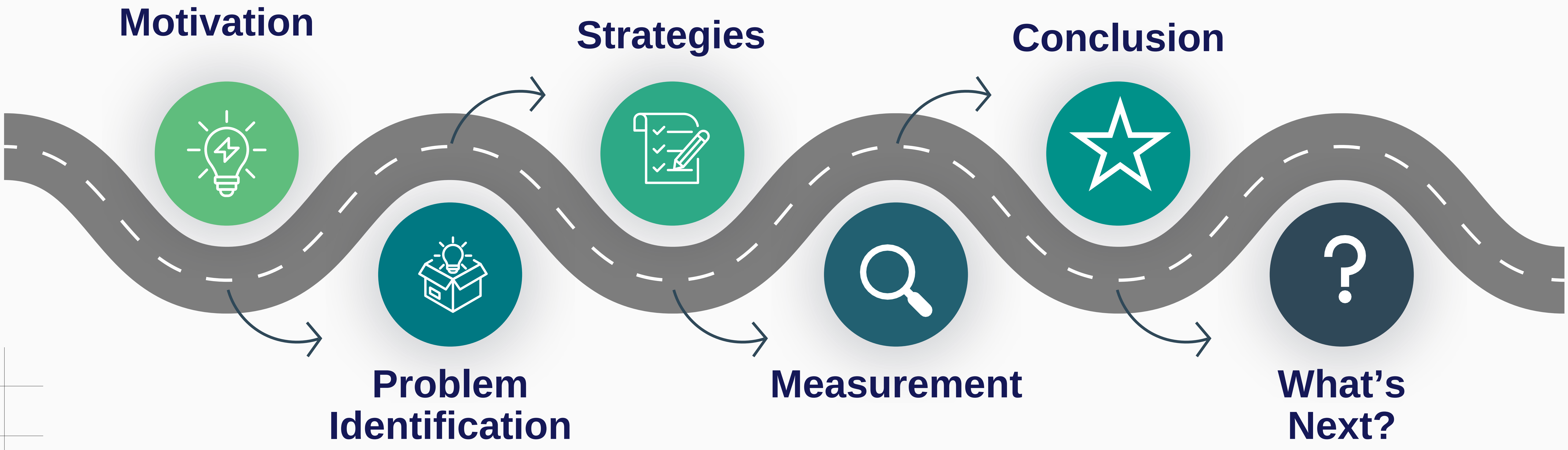
Reviewing “Resisting high-energy impact events through gap engineering in superconducting qubit arrays”

Umar Tariq Alhuwaymel

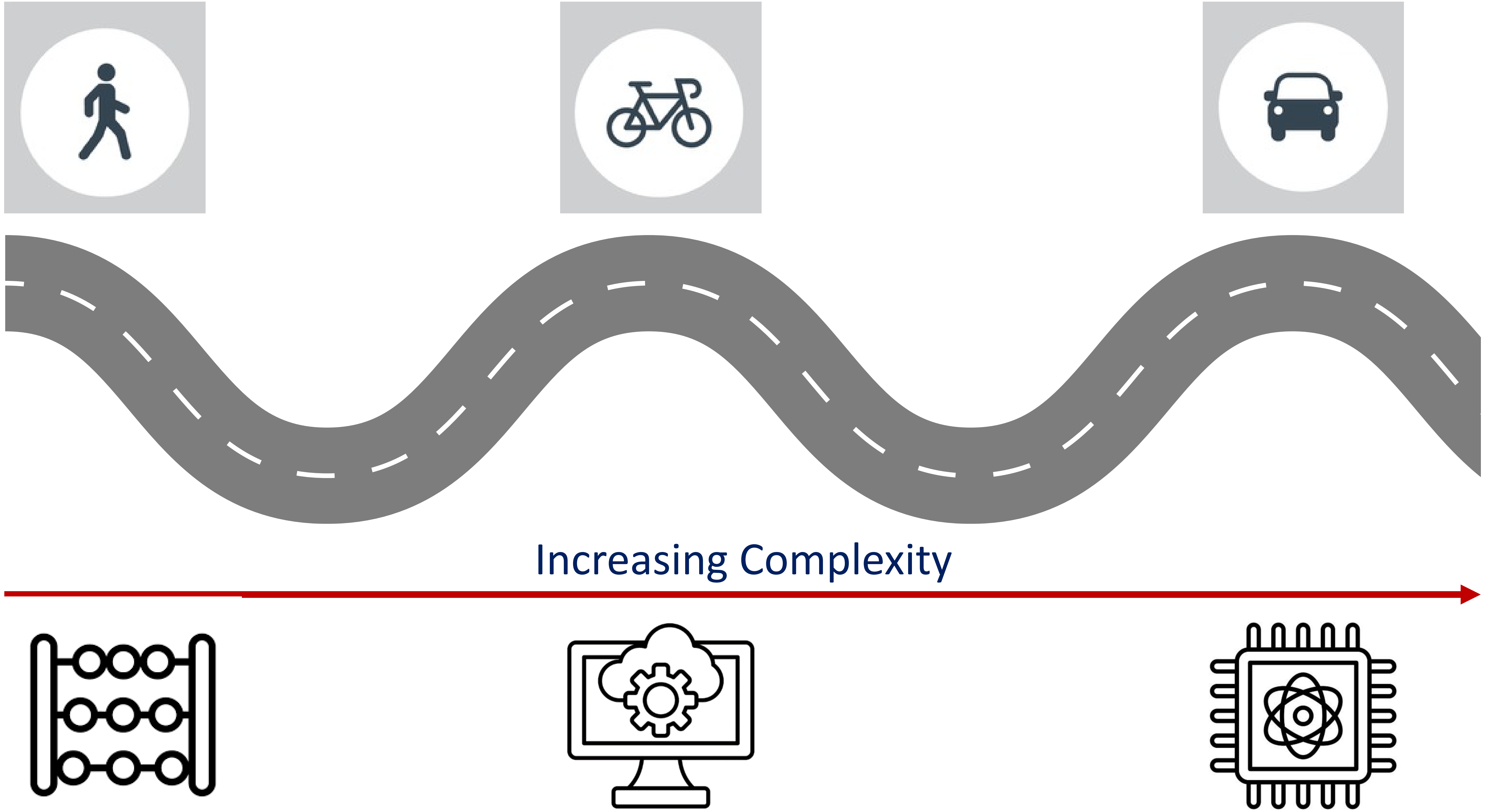
05/07/2025

❑ Outline

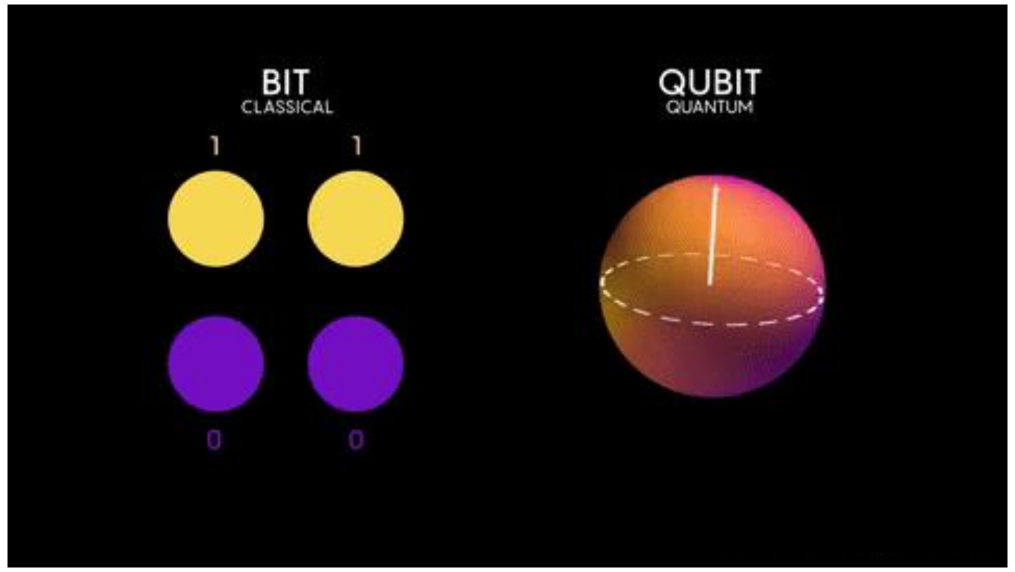

Motivation
Problem Identification
Strategies
Measurement
Conclusion
What’s Next?

