Black strings from TsT and irrelevant deformations

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Luis Apolo and WS, 1806.10127, 1907.03745
Luis Apolo, Stephane Detournay and WS, 1911.12359

Geometry from the Quantum, KITP, Jan 13-Jan 17, 2020

Which geometry from which quantum theory?

AdS/CFT →

Our real world:
non-AdS geometries

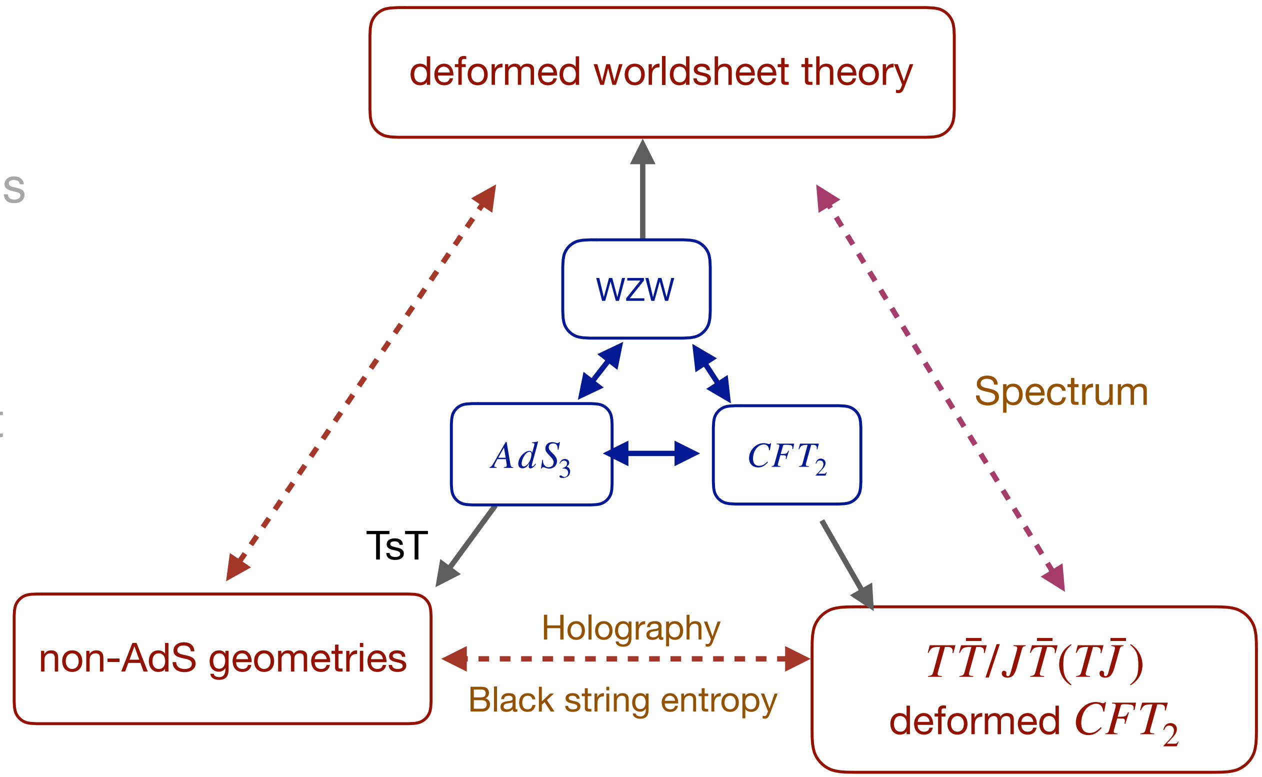
-Minkowski

-de Sitter

-Kerr

A class of toy models for non-AdS holography

- dual QFT
- supergravity
  TsT tranformations
  the vacuum
  black strings
- string worldsheet



[Zamolodchikov;Smirnov, Zamolodchikov; Cavaglia, Negro, Szecsenyi, Tateo; Cardy; Dubovsky, Flauger, Gorbenko; Dubovsky, Gorbenko, Mirbabayi; Conti, Iannella, Negro, Tateo; Frolov; …]

$T\bar{T}$ deformations

$$\frac{\partial S_{QFT}}{\partial \mu} = \int dx^2 \, (T_{xx}T_{\bar{x}\bar{x}} - T_{x\bar{x}}T_{\bar{x}x})$$

