

A Physics-based, AI-accelerated Codesign Approach for the Optimization of Superconducting Circuits

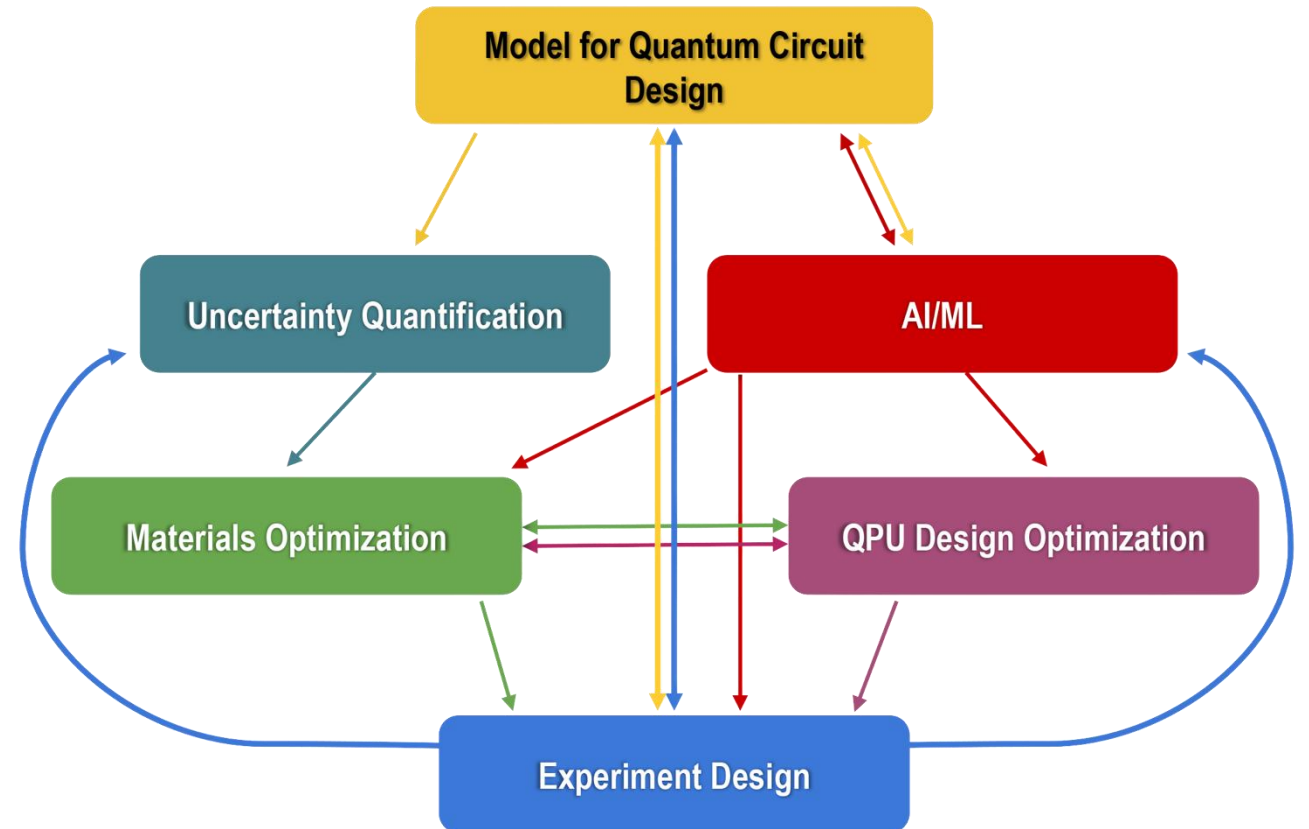
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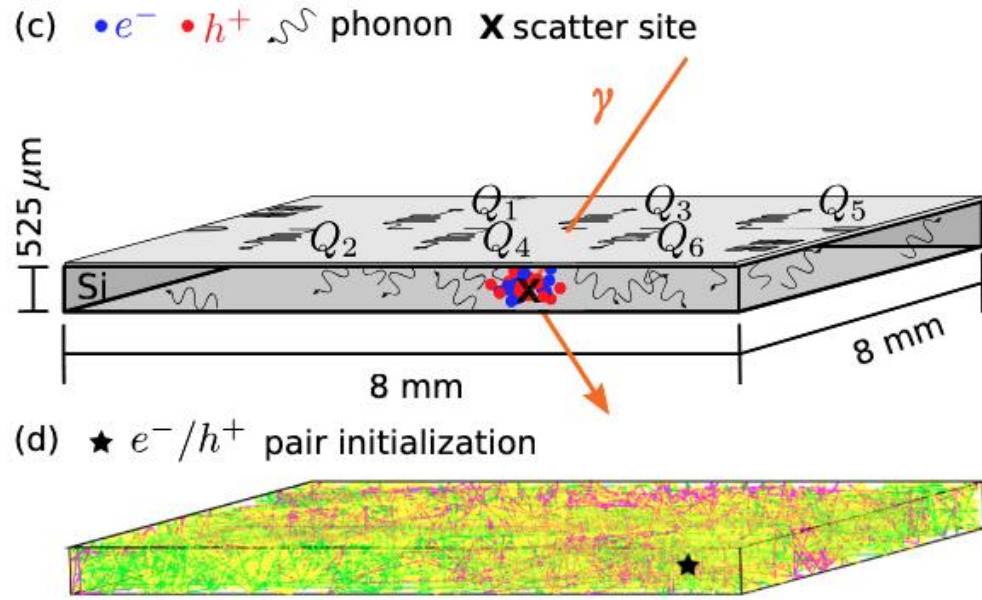
Date: March 16, 2026

Project Goals

- Establish architecture design protocols with machine learning and AI tools
- Develop models and objectives for device performance
- Focus on radiation impacts and quasiparticle poisoning

