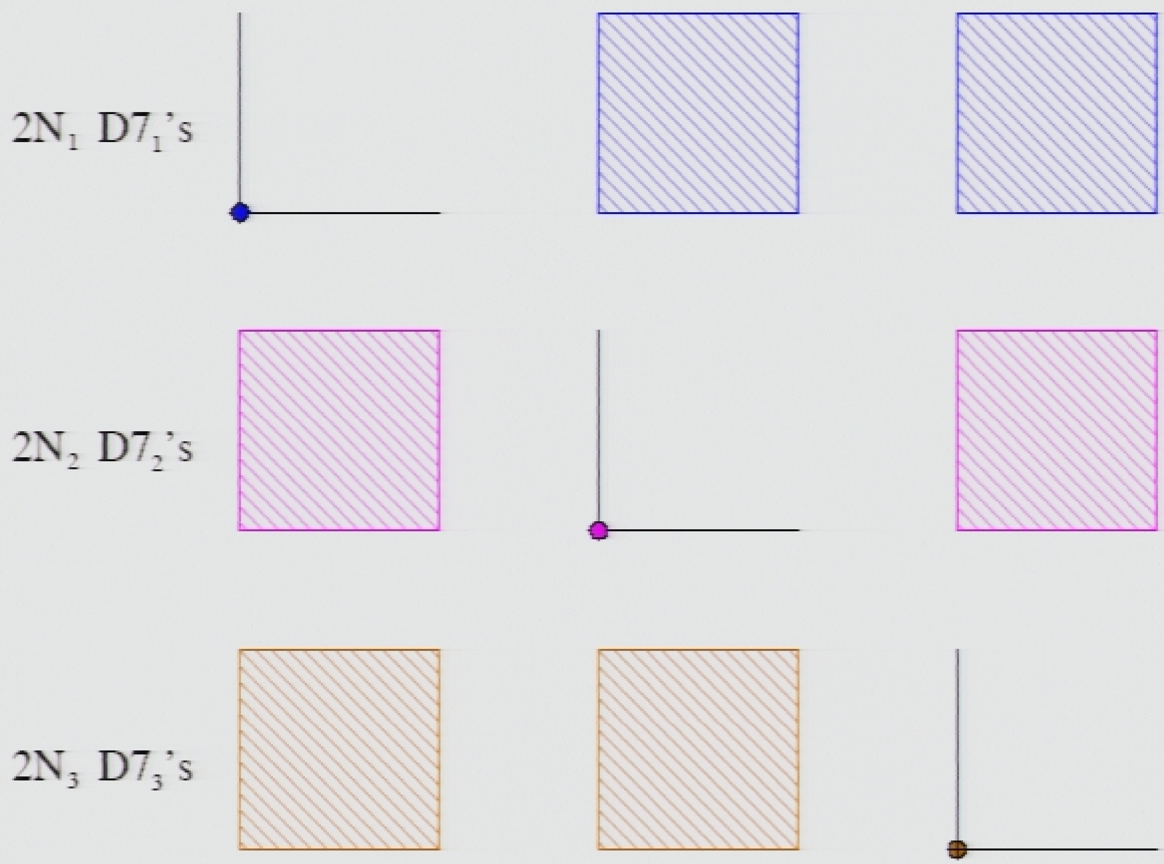
- This theory is however non-chiral. We may achieve chirality by introducing internal magnetic fluxes $F_{\mu\nu}$ on D7-branes. [Bachas,BGKL,AADS]
- T-dual to D6-branes at angles in $Z_2 \times Z_2$. [Berkooz, Douglas, Leigh] [Cvetič, Shiu, Uranga]



Magnetizing D-branes

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

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



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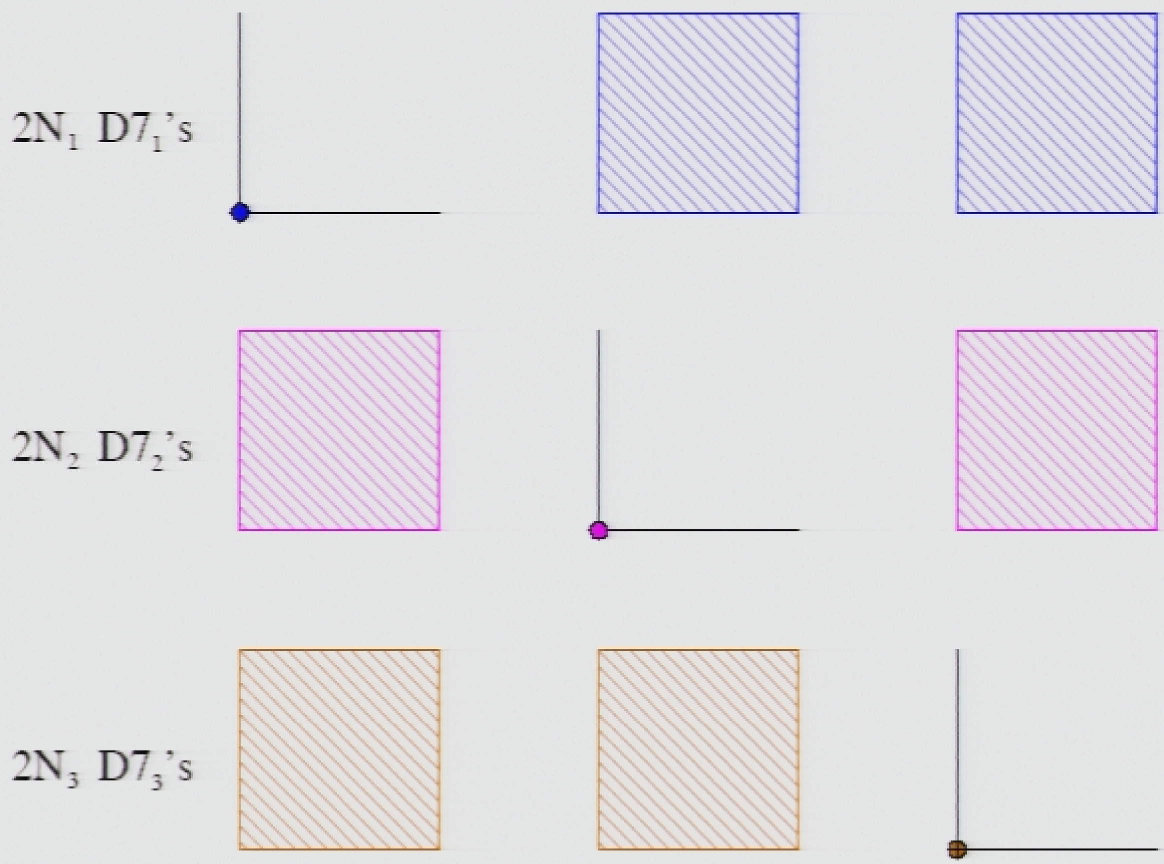

