

Implications of D-instantons:

Hierarchical Non-Perturbative Superpotential Couplings

Ralph Blumenhagen, M.C., Timo Weigand, hep-th/0609191

original paper

M.C., Robert Richter, T. Weigand, hep-th/0703028 CFT calculation

R. Blumenhagen, M.C., D. Lüst, R. Richter, T. Weigand, 0707.1871

(PRL) $10^{10} 10^5$ GUT coupling

M.C., P. Langacker, 0803.253 Dirac neutrino masses

M.C., T. Weigand, 0711.0209 (PRL), 0807.3953 & work in

progress first global semi-realistic models/SUSY breaking

[R. Blumenhagen, M.C., R. Richter, T. Weigand, 0708.0403

multi-instantons & recombination

M.C., R. Richter, T. Weigand, 0803.138 N=1 multi-BPS instantons]

Motivation

- Large classes of perturbatively constructed four-dimensional $N=1$ supersymmetric vacua
→ Major activity w/ Intersecting D6-brane (Type IIA) constructions: semi-realistic, supersymmetric three-family Standard Models and $SU(5)$ GUT models
 - Question: How non-perturbative effects modify features of perturbative string vacua ?
→ Focus on Type IIA Euclidean D-instanton effects: Euclidean D2 [E2]-instantons; W -superpotential corrections
- [In the last part: Type I (IIB) global constructions (magnetized D9 branes) with E1 instantons]

D-brane instantons may generate perturbatively absent couplings with new hierarchical scales, suppressed by $\exp(-g_s^{-1})$

→ Implications:

Hierarchical couplings in the supersymmetric Standard Model

- Small Neutrino masses:

- (i) seesaw: Majorana masses $10^{11} \text{ GeV} < M_M < 10^{15} \text{ GeV}$;

- (ii) small Dirac masses 10^{-3} eV

- Hierarchically small μ -terms of order $\mathcal{O}(\text{TeV})$

- Highly suppressed R -parity violating couplings

- Top $\mathcal{O}(100 \text{ GeV})$ – bottom $\mathcal{O}(10 \text{ GeV})$ mass hierarchy

- Hierarchically suppressed supersymmetry breaking

Extensive past literature on instantons in string theory ...

New string instanton effects in (open string) charged sector:

[Blumenhagen, M.C., Weigand, hep-th/0609191]

[Ibañez, Uranga hep-th/0609213]

- charged matter coupling corrections

[Florea, Kachru, McGreevy, Saulina 0610003]

- supersymmetry breaking

Further developments: many papers...

Outline

1. Motivation - done!
2. Focus on Type IIA: Euclidean D2-brane –focus on superpotential corrections due to $O(1)$ D-instantons
 - Zero mode structure
 - CFT instanton calculus-just results
3. Specific applications:
 - Small neutrino masses
 - (i) Majorana masses - local construction & explicit CFT calc.
 - (ii) Dirac neutrino masses due to D-instantons
 - Other couplings: 10105_H of $SU(5)$ GUT, μ of MSSM, Polonyi-type supersymmetry breaking
 - all local set-ups
4. Further developments: First semi-realistic global examples

Model Building with Intersecting D6-branes

Engineering of semi-realistic constructions – Standard Model:

- Non-Abelian gauge symmetry
 $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Chiral matter quarks & leptons
- Family replication 3-copies of fermion families



Non-abelian symmetry, chiral matter & family replication GEOMETRIC!

Status

- $\mathcal{O}(100)$ toroidal orbifold SM& GUT models (geometric phase) with semi-realistic features
 - typically suffer from chiral exotics
 - realistic Yukawa couplings?
 - moduli stabilization ?

though more promising models are being constructed... c.f. Antoniadis' talk...

- Rational Conformal Field Theory constructions-promising

[Schellekens et al.] :

- models without chiral exotics
- couplings in principle calculated, but hard & hierarchy?
- non-geometric phase-moduli stabilization?

- Exciting progress; (local) F-theory GUT's/SM's...

[Donagi, Wijnholt 0802.2969], [Beasley, Heckman, Vafa 0802.3391] ...

c.f. Heckman's, Wijnholt's... talks

Specific coupling issues:

- Neutrino masses (if there) -Dirac & of order of charged sector masses

Majorana neutrino masses – absent

- μ -parameter – typically absent
- SU(5) GUT models – absent $10 10 5_H$ -couplings

[no top (bottom) mass for GUT SU(5) (flipped SU(5))]

- Hierarchical supersymmetry breaking, e.g., à la Polonyi

Perturbative absence of all such couplings due to violation of “anomalous” U(1)

→ Turn to non-perturbative effects & non-perturbative violation of anomalous U(1)

Instantons–Heuristics

Probe for non-pert. terms by computing suitable amplitudes in D-instanton background.

