Flux supersymmetry breaking in MSSM string compactifications

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Plan of the talk

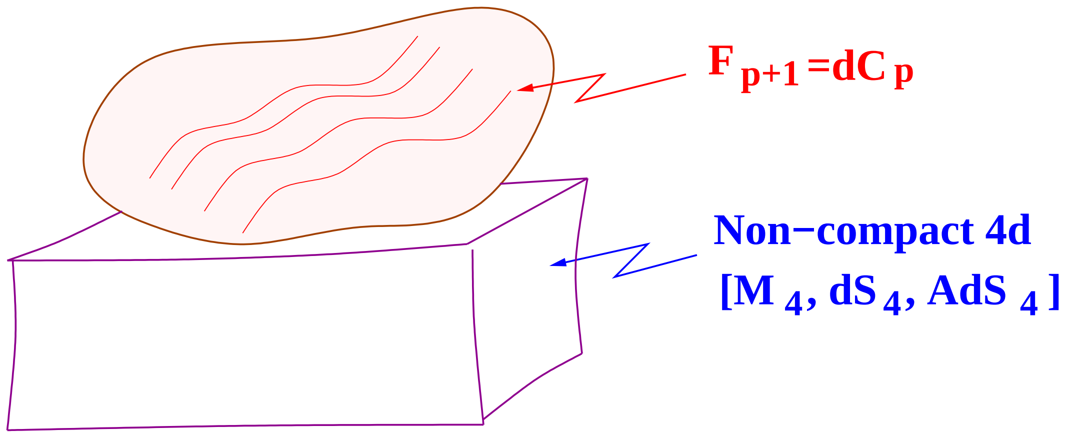
- Motivation
- Overview of flux compactifications
- MSSM Model building
- Flux susy breaking and soft terms
- Conclusions

Motivation

- Recent great interest in backgrounds/compactifications of string/M - theory with non-trivial field strength fluxes for diverse p-form fields

$$F_{\mu_1 \ldots \mu_{p+1}} = \partial_{[\mu_{p+1}} C_{\mu_1 \ldots \mu_p]}$$

PICTURE:



- Natural possibility in the construction, not exploited until recently

• These constructions lead to new and interesting features, compared with previous compactifications

- Stabilization of moduli
- Warped compactifications
- Breaking of supersymmetry

In a computable regime!

AIM: Overview of these aspects in a well-studied class of models

Type IIB string theory compactified on CY_3
with NSNS/RR 3-form fluxes H_3, F_3

With an eye on phenomenological applications

Type IIB on CY_3 orientifolds

A very general set of models with 4d $N = 1$ supersymmetry
F-theory on CY_4, or equivalent description in terms of
Type IIB string theory,

10d massless fields: NSNS $\rightarrow G_{MN}, B_{MN}, \Phi$

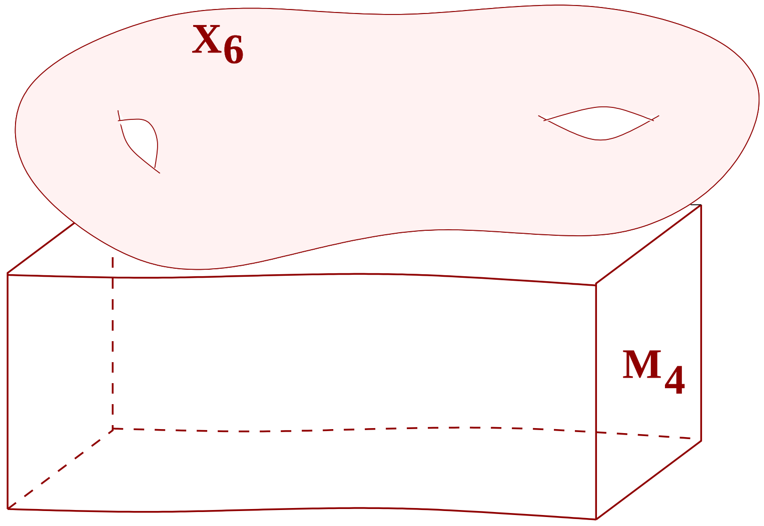
RR $\rightarrow a, \tilde{B}_{MN}, C_{MNPQ}$

Contains a number of solitonic objects (D-branes) with gauge fields localized on their volume

Background includes following ingredients

- IIB compactified on $M_4 \times CY_3$
- Stacks of 7-branes wrapped on 4-cycles
- O3-planes
- D3-branes at points on CY_3

Type IIB on CY_3 orientifolds



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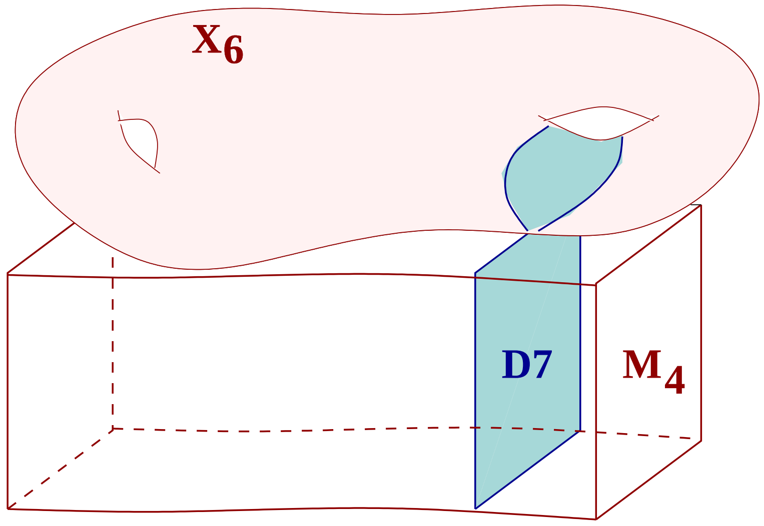

