A large-N tensor model with four supercharges

Davide Lettera and Alessandro Vichi. "A large-*N* tensor model with four supercharges". In: (Dec. 2020). arXiv: 2012.11600 [hep-th]

February 23, 2021

Sections

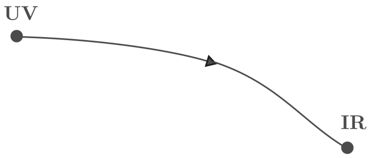
1. Introduction
2. Supersymmetry
3. Supersymmetric tensor model

Introduction

Motivations

Why Tensor Field Theories are interesting?

- The melonic limit is easier to deal with than others: such as the planar limit of matrix models,
- Look for hopefully non trivial CFT,



- Connection with the SYK model:
  Edward Witten. “An SYK-Like Model Without Disorder”. In: *J. Phys. A* 52.47 (2019), p. 474002. DOI: 10.1088/1751-8121/ab3752. arXiv: 1610.09758 [hep-th]

  I.R.Klebanov G.Tarnopolsky. “Uncolored Random Tensors, Melon Diagrams, and SYK Models”. In: (2017),
- Supersymmetry simplify computations and leads to a real spectrum.

Tensor Field Theories (TFT)

Tensor Field Theory

TFT are QFT built in terms of fields that are tensors of rank-r: $\phi_{a_1 a_2 \ldots a_r}$

We focus on the case: $r = 3$.

Igor R. Klebanov, Fedor Popov, and Grigory Tarnopolsky. "TASI Lectures on Large *N* Tensor Models". In: *PoS* TASI2017 (2018), p. 004. DOI: 10.22323/1.305.0004. arXiv: 1808.09434 [hep-th]

Razvan Gurau. "Notes on Tensor Models and Tensor Field Theories". In: (July 2019). arXiv: 1907.03531 [hep-th]

$$\mathcal{G} : \Phi_{abc} \quad \to \Phi'_{abc} = M_1^{aa'} M_2^{bb'} M_3^{cc'} \Phi_{a'b'c'} \qquad \mathcal{G} = O(N)^3$$

$$(M_1 \in O_1(N),\ M_2 \in O_2(N),\ M_3 \in O_3(N))$$

We describe the theory in terms of an $O(N)^3$-symmetryc Lagrangian $\mathcal{L}$

$$\mathcal{G} : \mathcal{L}[\Phi_{abc}] \quad \to \mathcal{L}'[\Phi'_{abc}] = \mathcal{L}[\Phi_{abc}]$$

Invariants

- There is only one possible quadratic term: $\Phi_{abc}\Phi_{abc}$.
- There are 3 quartic invariants:

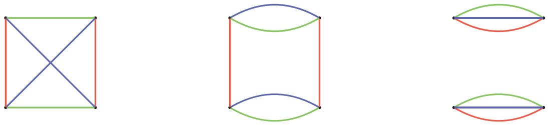


Figure 1: Each vertex represents a field and each colored lines represents two contracted indeces.

$$\mathcal{O}_t = \Phi_{a_1b_1c_1}\Phi_{a_1b_2c_2}\Phi_{a_2b_1c_2}\Phi_{a_2b_2c_1}$$

$$\mathcal{O}_p = \frac{1}{3}\left(\Phi_{a_1b_1c_1}\Phi_{a_2b_1c_1}\Phi_{a_1b_2c_2}\Phi_{a_2b_2c_2} + \text{perm.}\right)$$

$$\mathcal{O}_{dt} = \Phi_{a_1b_1c_1}\Phi_{a_1b_1c_1}\Phi_{a_2b_2c_2}\Phi_{a_2b_2c_2}$$

Large-N limit

We focus on a model with only $\mathcal{O}_t$ in $\mathcal{L}$. And we study the large-N limit

- Vector model: 1 index, snail digrams dominate, keep fixed gN.
- Matrix models: 2 indices , planar diagrams dominate, keep fixed gN^2.
- 3 indices (or more), melonic diagrams domiate, melonic dominance keeping fixed g^2N^3

Melonic diagrams are a subset of planar diagrams and can be summed exactly!

