D-brane instantons in Type II orientifolds

in collaboration with

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Motivation

Non-perturbative effects crucial for understanding of **vacuum structure** and **phenomenology of 4D string landscape**

despite suppression with $e^{-S_{n.p.}}$:
constitute leading contributions if corresponding interactions forbidden perturbatively

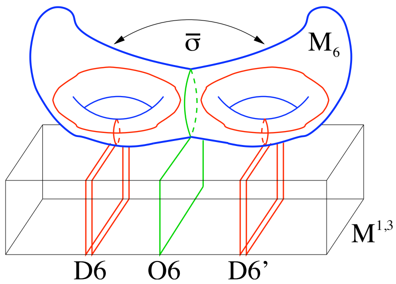
- relevant for very definition of vacuum
  Example: stabilisation of Kähler moduli in IIB orientifolds
- determine phenomenological properties of vacuum:
  perturbatively forbidden important matter couplings
  ⇝ Dynamical SUSY breaking
  ⇝ generation of observed hierarchies
  e.g. Majorana masses, certain Yukawas, μ-terms

D-brane instantons

D-brane instanton = Euclidean D-brane $\mathcal{E}$ along non-trivial cycle of compactification manifold and pointlike in spacetime

Type II orientifolds on quotient CY_3/σ

- Type IIA: D6-branes and E2-inst.
- Type IIB: D7/D3-branes and E3/E(-1)-inst.
- Type I: D9/D5-branes and E5/E1-inst.



Distinguish **2 types of D-brane instantons $\mathcal{E}$** on cycle Ξ

- cycle Ξ wrapped by spacetime-filling D-brane $\mathcal{D}$
  $\rightarrow$ **gauge instanton** associated with gauge group of D-brane
- cycle Ξ not wrapped by any D-brane
  $\rightarrow$ **'stringy/exotic instanton'**

Instantons

worldsheet instantons:

in heterotic compactifications [Dine,Seiberg,Wenn,Witten'86], [Distler,Greene'88], [Witten'99], [Buchbinder,Donagi,Ovrut'02]

in IIA brane models [Kachru et al.'00], [Aganacic,Vafa'00]

spacetime instantons:

in M/F-theory [Becker,Becker,Strominger'95],[Witten '96],[Ganor '96], [Harvey, Moore'99]

CFT aspects of D-instantons [Polchinski'94], [Green,Gutperle'97,'00]

ADHM instantons [Witten '95], [Douglas '95], [Billo et al.'02]

More recently: stringy instanton effects in matter sector of Type II [Blumenhagen,Cvetič,TW], [Ibanez,Uranga], [Florea,McGreevy,Kachru,Saulina] '06 see also [Haack,Krefl,Lüst,VanProeyen,Zagermann] '06

This talk: Focus on $F-$terms from BPS D-brane instantons
$\rightsquigarrow$ subtleties of F-term generation in type II setups
$\rightsquigarrow$ generation of hierarchical matter superpotentials

BPS-instanton zero modes

1) Open strings in $\mathcal{E}-\mathcal{E}$ sector

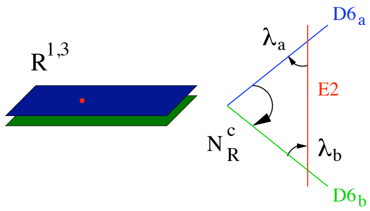
- universal zero modes:
  $\rightsquigarrow$ 4 bosonic modes x^i_E
  $\rightsquigarrow$ for generic BPS instanton $\mathcal{E} \neq \mathcal{E}'$:
  2 + 2 Goldstinos θ_α, $\overline{\tau}_{\dot\alpha}$

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

- deformation/Wilson line modes:
  E.g. E2 in IIA (generic $\mathcal{E} \neq \mathcal{E}'$): $c_I, \chi^\alpha_I, \quad \overline{c}_I, \overline{\chi}^{\dot\alpha}_I$, $I = 1, \ldots, b_1(\Xi)$

