Classification of BPS Objects in $\mathcal{N} = 6$ Chern-Simons Matter Theory

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Introduction

BPS configurations in M2-brane world-volume theory

Multiple M2-brane world-volume theory – ABJM, BLG models

- Basu-Harvey (2004) – fuzzy funnel – M2-M5 intersection – BLG model [Bagger-Lambart (2008), Gustavsson (2008)]
- Fuzzy funnel, domain wall solutions in ABJM model [Terashima (2008), Hanaki-Lin (2008)]
- Vortex solutions [Arai-Montonen-Sasaki (2009), Kawai-Sasaki (2009), Kim-Lee (2009), Kim-Kim-Kwon-Nakajima (2009), Auzz-Kumar (2009)]
- Various M-theoretical objects in BLG model

More general BPS configurations are possible in ABJM model – Our work

ABJM model [Aharony-Bergman-Jafferis-Maldacena (2008)]

Model

- $(2+1)$ dimensional superconformal Chern-Simons-Higgs model with level $(k, -k)$
- $U(N) \times U(N)$ gauge symmetry with gauge fields $A_\mu, \hat{A}_\mu$
- Matter fields Y^A, ψ_A $(A = 1, \cdots, 4)$ bi-fundamental repr of the gauge group, $SU(4)_R$ (anti) fundamental – Fluctuation along eight transverse directions.

Action of the model,

$$\mathcal{L} = \mathcal{L}_{CS} + \mathcal{L}_{kin} + \mathcal{L}_{pot} + \mathcal{L}_{ferm}$$

Three-dimensional $\mathcal{N} = 6$ supersymmetry. Low-energy effective theory of N coincident M2-branes probing $\mathbf{C}^4/\mathbf{Z}_k$ orbifold. Dual to the M-theory on $AdS_4 \times S^7/\mathbf{Z}_k$ at large-N.

1/2 BPS conditions

Projection conditions on SUSY parameters

$$\gamma \Xi_{ij} \epsilon_j = \epsilon_i, \quad (i, j = 1, 2, \cdots, 6), \quad \mathrm{Tr} \gamma \otimes \Xi = 0, \ (\gamma \otimes \Xi)^2 = \mathbf{1}_2 \otimes \mathbf{1}_6$$

ϵ_i : $\mathcal{N} = 6$ Majorana SUSY parameters. γ : 2×2 matrix with $SO(2,1)$ spinor indices, Ξ : 6×6 matrix acting on $SO(6)_R$ vector indices.
In general, we find

$$\gamma \Xi_{ij} = \begin{cases} \gamma_0 \otimes B \\ \gamma_2 \otimes C^{(m,n)} \end{cases}$$

$$B \equiv \pm \left(\begin{array}{c|c|c} i\sigma_2 & & \\ \hline & i\sigma_2 & \\ \hline & & i\sigma_2 \end{array} \right), \quad C^{(m,n)} \equiv \left(\begin{array}{c|c} \mathbf{1}_m & \\ \hline & -\mathbf{1}_n \end{array} \right), \quad m + n = 6$$

1/2 BPS equations

SUSY transformation of fermions

$$\begin{aligned}\delta\psi_A &= \left(\gamma^\mu D_\mu Y^B \delta^C_A + \Upsilon^{BC}_A\right)(\Gamma_i)_{BC}\,\epsilon_i \\ \Upsilon^{BC}_A &\equiv Y^B Y^\dagger_A Y^C + \frac{1}{2}\delta^B_A\left(Y^C Y^\dagger_D Y^D - Y^D Y^\dagger_D Y^C\right) - (B \leftrightarrow C)\end{aligned}$$

with projection condition B leads to

1/2 BPS equations

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Vortex type $\begin{cases} 0 = D_0 Y^B (\Gamma_j)_{BA} B_{ji} + \Upsilon^{BC}_A (\Gamma_i)_{BC}, \\ 0 = D_1 Y^B (\Gamma_i)_{BA} - D_2 Y^B (\Gamma_j)_{BA} B_{ji} \end{cases}$

while for $C^{(m,n)}$, we have

1/2 BPS equations

SUSY transformation of fermions

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Vertex type
$$\begin{cases} 0 = D_0 Y^B (\Gamma_j)_{BA} B_{ji} + \Upsilon^{BC}_A (\Gamma_i)_{BC}, \\ 0 = D_1 Y^B (\Gamma_i)_{BA} - D_2 Y^B (\Gamma_j)_{BA} B_{ji} \end{cases}$$

