Title: Islands and Light Gravitons in type IIB String Theory - Alessandra Gnecchi, MPI-Munich

Speakers:

Series: Quantum Fields and Strings

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Abstract: Higher dimensional models of black hole evaporation can be studied via double holographic constructions, which can be considered as holographic models of conformal interfaces. In string theory these are realized microscopically by appropriate systems of branes, and in particular limits they give rise to a light graviton mass in the effective gravity theory. For a specific model of D3-D5-NS5 branes in type IIB, I will discuss the properties of the lightest graviton and show how this constrains the existence of islands in Anti de Sitter. I will show a numerical study of islands surfaces for finite temperature black holes, and show how they are affected by a varying dilaton. I will finally comment on the EFT cutoff induced by a light graviton mass, in relation to the islands regime, in function of the microscopic parameters of the string theory construction.

Zoom Link: https://pitp.zoom.us/j/97993595112?pwd=dE1xRm42MmY3bEVYZ2c4VURtaWV4dz09

Islands and light gravitons in type IIB string theory

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May 17, 2022 - QFStrings Online Seminar - Perimeter Institute

Outline

- Introduction
  - Black hole evaporation and Karch-Randall braneworlds
- Holographic interfaces and boundary conformal field theories from type IIB string theory
- Graviton mass
- Islands surfaces

Based on 2204.03669 and w.i.p. with S. Demulder, I. Lavdas and D. Lüst

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

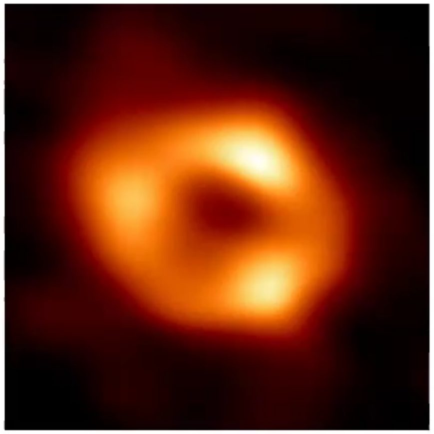


fig. from EHT (CC)

Entanglement entropy and black holes

Measures how information is stored in a quantum system.

$$\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$$

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: $B = A^C$

$$S_A = S_B$$

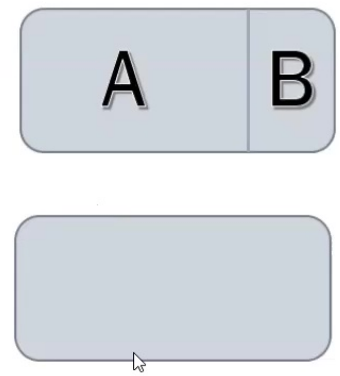
For a pure system

$$S = S_{AB} = S_{AA^C} = 0$$

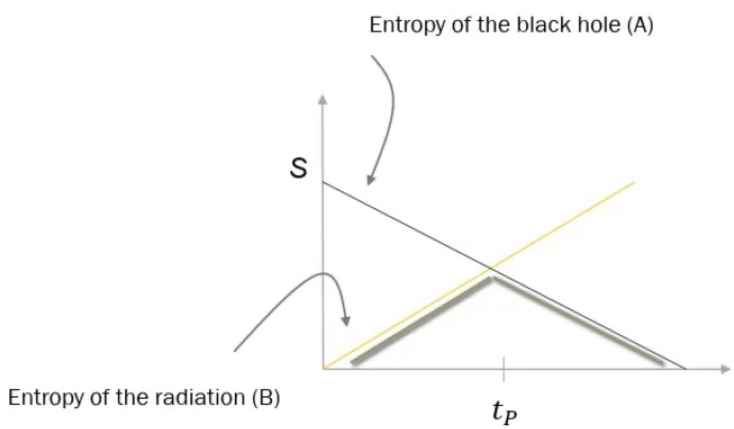
In the case of a black hole, the horizon is what separates the subsystem Hawking radiation, which is accessible to us, with the black hole interior, which is its complement quantum subsystem.

Page curve

Past the maximally entangled state, the EE of black hole and radiation sub-systems starts decreasing
(If the subsystem B is much larger than A, it already contains most of the dof of the full system)



Pure state at the end of evaporation: $S_{EE} = 0$

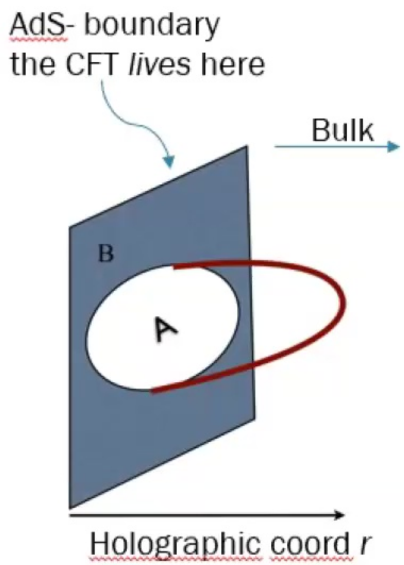


This evolution follows the *Page curve*
[Page '93]

