Holographic entanglement and causal shadow in the time-dependent Janus black hole†

Y. Nakaguchi,[*1,*2] N. Ogawa,[*3] and T. Ugajin[*4]

The relation between entanglement and the black hole interior has been attracting attention recently. For eternal AdS black holes, some interior information is captured by the entanglement entropy of an interval on the dual theory, i.e. a thermofield doubled CFT[1)].

In some kinds of black holes, the interior appears even more difficult to access since they have "causal shadow" regions inside. In this work, we consider one such black hole, called the three-dimensional time-dependent Janus black hole[2)],

$$ds^2 = L^2\left[dy^2 + \frac{r_0^2}{\tilde{g}(y)^2\cosh^2 r_0 t}(-dt^2+d\theta^2)\right],$$
$$\tilde{g}(y) = \sqrt{\frac{2}{1+\sqrt{1-2\gamma^2\cosh 2y}}}, \tag{1}$$

where γ is a deformation parameter from the BTZ black hole. This is a solution of the Einstein-scalar theory and it corresponds to a pair of two entangled 2D CFTs, whose coupling constants are different from each other.

This geometry has a horizontally extended Penrose diagram as shown in Fig. 1. The remarkable property of this geometry is the existence of a so-called "causal shadow region," which is causally inaccessible from both boundaries.

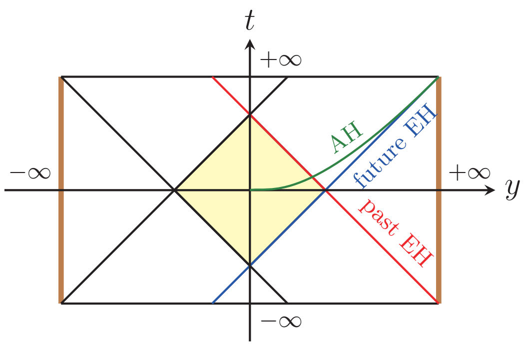

Fig. 1. Penrose diagram of the 3D time-dependent Janus black hole. The causal shadow is painted yellow. The apparent horizons (green line) in the time slices τ = const. are located inside the future event horizon.

We studied the time-evolution of the same entanglement entropy in this system in a holographic manner, by using the Ryu-Takayanagi formula. As in the BTZ black hole, there are two candidate extremal surfaces in the bulk, whose area gives the entanglement entropy. One of the extremal surfaces, which we call the connected surface, connects two asymptotic boundaries and probes the black hole interior. The other extremal surface, which we call the disconnected surface, localizes near each of the asymptotic boundaries.

In the Janus black hole, when the deformation from the BTZ black hole is not so large, we found a similar behavior but with the critical time t_c shorter than that of the BTZ black hole. Roughly speaking, this is because the deformation makes the wormhole region longer and results in a longer connected surface. The results for the time evolution of the entanglement entropy of each phase are plotted in Fig. 2.

In addition, we also found that with a sufficiently large deformation, the disconnected surface is always dominant, and that the holographic entanglement entropy is already proportional to the size of the subsystem from the initial time. This means that the entanglement entropy of this subsystem does not probe the black hole interior.

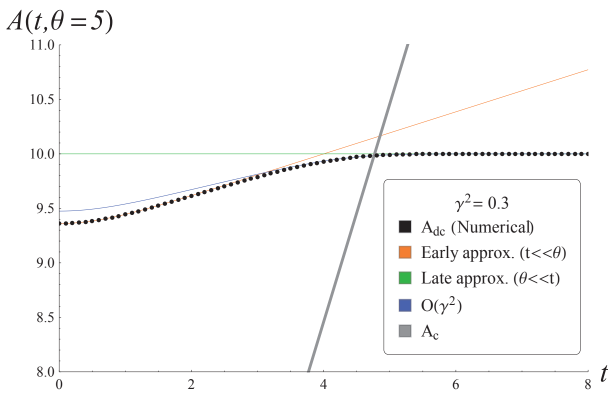

Fig. 2. The time t dependence of the extremal surface area A for a subsystem $\theta = 5$, in the disconnected phase (black dotted line, numerically obtained) and in the connected phase (gray line).

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*1 Institute for the Physics and Mathematics of the Universe, University of Tokyo
*2 Department of Physics, University of Tokyo
*3 RIKEN Nishina Center
*4 Kavli Institute for Theoretical Physics, University of California

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