Generalized Calabi-Yau compactifications with D-branes and Fluxes

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based on collaboration with:

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Introduction/Motivation

contact of string theory with particle physics:

➪ choose string vacuum with $N = 1$ supersymmetric Standard Model or GUT-type spectrum in $d = 4$

➪ ‘manufacture’ spontaneously broken $N = 1$ supersymmetry

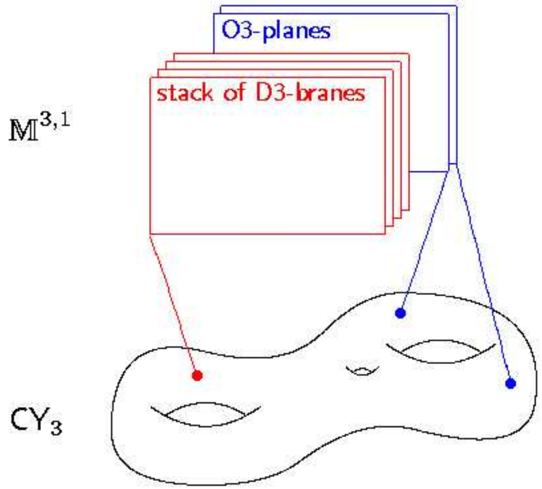
- traditionally
  - choose space-time background: $\mathcal{M}_4 \times Y_6$
    $\mathcal{M}_4$: $d = 4$ Minkowski-space
    Y_6: compact Calabi-Yau manifold – determines amount of supersymmetry
  - employ non-perturbative effects to spontaneously break supersymmetry
- recently: slight variation on the theme (Brane World Scenarios)
  - Standard Model/GUT on space-time filling D-branes
  - Y_6: Calabi-Yau orientifold
  - spontaneous supersymmetry breaking via background fluxes (& non-perturbative effects)

Charged Matter:

D3-branes

Consistency:

O3-planes



Bulk-moduli-stabil.:

Fluxes

Breaking SUSY:

Fluxes

Particle phenomenology needs:

➪ realistic spectrum (model building)

➪ soft supersymmetry breaking terms (measured by LHC)

depend on:

- mechanism of supersymmetry breaking
- communication to observable sector (messenger sector)

$\Rightarrow$ need effective action (matter-moduli couplings)

interesting asides:

- interplay supersymmetry $\leftrightarrow$ geometry

  often helps to compute the effective action, e.g. mirror symmetry

- cosmological aspects (deSitter - vacua) $\Rightarrow$ [see talk by R. Kallosh]

Outline of talk:

discuss ingredients separately and compute effective action

1. Calabi-Yau compactification of type II
2. Background fluxes
3. Manifolds of $SU(3)$ structure,
   spontaneous supersymmetry breaking, mirror symmetry
4. $N = 1$ Calabi-Yau orientifolds
5. D3/D7-branes
6. Soft supersymmetry breaking terms
7. Conclusions/open problems

1. Calabi-Yau compactification of type II

1.1 Calabi-Yau Threefold Y

- Ricci-flat Kähler manifold with holonomy $SU(3)$

  $\Rightarrow$ globally defined spinor exits on Y $\Rightarrow$ supercharges in $d = 4$ exists

- space-time background: $\mathcal{M}_4 \times Y_6$

$$\Delta_{10}\phi = (\Delta_4 + \Delta_6)\phi = (\Delta_4 + m^2)\phi = 0$$

  $\Rightarrow$ massless $d = 4$ spectrum = zero modes of Δ_6 = harmonic forms in $H^{(p,q)}(Y)$

- Hodge numbers: $h^{p,q} = \mathrm{dim} H^{p,q}(Y)$

$$\begin{array}{ccccccc} & & & 1 & & & \\ & & 0 & & 0 & & \\ & 0 & & h^{1,1} & & 0 & \\ 1 & & h^{1,2} & & h^{1,2} & & 1 \\ & 0 & & h^{1,1} & & 0 & \\ & & 0 & & 0 & & \\ & & & 1 & & & \end{array}$$

- deformations of Calabi-Yau metric form geometrical moduli space

$$\mathcal{M} = \mathcal{M}_{\mathrm{cs}}^{h^{(1,2)}} \times \mathcal{M}_{\mathrm{k}}^{h^{(1,1)}}$$

  cs: deformations of complex structure, k: deformations of Kähler form

1.2 Mirror Symmetry

conjecture:

for 'every' Y there exists a mirror manifold $\tilde{Y}$ with

$$h^{1,1}(Y) = h^{1,2}(\tilde{Y}) \ , \qquad h^{1,2}(Y) = h^{1,1}(\tilde{Y})$$

manifestation in string theory:

