Stringy black hole microstates

Stefano Massai

University of Padova

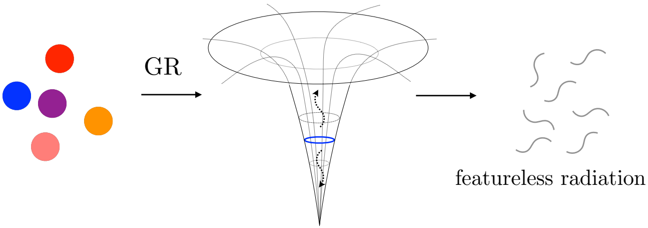
Based on work done with E. J. Martinec and D. Turton

1705.10844 - 1803.08505 - 1906.11473 - 2005.12344

Lisbon (virtual), September 24th, 2021

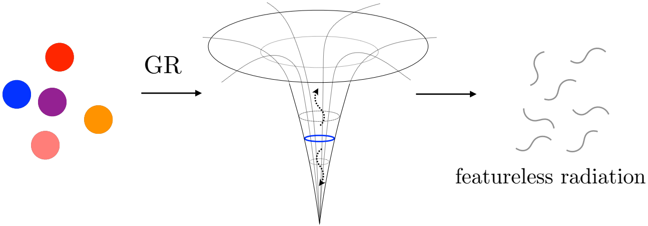
Introduction

Hawking: black holes emit a thermal radiation, losing the information on initial state. Computing quantum corrections that restore unitarity is a major challange for any theory of quantum gravity



Introduction

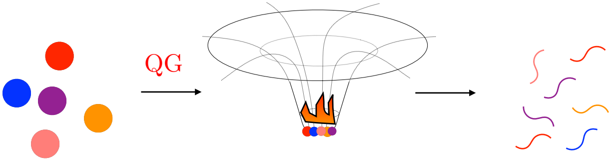
Hawking: black holes emit a thermal radiation, losing the information on initial state. Computing quantum corrections that restore unitarity is a major challange for any theory of quantum gravity



The tension between information transfer and causal structure of space-time leads to apparent violation of effective field theory at horizon

Introduction

Hawking: black holes emit a thermal radiation, losing the information on initial state. Computing quantum corrections that restore unitarity is a major challange for any theory of quantum gravity

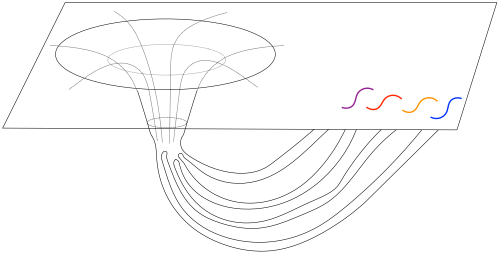


The tension between information transfer and causal structure of space-time leads to apparent violation of effective field theory at horizon

- [Mathur, AMPS] Structure at horizon (fuzzball/firewall)

Introduction

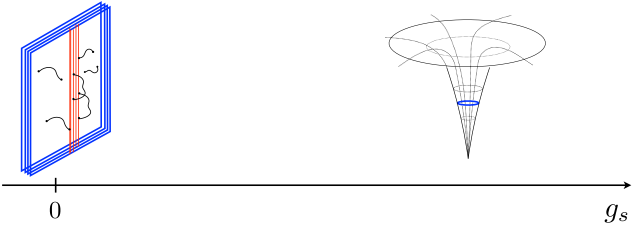
Hawking: black holes emit a thermal radiation, losing the information on initial state. Computing quantum corrections that restore unitarity is a major challange for any theory of quantum gravity



The tension between information transfer and causal structure of space-time leads to apparent violation of effective field theory at horizon

- [Mathur, AMPS] Structure at horizon (fuzzball/firewall)
- [Papadodimas-Raju, Maldacena-Susskind] Smoothness but large non-localities

These problems can be formulated more concretely in string theory, where we have control over the microscopic degrees of freedom that store the Bekenstein-Hawking entropy.
This picture is valid at a special point of the moduli space, where we adiabatically switch off the gravity interactions and we are left with strings and branes in flat space.



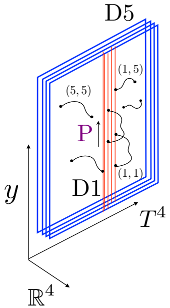
Weakly coupled analysis

Microstate counting at zero coupling [Strominger-Vafa]

N_5 D5-branes on $T^4 \times S_y$

N_1 D1-branes on S_y

N_P units of momentum
$P = n_y/R$ on S_y



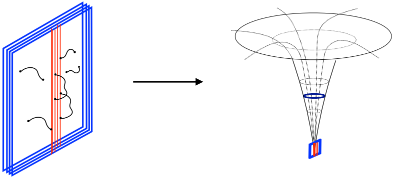
Entropy: long effective $(1,5)$ string on circle of radius $R_{eff} = N_1 N_5 R$.
Momentum fractionation: n_y/R_{eff}

Higgs branch: D-strings dissolve as zero-size instantons. CFT with target space $(T^4)^{N_1 N_5}/S_{N_1 N_5}$. Long effective string from twisted sector.

Questions we would like to answer:

- How do these microstates look like at finite coupling?
- What is their "effective" causal structure?

