Argyres-Seiberg duality and the Higgs branch

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in collaboration with
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[arXiv:0810.4541]

IPMU, December, 2008

Introduction

- Montonen-Olive S-duality in $\mathcal{N} = 4$ theory
- Seiberg-duality in $\mathcal{N} = 1$ theory

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Argyres-Seiberg, Nov 2007

a totally new class of S-duality in $\mathcal{N} = 2$ theory

- Richer structure !
- [Argyres-Wittig] [Aharony-YT] [Shapere-YT]

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a totally new class of S-duality in $\mathcal{N} = 2$ theory

- Richer structure !
- [Argyres-Wittig] [Aharony-YT] [Shapere-YT]

- Today: Higgs branch side of the story

Contents

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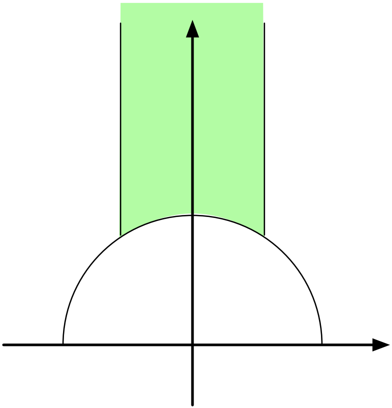
Montonen-Olive S-duality

$\mathcal{N} = 4$ SU(N)

$$\tau = \frac{\theta}{2\pi} + \frac{4\pi i}{g^2}$$

$$\tau \to \tau + 1, \qquad \tau \to -\frac{1}{\tau}$$

- Exchanges monopoles W-bosons
- Comes from S-duality of Type IIB



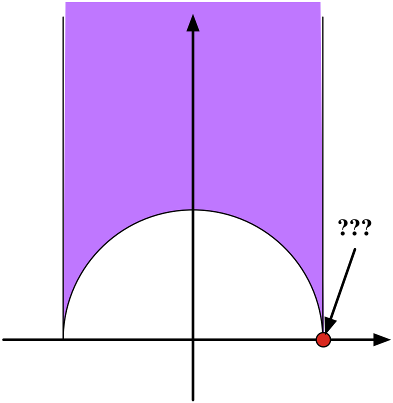
S-duality in $\mathcal{N} = 2$

SU(3) with $N_f = 6$

$$\tau = \frac{\theta}{\pi} + \frac{8\pi i}{g^2}$$

$$\tau \to \tau + 2, \qquad \tau \to -\frac{1}{\tau}$$

- Exchanges monopoles and quarks
- Infinitely Strongly coupled at $\tau = 1$



New S-duality [Argyres-Seiberg]

SU(3) + 6 flavors

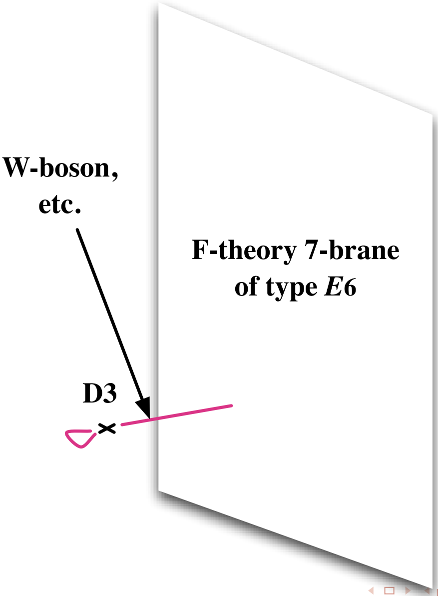
at coupling τ

$\updownarrow$

SU(2) + 1 flavor + SCFT[E_6]

at coupling $\tau' = 1/(1-\tau)$, $\mathbf{SU(2)} \subset E_6$ is gauged

SCFT[E_6]

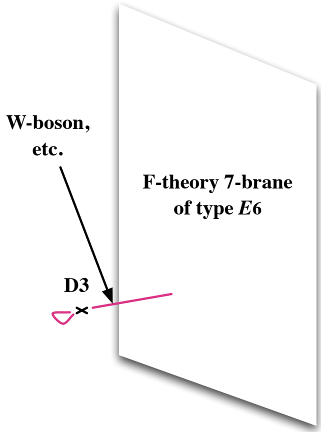


- a 3-brane probing F-theory singularity of type E_6.

