# Algorithmic Fault Tolerance for Fast Quantum Computing

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**QuEra Computing Inc.**

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Quantum Algorithms, TQCI conference

# About QuEra

- Headquartered in Boston, close to Harvard and MIT.
- We build quantum computers using neutral-atoms, the most promising quantum technology.
- Deployed on the AWS cloud in November 2022.
- The scientific and commercial leader in neutral-atoms
- Used today to solve simulation, machine learning and optimization problems.


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# Recent Milestones

Google makes strategic investment in QuEra

UK Research and Innovation

QuEra wins award to deploy neutral-atom testbed in the UK

AIST

QuEra wins award to deploy neutral-atom computer in Japan

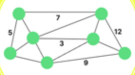
# Working with QuEra


## Machine Sales

- Purchase a QuEra computer.
- On-site installation, support, and community development.

## Cloud Access

- Secure remote access.
- Mentoring and support by QuEra scientists.




## Joint Development

- Long-term collaborations with strategic customers to develop “killer applications”

# QuEra Quantum Alliance

Driving Positive Change in the World with Neutral-Atom Quantum Computers

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Member of the QuEra Quantum Alliance

Jij
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QCWARE



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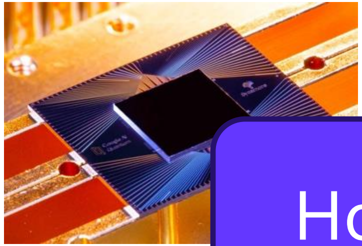
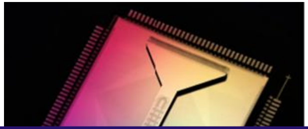
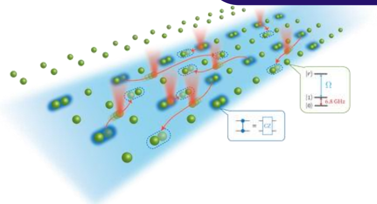
# Exciting Times for Early Quantum Computing Systems

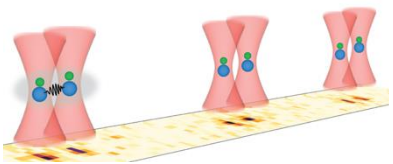
## Many experimental platforms

Superconduct

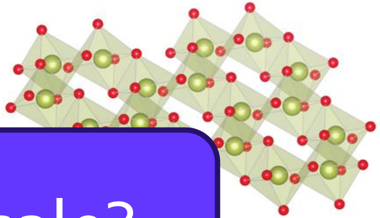


Neutral atoms

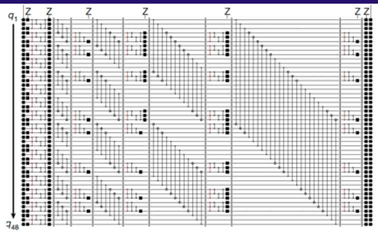


Cold molecules

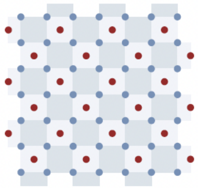
## Early algorithm implementations

& Chemistry



Sampling



Error correction

**How can we extend this to large-scale?**

Images: Google, Quantinuum, Harvard (Bluvstein et al., Nature 2024, Maskara et al., arXiv 2023), Princeton (Holland et al., Science 2023), Berkeley

# Challenge of Large-Scale Quantum Computation

Fighting decoherence and errors is **the central challenge** in large-scale quantum computation

Physical error rates today

What large-scale quantum algorithms require


**Error rate of encoded qubit**

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Image generated with DALL E

# Challenge of Large-Scale Quantum Computation

Quantum error correction (QEC)
will bridge this gap!

Physical error rates today

What large-scale quantum algorithms require


**Error rate of encoded qubit**

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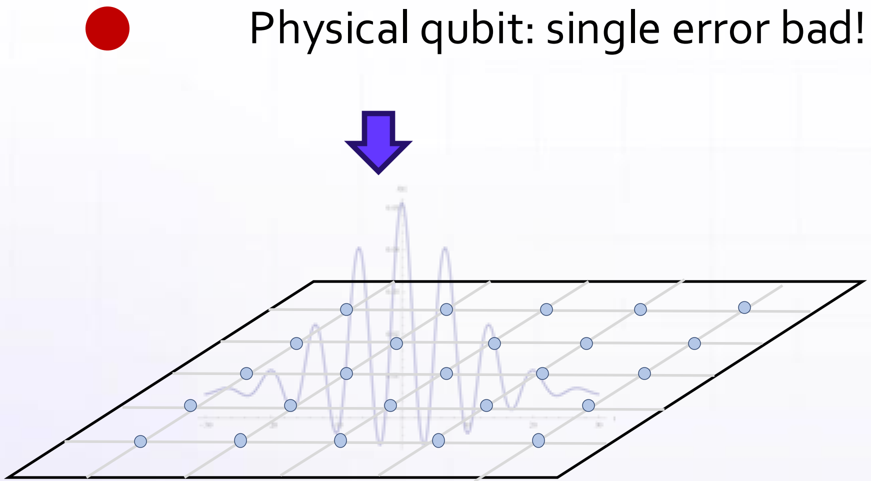
Image generated with DALL E

# Fault Tolerance (FT) and Quantum Information

Physical qubit: single error bad!



Logical qubit: delocalized across many qubits
- OK as long as not too many errors!

Fault tolerance offers a deep lens into physics of quantum info:

- Fundamentally, how can we protect quantum information?
- How can we structure the qubit to be insensitive to our errors?
- We are interested in not just qubits, but *computation*
- Can we design fault tolerance for the *whole algorithm*?
- Does this have consequences for the *cost of computation*?