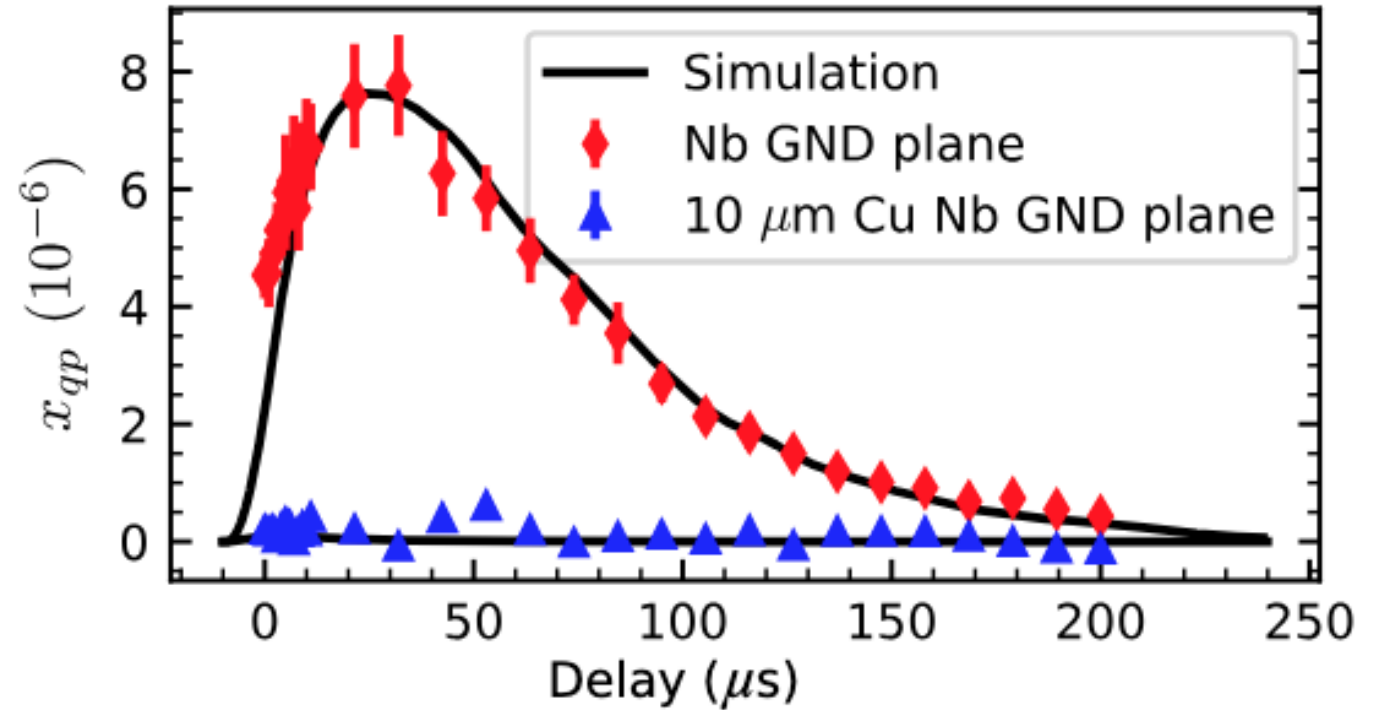


Model of Radiation Impact Events



Radiation impacts modeled with Geant4/G4CMP simulator developed by Yelton et al¹.

[1] E. Yelton et al. *Phys. Rev. B* **110**, 024519 (2024).



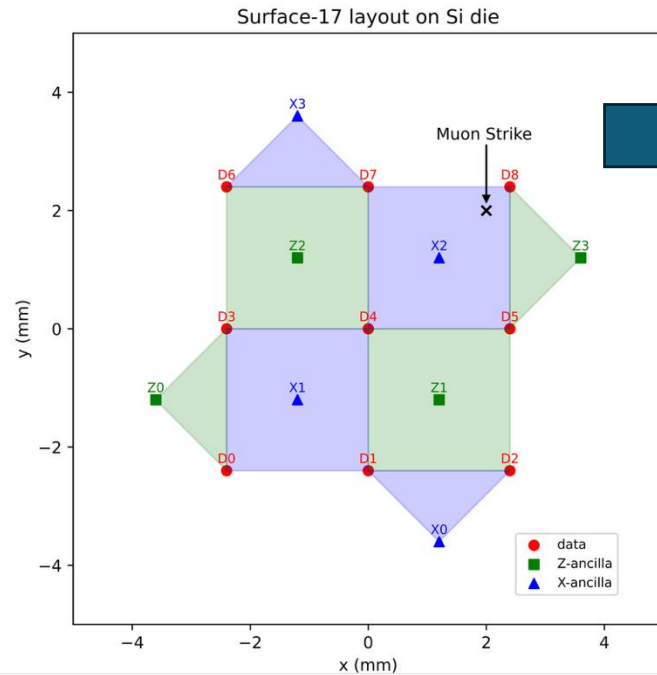
Quasiparticle density modeled following a phonon burst compared to experimental results.

Relaxation and Dephasing:

$$\Delta\Gamma_1 = \frac{x_{qp}}{\pi} \sqrt{2\Delta_{Al}\omega_{01}/\hbar}$$

$$\Delta\Gamma_\phi = \frac{E_C x_{qp}^2}{2\pi^2 \hbar} e^{\frac{W_0[4\pi/x_{qp}^2]}{2}}$$

