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Comments on entanglement entropy in the dS/CFT correspondence

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based on PRD 91 (2015) 8, 086009 [arXiv:1501.04903]

Plan of my talk

1. Introduction
2. Proposal for holographic entanglement entropy in Einstein gravity on dS
3. Comparison with a toy model
4. Conclusion & Discussion

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    i. dS/CFT correspondence
    ii. Entanglement entropy
2. Proposal for holographic entanglement entropy in Einstein gravity on dS
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dS/CFT correspondence

- AdS/CFT relates gravitational theories on AdS with non-gravitational theories.

  ➡ We can analyze quantum gravitational theories using non-gravitational theories.

- Toward a quantum description of our Universe, holography may be useful.

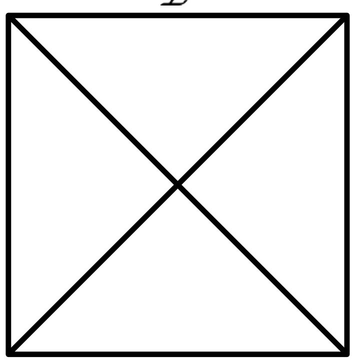
  ➡ We need dS/CFT instead of AdS/CFT since our Universe is approximately dS.

- dS/CFT was proposed by Witten & Strominger.

  [Witten, hep-th/0106109]
  [Strominger, JHEP 0110 (2001) 034]

  ➡ Dual CFTs live in $\mathcal{I}^+$ if they exist.

$\mathcal{I}^+$



Penrose diagram

dS/CFT correspondence

- In 2011, a concrete example of dS/CFT was proposed.

[Anninos-Hartman-Strominger, arXiv:1108.5735 [hep-th]]

4-dim Vasiliev's higher-spin gauge theory on dS $\Longleftrightarrow$ 3-dim Sp(N) vector model with anti-commuting scalars

(This duality is double Wick rotation of the duality between "4-dim Vasiliev's higher-spin gauge theory on AdS" and "3- dim O(N) vector model".)

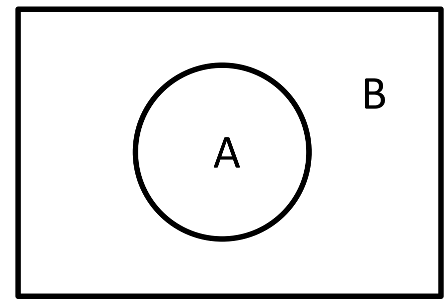
- The CFT holographic dual to Einstein gravity is not known yet.

If we perform analytic continuation of AdS/CFT obtained in String theory, gravity side's theories contain imaginary flux.

Entanglement entropy

- Definition

  (i) divide the total system into A and B



$$\mathcal{H}_{\mathrm{tot}} = \mathcal{H}_A \times \mathcal{H}_B$$

  (ii) introduce a reduced density matrix

$$\rho_A = \mathrm{tr}_B \rho_{\mathrm{tot}} \quad \text{where} \quad \rho_{\mathrm{tot}} = |\Psi\rangle\langle\Psi|$$

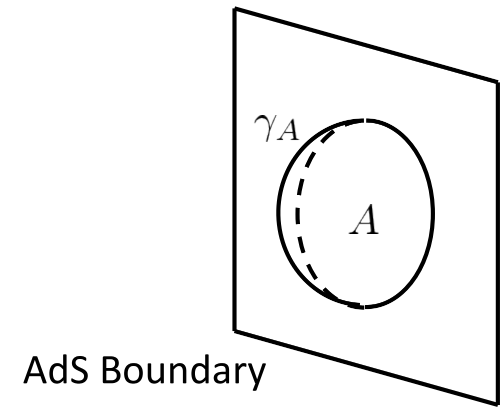
wave function

  (iii) entanglement entropy (EE) is defined as

$$S_A = \underbrace{-\mathrm{tr}_A \rho_A \log \rho_A}_{\text{definition}} = \underbrace{-\lim_{n\to 1} \frac{\partial}{\partial n} \mathrm{tr}_A \rho_A^n = -\lim_{n \to 1} \frac{\partial}{\partial n} \log \mathrm{tr}_A \rho_A^n}_{\text{analytic continuation}}$$

- Entanglement entropy measures how subsystems A & B correlate each other.

Ryu-Takayanagi formula



- Holographic dual of EE is given by Ryu-Takayanagi formula

[Ryu-Takayanagi, PRL 96 (2006) 181602]

$$S_A = \frac{\text{Area of } \gamma_A}{4G_{\rm N}} \longleftarrow \text{extremal surfaces}$$

- The holographic entanglement entropy (HEE) is a useful quantity to analyze gravitational theories.

