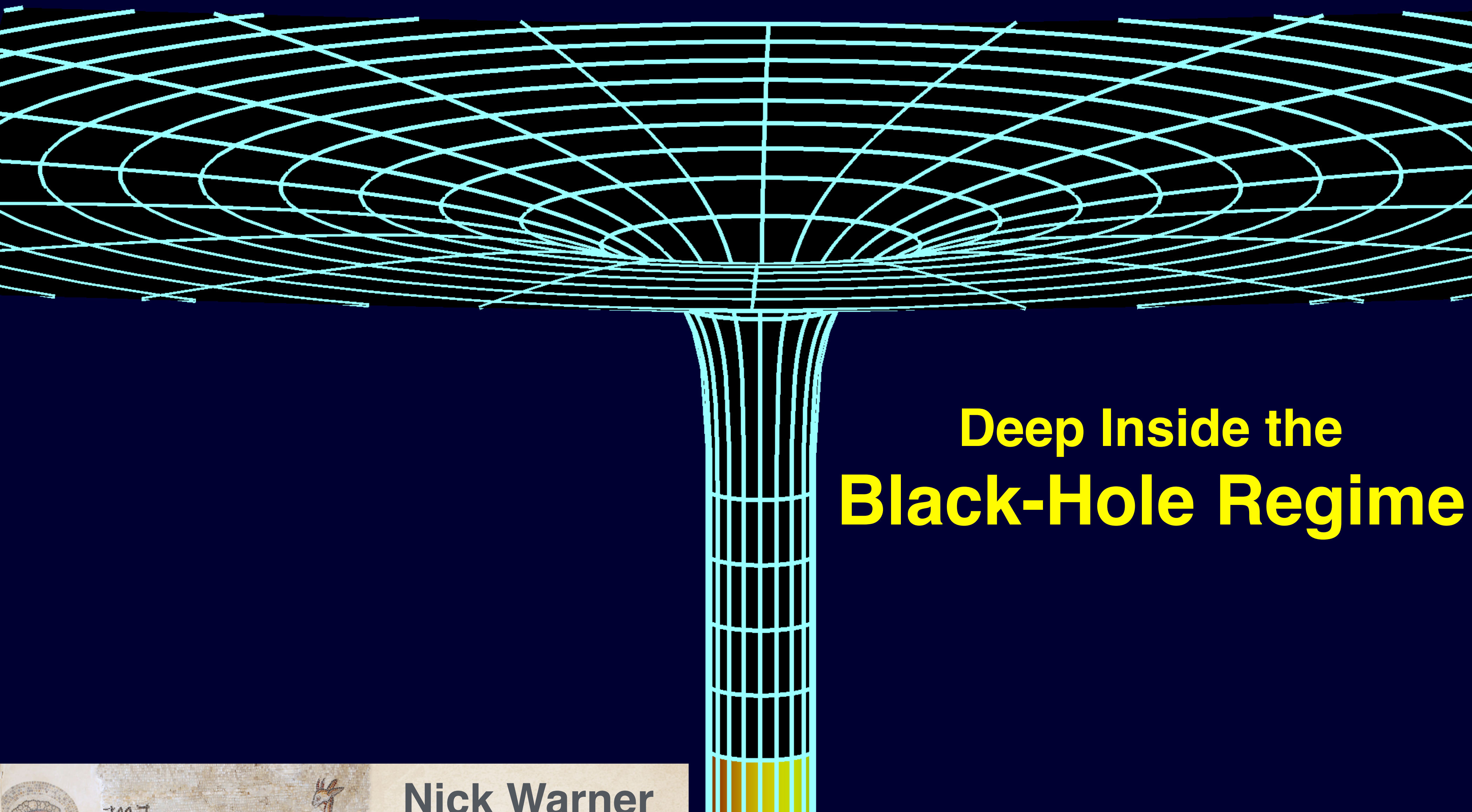
Microstate Geometries



Deep Inside the **Black-Hole Regime**

Research supported supported in part by
DOE grant DE- SC0011687

Outline

- Microstate Geometries D1-D5-P Holography
- Some families of D1-D5-P states
- Building the holographic duals: Microstate geometries with AdS_2/BTZ throats
- The MSW string
- Holographic duals of some MSW states

Based on Collaborations with:

I. Bena, S. Giusto, E. Martinec, R. Russo, M. Shigemori, D. Turton.

arXiv:1607.03908, arXiv:1703.10171, arXiv:1708.XXXXX

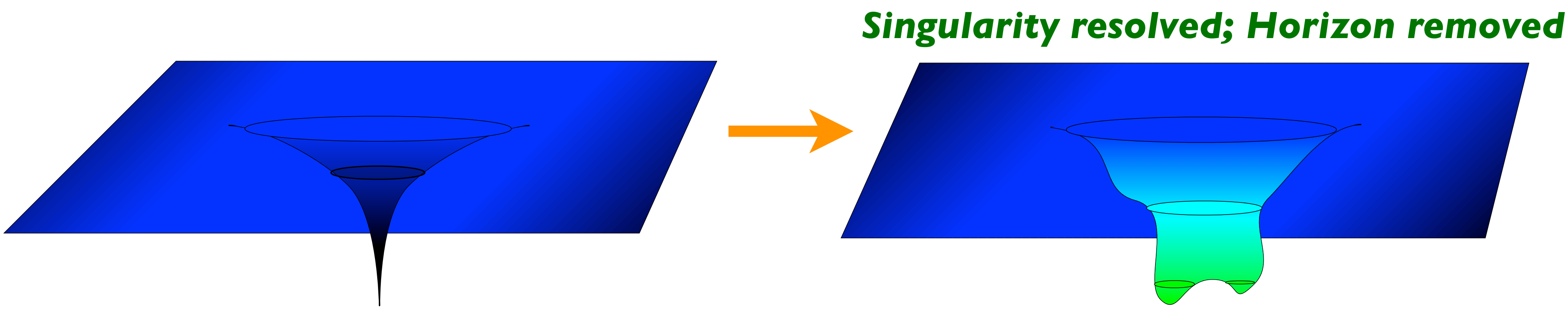
Microstate Geometry Program

Microstate Geometry ≡ Smooth, horizonless solutions to the bosonic sector of ***supergravity*** with the same asymptotic structure as a given black hole/ring

Singularity resolved; Horizon removed

Microstate Geometry Program

Microstate Geometry ≡ Smooth, horizonless solutions to the bosonic sector of ***supergravity*** with the same asymptotic structure as a given black hole/ring

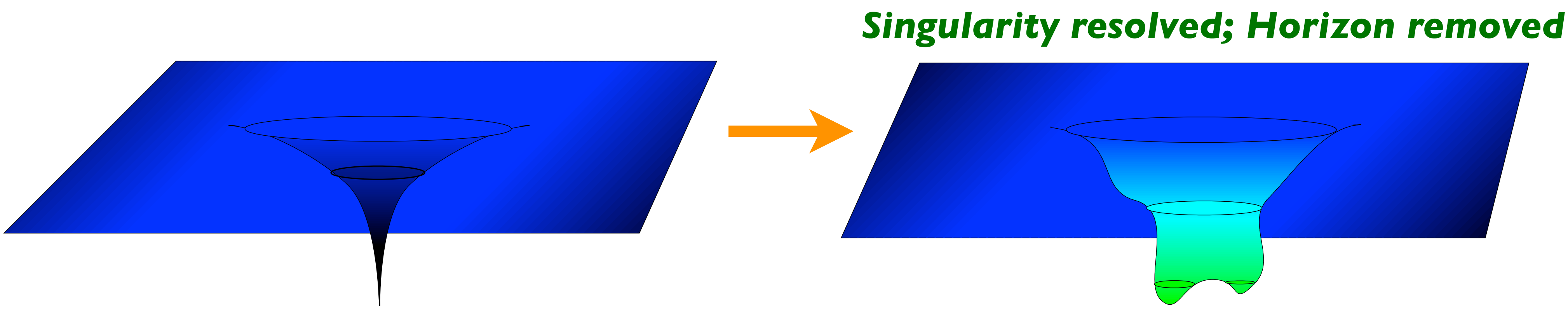


Supergravity because we seek stringy resolutions at the horizon scale

- *Very long-range effects* ⇒ Massless limit of strings …

Microstate Geometry Program

Microstate Geometry ≡ Smooth, horizonless solutions to the bosonic sector of ***supergravity*** with the same asymptotic structure as a given black hole/ring



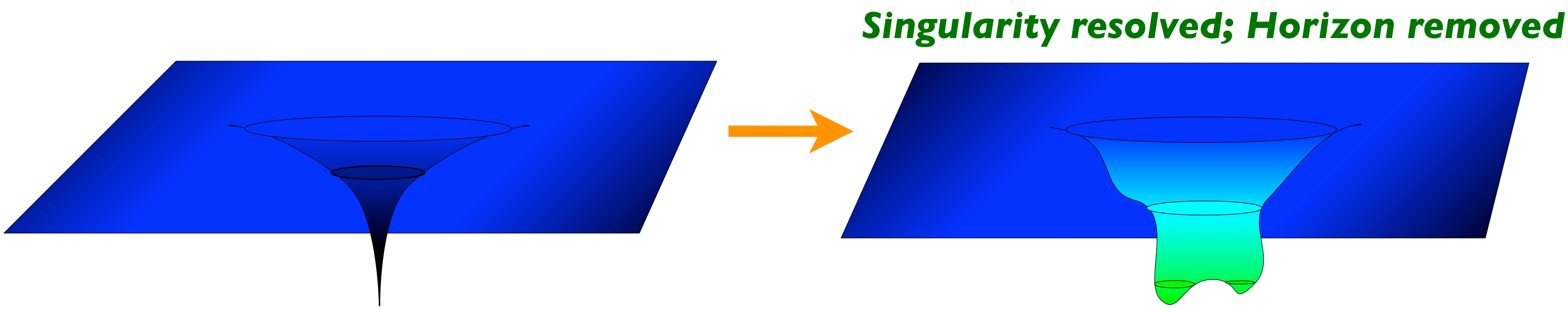
Supergravity because we seek stringy resolutions at the horizon scale

- *Very long-range effects* ⇒ Massless limit of strings …

What is the form of generic, BPS, time-independent horizonless, smooth solutions in supergravity?

Microstate Geometry Program

Microstate Geometry ≡ Smooth, horizonless solutions to the bosonic sector of ***supergravity*** with the same asymptotic structure as a given black hole/ring



Supergravity because we seek stringy resolutions at the horizon scale

- *Very long-range effects* ⇒ Massless limit of strings …

What is the form of generic, BPS, time-independent horizonless, smooth solutions in supergravity?

What CFT states do they describe?

Primary Motivation for Microstate Geometries

Resolving the black-hole information problem seems to require microstate structure to be encoded and supported at the horizon scale

Microstate Geometries

- ***The only (known) mechanism that can support structure at the horizon scale***

- ***Supergravity captures the universal, macroscopic features of microstate structure***

- Semi-classical analysis: ***To what extent can supergravity encode microstate structure?***

Black-Hole Microstates and CFT’s

Black-Hole Microstates and CFT's

- **D1-D5 CFT:** A (4,4) supersymmetric CFT with $c = 6\, N_1\, N_5$

¼ BPS states = (R,R)-ground states

⅛ BPS states = $(\underbrace{\text{any left-moving state}}_{N_P}$, R ground state$)$

Strominger-Vafa state counting for BPS black hole in five dimensions:

$$S \;=\; 2\,\pi\,\sqrt{N_1 N_5 N_P}$$

Black-Hole Microstates and CFT's

- **D1-D5 CFT:** A (4,4) supersymmetric CFT with c = 6 N_1 N_5

  ¼ BPS states = (R,R)-ground states

  ⅛ BPS states = (*any left-moving state*, R ground state)

  $\underbrace{\textit{any left-moving state}}_{N_P}$

  Strominger-Vafa state counting for BPS black hole in five dimensions:

$$S = 2\pi\sqrt{N_1 N_5 N_P}$$

- **MSW String:** A (0,4) supersymmetric CFT *(Maldacena-Strominger-Witten)*

  M5 brane wrapping a divisor in a **CY_3**. Dual class, ***P*** ∊ $H^2(CY_3, \mathbb{Z})$

  MSW string CFT lives on remaining (1+1) dimensions of M5 brane

  Central charge **c = 6 D**, $D = \frac{1}{6}\int_{CY_3} P^3$

  State counting for BPS black hole in four dimensions: $S = 2\pi\sqrt{D\, N_P}$

One Focus of the Microstate Geometry Program

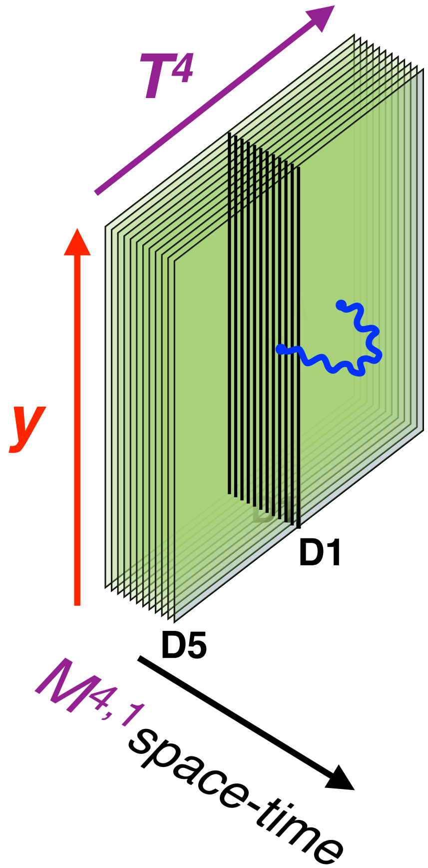
Describe the strongly coupled gravity duals of these CFT states.

To what extent can these CFT states be captured in supergravity?

$\Rightarrow$ Universal gravity dual of both D1-D5 and MSW.

