Title: The Quantum von Neumann Architecture and the Future of Quantum Computing with Superconducting Circuits

Date: Apr 25, 2013 11:30 AM

URL: http://pirsa.org/13040135

Abstract: <span>Superconducting quantum circuits have made significant advances over the past decade, allowing more complex and integrated circuits that perform with good fidelity. We have recently implemented a machine comprising seven quantum channels, with three superconducting resonators, two phase qubits, and two zeroing registers. I will explain the design and operation of this machine, first showing how a single microwave photon |1> can be prepared in one resonator and coherently transferred between the three resonators [1]. I will then demonstrate how this machine can be used as the quantum-mechanical analog of the von Neumann computer architecture, which for a classical computer comprises a central processing unit and a memory holding both instructions and data. The quantum version comprises a quantum central processing unit (quCPU) that exchanges data with a quantum random-access memory (quRAM) integrated on one chip, with instructions stored on a classical computer [2]. Finally, I will demonstrate that the quantum von Neumann machine provides one unit cell of a two-dimensional qubit-resonator array that can be used for surface code quantum computing. This will allow the realization of a scalable, fault-tolerant quantum processor with the most forgiving error rates to date [3].<br>[1] M. Mariantoni et al., Nature Physics 7, 287-293 (2011)<br>[2] M. Mariantoni et al., Science 334, 61-65 (2011)<br>[3] A. G. Fowler, M. Mariantoni, J. M. Martinis, and A. N. Cleland, Phys. Rev. A 86, 032324 (2012)</span>

# on the edge

| | |
|---|---|
| nano/micro meter | ***space*** |
| milli kelvin | ***temperature*** |
| giga hertz | ***frequency***<br>***time*** |

# on the edge

milli kelvin

***temperature***

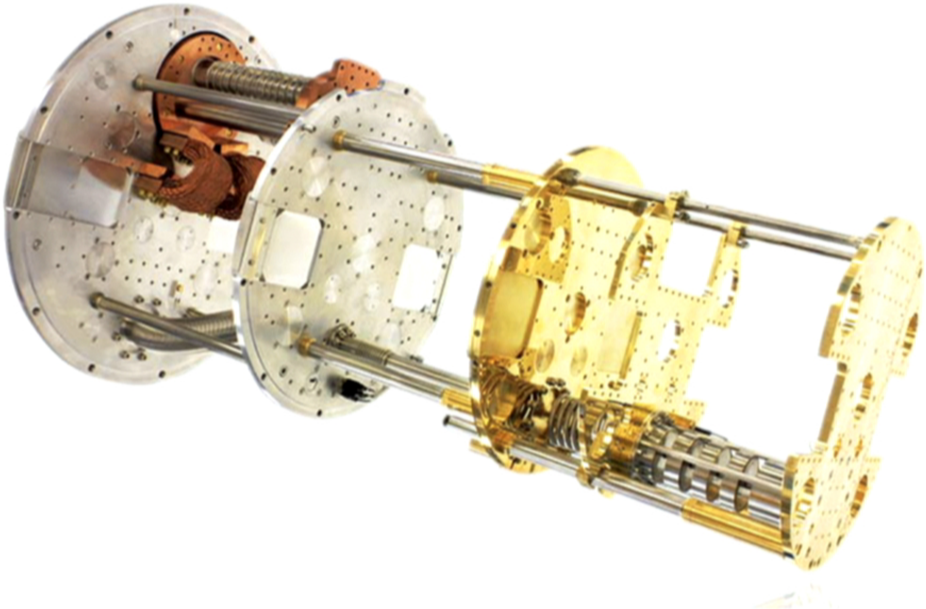
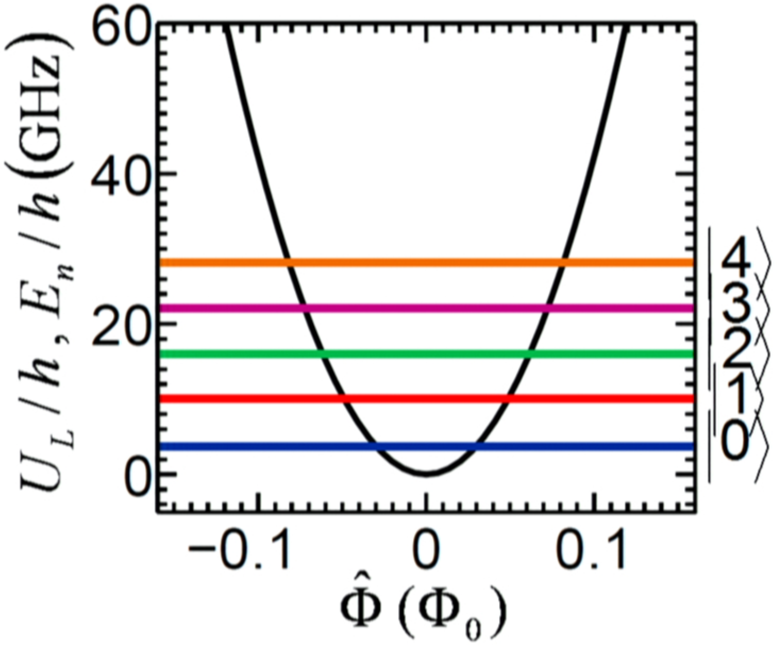


