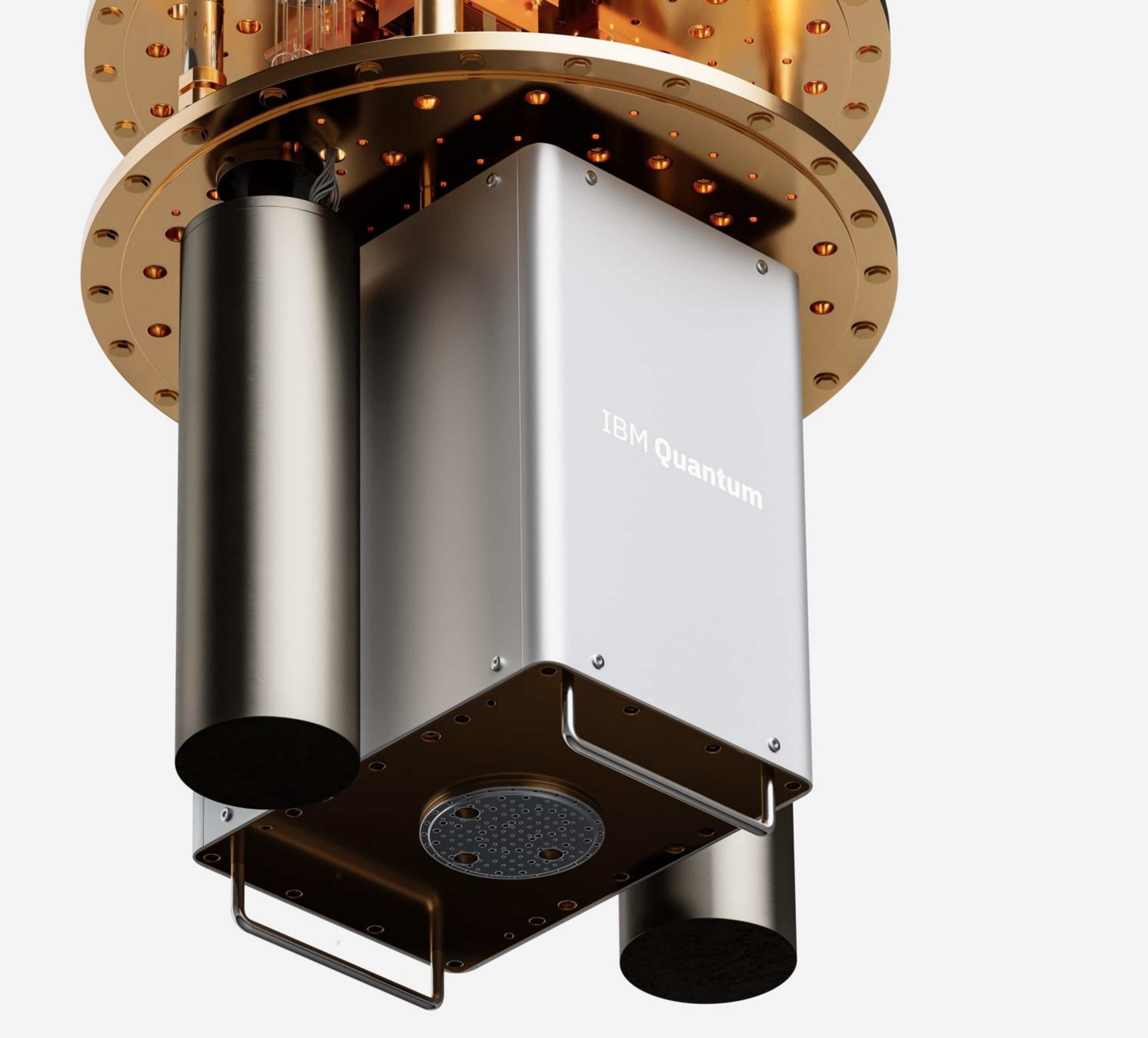
Quantum Computing Architectures with Superconducting Circuits

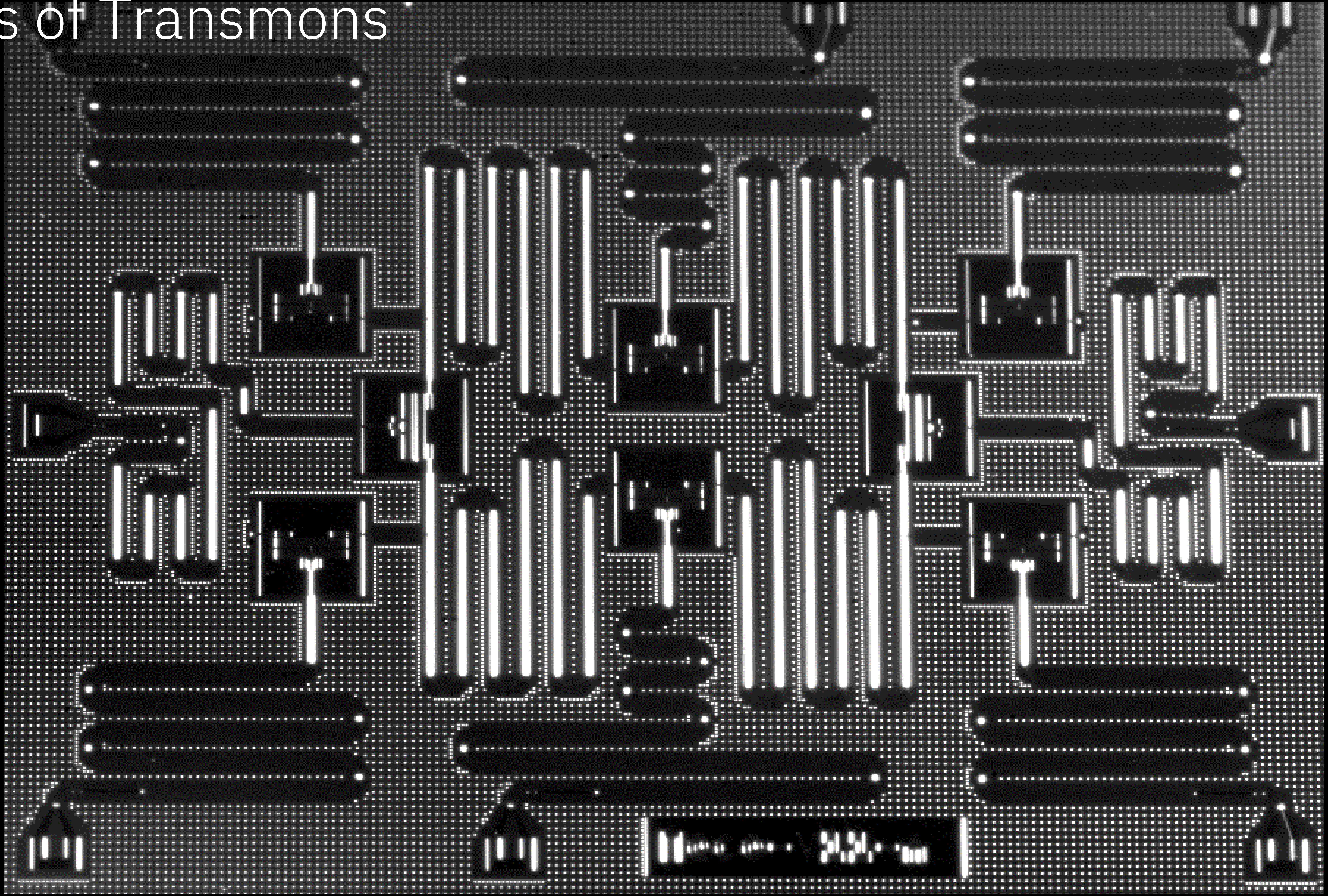
Oliver Dial

IBM Quantum mission

Bring useful quantum computing to the world



Circuits of Transmons



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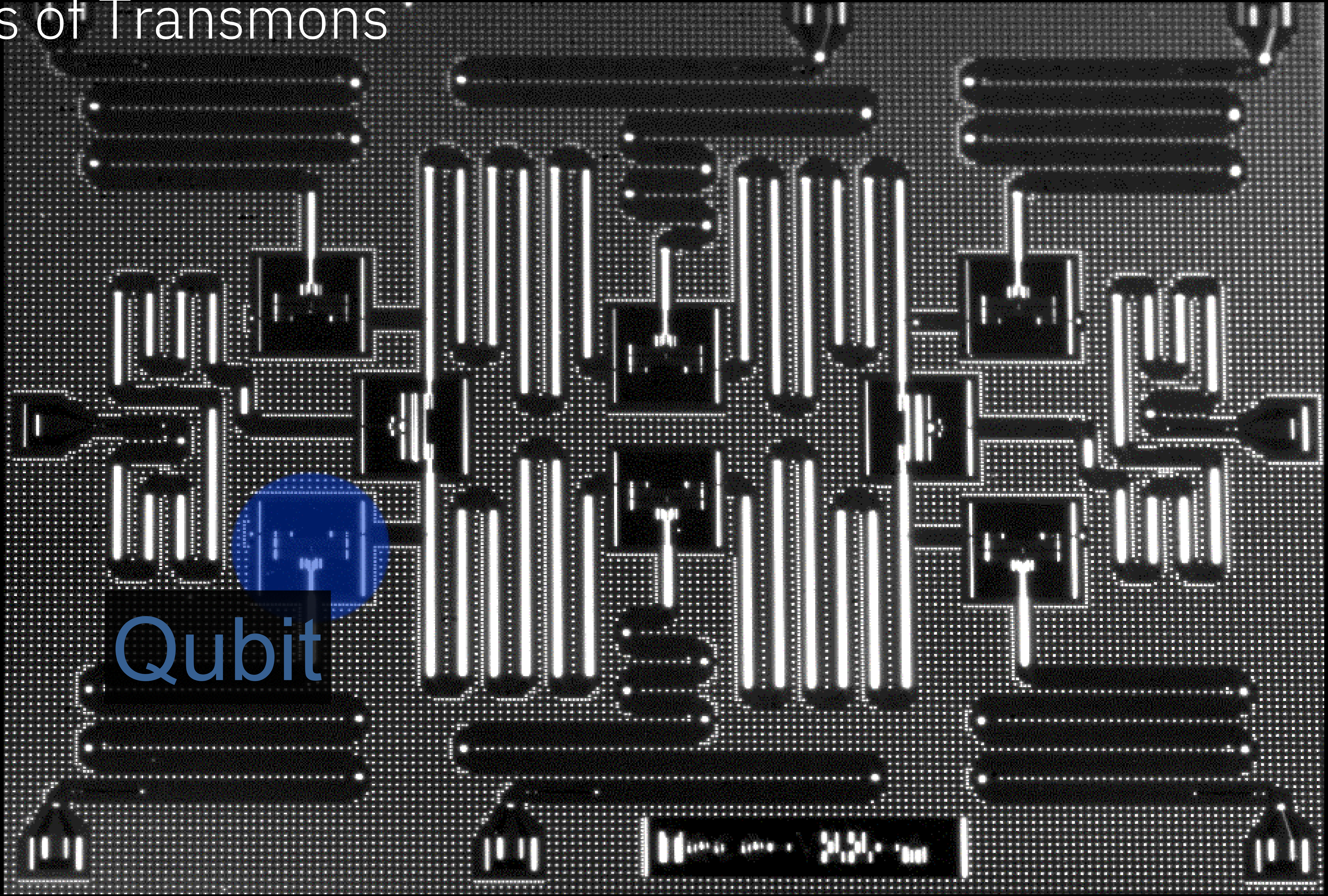
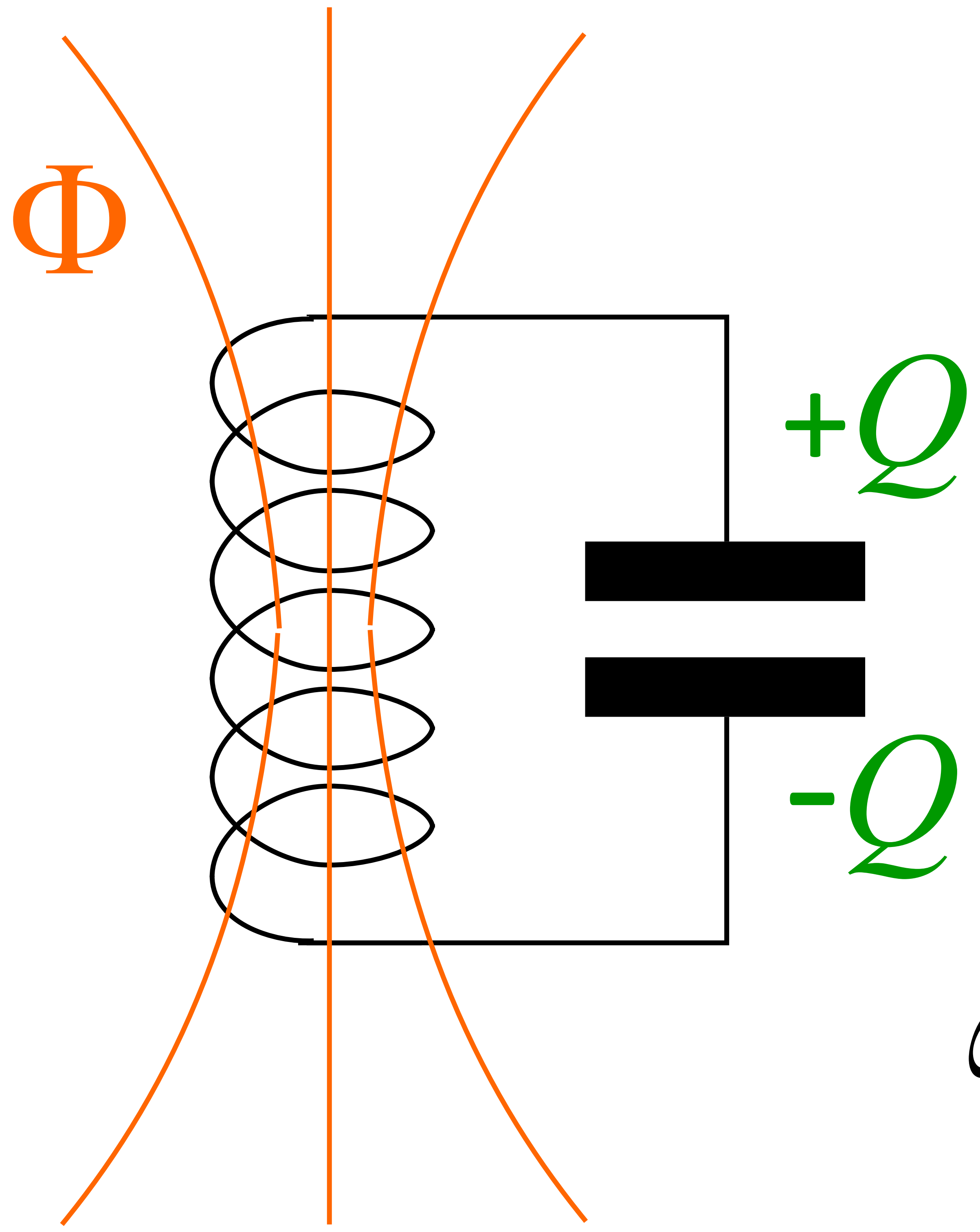


Quantum linear circuits



$L \sim 0.1$ nH
$C \sim 10$ pF

1 K ≈ 20 GHz

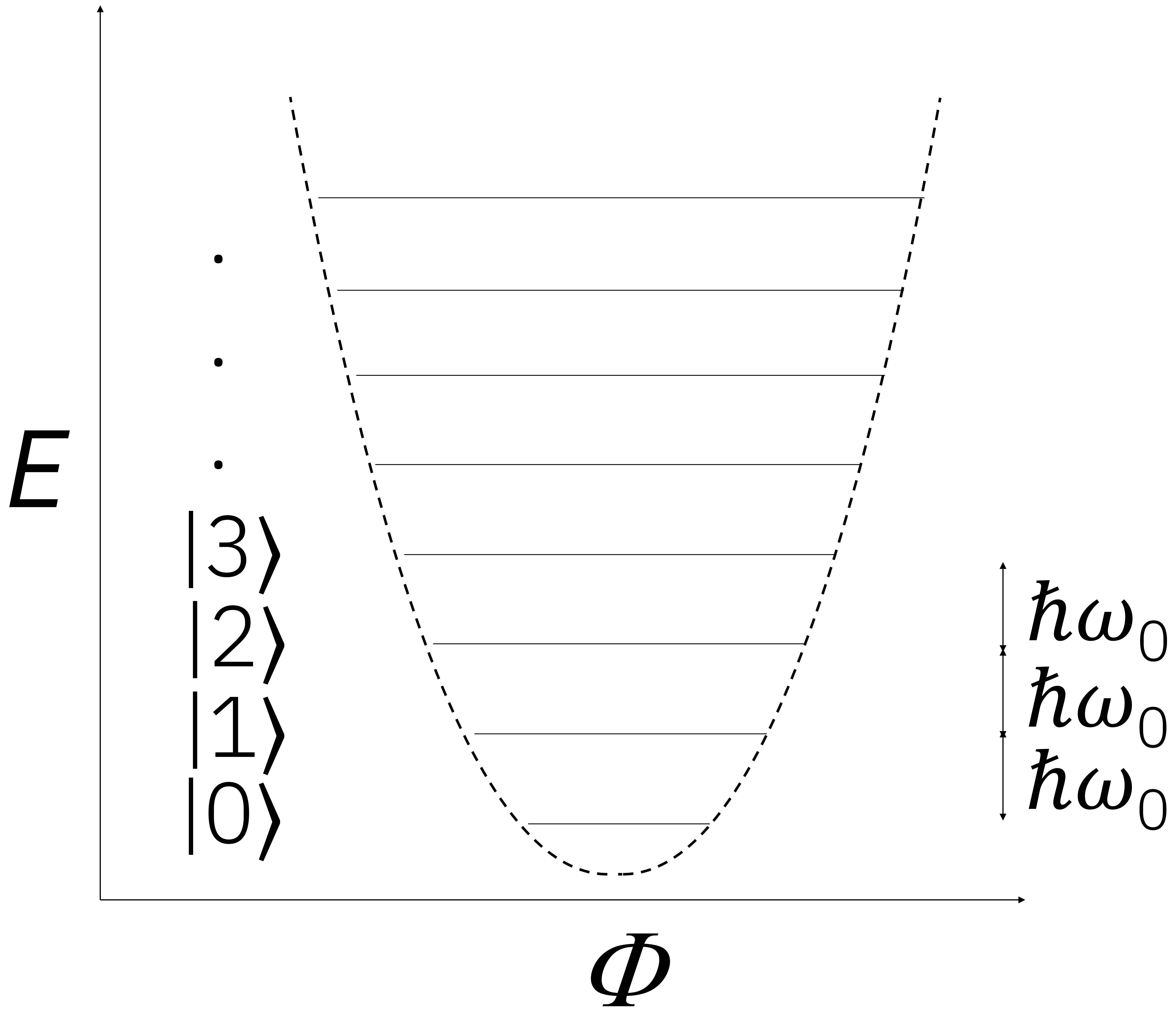
$$\omega_0/2\pi = 1/2\pi\sqrt{LC} \sim 5 \text{ GHz}$$

Quantum linear circuits

Quantum Hamiltonian

$$\hat{H} = \frac{1}{2C}\hat{Q}^2 + \frac{1}{2L}\hat{\Phi}^2$$

$$\hat{H} = \hbar\omega_0(\hat{n} + 1/2)$$



Need unique addressability for use as a qubit

Quantum non-linear circuits: Josephson junction

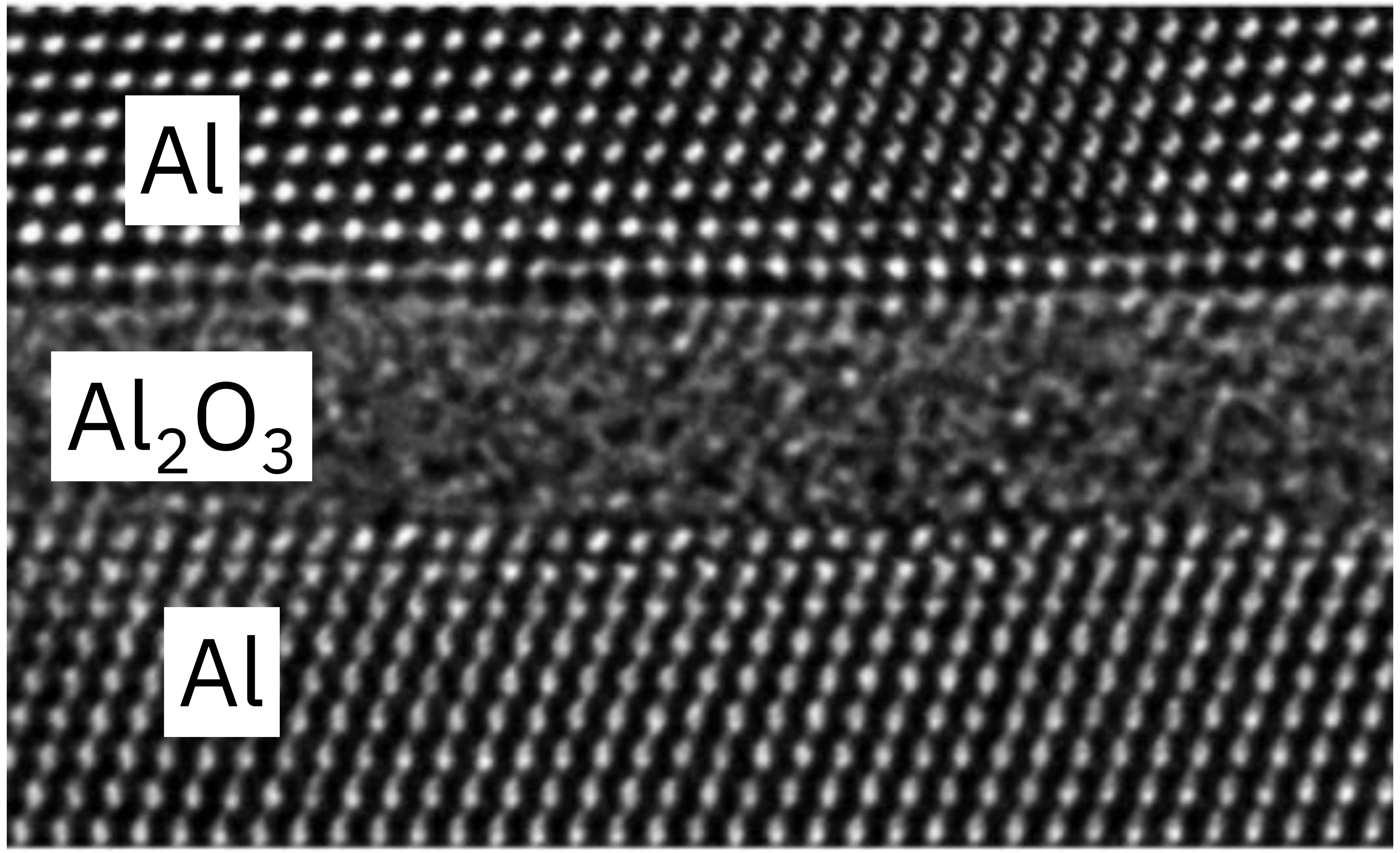
SC

$$\Psi_1 = \sqrt{\rho_1} e^{i\phi_1}$$

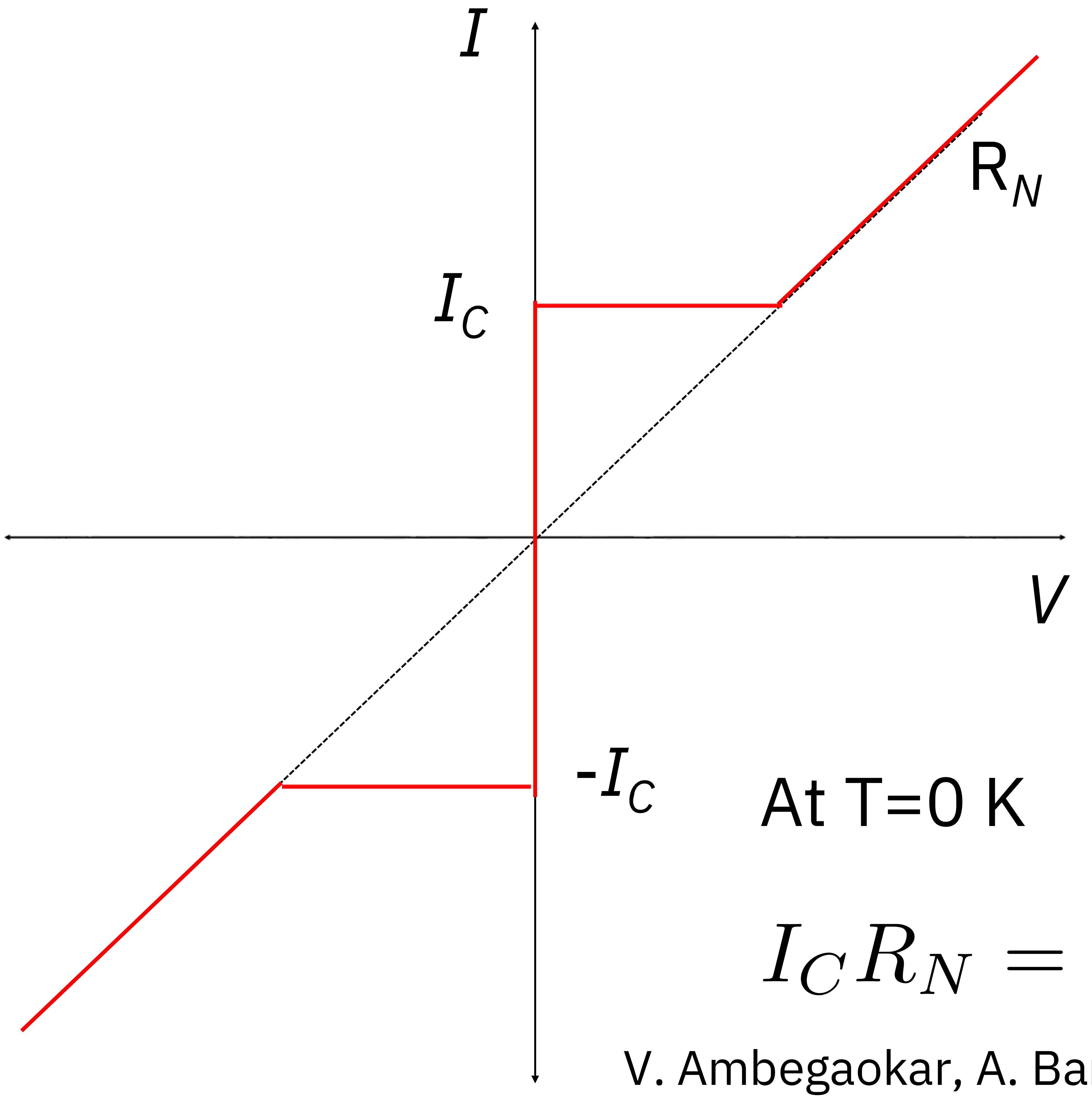
Insulator

SC

$$\Psi_2 = \sqrt{\rho_2} e^{i\phi_2}$$



JAP, 125(16), 165301, 2019



At T=0 K

$$I_C R_N = \frac{\pi}{2e} \Delta$$

V. Ambegaokar, A. Baratoff, PRL 10, 486-489 (1963)

Quantum non-linear circuits: Josephson junction

SC

$$\Psi_1 = \sqrt{\rho_1} e^{i\phi_1}$$

Insulator

SC

$$\Psi_2 = \sqrt{\rho_2} e^{i\phi_2}$$

Josephson phase

$$\delta = \phi_1 - \phi_2 = 2\pi\Phi/\Phi_0$$

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

$$V = \dot{\Phi}$$

Josephson Energy $U = \int V I dt$

$$U = \frac{I_c \Phi_0}{2\pi}(1 - \cos(2\pi\Phi/\Phi_0))$$

$$U = E_J(1 - \cos(2\pi\Phi/\Phi_0))$$

See Feynman's lectures Vol. III Sec 21-9 for a derivation

Quantum non-linear circuits: Josephson junction

SC $\Psi_1 = \sqrt{\rho_1} e^{i\phi_1}$

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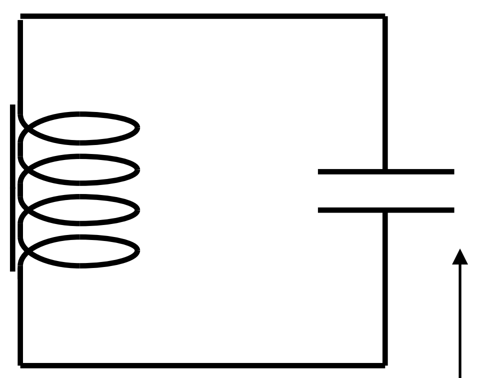
$$U = E_J(1 - \cos(2\pi\Phi/\Phi_0))$$

Inductance $\frac{dI}{dt} = \frac{1}{L} V(t)$

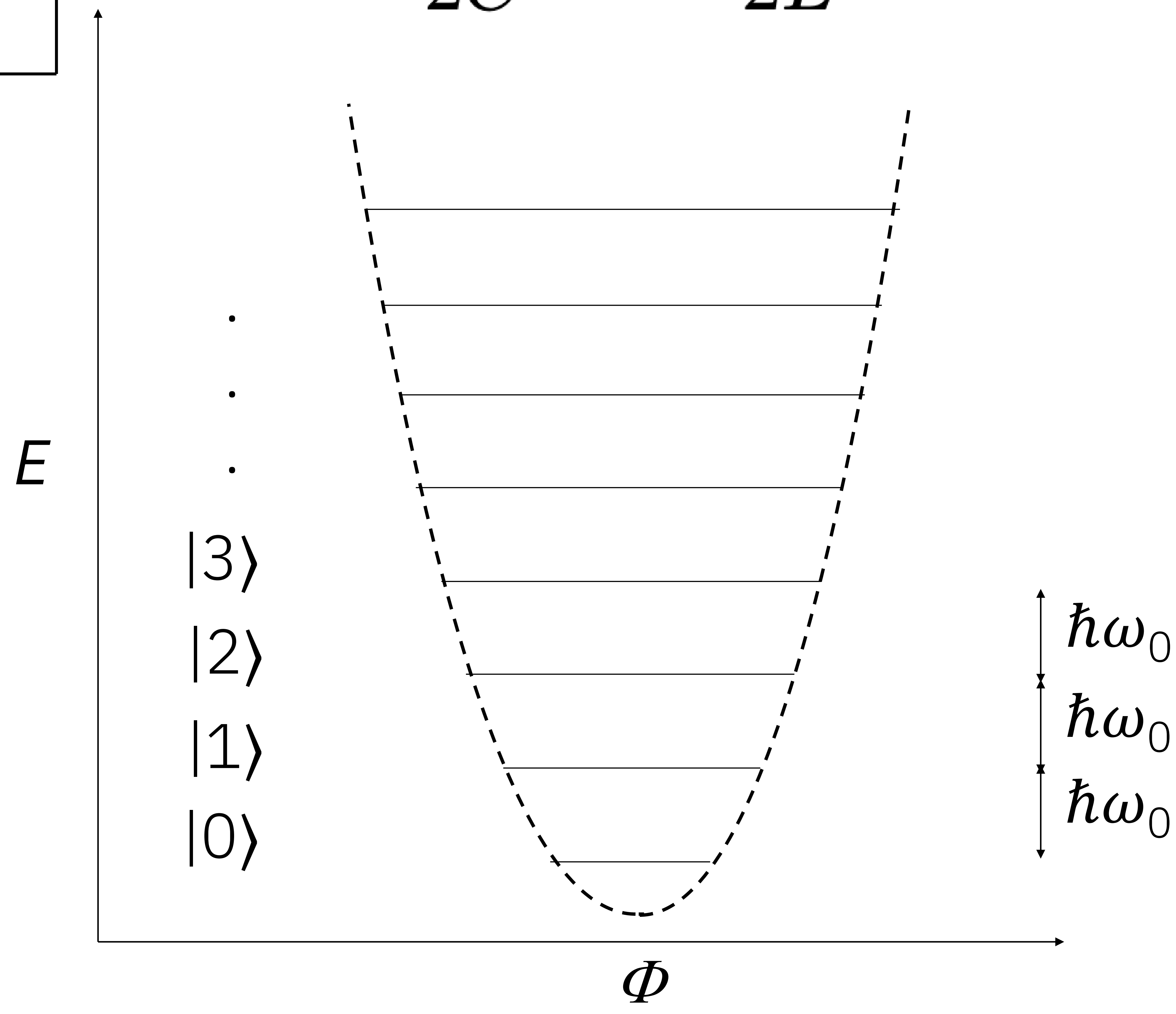
$$L = \frac{\Phi_0}{2\pi I_c \cos(2\pi\Phi/\Phi_0)}$$

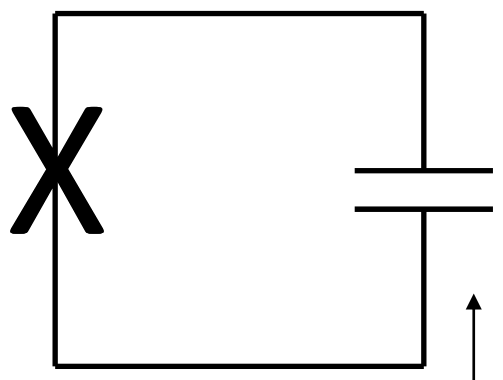
See Feynman's lectures Vol. III Sec 21-9 for a derivation

Quantum non-linear circuits: Josephson junction

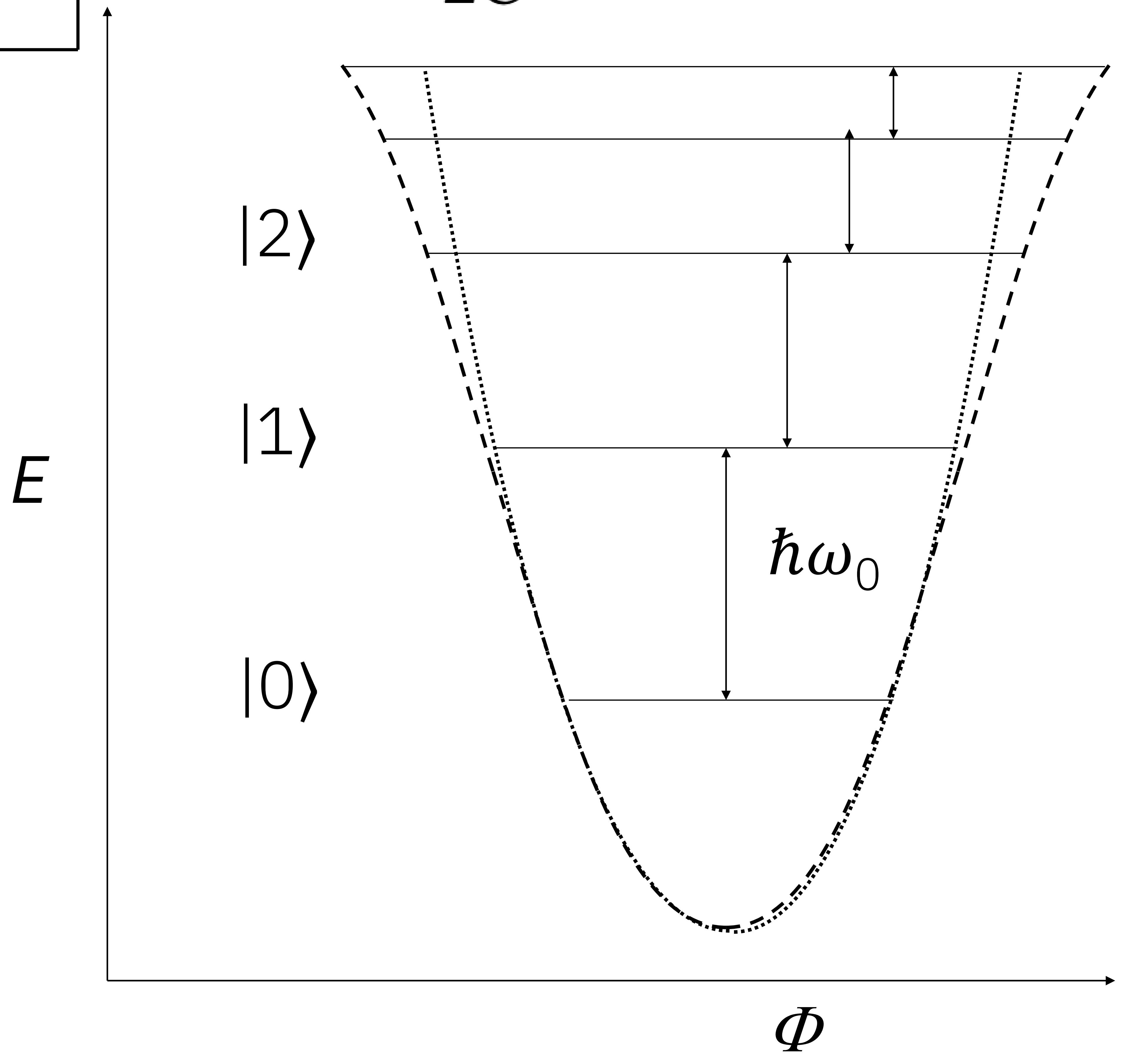


$$\hat{H} = \frac{1}{2C}\hat{Q}^2 + \frac{1}{2L}\hat{\Phi}^2$$



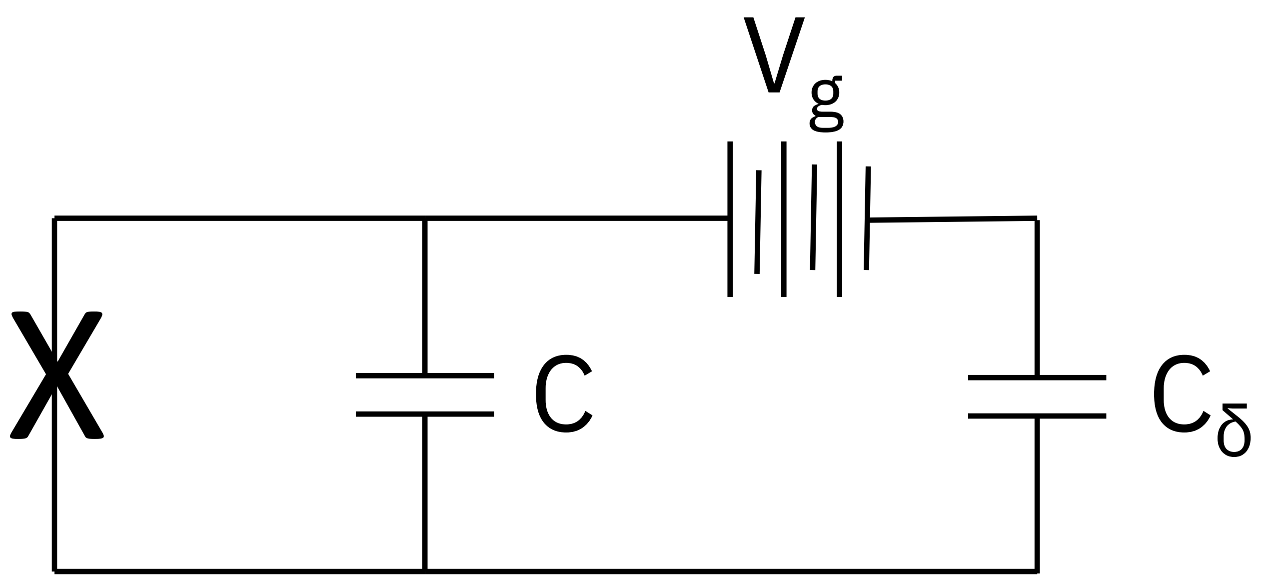


$$\hat{H} = \frac{1}{2C}\hat{Q}^2 - E_j \cos(\hat{\Phi}/\varphi_0)$$



Quantum non-linear circuits: Josephson junction

$$\hat{H} = \frac{1}{2C}\left(\hat{Q} - V_g C_\delta\right)^2 - E_j \cos(\hat{\Phi}/\varphi_0)$$



$$E_C = \frac{e^2}{2C} \quad n_g = \frac{V_g C_\delta}{4e^2}$$

n = number of Cooper pairs

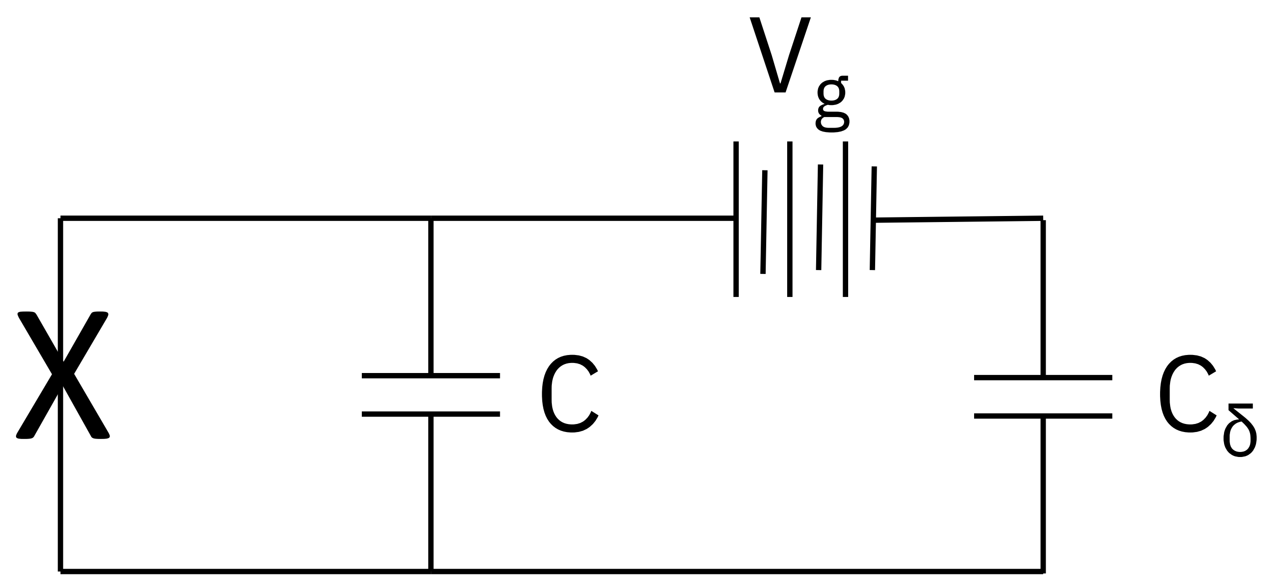
$$\hat{H} = 4E_c\left(\hat{n} - n_g\right)^2 - E_j \cos(\hat{\Phi}/\varphi_0)$$

$$e^{-ip\hat{\Phi}}|n\rangle = |n+p\rangle$$

(*n* and ϕ are conujugate variables)

Quantum non-linear circuits: Josephson junction

$E_j >> E_c$



$$\hat{H} = 4E_c\left(\hat{n} - n_g\right)^2 - E_j\cos(\hat{\Phi}/\varphi_0)$$

$$\hat{H} = 4E_c\left(\hat{n} - n_g\right)^2 + \frac{E_j}{2}\left(\frac{\hat{\Phi}}{\varphi_0}\right)^2 - \frac{E_j}{24}\left(\frac{\hat{\Phi}}{\varphi_0}\right)^4$$

"Duffing Oscillator"

$$Z_{tr} = \sqrt{L_j/C}$$

$$\hat{x} = \sqrt{\frac{1}{\hbar Z_{tr}}}\hat{\Phi}$$

$$\hat{y} = \sqrt{\frac{Z_{tr}}{\hbar}}\hat{Q}$$

$$\hbar\omega_0 = \sqrt{8E_jE_c}$$

$$\hat{H} = \frac{\hbar\omega_0}{2}\left(\hat{x}^2 + \hat{y}^2\right) - \frac{E_c\hat{x}^4}{3}$$

"Normal" SHO stuff

$$\hat{H} = \frac{\hbar\omega_0}{2}\left(\hat{x}^2 + \hat{y}^2\right) - \frac{E_c\hat{x}^4}{3}$$

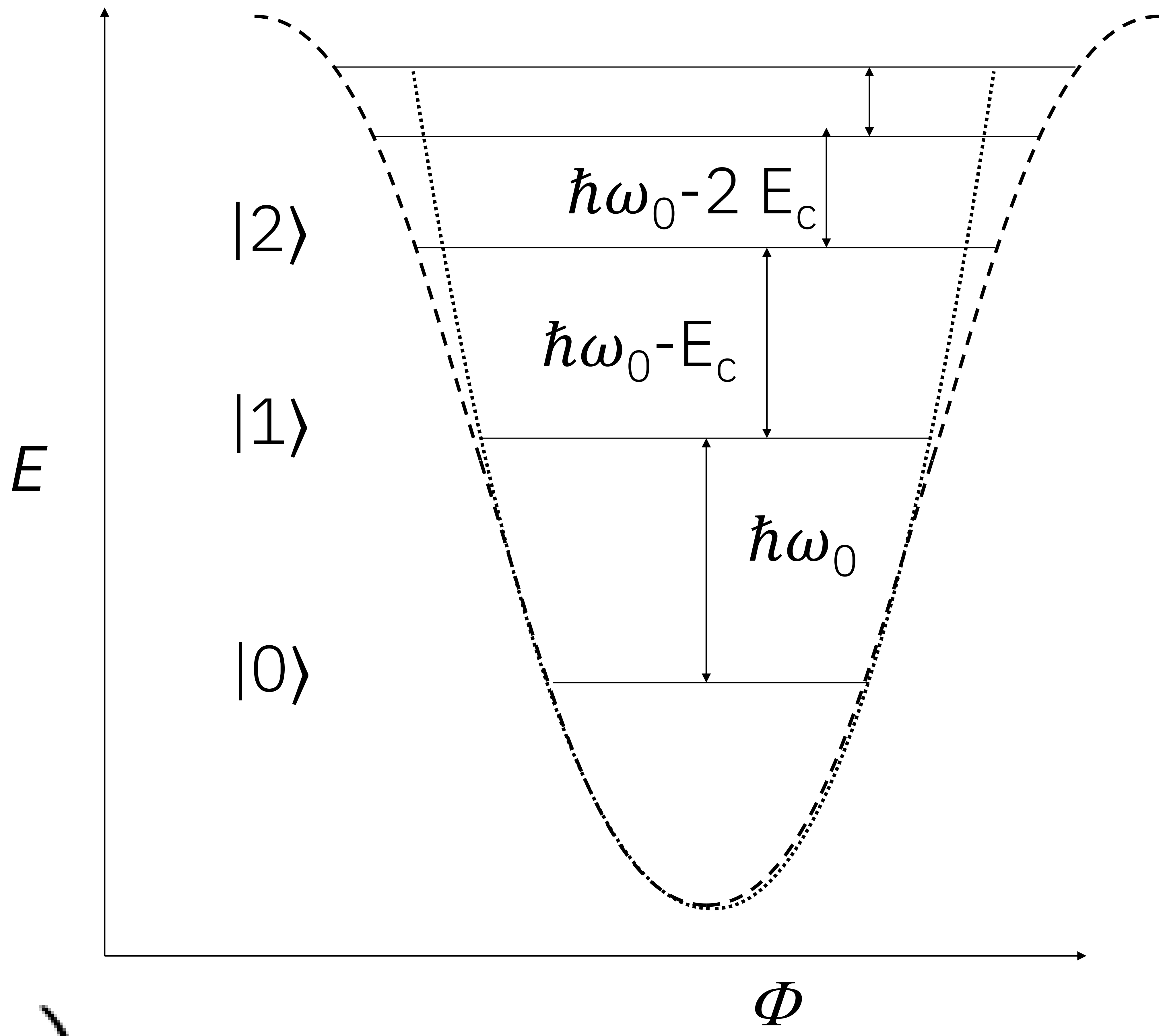
Quantum non-linear circuits: Josephson junction

$E_j >> E_c$

$$\hat{H} = \frac{\hbar\omega_0}{2}\left(\hat{x}^2 + \hat{y}^2\right) - \frac{E_c\hat{x}^4}{3}$$

$$\hat{x} = \frac{1}{\sqrt{2}}\left(\hat{a} + \hat{a}^\dagger\right)$$

$$\hat{y} = \frac{1}{\sqrt{2}}\left(\hat{a} - \hat{a}^\dagger\right)$$

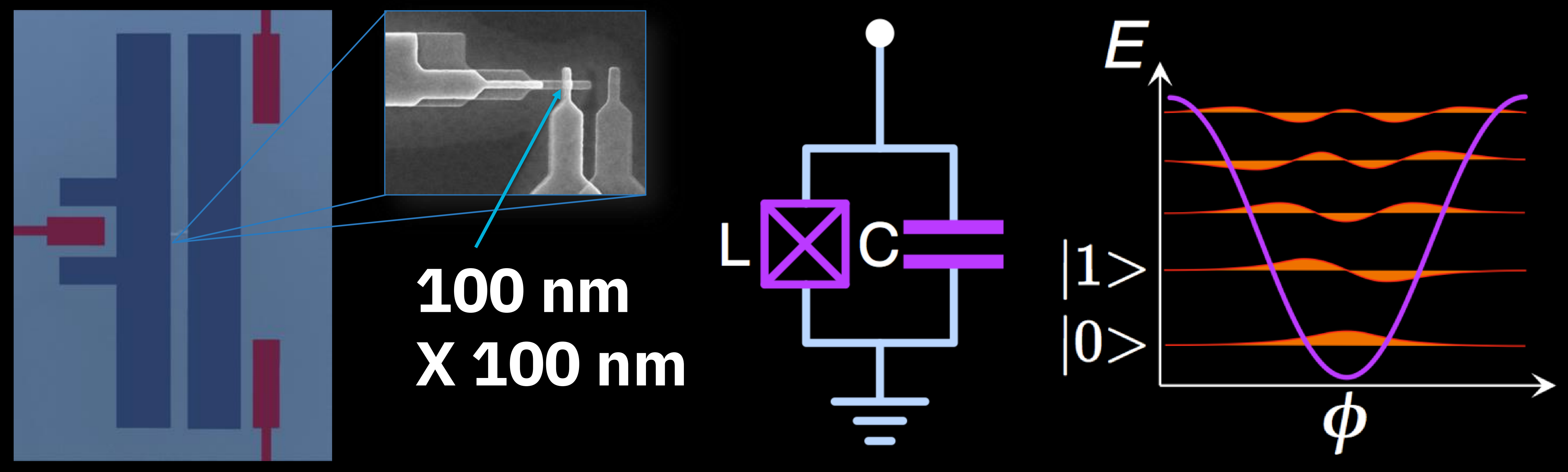


$$\hat{H} = \hbar\omega_0\hat{a}^\dagger\hat{a} - \frac{E_c}{2}\left(\left(\hat{a}^\dagger\hat{a}\right)^2 - \hat{a}^\dagger\hat{a}\right) + \text{Non-RWA terms}$$

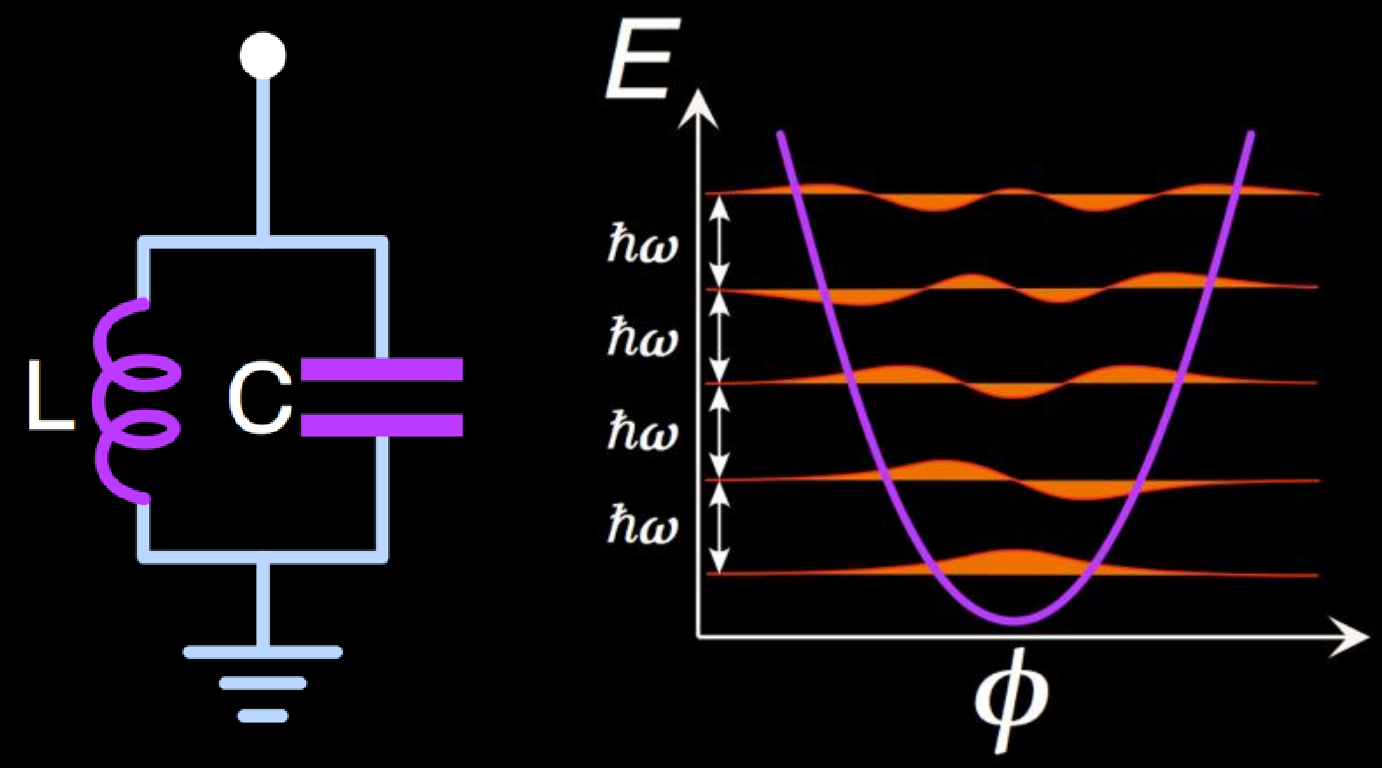
A Transmon

Superconducting Qubit:

- Josephson Junction as a non-linear inductor

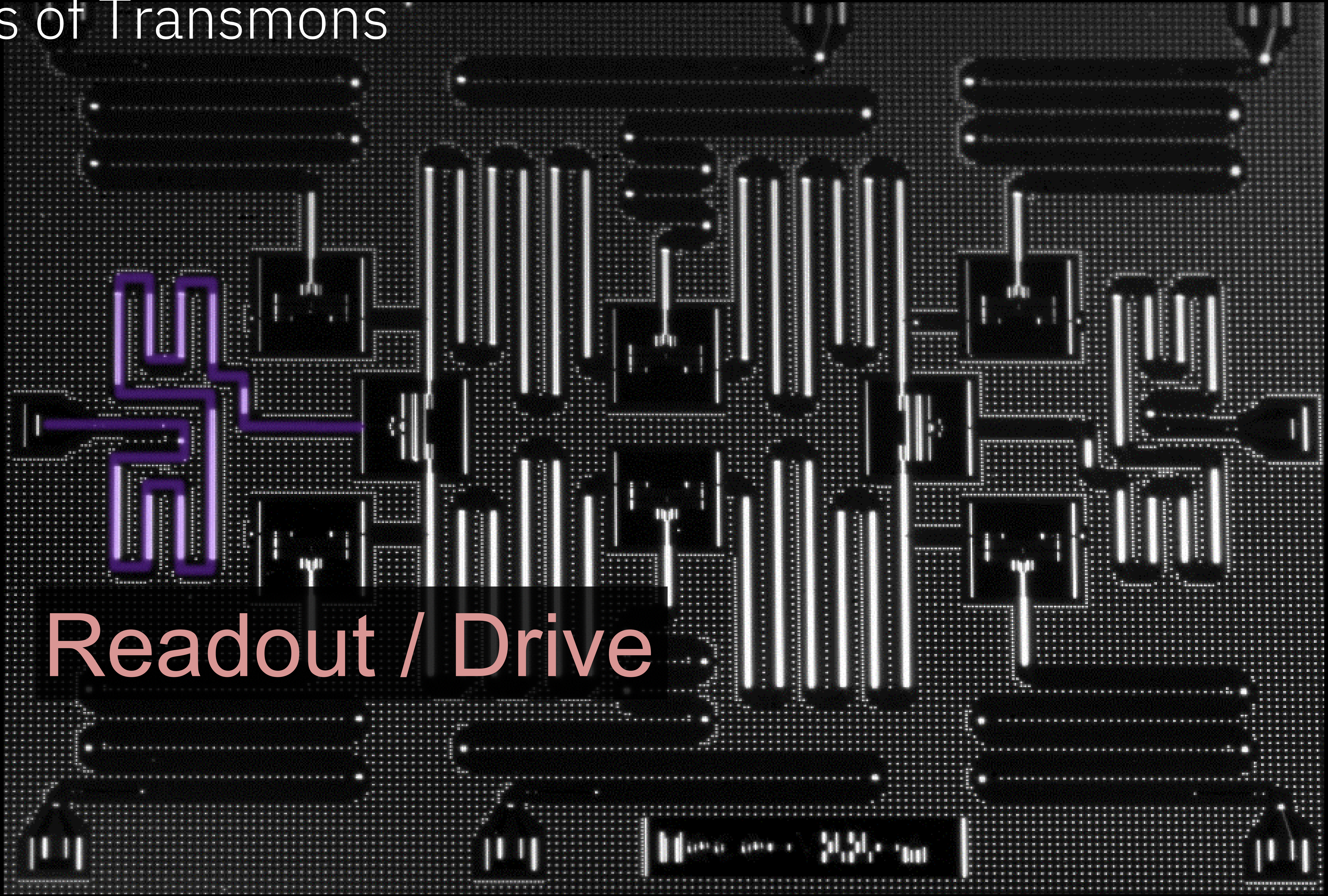


$E_{01} \approx 5\ GHz \approx\ 240\ mK$

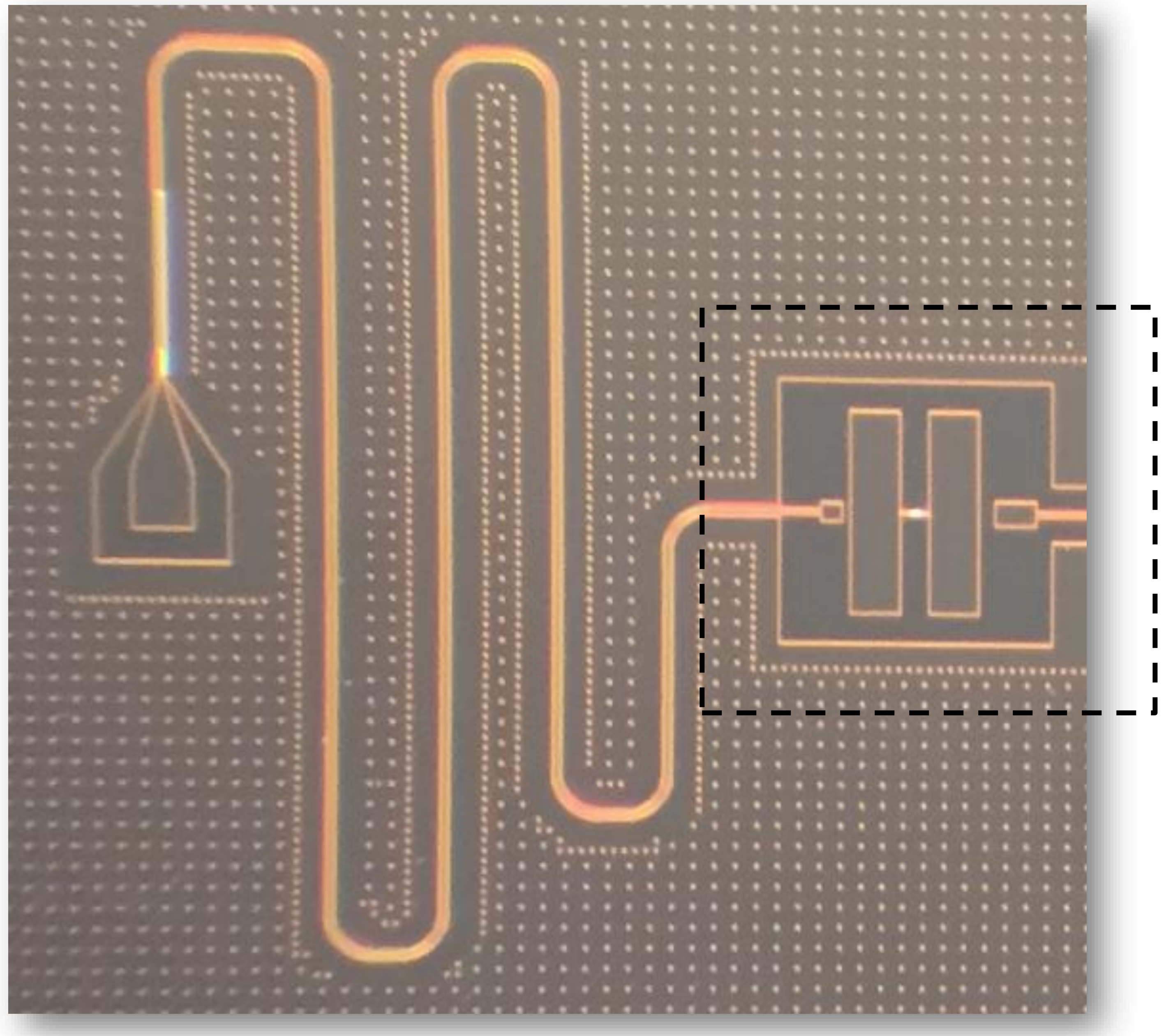


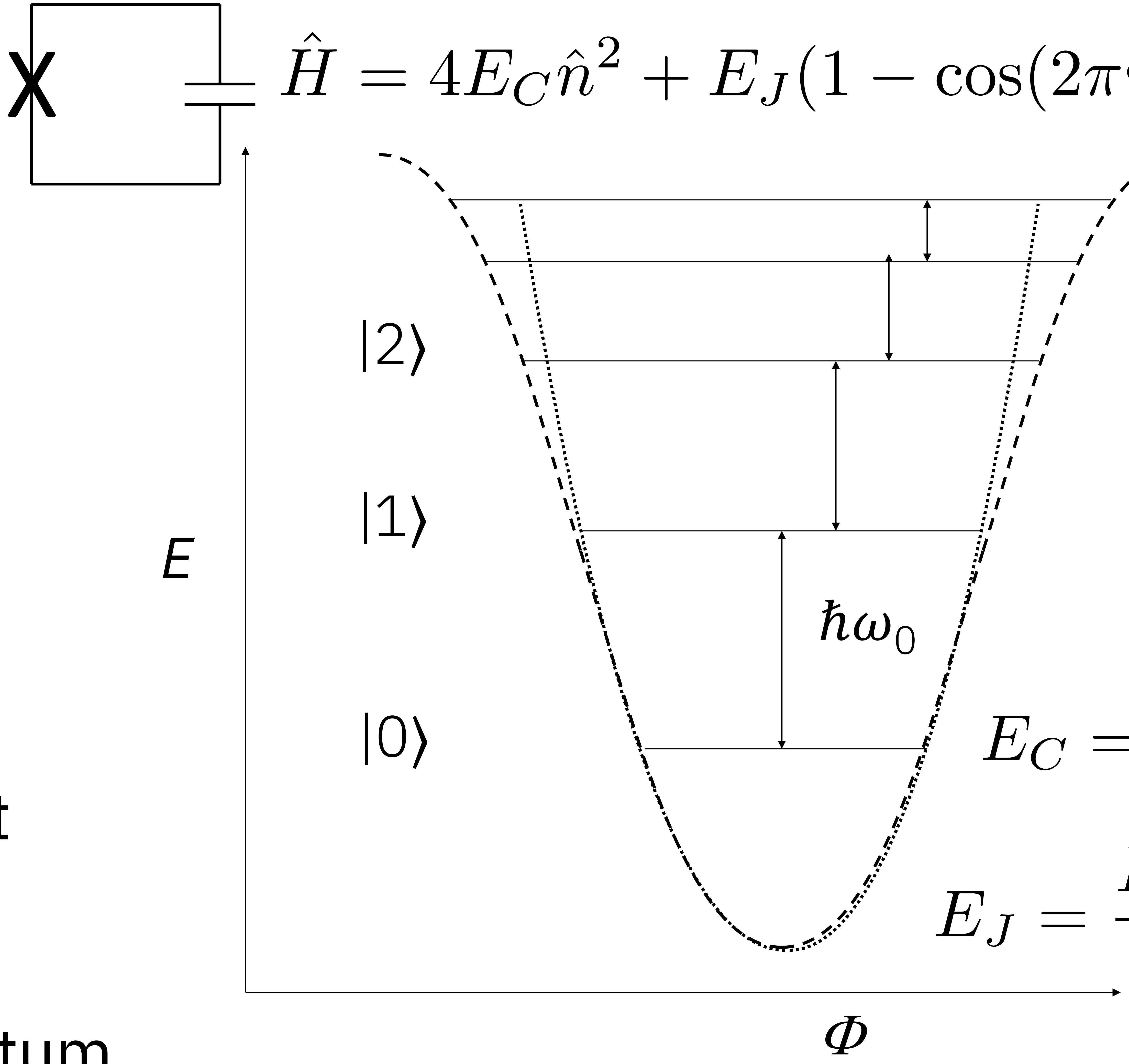
Phys. Rev. A **76**, 04319 (2007)

Circuits of Transmons



Single Qubit Control





$$\hat{H} = 4E_C\hat{n}^2 + E_J(1 - \cos(2\pi\hat{\Phi}/\Phi_0))$$

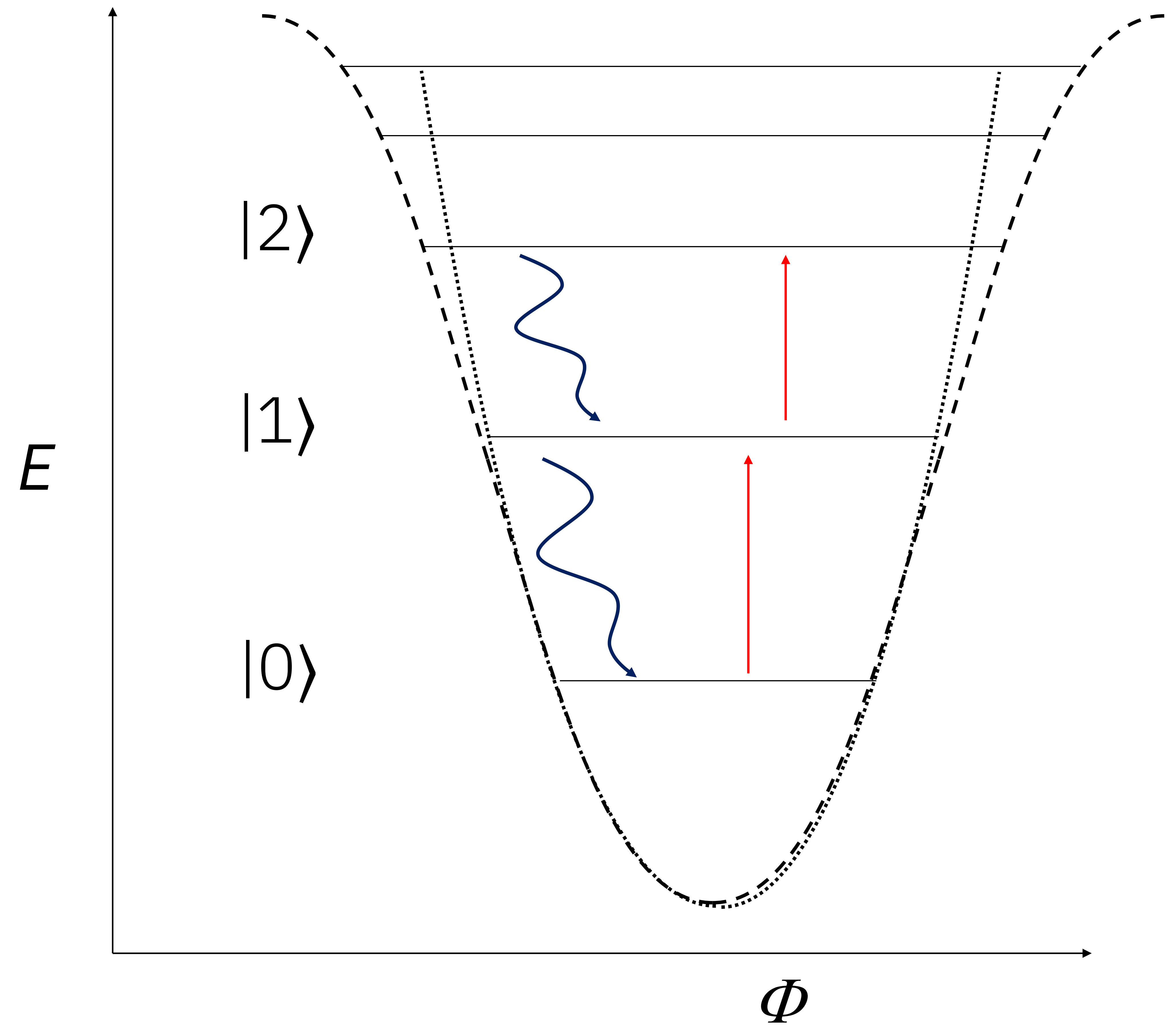
$$E_C = \frac{e^2}{2C}$$

$$E_J = \frac{I_c\Phi_0}{2\pi}$$

As discussed, we have a quantum object with a ladder of energy states:

- How do we start in the ground state?
- How do we prepare an arbitrary quantum state?

