



# $\text{AdS}_3$ at the String Scale

---

Matthias Gaberdiel  
ETH Zürich

AdS/CFT at 20 and Beyond  
ICTS Bangalore, 28 May 2018

Based on work with Lorenz Eberhardt, Kevin Ferreira, Rajesh Gopakumar, Chris Hull, Juan Jottar, and Wei Li.



# Overview

---

## I. The CFT dual of $\text{AdS}_3 \times S^3 \times S^3 \times S^1$

[Eberhardt, MRG, Gopakumar, Li '17]  
[Eberhardt, MRG, Li '17]

## II. Higher Spin Symmetry from Worldsheet

[MRG, Gopakumar, Hull '17]  
[Ferreira, MRG, Jottar '17]  
[MRG, Gopakumar '18]



# Symmetries

---

The **dual CFT** of string theory on

$$\text{AdS}_3 \times S^3 \times S^3 \times S^1$$

$$\text{Vir} \oplus \mathfrak{su}(2) \oplus \mathfrak{su}(2) \oplus \mathfrak{u}(1)$$

with 4 supercharges

is believed to have a **large  $\mathcal{N} = 4$  superconformal** symmetry.

[Boonstra, Peeters, Skenderis '98; Elitzur, Feinerman, Giveon, Tsabar '99; de Boer, Pasquinucci, Skenderis '99; Gukov, Martinec, Moore, Strominger '04; ...]



# Dual CFT

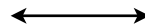
---

Despite the fact that this is, in some sense, a **bigger symmetry than the familiar small N=4 algebra**

small  $\mathcal{N} = 4$

$\text{AdS}_3 \times S^3 \times \mathbb{T}^4$

**string theory**

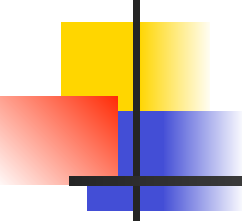


**symmetric orbifold**

$$\text{Sym}_{N+1}(\mathbb{T}^4) \equiv (\mathbb{T}^4)^{\otimes (N+1)} / S_{N+1}$$

the **dual CFT is not known** in this case.

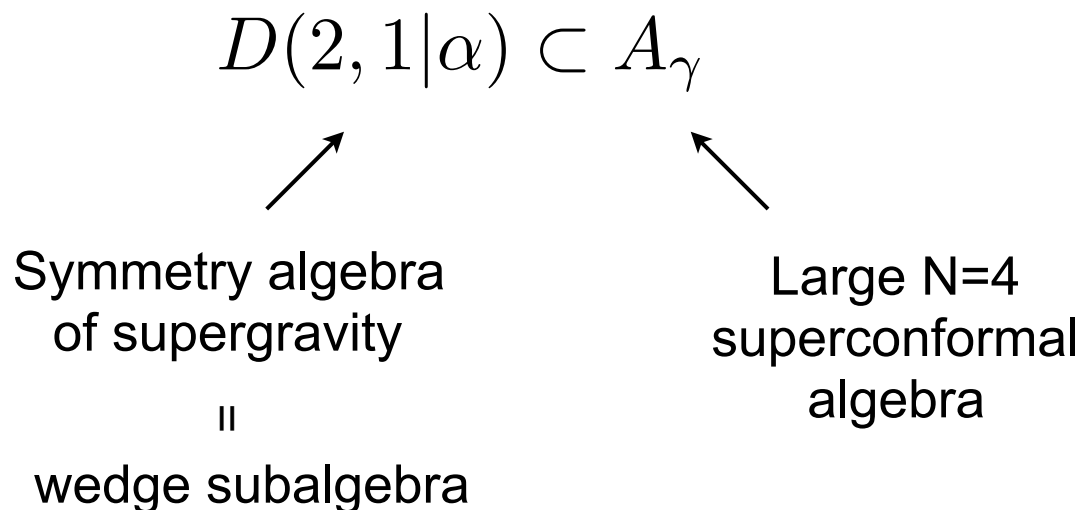
[Gukov, Martinec, Moore, Strominger '04]



