Superconducting Qubits

Coupling Superconducting Qubits Via a Cavity Bus

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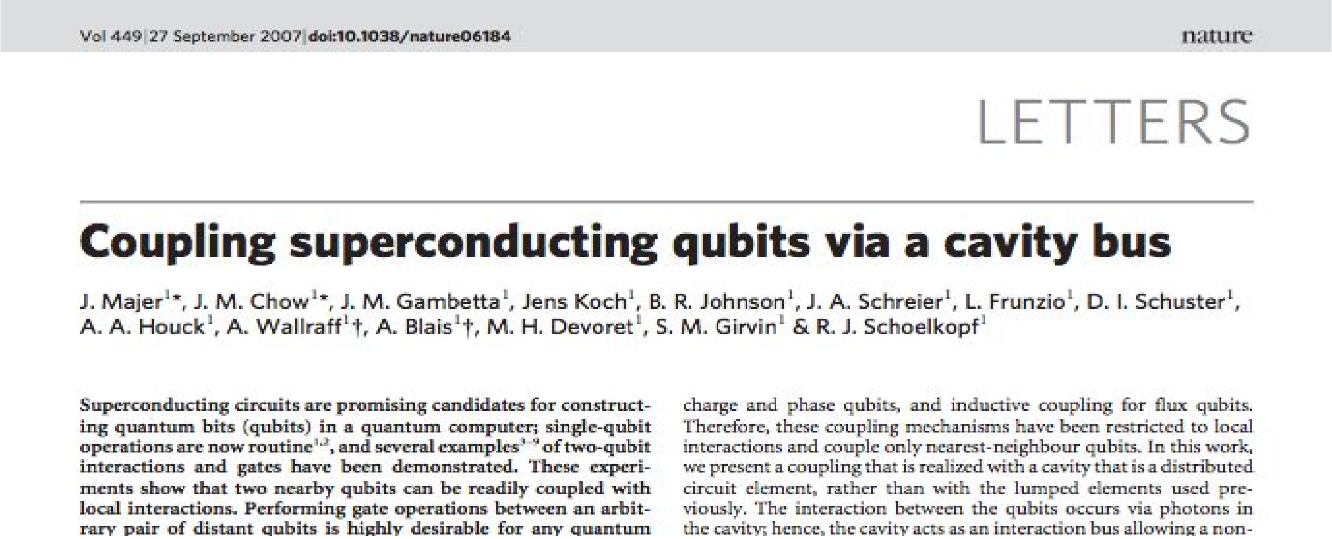
Outline

1. Introduction
2. Physical system setup
3. Operation principle
4. Readout and results
5. Conclusion



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LETTERS

Coupling superconducting qubits via a cavity bus

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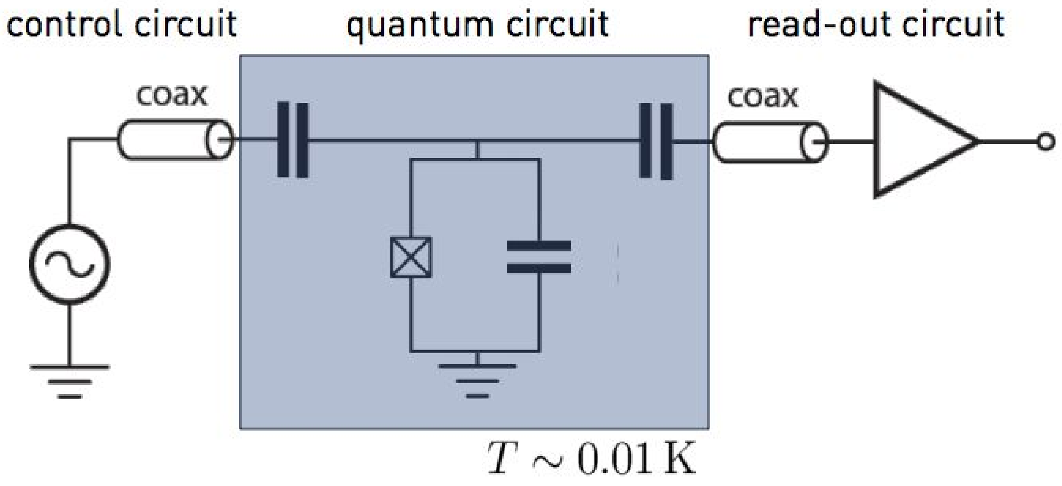
Superconducting circuits are promising candidates for constructing quantum bits (qubits) in a quantum computer; single-qubit operations are now routine[1,2], and several examples[3–9] of two-qubit interactions and gates have been demonstrated. These experiments show that two nearby qubits can be readily coupled with local interactions. Performing gate operations between an arbitrary pair of distant qubits is highly desirable for any quantum

charge and phase qubits, and inductive coupling for flux qubits. Therefore, these coupling mechanisms have been restricted to local interactions and couple only nearest-neighbour qubits. In this work, we present a coupling that is realized with a cavity that is a distributed circuit element, rather than with the lumped elements used previously. The interaction between the qubits occurs via photons in the cavity; hence, the cavity acts as an interaction bus allowing a non-