The model

We have studied a supersymmetric and melonic model:

$$S[\Phi, \bar{\Phi}] = \int d^d x \int d\theta^2 d\bar{\theta}^2 \left(\bar{\Phi}_{abc}\Phi_{abc}\right) + \int d^d y d\theta^2 W[\Phi] + \int d^d \bar{y} d\bar{\theta}^2 W[\bar{\Phi}],$$

$$W[\Phi] = \frac{1}{4} g \Phi_{abc}\Phi_{ade}\Phi_{fbe}\Phi_{fdc},$$

- Φ and $\bar{\Phi}$ are chiral and anti-chiral fields.
- $W[\Phi]$ is the chiral superpotential.
- The total amount of supercharges is 4.

Results

- Scaling dimension of Φ in the IR and large-N limit:
  $\Delta_\Phi = \Delta_{\bar{\Phi}} = \frac{d-1}{4}$.
- Spectrum of bilinear operators.
- Stress-energy tensor, $O(N)$ conserved currents.
- Large spin sector.
- Anomalous dimension of the Tetrahedral interaction.
- Results are: real, above unitarity bounds, matches with other known results.

Key equations: general

It is always possible to write:

- For the 2 point function $G(x_1, x_2)$ (SD equation):

$$G^{-1}(x_1, x_2) = G_0^{-1}(x_1, x_2) - \Sigma(x_1, x_2).$$

- For the 3 point function $v(x_1, x_2, x_3)$ (BS equation):

$$\int dx dx' \mathcal{K}(x_1, x_2, x, x') v(x, x', x_3) = v(x_1, x_2, x_3).$$

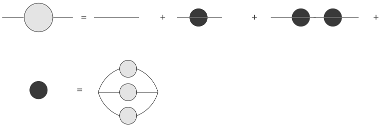
Where Σ is the self-energy and $\mathcal{K}$ is the kernel.

Not always possible to solve them!

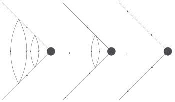
Key equations: melonic

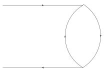
When melonic dominance occurs

- For the 2 pt function, relevant diagrams look like a melon.



- For the three point functions, relevant diagrams look like a ladder. The kernel operator adds a rung to the ladder.





Supersymmetry

Supersymmetry (SUSY)

SUSY

Supersymmetry: evade the Coleman-Mandula theorem

In the SUSY algebra: fermionic generators Q^I (supercharges) are allowed.

$$Q^I|Fermion\rangle = |Boson\rangle, \qquad Q^I|Boson\rangle = |Fermion\rangle.$$

Being fermions, Q^I obey to an anti-commutation relation

$$\{Q^I_\alpha, \bar{Q}^J_{\dot{\beta}}\} \;=\; 2\sigma^\mu_{\alpha\dot{\beta}} P_\mu \delta^{IJ} \qquad \text{(in 4d)}$$

Supermultiplets

Due to the anti-commuting nature of fermionic generators, each supermultiplet contains a finite number of states.

the more supercharges $\rightarrow$ the bigger are supermultiplets

Adel Bilal. "Introduction to supersymmetry". In: (Jan. 2001). arXiv: hep-th/0101055

For each supercharge in the algebra Q we introduce an associated Grassman variable θ

$$(x^\mu) \to (x^\mu, \theta_i), \qquad G(x, \theta, \bar{\theta}, \omega) = e^{ixP + i\theta Q + i\bar{\theta}\bar{Q} + \frac{1}{2}\omega M}$$

Superfields

Superfields are nothing but fields in **superspace**: $\Phi(x, \theta^I, \bar{\theta}^J)$

We can always expand in Grassman variables and few terms survive

$$\Phi(x, \theta, \bar{\theta}) = f(x) + \theta\psi(x)\bar{\theta}\bar{\chi} + \theta\theta m(x)\bar{\theta}\bar{\theta}n(x) + \theta\sigma^\mu\bar{\theta}v_\mu(x) +$$
$$+ \theta\theta\bar{\theta}\bar{\lambda}(x) + \bar{\theta}\bar{\theta}\theta\rho(x) + \theta\theta\bar{\theta}\bar{\theta}d(x),$$

This equation contains too many degrees of freedom.

