2024년 1월 19일

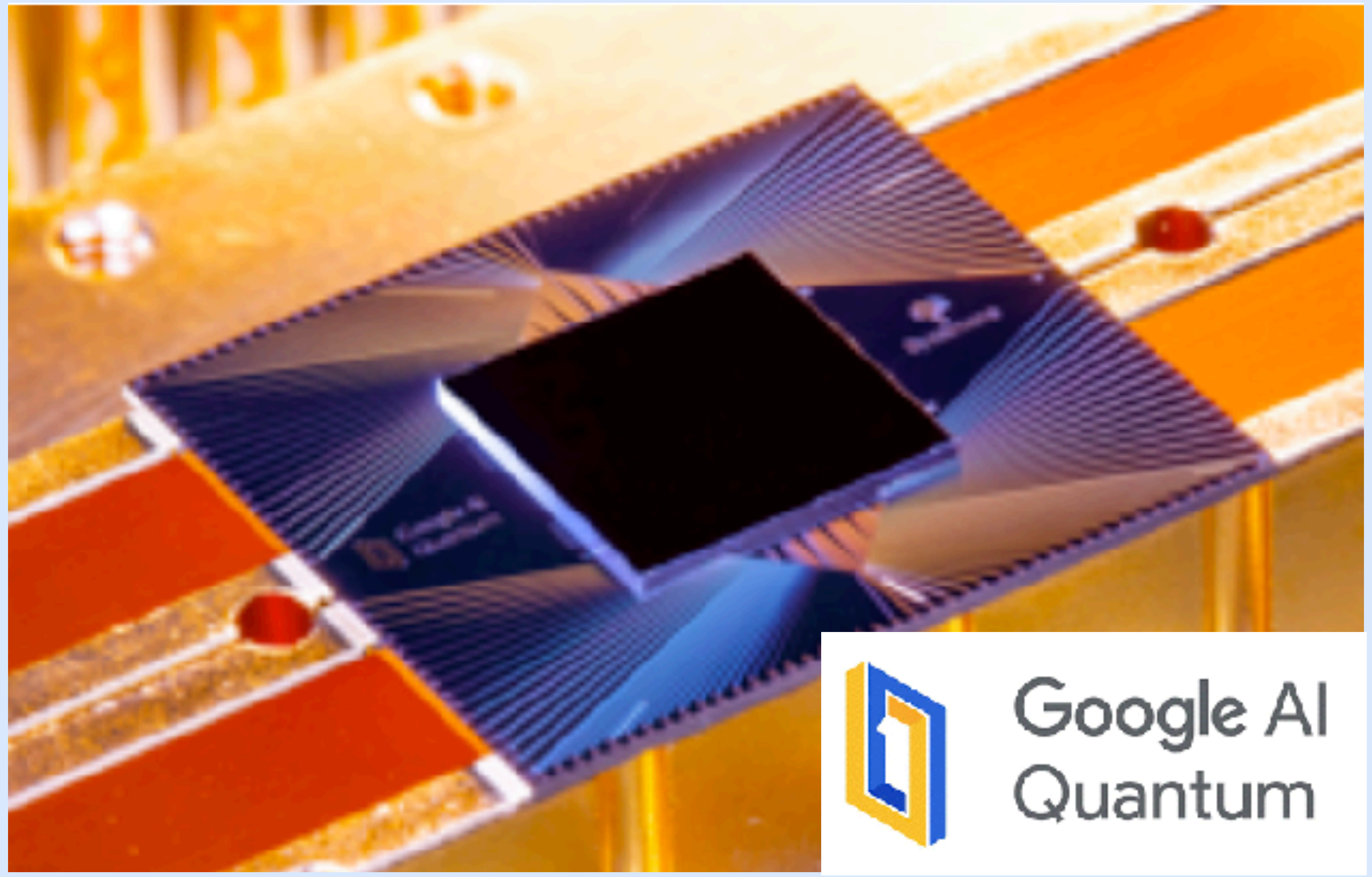
양자정보과학 겨울학교

초전도 회로 큐비트를 위한 양자 게이트 구현

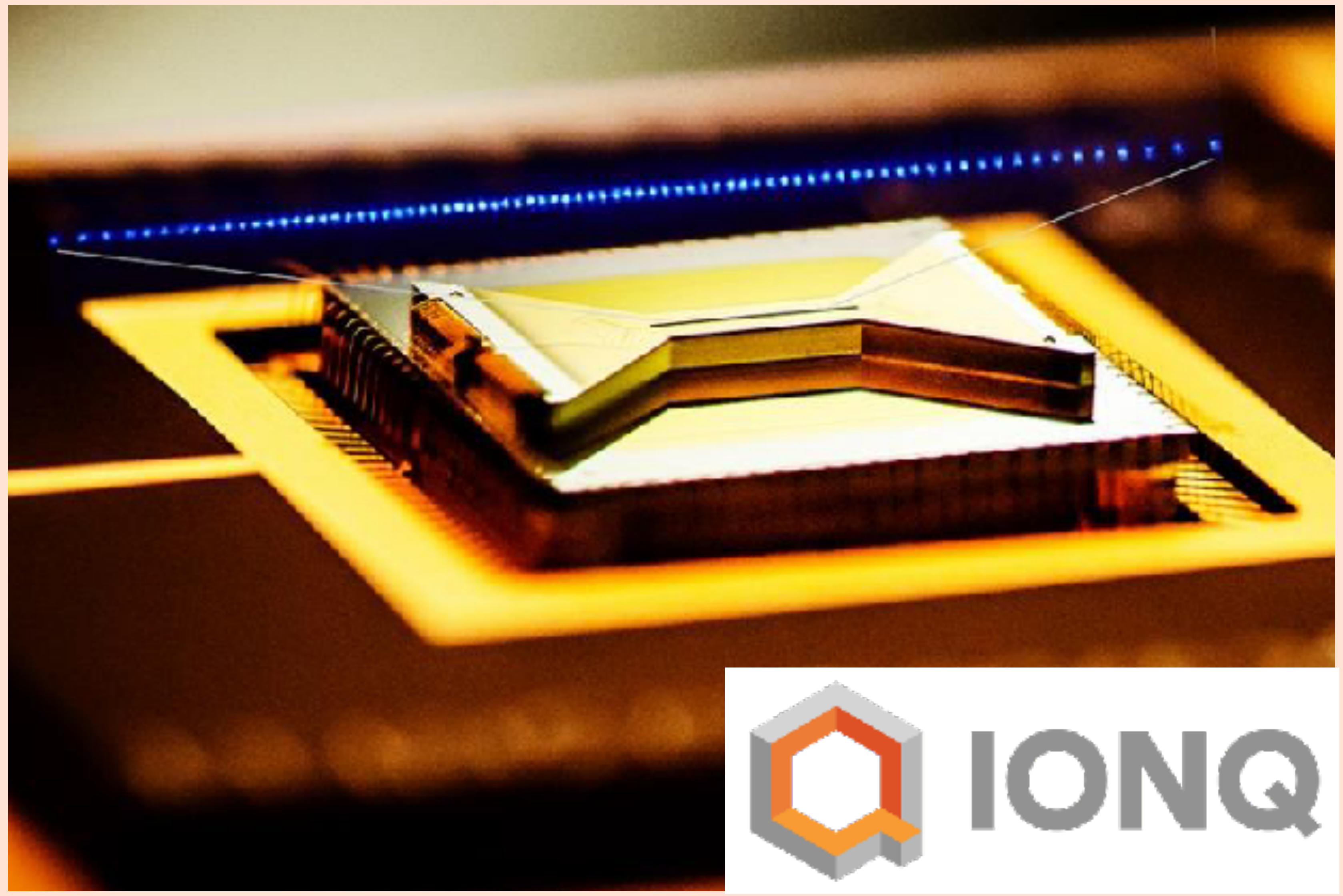
김요셉

고려대학교 물리학과

Superconducting
Quantum Information Lab

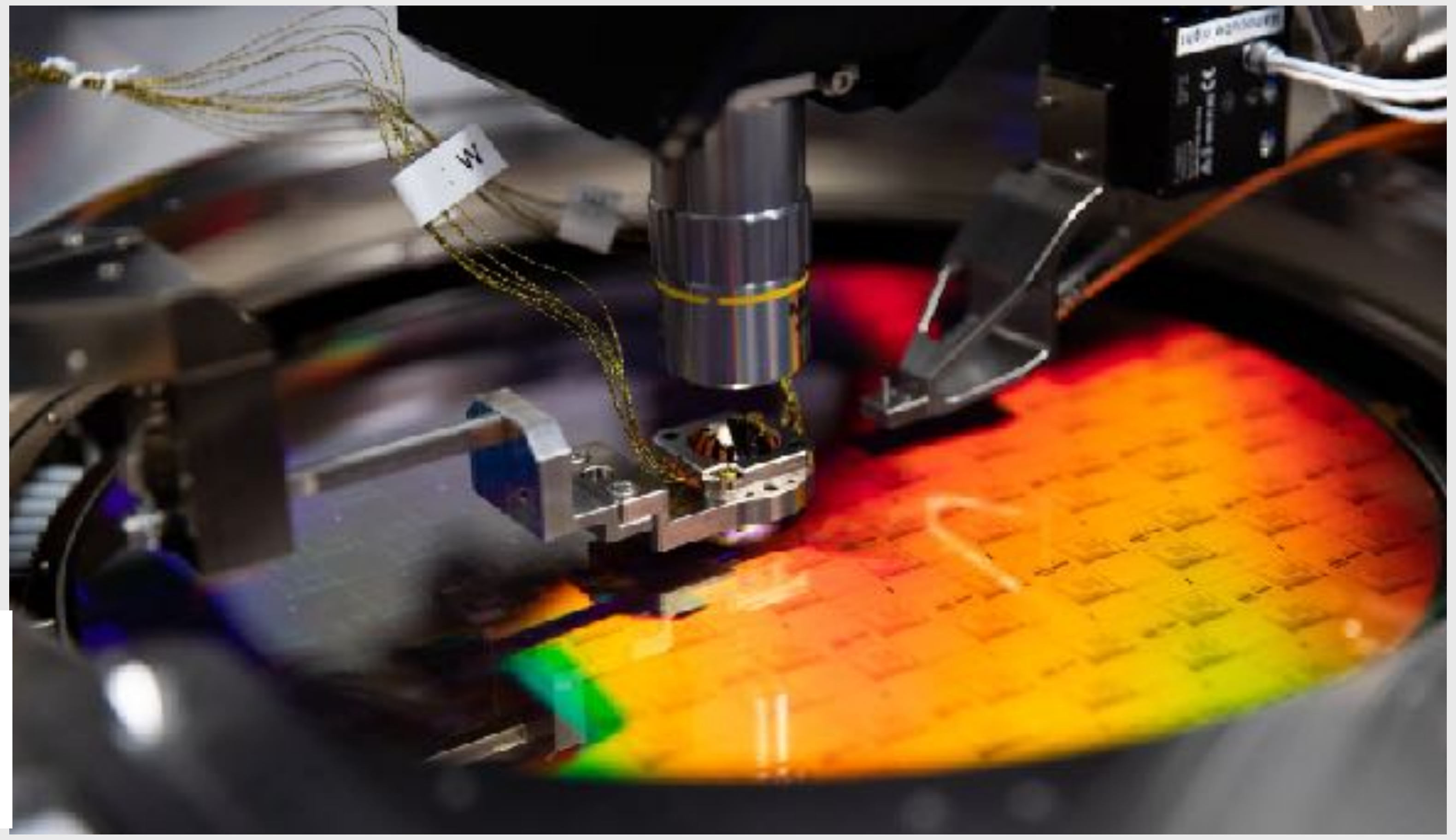


Superconducting circuits



Trapped ions

Ψ PsiQuantum



Quantum photonics

주식 시장 요약 > 리제티 컴퓨팅

0.98 USD

-8.93 (-90.13%) ↓ 전체 기간

1월 18일 오전 11:29 GMT-5 · 면책조항

1일 | 5일 | 1개월 | 6개월 | 연중 | 1년 | 5년 | 최대

시가	0.99	시가총액	1.43억	52-주 최고	3.43
최고	1.02	주가수익률	-	52-주 최저	0.36
최저	0.96	배당수익률	-		

주식 시장 요약 > 아이온큐

10.76 USD

-0.25 (-2.32%) ↓ 전체 기간

1월 18일 오전 11:30 GMT-5 · 면책조항

1일 | 5일 | 1개월 | 6개월 | 연중 | 1년 | 5년 | 최대

시가	11.39	시가총액	22.01억	52-주 최고	21.60
최고	11.40	주가수익률	-	52-주 최저	4.01
최저	10.62	배당수익률	-		

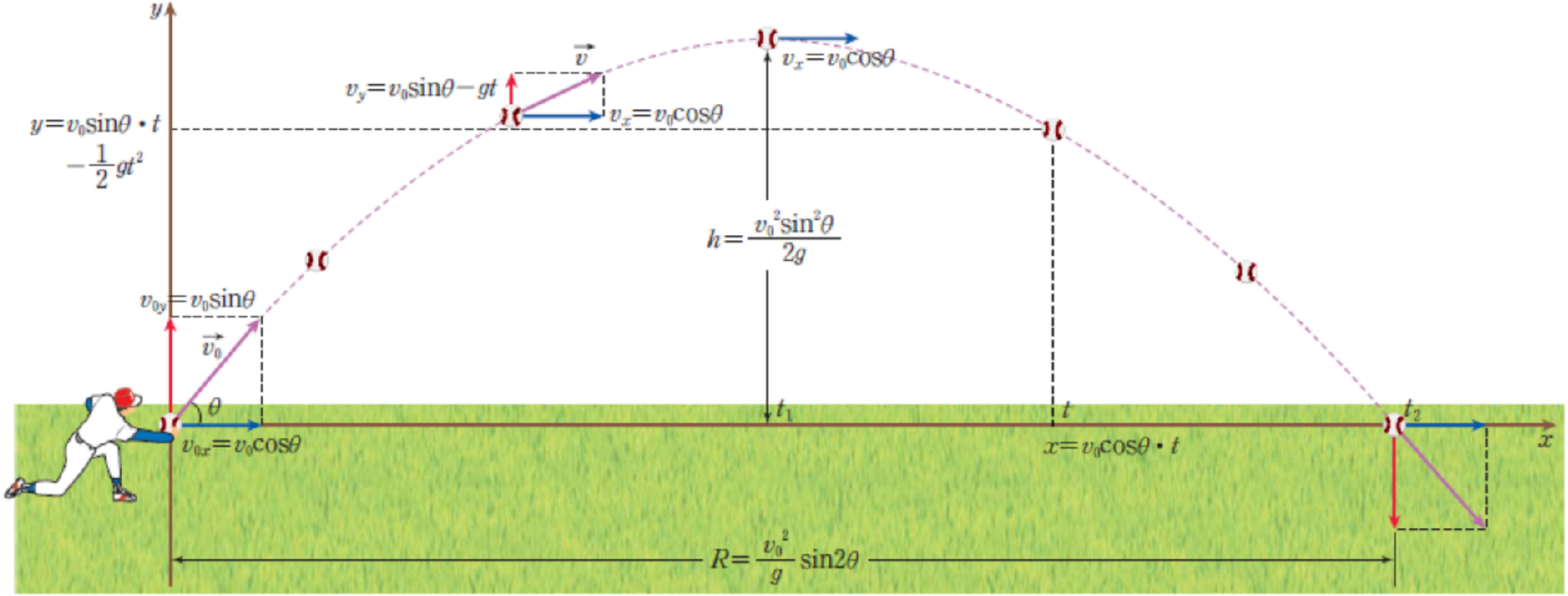
Development Roadmap

Executed by IBM ✓
On target

IBM Quantum

	2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023	2024	2025	2026+
	Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime
Model Developers					Prototype quantum software applications →		Quantum software applications Machine learning | Natural science | Optimization	
Algorithm Developers		Quantum algorithm and application modules ✓ Machine learning | Natural science | Optimization			Quantum Serverless	Intelligent orchestration	Circuit Knitting Toolbox	Circuit libraries
Kernel Developers	Circuits ✓		Qiskit Runtime ✓	Dynamic circuits ✓	Threaded primitives	Error suppression and mitigation		Error correction
System Modularity	Falcon ✓ 27 qubits	Hummingbird ✓ 65 qubits	Eagle ✓ 127 qubits	Osprey ✓ 433 qubits	Condor 1,121 qubits	Flamingo 1,386+ qubits	Kookaburra 4,158+ qubits	Scaling to 10K-100K qubits with classical and quantum communication
					Heron 133 qubits x p	Crossbill 408 qubits		

Prerequisite



Initial state

$$\vec{v}_0 = (v_x, v_y, v_z)$$
$$\vec{x}_0 = (0, 0, 0)$$

$$H = \frac{1}{2} m v^2 + mgh$$

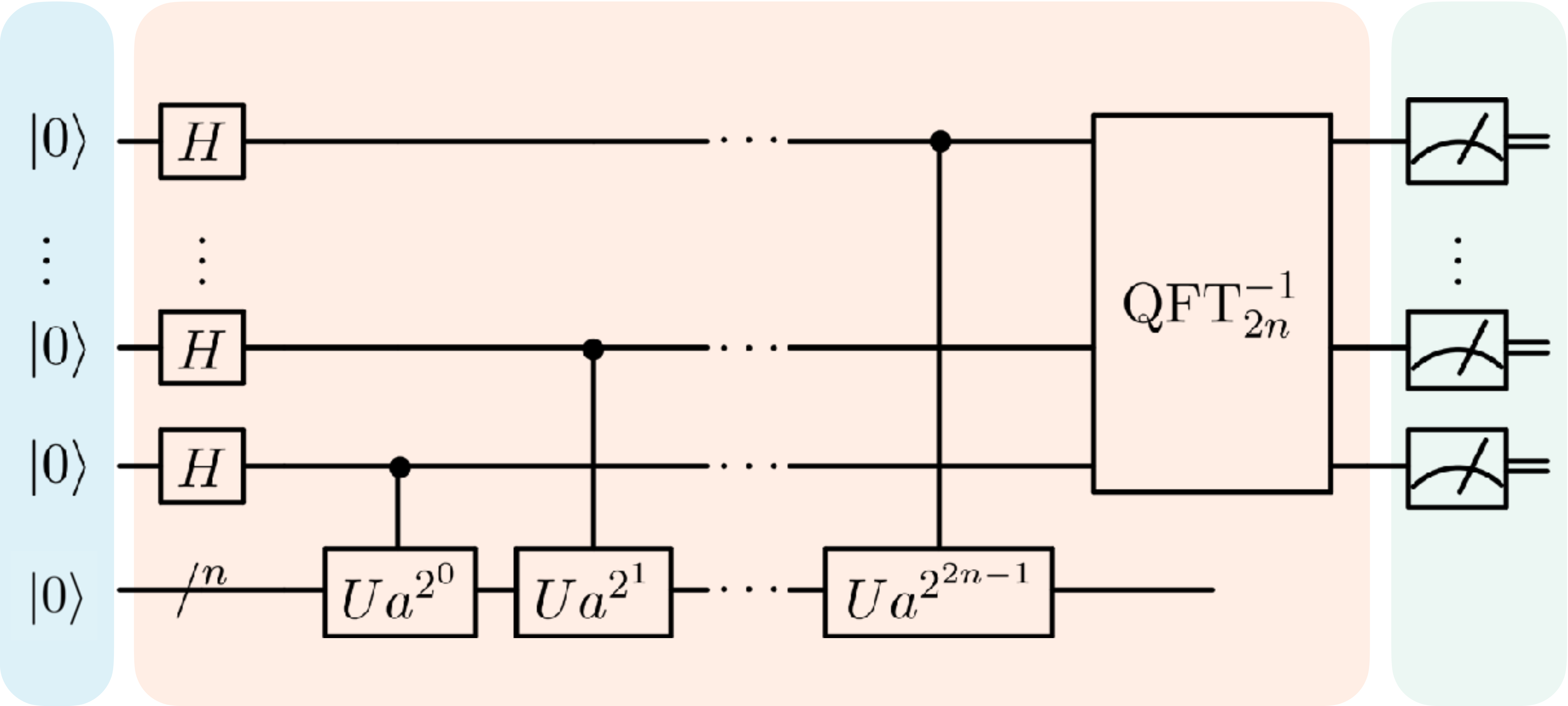
Hamiltonian

Prerequisite

Schrödinger's equation $$H|\psi(t)\rangle = i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle$$