Fuzzy funnel type
$$\begin{cases} 0 = D_2 Y^B (\Gamma_j)_{BA} C^{(m,n)}_{ji} + \Upsilon^{BC}_A (\Gamma_i)_{BC}, \\ 0 = D_0 Y^B (\Gamma_i)_{BA} - D_1 Y^B (\Gamma_j)_{BA} C^{(m,n)}_{ji} \end{cases}$$

Also the Gauss' law conditions should be satisfied

Physical interpretation

BPS conditions in eleven dimensions

Global symmetry $SO(10,1) \Longrightarrow SO(2,1) \times SU(4)$

11 dim		M2-brane world-volume
ξ : 16 SUSY	$\mathbf{Z}_k \overset{\text{orbifold}}{\Longrightarrow}$	$\epsilon = P\xi$: 12 SUSY,
Projection condition : $\hat{\Gamma}\xi = \xi$ $\hat{\Gamma}_{012}\xi = \xi$	$\overset{P}{\Longrightarrow}$	BPS conditions in ABJM : $\mathcal{A}\epsilon = \epsilon, \ \mathcal{A} \equiv P\hat{\Gamma}P^{\dagger}$, $\tilde{\mathcal{A}}\epsilon = 0, \ \tilde{\mathcal{A}} = \tilde{P}\hat{\Gamma}P^{\dagger}$
M-theory objects	$\Longrightarrow$	M-theory objects intersect with M2-branes

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$\hat{\Gamma}_{012}\xi = \xi$		$\mathcal{A}\epsilon = \epsilon, \ \mathcal{A} \equiv P\hat{\Gamma}P^\dagger$,
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M-theory objects	$\Longrightarrow$	M-theory objects intersect with M2-branes

$$\hat{\Gamma} = \begin{cases} \hat{\Gamma}^{(0)} \equiv \hat{\Gamma}_\mu \\ \hat{\Gamma}^{(2)} \equiv \frac{1}{2}\omega_{IJ}\hat{\Gamma}_{\mu IJ} \\ \hat{\Gamma}^{(4)} \equiv \frac{1}{4!}\omega_{IJKL}\hat{\Gamma}_{\mu IJKL} \end{cases} \qquad (\mu = 0,1,2, \ I,J,K,L = 3,\cdots,10)$$

Physical interpretation of the BPS equations

•$\hat{\Gamma} = \hat{\Gamma}^{(0)}$

From the condition $\mathcal{A}^2 = 1$, we can set $\hat{\Gamma}^{(0)} = \hat{\Gamma}_2$ by $SO(2,1)$

$$\begin{cases} \hat{\Gamma}_{01}\xi = \xi \\ \hat{\Gamma}_{0134\cdots10}\xi = \xi \end{cases} \overset{P}{\Longrightarrow} \mathcal{A} = \gamma_2 \otimes \mathbf{1}_6,\ \tilde{\mathcal{A}} = 0$$

1/2 BPS condition in ABJM model

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1/2 BPS condition in ABJM model

M-waves, M9-branes [Bergshoeff-Schaar (1999), M. de Roo (1997)]

	0	1	2	3	4	5	6	7	8	9	10
M2	•	•	•								
M9	•	•		•	•	•	•	•	•	•	•
M-wave	•	•									

Table: A possible configuration that corresponds to the condition.