Photo credit – BlueFors Cryogenics Oy

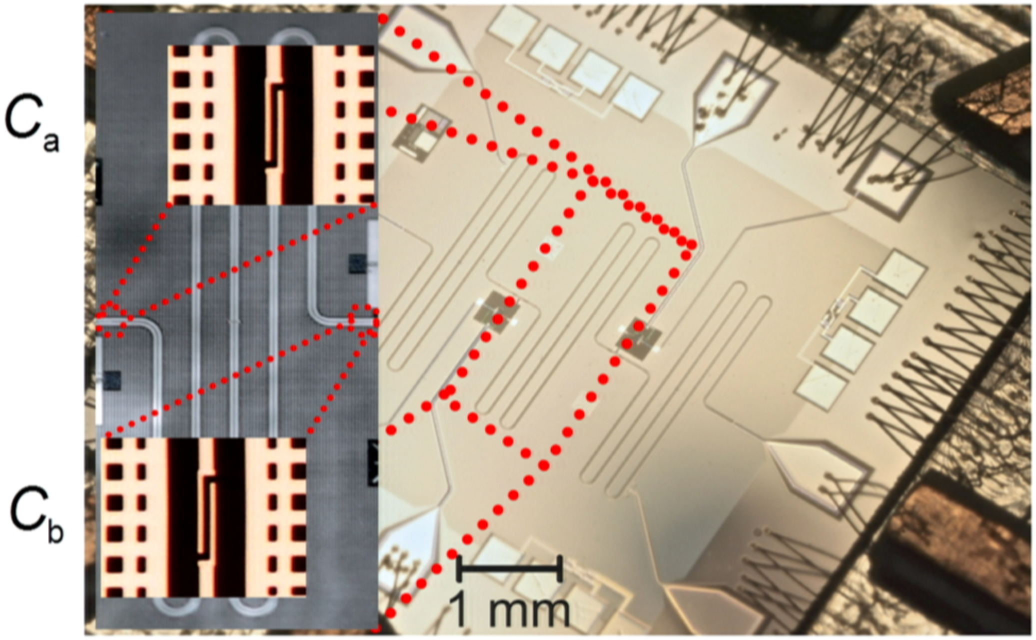
# superconducting quantum circuits

- *LC* resonator



# superconducting quantum circuits

- coplanar waveguide resonator



# superconducting quantum circuits

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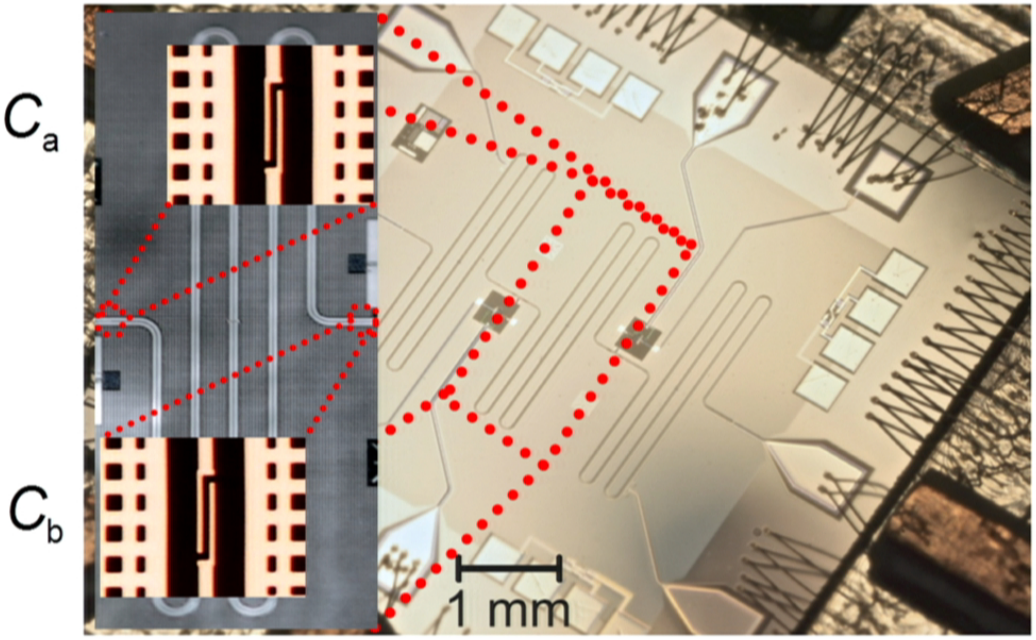
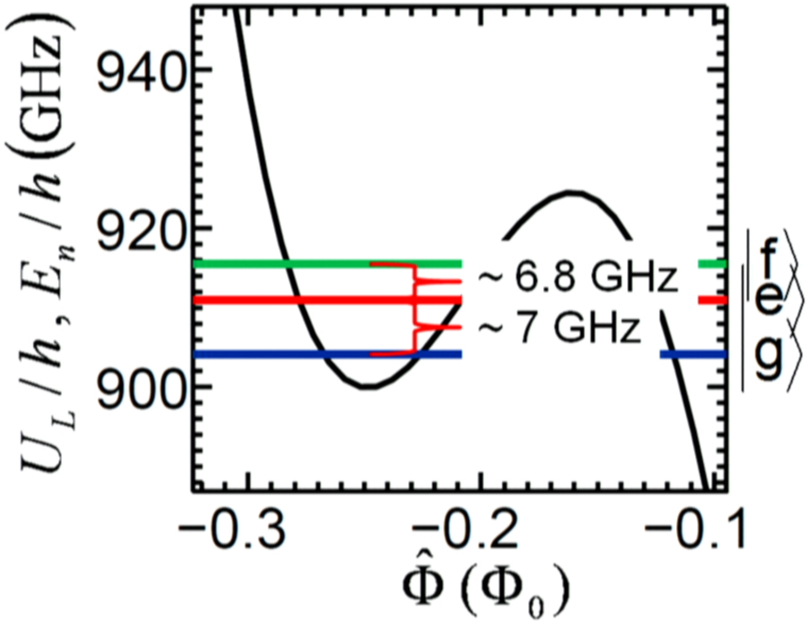


