Équipe de recherche en Physique de l'Information Quantique

Superconducting qubits

Alexandre Blais
Université de Sherbrooke, Québec, Canada

Which quantum computer is right for you?

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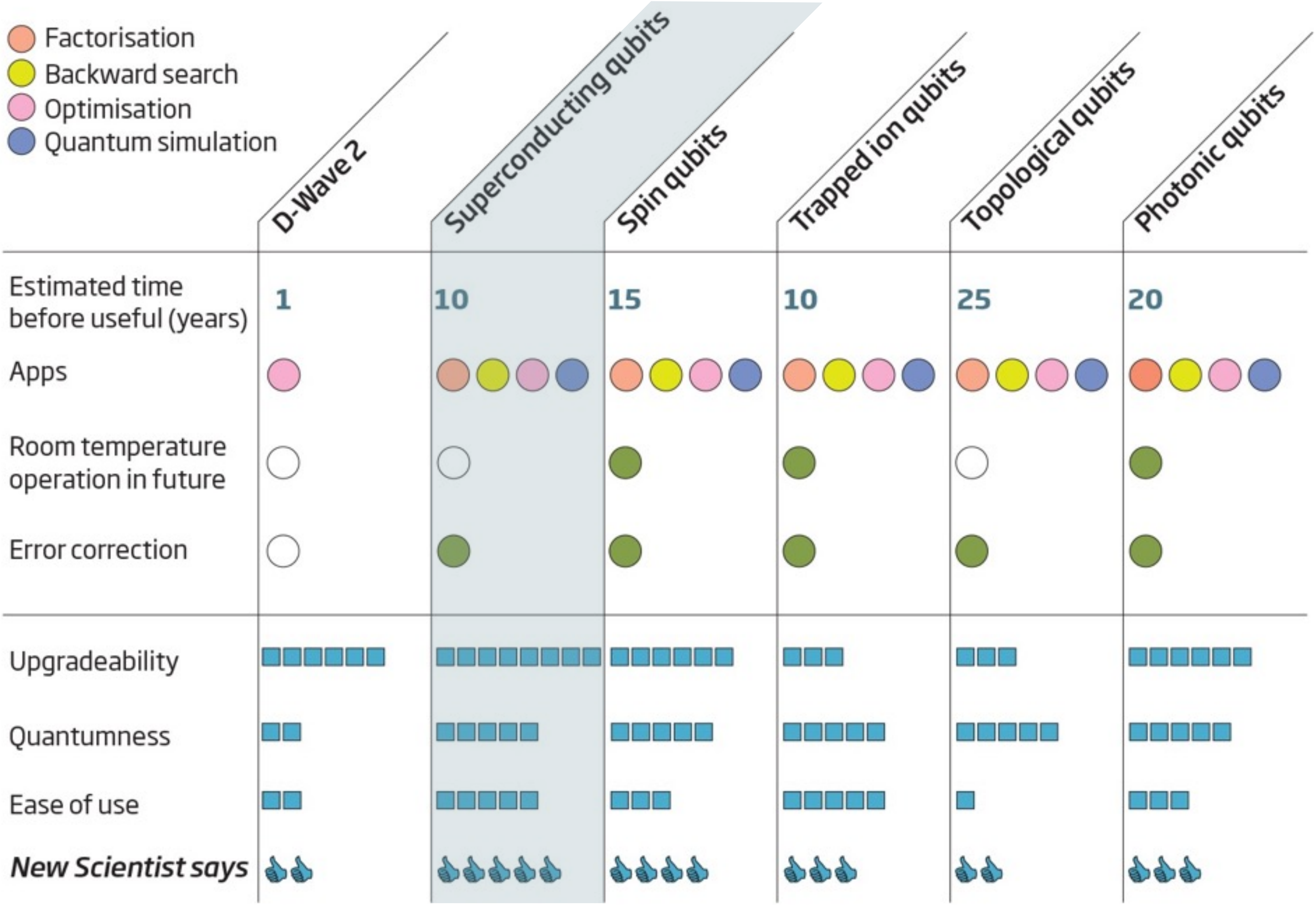
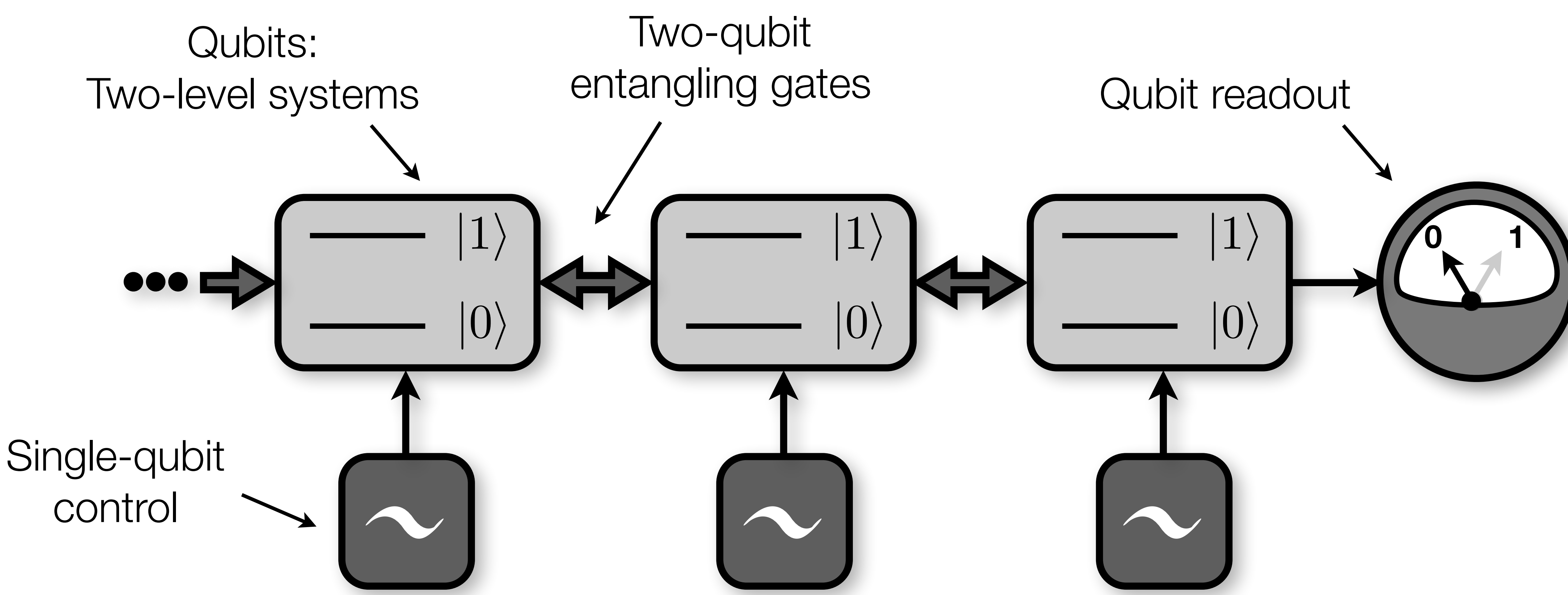
There are many types to choose from. Here's how they compare and our all-important verdict



Quantum information processing: the challenge



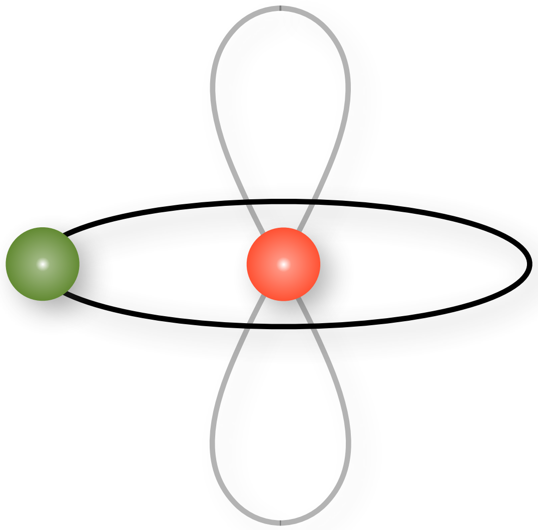
- Conflicting requirements: *long-lived* quantum effects, *fast* control and readout

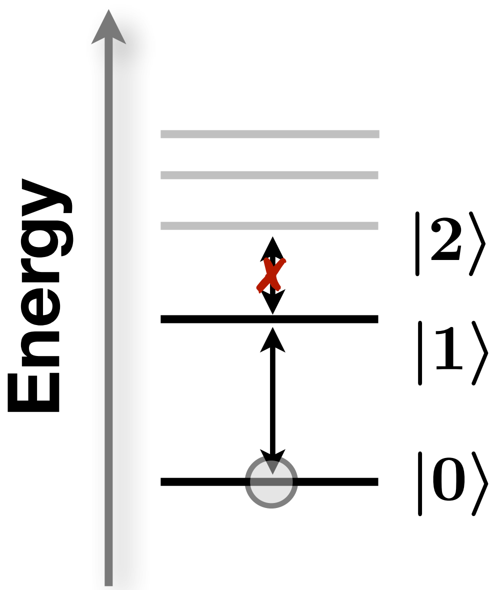
D. DiVincenzo, Fortschritte der Physik **48**, 771 (2000)

Outline

- **Artificial atoms**
  - Physics 101: Harmonic oscillators and basic electrical circuits
  - Superconductivity and Josephson junctions
- **Circuit QED: a possible QC architecture**
- **Recent realizations and challenges**

‘Atomic atoms’





Good «two-level atom» approximation

$$E_{01} = E_1 - E_0 = \hbar\omega_{01}$$

- Control by shining laser tuned at the desired transition frequency

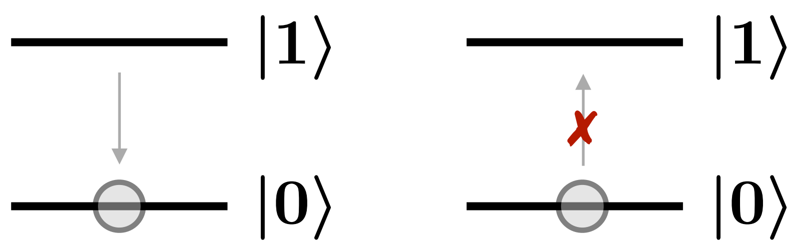
- Hyperfine levels of $^9Be_+$ have long relaxation and dephasing times

$$T_1 \sim \text{a few years} \qquad T_2 \gtrsim 10 \text{ seconds}$$

T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J. L. O’Brien, Nature **464**, 45 (2010)

Relaxation and dephasing times

- T_1: Relaxation = amplitude damping channel $\neq$ bit flip channel



(Energy is conserved)

Probability of qubit having relaxed at time t:

$$e^{-t/T_1} = e^{-\gamma_1 t}$$

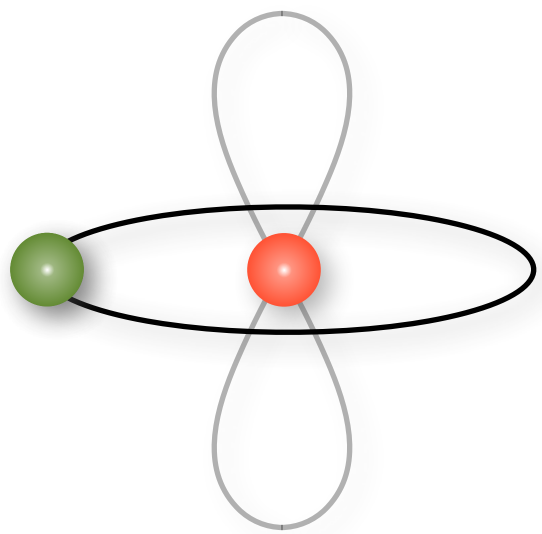
- T_2: Dephasing = phase damping channel = phase flip channel

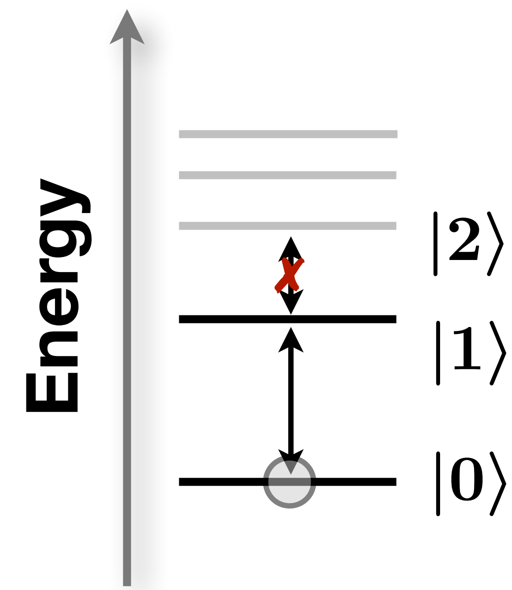
$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle \rightarrow \rho = \begin{pmatrix} |c_0|^2 & c_0 c_1^* e^{-t/T_2} \\ c_0^* c_1 e^{-t/T_2} & |c_1|^2 \end{pmatrix}$$

Probability of phase decay at time t:

$$e^{-t/T_2} = e^{-\gamma_2 t}$$

‘Atomic atoms’





Good «two-level atom» approximation

$$E_{01} = E_1 - E_0 = \hbar\omega_{01}$$

- Control by shining laser tuned at the desired transition frequency

- Hyperfine levels of $^9Be_+$ have long relaxation and dephasing times

$$T_1 \sim \text{a few years} \qquad T_2 \gtrsim 10 \text{ seconds}$$

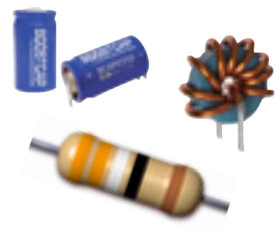
- Reasonably short gate time

$$T_{\text{not}} \sim 5\ \mu\text{s}$$

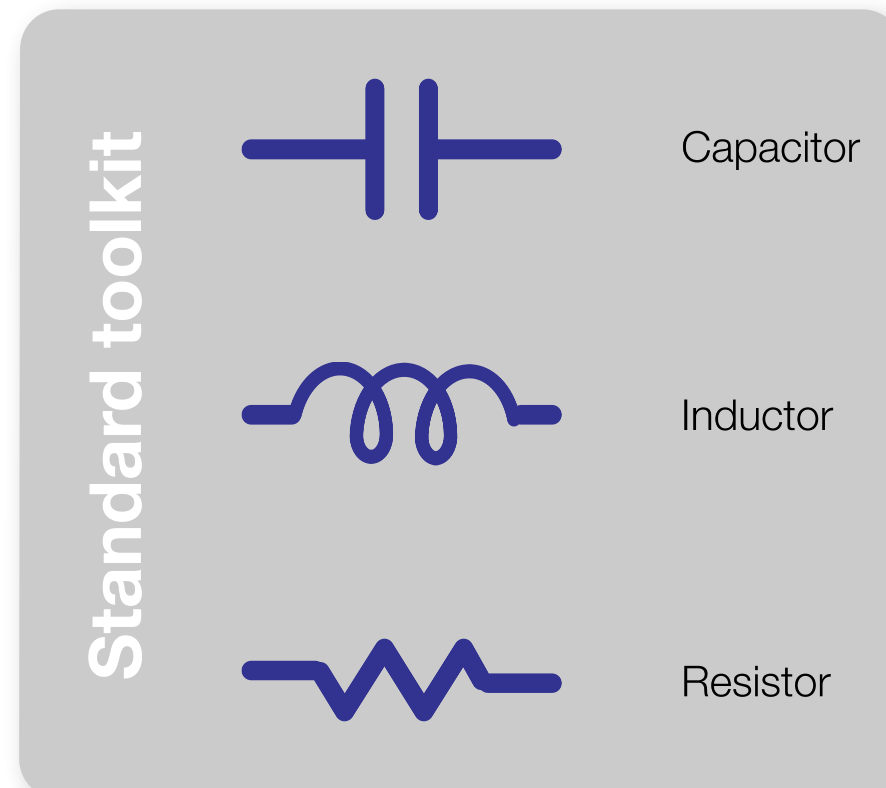
- Low error per gates: ~ 0.48%

T. D. Ladd, F. Jelezko, R. Laflamme, Y. Nakamura, C. Monroe, and J. L. O’Brien, Nature **464**, 45 (2010)

Artificial atoms

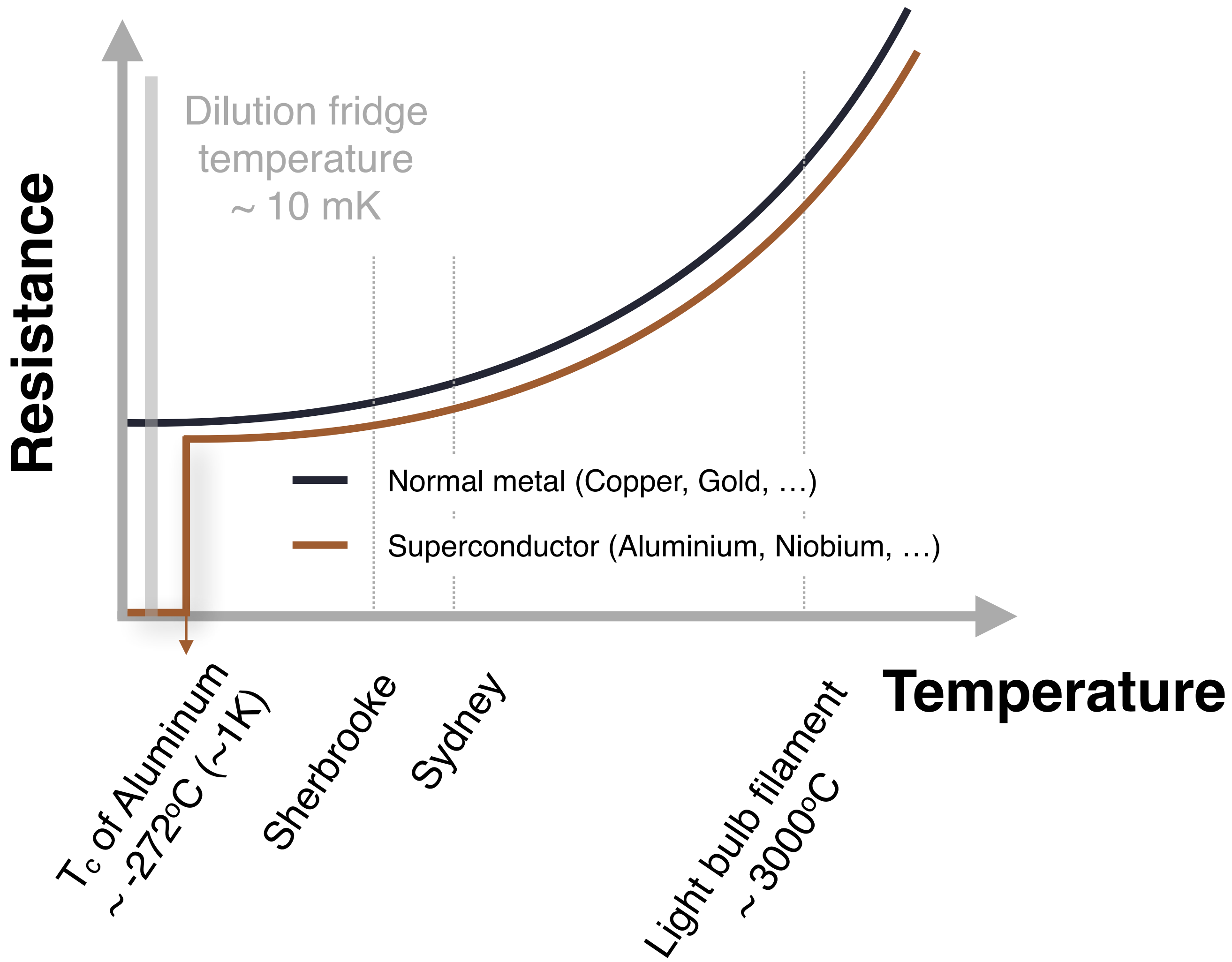


- Based on microfabricated circuit elements
- Well defined energy levels
- Nonlinear distribution of energy levels
- Maximize numbers of thumbs up!