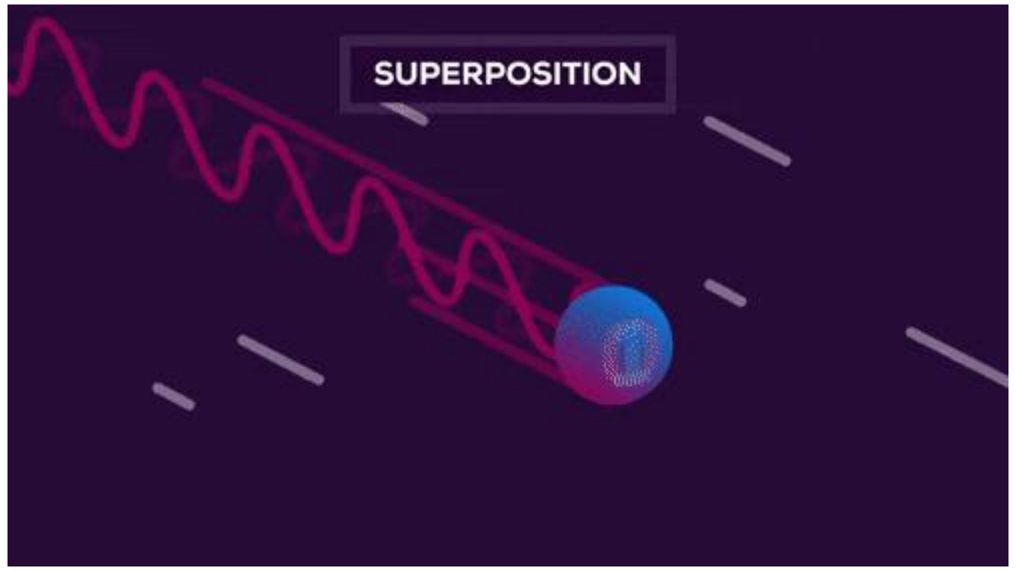
❑ Motivation

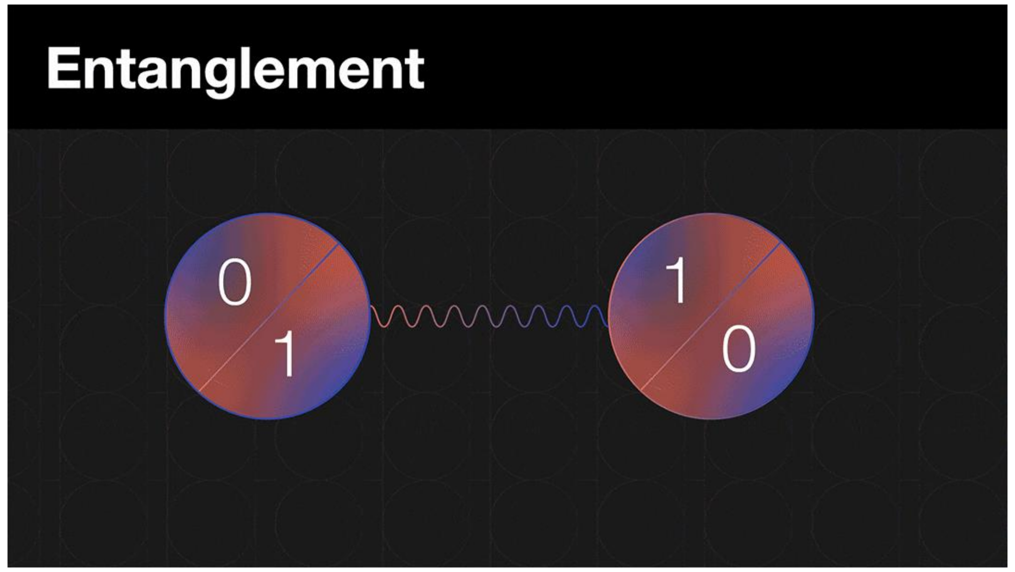
❑ Motivation



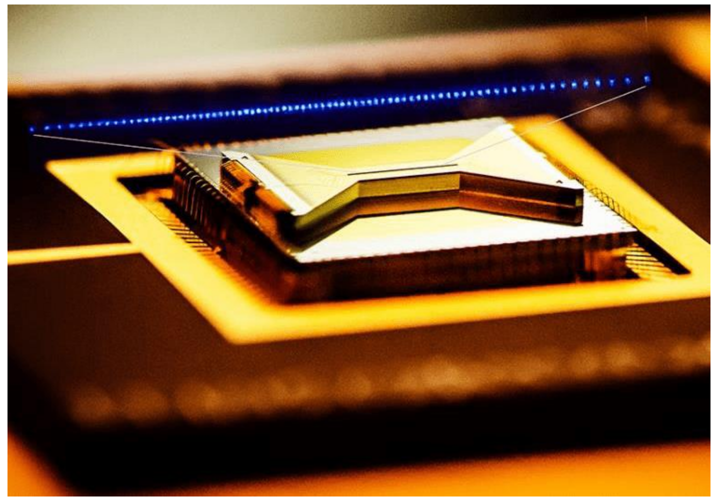
❑ Motivation

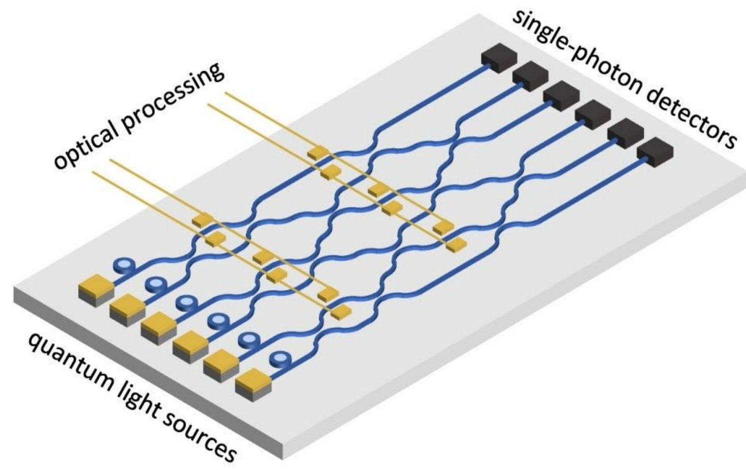

BIT
CLASSICAL
1
1
0
0
QUBIT
QUANTUM

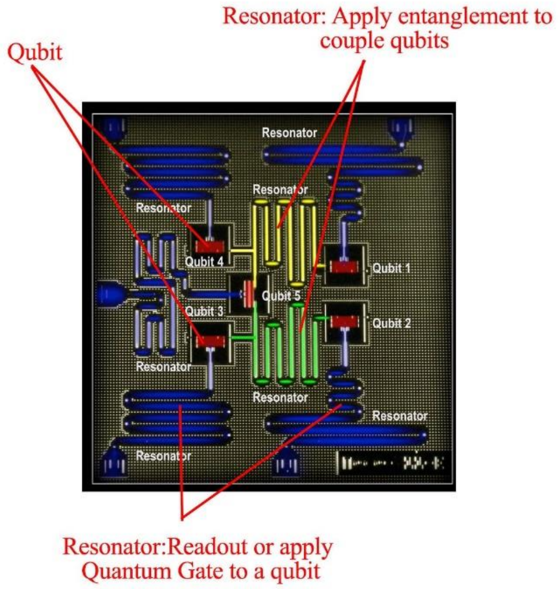

SUPERPOSITION


Entanglement
0
1
1
0

❑ Motivation



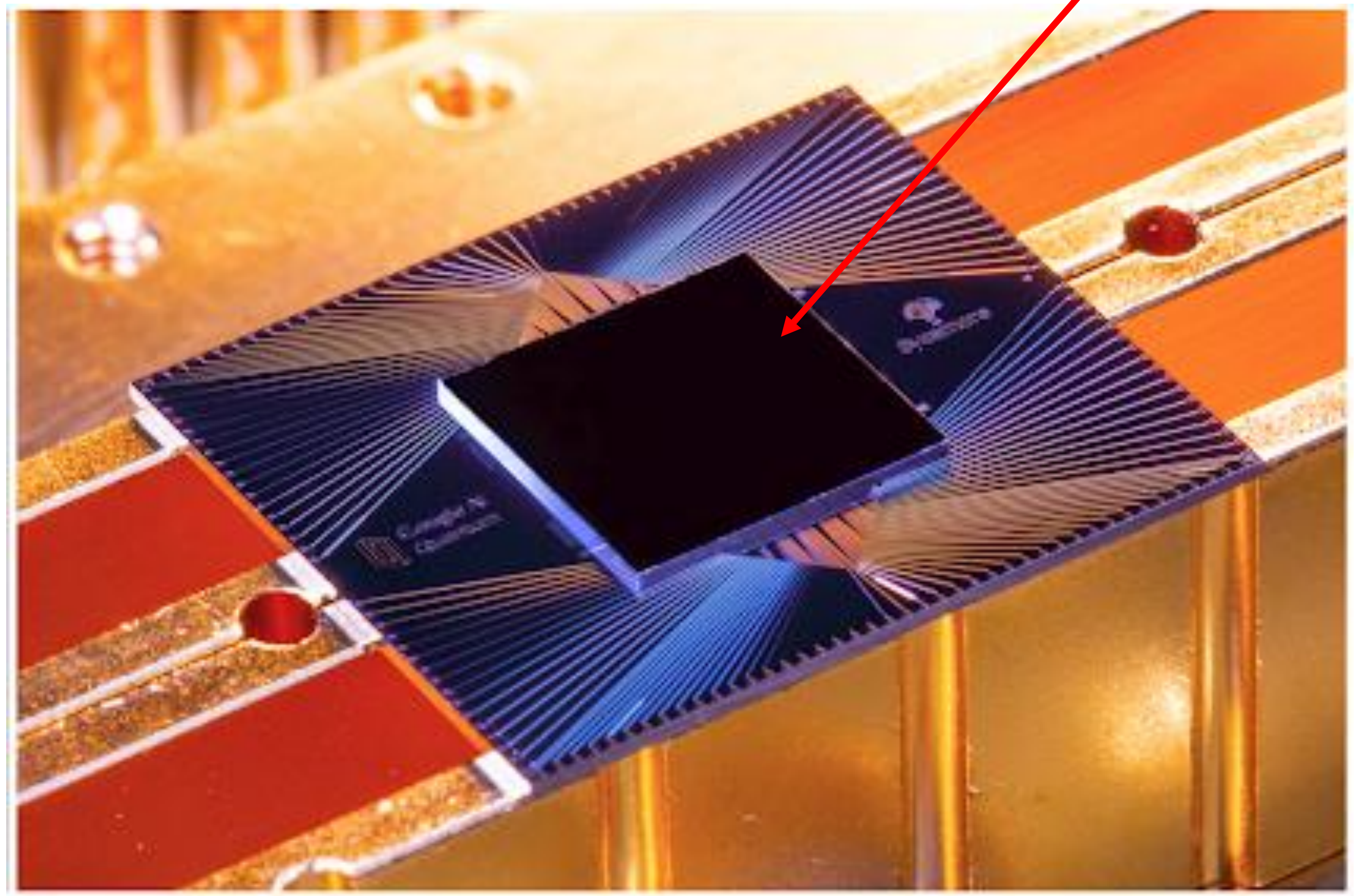

optical processing
single-photon detectors
quantum light sources


Resonator: Apply entanglement to couple qubits
Qubit
Resonator
Qubit 1
Qubit 2
Qubit 3
Qubit 4
Qubit 5
Resonator:Readout or apply Quantum Gate to a qubit