- Gauge symmetry on 7-brane
  → Flavor symmetry on 3-brane
- Motion transverse to 7-brane
  → Vector multiplet moduli u,
- Motion parallel to 7-brane
  → free hypermultiplet, discard

- Conformal when $u = 0$, $\dim(u) = 3$

- Family of Seiberg-Witten curve is the elliptic fibration of F-theory.



Argyres-Seiberg: Dimensions

SU(3) + 6 flavors

$$\dim(\mathrm{tr}\,\phi^2) = 2, \qquad \dim(\mathrm{tr}\,\phi^3) = 3$$

$$\Updownarrow$$

SU(2) + 1 flavor + SCFT[E_6]

$$u \text{ of SU(2)} : \dim = 2, \qquad u \text{ of SCFT}[E_6] : \dim = 3$$

Argyres-Seiberg: Flavor symmetry

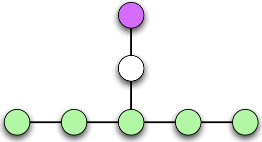
SU(3) + 6 flavors

- Flavor symmetry: $\mathbf{U(6)} = \mathbf{U(1)} \times \mathbf{SU(6)}$

$\Updownarrow$

SU(2) + 1 flavor + SCFT[E_6]

- $\mathbf{SO(2)}$ acts on 1 flavor = 2 half-hyper of $\mathbf{SU(2)}$ doublet
- $\mathbf{SU(2)} \subset E_6$ is gauged
- $\mathbf{SU(2)} \times \mathbf{SU(6)} \subset E_6$ is a maximal regular subalgebra



Current Algebra Central Charge

Normalize s.t. a free hyper in the fund. of $\mathbf{SU}(N)$ contributes $\mathbf{2}$ to k_G

$$J^a_\mu(x) J^b_\nu(0) = \frac{3}{4\pi^2} k_G \delta^{ab} \frac{x^2 g_{\mu\nu} - 2x_\mu x_\nu}{x^8} + \cdots$$

A bifundamental hyper under $\mathbf{SU}(N) \times \mathbf{SU}(M)$

$$\longrightarrow k_{\mathrm{SU}(N)} = 2M, \qquad k_{\mathrm{SU}(M)} = 2N$$

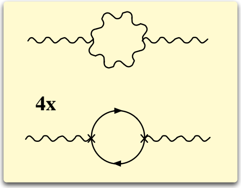
SU(3) + 6 flavors

$$k_{\mathrm{SU}(6)} = 6$$

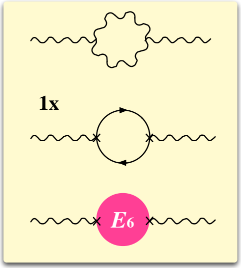
k for SCFT[E_6]

$\mathrm{SU}(2) \subset E_6$ central charge:

$SU(2)$ + 4 flavors

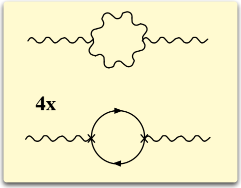


$SU(2)$ + 1 flavor + SCFT[E_6]

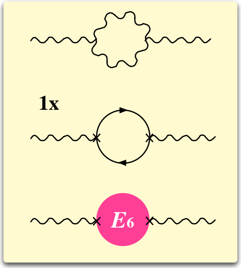


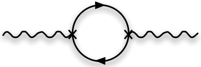
SU(2) $\subset E_6$ central charge:

$SU(2)$ + 4 flavors



$SU(2)$ + 1 flavor + SCFT[E_6]





