Title: Closed strings, moduli and Integrability in AdS3/CFT2

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Abstract: <p>I will review recent progress in computing the exact planar spectrum of closed strings in
AdS3 backgrounds with 8+8 supercharges, including the derivation of the protected spectrum.
Such theories have a multi-dimensional moduli space, and I will show what effect varying
the moduli has on the exact closed string spectrum, and how the integrable structure changes
as we do so, paying particular attention to the background supported by NS-NS flux.</p>

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GOAL: **ALL** closed string spectrum

$AdS_3 \times S^3 \times T^4$ (or $T^4 \to S^3 \times S^1$)

How do 20 moduli affect E?

Plan:
1. AdS_3 as n.h. of 1+5 branes
2. Moduli in asympt + n.h.
3. Spectrum at partic pt in Mod
4. Spectrum for gen. moduli

Background

$D1_{01}$

$F1_{01}$

$D5_{016789}$

$NS5_{016789}$

$Q_{D1} =$

$Q_{F1} =$

$Q_{D5} =$

$Q_{NS5} =$

2023

trum

$S^3 \times S^1)$

E?

branes

n.h.

in Mod

duli

Background

$$\left\{\begin{array}{l} D1_{01} \\ F1_{01} \\ D5_{016789} \\ NS5_{016789} \end{array}\right. \xrightarrow{\text{n.h.}} AdS_3 \times S^3 \times T^4 + \left\{\begin{array}{l} F^{(3)} = \quad (\Omega_{AdS} + \Omega_S) \\ H = \quad (\Omega_{AdS} + \Omega_S) \end{array}\right.$$

$Q_{D1} =$

$Q_{F1} =$

$Q_{D5} =$

$Q_{NS5} =$

$$(Q_{D3} = Q_{D7} = 0)$$

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string spectrum

$S^3 \times T^4$ (or $T^4 \to S^3 \times S^1$)

moduli affect E?

as n.h. of 1+5 branes

in asympt + n.h.

rum at partic pt in Mod

rum for gen. moduli

Background

$$\begin{cases} N_1 \ D1_{01} \\ N_{F1} \ F1_{01} \\ N_5 \ D5_{016789} \\ k \ NS5_{01\underbrace{6789}_{T^4}} \end{cases} \xrightarrow{\text{n.h.}} AdS_3 \times S^3 \times T^4 + \begin{cases} F^{(3)} = N_1 (\Omega_{AdS} + \Omega_S) \\ H = k (\Omega_{AdS} + \Omega_S) \end{cases}$$

$Q_{D1} = N_1$

$Q_{F1} =$

$Q_{D5} =$

$Q_{NS5} =$

$(Q_{D3} = Q_{D7} = 0)$

023

rum

$S^3 \times S^1)$

E?

branes

n.h.

in Mod

uli

Background

$$\left\{\begin{array}{l} N_1 \; D1_{01} \\ N_{F1} \; F1_{01} \\ N_5 \; D5_{016789} \\ k \; NS5_{01\underbrace{6789}_{T^4}} \end{array}\right.$$

$$Q_{D1} = N_1$$

$$Q_{F1} = N_{F1}$$

$$Q_{D5} = N_5$$

$$Q_{NS5} = k$$

$$\xrightarrow{\text{n.h.}} AdS_3 \times S^3 \times T^4 + \left\{\begin{array}{l} F^{(3)} = N_1 (\Omega_{AdS} + \Omega_S) \\ H = k (\Omega_{AdS} + \Omega_S) \end{array}\right.$$

$$(Q_{D3} = Q_{D7} = 0)$$

→ 4 Spectrum for gen. moduli

$Q_{D5} = N_5$

$Q_{NS5} = k$

Moduli

• Asympt flat 25 moduli $= \left\{ g_{ij},\ B_{ij},\ \phi,\ C^{(2)}_{ij},\ C^{(0)},\ C^{(4)}_{6789} \right\}$

• Near horizon attractor mech fixes 5 scalars

$$\mathrm{vol}(T^4),\quad C^{(4)}_{6789},\quad \begin{cases} B^-_{ij} & \text{D1/D5} \\ C^-_{ij} & \text{F1/NS5} \end{cases}$$

• "Simplest point" m_0 : $g_{ij} = \sqrt{v}\,\delta_{ij}$ all other moduli + scalar

• Maldacena Ooguri : WZW at m_0

③ Spectrum at partic pt in Mod

→ ④ Spectrum for gen. moduli

$Q_{D5} = N_5$

$Q_{NS5} = k$

$(Q_{D3} = Q$

Moduli

- Asympt flat 25 moduli $= \{ g_{ij}, B_{ij}, \phi, C^{(2)}_{ij}, C^{(0)}, C^{(4)}_{6789} \}$
- Near horizon attractor mech fixes 5 scalars

$$\mathrm{vol}(T^4),\ C^{(4)}_{6789},\ \begin{cases} B^-_{ij} & \text{D1/D5} \\ C^-_{ij} & \text{F1/NS5} \end{cases}$$