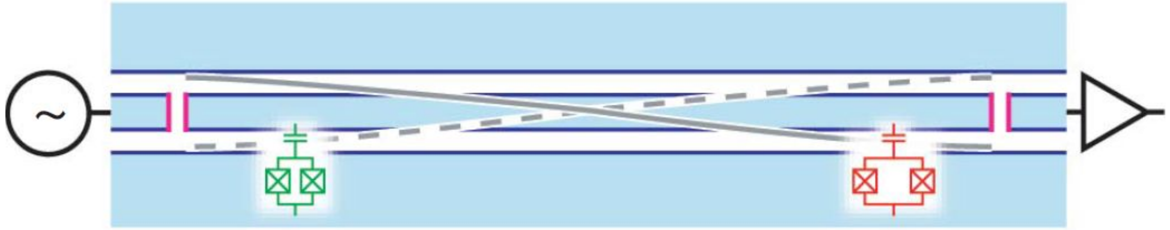
About the Experiment

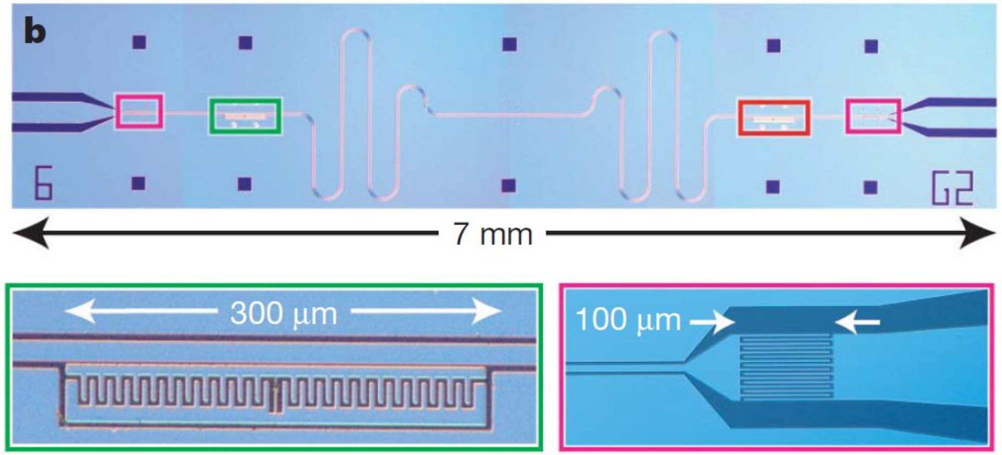
- quantum bus
- coherent, non-local coupling realized with cavity
- distributed circuit element rather than lumped elements



Lecture Slides, A. Wallraff, Quantum Information Processing: Implementations, ETH Zürich
Original Paper: M.H. Devoret, A.Wallraff and J.M. Martinis, *arXiv:condmat/0411172*(2004)

Experimental Setup





Two Transmons: superconducting qubits of modified Cooper pair box
Transmission line resonator

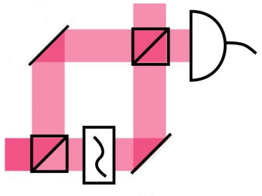
$$\frac{\omega_r}{2\pi} = 5.19\ GHz\ ;\ determined\ by\ capacitor$$

$$\frac{E_{c1}}{h} \approx 424\ MHz; \frac{E_{j1,max}}{h} = 14.9\ GHz$$

$$\frac{E_{c2}}{h} \approx 442\ MHz; \frac{E_{j2,max}}{h} = 18.9\ GHz$$

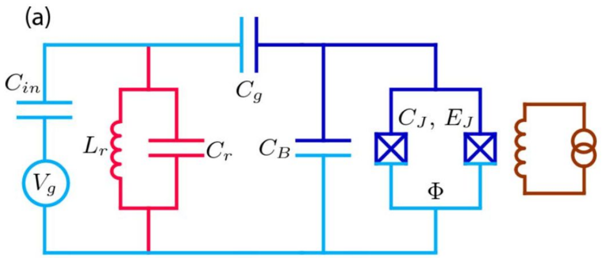
$$E_j = E_{j,max}|\cos{(\pi\phi/\phi_0)}| \qquad E_c = \frac{(2e)^2}{2C_\Sigma}$$

homodyne detection of the resonator



source: Wikipedia

Operation principle - Transmon

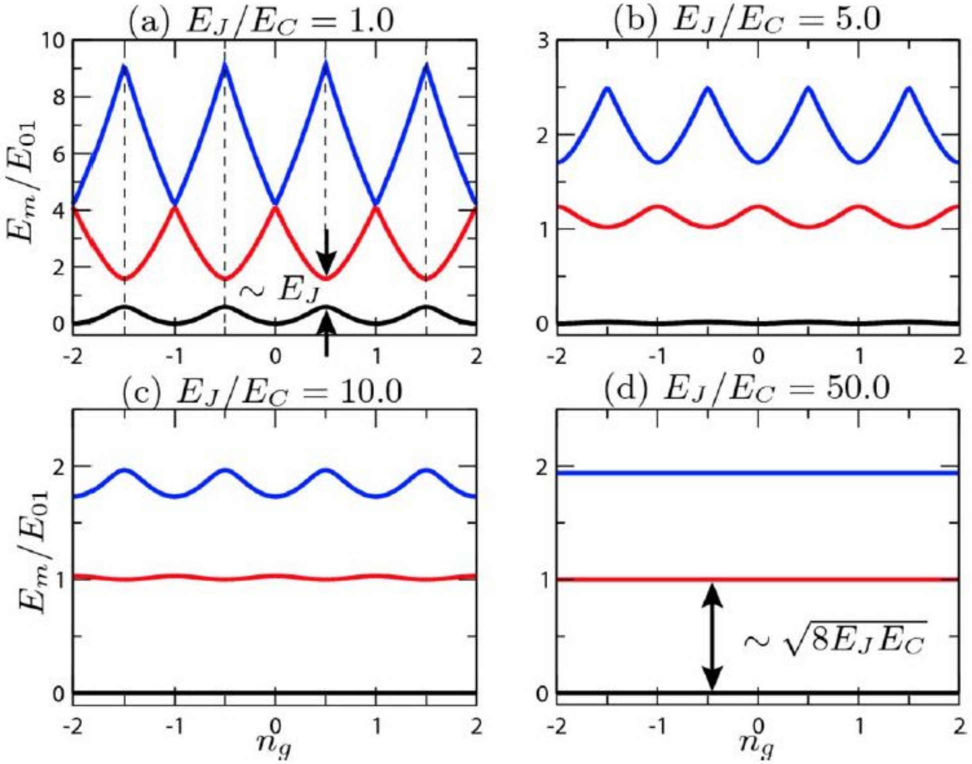


[2]

Qubits used: Transmons → charge-phase qubit, modified Cooper pair box

$E_J \gg E_C$

- flatter bands
- more resilient to noise [2]



[2]

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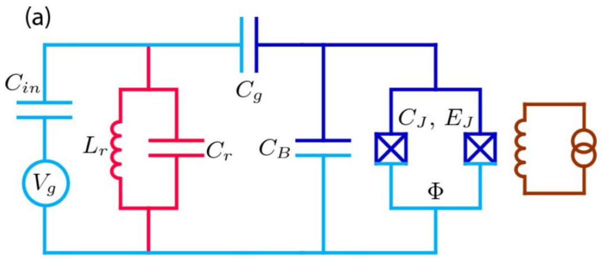
Operation principle - Transmon