Holographic entanglemente entropy

Question

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



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

γ is the minimal surface in the bulk enclosing A

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

Extend this formula to include the contribution to entanglement due to the quantum fields in the bulk

$$S_{gen} = \frac{Area(\gamma)}{4G_N} + S_{bulk}(\Sigma_\gamma)$$

[Faulkner, Lewkowicz, Maldacena '13][Engelhardt, Wall '14]

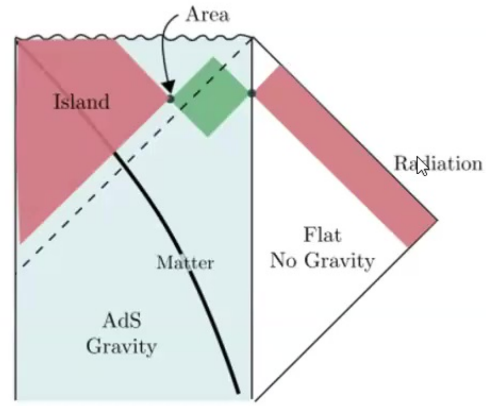
QES - Islands

Appearance of new contributions to the entropy from new kind of extremal surfaces *behind* the horizon [Penington '19][Almheiri,Engelhardt,Marolf,Maxfield '19]

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

At late times *islands* appear whose entropy decreases with black hole evaporation
[Almheiri, Mahajan, Maldacena, Zhao '19]

Couple the black hole in Anti de Sitter with a reservoir at infinity with non dynamical gravity. EE of the collected radiation computed holographically.



Replica Wormholes

[Almheiri, Hartman, Maldacena, Shaghoulian, Tajdini '19]
[Penington, Shenker, Stanford, Yang '19]

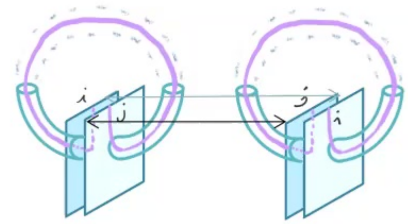
The island contribution from the gravitational path integral

$$Z \sim e^{-S_{Hawking}} + e^{-S_{wh}} + \dots$$

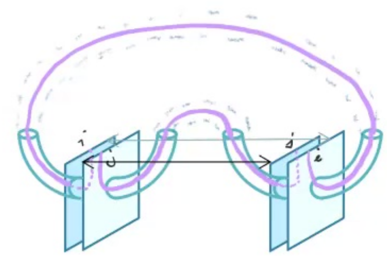
$\longrightarrow$ New gravitational saddle points: Replica Wormholes

Calcualtion of entanglement entropy in CFTs via replica trick

$$S_n \equiv \frac{1}{1-n} \log \mathrm{Tr}(\rho_A^n) \,, \qquad S_{EE} = \lim_{n \to 1} S_n$$



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

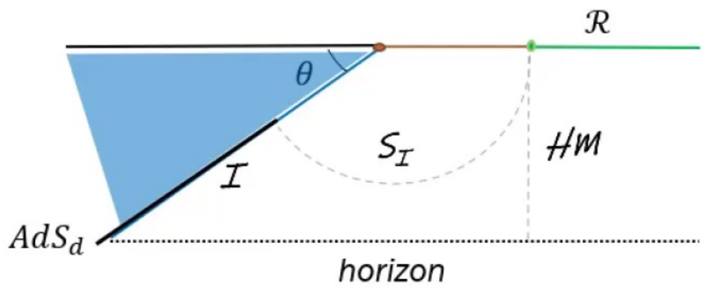


$\mathrm{Tr}\,[\rho^2] \approx \mathrm{Tr}[\rho]^2$

Higher dimensional realizations: KR braneworlds

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

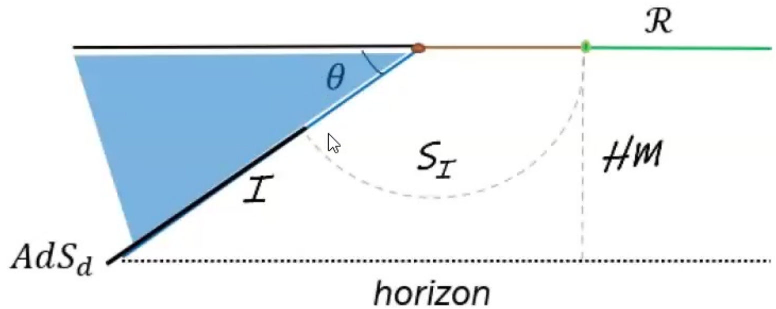
Double holographic setup:



- 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 $\mathbb{R}^{1,4}$.

