D-brane instantons in Type II orientifolds

based on:

R. Blumenhagen, M. Cvetič, T.W., hep-th/0609191

M. Cvetič, R. Richter, T.W., hep-th/0703028

R. Blumenhagen, M. Cvetič, D. Lüst, R. Richter, T.W., 0707.1871

R. Blumenhagen, M. Cvetič, R. Richter, T.W., 0708.0403

M. Cvetič and T.W., 0711.0209

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Motivation

Non-perturbative corrections to effective action of 4D string compactifications play a prominent role

crucial if corresponding interactions forbidden perturbatively

$\rightsquigarrow$ e.g. Kähler moduli stabilisation in IIB

In many string models, important matter couplings are perturbatively forbidden due to selection rules from massive U(1) gauge factors

e.g. Majorana masses, certain Yukawas, μ-terms, ...

If realized (only) non-perturbatively as

$$W_{np} \simeq \prod_{i=1}^{M} \Phi_i \, e^{-S_{inst.}}$$

they would be exponentially suppressed w.r.t. string scale

$\leftrightarrow$ stringy realisation of peculiar scale of certain MSSM couplings?

Motivation

Presence of perturbative U(1) selection rules and their non-pert. breakdown generic in many M-theory corners:

Type II orientifolds:

- Type IIA w/ intersecting D6-branes and E2-instantons
- Type IIB w/ D7/D3-branes and E3-instantons
- Type I w/ D9/D5-branes and E1-instantons

In general:

Chiral matter from (suitably magnetized) SUSY Dq-brane on $\mathbb{R}^{1,3} \times \Pi_{(q-3)}$ and Euclidean Dp-instanton (Ep-brane) on half-BPS cycle Π_{p+1}

IIA: D2-instanton on sLag SUSY w.r.t. orientifold

IIB: with D7/D3: D3-instanton on holomorphic divisor

I: D1-instanton on holomorphic curve

Some Literature

Various non-pert. effects studied in string literature, e.g.

worldsheet instantons in heterotic compactifications

[Dine,Seiberg,Wenn,Witten'86],[Distler,Greene'88],[Witten'99],

[Buchbinder,Donagi,Ovrut'02],[Beasley,Witten'03,'05]

worldsheet instantons in IIA brane models

[Kachru et al.'00],[Aganacic,Vafa'00]

M2/M5-brane effects in (heterotic) M-theory

[Becker,Becker,Strominger'95],[Harvey, Moore'99]

CFT aspects of D-instantons

[Polchinski'94],[Green,Gutperle'97],[Billo et al.'02]

Stringy instantons:

[Blumenhagen,Cvetič,T.W. 0609191],[Ibañez,Uranga 0609213],

[Haack,Krefl,Lüst,VanProeyen,Zagermann 0609211],

[Florea,Kachru,McGreevy,Saulina 0610003]

with many important further developments since

Massive $U(1)$ and gauging of axions

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 coupling

$$S_{CS} = \sum_a N_a \, \mu_q \int_{\mathbb{R}^{1,3} \times \Pi^a_{q-3}} e^{trF_a} \sum_p C_p$$

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

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

with $Q_a(\widetilde{\Pi}_{p+1}) \simeq N_a \int_{\mathcal{M}_6} \delta(\widetilde{\Pi}_{p+1}) \wedge \delta(\Pi^a_{q-3}) \wedge e^{F_a}$

Instantons-Generalities

Gauging of axions affects

Euclidean D_p-brane on internal $p+1$-cycle Ξ

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

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

$e^{-S_{Ep}} \longrightarrow e^{i\,Q_a(Ep)\,\Lambda_a}\, e^{-S_{Ep}}$: $Q_a = N_a \int \delta(\Xi)\wedge\delta(\Pi^a_{q-3})\wedge e^{F_a}$

Consequence:

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

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

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

Stringy instantons not describable as gauge instantons!