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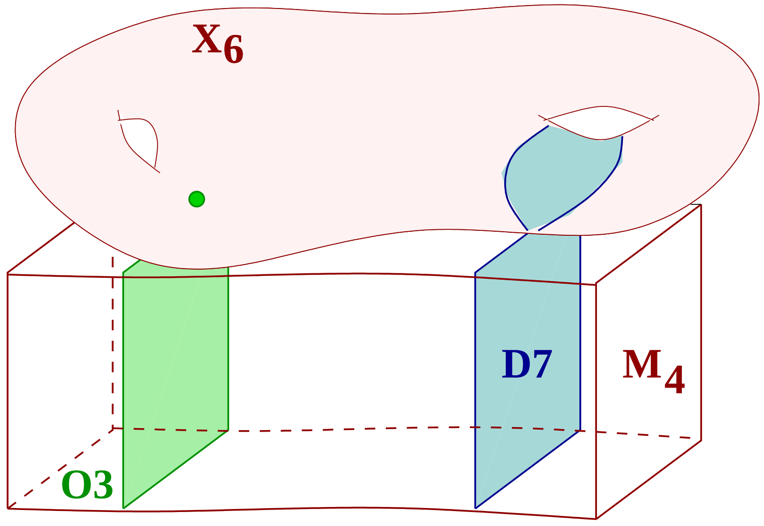

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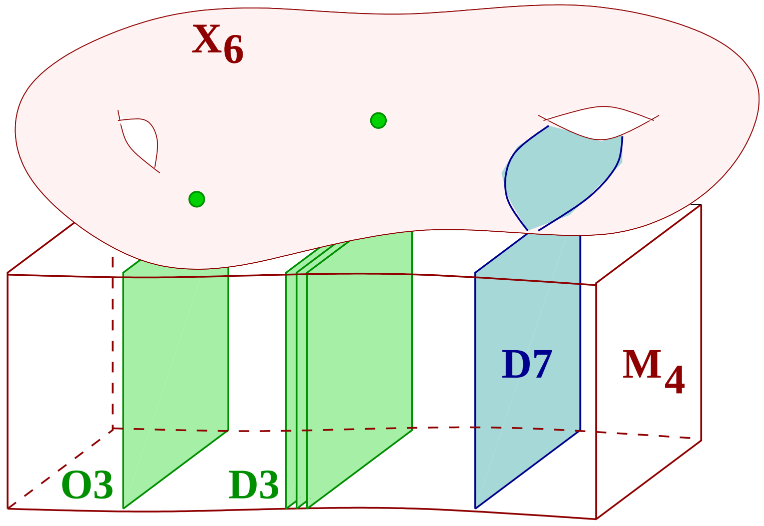

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- IIB compactified on $M_4 \times CY_3$
- Stacks of 7-branes wrapped on 4-cycles
- Quotient by an orientifold action: introduces O3-planes,
  objects of equal negative tension and RR 4-form charge
- D3-branes, objects of equal positive tension and RR 4-form charge

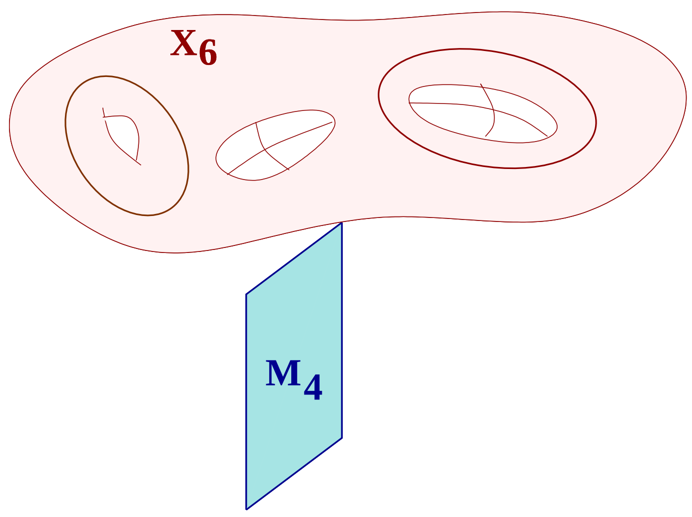
Obs: Changes and tensions of D3- and O3- cancel and allow for M_4 compactification.

Moduli in these models

Nice setup for model building, 4d $N = 1$ susy, and possibly realistic gauge sectors localized on the D3- and/or D7-branes (see later)

Several kinds of moduli:

- Dilaton-axion $\tau = a + i/g_s$
- Kähler moduli: size of 2- and 4-cycles
- Complex structure moduli: size of 3-cycles
- D-brane moduli: D-brane positions (and world-volume gauge field data)



How to get rid of these massless scalars?

