A playground for black hole evaporation from type IIB string theory

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@ “Geometry, Strings and the Swampland”

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Work in progress with
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Outline

- Motivations

- Introduction

  What is new with black hole evaporation?

- Higher dimensional construction of evaporating black holes.

  Karch-Randall models of "double holography"

- String Theory uplifts and study of island surfaces

  N=4 3d SCFT in type IIB and holographic dual backgrounds

Motivations

Black hole physics raise puzzles that cannot be addressed in classical General Relativity

BHs

Origin of black hole microstates

- String/M-theory microstates
  [Strominger, Vafa, '96]
  [Maldacena, Strominger, Witten, '97]
- AdS/CFT entropy matching
  [Benini, Hristov, Zaffaroni '15]

(Unitarity of) black hole evaporation

- No remnants
  [WGC, Swampland program, FL bound..]
- Page curve
  [Page, '93,'13][Penington, '19]
  [Almheiri,Engelhardt,Marolf,Maxfield, '19]

Investigate constraints/examples on evaporating black holes from String Theory

[Mathur '09, Almheiri, Marolf, Polchinski, Sully, '12]

Entanglement and black hole evaporation

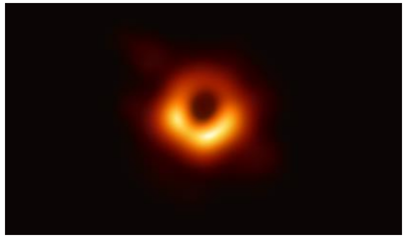
Quantum field theory in a black hole background, is in equilibrium with the BH at temperature $T_H = \frac{\kappa}{2\pi}$

First law: $T_H \, dS_{BH} = dM - \Phi dQ$

Bekenstein-Hawking entropy: $S_{BH} = \frac{k_B c^3}{\hbar} \frac{Area}{4G_N}$

$|\psi_1\rangle \otimes |\psi_2\rangle \otimes \ldots \otimes |\psi_n\rangle$ $\longrightarrow$

t = 0



t

$\longrightarrow$ Radiation state

t = +∞

The evolution is *Unitary* $\Rightarrow$ At every time *t* the state is in a *pure state*

How can a far away observer (that can measure properties of the infalling matter) retrieve information from Hawking radiation?

Entanglement and black hole evaporation

Initial state: infalling quantum matter

Pure quantum state

$$\rho = |\psi\rangle\langle\psi|$$

Black hole state +
Hawking radiation

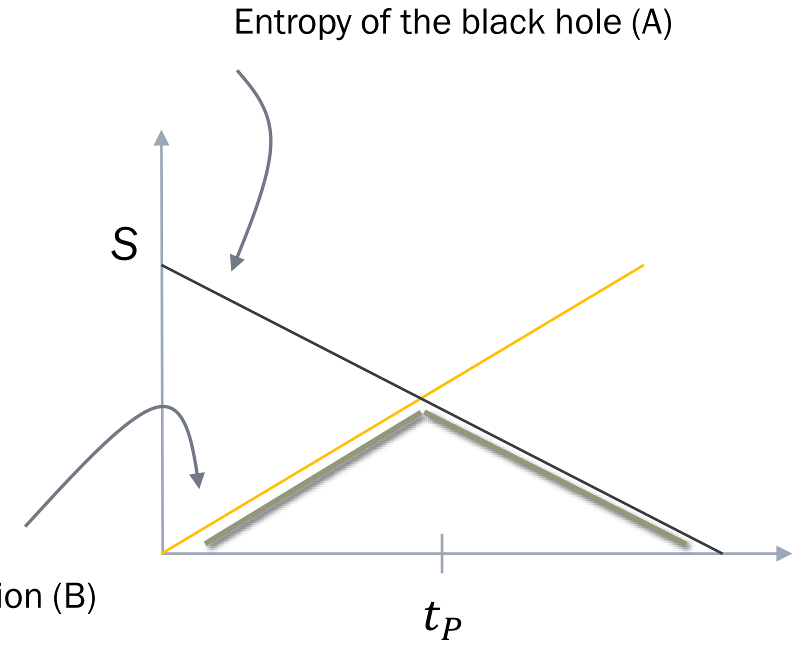
$$B = A^C$$

The information is in the entanglement of the radiation with the black hole interior

$$\rho_B = \mathrm{tr}_A\, \rho$$

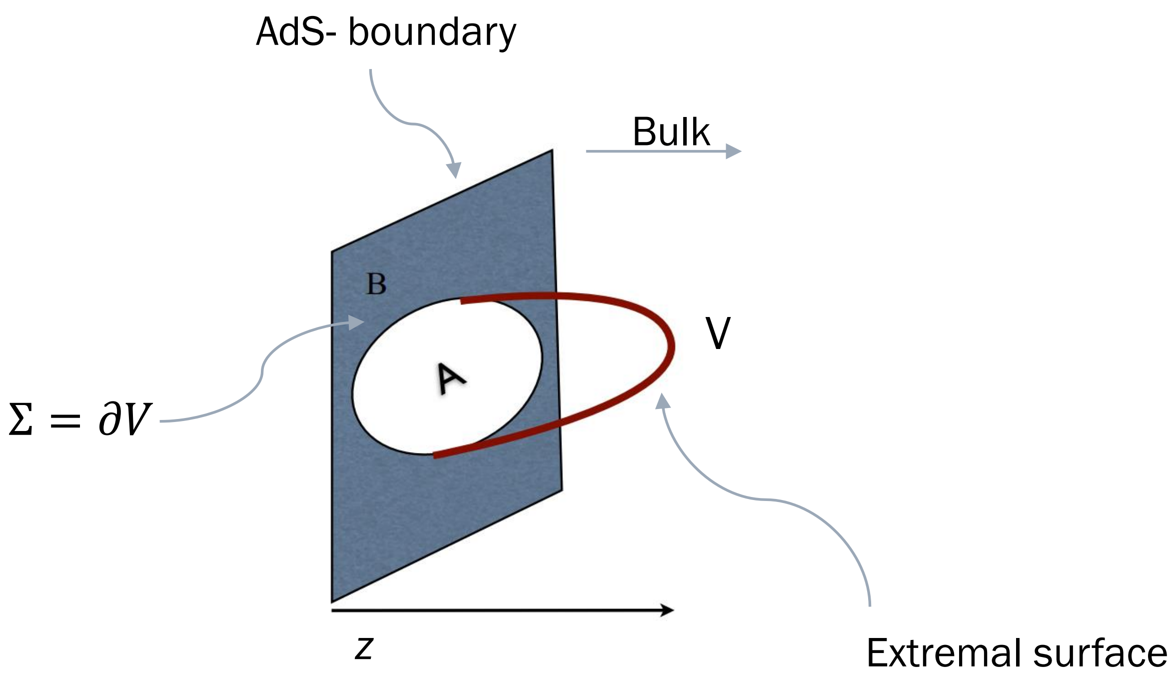
$$S_{VN} = S_B = -\,\mathrm{tr}\, \rho_B \log \rho_B$$