Zero mode structure

Distinguish 2 types of zero modes:
uncharged (Ep-Ep sector) or charged (Ep-Dq sector) under $U(1)_a$:

1) zero modes uncharged under $U(1)_a$:

- 4 bosonic modes $x_E^i \leftrightarrow$ Poincaré inv. in 4D
  For $Ep \neq Ep'$: 2 + 2 Goldstinos θ_α, $\overline{\tau}_{\dot{\alpha}} \leftrightarrow$ broken SUSY

$\mathcal{N} = 1$	$\mathcal{N} = 1'$
θ_α	τ_α
$\overline{\theta}_{\dot{\alpha}}$	$\overline{\tau}_{\dot{\alpha}}$

- zero modes due to deformation and/or Wilson lines
- additional bosonic and fermionic zero modes at intersection of Ep and Ep' (for $Ep \neq Ep'$)

Zero mode structure

Superpotential requires measure $\int d^4x_E\, d^2\theta$:

1) absence of $\overline{\tau}^{\dot\alpha}$

- $\overline{\tau}_{\dot\alpha}$ is projected out for $\Xi = \Xi'$ (O(1) instanton)
- lifting of $\overline{\tau}^{\dot\alpha}$ and $E - E'$ sector modes through couplings in effective instanton action ("instanton recombination") [B.,C.,R.,W., 0708.0403] (see talk of R. Richter)
- lifting of $\overline{\tau}^{\dot\alpha}$ in presence of background and gauge fluxes (see later)
- special case: "gauge instantons"

2) absence of deformation/Wilson line modes $\chi_I^{\alpha}, \overline{\chi}_I^{\dot\alpha}$

- Ξ has to be rigid/simply connected, or
- zero modes pair up e.g. by background fluxes, R-terms or open string couplings

Charged zero modes

2) zero modes charged under $U(1)_a$: from $E_p - Dq_a$ strings
DN-boundary conditions in 4D, mixed b. c. along CY_3

$\rightsquigarrow$ at chiral "intersection": chiral fermionic zero modes λ_a
(GSO-odd/even for instantons/anti-instantons)

total $U(1)_a$ charge of all zero modes in agreement with
$e^{-S_{Ep}} \longrightarrow e^{i\,Q_a(Ep)\,\Lambda_a}\;e^{-S_{Ep}}$

In presence of disk-level couplings to matter fields of type
$S = \int_\Xi \lambda_a\,\Phi_{ab}\overline{\lambda}_b$ in instanton effective action

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

Details of calculus incl. prescription for loop-computations cf.
[B.,C.,W. 0609191]

Instanton calculus - Summary

[Blumenhagen,Cvetič,T.W. 0609191]

$$\langle \Phi_{a_1,b_1}(p_1)\cdot \ldots \cdot \Phi_{a_M,b_M}(p_M)\rangle_{Ep-\mathrm{inst}} =$$

$$= \int d^4\tilde{x}\, d^2\tilde{\theta} \sum_{\mathrm{conf.}} \prod_a \left(\prod_i d\widetilde{\lambda}_a^i\right)\left(\prod_i d\widetilde{\overline{\lambda}}_a^i\right)$$

$$\exp(-S_{Ep}) \times \exp\left(Z_0'\right)$$

$$\times \langle \widehat{\Phi}_{a_1,b_1}[\vec{x}_1]\rangle^{\mathrm{tree}}_{\lambda_{a_1},\overline{\lambda}_{b_1}} \cdot \ldots \cdot \langle \widehat{\Phi}_{a_L,b_L}[\vec{x}_L]\rangle^{\mathrm{tree}}_{\lambda_{a_L},\overline{\lambda}_{b_L}} \times$$

$$\prod_k \langle \widehat{\Phi}_{c_k,c_k}[\vec{x}_k]\rangle^{\mathrm{loop}}_{A(Ep,Dq_{c_k})}$$

Type I = Type IIB/Ω on CY3

Stacks of $M_a = n_a \times N_a$ D9-branes with stable holomorphic $U(n_a)$ bundle V_a

- gauge group $U(N_a)$: $U(n_a) \subset U(M_a) \to U(N_a)$
- special case: $n_a = 1$: line bundles

$\leftrightarrow$ magnetized D9-branes carrying constant gauge field

- include orientifold images: Ω: $F_a \to -F_a \leftrightarrow V_a \to V_a^\vee$

Stacks of N_i D5-branes wrapping holomorphic curves Γ_i

- support gauge group $Sp(2N_i)$

Tadpoles:

$$
\begin{aligned}
\sum_a n_a N_a &= 16 \\
\sum_a N_a \mathrm{ch}_2(V_a) - \sum_i N_i \gamma_i &= -c_2(TX)
\end{aligned}
$$

