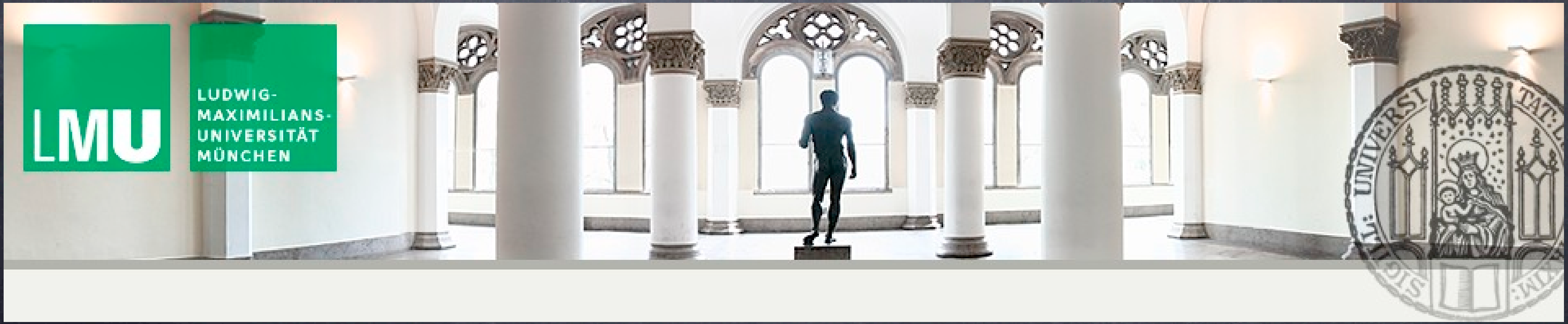
Coisotropic Model Building

Fernando Marchesano

Ludwig Maximilians Universität - München



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In collaboration with:
Anamaría Font and Luis Ibáñez
hep-th/0607219

String Model-Building

- A classical question in string theory is if we can reproduce the SM as an effective theory

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Four observable dimensions

3 Quarks & Leptons generations

Spontaneous EWSB

Chirality

SU(3) x SU(2) x U(1)

Gauge coupling constants

Yukawa couplings

and more...

String Model-Building

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- Problem: we have not solved String/M-theory

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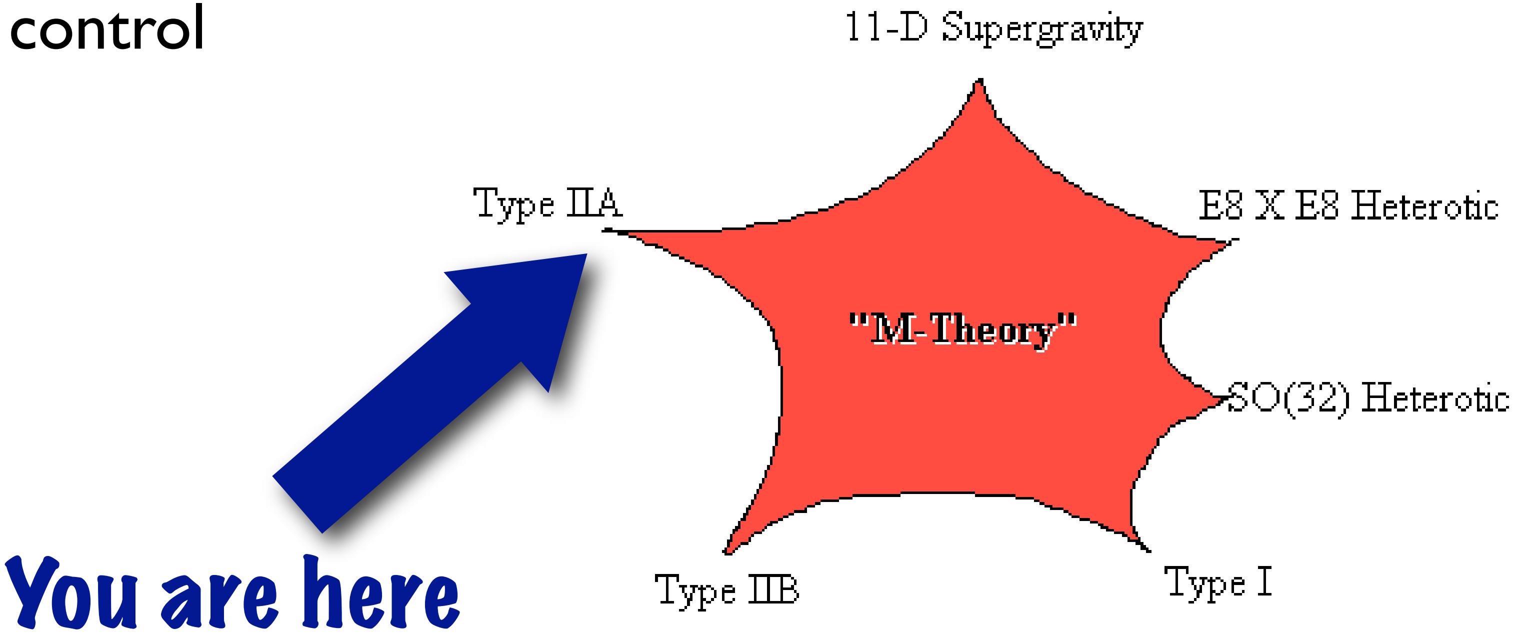
- **Strategy**: we explore a region of the theory which is under control



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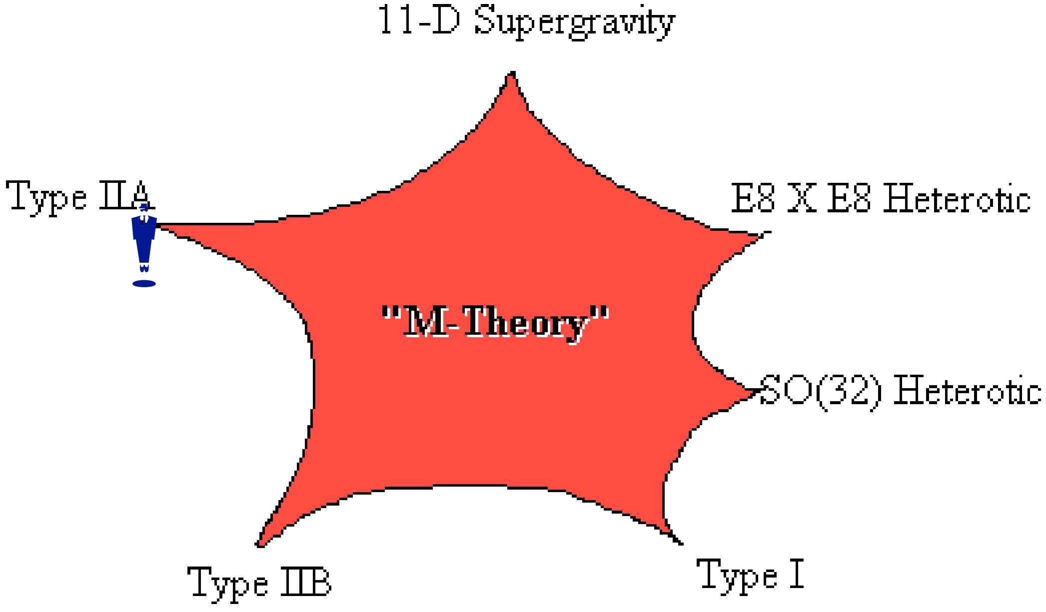

- Classical scheme: high string scale, $\Lambda_4 = 0$, D=4 N=1 gravity & MSSM sector + ~~SUSY~~ source

D-brane Model-Building

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- D=4 gravity
- U(N) theory
- Chiral fermions

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- D=4 gravity ← compactification on $M_4 \times X_6$
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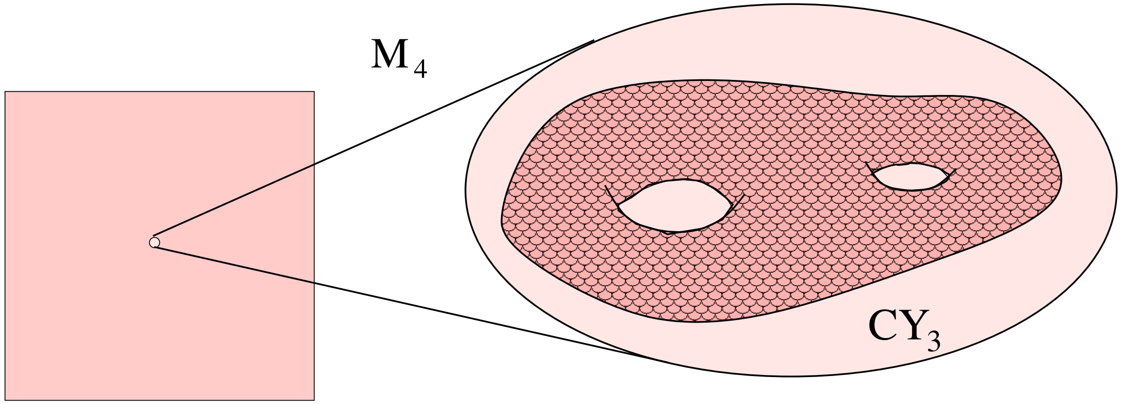

