# Technical challenges and realizations of quantum qubits: the example of superconducting charge qubits …

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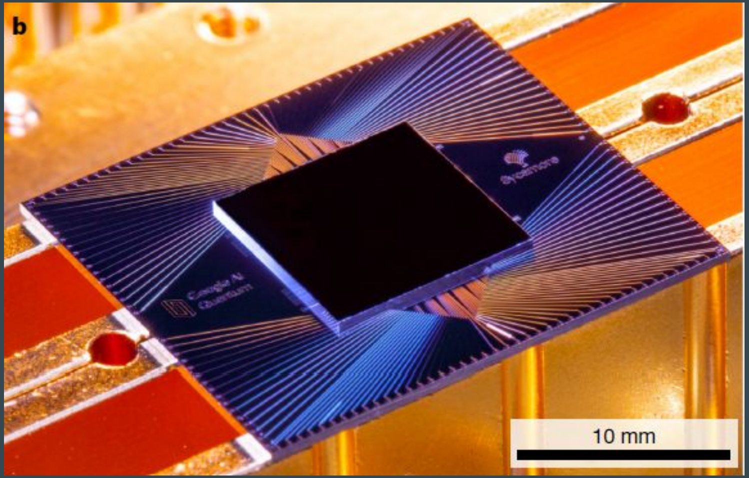


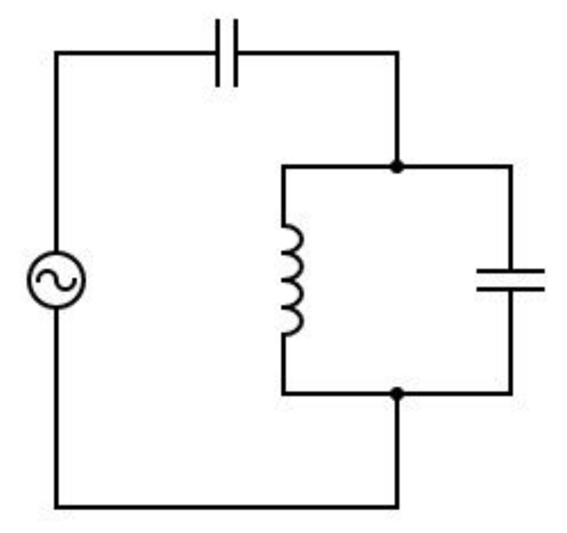
The Sycamore processor [F. Arute et al, 2019]

# The challenges

- Scalability
- Protected from decoherence (large relaxation time $T_1$ and dephasing time $T_2$)
- Protected from noise
- Implementation of single-qubit and two-qubit quantum gates
- Measurement apparatus

# Superconducting qubits: the Cooper Pair Box (CPB)

$$\hat{H} = Q^2/2C + \Phi^2/2L$$



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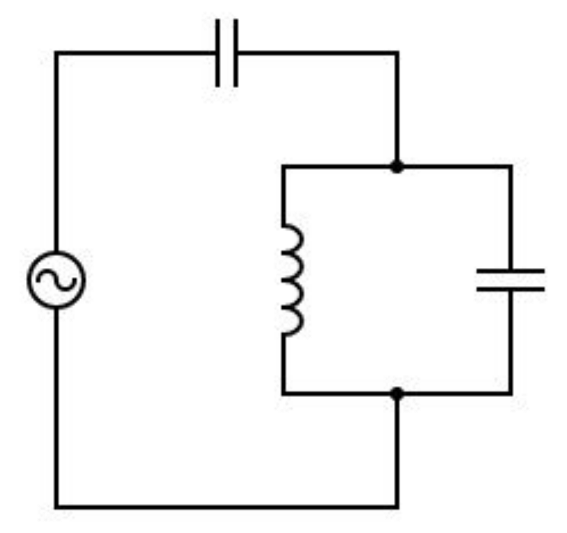
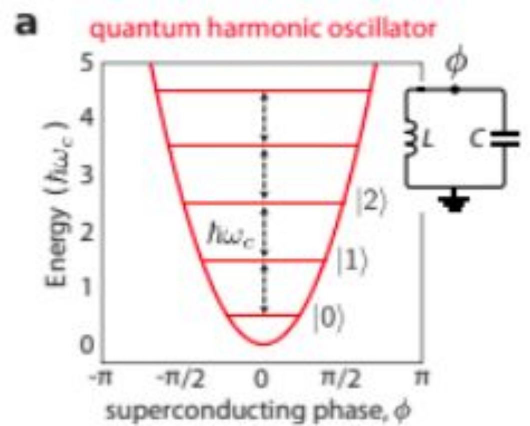