$$|\psi(t)\rangle = \underbrace{\boxed{e^{-iHt/\hbar}}}_{U(t)}|\psi(0)\rangle$$

Quantum computing



Quantum bits

$$|\Psi\rangle$$

Quantum circuits

$$|\Psi'\rangle = U|\Psi\rangle$$

State readout

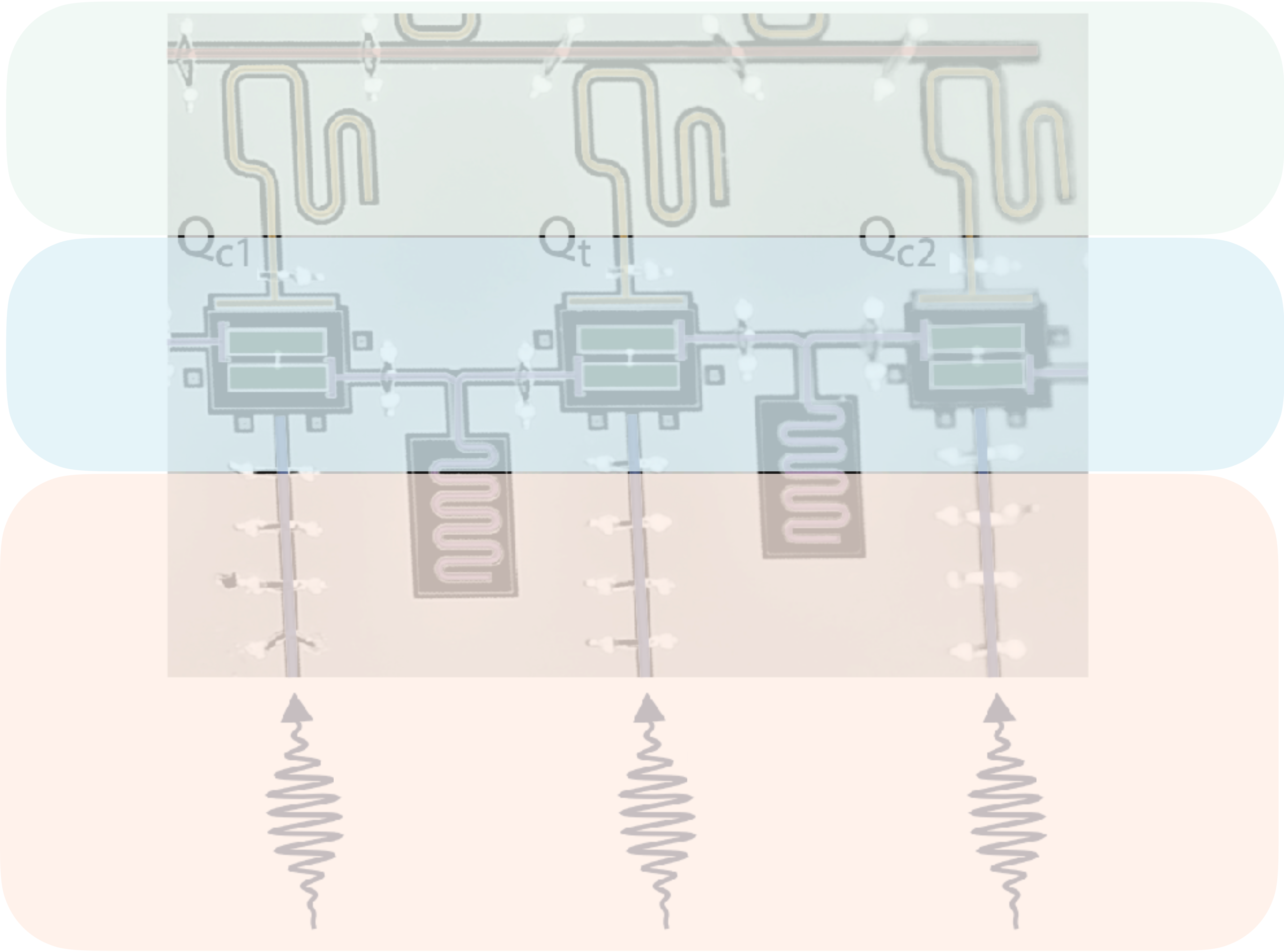
$$\langle\Psi'|\hat{O}|\Psi'\rangle$$

Superconducting quantum processor

State readout

Quantum bits

Quantum circuits

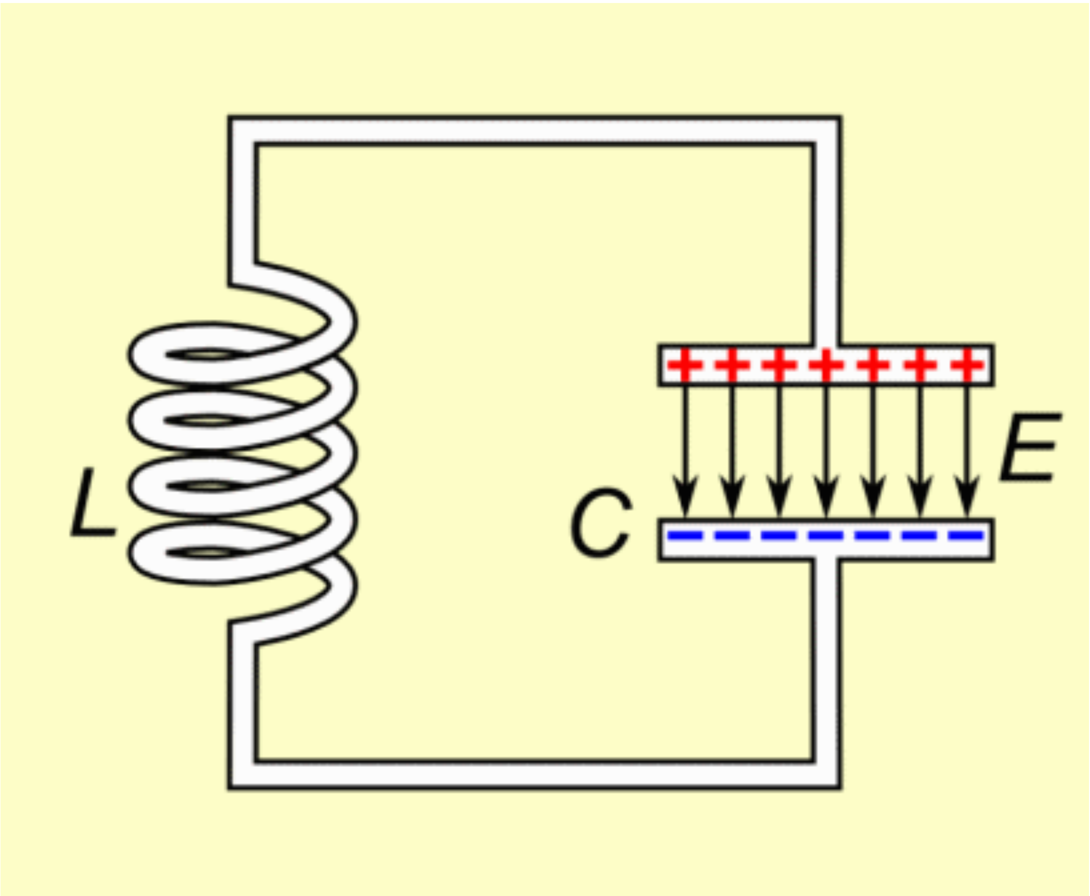


Operation principles of superconducting qubits

LC circuit

$\Phi(t)$

magnetic flux

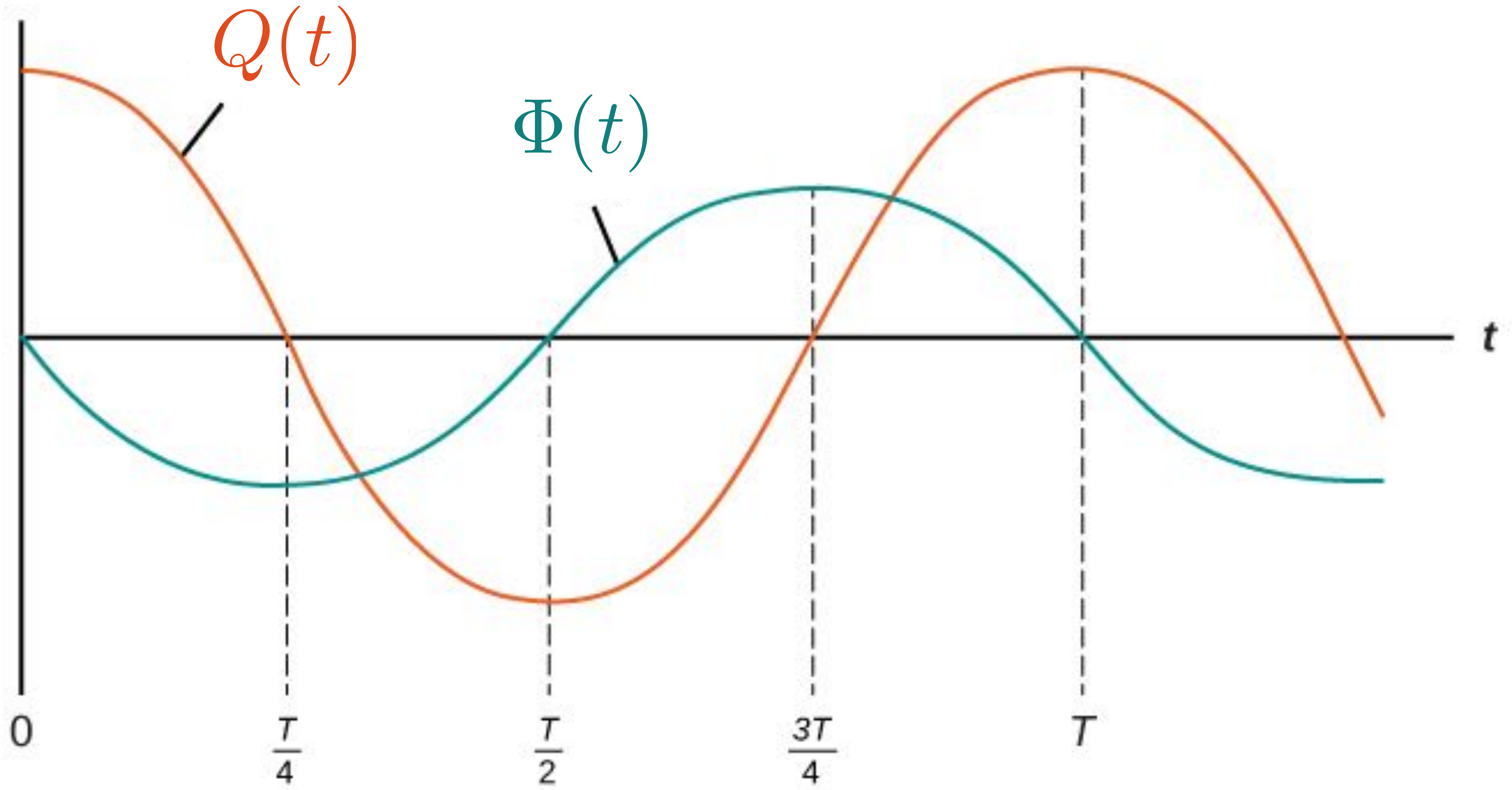


$Q(t)$

charge

$$\omega_r = \frac{1}{\sqrt{LC}}$$

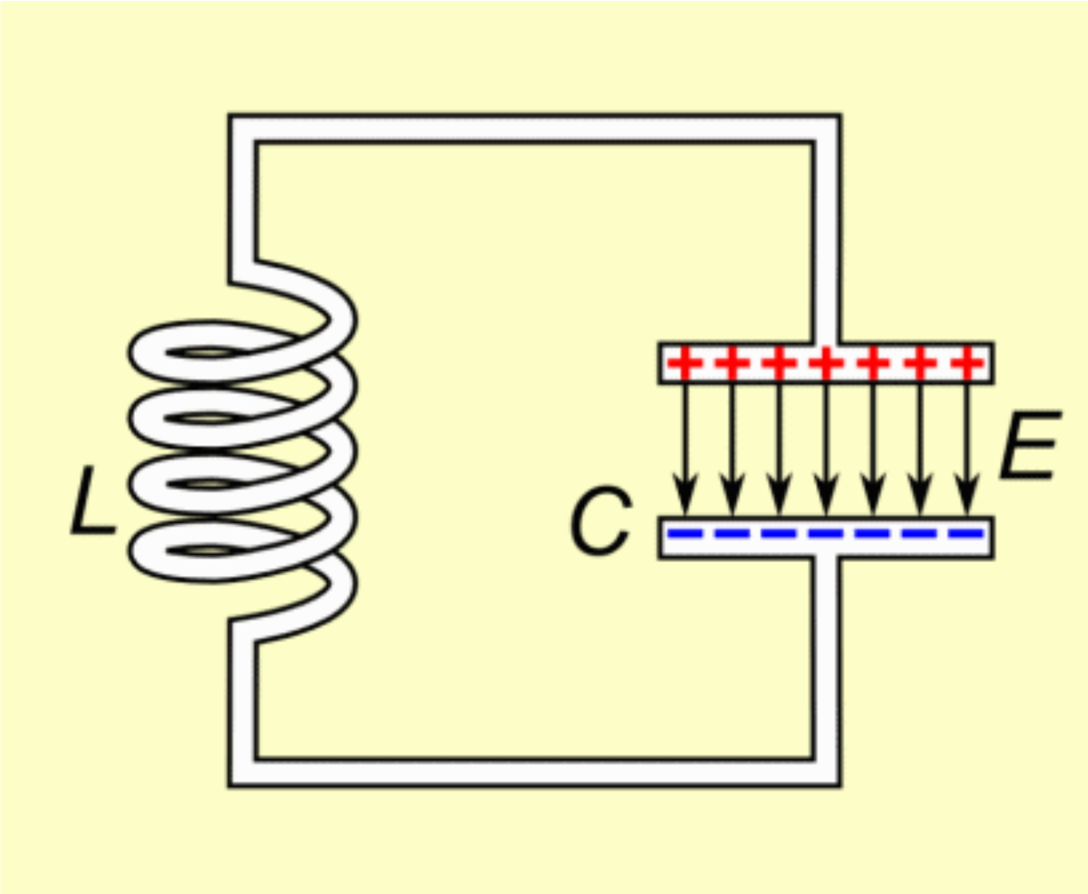
Resonance frequency



LC circuit

$\Phi(t)$

magnetic flux



$Q(t)$

charge

$$\omega_r = \frac{1}{\sqrt{LC}}$$

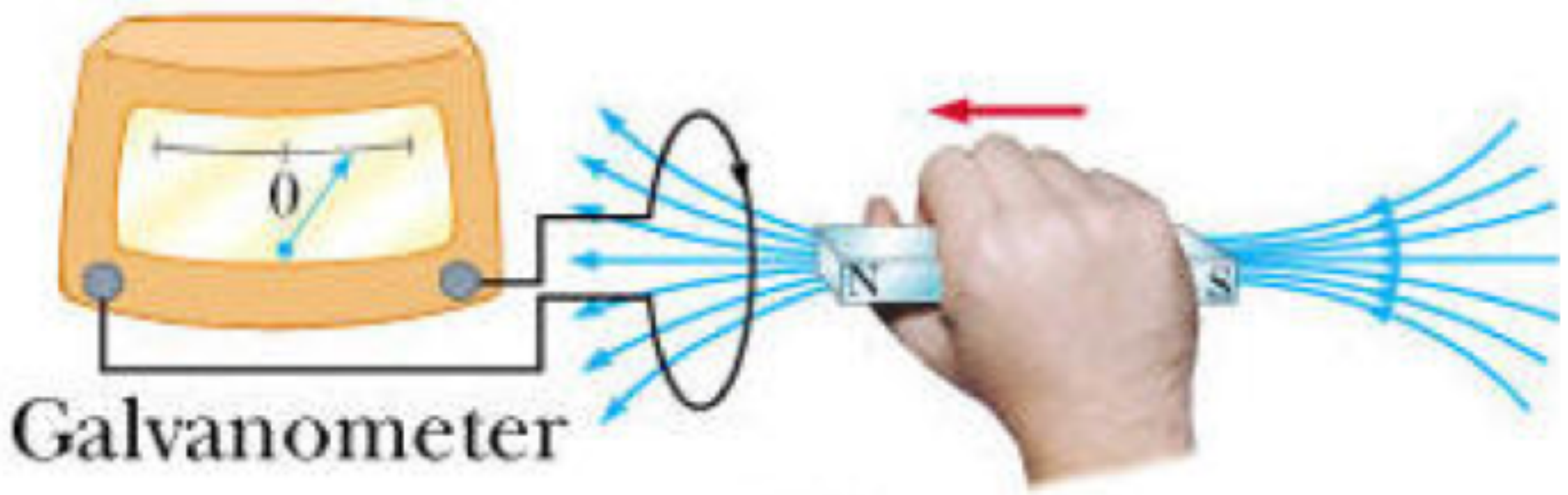
Resonance frequency

$$H = \frac{Q(t)^2}{2C} + \frac{\Phi(t)^2}{2L}$$

Charge energy H_Q

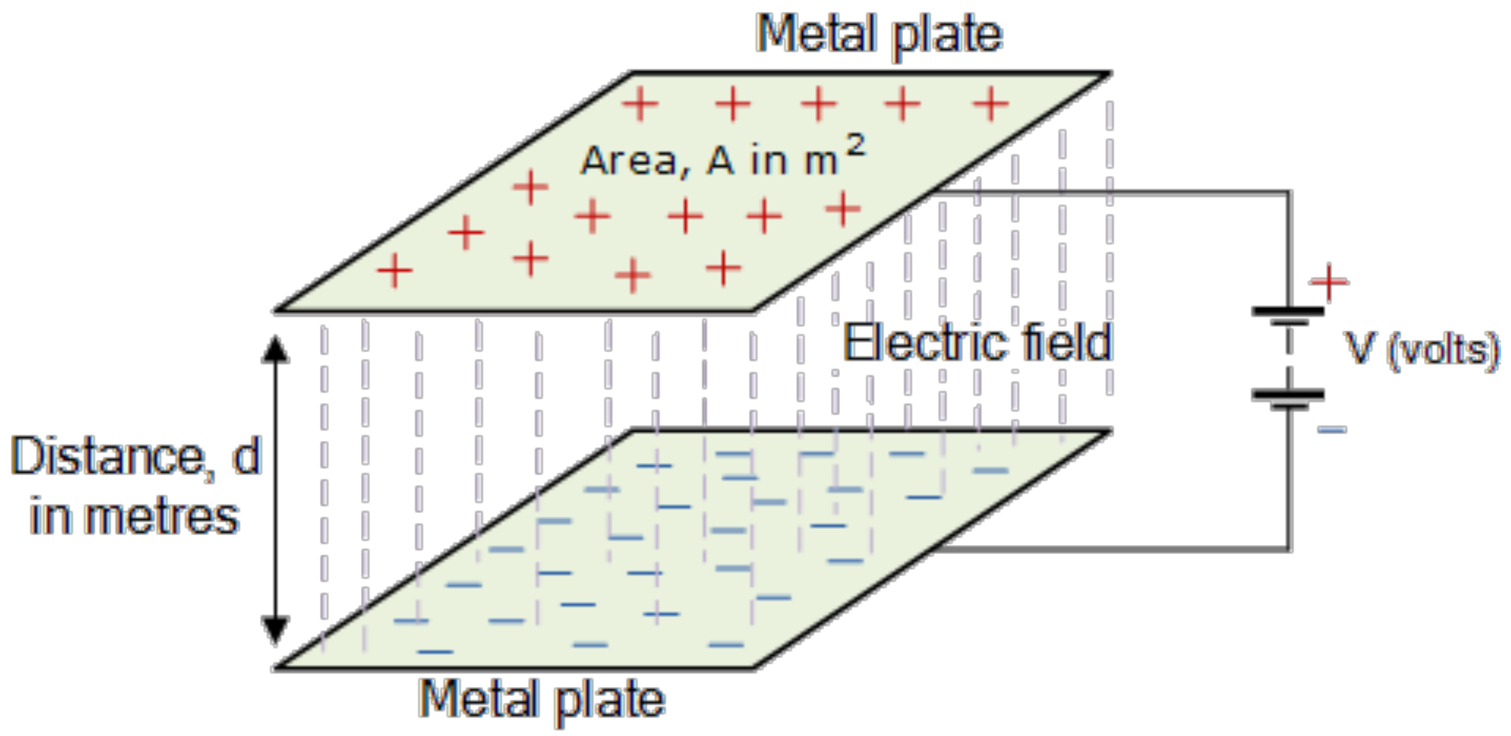
Flux energy H_Φ

LC circuit



Faraday's law

$$V(t) = -\frac{d\Phi(t)}{dt}$$



Capacitance charging

$$Q(t) = CV(t)$$

$$Q(t) = -C\frac{d\Phi(t)}{dt}$$

LC circuit

Charge energy H_Q Flux energy H_Φ

$$H = \frac{Q(t)^2}{2C} + \frac{\Phi(t)^2}{2L}$$

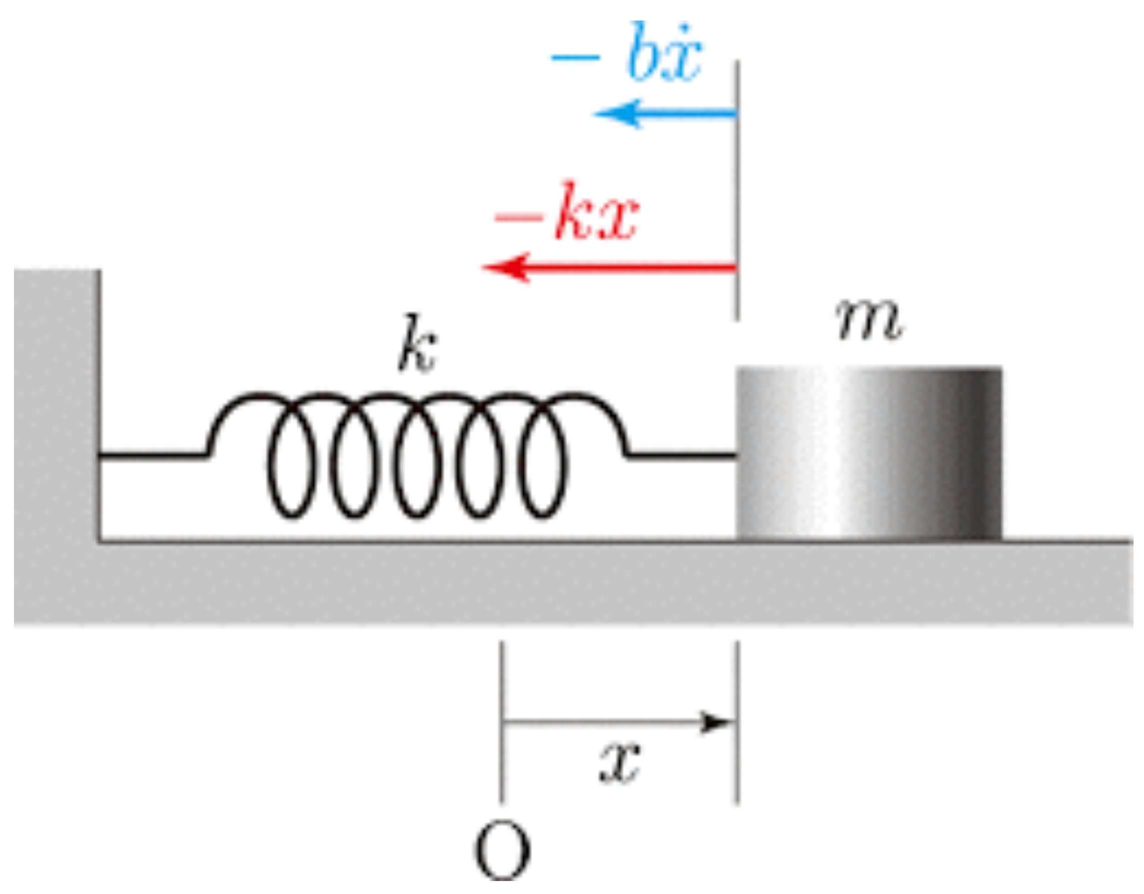
$$Q(t) = -C\frac{d\Phi(t)}{dt}$$

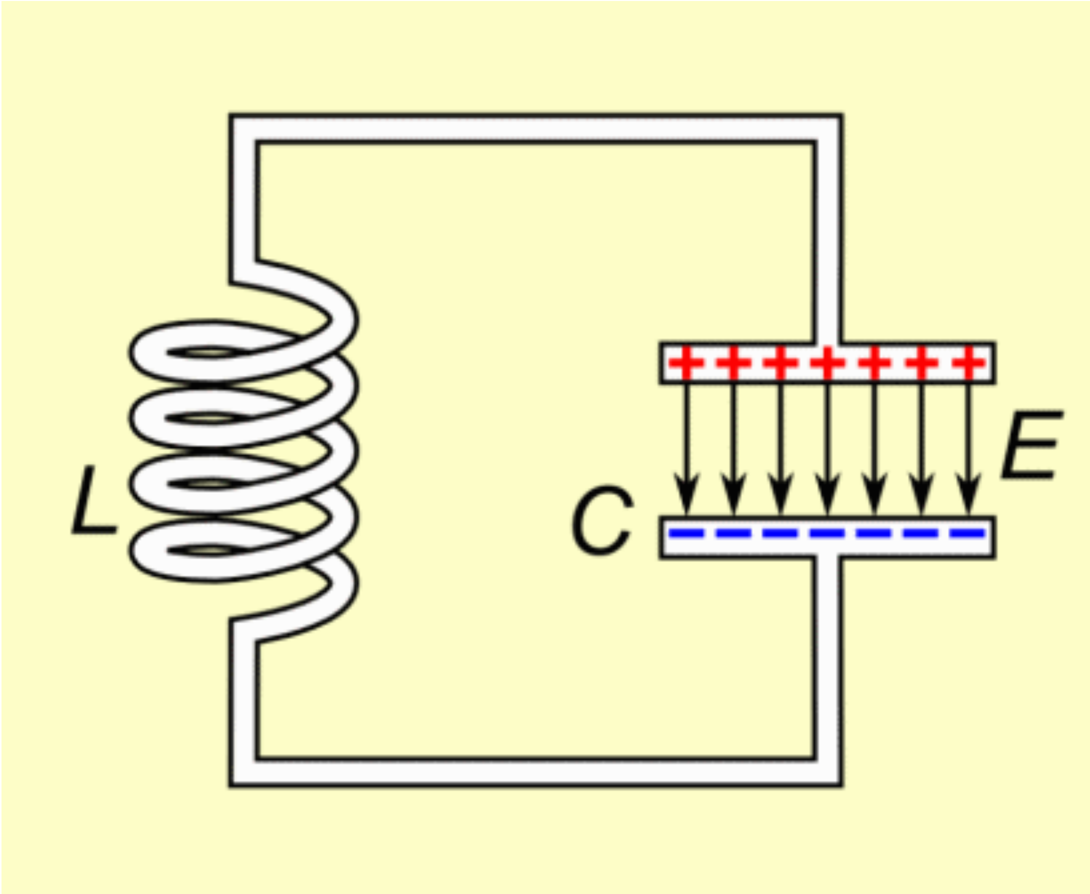
$$H = \frac{C}{2}\dot{\Phi}^2 + \frac{1}{2L}\Phi^2$$

