Google AI Quantum

Quantum Computing with Microwaves

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MTT-S Webinar
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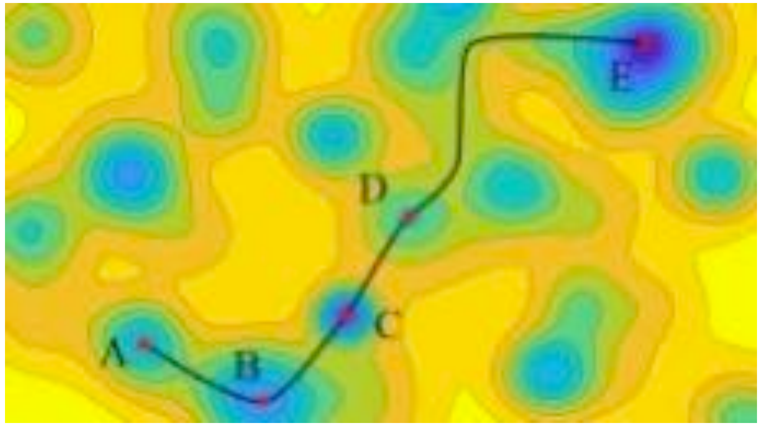
UMass Amherst

"... if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly, it's a wonderful problem because **it doesn't look so easy.**" - Richard Feynman, 1982

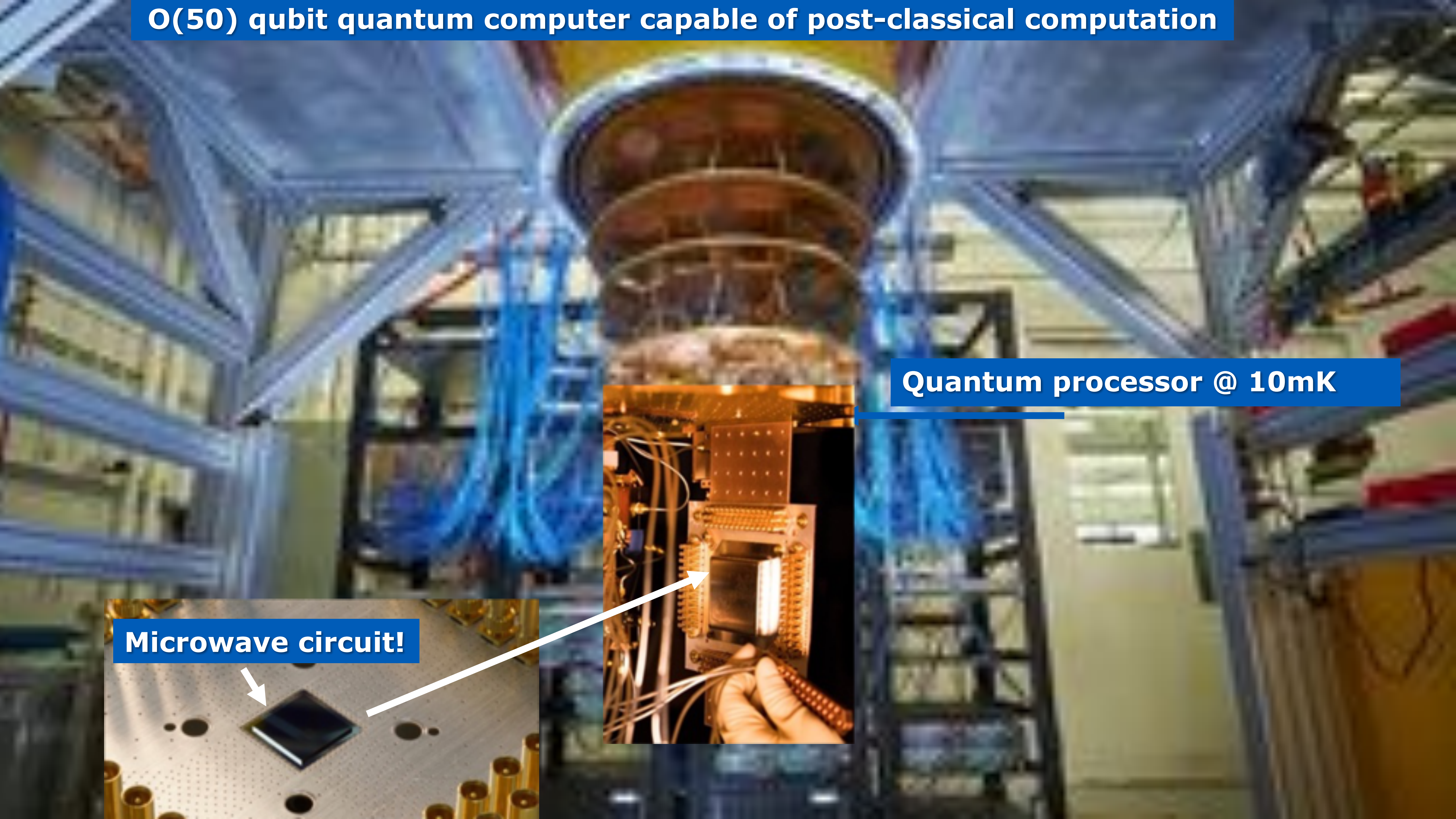
Cracking RSA Encryption

Quantum chemistry

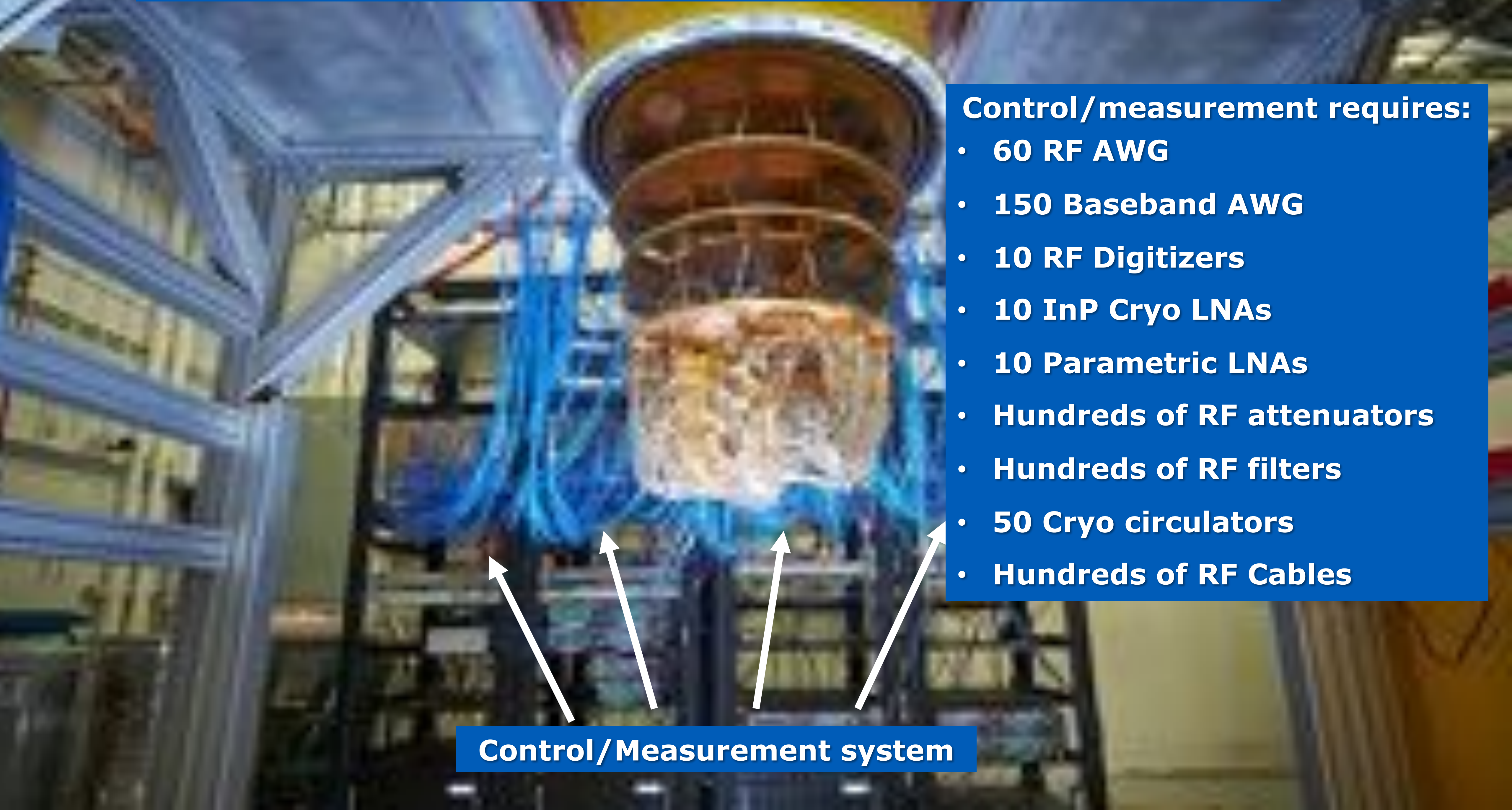


Optimization

Catalog of quantum algorithms: https://quantumalgorithmzoo.org/


O(50) qubit quantum computer capable of post-classical computation
Quantum processor @ 10mK
Microwave circuit!

O(50) qubit quantum computer capable of post-classical computation



Control/measurement requires:

- 60 RF AWG
- 150 Baseband AWG
- 10 RF Digitizers
- 10 InP Cryo LNAs
- 10 Parametric LNAs
- Hundreds of RF attenuators
- Hundreds of RF filters
- 50 Cryo circulators
- Hundreds of RF Cables

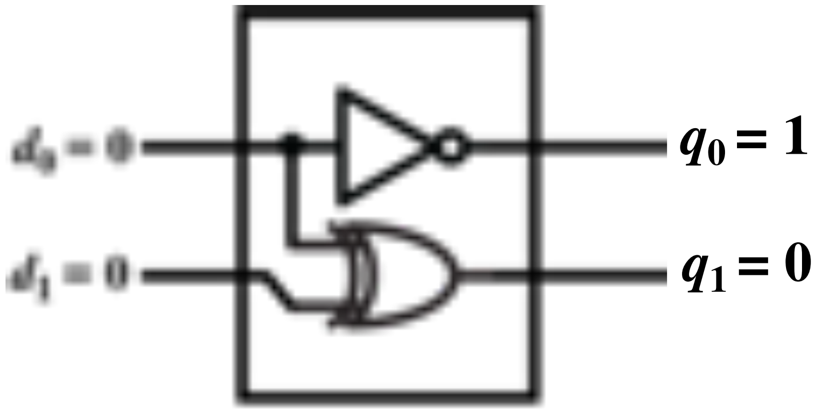
Quantum computers are enabled by microwave technology!

Agenda: four key questions

1. What is quantum computing?
2. How do we build quantum computers?
3. What can today's quantum computers do?
4. What microwave engineering is required for the future?

Classical Computing

Increment by 1



$q_0 = 0$

$q_1 = 1$

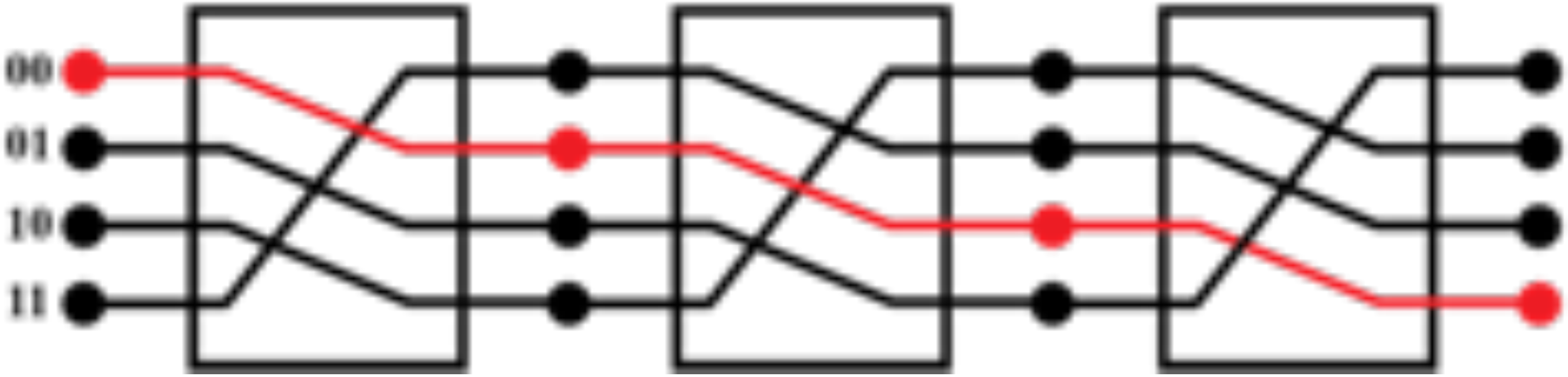
$d_1 d_0$		$q_1 q_0$
0 0	→	0 1
0 1	→	1 0
1 0	→	1 1
1 1	→	0 0

Classical Computing

<u>Key Properties</u>

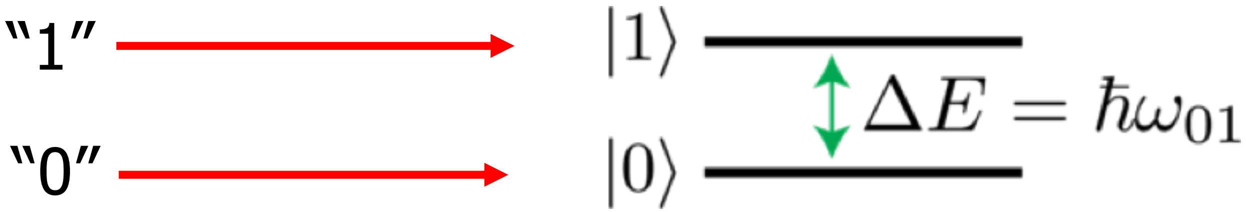
- **Each input bitstring maps to just one output bitstring**
- **Measurement and fanout are trivial**
- **Any possible classical operation realized using just NAND**

$d_1 d_0$		$q_1 q_0$
0 0	→	0 1
0 1	→	1 0
1 0	→	1 1
1 1	→	0 0



Properties of Quantum Bits

Qubit = quantum mechanical system w/two energy levels



Quantum mechanics: state fully described by wave function

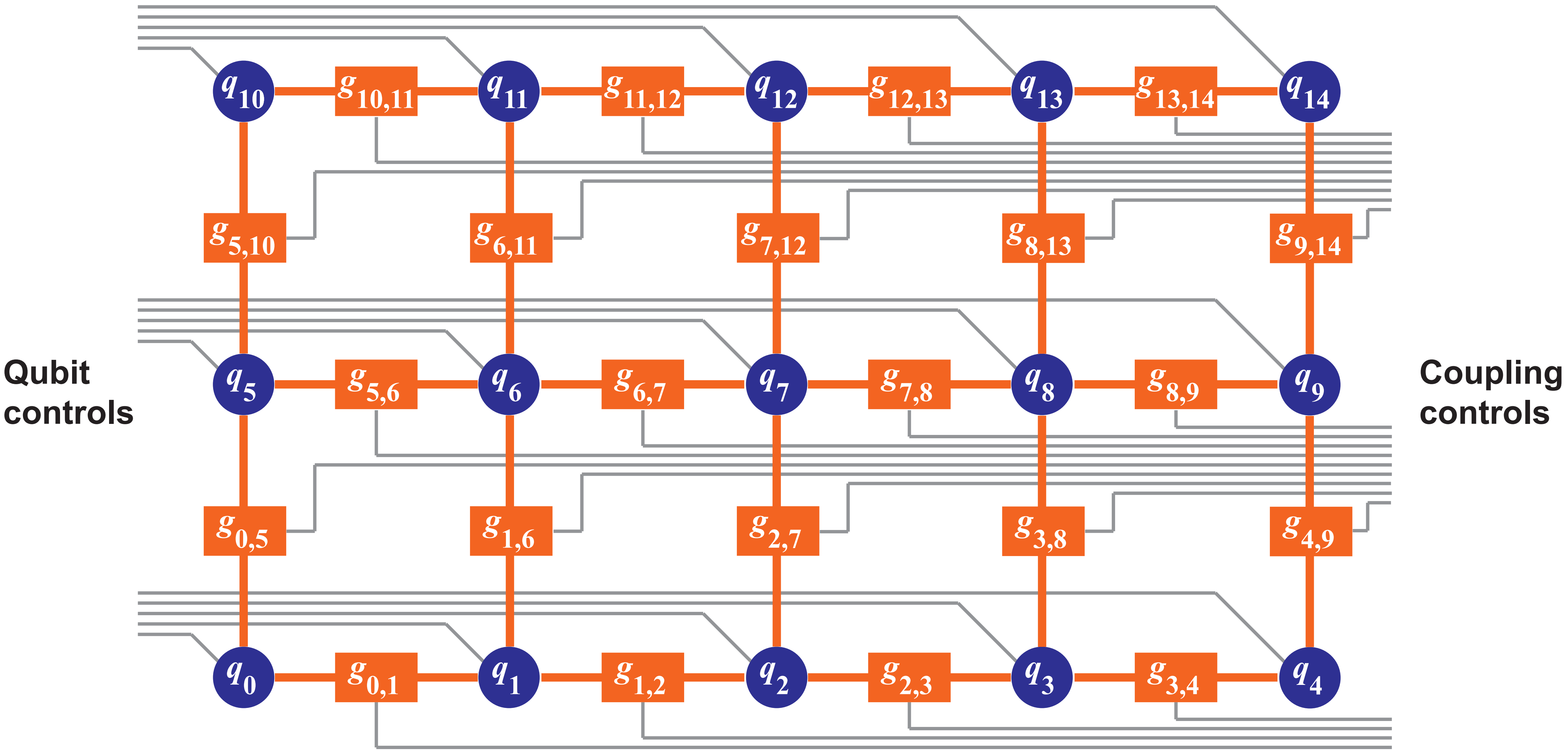
$$|\psi\rangle = \alpha_0 |0\rangle + \alpha_1 |1\rangle = \begin{bmatrix} \alpha_0 \\ \alpha_1 \end{bmatrix}$$

← Complex unit state-vector.