Euclidean Dp -brane wrapping internal $(p + 1)$ -cycle

→ for Type IIA relevant objects are **Euclidean $D2$ -branes (E2-branes)**, wrapping three-cycles

Rules:

- Instanton sector corresponds to **local minimum of (full) string action**

→ $E2$ -brane volume minimizing on internal sLag Ξ

- Integrate over zero modes localized on $E2$

→ **All fermionic zero modes** have to **appear for relevant instanton induced couplings exactly once**

Massive $U(1)$ and Axion gauging

Gauge group $\prod_a U(N_a) = \prod_a SU(N_a) \times U(1)_a$

In general $U(1)_a$ becomes massive via Chern-Simons terms:

$$S_{WS} = \sum_a N_a \mu_q \int_{\mathbb{R}^{1,3} \times \Pi_{q-3}^a} e^{tr F_a} \sum_p C_p$$

CS-coupling induces gauging of global axionic shift symmetry for axion from RR-form C_{p+1} reduced on $(p+1)$ -cycle $\tilde{\Pi}_{p+1}$:

$$\begin{aligned} A_a &\longrightarrow A_a + d\Lambda_a \\ \int_{\tilde{\Pi}_{p+1}} C^{(p+1)} &\longrightarrow \int_{\tilde{\Pi}_{p+1}} C^{(p+1)} + Q_a(\tilde{\Pi})\Lambda_a \end{aligned}$$

$$Q_a(\tilde{\Pi}_{p+1}) \simeq N_a \int_{\mathcal{M}_6} \delta(\tilde{\Pi}_{p+1}) \wedge \delta(\Pi_{q-3}^a) \wedge e^{F_a} \quad (p = 2, q = 6)$$

Effects of axion gauging for D-instantons:

Euclidean D_p -brane on internal $p + 1$ -cycle Ξ ($p=2$
E2-instanton)

$$W_{np} \propto e^{-S_{Ep}} = \exp \left[\frac{2\pi}{\ell_s^{p+1}} \left(-\frac{1}{g_s} \int_{\Xi} \text{Vol}_{\Xi} + i \int_{\Xi} C_{p+1} \right) \right]$$

exponential not gauge invariant under $U(1)_a$!

$$e^{-S_{Ep}} \rightarrow e^{i Q_a(Ep) \Lambda_a} e^{-S_{Ep}}: Q_a = N_a \int \delta(\Xi) \wedge \delta(\Pi_{q-3}^a) \wedge e^{F_a}$$

Consequence:

If $Q_a(Ep) \neq 0$ for some a , no terms $W = e^{-S_{Ep}}$ possible, but:

$$W = \prod_i \Phi_i e^{-S_{Ep}} \quad \text{with} \quad \sum_i Q(\Phi_i) + Q_a(Ep) = 0 \quad \forall a$$

Non-perturbative breakdown of global $U(1)$ symmetry possible.

Zero mode structure - Summary

Distinguish 2 types of zero modes:

(i) uncharged (E2-E2 sector)

(ii) charged (E2-D6 sector) under $U(1)_a$:

(i) Zero modes uncharged under $U(1)_a$ for O(1)-instantons:

4 bosonic modes $x_E^i \leftrightarrow$ Poincaré inv. in 4D &

only 2 fermionic modes: θ_α

Ensured for: $E2 = E2'$ (homologically), E2-wrap rigid
3-cycles Ξ , i.e. absence of additional zero modes.

→ yields correct superpot. measure: $\int d^4x_E d^2\theta$

Other (multi-)instanton superpotential contributions

multi-instantons & recombination, zero-mode lifting due to fluxes...

[Blumenhagen, MC, Richter, Weigand 0708.0403], [Garcia-Etxebarria, Uranga

0711.1430], [MC, Richter, Weigand 0803.2513],

[Garcia-Etxebarria, Marchesano, Uranga 0805.0713], [Buican, Franco

0806.1964]... c.f. Franco's, Kachru's... talks

(ii) Charged Zero modes (strings between $E2$ and $D6_a$):

→ Localized at the each intersection of $E2$ and $D6_a$ branes:

One fermionic zero mode λ_a per inters. Geometric!

