Brane SUSY and brane SUSY breaking

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(Short) Reviews:

I. Antoniadis, hep-th/9909212

I. Antoniadis and A.S., hep-th/9911205

A.S., hep-th/0001077

E. Dudas, hep-th/0006...

Plan

1. SUSY breaking and String Theory.

2. Scherk-Schwarz deformations and “brane SUSY”.

3. Klein bottle projections and “Brane SUSY breaking”.

4. Fradkin-Tseytlin magnetic deformations.

- **SUSY breaking:** a **very difficult** issue.

  a. SUSY: **space-time symmetry**, tied to gravity.

  b. [**Available models:** Lorentz-invariant breaking.]

  c. In **Field Theory**: SUSY breaking at scale Λ_s gives rise to a **vacuum energy** $V \sim (\Lambda_s)^4$.

Vacuum energy: not Minkowski

- In **String Theory**, can only study fluctuations of (Minkowski $\times$ Internal) backgrounds. SUSY breaking **alters** the background.

  Thus, **all** current studies of SUSY breaking are at best incomplete.

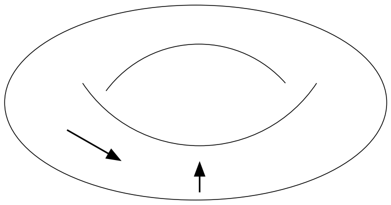
- Still, **instructive** to explore String Theory.

- **Open strings:** new possibilities.

SUSY breaking and type I strings

- **Closed strings:** one can induce **SUSY breaking** consistently on the whole string spectrum.

- **Modular invariance**
  (Gliozzi, Scherk, Olive, 1977; ...)



a. **Type-0 models**: SUSY broken in bulk.
(Dixon and Harvey, 1985; Seiberg and Witten, 1985)

- First **open descendants**: chiral but tachyonic.
  (Bianchi and A.S., 1990)

- **Non-tachyonic** descendants: **0B'**
  (A.S., 1995)

- **"Stable"** compactifications
  (Angelantonj, 1998; Blumenhagen, Font, Lüst, 1999)

- **Applications** to AdS/CFT
  (Klebanov, Tseytlin, 1998; Angelantonj, Armoni, 1999)

SUSY breaking and type I strings

- **Stable non-BPS** brane configurations.

  (Sen, 1998; ...)

- **Links** with the other SUSY strings?

  (Bergman and Gaberdiel, 1998)

b. **Scherk-Schwarz deformations**

(Scherk and Schwarz, 1979)

Example of S-S: in an internal circle, **periodic** bosons and **antiperiodic** fermions.

$$M_B \sim \frac{k}{R} \qquad M_F \sim \frac{k+1/2}{R}$$

- **SUSY recovered** in the decompactification limit.

- First **vacuum energy** correction: one loop.

- Related to (gaugings of) supergravity.

  (Cremmer et al, 1978, 1984)

  (Cremmer, Ferrara, Girardello, van Proeyen, 1982)

Scherk-Schwarz in closed strings:

$D = 9$

(Rohm, 1984)

(Ferrara, Kounnas, Porrati, Zwirner, 1989)

1. $SO(8)$ level-one characters: $(q = e^{2\pi i \tau})$

$$O_8 = \frac{\vartheta_3^4 + \vartheta_4^4}{2\eta^4} \qquad V_8 = \frac{\vartheta_3^4 - \vartheta_4^4}{2\eta^4}$$

$$S_8 = \frac{\vartheta_2^4 + \vartheta_1^4}{2\eta^4} \qquad C_8 = \frac{\vartheta_2^4 - \vartheta_1^4}{2\eta^4}$$

2. Type-IIB 10D superstring:

$$\mathcal{T} = |V_8 - S_8|^2$$

3. Circle reduction and lattice sums:

$$p_L = \frac{m}{R} + \frac{nR}{\alpha'} \quad , \quad p_R = \frac{m}{R} - \frac{nR}{\alpha'}$$

$$Z_{mn} \equiv \sum_{m,n} \frac{q^{\alpha' p_L^2/4} \; \bar{q}^{\alpha' p_R^2/4}}{\eta \bar{\eta}}$$

