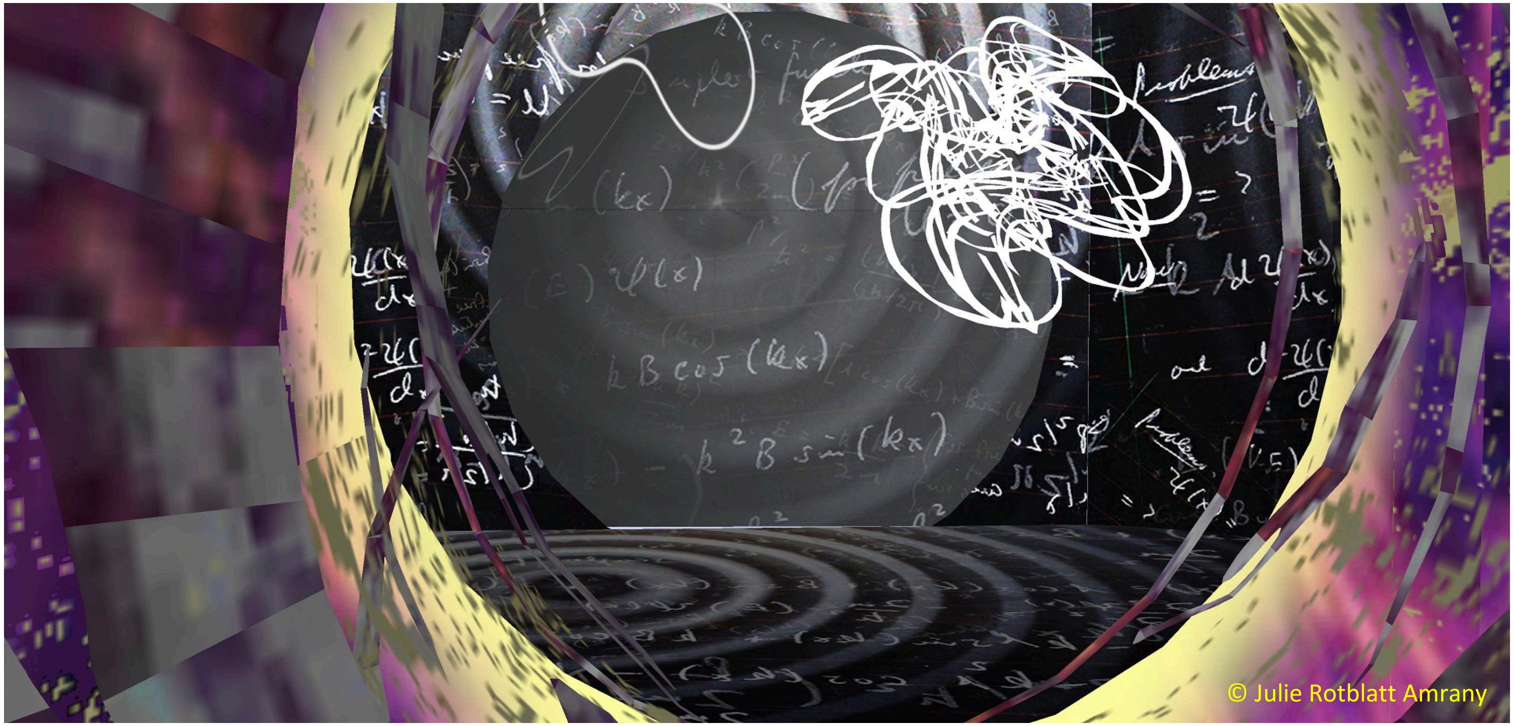
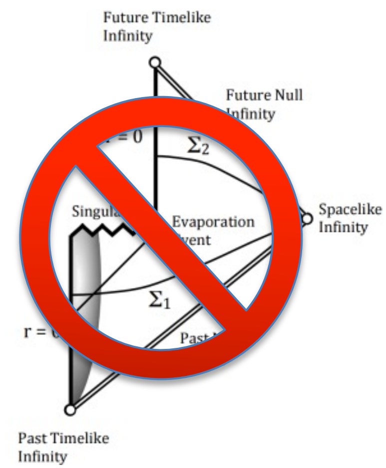
The branes behind black holes



Emil J. Martinec (UChicago)

Still crazy after all these years

- 45+ yrs of the black hole information problem: Effective QFT says locality, causality, & unitarity cannot **all** hold during BH evaporation



- Which one to give up? To preserve unitarity, we need some structure to store memories, and then to release that information in later stages of evaporation

- We also want to understand quantum stat mech underlying BH thermo

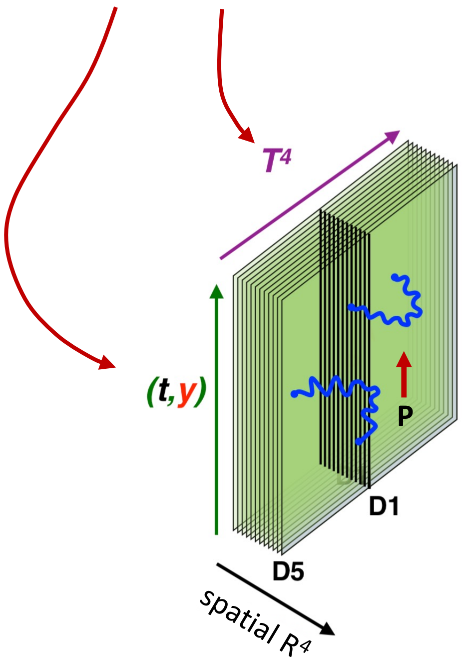
- String theory: 1^{st} steps toward a resolution via an accounting of near-extremal black hole microstates

Supersymmetric BH entropy

- A prime example: 3-charge BPS **D1**-**D5**-**P** bound states wrapped on $\mathbb{S}^1_y \times \mathcal{M}$ (where $\mathcal{M} = \mathbb{T}^4$ or K3) become black holes at strong coupling

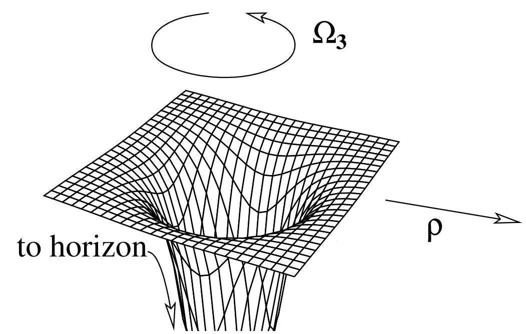
$$S_{BH} = 2\pi\sqrt{n_5 n_1 n_p}$$

(Strominger-Vafa '96)



Weak coupling

Strong coupling



- Bulk structure of generic μstates remains a mystery, but susy preserves the counting

~~Supersymmetric~~ BH entropy

- The geometry of general 3-charge black holes leads to an entropy which can be interpreted as a bound state of branes and anti-branes

(Horowitz-Maldacena-Strominger '96)

$$S_{BH} = 2\pi\left(\sqrt{n_5} + \sqrt{n_{\bar{5}}}\right)\left(\sqrt{n_1} + \sqrt{n_{\bar{1}}}\right)\left(\sqrt{n_p} + \sqrt{n_{\bar{p}}}\right)$$

