Mengxin Du

Research Statement

Introduction

I am a condensed matter physicist aiming to understand fundamental quantum phenomena and advance quantum simulation. I have an interdisciplinary background, merging experimental work, theoretical techniques and computational methods. My research fields span cold atomic physics, quantum many-body physics and quantum error correction. During my PhD work with Prof. Chuanwei Zhang and Michael Kolodrubetz at UT Dallas, I have made contributions to three main areas: (1) characterizing interaction effects in quantum kicked rotors, where we discovered novel dynamical phases and demonstrated experimental evidence of interaction-driven delocalization using ultracold atoms; (2) developing new frameworks for analyzing quantum error-correcting codes through the Knill-Laflamme conditions, leading to the discovery of new families of non-additive codes; and (3) investigating novel time crystal phases in cavity-coupled quantum systems. These projects share deep connections with each other: from mapping many-body dynamics to quantum circuits, applying phase transition techniques for analyzing algorithmic complexity, or leveraging error correction principles for robust quantum neural networks. All of these projects are within my research plans.Beyond this, I am interested in a wide range of topics in quantum physics, and aim to develop ideas at the frontier of quantum physics and quantum computing.

Current Research

Currently, my works aim to understand fundamental quantum phenomena and develop new quantum simulation techniques across three main projects:

In collaboration with Prof. Chuanwei Zhang and Prof. Subhadeep Gupta's laboratory at University of Washington, we used ultracold atomic gases under quasiperiodic driving to study the Anderson metal-insulator transition. Our experimental platform used a quasi-periodically kicked Bose-Einstein condensate in an optical lattice, providing a controlled environement to analyse the effects of interactions, disorder and driving. In later works, I also added and analyzed the impact of traps in different shapes. Through this setup, I discovered how many-body interactions coorporate with traps induce a "subdiffusive" dynamical phase that deviates significantly from non-interacting behavior, a result confirmed by numerical mean-field simulations. These simulations agree closely with experimental observations, and they enabled me to extract critical exponents that characterize a novel type of interaction-driven phase transition. Our work reveals the role of interactions in new dynamical phases of ultracold atoms under driving.

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In collaboration with Prof. Michael Kolodrubetz, I examined how cavity-mediated long-range interactions can stabilize time-crystalline order under equilibrium conditions, circumventing the conventional no-go theorem that prohibits such phases without external driving. Our approach discovered persistent oscillations and signatures of time-crystalline order within a time-independent Hamiltonian, carried out via a connection between Majorana-based models and an Ising spin model with Floquet drives. A critical emphasis of my work is on identifying experimentally measurable observables, such as stable oscillatory long-term correlations even under photon losses, that can unambiguously verify these phases in real laboratory settings. This work illuminates how strong, collective interactions in an open cavity system can stabilize genuinely new phases of quantum matter.

Finally, in joint work with Prof. Bei Zeng, we developed a method to discover and characterize non-additive quantum error-correcting codes by focusing on the matrix elements in the Knill-Laflamme conditions. We introduced a "signature vector" whose Euclidean norm, denoted λ^*, plays a central role in revealing the code's error-correcting properties which has local unitary invariance. Using this formalism, we identified new non-additive families of quantum codes, including ((6,2,3)) and ((7,2,3)), that lie outside the usual classification schemes. To capture these results more geometrically, we studied the structure of code spaces on the Stiefel manifold and uncovered continuous paths between known codes. By highlighting an analytical route in high-dimensional code spaces, this work offers a powerful means for designing robust, next-generation quantum protocols and provides fundamental insights into the geometry underlying quantum error correction.

Summarize and Research Plans

Taken together, my research explores quantum systems in diverse regimes: from phase transitions in driven ultracold atoms, to advanced quantum code design and equilibrium time crystals stabilized by cavity-mediated interactions. In future research, it would be of immense benefit to involve your faculty members' expertise in every facet of my work, not only to refine one specialized domain but also integrate these fields in various ways. I hope to advance quantum technology on multiple fronts and uncover fresh opportunities in quantum simulation, quantum information, and other rapidly evolving arenas of research, by combining my existing background with your faculty members insightful guidance. For a detailed research plan, please refer to the next section.

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Detailed Research Plan

Motivation and vision. My long-term aim is to understand the fundamental capacities of quantum mechanics and the overall framework that can be built from them. In particular, structured quantum correlations—coherence, entanglement, and related nonclassical resources—appear to be the organizing principles behind emergent phases, transport, and information processing. I am familiar with systems/platforms such as ultracold atoms, cavity QED, many-body systems and quantum error correction. I hope to extend my study in these directions while remaining flexible as new insights emerge, while also developing new expertise in other areas of research.

Near-term: Open questions derived from current projects.

- *Interacting kicked rotors (transport universality).* Quantify how interactions reshape dynamical Anderson transitions under quasi-periodic kicks. Targets: (i) extract critical exponents beyond single-particle predictions; (ii) identify the nature of the newly found phase (iii) coupled to other systems such as cavities to find more universal features.
- *Cavity-induced time crystals without drive.* Establish rigorous criteria under which cavity-mediated feedback yields persistent period doubling with realistic loss. Targets: (i) derive stability bounds for oscillations with photon leakage and measurement backaction; (ii) map spin/Majorana observables to directly accessible cavity signals; (iii) classify phases by correlation structure (e.g., operator spreading vs. synchronized modes), bridging Floquet and self-organized regimes.
- *Quantum error correction via off-diagonal Knill–Laflamme structure.* Develop the signature-vector/λ^* program to *design* codes from their correlational footprints. Targets: (i) quantify trade-offs among entanglement, "magic," and error-detectability; (ii) more universal geometry connecting stablized codes to current findings.