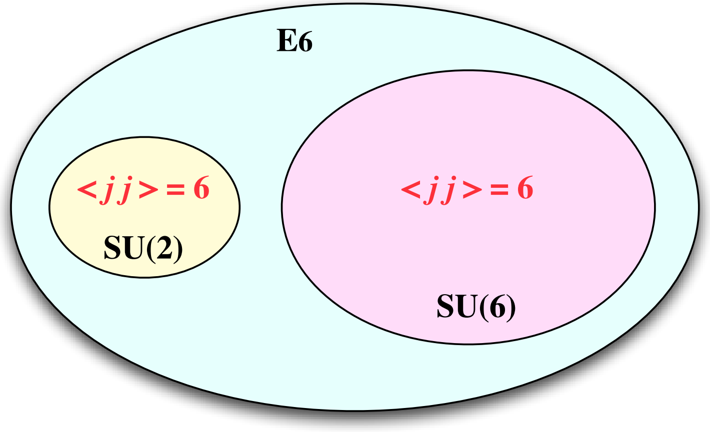
$= \langle j_\mu j_\nu \rangle_{\text{free hyper}}$

$= \langle j_\mu j_\nu \rangle_{\text{SCFT}[E_6]}$

$$\Rightarrow \quad \langle j_\mu j_\nu \rangle_{\text{SCFT}[E_6]} = 3 \langle j_\mu j_\nu \rangle_{\text{free hyper}}$$

$$= 6$$

k for SCFT[E_6]



$k_{\mathrm{U}(1)}$

$\mathrm{SU}(3) + 6$ flavors

- $k_{\mathrm{U}(1)} = 3 \times 6 = 18$

$$\updownarrow$$

$\mathrm{SU}(2) + 1$ flavor $+ \mathrm{SCFT}[E_6]$

- $k_{\mathrm{U}(1)} = 2 \times 1 \times q^2 \longrightarrow q = 3$

Matching Seiberg-Witten curves

Argyres & Seiberg studied the SW curve on the both sides, and found

$$\text{Curve of } \mathbf{SU(3)} \text{ theory with generic masses } \sum_i m_i Q^i \tilde{Q}_i$$

$$\text{at } \tau \to 1$$

$$\supset \text{Curve of } \mathbf{SCFT}[E_6] \text{ with masses to } \mathbf{SU(6)} \subset E_6$$

I won't (can't) explain it today ...

Another example: E_7

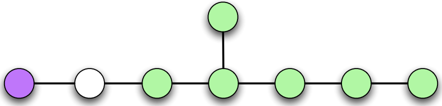
USp(4) + 12 half-hypers in 4

- $\dim(\mathrm{tr}\,\phi^2) = 2$, $\dim(\mathrm{tr}\,\phi^4) = 4$
- $k_{SO(12)} = 8$

$\updownarrow$

SU(2) w/ SCFT[E_7]

- $\dim(\mathrm{tr}\,\phi^2) = 2$ from SU(2), $\dim(u) = 4$ from SCFT[E_7]
- $SU(2) \times SO(12) \subset E_7$
- $k_{SU(2) \subset E_7} = 8$