# Large $\mathcal{N} = 4$ mysteries

---

Part of the reason why this dual has not yet been determined, is due to the complicated **structure of the BPS bounds** of





# Large $\mathcal{N} = 4$

---

Since the large  $\mathcal{N}=4$  algebra contains **two current algebras**, the algebra is characterised by two parameters: in addition to the **central charge**

$$c = \frac{6k^+k^-}{k^+ + k^-}$$

[Sevrin, Troost, Van Proeyen, Schoutens, Spindel, Theodoridis '88-'90; Goddard, Schwimmer '88]

have **parameter**

$$\gamma = \frac{k^-}{k^+ + k^-} \quad , \quad \alpha = \frac{k^-}{k^+} = \frac{\gamma}{1 - \gamma} \quad .$$

( $k^\pm$  : size of the two S3s.)

$$h_{A_\gamma} \geq \frac{1}{k^+ + k^-} \left[ k^+ j^- + k^- j^+ + u^2 + (j^+ - j^-)^2 \right] .$$



# BPS bound

---

This is to be compared with BPS bound of  $D(2,1|\alpha)$ ,  
i.e. the subalgebra generated by the wedge modes

$$L_0, L_{\pm 1} \ ; \ G_{\pm \frac{1}{2}}^a \ ; \ A_0^{\pm, i}$$

The relevant **highest weight representations** are  
parametrised by

$$(h; j^+, j^-)$$

since there is no  $u(1)$  charge.



# BPS bound



---

The **BPS bound** of  $D(2, 1|\alpha)$  is [de Boer, Pasquinucci, Skenderis '99]

$$h_{D(2,1|\alpha)} \geq \frac{1}{k^+ + k^-} \left[ k^+ j^- + k^- j^+ \right] .$$

This differs from the **BPS bound** of  $A_\gamma$  from above

$$h_{A_\gamma} \geq \frac{1}{k^+ + k^-} \left[ k^+ j^- + k^- j^+ + u^2 + (j^+ - j^-)^2 \right] .$$

u(1) charge  



# BPS bound

---

So even if we restrict to  $u=0$ , the **stringy BPS bound is stronger than the supergravity BPS bound**

$$h \geq h_{A_\gamma} \geq h_{D(2,1|\alpha)}$$

with equality only if  $j^+ = j^-$  .

This leads to the strange phenomenon that any sugra BPS state with  $j^+ \neq j^-$  **has** to acquire non-trivial quantum corrections, even just to satisfy the stringy BPS bound!

[de Boer, Pasquinucci, Skenderis '99]  
[Gukov, Martinec, Moore, Strominger '04]



# BPS spectrum

---

Furthermore, according to the analysis of [de Boer, Pasquinucci, Skenderis '99], the sugra BPS spectrum does contain such states.

In addition, none of the dual CFT candidates had a matching BPS spectrum... It was therefore argued that **only the index of** [Gukov, Martinec, Moore, Strominger '04] had to **agree**.

Constraint from index is however quite weak — as a consequence, no clear conclusion could be reached...



# Problem revisited

---

Decided to revisit this problem by studying the **world-sheet description of string theory** on this background.

[Eberhardt, MRG, Gopakumar, Li '17]

For pure NS-NS flux, can describe the background in terms of **WZW models**

[Elitzur, Feinerman, Giveon, Tsabar '99]

$$\mathfrak{sl}(2, \mathbb{R})_k^{(1)} \oplus \mathfrak{su}(2)_{k^+}^{(1)} \oplus \mathfrak{su}(2)_{k^-}^{(1)} \oplus \mathfrak{u}(1)^{(1)}$$

Criticality:  $\frac{1}{k} = \frac{1}{k^+} + \frac{1}{k^-} \Rightarrow k = \frac{k^+ k^-}{k^+ + k^-} .$



# Problem revisited

---

Impose **physical state condition** in covariant formulation (in NS-NS sector)

$$L_n \Phi = 0, \quad n > 0, \quad G_r \Phi = 0, \quad r > 0, \quad \left( L_0 - \frac{1}{2} \right) \Phi = 0$$

mass-shell condition  ↗

$$N = \frac{1}{2} + \frac{j_0(j_0 - 1)}{k} - \frac{j_0^+(j_0^+ + 1)}{k^+} - \frac{j_0^-(j_0^- + 1)}{k^-}.$$

