Islands and light gravitons in type IIB string theory

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Motivations

- Unitary black hole evaporation a crucial problem in understanding gravitational interactions coupled to quantum fields
- Exploiting holography would require a system in anti de Sitter, which in general is in equilibrium with radiation in the AdS box
- Obtain evaporation by *coupling* the black hole to a bath where gravity is not dynamical
- Quantum corrected formula for holographic entanglement entropy

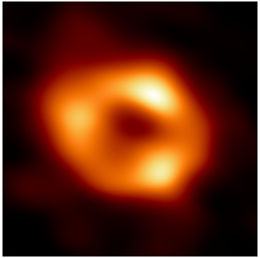


fig. from EHT (CC)

Entanglement entropy and Page curve

Each subsystem is described by a reduced density matrix
$\rho_A = \mathrm{Tr}_B \rho$

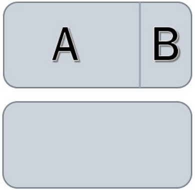
$$S_A = -\mathrm{Tr}\rho_A \log \rho_A$$

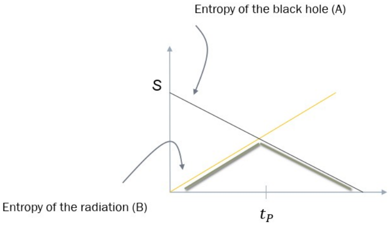
System B is the complement of A: $B = A^C$

$$S_A = S_B$$

For a pure system: $S = S_{AB} = S_{AA^C} = 0$

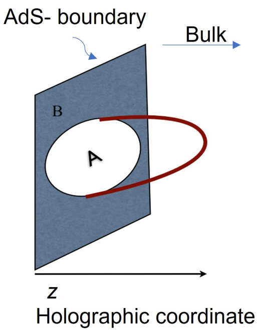
Black hole radiation is in a pure state at the end of evaporation: $S_{EE} = 0$





Holographic entanglemente entropy

Can we quantify the EE of radiation and prove it follows a Page curve?



$$S_{EE} = \frac{Area(\gamma)}{4G_N}$$

[Ryu,Takayanagi '06][Hubeny,Rangamani,Takayanagi '07]

Quantum corrections lead to *new contributions* to EE
$\rightarrow$ A new kind of extremal surfaces *behind* the horizon

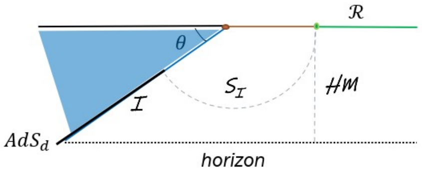
$$S_{rad} = \min_I \left\{ \text{ext}_I \left[\frac{Area(\partial I)}{4G} + S_{QFT}[\Sigma_{rad} \cup I] \right] \right\}$$

[Faulkner, Lewkowicz, Maldacena '13][Engelhardt, Wall '14][Penington '19][Almheiri,Engelhardt,Marolf,Maxfield '19]

Higher dimensional realizations

[Almheiri, Mahajan, Santos, '19][Chen, Myers, Neuenfeld & Reyes, Sandor '20] [Geng, Karch '20]
[Geng, Karch, Perez-Pardavila, Raju, Randall '20-'21]

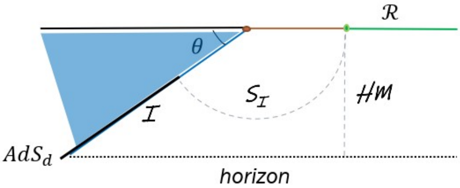
Double holographic setup:



- Gravity in AdS_{d+1} bulk with an EOW brane cutting the boundary in half
- d-dim CFT coupled to a $d-1$-dim conformal defect
- d-dim CFT coupled to gravity on AdS_d, with transparent boundary conditions coupled to a d-dim CFT on half of $\mathbb{R}^{1,4}$.

  $\rightarrow$ Geometrization of the islands

Karch-Randall braneworlds



- Transparent boundary conditions induce a graviton mass
- The brane tension is maximal against the boundary of AdS_5
- Critical angle needed to localize gravity on the AdS_4 brane

$$\theta \quad \leftrightarrow \quad m_g$$

- Maybe a graviton mass is required in higher dimensional islands setups..

