Suppressing unwanted ZZ-coupling, cross-resonance gate and anharmonicities

A. Blais et al., "Circuit quantum electrodynamics”, *arXiv:2005.12667* (2020)

(and other interesting papers)

Unwanted ZZ-coupling

Resonator mediated coupling

Two-qubit Hamiltonian:

$$\hat{H} = \hat{H}_{q1} + \hat{H}_{q2} + \hbar\omega_r \hat{a}^\dagger \hat{a} + \sum_{i=1}^{2} \hbar g_i (\hat{a}^\dagger \hat{b}_i + \hat{a}\hat{b}_i^\dagger).$$

the effective dispersive Hamiltonian

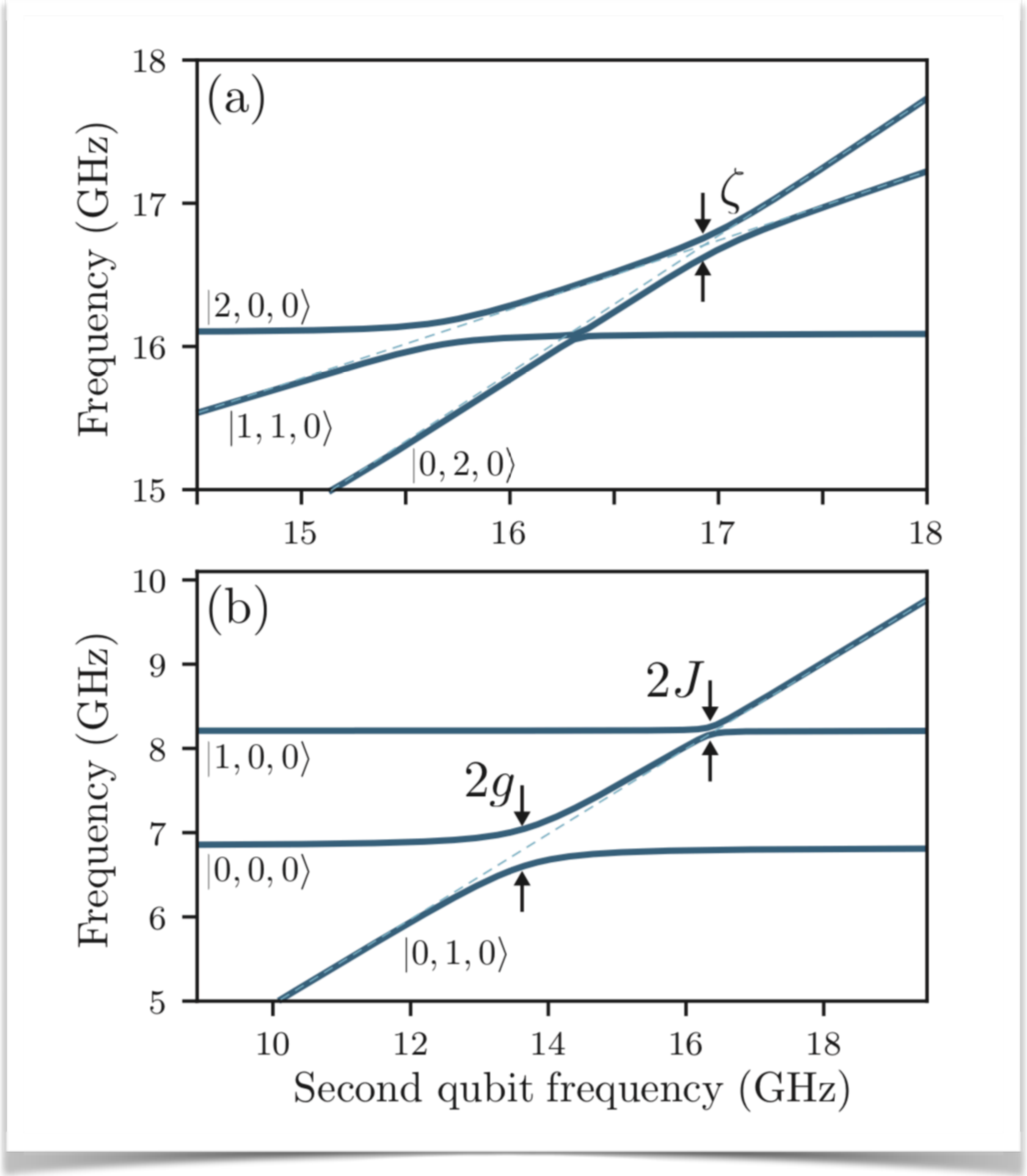
$$H/\hbar = \left(\omega_C + \chi_1\sigma_z^{(1)} + \chi_2\sigma_z^{(2)}\right) a^\dagger a + \frac{1}{2}\omega_1\sigma_z^{(1)} + \frac{1}{2}\omega_2\sigma_z^{(2)} + \frac{g_1 g_2 (\Delta_1 + \Delta_2)}{2\Delta_1\Delta_2}\left(\sigma_+^{(1)}\sigma_-^{(2)} + \sigma_-^{(1)}\sigma_+^{(2)}\right),$$

coupling strength $J = \dfrac{g_1 g_2 (\Delta_1 + \Delta_2)}{2\Delta_1\Delta_2}.$

