Landscape vs. swampland: the power of local symmetries

based on work with Giovanni Villadoro

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)

(courtesy of G. Villadoro)
Type-IIA

Type-IIA supergravity: \( N=2, D=10 \rightarrow N=8, D=4 \)

Bosonic degrees of freedom (from closed strings):
- NS sector: \( g_{MN} \) (metric) \( \phi \) (dilaton) \( B_{MN} \) (2-form)
- RR sector: \( A^{(1)} \leftrightarrow A^{(7)} \), \( A^{(3)} \leftrightarrow A^{(5)} \), \( A^{(9)} \) (dual, dual, non-dyn)

Extra d.o.f. from open strings on D-branes: discuss today only \( U(1) \) vectors associated with each stack, neglecting the remaining 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

\[
\left( \frac{T^6}{Z_2 \times Z_2'} ; \ 01 \right) \quad \text{orbifold + orientifold}
\]

\[
x^5 \ | \ x^6 \ | \ x^7 \ | \ x^8 \ | \ x^9 \ | \ x^{10} \quad \text{O6-planes:}
\]

\[
\begin{array}{cccccc}
Z_2 & - & - & - & - & + & + \\
Z'_2 & + & + & - & - & - & - \\
I_3 & - & + & - & + & - & + \\
\end{array}
\]

\[
\Omega = \begin{cases} 
+1 & \text{for } g_{MN}, \ \Phi, \ A^{(3)}, \ A^{(7)} \\
-1 & \text{for } B_{MN}, \ A^{(1)}, \ A^{(5)}, \ A^{(9)}
\end{cases}
\]

natural factorization

\[T^6 \Rightarrow T^2 \times T^2 \times T^2\]
Bulk moduli

\[ J^c = J + iB \quad \Omega^c = \mathfrak{K}(i e^{-\Phi} \Omega) + iC^{(3)} \]

\[ s = \sqrt{\frac{\hat{s}}{\hat{u}_1 \hat{u}_2 \hat{u}_3}} \]

\[ e^\phi \]

\[ \frac{R_1^{(A)}}{R_2^{(A)}} \]

\[ \hat{\hat{S}} \]

\[ \hat{u}_A \]

\[ S = s + i\sigma \]

\[ T_A = t_A + i\tau_A \]

\[ U_A = u_A + i\nu_A \]

\[ K = -\log \left( \frac{st_1 t_2 t_3 u_1 u_2 u_3}{\hat{u}_1 \hat{u}_2 \hat{u}_3} \right) \]

\[ K = -\log(\int J \wedge J \wedge J) - \log(\int \Omega \wedge \overline{\Omega}) \]
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”

\[ \omega_{mn}^r \quad (12) \]

will neglect here localized magnetic fluxes \( F^{(2)} \)
can add “non-geometrical” fluxes \( Q_m^{nr}, \ R^{mnr} \)
Bianchi 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 $\Rightarrow$ consistency constraints

**General expression** [Villadoro, unpublished]

$$ DD = [\nu] \quad DG = [\pi] \, e^F $$

NS-branes

D-branes

$$ D = d + \omega + H \wedge \quad \text{(torsion)} $$

Explicitly, in our example:

$$ \omega \omega \equiv \omega_{mn}^\rho \omega_{\rho r}^s \quad s = 0 $$ [Scherk-Schwarz, 1979]

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

D6/O6

(plus other conditions on fluxes automatically satisfied)
**General IIA effective superpotential**

Geometrical form:

\[ W = \frac{1}{4} \int_{\mathcal{M}_6} \overline{G} e^{iJ^c} - i (\overline{H} - i\omega J^c) \wedge \Omega^c \]

[Villadoro-FZ, 2005]

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:

\[
\frac{1}{9} G^{(6)} = -t_0^2 G^{(2)} = \frac{t_0 u_0}{6} \omega_1 = \frac{s_0 t_0}{2} \omega_2 = \frac{t_0 u_0}{6} \omega_3 \\
\frac{t_0}{3} G^{(4)} = \frac{t_0^3}{5} G^{(0)} = -\frac{s_0}{2} H_0 = \frac{u_0}{2} H_1
\]

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 $\Rightarrow$ 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

\[ p_0 = m_1 m_2 m_3 \quad p_1 = m_1 n_2 n_3 \quad p_2 = n_1 m_2 n_3 \quad p_3 = n_1 n_2 m_3 \]

\[ q^0 = n_1 n_2 n_3 \quad q^1 = n_1 m_2 m_3 \quad q^2 = m_1 n_2 m_3 \quad q^3 = m_1 m_2 n_3 \]
[U(1)] D terms in N=1 SUGRA