zero modes	Reps.	number
$\lambda_{a,I}$	$(-1_E, \square_a)$	$I = 1, \dots, [\Xi \cap \Pi_a]^+$
$\bar{\lambda}_{a,I}$	$(1_E, \bar{\square}_a)$	$I = 1, \dots, [\Xi \cap \Pi_a]^-$
$\lambda_{a',I}$	$(-1_E, \bar{\square}_a)$	$I = 1, \dots, [\Xi \cap \Pi'_a]^+$
$\bar{\lambda}_{a',I}$	$(1_E, \square_a)$	$I = 1, \dots, [\Xi \cap \Pi'_a]^-$

total $U(1)_a$ charge of all zero modes:

$$Q_a(E2) = N_a \Xi \circ (\Pi_a - \Pi'_a)$$

in agreement with $e^{-S_{E2}} \rightarrow e^{i Q_a(E2) \Lambda_a} e^{-S_{E2}}$

Contributions to Matter Couplings

In presence of disk-level couplings to matter fields of type

$S = \int_{\Xi} \lambda_a \Phi_{ab} \bar{\lambda}_b$ in instanton effective action

$$\int d^4x d^2\theta d\lambda_a d\bar{\lambda}_b e^{-S_{cl} + \int_{\Xi} \lambda_a \Phi_{ab} \bar{\lambda}_b} \rightsquigarrow \phi_{ab} e^{-S_{cl}}.$$

Details of calculus, including prescription for loop contribution in [Blumenhagen, M.C., Weigand hep-th/0609191]

Instanton calculus - Summary

[Blumenhagen, M.C., Weigand hep-th/0609191]

$$\begin{aligned}
 & \langle \Phi_{a_1, b_1}(p_1) \cdot \dots \cdot \Phi_{a_M, b_M}(p_M) \rangle_{Ep\text{-inst}} = \\
 & = \int d^4 \tilde{x} d^2 \tilde{\theta} \sum_{\text{conf.}} \prod_a (\prod_i d\tilde{\lambda}_a^i) (\prod_i d\tilde{\bar{\lambda}}_a^i) \\
 & \quad \exp(-S_{Ep}) \times \exp(Z'_0) \\
 & \quad \times \langle \widehat{\Phi}_{a_1, b_1}[\vec{x}_1] \rangle_{\lambda_{a_1}, \bar{\lambda}_{b_1}}^{\text{tree}} \cdot \dots \cdot \langle \widehat{\Phi}_{a_L, b_L}[\vec{x}_L] \rangle_{\lambda_{a_L}, \bar{\lambda}_{b_L}}^{\text{tree}} \times \\
 & \quad \prod_k \langle \widehat{\Phi}_{c_k, c_k}[\vec{x}_k] \rangle_{A(Ep, Dq_{c_k})}^{\text{loop}}
 \end{aligned}$$

Implications: Superpotential Couplings

One can generate perturbatively forbidden matter couplings:

I. Majorana masses for right-handed neutrinos

→ SM constructions with neutrino Dirac masses

$H^+ L_L (N_R)^c$. if present, of order of charged sector masses

Majorana masses $M_m (N_R)^c (N_R)^c$ perturbatively forbidden

N_R^c – SM singlets, typically charged under anomalous $U(1)_a \times$

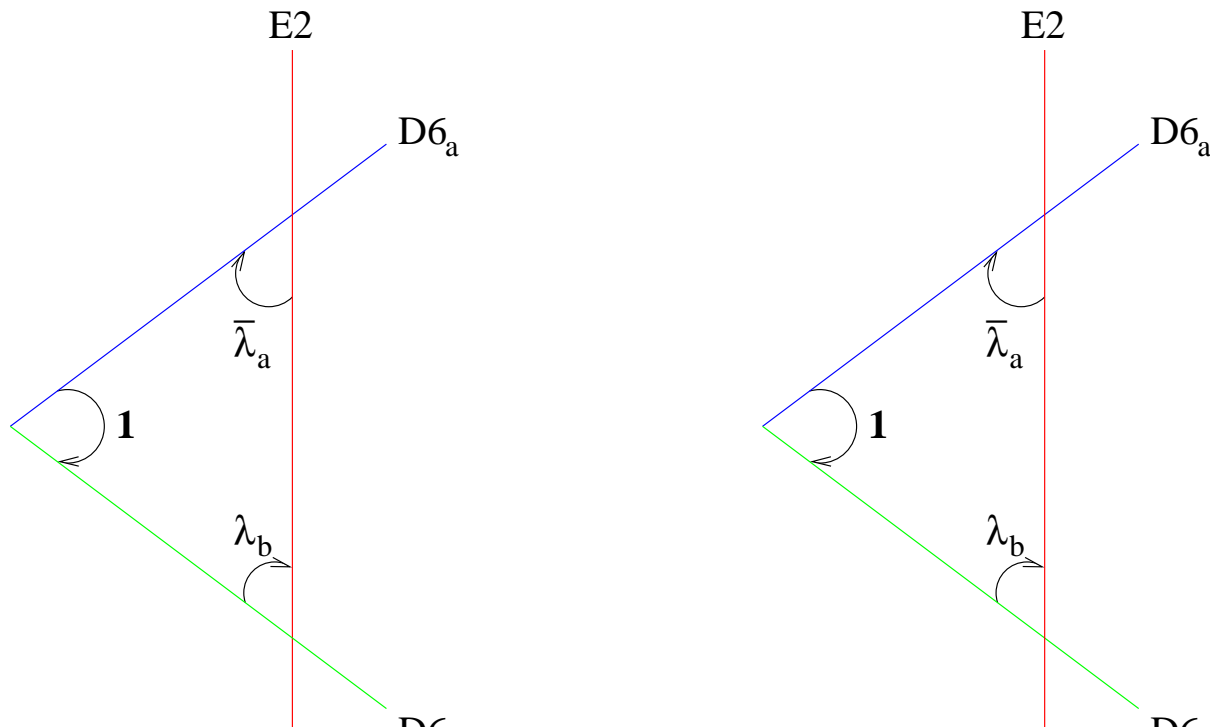
$U(1)_b$, say as $(1, -1)$.