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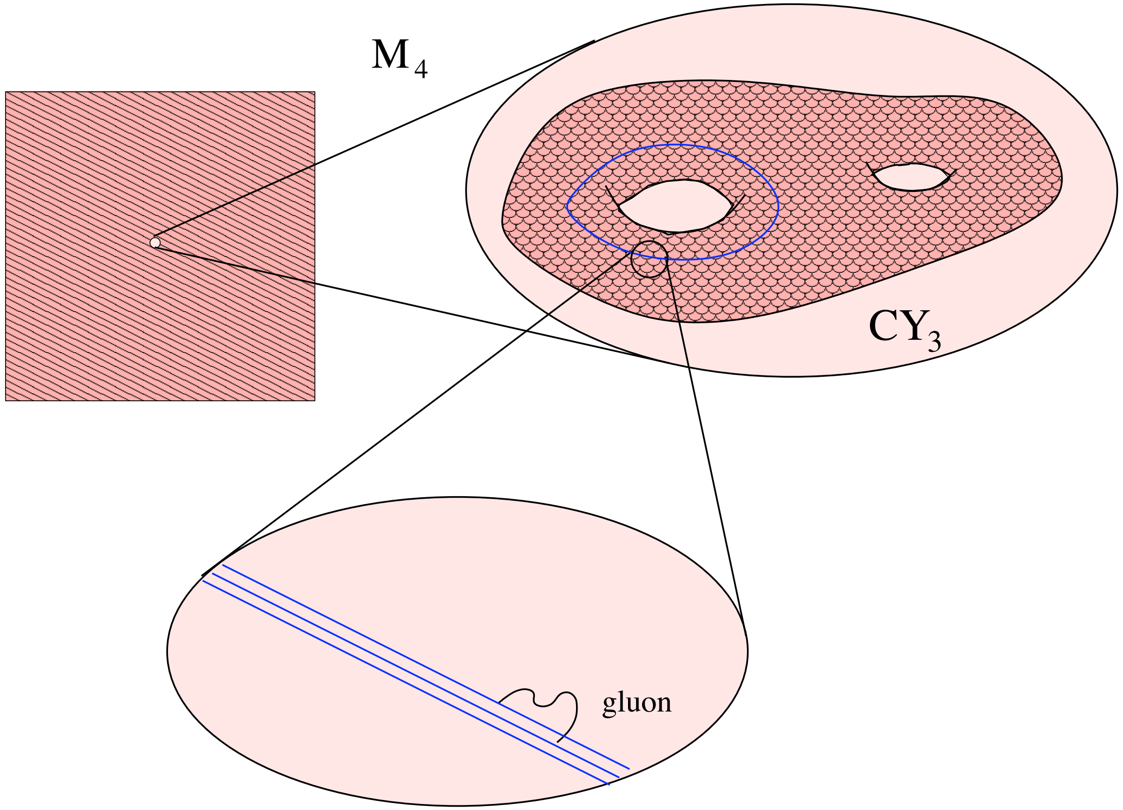

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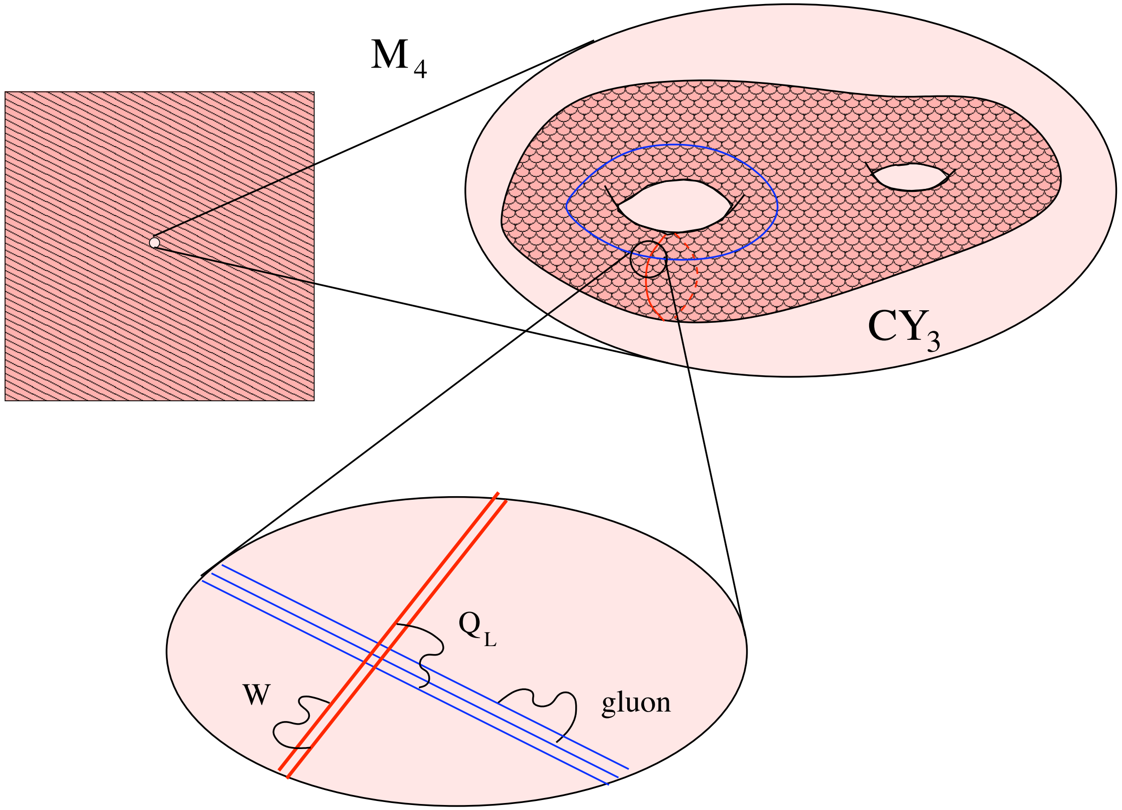
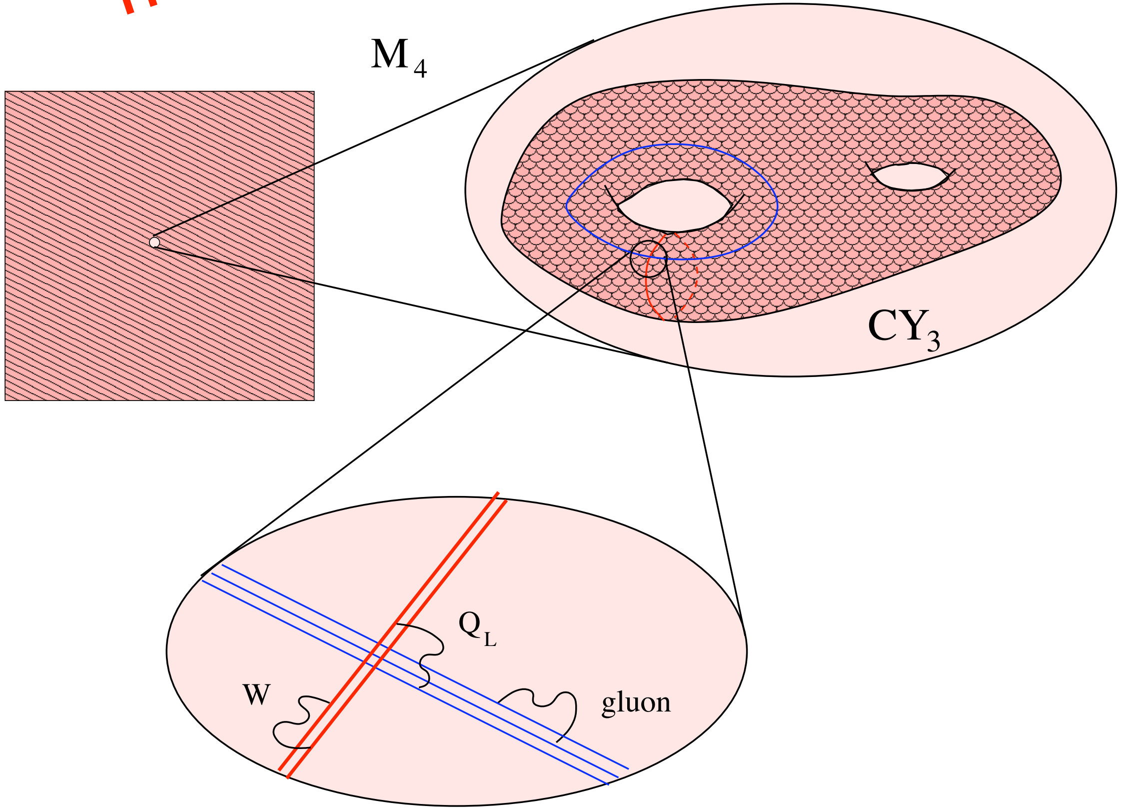


N=1 D-brane Model-Building

- D=4 ~~gravity~~ Sugra ← compactification on $M_4 \times X_6$ CY_3
- U(N) SYM theory ← BPS Dp-brane wrapping a submanifold $\Pi_{p-3} \subset X_6$
- Chiral ~~fermions~~ multiplets ← $(N_a, \overline{N_b})$ from $\Pi^a_{p-3} \cap \Pi^b_{p'-3}$



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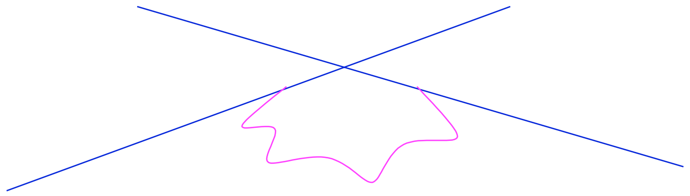
Berkooz et al. '96



