



From Large to Small $\mathcal{N} = (4, 4)$ Superconformal Surface Defects in Holographic 6d SCFTs

Based on 2402.11745

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(At the time) under the supervision of A. O'Bannon

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- ▶ Holographic entanglement entropy
- ▶ Holographic renormalization applied to $\langle T \rangle$ (and why it fails)
- ▶ Summary, open questions, and future directions



Motivations

1 Motivations, objectives and outline

Why 2d defects in 6d SCFTs? (non-exhaustive list)

1. The 6d $\mathcal{N} = (2, 0)$ is *special* (eg. Class- $\mathcal{S}$ and AGT, no known Lagrangian, strongly coupled...)
2. It admits 2d and 4d supersymmetric extended operators (defects)
3. Defects are needed to fully characterise the CFT (eg. order parameters in 4d, differentiation between gauge theories with same algebra but different groups, ...)
4. The tools are readily available (laziness argument)

Why holographic entanglement entropy?

1. Entanglement entropy of a region around the defect $\rightarrow$ universal information about the defect theory



Motivations

1 Motivations, objectives and outline

Holographically we can use:

1. Supergravity solutions with AdS_7 asymptotic regions
2. Systems of M5-branes in M-theory
3. Systems of M5-M2 brane intersections
4. All of the above (Asymptotically locally AdS_7 solutions to 11d supergravity)

Holographically, we can:

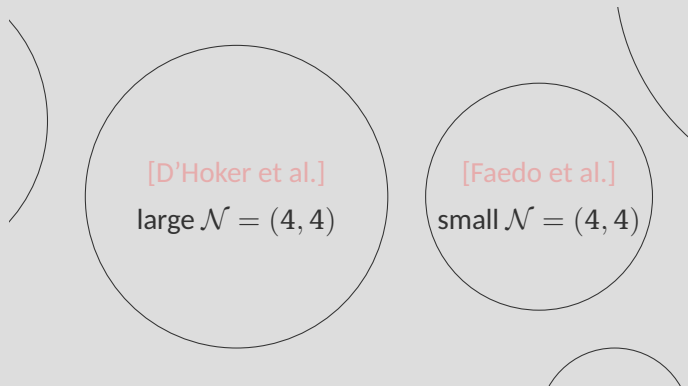
1. Use the Ryu-Takayanagi prescription to compute the entanglement entropy of a region in the 6d CFT
2. Use holographic renormalization to determine $\langle T \rangle$



Objectives

1 Motivations, objectives and outline

Zooming into the landscape of 11d supergravity solutions describing codimension-4 defects in 6d SCFTs:

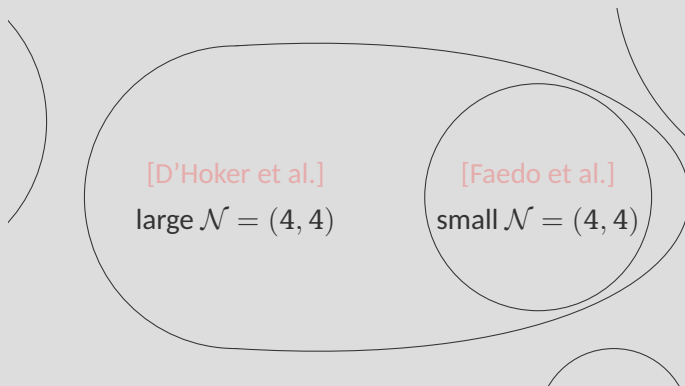




Objectives

1 Motivations, objectives and outline

Zooming into the landscape of 11d supergravity solutions describing codimension-4 defects in 6d SCFTs:





Objectives

1 Motivations, objectives and outline

1. Make precise the identification in the previous slide
2. Compute a holographic entanglement entropy
3. Extract Weyl anomaly coefficients
4. Compute stress-energy tensor one-point function $\langle T \rangle$
5. Identify A-type and B-type Weyl anomaly coefficients separately
6. Celebrate



Objectives

1 Motivations, objectives and outline

1. Make precise the identification in the previous slide
2. Compute a holographic entanglement entropy
3. Extract Weyl anomaly coefficients
4. ~~Compute stress-energy tensor one-point function $\langle T \rangle$~~
5. ~~Identify a-type and b-type Weyl anomaly coefficients separately~~
6. Still celebrate