The D1-D5 CFT

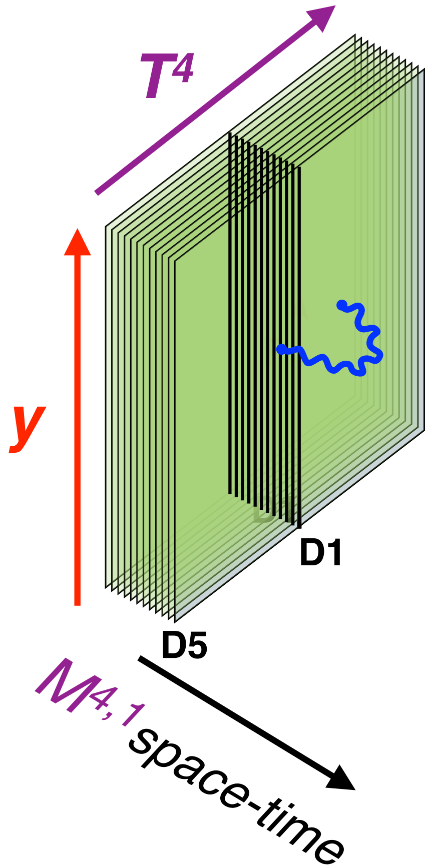
Open D1-D5 superstrings moving in T^4
with $N \equiv N_1 N_5$ Chan-Paton labels: $(T^4)^N/S_N$



⇒ CFT on common **D1-D5** direction, $(t,y) \Leftrightarrow (u,v)$
(4,4) supersymmetric CFT with $c = 6\, N_1 N_5$

The D1-D5 CFT

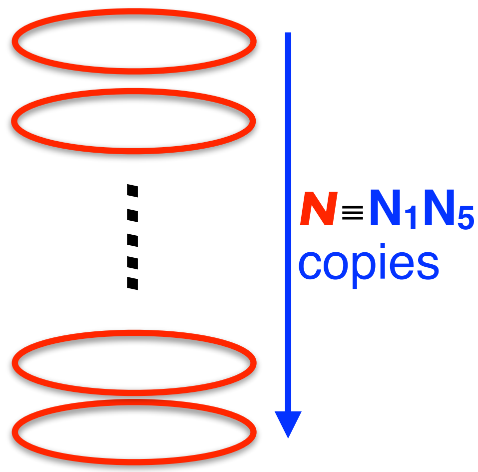
Open D1-D5 superstrings moving in T^4
with $N \equiv N_1 N_5$ Chan-Paton labels: $(T^4)^N/S_N$



$\Rightarrow$ CFT on common **D1-D5** direction, $(t,y) \Leftrightarrow (u,v)$
(4,4) supersymmetric CFT with $c = 6 N_1 N_5$

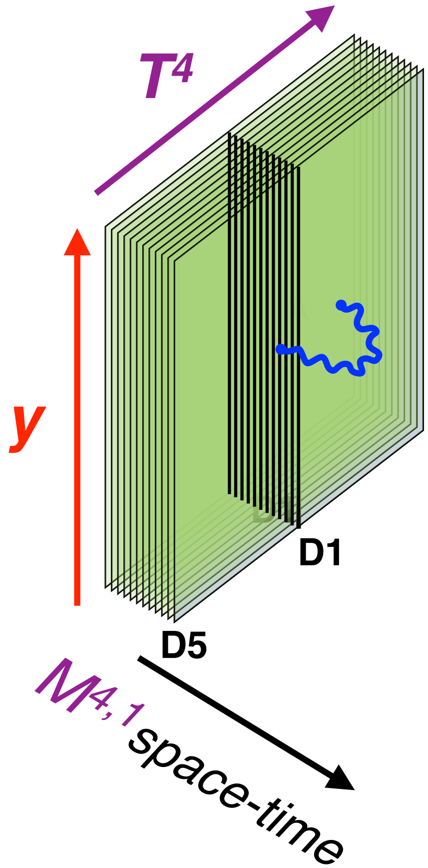
$y \equiv y + 2\pi R$

Maximally spinning (¼ BPS) RR-ground state:



The D1-D5 CFT

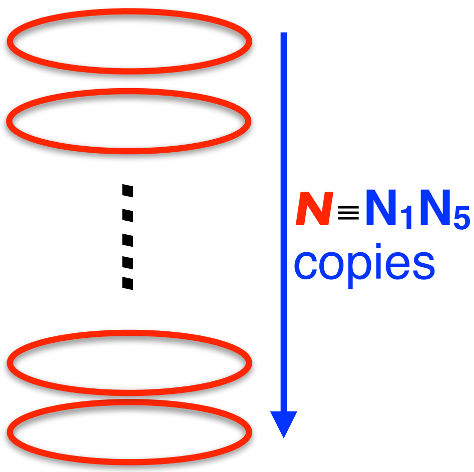
Open D1-D5 superstrings moving in T^4
with $N \equiv N_1 N_5$ Chan-Paton labels: $(T^4)^N/S_N$



$\Rightarrow$ CFT on common **D1-D5** direction, $(t,y) \Leftrightarrow (u,v)$
(4,4) supersymmetric CFT with $c = 6\, N_1 N_5$

$y \equiv y + 2\pi R$

Maximally spinning (¼ BPS) RR-ground state:



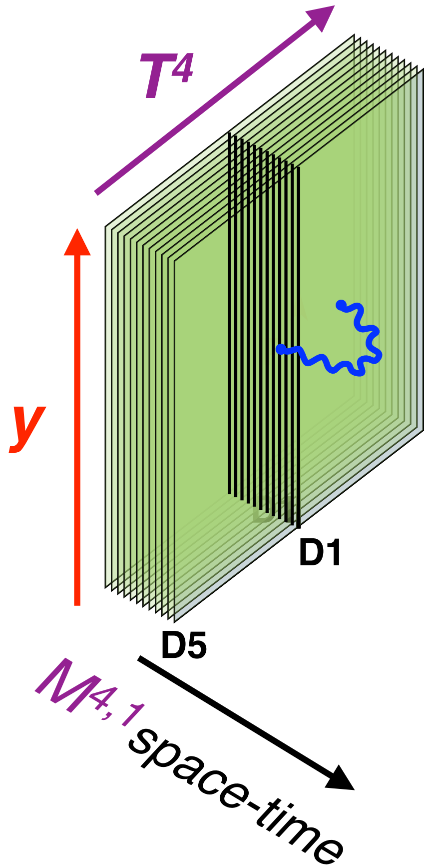
$(+,+)$
$(+,+)$
$\vdots$
$(+,+)$
$(+,+)$

space-time angular momenta

$(j_L, j_R) = \frac{1}{2}(N, N)$

The D1-D5 CFT

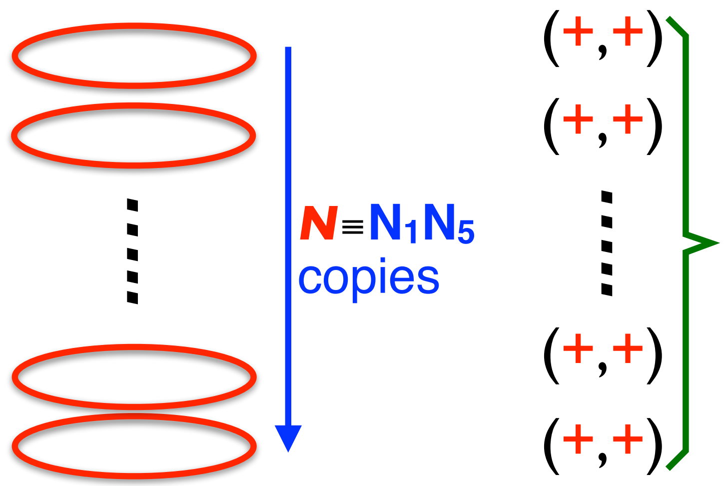
Open D1-D5 superstrings moving in T^4
with $N \equiv N_1 N_5$ Chan-Paton labels: $(T^4)^N/S_N$



⇒ CFT on common D1-D5 direction, (t,y) ⇔ (u,v)
(4,4) supersymmetric CFT with c = 6 $N_1 N_5$

$y \equiv y + 2\pi R$

Maximally spinning (¼ BPS) RR-ground state:



space-time angular momenta

$(j_L, j_R) = \frac{1}{2}(N, N)$

Holographic dual: Maximally spinning supertube in $R^{4,1}$

Supertube profile spins out into $M^{4,1}$ space-time

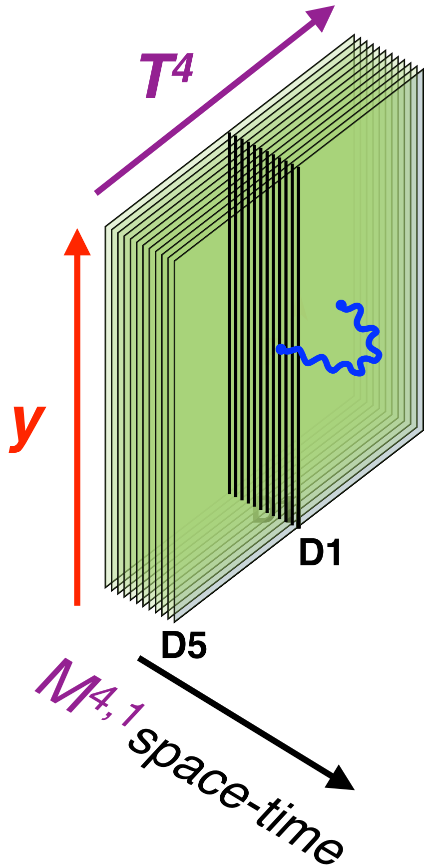
$$(g_1(v), g_2(v), g_3(v), g_4(v)) \in \mathbb{R}^4$$

$$g_1(v) + i g_2(v) = a\, e^{2\pi i v/R}$$

$$g_3(v) = g_4(v) = 0$$

The D1-D5 CFT

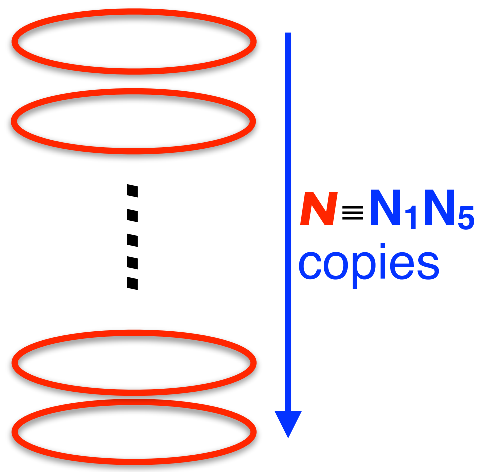
Open D1-D5 superstrings moving in T^4
with $N \equiv N_1 N_5$ Chan-Paton labels: $(T^4)^N/S_N$



⇒ CFT on common D1-D5 direction, (t,y) ⇔ (u,v)
(4,4) supersymmetric CFT with $c = 6 N_1 N_5$

$y \equiv y + 2\pi R$

Maximally spinning (¼ BPS) RR-ground state:



(+,+)
(+,+)
⋮
(+,+)
(+,+)

} space-time angular momenta

$(j_L, j_R) = \tfrac{1}{2}(N, N)$

Holographic dual: Maximally spinning supertube in $R^{4,1}$

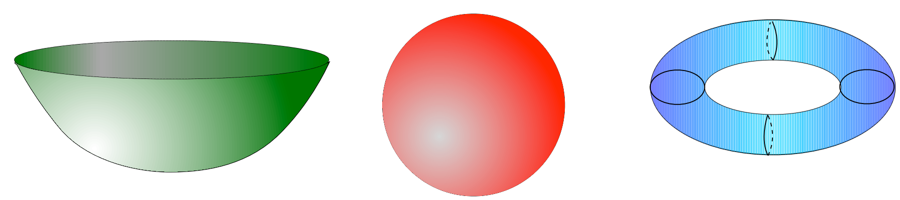
Supertube profile spins out into $M^{4,1}$ space-time

$$Q_1\, Q_5 = R^2\, \mathbf{a}^2$$

$$(g_1(v), g_2(v), g_3(v), g_4(v)) \in \mathbb{R}^4$$
$$g_1(v) + i g_2(v) = a\, e^{2\pi i v/R}$$
$$g_3(v) = g_4(v) = 0$$

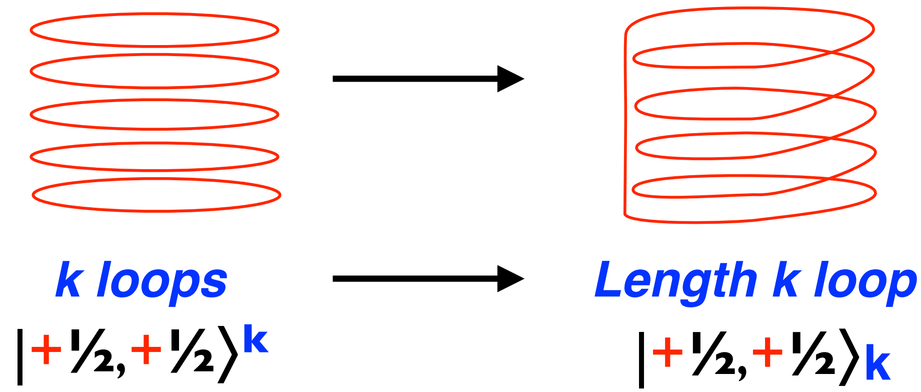
back-react →

AdS$_3$ × S^3 × T^4



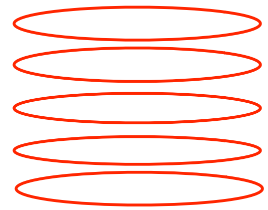
More general ¼ BPS profiles

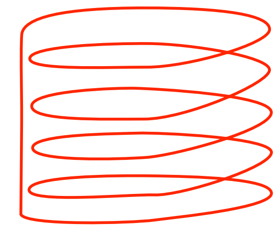
Orbifold CFT: ***k*** twisted sector



More general ¼ BPS profiles

Orbifold CFT: ***k*** twisted sector





k loops → ***Length k loop***

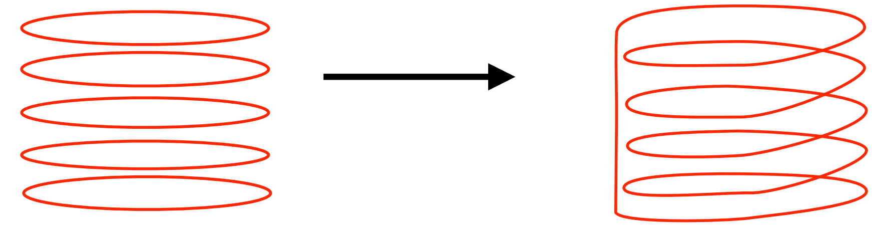
$|+\tfrac{1}{2},+\tfrac{1}{2}\rangle^{k}$ → $|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_{k}$

Act with fermion zero modes ↓

$|0,0\rangle^{k}$ → $|0,0\rangle_{k}$

More general ¼ BPS profiles

Orbifold CFT: ***k*** twisted sector



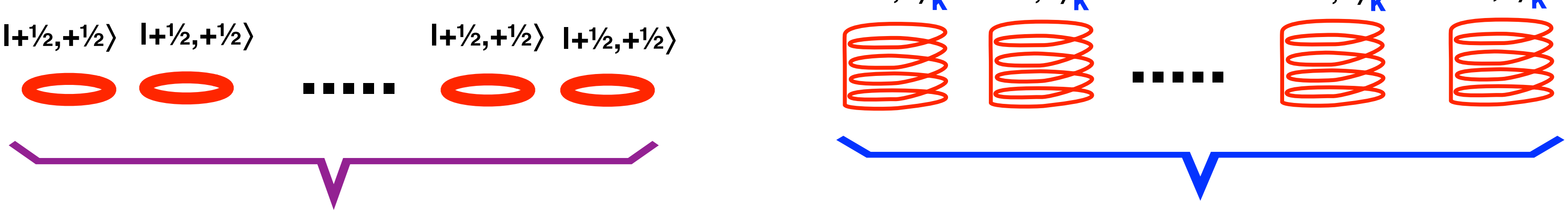
k* loops** → ***Length k loop

$|+\frac{1}{2},+\frac{1}{2}\rangle^{k}$ → $|+\frac{1}{2},+\frac{1}{2}\rangle_{k}$