  In fact, Einstein's equation and a radial component of AdS metric are constructed from HEE, for instance.

  [Nozaki-Ryu-Takayanagi, PRD 88 (2013) 2, 026012]
  [Lashkari-McDermott-Raamsdonk, JHEP 1404 (2014) 195]

- HEE is a generalised quantity of the black hole entropy.

  [Lewkowycz-Maldacena, JHEP 1308 (2013) 090]

  Black hole entropy formula holds even in dS and flat spacetime.

$\Rightarrow$ HEE formula should hold in dS!!

I investigate HEE in dS/CFT.

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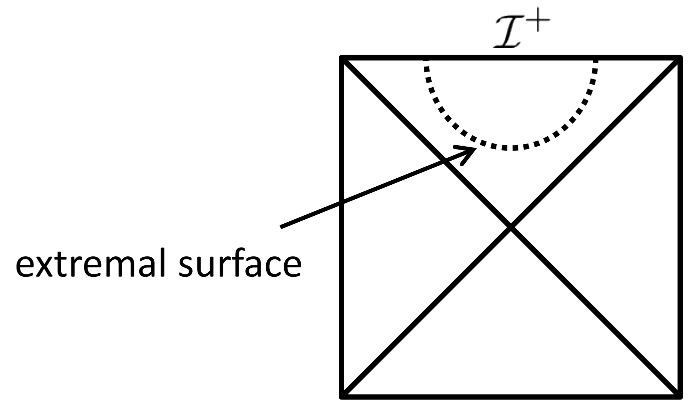
Proposal



- We need to find extremal surfaces whose boundaries sit in $\mathcal{I}^+$.

- We propose that

"extremal surfaces" in dS

= analytic continuations of that in Euclidean AdS.

- Comments

  i. You can obtain the same extremal surfaces using EOM obtained from the area functional if you allow that they extend in complex-valued coordinates.

  ii. Our proposal can be generalised to a more general set of asymptotically dS.

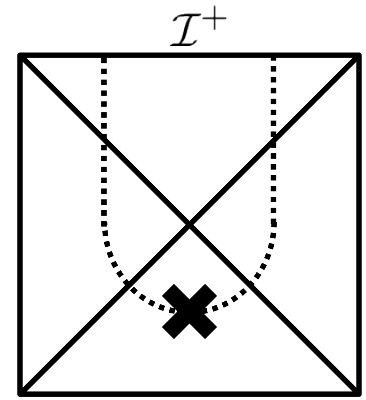
Comments on other possibilities

- time-like surface

Time-like surfaces at a constant position would be extremal.

However, they are not closed in general.

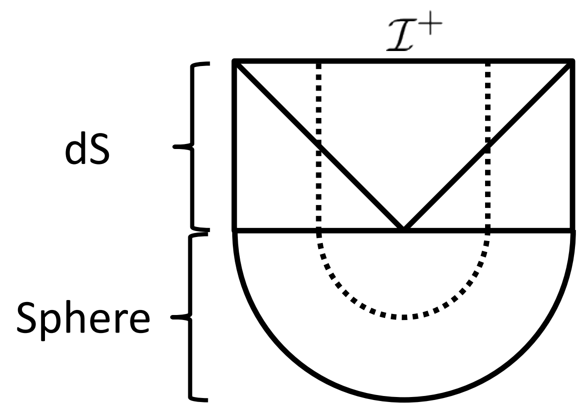
➡ This case is not appropriate.



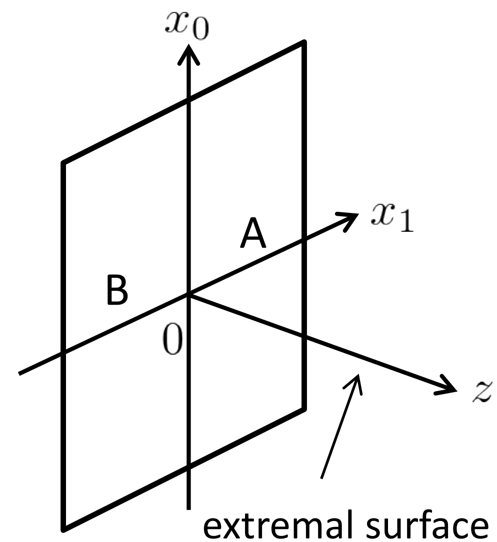
- Hartle-Hawking state (a half sphere + a half dS)

HEE becomes a sum of a pure real part and a pure imaginary part.

➡ This result largely disagrees with our results in Sp(N) model.