Is the Von Neumann, or *Entanglement entropy.*
If the system is in a pure state $S_A = S_{A^C}$



Entanglement and black hole evaporation

How to compute the entanglement entropy of Hawking particles during evaporation?



$$S_{EE} = \text{ext}\ \frac{A_V}{4G_N}$$

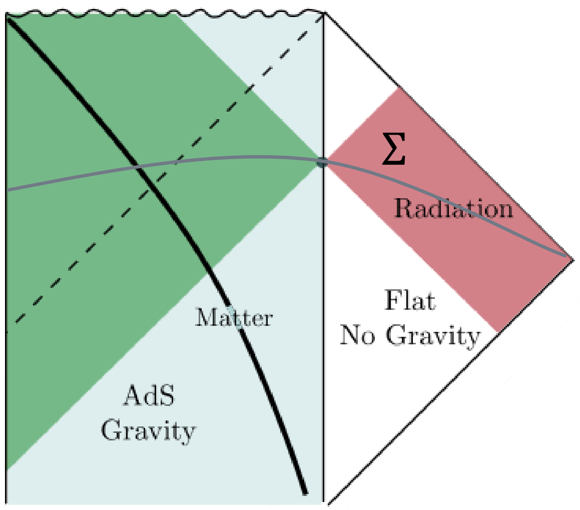
$$S_{EE} = \text{ext}\left\{\frac{A_V}{4G_N} + S_{QFT}(\Sigma)\right\}$$

[Ryu, Takayanagi ’06]
[Faulkner, Lewkowycz, Maldacena, ‘13]
[Engelhardt, Wall, ‘14]

Entanglement and black hole evaporation

How to construct the holographic setup?

Idea: Couple AdS black hole to an external heat bath

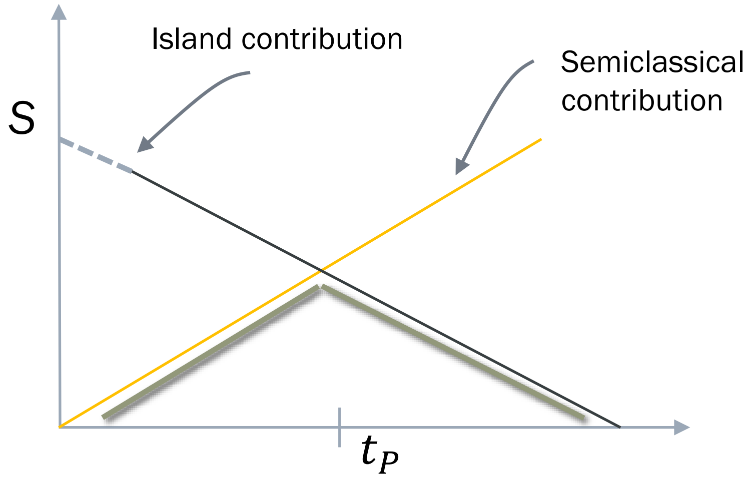


- Transparent boundary conditions on AdS
- Radiation is collected in a non-gravitational region, a holographic CFT
- The entanglement of the radiation is computed holographically according to the generalized entanglement entropy formula.

Quantum Extremal Islands

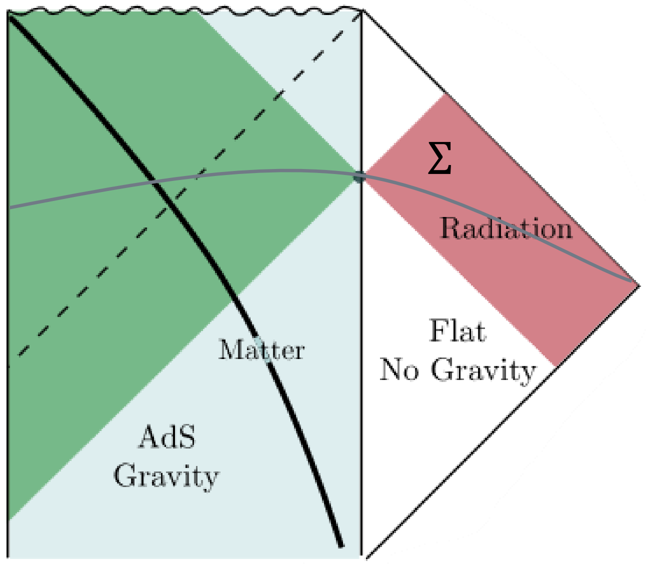
[Almheiry, Mahajan, Maldacena, Zhao, '19-'20]

$$S_{rad} = \min_X \ \{ \text{ext}_X \left[\frac{\text{Area}(X)}{4G_N} + S_{semi-class}(\Sigma_{rad} \cup \Sigma_{island})\right]$$



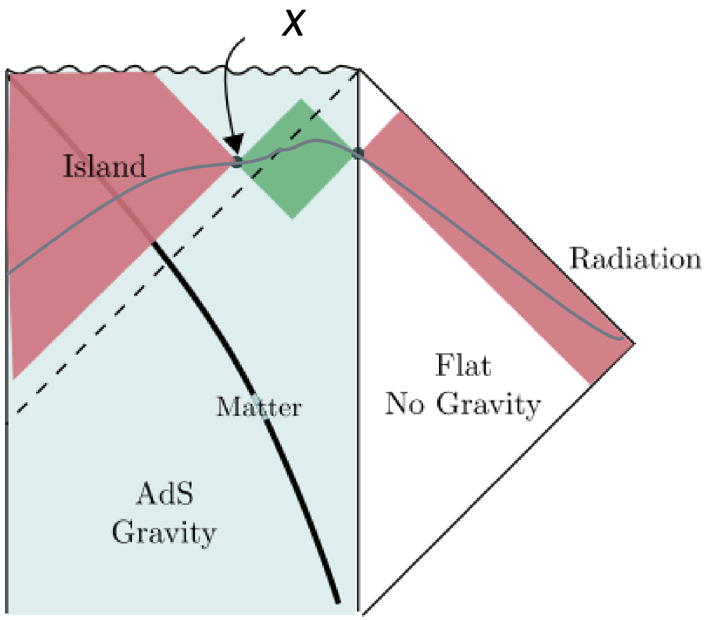
Early times:

The entanglement entropy of the radiation comes from the Σ (red) spacetime region, far away from the black hole



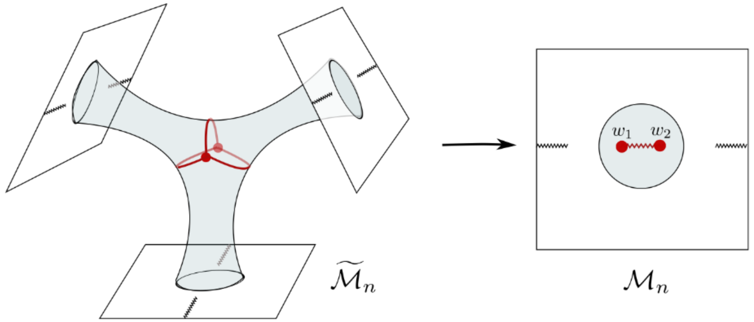
Late times:

Due to the presence of an island, the entanglement of radiation also comes from a spacetime region *inside* the black hole horizon



Lower dimensional results

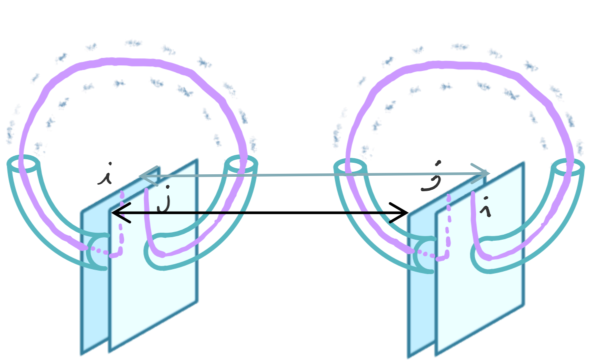
Explicit computations from gravity using replica geometries in *lower dimensional examples*



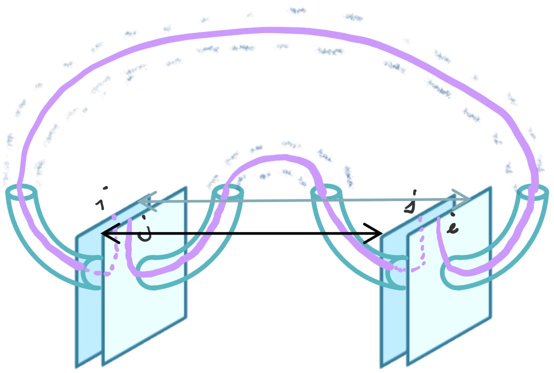
JT gravity coupled to conformal matter in 2D from string theory and SYK model
[Almheiri et al., '19]
[Penington et al., '19]

Gravitational interpretation of islands contribution as new gravitational saddle points: Wormhole geometries?

[Saad, Shenker, Stanford, '18-'19]
[Penington, Shenker, Stanford, Yang, '19]
[Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini, '19]
[McNamara, Vafa, '20]
And Thomas' talk,,



$\mathrm{Tr}\,[\rho^2] \ll \mathrm{Tr}[\rho]^2$

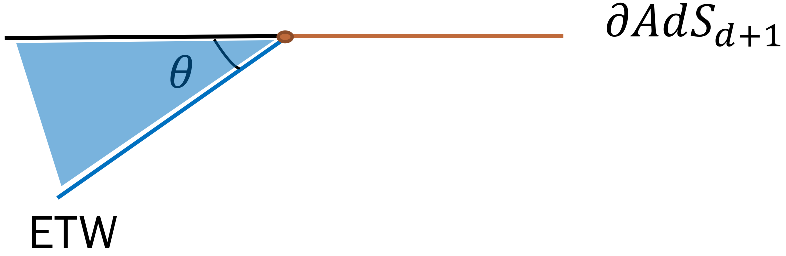


$\mathrm{Tr}\,[\rho^2] \approx \mathrm{Tr}[\rho]^2$

Transparent boundary conditions

Karch-Randall setup

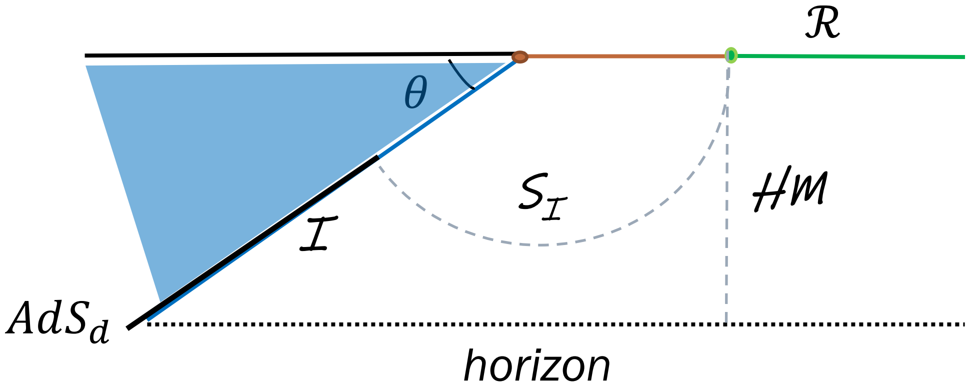
d-dim CFT coupled to a *d-1* conformal defect



a *d*-dim CFT coupled to a graviton in AdS_d with transparent boundary conditions to a *d*-dim CFT on half $\mathbb{R}^{1,d-1}$