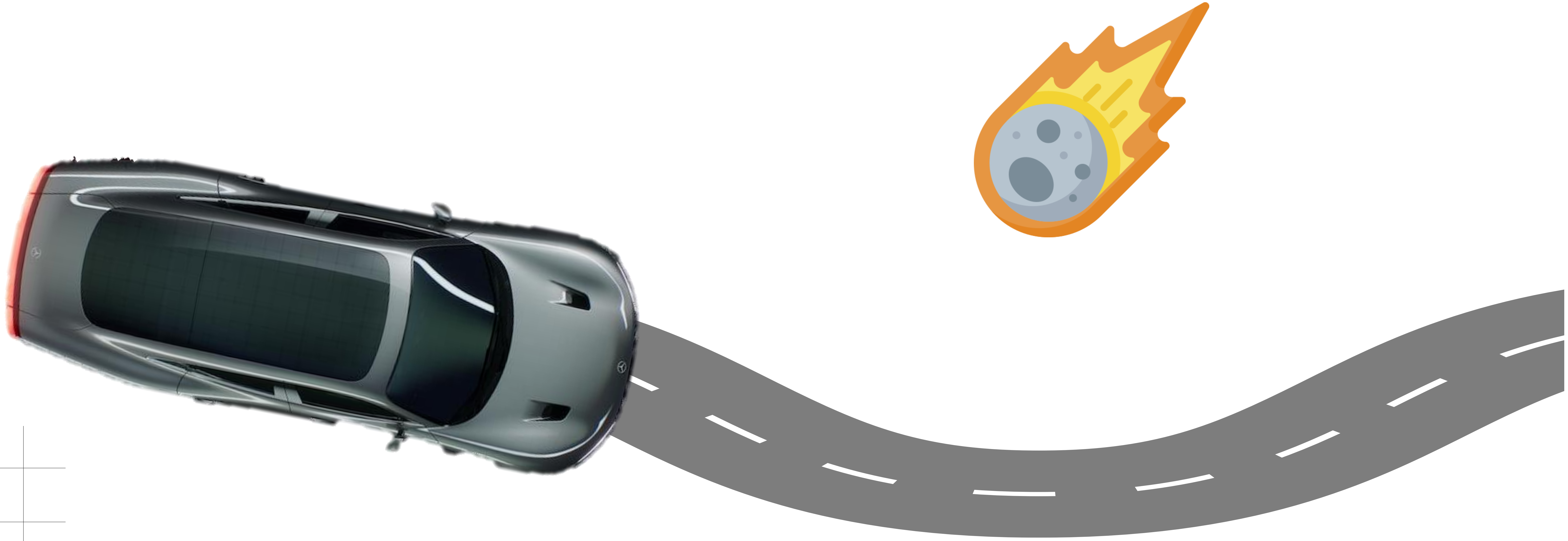
❑ Motivation

Car Issue	Quantum analogy	Type
Steering too hard	Pulse distortion	Control
Brakes delayed	Crosstalk in gates	Control
Faulty battery	TLS in dielectrics	Fab
Poor alignment	Parasitic coupling	Fab/ layout
Leaky fuel injector	QP poisoning	Fab

❑ Motivation



❑ Motivation



❑ Business Pitch

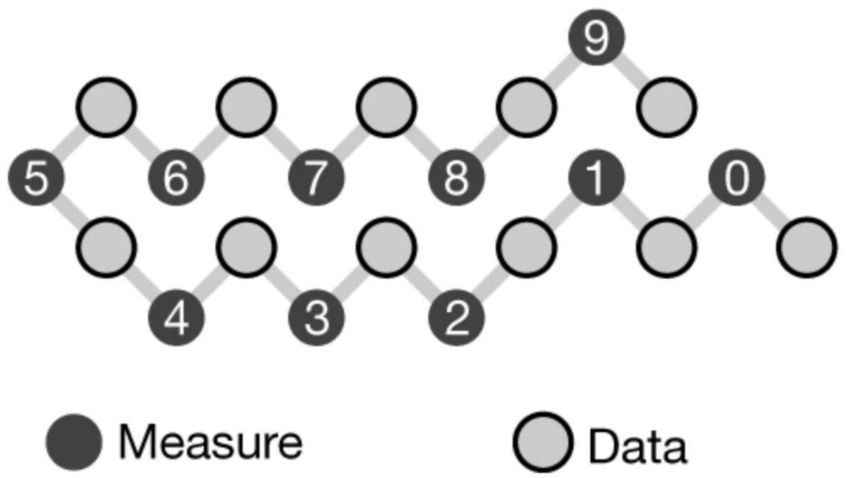
SC-Class

Engineered for Coherence.
Designed for Speed.

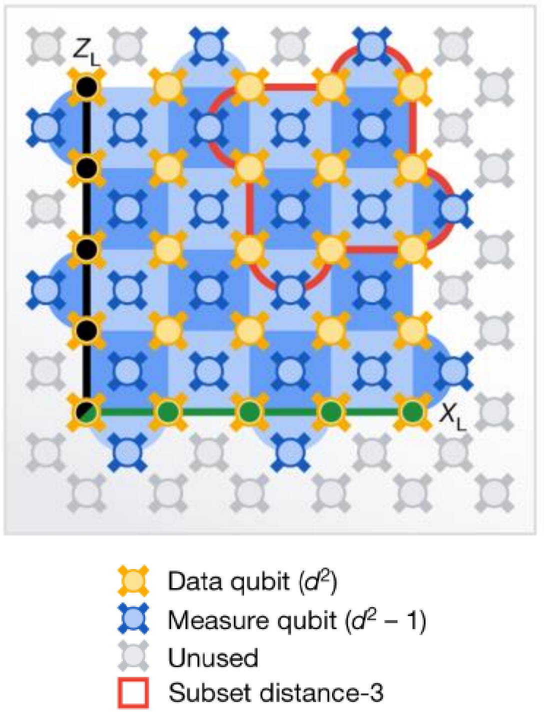
❑ Problem Identification

❑ QEC and Correlated Errors

- QEC necessity (physical vs. logical qubits)
- Architectures: repetition code, surface code etc.
- Errors are assumed to be: independent and local

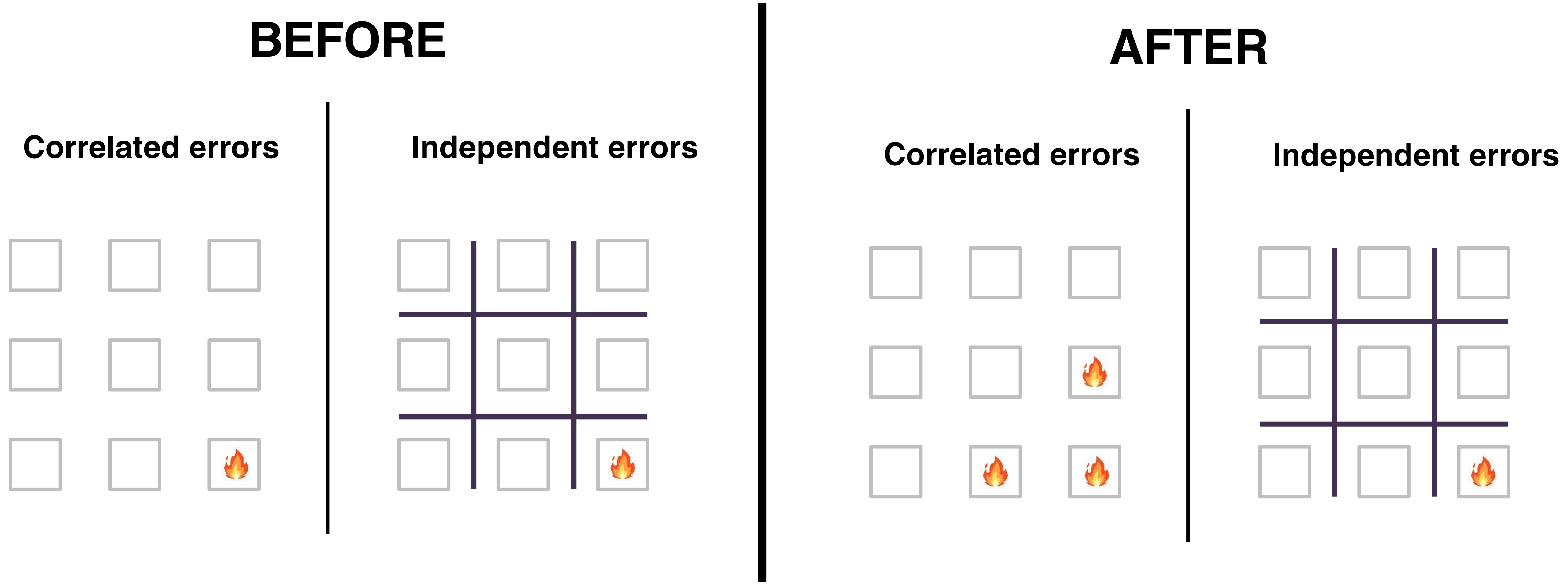


Exponential suppression of bit or phase errors with cyclic error correction by Google Quantum AI. Link: https://www.nature.com/articles/s41586-021-03588-y



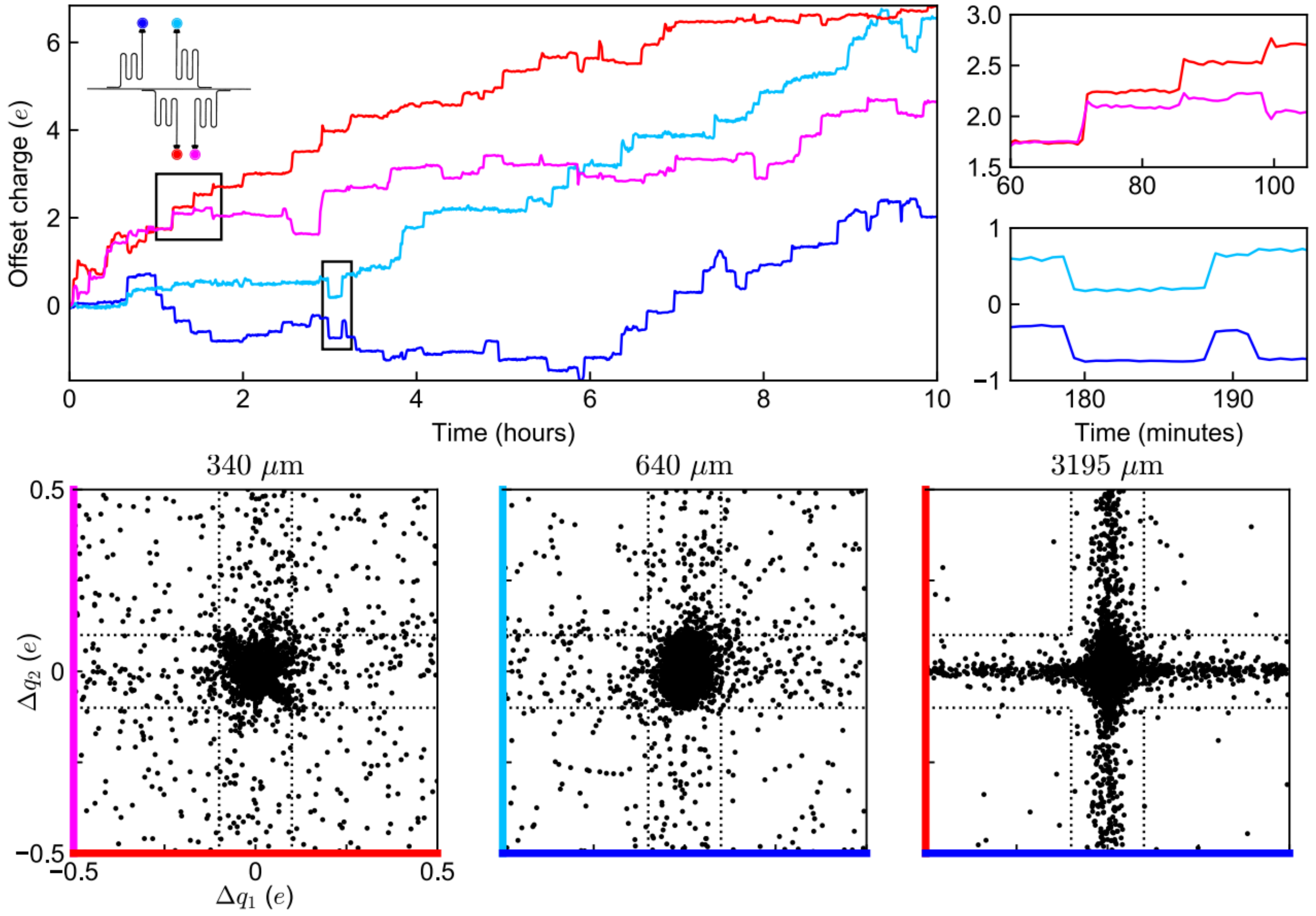
Suppressing quantum errors by scaling a surface code logical qubit by Google Quantum AI. Link: https://www.nature.com/articles/s41586-022-05434-1