IIA in background $\mathcal{M}_4 \times Y$ $\equiv$ IIB in background $\mathcal{M}_4 \times \tilde{Y}$

1.3 Kaluza-Klein reduction of type IIB on Y

- massless spectrum $d = 10$: $\tau,\ G_{MN},\ H_3 = dB_2,\ F_3 = dC_2,\ F_5^* = dA_4$

- massless $N = 2$ spectrum $d = 4$: determined by harmonic forms in $H^{(p,q)}(Y)$

  - $h^{(1,2)}$ vector multiplets $\big([1] \oplus 2 \times [1/2] \oplus 2 \times [0]\big)$

    vectors: $\int_{\gamma_3^I} A_4$

    scalars: complex structure deformations z of Y

  - $h^{(1,1)} + 1$ hyper-/tensor multiplets $\big(2 \times [1/2] \oplus 4 \times [0]\big)$

    scalars:

    – (τ, B_2, C_2)

    – $\int_{\gamma_4^A} A_4\ ,\quad \int_{\gamma_2^A} C_2\ ,\quad \int_{\gamma_2^A} (J + iB_2)$ (complexified Kähler deformations)

- low energy effective action: $N = 2$ supergravity

$$S = \int -\frac{1}{2}R * \mathbf{1} + \frac{1}{4}\mathrm{Re}\mathcal{M}_{KL}F^K \wedge F^L + \frac{1}{4}\mathrm{Im}\mathcal{M}_{KL}F^K \wedge *F^L$$
$$-g_{kl}dz^k \wedge *d\bar{z}^l - h_{AB}dq^A \wedge *dq^B \ ,$$

where $F^K = dV^K$, $\mathcal{M}(z)$: gauge couplings

moduli space:

$$\mathcal{M} = \mathcal{M}^{SK}_{2h^{(1,2)}} \times \mathcal{M}^{Q}_{4(h^{(1,1)}+1)} \ .$$

- $\mathcal{M}^{SK}_{2h^{(1,2)}}$:

$$g_{kl} = \frac{\partial}{\partial z^k}\frac{\partial}{\partial \bar{z}^l} K_{\mathrm{cs}} \ , \qquad K_{\mathrm{cs}} = -\ln\Big[-i\int_Y \Omega \wedge \bar{\Omega}\Big]$$

- $\mathcal{M}^{Q}_{4(h^{(1,1)}+1)}$

  $h_{AB}(q)$: quaternionic metric given by [Ferrara, Sabharwal]

- string tree level:
  - both metrics determined by holomorphic prepotential F via c-map [Cecotti, Ferrara, Girardello]
  - both F's known exactly by mirror symmetry

2. Background fluxes

2.1. General discussion

$$\text{allow} \qquad \int_{\gamma_p^I \in Y} F_p = e_I \neq 0 \qquad \text{keeping} \qquad dF_p = 0 = d^\dagger F_p$$

$$\Rightarrow F_p \;=\; e_I\, \omega_p^I \;, \qquad \omega_p \in H^p(Y)$$

$$e_I = \text{const.} = \begin{cases} \text{quantized in string theory} \\ \text{continuous in low energy approximation} \end{cases}$$

consistency: tadpole cancellation condition

properties:

- large Y: e_I small perturbation such that light spectrum does not change
- low energy supergravity $\Rightarrow$ gauged/massive supergravity
- potential generated $\Rightarrow$ vacuum degeneracy (partially) lifted
- supersymmetry spontaneously broken

2.2. Fluxes in IIB on Y

[Michelson; Taylor,Vafa; Mayr; Dall'Agata; Micu,JL; ...]