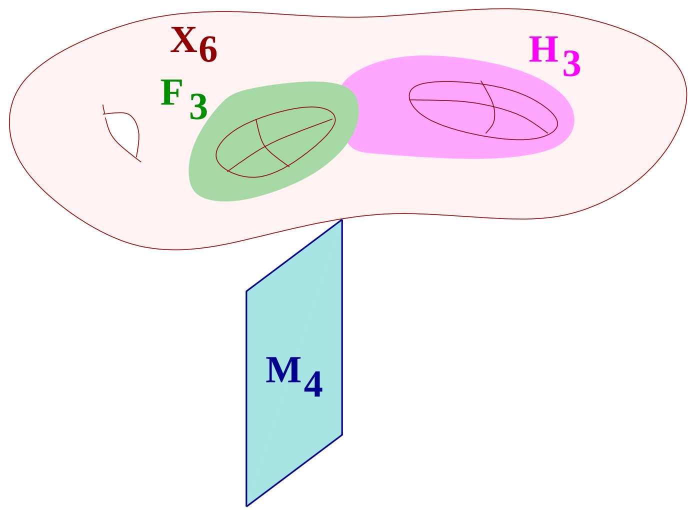
Type IIB on CY_3 with 3-form fluxes

[Becker's; Dasgupta, Rajesh, Sethi; Giddings, Kachru, Polchinski;...]

10d Type IIB: NSNS $\rightarrow G_{MN},\ B_{MN},\ \Phi$

RR $\rightarrow a,\ \tilde{B}_{MN},\ C_{MNPQ}$

Consider compactification to 4d on a 6d CY_3, with non-trivial background for internal components of NSNS/RR field strength 3-forms H_3 , F_3



Convenient to define the complex flux density $G_3 = F_3 - \tau H_3$

Fluxes have an energy density

$$E_{\mathrm{flux}} = \int_{X_6} d^6x\,(G_3)_{lmn}(\overline{G}_3)^{lmn} = \int_{X_6} G_3 \wedge *_6 \overline{G}_3$$

Fluxes are charged under the RR 4-form

$$Q_{\mathrm{flux}} = -i \int_{X_6} d^6x\,\epsilon_{lmnpqr}(G_3)_{lmn}(\overline{G}_3)_{pqr} = -i \int_{X_6} G_3 \wedge \overline{G}_3$$

Cancellation of 4-form charge requires

$$Q_{\mathrm{flux}} + Q_{D3} - Q_{O3} = 0$$

Notice that for $*_6 G_3 = i G_3$, tension equals charge, $E_{\mathrm{flux}} = Q_{\mathrm{flux}}$.
Charge cancellation implies cancellation of tension for ISD G_3
$\rightarrow$ Compactification to M_4 with zero c.c. (at leading approximation).

Conditions to have a consistent configuration

- Bianchi identities: $dH_3 = 0$, $dF_3 = 0$ (fluxes have no sources)

- Flux quantization

For a basis of 3-cycles Σ_a, $\int_{\Sigma_a} H_3 \in \mathbf{Z}$, $\int_{\Sigma_a} F_3 \in \mathbf{Z}$

- RR tadpole cancellation: Total C_4-charge in compact CY$_3$ = 0

$Q_{\text{flux}} + Q_{D3} - Q_{O3} = 0$

- Minimization of potential energy (scalar potential)

$$W = \int_{CY_3} G_3 \wedge \Omega$$

[Gukov, Vafa, Witten]

$$V = E_{\text{flux}} + T_{D3} - T_{O3} = \int_{CY_3} |G_3 - i * G_3|^2$$

Minima of potential $\rightarrow$ $G_3 = i *_{6d} G_3$ Flux density is ISD
$\rightarrow$ Moduli stabilization
- Since fluxes are quantized, their integrals over 3-cycles are fixed, and the flux density depends on complex structure moduli.
- In addition G_3 depends explicitly on τ.

$\rightarrow$ Generically, stabilization of 10d dilaton and complex structure moduli.
Kähler moduli are not stabilized.

4d effective theory description

4d effective action in terms of

$$K(\rho,\bar\rho) = -3\log(\rho+\bar\rho)$$
$$W(\phi_i) = \int_{X_6} G_3\wedge\Omega$$

No-scale supergravity structure

$$V = e^K\left(D_aW D_{\bar a}\bar W - 3|W|^2\right)$$

with $D_aW = \partial_a W + \partial_a K\, W$.

Cancellation leads to

$$V = e^K |\, D_iW\,|^2$$

V is definite positive, and vanishes for $D_iW = 0$, independently of Kähler moduli ρ.

Same number of equations and unknowns
$\rightarrow$ generically isolated solutions for dilaton and complex structure vevs.

Supersymmetry

The conditions that a flux combination G_3 preserves some supersymmetry are

- G_3 is $(2,1)$
- G_3 is primitive, $G_3 \wedge J = 0$ [Graña, Polchinski]

The primitivity condition is automatic in non-trivial CY compactifications (no 5-forms on CY)

The condition of ISD allows G_3 to have $(0,3)$ and $(2,1)$

- $(2,1)$ G_3 flux $\rightarrow$ supersymmetric 4d vacuum
- $(0,3)$ G_3 flux $\rightarrow$ non-supersymmetric, but zero vacuum energy
  (to leading order in α', g_s)
- IASD G_3 $\rightarrow$ non-supersymmetric, and leads to non-zero vacuum energy
  (rather, to runaway potential for Kähler moduli)

Many interesting new issues

• Questions: Values of moduli masses, vevs, ... ?
Susy breaking scale in gravit. sector? In SM?
Partial answers (and much work needed) by analysis of flux stabilized vacua
[Douglas et al.]