(the charge quanta $n_a, n_{\bar{a}}$ are determined by extremizing the free energy *i.e.* gravitational action, keeping the mass and net charges $n_a - n_{\bar{a}}$ fixed)

- Suggests that the brane picture applies even in the strongly coupled regime where supergravity and black holes are the effective description

- The fuzzball idea (Lunin-Mathur '02, Mathur '05) : Black holes are compact objects composed of the extended objects of string theory, which have *no horizons* and therefore a priori *no information problem.* We seek to understand whether this idea of black hole microstructure is correct via a better understanding of the ***bulk*** side of AdS/CFT

The importance of fractionation

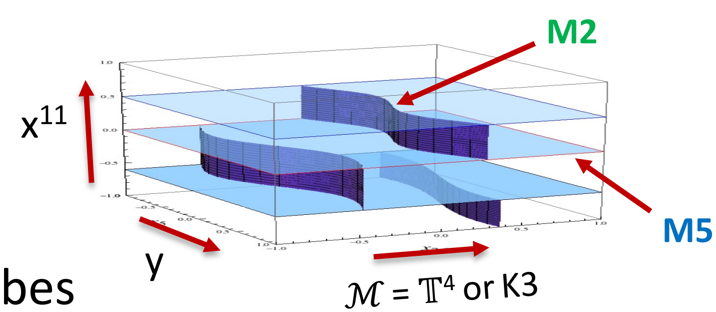
- A key feature of the entropy formula

$$S_{BH} = 2\pi(\sqrt{n_5} + \sqrt{n_{\bar{5}}})(\sqrt{n_1} + \sqrt{n_{\bar{1}}})\left(\sqrt{n_p} + \sqrt{n_{\bar{p}}}\right)$$

is that the entropy of a given constituent is *multiplicatively enhanced* by the presence of other types of constituent in the bound state

- This entropy enhancement is a result of *charge/tension fractionation:*
  - String winding fractionates momentum $\delta \mathrm{P} \propto \frac{n_p}{n_1}$
  - Fivebranes fractionate strings into n_5 constituent *little strings* whose tension is also fractionated $(\alpha')_{little} = n_5 \alpha'$ (Dijkgraaf-Verlinde[2] '96,'97, Seiberg '97)

- Cartoon: in the M-theory lift of IIA: **M2**-branes (the lift of IIA **F1**'s) break on the **M5**'s (the lift of IIA **NS5**'s)



- The symmetric orbifold $(\mathcal{M}^{n_1 n_5})/S_{n_1 n_5}$ describes the Fock space of *little strings* at weak coupling

Connecting branes to geometry

- We need to tie the intersecting brane picture (weak coupling) to bulk geometry (strong coupling)
- The **F1**-**NS5** duality frame is very useful here
- The availability of a solvable worldsheet description in this frame allows us to probe beyond the supergravity approximation (Giveon-Kutasov-Seiberg '98)
- The **NS5**-brane tension $\propto 1/g_s^2$ makes it a **solitonic** object in supergravity, therefore much structure will be revealed in semi-classical closed string dynamics, which incorporates the back-reaction of the heavy background
- The worldsheet theory keeps track of what the fivebranes are doing, even in regions of stringy curvature

Kinds of fuzzball

OVERVIEW:
Bena-EJM-Mathur-Warner 2204.13113

- ***Microstate geometries:*** Smooth horizonless solutions of supergravity whose field gradients are much less than string scale everywhere.
- ***Perturbative string microstates:*** Worldsheet constructions of horizonless solutions. Can have string-scale field gradients, and weakly-coupled brane sources.
- Examples of the above include supertubes and superstrata. The latter can have the same mass, charge and angular momenta as a black hole.
- ***Generic Fuzzballs:*** Objects which supplant the black-hole interior by some horizon-scale structure having itself no horizon. The fuzzball paradigm posits that *all black holes are such objects*.

μstate geometries $\subset$ **perturbative stringy** ***μstates*** $\subset$ ***generic fuzzballs***

***μstate geometries*** $\ll$ **# perturbative stringy** ***μstates*** $\ll$ **#** ***generic fuzzballs***

NS5-F1 supertube geometry

- The **½-BPS** **NS5-F1** supertube geometry is (NB: *u,v=t±y* are along both branes)

$$ds^2 = -Z_1^{-1}\big(du+\omega\big)\big(dv+\beta\big) + Z_5\, d\mathrm{x}_\perp \cdot d\mathrm{x}_\perp + ds^2_{\mathbb{T}^4} \qquad e^{2\Phi} = g_s^2\,\frac{Z_5}{Z_1}$$

$$B = \underbrace{\tfrac{1}{2}Z_1^{-1}}_{\text{electric H-flux for F1}}(du+\omega)\wedge(dv+\beta) + \underbrace{b_{ij}}_{\text{magnetic H-flux for NS5}}\, dx^i \wedge dx^j\,. \qquad db = *_\perp dZ_5$$

is specified by a set of harmonic forms sourced by functions $\mathsf{F}^I(v)$

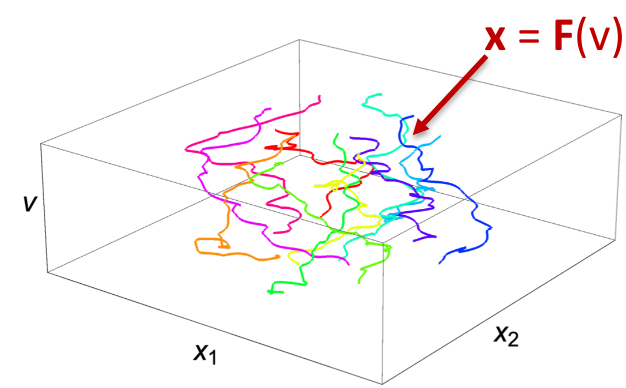
(Lunin-Mathur '01, Taylor '05, Kanitscheider-Skenderis-Taylor '07)

NS5 decoupling limit

$$Z_5 \;=\; \cancel{1} + \frac{n_5}{2\pi L}\int_0^{2\pi L}\frac{dv}{|\mathbf{x}-\mathsf{F}(v)|^2} \qquad \beta = \mathsf{A}+\mathsf{B} \;\;, \qquad \omega = \mathsf{A}-\mathsf{B}$$

$$\mathsf{A}_i \;=\; \frac{n_5}{2\pi L}\int_0^{2\pi L}\frac{dv\,\dot{F}_i(v)}{|\mathbf{x}-\mathsf{F}(v)|^2} \;\;, \qquad d\mathsf{B} = *_\perp d\mathsf{A}$$

$$Z_1 \;=\; 1 + \frac{n_5}{2\pi L}\int_0^{2\pi L}\frac{dv\,\dot{\mathsf{F}}_I\cdot\dot{\mathsf{F}}_I}{|\mathbf{x}-\mathsf{F}(v)|^2}$$



