Model Building in Type II String theory

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Plan of the talk

- D-brane model buildind

- Type IIA: Intersecting brane worlds

- Type IIB: ‘Magnetised D-branes’

- Model building

- Introduction of fluxes

Generalities

3-form fluxes on IIB: Moduli stabilization, effects on brane sectors

- Conclusions

Why type II and D-branes?

Gauge sectors in type II string theory are usually localized on D-branes

• Not more fundamental than other approaches
e.g. heterotic models [Several talks yesterday]

• But often more intuitive and easy to work with
$\longrightarrow$ Locality

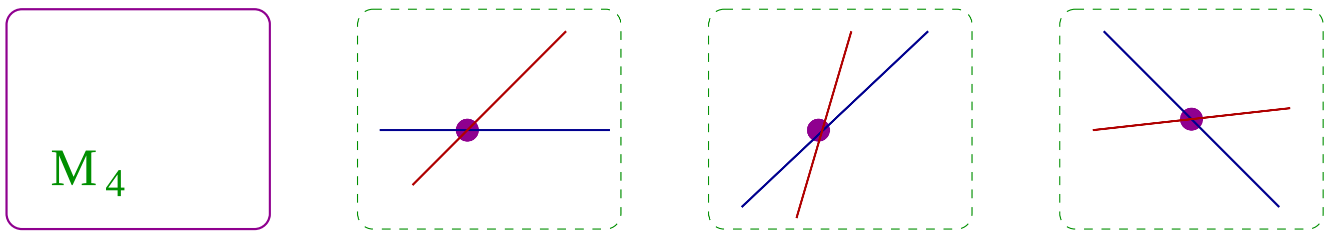
• Implement idea of brane-world in the well-defined setup of string theory

• Allow combination with other interesting model building ingredients
$\longrightarrow$ NSNS and RR field strength fluxes
$\longrightarrow$ Throats and AdS/CFT ideas
...

Two ways to get chirality

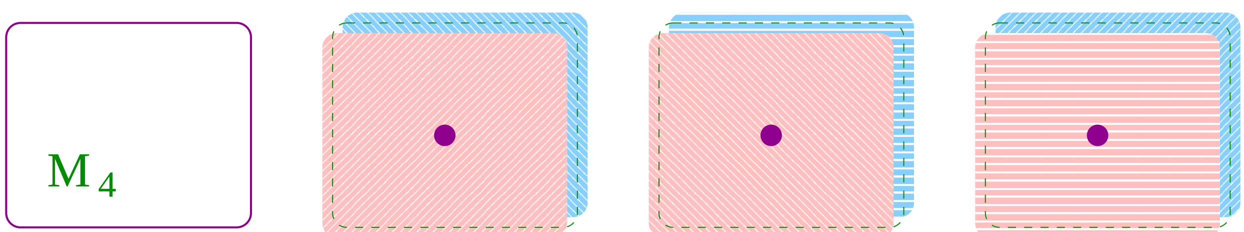
In geometric regime. Chirality $\rightarrow$ Breaking of 6d parity

• Intersecting D-branes [Berkooz, Douglas, Leigh]
Open strings stretched between two D6-branes intersecting over 4d
$\longrightarrow$ lead to 4d chiral fermions



- often related by duality to G_2 singularities, etc.

• Magnetic fields on D-branes [...,Bachas]
Open strings in on D-branes with magnetic fields. Modified KK reduction for higher-dim fermions$\longrightarrow$ leads to 4d fermions.



- related to branes at singularities in a particular sense
- arising from KK with gauge backgrounds, e.g. heterotic-like mechanism

Supersymmetric branes on CY compactifications

[Becker, Becker, Strominger; Ooguri, Oz, Yin]

- A-branes

Type IIA D6-branes wrapped on special lagrangian 3-cycles

Tension given by restriction of $Re(e^{i\theta}\Omega)$

- B-branes

Type IIB D-branes wrapped on holomorphic cycles, carrying holomorphic (and stable) world-volume gauge bundles

Tension given by restriction of $Re[e^{i\theta}e^{J+i(B+F)}]$

- The two kinds of D-branes are exchanged under mirror symmetry

- Comments:

\- θ determines the $N = 1$ subalgebra preserved by the D-brane.

