SHABANILAB: SUMMER Q CAMP

IBM QUANTUM HARDWARE ARCHITECTURE

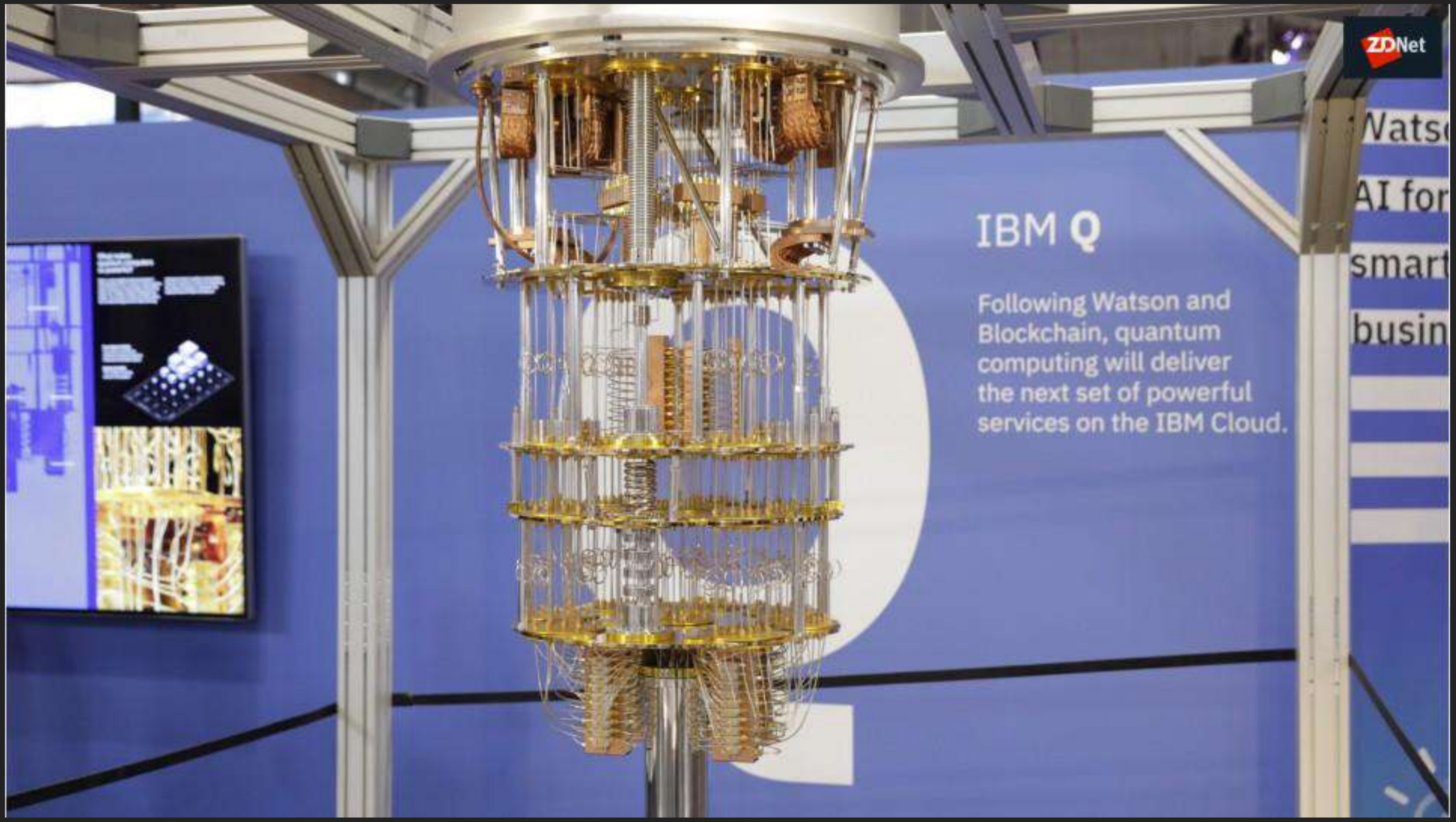
OVERVIEW

- Generic architecture
- Qubit implementation
- Qubit manipulation
- Errors in single qubits
- 2 qubit gates

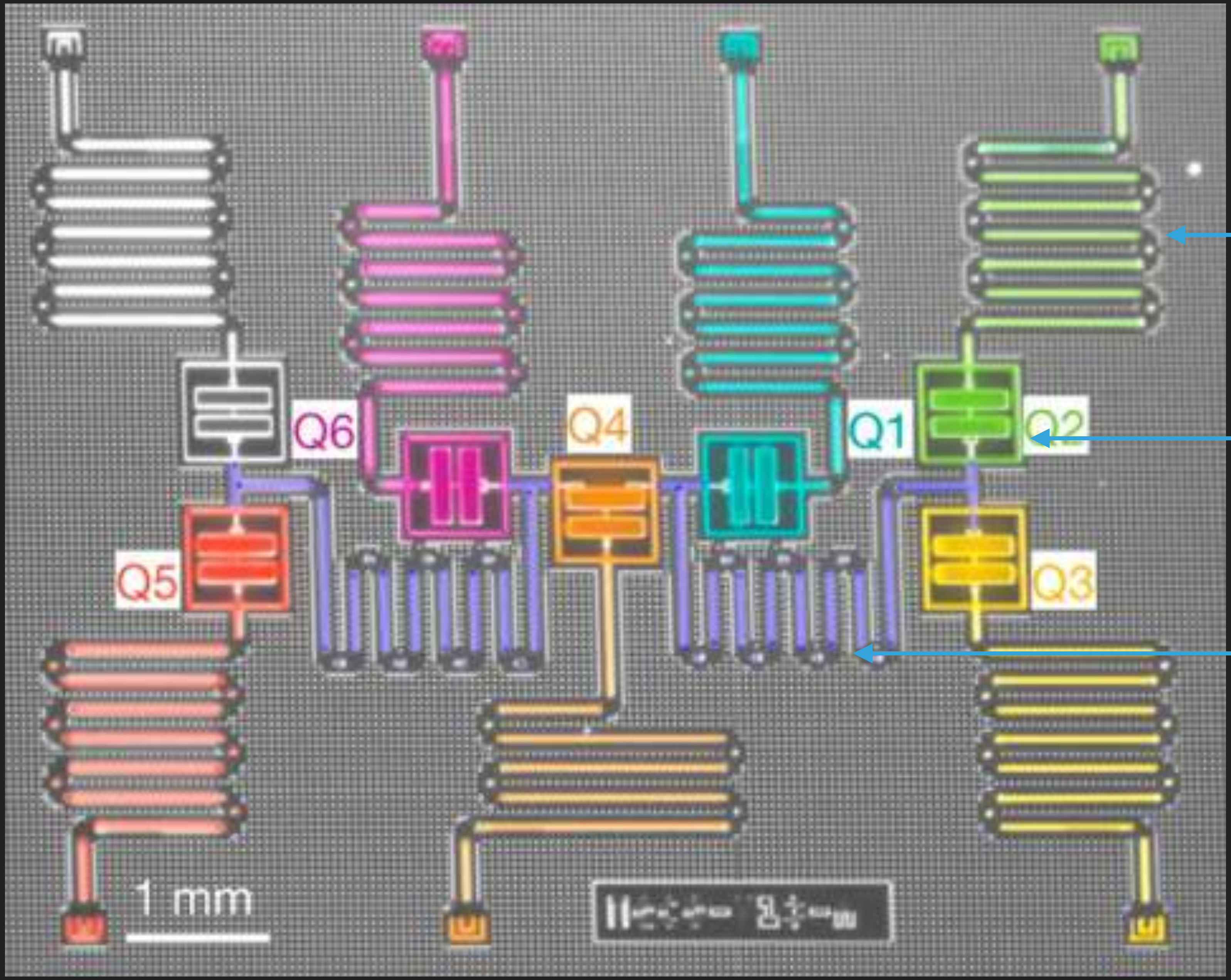
Sources: - http://www.quantum-lab.org/qip2015/slides/QIP2015-Alexandre%20Blais.pdf
- IBMQ
- https://medium.com/@jonathan_hui/qc-how-to-build-a-quantum-computer-with-superconducting-circuit-4c30b1b296cd