2) Boundary changing open strings with one end on $\mathcal{E}$

- $\mathcal{E}-\mathcal{E}'$ sector or $\mathcal{E}_i-\mathcal{E}_j$ sector (multi-instantons)
- Charged zero modes in $\mathcal{E}$-$\mathcal{D}$ sector
  at each chiral "intersection":
  1 chiral fermionic zero mode
  $\Rightarrow$ phenomenologically interesting couplings (see part II)



F-terms from Instantons

Superpotential measure: $\int d^4x\, d^2\theta$
$\rightsquigarrow$ General lore: need BPS instantons $\leftrightarrow$ minimal of Goldstinos
$\rightsquigarrow$ requires lifting all extra zero modes without inducing higher derivatives

The fate of Goldstinos $\overline{\tau}^{\dot\alpha}$

- gauge instantons:
  Lagrange multiplier enforcing bosonic ADHM constraints
  [Billo,Frau,Pesando,Fucito,Lerda,Liccardo 0211250];
  [Akerblom,Blumenhagen,Lüst,Plauschinn,Schmidt-Sommerfeld 0612132]
  special case: $\mathcal{E}$ parallel to single $(U(1))$ brane
  [Aharony,Kachru 0707.3126]; [Petersson 0711.1837]
- $\mathcal{O}(1)$ instanton along cycle $\Xi = \Xi'$ with suitable orientifold action:
  $\overline{\tau}^{\dot\alpha}$ projected out [Argurio,Bertolini,Franco,Kachru 0703236];
  [Argurio,Bertolini,Ferretti,Lerda,Petersson 0704.0262]; [Bianchi,Fucito,Morales 0704.0784]; [Ibanez,Schellekens,Uranga 0704.1079]

F-terms from Instantons

$\overline{\tau}^{\dot\alpha}$ lifting (continued)

- lifting via background flux [Blumenhagen,Cvetič,Richter,TW 0708.0403]

  $\rightsquigarrow$ **E3-instanton in $IIB/\Omega\sigma(-1)^{F_L}$**

  $S = \int_\Gamma \omega \left(e^{-\phi}\, \Gamma^{\tilde m} \nabla_{\tilde m} + \frac{1}{8}\, \widetilde{G}_{\tilde m \tilde n p}\, \Gamma^{\tilde m \tilde n p} \right) \omega$ [Tripathy,Trivedi; Bergshoeff et al.;Park; Martucci et al.'05]

  $\Rightarrow$ no lifting of $\overline{\tau}$ for (2,1) primitive or (0,3) 3-form flux alone

  But: lifting via $G_{ij\overline{k}}$ + terms linear self-dual magn. flux $\in H^2_-(E3)$:

  $S_{E3}(\mathcal{F}) = \int_\Gamma \omega\, \Gamma^{\tilde i p q} \omega\ \mathcal{F}_{\tilde i}^{\ \tilde j}\, G_{\tilde j p q}$ [BCRW 0708.0403]

  $\rightsquigarrow$ **Fractional D1-instantons:** also $(0,3)$ flux lifts $\overline{\tau}$:

  [Billo,Ferro,Frau,Fucito,Lerda,Morales 0807.1666, 0807.4098]

  see also in Type I: [Bianchi,Kiritsis 0702015]

- lifting via zero mode interactions from $\mathcal{E} - \mathcal{E}'$ sector:

  [Blumenhagen,Cvetič,Richter,TW 0708.0403], [Garcia,Uranga 0711.1430],

  [Cvetič,Richter,TW 0803.2513], [Garcia,Marchesano,Uranga 0805.0713]

Beasley-Witten F-terms

Unlifted $\overline{\tau}^{\dot\alpha}$ $\Rightarrow$ higher-derivative Beasley-Witten F-terms

[Blumenhagen,Cvetič,Richter, TW 0708.0403]

Reason: $\int d^4x\, d^2\theta\, d^2\,\overline{\tau}$ not associated with full $\mathcal{N}=1$ superspace!