\- Branes calibrated by different θ's are mutually non-BPS

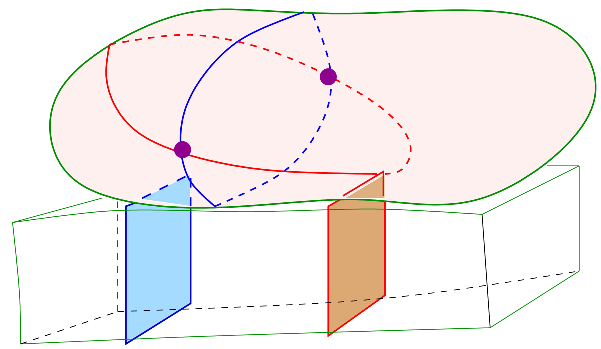
$\rightarrow$ D-term susy breaking.

\- Should be suitably generalized for non-CY geometries

Type IIA with A-type branes: Intersecting brane worlds

[Blumenhagen, Görlich, Körs, Lüst; Aldazabal, Franco, Ibáñez, Rabadán, A.U.;...]

• Type IIA on CY_3 X_6 with stacks of N_a D6-branes spanning $M_4 \times \Pi_a$ with Π_a different 3-cycles in X_6



• Each stack gives rise to a gauge factor $U(N_a)$

• At intersections of stacks a and b, local geometry is as above

$\longrightarrow$ 4d chiral fermion in $(\square_a, \bar{\square}_b)$

• In general, multiple intersections $I_{ab} = [\Pi_a] \cdot [\Pi_b]$

$\longrightarrow$ Replication of the fermions $(\square_a, \bar{\square}_b)$ in I_{ab} families

• Chiral Spectrum: $\prod_a U(N_a)$ with 4d chiral fermions $\sum_{a,b} I_{ab} \, (\square_a, \bar{\square}_b)$

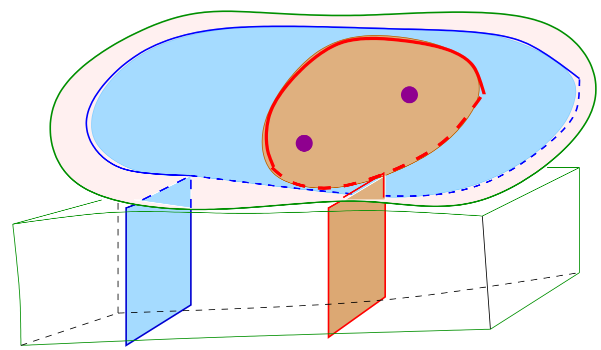
- Obs: Chiral content is topological.

Non-chiral depends on additional detailed features of the model.

Type IIB with B-type branes

[Bachas; Blumenhagen, Görlich, Körs, Lüst; Angelantonj, Antoniadis, Dudas, Sagnotti]

• Type IIB on CY_3 X_6 with stacks of N_a B-type D-branes spanning $M_4 \times \Pi_a$ with Π_a holomorphic cycles in X_6 and carrying gauge backgrounds F_a



• Each stack gives rise to a gauge factor $U(N_a)$

• At each sector of ab open strings, local geometry is as above

$\longrightarrow$ 4d chiral fermion in $(\Box_a, \bar{\Box}_b)$

• In general, multiple zero modes in KK reduction of fermions coupled to ab gauge background $I_{ab} = \int_{X_6} [Q_a] \wedge [Q_b]^*$, where now $[Q_a] = \mathrm{ch}(F_a) \wedge \delta(\Pi_a)$.