• Full stabilization of all moduli?
A proposal [Kachru, Kallosh, Linde, Trivedi]
Add non-perturbative effects to stabilize Kähler moduli
[Add susy breaking source ($\overline{D}3$'s) to lift to dS vacua]
Progress towards explicit models? [Denef, Douglas, Florea]

• Cosmological applications
Cosmological constant, brane inflation, cosmic strings, ...

TODAY: Center on several particle physics questions

Where is the (MS)SM? Susy breaking by fluxes and soft terms

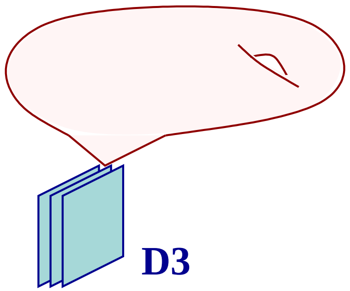
Phenomenological model building

Where is the SM in this picture?

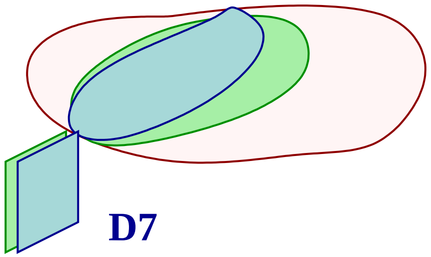
Embed the SM in configurations of D-branes in the model →
Take advantange of similar analysis in the absence of fluxes.

Chirality is non-trivial
→ Isolated branes at smooth points lead to non-chiral world-volume gauge theories.
Two well-studied classes of chiral D-brane configurations:

D-branes at singularities


D3

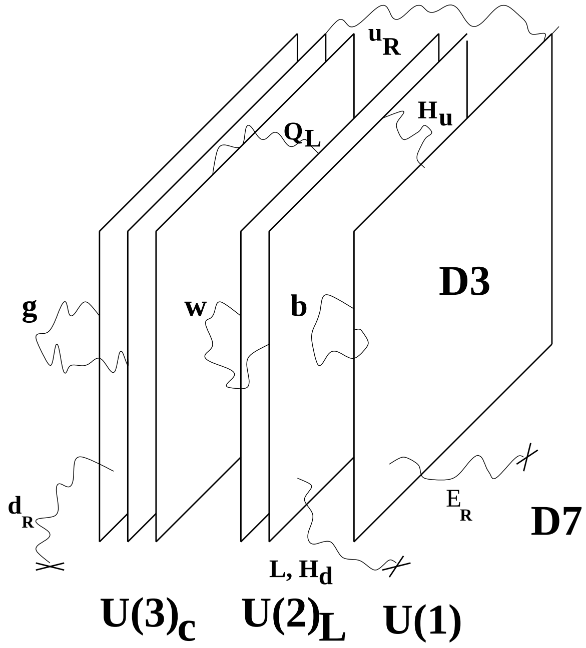
Intersecting/magnetised branes


D7

An MSSM-like example from D3's at singularities

[Aldazabal, Ibáñez, Quevedo, A.U.]

Consider D3- and D7-branes at a C^3/Z_3 orbifold singularity
Ensure consistency conditions etc



MSSM spectrum, plus some additional Higgs doublets (and global symmetries)
Not fully realistic, yet a very tractable toy model

MSSM-like constructions from magnetised D7-branes

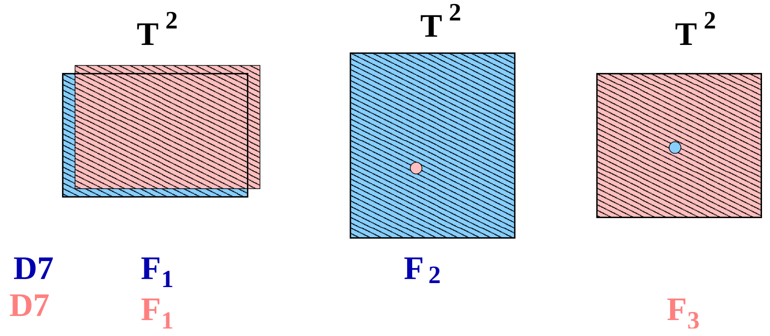
[Bachas; Angelantonj, Antoniadis, Dudas, Sagnotti; Blumenhagen, Gorlich, Kors, Lust; Aldazabal, Franco, Ibáñez, Rabadán, A.U.; Cvetic, Shiu, A.U.; Ibáñez, Marchesano, Rabadán; Cremades, Ibáñez, Marchesano; ...]

- Related to models of intersecting D6-branes (via mirror symmetry)

- Mostly considered in toroidal models:

Consider compactification on T^6 and D7-branes wrapped on T^4 subspaces, and carrying world-volume magnetic fields F_i

→ Chirality from open strings stretching between different D7-brane stacks



→ Non-susy models with just the SM spectrum.

Susy models extremely close to MSSM.

Soft terms

Effect of fluxes on D-branes is very important.

Center on supersymmetric sets of D-branes, and non-supersymmetric fluxes
Supersymmetry breaking by fluxes manifests as soft supersymmetry breaking terms on the D-brane gauge sector.

Two strategies:

• D-branes are sensitive only to local background around them.
Consider D-brane world-volume action coupled to the local supergravity background, and expand perturbatively on the fluxes.