Example: half plane



- Take the region A as a half plane.

Metric: $\mathrm{d}s^2 = \ell_{\mathrm{AdS}}^2 \dfrac{\mathrm{d}z^2 + \sum_{i=1}^d \mathrm{d}x_i^2}{z^2}$

Extremal surface: $0 \le z < \infty$

$$\Rightarrow \quad S_A = \frac{V_{d-2}}{4G_{\mathrm{N}}} \int_\varepsilon^\infty \mathrm{d}z \left(\frac{\ell_{\mathrm{AdS}}}{z} \right)^{d-1} = \frac{V_{d-2}\ell_{\mathrm{AdS}}^{d-1}}{4G_{\mathrm{N}}(d-2)} \cdot \frac{1}{\varepsilon^{d-2}}$$

- Double analytic continuation: $z \to -i\eta \,, \quad \ell_{\mathrm{AdS}} \to -i\ell_{\mathrm{dS}}$

Metric: $\mathrm{d}s^2 = \ell_{\mathrm{dS}}^2 \dfrac{-\mathrm{d}\eta^2 + \sum_{i=1}^d \mathrm{d}x_i^2}{\eta^2}$

Extremal surface: $0 \le \eta < i\infty$

Entanglement entropy: $S_A = (-i)^{d-1} \dfrac{V_{d-2}\ell_{\mathrm{dS}}^{d-1}}{4G_{\mathrm{N}}(d-2)} \cdot \dfrac{1}{\varepsilon^{d-2}}$

In general, extremal surfaces extend in complex-valued coordinates.

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Sp(N) model

- The CFT holographic dual to Einstein gravity on dS is not known yet.

  ➡ analyze the free Sp(N) model, which is the holographic dual of Vasiliev's higher-spin gauge theory

- Action (d-dim)

$$I = \int \mathrm{d}^d x \, \Omega_{ab} \partial \chi^a \cdot \partial \chi^b \quad \text{where} \quad \Omega_{ab} = \begin{pmatrix} 0 & 1_{N/2 \times N/2} \\ -1_{N/2 \times N/2} & 0 \end{pmatrix}$$

Introducing $\eta^a = \chi^a + i\chi^{a+\frac{N}{2}} \,, \quad \bar{\eta}^a = -i\chi^a - \chi^{a+\frac{N}{2}} \qquad (a = 1, \cdots, N/2)$

➡ $$I = \int \mathrm{d}^d x \, \partial \bar{\eta}^a \cdot \partial \eta^a$$

- χ^a , η^a and $\bar{\eta}^a$ are anti-commuting scalar fields.

Replica trick

- Entanglement entropy

$$S_A = -\mathrm{tr}_A \rho_A \log \rho_A = -\lim_{n\to 1} \frac{\partial}{\partial n} \mathrm{tr}_A \rho_A^n = -\lim_{n\to 1} \frac{\partial}{\partial n} \log \mathrm{tr}_A \rho_A^n$$

This calculation is difficult. Instead, we calculate $\mathrm{tr}_A \rho_A^n$.

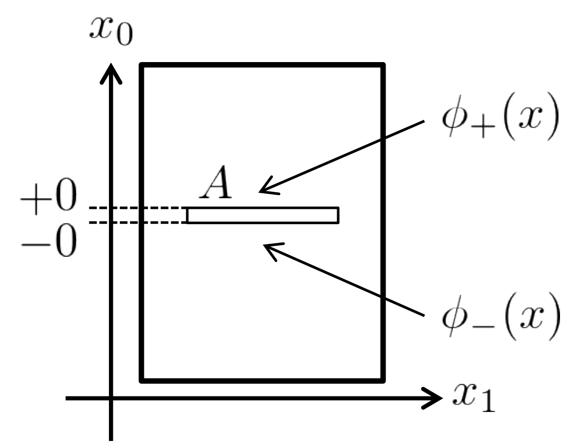
- Wave function for a ground state

$$\Psi[\phi(\boldsymbol{x}, x_0 = 0)] = \frac{1}{\sqrt{Z}} \int \prod_{-\infty < x_0 < 0} \prod_{\boldsymbol{x}} \mathrm{d}\phi \, \mathrm{e}^{-S[\phi]} \delta[\phi(0, \boldsymbol{x}) - \phi(\boldsymbol{x})]$$