IIB on Y: turn on three-form flux for $G_3 \equiv F_3 - \tau H_3$

$$\text{electric flux}: \qquad e_I(\tau) = e_I^{RR} - \tau e_I^{NS} = \int_{\gamma_I} G_3 \ ,$$

$$\text{magnetic flux}: \qquad m^I(\tau) = m^{IRR} - \tau m^{INS} = \int_{\gamma^{*I}} G_3$$

- electric fluxes e_I: gauged supergravity (gauged transl. isometry of hypermult.)

$$\partial_\mu q \to D_\mu q = \partial_\mu q + k_I(q) A_\mu^I \ , \qquad k_I = e_I = \int_{\gamma_I} G_3$$

- magnetic fluxes m^I: B_2, C_2 become massive

[Micu,JL; Dall'Agata,D'Auria,Sommovigo,Vaula]

$$M^2 = -m^K \mathrm{Im}\, \mathcal{M}_{KL}\, m^L$$

both cases: potential induced $V(z,\tau) = -(\bar{e} - \bar{\mathcal{M}} \cdot \bar{m})_K (\mathrm{Im}\mathcal{M})^{-1KL} (e - \mathcal{M} \cdot m)_L$

2.3. Mirror symmetry in the presence of fluxes

[Gukov,Vafa,Witten; Gurrieri,Micu,Waldram,JL; Fidanza,Graña,Minasien,Tomasiello; ...]

➪ RR-flux: IIB: $e = \int_\gamma F_3\ ,\qquad m = \int_{\gamma^*} F_3$

IIA: $\tilde{e} = \int_{\gamma_4} F_4\ ,\qquad \tilde{m} = \int_{\gamma_2} F_2$

mirror symmetry:

$$H^{(1,2)}(Y) \Longleftrightarrow H^{(1,1)}(\tilde{Y})$$

effective actions obey:

$$\mathcal{L}^{IIB}(Y, e, m) \ \equiv\ \mathcal{L}^{IIA}(\tilde{Y}, \tilde{e}, \tilde{m})\ , \qquad e = \tilde{e}, \quad m = \tilde{m}$$

➪ NS-flux:

no obvious mirror symmetry since flux of H_3 is along $H^3(Y)$ on both sides

$\Rightarrow$ missing fluxes can only come from metric/geometry

[Vafa]: compactify on different manifold $\widehat{Y}$ without any background flux

[GMLW]: $\widehat{Y}$ is 'half-flat manifold' [Hitchin; Chiossi,Salamon]

3. Manifolds of $SU(3)$-structure

3.1 derivation of Calabi-Yau condition

Lorentz group on space-time background $\mathcal{M}_{10} = R_{1,3} \times Y_6$ decomposes

$$SO(1,9) \to SO(1,3) \times SO(6)$$

spinor decompose accordingly:

$$\mathbf{16} \to (\mathbf{2}, \mathbf{4}) \oplus (\bar{\mathbf{2}}, \bar{\mathbf{4}})$$

impose two conditions:

1. demand that supercharge Q exist $\Rightarrow$ structure group of Y_6 has to be reduced

$$SO(6) \to SU(3) \quad \text{s.t.} \quad \mathbf{4} \to \mathbf{3} + \mathbf{1}$$

   $\Rightarrow$ invariant spinor η exists $\Rightarrow$ Y_6 has $SU(3)$-structure

2. background preserves supersymmetry

$$\delta\Psi_M = \nabla_M \eta + (\gamma \cdot F)_M = 0$$

   $\Rightarrow$ for $F = 0$: $\quad \nabla\eta \ = \ 0 \quad \Rightarrow$ Y_6 is Calabi-Yau manifold

3.2 spontaneously broken supersymmetry

insist on 1. (existence of Q) but relax 2. (background preserves susy)

$$\delta\Psi = \nabla\eta + (\gamma \cdot F) \;\neq\; 0 \;\Rightarrow \text{spontaneous breaking of supersymmetry}$$

$$\Rightarrow F \neq 0 \qquad \text{and/or} \qquad \nabla\eta \neq 0$$

- $F \neq 0$: non-trivial background flux
- $\nabla\eta \neq 0$: Y_6 is manifold of $SU(3)$ structure with torsion

  [Gray, Hervella, Salamon, Falcitelli, Farinola, Chiossi, Friedrich, Ivanov, Hitchin, ...]

  such manifolds are characterized by existence of invariant spinor η which obeys

  $$\nabla^{(T)}\eta \;\equiv\; (\nabla^{(LC)} + T_0)\,\eta \;=\; 0\;, \qquad T_0 : \text{intrinsic (con)-torsion}$$

