# Online decoding of surface code with a superconducting circuit

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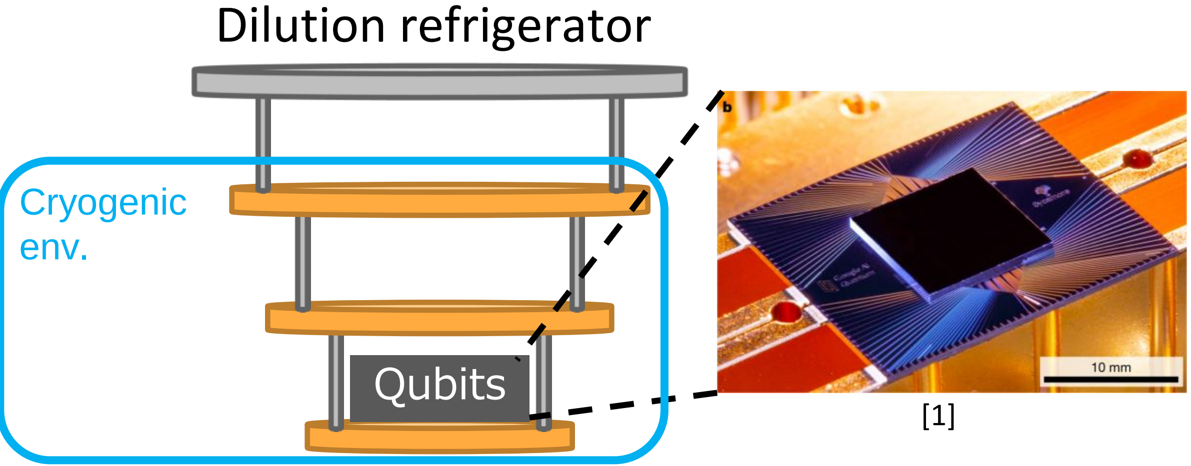
# Summary of this talk

- Decoding surface code is reduced to graph matching problem
- A practical decoder should be **accurate, fast, and scalable**
- For superconducting QCs, decoder also should be **power efficient** to be operated in **a cryogenic environment**
- Our solution: **online decoder** with **superconducting digital circuit**
- Our works on real-time decoding for FTQC
  - QECOOL: Online decoder with superconducting circuits (DAC'21, arXiv:2103.14209)
  - QULAIS: Extension of QECOOL for logical operation with lattice surgery (HPCA'22)
  - NEO-QEC: Extension of QECOOL/QULATIS with binarized NN for better accuracy (arXiv:2208.05758)

# Outline

- Introduction
  - Superconducting quantum computer
  - Quantum error correction with surface code (SC)
- Requirements for a practical decoder
- QECOOL: online decoder with a superconducting circuit
- Conclusion and advanced works

# Superconducting quantum computer (QC)




[1]

SoTA QC as of 2022

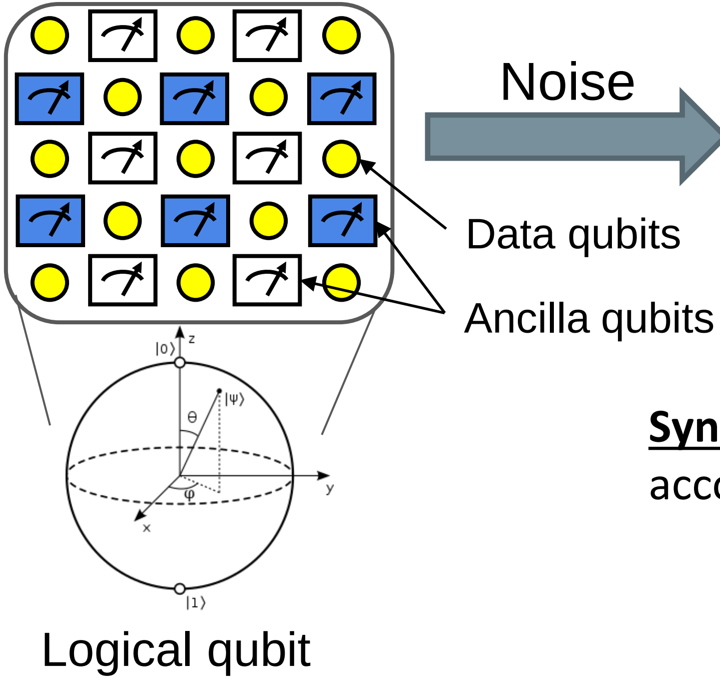
- # of qubits: 50~100
- Error rate: **0.1~1%**
- Noisy Intermediate Scale Quantum (**NISQ**) device

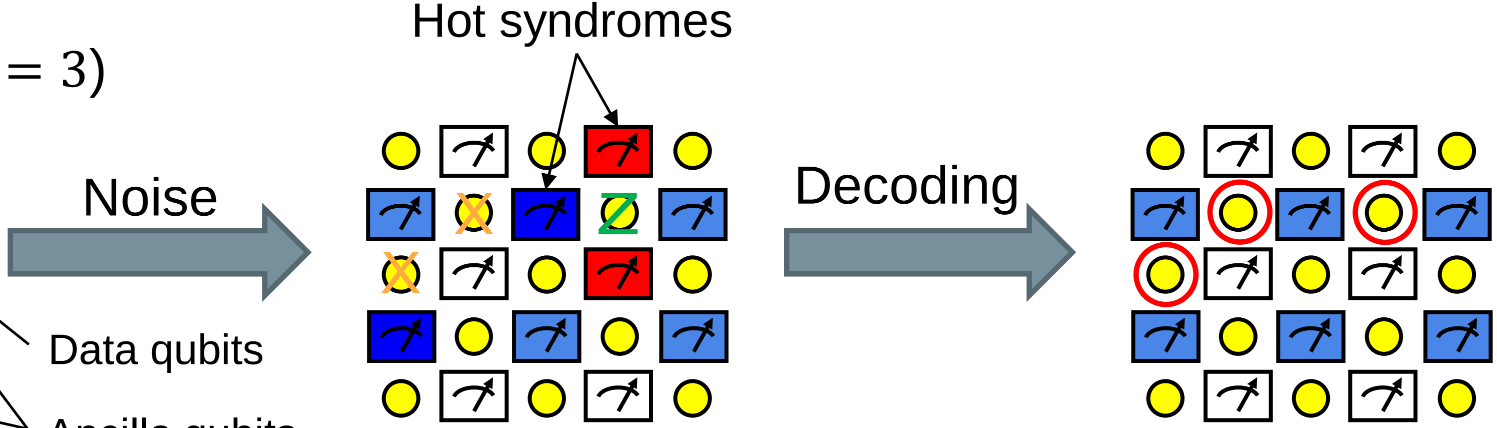
- Superconducting qubit: one of the most promising qubit implementation
  - Operate only at cryogenic environment (~20 mK)
- Qubits have very low error tolerance
  - **Quantum error correction (QEC) code**

[1] Frank Arute, Kunal Arya, Ryan Babbush, et al., Quantum supremacy using a programmable superconducting processor, Nature 574, 505–510 (2019).

