Holographic entanglement entropy at finite temperature

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Outline

Why *holography?*

Dualities $\rightarrow$ formal equivalence between different theories

AdS/CFT correspondence

AdS gravity in $d+1$ dimensions	$=$	CFT in d dimensions

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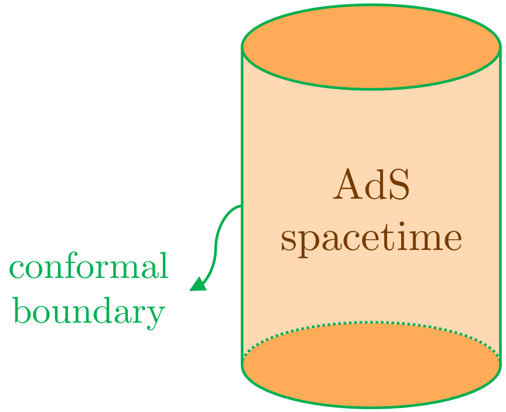
Holographic principle



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AdS/CFT correspondence

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Theory of Quantum Gravity $\Rightarrow$ QFT in flat spacetime

Classical supergravity $\Leftarrow$ Complex computations QFT

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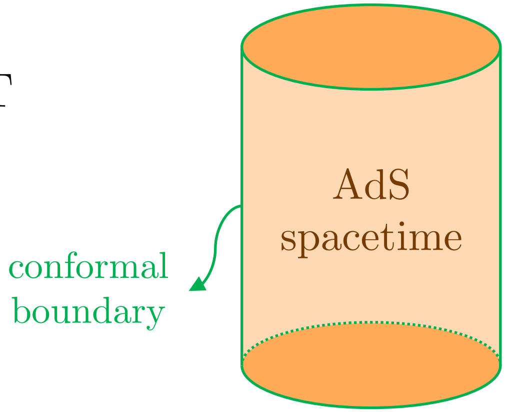

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AdS/CFT dictionary

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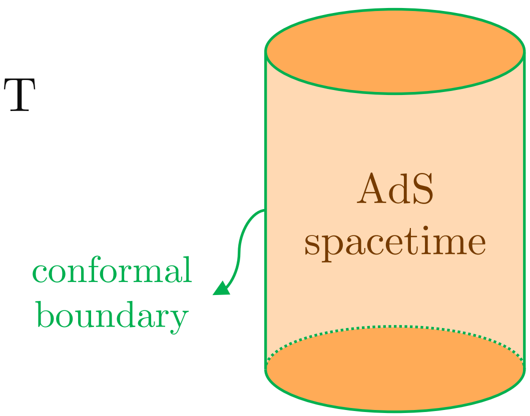

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Formulate holography through **universal quantities**

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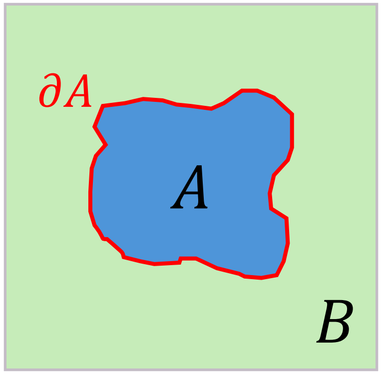
Entanglement entropy

- Non-local quantity, defined in any QM system
- Quantum entanglement complementary spatial regions ($\overline{A} = B$) at a fixed time



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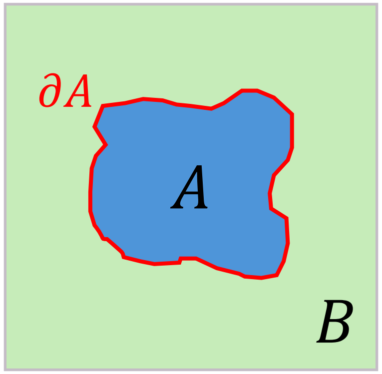

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Applications: - Quantum critical phenomena
- Phase transitions (confinement/deconfinement, ...)
- Characterize quantum phases of matter