  $\Rightarrow$ existence of two invariant tensors:

  almost complex structure $\quad J = \eta^\dagger\Gamma_2\eta\;, \quad J^2 = -1,$

  $(3,0)$-form $\quad \Omega = \eta^\dagger\Gamma_3\eta$

  generically: $dJ \neq 0, d\Omega \neq 0$, but obstructed by T_0

  $\Rightarrow$ manifolds are not complex, not Kähler, not Ricci-flat

3.3 compactifications on manifolds with $SU(3)$ structure

➪ manifolds mirror to Calabi-Yau $\oplus$ electric NS 3-form flux: [GLMW]

'half-flat' manifolds: $d\Omega^- = 0\,, \quad d\,(J \wedge J) = 0$

'missing' NS 4-form: $F_4^{NS} \sim d\Omega^+$

they obey

$$h^{(2)}(\hat{Y}) = h^{(1,1)}(Y) - 1\,, \qquad h^{(3)}(\hat{Y}) = h^{(3)}(Y) - 2$$

➪ manifolds mirror to Calabi-Yau $\oplus$ magnetic NS 3-form flux: ?

non-commutative manifold [Matthai,Rosenberg; Hull]

➪ generalization: $d\Omega \neq 0\,, \quad d\,(J \wedge J) = 0$ [Graña,Waldram,JL]

- family of manifolds with

$$h^{(2)}(\hat{Y}) = h^{(1,1)}(Y) - n\,, \qquad h^{(3)}(\hat{Y}) = h^{(3)}(Y) - 2n$$

- generalized geometrical mirror symmetry on $\hat{Y}$

4. $N = 1$ Calabi-Yau orientifolds in IIB

[Acharya,Aganagic,Brunner,Hori,Vafa]

4.1 the projection

String theory moded out by:

- world sheet parity: Ω_p
- holomorphic, isometric involution σ acting on Y_6: $\sigma^2 = 1$

$\Rightarrow$ Consider Calabi-Yau manifolds which admit such involutions

Two possible symmetry operations

(1) $\mathcal{O}_{(1)} = (-)^{F_L} \Omega_p \, \sigma \ , \quad \sigma\Omega = -\Omega \ , \quad O3/O7 - \text{planes}$

(2) $\mathcal{O}_{(2)} = \Omega_p \, \sigma \ , \quad \sigma\Omega = \Omega \ , \quad O5/O9 - \text{planes}$

Keep only invariant spectrum

- Ω_p: ϕ, G_{MN}, C_2 even, B_2, l, A_4 odd
- $(-)^{F_L}$: ϕ, G_{MN}, B_2 even, C_2, l, A_4 odd

Calabi-Yau cohomologies split under action of σ

$$H^{(p,q)} = H^{(p,q)}_+ \oplus H^{(p,q)}_- \ .$$

4.2 the spectrum [Brunner,Hori; Gidings,Kachru,Polchinski; Becker,Becker,Haack,Grimm,JL]

➪ $O3/O7$ $(\sigma\Omega = -\Omega)$

$h_+^{(2,1)}$	vector multiplets: $\int_{\gamma_3^\rho} A_4$
$h_-^{(2,1)}$	chiral multiplets: complex structure deformations z^i
$h_-^{(1,1)} + 1$	chiral multiplets: $\tau, \ \int_{\gamma_2^a} (C_2 - \tau B_2)$
$h_+^{(1,1)}$	chiral/linear multiplets: $\int_{\gamma_4^\alpha} (J^2 + iA_4) \leftrightarrow \int_{\gamma_2^\alpha} J, \ \int_{\gamma_2^\alpha} A_4$

➪ $O5/O9$ $(\sigma\Omega = \Omega)$

$h_-^{(2,1)}$	vector multiplets: $\int_{\gamma_3^i} A_4$
$h_+^{(2,1)}$	chiral multiplets: complex structure deformations z^ρ
$h_+^{(1,1)}$	chiral multiplets: $\int_{\gamma_2^\alpha} (J + iC_2)$
$h_-^{(1,1)} + 1$	chiral/linear multiplets: $\int_{\gamma_2^a} (B_2 + i *_6 A_4), \ e^{-\phi} + i *_4 C_2$

4.3 $d = 4, N = 1$ effective Lagrangian

standard form: [Wess,Bagger]

$$L = -\left(\tfrac{1}{2}R + K_{I\bar{J}} DM^I D\bar{M}^{\bar{J}} + \tfrac{1}{2}\mathrm{Re} f_{\kappa\lambda}\, F^\kappa \wedge *F^\lambda + \tfrac{1}{2}\mathrm{Im} f_{\kappa\lambda}\, F^\kappa \wedge F^\lambda + V\right) ,$$

$$V = e^K \left(K^{I\bar{J}} D_I W D_{\bar{J}} \bar{W} - 3|W|^2\right) + \tfrac{1}{2}\,(\mathrm{Re}\, f)^{-1\ \kappa\lambda} \mathcal{D}_\kappa \mathcal{D}_\lambda \ .$$