	$\mathfrak{g}$	w/ $\mathbf{r}$	=	$\widetilde{\mathfrak{g}}$	w/ $\widetilde{\mathbf{r}}$	$\oplus$ SCFT$[d:\mathfrak{h}]$
1.	sp(3)	$\mathbf{14}\oplus 11\cdot\mathbf{6}$	=	sp(2)		$[6:E_8]$
2.	su(6)	$\mathbf{20}\oplus\mathbf{15}\oplus\overline{\mathbf{15}}\oplus 5\cdot\mathbf{6}\oplus 5\cdot\overline{\mathbf{6}}$	=	su(5)	$\mathbf{5}\oplus\overline{\mathbf{5}}\oplus\mathbf{10}\oplus\overline{\mathbf{10}}$	$[6:E_8]$
3.	so(12)	$3\cdot\mathbf{32}\oplus\mathbf{32}'\oplus 4\cdot\mathbf{12}$	=	so(11)	$3\cdot\mathbf{32}$	$[6:E_8]$
4.	G_2	$8\cdot\mathbf{7}$	=	su(2)	$\mathbf{2}$	$[6:\mathrm{sp}(5)]$
5.	so(7)	$4\cdot\mathbf{8}\oplus 6\cdot\mathbf{7}$	=	sp(2)	$5\cdot\mathbf{4}$	$[6:\mathrm{sp}(5)]$
6.	su(6)	$\mathbf{21}\oplus\overline{\mathbf{21}}\oplus\mathbf{20}\oplus\mathbf{6}\oplus\overline{\mathbf{6}}$	=	su(5)	$\mathbf{10}\oplus\overline{\mathbf{10}}$	$[6:\mathrm{sp}(5)]$
7.	sp(2)	$12\cdot\mathbf{4}$	=	su(2)		$[4:E_7]$
8.	su(4)	$2\cdot\mathbf{6}\oplus 6\cdot\mathbf{4}\oplus 6\cdot\overline{\mathbf{4}}$	=	su(3)	$2\cdot\mathbf{3}\oplus 2\cdot\overline{\mathbf{3}}$	$[4:E_7]$
9.	so(7)	$6\cdot\mathbf{8}\oplus 4\cdot\mathbf{7}$	=	G_2	$4\cdot\mathbf{7}$	$[4:E_7]$
10.	so(8)	$6\cdot\mathbf{8}\oplus 4\cdot\mathbf{8}'\oplus 2\cdot\mathbf{8}''$	=	so(7)	$6\cdot\mathbf{8}$	$[4:E_7]$
11.	so(8)	$6\cdot\mathbf{8}\oplus 6\cdot\mathbf{8}'$	=	G_2		$[4:E_7]\oplus[4:E_7]$
12.	sp(2)	$6\cdot\mathbf{5}$	=	su(2)		$[4:\mathrm{sp}(3)\oplus\mathrm{su}(2)]$
13.	sp(2)	$4\cdot\mathbf{4}\oplus 4\cdot\mathbf{5}$	=	su(2)	$3\cdot\mathbf{2}$	$[4:\mathrm{sp}(3)\oplus\mathrm{su}(2)]$
14.	su(4)	$\mathbf{10}\oplus\overline{\mathbf{10}}\oplus 2\cdot\mathbf{4}\oplus 2\cdot\overline{\mathbf{4}}$	=	su(3)	$\mathbf{3}\oplus\overline{\mathbf{3}}$	$[4:\mathrm{sp}(3)\oplus\mathrm{su}(2)]$
15.	su(3)	$6\cdot\mathbf{3}\oplus 6\cdot\overline{\mathbf{3}}$	=	su(2)	$2\cdot\mathbf{2}$	$[3:E_6]$
16.	su(4)	$4\cdot\mathbf{6}\oplus 4\cdot\mathbf{4}\oplus 4\cdot\overline{\mathbf{4}}$	=	sp(2)	$6\cdot\mathbf{4}$	$[3:E_6]$
17.	su(3)	$\mathbf{3}\oplus\overline{\mathbf{3}}\oplus\mathbf{6}\oplus\overline{\mathbf{6}}$	=	su(2)	$n\cdot\mathbf{2}$	$[3:\mathfrak{h}]$

Table 2: Predicted dualities with one marginal operator.

Advertisement [Aharony-YT]

Central charges:

$$\langle T^\mu_\mu \rangle = a \cdot \textbf{Euler} + c \cdot \textbf{Weyl}^2$$

calculable for $\textbf{SCFT}[E_{6,7}]$ using

- **SU(3)** w/ 6 flavors ↔ **SU(2)** + 1 flavor + $\textbf{SCFT}[E_6]$
- **USp(4)** w/ 12 flavors ↔ **SU(2)** + $\textbf{SCFT}[E_7]$

We performed holographic calculation for $\textbf{SCFT}[E_{6,7,8}]$

G	E_6	E_7	E_8
k_G	6	8	12
$24a$	41	59	95
$6c$	13	19	31

It was done before publication of [Argyres-Wittig]
Perfectly agreed ! Power of string theory.

