电子科技大学

电子科学与工程学院
（示范性微电子学院）
School of Electronic Science and Engineering
(National Exemplary School of Microelectronics)

Neural Network based Surface Decoder for Scalable Quantum Error Correction

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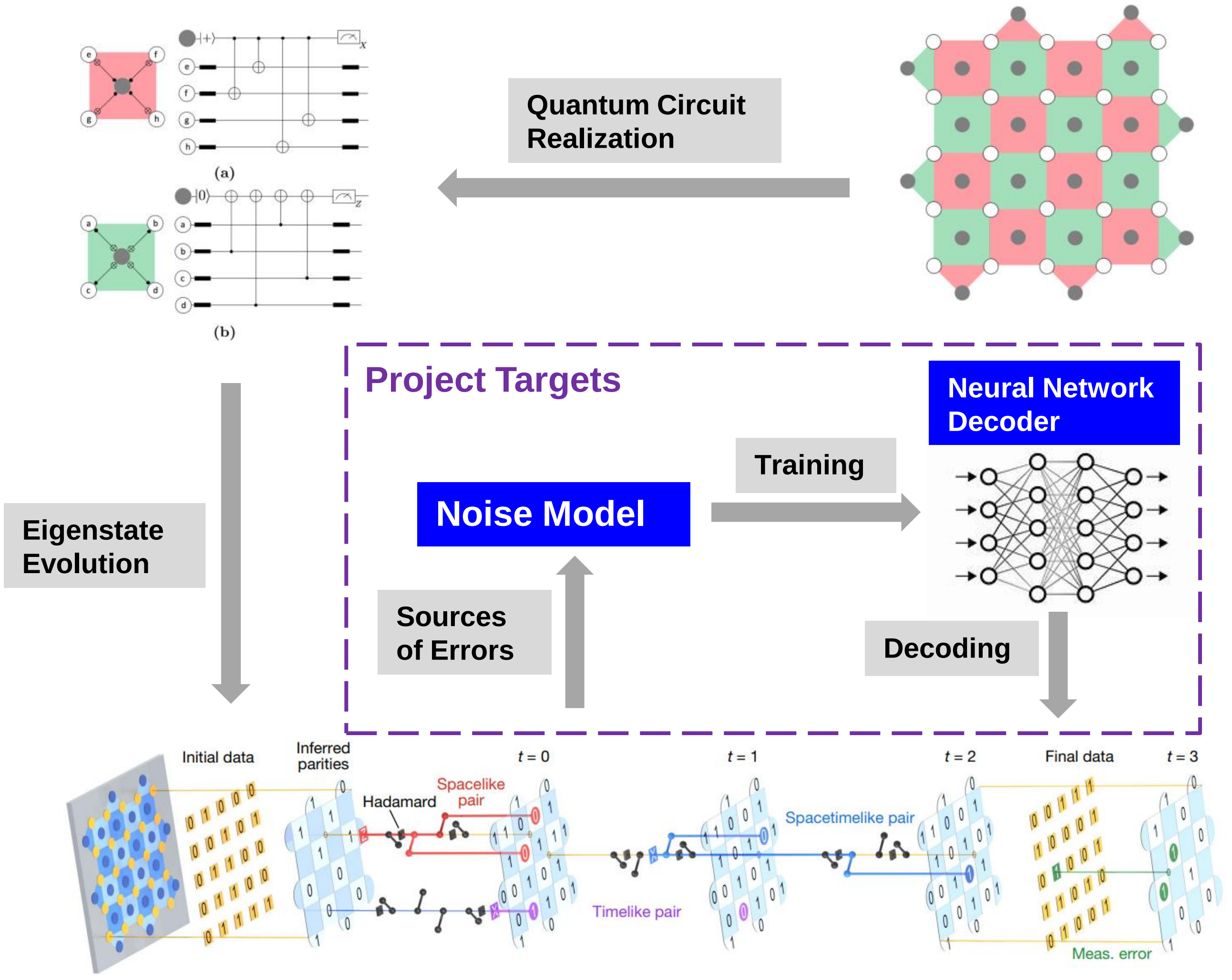
2024/XX/XX

Outline

- **Background & Motivation**
- **Project Overview**
- **Quantum Noise Modeling**
- **Noise Model Benchmarking**
- **Conclusion & Future Work**



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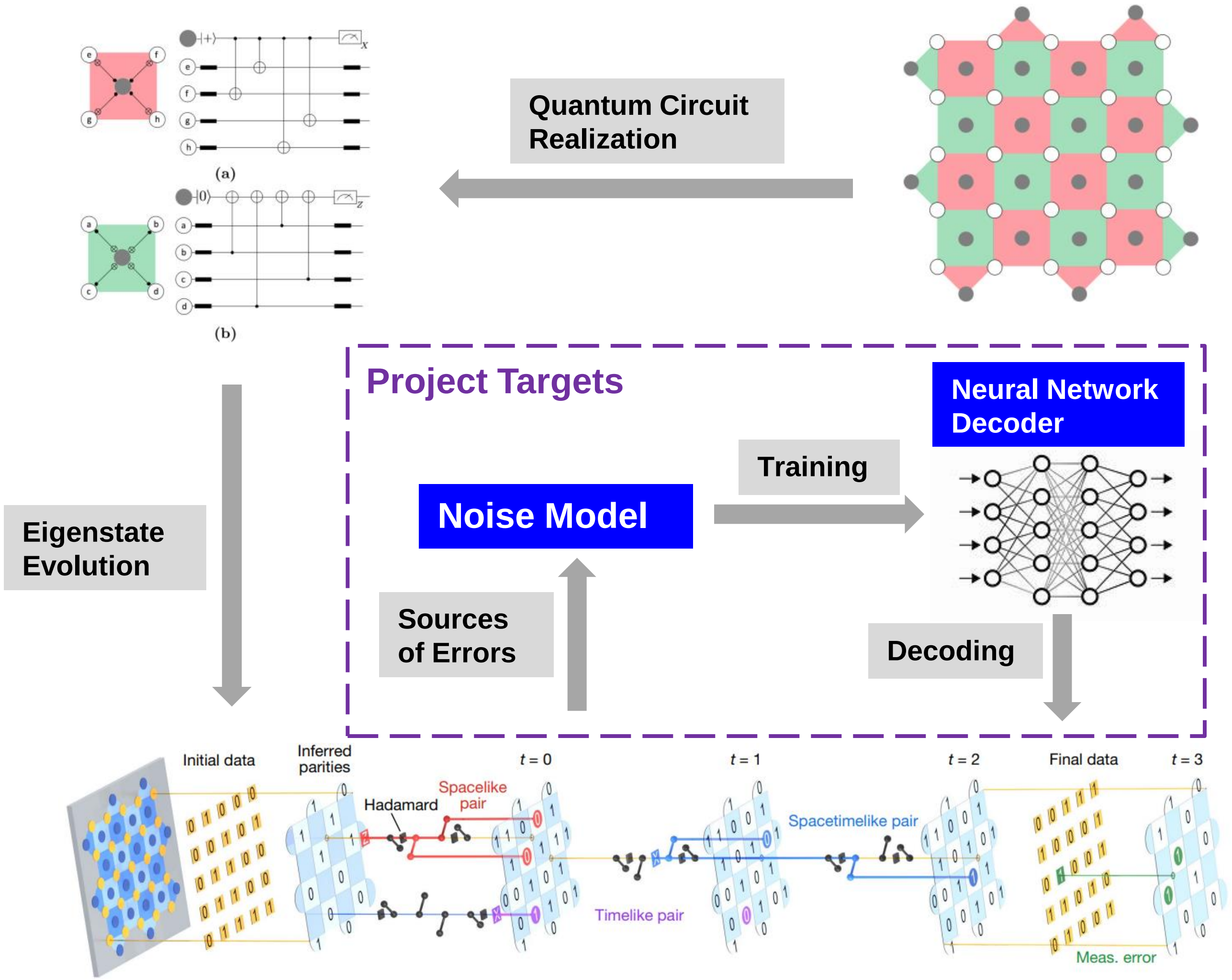
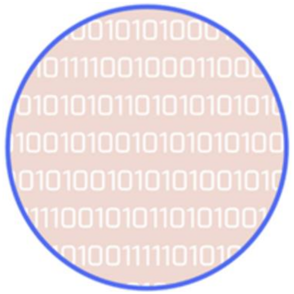
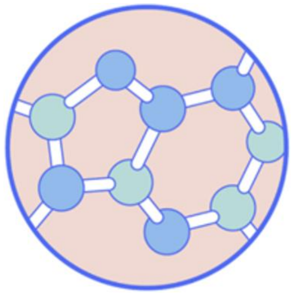


Background: Applications and Architecture of Quantum Computing

Breaking Classical Encryption
e.g. Shor Algorithm
$O(e^{logN}) \rightarrow O(logN)$

Database Searching
e.g. Grover Algorithm
$O(M) \rightarrow O(M^{0.5})$



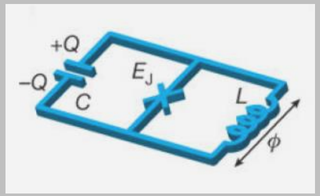


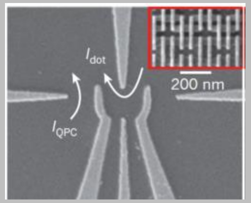
Quantum Simulation
Drug Discovery and
Molecular Simulation

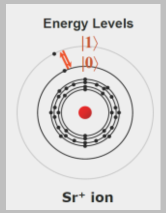
Quantum Algorithm
↓
Universal Logical Quantum Gates
↓
High-Fidelity Logical Qubits
↓
Quantum Error Correction — Research Scope
↓
Classical-Quantum Interface
↓
Noisy Physical Qubits
(e.g., Superconducting Qubits)

Background: The Necessity of Quantum Error Correction

Low Fidelity for Physical Qubit

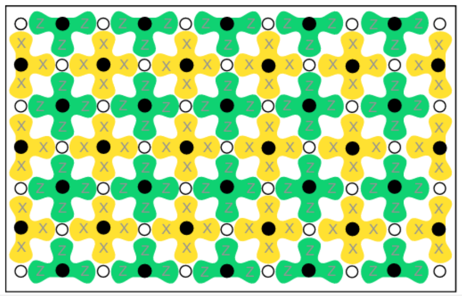






Typical Error Rate 10^{-3} per Gate

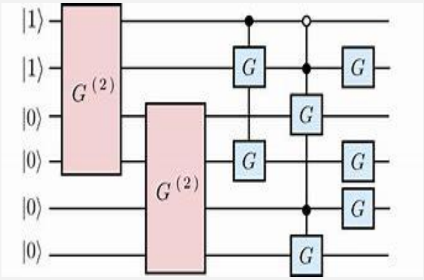
High Fidelity for Logical Qubit



D × D Square of Physical Qubits

Higher Error Rate with Larger Size

Billions of Quantum Operations



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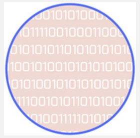
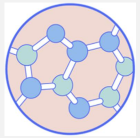
Practical Quantum Algorithms

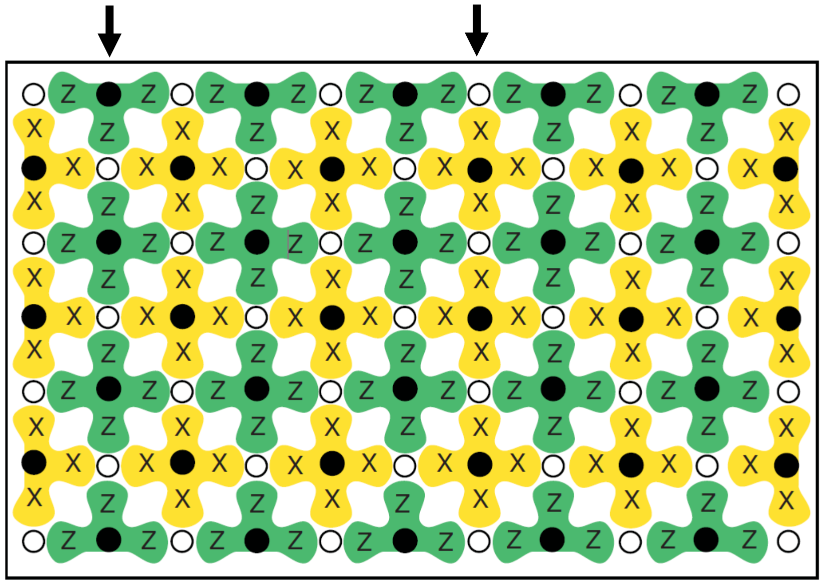




Background: Surface Code for High-fidelity Logical Qubits

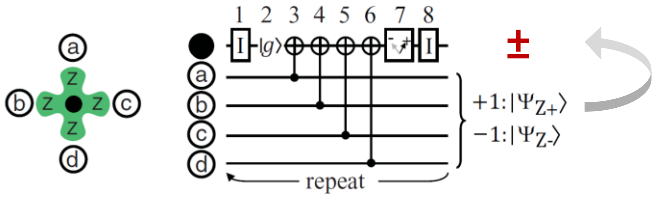
Measure-Z Qubit

Data Qubit



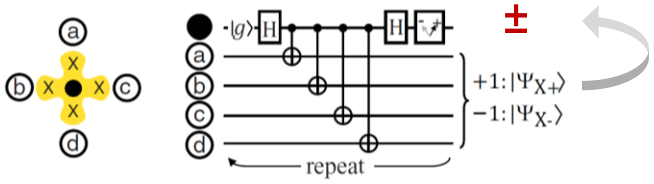
Measure-X Qubit

Measure-Z Circuits

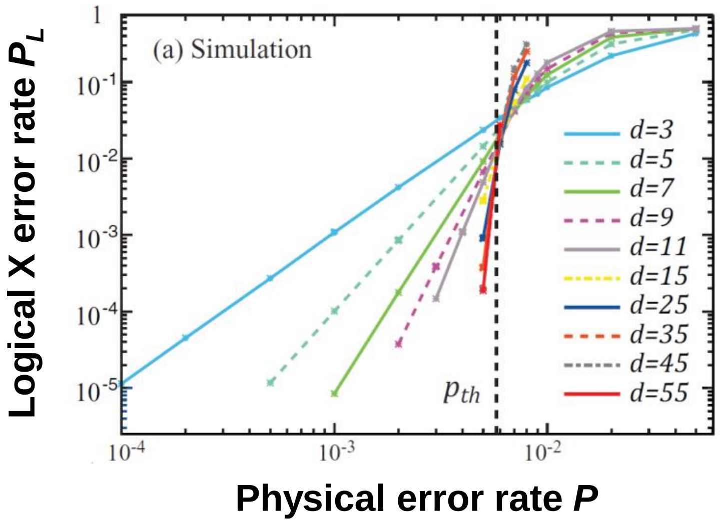


Parity

Measure-X Circuits



Parity



- **Physical Qubits Array → Logical Qubit**
- **Surface Code Distance d ↑ → Logical Qubit Fidelity↑**