Doubly holographic models

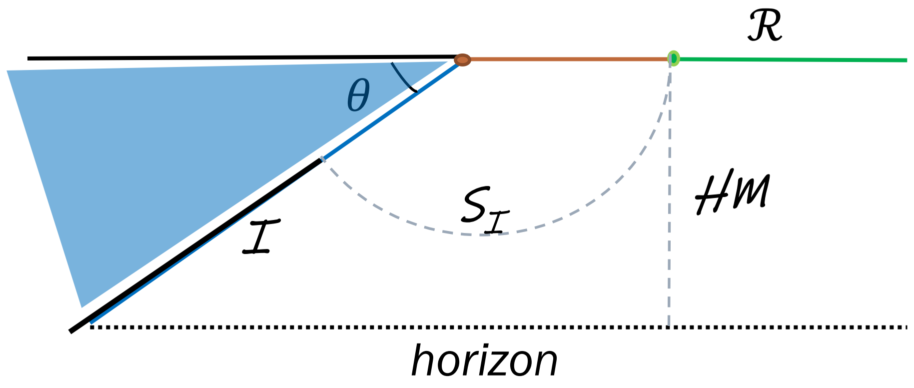
Geometrization of entanglement islands



[Karch,Randall, ‘00]
[Takayanagi, ‘11]

Black hole evaporation in higher dimensions

[Almheiri, Mahajan, Santos, '19]
[Geng,Karch '20]
[Geng,Karch,Perez-Pardavila,Raju,Randall '20-'21]
[Uhlemann '21]

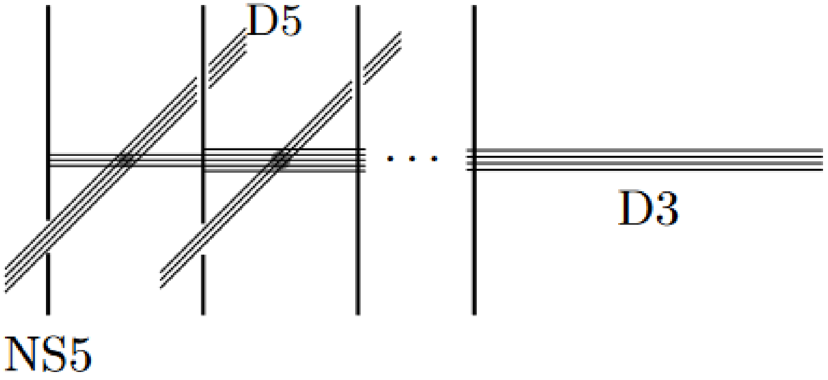


- The Hartman-Maldacena surface is one holographic surface that grows in time because it follows nice slices
- The angle of the ETW brane drives the existence of islands surfaces
- As $\theta \to 0$ the islands surfaces do not contribute to the entanglement entropy
- Requires a massive graviton

String theory uplift

[D'Hocker, Estes, Gutperle '07&'07]
[Aharony, Berdychevsky, Berkooz, Shamir, '11]
[Assel, Bachas, Estes, Gomis, '11]
[Bachas, Lavdas, '18]
[Uhlemann, '21]

UV complete realization of Karch-Randall setup from type IIB



[Uhlemann, '21]

$4d\ N = 4\ SYM$

$3d\ N = 4\ SCFT$

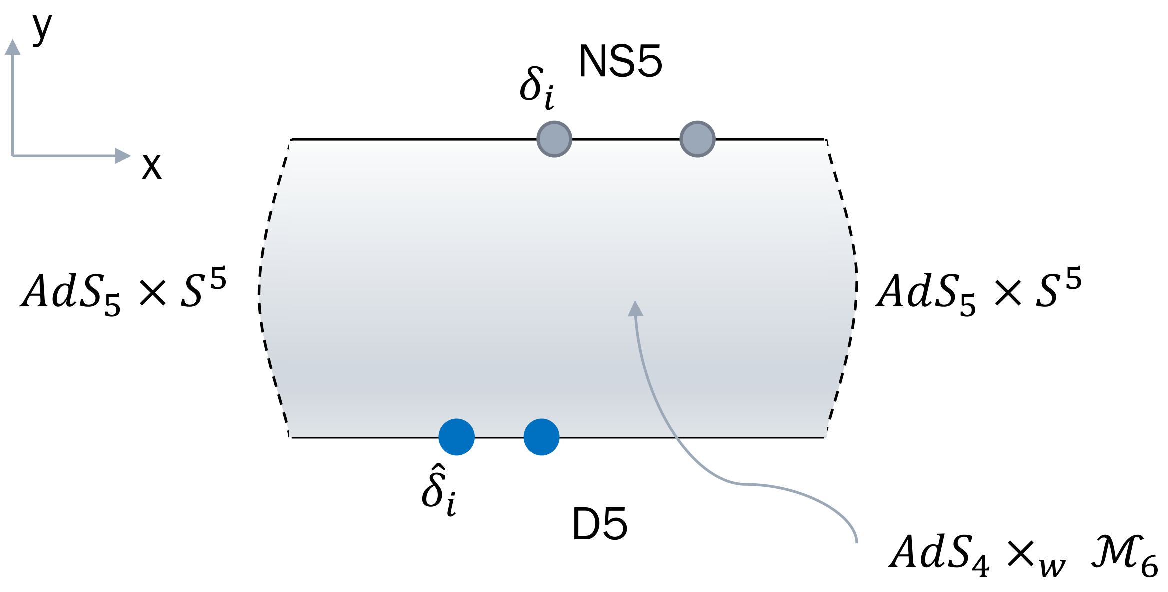
10d supergravity solutions with a region

$$AdS_4 \times_w \mathcal{M}_6$$

$$S^2 \times S^2 \times \Sigma$$

(x, y)