Act with fermion zero modes

$|0,0\rangle^{k}$ → $|0,0\rangle_{k}$

More general class of D1-D5 ground state

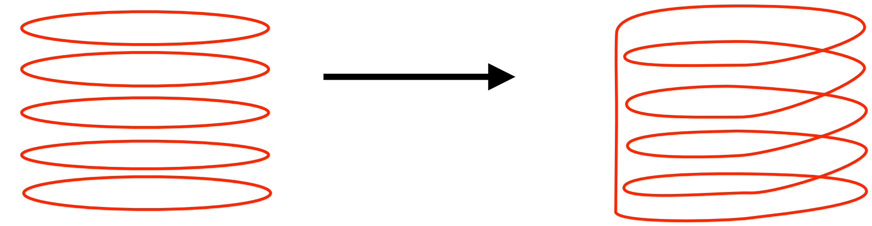


~ a^2 copies

~ b^2 copies

More general ¼ BPS profiles

Orbifold CFT: ***k*** twisted sector



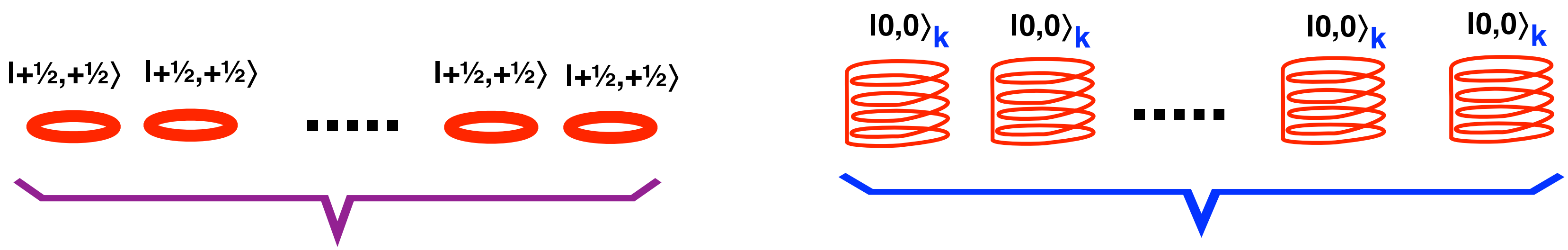
k* loops** → ***Length k loop

$|{+\tfrac{1}{2}},{+\tfrac{1}{2}}\rangle^{k}$ $\qquad$ $|{+\tfrac{1}{2}},{+\tfrac{1}{2}}\rangle_{k}$

Act with fermion zero modes ↓

$|0,0\rangle^{k} \longrightarrow |0,0\rangle_{k}$

More general class of D1-D5 ground state



~ $\mathbf{a}^2$ copies $\qquad$ ~ $\mathbf{b}^2$ copies

Holographic dual supertube profile

$$g_1(v) + i g_2(v) = \mathbf{a}\, e^{2\pi i v/R} \qquad \text{“}g_5(v)\text{”} = \mathbf{b}\, \sin(2\pi\, \mathbf{k}\, v/R)$$

Partitioning of charges: $\quad Q_1\, Q_5 \;=\; R^2\,(\mathbf{a^2} + \mathbf{b^2})$

Families ⅛ BPS states in the D1-D5-P system

Generic ⅛ BPS state: Add general left-moving excitations

Momentum charge, Q_P **= $L_{0,left}$** $$S = 2\pi\sqrt{Q_1 Q_5 Q_P}$$ *(Strominger-Vafa)*

Families ⅛ BPS states in the D1-D5-P system

Generic ⅛ BPS state: Add general left-moving excitations

Momentum charge, Q_P $= L_{0,left}$ $$S = 2\pi\sqrt{Q_1 Q_5 Q_P}$$ *(Strominger-Vafa)*

Very special families of momentum excitations: "Supergraviton gas"

$$\left(\left|+\tfrac{1}{2},+\tfrac{1}{2}\right\rangle_1\right)^{N_0} \otimes \left(\frac{1}{m!\,n!}\,(J^+_{-1})^m\,(L_{-1}-J^3_{-1})^n\,|00\rangle_k\right)^{N_{k,m,n}}$$

$$N_0 + \mathbf{k}\,N_{k,m,n} = N \equiv N_1\,N_5$$

Families ⅛ BPS states in the D1-D5-P system

Generic ⅛ BPS state: Add general left-moving excitations

Momentum charge, Q_P $= L_{0,left}$ $$S \;=\; 2\pi\sqrt{Q_1 Q_5 Q_P}$$ *(Strominger-Vafa)*

Very special families of momentum excitations: “Supergraviton gas”

$$\left(|+\tfrac{1}{2}\,,+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{m!\,n!}\,(J^+_{-1})^m\,(L_{-1}-J^3_{-1})^n|00\rangle_k\right)^{N_{k,m,n}}$$

$$N_0 \;+\; \mathbf{k}\,N_{k,m,n} \;=\; N \;\equiv\; N_1\,N_5$$

Quantum numbers

Define $\mathcal{N} \;=\; \dfrac{N_1 N_5}{a^2+b^2}$

$$j_L \;=\; \tfrac{1}{2}\,\mathcal{N}\left(\mathbf{a^2}+\frac{m}{k}\,\mathbf{b^2}\right)\,, \qquad \tilde{j}_R = \tfrac{1}{2}\,\mathcal{N}\,\mathbf{a^2}\,, \qquad N_P = \tfrac{1}{2}\,\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b^2}$$

$$Q_1\,Q_5 \;=\; R^2\,(\mathbf{a^2}+\mathbf{b^2})$$

Families ⅛ BPS states in the D1-D5-P system

Generic ⅛ BPS state: Add general left-moving excitations

Momentum charge, Q_P $= L_{0,left}$ $$S = 2\pi\sqrt{Q_1 Q_5 Q_P}$$ *(Strominger-Vafa)*

Very special families of momentum excitations: “Supergraviton gas”

$$\left(|+\tfrac{1}{2}\,,+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{m!\,n!}\,(J^+_{-1})^m\,(L_{-1} - J^3_{-1})^n|00\rangle_k\right)^{N_{k,m,n}}$$

$$N_0 + \mathbf{k}\,N_{k,m,n} = N \equiv N_1\,N_5$$

Quantum numbers

Define $\mathcal{N} = \dfrac{N_1 N_5}{a^2 + b^2}$

$$j_L = \tfrac{1}{2}\,\mathcal{N}\left(\mathbf{a^2} + \frac{m}{k}\,\mathbf{b^2}\right), \qquad \tilde{j}_R = \tfrac{1}{2}\,\mathcal{N}\,\mathbf{a^2}\,, \qquad N_P = \tfrac{1}{2}\,\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b^2}$$

$$Q_1\,Q_5 = R^2\,(\mathbf{a^2} + \mathbf{b^2})$$

Families ⅛ BPS states in the D1-D5-P system

Generic ⅛ BPS state: Add general left-moving excitations

Momentum charge, Q_P **= $L_{0,left}$** $$S = 2\pi\sqrt{Q_1 Q_5 Q_P}$$ *(Strominger-Vafa)*

Very special families of momentum excitations: "Supergraviton gas"

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{m!\,n!}\,(J^+_{-1})^m\,(L_{-1}-J^3_{-1})^n|00\rangle_k\right)^{N_{k,m,n}}$$

$$N_0 + \mathbf{k}\,N_{k,m,n} = N \equiv N_1 N_5$$

Quantum numbers

Define $$\mathcal{N} = \frac{N_1 N_5}{a^2+b^2}$$

$$j_L = \tfrac{1}{2}\mathcal{N}\left(\mathbf{a^2} + \frac{m}{k}\,\mathbf{b^2}\right), \qquad \tilde{j}_R = \tfrac{1}{2}\mathcal{N}\,\mathbf{a^2}, \qquad N_P = \tfrac{1}{2}\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b^2}$$

$$Q_1 Q_5 = R^2\left(\mathbf{a^2}+\mathbf{b^2}\right)$$

Families ⅛ BPS states in the D1-D5-P system

Generic ⅛ BPS state: Add general left-moving excitations

Momentum charge, Q_P $= L_{0,left}$ $\quad S = 2\pi\sqrt{Q_1 Q_5 Q_P}$ *(Strominger-Vafa)*

Very special families of momentum excitations: "Supergraviton gas"

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{m!\,n!}\,(J^+_{-1})^m\,(L_{-1}-J^3_{-1})^n|00\rangle_k\right)^{N_{k,m,n}}$$

$$N_0 + \mathbf{k}\,N_{k,m,n} = N \equiv N_1 N_5$$

Quantum numbers

Define $\mathcal{N} = \dfrac{N_1 N_5}{a^2+b^2}$

$$j_L = \tfrac{1}{2}\mathcal{N}\left(\mathbf{a^2} + \frac{m}{k}\mathbf{b^2}\right), \qquad \tilde{j}_R = \tfrac{1}{2}\mathcal{N}\,\mathbf{a^2}, \qquad N_P = \tfrac{1}{2}\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b^2}$$

D1-D5 |+½,+½⟩ residue

$$Q_1 Q_5 = R^2\left(\mathbf{a^2}+\mathbf{b^2}\right)$$

Families ⅛ BPS states in the D1-D5-P system

Generic ⅛ BPS state: Add general left-moving excitations

Momentum charge, Q_P $= L_{0,left}$ $$S = 2\pi\sqrt{Q_1 Q_5 Q_P}$$ *(Strominger-Vafa)*

Very special families of momentum excitations: "Supergraviton gas"

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{m!\,n!}\,(J^+_{-1})^m\,(L_{-1}-J^3_{-1})^n|00\rangle_k\right)^{N_{k,m,n}}$$

$$N_0 + \mathbf{k}\,N_{k,m,n} = N \equiv N_1 N_5$$

Quantum numbers

Define $$\mathcal{N} = \frac{N_1 N_5}{a^2+b^2}$$

$$j_L = \tfrac{1}{2}\mathcal{N}\left(\mathbf{a^2} + \frac{m}{k}\,\mathbf{b^2}\right), \qquad \tilde{j}_R = \tfrac{1}{2}\mathcal{N}\,\mathbf{a^2}, \qquad N_P = \tfrac{1}{2}\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b^2}$$

D1-D5 |+½,+½⟩ residue

$$Q_1\,Q_5 = R^2\,(\mathbf{a^2}+\mathbf{b^2})$$

Special forms:

Adding pure momentum: m = 0.

Vanishing angular momentum: m = 0, **a → 0.**

The "Supergraviton gas"

We know the supergravity duals of arbitrary superpositions of states of the form:

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left[\bigotimes_{k_i,m_i,n_i}\left(\frac{1}{m_i!\,n_i!}\,(J^+_{-1})^{m_i}\,(L_{-1}-J^3_{-1})^{n_i}\,|00\rangle_{k_i}\right)^{N_{k_i,m_i,n_i}}\right]$$

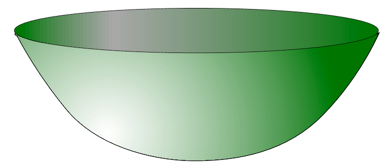
The "Supergraviton gas"

We know the supergravity duals of arbitrary superpositions of states of the form:

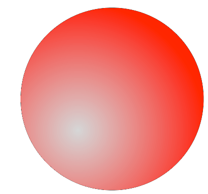
$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left[\bigotimes_{k_i,m_i,n_i}\left(\frac{1}{m_i!\,n_i!}\,(J^+_{-1})^{m_i}\,(L_{-1}-J^3_{-1})^{n_i}\,|00\rangle_{k_i}\right)^{N_{k_i,m_i,n_i}}\right]$$

Holographic duals

Add momentum and angular momentum excitations to D1-D5 profiles:



AdS$_3$ (u,**v**,r)



S^3 (θ,**ψ**,**φ**)

$$g_1(v)+ig_2(v)=\mathbf{a}\,e^{2\pi i v/R} \qquad \text{“}g_5(v)\text{”}=\mathbf{b}\,\sin(2\pi\,\mathbf{k}\,v/R)$$

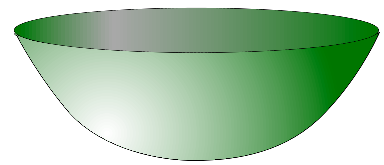
The “Supergraviton gas”

We know the supergravity duals of arbitrary superpositions of states of the form:

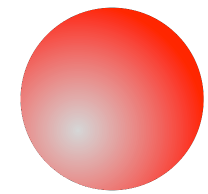
$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left[\bigotimes_{k_i,m_i,n_i} \left(\frac{1}{m_i!\,n_i!} \left(J^+_{-1}\right)^{m_i} \left(L_{-1} - J^3_{-1}\right)^{n_i} |00\rangle_{k_i} \right)^{N_{k_i,m_i,n_i}} \right]$$

Holographic duals

Add momentum and angular momentum excitations to D1-D5 profiles:



AdS$_3$ (u,**v**,r)



S^3 (θ,**ψ**,**φ**)

$$g_1(v) + i g_2(v) = \mathbf{a}\, e^{2\pi i v/R} \qquad \text{“}g_5(v)\text{”} = \mathbf{b}\,\sin(2\pi\,\mathbf{k}\,v/R)$$

to give:

$$j_L = \tfrac{1}{2}\mathcal{N}\left(\mathbf{a^2} + \frac{m}{k}\,\mathbf{b^2}\right), \qquad \tilde{j}_R = \tfrac{1}{2}\mathcal{N}\,\mathbf{a^2}, \qquad N_P = \tfrac{1}{2}\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b^2}$$

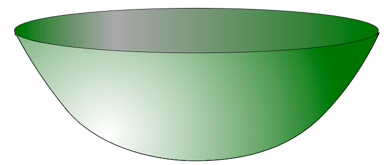
The "Supergraviton gas"

We know the supergravity duals of arbitrary superpositions of states of the form:

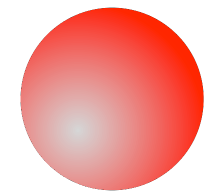
$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left[\bigotimes_{k_i,m_i,n_i} \left(\frac{1}{m_i!\,n_i!}\,(J^+_{-1})^{m_i}\,(L_{-1}-J^3_{-1})^{n_i}\,|00\rangle_{k_i}\right)^{N_{k_i,m_i,n_i}}\right]$$

Holographic duals

Add momentum and angular momentum excitations to D1-D5 profiles:



AdS_3 (u,**v**,r)



S^3 (θ,**ψ**,**φ**)

$$g_1(v)+ig_2(v) = \mathbf{a}\,e^{2\pi i v/R} \qquad \text{“}g_5(v)\text{”} = \mathbf{b}\,\sin(2\pi\,\mathbf{k}\,v/R)$$

to give: $$j_L = \tfrac{1}{2}\mathcal{N}\left(\mathbf{a^2}+\frac{m}{k}\,\mathbf{b^2}\right), \qquad \tilde{j}_R = \tfrac{1}{2}\mathcal{N}\,\mathbf{a^2}, \qquad N_P = \tfrac{1}{2}\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b^2}$$