Chiral and anti-chiral multiplets

Covariant Derivatives

Covariant derivatives are defined requiring that they anti-commute with supercharges

$$D_\alpha = \partial_\alpha + i\sigma^\mu_{\alpha\dot\beta}\bar\theta^{\dot\beta}\partial_\mu,$$
$$\bar D_{\dot\alpha} = \bar\partial_{\dot\alpha} + i\theta_\beta\sigma^\mu_{\beta\dot\alpha}\partial_\mu.$$

Chiral and anti-chiral fields

Chiral fields and **anti-chiral** fields can be defined requiring:

$$\bar D_{\dot\alpha}\Phi = 0, \qquad D_\alpha\bar\Phi = 0.$$

$$\Phi(y,\theta) = \phi(y) + \sqrt{2}\theta\psi(y) - \theta\theta F(y), \qquad y^\mu = x^\mu + i\theta\sigma^\mu\bar\theta$$

$$\bar\Phi(\bar y,\bar\theta) = \bar\phi(\bar y) + \sqrt{2}\bar\theta\bar\psi(\bar y) - \bar\theta\bar\theta\bar F(\bar y), \qquad y^\mu = x^\mu - i\theta\sigma^\mu\bar\theta$$

3d superspace

The super algebra in 3 dimension takes the form

$$\{Q^I_\alpha, Q^J_\beta\} \;=\; 2i\gamma^\mu_{\alpha\beta}P_\mu,$$

$$\gamma^0 = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \;\; \gamma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \;\; \gamma^2 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

$\mathcal{N} = 2 \rightarrow$ $Q = Q_1 + iQ_2$ and $\bar{Q} = Q_1 - iQ_2$ brings the algebra in the same form of $\mathcal{N} = 1$ in 4d.

$$\{Q_\alpha, \bar{Q}_\beta\} = 2\gamma^\mu_{\alpha\beta}P_\mu + 2i\epsilon_{\alpha\beta}Z$$

Where the central charge Z is the momentum in the reduced direction (say P_3).

Super conformal-multiplets

The recipe to build super-conformal multiplets is

- Defining a super-primary state $|\mathcal{O}\rangle$ such that $K_\mu|\mathcal{O}\rangle = S_\alpha|\mathcal{O}\rangle = 0$ and with scaling dimension $D|\mathcal{O}\rangle = \Delta_\mathcal{O}|\mathcal{O}\rangle$
- Using the algebra

$$[D, Q_\alpha] = -\frac{1}{2}Q_\alpha, \qquad [D, P_\mu] = -P_\mu,$$

we find that

$$D\left(P_\mu|\mathcal{O}\rangle\right) = \left(\Delta_\mathcal{O} + 1\right)\left(P_\mu|\mathcal{O}\rangle\right),$$
$$D\left(Q_\alpha|\mathcal{O}\rangle\right) = \left(\Delta_\mathcal{O} + \frac{1}{2}\right)\left(Q_\alpha|\mathcal{O}\rangle\right).$$

Notice

Since $Q^2 \sim P$ each descendant is also a super-descendant, but the contrary is not true.

Clay Cordova, Thomas T. Dumitrescu, and Kenneth Intriligator. "Multiplets of Superconformal Symmetry in Diverse Dimensions". In: *JHEP* 03 (2019), p. 163. DOI: 10.1007/JHEP03(2019)163. arXiv: 1612.00809 [hep-th]

Supersymmetric tensor model

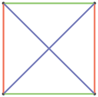
The model

We study the model with chiral (and anti-chiral) fields and $N_Q = 4$ supercharges

$$S[\Phi, \bar{\Phi}] = \int d^d x \int d\theta^2 d\bar{\theta}^2 \left(\bar{\Phi}_{abc}\Phi_{abc}\right) + \int d^d y d\theta^2 W[\Phi] + \int d^d \bar{y} d\bar{\theta}^2 W[\bar{\Phi}],$$

$$W[\Phi] = \frac{1}{4} g \Phi_{abc}\Phi_{ade}\Phi_{fbe}\Phi_{fdc}.$$

- Superpotentials W and $\bar{W}$ are exactly marginal in $d = 3$
- In the superpotentials we include only the Tetrahedron $\rightarrow$ melonic dominance.