String theory uplift



10d supergravity solution

$$ds^2_{(10)} = L_4^2\, ds_4^2 + f^2\, ds^2_{S^2} + \hat{f}^2\, ds^2_{\hat{S}^2} + 4\,\rho^2 dz\, d\bar{z}$$

and fluxes $\mathrm{H}_3\,, \mathrm{F}_3\,, \mathrm{F}_5\,, \mathrm{e}^{\phi}$

For Janus solutions the parameters β and $\hat{\beta}$ are related to the dilaton variation

$$\delta\phi = \beta - \hat{\beta}$$

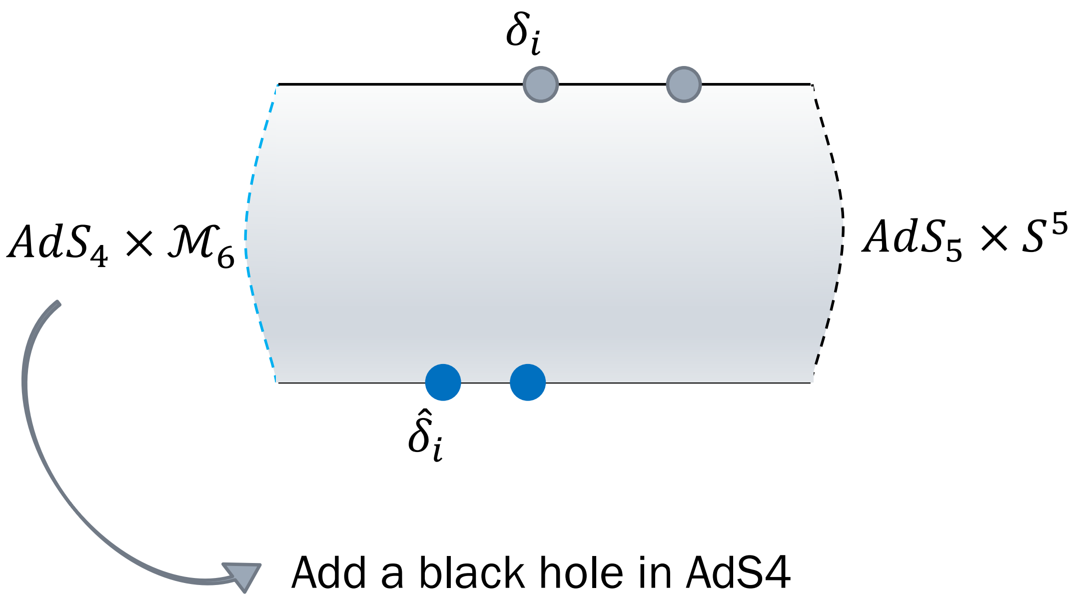
$$h = -i\alpha \sinh(z-\beta) - \sum_{a=1}^{N} \gamma_a \log\tanh\left(\frac{i\pi}{4} - \frac{z}{2} + \frac{\delta_a}{2}\right) + c.c.$$

$$\hat{h} = \hat{\alpha}\cosh(z-\hat{\beta}) - \sum_{b=1}^{\hat{N}} \hat{\gamma}_b \log\tanh\left(\frac{z}{2} - \frac{\hat{\delta}_b}{2}\right) + c.c.\,.$$

The AdS_5 regions can be capped off smoothly in supergravity

String theory uplift

$$\alpha e^{\beta} \to 0\,, \qquad \hat{\alpha}\, e^{\hat{\beta}} \to 0\,,$$
$$\alpha\, e^{-\beta} = c \qquad \hat{\alpha}\, e^{-\hat{\beta}} = \hat{c}$$



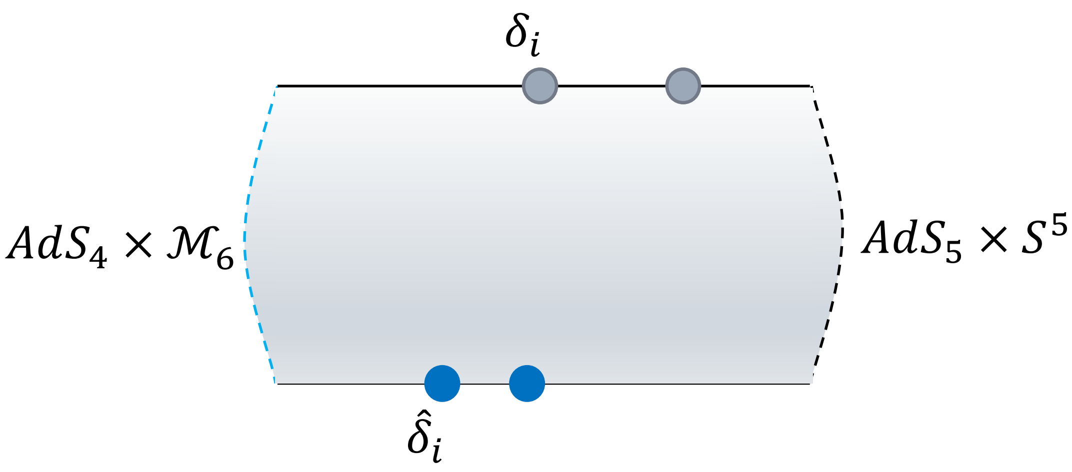
Realizes the set up of a black hole in AdS_4 radiating in the AdS_5 region to a non-gravitating bath
However, we are not in a thin brane approximation.

The left region caps off as $\quad e^{\phi_{-\infty}} \to +\infty$

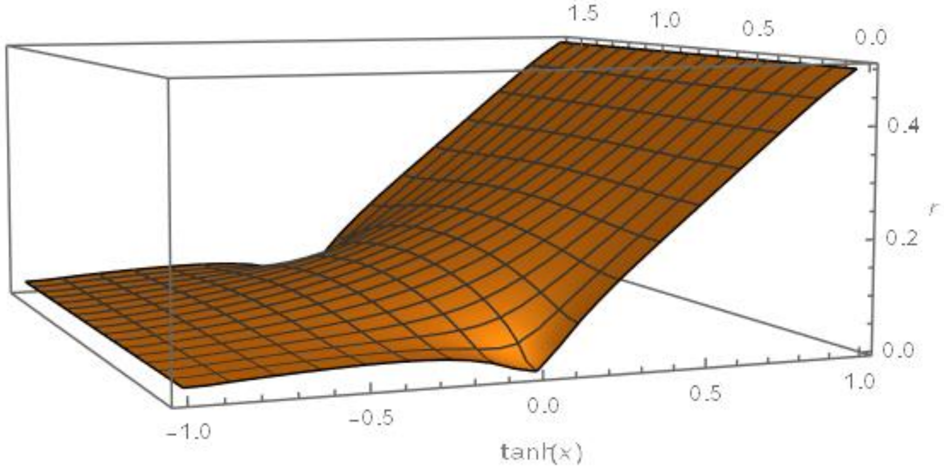
$$h = -ice^{z} - \sum_{a=1}^{N} \gamma_a \log\tanh\left(\frac{i\pi}{4} - \frac{z}{2} + \frac{\delta_a}{2}\right) + c.c.$$
$$\hat{h} = \hat{c}e^{z} - \sum_{b=1}^{N} \hat{\gamma}_b \log\tanh\left(\frac{z}{2} - \frac{\hat{\delta}_b}{2}\right) + c.c$$