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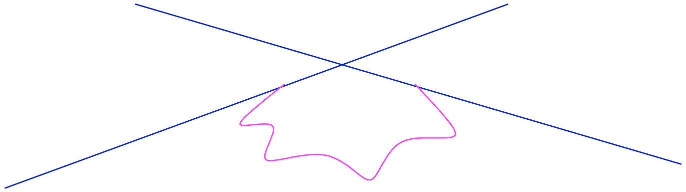

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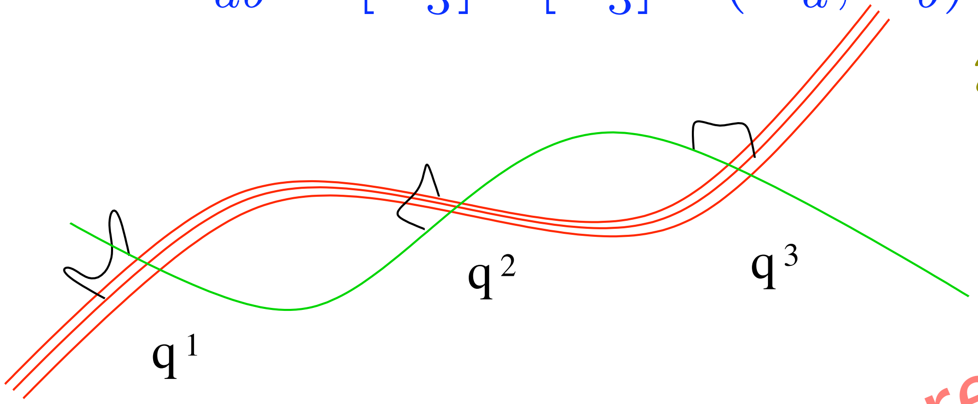

Blumenhagen et al. '00
Aldazábal et al. '00

Matter replication

Mariño et al. '99

D6-brane Model-Building

- SUSY conditions

Mariño et al. '99

$$\mathrm{F-flatness} \qquad \mathcal{F} + iJ|_{\Pi_3} = 0 \qquad \textit{Lagrangian}$$

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Special Lagrangian

- Gauge kinetic function

RR potential

$$f_a = \int_{\Pi_3^a} e^{-\phi}\mathrm{Re}\,\Omega + iC_3$$

Volume

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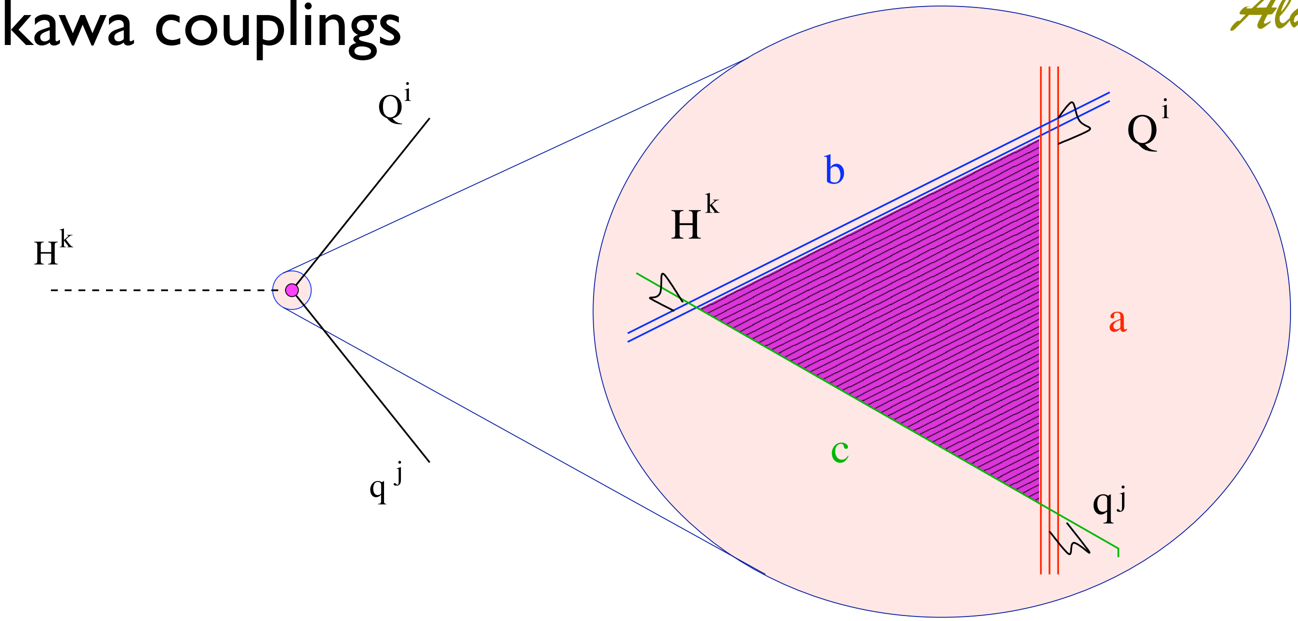

Very nice…

but…

...didn’t we miss something??

Let’s ⏪

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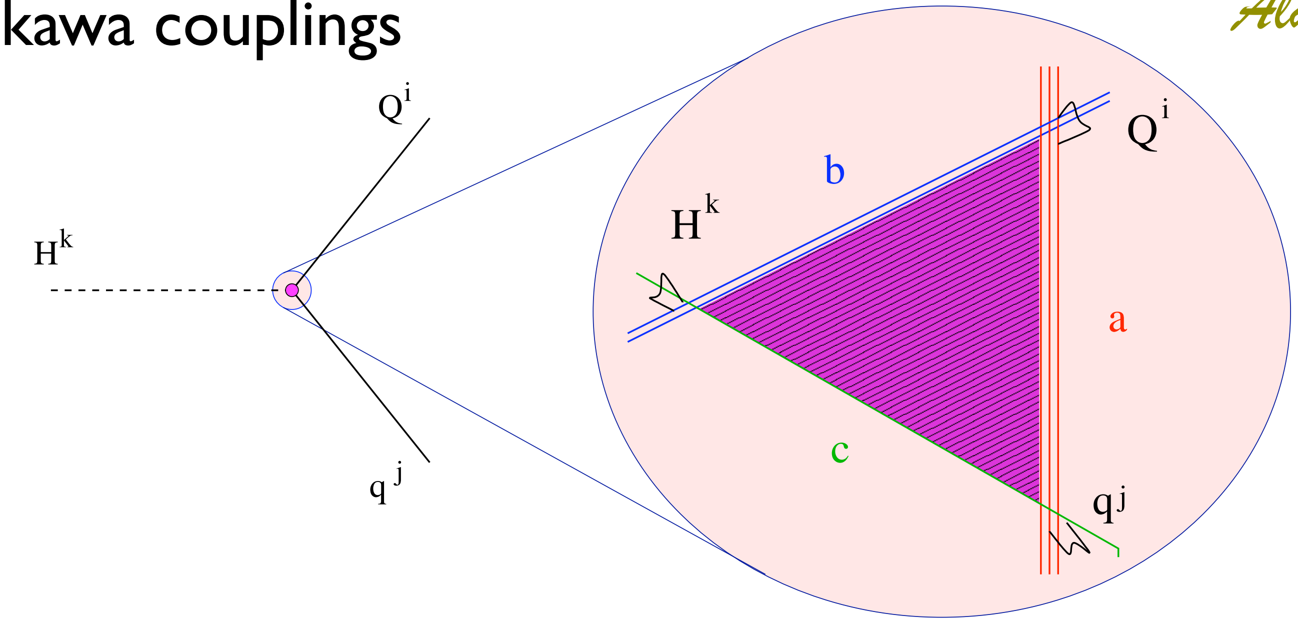

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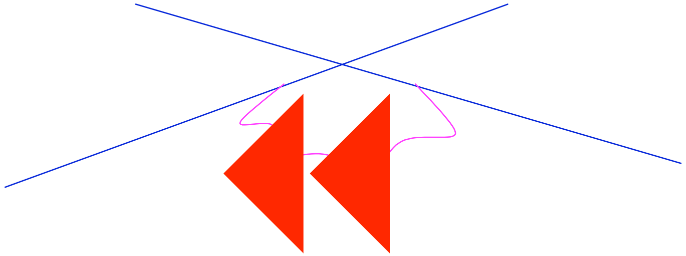

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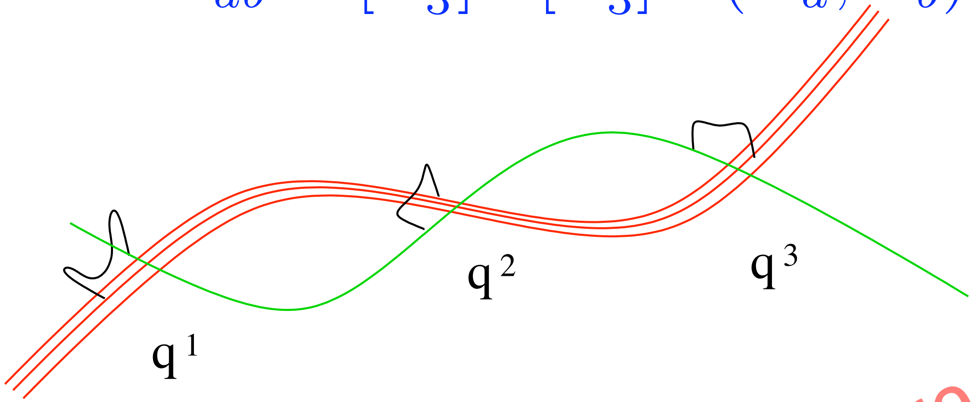