# Example of QEC code: Surface code (SC)

Surface code
(Code distance $d = 3$)

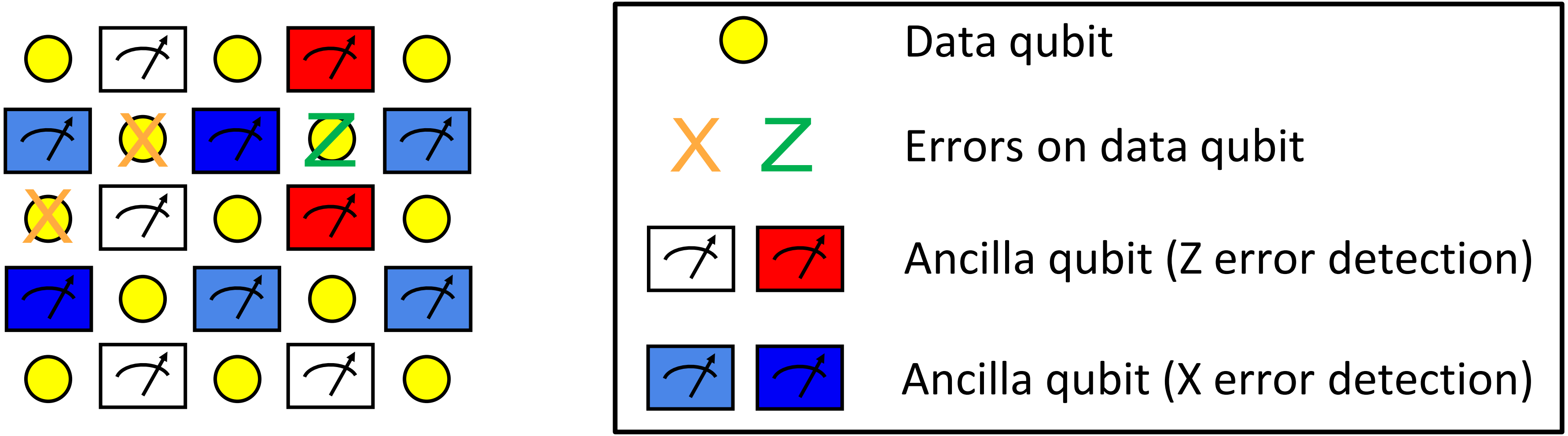



**Syndromes** change according to errors

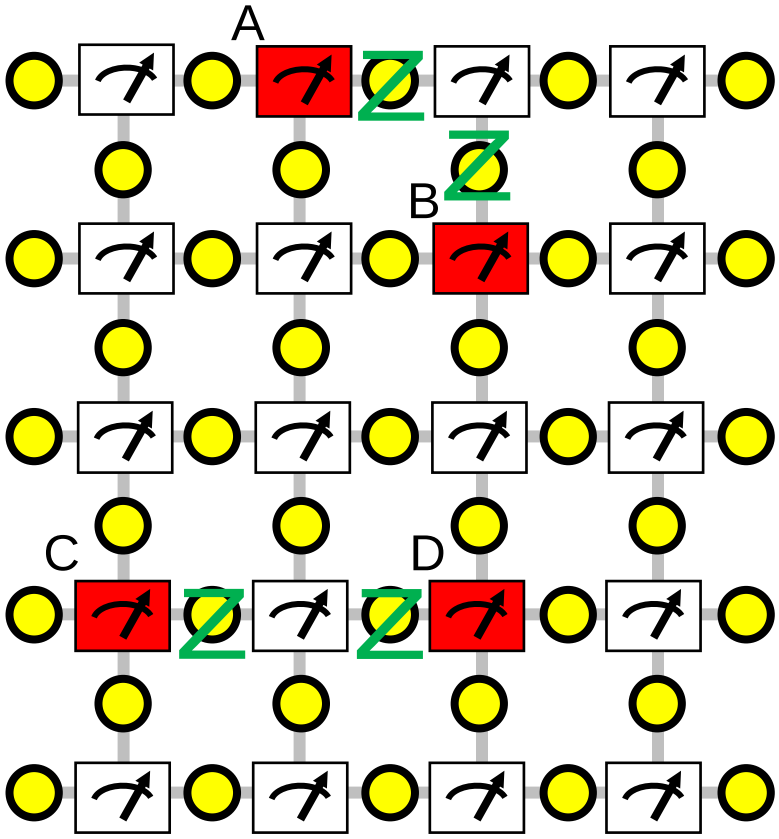
Decoding SC is specifying most likely errors from **hot syndromes**, and reduced to **graph matching problem**

# Function of surface code




- Each ancilla qubit is used for error parity detection of neighboring data qubits
    - Endpoints of error chains are expected to be **hot syndromes**
- Errors on data qubit can be detected without direct measuring

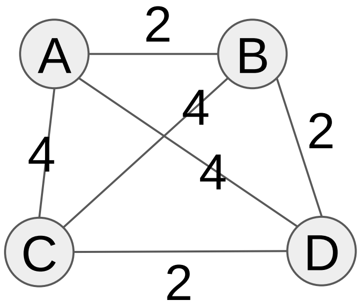
# Decoding surface code




Assumption

- $X$ and $Z$ errors can be decoded independently
- Shorter error chains are likely to occur

