

# 人工宇宙の量子動力学の制御

## Controlling the Quantum Dynamics of an Artificial Universe

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During October–December 2025, I conducted collaborative theoretical research at the University of Cambridge on emergent gauge structures and generalized symmetries in frustrated quantum matter. The visit enabled intensive discussions and joint work on (i) symmetry-based formulations of constrained spin ice models and their low-energy gauge descriptions, (ii) controlled characterization of topological defects and non-local observables, and (iii) connections to quantum-information viewpoints such as robust encoding and constrained dynamics. These activities clarified the conceptual framework linking microscopic models to effective field theories and provided concrete directions for follow-up projects, including manuscript preparation and extended collaboration between Cambridge and my home institute.

### 海外研究活動概要

The purpose of this overseas research period was to advance my ongoing program on emergent phenomena in quantum many-body systems—particularly emergent gauge structures, constrained dynamics, and generalized symmetry principles—through close collaboration with researchers at the University of Cambridge. The Cambridge environment was highly suitable for this project because of its strength in theoretical condensed matter physics, including frustrated magnetism, spin liquids, and modern field-theoretic approaches to strongly correlated systems.

During the visit, my research activities consisted of:

1. Regular research meetings and technical discussions with my host and local collaborators to identify tractable theoretical questions and efficient routes toward publishable results.
2. Focused derivations and model analysis to connect microscopic Hamiltonians to effective gauge-theory descriptions and to define diagnostics for emergent order and defect structure.

3. Seminar participation and internal presentations, which helped refine the positioning of the project within the broader landscape of quantum matter and symmetry-based frameworks.

A key benefit of the visit was the ability to hold frequent high-bandwidth discussions (whiteboard-level derivations and rapid iteration), which significantly accelerated the pace of conceptual development compared to remote collaboration.

### 成果

During the research stay at the University of Cambridge, the project produced clear scientific progress in two tightly connected directions: (1) exotic phases in quantum spin ice, with emphasis on flux-liquid regimes, and (2) quantum-error-correction concepts inspired by random Gauss's-law constraints. The visit was particularly effective because it enabled sustained in-person discussions and rapid iteration on technical derivations, which accelerated both conceptual clarity and concrete research outputs.

**(1) Exotic phases of quantum spin ice: flux-liquid regime.** A central outcome of this visit was progress in understanding exotic phases of quantum spin ice beyond conventional ordered states, focusing on regimes where the system supports a flux-liquid-like behavior. Quantum spin ice provides a paradigmatic setting in which local constraints—originating from ice rules—give rise to emergent gauge structures and fractionalized excitations. While much of the literature emphasizes stable spin-liquid phases with well-characterized emergent electrodynamics, our discussions and analysis during the visit emphasized a complementary perspective: how fluctuating gauge flux can dominate the physics and generate distinct dynamical and thermodynamic signatures.

**(2) Random Gauss's law inspired quantum error correction code.** A second major outcome of the visit was the development of a research direction connecting random Gauss's-law constraints to the design principles of quantum error correction (QEC). The motivation is that Gauss's-law-like constraints naturally impose a structured “error-detection landscape” by restricting physically allowed configurations and enforcing non-trivial global consistency conditions. Introducing randomness in the constraint structure provides an unconventional route to engineer codes with potentially useful robustness properties, while remaining grounded in the language of many-body physics.

Overall, the overseas research period substantially accelerated progress by enabling intensive in-person collaboration, and it produced clear scientific outputs and well-defined next steps in both flux-liquid physics in quantum spin ice and random Gauss's-law-inspired QEC codes.

## 今後の展望

Building on the progress achieved during the research stay at the University of Cambridge, I will pursue two

main follow-up directions. First, I will consolidate the results on flux-liquid regimes in quantum spin ice into a manuscript, focusing on a clear theoretical characterization of flux-dominated dynamics and on practical diagnostics (including flux-sensitive and non-local observables) that distinguish this regime from confined or symmetry-broken phases. These results will also motivate targeted numerical studies to validate the predicted signatures and to strengthen connections with experimental trends in frustrated magnetic materials.

Second, I will advance the program on random Gauss's-law-inspired quantum error correction, with emphasis on identifying the structure of logical degrees of freedom and evaluating robustness under physically motivated noise models. This includes clarifying how randomness reshapes error pathways, defect energetics, and decoding complexity. Finally, I will maintain and expand the Cambridge collaboration through joint writing and regular meetings, aiming for timely publication and sustained interdisciplinary exchange.

## 研究の発表

### 口頭発表

1. Seminar, TCM Group, The Cavendish Laboratory, University of Cambridge, U.K. 2025/11/07. Hyperbolic Fracton Models: Bridging AdS/CFT and Self-Correcting Code.
2. Seminar, Queen Mary University of London, U.K. 2025/11/06. Hyperbolic Fracton Models: Bridging AdS/CFT and Self-Correcting Code.
3. Seminar, LOMA, University of Bordeaux, France 2025/10/21. Designing Light in an Artificial Universe
4. Invited talk, Paul Scherrer Institute & Herzberg, Switzerland 2025/10/15. Dipolar-Octupolar Spin Ice in Magnetic Field. Second International Workshop on Quantum Spin Ice