LC circuit

Charge energy H_Q Flux energy H_Φ

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





Kinetic energy Potential energy

$$H = \frac{m}{2}\dot{x}^2 + \frac{k}{2}x^2$$

LC circuit

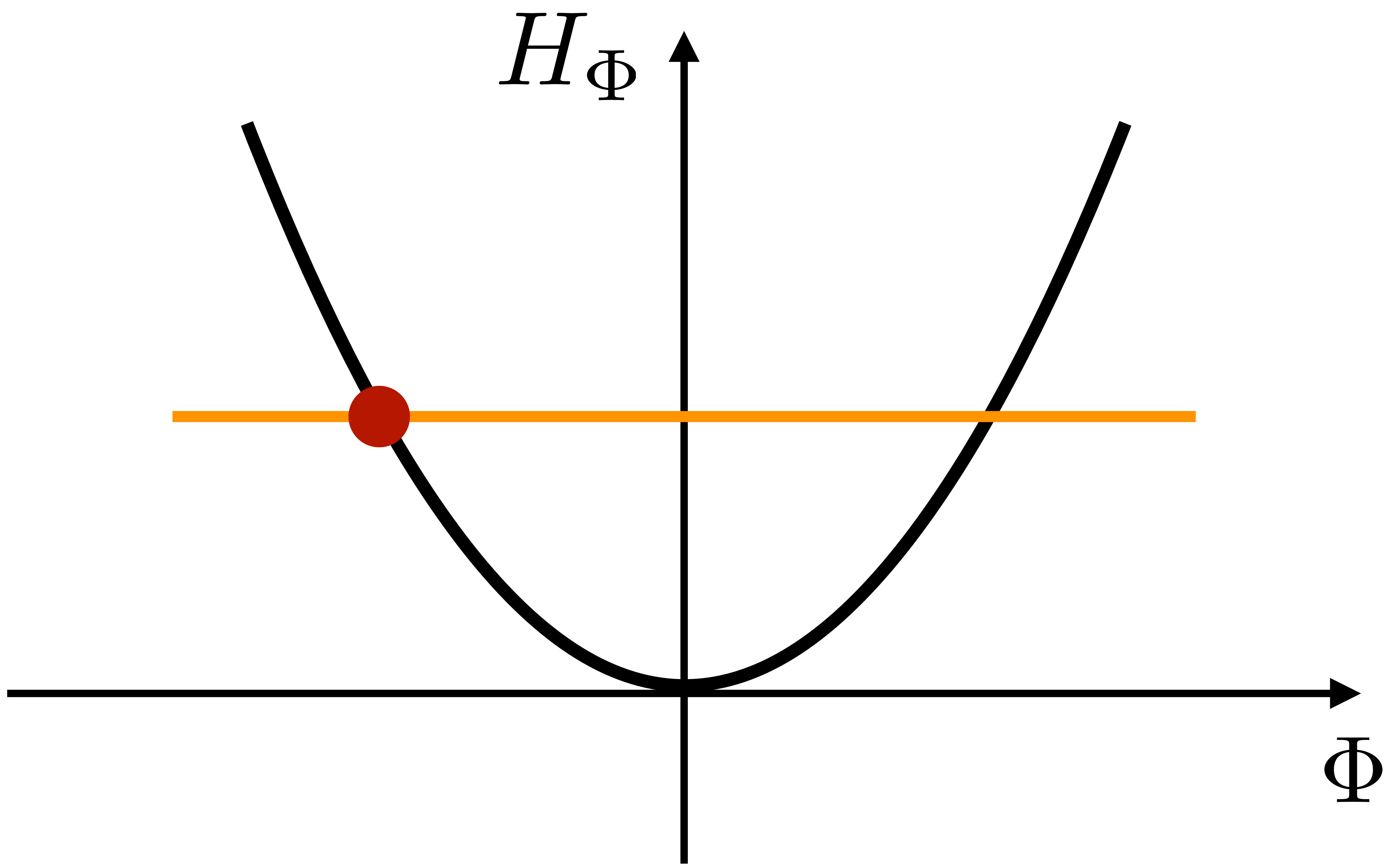
$$\omega_r = \frac{1}{\sqrt{LC}}$$

Energy conservation

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

Charge energy H_Q

Flux energy H_Φ



Classic regime

LC circuit

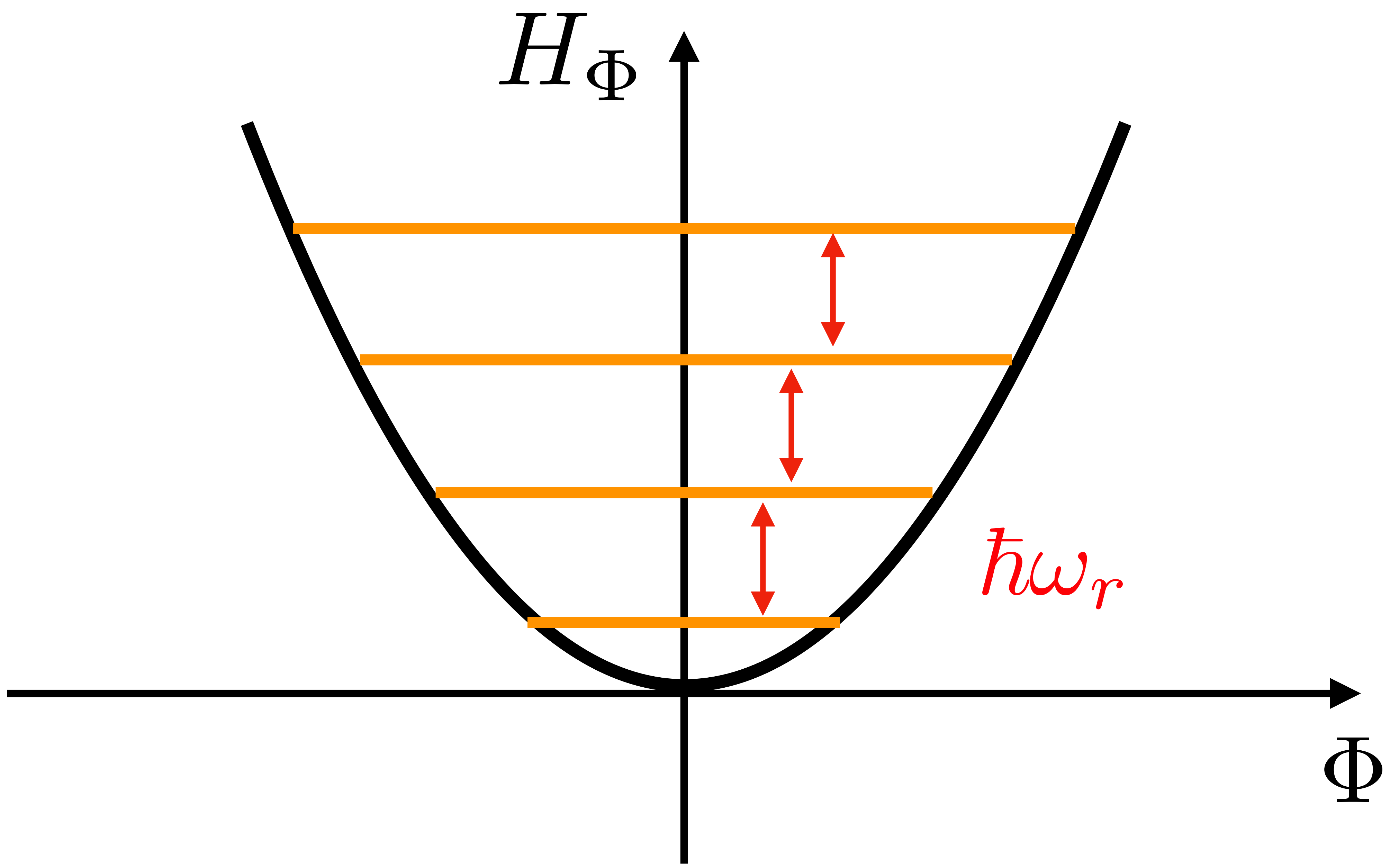
$$\omega_r = \frac{1}{\sqrt{LC}}$$

Energy conservation

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

Charge energy H_Q

Flux energy H_Φ



Quantum regime

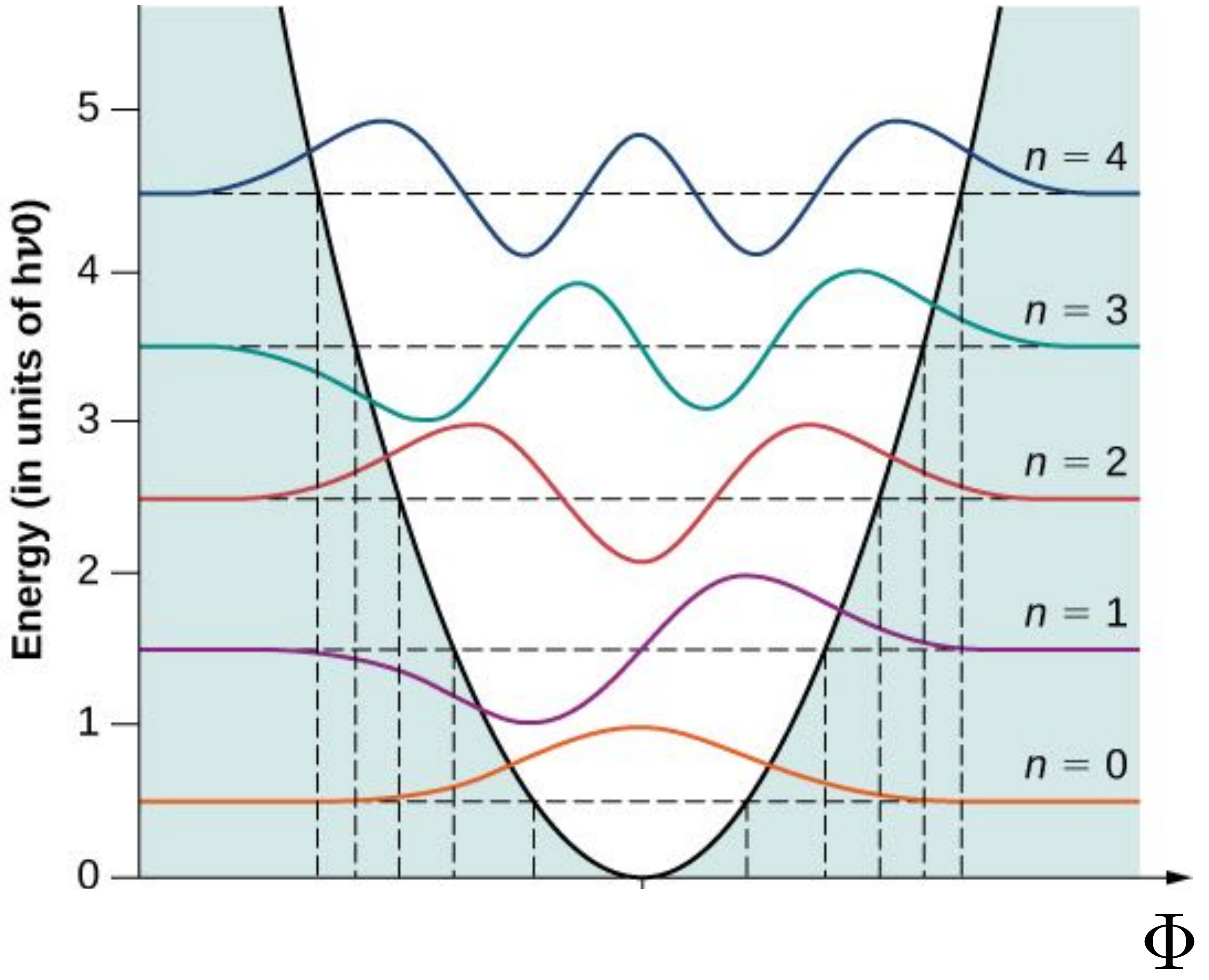
LC circuit

Energy conservation

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

Charge energy H_Q

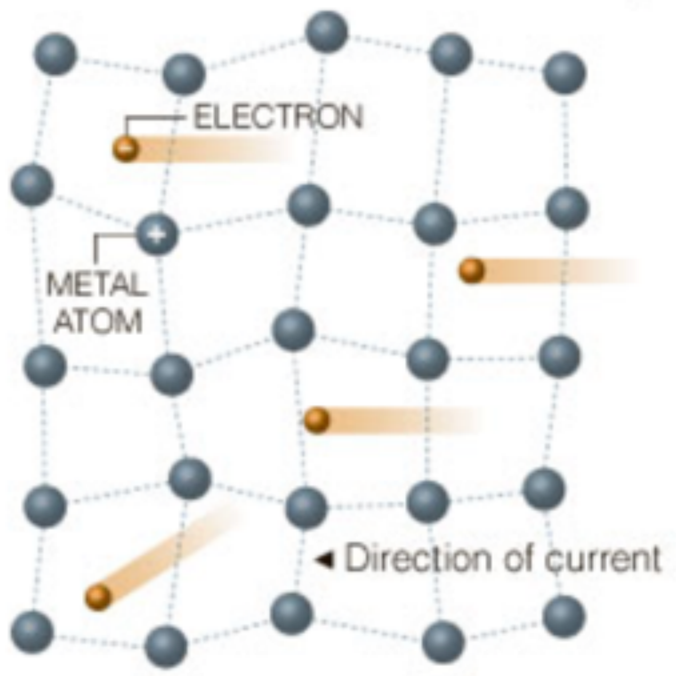
Flux energy H_Φ



Quantum regime

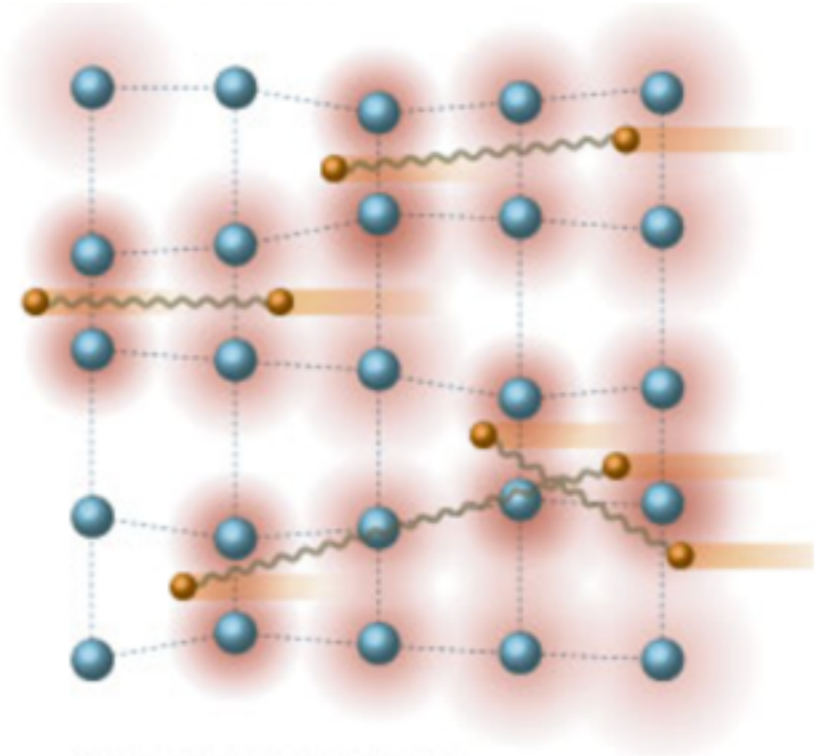
LC circuit

Normal metal



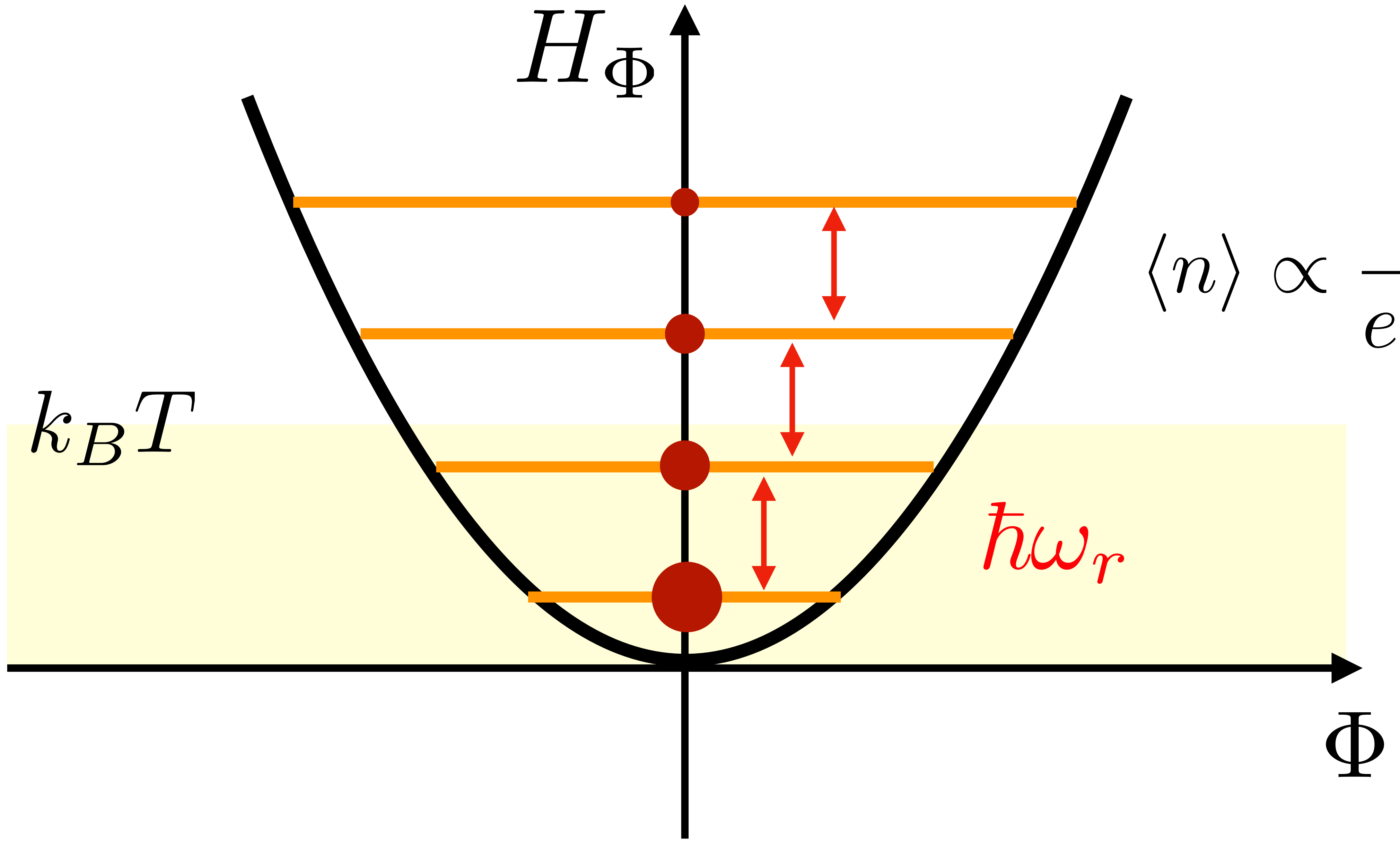
Electrons (fermion)

Superconductor



Cooper pairs (boson)

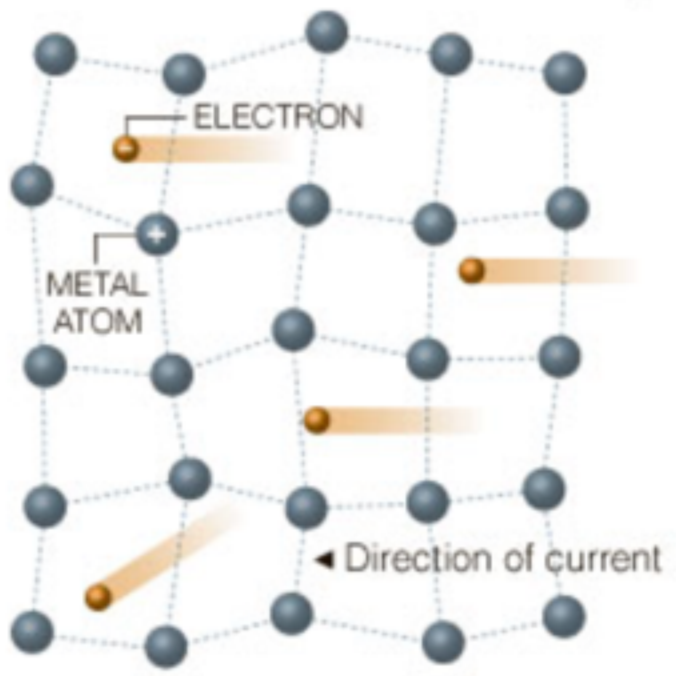
Bose-Einstein distribution



$$\langle n \rangle \propto \frac{1}{e^{H/k_B T} - 1}$$

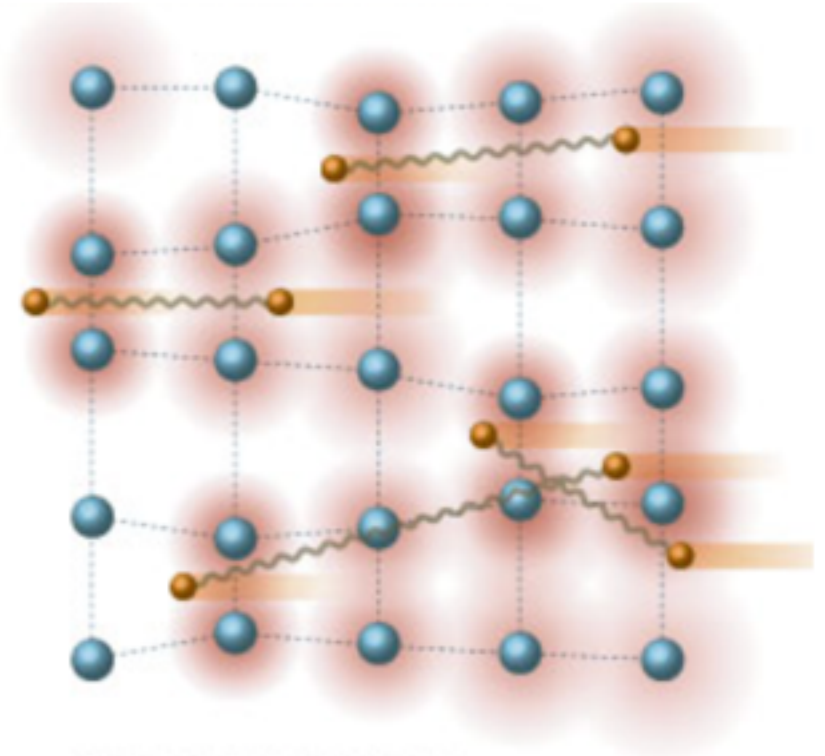
LC circuit

Normal metal



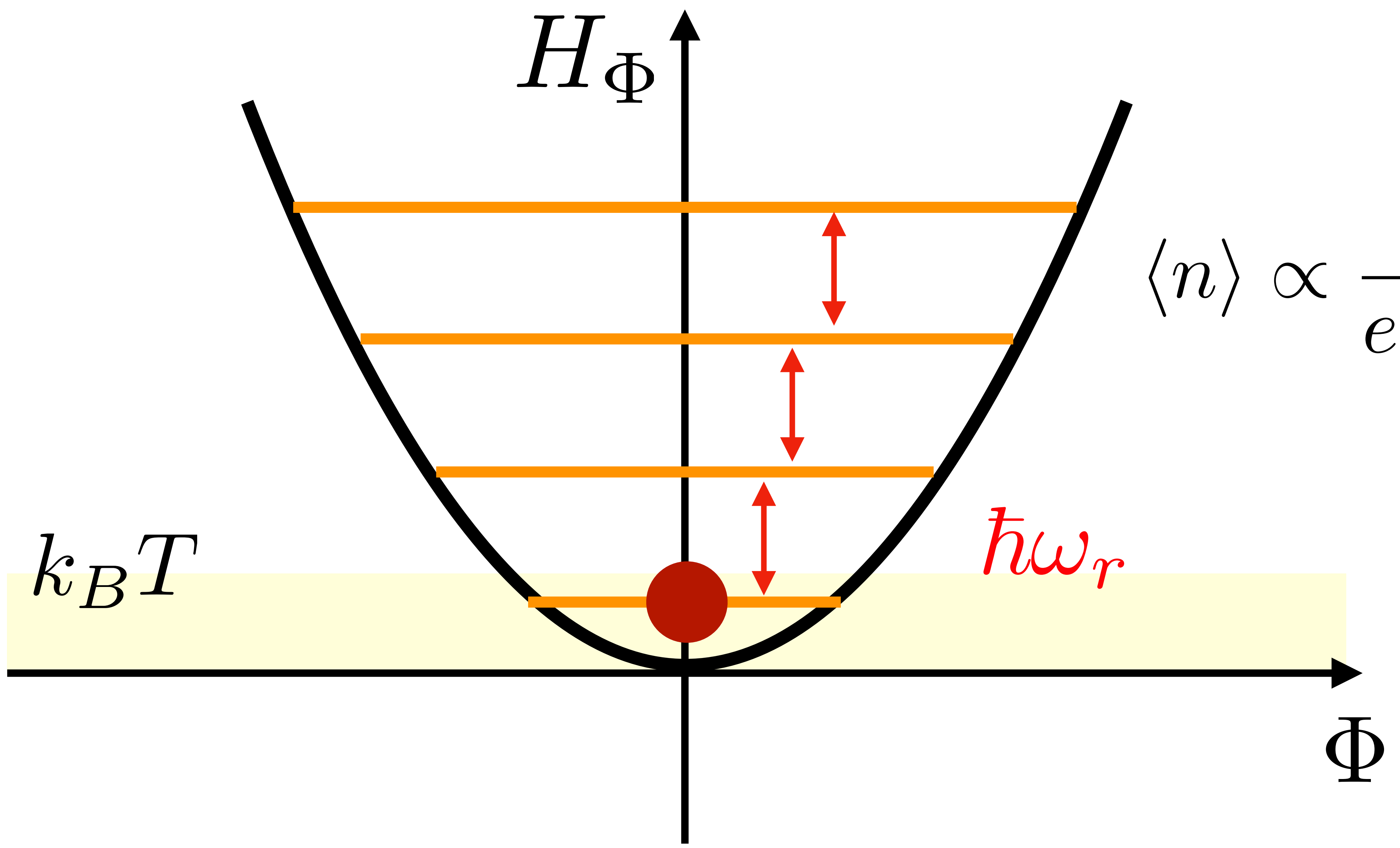
Electrons (fermion)

Superconductor



Cooper pairs (boson)

Bose-Einstein distribution



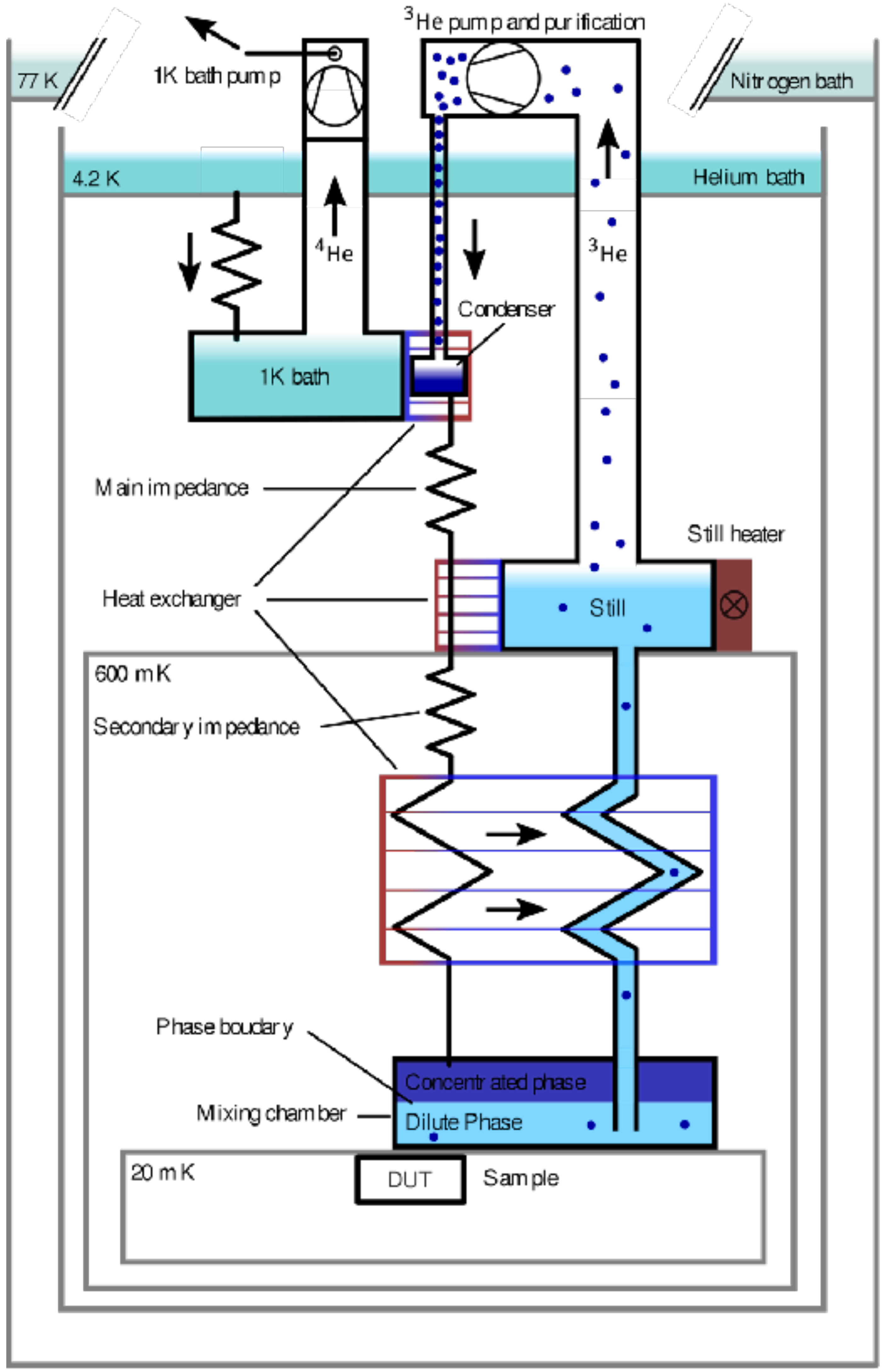
$$\langle n \rangle \propto \frac{1}{e^{H/k_B T} - 1}$$

$$\hbar\omega_r \gg k_B T$$

~5 GHz

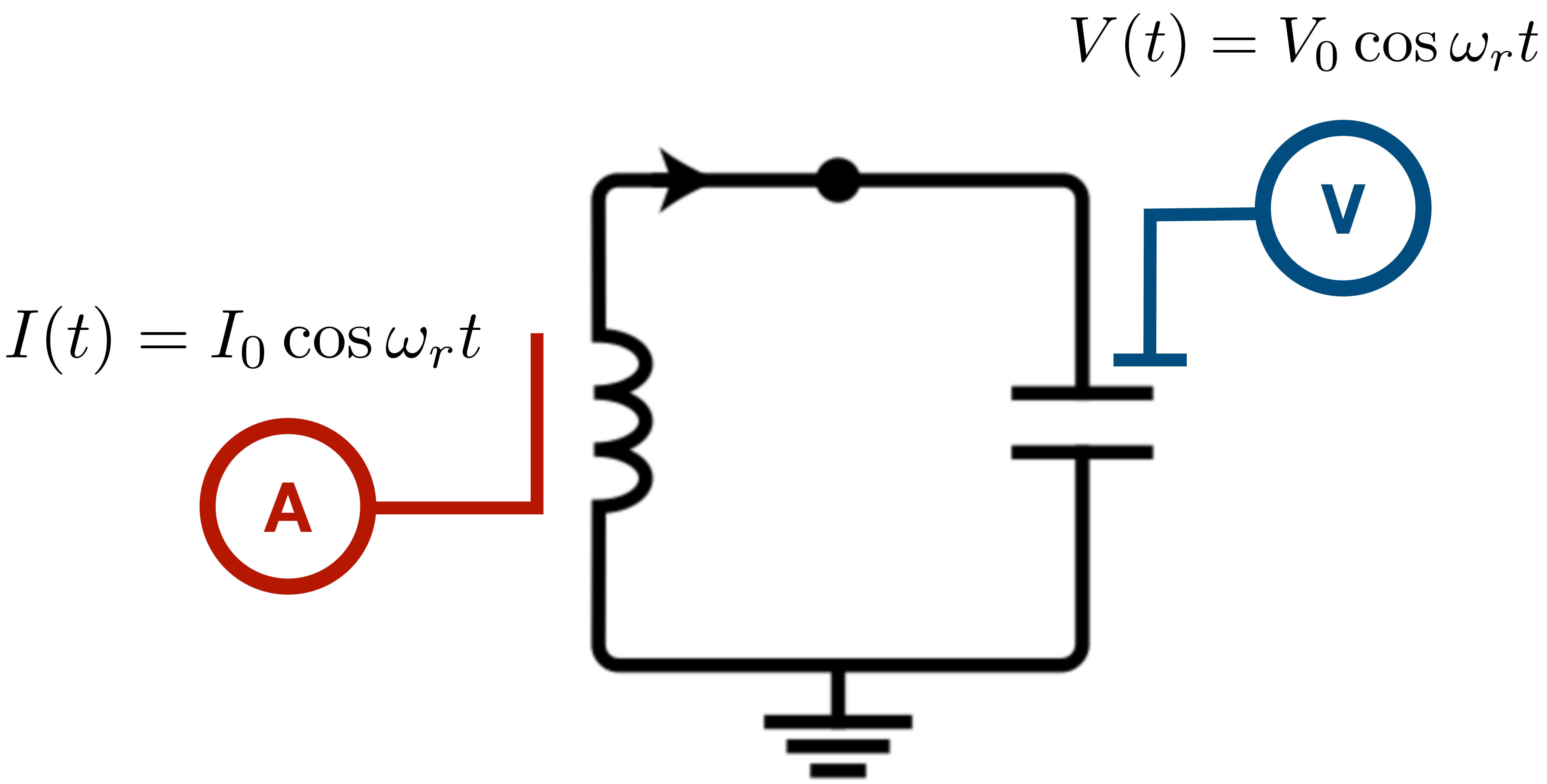
~0.2 GHz
(~10 mK)