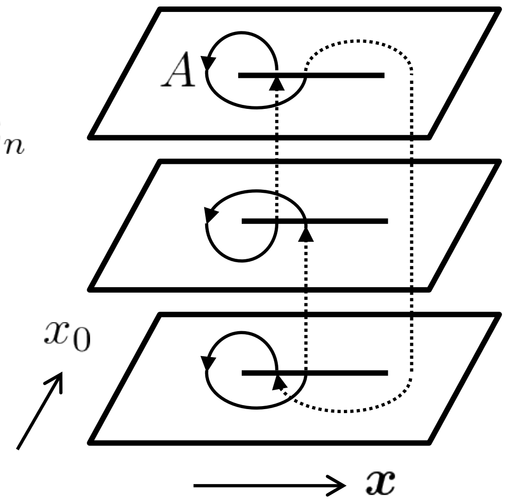
$$\Psi^*[\phi(\boldsymbol{x}, x_0 = 0)] = \frac{1}{\sqrt{Z}} \int \prod_{0 < x_0 < \infty} \prod_{\boldsymbol{x}} \mathrm{d}\phi \, \mathrm{e}^{-S[\phi]} \delta[\phi(0, \boldsymbol{x}) - \phi(\boldsymbol{x})]$$

- Path integral representation of ρ_A

$$[\rho_A]_{\phi_- \phi_+} = \frac{1}{Z} \int \prod_{x} \mathrm{d}\phi \, \mathrm{e}^{-S[\phi]} \prod_{\boldsymbol{x} \in A} \delta[\phi(-0, \boldsymbol{x}) - \phi_-(\boldsymbol{x})] \times \delta[\phi(+0, \boldsymbol{x}) - \phi_+(\boldsymbol{x})]$$



Replica trick



- $\mathrm{tr}\rho_A^n$ is given by a partition function on Riemann surface Σ_n

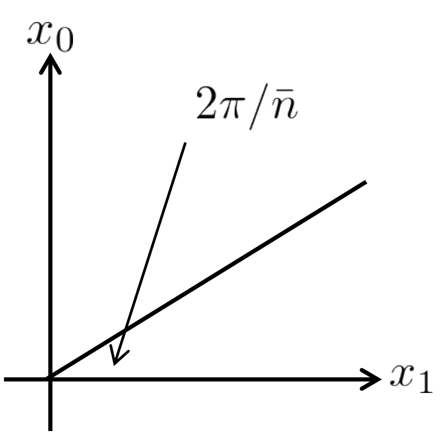
$$\mathrm{tr}\rho_A^n = \frac{1}{Z^n}\int \prod_{x\in\Sigma_n} \mathrm{d}\phi\, \mathrm{e}^{-S[\phi]}$$

- EE for a free scalar field theory (the subsystem is a half plane)

We take $n \to 1/\bar{n}$ where $\bar{n}$ is integer.

➡ We need to evaluate the partition function on $\mathbb{R}^2/Z_{\bar{n}} \times \mathbb{R}^{d-2}$.

$$\begin{aligned} S_A &= -\lim_{n\to 1}\frac{\partial}{\partial(1/n)}\left(\log Z_{\mathbb{R}^2/Z_n\times\mathbb{R}^{d-2}} - \frac{1}{n}\log Z_{\mathbb{R}^d}\right) \\ &= \frac{V_{d-2}}{6(d-2)(4\pi)^{(d-2)/2}}\cdot\frac{1}{\varepsilon^{d-2}} + \mathcal{O}(\varepsilon^{-(d-4)}) \end{aligned}$$



Entanglement entropy in Sp(N) model

- Differences from the scalar field theory

  (i) anti-commuting scalars

  ➡ EE in Sp(N) model is minus that of the usual scalar field theory.

  (ii) N complex fields

  ➡ EE is proportional to N.

$$\boxed{S_A = -\frac{NV_{d-2}}{6(d-2)(4\pi)^{\frac{d-2}{2}}} \cdot \frac{1}{\varepsilon^{d-2}}}$$

- Comment

  EE is a positive definite quantity in usual.

  However, EE in Sp(N) model is negative.

  ➡ Hilbert space of Sp(N) model is not positive definite.

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Conclusion & Discussion

- We have obtained HEE & EE.

  HEE behaves as $S_A \propto (-i)^{d-1}$ in dS_d+1.

  EE behaves as $S_A \propto -S_A^{\text{standard field theories}}$.

- dS_d+1/CFT_d correspondence makes senses only when $d+1 \in 4\mathbb{Z}$

  ➡ The most interesting case, dS_4/CFT_3, is included.

  The most simple case, dS_3/CFT_2, is excluded.

  This is consistent with the result in subsection 5.2 in [Maldacena, JHEP 0305 (2003) 013].

- Our proposal has been checked only in the simple case, half plane.

  However, our proposal holds in any entanglement surfaces.

Thank you for
your attention!!