• Describe effect of fluxes in the 4d effective lagrangian, which contains gauge sectors corresponding to the D-branes.

Local analysis for D3-branes

Stack of n D3-branes in flat space
$\rightarrow$ 4d $N = 4$ $U(n)$ gauge theory

In $N = 1$ terms:

Vector multiplet $V = (A_\mu, \lambda)$
3 Adjoint Ch. multiplets $\Phi_i = (\Phi_i, \Psi_i)$
$\rightarrow$ Goldstones = Scalars vevs are D3 transverse coordinates

DBI+CS action for world-volume fields $\leftrightarrow$ dynamics of D3-brane

At lowest order (D3-brane in flat space without fluxes)
$N = 1$ SYM coupled to three adjoint chiral multiplets with $W = \mathrm{tr}\, \Phi_1[\Phi_2 \Phi_3]$

Flux effects: soft terms breaking susy (to $N = 1$ or $N = 0$)

DBI+CS action for world-volume fields $\leftrightarrow$ dynamics of D3-brane

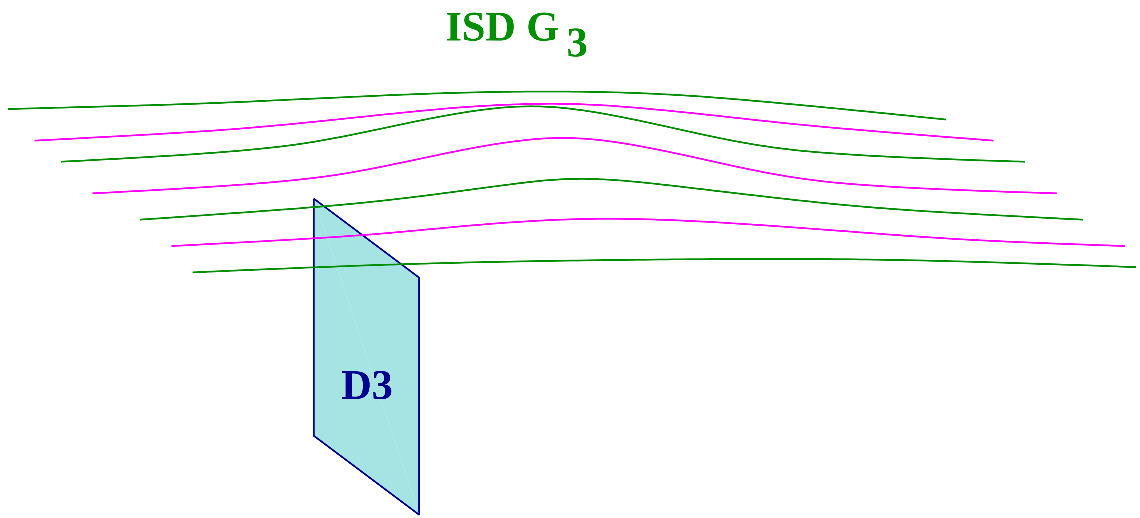
Split flux in ISD and IASD piece.

Equiv. Split 20 of local geometric $SO(6)$ symmetry into $10 + \overline{10}$.

• ISD flux has positive tension and RR 4-form charge

D3-brane suffers cancelling effects from gravitational attraction and Coulomb-like repulsion

$\longrightarrow$ No soft terms



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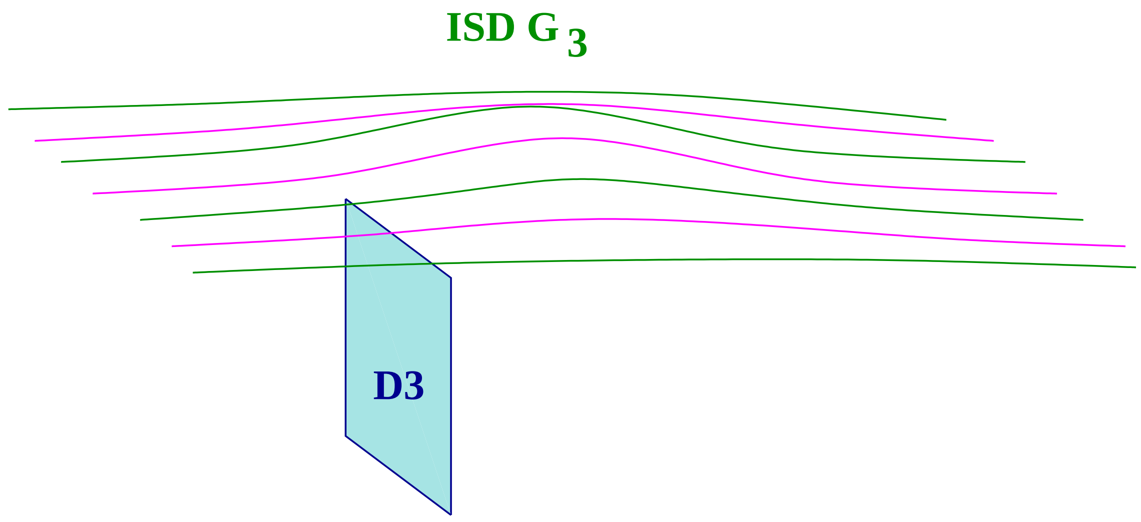