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- ▶ Review of large $\mathcal{N} = (4, 4)$ surface defect solutions
- ▶ **New** small $\mathcal{N} = (4, 4)$ surface defect solutions
- ▶ Holographic entanglement entropy
- ▶ Holographic renormalization applied to $\langle T \rangle$ (and why it fails)
- ▶ Summary, open questions, and future directions



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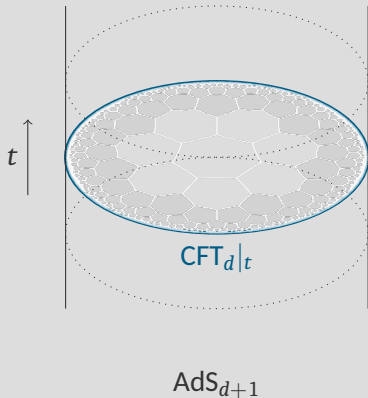
2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

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The holographic principle (hand wavy)

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions



- The bulk is a (quantum) gravity theory
- The CFT “lives” on the boundary
- The theories are **DUAL**
(all n-point functions match)
- In the low energy limit: Supergravity $\leftrightarrow$ CFT



The history

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

In a series of papers, [0806.0605], [0810.4647], [0906.0596], D'Hoker, Estes, Gutperle and Krym constructed a family of half-BPS solutions to 11d supergravity.

In other words, solutions to

$$R_{MN} - \frac{1}{12} F_{MPQR} F_N{}^{PQR} + \frac{1}{144} G_{NM} F_{PQRS} F^{PQRS} = 0 \quad (1)$$

$$d \star F + \frac{1}{2} F \wedge F = 0 \quad (2)$$

which preserve 16 real supercharges.

We will be looking at the slightly more recent formulation found in the followup paper Bachas et al. [1312.5477].



The supergravity solution in Bachas *et al.* [1312.5477]

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

We are looking at solutions of 11d supergravity, with isometry superalgebra $\mathfrak{d}(2, 1; \gamma) \oplus \mathfrak{d}(2, 1; \gamma)$, $\gamma \in \mathbb{R}$.

We identify the maximal bosonic subgroup of its real form

$$\mathfrak{d}(2, 1; \gamma; 0) \supset \mathfrak{so}(2, 1) \oplus \mathfrak{so}(3) \oplus \mathfrak{so}(3) \quad (3)$$

The geometry must thus contain

$$\text{AdS}_3 \times \mathcal{S}^3 \times \tilde{\mathcal{S}}^3$$

fibered over a Riemann surface, Σ_2 .



The supergravity solution in Bachas *et al.* [1312.5477]

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

The 11d generalized Killing spinor equation

$$\nabla \epsilon + \frac{1}{288} (\Gamma_m^{npqr} e^m - 8 \Gamma^{pqr} e^n) F_{npqr} \epsilon = 0 \quad (4)$$

is recast into a complex equation on Σ_2 , for two functions $h, \mathcal{G} : \Sigma_2 \rightarrow \mathbb{C}$.

$$\partial \bar{\partial} h = 0 \qquad \partial \mathcal{G} = \frac{1}{2} (\mathcal{G} + \bar{\mathcal{G}}) \partial \ln(h) \quad (5)$$

If Σ_2 has a boundary, we further impose the boundary conditions

$$h = 0 \qquad \mathcal{G} = \pm i \qquad \text{on } \partial \Sigma_2 \quad (6)$$



The supergravity solution in Bachas *et al.* [1312.5477]

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

Explicitly, the non-zero supergravity fields are given by

$$G = f_{\text{AdS}_3}^2 g_{\text{AdS}_3} + f_{S^3}^2 g_{S^2} + f_{\tilde{S}^3}^2 g_{\tilde{S}^3} + f_{\Sigma_2}^2 g_{\Sigma_2} \quad (7)$$

$$C_3 = b_{\text{AdS}_3} \text{vol}_{\text{AdS}_3} + b_{S^3} \text{vol}_{S^3} + b_{\tilde{S}^3} \text{vol}_{\tilde{S}^3} \quad (8)$$

where all coefficients depend only on h , $\mathcal{G}$ and γ (and $F = dC_3$).