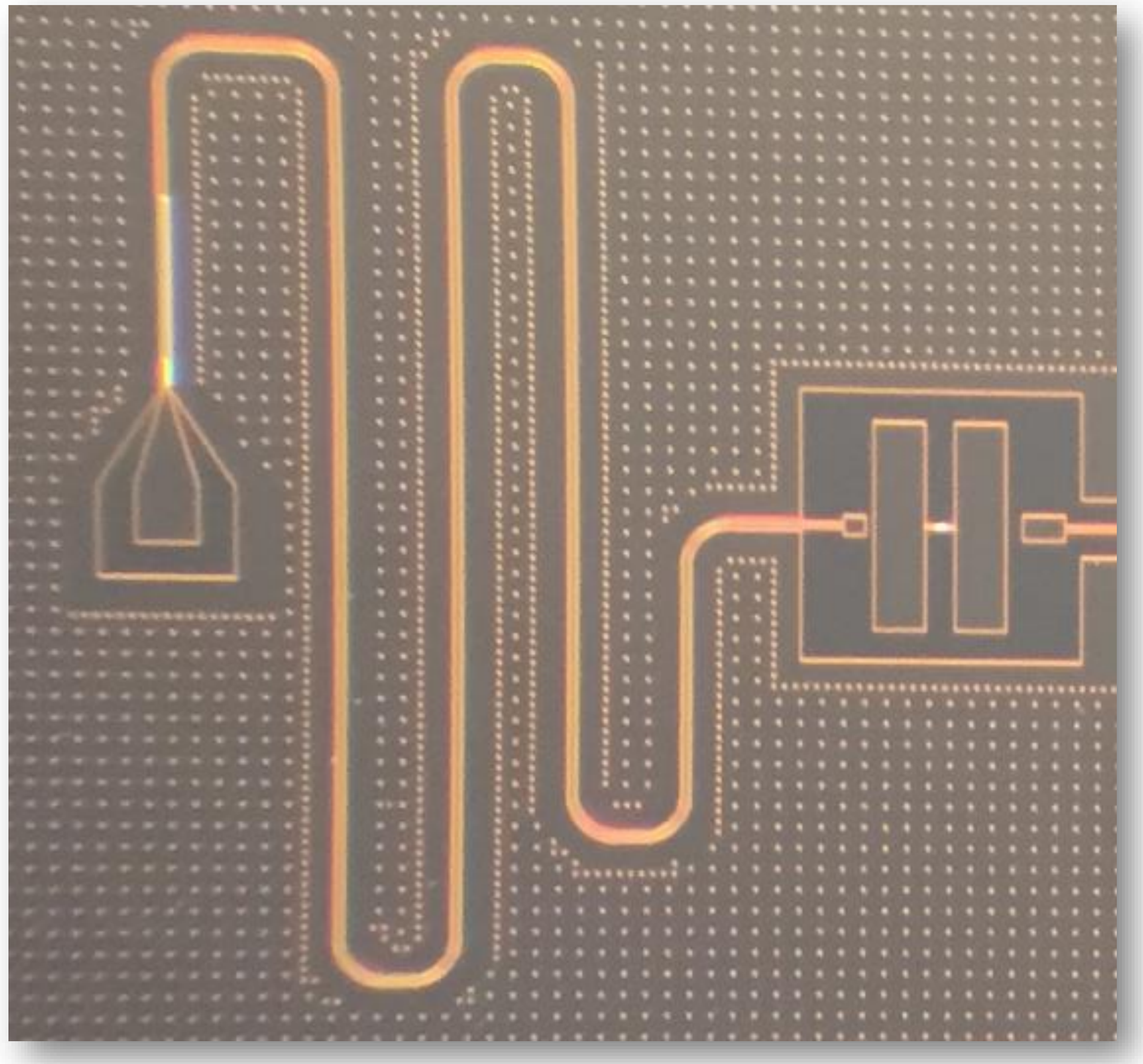
Preparing the Ground State

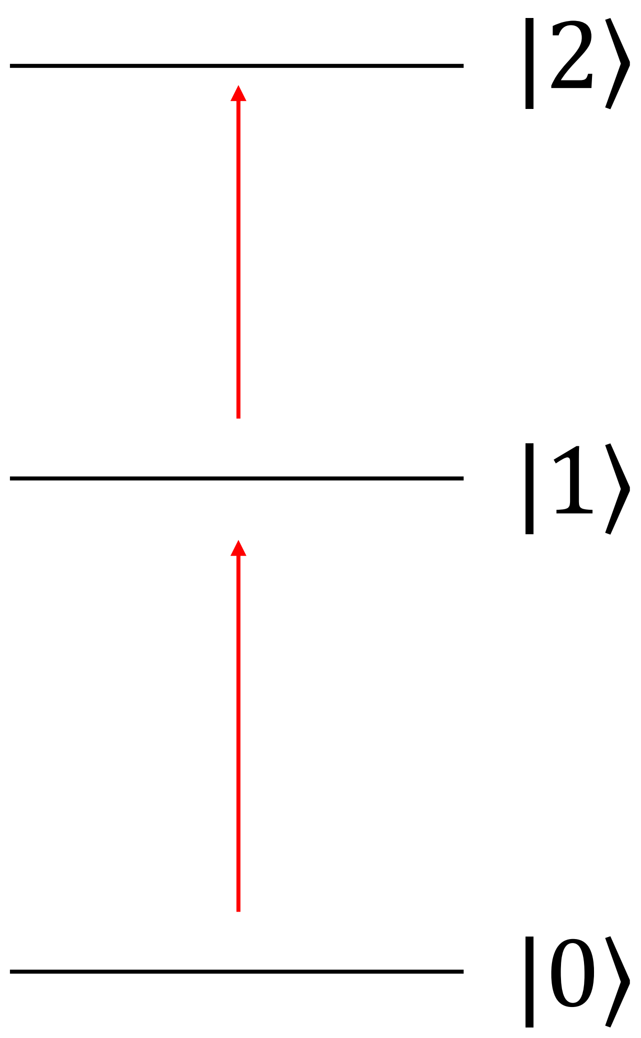


- The system has a natural decay from higher to lower levels (the "T1" time, which we will discuss in more detail later)
- There are competing heating processes, but given the temperature of the system is cold compared to the energy levels the final state should be well into the ground state
- Typical procedure is to allow the system to relax back to the ground state (see the problem set)
- "Active Reset" (some references):
  - https://arxiv.org/abs/1802.08980, https://arxiv.org/abs/1801.07689, https://arxiv.org/abs/1508.01385

Single Qubit Control

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





Transmon (Duffing model approximation)

$$H = \omega_Q \hat{a}^\dagger \hat{a} + \frac{\alpha}{2}\hat{a}^\dagger \hat{a}\left(\hat{a}^\dagger \hat{a} - 1\right)$$
$$+\Omega\left(\hat{a}^\dagger + \hat{a}\right)\cos(\omega_D t + \phi)$$

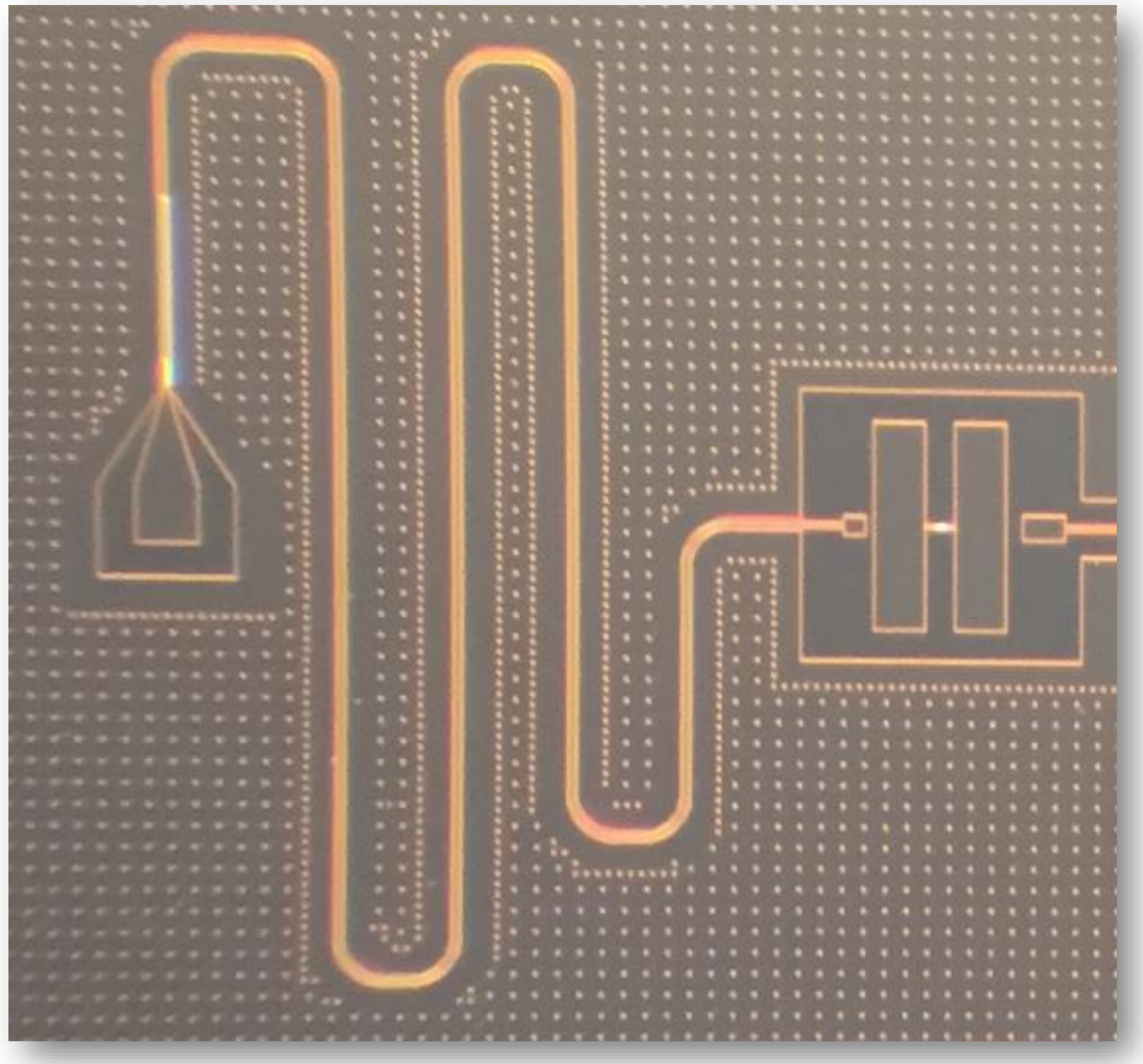
Coupling term

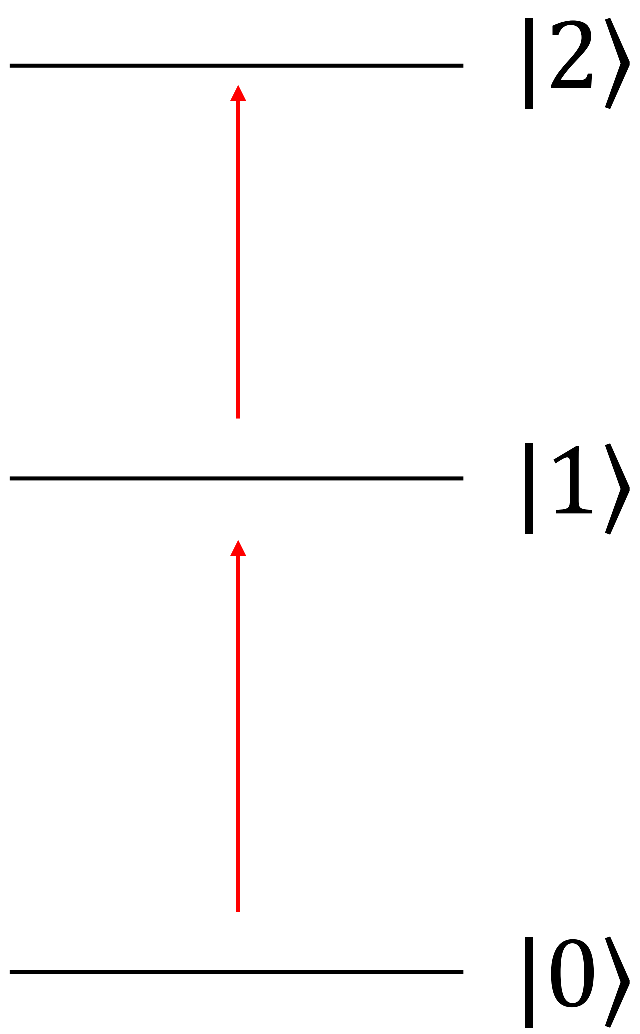
$$\begin{bmatrix} 0 & 0 & 0 \\ 0 & \omega_Q & 0 \\ 0 & 0 & 2\omega_Q + \alpha \end{bmatrix}$$

$$\begin{bmatrix} 0 & \Omega\cos(\omega_D t + \phi) & 0 \\ \Omega\cos(\omega_D t + \phi) & \omega_Q & \sqrt{2}\Omega\cos(\omega_D t + \phi) \\ 0 & \sqrt{2}\Omega\cos(\omega_D t + \phi) & 2\omega_Q + \alpha \end{bmatrix}$$

RWA

Go to a rotating frame at the drive frequency and assume the drive frequency and qubit frequency are similar





$$H = (\omega_Q - \omega_D)\hat{a}^\dagger \hat{a} + \frac{\alpha}{2}\hat{a}^\dagger \hat{a}(\hat{a}^\dagger \hat{a} - 1) + \frac{\Omega}{2}\left[\cos(\phi)\left(\hat{a}^\dagger + \hat{a}\right) + i\sin(\phi)\left(\hat{a}^\dagger - \hat{a}\right)\right]$$

On resonance, $\phi = 0$

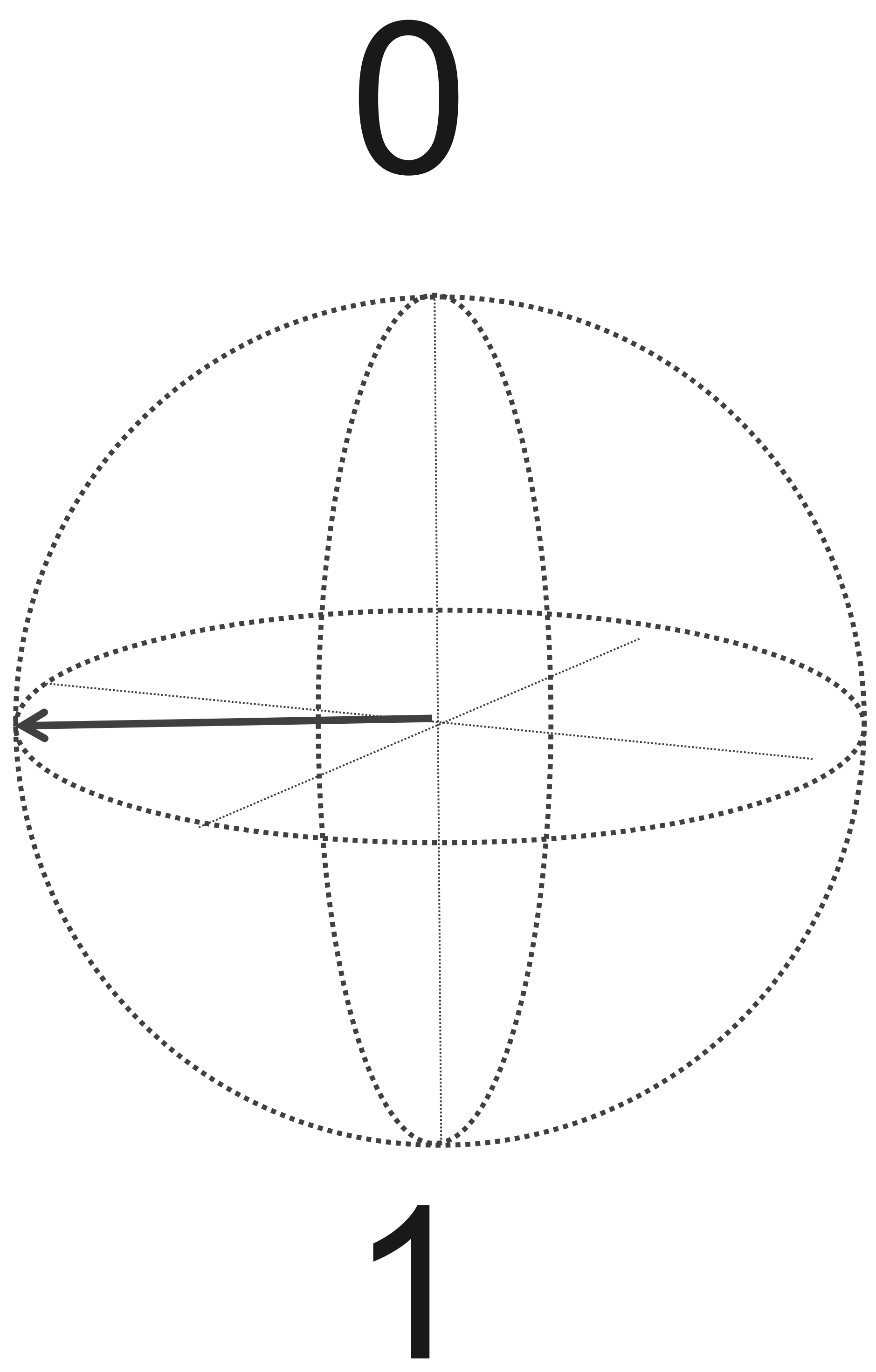
$$\begin{bmatrix} 0 & \frac{\Omega}{2}[\cos(\phi) + i\sin(\phi)] & 0 \\ \frac{\Omega}{2}[\cos(\phi) - i\sin(\phi)] & \omega_Q - \omega_D & \sqrt{2}\frac{\Omega}{2}[\cos(\phi) - i\sin(\phi)] \\ 0 & \sqrt{2}\frac{\Omega}{2}[\cos(\phi) - i\sin(\phi)] & 2\omega_Q - 2\omega_D + \alpha \end{bmatrix}$$

$$\begin{bmatrix} 0 & \frac{\Omega}{2} & 0 \\ \frac{\Omega}{2} & 0 & \sqrt{2}\frac{\Omega}{2} \\ 0 & \sqrt{2}\frac{\Omega}{2} & \alpha \end{bmatrix}$$

RWA

Restricted to two-levels:

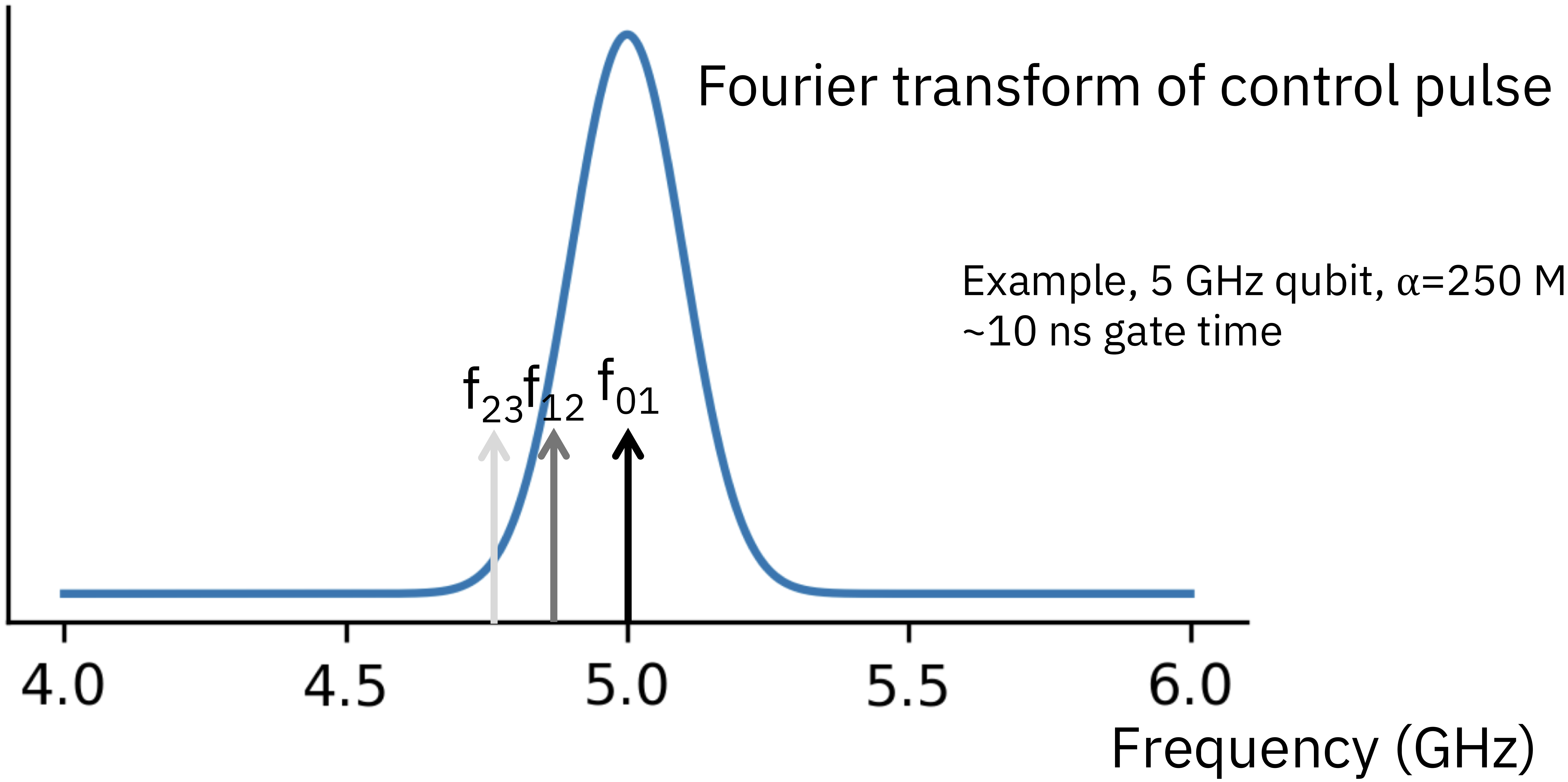
$$\begin{bmatrix} 0 & \frac{\Omega}{2}[\cos(\phi) + i\sin(\phi)] \\ \frac{\Omega}{2}[\cos(\phi) - i\sin(\phi)] & 0 \end{bmatrix} = \frac{\Omega}{2}\cos(\phi)\sigma_X + \frac{\Omega}{2}\sin(\phi)\sigma_Y$$



Apply for a time $t = \frac{\theta}{2\omega}$ to get the unitary

$$R(\theta,\phi) = \begin{bmatrix} \cos(\frac{\theta}{2}) & -ie^{-i\phi}\sin(\frac{\theta}{2}) \\ -ie^{i\phi}\sin(\frac{\theta}{2}) & \cos(\frac{\theta}{2}) \end{bmatrix}$$

Limitations on gate times



Example, 5 GHz qubit, α=250 MHz,
~10 ns gate time

Qubits and Errors

A qubit is a quantum two-level system

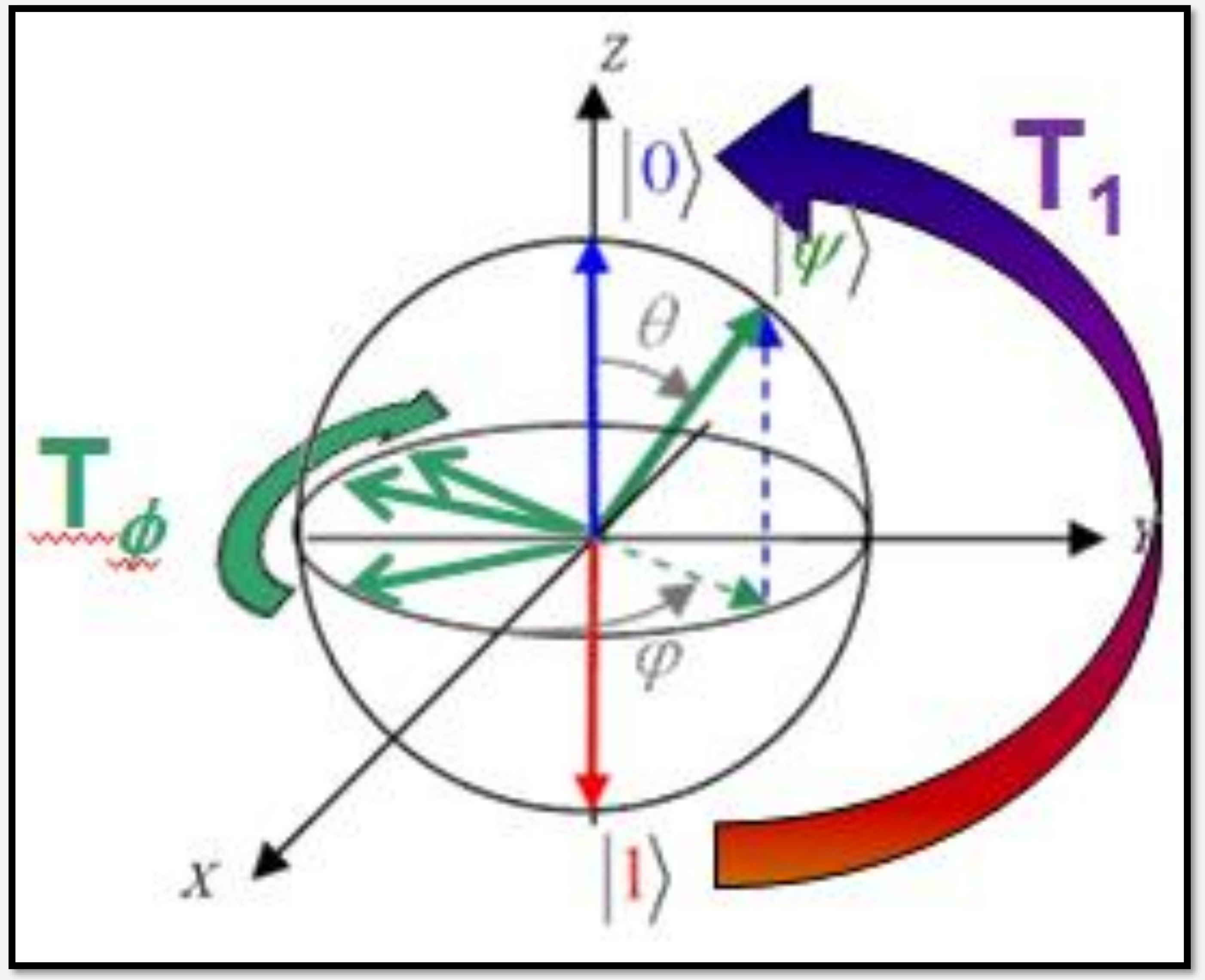
Finite qubit coherence times

- T_1: relaxation (dissipation - think resistor)
- T_ϕ: dephasing (randomization of f)
  - Results from measurement (intentional or not)
- T_2: parallel combination of above,

Imperfect control pulses

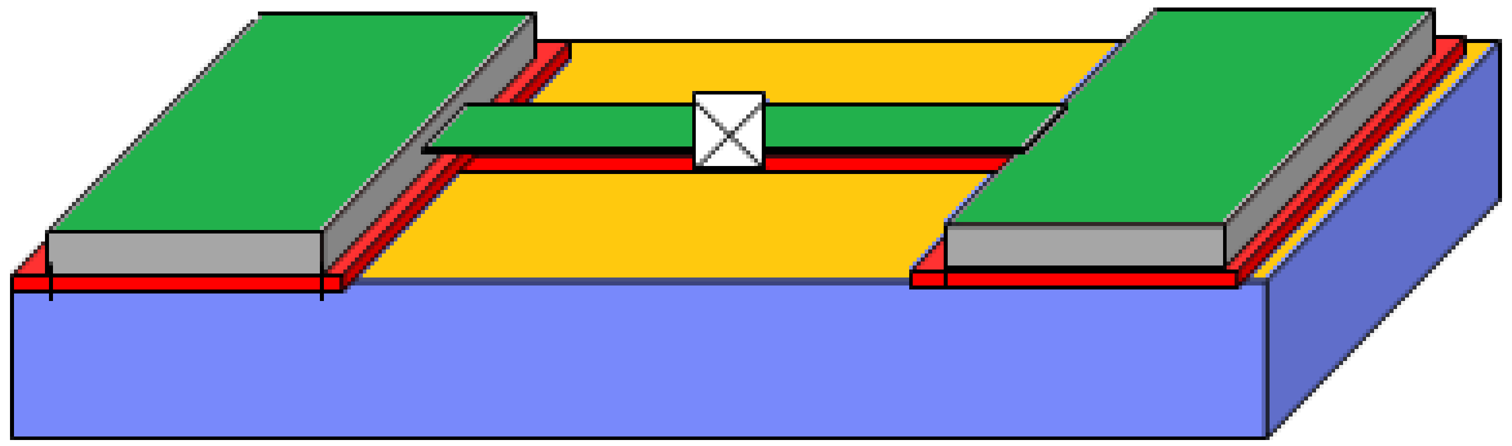
Spurious inter-qubit couplings

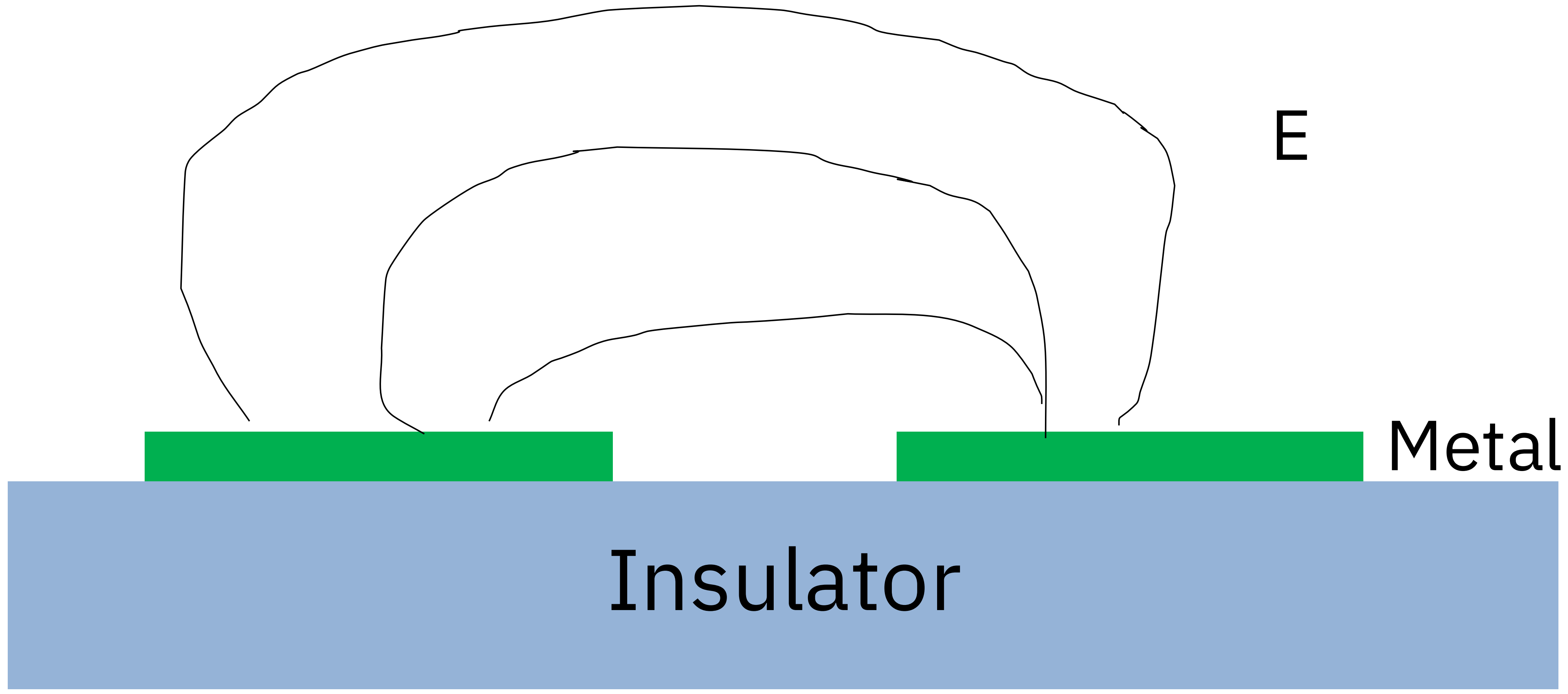
Imperfect qubit state measurements



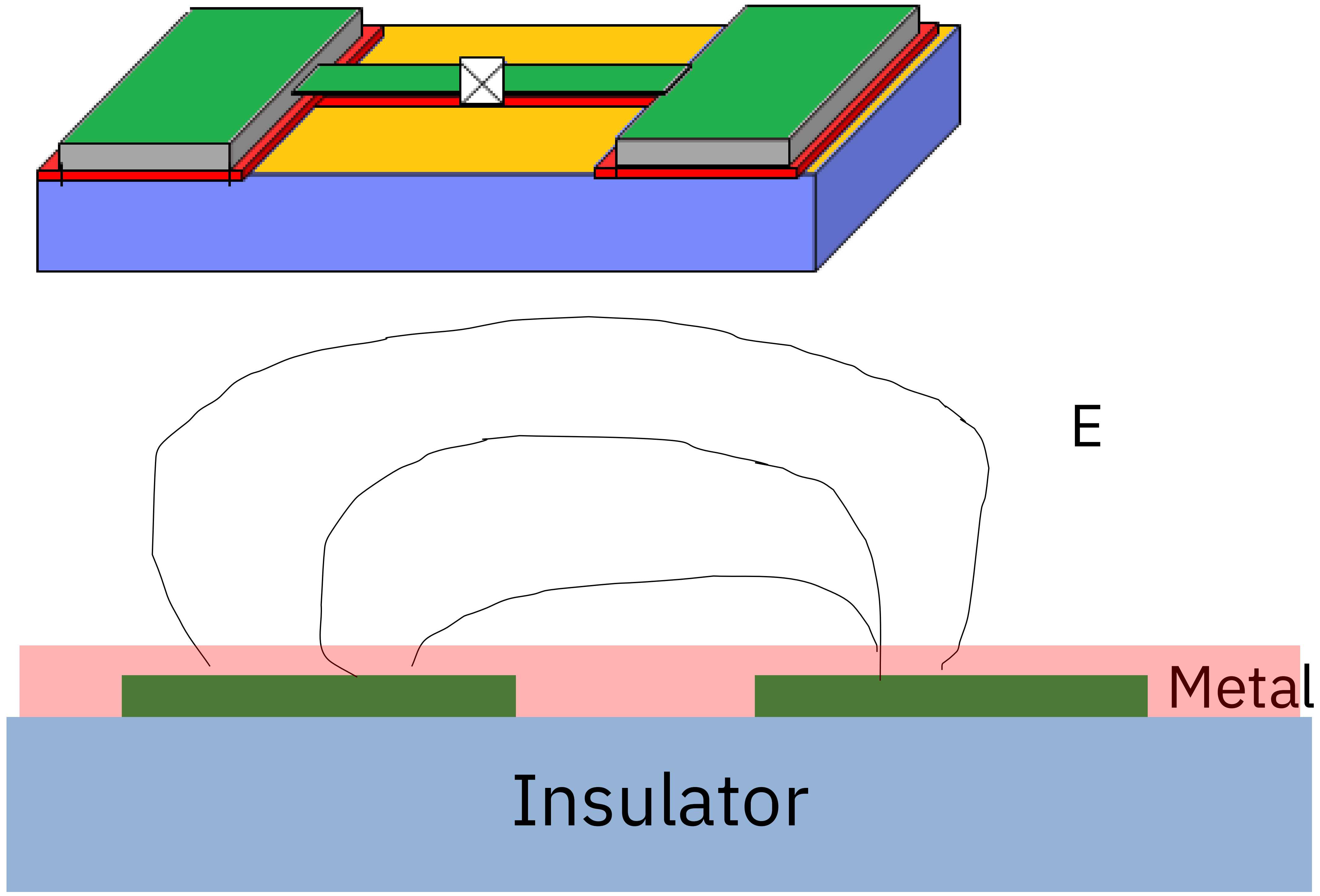
$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

T_1 and qubit size



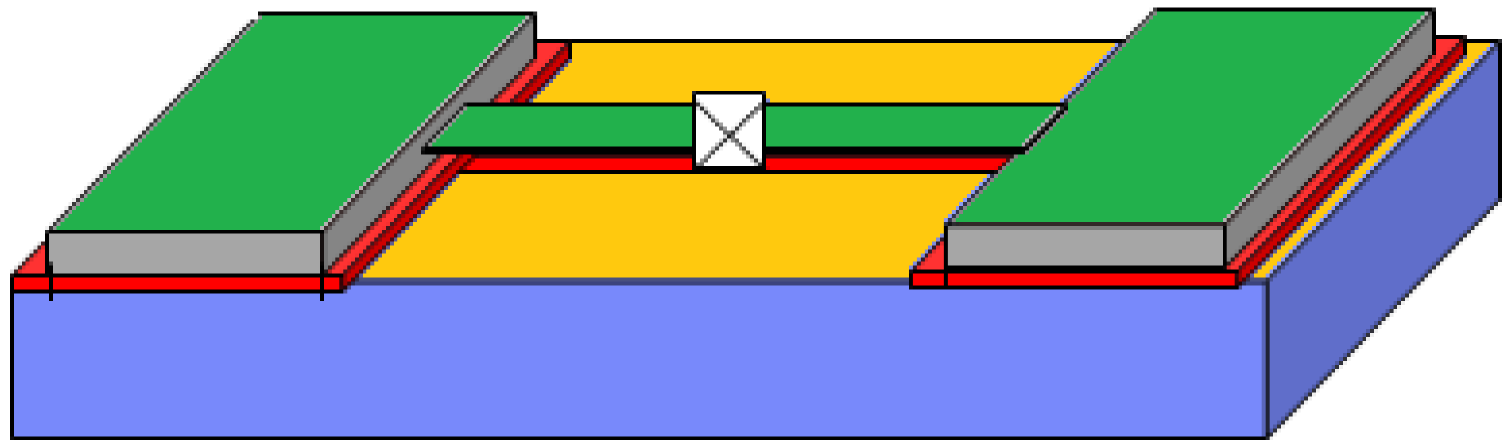


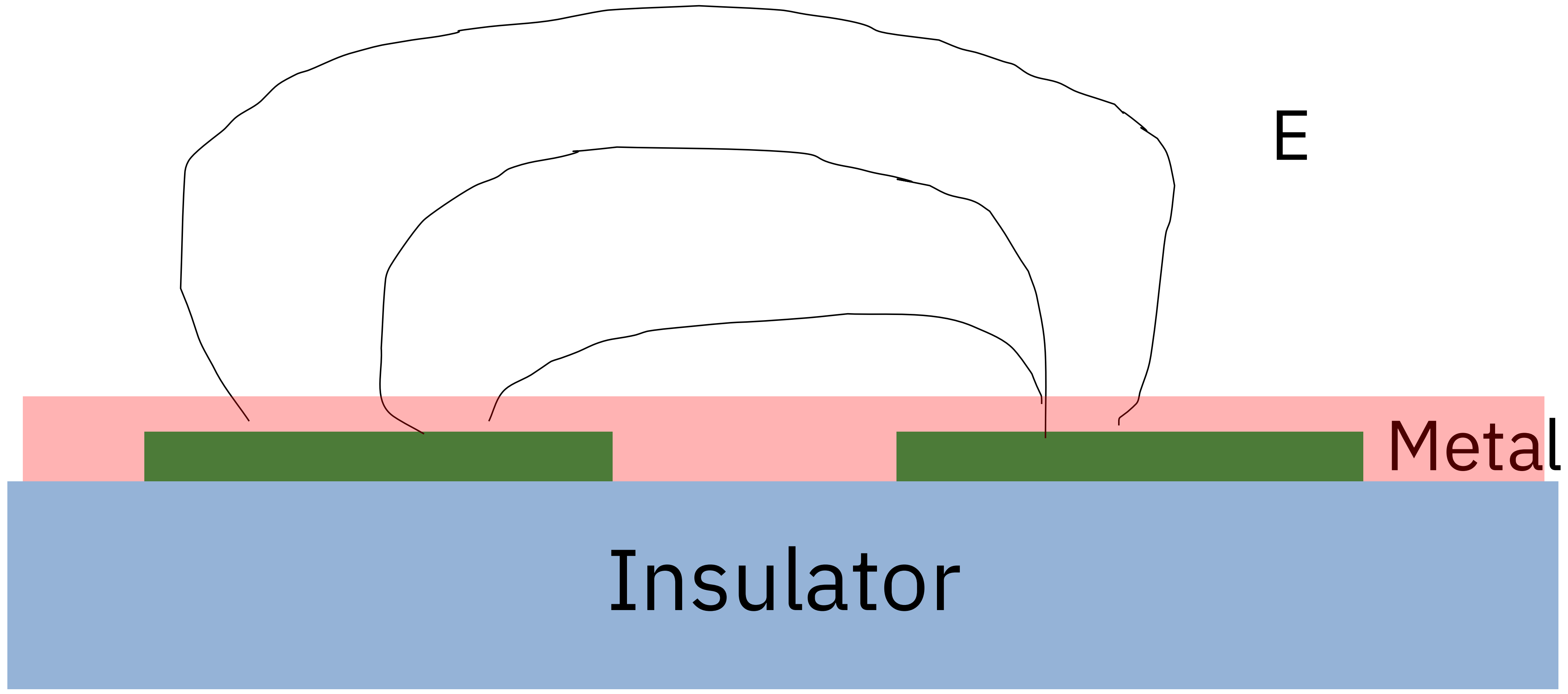
T_1 and qubit size

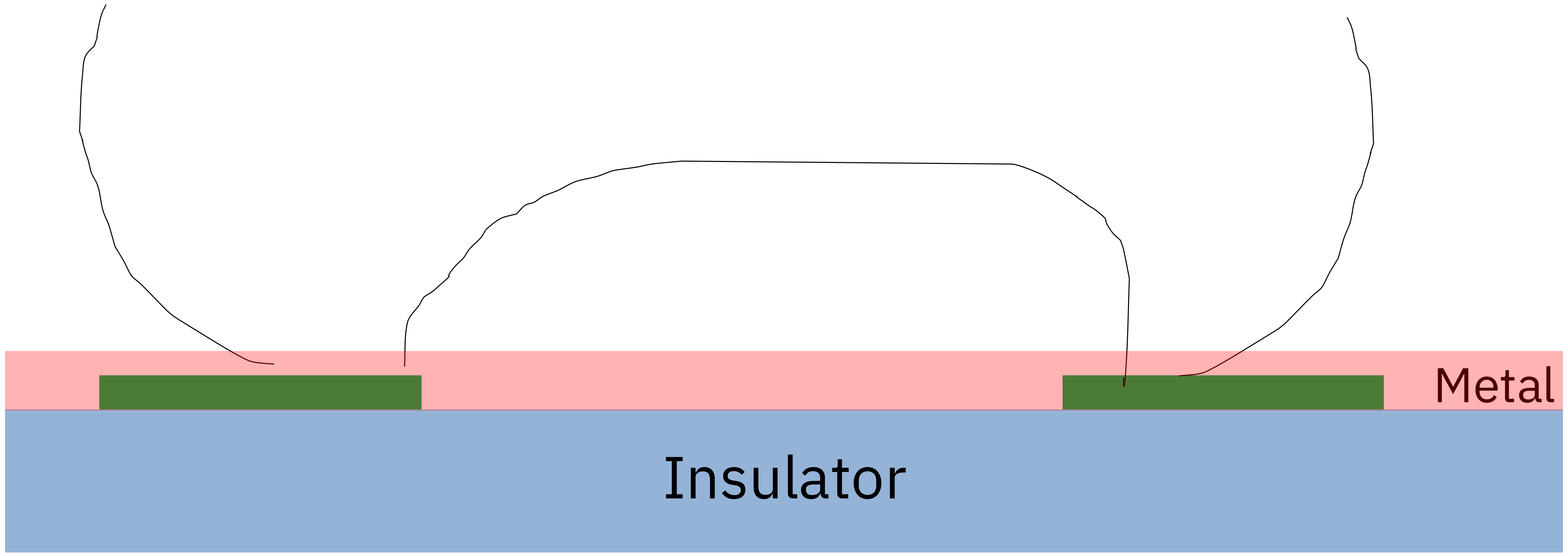


If there is a thin lossy interfacial layer, the loss from it will depend on how much electrical energy is stored in it

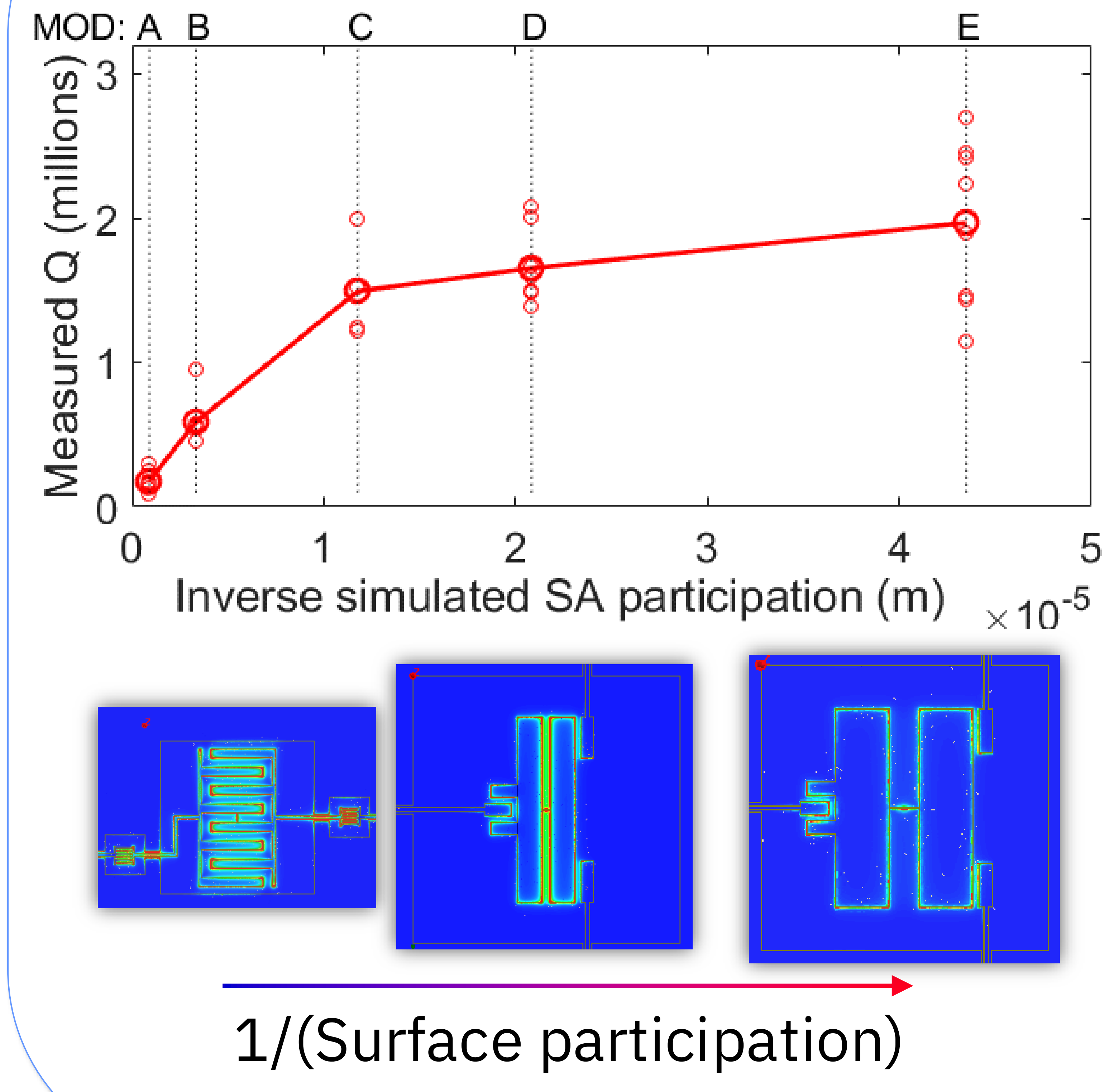
T_1 and qubit size



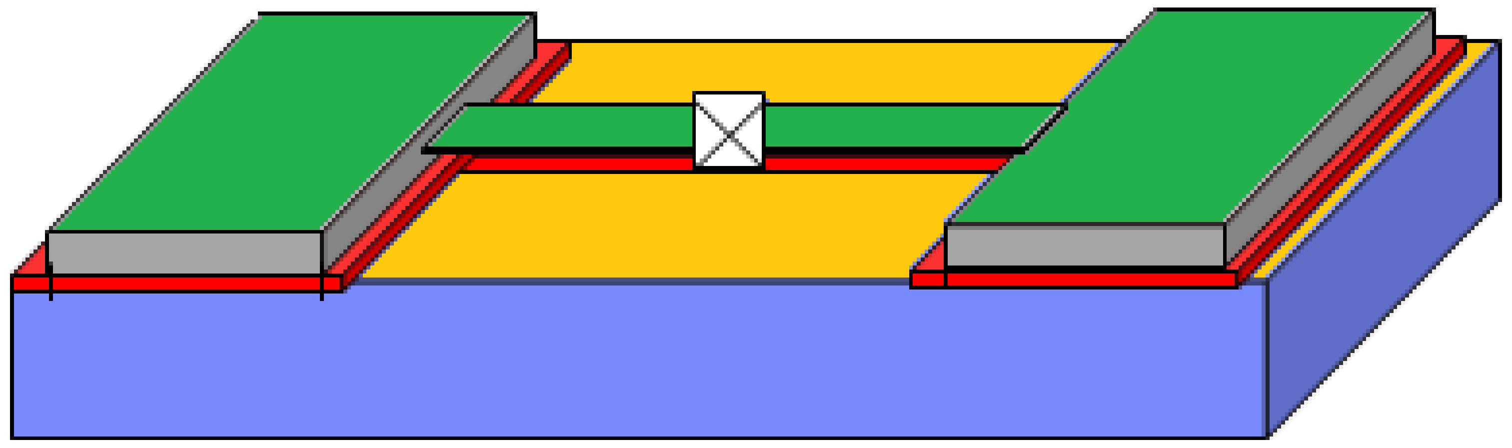


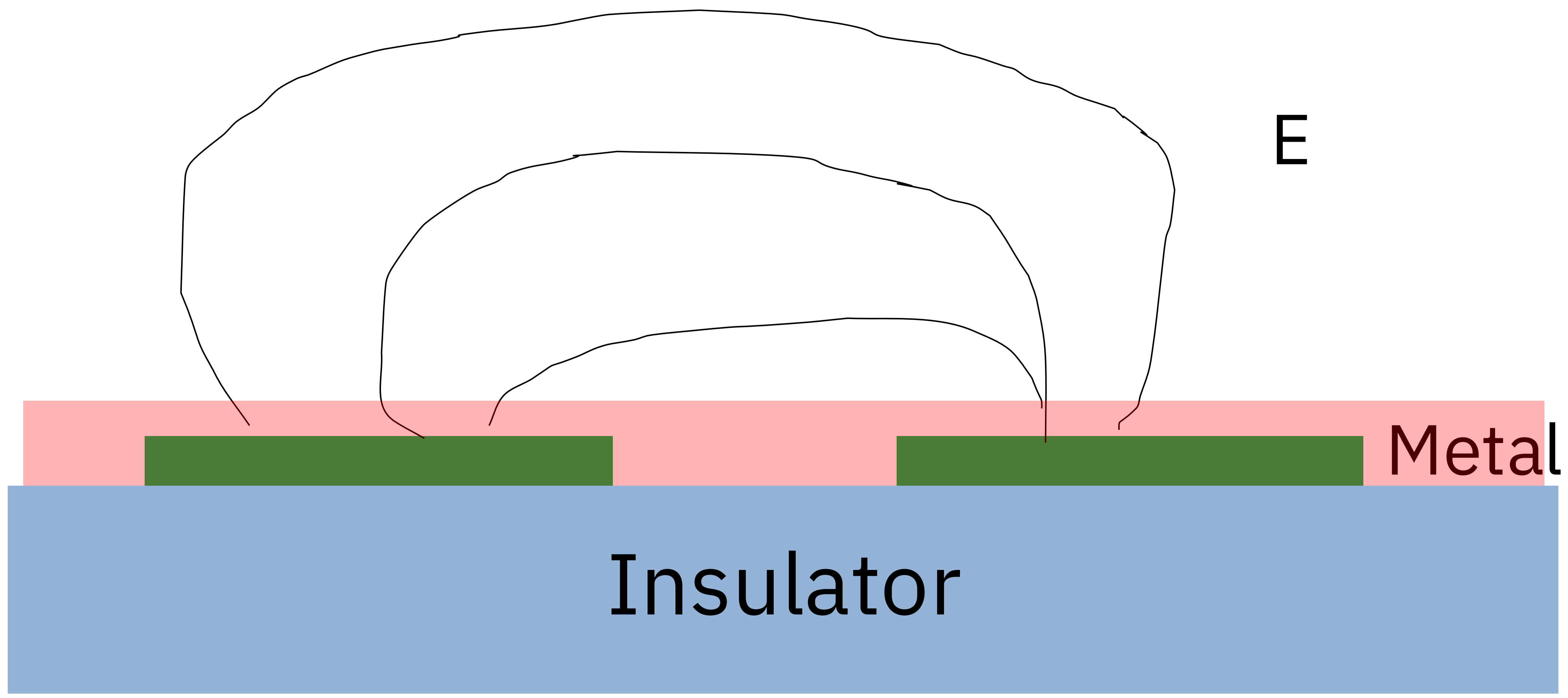


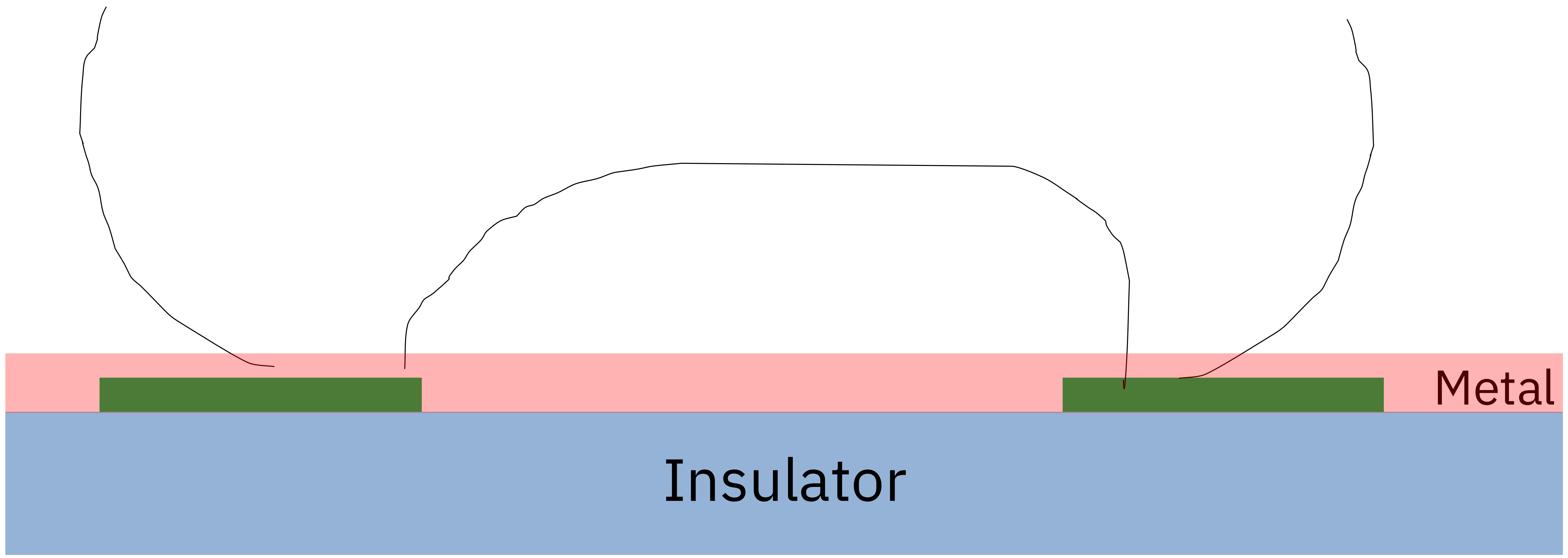
T_1 and qubit size



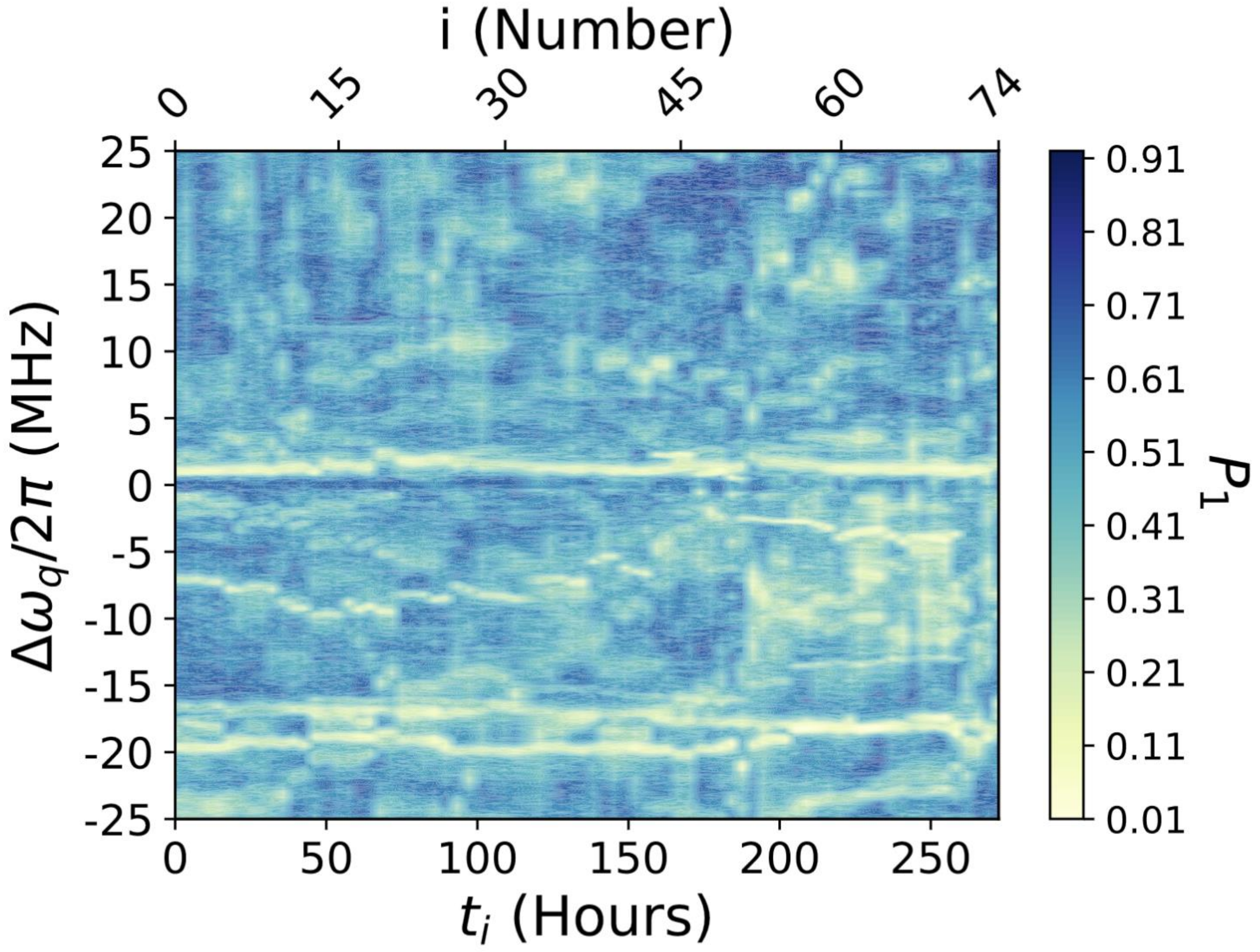
Gambetta et al, EEE Trans. on App. Superconductivity 27 1 (2017)