[Aharony, Berdychevsky, Berkooz, Shamir, ‘11]
[Assel, Bachas, Estes, Gomis, ‘11]
[Demulder, AG, Ioannis, Lüst, wip]

Islands surfaces in the type IIB setup



- Put a black hole in the AdS_4 region
- Look for the extremal surface:
  - Wraps S^2, $\hat{S}^2$, $\mathbb{R}^2$ coordinates on AdS_4 and on Σ it is parametrized as $r(x, y)$
  - Area functional $S_\gamma = \int L_\gamma$
  - Extremization $\frac{\delta L}{L} = 0$

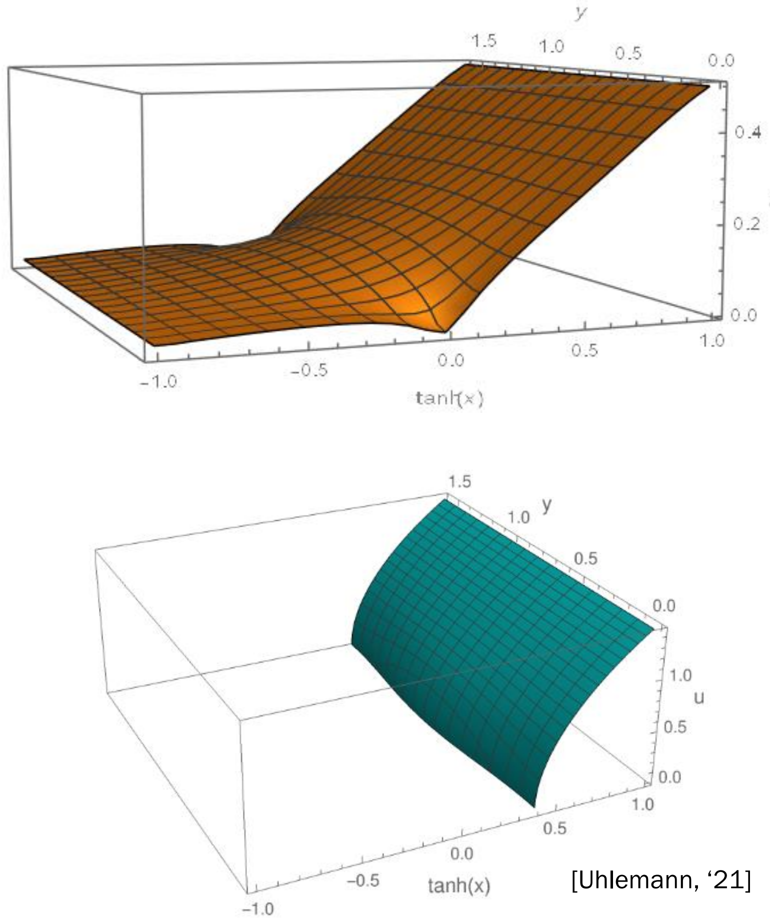


$$ds_\gamma^2 = e^{2r} f_4^2 ds^2_{\mathbb{R}^2} + f_1^2 ds^2_{S_1^2} + f_2^2 ds^2_{S_2^2} + 4\rho^2(dx^2 + dy^2) + \frac{f_4^2}{b(r)}\left(dx\, \partial_x r + dy \partial_y r\right)^2$$

Islands surfaces in the type IIB setup

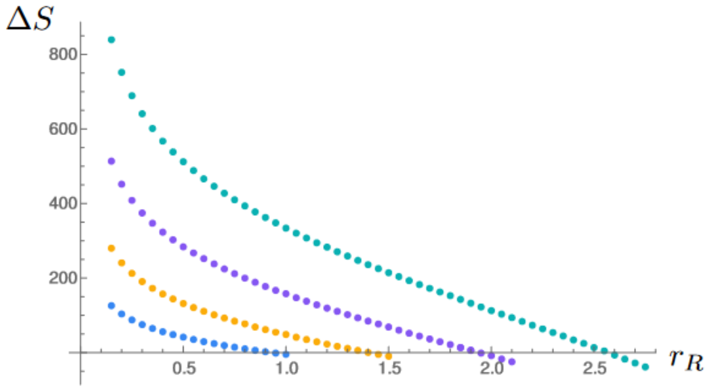
[Uhlemann, ‘21]
[Demulder, AG, Lavdas, Lüst, wip]

Comparison between the area of the island surface and the area of HM surfaces



[Uhlemann, ‘21]

At early times, HM surfaces dominates, at late times the islands dominate.



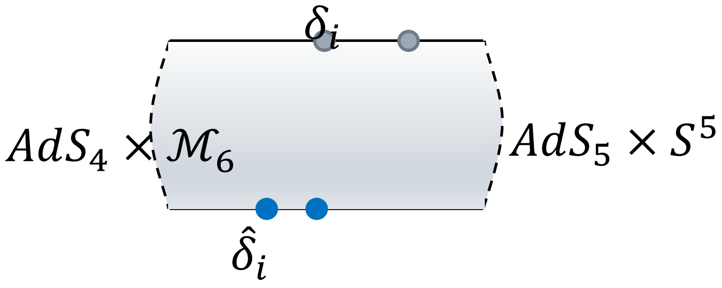
[Uhlemann, ‘21]

Introduce an additional variation of the dilaton between the left AdS4 and the right AdS5 region. What is the effect of a $\delta\phi \neq 0$?