IBM PLATFORM

- Fixed frequency superconducting qubit
- Cooled down to dilution fridge temperatures (10 mK)
- Manipulated and measured through microwave signals



IBM ARCHITECTURE



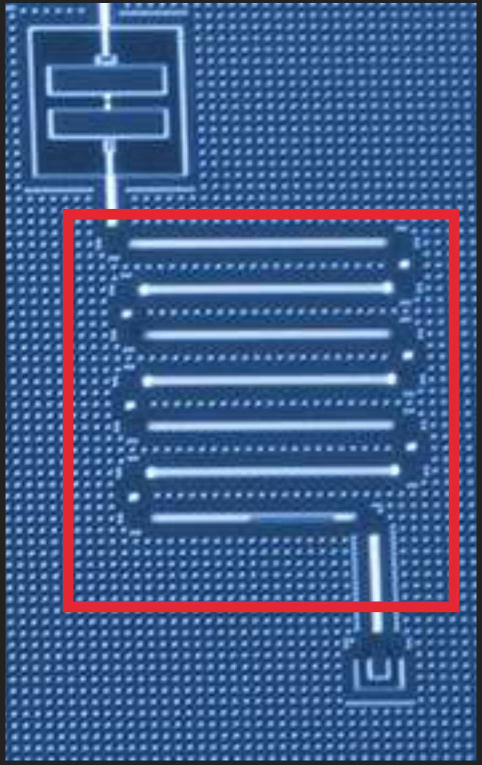
Readout cavity

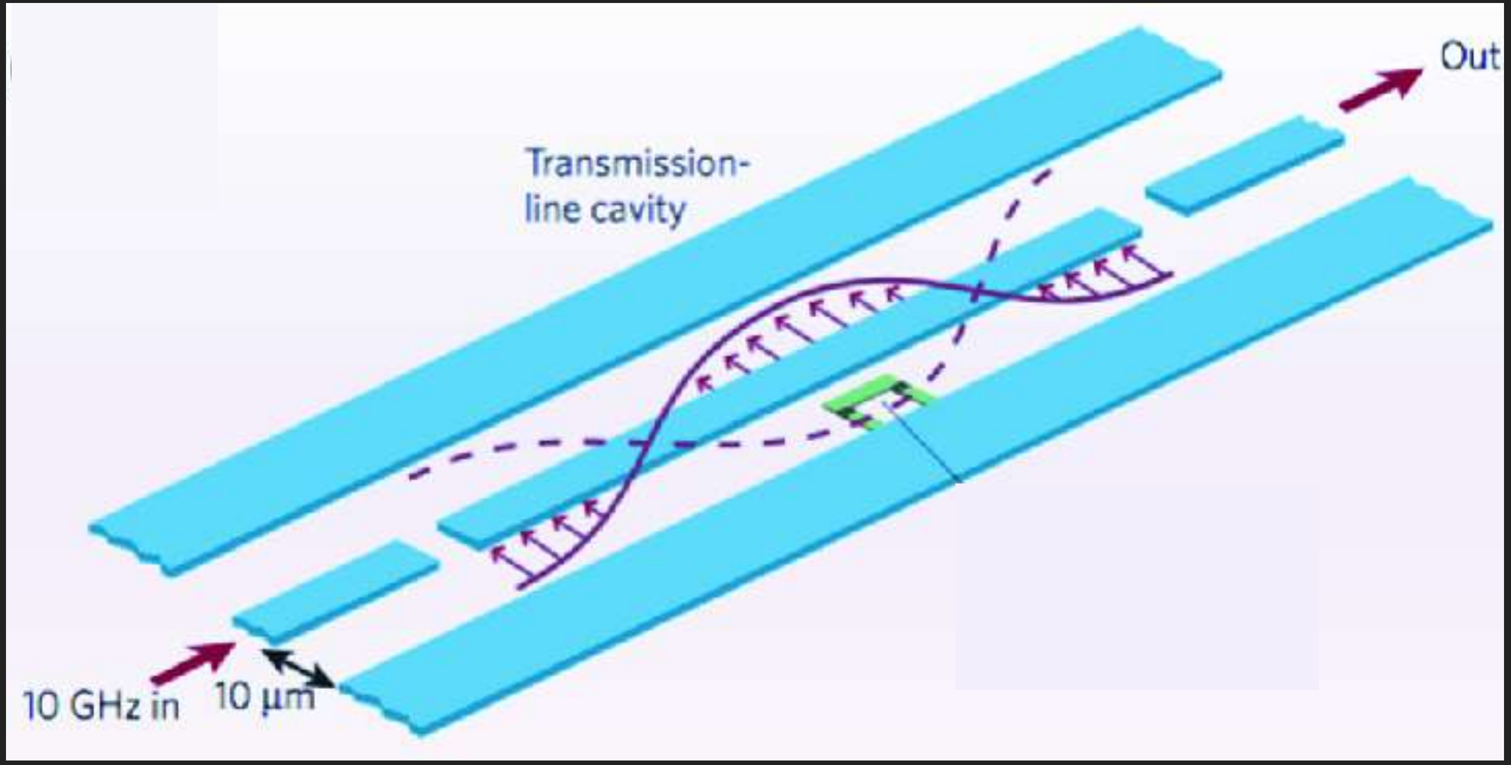
Qubit

Coupling cavity

A Kandala *et al. Nature* 549, 242–246 (2017) doi:10.1038/nature23879

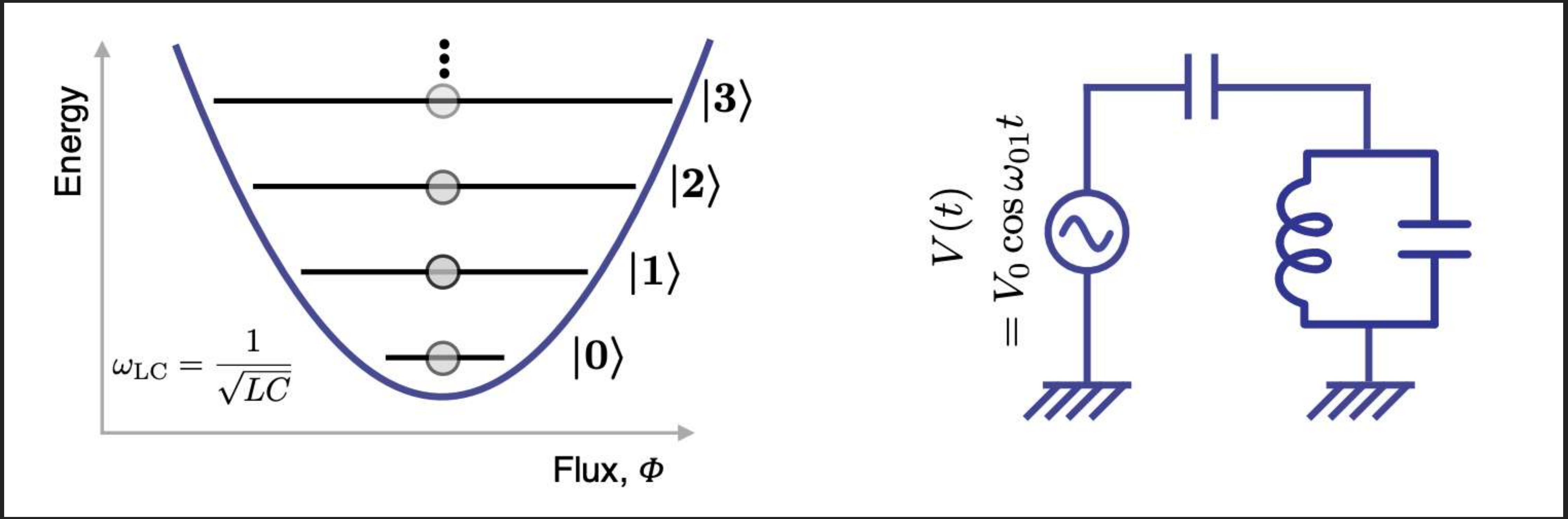
MICROWAVE CAVITY: AN HARMONIC OSCILLATOR