Quantum mechanics: measurement of qubit causes a probabilistic state collapse and returns single classical bit

$$P_{|0\rangle} = |\alpha_0|^2 \qquad P_{|1\rangle} = |\alpha_1|^2$$

Quantum Processor = Array of Coupled Qubits



Properties of Quantum Processors

- *N* qubit quantum processor has 2^N eigenstates (bitstrings):

$$|\psi\rangle = \alpha_{00\ldots0}|00\ldots0\rangle + \alpha_{00\ldots1}|00\ldots1\rangle + \ldots + \alpha_{11\ldots1}|11\ldots1\rangle = \begin{bmatrix} \alpha_{00\ldots0} \\ \alpha_{00\ldots1} \\ \vdots \\ \alpha_{11\ldots1} \end{bmatrix}$$

complex probability amplitudes: degrees of freedom

- Measurement has same interpretation as single qubit case, e.g.,

$$P_{|00\ldots0\rangle} = |\alpha_{00\ldots0}|^2$$

Quantum Computing

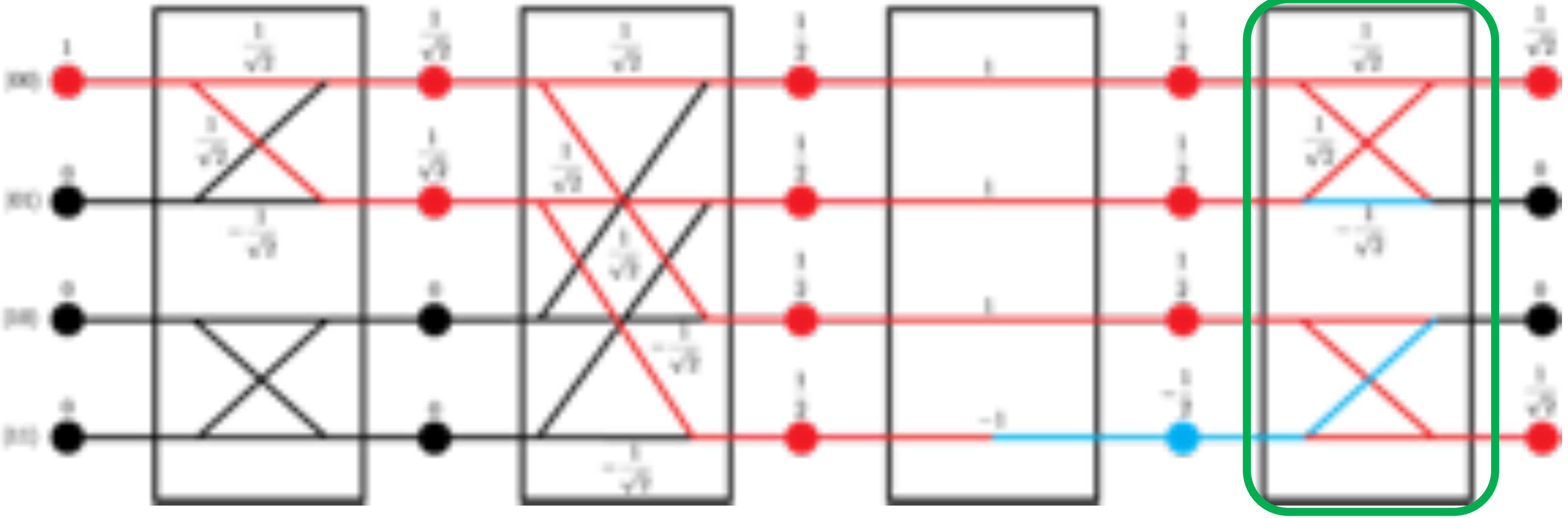
Key Ingredients

- Unitary gate operations
- Superposition
- Entanglement
- Interference
- Projective measurement

ting

$$\hat{U}_{H,0} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \otimes \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$

$$= \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$



Key Ingredients

- Unitary gate operations
- Superposition
- Entanglement
- Interference
- Projective measurement

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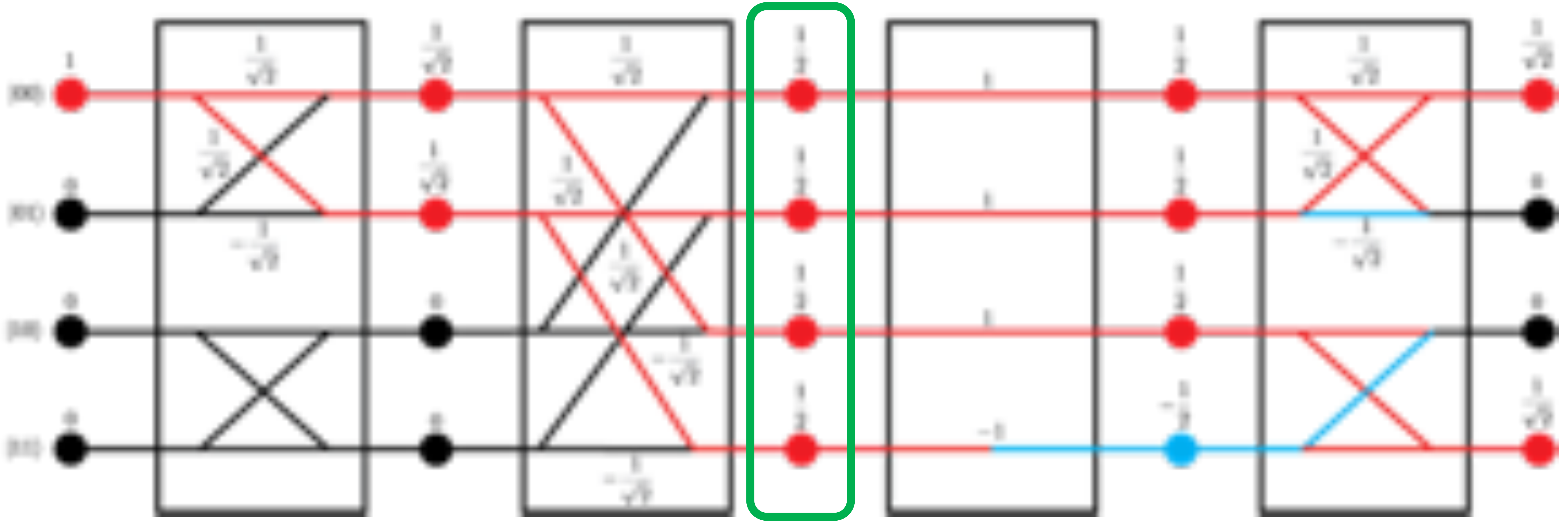
Coherent superposition:

$$|\psi\rangle = \frac{|00\rangle + |01\rangle + |10\rangle + |11\rangle}{2}$$



Key Ingredients

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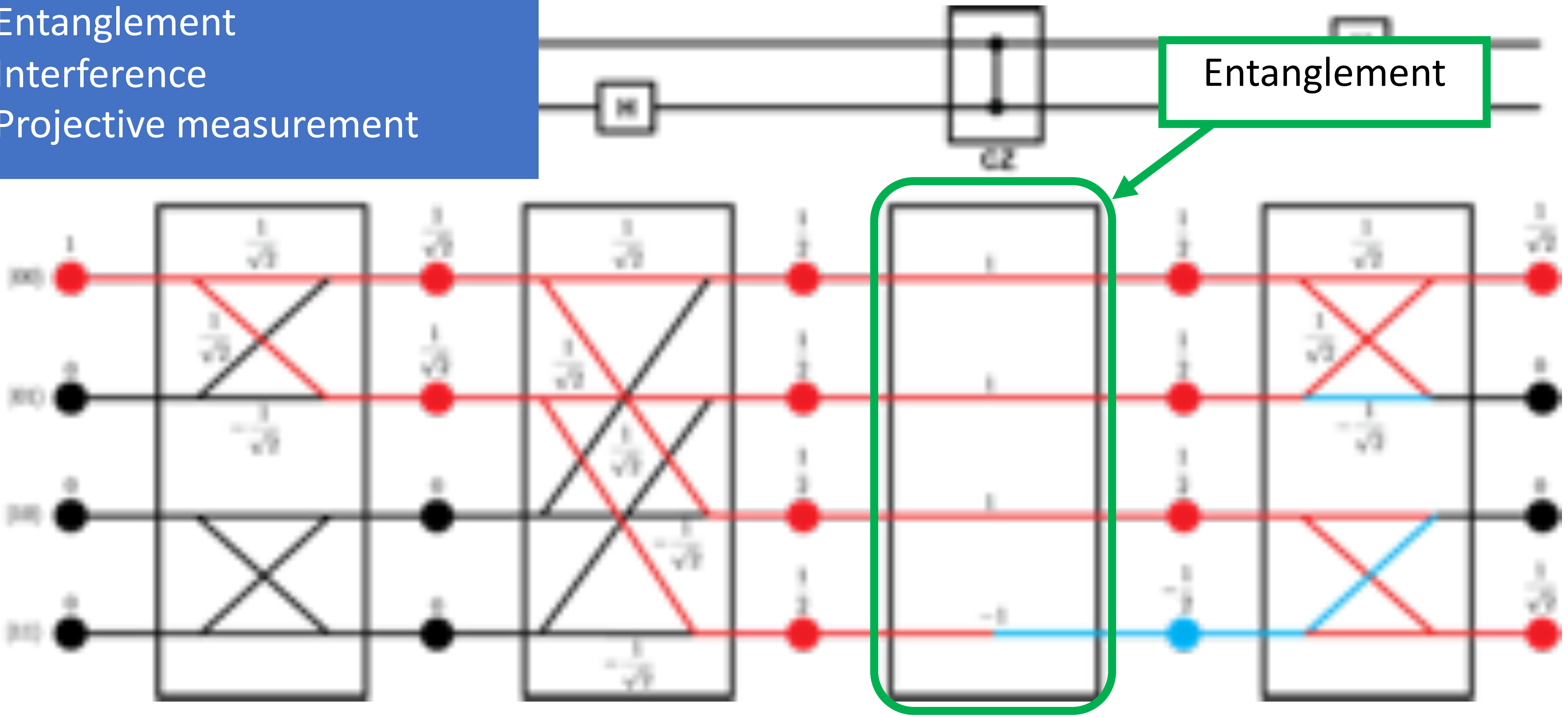

Key Ingredients

- Unitary gate operations
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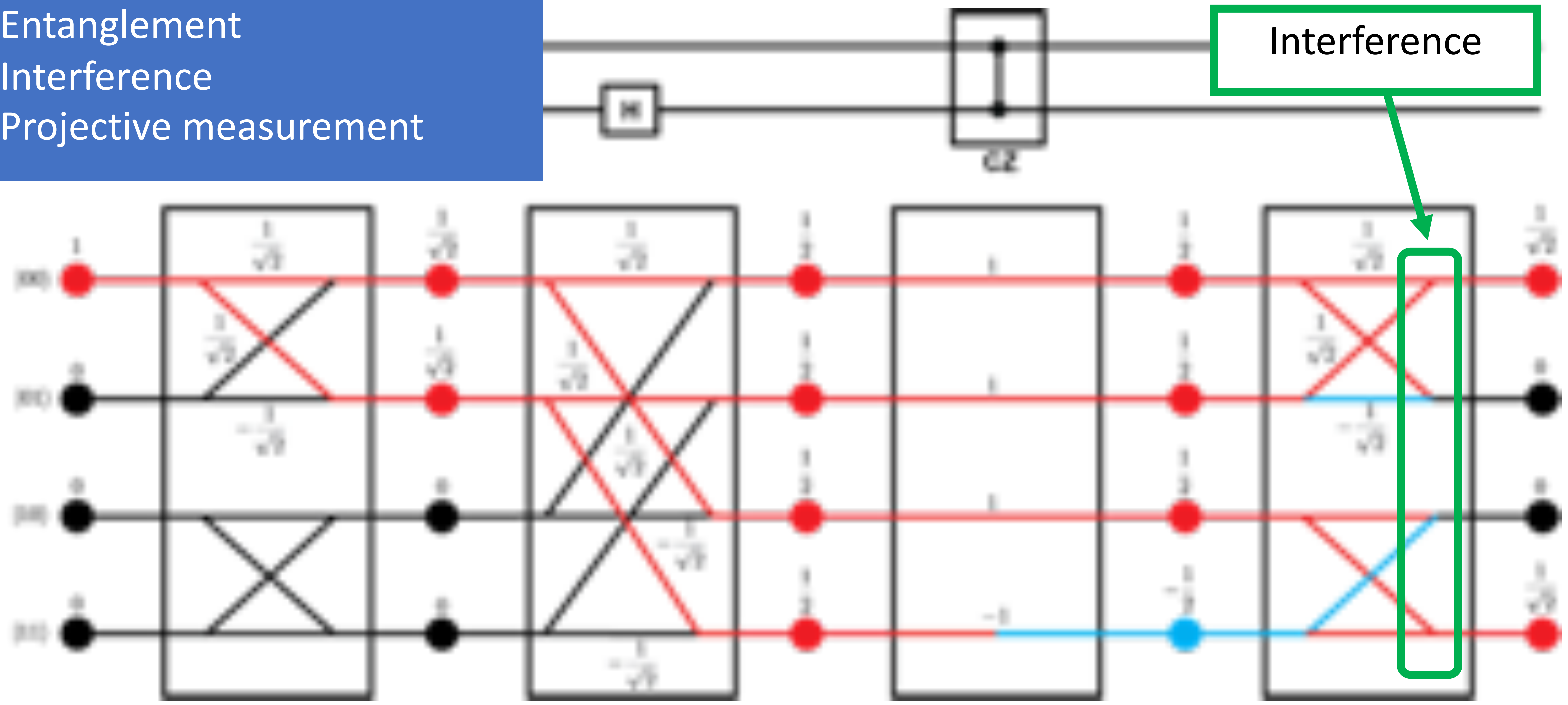
...ting



Key Ingredients

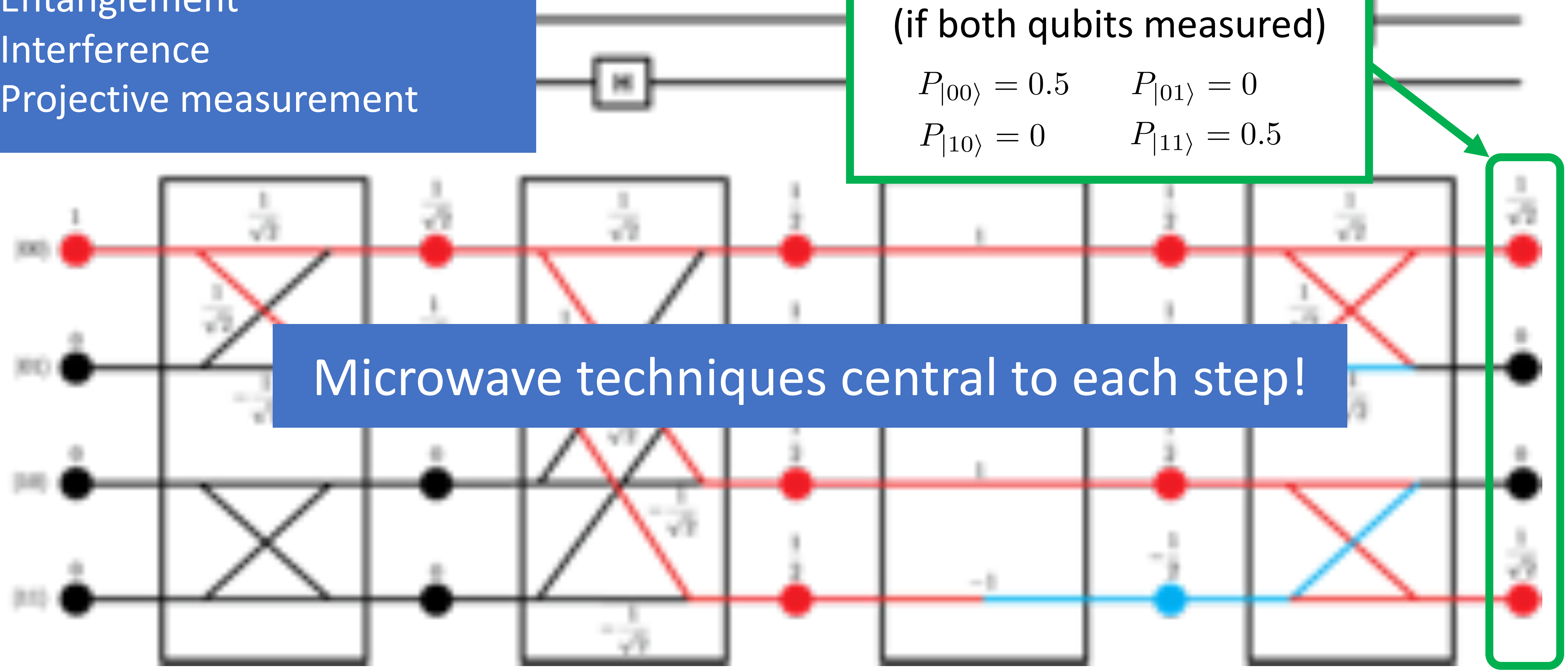
- Unitary gate operations
- Superposition
- Entanglement
- Interference
- Projective measurement

...ting

Projective measurement
(if both qubits measured)

$P_{|00\rangle} = 0.5 \qquad P_{|01\rangle} = 0$

$P_{|10\rangle} = 0 \qquad P_{|11\rangle} = 0.5$



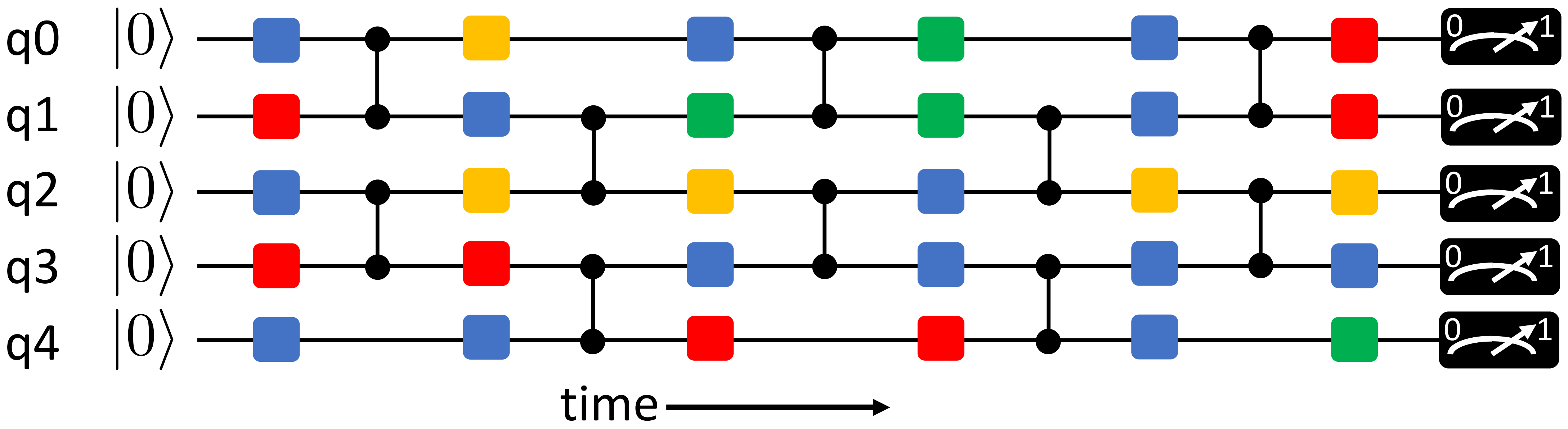
Microwave techniques central to each step!