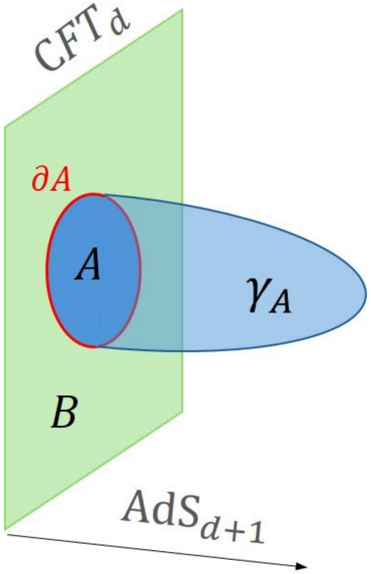
Holographic entanglement entropy

- **Ryu-Takayanagi formula**

  Static geometries

  CFTs dual to Einstein gravity

$$\boxed{S^{\mathrm{E}}_{\mathrm{HEE}}(A) = \frac{\text{Area of } \gamma_A}{4G}} \rightarrow \gamma_A \begin{cases} \text{Surface anchored to } \partial A \\ \text{Minimizes the area functional} \end{cases}$$



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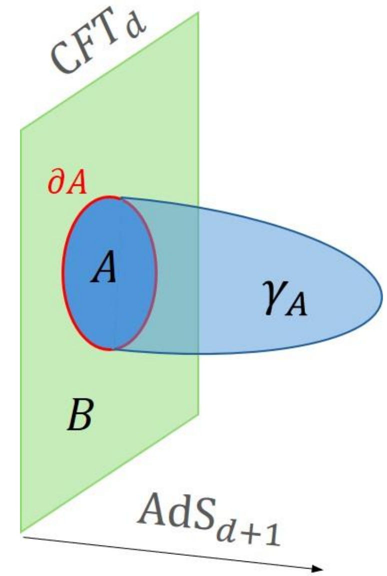

- **Generalized formula**

  Higher-curvature gravities $=$ Broaden spectrum of CFTs

Holographic entanglement entropy

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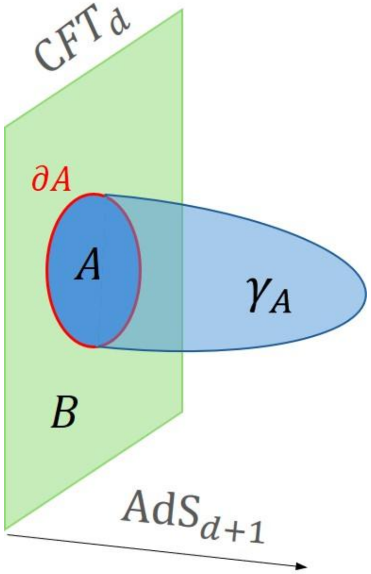