$\longrightarrow$ Replication of the fermions $(\Box_a, \bar{\Box}_b)$ in I_{ab} families

• Chiral Spectrum: $\prod_a U(N_a)$ with 4d chiral fermions $\sum_{a,b} I_{ab} \, (\Box_a, \bar{\Box}_b)$

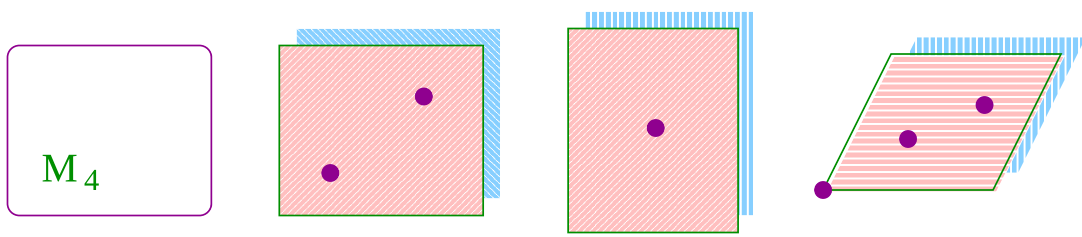
- Obs: Chiral content is topological.

Non-chiral depends on additional detailed features of the model.

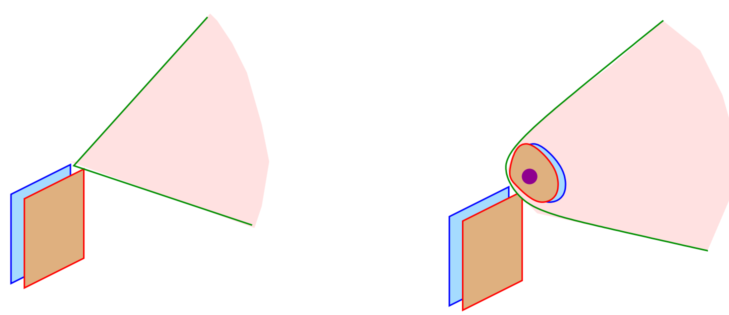
Particular cases of Type IIB with B-type branes

• Type I orbifolds [Angelantonj, Bianchi, Pradisi, Sagnotti, Stanev]
D9-branes wrapped on orbifolds of $\mathbf{T}^6$, with world-volume gauge bundle specified by embedding of orbifold action on Chan-Paton factors γ_θ

• Magnetised D-branes on tori [Above refs; talks by Bianchi, Antoniadis]
D-branes wrapped on products of $\mathbf{T}^2$'s in $\mathbf{T}^6$ (or quotients thereof), with constant magnetic fields



• D-branes at singularities [Douglas, Moore; Aldazabal, Ibáñez, Quevedo, A.U.]
D-branes wrapped on collapsed cycles at orbifold singularities



Orientifold planes

• In order to avoid RR tadpoles (Gauss law in compact space) and to have compactifications to M_4 without NSNS tadpoles (cancel tensions) one usually needs to introduce orientifold planes

• Quotient of type IIA/B on CY_3 by ΩR, where R is a $\mathbf{Z}_2$ geometric action

- Antiholomorphic $R \to$ type A orientifold, locally $(z_1, z_2, z_3) \to (\overline{z_1}, \overline{z_2}, \overline{z_3})$
- Holomorphic $R \to$ type B orientifold, eg locally $(z_1, z_2, z_3) \to (-z_1, -z_2, -z_3)$

• O-planes: locations fixed under R. They carry negative charge and tension (as compared to the corresponding D-branes)

• New features

- Need to introduce image D-branes (label by a')
- New sectors of open strings between original and new D-branes
- Additional projection, e.g. Dbranes on top of O-planes have SO or Sp gauge factors

RR tadpoles and anomalies

[Aldazabal, Franco, Ibáñez, Rabadán, A.U.]