Instantaneous deformations

$$\boxed{\frac{\partial S_{QFT}}{\partial \mu} = -4 \int J_{(1)} \wedge J_{(\bar{2})}}$$

universal form for $T\bar{T}, J\bar{T}, T\bar{J}, J\bar{J}$

$$J_{(1)} = T_{xx}dx + T_{x\bar{x}}d\bar{x}, \quad J_{(\bar{2})} = T_{\bar{x}x}dx + T_{\bar{x}\bar{x}}d\bar{x}\,.$$

$$d \star J_{(m)} = 0 \Longleftrightarrow \partial_\mu(\sqrt{-g}\,T_m{}^\mu) = 0 \Longleftrightarrow \nabla_\mu T_m{}^\mu = 0$$

- spectrum on a cylinder with $(x, \bar{x}) \sim (x + 2\pi R, \bar{x} + 2\pi R)$

$$E(\mu) = -\frac{R}{2\mu}\left(1 - \sqrt{1 + \frac{4\mu E}{R} + \frac{4\mu^2 J^2}{R^2}}\right), \quad J(\mu) = J$$

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- complex spectrum at high energy ⟷ cutoff AdS_3 [McGough, Mezei, Verlinde]
- real energy for the ground state
- no bounds for temperatures
- adding a Λ_2 flow ⟷ patch of dS [Gorbenko, Silverstein, Torroba]

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subluminal sign

$6k$*: central charge of the seed CFT*

- complex energy for the ground state if $\lambda \equiv \frac{k\mu}{R^2} > \frac{1}{2}$
- density of states $S_{T\bar{T}}(E_L(\mu), E_R(\mu)) = S_{Cardy}(E_L, E_R), \quad E_{L/R} = \frac{1}{2}(E \pm J)$
- Hagedorn growth at very high energy $E(\mu) \gg \frac{R}{\mu}, \quad S_{T\bar{T}} \sim 2\pi\sqrt{2k\mu}E(\mu)$
- temperatures $T_{L/R} \equiv \left(\partial S_{T\bar{T}} / \partial E_{L/R}\right)^{-1}$, have a bound $T_L T_R \leq \frac{1}{8\pi^2 k\mu}$

In a symmetric product theory $\left(\mathcal{M}_{6k}\right)^p / S_p$, one can define *a single trace version of $T\bar{T}$ deformation* by

$$\frac{\partial S_{QFT}}{\partial \mu} = -4 \sum_{i=1}^{p} \int J^i_{(1)} \wedge J^i_{(\bar{2})}$$

The total entropy assuming the same temperature(or even distribution of energy) in each copy of the CFT

$$S_{T\bar{T}}\left(E_L, E_R\right) = \sum_{i=1}^{p} S^i_{T\bar{T}}\left(E^i_L, E^i_R\right)$$

$$= 2\pi[\sqrt{\frac{c}{6} R E_L(\mu)\left[1 + \frac{2\mu}{Rp} E_R(\mu)\right]} + \sqrt{\frac{c}{6} R E_R(\mu)\left[1 + \frac{2\mu}{Rp} E_L(\mu)\right]}\,]$$

with total central charge of the seed CFT $c = 6kp$

and total energy $E_L = \sum_{i}^{p} E^i_L$

A holographic dual proposal

[Giveon, Itzhaki, Kutasov]

(the single trace version of) $T\bar{T}$ *(deformed QFT)* $\longleftrightarrow$ *LST (little string theory)*

Evidence :

- long string spectrum on a geometry interpolating between zero mass BTZ and linear dilaton solution $\longleftrightarrow$ the $T\bar{T}$ spectrum
- charged non-rotating black holes with 1-parameter $\longleftrightarrow$ the single-trace $T\bar{T}$ entropy with zero angular momentum

Questions:

[Apolo, Detournay, WS]

- Can we find the general **rotating black hole solutions**?
- Can we find the bulk dual to the **ground state** in the deformed theory?
- For the superluminal deformation, can we find the **critical value** $\lambda_c = \dfrac{1}{2}$?
- Is there a **systematic way** to find such solutions?

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- Is there a **systematic way** to find such solutions? Yes!