[2]

Qubits used: Transmons → charge-phase qubit, modified Cooper pair box

$E_J \gg E_C$ → flatter bands, more resilient to noise

$$E_J = E_J^{\max} |\cos(\pi\Phi/\Phi_0)|$$

Transition frequency: $\omega = \sqrt{8 E_J E_C}/\hbar$

$$\omega_{1,2} = \omega_{1,2}^{\max} \sqrt{|\cos(\pi\Phi/\Phi_0)|}$$

Transition frequency tuned *in situ* via varying magnetic flux through Josephson junction loop
Loop size differs for qubits → independent control

Qubits can be tuned in resonance/off-resonance with cavity + with each other

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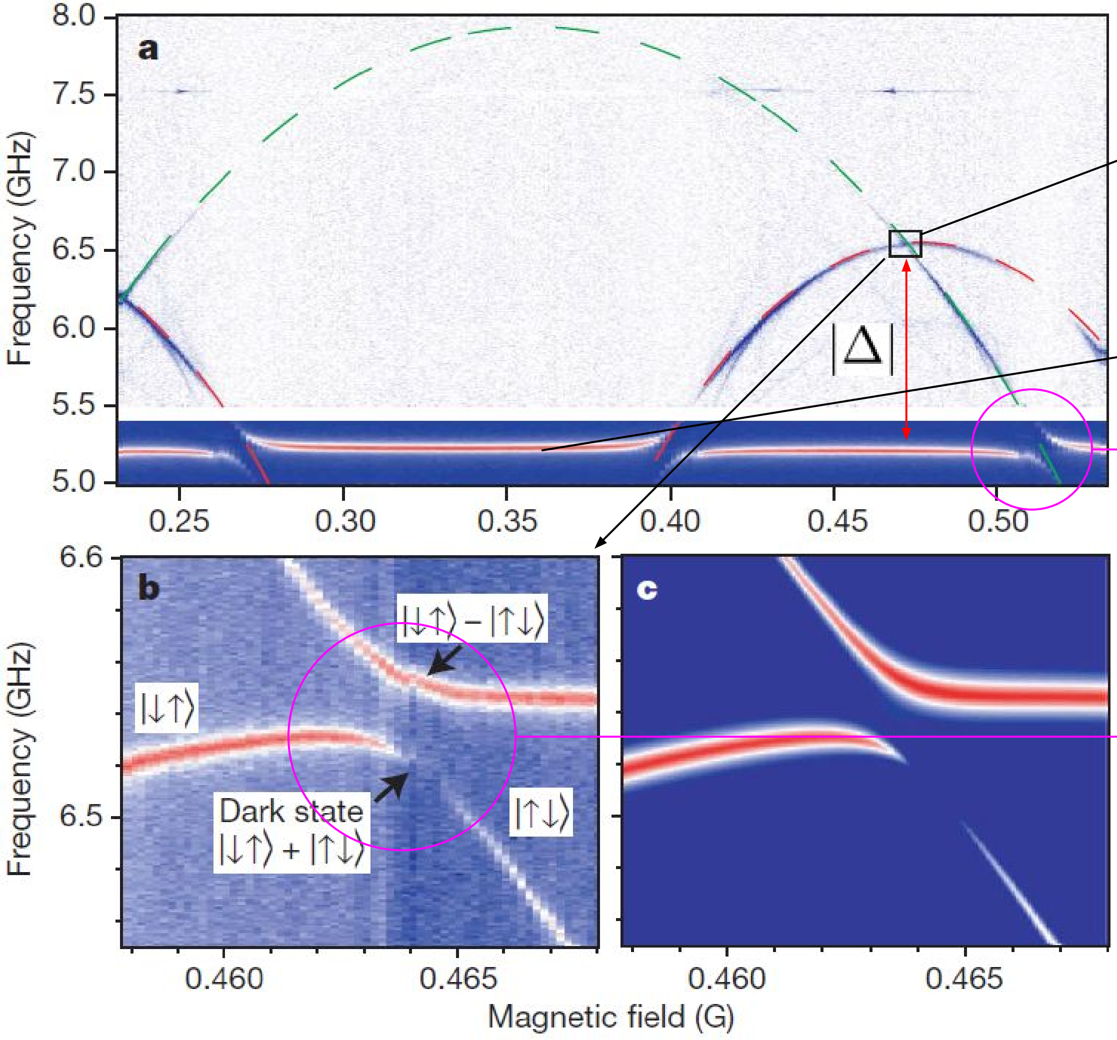
Operation principle - Coupling regimes



[1]

Qubit-qubit coupling in dispersive regime

$$\omega_{1,2} = \omega_{1,2}^{\max}\sqrt{|\cos(\pi\Phi/\Phi_0)|}$$

Resonator cavity

Vacuum Rabi splitting in qubit-resonator strong coupling limit

Qubit-qubit coupling: avoided crossing → vacuum Rabi splitting

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Operation principle - Coupling regimes

Strong coupling	Dispersive limit
- Qubits and cavity in resonance:	- Qubits detuned from resonator
$\|\Delta\| = \|\omega_{1,2} - \omega_r\| \to 0$	$\|\Delta\| = \|\omega_{1,2} - \omega_r\| \gg g_{1,2}$
- Excitation transferred from one qubit to photon in channel → can couple back into continuum → Purcell loss	- Qubits in resonance - Can interact directly via virtual photon
- Vacuum Rabi splitting observed	- Coherent state transfer in strong dispersive limit

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Operation principle - Dispersive regime

very short lifetime photon

Interaction/Coupling between qubits via $\underbrace{\text{virtual photons}}_{\text{no loss, energy conserved}}$ in cavity

interaction strength between qubits

Hamiltonian:

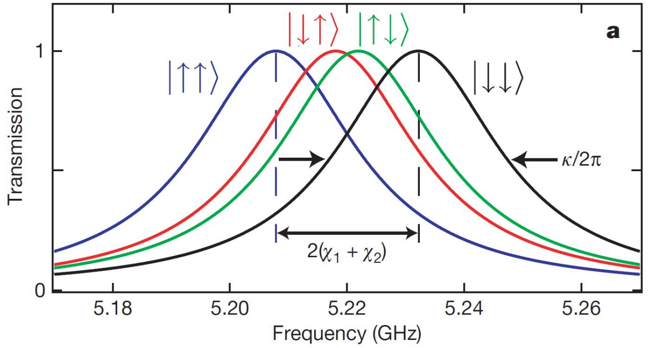
$$H = \underbrace{\frac{\hbar\omega_1}{2}\sigma_1^z}_{\text{qubit 1}} + \underbrace{\frac{\hbar\omega_2}{2}\sigma_2^z}_{\text{qubit 2}} + \underbrace{\hbar(\omega_r}_{\text{resonator}} + \underbrace{\chi_1\sigma_1^z + \chi_2\sigma_2^z}_{\text{coupling qubits-resonator}})a^+a + \underbrace{\hbar J(\sigma_1^-\sigma_2^+ + \sigma_2^-\sigma_1^+)}_{\text{coupling qubit 1-qubit 2}}$$

$\chi_{1,2}$ determined via detuning and g_1& g_2

qubit state-dependent shift of resonator frequency

measurement

[1]



ETH zürich

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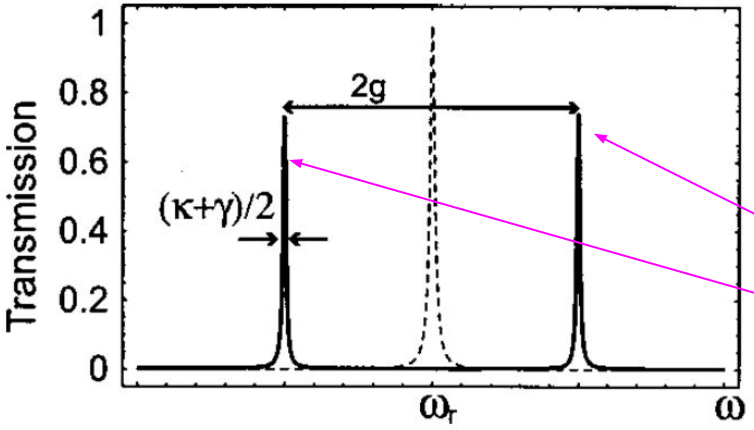
Operation principle - Vacuum Rabi splitting

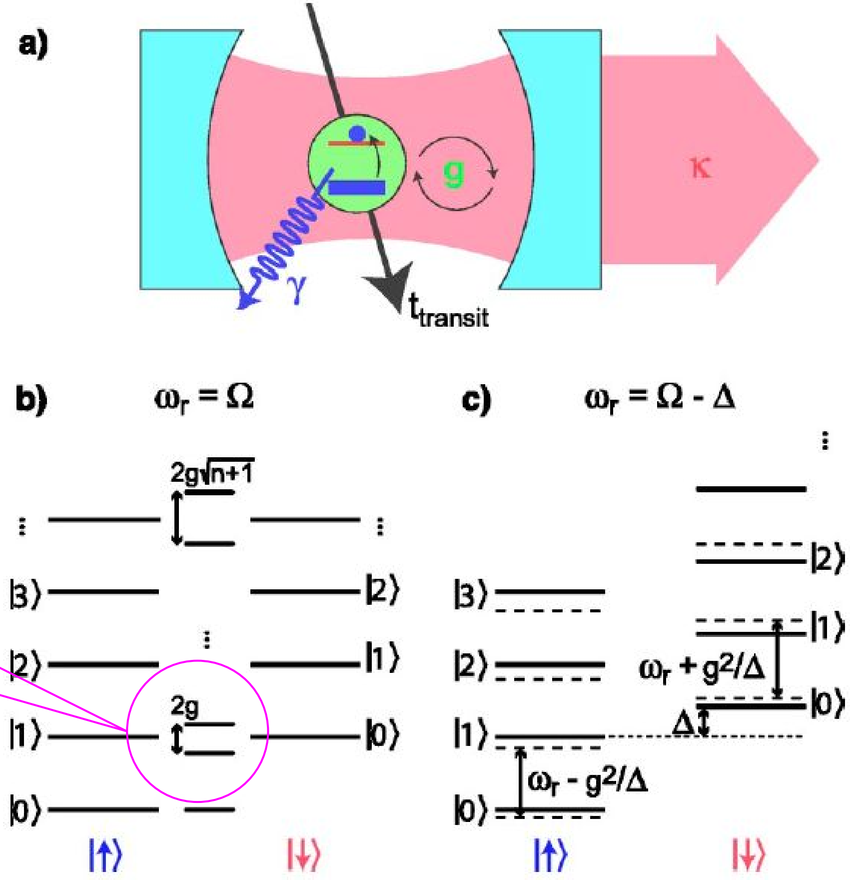
Occurs for:

- Qubit-qubit degeneracy
- Qubit-resonator degeneracy

Qubit-resonator degeneracy:



[3]



[3]