❑ Correlated Errors Analogy



❑ Correlated Errors

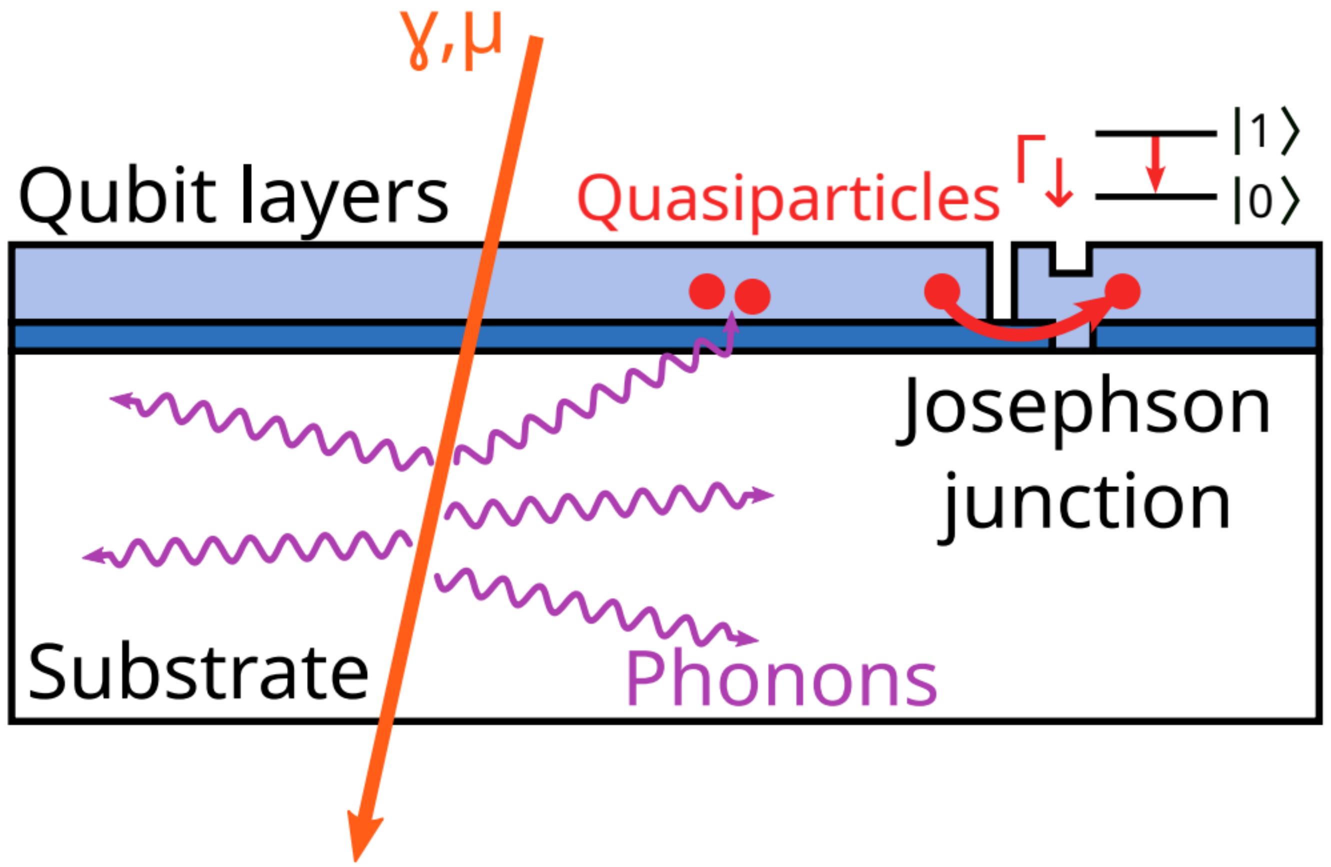
- Correlated error burst through space and time



Correlated Charge Noise and Relaxation Errors in Superconducting Qubits by C.D. Wilen et al. Link: https://arxiv.org/pdf/2012.06029

❑ High-energy Impact Events

- **High-energy radiation deposits up to 1 MeV, creating high-energy phonons**
- **High-energy impacts -> error bursts**

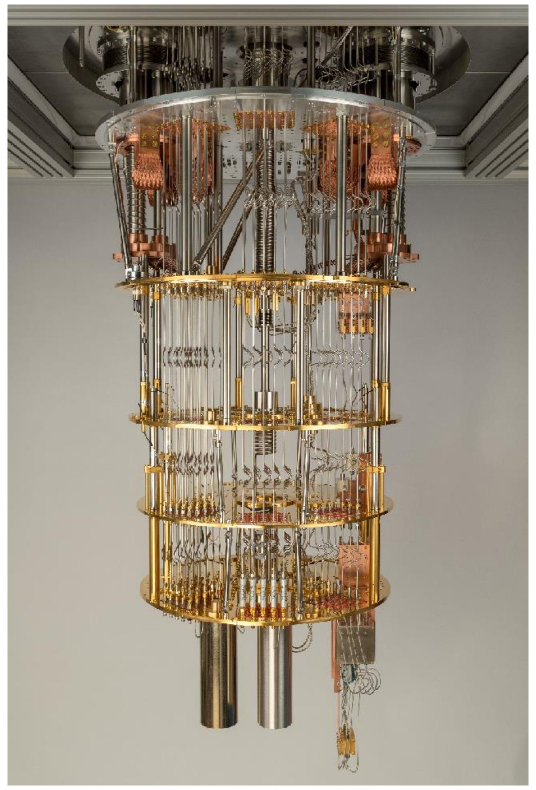


$$E_\mu \sim 3\ GeV$$
$$E_\gamma \sim 100\ keV$$

❑ Strategies

❑ Alternative Strategies

- Phonon or QP traps reduce both the temporal and spatial extent, but QP poisoning is still observed.

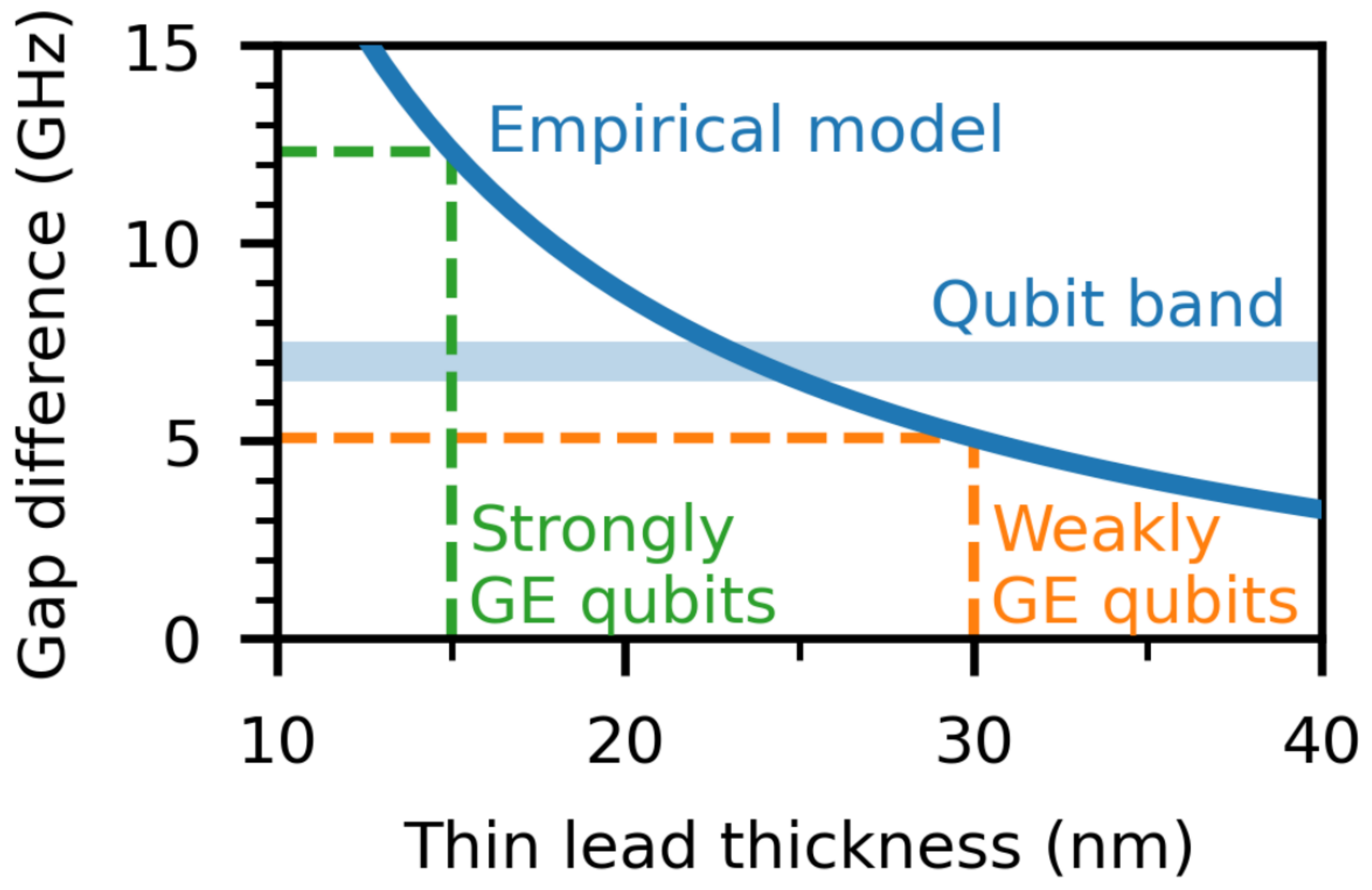


- Low-radiation underground facility reduces event rate of impacts, but remaining events remain unmitigated.