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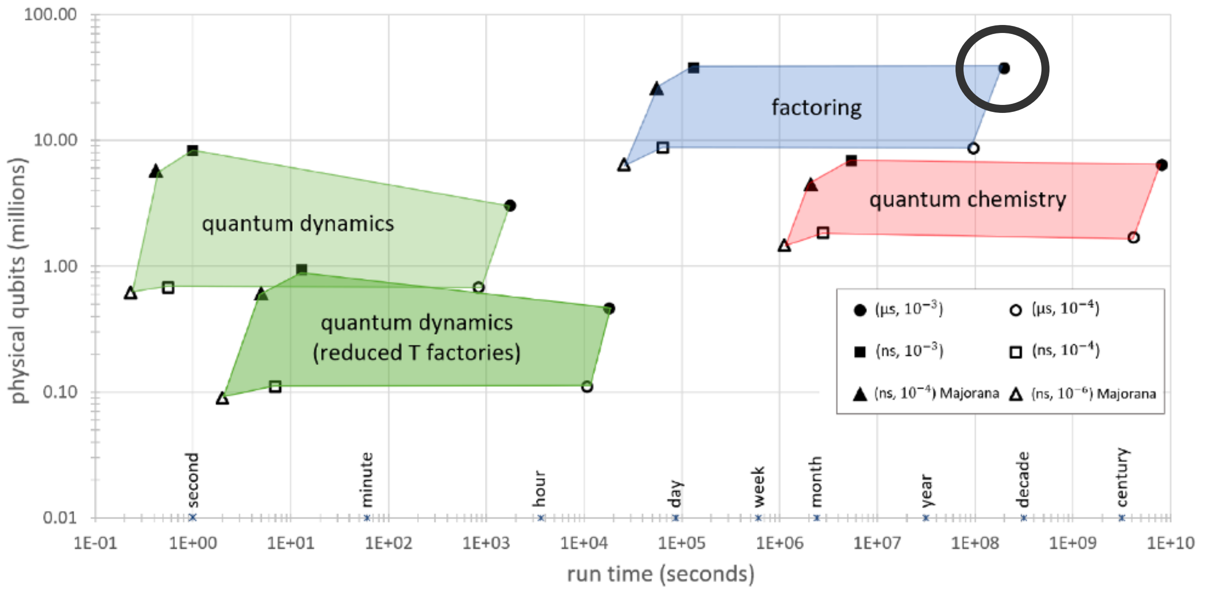
Aharanov, Ben'Or, STOC 1997; Knill, Laflamme, PRA 1997; Shor, PRA 1995; Kitaev, 1997; Gottesman, arXiv:0904.2557

# Space-Time Cost of Large-Scale Quantum Computation




Beverland et al., arXiv:2211.07629

With 100 us gate, 100 us measurement, large algorithms will take **almost a year**

Why?

Logical clock speed

≪

Physical clock speed

Logical clock speed is usually slower by a factor of *d*, where *d* is the code distance and typically around 30

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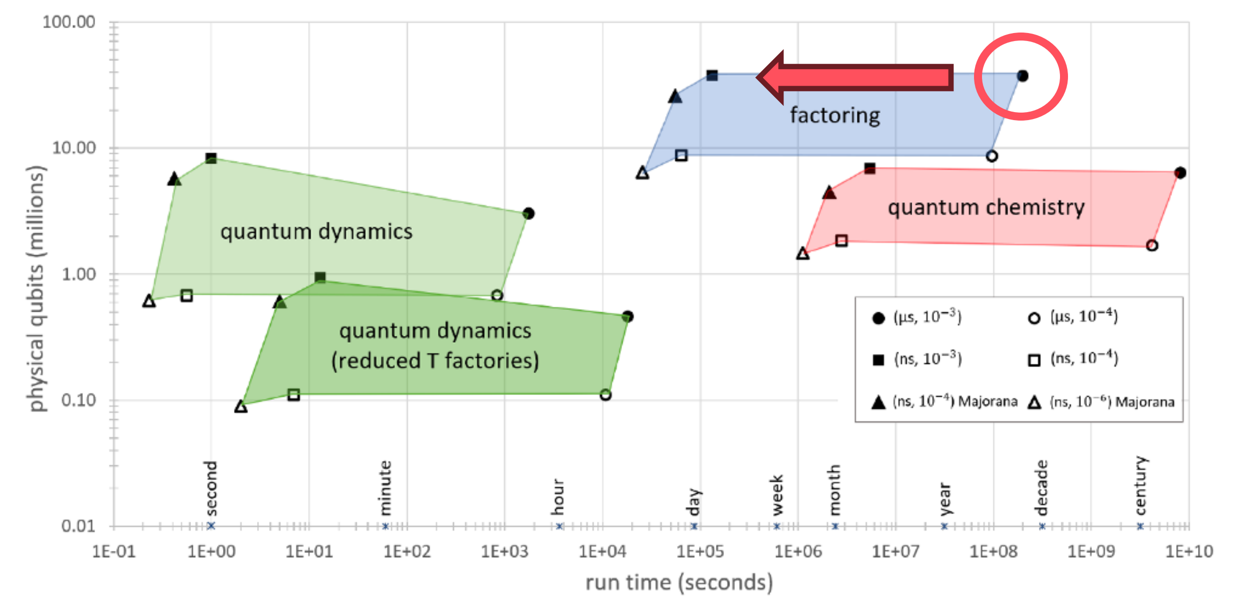
# Space-Time Cost of Large-Scale Quantum Computation




Beverland et al., arXiv:2211.07629

With 100 us gate, 100 us measurement, large algorithms will take ~~almost a year~~ **a few days**

Enabled by considering fault tolerance of the *entire* computation, and focusing on the *classical output* of it

