A Joint Effort for Solving Radiation Damage in Superconducting Quantum Computers

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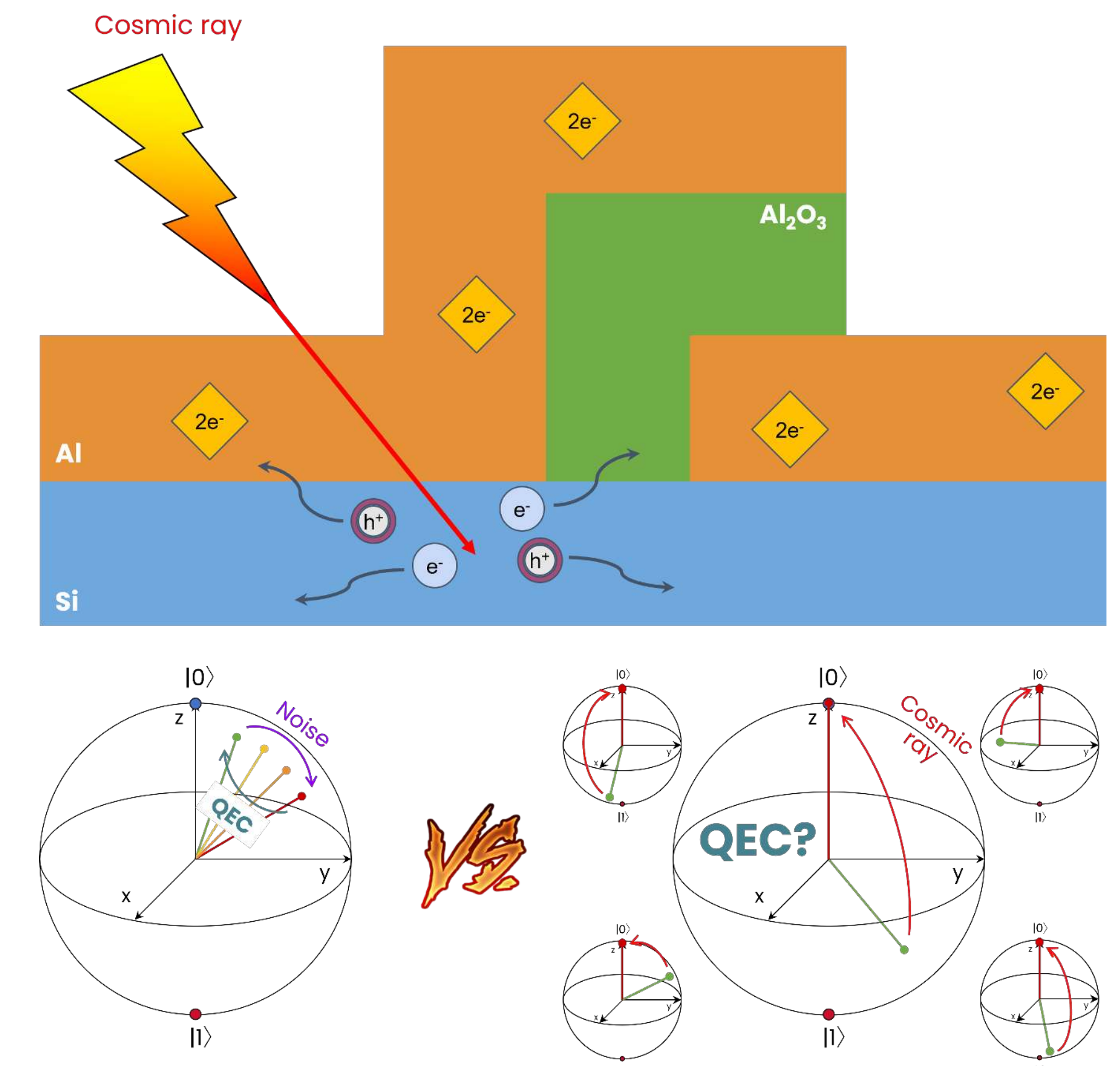
Abstract

Among the numerous technologies for the development of quantum computers, the cheapest and most easily scaleable one is the superconducting chip technology. These devices are built by employing the litographic process which has been perfected over decades for the assembly of classic transistor-based systems. As such, superconducting quantum computers inherited the same sensitivity to energy deposition on the Silicon substrate of the chip, a physical phenomena that originates from the byproducts of cosmic rays which can alter the encoded quantum information.

At HiCREST, we devised a clear path for understanding, modelling and correcting radiation-induced errors in superconducting quantum computers. The goal of this joint effort is to pave the way for reaching fault tolerance in quantum computers.