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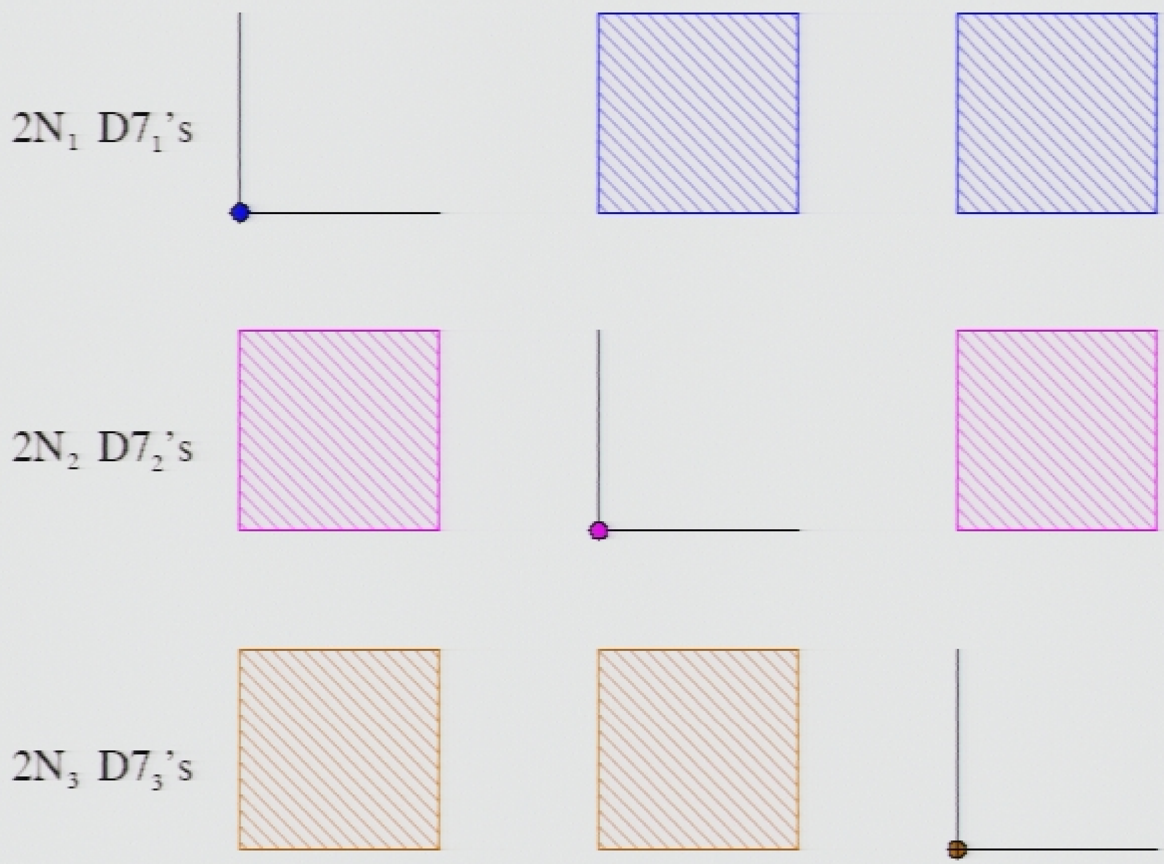

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$$U(N_1) \times USp(2N_2) \times USp(2N_3)$$

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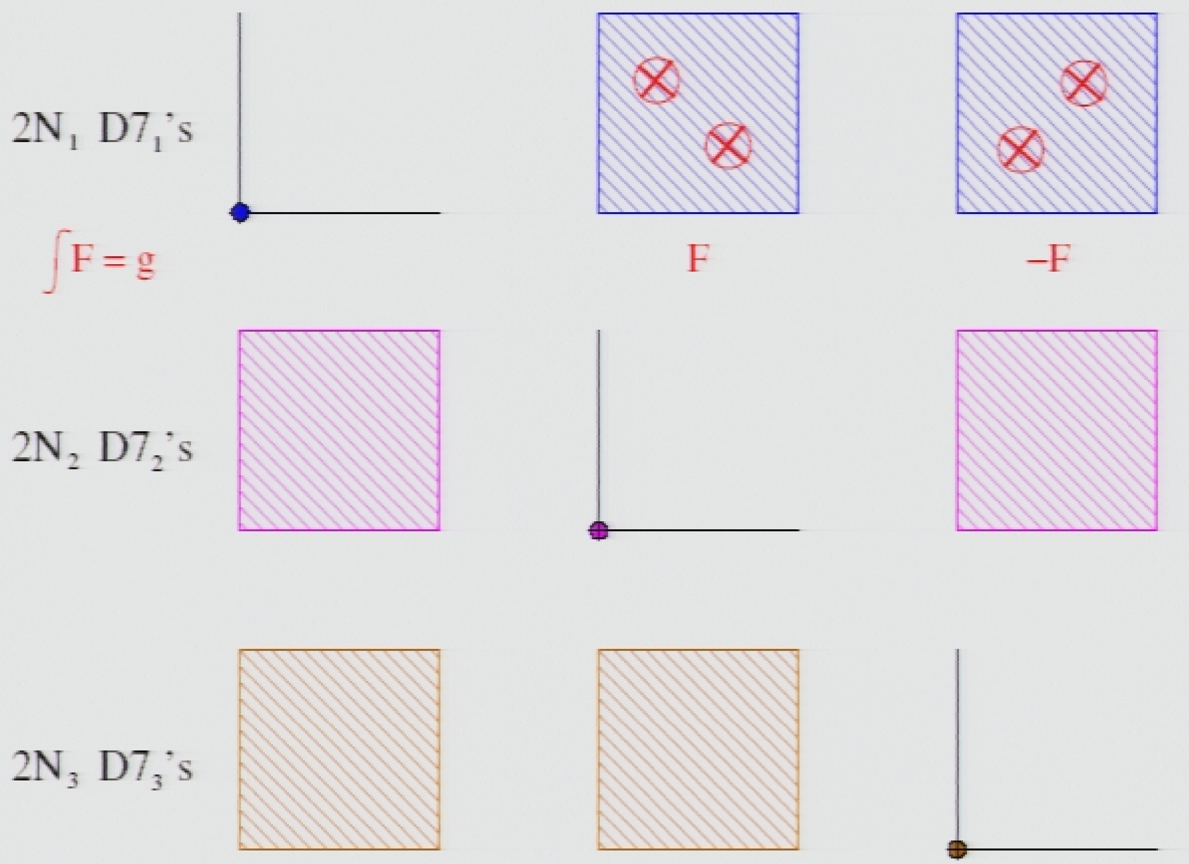