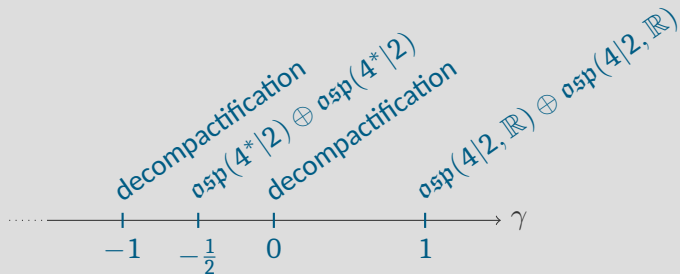
The supergravity solution in Bachas *et al.* [1312.5477]

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

So far, we take away:

- Fully specified by a triplet $(h, \mathcal{G}, \gamma)$
- $h, \mathcal{G} : \Sigma_2 \rightarrow \mathbb{C}$, where $\mathcal{G}$ is allowed to have singularities on $\partial\Sigma$
- Not all values of γ allow for asymptotic AdS solutions

Landscape of $\mathfrak{d}(2, 1; \gamma) \oplus \mathfrak{d}(2, 1; \gamma)$:





The supergravity solution in Bachas *et al.* [1312.5477]

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

From here on, we choose Σ_2 to be the half-plane.

The most general solution with one AdS asymptotic region and $\gamma < 0$ is given by

$$h = -i(w - \bar{w}) \quad \mathcal{G} = -i \left(1 + \sum_{j=1}^{2n+2} (-1)^j \frac{w - \xi_j}{|w - \xi_j|} \right) \quad (9)$$

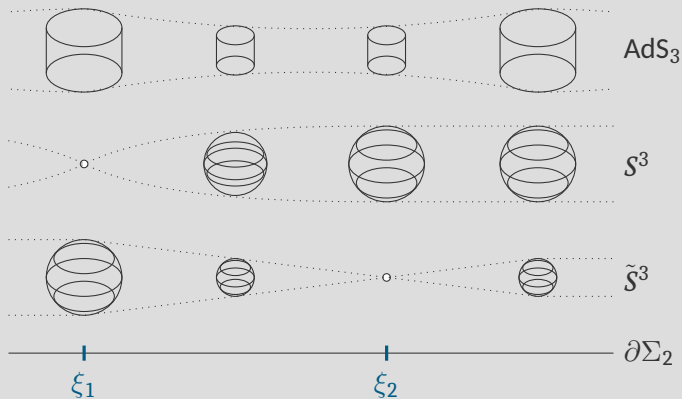
The simplest such solution, $n = 0$ gives $\text{AdS}_7 \times S^4$ (γ -deformed) globally.



The supergravity solution in Bachas *et al.* [1312.5477]

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

All solutions exhibit the following behaviour on $\partial\Sigma_2$





The supergravity solution in Bachas *et al.* [1312.5477]

2 Review of large $\mathcal{N} = (4, 4)$ surface defect solutions

The $\text{AdS}_7 \times S^4$ (γ -deformed) region is found at large radius on the half-plane

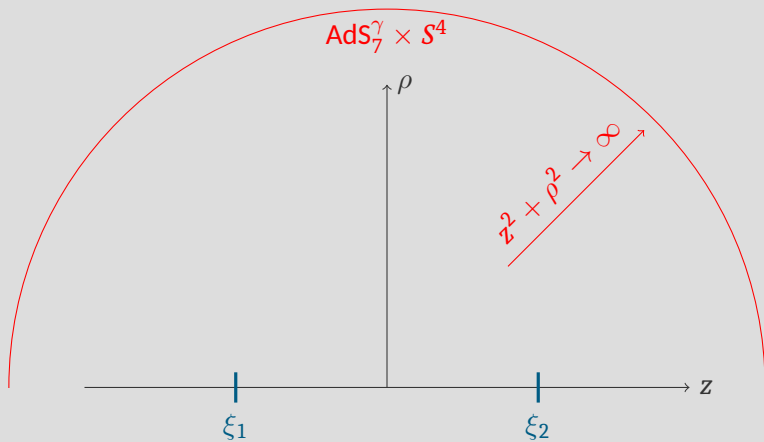




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Geometrical Derivation

3 **New** small $\mathcal{N} = (4, 4)$ surface defect solutions

Given the previous choice of $h, \mathcal{G}$, close to the boundary of AdS_7 (i.e. $v \rightarrow 0$)

$$G = \frac{4L^2}{v^2} \left(dv^2 + g_{\text{AdS}_3} + \frac{(1 + \gamma)^2}{\gamma^2} g_{S^3} \right) + L^2 (d\phi^2 + \sin^2(\phi) g_{\tilde{S}^3}) + \dots \quad (10)$$

$\hookrightarrow$ Asymptotically Locally “ γ -deformed” $\text{AdS}_7 \times S^4$ metric.