TsT transformations with two global $U(1)$ symmetries along $X^1, X^{\bar{2}}$:

T-duality along X^1, then a shift $X^{\bar{2}} = X^{\bar{2}} - \#\lambda\, X^1$, and finally T-duality along X^1.

TsT is a useful solution generating technique, and usually changes the solution locally.

[Lunin-Maldacena]

In IIB string theory on $AdS_5 \times S^5$ with RR background flux,

TsT with two $U(1)$s both in AdS_5 / one in AdS_5 and the other in S^5 / both in S^5

$\Updownarrow$

non-commutative / dipole / β deformations

A conjecture

[Apolo, Detournay, WS]

In IIB string theory $AdS_3 \times \mathcal{N}$ with NSNS background flux,

TsT with two $U(1)$s both in AdS_3 / one in AdS_3 and the other in $\mathcal{N}$ / both in $\mathcal{N}$

$\Updownarrow$

single trace $T\bar{T}$ / $J\bar{T}(\,T\bar{J}\,)$ / $J\bar{J}$ deformations

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A conjecture [Apolo, Detournay, WS]

In IIB string theory $AdS_3 \times \mathcal{N}$ with NSNS background flux,

patch of extremal Kerr [Chakraborty, Giveon, Kutasov;Apolo, WS]

TsT with two $U(1)$s both in AdS_3 / one in AdS_3 and the other in $\mathcal{N}$ / both in $\mathcal{N}$

$\Updownarrow$ [Guica]

single trace $T\bar{T}$ / $J\bar{T}(T\bar{J})$ / $J\bar{J}$ deformations

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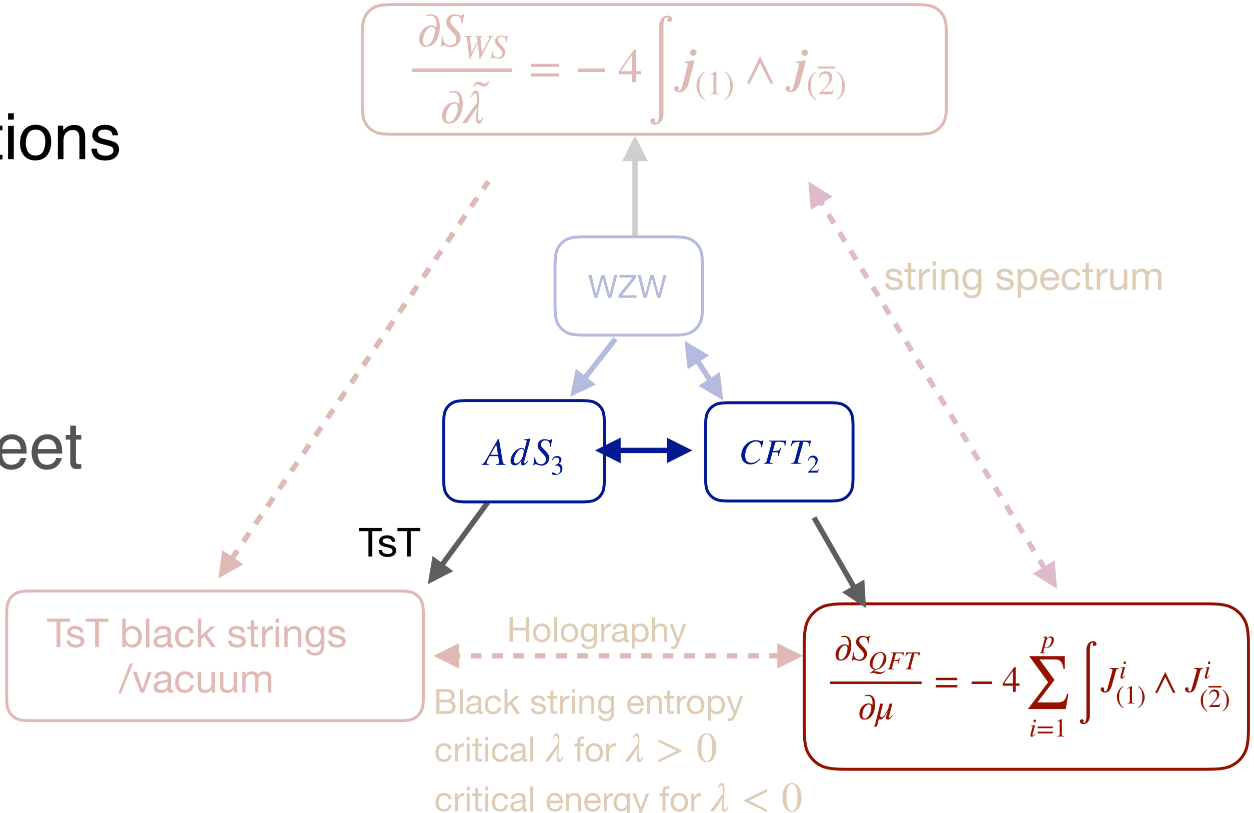