Type I = Type IIB/Ω on CY3

Massless matter:

counted by suitable cohomology groups of respective bundles

chiral/ antichiral superfields

- $\leftrightarrow$ odd/even degree for D9-D9
- $\leftrightarrow$ even/odd degree for D5-D9

reps.	$\prod_a SU(N_a) \times U(1)_a \times \prod_i SP(2N_i)$
$(\mathrm{Sym}_{U(N_a)})_{2(a)}$	$H^i(X, \bigwedge^2 V_a) \quad i = 1, 2$
$(\mathrm{Anti}_{U(N_a)})_{2(a)}$	$H^i(X, \bigotimes_s^2 V_a) \quad i = 1, 2$
$(N_a, N_b)_{1(a),1(b)}$	$H^i(X, V_a \otimes V_b) \quad i = 1, 2$
$(\overline{N}_a, N_b)_{-1(a),1(b)}$	$H^i(X, V_a^\vee \otimes V_b) \quad i = 1, 2$
$(N_a, 2N_i)_{1(a)}$	$H^i(\Gamma_i, V_a\|_{\Gamma_i} \otimes K_{\Gamma_i}^{1/2}) \quad i = 0, 1$

E1-instantons in Type I

E1-instanton wrapping holomorphic curve C

- gauge group $O(1) \rightsquigarrow$ universal zero modes $d^4x d^2\theta$
- for $C =$ isolated $\mathbb{P}^1$: no deformation modes

charged zero modes in $D9_a - E1$ sector:
cf. $D9_a - D5$ sector, but only chiral fermionic modes present counted by even degree cohomology, i.e.

$$\lambda_a : \quad (N_a, 1_E) \quad H^0(\mathbb{P}^1, V_a|_{\mathbb{P}^1} \otimes \mathcal{O}(-1))$$

$$\overline{\lambda}_a : \quad (\overline{N}_a, 1_E) \quad H^0(\mathbb{P}^1, V_a^\vee|_{\mathbb{P}^1} \otimes \mathcal{O}(-1))$$

in agreement with heterotic worldsheet instantons

E1-charge: $Q_a = \int_{\mathbb{P}^1} c_1(V_a) = \chi(\mathbb{P}^1, V_a|_{\mathbb{P}^1} \otimes \mathcal{O}(-1))$

extra zero modes in $D5_i - E1$ sector: only if $\Gamma_i \cap C \neq 0$

E1-instantons in Type I

Crucial object: $H^*(\mathbb{P}^1, V_a|_{\mathbb{P}^1} \otimes \mathcal{O}(-1))$

• for $rk(V_a) = n_a$: $V_a|_{\mathbb{P}^1} = \sum_{i=1}^{n_a} \mathcal{O}(k_i)$ with $\sum k_i = \int_{\mathbb{P}^1} c_1(V_a)$
splitting type in general varying over bundle moduli space
• for line bundles easy: $L_a|_{\mathbb{P}^1} = \mathcal{O}(k)$ with $k = \int_{\mathbb{P}^1} c_1(L_a)$

Further use Bott's theorem to deduce number of zero modes:
$h^0(\mathbb{P}^1, \mathcal{O}(k)) = \theta(k)(k+1), h^1(\mathbb{P}^1, \mathcal{O}(k)) = \theta(-k)(-k-1)$,
with $\theta(k) = 1$ for $k \geq 0$ and zero otherwise

Consequences:

$$\int_{\mathbb{P}^1} c_1(L_a) = k \geq 0 : \quad k \times \lambda_a \, \text{in} \, (N_a, 1_E)$$
$$\int_{\mathbb{P}^1} c_1(L_a) = -k \leq 0 : \quad k \times \overline{\lambda}_a \, \text{in} \, (\overline{N}_a, 1_E)$$

Matter couplings

Example: hierarchically large Majorana masses for right-handed neutrinos [Blumenhagen,Cvetič,T.W. 0609191]

For concreteness consider e.g. SU(5) GUT quiver,

$N_c = 5$: SU(5)-GUT stack $\qquad N_a = N_b = 1$

sector	representation	matter
(c, c')	Antisym	**10**
(c, a)	$(\overline{c}, a)$	$\overline{\mathbf{5}}$
(c, b)	$(c, \overline{b})$	$\mathbf{5}_H$
(a, b)	$(\overline{a}, b)$	N_R^c