[D.Bernal et al. , 2020]



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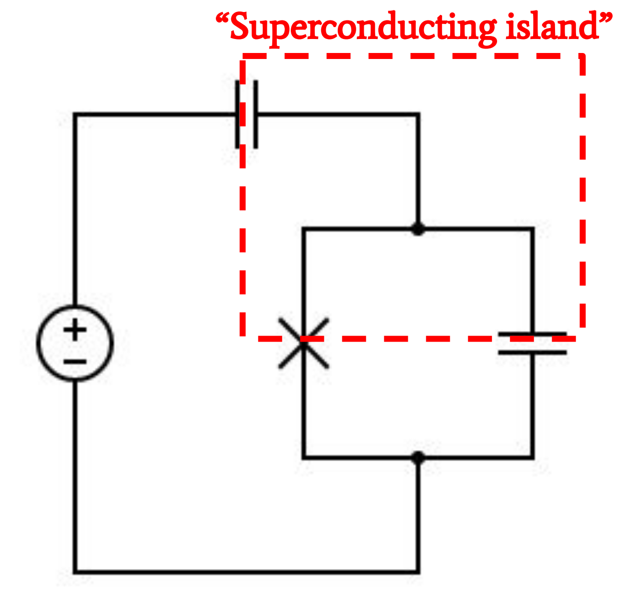
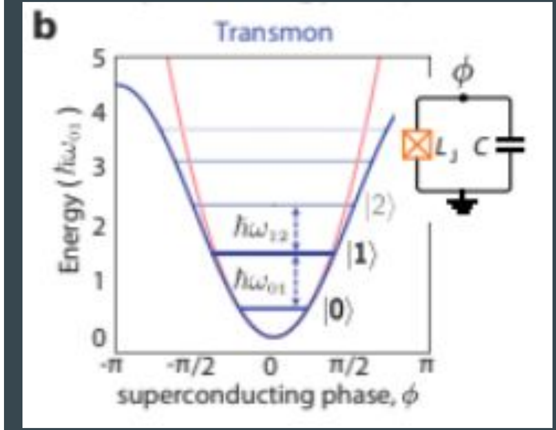
$$\hat{H} = E_C(\hat{n} - n_g)^2 - E_J \cos(\hat{\varphi})$$



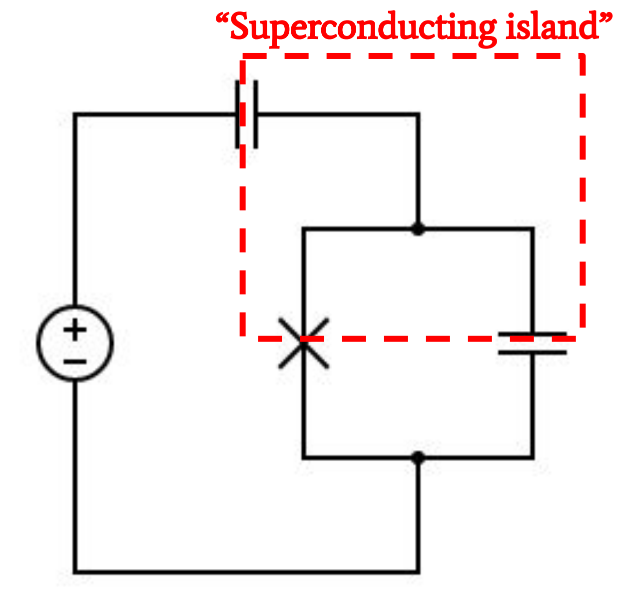
$$\hat{Q} = (2e)^2(\hat{n} - n_g)^2$$

[D.Bernal et al. , 2020]