Contents

Objective

- Argyres & Seiberg studied the story on the Coulomb branch side.
- I wanted to know the Higgs branch side of the story.

Objective

- Argyres & Seiberg studied the story on the Coulomb branch side.
- I wanted to know the Higgs branch side of the story.
- I have two friends who are experts on hyperkähler things !

$\mathcal{N} = 1$ Seiberg duality

SU(N) w/ N_f flavors q^i, $\tilde{q}_j$

- $m^i_j = q^i_a \tilde{q}^b_j$
- $b^{i_1 i_2 \cdots i_{N_f}} = \epsilon^{a_1 a_2 \ldots a_N} q^{i_1}_{a_1} q^{i_2}_{a_2} \cdots q^{i_N}_{a_N}$
- $\tilde{b}_{i_1 i_2 \cdots i_{N_f}} = \epsilon_{a_1 a_2 \ldots a_N} \tilde{q}^{a_1}_{i_1} \tilde{q}^{a_2}_{i_2} \cdots \tilde{q}^{a_N}_{i_N}$

$\Updownarrow$

SU(N') w/ N_f flavors Q_i, $\tilde{Q}^i$

- w/ singlets $M^i_{j'}$, $W = Q_i \tilde{Q}^j M^i_j$
- $N' = N - N_f$
- $B_{j_1 j_2 \cdots j_{N'}} = \epsilon_{a_1 a_2 \ldots a_{N'}} Q^{a_1}_{j_1} Q^{a_2}_{j_2} \cdots Q^{a_{N'}}_{j_{N'}}$
- $\tilde{B}^{j_1 j_2 \cdots j_{N'}} = \epsilon^{a_1 a_2 \ldots a_{N'}} \tilde{Q}^{j_1}_{a_1} \tilde{Q}^{j_2}_{a_2} \cdots \tilde{Q}^{j_{N'}}_{a_{N'}}$

$\mathcal{N} = 1$ Seiberg duality

Mapping of operators:

$$m^i_j = q^i \tilde{q}_j \leftrightarrow M^i_j$$
$$b^{i_1 i_2 \cdots i_N} \leftrightarrow \epsilon^{i_1 i_2 \cdots i_N j_1 \ldots j_{N'}} B_{j_1 j_2 \cdots j_{N_f - N_c}}$$
$$\tilde{b}_{i_1 i_2 \cdots i_{N_f}} \leftrightarrow \epsilon_{i_1 i_2 \cdots i_{N_f} j_1 \ldots j_{N'}} \tilde{B}^{j_1 j_2 \cdots j_{N'}}$$

Mapping of constraints:

$$m^{[i}_j b^{i_1 \cdots i_N]} = 0 \qquad (\tilde{q}^a_j q^i_{[a} q^{i_1}_{a_1} \cdots q^{i_N}_{a_N]} = 0)$$
$$\rightarrow \quad M^{i_1}_j B_{i_1 \ldots i_{N'}} = 0 \qquad (M^i_j Q^a_i = 0)$$

etc.

Computation of moduli space, $\mathcal{N} = 1$

$$\frac{\{F = 0, D = 0\}}{G} = \frac{\{F = 0\}}{G_{\mathbb{C}}}$$

Basically:

- List gauge-invariant chiral operators
- Impose F-term = 0
- Study the constraints

Computation of moduli space, $\mathcal{N} = 2$

$$\frac{\{F^A = 0, D^A = 0\}}{G} = \frac{\{F^A = 0\}}{G_{\mathbb{C}}}$$

- $W = Q\Phi\tilde{Q} \longrightarrow F^A = t^A_{a\bar{a}} Q^a \tilde{Q}^{\bar{a}}$
- $F^A = D^A = 0$ imposes **3 dim** G conditions
- $/G$ removes another **dim** G
- $\longrightarrow$ loose **4 dim** G dimensions