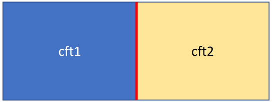
  [Geng, Karch, Perez-Pardavila, Raju, Randall '21]

$\rightarrow$ *Microscopic realization in string theory*

Conformal defects and holographic interfaces

[Erdmenger, Guralnik, Kirsch '02]

[Aharony, DeWolfe, Freedman, Karch '03][D'Hocker, Estes, Gutperle '07]



CFT in presence of a (planar) interface or defect, or boundary
Dual to N=4 SYM with a defect

$$AdS_4 \times S^2 \times S^2 \times \Sigma$$

- Σ is a Riemann surface with a boundary, where the geometry develops AdS_5 throats
- Janus solutions *doped* with D5 and NS5 branes
- May preserve supersymmetry

Can these models give rise to a small graviton mass?

Spin 2 spectrum

[Csaki, Erlich, Hollowood, Shirman '00][Bachas, Estes '11]

Study Laplace operator on warped backgrounds

$$ds^2 = e^{2A(y)}\bar{g}_{\mu\nu}(x)dx^\mu dx^\nu + \hat{g}_{ab}dy^a dy^b$$

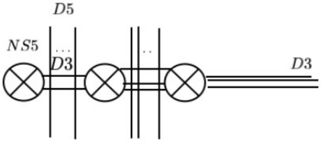
the spin 2 wave operator is universal in 10d (only depends on the background) ($\hat{g}_{ab} = e^{2A}\bar{g}_{ab}$)

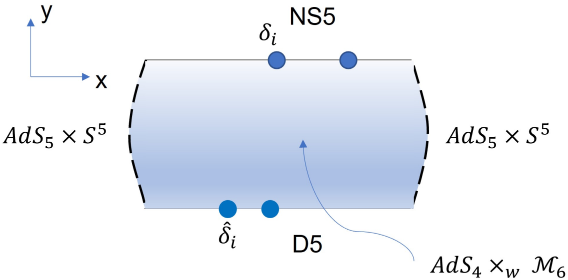
$$-\frac{e^{-2A}}{\sqrt{\hat{g}}}\left(\partial_a \sqrt{\hat{g}}\hat{g}^{ab}e^{4A}\partial_b\right)\psi = m^2\psi$$

- General interest also in view of Swampland conjectures
- The lowest eigenvalues are constant on the spheres of $AdS_4 \times S^2 \times S^2 \times \Sigma$
- Mass eigenstates are factorized $\chi_{\mu\nu}\psi(y)$
- Differently from uplifts of Kaluza Klein set-ups, in this case graviton has non-normalizable wave functions

Type IIB embedding

[Aharony, Berdychevsky, Berkooz, Shamir, '11] [Assel, Bachas, Estes, Gomis, '11]





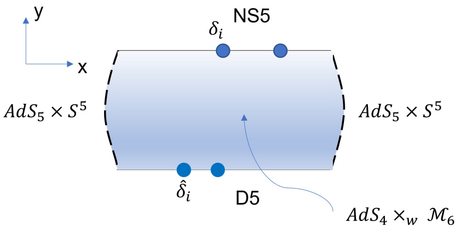
- Linear quivers constructions of D3-D5-NS5 branes dual to 1/4 BPS type IIB solutions of [D'Hocker, Estes, Gutperle '07]
- Holographic dual of 3d N=4 theories

Type IIB embedding

The full solution is specified by two harmonic functions

$$ds^2_{10} = L_4^2 ds^2_{\mathrm{AdS_4}} + f_1^2 ds_{S_1^2} + f_2{}^2 ds_{S_2{}^2} + 4\rho^2 dz d\bar{z},$$

The background has non-vanishing dilaton and H_3, F_3, F_5 fluxes



Moving along the strip takes the internal, 6-dim geometry to S^5.