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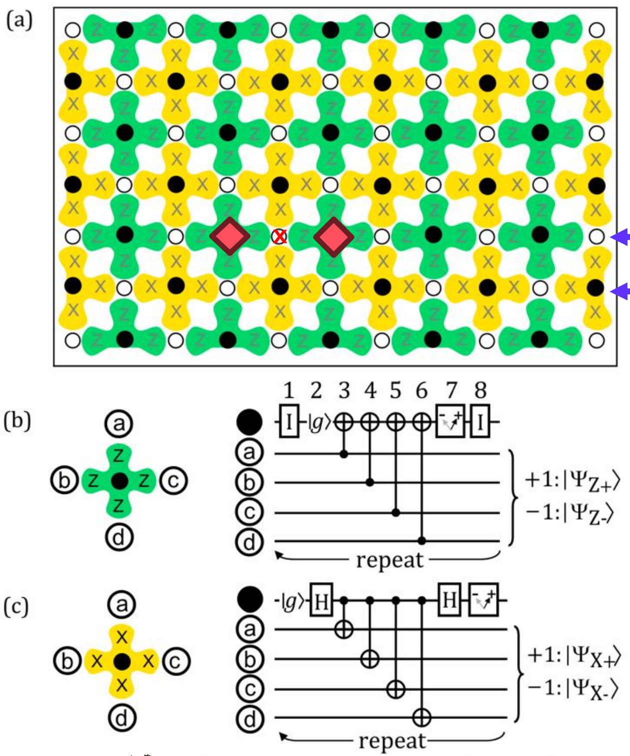
# The surface code in a nutshell




**[[*n*,*k*,*d*]] quantum code**

- Number of physical qubit – $n = O(d^2)$
- Number of logical qubit – $k = 1$
- Code distance – $d$

Data qubits (store logical information)

Ancilla qubit (measure syndrome and infer errors)

**Stabilizers – commutative Pauli operators**

**Logical qubit – common eigenstate of +1 for all stabilizers**

- ***Data errors*** can be detected by syndromes
- ***Syndrome errors*** can be detected by repeated measurements
- ***Logical errors*** are undetectable error configurations
- Logical error rates can be suppressed exponentially by increasing d

$$P_L \propto \left(\frac{p}{p_{\text{th}}}\right)^{O(d)}$$

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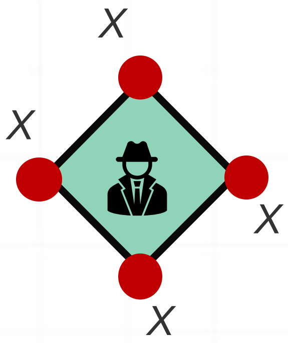
# Conventional fault tolerance

- Apply logical operation
- Repeatedly measure syndrome information to detect errors
- Decode and apply correction to get correct logical information




Stabilizer was +1!

Actually, it was -1!

Hmm, maybe +1…

Repeat to be sure (*d* rounds)…

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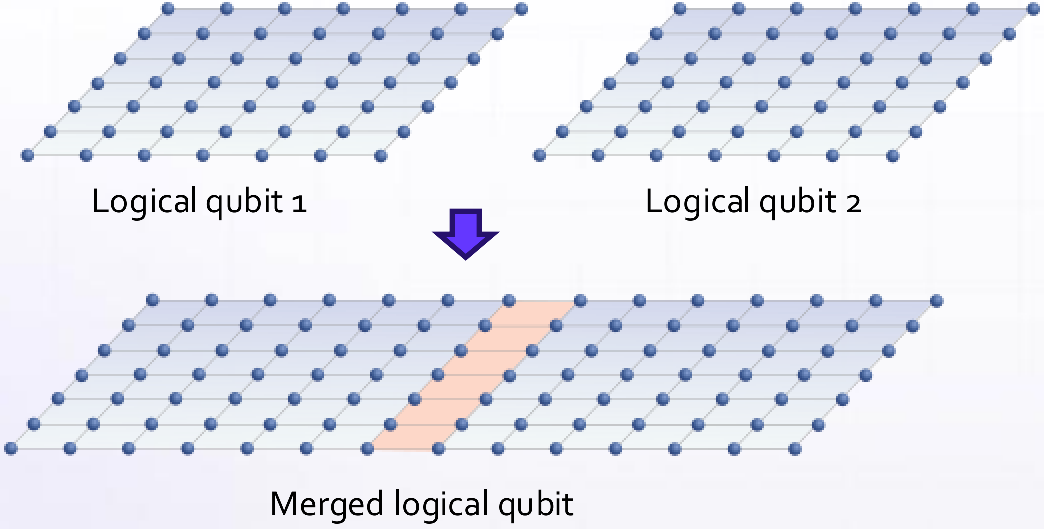
# Time Cost of QEC in Lattice Surgery

Example: 2D lattice surgery with surface code (standard paradigm)




- Introduce new stabilizers that result non-deterministic error mechanisms
- *d* rounds of SE is necessary to make error inference reliable (fault-tolerant)

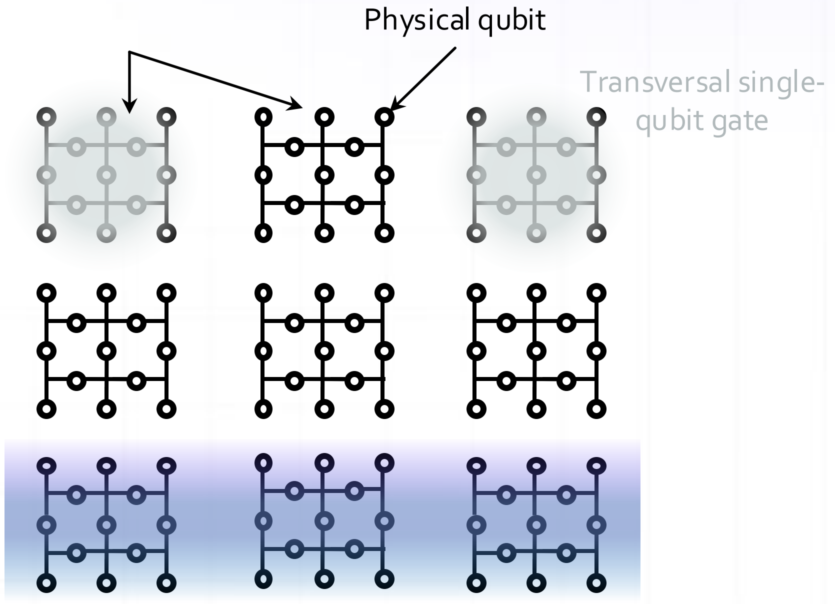
See e.g. Horsman et al., NJP 2012, Fowler, Gidney, arXiv 2018

