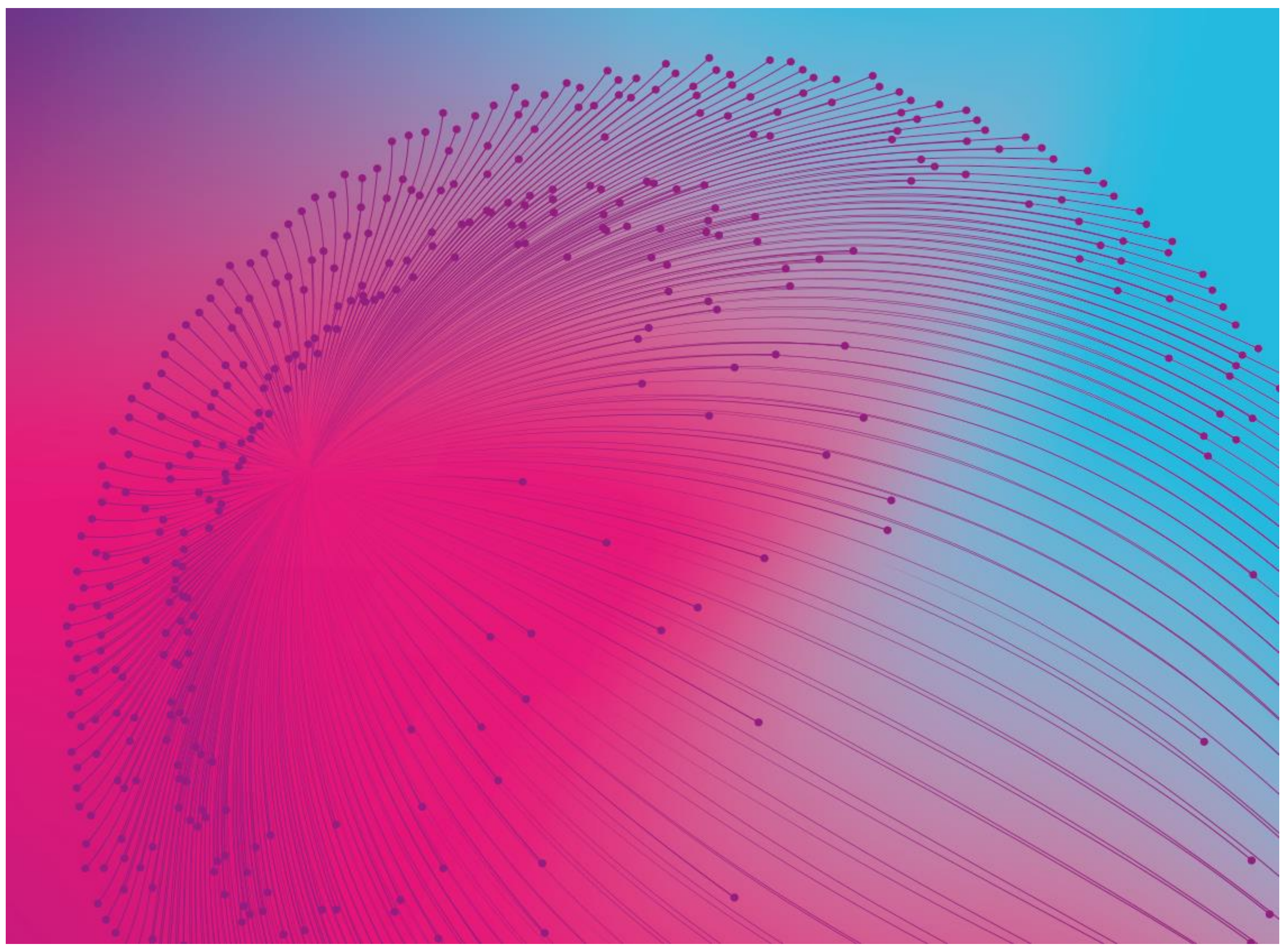
R-QIP
Reliable Quantum Information Processing

The R-QIP project aims to develop efficient and practical countermeasures against quantum errors in quantum computer systems. The focus is on solutions for medium-sized quantum computers that will be available in the near future.