# Superconducting qubits: the Cooper Pair Box (CPB)

$$\hat{H} = -E_J \sum_n \left( |n+1\rangle\langle n| + |n\rangle\langle n+1| \right)$$
$$+E_C \sum_n (n - n_g)^2 |n\rangle\langle n|$$



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$$n_g = C_g V_g / 2e$$

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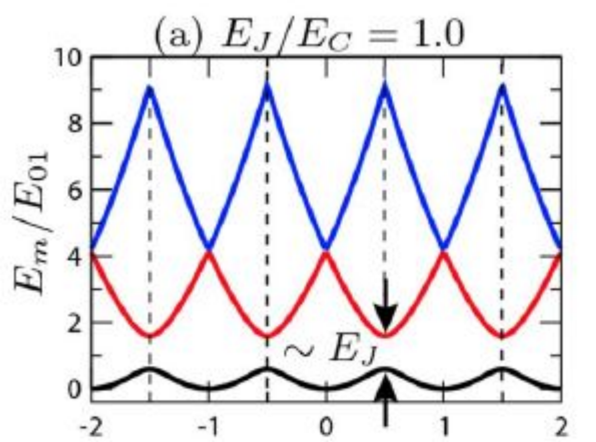
To obtain a qubit: tuning of $E_c$ and $n_g$ to maximize anharmonicity

$$\alpha = \Delta E_{12} - \Delta E_{01}$$



[J.Koch et al. , 2007]

$$E_J \sim constant$$

$$E_C = (2e)^2/2C_\Sigma$$

$$n_g = C_g V_g / 2e$$

# Superconducting qubits: the Cooper Pair Box (CPB)

$$\begin{aligned}\hat{H} = -E_J \left( |1\rangle\langle 0| + |0\rangle\langle 1| \right) \\ + E_C \left( n_g^2 |0\rangle\langle 0| - (1 - n_g)^2 |1\rangle\langle 1| \right)\end{aligned}$$