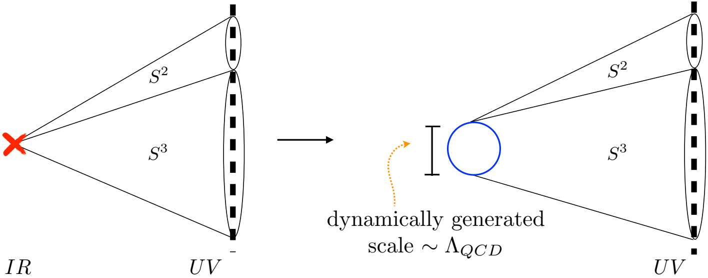
Naive expectation: as gravity becomes stronger, brane bound states become smaller. Horizon grows as coupling is increased: microstates confined at UV scale. [Horowitz-Polchinski, Damour-Veneziano]



But: less naive mechanisms from holography. Examples:

- Confining $\mathcal{N} = 1$ gauge theory [Klebanov-Strassler]
- Mass-deformed $\mathcal{N} = 4$ SYM / ABJM [Polchinski-Strassler, LLM]

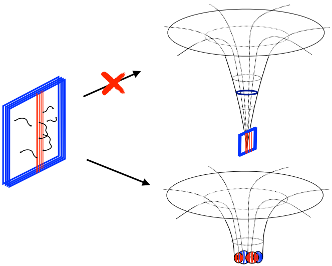
Naively singular RG flow resolved by new scale in the IR $\leftrightarrow$ topological cycles with flux



Microstate geometries

Many works on applying this principle to black holes
[Mathur, Bena-Warner, . . .]

- Brane bound states can expand as coupling is increased. After backreaction: smooth, horizonless, bubbling geometries
- Concrete mechanism to hold structure at horizon (non-perturbative black hole hairs). Topology with flux: evade "no solitons without horizon" theorem [Gibbons-Warner]



Long strings

Microstate geometries represent non-generic, coherent states.

$$S_{bubbles} \ll S_{BH}$$

Long strings

Microstate geometries represent non-generic, coherent states.

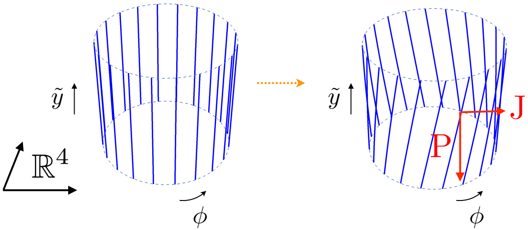
$$S_{bubbles} \ll S_{BH}$$

- They are still useful "classical islands". When perturbed, they decay toward more typical states and we are interested in studying this evolution.
- To do this, we would like an exact worldsheet description of these solutions. Remarkably, it can be done.

Circular supertube

- Focus on two-charge black hole
- Simplest example of microstate geometry is obtained by dualizing supertube bound states in NS5-P duality frame

$$\begin{pmatrix} NS5(5678\tilde{y}) \\ P(\tilde{y}) \end{pmatrix} \xrightarrow{T_{\tilde{y}}} \begin{pmatrix} NS5(5678y) \\ F1(y) \end{pmatrix} \xrightarrow{S} \begin{pmatrix} D5(5678y) \\ D1(y) \end{pmatrix}$$

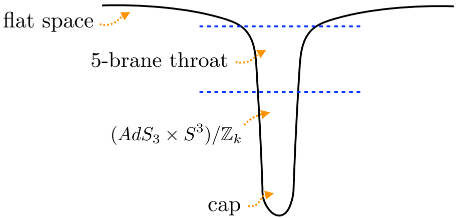


[Lunin Mathur 01]

Circular supertube

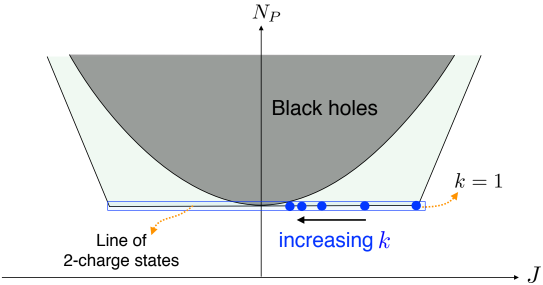
- Focus on two-charge black hole
- Simplest example of microstate geometry is obtained by dualizing supertube bound states in NS5-P duality frame

$$\begin{pmatrix} NS5(5678\tilde{y}) \\ P(\tilde{y}) \end{pmatrix} \xrightarrow{T_{\tilde{y}}} \begin{pmatrix} NS5(5678y) \\ F1(y) \end{pmatrix} \xrightarrow{S} \begin{pmatrix} D5(5678y) \\ D1(y) \end{pmatrix}$$



[Lunin Mathur 01]

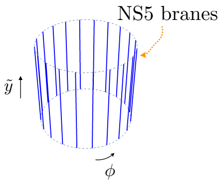
- Over-rotating solutions with $J = n_1 n_5 / k$
- We can approach the BH phase by increasing the orbifold order



$$S = \frac{A}{4G} = 2\pi \sqrt{N_1 N_5 N_P - J^2}$$

We'll show that the backreaction of this family of supertubes is under control at the exact level in α'.