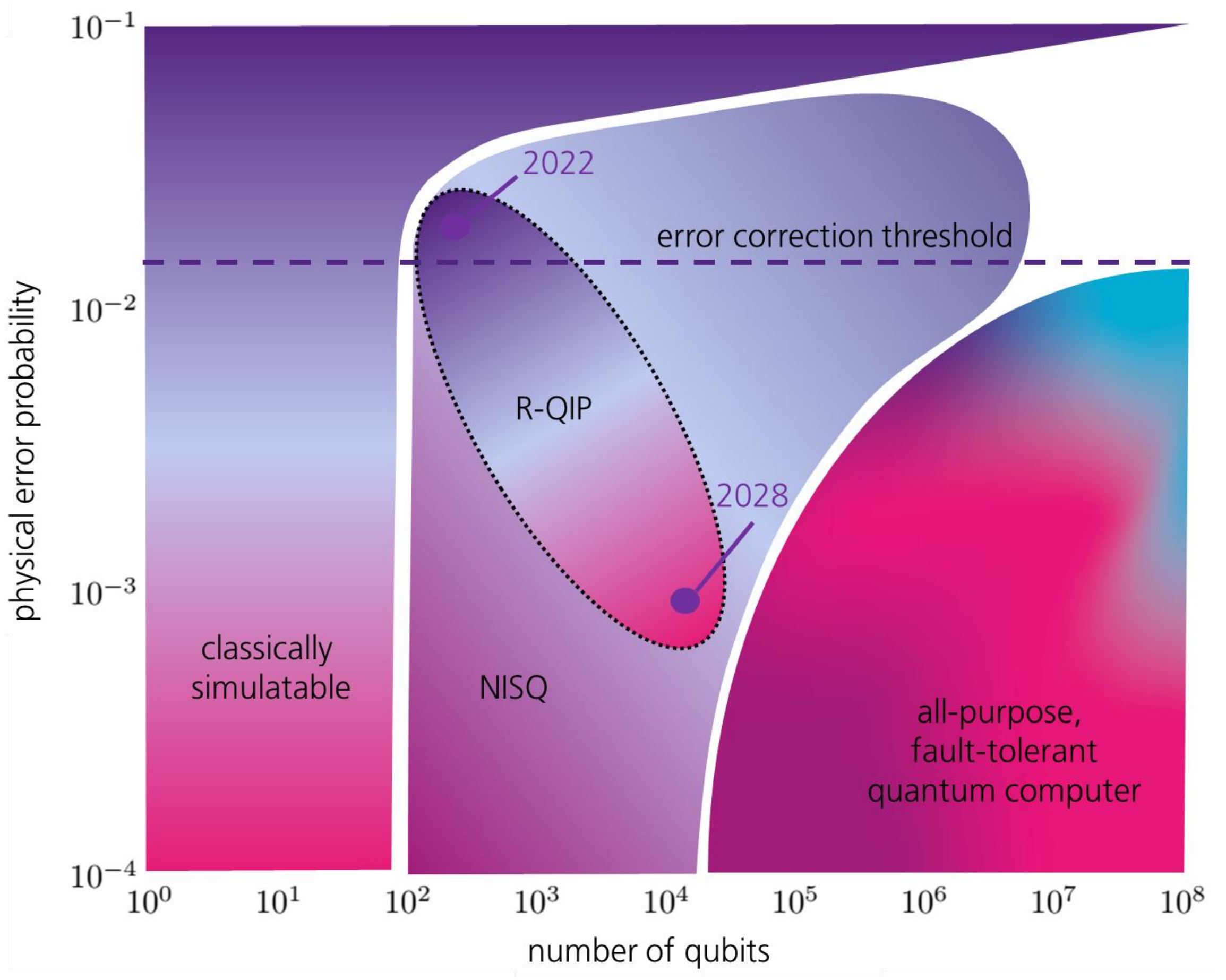
- Applications
- Middleware



Motivation

Current quantum hardware is prone to errors due to, among others, decoherence, i.e., uncontrolled and undesired interactions of the data qubits with the environment.
Although the quality of quantum hardware is improving, there is a consensus in the quantum computing community that quantum error correction will be necessary to carry out useful quantum computations.