# Superconducting qubits: the Cooper Pair Box (CPB)

$$\hat{H} = K(n_g)\mathbb{I} - E_c(n_g - 1/2)\sigma_z + E_J\sigma_x/2$$

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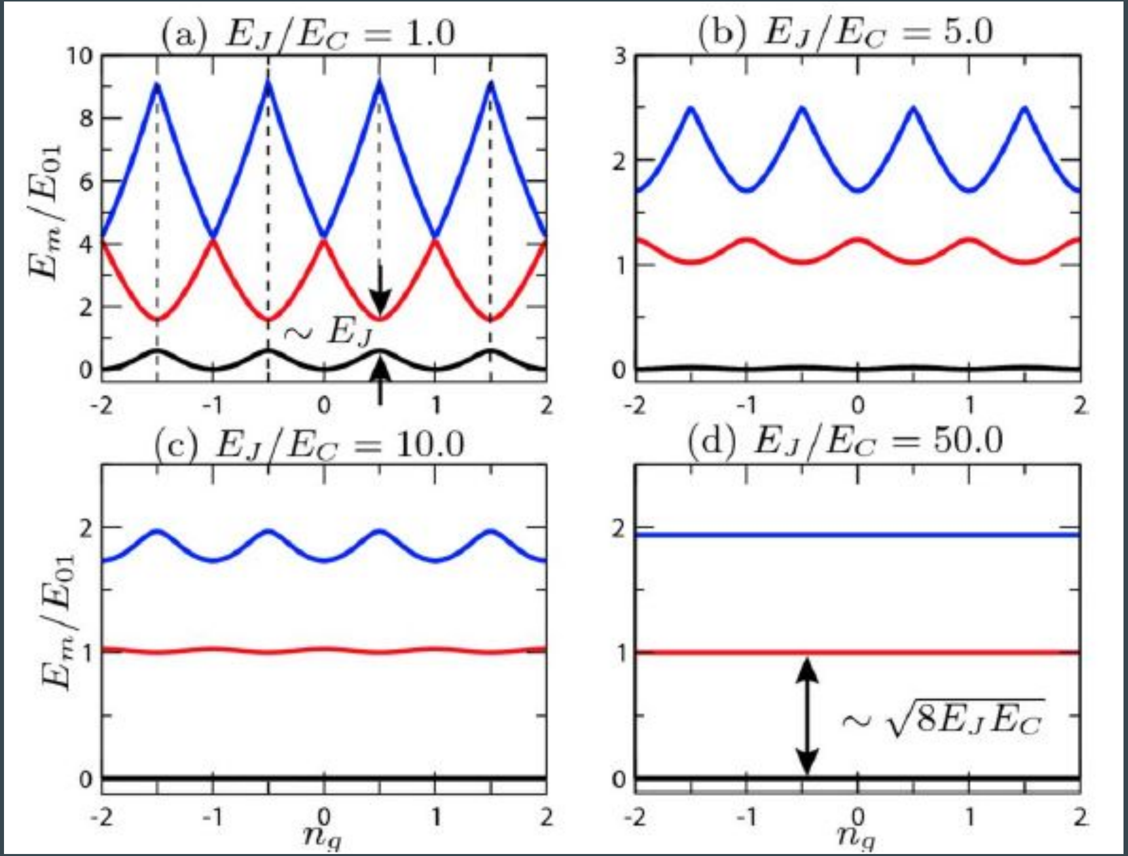
- adiabatic change (e.g. from $n_g$=0 to $n_g$ =½ to obtain |+> )
- fast change of $n_g$ leads to Rabi-like dynamics; then we control the onset time t to obtain the desired state.

# Superconducting qubits: the Cooper Pair Box (CPB)

Problem: sensitivity to charge noise, affecting the value of $n_g$ , inducing small dephasing time $T_2$ .