N=1 SUGRA $\Rightarrow$ gauge symmetries $\subseteq$ isometries

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

$X^i_a(\varphi)$ holomorphic Killing vectors

$\frac{-1}{4} \epsilon^4 \text{Re} f_{ab} F^a F^b + \frac{1}{2} \text{Im} f_{ab} F^a \wedge F^b$

$\delta \varphi^i = X^i_a \varepsilon^a$

$D_a = iG_iX^i_a = iK_iX^i_a + i\frac{W_i}{W}X^i_a$

$V = V_F + V_D = e^K (||K_iW - W_i||^2 - 3|W|^2) + \frac{1}{2}[(\text{Re} f)^{-1}]^{ab}D_aD_b$

Notice:

• Never pure D-breaking in (realistic) N=1 SUGRA
  (unless $m_{3/2}=0$ and $V_D$ is uncanceled, 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

\[ K = -p \log(S + \bar{S}) + K_0 \quad (0 < p \in \mathbb{R}) \]

\[ W = W_0 e^{-kS} \quad (k \in \mathbb{R}) \]

\[ X^S = i q \quad (q \in \mathbb{R}) \]

\[ f = S \]

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

but no concrete string realization has been found yet
Effective potential from DBI action

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

\[ \tilde{\Omega}_\pi \equiv \int_{\pi} i e^{-\Phi} \Omega \quad \Lambda^M_N = I_4 \bigotimes_{A=1}^{3} \begin{pmatrix} m_A & n_A \\ -n_A & m_A \end{pmatrix} \]

\[ \Rightarrow V_6 = \frac{N T_6}{su_1 u_2 u_3} \sqrt{(Re\tilde{\Omega}_\pi)^2 + (Im\tilde{\Omega}_\pi)^2} \]

\[ Re\tilde{\Omega}_\pi = p_0 s - \sum_{A=1}^{3} p_A u_A \quad Im\tilde{\Omega}_\pi = \sqrt{su_1 u_2 u_3} \left( \frac{q^0}{s} - \sum_{A=1}^{3} \frac{q^A}{u_A} \right) \]
The (standard) SUGRA limit

\[ V_6 = V_{6F} + V_D \]

\[ V_{6F} = \frac{NT_6}{su_1u_2u_3} \Re \tilde{\Omega}_\pi \]

\[ V_D = \frac{NT_6}{su_1u_2u_3} \left( \sqrt{(\Re \tilde{\Omega}_\pi)^2 + (\Im \tilde{\Omega}_\pi)^2} - \Re \tilde{\Omega}_\pi \right) \]

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

fits standard N=1 SUGRA for

\[ \left| \Im \tilde{\Omega}_\pi \right| \ll \Re \tilde{\Omega}_\pi \]

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

\[ f = NT_6 \left( p_0 s - \sum_{A=1}^{3} p_A U_A \right) \]

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

\[ iX^S = -2N\mu_6 q^0 \quad iX^{U_A} = 2N\mu_6 q^A \]
The standard SUGRA limit in a picture

\[ \text{Im} \tilde{\Omega}_\pi < \text{Re} \tilde{\Omega}_\pi \iff D \ll \frac{M^2_S}{g^2 M^2_P} \]

\[ \text{Im} \tilde{\Omega}_\pi \]

\[ \text{D9/D5 (D3/D7)} \]

\[ \text{D3/D7 (D9/D5)} \]

\[ \text{D9/D5 (D3/D7)} \]

[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)

\[ \text{dF} + H = 0 \quad \Rightarrow \quad \int_\pi H = 0 \quad \Leftrightarrow \quad \delta W = 0 \]

BI \quad FW \text{ anomaly} \quad \text{gauge invariance}

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

In the presence of geometrical fluxes:

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

\[ \text{type-IIB: } \quad De^F = 0 \Rightarrow \omega F + H = 0 \Rightarrow \delta W = 0 \]
Extension to non-geometrical fluxes

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

\[ \overline{H}_{mn} \xrightarrow{T_r} \omega_{mn} \xrightarrow{T_n} Q_{mnr} \xrightarrow{T_m} R^{mnr} \]

[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:

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

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

Localized BI:

\[ R [\pi] = 0 \quad \int [\gamma] \wedge Q [\pi] = 0 \quad (\forall \gamma) \]
Extension to non-perturbative superpotentials

Non-perturbative effects (gaugino condensation, Euclidean brane instantons) generate exponential superpotentials $\Downarrow$ 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 $\implies$ 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.