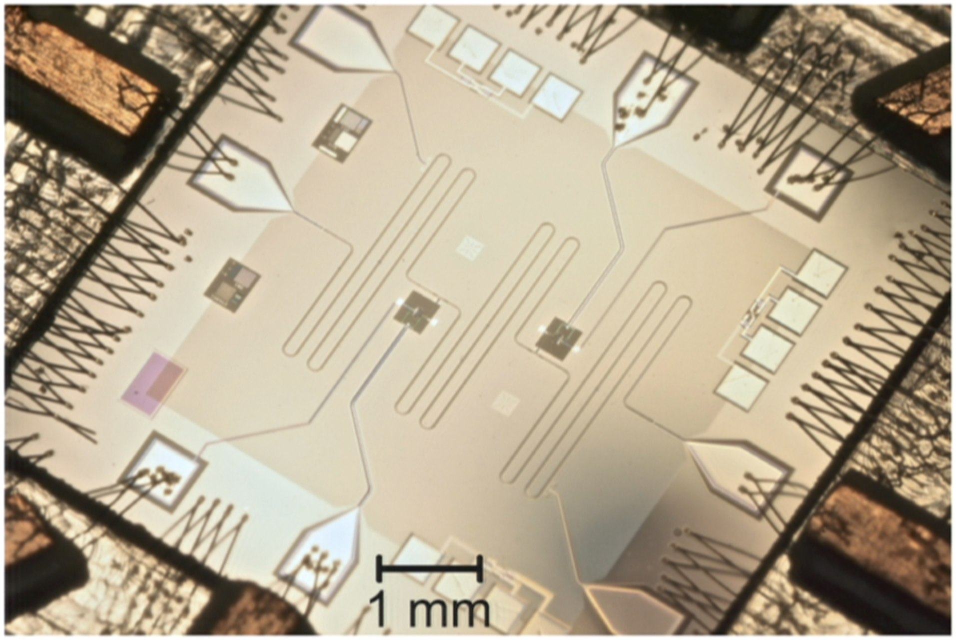
# superconducting quantum circuits

- qubit



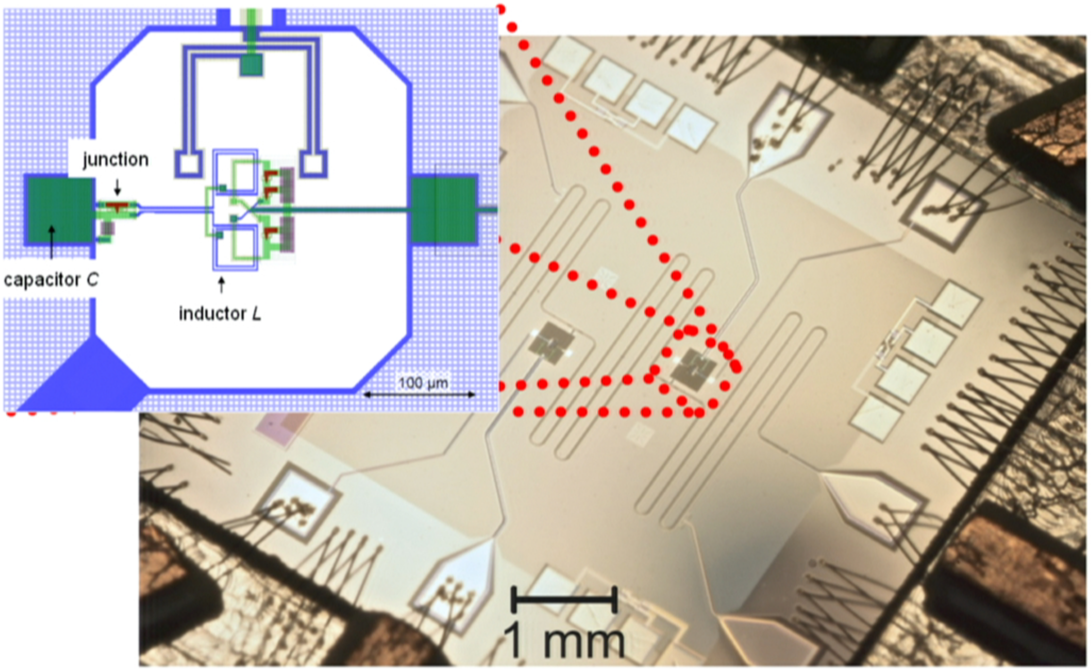
# superconducting quantum circuits

- qubit



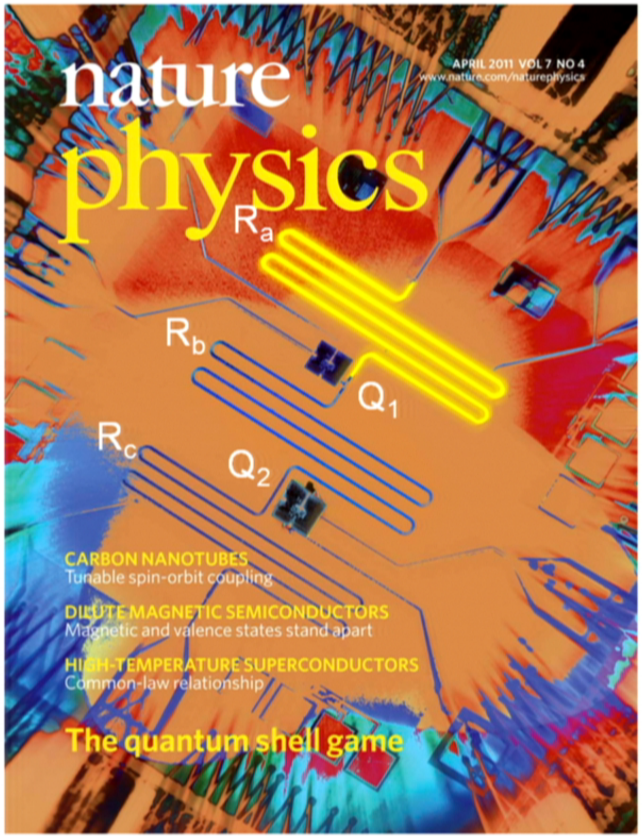
# superconducting quantum circuits

- qubit



M. Ansmann, Ph.D. Thesis 2009
http://web.physics.ucsb.edu/~martinisgroup/theses/Ansmann2009.pdf

# the quantum shell game



nature physics

APRIL 2011 VOL 7 NO 4
www.nature.com/naturephysics

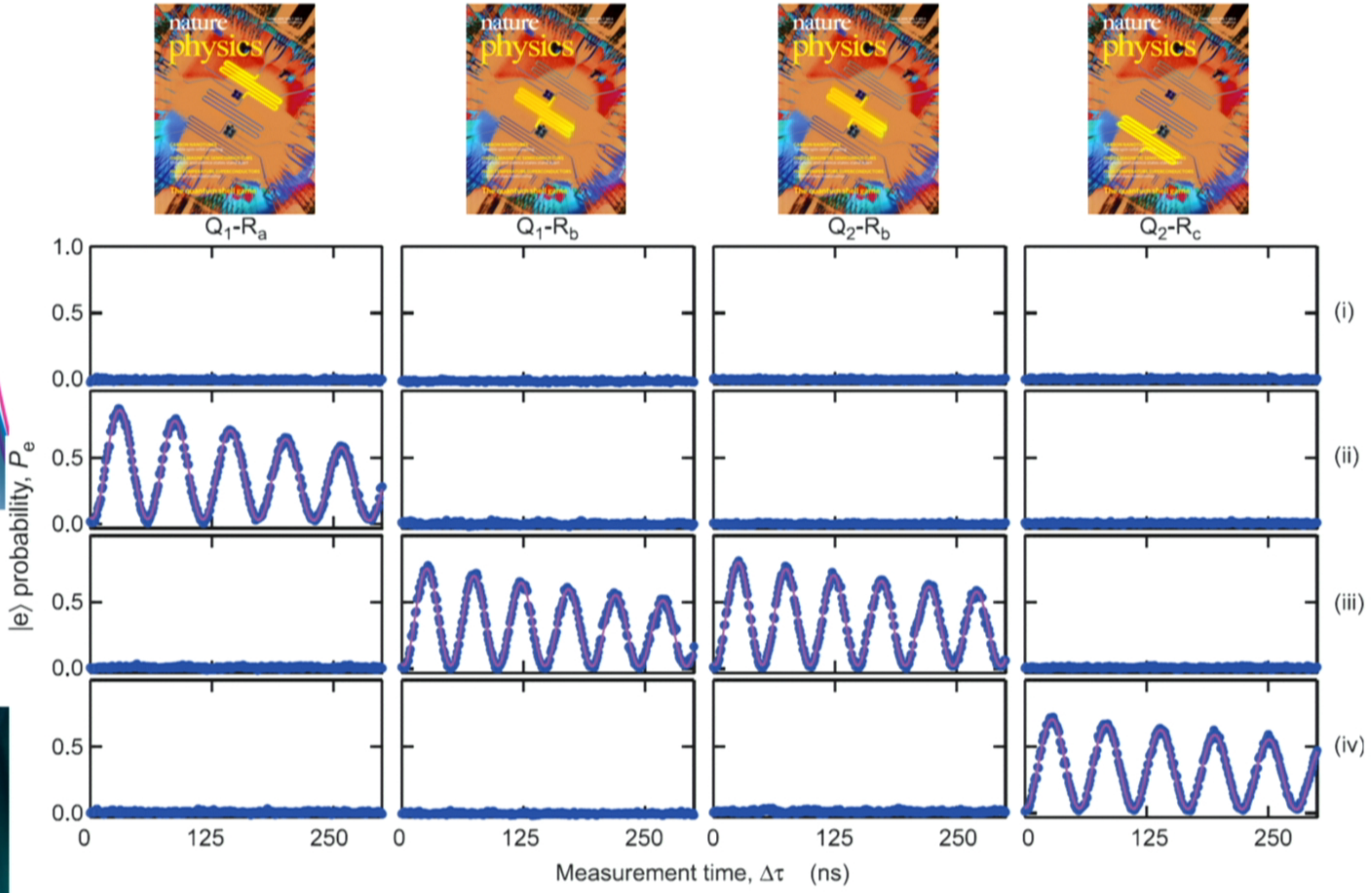
CARBON NANOTUBES
Tunable spin-orbit coupling

DILUTE MAGNETIC SEMICONDUCTORS
Magnetic and valence states stand apart

HIGH-TEMPERATURE SUPERCONDUCTORS
Common-law relationship

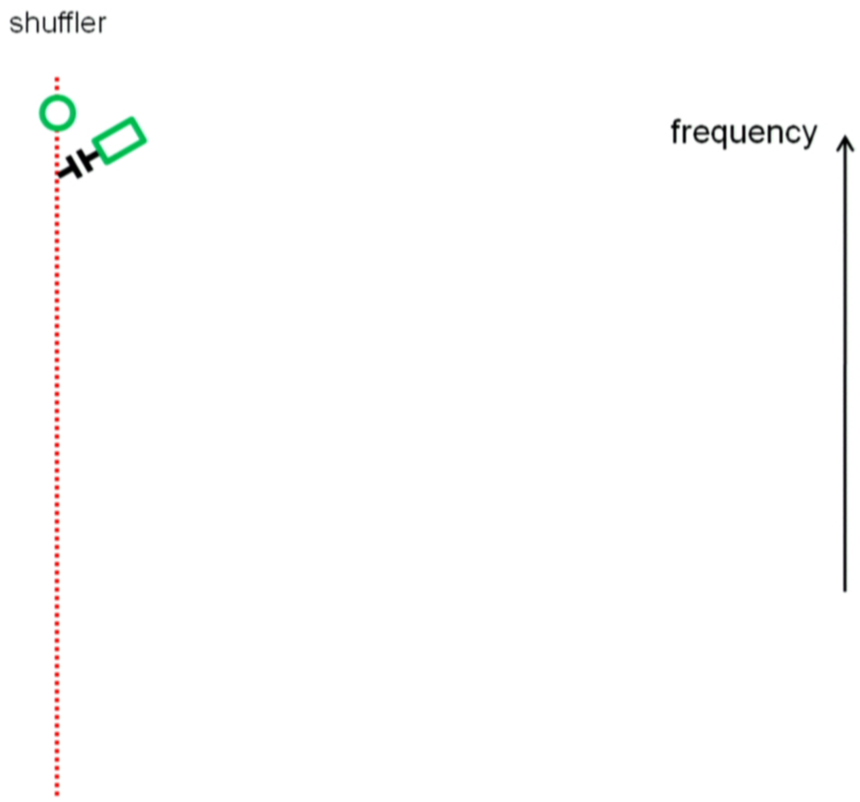
The quantum shell game

Photo credit –
D. Mariantoni,
E. Lucero, and
M. Mariantoni



M. Mariantoni *et al.*, Nature Phys. **7**, 287 (2011)
M. Mariantoni *et al.*, Science **334**, 61 (2011)

# scalability



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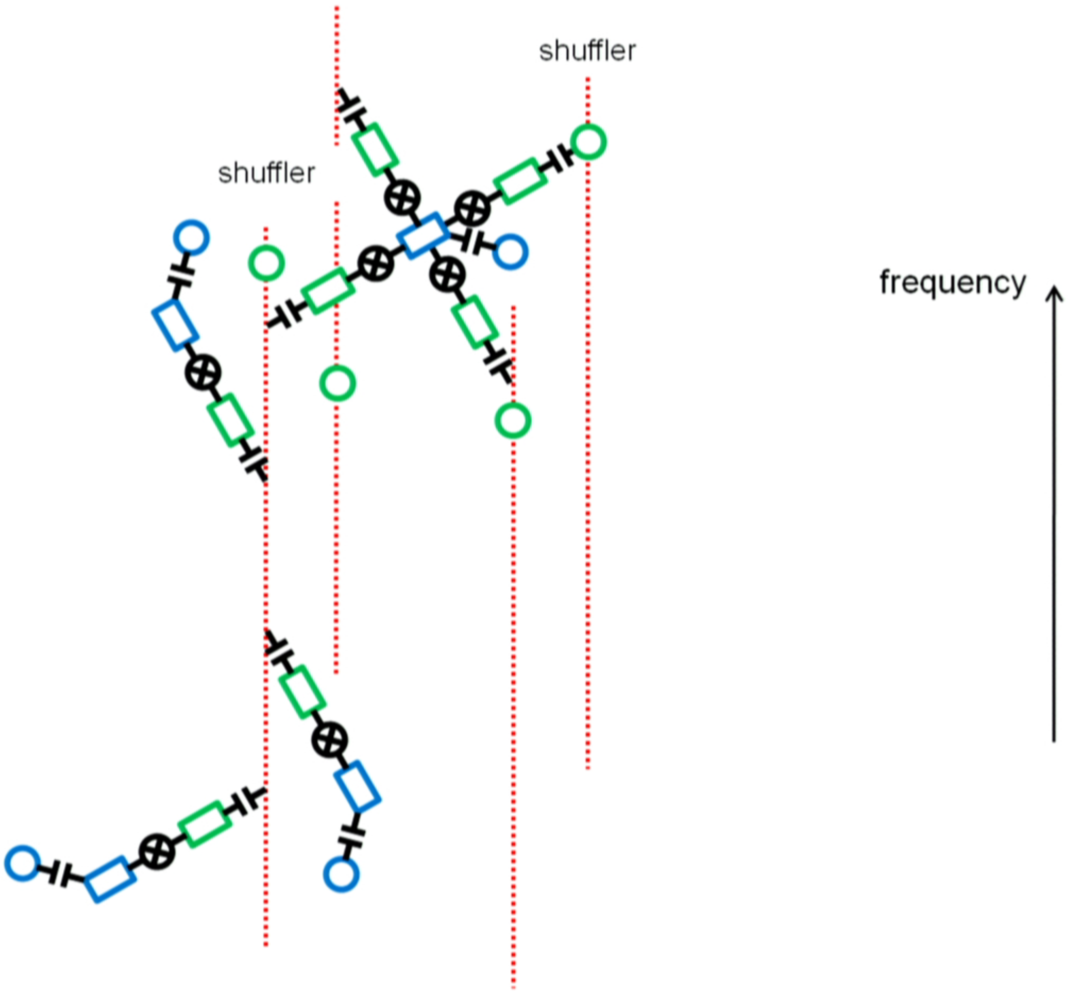