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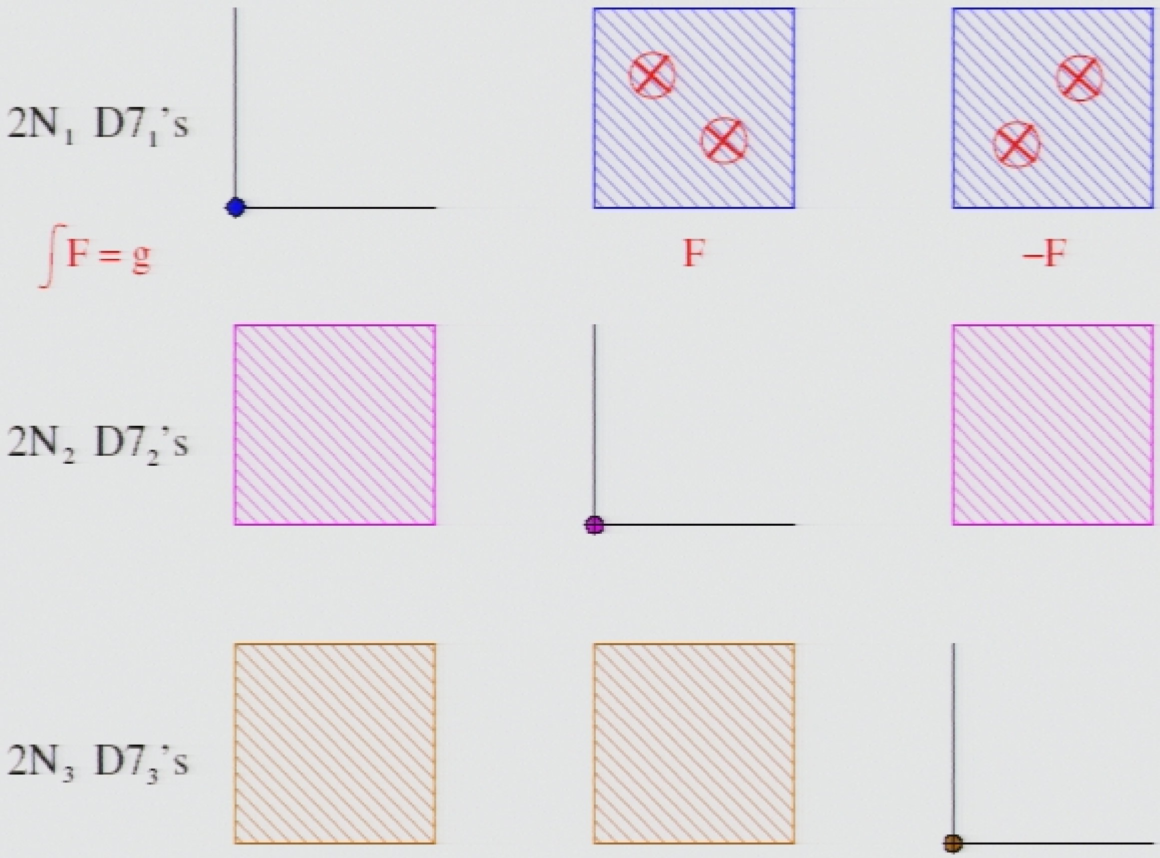

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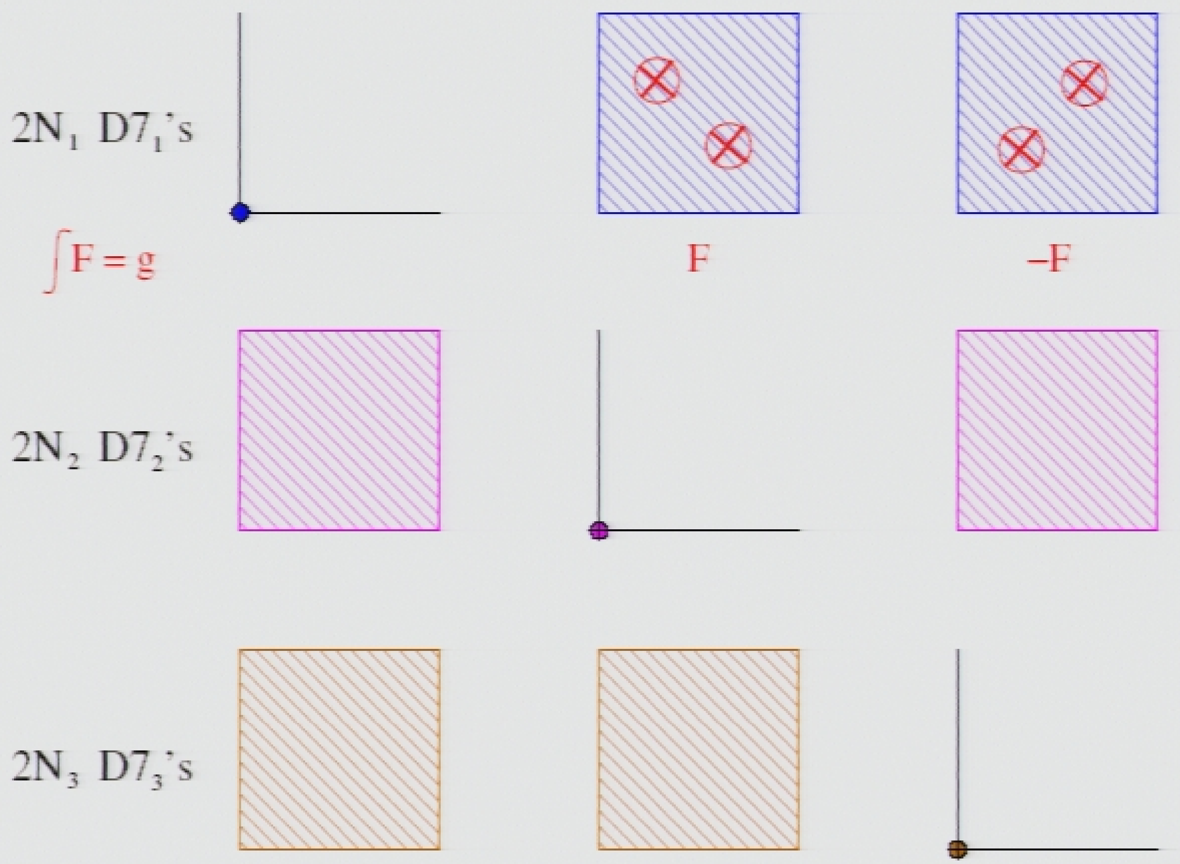