↑                      ↑                      ↑  
spins of ground state representation



# Problem revisited

---

Spacetime spectrum has  $A_\gamma$  symmetry at levels  $k^\pm$ ,  
and the spacetime conformal dimension is to be  
identified with

[Elitzur, Feinerman, Giveon, Tsabar '99]  
see also [Giveon, Kutasov, Seiberg '98]

$$L_0^{\text{spacetime}} = \mathcal{J}_0^{3\mathfrak{sl}(2,\mathbb{R})},$$

while the spins with respect to the two  $\mathfrak{su}(2)$ 's are  
directly the same.

With this dictionary in hand, we can then look for the  
**spacetime BPS states using the worldsheet  
description.**



# Spacetime BPS spectrum

We have **looked systematically** for the states with **smallest spacetime conformal dimension** for a given choice of spins.

[Eberhardt, MRG, Gopakumar, Li '17]

For these states  $N = \frac{1}{2}$  and  $j = j_0 - 1$ , and the smallest value of  $j$  turns to be

$$\begin{aligned} h = j &= -\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{k j^+ (j^+ + 1)}{k^+} + \frac{k j^- (j^- + 1)}{k^-}} \\ &= -\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{k^- j^+ (j^+ + 1)}{k^+ + k^-} + \frac{k^+ j^- (j^- + 1)}{k^+ + k^-}}. \end{aligned}$$

[This is the analysis in unflowed sector for  $u=0$ ; similar for flowed sectors.]



# Spacetime BPS spectrum

---

Using the Maldacena-Ooguri (unitarity) bound

$$j_0 \leq \frac{k^+ + 1}{2}$$

[Hwang '91]  
[Evans, MRG, Perry '98]  
[Maldacena, Ooguri '00]

where  $j = j_0 - 1$ , we have checked that these states where

$$h = -\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{k^- j^+ (j^+ + 1)}{k^+ + k^-} + \frac{k^+ j^- (j^- + 1)}{k^+ + k^-}}$$

satisfy the spacetime  $A_\gamma$  BPS bound,

$$h_{A_\gamma} \geq \frac{1}{k^+ + k^-} \left[ k^+ j^- + k^- j^+ + (j^+ - j^-)^2 \right] .$$



# Spacetime BPS spectrum

---

$$h = -\frac{1}{2} + \sqrt{\frac{1}{4} + \frac{k^- j^+ (j^+ + 1)}{k^+ + k^-} + \frac{k^+ j^- (j^- + 1)}{k^+ + k^-}}$$

satisfy the spacetime  $A_\gamma$  BPS bound,

$$h_{A_\gamma} \geq \frac{1}{k^+ + k^-} \left[ k^+ j^- + k^- j^+ + (j^+ - j^-)^2 \right] .$$

but only **saturate** it for

$$j^+ = j^-$$



# Sugra interpretation

---

Given the usual relation between string and sugra considerations, this suggests that the same conclusion should also hold in supergravity!

To confirm this, we have performed the KK reduction of 9d sugra, compactified on

$$S^3 \times S^3$$

adjusting the techniques of [Deger, Kaya, Sezgin, Sundell '98] to the present case.

[Restricted our analysis to the scalar NS-NS fields around a pure NS-NS background; note that this analysis had not been done by de Boer et.al. who had **assumed** that all harmonics would be BPS, and had only organised them in short multiplets using group theory.]



# Sugra calculation

---

The calculation is a real tour de force, but the end result is simple: it confirms precisely the stringy prediction, and in particular shows that **also in supergravity the only BPS states arise** for

$$j^{+} = j^{-} .$$

Furthermore, all supergravity states **satisfy** already **automatically** the  $A_{\gamma}$  **bound**, without the need for any miraculous quantum correction.

[Eberhardt, MRG, Gopakumar, Li '17]



# Consequences

---

This resolves this rather mysterious problem.