- Coplanar wave-guide -> propagation medium
- Capacitor -> equivalent to a mirror
  - Fabry-Perot resonator (two mirrors face to face)

MICROWAVE CAVITY: THE LC PICTURE

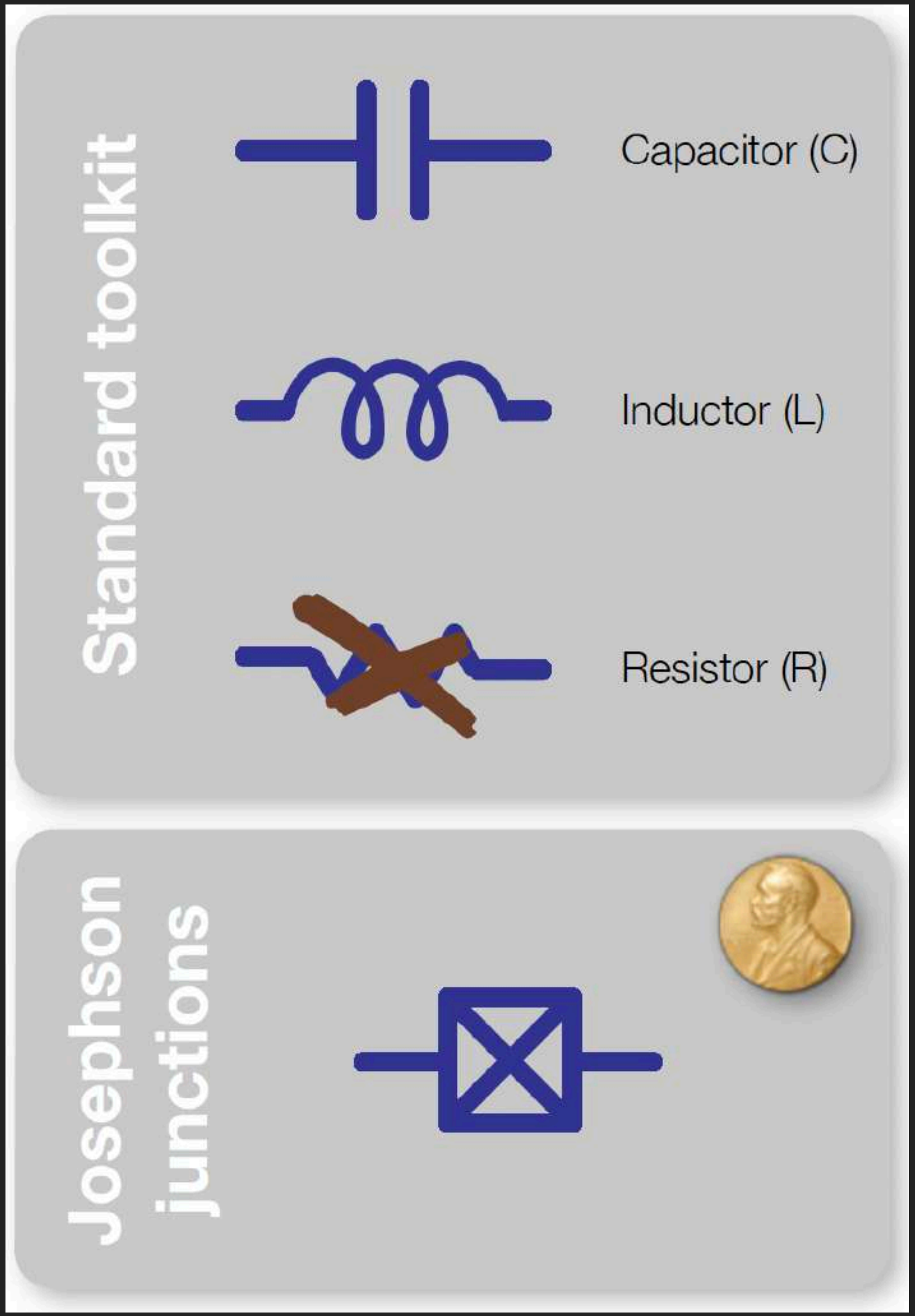


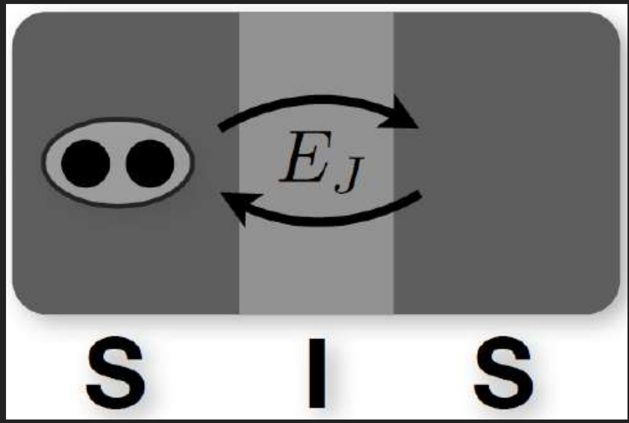
$$H = \underbrace{\frac{q^2}{2C}}_{E_C} + \underbrace{\frac{\phi^2}{2L}}_{E_L} \qquad \omega_{LC} \sim 10\,\text{GHz} \sim 0.5\,\text{K}$$