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

BPS instantons with extra anti-chiral zero modes $\rightarrow$ multi-fermion F-terms

$S = \int d^4x\, d^2\theta\, w_{\bar i_1 \ldots \bar i_n \bar j_1 \ldots \bar j_n}(\Phi)\, \overline{\mathcal{D}}^{\dot\alpha} \overline{\Phi}^{\bar i_1} \overline{\mathcal{D}}_{\dot\alpha} \overline{\Phi}^{\bar j_1} \ldots \overline{\mathcal{D}}^{\dot\alpha} \overline{\Phi}^{\bar i_n} \overline{\mathcal{D}}_{\dot\alpha} \overline{\Phi}^{\bar j_n}$

in context of heterotic worldsheet instantons: [Beasley,Witten '05]

Here: $\overline{\tau}$ modes couple at disk-level to closed hypermultiplets:
E.g. E2 in IIA with compl. struct. U^i $\langle \theta\, \overline{U}^i\, \overline{\tau} \rangle \rightarrow \theta\, \sigma^\mu\, \overline{\tau}\, \partial_\mu \overline{U}^i$

$S = \int d^4x\, d^2\theta\, e^{-\mathcal{U}(\Xi)}\, f_{\bar i, \bar j}\left(\Phi_{op}, e^{\mathcal{T}_i}, e^{\Delta_i}\right)\, \overline{\mathcal{D}}^{\dot\alpha} \overline{\mathcal{U}}^i\, \overline{\mathcal{D}}_{\dot\alpha} \overline{\mathcal{U}}^j + \ h.c.$

By contrast: D-terms require deviation from BPSness

[Garcia,Marchesano,Uranga 0805.0713]

F-terms from Instantons

Deformation modes:

Consider for simplicity only $\mathcal{O}(1)$ instantons in IIA

$\Longrightarrow$ deformations $c_I, \chi_I^\alpha, \overline{c}_I, \overline{\chi}_I^{\dot\alpha}$ subject to orientifold projection

- c_I, $\overline{c}_I$, $\overline{\chi}_I^{\dot\alpha}$ survives, χ_I^α projected out

  $\Rightarrow$ Beasley-Witten F-terms for vector-multiplets:

  e.g. IIA: $S = \int d^4x\, d^2\theta\, e^{-\mathcal{U}(\Xi)}\, f_{\overline{i},\overline{j}}\left(\Phi_{op}, e^{\mathcal{T}_i}, e^{\Delta_i}\right) \overline{\mathcal{D}}^{\dot\alpha}\overline{\mathcal{T}}^{\overline{i}}\overline{\mathcal{D}}_{\dot\alpha}\overline{\mathcal{T}}^{\overline{j}}$ [BCRW 0708.0403]

  more on BW-F-terms: e.g. [Matsuo,Park,Ryou,Yamamoto 0803.0798], [Billo et al. 0807.1666, 0807.4098]

- χ^α survives, c_I, $\overline{c}_I$, $\overline{\chi}_I^{\dot\alpha}$ projected out

  $\Rightarrow$ instanton corrections to gauge kinetic function

  [Akerblom,Blumenhagen,Lüst,Schmidt-Sommerfeld 0705.2366]

  in agreement with heterotic-Type I duality:

  [Camara,Dudas,Maillard,Pradisi 0710.3080]

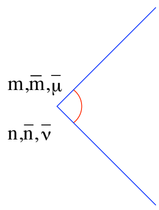
Lifting Goldstinos $\overline{\tau}^{\dot\alpha}$

Consider Type IIA w/ pair of $E2 - E2'$ instantons at SUSY angle and intersection on top of orientifold:

1) Minimal vector-like case:

$n^+ = n^- = 1$

$\mathcal{E} - \mathcal{E}'$ **modes**: $m_{\mathcal{E}-\mathcal{E}'}$, $\overline{m}_{\mathcal{E}'-\mathcal{E}}$, $\overline{\mu}^{\dot\alpha}{}_{\mathcal{E}'-\mathcal{E}}$,
$n_{\mathcal{E}'-\mathcal{E}}$, $\overline{n}_{\mathcal{E}-\mathcal{E}'}$, $\overline{\nu}^{\dot\alpha}{}_{\mathcal{E}-\mathcal{E}'}$



fermionic instanton moduli action: [Blumenhagen,Cvetič,Richter,TW 0708.0403]

$S_{fermionic} = m\,\overline{\mu}^{\dot\alpha}\,\overline{\tau}_{\dot\alpha} - n\,\overline{\nu}^{\dot\alpha}\,\overline{\tau}_{\dot\alpha}$