It also implies that in the search for the CFT dual, one may try again to **match directly the BPS spectrum** — without any need to invoke index arguments.

cf. also [Baggio, et.al. '17]

In fact, there is a rather natural proposal for the dual CFT (at least for certain combinations of charges).

[Eberhardt, MRG, Li '17]



# Dual CFT

---

The  $\text{AdS}_3 \times S^3 \times S^3 \times S^1$  background arises as the **near horizon limit** of

[Gukov, Martinec, Moore, Strominger '04]

$Q_5^+ = k^+$  D5-branes wrapping  $S^3 \times S^1$

$\uparrow$   
 $Q_5^- = k^-$  flux units

This suggests that **dual CFT should be symmetric orbifold** of

see also [Elitzur, Feinerman, Giveon, Tsabar '99]

$$S^3 \times S^1 \cong \mathfrak{su}(2)_k^{(1)} \oplus \mathfrak{u}(1)^{(1)}$$



# Symmetric orbifold

---

$$S^3 \times S^1 \cong \mathfrak{su}(2)_k^{(1)} \oplus \mathfrak{u}(1)^{(1)}$$

is generated by  $(\kappa = k - 2)$

- 4 free fermions + 1 free boson
  - $\mathfrak{su}(2)_\kappa$  current algebra
- $$\left. \vphantom{\begin{matrix} \bullet \\ \bullet \end{matrix}} \right\} \cong \mathcal{S}_\kappa \text{ theory}$$

has  $A_\gamma$  symmetry

We have analysed in detail the **single particle BPS spectrum** of this symmetric orbifold, ....



# Symmetric orbifold

---

[Eberhardt, MRG, Li '17]

... and it matches exactly that of sugra or world-sheet analysis with the parameters (for  $Q_5^- \geq Q_5^+$ )

$$\left( \mathcal{S}_{(Q_5^-/Q_5^+)-1} \right)^{Q_1 Q_5^+} / S_{Q_1 Q_5^+}$$

- only makes sense if  $Q_5^-/Q_5^+$  is integer (anomaly?)
- for  $Q_5^+ = 1$  it agrees with instanton moduli space prediction
- for  $Q_5^- \rightarrow \infty$  it leads to symmetric orbifold of  $\mathbb{T}^4$



# Symmetric orbifold

---

In fact, agreement of BPS spectra works as well as for the familiar case of  $\mathbb{T}^4$ :

- there are gaps in the worldsheet spectrum
- the agreement continues up to  $h = \frac{c}{12}$

Incidentally, all BPS states are N=2 chiral primaries; in particular also moduli agree.



# Other proposals

---

It would be very interesting to understand to which extent this fits together with the proposal of **Tong '14** that takes a different brane configuration as the starting point.

It would also be very interesting to understand the CFT dual for the cases that are not covered by this proposal (i.e. if  $Q_5^-/Q_5^+$  is not an integer.)



# Overview

---

## I. The CFT dual of $\text{AdS}_3 \times S^3 \times S^3 \times S^1$

[Eberhardt, MRG, Gopakumar, Li '17]

[Eberhardt, MRG, Li '17]

## II. Higher Spin Symmetry from Worldsheet

[MRG, Gopakumar, Hull '17]

[Ferreira, MRG, Jottar '17]

[MRG, Gopakumar '18]



# Motivation

---

At the tensionless point in moduli space, **string theory on AdS** is dual to a (nearly) free conformal field theory.

The conserved currents of the free CFT correspond to massless **higher spin fields in AdS**, and the tensionless string theory contains a Vasiliev higher spin theory as a (closed) subsector.

[Fradkin & Vasiliev, '87]  
[Vasiliev, '99...]

[Sundborg, '01], [Witten, '01], [Mikhailov, '02],  
[Klebanov & Polyakov, '02], [Sezgin & Sundell, '03..]