Variability of T_1



M. Carrol et al. npj Quantum Information volume 8, 132 (2022).

T_1 is highly variable from qubit to qubit and over time

Two Level Systems (TLS)

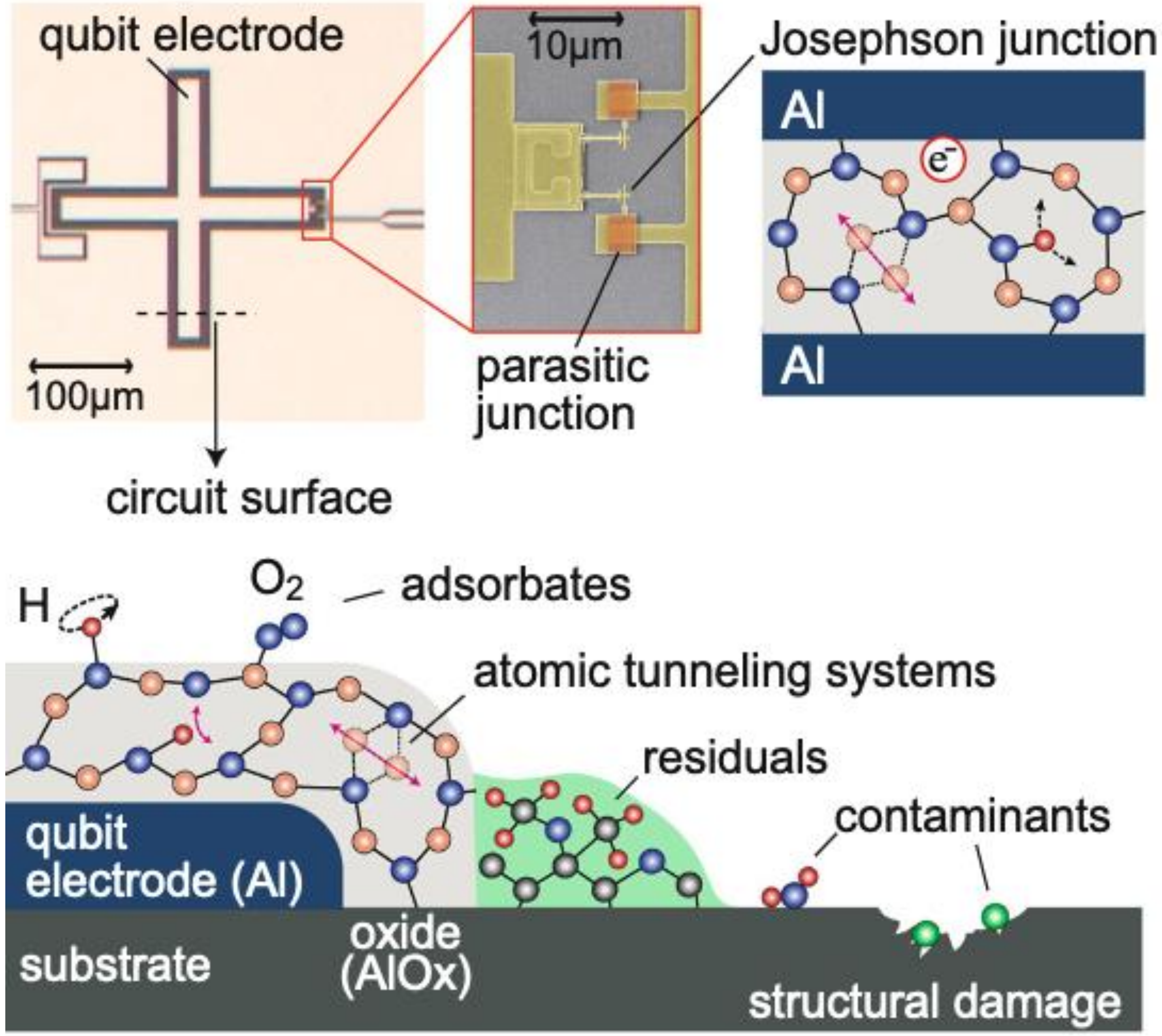
Atomic-scale defects that may reside in a number of places within the qubit environment

First detected as anomalous heat capacity in glasses at low temp (Zeller & Pohl)

Described by Standard tunneling Model (Phillips/Anderson 1972) w/ refinements (Burin+others 1990s, Ioffe+Faoro 2010s)

Shown to affect qubits (Martinis) and resonators (Gao)

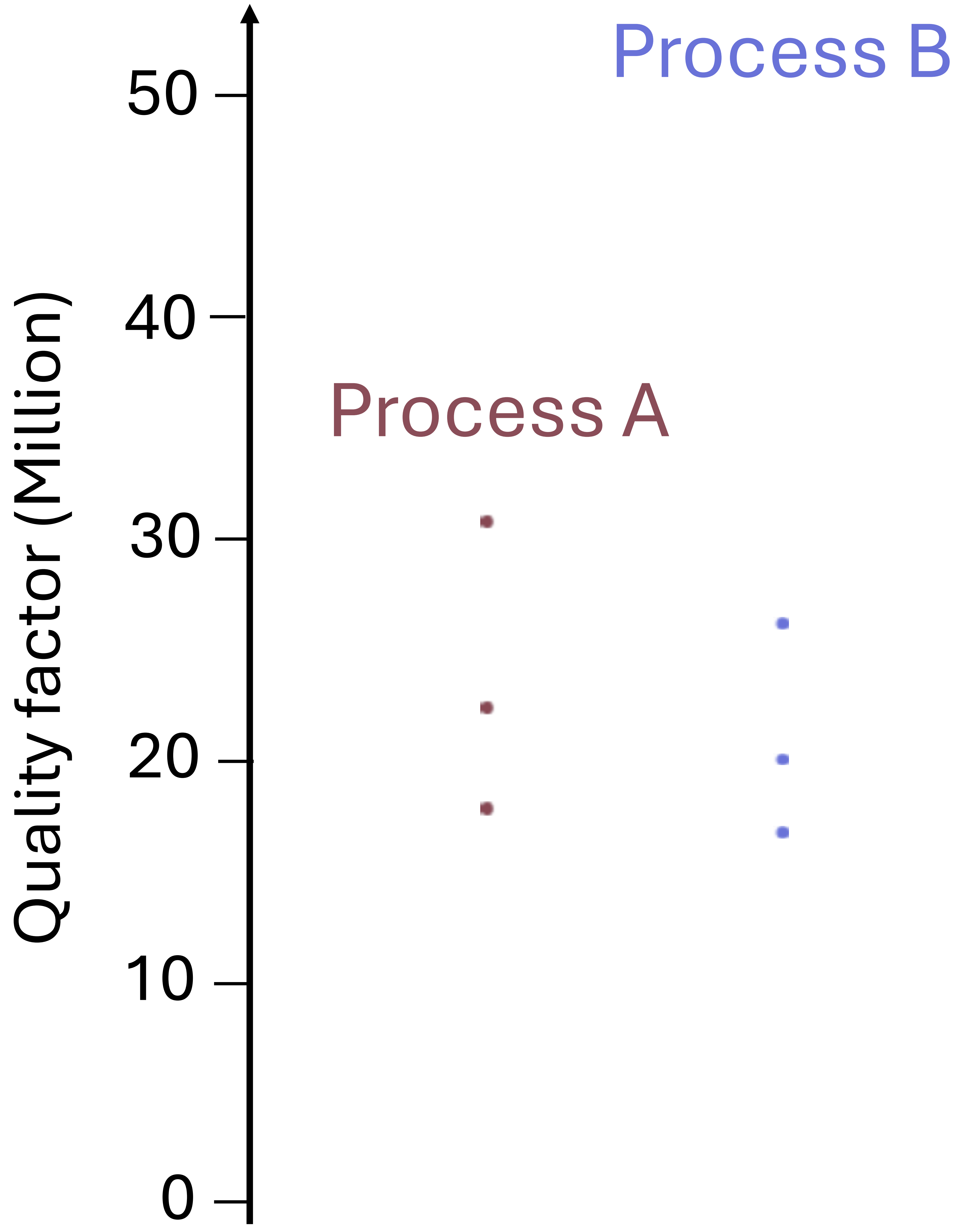
Zeller and Pohl, *PRB* 4, 2029 (1971)
Phillips, *JLTP* 7 351 (1972)
Anderson, Halperin, & Varma, *Phil. Mag.* 25, 1 (1972)
W. Phillips, Rep. Prog. Phys. **50,** 1657 (1987)
Burin & Kagan, *ZETF* 106, 633 (1994)
Gao et al, *Appl. Phys. Lett.* 92, 152505 (2008).
Faoro & Ioffe, *PRL* 109, 157005 (2012)
Martinis et al, *PRL* 95, 210503 (2005)



Lisenfeld et al., *npj Quant. Info.*, 5 105 (2019)

Doing research on T_1

- Is Process B better than process A?
- As T1 improves:
  - Measure more qubits
  - Measure each longer
- Open questions about how many and how long



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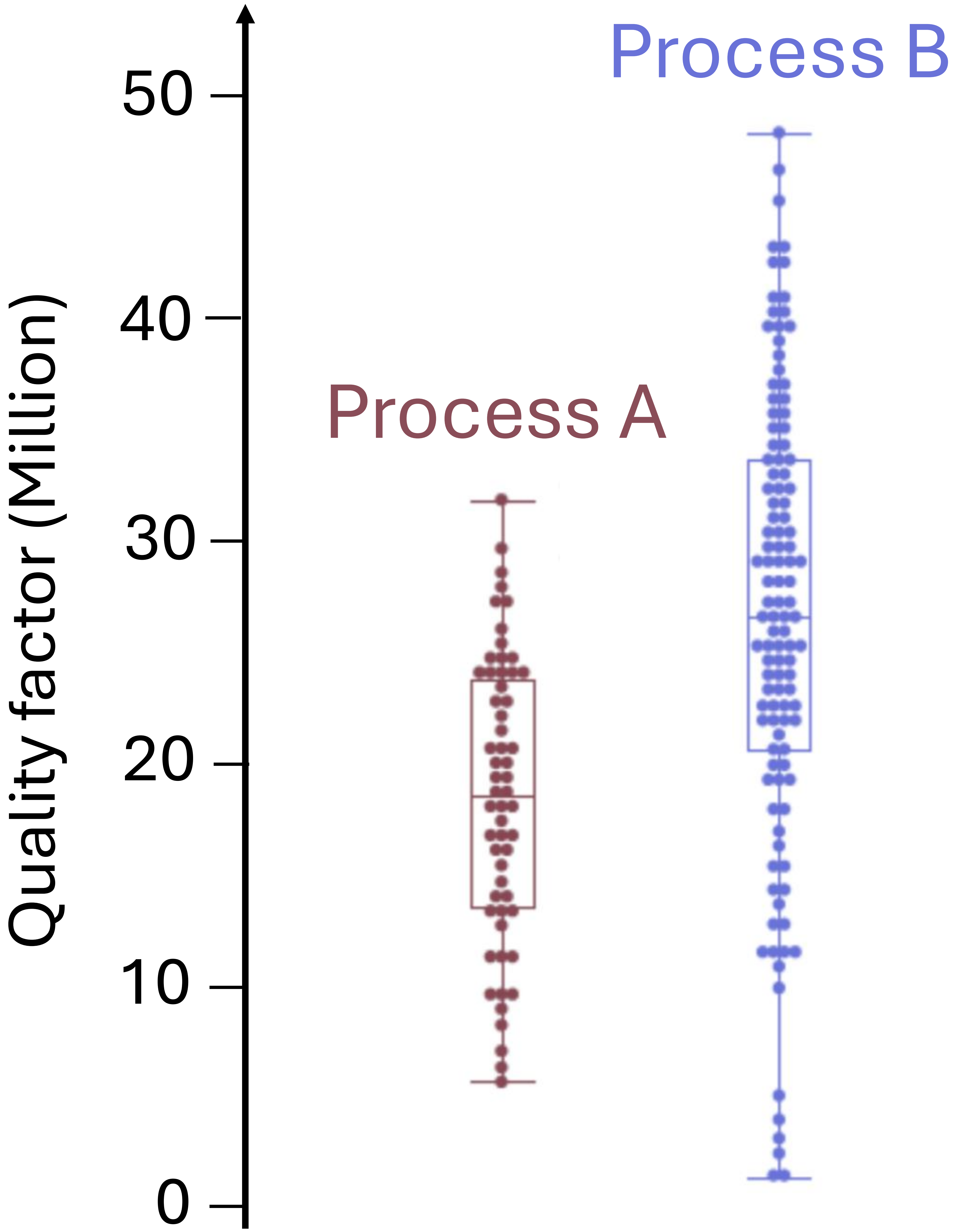


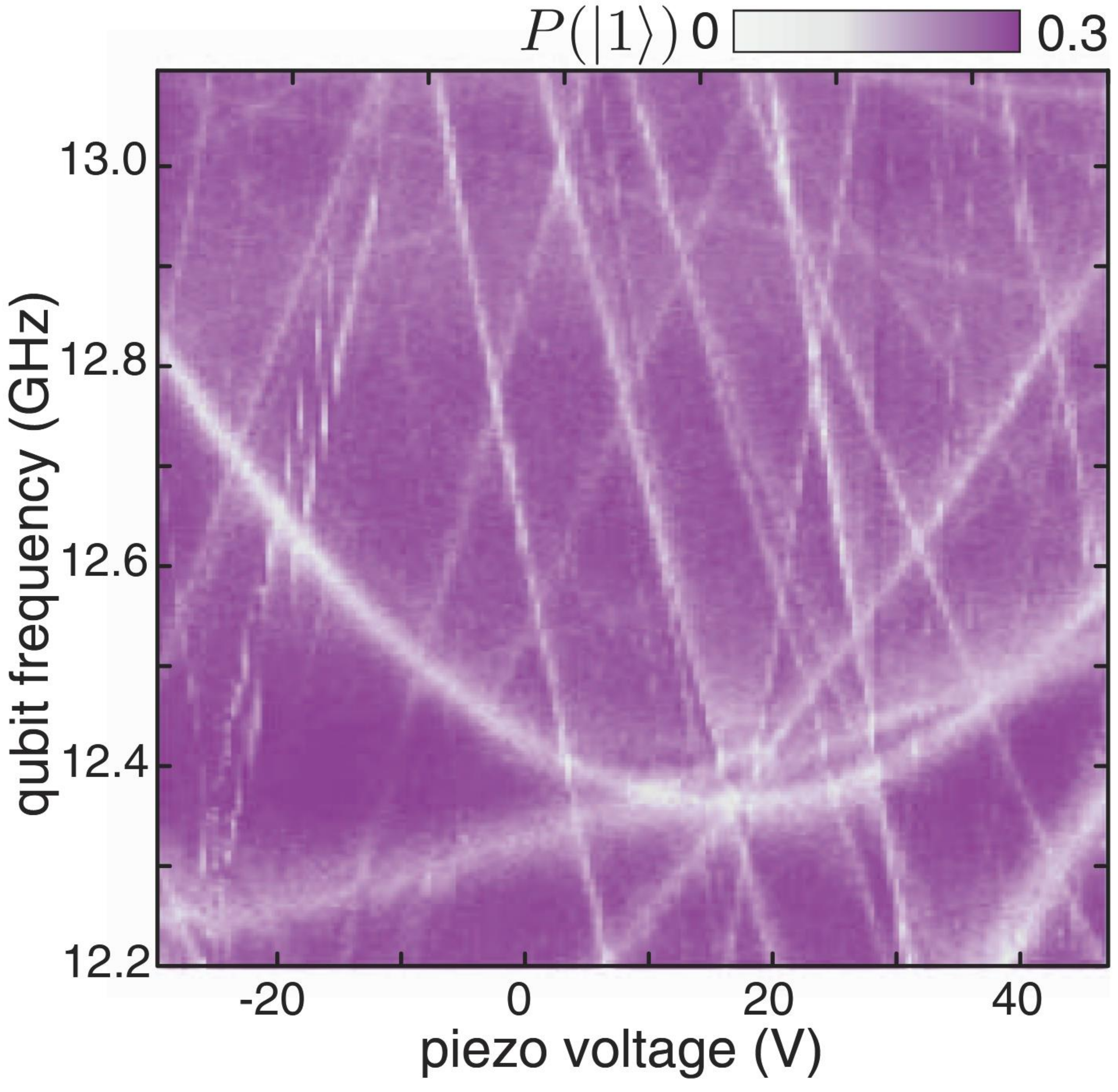
TLS Manipulation

We can directly control TLS energy by:

1) altering local strain
2) altering E-field at TLS

$$\hbar\omega_{TLS} = \sqrt{\Delta_0^2 + \varepsilon^2}$$

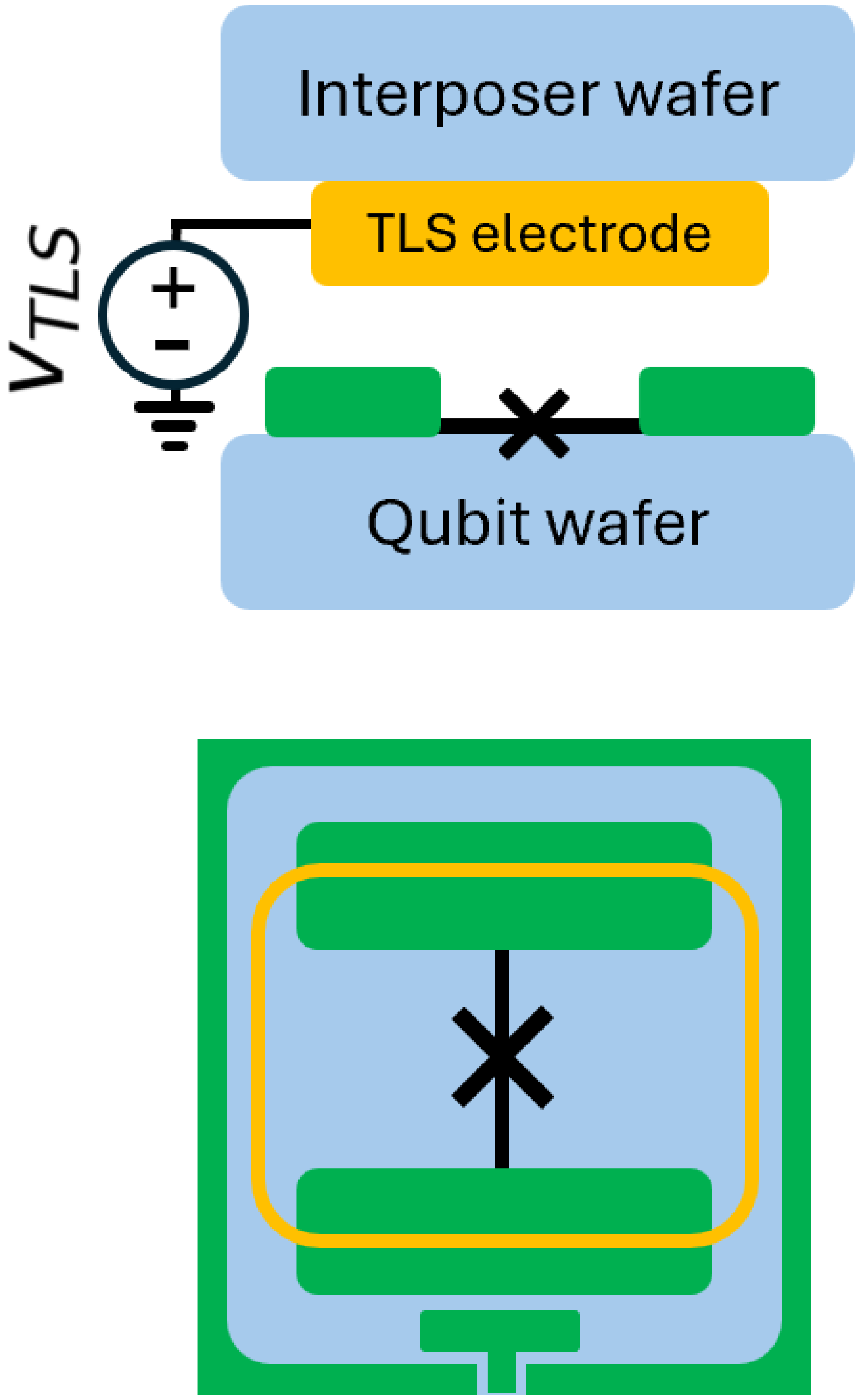
$$\varepsilon = 2\boldsymbol{\gamma} \cdot \boldsymbol{S} + 2\boldsymbol{p} \cdot \boldsymbol{E} + \varepsilon_0$$

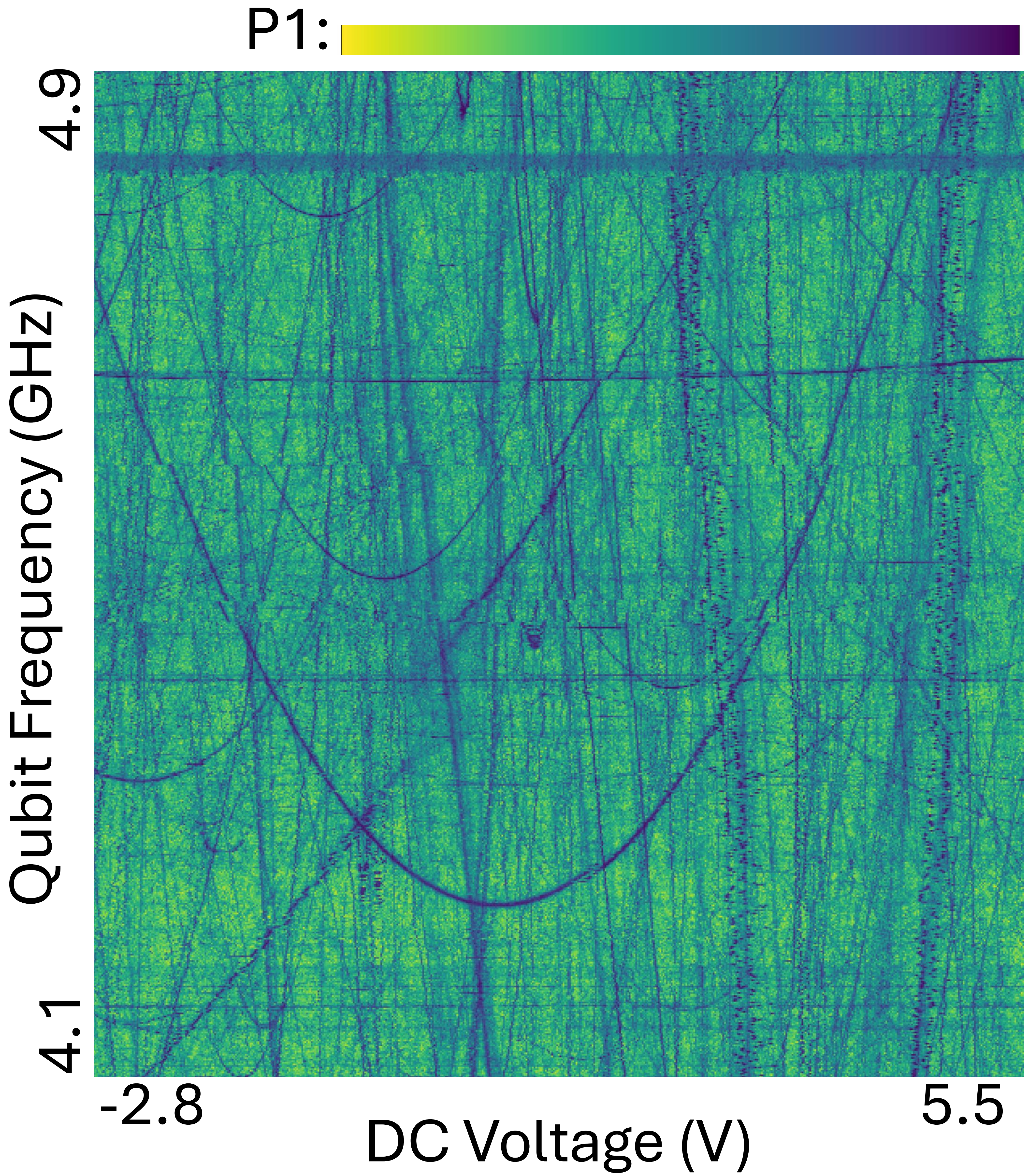


Grabovski et al, *Science* 338 (2012)

Local TLS Manipulation

- Transmon qubits
- Weakly coupled to RO resonator
- Electrode centered above qubit paddles on interposer wafer

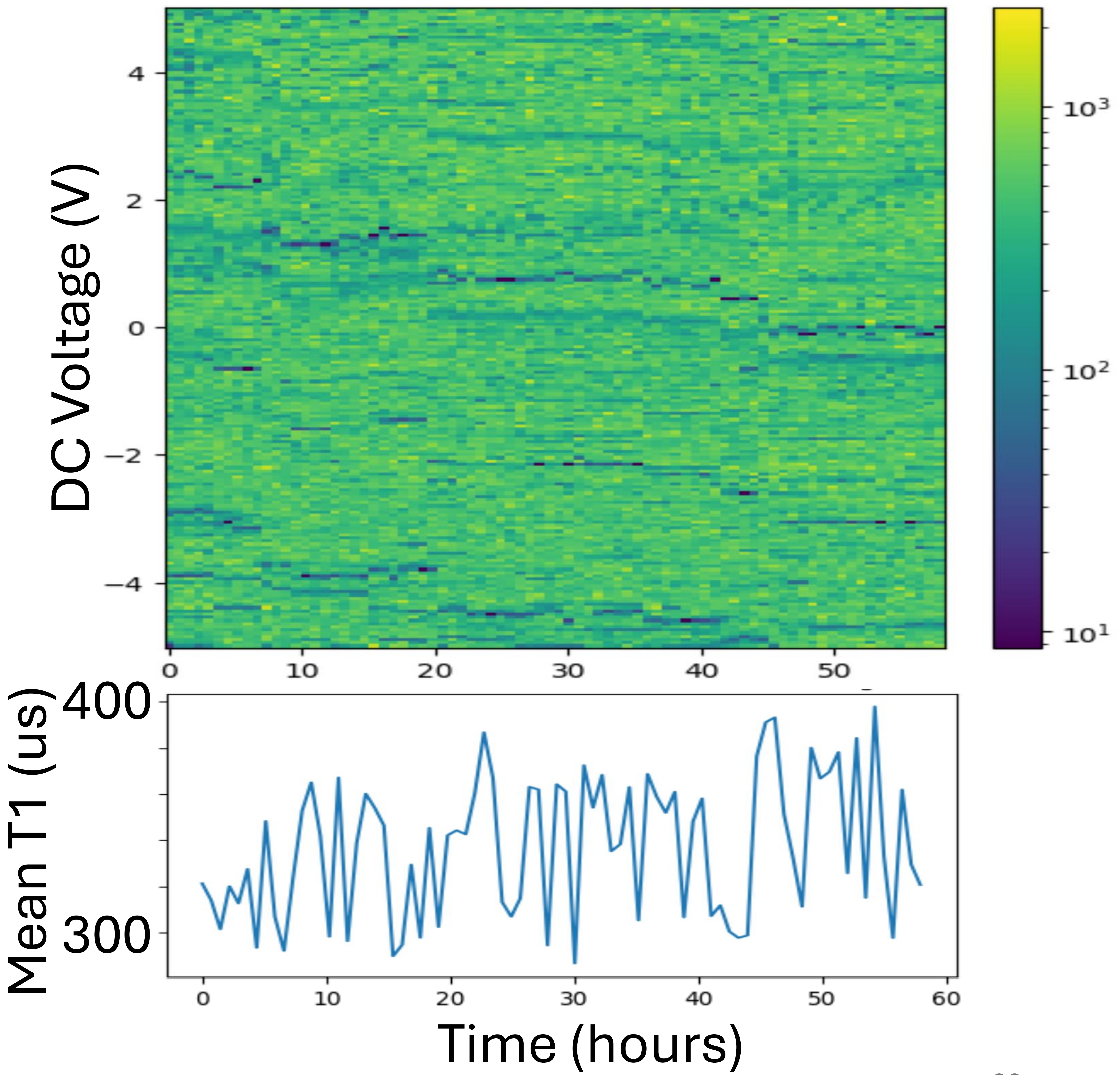




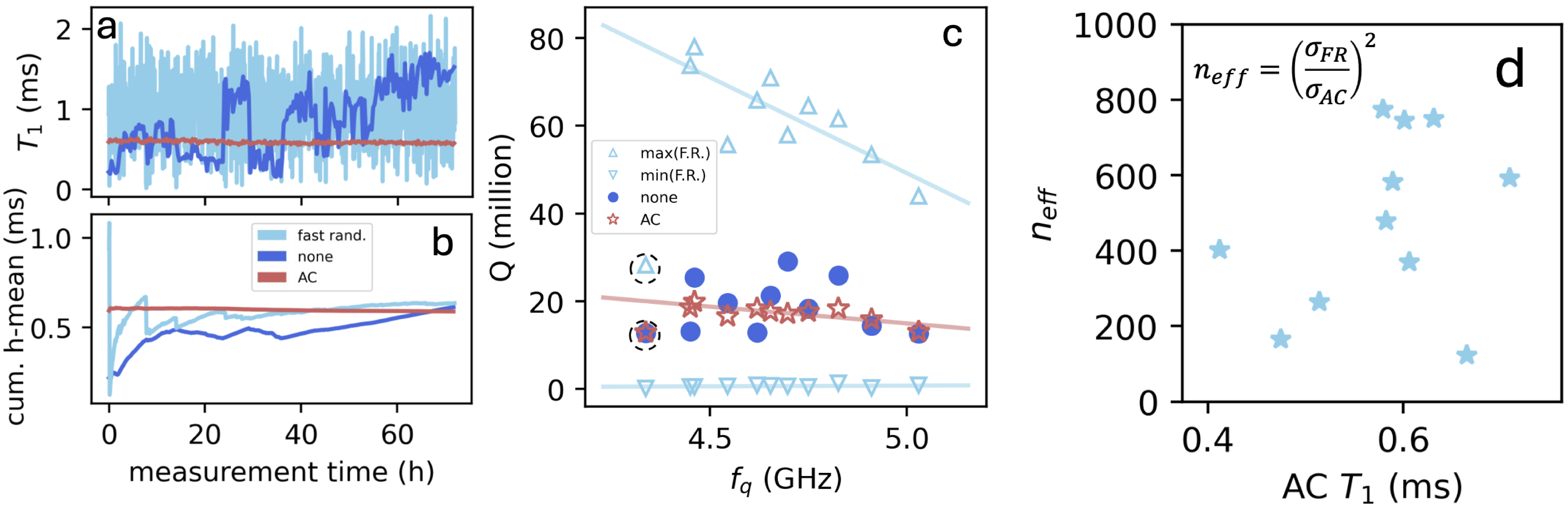
Dane et al., npj Quant. Info, 2026

Evolution vs. voltage and time

- Sweep DCV, measure P1 -> T1
- TLS losses (dark blue)
- Two major observations:
  - The vast majority of the voltage space has T1 100s of us
  - TLSes move around more than appear/disappear.
- T1 averaged over voltage is very stable (337 us +- 29 us)

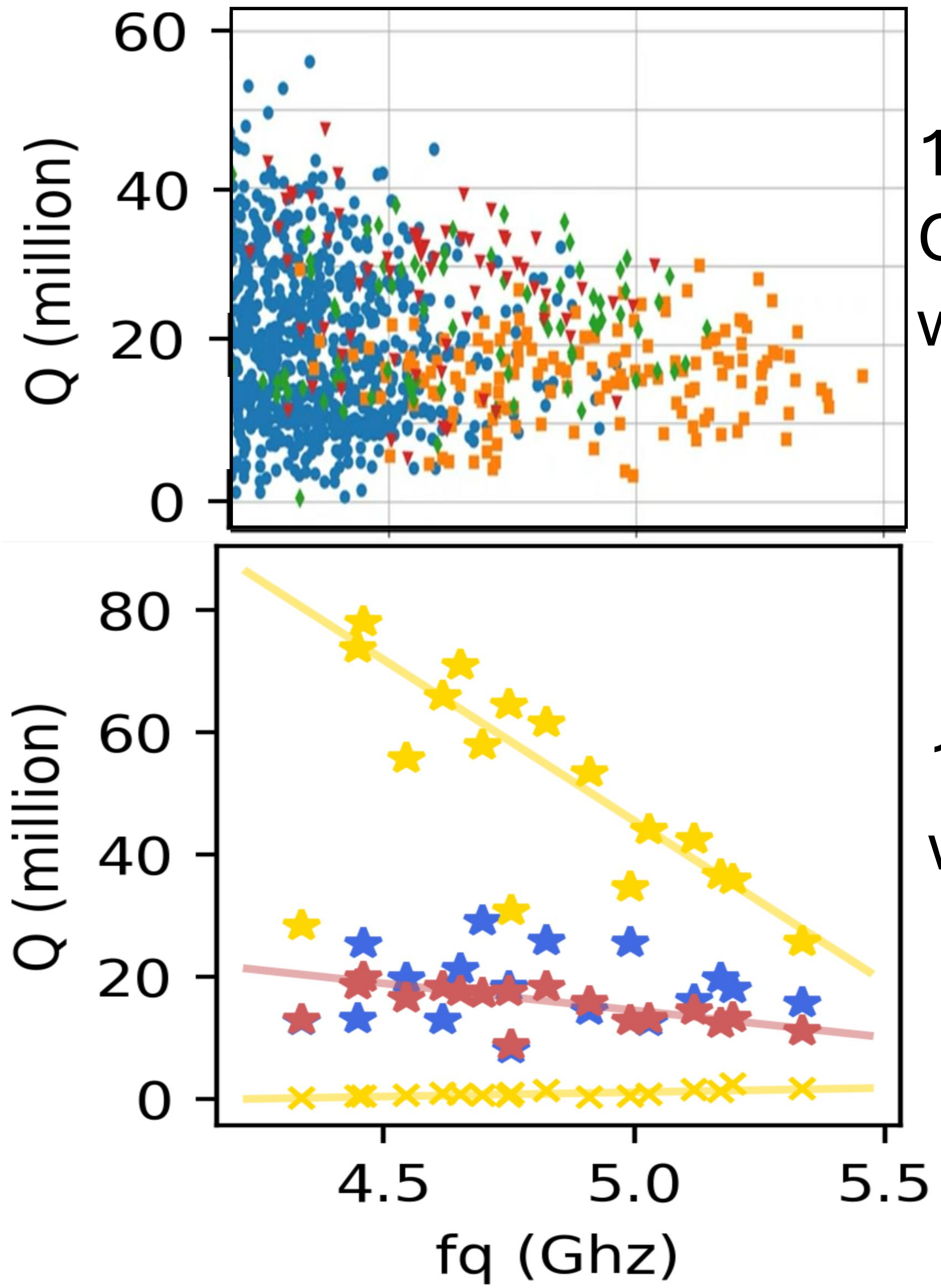


Better statistics with less data



Seeing trends with T_1 control

- Top: portion of Q vs frequency collected over thousands of qubits, many builds
- Bottom: Qs accessed using the TLS voltage pad.
- TLS control allows us to observe subtle trends with orders of magnitude fewer qubits



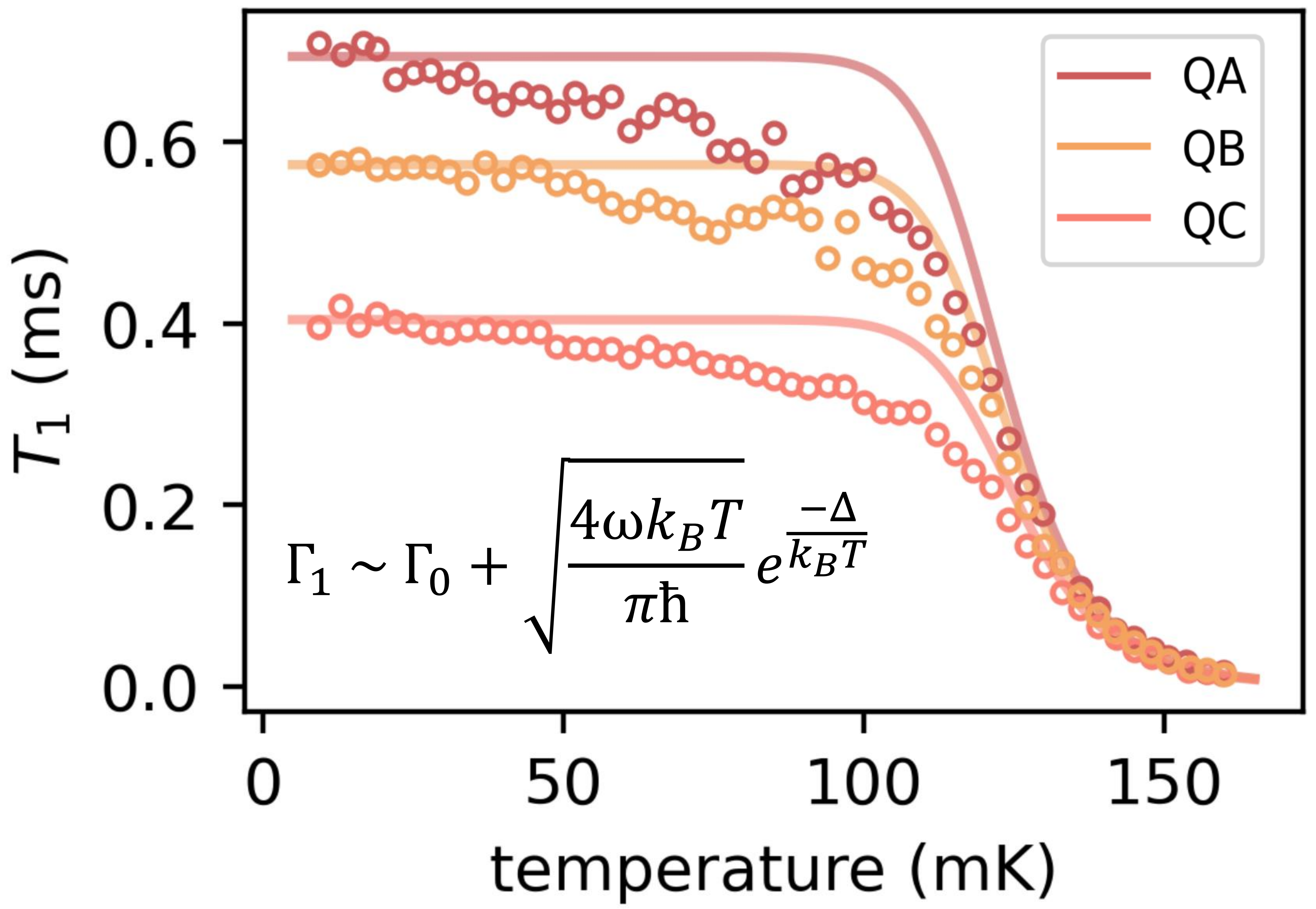
100s – 1000s Qubits w/o TLS control

15 Qubits w/ TLS control

Seeing trends with T_1 control

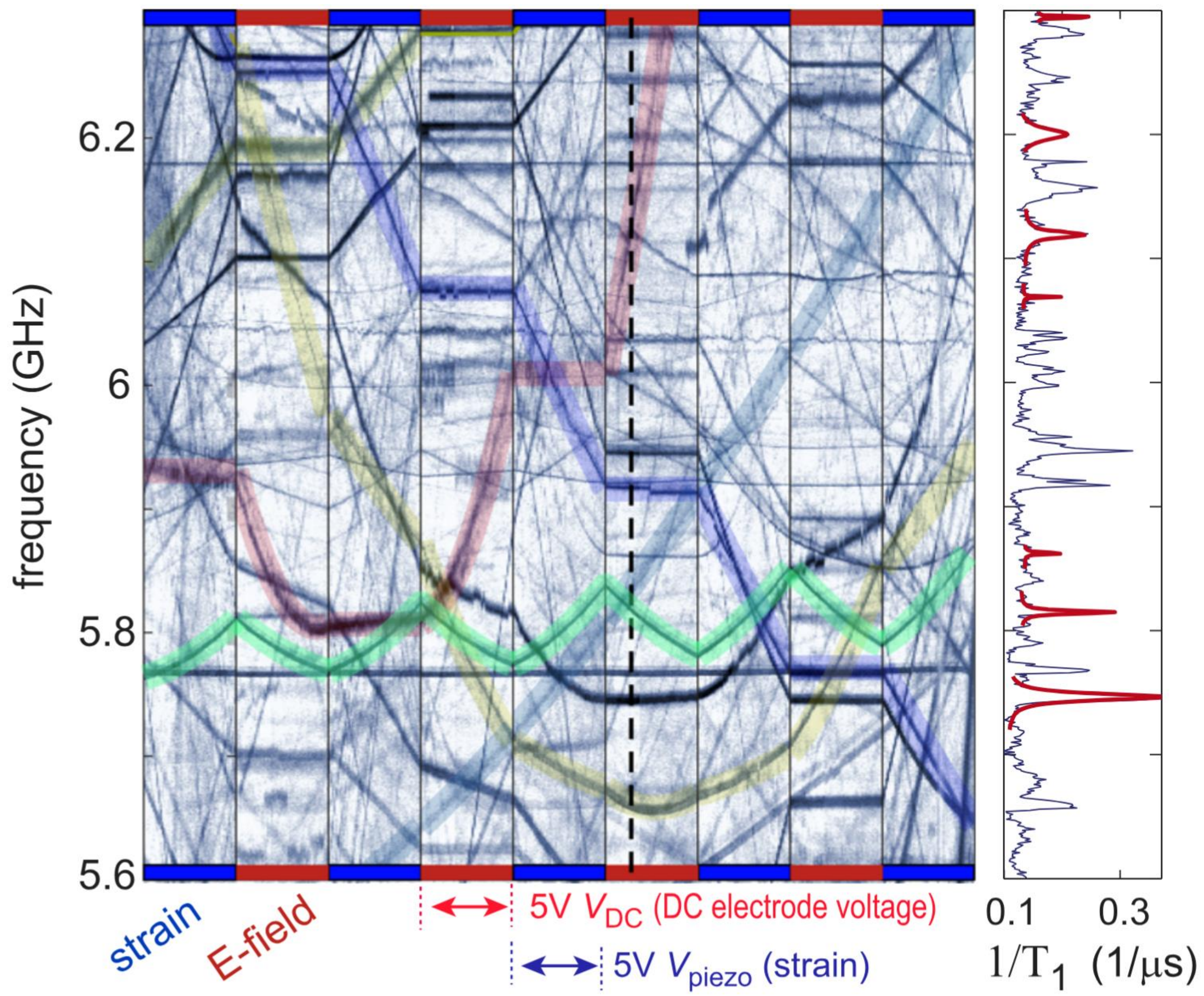
- Measure T1 with AC bias as a function of mixing plate temperature
- Functional form of T1 well explained by thermal QPs T > 100 mK
- Quasi-linear regime not understood
- Quasi-linear regime also seen when averaging together large # of qubits

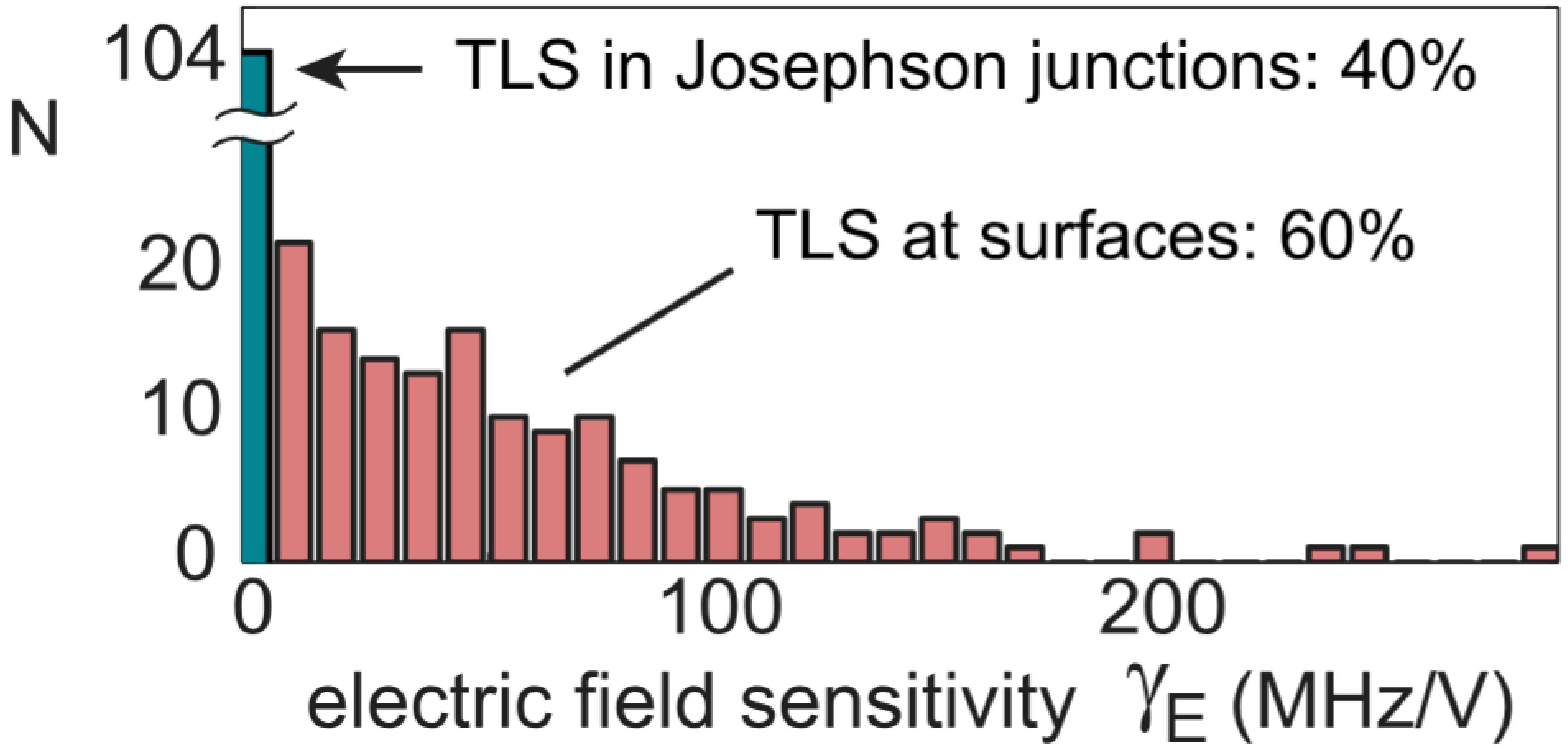
Dominant loss mechanism:
← TLS | Thermal QPs →



Non-tunable TLS's

- TLS only change frequency if the applied field reaches them
- Literature suggests ~40% of TLS do not respond to applied field
- These non-tunable TLS can't be moved by our AC fields

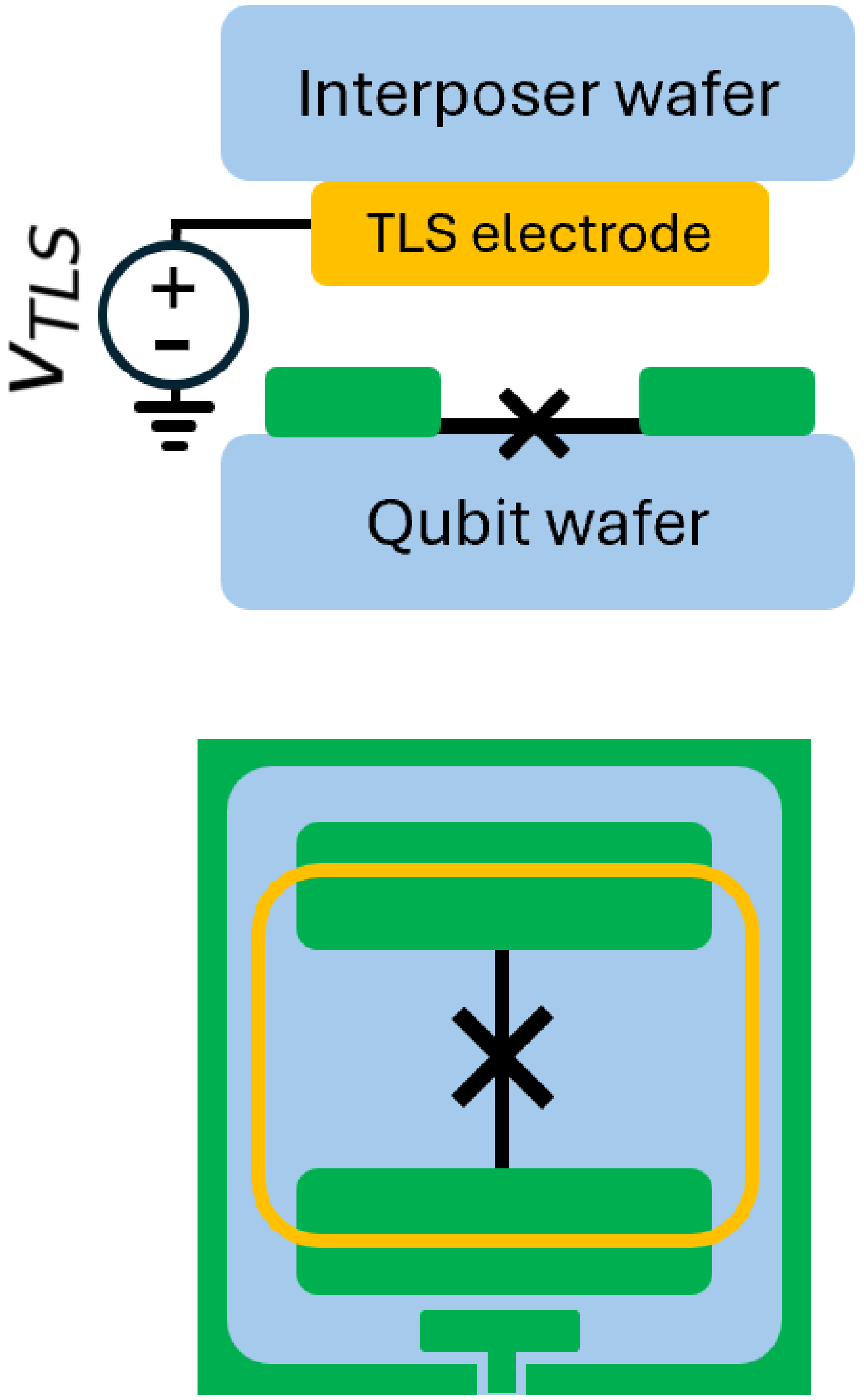


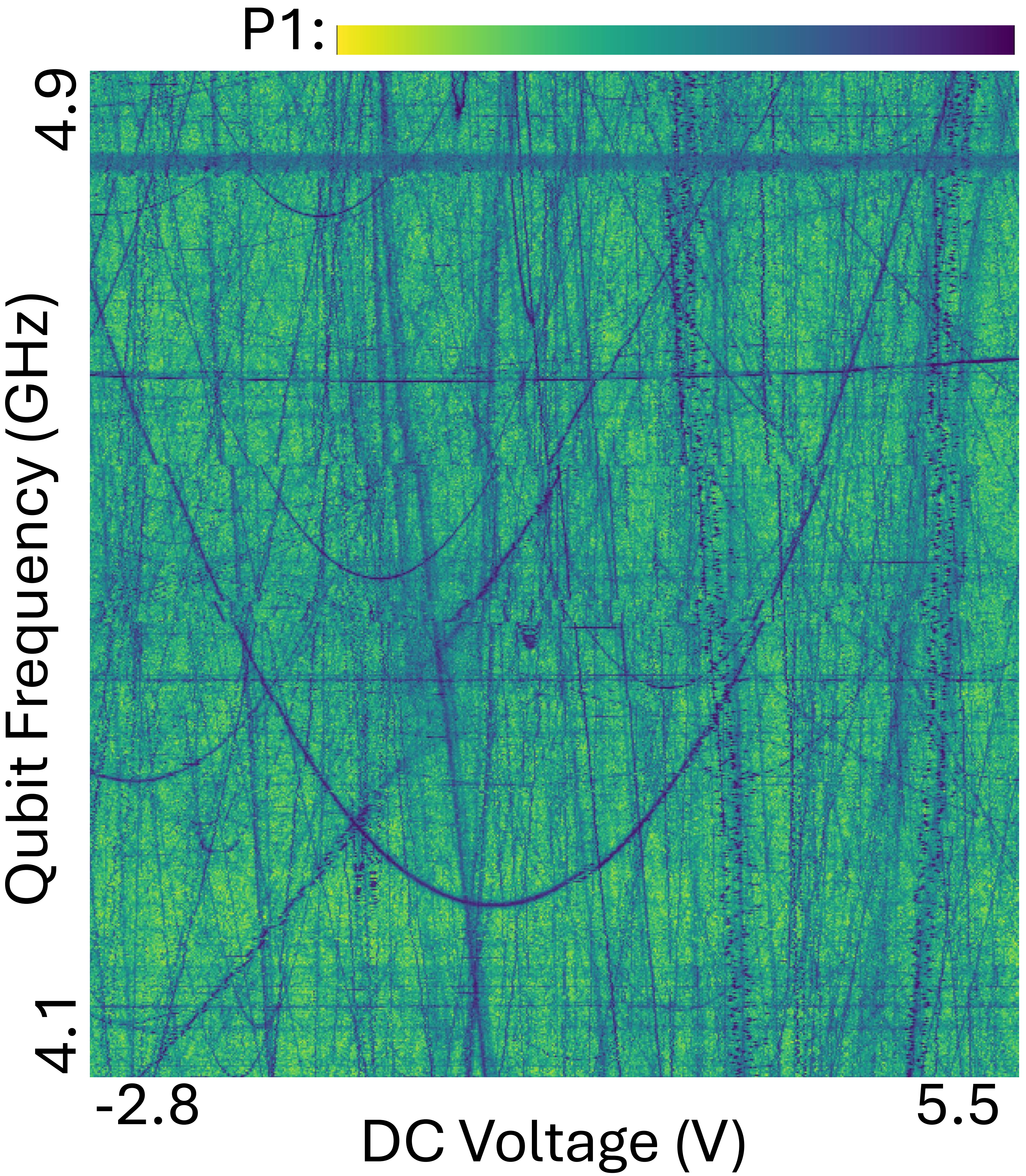


J. Lisenfeld et al. npj Quantum Information (2019) 105

Local TLS Manipulation

- Transmon qubits
- Weakly coupled to RO resonator
- Electrode centered above qubit paddles on interposer wafer

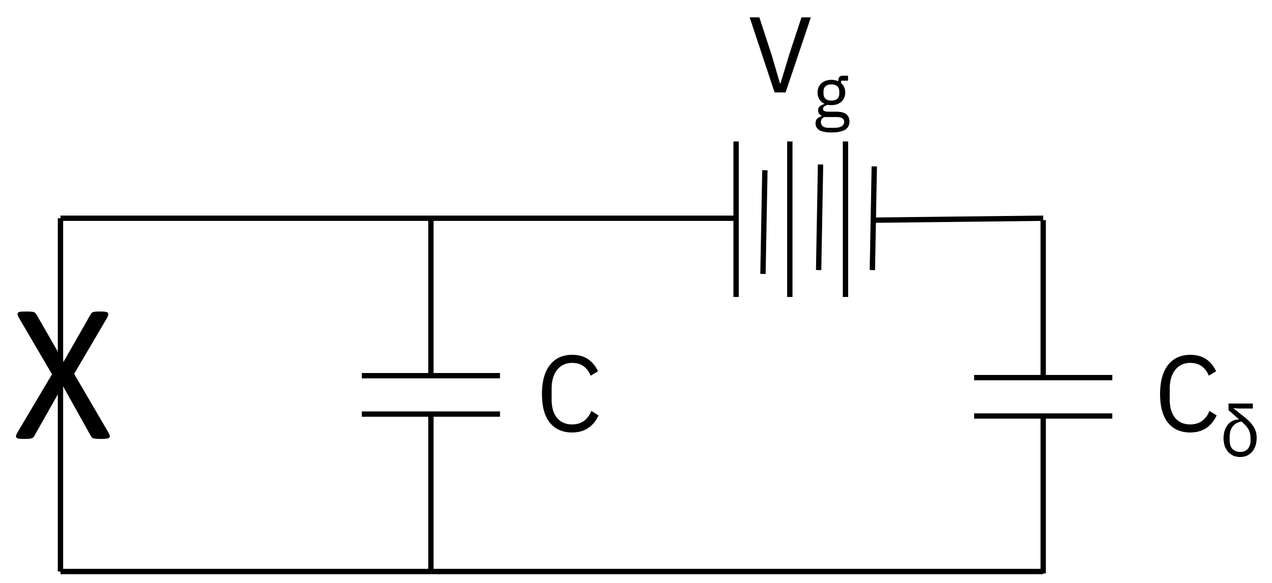




Dane et al., npj Quant. Info, 2026

Quantum non-linear circuits: Josephson junction

$$\hat{H} = \frac{1}{2C}\left(\hat{Q} - V_g C_\delta\right)^2 - E_j \cos(\hat{\Phi}/\varphi_0)$$



$$E_C = \frac{e^2}{2C} \quad n_g = \frac{V_g C_\delta}{4e^2}$$

n = number of Cooper pairs

$$\hat{H} = 4E_c\left(\hat{n} - n_g\right)^2 - E_j \cos(\hat{\Phi}/\varphi_0)$$

$$e^{-ip\hat{\Phi}}|n\rangle = |n+p\rangle$$

(*n* and ϕ are conujugate variables)

Charge qubit: The cooper pair box

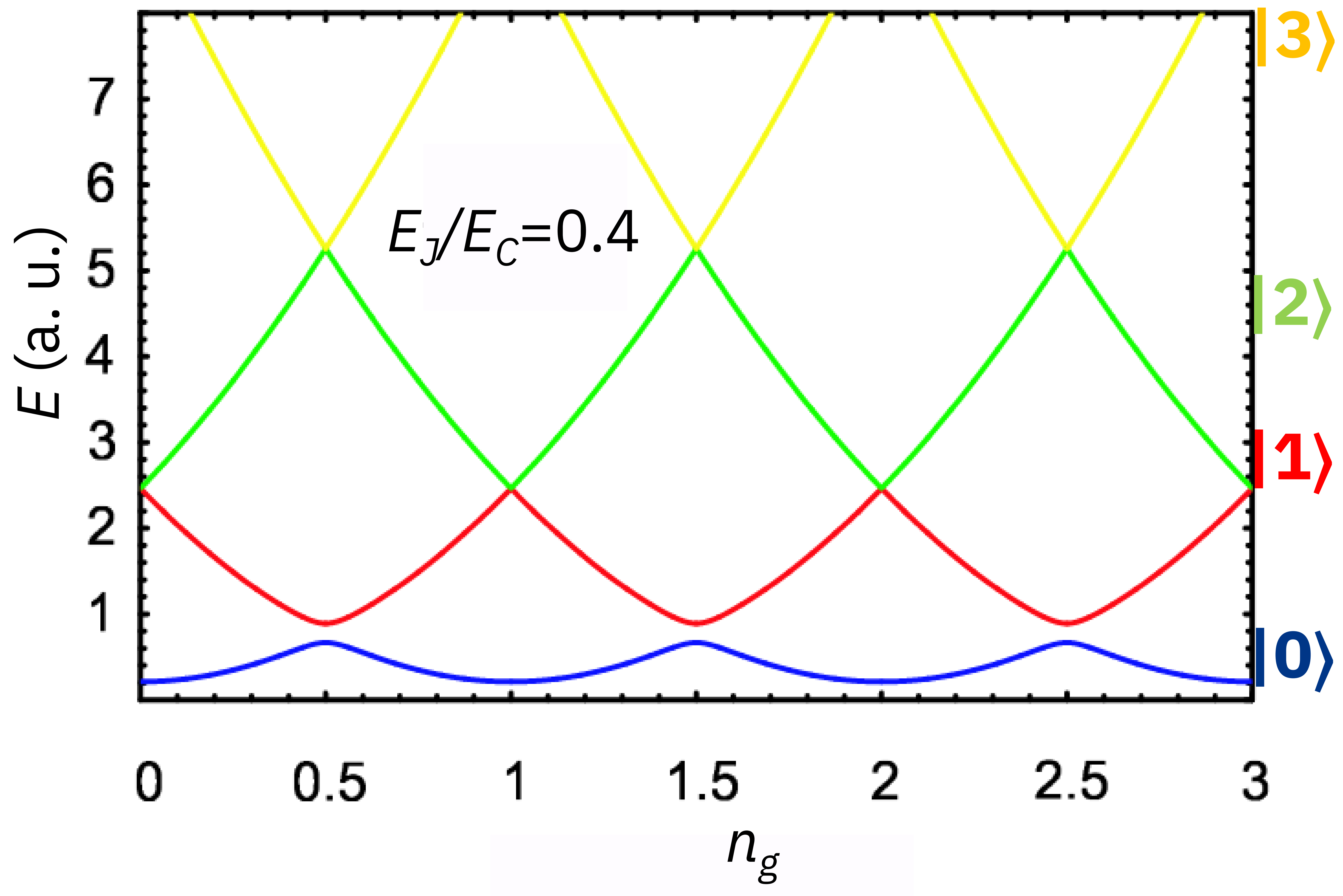
$$\hat{H} = 4E_C(\hat{n} - n_g)^2 - E_J \cos(\hat{\Phi})$$

Define charge basis $$\hat{n}|n\rangle = n|n\rangle$$

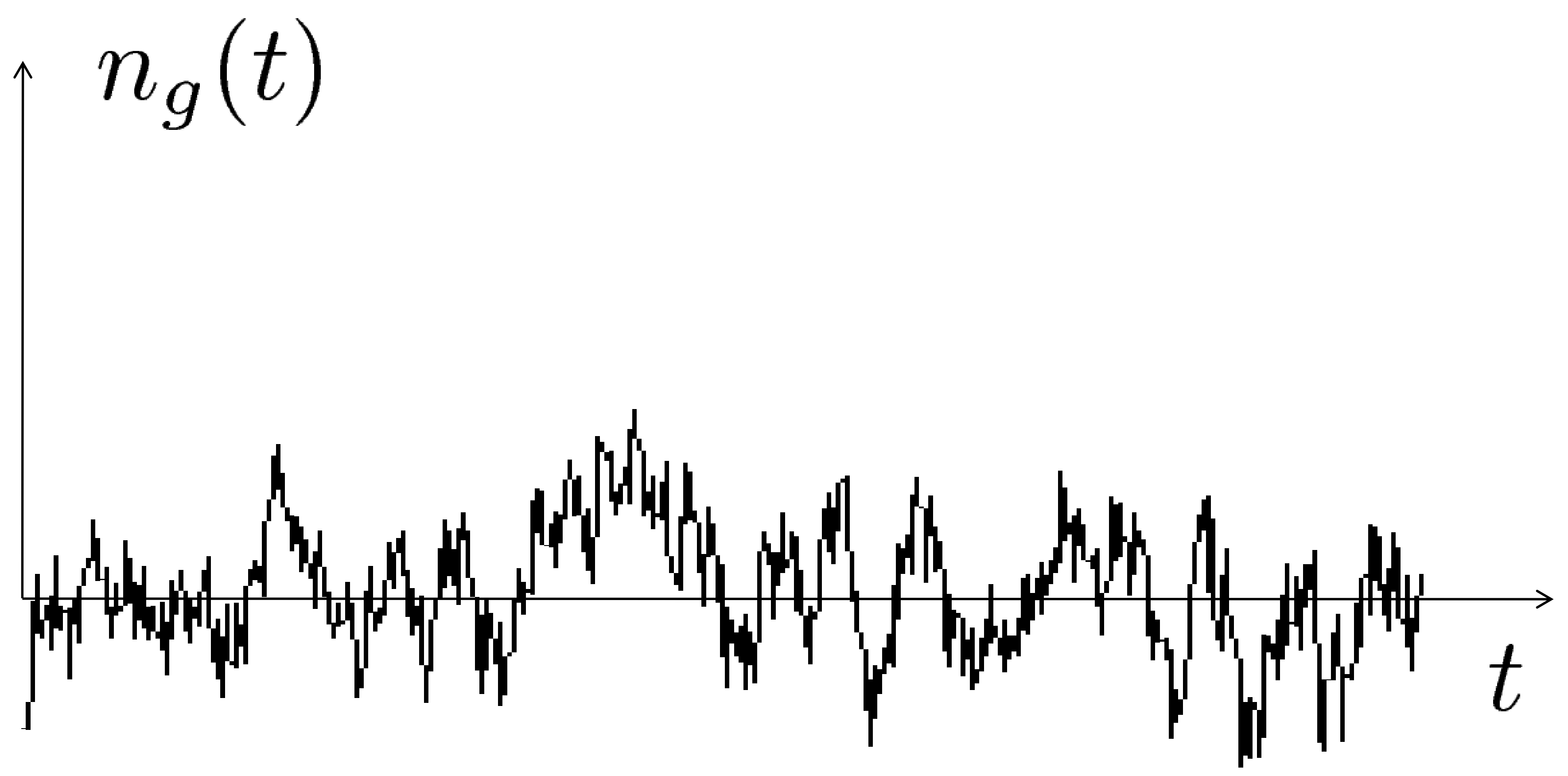
Conjugate variables $$e^{-ip\hat{\Phi}}|n\rangle = |n+p\rangle$$

$$\hat{H} = \sum_n 4E_C(n - n_g)^2|n\rangle\langle n| - \frac{E_J}{2}(|n+1\rangle\langle n| + |n\rangle\langle n+1|)$$