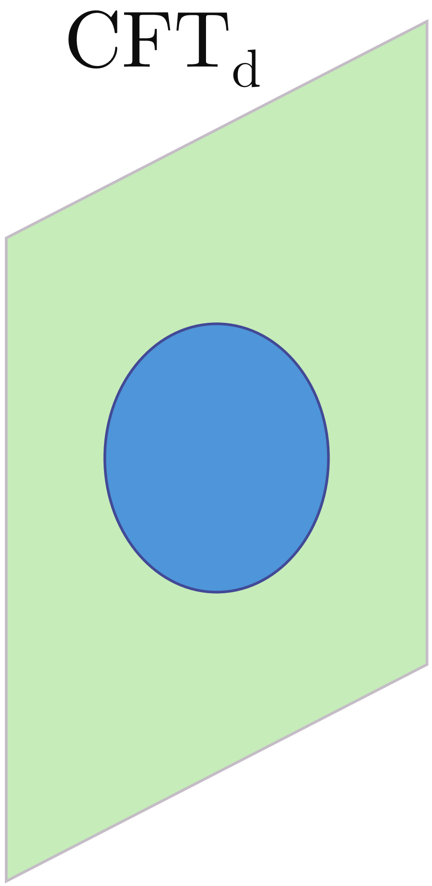
- **Generalized formula**

  Higher-curvature gravities = Broaden spectrum of CFTs

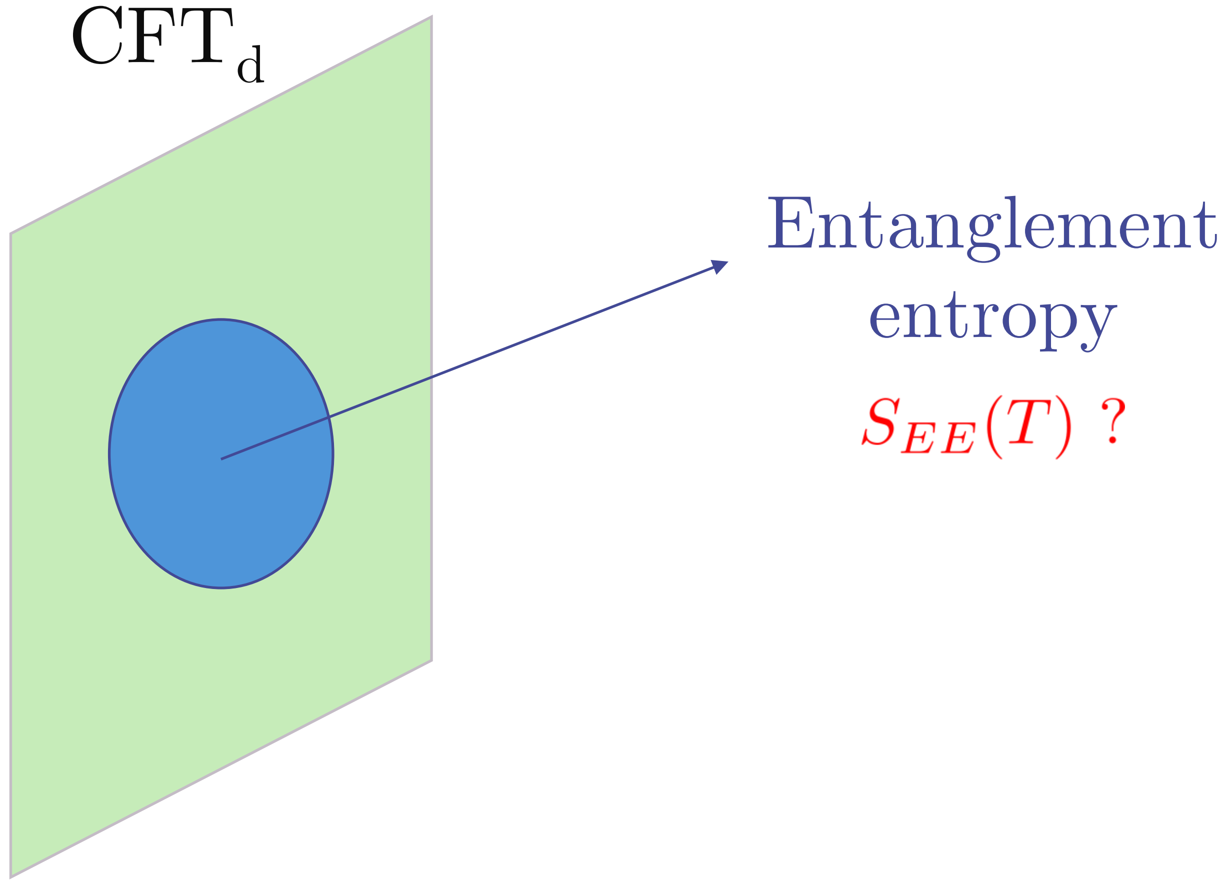
  CFTs dual to Gauss-Bonet (GB) gravity

$$\boxed{S^{\mathrm{GB}}_{\mathrm{HEE}}(A) = \frac{\text{Area of } \gamma_A}{4G} + \frac{1}{4G}\frac{2L^2\lambda}{(d-2)(d-3)}\int_{\gamma_A} d^{d-1}x\sqrt{|h|}\; R} \longrightarrow \gamma_A$$