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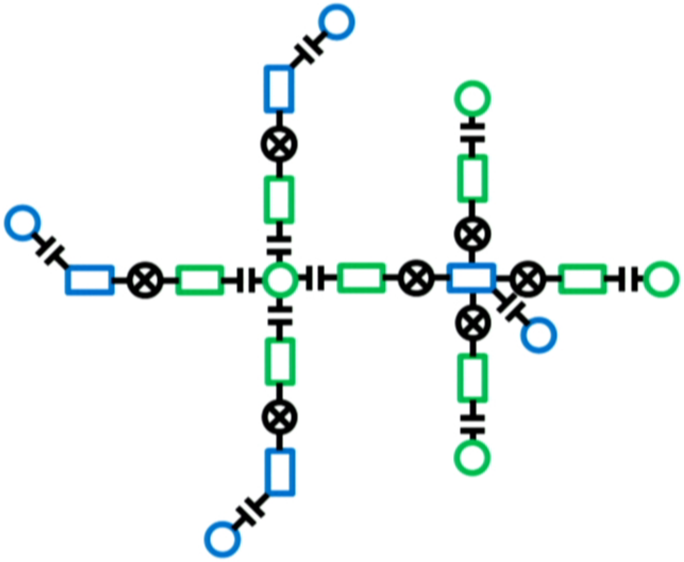
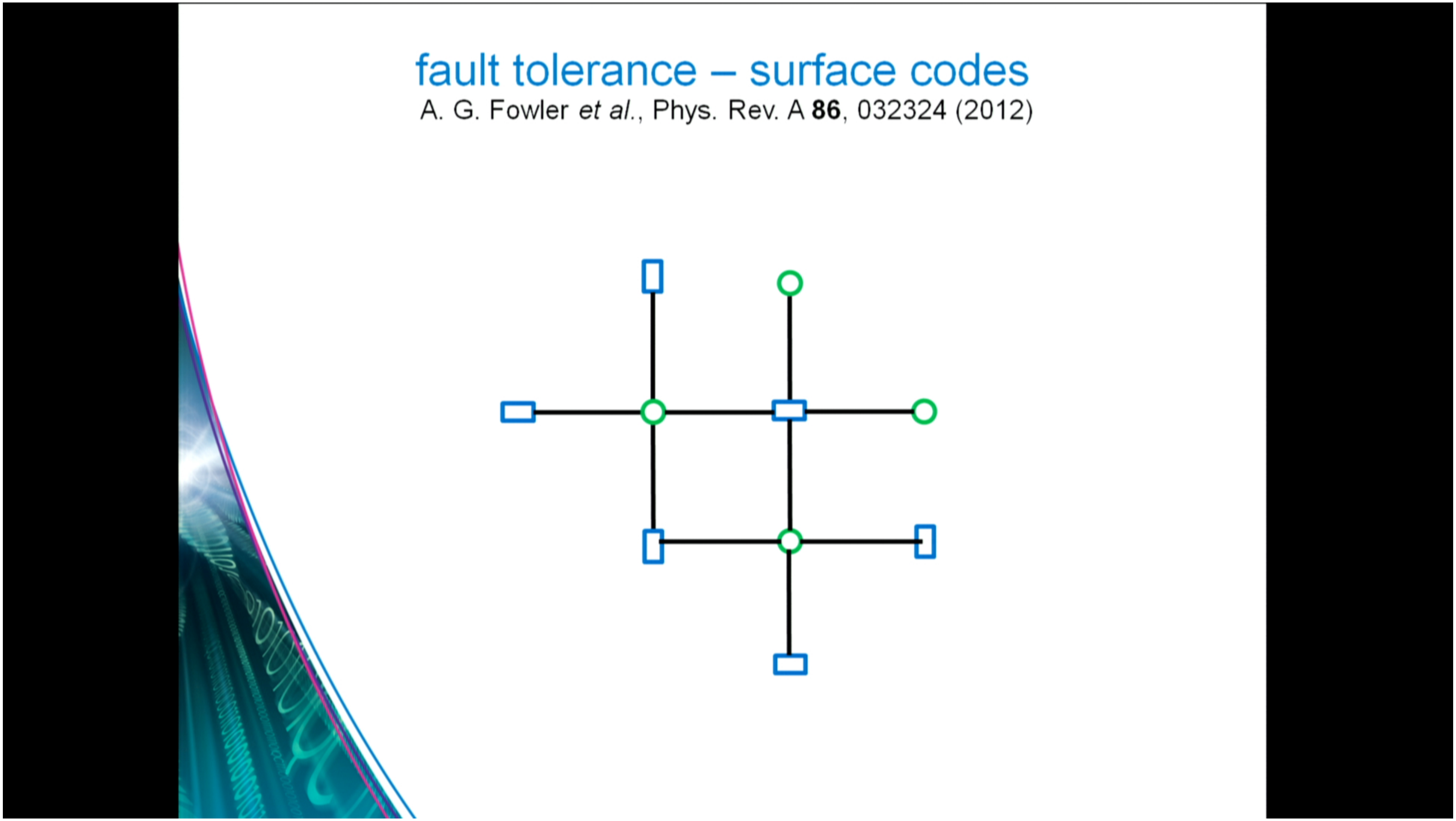
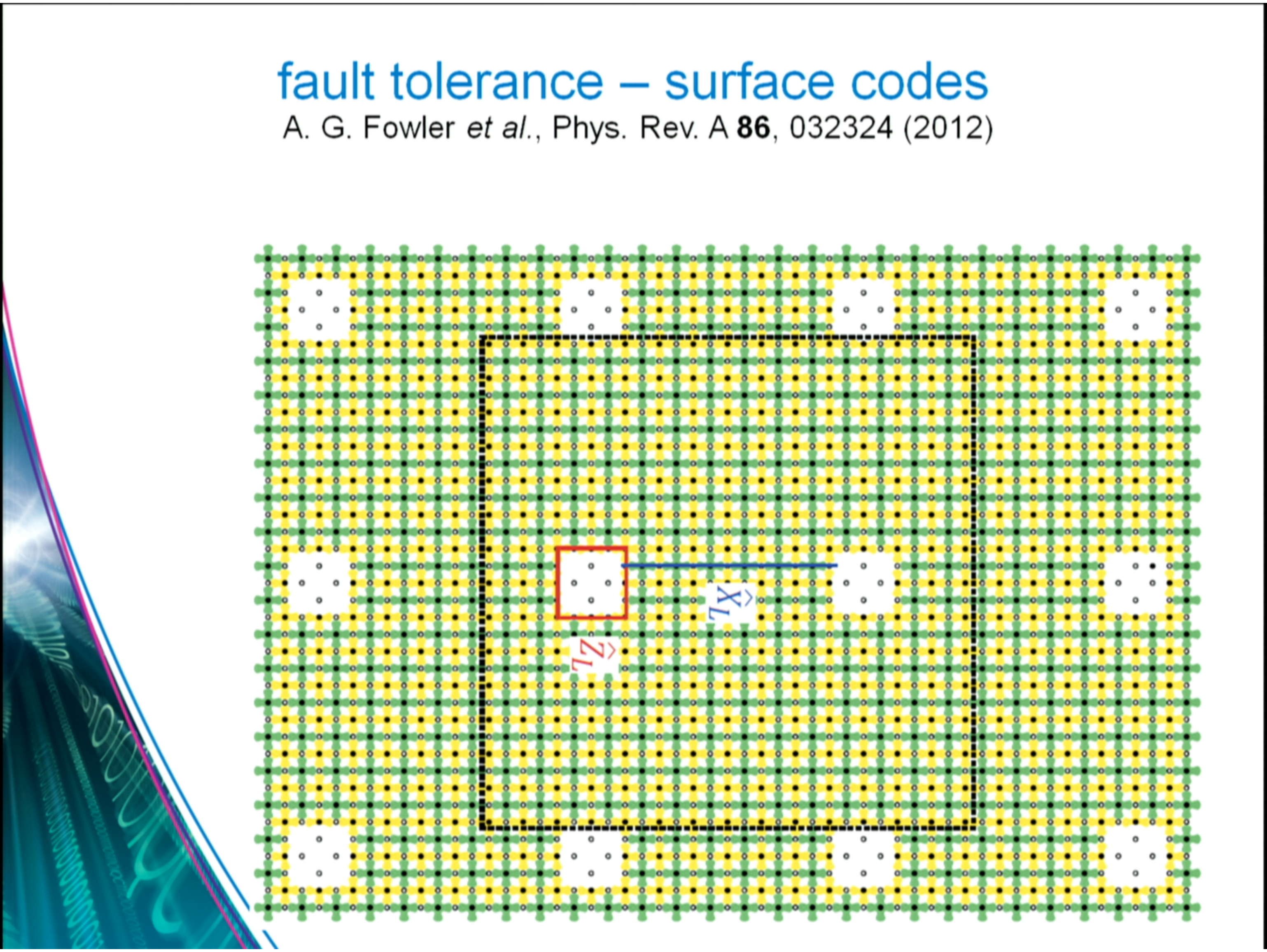