# Superconducting qubits: the Transmon

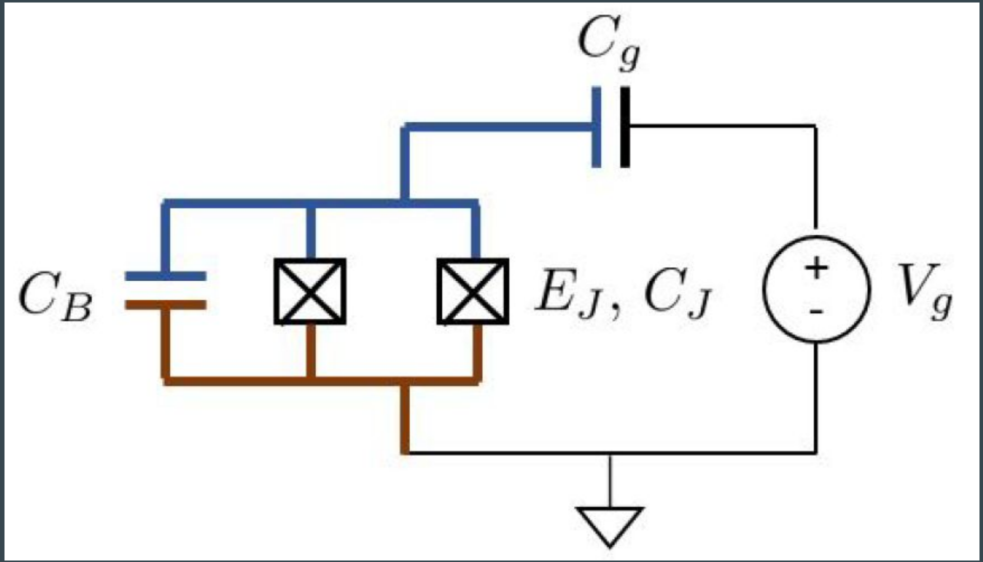


In the transmon regime, $E_J/E_c$ is tuned so that $E(n_g)$ dispersion becomes negligible, and some hanarmonicity is preserved.

$n_g$ becomes irrelevant.

[J.Koch et al. , 2007]

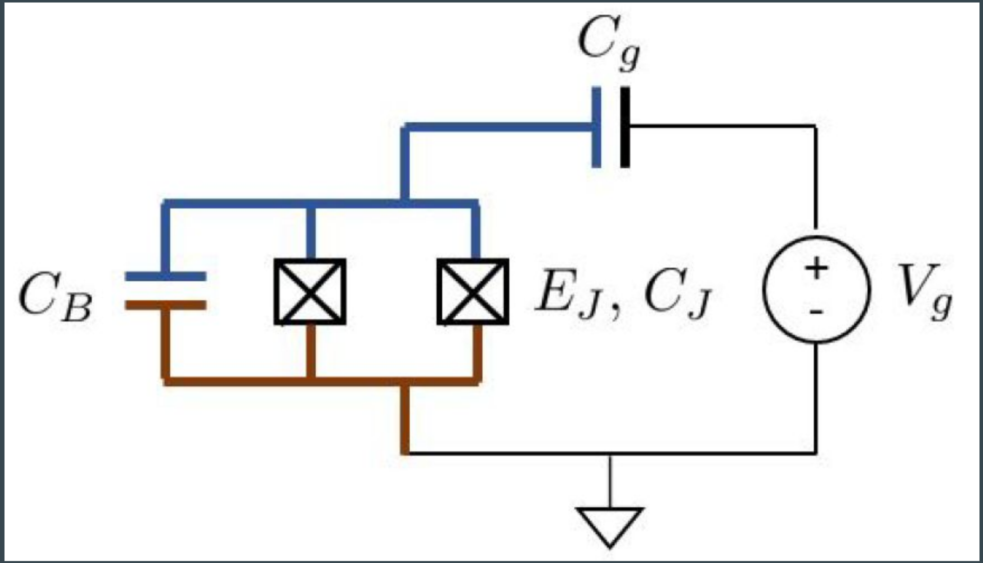
# Superconducting qubits: the Transmon



[T. Roth et al. , 2021]

In practice, $E_C$ is tuned by increasing total capacitance.

# Superconducting qubits: the Transmon



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In practice, $E_C$ is tuned by increasing total capacitance.

New problem is the weak anharmonicity: risks of leakage. Pulse shaping allows fast transitions with fine frequency control.

# Superconducting qubits: the Transmon

The transmon qubits can be coupled (entangled), through a resonator, which is expressed by a Jaynes-Cummings Hamiltonian:

$$\hat{H} = \hat{H}_r + \sum_{j=1,2} \hat{H}_j + \sum_{j=1,2} g(a^\dagger \sigma_j^- + a\sigma_j^+)$$