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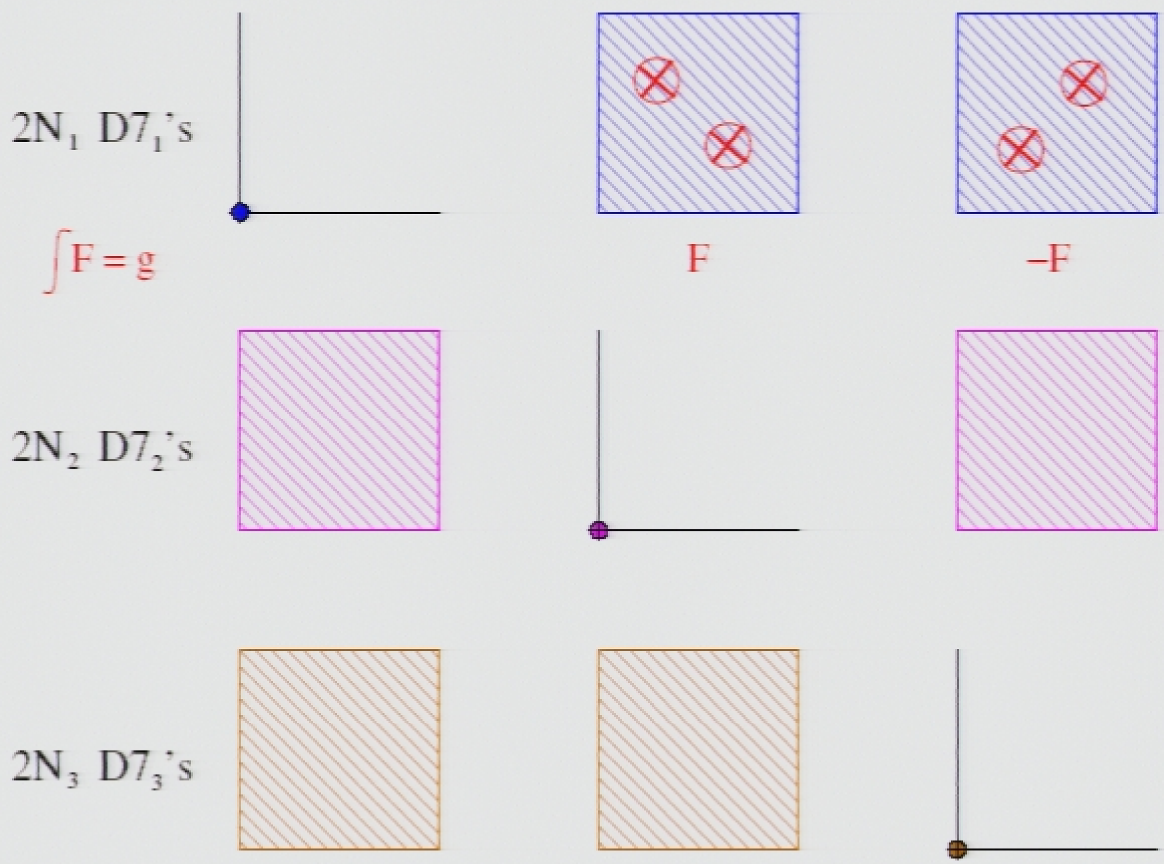

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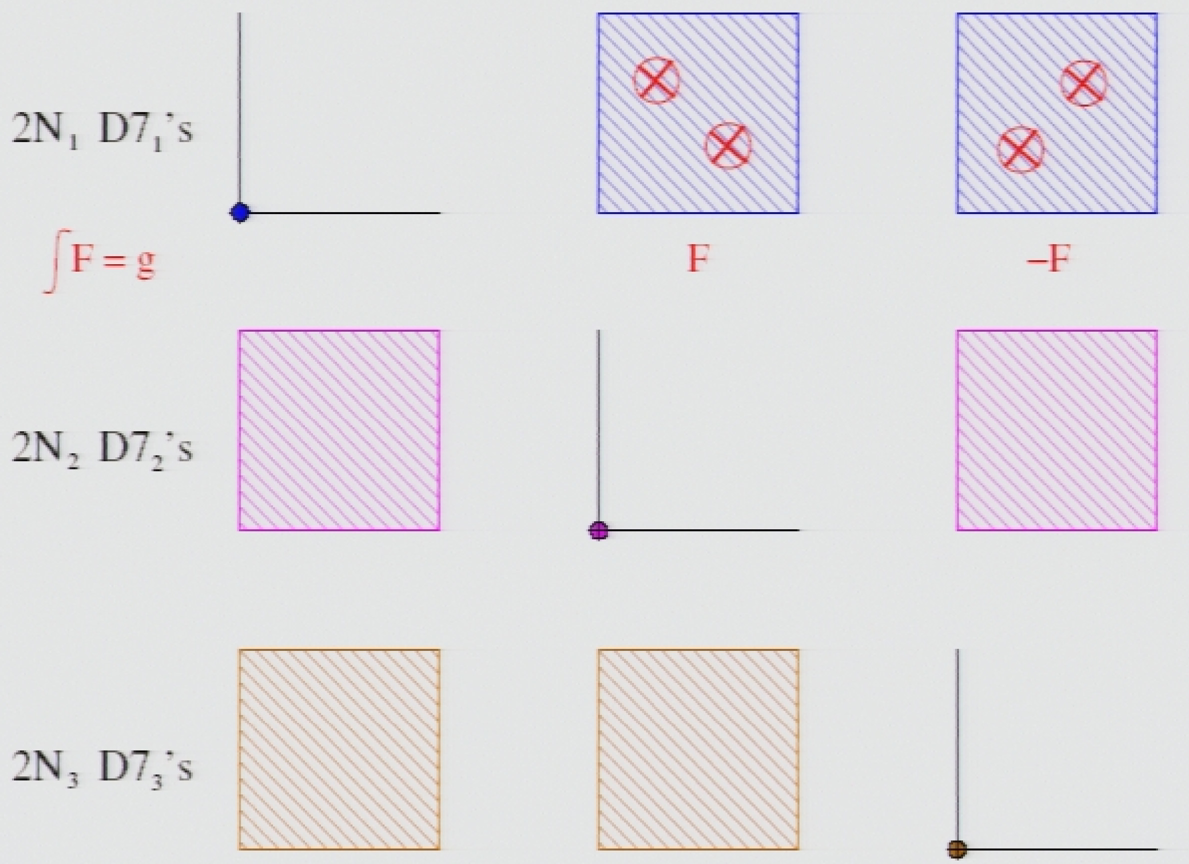