Engineering cryogenic setups for 100-qubit scale superconducting circuit systems by S. Krinner et al. Link: https://epjquantumtechnology.springeropen.com/articles/10.1140/epjqt/s40507-019-0072-0

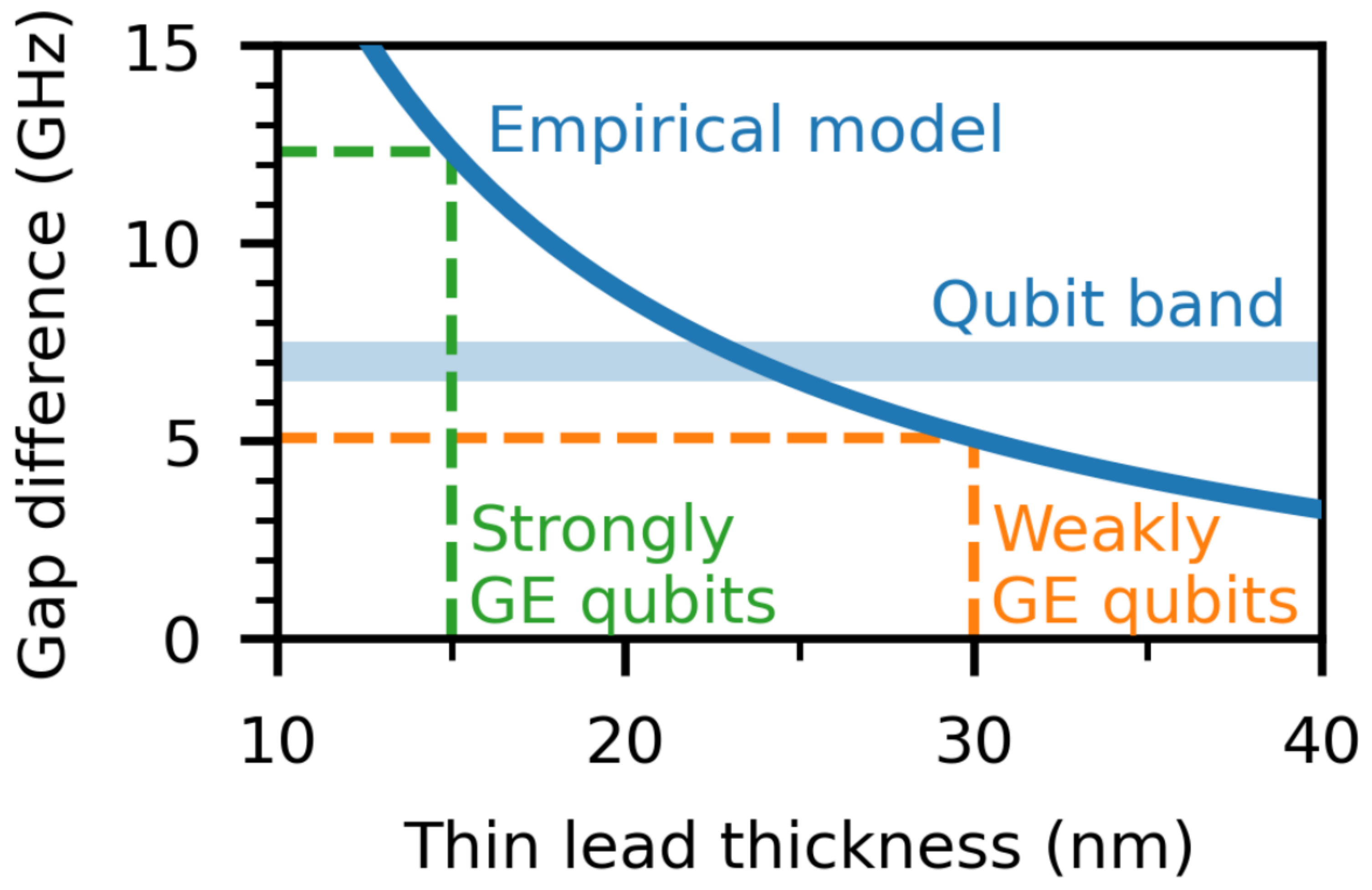
❑ Chosen Strategy

- **GAP ENGINEERING**



❑ Chosen Strategy

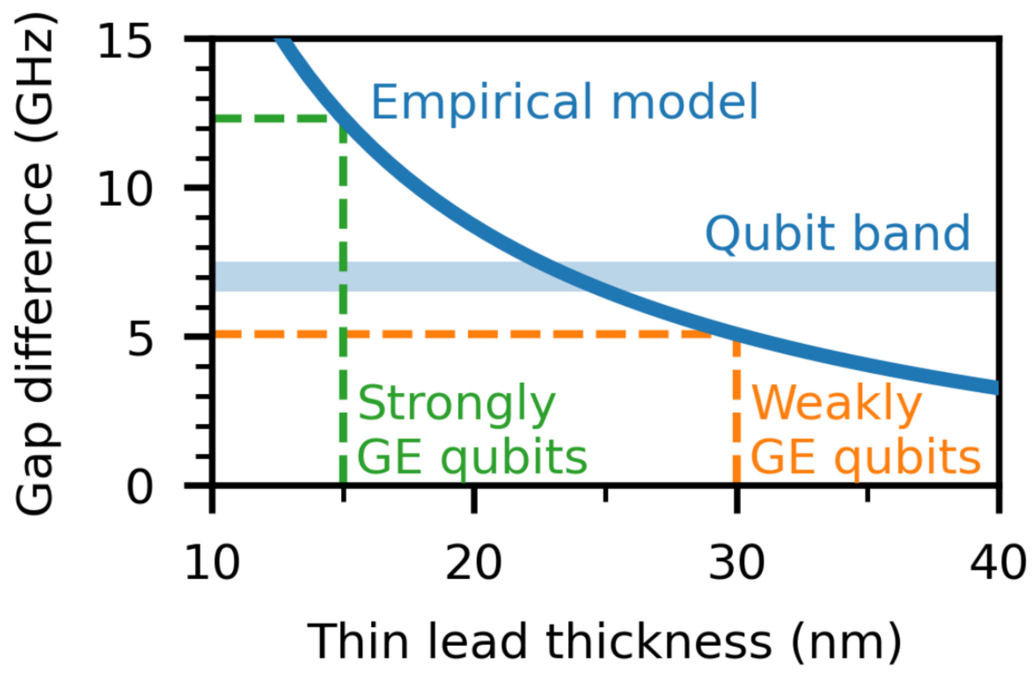
- Δ_{Al} is sensitive to thickness
- Gap difference: $\delta\Delta = \Delta_{thin} - \Delta_{thick}$
- $E_q = hf_q$
- If $Eq \gg \delta\Delta$ -> QPs with $E_{QP} \sim E_{\Delta}$ are further away from E_q
- $\Delta_{bulk} = 180\mu eV$