Universal Quantum Computing

Transformed state (2^N x 1) → $|\psi'\rangle = \hat{U}|\psi\rangle$ ← Initial state (2^N x 1)

Unitary operation (2^N x 2^N)

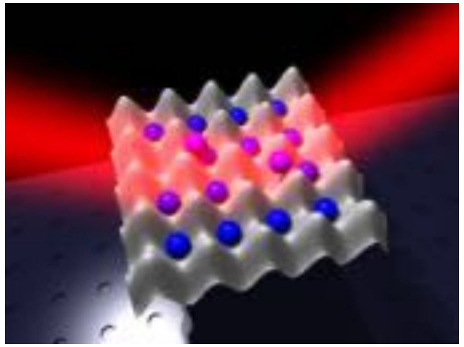
Ingredients:



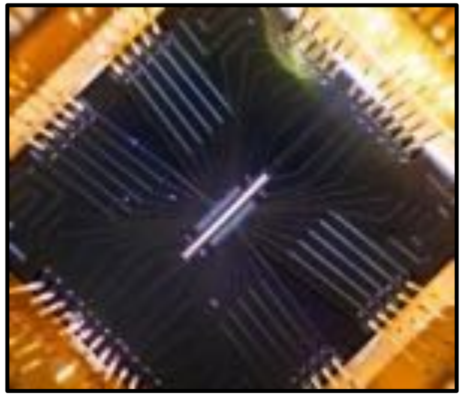
Building a quantum computer

Many Possible Qubit Technologies

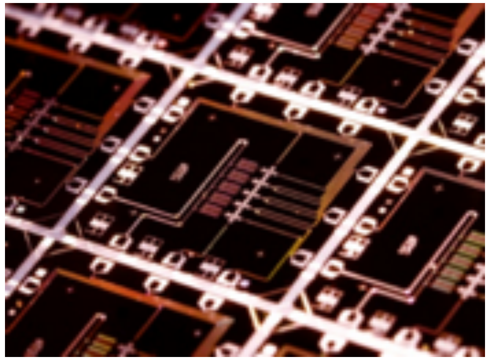
Atoms



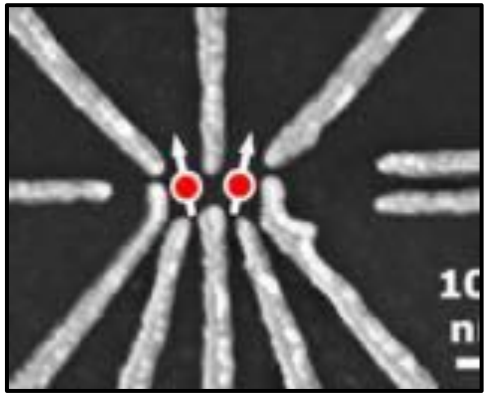
Ions



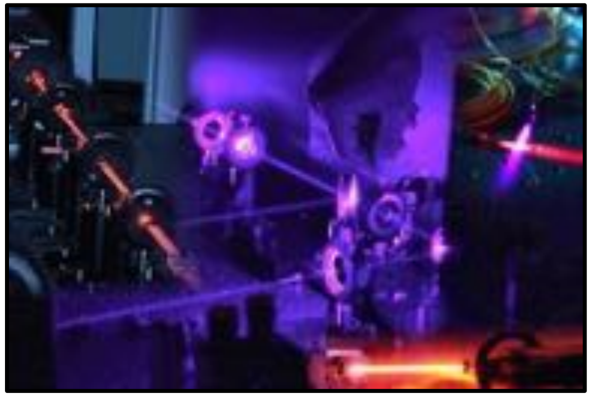
Superconducting circuits



Spins

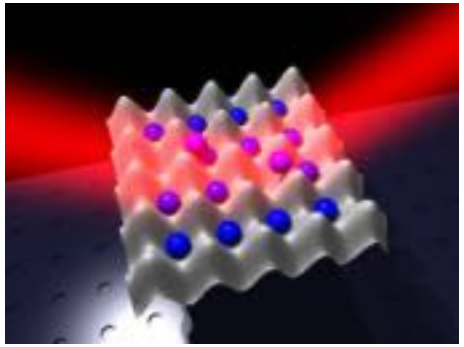


Optics



Many Possible Qubit Technologies

Atoms



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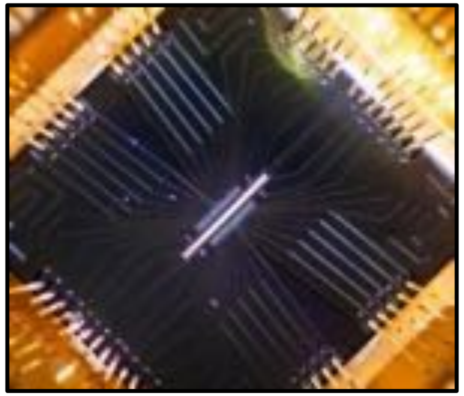
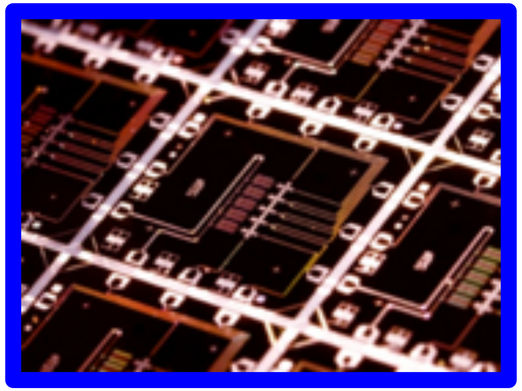
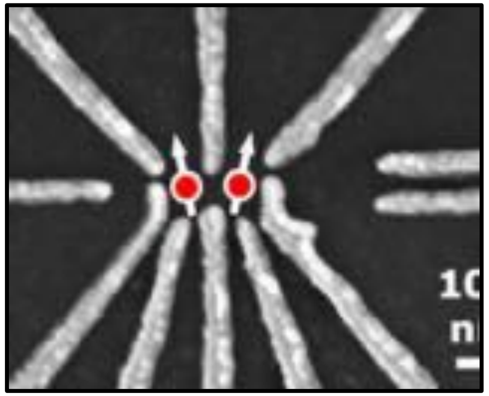


Superconducting circuits

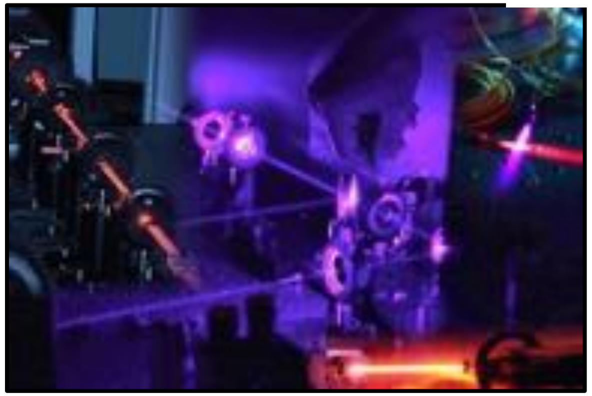


Google

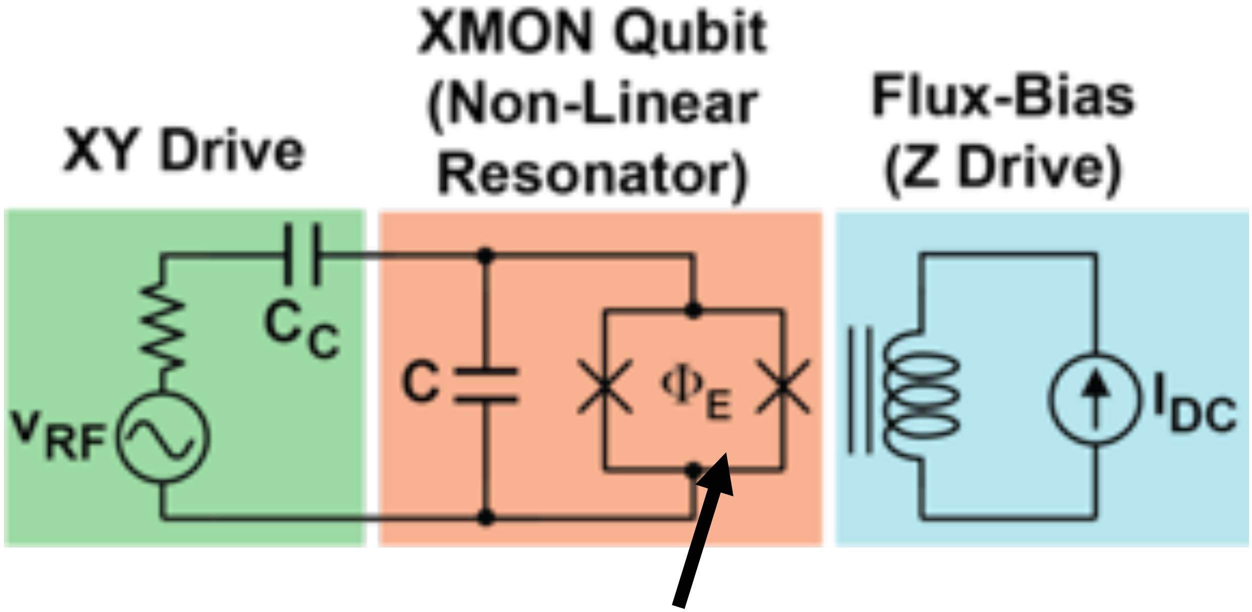
Spins



Optics

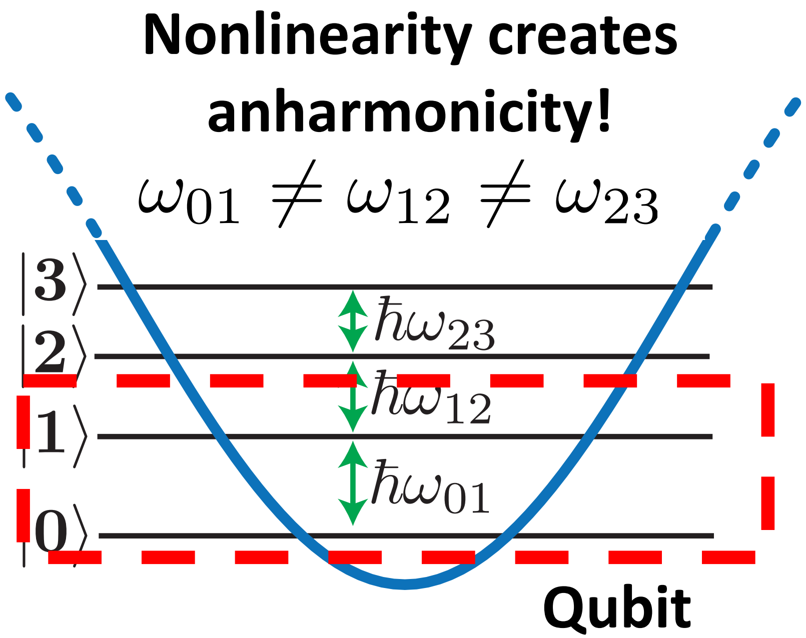


Transmon Superconducting Qubit



$$T \ll \frac{\hbar\omega_{01}}{k}$$

Cool to ~10mK

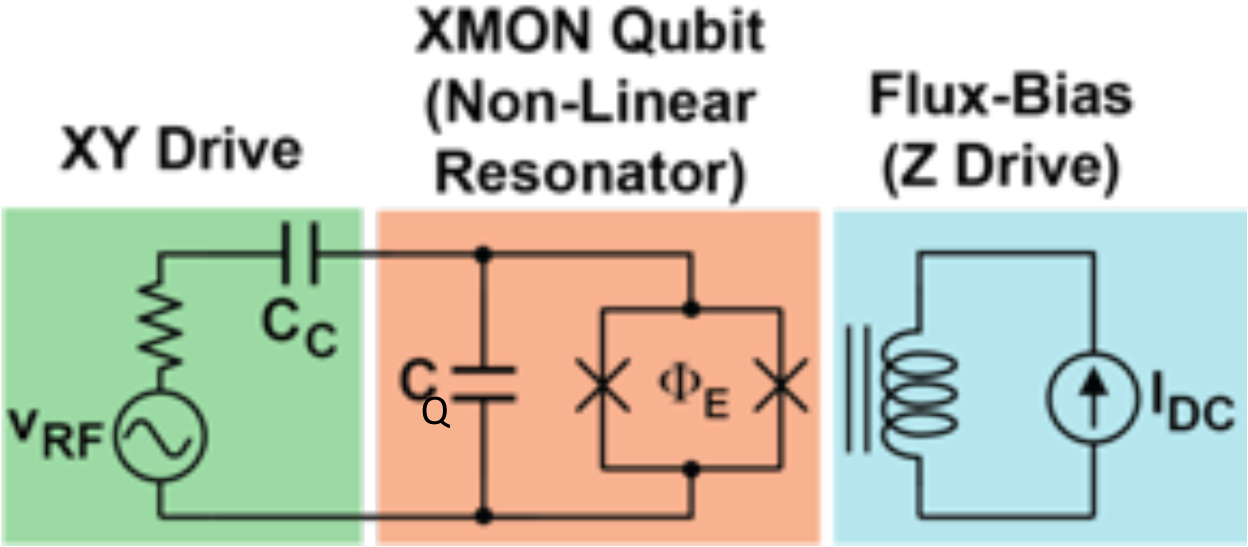


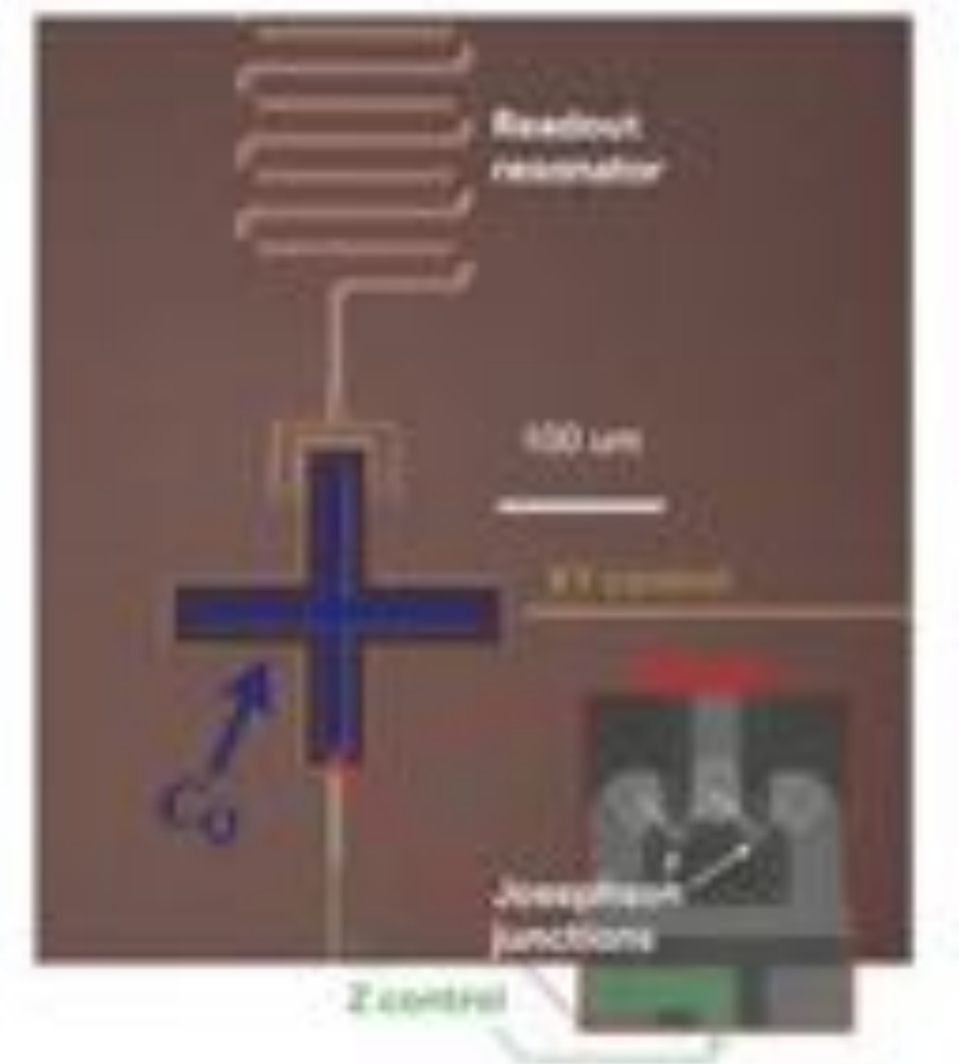
Josephson Junction loop ⇒ flux-tunable lossless nonlinear inductor

Behaves as 2-level qubit if we selectively drive ω_{01}

$$\omega_{01} \approx \frac{1}{\sqrt{L_{\mathrm{J0,e}}\left(\Phi_{\mathrm{E}}\right)C}} \Rightarrow \textbf{4-8GHz} \qquad \omega_{01} - \omega_{12} = \frac{q^2}{2\hbar C} \Rightarrow \textbf{0.15-0.35GHz}$$

Transmon Superconducting Qubit





Typical component values

C_Q: 80fF

L: 8nH

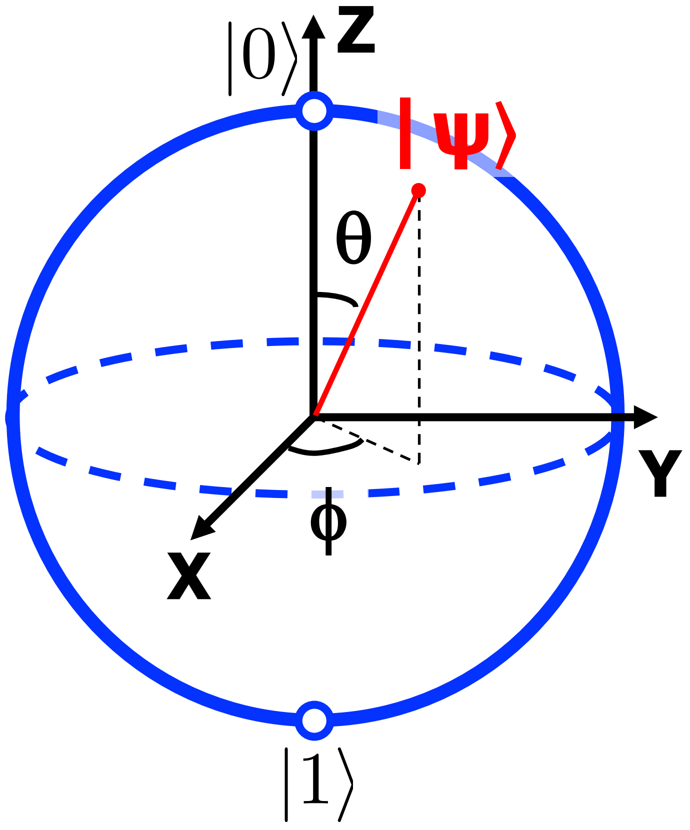
C_C: 30aF

M: 2pH

Bloch Sphere and Single Qubit Gates

- During computation: can be in **superposition state (vector)**

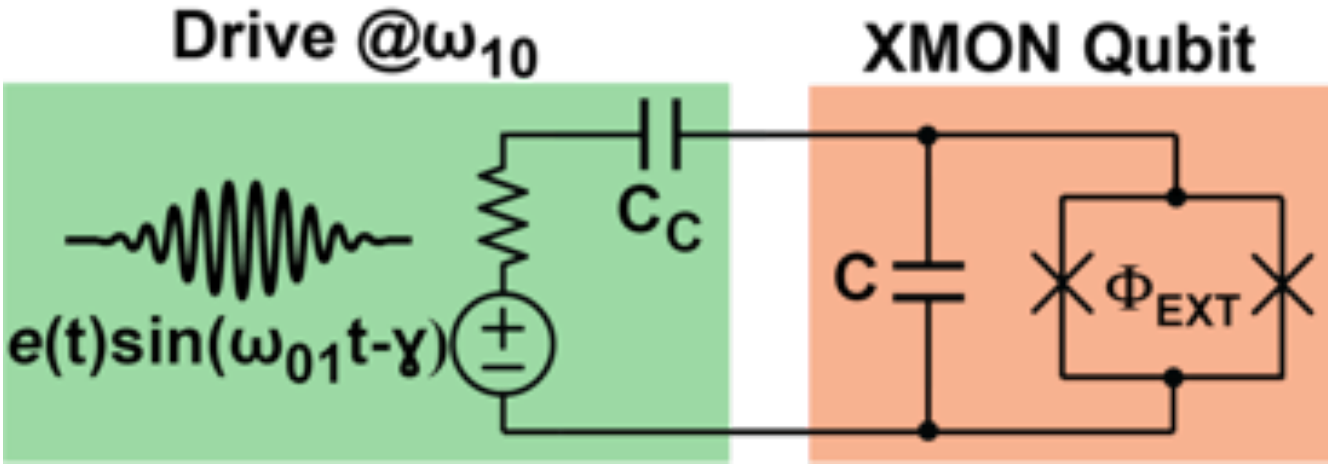
$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + \exp\{j\phi\}\sin\left(\frac{\theta}{2}\right)|1\rangle$$



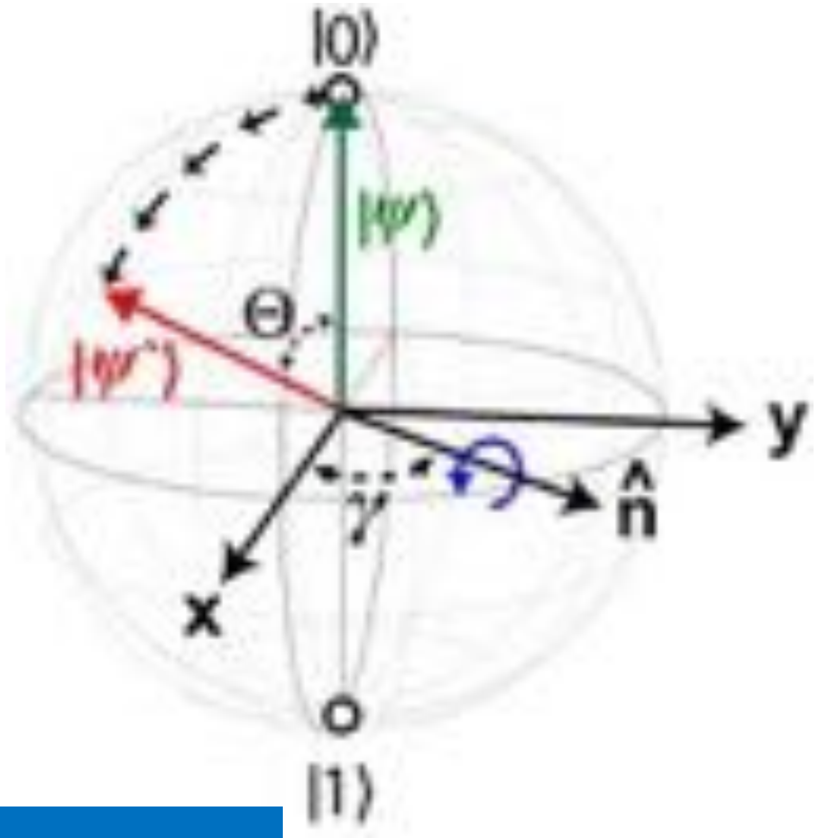
- **Single qubit gate operations** correspond to **rotations** of Bloch vector.