Enumerating supertubes

- The **½-BPS** bound states of strings and fivebranes have occupation #'s N_k^I for the Fourier modes of $\mathsf{F}^I(v)$ – w/choice of 8B+8F polarizations I (for $\mathbb{T}^4$), including $\mathsf{F}^{\alpha\dot\beta}$ = fivebrane position in the transverse $\mathbb{R}^4$

$$x^1 \pm i x^2 \longleftrightarrow |\alpha\dot\beta\rangle = |\pm\pm\rangle$$
$$x^3 \pm i x^4 \longleftrightarrow |\alpha\dot\beta\rangle = |\pm\mp\rangle$$

$$|\Psi\rangle = \prod_{\substack{k,\ell,p,q \\ pol\text{'}s\ I}} \overbrace{\Big(\underbrace{|\alpha\dot\beta\rangle}_{\perp\ \text{scalars}}{}_k\Big)^{N_k^{\alpha\dot\beta}} \Big(\underbrace{|AB\rangle}_{\substack{\text{internal} \\ \text{(NS5 gauge multiplet)}}}{}_\ell\Big)^{N_\ell^{AB}}}^{\text{bosons}} \overbrace{\Big(|\alpha B\rangle_p\Big)^{N_p^{\alpha B}} \Big(|A\dot\beta\rangle_q\Big)^{N_q^{A\dot\beta}}}^{\text{fermions}} \qquad \sum_{k,I} k N_k^I = N = n_1 n_5$$

mode number = *little string* winding

- Easily understood via T-duality to **NS5**-**P** where this is the Fock space of fractionated BPS momentum modes on a single NS5 wrapping $\mathbb{S}^1_{\tilde y}$ n_5 times.

- For K3, there are no fermionic modes, and 16 extra internal bosonic modes

- ***Coherent states correspond to particular horizonless supertube geometries.*** *(Typical state is highly quantum)* (Lunin-Mathur '01, Taylor '05, Kanitscheider-Skenderis-Taylor '07)

NS5-F1 interplay

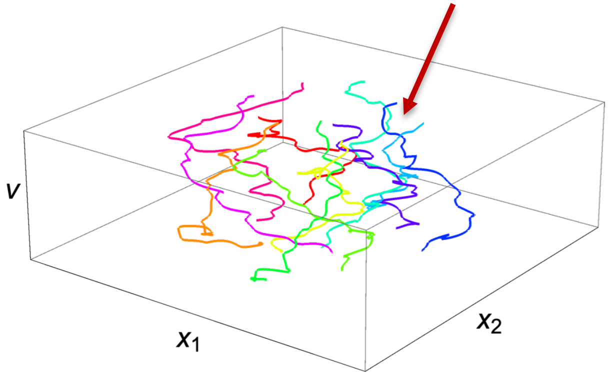
- The profile functions specify a string condensate bound to the fivebranes, which in turn back-reacts to determine the fivebrane configuration/geometry

$$ds^2 = -Z_1^{-1}\Big[(du+\omega)(dv+\beta)\Big] + Z_5\, ds_\perp^2 + ds_{\mathbb{T}^4}^2$$

$$Z_5 = \frac{n_5}{2\pi L}\int_0^{2\pi L}\frac{dv}{|\mathbf{x}-\mathsf{F}(v)|^2}$$

$$Z_1 = 1 + \frac{1}{2\pi L}\int_0^{2\pi L}\frac{dv\,\dot{\mathsf{F}}\cdot\dot{\mathsf{F}}}{|\mathbf{x}-\mathsf{F}(v)|^2}$$

$\mathbf{x} = \mathsf{F}(v)$



- More compact profiles $\mathsf{F}(v)$ (fewer transverse modes) $\Longrightarrow$ smaller J^2, and larger Z_1, leading to deeper redshifts into the core of the geometry

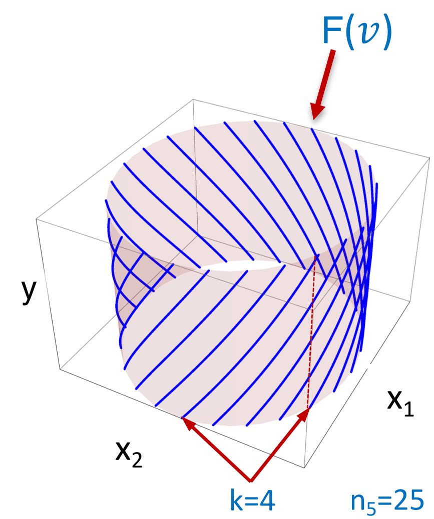
The Return of the String

- In the absence of RR sources, the worldsheet NLSM is exactly conformal to all orders in α' (Horowitz-Tseytlin '94)

- Non-perturbative effects in α' are also understood – giving us control over the regime of stringy sources

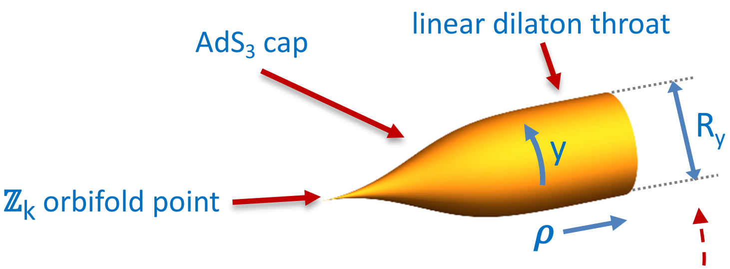
- **The worldsheet string dynamics in the fivebrane throat is *exactly solvable* when the n_5 fivebranes are evenly distributed along a circle in a ⊥ plane.** (Giveon-Kutasov '99, EJM-Massai '17)

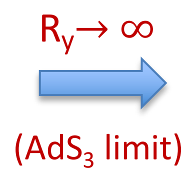
- This circular supertube corresponds to the fivebrane state with only a single transverse scalar mode $|{+}{+}\rangle_k$ populated macroscopically

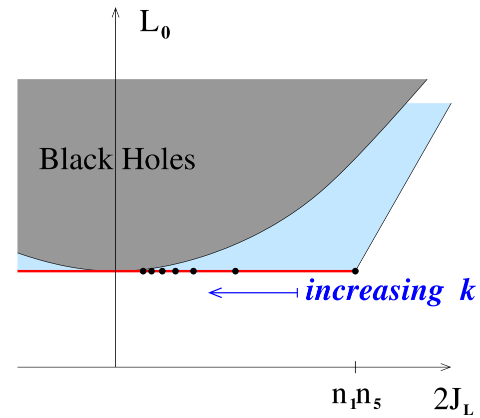


$$|\Psi\rangle = \Big(\underbrace{|{+}{+}\rangle}_{\perp\ \text{scalar}}{}_k\Big)^{N/k}$$

The Return of the String







- The worldsheet theory is a gauged WZW model for

$$\frac{\mathcal{G}}{\mathcal{H}} = \frac{\left(\mathbb{R}_t \times \mathbb{S}^1_y \times \mathbb{T}^4\right)_{||} \times \left(SL(2,\mathbb{R}) \times SU(2)\right)_{\perp}}{U(1)_L \times U(1)_R}$$

where the gauge orbits under $\mathcal{H}$ are null isometries of $\mathcal{G}$ generated by L/R null currents

$$\mathcal{J} = J^3_{\rm sl} + J^3_{\rm su} - kR_y(\partial t - \partial y)$$

$$\bar{\mathcal{J}} = \bar{J}^3_{\rm sl} + \bar{J}^3_{\rm su} - kR_y(\bar{\partial} t + \bar{\partial} y)$$

supertube source perturbations

- ½-BPS string vertex operators $\mathcal{V}^{\alpha\dot\beta}_{j,w_y}$ (NS·NS) and $\mathcal{S}^{AB}_{j,w_y}$ (R·R) implement transitions

$$\mathcal{V}^{\alpha\dot\beta}_{j,w_y} \;:\; \big(|{+}{+}\rangle_k\big)^{2j+1} \;\longrightarrow\; |\alpha\dot\beta\rangle_{(2j+1)k+w_y n_5}$$

$$\mathcal{S}^{AB}_{j,w_y} \;:\; \big(|{+}{+}\rangle_k\big)^{2j+1} \;\longrightarrow\; |AB\rangle_{(2j+1)k+w_y n_5}$$

16 extra of these for K3

to nearby ½-BPS supertubes, by extracting some strings from the background, sewing them together, and changing the polarization state.

