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Landscape vs. swampland: the power of local symmetries

based on work with Giovanni Villadoro
JHEP 0603 (2006) 087 [hep-th/0602120] & in preparation

String Phenomenology
KITP, Santa Barbara, 1 September 2006

Some approaches to string phenomenology

Bottom-up: string-inspired D>4 models
motivated by phenomenological questions
very fruitful in some cases (e.g. ADD, RS)

Top-down: full-fledged string constructions
automatically consistent but still technically limited

Intermediate: effective D=10,11 SUGRA
[g_s, $1/M_s$] compactified with branes and fluxes
Not full-fledged string constructions, yet strong
consistency constraints from local symmetries:
GCT, SUGRA, gauge invariance (bulk & brane)
as long as exact or broken at field-theory scales

Plan of the talk

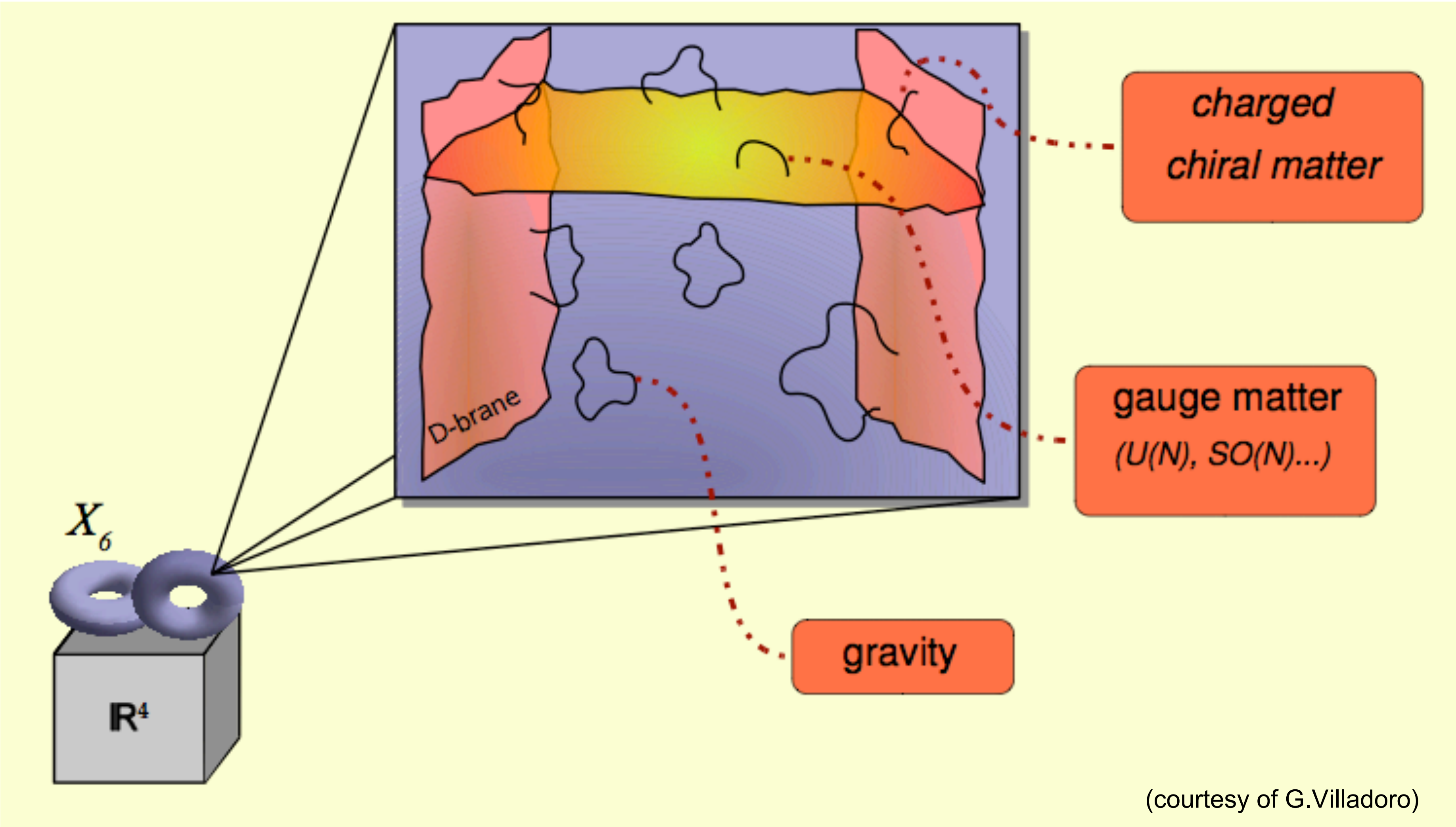
Illustrate some general results by a class of simple type-IIA compactifications with exact or spontaneously broken N=1

