# *Status of D6-brane Flux Models and their Effective Field Theories*

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# Outline

- Short introduction
- Mini-review on known type-IIA vacua
- Consistency constraints in compactifications
- Constructing the EFT
  - bulk sector
  - vector fields
  - chiral sector
- Leftover and conclusions

## *Renewed interests in type-IIA compactifications:*

- New 4d classical vacua *(more generic than in type-IIB and Heterotic cases)*
- Improvement in understanding of generalized geometries

  *(i.e. non CY compactifications with fluxes and torsion...)*
- $AdS_4/CFT_3$ in IIA/M-theory

  *(may provide non-perturbative description of IIA string in AdS backgrounds)*
- Intersecting brane model building – phenomenology

  *(easy geometrical construction of chiral gauge theories)*
- ...

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## *Final goal:*

*– Find a "reliable" string construction (aka vacuum) compatible with experiments –*

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– top-down

*(start from the strings, find vacuum, stab. moduli...)*

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less powerful from the phenomenology side and viceversa...

**key** – "try to find a good compromise":

derive an EFT from string theory *such that* it allows
to implement both the constraints and the corrections from string theory
*and*
to model a successful low energy description

# Mini-review on type-IIA *'classical'* known vacua I

- **<u>Susy $AdS_4$:</u>**
  - Many types:
    - Toroidal Orbifolds ($T^6/Z_2 x Z_2$, $T^6/Z_3 x Z_3$, ...);
    - Group manifolds ($S^3 x S^3$, twisted tori...);
    - Coset manifolds ($CP_3$, SU(3)/U(1)xU(1), ...);
    - ...
  - <u>All moduli stabilized;</u>
  - infinite number, with small $g_s$ large $V_6$;
  - good for AdS/CFT;
  - <u>not good for phenomenology;</u>

*GV, Zwirner, DeWolfe et al, Camara, Font, Ibanez...*

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- **<u>Non susy AdS$_4$:</u>**
  - (twisted)-Toroidal Orbifolds (+fluxes+sources);
  - <u>All moduli stabilized;</u>
  - <u>good for phenomenology</u> (uplifting with D-terms?, other F-terms?...);

*Camara, Font, Ibanez...*

*continue...*

# Mini-review on type-IIA *'classical'* known vacua II

*...continue*

- **Susy $\text{Mink}_4$:**
  - flat directions with geometrical fluxes;
  - All moduli fixed with non-geometrical fluxes?
  - large $V_6$ and small $g_s$? (*Micu, Palti, Tasinato '07*);
  - not good for phenomenology;

*Aldazabal et al.*

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- **<u>No-scale models:</u>**
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  - $\Omega$-dominated? ($J$-dominated? - non geom.)

*see e.g.*
*Derendinger et al.,...*
*Camara, Grana...*

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- **<u>dS4 vacua?</u>**
  - *Silverstein '07* (EFT?)

# From the compactification to the EFT

| | | |
|---|---|---|
| closed strings | $\longrightarrow$ | metric [ $g$ $(J,\Omega)$ ], dilaton [ $\Phi$ ], |
| | | [$B_{\text{NS}}$]-field, RR-fields [ $C^{(p)}$ ], ... |
| open strings | $\longrightarrow$ | D6-D6 gauge sector [ $A_\mu$, $Z^k$ ], |
| | | D6-D6' chiral sector [ $\phi^i$ ] |

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D6-D6' chiral sector [ $\phi^i$ ]

*N=1* 4d Effective SUGRA determined by:

- **Kahler function** $G(q,q^*) = K(q,q^*) + \log|W(q)|^2$
- **Gauge kinetic function** $f_{\mathrm{AB}}(q)$
- **Killing vectors** $X(q)$

Most of the 4d EFT can be derived from dim.red. from 10d SUGRA
EFT only partially known for generic background
Explicit formulae known for particular orbifolds