Two ways of removing the deformation:

- $\gamma = -\frac{1}{2}$: Wilson surface defects in 6d SCFT
- $\gamma \rightarrow -\infty$: **New** surface defects



Geometrical Derivation

3 New small $\mathcal{N} = (4, 4)$ surface defect solutions

Let's not be too naïve

$$G = f_{\text{AdS}_3}^2(h, \mathcal{G})g_{\text{AdS}_3} + f_{S^3}^2(h, \mathcal{G})g_{S^2} + f_{\tilde{S}^3}^2(h, \mathcal{G})g_{\tilde{S}^3} + f_{\Sigma_2}^2(h, \mathcal{G})g_{\Sigma_2} \quad (11)$$

$\gamma \rightarrow -\infty$ is ill defined (interior blows up).

Solution: rescale the critical points of $\mathcal{G}$ accordingly,

$$\xi_j = \nu_j - \gamma^{-1} \hat{\xi}_j \quad \nu_1 = \nu_2, \quad \nu_3 = \nu_4, \quad \text{etc} \quad (12)$$

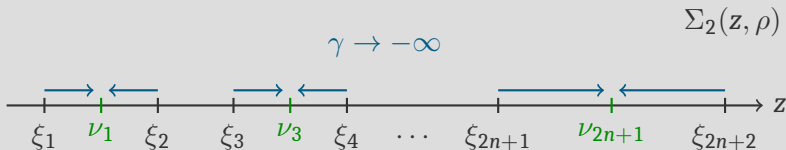
They are now grouped in pairs, in the limit $\gamma \rightarrow -\infty$.



Geometrical Derivation

3 New small $\mathcal{N} = (4, 4)$ surface defect solutions

Taking the $\gamma \rightarrow -\infty$ limit



The general metric solution takes the form

$$G = h_1 H^{-\frac{1}{3}} (g_{\text{AdS}_3} + g_{S^3}) + H^{\frac{2}{3}} (dz^2 + d\rho^2 + \rho^2 g_{\tilde{S}^3}) , \quad (13)$$

where

$$H(z, \rho) = \frac{h_1}{2} \sum_{j=1}^{2n+2} \frac{(-1)^j \hat{\xi}_j}{(\rho^2 + (z - \nu_j)^2)^{3/2}} . \quad (14)$$



Geometrical Derivation

3 New small $\mathcal{N} = (4, 4)$ surface defect solutions

$$G = h_1 H^{-\frac{1}{3}} (g_{\text{AdS}_3} + g_{S^3}) + H^{\frac{2}{3}} (dz^2 + d\rho^2 + \rho^2 g_{\tilde{S}^3}) \quad (15)$$

is precisely the metric part of the solution proposed by Faedo *et al.* [2007.16167]

Advantage of our formulation:

- Found a large set of H that solve the e.o.m.
- Geometry is Ricci-finite
- Allows for an identification of the 2d defect rep. from its Young tableau



The new small $\mathcal{N} = (4, 4)$ solution

3 New small $\mathcal{N} = (4, 4)$ surface defect solutions

All in all, the supergravity solution is fully specified by the following data,

$$G = h_1 H^{-\frac{1}{3}} (g_{\text{AdS}_3} + g_{S^3}) + H^{\frac{2}{3}} (dz^2 + d\rho^2 + \rho^2 g_{\tilde{S}^3}) \quad (16)$$

$$F = 2h_1 \text{vol}_{\text{AdS}_3} \wedge dz + 2h_1 \text{vol}_{S^3} \wedge dz + \partial_z H \rho^3 d\rho \wedge \text{vol}_{\tilde{S}^3} - \partial_\rho H \rho^3 dz \wedge \text{vol}_{\tilde{S}^3} \quad (17)$$

$$H = \frac{h_1}{2} \sum_{j=1}^{2n+2} \frac{(-1)^j \hat{\xi}_j}{(\rho^2 + (z - \nu_j)^2)^{3/2}} \quad (18)$$