Quantum Error Correction Model

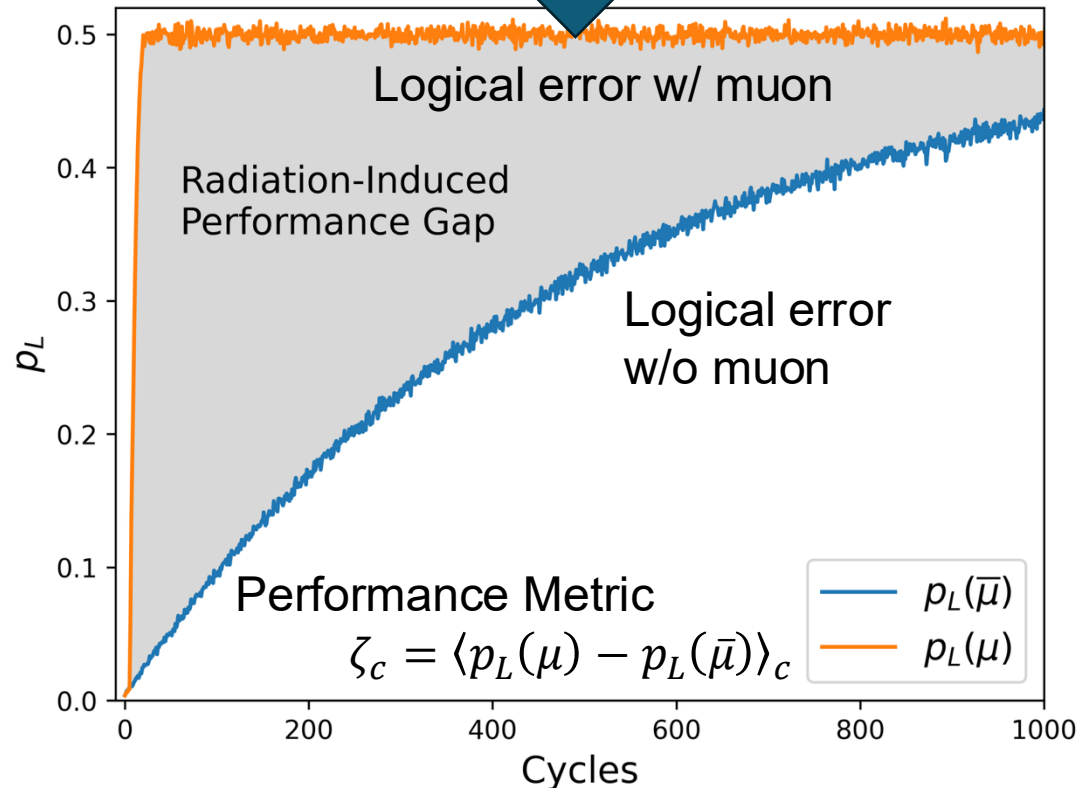


T_1, T_2

Noise Model:

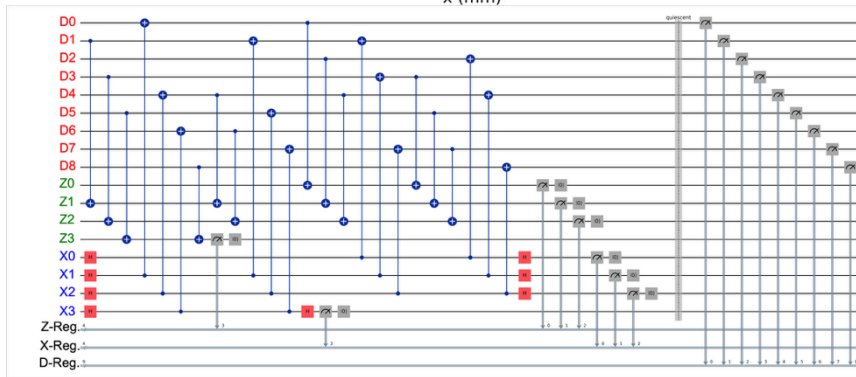
- Generalized Amplitude Damping Channel
- Applied to gate and readout operations

Stim

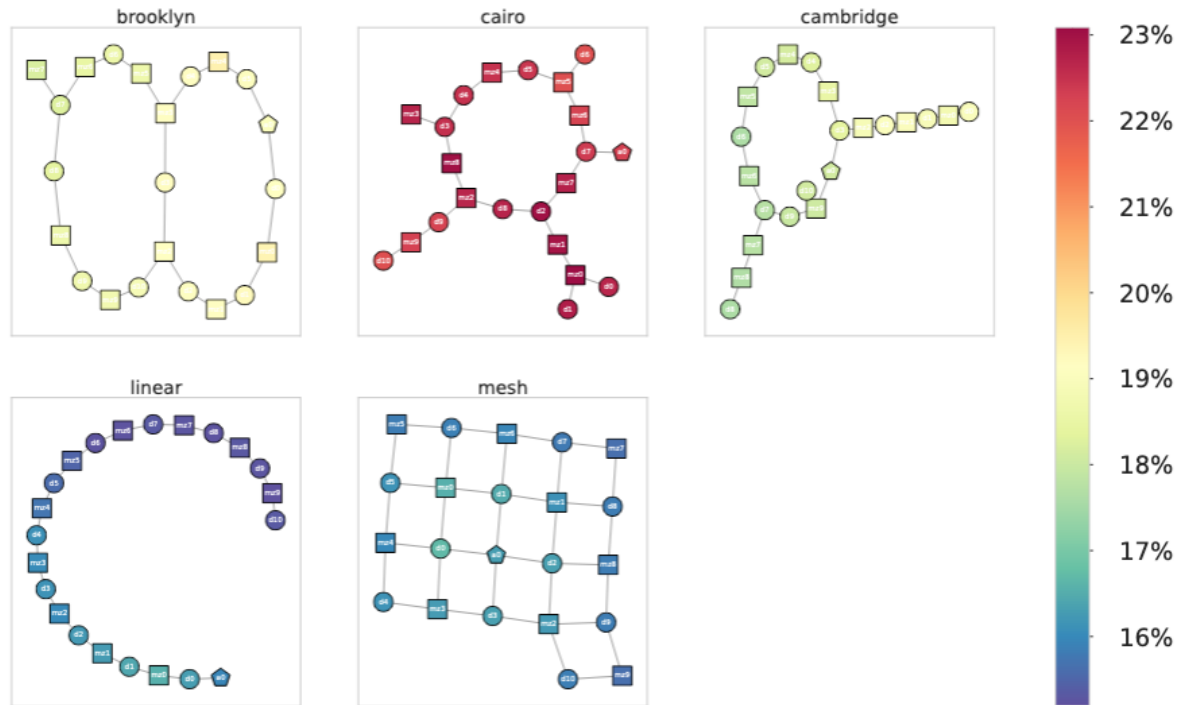


Memory Test:

- Encode logical state
- Cycle-dependent error rate
- Decoded with Minimum Weight Perfect Matching decoder



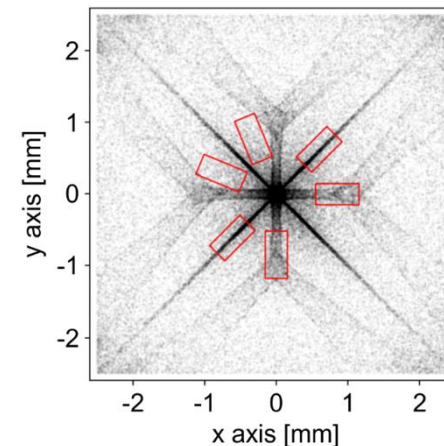
Architecture Optimization



Test of various architectures
w/ phenomenological noise model
[3] M. Vallero et al. SC24, 1 (2024).