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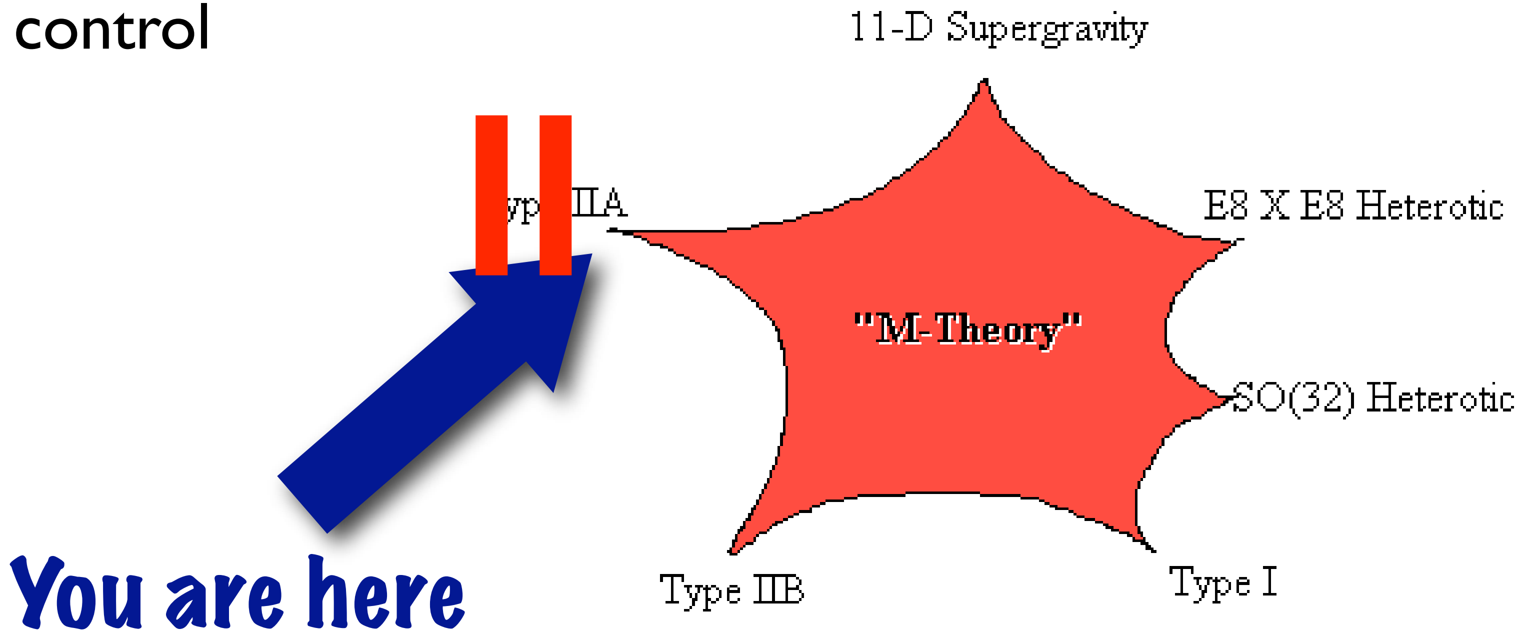

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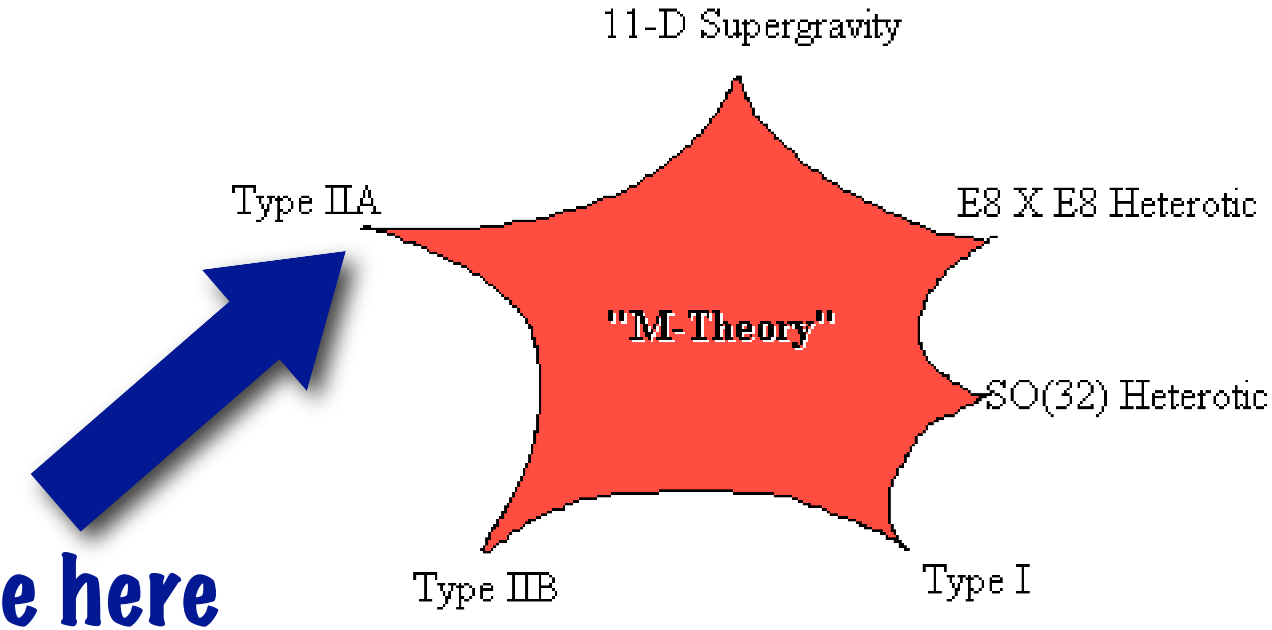

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Type IIA D-branes

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  - D4-branes
  - D6-branes
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vanishes $\Rightarrow$ No central charge $\Rightarrow$ No BPS D4-brane

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- Naively, the same argument works for D8-branes:
  - $b_1 = b_5 = 0 \quad \Rightarrow \quad \Pi_5$ is homologically trivial
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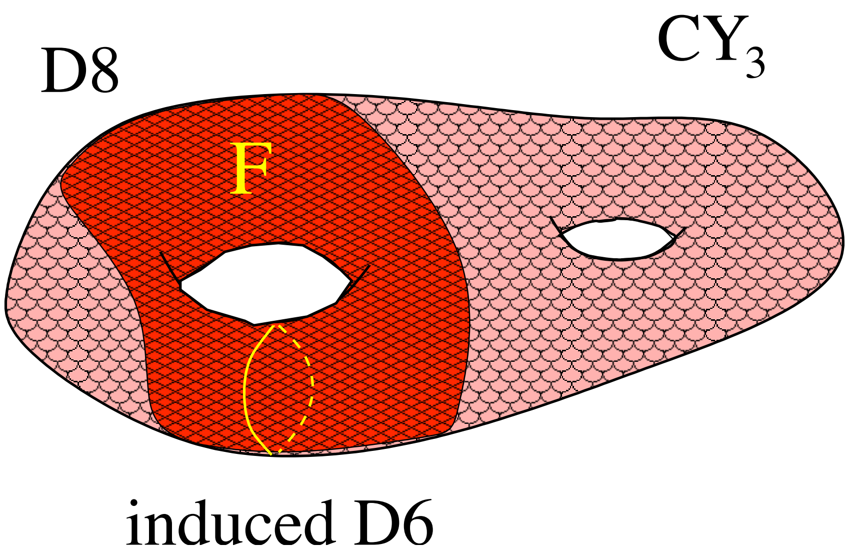
The second term will not vanish iff there is a dissolved D6-brane charge on our D8-brane

Douglas '95

What about D8-branes?

- Idea: we can have a D8-brane with
  - Trivial D8-brane charge
  - Non-trivial induced D6-brane charge



* So, in principle, we can also have BPS D8-branes !!!

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- We are interested in the case *n*=3, which means that coisotropic A-branes must wrap 5-cycles with $\mathcal{F} \neq 0$
- Because those *5*-cycles are trivial in homology, they are difficult to construct. No examples in the coisotropic literature

Going Coisotropic

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- The BPS conditions for A-branes read

	D6-branes
F-flatness	$\mathcal{F} + iJ\|_{\Pi_3} = 0$
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	D6-branes	D8-branes	
F-flatness	$\mathcal{F} + iJ\vert_{\Pi_3} = 0$	$(\mathcal{F} + iJ)^2\vert_{\Pi_5} = 0$	*Kapustin & Orlov '01*
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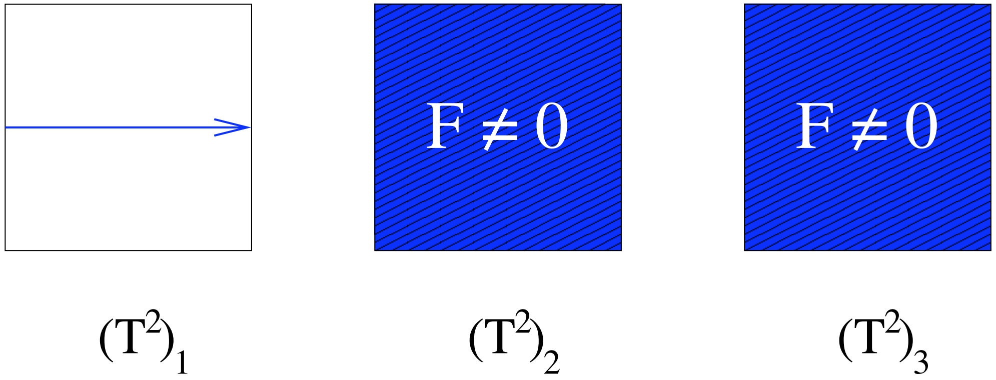
- Let us consider the case where $\mathcal{F} = 2\pi\alpha' F$, and $[\Pi_3^F]$ to be the Poincaré dual of $[F/2\pi]$. Then the BPS conditions suggest

$$\begin{array}{rcl} J|_{\Pi_3^F} = 0 & \sim & \mathcal{F} \wedge J|_{\Pi_5} = 0 \\ \mathrm{Im}\,\Omega|_{\Pi_3^F} = 0 & \sim & \mathcal{F} \wedge \mathrm{Im}\,\Omega|_{\Pi_5} = 0 \end{array}$$