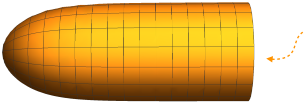
A well known cap



Exact description of near-horizon region:
[Ooguri-Vafa, Giveon-Kutasov]

$$\mathcal{M} = \mathbb{R}^{5,1} \times \left(\frac{SL(2,\mathbb{R})}{U(1)} \times \frac{SU(2)}{U(1)} \right) \Big/ \mathbb{Z}_{n_5}$$

Non-singular CFT: capped version of NS5's throat



$$ds^2 = d\rho^2 + \tanh^2 \rho \, d\psi^2$$

When branes come together: cigar $\rightarrow$ tube

$$\left(\frac{SL(2,\mathbb{R})}{U(1)} \times \frac{SU(2)}{U(1)} \right) \Big/ \mathbb{Z}_{n_5} \rightarrow \mathbb{R} \times \underbrace{\boxed{\left(U(1) \times \frac{SU(2)}{U(1)} \right) \Big/ \mathbb{Z}_{n_5}}}_{SU(2)}$$

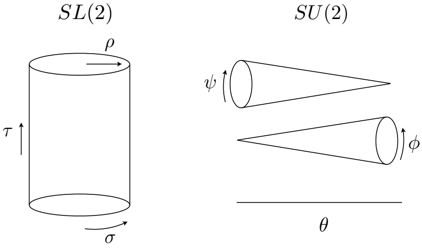
F-theory for NS5 branes

An equivalent construction lifts the dynamics to $(10,2)$ dimensions:

$$\mathcal{M} = \mathcal{G}/\mathcal{H} = \mathbb{R}^{5,1} \times \frac{SL(2,\mathbb{R}) \times SU(2)}{U(1)_L \times U(1)_R}$$

$$g_{\rm sl} = e^{i(\tau-\sigma)\sigma_3} e^{\rho\sigma_1} e^{i(\tau+\sigma)\sigma_3}$$

$$g_{\rm su} = e^{i(\psi-\phi)\sigma_3} e^{i\theta\sigma_1} e^{i(\psi+\phi)\sigma_3}$$



Gauge action generated by null directions in $SL(2) \times SU(2)$

$$\mathcal{H}: \quad (g_{\sf sl}, s_{\sf su}) \to (e^{i\alpha\sigma_3} g_{\sf sl} e^{i\beta\sigma_3}, e^{-i\alpha\sigma_3} g_{\sf su} e^{i\beta\sigma_3})$$

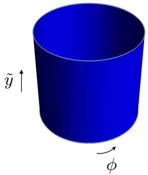
Gauged WZW action:

$$S = S_{WZW} + \frac{n_5}{\pi} \int d^2 z \, [\mathcal{A}\bar{\mathcal{J}} + \bar{\mathcal{A}}\mathcal{J} + \Sigma \mathcal{A}\bar{\mathcal{A}}]$$

Integrating out the gauge fields gives a "smeared" geometry

$$ds^2 = n_5 \left[d\rho^2 + d\theta^2 + \frac{1}{\Sigma}(\sin^2\theta \cosh^2\rho d\phi^2 + \cos^2\theta \sinh^2\rho d\psi^2) \right] \, ,$$

$$H_5 = \sum_{l=1}^{n_5} \frac{1}{|\mathbf{x} - \mathbf{x}_k|^2} \sim \frac{n_5}{a^2(\cosh^2\rho - \sin^2\theta)} = \frac{n_5}{a^2 \Sigma}$$



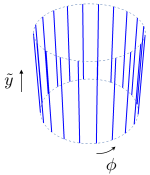
Gauged WZW action:

$$S = S_{WZW} + \frac{n_5}{\pi}\int d^2z\,\left[\mathcal{A}\bar{\mathcal{J}} + \bar{\mathcal{A}}\mathcal{J} + \Sigma\mathcal{A}\bar{\mathcal{A}}\right]$$

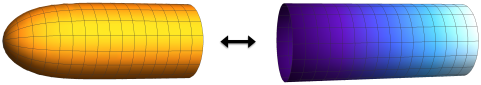
Integrating out the gauge fields gives a "smeared" geometry

$$ds^2 = n_5\left[d\rho^2 + d\theta^2 + \frac{1}{\Sigma}\left(\sin^2\theta\cosh^2\rho\, d\phi^2 + \cos^2\theta\sinh^2\rho\, d\psi^2\right)\right]\,,$$

$$H_5 = \sum_{l=1}^{n_5}\frac{1}{|\mathbf{x}-\mathbf{x}_k|^2} \sim \frac{n_5}{a^2(\cosh^2\rho - \sin^2\theta)} = \frac{n_5}{a^2\Sigma}$$

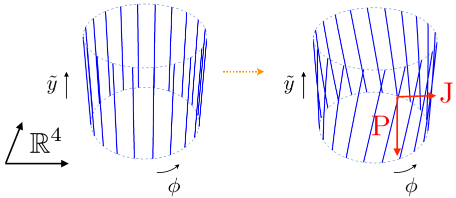


Source locations are distinguished by non-perturbative effects in α'. They are not encoded in the geometry, but rather in a Liouville superpotential [Fateev-Zamolodchikov-Zamolodchikov]