Use Case

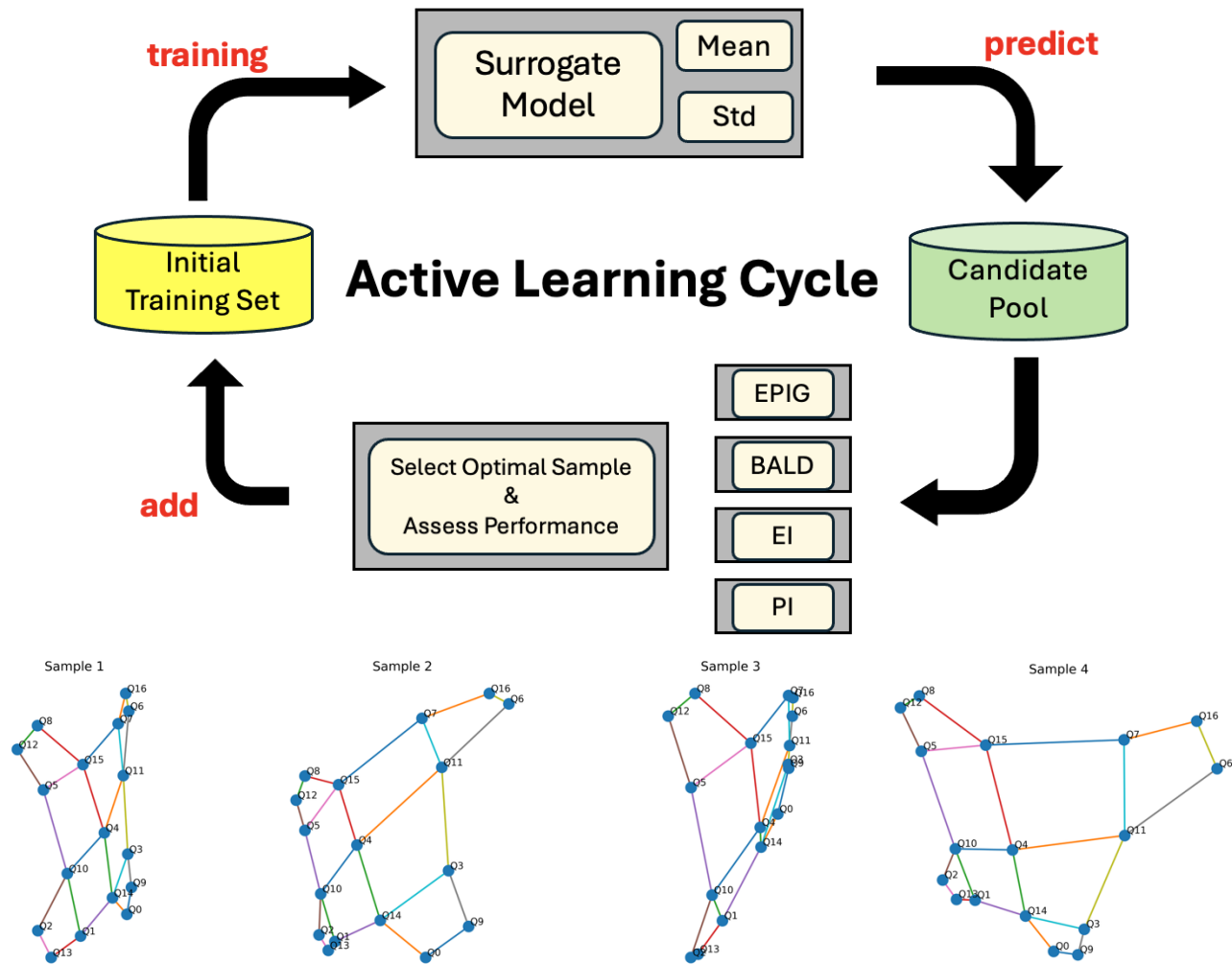
- Discover new architectures
- Optimize against radiation
- Use quantitative noise model
- Impose constraints:
 - qubit spacings
 - planar vs non-planar designs
- Apply to arbitrary materials
 - e.g., Si vs sapphire



Phonon Caustics:

[4] M. H. Kelsey et al. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1055**, 168473 (2023).

Active Learning for Device Optimization



Surrogate Model

- Computationally demanding simulations
- Trained predictor of simulation
- Fast enough to perform optimization