Three mode numbers, (k,m,n) ⇒ Supergravity duals depend on:

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}\,k\,\phi$$

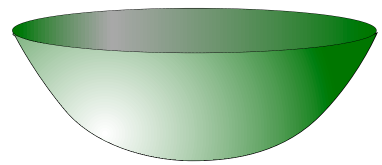
<u>The "Supergraviton gas"</u>

We know the supergravity duals of arbitrary superpositions of states of the form:

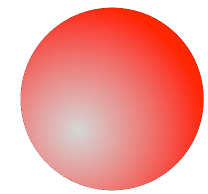
$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left[\bigotimes_{k_i,m_i,n_i} \left(\frac{1}{m_i!\,n_i!}\,(J^+_{-1})^{m_i}\,(L_{-1}-J^3_{-1})^{n_i}\,|00\rangle_{k_i}\right)^{N_{k_i,m_i,n_i}}\right]$$

<u>Holographic duals</u>

Add momentum and angular momentum excitations to D1-D5 profiles:



AdS$_3$ (u,**v**,r)



S^3 (θ,**ψ**,**φ**)

$$g_1(v) + i g_2(v) = \mathbf{a}\, e^{2\pi i v/R} \qquad \text{“}g_5(v)\text{”} = \mathbf{b}\,\sin(2\pi\,\mathbf{k}\,v/R)$$

to give: $j_L = \frac{1}{2}\mathcal{N}\left(\mathbf{a}^2 + \frac{m}{k}\,\mathbf{b}^2\right)$, $\tilde{j}_R = \frac{1}{2}\mathcal{N}\,\mathbf{a}^2$, $N_P = \frac{1}{2}\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b}^2$

Three mode numbers, (k,m,n) ⇒ Supergravity duals depend on:

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$

k-mode: (ψ-φ) ↔ $j_L = j_R$ responsible for $j_L = \tilde{j}_R = \frac{1}{2}\mathcal{N}\,\mathbf{a}^2$

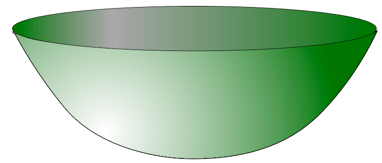
The "Supergraviton gas"

We know the supergravity duals of arbitrary superpositions of states of the form:

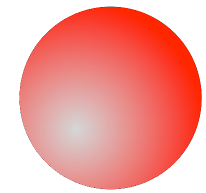
$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left[\bigotimes_{k_i,m_i,n_i} \left(\frac{1}{m_i!\,n_i!}(J^+_{-1})^{m_i}\,(L_{-1}-J^3_{-1})^{n_i}\,|00\rangle_{k_i}\right)^{N_{k_i,m_i,n_i}}\right]$$

Holographic duals

Add momentum and angular momentum excitations to D1-D5 profiles:



AdS$_3$ (u,v,r)



S^3 (θ,ψ,φ)

$$g_1(v)+ig_2(v)=\mathbf{a}\,e^{2\pi i v/R} \qquad \text{“}g_5(v)\text{”} = \mathbf{b}\,\sin(2\pi\,\mathbf{k}\,v/R)$$

to give: $$j_L = \tfrac{1}{2}\mathcal{N}\left(\mathbf{a}^2+\frac{m}{k}\mathbf{b}^2\right), \qquad \tilde{j}_R=\tfrac{1}{2}\mathcal{N}\,\mathbf{a}^2, \qquad N_P=\tfrac{1}{2}\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b}^2$$

Three mode numbers, (k,m,n) ⇒ Supergravity duals depend on:

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$

k-mode: (ψ-φ) ↔ $j_L = j_R$ responsible for $j_L = \tilde{j}_R = \tfrac{1}{2}\mathcal{N}\,\mathbf{a}^2$

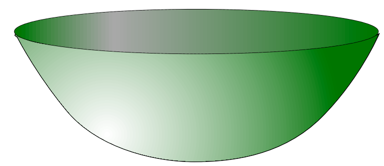
m-mode (v-ψ) ↔ j_L, N_P responsible for $\tilde{j}_R = \tfrac{1}{2}\mathcal{N}\,\frac{\mathbf{m}}{\mathbf{k}}\,\mathbf{b}^2$ $\quad N_P = \tfrac{1}{2}\mathcal{N}\,\frac{\mathbf{m}}{\mathbf{k}}\,\mathbf{b}^2$

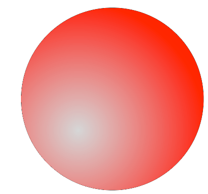
The "Supergraviton gas"

We know the supergravity duals of arbitrary superpositions of states of the form:

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left[\bigotimes_{k_i,m_i,n_i}\left(\frac{1}{m_i!\,n_i!}(J^+_{-1})^{m_i}(L_{-1}-J^3_{-1})^{n_i}|00\rangle_{k_i}\right)^{N_{k_i,m_i,n_i}}\right]$$

Holographic duals





Add momentum and angular momentum excitations to D1-D5 profiles:

AdS$_3$ (u,**v**,r) S^3 (θ,**ψ**,**φ**)

$$g_1(v) + i g_2(v) = \mathbf{a}\, e^{2\pi i v/R} \qquad \text{“}g_5(v)\text{”} = \mathbf{b}\,\sin(2\pi\,\mathbf{k}\,v/R)$$

to give: $j_L = \frac{1}{2}\mathcal{N}\left(\mathbf{a^2} + \frac{m}{k}\mathbf{b^2}\right)$, $\tilde{j}_R = \frac{1}{2}\mathcal{N}\,\mathbf{a^2}$, $N_P = \frac{1}{2}\mathcal{N}\,\frac{m+n}{k}\,\mathbf{b^2}$

Three mode numbers, (k,m,n) ⇒ Supergravity duals depend on:

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$

k-mode: (ψ-φ) ↔ $j_L = j_R$ responsible for $j_L = \tilde{j}_R = \frac{1}{2}\mathcal{N}\,\mathbf{a^2}$

m-mode (v-ψ) ↔ j_L, N_P responsible for $\tilde{j}_R = \frac{1}{2}\mathcal{N}\,\frac{\mathbf{m}}{\mathbf{k}}\,\mathbf{b^2}$ $N_P = \frac{1}{2}\mathcal{N}\,\frac{\mathbf{m}}{\mathbf{k}}\,\mathbf{b^2}$

n-mode (v) ↔ N_P responsible for $N_P = \frac{1}{2}\mathcal{N}\,\frac{\mathbf{n}}{\mathbf{k}}\,\mathbf{b^2}$

Building the Fluctuating BPS Microstate Geometries

IIB Supergravity on T^4: Supergravity + two (anti-self-dual) tensor multiplets in six-dimensions

Six-dimensional metric ansatz:

(Gutowski, Martelli and Reall)

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\big(du+\omega-\tfrac{1}{2}Z_3(dv+\beta)\big) + \sqrt{\mathcal{P}}\,V^{-1}(d\psi+A)^2 + \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

Building the Fluctuating BPS Microstate Geometries

IIB Supergravity on *T^4*: Supergravity + two (anti-self-dual) tensor multiplets in six-dimensions

Six-dimensional metric ansatz: *(Gutowski, Martelli and Reall)*

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\big(du+\omega-\tfrac{1}{2}Z_3(dv+\beta)\big) + \sqrt{\mathcal{P}}\,V^{-1}(d\psi+A)^2 + \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

u = null time; (v, ψ) define a double ***S^1*** fibration over a flat ***R^3*** base with coordinates, y.

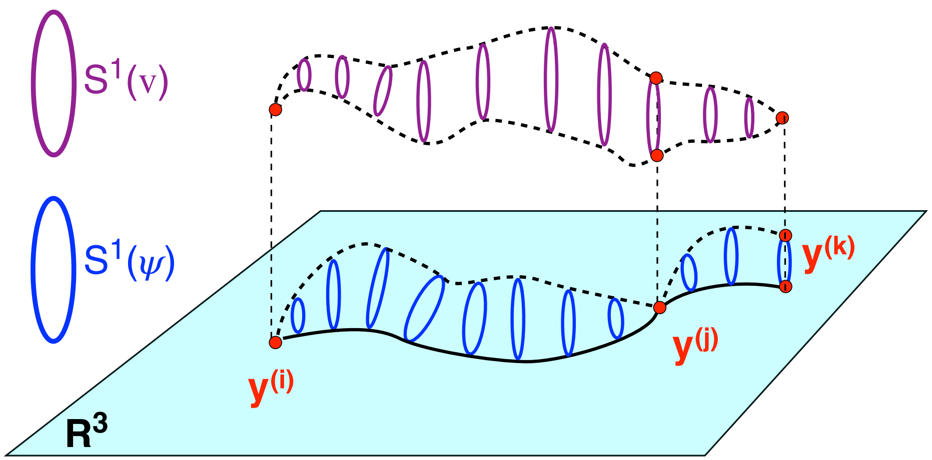
Building the Fluctuating BPS Microstate Geometries

IIB Supergravity on T^4: Supergravity + two (anti-self-dual) tensor multiplets in six-dimensions

Six-dimensional metric ansatz: *(Gutowski, Martelli and Reall)*

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\big(du+\omega-\tfrac{1}{2}Z_3(dv+\beta)\big) + \sqrt{\mathcal{P}}\,V^{-1}(d\psi+A)^2 + \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

u = null time; (v, ψ) define a double S^1 fibration over a flat R^3 base with coordinates, y.



The non-trivial homology cycles are defined through the pinching off of the $S^1 \times S^1$ fibration at special points in the R^3 base.

Building the Fluctuating BPS Microstate Geometries

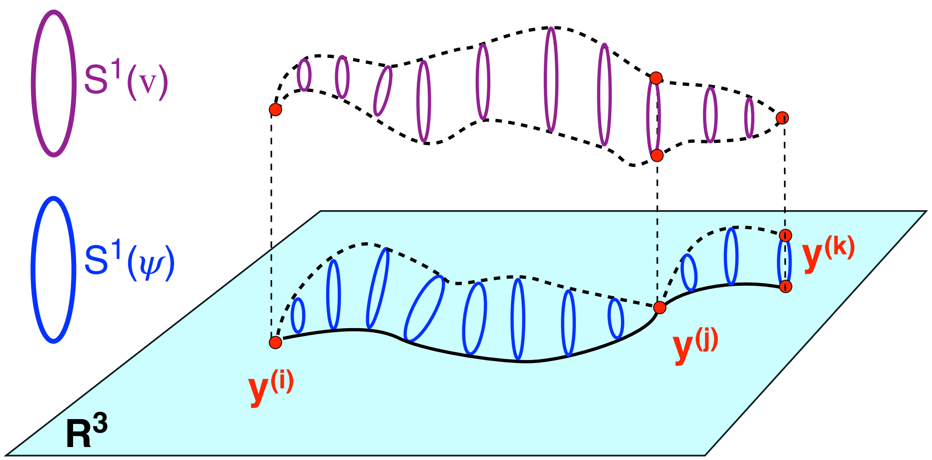
IIB Supergravity on T^4: Supergravity + two (anti-self-dual) tensor multiplets in six-dimensions

Six-dimensional metric ansatz: *(Gutowski, Martelli and Reall)*

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\big(du+\omega-\tfrac{1}{2}Z_3(dv+\beta)\big) + \sqrt{\mathcal{P}}\,V^{-1}(d\psi+A)^2 + \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

u = null time; (v, ψ) define a double S^1 fibration over a flat R^3 base with coordinates, y.

The scale of everything is set by the "warp factors:" ***V, P*** and Z_3



The non-trivial homology cycles are defined through the pinching off of the $S^1 \times S^1$ fibration at special points in the R^3 base.

Building the Fluctuating BPS Microstate Geometries

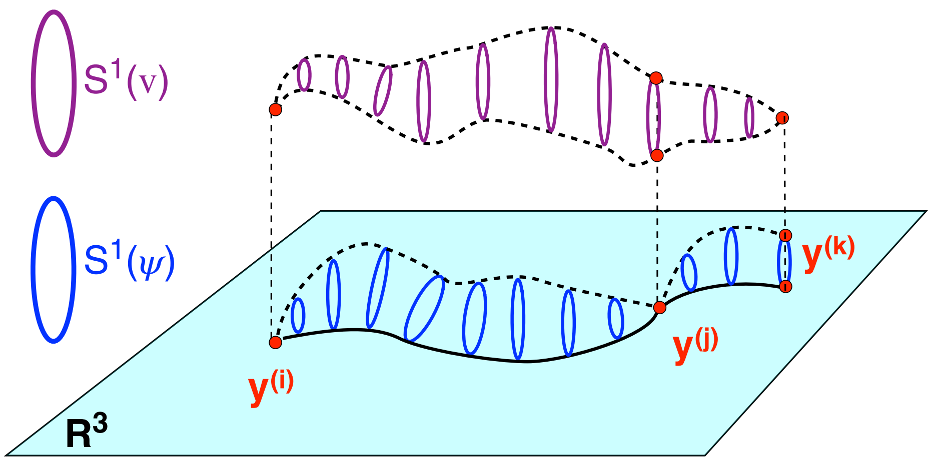
IIB Supergravity on T^4: Supergravity + two (anti-self-dual) tensor multiplets in six-dimensions

Six-dimensional metric ansatz: *(Gutowski, Martelli and Reall)*

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\big(du+\omega-\tfrac{1}{2}Z_3(dv+\beta)\big) + \sqrt{\mathcal{P}}\,V^{-1}(d\psi+A)^2 + \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

u = null time; (v, ψ) define a double S^1 fibration over a flat R^3 base with coordinates, y.

The scale of everything is set by the "warp factors:" ***V, P*** and ***Z_3***



The non-trivial homology cycles are defined through the pinching off of the $S^1 \times S^1$ fibration at special points in the R^3 base.