- Equally spaced levels
  - Impossible to go from 0 to 1 using classical drive

A qubit requires a non-linear element to create unequal spacing

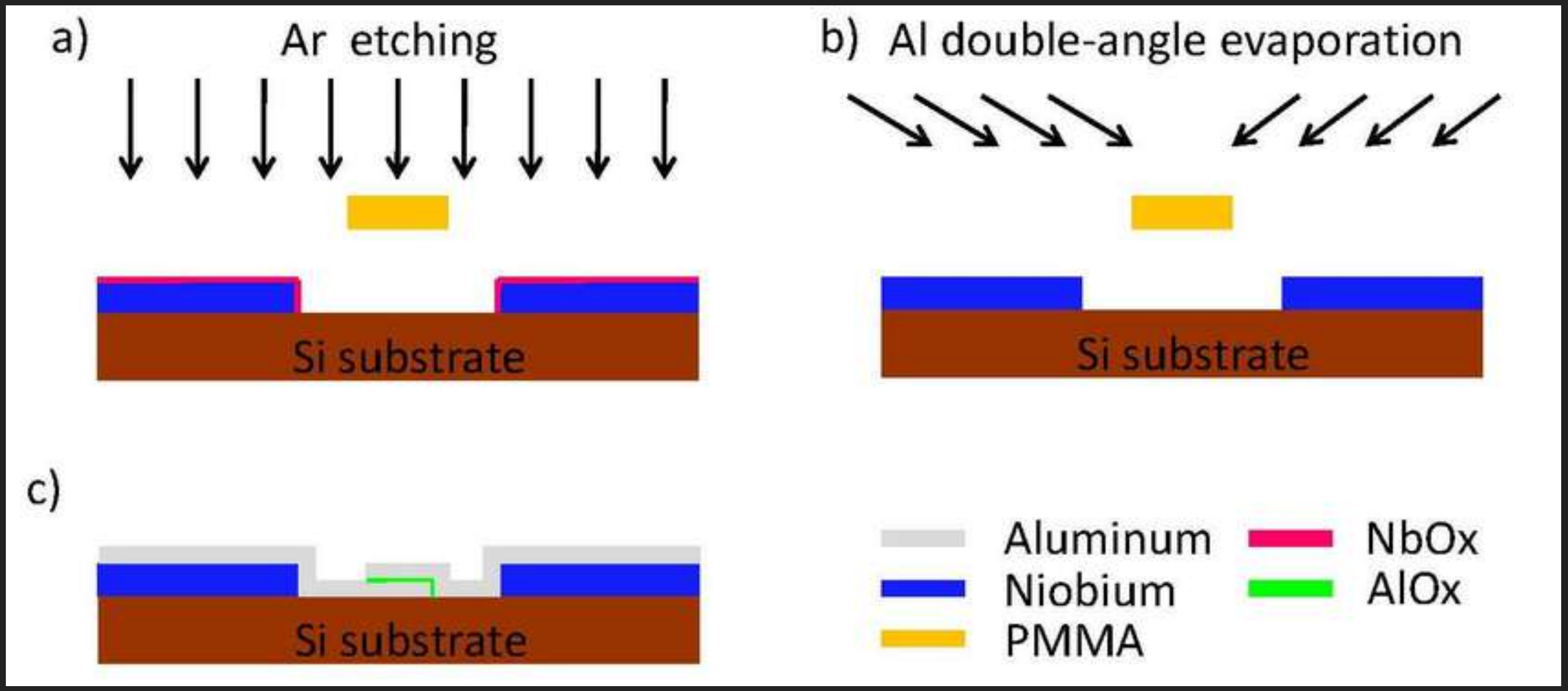
THE JOSEPHSON JUNCTION: A NON-LINEAR, NON-DISSIPATIVE ELEMENT

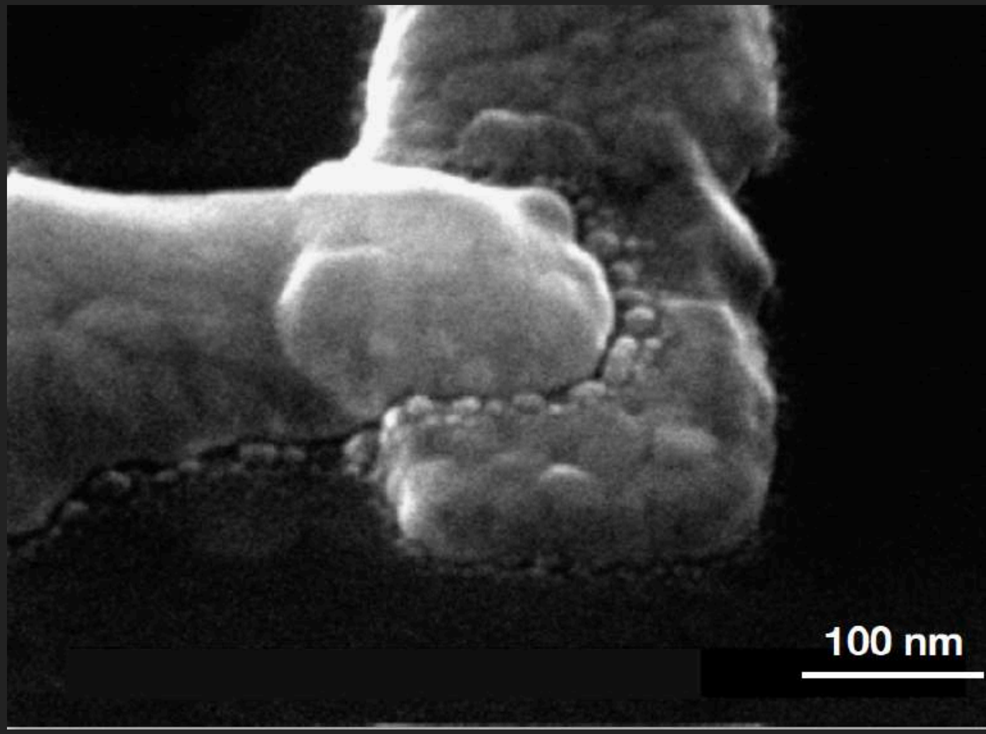




$$E_J(\phi) = -E_J \cos(2\pi \frac{\phi}{\phi_0})$$

THE JOSEPHSON JUNCTION: FABRICATION



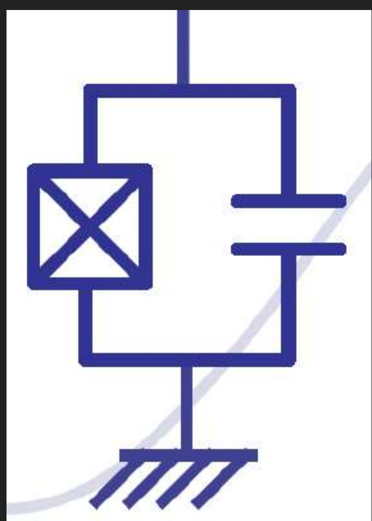


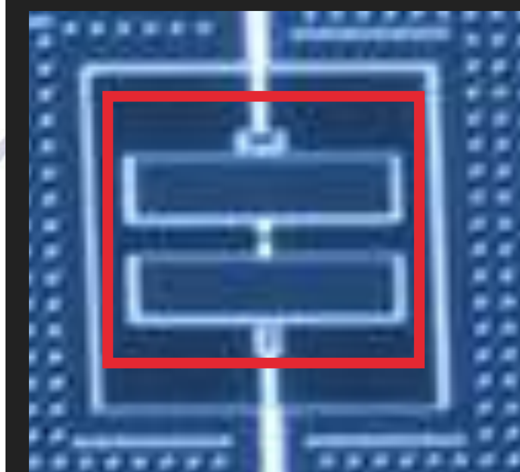
Most common technology relies on Al/AlOx/Al junctions