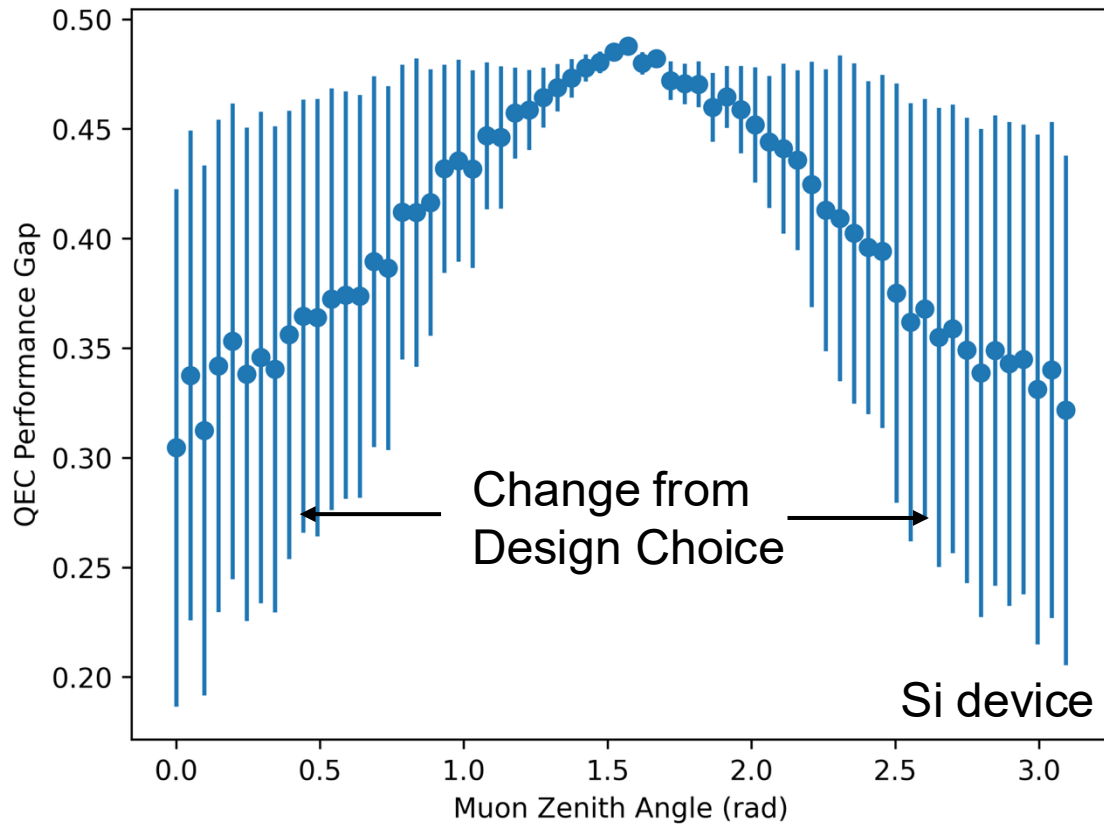
Active Learning

- Identify simulation data that best improves the surrogate model
- Simulate chosen design and add into training set
- Retrain surrogate, identify new candidate

Enforce Constraints

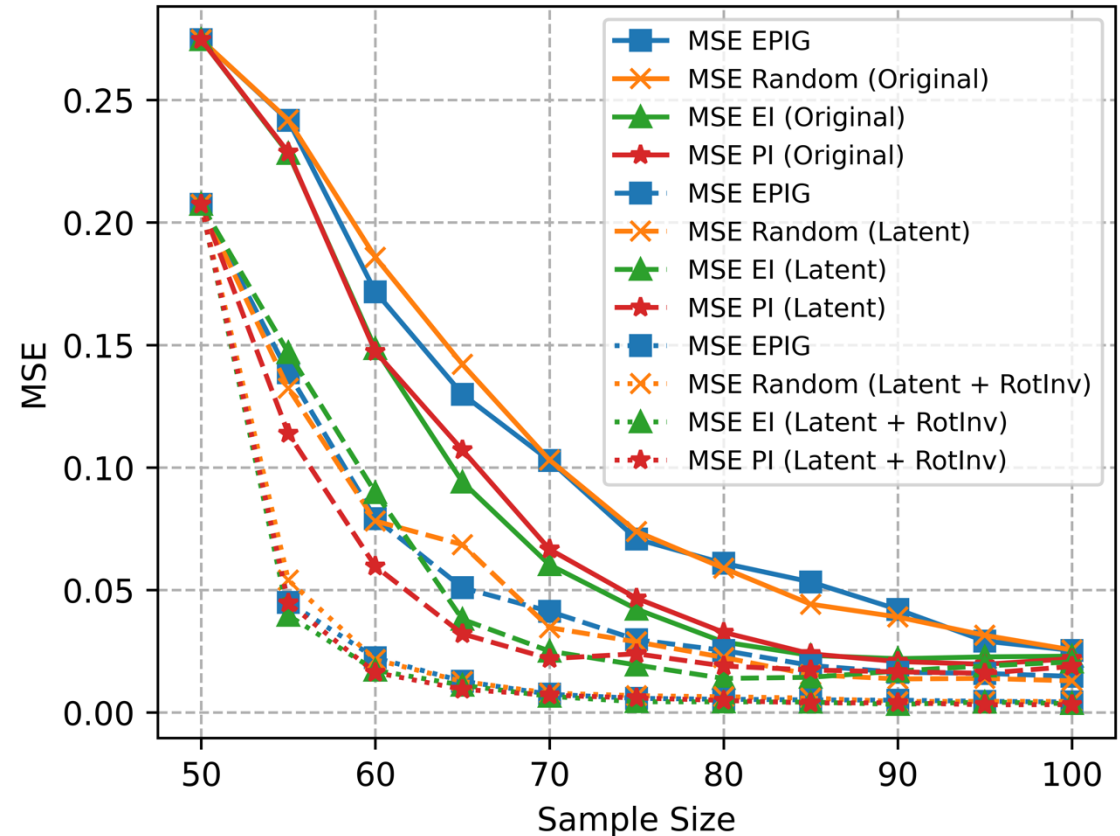
- Planar vs non-planar designs
- No qubit overlap