Avoiding dissipation: superconductivity

- Normal metals dissipate energy

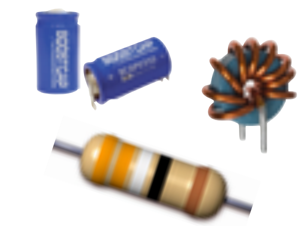


- No resistance in superconducting state $\Rightarrow$ no dissipation

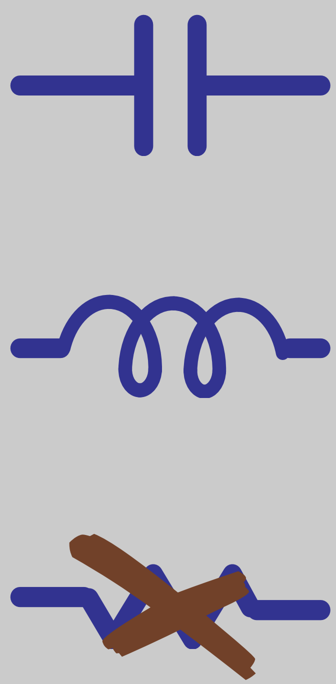
- Superconductivity is a (macroscopic) quantum effect

- A good starting point for a quantum device…

Basic circuit elements *(classical version)*



Standard toolkit

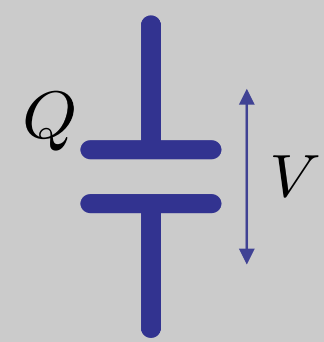


Capacitor (C)

Inductor (L)

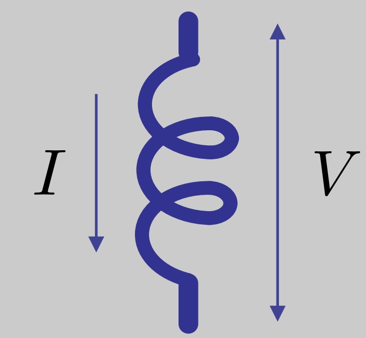
Resistor (R)

Capacitor:
- Two metal plates separated by an insulator
- Relates voltage to charge



$$Q = CV$$

Inductor:
- A non-resistive wire
- Relates voltage to change of current

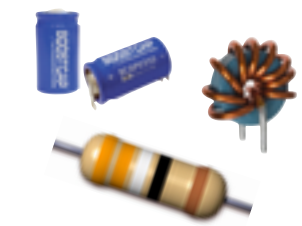


$$V = L\frac{dI}{dt}$$

$$\Phi = LI$$

$$\Phi = \int_{-\infty}^{t} dt'\, V(t')$$

Basic circuit elements *(classical version)*



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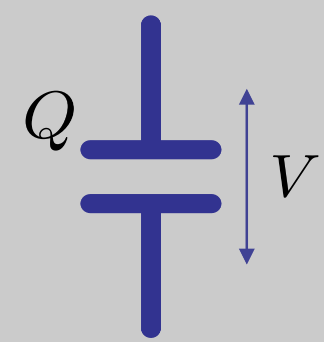

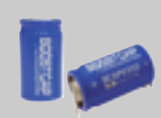

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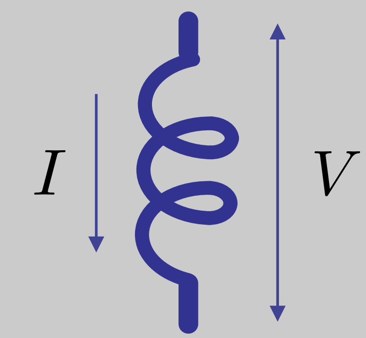
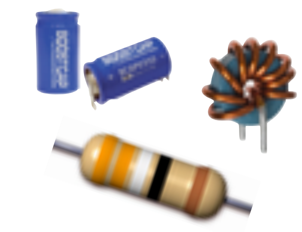


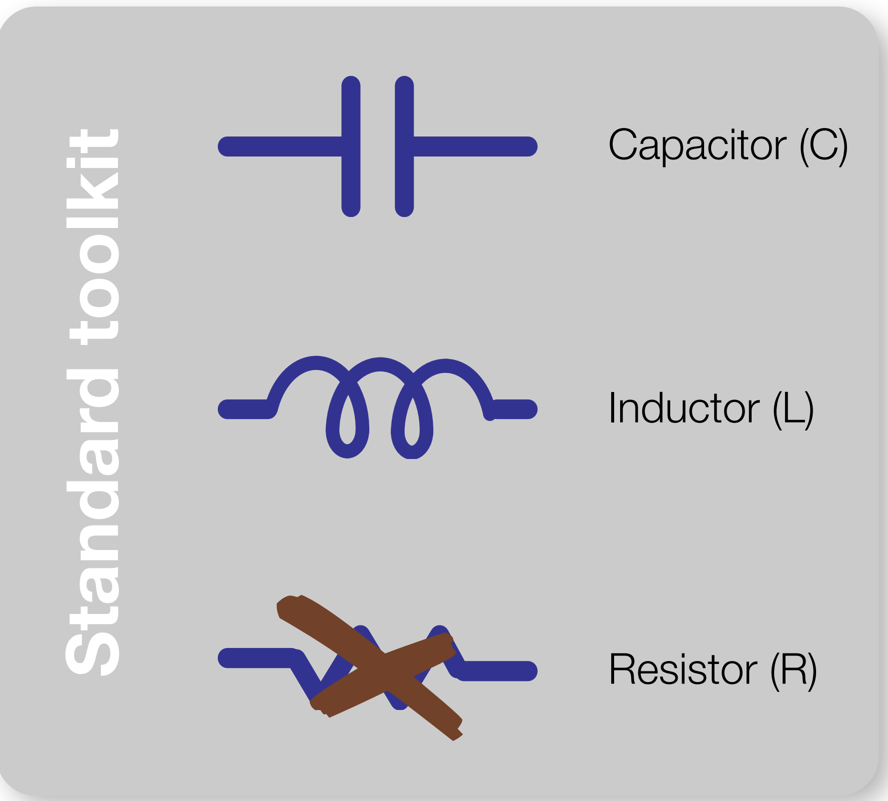
$$V = L\frac{dI}{dt}$$

Current:
Change of charge in time

$$I = \frac{dQ}{dt}$$

Basic circuit elements *(classical version)*





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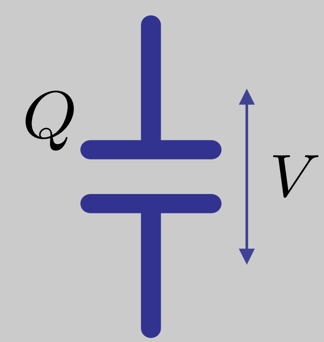

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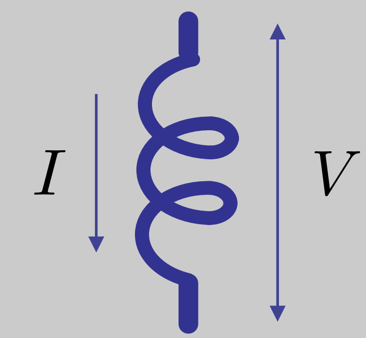


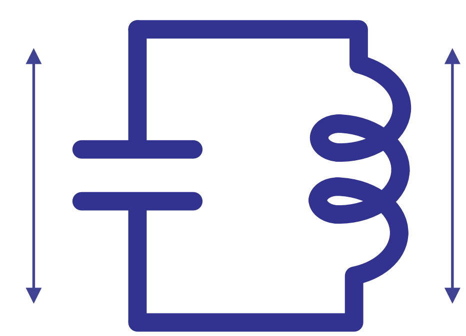
$$V = L\frac{dI}{dt}$$

Voltage is the same across L and C:

$$\frac{Q}{C} = L\frac{d^2Q}{dt^2}$$

$$Q(t) = Q(0)\cos(\omega_{\mathrm{LC}} t) \qquad \omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}}$$

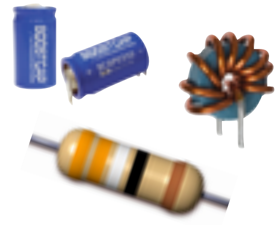
$$V = \frac{Q}{C}$$



$$V = L\frac{dI}{dt}$$

LC oscillator

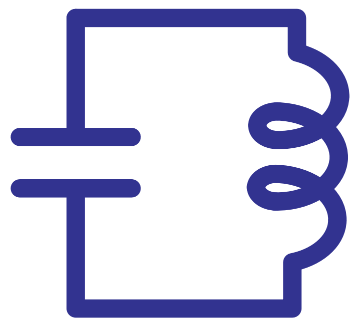
Basic circuit elements *(classical version)*

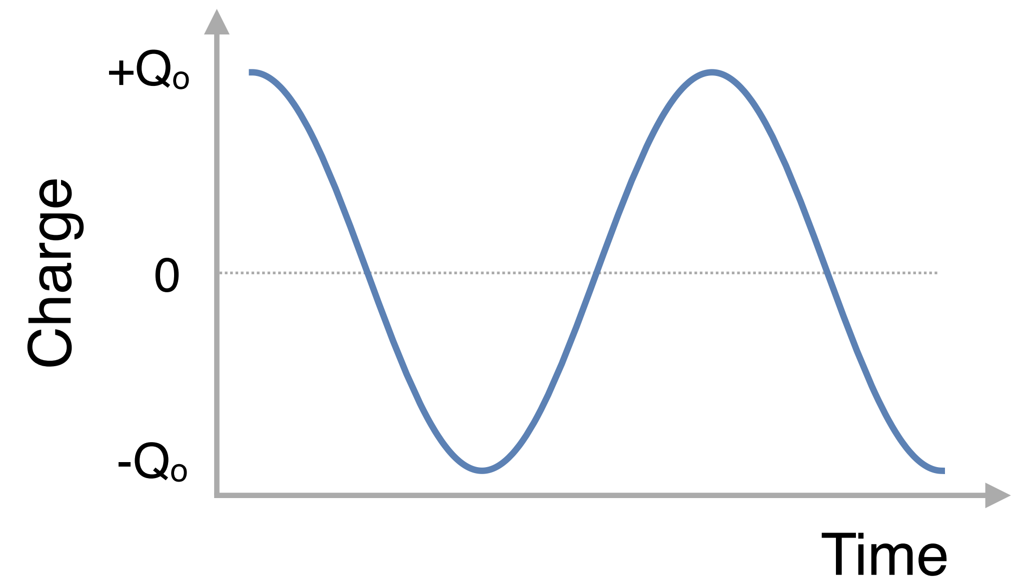


Oscillations of the charge:

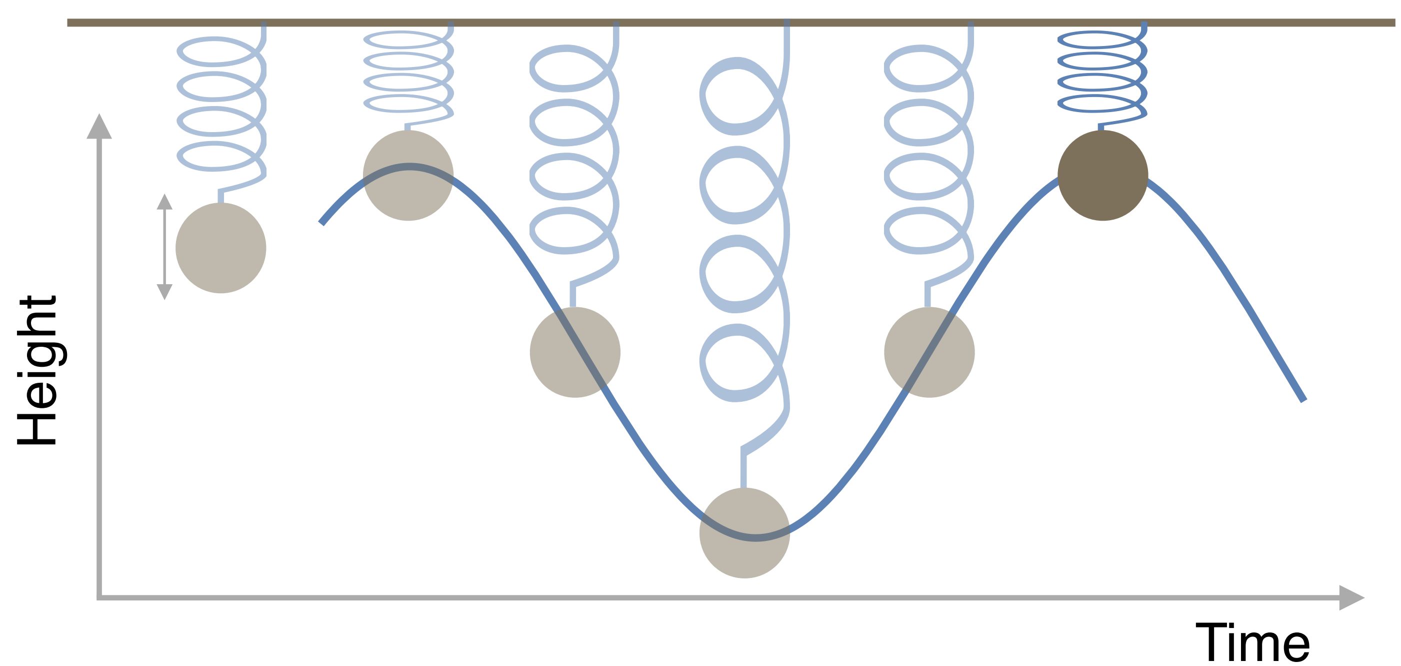
$$Q(t) = Q(0)\cos(\omega_{\mathrm{LC}} t)$$

$$\omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}}$$

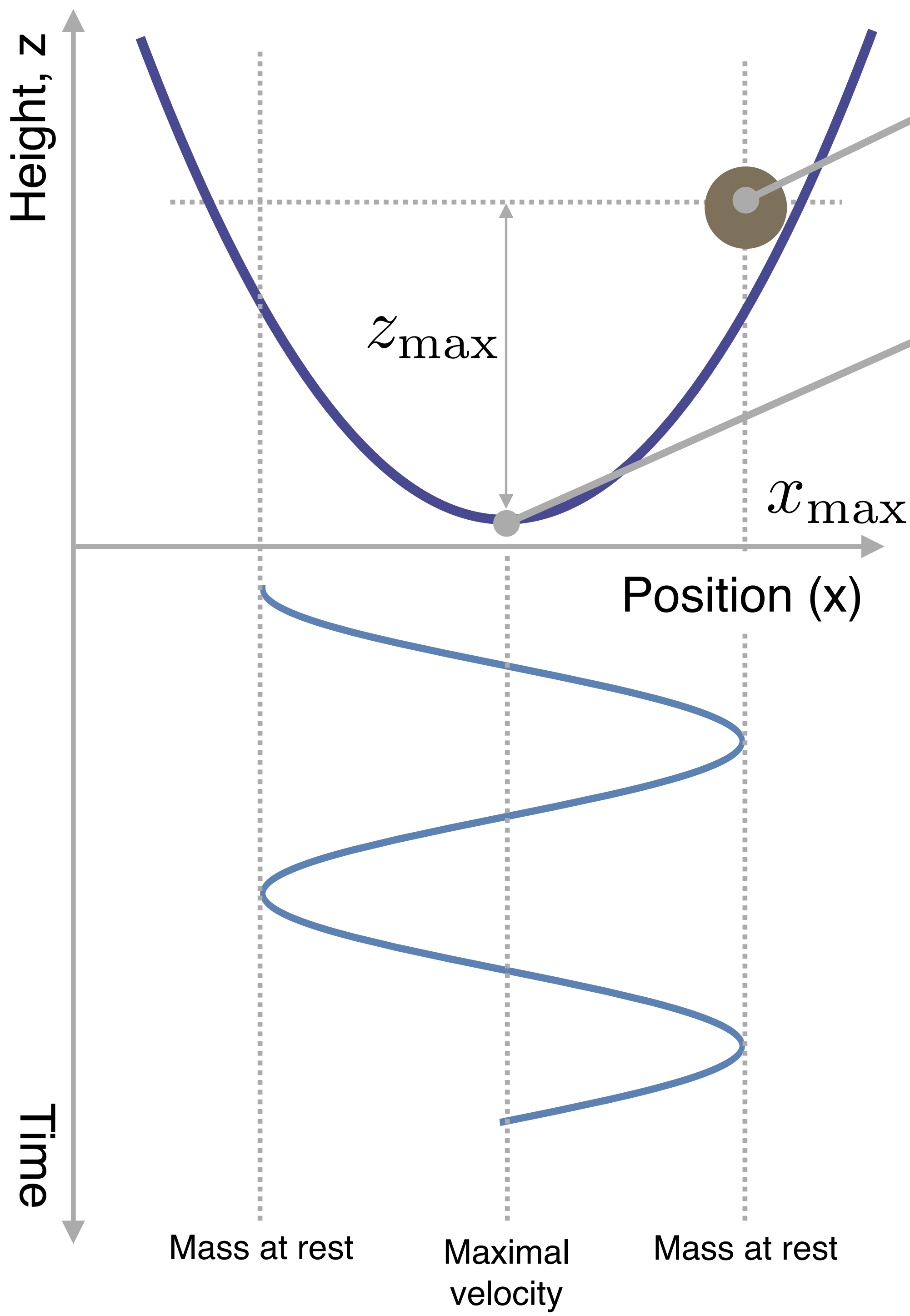




One out of countless examples of *harmonic oscillator*



Classical harmonic oscillator



$$E = \frac{1}{2}kx_{\max}^2$$

$$E = \frac{1}{2}mv_{\max}^2 = \frac{p_{\max}^2}{2m} \quad (p = mv)$$

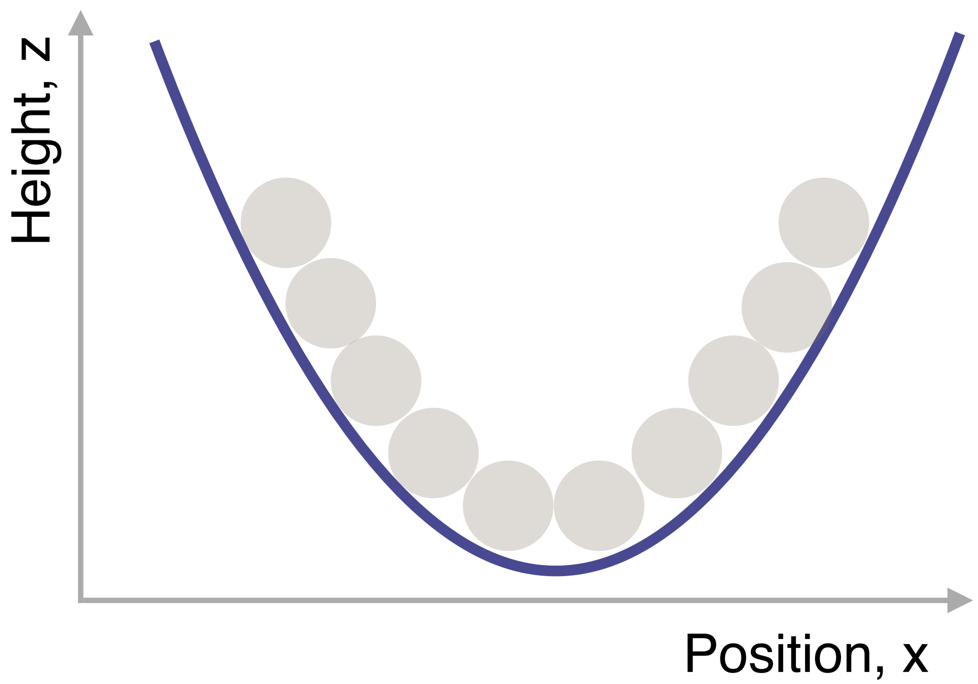
Momentum

Energy at arbitrary *x*: $H = \frac{p^2}{2m} + \frac{1}{2}kx^2$

= Hamiltonian

Frequency of oscillation: $\omega = \sqrt{k/m}$

Quantum harmonic oscillator



Energy at arbitrary *x*:

= Hamiltonian

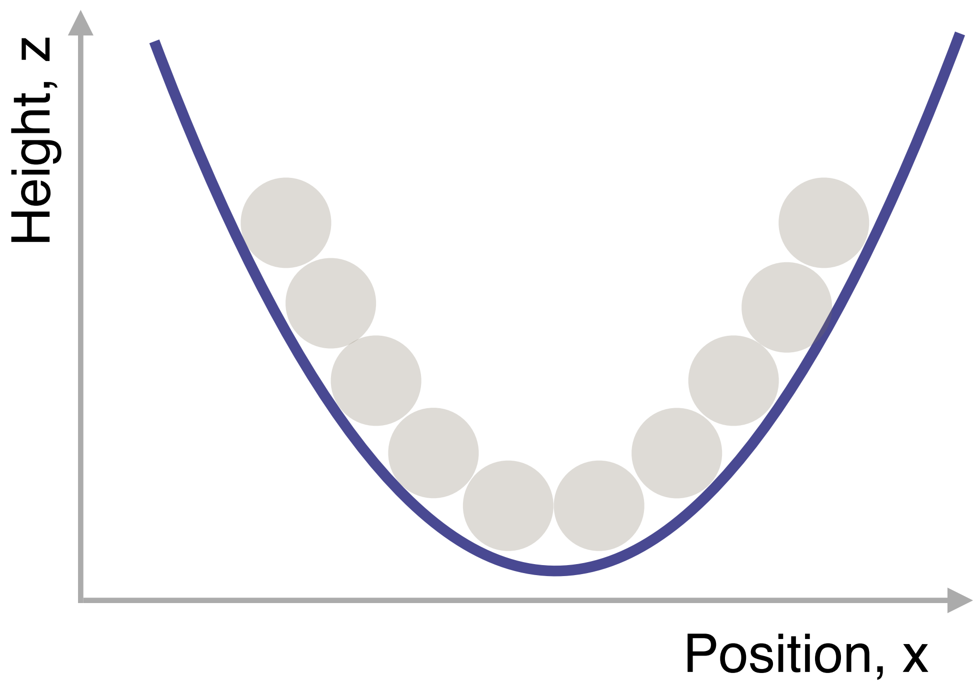
$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2}k\hat{x}^2$$

Heisenberg uncertainty principle:
Impossible to know precisely both *x* and *p*

Classical variables are promoted to hermitian operator acting on Hilbert space

$$x \rightarrow \hat{x} \qquad p \rightarrow \hat{p} \qquad \boxed{[\hat{x}, \hat{p}] = i\hbar}$$

Quantum harmonic oscillator



Energy at arbitrary *x*: $\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2}k\hat{x}^2$

Classical variables are promoted to hermitian operator acting on Hilbert space

$$x \to \hat{x} \qquad p \to \hat{p} \qquad [\hat{x}, \hat{p}] = i\hbar$$

Useful to introduce:

$$\hat{a} = \left(\frac{mk}{4\hbar^2}\right)^{1/4}\left(\hat{x} + i\frac{\hat{p}}{\sqrt{mk}}\right)$$

$$\hat{a}^\dagger = \left(\frac{mk}{4\hbar^2}\right)^{1/4}\left(\hat{x} - i\frac{\hat{p}}{\sqrt{mk}}\right)$$

Commutation relation:

$$[\hat{x}, \hat{p}] = i\hbar \rightarrow [\hat{a}, \hat{a}^\dagger] = 1$$

$$\hat{H} = \hbar\omega\hat{a}^\dagger\hat{a} = \hbar\omega\hat{n}$$

$$(\omega = \sqrt{k/m})$$

Quantum harmonic oscillator

$$\hat{H} = \hbar\omega\hat{a}^\dagger\hat{a} = \hbar\omega\hat{n} \qquad [\hat{a}, \hat{a}^\dagger] = 1 \qquad \hat{n}|n\rangle = n|n\rangle$$

$$\boxed{\begin{aligned} \hat{a}|n\rangle &=? \\ \hat{a}^\dagger|n\rangle &=? \end{aligned}}$$

What is the action of $\hat{a}$ and $\hat{a}^\dagger$ on the eigenstates of $\hat{n}$?

First observation: $[\hat{n}, \hat{a}] = -\hat{a}$ and $[\hat{n}, \hat{a}^\dagger] = \hat{a}^\dagger$

$$\Rightarrow \quad \hat{n}(\hat{a}|n\rangle) = \hat{a}\hat{n}|n\rangle - \hat{a}|n\rangle = (n-1)\hat{a}|n\rangle$$

$$\boxed{\hat{a}|n\rangle \propto |n-1\rangle}$$

Second observation: $||\hat{a}|n\rangle||^2 = \langle n|\hat{a}^\dagger\hat{a}|n\rangle = \langle n|\hat{n}|n\rangle = n \quad \Rightarrow \quad n \in \mathbb{N}_0$

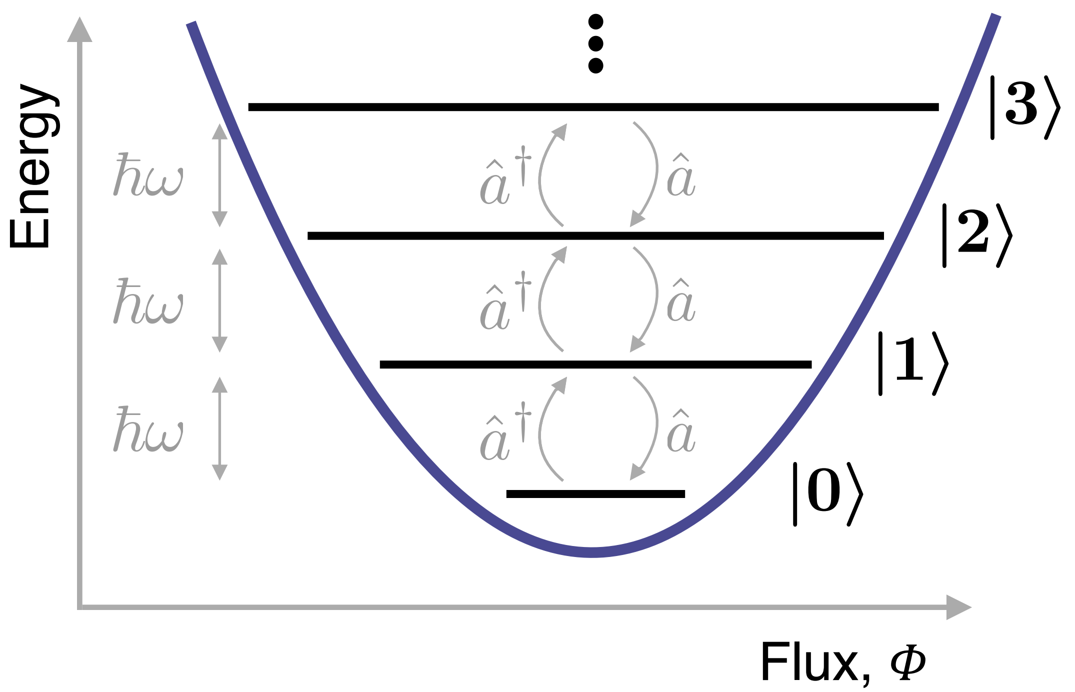
$$\hat{a}|n\rangle = \sqrt{n}|n-1\rangle \qquad \hat{a}^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle$$

Quantum harmonic oscillator

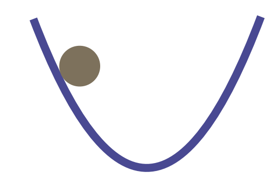
$$\hat{H} = \hbar\omega \hat{a}^\dagger \hat{a} = \hbar\omega\hat{n} \qquad \hat{n}|n\rangle = n|n\rangle \qquad n \geq 0$$

$$\hat{a}|n\rangle = \sqrt{n}|n-1\rangle$$

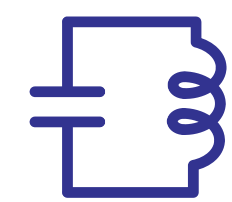
$$\hat{a}^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle$$



$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2}k\hat{x}^2 \qquad \omega = \sqrt{k/m}$$



$$\hat{H} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L} \qquad \omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}}$$



Flux: $\Phi = \int dt V(t)$

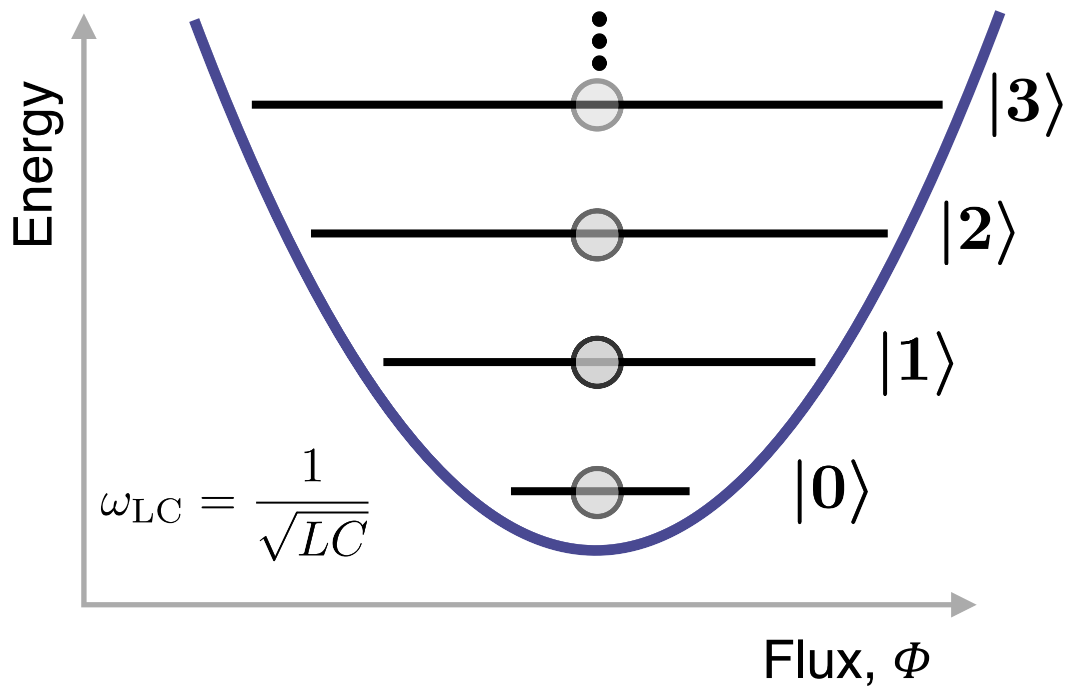
$$\hat{a}^\dagger = \left(\frac{C}{4L\hbar^2}\right)^{1/4} \left(\hat{\Phi} - i\frac{\hat{Q}}{\sqrt{C/L}}\right)$$

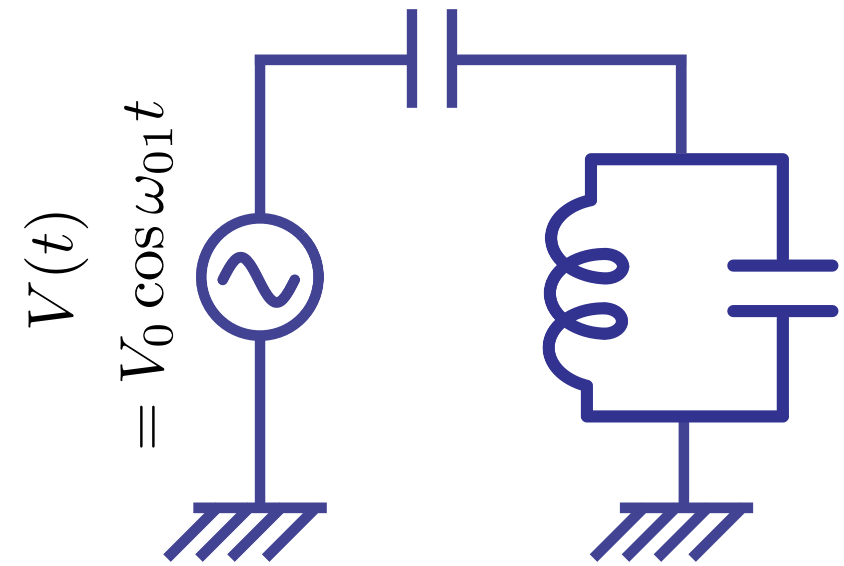
(Magnetic field) *(Electric field)*

$\hat{a}^\dagger$ adds a photon to the LC circuit

n = number of photons stored in the LC circuit

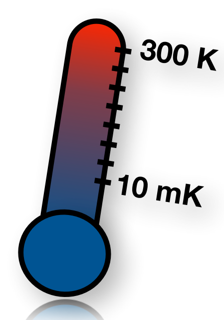
Artificial atom

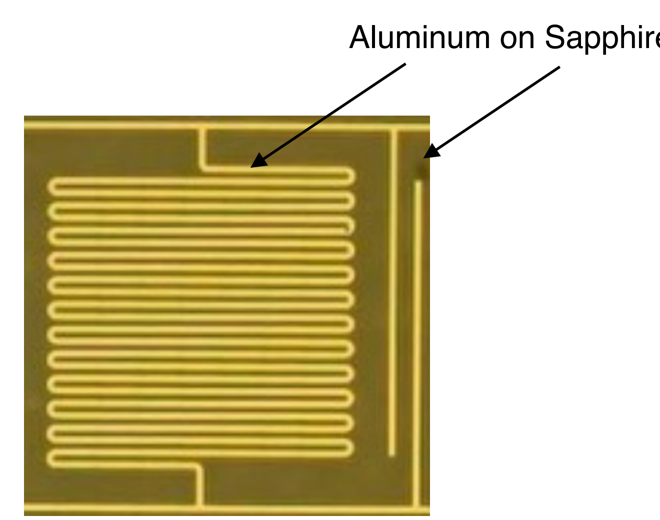




- Initialization to ground state is simple

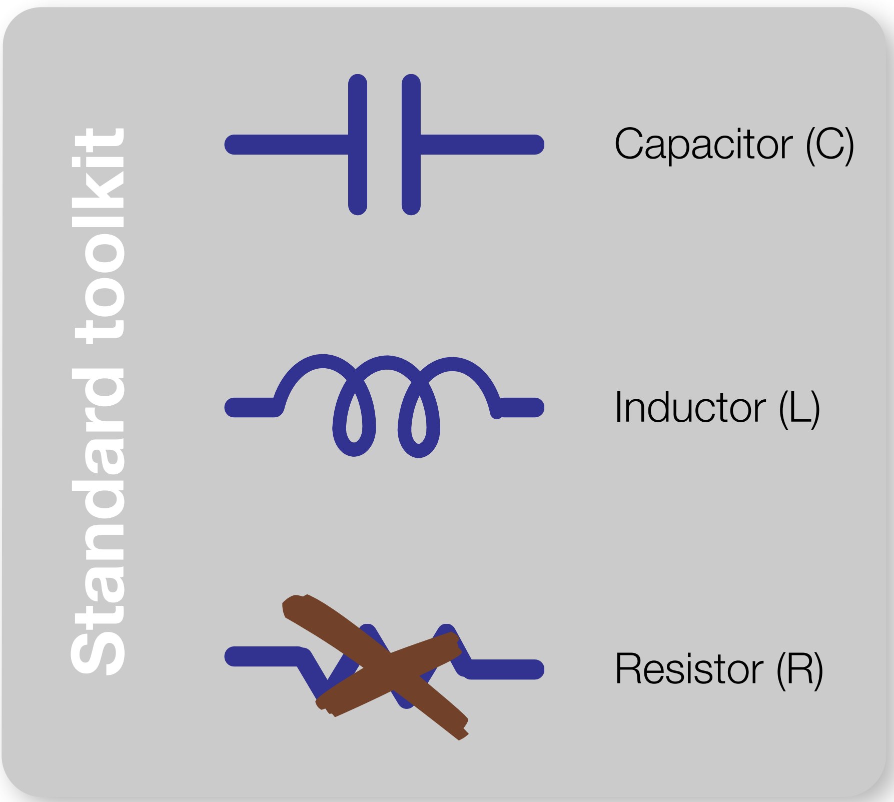
$$\omega_{01} = 1/\sqrt{LC} \sim 10\ \mathrm{GHz}$$
$$\sim 0.5\ \mathrm{K}$$