unwanted ZZ coupling $\zeta\, \hat{\sigma}_{z1}\hat{\sigma}_{z2}$

$$\zeta = \frac{g_1^2 g_2^2 (\Delta_1 + \Delta_2)}{\Delta_1^2 \Delta_2^2}.$$

Spectrum of two transom qubits coupled to a common resonator

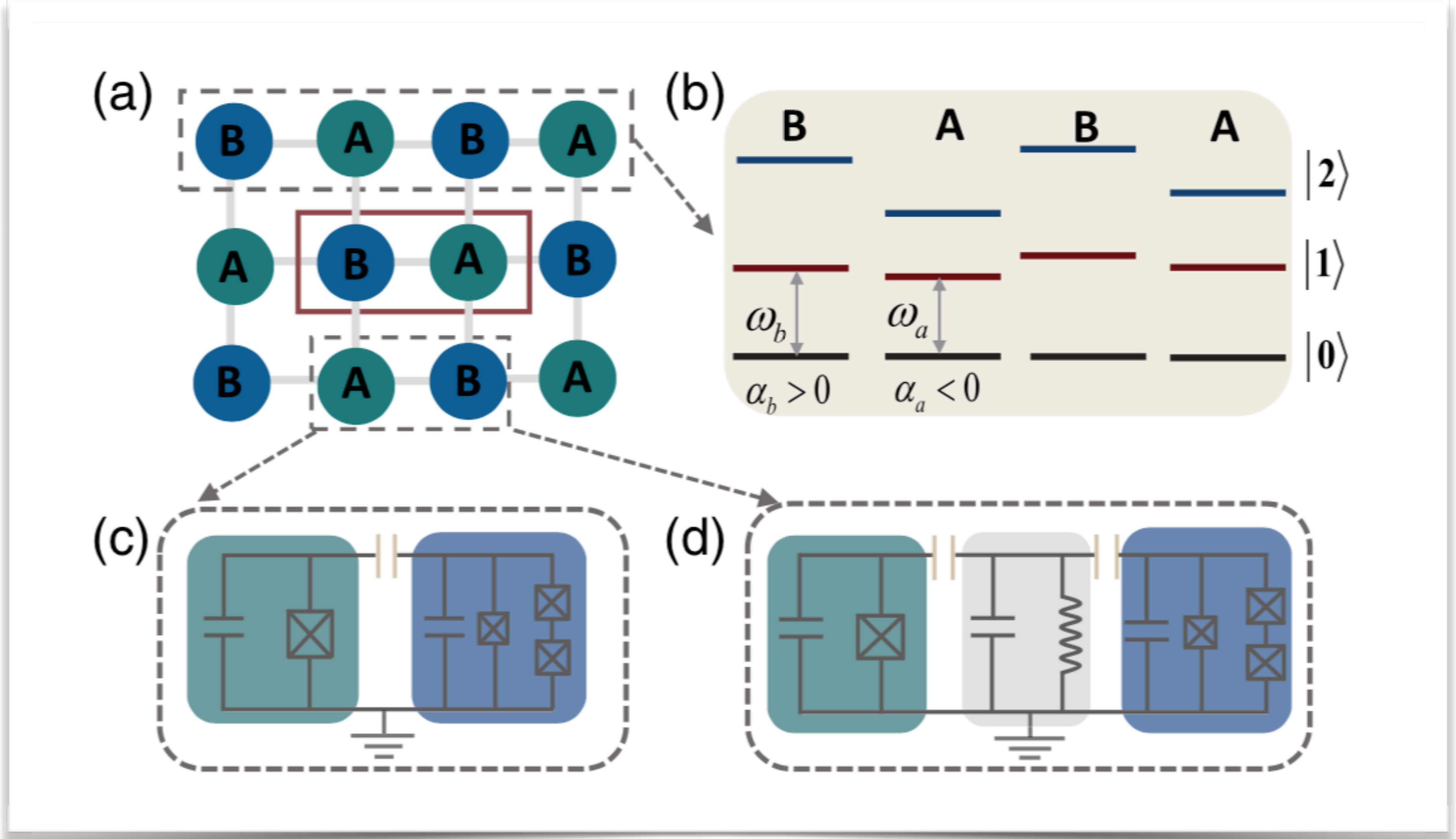


High contrast ZZ-interaction

Controlling qubit anhormonicity

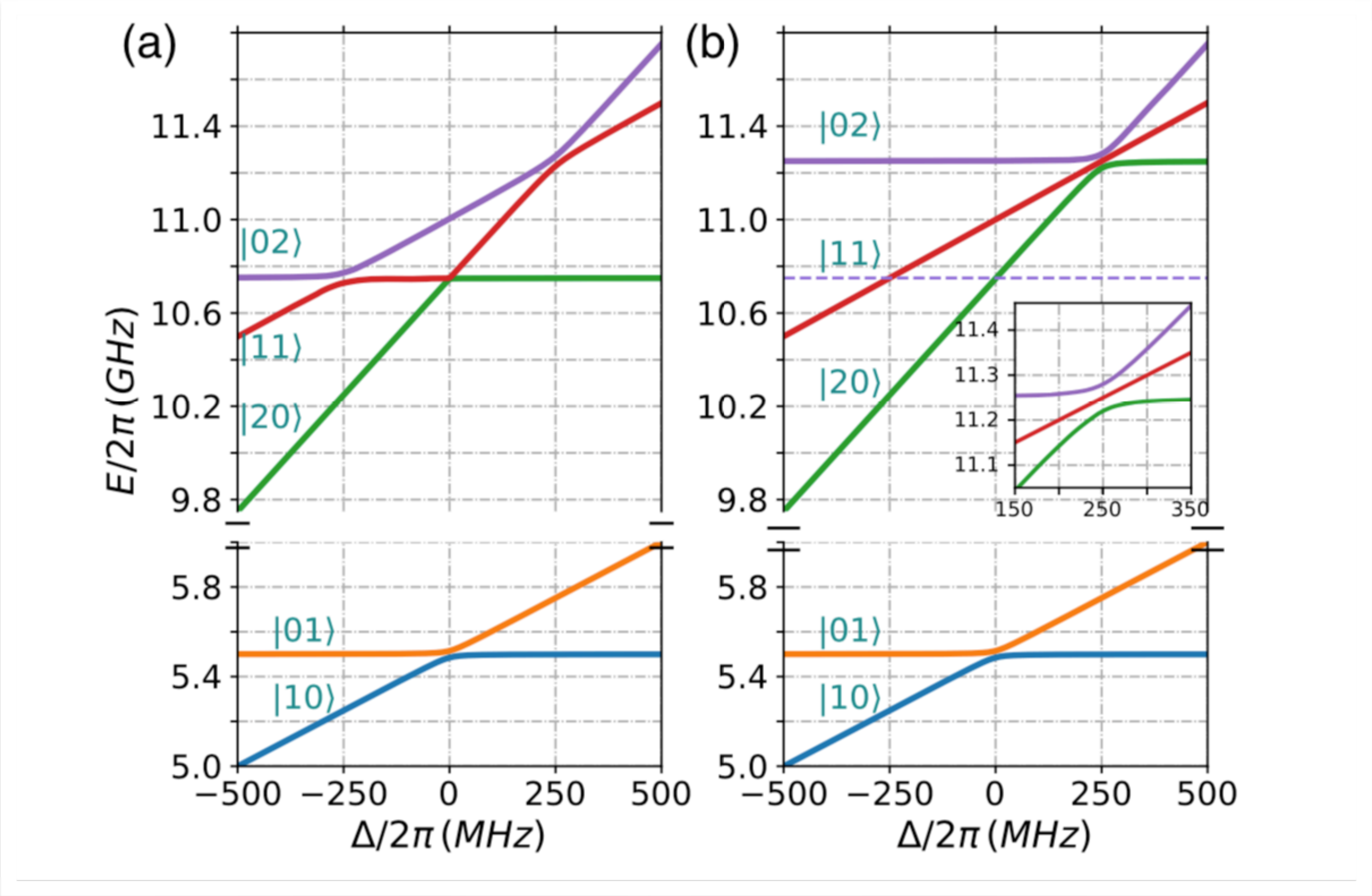
P. Zhao et al., *Physical Review Letters* 125.20 (2020): 200503.