Maxwell Fields

$$G^{(a)} = d\Big[-\frac{1}{2}\frac{\eta^{ab}Z_b}{\mathcal{P}}(du+\omega)\wedge(dv+\beta)\Big] + \tfrac{1}{2}\eta^{ab}*_4 DZ_b + \tfrac{1}{2}(dv+\beta)\wedge\Theta^{(a)}$$

$$\mathcal{P} \equiv \tfrac{1}{2}\eta^{ab}Z_aZ_b \equiv Z_1Z_2 - \tfrac{1}{2}{Z_4}^2$$

Building the Fluctuating BPS Microstate Geometries

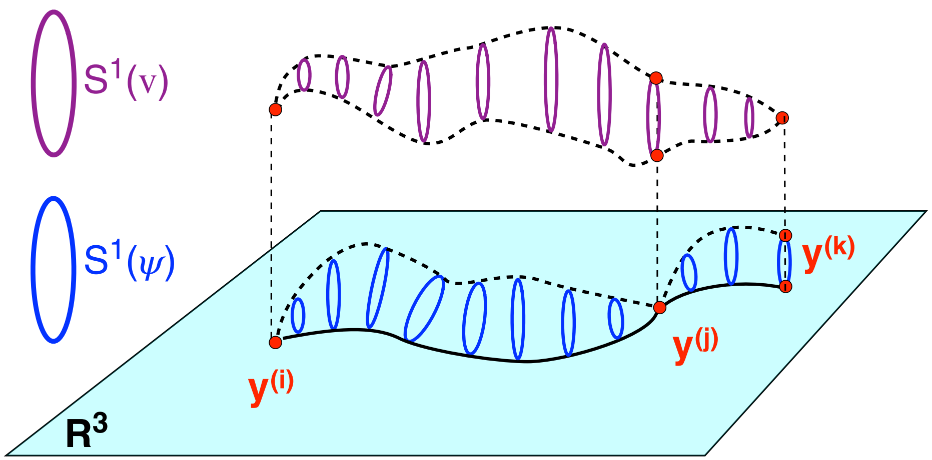
IIB Supergravity on T^4: Supergravity + two (anti-self-dual) tensor multiplets in six-dimensions

Six-dimensional metric ansatz: *(Gutowski, Martelli and Reall)*

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\big(du+\omega-\tfrac{1}{2}Z_3(dv+\beta)\big) + \sqrt{\mathcal{P}}\,V^{-1}(d\psi+A)^2 + \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

u = null time; (v, ψ) define a double S^1 fibration over a flat R^3 base with coordinates, y.

The scale of everything is set by the "warp factors:" ***V, P*** and Z_3



The non-trivial homology cycles are defined through the pinching off of the $S^1 \times S^1$ fibration at special points in the R^3 base.

Maxwell Fields

Electric Potentials

Magnetic Fluxes

$$G^{(a)} = d\Big[-\frac{1}{2}\,\frac{\eta^{ab}Z_b}{\mathcal{P}}(du+\omega)\wedge(dv+\beta)\Big] + \tfrac{1}{2}\eta^{ab} *_4 DZ_b + \tfrac{1}{2}(dv+\beta)\wedge\Theta^{(a)}$$

$$\mathcal{P} \equiv \tfrac{1}{2}\eta^{ab}Z_aZ_b \equiv Z_1Z_2 - \tfrac{1}{2}{Z_4}^2$$

The BPS Equations

The BPS Equations

Layer 1: Conditions on Maxwell Fields

*A homogeneous **linear** system*

$$\Theta^{(a)} = *_4\Theta^{(a)} \,, \qquad *_4 D(\partial_v Z_a) = \eta_{ab} D\Theta^{(b)} \,, \qquad D *_4 D Z_a = -\eta_{ab}\Theta^{(b)} \wedge d\beta \,.$$

where $D\Phi \equiv d_{(4)}\Phi - \beta \wedge \partial_v \Phi$

$\left(Z_a \,, \Theta^{(a)}\right)$ depend upon (r, θ) and

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$

The BPS Equations

Layer 1: Conditions on Maxwell Fields *A homogeneous **linear** system*

$$\Theta^{(a)} = *_4 \Theta^{(a)} \,, \qquad *_4 D(\partial_v Z_a) = \eta_{ab} D\Theta^{(b)} \,, \qquad D *_4 DZ_a = -\eta_{ab}\Theta^{(b)} \wedge d\beta \,.$$

where $D\Phi \equiv d_{(4)}\Phi - \beta \wedge \partial_v \Phi$

$\left(Z_a \,, \Theta^{(a)}\right)$ depend upon (r, θ) and

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}\,k\,\phi$$

General solution known for two-centered geometries!

The BPS Equations

Layer 1: Conditions on Maxwell Fields

*A homogeneous **linear** system*

$$\Theta^{(a)} = *_4\Theta^{(a)} \,, \qquad *_4 D(\partial_v Z_a) = \eta_{ab} D\Theta^{(b)} \,, \qquad D *_4 D Z_a = -\eta_{ab}\Theta^{(b)} \wedge d\beta \,.$$

where $$D\Phi \equiv d_{(4)}\Phi - \beta \wedge \partial_v \Phi$$

$\big(Z_a \,, \Theta^{(a)}\big)$ depend upon (r, θ) and

$$\chi_{k,m,n} \equiv R^{-1}\,(m+n)\,v \;+\; \tfrac{1}{2}\,(k-2m)\,\psi \;-\; \tfrac{1}{2}\,k\,\phi$$

General solution known for two-centered geometries!

Layer 2: Conditions on Metric pieces

*An inhomogeneous **linear** system*

$$ds_6^2 \;=\; -\frac{2}{\sqrt{\mathcal{P}}}\,(dv+\beta)\big(du+\omega-\tfrac{1}{2}\,Z_3\,(dv+\beta)\big) \;+\; \sqrt{\mathcal{P}}\,V^{-1}\,(d\psi+A)^2 \;+\; \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

$$D\omega + *_4 D\omega - Z_3\,d\beta \;=\; Z_a\Theta^{(a)}$$

$$*_4 D *_4\Big(\partial_v\omega + \tfrac{1}{2}\,DZ_3\Big) \;=\; \partial_v^2\mathcal{P} - \big((\partial_v Z_1)(\partial_v Z_2) - \tfrac{1}{2}(\partial_v Z_4)^2\big) - \tfrac{1}{4}\eta_{ab} *_4\Theta^{(a)} \wedge \Theta^{(b)}$$

$\big(Z_3 \,, \omega\big)$ depend upon (r, θ) and (quadratic) products of harmonics that depend upon

$$\chi_{k_i,m_i,n_i} \;=\; R^{-1}\,(m_i+n_i)\,v \;+\; \tfrac{1}{2}\,(k_i-2m_i)\,\psi \;-\; \tfrac{1}{2}\,k_i\,\phi$$

The BPS Equations

Layer 1: Conditions on Maxwell Fields — *A homogeneous **linear** system*

$$\Theta^{(a)} = *_4\Theta^{(a)}\,, \qquad *_4 D(\partial_v Z_a) = \eta_{ab} D\Theta^{(b)}\,, \qquad D *_4 DZ_a = -\eta_{ab}\Theta^{(b)} \wedge d\beta\,.$$

where $D\Phi \equiv d_{(4)}\Phi - \beta \wedge \partial_v \Phi$

$\left(Z_a\,, \Theta^{(a)}\right)$ depend upon (r, θ) and

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$

General solution known for two-centered geometries!

Layer 2: Conditions on Metric pieces — *An inhomogeneous **linear** system*

$$ds_6^2 = -\frac{2}{\sqrt{\mathcal{P}}}(dv+\beta)\big(du + \omega - \tfrac{1}{2}Z_3(dv+\beta)\big) + \sqrt{\mathcal{P}}\,V^{-1}(d\psi + A)^2 + \sqrt{\mathcal{P}}\,V\,d\vec{y}\cdot d\vec{y}$$

$$D\omega + *_4 D\omega - Z_3\,d\beta = Z_a\Theta^{(a)}$$

$$*_4 D *_4\Big(\partial_v\omega + \tfrac{1}{2}DZ_3\Big) = \partial_v^2\mathcal{P} - \big((\partial_v Z_1)(\partial_v Z_2) - \tfrac{1}{2}(\partial_v Z_4)^2\big) - \tfrac{1}{4}\eta_{ab} *_4\Theta^{(a)} \wedge \Theta^{(b)}$$

$\left(Z_3\,, \omega\right)$ depend upon (r, θ) and (quadratic) products of harmonics that depend upon

$$\chi_{k_i,m_i,n_i} = R^{-1}(m_i+n_i)\,v + \tfrac{1}{2}(k_i-2m_i)\,\psi - \tfrac{1}{2}k_i\,\phi$$

Interesting families of particular solutions known. General solution not known.

Linear system of gravitational BPS equations:

Critical to constructing the holographic duals of a generic superpositions of the states on multiple, independent strands:

$$\left(\left|+\tfrac{1}{2},+\tfrac{1}{2}\right\rangle_1\right)^{N_0}\otimes\left[\bigotimes_{k_i,m_i,n_i}\left(\frac{1}{m_i!\,n_i!}\left(J^+_{-1}\right)^{m_i}\left(L_{-1}-J^3_{-1}\right)^{n_i}|00\rangle_{k_i}\right)^{N_{k_i,m_i,n_i}}\right]$$

A Family of Microstate Geometries deep in the Black-Hole Regime

Add pure momentum states

$N_0 + N_{1,0,n} =$ **$N_1 N_5$** $\qquad \left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{n!}\left(L_{-1}-J^3_{-1}\right)^n|00\rangle_1\right)^{N_{1,0,n}}$

A Family of Microstate Geometries deep in the Black-Hole Regime

Add pure momentum states

$N_0 + N_{1,0,n} =$ **$N_1 N_5$**

$$Q_1\, Q_5 \;=\; R^2\,(\mathbf{a^2} + \mathbf{b^2})$$

$$\big(|+\tfrac{1}{2}\,,+\tfrac{1}{2}\rangle_1\big)^{N_0} \otimes \Big(\frac{1}{n!}\,(L_{-1} - J^3_{-1})^n\,|00\rangle_1\Big)^{N_{1,0,n}}$$

$$j_L \;=\; \tilde{j}_R \;=\; \tfrac{1}{2}\,\mathcal{N}\,\mathbf{a^2}$$

D1-D5 residue

All angular momentum

$$N_P \;=\; \tfrac{1}{2}\,\mathcal{N}\,\frac{n}{k}\,\mathbf{b^2}$$

P excitations

Angular momentum ≡ 0

A Family of Microstate Geometries deep in the Black-Hole Regime

Add pure momentum states

$N_0 + N_{1,0,n} =$ **N_1 N_5**

$$Q_1\, Q_5 \;=\; R^2\,(\mathbf{a^2} + \mathbf{b^2})$$

Can make **N_P** large, **j_L = j_R → 0**

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\tfrac{1}{n!}\,(L_{-1} - J^3_{-1})^n\,|00\rangle_1\right)^{N_{1,0,n}}$$

$$j_L \;=\; \tilde{j}_R \;=\; \tfrac{1}{2}\,\mathcal{N}\,\mathbf{a^2}$$

D1-D5 residue

All angular momentum

$$N_P = \tfrac{1}{2}\,\mathcal{N}\,\frac{n}{k}\,\mathbf{b^2}$$

P excitations

Angular momentum ≡ 0

A Family of Microstate Geometries deep in the Black-Hole Regime

Add pure momentum states

$N_0 + N_{1,0,n} = N_1 N_5$

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\tfrac{1}{n!}\,(L_{-1} - J^3_{-1})^n |00\rangle_1\right)^{N_{1,0,n}}$$

$$Q_1 Q_5 = R^2\,(\mathbf{a^2} + \mathbf{b^2})$$

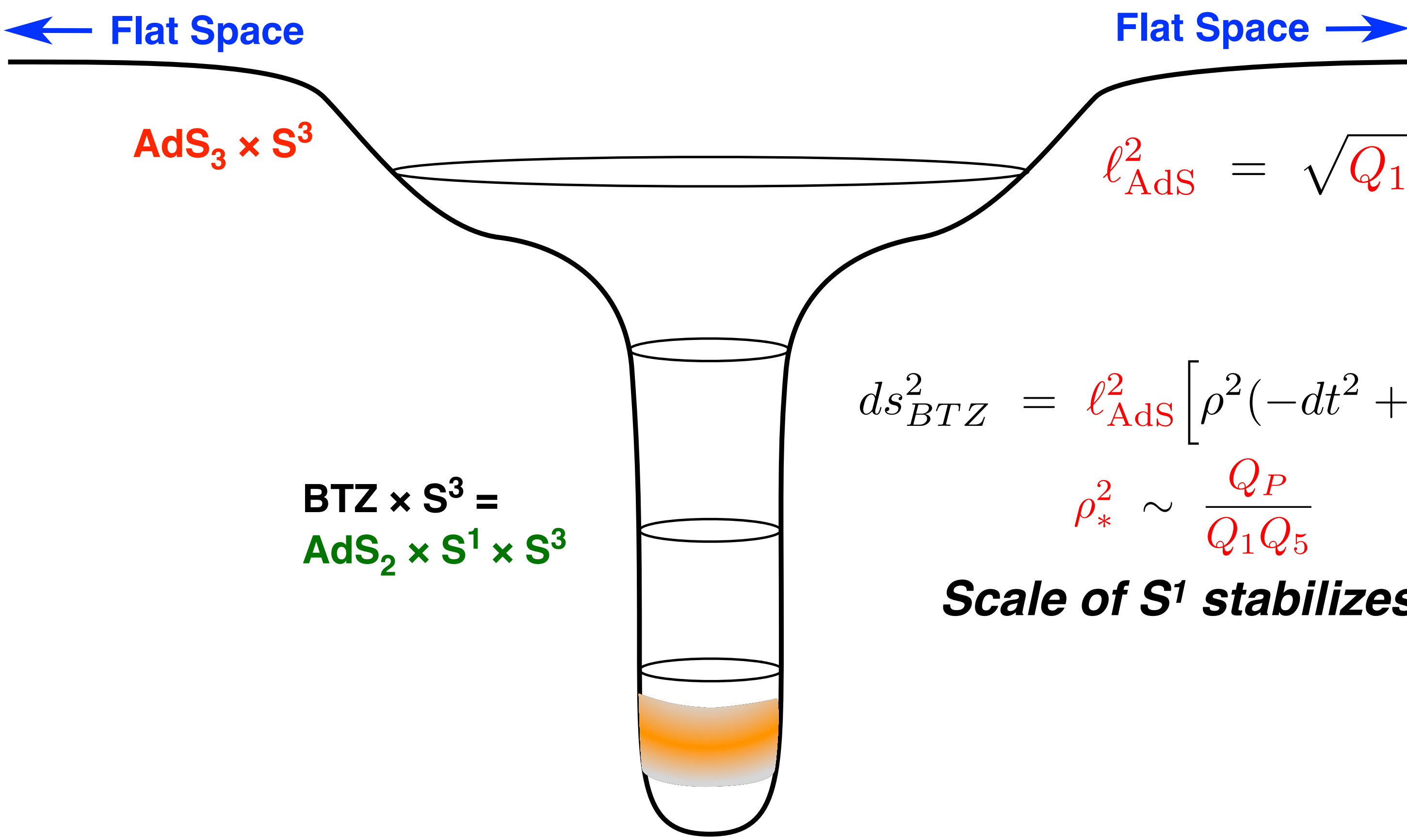
$$j_L = \tilde{j}_R = \tfrac{1}{2}\mathcal{N}\,\mathbf{a^2} \qquad N_P = \tfrac{1}{2}\mathcal{N}\,\frac{n}{k}\,\mathbf{b^2}$$