$\mathcal{W} = e^{-\sqrt{n_5}(\rho + i\Phi)}$

NS5-P supertube



We tilt the NS5 branes in order to make a single NS5-P supertube wrapping the (n_5, k) cycle of the $(\phi, \tilde{y})$ torus

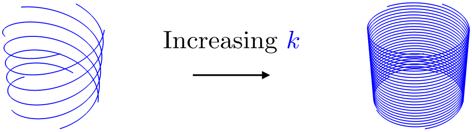
$$\frac{d\phi}{d\tilde{y}} = \frac{k}{n_5 R_{\tilde{y}}}$$

This is implemented by a tilting of the null currents in 10+2 dimensions

$$\mathcal{G}/\mathcal{H} = T^4 \times \frac{SL(2,\mathbb{R}) \times SU(2) \times R_t \times S_{\tilde{y}}}{U(1)_L \times U(1)_R}$$

$$\mathcal{J} = J_{\mathsf{ns5}} + \frac{k}{R_{\tilde{y}}}(\partial t + \partial \tilde{y}) \,, \quad \bar{\mathcal{J}} = \bar{J}_{\mathsf{ns5}} + \frac{k}{R_{\tilde{y}}}(\bar{\partial} t + \bar{\partial} \tilde{y}) \,.$$

NS5-P supertube



$k = 5$ $\qquad$ $k = 25$

We tilt the NS5 branes in order to make a single NS5-P supertube wrapping the (n_5, k) cycle of the $(\phi, \tilde{y})$ torus

$$\frac{d\phi}{d\tilde{y}} = \frac{k}{n_5 R_{\tilde{y}}}$$

This is implemented by a tilting of the null currents in 10+2 dimensions

$$\mathcal{G}/\mathcal{H} = T^4 \times \frac{SL(2,\mathbb{R}) \times SU(2) \times R_t \times S_{\tilde{y}}}{U(1)_L \times U(1)_R}$$

$$\mathcal{J} = J_{\textsf{ns5}} + \frac{k}{R_{\tilde{y}}}(\partial t + \partial\tilde{y}) \,, \quad \bar{\mathcal{J}} = \bar{J}_{\textsf{ns5}} + \frac{k}{R_{\tilde{y}}}(\bar{\partial} t + \bar{\partial}\tilde{y}) \,.$$

NS5-P supertube

Integrating out the gauge fields produces the (9+1)d geometry:

$$ds^2 = -du\,dv + n_5\big(d\rho^2 + d\theta^2\big) + \overbrace{\boxed{\frac{n_5^2}{\Sigma}\Big[\sin^2\theta\,\cosh^2\rho\,d\phi^2 + \cos^2\theta\,\sinh^2\rho\,d\psi^2\Big]}}^{\text{NS5 ring}}$$

$$+ \boxed{\frac{1}{\Sigma}\Big[\underbrace{\frac{2kn_5}{R_{\tilde{y}}}\sin^2\theta dv d\phi}_{J_\phi} + \underbrace{\frac{k^2}{R_{\tilde{y}}^2}dv^2}_{Q_p}\Big]} + dz_a dz^a$$

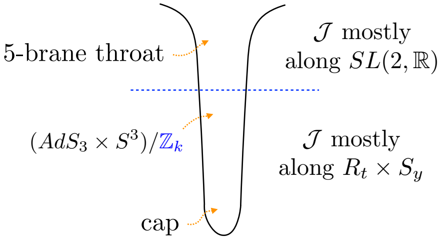
- Stringy effects resolve the location of the supertube strands
- Naive singularity at brane source $\Sigma = 0$ is a mirage; it is a locus where the gauge action degenerates. The 10+2 geometry is smooth [cf Witten 91]

NS5-F1 supertube

Switching vector to axial gauging in y gives the T-dual frame

$$\begin{pmatrix} NS5(5678\tilde{y}) \\ P(\tilde{y}) \end{pmatrix} \xrightarrow{T_{\tilde{y}}} \begin{pmatrix} NS5(5678y) \\ F1(y) \end{pmatrix}$$

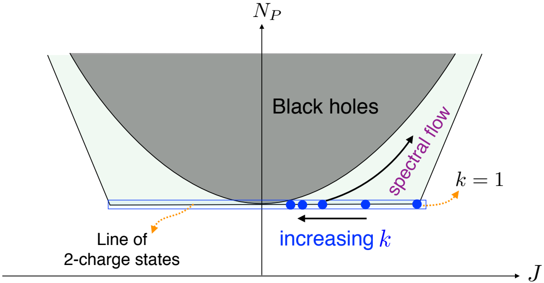
- We obtain a dilaton: $e^{-2\Phi} = (kR_y)^2/n_5^2 + \Sigma$.
  Large R_y = large AdS region
- The supertube monodromy now links together the vanishing cycles of the $\mathbb{Z}_k$ orbifold.



Three-charge supertubes

How much of this structure carry over to three-charge NS5-F1-P black holes with large horizon?