Layout of a 2D qubit architecture
with different sign anharmonicities



Energy levels of the coupled qubit system

++ anharmonicities   +- anharmonicities



at the triple degeneracy point the eigenstates are:

$$(|02\rangle + |20\rangle - \sqrt{2}|11\rangle)/2, \qquad E_{11} - \sqrt{2}J,$$
$$(|02\rangle - |20\rangle)/\sqrt{2}, \qquad E_{11},$$
$$(|02\rangle + |20\rangle + \sqrt{2}|11\rangle)/2 \qquad E_{11} + \sqrt{2}J$$

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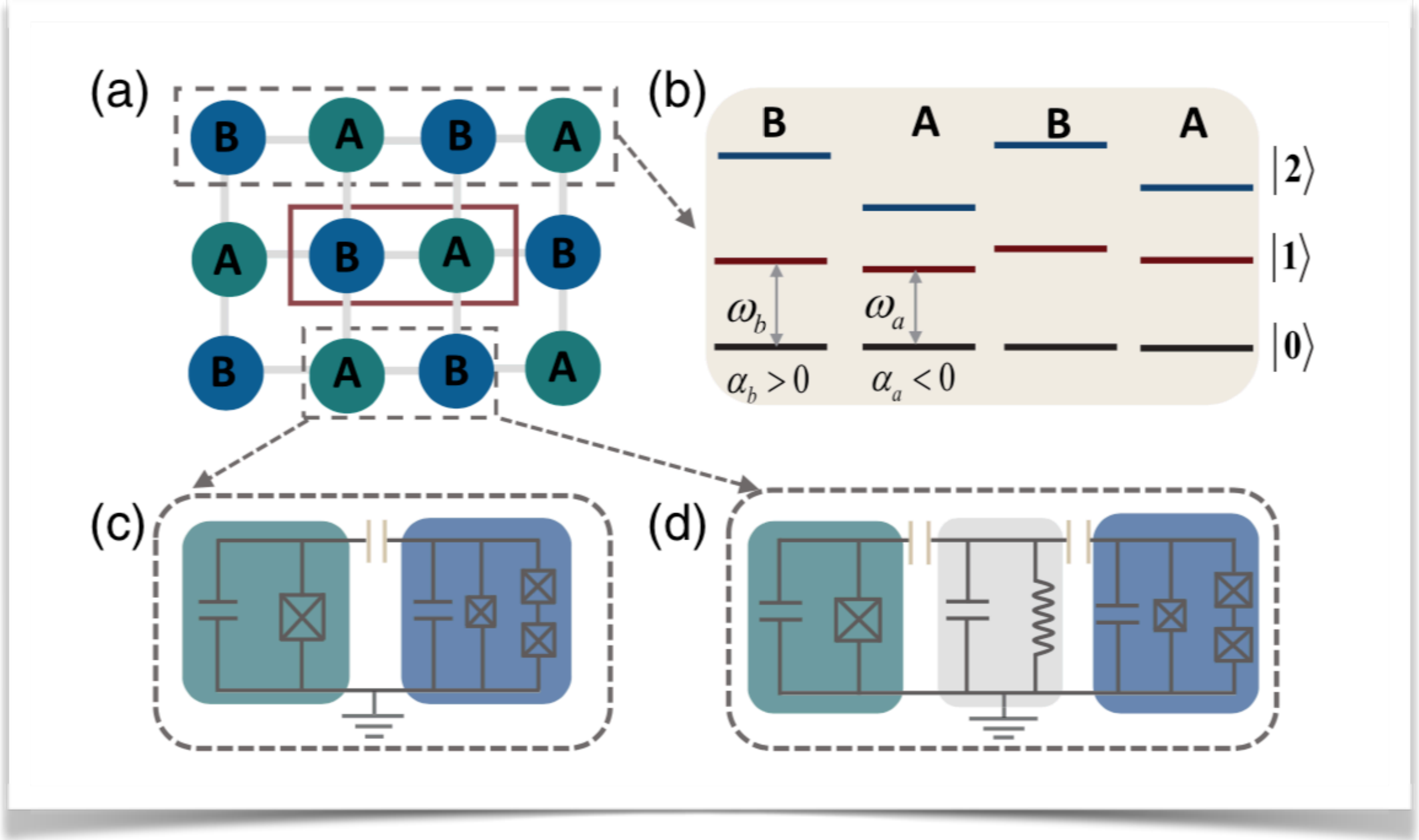
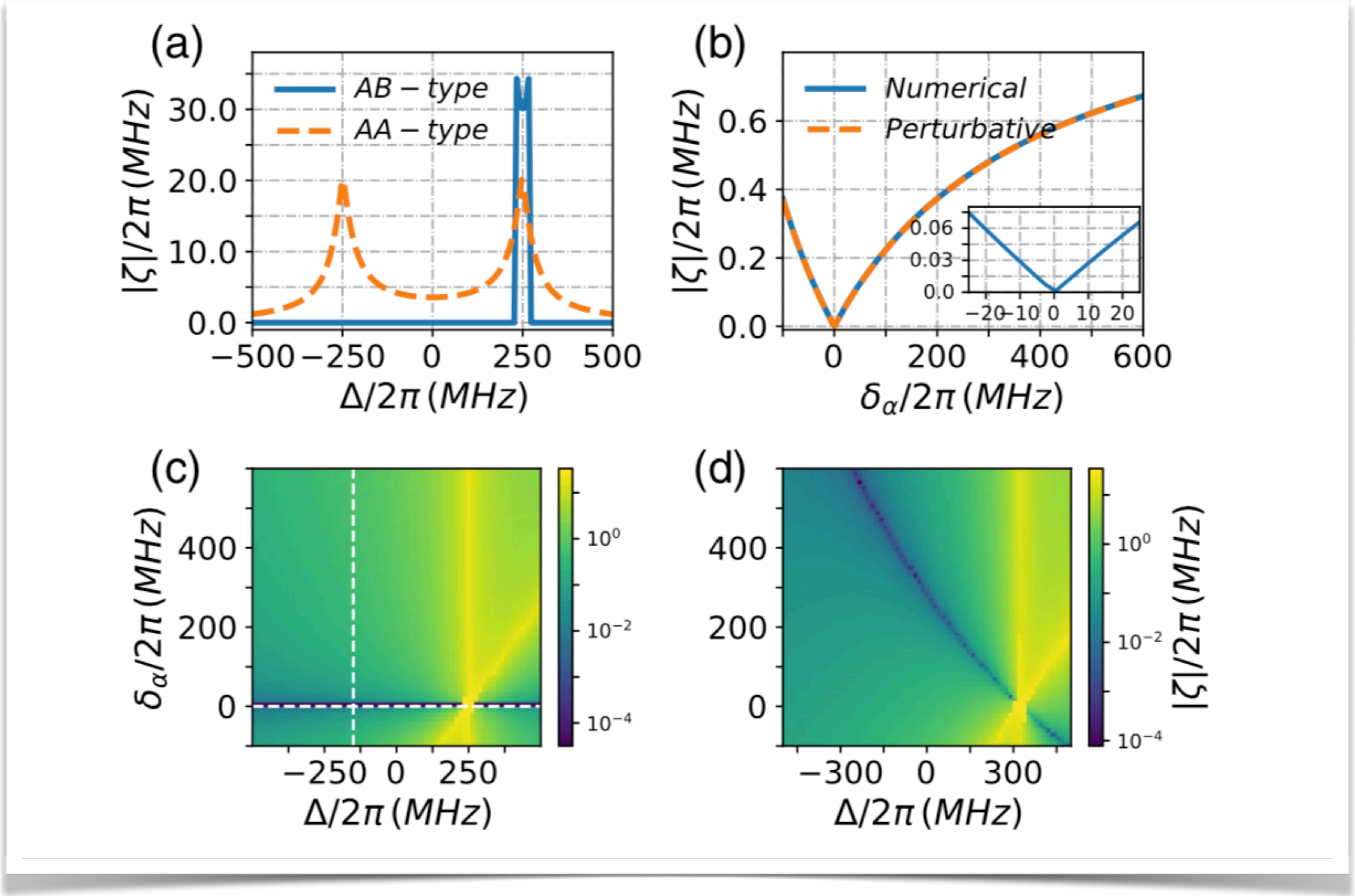


