Heterotic M2-branes

Rishi Mouland

Department of Mathematics
King's College London

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Outline

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   - Membrane worldvolume theories
2. M-theory dualities, and our problem
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- It has been conjectured that all of these superstring theories can be realised as various limits of a single theory 11-dimensional theory, which we call M-theory
- M-theory is (a UV completion of) 11d supergravity, with two types of extended objects: M2- and M5-branes. Here, we're interested in the former, also called a membrane

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- Equivalently, starting with M-theory and wrapping one direction on S^1, we arrive at IIA string theory. By choosing the circle to lie either within or transverse to the M2- and M5-branes, we can get all of the extended objects of string theory
- In particular, wrapping one of the (spatial) directions of an M2-brane, we get a 1-brane in 10d - this is the string!

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- Things are harder for branes in M-theory, and especially for the M5-brane. However, much progress has been made in writing down worldvolume theories describing the low-energy dynamics of multiple M2-branes

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- Shortly after, brane constructions uplifted from string to M-theory lead to the ABJM theory [Aharony et al. '08]
- This is an $\mathcal{N} = 6$ superconformal $U(N)_k \times U(N)_{-k}$ Chern-Simons matter theory, conjectured to describe the low-energy dynamics of N M2-branes on a $\mathbb{C}^4/\mathbb{Z}_k \cong \mathbb{R}^8/\mathbb{Z}_k$ transverse space

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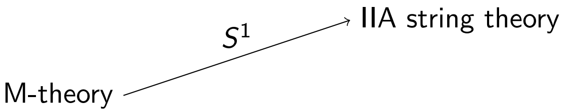
M-theory dualities

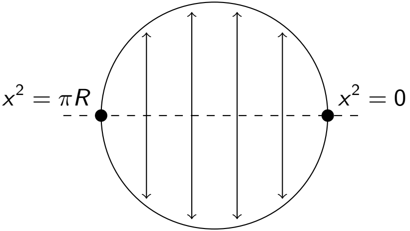


M-theory dualities

M-theory $\xrightarrow{S^1}$ IIA string theory

M-theory $\xrightarrow{S^1/\mathbb{Z}_2}$ $E_8 \times E_8$ heterotic string theory [Horava, Witten '95]

where $S^1/\mathbb{Z}_2 =$



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- How can the transverse space change in the KK limit?

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Orbifolding by parity

- The $G = U(N)_k \times U(N)_{-k}$ ABJM action on $Q = M' \times S^1$ is $S = S_0 + S_{\text{CS}} + S_{\text{int}}$, where

$$S_0 = -\text{tr} \int_Q d^3x \left((D^m Z_A) \left(D_m Z^A \right) + i\bar{\psi}^A \gamma^m D_m \psi_A \right)$$

$$S_{\text{CS}} = \frac{k}{4\pi} \text{tr} \int_Q \left(\left(A^L \wedge dA^L - \tfrac{2i}{3} A^L \wedge A^L \wedge A^L \right) - \left(A^R \wedge dA^R - \tfrac{2i}{3} A^R \wedge A^R \wedge A^R \right) \right)$$

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- Invariant under the $\mathbb{Z}_2$ symmetry

$$Z^A(x^2) \to Z^A(-x^2)^T$$
$$\psi_A(x^2) \to \gamma_2 \psi_A(-x^2)^T$$
$$A_\mu^{L/R}(x^2) \to -A_\mu^{R/L}(-x^2)^T$$
$$A_2^{L/R}(x^2) \to A_2^{R/L}(-x^2)^T$$

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- Half the supersymmetry is broken
- We are able to reduce the theory onto the 'slab' $M := M' \times [0, \pi R]$, with orbifold conditions becoming *boundary conditions* on the fields and allowed gauge transformations

Orbifolding by parity

$$S = \int_Q \mathcal{L} = 2 \int_M \mathcal{L}$$

subject to boundary conditions on ∂M, given by

$$Z^A(x) = Z^A(x)^T, \qquad \partial_2 Z^A(x) = -\partial_2 Z^A(x)^T$$

$$\psi_A(x) = \gamma_2 \psi_A(x)^T \qquad \partial_2 \psi_A(x) = -\gamma_2 \partial_2 \psi_A(x)^T$$

$$A^L_\mu(x) + A^R_\mu(x)^T = 0 \qquad \partial_2 \left(A^L_\mu(x) - A^R_\mu(x)^T \right) = 0$$

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  - Depending on the choice of M', we may also have non-trivial winding around M'
- We find that these remain a symmetry of e^{iS}, provided we have $k = \frac{k'}{2} \in \frac{1}{2}\mathbb{Z}$. Thus, the set of allowed Chern-Simons levels is enhanced.