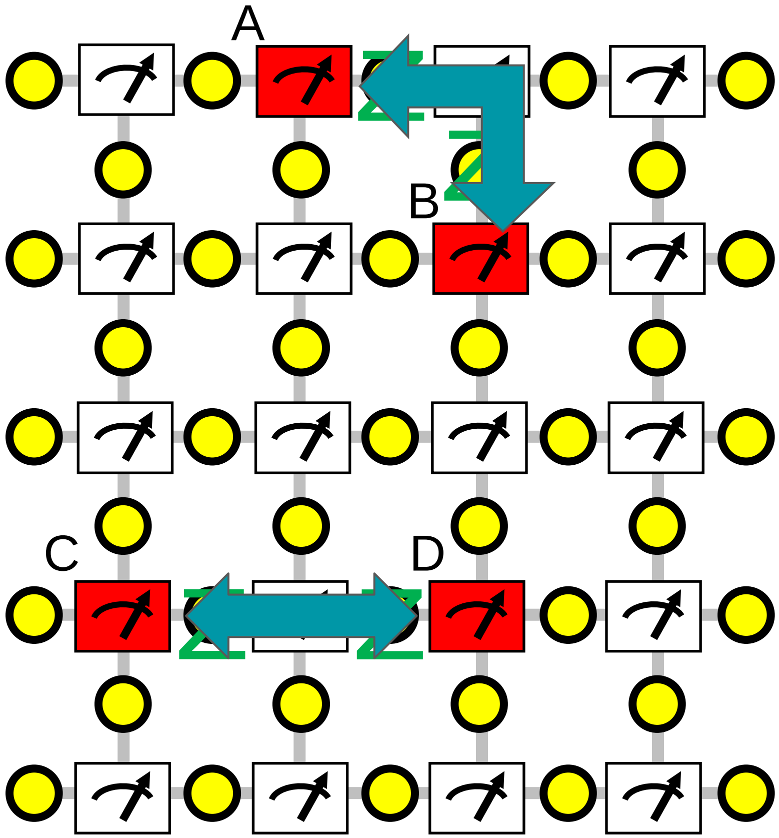
Minimum Weight Perfect Matching (MWPM)




$V$: Hot syndromes
$W_e$: Manhattan distance

Exact solution: **Blossom algorithm ($O$(n$^3$))**

# Decoding surface code




## Assumption

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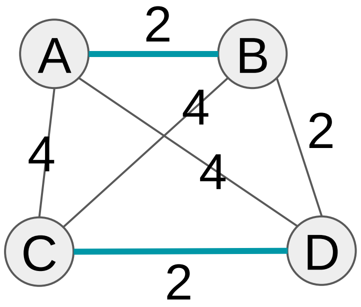
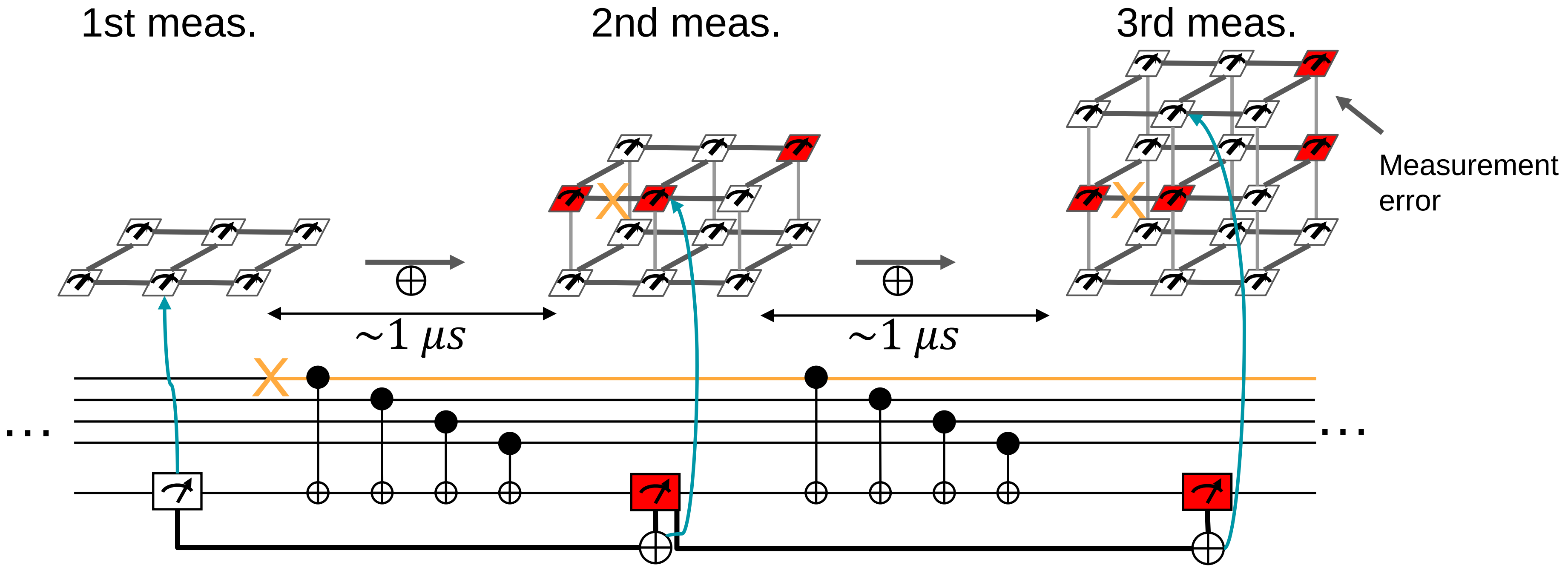
## Minimum Weight Perfect Matching (MWPM)




$V$: Hot syndromes
$W_e$: Manhattan distance

Exact solution: **Blossom algorithm ($O$(n$^3$))**

# Measurement error on ancilla qubit




- If ancilla qubit measurement is susceptible to read errors, multiple measurement processes are required
  - For every new measurement, the new syndrome is **XORed** with the latest value

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# Requirements for a practical decoder

## Requirements

1. Power consumption
   - Decoder must operate in **a cryogenic environment** with limited power budget
2. Latency
   - Slow decoding leads to **accumulation of errors** and **slow quantum computation**
3. Scalability
   - Decoder must protect not only single qubit but also **logical operations**
4. Accuracy
   - Decoder must have a **high error threshold**