[A.G. Fowler, Physical Review A, 2012]

Background: Eigenstate Evolution & Real-world Experiement

Evolution of Measurement Outcomes (Syndrome)

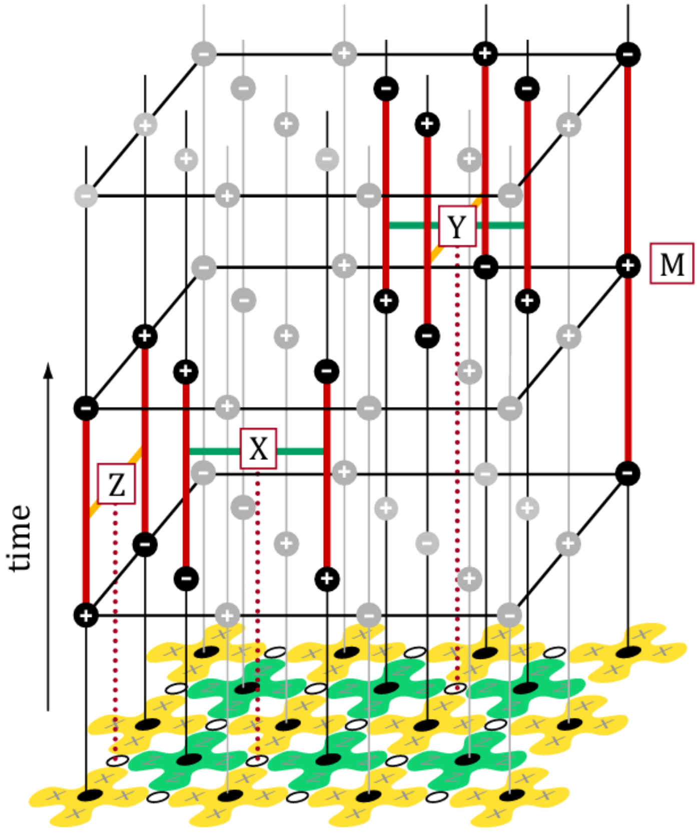
M: Measurement Error

Y: $\hat{Y} = \hat{Z}\hat{X}$ Error

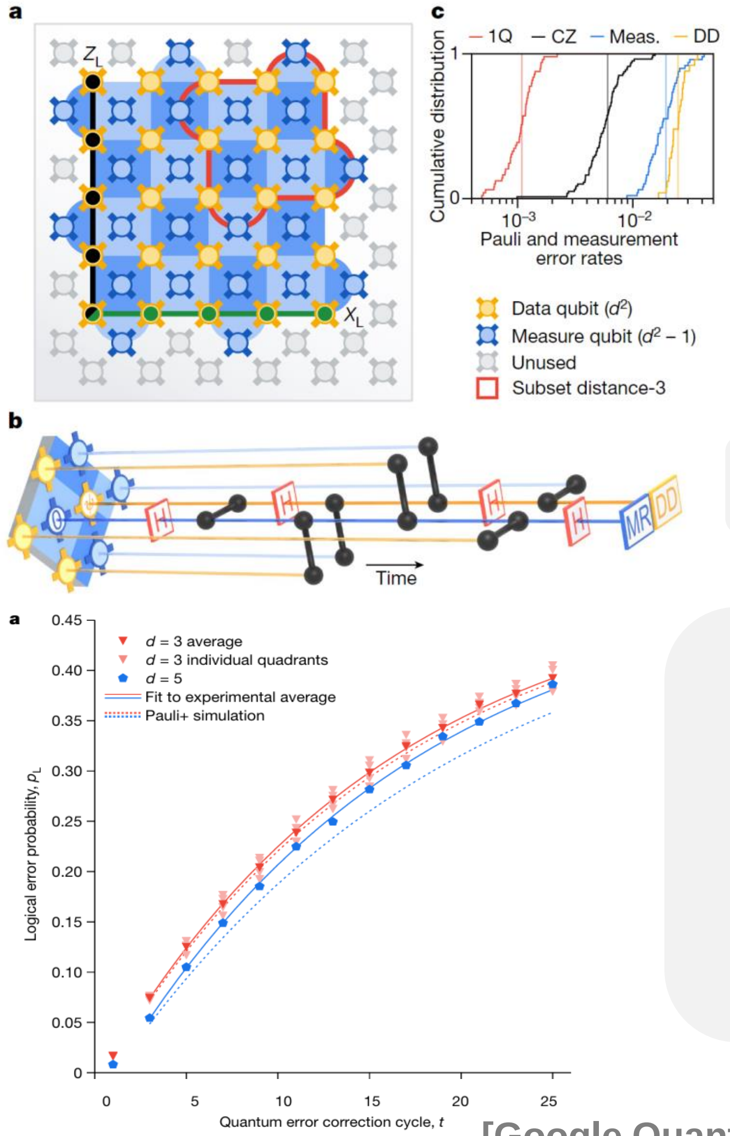
X: $\hat{X}$ Bit-flip Error

Z: $\hat{Z}$ Phase-flip Error

Requires a DECODER to infer the error of data qubits based on the syndrome



[A.G. Fowler, Physical Review A, 2012]



Google Sycamore $d = 5$, $N = 49$

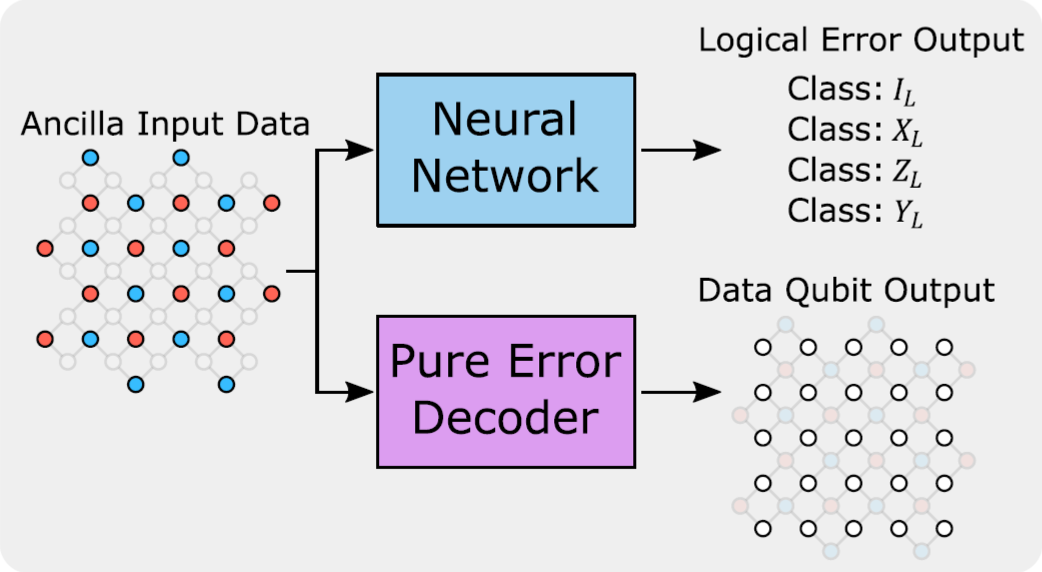
MWPM Decoder

Blue Line d=5
Red Line d=3

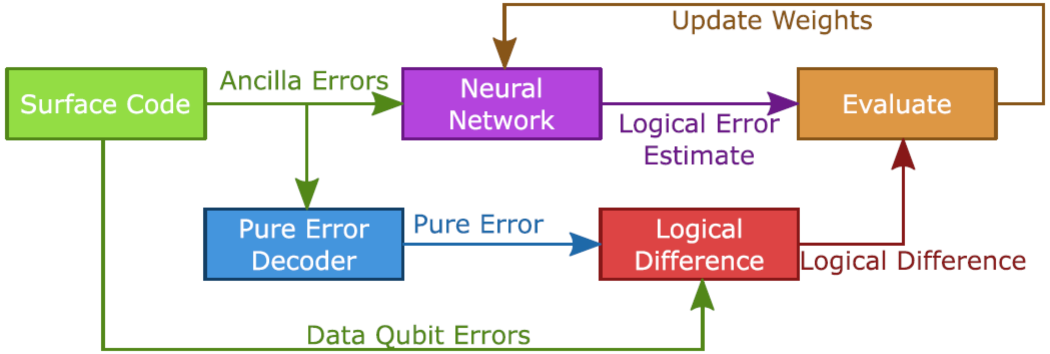
First time verified the effectiveness of Surface Code

[Google Quantum AI, Nature, 2023]

Motivation: Neural Network Decoding Algorithm for Surface Decode



Pure error decoder w/ NN classifier



NN simulation setup

Performance parameter	Used Decoder	Distance 3	5	7	9
p_{th}	MWPM	0.08251	0.10372	0.11368	0.11932
	[33]	0.09815	0.12191	0.12721	0.12447
	Float	0.09769	0.12657	0.12917	0.12490
	Fixed	0.09781	0.12637	0.12934	0.12430
Slope	MWPM	1.856	2.723	3.601	4.496
	Float	1.886	2.869	3.812	4.663
	Fixed	1.894	2.866	3.820	4.667
Min. Bits	Fixed	3	4	5	7

Preliminarily validated that neural network decoder can outperform the accuracy of classic MWPM algorithm

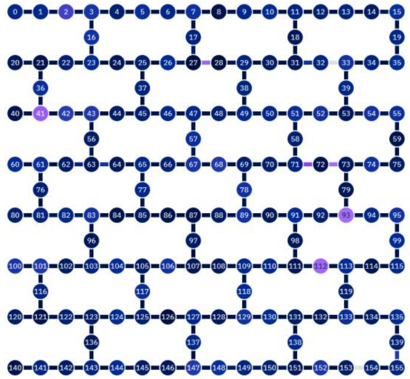
[R. W. J. Overwater et al., IEEE TQE 2022]

Challenge1: Lack of Realistic Datasets for Training

Current Quantum Computer Limitations

Limited number of qubits (Typical ~ 10^2, d≤ 7)

Unsupported Connectivity (e.g. IBM)



Current NN Decoder Training Limitations

Small dataset scale from real-world experiments

Overly simplified error models cannot reflect realistic syndromes

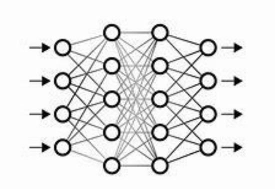
Unreliable decoding performance on real-world quantum computer

Our Objective

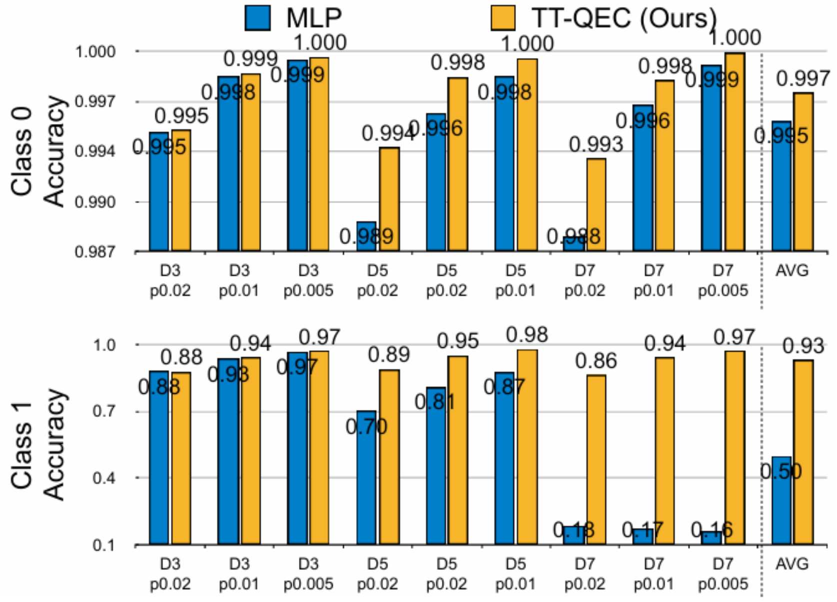
Fast classical simulation to provide large datasets

Construct a comprehensive error model to reveal realistic syndromes

High-quality & Sufficient Input Datasets



Challenge2: Decoding Performance Optimization



Design Decoding Algorithms w/ Higher Accuracy

COMPARISON OF LOGICAL ERROR RATES UNDER DIFFERENT CODE DISTANCE AND PHYSICAL ERROR RATES.

Distance	Phys. Err. Rate	Logical Error Rate ↓ UF	MWPM	MLP	TT-QEC
3	0.0500	0.16745	0.14063	0.14794	**0.13005**
	0.0100	0.01039	0.00800	0.00903	**0.00784**
5	0.0500	0.24120	0.17279	0.20888	**0.17232**
	0.0100	0.00406	0.00268	0.00443	**0.00254**
7	0.0500	0.29813	0.20178	0.28454	**0.20590**
	0.0100	0.00113	0.00064	0.00197	**0.00059**
9	0.0500	0.35250	0.23161	0.32770	**0.23144**
	0.0100	0.00028	0.00002	0.00017	**0.00001**

COMPARISON OF LOGICLA ERROR RATES UNDER DIFFERENT MODEL SIZE.