- Special class of three-charge solutions are “spectrally flowed” two-charge supertubes [Giusto, Lunin, Mathur, Saxena, Turton 04 - 12]



Three-charge supertubes

In worldsheet theory, this is obtained by rotating the null currents:

$$\mathcal{G}/\mathcal{H} = T^4 \times \frac{SL(2,\mathbb{R}) \times SU(2) \times R_t \times S_{\tilde{y}}}{U(1)_L \times U(1)_R}$$

with

$$\begin{aligned} U(1)_L: &\quad \mathcal{J} = l_1 J_3^{sl} + l_2 J_3^{su} + l_3 \partial t + l_4 \partial \tilde{y}\,, \quad \langle \mathbf{l}, \mathbf{l} \rangle = 0 \\ U(1)_R: &\quad \bar{\mathcal{J}} = r_1 \bar{J}_3^{sl} + r_2 \bar{J}_3^{su} + r_3 \bar{\partial} t + r_4 \bar{\partial} y\,, \quad \langle \mathbf{r}, \mathbf{r} \rangle = 0 \end{aligned}$$

- $r_1 = r_2 = 1$, $r_3 = r_4 = \alpha$: preserves SUSY
- Arbitrary left/right gauging: non-extremal microstates

Non-extremal microstates: JMaRT solution

$$\begin{aligned} ds^2 = {} & \frac{f_0}{\Sigma}\left(-\,dt^2 + dy^2\right) + \frac{M}{\Sigma}\left(c_p\,dt + s_p\,dy\right)^2 + Q_5\left(d\rho^2 + d\theta^2\right) \\ & + \frac{Q_5}{\Sigma}\Big(\left(r_+^2 - r_-^2\right)\cosh^2\rho + r_-^2 + a_2^2 + M s_1^2\Big)\sin^2\theta\,d\phi^2 \\ & + \frac{Q_5}{\Sigma}\Big(\left(r_+^2 - r_-^2\right)\sinh^2\rho + r_+^2 + a_1^2 + M s_1^2\Big)\cos^2\theta\,d\psi^2 \\ & - \frac{\sqrt{MQ_5}\cos^2\theta}{\Sigma}\Big[\left(a_1c_1c_p - a_2s_1s_p\right)dt + \left(a_2s_1c_p - a_1c_1s_p\right)dy\Big]\,d\psi \\ & - \frac{\sqrt{MQ_5}\sin^2\theta}{\Sigma}\Big[\left(a_2c_1c_p - a_1s_1s_p\right)dt + \left(a_1s_1c_p - a_2c_1s_p\right)dy\Big]\,d\phi \\ & + \left(dz_a dz^a\right) \end{aligned}$$

$$r_\pm^2 = -a_1a_2\left(\frac{s_1s_p}{c_1c_p}\right)^{\pm 1}, \quad M = a_1^2 + a_2^2 - a_1a_2\frac{c_1^2c_p^2 + s_1^2s_p^2}{c_1c_ps_1s_p}\,, \quad \Sigma = f_0 + Ms_1^2\,.$$

$$f_0 = \frac{1}{2}\Big[(r_+^2 - r_-^2)\cosh 2\rho + (a_2^2 - a_1^2)\cos 2\theta + r_+^2 + r_-^2 + a_2^2 + a_1^2\Big]\,.$$

[Jejjala, Madden, Ross, Titchener 05]

Non-extremal microstates: JMaRT solution

$$
\begin{aligned}
ds^2 = {} & \frac{f_0}{\Sigma}\left(-\,dt^2 + dy^2\right) + \frac{M}{\Sigma}\left(c_p\,dt + s_p\,dy\right)^2 + Q_5\left(d\rho^2 + d\theta^2\right) \\
& + \frac{Q_5}{\Sigma}\Big(\left(r_+^2 - r_-^2\right)\cosh^2\rho + r_-^2 + a_2^2 + M s_1^2\Big)\sin^2\theta\, d\phi^2 \\
& + \frac{Q_5}{\Sigma}\Big(\left(r_+^2 - r_-^2\right)\sinh^2\rho + r_+^2 + a_1^2 + M s_1^2\Big)\cos^2\theta\, d\psi^2 \\
& - \frac{\sqrt{MQ_5}\cos^2\theta}{\Sigma}\Big[\left(a_1 c_1 c_p - a_2 s_1 s_p\right) dt + \left(a_2 s_1 c_p - a_1 c_1 s_p\right) dy\Big]\, d\psi \\
& - \frac{\sqrt{MQ_5}\sin^2\theta}{\Sigma}\Big[\left(a_2 c_1 c_p - a_1 s_1 s_p\right) dt + \left(a_1 s_1 c_p - a_2 c_1 s_p\right) dy\Big]\, d\phi \\
& + \left(dz_a\, dz^a\right)
\end{aligned}
$$

$$
J_L = (2s+1)\,\frac{n_1 n_5}{2k}
$$

$$
J_R = (2\bar{s}+1)\,\frac{n_1 n_5}{2k}
$$

$$
r_\pm^2 = -a_1 a_2 \left(\frac{s_1 s_p}{c_1 c_p}\right)^{\pm 1}, \quad M = a_1^2 + a_2^2 - a_1 a_2\,\frac{c_1^2 c_p^2 + s_1^2 s_p^2}{c_1 c_p s_1 s_p}\,, \quad \Sigma = f_0 + M s_1^2\,.
$$

$$
f_0 = \frac{1}{2}\Big[\left(r_+^2 - r_-^2\right)\cosh 2\rho + \left(a_2^2 - a_1^2\right)\cos 2\theta + r_+^2 + r_-^2 + a_2^2 + a_1^2\Big]\,.
$$