A two parameter family of classical solutions in IIB SUGRA with NSNS fluxes in string frame

$$d\tilde{s}_3^2 = \ell^2 \left\{ \frac{dr^2}{4\left(r^2 - 4T_u^2 T_v^2\right)} + r du dv + T_u^2 du^2 + T_v^2 dv^2 \right\},$$

$$e^{2\tilde{\Phi}} = \frac{k}{p}$$

k → *# of NS5 branes, magnetic charge*

p → *# of NS1 branes, electric charge*

$$(u, v) \sim (u + 2\pi, v + 2\pi)$$

The holographic dictionary

- coordinates $u \leftrightarrow x, \quad v \leftrightarrow \bar{x};$
- gravitational Noether charge of $\partial_u \leftrightarrow$ Noether charge of ∂_x

$$\mathcal{Q}_{\partial_u} = \frac{1}{2}(M + J) = \frac{c}{6}T_u^2 \leftrightarrow E_L$$

- global AdS_3, $(T_u = T_v = \frac{i}{2}) \leftrightarrow$ ground state on the cylinder, NS vaccum
- zero mass BTZ($T_u = T_v = 0) \leftrightarrow$ Ramond vacuum
- The Bekenstein-Hawking entropy $\leftrightarrow$ Cardy formula in the dual CFT_2

- symmetric product CFT $\left(\mathcal{M}_{6k}\right)^p / S_p$ [Argurio, Giveon, Shomer; Eberhardt and M. R. Gaberdiel]

- Brown-Henneaux central charge $c = 6pk$
- T_u, T_v : parameters for the states

stationary solutions dual to the single trace $T\bar{T}$ deformed CFT_2 can be obtained from the solution via the following TsT transformations:

T-dualize along u, shifting $v \to v - \frac{2\lambda}{k} v$, and T-dualizing along u once more

$$\frac{ds_3^2}{\ell^2} = \frac{dr^2}{4\left(r^2 - 4T_u^2T_v^2\right)} + \frac{r du dv + T_u^2 du^2 + T_v^2 dv^2}{1 + 2\lambda r + 4\lambda^2 T_u^2 T_v^2} \qquad (u, v) \sim (u + 2\pi, v + 2\pi)$$

$$e^{2\Phi} = \frac{k}{p}\left(\frac{1 - 4\lambda^2 T_u^2 T_v^2}{1 + 2\lambda r + 4\lambda^2 T_u^2 T_v^2}\right) e^{-2\phi_0}$$

A quick look at the phase space

- TsT black strings for $T_u^2 \geq 0, T_v^2 \geq 0$, horizon $r_+ = 2T_uT_v$
- $T_u = T_v = 0, \phi_0 = 0$, the LST background of [Giveon, Itzhaki, Kutasov]
- conical defects for general $T_u^2 < 0, T_v^2 < 0$,
- smooth and geodesic complete solution exist

stationary solutions dual to the single trace $T\bar{T}$ deformed CFT$_2$ can be obtained from the solution via the following TsT transformations:

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SUGRA EOMs allow

- *ϕ_0: arbitrary constant*
- *the B field is up to an exact term*

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The ground state can be obtained by assuming $T_u^2 = T_v^2 \equiv -\rho_0^2, \quad \rho_0 > 0$ and requiring smoothness at the origin. After a change of coordinate, the metric is

$$ds_3^2 = \ell^2 \left\{ \frac{d\rho^2}{\rho^2+1} + \frac{\rho^2 d\varphi^2 - \left(\rho^2+1\right) dt^2}{1+2\lambda\rho^2} \right\}$$

$$\rho \in [0,\infty), \quad \varphi \sim \varphi + 2\pi$$

$$\rho_0 = \frac{1}{2\lambda}(1-\sqrt{1-2\lambda})$$

$$B = -\frac{\ell^2\left(\rho^2+\rho_o\right)}{2(1+2\lambda\rho^2)} du \wedge dv, \quad e^{2\Phi} = \frac{k}{p}\frac{\left(1-2\lambda\rho_o^2\right)}{2\rho_o\left(1+2\lambda\rho^2\right)} e^{-2\phi_0}$$