Error Rate	0.0200	0.0150	0.0100	0.0075	0.0050
503K Params	0.01812	0.00860	0.00290	0.00127	0.00045
7,911K Params	**0.01744**	**0.00802**	**0.00254**	**0.00103**	**0.00035**

[H. Wang et al., ICCAD 2023]

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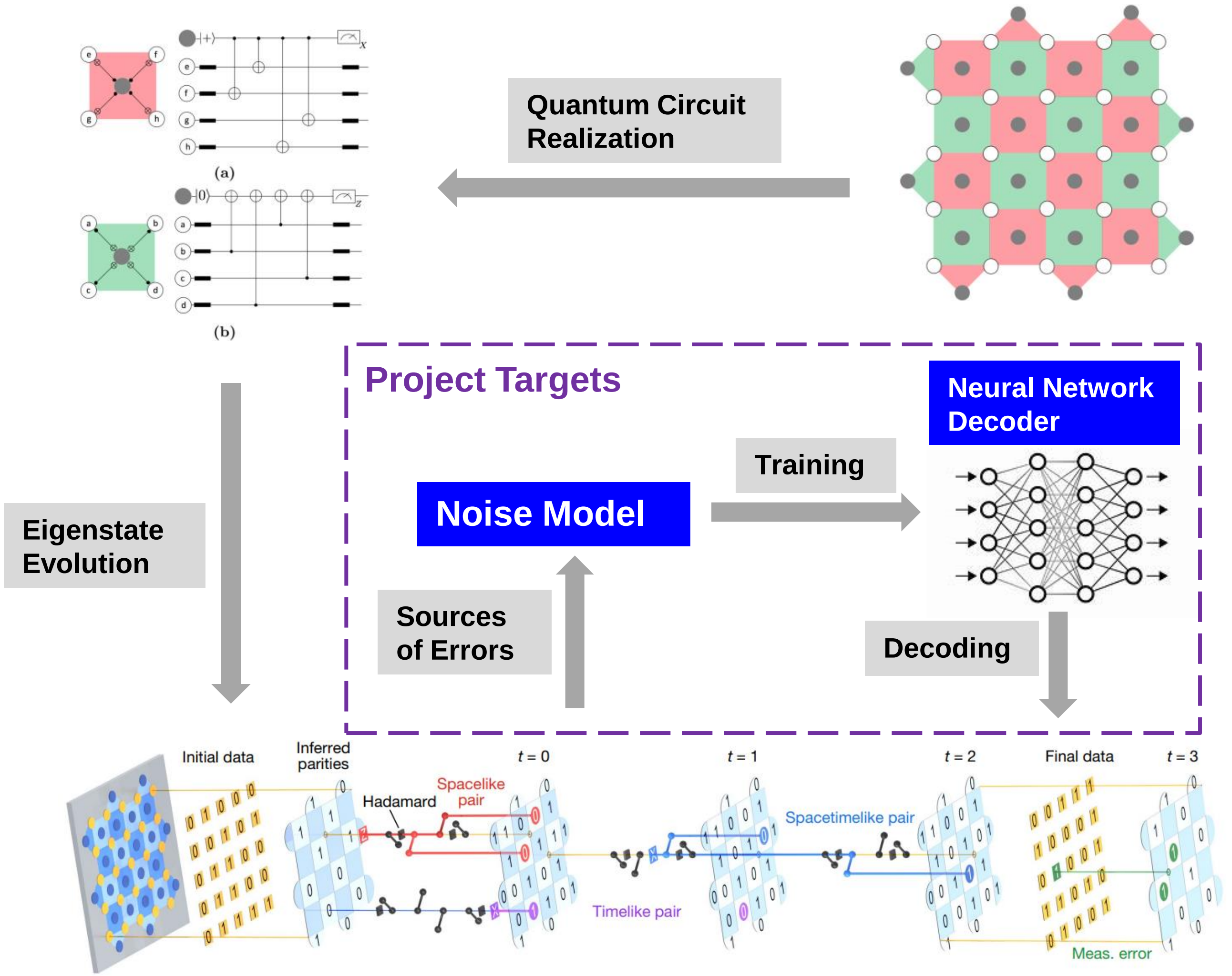


Project Overview & Current Status

Part I: Noise Modelling and Simulation

Overview: Develop a comprehensive quantum noise model encompassing measurement errors, data qubit idling errors, syndrome extraction circuit errors, and qubit leakage errors.

Status: Completed

Part II: Noise Model Benchmarking

Overview: Compare our noise model against other common error models by evaluating the similarity between the error pair correlation matrices derived from repetition code experiments and simulations.

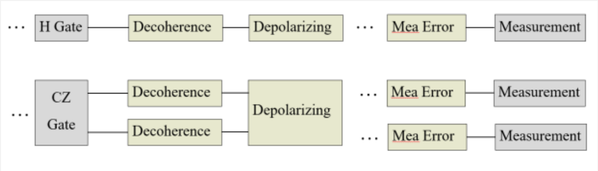
Status: Near Completion

Project Overview & Current Status

Part III: Neural Network Design and Benchmarking

Overview: Based on the designed noise model, implement a neural network-based decoder aimed at improving upon traditional MWPM algorithm.

Status: **Early Development**



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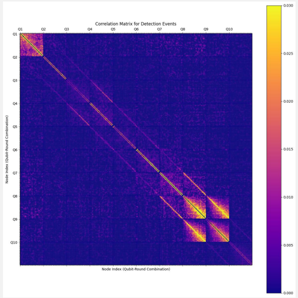
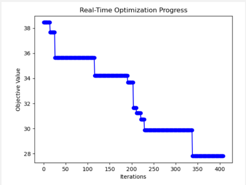
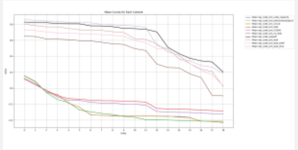
Leakage Simulation

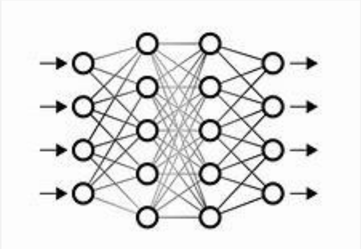
Noise Model Design







Noise Model Benchmarking



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Neural Network Decoder

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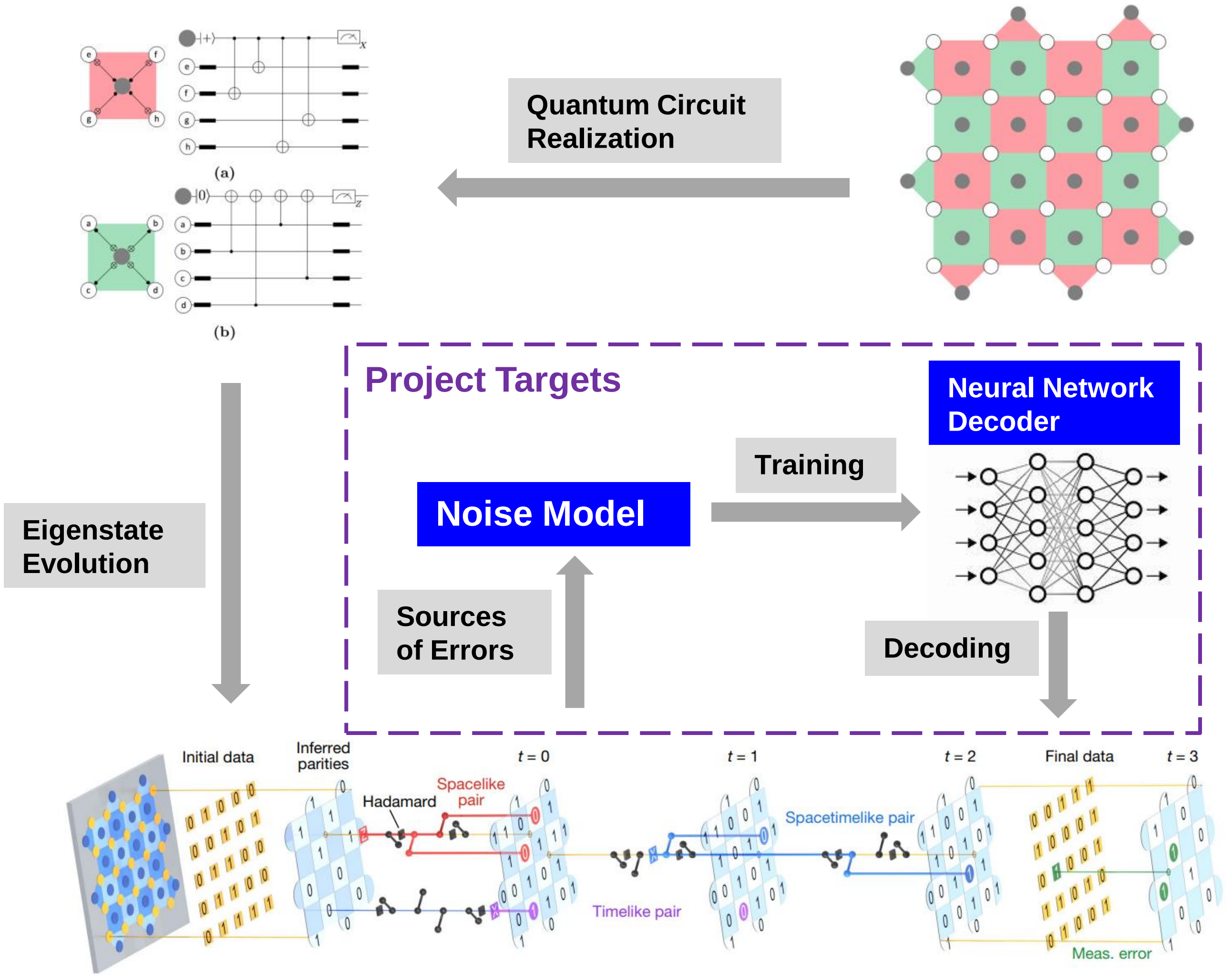
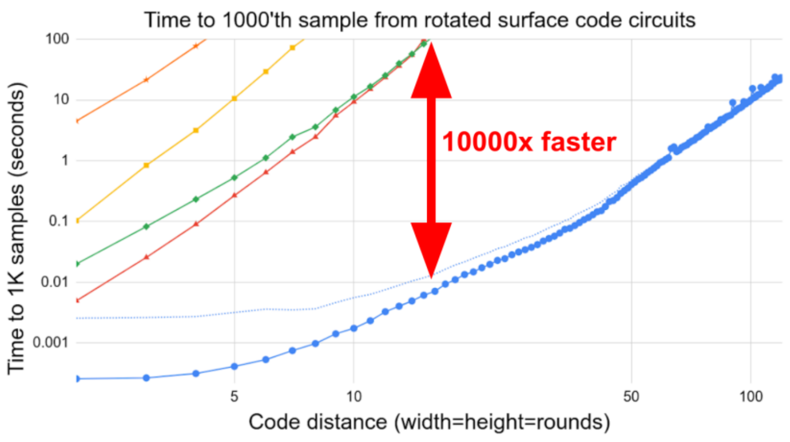


Platforms Chosen

Stim: Python Library for Quantum Stabilizer Circuits Simulation

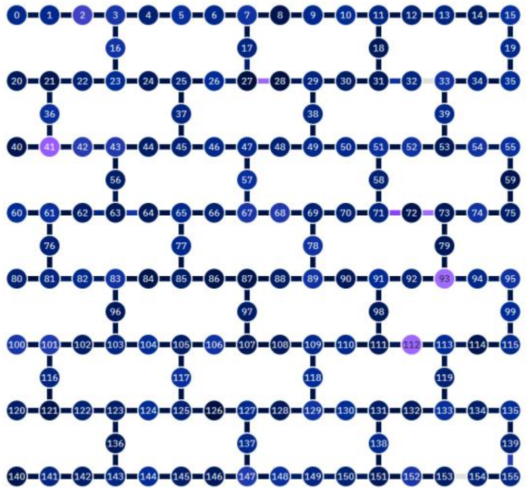


Simulate in Classic Methods → *Fast*

Support Different Quantum Operations → *Efficient*

[Gidney, Craig, Quantum 2021]

IBM Quantum Platform for Parameters Extraction & Experiment Verification



Large # of High-fidelity Qubits

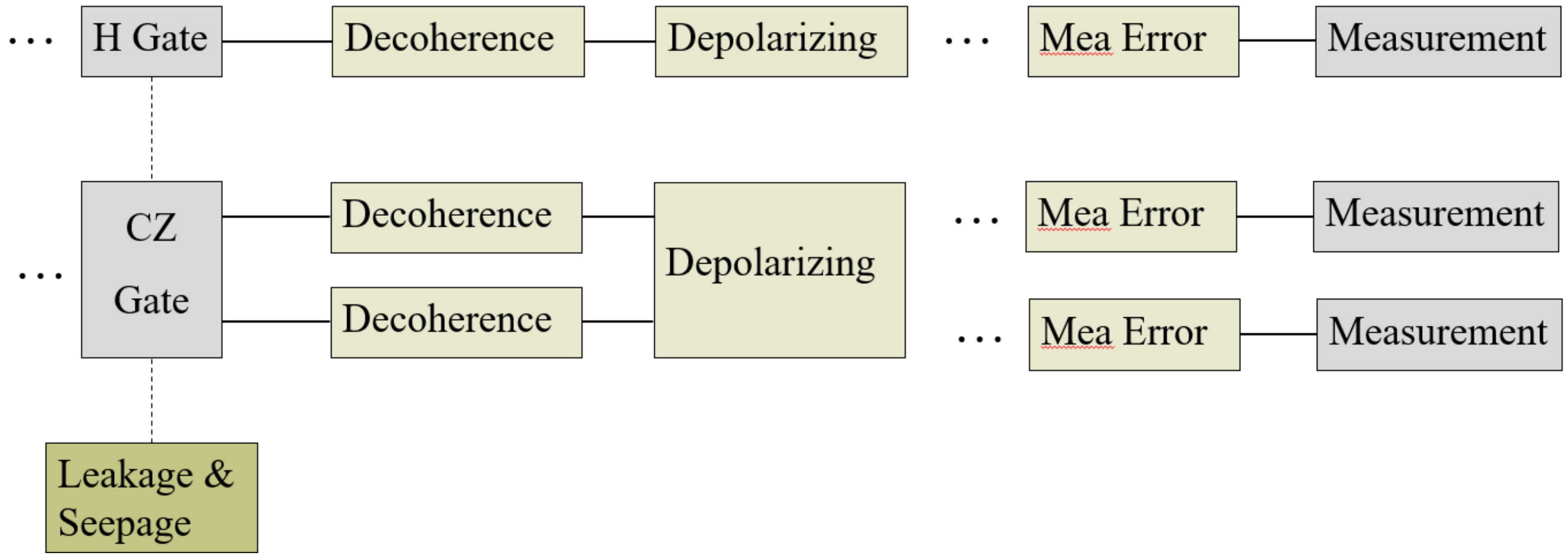
Easily Operates w/ Qiskit

Bad Connectivity → Using 1dim Repetition Code*

*Currently, no quantum cloud platforms support connectivity for surface code, repetition code is like a 1-dimensional version of surface code

Noise Model Components

- **Measurement Error**
- **Depolarizing Error**
- **Decoherent Error**
- **Leakage Error**



Measurement Error

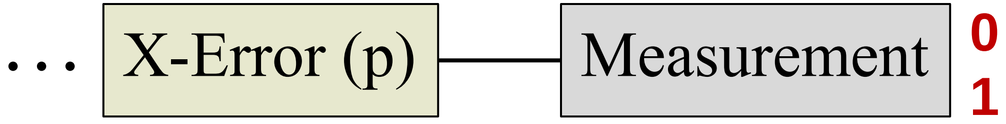
- The measurements used to gather information from qubits have the **highest error rates** of any instruction on a quantum computer.