The goal in R-QIP is advancing towards fault tolerant quantum computers by focusing on a specific hardware platform (ion traps) and trying to demonstrate a small instance of quantum error correction code, optimizing its implementation as much as possible.



Quantum Hardware

The work carried out in R-QIP will be tailored to the quantum computing demonstrator developed in the Q-Sea I project. This hardware implements a MAGIC (Magnetic Gradient Induced Coupling) quantum processor with 10 qubits and comes along with a hardware-optimized compiler and digital twin of ParityQC. One of the advantages of ion traps is that they offer all-to-all connectivity, which allows to go beyond topological quantum error correcting codes (e.g., surface codes).

Digital Twin

In order to avoid running many time-consuming experiments on the quantum hardware, the work in R-QIP strongly relies on the Digital Twin developed by ParityQC in the Q-Sea I project. This Digital Twin is a detailed simulation of the physics underpinning the ion trap and is able to model the behavior of the hardware in a realistic manner.

Effective Noise Models

While the Digital Twin with its close match to the hardware is always available for verification at later stages, the simulations including all effects are both quite resource-expensive and might not be very insightful, due to the combined presence of multiple quantum effects. Therefore, within R-QIP we will develop so-called effective noise models that describe most of the effects in a better-understandable and easier-to-simulate way.