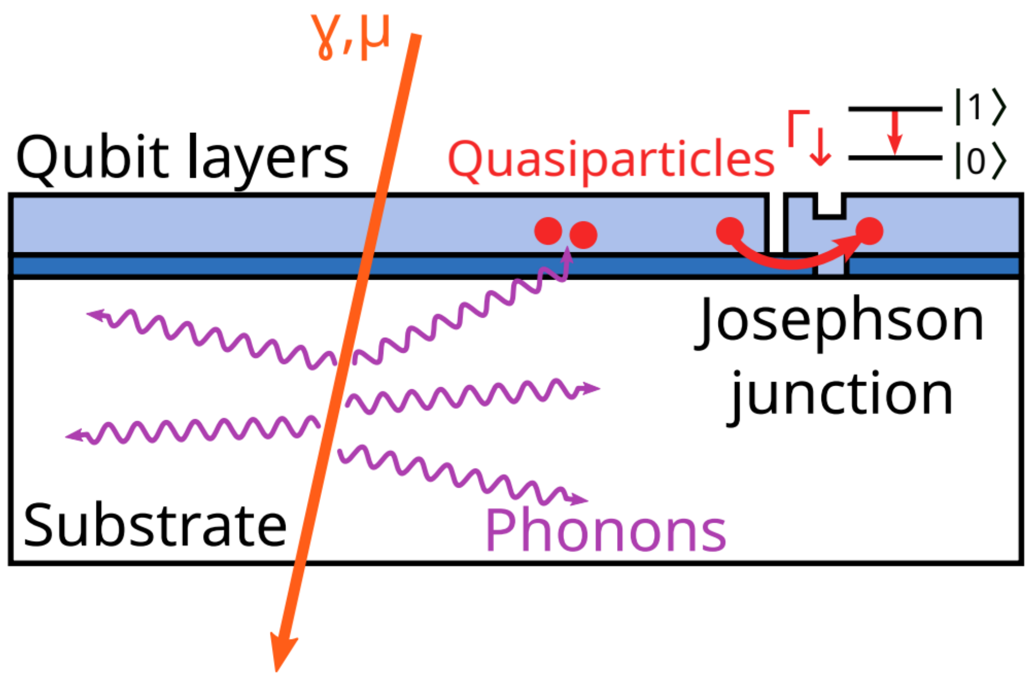


❑ Recap

- $\boldsymbol{\Delta_{bulk} = 180\mu eV}$

$$E_\mu = ?$$
$$E_\gamma = ?$$





❑ Recap

- $\boldsymbol{\Delta_{bulk} = 180\mu eV}$

$$E_\mu = ?$$
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$$E_\mu \sim 3\ GeV$$
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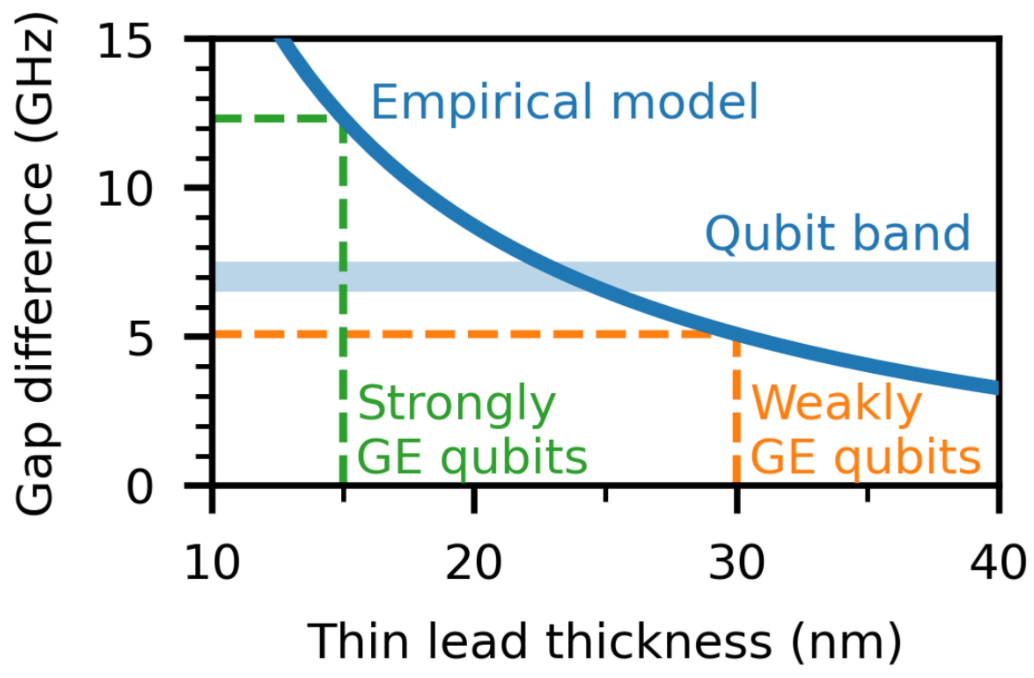
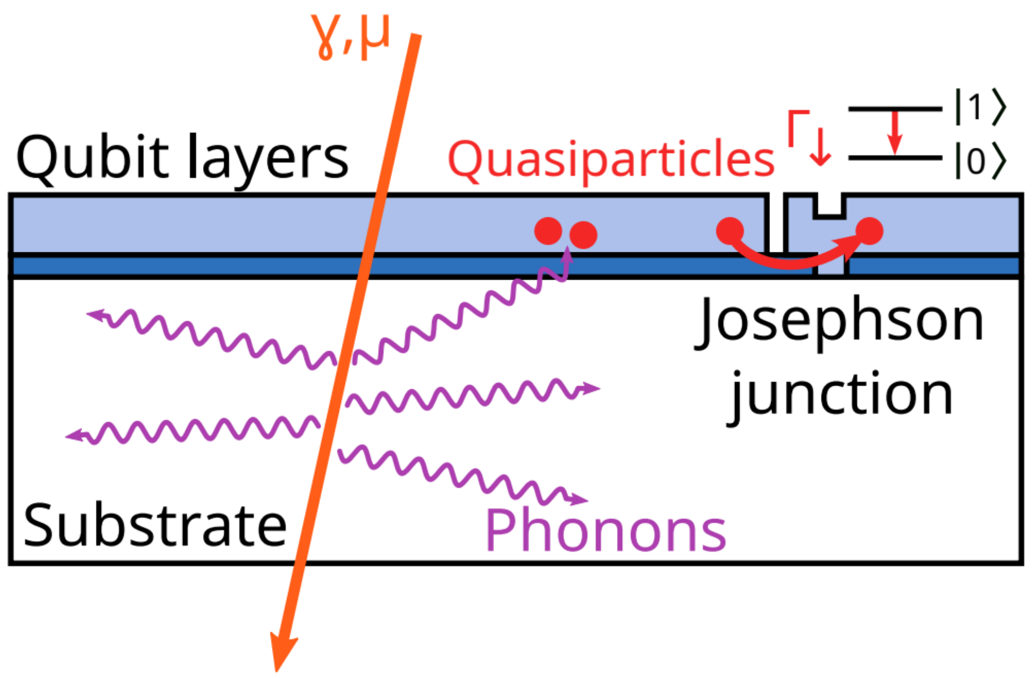
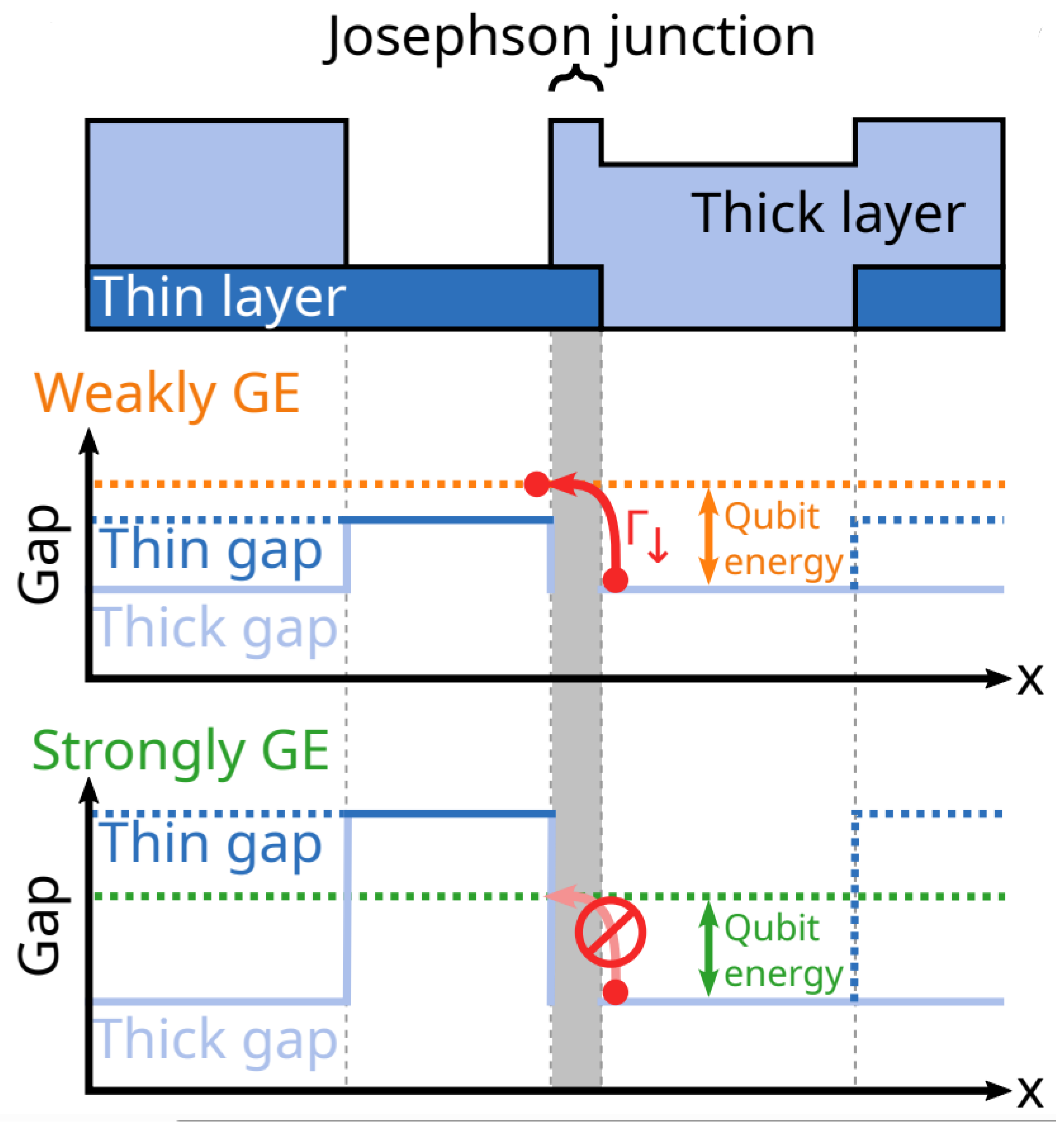