Non-pert. coupling possible if CY_3 possesses **rigid** 3-cycle Ξ with zero mode structure:

$$\Xi \cap \Pi_{SM} = \Xi \cap \Pi_a = \Xi \cap \Pi'_b = 0$$

$$[\Xi \cap \Pi'_a]^- = 2, [\Xi \cap \Pi'_a]^+ = 0, [\Xi \cap \Pi_b]^+ = 2, [\Xi \cap \Pi_b]^- = 0.$$

Four – $\bar{\lambda}_a^{1,2}$ and $\lambda_b^{1,2}$ absorbed via the **two disk** diagrams:



→ Non-pert. Majorana coupling:

$$W_m = M_m (N_R)^c (N_R)^c \text{ with } M_m = x M_s e^{-\frac{2\pi}{\ell_s^3 g_s} \text{Vol}_{E2}}$$

$$\text{Use } \frac{1}{\alpha_{\text{GUT}}} = \frac{1}{\ell_s^3 g_s} \text{Vol}_{D6} \longrightarrow M_m = x M_s e^{-\frac{2\pi}{\alpha_{\text{GUT}}} \frac{\text{Vol}_{E2}}{\text{Vol}_{D6}}}$$

For seesaw mechanism need $10^{11} \text{GeV} < M_m < 10^{15} \text{GeV}$

Possible within natural regime for

$$0.4 \cdot R_{D6} > R_{E2} > 0.2 \cdot R_{D6} \text{ (w/ } x = \mathcal{O}(1)\text{)}.$$

→ Concrete local realization on $T^6 / \mathbb{Z}_2 \times \mathbb{Z}'_2$

[M. C., Robert Richter, Timo Weigand, hep-th/0703028]

Local 4-family supersymmetric 3-stack GUT model:

$$U(5)_c \times U(1)_a \times U(1)_b \text{ w/ } O(1) \text{ E2-instanton}$$

Result: $\langle \nu^A \nu^B \rangle_{E2_i} = \frac{2\pi}{g_s} \mathcal{V}_{E2} \vec{v}^T \mathcal{M} \vec{v} (2\pi)^4 \delta^4(k^A + k^B)$

$$\mathcal{M} = x M_s e^{-\frac{2\pi}{\alpha_{\text{GUT}}} \frac{8}{57}} \begin{pmatrix} A_i & 0 & B_i & 0 \\ 0 & C_i & 0 & D_i \\ B_i & 0 & E_i & 0 \\ 0 & D_i & 0 & F_i \end{pmatrix},$$

$x =$

$$\frac{(4\pi)^{3/2} \pi^2}{16} \left[\Gamma_{1-\theta_{ab}^1, 1-\theta_{E2a}^1, 1+\theta_{E2b}^1} \prod_{I=2}^3 \Gamma_{-\theta_{ab}^I, -\theta_{E2a}^I, 1+\theta_{E2b}^I} \right]^{\frac{1}{2}} e^{Z'}$$

$e^{Z'}$ **one-loop contribution** [Akerblom et al. arXiv:0705.236[he-th]]

Overall **exponential suppression scale** fixed by SUSY:

$$\frac{\text{Vol}_{E2}}{\text{Vol}_{\Pi_c}} = \left(\prod_I \frac{(n_{E2}^I)^2 + (\tilde{m}_{E2}^I)^2 U_I^2}{(n_c^I)^2 + (\tilde{m}_c^I)^2 U_I^2} \right)^{1/2} = \frac{8}{57}$$