# Fault-tolerant quantum computing

## Different implementations of logical operations have different costs

### Transversal gates

- Logical CNOT is implemented by applying pair-wise physical CNOTs
- Transversal CNOT is natually fault-tolerant – errors cannot spread within a patch
- Require **higher-dimensional connectivity**
- **Natural for atom arrays – efficient and highly parallel**

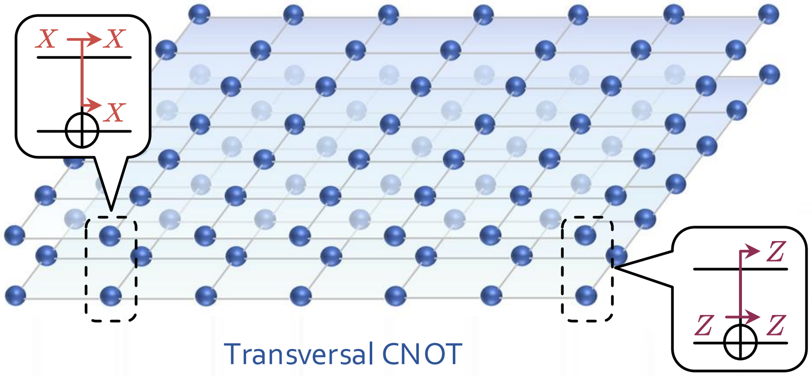


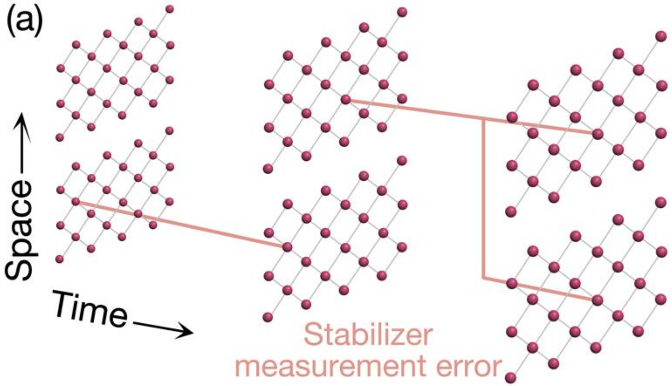

Transversal entangling gate

Shor 1996, Dennis *et al.* 2001

# Error mechanisms in transversal logical gates

**Transversal gates do not introduce new stabilizers – error mechanisms are deterministic**




**Error correlation in space**

Physical errors on a logical qubit contain information about which errors occurred on other logical qubits

**Error correlation in time**

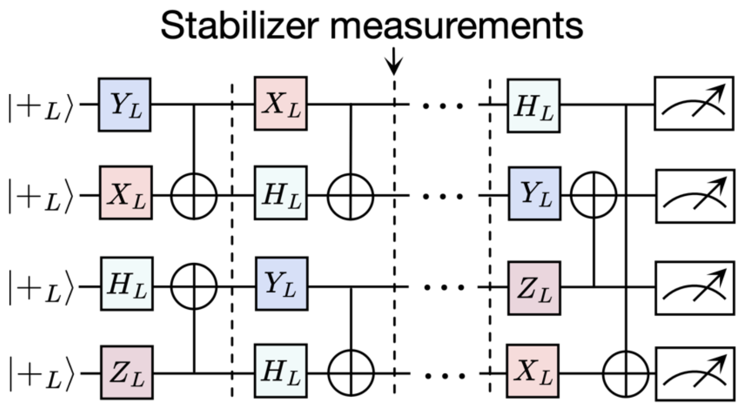
Syndrome measurement in future transversal logical operations can be used to validate previous syndrome measurement

**Decoder should utilize the correlation between errors**

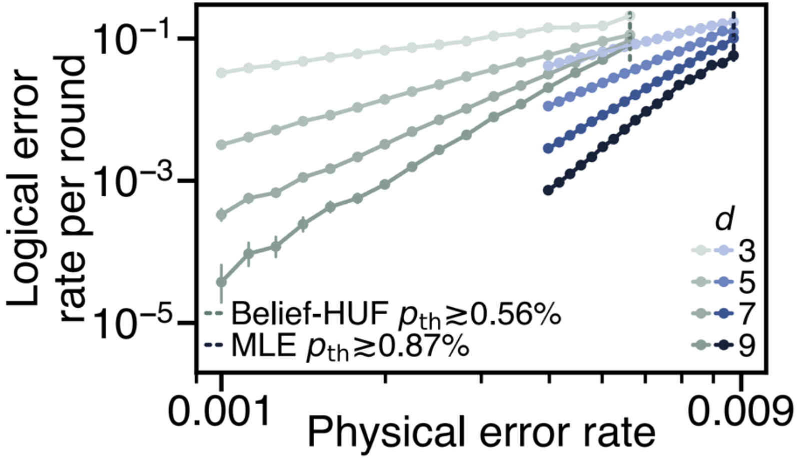
# Spacetime advantage of transversal logical gates

**Transversal gates + correlated decoding**

**Fault tolerance of Clifford circuits with *O(1)* time overhead**




Transversal gates + *O(1)* rounds of SE




How to generalize the results to universal quantum computing?