So Π_3^F looks like an special Lagrangian 3-cycle in $\mathbf{CY}_3$

A toroidal example

- Let us consider $\mathbf{T}^2 \times \mathbf{T}^2 \times \mathbf{T}^2$ and the D8-brane



$$\begin{aligned} \Pi_5 &= (1,0)_1 \times (\mathbf{T}^2)_2 \times (\mathbf{T}^2)_3 \\ F/2\pi &= dx^2 \wedge dx^3 - dy^2 \wedge dy^3 \end{aligned}$$

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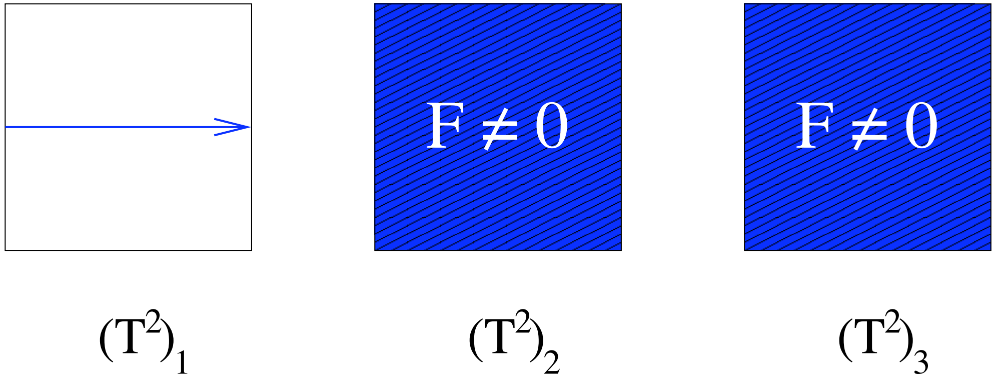

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- The BPS conditions read
  - D-term ➠ Trivial
  - F-term ➠ $\begin{cases} J_c \wedge F = 0 & ✓ \\ J_c^2 + F^2 = 0 & \iff \quad T_2 T_3 = 1 \end{cases}$

$$J_c = B + iJ \qquad T_j = A_j + iB_j$$

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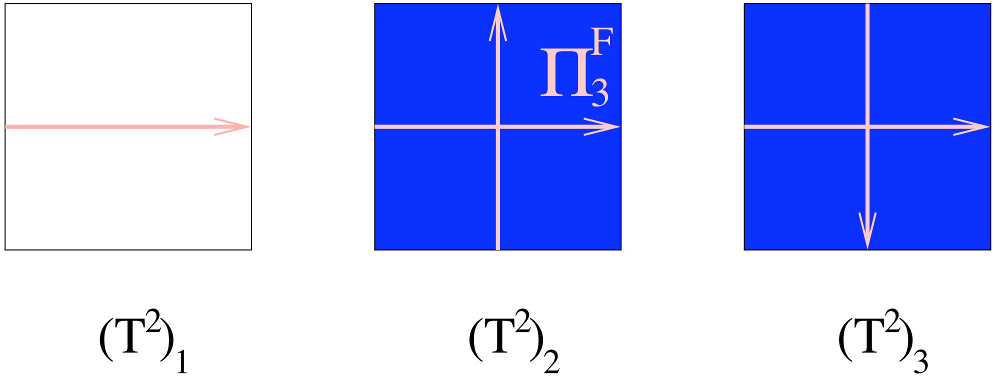

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- Notice that

$$[\Pi_3^F] = [(1,0)(1,0)(1,0)] + [(1,0)(0,1)(0,-1)]$$

and so the D6-brane charge is not of the form (1-cycle) x (1-cycle) x (1-cycle), like for CFT D6-branes

D8-branes on Z_2 x Z_2

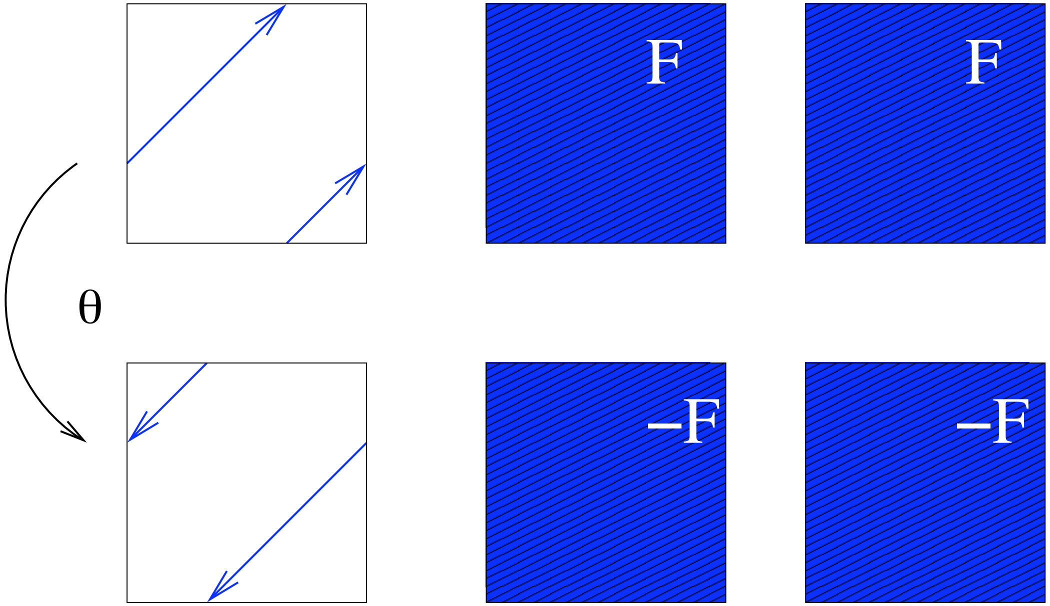
$b_1(\mathbf{T}^6) \neq 0$

D8-branes on Z_2 x Z_2

- Notice that $b_1(\mathbf{T}^6) \neq 0$, so finding BPS D8-branes is not that surprising.

D8-branes on Z_2 x Z_2

- Notice that $b_1(\mathbf{T}^6) \neq 0$, so finding BPS D8-branes is not that surprising.
- Let us set $b_1 = 0$ by orbifolding our theory by $\mathbf{Z}_2 \times \mathbf{Z}_2$:



	D8	D6	D4
D8	$[\Pi_5]$	$[\Pi_3^F]$	$[\Pi_1^{F^2}]$
q D8	$-[\Pi_5]$	$[\Pi_3^F]$	$-[\Pi_1^{F^2}]$

Tadpoles

Tadpoles

- Because is the only surviving one, D8-branes contribute to RR tadpoles via its induced D6-brane charge

$$\sum_{a \in D6} N_a [\Pi_3^a] + \sum_{b \in D8} N_b [\Pi_3^{F_b}] = 4[\Pi_3^{O6}]$$

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- SUSY guarantees the cancellation of NSNS tadpoles, which are related to D-branes tensions. These tensions are also related to the gauge coupling constants:

$$\frac{1}{g_b^2} = \int_{\Pi_5^b} e^{-\phi}\frac{F_b}{2\pi} \wedge \mathrm{Re}\,\Omega = \int_{\Pi_3^{F_b}} e^{-\phi}\mathrm{Re}\,\Omega$$

- In fact, the gauge kinetic function reads

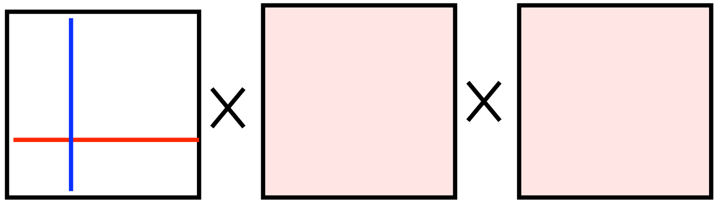
$$f_b = \int_{\Pi_3^{F_b}} e^{-\phi}\mathrm{Re}\,\Omega + iC_3$$

Chirality

Chirality

- Chirality arises from a mixture of intersection and magnetization mechanisms, as in type IIB

$D8_a - D8_b$



$$I_{ab} = (n_1^a m_1^b - m_1^a n_1^b) \int_{T^2 \times T^2} (F_a - F_b)^2$$

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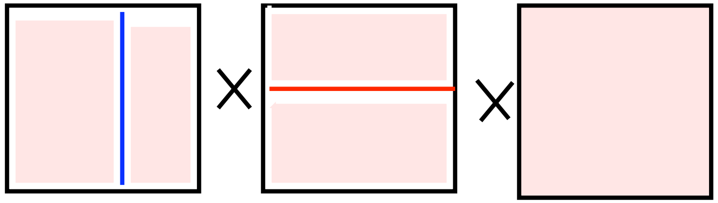