- Sum up contributions from all 64 factorizable E2-instantons, **taking leading contribution (smallest triangle)**
 → $M_M \simeq 10^{10} \text{GeV}$
 for triangles of order string scale (as required)
- Together with **perturbative Dirac masses of $\mathcal{O}(\text{TeV})$** (due to Yukawa couplings of the type $\bar{5} 5_H 1$)
 → **Can engineer small neutrino masses of $\mathcal{O}(1\text{eV})$ via see-saw mechanism.**

Further applications:

- μ -term $\mu H^+ H^-$ forbidden perturbatively
→ can well be generated by $E2$ -instantons
→ appropriate volume ratio may yield $\mu \simeq \mathcal{O}(\text{TeV})$
- R-parity violating couplings in the MSSM can be induced
- GUT $SU(5)$ suffer from absence of pert. Yukawa couplings $10 10 5_H$, where 10 from (a, a') -intersection
Can be generated by $E2$ -instantons

[R.Blumenhagen, M.C., D. Lüst, R.Richter, T.Weigand, 0707.1871]

→ Opens the door for (flipped) $SU(5)$ phenomenology

Two more cases:

I. Small Dirac Neutrino Masses

II. Polonyi Term and gauge mediated SUSY breaking

I. Small Dirac Neutrino Masses

[M.C., P. Langacker, 0803.253]

Starting point: due to $U(1)$ charges of $5, \bar{5}, N_R$, within $U(5)_a \times U(1)_b \times U(1)_c$ GUT, perturbative Dirac neutrino Yukawa couplings $\bar{5} 5_H N_R$ absent

Specifically, non-zero intersection nos:

$$[\Pi_a \cap \Pi'_b]^- \neq 0, \quad [\Pi_b \cap \Pi'_c]^- \neq 0, \quad [\Pi_a \cap \Pi'_c]^+ \neq 0$$

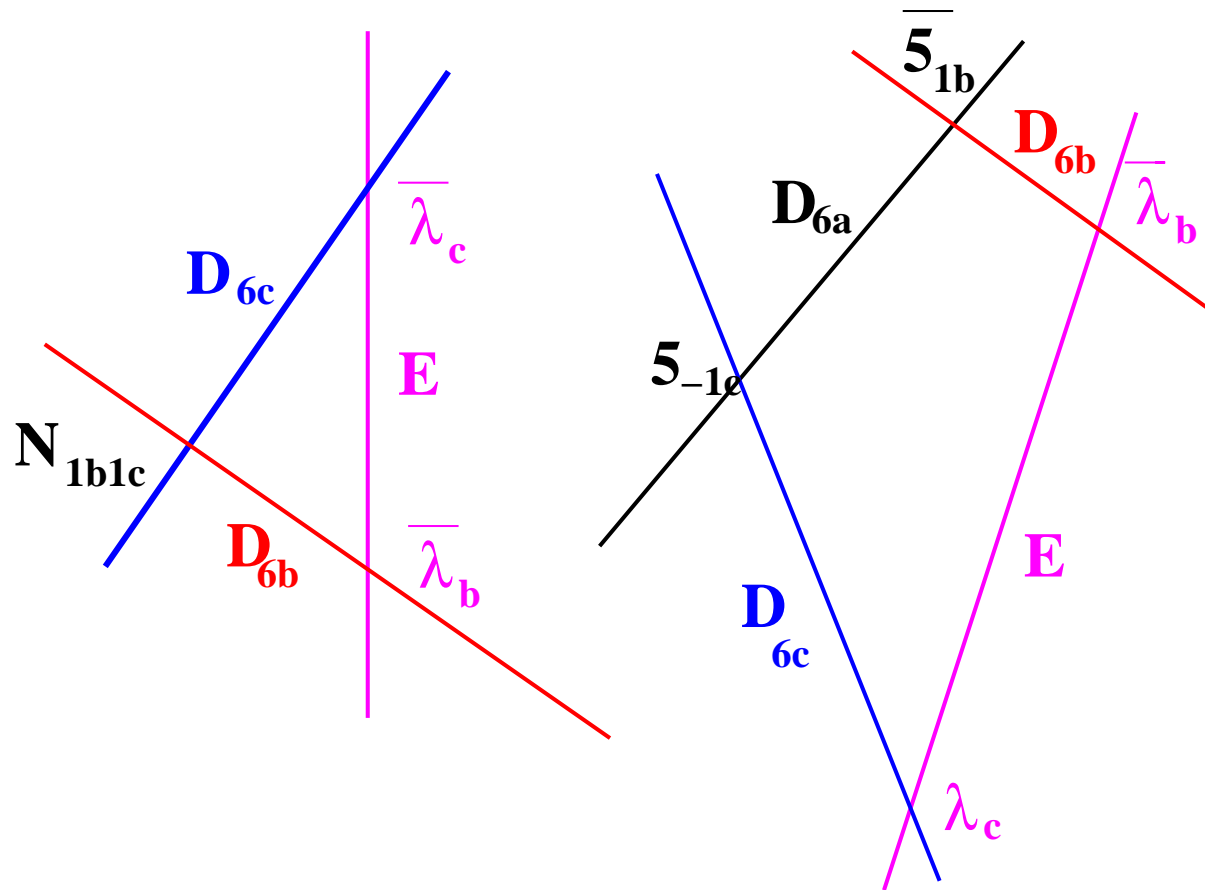
produce spectrum: $5_{(1_a, 1_b, 0)}, \bar{5}_{(-1_a, 0, -1_c)}, N_R_{(0, 1_b, 1_c)}$ - Dirac coupling absent