- A simple linear system describes measurement as:

$$\overrightarrow{p_{noisy}} = \begin{vmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{vmatrix} \overrightarrow{p_{ideal}}$$

  where, $\overrightarrow{p_{noisy}}$ and $\overrightarrow{p_{ideal}}$ represent noisy and ideal output probability, p_{ab} represents the probability of measured state a but actually state b

- To simulate it, we apply **an X-error gate** right before ideal Z-basis measurement operation, with probability extracted from IBM backend calibration data.



Decoherent Error

- The decoherence of qubits can be represented by **amplitude and phase damping channel** ε_{APD}, which compressing amplitude damping channel ε_{AD}, and phase damping channel ε_{PD}

- The channel can be described by the operator-sum representation, where the impact of a noisy channel on an initial density matrix ρ is described by $\mathrm{N}(\rho) = \sum_k K_k \rho K_k^\dagger$. Here, the Kraus Operators are:

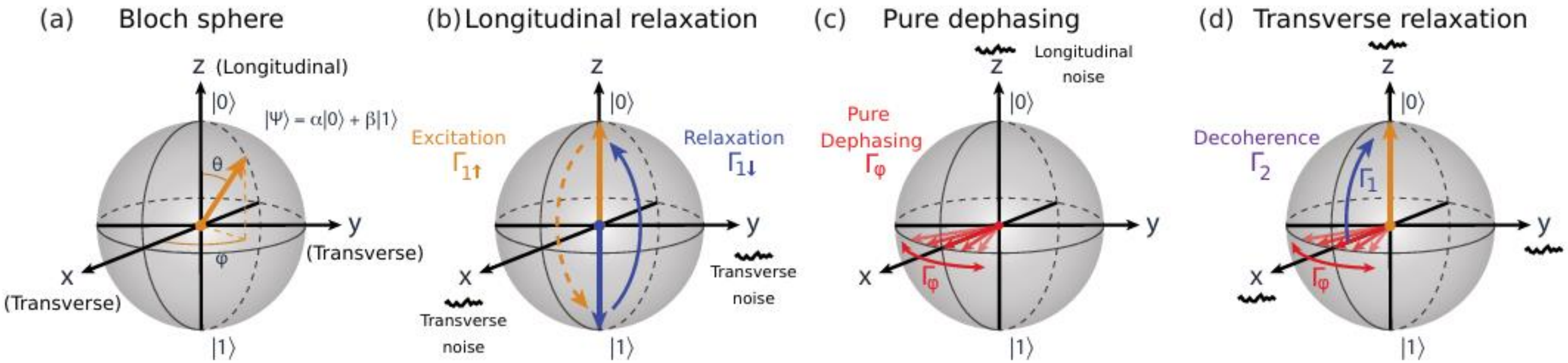
$$K_0 = \begin{vmatrix} 1 & 0 \\ 0 & \sqrt{1-P_{AD}}\sqrt{1-P_{PD}} \end{vmatrix}$$

$$K_1 = \begin{vmatrix} 0 & \sqrt{P_{AD}} \\ 0 & 0 \end{vmatrix}$$

$$K_2 = \begin{vmatrix} 0 & 0 \\ 0 & \sqrt{1-P_{AD}}\sqrt{P_{PD}} \end{vmatrix}$$

Decoherent Error

- Where, $e^{-t/T1} = 1 - P_{AD},\ e^{-t/T2} = \sqrt{(1 - P_{AD})(1 - P_{PD})}$ (t is gate execution time)
- T1 (Longitudinal Relaxation Time): represents the time it takes for a qubit to lose energy and relax from its excited state to its ground state ($\Gamma_1 \equiv \frac{1}{T_1}$)
- T2 (Transverse Relaxation Time): measures the time over which a qubit maintains phase coherence ($\Gamma_2 \equiv \frac{1}{T_2} = \frac{\Gamma_1}{2} + \Gamma_\varphi$)



[P. Krantz et al., Applied Physics Reviews 2019]

Decoherent Error

- However, for fast simulation, stim does not support matrices calculation.
- we must conduct Pauli Twirling Approximation, convert decoherence noise into an Asymmetric Depolarizing Channel (ADC) that supports classic calculation by stim

$$\varepsilon_{ADC}(\rho) = (1 - p_{\Sigma})\rho + p_X X\rho X + p_Y Y\rho Y + p_Z Z\rho Z$$

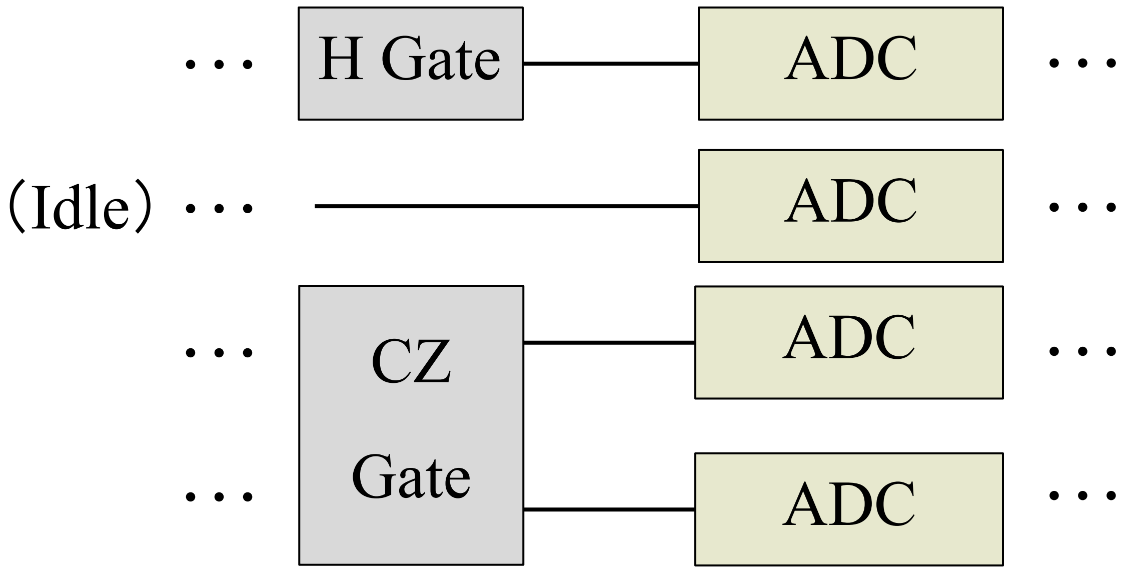
$$p_X = p_Y = \frac{1 - e^{-t/T1}}{4}$$

$$p_Z = \frac{1 - e^{-t/T2}}{2} - \frac{1 - e^{-t/T1}}{4}$$

[J. Ghosh et al., PRA 2012]

Decoherent Error

- To simulate decoherent error, we apply ADC to each gate (including idle) with parameters t, T1, T2 extracted from IBM calibration data



Depolarizing Error for Compensation

- Since decoherence errors do not cover all gate errors, a Symmetric Depolarizing Channel (SDC) is added to compensate for other errors

- The total error channel for each gate is:

$$\mathcal{E} = \mathcal{E}_{SDC} \circ \mathcal{E}_{APD} \approx \mathcal{E}_{SDC} \circ \mathcal{E}_{ADC}$$

- We can compute the p parameter for SDC by:

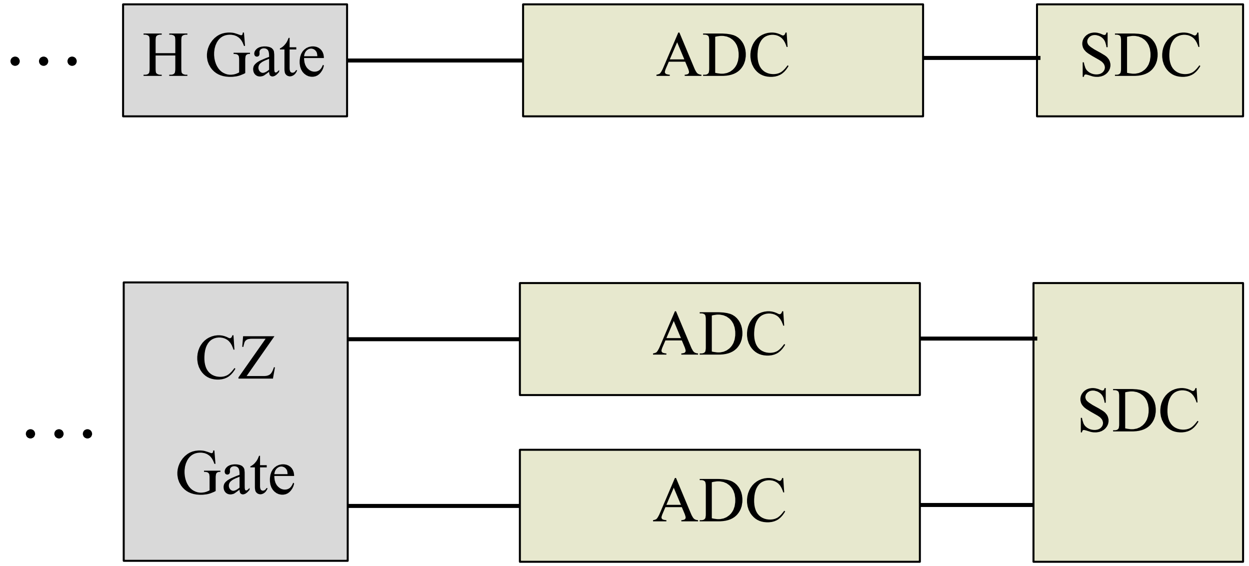
$$p = \frac{dim \times (F_{APD} - F)}{dim \times F_{APD} - 1}$$

where, $F(\varepsilon) = \int \langle\psi|\varepsilon(|\psi\rangle\langle\psi|)|\psi\rangle \, d\psi$

Depolarizing Error for Compensation

- We add SDC to each gate to compensate for fidelity of ADC, where p parameter is calculated from fidelity of each gate and fidelity of decoherence.

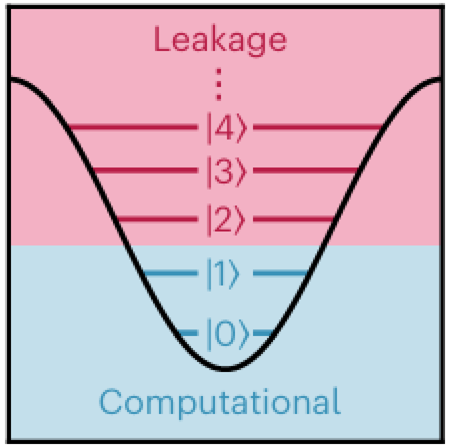
- Fidelity of each gate is extracted from IBM Calibration data

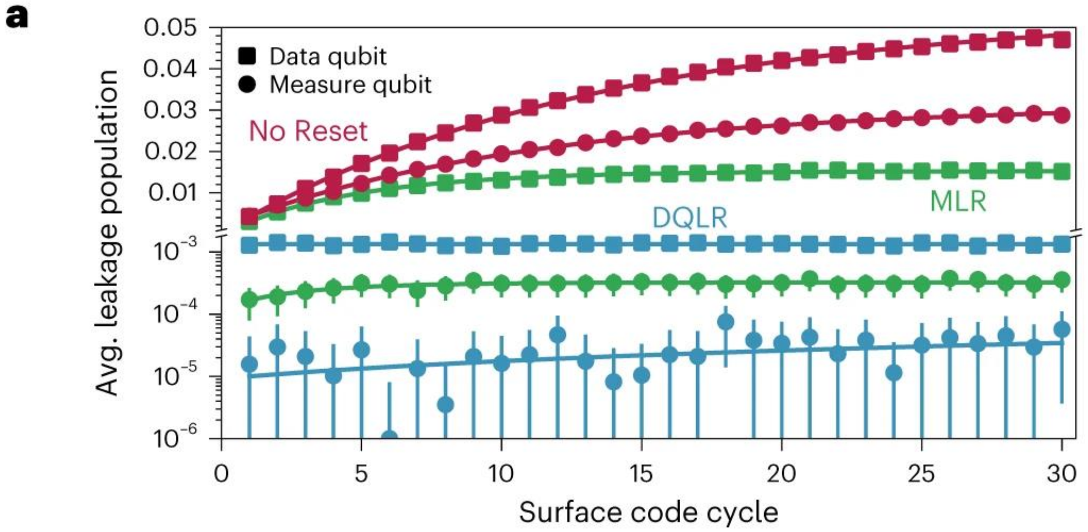


Innovation：Leakage Error Simulation

- Qubit leakage occurs when a qubit transitions out of its defined computational states (|0⟩ and |1⟩) into unwanted higher energy states, which can disrupt quantum computations.