$W_m = M_m \, (N_R)^c{}_{(-1_a,1_b)} \, (N_R)^c{}_{(-1_a,1_b)}$ not $U(1)$-invariant

for non-pert. effect need 2 λ_a in $(1_E, 1_a)$, 2 $\overline{\lambda}_b$ in $(-1_b, 1_E)$

$\rightsquigarrow L_a|_{\mathbb{P}^1} = \mathcal{O}_{\mathbb{P}^1}(2), \qquad L_b|_{\mathbb{P}^1} = \mathcal{O}_{\mathbb{P}^1}(-2)$

Majorana Masses

absence of extra charged modes:

- $V_c|_{\mathbb{P}^1} = \mathcal{O}(0)$
- D5-branes needed for TAD must not hit $\mathbb{P}^1$ wrapped by E1

Suppression scale:

$W_m = M_m \, (N_R)^c \, (N_R)^c$ with $M_m = x \, M_s \, e^{-\frac{2\pi}{\ell_s^2 \, g_s} \mathrm{Vol}_{E1}}$

Use $\frac{1}{\alpha_{\mathrm{GUT}}} = \frac{1}{\ell_s^6 \, g_s} f_c \rightsquigarrow M_m = x \, M_s \, e^{-\frac{2\pi \, \ell_s^4}{\alpha_{GUT}} \frac{Vol_{E1}}{f_c}}$

$$f_c = \frac{1}{3!} \int_X J \wedge J \wedge J - \ell_s^4 \int_X J \wedge \left(\mathrm{ch}_2(L_c) + \frac{1}{24} \, c_2(T) \right)$$

constrained by D-term SUSY conditions:

$$\int_X \frac{1}{2} J \wedge J \wedge c_1(V_a) - \ell_s^4 \left(\mathrm{ch}_3(V_a) + \frac{1}{24} \, c_1(V_a) \, c_2(T) \right) = 0$$

For seesaw mechanism need $10^8 \mathrm{GeV} < M_m < 10^{15} \mathrm{GeV}$

Possible <u>without fine tuning</u> for $\frac{\mathcal{V}ol_{E1}}{\mathcal{V}ol_{CY_3}} \simeq 3.5 - 15 \times 10^{-2}$

E1-instantons in Type I

Family structure: determined by details of $\int_{E1} c_{ijk} \lambda_a^i \, (N_R^c)^j \, \overline{\lambda}_b^k$ associated with map

$$H^0(\mathbb{P}^1, L_a|_{\mathbb{P}^1}(-1)) \times H^1(X, L_a^\vee \otimes L_b) \times H^0(\mathbb{P}^1, L_b^\vee|_{\mathbb{P}^1}(-1)) \to \mathbb{C}$$

$\longrightarrow$ only $N_R^c \in H^1(\mathbb{P}^1, L_a^\vee \otimes L_b|_{\mathbb{P}^1})$ participate

$$\underbrace{H^0(\mathbb{P}^1, \mathcal{O}(1))}_{a_0, a_1 \simeq \lambda_a^1, \lambda_a^2} \times \underbrace{H^0(\mathbb{P}^1, \mathcal{O}(1))}_{b_0, b_1 \simeq \overline{\lambda}_b^1, \overline{\lambda}_b^2} \longrightarrow \underbrace{H^0(\mathbb{P}^1, \mathcal{O}(2))}_{c_0, c_1, c_2 \simeq (N_R^c)^1, (N_R^c)^2, (N_R^c)^3}$$

$$\begin{aligned} c_0 &= a_0 \, b_0 & \leftrightarrow && \lambda_a^1 \, (N_R^c)^1 \, \overline{\lambda}_b^1 \\ c_1 &= a_0 \, b_1 + a_1 \, b_0 & \leftrightarrow && \lambda_a^1 \, (N_R^c)^2 \, \overline{\lambda}_b^2 + \lambda_a^2 \, (N_R^c)^2 \, \overline{\lambda}_b^1 \\ c_2 &= a_1 \, b_1 & \leftrightarrow && \lambda_a^2 \, (N_R^c)^3 \, \overline{\lambda}_b^2 \end{aligned}$$

$\rightsquigarrow$ family structure for Majoranas: $(N_R^c)^1 (N_R^c)^3 + (N_R^c)^2 (N_R^c)^2$

Global example on X over dP_4

[Cvetič, T.W. 0711.0209]