Integrate out $\overline{\tau}^{\dot\alpha}$ and combination $(\overline{\mu}^{\dot\alpha} - \overline{\nu}^{\dot\alpha})$

In absence of further interactions

$\overline{\chi}^{\dot\alpha} = \overline{\mu}^{\dot\alpha} + \overline{\nu}^{\dot\alpha}$ unlifted $\Rightarrow$ no superpotential, but higher fermionic F-terms of Beasley-Witten type

If $\exists$ quartic F-terms $(MN)^2$ [Garcia-Etxebarria,Uranga 0711.1430]:

$\Rightarrow$ $\overline{\chi}^{\dot\alpha}$ lifted and superpotential contributions possible

Instantons and threshold stability

In agreement with moduli dependence of distinction between invariant/ non-invariant cycle

bosonic modes $m, n \Longleftrightarrow$ (re)combination moduli! [BCRW 0708.0403]

(re)combination governed by usual D-term in instanton effective action:

$S_D = \frac{1}{2g_{\mathcal{E}}^2}(2m\overline{m} - 2n\overline{n} - \xi)^2$

in $\mathcal{M}_0$: $\xi = 0$, instanton (singular) union $\mathcal{E} \cup \mathcal{E}'$: U(1) locus

in $\mathcal{M}_+$: $\xi > 0$, condensation of $m \to$ bound state $\mathcal{E}'\#\mathcal{E}$

in $\mathcal{M}_-$: $\xi < 0$, condensation of $n \to$ bound state $\mathcal{E}\#\mathcal{E}'$

$\Rightarrow$ in $\mathcal{M}_\pm$: single invariant $O(1)$ instanton $\leftrightarrow$ universal measure $d^4x\, d^2\theta$

- if rigid: superpotential contribution
- if $\exists$ deformation modes: higher fermionic F-terms of Beasley-Witten type

General lesson: [GU 0711.1430]

Lifting of modes on $\mathcal{M}_0$ $\leftrightarrow$ continuity of F-terms across line of threshold stability to ensure holomorphicity of F-terms

Instantons and marginal stability

2) Chiral intersection $n^+ = 1, n^- = 0$ [BCRW, 0708.0403]

$E - E'$ modes: $m, \overline{m}, \overline{\mu}^{\dot{\alpha}}$ $\quad S_D = \frac{1}{2g_{\mathcal{E}}^2}(2m\overline{m} - \xi)^2$

in $\mathcal{M}_0$: $\xi = 0$, instanton (singular) union $\mathcal{E} \cup \mathcal{E}'$: U(1) locus

in $\mathcal{M}_+$: $\xi > 0$, condensation of $m \to$ bound state $\mathcal{E}'\#\mathcal{E}$

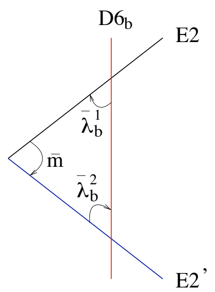
in $\mathcal{M}_-$: $\xi < 0$, no BPS state of charge $[\mathcal{E}] + [\mathcal{E}']$ exists!

$\mathcal{E} \cup \mathcal{E}'$ and $\mathcal{E}'\#\mathcal{E}$ do not contribute F-terms **due to global constraints**

Consider $\mathcal{E} \cup \mathcal{E}'$ on $\mathcal{M}_0$:

by tadpole cancellation $\exists$ charged fermionic zero modes λ^i in instanton - D-brane sector of charge $Q_{\mathcal{E}} = -4\Xi \circ \Pi_{O6}$ under $U(1)_{\mathcal{E}}$

No perturbative couplings in instanton effective action can lift these chiral excess modes λ^i



Instantons and marginal stability

Non-perturbative lifting of λ^i via multi-instanton possible! [CRW, 0803.2513]