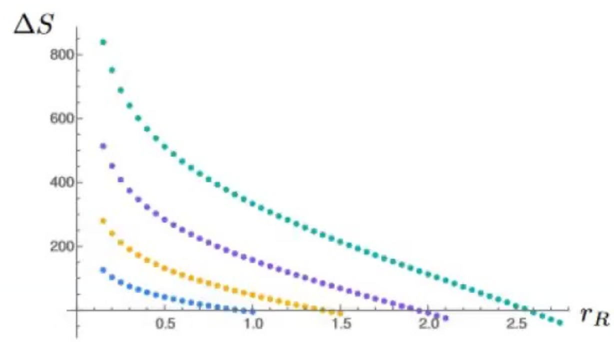
  $\rightarrow$ Geometrization of the islands

KR braneworlds



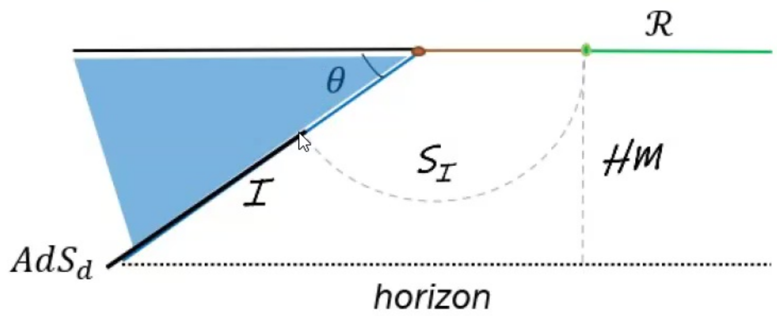
Competition between

- HM surfaces
- Islands surfaces



[Uhlemann '21]

KR braneworlds



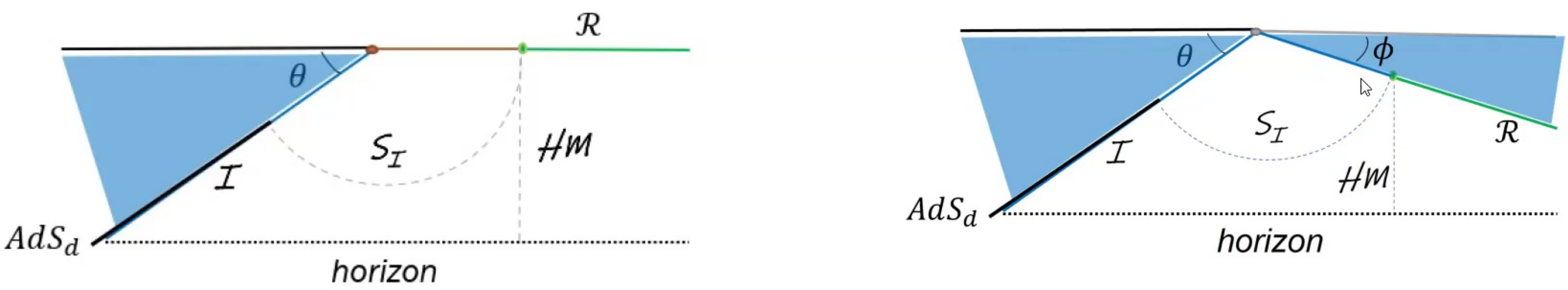
- Transparent boundary conditions induce a graviton mass
- The brane tension is maximal against the boundary of AdS_5
- Critical angle needed to localize gravity on the AdS_4 brane

$$\theta \qquad \leftrightarrow \qquad m_g$$

- Maybe a graviton mass is required in higher dimensional islands setups..
  [Geng, Karch, Perez-Pardavila, Raju, Randall '21]

KR braneworlds

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



→ By closing off the boundary with another EOW brane, gravity is dynamical on the radiation region.

→ The Page curve reconstruction does not translate to the gravitating bath case and the entropy is simply constant.

[Geng et al. '20][Laddha, Prabhu, Raju, Srivastava '20]

→ Different surfaces need to be considered

[Uhlemann '21]

Microscopic realization in String Theory

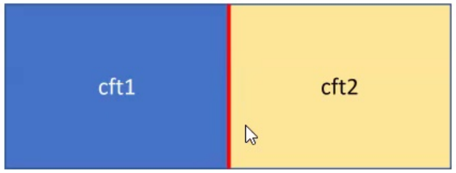
- § Microscopic construction of black holes for entropy matching
  [Strominger, Vafa '96] [Maldacena, Strominger, Witten, '97][Benini, Hristov, Zaffaroni '15]
- § Control on the low energy effective theory
- § Spectrum of spin 2 fields
  [Csaki,Erlich,Hollowood,Shirman '00][Bachas, Estes '11][De Luca, De Ponti, Mondino, Tomasiello '21]

$\Rightarrow$ Braneworld models realize the junction between a BCFT and a bulk CFT.