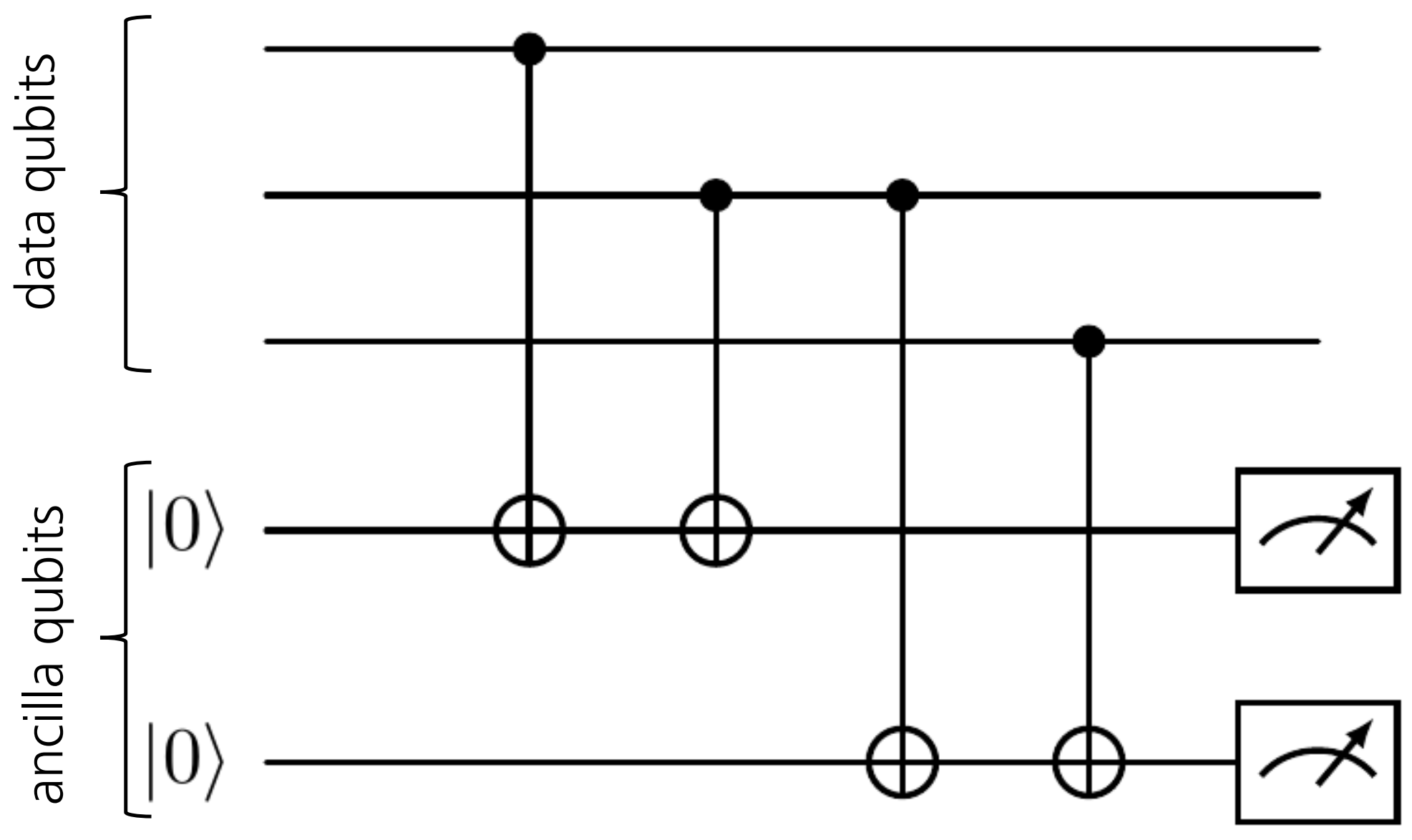
Quantum Error Correction

At a high level of abstraction, quantum error correction (QEC) consists of implementing a small number of reliable logical qubits by mapping them into a larger number of unreliable physical qubits. QEC thus implies a certain level of overhead, however, it has been shown that it can exponentially suppress quantum errors.