QULATIS, HPCA'22

## Our solutions

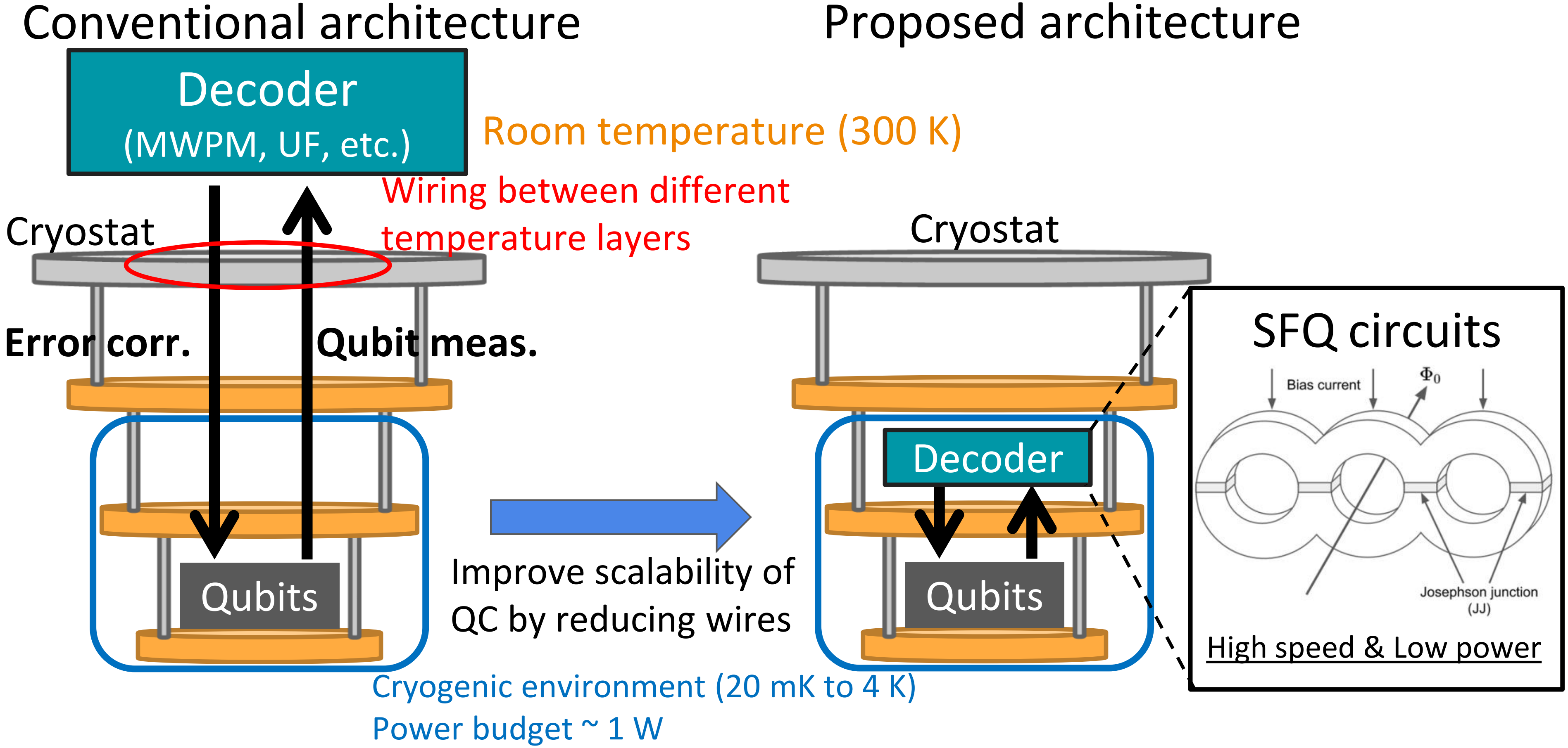
Superconducting digital circuits

Online-QEC manner

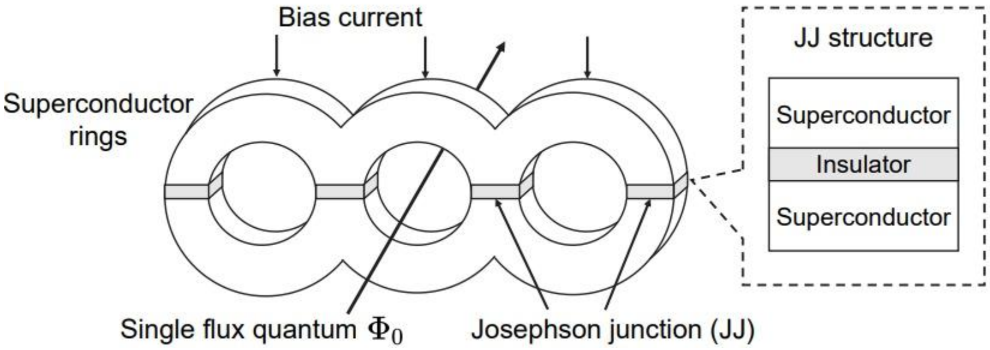
Binarized neural network

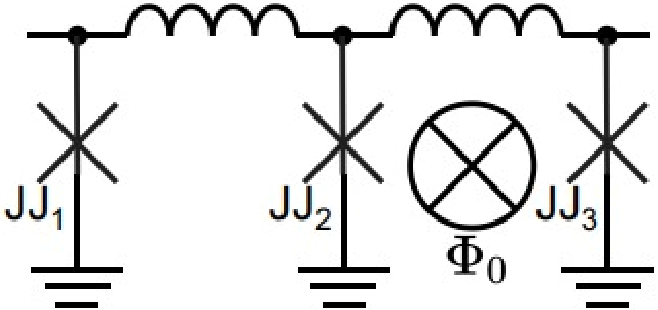
NEO-QEC arXiv:2022.05758

# QEC architecture for superconducting QCs



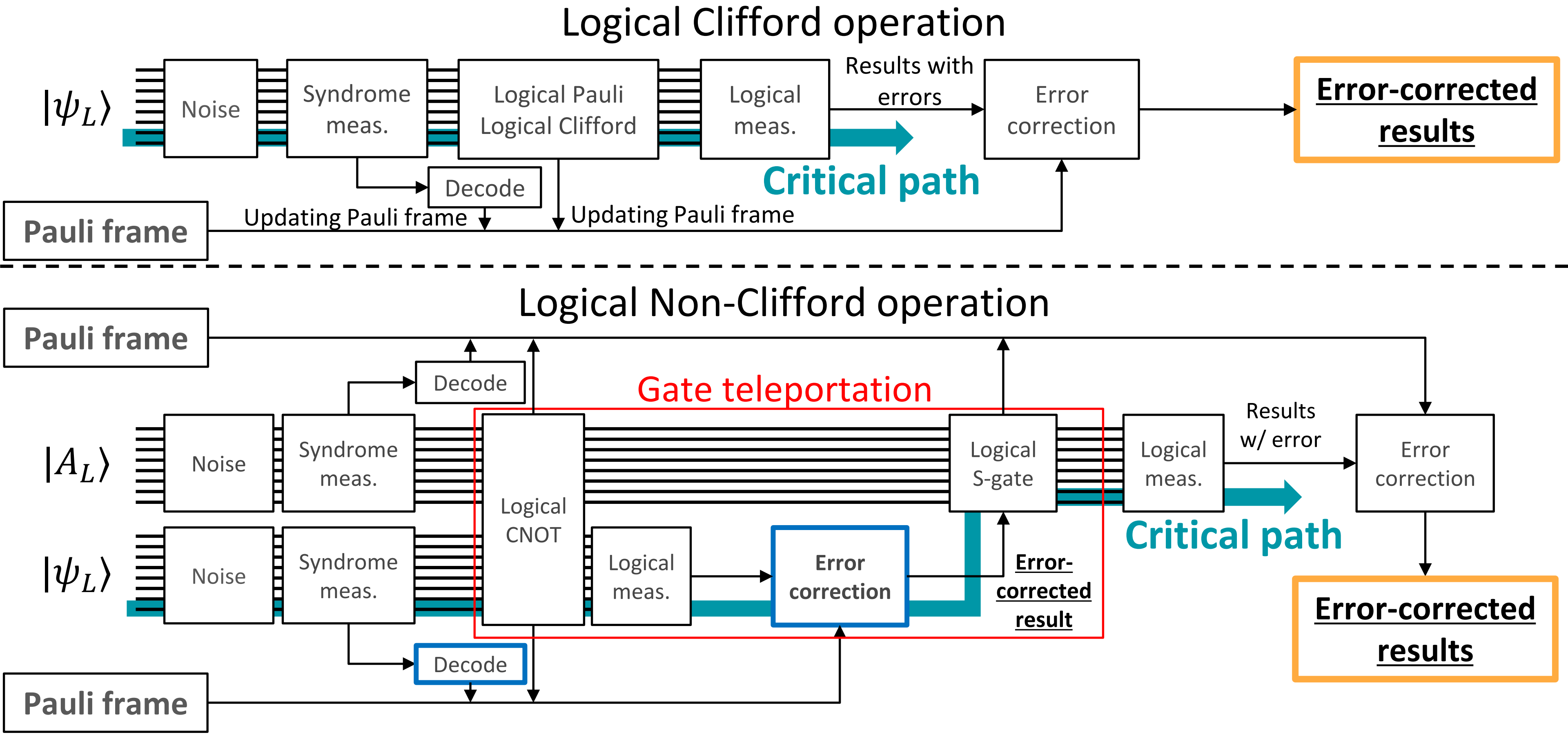