The new small $\mathcal{N} = (4, 4)$ solution

3 New small $\mathcal{N} = (4, 4)$ surface defect solutions

What does this solution actually describe?

$$\gamma = -\frac{1}{2} : \quad \mathfrak{d}(2, 1; -\frac{1}{2}; 0) \oplus \mathfrak{d}(2, 1; -\frac{1}{2}; 0) = \mathfrak{osp}(4^*|2) \oplus \mathfrak{osp}(4^*|2) \subset \mathfrak{osp}(8^*|4)$$

Generically it the algebra is not a subalgebra of the 6d $\mathcal{N} = (2, 0)$!

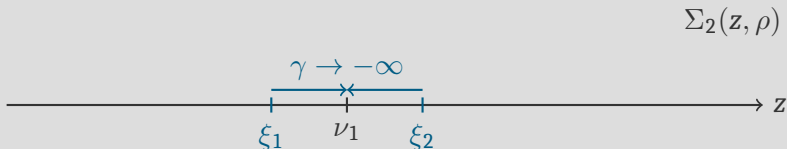
The theory must be deformed somehow... We must be careful when choosing what to call the *vacuum*!



The 1PT vacuum

3 New small $\mathcal{N} = (4, 4)$ surface defect solutions

The simplest configuration we can consider is $n = 0$, a single singularity in H



which is the $\gamma \rightarrow -\infty$ limit of the γ -deformed $\text{AdS}_7 \times S^4$ vacuum.

We call this the *1PV vacuum*.



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Weyl anomaly coefficients

4 Holographic entanglement entropy

Conformal symmetry breaking is characterised by the Weyl anomaly coefficients,

$$\langle T^\mu{}_\mu \rangle = \frac{1}{(4\pi)^3} \left(a\mathcal{E}_6 + b_1 W_{\mu\lambda\nu\rho\nu} W^{\lambda\sigma\tau\rho} W_{\sigma\tau}{}^{\mu\nu} + \dots \right) \quad (19)$$

Including a p -dimensional defect we also get a contribution localized on the defect as

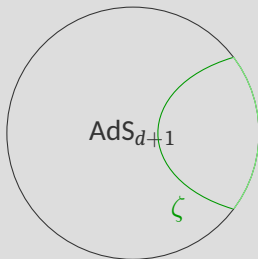
$$T = T_{\text{ambient}} + \delta^p(\Upsilon) T_{\text{defect}} \quad (20)$$



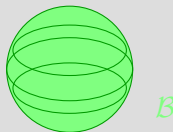
The Ryu-Takayanagi Prescription

4 Holographic entanglement entropy

For a CFT with a weakly-coupled static gravity dual the RT formula allows us to recast the field theory computation of S_{EE} into a Plateau problem in the bulk,



$$S_{EE} = \min_{\zeta} \frac{\mathcal{A}[\zeta]}{4G_N}$$



CFT_d

$$S_{EE} = -\text{tr}_{\mathcal{B}}(\rho_{\mathcal{B}} \ln(\rho_{\mathcal{B}}))$$



The Ryu-Takayanagi Prescription

4 Holographic entanglement entropy

When $\mathcal{B} = B^{d-1}(l)$ is a ball of radius l in CFT_d ,

$$S_{EE} = \begin{cases} p_1 \left(\frac{l}{\epsilon}\right)^{d-2} + \cdots + p_{d-2} \frac{l}{\epsilon} + \textcolor{red}{p}_{d-1} + o(1) & d: \text{ odd} \\ p_1 \left(\frac{l}{\epsilon}\right)^{d-2} + \cdots + p_{d-3} \left(\frac{l}{\epsilon}\right)^2 + \textcolor{red}{q} \ln \left(\frac{l}{\epsilon}\right) + o(1) & d: \text{ even} \end{cases} \quad (21)$$

eg. $d = 2$, $S_{EE} = \frac{c}{3} \ln \left(\frac{l}{a}\right)$

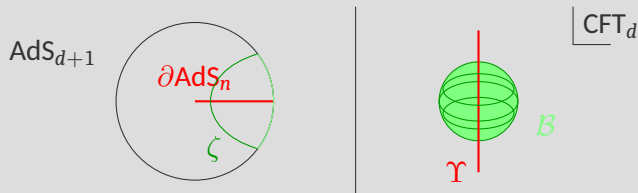
In general, $\textcolor{red}{q}$ or $\textcolor{red}{p}_{d-1}$ contain information about the Weyl anomaly coefficients of the CFT.