Charge qubit: The cooper pair box



Charge fluctuations



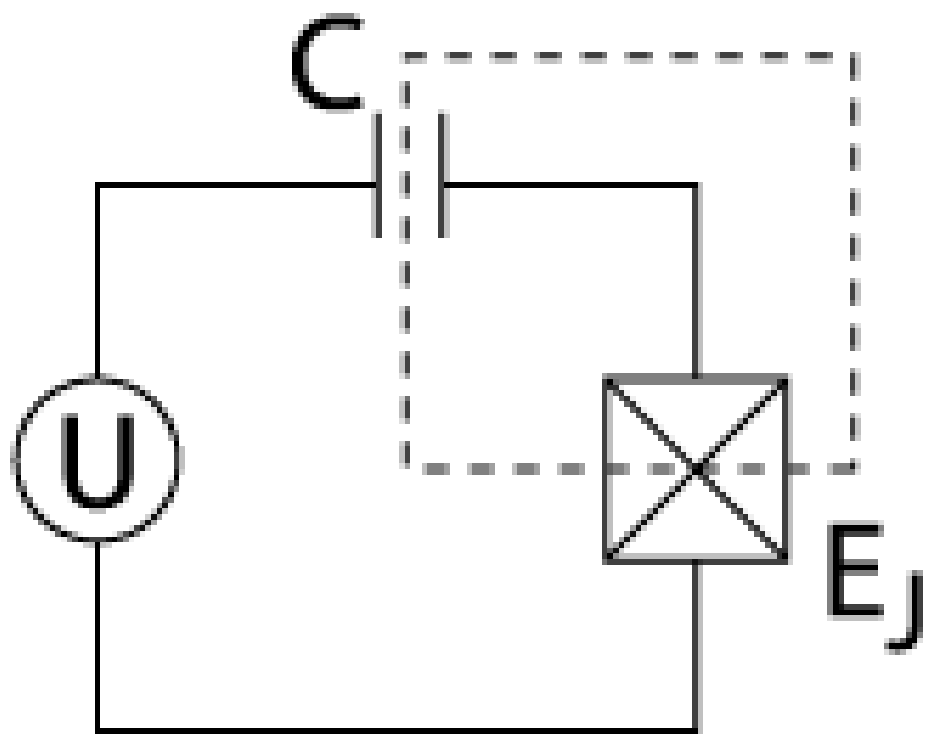
First experiment in 1999: T_2 ~ 1 ns
Sweet spot operation in 2002
T_2 ~ 500 ns   Nakamura, Nature 1999

$$\hat{H} = \sum_n 4E_C(n - n_g)^2 |n\rangle\langle n| - \frac{E_J}{2}\left(|n+1\rangle\langle n| + |n\rangle\langle n+1|\right)$$

The tale of two energies

J. Koch et al, Phys. Rev. A 76, 042319 (2007)
L. Bishop. PhD Thesis

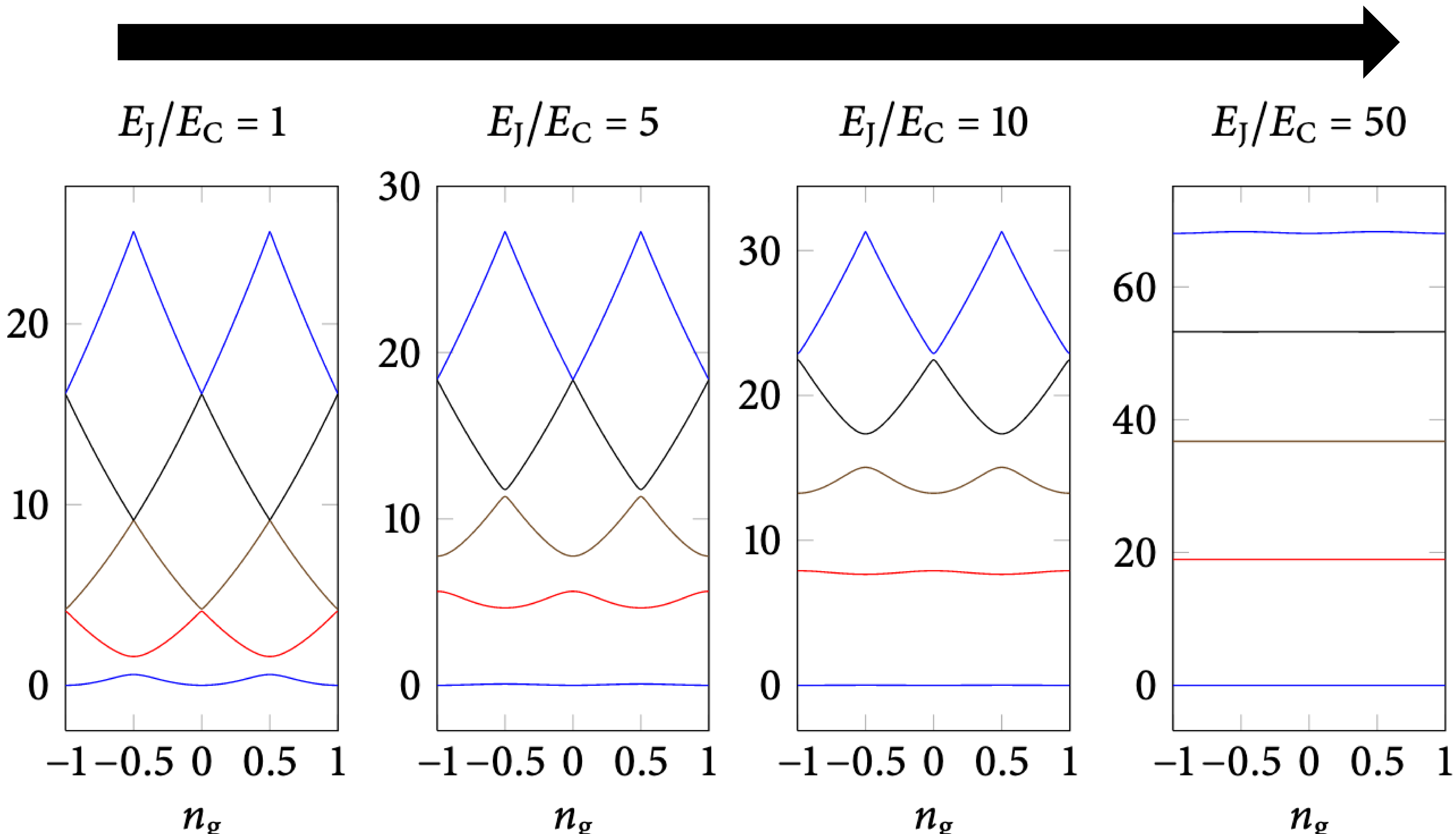
IBM **Quantum**

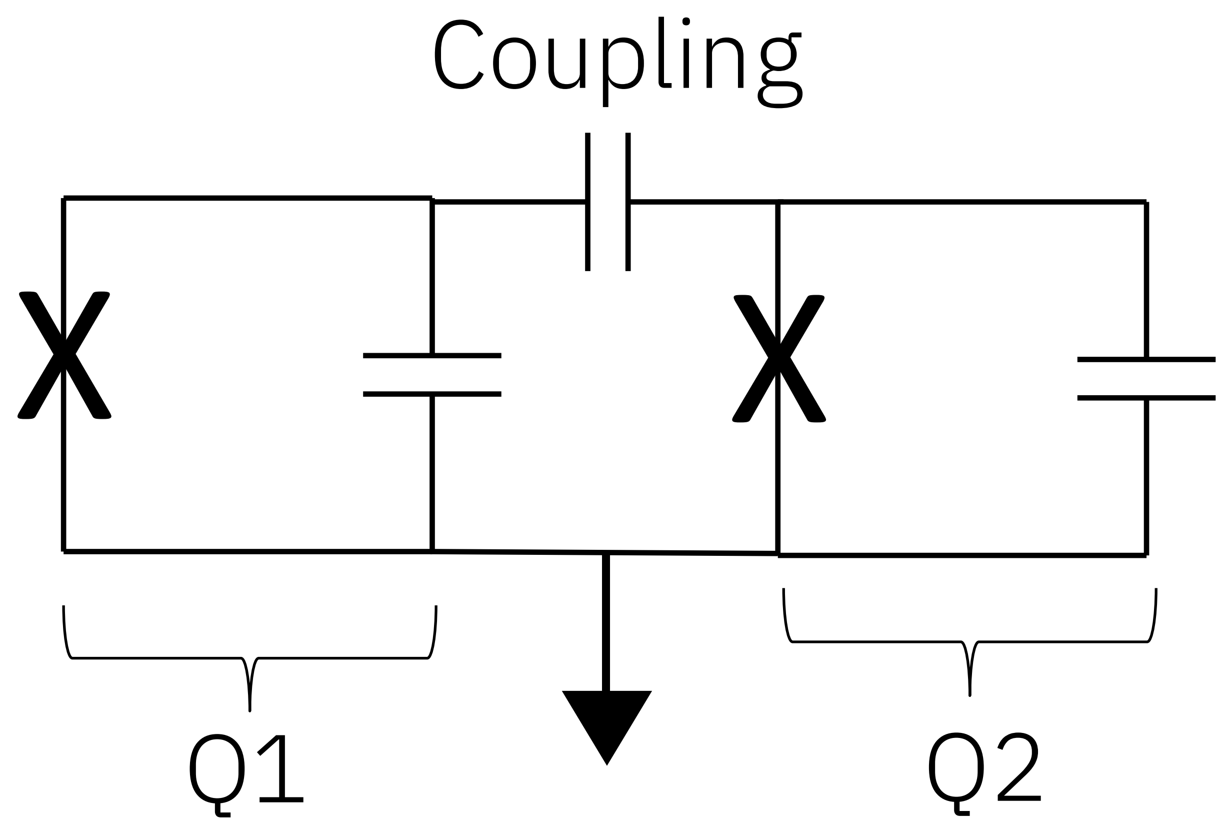


$$E_J = \frac{I_c \Phi_0}{2\pi}$$

$$E_C = \frac{e^2}{2C}$$

Charge dispersion suppressed faster than anharmonicity





Introduction to Quantum Electromagnetic Circuits

Uri Vool* and Michel Devoret†

Department of Applied Physics,
Yale University, New Haven, CT 06520

arXiv:1610.03438v2

This is how to write these Hamiltonians down correctly!

$$\hat{H} = \underbrace{\hbar\omega_1 \hat{a}^\dagger \hat{a} - \frac{\alpha_1}{2}\left(\left(\hat{a}^\dagger \hat{a}\right)^2 - \hat{a}^\dagger \hat{a}\right)}_{H_{Q1}} + \underbrace{\hbar\omega_2 \hat{b}^\dagger \hat{b} - \frac{\alpha_2}{2}\left(\left(\hat{b}^\dagger \hat{b}\right)^2 - \hat{b}^\dagger \hat{b}\right)}_{H_{Q2}} + \underbrace{C_c(\hat{Q}_1 \hat{Q}_2)}_{H_{couple}}$$

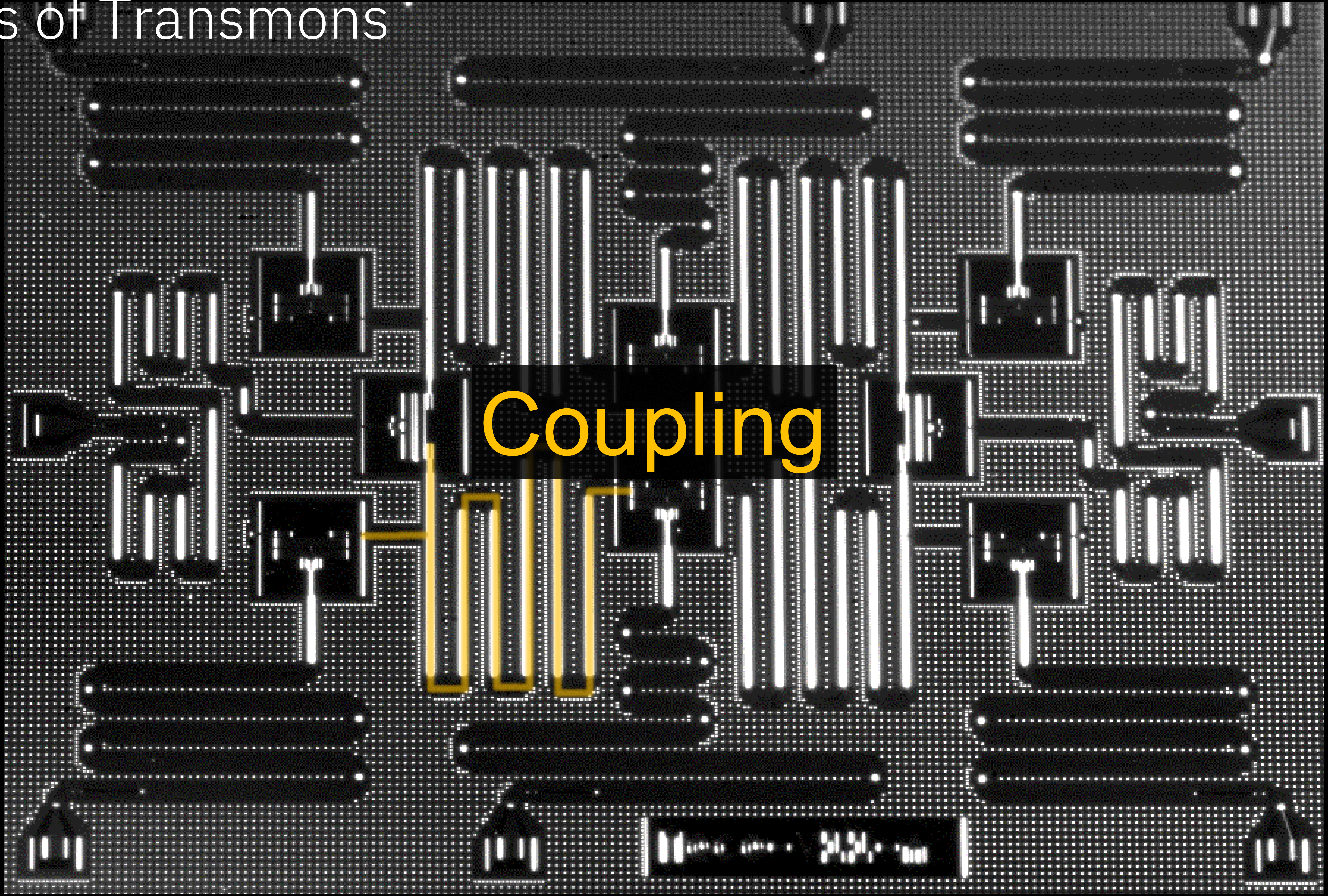
$$H_{couple} = J\left(\hat{a}^\dagger + \hat{a}\right)\left(\hat{b}^\dagger + \hat{b}\right) = J\left(\hat{a}^\dagger \hat{b} + \hat{b}^\dagger \hat{a} + \text{Non-RWA terms}\right)$$

We call this exchange coupling because, in the RWA, it allows excitations to swap between the qubits.

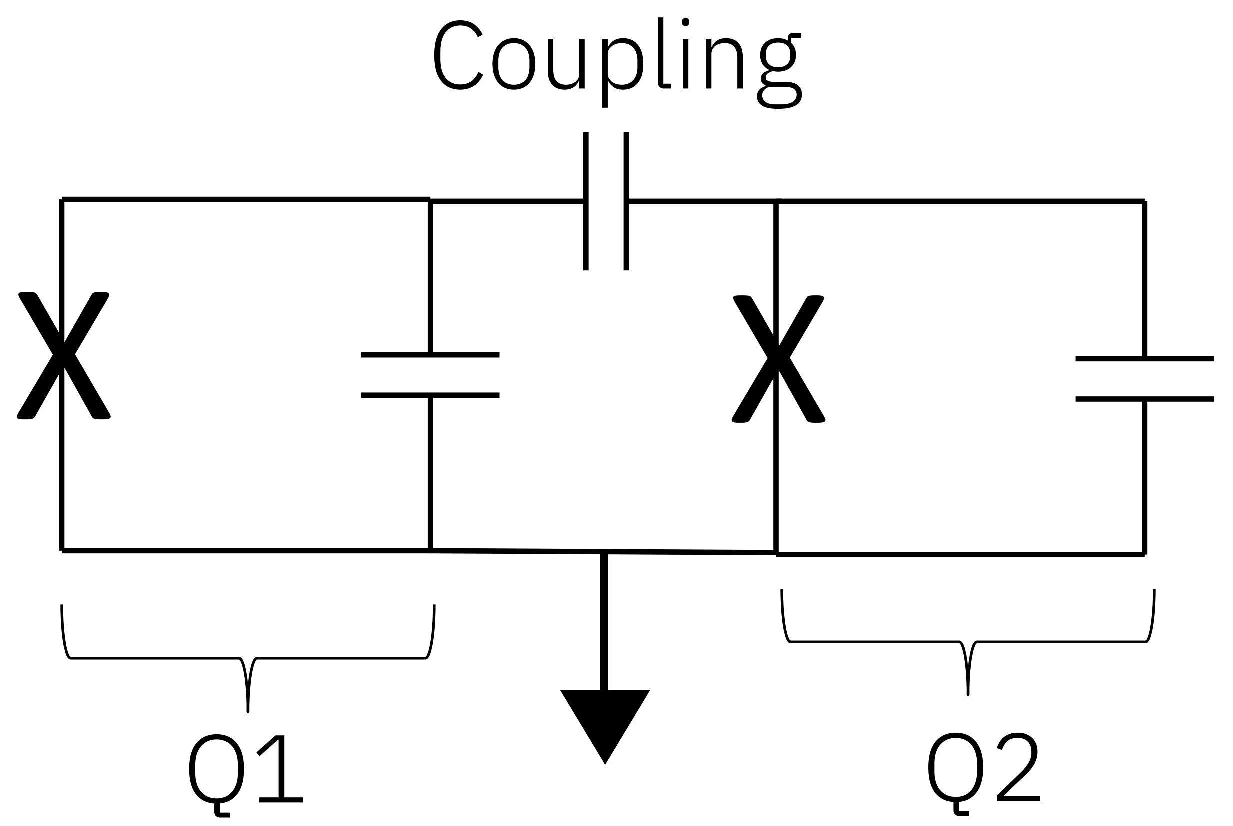
You can also get inductive exchange couplings, if, unlike this circuit, you have inductances.

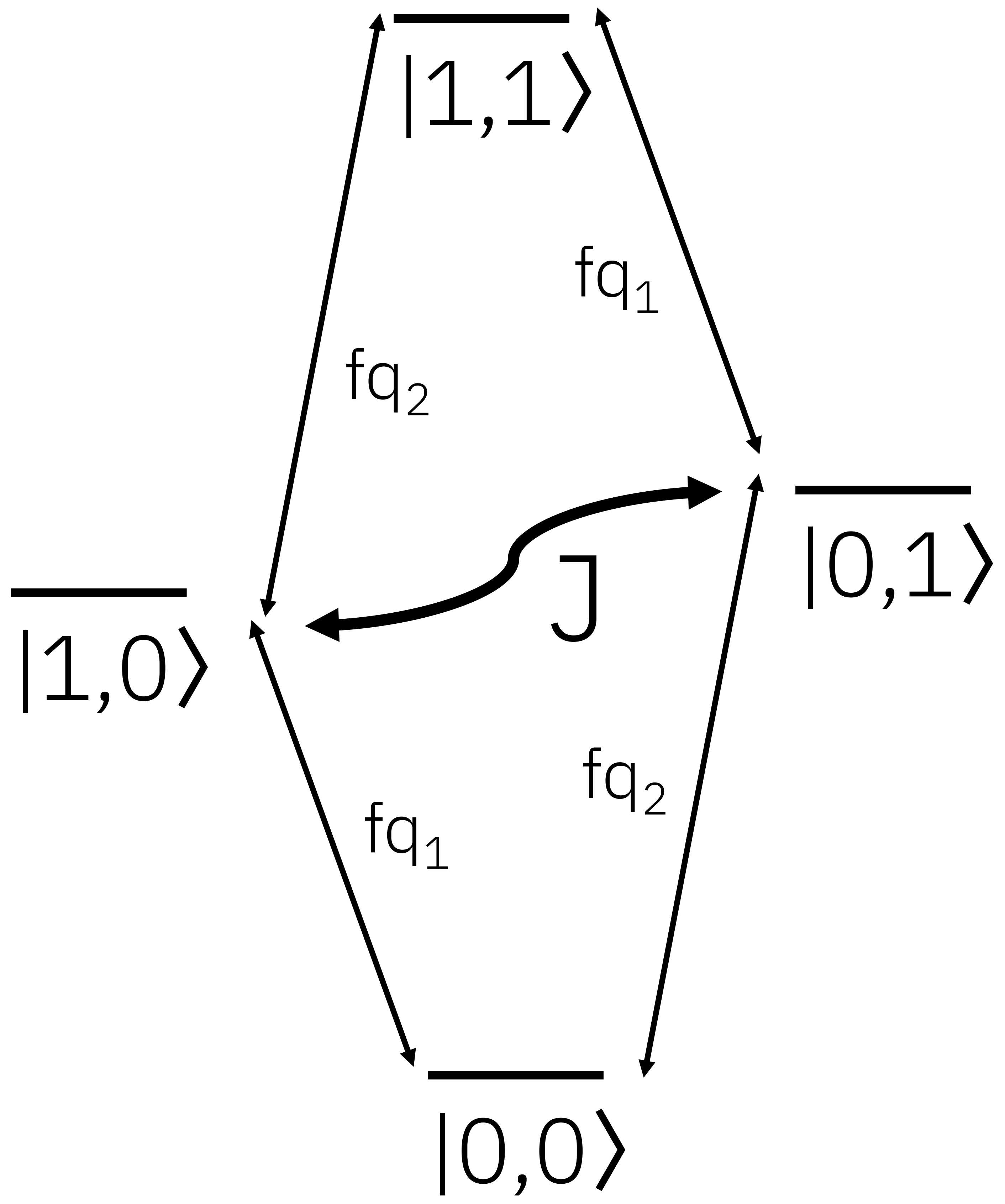
α is the anharmonicity of the qubits; in the large E_j/E_c limit it is given by E_c

Circuits of Transmons



Two qubit gates: idle ZZ





$$H_{couple} = J\left(\hat{a}^{\dagger}\hat{b} + \hat{b}^{\dagger}\hat{a} + \text{Non-RWA terms}\right)$$

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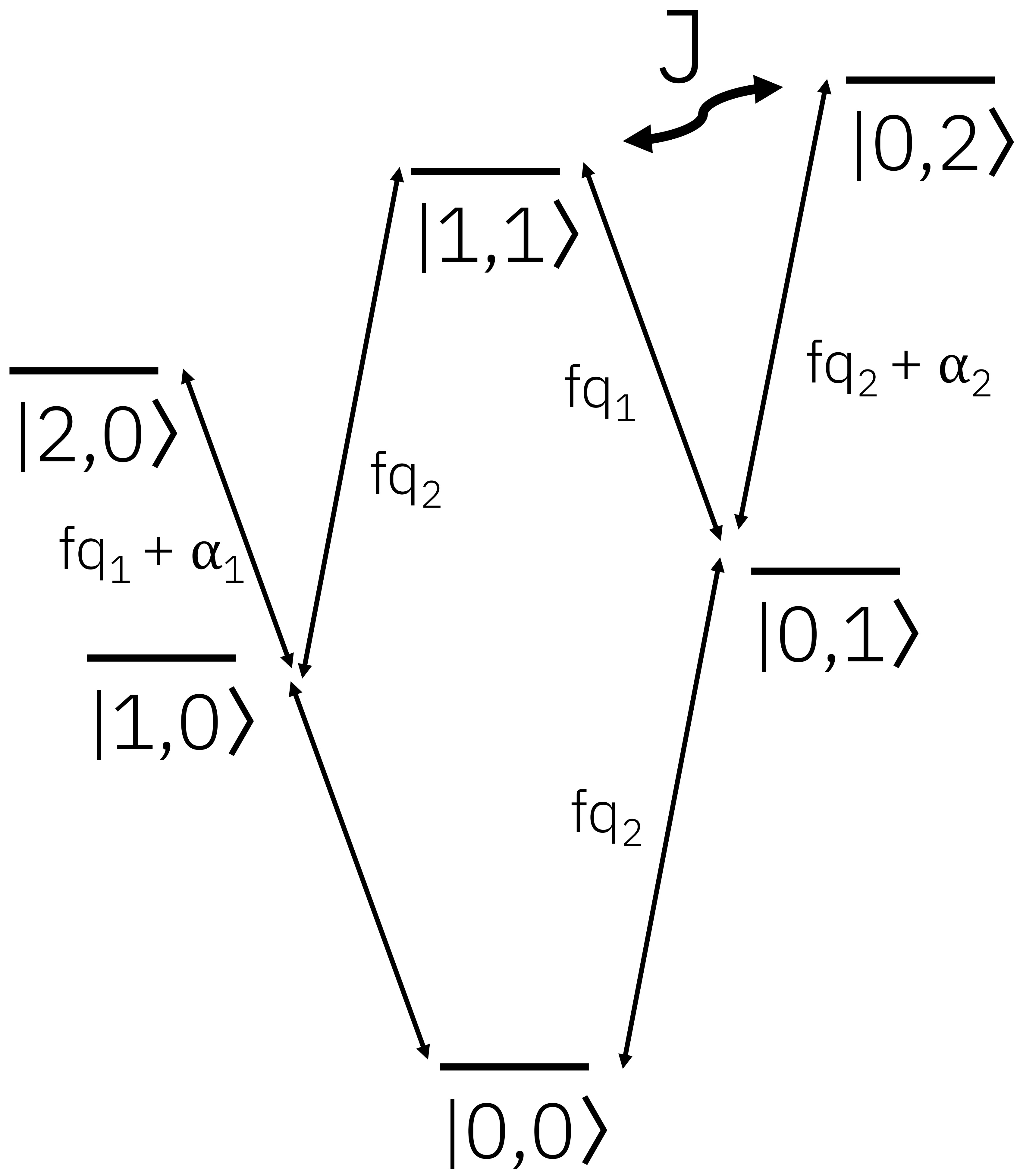

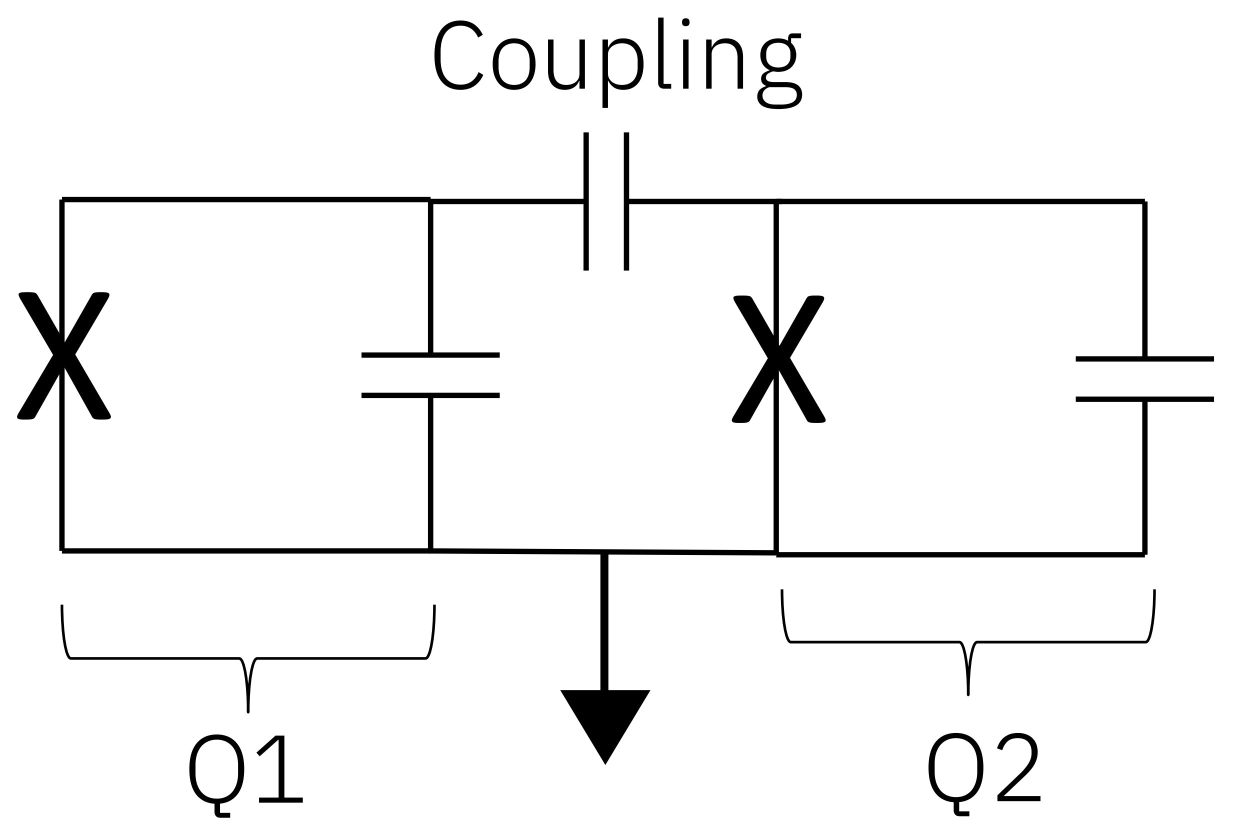

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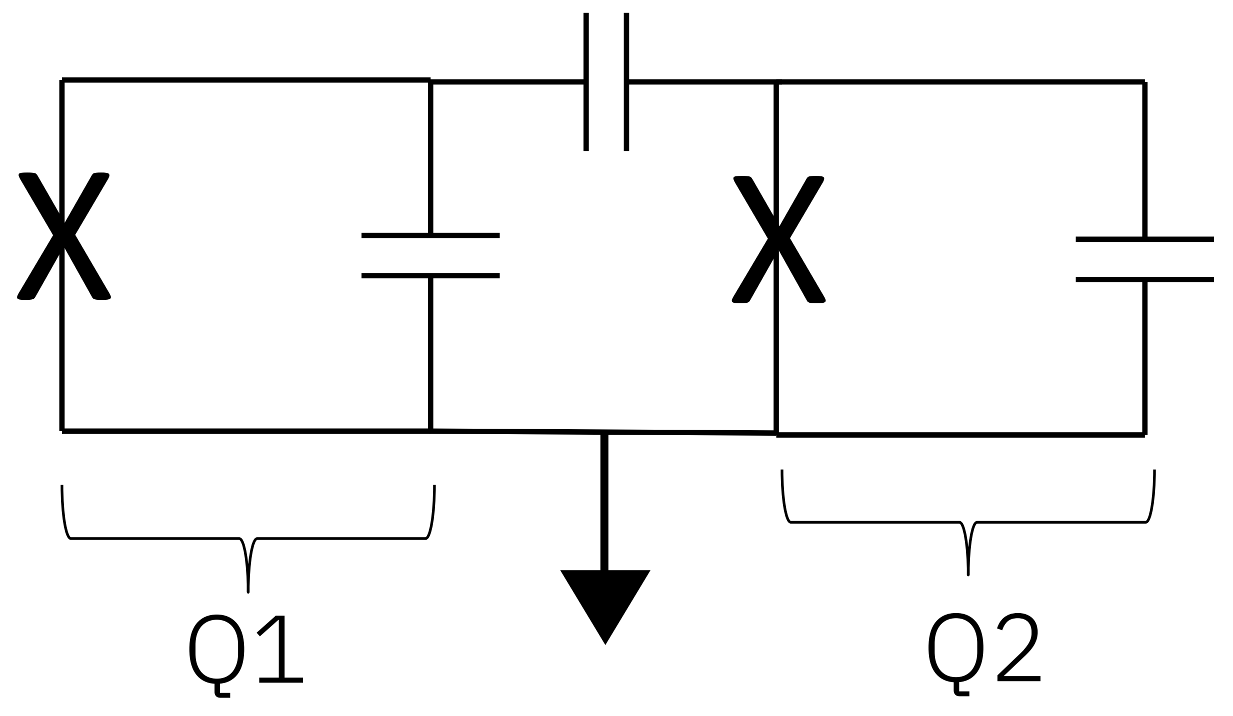
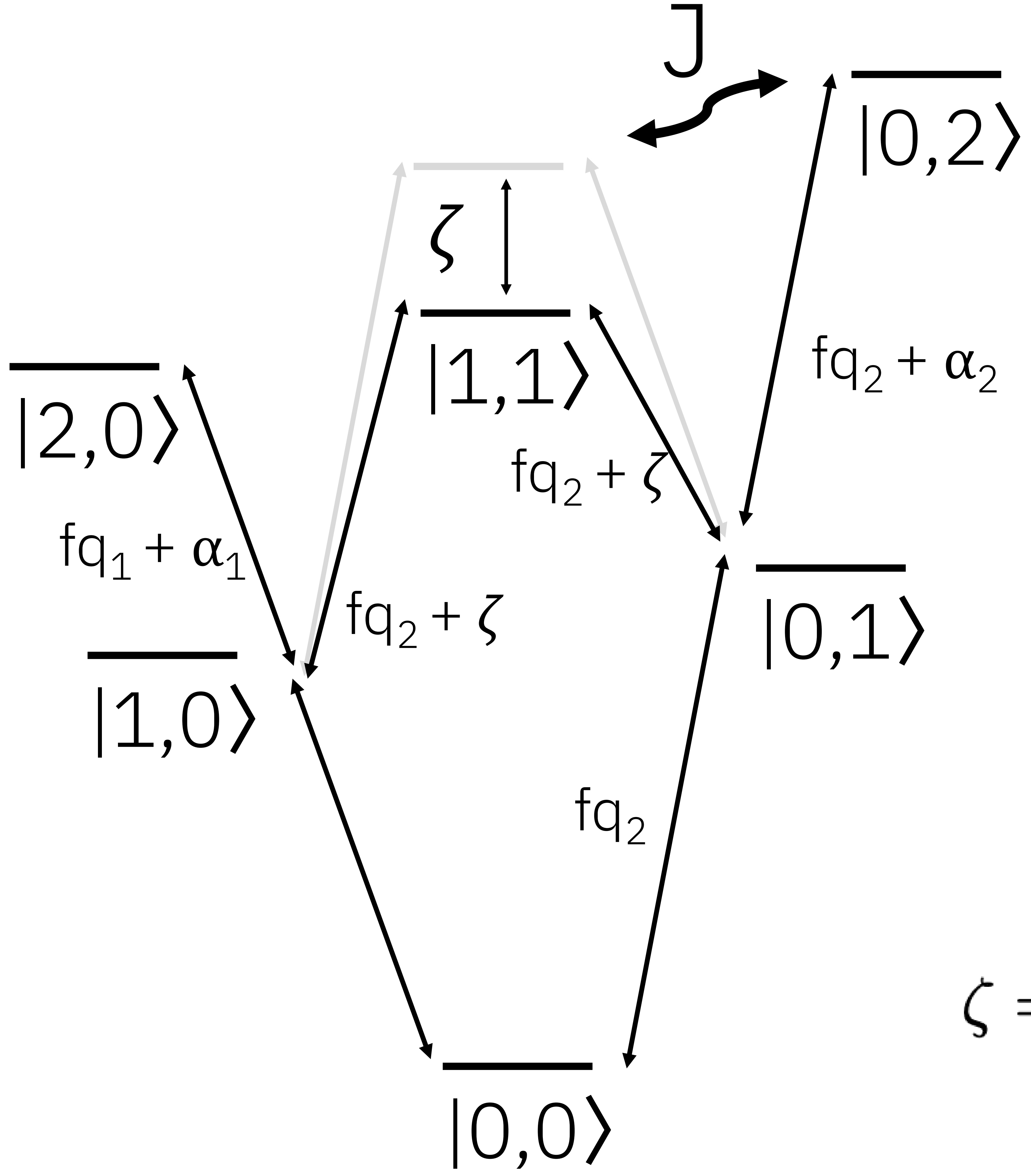
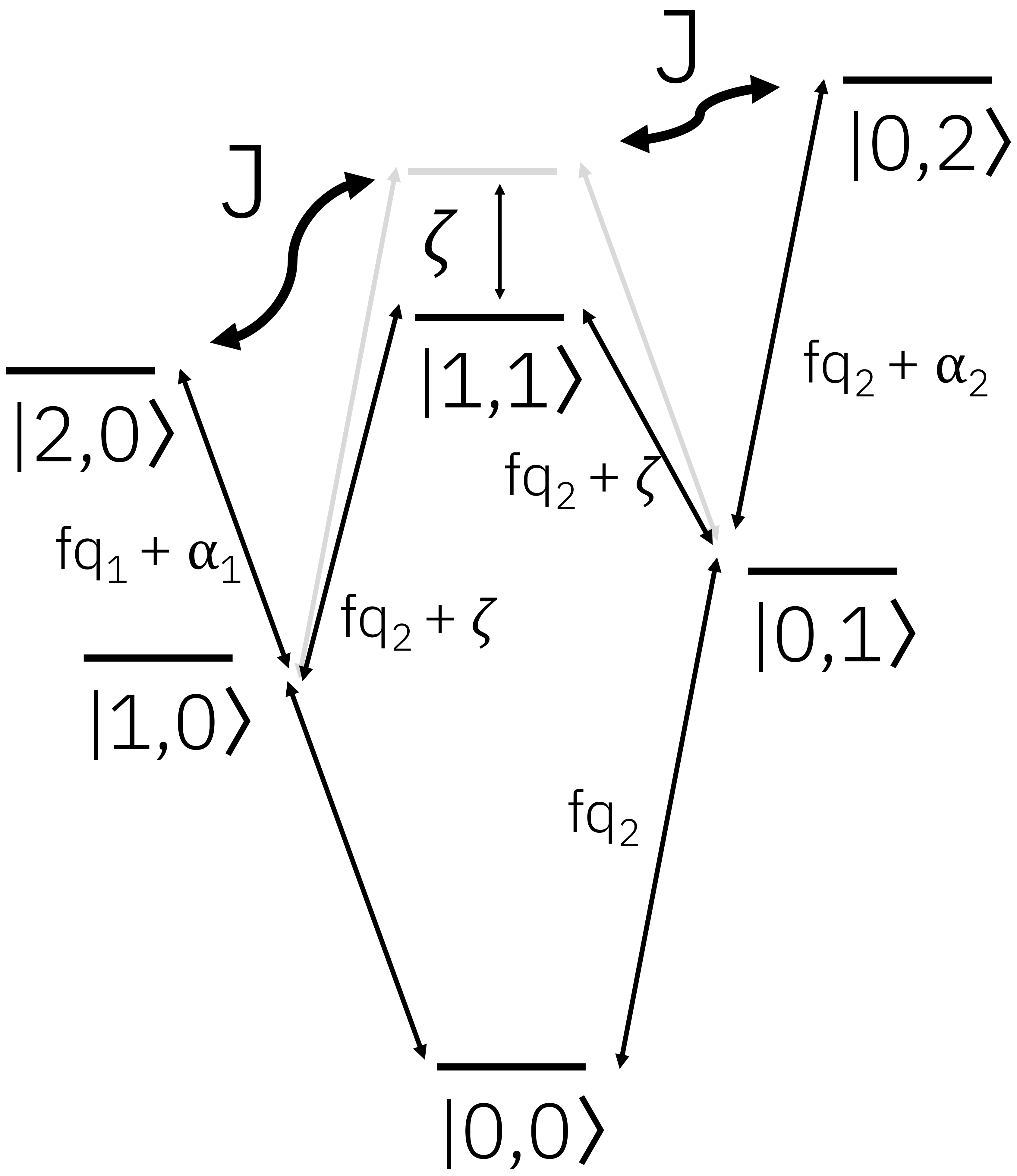


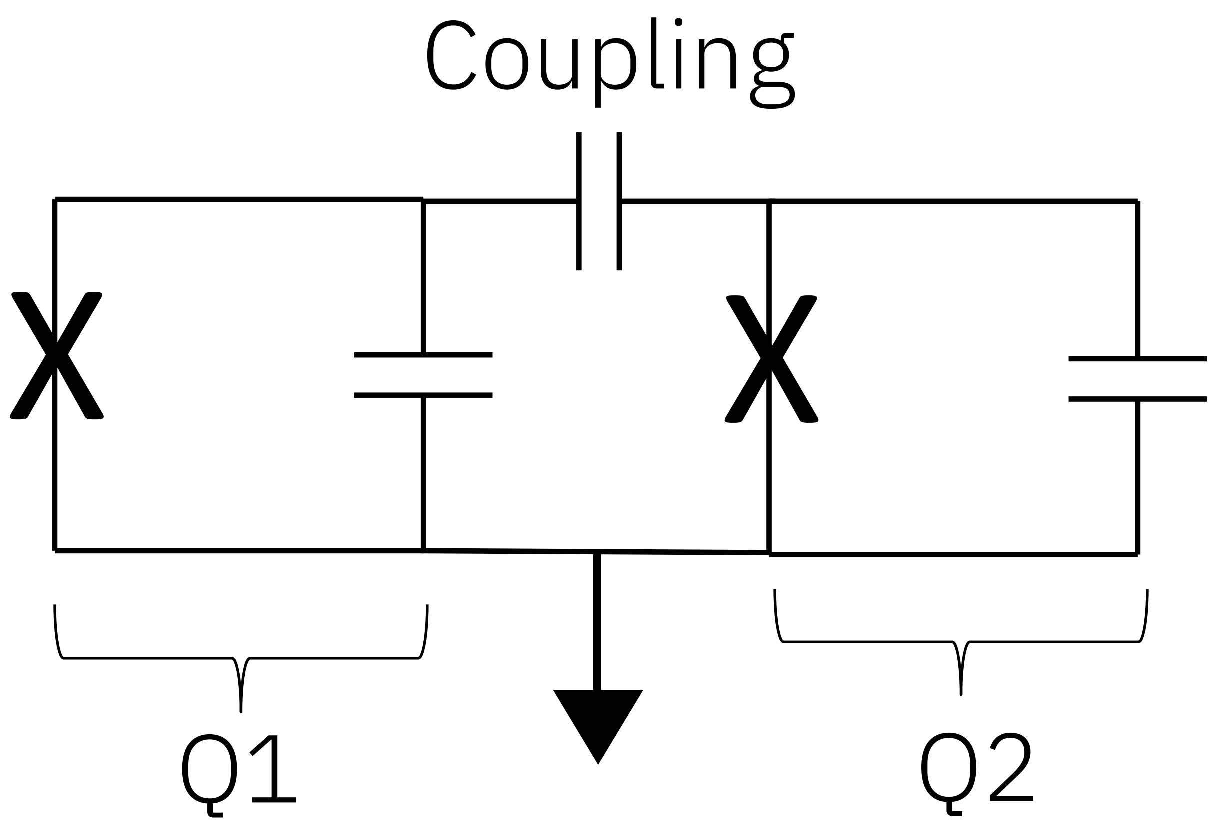


Two qubit gates: idle ZZ

$$\zeta = \frac{|\langle 0,2|H_{couple}|1,1\rangle|^2}{E_{11} - E_{02}} = \frac{J^2}{\omega_1 + \omega_2 - 2\omega_2 - E_{c,b}} \equiv \frac{J^2}{\Delta_{12} - \alpha_2}$$

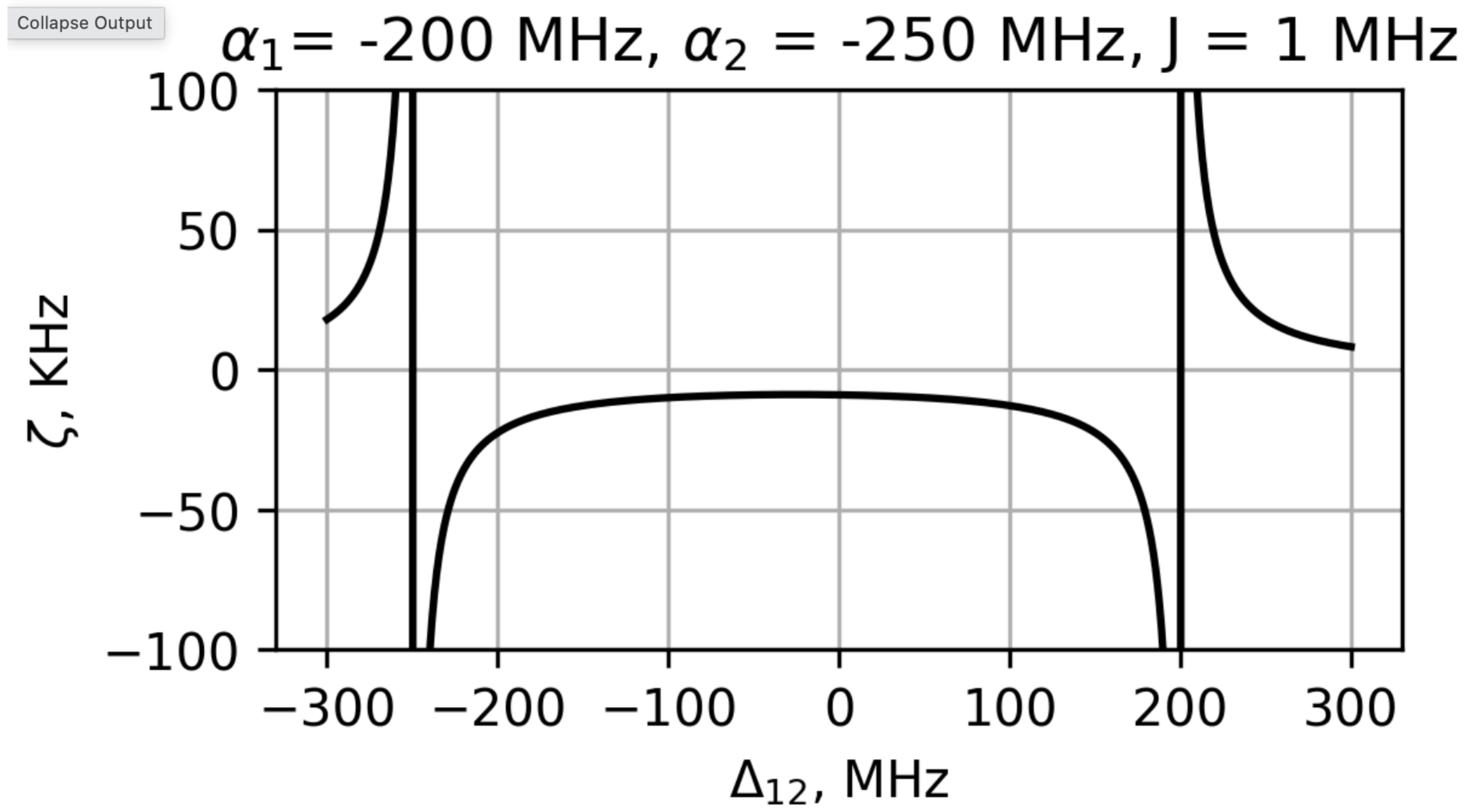
Two qubit gates: idle ZZ





$$\zeta = \frac{J^2}{\Delta_{12} - \alpha_2} + \frac{J^2}{-\Delta_{12} - \alpha_1} = \frac{J^2\left(\alpha_1 + \alpha_2\right)}{\left(\alpha_2 - \Delta_{12}\right)\left(\alpha_1 + \Delta_{12}\right)}$$

Two qubit gates: idle ZZ



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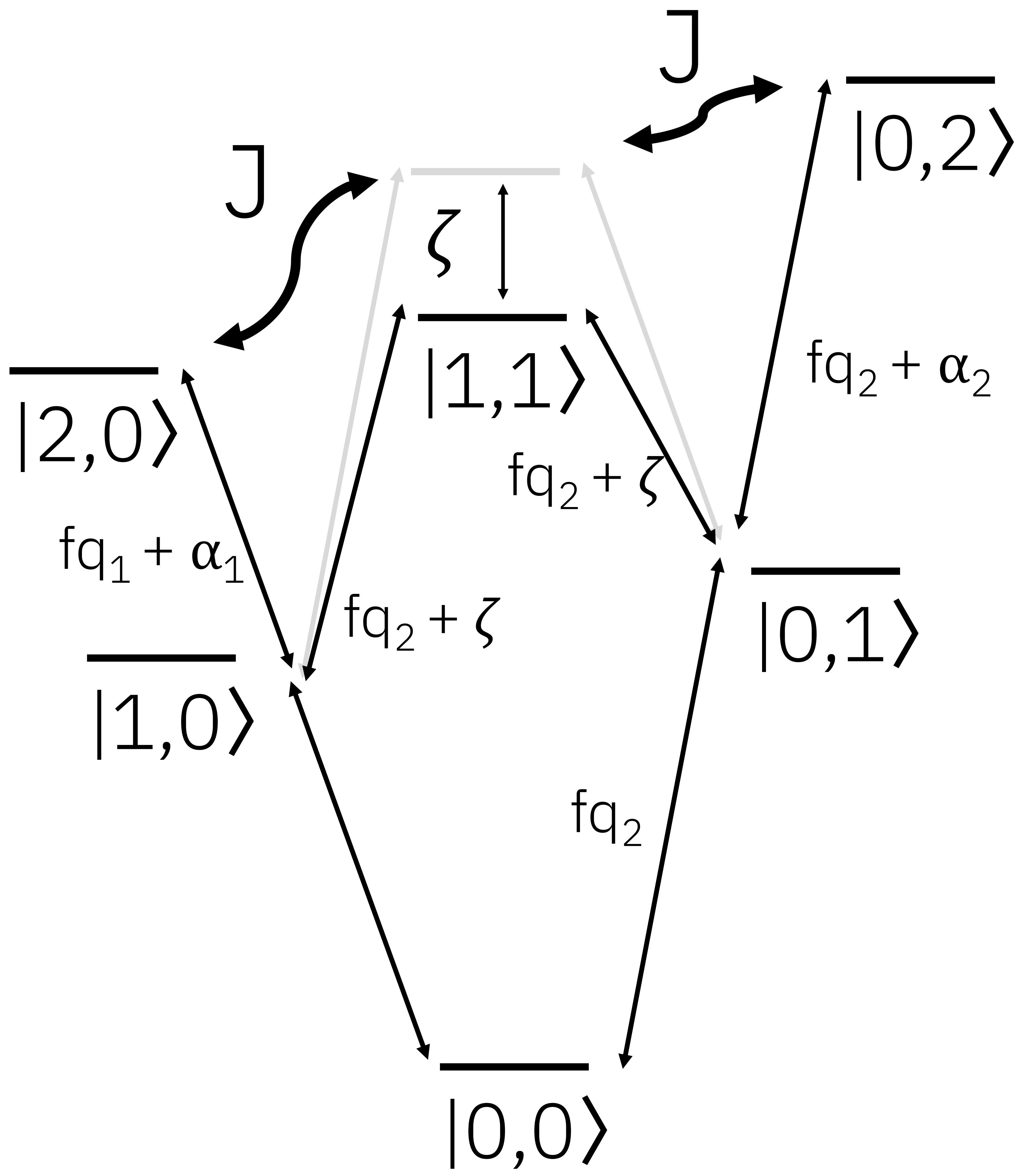
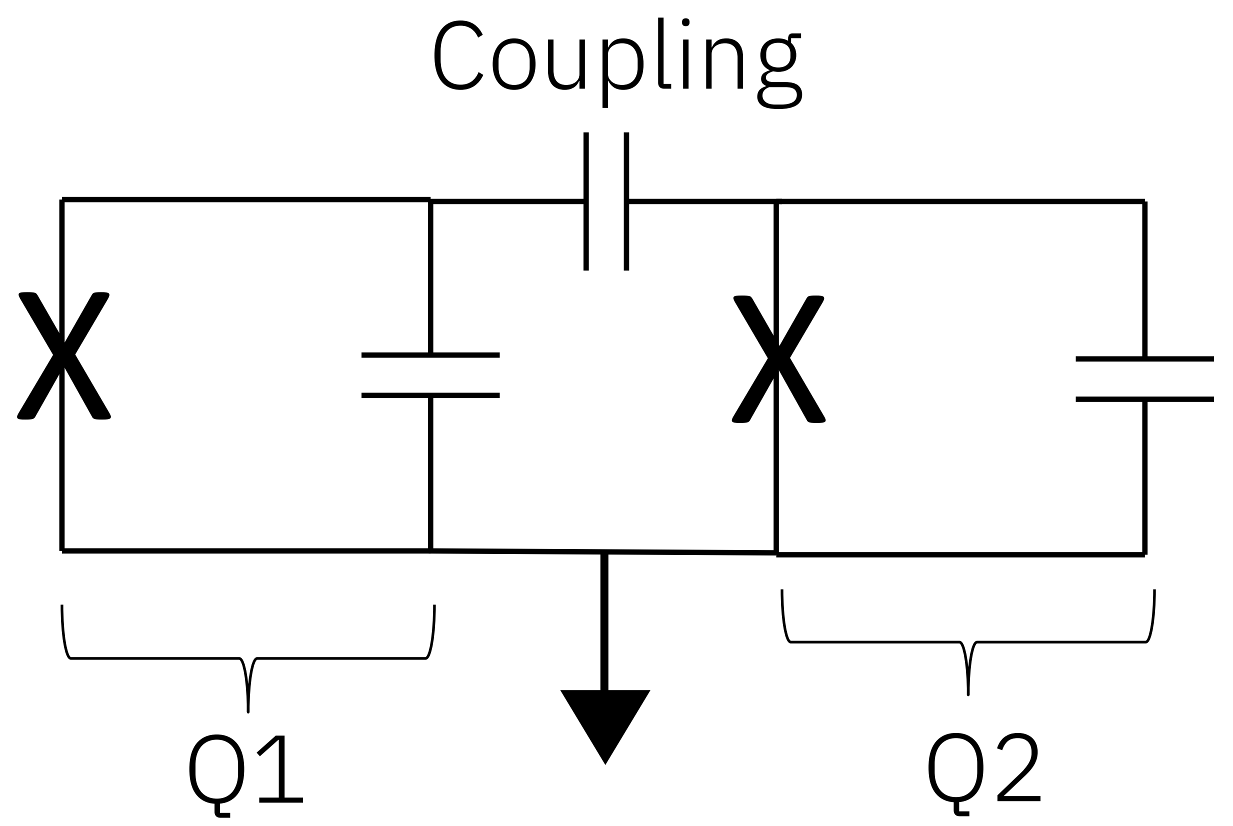




$$H = (\omega_1 - \zeta/2)\left[\hat{\sigma}_z \otimes \hat{I}\right] + (\omega_2 - \zeta/2)\left[\hat{I} \otimes \hat{\sigma_z}\right] + \frac{\zeta}{2}\left[\hat{\sigma}_z \otimes \hat{\sigma}_z\right]$$

$$H = \frac{\zeta}{2}\left[\hat{\sigma}_z \otimes \hat{\sigma}_z\right] \text{ co-rotating frame}$$

Two qubit gates: idle ZZ

$$H = \frac{\zeta}{2}\left[\hat{\sigma}_z \otimes \hat{\sigma}_z\right] \text{ co-rotating frame}$$

Recall: single qubit Z rotations

$$e^{-iHt} = \begin{bmatrix} e^{-i\zeta t/2} & 0 & 0 & 0 \\ 0 & e^{i\zeta t/2} & 0 & 0 \\ 0 & 0 & e^{i\zeta t/2} & 0 \\ 0 & 0 & 0 & e^{-i\zeta t/2} \end{bmatrix}$$

$$Z(\phi) \otimes I = \begin{bmatrix} e^{i\phi/2} & 0 & 0 & 0 \\ 0 & e^{i\phi/2} & 0 & 0 \\ 0 & 0 & e^{-i\phi/2} & 0 \\ 0 & 0 & 0 & e^{-i\phi/2} \end{bmatrix}$$

$$I \otimes Z(\gamma) = \begin{bmatrix} e^{i\gamma/2} & 0 & 0 & 0 \\ 0 & e^{-i\gamma/2} & 0 & 0 \\ 0 & 0 & e^{i\gamma/2} & 0 \\ 0 & 0 & 0 & e^{-i\gamma/2} \end{bmatrix}$$

at $t = \frac{\theta}{2\zeta}$

$$e^{-i\frac{\theta H}{2\zeta}} = \begin{bmatrix} e^{-i\theta/2} & 0 & 0 & 0 \\ 0 & e^{i\theta/2} & 0 & 0 \\ 0 & 0 & e^{i\theta t/2} & 0 \\ 0 & 0 & 0 & e^{-i\theta t/2} \end{bmatrix} \equiv R_{zz}(\theta)$$

This is an entangling gate!

Two qubit gates: idle ZZ

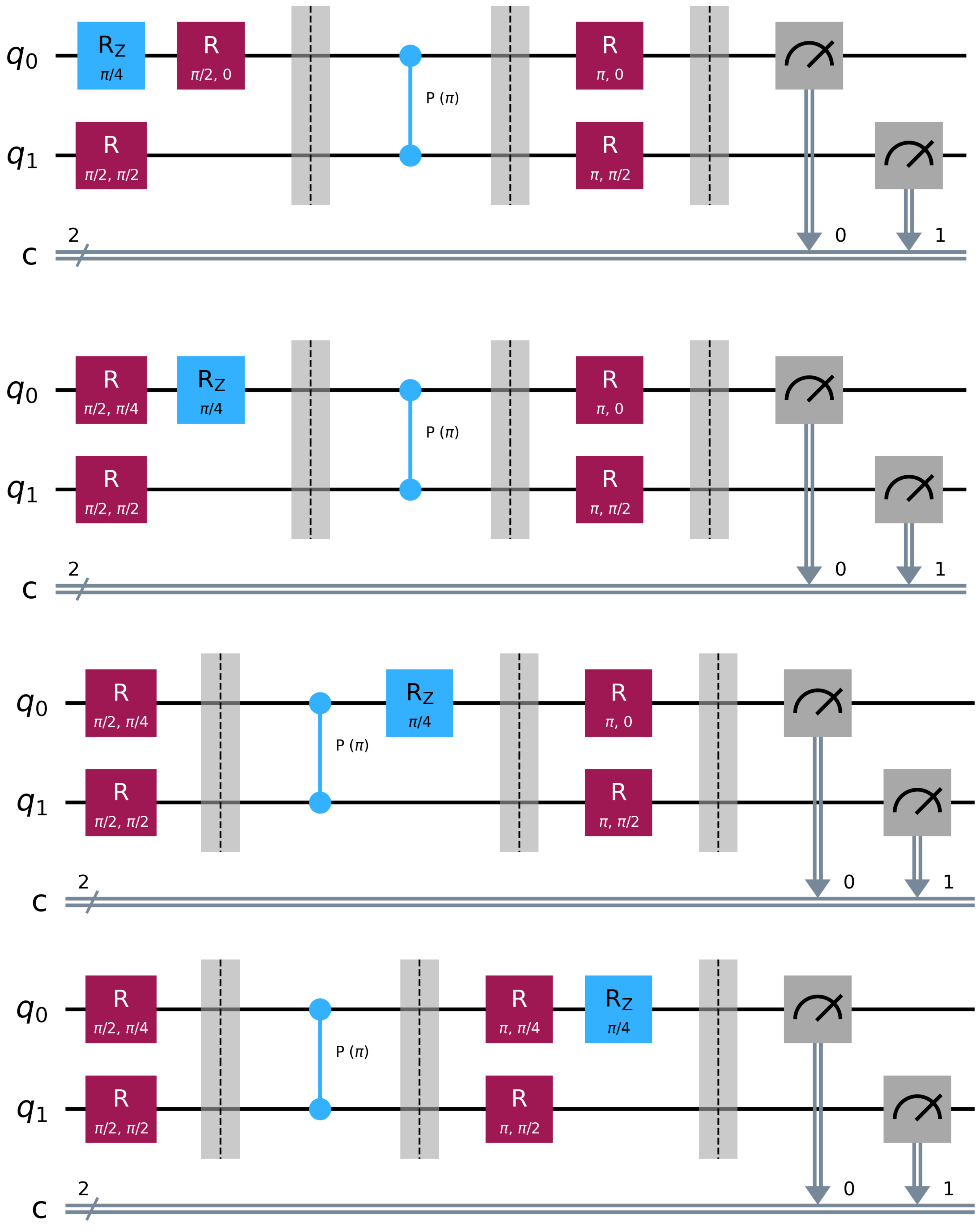
Recall: single qubit Z rotations

$$Z(\phi) \otimes I = \begin{bmatrix} e^{i\phi/2} & 0 & 0 & 0 \\ 0 & e^{i\phi/2} & 0 & 0 \\ 0 & 0 & e^{-i\phi/2} & 0 \\ 0 & 0 & 0 & e^{-i\phi/2} \end{bmatrix} \quad Z(\phi) \otimes I = \begin{bmatrix} e^{i\phi/2} & 0 & 0 & 0 \\ 0 & e^{i\phi/2} & 0 & 0 \\ 0 & 0 & e^{-i\phi/2} & 0 \\ 0 & 0 & 0 & e^{-i\phi/2} \end{bmatrix}$$

$$R_{zz}(\theta)\,[I \otimes Z(\gamma)]\,[Z(\phi) \otimes I] = \mathrm{diag}\left(e^{i(\theta+\phi+\gamma)},\, e^{i(-\theta+\phi-\gamma)},\, e^{i(-\theta-\phi+\gamma)},\, e^{i(\theta-\phi-\gamma)}\right)$$

With a little algebra, for $\theta = -\phi = -\gamma = \frac{\pi}{4}$ this is a CPHASE gate

Virtual z-gates



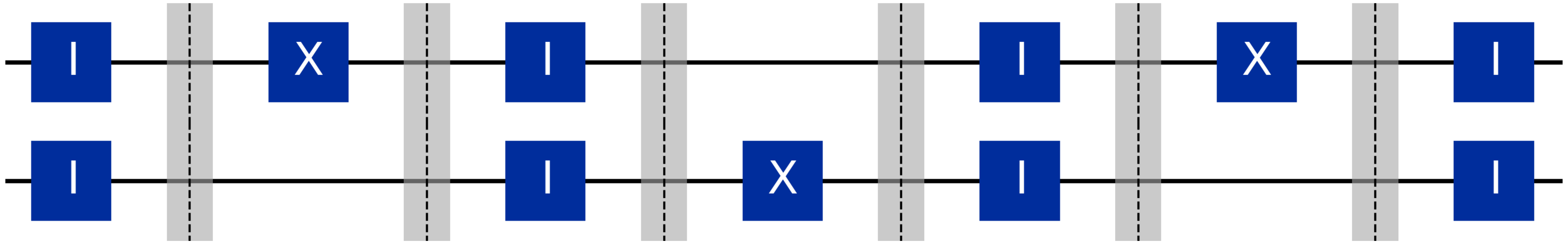
As long as the Z-gates commute with our physical basis gates, or map them to other basis gates ***without spreading to other qubits***, we can apply them virutally just by modfiying remaining gates in the circuit, with ***constant overhead book-keeping***. This true even real-time!