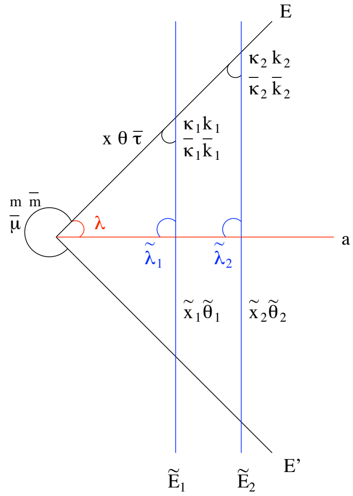
Consider in addition 2 $O(1)$ instantons $\widetilde{E}_1, \widetilde{E}_2$ along $\widetilde{\Xi}_1, \widetilde{\Xi}_2$

- lifts all fermionic zero modes
- bosonic moduli action:

$S_D = \frac{1}{2g_E^2}\left(2m\overline{m} - k_1\overline{k}_1 - k_2\overline{k}_2 - \xi\right)^2,$

$S_F = l^2\left(|k_1^2 + k_2^2|^2 + |m\, k_1|^2 + |m\, k_2|^2\right)$

$\exists$ BPS bound state for $\xi > 0$ and for $\xi < 0$! no jump in BPS spectrum relevant for W



Microscopic explanation of general phenomenon:
details of instanton recombination guarantee holomorphicity of superpotential [GMU 0805.0713]

More on multi-instantons

2-instanton systems $\mathcal{E} - \mathcal{E}'$ inevitable on covering space of Type II orientifolds [BCRW 0708.0403]

Extension to multi-instantons $\mathcal{E}_i - \mathcal{E}_j$:

- lifting of $\mathcal{E}_i - \mathcal{E}_j$ couplings by tree-level couplings of similar type as in $\mathcal{E} - \mathcal{E}'$ sector [GU 0711.1430],[GMU 0805.0713]
- higher instanton corrections due to lifting of modes at loop-level [Blumenhagen,Schmidt-Sommerfeld 0803.1562] [Camara,Dudas 0806.3102]

  applications to moduli stabilisation/generation of hierarchies: [Blumenhagen,Moster,Plauschinn 0806.2667]

Perturbatively forbidden couplings

gauge group on D-branes $\prod_a U(N_a) = \prod_a SU(N_a) \times U(1)_a$
in general: $U(1)_a$ becomes massive via CS-couplings to RR-forms

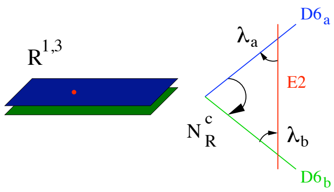
$\Rightarrow$ charged axions $a_\Xi = \int_\Xi C$: $A_a \rightarrow A_a + d\Lambda_a$, $\quad a_a \rightarrow a_a + \Lambda_a \, (\Xi \circ \Pi_a)$

$\Rightarrow \quad e^{-S_\mathcal{E}} = \exp\left[2\pi\left(-\frac{\mathrm{Vol}_\Xi}{g_s} + i a_\Xi\right)\right]$ not $U(1)_a$ invariant if $\Xi \circ \Pi_a \neq 0$

only $W = \prod_i \Phi_i \; e^{-S_\mathcal{E}}$ $\quad$ with $\quad \sum_i Q_a(\Phi_i) + Q_a(\Xi) = 0 \;\; \forall a$ possible

Microscopic origin:

disk-level couplings $S = \int_\Xi \lambda_a \, \Phi_{ab} \lambda_b$
$Z = \int d^4x \, d^2\theta \, d\lambda \, e^{-S_{cl} + \int_\Xi \lambda_a \, \Phi_{ab} \lambda_b}$
$\Longrightarrow W = \prod_i \phi^i e^{-S_{cl.}}$



[Blumenhagen,Cvetič,TW], [Ibanez,Uranga], [Florea,McGreevy,Kachru,Saulina] '06

Details of loop-computations [BCW] '06; [Abel,Goodsell 0612110],
[Akerblom,Blumenhagen,Lüst,Schmidt-Sommerfeld 0612132, 0705.2366],
[Billo,Frau,Pesano,DiVecchia,Lerda,Marotta 0708.3806, 0709.0245]

Applications

2 far-reaching consequences for string phenomenology:

1.) Generation of perturbatively forbidden open string couplings $\prod_i \Phi_i$
$\rightsquigarrow$ Majorana masses for right-handed neutrinos
[Blumenhagen,Cvetič,TW],[Ibanez,Uranga] '06; [Cvetič,Richter,TW];
[Ibanez,Schellekens,Uranga]; [Antusch,Ibanez,Macri]; [Cvetič,TW] '07
$\rightsquigarrow$ or suppressed Dirac neutrino masses [Cvetič,Langacker '08]
$\rightsquigarrow$ generation of weak-scale μ-term $\mu \, H_u \, H_d$ [BCW;IU '06];
$\rightsquigarrow$ perturbatively forbiden **10 10 5** in (flipped) SU(5) GUT
$\leftrightarrow$ low g_s analogue of M/F-theory! [Blumenhagen,Cvetič,Richter,Lüst,TW] '07;
$\rightsquigarrow$ applications to SUSY breaking F-terms [Florea,McGreevy,Kachru,Saulina]'06
$\rightsquigarrow$ instanton-induced SUSY breaking mediation [Buican,Franco]'08

2.) moduli stabilisation if $\langle \Phi_i \rangle = 0$ (e.g. as in applications above)
volume modulus of instanton cycle cannot be stabilised by non-pert. terms!
need D-terms [Blumenhagen,Plauschinn,Moster]'07
and/or non-trivial Kähler potential corrections [Cicoli,Conlon,Quevedo]'08

F-term SUSY breaking

Stringy Polonyi models:

$\mathbf{W} = \mu^2 \mathbf{S} + \mathbf{c}, \qquad \mu^2 = \mathbf{x}\, \mathbf{M_s^2}\, \mathbf{e}^{-\mathbf{S}_\mathcal{E}}$ [Aharony,Kachru,Silverstein 0708.0493]

$\rightsquigarrow$ either: S adjoint open modulus $\Leftrightarrow$ instanton w/vectorlike zero modes
$\rightsquigarrow$ or charged field $S_{(-1_a,1_b)}$ from massive $U(1)_a \times U(1)_b$ sector

suitable for gauge mediation $\leftrightarrow$ messenger pair $q, \tilde{q}$ with $\lambda\, S\, q\, \tilde{q}$
$\Rightarrow$ requires stabilisation of $\langle S \rangle \neq 0$ in metastable minimum, e.g

- in absence of any other terms involving S in W:
  quartic corrections in Kähler potential stabilise S in SUGRA
  $K = SS^\dagger - \frac{|c|}{\Lambda^2}(SS^\dagger)^2$ [Kitano 0607090],[Kallosh,Linde 0611183]
  W realised in global Type I models in [Cvetič,TW 0711.0209];
  and in local F-theory GUTs: [Heckman,Marsano,Saulina,Schäfer-Nameki,Vafa 0808.1286],[Marsano,Saulina,Schäfer-Nameki 0808.1571]
- or by quartic non-renormalisable terms involving $\tilde{S}_{(1_a,-1_b)}$ in W
  [Cvetič,TW 0807.3953]

E1-instantons in Type I

Consider Type I with stacks of $n_a \times N_a$ D9-branes w/ stable holomorphic $U(n_a)$ bundle V_a
$\Rightarrow$ gauge group $U(N_a)$: $U(n_a) \subset U(n_a \times N_a) \to U(N_a)$

E1-instanton wrapping holomorphic curve C
- 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:
only chiral fermionic modes present

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

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 $\Gamma_i \cap C \neq 0$

Hidden sector dynamics from instantons

Implementation of hidden sector e.g. in context of SU(5) GUT quiver

$N_c = 5$: SU(5)-GUT stack, $N_d = 1$ Hidden sector: $N_a = N_b = 1$

Particle	Charge	Sector	Particle	Charge	Sector
(Q_L, U_R^c, e_R^c)	$\mathbf{10}_{2c}$	(c', c)	S	$(-1_a, 1_b)$	(a, b)
(L, D_R^c)	$\overline{\mathbf{5}}_{(1_d, -1_c)}$	(c, d)	$\tilde{S}$	$(1_a, -1_b)$	(b, a)
Higgs	$\mathbf{5}_{(1_d, 1_c)}$	(d', c)	q	$\mathbf{5}_{(-1_b, 1_c)}$	(b, c)
N_R^c	1_{-2d}	(d, d')	$\tilde{q}$	$\overline{\mathbf{5}}_{(1_a, -1_c)}$	(c, a)