The Ryu-Takayanagi Prescription

4 Holographic entanglement entropy

Including defects



In general, properly extracting out defect contributions is *hard*.

The solution, subtracting out the contribution from the ambient CFT,

$$q_\Upsilon = l \frac{d}{dl} (S_{EE}[\Upsilon] - S_{EE}) \quad (22)$$



The Ryu-Takayanagi Prescription

4 Holographic entanglement entropy

Importantly, for a 2d defect in a 6d ambient CFT

$$q_{\Upsilon} = \frac{1}{3} \left(a_{\Upsilon} + \frac{3}{5} d_2 \right) \quad (23)$$

where

$$\langle T^{\mu}_{\mu} \rangle_{\Upsilon} = \frac{1}{24\pi} \left(a_{\Upsilon} \tilde{R} + d_1 \overset{\circ}{\Pi}^2 + d_2 W_{ab}{}^{ab} \right) + \dots \quad (24)$$

(Note that more terms may appear here than for a standalone 2d CFT one-point function)



Holographic Entanglement Entropy for the new defects

4 Holographic entanglement entropy

Applying the RT prescription on the new supergravity solutions, with $S_{EE} = 1PV$, we find

$$q_{\Upsilon} = -\frac{(\varpi, \varpi)}{5} = \frac{1}{3} \left(a_{\Upsilon} + \frac{3}{5} d_2 \right) \quad (25)$$

where ϖ is the highest weight of the irrep. describing the defect.

Can we now separate out a_{Υ} and d_2 ?



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Brief reminder of [de Haro et al. 2000]

5 Holographic renormalization applied to $\langle T \rangle$ (and why it fails)

Asymptotic solutions to Einstein's equation $R_{\mu\nu} - \frac{1}{2}RG_{\mu\nu} = \Lambda G_{\mu\nu}$ may be written in Fefferman-Graham (FG) form

$$G = l^2 \left(\frac{d\rho^2}{4\rho^2} + \frac{1}{\rho}g \right) \quad (26)$$

$$g = g_{(0)} + \cdots + \rho^{d/2}g_{(d)} + f_{(d)}\rho^{d/2}\ln(\rho) + \cdots \quad (27)$$

and obey

$$\rho[2g'' - 2g'g^{-1}g' + \text{Tr}(g^{-1}g')g'] + \text{Ric}(g) - (d-2)g' - \text{Tr}(g^{-1}g')g = 0 \quad (28a)$$

$$\nabla_i \text{Tr}(g^{-1}g') - \nabla^j g'_{ij} = 0 \quad (28b)$$

$$\text{Tr}(g^{-1}g'') - \frac{1}{2}\text{Tr}(g^{-1}g'g^{-1}g') = 0 \quad (28c)$$



Brief reminder of [de Haro et al. 2000]

5 Holographic renormalization applied to $\langle T \rangle$ (and why it fails)

$$g = g_{(0)} + \rho g_{(2)} + \rho^2 g_{(4)} + \rho^3 g_{(6)} + f_{(6)} \rho^3 \ln(\rho) + \dots$$

For Asymptotically locally AdS_7 solutions, we can solve for $g_{(2)}$, $g_{(4)}$ and $f_{(6)}$ in terms of $g_{(0)}$.

The final component, $g_{(6)}$ is related to the stress-energy tensor

$$\langle T_{ij} \rangle = \frac{3}{8\pi G_N} (g_{(6)ij} - A_{(6)ij} + \frac{1}{24} S_{ij}) \quad (29)$$

$\hookrightarrow$ source of Weyl anomaly coefficients

What about $\text{AlAdS}_7 \times S^4$ solutions?



Brief reminder of [de Haro et al. 2000]

5 Holographic renormalization applied to $\langle T \rangle$ (and why it fails)

What about $\text{AlAdS}_7 \times S^4$ solutions?