# fault tolerance – surface codes

A. G. Fowler *et al.*, Phys. Rev. A **86**, 032324 (2012)



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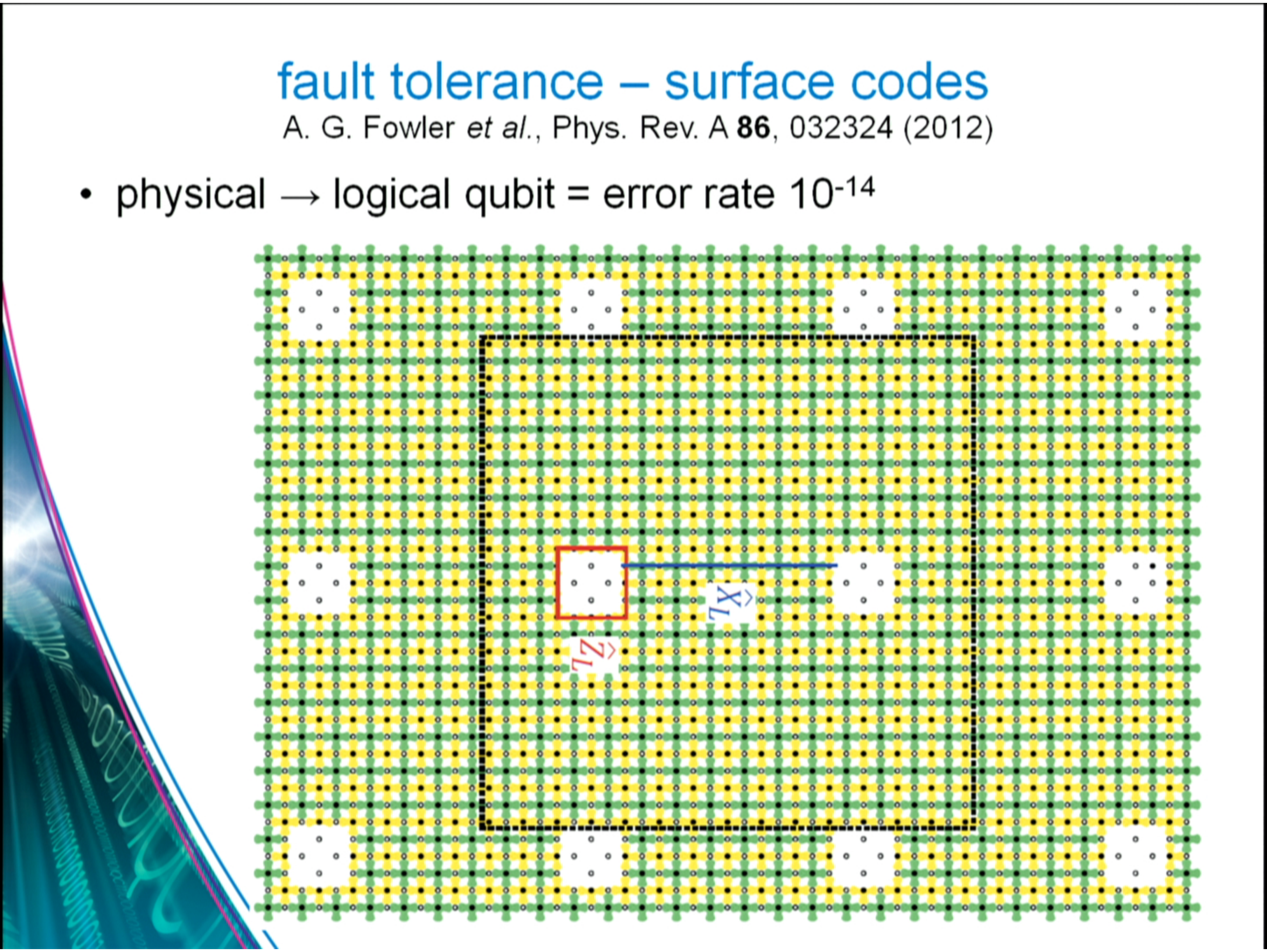

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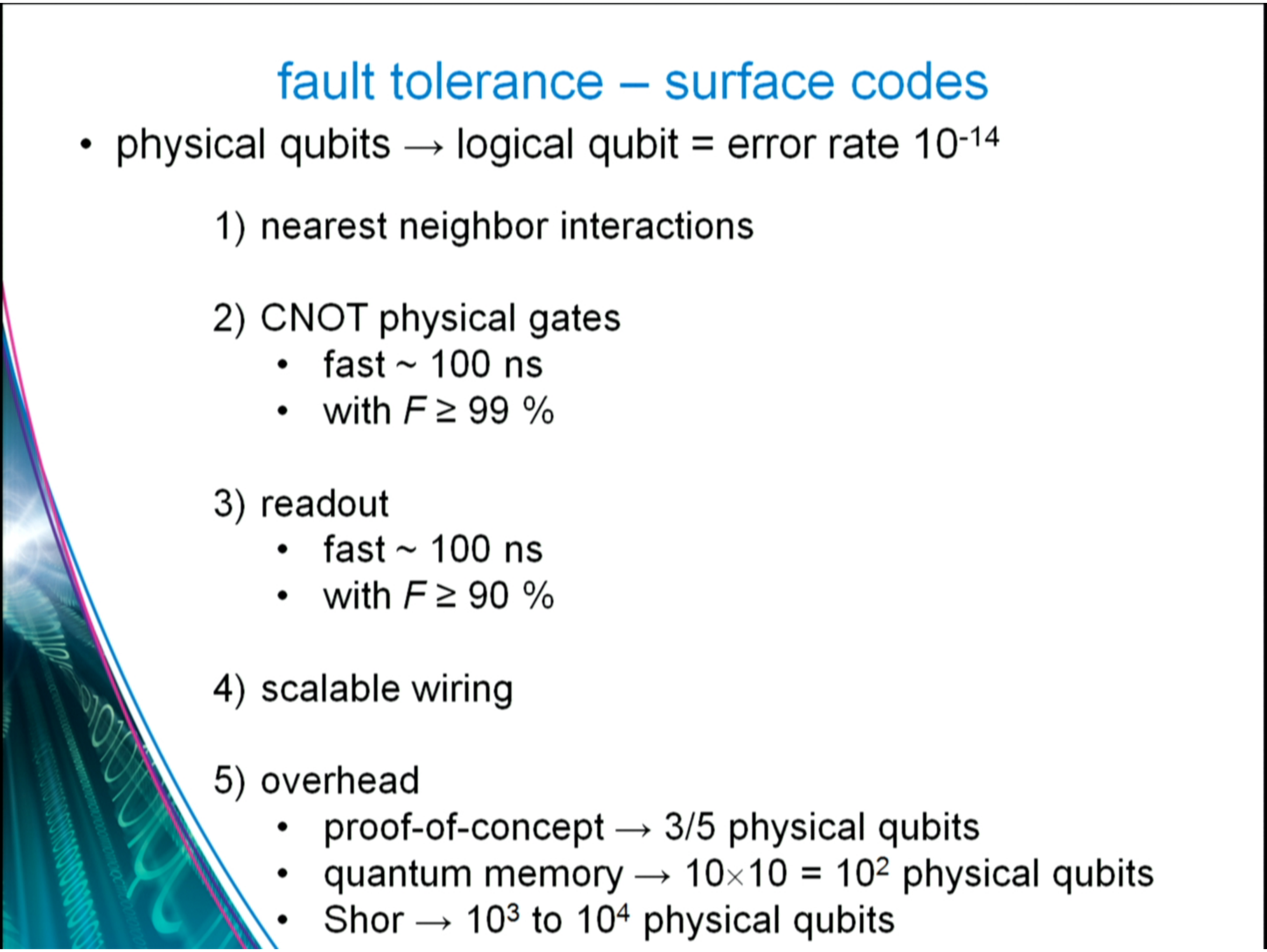
A. G. Fowler *et al.*, Phys. Rev. A **86**, 032324 (2012)