If we had, for example a two-qubit SWAP gate, this would no longer be true.

McKay et al, Phys. Rev. A **96**, 022330 (2017)

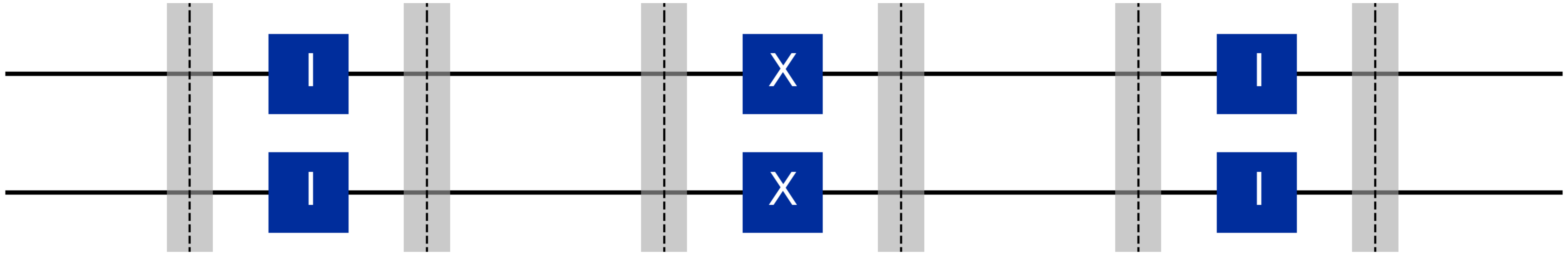
In practice...

Leaves no Z rotations



In principle, if single qubit gates are very fast compared to **ζ**, we can selectively turn on or off this gate with refocusing sequences

Leaves only ZZ interaction



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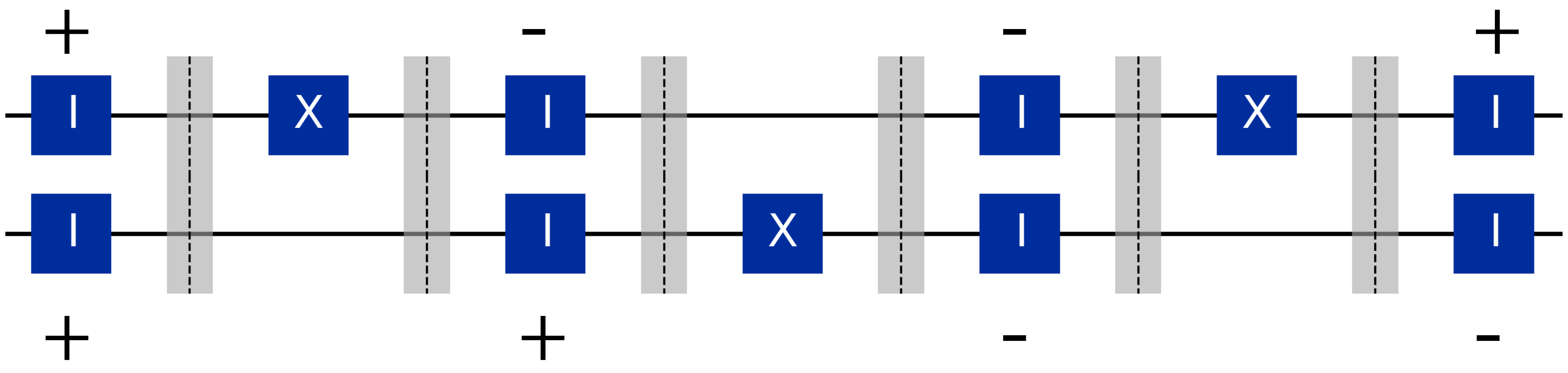

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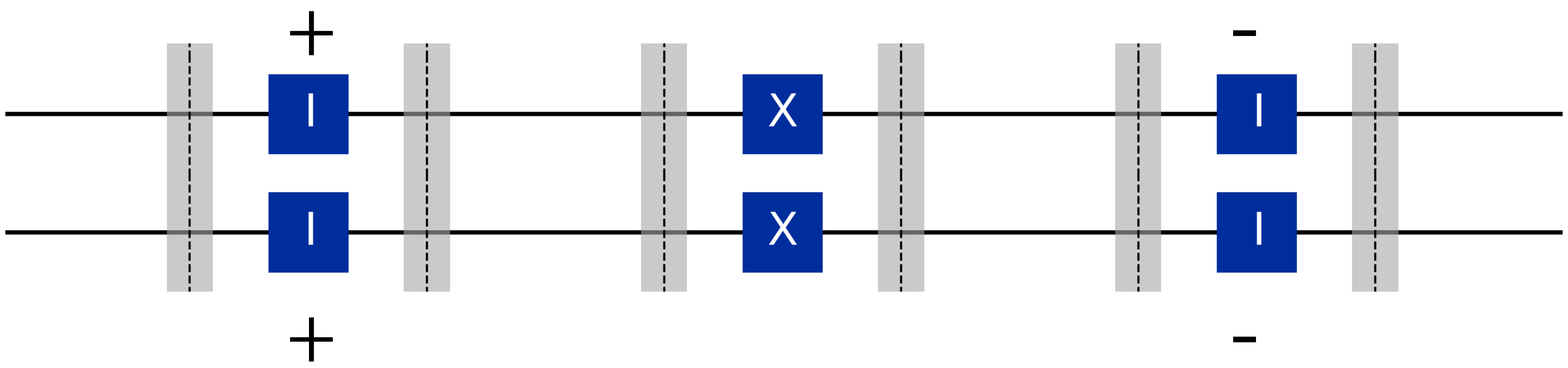

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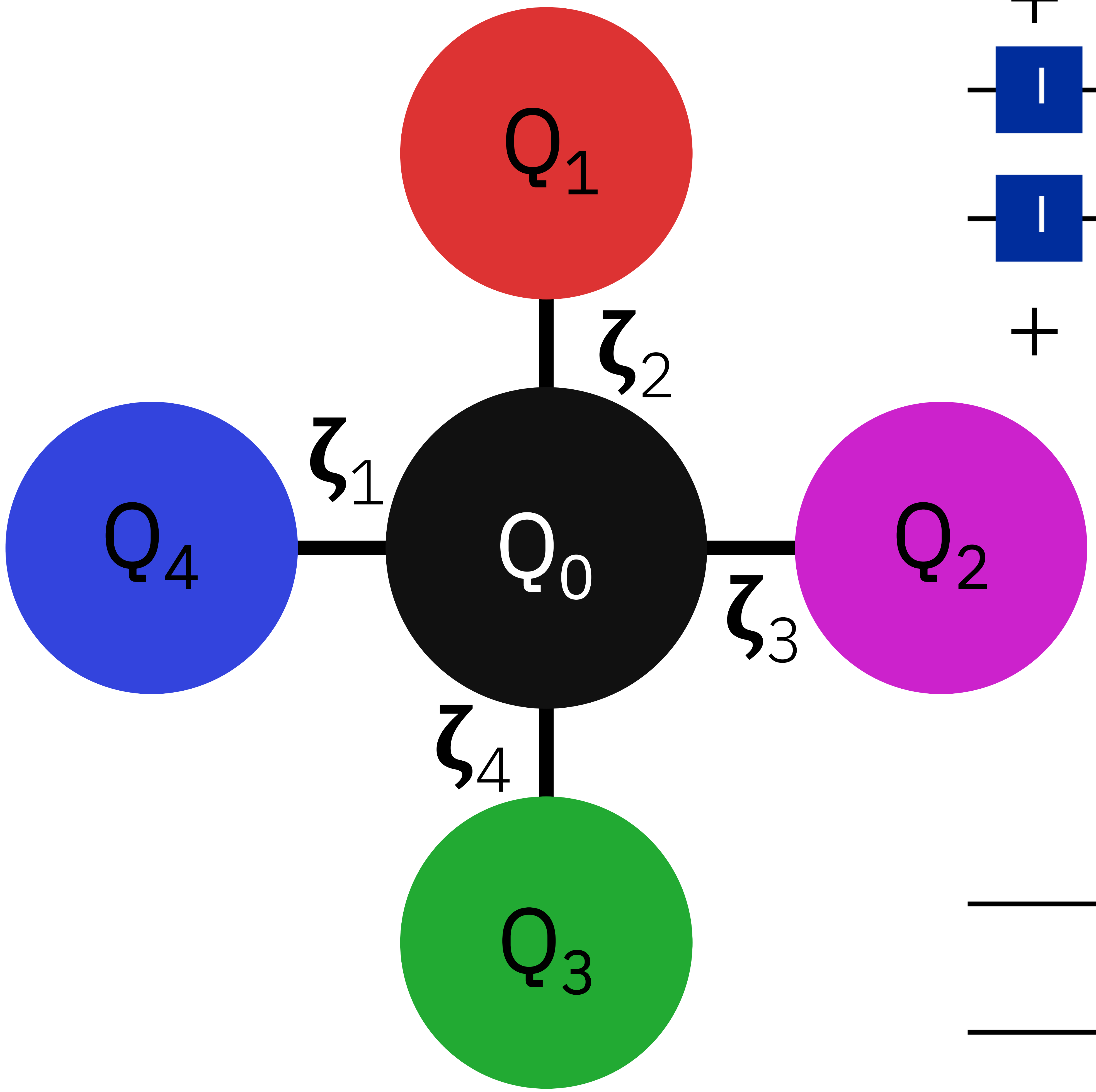

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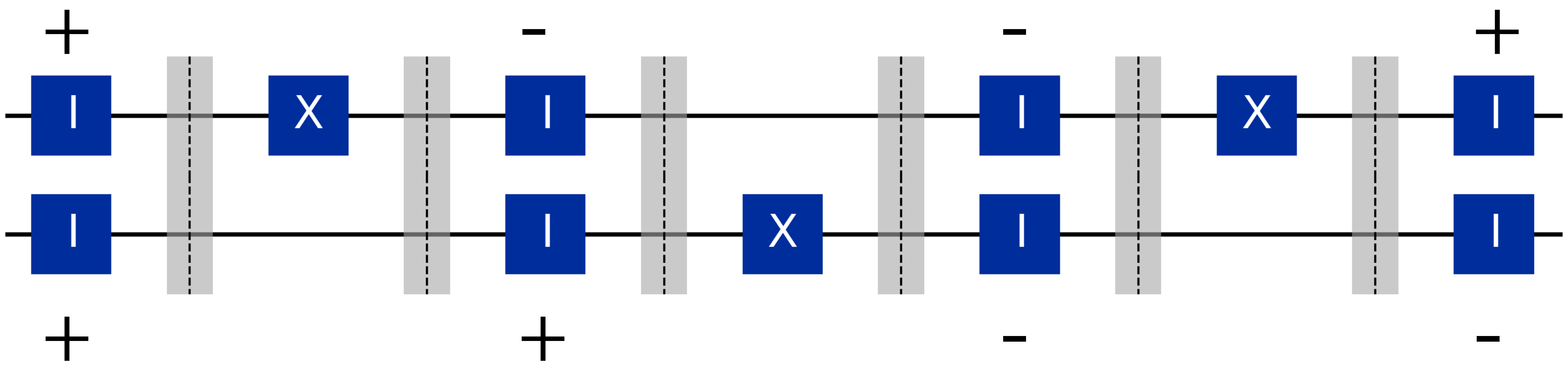

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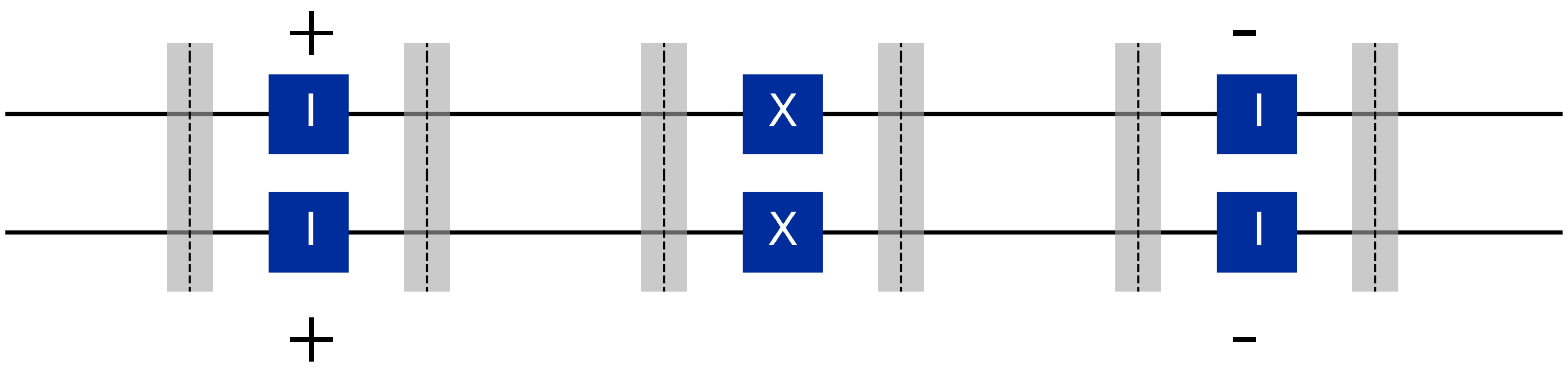
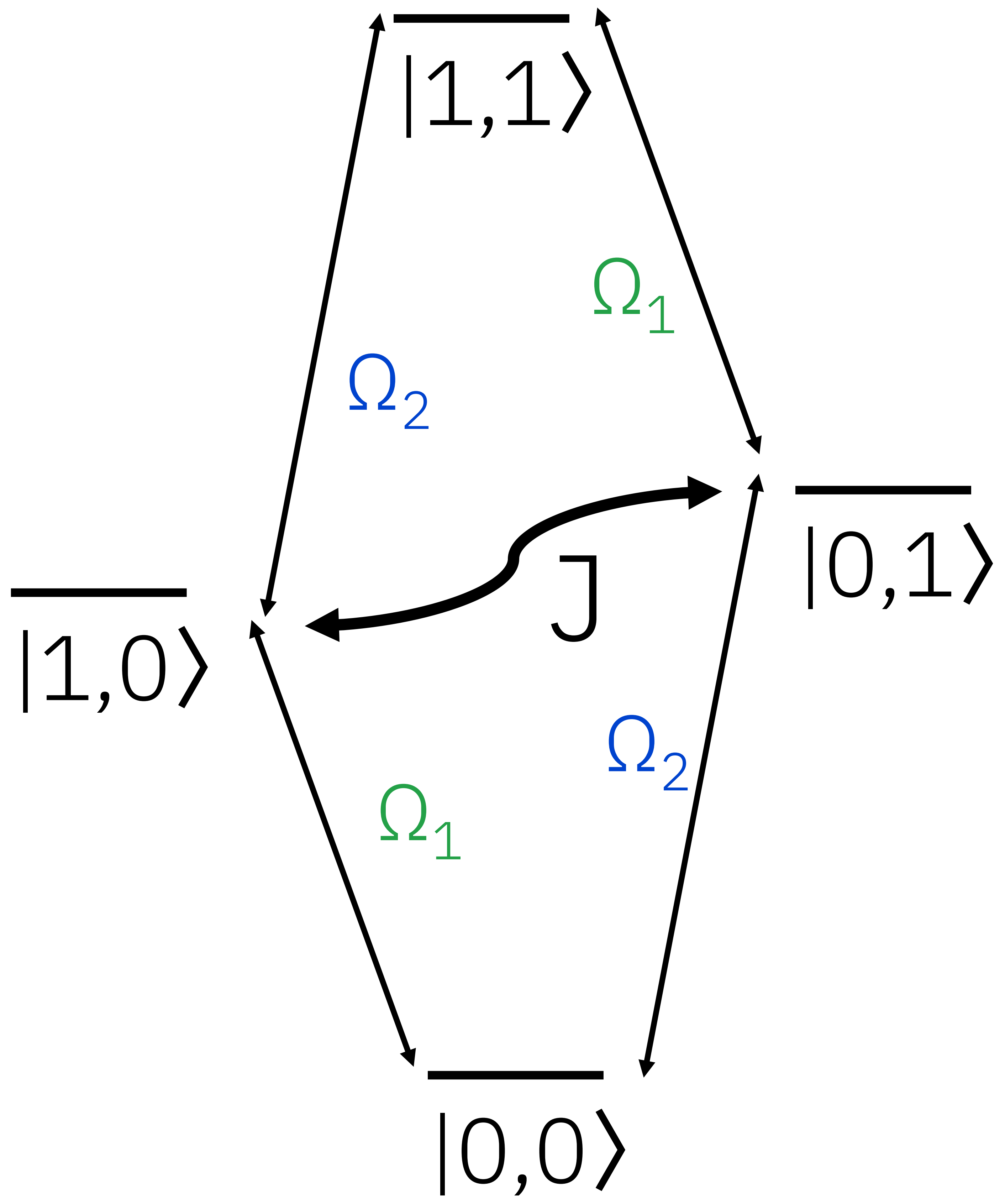
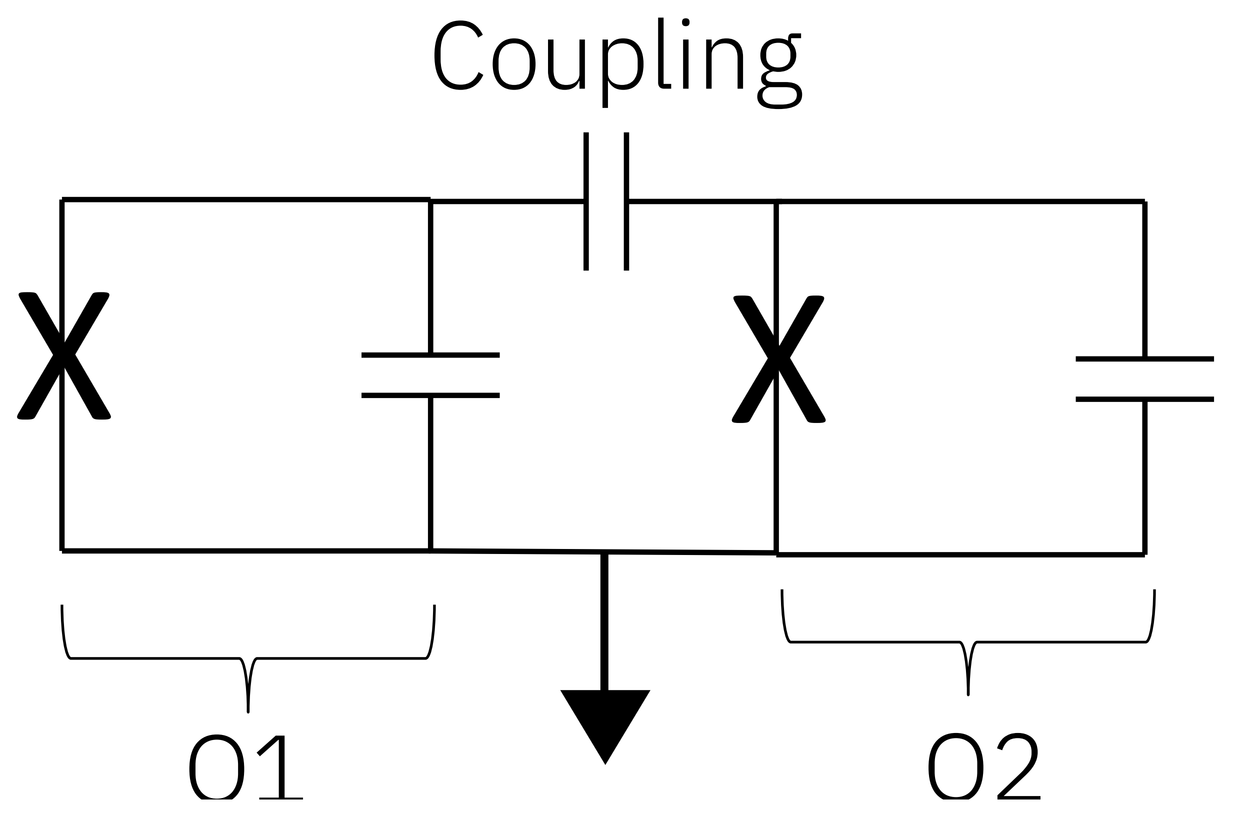


Two qubit gates: cross-resonance

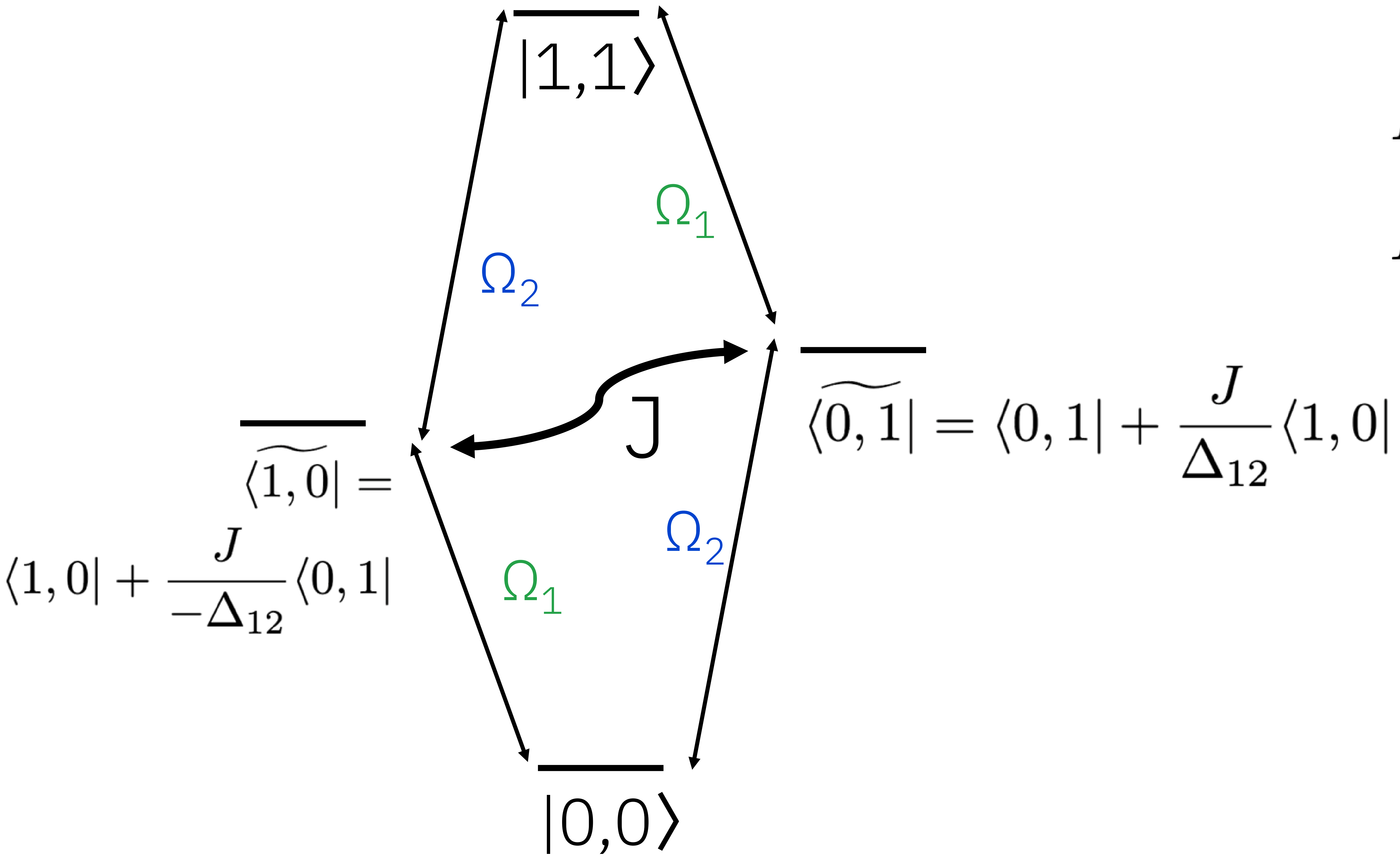


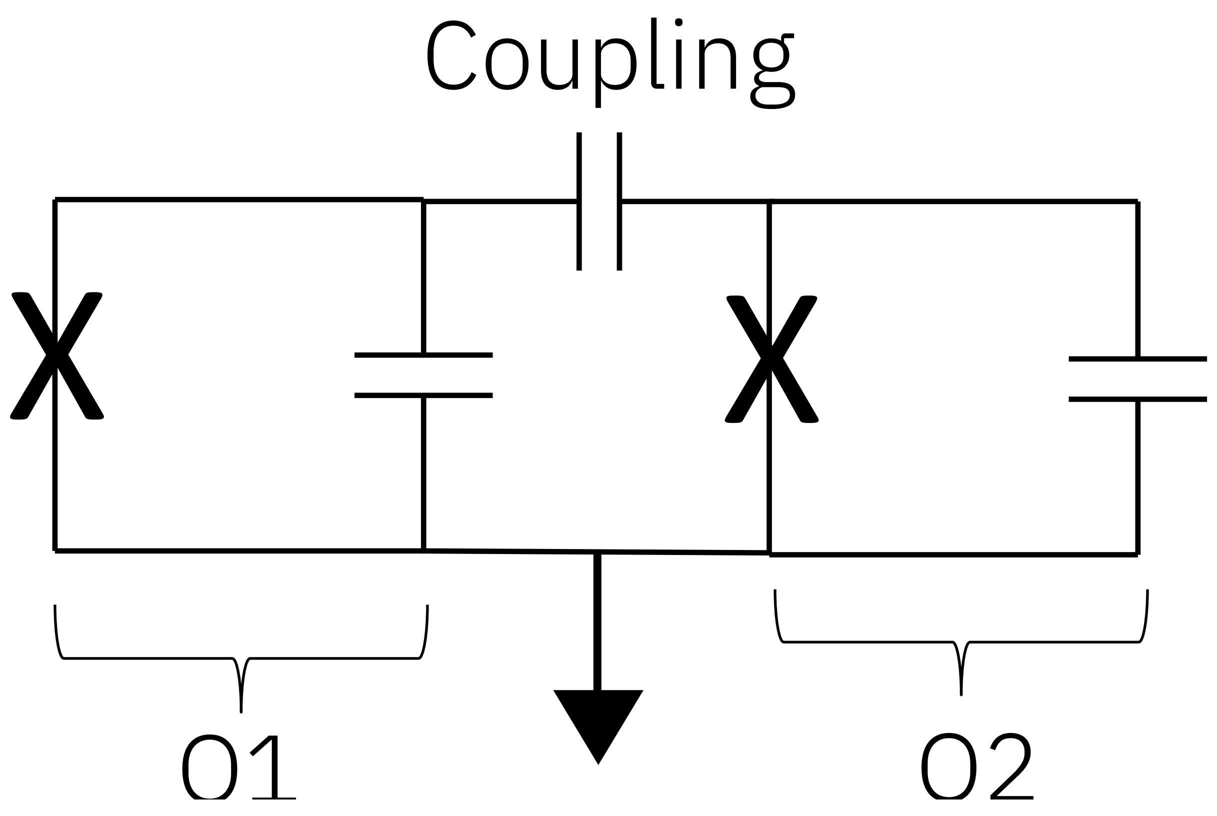


$$H_{couple} = J\left(\hat{a}^{\dagger}\hat{b} + \hat{b}^{\dagger}\hat{a} + \text{Non-RWA terms}\right)$$

$$H_{dr} = \Omega_1(t)(\hat{a}^{\dagger} + \hat{a}) + \Omega_2(t)(\hat{b}^{\dagger} + \hat{b})$$

Two qubit gates: cross-resonance





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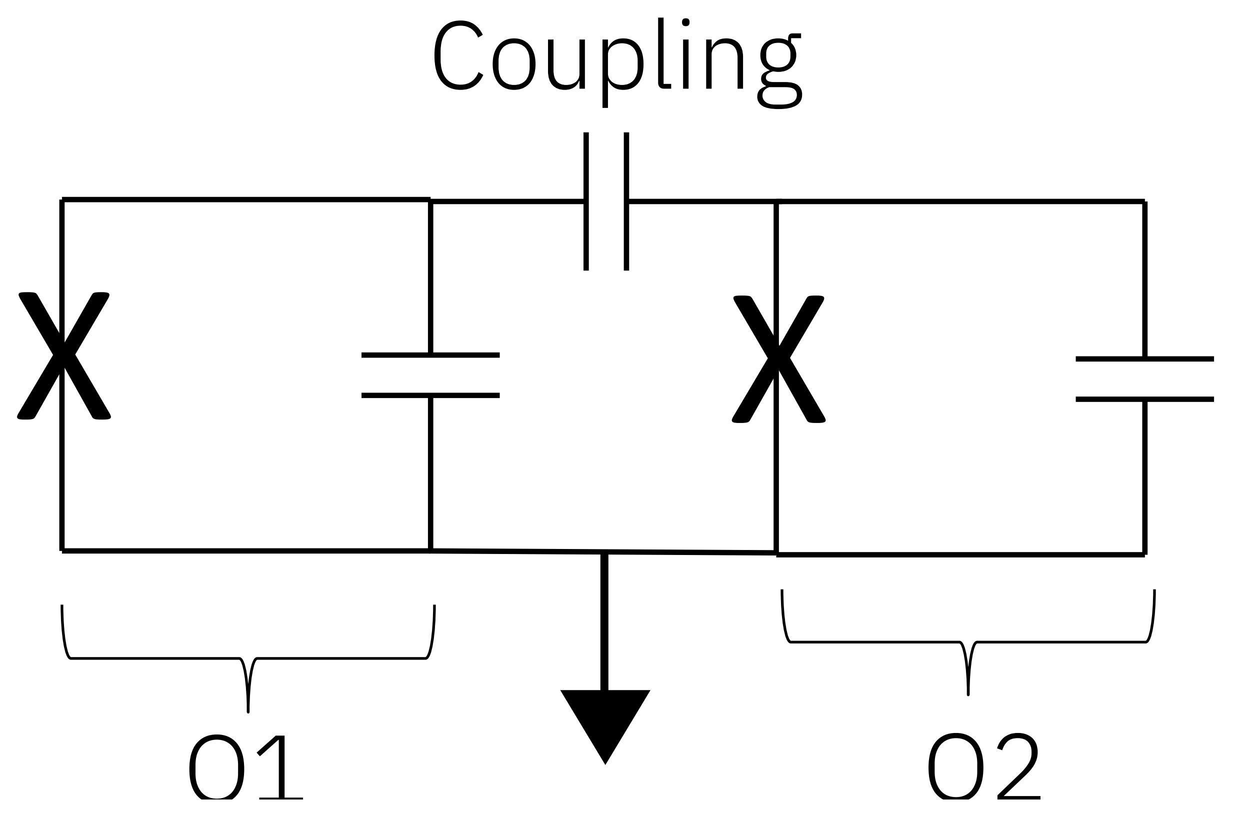

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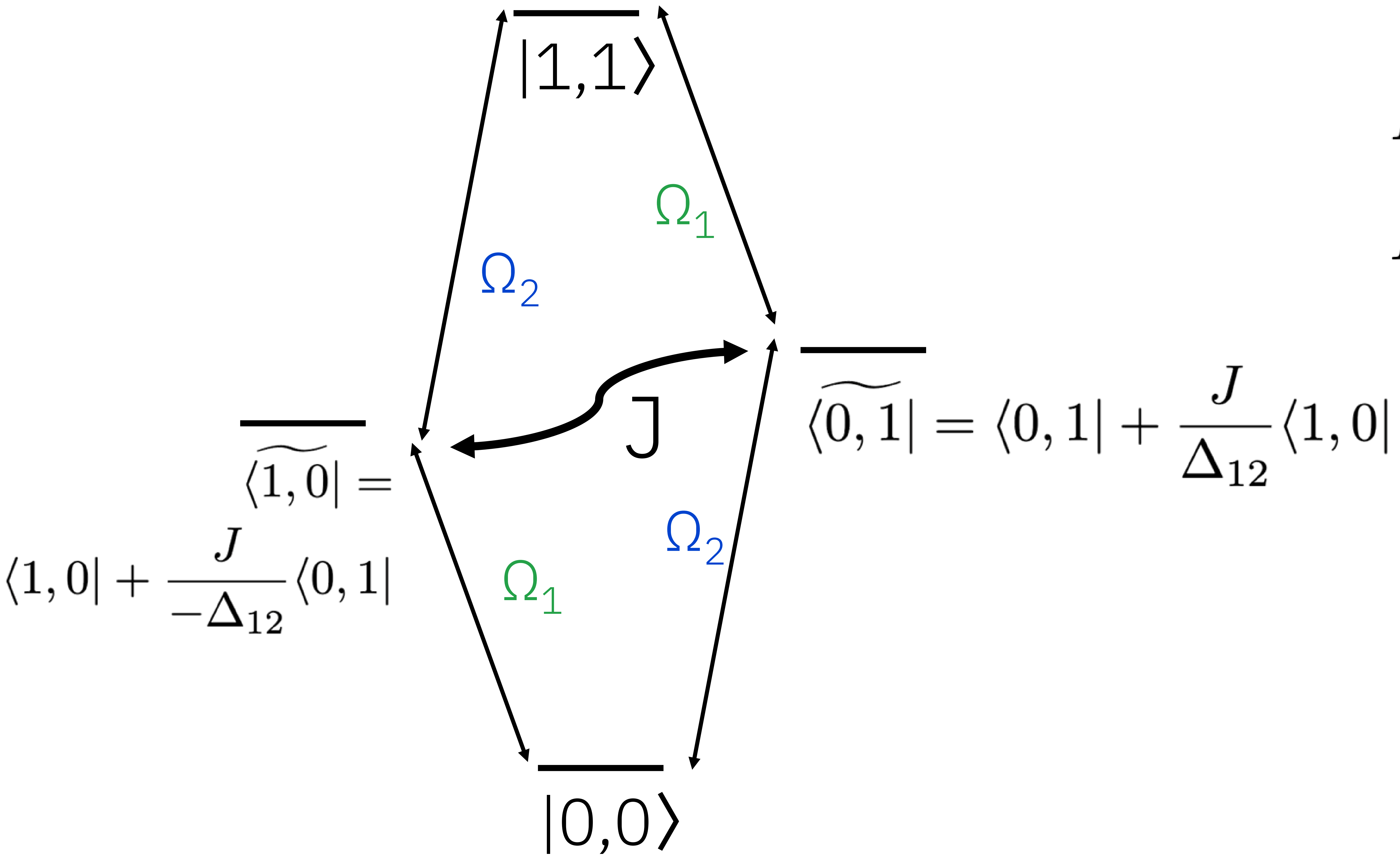
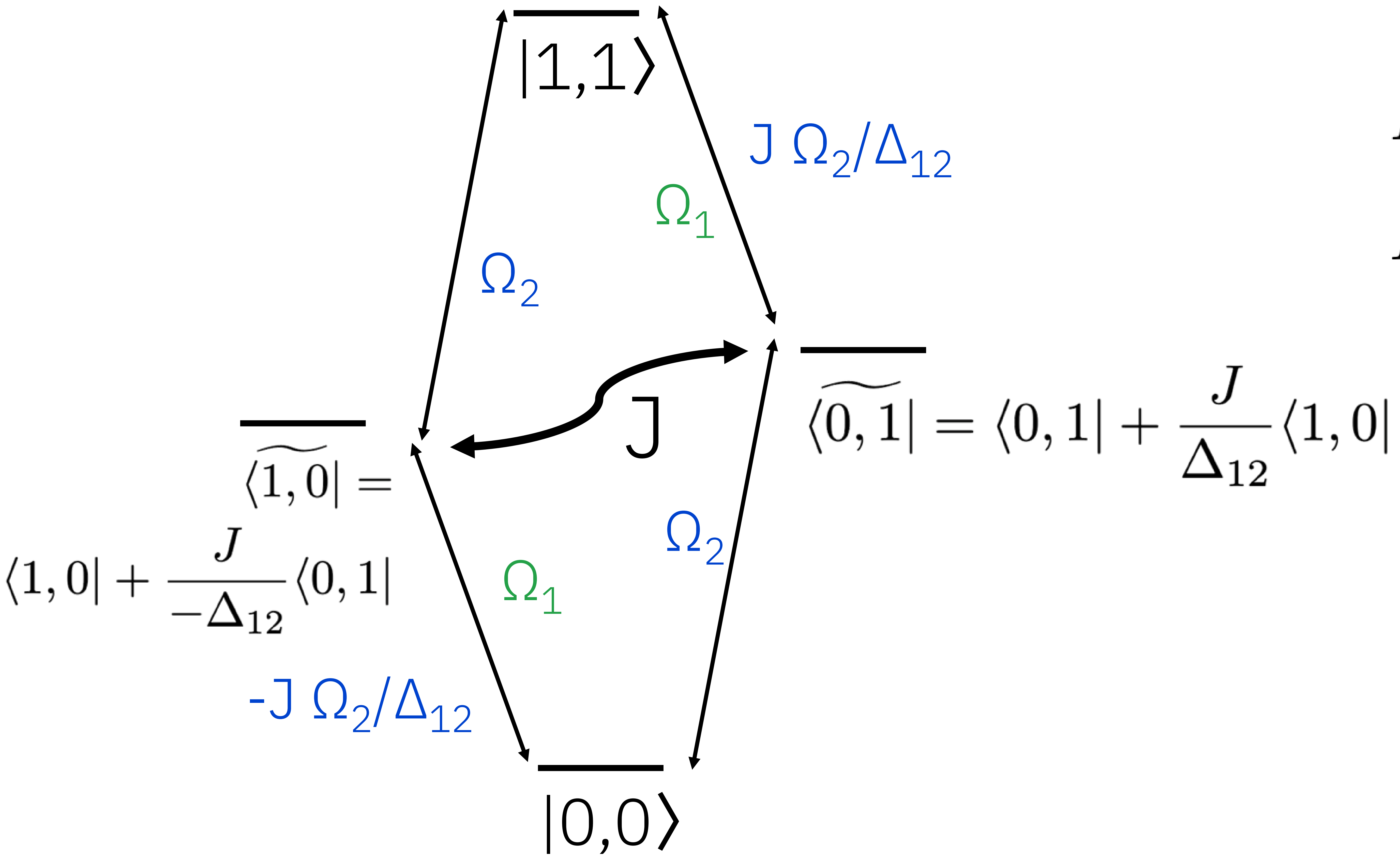
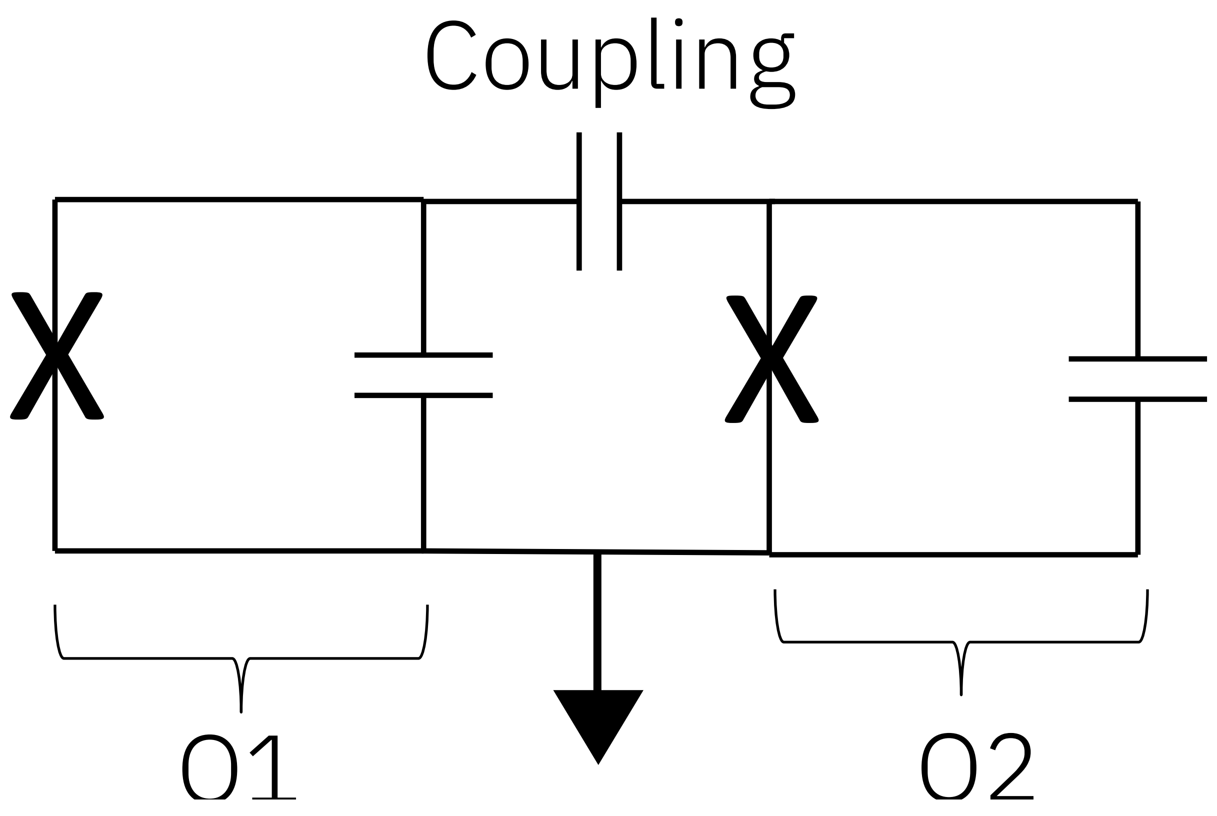


Two qubit gates: cross-resonance





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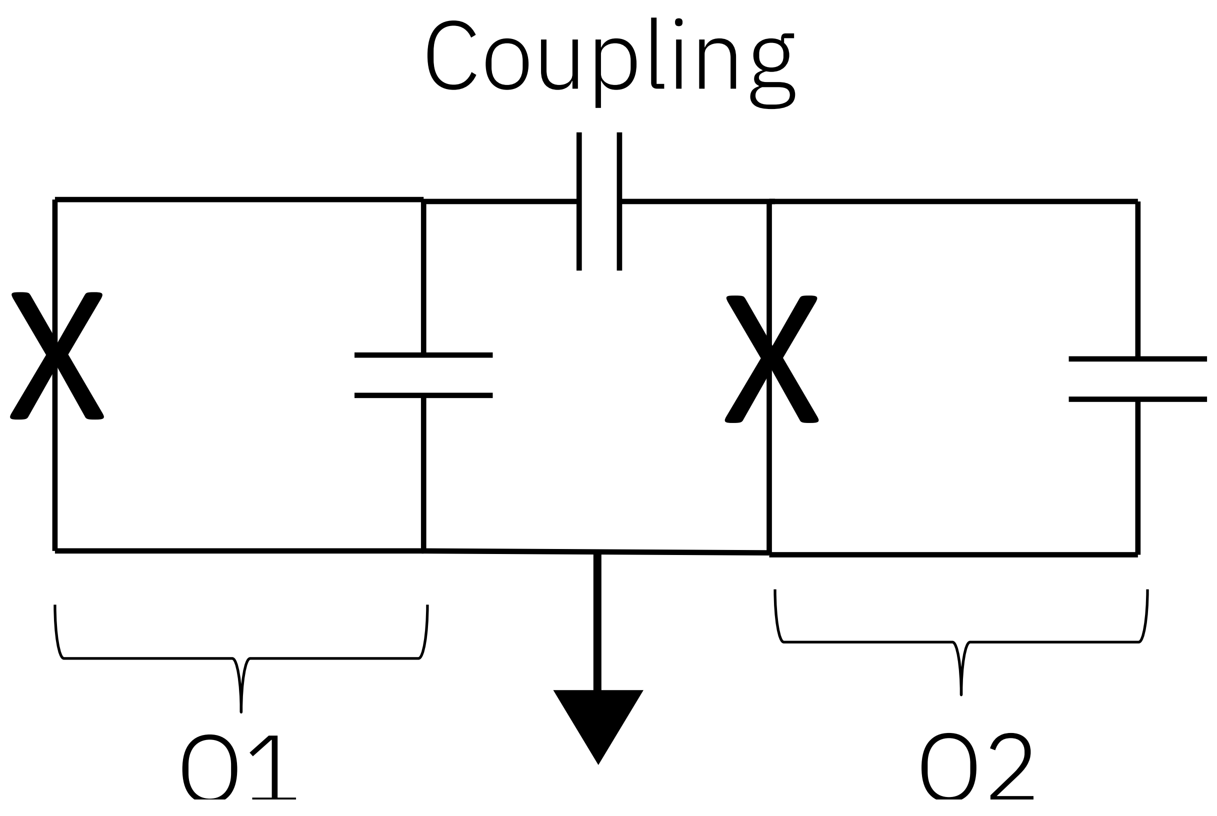
Two qubit gates: cross-resonance



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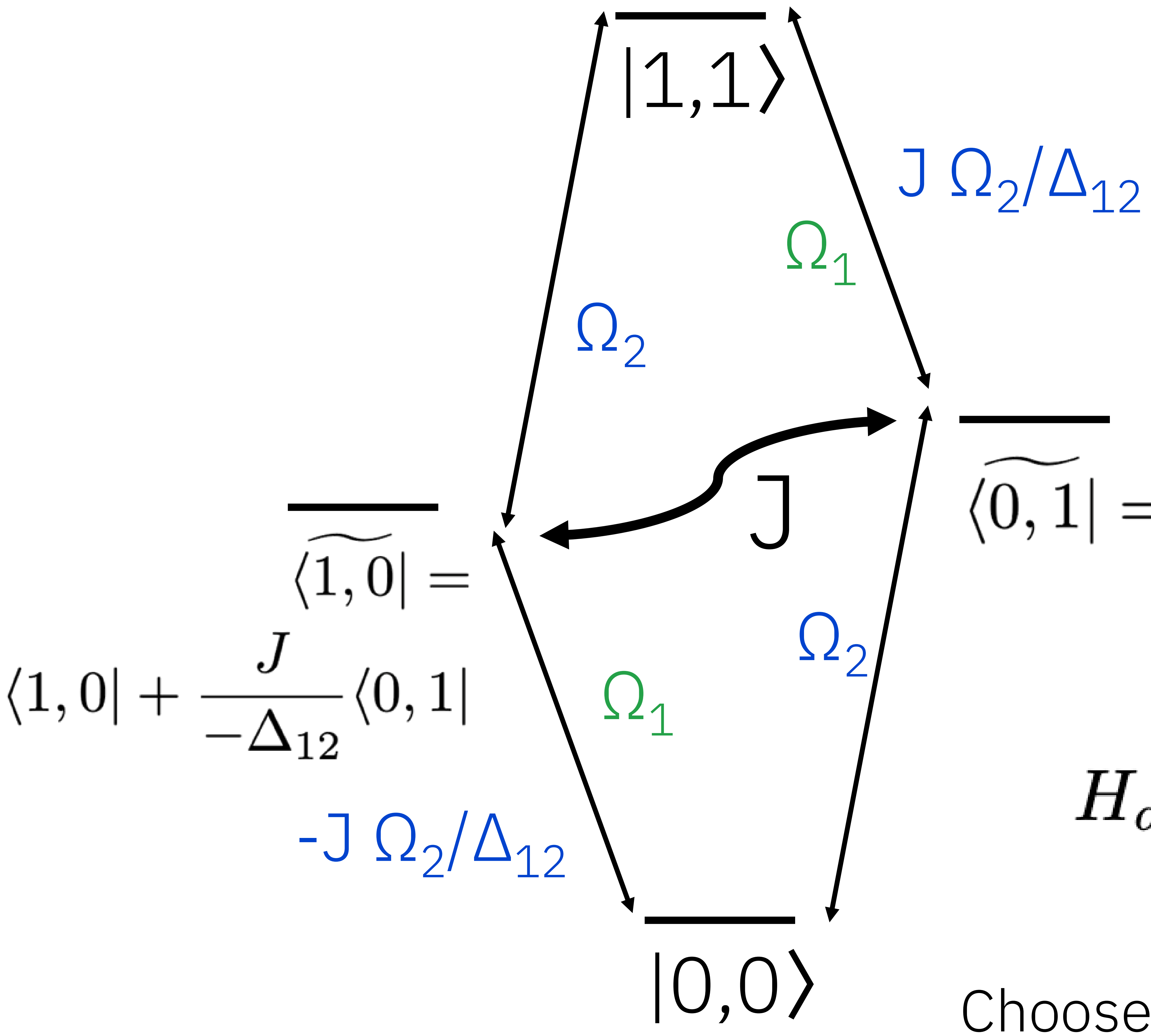
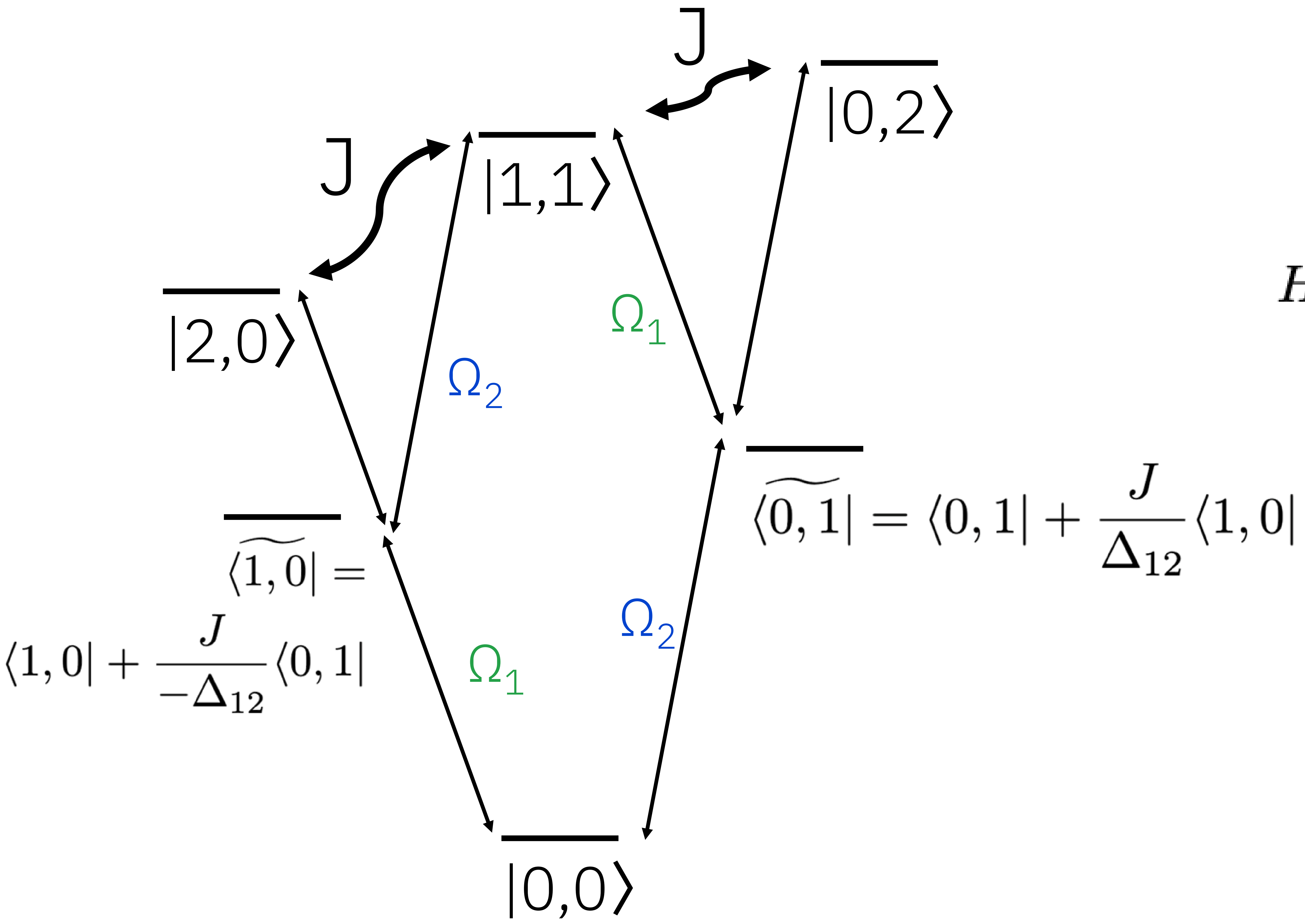


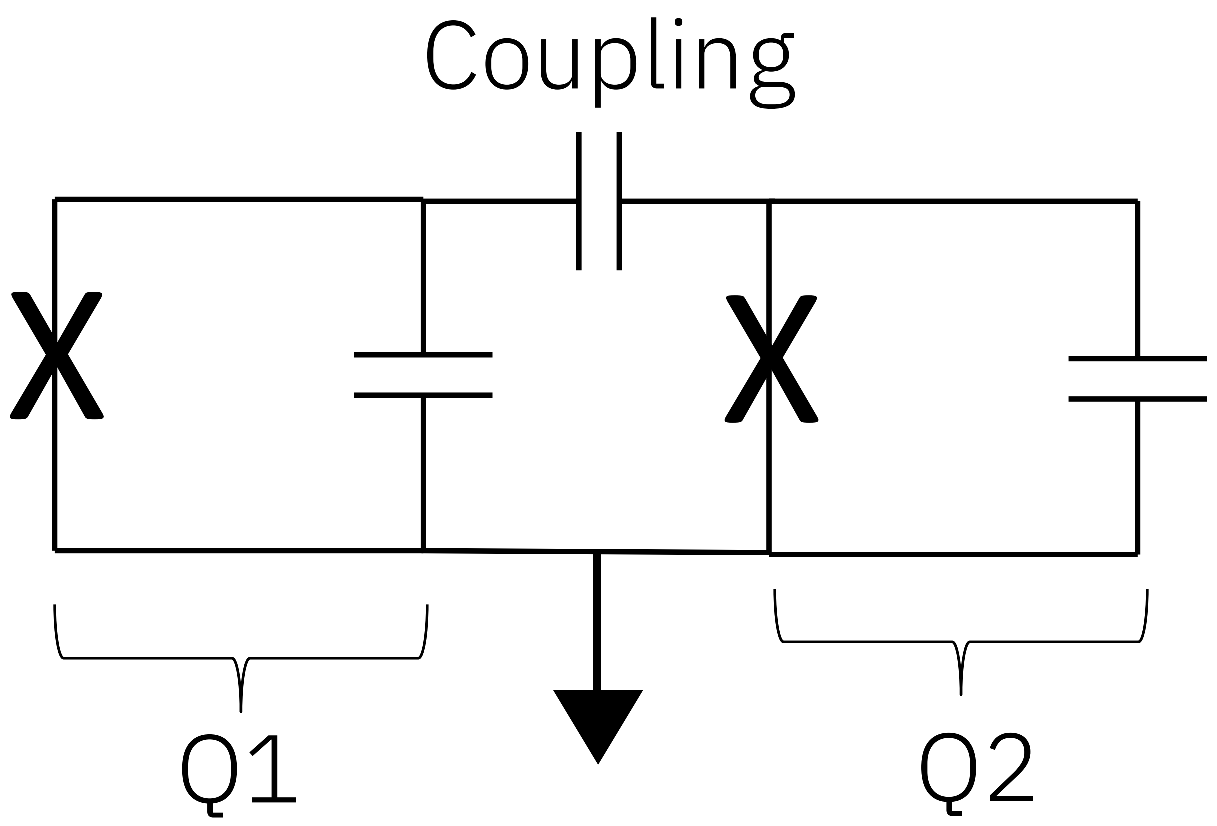
$$\widetilde{\langle 0,1|} = \langle 0,1| + \frac{J}{\Delta_{12}}\langle 1,0|$$

$$H_{dr} = \Omega_1(t)(\hat{X} \otimes \hat{I} - \frac{J}{\Delta}\hat{X} \otimes \hat{Z}) + \Omega_2(t)(\hat{I} \otimes \hat{X} + \frac{J}{\Delta}\hat{Z} \otimes \hat{X})$$

Choose between the conditional and unconditional drives with the drive frequency, provided the qubits are at different frequencies

Two qubit gates: cross-resonance





$$\begin{aligned} H_{dr} &= \Omega_1(t)(\hat{X}\otimes\hat{I} - \nu_1\hat{I}\otimes\hat{X} - \mu_1\hat{Z}\otimes\hat{X}) \\ &+ \Omega_2(t)(\hat{I}\otimes\hat{X} + \nu_2\hat{X}\otimes\hat{I} + \mu_2\hat{X}\otimes\hat{Z}) \end{aligned}$$

$$\nu_1 = \frac{J}{\delta_1 + \Delta_{12}} \qquad \mu_1 = \frac{J\delta_1}{\Delta_{12}(\delta_1 + \Delta 12)}$$

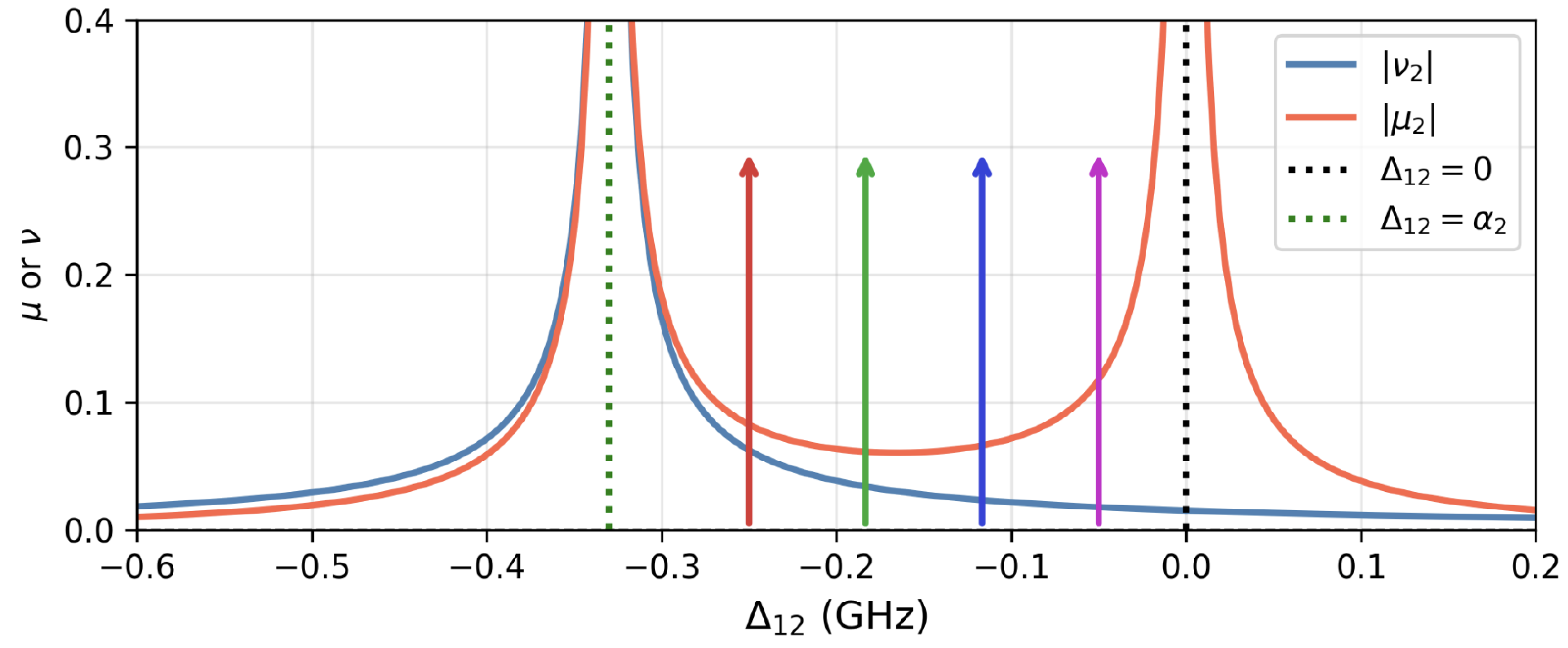
$$\nu_2 = \frac{-J}{\delta_2 - \Delta_{12}} \qquad \mu_2 = \frac{J\delta_2}{\Delta_{12}(\delta_2 - \Delta 12)}$$

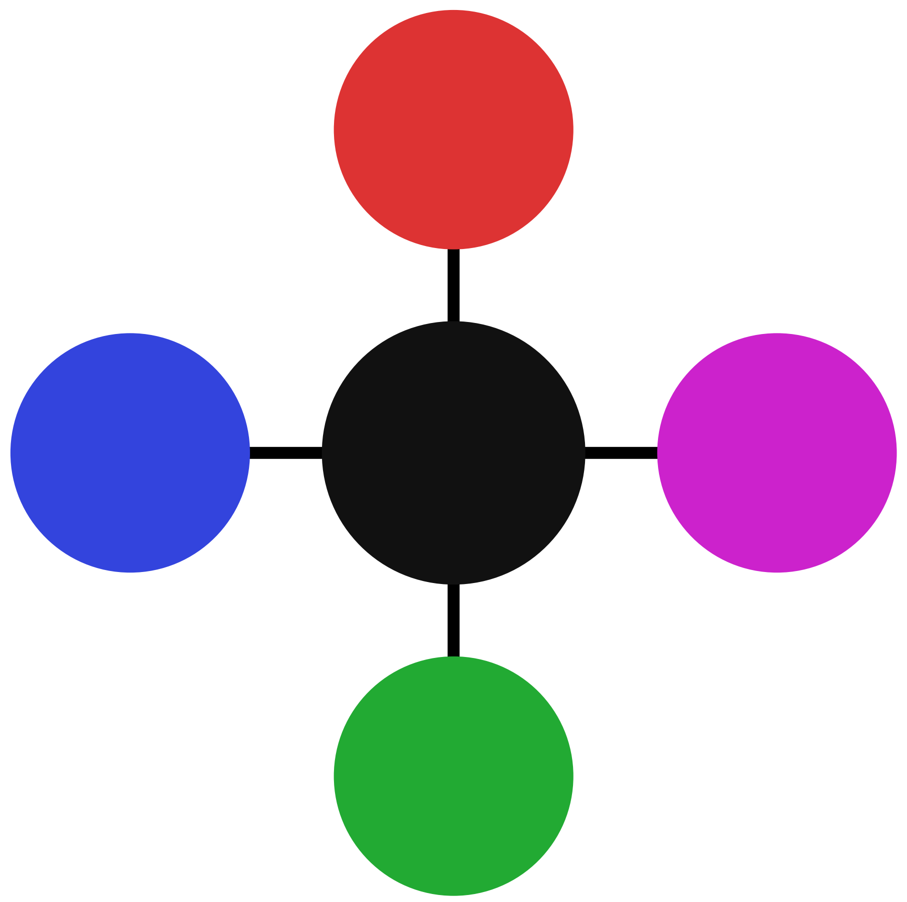
“Exercise for the reader”

The 1,1 state also hybridizes with the 0,2 and 2,0 states, which gives two more transitions you can drive!

Note that in the limit $\delta \rightarrow 0$, this effect vanishes, and in the limit $\delta \rightarrow \infty$ we recover our previous expression

Two qubit gates: cross-resonance





Zhang et al, *Sci. Adv.* **8**, eabi6690, 2022.