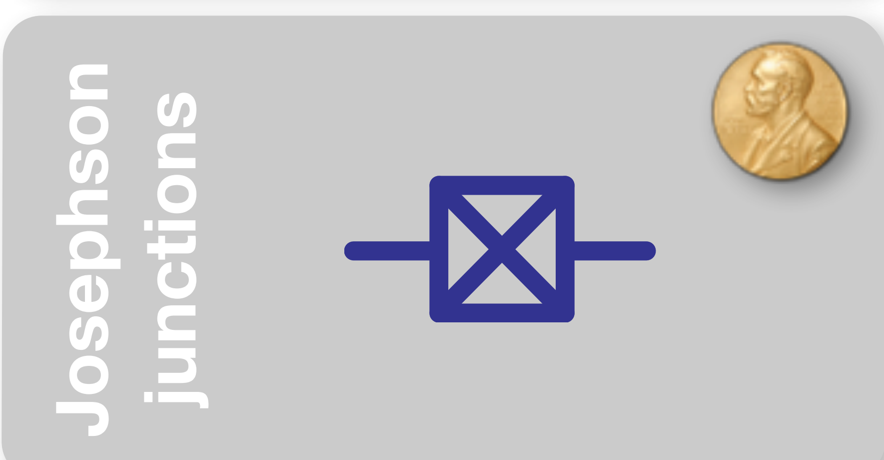


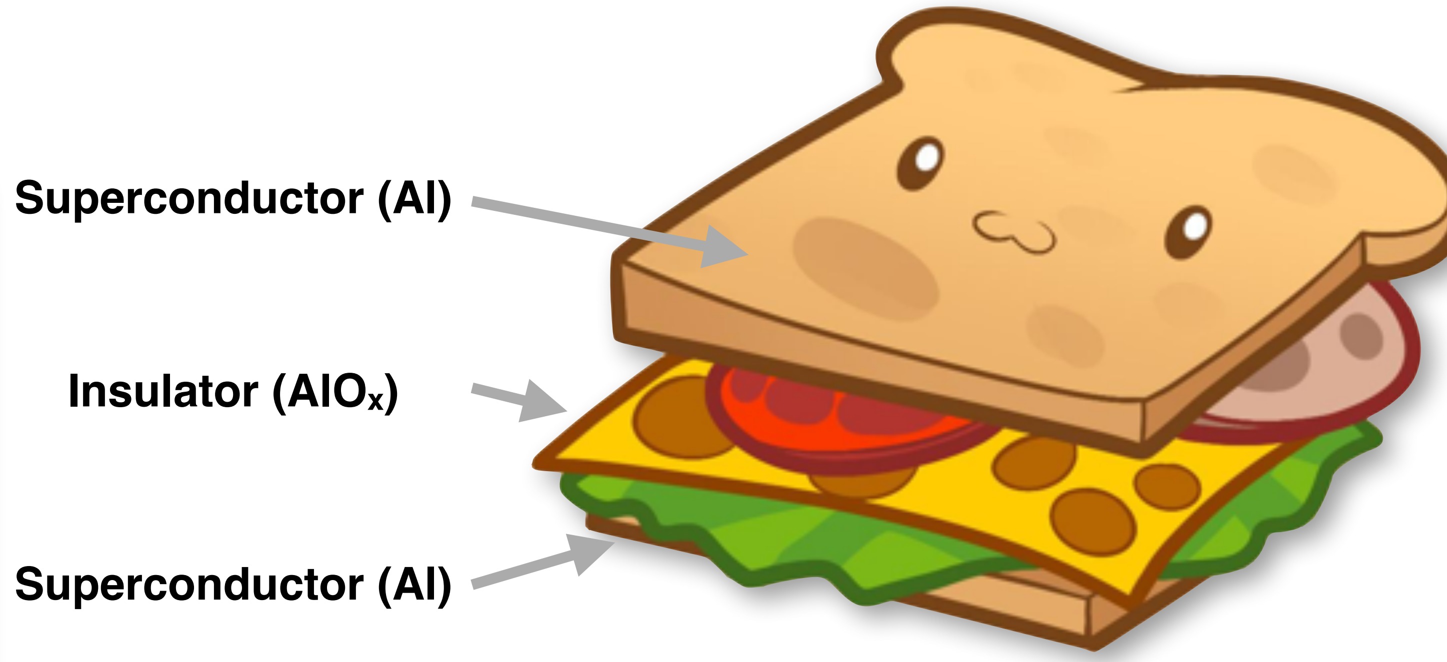


- Not a good «two-level» atom, not a qubit…

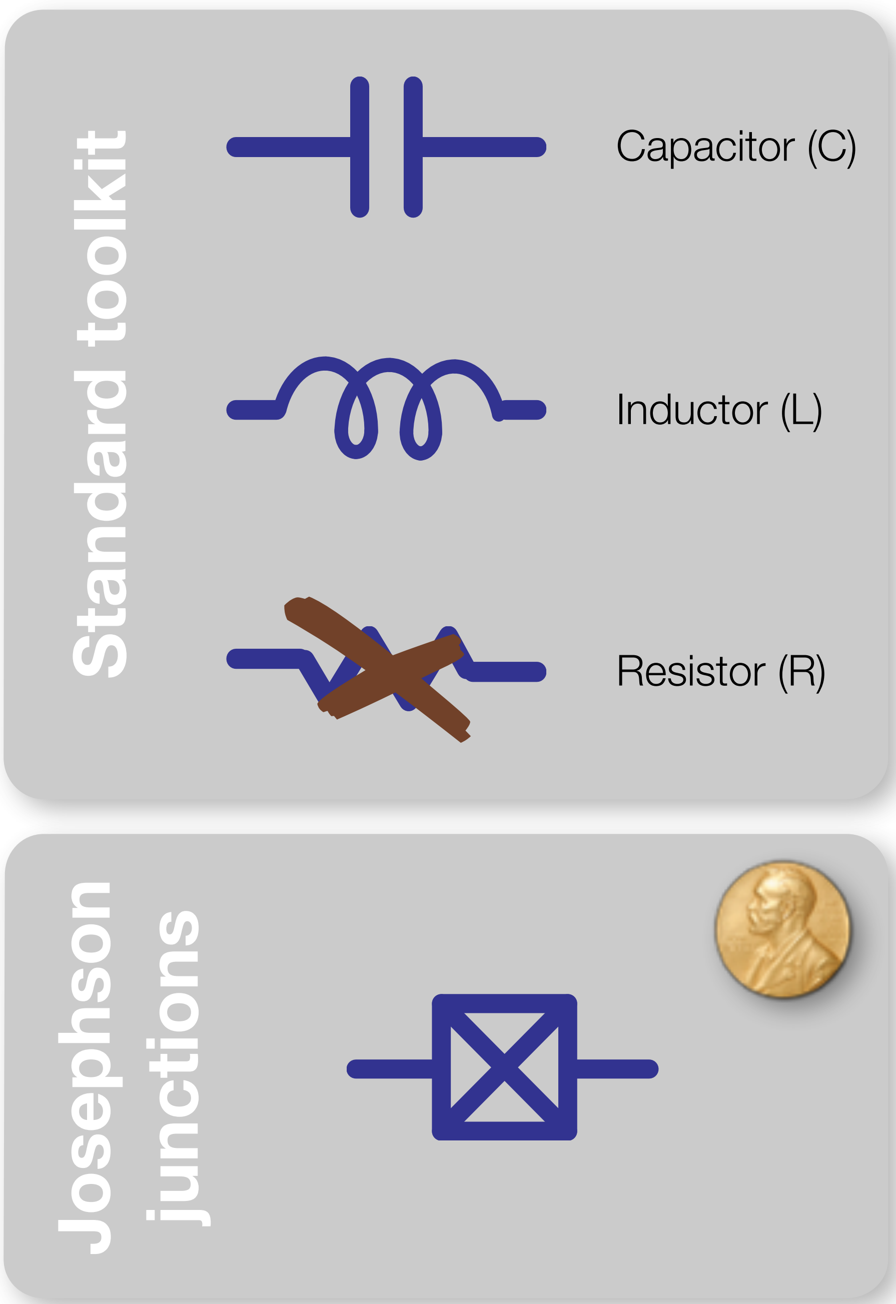
Josephson junction

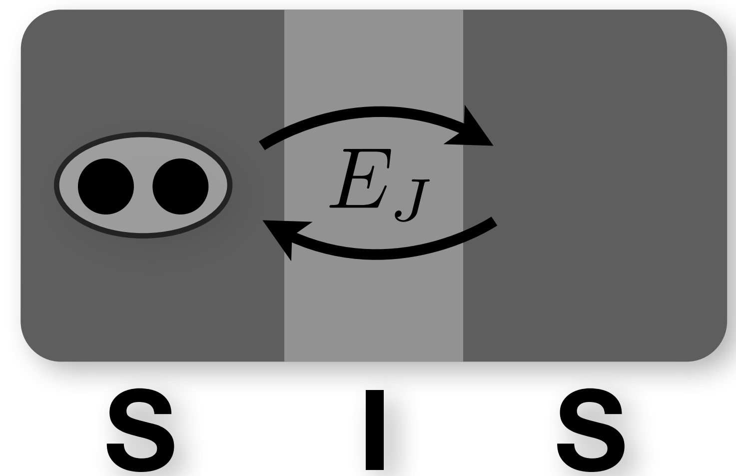


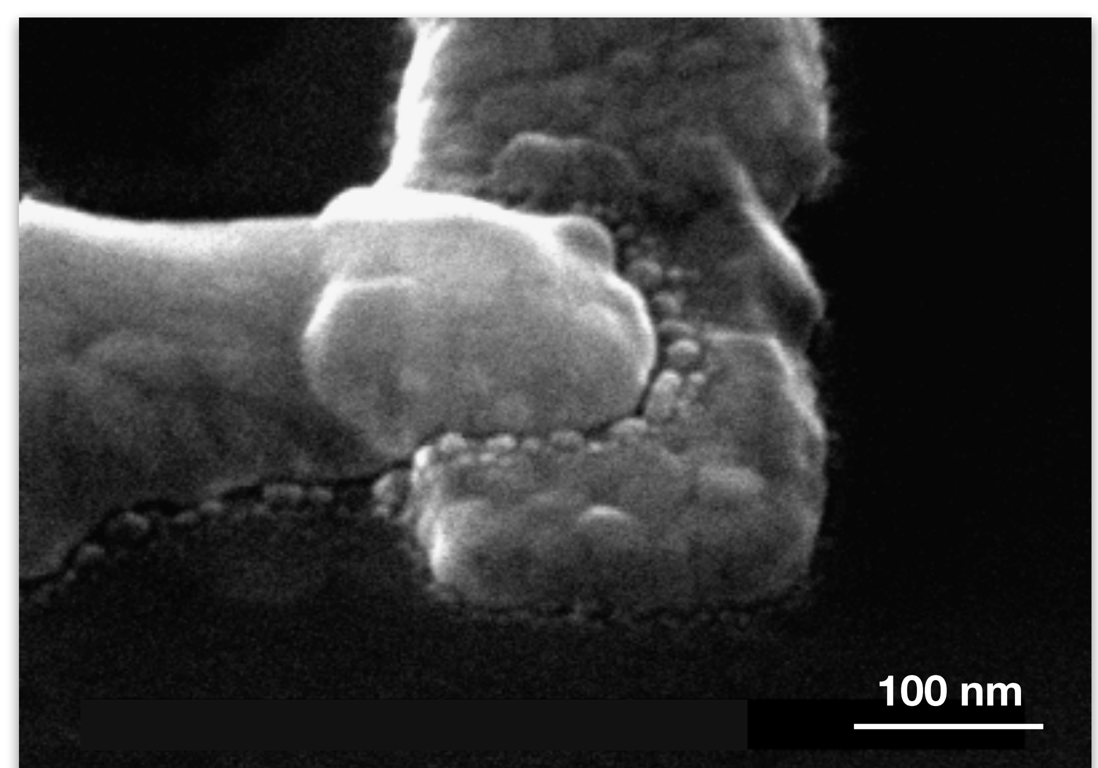




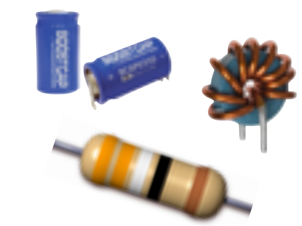
Josephson junction







Artificial atom toolkit



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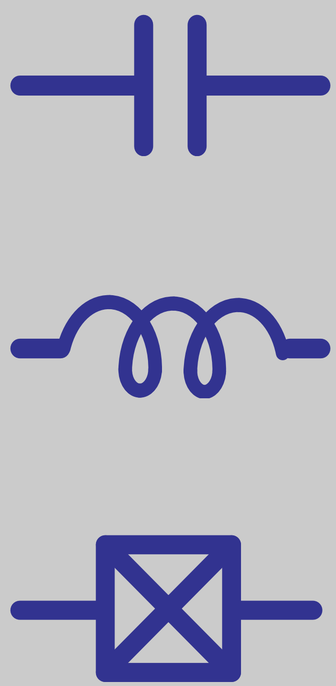
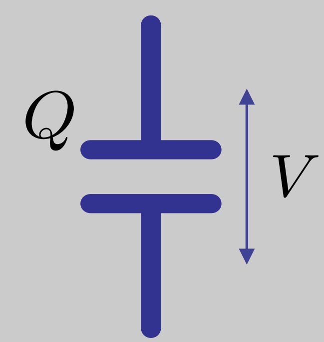
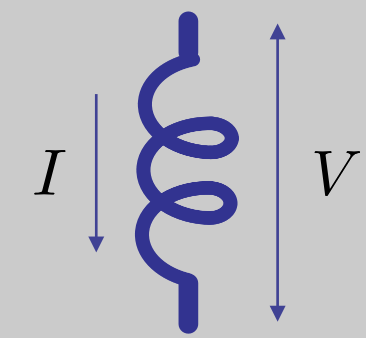


Capacitor:
- Two metal plates separated by an insulator
- Relates voltage to charge



$$Q = CV$$

Inductor:
- A non-resistive wire
- Relates current to flux

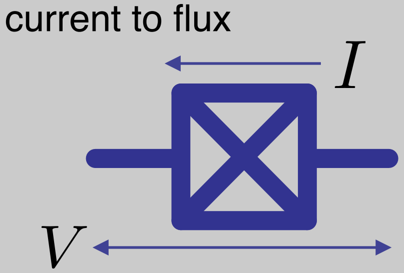


$$V = L\frac{dI}{dt}$$

$$\Phi = LI$$

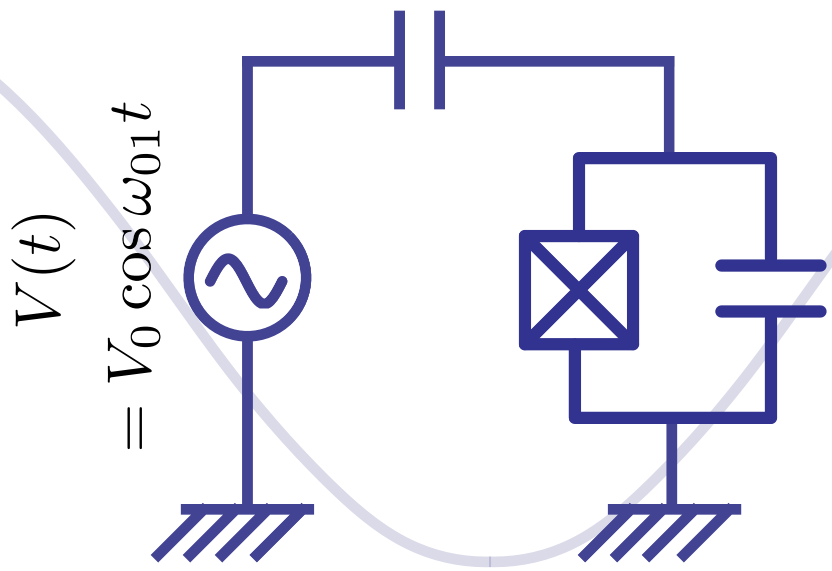
$$\Phi = \int_{-\infty}^{t} dt'\, V(t')$$

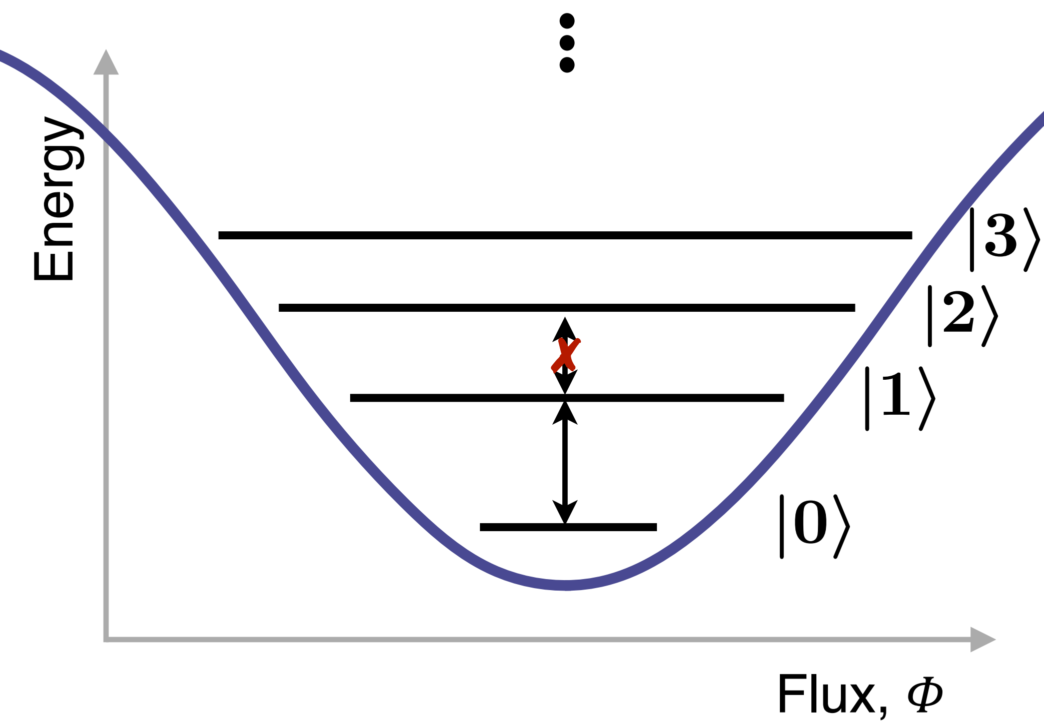
Josephson junction:
- Two superconductors separated by an insulator
- Relates current to flux