- The generic supertube state

$$|\Psi\rangle = \prod_{\substack{p,q,r,\ell \\ pol's\ I}} \overbrace{\Big(\underbrace{|\alpha\dot\beta\rangle_p}_{\perp\text{ scalar}}\Big)^{N_p^{\alpha\dot\beta}} \Big(\underbrace{|AB\rangle_q}_{\text{internal}}\Big)^{N_q^{AB}}}^{\text{bosons}} \overbrace{\Big(|\alpha B\rangle_r\Big)^{N_r^{\alpha B}} \Big(|A\dot\beta\rangle_\ell\Big)^{N_\ell^{A\dot\beta}}}^{\text{fermions}}$$

is in principle obtained by condensing the ½-BPS vertex ops (exponentiating them into the worldsheet action).

supertube source perturbations

- These vertex operators have both a supergraviton aspect and a winding string aspect due to an identity of affine SL(2,R) representations

(Maldacena-Ooguri ’01, Giveon-Izhaki-Kutasov ’16)

$$(\mathcal{D}_j^+)^{\boldsymbol{w=0}} \equiv (D^-_{n_5/2+1-j})^{\boldsymbol{w=1}}$$

- **All the supertube backgrounds thus are both coherent string winding condensates bound to the NS5’s, *and* supergravity states.**

- As we briefly describe below, the winding string aspect is closely related to the profile function $\mathsf{F}(v)$, and thus the fivebrane source configuration (this is useful for understanding the breakdown of the worldsheet description)

BPS worldsheet vertex ops

- The ½-BPS supergravity deformations have **¼-BPS** generalizations, $e.g$

½-BPS $$\mathcal{V}^{++}_{j,w_y} = \big(J\bar{J}\,\Phi^{sl}_{j+1}\big)_{j;j,j}\,\Phi^{su}_{j;-j,-j}\;e^{iw_yR_y(t+\tilde{y})} \quad + \dots$$

BPS condition selects highest weight states in SL(2,R) and SU(2)

¼-BPS $$\mathcal{V}^{++}_{j,n,m} = \big(J\bar{J}\Phi^{sl}_{j+1}\big)_{j;j+n,j}\;\Phi^{su}_{j;-j+m,-j}\;\exp\Big[i\frac{n_y}{R_y}(t+y)\Big] \quad + \dots$$

not highest wt ⇒ not BPS on left   carrying momentum on $\mathbb{S}^1_y$

- The null gauge constraint sets $\boldsymbol{m+n=k\,n_y}$ (thus these vertex operators indeed perturbatively add $\mathbb{S}^1_y$ momentum charge $\boldsymbol{n_p=n_y}$ to the background).
- Worldsheet ops $(J^+_0)_{\rm sl}$ & $(J^+_0)_{\rm su}$ that add this momentum correspond to global symmetries $\mathcal{L}_{-1}$ & $\mathcal{J}^+_0$ in spacetime (spectrally flowed to the Ramond sector, and on the covering space of the $\mathbb{Z}_k$ orbifold so that momenta ∝ *1/k*).
- For $\mathbb{T}^4$ one has $(8\mathrm{NS}+8\mathrm{R})_{\mathrm{L}}$ generic & $(2\mathrm{NS}+2\mathrm{R})_{\mathrm{R}}$ BPS supergraviton polarizations

¼-BPS (& Stringy) perturbations

- There are further **¼-BPS** generalizations which are stringy, *e.g.*

½-BPS $\mathcal{V}^{++}_{j,w_y} = \big(J\bar{J}\,\Phi^{sl}_{j+1}\big)_{j;j,j}\,\Phi^{su}_{j;-j,-j}\,e^{iw_yR_y(t+\tilde{y})} + \dots$

BPS condition selects highest weight states in SL(2,R) and SU(2)

¼-BPS $\mathcal{V}^{++}_{j,n,m} = \big(J\bar{J}\Phi^{sl}_{j+1}\big)_{\underbrace{j;j+n,j}_{\text{not highest wt}}}\,\Phi^{su}_{\underbrace{j;-j+m,-j}_{\text{not BPS on left}}}\,\exp\Big[i\underbrace{\frac{n_y}{R_y}}_{\text{carrying momentum on } \mathbb{S}^1_y}(t+y)\Big] + \dots$

not highest wt ⇒ not BPS on left   carrying momentum on $\mathbb{S}^1_y$

¼-BPS Stringy $\mathcal{P}(\underline{L\ osc.})\big(\bar{J}\Phi^{sl}_{j+1}\big)_{\underline{j,j+n},j}\,\Phi^{su}_{\underline{j,-j+m},-j}\,\exp\Big[i\underline{\frac{n_y}{R_y}}(t+y) + \underline{iw_yR_y}(t+\tilde{y})\Big] + \dots$

L stringy excitations

not L highest wt ⇒ not BPS on L

carrying momentum **and** winding on $\mathbb{S}^1_y$ ⇒ $n+m = kn_y = \underbrace{\frac{k}{w_y}(N_L-1)}_{\text{level matching}}$

oscillator excitations required by world sheet constraints

- ***There are many more stringy deformations than supergravity deformations, yet still falling short of the BTZ entropy.***

The logic in the gap

- The constraints

$$n+m = kn_y = \frac{k}{w_y}(N_L-1)$$

show that center-of-mass momentum is fractionated by the conical defect redshift $1/k$ while the string oscillator contribution is fractionated by the **F1** winding $1/w_y$. On the other hand, the vertex operator creates a contribution to the background with *little string* winding $\underbrace{(2j+1)}_{2j+1\,<\,n_5}k+n_5w_y$.