- Easy to fabricate
- Not perfectly reproducible

Source: https://iopscience.iop.org/article/10.1088/0953-2048/28/2/025009

THE TRANSMON QUBIT



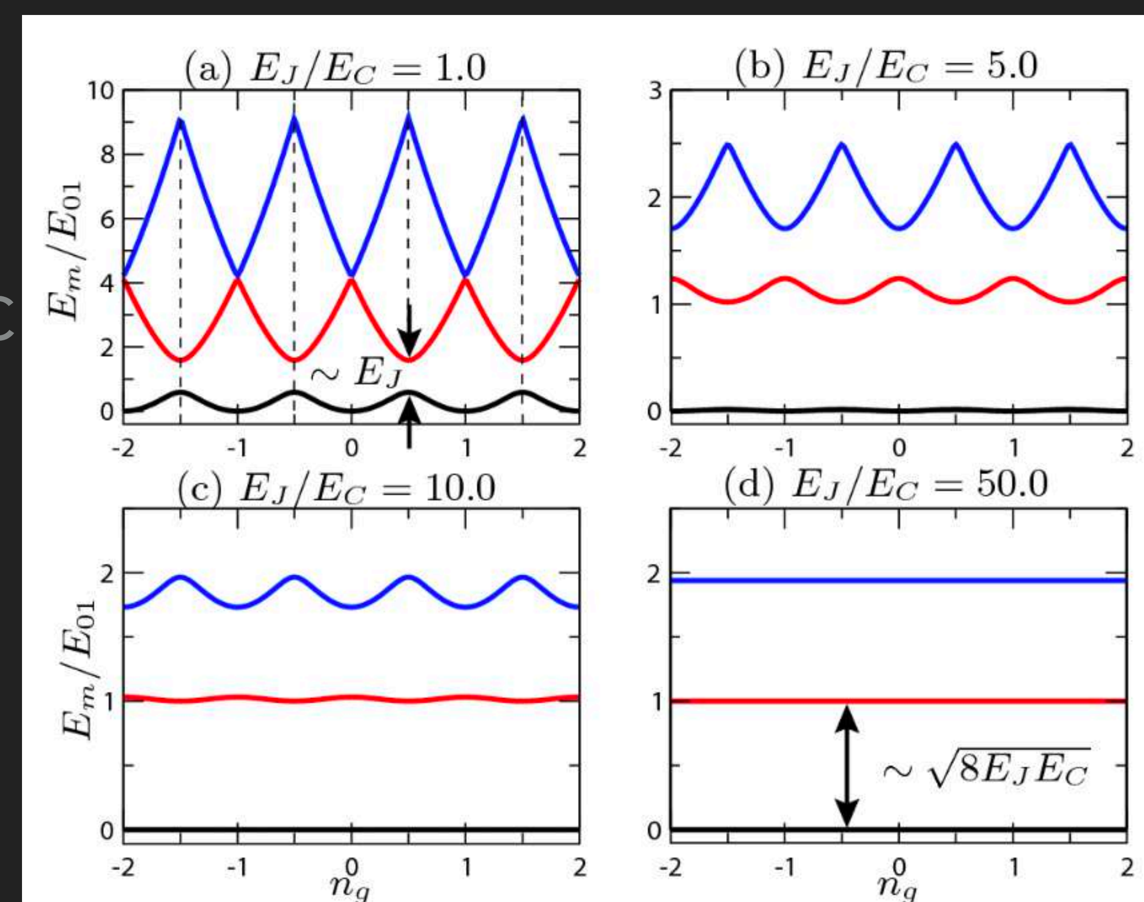


Start from a LC resonator

- Replace the inductance with a junction

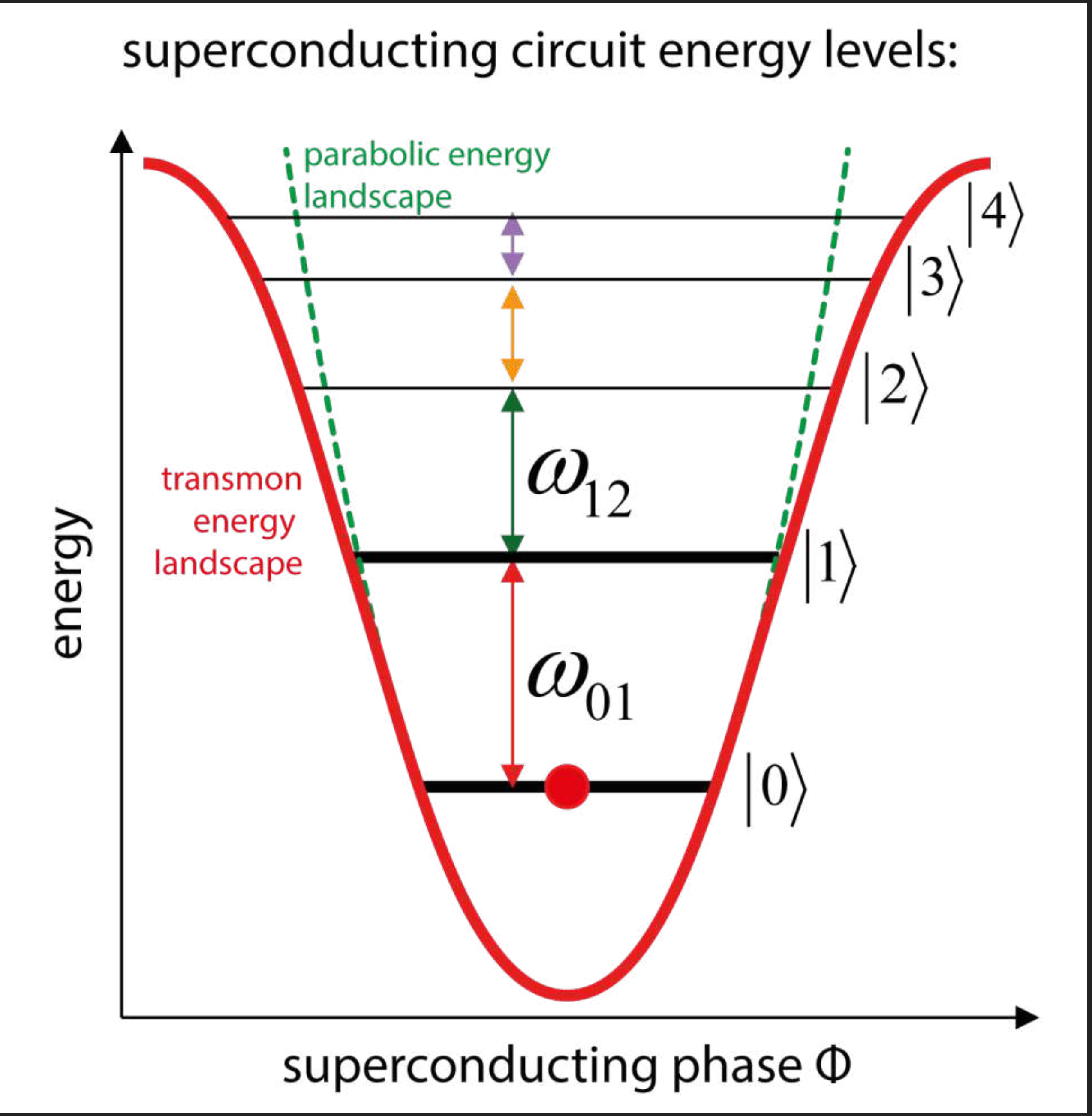
Use a large capacitance to reduce E_C

- Reduced charge noise sensitivity
- Limited non-linearity



Source: https://journals.aps.org/pra/abstract/10.1103/PhysRevA.76.042319

THE TRANSMON QUBIT



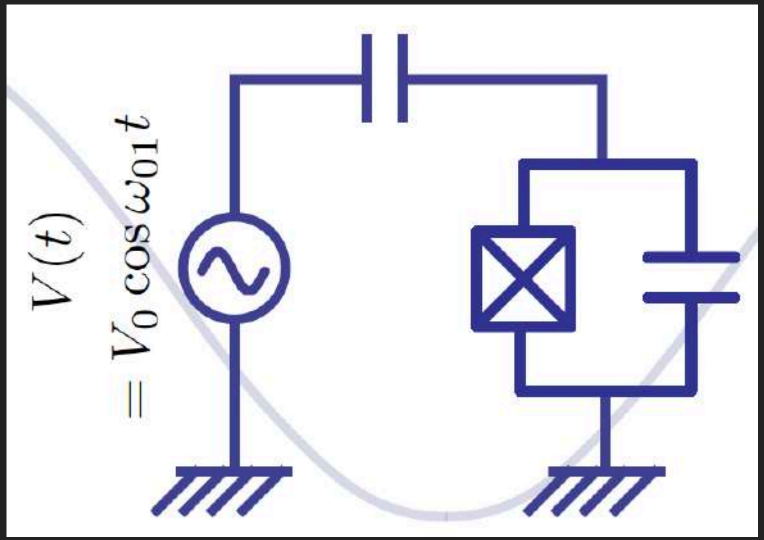
$$\hbar\,\omega_{01} = \sqrt{8\,E_J\,E_C}$$