Instanton intersection nos.:

$$[\Xi \cap \Pi_a] = 0, \quad [\Xi \cap \Pi_b]^- = 2 \quad [\Xi \cap \Pi_c]^- \stackrel{N=2}{=} 1$$

i.e. $2 \bar{\lambda}_b$ with $(-1_b, 1_E)$ & one vector pair: $\lambda_c + \bar{\lambda}_c$ with $(-1_c, 1_E) + (1_c, -1_E)$

Fermionic zero modes contribute to disk diagrams:



Generating non-perturbative Dirac neutrino couplings.

Local construction $[(\nu_2, n_2) \text{ integ.; c.s. moduli } \chi_1 = \chi_2 = 1/\sqrt{5}, \chi_3 = n_2\sqrt{5}/2]$:

nos	(n_a^1, m_a^1)	(n_a^2, m_a^2)	(n_a^3, m_a^3)
5_a	$(\nu_2, 2\nu_2/n_2)$	$(1, 1)$	$(0, -1)$
1_b	$(n_2, 2)$	$(-1, 2)$	$(-1, 1)$
1_c	$(-1, 0)$	$(1, 1)$	$(-1, 1)$
1_E	$(1, 0)$	$(0, 1)$	$(0, -1)$

Spectrum $[(\nu_2, n_2)=(1,1), (3,3)\text{-4-family}]$:

sector	number	$U(5)_a \times U(1)_b \times U(1)_c$
(a, a')	$4(\nu_2 - 2\frac{\nu_2}{n_2})$	$\mathbf{10}_{(2,0,0)} + \overline{\mathbf{15}}_{(-2,0,0)}$
(a, b')	$16\nu_2$	$\mathbf{5}_{(1,1,0)}$
(a, c')	$16\frac{\nu_2}{n_2}$	$\overline{\mathbf{5}}_{(-1,0,-1)}$
(b, c')	16	$\mathbf{1}_{(0,1,1)}$

Non-perturbative Dirac neutrino Yukawa coupling:

$$Y = \exp(-S_{inst}) = x \exp\left(-\frac{2\pi}{\alpha_{GUT}} \frac{Vol_{E2}}{Vol_{D6a}}\right)$$

$\frac{Vol_{E2}}{Vol_{D6a}} = (6\nu_2)^{-1}$ for the specific local construction.

Taking: $\nu_2 = 1$ and $\alpha_{GUT} \sim \{25^{-1}, 30^{-1}\}$ and VEV of the Higgs doublet ~ 100 GeV, in turn yields neutrino Dirac masses in the range

$$m_{Dirac} \sim \{2 \cdot 10^{-3}, 0.4\} \text{ eV}$$

Reasonable regime for the allowed range of neutrino masses.

II. Gauge Mediated SUSY Breaking & String Theory

E.g., early approach: [Diaconescu, Florea, Kachru, Svrcek 0512170]

- **Polonyi field: Charged hidden sector** $S_{-1_a, 1_b}$ **chiral field** at intersection of a and b stack of D-branes with “anomalous” gauge symmetry, say $U(1)_a \times U(1)_b$. Monomials in S forbidden perturbatively, but due to D-instantons **Polonyi term:**

$$W = \mu^2 S, \quad w/ \quad \mu^2 = M_s^2 e^{-S_{inst}}$$

Type IIB—[Aharony, Kachru, Silverstein 0708.0493];

Type I/IIA GUT's—[MC, Weigand 0711.0209, 0807.3953];

F-theory GUT's—[Heckman, Marsano, Saulina, Schafer-Nameki, Vafa 0808.1286], [Marsano, Saulina, Schafer-Nameki 0808.1571]