  - λ : GB coupling
  - h : determinant induced metric on γ_A
  - R : Ricci scalar on γ_A



Flat spacetime
Finite temperature



Flat spacetime
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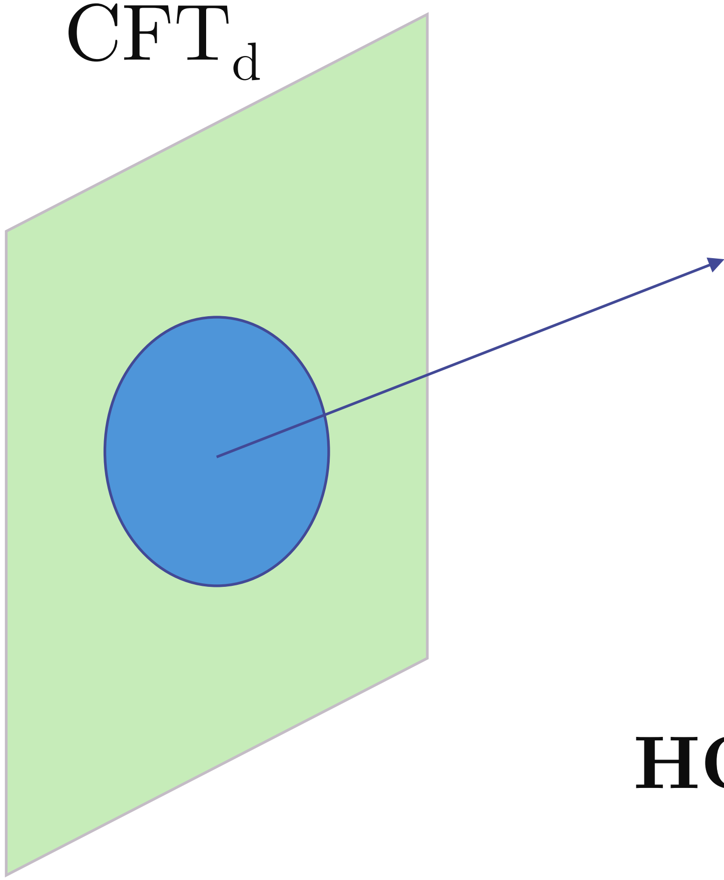
$\mathrm{CFT_d}$



Entanglement entropy

$S_{EE}(T)$?

HOLOGRAPHY!!!

Flat spacetime
Finite temperature

How?

1

AdS/CFT correspondence

- **Zero T** $\mathrm{CFT_d}$ flat spacetime = **Empty** $\mathrm{AdS_{d+1}}$ in Poincaré coordinates
- **Finite T** $\mathrm{CFT_d}$ flat spacetime = **Black** hole $\mathrm{AdS_{d+1}}$ planar horizon

How?

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HEE formula

- RT formula → BH in **Einstein gravity**
- Generalized formula → BH in **GB gravity**

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Low T expansion

- Perturbative expansion around vacuum solution

  ⇒ Universal character of the coefficients?

Zero temperature

Empty AdS_{d+1}

$$ds^2 = \frac{L^2}{z^2}\left(-dt^2 + \sum_{i=1}^{d-1} dx_i^2 + dz^2\right) \qquad z = 0 \rightarrow \text{boundary}$$