1. Constraints on branes and fluxes from bulk local symmetries, effective superpotential and F-terms

2. Constraints on branes and fluxes from brane U(1) symmetries, structure of D-terms, the (standard) SUGRA limit, relation with Freed-Witten anomaly

3. Extensions: other compactifications, non-geometrical fluxes, non-perturbative superpotentials (preliminary)

A picture of the brane-world (IIA)



Type-IIA

Type-IIA supergravity: N=2, D=10 ➔ N=8, D=4

Bosonic degrees of freedom (from closed strings):

NS sector: g_{MN} (metric) ϕ (dilaton) B_{MN} (2-form)

RR sector: $A^{(1)} \leftrightarrow A^{(7)}$ (dual), $A^{(3)} \leftrightarrow A^{(5)}$ (dual), $A^{(9)}$ (non-dyn)

Extra d.o.f. from open strings on D-branes: discuss today only U(1) vectors associated with each stack, neglecting the remaning gauge and matter degrees of freedom living on branes or at brane intersections

(moduli stabilization, SUSY breaking, vacuum energy; no realistic model-building yet with these d.o.f. only)

Simple N=1 compactification

$$\left(\frac{T^6}{Z_2 \times Z_2'}\,;\ \Omega I_3\right)$$

orbifold + orientifold

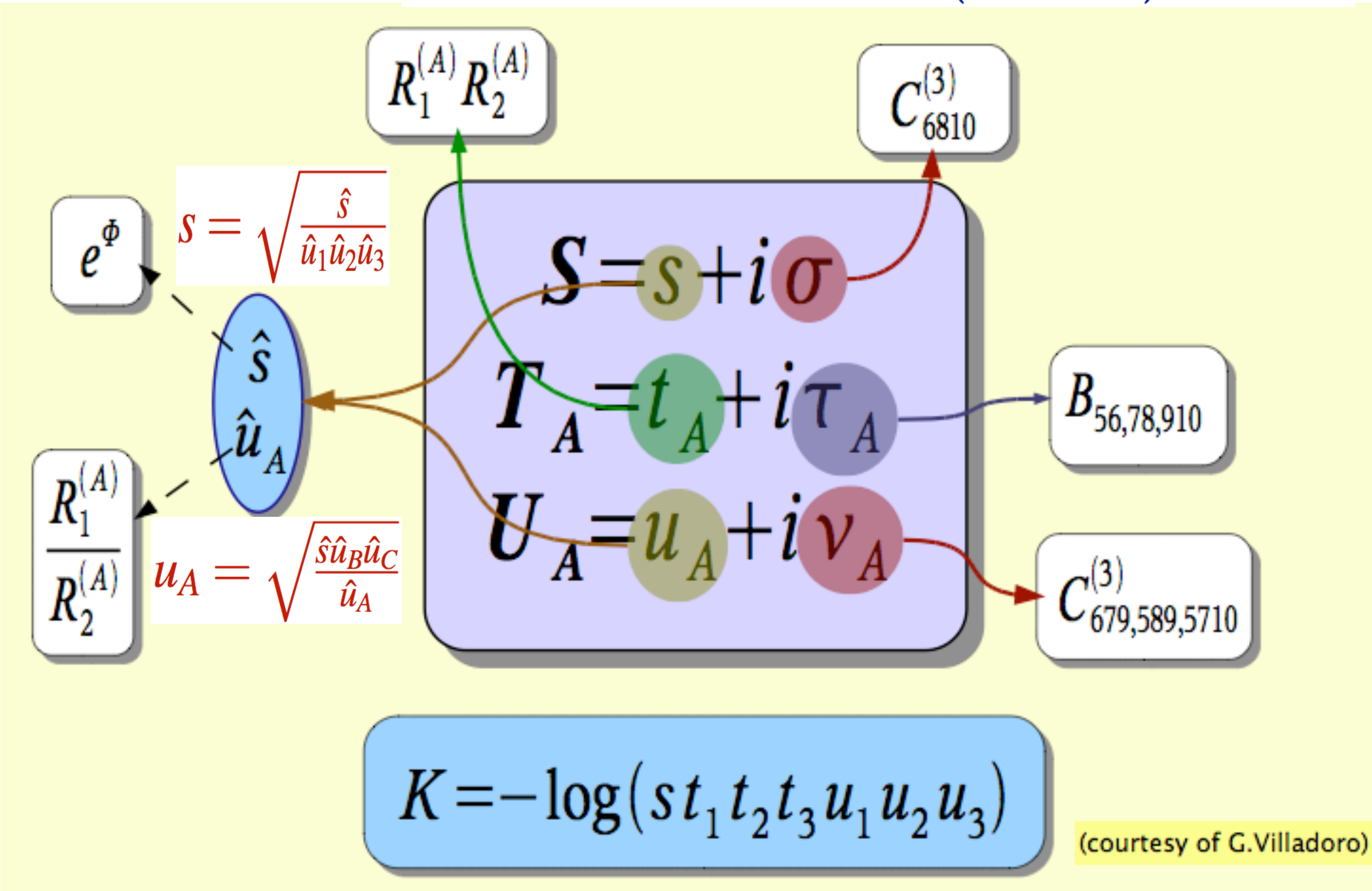
	x^5	x^6	x^7	x^8	x^9	x^{10}
Z_2	$-$	$-$	$-$	$-$	$+$	$+$
Z_2'	$+$	$+$	$-$	$-$	$-$	$-$
I_3	$-$	$+$	$-$	$+$	$-$	$+$