- $AdS_5 \times S^5$ asymptotic throats

$$h = -i\alpha \sinh(z-\beta) - \gamma \log\left[\tanh\left(\frac{i\pi}{4} - \frac{z-\delta}{2}\right)\right] + \text{c.c.}$$

$$\hat{h} = \hat{\alpha} \cosh(z-\hat{\beta}) - \hat{\gamma} \log\left[\tanh\left(\frac{z-\hat{\delta}}{2}\right)\right] + \text{c.c.}$$

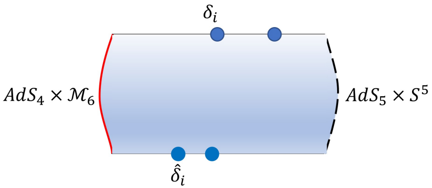
- Global $AdS_5 \times S^5$ for $\beta = \hat{\beta} = 0$, constant dilaton $e^{2\phi} = \hat{\alpha}/\alpha$

Type IIB embedding

[Aharony, Berdychevsky, Berkooz, Shamir, '11] [Assel, Bachas, Estes, Gomis, '11]

Cap-off only one boundary

$$\alpha e^{\beta}\,,\;\hat{\alpha} e^{\hat{\beta}} \to 0 \qquad \alpha e^{-\beta} = \kappa\,,\quad \hat{\alpha} e^{-\hat{\beta}} = \hat{\kappa}$$



The solution has three parameters $\kappa, \hat{\kappa}, N$

$$h = -\frac{i\pi}{4} e^{z}\kappa - \frac{N}{4}\log\tanh\left(\frac{i\pi}{4} - \frac{z}{2}\right) + \mathrm{c.c}$$

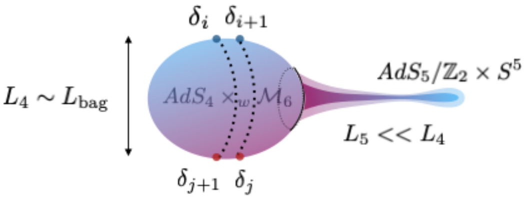
$$\hat{h} = \frac{\pi}{4} e^{z}\hat{\kappa} - \frac{N}{4}\log\tanh\left(\frac{z}{2}\right) + \mathrm{c.c}$$

- N D5 and NS5 branes

The dilaton varies from the bag region $AdS_4 \times M_6$ to the asymptotic $AdS_5 \times S^5$

$$e^{2\delta\phi} = \frac{\hat{\kappa}}{\kappa}$$

Type IIB embedding



- Due to no-scale separation: $L_4 \sim L_{bag}$
- A hierarchy can be realized between the internal geometries by tuning

$$\alpha = \sqrt{\frac{N^2}{\kappa\hat{\kappa}}} \sim \left(\frac{L_4}{L_5}\right)^8$$

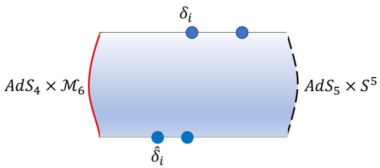
- The dilaton is linear in the throat, at infinite dilaton the asymptotic AdS_5 region decouples [Bachas '19]

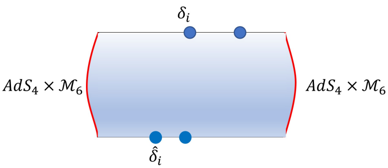
Realization of models of localized gravity

- EOW brane tension translates in the parameter α

$$\theta^{-1} \qquad \leftrightarrow \qquad \alpha \sim \frac{F_3}{F_4} \sim \frac{\text{dof BCFT}}{\text{dof CFT}}$$

- Bag region as a *composite* Karch-Randall brane
- Transparent boundary conditions correspond to leaking into the AdS_5 region where gravity is non-dynamical: non gravitating bath
- When both regions are capped off, the internal geometry is compact and the graviton is massless





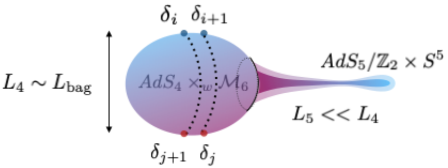
Massive Graviton

Leaking of radiation due to nonconservation of the stress tensor

$$m_g^2 L_4^2 = \Delta(\Delta - 3) \xrightarrow{\Delta=3+\varepsilon} m_g^2 L_4^2 \sim \varepsilon$$