- L : AdS curvature radius

Zero temperature

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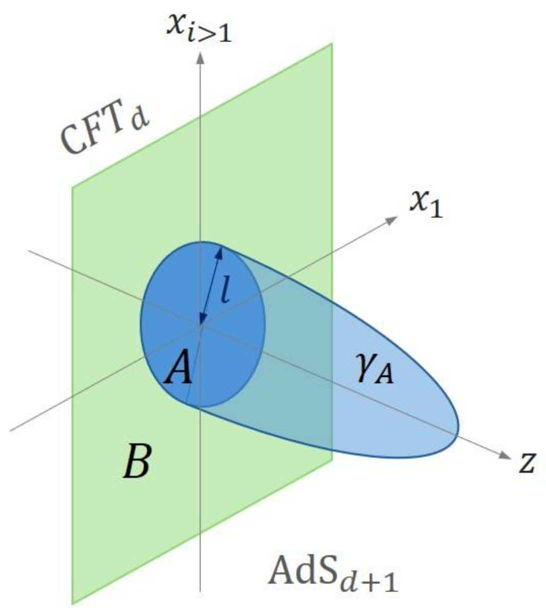
Disk of radius l in a time slice

- Induced metric
- RT functional: $S_{\mathrm{HEE}}^{\mathrm{E,\ vac}}[z(\rho)]$



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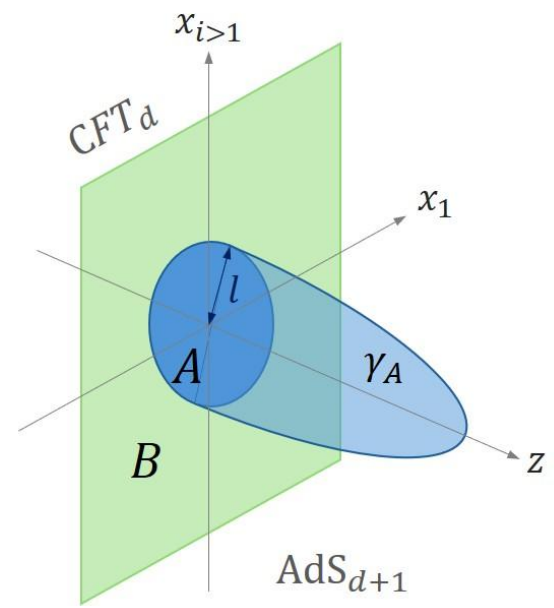

Disk of radius l in a time slice

- Induced metric
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Find the holographic surface γ_A

- Minimizing the functional: $\boxed{z_0(\rho) = \sqrt{l^2 - \rho^2}} \longrightarrow$ half $(d-1)$-dimensional sphere

Finite temperature

AdS$_{\mathrm{d+1}}$ planar BH

$$ds^2 = \frac{L^2}{z^2}\left[-f(z)dt^2 + \sum_{i=1}^{d-1} dx_i^2 + \frac{1}{f(z)}dz^2\right], \quad f(z) \equiv 1 - \left(\frac{r_h z}{L^2}\right)^d$$

- r_h : horizon

Same procedure as before $\rightarrow$ RT functional: $S_{\mathrm{HEE}}^{\mathrm{E,T}}[z(\rho)]$

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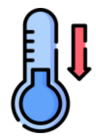
Find $\gamma_A \rightarrow$ Not analytically $\Longrightarrow$  **Low T:** $lT \ll 1 \iff r_h/L \ll 1$

- Metric approaches the empty $\mathrm{AdS}_{d+1} \rightarrow$ Main contribution = zero T result
- Corrections $\rightarrow$ perturbatively, up to 2nd order

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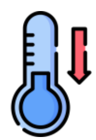
Find $\gamma_A \rightarrow$ Not analytically $\Longrightarrow$  **Low T:** $lT \ll 1 \iff r_h/L \ll 1$

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Divergent $\Rightarrow$ Finite quantity = **relative entropy:** $\Delta S_{\mathrm{HEE}}^{\mathrm{E}} \equiv S_{\mathrm{HEE}}^{\mathrm{E},T} - S_{\mathrm{HEE}}^{\mathrm{E,vac}}$