$$I = I_0 \sin(2\pi\Phi/\Phi_0)$$

Superconducting artificial atom



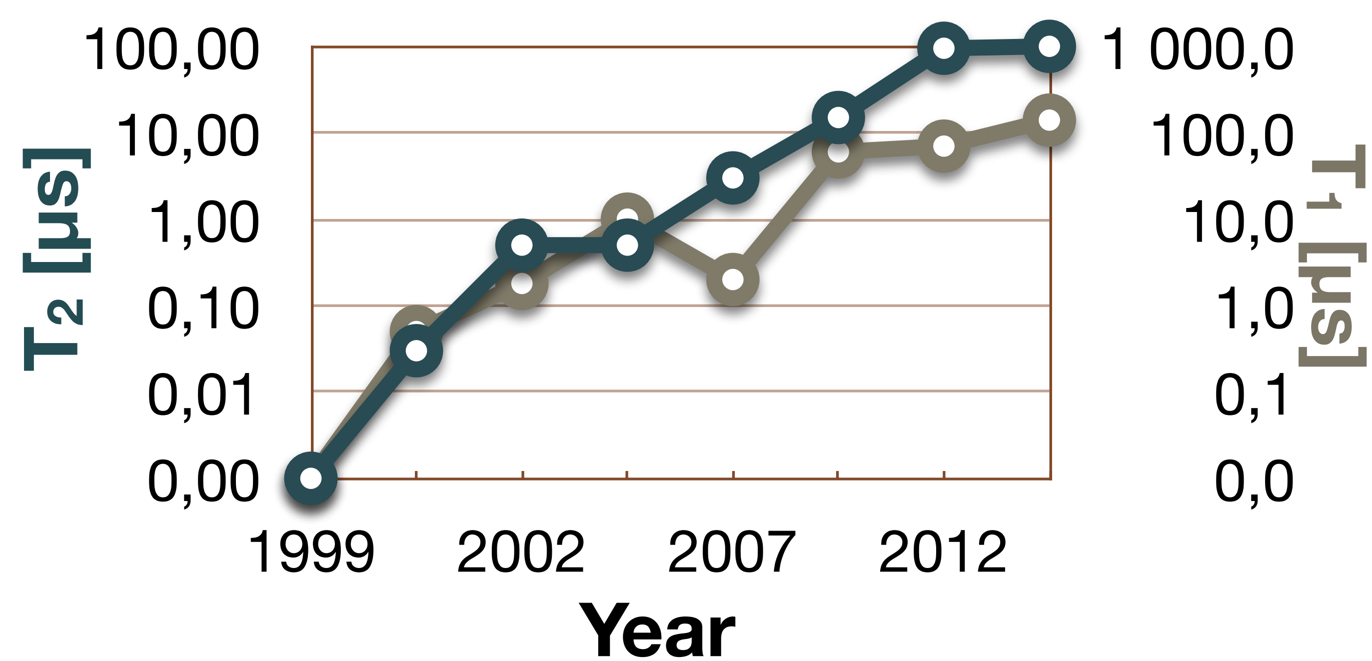


- Very short π-pulse time

$$T_\pi \sim 4 - 20 \text{ ns}$$

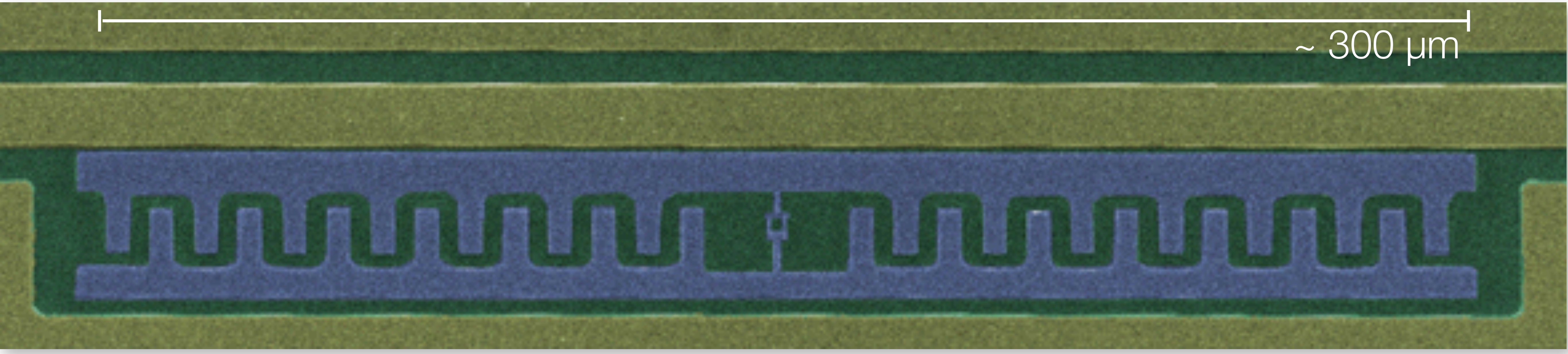
- Big improvements in relaxation and dephasing times in last 10 years

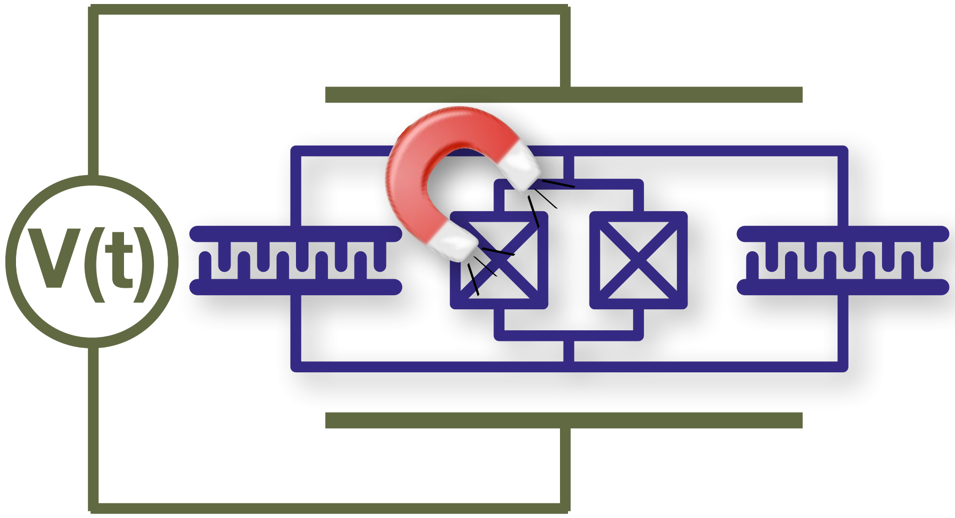
- Error per gates of 0.2%, similar to trapped ion results

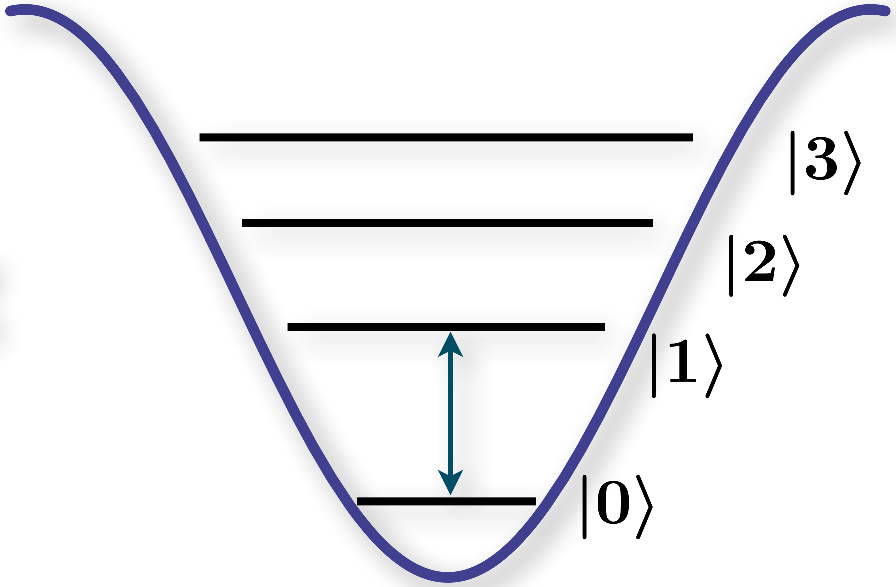


Low error per gates: E. Magesan *et al*, Phys. Rev. Lett. **109**, 080505 (2012)
Long T_1 and T_2: H. Paik *et al*, Phys. Rev. Lett. **107**, 240501 (2011)

Superconducting *transmon* qubits



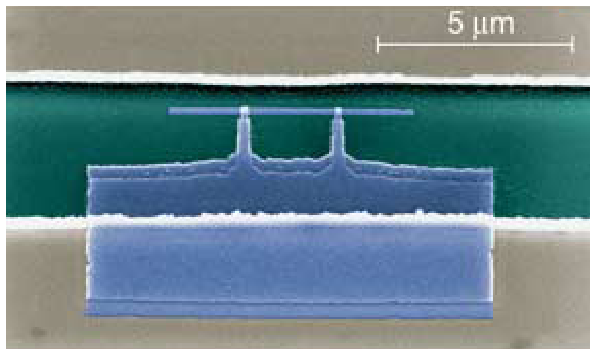




J. Koch et al. Phys. Rev. A **76**, 042319 (2007)

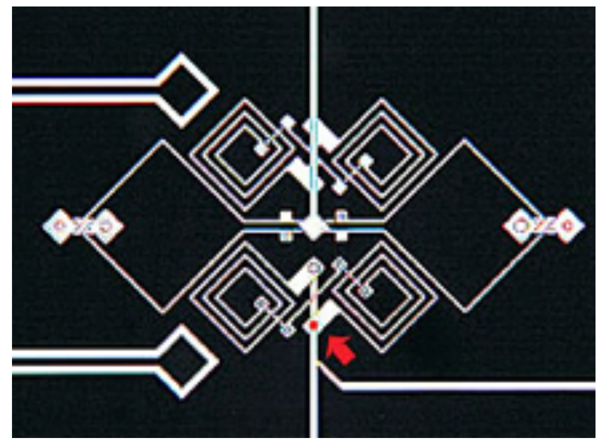
Superconducting qubits, a family tree

Charge



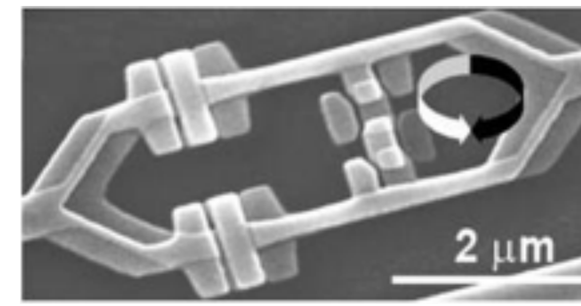
NEC, Saclay, 1999

Phase



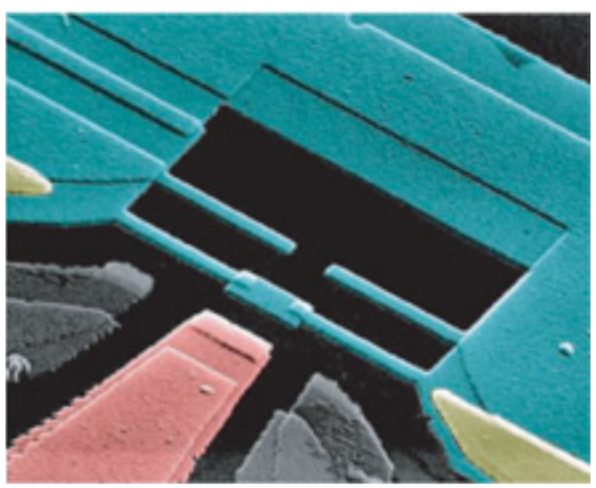
NIST 2002

Flux



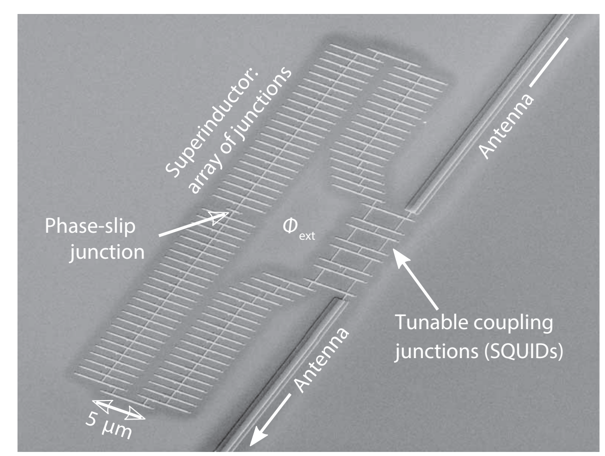
Delft, 1999

Quantronium



Saclay, 2002

Fluxonium



Yale, 2009

Transmon

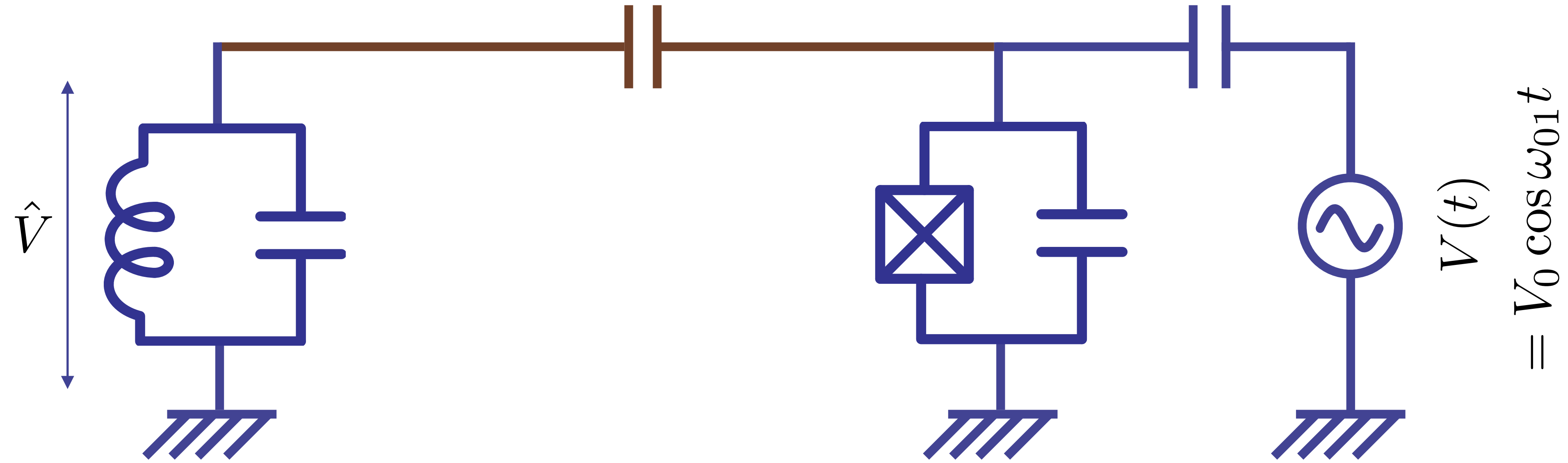
Yale, 2007

=

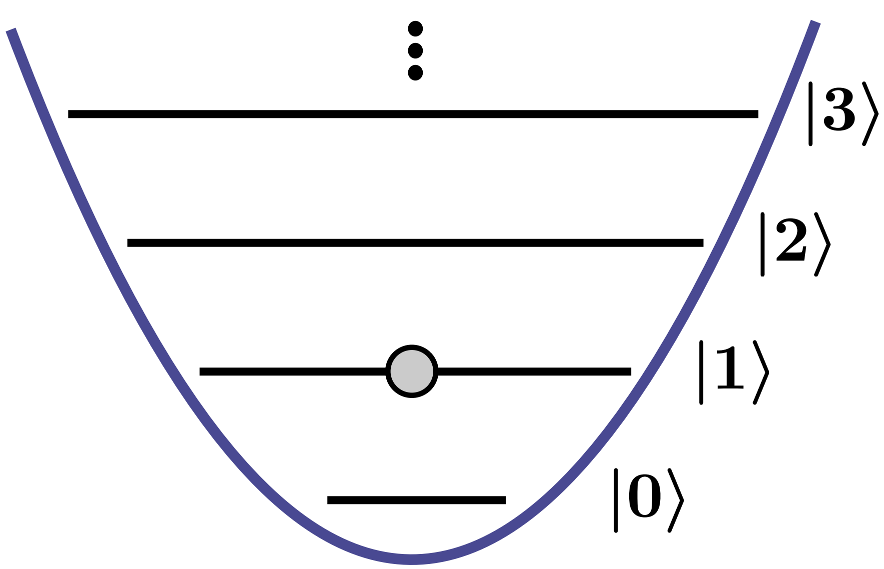
xmon

UCSB, 2013

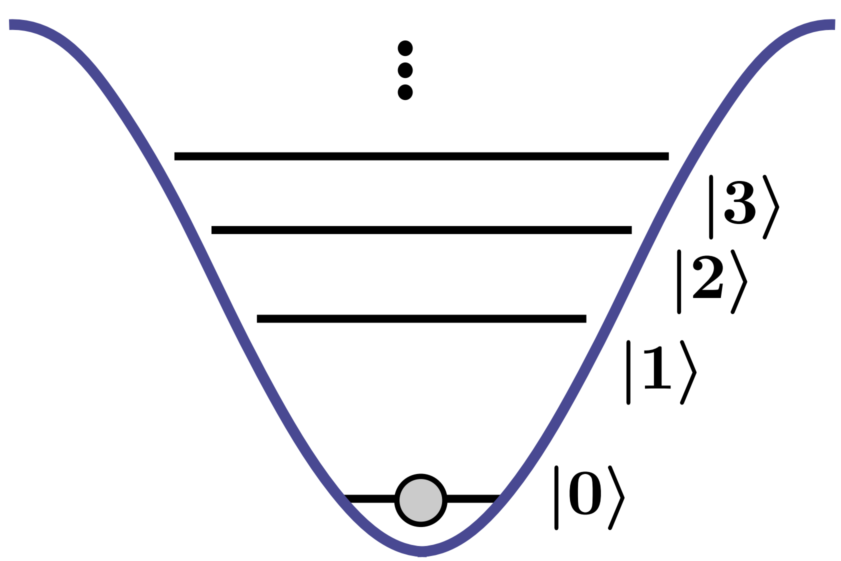
Circuit QED



$\hat{V}$
$V(t)$
$= V_0 \cos \omega_{01} t$

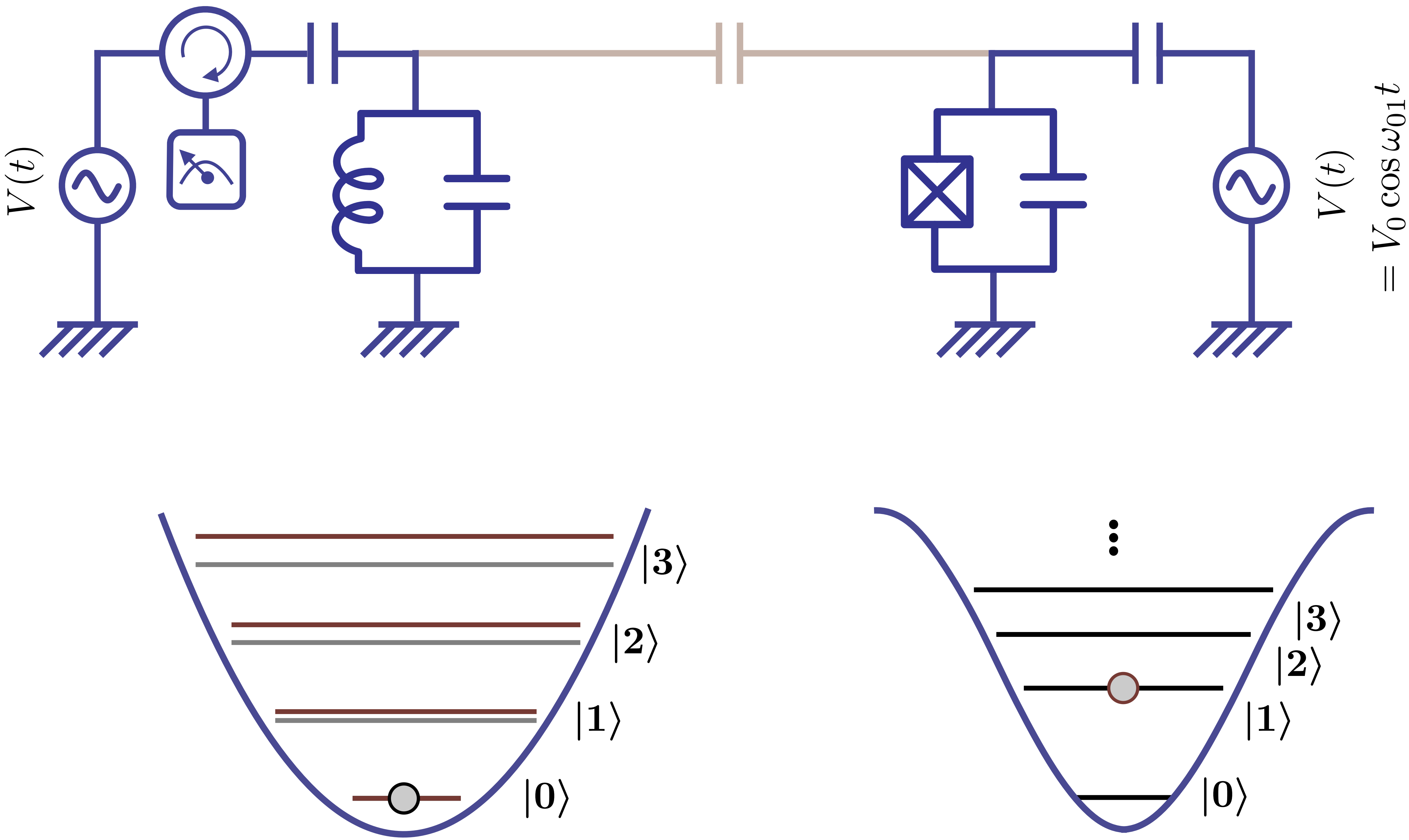


$|\mathbf{3}\rangle$
$|\mathbf{2}\rangle$
$|\mathbf{1}\rangle$
$|\mathbf{0}\rangle$