M^I: all scalar fields, $F^\kappa = dV^\kappa$,

- Kähler metric: $K_{I\bar{J}} = \partial_I \bar{\partial}_J K(M, \bar{M})$
- holomorphic superpotential: $W(M)$, $D_I W = \partial_I W + (\partial_I K) W$
- holomorphic gauge kinetic function: $f(M)$

next: determine K, W, f
by KK reduction from $d = 10, IIB$
or from truncating previous $d = 4, N = 2$ action

problem: find Kähler structure on space of fields

4.4 Kähler potential for $O3/O7$ case

[GKP, BBHL, GL]

- good Kähler variables:

$$\tau = l + ie^{-\phi}\,, \qquad G^a = \int_{\gamma_2^a} G_2\,, \qquad G_2 \equiv (C_2 - \tau B_2)\,,$$

$$T_\alpha = \int_{\gamma_4^\alpha} J^2 + iA_4 + \tfrac{1}{\tau_2} G_2 \wedge (G_2 - \bar{G}_2)\,,$$

- Kähler potential: $K = K_{\mathrm{cs}}(z,\bar{z}) + K_k(\tau, T, G)$

$$K_{\mathrm{cs}} = -\ln\Big[-i\int \Omega(z)\wedge\bar{\Omega}(\bar{z})\Big]\,,$$

$$K_k = -\ln\big[-i(\tau-\bar{\tau})\big] - 2\ln\Big[\mathcal{V}(\tau, T, G)\Big]\,, \qquad \mathcal{V} \equiv \int J^3$$

Note: $\mathcal{V}$ only implicitly given in terms of Kähler variables T_α

- moduli space: $\mathcal{M} = \mathcal{M}_{\mathrm{cs}}^{h_-^{(1,2)}} \times \mathcal{M}_{\mathrm{k}}^{h^{(1,1)}+1}$ [Alekseevsky,Marchiafava]

- no-scale-type property: [Cremmer,Ferrara,Kounnas,Nanopoulos]

$$\partial_I K_k (K_k^{-1})^{I\bar{J}}\,\bar{\partial}_J K_k = 4$$

4.5 Effective action in terms of linear multiplets [Binetruy,Girardi,Grimm]

Linear multiplet L: obeys superspace constraint $D^2 L = 0 = \bar{D}^2 L$

bosonic components: $(L, dA_2) \longleftrightarrow$ dual to chiral multiplet T (if massless)

$$L^\alpha = \int_{\gamma_2^\alpha} J \,, \qquad A_2^\alpha = \int_{\gamma_2^\alpha} A_4$$

$$\begin{aligned} K &= K_{\mathrm{cs}}(z,\bar{z}) - \ln\big[-i(\tau-\bar{\tau})\big] + \ln\big[\mathcal{V}\big] \,, \qquad \mathcal{V} \equiv \int J^3 \\ V &= e^K \Big(|DW|^2 - (3 - L^\alpha K_{L^\alpha})|W|^2 \Big) \,, \end{aligned}$$

Note:

- $L^\alpha K_{J^\alpha} = 3 \Rightarrow V \geq 0$
- duality in superspace $L^\alpha \leftrightarrow T_\alpha$ yields Kähler structure
- new class of no-scale Kähler potentials [Barbieri,Cremmer,Ferrara]
  (classification?, perturbative stability?)

4.6 Turn on background flux

$$e_i(\tau) = \int_{\gamma_3^i} G_3 \ , \qquad m^i(\tau) = \int_{\gamma_3^{*i}} G_3 \ , \qquad G_3 = F_3 - \tau H_3$$

after KK-reduction: positive semi-definite potential arises.