4. Circle reduction of type-IIB to D=9:

$$\mathcal{T} = Z_{mn} |V_8 - S_8|^2$$

Scherk-Schwarz in closed strings: $D = 9$

1. Scherk-Schwarz breaking from **momentum shifts**:

$$\mathcal{T}_1 = Z_{m,2n}(V_8\bar{V}_8 + S_8\bar{S}_8) + Z_{m,2n+1}(O_8\bar{O}_8 + C_8\bar{C}_8) - Z_{m+1/2,2n}(V_8\bar{S}_8 + S_8\bar{V}_8) - Z_{m+1/2,2n+1}(O_8\bar{C}_8 + C_8\bar{O}_8)$$

- Notice: **tachyon instability** for $R \leq \sqrt{\alpha'}$.

  Must be consistent in the **large-radius limit**.

2. Scherk-Schwarz breaking from **winding shifts**:

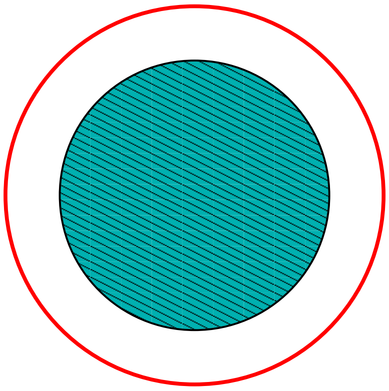
$$\mathcal{T}_2 = Z_{2m,n}(V_8\bar{V}_8 + S_8\bar{S}_8) + Z_{2m+1,n}(O_8\bar{O}_8 + C_8\bar{C}_8) - Z_{2m,n+1/2}(V_8\bar{S}_8 + S_8\bar{V}_8) - Z_{2m+1,n+1/2}(O_8\bar{C}_8 + C_8\bar{O}_8)$$

- Notice: **tachyon instability** for $R \geq \sqrt{\alpha'}$.

  Must be consistent in the **small-radius limit**.

- **What** can one deform, **momenta** or **windings**?

$$X(\sigma,\tau) = x + (2\alpha')\frac{m}{R}\tau + 2nR\sigma + \ldots$$



- **T-duality:** for **closed** strings the two are equivalent (aside from some action on the R-R fields: $IIA \leftrightarrow IIB$ and ($\leftrightarrow$) "heterotics").

(Ginsparg, 1987)

- For **open** strings **T-duality** is more subtle.

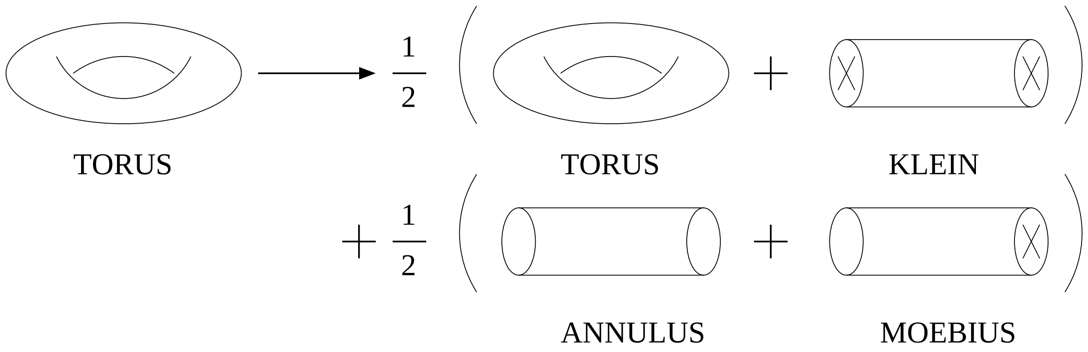
(Horava, 1989)

(Dai, Leigh, Polchinski, 1989)

- **Type I strings** are **more complicated**: they include both unoriented **closed** and **open** strings.