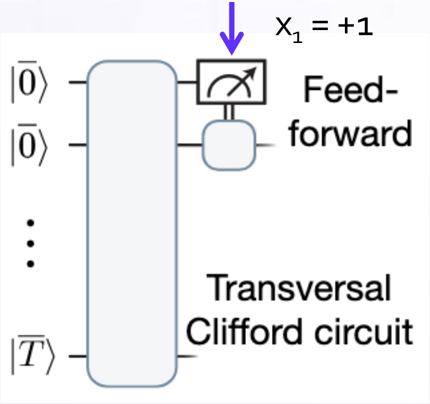
- Fault-tolerant logical measurement with other remaining qubits
- Non-Clifford operation

M. Cain, C. Zhao et al., arXiv:2403.03272

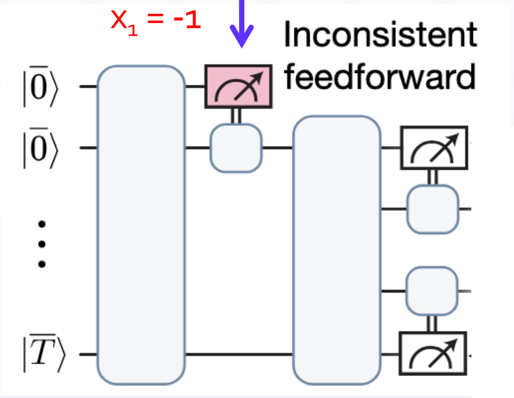
# Rethinking fault tolerance

- **Quantum computing:** observe classical outputs from quantum circuits
  ***Ideal distribution*** $P(x_1, \dots, x_n)$
- **FTQC:** reliably reproduce joint logical measurement distribution of an ideal circuit, using noisy components

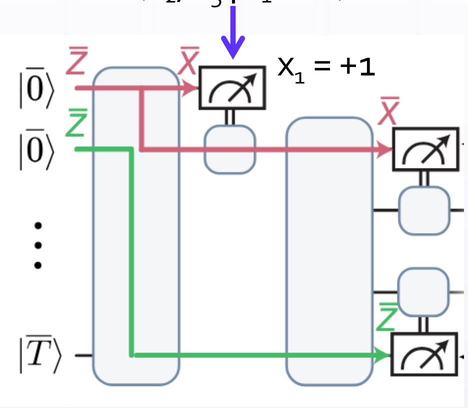
Correlated decoding reproduces *P(x₁)*




Correlated decoding reproduces $P(x_1, x_2, x_3)$ but with different $x_1$




Frame flipping fixes inconsistency $P(x_2, x_3 | x_1 = +1)$

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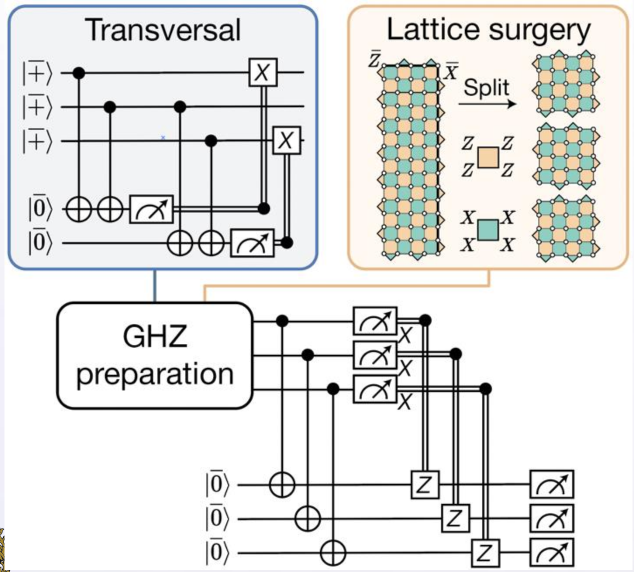
**Transversal gates + correlated decoding + frame flipping**

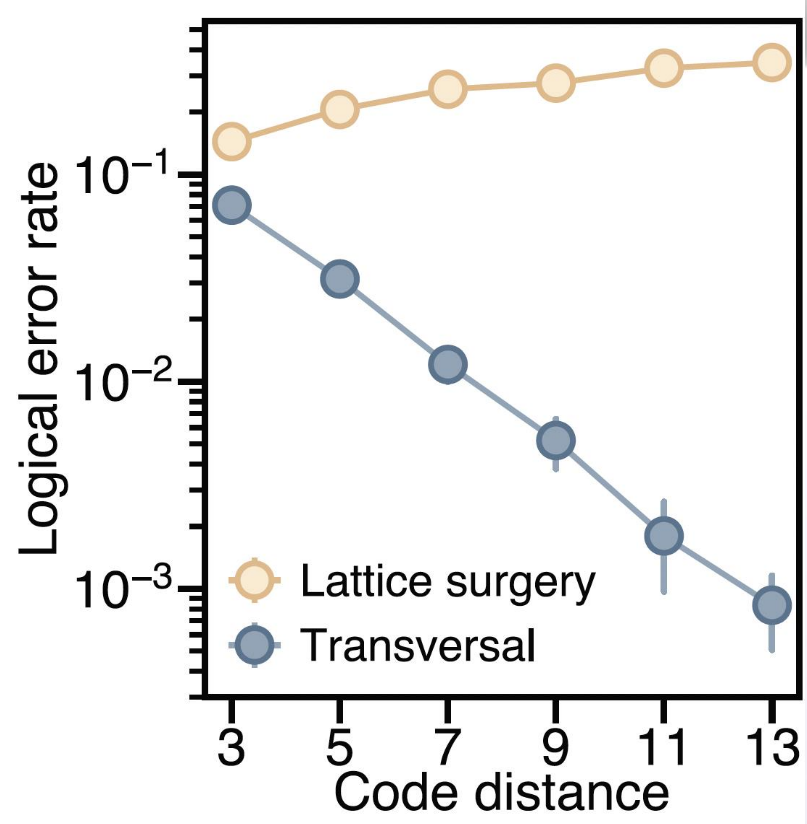
⬇

**Algorithmic fault-tolerance for arbitrary quantum circuits with O(1) time overhead**

# Transversal Gates vs. Lattice Surgery

- Transversal gates with single round shows exponential error suppression ✓
- Lattice surgery with single round is not FT and error increases with code distance ✗