[Jejjala, Madden, Ross, Titchener 05]

Closed string spectrum

Gauging of null isometries is implemented by constructing appropriate BRST charge

$$\mathcal{Q}_{\mathsf{BRST}} = \oint \left[cT^g + \gamma G^g + \hat{c}\mathcal{J} + \hat{\gamma}\psi + \mathsf{ghosts} \right]$$

resulting in linear constraints among quantum numbers:

$$l_1(2m_{\rm sl} + n_5 w_{\rm sl}) - l_2(2m_{\rm su} + n_5 w_{\rm su}) + l_3 E - l_4 P_{y,l} = 0$$

$$r_1(2\bar{m}_{\rm sl} + n_5 \bar{w}_{\rm sl}) - r_2(2\bar{m}_{\rm su} + n_5 \bar{w}_{\rm su}) + r_3 E - r_4 P_{y,r} = 0$$

Closed string spectrum

Gauging of null isometries is implemented by constructing appropriate BRST charge

$$\mathcal{Q}_{\mathsf{BRST}} = \oint \left[cT^g + \gamma G^g + \hat{c}\mathcal{J} + \hat{\gamma}\psi + \text{ghosts} \right]$$

resulting in linear constraints among quantum numbers:

$$\begin{aligned} l_1(2m_{\mathrm{sl}} + n_5 w_{\mathrm{sl}}) - l_2(2m_{\mathrm{su}} + n_5 w_{\mathrm{su}}) + l_3 E - l_4 P_{y,l} &= 0 \\ r_1(2\bar{m}_{\mathrm{sl}} + n_5 \bar{w}_{\mathrm{sl}}) - r_2(2\bar{m}_{\mathrm{su}} + n_5 \bar{w}_{\mathrm{su}}) + r_3 E - r_4 P_{y,r} &= 0 \end{aligned}$$

- Principal discrete series $\mathcal{D}_j^{\pm}$: states bound to the cap

Closed string spectrum

Gauging of null isometries is implemented by constructing appropriate BRST charge

$$\mathcal{Q}_{\mathsf{BRST}} = \oint \left[cT^g + \gamma G^g + \hat{c}\mathcal{J} + \hat{\gamma}\psi + \text{ghosts} \right]$$

resulting in linear constraints among quantum numbers:

$$\begin{aligned} l_1(2m_{\rm sl} + n_5 w_{\rm sl}) - l_2(2m_{\rm su} + n_5 w_{\rm su}) + l_3 E - l_4 P_{y,l} &= 0 \\ r_1(2\bar{m}_{\rm sl} + n_5 \bar{w}_{\rm sl}) - r_2(2\bar{m}_{\rm su} + n_5 \bar{w}_{\rm su}) + r_3 E - r_4 P_{y,r} &= 0 \end{aligned}$$

- Principal discrete series $\mathcal{D}_j^{\pm}$: states bound to the cap
- Constraints correlate cap energy E_{cap} with asymptotic energy E. For non-SUSY JMaRT solution: $\mathcal{D}_j^{-}$ states have $E > 0$ but $E_{\mathsf{cap}} < 0$. Reservoir of unstable modes: ergoregion instability

Closed string spectrum

Gauging of null isometries is implemented by constructing appropriate BRST charge

$$\mathcal{Q}_{\mathsf{BRST}} = \oint \left[cT^g + \gamma G^g + \hat{c}\mathcal{J} + \hat{\gamma}\psi + \text{ghosts} \right]$$

resulting in linear constraints among quantum numbers:

$$\begin{aligned} l_1(2m_{\rm sl} + n_5 w_{\rm sl}) - l_2(2m_{\rm su} + n_5 w_{\rm su}) + l_3 E - l_4 P_{y,l} = 0 \\ r_1(2\bar{m}_{\rm sl} + n_5 \bar{w}_{\rm sl}) - r_2(2\bar{m}_{\rm su} + n_5 \bar{w}_{\rm su}) + r_3 E - r_4 P_{y,r} = 0 \end{aligned}$$

- Principal discrete series $\mathcal{D}_j^{\pm}$: states bound to the cap
- Constraints correlate cap energy E_{cap} with asymptotic energy E. For non-SUSY JMaRT solution: $\mathcal{D}_j^{-}$ states have $E > 0$ but $E_{\mathsf{cap}} < 0$. Reservoir of unstable modes: ergoregion instability
- Continuous series $\mathcal{C}_j$ describes scattering states