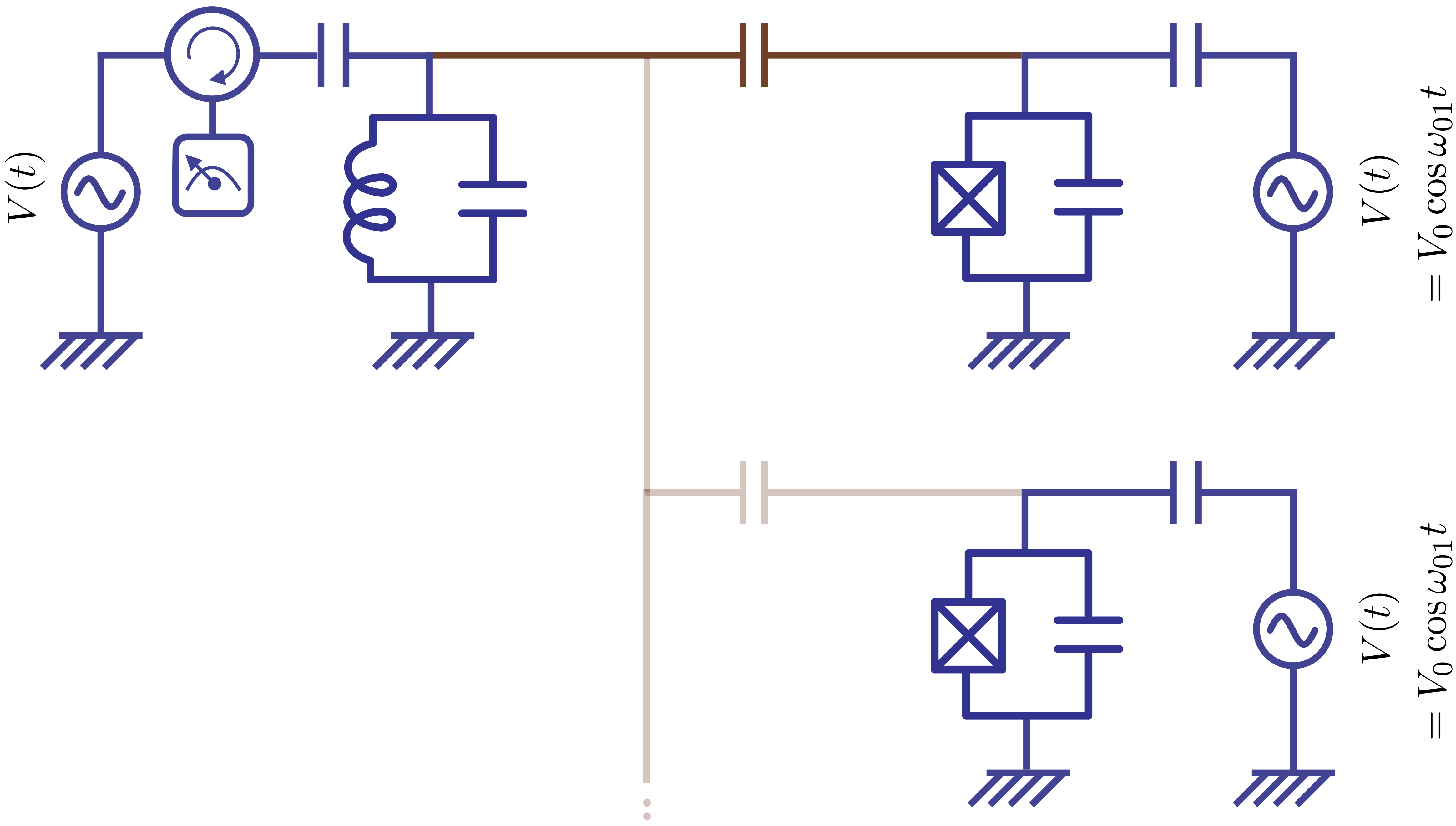
$|\mathbf{3}\rangle$
$|\mathbf{2}\rangle$
$|\mathbf{1}\rangle$
$|\mathbf{0}\rangle$

Circuit QED

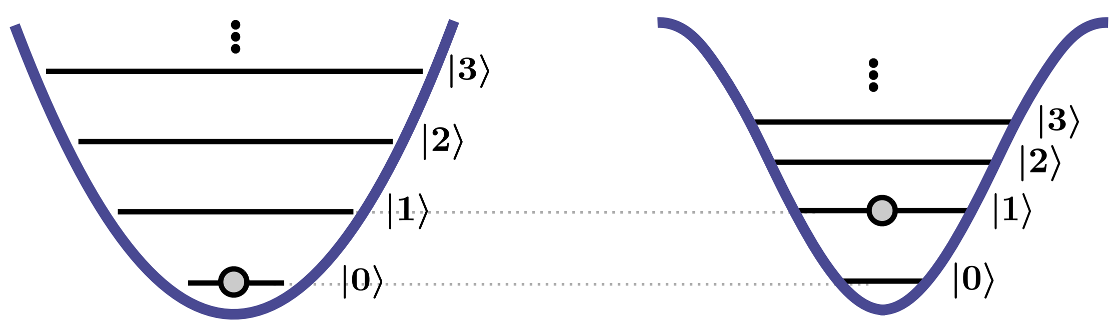


$V(t)$
$V(t)$
$= V_0 \cos \omega_{01} t$
$|\mathbf{3}\rangle$
$|\mathbf{2}\rangle$
$|\mathbf{1}\rangle$
$|\mathbf{0}\rangle$
$|\mathbf{3}\rangle$
$|\mathbf{2}\rangle$
$|\mathbf{1}\rangle$
$|\mathbf{0}\rangle$

Circuit QED: Multi-qubit architecture

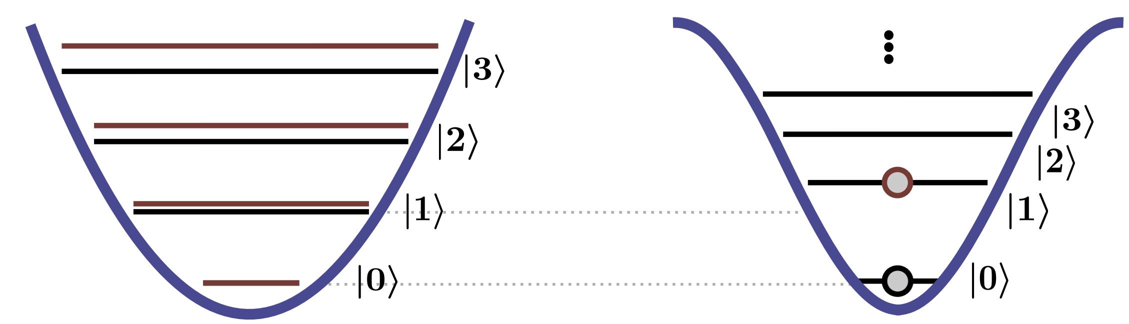


Circuit QED: Resonant and dispersive regimes



Resonant regime:

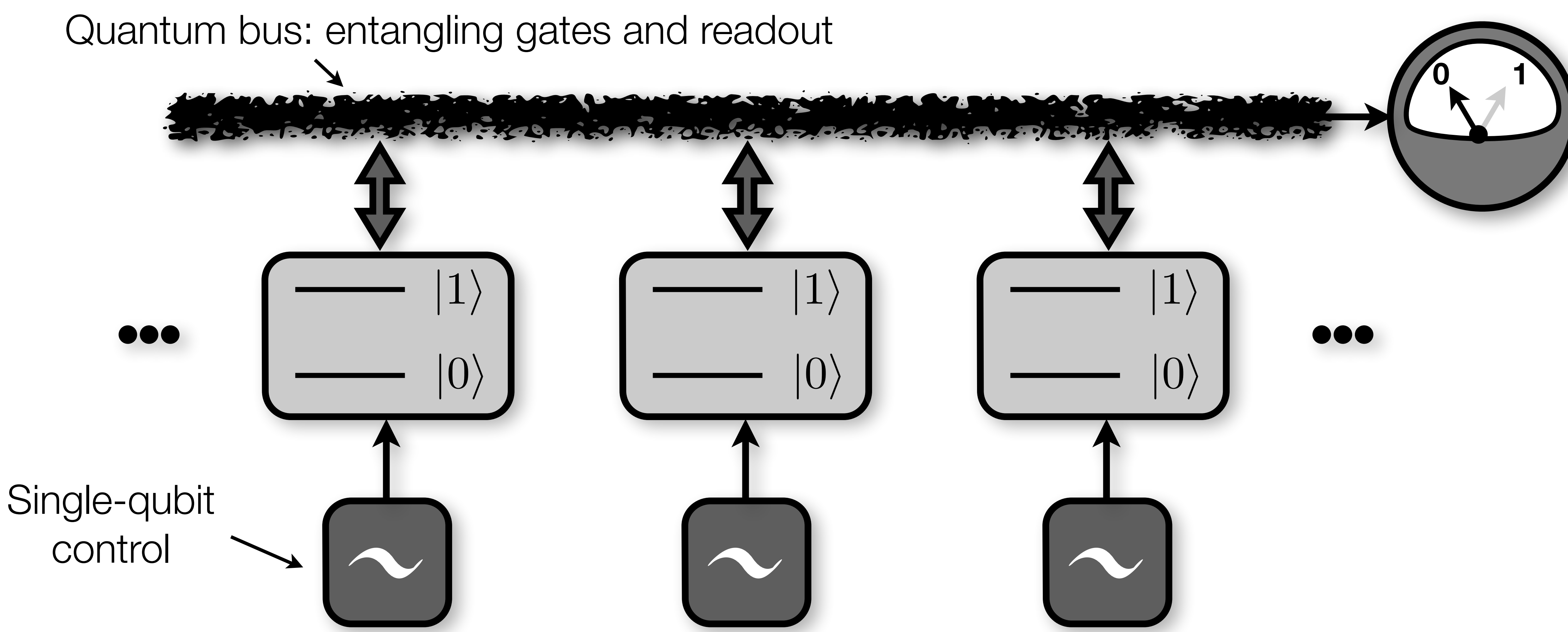
- Identical 0-1 transition frequencies
- Energy exchange between qubits and oscillator
- Oscillator acts as quantum bus for entangling qubits



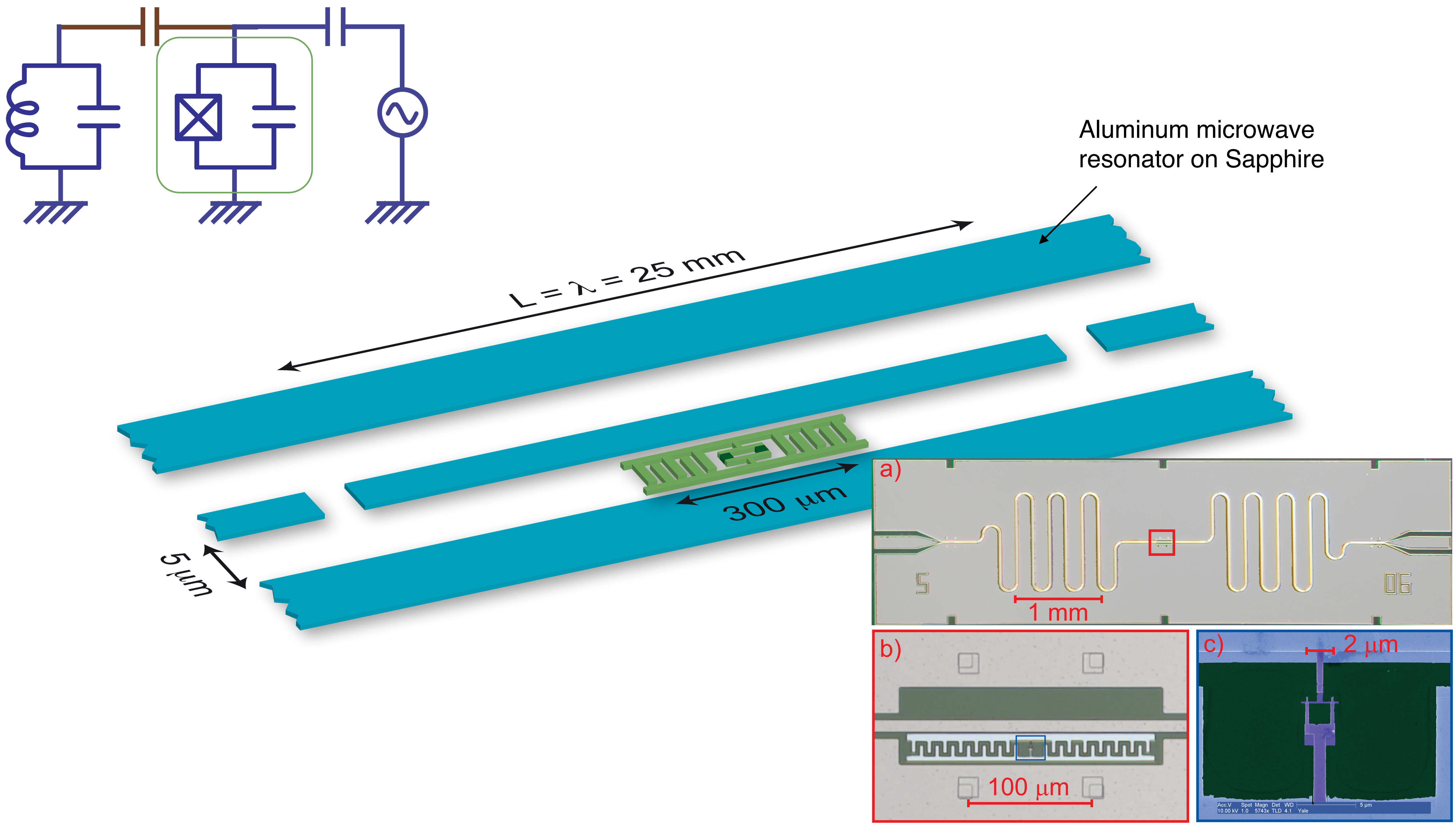
Dispersive regime:

- Different 0-1 transition frequencies
- No energy exchange between qubits and oscillator
- Qubit-state dependent oscillator frequency leads allows qubit readout

Circuit QED: Multi-qubit architecture

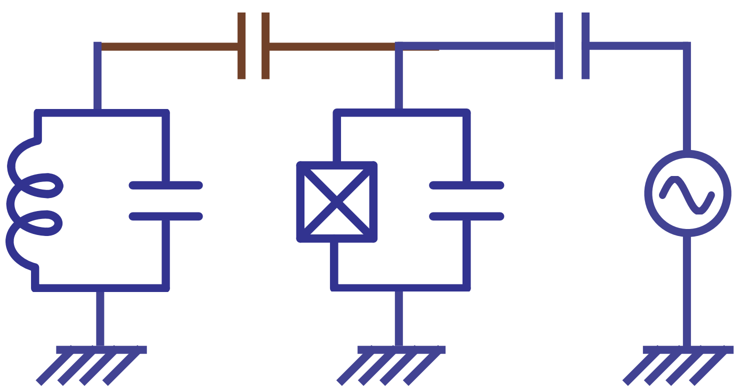


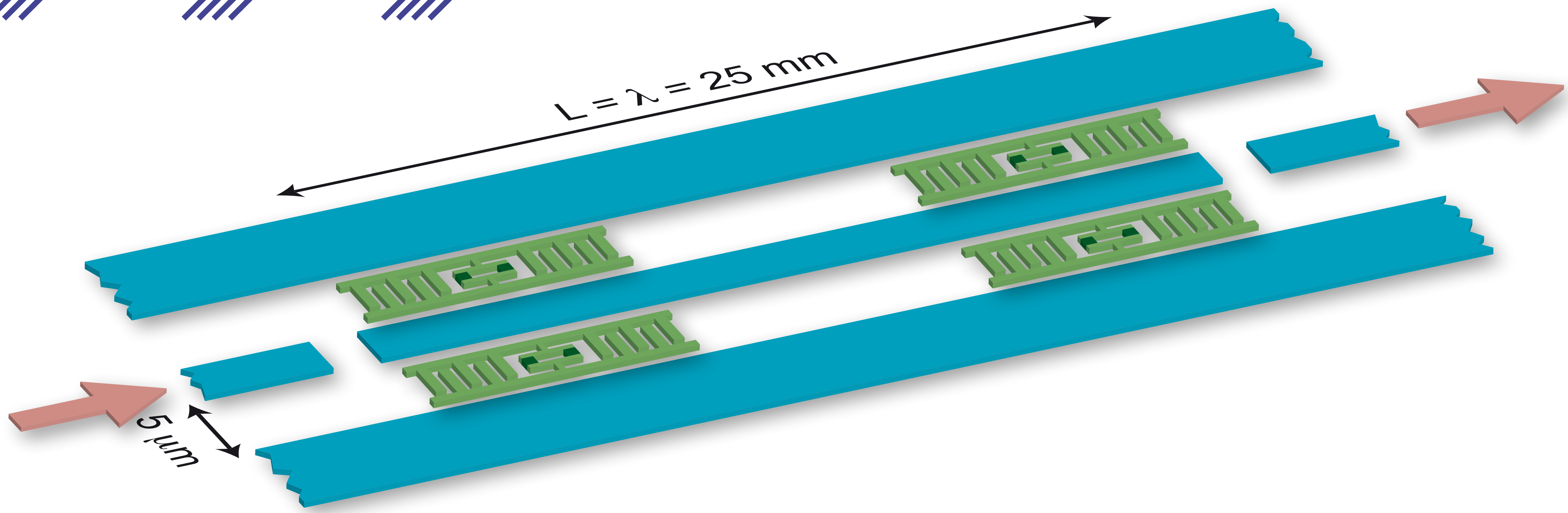
Circuit QED: ‘1D’ realization



Proposal: Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)
First realization: Wallraff, Schuster, Blais, Frunzio, Huang, Majer, Kumar, Girvin & Schoelkopf. Nature **431**, 162 (2004)