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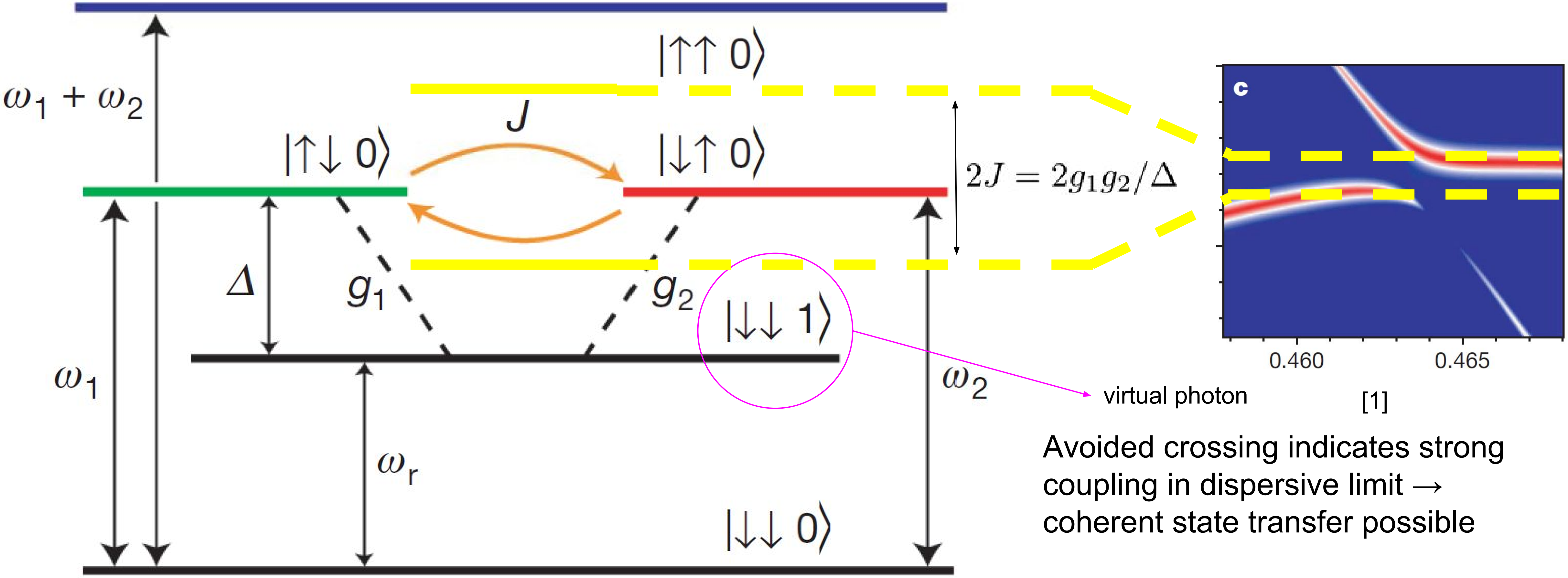
Operation principle - Qubit-qubit coupling

$$H = \frac{\hbar\omega_1}{2}\sigma_1^z + \frac{\hbar\omega_2}{2}\sigma_2^z + \hbar(\omega_r + \chi_1\sigma_1^z + \chi_2\sigma_2^z)a^+a + \hbar J(\sigma_1^-\sigma_2^+ + \sigma_2^-\sigma_1^+)$$



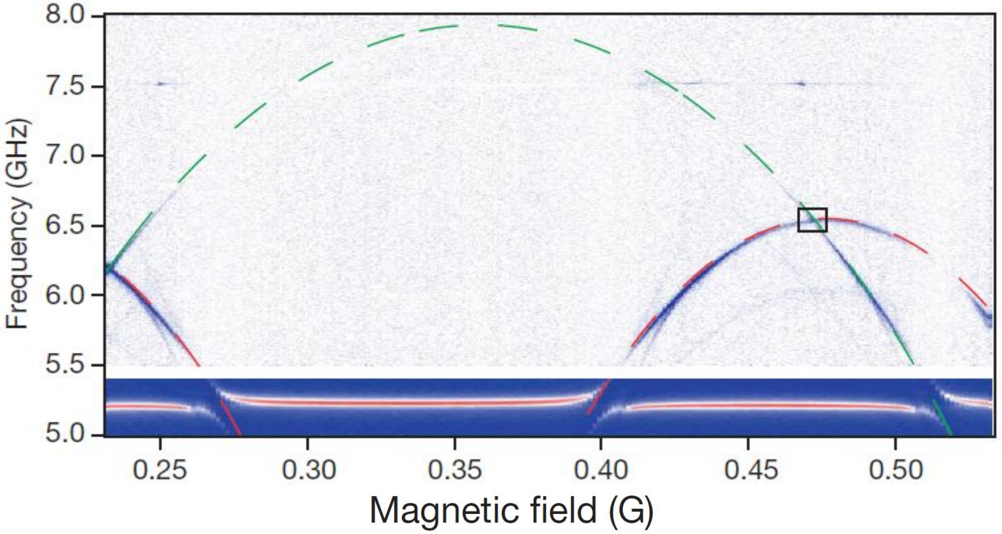
virtual photon

[1]

Avoided crossing indicates strong coupling in dispersive limit → coherent state transfer possible

[1]

Cavity Transmission and Spectroscopy of Single and Coupled Qubits



vary Φ tune both qubits into resonance with cavity

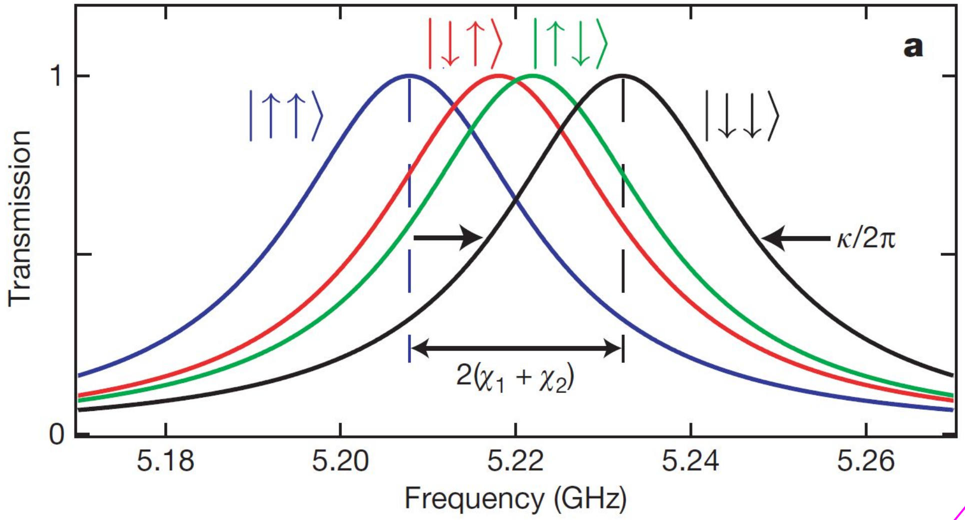
vacuum Rabi splitting

Superposition of Qubit-exc. and Cavity-Photon

g_1& g_2 : Difference at maximal splitting

Multiplexed Control and Read-out

$$|\Delta| = |\omega_{1,2} - \omega_r| \gg g_{1,2}$$



Dispersive Limit: Qubits detuned from Resonator
→ Effective resonator frequency depends on the states of the 2 qubit