D1-D5 residue
All angular momentum

P excitations
Angular momentum ≡ 0

Can make N_P large, $j_L = j_R \to 0$

Geometry:



$$\ell^2_{\rm AdS} = \sqrt{Q_1 Q_5}$$

$$ds^2_{BTZ} = \ell^2_{\rm AdS}\left[\rho^2(-dt^2 + dy^2) + \frac{d\rho^2}{\rho^2} + \rho^2_*\,(dt + dy)^2\right]$$

$$\rho^2_* \sim \frac{Q_P}{Q_1 Q_5}$$

Scale of S^1 stabilizes at $\rho_* \ell_{AdS} R$

A Family of Microstate Geometries deep in the Black-Hole Regime

Add pure momentum states

$N_0 + N_{1,0,n} =$ **$N_1 N_5$**

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{n!}\,(L_{-1} - J^3_{-1})^n |00\rangle_1\right)^{N_{1,0,n}}$$

$$Q_1\,Q_5 \;=\; R^2\,(\mathbf{a^2} + \mathbf{b^2})$$

$$j_L \;=\; \tilde{j}_R \;=\; \tfrac{1}{2}\,\mathcal{N}\,\mathbf{a^2} \qquad N_P = \tfrac{1}{2}\,\mathcal{N}\,\frac{n}{k}\,\mathbf{b^2}$$

D1-D5 residue

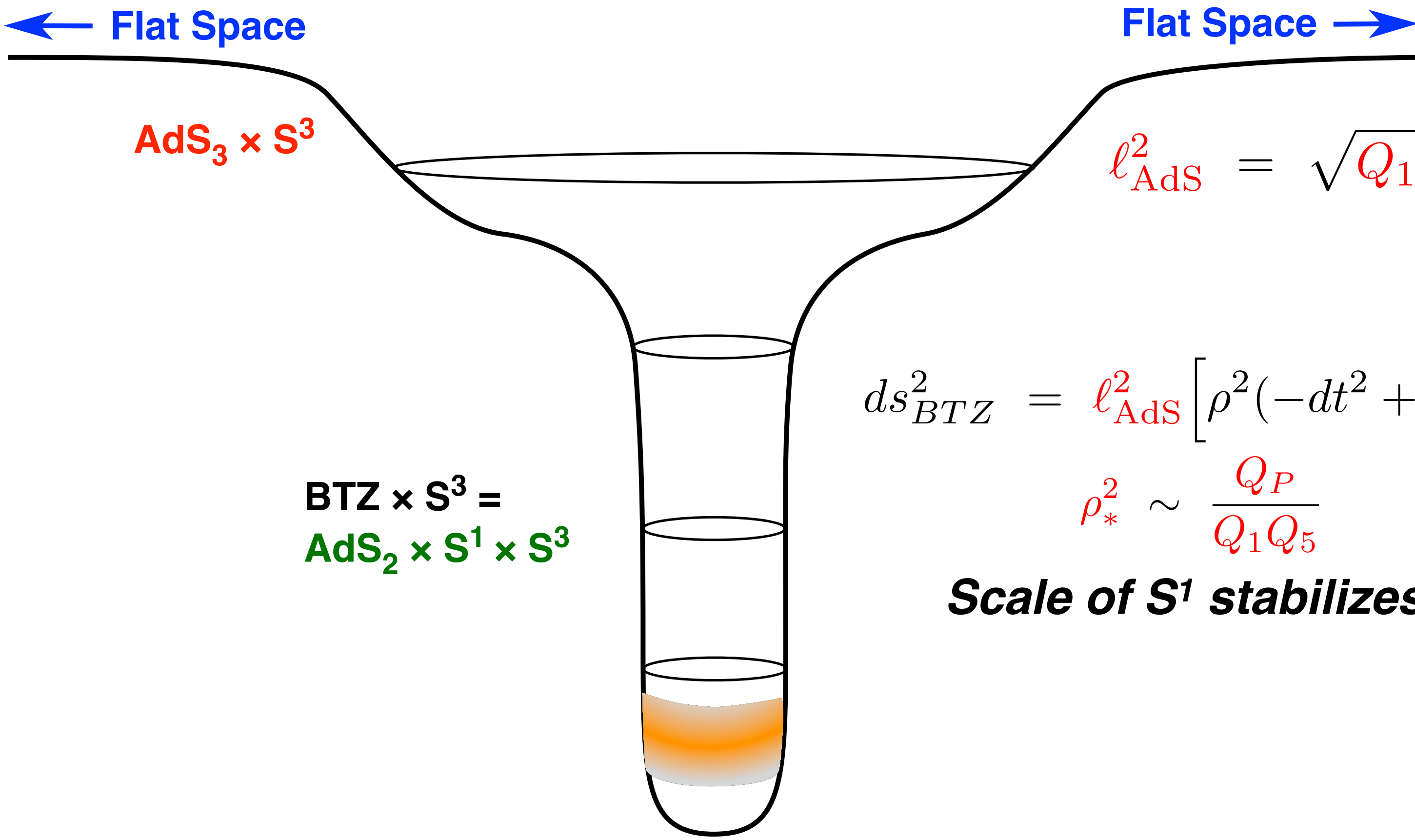
All angular momentum

P excitations

Angular momentum ≡ 0

Can make **N_P** large, **$j_L = j_R \to 0$**

Geometry:



$$\ell^2_{\rm AdS} \;=\; \sqrt{Q_1 Q_5}$$

$$ds^2_{BTZ} \;=\; \ell^2_{\rm AdS}\left[\rho^2(-dt^2 + dy^2) + \frac{d\rho^2}{\rho^2} + \rho_*^2\,(dt + dy)^2\right]$$

$$\rho_*^2 \;\sim\; \frac{Q_P}{Q_1 Q_5}$$

Scale of S^1 stabilizes at $\rho_*\,\ell_{AdS}\,R$

Smooth cap

A Family of Microstate Geometries deep in the Black-Hole Regime

Add pure momentum states

$N_0 + N_{1,0,n} = N_1 N_5$

$$\left(|+\tfrac{1}{2},+\tfrac{1}{2}\rangle_1\right)^{N_0} \otimes \left(\frac{1}{n!}\,(L_{-1} - J^3_{-1})^n |00\rangle_1\right)^{N_{1,0,n}}$$

$$Q_1\,Q_5 \;=\; R^2\,(\mathbf{a^2} + \mathbf{b^2})$$

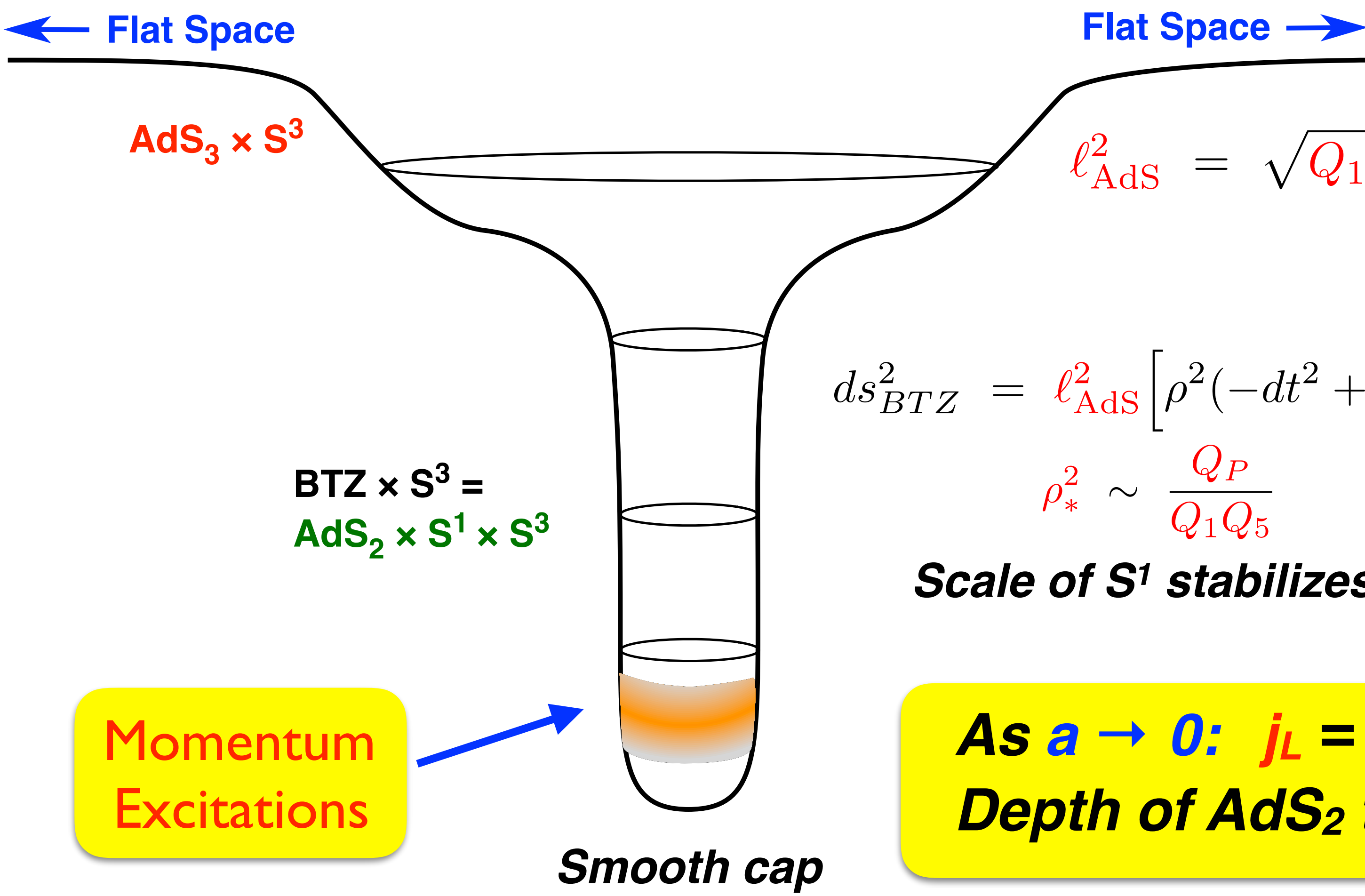
$$j_L \;=\; \tilde{j}_R \;=\; \frac{1}{2}\,\mathcal{N}\,\mathbf{a^2} \qquad\qquad N_P = \frac{1}{2}\,\mathcal{N}\,\frac{n}{k}\,\mathbf{b^2}$$

D1-D5 residue
All angular momentum

P excitations
Angular momentum ≡ 0

Can make $\mathbf{N_P}$ large, $\mathbf{j_L = j_R \to 0}$

Geometry:



$$\ell^2_{\rm AdS} \;=\; \sqrt{Q_1 Q_5}$$

$$ds^2_{BTZ} \;=\; \ell^2_{\rm AdS}\left[\rho^2(-dt^2+dy^2) + \frac{d\rho^2}{\rho^2} + \rho_*^2\,(dt+dy)^2\right]$$

$$\rho_*^2 \;\sim\; \frac{Q_P}{Q_1 Q_5}$$

Scale of S^1 stabilizes at $\rho_*\,\ell_{AdS}\,R$

As $a \to 0$: $j_L = j_R \to 0$
Depth of AdS_2 throat $\to \infty$

Several significant results

Several significant results

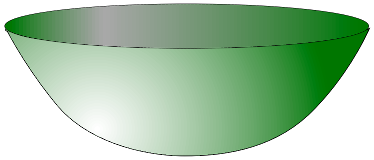
- ***First deep, scaling microstate geometry in Black-Hole regime with $j_L = j_R \to 0$***
- ***Deep, scaling microstate geometry that goes to BTZ***
- ***Deep, scaling ⇒ Arbitrarily large red-shifts***

  Microstate Geometry ⇒ Smooth cap-off
- ***Momentum excitations localize at the bottom of the*** BTZ ***throat***
- ***Holographic dictionary in*** AdS_3 ***for deep*** AdS_2/BTZ ***throat***
- ***Geometry dual to states counted by Strominger-Vafa***

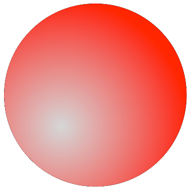
Microstate Geometries for MSW Black Holes

Phase dependence of fluctuations:

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$



AdS_3 (u,v,r)

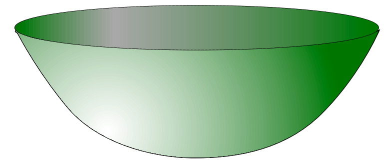


S^3 (θ,ψ,ϕ)

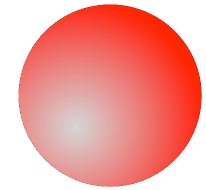
Microstate Geometries for MSW Black Holes

Phase dependence of fluctuations:

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$



AdS_3 (u,v,r)



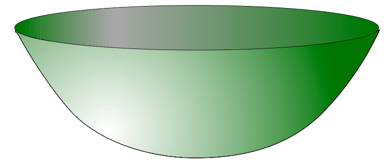
S^3 (θ,ψ,ϕ)

<u>Standard dimensional reduction</u> to five dimensions on *v fiber: Must set m = n =0*

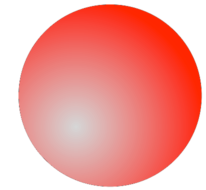
Microstate Geometries for MSW Black Holes

Phase dependence of fluctuations:

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$



AdS$_3$ (u,v,r)



S^3 (θ,ψ,ϕ)

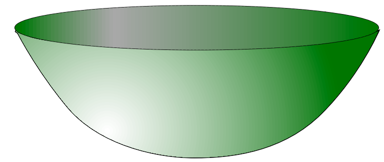
Standard dimensional reduction to five dimensions on *v fiber: Must set m = n =0*

$\Rightarrow$ ***Kill all the interesting modes***

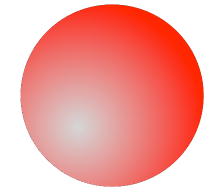
$$\left(\frac{1}{m!\,n!}\,(J^+_{-1})^m\,(L_{-1}-J^3_{-1})^n\,|00\rangle_k\right)^{N_{k,m,n}}$$

Microstate Geometries for MSW Black Holes

Phase dependence of fluctuations:



AdS_3 (u,v,r)



S^3 (θ,ψ,ϕ)

$$\chi_{k,m,n} \equiv R^{-1}\,(m+n)\,v \;+\; \tfrac{1}{2}\,(k-2m)\,\psi \;-\; \tfrac{1}{2}\,k\,\phi$$

Standard dimensional reduction to five dimensions on *v fiber: Must set m = n =0*

$$\left(\frac{1}{m!\,n!}\,(J^{+}_{-1})^{m}\,(L_{-1}-J^{3}_{-1})^{n}|00\rangle_k\right)^{N_{k,m,n}}$$

⇒ ***Kill all the interesting modes***

However:

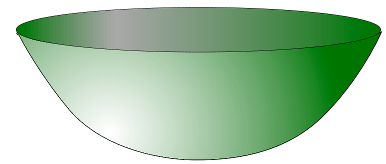
For *k = 2m* the solutions are independent of ψ, the Hopf fiber of the ***S^3***

➔ Reduction of fluctuating D1-D5 solutions (superstrata) to five-dimensional microstate geometries: *capped BTZ* × ***S^2***