- $\lambda > \frac{1}{2}$ complex solution;
- $\lambda_c = \frac{1}{2}, \ e^{2\Phi} \to 0$ unless ϕ_0 is fine tuned, infinitely weak string coupling everywhere
- $0 < \lambda < \frac{1}{2}$, smooth and real solution
  IR: $\rho \to 0$, global AdS_3 , smooth, no horizons
  UV: $R^{1,1} \times S^1$, locally flat with linear dilaton, infinitely weak coupled strings
- $\lambda < 0$, CTC and curvature singularity at $\rho_c^2 = 1/2|\lambda|$

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TsT/$T\bar{T}$ matching: $\ell \leftrightarrow R, \quad \lambda\ell_s^2 \leftrightarrow \mu$
Noether charges $\mathcal{Q}_{\partial_u} \leftrightarrow E_L^{vac}$

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Black strings $T_u, T_v > 0$, asymptotic to $R^{1,1} \times S^1$ at large radius.
Horizon at $r_+ = 2T_uT_v$, independent of λ
Electric and magnetic charges $Q_e = pe^{2\phi_0}, \quad Q_m = k$

TsT/$T\bar{T}$ dictionary for $\phi_0 = 0$, i.e. fixed Q_e, Q_m

- Noether charges $\mathcal{Q}_{\partial_u} \leftrightarrow E_L$
- smooth Euclidean geometry at the horizon $\leftrightarrow$ torus parameters $(u, v) \sim \left(u + i/\ell T_L, v - i/\ell T_R\right)$
- Bekenstein Hawking entropy $\leftrightarrow$entropy of single trace $T\bar{T}$

$$S_{TsT} = 2\pi\{\sqrt{\mathcal{Q}_{\partial_u}\left(Q_eQ_m + 2\lambda\mathcal{Q}_{-\partial_v}\right)} + \sqrt{\mathcal{Q}_{-\partial_u}\left(Q_eQ_m + 2\lambda\mathcal{Q}_{\partial_u}\right)}\} = S_{T\bar{T}}$$

- $T_u = T_v = \dfrac{i}{2\lambda}(1 - \sqrt{1 - 2\lambda})$ $\leftrightarrow$ ground state, NS vacuum
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- upper bound for the temperatures by requiring real dilaton

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Horne-Horowitz black string

- *reparameterization of the radial coordinates*
- $\lambda = \frac{1}{2}, T_u = T_v, \phi_0 = 0$
- $B_{HH} = B_{TsT} + \frac{\ell^2}{2} du \wedge dv$

The effect is a shift of the zero energy point proportional to the the electric charge

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Horne-Horowitz black string

- $\lambda = \dfrac{1}{2}, T_u = T_v, \phi_0 = 0$
- $B_{HH} = B_{TsT} - \dfrac{\ell^2}{2} du \wedge dv$

The effect is a shift of the zero energy point proportional to the the electric charge

Giveon-Itzhaki-Kutasov black string

- $\lambda = \dfrac{1}{2}, T_u = T_v$
- $B_{GIK} = B_{TsT} + \dfrac{\ell^2}{2} du \wedge dv$
- ϕ_0 *depends on temperature*
- $\mathcal{Q}_{\partial_t} \leftrightarrow E_L$
- Q_e *varies with the mass, and the* $T\bar{T}$ *temperature is not the Hawking temperature*

How about $\lambda < 0$?