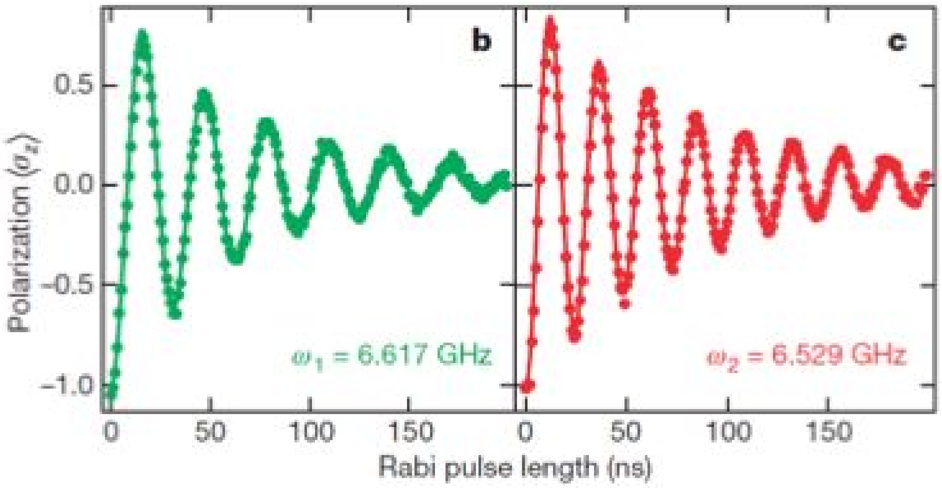
Get $\frac{\chi_1}{2\pi} = -5.9\,MHz$ & $\frac{\chi_2}{2\pi} = -7.4\,MHz$ by operating qubits at transmission frequencies.

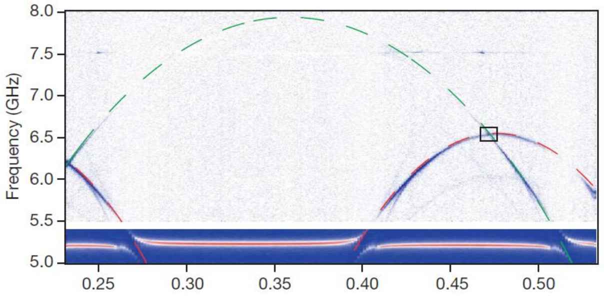
Reconsctruct two-qubit state from homodyne measurement of the cavity

$$H = \frac{\hbar\omega_1}{2}\sigma_1^z + \frac{\hbar\omega_2}{2}\sigma_2^z + \hbar(\omega_r + \boxed{\chi_1\sigma_1^z + \chi_2\sigma_2^z})a^+a + \hbar J(\sigma_1^-\sigma_2^+ + \sigma_2^-\sigma_1^+)$$

Multiplexed Control and Read-out

$$|\Delta| = |\omega_{1,2} - \omega_r| \gg g_{1,2}$$





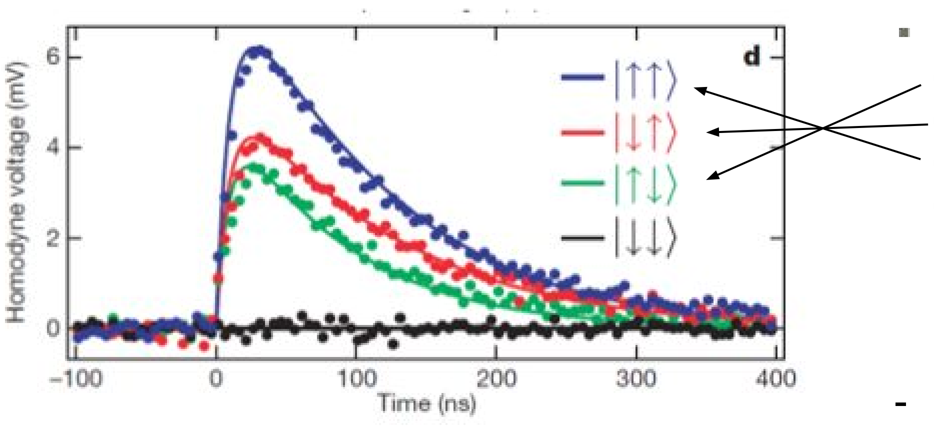
Rabi Oscillations of Q1 & Q2 ; aka ‘Ramsey Fringes’ → Rabi oscillations: oscillatory energy exchange between the qubit and the cavity

- tune flux such that transmission-frequency difference is 88 MHz → qubit-qubit coupling negligible

Apply drive pulse (RF) at qubit transmission frequency; measure cavity transmission
→ ability of simultaneous read-out of both qubits

- deduction of relaxation times and coherence times for both qubits → 78 ns, 120 ns for qubit-1 & 120 ns, 160 ns for qubit-2