$\Rightarrow$ Holographic interfaces realized in String Theory with (deformation of) Janus configurations

Conformal defects and holographic interfaces

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



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

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

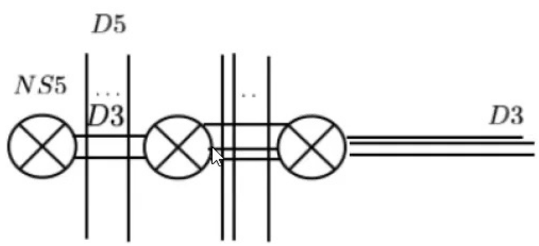
the spin 2 wave operator is universal in 10d (only depends on the background) ($\hat{g}_{ab} = e^{2A}\bar{g}_{ab}$)

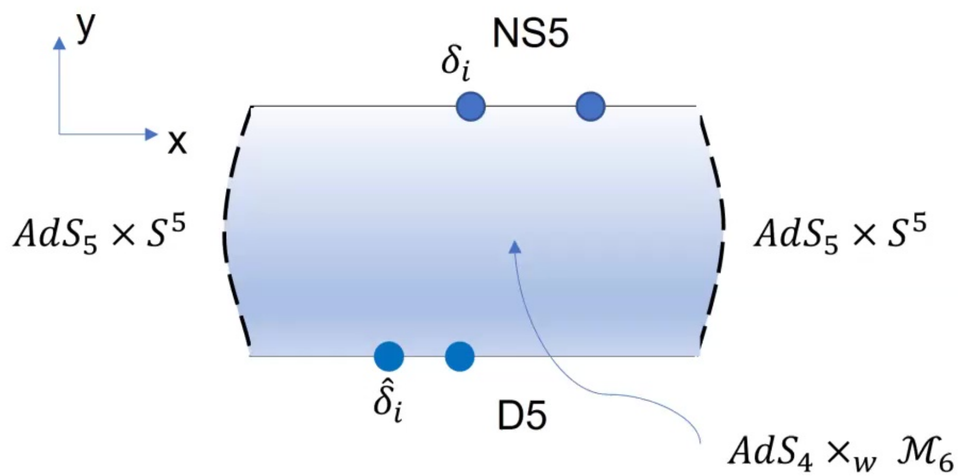
$$-\frac{e^{-2A}}{\sqrt{\hat{g}}}\left(\partial_a\sqrt{\hat{g}}\hat{g}^{ab}e^{4A}\partial_b\right)\psi = m^2\psi$$

- 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

Holographic dual of 3d N=4 thories: the Type IIB embedding

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





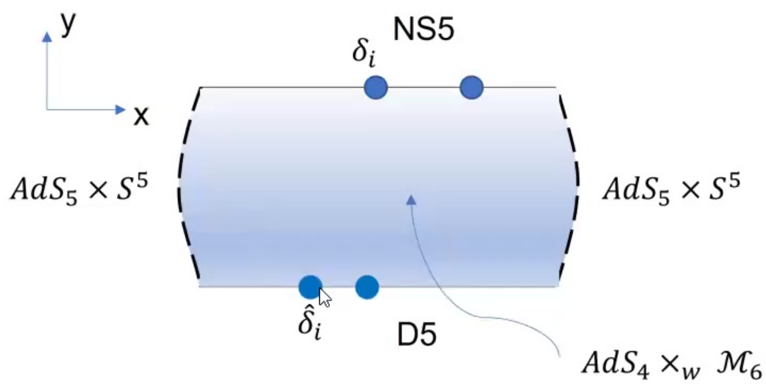
- Linear quivers constructions of D3-D5-NS5 branes dual to 1/4 BPS type IIB solutions of [D'Hocker, Estes, Gutperle '07]
- The theory flows in the IR to a strongly coupled 3d SCFT

Holographic dual of 3d N=4 theories - they Type IIB embdedding

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

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

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

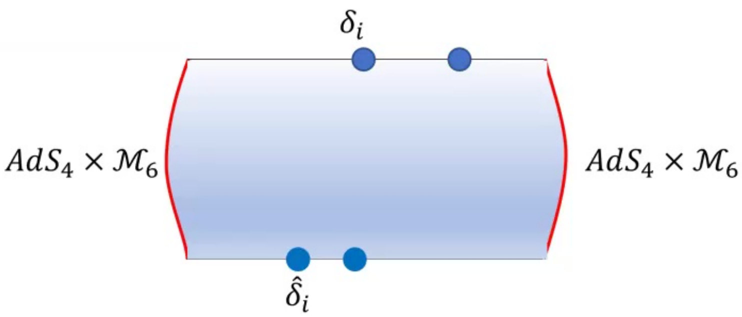
- Global $AdS_5 \times S^5$ for $\beta = \hat{\beta} = 0$, constant dilaton $e^{2\phi} = \hat{\alpha}/\alpha$