DSE (1)

Let G be the 2pt function. Let G_0 be the propagator. Then

$$G = G_0 + \lambda^2 G_0 G^3 G, \qquad \lambda^2 = g^2 N^3.$$

- Exploiting the analogy with the $d = 4$ $\mathcal{N} = 1$ case, we can use the standard form of the propagator:

$$G_0(p, \theta_1, \bar{\theta}_2) = \langle \Phi(-p, \theta_1) \bar{\Phi}(p, \bar{\theta}_2) \rangle_0 = \frac{e^{-2(\bar{\theta}_2 \gamma^\mu \theta_1) p_\mu}}{p^2}$$

- For the 2pt function G we use a conformal ansatz

$$G(p, \theta_1, \bar{\theta}_2) = \langle \Phi(-p, \theta_1) \bar{\Phi}(p, \bar{\theta}_2) \rangle = A_2 \frac{e^{-2(\bar{\theta}_2 \gamma^\mu \theta_1) p_\mu}}{p^{2\Delta}}$$

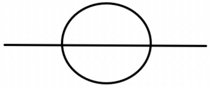
DSE (2)

$$-\frac{e^{2(\bar{\theta}_1\gamma^\mu\theta_2)p_\mu}}{p^2} = +2A_2^4\lambda^2\int\frac{d^dk_1}{(2\pi)^d}\frac{d^dk_2}{(2\pi)^d}\frac{\mathcal{J}_{\mathcal{N}=2}(p,\bar{\theta}_1,\theta_2)}{p^2|p-k_1-k_2|^{2\Delta}k_1^{2\Delta}k_2^{2\Delta}p^{2\Delta}},$$

$$\mathcal{J}_{\mathcal{N}=2}(p,\bar{\theta}_1,\theta_2) = \int d^2\theta' d^2\bar{\theta}'' e^{2(\bar{\theta}_1\gamma^\mu\theta' p_\mu)}e^{-2(\bar{\theta}''\gamma^\mu\theta')p_\mu}e^{2(\bar{\theta}''\gamma^\mu\theta_2)p_\mu}.$$

Notice!

Integrated momenta running into a loop cancel in the exponets !



Integrals over momenta can be performed.
Integrals over Grassman variables can be computed straightforwardly.

$$\Delta = \frac{d+1}{4},$$
$$A_2^4 = \frac{1}{8}\frac{(4\pi)^d}{\lambda^2}\frac{\Gamma^3(\frac{d+1}{4})\Gamma(3\frac{d-1}{4})}{\Gamma^3(\frac{d-1}{4})\Gamma(\frac{3-d}{4})}$$

- Δ is related to the dimension of Φ: $\Delta_\Phi = \frac{d}{2} - \Delta = \frac{d-1}{4}$
- In $d = 3 - \epsilon$ we find $\gamma_\Phi = \frac{\epsilon}{4}$
- We cannot set ϵ to 0.
- The super conformal algebra fixes the dimension of chiral operators: $\Delta_\Phi = \frac{d-1}{2} R_\Phi = \frac{d-1}{4}$.