Data Collection and Training



64 Muon Trajectories

- 4D Sobol sequence
- 16064 Designs



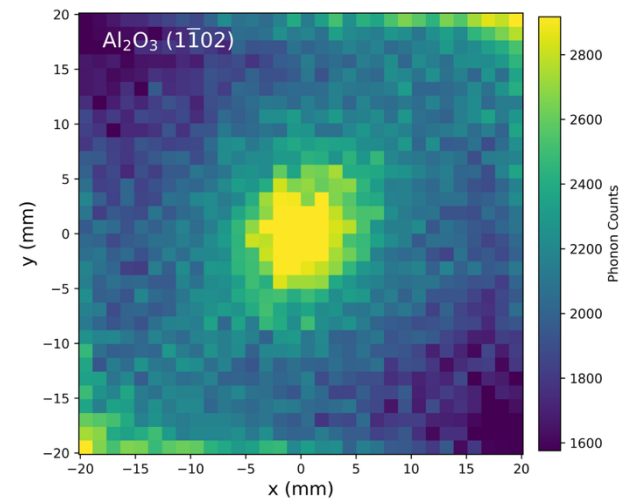
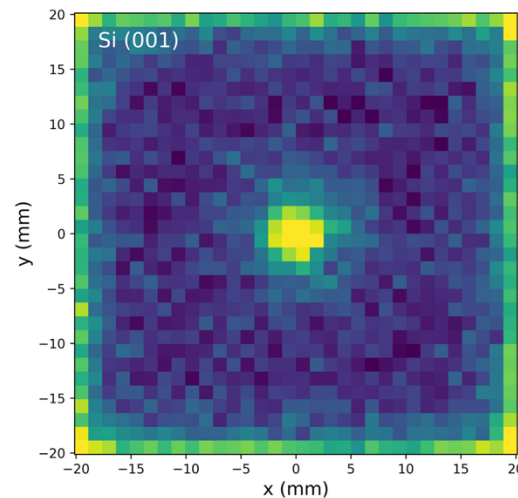
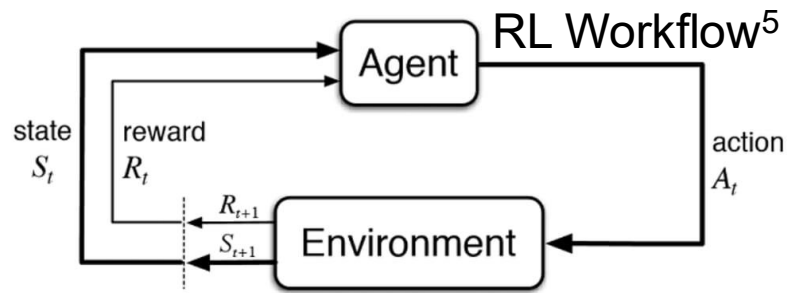
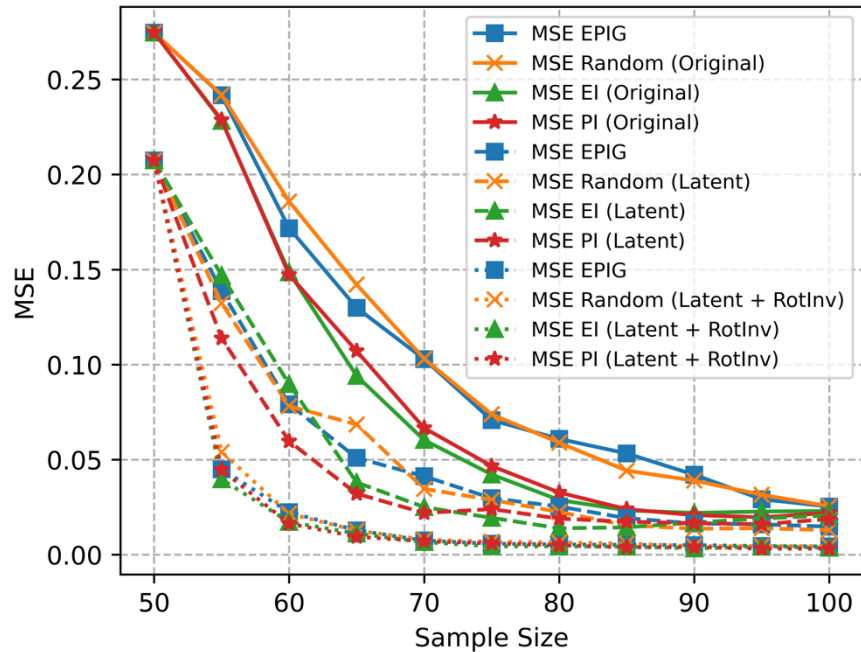
Test of various ML set ups

- Model and acquisition functions
- Need to find a global minimum for a variety of muon trajectories