Finite temperature

- **Relative entropy result**

$$\Delta S^{\mathrm{E}}_{\mathrm{HEE}} = \frac{2^{2d+1}\pi^{\frac{3d+1}{2}}}{d^d(d+1)\Gamma\left(\frac{d-1}{2}\right)}\left(\frac{L}{l_p}\right)^{d-1}(lT)^d + \frac{8^{d-1}\pi^{\frac{5d}{2}+1}\left[d^2(7d+12)-3\right]\Gamma(d)}{d^{2d}(d+1)\Gamma\left(\frac{d-1}{2}\right)\Gamma\left(d+\frac{5}{2}\right)}\left(\frac{L}{l_p}\right)^{d-1}(lT)^{2d}$$

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- **Central charges**

• **2-point function:** $\langle T_{ab}(x)T_{cd}(0)\rangle = \frac{\boldsymbol{C_T}}{x^{2d}}\,\mathcal{I}_{ab,cd}(x)$

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• **Entropy density:** $s = \boldsymbol{C_s}\, T^{d-1}$

$$C^{\mathrm{E}}_s = 2\pi\left(\frac{4\pi}{d}\right)^{d-1}\left(\frac{L}{l_p}\right)^{d-1}$$

Finite temperature

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$$C^{\mathrm{E}}_T \propto \frac{L}{l_p}\,,\; C^{\mathrm{E}}_s \propto \frac{L}{l_p}$$

1 dimensionless parameter in Einstein gravity

⇓

Expansion coefficients are fixed

$\Rightarrow$ C^{E}_T and C^{E}_s indistinguishable

Zero temperature

Empty $\mathrm{AdS}_{\mathrm{d+1}}$

$$ds^2 = \frac{L^2}{z^2}\left(-dt^2 + \sum_{i=1}^{d-1} dx_i^2 + \frac{1}{f_\infty} dz^2\right), \qquad f_\infty = \frac{1-\sqrt{1-4\lambda}}{2\lambda}$$

- $f_\infty \equiv f(z=0)$
- $\tilde{L} = L/\sqrt{f_\infty}$: AdS curvature radius

Generalized HEE formula

- Functional: $S_{\mathrm{HEE}}^{\mathrm{GB,\ vac}}[z(\rho)]$

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Find the holographic surface γ_A

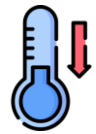
- $\boxed{z_0(\rho) = \sqrt{f_\infty(l^2-\rho^2)}} \longrightarrow$ half $(d-1)$-dimensional ellipsoid

Finite temperature

GB planar BH

$$ds^2 = \frac{L^2}{z^2}\left(-\frac{f(z)}{f_\infty}dt^2 + \sum_{i=1}^{d-1} dx_i^2 + \frac{1}{f(z)}dz^2\right), \quad f(z) = \frac{1}{2\lambda}\left[1 - \sqrt{1 - 4\lambda\left(1 - \left(\frac{r_h z}{L^2}\right)^d\right)}\right]$$

- r_h : horizon

Find $\gamma_A \rightarrow$ Not analytically $\Longrightarrow$  **Low T:** $lT \ll 1$

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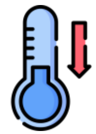
Find $\gamma_A \rightarrow$ Not analytically $\Longrightarrow$  **Low T:** $lT \ll 1$

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▶ Relative entropy result

$$\Delta S^{\mathrm{GB}}_{\mathrm{HEE}} = \frac{4^d \pi^{\frac{3d}{2}+1}(f_\infty)^{d-1}}{d^d(d+1)\Gamma\left(\frac{d}{2}\right)}\left(\frac{\tilde{L}}{l_p}\right)^{d-1}(lT)^d + \frac{2^{4d-5}\pi^{\frac{5d}{2}+1}\Gamma\left(\frac{d+1}{2}\right)K(d,f_\infty)}{d^{2d}(d-3)(d+1)\Gamma\left(d+\frac{5}{2}\right)}\frac{(f_\infty)^{2d-1}}{(f_\infty-2)^2}\left(\frac{\tilde{L}}{l_p}\right)^{d-1}(lT)^{2d}$$

$$K(d,f_\infty) \equiv -\left[d\Big(d(d(7d+51)+52)-23\Big)-15\right]f_\infty + 2d\Big[d(7d(d+3)+8)-13\Big]-6$$