HZ*, C. Zhao* et al., arXiv:2406.17653

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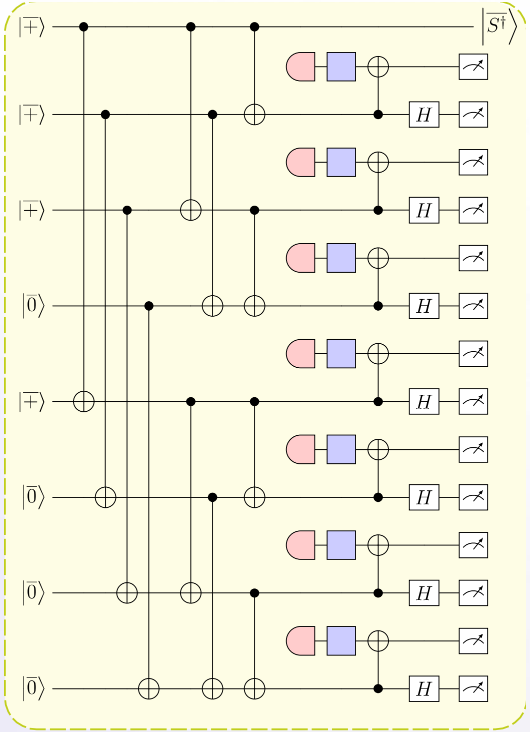
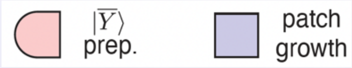
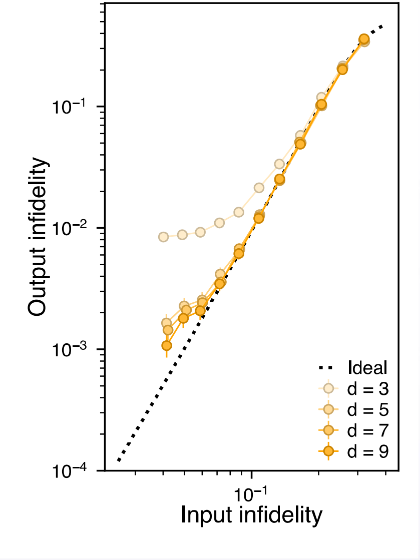
# State Distillation Factory

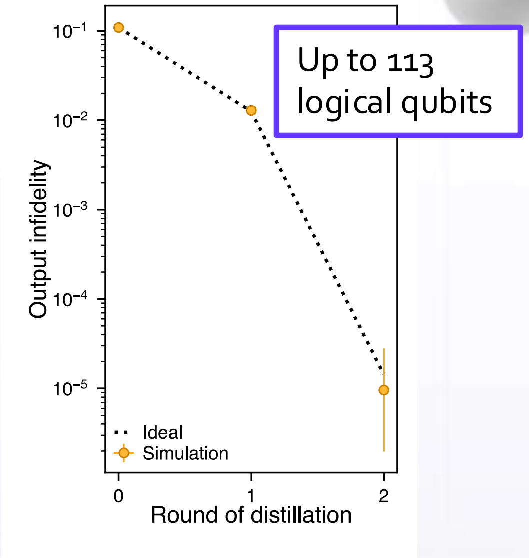



Output error vs. input error




Output error vs. # factory stages




Up to 113 logical qubits

- Distill good resource states from noisy ones, key subroutine in large-scale algorithms
- Here: Distill |Y>=S|+> (points along Y axis)

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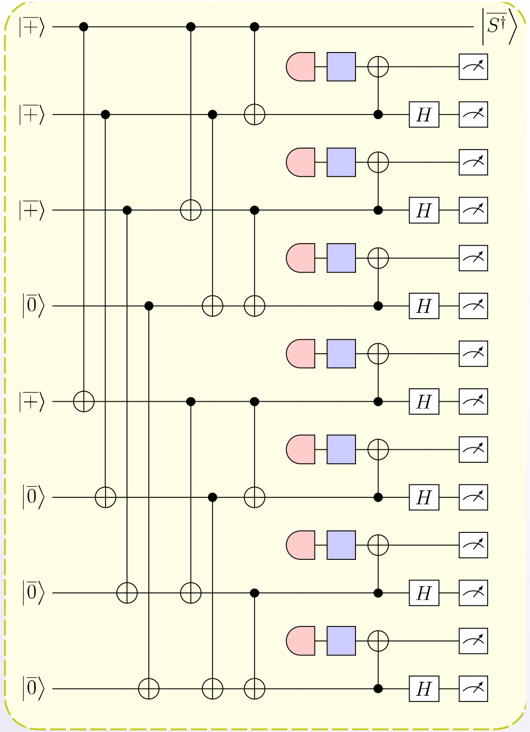
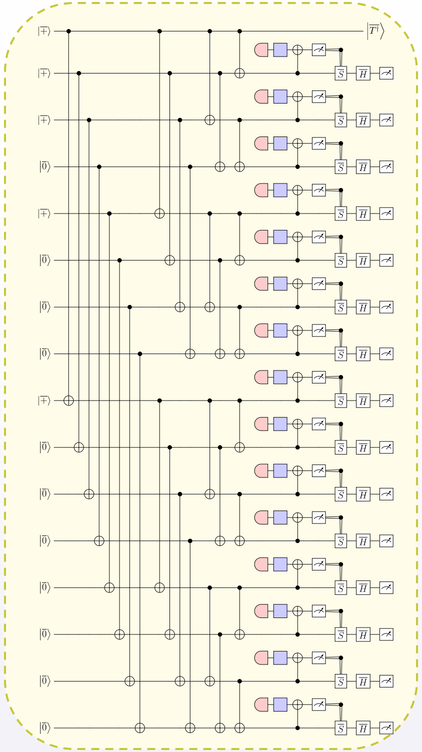
HZ*, C. Zhao* et al., arXiv:2406.17653

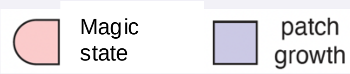
# Magic State Distillation Factories




S factory



T factory




- Very similar structure between |S>=S|+> and |T>=T|+> magic state distillation factory
- State injection is state-agnostic, and we expect that the conclusions still hold
- |T> distillation **allows universal quantum computation**

