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科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Exploring de Sitter Holography via Quantum Information

研究課題名（英文）Exploring de Sitter Holography via Quantum Information

研究代表者
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交付決定額（研究期間全体）：（直接経費）　　2,200,000円

研究成果の概要（和文）：この研究プロジェクトでは、量子情報理論と量子重力が交差する新しい視点を探求した。具体的には、大域的なdS空間を時間的な境界で切断することで、新しいバージョンのde Sitterホログラフィーを提案した。我々は、半分のdS空間における重力が、その境界に存在する高度に非局所的な場の理論と双対であることを示した。この非局所性は、ホログラフィックなもつれエントロピーの亜加法性の違反によって反映される。
さらに、ホログラフィックな複雑性の新しい候補として、無限共次元ゼロの重力観測量を導入した。また、この提案を応用して、AdSブラックホールの内部形状を調べ、ブラックホールの特異点を探る。

研究成果の学術的意義や社会的意義
Our research bridges quantum information theory, and quantum computing with quantum gravity, offering fresh insights into the enigmas of black holes and cosmology spacetime. de Sitter holography may provide new perspectives on understanding the universe's origin and evolution.

研究成果の概要（英文）：This research project explored new perspectives on the intersection of quantum information theory and quantum gravity. Specifically, we proposed a new version of de Sitter (dS) holography by cutting the global dS space with a timelike boundary. By exploring the holographic entanglement entropy in half de Sitter space, we demonstrated that gravity in a (d+1)-dimensional half dS space is dual to a highly non-local field theory residing on its d-dimensional de Sitter boundary. This non-locality is reflected by the violation of the subadditivity of holographic entanglement entropy.
Additionally, based on the "complexity=anything" proposal, we introduced infinite codimension-zero gravitational observables as new candidates for holographic complexity. These observables exhibit universal features such as linear growth over time and the switchback effect. We also applied this proposal to investigate the interior geometry of AdS black holes and probe the black hole singularity.

研究分野：Theoretical Physics

キーワード：de Sitter space　de Sitter Holography　Holographic Complexity　AdS/CFT Correspondence　Black Hole　Singularity

１．研究開始当初の背景

Over the past ten years, fruitful developments have shown that concepts and techniques from quantum information theory have provided profound insights and have driven important advances in quantum field theory, condensed matter physics, and quantum gravity. The connection of quantum gravity with quantum information opens the possibility of a novel and fruitful collaboration between distinct disciplines and communities.
(1) Built on the celebrated Ryu-Takayanagi formula, extraordinary developments over the last decade have deepened our understanding of many deepest problems in quantum gravity, e.g., the black hole information paradox and the emergence of spacetime. However, most progress is achieved in the framework of the AdS/CFT correspondence (or gauge/gravity duality) and only applies to an asymptotically anti-de Sitter (AdS) spacetime. A long-standing and intriguing question is: does the holographic principle apply to cosmologies like de Sitter spacetime?

(2) It has become clear that entanglement entropy alone is not sufficient to fully capture the time evolution of a quantum system. For example, it grows only for a short time until the system is thermalized. From a holographic perspective, this is reflected in the fact that holographic entanglement entropy is unable to probe the bulk of spacetime far beyond the event horizon of black holes. To overcome these limitations, it is essential to investigate alternative quantum information measures. A fascinating concept that has recently entered this discussion is the quantum circuit complexity. In terms of the bulk gravitational theory, the discussion of quantum complexity has drawn attention to new kinds of observables. The three proposals that have been studied most extensively are: complexity=volume, complexity=action and complexity=spacetime volume.

２．研究の目的

(1) Recent developments on the interface between quantum information theory and quantum gravity have suggested that quantum information perspectives led to fascinating new insights into fundamental questions about quantum gravity. Based on those previous lessons from the AdS/CFT correspondence and quantum information theory, this research project aims to explore de Sitter entropy and de Sitter holography by bringing to bear the mindset and tools of quantum information theory.

(2) Quantum complexity has recently triggered much interest in the context of black holes and holography, as a new twist in the ongoing effort connecting quantum information theory to quantum gravity. It is important to note that the definition of circuit complexity is ambiguous because the exact value of the complexity is sensitive to the choice of the reference state, the set of gates and the costs assigned to different types of gates. These ambiguities are inherent to the concept itself. Therefore, a gravitational dual for complexity should naturally reflect these conventional ambiguities. This project also aims to investigate the definition of holographic complexity in the AdS/CFT correspondence.