Example: X$=$ elliptic fibration over $B = dP_r$: $\pi : X \rightarrow B$

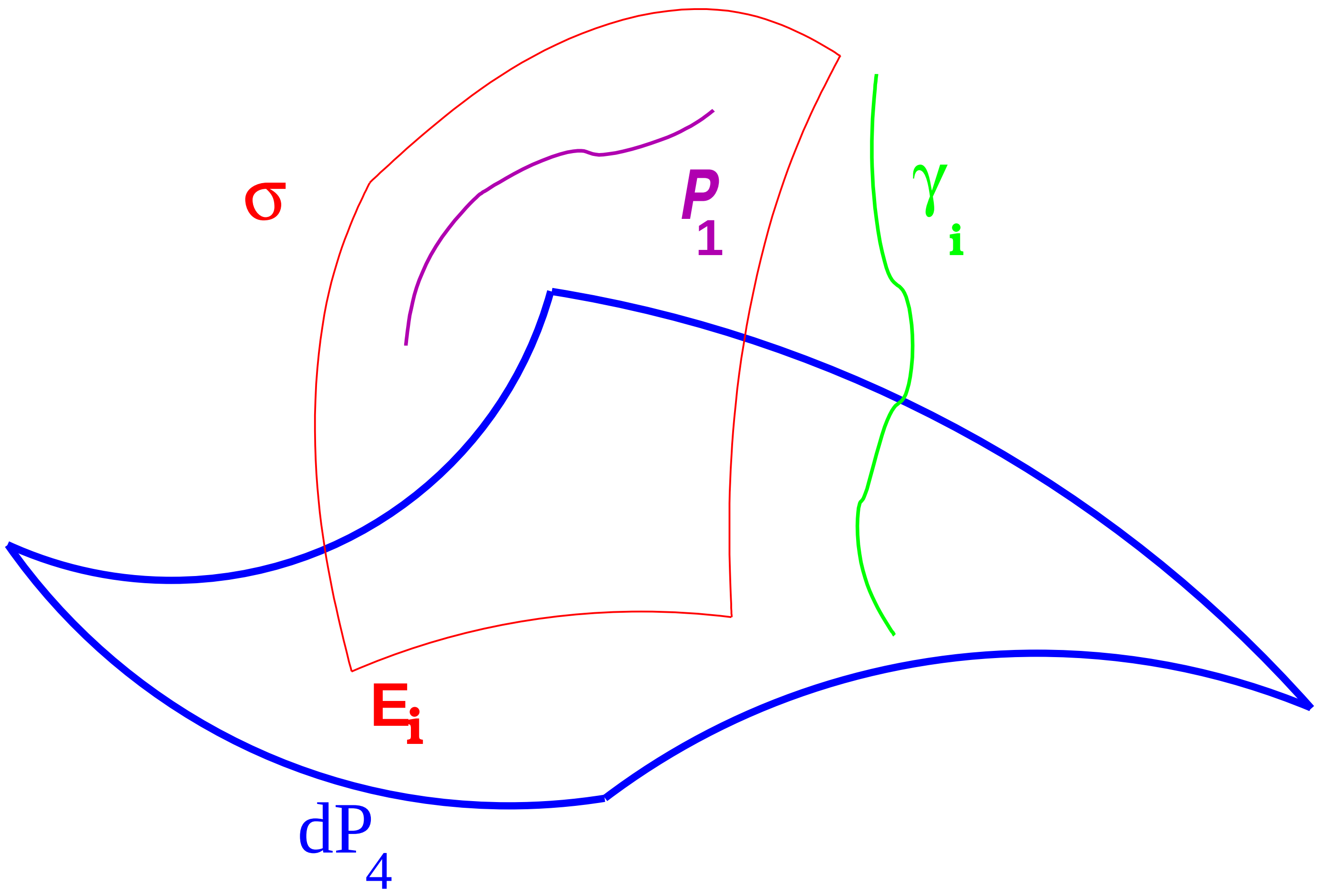
Specify line bundles by first Chern class $c_1(L) \in H^2(X, \mathbb{Z})$:
$\rightsquigarrow c_1(L) = q\sigma + \pi^*(a_0 l + \sum_i a_i E_i)$

σ: fiber class and $l, E_i \in H^2(B, \mathbb{Z})$:
l: hyperplane class, E_i, $i = 1, \ldots, r$: blow-up $\mathbb{P}^1$