- ***Naively, perturbative string excitations do not carry the finest fractionations one might expect from the little string picture*** (and that one also sees in the weakly-coupled symmetric product orbifold)***.***

- Very likely this is because one is working in a regime where fivebrane dynamics is "abelianized" by the spatial separation of the fivebranes caused by the winding string condensate they are carrying (see below).

nonlinear *sugra* solutions: superstrata

- Coherent condensates of the ¼-BPS *supergravity* perturbations (again exponentiating such vertex operators into the worldsheet action) yield an enormous variety of smooth supergravity solutions of the form.

$$ds^2 = -\frac{Z_5}{\mathcal{P}}\Big[(dv+\beta)\big(du+\omega - \tfrac{1}{2}\underbrace{\mathcal{F}}_{\text{momentum along } y}(dv+\beta)\big)\Big] + Z_5\, ds_\perp^2 + ds_{\mathbb{T}^4}^2$$

$\mathcal{P} = Z_1 Z_5 - Z_{AB}^2$

$u, v = t \pm y$

- The harmonic forms $Z_{1,5,AB}$, ω, β, $\mathcal{F}$, appearing in the geometry solve a hierarchy of linear equations, with each level sourced by the previous level:
  - 0^{th} level: solve for ($ds_\perp^2$ = hyperkähler ⊥ space to **NS5**'s, w/SD $d\beta$)
  - 1^{st} level: solve for (Z_I , Θ_I scalars/2-forms sourced by branes)
  - 2^{nd} level: solve for ($\mathcal{F}$ = $\mathbb{S}_y^1$ momentum, ω = ang mom 1-form)

- There are similar expressions for other supergravity fields

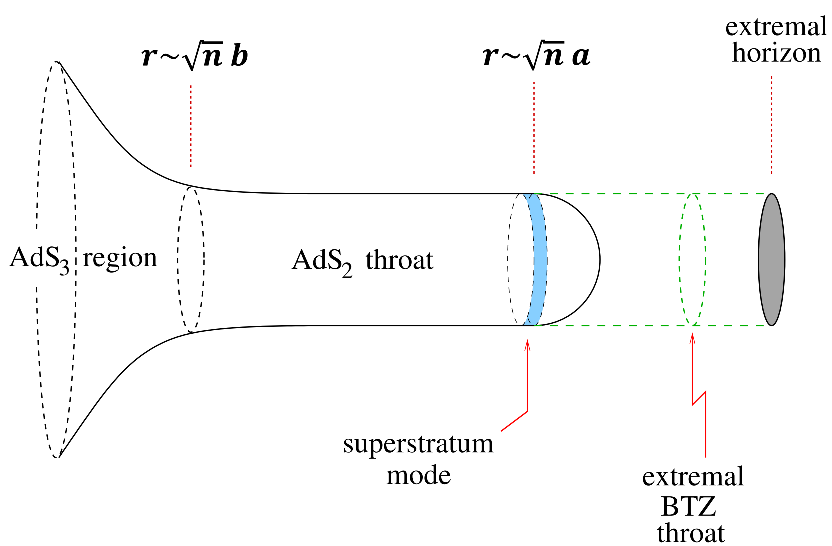
Giusto-Martucci-Petrini-Russo '15

nonlinear *sugra* solutions: superstrata

- String theory engineers smoothness of fields & absence of horizons by delicately tuning the residues of poles in harmonic forms/functions – the supergravity hair is "*coiffured*"

Bena-Giusto-Russo-Shigemori-Warner '15
Bena-Giusto-EJM-Russo-Shigemori-Turton-Warner '16,'17

- In the appropriate regime of parameters, the geometry looks like BTZ until very large redshift, where the geometry caps off, with solutions differing by the choice of superstratum momentum wave:



a **codes S^3 angular momentum**
(~radius of gyration of supertube profile)
stabilizes cap redshift/AdS_2 throat length

$\sqrt{n}\, b$ **codes AdS_3 (angular) momentum,**
stabilizes size of S^1 fibered over AdS_2

redshift along AdS_2 throat ~b/a

nonlinear *sugra* solutions: superstrata

- Superstrata have been constructed for coherent state superpositions of arbitrary combinations of supergravity wave modes

$$|\Psi\rangle = \Big(|{+}{+}\rangle_1\Big)^{N_{++}} \prod_{k,m,n,q} \Big(|m,n,q\rangle_k\Big)^{N_{kmnq}} \qquad (\, m\leq k\text{-}2q\,;\ q=0,1\,;\ n=0,1,\dots)$$

(a particular RR mode)

$$|m,n,q\rangle_k = (J^+_{-1})^{m-q}(L_{-1}+\dots)^{n-q}\Big(G^{+1}_{-1}G^{+2}_{-1}+\dots\Big)^q\,|00\rangle_k$$

for which the underlying supertube is still circular in the x^1-x^2 plane.

Bena-Giusto-Russo-Shigemori-Warner '15,
Bena-Giusto-EJM-Russo-Shigemori-Turton-Warner '16, '17
Bakhshaei-Bombini '18, Ceplak-Russo-Shigemori '18
Heidmann-Warner '19, Heidmann-Mayerson-Walker-Warner '19
Ganchev-Houppe-Warner '21
REVIEW: Shigemori 2002.01592

- 6d vector multiplet deformations associated to symmetries of $\mathbb{T}^4$ can also be constructed and BPS equations again simplify (Ceplak-Hampton-Warner '22)

Are they black holes?

- ***Superstrata are microstate geometries that can live in the part of the phase diagram where black holes are generic elements of the density of states***

- However they are atypical, coherent states of the supergravity fields

- One expects that when sufficiently perturbed, they will scramble into more generic microstates. We wish to follow this evolution as far as possible.

- The **fuzzball** paradigm posits that **all** microstates have coherent structure at the scale of the would-be horizon, *e.g.* the wavefunction of the stringy *d.o.f.*'s responsible for the entropy should have support on this scale.

- Questions:
  - How well do superstrata and other microstate geometries approximate the generic BH microstate in their structure and response to probes?
  - Can we see hints of fuzzball structure emerging in scrambling dynamics?

checks of & predictions for holography

- HHL correlators are vevs $\langle H|\mathcal{O}_L|H\rangle$ of supergravity fields with $\Delta_L \sim O(1)$ in simplest superstratum backgrounds, which have $\Delta_H \sim O(N)$

- These are BPS and can be computed on both sides of the duality, exhibiting perfect agreement. Along the way one must understand many subtleties of the AdS $\longleftrightarrow$ CFT operator map.

  Bena, Bombini, Ceplak, Chen, Galliani, Garcia I Tormo, Giusto, Heidmann, Hou, Hughes, Hulik, Kanitscheider, Monten, Moscato, Raeymaekers, Rawash, Russo, Skenderis, Taylor, Tian, Turton, Tyukov, Vasilakis, Warner, Wen

- HHLL correlators are not protected. They provide a prediction for CFT correlators at strong coupling

  Bombini-Galliani-Giusto-Moscato-Russo ’16 - ’19
  Bena-Heidmann-Monten-Warner ’19
  Bufalini-Iguri-Kovensky-Turton ‘22

- One can take a $H \rightarrow L$ limit to extract predictions for LLLL correlators that have passed several non-trivial checks