Weak dissipation

$$m_g^2 L_4^2 \sim \frac{\text{bulk dof}}{\text{bdy dof}} \sim \alpha^{-1}$$



On these backgrounds the spin-2 eigenstates factorize as $\chi_{\mu\nu}\psi(y)$ with $\chi_{\mu\nu}$ a transverse traceless eigenfunction of the Anti de Sitter wave operator, the eigenvalues equation reduces to

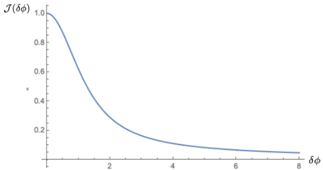
$$\mathcal{M}^2\psi = -\frac{L_4^{-2}}{\sqrt{g}}\partial_i(L_4^4\sqrt{g}g^{ij}\partial_j\psi) = (\lambda+2)\psi \ , \qquad \lambda+2 = m_g^2(y)L_4^2(y)$$

[Bachas, Lavdas '18]

Massive graviton

In this approximation

$$m_g^2 L_4^2 \equiv \bar{m}_g^2 \simeq \frac{3\pi^3}{4}\left(\frac{L_5}{L_{\rm bag}}\right)^8 \mathcal{J}(\mathrm{ch}(\delta\varphi))$$



$\Rightarrow$ Large dilaton variation lowers the mass of the lightest spin 2. Can we take the limit to a massless graviton? [Bachas '19]

- Analysis of bimetric gravity low energy description, where one spin-2 acquire a mass thanks to gauging of a common isometry.
- Massless limit is at *infinite distance* in moduli space corresponding to the limit where an infinite tower of unprotected spin 2 becomes massless.
- The decoupling of the boundary dof is singular

$\rightarrow$ Consistent with the non continuous behaviour of the islands surfaces in going from the gravitating to the non-gravitating case

Massive graviton and EFT

[de Rham, Tolley, Zhou '16][Bachas '19]

In the regime where $m^2 L^2_{AdS} \ll 1$, consistency of the massive gravity EFT requires the UV cutoff

$$\Lambda_* = \frac{m_g^{\frac{1}{3}} M_{\mathrm{Pl}}^{\frac{1}{3}}}{L_{(4)}^{\frac{1}{3}}},$$

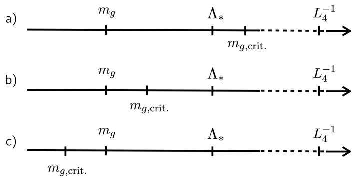
Questions

- Low energy theory from type IIB consistent with the EFT cutoff
- Are QEI surfaces affected by this regime?

Nontrivial chekcs, as the existence of islands is sensitive to the geometric parameters

→ In the same way as the existence of islands in AdS in the KR requires a maximum brane tension (minimum angle θ), in this case the islands are sensitive to the ration between bulk and boundary dof. [Uhlemann '20]

Massive graviton and Island surfaces



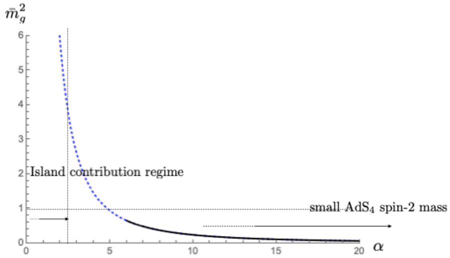
Islands below the cutoff

$$m_{g\,\text{crit.}} < \Lambda_* \quad \Rightarrow \quad K_{\text{crit.}} < K^{1/3} N^{5/6} \ll N^{7/6}$$

Graviton mass above the critical value

$$m_{g\,\text{crit.}} < m_g \quad \Rightarrow \quad K_{\text{crit.}} < K$$

- The results of Uhlemann, '21 show that at $\delta\phi = 0$ there is a critical value of $\alpha \sim \mathcal{O}(1)$ above which islands cease do exist in empty Anti de Sitter
- Not large enough to be in the $m^2 L_{AdS}^2 \ll 1$ regime



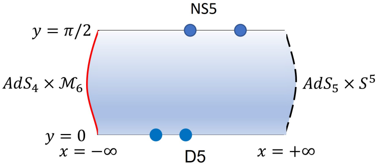
$\rightarrow$ Backgrounds with varying dilaton

Islands surfaces in type IIB

10d geometry with black hole in AdS_4

$$ds_{10}^2 = L_4^2 ds_{\mathrm{AdS_4}}^2 + f_1^2 ds_{S_1^2} + f_2{}^2 ds_{S_2{}^2} + 4\rho^2 dz d\bar{z}$$

The black hole radiation reaches a region in the 4d CFT at $x = +\infty$.
$r(x, y)$ 8d RT surface in the 10d full metric.