$W = M_s^2\, S_{(-1_a, 1_b)}$ not $U(1)$-invariant

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

$\Rightarrow V_a|_{\mathbb{P}^1} = \mathcal{O}_{\mathbb{P}^1}(1), \qquad V_b|_{\mathbb{P}^1} = \mathcal{O}_{\mathbb{P}^1}(-1)$

Challenge in global constructions: ensure absence of additional charged zero modes from other branes:

$V_c|_{\mathbb{P}^1} = \mathcal{O}_{\mathbb{P}^1}(0), \quad V_d|_{\mathbb{P}^1} = \mathcal{O}_{\mathbb{P}^1}(0)$

Hierarchies from instantons

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

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

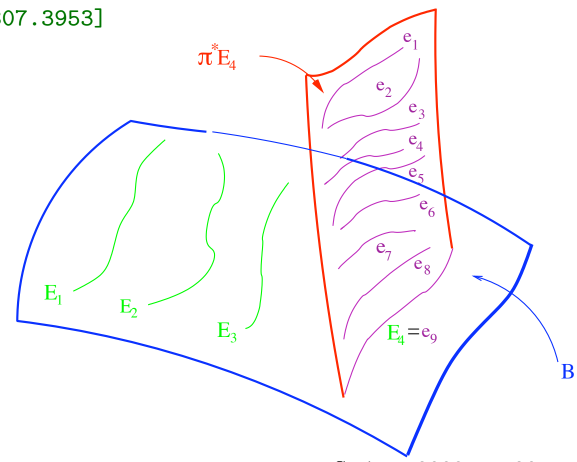
Type I relation: $M_s \simeq \mathcal{O}(10^{17} GeV)$ from $M_s^2 = 2\pi\,(M_{Pl.}^{\mathrm{red}})^2\, g_s\, \alpha_{GUT}$

for TeV soft masses need $\mu = 10^{-10} M_s^{1/4} \leftrightarrow \mathrm{Vol}_C/\tilde{f}_{GUT} \simeq 0.27$

realised in explicit globally defined toy models on elliptic fibration

$\pi : X \longrightarrow dP_4$ [Cvetič,TW 0711.0209 and 0807.3953]

- divisors $\pi^*(E_i) \subset X$ contain rigid $\mathbb{P}^1$ contributing as instantons
- engineer line bundles on D9-branes to satisfy zero mode constraints



Hierarchies from instantons

Globally consistent toy model with 4 chiral families of **10** (+ vector pairs)

- explicit cancellation of D9-, D5- tadpoles and K-theory charges
- D-term supersymmetry conditions on line bundles have solutions inside Kähler cone such that $Vol_C = 2.6\ell_s^2 \Rightarrow \mu = 10^{-10}$ for $g_s = 0.4$

Clearly just first step: have to stabilise closed moduli in this regime
If $F_{closed} \neq 0$: gravity/anomaly mediation from closed sector may be compatible or dominant

$\Longrightarrow$ Aim: Implementation in semi-realistic vacua worth further phenomenological studies

Construction of similar globally defined SU(5) toy models with instanton-induced Majorana masses for N_R^c [Cvetič,TW 0711.0209]

Summary

Since Strings 2007: a lot of activity related to D-brane instantons in Type II orientifolds, including (and not restricted to) :

Technical aspects:

$\rightsquigarrow$ F-terms from instantons along non-invariant cycles
$\rightsquigarrow$ role of multi-fermion F-terms
$\rightsquigarrow$ towards better understanding of effects of background fluxes
$\rightsquigarrow$ incorporation of multi-instanton effects
$\rightsquigarrow$ behaviour across lines of threshold/marginal stability
so far: explicit analysis restricted to local behaviour near lines of stability
What can be said beyond? summation of D-brane instanton effects?

Phenomenological applications:

$\rightsquigarrow$ new phenomenologically desirable couplings
$\rightsquigarrow$ implementation into globally consistent string vacua
$\rightsquigarrow$ interplay of charged zero modes - moduli stabilisation
$\rightsquigarrow$ applications to SUSY breaking and its mediation