O6-planes:
(6,8,10)
(6,7,9)
(5,8,9)
(5,7,10)

Ω = +1 for g_{MN}, ϕ, $A^{(3)}$, $A^{(7)}$
-1 for B_{MN}, $A^{(1)}$, $A^{(5)}$, $A^{(9)}$

natural factorization
$T^6 \rightarrow T^2 \times T^2 \times T^2$

Bulk moduli $J^c = J + iB \quad \Omega^c = \Re(ie^{-\Phi}\Omega) + iC^{(3)}$



(courtesy of G.Villadoro)

$$K = -\log\left(\int J \wedge J \wedge J\right) - \log\left(\int \Omega \wedge \overline{\Omega}\right)$$

Bulk fluxes

To generate a (super) potential, can introduce FLUXES
background values for the NSNS and RR field strengths
compatible with the orbifold and orientifold projections

$H^{(3)}$; $G^{(0)}$, $G^{(2)}$, $G^{(4)}$, $G^{(6)}$

(4) (1) (3) (3) (1)

can also introduce "geometrical fluxes"
~ "background values for the spin connection"

$\omega_{mn}{}^{r}$ (12)

will neglect here localized magnetic fluxes $F^{(2)}$

can add "non-geometrical" fluxes $Q_m{}^{nr}$, R^{mnr}

Biianchi Identities for bulk local symmetries

- Generalize Gauss law in the compact space
- Can be derived from `dual SUGRA formulation'
- Receive contributions from localized sources
- Integrability conditions ➔ consistency constraints

General expression [Villadoro, unpublished]

$$D\,D = [\nu] \qquad D\,G = [\pi]\,e^F$$

NS-branes D-branes

$$D = d + \omega + H\wedge$$ (torsion)

Explicitly, in our example:

$$\omega\,\omega \equiv \omega_{mn}{}^{p}\omega_{pr}{}^{s} = 0$$ [Scherk-Schwarz, 1979]

$$\omega\,G^{(2)} + H\,G^{(0)} = \sum_a N_a \mu_a [\pi_a]$$ [Villadoro-FZ, 2005]