Type IIB embdedding

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

The geometry can be capped off smoothly at both asymptotics

$$\alpha, \hat{\alpha} \to 0$$



- The internal geometry becomes compact
- AdS_4 geometry has size

$$L^4_{(AdS_4)} \sim \gamma\hat{\gamma}$$

Both set of branes are required

- Generalize to stack of branes by simply

$$\gamma \log \left[\tanh \left(\frac{i\pi}{4} - \frac{z-\delta}{2} \right) \right] \quad \to \quad \sum_a \gamma_a \log \left[\tanh \left(\frac{i\pi}{4} - \frac{z-\delta_a}{2} \right) \right]$$

Type IIB embdedding

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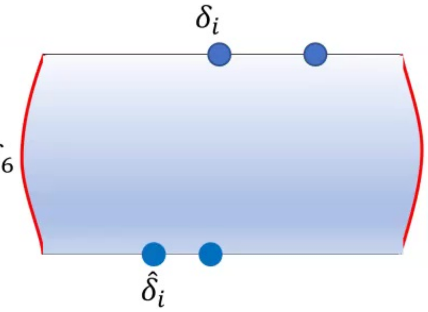

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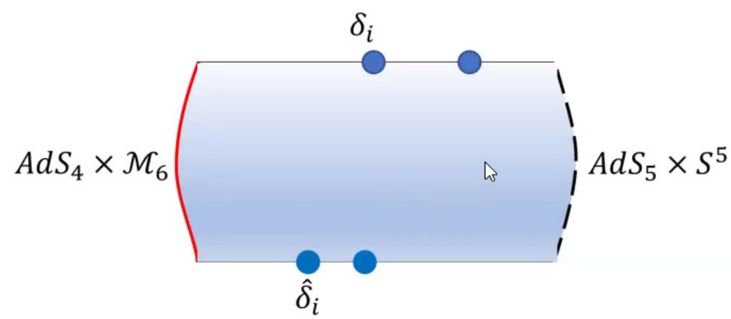
Type IIB embedding

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

Cap-off only one boundary

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



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

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

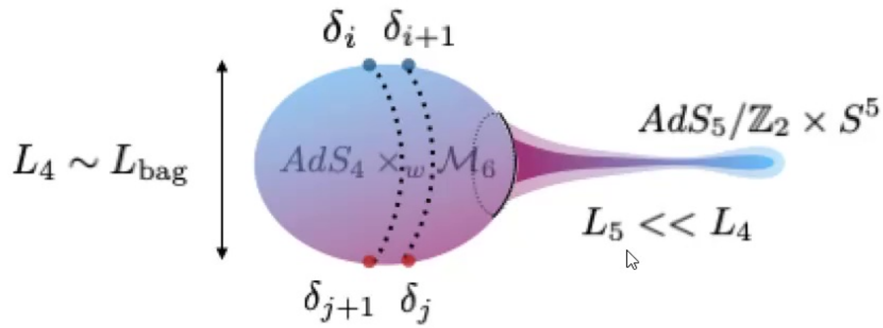
$$\hat{h} = \frac{\pi}{4} e^{z}\hat{\kappa} - \frac{N}{4}\log\tanh\left(\frac{z}{2}\right) + \text{c.c}$$

- 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

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

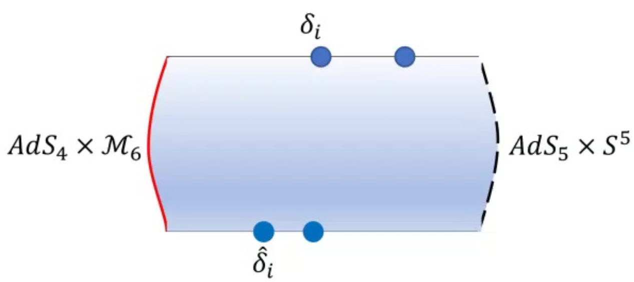
- The dilaton is linear in the throat, at infinite dilaton the asymptotic AdS_5 region decouples [Bachas '19]