• D-branes and O-planes carry charges under diverse components of the RR fields. → Denote $\vec{Q}_a$ the vector of charges

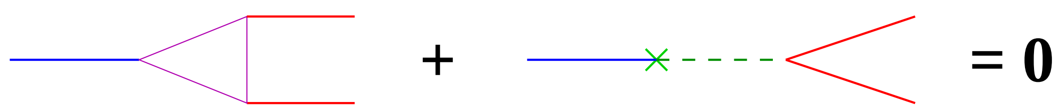
- Type IIA: Homology class $[\Pi_a]$ of the wrapped 3-cycle
- Type IIB: Chern character of the bundle/sheaf $[Q_a]$

• In a compact space, total charge must be zero

$$\sum_a N_a \vec{Q}_a + \sum_a N_a \vec{Q}_{a'} + \vec{Q}_{Opl} = 0$$

• Cancellation of RR tadpoles guarantees cancellation of anomalies

- Cubic non-abelian are automatically zero - Mixed $U(1)$ anomalies cancel by Green-Schwarz mechanism



• Any $U(1)$ field with $B \wedge F$ couplings gets string scale Stuckelberg mass, even if non-anomalous [Ibáñez, Marchesano, Rabadán; Antoniadis, Kiritsis]

• Additional discrete constraints coming from cancellation of K-theory torsion classes → Cancellation of global gauge anomalies [A.U.]

Protomodels

• Topological nature of chiral matter allows us to design protomodels: Sets of numbers consistent with anomaly/tadpole cancellation, such that when realized in a concrete model reproduce the SM spectrum.

• [Ibáñez, Marchesano, Rabadán]
D-branes giving $U(3)_a \times U(2)_b \times U(2)_c \times U(1)_d$, and with

$$I_{ab} = 1 \qquad I_{ab'} = 2 \qquad I_{ac} = -3 \qquad I_{ac'} = -3$$
$$I_{bd} = 0 \qquad I_{bd'} = -3 \qquad I_{cd} = -3 \qquad I_{cd'} = 3$$

give SM with hypercharge $Q_y = \frac{1}{6}Q_a - \frac{1}{2}Q_c + \frac{1}{2}Q_d$

• [Cremades, Ibáñez, Marchesano]
D-branes giving $U(3)_a \times USp(2)_b \times U(1)_c \times U(1)_d$, and with

$$I_{ab} = 3 \qquad I_{ab'} = 3 \qquad I_{ac} = -3 \qquad I_{ac'} = -3$$
$$I_{db} = 3 \qquad I_{db'} = 3 \qquad I_{dc} = -3 \qquad I_{dc'} = 3 \quad I_{bc} = -1 \qquad I_{bc'} = 1$$

give SM with hypercharge $Q_Y = \frac{1}{6}Q_a - \frac{1}{2}Q_c - \frac{1}{2}Q_d$

$\rightarrow$ Latter is easily obtained from Pati-Salam $U(4)_a \times Sp(2)_b \times Sp(2)_c$ with $I_{ab} = 3 \quad , I_{ac} = -3$ $\rightarrow$ 'Guay model' [Cremades, Ibáñez, Marchesano]

Explicit implementatation: Full Models

[Several talks today]

• IIA and IIB on Toroidal orientifolds:
Non-susy SM's:
[Ibáñez, Marchesano, Rabadán; Cremades, Ibáñez, Marchesano]

• IIA on Orientifolds of toroidal orbifolds:
Supersymmetric SM's:
[Honecker, Ott]
[Cvetic, Li, Liu; Marchesano, Shiu]

• IIB on Orientifolds of Gepner models:
Huge amount of Supersymmetric MSSM's
[Dijkstra, Huiszoon, Schellekens]

• Much other work on these and other alternatives: GUTs, Pati-Salam, ...
[..., ..., ...]