D6/O6

(plus other conditions on fluxes automatically satisfied)

General IIA effective superpotential

Geometrical form:

[Villadoro-FZ, 2005]

$$W = \frac{1}{4}\int_{\mathcal{M}_6} \overline{\mathbf{G}}\, e^{iJ^c} - i\left(\overline{H} - i\omega J^c\right) \wedge \Omega^c$$

generalizes previous heterotic, IIB [Gukov,Vafa,Witten;Taylor,Vafa;…] & IIA [Gukov; Gukov,Haack; Cardoso et al.; Gurrieri et al.; Grana et al; ,,,] results

Matches the general form previously derived from N=4 gaugings: degree-7 polynomial in (S,T_A,U_A), at most degree-1 in each field (automatic incorporation of non-geometrical fluxes)

[Kounnas-Derendinger-Petropoulos-FZ 2005]

Corresponding IIA effective potential (SUSY branes):

$V=V_E+V_H+V_G+V_6$ explicitly derived by dimensional reduction matches the standard F-term potential of N=1 D=4 SUGRA

generalized BI ➔ trade D6/O6 data for bulk fluxes

Stable N=1 AdS_4 vacua in type-IIA

[Villadoro-FZ, hep-th/0503169]

Choose the (plane-interchange-symmetric) system of fluxes:

$$\frac{1}{9}\overline{G}^{(6)} = -t_0^2\,\overline{G}^{(2)} = \frac{t_0\,u_0}{6}\omega_1 = \frac{s_0\,t_0}{2}\omega_2 = \frac{t_0\,u_0}{6}\omega_3$$

$$\frac{t_0}{3}\overline{G}^{(4)} = \frac{t_0^3}{5}\overline{G}^{(0)} = -\frac{s_0}{2}\overline{H}_0 = \frac{u_0}{2}\overline{H}_1$$

compatible with all Bianchi Identities

first example of classical (flux) stabilization
of all seven geometrical moduli

further examples:

DeWolfe-Giryavets-Kachru-Taylor hep-th/0505160
Camara-Font-Ibanez hep-th/0506066

Not possible in the heterotic, type-I and type-IIB cases
due to the more limited set of (perturbative) fluxes

[U(1)] D terms from D-branes

In our simple type-IIA example, we ignored so far the [U(1)] gauge fields from D6-branes and their D-term contributions to the potential, but they do play some very important roles

- •extra BI for the `localized' gauge fields ➔ new constraints
- •even when <D>=0, D terms can affect the moduli masses
- •a U(1) Higgs effect a la Stueckelberg can remove axions

$$\pi = (m_1, n_1) \otimes (m_2, n_2) \otimes (m_3, n_3)$$ wrapping numbers on A-th 2-torus

$$\pi = p_I \alpha^I + q^I \beta_I$$ components along even/odd 3-cycles

$p_0 = m_1 m_2 m_3$ $p_1 = m_1 n_2 n_3$ $p_2 = n_1 m_2 n_3$ $p_3 = n_1 n_2 m_3$

$q^0 = n_1 n_2 n_3$ $q^1 = n_1 m_2 m_3$ $q^2 = m_1 n_2 m_3$ $q^3 = m_1 m_2 n_3$

[U(1)] D terms in N=1 SUGRA

N=1 SUGRA ➔ gauge symmetries $\subset$ isometries

$f_{ab}(\varphi)$ gauge kinetic function

$X_a^i(\varphi)$ holomorphic Killing vectors

[Maxwell] Yang-Mills

$$-\frac{1}{4}\tilde{e}_4 Re f_{ab}\, F^a F^b + \frac{1}{2} Im f_{ab}\, F^a \wedge F^b$$

$$\delta\varphi^i = X_a^i \varepsilon^a \qquad D_a = iG_i X_a^i = iK_i X_a^i + i\frac{W_i}{W} X_a^i$$

constant FI term

$$V = V_F + V_D = e^K(||K_i W - W_i||^2 - 3|W|^2) + \frac{1}{2}[(Re\, f)^{-1}]^{ab} D_a D_b$$

Notice:

- Never pure D-breaking in (realistic) N=1 SUGRA (unless $m_{3/2}$=0 and V_D is uncancelled, as in the unphysical limit of global supersymmetry)
- No D-term uplifting of N=1 SUSY adS_4 vacua to dS_4 [Choi-Falkowski-Nilles-Olechowski 2005; de Alwis 2005]

A toy model with a dS vacuum

[G.Villadoro, F.Z. PRL 95 (2005) 231602]

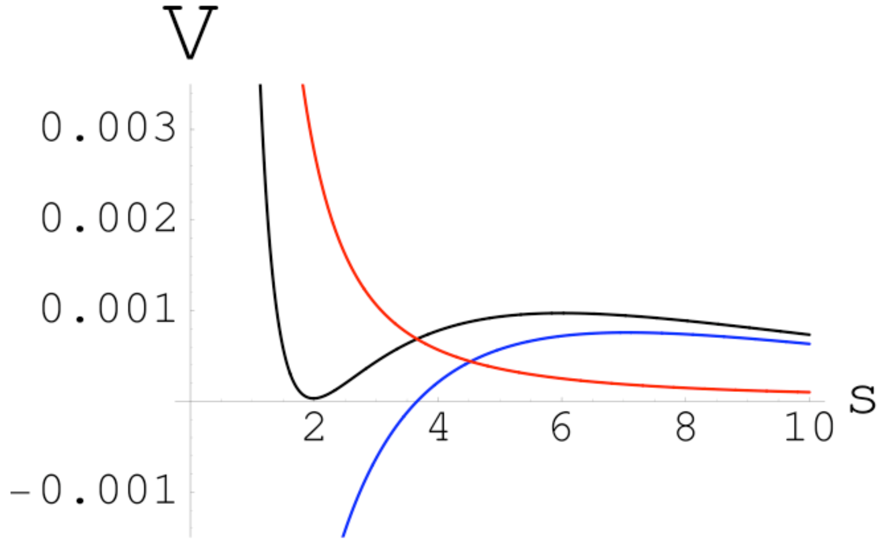
gauge a U(1) combination of axionic shift and R-symmetry

$$K = -p\log(S+\overline{S}) + K_0 \quad (0 < p \in \mathbf{R})$$

$$W = W_0 e^{-kS} \quad (k \in \mathbf{R})$$

$$X^S = iq \quad (q \in \mathbf{R})$$

$$f = S$$



$$V = \frac{e^{G_0} e^{-2ks}}{(2s)^p}\left[\frac{(2s)^2}{p}\left(k+\frac{p}{2s}\right)^2 - 3\right] + \frac{q^2}{2s}\left(k+\frac{p}{2s}\right)^2$$

but no concrete string realization has been found yet

Effective potential from DBI action

$$S_{DBI} = -N T_6 \int_{\mathbb{R}^4 \times \pi} d^7x \, e^{-\Phi} \sqrt{-\det\left(g_{\alpha\beta} + B_{\alpha\beta} + F_{\alpha\beta}\right)}$$

$$\widetilde{\Omega}_\pi \equiv \int_\pi i \, e^{-\Phi} \Omega \qquad \Lambda^M{}_N = \mathbf{I}_4 \bigotimes_{A=1}^{3} \begin{pmatrix} m_A & n_A \\ -n_A & m_A \end{pmatrix}$$

brane embedding

$$\rightarrow \quad V_6 = \frac{N T_6}{s u_1 u_2 u_3} \sqrt{(Re\widetilde{\Omega}_\pi)^2 + (Im\widetilde{\Omega}_\pi)^2}$$

$$Re\widetilde{\Omega}_\pi = p_0 s - \sum_{A=1}^{3} p_A u_A \qquad Im\widetilde{\Omega}_\pi = \sqrt{s u_1 u_2 u_3} \left(\frac{q^0}{s} - \sum_{A=1}^{3} \frac{q^A}{u_A} \right)$$

The (standard) SUGRA limit

$$V_6 = V_{6F} + V_D \qquad V_{6F} = \frac{N T_6}{s u_1 u_2 u_3} Re\widetilde{\Omega}_\pi$$

$$V_D = \frac{N T_6}{s u_1 u_2 u_3} \left(\sqrt{(Re\widetilde{\Omega}_\pi)^2 + (Im\widetilde{\Omega}_\pi)^2} - Re\widetilde{\Omega}_\pi \right)$$