- **Gauge mediation messengers** $q_{-1_b, N_c}, \tilde{q}_{1_a, \overline{N}_c}$ (visible sector N_c , say, $SU(N_c=5)$ -GUT)

$$W = S_{-1_a, 1_b}, q_{-1_b, N_c}, \tilde{q}_{1_a, \overline{N}_c} \text{ generated perturbatively.}$$

GUT: $U(1)_a \times U(1)_b \times U(5)_c$ w/ $O(1)$ instanton wrapping Ξ and zero mode structure:

$$\Xi \cap \Pi_{SM} = \Xi \cap \Pi_a = \Xi \cap \Pi'_b = 0$$

$$[\Xi \cap \Pi'_a]^- = 1, [\Xi \cap \Pi'_a]^+ = 0, [\Xi \cap \Pi_b]^+ = 1, [\Xi \cap \Pi_b]^- = 0.$$

Zero modes absorbed via one disk diagram.

Non-perturbative couplings engineered to have correct hierarchy for Polonyi term.

Summary

- Focus on $O(1)$ E2-brane instantons in Type IIA
General CFT calculus: for generating superpotential disk and one-loop contributions
 - Formalism applicable to vacua with exactly solvable CFT: toroidal orientifolds, RCFT (Gepner Model orientifolds)
 - Implications:
Hierarchical couplings:
neutrino Majorana masses or small Dirac masses/
 μ -terms/Yukawa couplings
→ Only explicit local examples exist!
- Challenge: search for semi-realistic global models

Type I picture:

Constructions of (semi-realistic) examples on globally defined Calabi-Yau spaces (algebraic geometry):

[M.C., T. Weigand 0711.0209, 0807.3953]

- Elliptically fibered Calabi-Yau spaces X (Example:
 $\pi : X \rightarrow B = dP_4$)
- Introduce N_a (magnetized) D9-branes via holomorphic stable line bundles E_a (and extensions) - $U(N_a)$
- Stacks of N_i D5-branes wrapping the holomorphic curve Γ_i - $Sp(2N_i)$
- **Spectrum:** encoded in various cohomology groups (technical: c.f., Blumenhagen, Honecker, Weigand'05)
- **Tadpole cancellation associated w/ D5:** $\sum_a N_a \text{ch}_2(E_a) - \sum_i N_i \gamma_i = -c_2(TX)$ **w/ D9:** $\sum_a N_a c_1(V_a) \in H^2(X, 2\mathbf{Z})$.

Instantons: $E1$ -instantons

wrap rigid $C = \mathbf{P}^1$ curves - $O(1)$ -instantons

Charged zero modes λ in the D9-E1 sector:

state	rep	cohomology
λ_a	$(N_a, 1_E)$	$H^0(\mathbf{P}^1, V_a^\vee(-1) _{\mathbf{P}^1})$
$\bar{\lambda}_a$	$(\bar{N}_a, 1_E)$	$H^1(\mathbf{P}^1, V_a^\vee(-1) _{\mathbf{P}^1})^*$

For line bundles $V_a = L_a$: $K_{\mathbf{P}^1} = \mathcal{O}(-2)$, and $L_a(-1)|_{\mathbf{P}^1} = \mathcal{O}(x_a - 1)$, w/
 $x_a = \int_{\mathbf{P}^1} L_a$.

Additional zero modes from the D5-E1 counted by the extension groups $Ext_X(j_*\mathcal{O}|_{\Gamma_i}, i_*\mathcal{O}|_C)$: vanish Γ_i and C do not intersect