# Consistency Constraints

**RR-tadpole** $\Leftrightarrow$ RR Bianchi Id.

$$d_H G = Q_{\mathrm{RR}} \quad \Rightarrow \quad \omega\, G^{(2)} + H \wedge G^{(0)} = \Sigma\, [\pi_6]$$

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$d_H d_H = 0, \Rightarrow \omega\omega = 0,\ \omega H = 0$

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( + branes on branes)

*Freed, Witten,*
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Crucial for gauge (+susy) inv. of the EFT:

- classical: gauge inv. of *W*
- perturbative: cancellation of 1-loop anomalies
- non-perturbative: gauge inv. of instanton corrections

# 1. EFT for bulk fields

**Kahler potential:** $$K = -\log\left(\frac{1}{3!}\int J\wedge J\wedge J\right) - 2\,\log\left(\frac{1}{3!}\int \Omega'\wedge\overline{\Omega}'\right)$$

From dim. red. on $T^6/Z_2 x Z_2 \Rightarrow$

$$K = -\log(su_1u_2u_3) - \log(t_1t_2t_3) + \ldots$$ *(twisted sector)*

*see Lust, Reffert, Stieberger...*

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**Superpotential:**

$$W = \frac{1}{4}\int_{\mathcal{M}_6} e^{iJ^c}\left(\overline{\mathbf{G}} - i d_H \Omega'^c\right)$$

$$J^c \equiv J + i\,B\,, \qquad \Omega'^c \equiv \mathrm{Re}\,\Omega' + i\,C^{(3)}\,,$$

$$d_H \equiv d + \omega + \overline{H} \qquad \overline{\mathbf{G}} = \sum_{p=even} \overline{G}^{(p)}$$

D2 domain wall argument: $\Delta W \sim \int \Delta G^{(6)}$

*a la' Gukov Vafa Witten*

$$W = \int G^{(6)}$$

with $G^{(6)}$ complexification of the solution of $d_H G=0$

## **Gauge kinetic function:** (from DBI+WZ)

$$f_{ab} = \delta_{ab} N_a \left( \mathrm{Re}\, \Omega'_{\pi_a} + i \int_{\pi_a} C^{(3)} \right) = \delta_{ab} N_a\, \Omega'^{c}_{\pi_a}$$

From dim. red. on $T^6/Z_2 x Z_2 \Rightarrow$

$$f \,=\, N\, T_6\ \left( m_1 m_2 m_3 S - m_1 n_2 n_3 U_1 - n_1 m_2 n_3 U_2 - n_1 n_2 m_3 U_3 \right)$$

*Cremades, Ibanez, Marchesano '02*

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## **Killing vectors:** (of the gauging)

$$\begin{aligned} i\, X^S &= -2\, N\, \mu_6\, n_1\, n_2\, n_3 = -2\, N\, \mu_6\, q^0\,, \\ i\, X^{U_A} &= 2\, N\, \mu_6\, n_A\, m_B\, m_C = 2\, N\, \mu_6\, q^A\,, \end{aligned}$$

**D-terms:** (= $i\,K_a X^a$)

$$\operatorname{Im}\widetilde{\Omega}_\pi = \frac{\sqrt{s u_1 u_2 u_3}\; D}{N\, T_6}$$

$$D = N\,\mu_6\,\left(\frac{n_1 n_2 n_3}{s} - \sum_{A=1}^{3} \frac{n_A m_B m_C}{u_A}\right) = N\,\mu_6\,\left(\frac{q^0}{s} - \sum_{A=1}^{3} \frac{q^A}{u_A}\right)$$

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*...but from DBI reduction on generic configurations*

*Re f* = $N\,T_6 \sqrt{(\mathrm{Re}\,\widetilde{\Omega}_\pi)^2 + (\mathrm{Im}\,\widetilde{\Omega}_\pi)^2}$

$$V_D = \frac{1}{2}\frac{1}{N\,T_6\ \mathrm{Re}\,\widetilde{\Omega}_\pi}\,D^2\ \frac{2}{\sqrt{1+\left(\frac{\mathrm{Im}\,\widetilde{\Omega}_\pi}{\mathrm{Re}\,\widetilde{\Omega}_\pi}\right)^2}+1}$$

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*Right SUGRA results*
*only in the 2-der. limit*

i.e. $\left| \frac{\mathrm{Im}\,\widetilde{\Omega}_\pi}{\mathrm{Re}\,\widetilde{\Omega}_\pi} \right| \ll 1$

*GV, Zwirner '06*

lesson for anti-D-branes....