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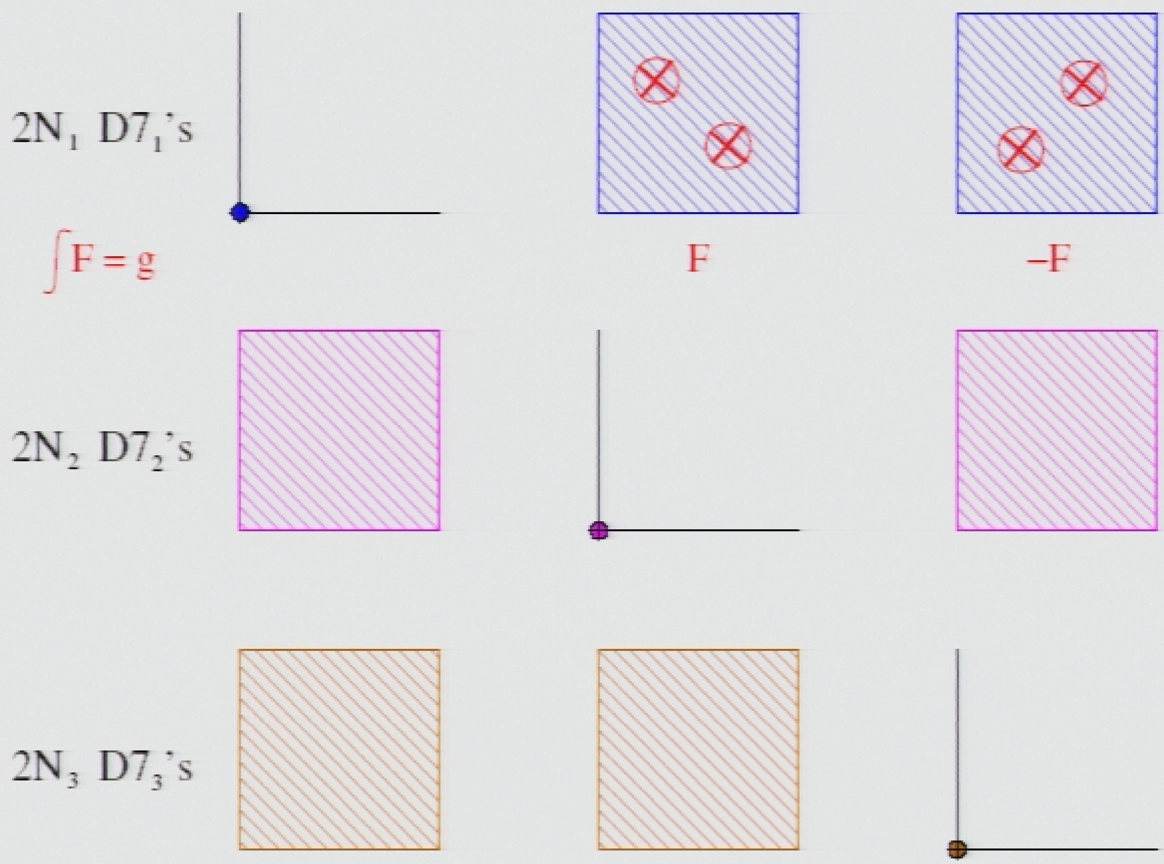

A Left-Right MSSM Example

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

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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.]

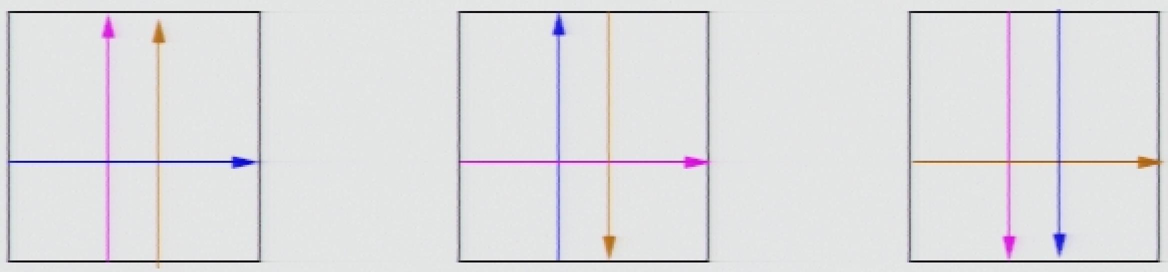
$$SU(3) \times SU(2) \times SU(2) \times U(1)_{B-L}$$

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

T-dual picture

- The appearance of chirality is easier to visualize in the intersecting D-brane picture

before



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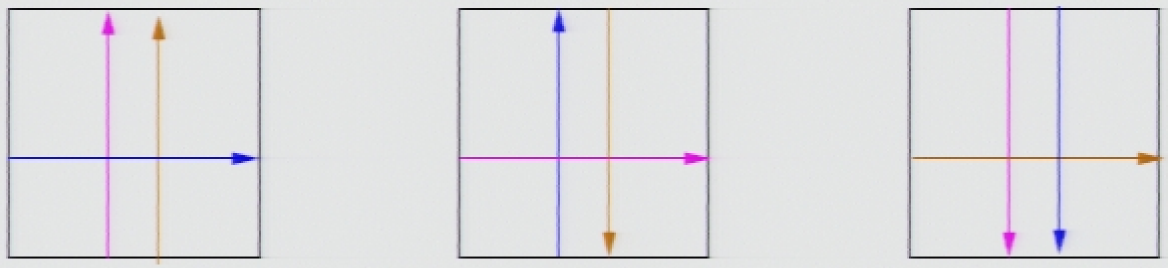

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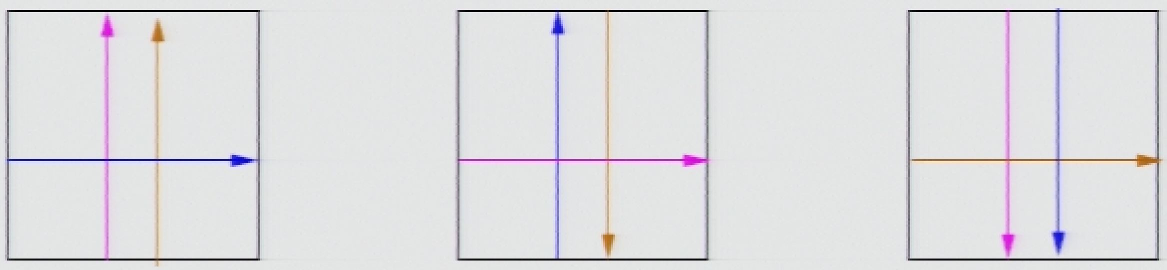

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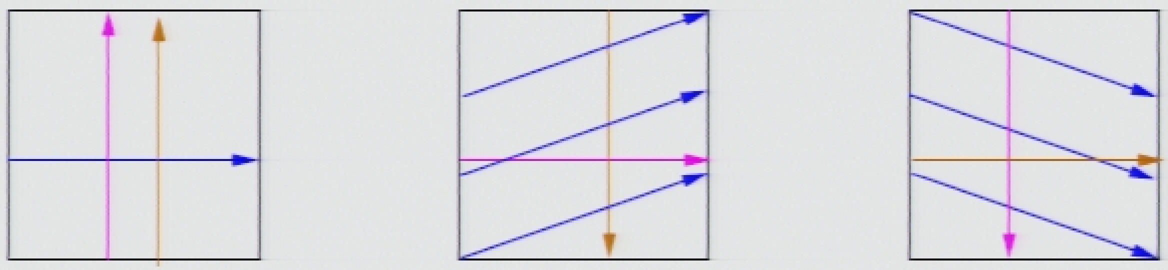

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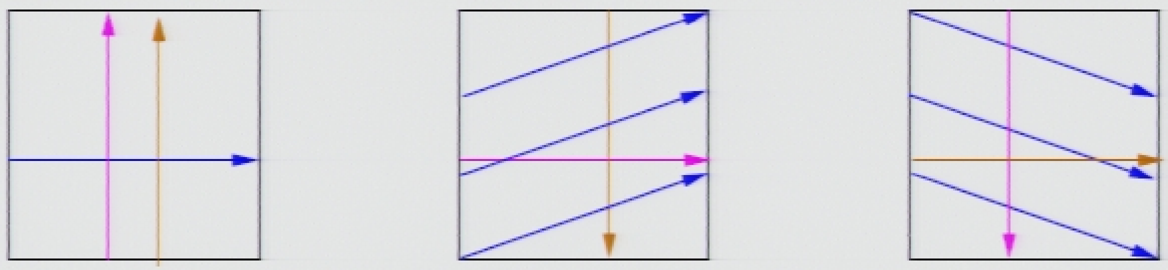