- physical → logical qubit = error rate $10^{-14}$



# fault tolerance – surface codes

- physical qubits → logical qubit = error rate $10^{-14}$

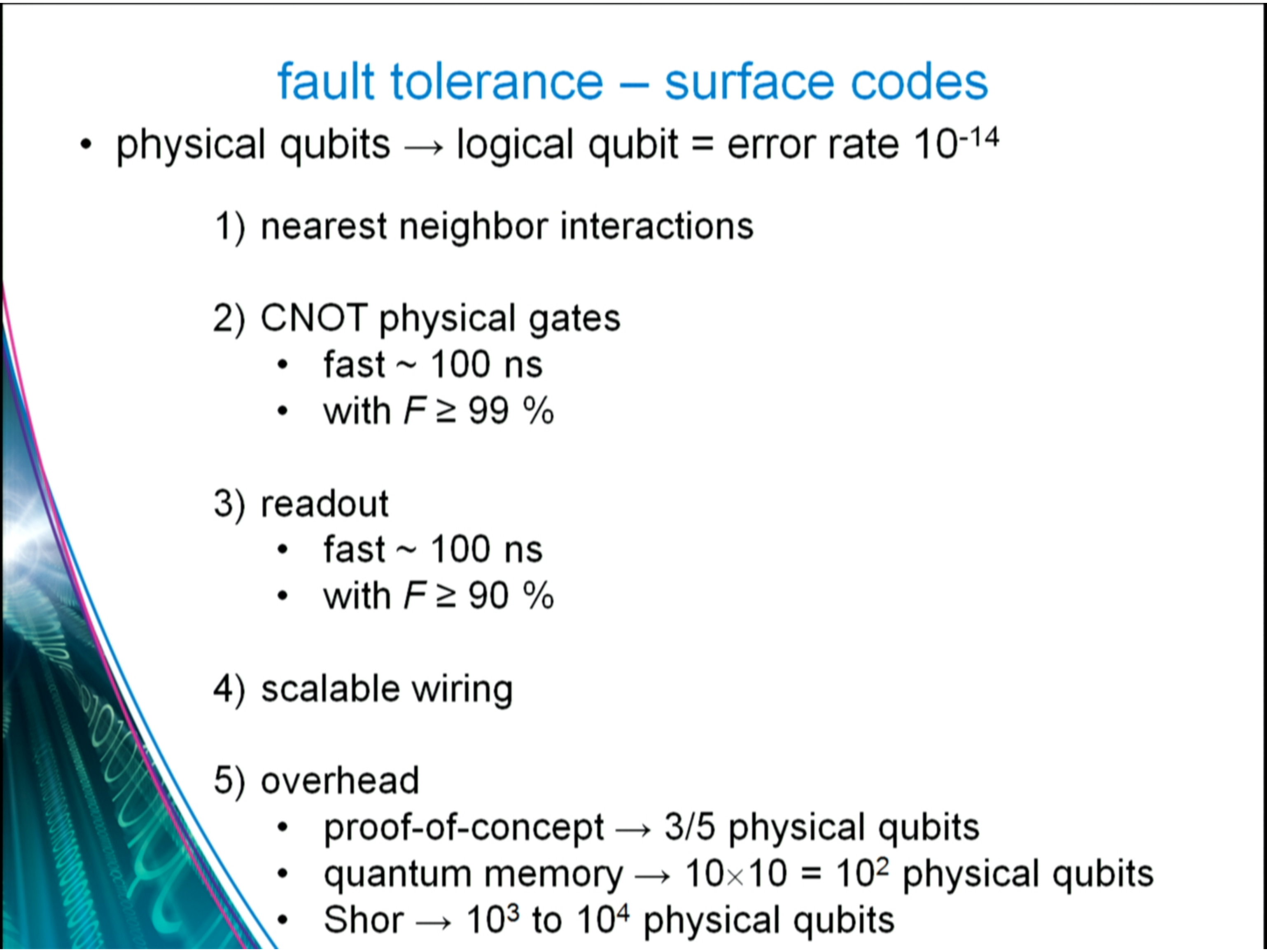
1) nearest neighbor interactions

2) CNOT physical gates
    - fast ~ 100 ns
    - with $F \geq 99$ %

3) readout
    - fast ~ 100 ns
    - with $F \geq 90$ %

4) scalable wiring

5) overhead
    - proof-of-concept → 3/5 physical qubits
    - quantum memory → $10\times10 = 10^2$ physical qubits
    - Shor → $10^3$ to $10^4$ physical qubits



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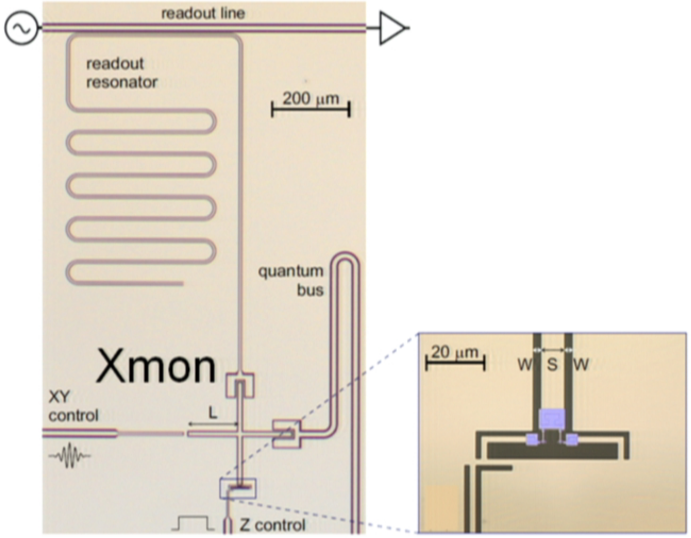
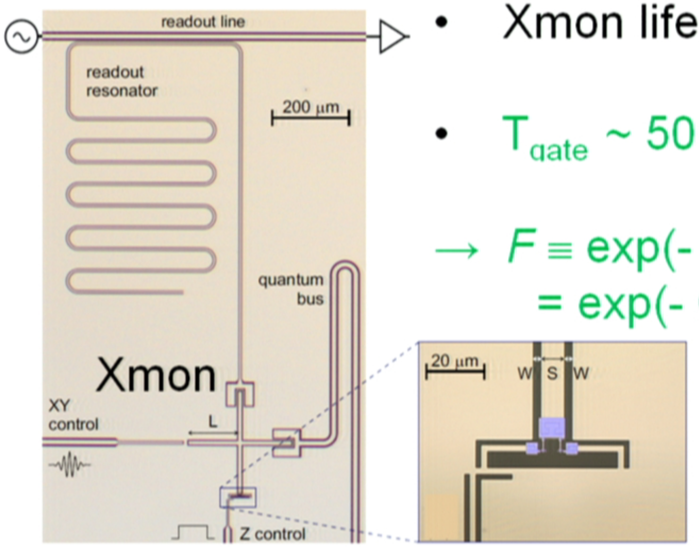


R. Barends *et al.*, e-print arXiv:1304.2322

# fault tolerance – surface codes

## 1) CNOT physical gates



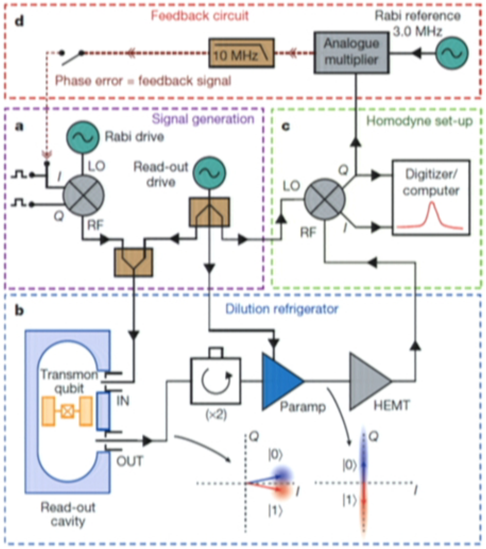
- Xmon lifetime $T_1 \sim 50\ \mu s$
- $T_{gate} \sim 50\ ns = 0.05\ \mu s$

$\rightarrow F \equiv \exp(-\,T_{gate} / T_1)$
$= \exp(-\,0.05\ \mu s / 50\ \mu s) \sim 99.9\ \%$

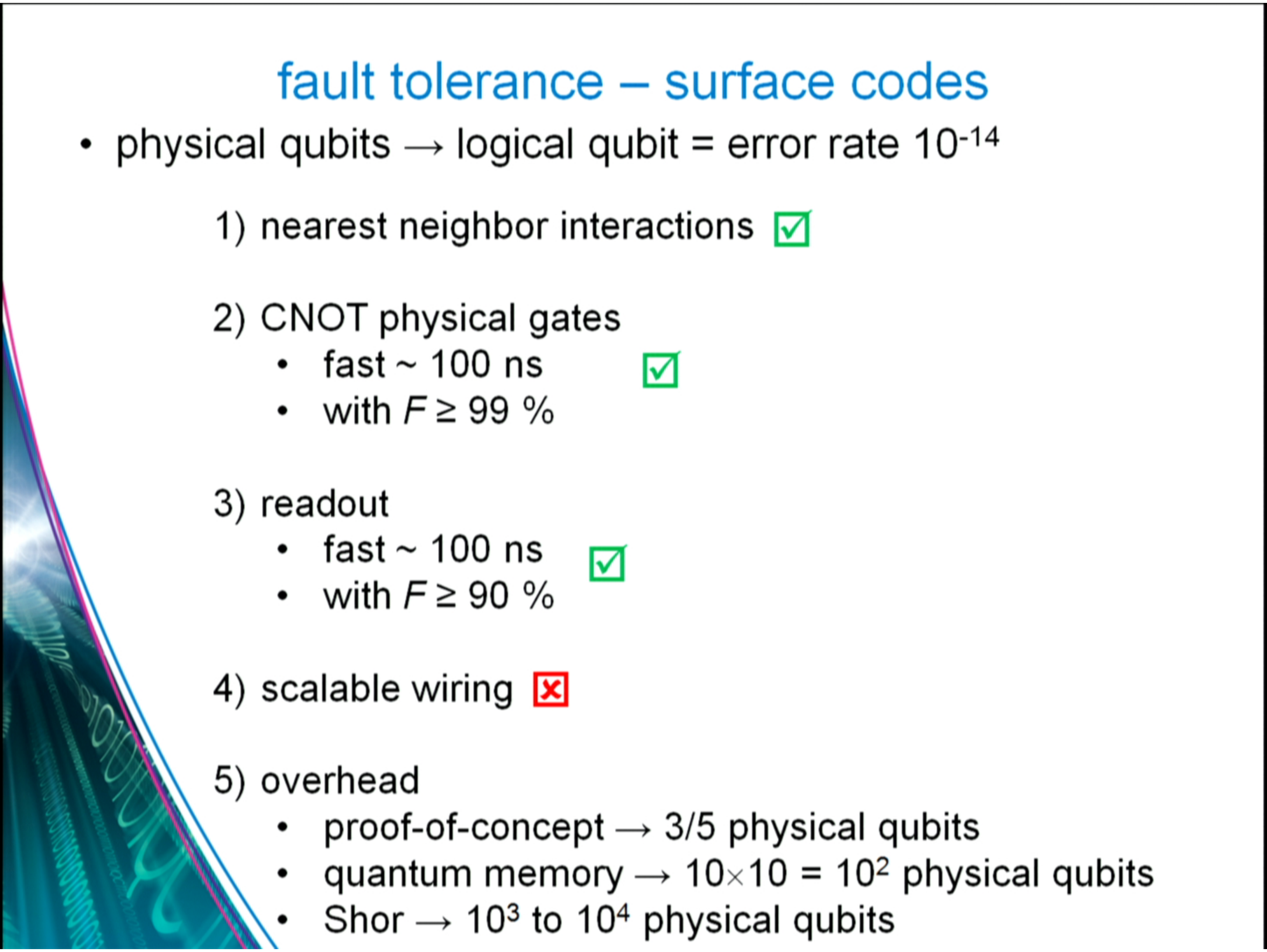
R. Barends *et al.*, e-print arXiv:1304.2322