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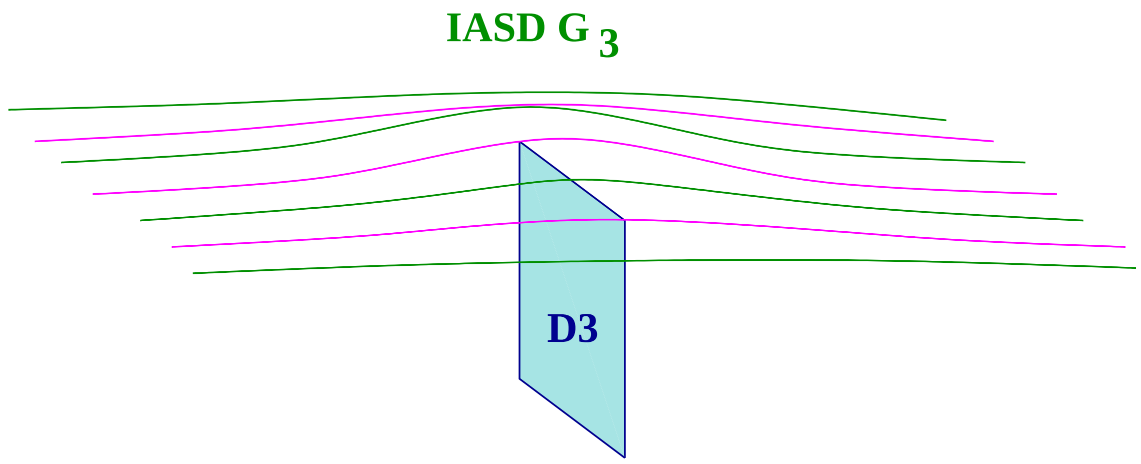
- IASD flux has positive tension and negative RR 4-form charge
Gravitational and Coulomb effects on D3-brane add up
D3-branes are attracted to region of maximum IASD flux density.
$\rightarrow$ Non-trivial soft terms.



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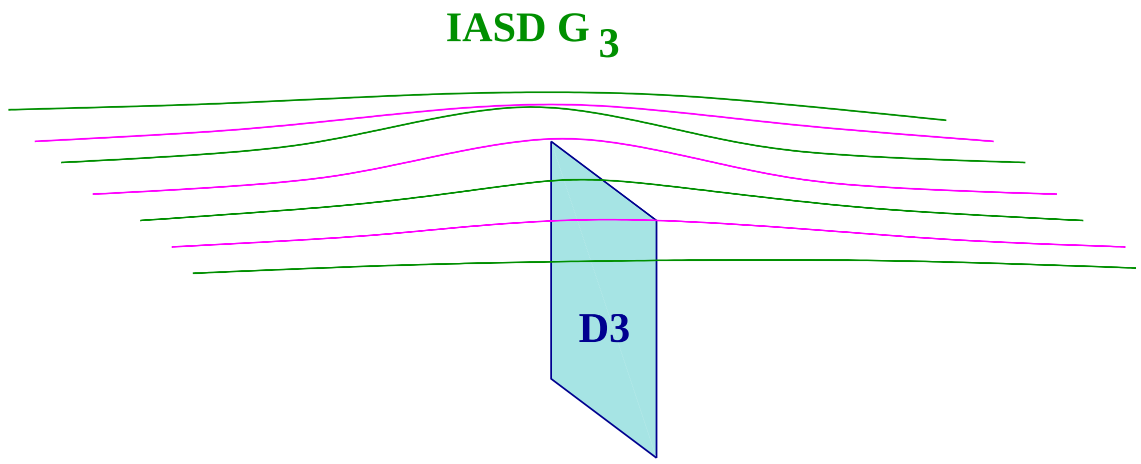


Sketch of soft term lagrangian

Scalar masses m: $\quad \mathrm{Tr}\, m^2 = \frac{g_s}{6}\left(\sum |G^-_{lmn}|^2 - Re(G^-_{lmn}\overline{G}^+_{lmn})\right)$

Scalar trilinears A: $\quad \frac{g_s}{3} G^-_{lmn}\phi^l\phi^m\phi^n$

Fermion masses M: $\quad \frac{g_s^{1/2}}{\sqrt{2}} G^-_{lmn}\Psi\Gamma^{lmn}\Psi$

$\longrightarrow$ No soft terms for pure ISD flux. Need IASD component

Example: (3,0) G_3

$$m^2 = \frac{g_s}{6}|G_{123}|^2 \ ; \ M^a \ = \ \frac{g_s^{1/2}}{\sqrt{2}} G_{123} \ ; \ A^{ijk} \ = \ -\epsilon^{ijk} g_s \, G_{123} \qquad (1)$$

Obs: For $\overline{D3}$-branes, the reverse: Soft terms only for ISD flux (e.g. KKLT).

D3$\longleftrightarrow \overline{D3}$, $\qquad G_3^- \longleftrightarrow G_3^+$

Local analysis for D7-branes [Camara, Ibáñez, A.U.]