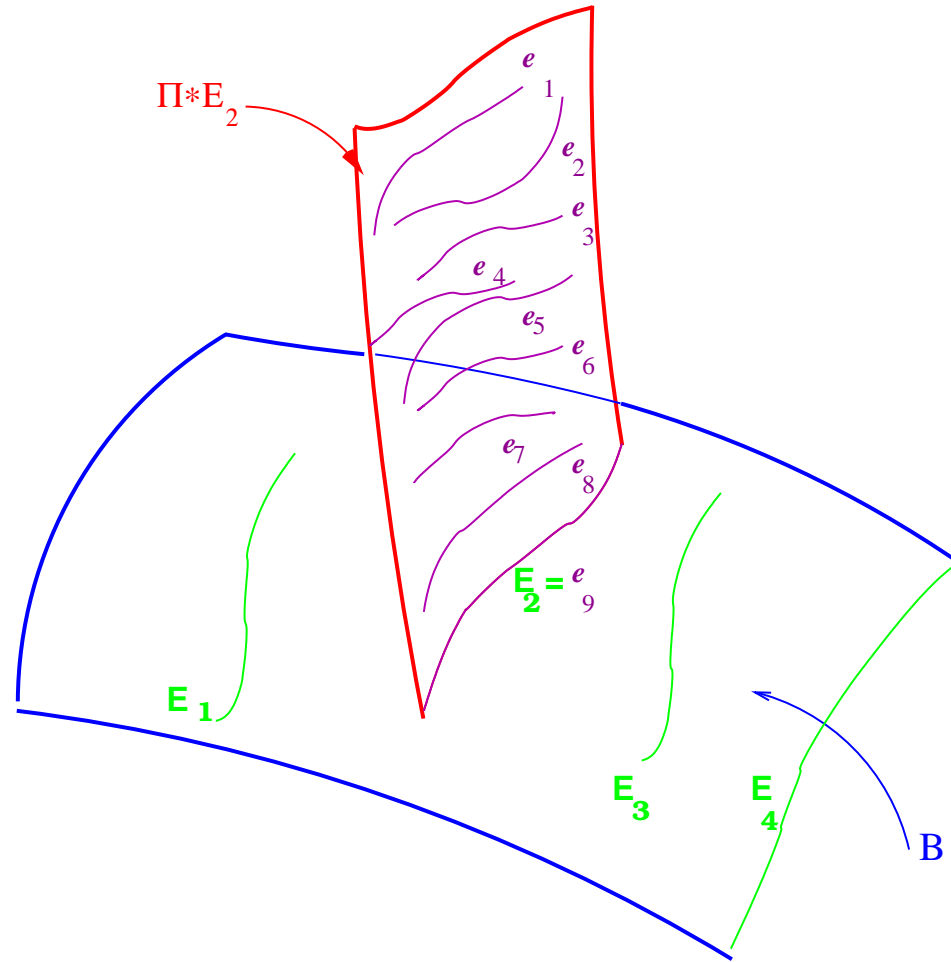


Figure 1: The dP_9 surface π^*E_4 inside the fibration $\pi : X \rightarrow B = dP_4$

- Global four-family $U(5)_a \times U(1)_b \times U(1)_c$ models with Majorana masses [MC,T.Weigand, 0711.0209]

Bundle	N	$c_1(L) = q\sigma + \pi^*(\zeta)$
L_a	5	$\pi^*(-2E_3)$
L_b	1	$2\sigma + \pi^*(-2l - 2E_1 + 3E_2 + 2E_3 + 2E_4)$
L_c	1	$-2\sigma + \pi^*(2l - E_2 - 2E_3 - 2E_4)$

- Global four-family $U(5)_c \times U(1)_a \times U(1)_b$ models with Polonyi-type terms responsible for supersymmetry breaking

[MC,T.Weigand 0711.0209,0807.3953]

Bundle	N	$c_1(L) = q\sigma + \pi^*(\zeta)$
L_a	1	$\pi^*(-l + 2E_1 + 2E_2 - 2E_3 - E_4)$
L_b	1	$4\sigma + \pi^*(l - 2E_2 + E_4)$
L_c	5	$\pi^*(2E_1 - 2E_2 - 2E_3)$

Engineered Hierarchies from instantons

Suppression scale: $\mu^2 = x M_s^2 e^{-\frac{2\pi}{g_s} \text{Vol}_{E1}} = x M_s^2 e^{-\frac{2\pi}{\alpha_{GUT}} \frac{\text{Vol}_{E1}}{\tilde{f}_{GUT}}}$

$$\tilde{f}_{GUT} = \frac{1}{3!} \int_X J \wedge J \wedge J - \int_X J \wedge (\text{ch}_2(L_c) + \frac{1}{24} c_2(T))$$

Type I relation: $M_s^2 = (M_{Pl})^2 g_s \alpha_{GUT} = \mathcal{O}(10^{17} \text{GeV})$

for **TeV soft masses** need $\mu = 10^{-10} M_s^{1/4} \leftrightarrow$

$$\text{Vol}_C / \tilde{f}_{GUT} \simeq 0.27$$

For the model D-term supersymmetry conditions on line bundles have solutions inside Kähler cone such that

$$\text{Vol}_C = 2.6 \ell_s^2 \Rightarrow \mu = 10^{-10} \text{ for } g_s = 0.4$$

Summary

Progress on D-instantons:

- i) Technical (multi-instantons, lifting of zero modes via fluxes etc.)
- ii) Implications for charged matter couplings w/ new hierarchy: mainly $O(1)$ instantons (neutrino masses, SUSY breaking, etc.)

Challenges: constructions of semi-realistic (three-family) global models w/ stabilized closed sector moduli in the desired regime.

Nevertheless some new insights into stringy non-perturbative effects