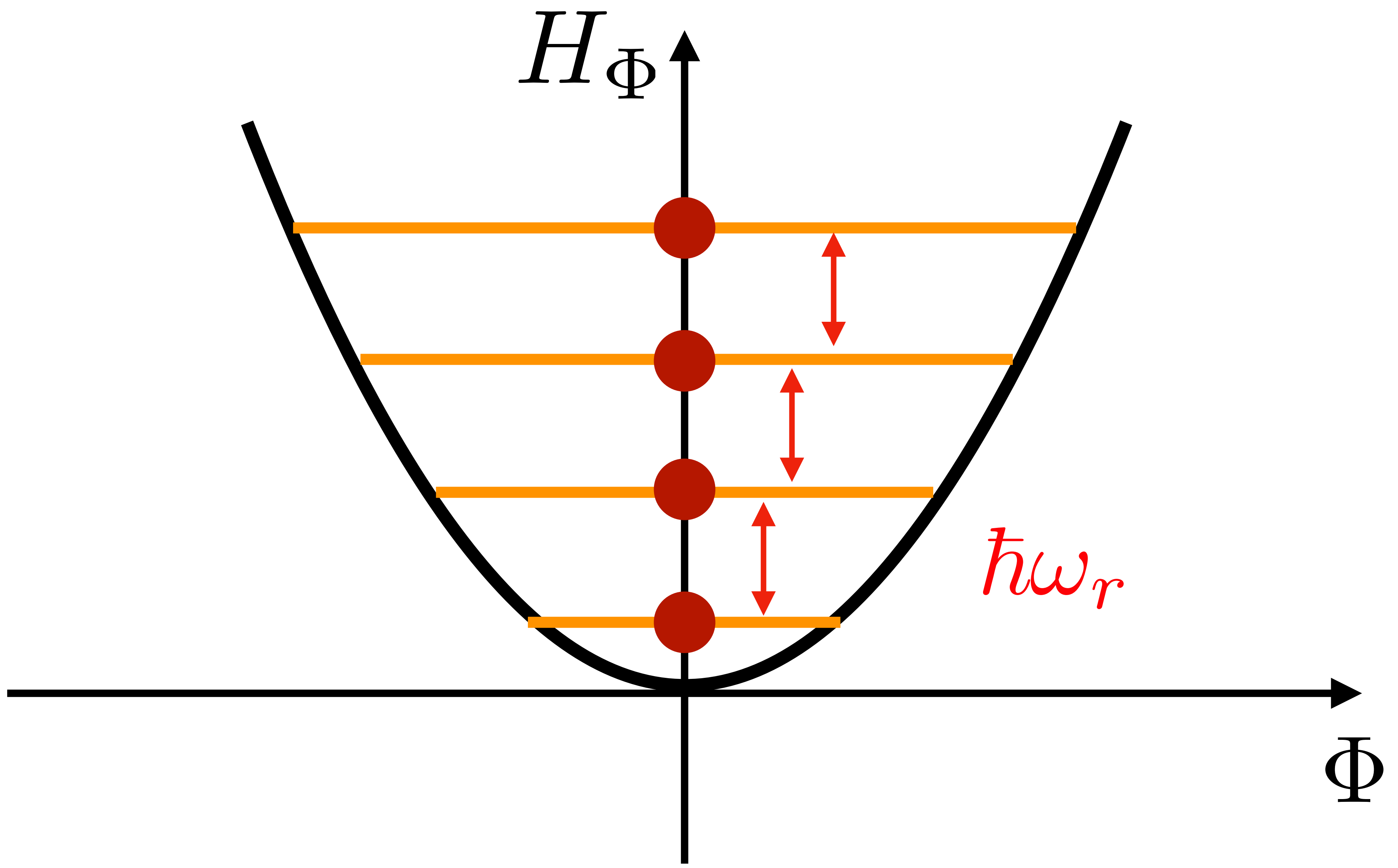
Dilution refrigerator



T < 30 mK

LC circuit

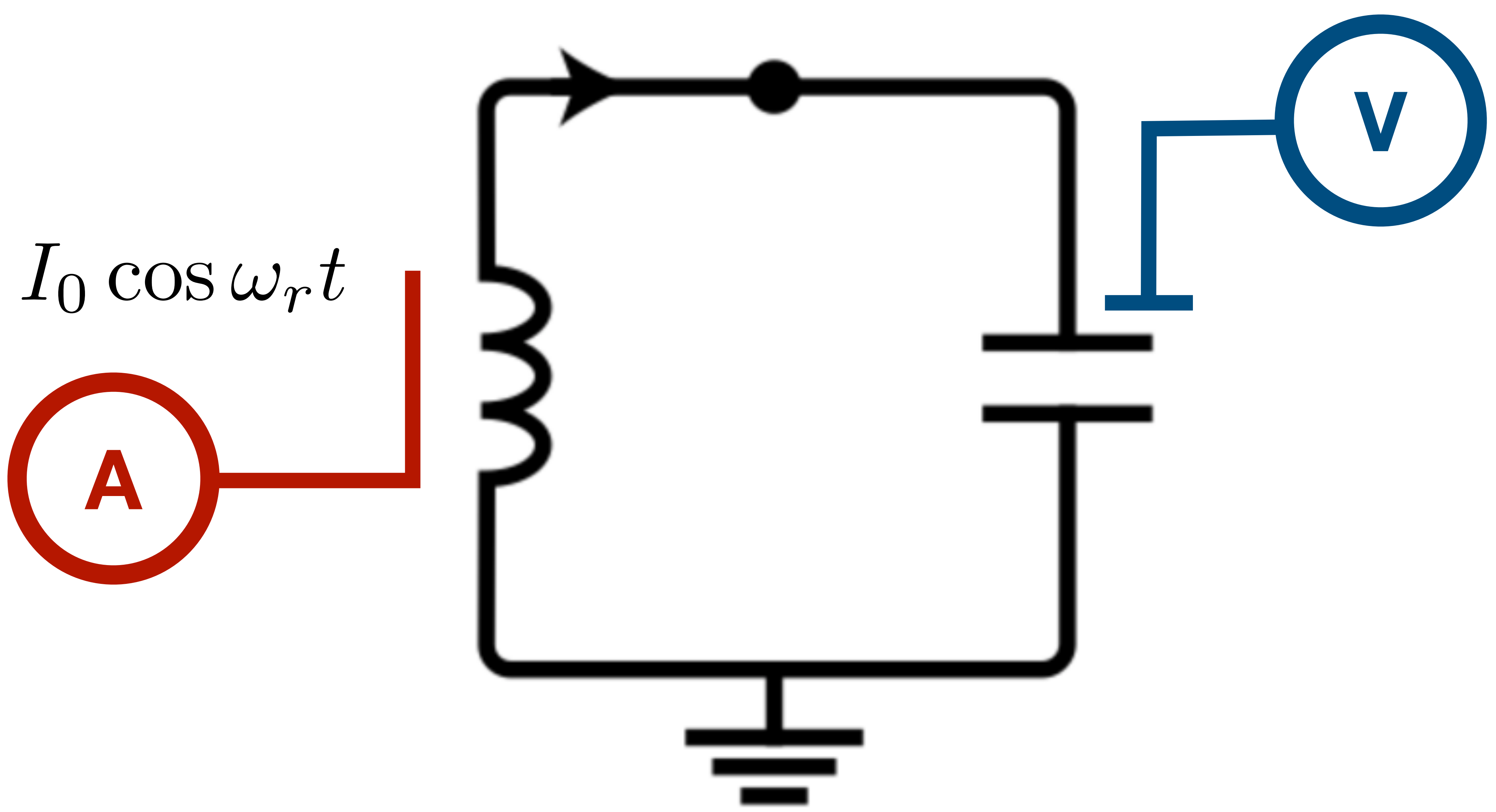


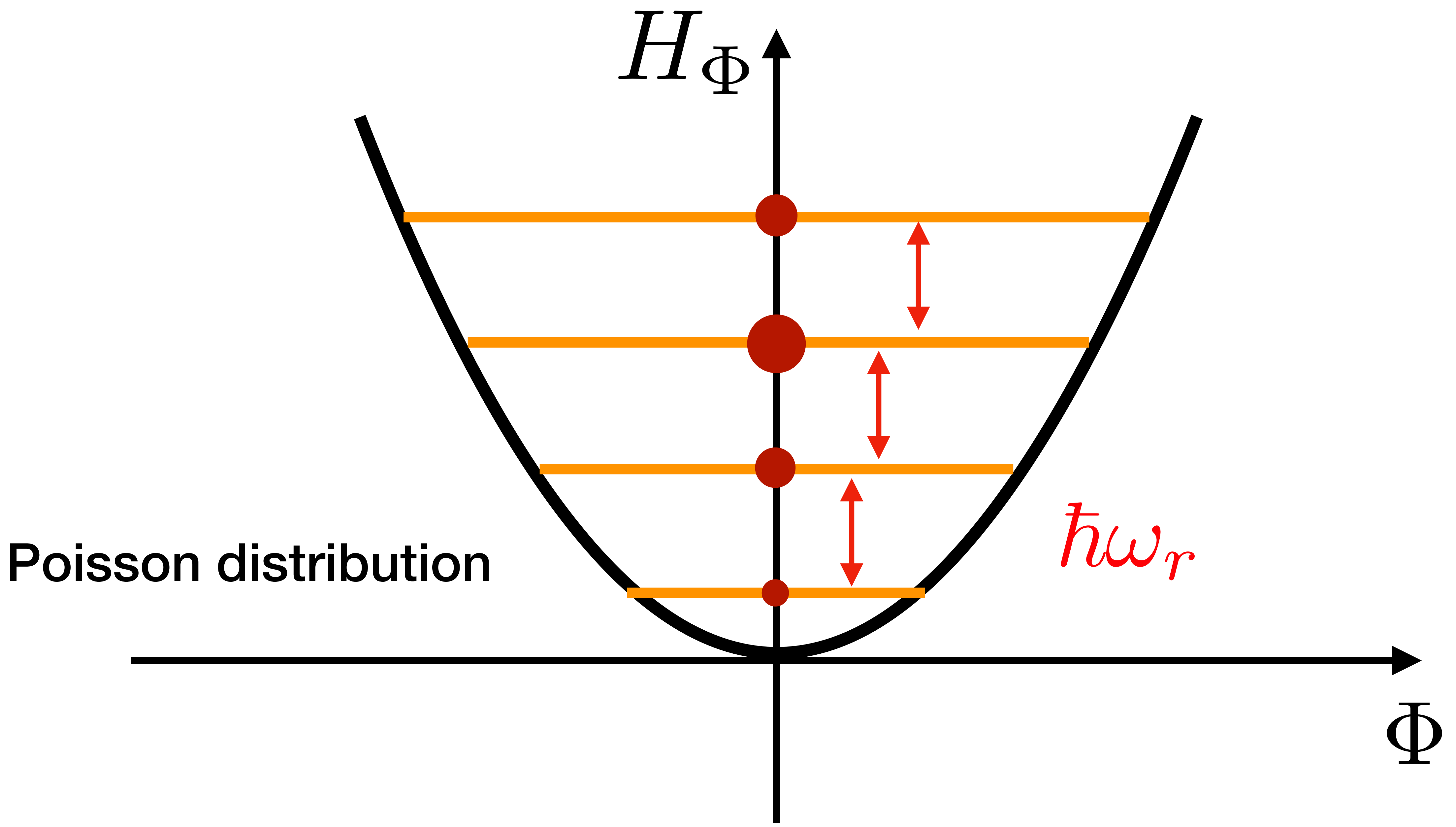


LC circuit

$V(t) = V_0 \cos \omega_r t$

$I(t) = I_0 \cos \omega_r t$

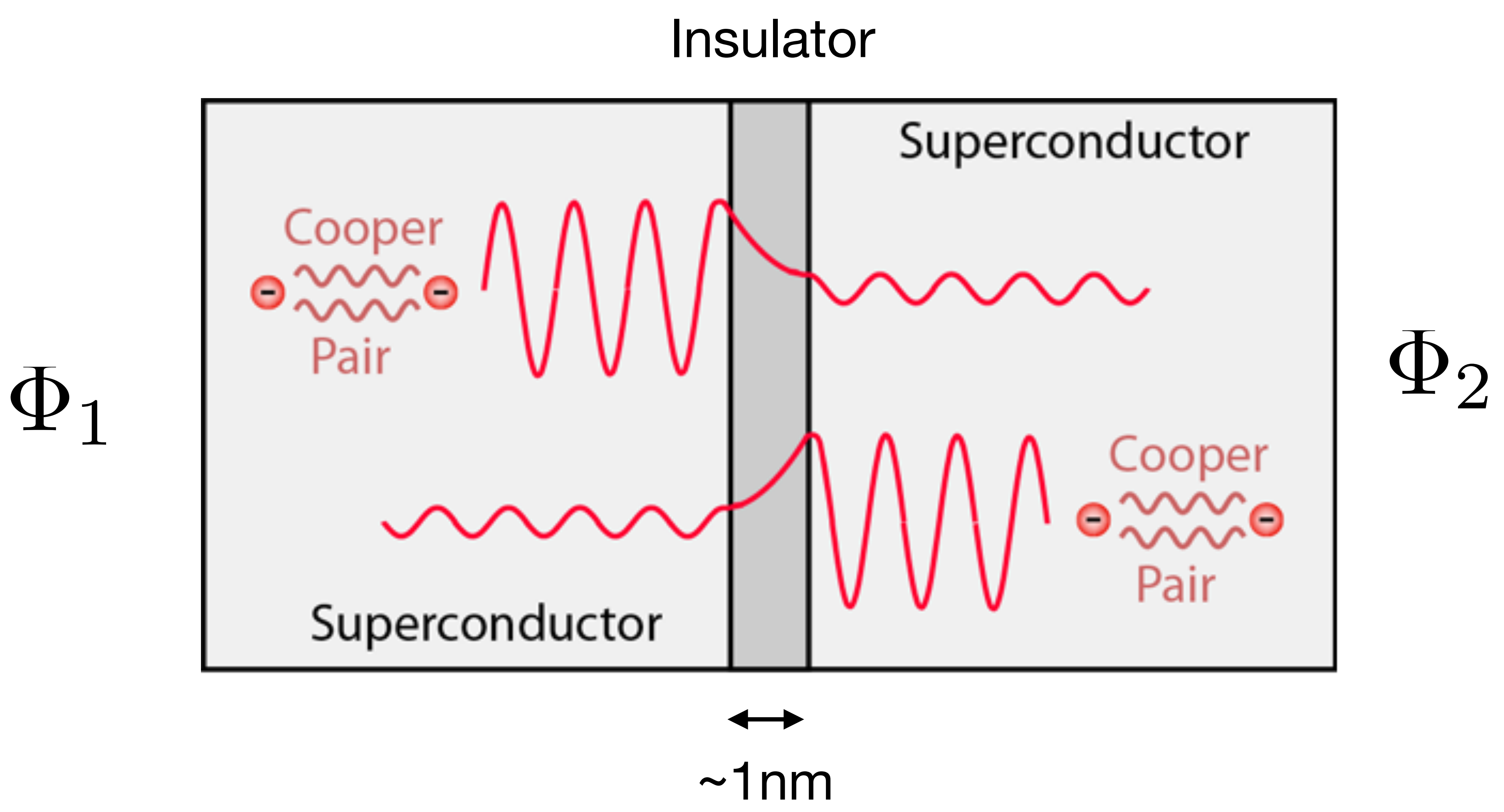




As all transitions are degenerate, one cannot steer the system to an arbitrary state

We need a non-linear circuit element!!

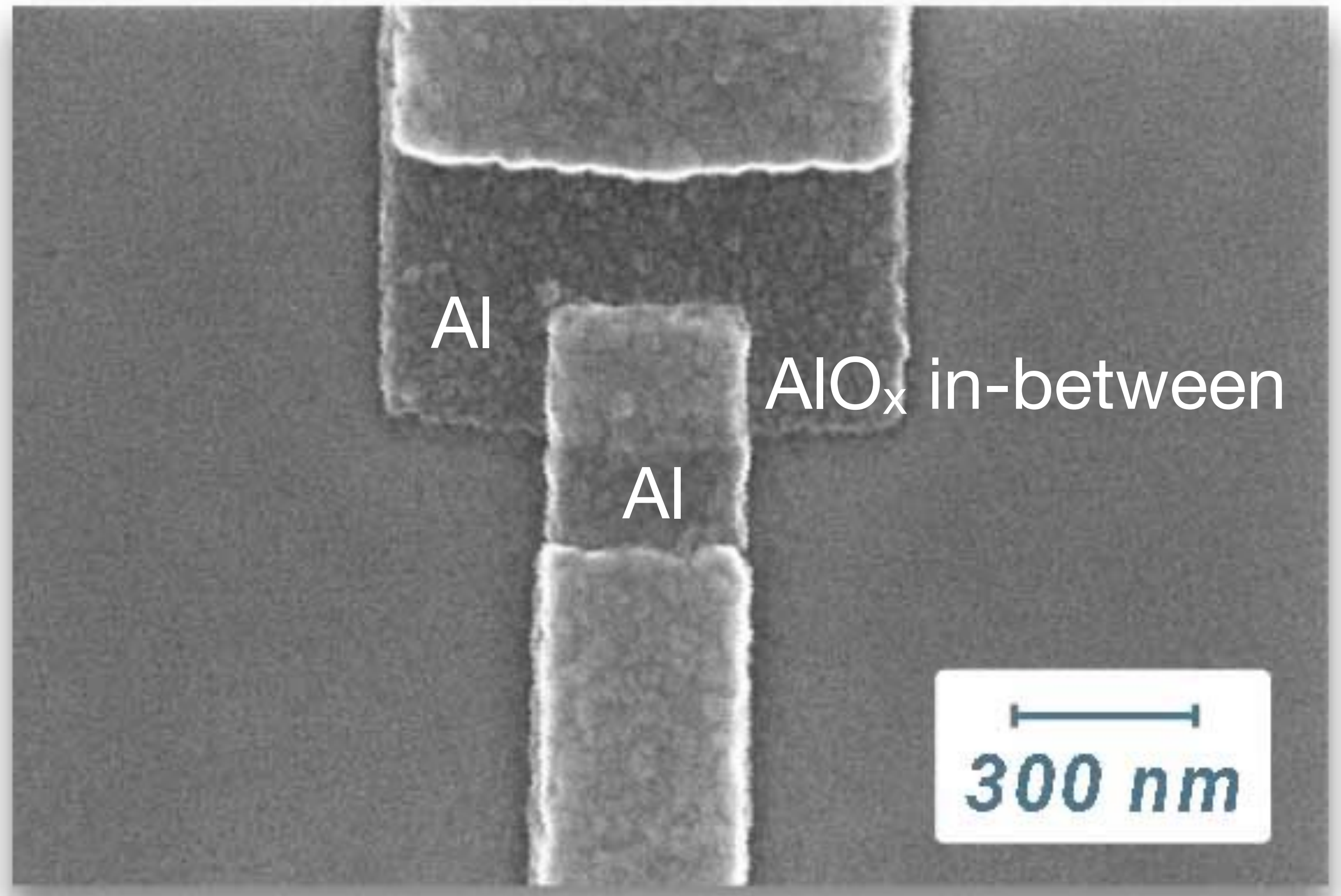
Josephson Junction



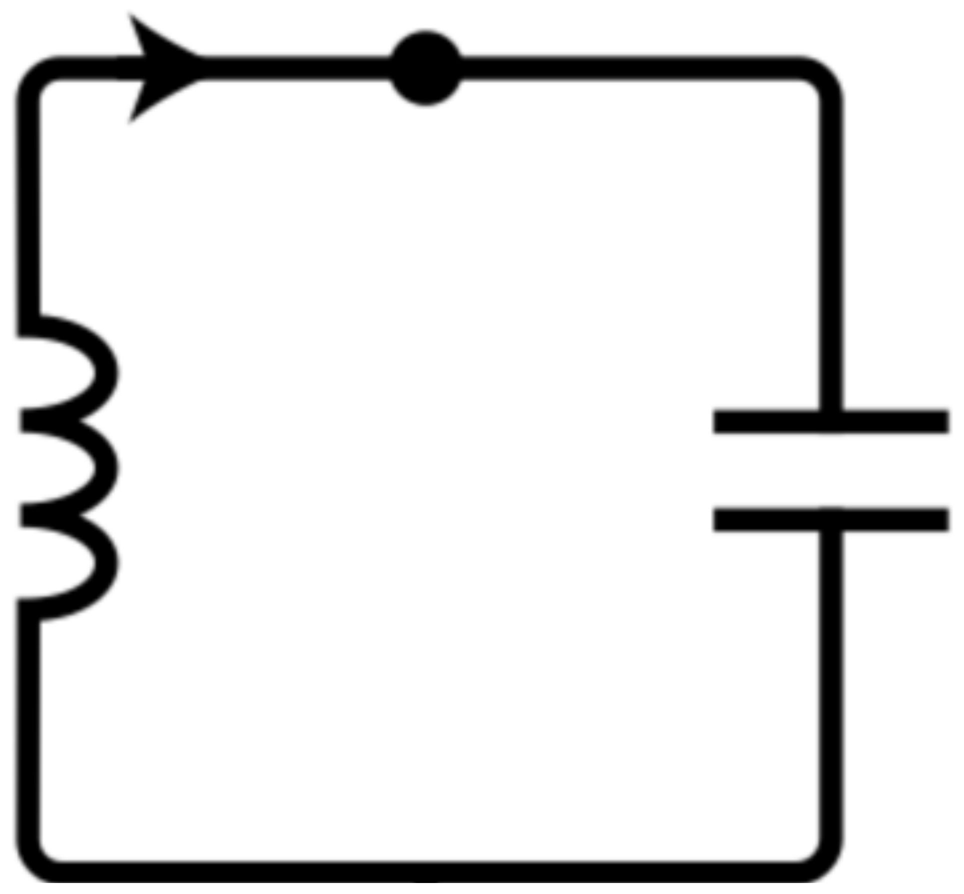
$$I_J = I_c \sin\left(\frac{2\pi\Phi}{\Phi_0}\right)$$

Josephson current

$$\Phi = \Phi_2 - \Phi_1$$



Josephson Junction

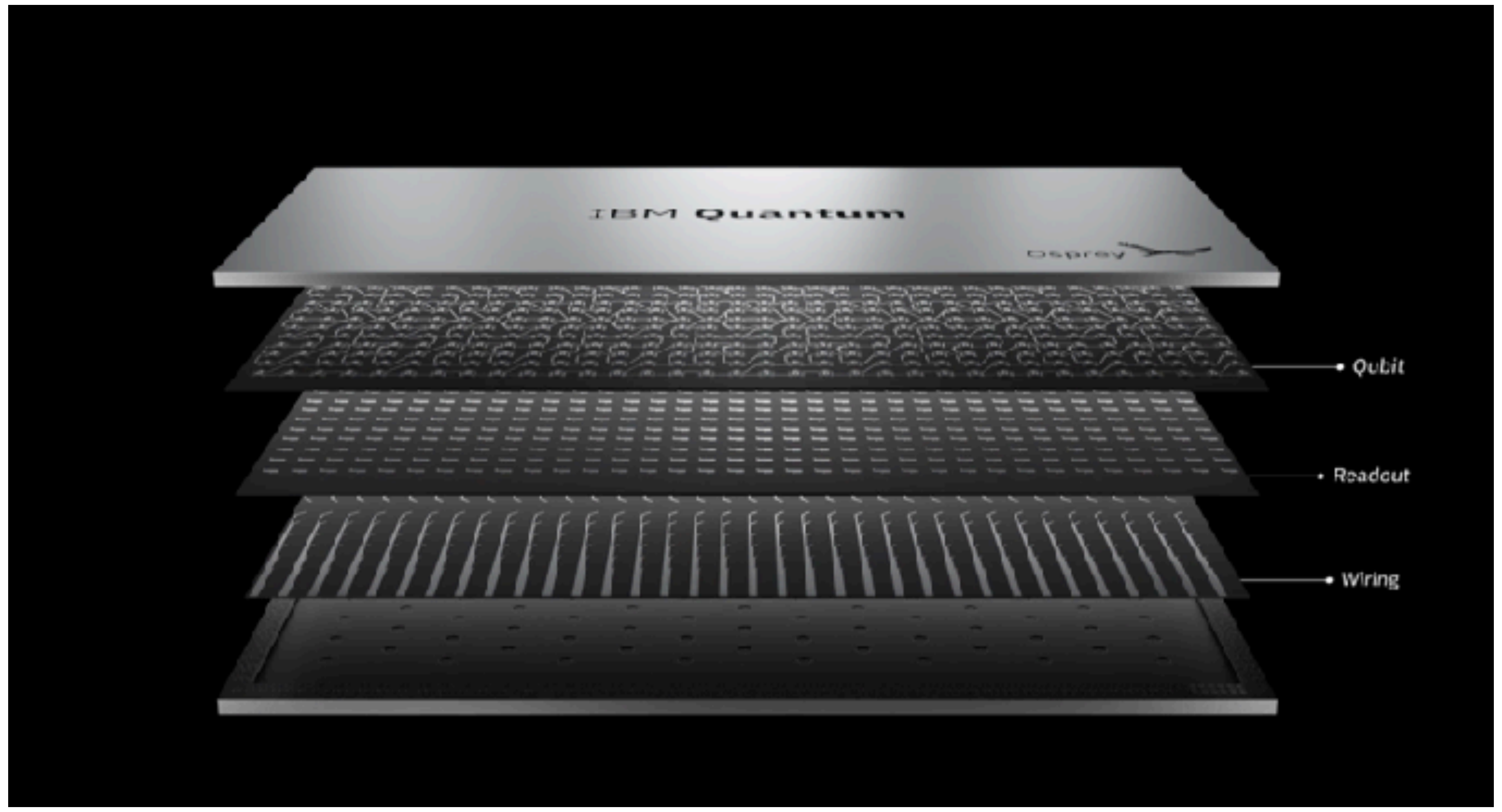


Charge energy Flux energy

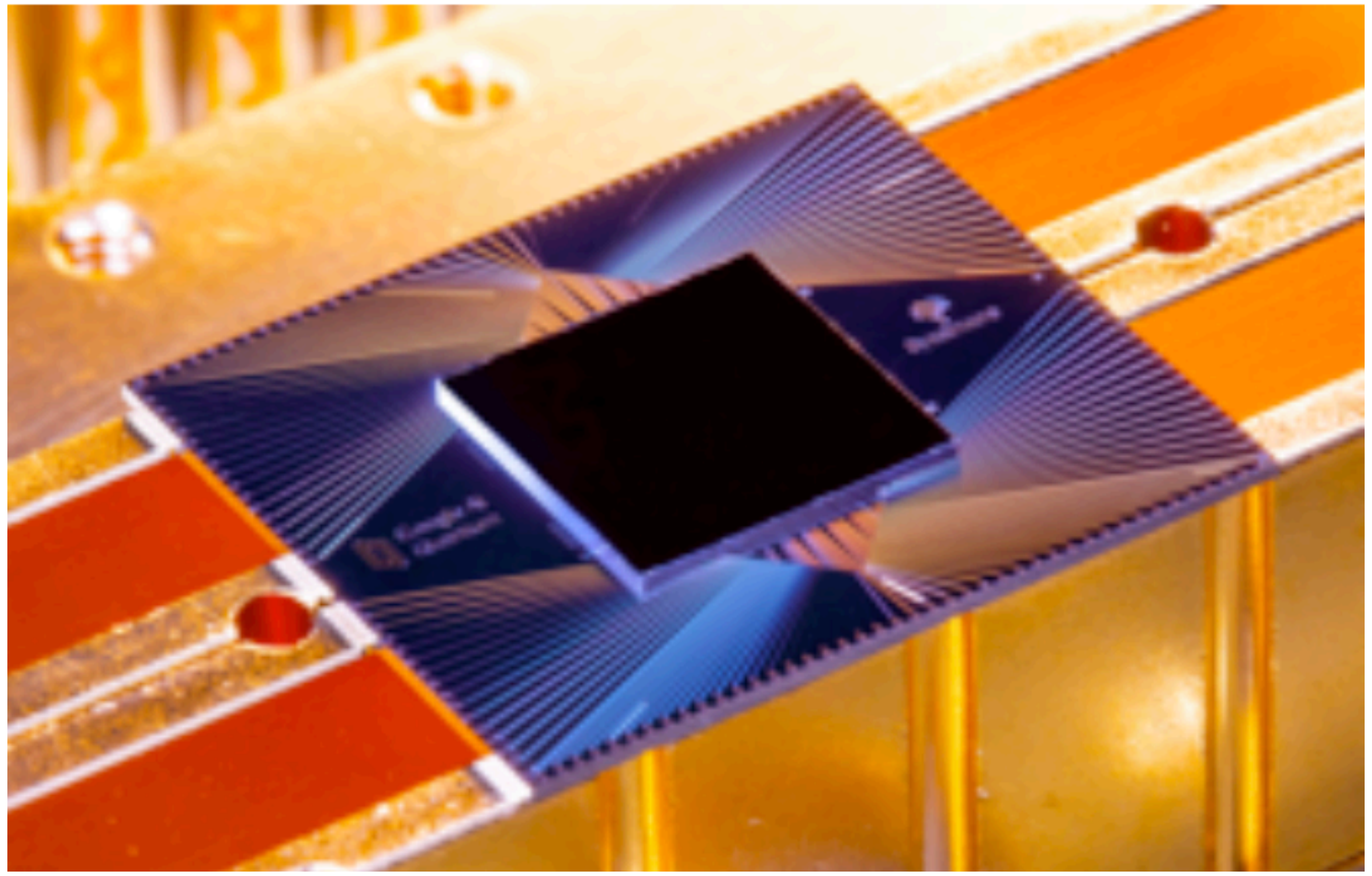
$$H_{\text{linear}} = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}$$

$$H_{\text{JJ}} = \frac{Q^2}{2C_J} - \frac{\hbar I_c}{2e}\cos\left(\frac{2\pi\Phi}{\Phi_0}\right)$$

Quantum processors: IBM vs Google



433-qubit Osprey processor (IBM)

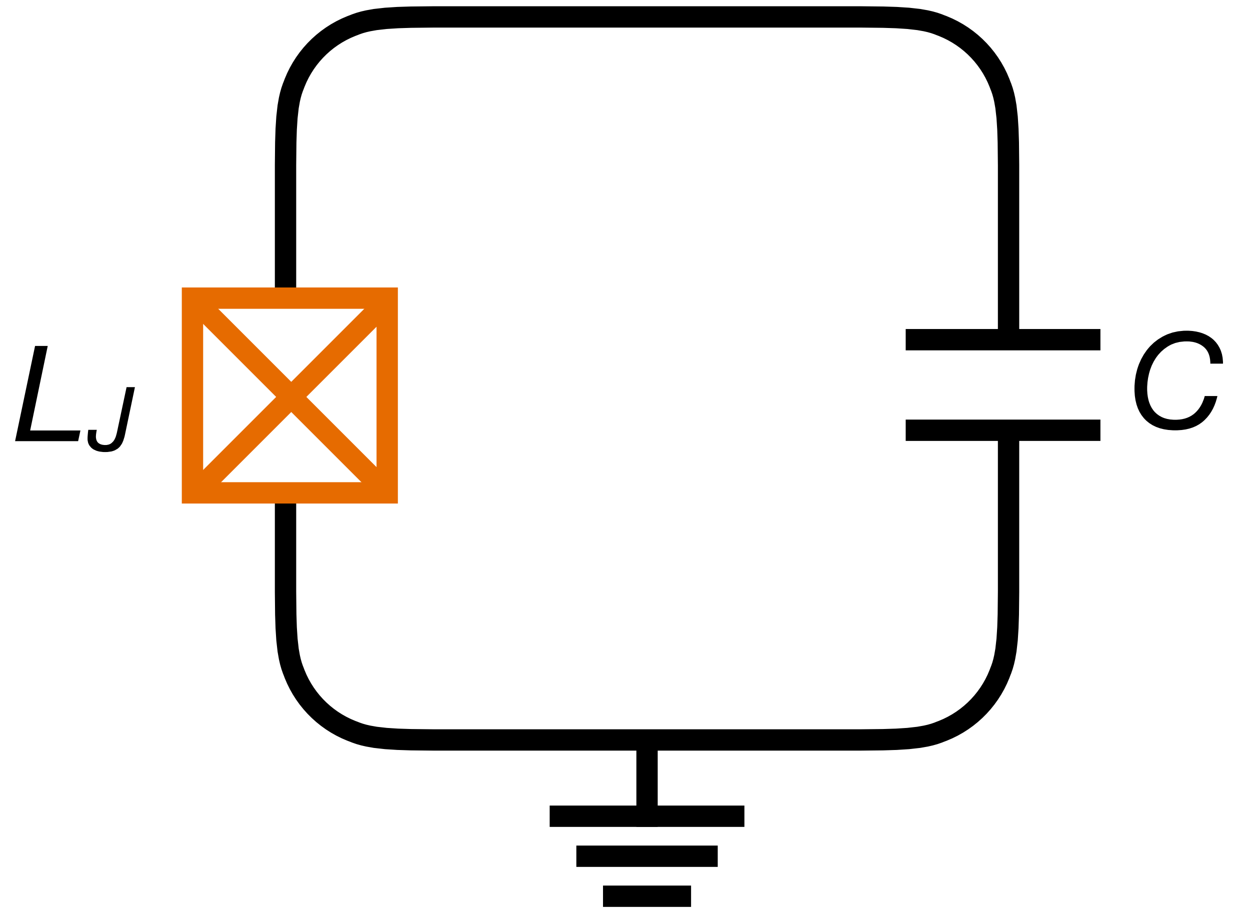


72-qubit Sycamore processor (Google)

Quantum processors: IBM vs Google

IBM

Fixed-frequency qubit

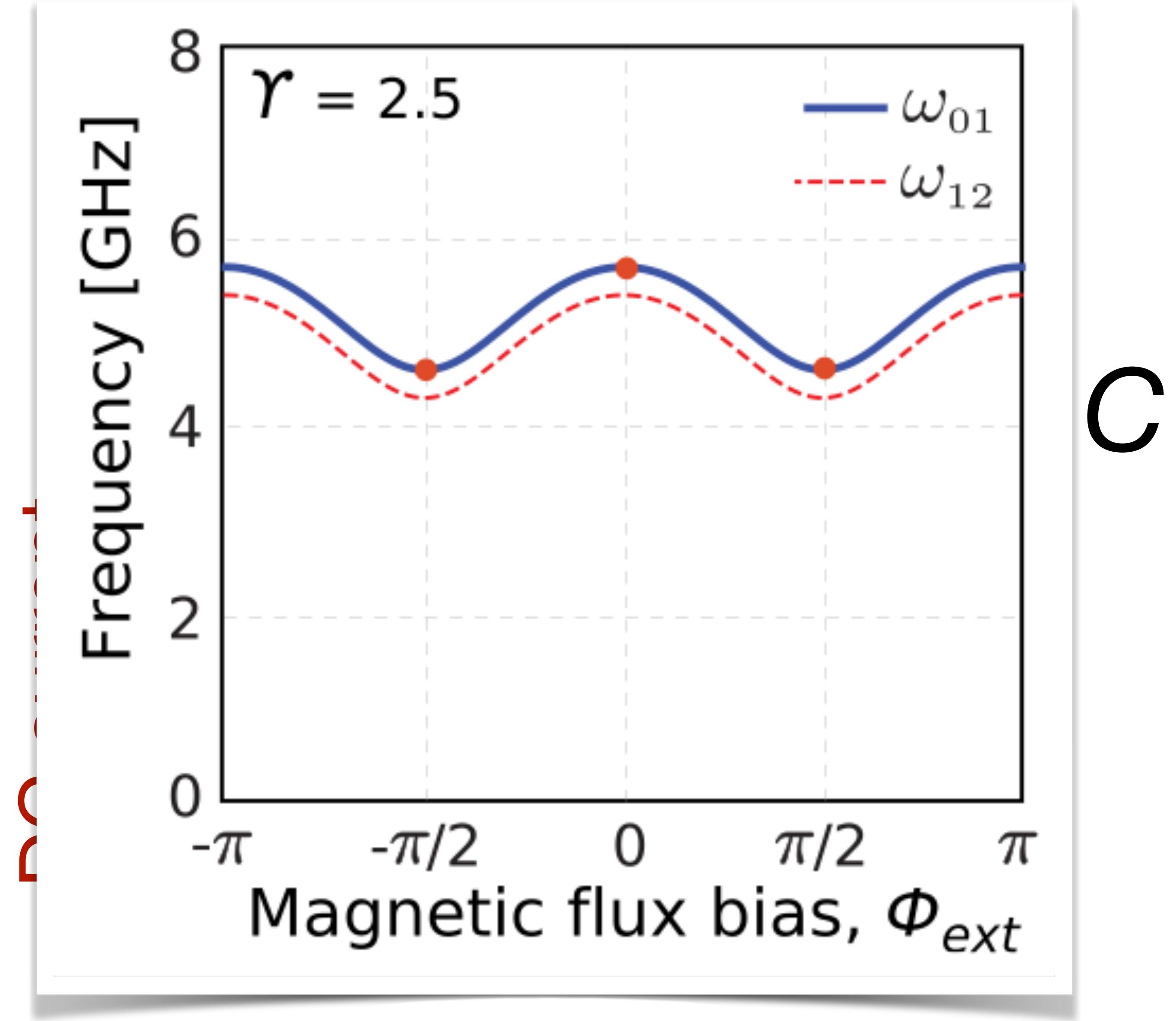


Coherence time (T_1) : **>400 μs**

arXiv:2106.00675

Google

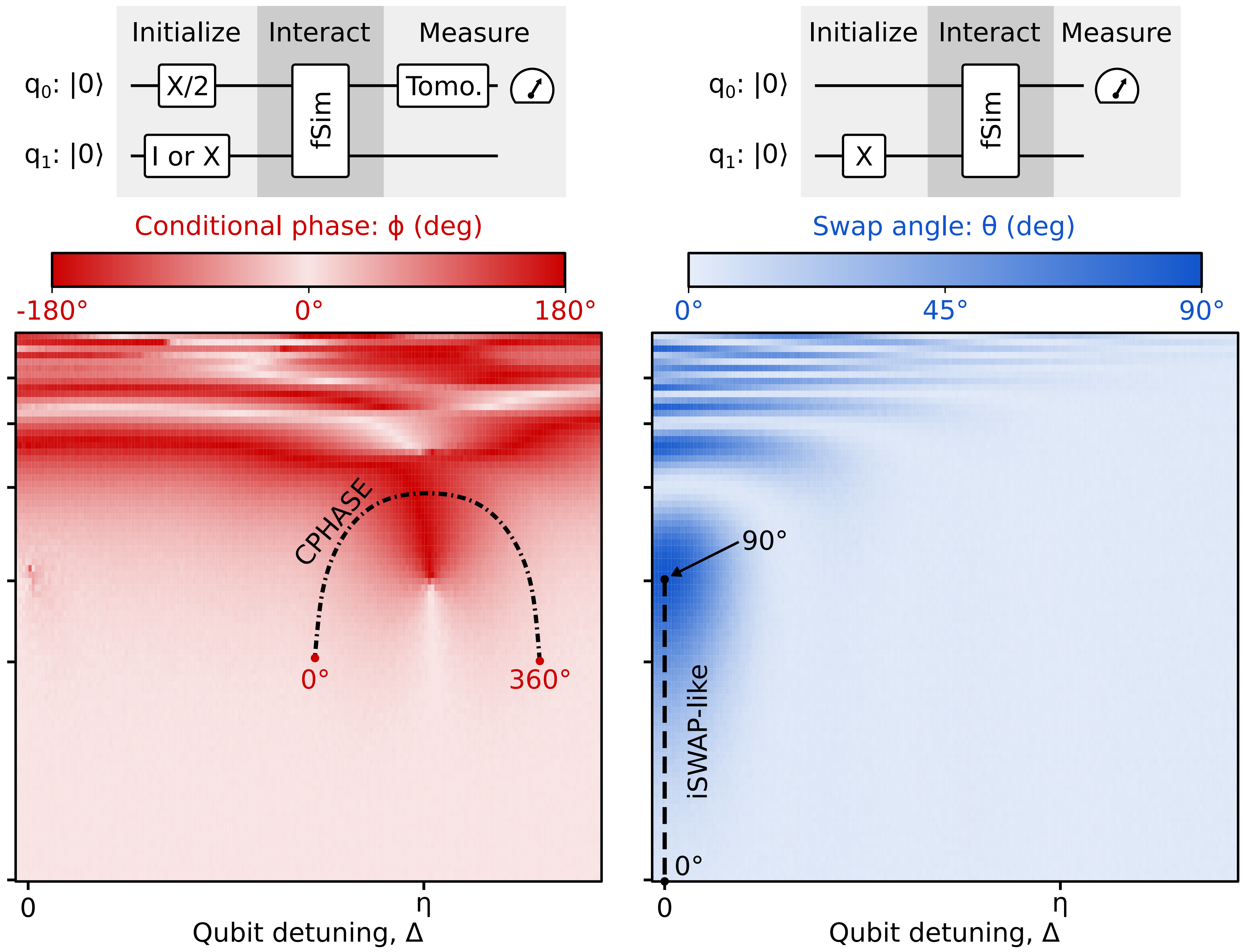
Frequency-tunable qubit



Coherence time (T_1) : **~20 μs**

Nature **614**, 676 (2023)