# 2. EFT for the D6-D6 sector

**Kahler potential:** *for arbitrary configuration of D6-branes*

From dim.red. of DBI action (*involving highly non-trivial field-redefinition*)

(assuming $S_{DBI} = \Sigma_k S_{DBI}(D6_k)$ from dim. red. on $T^6/Z_2 x Z_2$)

$$K = -\log\left[t_1 t_2 t_3 \left(s + \sum_{A=1}^{3} p_A^a \frac{z_A^{i_a\,2}}{t_A}\right) \prod_{A=1}^{3} \left(u_A - p_0^a \frac{z_A^{i_a\,2}}{t_A} + \sum_{B,C=1}^{3} d_{ABC}\, p_B^a \frac{z_C^{i_a\,2}}{t_C}\right)\right]$$

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up to quadratic fluctuations it gives:

$$K = -\log\left(t_1\, t_2\, t_3\, s\, u_1\, u_2\, u_3\right) + p_0^a \sum_{A=1}^{3} \frac{z_A^{i_a\,2}}{t_A\, u_A} - \sum_{A=1}^{3}\left(p_A^a \frac{z_A^{i_a\,2}}{s\, t_A} + \sum_{B,C=1}^{3} d_{ABC}\, p_B^a\, \frac{z_A^{i_a\,2}}{t_A\, u_C}\right) + \mathcal{O}(z^4)$$

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Notice that $z_A$=*Re* $Z_A$

i.e. there are Giudice-Masiero-like terms (like in Heterotic) good for $\mu$-terms

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In several cases these results seem not to agree with ours,
in particular $O(z^2)$ coefficients are not constant but proportional to

$$(m_A^2 + n_A^2)\sqrt{\frac{\Upsilon_B\,\Upsilon_C}{\Upsilon_A}} \qquad\qquad \Upsilon_A = \frac{m_A^{a\,2}}{u'_B u'_C} + \frac{n_A^{a\,2}}{s' u'_A}$$

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however they simplify (and agree with our results) when we notice that

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*these terms must be discarded for consistency*

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*these terms must be discarded for consistency*

*Notice also that mixed* $O(z^2 z^2)$ terms do not agree in the $N$=2 limit
with the prepotential proposed by
*Ferrara, Minasian, Sagnotti,... Antoniadis et al...*
connected with $\rho$-problem, see below...

## Superpotential:

from dim.red. + DBI fluctuations

agrees with the domain-wall argument: $W = \int G^{(6)}$

(with $G^{(6)}$ complexification of the solution of $d_H G = Q_{\mathrm{RR}}$)

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$$W = \frac{1}{4}\int_{\mathcal{M}_6} e^{iJ^c}\left(\overline{\mathbf{G}} - i d_H \Omega^c\right) + \frac{1}{4}\int_{\pi_a} \omega^c_{YM}$$

*unpublished with F.Zwirner '06*

$$\omega^c_{YM} = Z^{i_a} \wedge \omega Z^{i_a} + \frac{2}{3} i f_{i_a i_b i_c} Z^{i_a} \wedge Z^{i_b} \wedge Z^{i_c}$$

$$Z^{i_a} = \left[ Z_1^{i_a} \frac{n_1^a dx^5 + m_1^a dx^6}{\sqrt{(m_1^a)^2 + (n_1^a)^2}} + Z_2^{i_a} \frac{n_2^a dx^7 + m_2^a dx^8}{\sqrt{(m_2^a)^2 + (n_2^a)^2}} + Z_3^{i_a} \frac{n_3^a dx^9 + m_3^a dx^{10}}{\sqrt{(m_3^a)^2 + (n_3^a)^2}} \right]$$