# AdS<sub>3</sub> example

---

[MRG, Gopakumar, '14]

**Concrete realisation** of this idea in context of AdS<sub>3</sub> :  
CFT dual of string theory on AdS<sub>3</sub> × S<sup>3</sup> × T<sup>4</sup> at  
tensionless point is

$$\text{Sym}(\mathbb{T}^4) \equiv (\mathbb{T}^4)^{\otimes (N+1)} / S_{N+1}$$

∪

$$\mathcal{W}_{\infty}^{(\mathcal{N}=4)}[0]$$

CFT dual of Vasiliev  
higher spin theory  
on AdS<sub>3</sub>



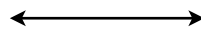
# HS theories vs string theory

[MRG, Gopakumar '13]

This example arose as a particular limit of the duality between Higher Spin theories and dual CFTs with large  $\mathcal{N} = 4$  superconformal symmetry.

hs theory based on

$$\text{shs}_2[\lambda]$$



$$\frac{\mathfrak{su}(N+2)_k \oplus \mathfrak{so}(4N+4)_1}{\mathfrak{su}(N)_{k+2} \oplus \mathfrak{u}(1)_\kappa} \oplus \mathfrak{u}(1)_\kappa .$$

Wolf space cosets

[Sevrin, Troost, Van Proeyen,  
Schoutens, Spindel, .. '88/'89]

in 't Hooft limit with  $\lambda = \frac{N+1}{N+k+2}$  .



# Direct understanding

---

The **identification** between higher spin theories and string theory is, so far, however rather **indirect**, i.e. can only see the higher spin symmetry via the dual CFT.

Try to find more direct description of it. This **requires a world-sheet approach** since the higher spin symmetry is only expected to emerge in the tensionless (stringy) limit — far away from usual supergravity regime.



# Dual CFT

---

To start with, let us consider bosonic case, i.e. [WZW model based on  \$sl\(2, \mathbb{R}\)\$](#) .

[Maldacena, Ooguri '00]

The dual ('spacetime') CFT lives on the boundary of  $AdS_3$ , and we have, as before, the identifications

$$L_0^{\text{CFT}} = J_0^3, \quad L_1^{\text{CFT}} = J_0^-, \quad L_{-1}^{\text{CFT}} = J_0^+,$$

with a similar relation for the right-movers.

The **spacetime energy and spin** are then given as

$$E = \underset{\nearrow}{h} + \bar{h}, \quad s = h - \underset{\nwarrow}{\bar{h}}.$$

spacetime conformal dimension of left- and right-movers



# Massless higher spins

---

On the other hand, the AdS mass is

$$m_{\text{AdS}_3}^2 = (E - |s|)(E + |s| - 2)$$

Given that spacetime conformal dimensions are non-negative, **massless higher spin fields** only arise for

$$E = \pm s \quad h = 0 \text{ or } \bar{h} = 0.$$

chiral fields of spacetime CFT



# Physical states

---

This description is again covariant, i.e. we need to **impose physical state condition**

$$L_n^{\text{tot}} \Phi = 0 \quad n > 0$$
$$(L_0^{\text{tot}} - 1) \Phi = 0 .$$

In particular, the second condition (mass-shell) condition implies that

$$\frac{C}{k-2} + h_0 + N = 1 .$$

Casimir of  $\text{sl}(2, \mathbb{R})$       World-sheet conformal dim. of internal CFT



# Representations I

---

The  $\mathfrak{sl}(2, \mathbb{R})$  ground state representations that appear in the world-sheet spectrum are the

**Discrete lowest weight reps:**

$$\mathcal{D}_j^+ : \quad C = -j(j-1) \ , \quad J_0^- |j, j\rangle = 0$$

↑  
quasi-primary from spacetime CFT perspective!

**Continuous reps:**

$$\mathcal{C}(p, \alpha) : \quad C = \frac{1}{4} + p^2 \ , \quad |j, m\rangle \text{ with } m \in \alpha + \mathbb{Z}$$



# No-ghost theorem

---

Because of the Maldacena-Ooguri (unitarity) bound,

MO-bound:  $\frac{1}{2} < j < \frac{k-1}{2}$  [Hwang '91]  
[Evans, MRG, Perry '98]  
[Maldacena, Ooguri '00]

the **spectrum is bounded** from above. Additional states are **spectrally flowed images** of these two classes of representations

[Maldacena, Ooguri '00]  
see also [Henningson et.al. '91]

They are not Virasoro highest weight, and are therefore best described in terms of the spectral flow automorphism.