３．研究の方法

(1) To explore de Sitter holography via the standard holographic formalism, wherein gravity in the bulk space is dual to a non-gravitational theory on its timelike boundary. Instead of considering global dS space, we can introduce a timelike boundary by cutting the bulk dS space into a half. We focus on analyzing the holographic entanglement entropy in this half de Sitter space and comparing it with that in the AdS/CFT correspondence.

(2) The various holographic complexity proposals have certainly drawn attention to new kinds of gravitational observables in the bulk, as well as highlighting their possible role in the AdS/CFT correspondence. In our previous work, we construct an infinite class

of new (diffeomorphisminvariant) gravitational observables on codimension-one surfaces, which has been dubbed "complexity equals anything". The most interesting feature of this family of new observables is that infinitely many of them can exhibit the universal behaviour (i.e., linear late-time growth for the thermofield-double state and the switchback effect for perturbations of this state) that is expected of holographic complexity. Built on the same idea: complexity=anything, it is natural to explore another infinite class of gravitational observables defined in codimension-zero regions of the bulk spacetime.

4．研究成果

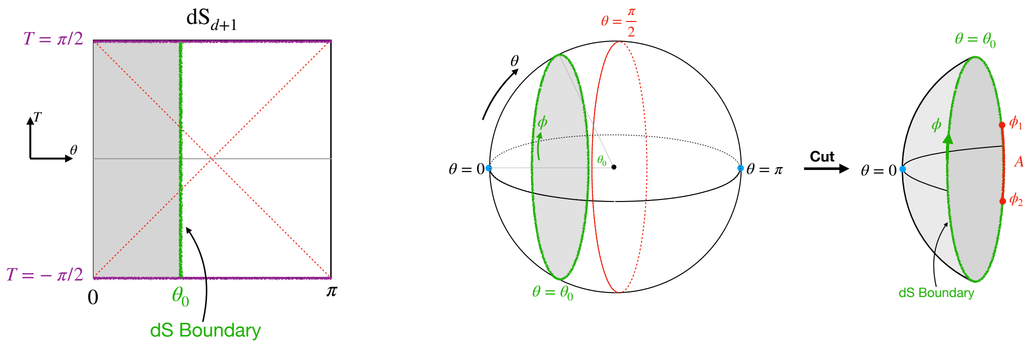

Figure 1. Left: The Penrose diagram of de Sitter bulk spacetime. We introduce a timelike boundary which is described by a d-dimensional dS spacetime. The dual bulk dS spacetime is given by the gray shaded region. Right: The geometry of time slices for a global de Sitter and a half de Sitter.

(1) a Half de Sitter Holography: In this work, we consider a half dS spacetime wherein a timelike boundary encloses the bulk spacetime, presenting a new version of de Sitter holography, as depicted in Figure 1. By analyzing the holographic entanglement entropy in this space and comparing it with that in AdS/CFT, we argue that gravity on a (d+1)-dimensional half dS is dual to a highly non-local field theory residing on its d-dimensional dS boundary. This non-locality induces a breach in the subadditivity of holographic entanglement entropy. Remarkably, this observation can be linked to another argument that time slices in global de Sitter space overestimate the degrees of freedom by redundantly counting the same Hilbert space multiple times.

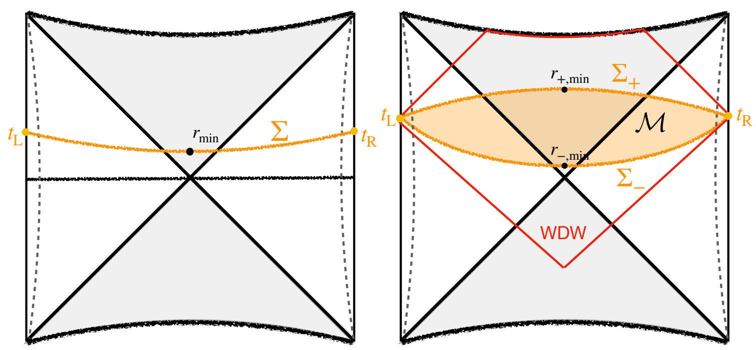

Figure 2. The left panel shows an extremal codimension-one hypersurface, represented by the orange curve. On the right, the orange region denotes the codimension-zero subregion bounded by the two surfaces as in the complexity=anything proposal. In a certain limit, the subregion can extend to the WDW patch with its null boundaries, as shown by the red lines.