Obs: In all models, extra vector-like matter.
Can be improved in different ways e.g. [Blumenhagen, Cvetic, Marchesano, Shiu]

Non-topological information

• Gauge couplings

From the KK reduction of higher-dimensional gauge fields, gauge coupling is related to wrapped 'volume' (rather, value of the calibrating form)

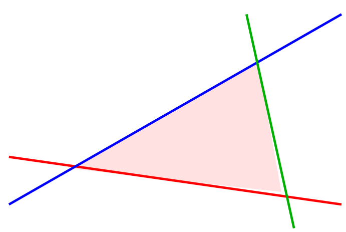
$$\frac{1}{g_{YM,a}^2} = \frac{|V_a|}{g_s} \text{ with } V_a = \int_{\Sigma_a} \Omega \text{ or } V_a = \int_{\Sigma_a} e^{J+i(B+F_a)}.$$

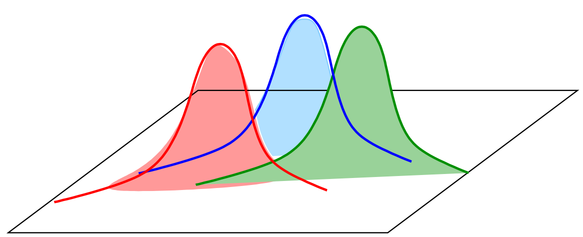
Non-standard normalization of hypercharge linear combination

• Superpotential Yukawa couplings [Cremades, Ibáñez, Marchesano; Cvetic, Papadimitriou; etc]

Type IIA: Sum over holomorphic disk world-sheet instantons. Dependence on Kahler moduli

Type IIB: Leading α' expression is exact. Overlap of charged particle wavefunctions. Dependence on complex structure moduli.





• Many other quantities: Kähler potential for charged matter, threshold corrections to gauge couplings, etc,...

[Lust, Stieberger; Lust, Mayr, Richter, Stieberger; ...]

Flux compactifications

• A particular promising direction to address open issues: moduli stabilization, supersymmetry breaking (or other hierarchy mechanism), ...
- Not unique: non-perturbative effects, DSB, non-BPS systems,... maybe complementary (e.g. [Kachru, Kallosh, Linde, Trivedi])

• Basic idea: Excite other possible backgrounds of 10d theory.

Beyond the CY ansatz

• The relation CY $\leftrightarrow$ $N = 1$ susy actually holds if the ansatz for compactification does not include backgrounds other than the metric.

• Rich structure of local $N = 1$ supersymmetric string backgrounds
The requirement is not $SU(3)$ holonomy, but $SU(3)$ structure
Towards classifications
[Gurrieri, Louis, Micu, Waldram; Dall'Agata, Prezas; Graña, Minasian, Petrini, Tomasiello; Lüst, Tsimpis; Behrndt, Cvetic, Gao; ... ; see Behrndt's talk]
Include NSNS and RR fluxes, and non-Ricci-flat metrics (torsions)

• Some non-CY topologies are compatible with compactification and susy
From T-duality / mirror symmetry to familiar backgrounds of IIB with 3-form fluxes (see later)
[Gurrieri, Louis, Micu, Waldram; Kachru, Schulz, Tripathy, Trivedi; Schulz; ...]

• Complicated, lack of explicit models
Most examples are known by duality, or by twisting tori.
Still, group structures may allow to determine basic features of low-energy effective theory [Graña, Louis, Waldram; see Louis' talk]

• For twisted tori, very explicit description from 4d effective action viewpoint $\longrightarrow$ Relation to gaugings
[Andrianopoli, Angelantonj, Dall'Agata, D'Auria, Ferrara, Lledo, Trigiante, Vaula, ...]
[Derendinger, Kounnas, Petropoulos, Zwirner; Villadoro, Zwirner;
Cámara, Ibáñez, Font; see Ferrara's, Dall'Agata's, Derendinger's and Zwirner's talks]

• Towards model building in more and more general backgrounds.