Consider divisor $\pi^* E_i \sim dP_9$ containing ∞ number of rigid $\mathbb{P}^1$
Consider E1 instanton around $\mathcal{C} = \mathbb{P}^1 \in \pi^* E_i$ that does not intersect B
$\rightsquigarrow L_a|_{\mathbb{P}^1} = \mathcal{O}(-a_i)$

For D5-TAD: $\sum N_i \gamma_i = a_f F + \sigma \cdot \pi^*(\xi)$, $\xi \in H^2(B, \mathbb{Z})$
corresponding curves generically don't hit instanton

Global example on X over dP_4



Global example on X over dP_4

$$L_a \qquad c_1(L_a) = -2\sigma + 2l - E_2 - 2E_3 - 2E_4$$

$$L_b \qquad c_1(L_b) = 2\sigma - 2l - 2E_1 + 3E_2 + 2E_3 + 2E_4$$

$$L_c \qquad c_1(L_c) = -2E_3 + 0E_4$$

4 chiral gen of $\overline{\mathbf{10}}$ and of N_R^c
required 5-brane class for TAD: $\sum N_i \gamma_i = 41F + 16l - 12E_1$
D-term cond. satisfied e.g. for
$r_\sigma = 1, r_l = 10.39, r_1 = -7$, $r_2 = r_3 = r_4 = -1 \rightsquigarrow f_c = 9.56$

Consider single instanton on $\mathbb{P}^1 \in \pi^*(E_4)$
for $M_s = 10^{18}\, GeV$ and above moduli $M_{maj} = \mathcal{O}(10^{11})$ GeV

final result requires summing up all possible contribution, in part. from the other $\mathbb{P}^1 \in \pi^*(E_4)$

Further applications

• Absence of pert. trilinear Yukawas $\mathbf{10}\,\mathbf{10}\,\mathbf{5}_H$ in Type IIA GUT $SU(5)$
at odds in particular with strong coupling dual M-theory on G2-manifold: U(1) selection rule not present since massive U(1) decouples as $g_s \to \infty$
Solution similar to case of Majorana masses:

[B.,C.,R.,L.,W. 0707.1871]

$$W_Y = Y_\alpha\, Y_\beta\, \epsilon^{ijklm}\; \mathbf{10}^\alpha_{ij}\, \mathbf{10}^\beta_{kl}\, \mathbf{5}^H_m\; e^{-S_{inst}}\; e^{Z'}$$

• in many concrete D-brane constructions:
μ -term $\mu H^+ H^-$ forbidden perturbatively
$\rightsquigarrow$ can well be generated by Ep-instantons!
$\rightsquigarrow$ appropriate volume ratio may "explain" why $\mu \simeq \mathcal{O}(M_Z)$

Further applications

• use instantons to decouple exotic matter states
e.g. matter $\psi^I_{[ij]}$ in $\mathbf{6}$ of U(4) can receive non-perturbative mass

$$\mathcal{L}_{\rm mass} = C' M_s \, e^{-S_{E2}} \; \epsilon^{ijkl} \, M_{IJ} \, \psi^I_{ij} \, \psi^J_{kl}$$

due to factorisation: $rk(M) = 1$
$\rightsquigarrow$ demonstrated in global IIA orientifold model on $T^6/\mathbb{Z}_2 \times \mathbb{Z}'_2$ [B.,C.,R.,L.,W. 0707.1871]

• Dynamical SUSY Breaking without strong gauge dynamics

[Aharony,Kachru,Silverstein 0708.0493], [Aganacic,Beem,Kachru 0709.4277]

Background fluxes

[Blumenhagen,Cvetič,Richter,T.W. 0708.0403]

Consider Type IIB/$\Omega\sigma$ on conformal CY_3 with O7/O3 in presence of (2,1) primitive 3-form flux $G = F - \tau H$

E3-instanton on hol. divisor $\widetilde{\Gamma} = \Gamma + \sigma\Gamma$

Use SUGRA expression of [Bergshoeff et al.,0507069] for S_{E3}:

$$S = \int_{\Gamma} d^4\zeta \sqrt{\det g}\, \omega \, \left(e^{-\phi}\, \Gamma^{\tilde{m}} \nabla_{\tilde{m}} + \frac{1}{8} \widetilde{G}_{\tilde{m}\tilde{n}p}\, \Gamma^{\tilde{m}\tilde{n}p} \right) \omega$$

internal part of zero modes ω:

$$\epsilon_+ = \phi|\Omega\rangle + \phi_{\overline{a}} \Gamma^{\overline{a}} |\Omega\rangle + \phi_{\overline{a}\overline{b}} \Gamma^{\overline{a}\overline{b}} |\Omega\rangle,$$

$$\epsilon_- = \phi_{\overline{z}} \Gamma^{\overline{z}} |\Omega\rangle + \phi_{\overline{a}\overline{z}} \Gamma^{\overline{a}\overline{z}} |\Omega\rangle + \phi_{\overline{a}\overline{b}\overline{z}} \Gamma^{\overline{a}\overline{b}\overline{z}} |\Omega\rangle$$

universal modes: $\omega_0^{(1)} = \theta \otimes \phi|\Omega\rangle, \quad \omega_0^{(2)} = \overline{\tau} \otimes \phi_{\overline{a}\overline{b}\overline{z}} \Gamma^{\overline{a}\overline{b}\overline{z}} |\Omega\rangle$

$\chi = \frac{1}{2}(N_+ - N_-) \leftrightarrow$ arith. genus for M5-branes

Background fluxes

no lifting of $\overline{\tau}$ for (2,1) primitive 3-form flux:
$\widetilde{G}_{\overline{a}bz}\Gamma^{\overline{a}bz}\Gamma^{\overline{1}}\Gamma^{\overline{2}}\Gamma^{\overline{3}}|\Omega\rangle = \widetilde{G}_{\overline{a}bz}g^{b\overline{a}}g^{z\overline{3}}\Gamma^{\overline{1}}\Gamma^{\overline{2}}|\Omega\rangle = 0$ etc.

Does gauge flux $\mathcal{F} = F - B$ on $E3$-instanton change this?
Analyse full E3-brane action of [Tripathy, Trivedi, 0503072]:
$S_{E3} = S_{E3}(\mathcal{F}) + S_{E3}(\mathcal{F}^2)$

- $S_{E3}(\mathcal{F}^2)$: inherits index structure of case with no gauge flux $\longrightarrow$ no $\overline{\tau}$-lifting
- $S_{E3}(\mathcal{F}) \simeq \int_\Gamma d^4\zeta\sqrt{\det g}\,\omega\,\Gamma^{\widetilde{i}pq}\omega\;\; \mathcal{F}_{\widetilde{i}}^{\;\widetilde{j}}\, G_{\widetilde{j}pq}$
  $\rightsquigarrow$ e.g. $G_{\overline{a}bz}F^{b\overline{a}}g^{z\overline{3}}\Gamma^{\overline{1}}\Gamma^{\overline{2}}|\Omega\rangle \neq 0$

  couples $\overline{\tau}$ to deformation modes in $H^{(0,2)}(\widetilde{\Gamma})$
  if the latter unobstructed $\longrightarrow$ $\overline{\tau}$- lifting possible!
  Note: Index $\chi = \frac{1}{2}(N_+ - N_-)$ unchanged

Background fluxes

Local example on $T^2 \times T^2 \times T^2/\mathbb{Z}_2$
with $ds^2 = \sum_I dz_I \, d\overline{z}_I$ and $\mathbb{Z}_2$-action $\sigma : z_2 \to -z_2$

- E3 on divisor Γ along z_1, z_2
(with Wilson line such that non-invariant under σ)
- gauge flux: $F^{1,\overline{2}}$ survives $\Omega\sigma$

$\longrightarrow G_{\overline{a}bz} F^{\overline{a}b} = G_{\overline{1}23} F^{\overline{1}2}$ non-vanishing can lift τ-modes

Problem: Global consistency requires O3-planes to cancel flux tadpoles

E.g. by orbifolding $z_{1,3} \to -z_{1,3} \rightsquigarrow F^{1,\overline{2}}$ no longer invariant

Open: Construct global flux vacua with divisors of this type and study $\overline{\tau}$-lifting

Summary

Stringy instanton effects are interesting conceptually and for string phenomenology:

- generation of hierarchies without fine-tuning in context of Majorana masses, μ-terms, Yukawas in SU(5) GUTs, lifting exotic matter, DSB...
- general rules for disk and one-loop contributions
- formalism applicable to vacua with exactly solvable CFT: toroidal orientifolds, Gepner Model orientifolds
- Gave explicit globally defined example for Majorana masses and Polonyi DSB in Type I

Complete set of D-brane instantons with contributions to superpotential in Type II orientifolds yet to discover