Radiation events

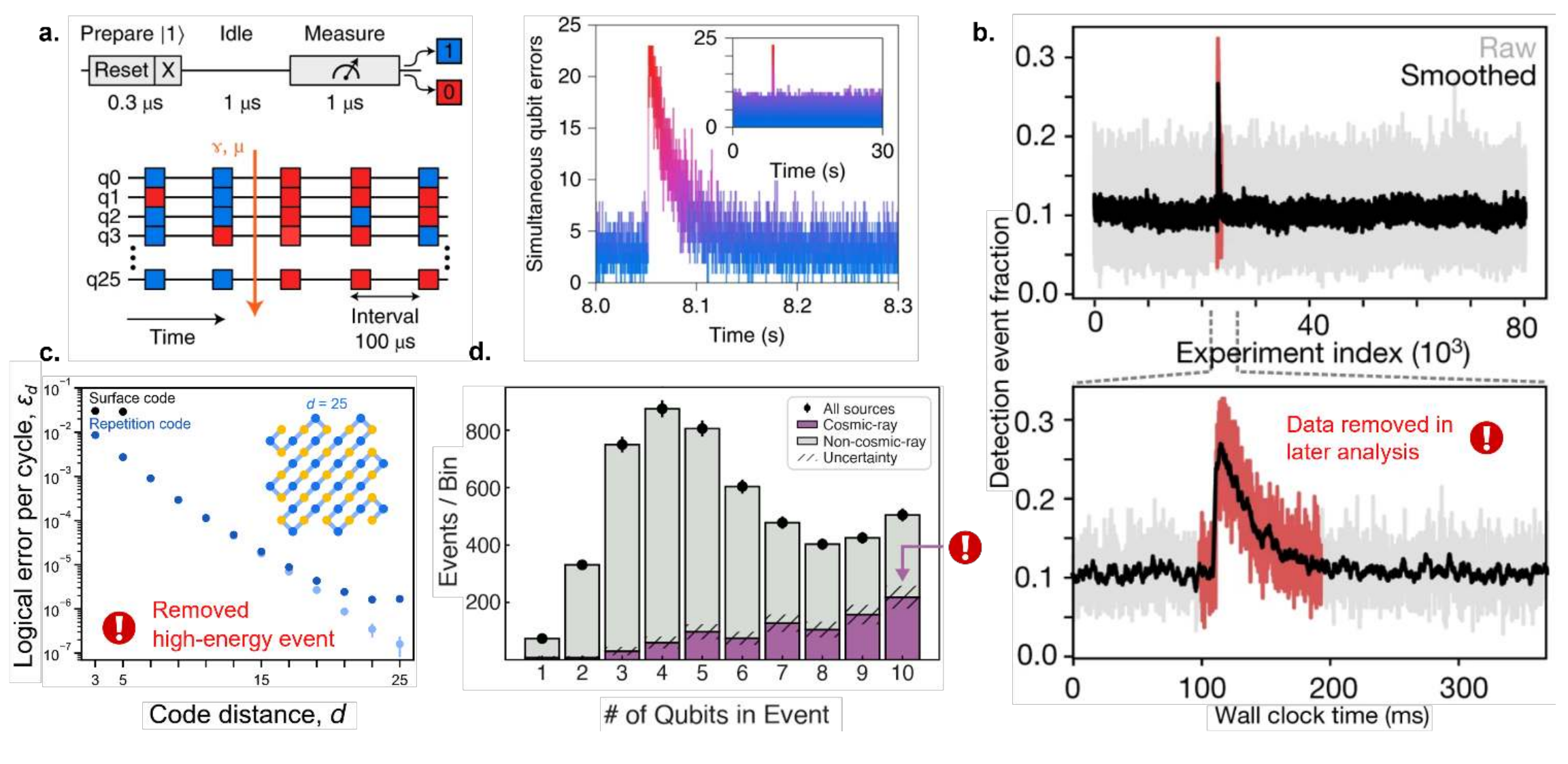
Particle impacts, which naturally occur as a byproduct of cosmic ray decay, alter the state of qubit(s) by forcing them into decoherence for long periods of time. The fault mechanism involves the generation of electron-hole pairs in the Silicon substrate of the quantum chip, which in turn break cooper pairs in the Josephson junction forming quasiparticles, that rapidly give rise to long-lasting phonons, responsible for spreading the energy across the lattice of the quantum computer's substrate and interconnections.



Radiation impact. Top: impinging particles liberate $e^- - h^+$ pairs, which produce long lasting phonons, thus inducing decoherence. Bottom: noise slowly deteriorates information, while radiation forces multiple qubits into decoherence.

Experimental observations

Numerous experimental papers report that impinging particles have been shown to induce faults in superconducting quantum devices. While CMOS are only sensitive to high energy neutrons, superconducting qubits are also sensitive to a wider array of low-interacting particles. Naturally occurring events can are registered with frequencies of once every ten seconds, impact almost if not all the qubits in the quantum chip, and induce a transient effect that can last for upwards of *seconds*. For reference, a single quantum circuit execution lasts for a few hundred *nanoseconds*.



Experimental evidence. Many recent papers highlighted radiation induced correlated multi-qubit errors. **a.** McEwen et al., 2022. **b.** Chen et al., 2021. **c.** Acharya et al., 2023. **d.** Harrington et al., 2024.

References

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[2] **Marzio Vallero**, **Gioele Casagranda**, et al. On the efficacy of surface codes in compensating for radiation events in superconducting devices. In *SC24: International Conference for High Performance Computing, Networking, Storage and Analysis*, pages 1–15, 2024.