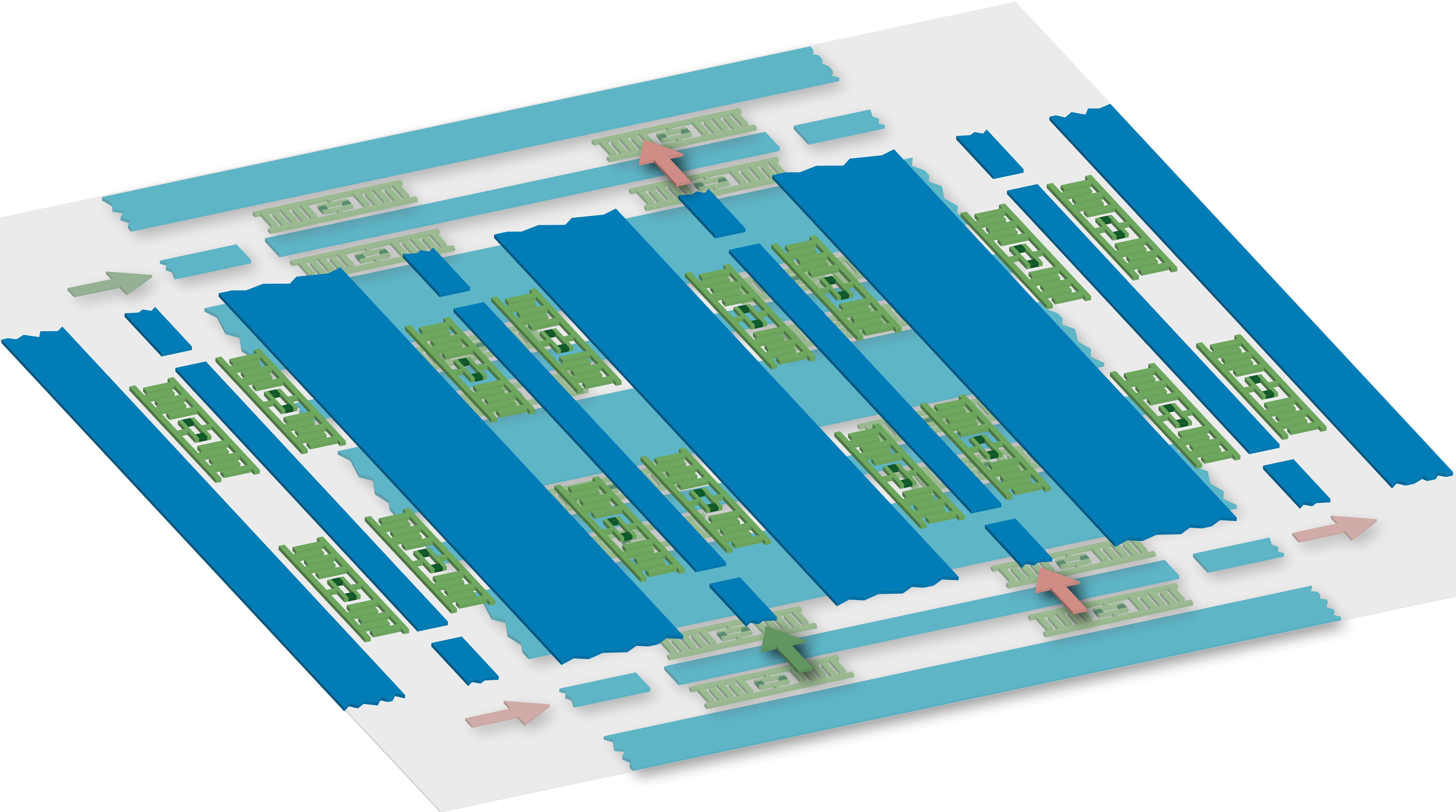
Circuit QED: ‘1D’ realization





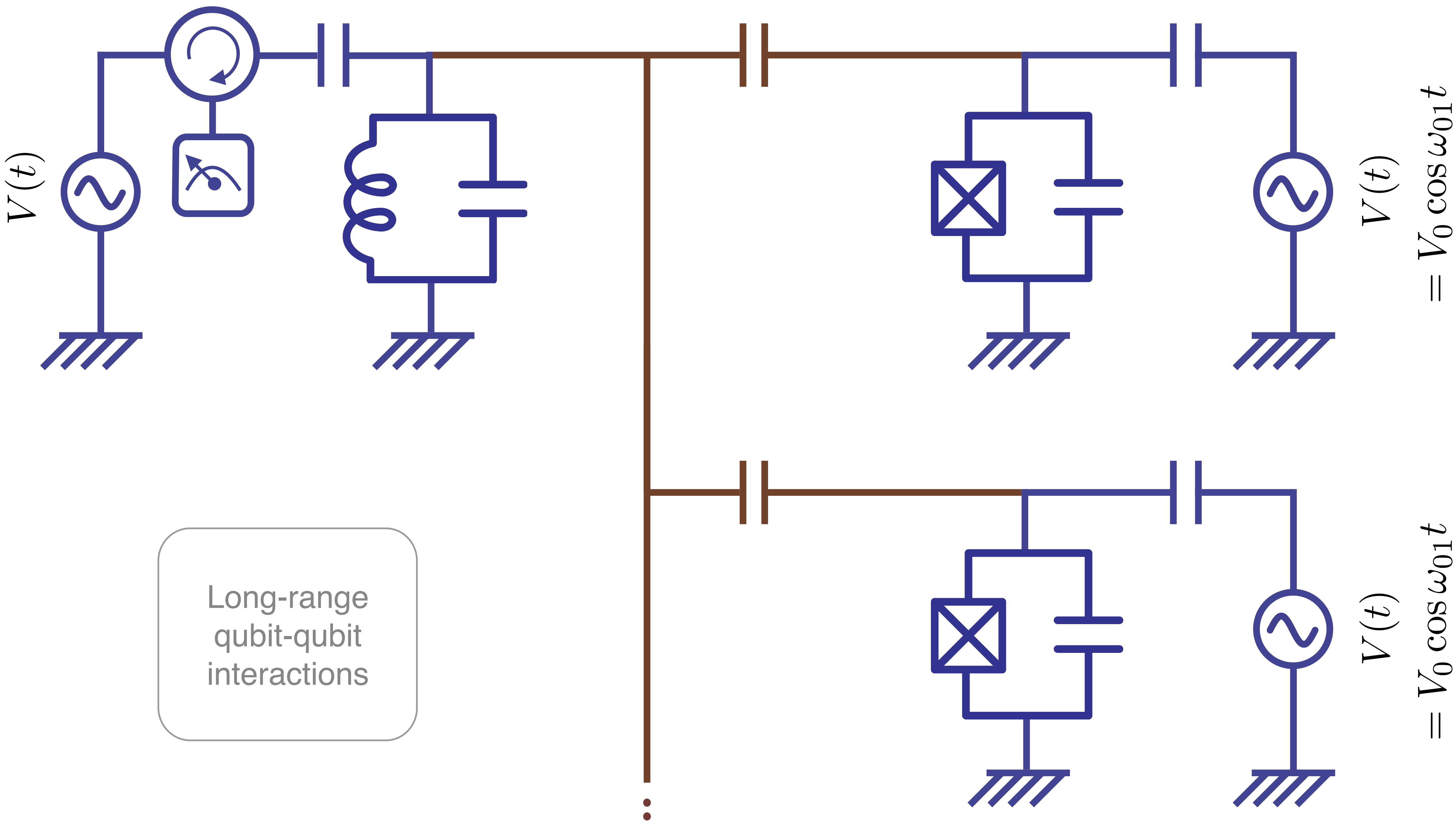
Proposal: Blais, Huang, Wallraff, Girvin & Schoelkopf, Phys. Rev. A **69**, 062320 (2004)
First realization: Wallraff, Schuster, Blais, Frunzio, Huang, Majer, Kumar, Girvin & Schoelkopf. Nature **431**, 162 (2004)

Circuit QED: scaling up

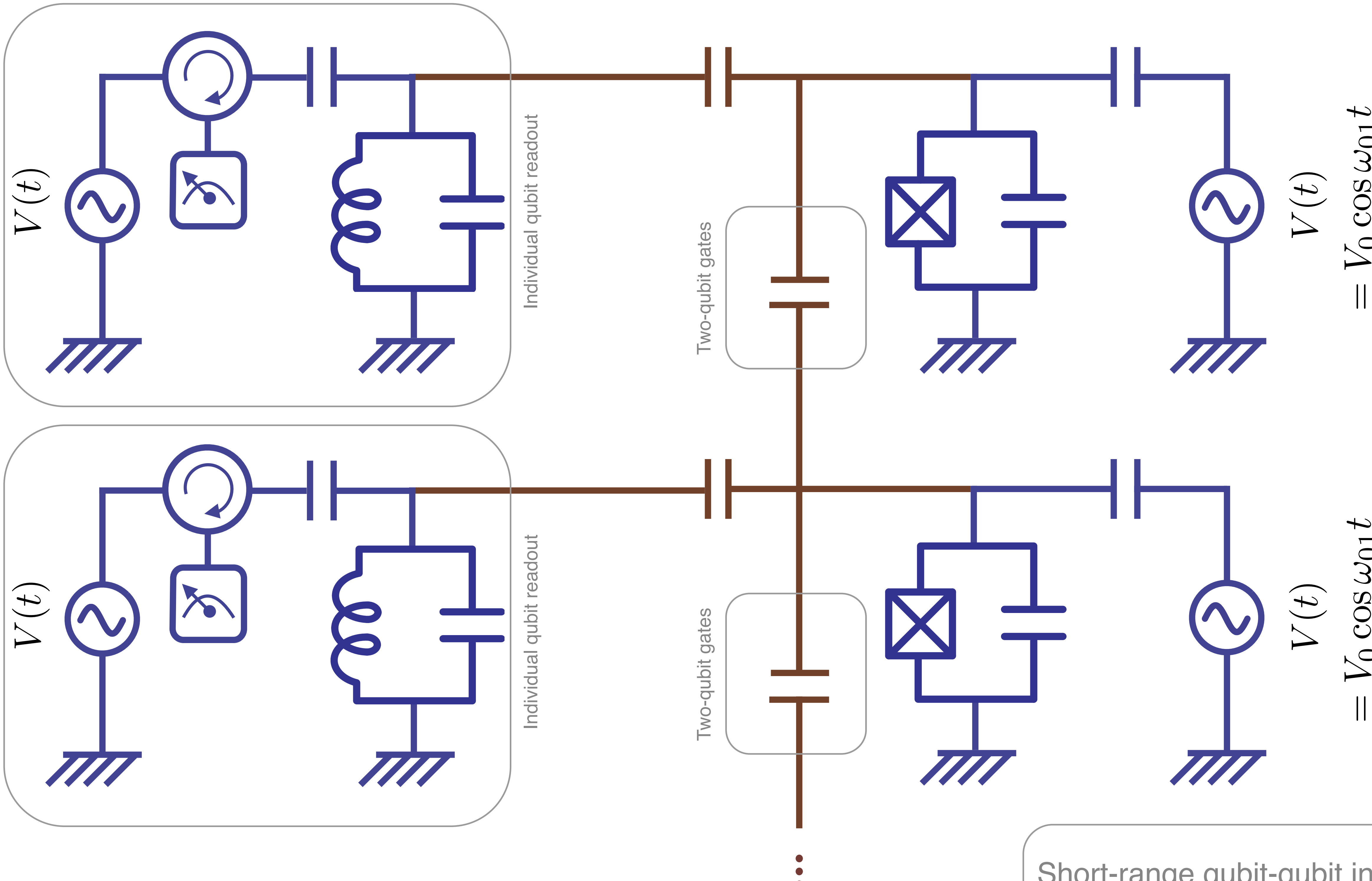


F. Helmer *et al,* Europhys. Lett. **85**, 50007 (2009)

Circuit QED: Multi-qubit architecture



Circuit QED: alternative architecture



Short-range qubit-qubit interactions

Circuit QED: recent realizations and challenges

A. Wallraff's lab @ ETH Zurich

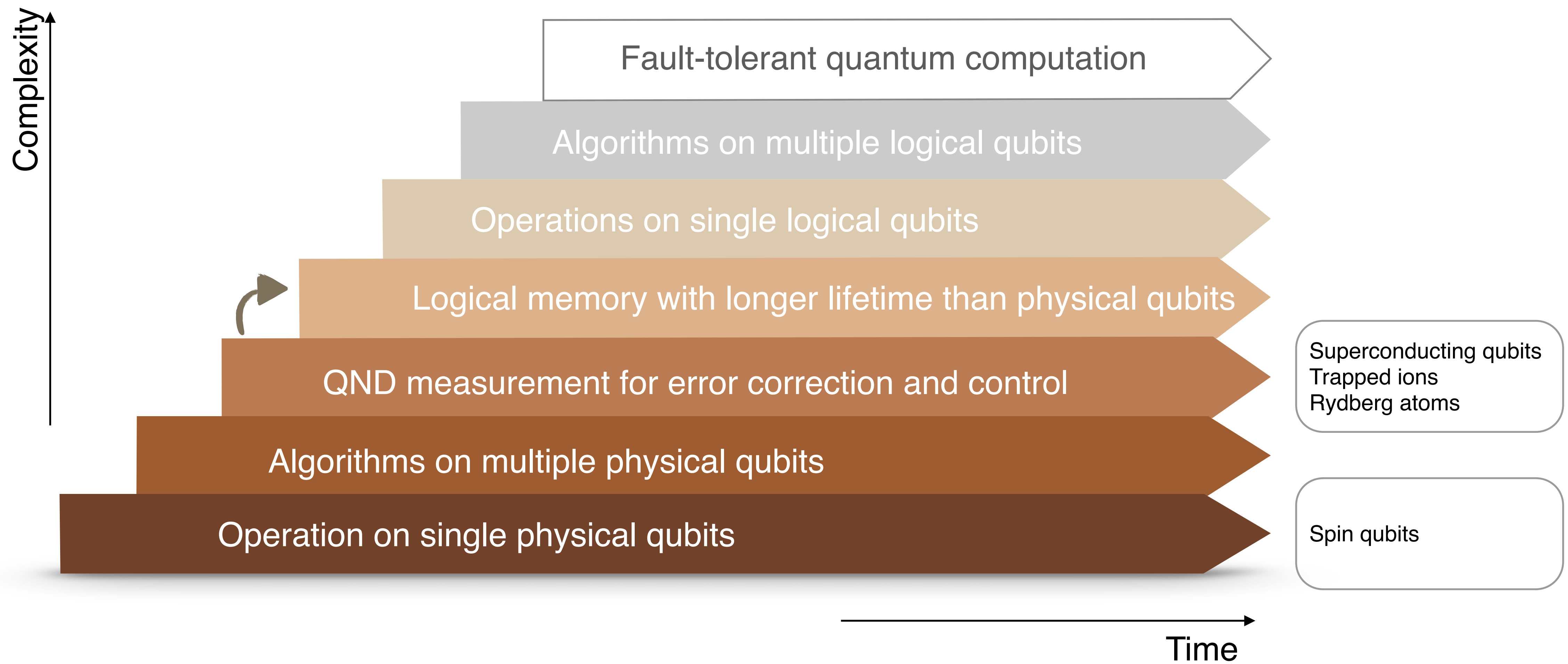
10 years of circuit QED

Yale: Wallraff et al., Nature **431**, 162 (2004)
Delft: Chioresco et al., Nature **431**, 159 (2004)

Quantum optics on a chip
with artificial atoms

Quantum information
processing

Past, present and future



M. H. Devoret and R. J. Schoelkopf, Science **339**, 1169 (2013)

High-fidelity gates and readout

Gates

Single-qubit gate

Average fidelity: > 99.92%

Error when simultaneously operating neighbour qubits: < 10^{-4}

UCSB: Nature **508**, 500 (2014)

Two-qubit gate (direct)

Average fidelity: up to 99.4%

UCSB: Nature **508**, 500 (2014)

Two-qubit gate (via bus)

Average fidelity: > 96.75%

IBM: PRL **109**, 060501 (2012)

Readout

Single-qubit readout

Fidelity: up to 99.8% in 140 ns

Multiplexed readout of 4 qubits

UCSB: PRL **112**, 190504 (2014)

Two-qubit readout (logical basis)

Fidelity: > 90%

ETH Zurich: Nature **500**, 319 (2013)

Two-qubit readout (Bell basis)

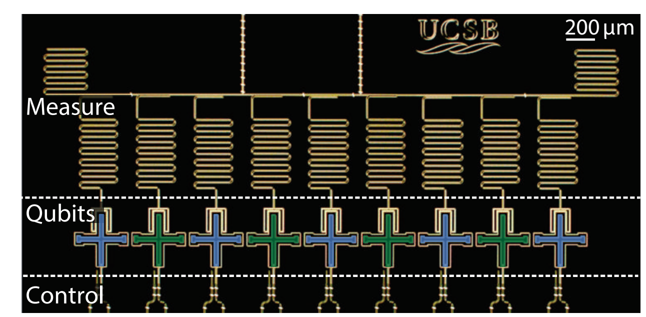
Bell state concurrence: ~ 35%

UCB: PRL **112**, 170501 (2014)
Delft: Nature **502**, 350 (2013)

Complexity

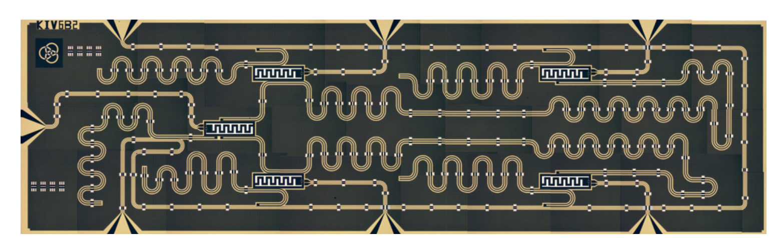
Max number of qubits and resonators

Direct: 9 qubits and 10 resonators



UCSB: 1411.7403

Bus: 5 qubits and 7 resonators



Delft: 1411.5542

Recent realizations

Simple algorithms

Deutsch–Jozsa

Yale: Nature **460**, 240 (2009)

Grover (N=4)

Yale: Nature **460**, 240 (2009)
Saclay: PRB **85**, 140503 (2012)

QFT

UCBS: Science **334**, 61 (2011)

Shor (15; compiled)