Start by writing the 11d metric as a perturbation around $\text{AdS}_7 \times S^4$,

$$G = g_{\text{AdS}_7} \oplus g_{S^4} + h_{11} \quad (30)$$

and dimensionally reduce on the S^4

$$g_7 = \left(1 + \frac{\bar{\zeta}}{5}\right) g_{\text{AdS}_7} + \bar{h}_7 \quad (31)$$

Only 0-modes of the internal space contribute.



FG expansion and asymptotic equations

5 Holographic renormalization applied to $\langle T \rangle$ (and why it fails)

Recall that our 11d metric is $\text{AlAdS}_7 \times S^4$ and can be written in the FG gauge

$$g = \frac{L^2}{\rho^2} (d\rho^2 + 4\rho g_6) \oplus L^2 g_4 \quad (32)$$

while the four-form flux

$$F = -\frac{8L^3 \cos(\phi)}{\rho^2} d\rho \wedge (\text{vol}_{\text{AdS}_3} + \text{vol}_{S^3}) - \frac{8L^3 \sin(\phi)}{\rho} d\phi \wedge (\text{vol}_{\text{AdS}_3} + \text{vol}_{S^3}) \quad (33) \\ + 3L^3 \sin^3(\phi) d\phi \wedge \text{vol}_{\tilde{S}^3} + o(1)$$



FG expansion and asymptotic equations

5 Holographic renormalization applied to $\langle T \rangle$ (and why it fails)

Asymptotically close to the boundary, $\rho \rightarrow 0$, the supergravity e.o.m. may be recast into equations for g_6 and g_4 . For example, the (ρ, ρ) component is

$$\begin{aligned} & \frac{1}{2} \text{Tr}(g_6^{-1} g_6' g_6^{-1} g_6') - \text{Tr}(g_6^{-1} g_6'') + (g_6 \leftrightarrow g_4) - \frac{d}{2\rho^2} - \frac{1}{\rho} \text{Tr}(g_4^{-1} g_4') \\ &= -\frac{1}{6} F_{\rho MNP} F_{\rho}{}^{MNP} - \frac{1}{72} \frac{L^2}{\rho^2} F_{MNPQ} F^{MNPQ} \end{aligned} \quad (34)$$

This can be used to solve $g_{6(2)}$ in terms of $g_{6(0)}$, $g_{4(0)}$, $g_{4(2)}$ and F etc.

Problem: F doesn't have the right asymptotics to recover [de Haro]'s equations in 7d.



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Summary of Results

6 Summary, open questions, and future directions

- Identified the supergravity solution from Faedo *et al.* [2007.16167] as the limit of Bachas *et al.* [1312.5477]
- Found new explicit solutions to the e.o.m. of the former (Ricci finite)
- Computed the holographic entanglement entropy of a region around the defect and extracted out a linear combination of Weyl anomaly coefficients
- (not shown here) Established the defect Young tableau - allowing for an identification of the M2/M5-brane charges



Open Questions

6 Summary, open questions, and future directions

- Asymptotically, 4-form flux has YT-independent leading-order term
 - ↪ supergravity solution doesn't admit global $\text{AdS}_7 \times S^4$ configurations
 - ↪ no way of "removing" the defect
 - ↪ isometry superalgebra isn't a subalgebra of $\mathfrak{osp}(8^*|4)$

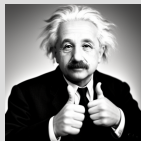
⇒ The $\mathcal{N} = (2, 0)$ theory is deformed... by what? $\text{Tr}(H\phi)$?

- Standard holographic renormalization techniques can't be applied here. How can we fix this?