- **Universal single-qubit gateset requires rotations about X, Y, & Z axes**

Single Qubit Gates on Transmon: XY Rotations

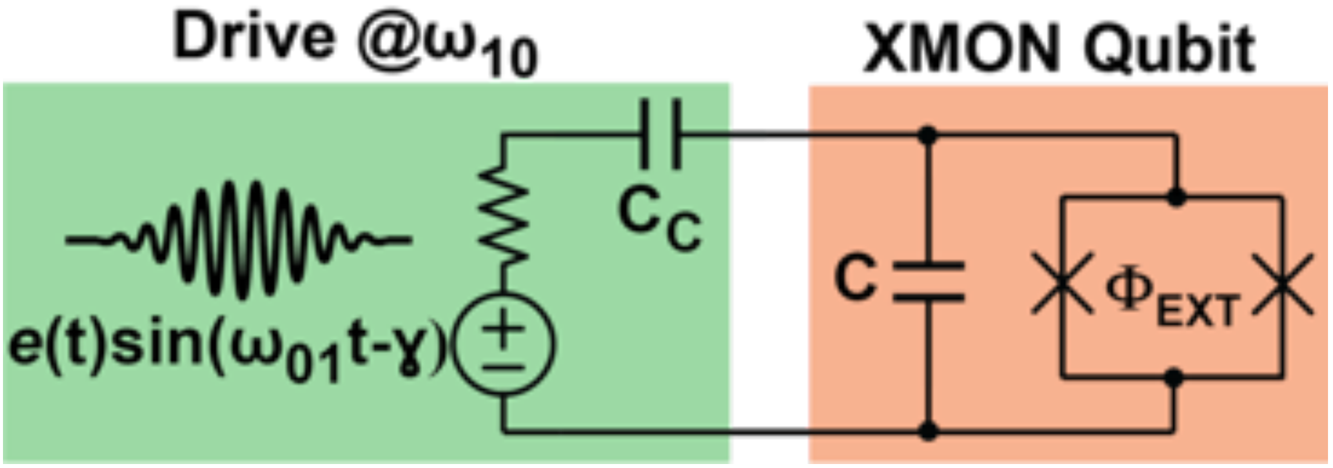


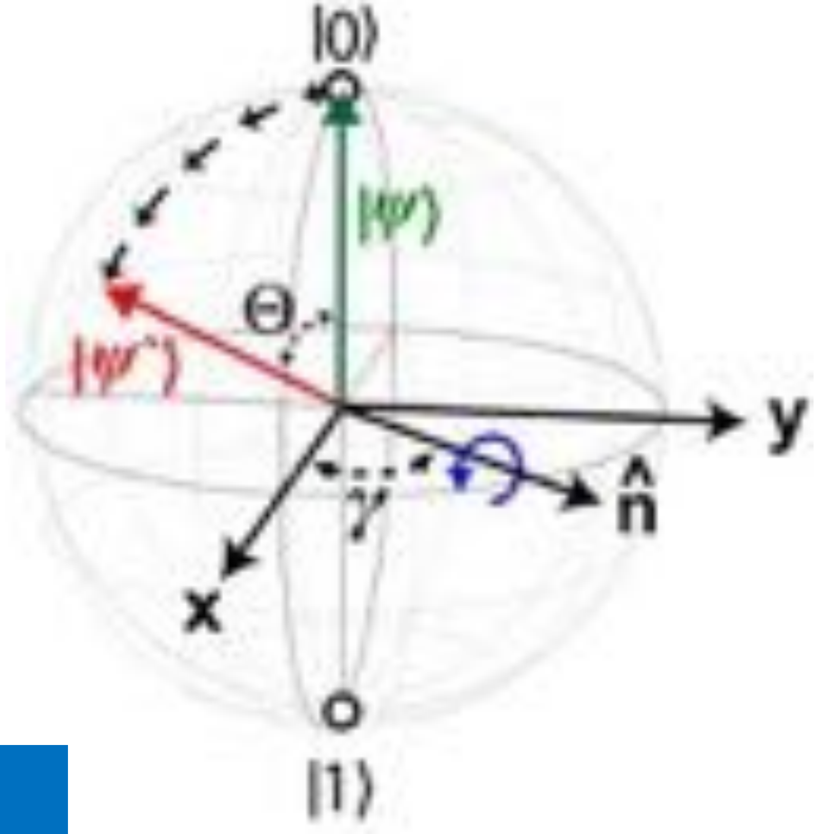
$$\Theta = \frac{\alpha}{\hbar}\int_{t_0}^{t} e\left(t'\right)dt'$$



XY Gates: resonant microwave drive
Angle of rotation: integrated envelope amplitude
Axis of rotation: microwave carrier phase

Single Qubit Gates on Transmon: XY Rotations



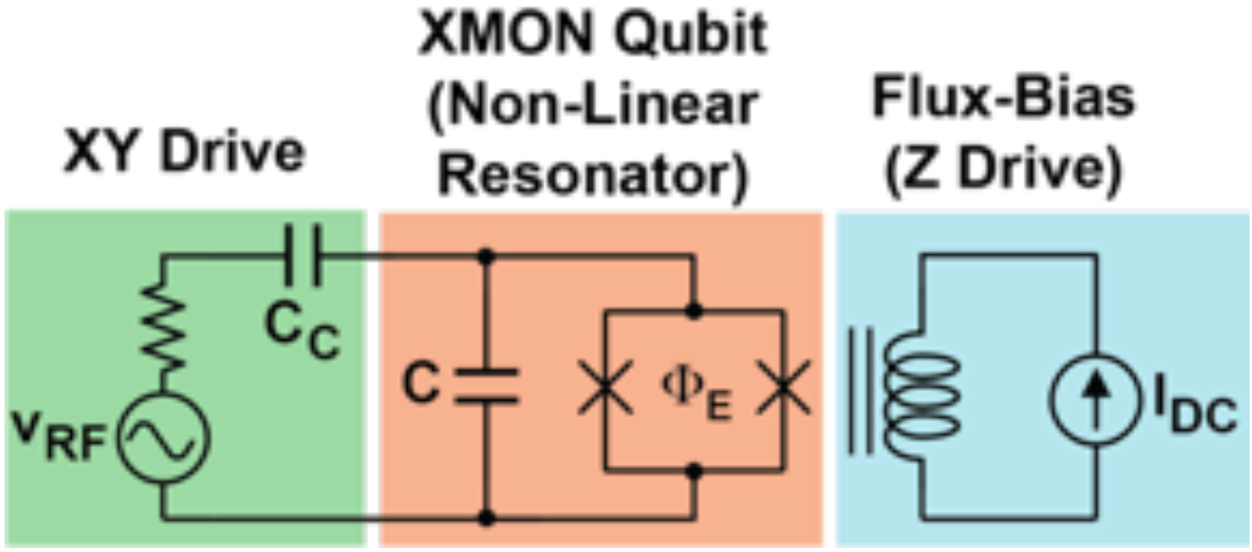


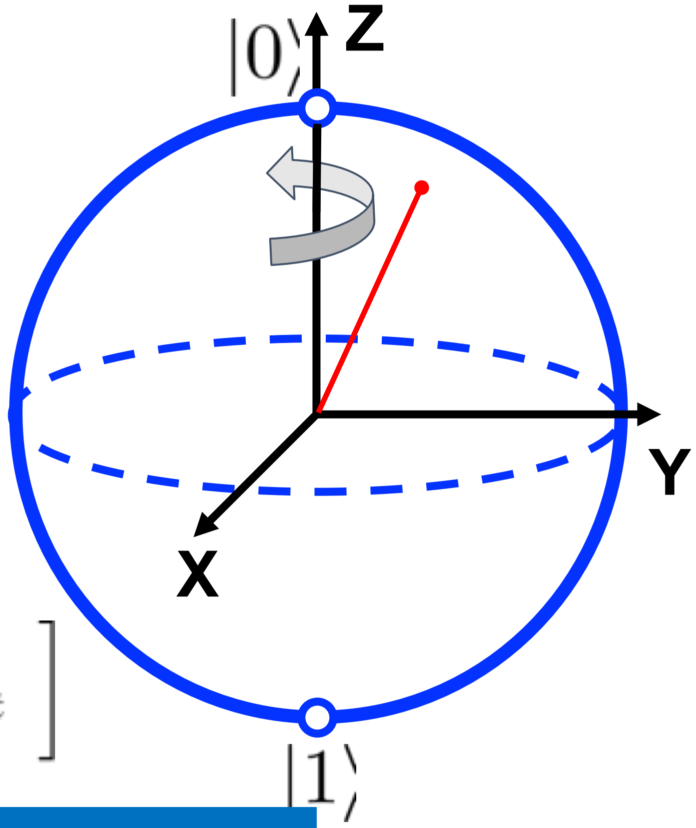
$$\Theta = \frac{\alpha}{\hbar} \int_{t_0}^{t} e\left(t'\right) dt'$$

Typical values

- **Duration: 10-30 ns**
- **Peak power: -70 dBm**
- **Noise floor: -204 dBm/Hz**

Single Qubit Gates on Transmon: Z Rotations



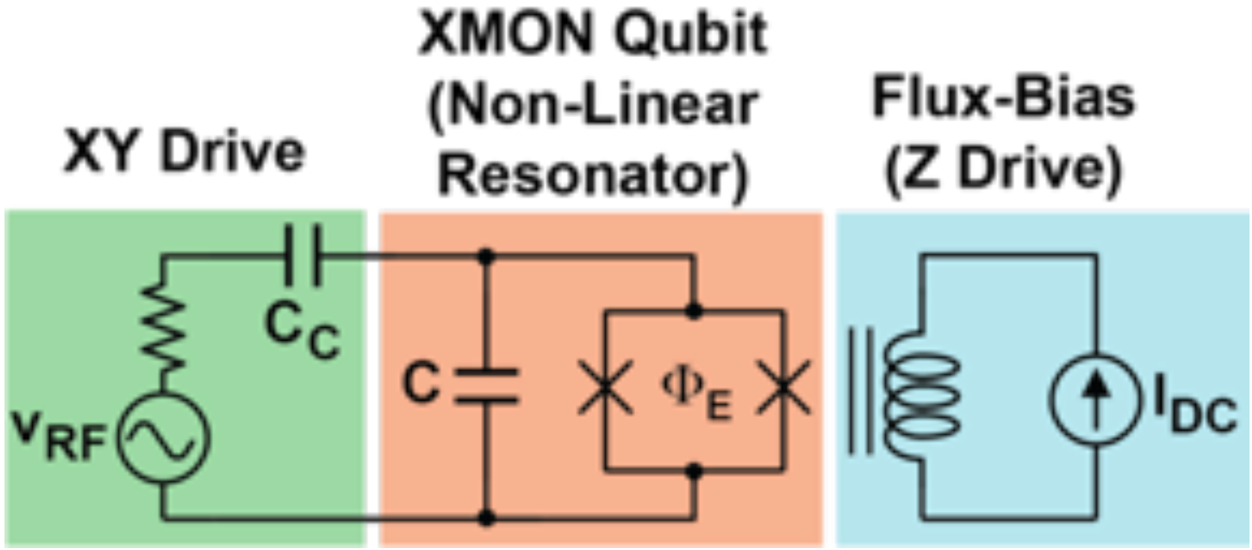


Use frequency control knob (flux bias current)

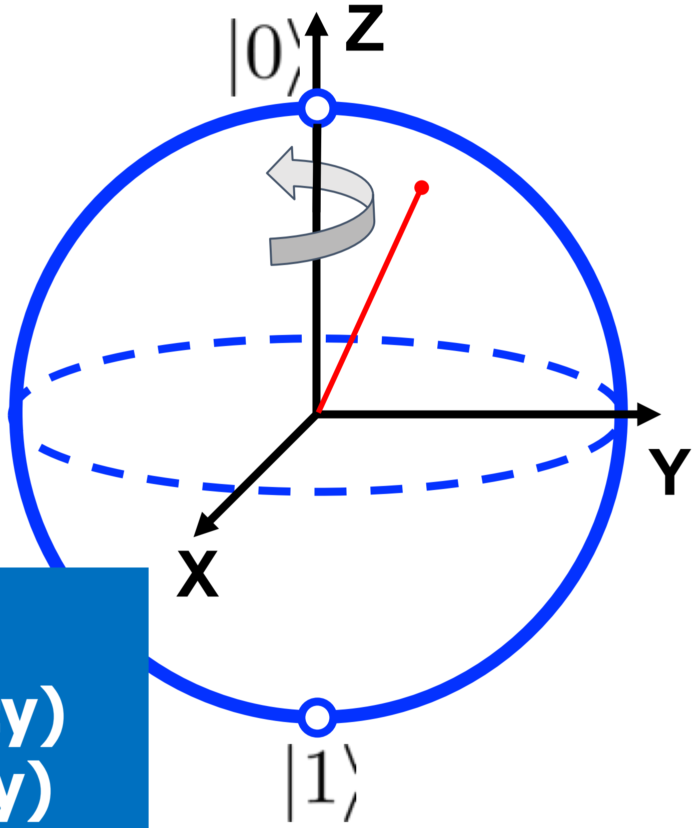
Detune by $\Delta\omega_{01}$ for duration Δt ⇨ $\hat{U}_Z = \begin{bmatrix} 1 & 0 \\ 0 & e^{-j\Delta\omega_{01}\Delta t} \end{bmatrix}$

Z gate design: duration and amplitude of current pulse

Single Qubit Gates on Transmon: Z Rotations



Use frequency control knob (flux bias current)

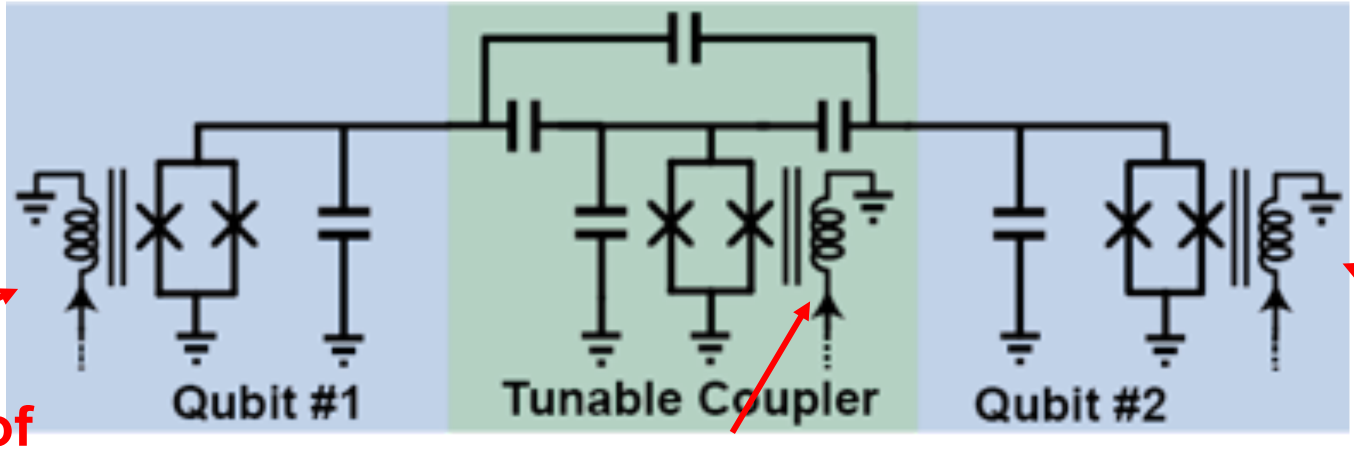


Detune by

Typical values

- **Static Z-bias: 50-500μA (14 bit accuracy)**
- **Pulsed Z-bias: 1-500uA (14 bit accuracy)**
- **Pulse duration: 5-50ns**