Dimensions

SU(3) + 6 flavors $Q^i, \tilde{Q}_i$

$$4 \times 3 \times 6 - 4 \dim \mathrm{SU}(3) = 40$$

$$\Updownarrow$$

SU(2) + 1 flavor $q, \tilde{q}$ +SCFT$[E_6]$

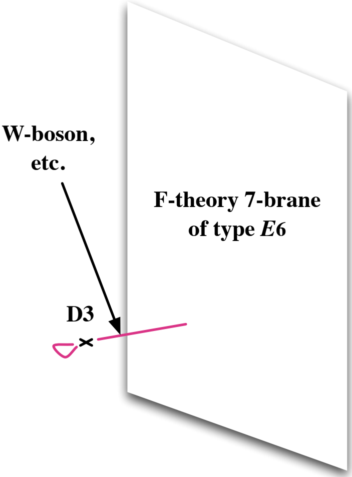
$$4 \times 2 + ???? - 4 \dim \mathrm{SU}(2)$$

Higgs branch of SCFT[E_6]

D3 brane absorbed into the 7-brane
$\longrightarrow$ becomes an instanton of type E_6 !
Center of mass along the 7-brane decoupled .

$$\dim(\text{centered } k\text{-instanton moduli}) = 4h_{E_6}k - 4$$

$$k = 1,\ h_{E_6} = 12 \longrightarrow \dim = 44$$



Dimensions

SU(3) + 6 flavors Q^i, $\tilde{Q}_i$

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SU(2) + 1 flavor $q, \tilde{q}$ +SCFT$[E_6]$

$$4 \times 2 + 44 - 4 \dim \mathrm{SU}(2) = 40$$

Operators

SU(3) + 6 flavors Q^i, $\tilde{Q}_i$

- $M^i_j = Q^i_a \tilde{Q}^a_j$
- $B^{[ijk]} = \epsilon^{abc} Q^i_a Q^j_b Q^k_c$
- $\tilde{B}_{[ijk]} = \epsilon_{abc} \tilde{Q}^a_i \tilde{Q}^b_j \tilde{Q}^c_k$
- Lots of constraints.

$\Updownarrow$

SU(2) + 1 flavor $q, \tilde{q}$ +SCFT[E_6]

- ??? $\longrightarrow$ Need to know more about the E_6 instanton moduli space.
- But how? We don't have ADHM for exceptional groups...

One-instanton moduli

- Any one-instanton of G is an embedding of the $\mathbf{SU(2)}$ BPST instanton via $\mathbf{SU(2)} \subset G$
- Space equivalent to a subspace of $g_{\mathbb{C}}$, minimal nilpotent orbit

$$G_{\mathbb{C}} \cdot T^{\rho}, \qquad \rho : \text{highest root}$$

- Equations explicitly known. Just quadratic. [Joseph,Kostant]
- Let $V(\alpha)$: irrep with highest weight α, and $g_{\mathbb{C}} = V(\rho)$.
- Decompose

$$\mathbf{Sym}^2 V(\rho) = V(2\rho) \oplus \mathcal{I}$$

then

$$\{G_{\mathbb{C}} \cdot T^{\rho}\} = \{\mathbb{X} \in g_{\mathbb{C}} \,|\, \quad (\mathbb{X} \otimes \mathbb{X})\big|_{\mathcal{I}} = 0\}$$

One-instanton moduli of SU(2)

- Equations explicitly known. Just quadratic. [Joseph,Kostant]
- Let $V(\alpha)$: irrep with highest weight α, and $g_{\mathbb{C}} = V(\rho)$.
- Decompose

$$\mathsf{Sym}^2 V(\rho) = V(2\rho) \oplus \mathcal{I}$$

then

$$\{G_{\mathbb{C}} \cdot T^{\rho}\} = \{\mathbb{X} \in g_{\mathbb{C}} \big| \quad (\mathbb{X} \otimes \mathbb{X})\big|_{\mathcal{I}} = 0\}$$

- Parametrize **su(2)** by $x_{1,2,3}$
- $\mathsf{Sym}^2\, 3 = 5 \oplus 1$
- $x_1^2 + x_2^2 + x_3^2 = 0$: just $\mathbb{C}^2/\mathbb{Z}_2$.