# Single flux quantum (SFQ) logic



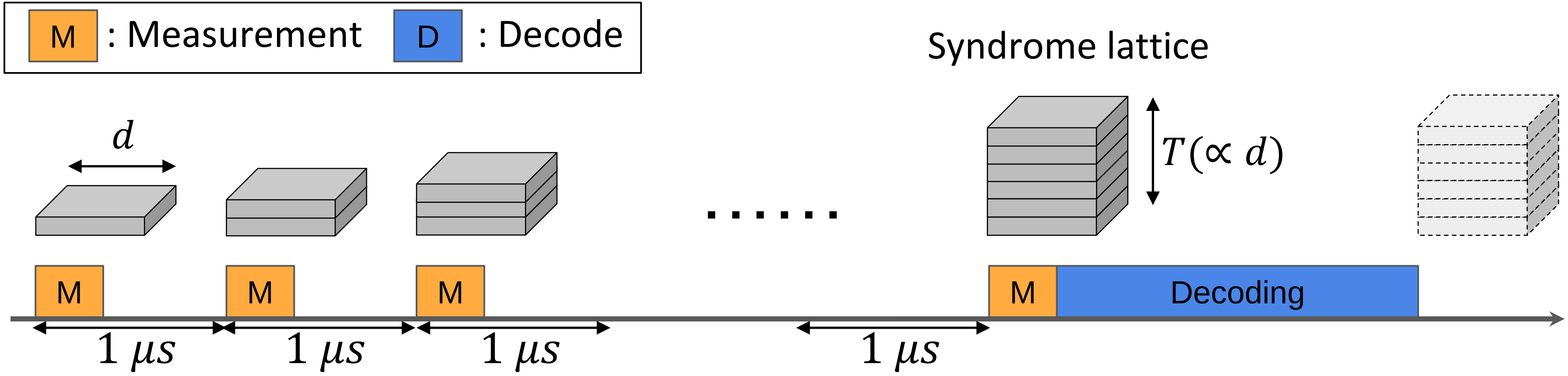




- Absence (presence) of flux quanta within the ring represents digital ‘0’ (‘1’)
- Operates only in a cryogenic environment (~ 4 K)
- High speed and low latency compared to CMOS circuits
- Limitation: Large amount of RAM is expensive
  - -> Conventional decoders such as MWPM are not implementable with SFQ