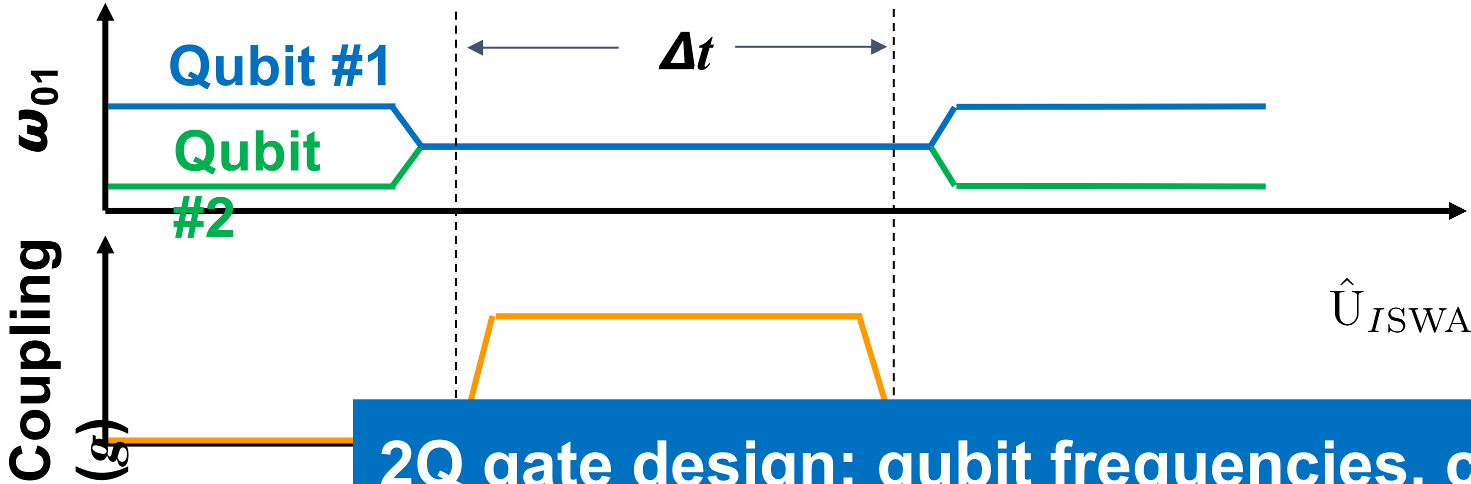
2Q Gates Require Deterministic Interactions



Current control of ω_{01} for Qubit #1

Current control of qubit-qubit coupling strength (g)

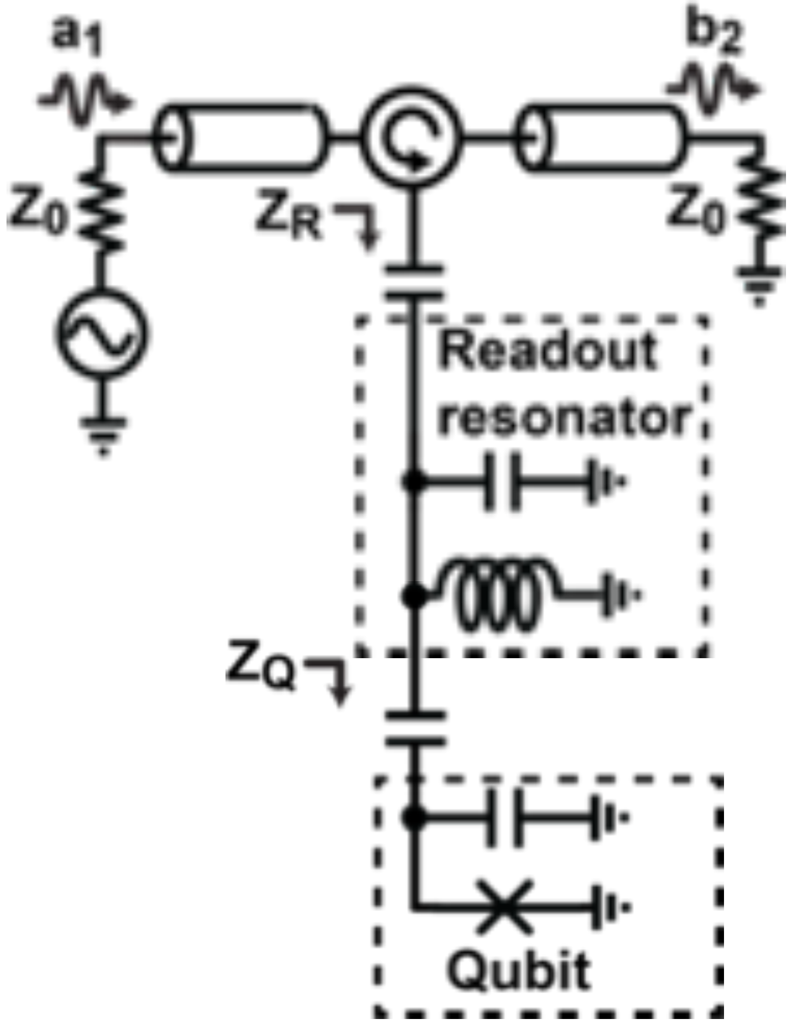
Current control of ω_{01} for Qubit #2

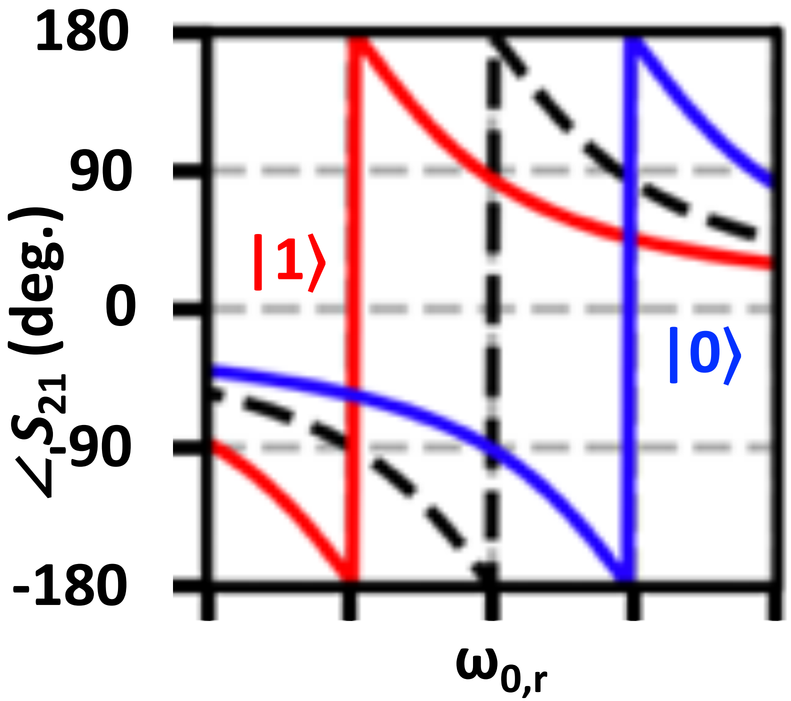


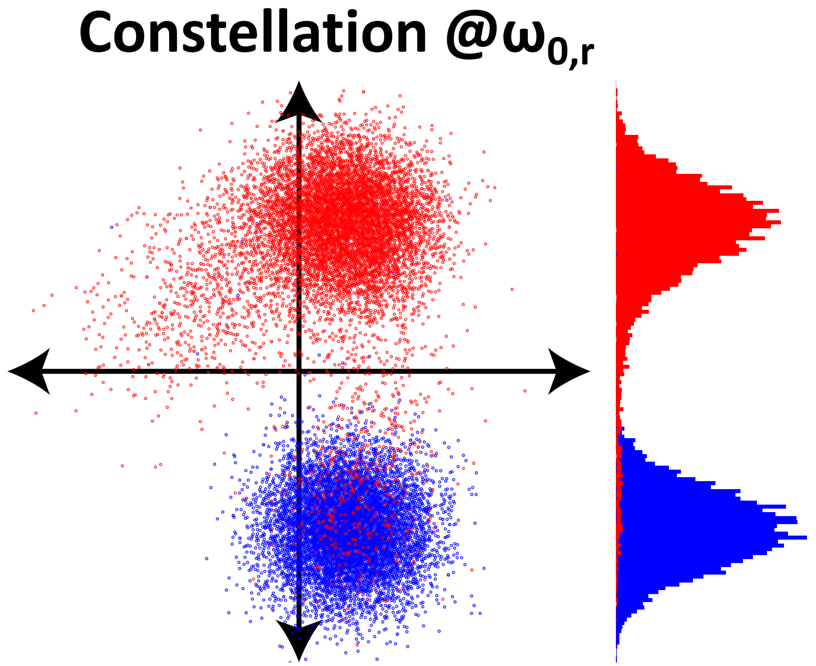
$$\hat{U}_{ISWAP} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\left(\frac{g\Delta t}{2}\right) & -j\sin\left(\frac{g\Delta t}{2}\right) & 0 \\ 0 & -j\sin\left(\frac{g\Delta t}{2}\right) & \cos\left(\frac{g\Delta t}{2}\right) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

2Q gate design: qubit frequencies, coupling

Dispersive Readout of Transmon

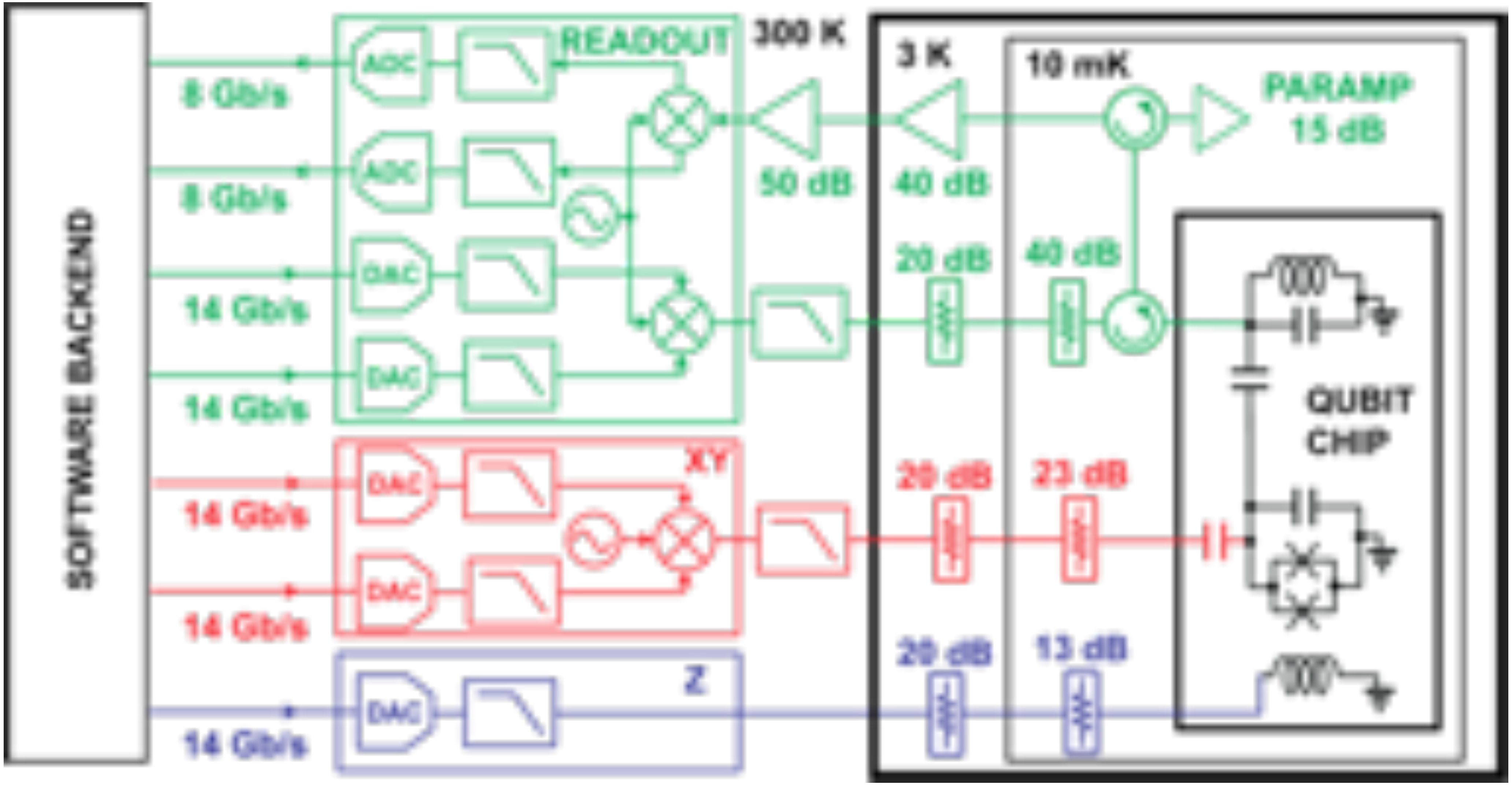






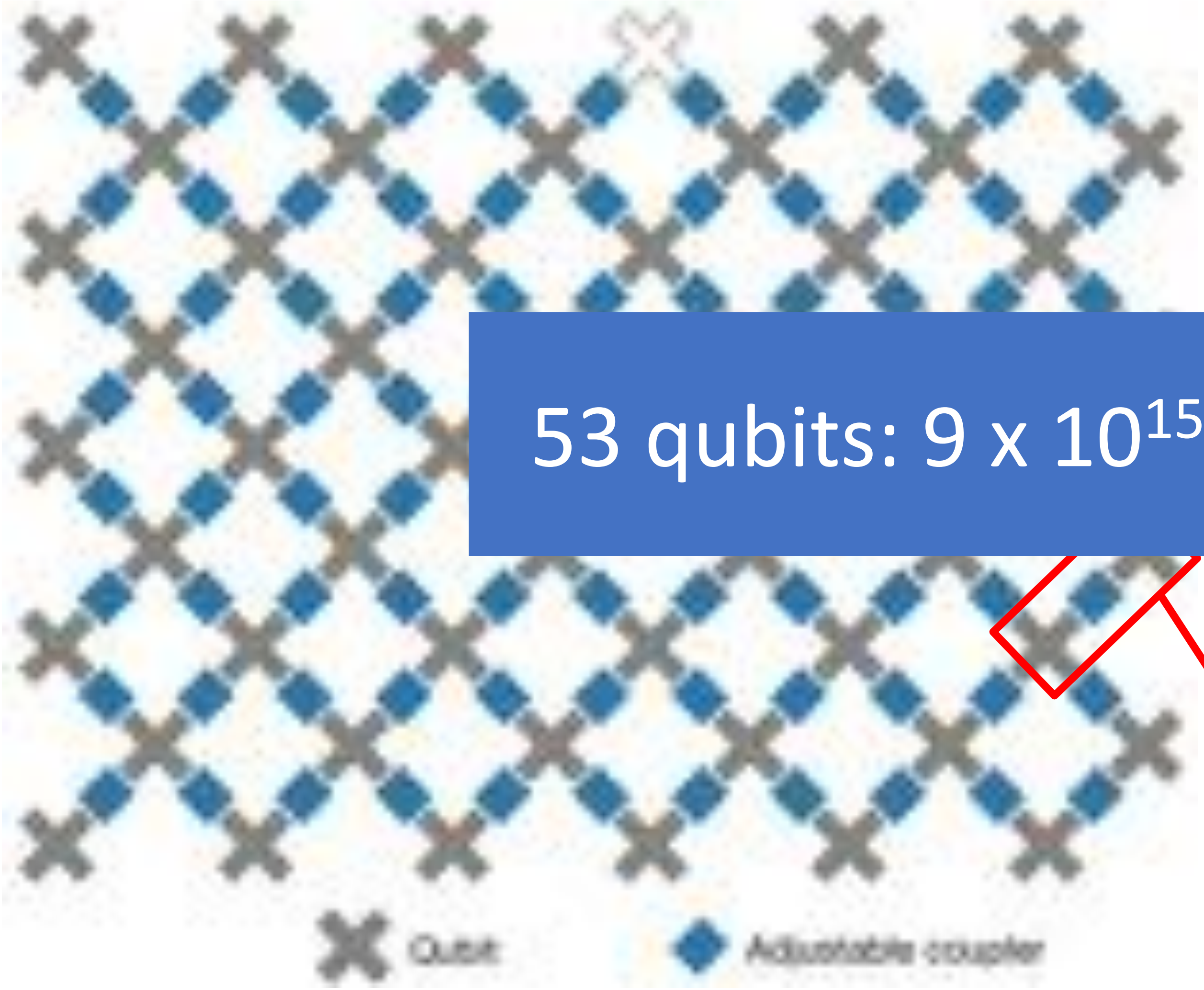
- Projective measurement: qubit assumes result
- State info encoded in phase (BPSK-like)
- One-shot meas. in 0.2-1us
- 5-10 qubits on one readout line
- Requires quantum limited amplification

Control/Measurement for One Qubit

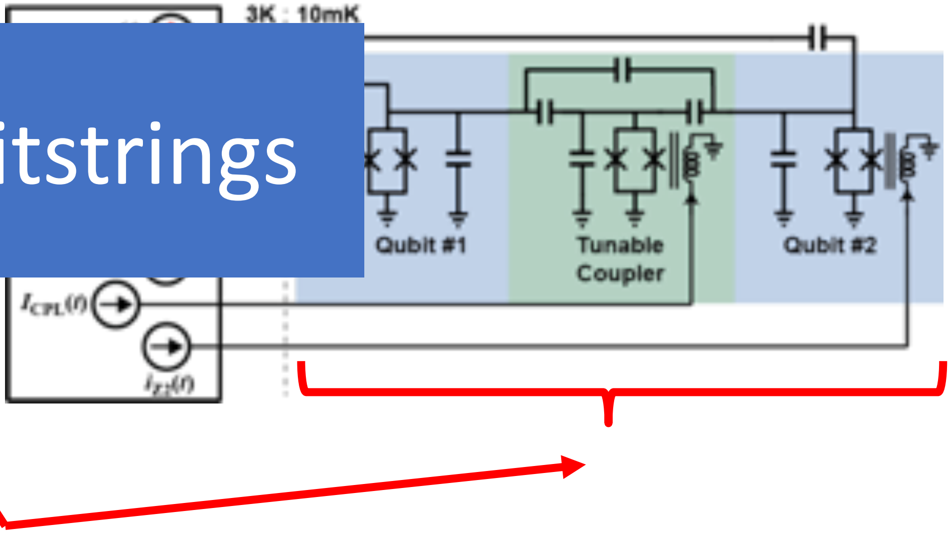


What can today’s quantum computers do?