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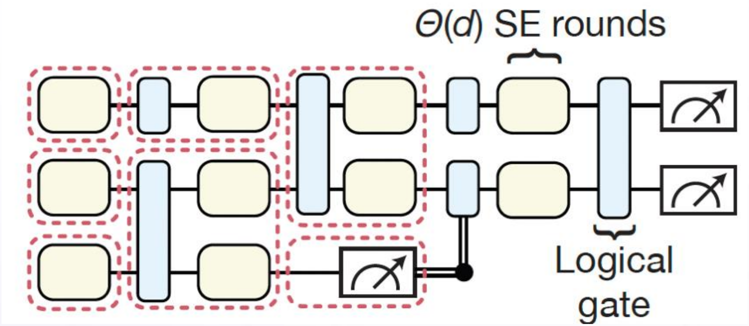
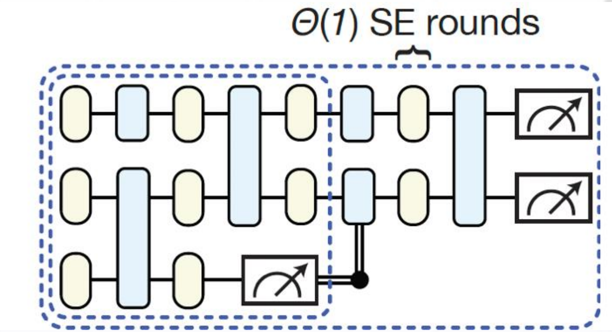
HZ*, C. Zhao* et al., arXiv:2406.17653

# Approaches to Fault Tolerance




Conventional FT

- FT individual operations
- Guarantee quantum state

-> O(d) syndrome extraction (SE) rounds per operation

Transversal Algorithmic FT

- FT only when considering full algorithm
- Guarantee classical output only

-> O(1) SE rounds per operation

- Utilize structure of initialization errors

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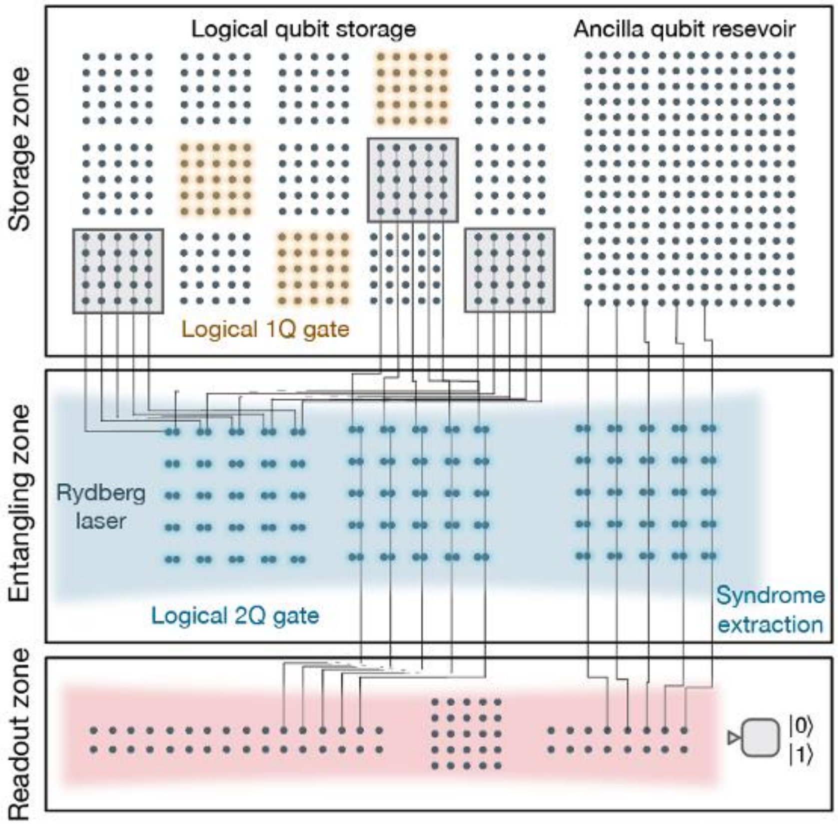
HZ*, C. Zhao* et al., arXiv:2406.17653

# Quantum Hardware for Transversal Algorithmic Fault Tolerance

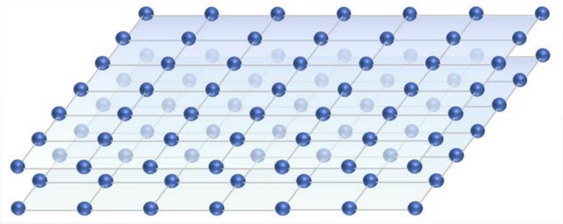
- **Wired systems** (SC qubits, photonics) incur an **extra cost** for reconfiguring and increasing number of connections per qubit
  - Appears to be distinct requirement from long-range connectivity

- **Atomic systems** natively support **arbitrary-degree reconfiguration**
  - Native transversal logic implementation
  - 10-100x logical clock speed advantage

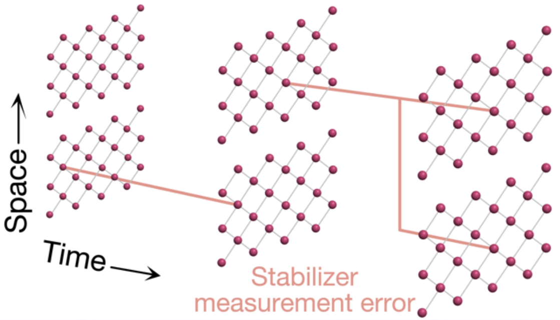



Bluvstein et al., Nature 2024 (Harvard-led)