- CTC & conical singularity at large radius

- real dilaton $\leftrightarrow$ real spectrum

$$T_u T_v \leq \frac{1}{2|\lambda|} \leftrightarrow E(\mu) \leq \frac{pR^2}{2|\mu|}$$

"=" when the horizon coincides with the CTC & conical singularity

- the vaccum is always a real solution with CTC & conical singularity at $\rho^2 = 1/2|\lambda|$

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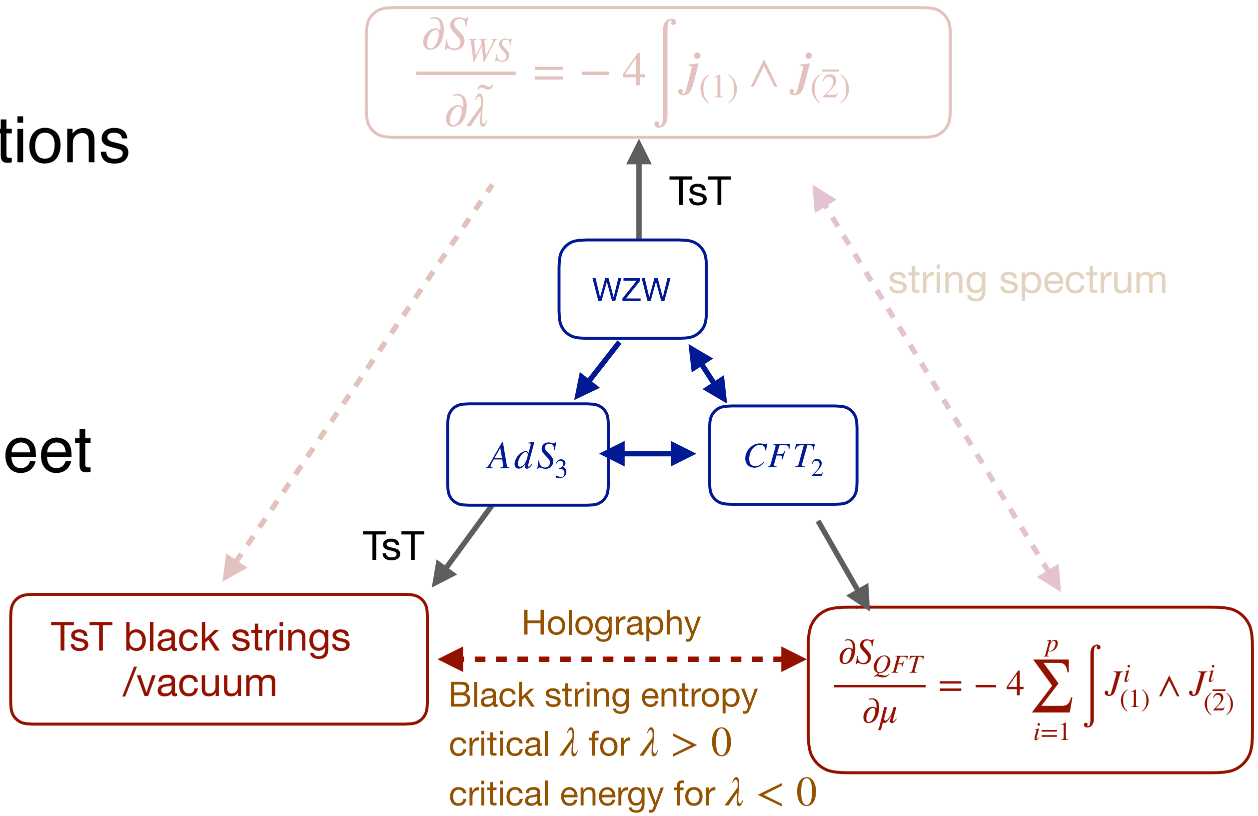

TsT transformations: T-duality along X^1, then a shift $X^{\bar{2}} = X^{\bar{2}} - 2\tilde{\lambda}\, X^1$, and finally T-duality along X^1

string worldsheet deformation $$\frac{\partial S_{WS}}{\partial \tilde{\lambda}} = -4 \int \boldsymbol{j}_{(1)} \wedge \boldsymbol{j}_{(\bar{2})}$$

-true for any consistent background
-not necessarily chiral/anti-chiral

$\boldsymbol{j}_{(1)}, \quad \boldsymbol{j}_{(\bar{2})}$ *are* **worldsheet** *Noether 1-forms associated to* ∂_{X^1}*, and* $\partial_{X^{\bar{2}}}$