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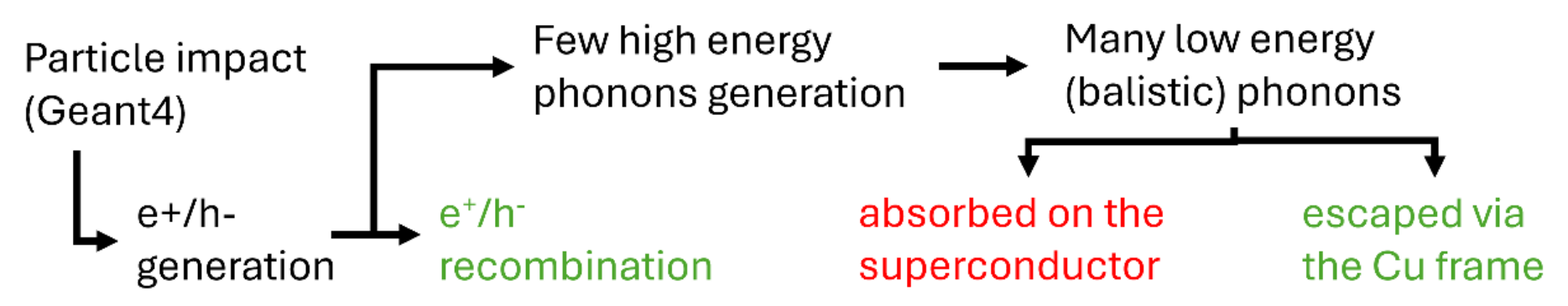
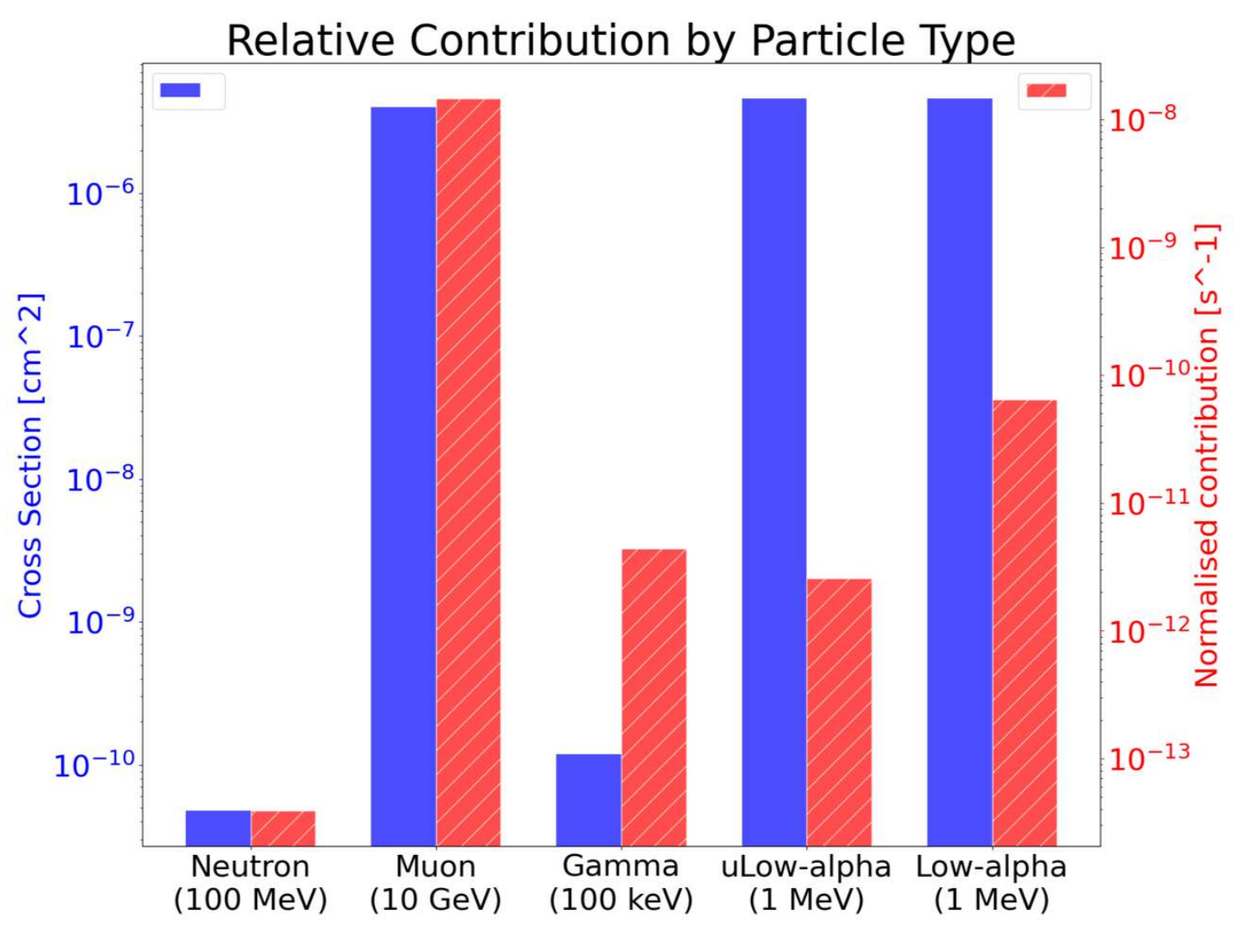
Geant4 simulations