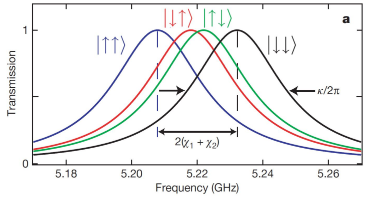
Multiplexed Control and Read-out



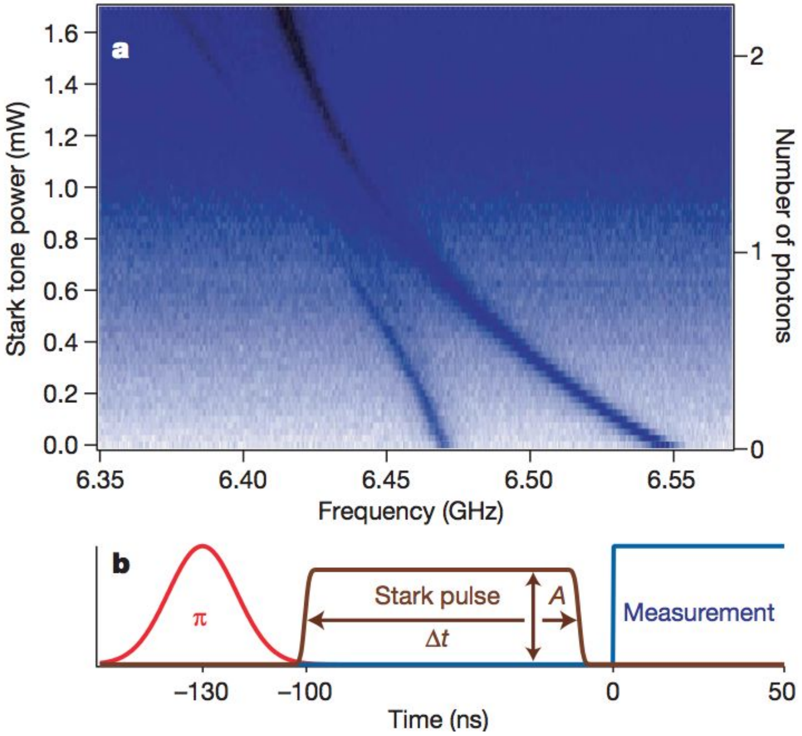
- 1 million traces of homodyne responses for:
  - → π-pulse for qubit 1
  - → π-pulse for qubit 2
  - → π-pulse for qubit 1 & 2
  - → no π-pulses

- Apply RF pulse at both of the qubit resonant frequencies; measure the pulse of resonator frequency
- Simultaneous read-out of the both qubits, by measuring cavity phase shift

difference in cavity frequency shifts of the two qubits result in **distinguishment of four states** (especially red and green)

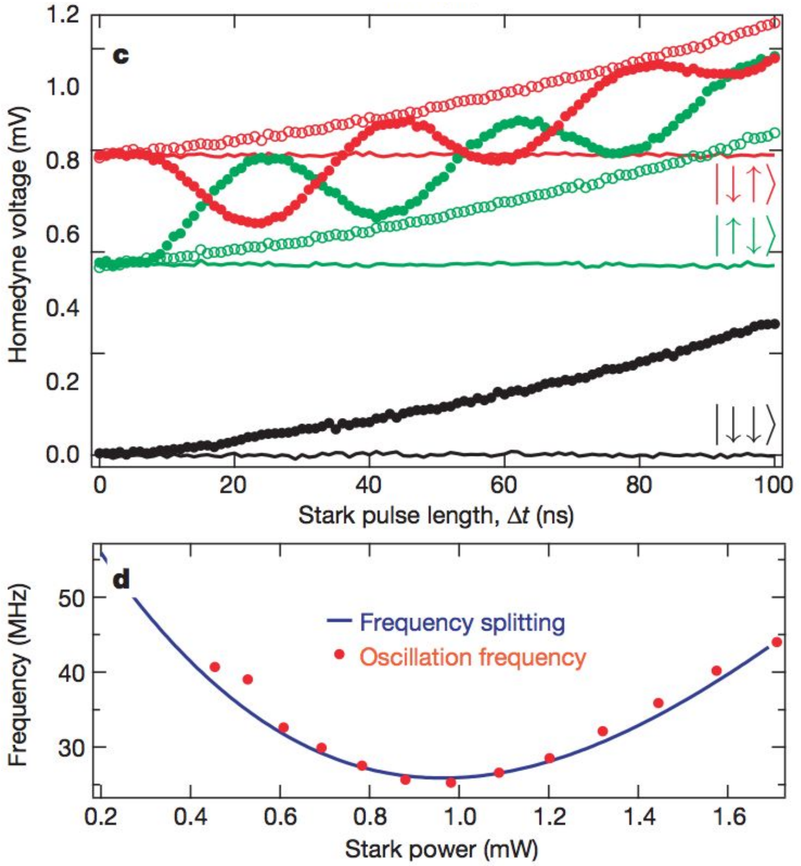


Off-Resonant Stark Shift



1) Qubits initially detuned by 80 Mhz
2) Pi-pulse applied → One qubit excited
3) Off-resonant Stark drive applied → Qubits brought to resonance for delta-t

- qubit frequencies pushed into resonance → Avoided Crossing
- transfer of state of qubits from one to other (coherent oscillation)



$$H_{\triangle_{qr}} = \hbar\left(\omega_r + \boxed{\frac{g^2}{\triangle_{qd}}\hat{\sigma}_z}\right) a^\dagger a + \frac{\hbar}{2}\left(\omega_q + \frac{g^2}{\triangle_{qd}}\right)\hat{\sigma}_z$$