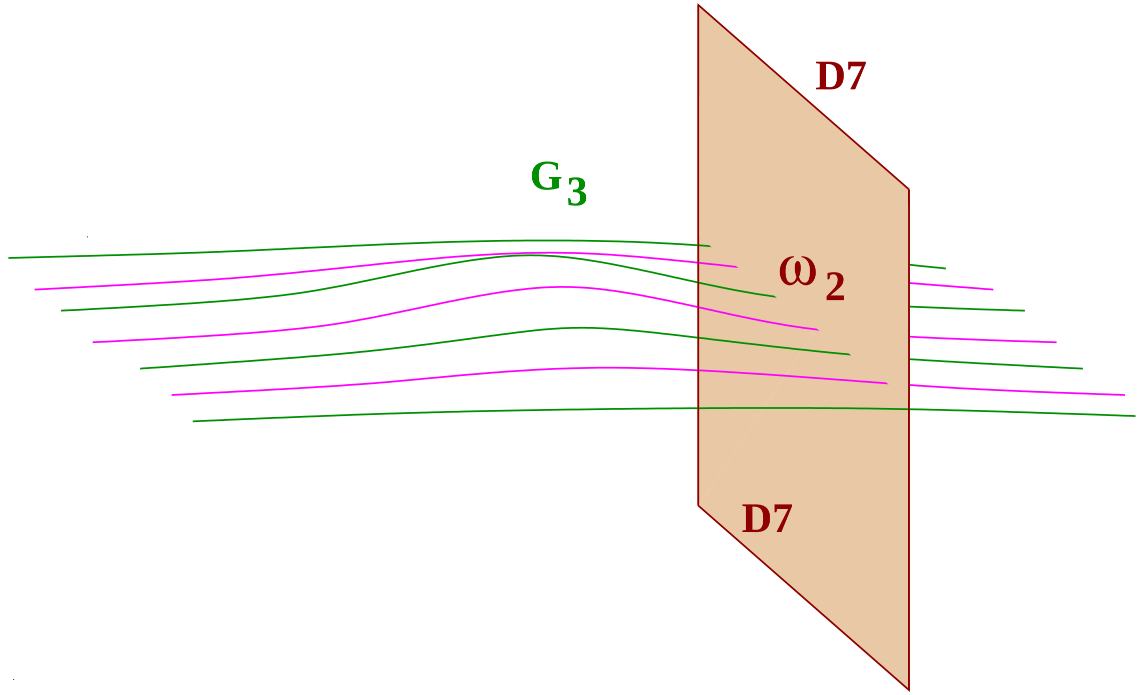
Apply similar strategy to D7-branes.

More involved: D7's wrap 4-cycles Σ_4 in X_6,...

Simple physical interpretation: X_6 is locally $\Sigma_4 \times R^2$

Split 3-form G_3 in X_6 as 2-form ω_2 on Σ_4 1-form R^2

SD/ASD ω_2 on D7 induces D3/$\overline{D3}$ on D7-worldvolume



Soft terms from interaction of induced D3-charge with G_3 background

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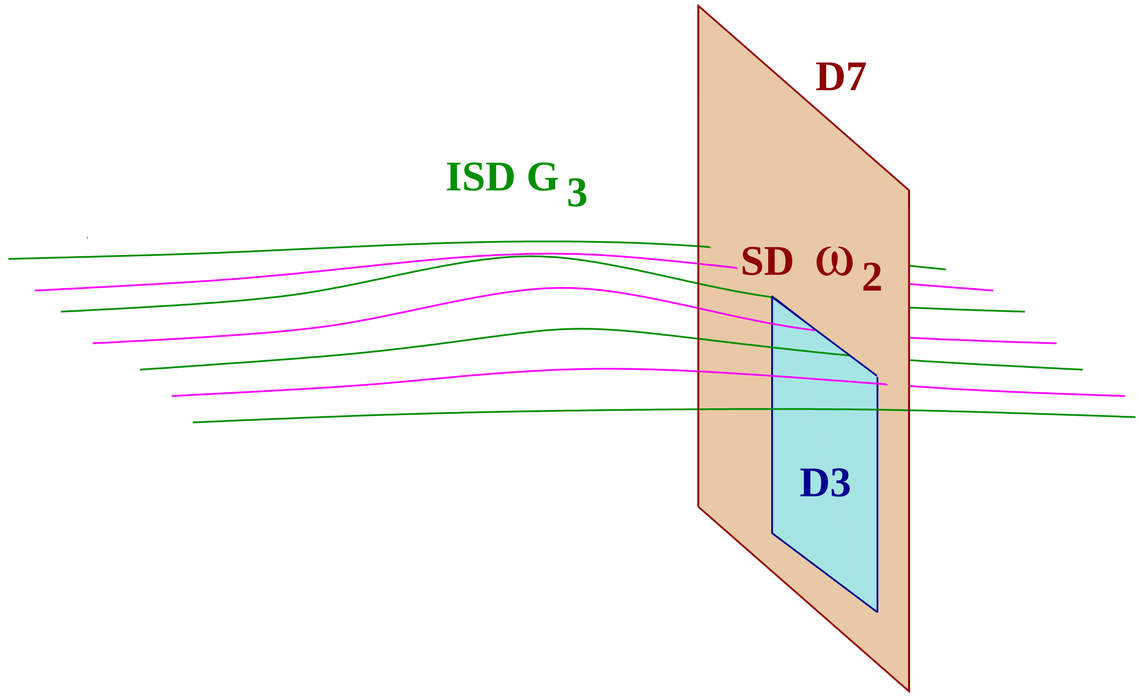

G Gives D3 on D7, no interaction with ISD $\rightarrow$ No soft terms

(similar for IASD G_3 with ASD ω_2)