- Extends along both S^2's, anchored at r_R at $x = +\infty$ (Dirichelet boundary condition)
- Regularity at the boundary of the strip requires Neumann boundary conditions

[Uhlemann '21]

Numerical setup

Surface equation

$$\frac{1}{1+g(\nabla r)^2}\left[2-\nabla(g\nabla r)+\frac{1}{2}g\nabla r\cdot\nabla\ln\left(\frac{1+g(\nabla r)^2}{b(r)f^2}\right)\right]=0$$

- $r(x,y)$ is the surface function
- $b(r)$ is the black hole warp factor $b(r)=1-e^{3(r_h-r)}$
- f,g are constructed out of the harmonic functions $h,\hat{h}$ and their derivatives. They are sensitive to the choice of background

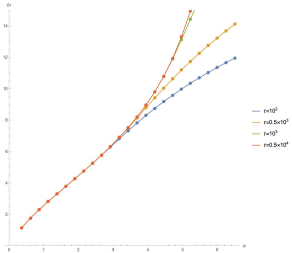
$\rightarrow$ The dilaton variation does not affect the boundary conditions. It is constant in the $AdS_5\times S^5$ region.

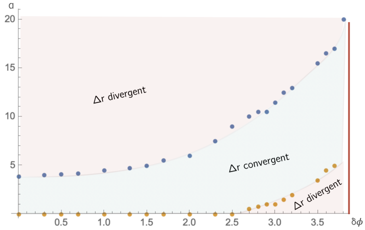
- Finite difference method to reduce the PDE to ODE
- Relaxation method

$$\partial_\tau r(x,y,\tau)=-\frac{1}{1+g(\nabla r)^2}\left[2-\nabla(g\nabla r)+\frac{1}{2}g\nabla r\cdot\nabla\ln\left(\frac{1+g(\nabla r)^2}{b(r)f^2}\right)\right]$$

Zero temperature surfaces

Dilaton dependence of the critical parameter



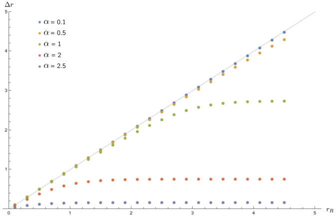


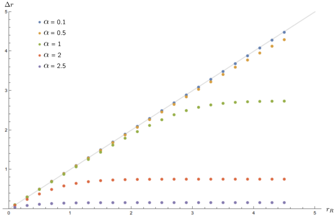
$\Rightarrow$ A dilaton variation pushes the critical parameter high enough to be able to create a hierarchy betweem the bag and the throat.

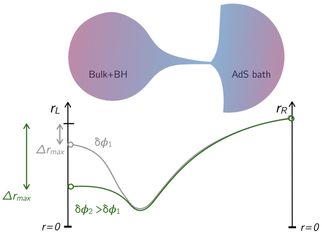
$\Rightarrow$ For larger $\delta\phi$, intervals of non-convergence at small α arise that need to be studied.

$\Rightarrow$ No convergence above $\delta\phi \sim 4$.

Finite temperature







- The point where the surfaces reaches $x = -\infty$ is forced to be anchored until the value of Δr reaches the value at zero temperature, then it stays constant
- The dilaton pushes this value higher, keeping the anchoring point fixed longer

Summary and Outlook

- Understanding quantum extremal islands in higher dimensions is of great importance for understanding the principles of black hole evaporation
- Uplifts to Type IIB clarify the role of the graviton mass
- Possible tension between existence of islands and very light spin 2?

Possible extensions:

- Is there a phase transition for islands at finite temperature?
- Possible limits of the quiver diagrams (factorization, ‘weak limits’)
- Different internal geometries *with a neck*
- Quantitative results matching bottom up studies [Anous, et al. ‘22]

Thank you!