Mengxin Du

Research Statement

Introduction

My interdisciplinary background combining experimental insights, theoretical techniques, and computational methods positions me well to advance the emerging field of physics-inspired quantum algorithms. My research fields spans among cold atomic physics, quantum many-body physics, quantum error correction. During my PhD work with Prof. Chuanwei Zhang 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. I believe these projects share deep connections with quantum algorithms and machine learning - from mapping many-body dynamics to quantum circuits, to applying phase transition techniques for analyzing algorithmic complexity, to leveraging error correction principles for robust quantum neural networks. Looking ahead, Although specialties listed above, my interests are broad across all quantum physics regime. I aim to explore quantum physics and quantum computing with all my expertise and new ideas.

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 investigated 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 access to the interplay of interactions, disorder, and driving in a controlled environment. 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 quantitative 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. By clarifying how ultracold atoms respond to periodic or quasi-periodic kicks, this research underscores the fundamental role of interactions in driving new dynamical phases.

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 connected between Majorana-based models and an Ising spin model with Floquet drives, discovered persistent oscillations and signatures of time-crystalline order within a time-independent Hamiltonian. 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. By mapping between different formulations of the same physical phenomenon, this project 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 quantum error-correcting codes by focusing on the off-diagonal 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.

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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. In my humble opinion, I hope to extend my study in these directions while remaining flexible as new insights emerge.

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 (conceptual import).* 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 aim to pair 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 welcome collaboration on benchmarking datasets, code discovery, and joint theory–experiment loops that turn correlation maps into operational advantages (stability, sensitivity, and robustness).

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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