Bilinear operators

The possible bilinear operators are:

$$\Phi_{abc}\,\Box^h\Phi_{abc}, \qquad \bar{\Phi}_{abc}\,\Box^h\bar{\Phi}_{abc}$$

$$\Phi_{abc}\,\Box^h D^2\Phi_{abc}, \qquad \bar{\Phi}_{abc}\,\Box^h\bar{D}^2\bar{\Phi}_{abc}$$

$$\bar{\Phi}_{abc}\,\Box^h\Phi_{abc}, \qquad \bar{\Phi}_{abc}\,\Box^h D^2\Phi_{abc}.$$

- In blue: chiral or anti-chiral $\rightarrow$ fixed dimension.
- In red: are not chiral or anti-chiral: but there are no corrections at large N.
- In brown: receive radiative corrections: but it is sufficient to study $\bar{\Phi}_{abc}\,\Box^h\Phi_{abc}$

$\bar{\Phi}D^2\Phi$ is a super-descendats of $\bar{\Phi}\Phi$

$$D^2\left(\bar{\Phi}\Phi\right) = \frac{1}{2}D^\alpha D_\alpha\left(\bar{\Phi}\Phi\right) = \frac{1}{2}D^\alpha\left(\bar{\Phi}D_\alpha\Phi\right) = \bar{\Phi}D^2\Phi,$$

$$D_\alpha\bar{\Phi} = D^\alpha\bar{\Phi} = 0.$$

Scalar singlet sector (1)

We study the 3pt function of $O = \bar{\Phi}_{abc}\Phi_{abc}$ with Φ and $\bar{\Phi}$. Super conformal symmetry constrains its form. We choose the ansatz

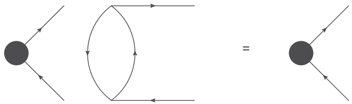
Fedor K. Popov. "Supersymmetric tensor model at large N and small ϵ". In: *Phys. Rev. D* 101.2 (2020), p. 026020. DOI: 10.1103/PhysRevD.101.026020. arXiv: 1907.02440 [hep-th]

$$V(p, \theta_1, \bar{\theta}_2) = \langle O(0)\Phi(-p, \theta_1)\bar{\Phi}(p, \bar{\theta}_2)\rangle = \frac{e^{-2(\bar{\theta}_2\gamma^\mu\theta_1)p_\mu}}{p^{2\Delta+\Delta_O}}.$$

We require that it is an eigenfunction of the kernel

$$(\mathcal{K}V)(p, \theta_1, \bar{\theta}_2) = g_{\mathcal{N}=2}(\Delta_O)V(p, \theta_1, \bar{\theta}_2)$$

$$\mathcal{K}(y_1\theta_1, \bar{y}_2\bar{\theta}_2, y'\theta', \bar{y}''\bar{\theta}'') = 3\lambda^2 G^2(y'\theta', \bar{y}''\bar{\theta}'')G(y_1\theta_1, \bar{y}''\bar{\theta}'')G(\bar{y}_2\bar{\theta}_2, y'\theta')$$



Scalar singlet sector (2)

$$g_{\mathcal{N}=2}(\Delta_{\mathcal{O}}) = -3\frac{\Gamma(\frac{d+1}{4})\Gamma(3\frac{d-1}{4})\Gamma(\frac{d-1}{4}-\frac{\Delta_{\mathcal{O}}}{2})\Gamma(\frac{3-d}{4}-\frac{\Delta_{\mathcal{O}}}{2})}{\Gamma(\frac{d-1}{4})\Gamma(\frac{3-d}{4})\Gamma(\frac{d+1}{4}+\frac{\Delta_{\mathcal{O}}}{2})\Gamma(3\frac{d-1}{4}-\frac{\Delta_{\mathcal{O}}}{2})} = 1.$$

The dimensions of operators are the solutions of $g_{\mathcal{N}=2}(\Delta_O) = 1$.

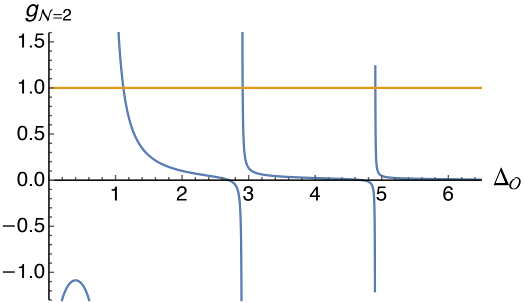


Figure 2: Plot in $d = 2.8$.