Noether charges $p_{(m)} \propto \oint \boldsymbol{j}_m$

---

dual quantum field theory $$\frac{\partial S_{QFT}}{\partial \mu} = -4 \sum_{i=1}^{p} \int J^i_{(1)} \wedge J^i_{(\bar{2})}$$

$J_{(1)}, \quad J_{(\bar{2})}$ *are the* **boundary spacetime** *Noether 1-forms associated to* ∂_{X^1}*, and* $\partial_{X^{\bar{2}}}$

Noether charges $P_{(m)} \propto \oint J_m$

After the TsT, string spectrum on a cylinder can be obtained by two observations:

1. Before the TsT, string spectrum on a cylinder with
$\oint \partial_\sigma u = 2\pi w, \quad \oint \partial_\sigma v = 2\pi w$ can be obtained from zero winding by "spectral flow" with parameter w [Maldacena,Ooguri]

2. TsT on the WS⇔ field redefinition: [Alday]
string solutions on new background with periodic b.c.
$\Longleftrightarrow$ strings on the old background with twisted boundary conditions depending on the momentum $p_{(1)}, p_{(\bar{2})}$.
assuming $j_{(1)}/j_{(\bar{2})}$ to be chiral/antichiral up to total derivative terms (satisfied for the WZW model)
$\Longleftrightarrow$ momentum dependent "spectral flow"

The final string spectrum on a cylinder after TsT can hence be obtained from string spectrum on a cylinder before TsT with a momentum dependent "spectral flow". Comparing the Virasoro constraints can give us the relation between the spectrum before and after the TsT. This relation is just the $T\bar{T}/J\bar{T}(T\bar{J})$ spectrum [Apolo, WS;Apolo, WS; Apolo,Stephane,WS;]

A class of toy models for non-AdS holography

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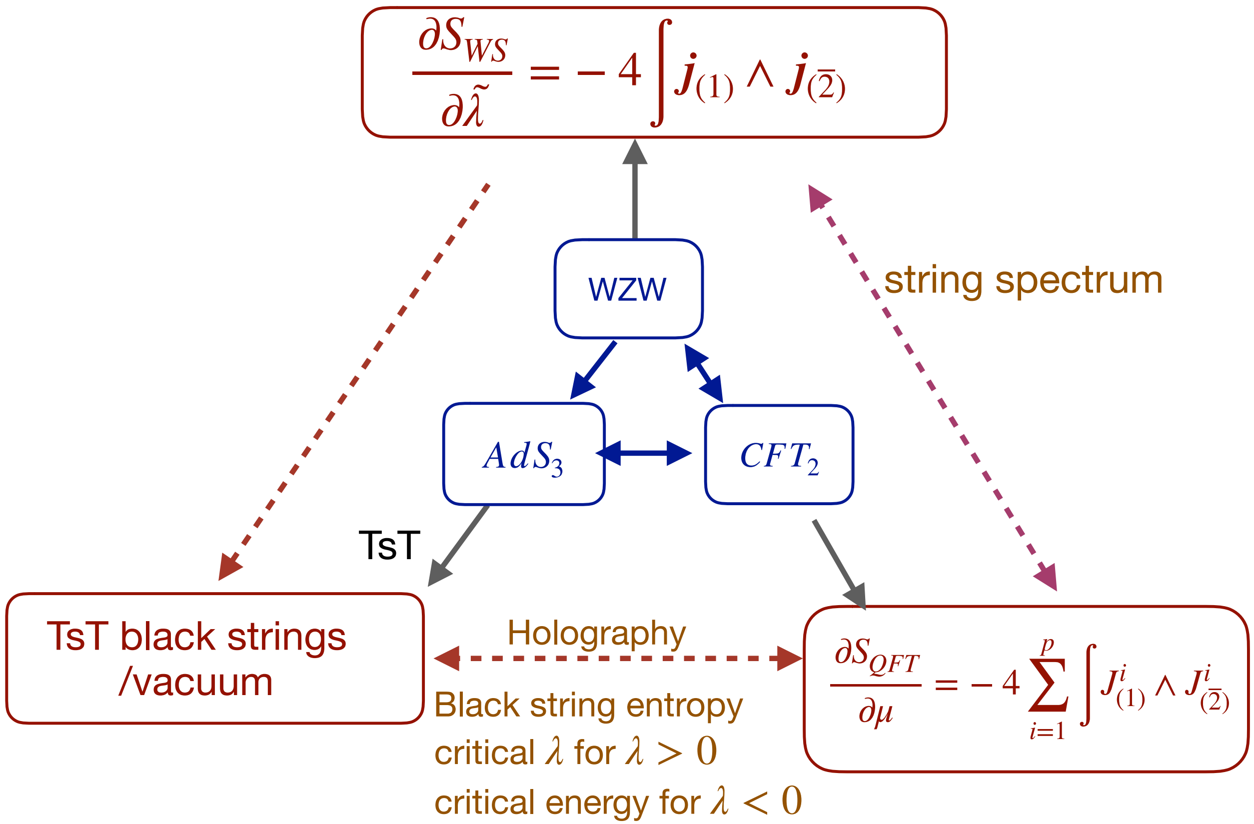