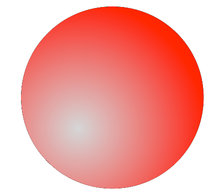
Microstate Geometries for MSW Black Holes

Phase dependence of fluctuations:

$$\chi_{k,m,n} \equiv R^{-1}(m+n)\,v + \tfrac{1}{2}(k-2m)\,\psi - \tfrac{1}{2}k\,\phi$$



AdS$_3$ (u,v,r)



S^3 (θ,ψ,ϕ)

Standard dimensional reduction to five dimensions on *v fiber: Must set m = n =0*

$$\left(\frac{1}{m!\,n!}\,(J^+_{-1})^m\,(L_{-1}-J^3_{-1})^n|00\rangle_k\right)^{N_{k,m,n}}$$

$\Rightarrow$ ***Kill all the interesting modes***

However:

For *k = 2m* the solutions are independent of ***ψ***, the Hopf fiber of the ***S^3***

➔ Reduction of fluctuating D1-D5 solutions (superstrata) to five-dimensional microstate geometries: *capped BTZ* × ***S^2***

Before doing this: first enrich the family of solutions

It is relatively easy to generalize the entire IIB construction to include a KKM dipole charge, ***κ***, to the D1-D5 system

Some T-dualities

Starting configuration

IIB	0	1	2	3	4	5	6	7	8	9
D1	⬆	✶	✶	✶	✶	⬆	↔	↔	↔	↔
D5	⬆	✶	✶	✶	✶	⬆	⬆	⬆	⬆	⬆
KKM	⬆	✶	✶	✶	⬆	⬆	⬆	⬆	⬆	⬆

Some T-dualities

Starting configuration

IIB	0	1	2	3	4	5	6	7	8	9
D1	↑	✶	✶	✶	✶	↑	↔	↔	↔	↔
D5	↑	✶	✶	✶	✶	↑	↑	↑	↑	↑
KKM	↑	✶	✶	✶	↑	↑	↑	↑	↑	↑

T-dualize 3 times to IIA:

IIA	0	1	2	3	4	5	6	7	8	9
D4	↑	✶	✶	✶	↑	↑	↔	↔	↑	↑
D4	↑	✶	✶	✶	↑	↑	↑	↑	↔	↔
NS5	↑	✶	✶	✶	↔	↑	↑	↑	↑	↑

Some T-dualities

Starting configuration

IIB	0	1	2	3	4	5	6	7	8	9
D1	⬆	✶	✶	✶	✶	⬆	↔	↔	↔	↔
D5	⬆	✶	✶	✶	✶	⬆	⬆	⬆	⬆	⬆
KKM	⬆	✶	✶	✶	⬆	⬆	⬆	⬆	⬆	⬆

T-dualize 3 times to IIA:

IIA	0	1	2	3	4	5	6	7	8	9
D4	⬆	✶	✶	✶	⬆	⬆	↔	↔	⬆	⬆
D4	⬆	✶	✶	✶	⬆	⬆	⬆	⬆	↔	↔
NS5	⬆	✶	✶	✶	↔	⬆	⬆	⬆	⬆	⬆

Uplift to M theory

M	0	1	2	3	5	4	10	6	7	8	9
M5	⬆	✶	✶	✶	⬆	⬆	⬆	↔	↔	⬆	⬆
M5	⬆	✶	✶	✶	⬆	⬆	⬆	⬆	⬆	↔	↔
M5	⬆	✶	✶	✶	⬆	↔	↔	⬆	⬆	⬆	⬆

M-theory background

D1-D5-KKM solution ➔ M5-M5-M5 charges: $(\boldsymbol{Q_1}, \boldsymbol{Q_5}, \boldsymbol{\kappa})$

+ dipolar/dissolved M2-M2-M2 charges

Dualities + compactification on ψ lattice:

D1-D5-KKM (4,4) supersymmetry ➔ M5-M5-M5 (0,4) supersymmetry

M-theory background

D1-D5-KKM solution ➔ M5-M5-M5 charges: $(\boldsymbol{Q_1}, \boldsymbol{Q_5}, \boldsymbol{\kappa})$

+ dipolar/dissolved M2-M2-M2 charges

Dualities + compactification on ψ lattice:

D1-D5-KKM (4,4) supersymmetry ➔ M5-M5-M5 (0,4) supersymmetry

Add momentum along common circle (5) … untouched in duality

IIB	0	1	2	3	4	5	6	7	8	9
D1	⬆	✶	✶	✶	✶	⬆	↔	↔	↔	↔
D5	⬆	✶	✶	✶	✶	⬆	⬆	⬆	⬆	⬆
KKM	⬆	✶	✶	✶	⬆	⬆	⬆	⬆	⬆	⬆
P	⬆					⬆				

M	0	1	2	3	5	4	10	6	7	8	9
M5	⬆	✶	✶	✶	⬆	⬆	⬆	↔	↔	⬆	⬆
M5	⬆	✶	✶	✶	⬆	⬆	⬆	⬆	⬆	↔	↔
M5	⬆	✶	✶	✶	⬆	↔	↔	⬆	⬆	⬆	⬆
P	⬆				⬆						

M-theory background

D1-D5-KKM solution ➔ M5-M5-M5 charges: $(\boldsymbol{Q_1, Q_5, \kappa})$

+ dipolar/dissolved M2-M2-M2 charges

Dualities + compactification on ψ lattice:

D1-D5-KKM (4,4) supersymmetry ➔ M5-M5-M5 (0,4) supersymmetry

Add momentum along common circle (5) … untouched in duality

IIB	0	1	2	3	4	5	6	7	8	9
D1	↑	✶	✶	✶	✶	↑	↔	↔	↔	↔
D5	↑	✶	✶	✶	✶	↑	↑	↑	↑	↑
KKM	↑	✶	✶	✶	↑	↑	↑	↑	↑	↑
P	↑					↑				

M	0	1	2	3	5	4	10	6	7	8	9
M5	↑	✶	✶	✶	↑	↑	↑	↔	↔	↑	↑
M5	↑	✶	✶	✶	↑	↑	↑	↑	↑	↔	↔
M5	↑	✶	✶	✶	↑	↔	↔	↑	↑	↑	↑
P	↑				↑						

➔ *Momentum excitations of MSW string wrapping (5) direction ..*

MSW string vs M5 on T^6 (or $K3 \times T^2$)

- MSW: Single M brane wrapped on very ample divisor of CY_3
- Here: Multiple, disjoint M branes T^4's in T^6

MSW string vs M5 on T^6 (or K3 × T^2)

- MSW: Single M brane wrapped on very ample divisor of CY_3
- Here: Multiple, disjoint M branes T^4's in T^6

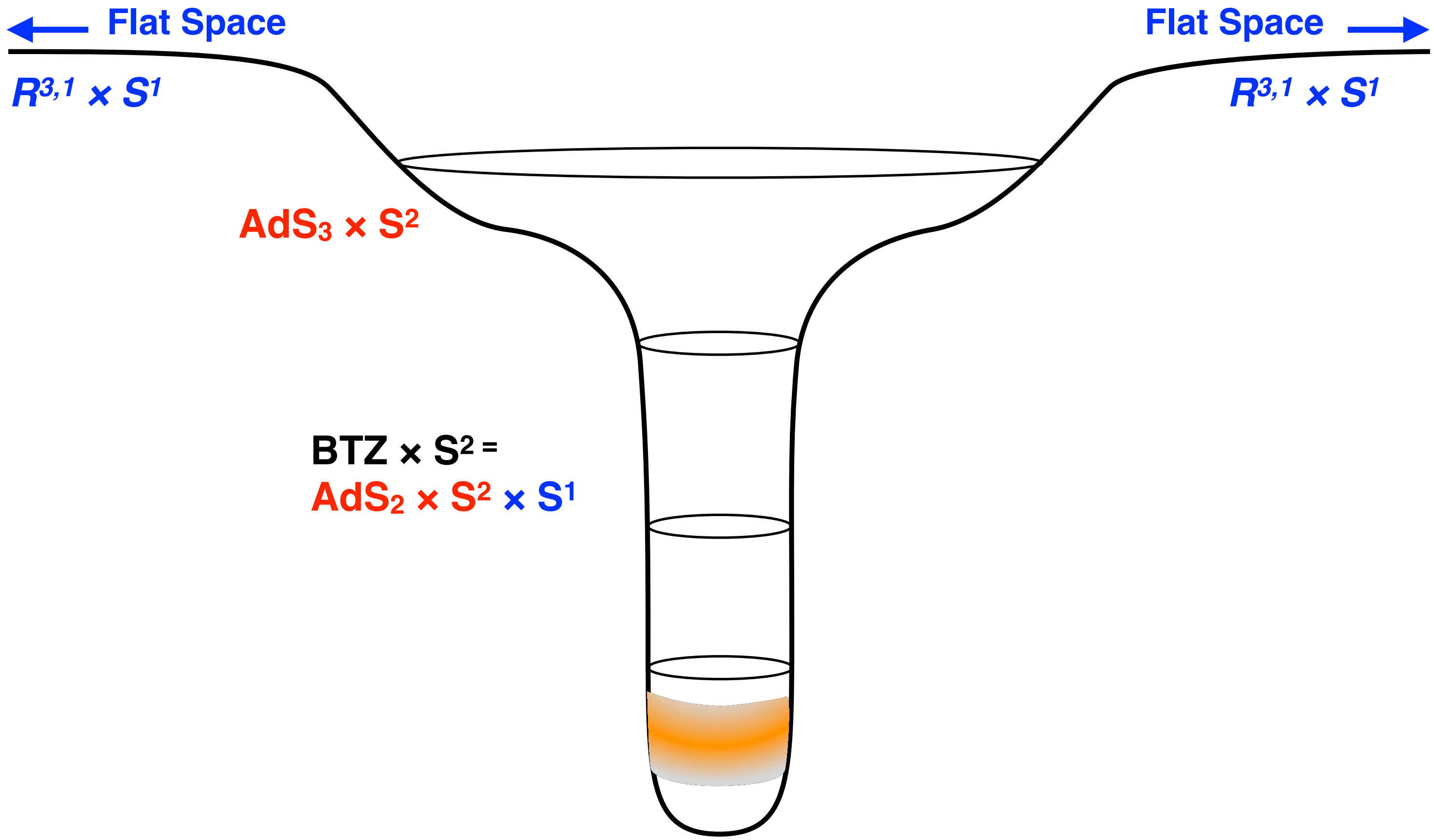
- Non-trivial fluctuations require turning deforming Kahler moduli of the tori, "bending" disjoint M5's into one another …

Universality of the five-dimensional solution:

- We have reduced to five-dimensions and so our solution is valid for any Calabi-Yau compactification with the same set of M5-brane charges

Fluctuating Microstate Geometries for MSW Strings

Previous picture compactified on Hopf fiber of S^3.

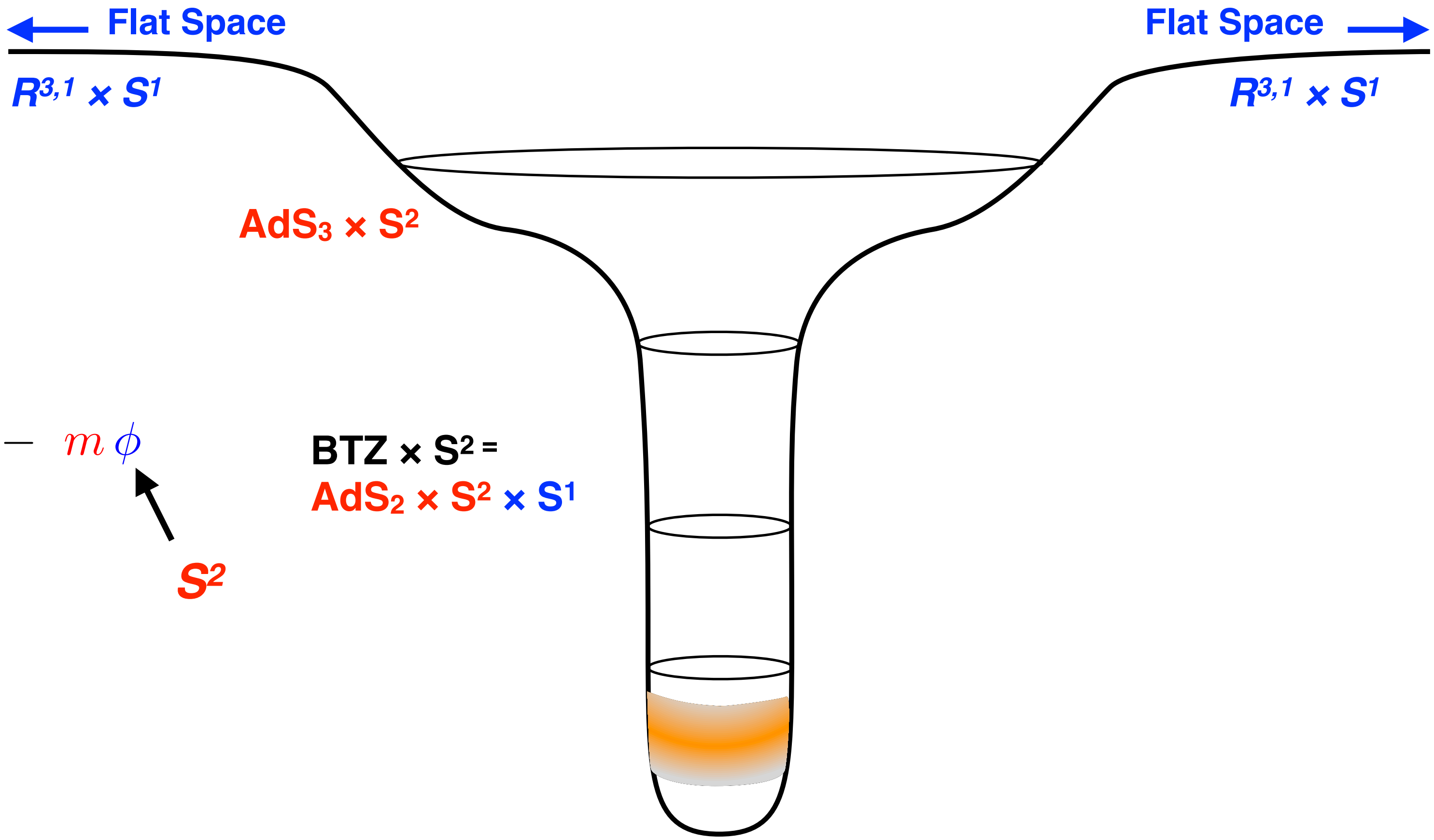


Fluctuating Microstate Geometries for MSW Strings

Previous picture compactified on Hopf fiber of S^3.