In $d = 3 - \epsilon$

$$\Delta_{\bar{\Phi}\Phi} = 1 + \epsilon + O(\epsilon^2)$$

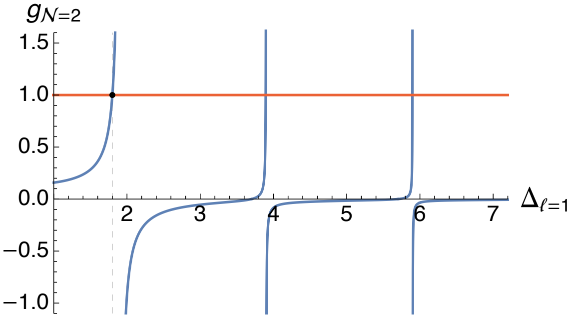
$$\Delta_{\bar{\Phi}D^2\Phi} = 2 + \epsilon + O(\epsilon^2)$$

Spinning singlet sector

Spinning bilinear operators: $\mathcal{O}^{(\ell)} = \bar{\Phi}_{abc}\partial_{\mu_1}..\partial_{\mu_\ell}\,\Box^h\Phi_{abc}$.

$$V^{\ell}_{\mu_1..\mu_\ell}(p,\theta_1,\bar{\theta}_2) = \langle \mathcal{O}^{(\ell)}(0)\Phi(-p,\theta_1)\bar{\Phi}(p,\bar{\theta}_2)\rangle = \frac{e^{-2(\bar{\theta}_2\gamma^\mu\theta_1)p_\mu}}{p^{2\Delta+\Delta_\ell+\ell}}p_{\mu_1}...p_{\mu_\ell}.$$

$$g_{\mathcal{N}=2}(\Delta_\ell,\ell) = -(-1)^\ell 3\frac{\Gamma\left(\frac{3(d-1)}{4}\right)\Gamma\left(\frac{d+1}{4}\right)\Gamma\left(\frac{d-1}{4}+\frac{\ell-\Delta_\ell}{2}-\right)\Gamma\left(\frac{3-d}{4}+\frac{\Delta_\ell+\ell}{2}\right)}{\Gamma\left(\frac{3-d}{4}\right)\Gamma\left(\frac{d-1}{4}\right)\Gamma\left(\frac{3(d-1)}{4}+\frac{\ell-\Delta_\ell}{2}\right)\Gamma\left(\frac{d+1}{4}+\frac{\Delta_\ell+\ell}{2}\right)}.$$



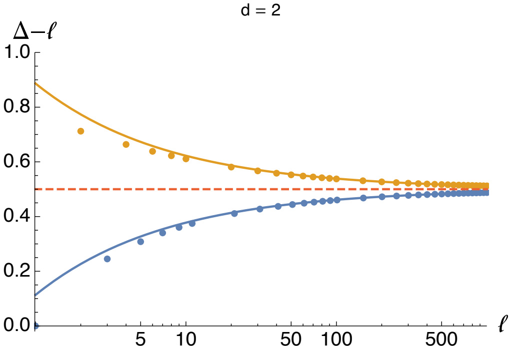
Large spin

- In $d = 3 - \epsilon$

$$\Delta_\ell = 2\Delta_\Phi + \ell + \frac{3(-1)^\ell}{4\ell + 2}\varepsilon + O(\epsilon^2)$$

- For any d: $\Delta_\ell = 2\Delta_\Phi + \ell + \gamma$ and we can expand in small γ

$$\gamma \simeq \frac{1}{e}\frac{6(-1)^\ell \Gamma\left(\frac{3(d-1)}{4}\right)\Gamma\left(\frac{d+1}{4}\right)}{\Gamma\left(\frac{3-d}{4}\right)\Gamma\left(\frac{d-1}{4}\right)\Gamma\left(\frac{d-1}{2}\right)}\frac{1}{\ell^{2\Delta_\Phi}} + \ldots, \qquad e = 1, +3, -3.$$