[Blumenhagen, Braun, Kors, Lust, hep-th/0206038]

fits standard N=1 SUGRA for $\left| Im\widetilde{\Omega}_\pi \right| \ll Re\widetilde{\Omega}_\pi$

$$D = N \mu_6 \left(\frac{q^0}{s} - \sum_{A=1}^{3} \frac{q^A}{u_A} \right)$$

identical form in type-IIB with D3/D7 (u_A ⇔ t_A) VZ

$$f = N T_6 \left(p_0 S - \sum_{A=1}^{3} p_A U_A \right)$$

[Cremades, Ibanez, Marchesano hep-th/0201205+hep-th/0203160]

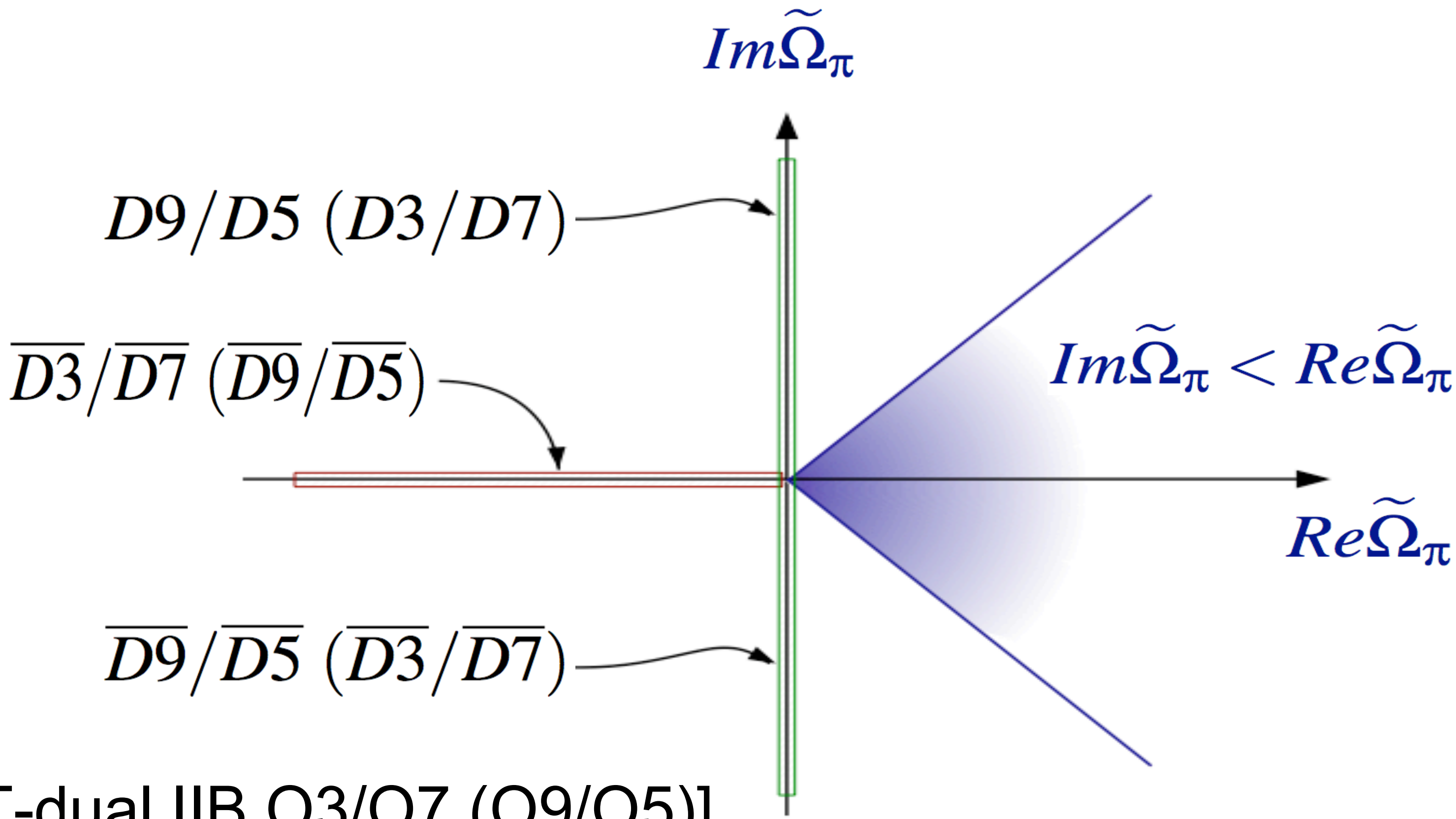
Gauged U(1) = shift on 4 RR axions [CFI, hep-th/0506066]