We performed simulations of particle interactions on SQUIDs and Xmon qubits. The particles that have been tested are neutrons (1, 10, 100 MeV), muons (0.1, 1, 10 GeV), gamma rays (0.1, 1, 2 MeV) and alpha particles (1, 3, 5, 7, 10 MeV). In order to resolve ionising, indirect ionising (for neutral particles) and non-ionising radiation processes, we employ QGSP_BIC_HP physics list in Geant4. In addition to that, G4CMP physics list allows for the ultralow temperature ($T \ll 1$ K) with the following scheme:


Particle impact (Geant4)
e+/h- generation
Few high energy phonons generation
e^+/h^- recombination
Many low energy (balistic) phonons
absorbed on the superconductor
escaped via the Cu frame

An important aspect is to understand which kind of particle is more likely to corrupt a qubit. This has been done by measuring the cross-section of the worst-case event for each particle species and then normalising the contribution according to the respective flux at the sea level.



Neutrons, biggest concern for CMOS, are the **most insignificant** contribution

Muons are **extremely interacting** and they are **really abundant**

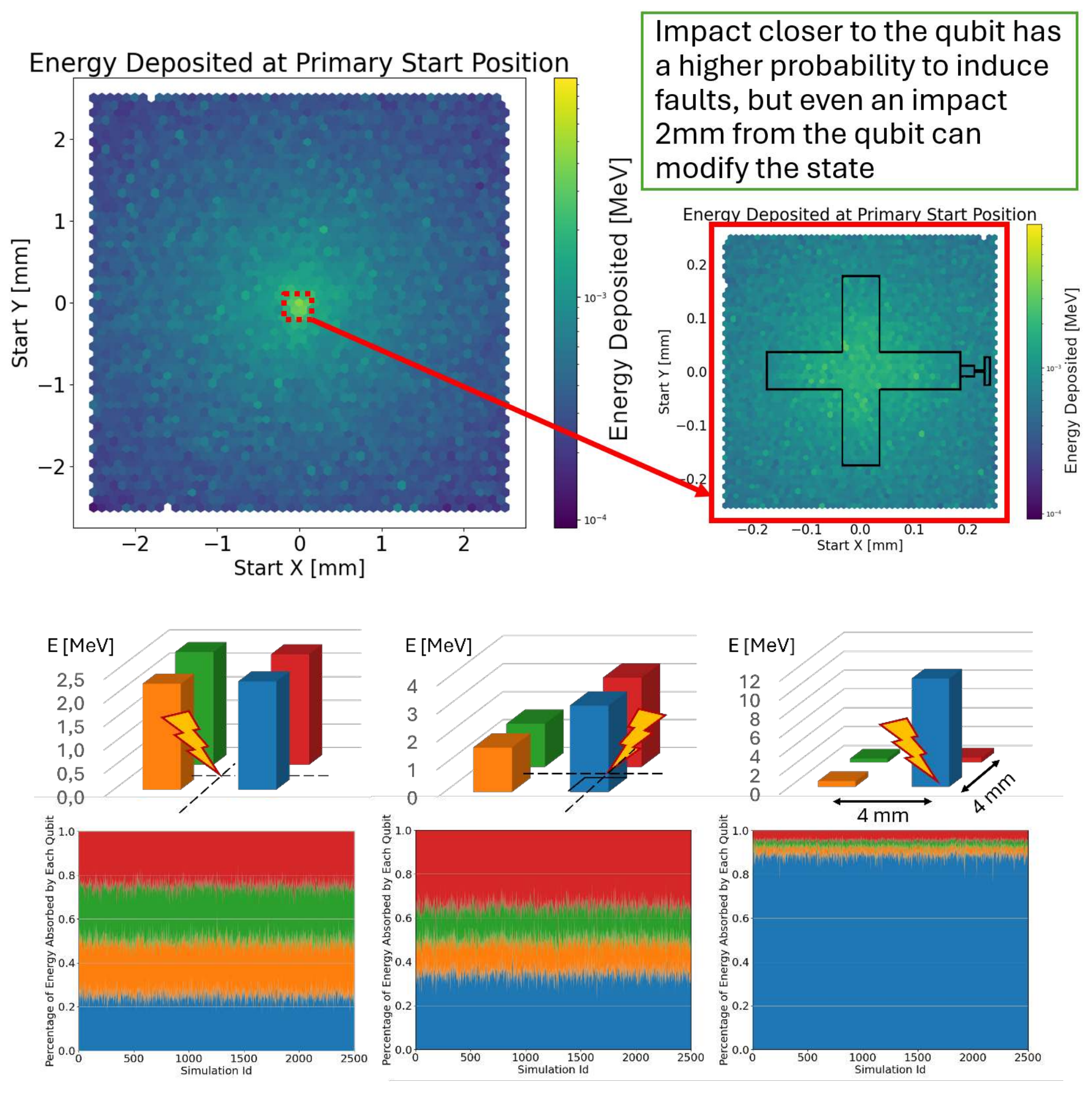
Gamma rays, despite being **less interacting,** they are the **most abundant**

Alpha particles contribution even from ultra-low alpha materials is significant

Different particles contribution. The left axis shows the cross-section (blue) and the right one is the cross-section multiplied by the flux of that particle at sea level (red).