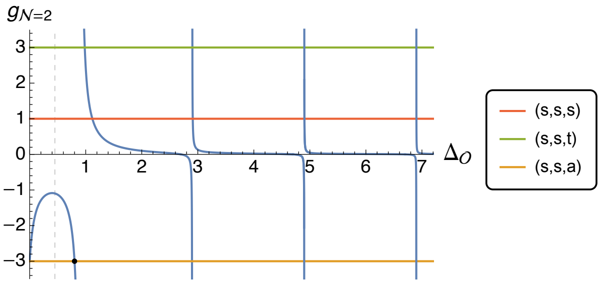


The possible irreps are 10:

$$(v,v,v)\otimes(v,v,v)\sim(s,s,s)\oplus(s,s,t)\oplus(s,s,a)\oplus(s,t,t)\oplus\ldots$$

We checked which irrp gets corrections in the large N

$$(s,s,s): \qquad g_{\mathcal{N}=2}(\Delta_{\mathcal{O}})=1$$
$$(s,s,a): \qquad g_{\mathcal{N}=2}(\Delta_{\mathcal{O}})=-3$$
$$(s,s,t): \qquad g_{\mathcal{N}=2}(\Delta_{\mathcal{O}})=3$$



Perturbative check

In perturbation theory we find

$$\gamma_\Phi = \frac{\epsilon}{4}.$$

$$\left(\frac{\partial\beta}{\partial\lambda}\right)_{ij} = \begin{pmatrix} 2\epsilon & 0 & 0 \\ 2\epsilon^{\frac{1}{2}}\lambda_p & 0 & 0 \\ 2\epsilon^{\frac{1}{2}}\lambda_{dt} & 0 & 0 \end{pmatrix}.$$

- The two null eigenvalues corresponds to two exactly marginal operators O_p e O_{dt}
- The eigenvalue 2ϵ means that an anomalous dimension for O_t is generated.

$$\Delta_t = 2 + \epsilon + O(\epsilon^2) = \Delta_{\bar{\Phi}D^2\Phi}$$

J.A. Gracey et al. "a-function for $N = 2$ supersymmetric gauge theories in three dimensions". In: *Phys. Rev. D* 95.2 (2017), p. 025005. DOI: 10.1103/PhysRevD.95.025005. arXiv: 1609.06458 [hep-th]

Remarks

We need to interpret the anomalous dimension of $\mathcal{O}_t$
Being chiral we did not expect $\gamma_{\mathcal{O}_t} \neq 0$!

In the IR, a multiplet recombination must happen $\rightarrow$ and O_t became a super descendant of $\bar{\Phi}\Phi$: $D^2\left(\bar{\Phi}\Phi\right) \propto O_t$.

Clay Cordova, Thomas T. Dumitrescu, and Kenneth Intriligator. "Multiplets of Superconformal Symmetry in Diverse Dimensions". In: *JHEP* 03 (2019), p. 163. DOI: 10.1007/JHEP03(2019)163. arXiv: 1612.00809 [hep-th]

$U(1)$ explicit symmetry breaking

The free theory has an additional $U(1)$ symmetry: rotating Φ and $\bar{\Phi}$ (but not θ and $\bar{\theta}$). The superpotential $W[\Phi]$ in $d < 3$ is relevant and, in the IR **breaks explicitely** $U(1)$. We expect

$$D^2(\bar{\Phi}\Phi) = B$$

B being an operator that breaks $U(1)$. We guess $B = O_t$ because it has the correct scaling dimension and R-charge!

Conclusions

- Spectrum of bilinear operators: real and above unitarity bound (also in d=2)

  Chi-Ming Chang, Sean Colin-Ellerin, and Mukund Rangamani. "Supersymmetric Landau-Ginzburg Tensor Models". In: *JHEP* 11 (2019), p. 007. DOI: 10.1007/JHEP11(2019)007. arXiv: 1906.02163 [hep-th]

- The structure of superspace with $N_Q = 4$ helps us: non-renormalization theorems, chiral-antichiral fields
- We observed a multiplet recombination
- Results in the large spin sector

Future directions

- Investigate the large spin sector with analytical bootstrap
- Compute the $\frac{1}{N}$ corrections

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