Two-point functions

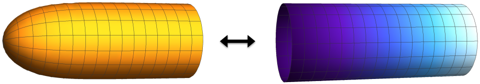
$$\langle \Phi^{\mathrm{sl}}_{j_{\mathrm{sl}};m_{\mathrm{sl}},\bar{m}_{\mathrm{sl}}} \Phi^{\mathrm{sl}}_{j_{\mathrm{sl}};-m_{\mathrm{sl}},-\bar{m}_{\mathrm{sl}}} \rangle = n_5 \mu^{2j_{\mathrm{sl}}-1} \frac{\Gamma(1-\frac{2j_{\mathrm{sl}}-1}{n_5})}{\Gamma(\frac{2j_{\mathrm{sl}}-1}{n_5})} \times \frac{\Gamma(-2j_{\mathrm{sl}}+1)\Gamma(j_{\mathrm{sl}}-m_{\mathrm{sl}})\Gamma(j_{\mathrm{sl}}+\bar{m}_{\mathrm{sl}})}{\Gamma(2j_{\mathrm{sl}}-1)\Gamma(-j_{\mathrm{sl}}-m_{\mathrm{sl}}+1)\Gamma(-j_{\mathrm{sl}}+\bar{m}_{\mathrm{sl}}+1)}$$

stringy

SUGRA

Discrete series of $SL(2,\mathbb{R})$ arise as poles of two-point correlator. For low-lying states it agrees with solutions of wave equation in the classical geometry.

For scattering states, stringy contribution to phase shift. In the T-dual Liouville picture this arises because energetic probes can explore stringy structure "beyond the cap" (the finer supertube strands). Breakdown of naive coset metric.



[Giveon-Itzhaki-Kutasov]

Brane/flux transitions

Let us consider the sector of strings winding along $\mathbb{S}_y$.

Brane/flux transitions

Let us consider the sector of strings winding along $\mathbb{S}_y$. Gauge symmetry relates winding on $\mathbb{S}_y$ with winding on the $SL(2,\mathbb{R})$ circle σ. In the cap, this allows for unwinding processes.

Brane/flux transitions

Let us consider the sector of strings winding along $\mathbb{S}_y$. Gauge symmetry relates winding on $\mathbb{S}_y$ with winding on the $SL(2,\mathbb{R})$ circle σ. In the cap, this allows for unwinding processes. Consider an operator that implements (worldsheet) spectral flow in the null directions we are gauging. Action on zero modes:

Background angular momenta

$$w_{\rm sl} \to w_{\rm sl} + q \quad , \quad w_{\rm su} \to w_{\rm su} + \boxed{(2s+1)q} \quad , \quad \bar{w}_{\rm su} \to \bar{w}_{\rm su} + \boxed{(2\bar{s}+1)q}$$

$$E \to E + \boxed{kR\varrho\, q} \quad , \quad n_y \to n_y \boxed{-\frac{s(s+1)-\bar{s}(\bar{s}+1)}{k} n_5 q} \quad , \quad \boxed{w_y \to w_y + kq}$$

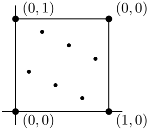
ADM mass

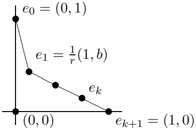
ADM momentum

Orbifold structure in the cap

Three-charge geometries have intersting orbifold structure at the cap

$(\rho = 0, \theta = 0):\quad \mathbb{Z}_{\ell_1}$ orbifold
$(\rho = 0, \theta = \pi/2):\quad \mathbb{Z}_{\ell_2}$ orbifold
$\ell_1 = \mathsf{gcd}(k, \mathfrak{m})\,,\quad \ell_2 = \mathsf{gcd}(k, \mathfrak{n})$

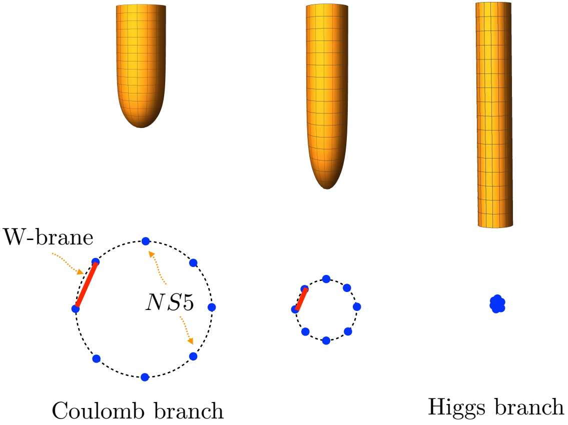


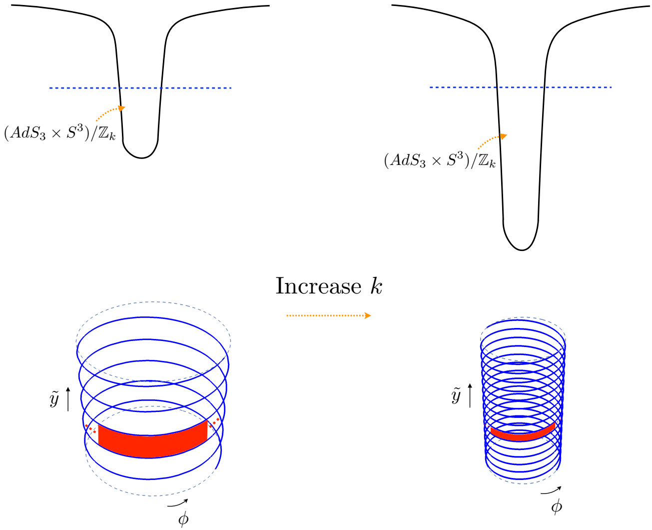


- For non-SUSY solutions, Hirzebruch-Jung type singularities. Expect tachyons in twisted sectors [Adam-Polchinski-Silverstein, Martinec-Moore]
- Worldsheet is not orbifold CFT: no stringy instability of JMaRT

D-branes

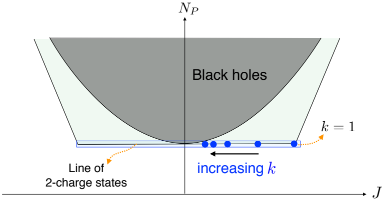
Supertube configurations arise from Coulomb branch of NS5 branes. Bringing NS5 brane together: Colulomb/Higgs transition associated to light stretched W-branes. Cap becomes the linear dilaton tube dual to little string theory.