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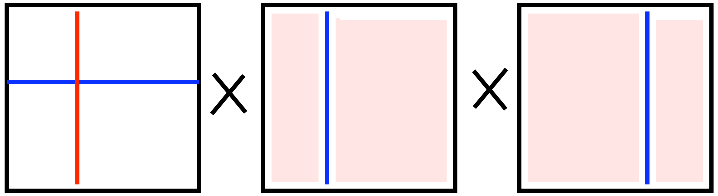

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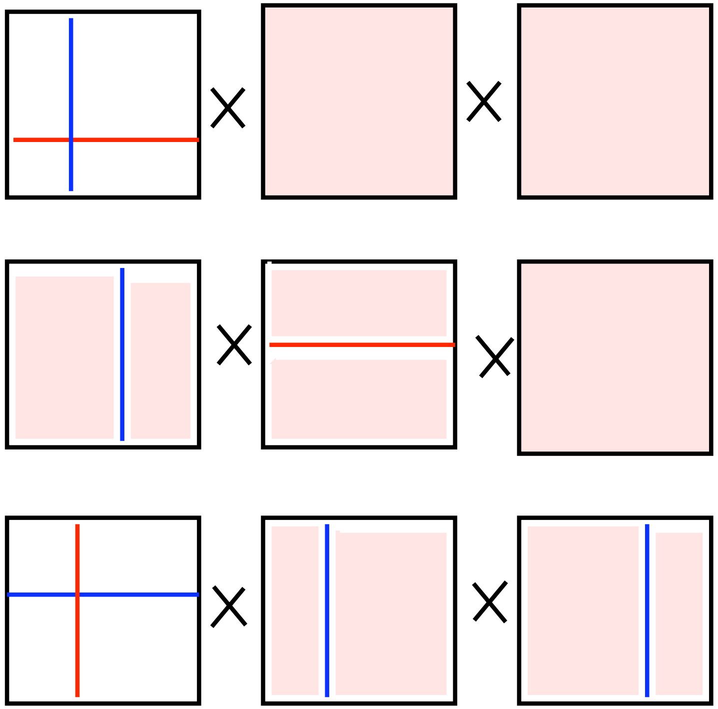

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$D8_a - D6_b$ $\quad I_{ab} = (n_1^a m_1^b - m_1^a n_1^b) \int_{C^2} (F_a - F_b)$

- However, the net number of chiral fermions is given by

$$I_{ab} = [\Pi_3^{D8_a}] \circ [\Pi_3^{D8_b}] \quad \text{or} \quad I_{ab} = [\Pi_3^{D6_a}] \circ [\Pi_3^{D8_b}]$$

Yukawa couplings

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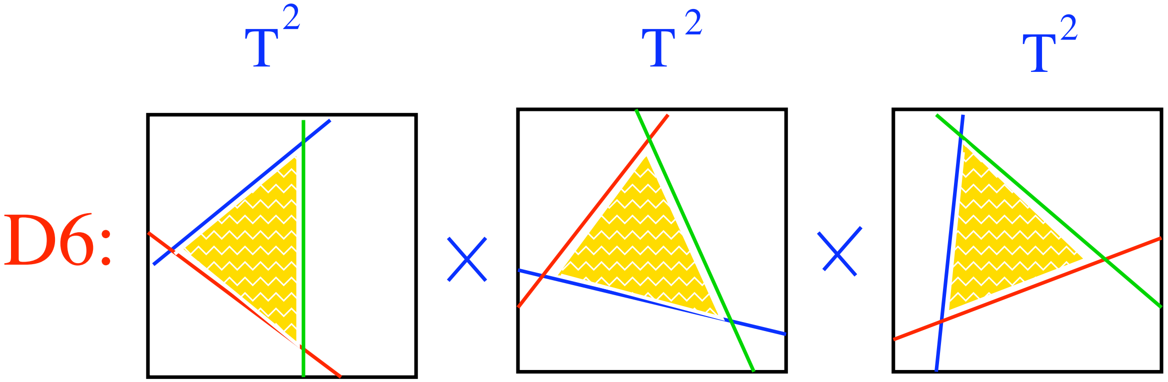
- For D6-branes Yukawas arise from worldsheet instantons



Cremades et al. '03

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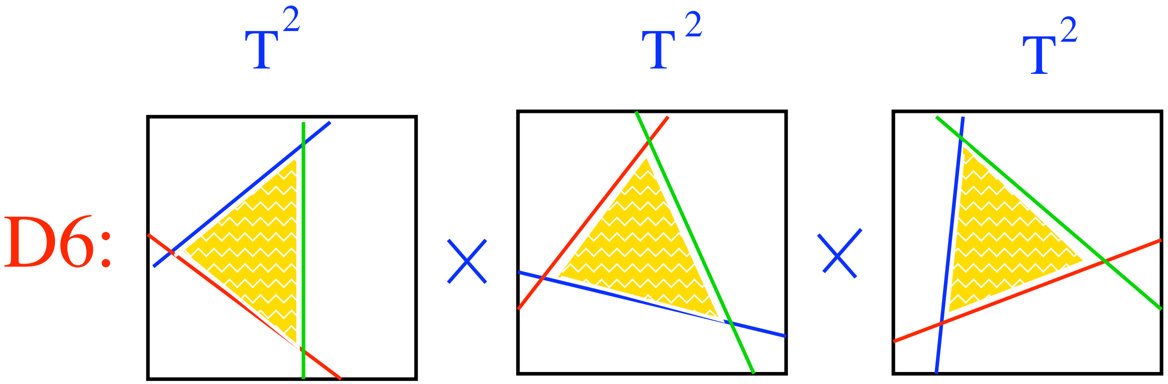
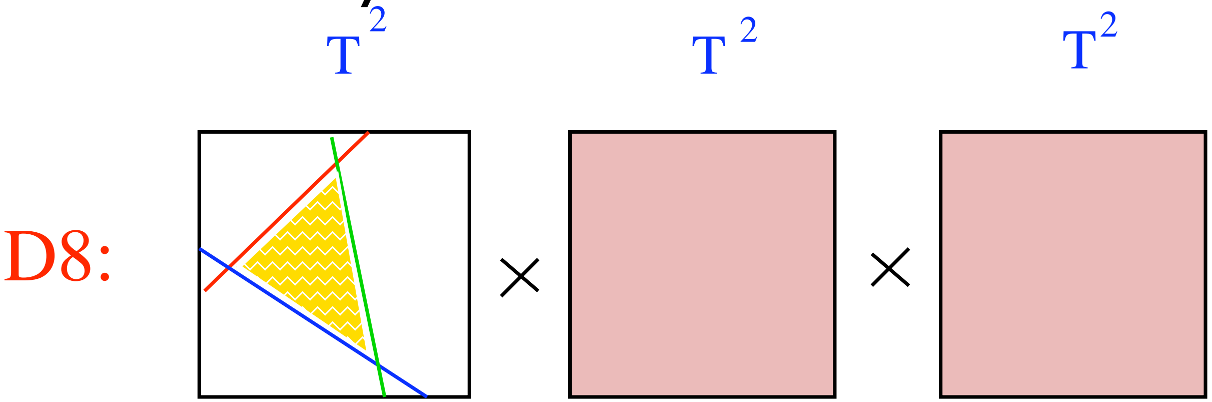
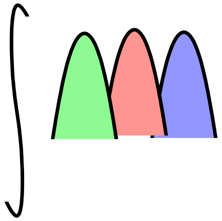


Cremades et al. '03

- For D8-branes both instantons and overlapping wavefunctions may be at work



- New kinds of textures...



Cremades et al. '04

Superpotential

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$$V_{NSNS} = \sum_a T_{D6_a} + \sum_b T_{D8_b} - 4T_{O6}$$

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  - D-term
  - F-term ➠ Can be derived from the superpotential

$$W = X_i(T_jT_k - n)$$

X_i : open string field (location + Wilson line)

$n = n^{xy}n^{yx} - n^{xx}n^{yy}$

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- In this case the F-flatness condition reads

$$\frac{\partial W}{\partial X_i} = (T_j T_k + X_j X_k - n) = 0$$

and only a combination of open and closed string moduli is fixed (like for D-term potentials).