• Today we center on the best known class: IIB on CY_3 with NSNS and RR 3-form fluxes (Metric is conformal CY)
Statements in the mirror are valid, but may involve unfamiliar non-CY geometries

Simple setup: IIB on CY_3 with ISD G_3

[Dasgupta, Rajesh, Sethi; Giddings, Kachru, Polchinski; ...; several talks]

IIB perspective

• Consider IIB on CY_3, modded out by O3-plane action, with D3- and (possibly magnetised) D7-branes (or more generally, (p, q) 7-branes).
Turn on NSNS and RR 3-form flux $G_3 = F_3 + \tau H_3$ with $\tau = a + i/g_s$.

• From the flux superpotential $W = \int_{CY_3} G_3 \wedge \Omega$ [Taylor, Vafa], consistent compactification to M_4 (spacetime is warped product of M_4 and the CY_3) for

- ISD G_3, $*_6 G_3 = i G_3$
- Branes wrap supersymmetric cycles in CY_3 (holomorphic, and with instanton gauge backgrounds on world-volume, $F = *_4 F$)

• Supersymmetry:

pure $(2, 1)$ G_3 implies $N = 1$ susy, $(0, 3)$ component breaks susy [Graña, Polchinski]

M/F-theory description of IIB on CY_3 with ISD G_3

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

F/M-theory perspective

• Consider M/F-theory on elliptically fibered CY_4, with D3-branes

Degenerations of the $\mathbf{T}^2$ fiber at 4-cycles on base B_6 correspond to 7-branes from the IIB viewpoint.

Turn on 4-form field strength G_4

- G_4 components supported away from degenerate fibers becomes IIB G_3
- G_4 components supported on harmonic 2-form ω_a near degenerate fibers becomes 7-brane worldvolume abelian magnetic field

$$G_4 = \frac{G_3\, d\overline{w}}{\overline{\tau}-\tau} + hc. + \sum_a \omega_a F_a$$

• From the flux superpotential $W = \int_{CY_4} G_4 \wedge \Omega_4$, with $\Omega_4 = \Omega_3 dw$ [Gukov, Vafa, Witten] consistent compactification to M_4 for SD G_4 namely ISD G_3 and SD F.

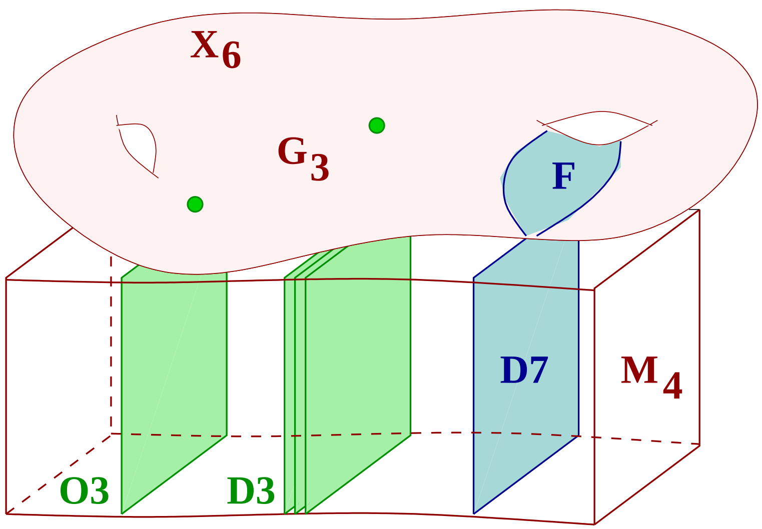
• Supersymmetry pure $(2,2)$ G_4 implies $N = 1$ susy, $(0,4)$ component breaks susy [Becker,Becker]