Expressed via [Gukov,Taylor,Vafa,Witten]

$$W(\tau, z^i) = \int_Y \Omega(z) \wedge G_3(\tau) \ , \qquad \mathcal{D} = 0$$

order parameters for supersymmetry breaking: $F_I = D_I W, \ \ \mathcal{D}$

unbroken supersymmetry: $G_3 \in H_-^{(2,1)}$

broken supersymmetry with $V = 0$: $G_3 \in H_-^{(0,3)}$

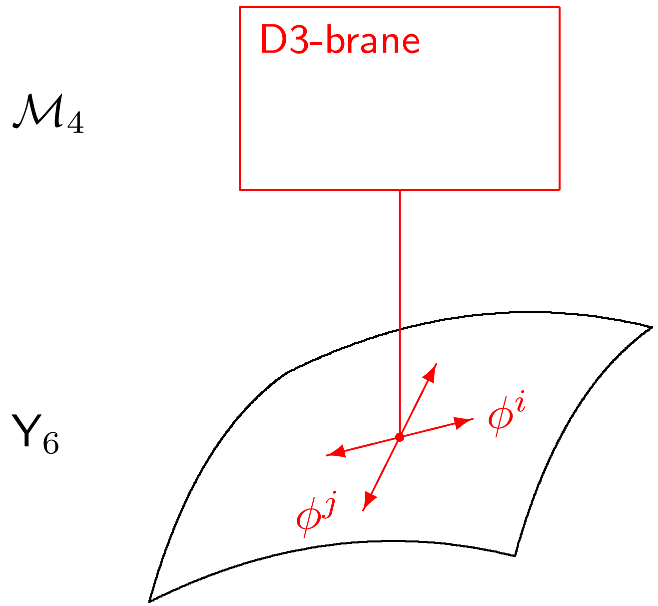
unstable vacua $G_3 \in H_-^{(3,0)} \oplus H_-^{(1,2)}$

5. D3/D7-branes

5.1 D3-branes spectrum

stack of N D3-branes

- $U(N)$ gauge theory
- matter ϕ^i , $(i = 1, 2, 3)$ in adjoint of $U(N)$



5.2 Effective action including D3-branes

[Camara,Ibanez,Uranga; Graña,Grimm,Jockers,JL]

➪ KK reduction of DBI ⊕ CS action in a low energy and small ϕ^i expansion

- Dirac-Born-Infeld action

$$S_{\text{DBI}}^{\text{sf}} = -\mu_3 \int_{\mathcal{W}} d^4\xi \, e^{-\phi} \sqrt{-\det\left(\varphi^*(g_{\mu\nu} + B_{\mu\nu}) + 2\pi\alpha' F_{\mu\nu}\right)}$$

- Chern-Simons action

$$S_{\text{CS}} = \mu_3 \int_{\mathcal{W}} \varphi^* \Big(\sum_q C^{(q)} e^B \Big) \, e^{2\pi\alpha' F}$$

(Generalization to non-Abelian DBI ⊕ CS for a stack of N D3-branes: [Myers])

➪ Add reduced action to bulk orientifold action and rewrite in standard supergravity form

Result: [Graña,Grimm,Jockers,JL]

- Kähler potential: $K = K_{\text{cs}}(z,\bar z) + K_k(\tau, T, G, z, \phi)$

$$K_k = -\ln\big[-i(\tau-\bar\tau)\big] - 2\ln\Big[\mathcal{V}(\tau,T,G,z,\phi)\Big]\ , \qquad \mathcal{V} \equiv \int J^3$$

$$T_\alpha = \int_{\gamma_4^\alpha} \big(J^2 + iA_4 + \tfrac{1}{\tau_2} G_2 \wedge (G_2 - \bar G_2)\big) + \omega_{\alpha i\bar j}\, Tr\phi^i \big(\bar\phi^{\bar j} - \bar z^k (\chi_k)^{\bar j}_l \phi^l\big)\ ,$$

$$\omega_\alpha \in H_+^{(1,1)}, \quad \chi_k \in H_-^{(1,2)}$$

$\Rightarrow$ complex structure moduli z^k couple to ϕ. (C_4 couples to $D3$-branes)

$\Rightarrow$ moduli space no longer direct product

example: $h_+^{(1,1)} = 1,\ G = 0$

$$-2\ln\big[\mathcal{V}(T,z,\phi)\big] = -3\ln\big[T + \bar T + \omega_{i\bar j} Tr\phi^i(\bar\phi^{\bar j} - \bar z^k(\chi_k)^{\bar j}_l \phi^l)\big]$$

- gauge kinetic function: $f \sim \tau$

- superpotential $W = W_{\text{flux}}(\tau, z) + \tfrac{1}{3} Y_{ijk}\, Tr\phi^i\phi^j\phi^k\ , \qquad Y_{ijk} = \Omega_{ijk}(z)$