Finite temperature

- **Central charges**

  - **2-point function:**

$$C_T^{\mathrm{GB}} = \frac{d+1}{d-1}\frac{\Gamma(d+1)}{\pi^{\frac{d}{2}}\Gamma\left(\frac{d}{2}\right)}\left(\frac{\tilde{L}}{l_p}\right)^{d-1}\left(1-2f_\infty\lambda\right)$$

  - **Entropy density:**

$$C_s^{\mathrm{GB}} = 2\pi\left(\frac{4\pi f_\infty}{d}\right)^{d-1}\left(\frac{\tilde{L}}{l_p}\right)^{d-1}$$

Finite temperature

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2 dimensionless parameters in GB gravity

$\Rightarrow$ C_T^{GB} and C_s^{GB} independent

Finite temperature

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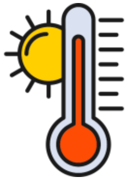
Results

- $C_T^{\text{GB}} \rightarrow$ expansion coefficients depend non-trivially on f_∞
- $C_s^{\text{GB}} \rightarrow$ $\boxed{\Delta S_{\text{HEE}}^{\text{GB},C_s} = \frac{2\pi^{\frac{d}{2}+1}}{d(d+1)\Gamma\left(\frac{d}{2}\right)}C_s^{\text{GB}}(lT)^d + \mathcal{O}\left((lT)^{2d}\right)}$

Universal character of the 1st order term??



High temperature

Leading contribution = thermal entropy

Incomplete AdS/CFT dictionary

Simple expression for the expansion coefficients

Other gravitational theories

Same behavior?

Thank you!!

Backup

Gravitational action (d+1 dimensions)

- **Einstein-Hilbert action + cosmological constant term**

$$\boxed{I_{\mathrm{E}} = \frac{1}{16\pi G}\int d^{d+1}x\sqrt{|g|}\left[\frac{d(d-1)}{L^2} + R\right]}$$

- **+ Gauss-Bonnet term**

Quadratic correction to General Relativity

$$\boxed{I_{\mathrm{GB}} = \frac{1}{16\pi G}\int d^{d+1}x\sqrt{|g|}\left[\frac{d(d-1)}{L^2} + R + \frac{L^2\lambda}{(d-2)(d-3)}\mathcal{X}_4\right]}$$

  - $\mathcal{X}_4 = R_{\mu\nu\gamma\delta}R^{\mu\nu\gamma\delta} - 4R_{\mu\nu}R^{\mu\nu} + R^2$
  - λ: GB coupling

Low temperature expansion

Expansion parameter: $\varepsilon = (r_h/L)^d$

- RT functional

$$S^{\mathrm{E},T}_{\mathrm{HEE}}[z] = S_0[z] + \varepsilon \mathcal{S}_1[z] + \varepsilon^2 S_2[z] + \mathcal{O}(\varepsilon^3) \;\rightarrow\; S_0 \equiv S^{\mathrm{E,\,vac}}_{\mathrm{HEE}}\text{: zero T functional}$$

- Holographic surface

$$z(\rho) = z_0(\rho) + \varepsilon z_1(\rho) + \varepsilon^2 z_2(\rho) + \mathcal{O}(\varepsilon^3) \;\rightarrow\; z_0(\rho)\text{: zero T surface}$$

$$\boxed{S^{\mathrm{E},T}_{\mathrm{HEE}} = S^{\mathrm{E,vac}}_{\mathrm{HEE}}[z_0] + \varepsilon S_1[z_0] + \varepsilon^2 \left(S_2[z_0] + \frac{1}{2}\int d\rho' \frac{\delta S_1[z_0]}{\delta z(\rho')} z_1(\rho') \right) + \mathcal{O}(\varepsilon^3)}$$

$$\begin{cases} S_1, S_2 \;\rightarrow\; \text{known} \\ z_0 \;\rightarrow\; \text{known} \\ z_1 \;\rightarrow\; \text{1st order solution of the Euler-Lagrange equation} \end{cases}$$

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