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in agreement with *Martucci, Marchesano, Camara, Grana*

but valid also for susy-breaking and/or non-Mink vacua,

automatically holomorphic

## D-terms:

- D6-D6 sector uncharged under U(1) part

$$D_a = \frac{q_a^0}{s'} - \sum_{A=1}^{3} \frac{q_a^A}{u'_A} = \frac{q_a^0}{s + \sum_{A=1}^{3} p_A^a \frac{z_A^{i_a\,2}}{t_A}} - \sum_{A=1}^{3} \frac{q_a^A}{u_A - p_0^a \frac{z_A^{i_a\,2}}{t_A} + \sum_{B,C=1}^{3} d_{ABC}\, p_B^a \frac{z_C^{i_a\,2}}{t_C}}$$

- Only non-abelian D-term

$$D_{i_a} = iK_{Z_A^{i_b}} (X_{i_a})_A^{i_b} = Q_A^a \; f_{i_a\, j_a\, k_a} \; \frac{z_A^{j_a} \, \zeta_A^{k_c}}{t_A}$$

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- D6-D6 sector uncharged under U(1) part

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$$f_a \propto \Omega'^{c}_{\pi_a} = \Omega^c_{\pi_a} + \sum_b \int_{\pi_a} Z^{i_b} \phi^{i_b}[\pi_b] = \Omega^c_{\pi_a} + \sum_b (non \;\; hol.) \times I_{ab}$$

dual to the type-IIB "*ρ–problem*":

- *solution 1:* (*Berg, Haack, Kors '04*) – 1-loop from open strings (see *Akerblom et al. '07 for IIA)*
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*Conclusions:*

EFT is known up to quadratic fluctuations,

higher-power terms only partially known, not under control...

# 3. EFT for the D6-D6' sector

(not from supergravity)

**Kahler potential:** from string amplitudes (*Lust et al... Bertolini et al...*)

$$K_{ij}^{ab} = \delta_{ij}\, S^{-\alpha} \prod_{I=1}^{3} U_I^{-(\beta+\xi\,\theta_{ab}^I)}\ T_I^{-(\gamma+\zeta\,\theta_{ab}^I)} \sqrt{\frac{\Gamma(\theta_{ab}^1)\Gamma(\theta_{ab}^2)\Gamma(1+\theta_{ab}^3)}{\Gamma(1-\theta_{ab}^1)\Gamma(1-\theta_{ab}^2)\Gamma(-\theta_{ab}^3)}},$$

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**Superpotential:**

$$W = Y_{ijk}\,\phi^i\phi^j\phi^k + \mu_{1ijk}\,\phi^i\phi^j Z^k + \mu_{2ij}\,\phi^i\phi^j + \ldots$$

$Y_{ijk}$ from w.s. instantons,
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$$Y_{ijk} = h_{qu}\sigma_{abc} \prod_{r=1}^{n} \vartheta \begin{bmatrix} \delta^{(r)} \\ \phi^{(r)} \end{bmatrix} (\kappa^{(r)})$$

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**Killing vectors:** known (gauge transformation properties of chiral fields)
**Gauge kinetic functions:** (corrections are higher order, from threshold....)

# Extra interesting ingredients:

- *KK5-monopoles:*
  - $\omega\,\omega \neq 0$ *(alternative description of twisted sector, stabilization, ...)*
  - Phenomenology *(N=1 configurations)*
    - dual to D6-branes
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- *Other important subjects not discussed here:*
  - $\alpha'$, $g_s$ corrections to EFT (threshold corrections...);
  - Non-perturbative corrections (E2-instantons...);
  - Inflation...

# Conclusions:

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*Next step – Start putting everything together....*