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



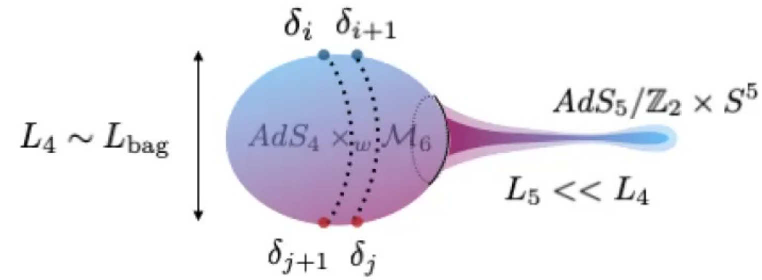
Massive Graviton

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

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



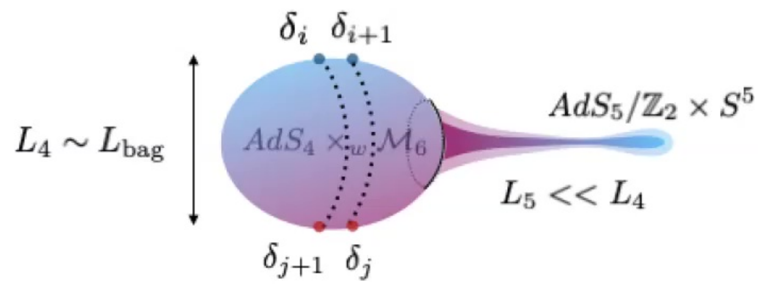
On these backgrounds the spin-2 eigenstates factorize as $\chi_{\mu\nu}\psi(y)$ with $\chi_{\mu\nu}$ a transverse traceless eigenfunction of the Anti de Sitter wave operator, the eigenvalues equation reduces to

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

[Bachas, Lavdas '18]

Spin 2 spectrum

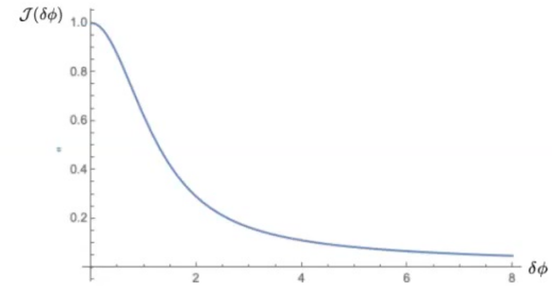
- Graviton spectrum is interesting for questions of scale separation: $m^2_{KK} \gg \Lambda$
- Generically related to the *size* of the internal manifolds
- Special case of geometries "with a neck" where the wake operator spectrum can be studied and gives rise to very small masses. [De Luca, De Ponti, Mondino, Tomasiello '21]
- Proposed as *quantum gates* in relation to double trace deformations and bimetric gravity [Bachas, Lavdas '17]



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

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

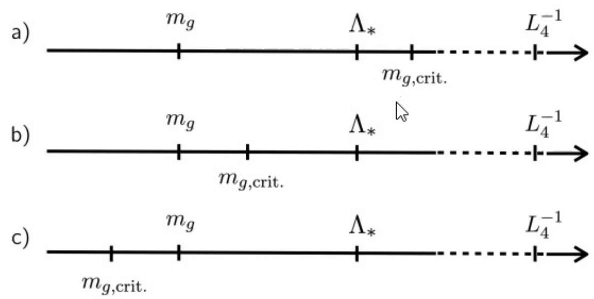
Questions

- 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

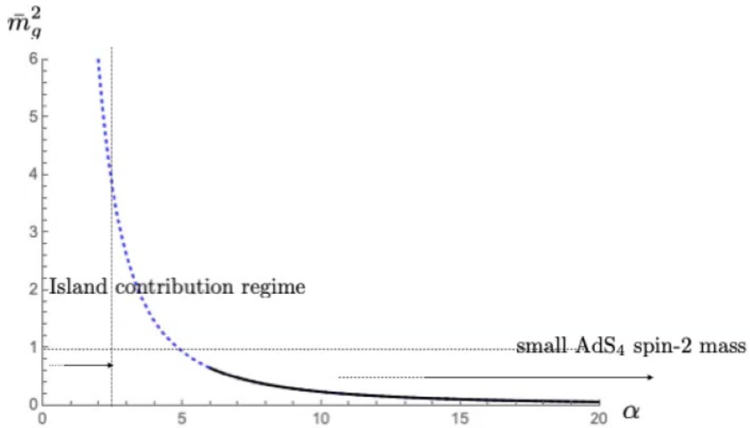


Islands below the cutoff

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

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

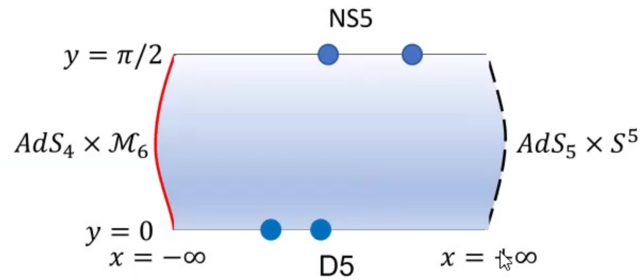
$\rightarrow$ Backgrounds with varying dilaton

Islands surfaces in type IIB

10d geometry with black hole in AdS_4

$$ds_{10}^2 = L_4^2 ds^2_{\mathrm{AdS}_4} + f_1^2 ds_{S_1^2} + f_2^{\,2} ds_{S_2{}^2} + 4\rho^2 dz d\bar{z}$$