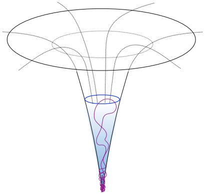



$(AdS_3 \times S^3)/\mathbb{Z}_k$
$(AdS_3 \times S^3)/\mathbb{Z}_k$
Increase k
$\tilde{y}$
ϕ
$\tilde{y}$
ϕ

Threshold of BH formation associated to Coulomb/Higgs transition.
Light degrees of freedom (the W-branes) modify the effective dynamics.

Hope: new degrees of freedom with fractionated tension (long/little strings) modify the "effective" causal structure, and the scale of their wavefunction is the horizon scale.





In this picture, the experience of an infalling observer is determined by the effective theory of the interactions with W-branes.
[Martinec 14]

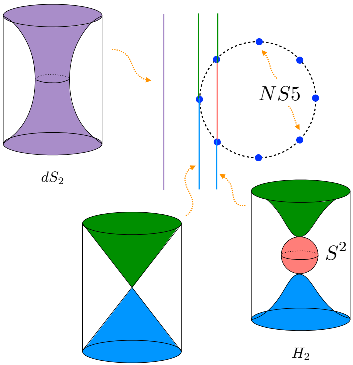
D-branes in supertubes are described by (twisted) conjugacy classes in $SL(2,\mathbb{R}) \times SU(2) \times \mathbb{R}_t \times S_y$, smeared along the gauge orbits in order to obtain boundary states that can be projected to the coset

$$\mathcal{D} = \mathcal{C}_G \cdot \mathcal{C}_H , \quad \mathcal{C}_G = \mathsf{Tr}\{h f_G \Omega(h^{-1}), h \in G\}$$

[Martinec, SM, Turton, 1906.11473]

D-branes in supertubes are described by (twisted) conjugacy classes in $SL(2,\mathbb{R}) \times SU(2) \times \mathbb{R}_t \times S_y$, smeared along the gauge orbits in order to obtain boundary states that can be projected to the coset

$$\mathcal{D} = \mathcal{C}_G \cdot \mathcal{C}_H\,, \quad \mathcal{C}_G = \mathsf{Tr}\{h f_G \Omega(h^{-1}), h \in G\}$$



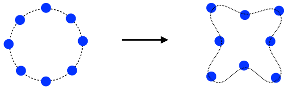
[Martinec, SM, Turton, 1906.11473]

Linerarized deformations

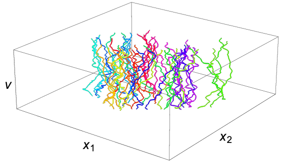
Representation theory and the BRST cohomology dictate the form of vertex operators that represent geometrical deformations of the supertube.

$$\mathcal{V} = P(\partial t, \partial y, j_{su}, j_{sl}, \psi)\Phi^{sl}_{j_{sl}, m_{sl}\bar{m}_{sl}} \Psi^{su}_{j_{su}, m_{su}\bar{m}_{su}} e^{in_y(t+y)R_y}$$

- For circular array of NS5 branes: $4(N_5 - 1)$ marginal deformations

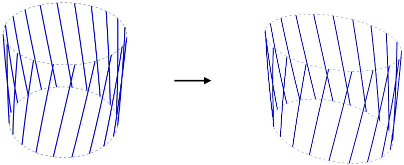


- For supertube we describe general profile for the strands

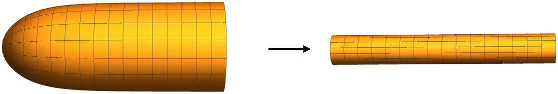


Singular limits

Some perturbations are known at non-linear level. Example: elliptical supertube



We can probe singular limits in the phase space when two NS5 strands coincide. Perturbation theory breaks down and the non-abelian dynamics is dominated by light D-brane states. Such strong coupling limits are presumably associated to the formation of the typical microstates.



Recap

- Non-perturbative stringy effects reveal rich structure of two and three-charge supertubes.
- Singular limits in the phase space of microstate geometries are associated to Coulomb/Higgs transitions: dynamics dominated by condensation of light D-branes.
- Coherent quantum structure over horizon scale?
- Much to do: study of correlators and matching with dual CFT, counting of perturbative stringy supertubes, RR fluxes ...

Recap

- Non-perturbative stringy effects reveal rich structure of two and three-charge supertubes.
- Singular limits in the phase space of microstate geometries are associated to Coulomb/Higgs transitions: dynamics dominated by condensation of light D-branes.
- Coherent quantum structure over horizon scale?
- Much to do: study of correlators and matching with dual CFT, counting of perturbative stringy supertubes, RR fluxes ...

Thank you!