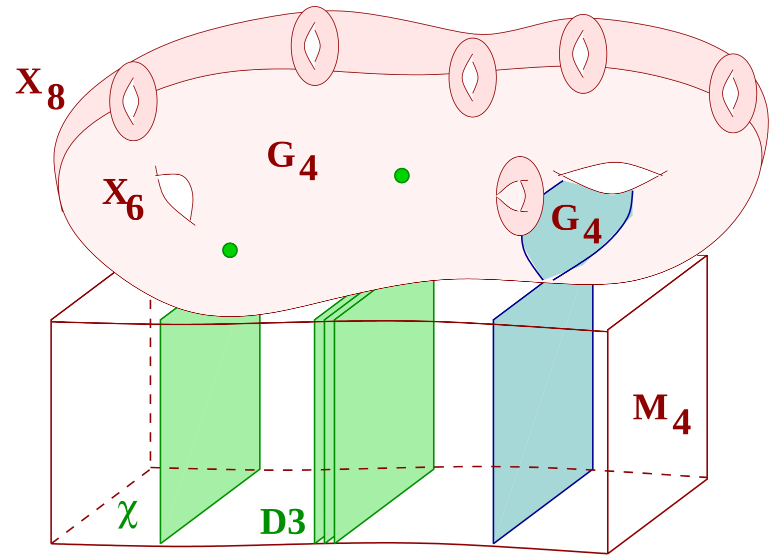
Type IIB and F-theory perspectives on flux compactifications

- Relation IIB $\rightarrow$ M-theory via T-duality and lift

Geometrization of 7-brane positions: complex structure moduli of X_8

Geometrization of non-perturbative effects, e.g. splitting of O7's. [Sen]





- Dictionary:

X_6 mod $\Omega R \leftrightarrow$ Base B_6 of X_8

IIB coupling $\tau \leftrightarrow \mathbf{T}^2$ fiber

7-branes, 07-planes $\leftrightarrow$ degenerate fibers

Negative RR 4-form charges $\leftrightarrow \chi(X_8)/24$

NSNS, RR flux $G_3 \leftrightarrow G_4$ away from degenerate fibers

7-brane worldvolume $F_2 \leftrightarrow G_4$ supported on degenerate fibers

Model building

• It is possible to combine D-brane model building in IIB with flux compactifications

• Magnetised D-branes and 3-form fluxes
- Basic setup and simple models: [Blumenhagen, Lüst, Taylor; Cascales, A. U.]
- Supersymmetric SM's and susy fluxes: [Marchesano, Shiu; Cvetic, Li, Liu;]
- Supersymmetric SM's and non-susy fluxes: [Camara, Ibáñez, A.U; Lüst, Reffert, Stieberger; Marchesano, Shiu; Cvetic, Li, Liu; ...]
→ Susy breaking without NSNS tadpoles and with non-trivial soft terms

• D-branes at singularities
- Toroidal orbifold models [Cascales, A. U; Marchesano, Shiu, Wang]
- Warped throats [Cascales, García del Moral, Quevedo, A. U; Cascales, Saad, A. U.]

• Combination is non-trivial in subtle respects:
- Freed-Witten anomaly: Modification of possible D-brane wrappings in presence of fluxes ('twisted K-theory')
- In general, fluxes have non-trivial effects on D-branes, see later

Flux effects: Moduli stabilization, susy breaking

• Constraints like ISD $*_6 G_3 = iG_3$ impose constraints on moduli vevs
• Equiv. energy to turn on a flux depends on the moduli
$\rightarrow$ 4d scalar potential for moduli