- Currently，most of common noise models do not consider the effect of leakage





Leakage Effects w/o Mitigation

Google Leakage Mitigation Methods

[Google Quantum AI, Nature, 2023]

Innovation：Leakage Error Simulation

Leakage Simulation:

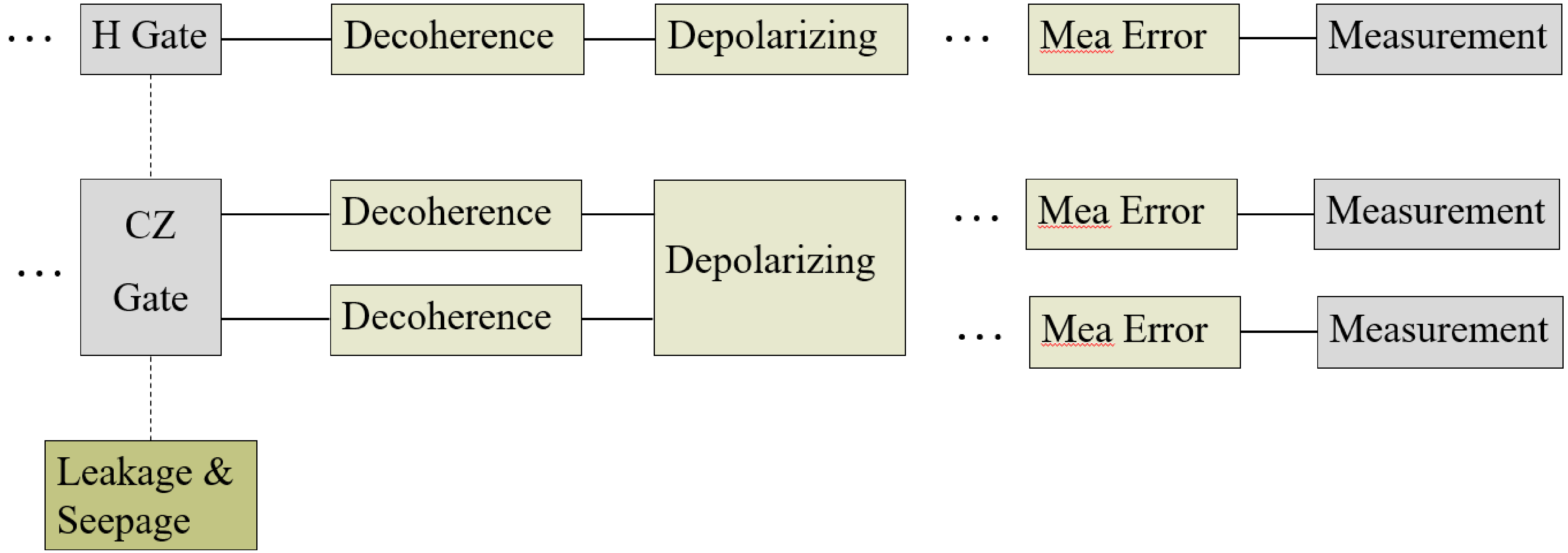
- **Part I: Assume that leakage noise occurs only after the H gate and CZ gate. If leakage occurs, it does not participate in subsequent errors, and the measurement result of the leaked qubit is random**

- **Part II: After each gate, a leaked qubit has a "seepage" probability of returning to a random computational state**

- **Part III: If a CZ gate occurs between a leaked qubit and a non-leaked qubit, the non-leaked qubit will become a random state after the CZ gate**

[Fowler, Austin G., PRA, 2013]

Overall Noise Model



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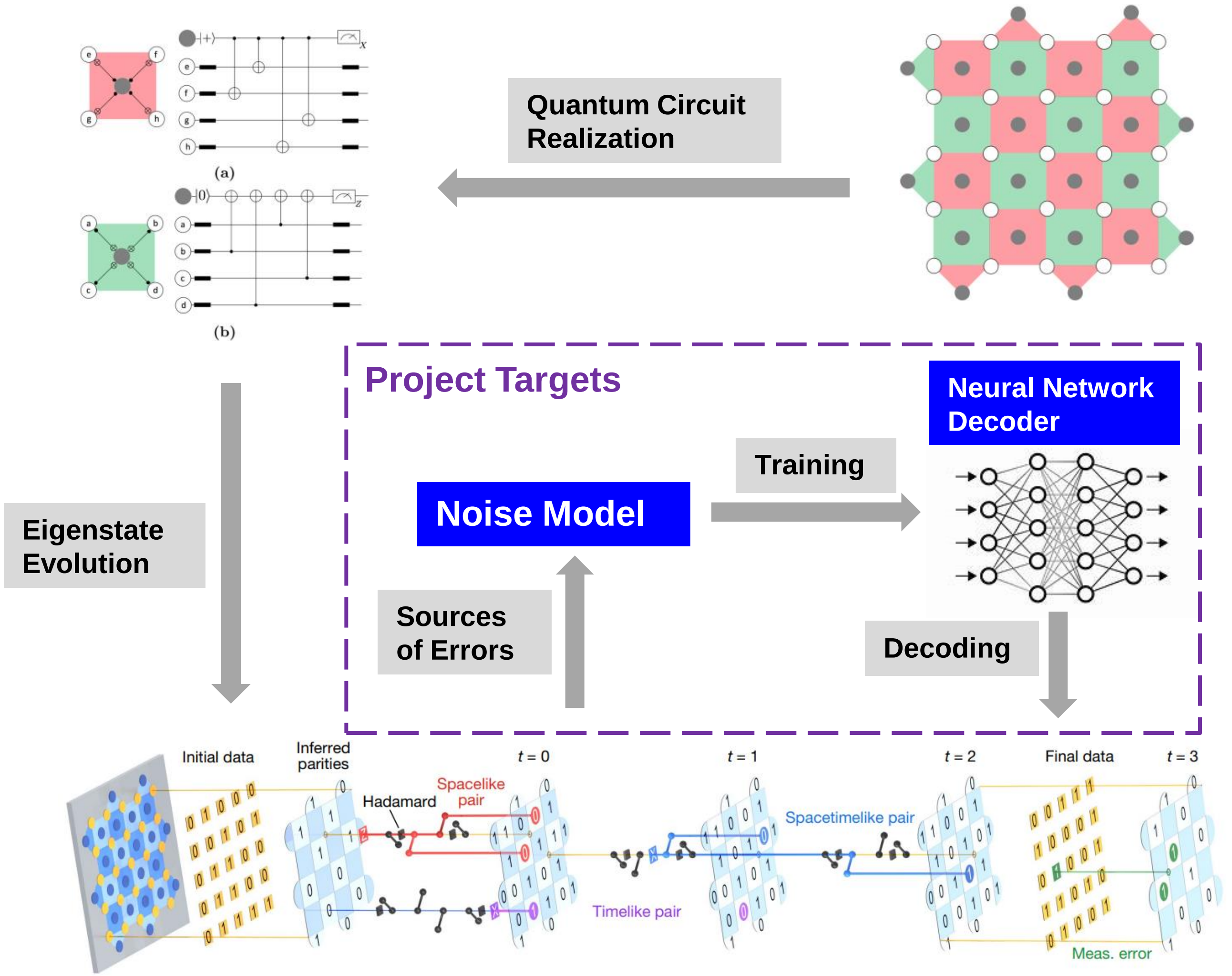
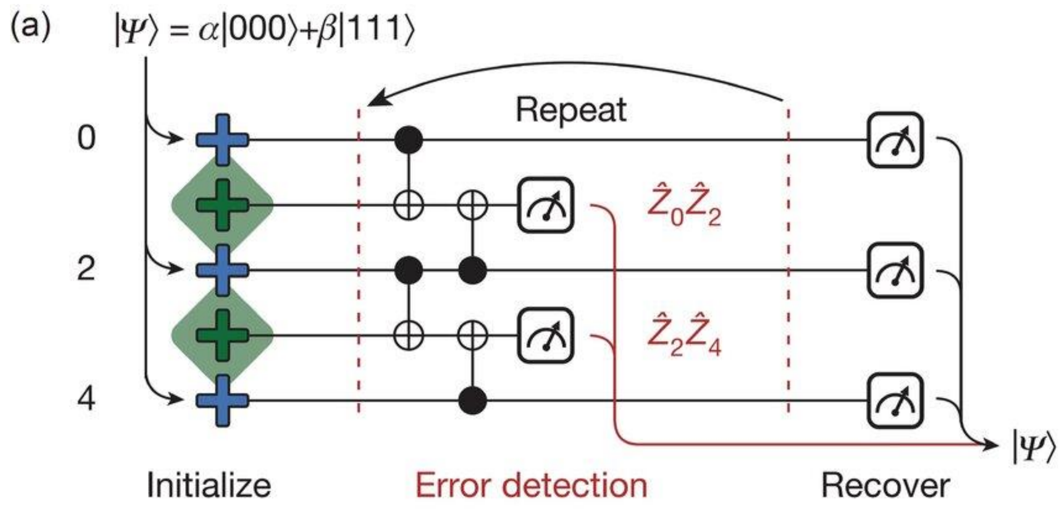


Noise Model Verification

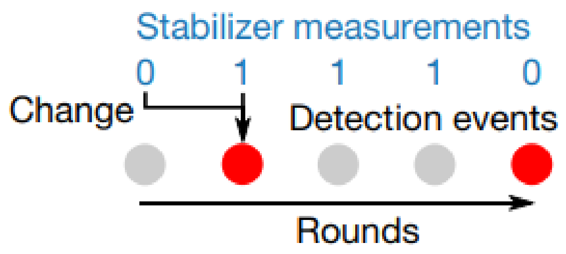
- Utilize the experiment result of certain circuits as benchmark, comparing our model with other common models
- The IBM Quantum platform was selected as the experimental platform
- Since the layout topology of IBM backends does not satisfy the requirements of surface code, we choose to perform repetition code, which is like one-dimensional surface code



[Kelly, et al., Nature, 2015]

Analysis of Repetition Code Results - Detection Event

- **A Detection Event refers to an event where the results of two consecutive qubit measurements are inconsistent.**

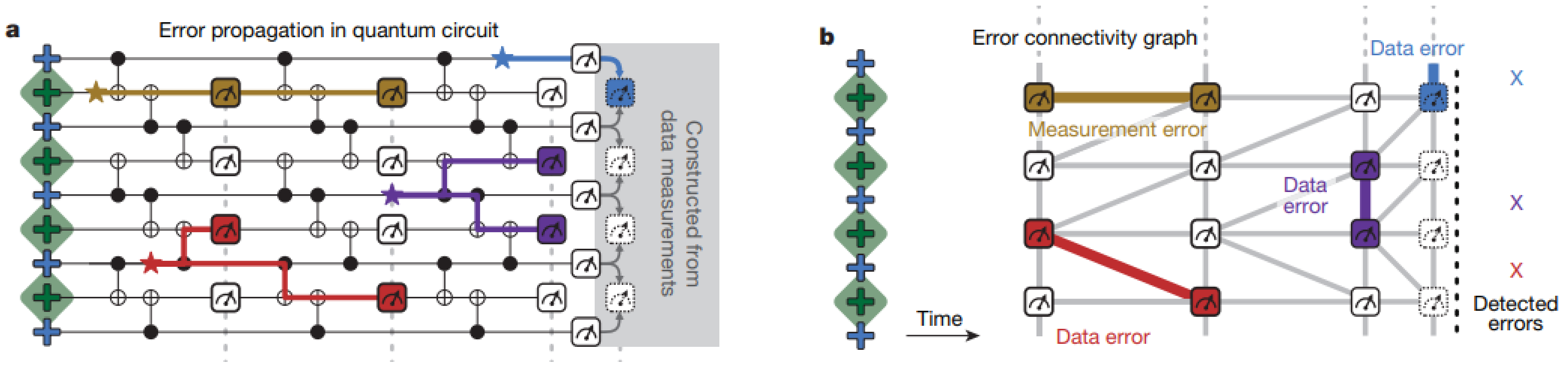


- **Since each measurement qubit is reset to zero after each round, an inconsistent measurement result indicates an error occurred between the two measurements. The errors can be categorized into three types.**

Detection Pair Error Type

- Three types of error: Spacelike pair，Timelike pair，and Spacetimelike pair

- A Spacelike pair occurs when a data qubit error causes adjacent measurement qubits in the same round to change, resulting in a detection error, as shown by the purple lines in the figure.

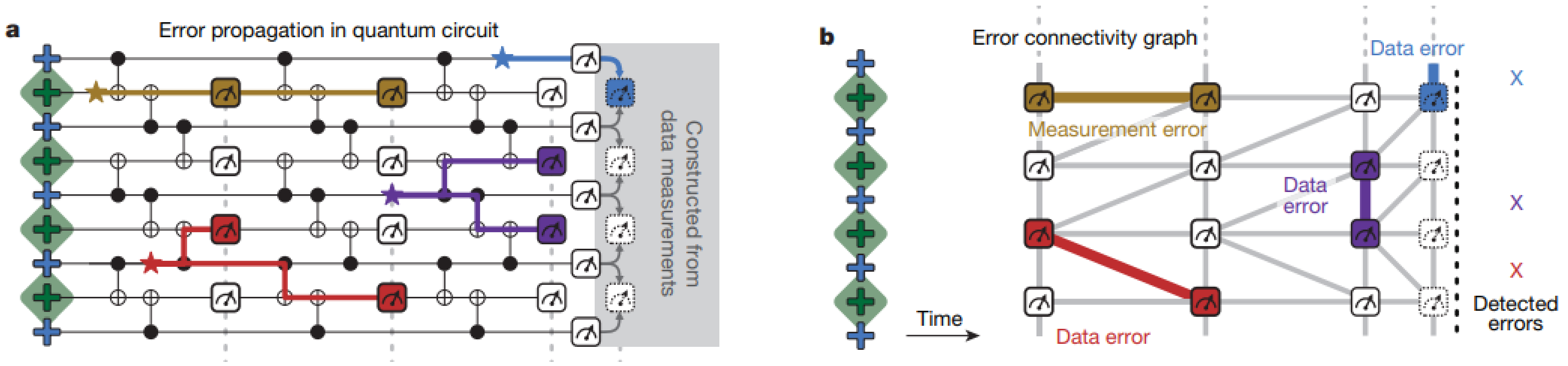


[Kelly, et al., Nature, 2015]

Detection Pair Error Type

- Three types of error: Spacelike pair，Timelike pair，and Spacetimelike pair

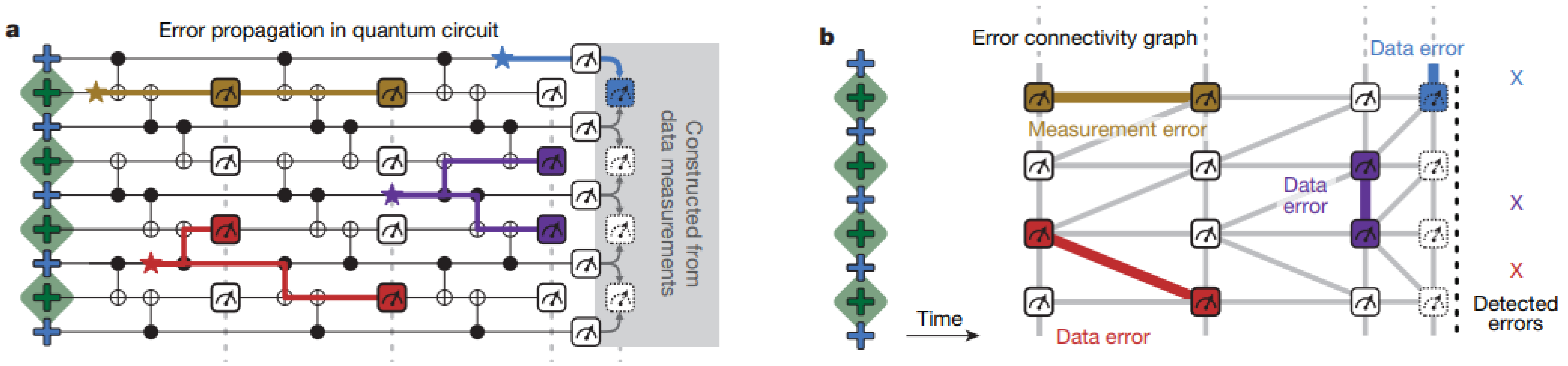
- A Timelike pair occurs when an error in a measurement qubit causes detection errors in consecutive rounds, as shown by the brown lines