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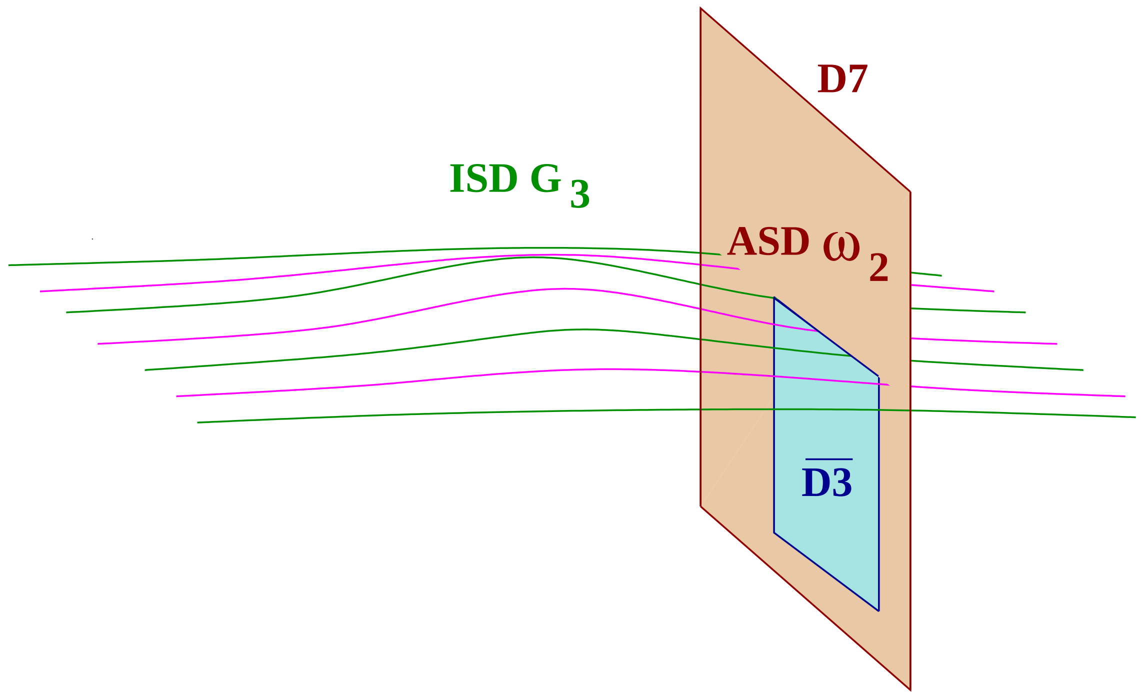

G' gives $\overline{D3}$ on D7, interaction with ISD → Soft terms
(similar for IASD G_3 with SD ω_2)

Sketch of the results

Complete determination of soft terms as functions of the flux background

Main novelty: Non-zero soft terms even with ISD fluxes

String compactification with supersymmetry breaking
and non-trivial soft terms, solving classical supergravity equations of motion

- Not possible for D3-branes

- First such model of its kind

More work is needed to generalized the simple examples we have analyzed

Soft terms in MSSM-like models

Soft term scale: $M_{\text{soft}} = \frac{\alpha'}{R^3} = \frac{M_s^2}{M_P}$, for homogeneous flux

Choose $M_s \simeq 10^{11}$ GeV

($M_{\text{soft}} =$ local string scale, for warped throats.)

MSSM group on D3-branes:

- Naturally universal squark masses
- Relation between soft terms: $M = A$, etc
- μ-term allowed only for some orbifolds

MSSM group on D7-branes:

- Many features similar to above
- Promising setup: MSSM on magnetised D7-branes

Universality, absence of dangerous phases, etc is automatic from ISD fluxes.

[Ibáñez]

Effective lagrangian approach

Consider the 4d effective action including the D3- and D7- gauge sectors

Gauge kinetic functions

$$f_{D3} = -i\tau \quad ; \quad f_{D7} = \rho$$

Kahler potential (at large volume) [Ibáñez, Muñoz, Rigolin]

$$K = -\log(S+S^*) - 3\log(T+T^*) + \frac{|\Phi_{77}|^2}{(\tau+\tau^*)} + \\ + \frac{1}{(\rho+\rho^*)}[(\sum_{a=1}^{3} |\Phi_{33}^a|^2) + (\sum_{b=1}^{2} |\Phi_{77}^b|^2) + (|\Phi_{37}|^2 + |\Phi_{73}|^2)]$$

Flux components correspond to auxiliary fields of dilaton, Kahler and complex structure moduli chiral multiplets

$\rightarrow$ Spontaneous breaking of supersymmetry in closed string sector

$$F_\tau \simeq \int {G_{(3)}}^* \wedge \Omega$$
$$F_\rho \simeq \int G_{(3)} \wedge \Omega$$

Results for soft terms in full agreement with local analysis

Conclusions

- Flux compactifications provide a canonical way to stabilize large number of moduli in string compactifications

    Overview of setup of type IIB on CY_3 with 3-form fluxes

- They lead to interesting new effects

    Warped compactifications

    Supersymmetry breaking

- Possible to combine with D-brane model building techniques

    D-branes at singularities

    Intersecting/magnetised D-branes

- Supersymmetry breaking soft terms on D-branes

    Explored for D3/D7-brane systems

- Soft terms encode the background around the D-branes

    Bottom-up approach to reconstruct the
    relevant information of our string vacuum.