# fault tolerance – surface codes

## 2) readout



R. Vijay *et al.*, Nature (London) **490**, 77 (2012)



# fault tolerance – surface codes

- physical qubits → logical qubit = error rate $10^{-14}$

1) nearest neighbor interactions ☑

2) CNOT physical gates ☑
    - fast ~ 100 ns
    - with $F \geq 99$ %

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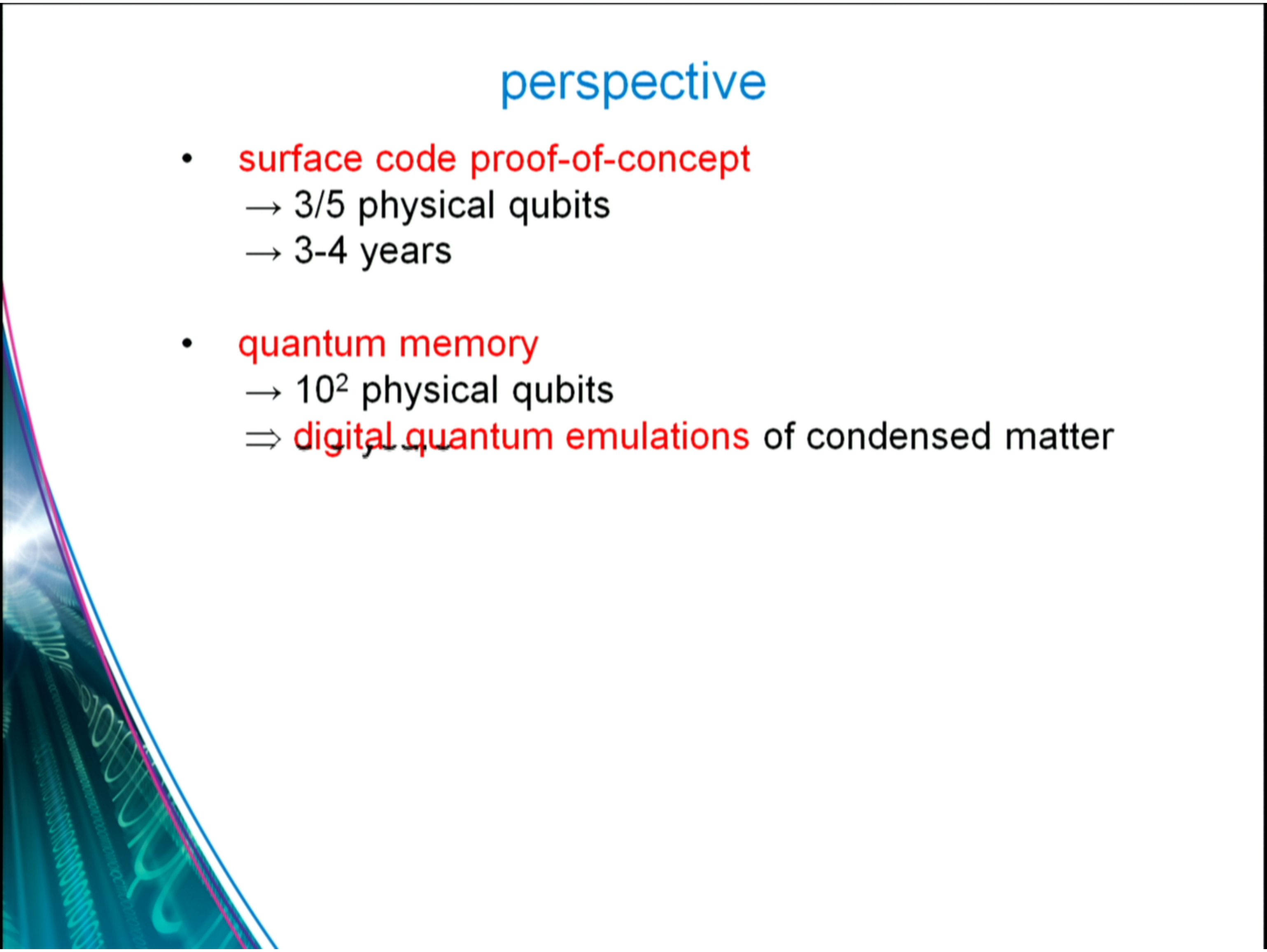
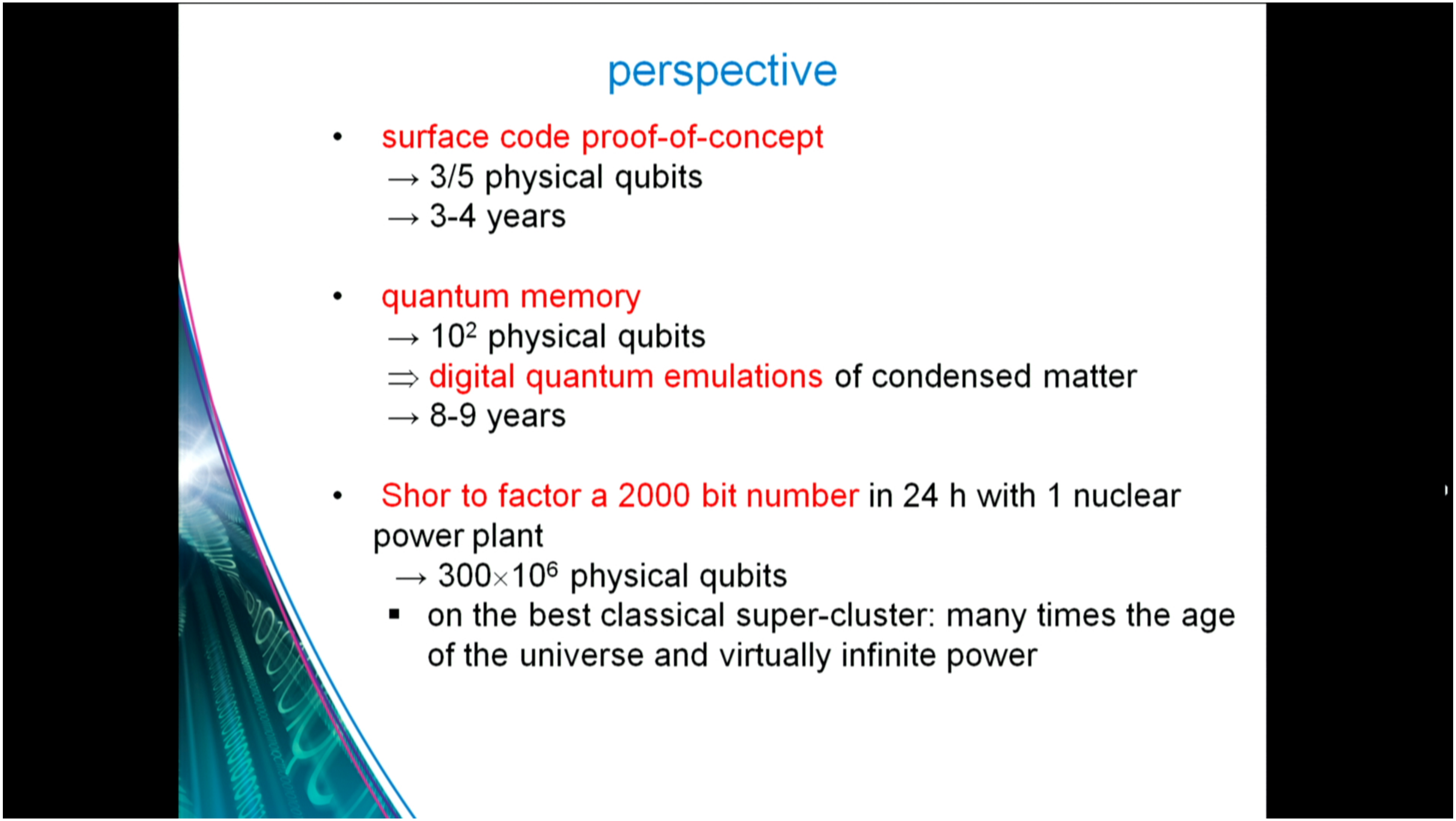


# perspective

- surface code proof-of-concept
  → 3/5 physical qubits
  → 3-4 years

- quantum memory
  → $10^2$ physical qubits
  ⇒ digital quantum emulations of condensed matter



# perspective

- surface code proof-of-concept
  → 3/5 physical qubits
  → 3-4 years

- quantum memory
  → $10^2$ physical qubits
  ⇒ digital quantum emulations of condensed matter
  → 8-9 years