  Ceplak, Giusto, Hughes, Russo, Tyukov, Wen, ’18 - ’21

HHLL: doing a deep dive on superstrata

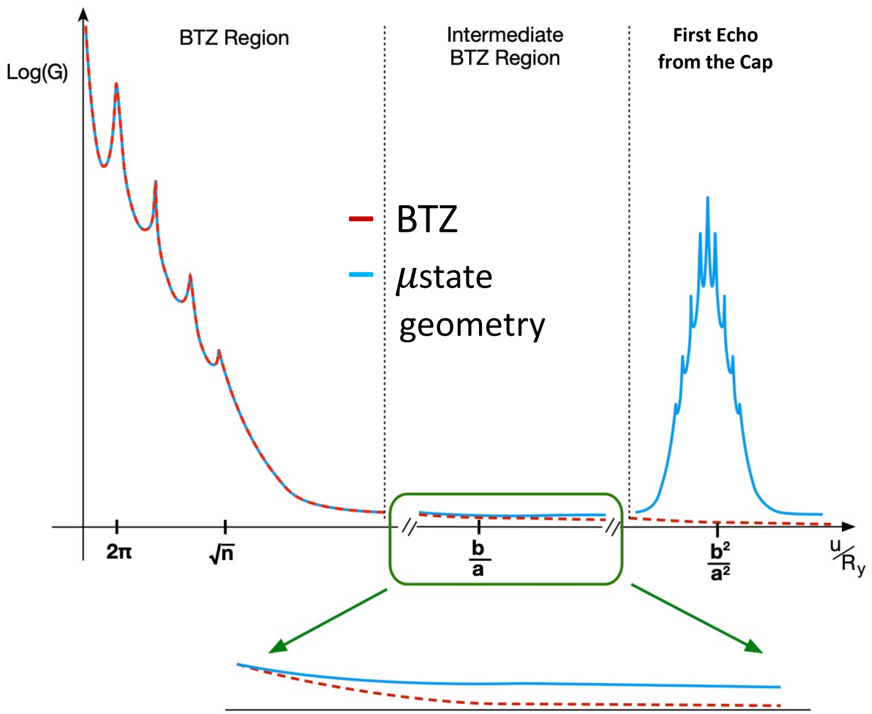
- Simple superstrata (*e.g.* single-mode $k,m,n,q = 1,0,n,0$) can have many Killing vectors: $\underbrace{\partial_{\varphi_1}\,,\quad \partial_{\varphi_2}\,,}_{S^3}\quad \underbrace{\partial_u\,,\quad \partial_v}_{AdS_3}$

- The wave equation is then separable
  (Bena-Turton-Walker-Warner '17)
  (also for BTZ x S^3, where it's group th)

- Solve the radial eq by matching WKB asymptotics at the top of the throat
  (Bena-Heidmann-Monten-Walker-Warner '19)

- Initial decay mimics BTZ QN modes

- Then naïvely get echoes due to the cap at finite redshift . . .



High-energy probes: tidal trapping

- However, this latter conclusion (that ∃ strong echoes) is a bit **too** naïve:
  - For BTZ, the geometry is locally $AdS_3 \times S^3$ everywhere; tidal forces are small everywhere
  - For superstrata, tidal forces grow large “midway” down the throat (large means string scale or greater)

Tyukov-Walker-Warner ’17, Bena-EJM-Walker-Warner ’18, Bena-Houppe-Warner ‘20, Ceplak-Hampton-Li ‘21

- Why are the tides so large? Because the capped geometry has tiny but nontrivial multipoles (absent for BTZ) whose tidal effects

$$\mathcal{A}_{\mu\nu} = \mathcal{R}_{\mu\lambda\rho\nu}\, v^{\lambda}\, v^{\rho}$$

are **amplified** by the relativistic **blueshift** of the probe’s velocity **v** as it falls down the throat

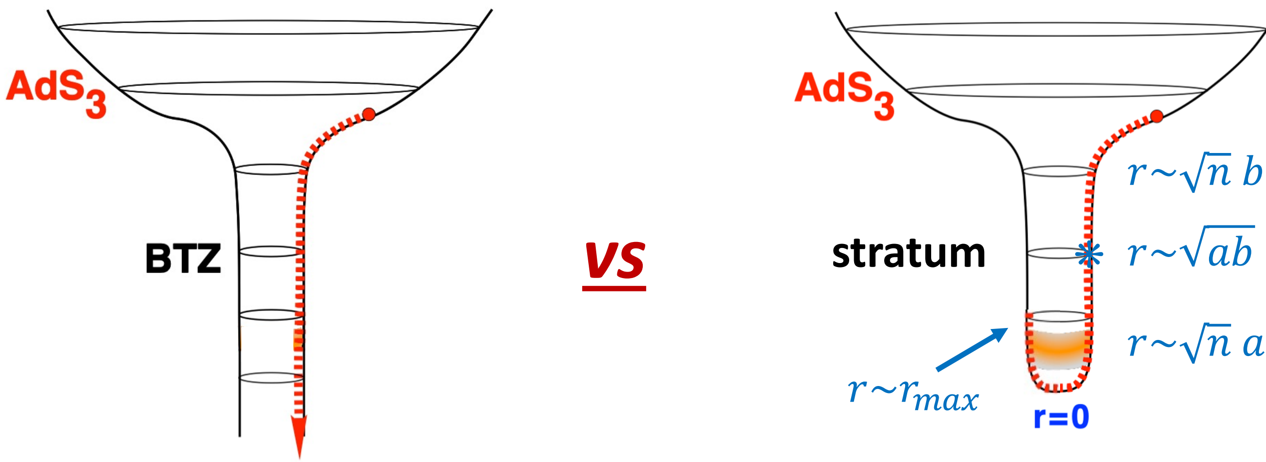
Strings, out of the blue$^{\text{(shift)}}$

- Tidal disruption diverts string probe KE into string stretching energy, trapping it in the cap:

$$r_{\max} \sim \left(n^3 a^3 b\, g_s^2\, \frac{\alpha'^2}{V_{\mathbb{T}^4}}\right)^{\frac{1}{4}}$$

(EJM-Warner '20)

- True *even for massless strings* – **any** probe falling into the throat is **absorbed** into excitations in the cap, which subsequently thermalize

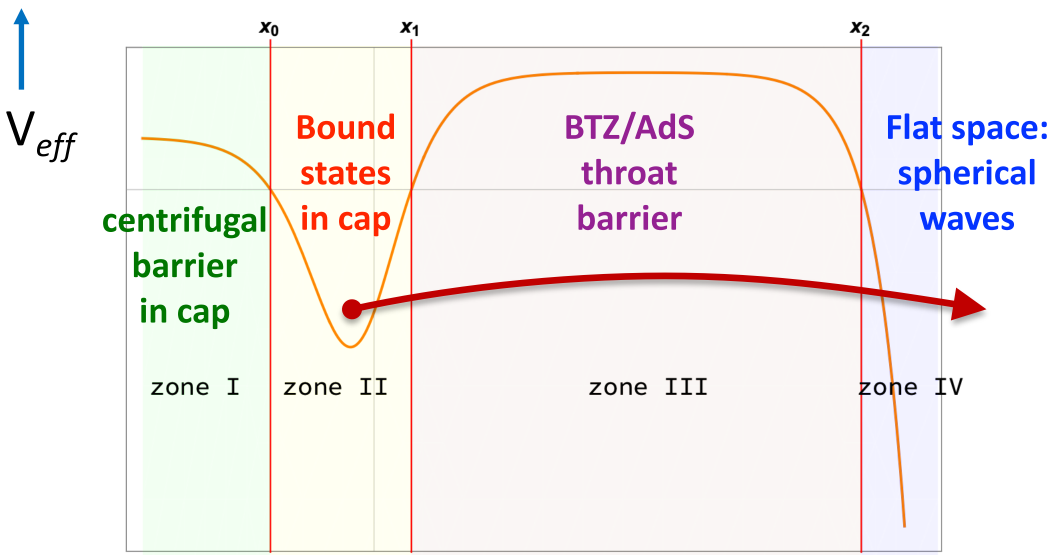


- *Scrambling time scales are still wrong (related to perturbative string scales and not gravitational phenomena), nevertheless behavior is beginning to be BH-like*