Quantum processors: IBM vs Google

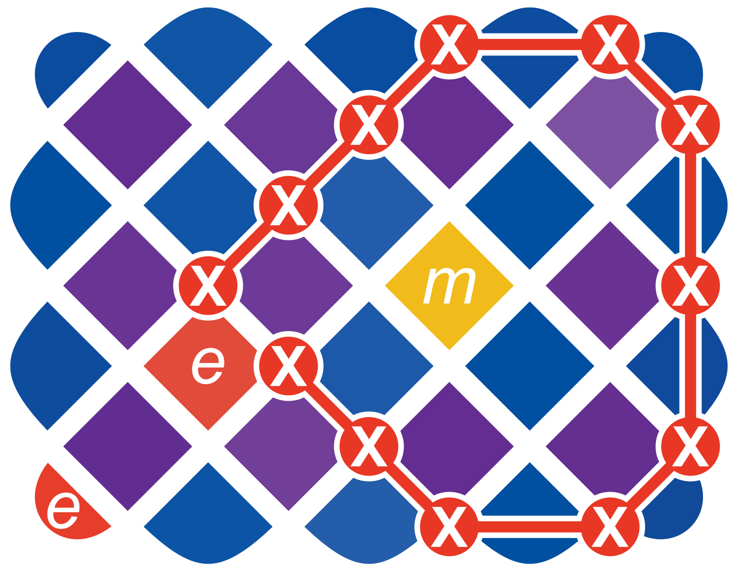


PRL **125**, 120504 (2020)

Frequency-tunable architecture
has **more interaction types**

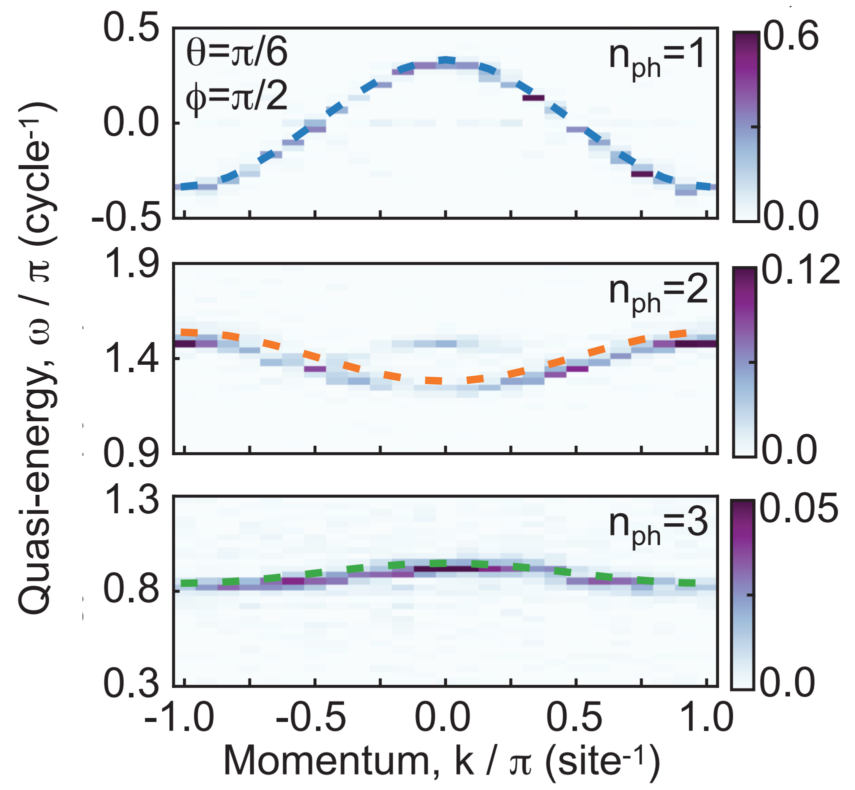
Topologically ordered states

$U_4|E\rangle = e^{i\pi}|E\rangle$



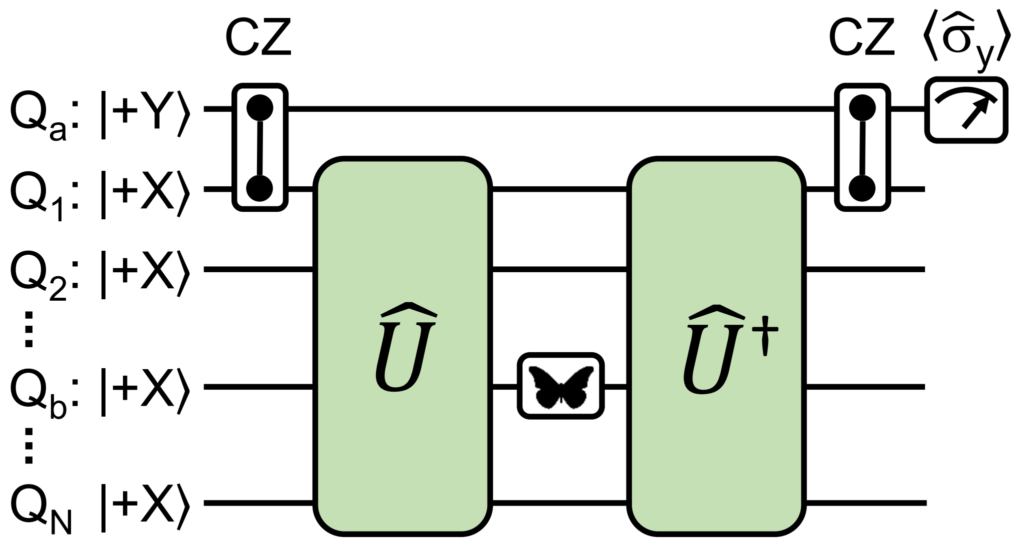
Science **374**, 1237 (2021)

Multi-photon bound states



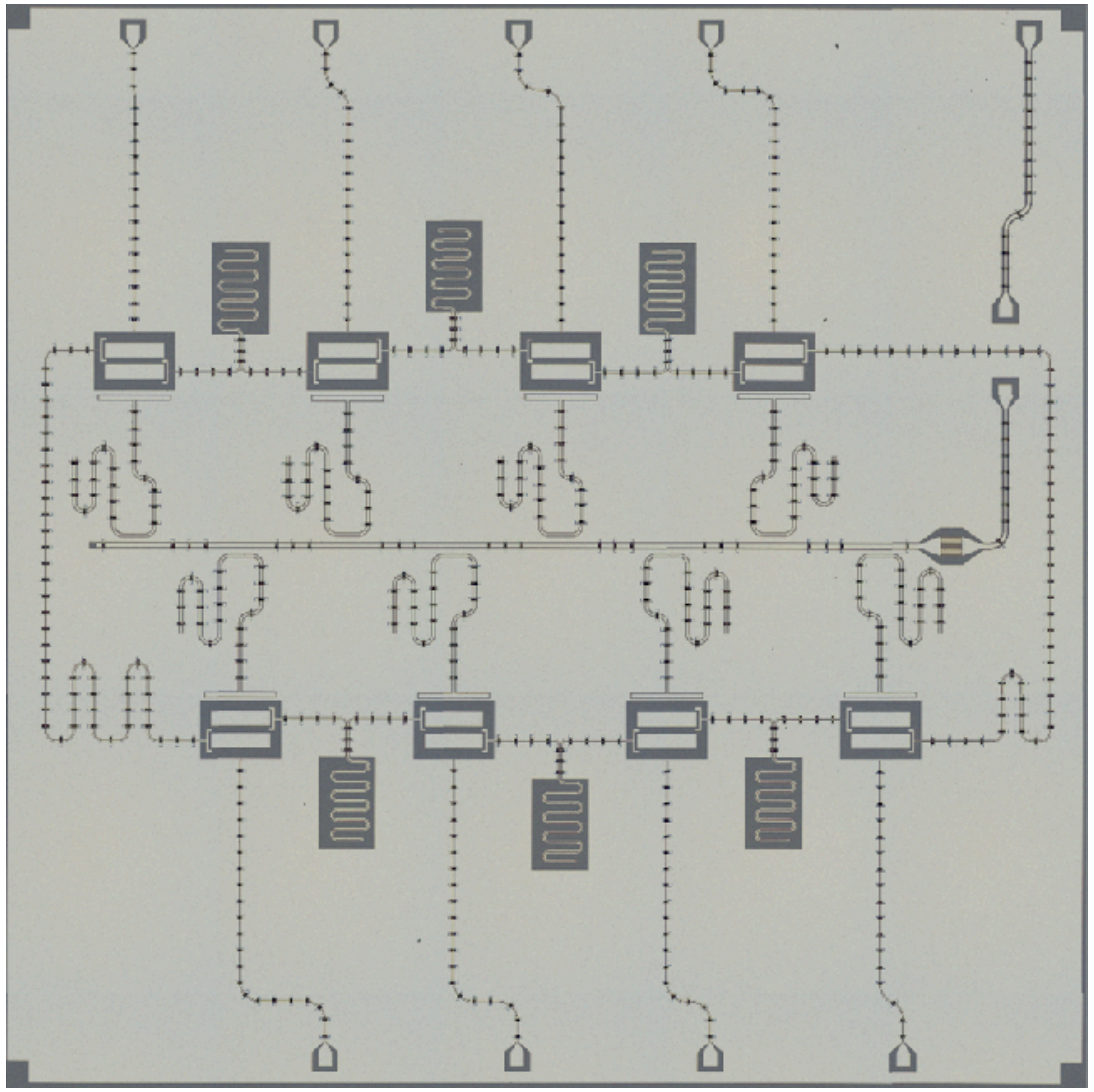
arXiv:2206.05254

Information scrambling



Science **374**, 1479 (2021)

Challenges in superconducting devices



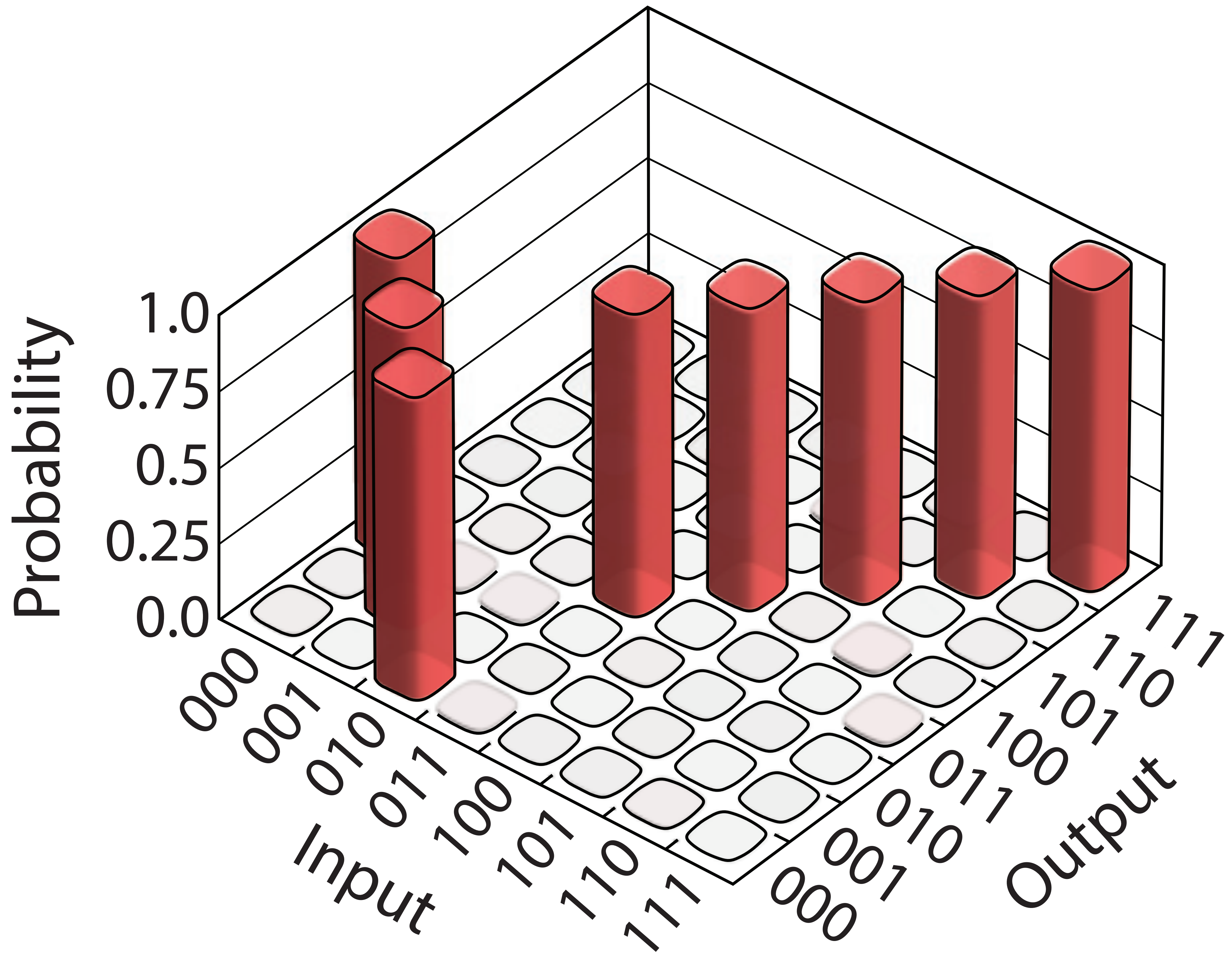
1. Trade-off between robustness and tunability

➔ Lack of versatile, high-coherence interactions

2. Limited range of interactions

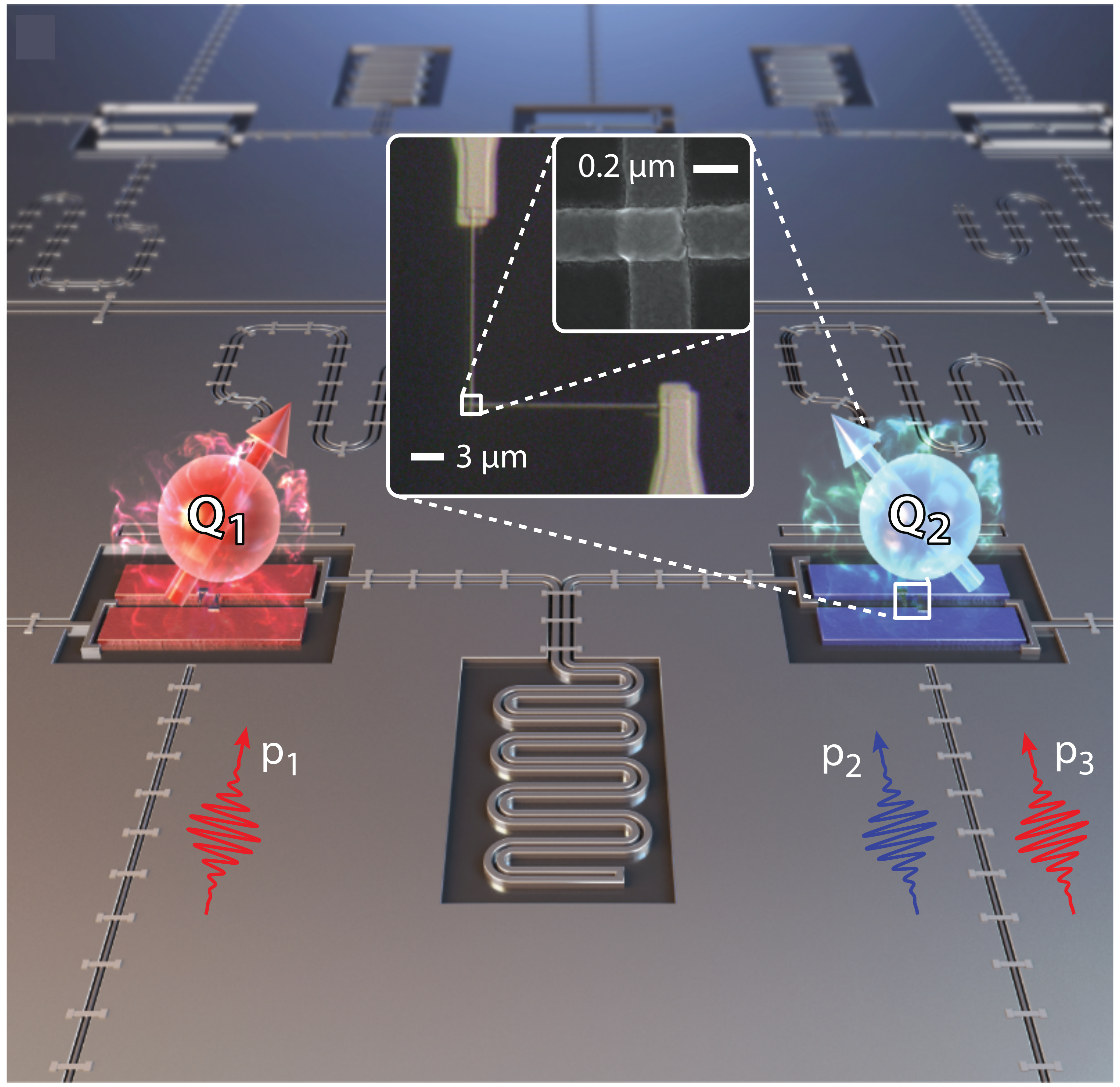
➔ Lack of efficient multi-qubit interactions

High-fidelity three-qubit iToffoli gate



Y. Kim *et al.*, Nat. Phys. **124**, 210401 (2020)

Programmable Heisenberg interactions between Floquet qubits

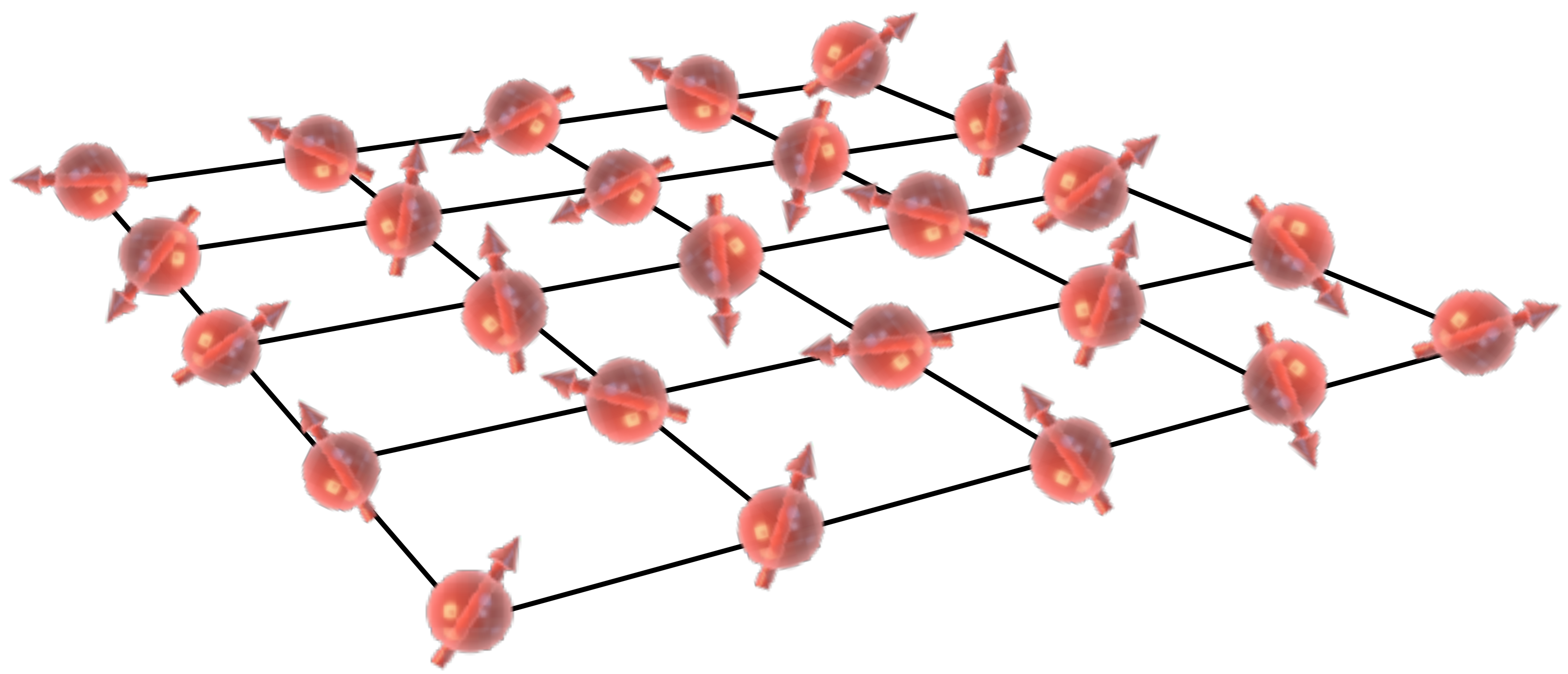


L. B. Nyguen*, **Y. Kim*** *et al.*, Nat. Phys. (2024)

Programmable Heisenberg interactions for fixed-frequency qubits

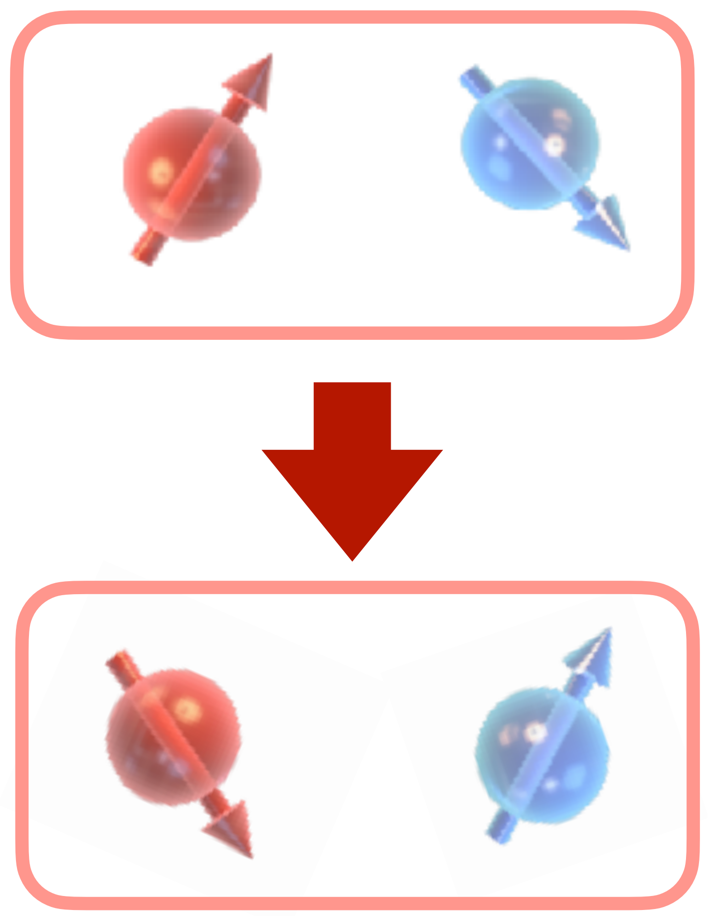
XXZ Heisenberg model

XXZ Heisenberg model

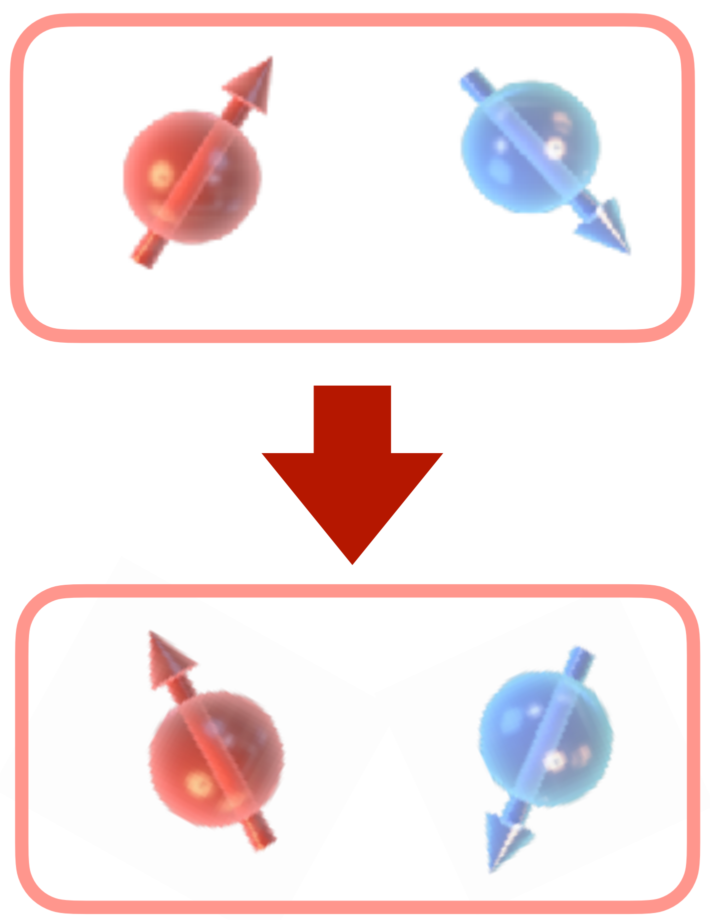


$$\hat{H}_{\mathrm{XXZ}} = \sum_{ij} J_{\mathrm{XY}} \left(\hat{X}_i \hat{X}_j + \hat{Y}_i \hat{Y}_j \right) + J_{\mathrm{ZZ}} \hat{Z}_i \hat{Z}_j$$