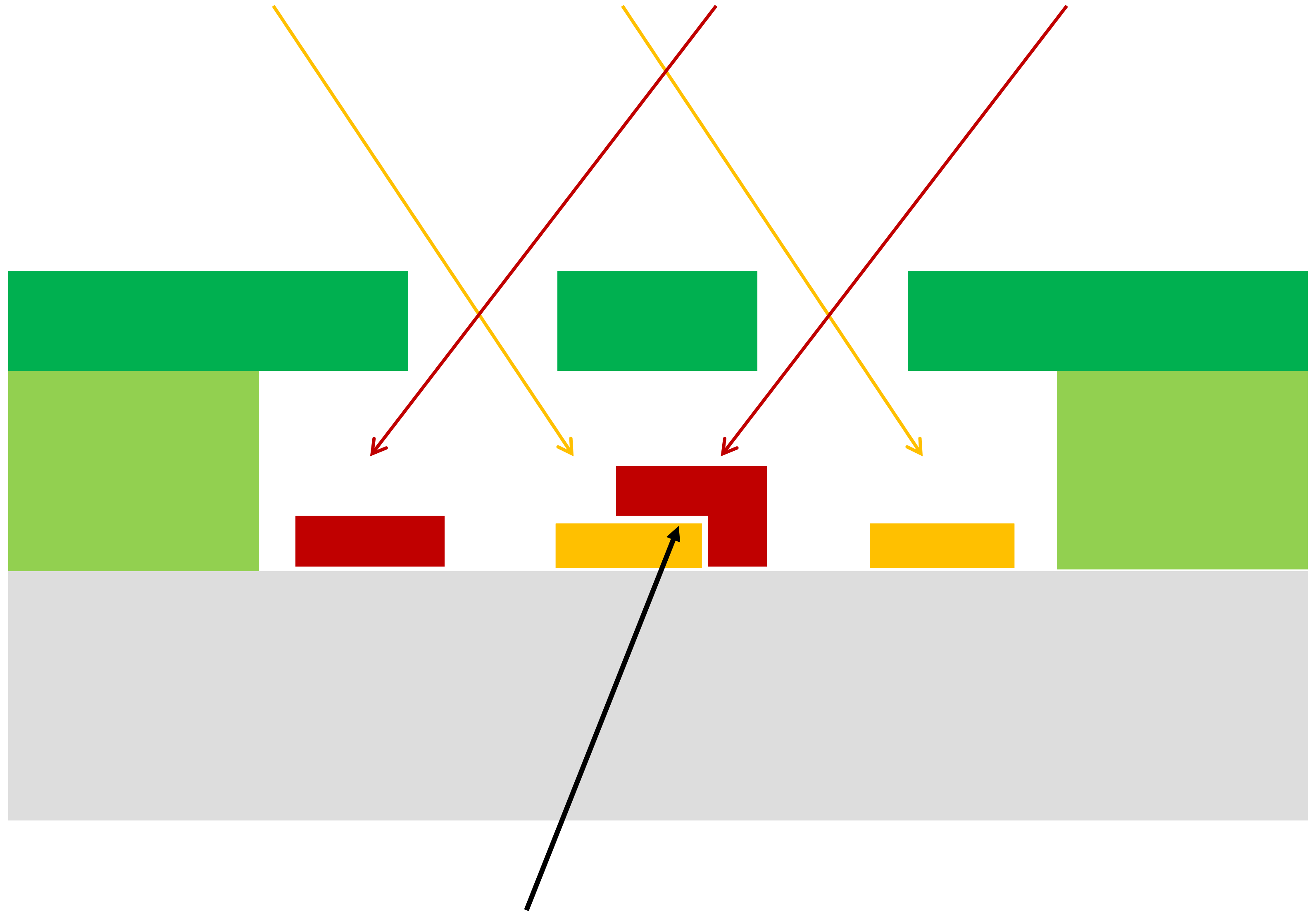
Transmon fabrication (Dolan bridge)

1. Clean wafer
2. Sputter superconductor

3. Pattern resonators and capacitors using photolithography

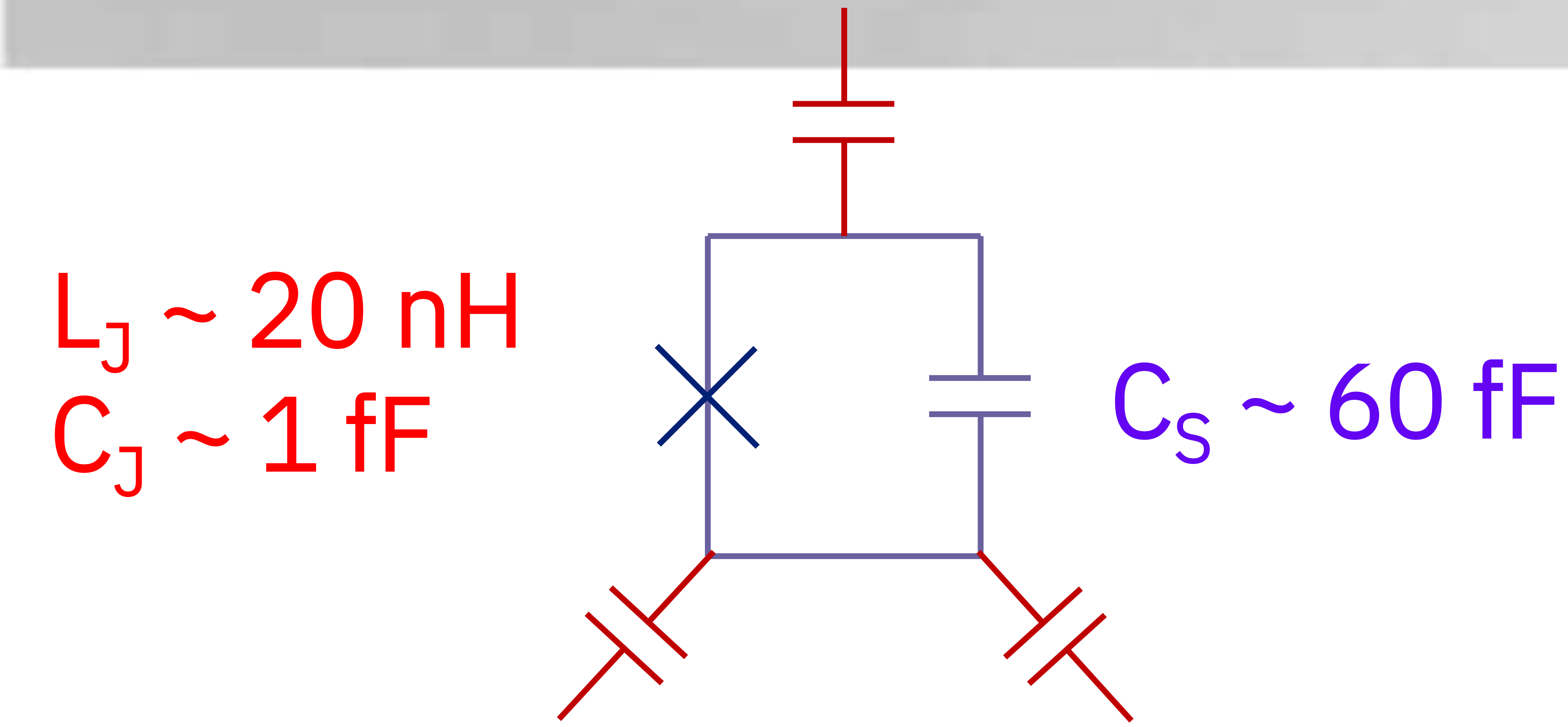
Superconductor
Substrate
MMA / PMMA
1st Al evaporation
Al oxide
2nd Al evaporation

1. Form Dolan bridge structure in MMA/PMMA resist stack using e-beam lithography
2. Deposit Al/AlOx/Al Josephson junction using double-angle evaporation, in-situ oxidation and liftoff



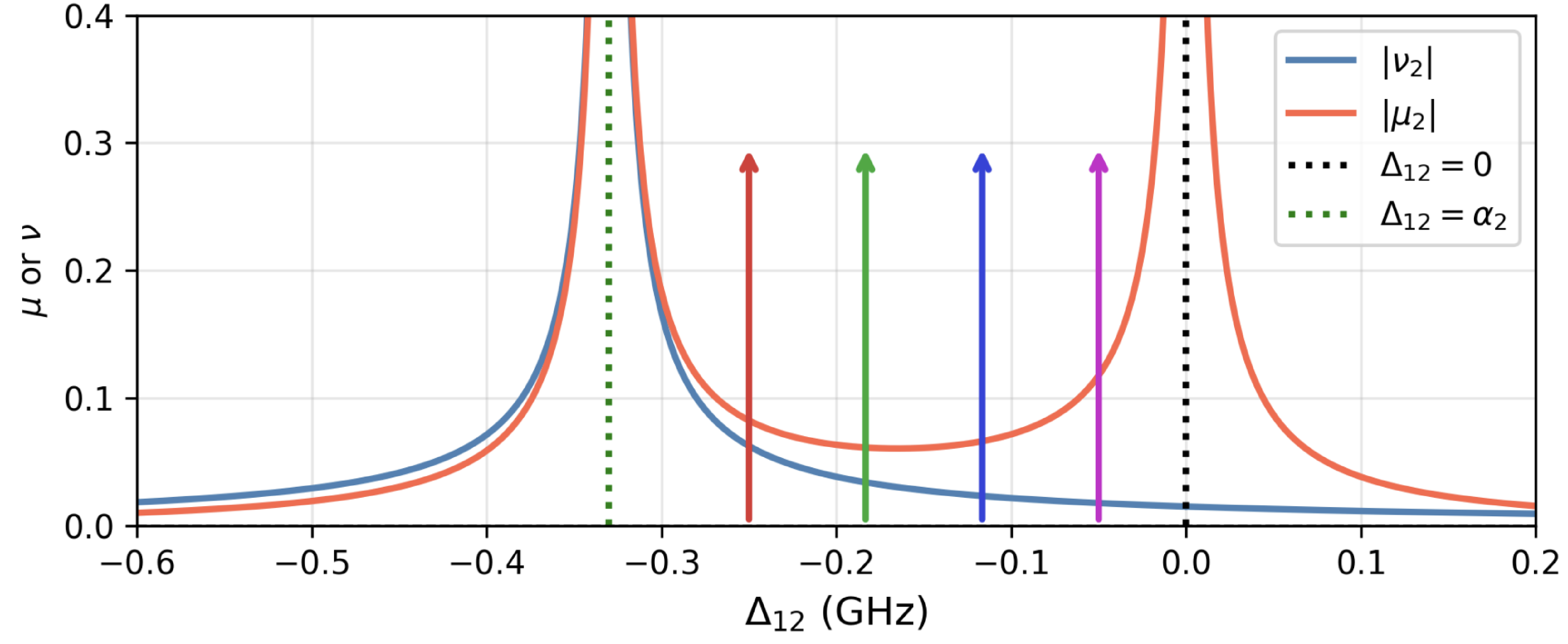
Josephson Junction

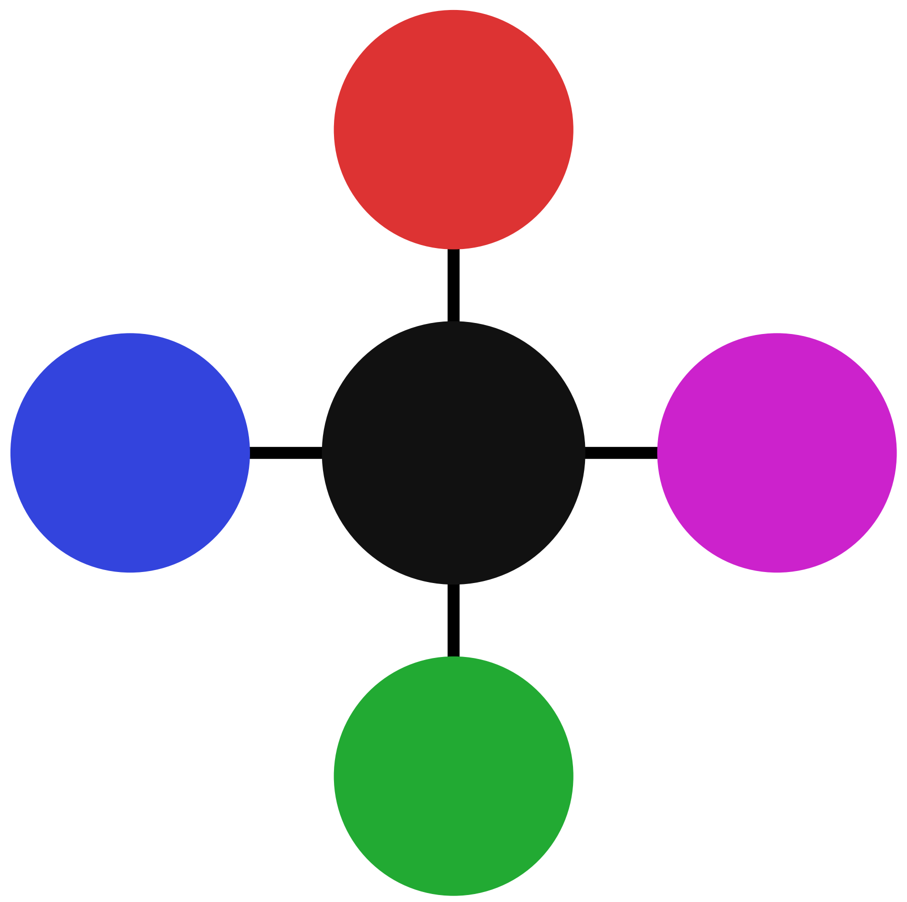
Transmon fabrication (Dolan bridge)

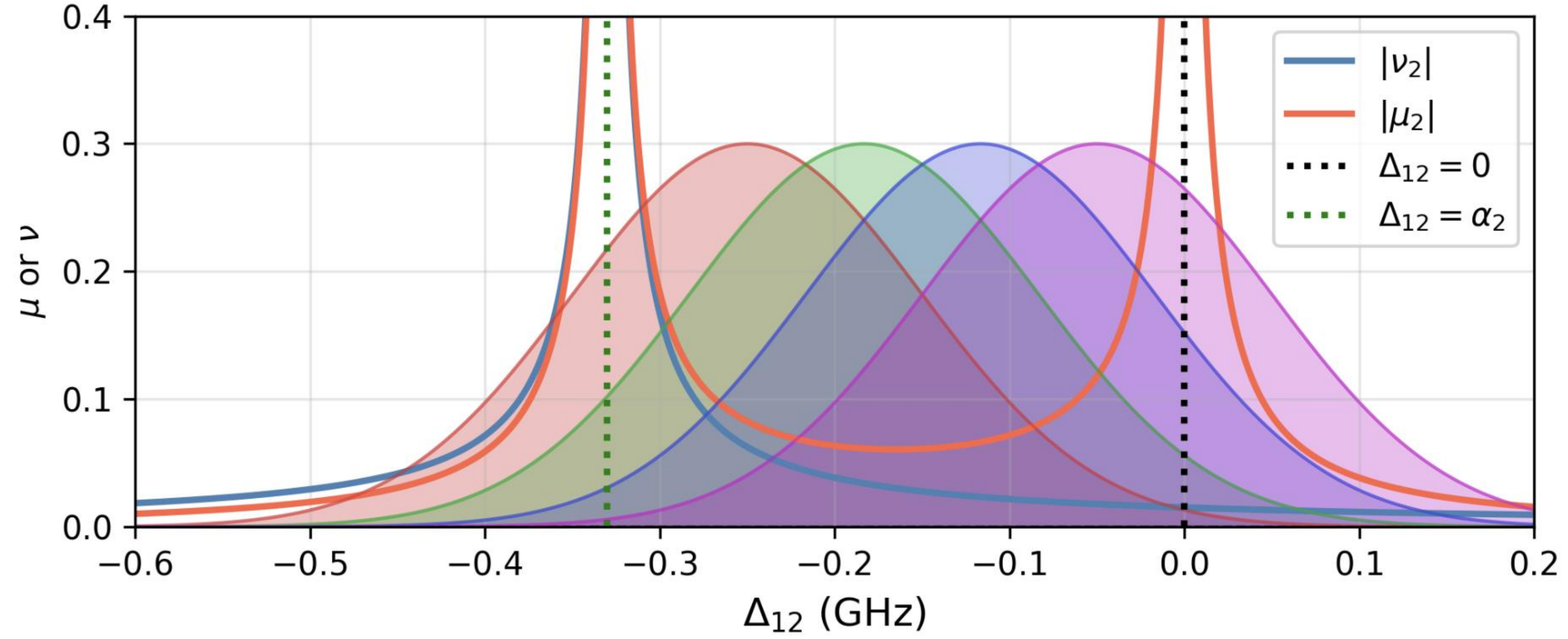


Nb pads
Al $-Al_2O_3$ $-$Al JJ
ω_{01} ~ 5 GHz
ω_{01}- ω_{12} ~ 0.330 GHz

Two qubit gates: cross-resonance



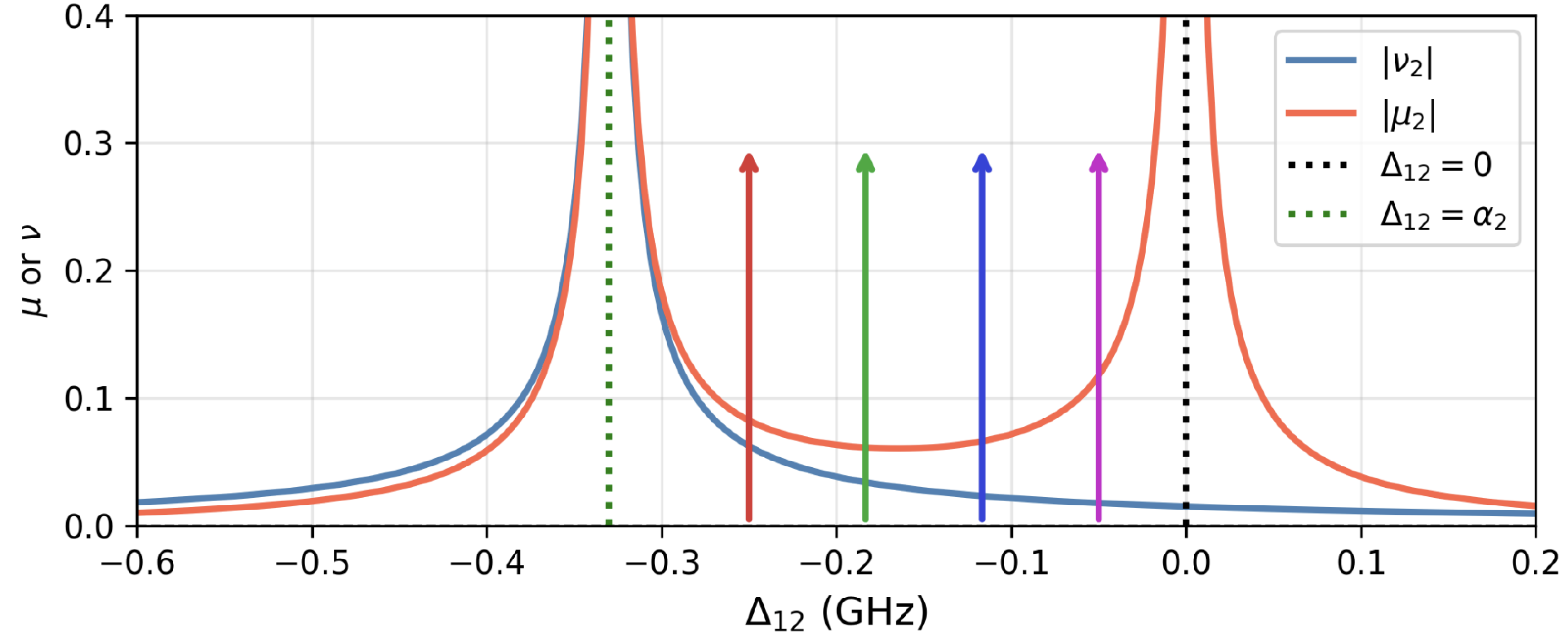


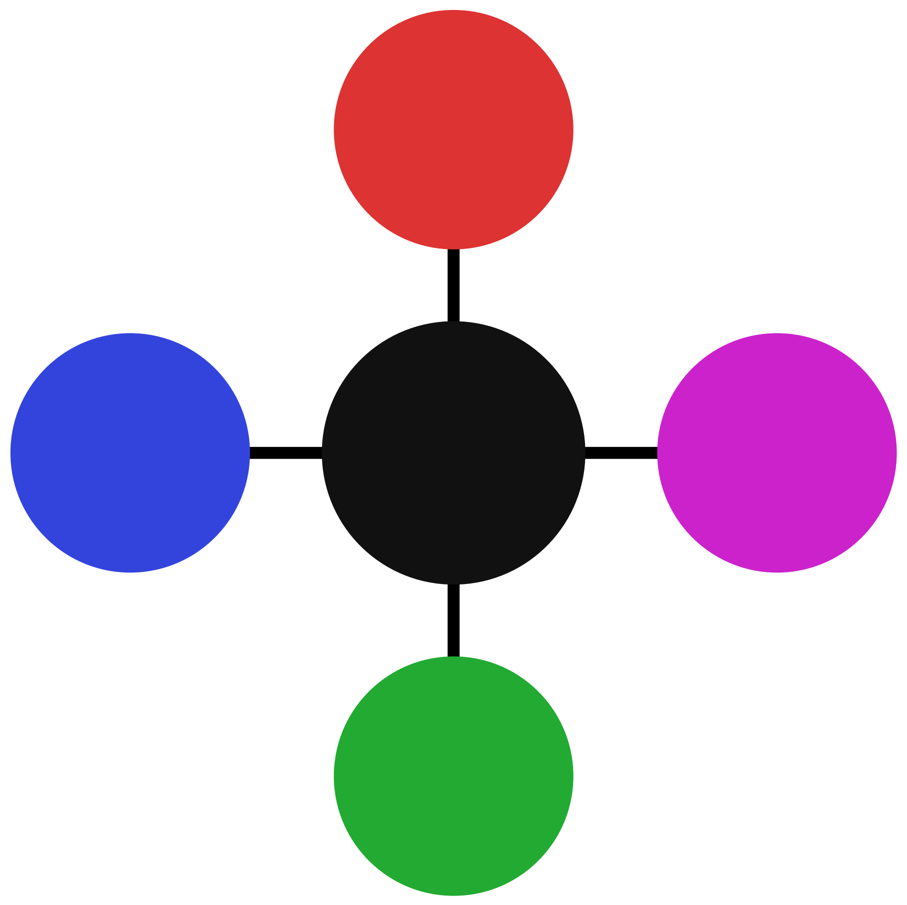


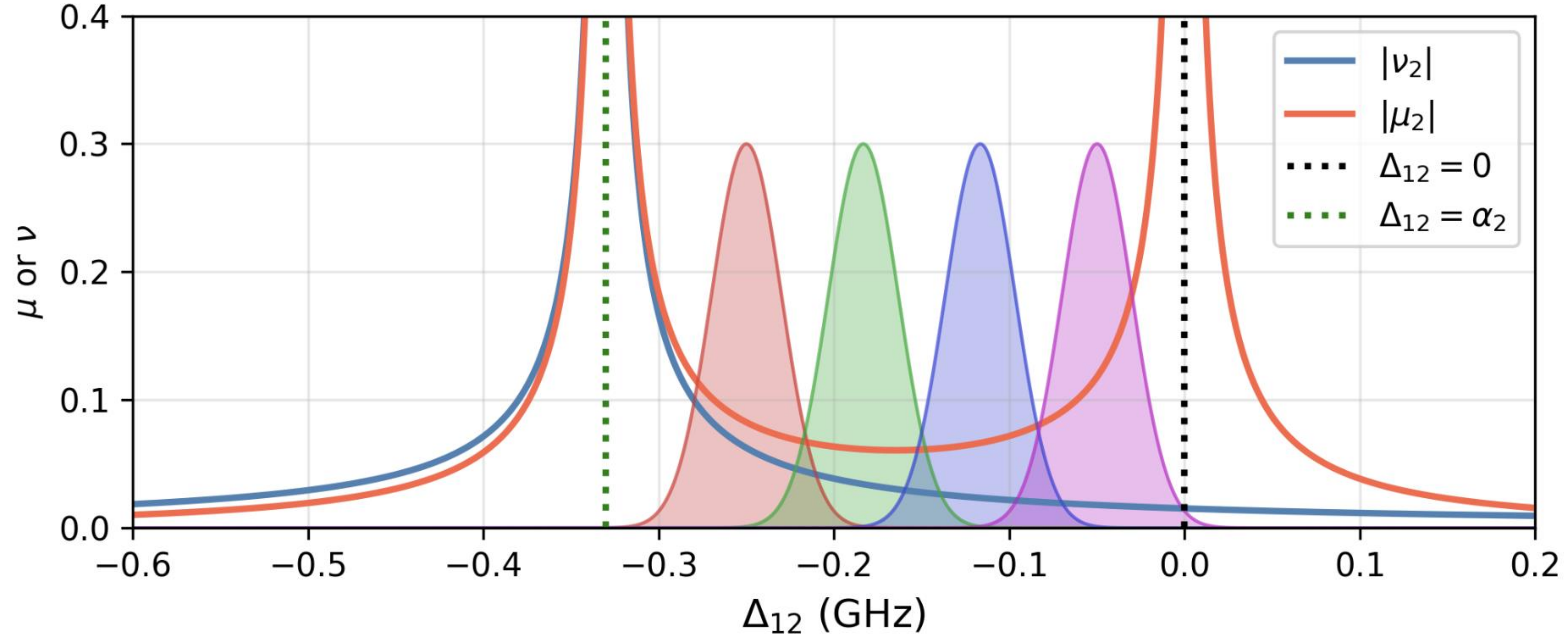
Fabrication spread makes frequency collisions certain in large devices

Zhang et al, *Sci. Adv.* **8**, eabi6690, 2022.

Two qubit gates: cross-resonance





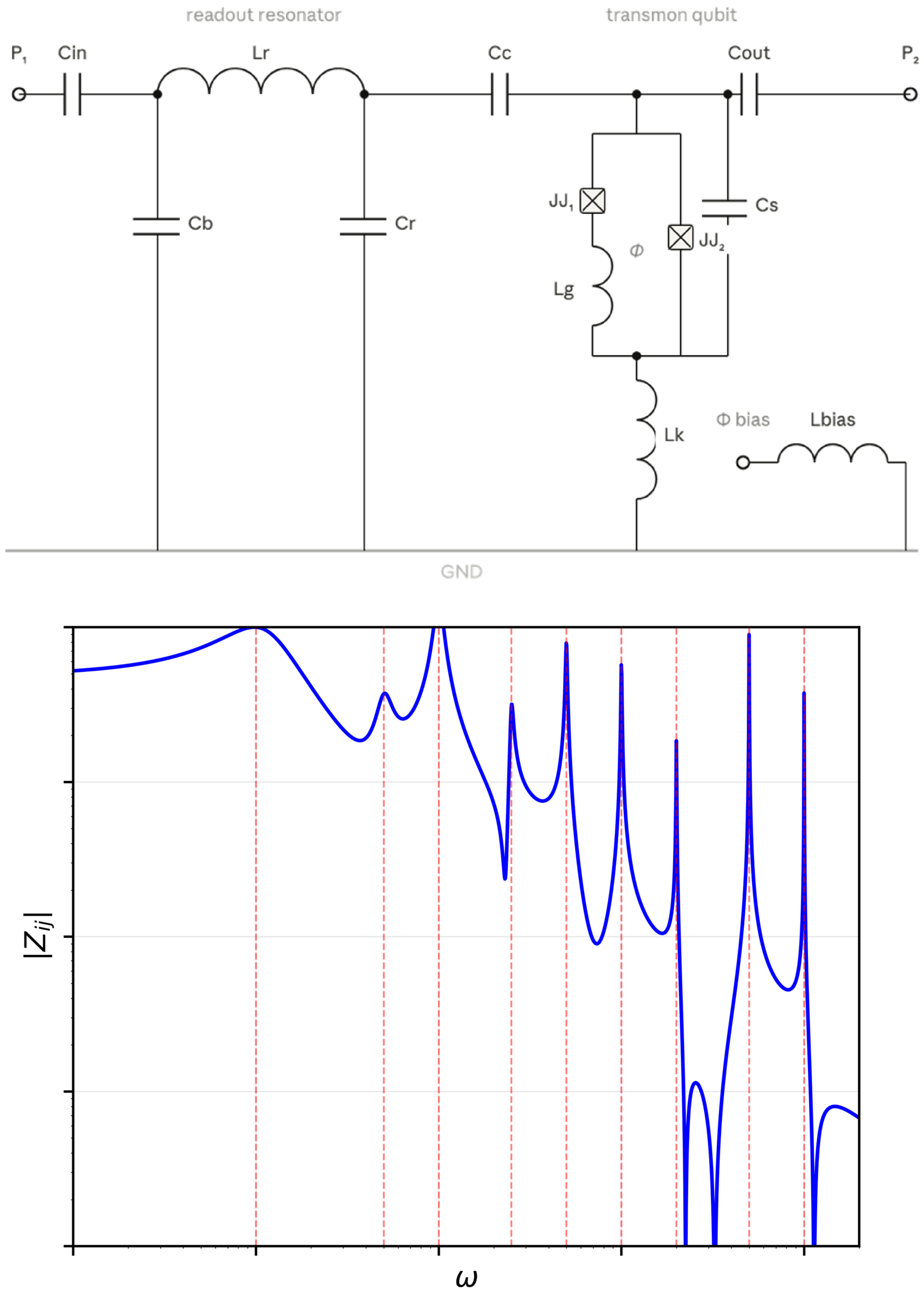


Fabrication spread makes frequency collisions certain in large devices

Even with laser tuning of junctions

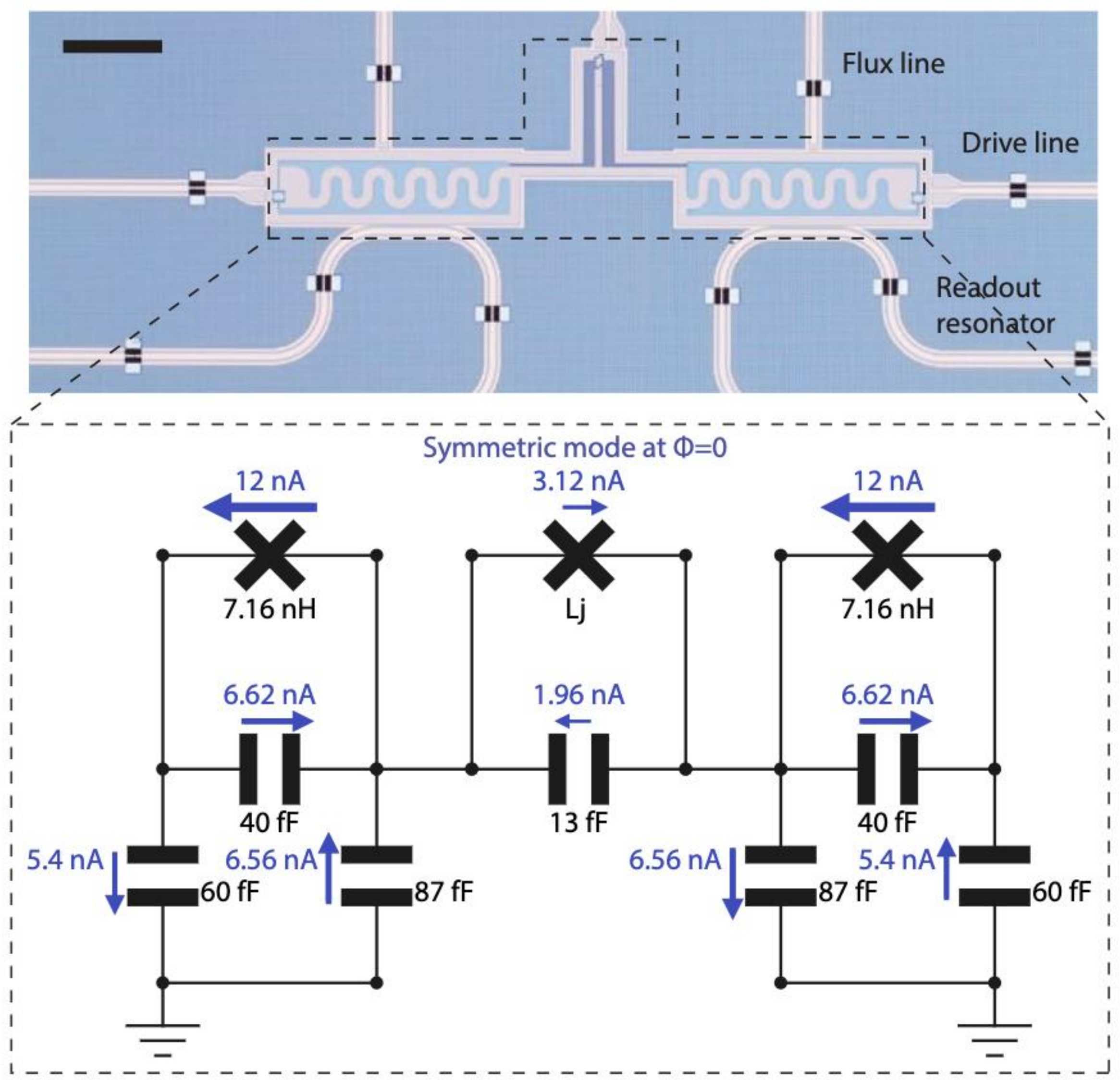
Zhang et al, *Sci. Adv.* **8**, eabi6690, 2022.

Circuit models to Hamiltonians



$\rightarrow \mathcal{H}$

Circuit models to Hamiltonians



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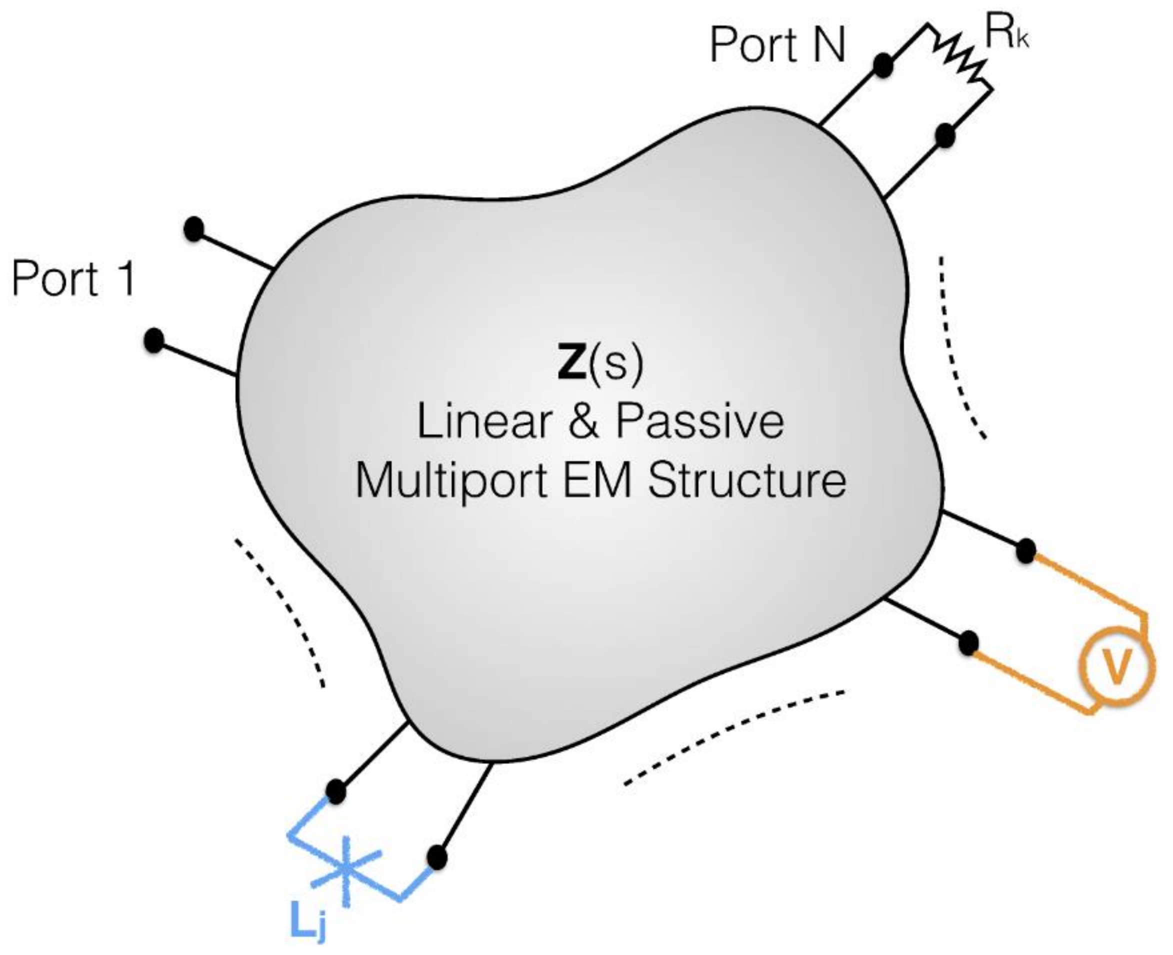

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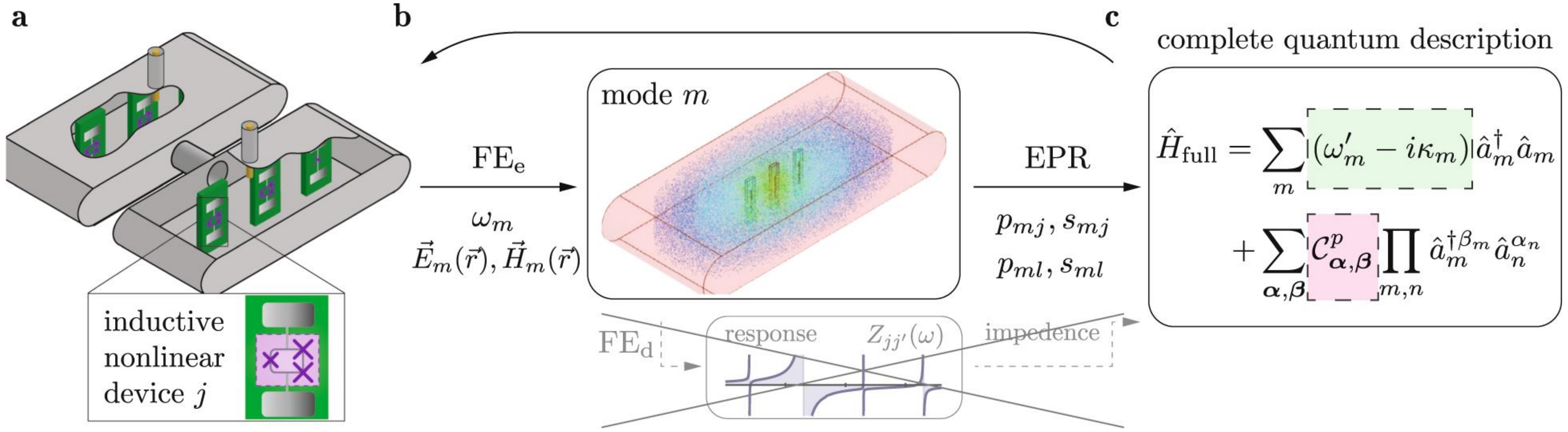


From [4]

[1] S. Nigg et al. “Black-Box Superconducting Circuit Quantization.” Phys. Rev. Lett. **108**, 240502 (2012).

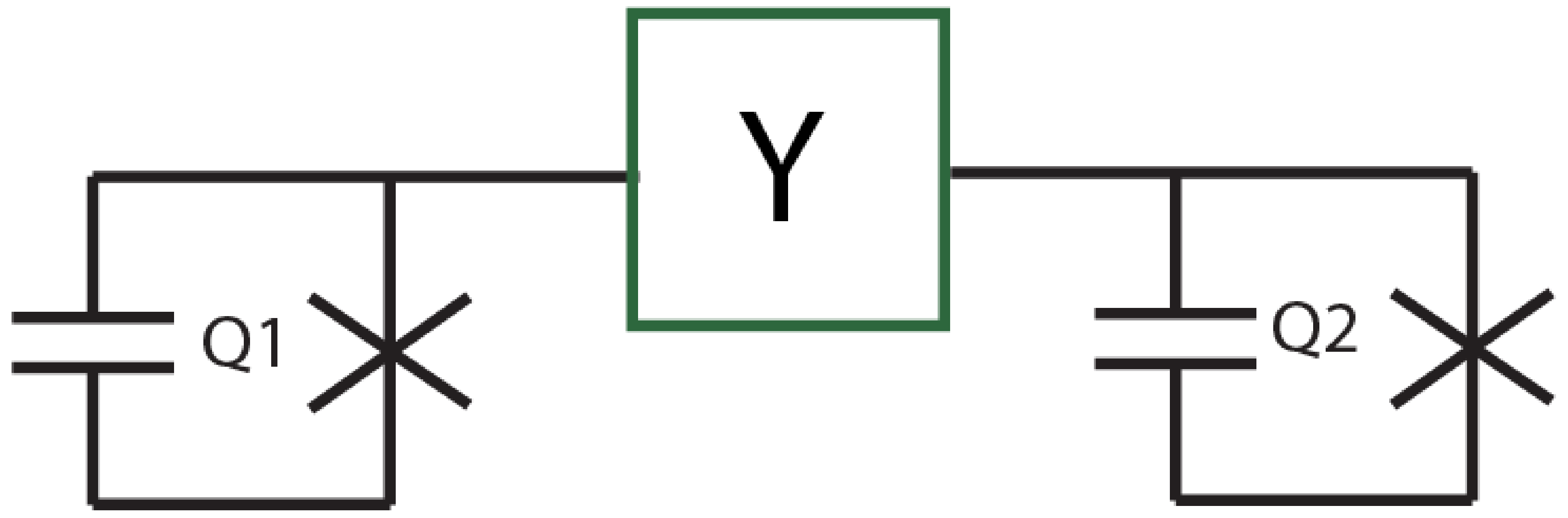
[2] F. Solgun and D. DiVincenzo, “Mutliport Impedance Quantization.” Annals of Physics, Volume 361, (2015).

[3] Mario F. Gely and Gary A. Steele. “QuCAT: quantum circuit analyzer tool in Python.” *New Journal of Physics* **22.1** (2020).

[4] Zlatko Minev et al. ”Energy-participation quantization of Josephson circuit.” *npj Quantum Inf* **7**, 131 (2021).

Weakly coupled, weakly anharmonic oscillators

$$J_{ij} = -\frac{1}{4}\sqrt{\frac{\omega_i\omega_j}{L_iL_j}}\mathrm{Im}\left[\frac{Z_{ij}(\omega_i)}{\omega_i} + \frac{Z_{ij}(\omega_j)}{\omega_j}\right]$$

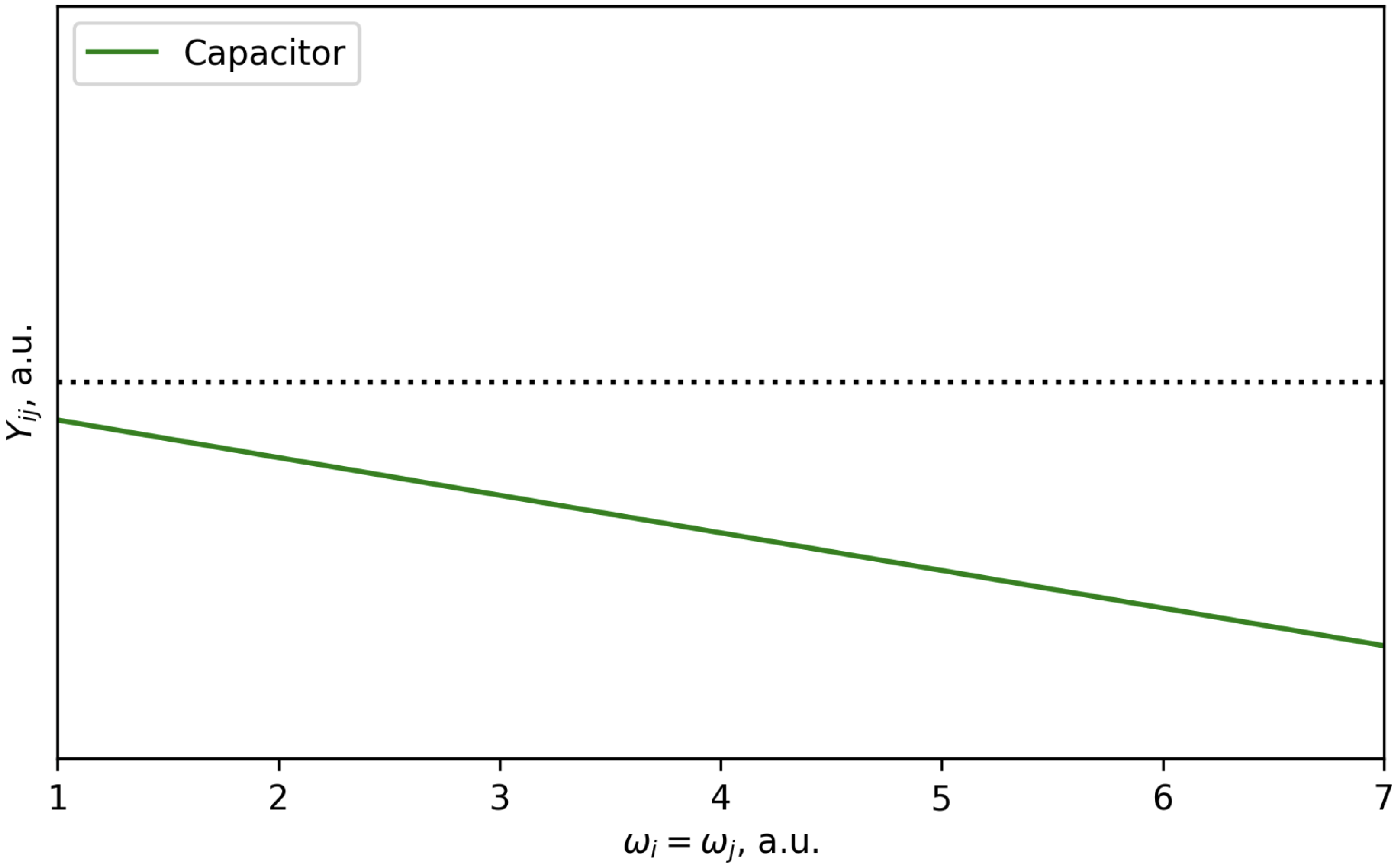


$Y_{ii} << Y_{ij}$

$$J_{ij} = -\frac{(\omega_i\omega_j)^{3/2}}{4\sqrt{C_iC_j}}\left[\frac{Y_{ij}(\omega_i)}{\omega_i^3} + \frac{Y_{ij}(\omega_j)}{\omega_j^3}\right]$$

F. Solgun, D. DiVincenzo, J. Gambetta, "Simple Impedance Response Formulas for the Dispersive Interaction Rates in the Effective Hamiltonians of Low Anharmonicity Superconducting Qubits." *IEEE Transactions on Microwave Theory and Techniques* **67**(3) (2019).

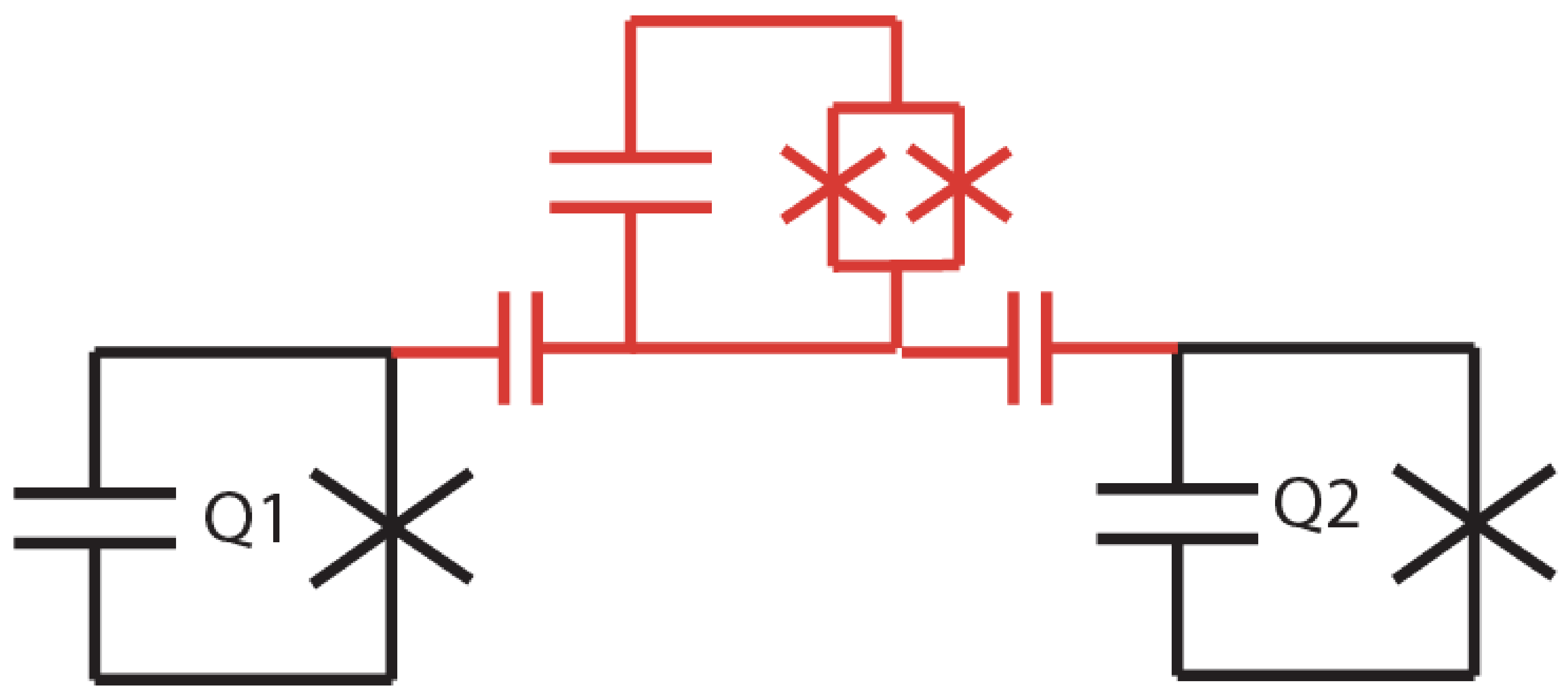
Flux Tunable Couplers

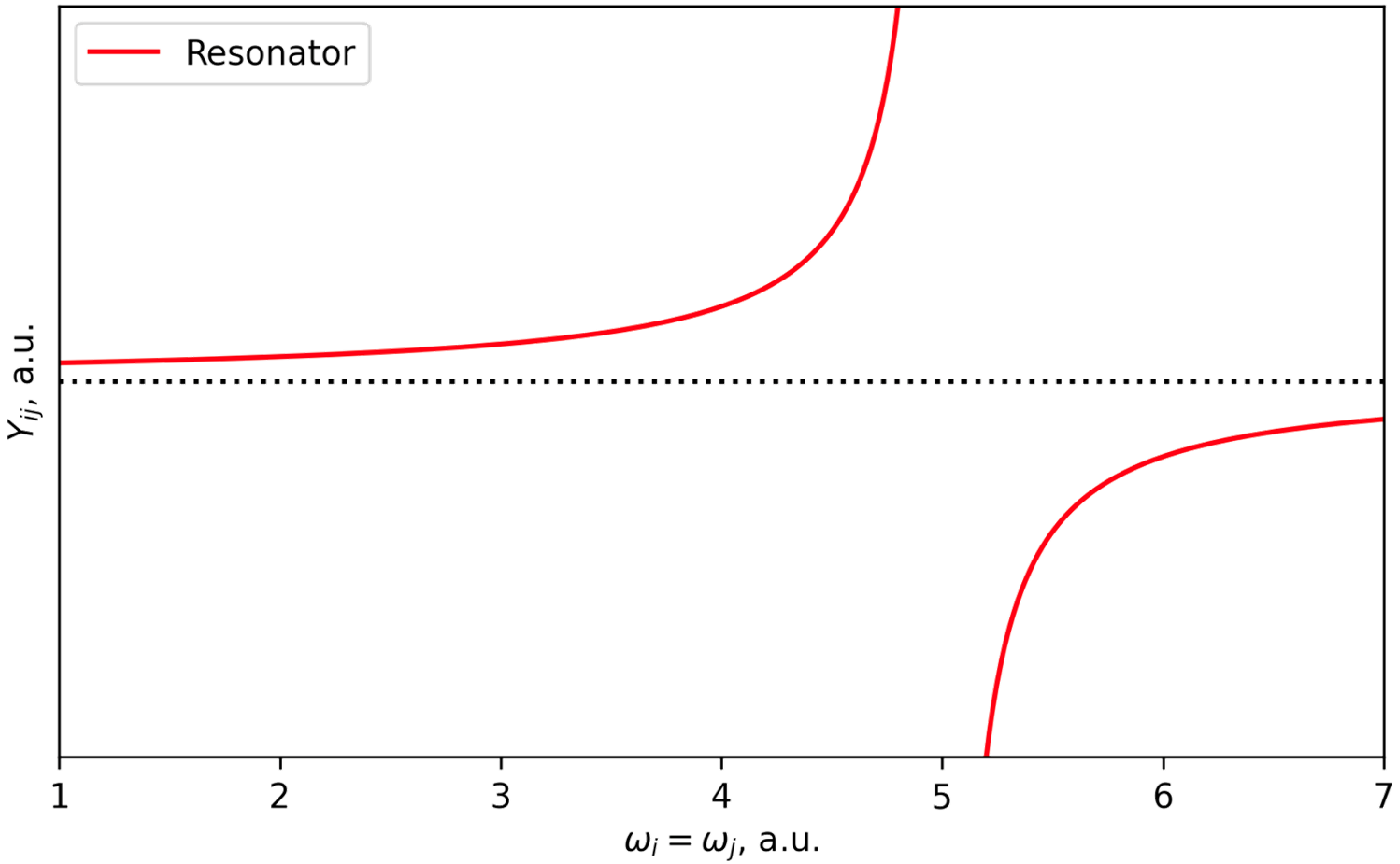


[1] F. Yan et al. “Tunable Coupling Scheme for Implementing High-Fidelity Two-Qubit Gates.” Phys. Rev. Applied 10, 054062 (2018).

With techniques of F. Solgun et al., IEEE Transactions on Microwave Theory and Techniques 67(3) (2019).

Coupling qubits 101





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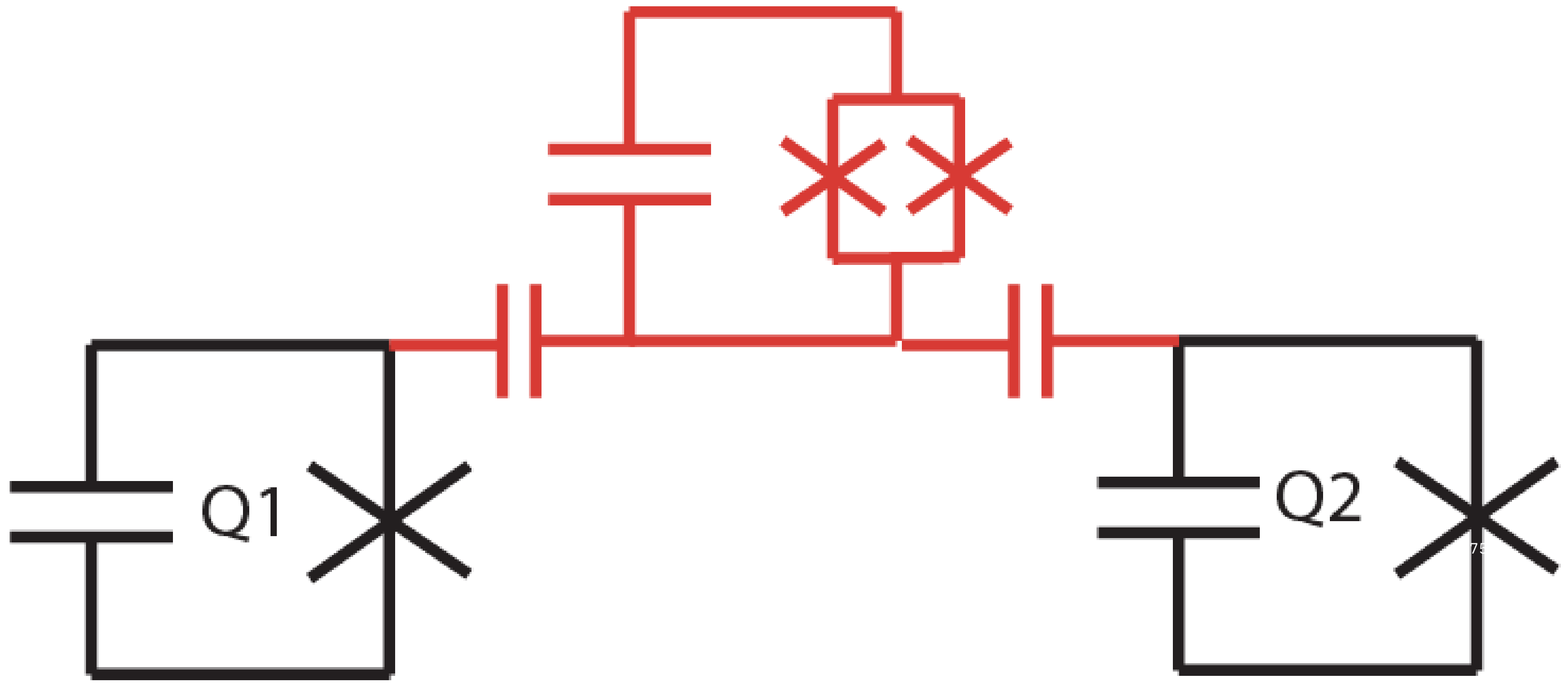

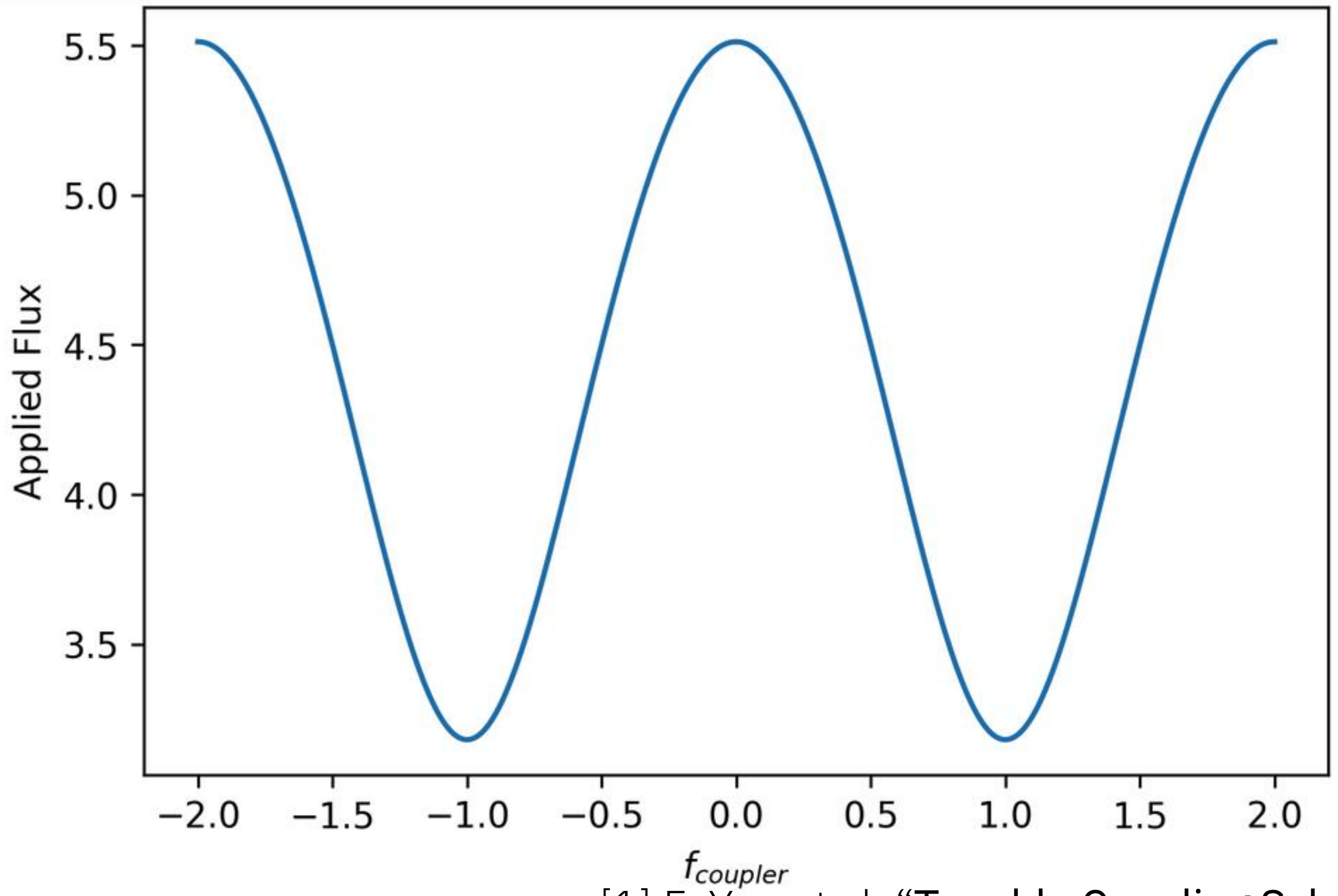

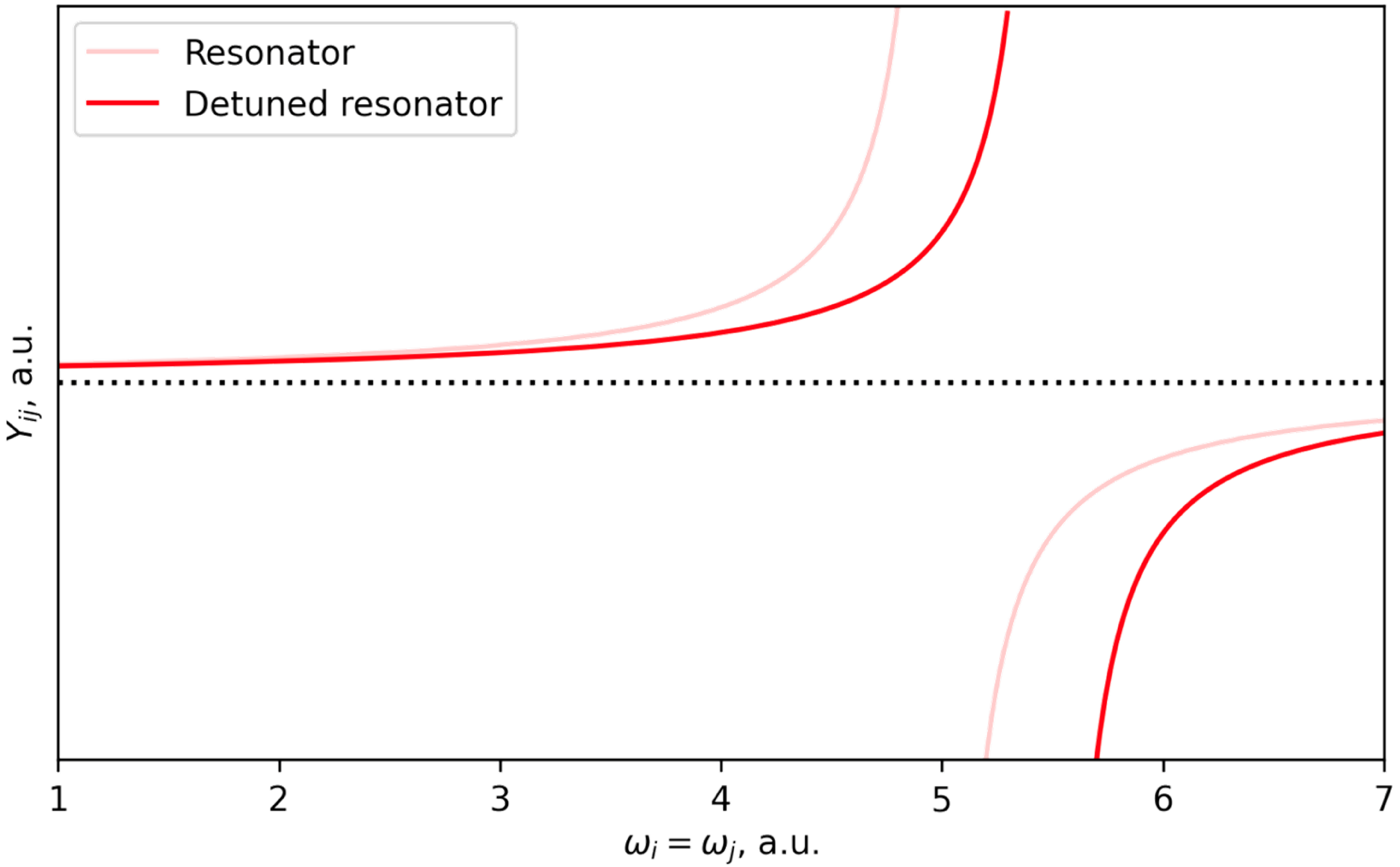

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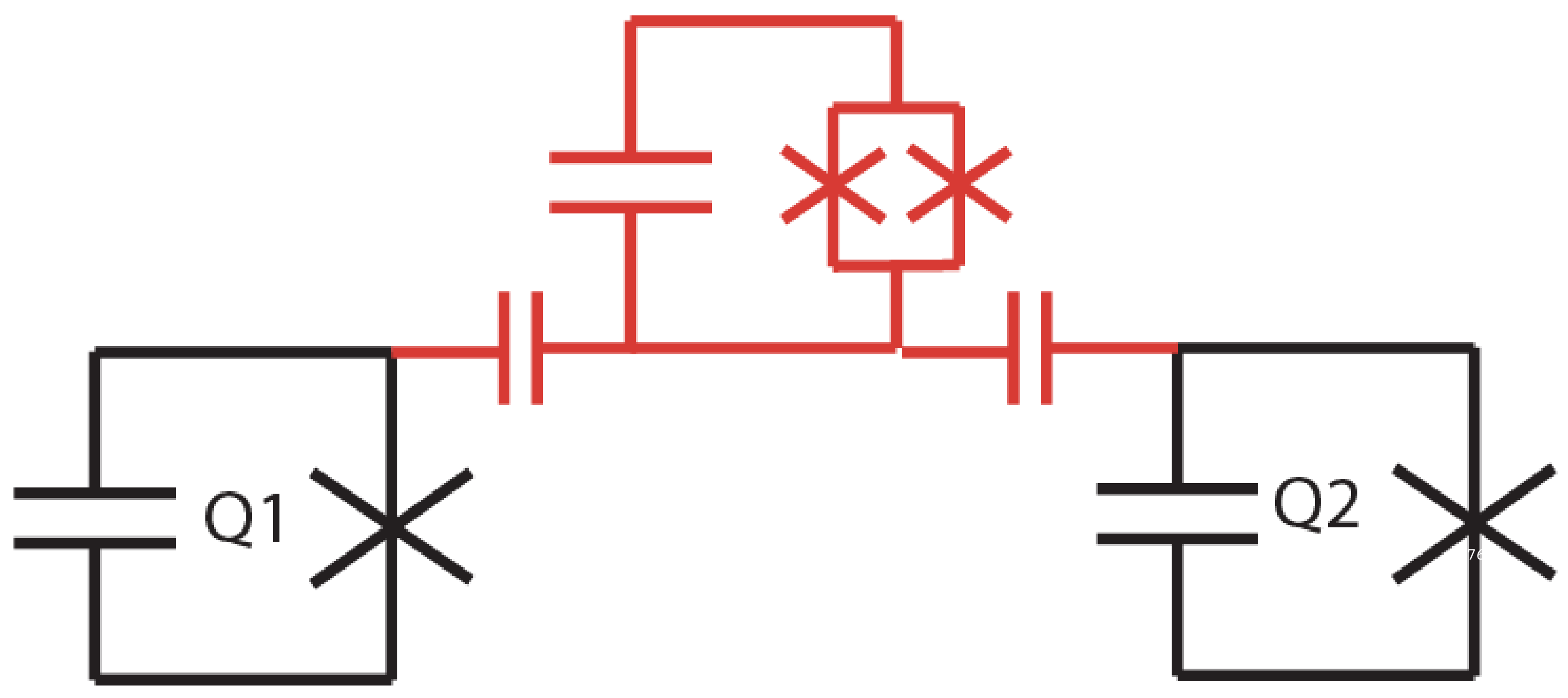