SUSY breaking and type I strings

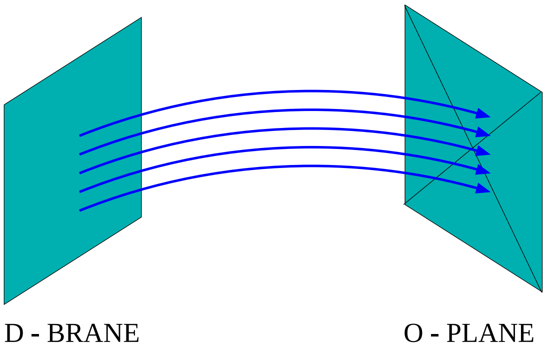
- **Type I:** can be **derived systematically** from "parent" oriented closed strings (**"parameter-space orbifolds"**, or **"orientifolds"**).



(A.S., 1987)
(Angelantonj, Bianchi, Pradisi, Stanev, 1987-1996)
(.., Harvey, Minahan, Bern, Dunbar, Horava, ..)
(Cardy, Ishibashi, Lewellen, .., Fuchs, Schweigert, ..)

- Vacuum configurations of **gravity** (with its "frozen modes") in the presence of suitable sets of **D branes** (and "orientifolds").

(Green, 1994 ; Polchinski, 1995 ; Bachas, 1995; ...)



SUSY breaking and type I strings

- These **branes** can in principle be the arena for our **low-energy physics**:

  (Brane) KALUZA-KLEIN: gravity invades extra dimensions, while some fields are **confined to branes** floating in the internal space.

- **Why is this interesting?**

  a. **For oriented closed strings:** Scherk-Schwarz breakings are O(1/R).

  (Antoniadis, Bachas, Lewellen, Tomaras, 1988)

  b. Low scale SUSY breaking → **large extra dimensions** → **Kaluza-Klein excitations**.

- In **conventional** Kaluza-Klein, as in the **heterotic** string, the string scale $l_H \sim 1/E_{Pl}$ and then $g_H \sim V_H/l_H^6$.

- In other words, the string description **breaks down** in the limit of **large** extra dimensions.

  (Antoniadis, 1990)

SUSY breaking and type I strings

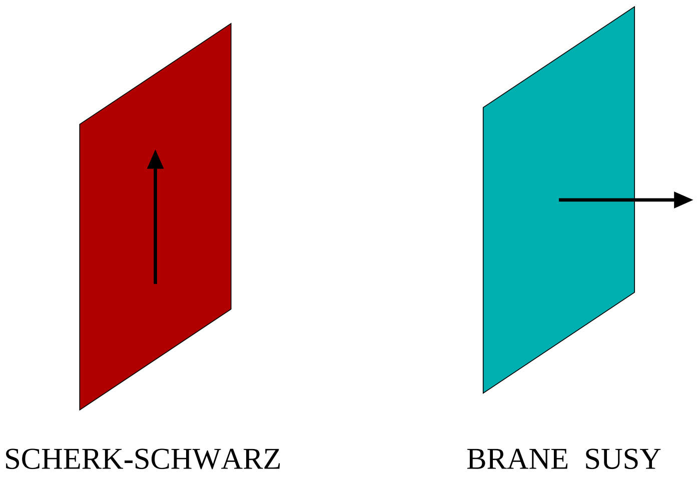
- In **"brane Kaluza-Klein"** the fields living on a brane do not "feel" the extra dimensions.

- [Are the extra dimensions **compact**?]
  (Randall and Sundrum, 1999)

- **Inequivalent Scherk-Schwarz deformations**:

  a. **Parallel** to a brane.

  b. **Orthogonal** to a brane: **BRANE SUSY**
  (Antoniadis, Dudas, A.S., 1998; + D'Appollonio, 1999)



b: **Entire SUSY towers** of string excitations.
(Blumenhagen, Görlich; Angelantonj, Antoniadis, Förger)

b: Expect $O(M_s^2/M_{Pl})$, rather than $O(M_s)$ **splittings**.