Islands surfaces in the type IIB setup

The behaviour of the QEI is governed by the ratio

$$k = \frac{ND3_{susp}}{ND3_{semi-\infty}} \sim \frac{F_3}{F_4}$$

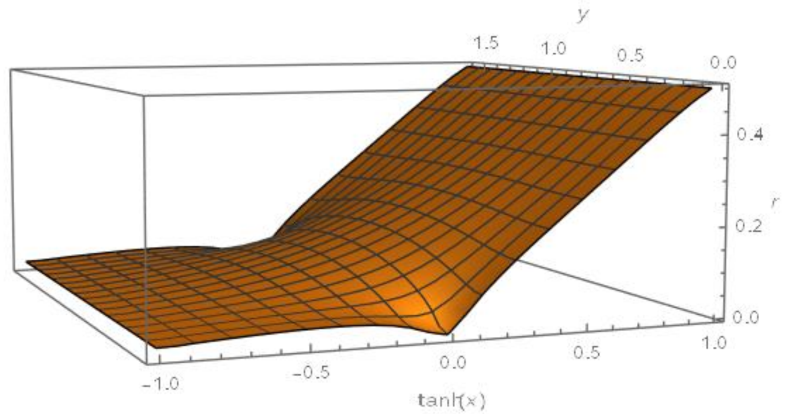


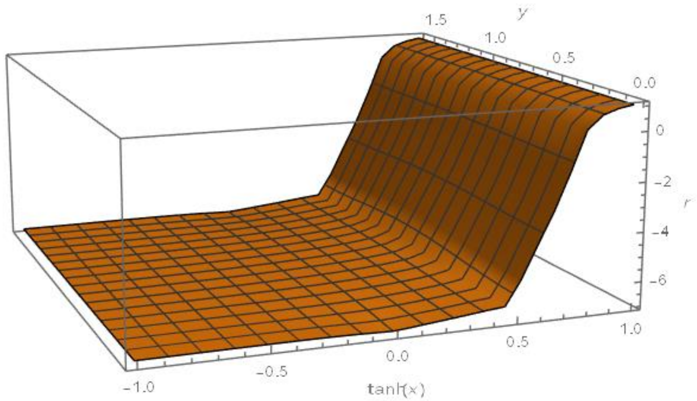
k governs the ration between the 3d BCFT dof with respect to the 4d CFT ones:

ETW brane tension $\quad k \leftrightarrow \theta^{-1}$

Critical brane tension in KR models → Critical value of **k** for the existence of islands

As we increase k the surface tends to settle on the horizon





Massive graviton

Transparent boundary conditions means energy leaking from AdS

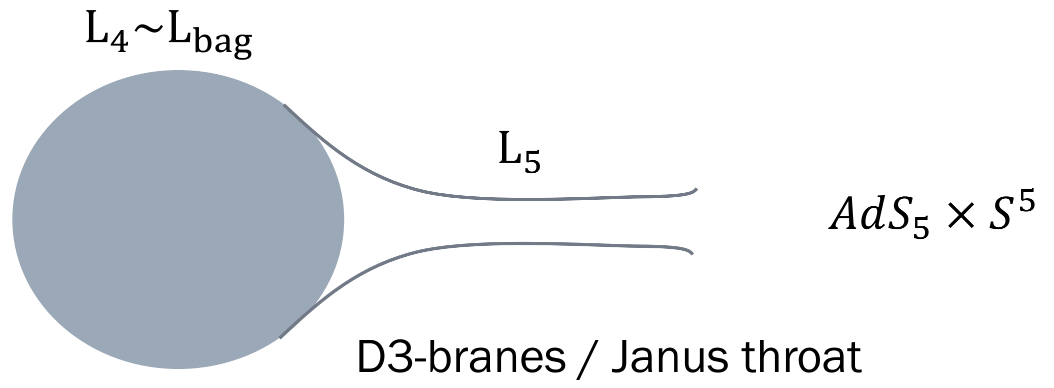
$$\partial_a T^{ab} \neq 0 \qquad \Delta\,(\Delta - d) = m^2\, L^2_{AdS_{d+1}} \qquad \Delta = 3 + \epsilon$$

Weak dissipation if the 3d dof are much larger than the 4d CFT ones: $N_{3d} \gg N_{4d}$

Set up a hierarchy of scales that allows the study of the spin 2 field Laplacian on $AdS_4 \times \mathcal{M}_6$

No scale separation

$AdS_4 \times \mathcal{M}_6$ geometry

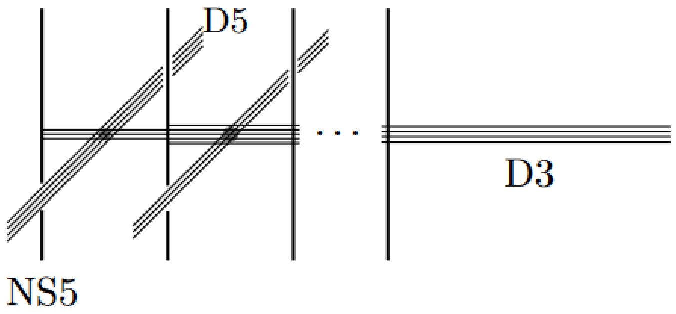


$$\frac{L_5}{L_4} \ll 1$$

[Bachas, Estes, ‘11]
[Bachas, Lavdas, ‘18]

Massive graviton

Translates to branes parameters



$$m^2 L_4^2 \sim \left(\frac{L_5}{L_{bag}}\right)^8$$

Modified by a varying dilaton

$$m^2 L_4^2 \sim \left(\frac{N_{D3\infty}}{N_{D3\,fin}}\right) \sim k^{-1}$$

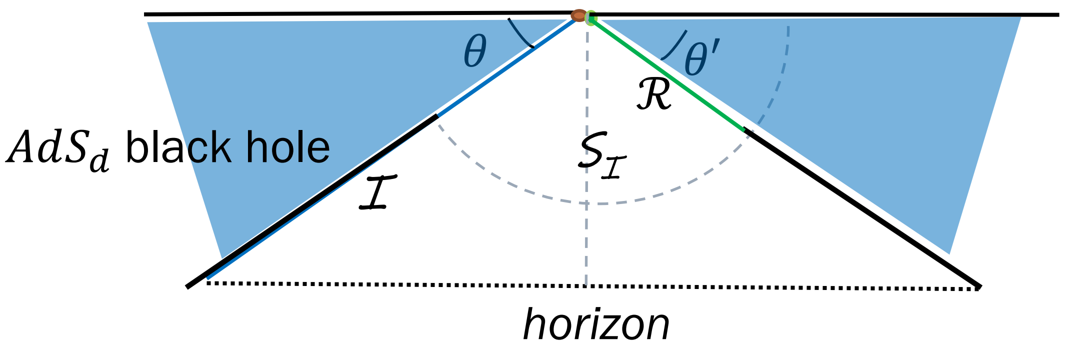
$$m^2 L_4^2 \sim \left(\frac{L_5}{L_{bag}}\right)^8 J(cos\delta\phi)$$