# Spectral flow automorphism

---

Basic idea: work with **original representation space**,  
but define on it a **new action (by automorphism)**:

$$\hat{J}_n^\pm \equiv \alpha_w(J_n^\pm) = J_{n \mp w}^\pm$$

$$\hat{J}_n^3 \equiv \alpha_w(J_n^3) = J_n^3 + \frac{k}{2}w\delta_{n,0} \quad (w \in \mathbb{N})$$

$$\hat{L}_n \equiv \alpha_w(L_n) = L_n - wJ_n^3 - \frac{k}{4}w^2\delta_{n,0} .$$

Since the **automorphism is outer**, get a **new representation** in this manner: spectrally flowed rep.



# Long Strings

---

Here the interpretation is that  $w$  is the winding number of the string around the boundary of AdS.

In particular, the  $w=1$  continuous representation describes the long string running near the boundary of AdS. It is stable since

tension is compensated by the NS flux of the AdS space.



# Physical spectrum

---

With these preparations at hand, we can now study the **physical spectrum of the theory**.

In particular, we can look systematically for **massless (higher spin) fields**, i.e., physical states with  $h=0$ , say.

Let us begin by analysing the unflowed discrete representations.



# Unflowed discrete reps

---

Let us begin by analysing the unflowed discrete representations.

In this case, the **mass-shell condition** becomes

$$-\frac{j(j-1)}{k-2} + N = 1$$

where we have set  $h_0 = 0$  . This can be rewritten as

$$j^2 - j - (k-2)(N-1) = 0$$



# Unflowed discrete reps

---

At level  $N$  the  $sl(2, \mathbb{R})$  spin is at least

$$h = j - N \xrightarrow{h=0} j = N .$$

Plugging into the above equation then leads to

$$N^2 - N - (k - 2)(N - 1) = 0$$

There is **one obvious solutions**:

$$N = j = 1 : \quad \text{graviton}$$



# Unflowed discrete reps

---

The other solution of the quadratic equation arises for

$$N = k - 2 .$$

However, since  $N=j$ , this implies

$$j = k - 2 \geq \frac{k - 1}{2} \quad \left( \text{for } j = N = 2, 3, \dots, \right. \\ \left. \text{i.e., } k = 4, 5, \dots \right)$$

**Not allowed by the MO-bound!**

Thus there are **no massless higher spin fields from discrete unflowed representations.**



# Flowed representations

---

For the **spectrally flowed representations** the mass-shell condition becomes

Casimir of ground state rep

$$\frac{C}{k-2} - wm - \frac{k}{4}w^2 + N = 1$$

$J_0^3$  eigenvalue before spectral flow

Demanding  $h=0$  then leads to

$$h = m + \frac{k}{2}w = 0 \quad \implies \quad m = -\frac{wk}{2} ,$$

i.e.

$$\frac{C}{k-2} + \frac{k}{4}w^2 + N = 1$$



# Flowed representations

---

It is not difficult to see that there are **no solutions for the discrete representations** (using the MO/unitarity bound for the original representations) but **something interesting happens for the  $w=1$  spectrally flowed continuous reps.**



# Flowed representations

---

For **continuous** representations with  $w=1$  and  $N=0$

$$\frac{C}{k-2} + \frac{k}{4}w^2 + N = 1$$

becomes

$$p^2 + \frac{1}{4} = -\frac{k^2}{4} + \frac{3}{2}k - 2$$

which has a solution for

$$k = 3 \quad \text{and} \quad p = 0 .$$



# Higher Spin Symmetry

---

In fact, an **infinite set of higher spin fields** becomes **massless** at this point: for the right-movers we have to solve the right-moving analogue of

$$\boxed{\frac{C}{k-2} - wm - \frac{k}{4}w^2 + N = 1} \quad (k=3, p=0, w=1)$$

i.e.

$$\frac{1}{4} - \bar{m} - \frac{3}{4} + \bar{N} = 1$$

which is solved by  $\bar{m} = -\frac{3}{2} + \bar{N}$ .