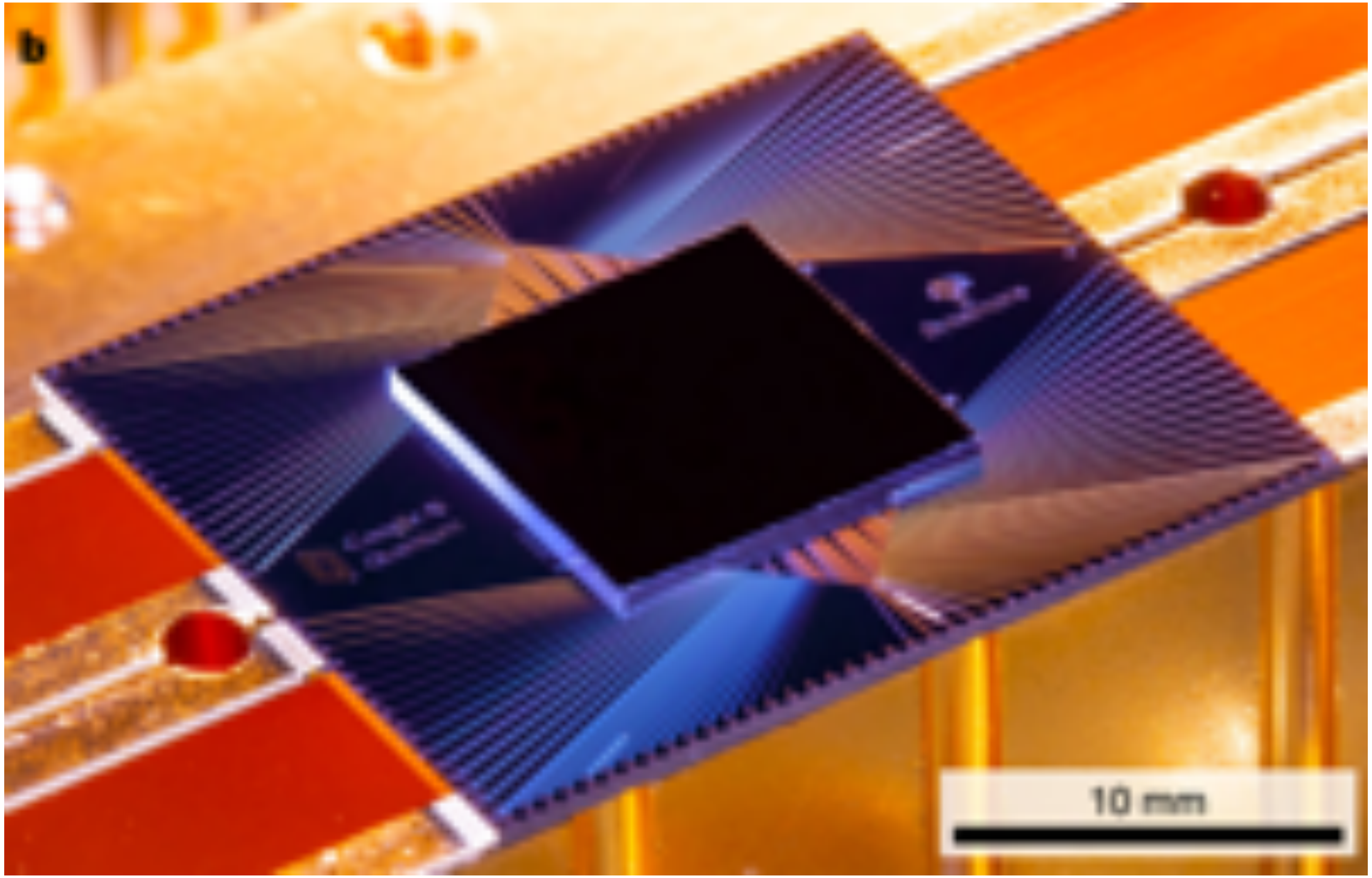
Sycamore Processor (53 qubits)



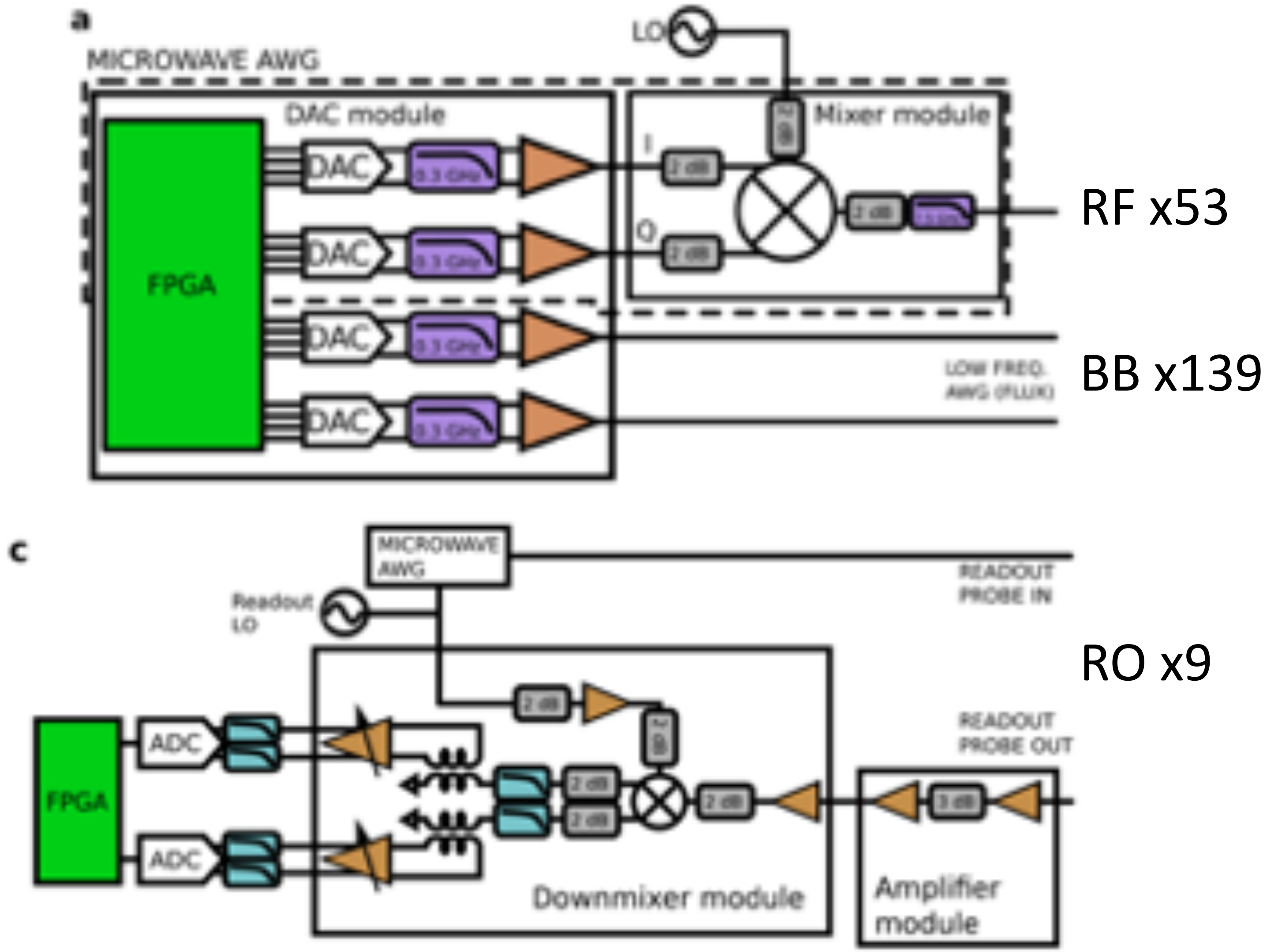
53 qubits: 9×10^{15} bitstrings



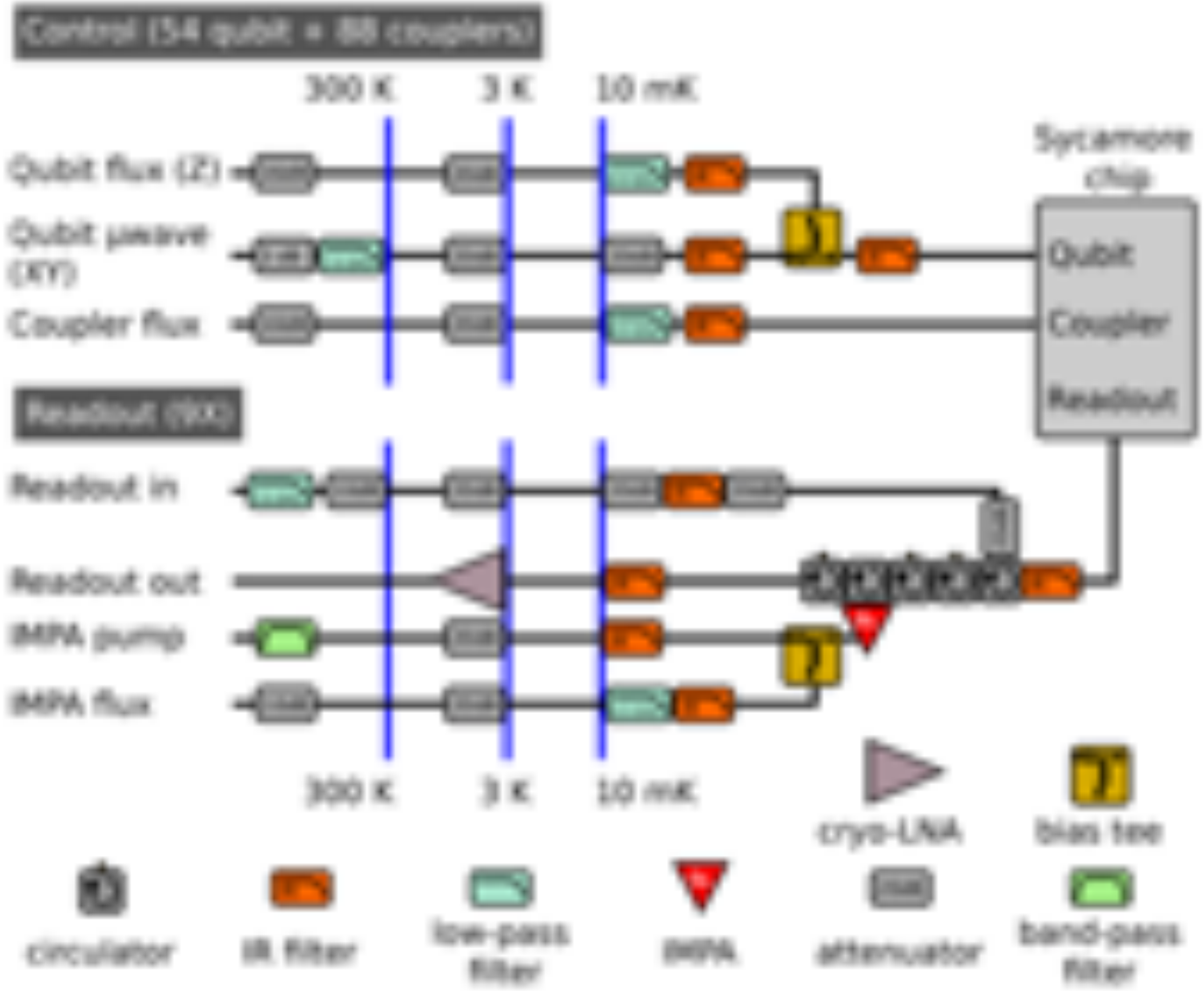
Sycamore Processor



Room Temperature Microwave Electronics



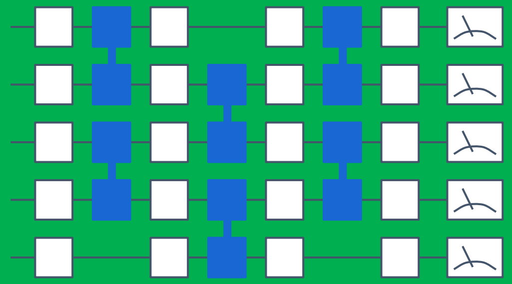
Cryogenic Microwave Electronics



Recipe to demonstrate beyond-classical performance

Algorithm: Sample bitstrings from 2^N Hilbert space (classically hard)

Run on quantum computer



Simulate on supercomputer

Measured bitstring statistics

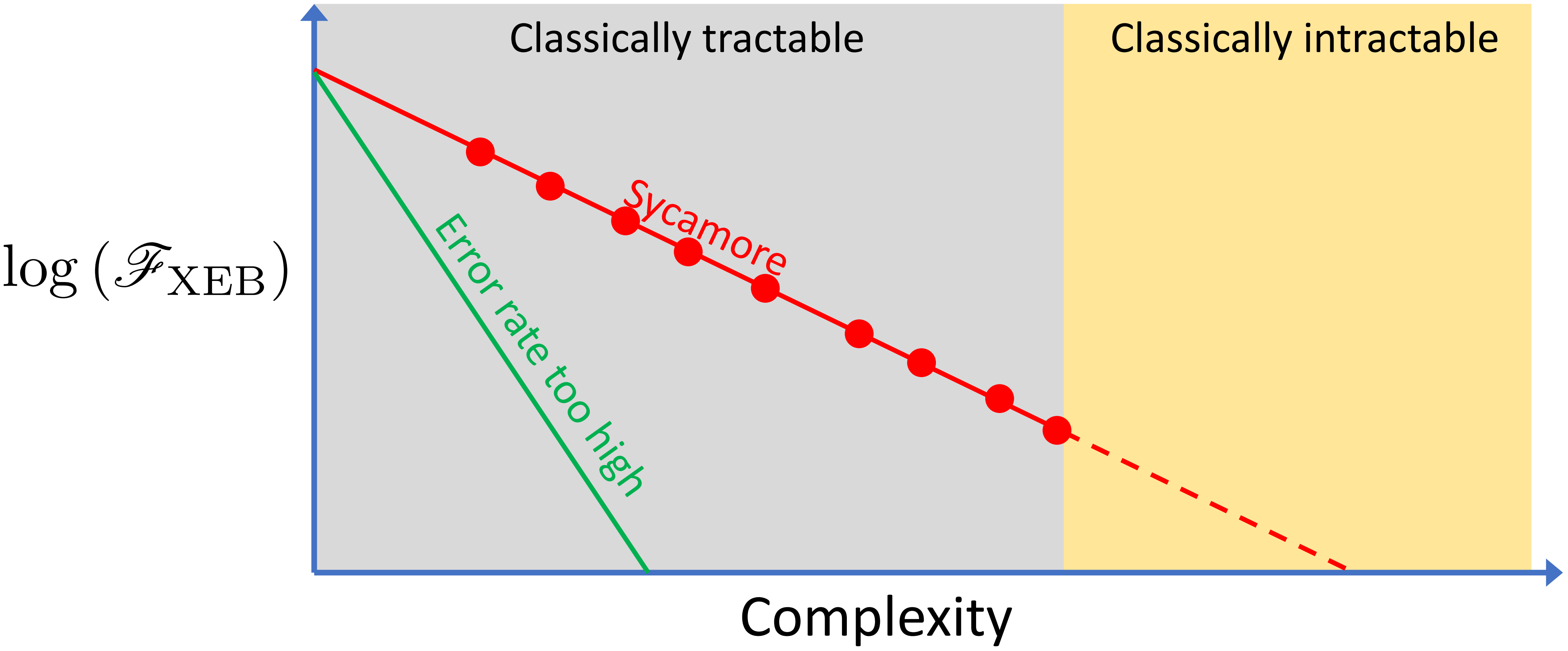
Benchmark

$$\mathscr{F}_{\mathrm{XEB}} \in [0, 1]$$

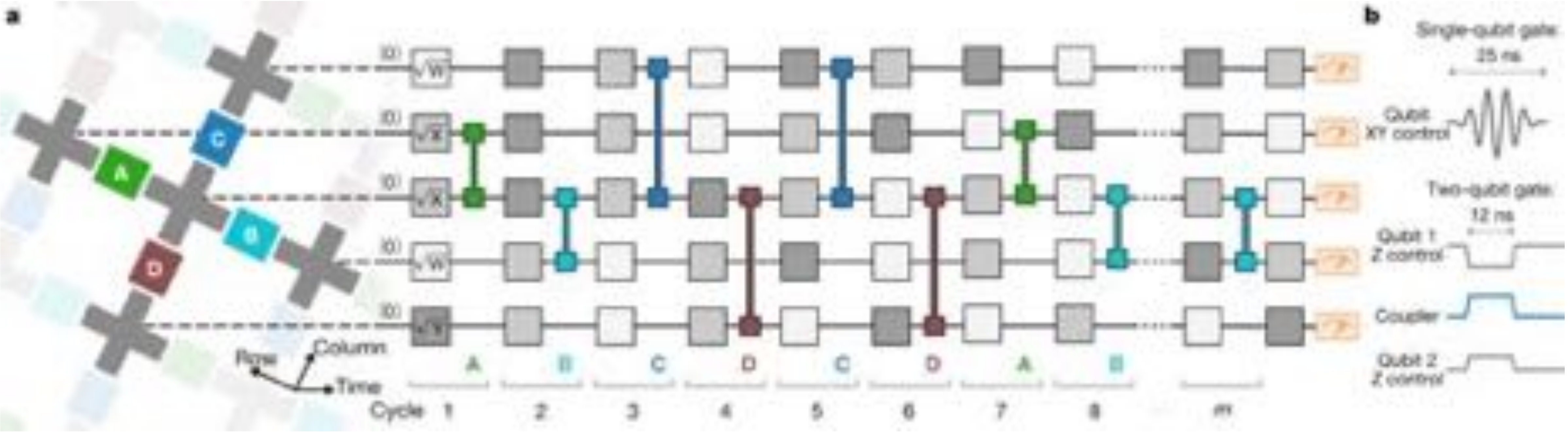
Probability of no errors

Computed bitstring probabilities

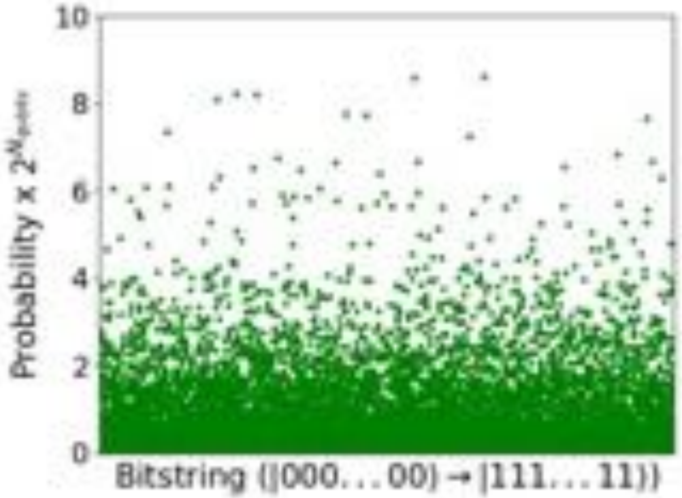
Recipe to demonstrate beyond-classical performance



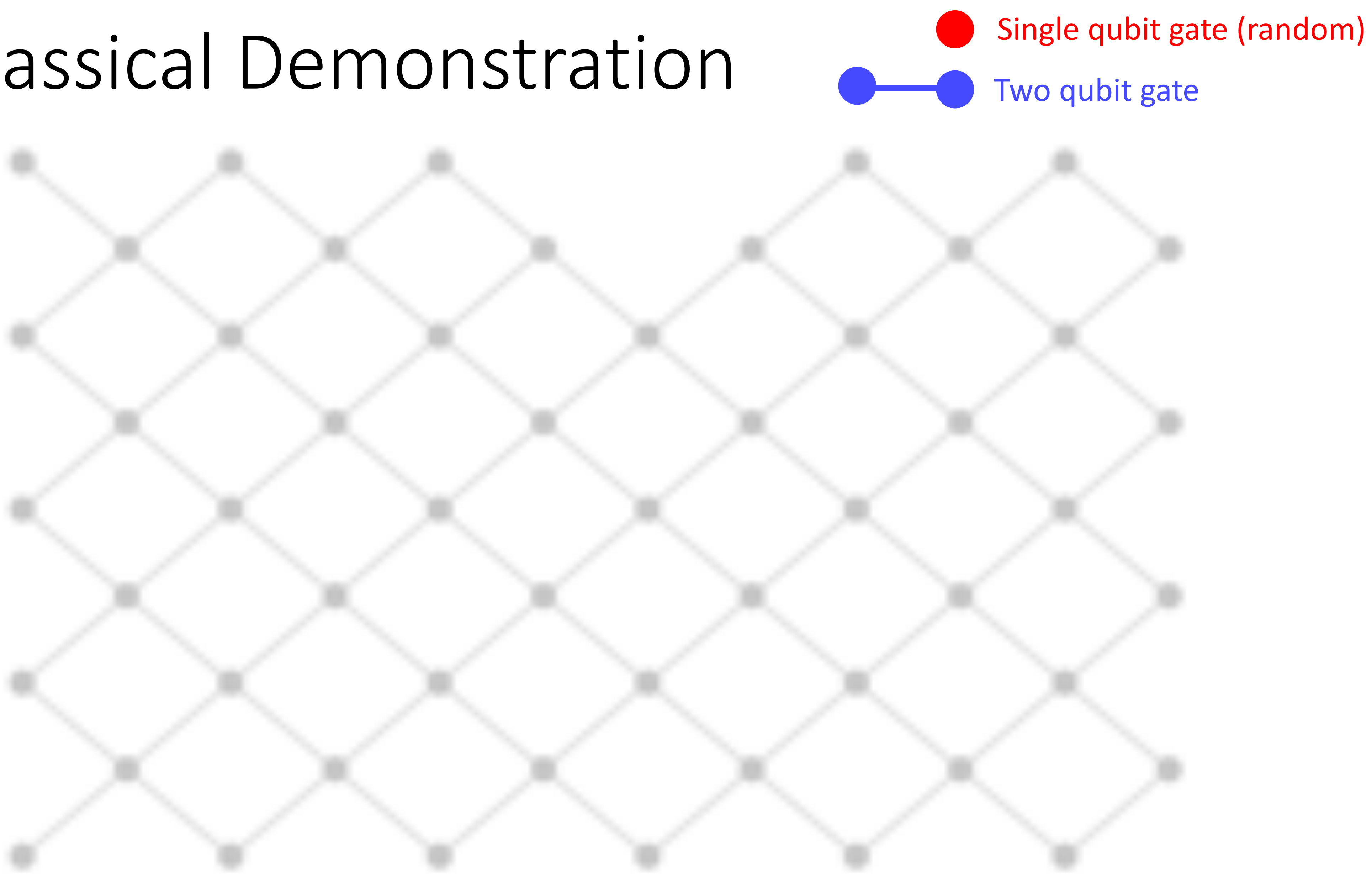
Post-Classical Demonstration



- Randomly selected single qubit gates
- Two qubit gates in repeating pattern
- Statistics quickly approach Porter-Thomas exponential distribution