Scherk-Schwarz breaking and open strings

D=9

1. **For model 1 (momentum shifts):**

$$
\begin{aligned}
\mathcal{K}_1 &= \frac{1}{2}\,(V_8 - S_8)\ Z_m \\
\mathcal{A}_1 &= \frac{n_1^2+n_2^2}{2}(V_8 Z_m - S_8 Z_{m+1/2}) \\
&+ \ n_1 n_2 (V_8 Z_{m+1/2} - S_8 Z_m) \\
\mathcal{M}_1 &= -\frac{n_1+n_2}{2}(\hat{V}_8 Z_m - \hat{S}_8 Z_{m+1/2})
\end{aligned}
$$

- **The tadpole conditions** require:

$$n_1 + n_2 = 32$$

- **SUSY is recovered** in the limit $R \to \infty$. The vacuum channel contains **winding modes**, that become more and more spaced in the limit $R \to \infty$.

- As in the closed spectrum, for large R bosons and fermions have **mass splittings** $O(1/R)$.

Scherk-Schwarz breaking and open strings

D=9

2. **For model 2 (winding shifts)**, after imposing the **tadpole conditions** ($n_1 + n_2 = n_3 + n_4 = 16$):

$$
\begin{aligned}
\mathcal{K}_2 &= \frac{1}{2}\,(V_8 - S_8)\;Z_{2m} + \frac{1}{2}\,(O_8 - C_8)\;Z_{2m+1} \\
\mathcal{A}_2 &= \left[\frac{n_1^2 + {n_2}^2 + {n_3}^2 + n_4^2}{2}(V_8 - S_8)\right. \\
&+ \left.(n_1 n_3 + n_2 n_4)(O_8 - C_8)\right] Z_m \\
&+ \left[(n_1 n_2 + n_3 n_4)(V_8 - S_8)\right. \\
&+ \left.(n_1 n_4 + n_2 n_3)(O_8 - C_8)\right] Z_{m+1/2} \\
\mathcal{M}_2 &= -\frac{n_1 + n_2 + n_3 + n_4}{2}\hat{V}_8 Z_m \\
&+ \frac{n_1 - n_2 - n_3 + n_4}{2}\hat{S}_8 (-1)^m Z_m
\end{aligned}
$$

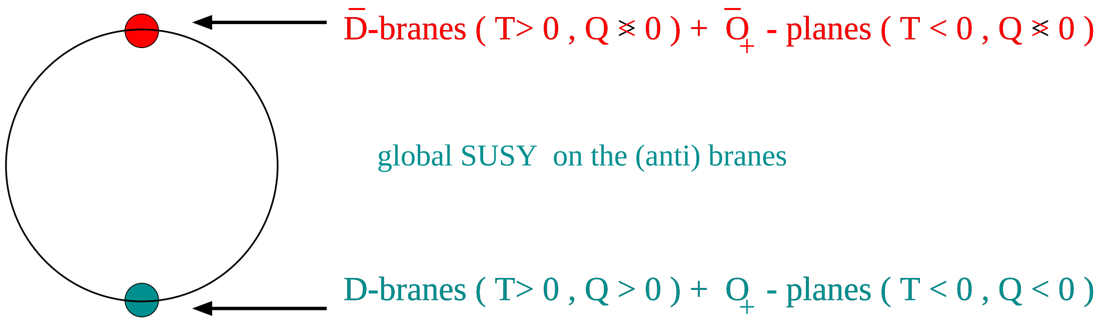
- **However:** as $R \to 0$ **new** tadpoles appear (**collapsing winding modes**): $n_2 = n_3 = 0$.
  (Polchinski and Witten, 1995)

- **Massless SUSY** and gauge group $SO(16) \times SO(16)$. **Full recovery** as $R \to 0$.