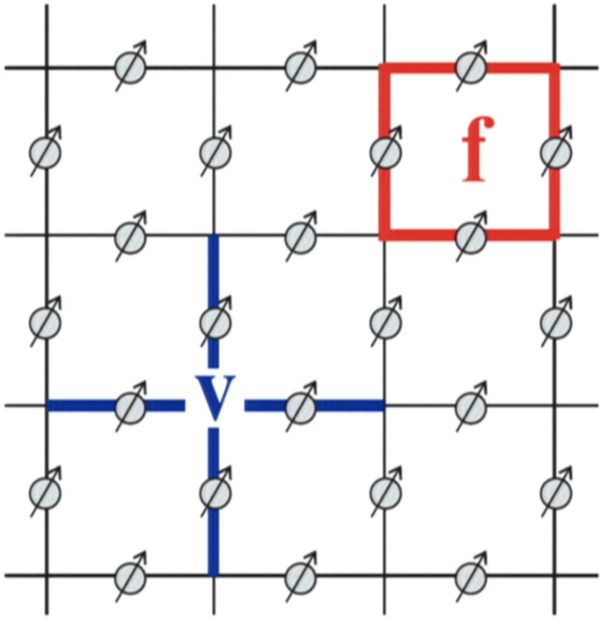
- Shor to factor a 2000 bit number in 24 h with 1 nuclear power plant
  → $300\times10^6$ physical qubits
  - on the best classical super-cluster: many times the age of the universe and virtually infinite power

# Kitaev's toric model in 2D

$$\hat{H}_{SC} = \sum_{v} \hat{A}_{v} + \sum_{f} \hat{B}_{f}$$

$$\hat{A}_{v} = \prod_{j \in v} \hat{X}_{j}$$

$$\hat{B}_{f} = \prod_{j \in f} \hat{Z}_{j}$$

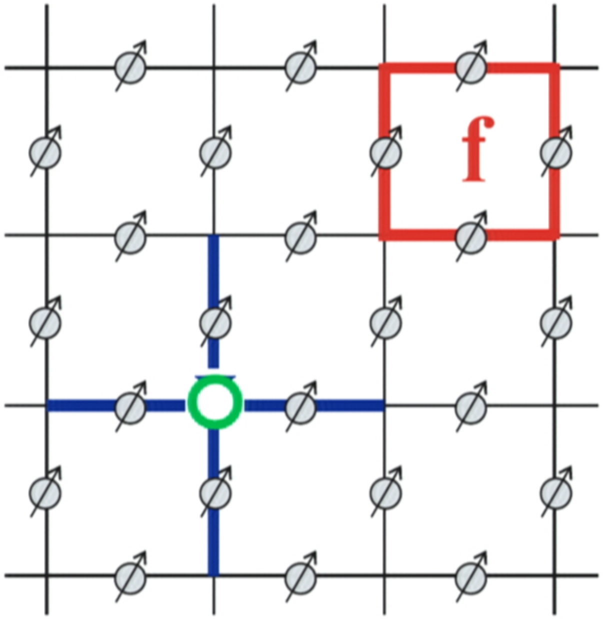


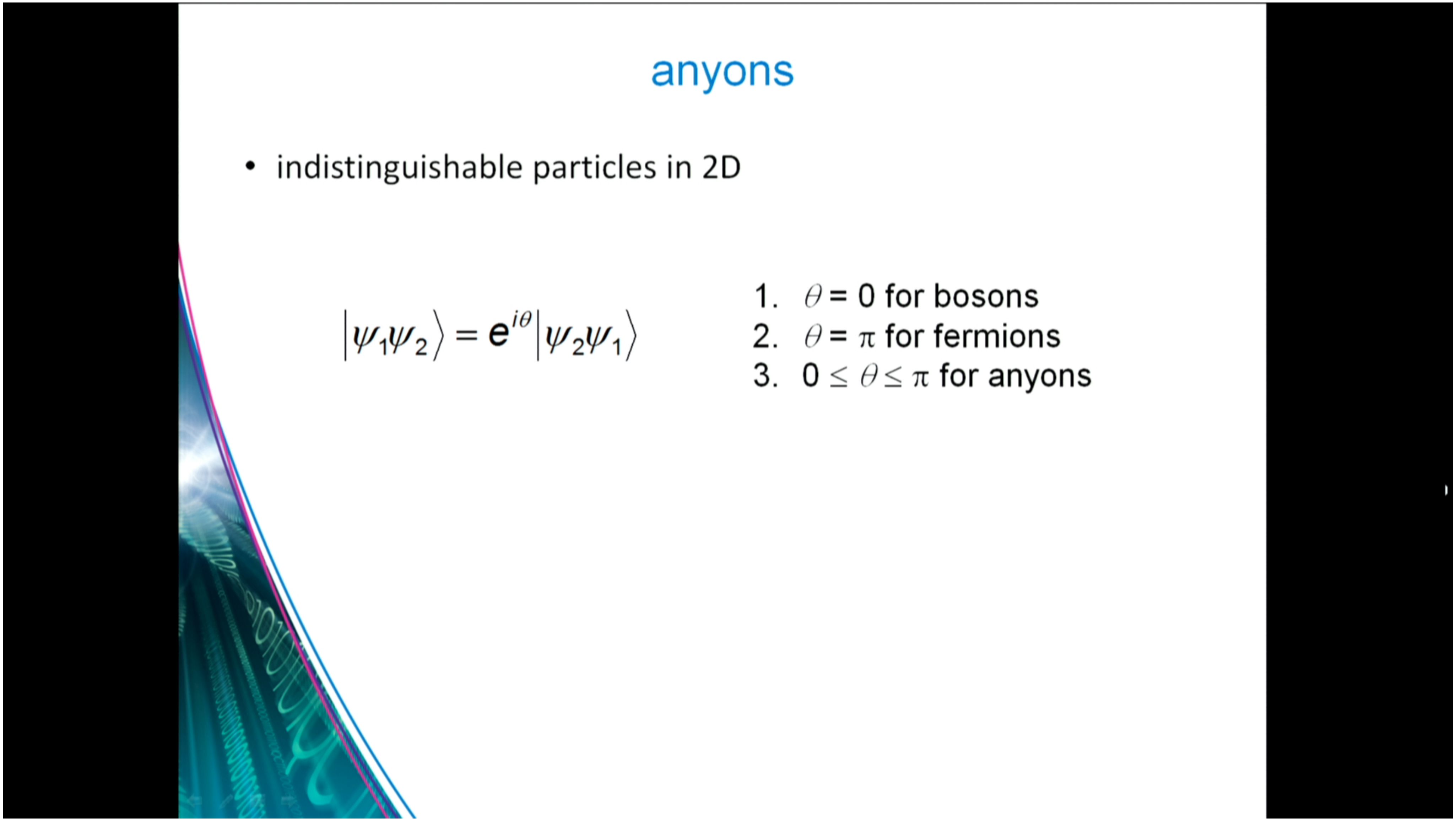
# Kitaev’s toric model in 2D

$$\hat{H}_{\mathrm{SC}} = \sum_{\mathrm{v}} \hat{A}_{\mathrm{v}} + \sum_{\mathrm{f}} \hat{B}_{\mathrm{f}}$$

$$\boxed{\hat{A}_{\mathrm{v}} = \prod_{j\in \mathrm{v}} \hat{X}_j}$$

$$\hat{B}_{\mathrm{f}} = \prod_{j\in \mathrm{f}} \hat{Z}_j$$





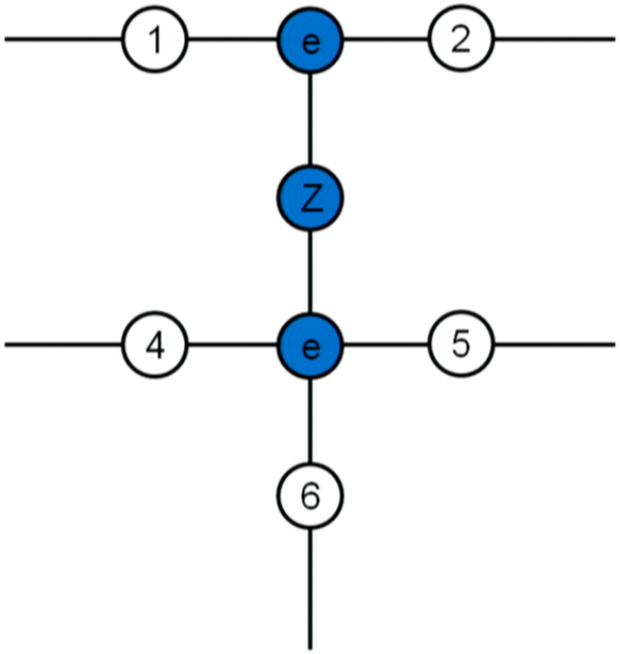
# anyons

- indistinguishable particles in 2D

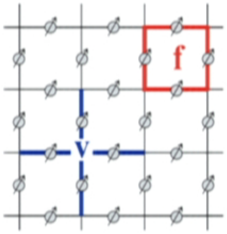
$$|\psi_1\psi_2\rangle = e^{i\theta}|\psi_2\psi_1\rangle$$

1. $\theta = 0$ for bosons
2. $\theta = \pi$ for fermions
3. $0 \leq \theta \leq \pi$ for anyons

# proof-of-concept



# beyond proof-of-concept – quantum memory



Laboratory *for*

DQM

Digital Quantum Matter

UNIVERSITY OF WATERLOO | IQC Institute *for* Quantum Computing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