An MSSM-like model

$\mathbf{Z}_2 \times \mathbf{Z}_2$

$xx \quad xy \quad yx \quad yy$

$D8_a$	$N_a = 3+1$	$(1,0)_1 \times (1,3,-3,-10)_{23}$
$D6_b$	$N_b = 1$	$(0,1)_1(1,0)_2(0,-1)_3$
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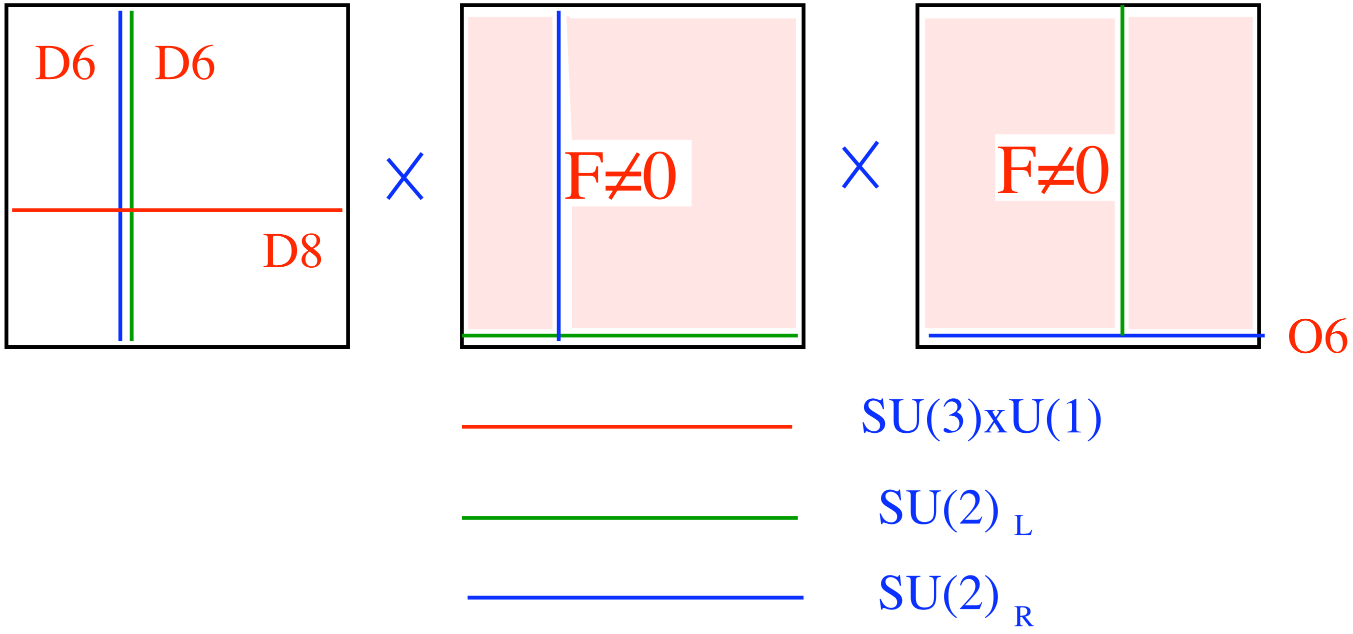

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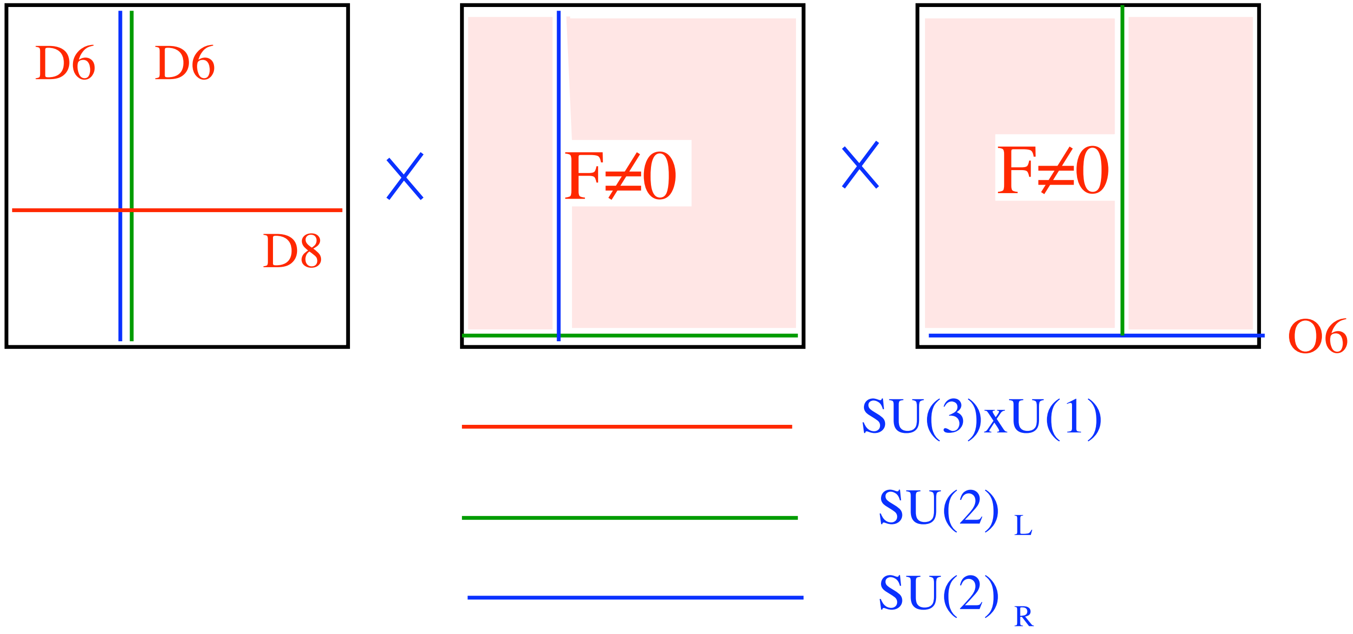

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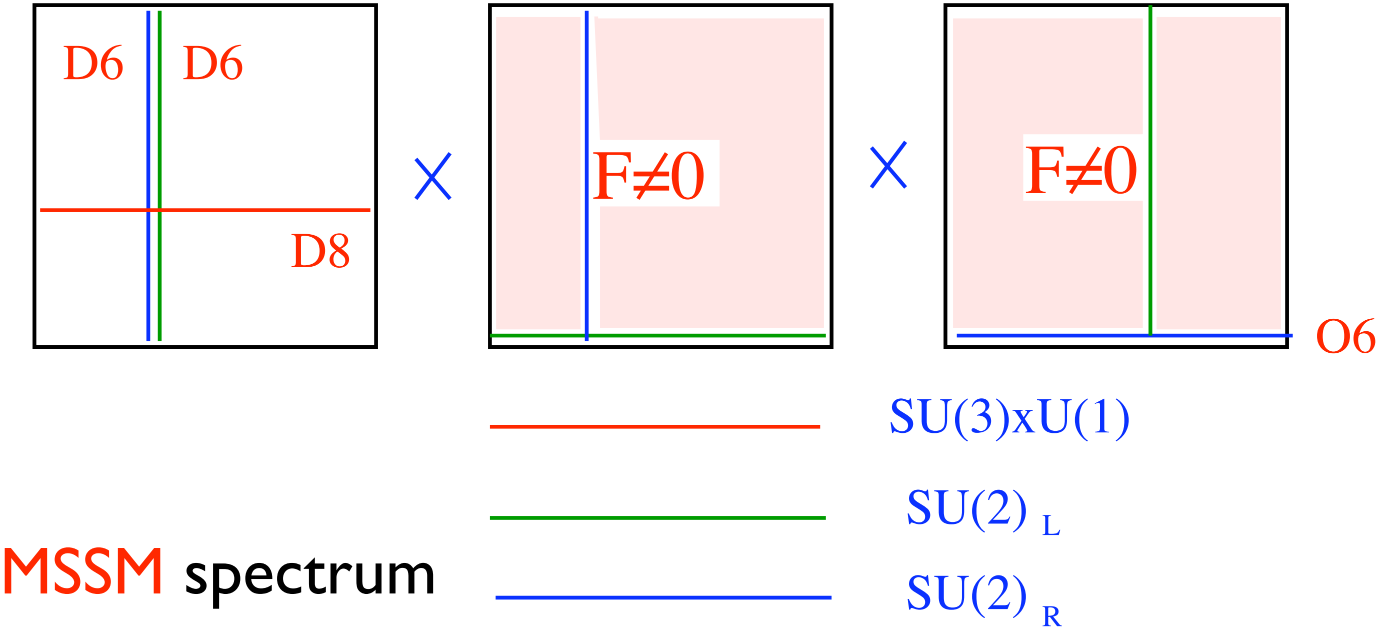
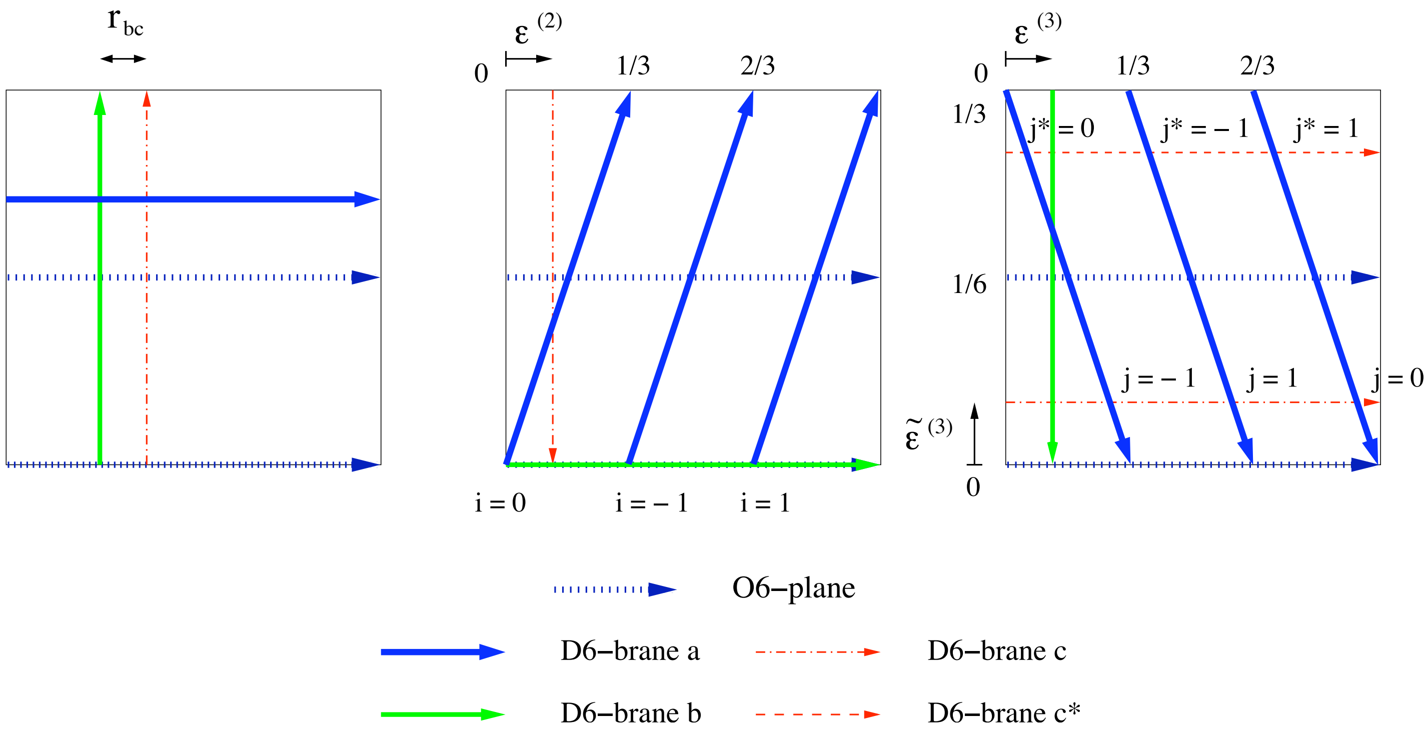


☑ LR MSSM spectrum

Very similar to the previous D6-model...