- For $n_2 = n_3 = 0$:

$$
\begin{aligned}
\mathcal{A}_2 &= \frac{n_1^2 + n_4^2}{2}(V_8 - S_8) + n_1 n_4 (O_8 - C_8) Z_{m+1/2} \\
\mathcal{M}_2 &= -\frac{n_1 + n_4}{2}\hat{V}_8 Z_m + \frac{n_1 + n_4}{2}\hat{S}_8 (-1)^m Z_m
\end{aligned}
$$

- Can we understand this in **pictorial** terms? **YES**



- Neatly displayed by **transverse-channel**.

- **Basic tool**: express the (even) winding sums in $\tilde{\mathcal{K}}$ via projectors. For instance:

$$
\sum_n q^{\frac{(2nR)^2}{4\alpha'}} = \sum_n q^{\frac{(nR)^2}{4\alpha'}} \, \frac{1 + (-1)^n}{2}
$$

(Dudas, 2000)

Winding shifts: M-theory breaking D=9

- **Momentum shifts:** a rather conventional open spectrum. SUSY splittings $\sim 1/R$ at all levels.

- **Winding shifts:** Chan-Paton unpairing at alternate levels. **SUSY for massless modes**:

"Brane Supersymmetry"

Can we understand this better?

- **11D Scherk-Schwarz deformations**

(Antoniadis and Quiros, 1997)

(Dudas and Grojean, 1997)

- Can connect D=9 heterotic and type I by a sequence of dualities.

(Horava and Witten, 1996)

- **11D momentum** shifts $\rightarrow$ type I **winding** shifts.

Comparing 9D BPS states:

- **K-K and membrane wrapping masses** in M theory, type I, heterotic $SO(32)$ and heterotic $E_8 \times E_8$:

$$
\begin{aligned}
M^2 &= \frac{l^2}{R_{11}^2} + \frac{m^2}{R_{10}^2} + n^2 R_{10}^2 R_{11}^2 M_{11}^6 \\
M_I^2 &= l^2 R_I^2 M_I^4 + \frac{m^2 R_I^2 M_I^4}{g_I{}^2} + \frac{n^2}{R_I^2} \\
M_{E_8}^2 &= \frac{l^2 M_H^2}{g_{E_8}{}^2} + \frac{m^2}{R_{E_8}^2} + n^2 R_{E_8}^2 M_H^4 \\
M_H^2 &= l^2 \frac{R_H^2 M_H^4}{g_H{}^2} + m^2 R_H^2 M_H^4 + \frac{n^2}{R_H^2}
\end{aligned}
$$

- **Scherk-Schwarz shifts** along 11th dimension:

$$l \to l + s$$

- **Perturbative in type I.**

- **Non-perturbative in heterotic strings.**

- **In type I $\to$ winding shifts.**

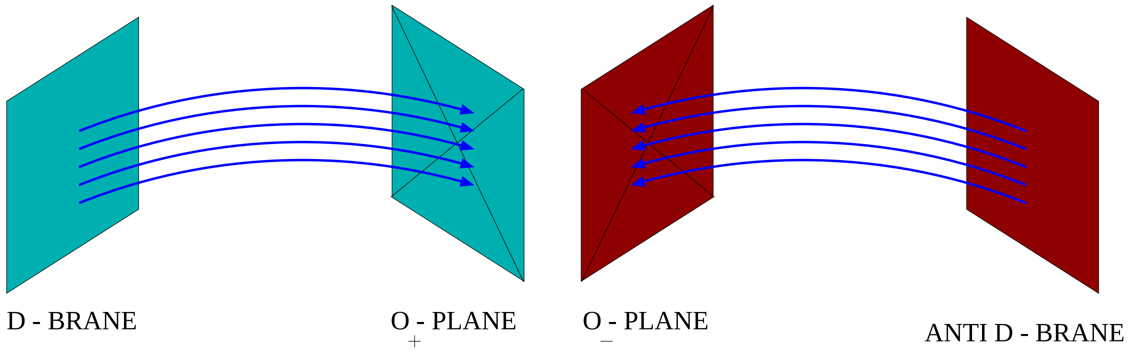
- **Another remarkable possibility :**

BRANE SUSY BREAKING

(Sugimoto, 1999 ; Antoniadis, Dudas, A.S., 1999)
(+ Angelantonj, D'Appollonio)
(Aldazabal, Uranga, 1999, + Ibanez, Quevedo, 1999)

- The (closed) projection can introduce **O_--planes**, that **can only absorb the charge of antibranes**.