One-instanton moduli of E_6

$$\mathbb{X} \in \mathbf{adj}(E_6), \qquad (\mathbb{X} \otimes \mathbb{X})\big|_{\mathcal{I}} = 0$$

- We couple $\mathbf{SU(2)}$ gauge field Φ to $\mathbb{X}$.
- Convenient to decompose under $\mathbf{SU(2)} \times \mathbf{SU(6)} \subset \mathbb{X}$

$$X^i_j, \quad Y^{[ijk]}_\alpha, \quad Z_{(\alpha\beta)}$$

- Superpotential is $W = \Phi^{\alpha\beta} Z_{\alpha\beta}$.

Operators

SU(3) + 6 flavors Q^i, $\tilde{Q}_i$

- $M^i_j = Q^i_a \tilde{Q}^a_j \longrightarrow$ tr M, $\hat{M}^i_j$
- $B^{[ijk]} = \epsilon^{abc} Q^i_a Q^j_b Q^k_c$, $\qquad \tilde{B}_{[ijk]} = \epsilon_{abc} \tilde{Q}^a_i \tilde{Q}^b_j \tilde{Q}^c_k$

$$\updownarrow$$

SU(2) + 1 flavor $v, \tilde{v}$ +SCFT[E_6]

- X^i_j, $\quad Y^{[ijk]}_\alpha$, $\quad Z_{(\alpha\beta)}$
- F-term=0 $\longrightarrow$ $Z_{(\alpha\beta)} + v_{(\alpha} \tilde{v}_{\beta)} = 0$
- $\hat{M}^i_j = X^i_j$
- $M = \epsilon^{\alpha\beta} v_\alpha \tilde{v}_\beta$
- $B^{[ijk]} = \epsilon^{\alpha\beta} v_\alpha Y^{ijk}_\beta$, $\qquad \tilde{B}^{[ijk]} = \epsilon^{\alpha\beta} \tilde{v}_\alpha Y^{ijk}_\beta$

U(1) charge

$$B^{[ijk]} = \epsilon^{abc} Q_a^i Q_b^j Q_c^k \qquad \tilde{B}_{[ijk]} = \epsilon_{abc} \tilde{Q}_i^a \tilde{Q}_j^b \tilde{Q}_k^c$$

$$B^{[ijk]} = \epsilon^{\alpha\beta} v_\alpha Y_\beta^{ijk} \qquad \tilde{B}^{[ijk]} = \epsilon^{\alpha\beta} \tilde{v}_\alpha Y_\beta^{ijk}$$

U(1) charge of Q: 1 $\longrightarrow$ U(1) charge of v: 3

SU(3) + 6 flavors

- $k_{\mathrm{U(1)}} = 3 \times 6 = 18$

SU(2) + 1 flavor + SCFT[E_6]

- $k_{\mathrm{U(1)}} = 2 \times 1 \times (\text{charge of } v)^2 \longrightarrow \text{charge of } v = 3$

Constraints

Constraints of min. nilpotent orbit $E_{6,\mathbb{C}} \cdot T^\rho$

$$(\mathbb{X} \otimes \mathbb{X})\big|_{\mathcal{I}} = 0 \text{ where } \mathrm{Sym}^2 V(\rho) = V(2\rho) \oplus \mathcal{I}$$

- We decompose $\mathbb{X} = (X^i_j, Y^{[ijk]}_\alpha, Z_{(\alpha\beta)})$
- Decompose $\mathcal{I}$ under $SU(2) \times SU(6)$
- Coefficients laboriously fixed