- "Simplest point" m_0: $g_{ij} = \sqrt{v}\,\delta_{ij}$ all other moduli + scalars $= 0$
- Maldacena Ooguri: WZW at m_0

Spectrum from integrability

What

- $p^i = w^i = 0$ $\mathcal{H}_{(0,0)}$ sector
- gauge fix Green-Schwarz action at m_0
- Spectrum $K^+_{p_1} \eta^+_{p_2} \alpha^+_{p_3} \chi^+_{p_4} |J\rangle_{BMN}$ $\sum p_i = 0$

p_i satisfy BETHE EQS

- $$E(p_i) = \sqrt{\left(m_i + \frac{k p_i}{2\pi}\right)^2 + 4\tilde{q}^2 h^2 \sin^2(p_i/2)}$$

$h =$

$$0 \leq \tilde{q} = \frac{N_5 g_s}{\sqrt{k^2 + N_5^2 g_s^2}} \leq 1$$

bility

sector

warz action at m_0

$\chi^{+}_{p_4} |J\rangle_{BMN}$ $\qquad \sum p_i = 0$

ss

$\overline{\qquad\qquad\qquad}$
$g^2 h^2 \sin^2(p_i/2))$

g_s

∘ What does $S^{2\to 2}$ wsheet look like?

∘ S known R_{AdS} to all orders

S satisfies YBE

$$R^2 = \alpha' \sqrt{k^2 + N_5^2 g_s^2}$$

$$h \equiv h(R) = \frac{R^2}{\alpha'} + \ldots$$

Spectrum from integrability

- $p^i = w^i = 0 \quad \mathcal{H}_{(0,0)}$ sector
- gauge fix Green-Schwarz action at m_0
- Spectrum $\underbrace{K^+_{p_1}}_{m^2=1} \underline{\eta^+_{p_2}} \underbrace{\alpha^+_{p_3}}_{m^2=0} \underline{\chi^+_{p_4}} |J\rangle_{BMN}$ $\quad \sum p_i = 0$

p_i satisfy BETHE Eqs

- $E(p_i) = \sqrt{\left(m_i + \frac{k p_i}{2\pi}\right)^2 + 4\tilde{q}^2 h^2 \sin^2(p_i/2)}$

$$0 \leq \tilde{q} = \frac{N_5 g_s}{\sqrt{k^2 + N_5^2 g_s^2}} \leq 1$$

- What does
- S known
$S \quad S$

$h \equiv h(R$

- gauge fix Green-Schwarz action at m_0

$m^2 = 1 \qquad m^2 = 0$

- Spectrum $\underline{K^+_{p_1}}\ \underline{\eta^+_{p_2}}\ \underline{\alpha^+_{p_3}}\ \underline{\chi^+_{p_4}}\ |J\rangle_{BMN}$ $\qquad \sum p_i = 0$

p_i satisfy BETHE Eqs

- $E(p_i) = \sqrt{\left(m_i + \frac{k p_i}{2\pi}\right)^2 + 4\tilde{q}^2 h^2 \sin^2(p_i/2)}$ $\qquad h \equiv h(R$

NSNS $\quad 0 \leq \tilde{q} = \frac{N_5 g_s}{\sqrt{k^2 + N_5^2 g_s^2}} \leq 1 \quad$ RR

Green-Schwarz action at m_0

$m^2 = 1 \qquad m^2 = 0$

$K^+_{p_1} \, \eta^+_{p_2} \, \alpha^+_{p_3} \, \chi^+_{p_4} \, |J\rangle_{BMN} \qquad \sum p_i = 0$

S satisfies YBE

$R^2 = \alpha' \sqrt{k^2 + N_5^2 g_s^2}$

...y BETHE Eqs

$\sqrt{\left(m_i + \frac{k p_i}{2\pi}\right)^2 + 4 \tilde{q}^2 h^2 \sin^2(p_i/2)}$

$h \equiv h(R) = \frac{R^2}{\alpha'} + \dots$

$h(\lambda)$

$\leq \tilde{q} = \frac{N_5 g_s}{\sqrt{k^2 + N_5^2 g_s^2}} \leq 1$ RR

$$q = \frac{\quad}{\sqrt{K^2 + N_5^2 g_s^2}} = 1$$

Spectrum

$p_i = 0$

h.w. states $\left(\chi^{a\,+}_{p_i=0}\right)^n |J\rangle_{BMN}$

16 states for each J

de Boer '98 sugra $\mathrm{Sym}^N(T^4)$

Protected Spectrum

$m_i = 0 \qquad p_i = 0$

h.w. states $\left(\chi^{a\,\dagger}_{p_i=0}\right.$ |

- matches de Boer '98 sugra $\mathrm{Sym}^N(T^4)$
- $AdS_3 \times S^3 \times S^3 \times S^1$ '99 de Boer X