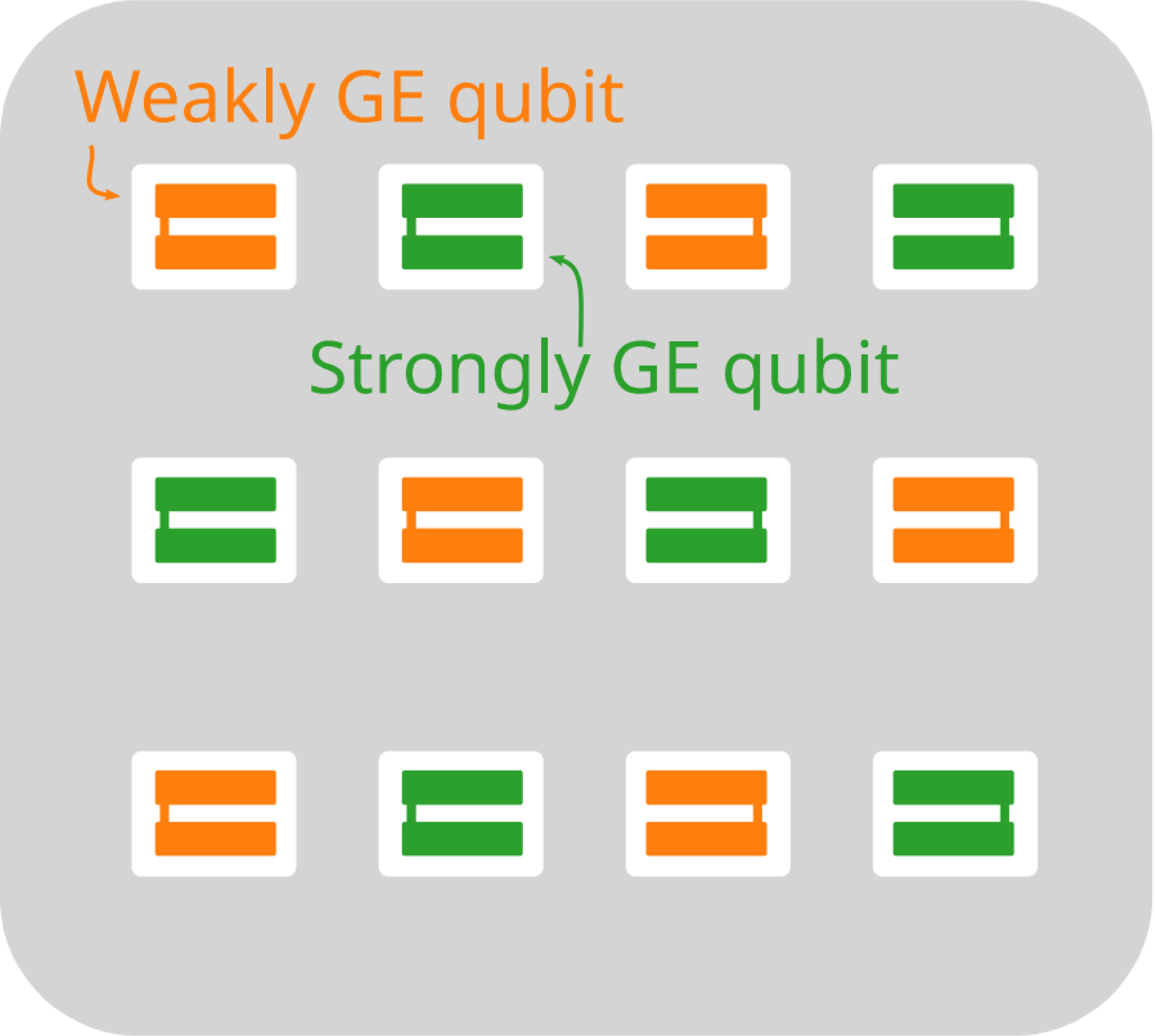


❑ Gap Engineering



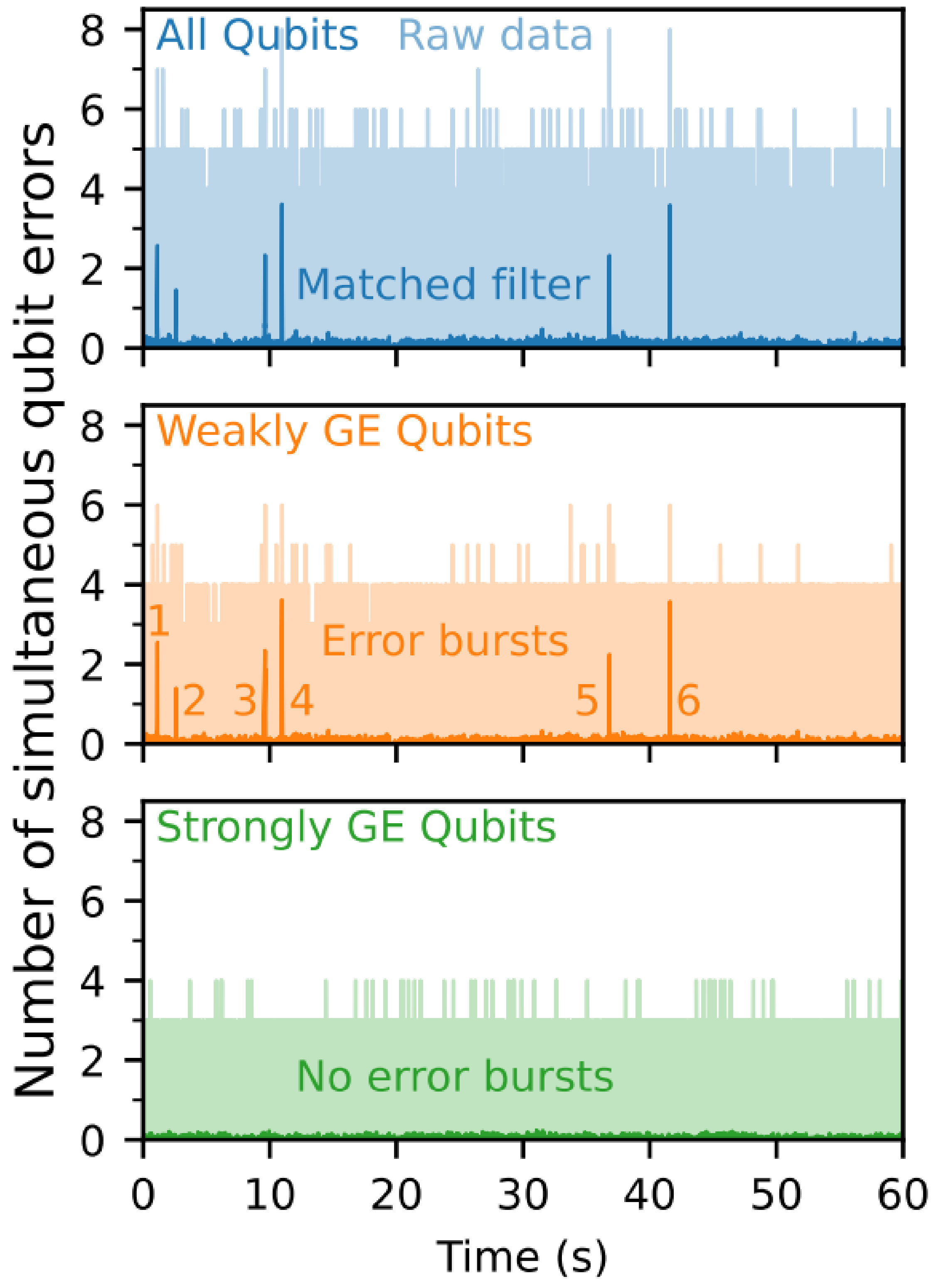
❑ Gap Engineered Qubits

- $f_{max} = 7 - 7.3\ GHz$
- $\Delta_{WGE} \sim 5\ GHz$
- $\Delta_{WGE} \sim 12\ GHz$