Light fields in flux compactifications
• Dilaton and complex structure moduli of X_6: Stabilized by G_3 fluxes
• Kahler moduli: enter D-term potential due to effect on D7-brane F_2.
[Douglas; Cremades, Ibáñez, Marchesano; Blumenhagen, Braun, Körs, Lüst; Antoniadis, Kumar, Maillard; ... ; see Antoniadis' talk]
Stabilized? See later
• Open string fields (often, related to open string moduli):
Flux-induced terms can be computed from D-brane action in general background [Graña; Cámara, Ibáñez, A.U; Graña, Grimm, Jockers, Louis]
For non-susy flux components, correspond to soft susy breaking terms
- D3-branes: no flux-induced terms for ISD G_3 $\rightarrow$ unstabilized (but stabilized $\overline{D3}$-branes)
- D7-branes: $(2,1)$ G_3 leads to superpotential masses μ terms
$(0,3)$ leads to other scalar masses, fermion masses, trilinears for fields at ab sectors (chiral matter!)

• For negligible warping, possible to study from IIB effective action with $W = \int G_3 \wedge \Omega$ [above; Lüst, Reffert, Stieberger; Font, Ibáñez]
Fluxes break susy spontaneously by vevs for auxiliary fields of moduli multiplets $< F_T >$, $< F_S$, and lead to soft terms

– But some important pieces are missing: E.g. Flux induced μ term is supersymmetric.

• Happily, visible in F-theory with $W_4 = \int G_4 \wedge \Omega_4$
[Görlich, Kachru, Tripathy, Trivedi; Lüst, Mayr, Reffert, Stieberger]
D7-branes locations geometrized in Ω_4
Plus additional effects: Splitting of O7-planes when D7's away, etc.

– But F-theory has difficulties dealing with bundle moduli (typically non-abelian), and charged matter (non-geometric states, not in W_4)

Need combined approach to understand model in full
e.g. toroidal models [Lüst, Mayr, Reffert, Stieberger]

Obs: All at leading order. Both α' and g_s corrections lead to additional contributions e.g. [Choi, Falkowski,Nilles, Olechowski; Conlon, Quevedo, Suruliz]

Kahler moduli

• D7-brane world-volume magnetic fields lead to D-term potential for Kahler moduli (Kahler couple as FI terms for D7 $U(1)$'s)
• D-term (or susy condition) has been argued to stabilize of Kahler moduli
Indeed stabilized?
• Recall story in the absence of G_3 fluxes [Cvetic, Shiu, A.U.]
Crucial to include ab chiral multiplets $\rightarrow V_D = \sum_a (\sum_b q_{ab} |\Phi_{ab}|^2 + \xi)^2$
Change of Kahler parameter usually canceled by Φ_{ab} vev
$\rightarrow$ Vacuum re-stabilization via D-brane bound state
$\rightarrow$ Un-fixed lfinear combination of Kahler modulus and Φ_{ab}

• Story in the presence of G_3 fluxes [García del Moral]
Crucial! Fluxes induce masses for ab charged scalars on D7-branes
$V_D = \sum_a (\sum_b q_{ab} |\Phi_{ab}|^2 + \xi)^2 + \sum_{a,b} m_{ab}^2 |\Phi_{ab}|^2$
$\rightarrow$ Flux induced mass terms prevent Φ_{ab} vevs
$\rightarrow$ With Φ_{ab} frozen to zero, $V_D = \xi^2$ stabilizes Kahler moduli.

Obs: Importance of flux-induced effects already at this level
Obs: Importance of D-term potentials in Kahler moduli discussions

Conclusions

- New ideas in type II compactifications are unveiling a beautiful picture

- Brane configurations lead naturally to non-abelian gauge groups and replicated charged chiral matter

- Fluxes lead naturally to moduli stabilization and supersymmetry breaking

- Locality of D-brane dynamics is of great help

- Good handle on realisitc model building

- D-brane dynamics leads to deep understanding of the models: e.g. flux-induced terms

- Where are we going?

I don't know for sure...

But clearly on the way to better and better phenomenological string models

- Some interesting new directions

- Open string side:

Model building can still be improved (mainly in non-chiral sector)

- Closed string side:

Bring other backgrounds to same high-tech level of IIB with 3-form fluxes.

- And do not forget their rich interplay!