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- We thus add to S,

$$S_b = -\int_{x^2=0} d^2x \; i\bar{\lambda}^a_- \gamma^\mu D_\mu \lambda^a_- - \int_{x^2=\pi R} d^2x \; i\bar{\lambda}^{a'}_- \gamma^\mu D_\mu \lambda^{a'}_-$$

where

$$D_\mu \lambda^a = \partial_\mu \lambda^a_- \mp i A^L_\mu \lambda^a_- = \partial_\mu \lambda^a_- \mp i \left(-{A^R_\mu}^T \right) \lambda^a_-,$$

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The vacuum moduli space

- To determine what physical configuration of M2-branes our action on $M = M' \times [0, \pi R]$ describes, we look at the vacuum moduli space (VMS): the space of vacua, modulo gauge transformations

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  plus the (discrete) Weyl subgroup of each factor, which permutes the diagonal elements
- Action reduces to N copies of the $N = 1$ ABJM action, with fields charged only under the difference of the two $U(1)$ factors, i.e. $Z^A \to e^{i(\theta^L - \theta^R)} Z^A$. As such, for brevity we look at $N = 1$

The vacuum moduli space

- After integrating out A^+, the covariant derivatives take the form

$$DZ^A = dZ^A - i\,(d\sigma)\,Z^A$$
$$D\psi_A = d\psi_A - i\,(d\sigma)\,\psi_A$$
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- We can therefore soak up the remnant gauge symmetry by defining new fields

$$\hat{Z}^A = e^{-i\sigma} Z^A, \quad \hat{\psi}_A = e^{-i\sigma}\psi_A, \quad \hat{\lambda}^{a,a'} = e^{\mp i\sigma/2}\lambda^{a,a'}$$

The vacuum moduli space

- The action is just

$$\implies S = -\int_Q d^3x \left(\left(\partial^m \hat{Z}_A\right) \left(\partial_m \hat{Z}^A\right) + i\bar{\hat{\psi}}^A \gamma^m \partial_m \hat{\psi}_A \right)$$
$$- \int_{x^2=0} d^2x \; i\bar{\lambda}^{\underline{a}}_- \gamma^\mu D_\mu \lambda^{\underline{a}}_- - \int_{x^2=\pi R} d^2x \; i\bar{\lambda}^{\underline{a}'}_- \gamma^\mu D_\mu \lambda^{\underline{a}'}_-$$

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- A remnant discrete gauge symmetry $\mathbb{Z}_{k'}$ arises from the periodicity of σ, which imposes the identifications

$$\hat{Z}^A \cong \exp\left(\frac{4\pi}{k'} i\right) \hat{Z}^A$$

$$\hat{\psi}^A \cong \exp\left(\frac{4\pi}{k'} i\right) \hat{\psi}^A$$

$$\hat{\lambda}^{a,a'} \cong \exp\left(\pm\frac{2\pi}{k'} i\right) \hat{\lambda}^{a,a'}$$

The vacuum moduli space

- The embedding coordinates $\hat{Z}^A$ parameterise the space transverse to the branes. We find that this space is

$$\frac{\left(\mathbb{C}^4/\mathbb{Z}_{k'}\right)^N}{S_N} = \mathrm{Sym}_N\left(\mathbb{C}^4/\mathbb{Z}_{k'}\right) \qquad \text{for } k' \text{ odd}$$

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- These identifications survive the straightforward KK reduction to the $E_8 \times E_8$ heterotic worldsheet action

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Summary of results

- In this work, we've shown that the $U(N)_k \times U(N)_{-k}$ ABJM theory compactified on $S^1/\mathbb{Z}_2$ describes N indistinguishable M2-branes that are topologically $M' \times I$, for M' some 2-fold, and I an interval

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- These branes propagate on a transverse $\mathbb{Z}_{k'}$ orbifold for k' odd, or $\mathbb{Z}_{k'/2}$ for k' even
- In the KK limit, we retrieve the worldsheet action for the $E_8 \times E_8$ heterotic string

Next steps

- Need to understand the role of the $\mathbb{Z}_{k'}$ identification of the boundary fermions $\lambda_-^{a,a'}$. $k' = 2$ case: good evidence to say this is the $SO(16) \times SO(16)$ non-supersymmetric heterotic theory

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- If so: how does this come about at the supergravity level?
- Consider more general ways to arrive at a consistent quantum theory
    - Different fermions
    - CS-type anomaly inflow from bulk to boundary