N_α	(n^1_α, m^1_α)	(n^2_α, m^2_α)	(n^3_α, m^3_α)
$N_a = 3 + 1$	$(1, 0)$	$(3, 1)$	$(3, -1)$
$N_b = 1$	$(0, 1)$	$(1, 0)$	$(0, -1)$
$N_c = 1$	$(0, 1)$	$(0, -1)$	$(1, 0)$



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Cremades et al. '03

F.M. & Shiu '04

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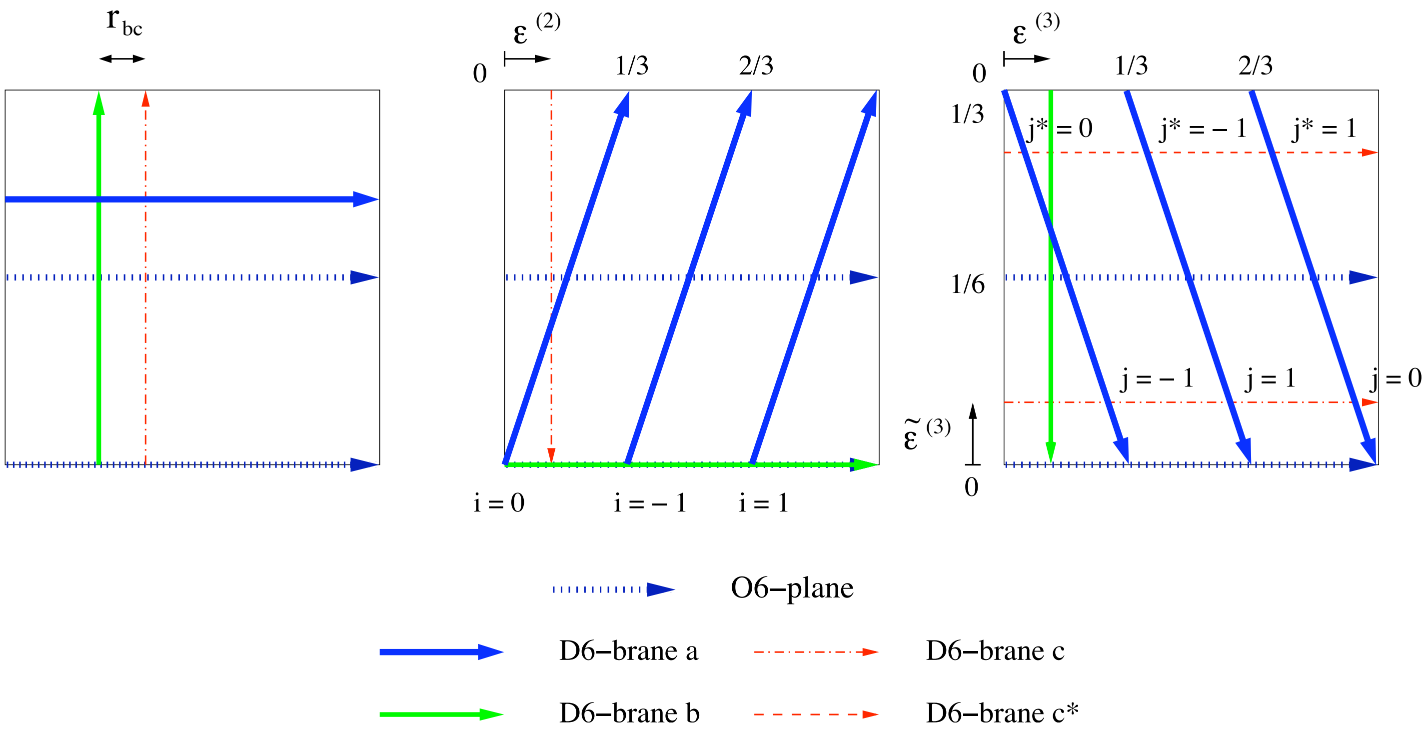

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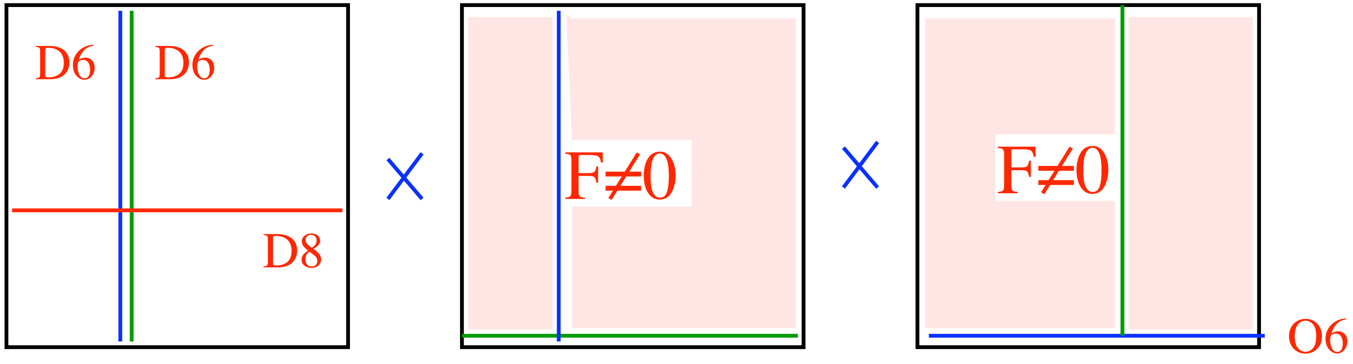

🟥 SU(3)xU(1)

🟩 $SU(2)_L$

🟦 $SU(2)_R$

☑ LR MSSM spectrum

An MSSM-like model

An MSSM-like model

- We can introduce additional D-branes to cancel tadpoles:

$xx \quad xy \quad yx \quad yy$

$D8_Z$	$N_Z = 1$	$(0,1)_1(0,-1,-1,0)_{23}$
$D6_M$	$N_M = 2$	$(-2,1)_1(-3,1)_2(-3,1)_3$
$D6_F$	$N_F = 4$	$(1,0)_1(1,0)_2(1,0)_3$

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- The D6-brane charge induced on the D8-branes is

$$D8_a \; : \; (1,0)_1 \times (1,3,-3,-10)_{23} = (1,0)_1 \times [(3,1)(3,-1) + (1,0)(1,0)]$$

$$D8_Z \; : \; (0,1)_1 \times (0,-1,-1,0)_{23} = (0,1)_1 \times [(1,0)(0,-1) + (0,-1)(1,0)]$$

- Many more variants may be built...

An MSSM-like model

- The chiral spectrum of this model is quite minimal

sector	Matter	Representation
ab	$Q_L + L$	$3\,(3+1,2,1)$
ac	$Q_R + R$	$3\,(\overline{3}+1,1,2)$
bc	H	$(1,2,2)$
bM	L'	$6\,(1,2,1;2_M)$
cM	R'	$6\,(1,1,2;2_M)$

and one may get rid of the extra matter by performing a Higgsing of the form $U(2)_M \rightarrow SO(2)_M$

Conclusions

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- There is more than meets the eye: D6-branes need not be the only BPS objects of a Calabi-Yau compactification
- We have shown this by explicitly constructing BPS coisotropic D8-branes, in the sense of Kapustin and Orlov, in a $\mathbf{Z}_2 \times \mathbf{Z}_2$ orientifold

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- There is more than meets the eye: D6-branes need not be the only BPS objects of a Calabi-Yau compactification
- We have shown this by explicitly constructing BPS coisotropic D8-branes, in the sense of Kapustin and Orlov, in a $\mathbf{Z}_2 \times \mathbf{Z}_2$ orientifold
- These D8-branes show interesting model building features, like producing D=4 chiral fermions when intersecting other D8 or D6-branes
- We have analyzed the effective theory of these D8's. Many features are similar to D6-branes, but others are new, like a superpotential involving Kähler moduli

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- Recently a statistical analysis of semi-realistic models in the same $\mathbf{Z}_2 \times \mathbf{Z}_2$ orientifold has been performed.

Blumenhagen et al. '04
Douglas & Taylor '06

- This analysis did not take into account the presence of coisotropic D8-branes, so the statistical results could in principle be modified.