Quantum technologies, including quantum computing, offer innovative approaches to scientific exploration contingent on our capacity to control microscopic systems. Since these quantum systems are inherently open, it is crucial to characterize, manage, and exploit their dynamics to unlock the full potential of quantum technologies. A prevalent assumption in quantum information science is that open systems undergo completely positive trace-preserving (CPTP) evolution. When these CPTP maps emerge as noise in quantum devices, quantum error correction (QEC) is necessitated to safeguard information. The talk will commence with a concise introduction of CPTP dynamics and QEC.

The second part of the talk will focus on our recent results on these fronts. I will first examine the CPTP assumption. Our research reveals more complex dynamics beyond CPTP by constructing experimentally viable dynamical maps. We mathematically and geometrically fully characterize these maps and study their properties and physical interpretations. It turns out that these non-CP dynamics are closely related to a certain type of Markovianity and information backflow. I will then examine the possibility of correcting nonCP errors. Given the high costs of fault-tolerant quantum computing regarding physical qubit requirements, we discuss Quantum Error Mitigation (QEM) techniques, offering a mathematical framework to unify these methods and assess their constraints.

Lastly, I will highlight the positive aspects of open system dynamics. We propose designing quantum algorithms and protocols based on general quantum dynamics. We also study non-Markovian dynamics to leverage potential advantages in specific tasks.