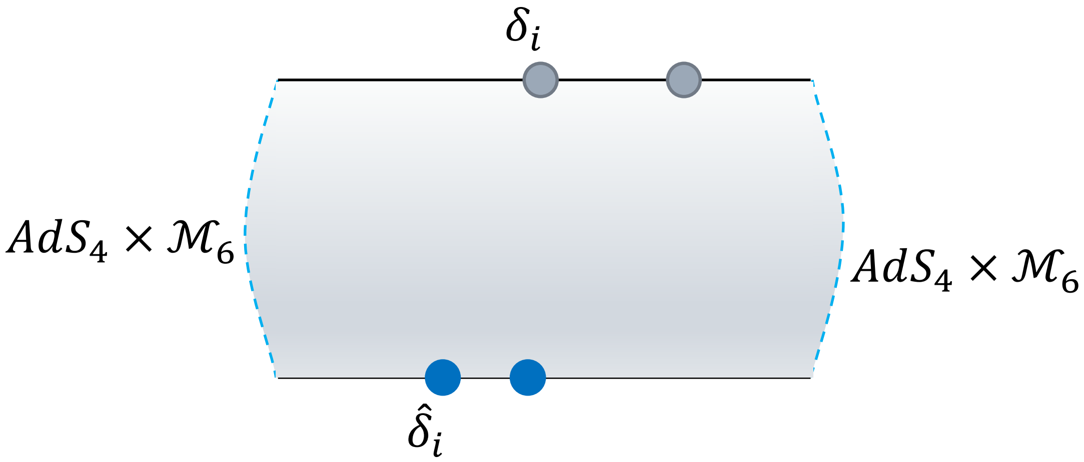
Require $k \ll 1$ for the treatment of small graviton mass

$$k \sim \theta^{-1}$$

- Tuning the mass of the graviton to zero is a decoupling limit of the two CFT (3d and 4d)
- This is analogous to the KR setup for $\theta \to 0$

Coupling to a gravitating bath





If the radiation region has also dynamical gravity,
one cannot easily separate local dof in separate regions

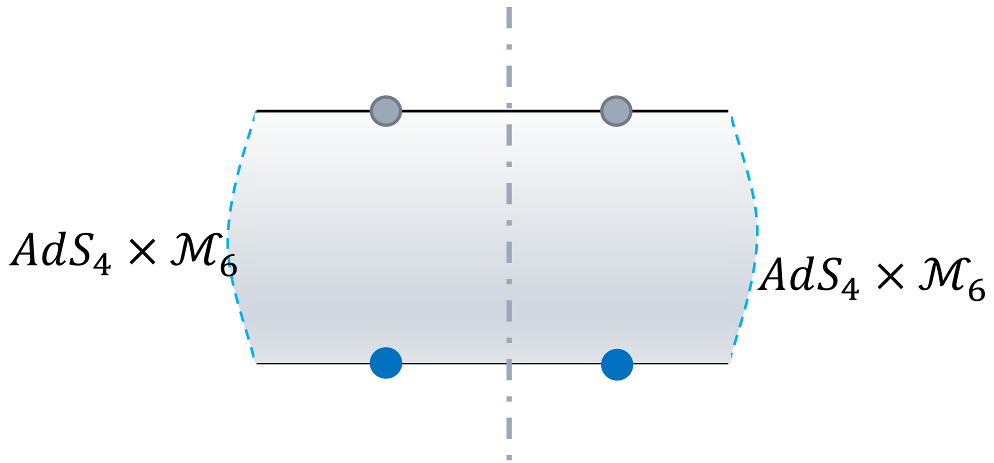
The surfaces cannot anchor at an AdS_5 region, instead of Dirichelet bc - now one imposes Neumann bc but then minimal surfaces settle completely on the horizon, in accordance with the expectation from KR setup, where no Page curve is expected for gravitating bath.

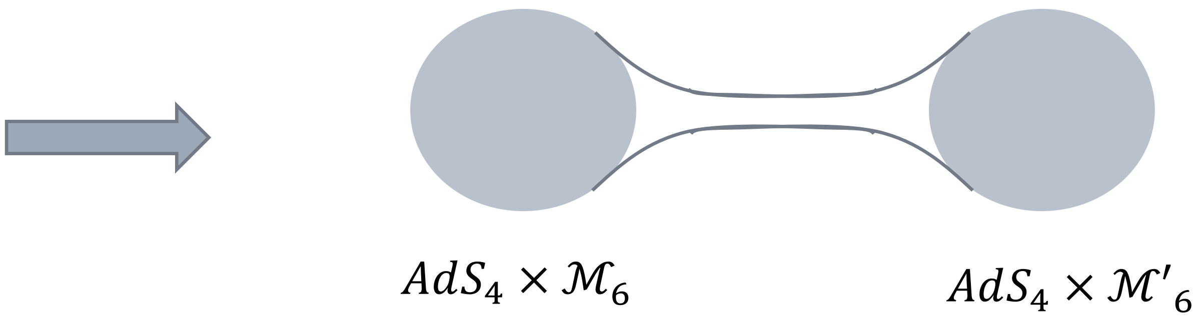
Define new quantities that follows the Page curve?

[Geng,Karch,Perez-Pardavila,Raju,Randall '20-'21]

Factorization limit

Start from the compact geometry and create a pinching by moving the branes far from each other





- Two black holes radiating in a common radiation region
- Quiver factorization
- Two different critical “angles” ?

Summary and Outlook

- A higher dimensional setup to study black hole evaporation
- Type IIB uplift allows to explicitly compute entanglement surfaces
- Entanglement surfaces can dominate over the EE from nice slices (HM surfaces)
- Constructing a background with varying dilaton can affect the behaviour of the islands surfaces

To do..

- Understand the critical value where islands settle at the horizon
- Extend to backgrounds with varying dilaton
- Compare the contribution of the island surface to the HM surface in more generic cases
- Graviton mass from KR and from type IIB
- Quantify the break down of the “Hawking picture” in the computation of radiation entropy


THANK YOU!