The 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

→ 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

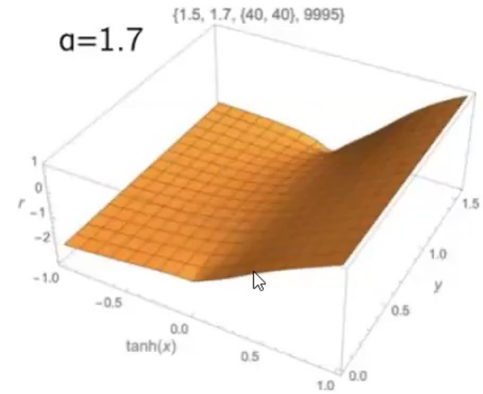
$$\partial_\tau r(x,y,\tau)=-\frac{1}{1+g(\nabla r)^2}\left[2-\nabla(g\nabla r)+\frac{1}{2}g\nabla r\cdot\nabla \ln\left(\frac{1+g(\nabla r)^2}{b(r)f^2}\right)\right]$$

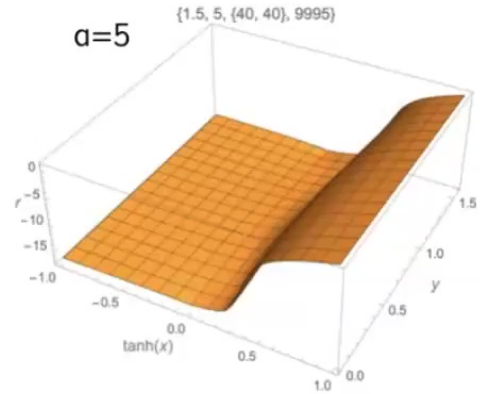
Zero temperature surfaces

- Surfaces are translational invariant in r_R due to conformal symmetry
- The difference $r_R - r_L$ is sensitive *both* to $\alpha = \sqrt{N^2/\kappa\hat{\kappa}}$ and $\delta\phi$
- Critical values appear above which the code does not converge

(surfaces at $\delta\phi = 1.5$)

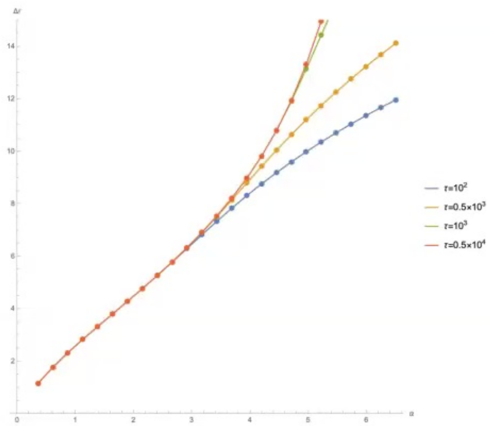
- Increasing alpha stretches the surface more and more along the horizon

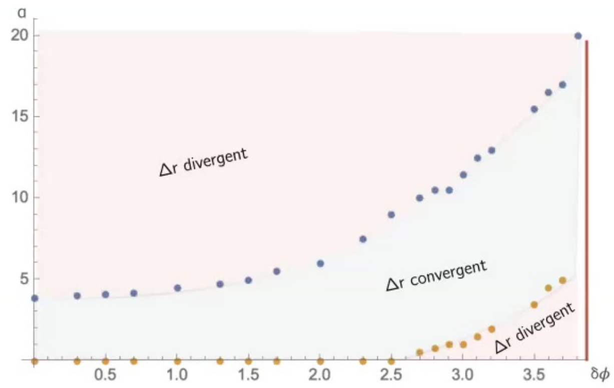




Zero temperature surfaces

Dilaton dependence of the critical parameter



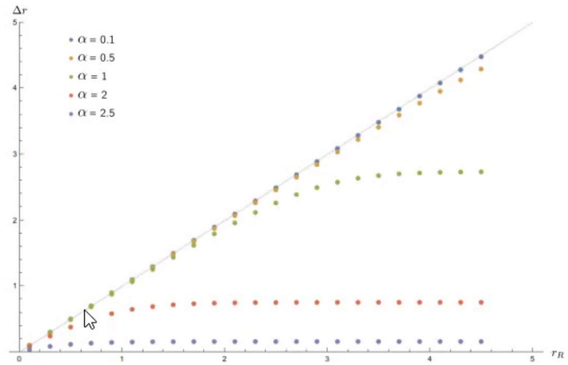


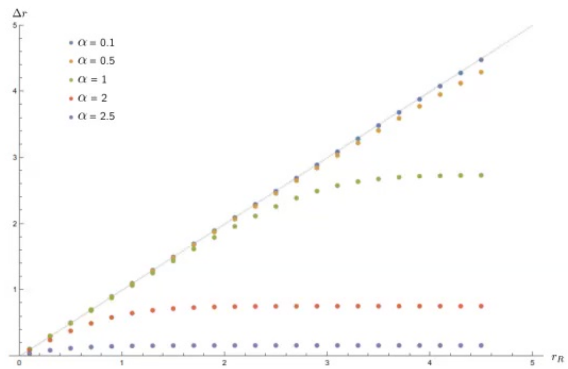
⇒ A dilaton variation pushes the critical parameter high enough to be able to create a hierarchy betweem the bag and the throat.