• $\hat{\Gamma} = \hat{\Gamma}^{(2)}$

	$SO(8)$ $\overset{\mathbf{Z}_k \text{ orbifold}}{\Longrightarrow}$	$SU(4) \times U(1) \sim SO(6) \times U(1)$
ω_{IJ}	**28**	$\mathbf{6}_2 \oplus (\mathbf{15}_0 \oplus \mathbf{1}_0) \oplus \mathbf{6}_{-2}$

$$\tilde{f} : \hat{\Gamma} \to \tilde{\mathcal{A}}, \quad \mathrm{Ker}\ \tilde{f} = \mathbf{15}_0 \oplus \mathbf{1}_0$$

ω should belong to $\mathbf{15}_0 \oplus \mathbf{1}_0$ – $(1,1)$-type 2-forms $\omega_{A\bar{B}}$ ($\mathbf{Z}_k$ orbifold invariant)

$$\hat{\Gamma} = \frac{1}{2}\omega_{IJ}\hat{\Gamma}_{0IJ}, \quad (\omega_{IJ} dx^I \wedge dx^J = \omega_{A\bar{B}} dy^A \wedge d\bar{y}^{\bar{B}})$$

$$\begin{cases} \frac{1}{2}\omega_{IJ}\hat{\Gamma}_{0IJ}\xi = \xi \\ \frac{1}{6!}\tilde{\omega}_{IJKLMN}\hat{\Gamma}_{0IJKLMN}\xi = -\xi \end{cases} \Longrightarrow \begin{array}{l} \mathcal{A} = \gamma_0 \otimes B, \ \tilde{\mathcal{A}} = 0, \\ \text{1/2 BPS condition in ABJM model} \end{array}$$

$\tilde{\omega} = *\omega$ on $\mathbf{C}^4/\mathbf{Z}_k$

$$\begin{cases} \frac{1}{2}\omega_{IJ}\hat{\Gamma}_{0IJ}\xi = \xi \\ \frac{1}{6!}\tilde{\omega}_{IJKLMN}\hat{\Gamma}_{0IJKLMN}\xi = -\xi \end{cases} \Longrightarrow \mathcal{A} = \gamma_0 \otimes B,\ \tilde{\mathcal{A}} = 0,$$

1/2 BPS condition in ABJM model

$\tilde{\omega} = *\omega$ on $\mathbf{C}^4/\mathbf{Z}_k$

M2-branes, KK-monopoles.

	0	1	2	3	4	5	6	7	8	9	10
M2	•	•	•								
M2	•									•	•
KK	•			•	•	•	•	•	•		

Table: Intersecting M2-branes and KK-monopoles.

•$\hat{\Gamma} = \hat{\Gamma}^{(4)}$

	$SO(8)$	$\xrightarrow{\mathbf{Z}_k \text{ orbifold}}$	$SU(4) \times U(1) \sim SO(6) \times U(1)$
ω_{IJKL}	$\mathbf{35} \oplus \mathbf{35}'$		$\mathbf{1}_4 \oplus (\mathbf{6}_2 \oplus \mathbf{10}_2) \oplus (\mathbf{1}_0 \oplus \mathbf{15}_0 \oplus \mathbf{20}_0)$ $\oplus(\mathbf{6}_{-2} \oplus \overline{\mathbf{10}}_{-2}) \oplus \mathbf{1}_{-4}$

$$\mathrm{Ker}\,\tilde{f} \;=\; \mathbf{1}_4 \oplus \mathbf{10}_2 \oplus (\mathbf{1}_0 \oplus \mathbf{15}_0 \oplus \mathbf{20}_0) \oplus \overline{\mathbf{10}}_{-2} \oplus \mathbf{1}_{-4}$$

We find

$$\hat{\Gamma}^{(4)} = \frac{1}{4!}\omega_{IJKL}\hat{\Gamma}_{2IJKL}, \;\; \omega \notin \mathbf{6}_2 \oplus \mathbf{6}_{-2}$$

$$\Longrightarrow \;\; \mathcal{A} = \gamma_2 \otimes C^{(m,n)}, \quad \tilde{\mathcal{A}} = 0,$$