[Kelly, et al., Nature, 2015]

Detection Pair Error Type

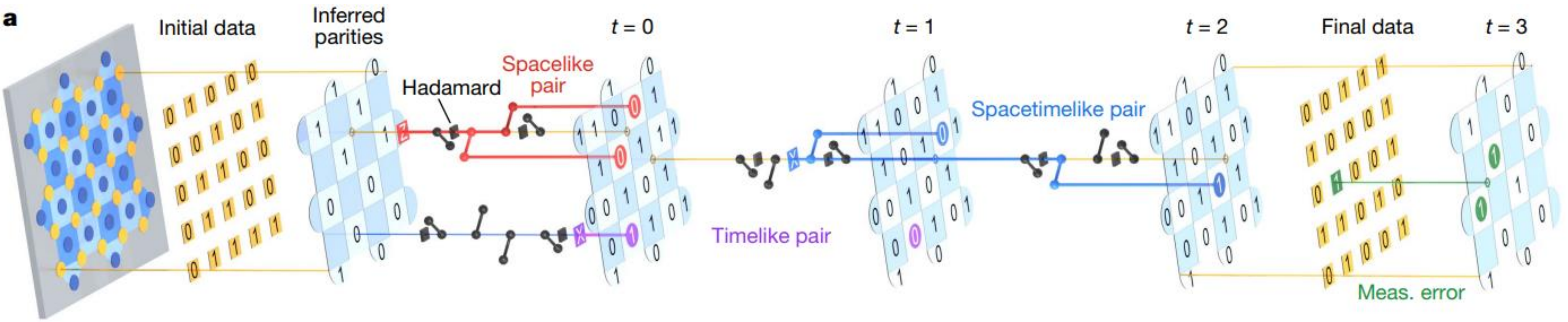
- Three types of error: Spacelike pair， Timelike pair， and Spacetimelike pair
- A Spacetimelike pair occurs when a data qubit error happens between CZ gates, causing detected errors to shift by one unit in both space and time, as shown by the red lines



[Kelly, et al., Nature, 2015]

Same Error Types in Surface Code

- **Similar to the Repetition Code, the Surface Code also has three types of pair errors**



Correlations of Error Detection Events

- **The correlation between measurements of different qubits across rounds can be determined by the following formula:**

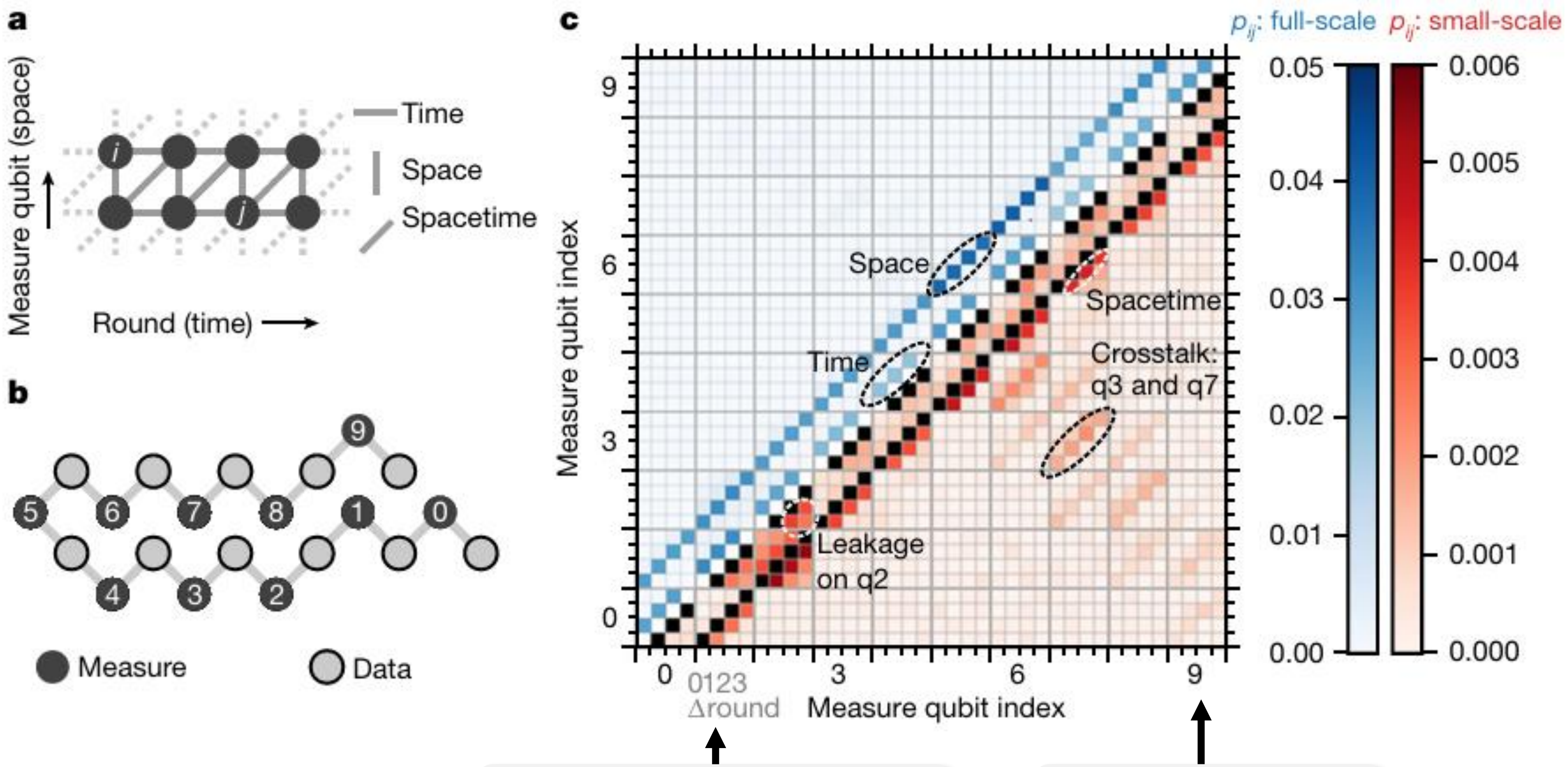
$$p_{ij} \approx \frac{\langle x_i x_j \rangle - \langle x_i \rangle \langle x_j \rangle}{(1 - 2\langle x_i \rangle)(1 - 2\langle x_j \rangle)}$$

- $\langle x_i \rangle$ **is the probability of a detection error in event i, and** $\langle x_i x_j \rangle$ **is the probability of detection errors in both events i and j in the same experiment. Indices i,j refer to different qubits in different rounds.**

[Google Quantum AI, Nature, 2021]

Experimental Correlation Matrix by Google

- **Google's experimental correlation matrix results for the 21-qubits Repetition Code:**



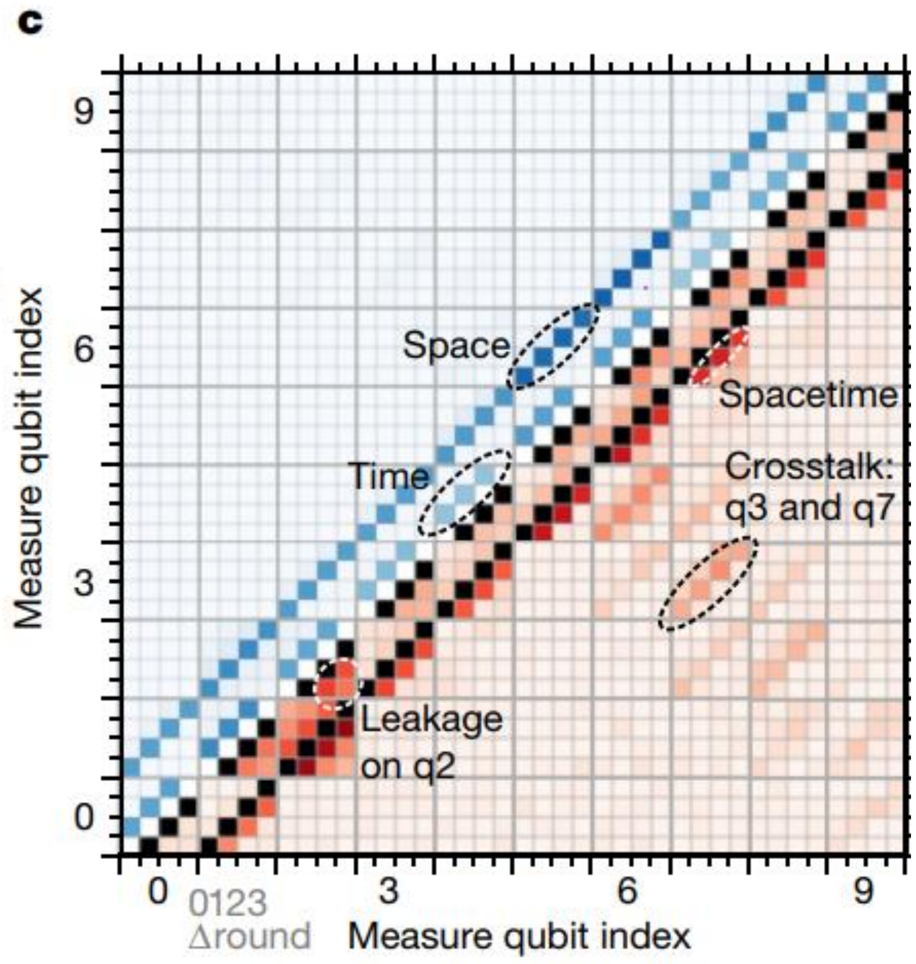
Minor Ticks → Difference in Rounds

Major Ticks → Measure Qubits

[Google Quantum AI, Nature, 2021]

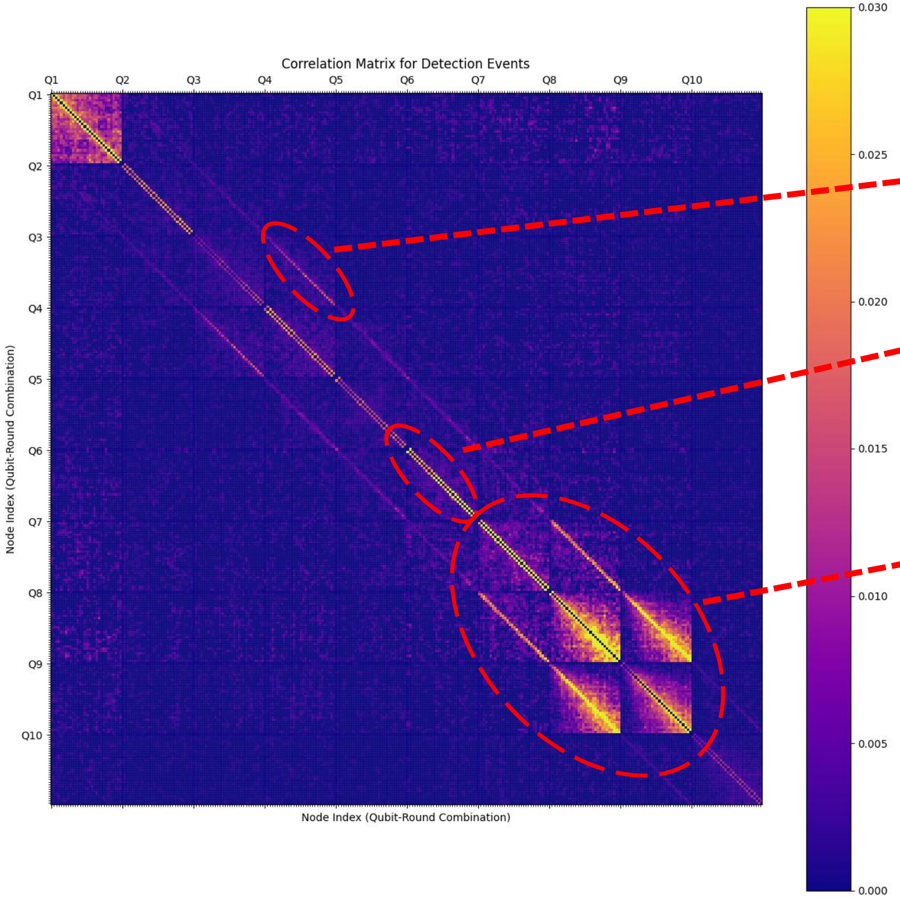
Experimental Correlation Matrix by Google

- **Main Error Types: Spacelike pair, Timelike pair, and Spacetimelike pair**
- **However, exists a certain degree of crosstalk and leakage**
- **Crosstalk: correlations between different qubits**
- **Leakage: additional small-scale spacetime errors**



Experimental Correlation Matrix on IBM Quantum Platform

- **Repetition Code Experiment: # of Qubits: 21, Rounds: 30, Shots: 4096 Basis: Z Backend: “sherbrooke” Date: 2024-10-9**