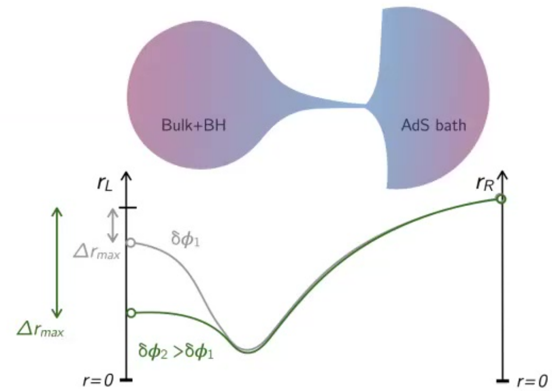
⇒ For larger $\delta\phi$, intervals of non-convergence at small α arise that need to be studied.

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

Finite temperature

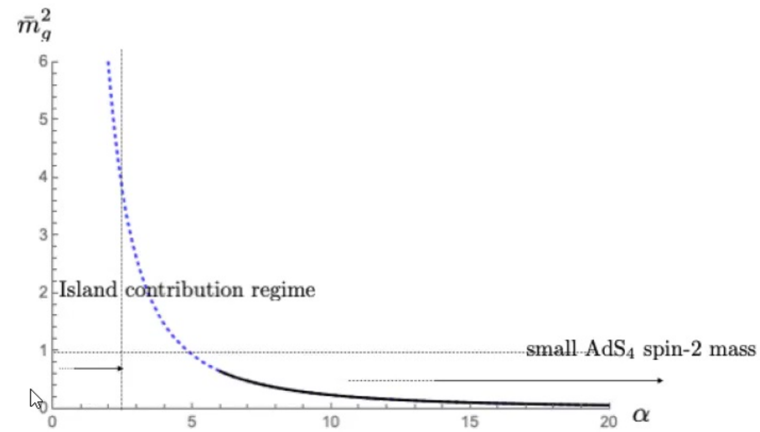






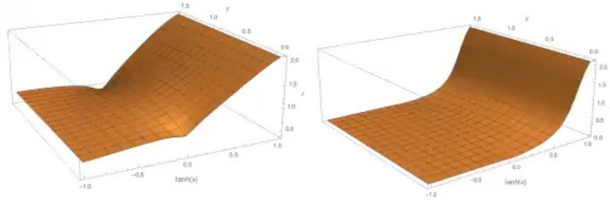
- The point where the surfaces reaches $x = -\infty$ is forced to be anchored until the value of Δr reaches the value at zero temperature, then it stays constant
- The dilaton pushes this value higher, keeping the anchoring point fixed longer

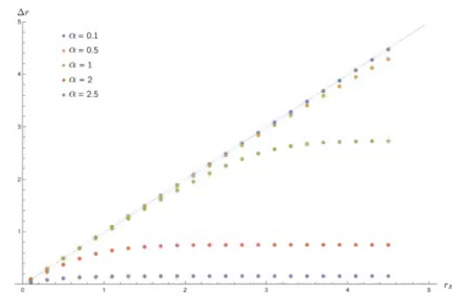
Graviton mass regime



- We can study backgrounds where $\alpha \sim 10$ for which we can trust the massive gravity low energy theory
- There is eventually a cap on α that forbids to completely decouple the mass when there is an islands contribution at zero temperature
- A discontinuity is encountered in reaching the gravitating bath scenario... study in the large α approximation?

Critical parameter at finite temperature





- Surfaces exist also above the critical parameter
- They have a constant entropy that eventually wins over HM surfaces, whose keeps growing due to the stretching of the horizon
- Phase transition between the surfaces anchored for small Δr and those for which the anchoring point is fixed for longer?
- What is the physical consequence of this phase transition, if in both cases the surface contribute to the Page curve, anyway?

Summary

- 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
- In empty anti de Sitter there is a critical value of the graviton for which the islands cease to exist
- Signals a possible tension between existence of islands and very light spin 2

Outlook

- Possible configurations in other dimensions
- Possible limits of the quiver diagrams (factorization, ‘weak limits’)
- Different internal geometries *with a neck*
- Quantitative results from correlation functions [Anous, et al. ‘22]

Thank you!