Constraints

$$0 = X^i{}_j Z_{\alpha\beta} + \frac{1}{4} Y^{ikl}_{(\alpha} Y_{jkl\beta)},$$
$$0 = X^l{}_{\{i} Y_{[jk]\}l\alpha},$$
$$0 = X^{\{i}{}_l Y^{[jk]\}l}_{\alpha},$$
$$0 = Y^{ijk}_{\alpha} Z_{\beta\gamma} \epsilon^{\alpha\beta} + X^{[i}{}_l Y^{jk]l}_{\gamma},$$
$$0 = (Y^{ijm}_{\alpha} Y_{klm\beta} \epsilon^{\alpha\beta} - 4 X^{[i}{}_{[k} X^{j]}{}_{l]}) \Big|_{0,1,0,1,0},$$
$$0 = X^i{}_k X^k{}_j - \frac{1}{6} \delta^i{}_j X^k{}_l X^l{}_k,$$
$$0 = Y^{ijk}_{\alpha} Y_{ijk\beta} \epsilon^{\alpha\beta} + 24 Z_{\alpha\beta} Z_{\gamma\delta} \epsilon^{\alpha\gamma} \epsilon^{\beta\delta},$$
$$0 = X^i{}_j X^j{}_i + 3 Z_{\alpha\beta} Z_{\gamma\delta} \epsilon^{\alpha\gamma} \epsilon^{\beta\delta}.$$

Constraints

F-term eq.

$$Z_{(\alpha\beta)} + v_{(\alpha}\tilde{v}_{\beta)} = 0.$$

Identifications

$$\hat{M}^i_j = X^i_{j'}, \qquad \text{tr}\, M = \epsilon^{\alpha\beta} v_\alpha \tilde{v}_\beta$$
$$B^{[ijk]} = \epsilon^{\alpha\beta} v_\alpha Y^{ijk}_\beta$$

$$0 = X^i_k X^k_j - \frac{1}{6}\delta^i_j X^k_l X^l_k,$$
$$0 = X^i_j X^j_i + 3 Z_{\alpha\beta} Z_{\gamma\delta} \epsilon^{\alpha\gamma}\epsilon^{\beta\delta},$$
$$0 = Y^{ijk}_\alpha Z_{\beta\gamma}\epsilon^{\alpha\beta} + X^{[i}_l Y^{jk]l}_\gamma$$

$\longrightarrow$

$$\hat{M}^i_j \hat{M}^j_k = \frac{1}{6}\delta^i_j M^m_n M^n_m,$$
$$\hat{M}^i_j \hat{M}^j_i = \frac{1}{6}(\text{tr}\, M)^2,$$
$$\hat{M}^{[i}_j B^{kl]j} = \frac{1}{6}(\text{tr}\, M) B^{ikl},$$

Constraints

$$W = Q^i \Phi \tilde{Q}_i \longrightarrow Q^i_a \tilde{Q}^b_i - \frac{1}{3}\delta^b_a Q^i_c \tilde{Q}^c_i = 0 \longrightarrow$$

$$M^i_j M^j_k = \frac{1}{3}(\mathrm{tr}\, M) M^i_k, \qquad M^{[i}_j B^{kl]j} = \frac{1}{3}(\mathrm{tr}\, M) B^{ijk}, \quad \text{etc.}$$

$$\hat{M}^i_j \hat{M}^j_k = \frac{1}{6}\delta^i_j \hat{M}^m_n \hat{M}^n_m,$$
$$\hat{M}^i_j \hat{M}^j_i = \frac{1}{6}(\mathrm{tr}\, M)^2,$$
$$\hat{M}^{[i}_j B^{kl]j} = \frac{1}{6}(\mathrm{tr}\, M) B^{ikl}, \ldots$$

Contents

Summary

Done

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To do

- Other cases E_7 ?
- String theoretic realization of the duality