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

What is the physical mechanism of the origin of the Universe? - challenges over transcending scales through the integration of theory, observations, and experiments

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Project Information	Project Number : 26A204 Keywords : Inflation, Structure Formation, Axion, Gravitational Wave, Quantum	Project Period (FY) : 2026-2030

Purpose and Background of the Research

●Outline of the Research

The observable universe today was much smaller than the size of an atom at its birth where quantum physics ruled and the known laws of physics broke down. To address this huge problem, we assemble scientists from different areas, to employ not only astrophysical observations but also elementary particles that governed the microscopic universe, cutting-edge technology in quantum measurements and AI/ML that go beyond the past limits of measurements and observations, and theories that can lead to new laws of physics.

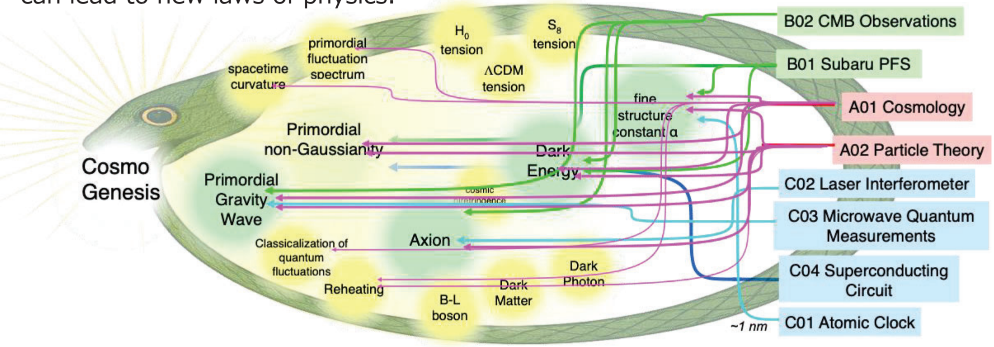

Figure 1 Conceptual Depiction of the Research

●Our Approach in Research

The birth of the Universe is the ultimate subject in natural sciences. The biggest problem we face is how to observe it. When we look 10 billion light years away in astronomy, we observe the way the universe was 10 billion years ago. When the universe was younger than 380,000 years, however, we cannot observe it directly because light was scattered by atoms broken down to electrons and nuclei. Yet there are potential signals that come straight from the earliest moments, such as gravity wave and axion that interact little with the primordial soup. They are in turn extremely difficult to detect, but we can develop new technologies, similarly to the way we can now see the core of the Sun using neutrinos.

The current theory says that the universe was stretched from its super-microscopic size at the quantum level to a macroscopic one by an enormous accelerating expansion called inflation right after its birth. Uncertainty principles lead to tiny quantum fluctuations in the super-microscopic universe that became burned into the primordial density fluctuations at the level of one part in a hundred thousand. They grew further by the gravitational pull of dark matter and led to formation of stars and galaxies in the current universe. At large distances the density fluctuations must have retained their inflationary origin. We can study the birth of the universe using cutting-edge observational data on density fluctuations.

Another approach is to study systems that simulate the earliest moments of the universe. In addition, we look for possible changes in the laws of physics at the highest possible precisions knowing that they must have been different at the birth of the universe.

●Research Groups

We employ four approaches and eight research groups to address the big questions.

I. Signals from Cosmogenesis: I.a primordial density fluctuations in the oldest light CMB (B02) and 3d data in galaxy distributions (B01), I.b primordial gravity wave in the polarization of CMB (B02) and GHz observations (C03), I.c primordial axions at laser interferometers (C02) or rotation in polarization planes of CMB (B02).

II. Simulators: II.a Inflation in the laboratory with superconducting quantum circuits (C04), II.b Observation of the current accelerating expansion by dark energy (B01).

III. Time Variation: ultra-high precision optical lattice clocks (C01) and observation of galaxies 10B years ago (B01) .

IV. Theory of Cosmogenesis: approaches both from the universe (A01) and elementary particles (A02) . And their intimate interactions.

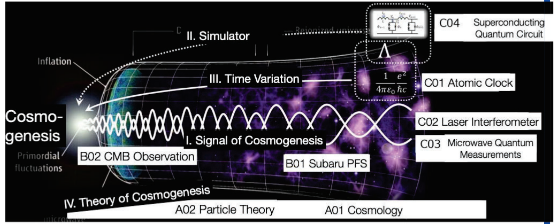

Figure 2 Research Groups

Expected Research Achievements

●What may Emerge from this Research

Once the multi-faceted research program on the birth of the Universe makes progress, following outcomes may arise: “Time evolution of dark energy is established by Subaru PFS. It sheds new lights on how inflation ended and turned into a decelerating expansion. By simulating this process using the quantum circuit with superconductors, the theory on primordial gravitational waves from the earliest moments of the universe advances, and the strategy for detecting GHz gravitational waves becomes clear. On the other hand, a slow motion of an axion field is observed from the time variation of the strength in the electromagnetic force called fine-structure constant and the rotation of polarization planes in CMB. At the same time, we find an axion to be the dark matter using laser interferometers. Such results on axions will provide crucial information for ultimate laws of physics such as string theory.” For obvious reasons, we hope to see completely unanticipated outcomes. We are confident that we can create a new community of scientists that cross borders of traditional fields, and nurture researchers especially in their early stages with leaderships, ambitions, global perspectives, and high-level knowledge base and technologies, exploiting most advanced data and healthy research environments.

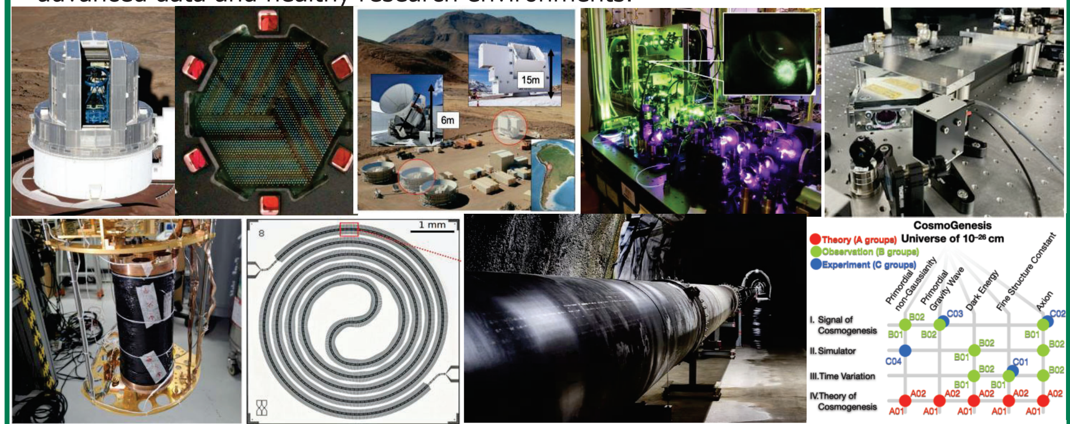

Figure 3 Facilities and equipment for the research program and their interconnectedness

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