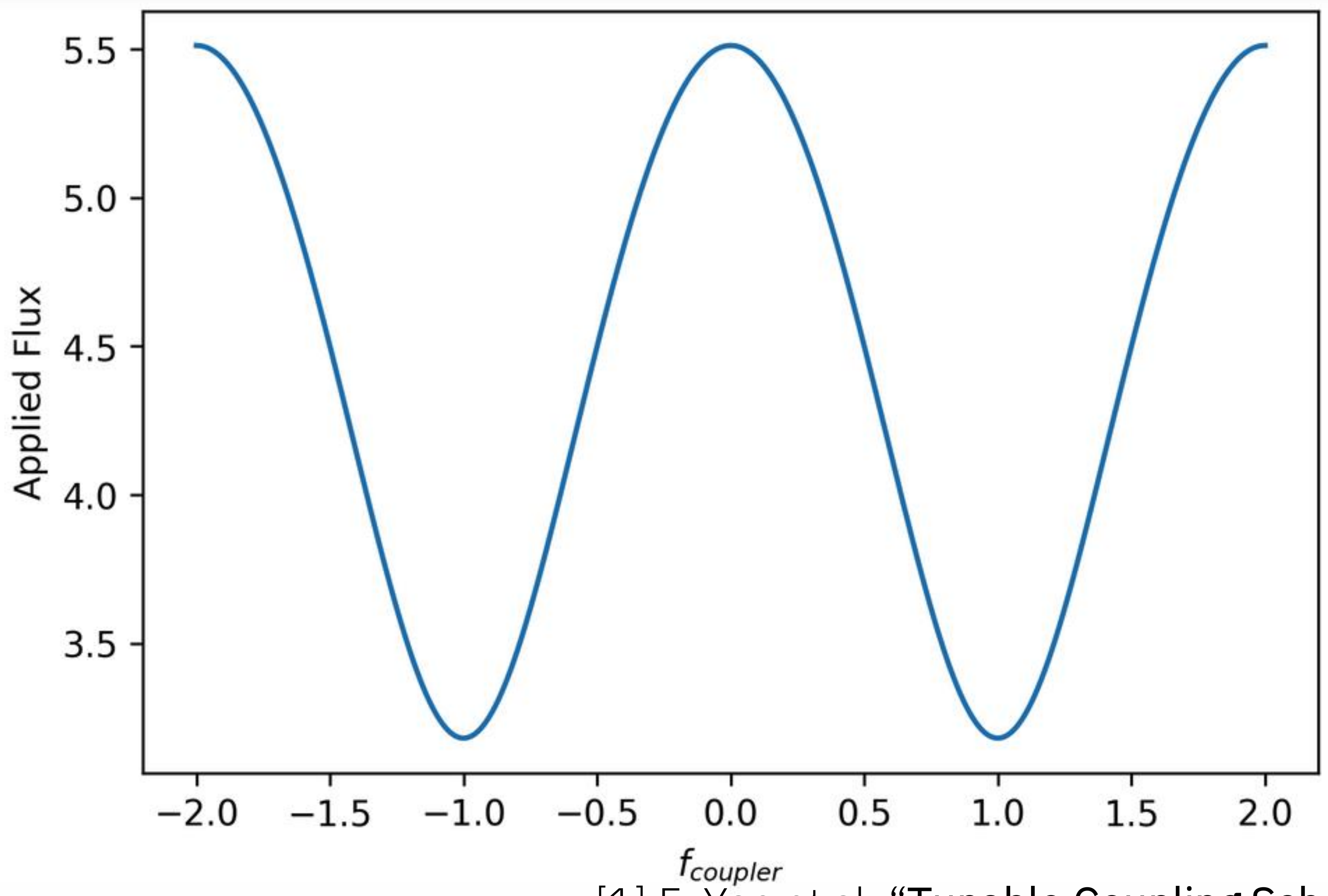

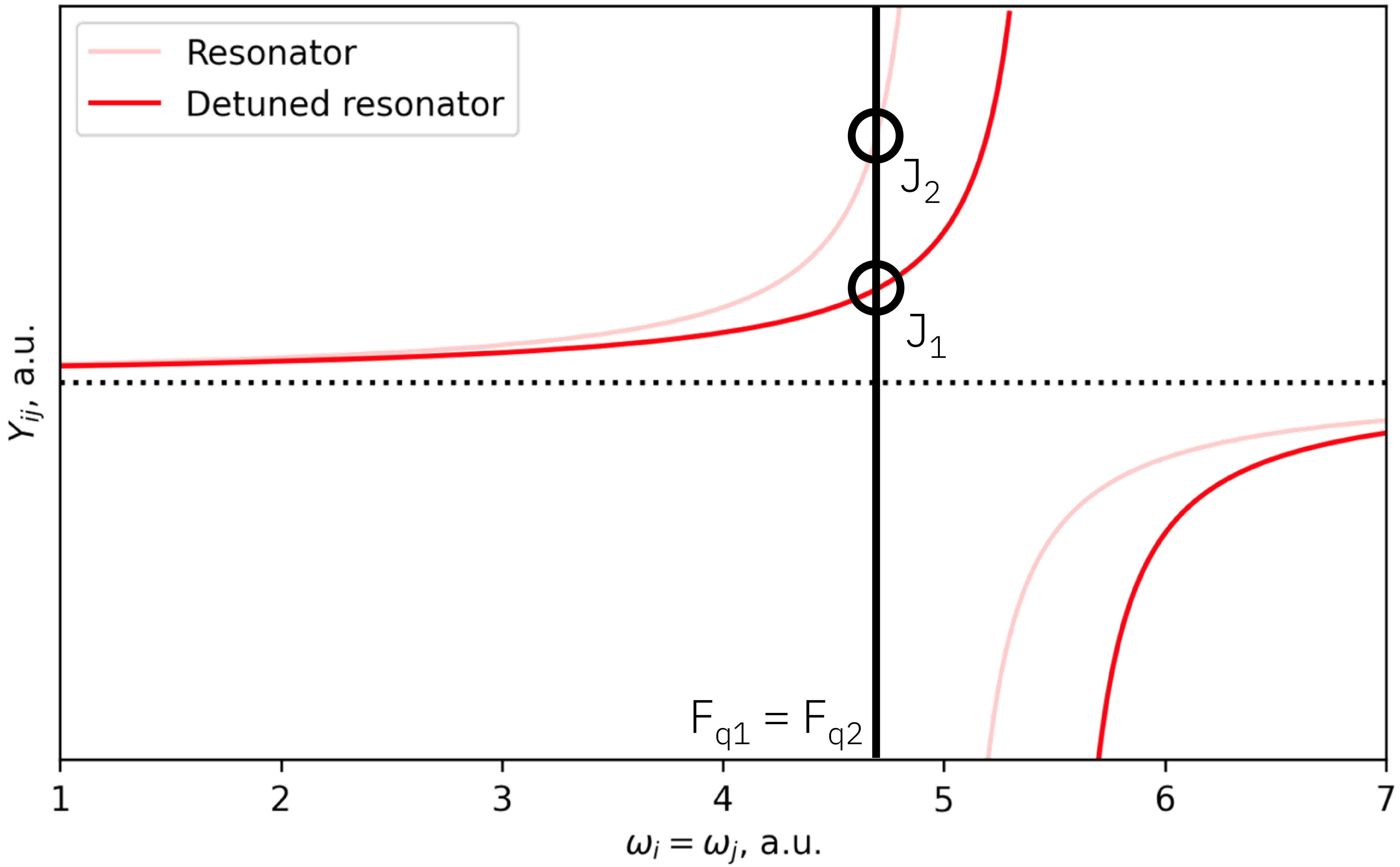

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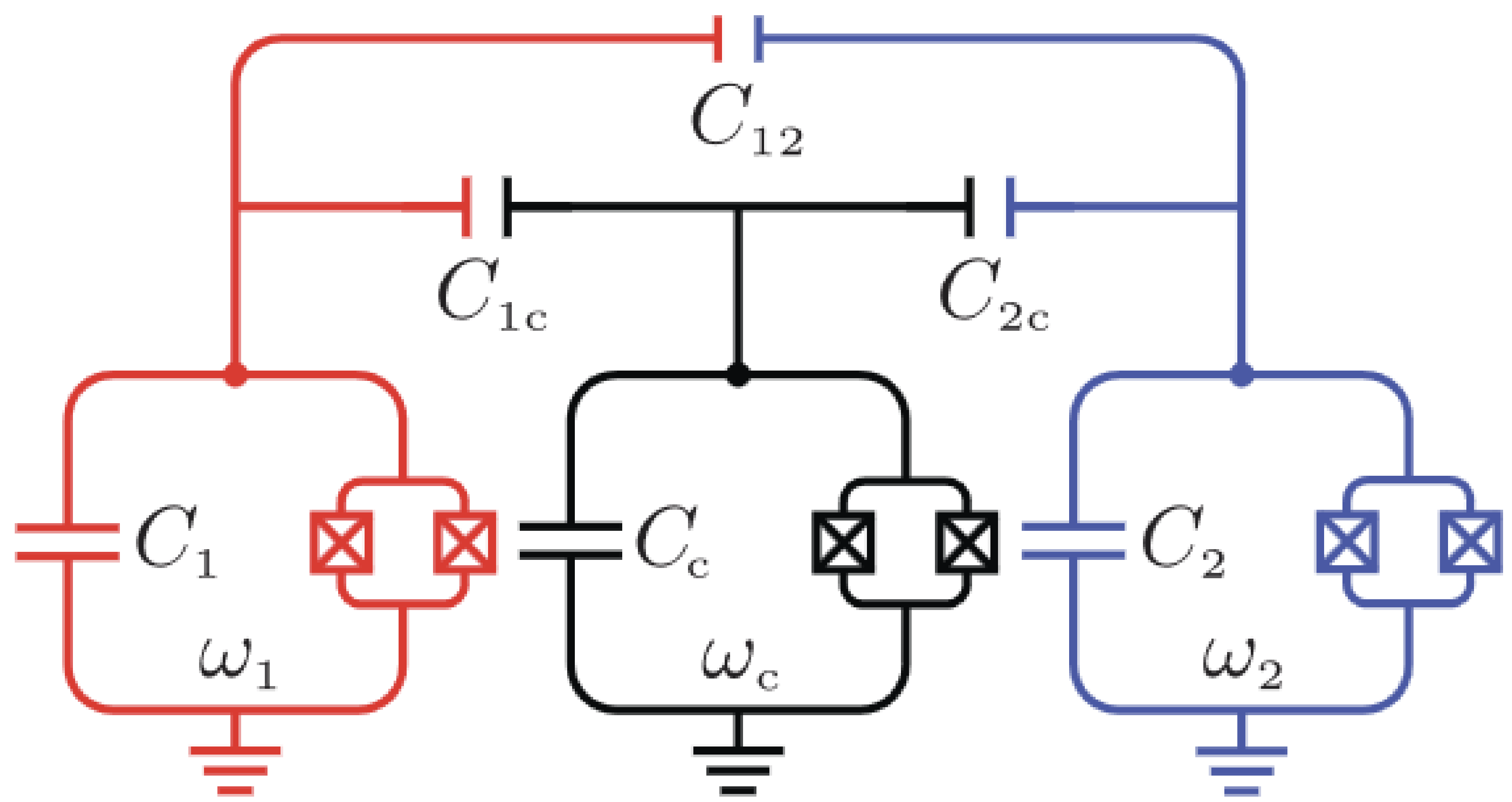

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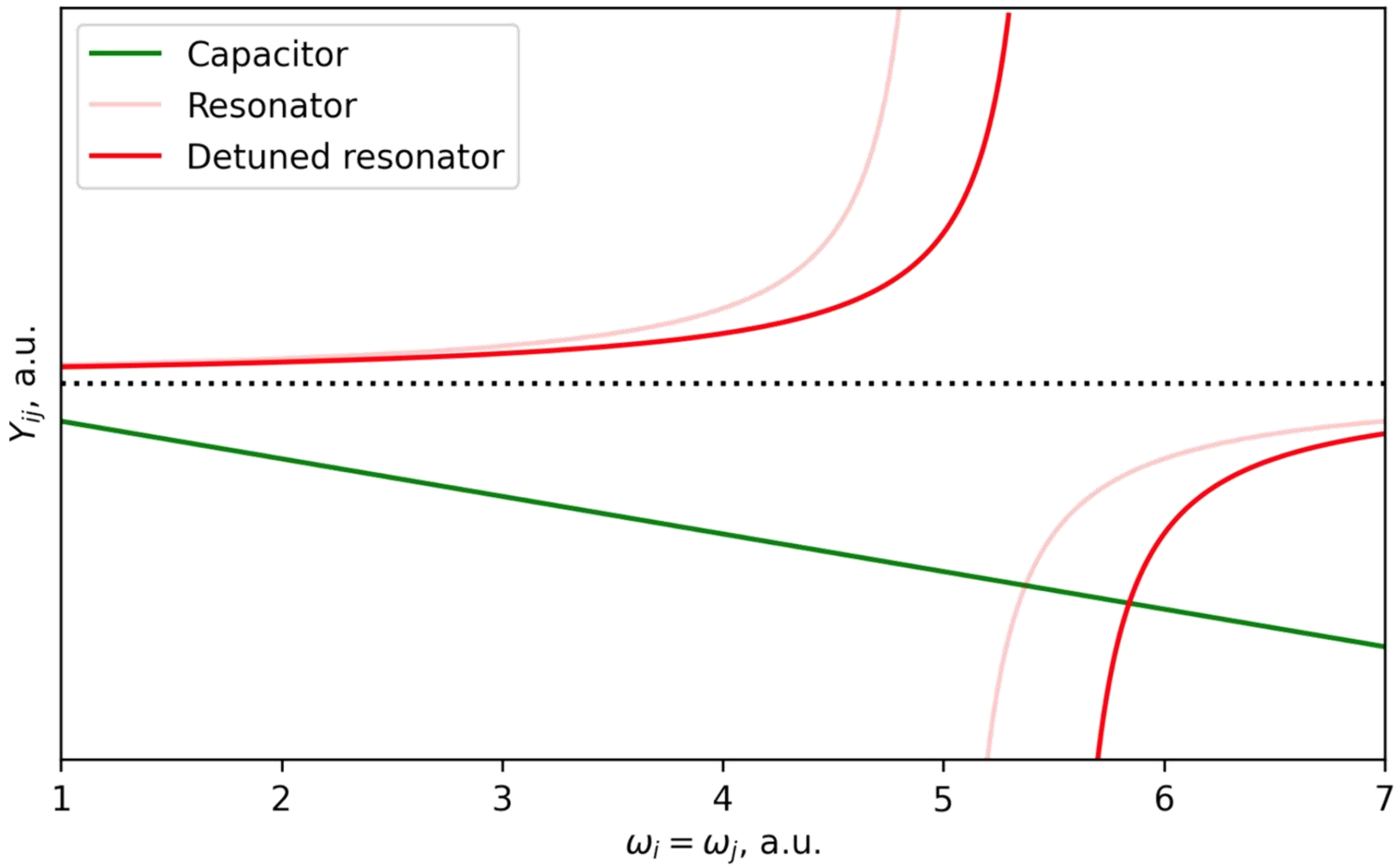

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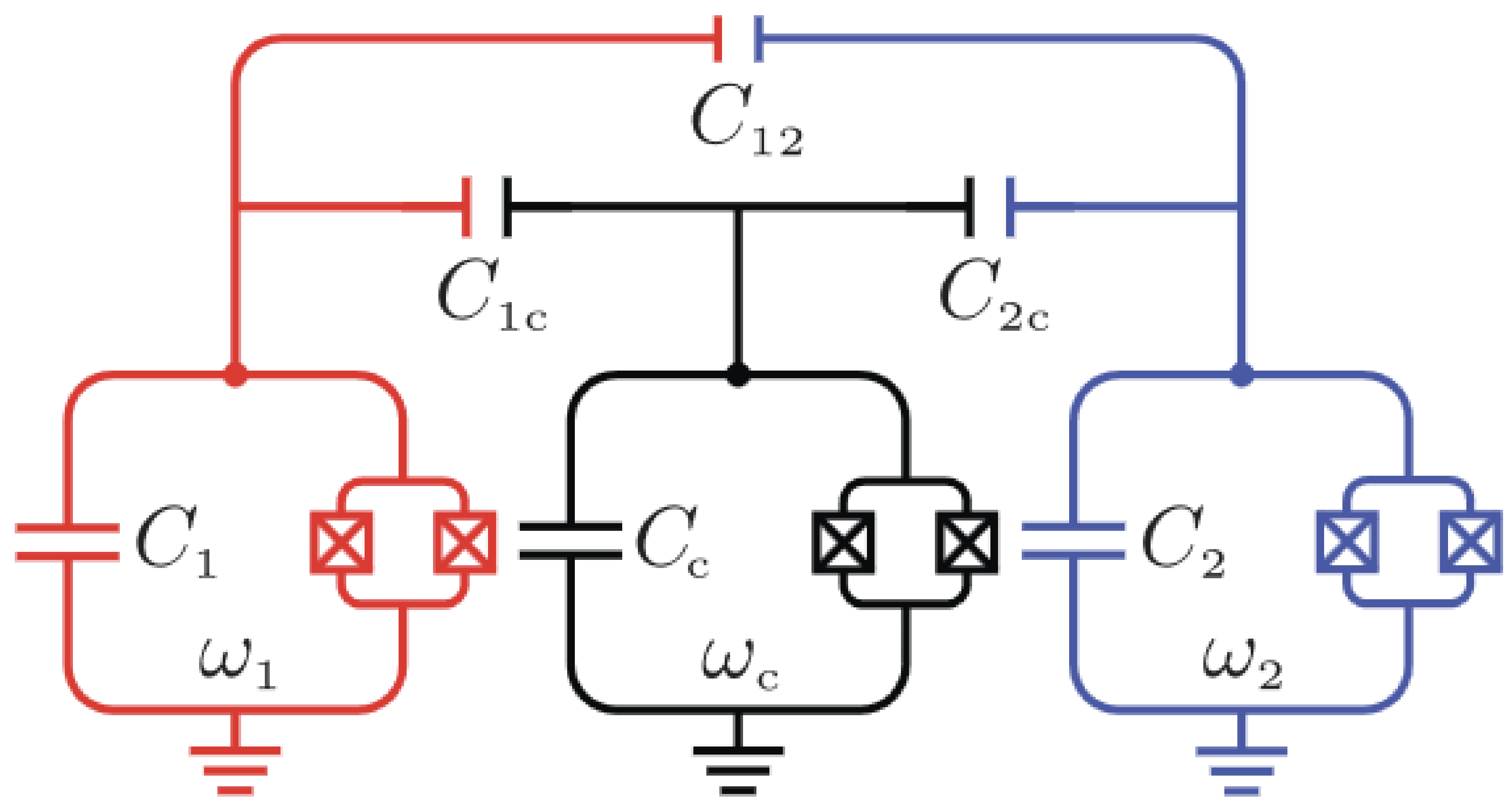

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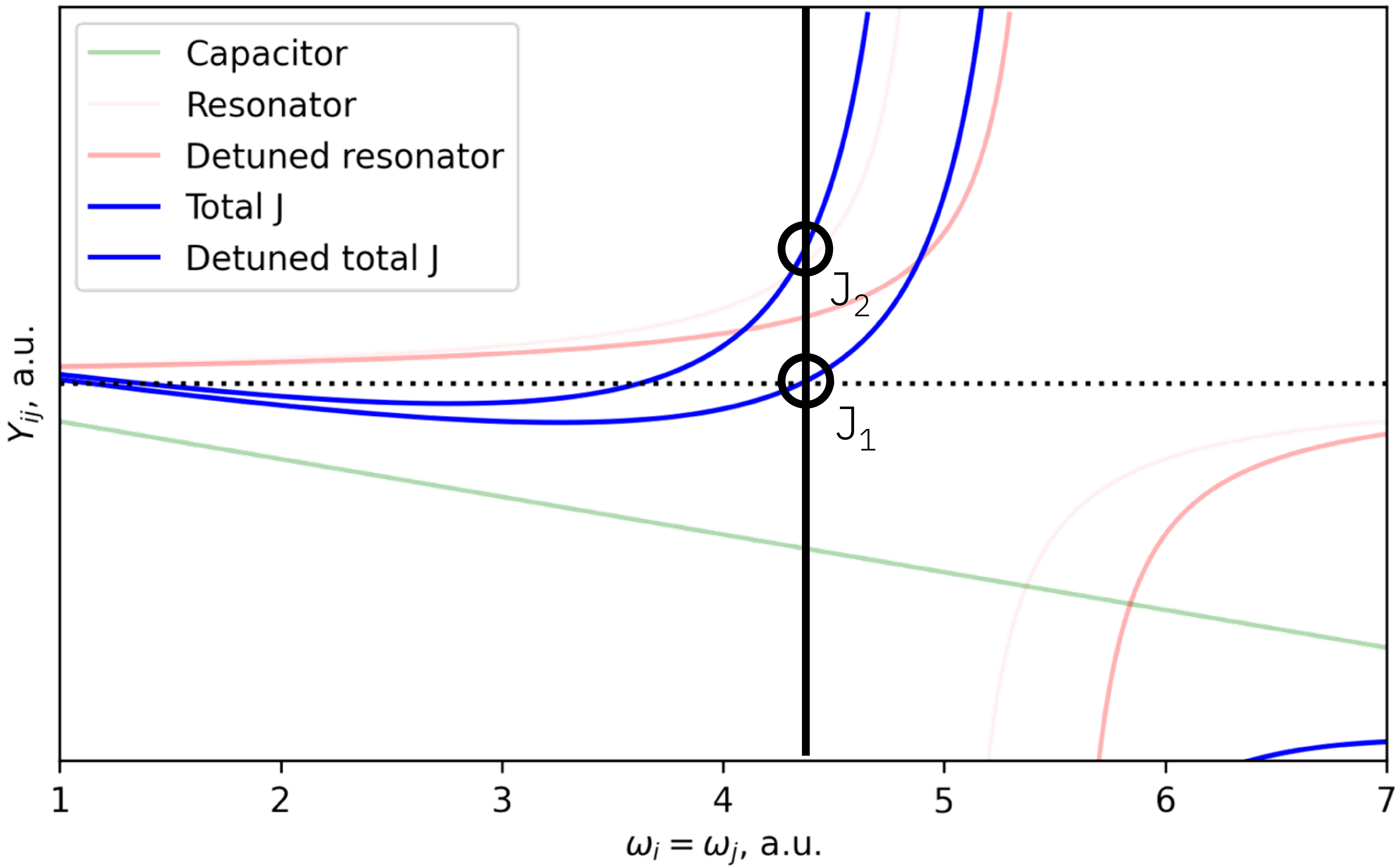

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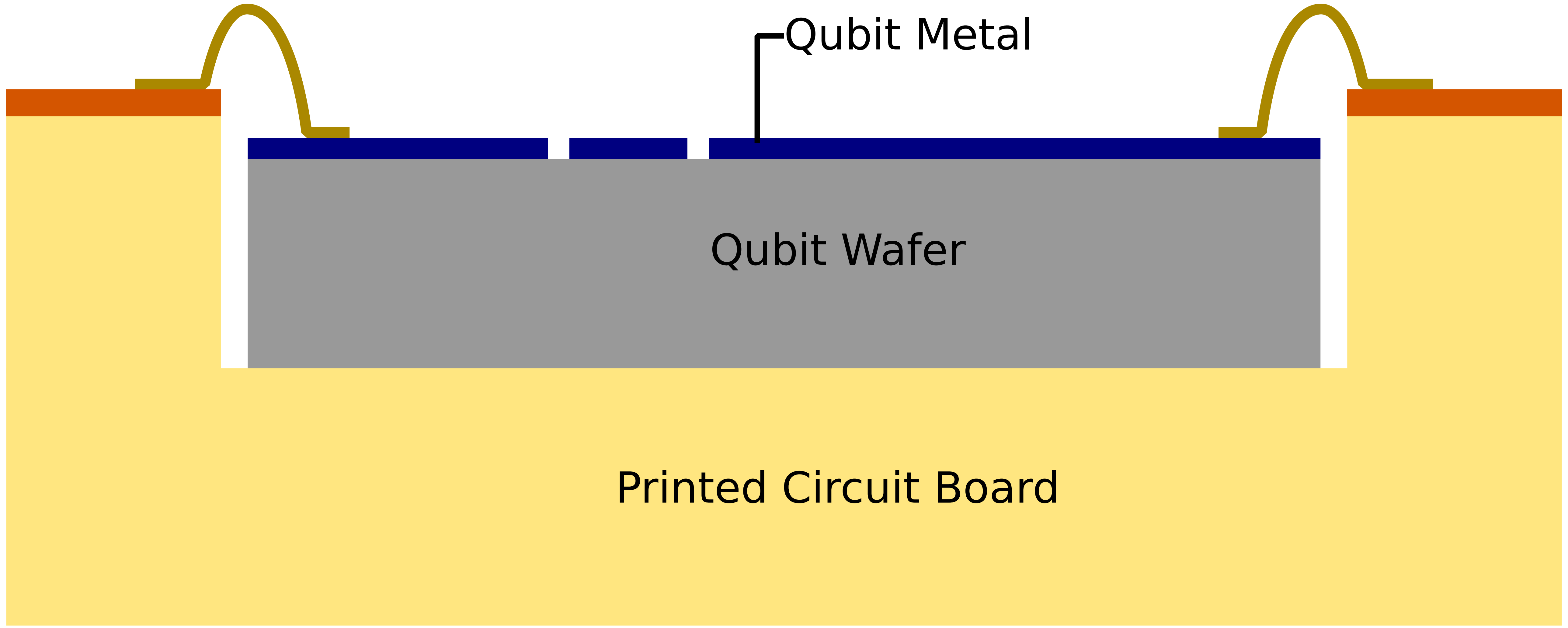
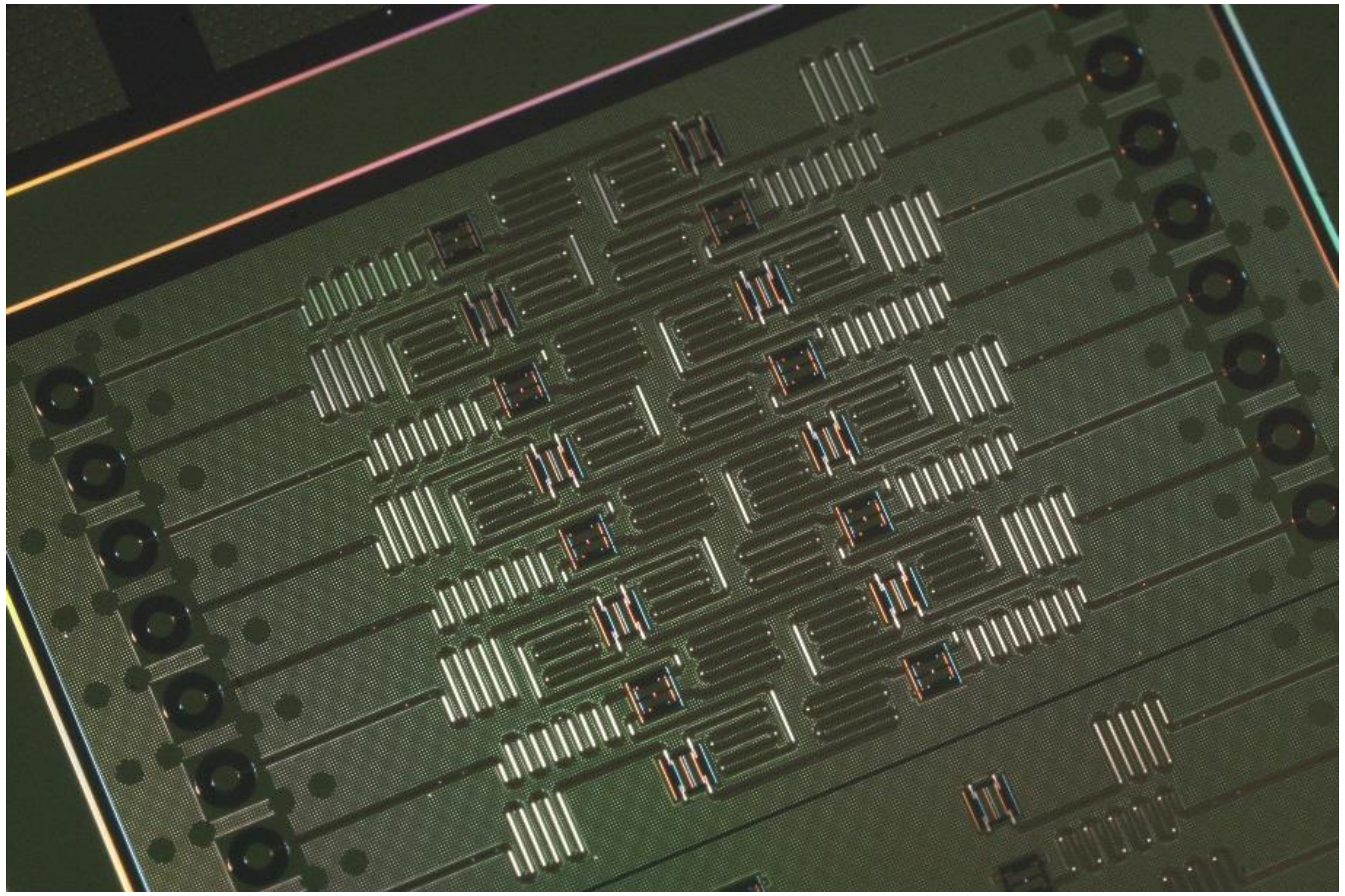
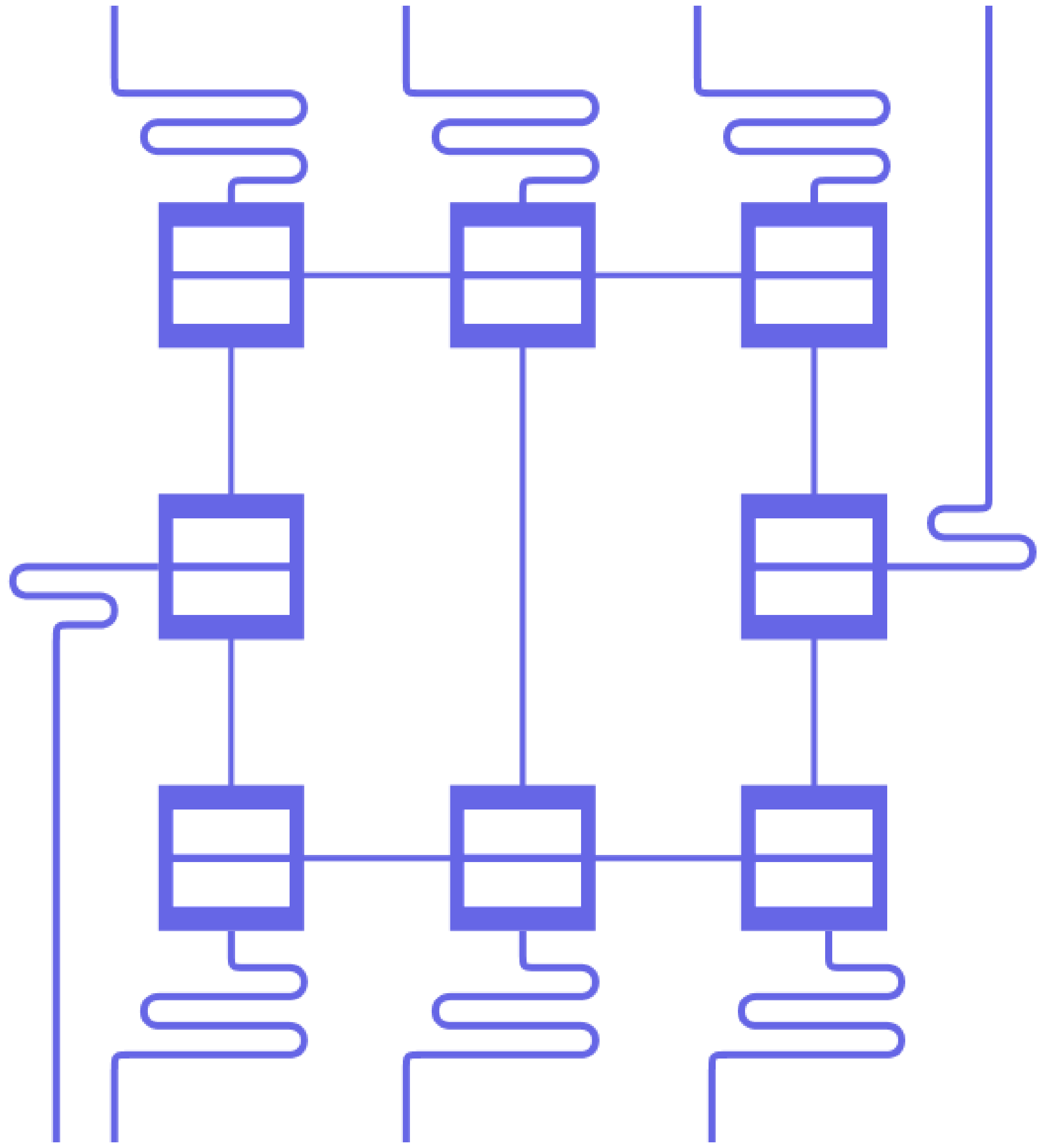
Architecture

Evolution of Packaging Schemes: Generation 1

- Single layer of metal
  - Works fine for “Ring” topologies
  - Breaks down if there are any qubits inside ring







[1] Roushan, P. et al. Science **358**. (2017)

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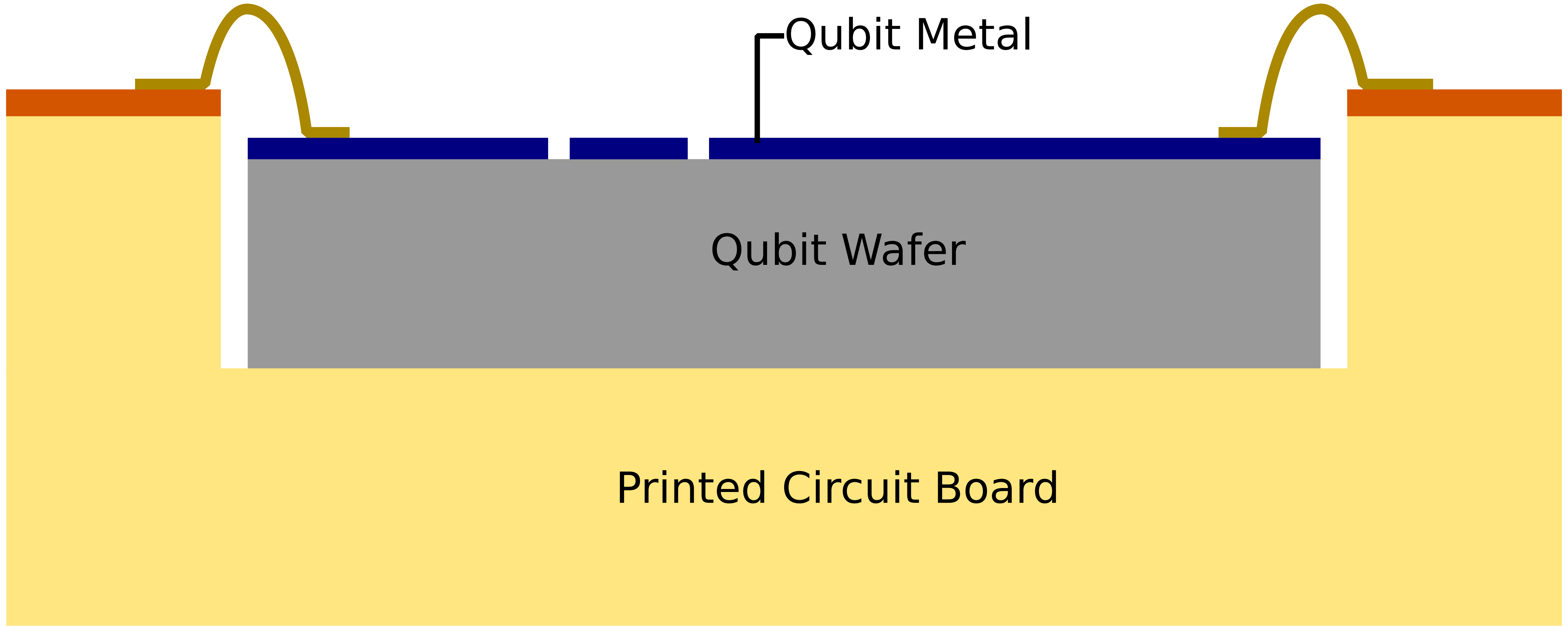
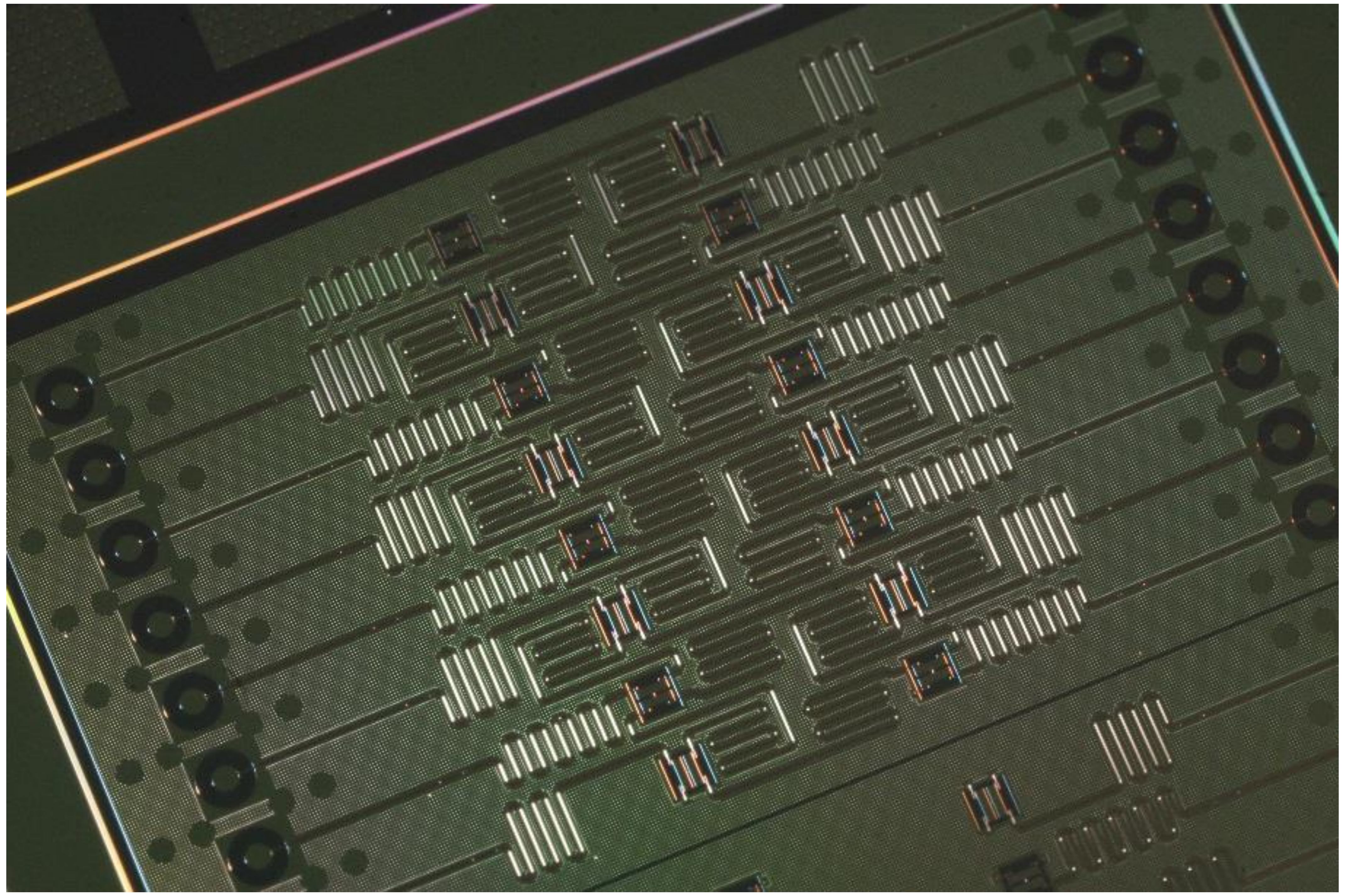
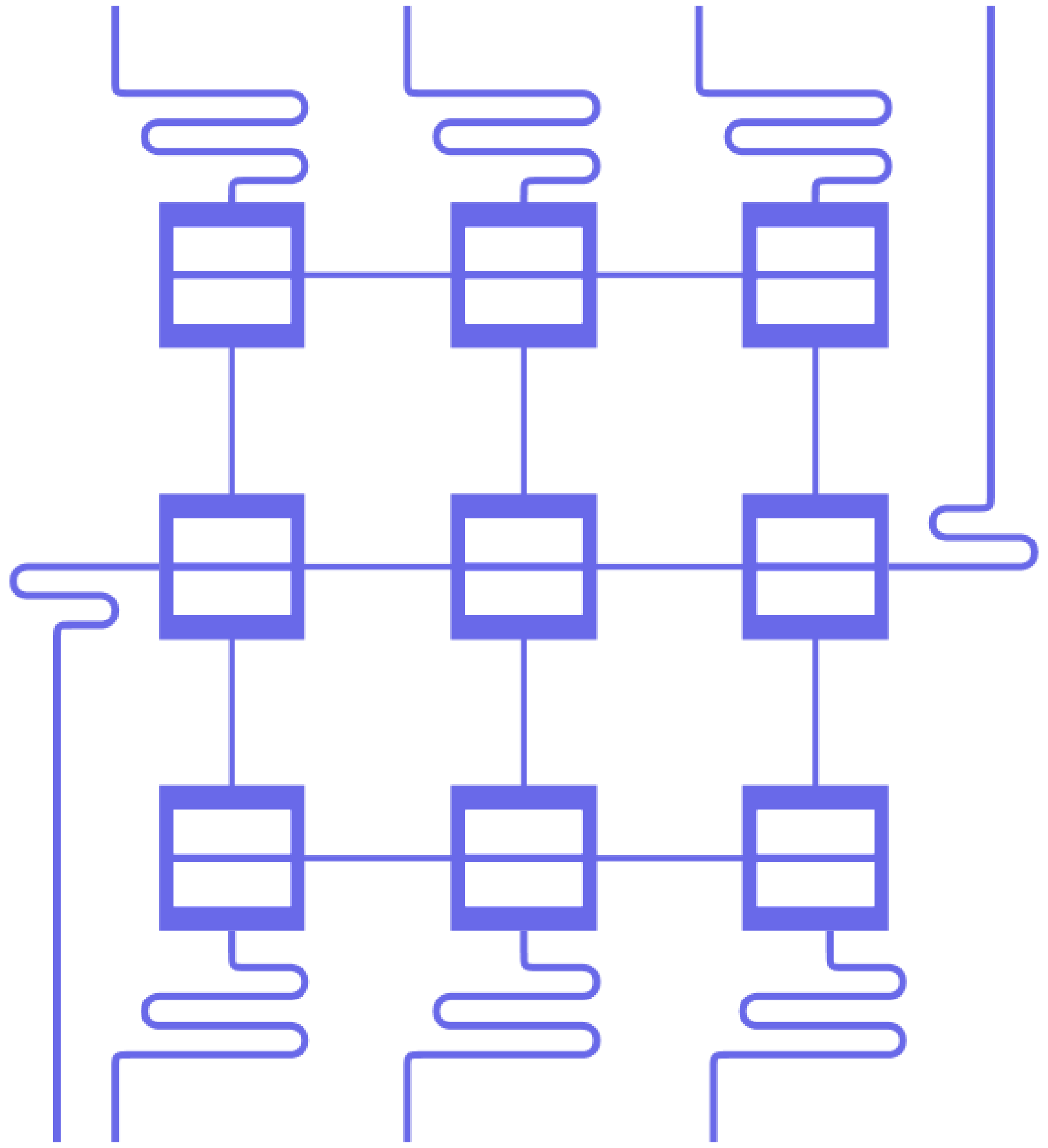


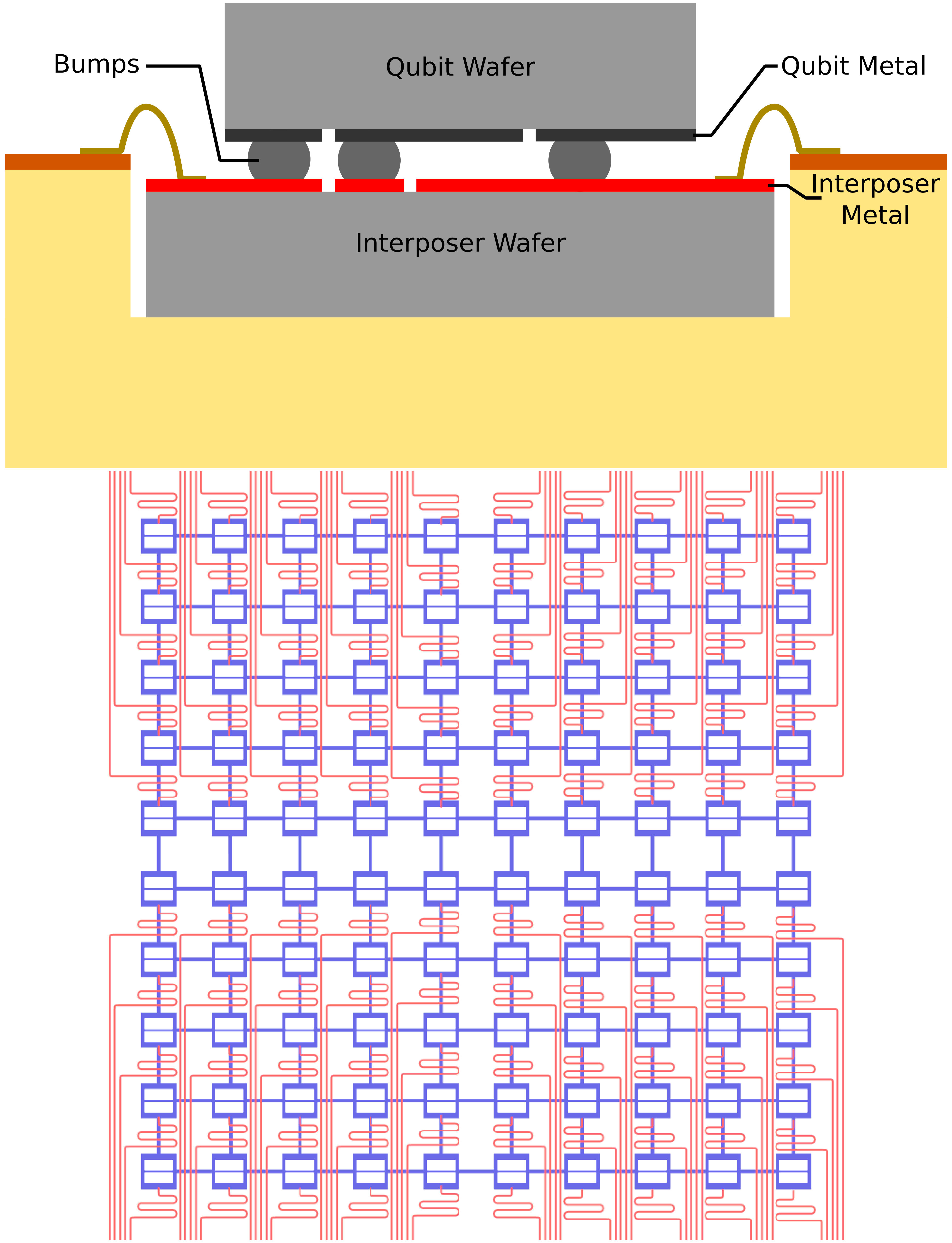


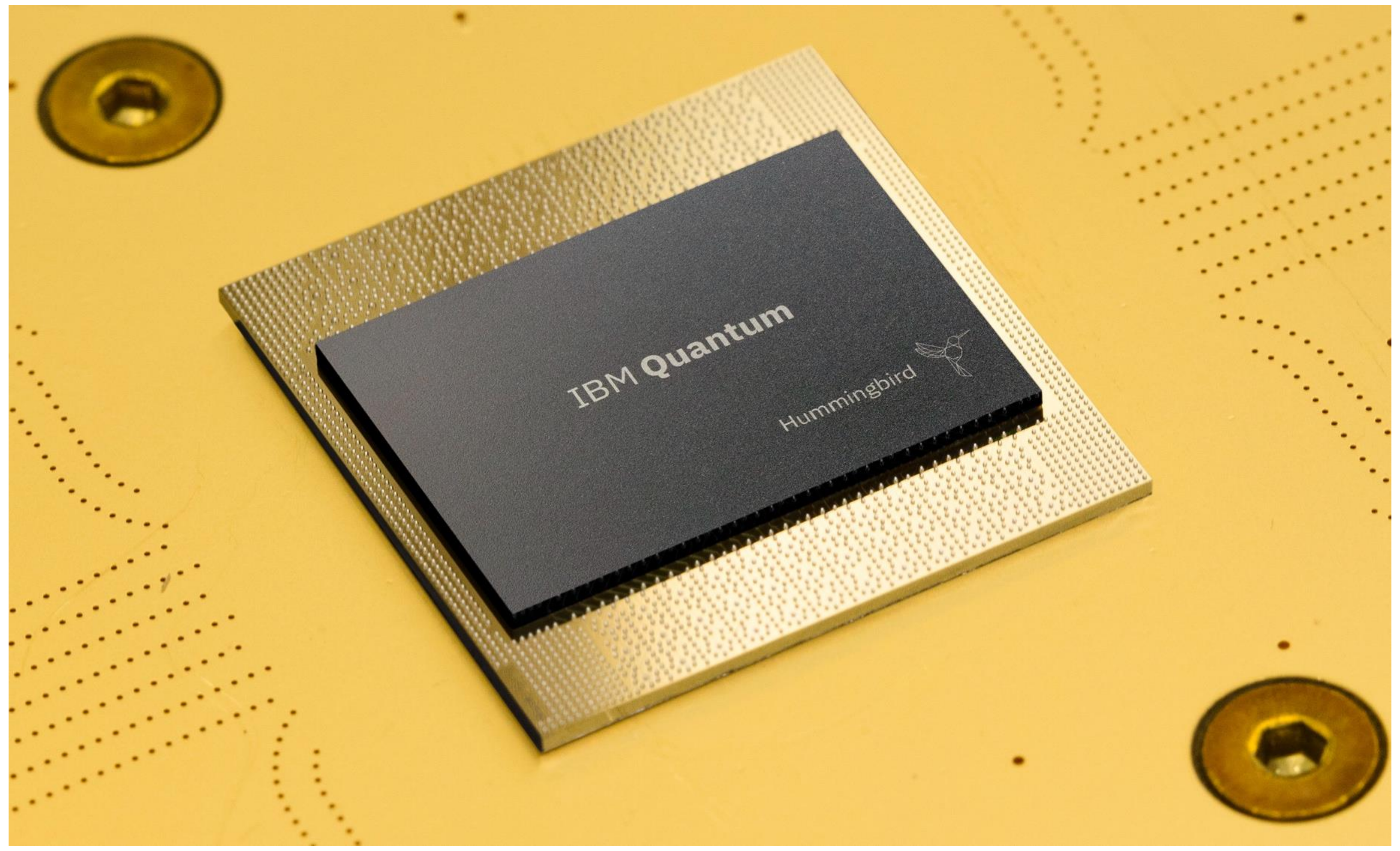


[1] Roushan, P. et al. Science **358**. (2017)

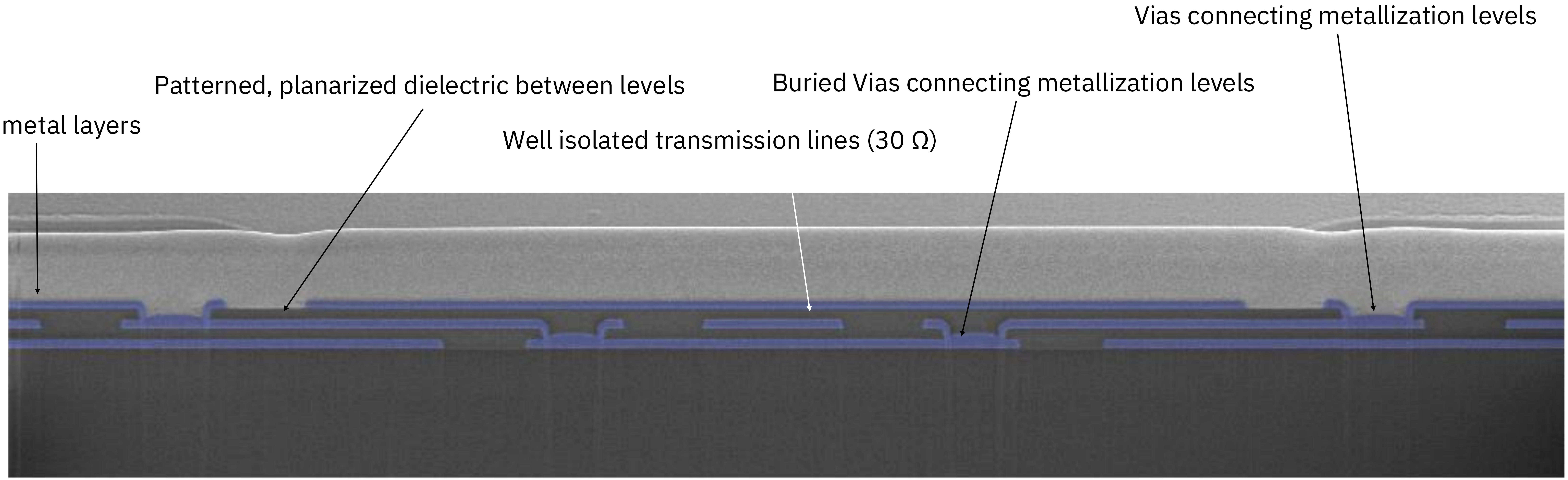
Evolution of Packaging Schemes: Generation 2

- Two separate chips, each with one layer of patterned metal
  - Joined via superconducting bump bonds
  - Allows nearest-neighbor qubit coupling
  - All control and readout lines must be routed to periphery of chip
  - Metal layers are not isolated from each other



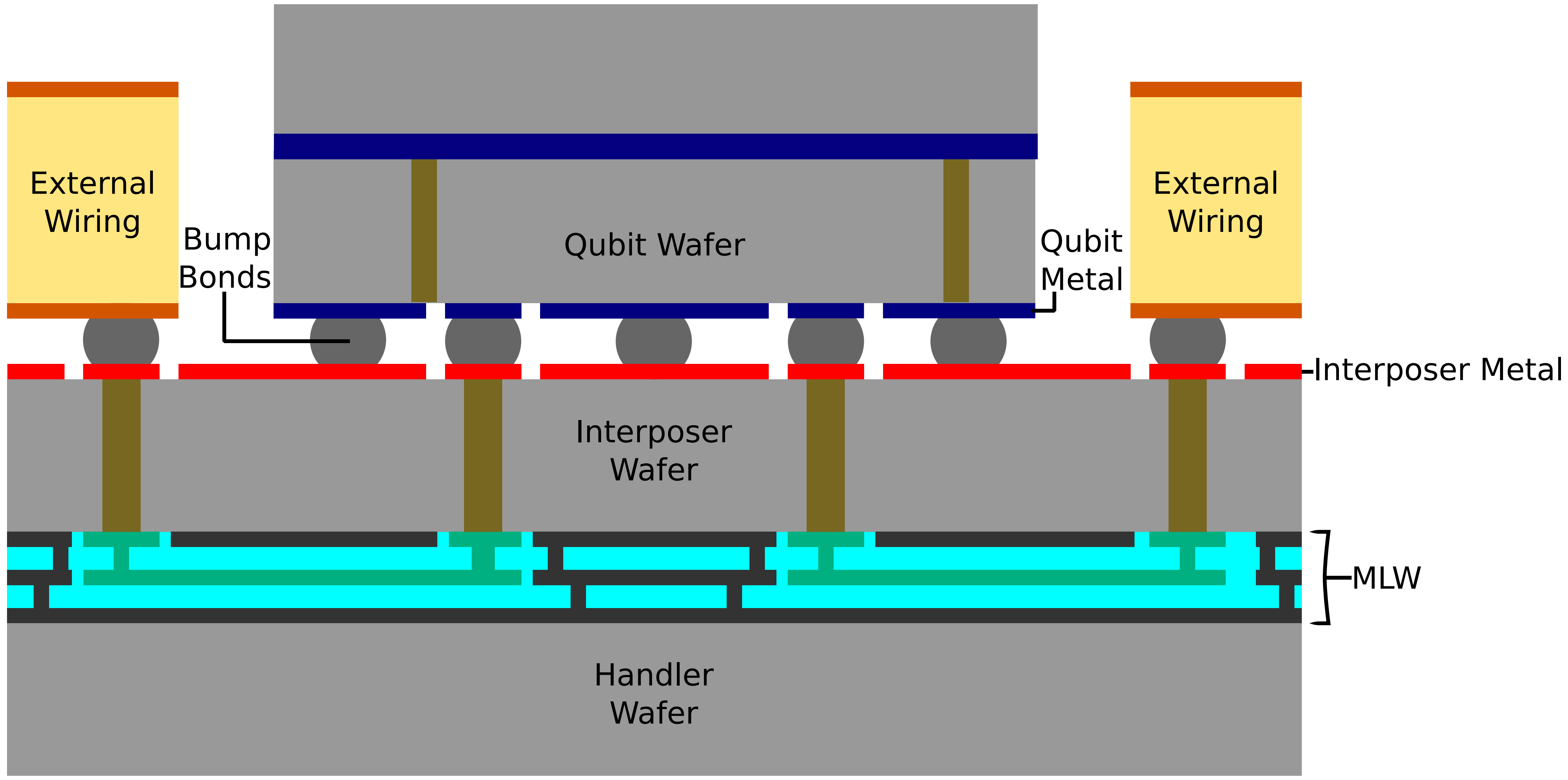


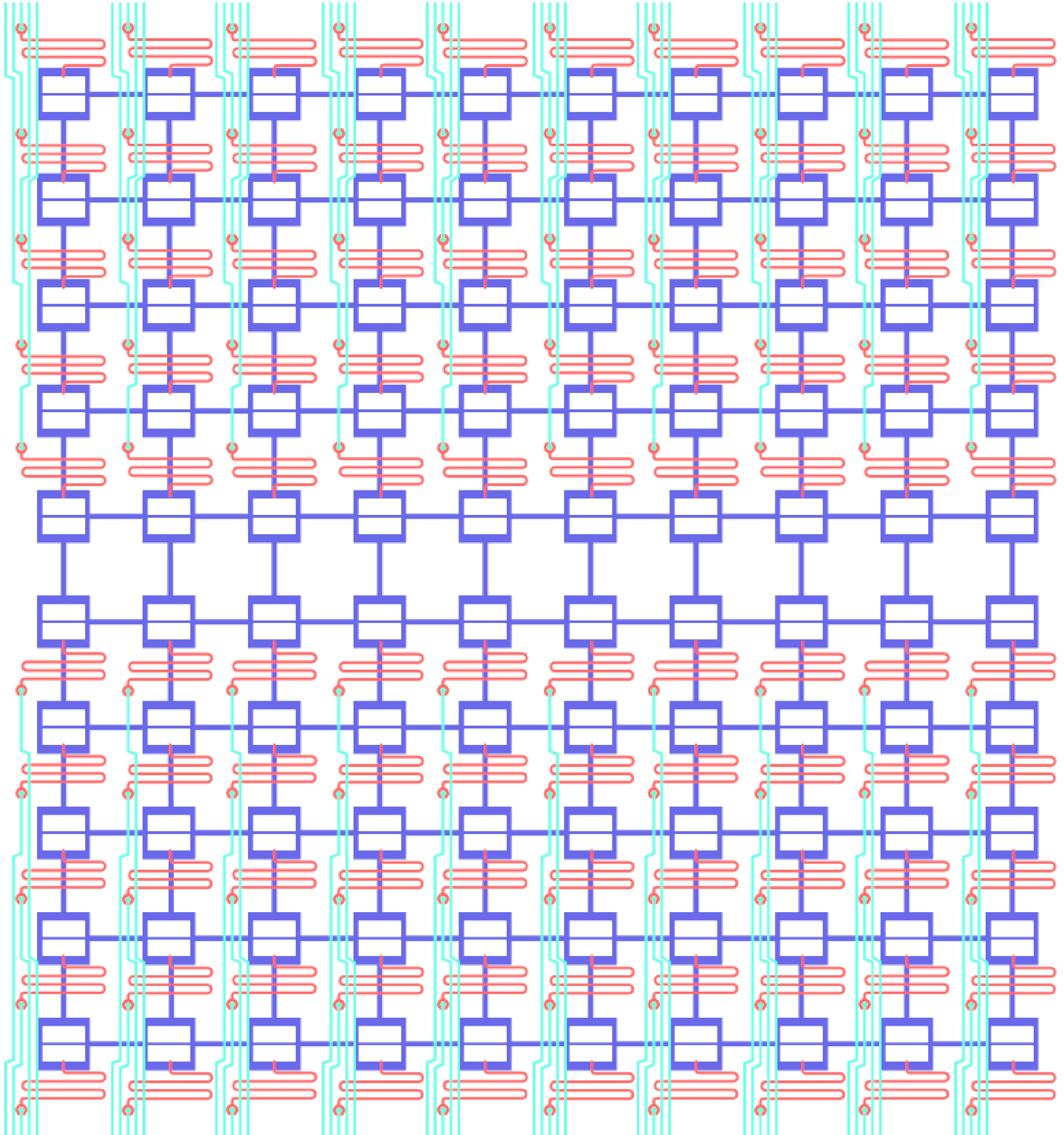
Beyond breaking the plane: Superconducting Multi-Layer Wiring



Evolution of Packaging Schemes: Generation 3

- Two chips, as before
  - Add “Multi-level Wiring” (MLW) level formed on backside of interposer
  - Control and readout signals routed as striplines in the MLW
  - Well isolated from Interposer and Qubit metal levels
  - Connect to MLW via superconducting Through-Substrate-Vias (TSVs)