Spin-exchange Interaction

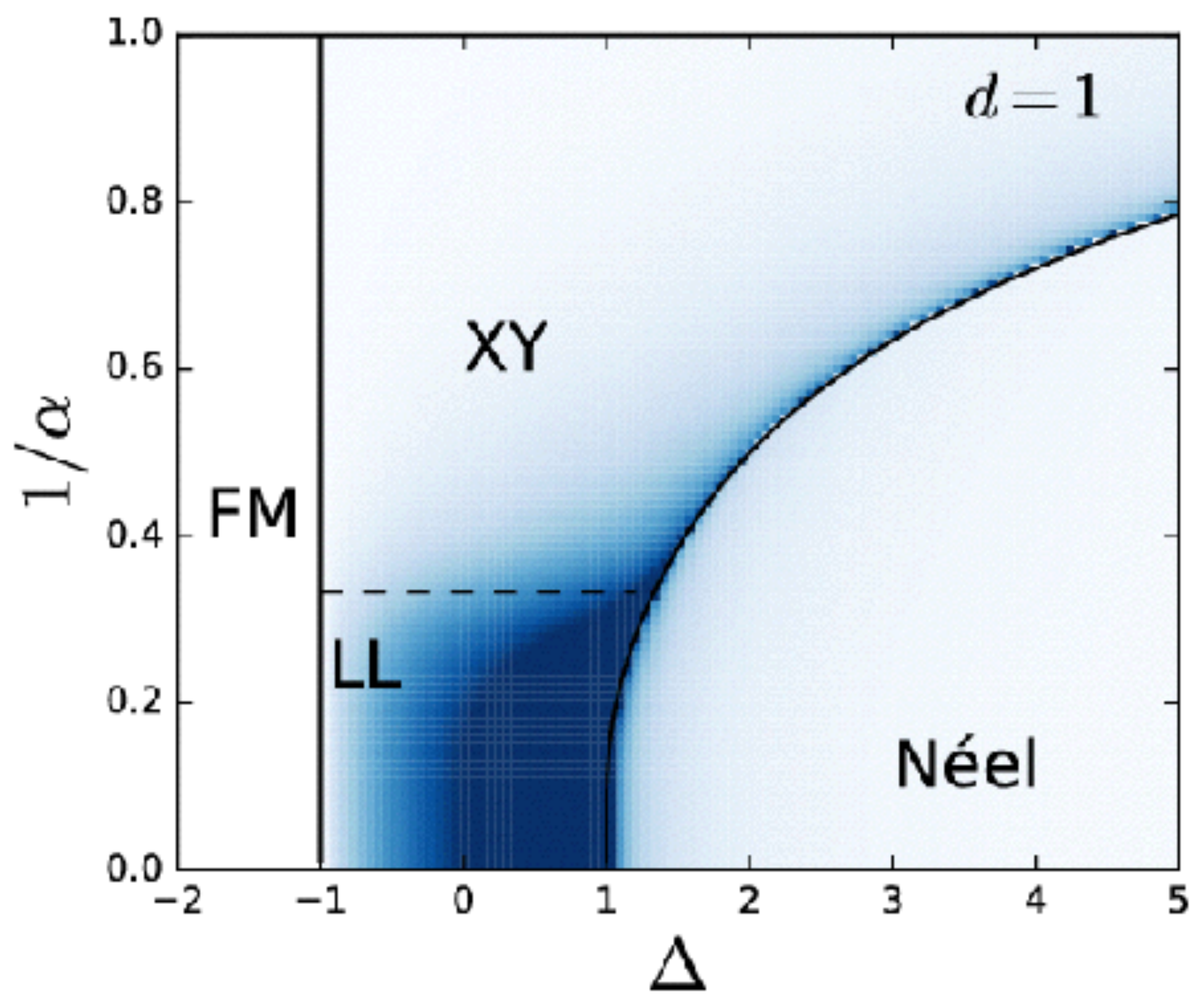


Spin-spin Interaction



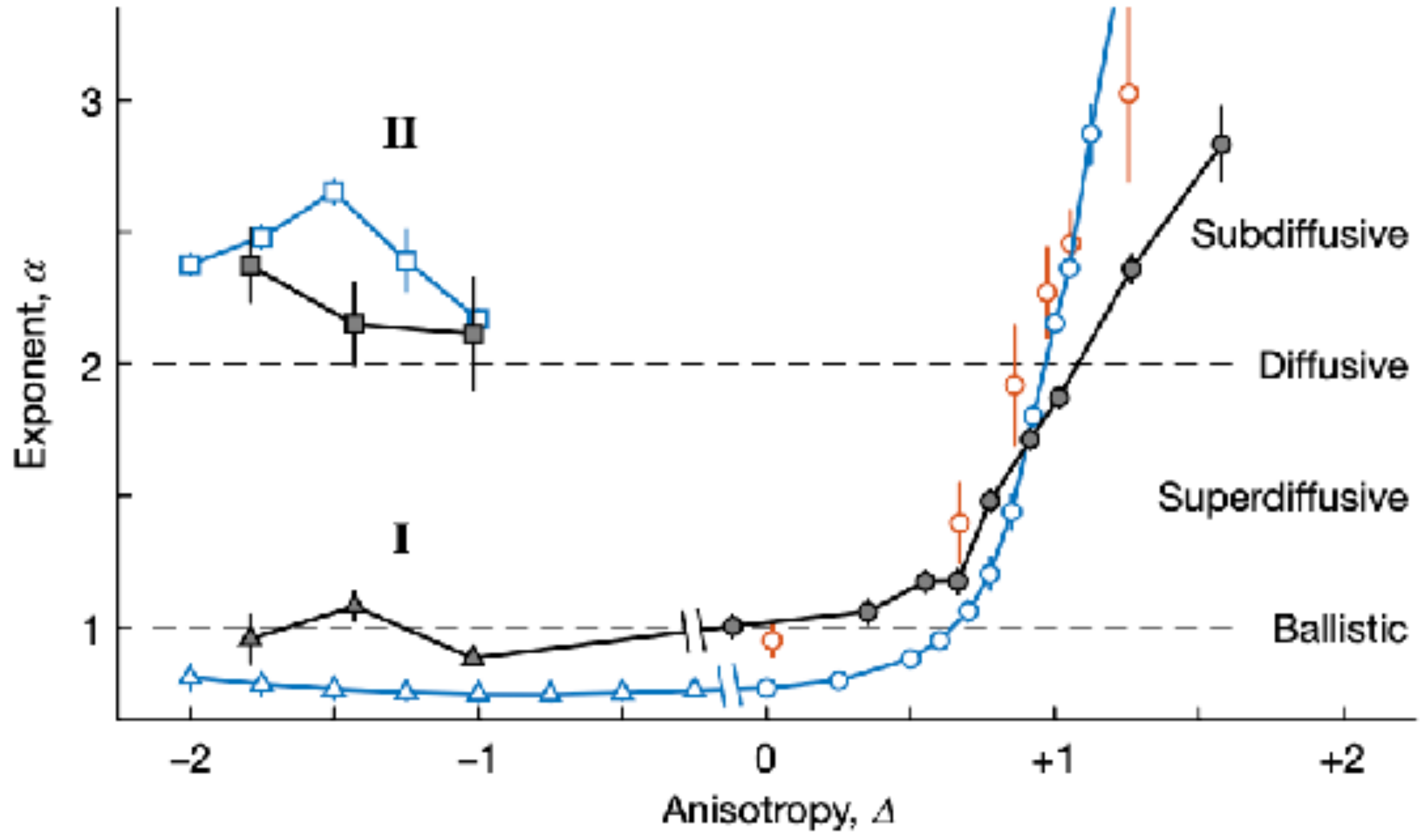
XXZ Heisenberg model

Phase transition of many-body systems



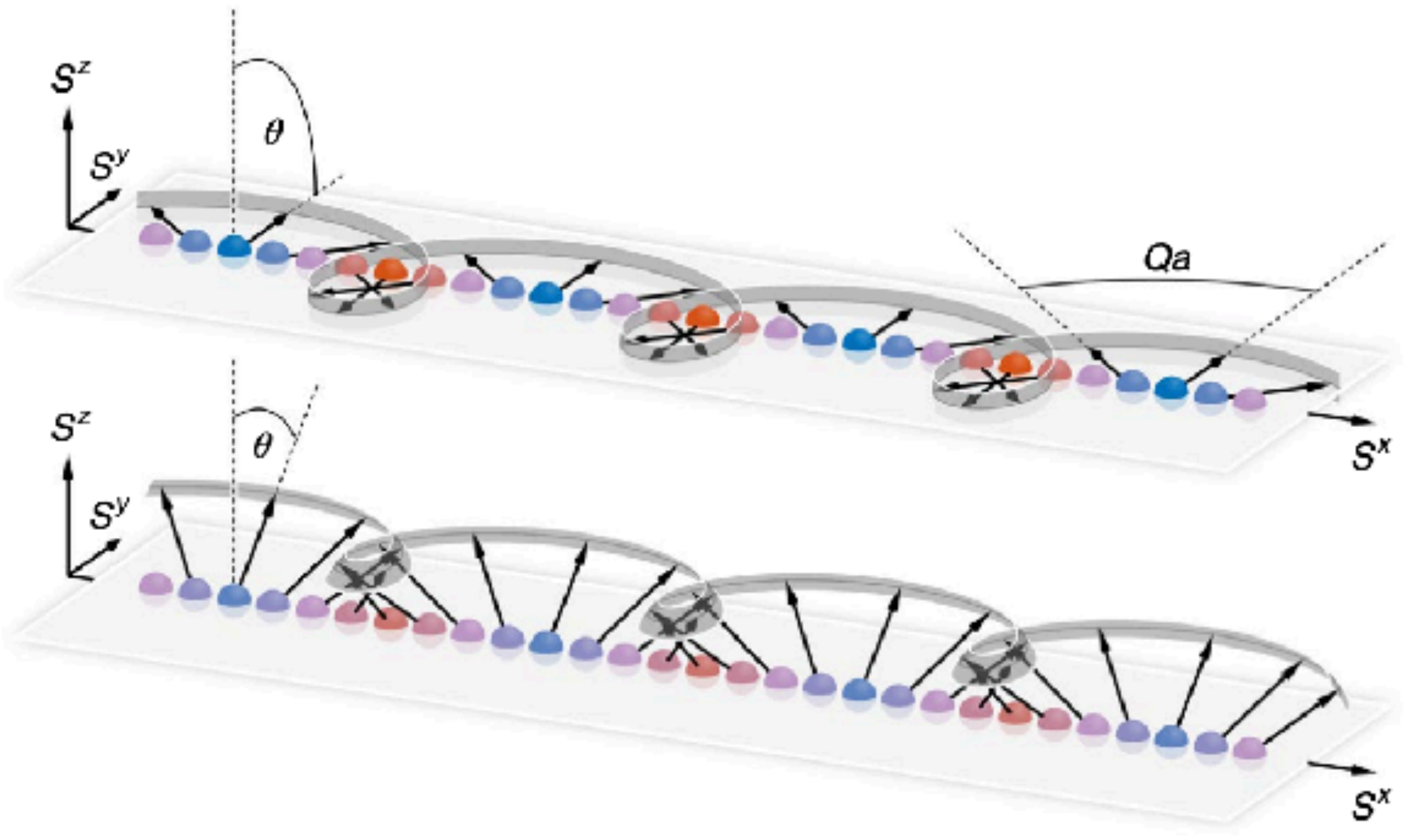
Rep. Prog. Phys. **80**, 016502 (2017)

Phase transition on spin transport



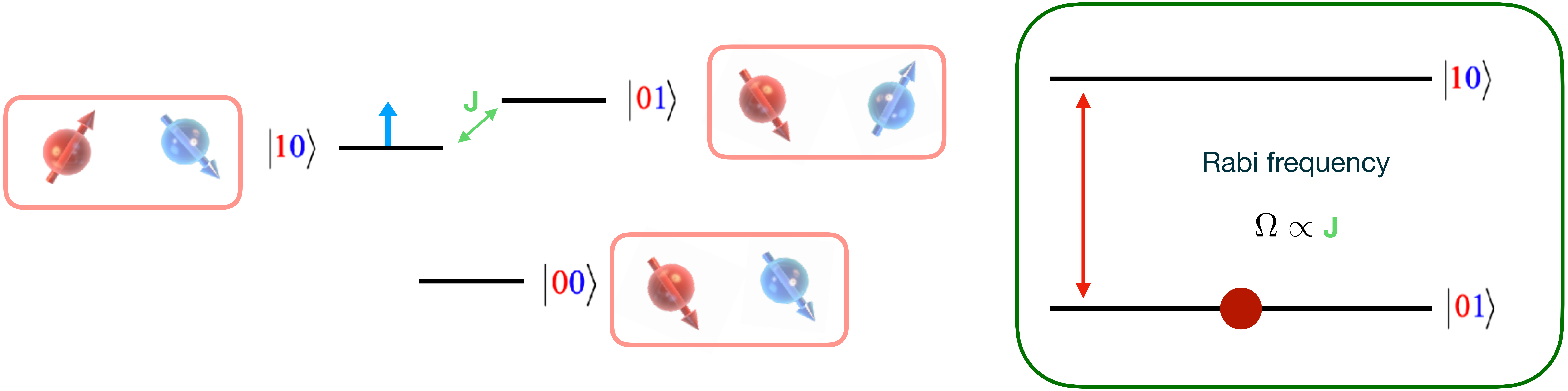
Nature **588**, 403 (2020)

Anomalous spin transport



Nat. Phys. **18**, 899 (2022)

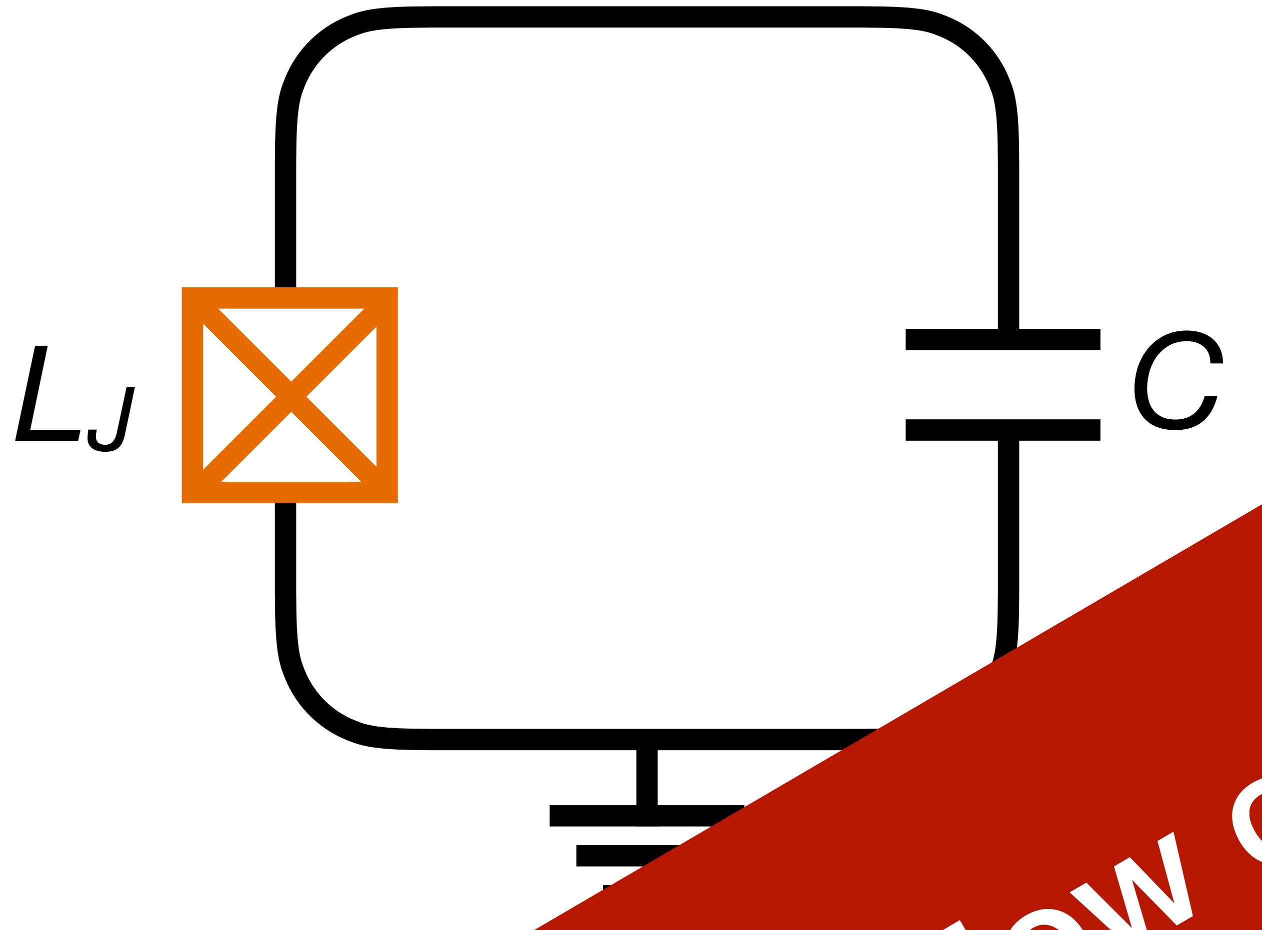
Spin-exchange interaction



Quantum processors: IBM vs Google

IBM

Fixed-frequency qubit

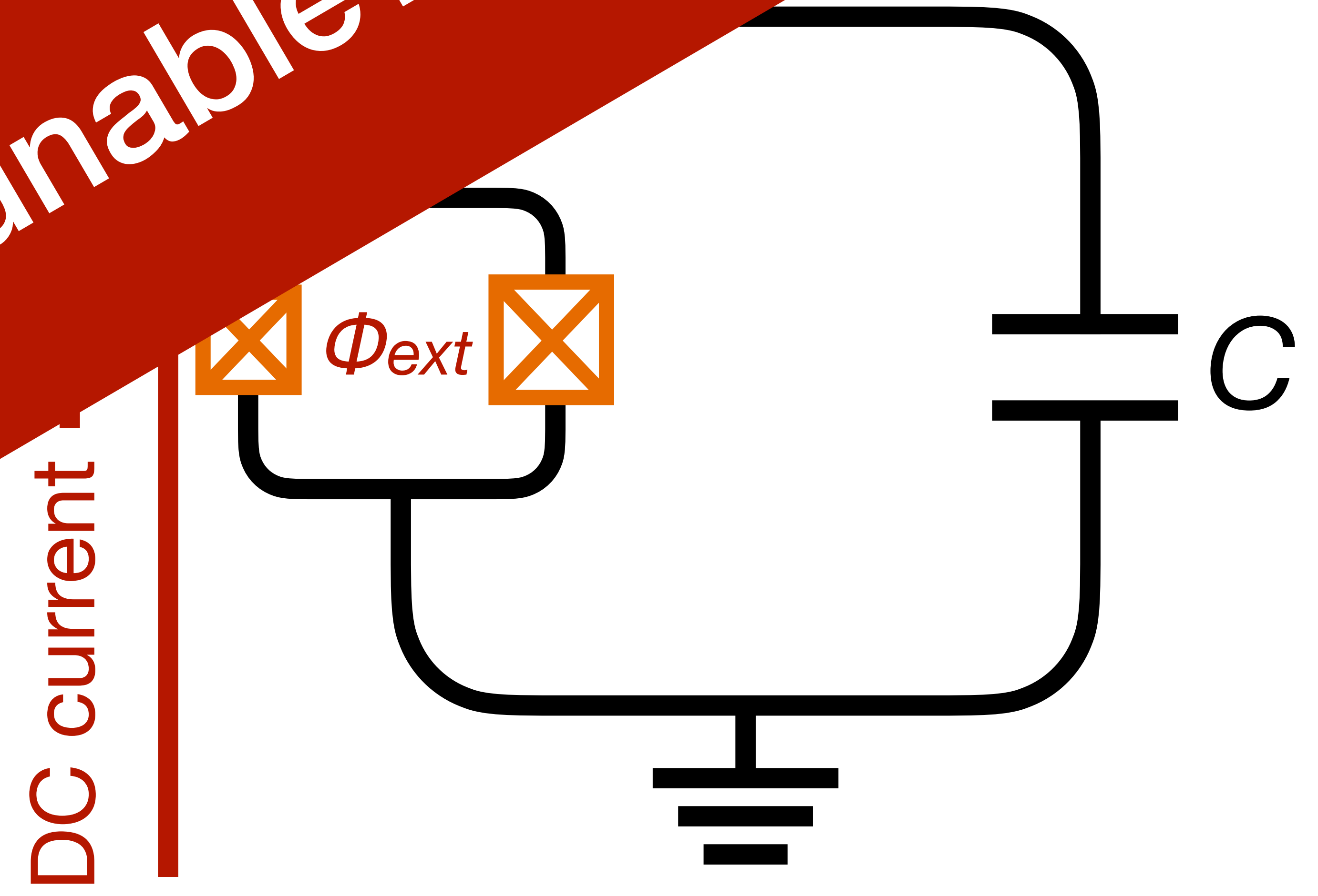


Coherenc ... 00 μs

arXiv. ... .00675

Google

Freq ... e qubit

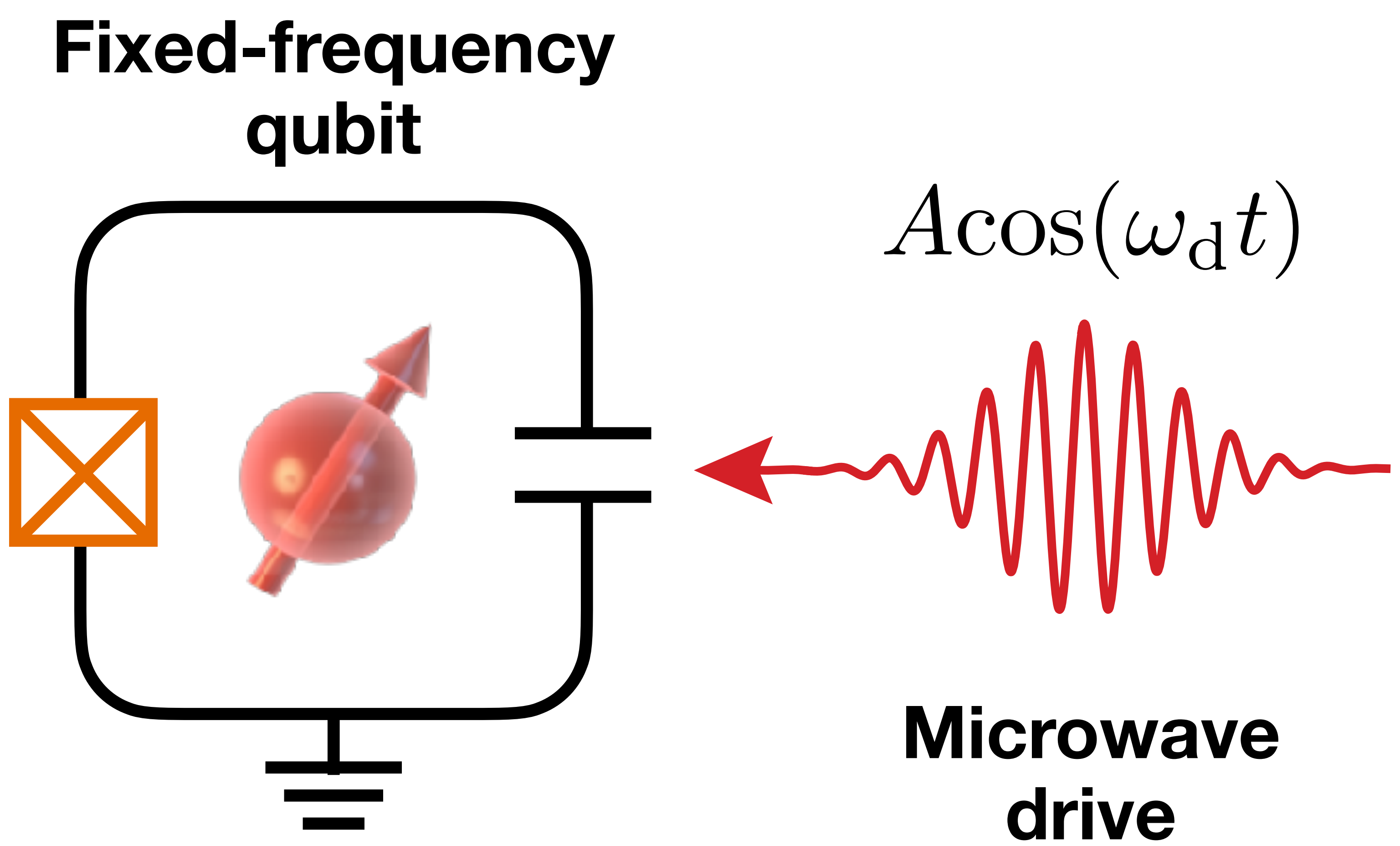


Coherence time (T_1) : ~20 μs

Nature **614**, 676 (2023)

How can we make it tunable?

Frequency tuning of fixed-frequency qubits



$$\hat{H}_{\mathrm{q}}(t) = -\frac{\omega_{\mathrm{q}}}{2}\hat{\sigma}_{\mathrm{z}} + A\cos(\omega_{\mathrm{d}}t)\,\hat{\sigma}_{\mathrm{x}}$$

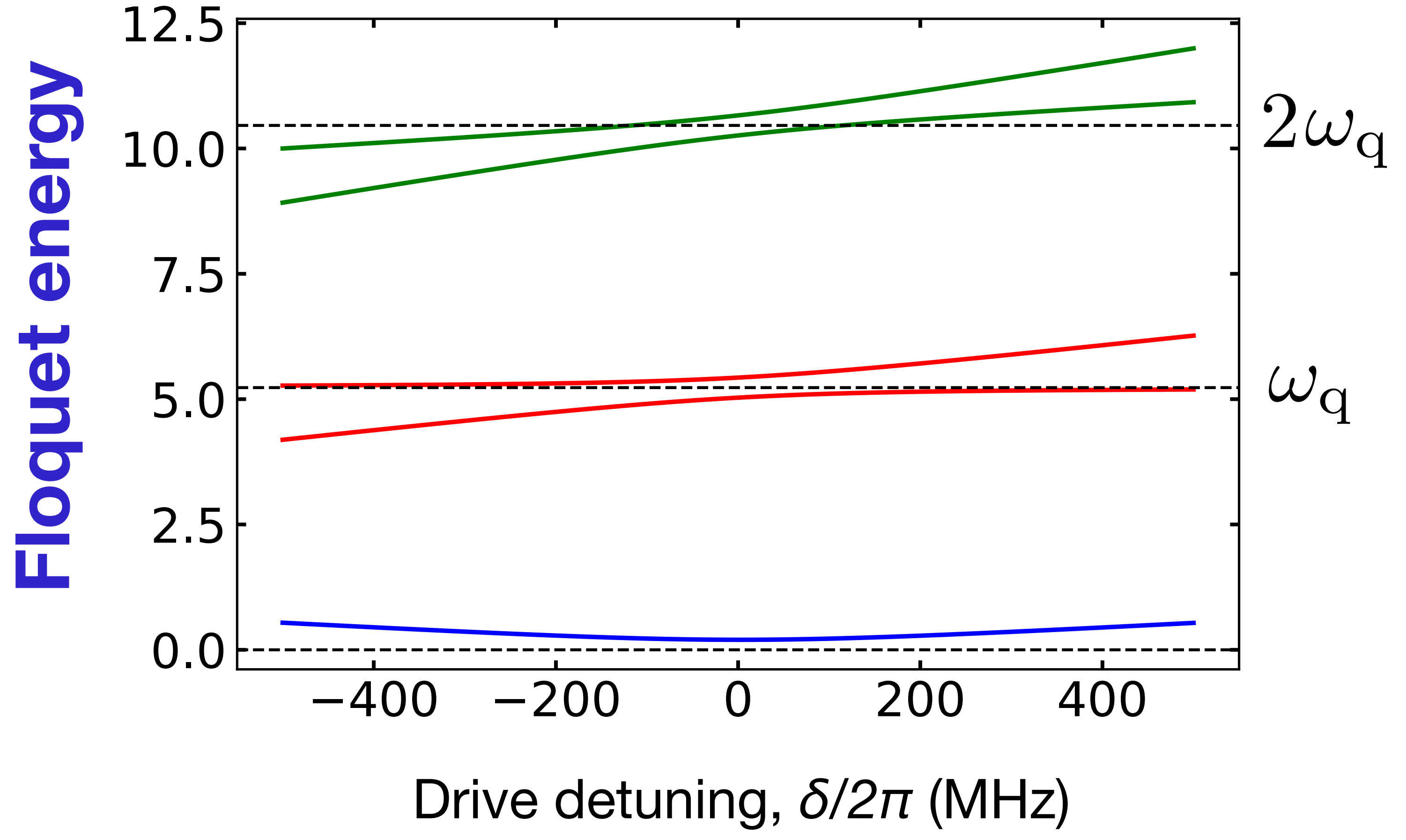
Schrödinger Equation

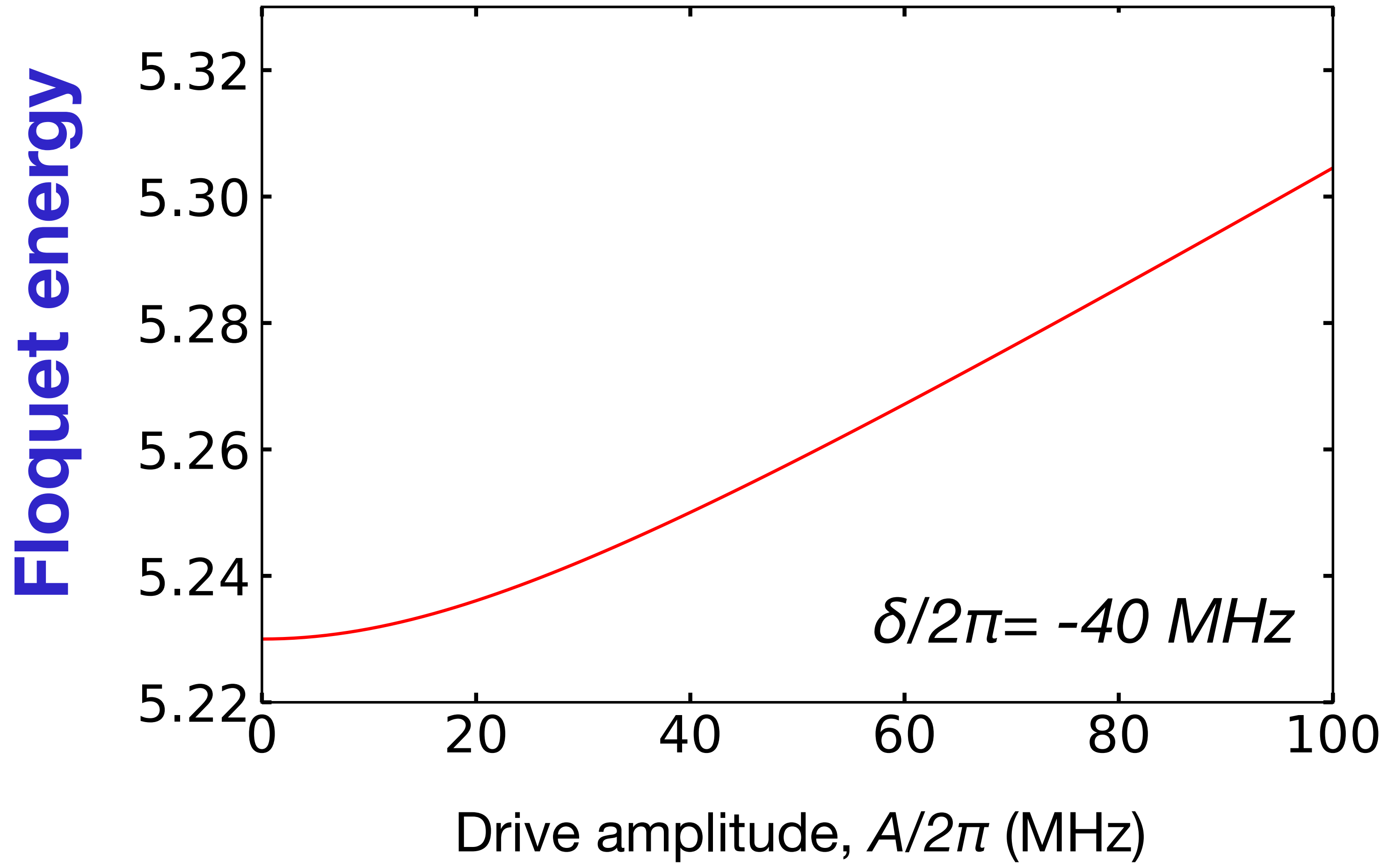
$$i\hbar\frac{\partial}{\partial t}|\psi(t)\rangle = \hat{H}_{\mathrm{q}}(t)|\psi(t)\rangle$$

$$\hat{H}_{\mathrm{q}}(t) = \hat{H}_{\mathrm{q}}(t+T)$$

Floquet Equation

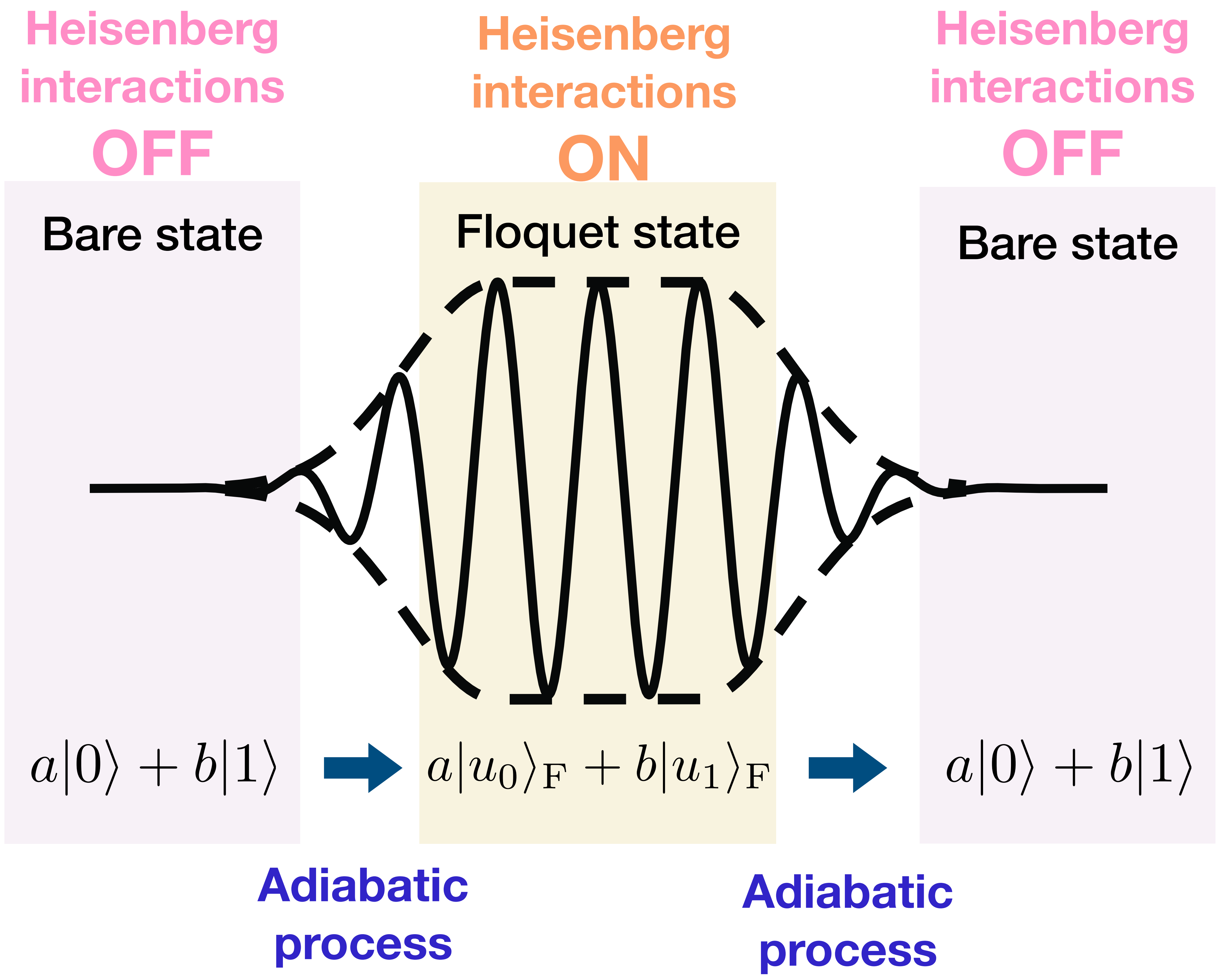
$$\left(\hat{H}_{\mathrm{q}}(t) - i\hbar\frac{\partial}{\partial t}\right)\underbrace{|u_n(t)\rangle_{\mathrm{F}}}_{\text{Floquet state}} = \overbrace{\hbar\epsilon_n}^{\text{Floquet energy}}|u_n(t)\rangle_{\mathrm{F}}$$