$$iX^S = -2N\mu_6 q^0 \qquad iX^{U_A} = 2N\mu_6 q^A$$

VZ

The standard SUGRA limit in a picture

$$Im\widetilde{\Omega}_\pi < Re\widetilde{\Omega}_\pi \quad \Longleftrightarrow \quad D \ll \frac{M_S^2}{g^2 M_P^2}$$



[T-dual IIB O3/O7 (O9/O5)]

Localized Bianchi Identities

- There are new BI for the localized gauge fields, leading to new compatibility constraints for branes and fluxes, which ensure gauge invariance of the superpotential W (and the automatic cancellation of gauge anomalies)

dF+H=0 ➔ $\int_\pi H = 0$ ↔ $\delta W = 0$

BI   FW anomaly   gauge invariance

[as also observed by Camara-Font-Ibanez hep-th/0506066]

In the presence of geometrical fluxes:

$$D[\pi] = 0 \Rightarrow \int_\pi H = 0\,,\ \omega[\pi] = 0 \Rightarrow \delta W = 0$$

$$\Rightarrow \partial\pi = 0$$

type-IIB: $De^F = 0 \Rightarrow \omega F + H = 0 \Rightarrow \delta W = 0$

Extension to non-geometrical fluxes

Applying repeatedly T-duality to NSNS 3-form fluxes:

$$\overline{H}_{mnr} \overset{T_r}{\longleftrightarrow} \omega_{mn}{}^{r} \overset{T_n}{\longleftrightarrow} Q_{m}{}^{nr} \overset{T_m}{\longleftrightarrow} R^{mnr}$$

[Shelton-Taylor-Wecht hep-th/0508133]
[see also: KSTT hep-th/0211182; DFKZ hep-th/0411276]

Bulk BI: $d+\omega+H \rightarrow d+\omega+H+Q+R$

Effective superpotential:

$$W = \frac{1}{4}\int e^{iJ^c}[\overline{G} - i(\overline{H}+\omega+Q+R)\Omega^c]$$

(with analogous expressions for type-IIB O3/O7 & O9/O5)

Localized BI:

$$R\,[\pi] = 0 \qquad \int [\gamma] \wedge Q\,[\pi] = 0 \quad (\forall \gamma)$$

Extension to non-perturbative superpotentials

Non-perturbative effects (gaugino condensation, Euclidean brane instantons) generate exponential superpotentials ➔ there must be an obstruction that forbids explicit breaking of gauged shift symmetries

A general characterization from M-theory is possible
[Villadoro-FZ, work in progress]

An example (NS5 in IIA): $\int_{V_5} G = 0$

to be added to some already existing examples:

D2 in IIA [KashaniPoor-Tomasiello hep-th/0505208]

NS5 in het.M-theory [Anguelova-Zoubos hep-th/0606271]

Conclusions and outlook

- Effective supergravity is a reliable and powerful tool for studying string compactifications with fluxes and branes
- Bulk and brane local symmetries ➔ strong constraints
- Closed string moduli can be classically stabilized on SUSY AdS_4, but some obstructions to stabilize them in Minkowski or dS_4, even after including D terms
- It would be interesting to examine systematically what can change when including matter fields localized on branes or brane intersections, as well as warp factors: this should finally allow to attack more realistic models
- Perturbative and non-perturbative quantum corrections are also strongly constrained by the local symmetries: a systematic discussion of the latter is in progress