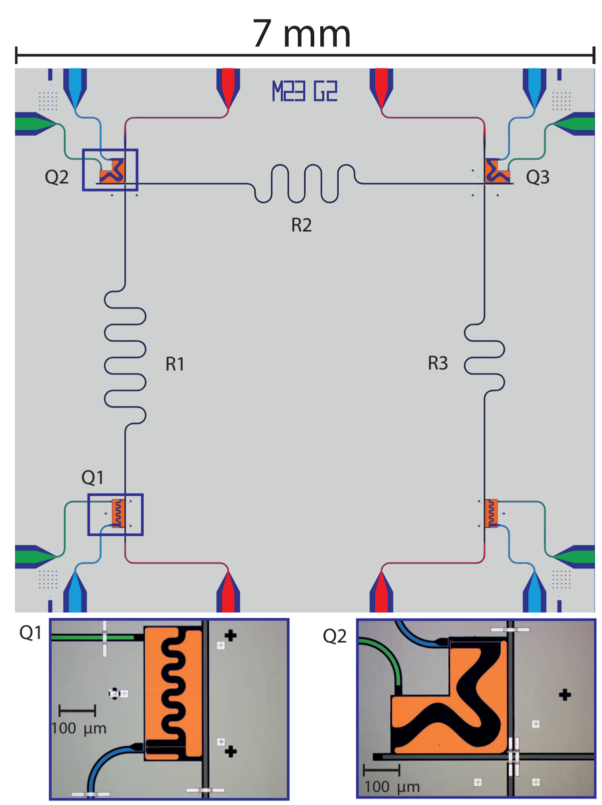
UCBS: Nature Physics **8**, 719 (2012)

⋮

Protocols

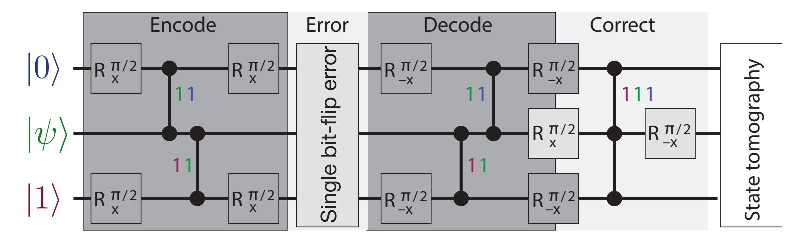
Deterministic teleportation

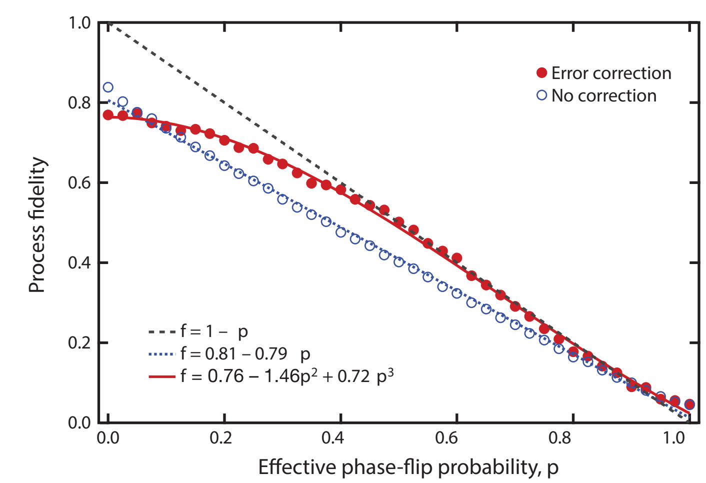
ETH Zurich: Nature **500**, 319 (2013)



Quantum error correction

3-qubit code





Yale: Nature **482**, 382 (2011)

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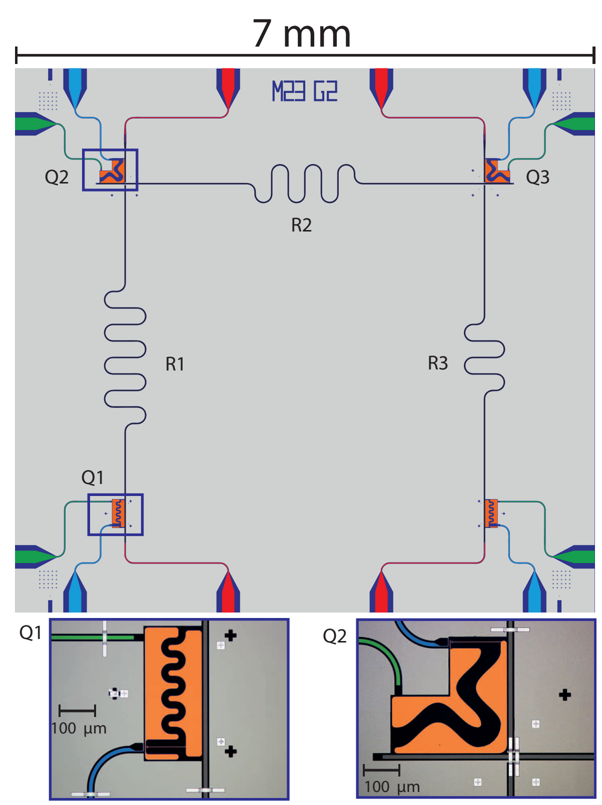
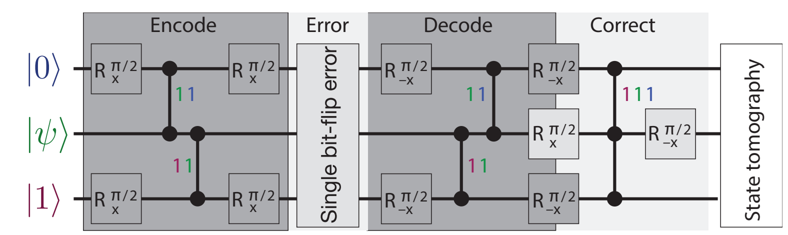


Quantum error correction

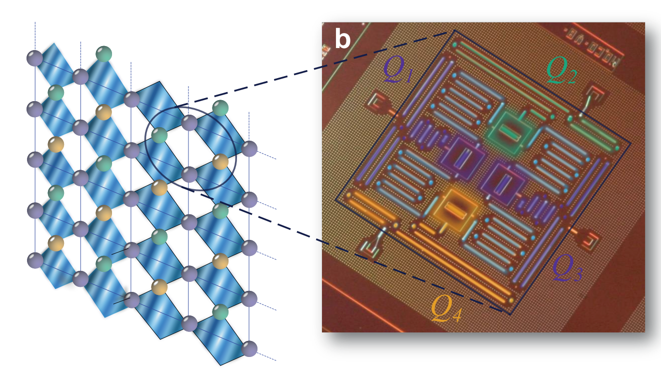
3-qubit code



Yale: Nature **482**, 382 (2011)

Error detection via parity meas.

« … using a two-by-two lattice of superconducting qubits to perform syndrome extraction and arbitrary error detection via simultaneous quantum non-demolition stabilizer measurements. This lattice represents a primitive tile for the surface code … »



IBM: 1410.6419
Delt: 1411.5542

Recent realizations

Simple algorithms

Deutsch–Jozsa

Yale: Nature **460**, 240 (2009)

Grover (N=4)

Yale: Nature **460**, 240 (2009)
Saclay: PRB **85**, 140503 (2012)

QFT

UCBS: Science **334**, 61 (2011)

Shor (15; compiled)

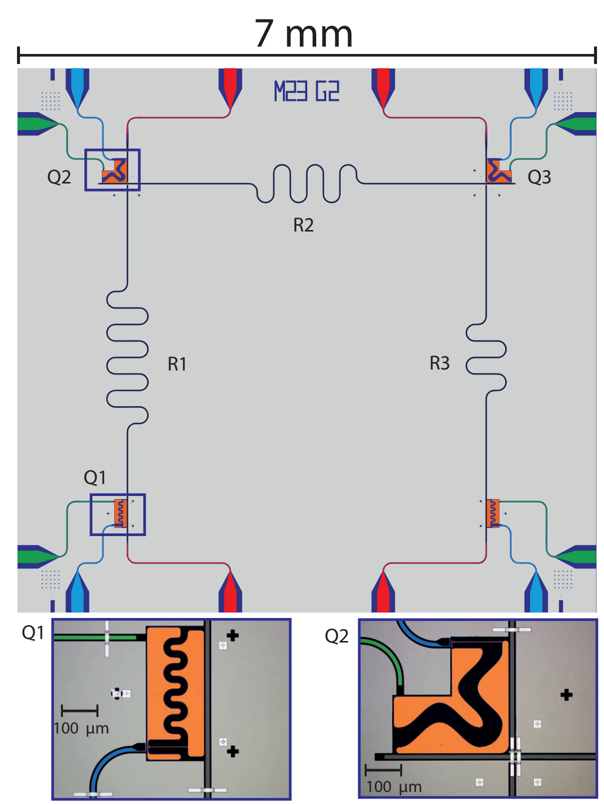
UCBS: Nature Physics **8**, 719 (2012)

⋮

Protocols

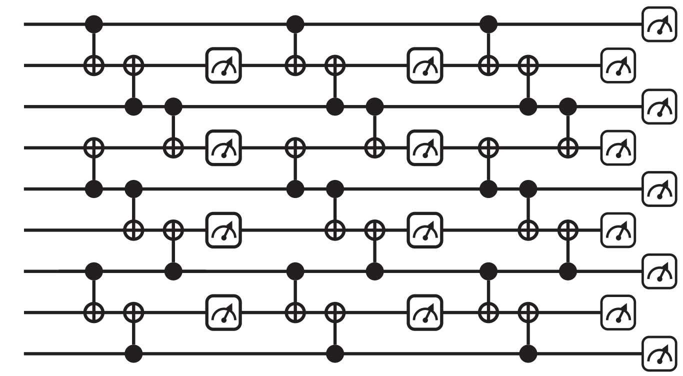
Deterministic teleportation

ETH Zurich: Nature **500**, 319 (2013)

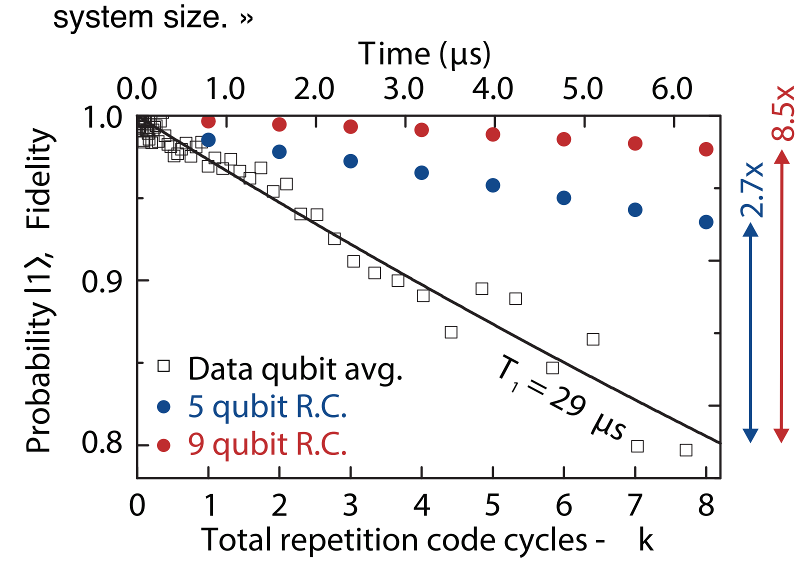


Quantum error correction

Error detection via parity meas.

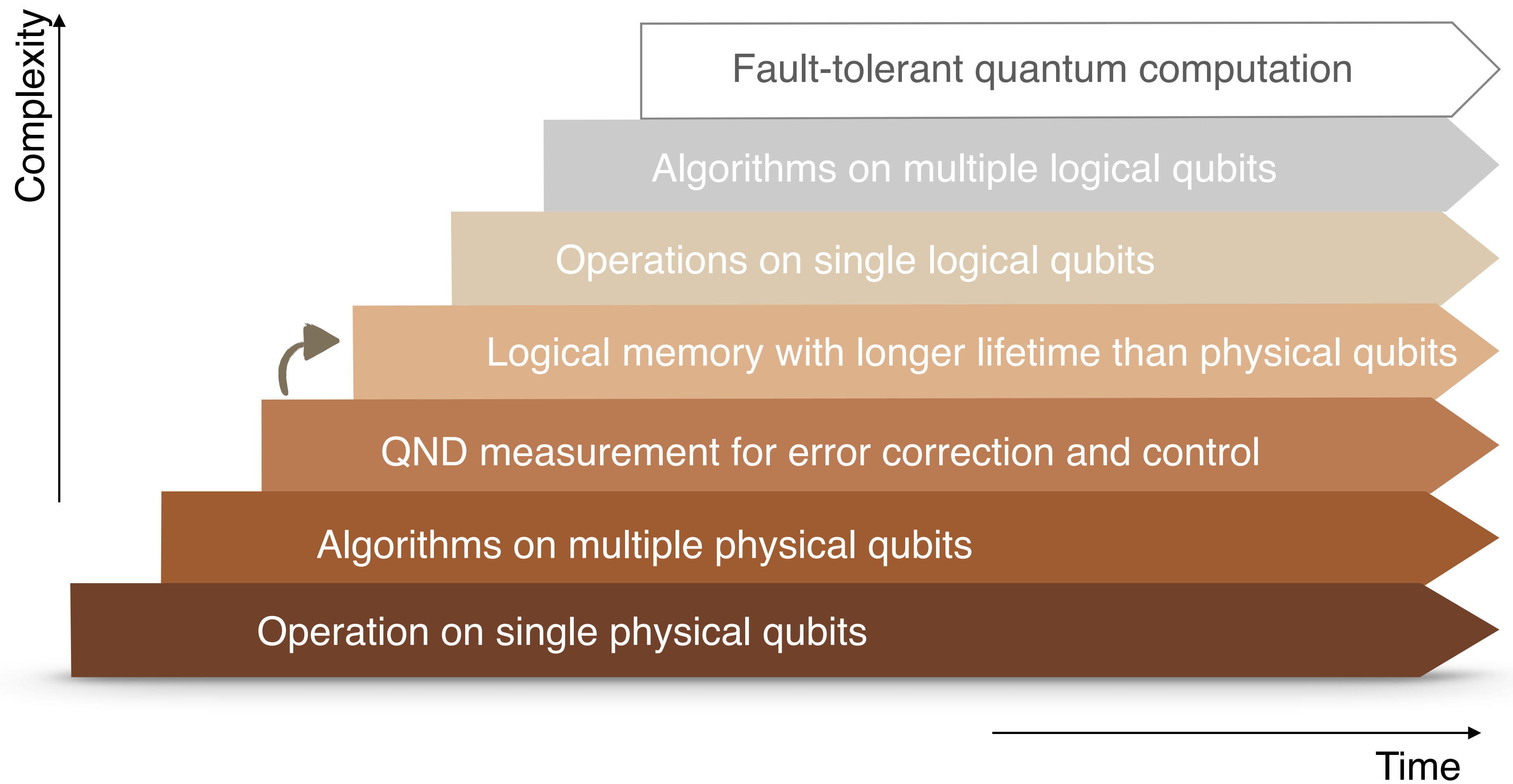


« … we report the protection of **classical states** from environmental bit-flip errors and demonstrate the suppression of these errors with increasing system size. »



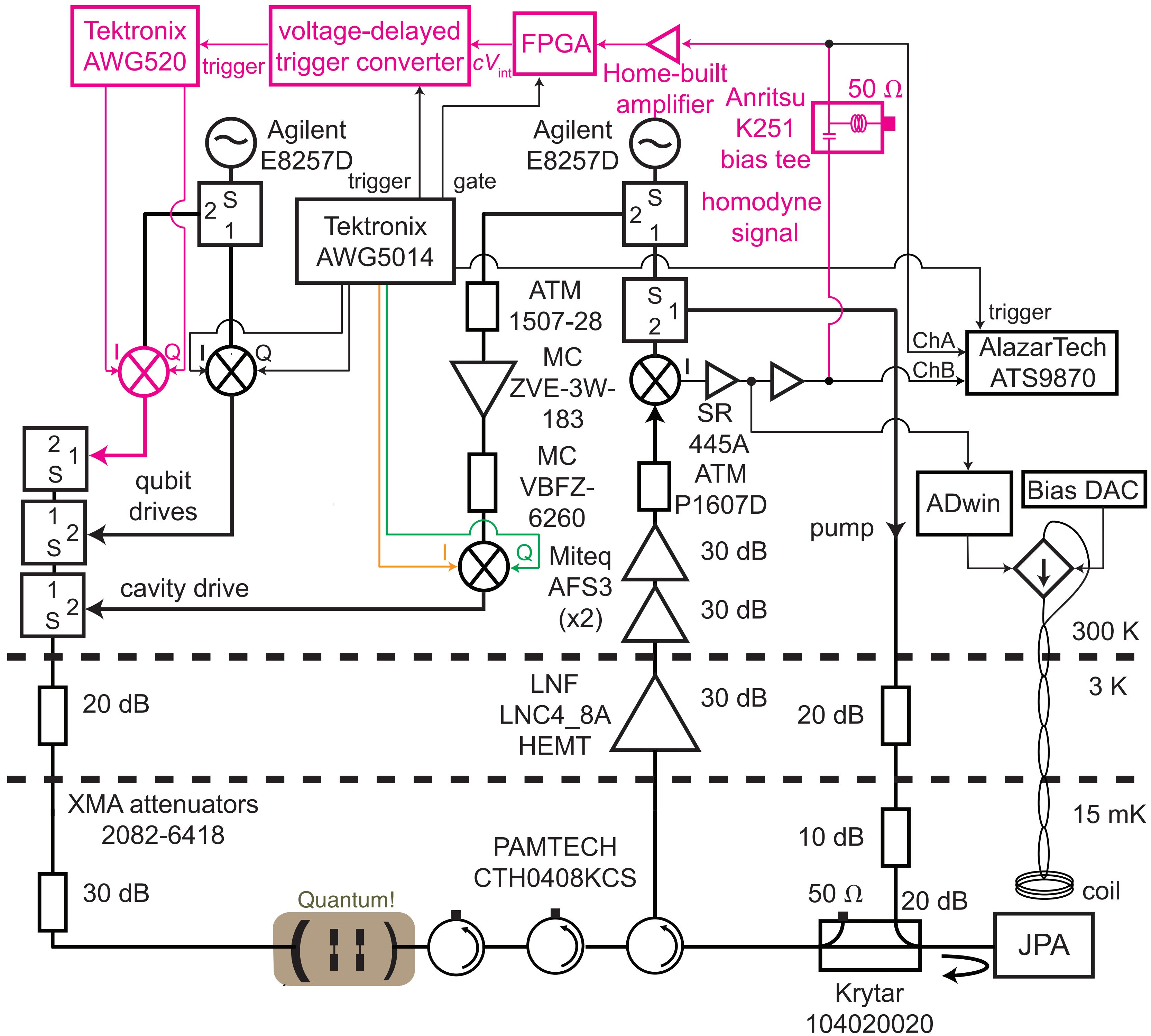
UCSB: 1411.7403

Past, present and future



M. H. Devoret and R. J. Schoelkopf, Science **339**, 1169 (2013)

Under the rug…



Summary

- Artificial atoms based on Josephson junctions
  - Low error per gate
  - Steady improvement
- Circuit QED
    - Resonator acts as bus for entangling gates
    - Dispersive regime: high-fidelity qubit readout
  - Basic protocols being implemented

J. Mlynek *et al.*, Quantum Device Lab, ETH Zurich (2012)

UNIVERSITÉ DE SHERBROOKE

- ✤Superconducting qubits and circuit QED
- ✤Quantum error correction, quantum algorithms, …
- ✤Quantum dots, NV centers, …
- ✤ Full counting statistics and quantum noise

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