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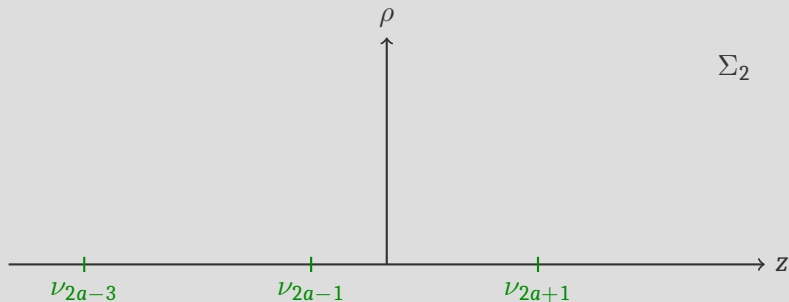
Thank you for your attention





Young tableaux

6 Summary, open questions, and future directions

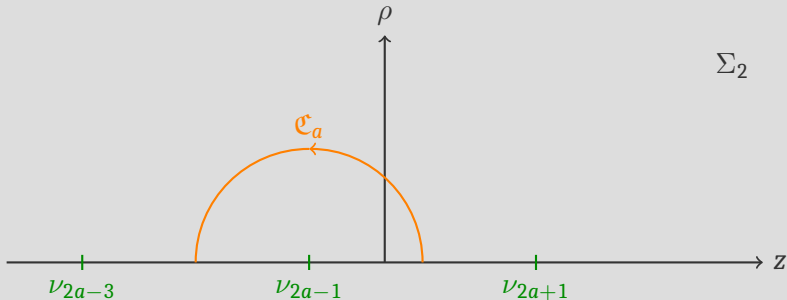


(35)



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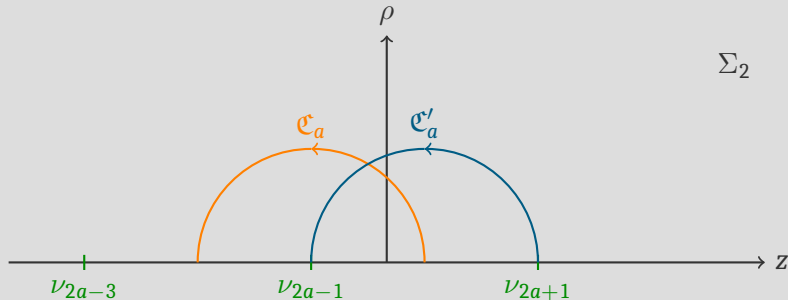


$$M_a = \frac{1}{2(4\pi^2 G_N)^{1/3}} \int_{\mathfrak{C}_a} P_{\mathfrak{C}_a}[\mathcal{F}_{(4)}] \quad (35)$$



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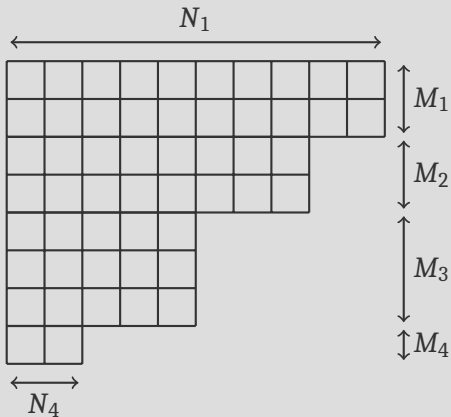


$$M_a = \frac{1}{2(4\pi^2 G_N)^{1/3}} \int_{\mathfrak{C}_a} P_{\mathfrak{C}_a}[\mathcal{F}_{(4)}] \quad M'_a = \frac{1}{2(4\pi^2 G_N)^{1/3}} \int_{\mathfrak{C}'_a} P_{\mathfrak{C}'_a}[\mathcal{F}_{(4)}] \quad (35)$$



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Abstract

6 Summary, open questions, and future directions

In 11d supergravity, there are known solutions with superisometry algebra $d(2,1;\gamma)+d(2,1;\gamma)$ which are holographically dual to the 6d maximally superconformal field theory with 2d superconformal defects. In this talk I will present our work from 2402.11745 in which we show that a limit of these solutions, for which $\gamma \rightarrow -\infty$, reproduces another known class of solutions, holographically dual to small $N=(4,4)$ superconformal surface defects. Notably, our construction produces a finite Ricci scalar, in contrast to the known small $N=(4,4)$ solutions. Using the Ryu-Takayanagi prescription, one can calculate the Entanglement Entropy of a spherical region centered around the defect. I will show how this was done for these new small $N=(4,4)$ solutions, allowing us to extract a linear combination of defect Weyl anomaly coefficients. Finally, I will argue why the standard stress-energy tensor one-point function computation can't be done here, explaining why we can't separate out the A-type and B-type coefficients using these computations alone.