$$\hbar\,\omega_{12} \simeq \hbar\,\omega_{01} - E_C$$

E_C is a compromise between non-linearity and sensitivity to charge-noise

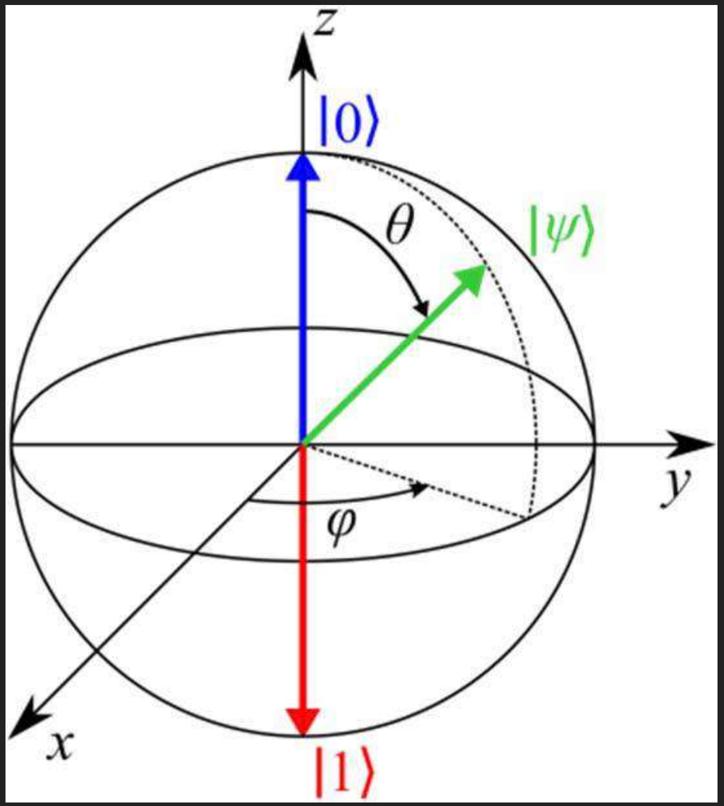
Source: https://blog.qutech.nl/index.php/2017/08/13/how-to-make-artificial-atoms-out-of-electrical-circuits-part-ii-circuit-quantum-electrodynamics-and-the-transmon/

THE TRANSMON QUBIT: MANIPULATION



- Microwave drive applied at the qubit frequency allow to induce transition between 0 and 1

- Through proper calibration of the duration of the pulse we can get arbitrary rotation along one axis (x)

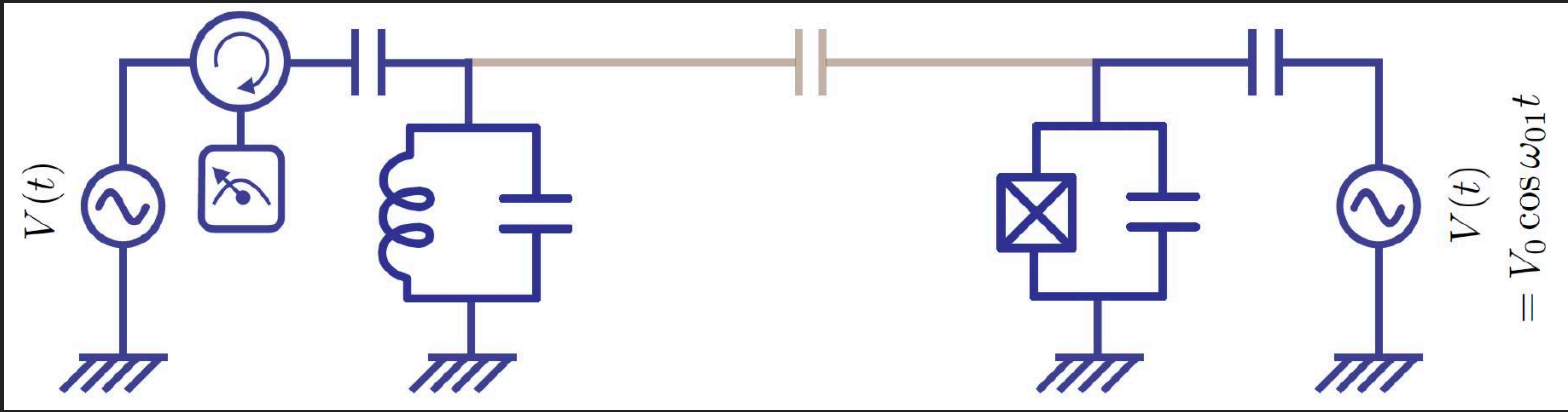


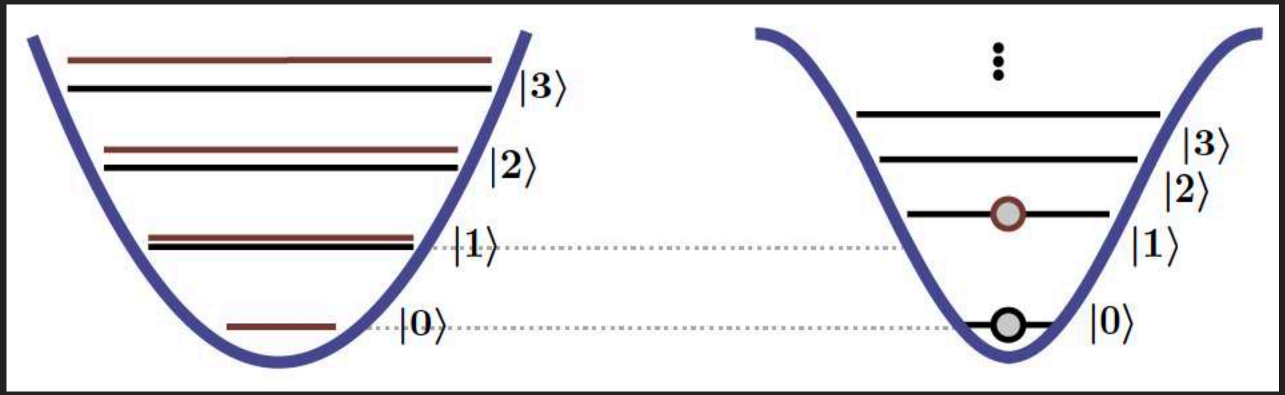
- Universal control requires a second axis, which can be obtained using the phase of the microwave signal: dephasing the signal by π/2 allow to rotate along y.
  → z-gates are actually purely software gates.

THE TRANSMON QUBIT: MANIPULATION (QISKIT SIDE)

- IBM backend is regularly calibrated to determine the qubit frequencies and proper gate times (Those drift)
- Each single qubit gate is decomposed in term of rotations
- Proper pulses are synthesized (1-2 GSample/s) and unconverted to the qubit frequency (~ 5 GHz) using microwave components.
- OpenPulses give low level access to control shaping.