- **Branes** + **antibranes** = **SUSY breaking**.



- This solves **old "puzzles"** in type I constructions.
(Bianchi, Ph.D. Thesis; A.S., 1993; Zwart, 1998 ...)

- More **brane-antibrane "dipoles"**.

- Are such systems **stable**?
(Angelantonj, Blumenhagen, Gaberdiel, 2000)

Brane supersymmetry breaking

- In some SUSY models some tadpole conditions are **problematic**.

1. 4D $Z_2 \times Z_2$ with **discrete torsion** ($\prod_i \epsilon_i = \epsilon$):

$$\mathcal{K}=\frac{1}{8}\Big\{(P_1P_2P_3 + P_1W_2W_3 + W_1P_2W_3 + W_1W_2P_3)T_{oo}$$
$$+2\big[\epsilon_1(P_1+\epsilon W_1)T_{go}+\epsilon_2(P_2+\epsilon W_2)T_{fo}+\epsilon_3(P_3+\epsilon W_3)T_{ho}\big]\Big\}$$

$$\tilde{\mathcal{K}}_0=\frac{2^5}{8}\Bigg\{\left(\sqrt{v_1v_2v_3}+\epsilon_1\sqrt{\frac{v_1}{v_2v_3}}+\epsilon_2\sqrt{\frac{v_2}{v_1v_3}}+\epsilon_3\sqrt{\frac{v_3}{v_1v_2}}\right)^2\tau_{oo}$$
$$+\left(\sqrt{v_1v_2v_3}+\epsilon_1\sqrt{\frac{v_1}{v_2v_3}}-\epsilon_2\sqrt{\frac{v_2}{v_1v_3}}-\epsilon_3\sqrt{\frac{v_3}{v_1v_2}}\right)^2\tau_{og}$$
$$+\left(\sqrt{v_1v_2v_3}-\epsilon_1\sqrt{\frac{v_1}{v_2v_3}}+\epsilon_2\sqrt{\frac{v_2}{v_1v_3}}-\epsilon_3\sqrt{\frac{v_3}{v_1v_2}}\right)^2\tau_{of}$$
$$+\left(\sqrt{v_1v_2v_3}-\epsilon_1\sqrt{\frac{v_1}{v_2v_3}}-\epsilon_2\sqrt{\frac{v_2}{v_1v_3}}+\epsilon_3\sqrt{\frac{v_3}{v_1v_2}}\right)^2\tau_{oh}\Bigg\}$$

2. **Simpler example:** 6D T^4/Z_2 with "exotic" Klein.

- R-R tadpoles unpair NS and R : **anti-branes**.
- Anomaly free. **SUSY broken on branes**, $V > 0$.

$$\begin{aligned}\mathcal{T} &= \frac{1}{2}|Q_o+Q_v|^2\Lambda+\frac{1}{2}|Q_o-Q_v|^2\left|\frac{2\eta}{\theta_2}\right|^4\\ &+ \frac{1}{2}|Q_s+Q_c|^2\left|\frac{2\eta}{\theta_4}\right|^4+\frac{1}{2}|Q_s-Q_c|^2\left|\frac{2\eta}{\theta_3}\right|^4\end{aligned}$$

$$\begin{aligned}Q_o &= V_4O_4-C_4C_4 \quad , \quad Q_v=O_4V_4-S_4S_4\\ Q_s &= O_4C_4-S_4O_4 \quad , \quad Q_c=V_4S_4-C_4V_4\end{aligned}$$

$$\mathcal{K}=\frac{1}{4}\Big\{(Q_o+Q_v)(P+W)+2\ \epsilon\times 16(Q_s+Q_c)\Big\}$$

1. $\epsilon=1$ (without B_{ab}): **1 tensor multiplet**.