It is fundamental to track the time persistence and the spatial propagation of the energy deposited in the substrate. We observe significant transmission to the superconductor for 75 μs from the particle impacts. Nonetheless, even after hundreds of μs, a Cooper-pair breaking absorption by the superconductor can still occur. This persistence does not completely justify the hundreds of seconds event observed. Probably, the persistency of the phonon-induced effect (Cooper-pairs breaking) lasts longer in the superconductor.

The work, titled "Understanding the Contributions of Terrestrial Radiation Sources to Error Rates in Quantum Devices" is running for the **Best Paper Award** at the 61st IEEE Nuclear & Space Radiation Effects Conference.

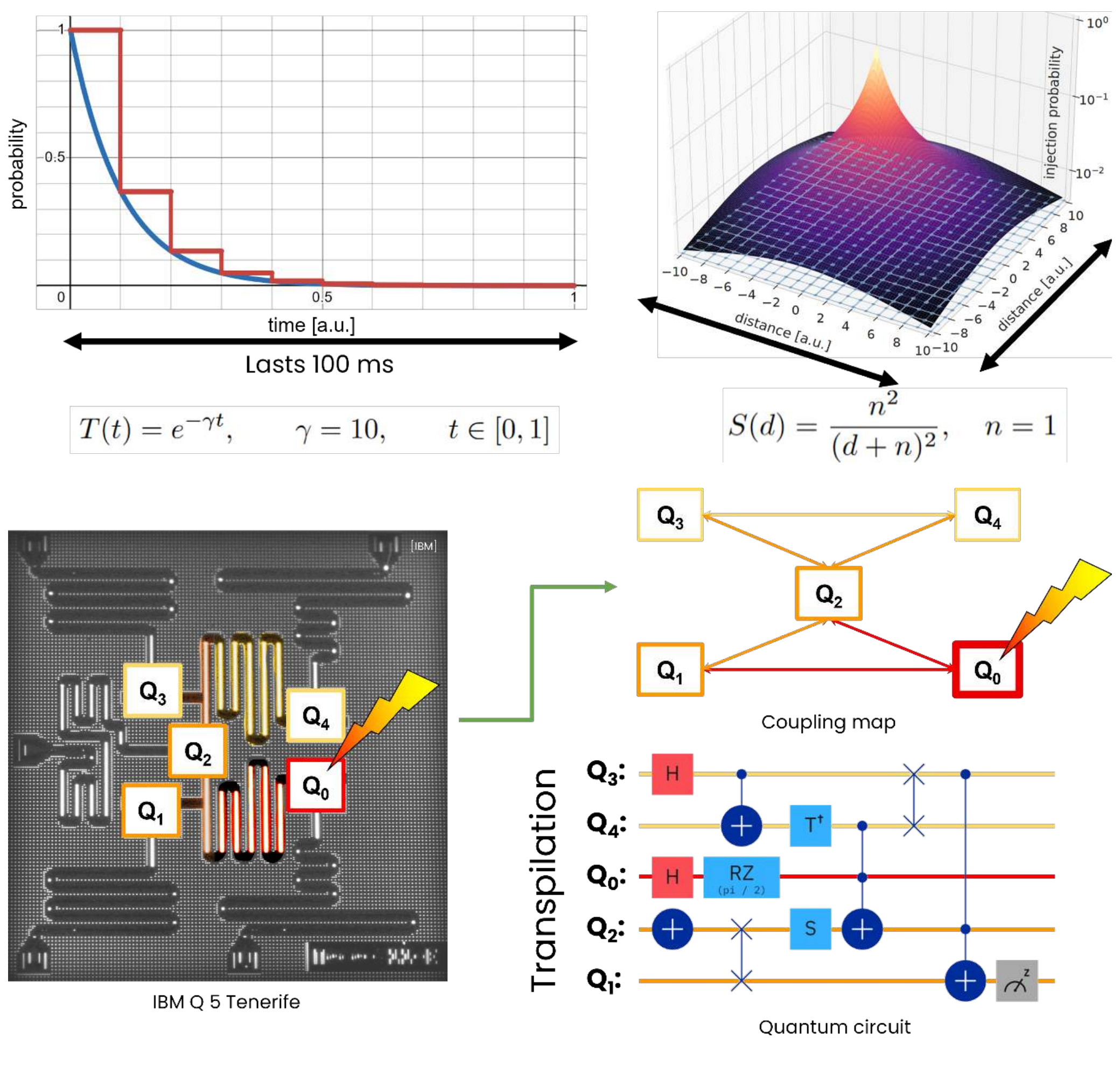


Impact closer to the qubit has a higher probability to induce faults, but even an impact 2mm from the qubit can modify the state

Superconductor simulation results. Top: energy absorbed with respect to the impact position. Bottom: energy deposited by 100 MeV positive muons across four qubits, considering different injection points, and the absorption share of each qubit.