High Spacelike Error Rates

High Timelike Error Rates

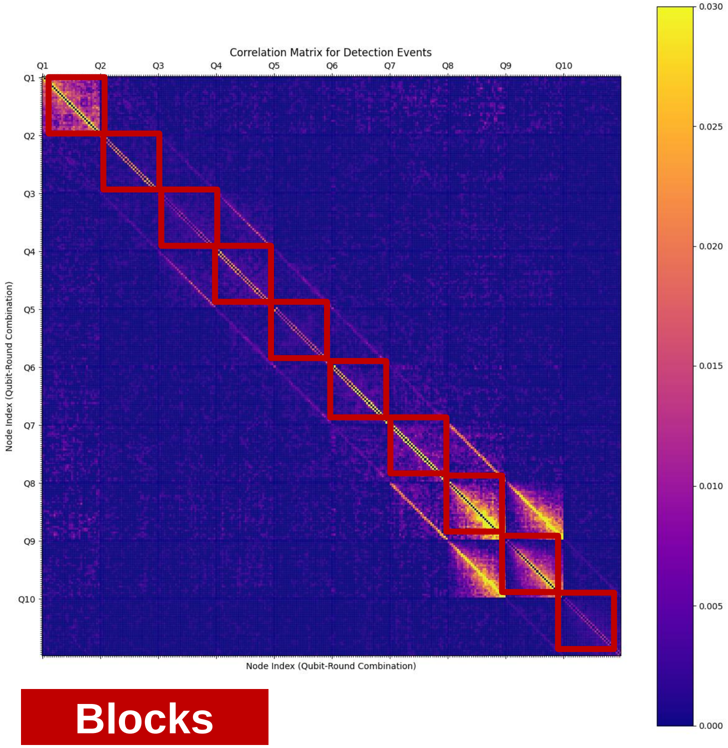
High Leakage Rates
Unexpected Spacetimelike Errors

Nearly Zero Crosstalk Due to IBM Backend Layout

Leakage & Seepage Parameters Optimization

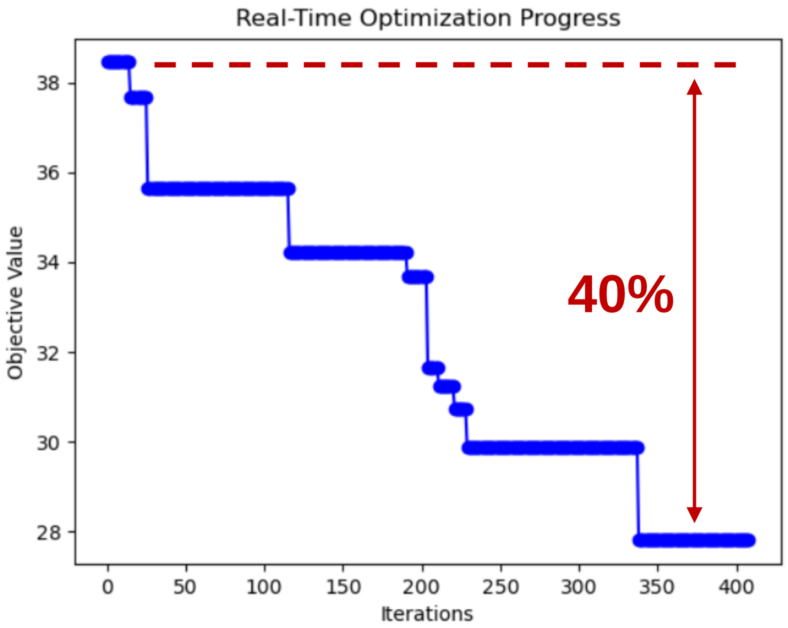
- **Since IBM backend does not provide calibration data about leakage, we must fit the leakage rate and seepage rate of each qubit using experiment data**

- **Objective Function: *Summed Difference* =** $\sum_{blocks}\left(\sum_{\substack{i,j\, \in\, block,\\ i\neq j}} \left|p_{ij,simulation} - p_{ij,experiment}\right|\right)$

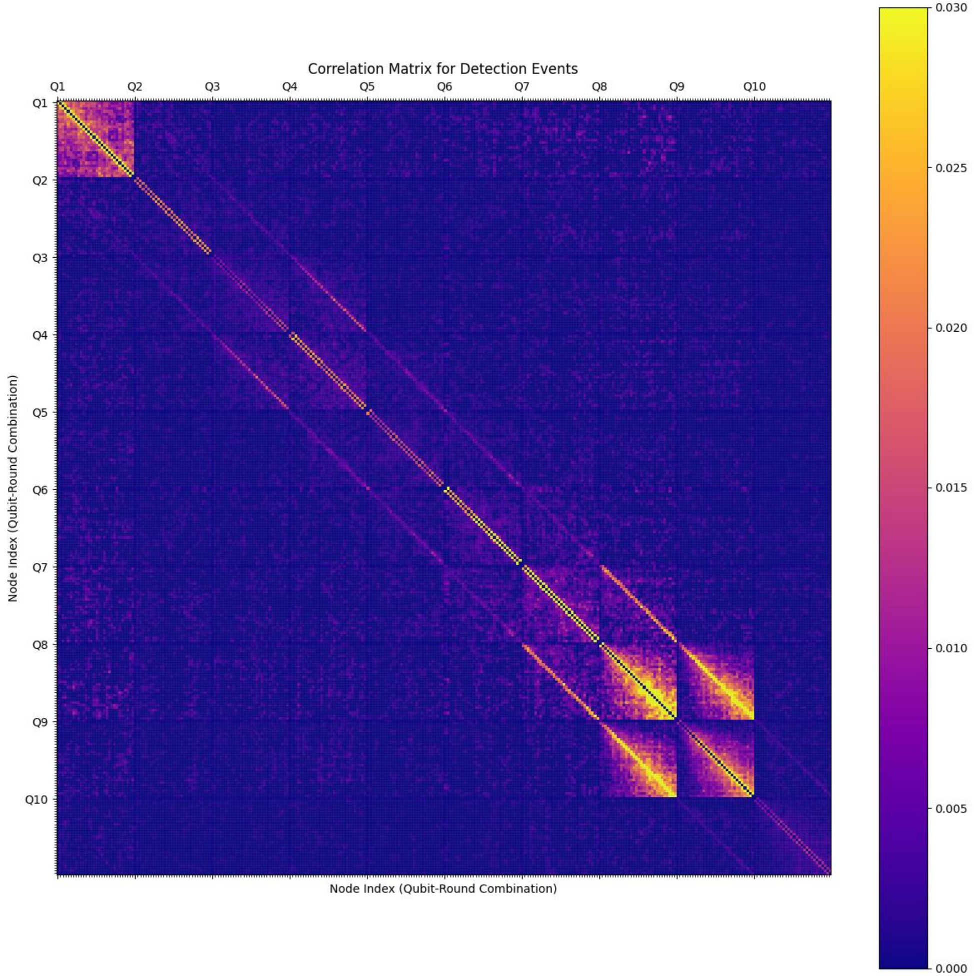


Blocks

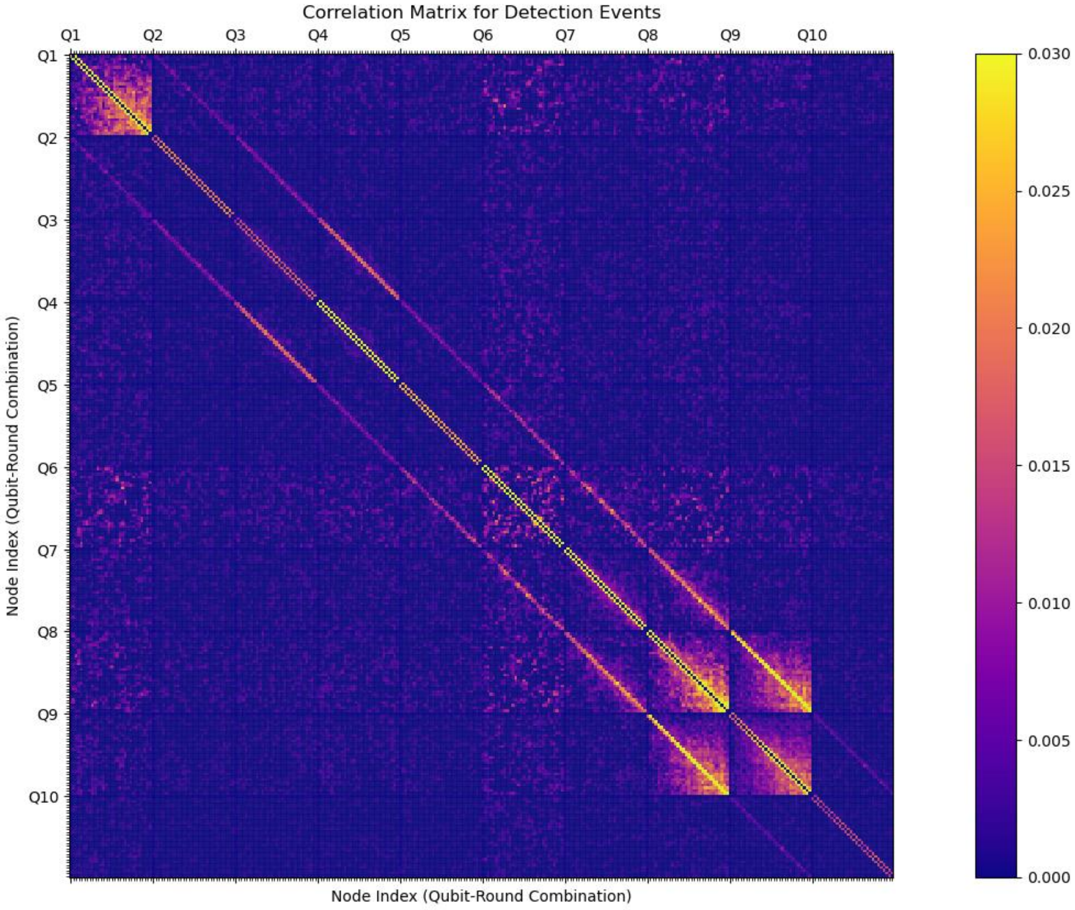
Bayesian Optimization



Comparison of Experiment Results & Simulation Results



Experiment Result Matrix on IBM



Simulation Result Matrix on Our Model

Other Noise Model

- ①Code Capacity
- ②Phenomenological
- ③Circuit
- ④SD6
- ⑤SI1000
- ⑥pauli+leakage （ours）

Error model:	Data qubit errors:	Measurement gate errors:	Syndrome extraction circuit errors:
Code capacity	yes	no	no
Phenomenological	yes	yes	no
Circuit	yes	yes	yes

[Andrew J. Landahl et al., arxiv, 2011]

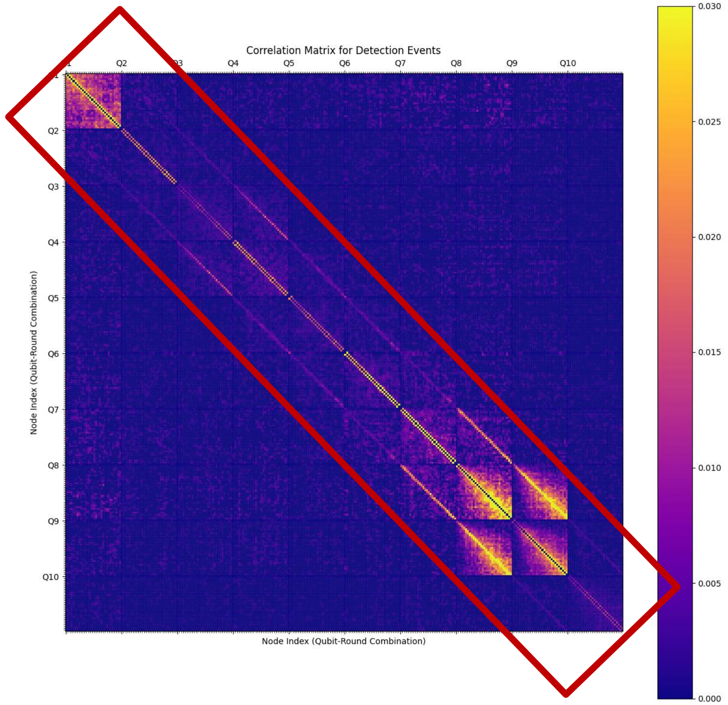
SD6	SI1000
Standard Depolarizing	Superconducting Inspired
$\mathrm{CX}(p)$ $\mathrm{AnyClifford}_1(p)$ $\mathrm{Init}_Z(p)$ $M_Z(p)$ $\mathrm{Idle}(p)$	$\mathrm{CZ}(p)$ $\mathrm{AnyClifford}_1(p/10)$ $\mathrm{Init}_Z(2p)$ $M_Z(5p)$ $\mathrm{Idle}(p/10)$ $\mathrm{ResonatorIdle}(2p)$
Yes	Yes
6 time steps	7 time steps ($\approx$ 1000ns)

[Gidney Craig, Newman Michael, McEwen Matt, Quantum, 2022]

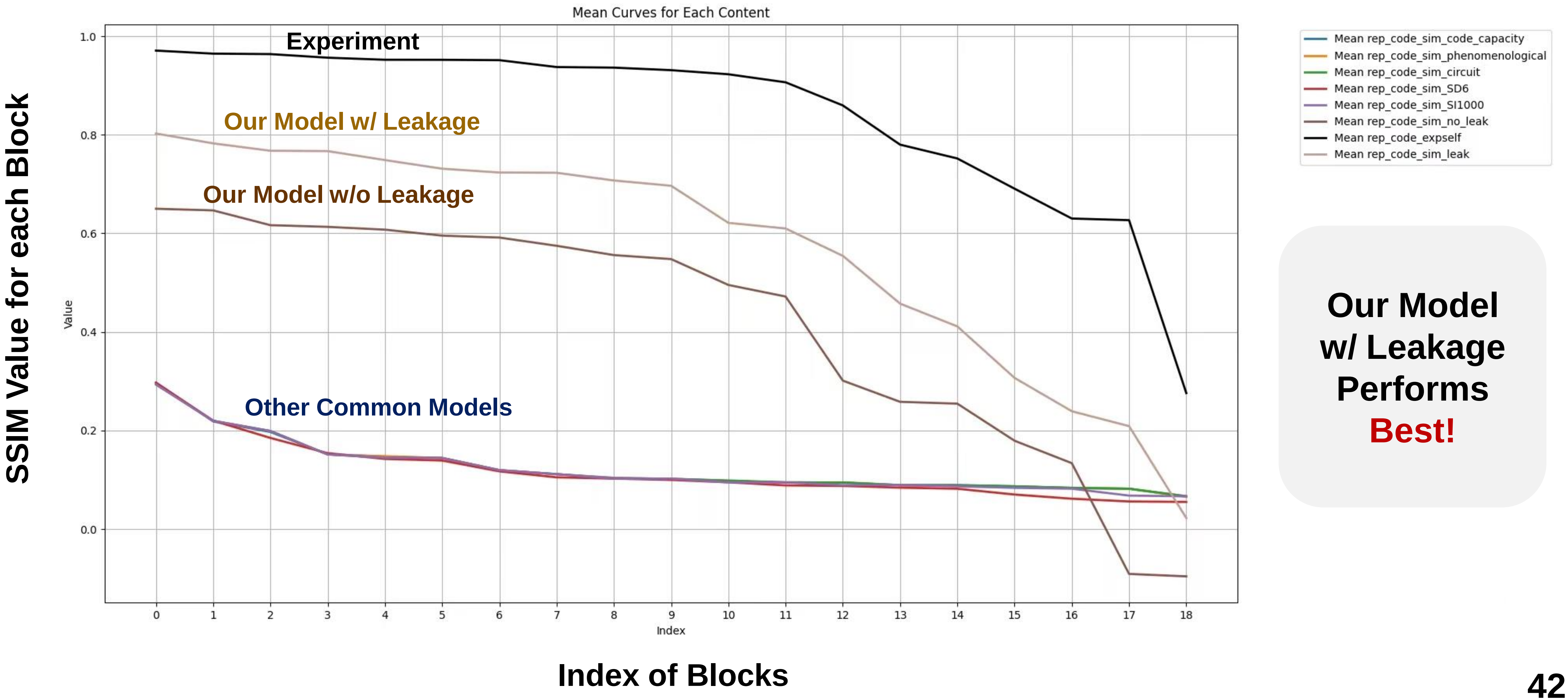
Quantitative Comparison Method - SSIM

- SSIM characterizes image similarity through three dimensions: brightness, contrast, and structure, with each dimension assigned a different weight.