# High-latency decoding slows down quantum computation



# Why is MWPM not practical?

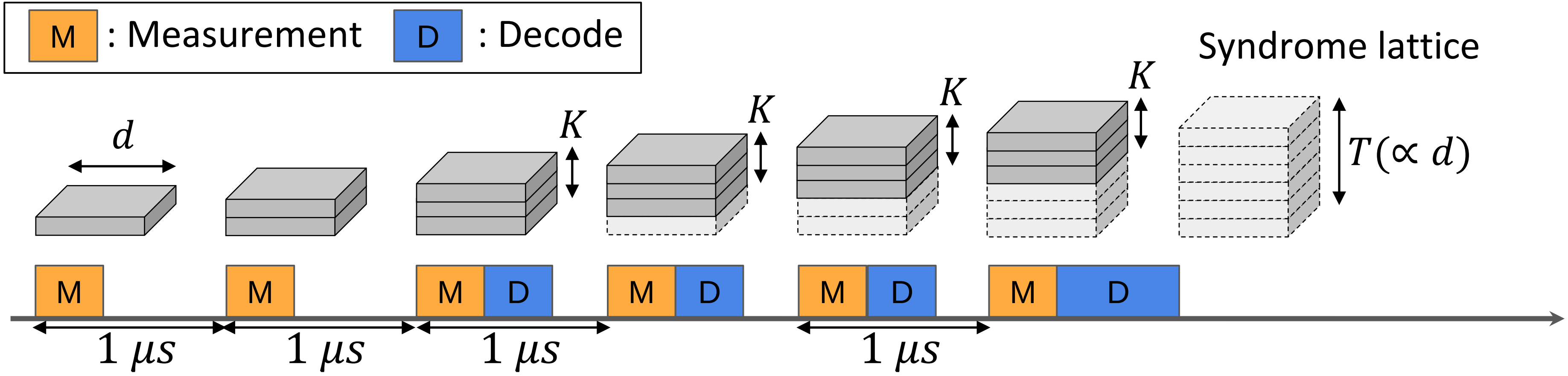


Measurement and decoding processes with the MWPM decoder

**Batch-QEC manner**

+ Accurate decoding
− Slow decoding
− $O(Td^2)$ bits of storage

# Our solution: Online-QEC manner




Measurement and decoding processes with a practical decoder

**Online-QEC manner**

− Degradation of decoding accuracy

\+ Fast decoding

\+ $O(Kd^2)$ bits of storage

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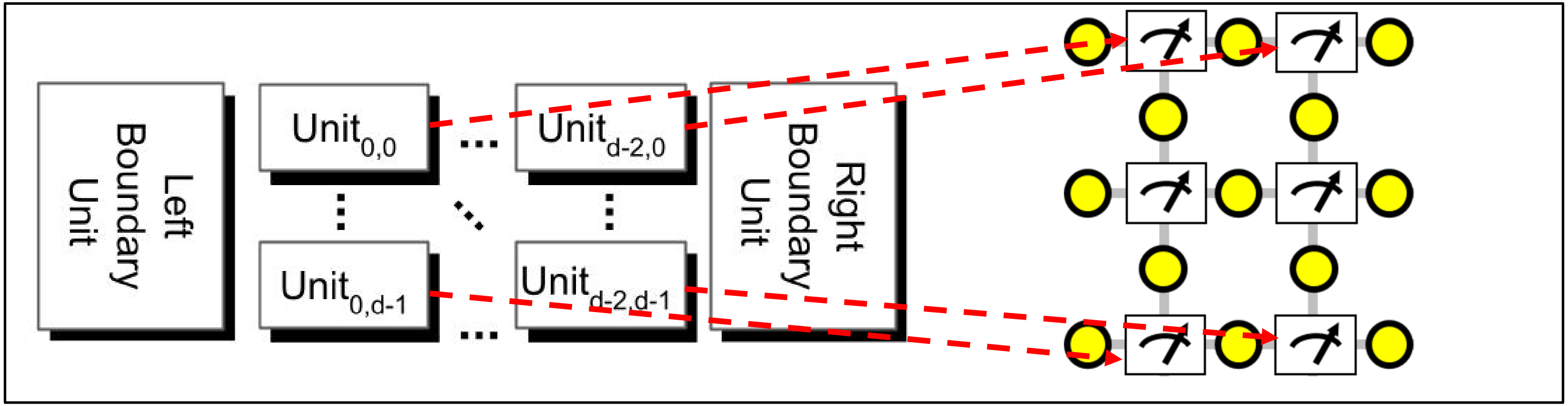
# QECOOL

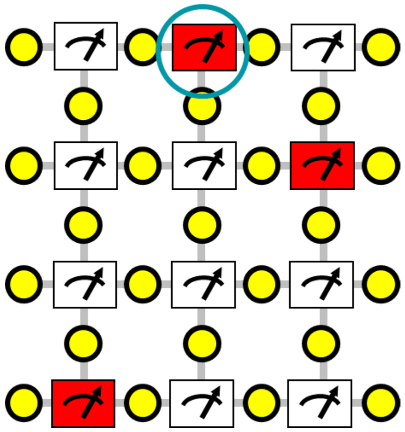



Architecture overview of QECOOL decoder

- Quantum Error COrrection by On-Line decoding algorithm
- **A distributed architecture** without large amount of RAM
  - Multiple processing elements (***Units***) corresponding one-to-one with ancilla qubits
  - Matching problems are solved by signal propagation among Units