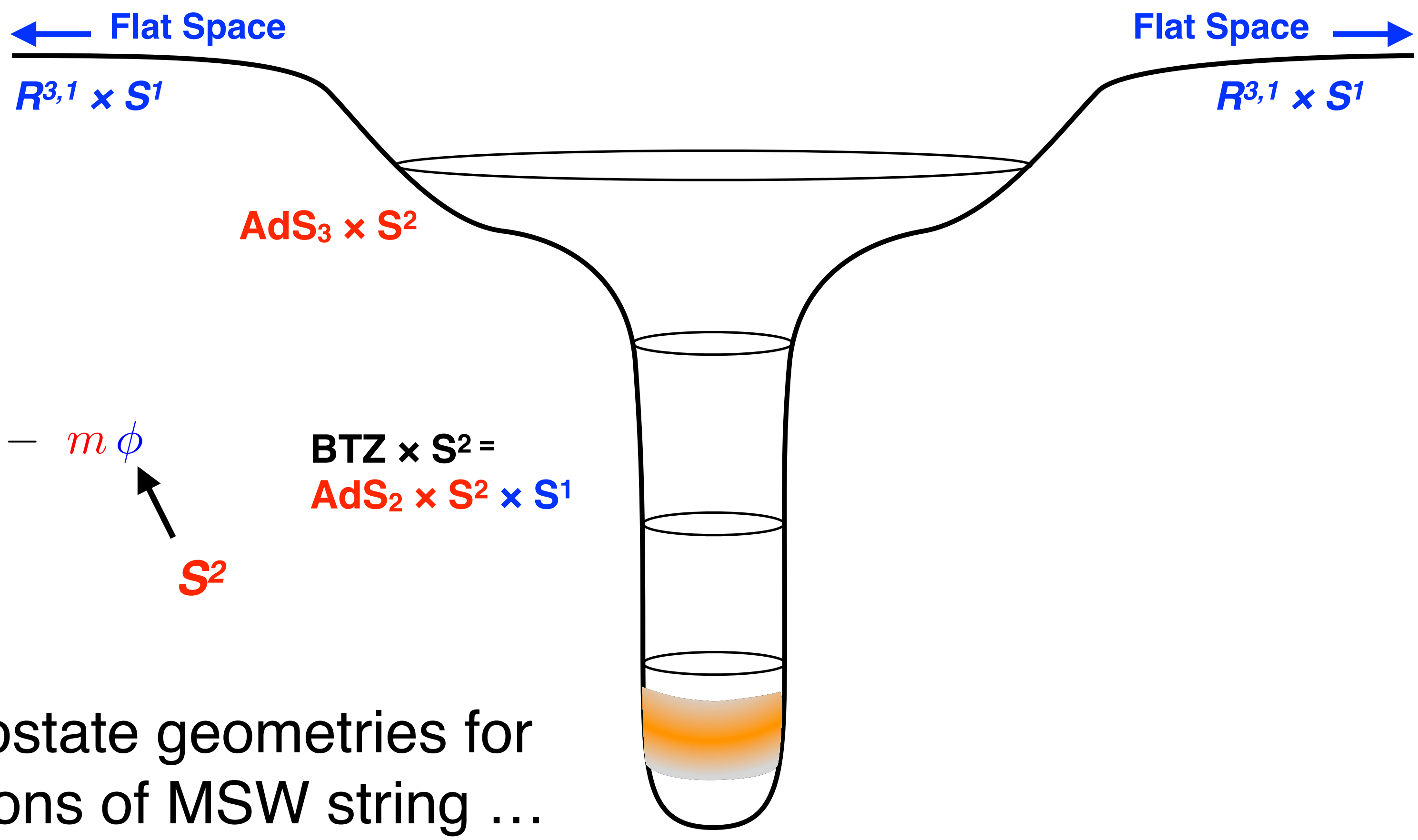
Fluctuations:

$$\chi_{m,n} \equiv R^{-1}\,(m+n)\,v \;-\; m\,\phi$$



Fluctuating Microstate Geometries for MSW Strings

Previous picture compactified on Hopf fiber of S^3.



Fluctuations:

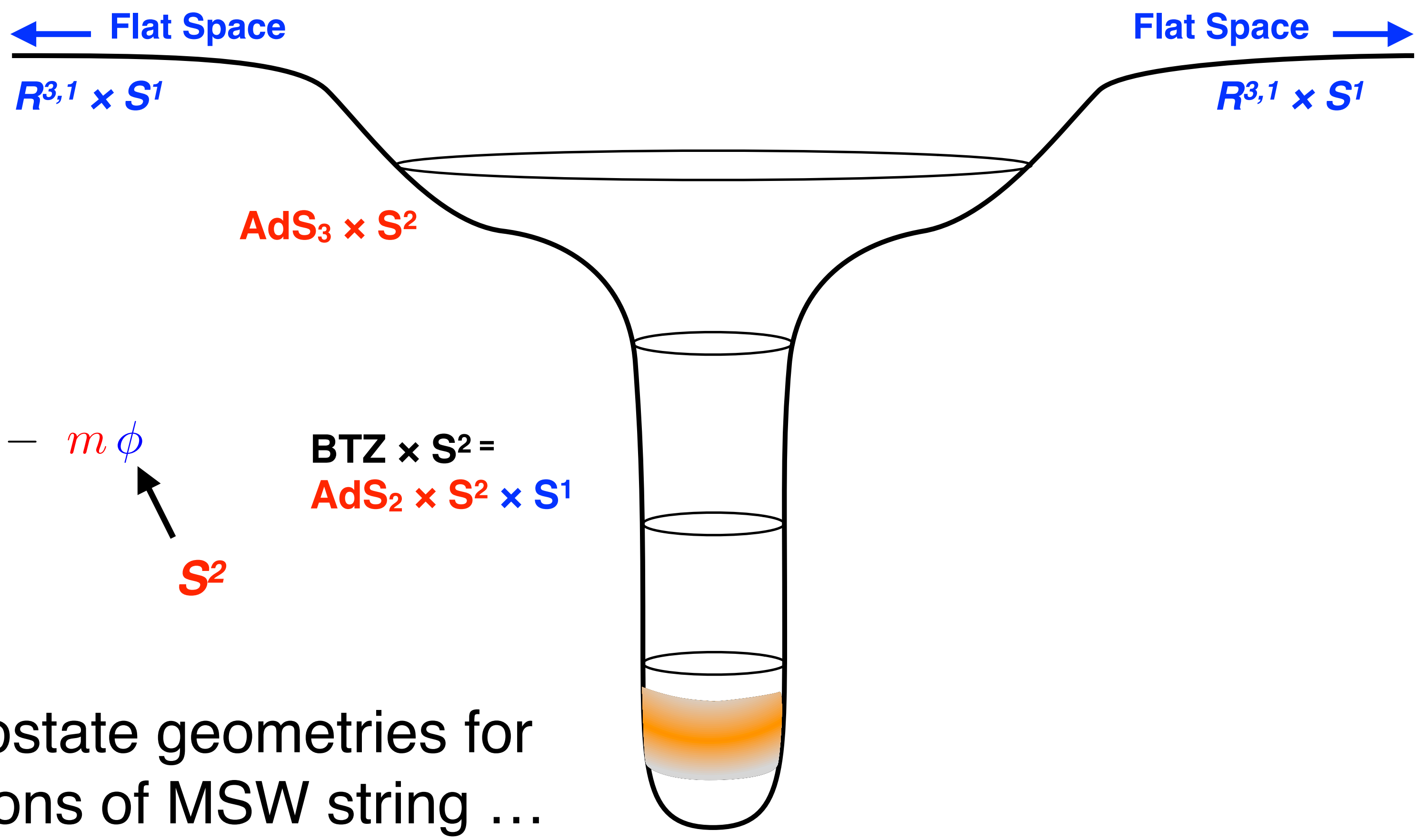
$$\chi_{m,n} \equiv R^{-1}\,(m+n)\,v \;-\; m\,\phi$$

AdS_3 or S^1 (for v) ***S^2*** (for ϕ)

Deep scaling, microstate geometries for momentum excitations of MSW string …

Fluctuating Microstate Geometries for MSW Strings

Previous picture compactified on Hopf fiber of S^3.



Fluctuations:

$$\chi_{m,n} \equiv R^{-1}(m+n)\,v - m\,\phi$$

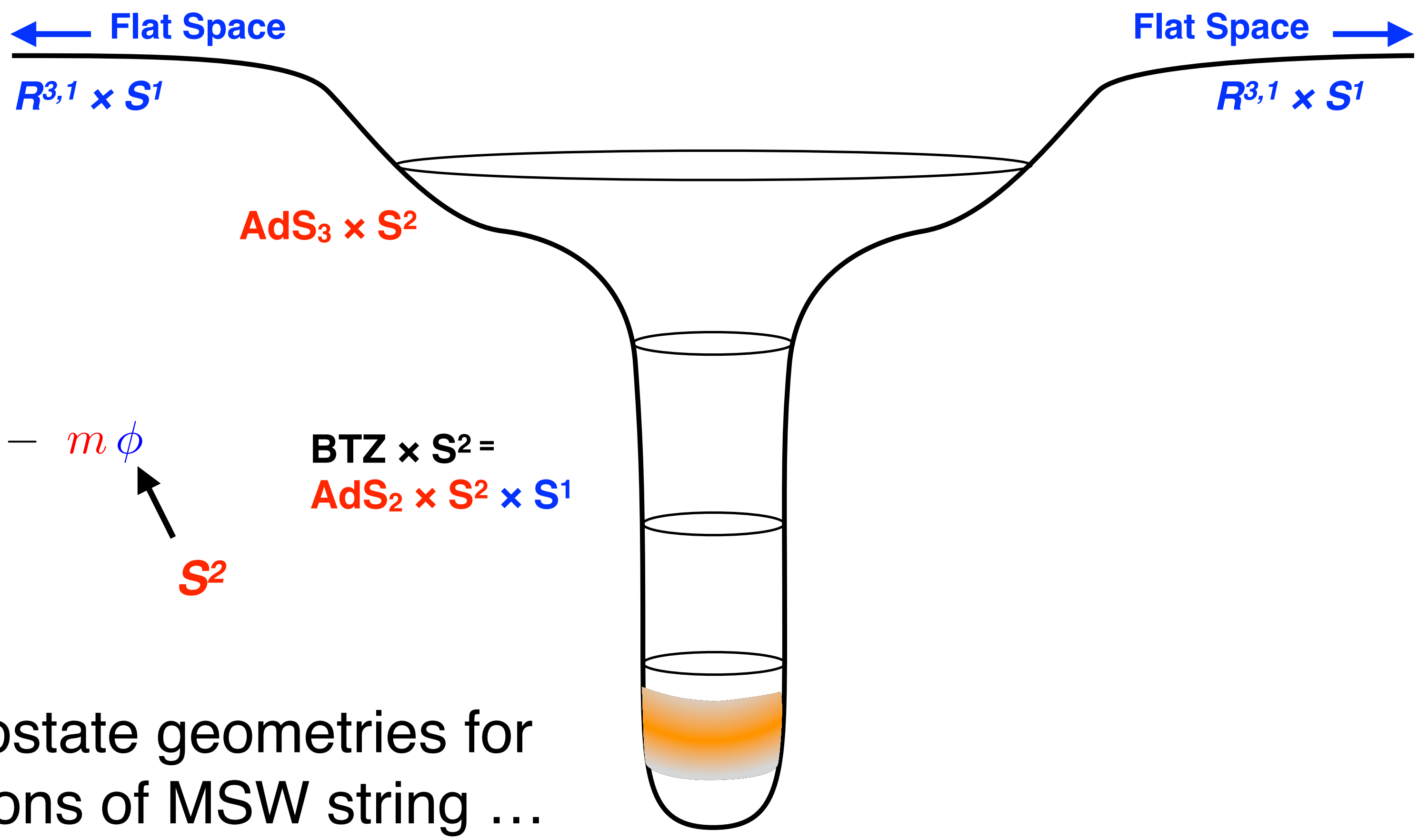
AdS_3 or S^1 S^2

Deep scaling, microstate geometries for momentum excitations of MSW string …

Deconstruction: *Attempts to realize black-hole microstate structure with perturbative/singular D0 branes or perturbative momenta on "Deconstructed" MSW string*

Fluctuating Microstate Geometries for MSW Strings

Previous picture compactified on Hopf fiber of S^3.



Fluctuations:

$$\chi_{m,n} \equiv R^{-1}\,(m+n)\,v \;-\; m\,\phi$$

v: AdS_3 or S^1 $\qquad$ ϕ: S^2

Deep scaling, microstate geometries for momentum excitations of MSW string …

Deconstruction: *Attempts to realize black-hole microstate structure with perturbative/singular D0 branes or perturbative momenta on "Deconstructed" MSW string*

Here: Precise, fully back-reacted, capped-off BTZ × S^2 realization of the deconstructed configurations …

….. related to D1-D5-P microstate structure

Conclusions

Conclusions

- We have explicit microstate geometries that are holographic duals to precise families of D1-D5-P CFT states

Conclusions

- We have explicit microstate geometries that are holographic duals to precise families of D1-D5-P CFT states
- First deep, scaling microstate geometry in *Black-Hole Regime* with $j_L = j_R \to 0$
- Deep, scaling geometry going to BTZ × S^3 or BTZ × S^2
- Momentum excitations localize at bottom of throat and create smooth cap
- Holographic dictionary in AdS_3 for deep AdS_2/BTZ throat

Conclusions

- We have explicit microstate geometries that are holographic duals to precise families of D1-D5-P CFT states
- First deep, scaling microstate geometry in *Black-Hole Regime* with $j_L = j_R \to 0$
- Deep, scaling geometry going to BTZ × S^3 or BTZ × S^2
- Momentum excitations localize at bottom of throat and create smooth cap
- Holographic dictionary in AdS_3 for deep AdS_2/BTZ throat
- Microstate geometries for MSW … and that fully realize deconstruction

Conclusions

- We have explicit microstate geometries that are holographic duals to precise families of D1-D5-P CFT states
- First deep, scaling microstate geometry in *Black-Hole Regime* with **$j_L = j_R \to 0$**
- Deep, scaling geometry going to BTZ × S^3 or BTZ × S^2
- Momentum excitations localize at bottom of throat and create smooth cap
- Holographic dictionary in AdS_3 for deep AdS_2/BTZ throat
- Microstate geometries for MSW … and that fully realize deconstruction
- Microstate geometries capture large-scale universal features of all(?) black-hole microstate descriptions: ***MSW/D1-D5-P/Denconstruction/Quiver QM***

Conclusions

- We have explicit microstate geometries that are holographic duals to precise families of D1-D5-P CFT states
- First deep, scaling microstate geometry in *Black-Hole Regime* with **$j_L = j_R \to 0$**
- Deep, scaling geometry going to BTZ × S^3 or BTZ × S^2
- Momentum excitations localize at bottom of throat and create smooth cap
- Holographic dictionary in AdS_3 for deep AdS_2/BTZ throat
- Microstate geometries for MSW … and that fully realize deconstruction
- Microstate geometries capture large-scale universal features of all(?) black-hole microstate descriptions: ***MSW/D1-D5-P/Denconstruction/Quiver QM***

Open issues

- Twisted sector excitations. Relation to multi-centered geometries?
- Holography/CFT states of MSW string dual to new microstate geometries
- Probe the IR physics/large-t correlators of these new geometries