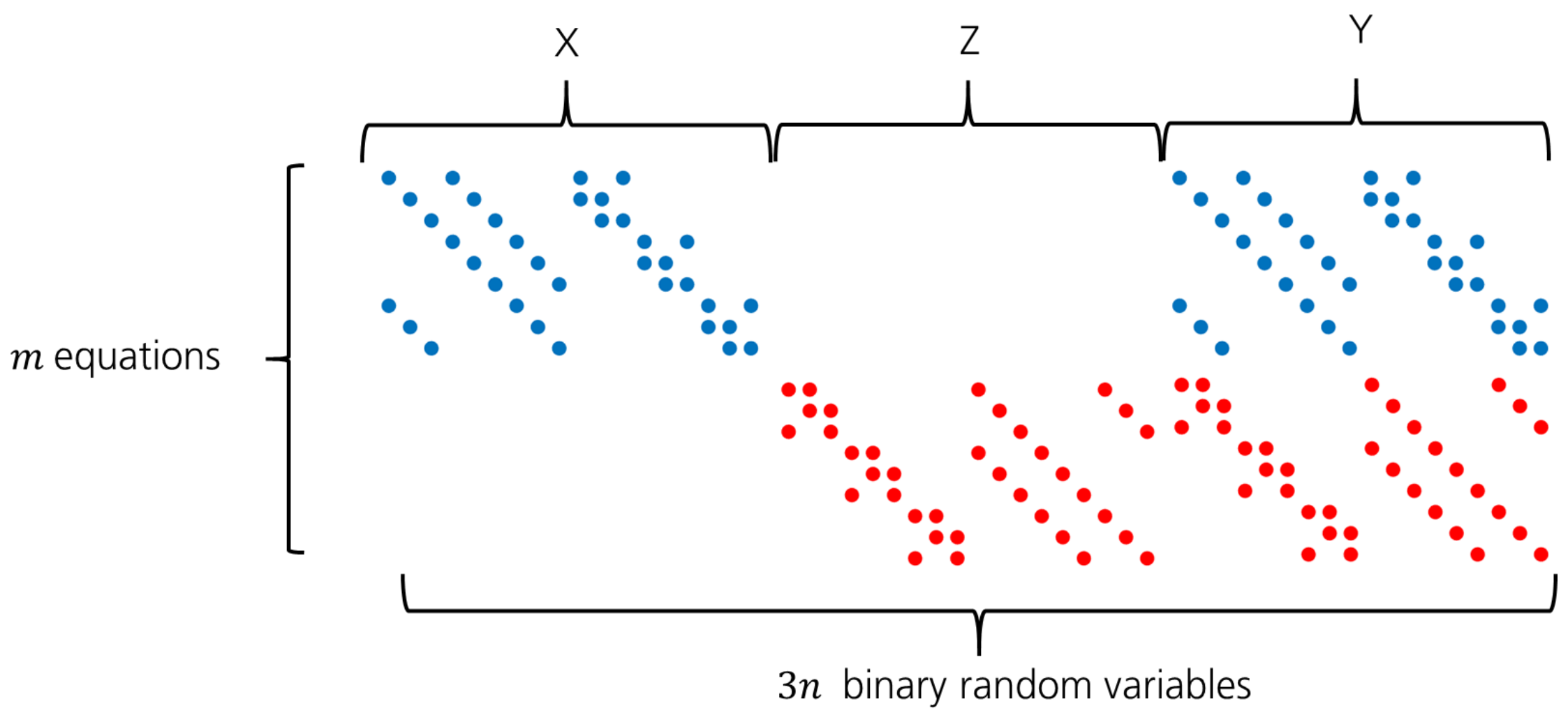
Based on the effective error models for ion trap-based quantum computers, QEC codes will be developed that are specially optimized to offer protection against the main sources of quantum noise in the actual hardware.

Additionally, the focus is also on designing optimized quantum circuits for the syndrome measurements associated to QEC. This includes considering errors in the ancillary qubits that need to be injected to carry out syndrome measurements as well as tracking how the different errors propagate in the associated quantum circuit.

Given a syndrome measurement circuit and the effective noise model, one can identify all the possible error locations in the circuit and propagate all possible errors (i.e. Pauli X, Y, or Z) to determine whether they affect the measurement of each of the ancillas – and how strongly they do so.