WZW pt $\tilde{q} \to 0$

$+$ S_{mat} BEs are finite

$-$ c. ext. $\propto \tilde{\hat{q}} \longrightarrow 0$

Conclusion: Need just 1 DS br

$\tilde{q} \to 0$

at BEs are finite in $\tilde{q} \to$

t. $\alpha \tilde{q} \longrightarrow 0$

: Need just 1 D5 brane

D1/D5 Spectrum & moduli

g_{ij} $\quad H_{(0,0)}$ $\quad$ CS action & periodicity c

$C^{(2)}$

$$F^{(p+1)} = dC^{(p)} - C^{(p-2)} \wedge H$$

1

2

& moduli

S action & periodicity conditions don't change

$$dC^{(p)} - C^{(p-2)} \wedge H$$

① Eom stay same

② GS action same

D1/D5 Spectrum & moduli

g_{ij} $\quad H_{(0,0)}$ $\quad$ CS action & periodicity

$C^{(2)}$

$$F^{(p+1)} = dC^{(p)} - C^{(p-2)} \wedge H \qquad 1$$

$$Q_{D3} = \int F^{(5)} + C^{(2)} \wedge H = 0 \qquad 2$$

$C^{(0)}$

B^{+}_{ij}

1. eom + Bianchi
2. GS action H

$$Q_{D3} = \int F^{(5)} - B^{+} \wedge F^{(3)} \neq 0$$

$$dC^{(4)} = B^{+} \wedge F^{(3)}$$ solves eom

$$F^{(5)} \neq 0$$ has correct charges

$\underline{B^{+}_{ij}}$

1. eom + Bianchi
2. GS action H

$$Q_{D3} = \int F^{(5)} - B^{+} \wedge F^{(3)} \neq 0$$

$$dC^{(4)} = B^{+} \wedge F^{(3)}$$

$F^{(5)} \neq 0$

solves eom

has correct charges

A $(\mathrm{Tr}\,T)^2_\varphi$ + B $B^+ = cst$ to get right changes

$$T_6 + \begin{pmatrix} \tilde{X}^6 \\ \tilde{X}^7 \end{pmatrix} = \begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix} \begin{pmatrix} X^6 \\ X^7 \end{pmatrix} + T_{\tilde{6}}$$

$D_3 \quad \ldots + C_1 M = 0$

(A) $(TrT)^2_\varphi$ + (B) $B^+ = cst$ to get right charges

$$T_6 + \begin{pmatrix} \tilde{X}^6 \\ \tilde{X}^7 \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{pmatrix}}_{} \begin{pmatrix} X^6 \\ X^7 \end{pmatrix} \quad \times + T_7$$

$$(TrT)^2_\varphi$$

$$R^2 = \alpha' g_s N_5 \sqrt{1 + \tfrac{1}{2} B^{+2}} \quad \begin{pmatrix} \hat{P}_6 \\ \hat{X}'_7 \end{pmatrix} = O^t_\varphi \begin{pmatrix} P_6 \\ X'_7 \end{pmatrix} \quad \begin{pmatrix} \tilde{P}_7 \\ \hat{X}'_6 \end{pmatrix} = O_\varphi \begin{pmatrix} P_7 \\ X'_6 \end{pmatrix}$$

...um & moduli

nothing

$$C^{(4)}_{6789} = -C_0$$

① EoM + Bianchi's ✓

② Charges are also OK

$\left(\begin{array}{c} 6 \\ \hat{x} \end{array}\right) = O^t_6 \left(\begin{array}{c} p_r \end{array}\right) \quad \left(\begin{array}{c} p_z \end{array}\right) = \Omega \left(\begin{array}{c} P \end{array}\right)$

$C^{(0)} = C_0 = cst \qquad C^{(4)}_{6789} = -C_0$

① EoM

② Charge

$$Q_{D5} = \int F^{(3)} + C^{(0)} H$$

$$= \int -C_0 H + C_0 H = 0$$

$$(\mathrm{Tr}T)^2_\varphi$$

$$\begin{pmatrix} \hat{P}_6 \\ \hat{x}'_7 \end{pmatrix} = O^t_\varphi \begin{pmatrix} P_6 \\ x'_7 \end{pmatrix}$$