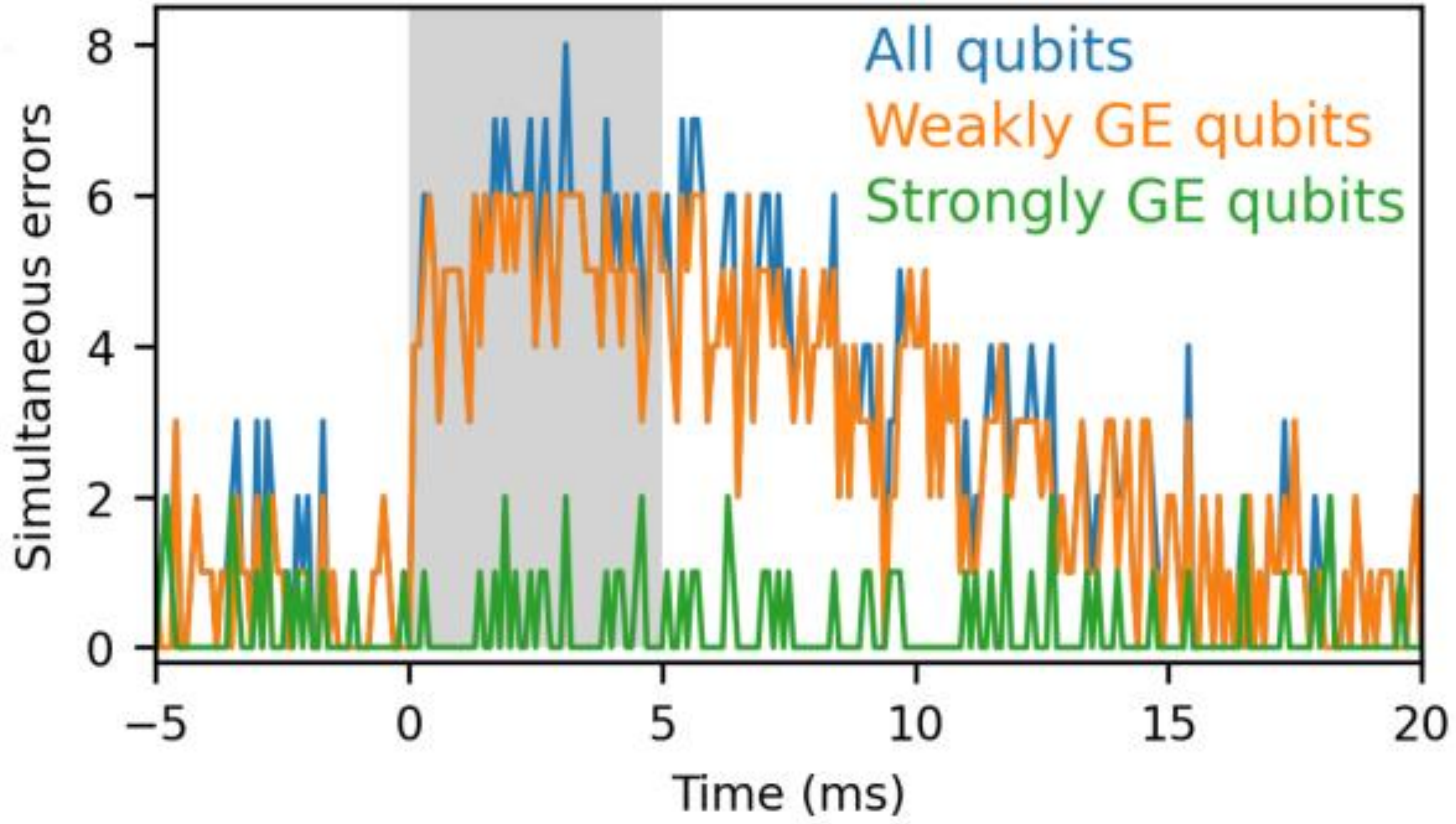


❑ Measurement

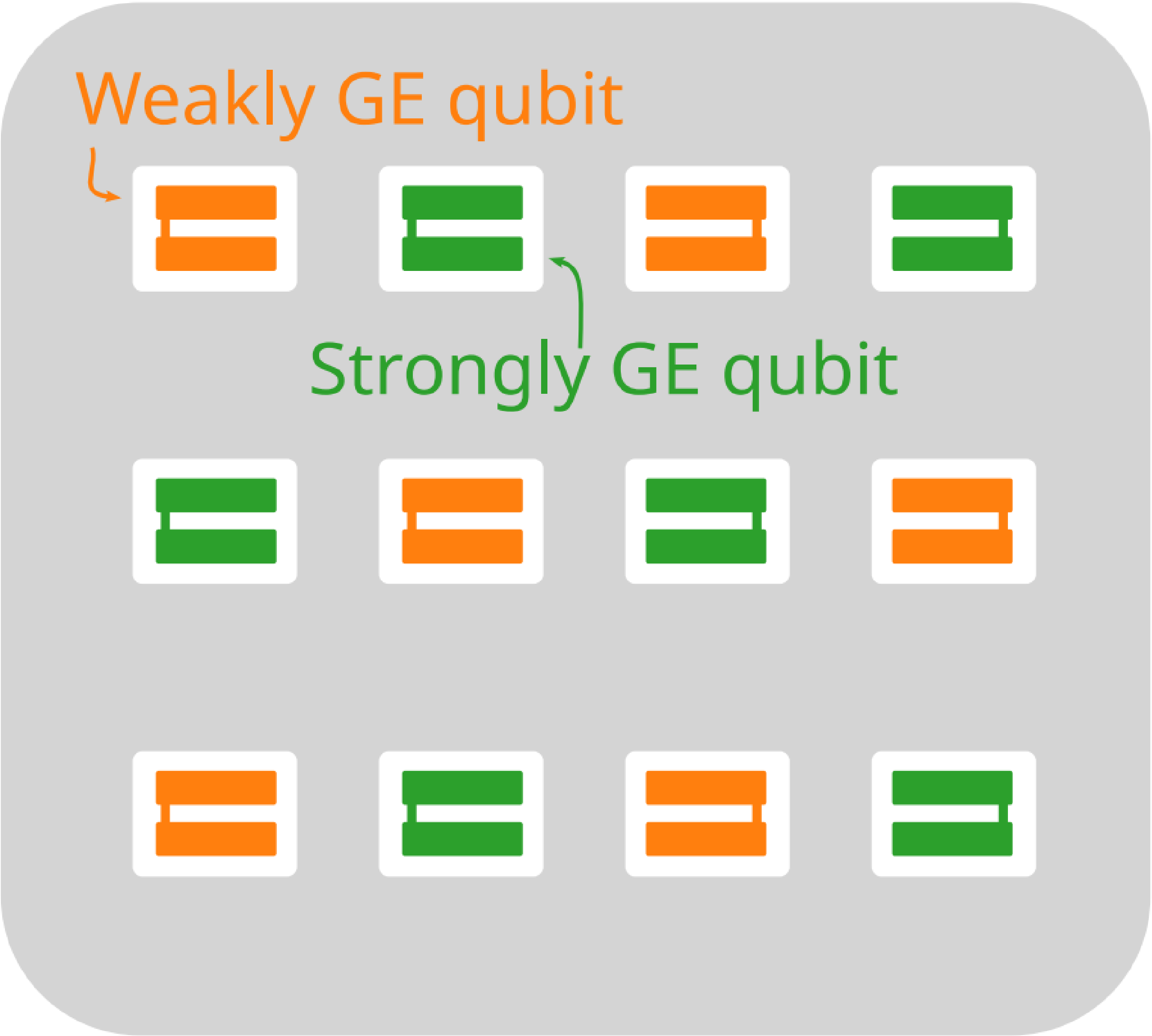
❑ Measuring Correlated Errors

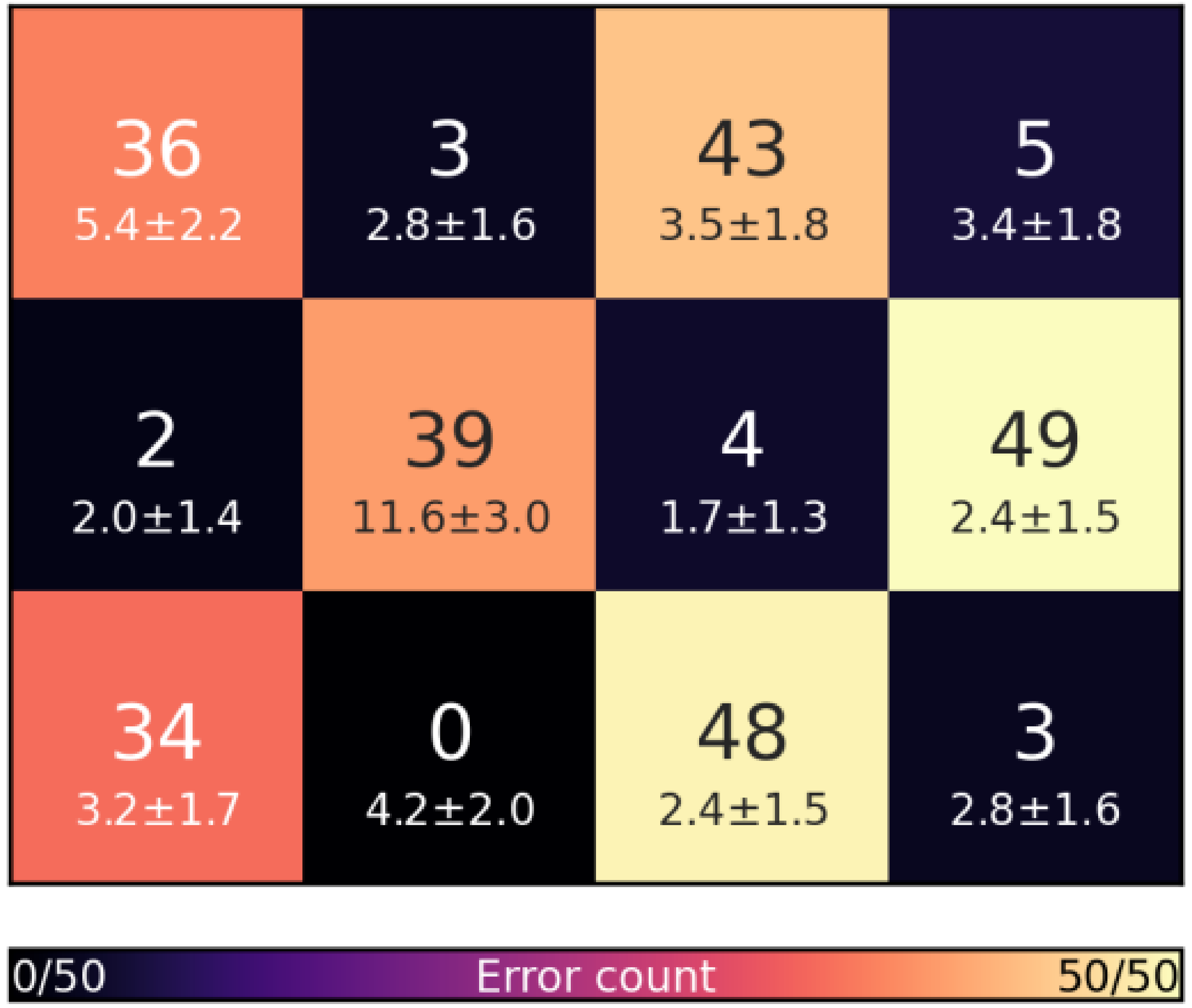


❑ Detecting High-energy Impact Event



❑ Errors in GE Qubits





❑ Conclusion

❑ References

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❑ What's Next?

❑ What's Next?

Correlated Error Bursts in a Gap-Engineered Superconducting Qubit Array

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(Dated: June 24, 2025)

One of the roadblocks towards the implementation of a fault-tolerant superconducting quantum processor is impacts of ionizing radiation with the qubit substrate. Such impacts temporarily elevate the density of quasiparticles (QPs) across the device, leading to correlated qubit error bursts. The most damaging errors—T_1 errors—stem from QP tunneling across the qubit Josephson junctions (JJs). Recently, we demonstrated [Phys. Rev. Lett. **133**, 240601 (2024)] that this type of error can be strongly suppressed by engineering the profile of superconducting gap at the JJs in a way that prevents QP tunneling. In this work, we identify a new type of impact-induced correlated error that persists in the presence of gap engineering. We observe that impacts shift the frequencies of the affected qubits, and thus lead to correlated *phase* errors. The frequency shifts are systematically negative, reach values up to 3 MHz, and last for ~ 1 ms. We provide evidence that the shifts originate from QP-qubit interactions in the JJ region. Further, we demonstrate that the shift-induced phase errors can be detrimental to the performance of quantum error correction protocols.

I. INTRODUCTION

Realization of a fault-tolerant quantum processor hinges on the ability to correct errors affecting individual physical qubits. When errors are rare and uncorrelated, they can be dealt with using quantum error correction (QEC). The performance of many QEC codes (e.g., the surface code) is expected to improve exponentially with the number of physical qubits; in principle, one should be able to reach an arbitrarily low logical error rate (LER) by scaling up the system [1]. However, this scaling behavior breaks down when correlated error *bursts* exist that simultaneously affect a large fraction of qubits. Such bursts then set a floor on the LER for QEC codes.

In superconducting quantum processors, one source of correlated error bursts is *impacts* of ionizing radiation with the qubit substrate [2–10]. The impacts generate a large number of high-energy phonons in the substrate that rapidly spread across the qubit array, see Fig. 1(a). The superconducting films comprising the qubits efficiently absorb these phonons; in the process, the phonon energy converts into Bogoliubov quasiparticle (QP) excitations. It is the proliferation of QPs that leads to correlated qubit errors. The most detrimental situation is realized when QPs tunnel across the qubits' Josephson junctions (JJs). A tunneling QP strongly couples to the electric field of the qubit, and readily absorbs a qubit excitation [11–17]. As a result, the qubit T_1 degrades to sub-μs scale following impacts [6]. The degradation persists for thousands of QEC cycles (a cycle duration is $\sim 1\,\mu s$ [18–20]) and, therefore, leads to a logical error with a high probability [21].

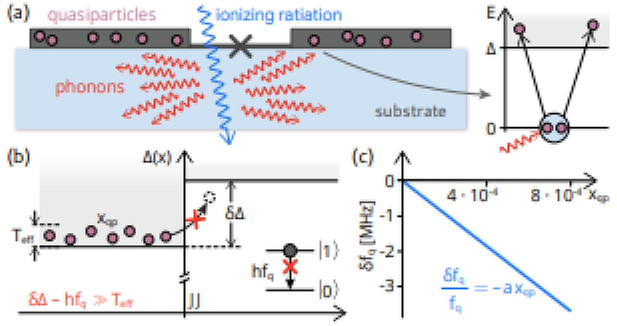

FIG. 1. **The fallout from ionizing radiation in gap engineered qubits. (a)** Ionizing radiation impacts deposit large energies in the qubit substrate, which propagate throughout the device in the form of high-energy phonons. These phonons break Cooper pairs in the superconductors leading to elevated quasiparticle (QP) densities, x_{qp}. The presence of QPs near the Josephson junctions (JJs) of the qubits results in correlated errors. **(b)** A difference $\delta\Delta$ in the superconducting gaps of the JJ leads exponentially suppresses QP tunneling, provided the characteristic QP energy, $T_{\rm eff}$, satisfies $\delta\Delta - hf_q \gg T_{\rm eff}$ [f_q is the qubit frequency]. This protects the qubits from QP-induced T_1 errors. **(c)** Even though QPs cannot tunnel, their elevated density results in qubit frequency shifts δf_q and thus leads to correlated phase errors [to produce the plot, we use Eq. (1) with $a = 0.77$ computed in Appendix G].

Fortunately, there exists a way to inhibit QP tunneling at the hardware level. The idea is to engineer the profile of the superconducting gap across the JJs to form a potential barrier for QPs, see Fig. 1(b). If the barrier is sufficiently large then QPs cannot tunnel [22–28]. This protects the qubits from QP-induced T_1 errors. In an earlier work, we verified the effectiveness of this strategy

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