THE TRANSMON QUBIT: READOUT

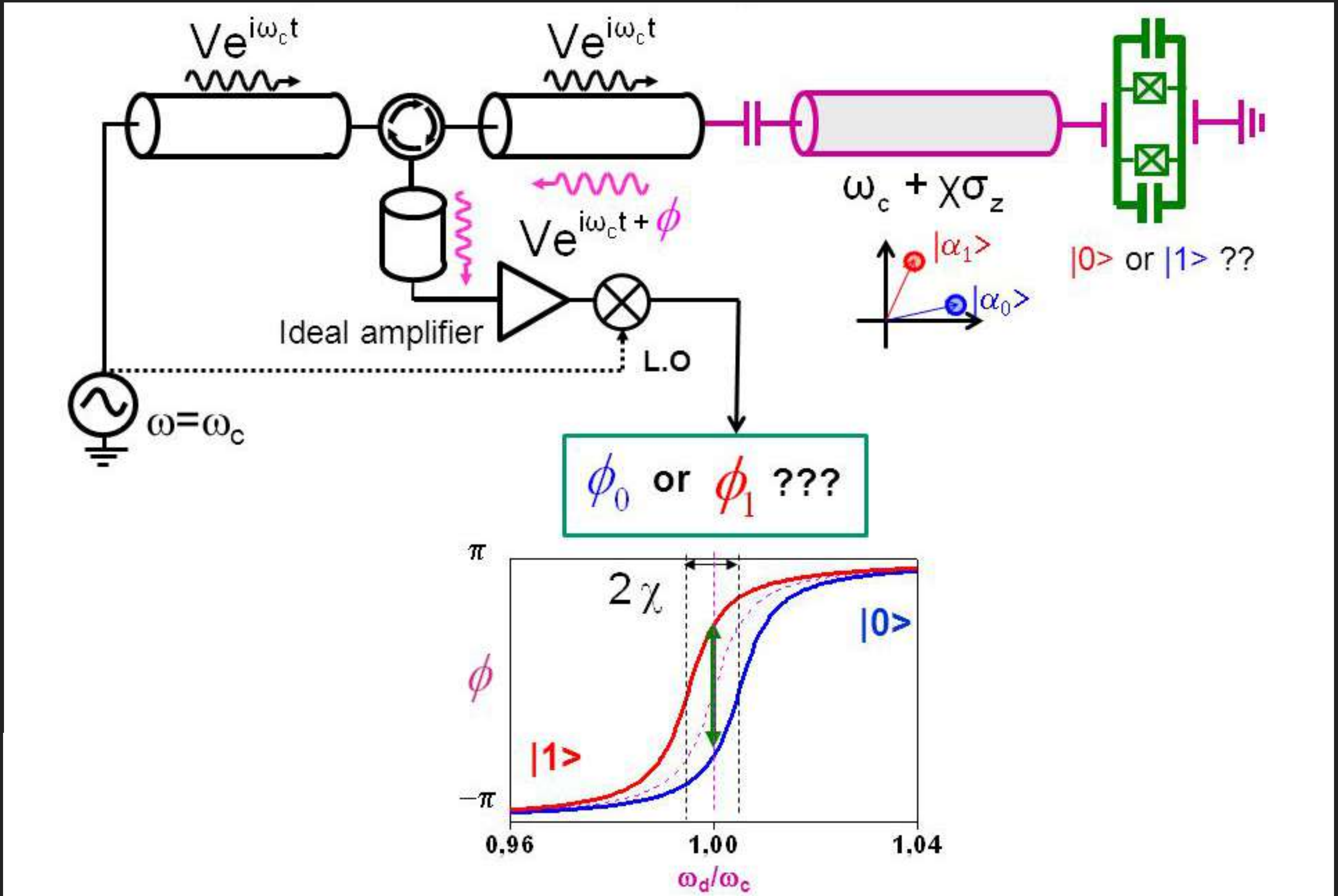




Dispersive regime:

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

THE TRANSMON QUBIT: READOUT



THE TRANSMON QUBIT: READOUT (QISKIT SIDE)

- In IBM architecture all qubit are statically coupled
- Measurement outcomes carry information about more than a single qubit.
- Through proper thresholding and calibration readout fidelity is improved → requires to read all qubits
- OpenPulses provide access to all three levels.

REAL QUBIT ERROR SOURCES

- Bit-flip error: $|1\rangle \rightarrow |0\rangle$
- Phase-flip error: $|0\rangle + |1\rangle \rightarrow |0\rangle - |1\rangle$
- Initialization error: Initial state is $|1\rangle$
- Readout error: misinterpreted value
- Leakage error:
  Qubit state is not confined anymore to the lowest two levels

THE TRANSMON QUBIT: RELAXATION AND DECOHERENCE

- A transmon can relax from $|1\rangle$ to $|0\rangle$ by emitting a photon for example in the readout cavity
  → this happens on a typical time called T_1
- Fluctuations of the qubit frequency can lead to error in the phase used to manipulate the qubit
  → this happens on a typical time called T_2
- The finite temperature of the system can lead to spontaneous excitation of the qubit in $|1\rangle$

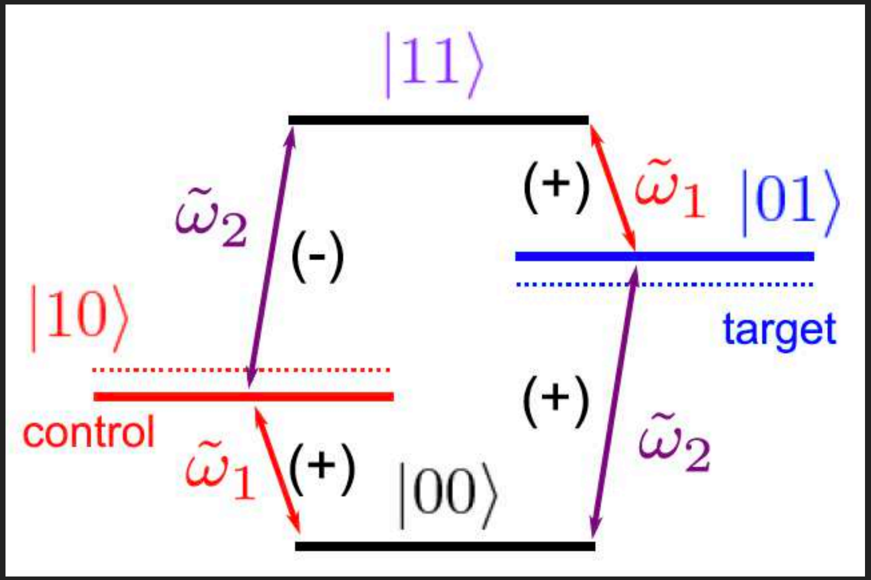
THE TRANSMON QUBIT: MANIPULATION ERROR

- Frequency error: rotation axis error
- Timing error: wrong end point
- Leakage outside of the lowest states of the qubit: comes from short pulses which are wide in frequency domain and can overcome the anharmonicity
- Requires regular tuning and pulse shape optimization

IMPLEMENTING A TWO-QUBIT GATE

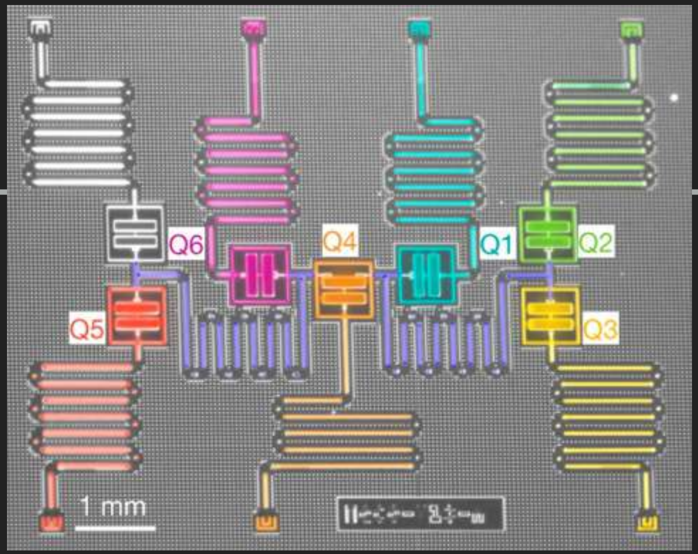
https://journals.aps.org/pra/pdf/10.1103/PhysRevA.87.030301

- Multi-qubit gates required to generate entanglement
- IBM uses a cross-resonance gate
  Because qubits have a static coupling, applying a drive at the qubit 2 frequency on qubit 1 will induce a state dependent rotation on qubit 2.