- Comparing between blocks, only concern blocks on the blocks or 1-offset to the diagonal blocks



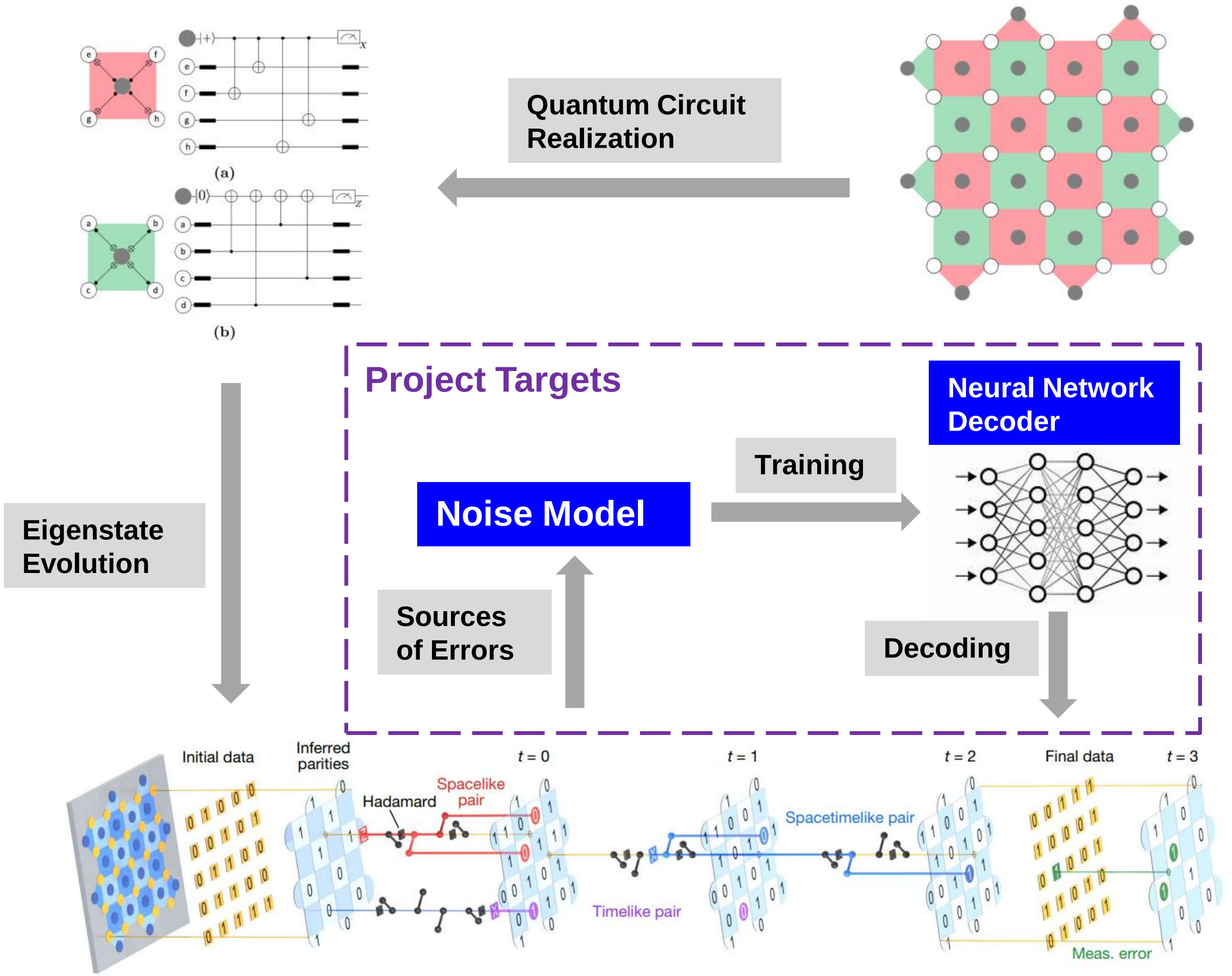
Quantitative Comparison



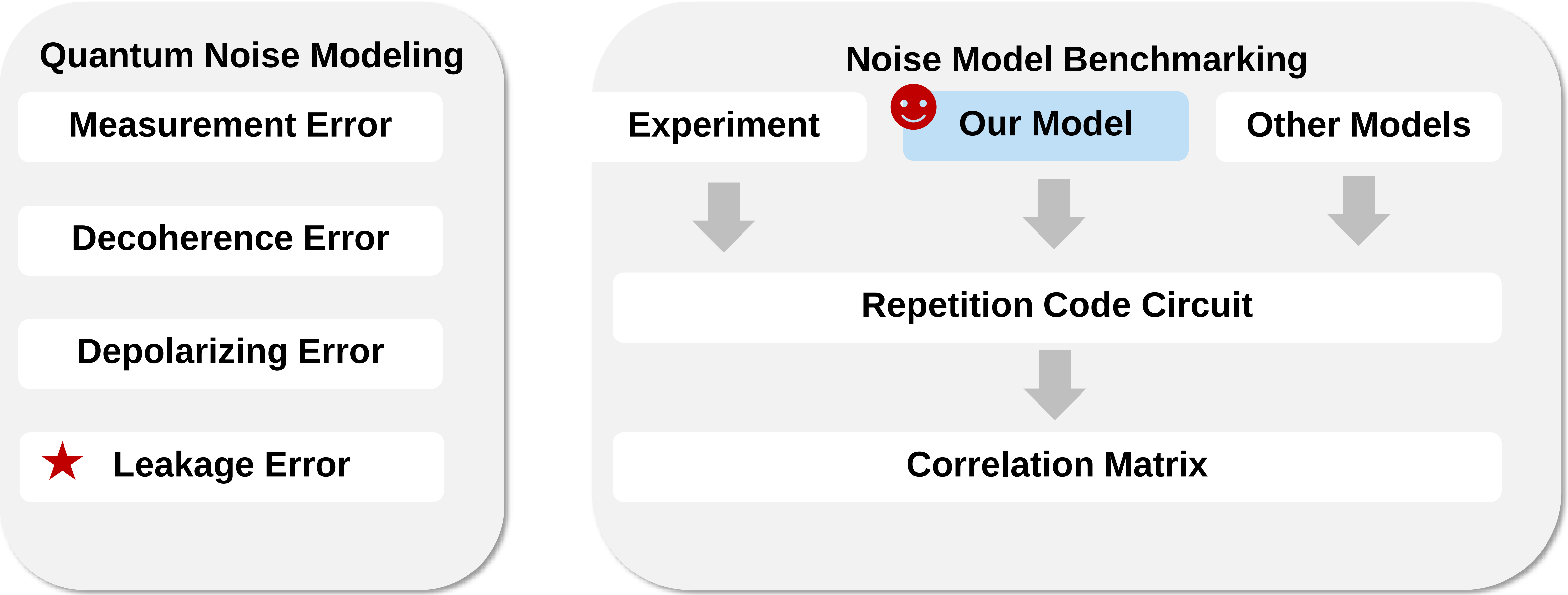
Our Model w/ Leakage Performs Best!

Outline

- Background & Motivation
- Project Overview
- Quantum Noise Modeling
- Noise Model Benchmarking
- **Conclusion & Future Work**

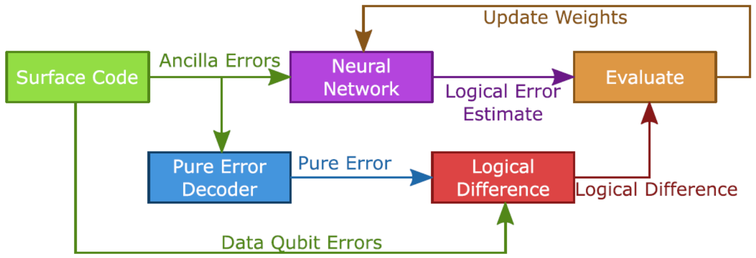


Conclusion



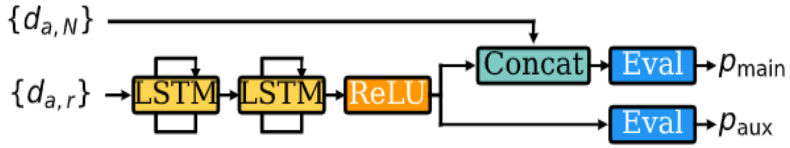
Quantum Noise Modeling
Measurement Error
Decoherence Error
Depolarizing Error
Leakage Error
Noise Model Benchmarking
Experiment
Our Model
Other Models
Repetition Code Circuit
Correlation Matrix

Future Work – NN Decoding Algorithm Design



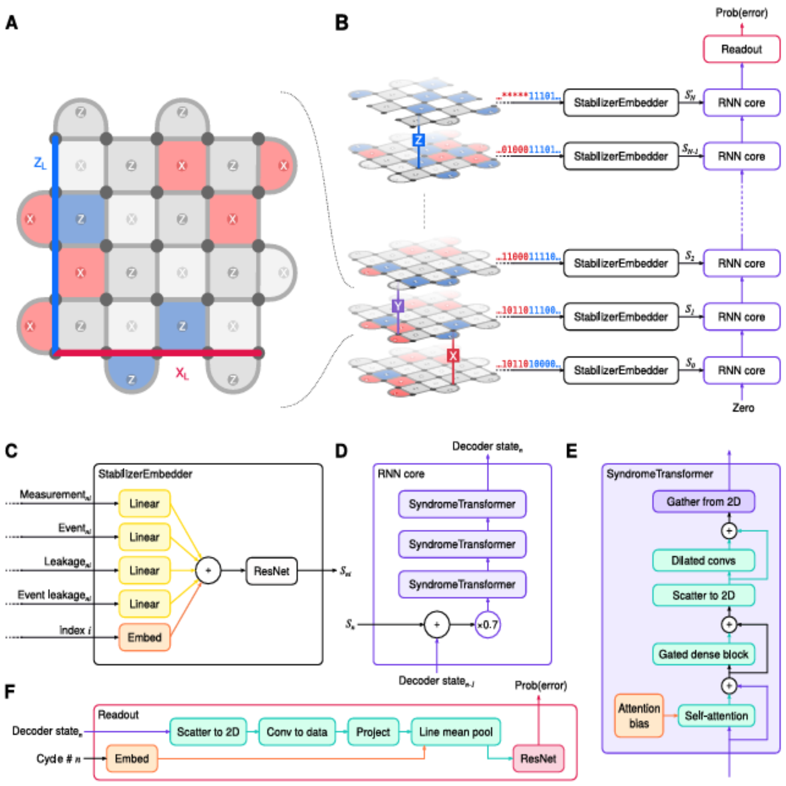
[R. W. J. Overwater et al., IEEE TQE 2022]

Feedforward NN



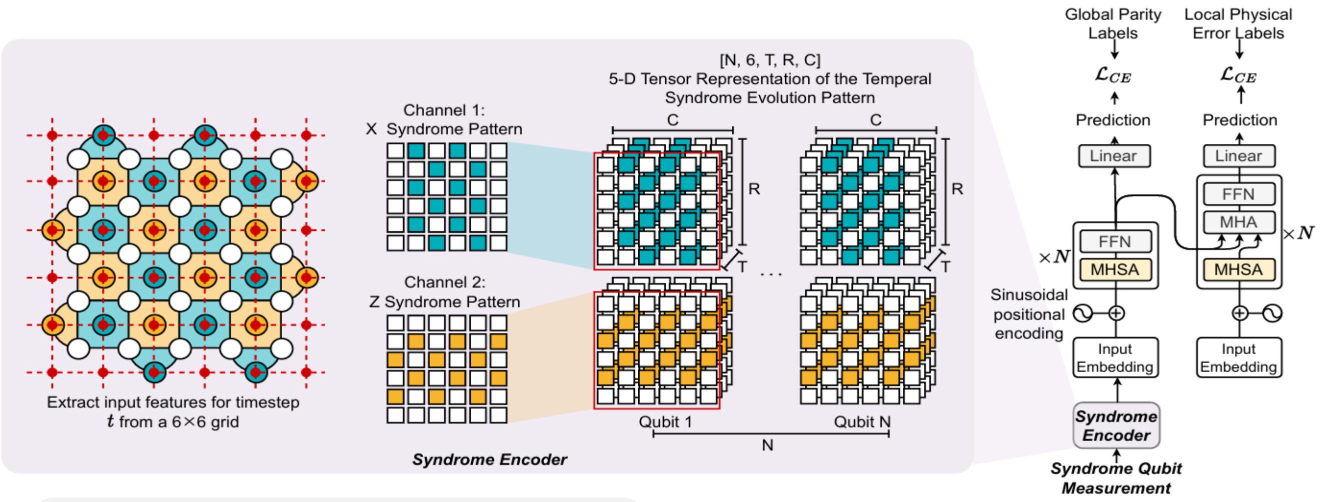
[Boris M. Varbanov et al., arxiv, 2023]

LSTM



Recurrent Transformer

[Johannes Bausch et al., arxiv, 2023]



Transformer

[H. Wang et al., ICCAD 2023]