Conclusion

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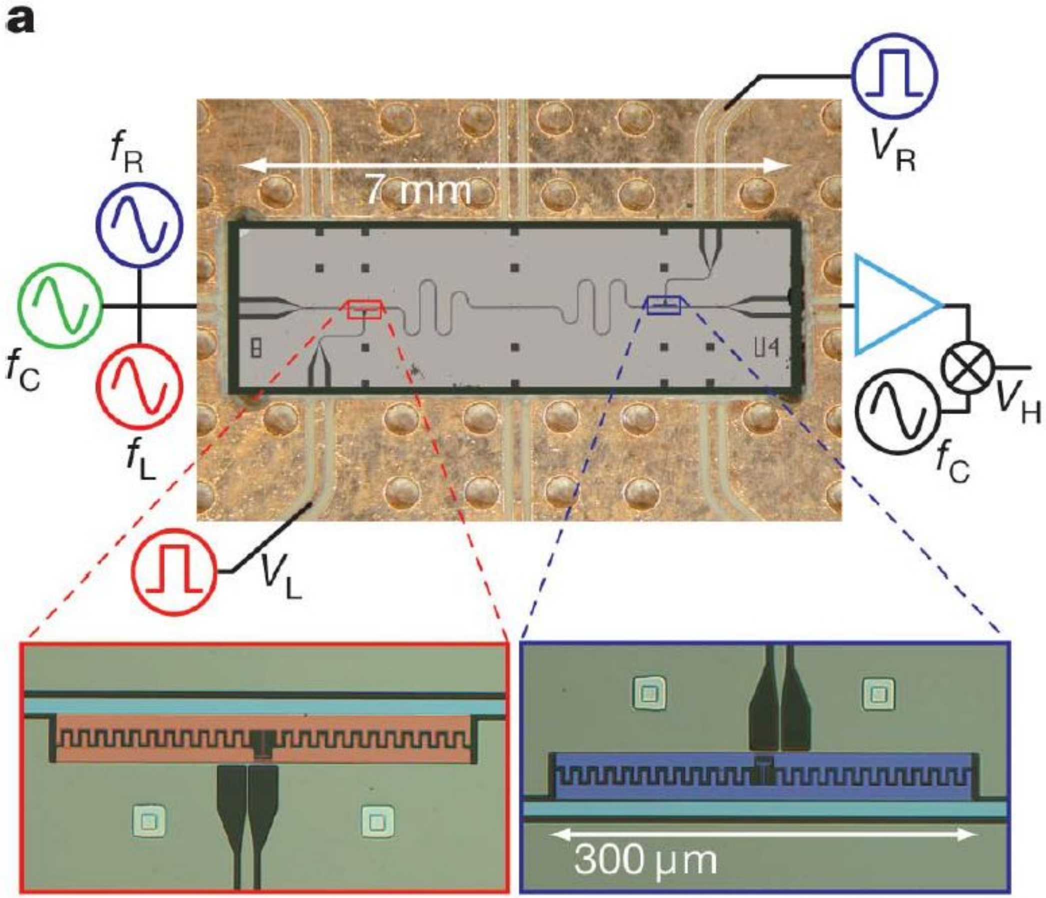
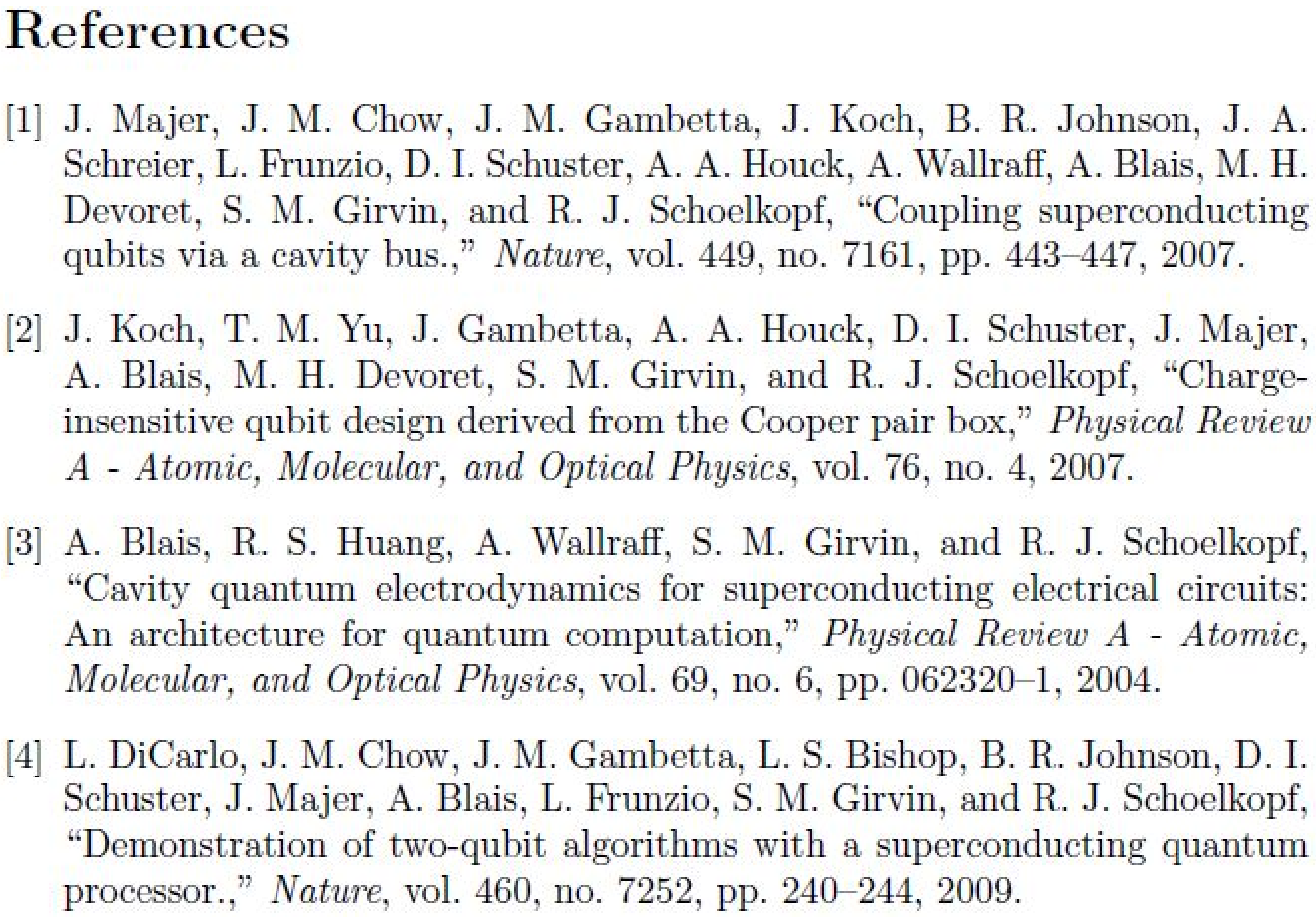
- Cavity bus enables coherent, non-local coupling between qubits → can be extended to more qubits → promising architecture for SC quantum circuit
- Virtual photons avoid cavity loss
- Tuning via magnetic flux control of Josephson junction
- Fast control enables state switching
- Cavity used for multiplexed readout and control

Outlook

Next week: Implementation of two-qubit algorithms (Deutsch-Josza, Grover search) on cavity bus SC circuit architecture [4]





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[2] J. Koch, T. M. Yu, J. Gambetta, A. A. Houck, D. I. Schuster, J. Majer, A. Blais, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, "Charge-insensitive qubit design derived from the Cooper pair box," *Physical Review A - Atomic, Molecular, and Optical Physics*, vol. 76, no. 4, 2007.

[3] A. Blais, R. S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, "Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation," *Physical Review A - Atomic, Molecular, and Optical Physics*, vol. 69, no. 6, pp. 062320–1, 2004.

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Thank you for your attention!