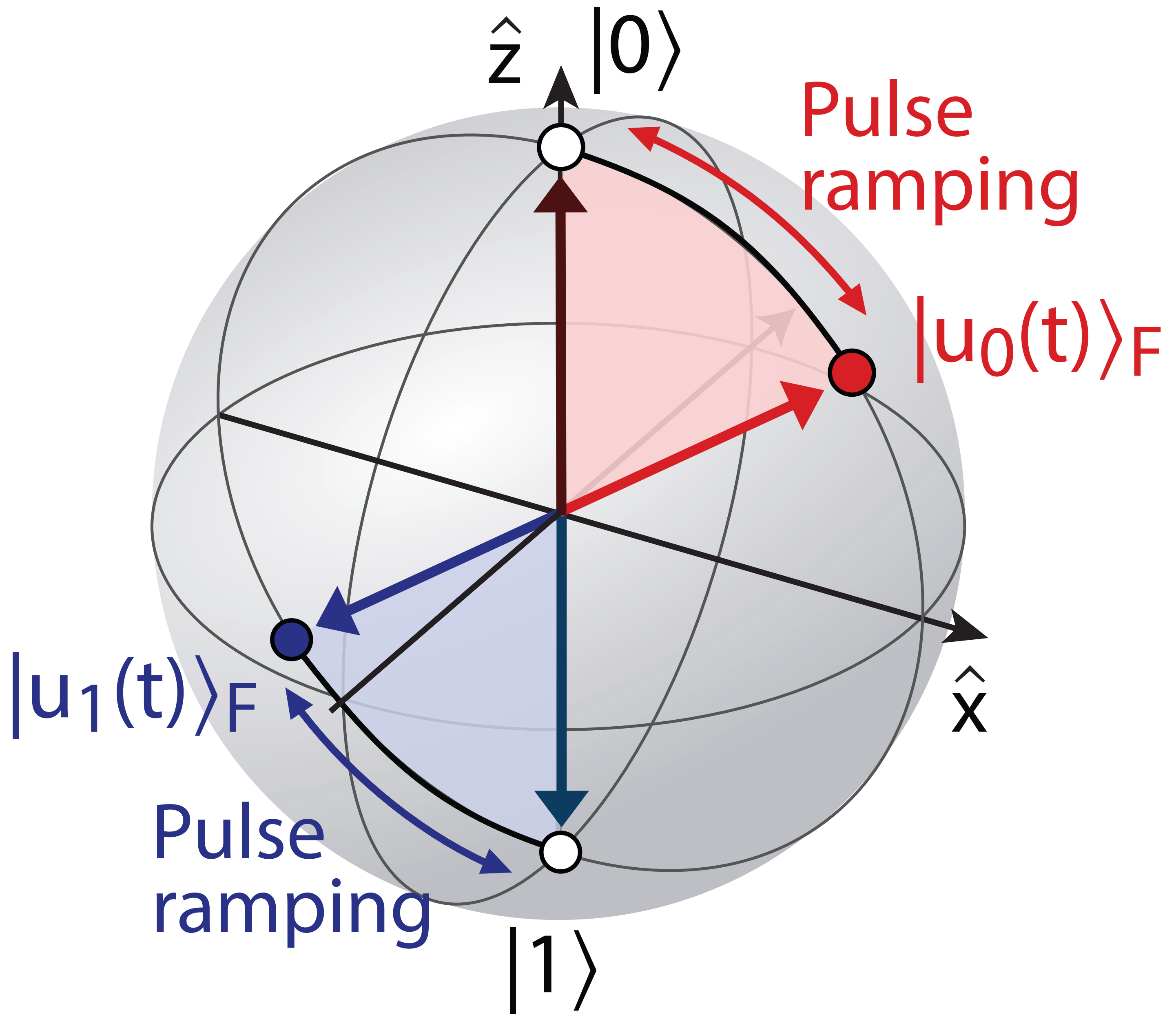




Synthesizing Floquet qubit

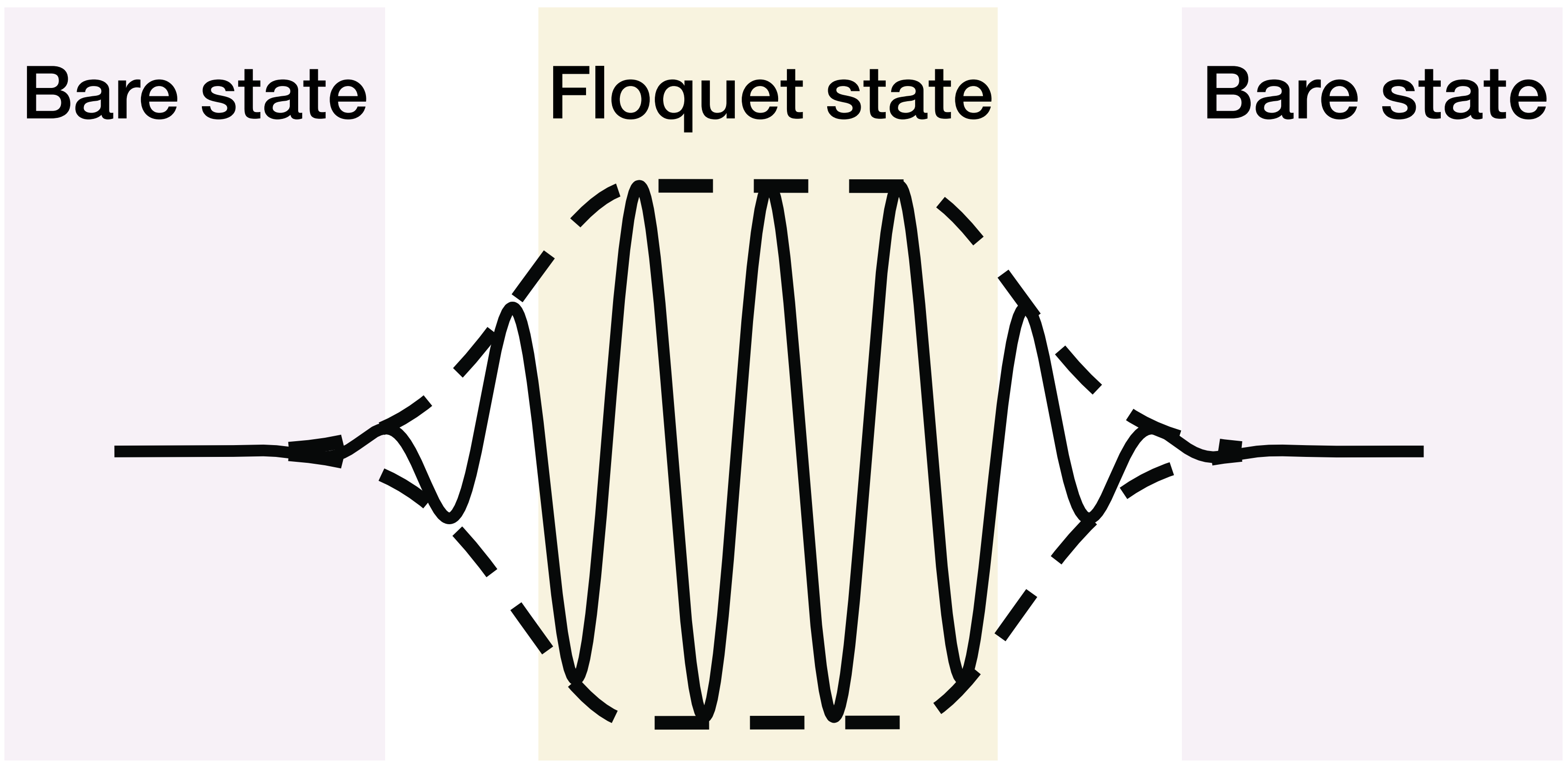
$$\hat{H}_{\mathrm{q}}(t) = -\frac{\omega_{\mathrm{q}}}{2}\hat{\sigma}_{\mathrm{z}} + A\cos(\omega_{\mathrm{d}} t)\,\hat{\sigma}_{\mathrm{x}}$$





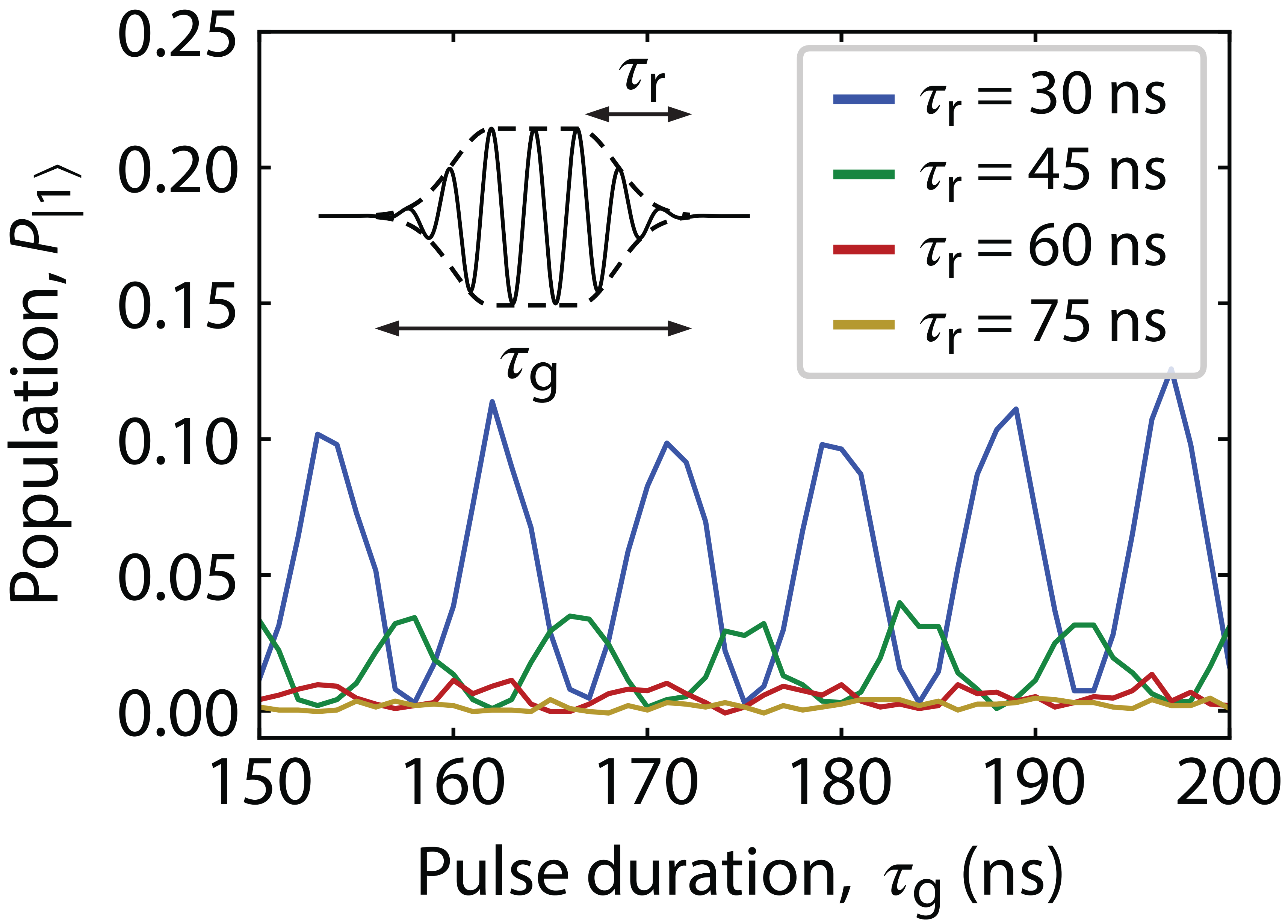
Adiabatic transition to Floquet qubit

$$\hat{H}_{\mathrm{q}}(t) = -\frac{\omega_{\mathrm{q}}}{2}\hat{\sigma}_{\mathrm{z}} + A\cos(\omega_{\mathrm{d}}t)\,\hat{\sigma}_{\mathrm{x}}$$

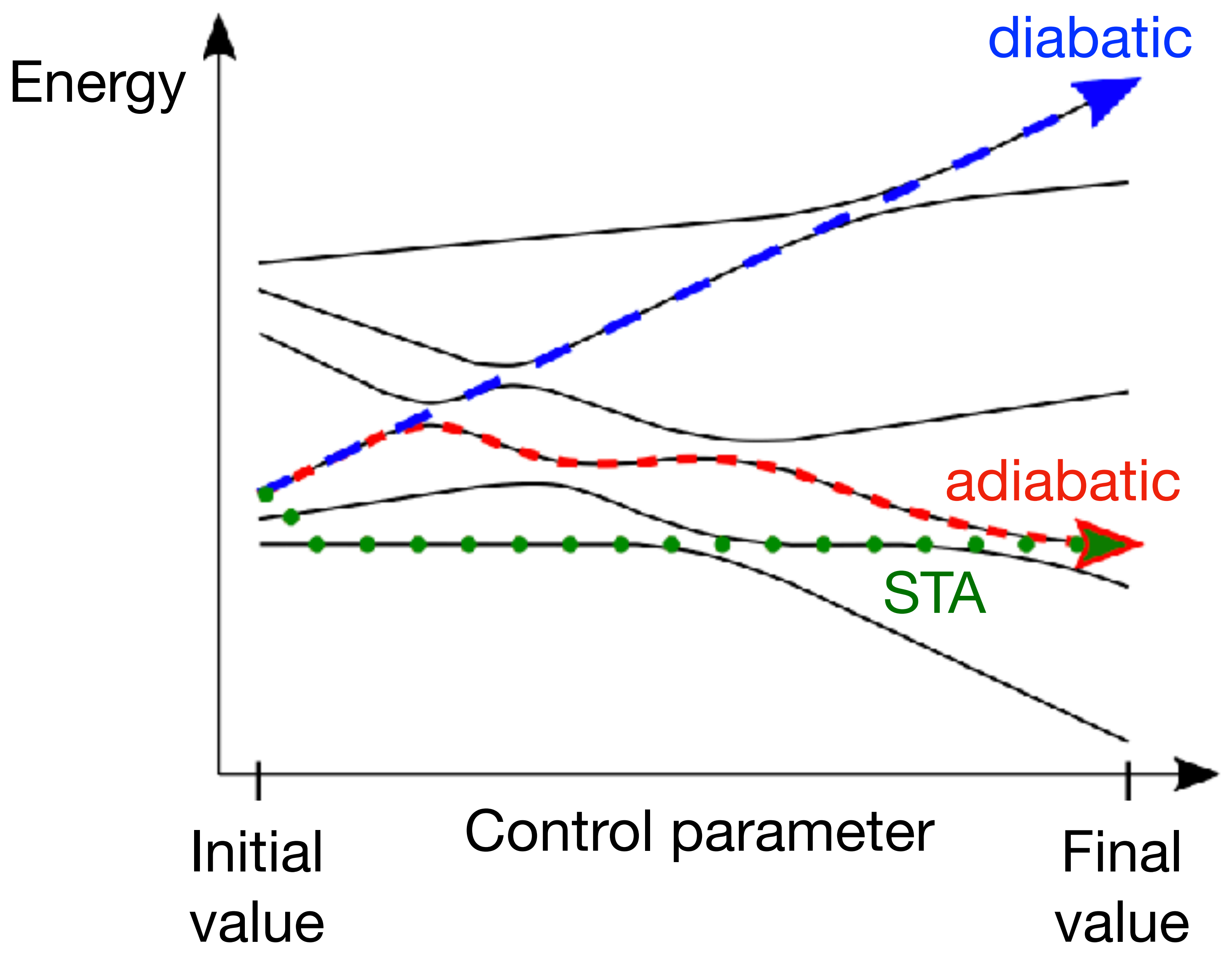


Adiabatic: $|0\rangle \rightarrow \quad |u_0\rangle_{\mathrm{F}} \quad \rightarrow |0\rangle$

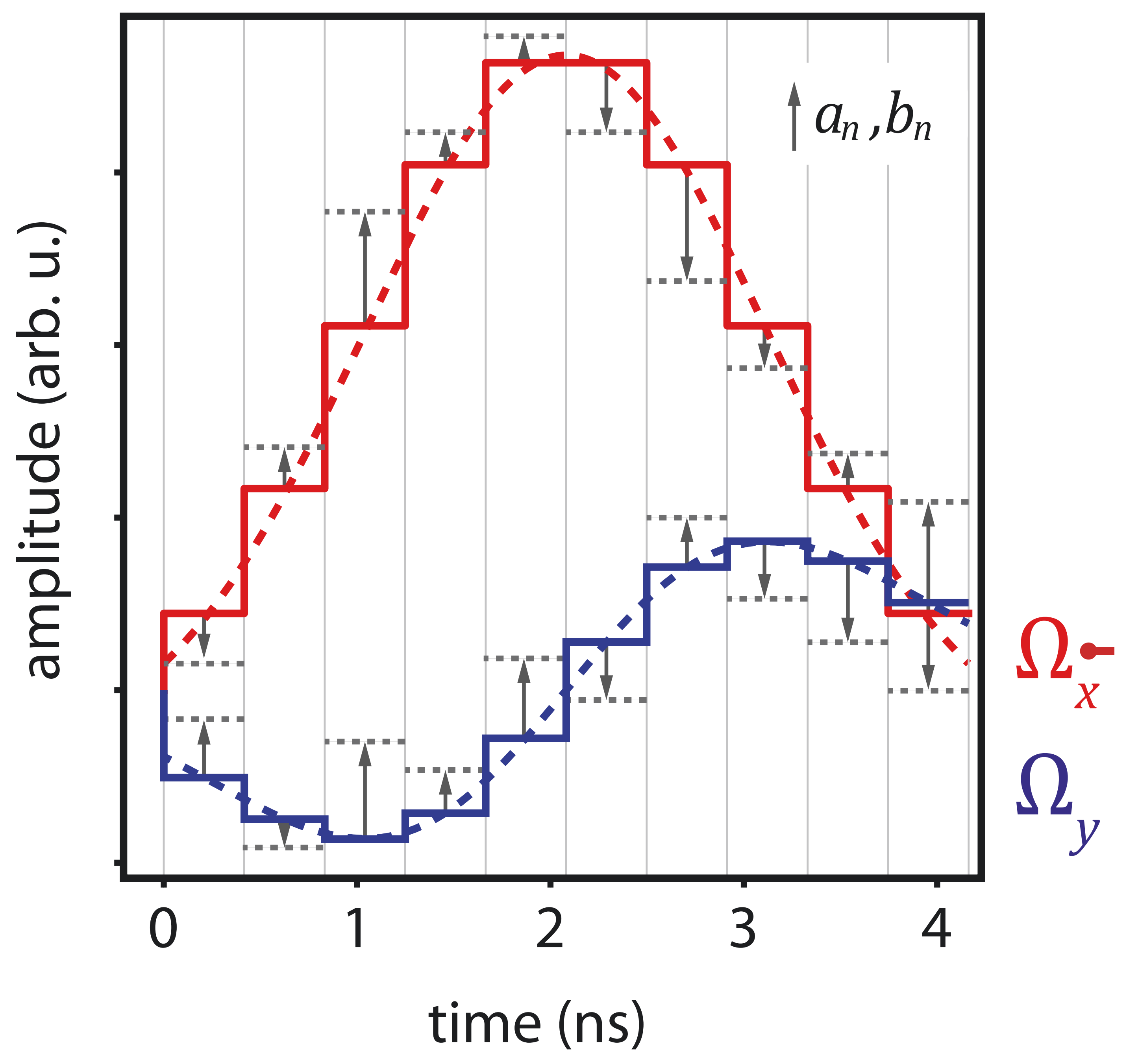
Diabatic: $|0\rangle \rightarrow a|u_0\rangle_{\mathrm{F}} + b|u_1\rangle_{\mathrm{F}} \rightarrow \alpha|0\rangle + \beta|1\rangle$



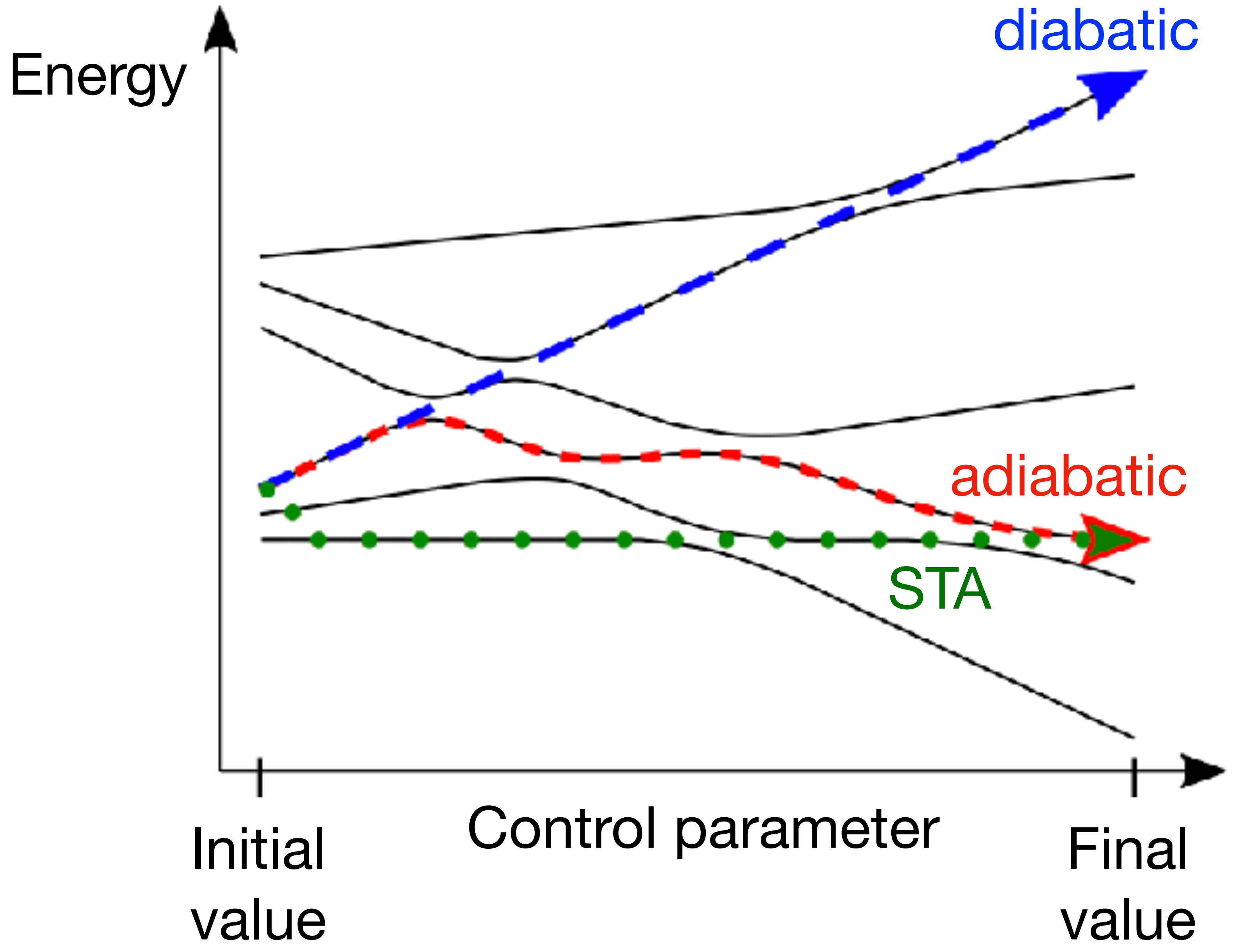
Shortcuts to adiabaticity (STA)

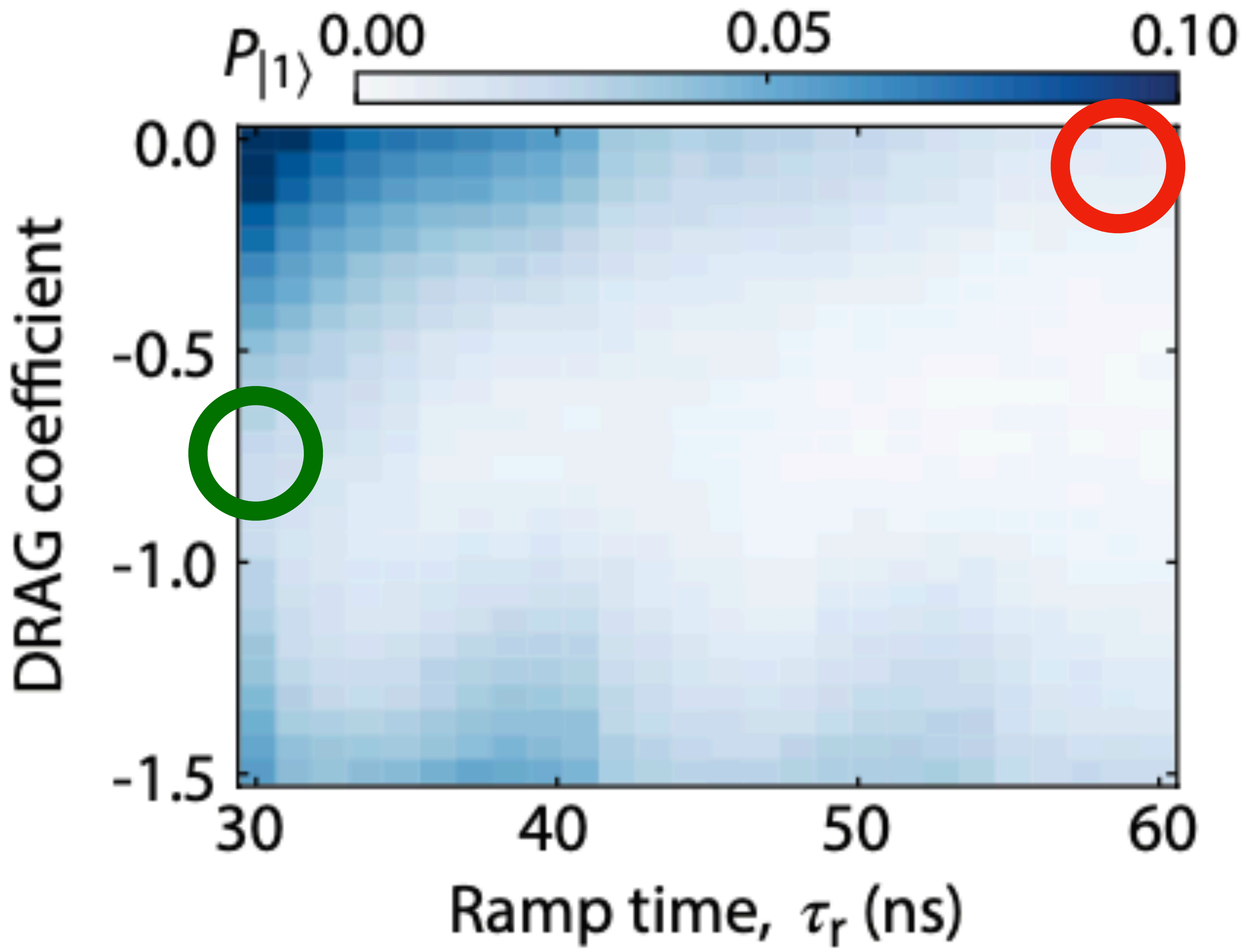


Derivative removal by adiabatic gate (DRAG)



Shortcuts to adiabaticity (STA)