(2) Complexity Equals Anything II: We expand on our results to present a broad new class of gravitational observables in asymptotically Anti-de Sitter space living on general codimension-zero regions of the bulk spacetime, as depicted in Figure 2. By taking distinct limits, these observables can reduce to well-studied holographic complexity proposals, e.g., the volume of the maximal slice and the action or spacetime

volume of the Wheeler-DeWitt patch. As with the codimension-one family, these new observables display two key universal features for the thermofield double state: they grow linearly in time at late times and reproduce the switchback effect. Hence, we argue that any member of this new class of observables is an equally viable candidate as a gravitational dual of complexity. Moreover, using the Peierls construction, we show that variations of the codimension-zero and codimension-one observables are encoded in the gravitational symplectic form on the semi-classical phase-space, which can then be mapped to the CFT.

Other results/publications obtained during this project period include:

(3) Gluing AdS/CFT: We investigate gluing together two Anti-de Sitter (AdS) geometries along a timelike brane, which corresponds to coupling two brane field theories (BFTs) through gravitational interactions in the dual holographic perspective. By exploring the general conditions for this gluing process, we show that the energy stress tensors of the BFTs backreact on the dynamical metric in a manner reminiscent of the TTbar deformation. In particular, we present explicit solutions for the three-dimensional case with chiral excitations and further construct perturbative solutions with non-chiral excitations.

(4) Complexity=Anything: Singularity Probes: We investigate how the complexity=anything proposal can be used to investigate the interior geometry of AdS black holes. In particular, we illustrate how the flexibility of the complexity=anything approach allows us to systematically probe the geometric properties of black hole singularities. We contrast our results for the AdS Schwarzschild and AdS Reissner-Nordstrom geometries, i.e., for uncharged and charged black holes, respectively. In the latter case, the holographic complexity observables can only probe the interior up to the inner horizon.

５．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　5件）

１．著者名	４．巻
Belin Alexandre、Myers Robert C.、Ruan Shan-Ming、S?rosi G?bor、Speranza Antony J.	2023
２．論文標題 Complexity equals anything II	５．発行年 2023年
３．雑誌名 Journal of High Energy Physics	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP01(2023)154	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名	４．巻
Jorstad Eivind、Myers Robert C.、Ruan Shan-Ming	2023
２．論文標題 Complexity=anything: singularity probes	５．発行年 2023年
３．雑誌名 Journal of High Energy Physics	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP07(2023)223	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名	４．巻
Kawamoto Taishi、Ruan Shan-Ming、Suzuki Yu-ki、Takayanagi Tadashi	2023
２．論文標題 A half de Sitter holography	５．発行年 2023年
３．雑誌名 Journal of High Energy Physics	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP10(2023)137	査読の有無 有
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１．著者名	４．巻
Kawamoto Taishi、Ruan Shan-Ming、Takayanagi Tadashi	2023
２．論文標題 Gluing AdS/CFT	５．発行年 2023年
３．雑誌名 Journal of High Energy Physics	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP07(2023)080	査読の有無 有
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1．著者名 Belin Alexandre、Myers Robert C.、Ruan Shan-Ming、S?rosi G?bor、Speranza Antony J.	4．巻 2023
2．論文標題 Complexity equals anything II	5．発行年 2023年
3．雑誌名 Journal of High Energy Physics	6．最初と最後の頁 1-79
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/JHEP01(2023)154	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計7件（うち招待講演　4件／うち国際学会　5件）

1．発表者名 Ruan Shan-Ming
2．発表標題 Double Holography of Entangled Universes
3．学会等名 The 2nd young researchers' workshop of the Extreme Universe Collaboration（招待講演）
4．発表年 2024年

1．発表者名 Ruan Shan-Ming
2．発表標題 A half de Sitter Holography
3．学会等名 ExU-YITP Workshop on Holography, Gravity and Quantum Information（国際学会）
4．発表年 2023年

1．発表者名 Ruan Shan-Ming
2．発表標題 Complexity Equals Anything: Singularity Probes
3．学会等名 Asia-Pacific School and Workshop on Gravitation and Cosmology 2023（国際学会）
4．発表年 2023年

１．発表者名 Ruan Shan-Ming
２．発表標題 Gluing AdS/CFT
３．学会等名 Black holes, Islands and Braneworlds（招待講演）（国際学会）
４．発表年 2023年

１．発表者名 Ruan Shan-Ming
２．発表標題 Complexity Equals Anything: Singularity Probes
３．学会等名 6th International Conference on Holography, String Theory and Spacetimes（招待講演）（国際学会）
４．発表年 2023年

１．発表者名 Shan-Ming Ruan
２．発表標題 Complexity Equals Anything
３．学会等名 The first young researchers' workshop of the Extreme Universe Collaboration"（招待講演）
４．発表年 2023年

１．発表者名 Shan-Ming Ruan
２．発表標題 Complexity Equals Anything
３．学会等名 2nd International Symposium Trans-Scale Quantum Science（国際学会）
４．発表年 2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関