$R^2 = \alpha' g N \sqrt{1 + \frac{1}{R}[illegible]}$

m & moduli

nothing

$$C^{(4)}_{6789} = -C_0$$

$$F^{(3)} + C^{(0)} H$$

$$\int -c_0 H + c_0 H = 0$$

$$F^{(3)} = dC^{(2)} - C^{(0)} H = -c_0 H$$

1. EoM + Bianchis ✓
2. Charges are also OK ✓
3. GS action changes

$$R^2 = \alpha' k \sqrt{1 + g_s^2 C_0}$$

$$\tilde{q}\, h(R) = - \frac{c_0 k\, g_s}{2\pi}$$

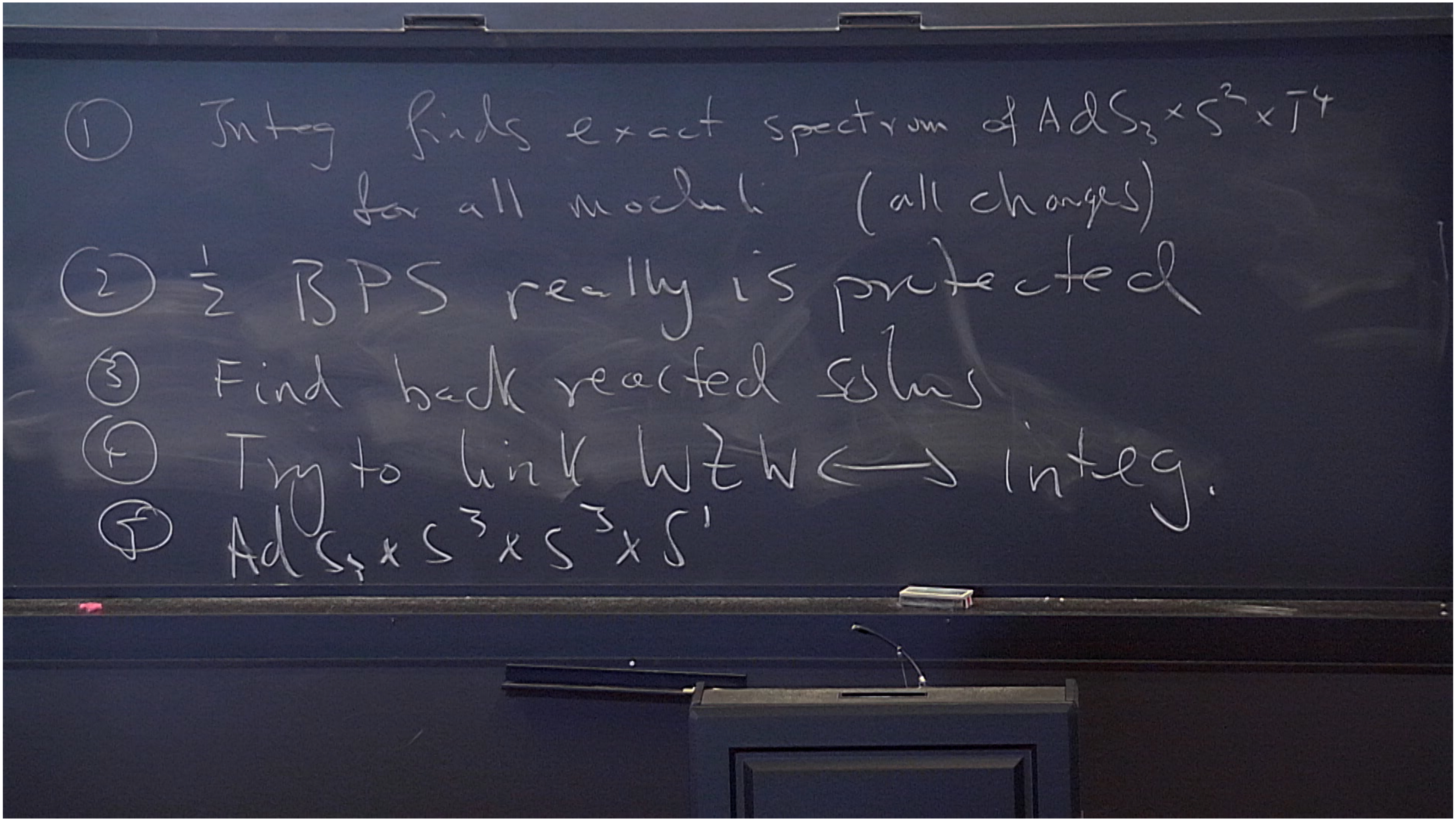
$C^{(2)*}$

$$1 + g_s^2 C_0$$

$$\frac{C_0 K g_s}{2\pi}$$

$$\lambda \sim C_0 K$$

1 + 't Hooft coupling


① Integ finds exact spectrum of $AdS_3 \times S^3 \times T^4$
for all moduli (all charges)
② $\frac{1}{2}$ BPS really is protected
③ Find back reacted solns
④ Try to link WZW ⟷ integ.
⑤ $AdS_3 \times S^3 \times S^3 \times S^1$