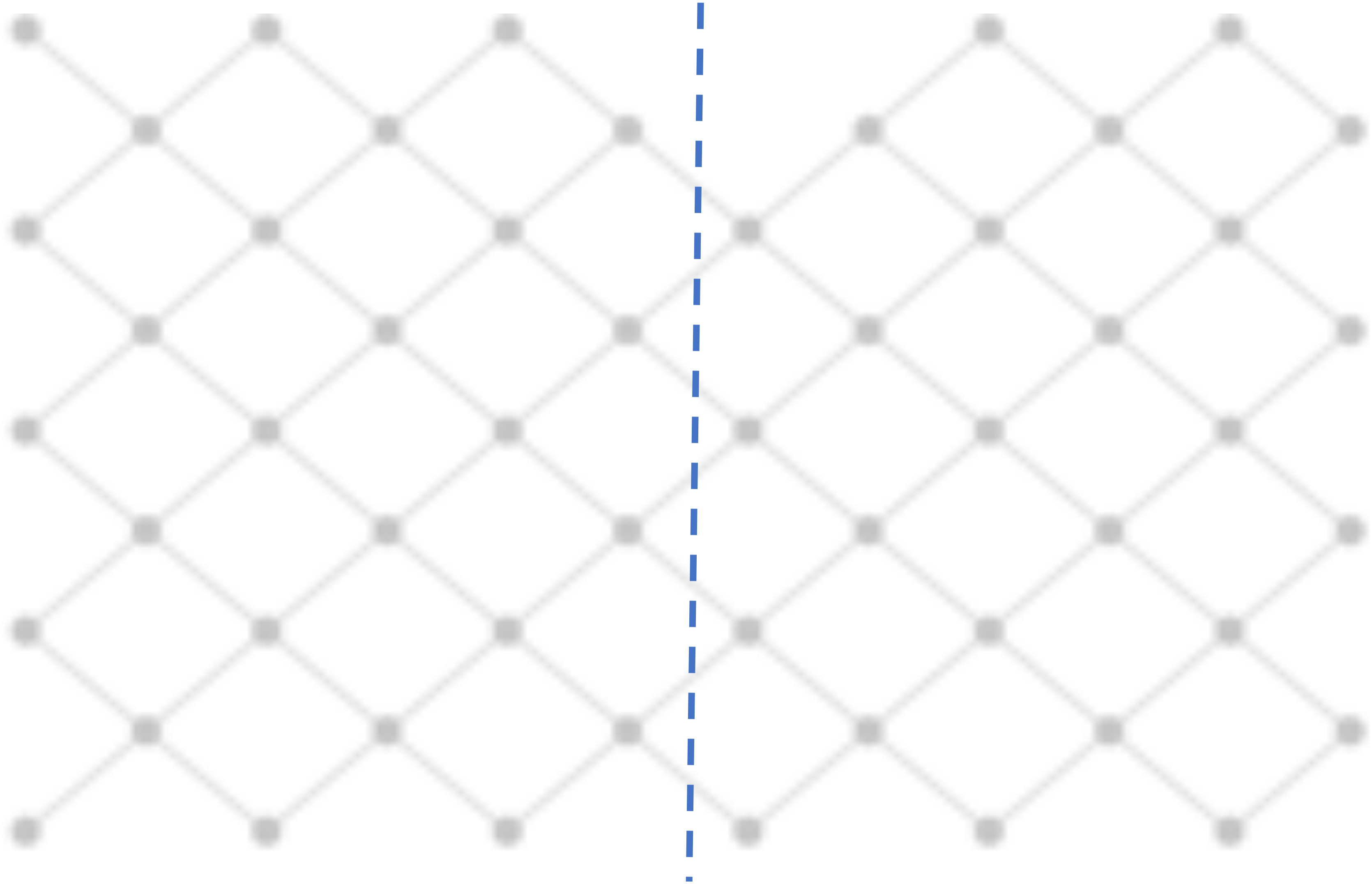
Post-Classical Demonstration



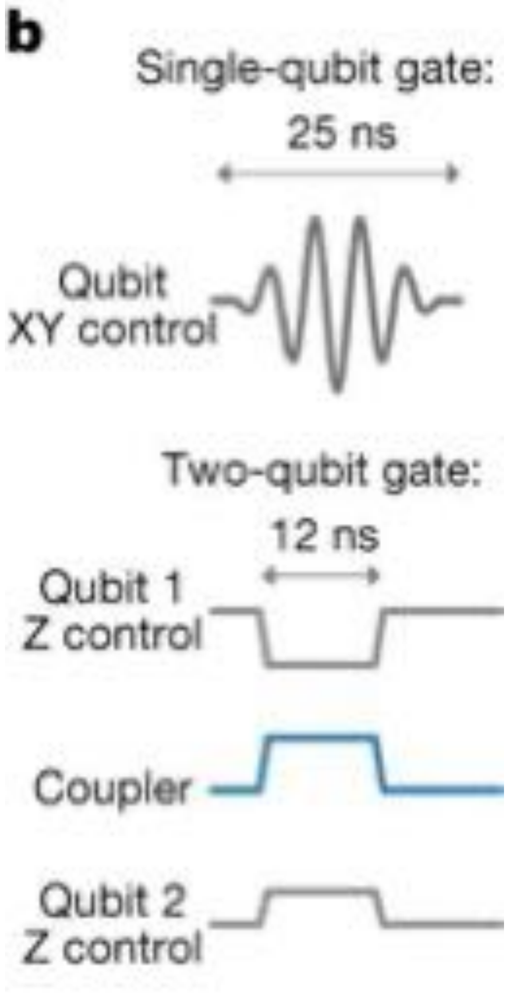
Simplified 'patch' circuits

Single qubit gate (random)

Two qubit gate



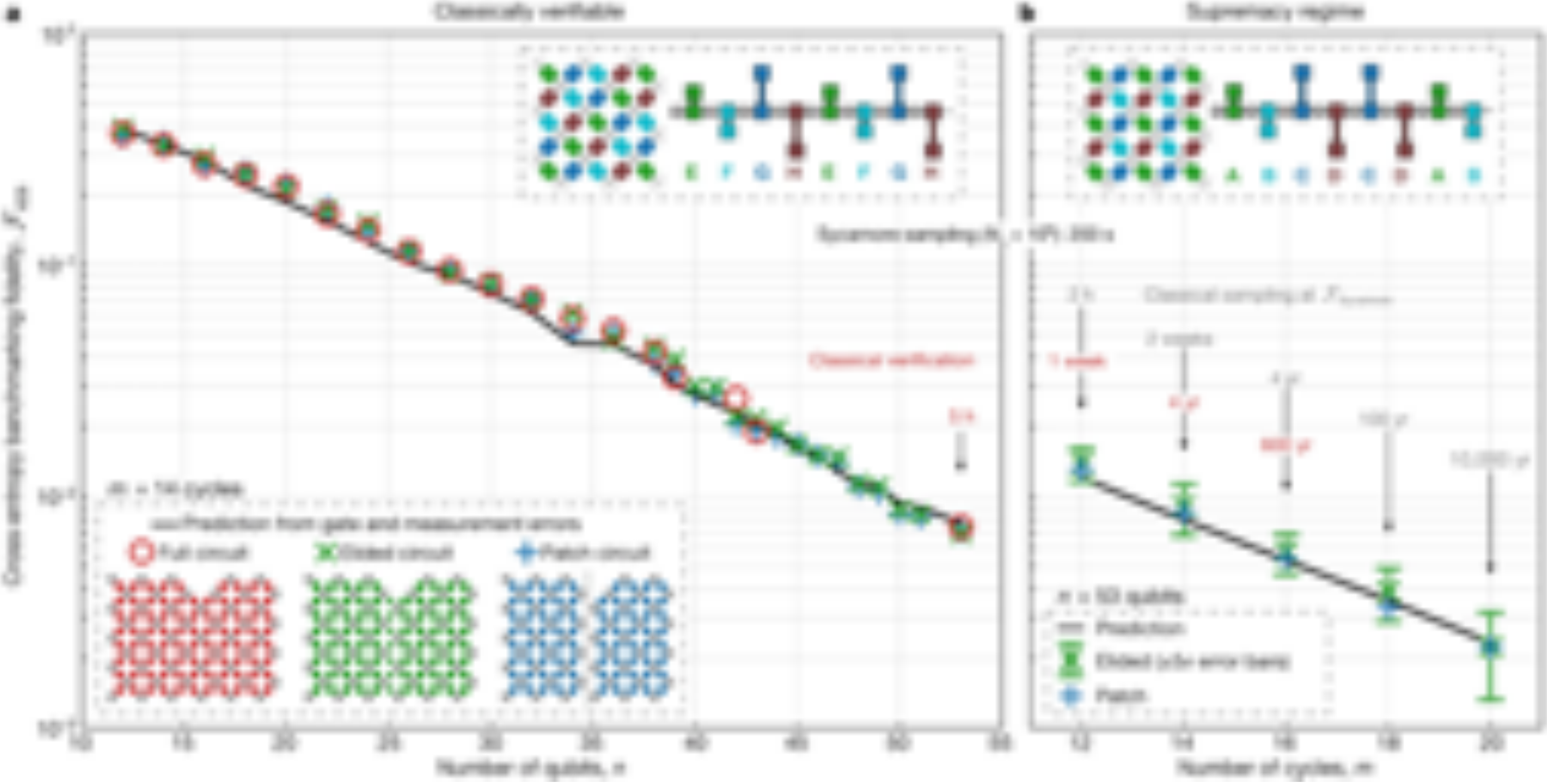
Signal requirements for largest circuits



1113 single qubit gates = 1113 microwave pulses

430 two qubit gates = 1290 baseband pulses

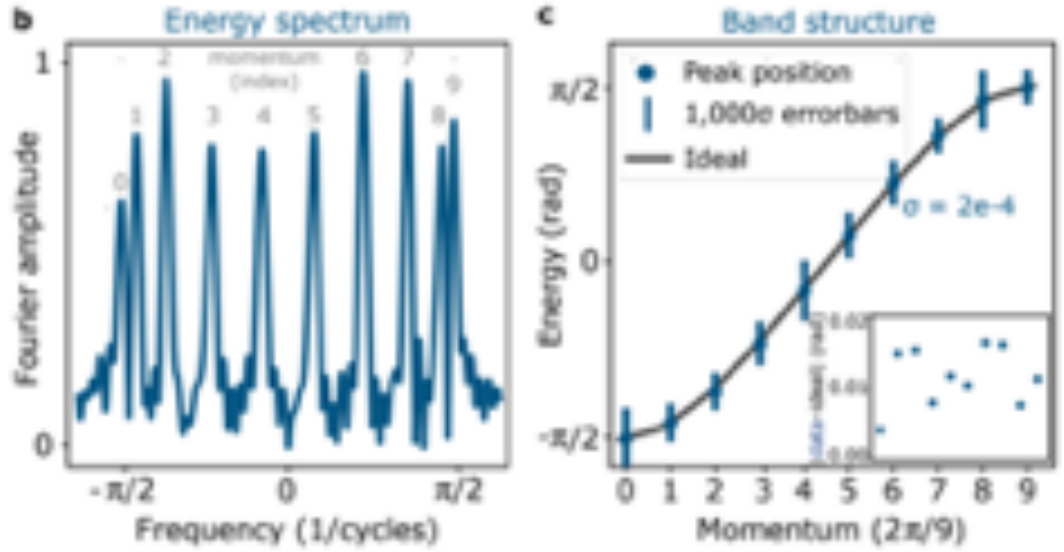
Experimental results



Arute et al, Nature 2019

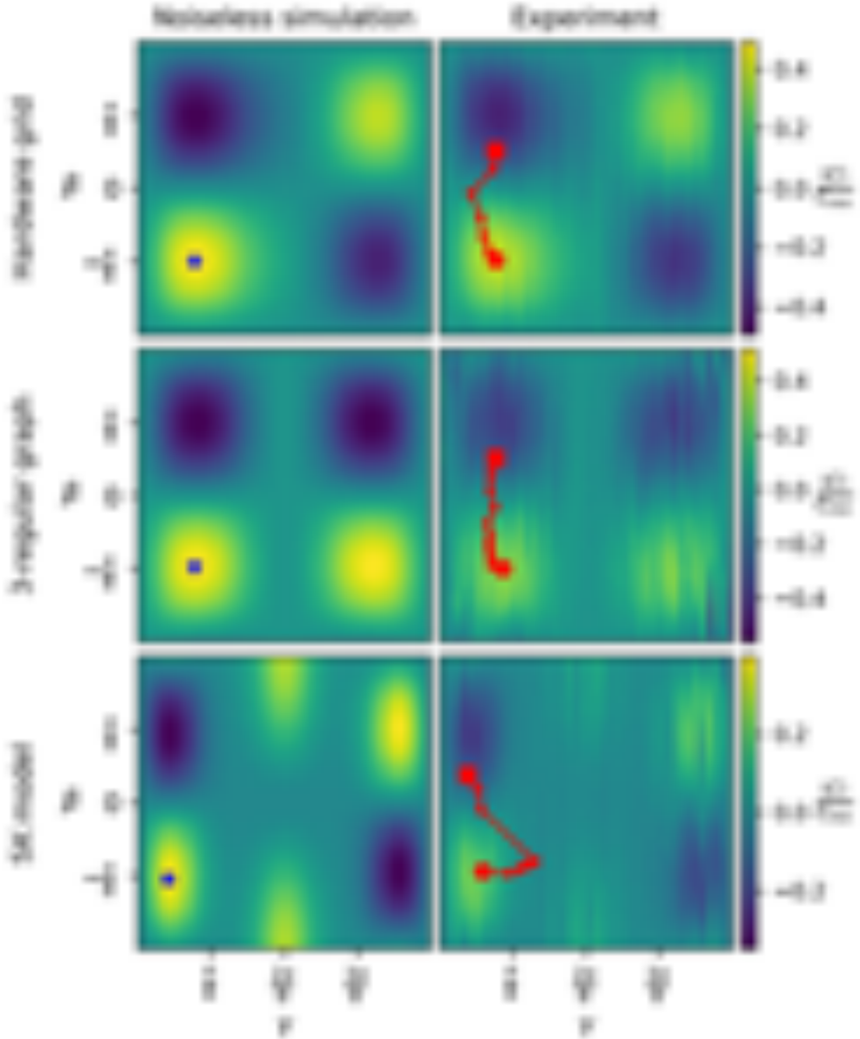
Applications of Sycamore

Band Structure



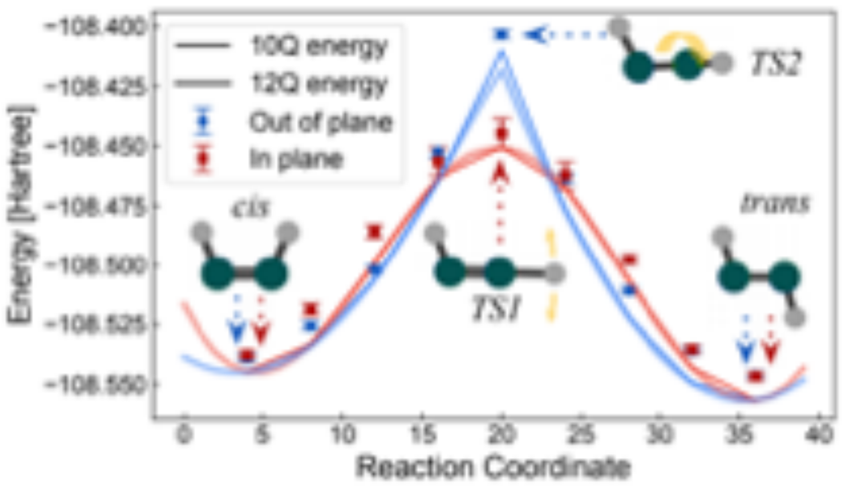
(Arute et al, ARXIV, 2020)

Optimization



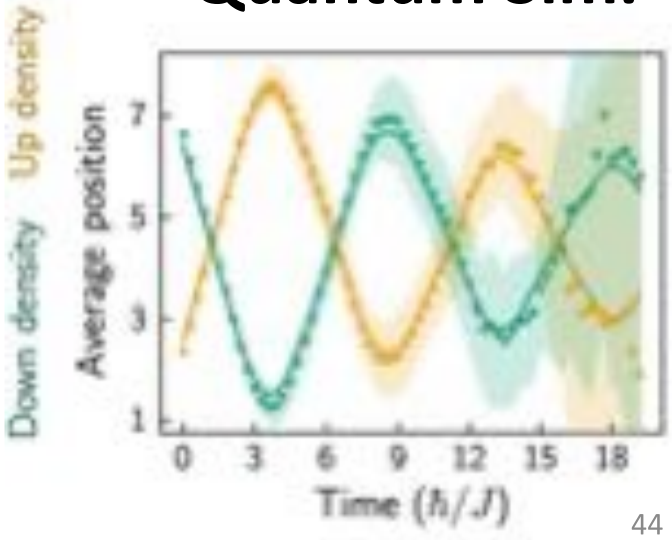
(Arute et al, Nature Physics, in press)

Chemistry



(Arute et al, Science, 2020)

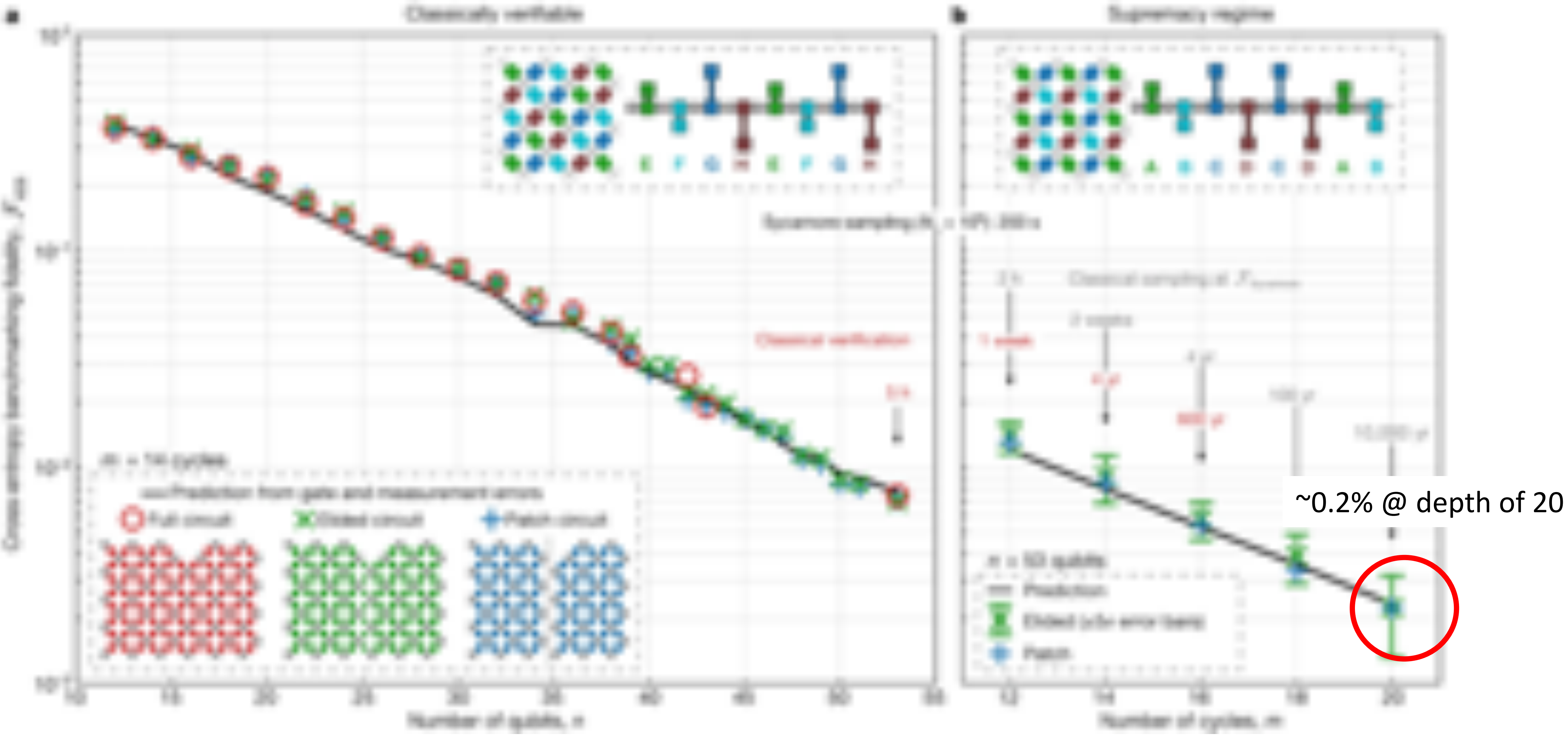
Quantum Sim.