Optimal Design Selection

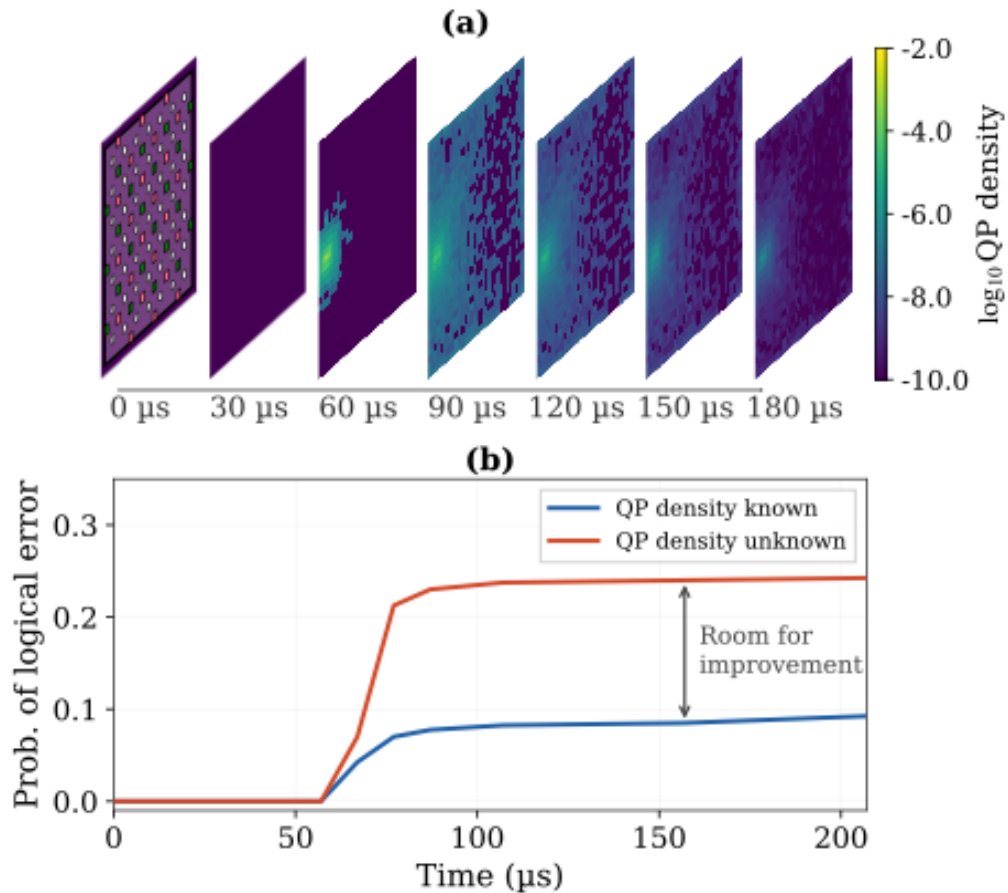
Current Work

- Determine optimal designs using trained surrogate
- Active learning only selects the most informed data
- Reinforcement learning (RL) or gradient-based method
- Apply optimization to alternative substrates materials

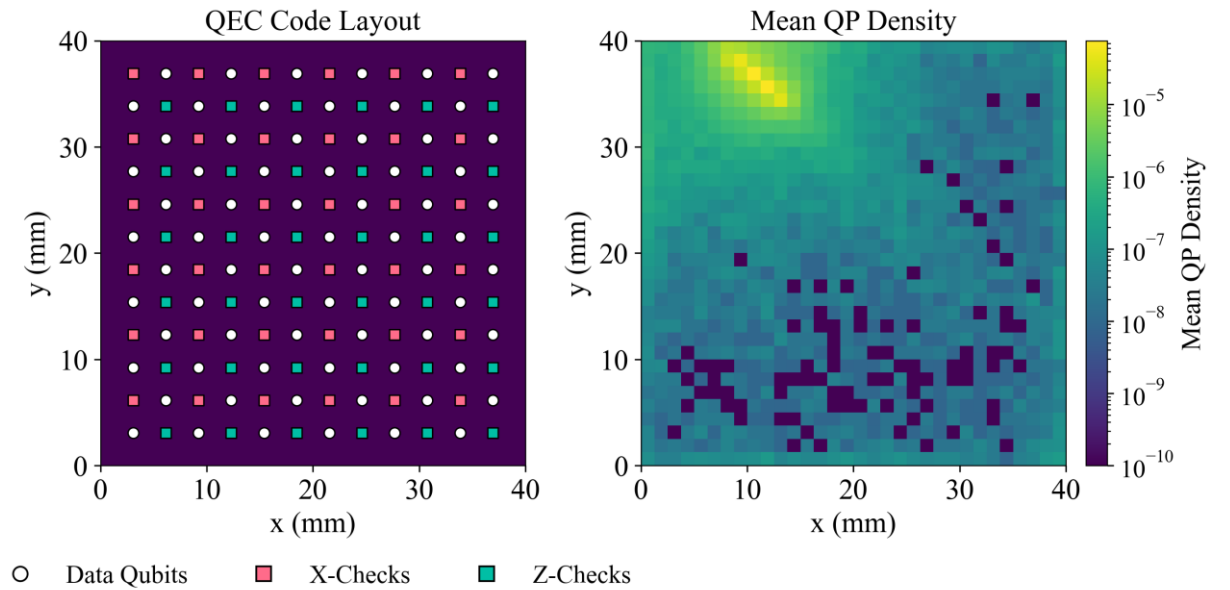


Open Question: Relationship between optimal designs and phonon caustics?

Quasiparticle-Aware QEC



Logical error rate after muon strike.

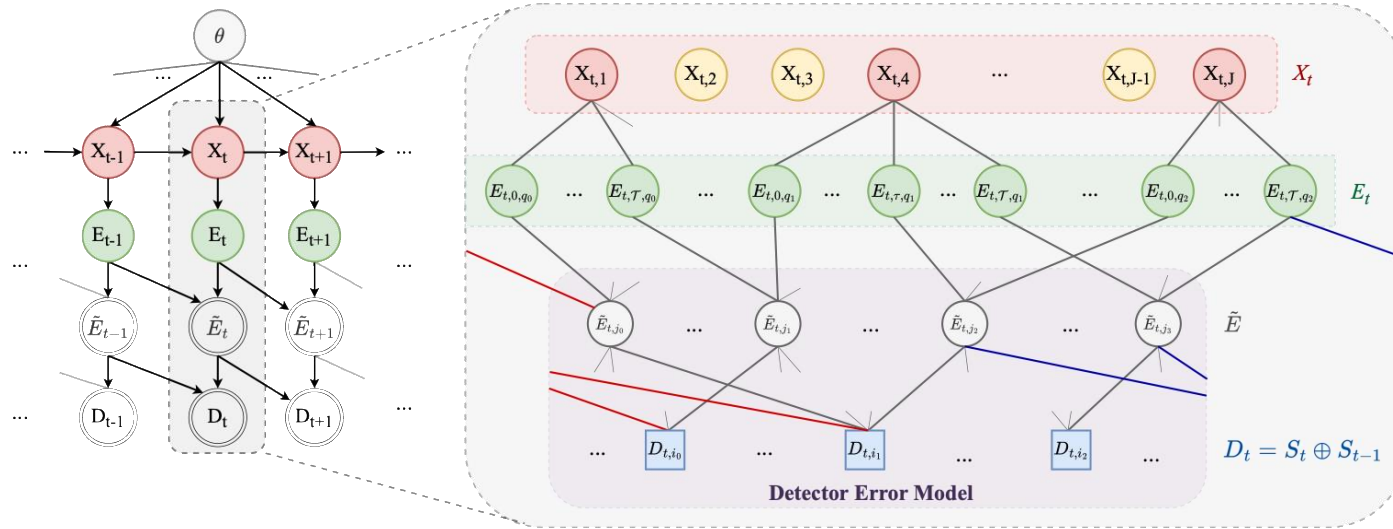


QLDPC code layout and distribution of QP density for a grid of qubits after muon strike.