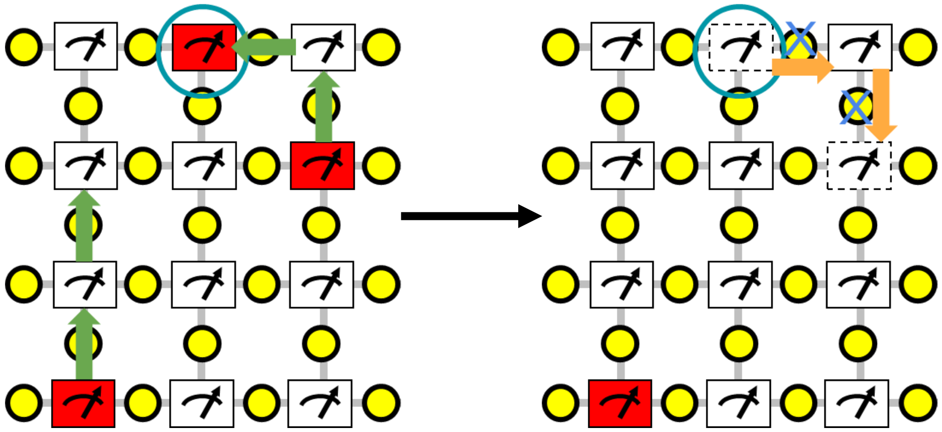
# Overview of QECOOL algorithm

## Step 1



Determine the starting point for finding a hot syndrome pair

## Step 2

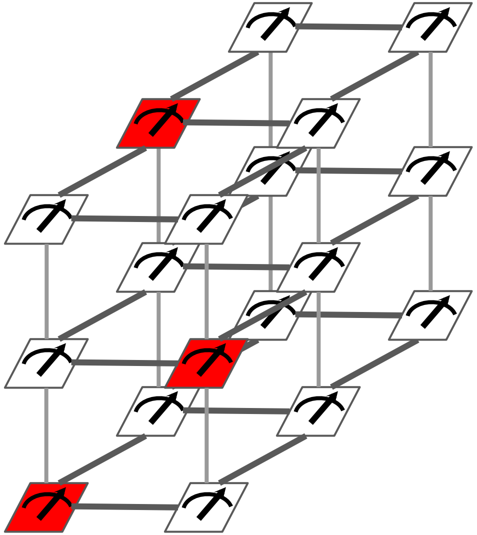


Perform **nearest neighbor search** using two types of signals among Units

Based on a **greedy graph matching algorithm**

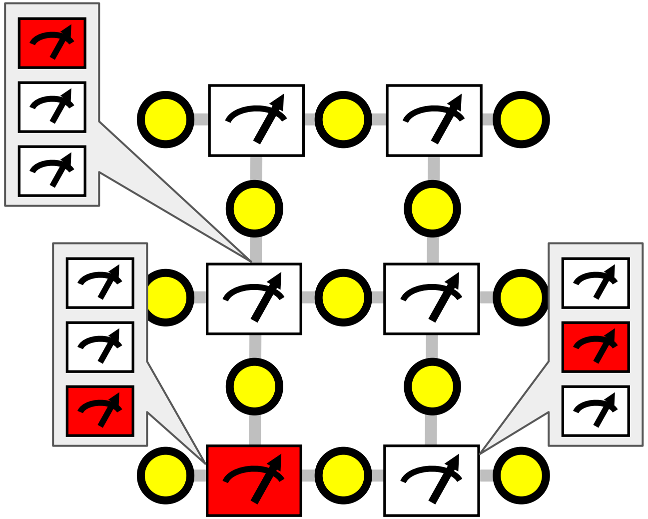
$O(n^2)$, approximation degree 1/2

# Matching problem on a 3-D lattice



3-D syndrome lattice

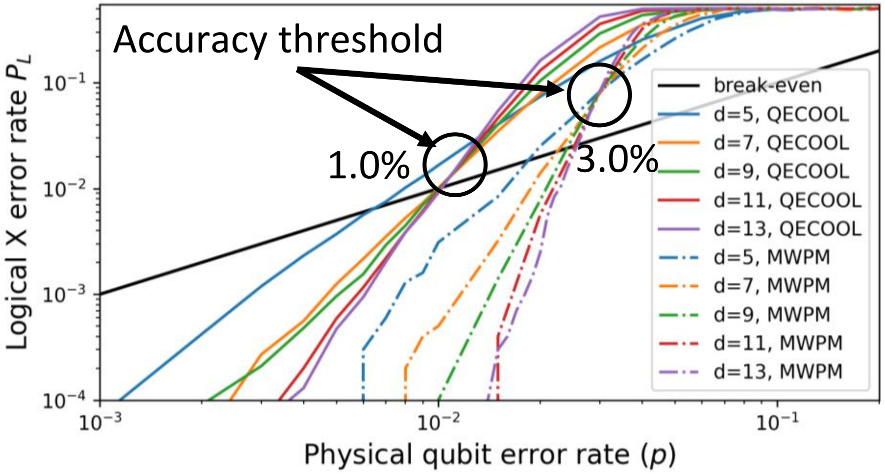
Map 3-D lattice to Units on 2-D grid

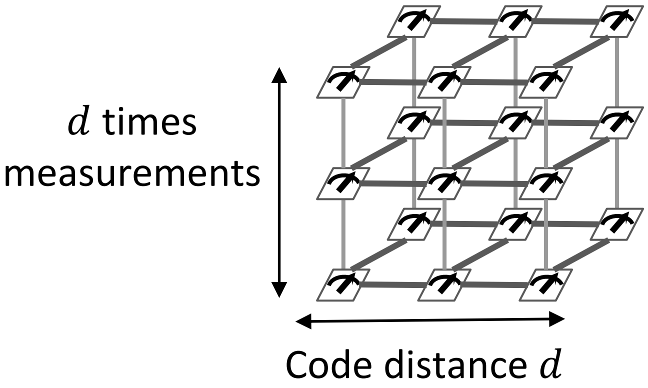


Units with $O(K)$ memory

- Each Unit has a $O(K)$ buffer to store multiple syndrome values
- Almost the same procedure as in case of 2-D lattice

# Decoding performance of QECOOL



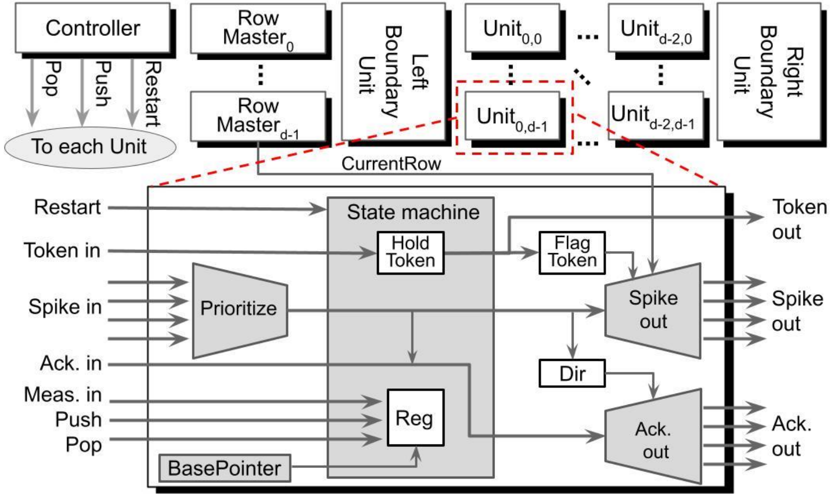

Target lattice shape

Experimental condition

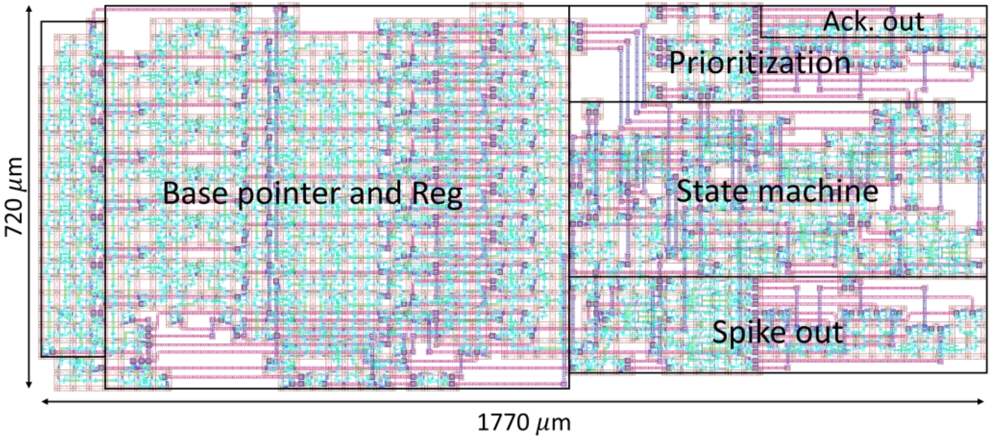
- Measurement process is performed **once every 1 $\mu s$**
- Each QECOOL Unit has a **7-bit** buffer to store syndrome values
- If buffer entry size is greater than $K = 3$, QECOOL is performed; otherwise, each Unit waits for measurement process
- MWPM operates with batch-QEC manner