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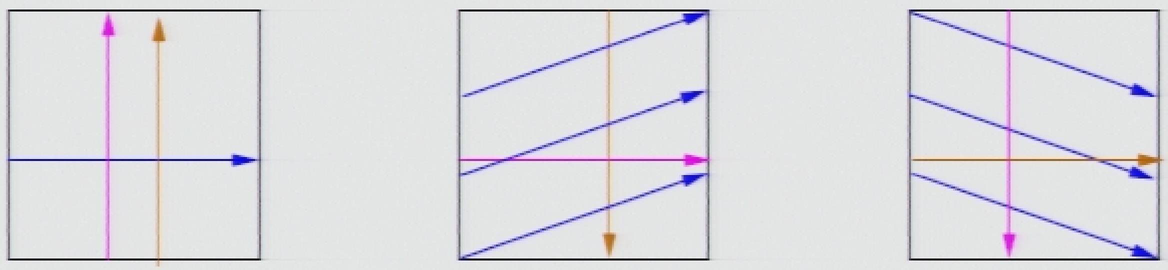
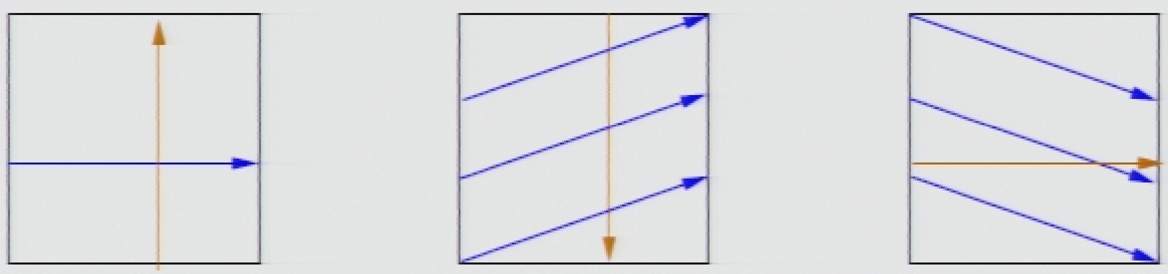


- As well as the adjoint Higgsing

before



Magnetic Numbers

- Intersecting branes also inspire a description of these models in terms of topological quantities

$$
\begin{array}{ll}
N_a & \text{Number of D}-\text{branes} \\
m_a^i & \text{Number of times wrapped on } (\mathrm{T}^2)_i \\
n_a^i & \text{Units of magnetic flux on } (\mathrm{T}^2)_i
\end{array}
\Bigg\} \quad \frac{m_a^i}{2\pi}\int_{\mathrm{T}_i^2} F_a^i = n_a^i .
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			$(\mathrm{T}^2)_1$	$(\mathrm{T}^2)_2$	$(\mathrm{T}^2)_3$
$D9$	$\rightarrow$	N_a	(n_a^1, m_a^1)	(n_a^2, m_a^2)	(n_a^3, m_a^3)
$D7_1$	$\rightarrow$	N_a	$(1, 0)$	(n_a^2, m_a^2)	(n_a^3, m_a^3)
$D5_1$	$\rightarrow$	N_a	(n_a^1, m_a^1)	$(1, 0)$	$(1, 0)$
$D3$	$\rightarrow$	N_a	$(1, 0)$	$(1, 0)$	$(1, 0)$

- The orientifold action maps these numbers as

$$\Omega\mathcal{R} \;:\quad (n_a^i, m_a^i) \;\mapsto\; (n_a^i, -m_a^i)$$

Magnetic Numbers II

- In this notation, our previous Left-Right example reads

N_α	(n_α^1, m_α^1)	(n_α^2, m_α^2)	(n_α^3, m_α^3)
$N_a = 6$	$(1, 0)$	$(g, 1)$	$(g, -1)$
$N_b = 2$	$(0, 1)$	$(1, 0)$	$(0, -1)$
$N_c = 2$	$(0, 1)$	$(0, -1)$	$(1, 0)$
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- The chiral spectrum can be computed by means of the intersection product

$$I_{ab} = [\mathrm{Q}_a] \cdot [\mathrm{Q}_b] = \prod_{i=1}^{3} \left(n^i_a m^i_b - m^i_a n^i_b \right)$$

Adding Background Fluxes

- We now want to include a background 3-form flux $G_3 = F_3 - \tau H_3$. It must satisfy
  - Bianchi identities: $dF_3 = dH_3 = 0$
  - Quantization conditions: $\int_\Sigma F_3,\ \int_\Sigma H_3\ \in\ \mathbf{Z}, \quad \forall \Sigma \in H_3(\mathbf{X_6}, \mathbf{Z})$

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- It is easier to characterize fluxes in the covering space $T^2 \times T^2 \times T^2$. $T^6/(Z_2 \times Z_2)$ contains 3-cycles whose volume is 1/4 of those in T^6, hence

$$\int_\Sigma F_3, \ \int_\Sigma H_3 \ \in \ 4\mathbf{Z}, \qquad \forall \Sigma \in H_3(T^6, \mathbf{Z})$$

- The orientifold modding $\Omega\mathcal{R}$ adds an extra factor of 2, unless Σ contains an odd number of exotic $O3$-planes (i.e., O3's with positive tension and/or RR charge) [Frey, Polchinski]

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- We choose a constant ISD flux 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

Tadpoles

- In order to build a consistent D-brane model, RR tadpoles must cancel. In particular, D3-brane tadpoles read

$$\sum_\alpha \mathrm{N}_\alpha \mathrm{n}_\alpha^1 \mathrm{n}_\alpha^2 \mathrm{n}_\alpha^3 + \tfrac{1}{2}\mathrm{N}_{\text{flux}} = \tfrac{1}{4}\mathrm{N}_{\mathrm{O3}}$$

- In the present context we have

$$\left.\begin{array}{rcl} N_{O3} & = & 64 \\ N_{\text{flux}} & = & n \cdot 64, \ n \in \mathrm{N} \end{array}\right\} \quad \Rightarrow \quad \sum_\alpha N_\alpha n_\alpha^1 n_\alpha^2 n_\alpha^3 < 0 \text{ for } G_3 \neq 0$$

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- These objects are usually non-BPS stable objects which break SUSY but, by introducing suitable magnetic fluxes