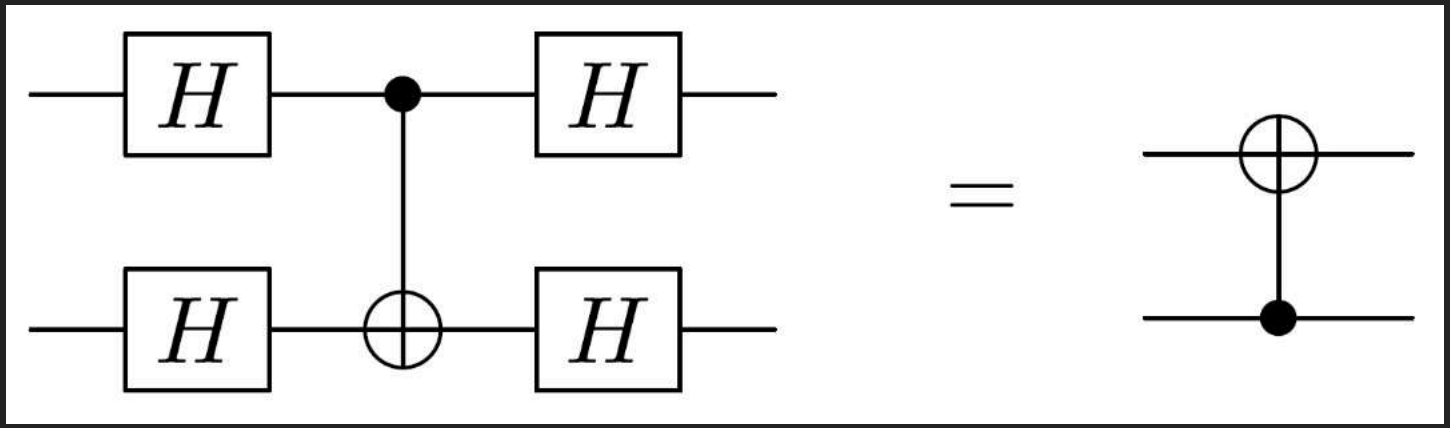
- This procedure is more efficient if the control qubit has a higher frequency than the target qubit
  → CNOT gate are directional in the hardware

The CNOT gate has a lower fidelity than single qubit gates

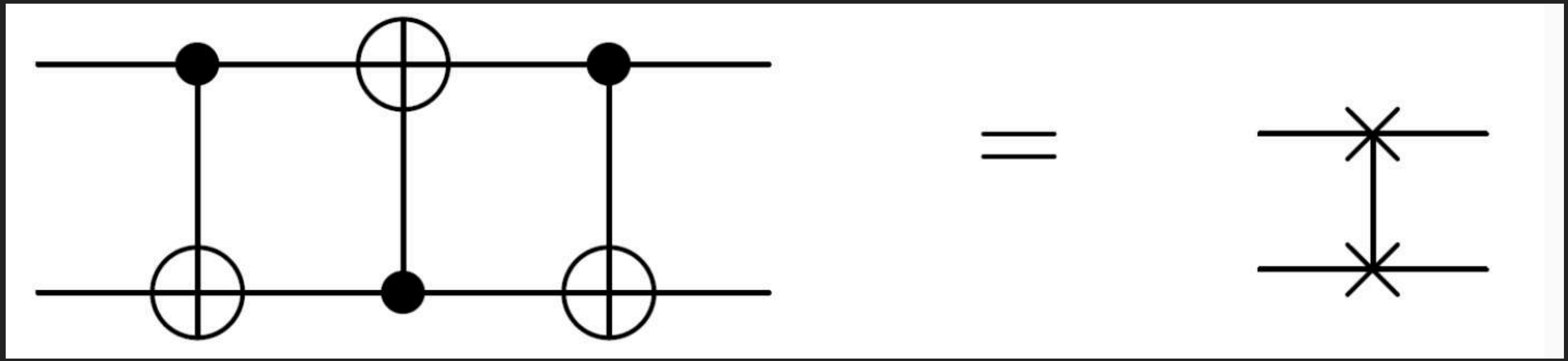


COST TO MAP ON REAL HARDWARE

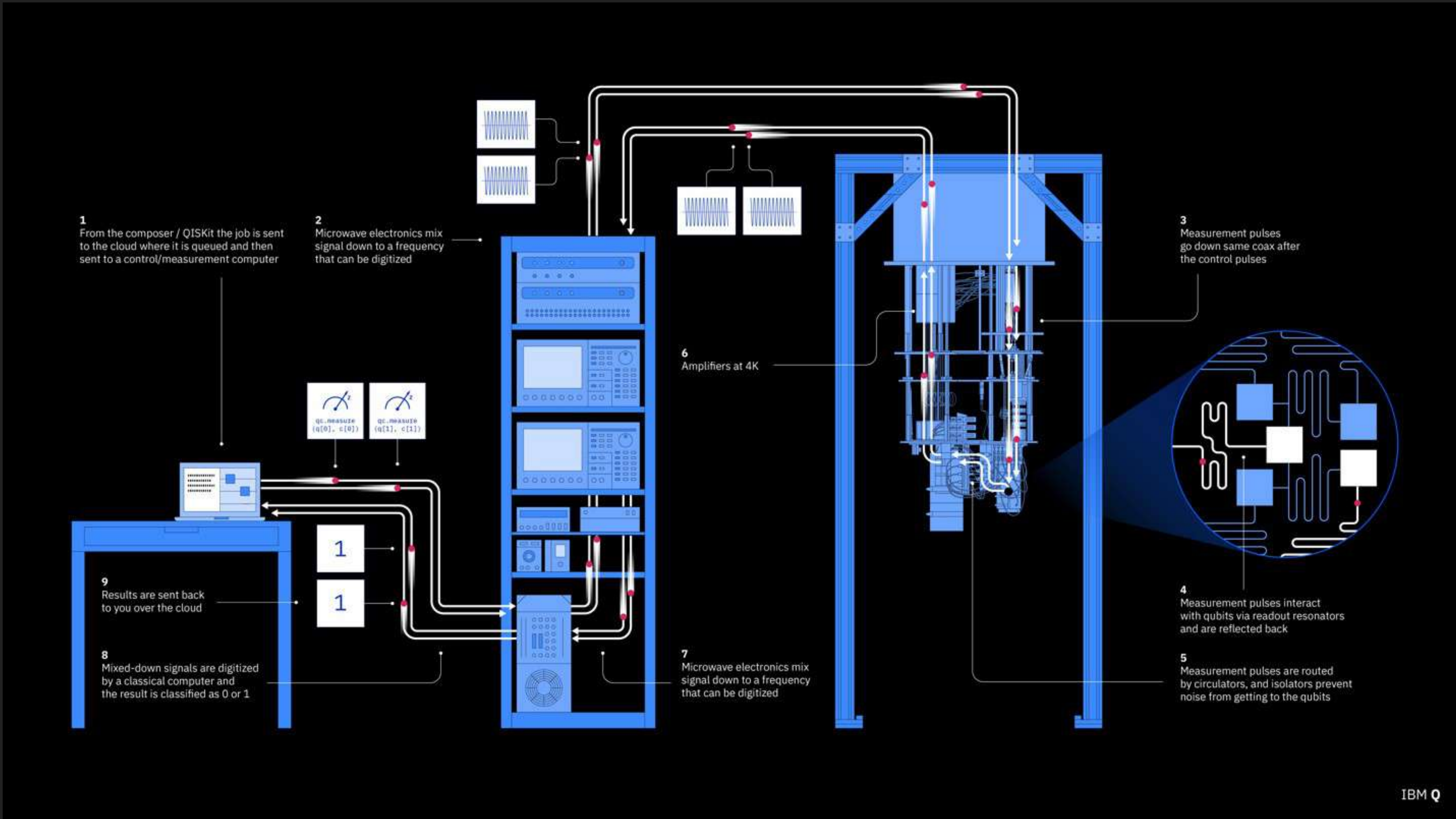
- CNOT is unidirectional, using single qubit gate one can get the other direction



- If circuit requires to perform operation on non-adjacent/coupled qubits SWAP operations need to be inserted.



QISKIT COMPILER PIPELINE



QISKIT COMPILER PIPELINE

- Optimization:
  - compaction of gate, simplification of redundant gates
- Mapping:
  - reduce the number of SWAP gates

Strong interdependence