ZZ coupling strength

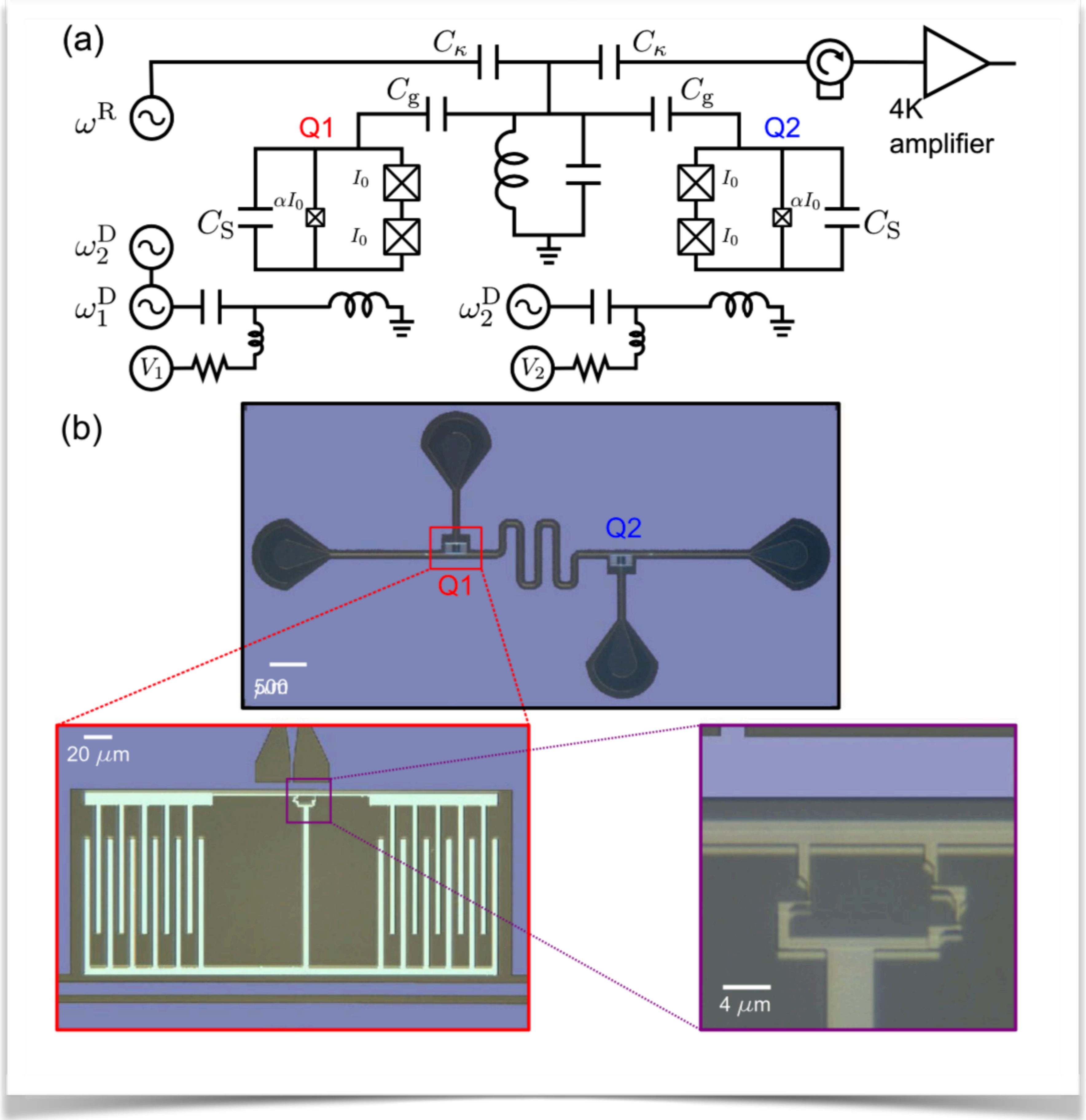


Cross-resonance gate

All microwaves gate

J.M. Chow et al., *Physical Review Letters* 107.8 (2011): 080502.
C. Rigetti and M. Devoret, *Physical Review B* 81.13 (2010): 134507.

2 qubit device

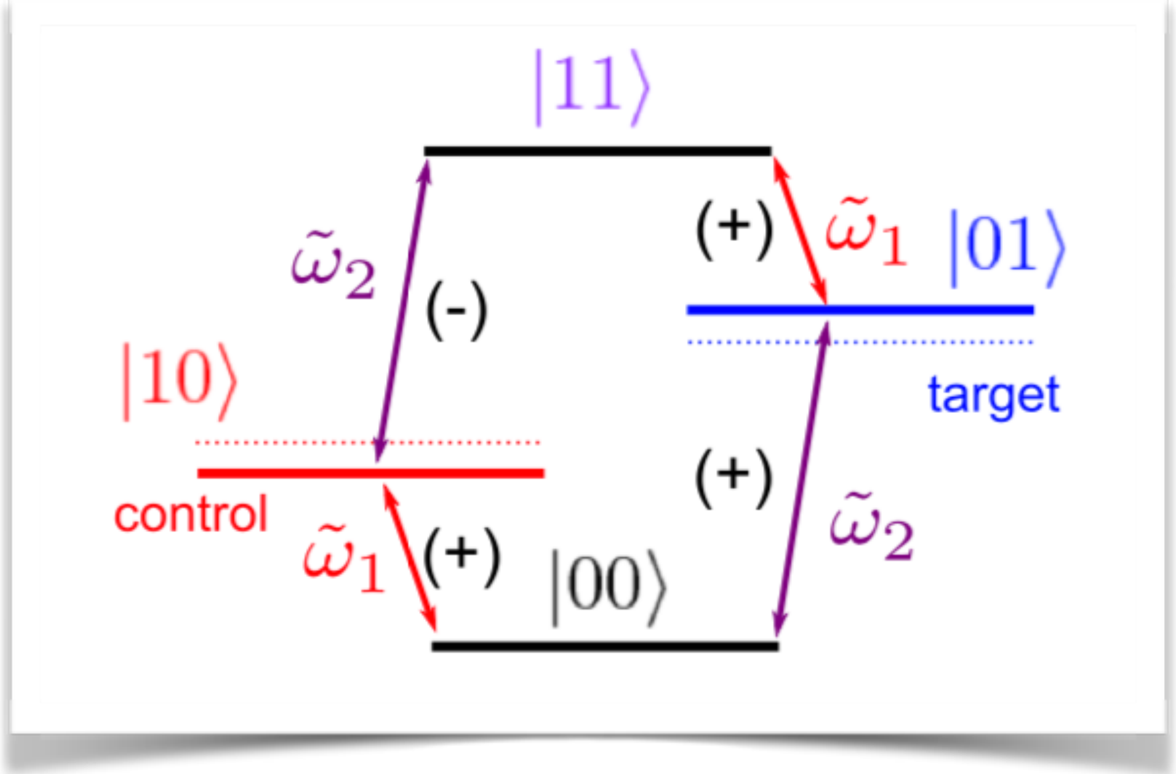


Dispersively coupled two qubits:

$$\hat{H} = \frac{\hbar\omega_{q1}}{2}\hat{\sigma}_{z1} + \frac{\hbar\omega_{q2}}{2}\hat{\sigma}_{z2} + \hbar J(\hat{\sigma}_{+1}\hat{\sigma}_{-2} + \hat{\sigma}_{-1}\hat{\sigma}_{+2}).$$