Radiation fault model

The probability for qubits to reset can be modelled according to their distance from the impinging particle's impact point and time. In the temporal domain, deposited charge in Silicon recombines and is released following a negative exponential: the lower the presence of charge, the lower the chance for the qubit to spontaneously lose information. In the spatial domain, deposited charge in Silicon decreases following an inverse square law: the farther a qubit is from the impact point, the more likely it is to retain information.



$$T(t) = e^{-\gamma t}, \qquad \gamma = 10, \qquad t \in [0,1]$$

$$S(d) = \frac{n^2}{(d+n)^2}, \qquad n = 1$$

Radiation fault model. Top: plots of the physics of a radiation event's evolution. Bottom: graphical example of the fault model in action.

Surface code efficacy

Given the correlated multiple error nature of radiation events, we leveraged the logical fault model to extract the logical error thresholds of the Repetition code and the XXZZ code classes, in various configurations. The objective was to understand how radiation impacts Quantum Error Correction (QEC) and how to improve their reliability. We compared the effects of intrinsic noise, modelled as random Pauli operators, and radiation noise. It is possible to identify an operational threshold for the surface code under the effects of radiation, which highlights that for the 25% of the fault event QEC is not able to work as intended: technological improvements are thus insufficient to cope with these error mechanisms. Furthermore, intrinsic noise and radiation's effects stack up, shifting the encoded logical quantum state away from the intended one. Additional analyses and approaches to improve reliability of future QEC designs, such as the impact of code distance or qubit interconnections, can be found in the full paper.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Best Student Paper
On the Efficacy of Surface Codes in Compensating for Radiation Events in Superconducting Devices
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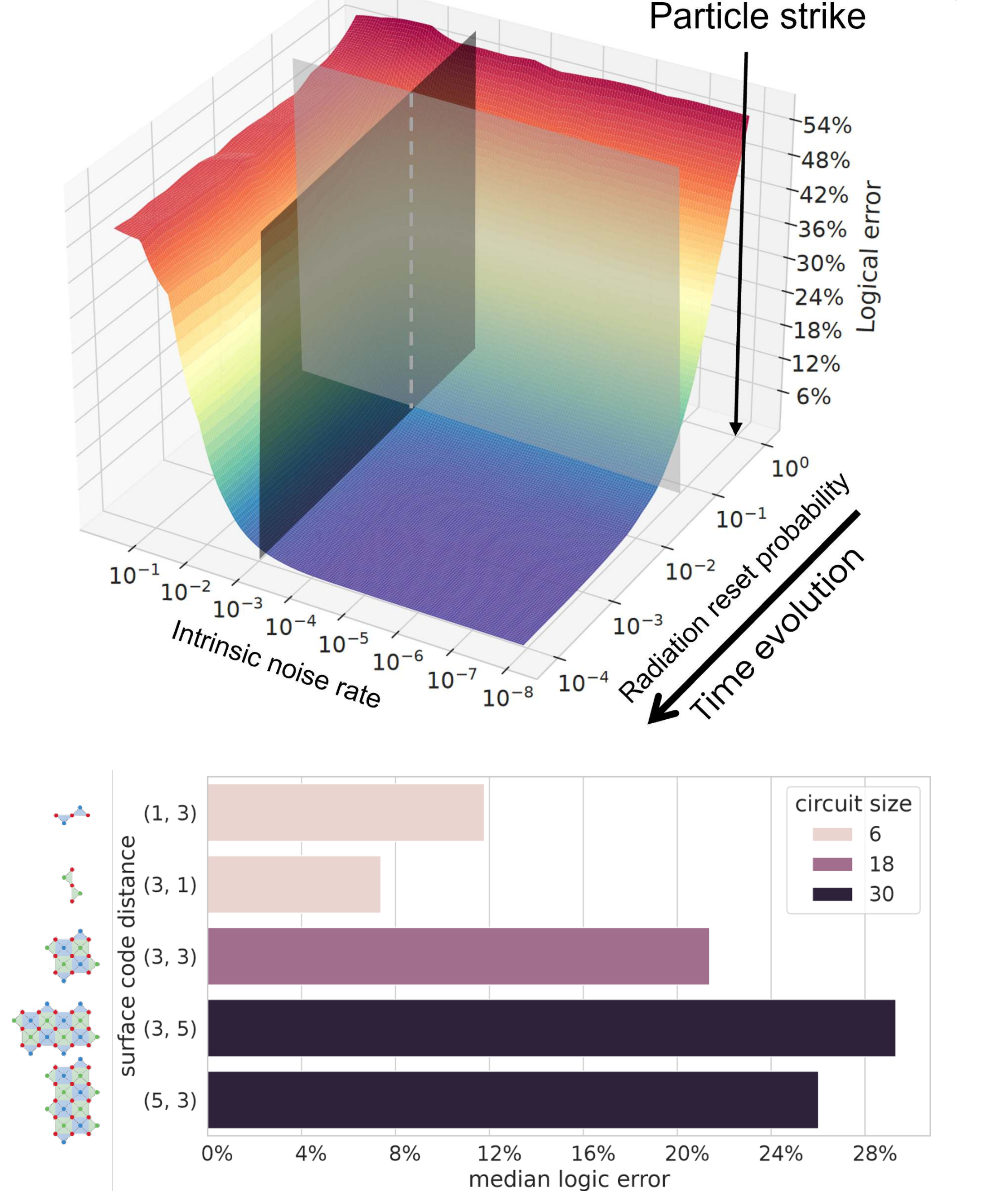
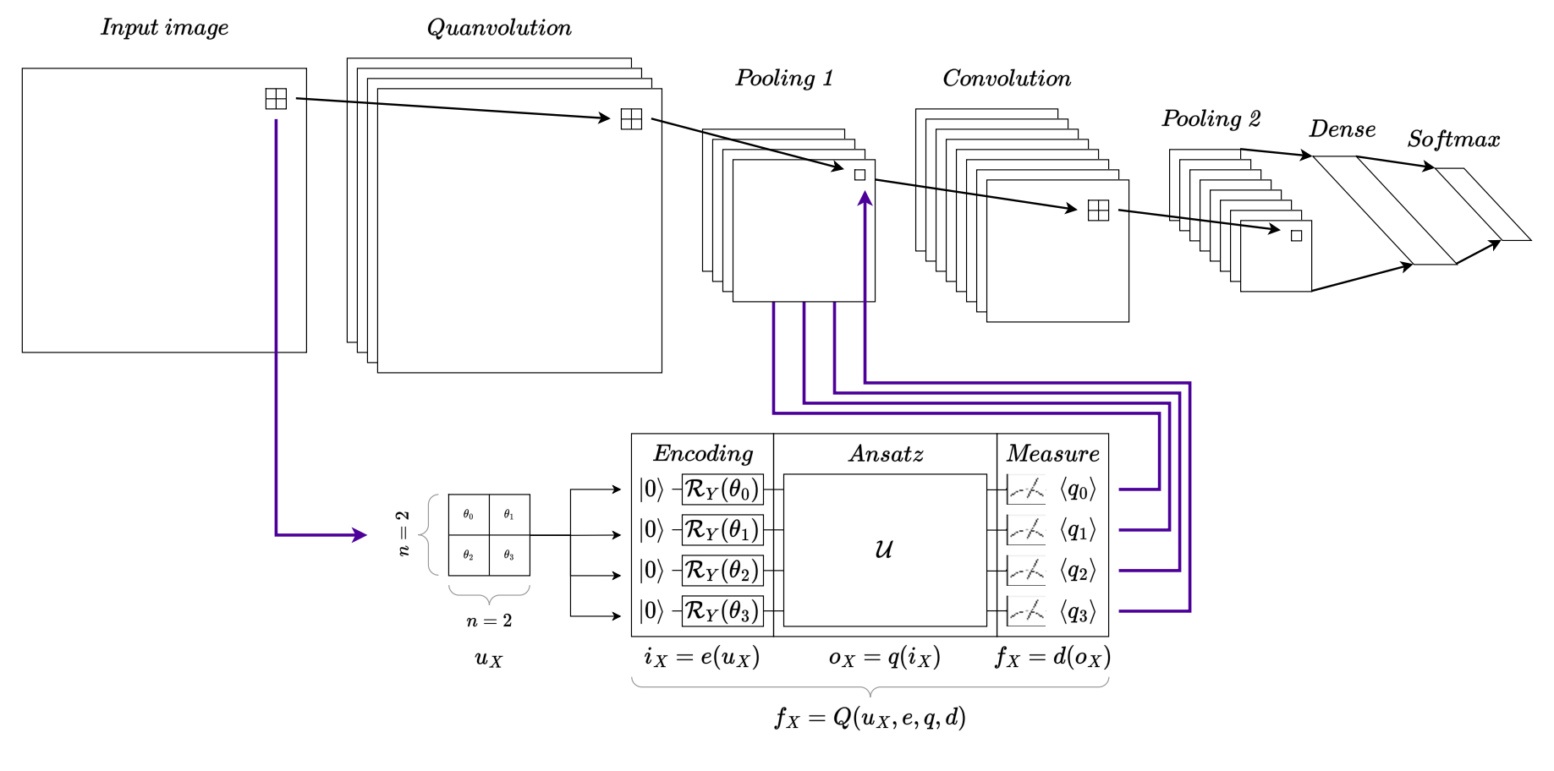


XXZZ code results. Top: logical error (vertical axis), i.e. the chance for the surface code to fail given the radiation fault's time evolution and noise intensity. Bottom: how the code's distance, i.e. the number of time the information is replicated, affects the logical error.