1/2 BPS condition in ABJM model

M-theory objects – M5-branes

$$\omega^{(6,0)} = \frac{1}{16} dy^A \wedge dy^B \wedge d\bar{y}_A \wedge d\bar{y}_B,$$
$$\omega^{(5,1)} = \frac{1}{64} \left[\mathcal{J}_{AB} \mathcal{J}_{\bar{C}\bar{D}} - \delta_{A\bar{C}} \delta_{B\bar{D}} + \delta_{A\bar{D}} \delta_{B\bar{C}} \right] dy^A \wedge dy^B \wedge d\bar{y}^{\bar{C}} \wedge d\bar{y}^{\bar{D}},$$
$$\omega^{(4,2)} = \frac{1}{4} dy^1 \wedge dy^3 \wedge d\bar{y}^1 \wedge d\bar{y}^3,$$
$$\omega^{(3,3)} = \mathrm{Re}\, d\check{y}^1 \wedge \mathrm{Re}\, d\check{y}^2 \wedge \mathrm{Re}\, d\check{y}^3 \wedge \mathrm{Re}\, d\check{y}^4,$$

M5-branes specified by the volume form $\omega^{(m,n)}$ preserving $\mathcal{N} = (m, n)$ SUSY in $(1+1)$ dimensions.

	0	1	2	3	4	5	6	7	8	9	10
M2	•	•	•								
M5	•	•		•	•			•	•		
M5	•	•				•	•			•	•

Table: M2-M5 configuration : $(m, n) = (4, 2)$.

BPS conditions with lower SUSYs

M2-M2 intersections with angles

v_1^I, v_2^I $(I = 3, \cdots, 10)$: M2-brane directions. 11 dim projector is given by

$$\hat{\Gamma} = \frac{1}{2}(v_1^I v_2^J - v_2^I v_1^J)\Gamma_{0IJ}$$

Define a matrix which specifies M2-brane configurations

$$\Lambda_{\mathrm{M2}} \equiv \begin{pmatrix} u_1^1 & u_2^1 \\ u_1^2 & u_2^2 \\ u_1^3 & u_2^3 \\ u_1^4 & u_2^4 \end{pmatrix} \underset{GL(2,\mathbf{R}),SU(4)}{\Longrightarrow} \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ i\sin\theta & 0 \\ \cos\theta & i \end{pmatrix}$$

11 dim projector for this matrix is

$$\hat{\Gamma} = \hat{\Gamma}_0(\sin\theta\,\hat{\Gamma}_8 + \cos\theta\,\hat{\Gamma}_9)\hat{\Gamma}_{10}$$

Corresponding ABJM projector is $\mathcal{A} = \gamma_0 \otimes \Xi$ and $\tilde{\mathcal{A}} = \gamma_0 \otimes \tilde{\Xi}$ with

$$\Xi = -g^T \mathrm{diag}(\, i\sigma_2\,,\ i\sigma_2\,,\ i\cos\theta\sigma_2\,)\, g, \widetilde{\Xi} = \begin{pmatrix} 0 & 0 & 0 & 0 & -\sin\theta & 0 \\ 0 & 0 & 0 & 0 & 0 & \sin\theta \end{pmatrix} g$$

$g \in SO(6)_R$

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$g \in SO(6)_R$

$\mathcal{A}\epsilon = \epsilon,\ \tilde{\mathcal{A}}\epsilon = 0 \Longrightarrow$ 4 SUSY among 12 SUSY (1/3 BPS condition)

	0	1	2	3	4	5	6	7	8	9	10
M2	●	●	●								
M2	●								○ $\sin\theta$	○ $\cos\theta$	●

Table: 1/3 BPS configuration of intersecting M2-branes.

$\theta = 0, \pi \Longrightarrow$ 4 SUSY (1/3 BPS) is enhanced to 6 SUSY (1/2 BPS).

M2-M5 intersections with angles

$$\hat{\Gamma} \sim \frac{1}{4!}\epsilon^{abcd} v_a^I v_b^J v_c^K v_d^L \hat{\Gamma}_{01IJK}$$

$$\Lambda_{\rm M2} \equiv \begin{pmatrix} u_1^1 & u_2^1 & u_3^1 & u_4^1 \\ u_1^2 & u_2^2 & u_3^2 & u_4^2 \\ u_1^3 & u_2^3 & u_3^3 & u_4^3 \\ u_1^4 & u_2^4 & u_3^4 & u_4^4 \end{pmatrix} \underset{GL(2,\mathbf{R}),SU(4)}{\Longrightarrow} \begin{pmatrix} 1 & i\cos\theta_1 & 0 & 0 \\ 0 & \sin\theta_1 & 0 & 0 \\ 0 & 0 & 1 & i\cos\theta_2 \\ 0 & 0 & 0 & \sin\theta_2 \end{pmatrix}$$