- Threshold value: QECOOL p=0.01, MWPM p=0.03

# SFQ implementation of QECOOL decoder




Architecture overview of QECOOL decoder




SFQ layout of QECOOL Unit

| | | | |
|---|---|---|---|
| JJs: 3177 | Area: 1.274 mm$^2$ | Latency: 215 ps | Power cons.: **2.78 $\mu$W** |

**# of protectable logical qubits on 4-K environment**

Suppose $d = 9$, and power budget is 1 W

$$1_{[W]}/(9 \times 8 \times 2 \times 2.78_{[\mu W]}) = \boxed{2498 \text{ logical qubits}}$$

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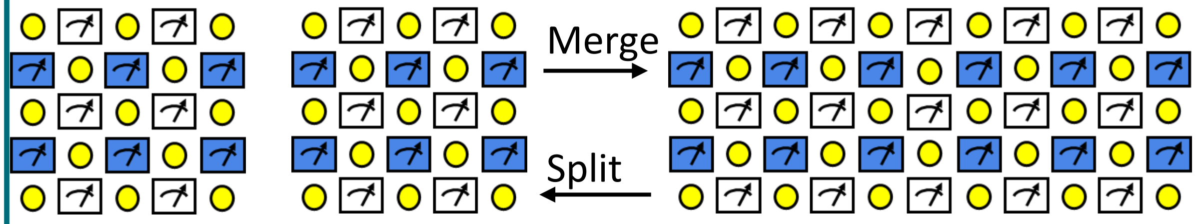
# Conclusion and advanced works

- Online decoding of surface code in a cryogenic environment is necessary for a scalable superconducting quantum computer
- QECOOL decoder is power-efficient enough to protect around 2500 logical qubits with distance-9 SC in a cryogenic env.
- Next step is supporting logical operations of the universal quantum gate set $\{H, \mathrm{CNOT}, T\}$
  - **QULATIS**: Extension of QECOOL for logical operation with lattice surgery (HPCA’22)
- Accuracy of QECOOL is lower than MWPM due to its greedy and online nature
  - **NEO-QEC**: Extension of QECOOL/QULATIS with binarized NN for better accuracy (arXiv:2208.05758)

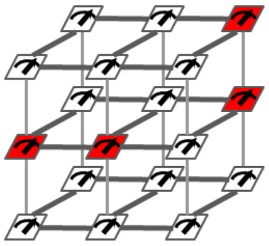
# QULATIS: QEC methodology towards lattice surgery

## Lattice surgery

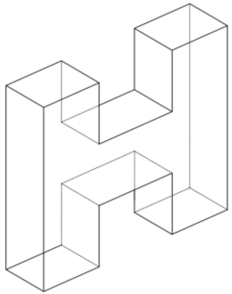



Framework to perform logical operations with SC-based QEC

## Target lattice shape



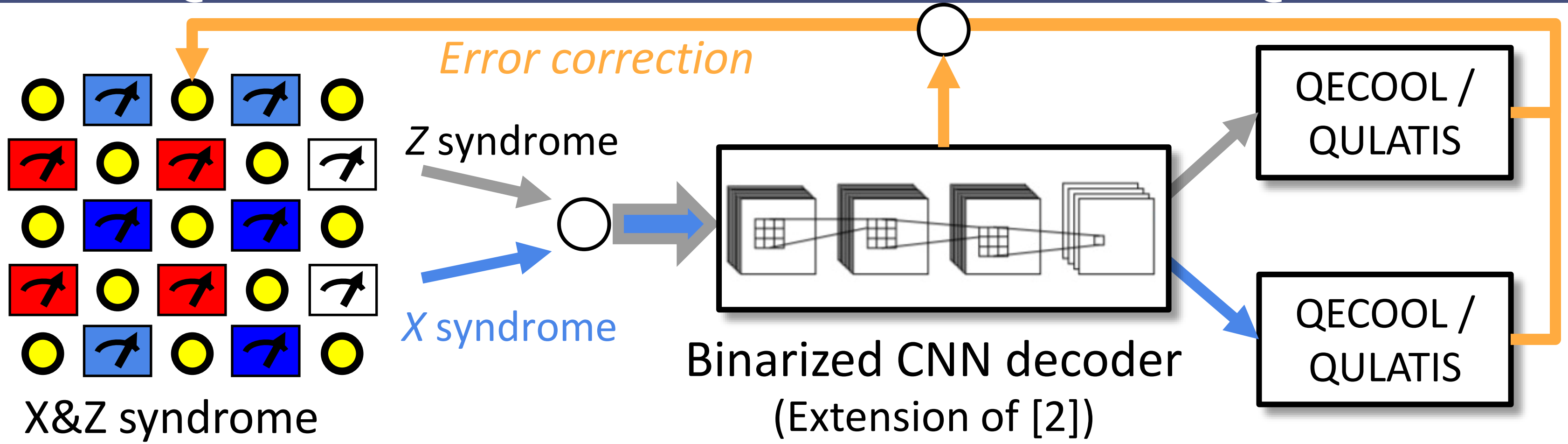
Single logical qubit (QECOOL)



Lattice surgery QULATIS

- Extension of QECOOL for decoding of lattice surgery
  - Supporting logical operations of the universal quantum gate set $\{H, \mathrm{CNOT}, T\}$
- SFQ circuit design of QULATIS decoder is suitable for **<u>online decoding in a cryogenic environment</u>**

# NEO-QEC: NN enhanced online QEC




- A two-stage decoder with binarized CNN and QECOOL/QULATIS
  - Improve threshold of QECOOL/QULATIS (Single: 1.5% -> 2.5%, LS: 0.6% -> 1.0%)
- SFQ design of **Neural Processing Unit** for binarized CNN
  - Suitable for **online decoding in a cryogenic environment**


[2] S. Gicev, L. C. Hollenberg, and M. Usman, A scalable and fast articial neural network syndrome decoder for surface codes, arXiv preprint arXiv:2110.05854 (2021).