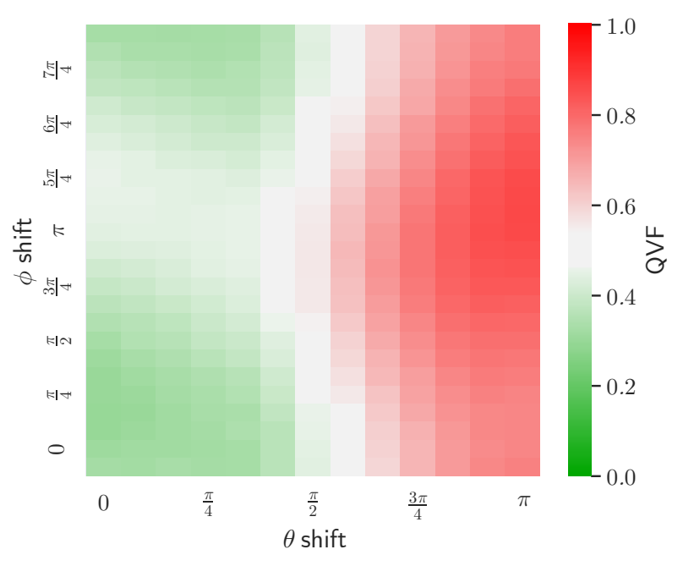
Fault impact on Quantum Neural Networks

Once the logical qubit error of small a small ensemble of physical qubits had been characterised, it was necessary to test the fault tolerance of quantum algorithms at a higher abstraction layer, specifically at the logical and algorithmic level. Some of the promising applications of quantum algorithms include hybrid machine learning approaches, such as the Quanvolutional Neural Network (QNN), which offers improved convergence and accuracy performance. We used a fault injector of our own development to induce and track the propagation of logical-shift errors in QNNs.

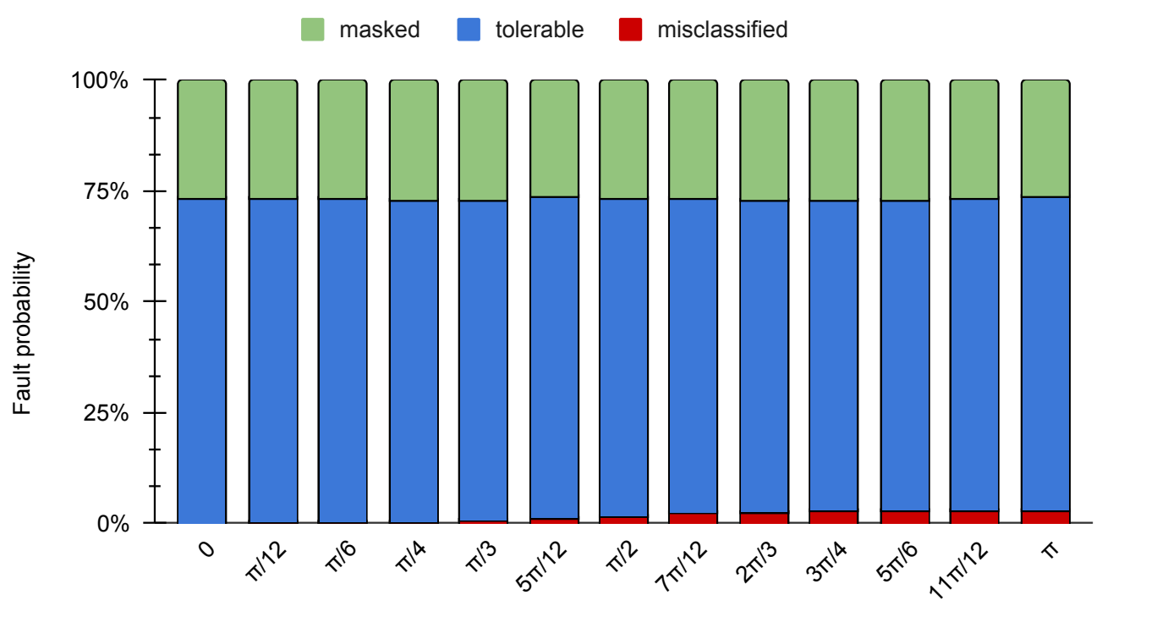


Quanvolutional neural network. In this hybrid model, a quantum convolutional layer feeds into other classical layers to perform image classification.

In the paper, we concluded that the corruption of the quantum layer significantly impacts QNNs' operations and classification. Our data shows that Z-basis logical-shifts are more likely to propagate to the output and that up to 10% of faults impair classification. The probability of classification failure depends on the logical-shift magnitude, on which input portion has been corrupted, on the training data set, and on the number of classical layers that follow the corrupted quantum component.



Quantum layer response to logical errors. Quantum Vulnerability Factor for *single* logical-shift fault injections.



QNN error ratio. Percentage of misclassifications with respect to logical shift amplitude, considering a single failed quantum convolution per input image.