Low-energy probes: soft radiation

- Low-energy modes are trapped in the cap, but can tunnel out to the asymptotically flat region (NB: can still solve BPS eqs w/flat asymptotics)
- The wave equation in the simplest superstrata is separable; one finds an effective potential for radial modes

Chakrabarty-Ghosh-Virmani '19
Bena-Eperon-Heidmann-Warner '20



In the absence of a horizon, Hawking-like radiation is a standard tunneling process by which trapped quanta radiate into the asymptotically flat region

more generic superstrata

- While there are an enormous number of generalized superstrata, they they are not typical elements of the ¼-BPS state space:

$$S_{stratum} \sim \sqrt{n_5 n_1}\, n_p^{1/4}$$

(Shigemori ’19)

- In the perturbative limit $N_{\rm kmnq} \sim O(1)$ about the round supertube, each deformation mode matches a ¼-BPS *supergravity* vertex operator in the worldsheet construction (EJM-Massai-Turton ‘20, WiP)

- The choice of $(8\mathrm{NS}+8\mathrm{R})$ left-generic and $(2\mathrm{NS}+2\mathrm{R})$ right-BPS polarizations of the worldsheet vertex ops suggests the full extent of possible superstrata

- They seem associated to symmetries acting on individual background strings

$$\underbrace{L_{-1}\,, G^{\alpha A}_{-1/2}\,,\ J^{\alpha\beta}_{-1}}_{\text{superconf symmetry}}\,;\ \underbrace{K^{A\dot{B}}_{-1}}_{\text{vector modes}}$$

- The corresponding states in $(\mathbb{T}^4)^N/S_N$ have mostly been identified

non-susy extensions: *microstrata*

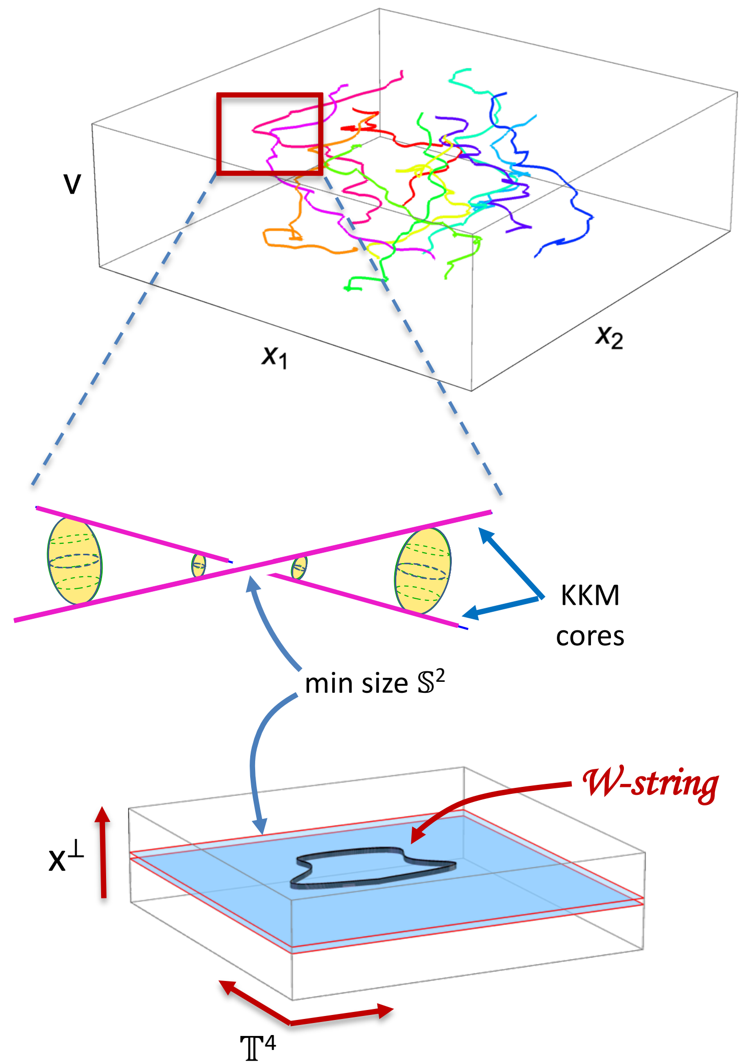
- The supergravity equations can be simplified for certain classes of non-BPS supergravity backgrounds similar to superstrata *i.e.* non-BPS gravitational waves added to the round supertube – roughly $(L_{-1})^{n+p}(\tilde{L}_{-1})^{p}|00\rangle$
- Assume a restrictive ansatz in which a limited number of $AdS_3 \times S^3$ angular harmonics participate, leading to a "consistent truncation" of the 6d equations of motion   Mayerson-Walker-Warner '20, Houppe-Warner '21
- Simplest examples involve 11 functions of one variable (roughly the AdS_3 radial coordinate) coding the various supergravity fields
- Find horizonless non-BPS solutions via perturbation theory and numerics
  Ganchev-Houppe-Warner '21, '22;   Ganchev-Giusto-Houppe-Russo '21
- Find *e.g.* frequencies of non-BPS deformations depend on their amplitudes

The breakdown of supergravity

- As discussed above, smooth supergravity solutions are associated to an "abelianized" regime of fivebrane dynamics, where the fivebrane source is well-separated in its transverse space.
- High redshifts are associated to more compact sources, with smaller radius of gyration. The "Higgsing" of non-abelian fivebrane dynamics (*i.e. little string* theory) goes away as we approach the black hole threshold
- We can see the restoration of non-abelian dynamics develop locally where the wiggly fivebrane profile develops a self-intersection . . .
- The partial restoration of non-abelian structure is manifested by the appearance of light "W-strings" of *little string theory* which are expected to be the entropic degrees of freedom in the black hole phase.
- ***Note that we are seeing all of this in the bulk gravity description of the AdS_3/CFT_2 regime***

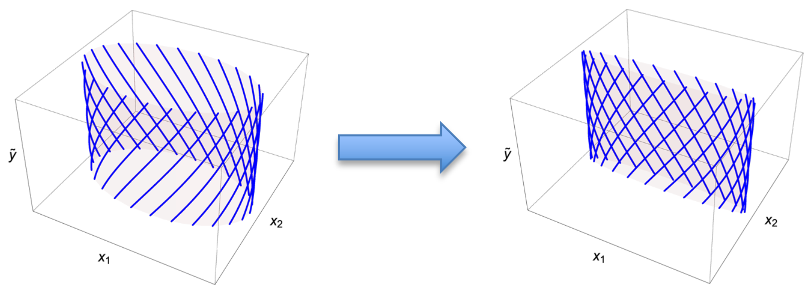
supertube singularities

- The geometry has a **KKM** core located along the contour $\mathbf{x} = F(v)$ where a fibered circle smoothly degenerates.
- Local **KKM** pairs form a minimal $\mathbb{S}^2$ that shrinks away if/where they collide
- Singularities arise when the profile $F(v)$ self-intersects; this is the manifestation of *intersecting fivebranes* in the effective geometry
- The singularity is resolved by D3-branes wrapping the vanishing $\mathbb{S}^2$. These are the *little W-strings* of nonabelian fivebrane dynamics; string perturbation theory breaks down . . .



