【Grant-in-Aid for Transformative Research Areas（A）】

Section II

Title of Project： The Natural Laws of Extreme Universe --A New Paradigm for Spacetime and Matter from Quantum Information

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【Purpose of the Research Project】

Until now, physics has explained the laws of nature using space, time, and matter as its basic elements. However, in extreme situations in the natural world (which we call extreme universe in this program), we face difficulties as the conventional view of space, time, and matter gets collapsed due to fluctuations caused by strong quantum effects. Extreme universe refers to the three limits in nature: the limit of space: quantum theory of black holes, the limit of time: mechanism of the creation of the universe, and the limit of matter: dynamics of quantum matter.

However, owing to the discovery of the gauge-gravity duality, gravitational theory gets equivalent to the theory of quantum matter. In this duality, the Ryu-Takayanagi formula shows that the entanglement entropy, a quantity that measures the amount of quantum information, is equal to the area of the surface in the theory of gravity. On the other hand, the accumulation of quantum information provides a high-precision numerical method for quantum matter, called tensor network. In this program, we aim to clarify the three problems of the extreme universe by integrating quantum information and physics.

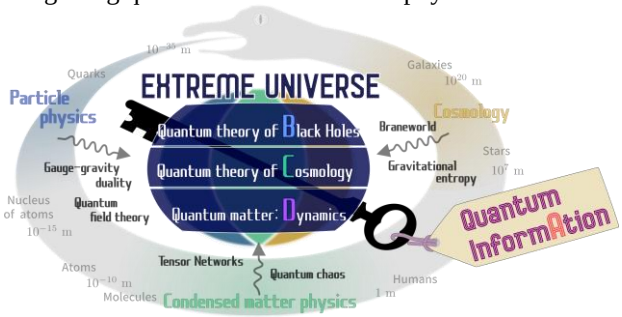

Figure 1: Exploring Extreme Universe by Introducing Quantum Information Theoretic Ideas into Physics

【Content of the Research Project】

The nine Planned Research projects are divided into four groups A, B, C and D. Group A (A01) focuses on fundamental research on quantum information theory for physics, Group B (B01, B02, B03) explores the quantum theory of black holes, Group C (C01, C02, C03) investigates the dynamics of the creation of the universe, and finally, Group D (D01, D02) analyzes the dynamics of quantum matter. In addition, groups B, C, and D are subdivided into research projects that take approaches from particle theory (01), condensed matter physics (02), and cosmology (03). In this way, this program aims to promote the fusion of disciplines and achieve breakthroughs by successfully intertwining both the warp (connections between conventional research fields) and the woof (common research goals). We will also conduct condensed matter experiments on cold atoms (B02) and the quantum Hall effect (C02), to simulate black holes and the creation of the universe. We will also develop methods for analyzing quantum matter (D01 and D02) by using quantum computers, expected to be the next generation of computational technology. Complementary research will be conducted through an open call for proposals.

【Expected Research Achievements and Scientific Significance】

By introducing the viewpoint of quantum information into physics, we expect to make significant progress in elucidating three problems in the extreme universe: (1) quantum theory of black holes, (2) mechanism of creation of universe, and (3) dynamics of quantum matter. First, we combine gauge-gravity duality and quantum information theory to explain the black hole information problem for evaporating black holes. At the same time, we conduct a cold atom experiment which simulates a quantum black hole. Next, we explain the basic principle of gauge-gravity duality from the viewpoint of quantum information theory, and generalize it to construct a quantum gravity theory that describes the creation of the universe. At the same time, we will conduct quantum Hall experiments which simulate the creation of the universe by using expanding edge states. In addition to mathematical methods using quantum information theory, we will develop numerical methods for analyzing the dynamics of quantum matter, such as the high-dimensional tensor network method and algorithms for analyzing quantum field theory on a quantum computer. As a goal, we will reconstruct physics from the viewpoint of quantum information, and develop quantum information theory with physics in mind, thereby creating a new interdisciplinary field.

【Key Words】

Gauge-Gravity Duality: a conjecture which claims that gravitational theory in an anti de-Sitter universe is equivalent to a gauge theory (a special kind of quantum matter) that lives on the boundary of the universe.
Tensor Network: A method of analyzing quantum matter via a network of quantum information. It offers a highly accurate numerical method for quantum matter. It gives a hint for space-time emergence in gauge-gravity duality.

【Term of Project】 FY2021-2025
【Budget Allocation】 1,032,400 Thousand Yen
【Homepage Address and Other Contact Information】
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