5.3 space-time filling D7-brane wrapped on 4-cycle S^Λ

[Lüst,Mayr,Reffert,Richter,Stieberger; Camara,Ibanez,Uranga; Jockers,JL]

➪ spectrum

matter fields:	fluctuations of the 4-cycle $\zeta \in H^0(S^\Lambda)$
moduli:	Wilson lines $a \in H^1(S^\Lambda)$

➪ Kähler coordinates

$$S = \tau + \zeta \cdot \bar{\zeta} \,, \qquad T = T_{\rm of} + a \cdot \bar{a}$$

➪ Kähler potential

$$K = K_{cs} - \ln[S - \bar{S} - \zeta \cdot \bar{\zeta}] - 2\ln\left[\mathcal{V}(T, G, S, a)\right]$$

➪ gauge coupling

$$f \sim T_\Lambda$$

➪ superpotential

$$W = W_{\rm flux} + \tfrac{1}{2} m \cdot \zeta\zeta + \tfrac{1}{3} Y \cdot \zeta\zeta\zeta \,,$$

6. Soft Supersymmetry Breaking

6.1 Supergravity Perspective [Barbieri,Ferrara,Savoy; Kaplunovsky,JL; Brignole,Ibanez,Munoz]

In the limit $M_{\rm Pl} \to \infty$, $m_{3/2} =$ const.:

$N = 1$ spontaneously broken sugra $\to$ global supersymmetry $\oplus$ soft breaking terms

$$V^{(\rm eff)} = \tfrac{1}{2}\mathcal{D}^2 + |\partial_i W^{(\rm eff)}|^2 + m^2_{i\bar{\jmath}}\phi^i\bar{\phi}^{\bar{\jmath}} + \tfrac{1}{3}A_{ijk}\phi^i\phi^j\phi^k + \tfrac{1}{2}B_{ij}\phi^i\phi^j + \text{h.c.}$$

where

$$\begin{aligned} m^2_{i\bar{\jmath}} &= (|m_{3/2}|^2 + V_0)\, Z_{i\bar{\jmath}} - F^I F^{\bar{J}} R_{I\bar{J}i\bar{\jmath}} \,, \qquad m_{3/2} \equiv e^{K/2} W \\ A_{ijk} &= F^I D_I Y_{ijk} \,, \\ B_{ij} &= B_{ij}\big(\partial_i\partial_j K|_{\phi=0}\big) \,, \end{aligned}$$

gaugino mass:

$$m_g = F^I \partial_I \ln g^{-2}$$

6.2 String Perspective

- SM on D3 [Körs,Nath; Camara,Ibanez,Uranga; Graña,Grimm,Jockers,JL]

  $G_3 \in H_-^{(2,1)}$: unbroken supersymmetry $\Rightarrow$ soft terms vanish

  $G_3 \in H_-^{(0,3)}$: broken supersymmetry ($F^T \neq 0$) with $V = 0$
  but all soft terms vanish ('strict' no scale)

  $G_3 \in H_-^{(3,0)} \oplus H_-^{(1,2)}$: $V > 0$ and unstable
  non-vanishing soft terms with properties:
  – universal scalar masses (due to no-scale K)
  – $A \sim Y$
  – $B \neq \mu$

- SM on D7 [Lüst,Reffert,Stieberger; Camara,Ibanez,Uranga]

  $G_3 \in H_-^{(0,3)}$: broken supersymmetry ($F^T \neq 0$) with $V = 0$
  soft terms generated:

$$m_g \sim m_{3/2} \ , \quad m^2 \sim m_{3/2} \ , \quad A \sim Y$$

reason for difference: different K, f

7. Conclusions/open problems

- background fluxes break supersymmetry spontaneously and fix some of the moduli
- spontaneous supersymmetry breaking can also be achieved by compactification on manifolds with $SU(3)$ structure
- $N = 1$ effective action for Calabi-Yau orientifold including background fluxes and space-time filling $D3/D7$-branes has been computed

  $\Rightarrow$ new class of no-scale Kähler potentials arises
- resulting soft supersymmetry breaking terms are computed and analyzed

  $\Rightarrow$ promising structure for $D3/D7$-branes

- include warped space-time properly
- study phenomenology of $SU(3)$-structure orientifolds
- effect of quantum corrections
- supersymmetric flavor problem