The black hole threshold

- One can analyze the degeneration explicitly for the elliptical supertube deformation and see stretched D-branes become massless in the DBI approximation. (EJM-Massai-Turton '20)



- The analogous superstratum develops a long AdS2 throat (Ganchev-Houppe-Warner '22)

- Fivebrane intersections and the associated little string physics are expected to underly generic microstates. *As in other examples of AdS/CFT, "horizon" formation amounts to the liberation of nonabelian degrees of freedom.*

- Here we are seeing the onset of this dynamics in an explicit **bulk** realization. ***It is not clear that there is an effective geometrical picture of the interior, if these stringy modes overwhelm the gravitational degrees of freedom . . .***

a dual perspective

- The local KKM σ-model has a worldsheet-dual CFT counterpart whose superpotential

$$\mathcal{W} = \prod_{\ell=1}^{n_5} \Big(\mathsf{Z}\, e^{ik\mathsf{v}/n_5} - \mu_\ell(\mathsf{v})\, e^{\mathsf{X}} \Big)$$

***is** the string winding condensate,* in a non-compact version of CY/LG duality that generalizes the duality between the SL(2,R)/U(1) "cigar" coset and $\mathcal{N}=2$ Liouville

(Ooguri-Vafa '95, Giveon-Kutasov '99, Giveon-Itzhaki-Kutasov '16, **EJM-Massai-Turton '20**)

- **The Liouville/LG superpotential is determined by the supertube profile F(v).**
Its n_5 zeros μ_ℓ(v) code the locations of the fivebranes in their transverse space.
(This winding string condensate wavefunction vanishes at **isolated** NS5's because F1's can't fit into the throat of a single NS5, whose angular size is the string scale.)

- The degeneration of the geometry is dual to the degeneration of the Liouville/LG superpotential; the Liouville wall recedes and **F1** strings see a long throat develop, with a strong coupling region at the bottom.
(F1's **can** fit into the throat of two or more coincident NS5's.)

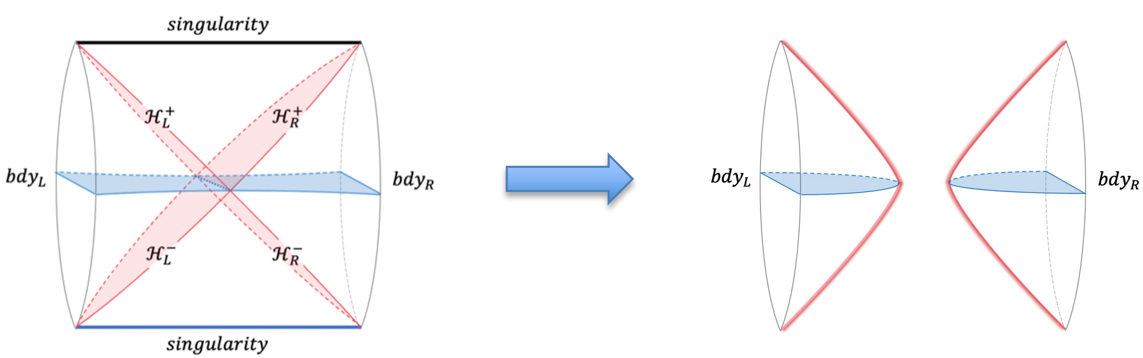
- Intersecting fivebrane profiles are again associated to lengthening probe return times, and nontrivial IR dynamics

Making the *little string* go away

- The BTZ entropy is accounted for by little string oscillations along $\mathbb{T}^4$ rather than **F1**'s bound to the cap, wiggling in all 10 dimensions. One sees this as well in the missing fractionation in the worldsheet ¼-BPS spectrum.

- One can corroborate this thesis by *eliminating* the $\mathbb{T}^4$. This eliminates little string entropy and makes a bulk *noncritical* string theory on $\mathrm{AdS}_3 \times \mathbb{S}^3_b$

- **NB: The thermofield double corresponds to an entangled string gas; *there are no black holes in the spectrum*. There are fundamentally no horizons . . .**



EPR ≠ ER

A brief correspondence course

- These models lie below a *correspondence transition* at $k_{\rm sl} = (R_{\rm AdS}/\ell_{\rm str})^2 = 1$

- Above the transition $k_{\rm sl} > 1$, the SL(2,R) invariant vacuum is normalizable, and the asymptotic spectrum is that of BTZ black holes. (Cardy '86, Strominger '97)

- For $k_{\rm sl} < 1$, the SL(2,R) invariant state is **not** normalizable, and the asymptotic density of states is saturated by long **F1** strings winding the AdS_3 azimuthal direction, rather than BTZ black holes. (Giveon-Kutasov-Rabinovici-Sever '05)

- The dual spacetime CFT is once again a deformation of a symmetric product $(\mathcal{M}^{\rm N})/S_{\rm N}$ (by a $\mathbb{Z}_2$ twist interaction that implements string interactions), but now $\mathcal{M} = \mathbb{R}_\phi \times \mathbb{S}^3_b$ describes the configuration space of **F1**'s *transverse* to the fivebranes rather than the space of little strings *internal* to the fivebranes as one has in the critical dimension (think of these as different phases for **F1**'s)

(Balthazar-Giveon-Kutasov-EJM '21)

Approximating black holes

- The highly excited quasi-bound states that best approximate black holes will be supported on symprod twisted sectors involving long cycles
- The formation and decay of these states, and the extent to which this process approximates the formation and decay of black holes, will be interesting to study if we can develop the tools. Do they trap infalling energy for extended periods of time? Level statistics? What is the chaos exponent? OTOC's? *etc.*
- There are many intriguing parallels with another non-critical string duality – that of 2d string theory and matrix QM – including **(1)** the presence of the radial direction as an explicit component of the configuration space on **both** sides of the duality; **(2)** asymptotically free dynamics; and **(3)** the *absence of black holes in the spectrum* (even though there is a region of strong coupling).
- However, the 6d dynamics is much richer than 2d noncritical string theory, and may teach us about aspects of little string theory.

Summary

- AdS_3/CFT_2 is fertile ground in which to explore gauge/gravity duality. The BPS supergravity equations are particularly tractable and yield an enormous variety of solutions, some of which closely approximate black holes in their structure and properties.

- The existence of a worldsheet formulation admitting a discretuum of exact solutions allows us to explore beyond the supergravity regime, while enriching our understanding of the supergravity regime itself.

- The worldsheet keeps track of the underlying brane constituents in the background. A *little string* picture of black hole microphysics emerges and appears to be key to understanding BTZ black hole entropy.

- Horizon formation, even in the AdS limit, is a process of liberating these nonabelian *d.o.f.*'s, suggesting that the black hole interior might not have a geometrical description. *This was always true in the CFT at weak coupling, but now we see the same physics in the gravity description…*