ABJM projector $\mathcal{A} = \gamma_0 \otimes \Xi$, $\tilde{\mathcal{A}} = \gamma_0 \otimes \tilde{\Xi}$ with

$$\Xi = g^T \mathrm{diag}\big(1\,,\,1\,,\,\cos(\theta_1-\theta_2)\,,\,\cos(\theta_1+\theta_2)\,,-1,-1\big)\,g,$$

$$\tilde{\Xi} = \begin{pmatrix} 0 & 0 & -\sin(\theta_1-\theta_2) & 0 & 0 & 0 \\ 0 & 0 & 0 & \sin(\theta_1+\theta_2) & 0 & 0 \end{pmatrix} g$$

4 SUSY among 12 SUSY is preserved (1/3 BPS condition).

	0	1	2	3	4	5	6	7	8	9	10
M2	•	•	•								
M5	•	•		•	○ $\cos\theta_1$	○ $\sin\theta_1$		•	◇ $\cos\theta_2$	◇ $\sin\theta_2$	

Table: 1/3 BPS configuration of M2/M5-branes.

Either $\theta_1 \pm \theta_2 = 0, \pi \Longrightarrow$ 4 SUSY is enhanced to 5 SUSY
(5/12 BPS condition)

Both $\theta_1 \pm \theta_2 = 0, \pi \Longrightarrow$ 4 SUSY is enhanced to 6 SUSY
(1/2 BPS condition)

M2-M2 intersections with lower SUSY

Consider the ABJM projection

$$\gamma_0 \otimes \Xi^{(I,J)} = P\hat{\Gamma}_{0IJ}P^{\dagger}$$

Impose multiple conditions

M2-M2 intersections with lower SUSY

Consider the ABJM projection

$$\gamma_0 \otimes \Xi^{(I,J)} = P\hat{\Gamma}_{0IJ}P^\dagger$$

Impose multiple conditions

$$(-\gamma_0 \otimes \Xi^{(5,6)})\epsilon = \epsilon, \quad (\gamma_0 \otimes \Xi^{(9,10)})\epsilon = \epsilon$$

with

$$\Xi^{(5,6)} = -\mathrm{diag}(-i\sigma_2, -i\sigma_2, i\sigma_2), \quad \Xi^{(9,10)} = -\mathrm{diag}(i\sigma_2, i\sigma_2, i\sigma_2)$$

M2-M2 intersections with lower SUSY

Consider the ABJM projection

$$\gamma_0 \otimes \Xi^{(I,J)} = P\hat{\Gamma}_{0IJ}P^\dagger$$

Impose multiple conditions

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with

$$\Xi^{(5,6)} = -\mathrm{diag}(-i\sigma_2, -i\sigma_2, i\sigma_2), \quad \Xi^{(9,10)} = -\mathrm{diag}(i\sigma_2, i\sigma_2, i\sigma_2)$$

These conditions keep 4 SUSY among 12 SUSY (1/3 BPS condition)

	0	1	2	3	4	5	6	7	8	9	10
M2	•	•	•								
$\overline{\text{M2}}$	•					•	•				
M2	•									•	•

Table: 1/3 BPS intersecting M2-branes.

Additional conditions can be imposed

$$(\gamma_0 \otimes \Xi^{(7,8)})\epsilon = \epsilon, \;\; \Xi^{(7,8)} = -\mathrm{diag}(i\sigma_2, -i\sigma_2, -i\sigma_2).$$

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$$(\gamma_0 \otimes \Xi^{(7,8)})\epsilon = \epsilon, \ \ \Xi^{(7,8)} = -\mathrm{diag}(i\sigma_2, -i\sigma_2, -i\sigma_2).$$

These keep 2 SUSY among 12 SUSY (1/6 BPS condition)

	0	1	2	3	4	5	6	7	8	9	10
M2	•	•	•								
$\overline{\text{M2}}$	•			•	•						
$\overline{\text{M2}}$	•					•	•				
M2	•							•	•		
M2	•									•	•

Table: 1/6 BPS intersecting M2-branes.