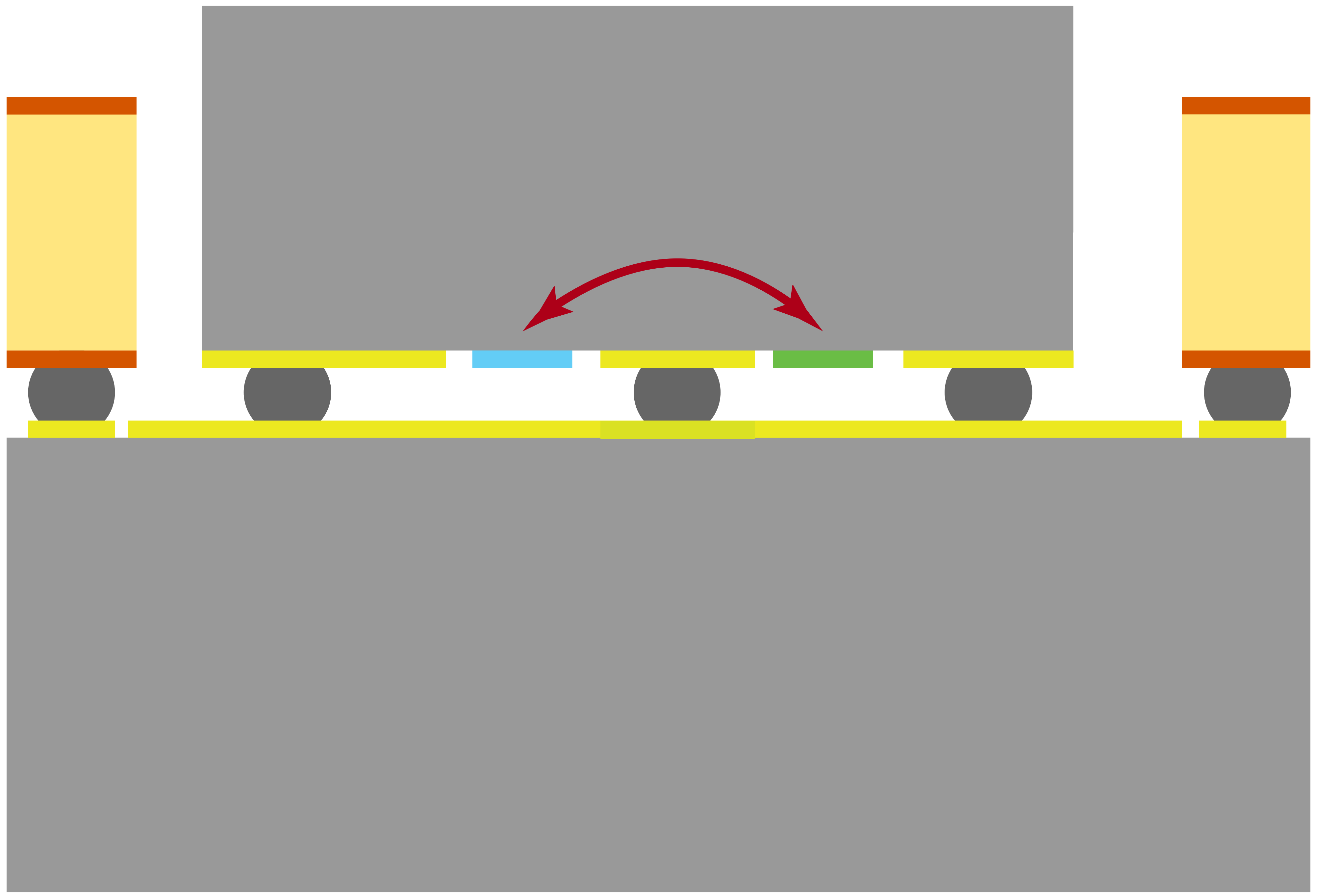




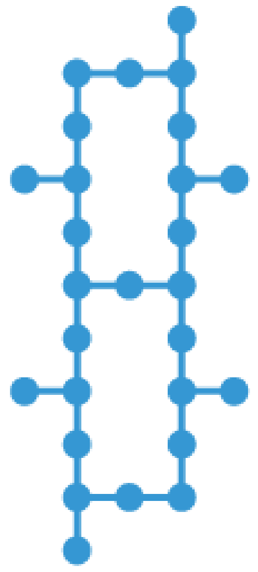
[1] Licata, T.J. et al. IBM Journal of R&D **39**. (1995)

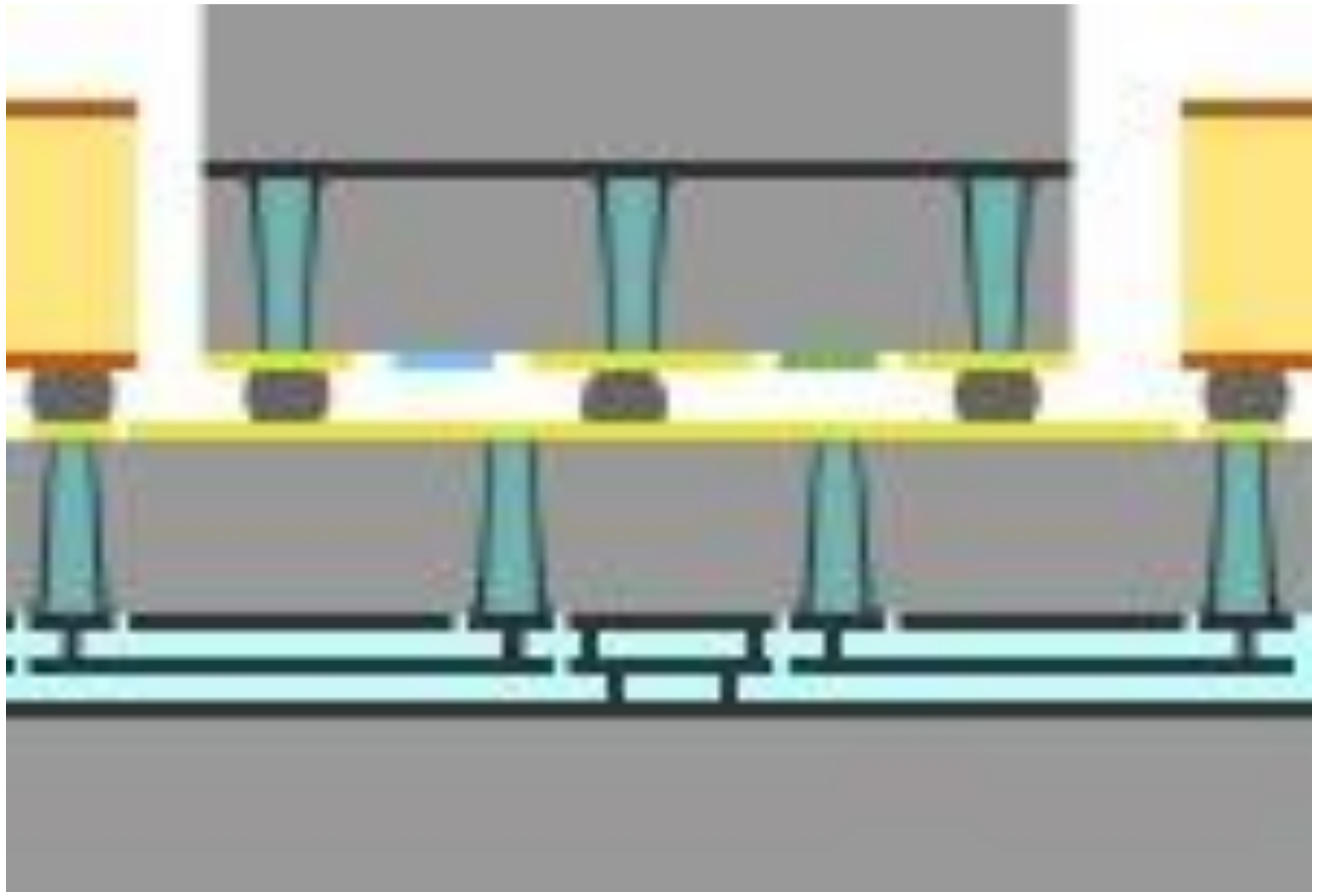
[2] Edelstein, D. et al. International Electron Devices Meeting. IEDM Technical Digest (1997)

Crosstalk

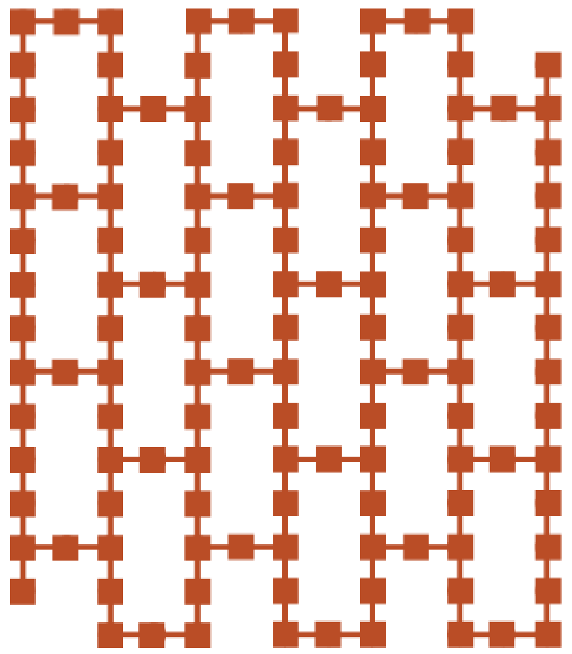


Generation 2 = Falcon
(via fencing impossible)

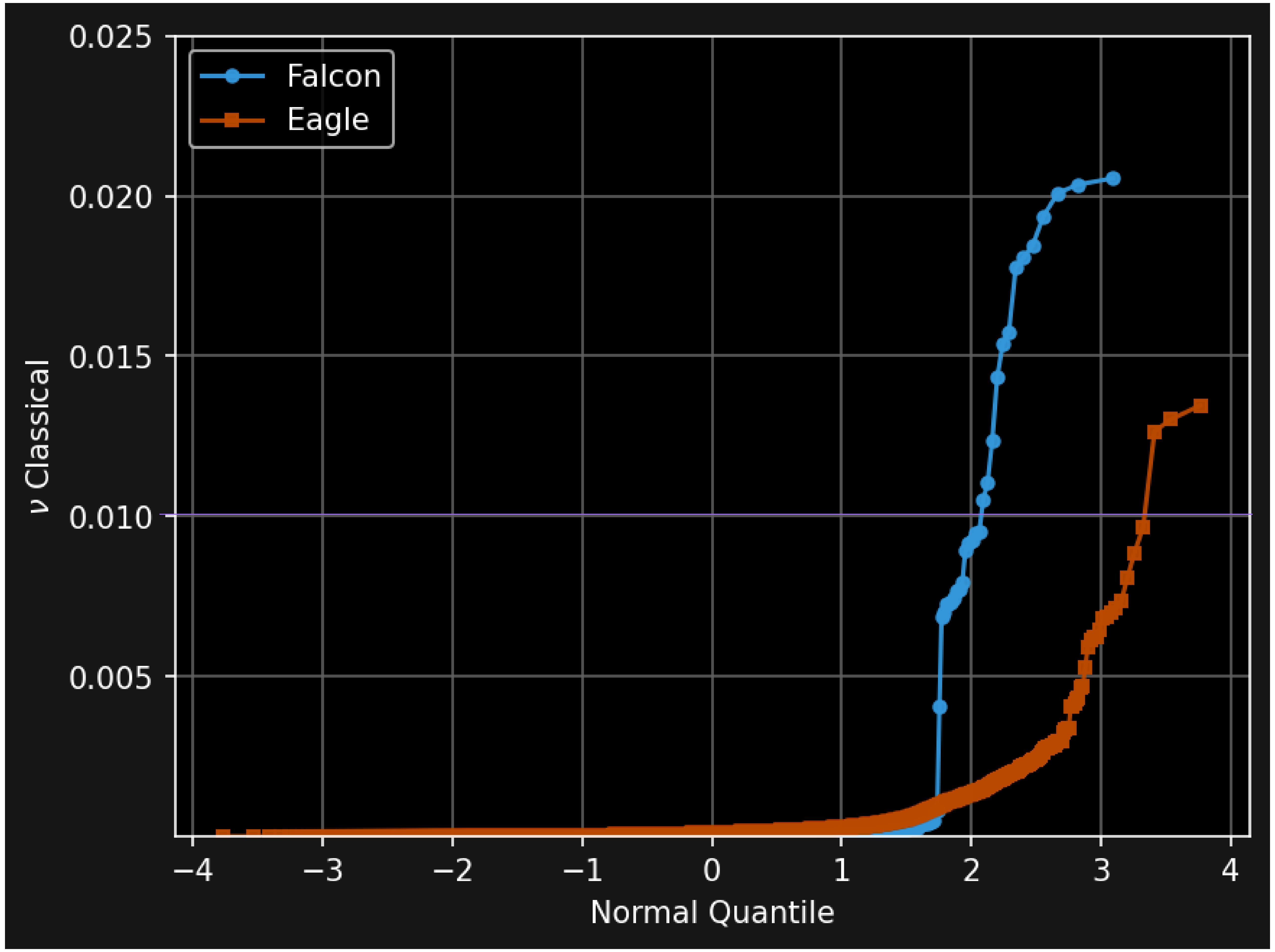


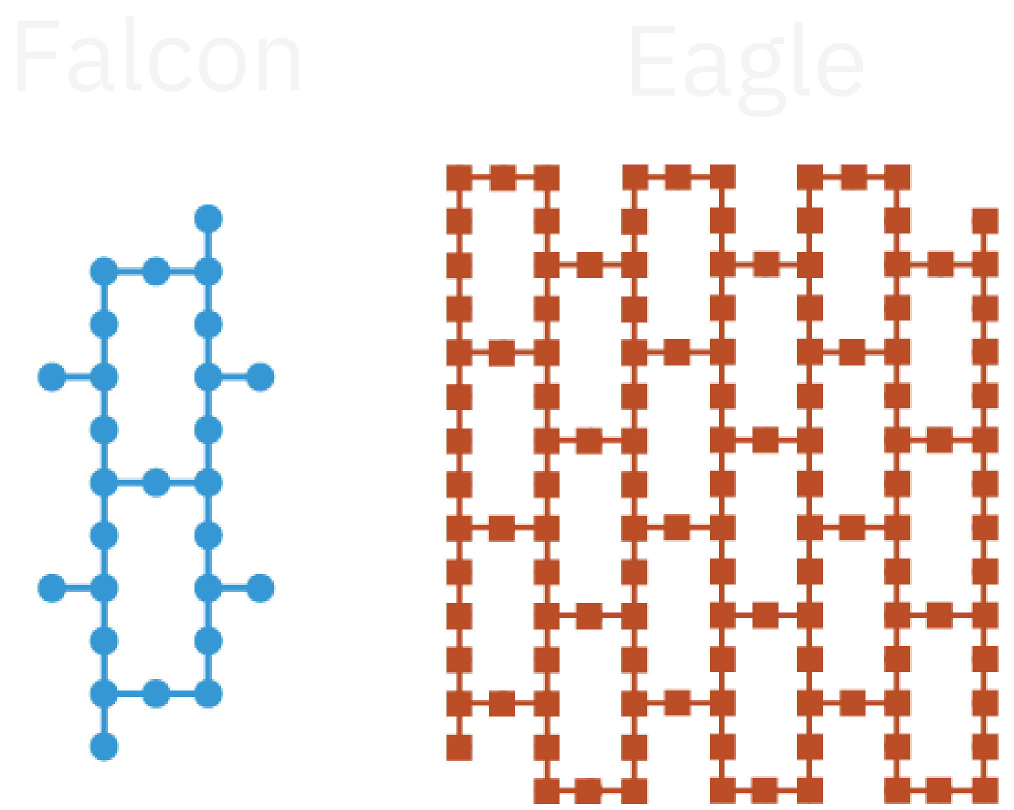


Generation 3 = Eagle
(via fencing possible)



Crosstalk





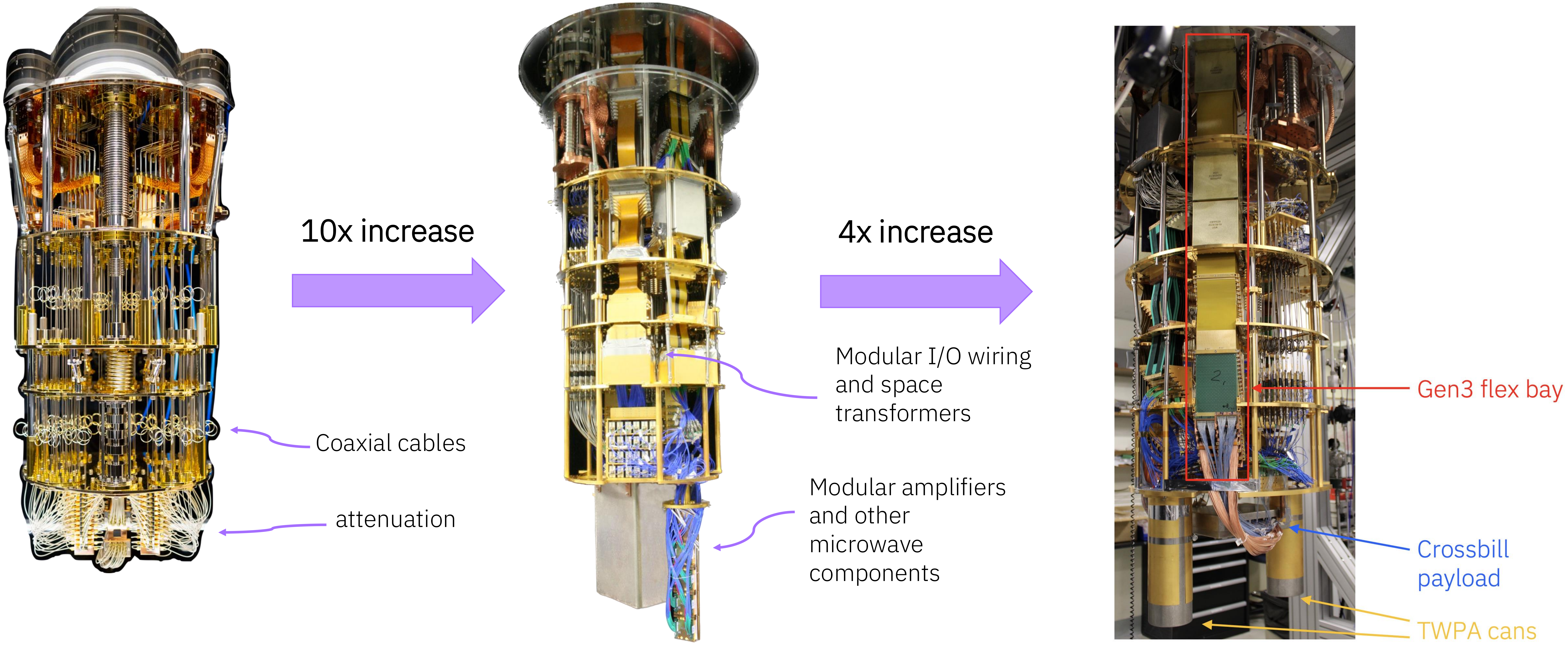
Many fewer (as a fraction) high fliers in crosstalk on Eagle

Which pairs of qubits have high crosstalk is consistent from chip-to-chip in both instances

Eagle has 16,000 pairs of qubits! If measured 1 by 1, finding the 3 qubits with >1% crosstalk would take 11 days…


IBM Q
IBM
HELIUM
HELIUM

Scaling number of qubits in a single cryogenic fridge with better signal lines (Flex)



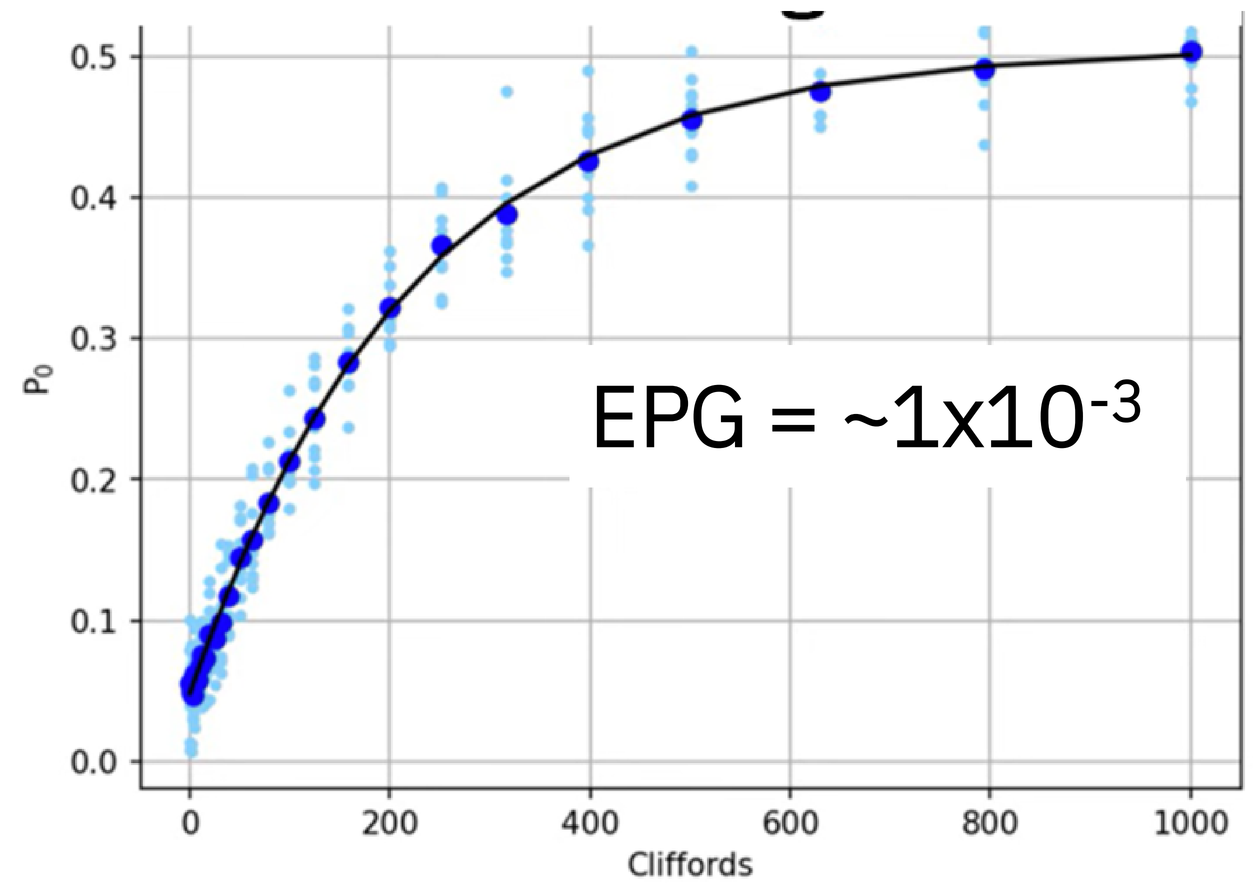
Configuration for 50 cross-resonance qubits

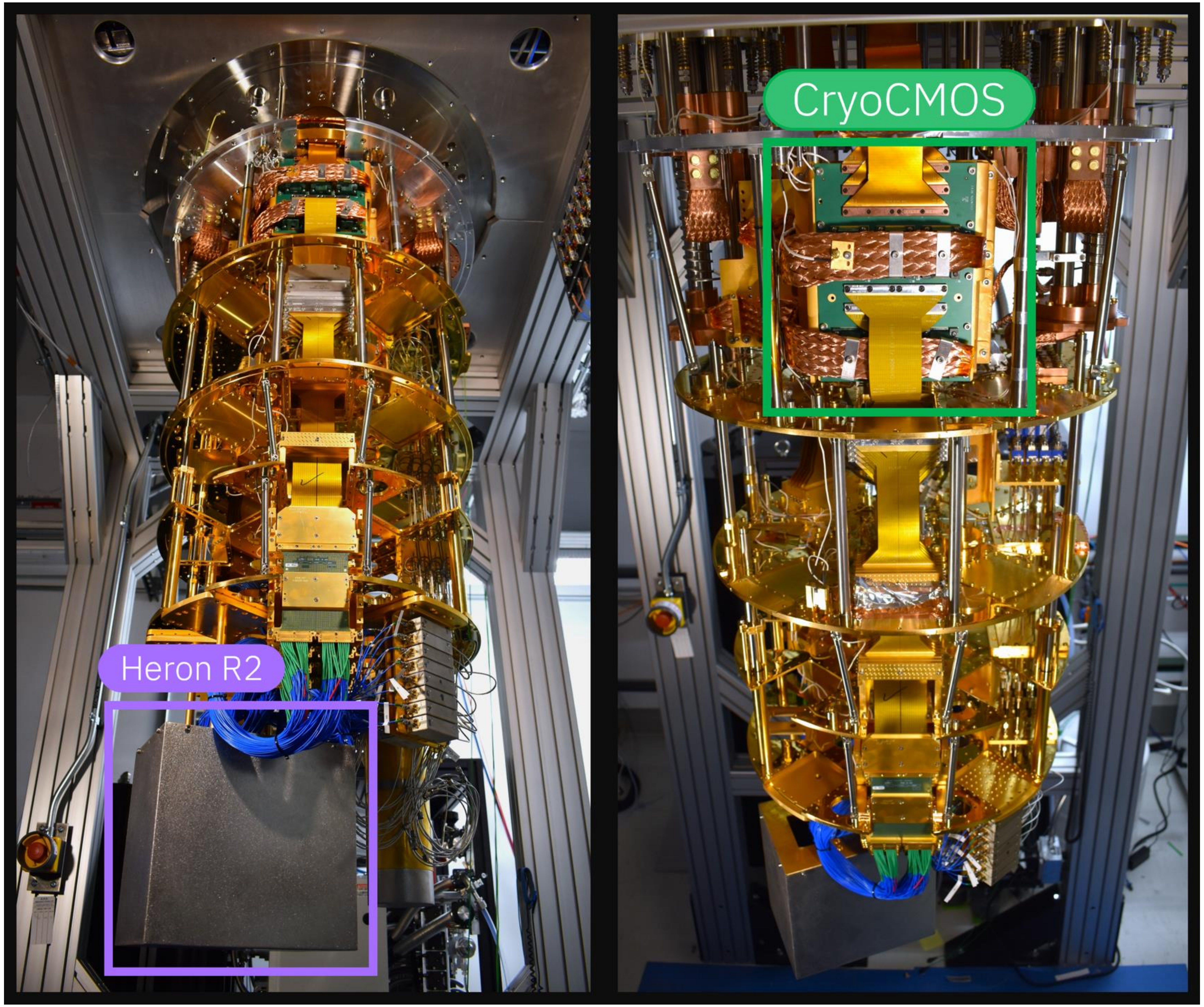
Configuration for 500 cross-resonance qubits

Configuration for 1000 tunable coupler qubits (additional signal lines per qubit)

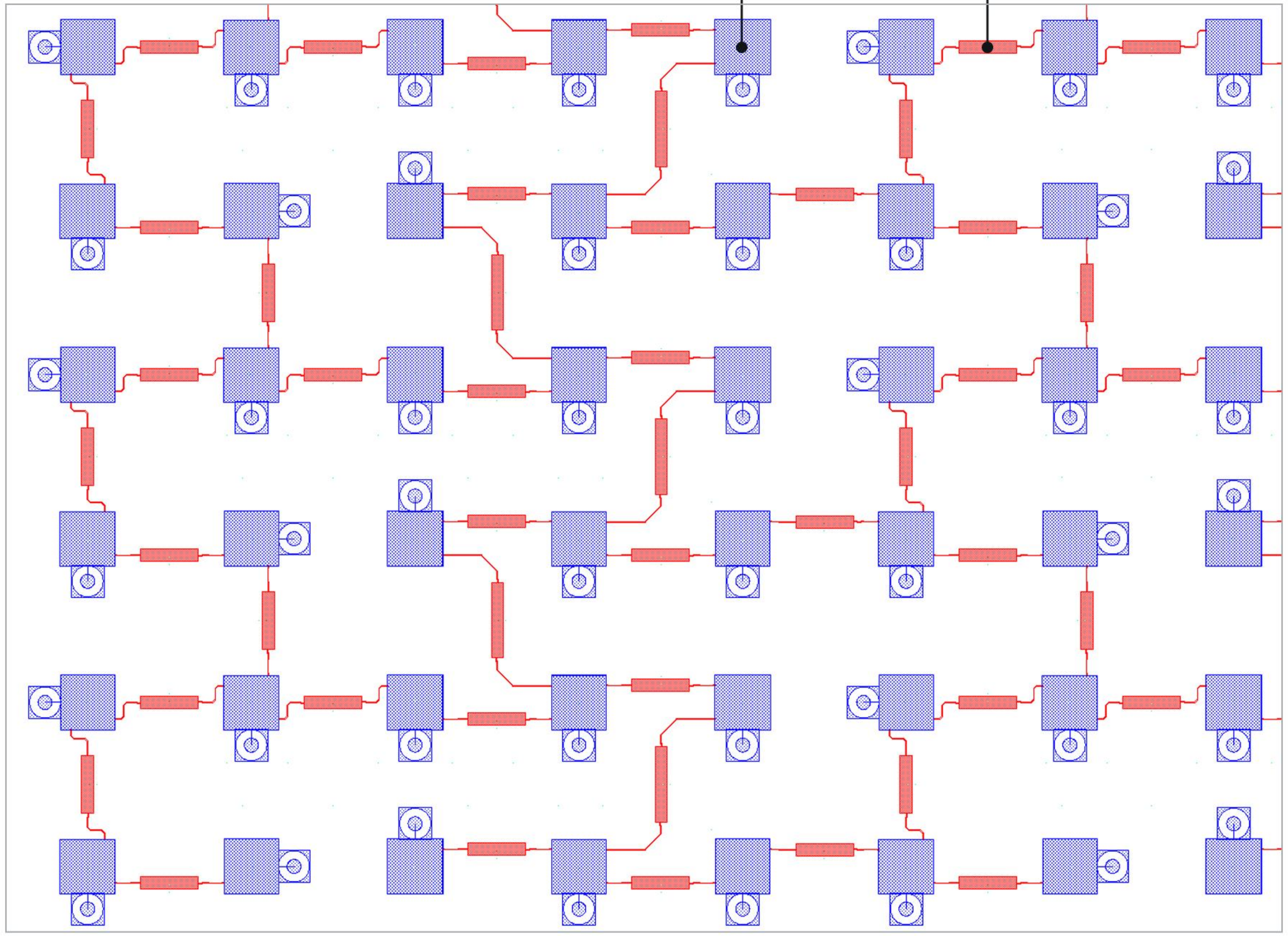
Cryo-CMOS for scalable control

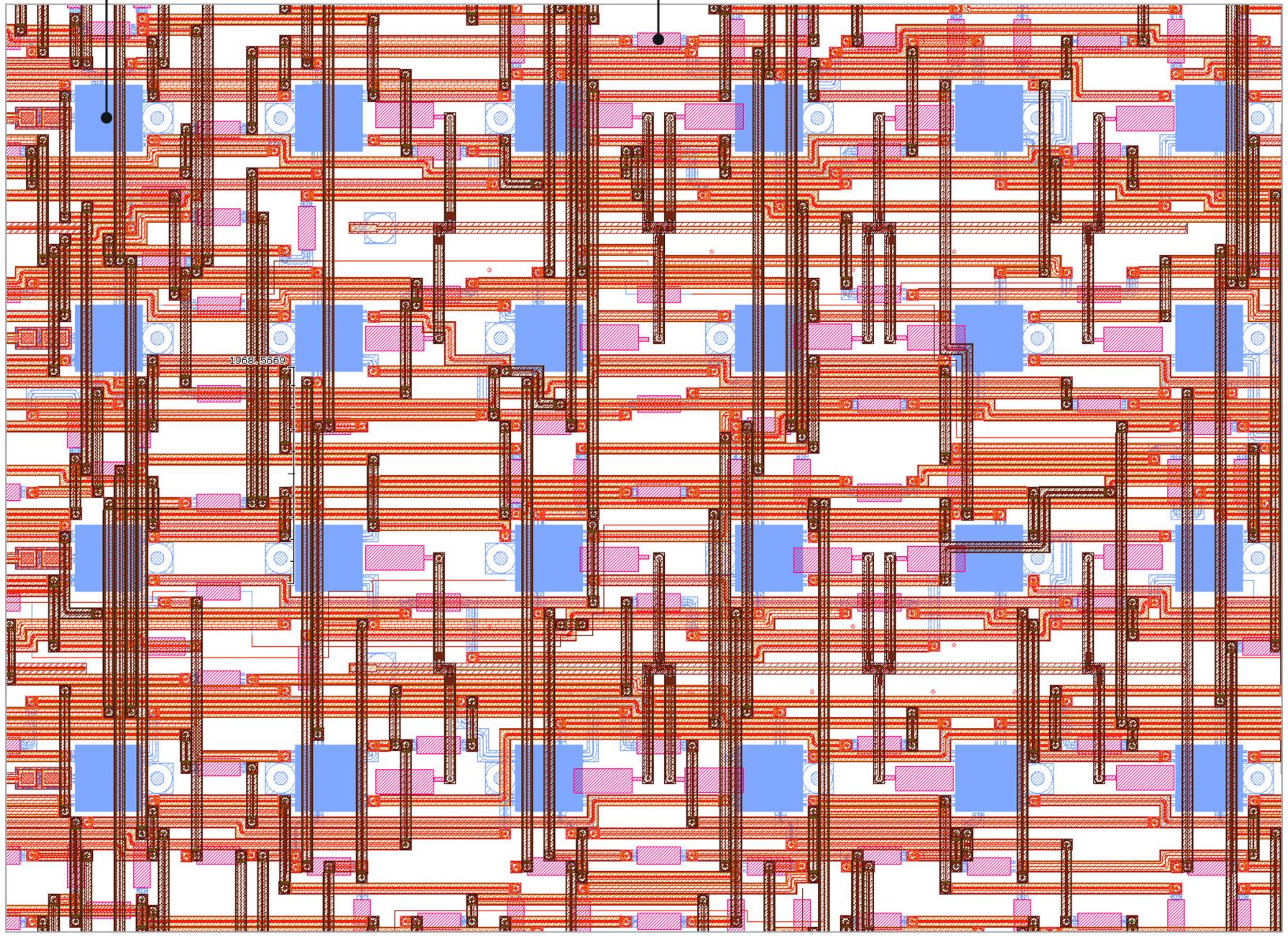
- Overcome control bottlenecks into and out of cryostat
- 94 tunable couplers on a Heron device controlled with 12 "Cedar" cryo-CMOS AWGs on two printed circuit boards
- Gate fidelities as high as 99.9%
- Integrated with conventional RF control and readout hardware as well as software stack.





PRX Quantum **5**, 010326 – Published Feb 14, 2024





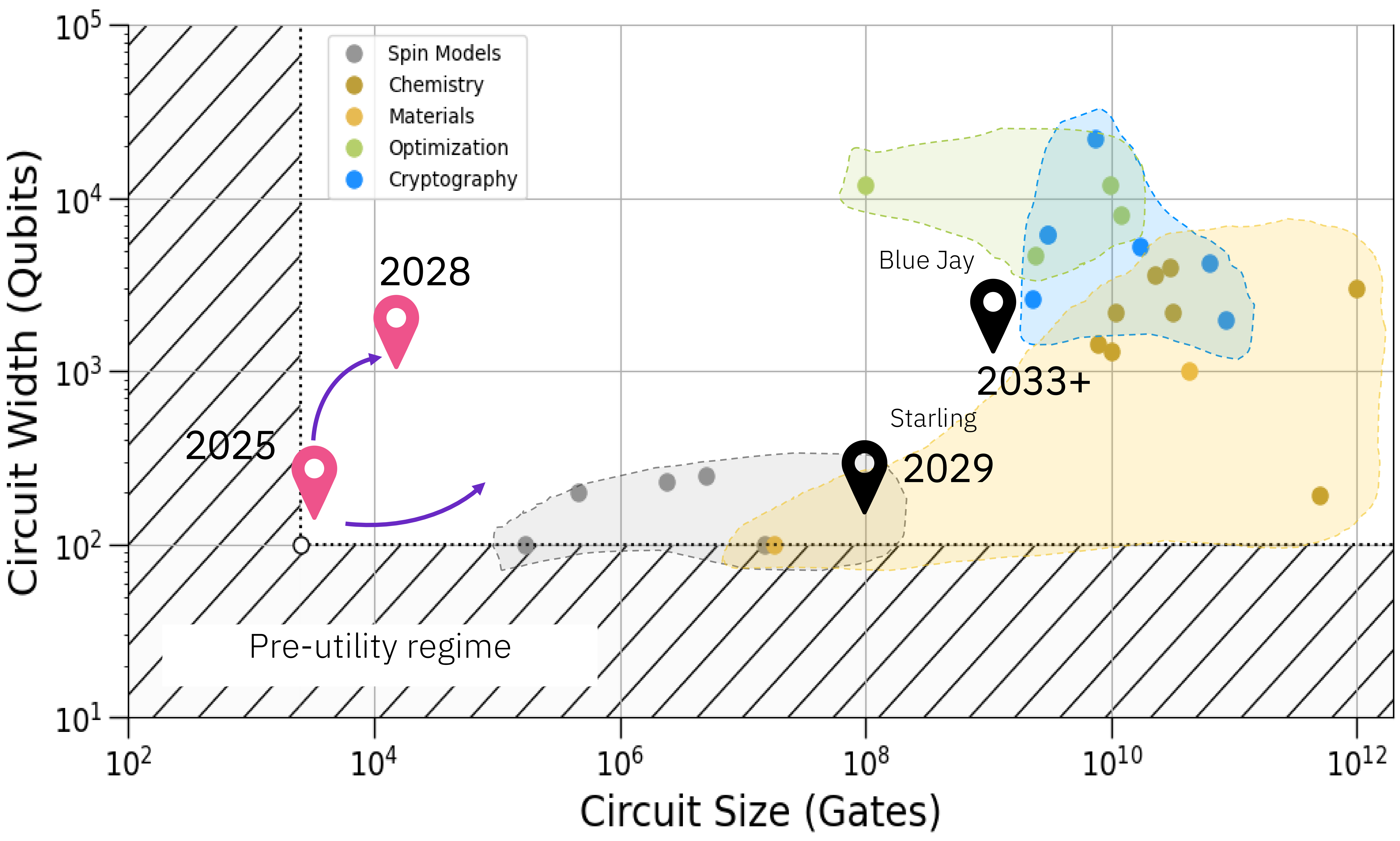
Heron architecture

Above is a schematic of IBM's lattice for connecting qubits within its IBM Quantum Heron processor, in which the blue boxes represent qubits and the red lines and boxes represent connectors, or couplers.

Loon architecture

Above is a schematic of IBM's forthcoming quantum processor architecture, beginning to be developed in 2025 with the IBM Quantum Loon processor, which depicts a more complex lattice to allow a vastly increased number of connections between the qubits.

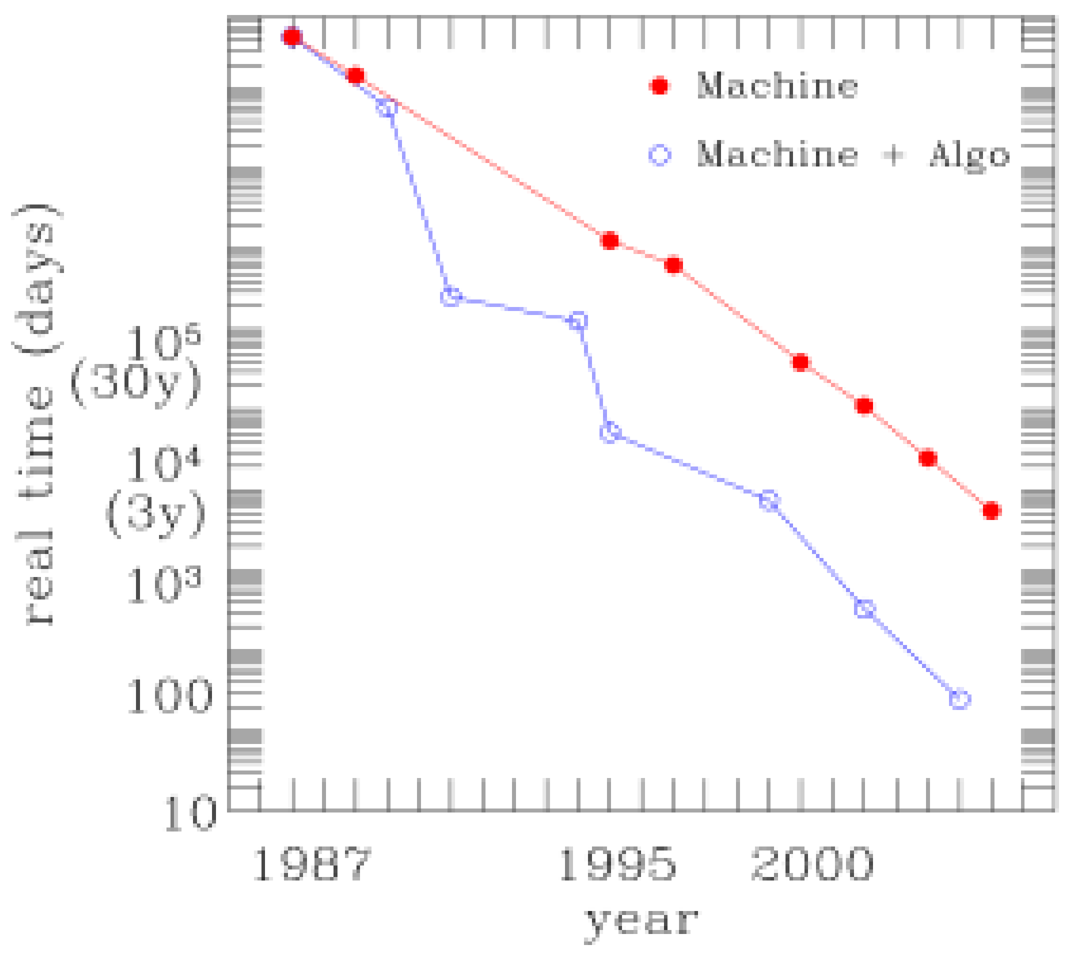
What can you do with a large-scale, fault-tolerant quantum computer?



Algorithmic advances..

Computer and algorithm development over the years

time estimates for simulating $32^3 \cdot 64$ lattice, 5000 configurations



→ O(few months) nowadays with a typical collaboration supercomputer contingent

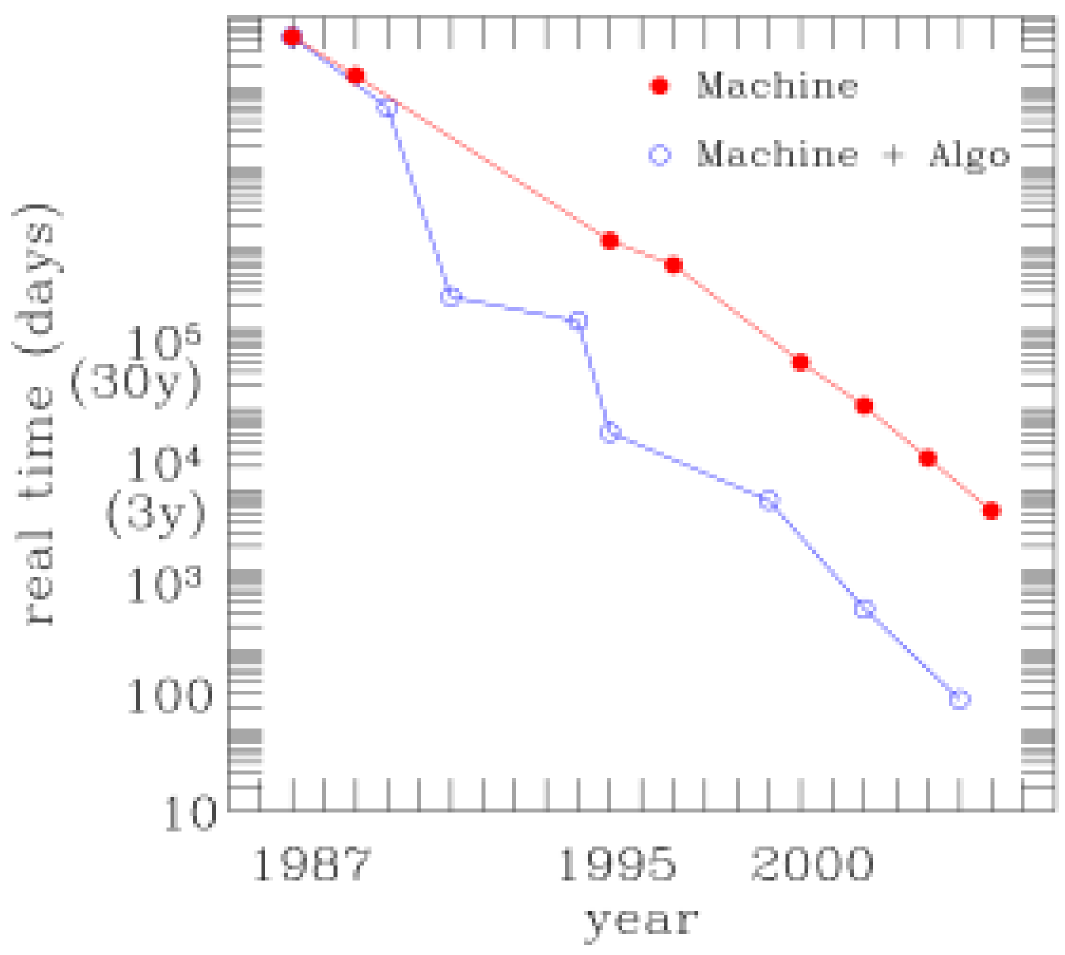
Courtesy Karl Jansen, CQTA DESY

Algorithmic vs. compute improvements in simulating a lattice gauge theory

And discovery

Computer and algorithm development over the years

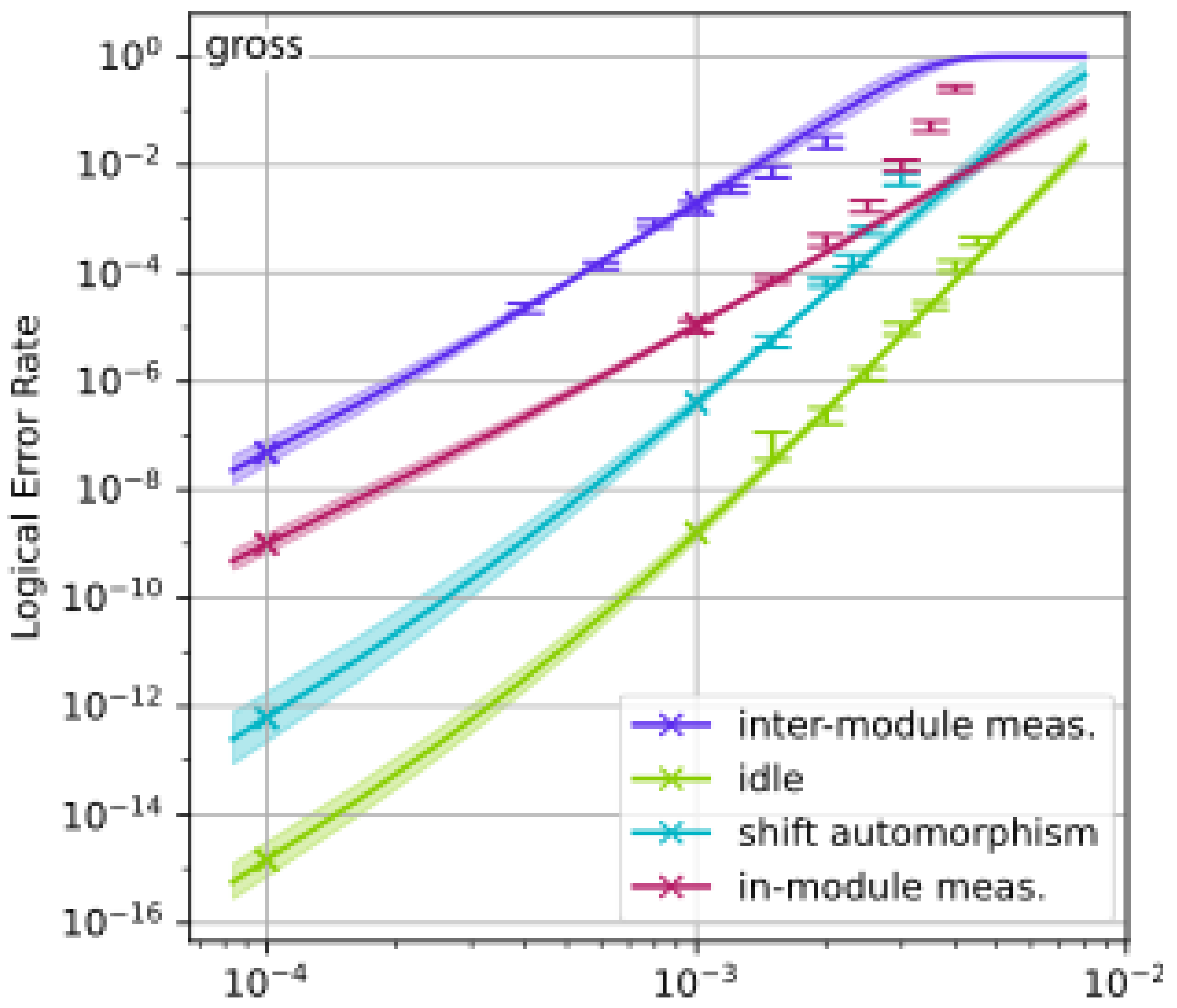
time estimates for simulating $32^3 \cdot 64$ lattice, 5000 configurations



→ O(few months) nowadays with a typical collaboration supercomputer contingent

Courtesy Karl Jansen, CQTA DESY

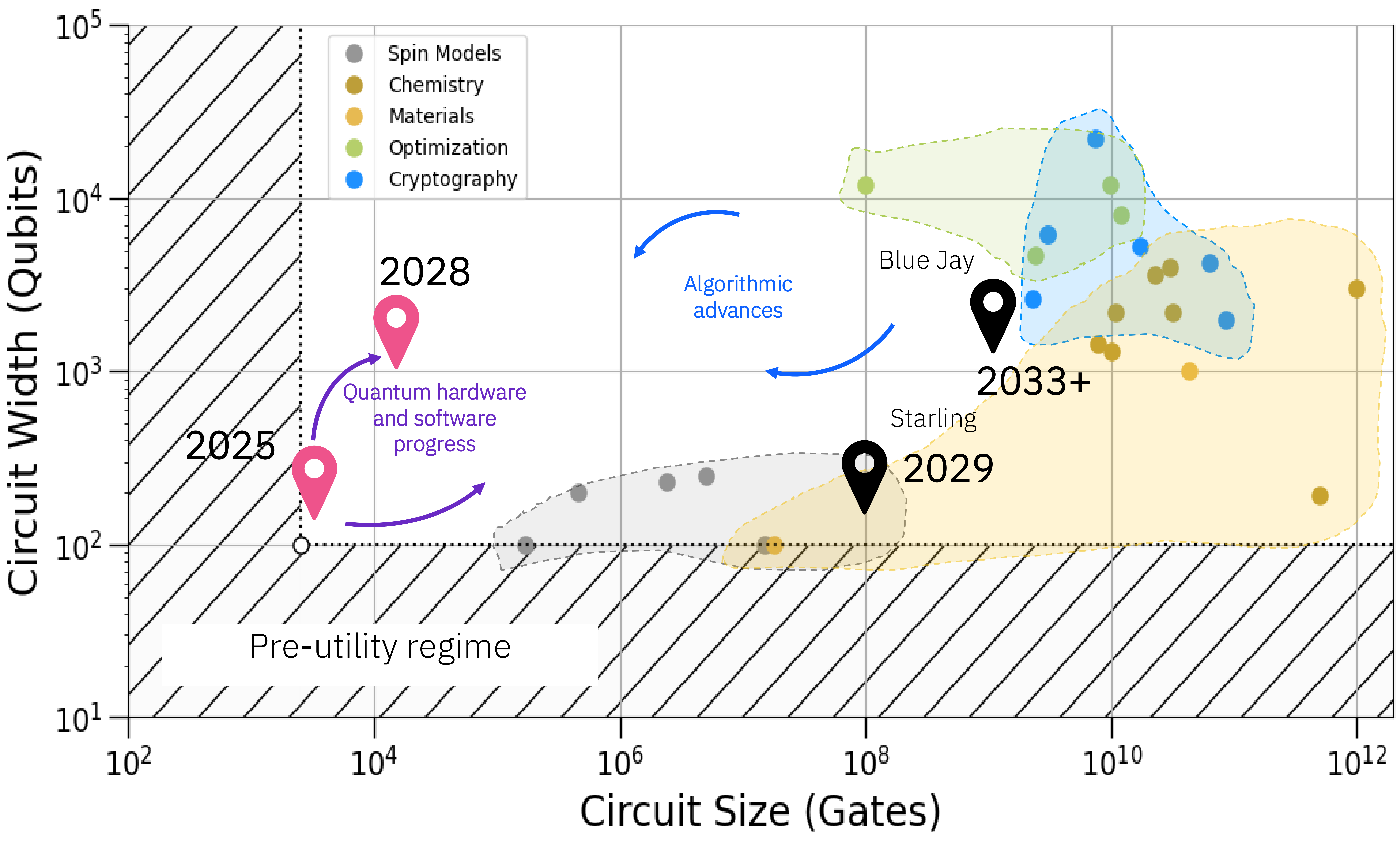
Algorithmic vs. compute improvements in simulating a lattice gauge theory



Tour de gross: A modular quantum computer based on bivariate bicycle codes

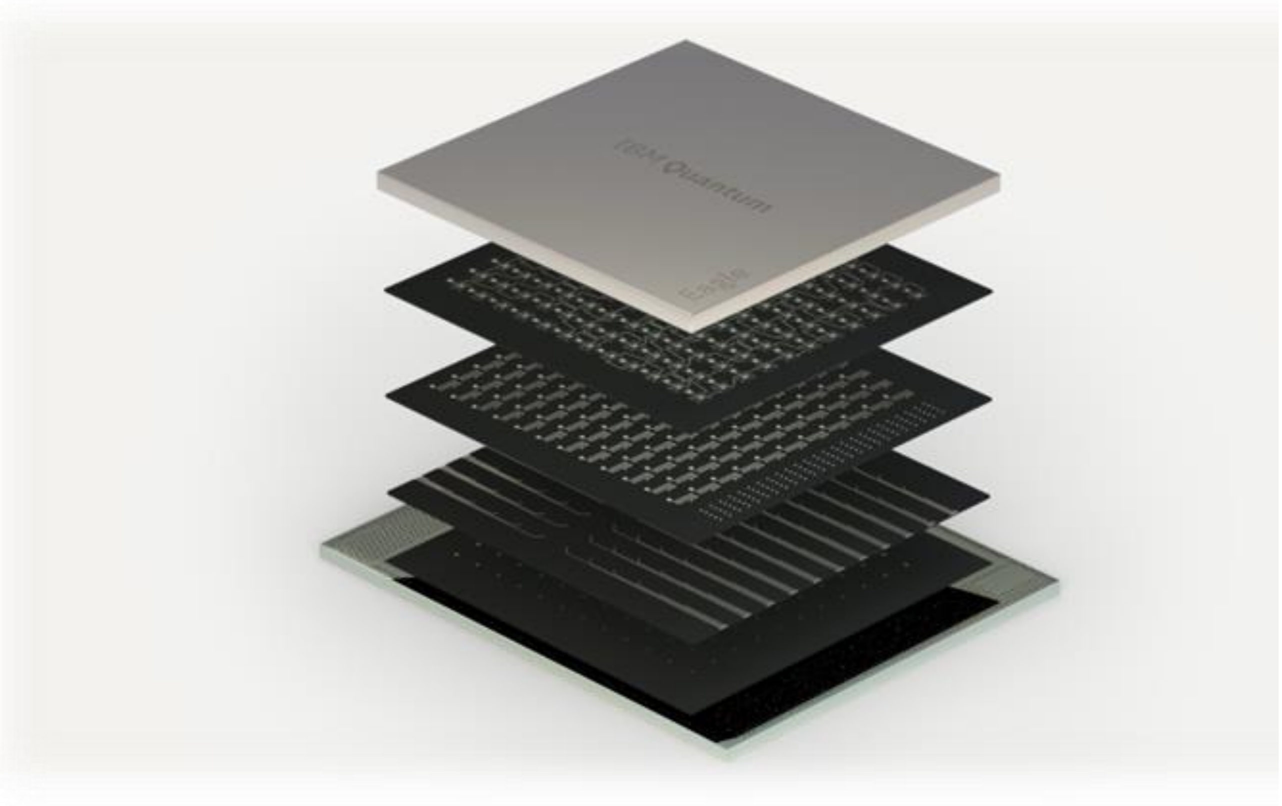
Theodore J. Yoder[1], Eddie Schoute[1], Patrick Rall[1], Emily Pritchett[1], Jay M. Gambetta[1], Andrew W. Cross[1], Malcolm Carroll[1], and Michael E. Beverland[*1]

What can you do with a large-scale, fault-tolerant quantum computer?

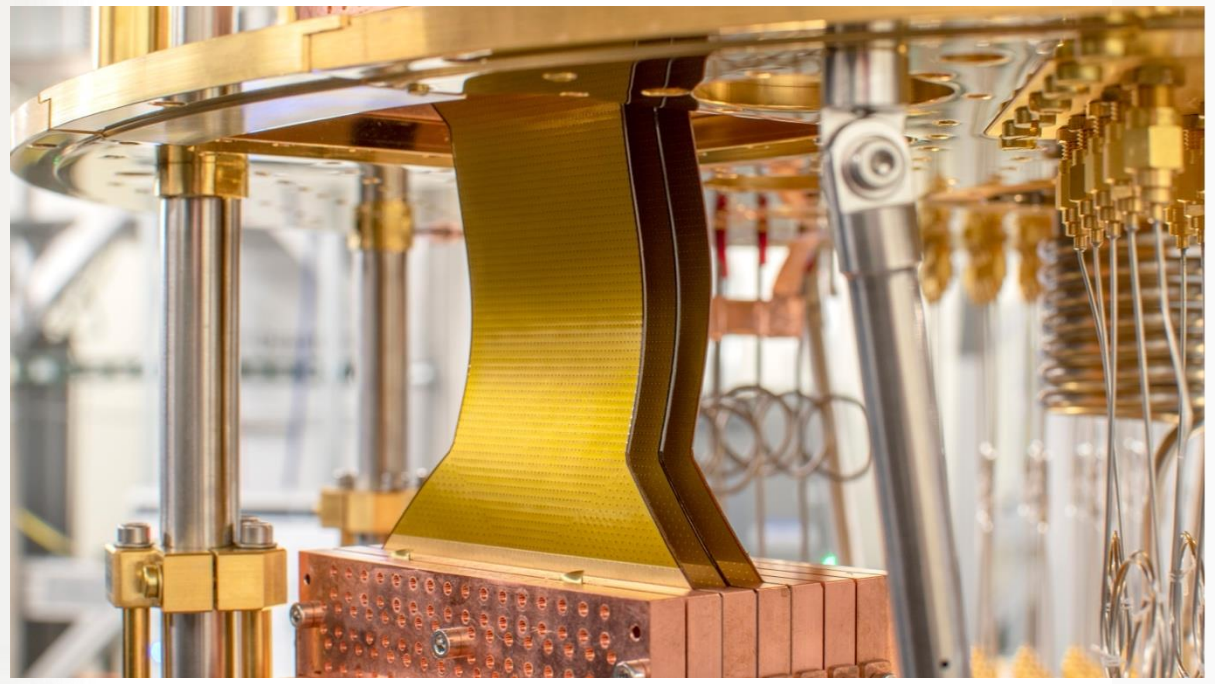


Scaling

Processors



I/O wiring and space transformers

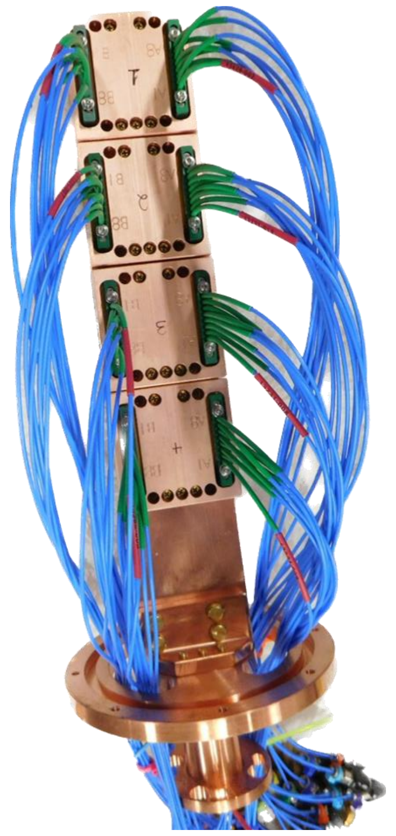


Control electronics

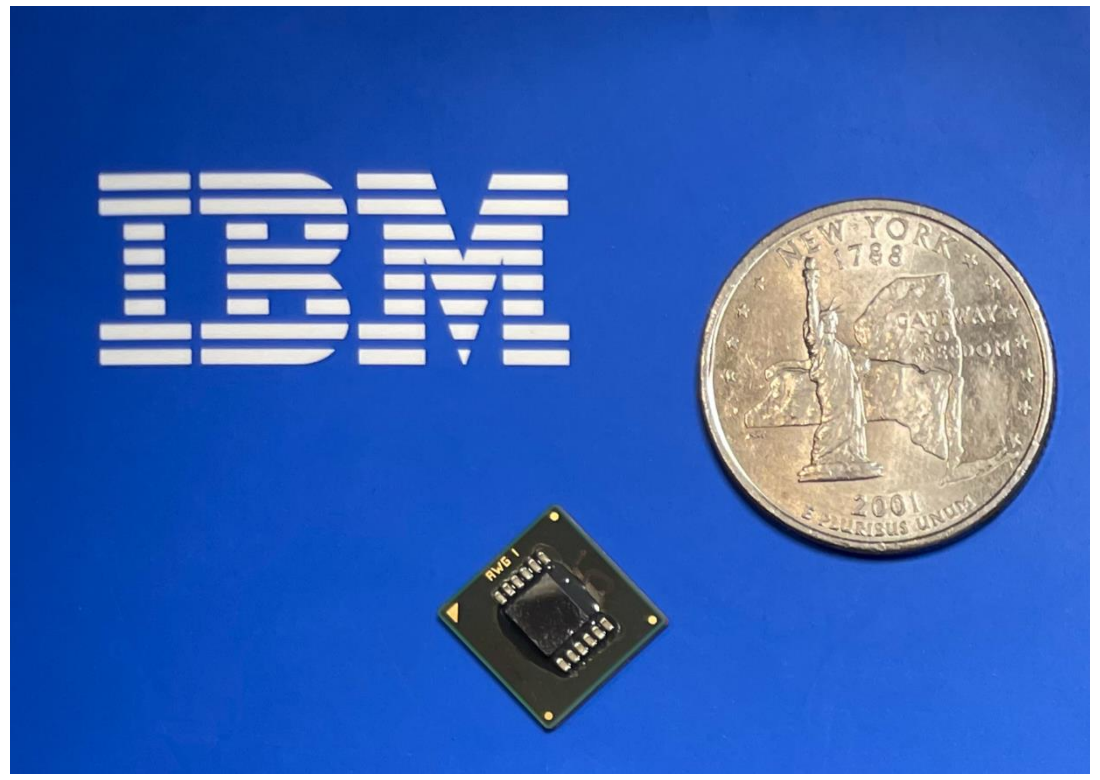
Runtime Infrastructure

Software

Amplifiers and other microwave components



Full-featured 4K cryo-CMOS qubit controller



Cyro Infrastructure


UTILITY
RTE 02
RTE 01
CRYOGENIC ENCLOSURE
IBM Quantum
System Two
IBM
RTE 01
RTE 02

Wrapping it up

Superconducting qubits in isolation are misleadingly easy

Progress will be faster than we expect

We want to build large systems – statistics matter

This talk only went down one path! P. Krantz et al., Appl. Phys. Rev. 6, 021318 (2019). is a nice review to learn on devices

Similarly, Bravyi et al, J. Appl. Phys. 132, 160902 (2022) for architecture.

BACKUPS