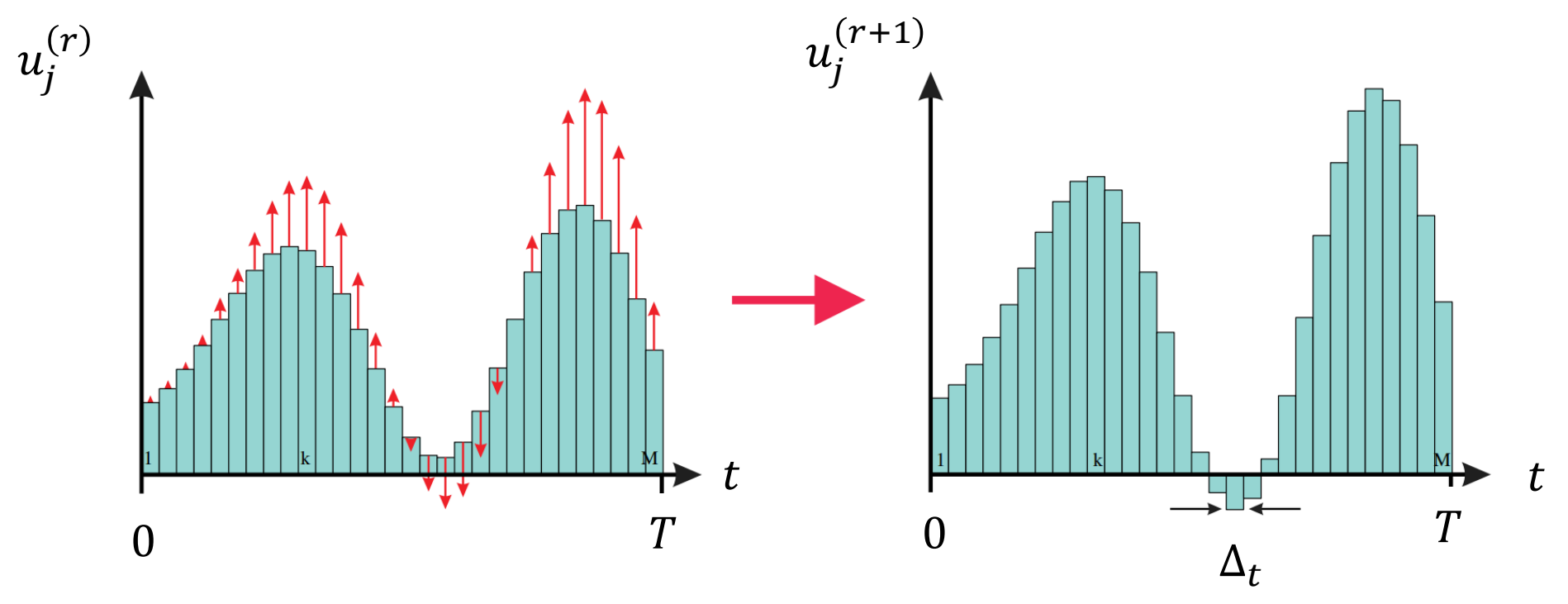


Assuming depolarizing Pauli noise, for a circuit performing m syndrome measurements and with n possible fault locations, one obtains a system with m equations and $3n$ random variables. Determining exactly which errors have affected our syndrome measurements reduces to applying classical postprocessing to the syndrome measurement outcomes, relying on this aforementioned system of equations.



Gate-to-Pulse Translation

Given the quantum circuits necessary for QEC, the next step is translating them into a sequence of control pulses that apply the desired operations on the qubits in the quantum hardware. This can be achieved relying on the GRAPE algorithm (gradient ascent pulse engineering).



① Choose an initial control sequence $u_j(t_k)$ with duration T

② Calculate forward propagation from initial state

$$U(t_k) = e^{-i\Delta_t H_k} e^{-i\Delta_t H_{k-1}} \dots e^{-i\Delta_t H_1}$$

③ Calculate backward propagation from target state

$$\lambda(t_{k+1}) = e^{i\Delta_t H_{k+1}} e^{i\Delta_t H_{k+2}} \dots e^{i\Delta_t H_M} \lambda(T)$$

④ Calculate the gradient

$$\frac{\partial h\big(U(t_k)\big)}{\partial u_j} = \mathrm{Re}\ \mathrm{tr}\left\{\lambda^\dagger(t_{k+1})\left(-iH_{\mathrm{control},j}\right)U(t_k)\right\}$$

⑤ Update the control sequence

$$u_j(t_k) \to u_j(t_k) + \epsilon \left.\frac{\partial h}{\partial u_j}\right|_{t=t_k}$$

and go to step ②

Demonstration

At the end of R-QIP, two demonstrations of QEC will be carried out, one relying on the Digital Twin and another one running on the real quantum hardware.
The main outcome from this demonstration will be the knowledge about the symbiosis of the different techniques required to implement quantum error correction in near term quantum computers.

Quantum Hardware → **Digital Twin** → **Effective Noise Models** → **QEC** → **Gate-to-Pulse translation** → **Demonstration**

More information about the project on our website

A project of

DLR Institute of Communications and Navigation
DLR Institute of Quantum Technologies
DLR Institute of Software Technology
DLR Space Operations and Astronaut Training

Contractor

Tenders ongoing

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