- **(1,0) SUSY** with $U(16)_9\times U(16)_5$.

(Bianchi and A.S., 1990)
(Gimon and Polchinski, 1996)

2. $\epsilon=-1$ (without B_{ab}): **17 tensor multiplets**

$$\tilde{\mathcal{K}}_0=\frac{2^5}{4}\left\{Q_o\left(\sqrt{v}+\epsilon\frac{1}{\sqrt{v}}\right)^2+Q_v\left(\sqrt{v}-\epsilon\frac{1}{\sqrt{v}}\right)^2\right\}$$

- **$D9$ and $D\bar{5}$:** **non SUSY**, chiral, tachyon-free.

- $[SO(16)\times SO(16)]_9\times[USp(16)\times USp(16)]_{\bar{5}}$.

(Antoniadis, Dudas, A.S., 1999)

Fradkin-Tseytlin magnetic deformations

- One can also introduce **magnetic deformations**.

  (Fradkin and Tseytlin, 1985)

- A beautiful result: **Born-Infeld action**.

- A suggestion of the role of **string solitons**.

$$S = \frac{1}{g_s\,(2\pi)^p\,\alpha'^{\frac{p+1}{2}}} \int d^{p+1}x\,\sqrt{-\det\left(g + 2\pi\alpha' F\right)}$$

- **Canonical formalism:** role of Landau levels.

  (Abouelsaood, Callan, Nappi and Yost, 1986)

- **Magnetized tori**: **chirality** and broken SUSY from **non-chiral extended SUSY** via magnetic moments.

  (Witten, 1984 ; Bachas, 1995)

- **Nielsen-Olesen instabilities:** symmetry breaking.

Fradkin-Tseytlin magnetic deformations

- **New effects in open-string vacua.**

- An interesting **6D example**:
$(T^2 \times T^2)/Z_2$ with **aligned** (H_1, H_2) in the two T^2's.
(Angelantonj, Antoniadis, Dudas, A.S., 2000)

- Start from U(16) × U(16) (or from "brane SUSY breaking" O(16) × O(16) × USp(16) × USp(16)).

- **Dilaton tadpole** → **Born-Infeld**:

$$\tilde{\mathcal{A}} \to \sqrt{(1 + \frac{\pi^2 H_1^2}{4})(1 + \frac{\pi^2 H_2^2}{4})}$$

- **Internal metric tadpole** → **Born-Infeld**:

$$\tilde{\mathcal{A}} \quad \to \quad \sqrt{(1 + \frac{\pi^2 H_1^2}{4})} \, \frac{1 - \frac{\pi^2 H_2^2}{4}}{\sqrt{(1 + \frac{\pi^2 H_2^2}{4})}} \quad =$$

$$= \frac{d}{dy} \left\{ \sqrt{(1 + \frac{\pi^2 H_1^2}{4})} \, \sqrt{(y^2 + \frac{\pi^2 H_2^2}{4 y^2})} \right\} \Bigg|_{y=1}$$

Fradkin-Tseytlin magnetic deformations

- **R-R tadpoles: a magnetic D9 mimics a D5**.

- An amusing application of the **WZ coupling**:

$$S \sim \int_{\Sigma_{p+1}} \mathrm{tr} e^{iF} \wedge C \wedge \ldots$$

(Green, Harvey and Moore, 1996)

- Gravitational part plays a role in **orbifold projections** of open descendants.

- [**No tachyons** and **SUSY** for certain backgrounds.]

- New consistent **anomaly-free** spectra in a Z_2 orbifold with **only D9-branes**.

  e.g. **one tensor multiplet** and U(12) × U(4) with **SUSY massless matter** in:

$$(66 + \overline{66}, 1) + 5 \times (1, 6 + \overline{6}) + 4 \times (12, \overline{4})$$

- More examples in 6D and 4D ...