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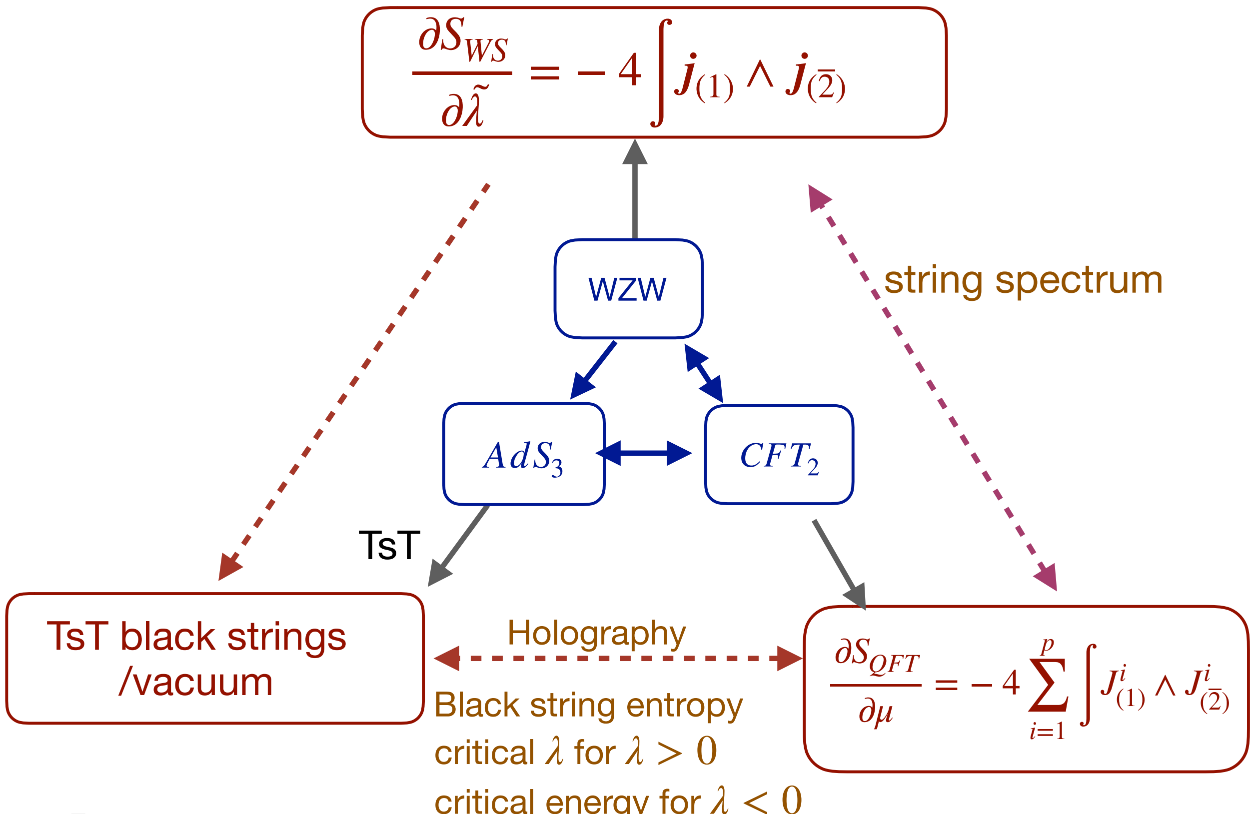

Thank you !