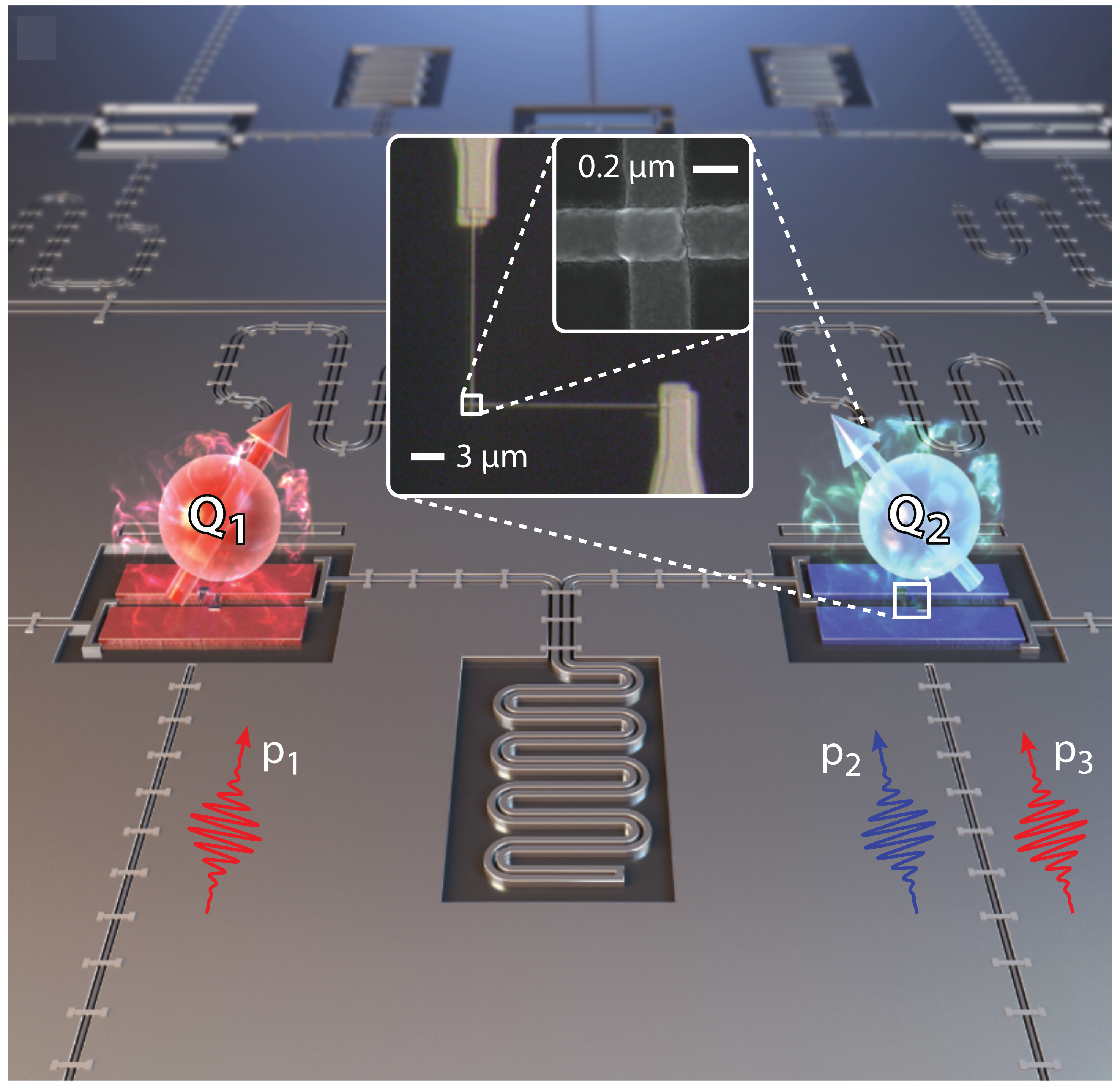




Ramp time is reduced from 60 ns to 30 ns

Programmable Heisenberg interactions

XXZ Heisenberg interactions between Floquet qubits

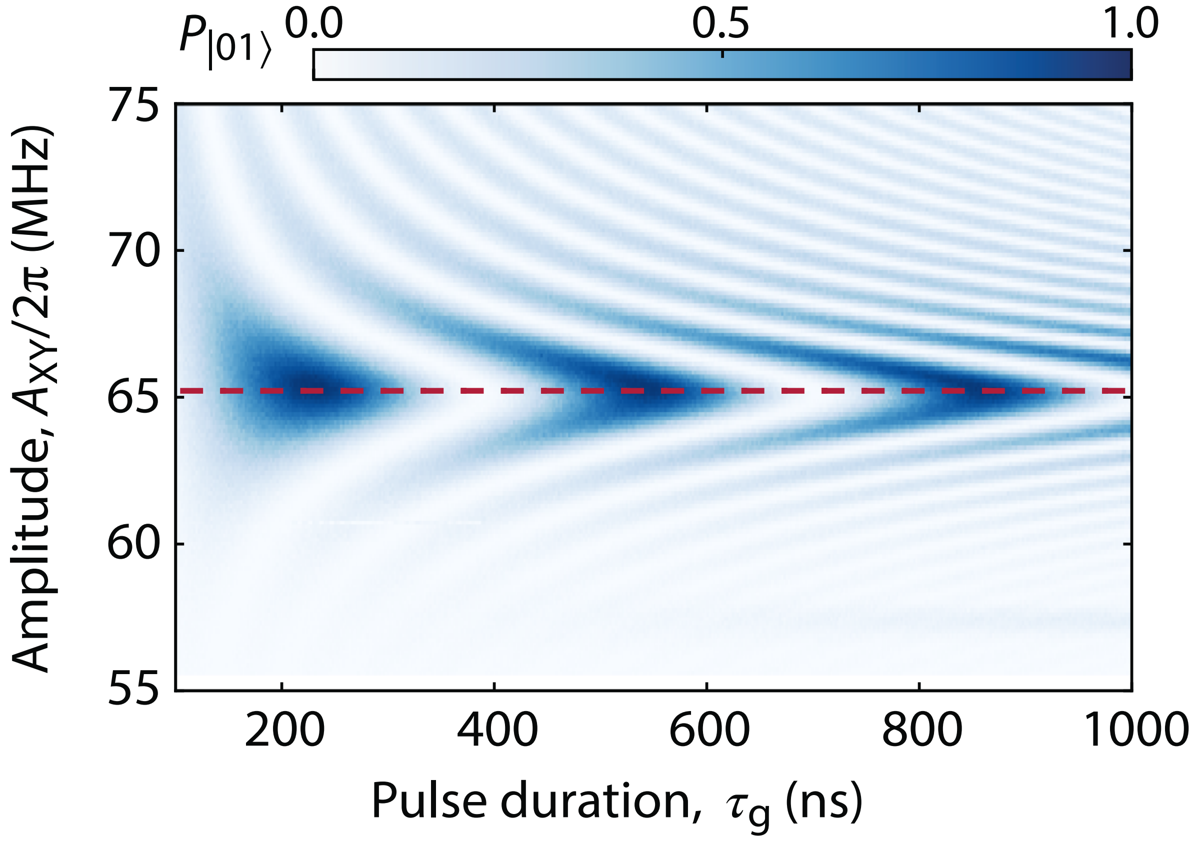


$$\sum_{ij} J_{\mathrm{XY}}(\hat{X}_i\hat{X}_j + \hat{Y}_i\hat{Y}_j) + J_{\mathrm{ZZ}}\hat{Z}_i\hat{Z}_j$$

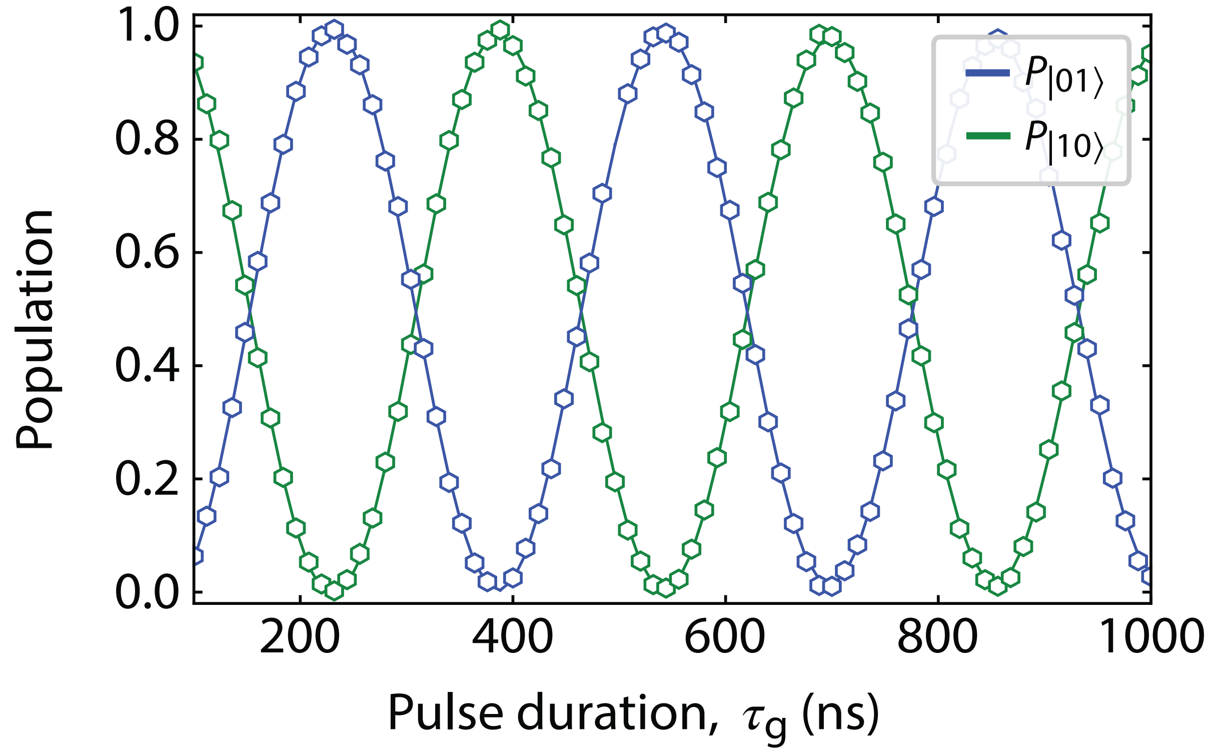
Spin-exchange Interaction

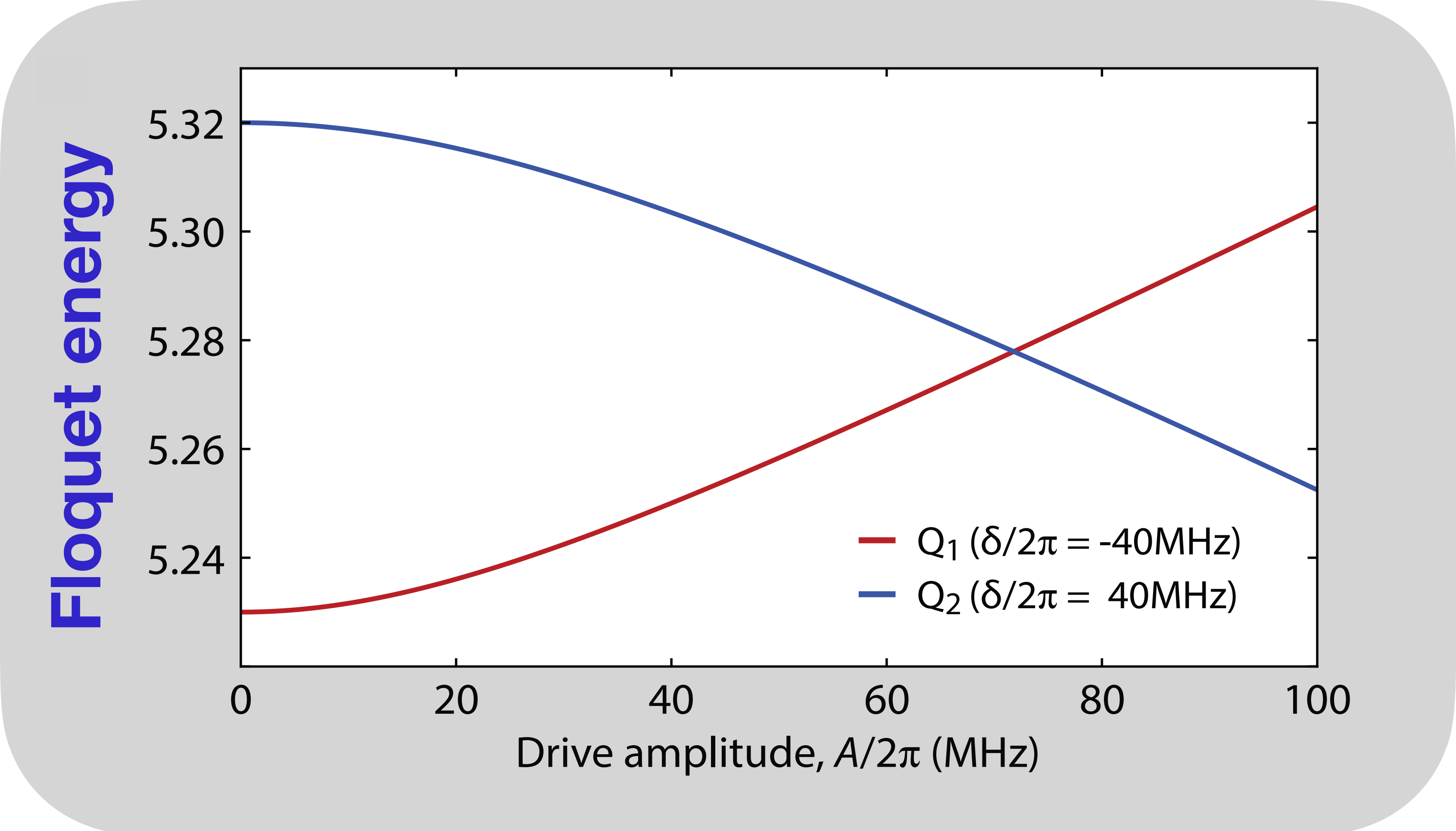
Spin-spin Interaction

1. Spin-exchange Interaction

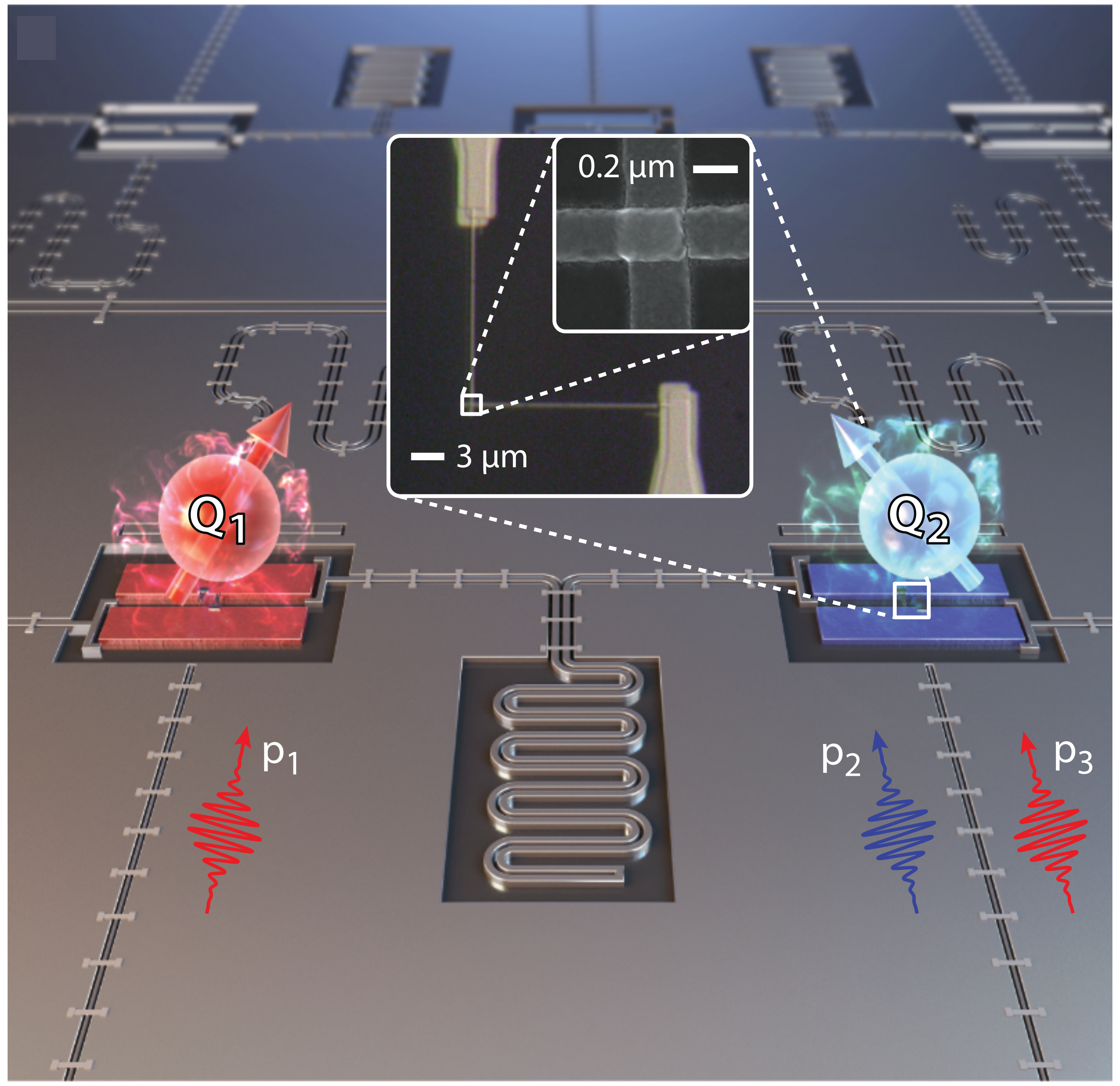


$$J_{\mathrm{XY}} = J\frac{(|\delta| + \sqrt{A^2+\delta^2})^2}{4(A^2+\delta^2)}$$





XXZ Heisenberg interactions between Floquet qubits



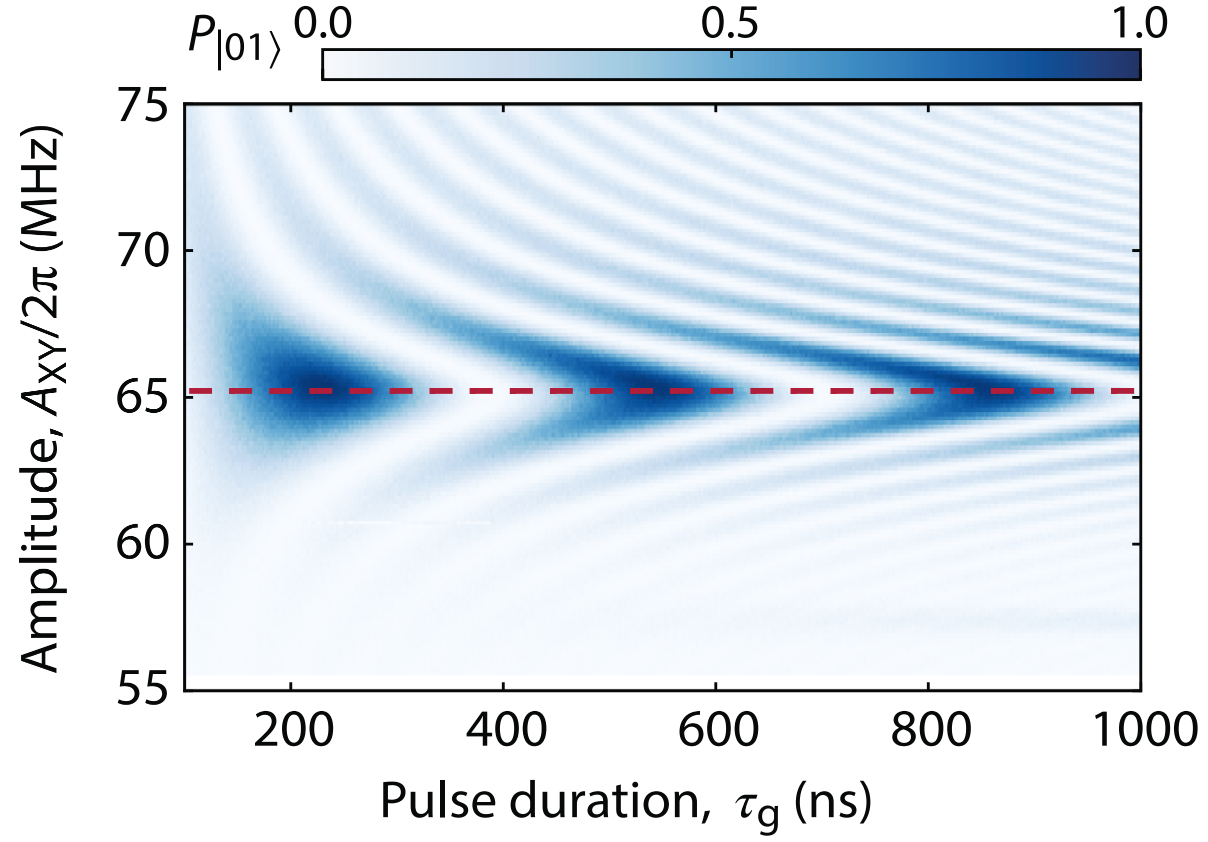
$$\sum_{ij} J_{\mathrm{XY}}\left(\hat{X}_i\hat{X}_j + \hat{Y}_i\hat{Y}_j\right) + J_{\mathrm{ZZ}}\hat{Z}_i\hat{Z}_j$$

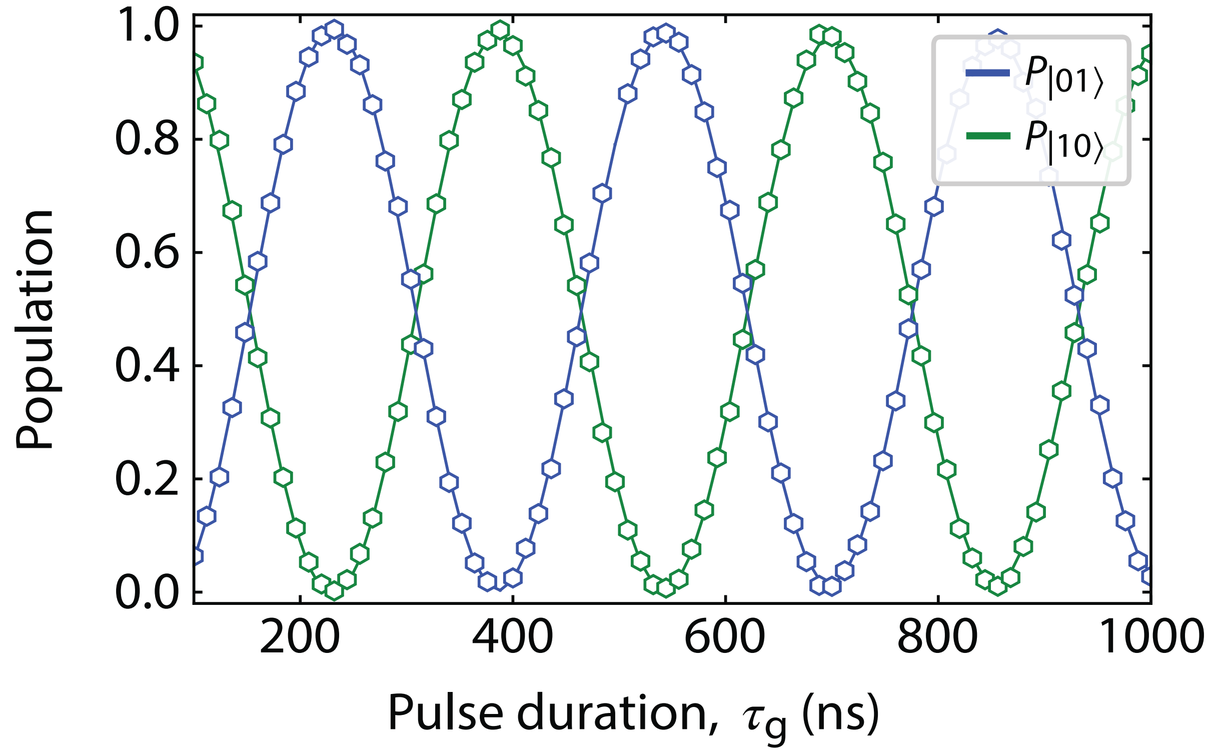
Spin-exchange Interaction

Spin-spin Interaction

1. Spin-exchange Interaction

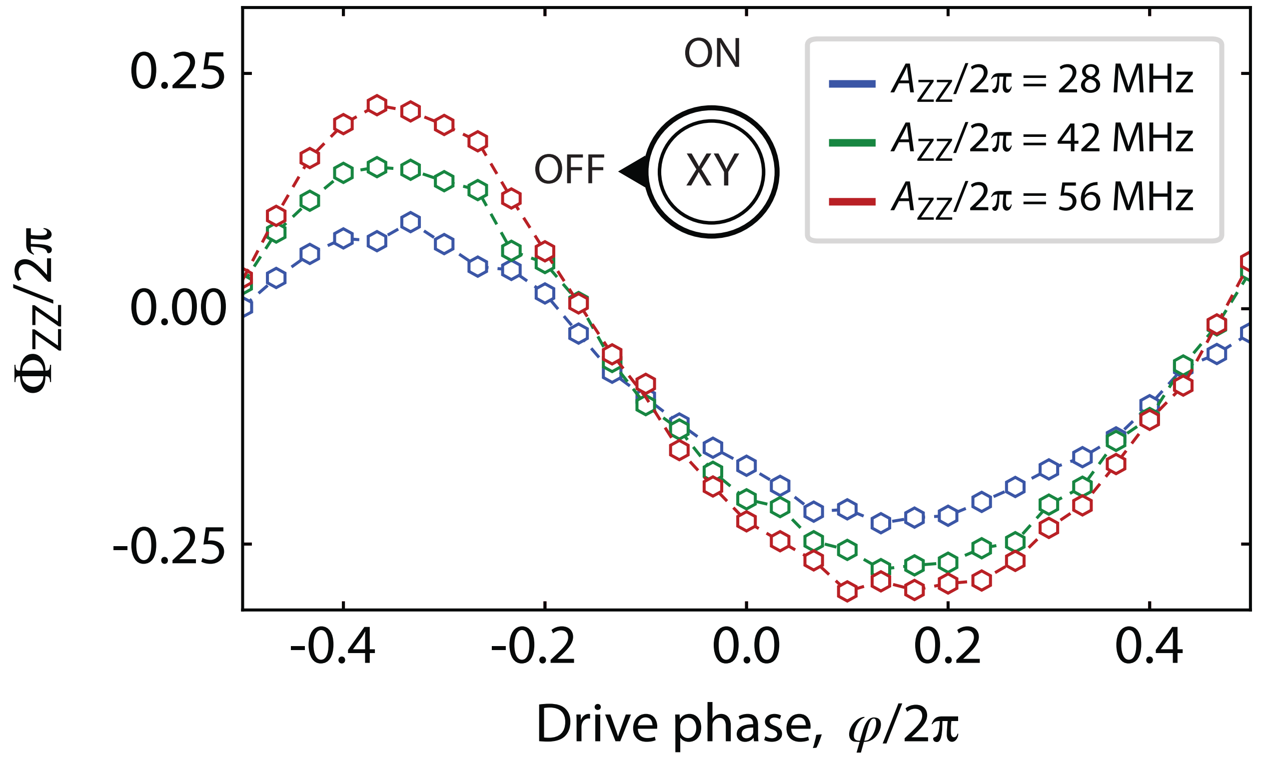
$$J_{\mathrm{XY}} = J\frac{(|\delta| + \sqrt{A^2+\delta^2})^2}{4(A^2+\delta^2)}$$

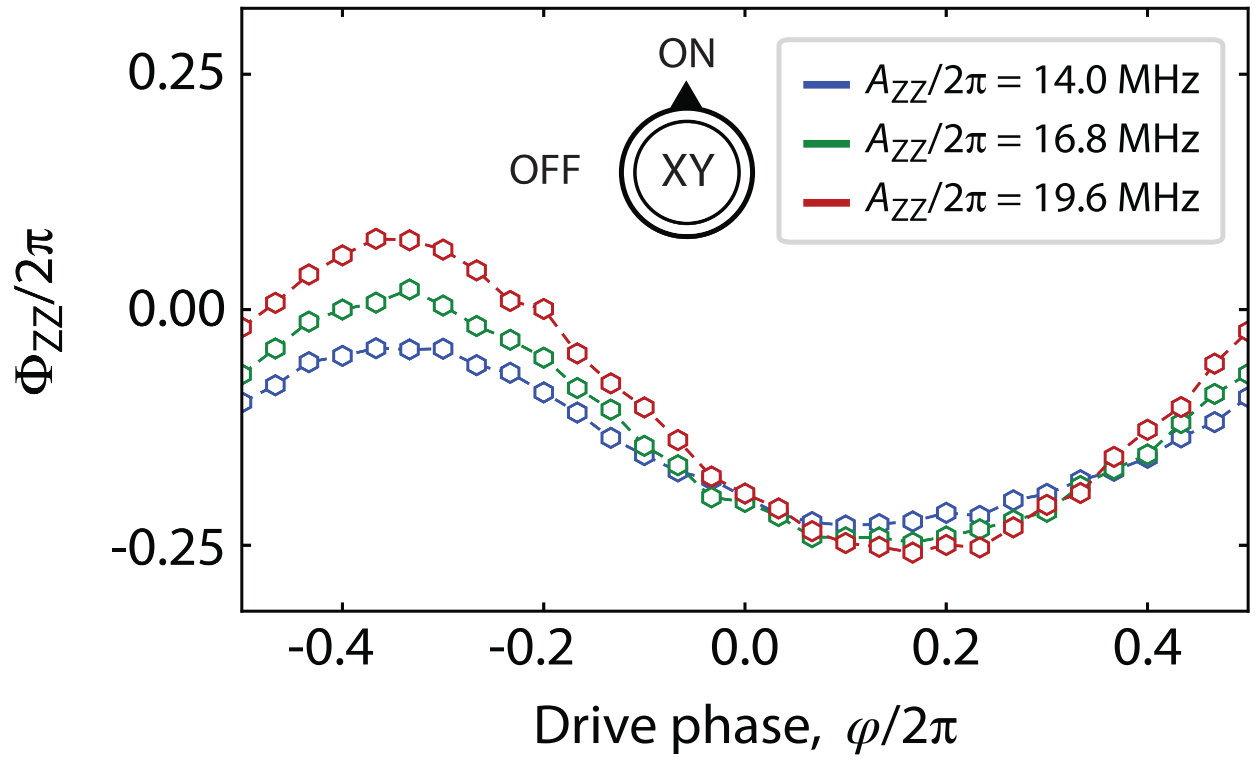




2. Spin-spin Interaction

$$J_{\mathrm{ZZ}} = J\frac{2A_1A_2\cos(\varphi)}{\sqrt{(A_1^2+\delta_1^2)(A_2^2+\delta_2^2)}}$$





Conclusion

- Fast Floquet qubit synthesis using an STA technique
- Programmable interactions for high-coherence devices