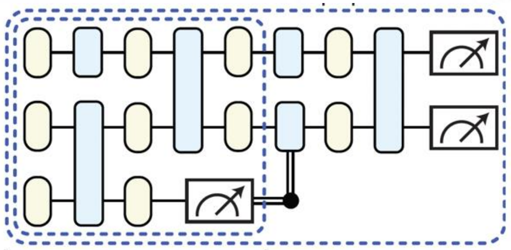
# Summary



Transversal Logical Gates




Correlated Decoding



Handling Feed-Forward & Non-Cliffords

**Transversal Algorithmic Fault Tolerance**
**Factor of *d* speedup**

Supported by proof and numerics

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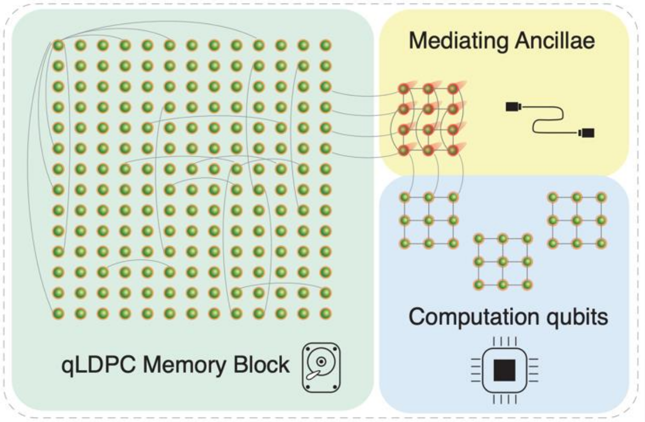
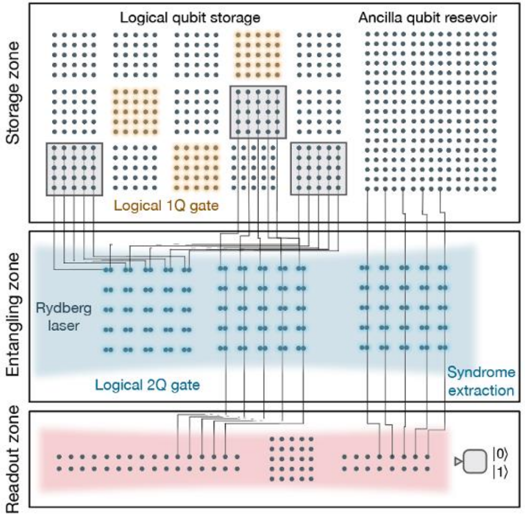
HZ*, C. Zhao* et al., arXiv:2406.17653; M. Cain, C. Zhao, HZ et al., arXiv:2403.03272; Bluvstein, Evered, Geim, Li, HZ et al., Nature 2024

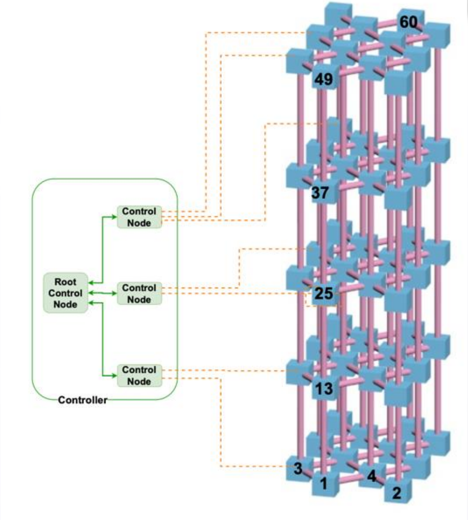
# Outlook




Combine with low-space-overhead schemes such as qLDPC codes




Hardware architecture design for neutral atom systems




Fast decoder development

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Images from: Q. Xu*, P. Bonilla*,..., HZ, Nature Physics 2024; Bluvstein et al., Nature 2024; Liyanage et al., QCE 2023

# Acknowledgement

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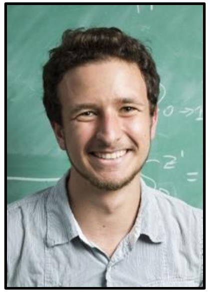
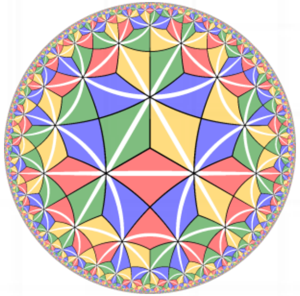


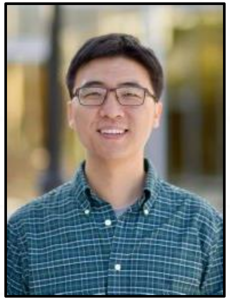
Dolev Bluvstein

Arthur Jaffe



Casey Duckering

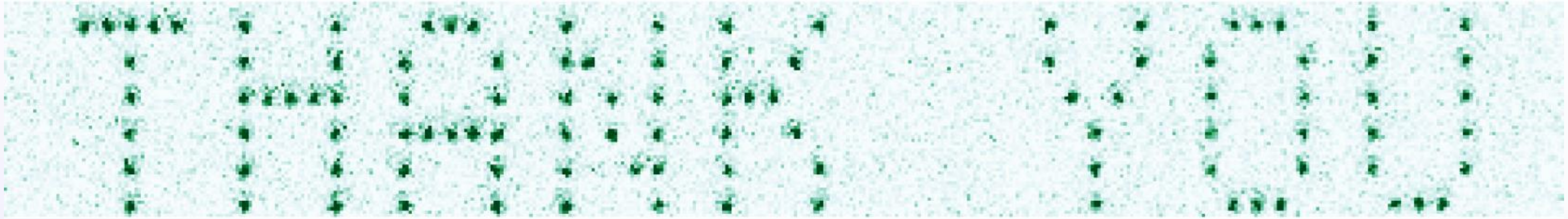
Hong-Ye Hu



Shengtao Wang

Alex Kubica

Mikhail Lukin


THANK YOU

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Quantum Algorithms, TQCI conference