  $\rightarrow$ They preserve $\mathcal{N} = 1$

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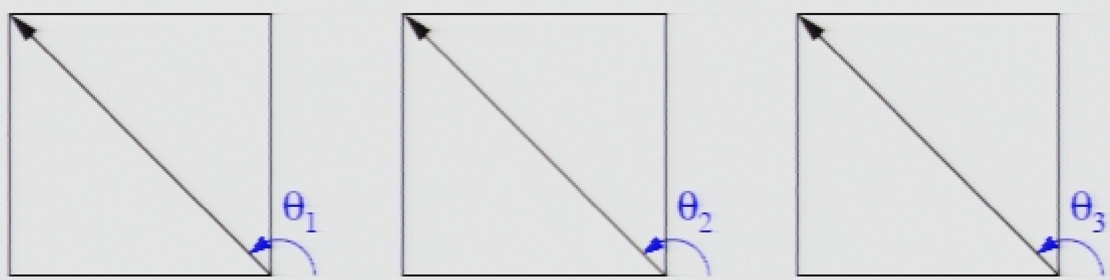
The $D9 - \overline{D9}$ mirror system

- Let us consider the magnetic numbers

$$(-1, 1)\,(-1, 1)\,(-1, 1)$$

- In the mirror picture



$$\theta_1 + \theta_2 + \theta_3 \equiv 0 \text{ mod } 2\pi$$

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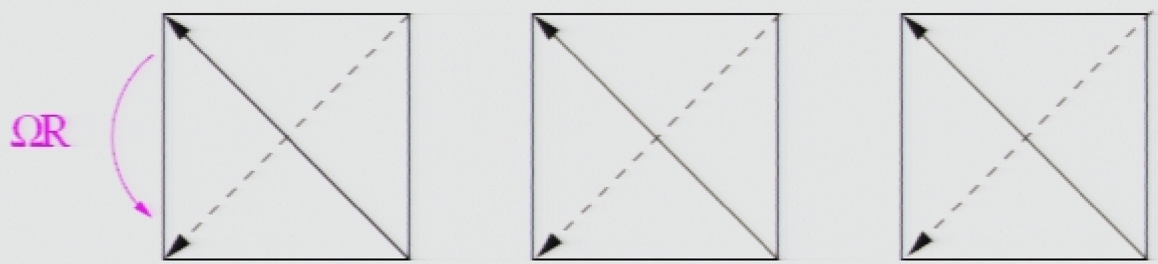

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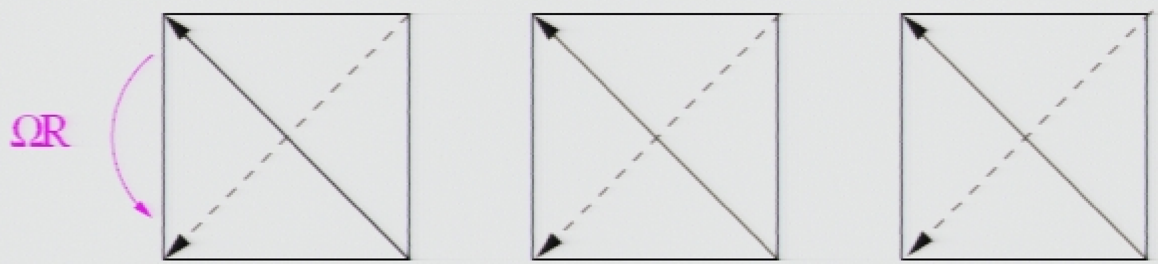

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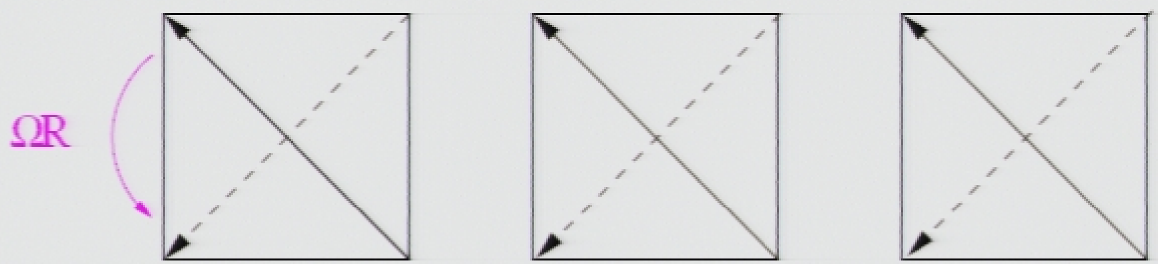

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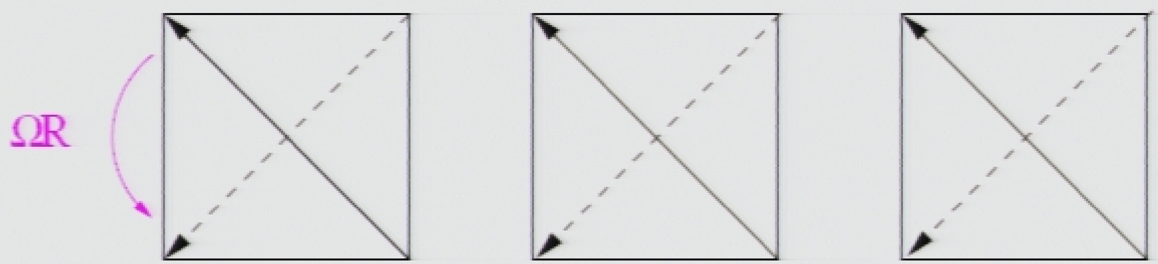

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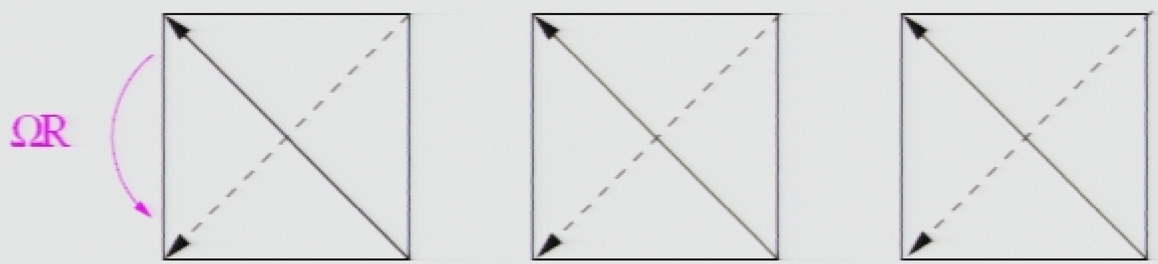

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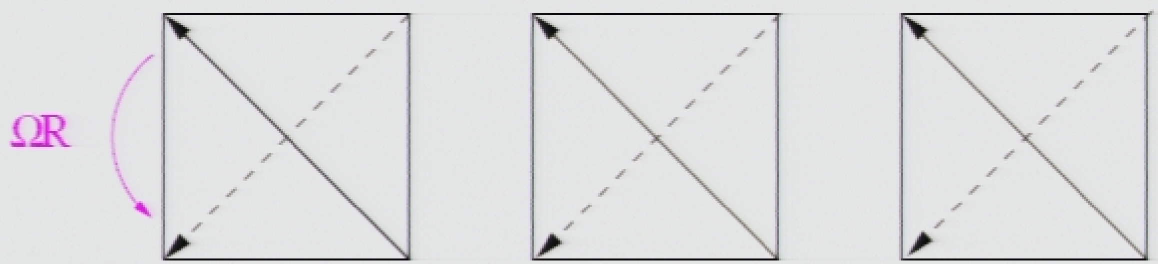