Thus get a massless higher spin field for every right-moving excitation (and similarly for left-movers)!



# Supersymmetric version

---

The analysis of the **supersymmetric version** of this theory is similar. Consider the case

$$\text{AdS}_3 \times S^3 \times \mathbb{T}^4$$
$$\updownarrow$$
$$\mathfrak{sl}(2, \mathbb{R})_k^{(1)} \oplus \mathfrak{su}(2)_{k'}^{(1)} \oplus (\mathfrak{u}(1)^{(1)})^4$$

[N=1 susy WZW models]

Criticality requires that the **two levels are the same**

$$k = k' .$$



# Supersymmetric bounds

---

Since

$$\mathfrak{su}(2)_k^{(1)} \cong \mathfrak{su}(2)_{k-2} \oplus 3 \text{ free fermions}$$

[bosonic WZW model]

unitarity of the  $\mathfrak{su}(2)$  factor implies that  $k \geq 2$ .

In addition, for the **discrete representations** the unitarity = MO-bound takes now the form

$$\frac{1}{2} < j < \frac{k+1}{2}$$



# Massless higher spins

---

The analogue of  $k=3$  in the bosonic case is now

$$k = 1$$

[corresponds to  $k = 3$   
for bosonic  $\mathfrak{sl}(2)$ ]

For this value of the level, an **infinite tower of massless higher spin fields** appears in the  $w=1$  spectrally flowed continuous representation with  $p=0$ .

[Note that  **$k=1$  is strictly speaking not allowed** because of the  $k \geq 2$  bound coming from the  $\mathfrak{su}(2)$  unitarity. However, this conclusion can be avoided for  $\text{AdS}_3 \times S^3 \times S^3 \times S^1$ . Also,  $\mathfrak{su}(2)$  at  $k = -1$  has a free field description in terms of 4 symplectic bosons — can use this to make sense of this theory.]

[Goddard, Olive, Waterson '87]



# Full spectrum

---

In fact, a **stronger statement** is true. At  $k=1$ , the mass-shell condition for the **spectrally flowed continuous reps** with  $p=0$  and generic  $w$  is

$$\frac{1}{4} - w\left(m + \frac{w}{4}\right) + N = \frac{1}{2} .$$

Solving for  $m$  and observing that the actual  $J_0^3$  eigenvalue is

$$h = m + \frac{w}{2} = \frac{N}{w} + \frac{w^2 - 1}{4w} .$$

w-twisted modes

ground state energy in  
w-twisted sector



# Full spectrum

---

Thus, we recover the full single-particle part of the symmetric orbifold from the world-sheet, where

spectral flow parameter  $w$  = length of twist-cycle

[MRG, Gopakumar '18]  
see also [Giribet, et.al. '18]

This suggests that this higher spin symmetry is indeed related to that appearing at the symmetric orbifold point (which in turn seems to be connected to tensionless strings).



# Conclusions I

---

- Shown that the **BPS spectrum of string theory and supergravity** on

$$\text{AdS}_3 \times S^3 \times S^3 \times S^1$$

**agrees** and contains only states with  $j^+ = j^-$  .

- Identified a **natural candidate for dual CFT** that reproduces correct BPS spectrum:

$$\left( \mathcal{S}_{(Q_5^-/Q_5^+)-1} \right)^{Q_1 Q_5^+} / S_{Q_1 Q_5^+}$$



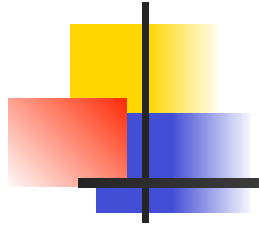
# Conclusions II

---

- ▶ Analysed whether string theory on AdS3 has massless higher spin fields, using the WZW world-sheet approach

massless higher spin fields appear for  $k=1$  from long strings

- ▶ In fact, the  $k=1$  theory contains a sector that matches exactly the spectrum of the symmetric orbifold.



Thank you!