(Arute et al, ARXIV, 2020)

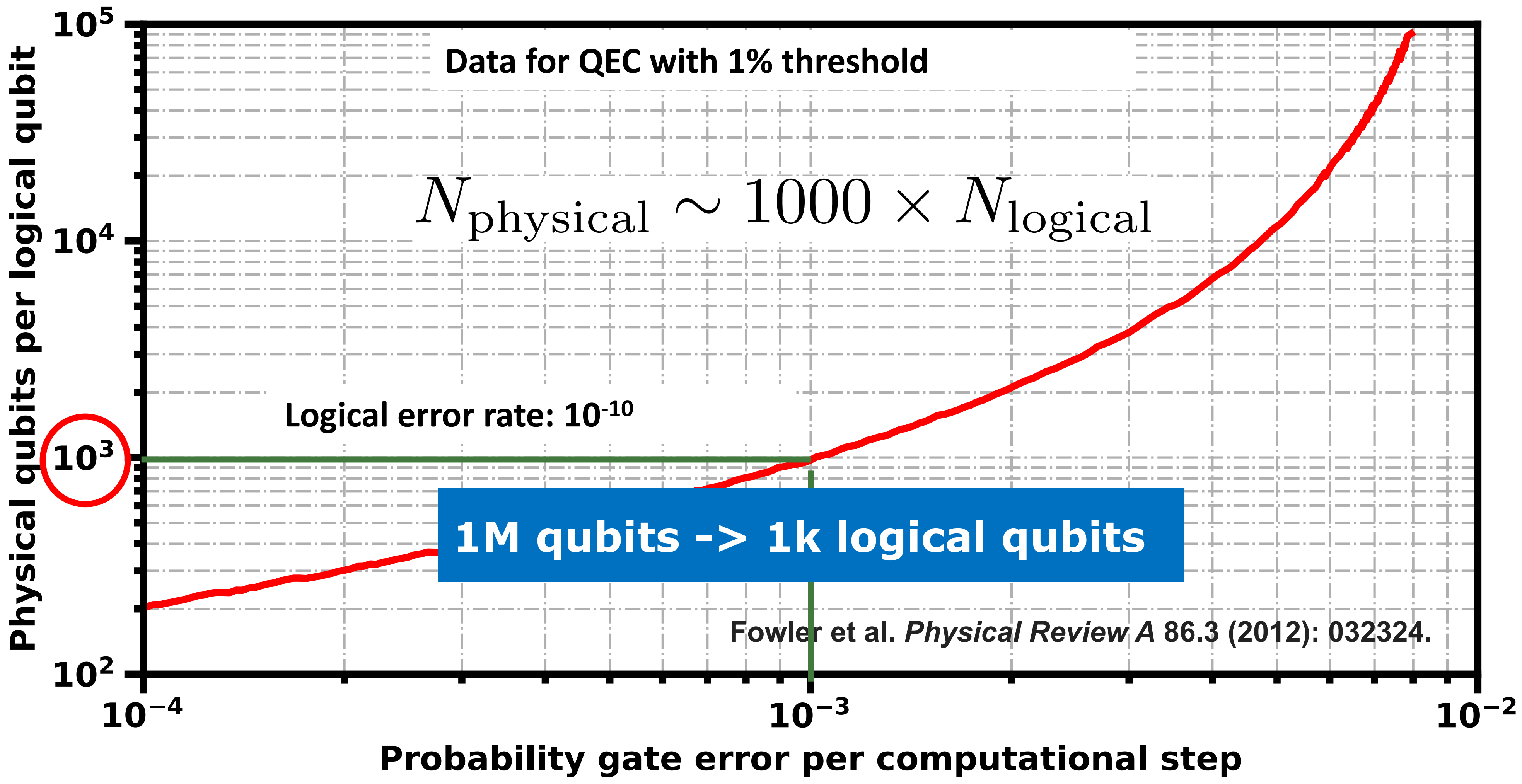
What microwave engineering is needed for the future?

53 qubits and depth of 20: probability of success ~ 0.2%



Arute et al, Nature 2019

Quantum error correction requires redundancy



1M Qubit Quantum Computers Targeted by Industry

MIT Tech Rev. 4/2020

Inside the race to build the best quantum computer on Earth

power of 1,000 qubits, you'd need a million actual ones. Google "conservatively" estimates it can build a million-qubit processor within 10 years, Neven says, though there are some big technical hurdles to overcome,

Science 9/15/2020

IBM promises 1000-qubit quantum computer—a milestone—by 2023

announced," she says. "The plan includes building intermediate-size machines of 127 and 433 qubits in 2021 and 2022, respectively, and envisions following up with a million-qubit machine at some unspecified date. Dario Gil, IBM's director of research, says he is confident his team can keep

Global Times 8/26/2020

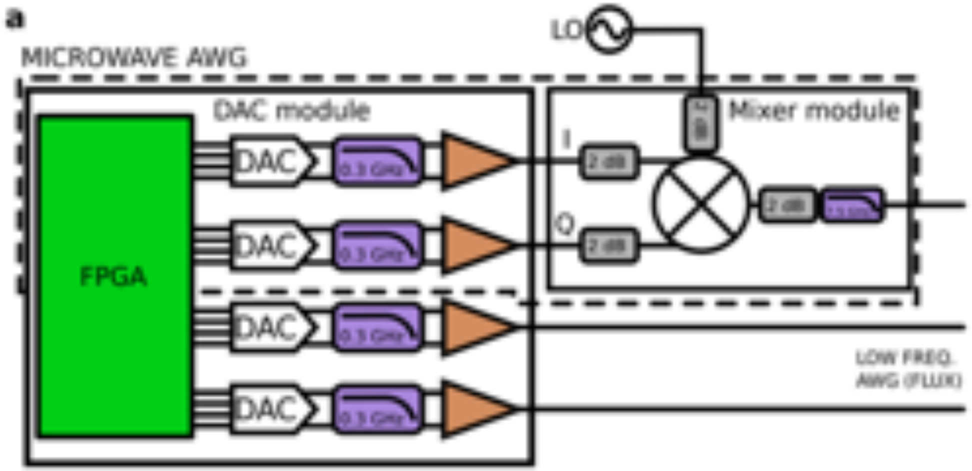
Chinese researchers expect quantum leap in computing, challenging Google's supremacy

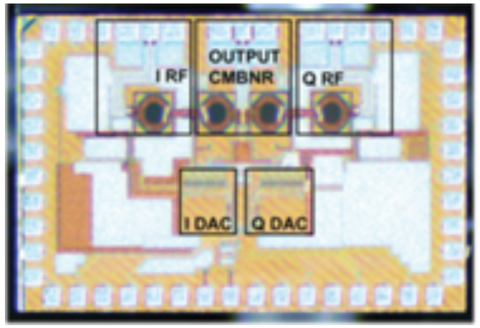
Chinese quantum computing researchers recently disclosed that a 60-qubit superconductivity quantum computing system with 99.5 percent fidelity could be achieved this year, and in 10 years, the system could evolve into a million-qubit level with a 99.8 percent fidelity, equivalent to, if not better than, its Google counterpart.

https://www.technologyreview.com/2020/02/26/916744/quantum-computer-race-ibm-google/
https://www.sciencemag.org/news/2020/09/ibm-promises-1000-qubit-quantum-computer-milestone-2023
https://www.globaltimes.cn/content/1198916.shtml

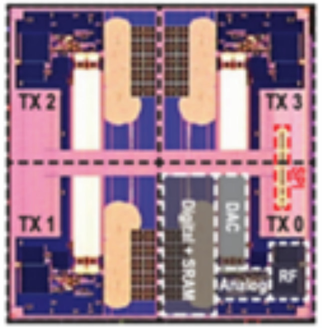
Microwave Challenges: Control of 1M qubit QC

- 1M XY and 3M baseband AWGs required
- Thermalize at 4K? 300? Other?
  - 4K simplifies system design, but <1mW/qubit required.
  - 300K eases power, but interconnects become harder.
- XY Challenges:
  - Frequency planning
  - Synchronization
  - Crosstalk
  - Waveform optimization
- Z Challenges:
  - Reflections
  - Z-tails (requires extensive calibration)
  - IR drops





Bardin, ISSCC, 2019
2mW/qubit XY controller @3K



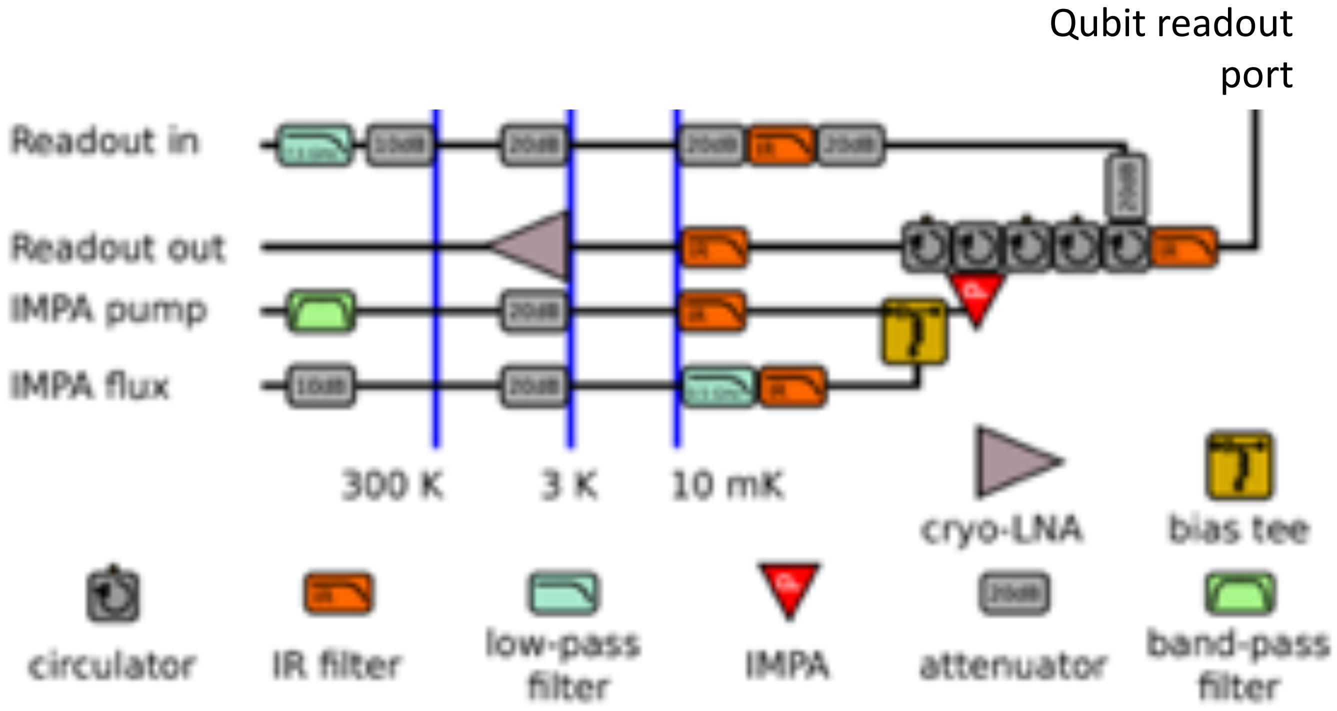
Patra, ISSCC, 2020
12mW/qubit 4x32 FDM
XY controller @3K

Microwave Challenges: Readout of 1M qubit QC

- Cryogenic semiconductor LNAs
  - Today: III-V amplifiers, individually tested, several mW
  - Future: Silicon amplifiers, spot tested, µW power?

- Parametric LNAs and 10mK passives
  - Par amps still 'boutique technology': needs maturation to improve yield
  - Currently several circulators per readout channel: either remove need or determine method to miniaturize

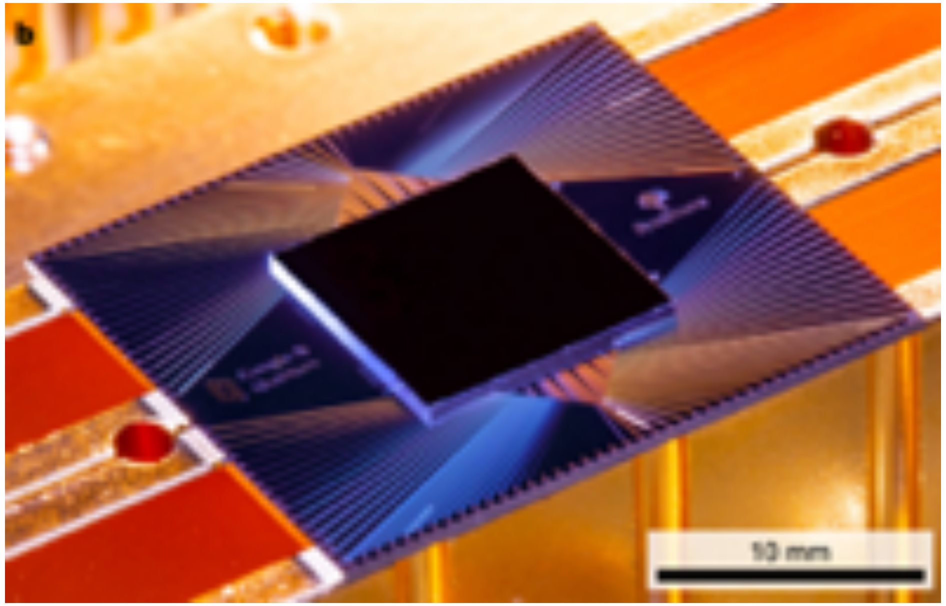
<u>~100,000 near quantum limited readout channels</u>



Microwave Challenges: Interconnects & Packaging

- Interconnects for 1M qubit QC:
  - 1M qubits => ~4.2M interconnects
  - High density (order mm pitch)
  - High thermal isolation
  - Superconducting from 4K to 10mK
  - Minimum thermal loading from room temp to 3K
  - Cross-talk must be controlled

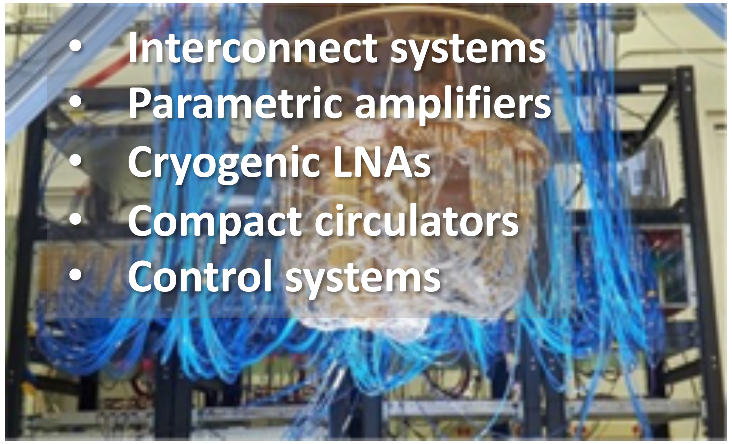
- Package for 1M qubit QC:
  - ~5,000 interconnects per package/module
  - Very low RF loss
  - No relevant moding
  - High isolation
  - Excellent matching
  - Low contact resistance to package
  - EM simulation of packaged processor

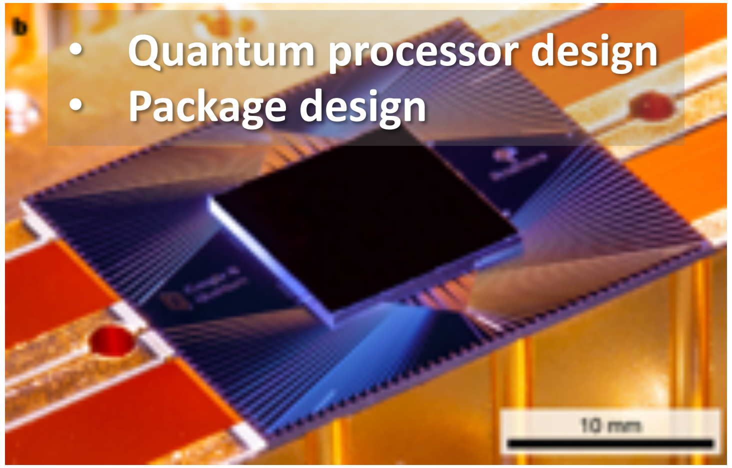


Conclusions

- Quantum computing largely enabled by microwave technologies
- Today's systems can already operate beyond the limits of classical computers for certain tasks
- Microwave engineers will be essential in the quest to implement a fault-tolerant quantum computer!
- Want to contribute? Please reach out!
  bardinj@google.com
  jbardin@engin.umass.edu

Many opportunities for µW engineers!





Google AI Quantum

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More details

Microwaves in Quantum Computing

End of presentation