M2-M5 intersections with lower SUSY

M2, M5-branes share x^1-direction. Projection

$$\gamma_2 \Xi_{ij} \epsilon_j = \epsilon_i, \quad \Xi = \mathrm{diag}(\underbrace{1, \cdots, 1}_{m}, \underbrace{-1, \cdots, -1}_{n}, *_{6-m-n}), \quad (m + n \leq 6)$$

This preserves $\mathcal{N} = (m, n)$ SUSY from the viewpoint of $(1 + 1)$ dimensions (x^0, x^1).

$$\Xi = \left(\begin{array}{c|c} 1 & \\ \hline & *_5 \end{array}\right)$$

$$\Xi = \left(\begin{array}{c|c} 1 & \\ \hline & *_5 \end{array} \right)$$

keeping $\mathcal{N} = (m, n) = (1, 0)$ SUSY (1/12 BPS condition)

	0	1	2	3	4	5	6	7	8	9	10
M2	•	•	•								
M5	•	•		•		•			•		•
$\overline{\text{M5}}$	•	•		•			•	•			•
$\overline{\text{M5}}$	•	•			•	•		•			•
$\overline{\text{M5}}$	•	•			•		•		•		•
M5	•	•		•	•					•	•
M5	•	•				•	•			•	•
$\overline{\text{M5}}$	•	•						•	•	•	•

Table: An example of $\mathcal{N} = (1, 0)$ BPS configuration. The Hodge-dual branes are omitted.

$$\Xi = \left(\begin{array}{c|c} \mathbf{1}_2 & \\ \hline & *_4 \end{array}\right)$$

$$\Xi = \left(\begin{array}{c|c} \mathbf{1}_2 & \\ \hline & *_4 \end{array} \right)$$

This keeps $\mathcal{N} = (2,0)$ SUSY – (1/6 BPS condition).

	0	1	2	3	4	5	6	7	8	9	10
M2	•	•	•								
M5	•	•		•	•					•	•
M5	•	•				•	•			•	•
$\overline{\text{M5}}$	•	•						•	•	•	•

Table: $\mathcal{N} = (2,0)$ BPS configuration. The Hodge-dual branes are omitted.

Conclusions and discussions

Conclusion and discussions

Conclusions in this talk

1. We find $n/12$ $(n = 1, \cdots, 5)$ BPS conditions in $\mathcal{N} = 6$ ABJM model
2. Maps from eleven-dimensional projection conditions to the BPS conditions in ABJM model is analyzed
3. Configurations of M-theory objects are studied
4. Reduction to type IIA – brane configurations with D2-branes are studied

Future research

- Existence of solutions
- Explicit solutions
- Dynamics of various M-theory objects
- etc..

$\mathcal{N}$	Residual symmetry	Intersecting branes
6	$SU(3) \times U(1)^2$	M2, KK-monopoles
6	$SU(4)$	M2, M9, M-waves
6	$SU(2) \times SU(2) \times \mathrm{U}(1)^2$	M5
5	$SU(2) \times SU(2)$	M5 with angles
4	$U(1)^3$	M5 with angles
4	$SU(2) \times U(1)^2$	M2, KK-monopoles
4	$SU(2) \times U(1)^2$	M2 with angles
3	$SO(3)$	M2 ending on M5
2	$SU(2) \times SU(2) \times U(1)^2$	M2, KK-monopoles
2	$U(1) \times U(1)$	M2 ending on M5
1	$SU(2) \times SU(2)$	M2 ending on M5, M9, M-waves
$n+m$	$Spin(n) \times Spin(m) \times Spin(6-n-m)$	M5, M9, M-waves

Table: Classification of the BPS equations in the number of preserved supercharges, the symmetry of BPS equations and the corresponding M-theoretical objects. $\mathcal{N}$ is the number of preserved supercharges.