# Superconducting qubits: the Transmon

The transmon coupled to a circuit resonator can be expressed, after some manipulations, by a (approximated) Jaynes-Cummings Hamiltonian:

$$\hat{H} = (\omega_r - \chi|1\rangle\langle 1| + \chi|0\rangle\langle 0|)a^\dagger a$$

$$+ (\omega_1 + \chi)\sigma_z$$

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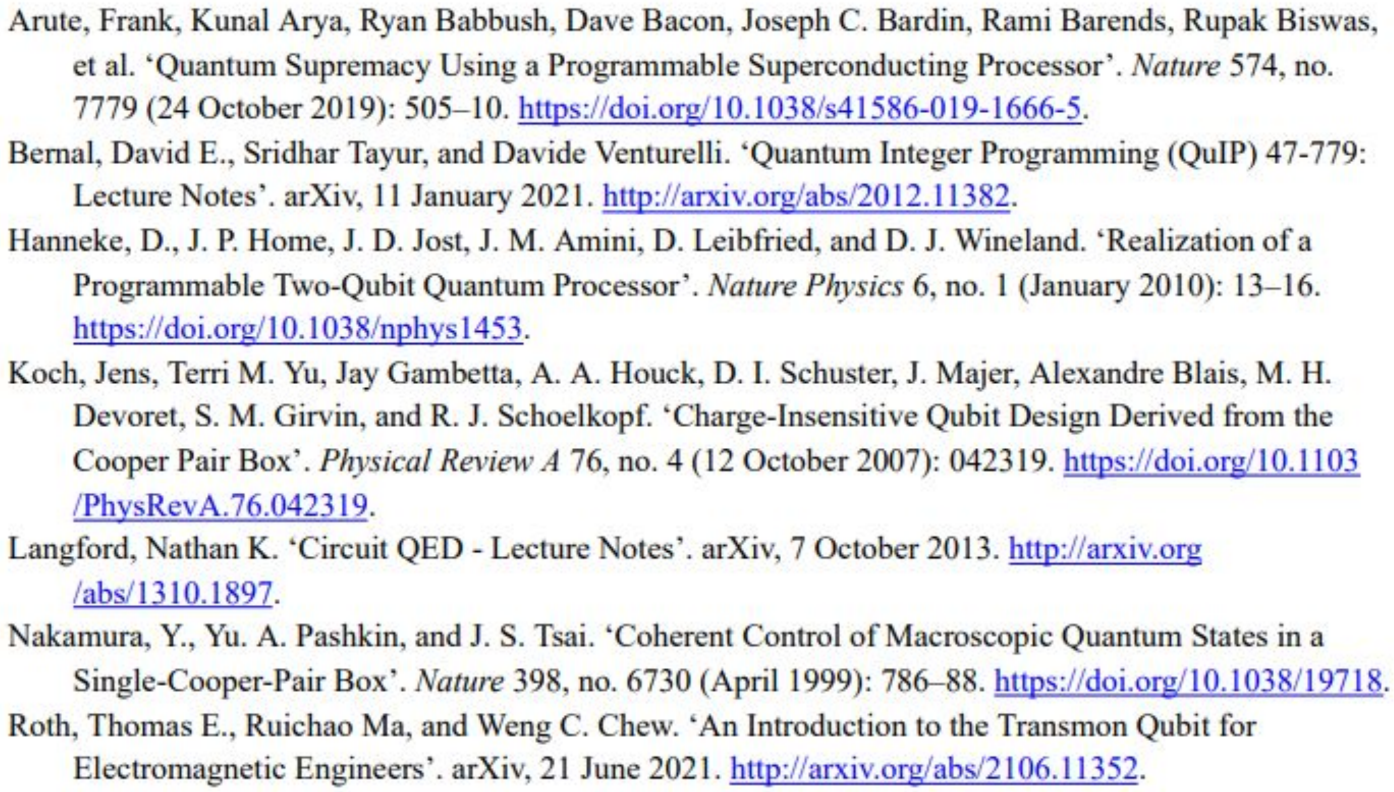
$$+ (\omega_1 + \chi)\sigma_z$$

The resonator frequency depends on the transmon state; it is then measured by microwave spectroscopy.

# Superconducting qubits: advantages

- Easy to embed into a larger circuit
- 1D junctions effectively smaller than 3D cavity
- Easy control transition frequencies: protection from thermal noise
- Macroscopic quantum state with high coupling strength
- Straightforward measurement



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# Thank you.