More Details:

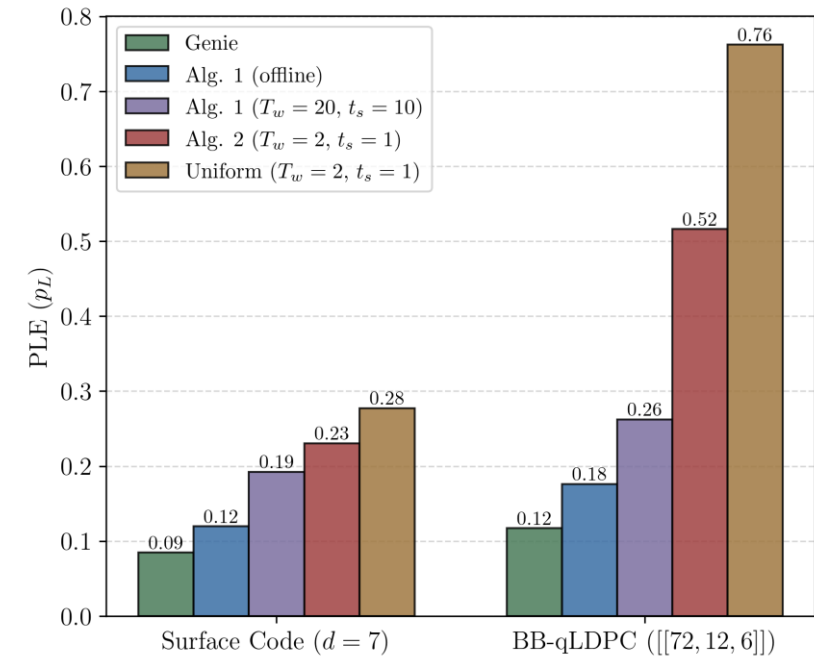
A. K. Nayak et al. arXiv:2603.18231 [quant-ph] (2026).

Quasiparticle-Aware QEC



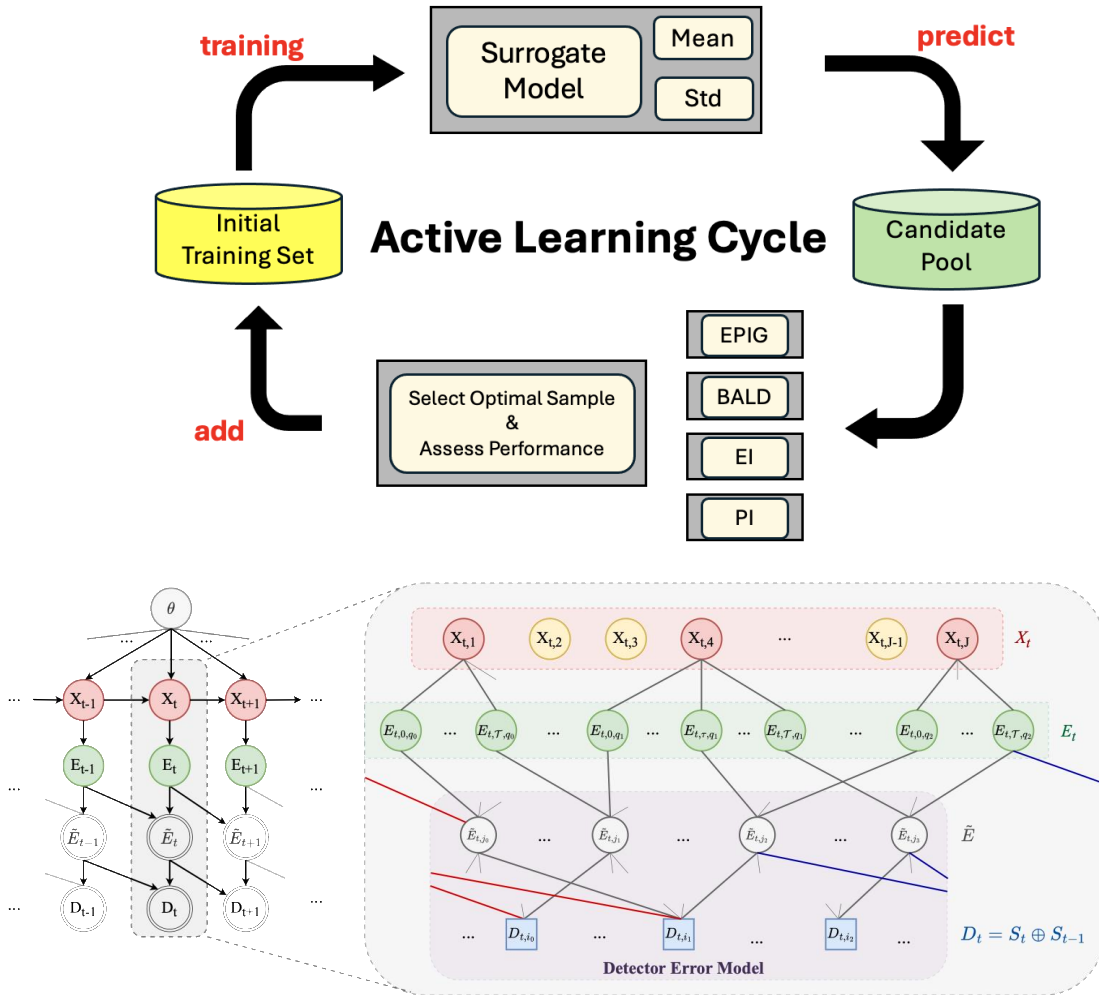
Belief propagation decoder with Markov chain that predicts QP-density $X_{t,i}$ during each syndrome measurement cycle.

More Details: A. K. Nayak et al. arXiv:2603.18231 [quant-ph] (2026).



Logical error rates benchmarked with G4CMP simulations.

Conclusions



Current Results

- ✓ Numerical model of QEC with radiation impacts
- ✓ Data efficient active learning framework
- ✓ New algorithms for QP-aware QEC decoding

Current Work

- Optimal design selection and evaluation
- Material and architecture co-design