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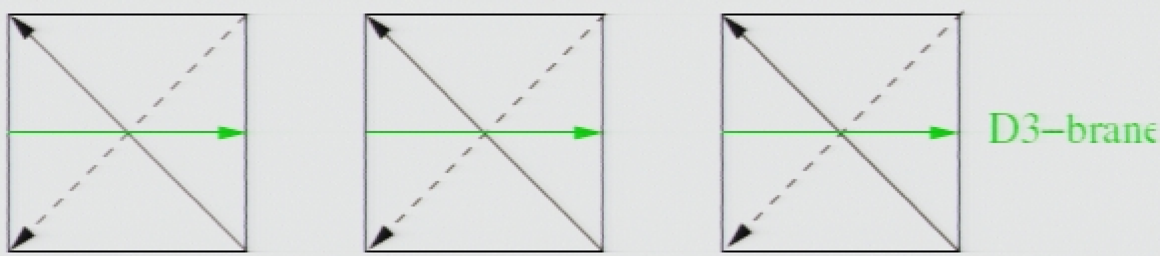

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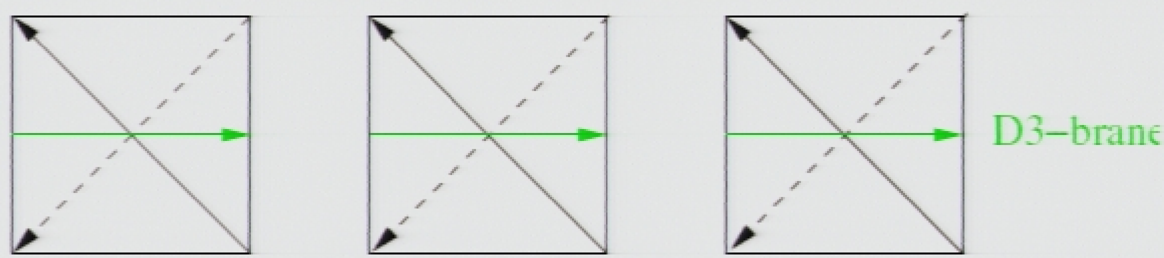

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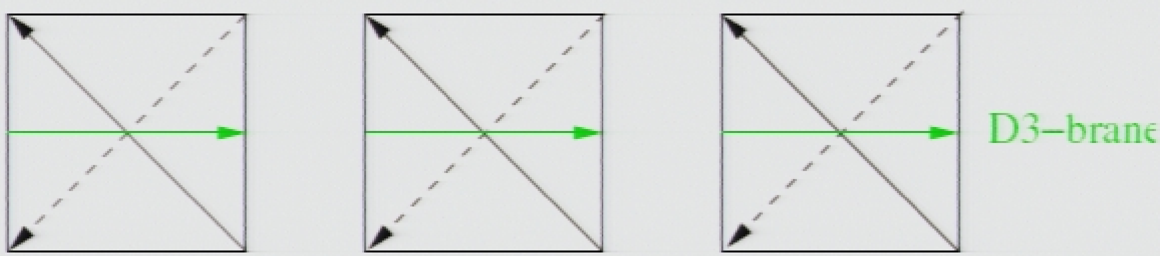

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We have analized type IIB flux compactification in one of the simplest Calabi-Yau in the market, namely $\mathbf{T}^6/(\mathbf{Z}_2 \times \mathbf{Z}_2)$, with $(h_{11}, h_{21}) = (3, 51)$.

Tadpole conditions

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- From supergravity e.o.m. we obtain the homological constraints

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\sum_\alpha N_\alpha n_\alpha^1 n_\alpha^2 n_\alpha^3 + \tfrac{1}{2} N_{\text{flux}} &= 16 \\
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The model

- An example of all the above is given by the magnetic numbers

N_α	(n_α^1, m_α^1)	(n_α^2, m_α^2)	(n_α^3, m_α^3)
$N_a = 6$	$(1, 0)$	$(g, 1)$	$(g, -1)$
$N_b = 2$	$(0, 1)$	$(1, 0)$	$(0, -1)$
$N_c = 2$	$(0, 1)$	$(0, -1)$	$(1, 0)$
$N_d = 2$	$(1, 0)$	$(g, 1)$	$(g, -1)$
$N_{h1} = 2$	$(-2, 1)$	$(-3, 1)$	$(-4, 1)$
$N_{h2} = 2$	$(-2, 1)$	$(-4, 1)$	$(-3, 1)$
$8N_{D3}$	$(1, 0)$	$(1, 0)$	$(1, 0)$

which contains the Left-Right MSSM system described before

The model II

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- This D-brane system preserves $\mathcal{N} = 1$ supersymmetry if we impose

$$\mathcal{A}_2 = \mathcal{A}_3$$
$$\tan^{-1}(\mathcal{A}_1/2) + \tan^{-1}(\mathcal{A}_2/3) + \tan^{-1}(\mathcal{A}_3/4) = \pi$$

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

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The spectrum

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

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

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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

$$h_1 + h_2' \rightarrow h$$

Higgsing away chiral exotics

- Let us consider a Pati-Salam spectrum in the case $g = 3$, $N_f = 5$

Sector	Matter	$SU(4) \times SU(2) \times SU(2) \times [USp(40)]$	Q_a	Q_{h_1}	Q_{h_2}	Q'
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- Besides chiral exotics, these models also present non-chiral matter beyond the MSSM, like
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- In the simple model above, however, non-geometrical moduli as D7-brane Wilson lines are not lifted

[Cámara, Ibáñez, Uranga]

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

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Solution: D-branes wrapping rigid cycles

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Type IIB recipe for chiral flux vacua

Let us describe the strategy that we have followed:

- Choose a CY_3 background that admits O3-planes and/or O7-planes

- Introduce B-type D-branes such that they preserve $\mathcal{N} = 1$ supersymmetry in this background. Try to build a chiral (semi-realistic) spectrum form them.

- Introduce ISD 3-form fluxes. Look at the effects that it creates on the metric background and on the D-branes.

- Look for new BPS-like objects that need to be introduced to build tadpole-free models as, e.g. $D9-\overline{D9}$ pairs, and analize their properties.

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 have analyzed some phenomenological features of these models, like the Higgsing processes, which can be understood 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, and without first order NSNS tadpoles.

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

- This simplicity encourages to extend this construction to most involved CY geometries. We expect the appealing features to survive, while including new ones (warped throats, etc.)

- A key ingredient in these constructions is the presence of magnetised $D9 - \overline{D9}$ pairs. It would be interesting to study the properties of these objects in general flux compactifications.

- Not only do these $D9 - \overline{D9}$ pairs help finding flux vacua, but also new $\mathcal{N} = 1$ vacua, like in $\mathbf{Z}_2 \times \mathbf{Z}_2$ orientifolds with 'brane supersymmetry breaking'.