Mid-term: Adjacent fields and new techniques to expand capability.

- *TEBD and tensor networks (finite-T, driven, and open chains).* Use TEBD/finite-χ scaling to extract entanglement growth, operator entanglement, and measurement-induced phase transitions; benchmark against mean-field/kinetic theories developed in the projects above.
- *MCTDH and open dynamics.* Treat multimode cavity–matter systems (beyond single-mode) and structured reservoirs to test robustness of self-organized oscillations and dissipative phases.
- *Transformers for quantum dynamics and information.* Learn effective causal structure, quasi-conserved quantities, and task-relevant labels directly from time-series data; use attention as a data-driven diagnostic of correlations/resources and as a general simulator to accelerate parameter scans for experiments and protocols.
- *Non-Hermitian physics and exceptional topology.* Probe correlation structure and stability near exceptional points using Keldysh formalisms; relate nonunitary symmetries to enhanced response, noise shaping, and new universality classes in driven–dissipative media.

Long-term: Broader frontiers

- *Black holes, scrambling, and holography.* Use out-of-time-order correlators and random-circuit/sYK-inspired models to probe universal bounds on chaos and information flow; contrast fast scramblers with constrained/fractonic dynamics where correlations remain atypical.
- *Measurement-induced phases and monitored dynamics.* Use hybrid circuits and continuous-measurement models to chart entanglement transitions (volume to area–law), identify correlation order parameters, and connect trajectory-level statistics to operational resources for sensing and error correction.

Collaboration and fit. I would like to discover and build upon new ideas in experiment-aware theory with scalable numerics, co-developing protocols and diagnostics that are falsifiable in current platforms (ultracold atoms, superconducting/cavity QED, trapped ions). I am interested in and have experience in the collaboration with experimentalists and I am willing to lead or contribute to future joint theory–experiment loops that explore quantum physics in an effective way.

I would like to restate that this roadmap is adaptable and I am fully open to joining or initiating projects that better match group priorities and shared scientific aims.

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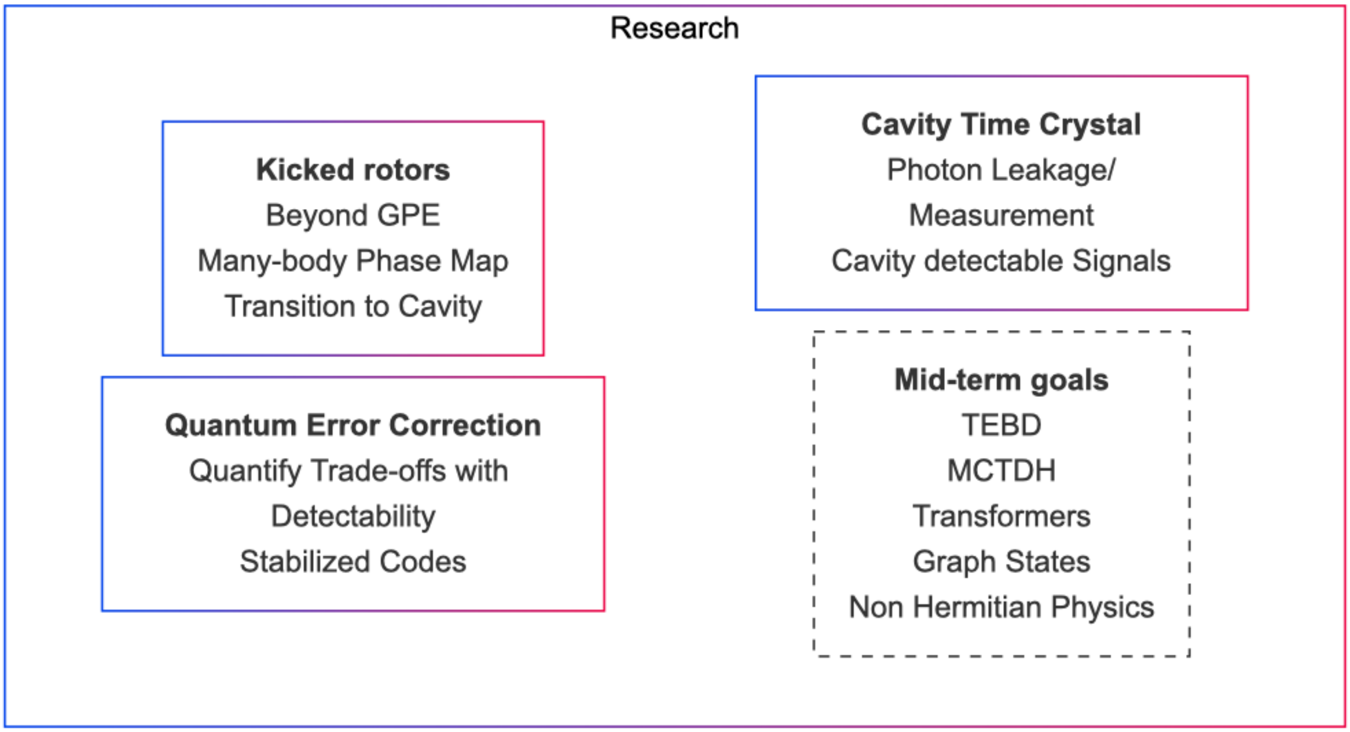

Schematic research roadmap.