renormalised qubit frequencies

$$\tilde{\omega}_{q1} \approx \omega_{q1} + J\ /\Delta_{12} \text{ and } \tilde{\omega}_{q2} \approx \omega_{q2} - J\ /\Delta_{12}$$



the drive Hamiltonian on qubit 1:

$$\approx \hbar\Omega_R(t)\cos(\omega_d t)\left(\hat{\sigma}_{x1} + \frac{J}{\Delta_{12}}\hat{\sigma}_{z1}\hat{\sigma}_{x2}\right),$$

$$\text{CNOT} = [ZI]^{-1/2}[ZX]^{1/2}[IX]^{-1/2}.$$

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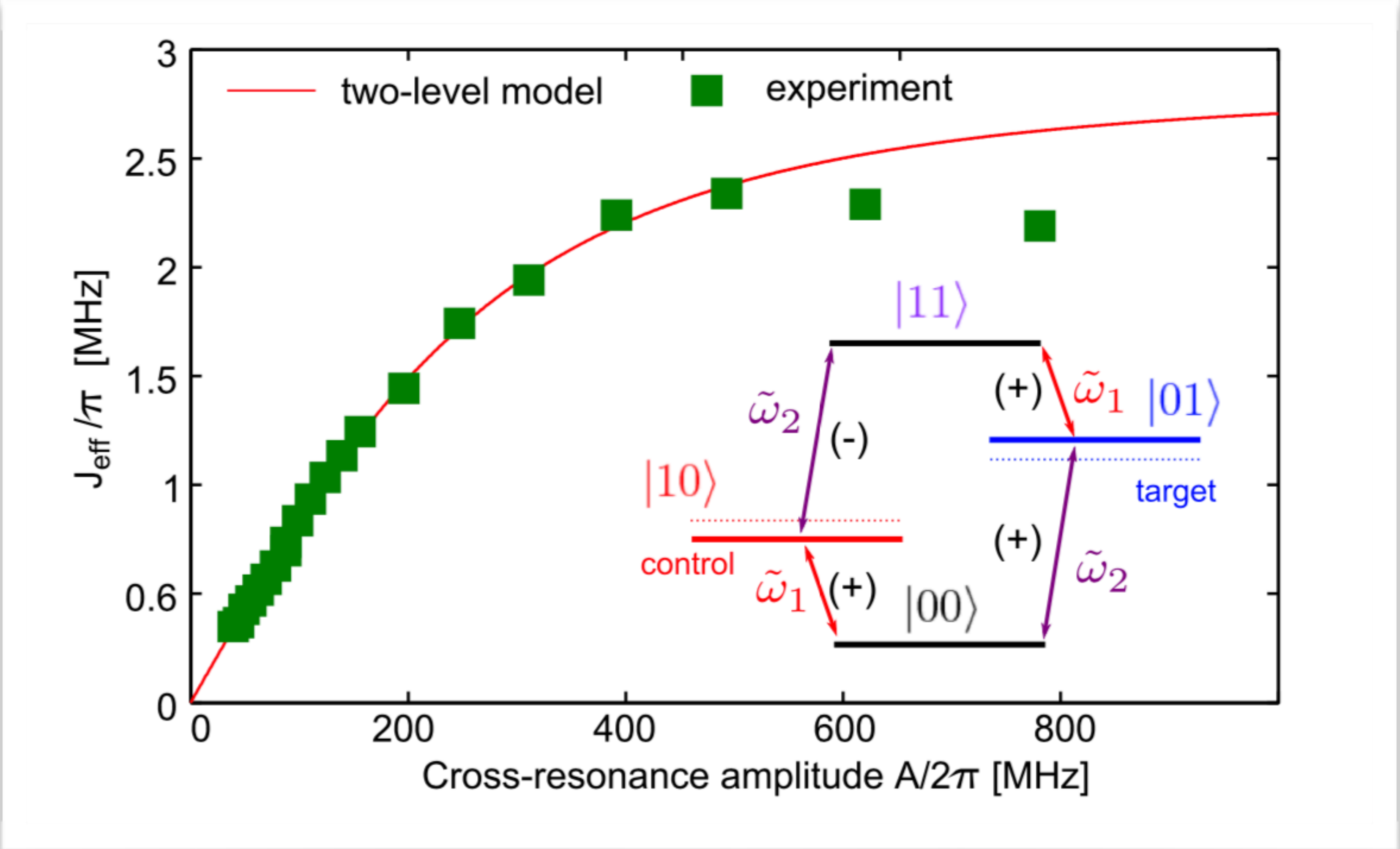
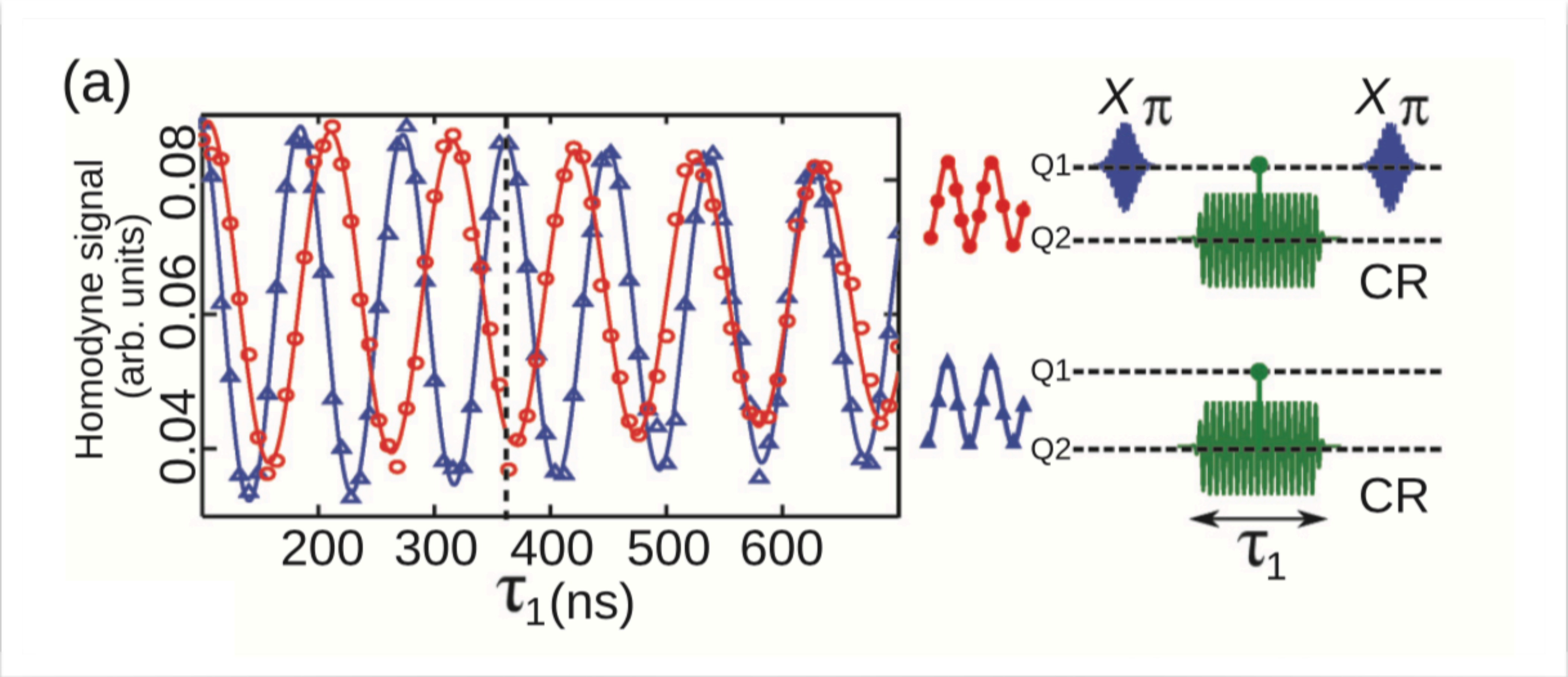
tunable coupling strength:



pulse sequence to measure CR effective coupling



A.D. Córcoles et al., *Physical Review A* 87.3 (2013): 030301.

Cross-resonance gate

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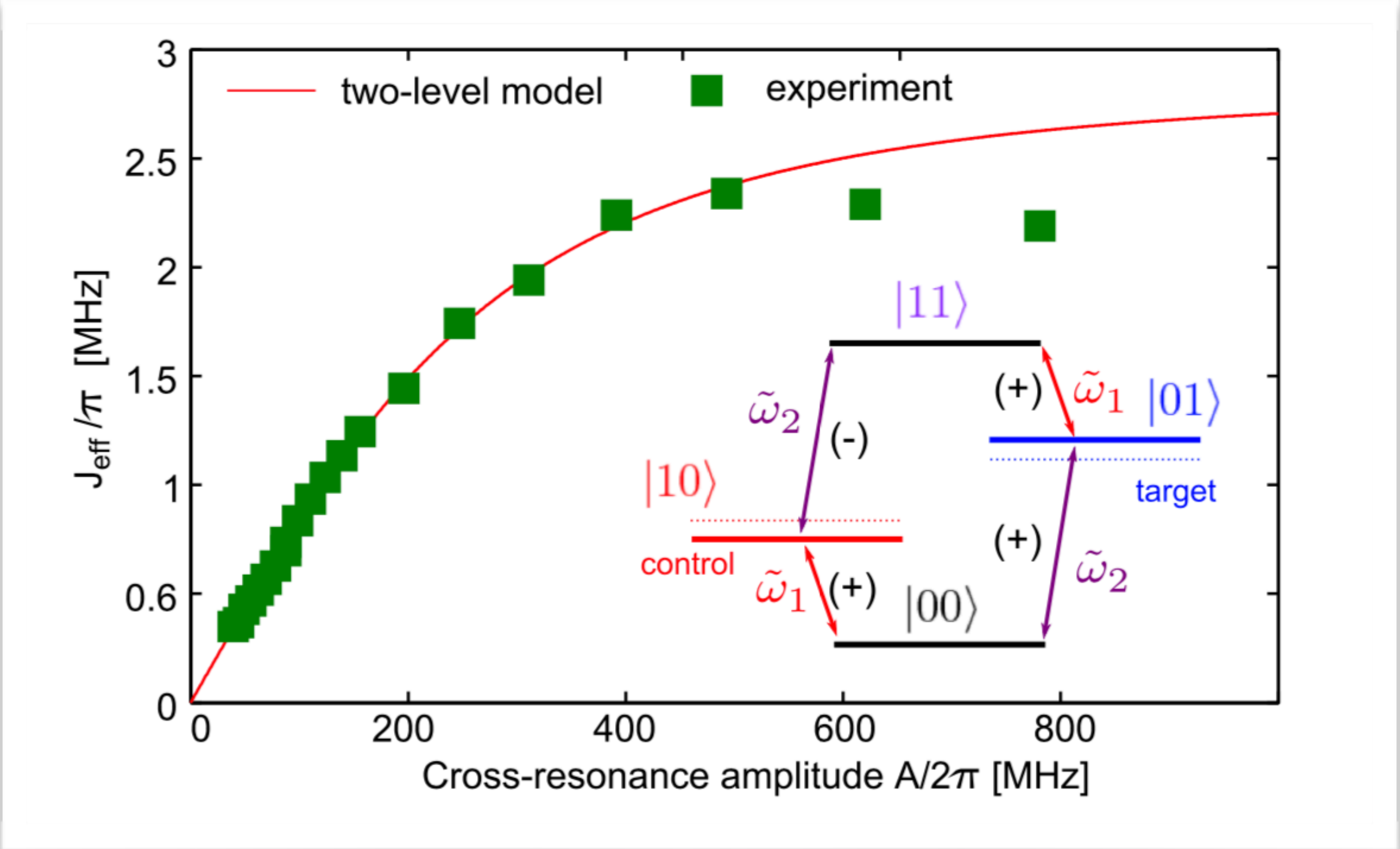
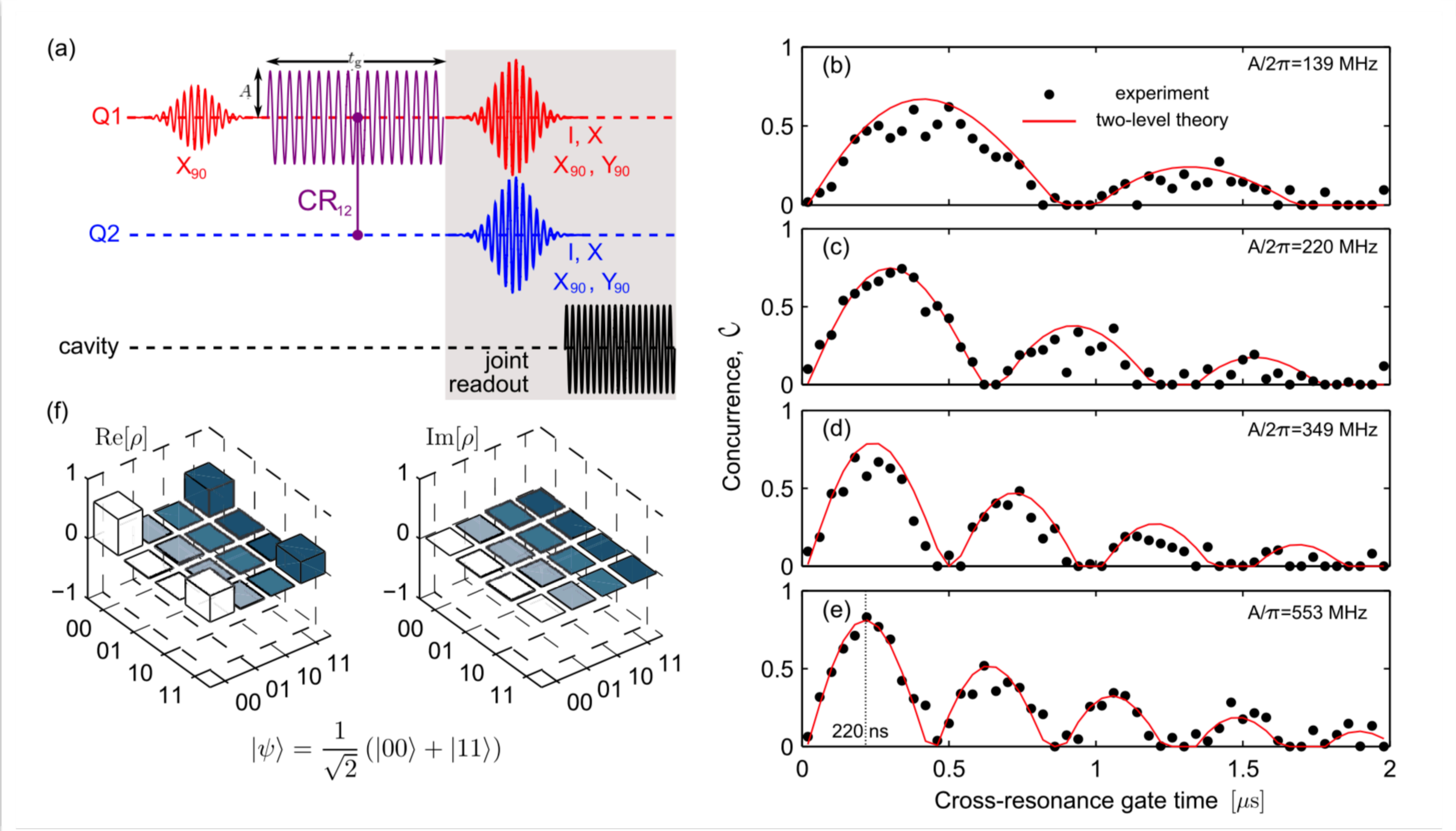
Entangled states and concurrence oscillations

tunable coupling strength:





$$\mathcal{F} = \langle \psi_{\text{Bell}} | \rho | \psi_{\text{Bell}} \rangle = 90\% \pm 0.04$$
$$\mathcal{C} = 0.88 \pm 0.05.$$

Cross-resonance gate

All microwaves gate

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C. Rigetti and M. Devoret, *Physical Review B* 81.13 (2010): 134507.

Calculation results with more levels of transmon

$$\hat{H}' \simeq \frac{\hbar\tilde{\delta}_{q1}}{2}\hat{\sigma}_{z1} + \frac{\hbar\tilde{\delta}_{q2}}{2}\hat{\sigma}_{z2} + \frac{\hbar\chi_{12}}{2}\hat{\sigma}_{z1}\hat{\sigma}_{z2} + \hbar\varepsilon(t)\left(\hat{\sigma}_{x1} - J'\hat{\sigma}_{x2} - \frac{E_{C_1}}{\hbar}\frac{J'}{\Delta_{12}}\hat{\sigma}_{z1}\hat{\sigma}_{x2}\right)$$

$$\chi_{12} = \frac{J^2}{\Delta_{12} + \frac{E_{C_2}}{\hbar}} - \frac{J^2}{\Delta_{12} - \frac{E_{C_1}}{\hbar}},$$

$$J' = \frac{J}{\Delta_{12} - \frac{E_{C_1}}{\hbar}}.$$

dressed qubit frequencies in the rotating frame

$$\tilde{\delta}_{q1} = \omega_{q1} + J^2/\Delta_{12} + \chi_{12} - \omega_{\mathrm{d}}$$

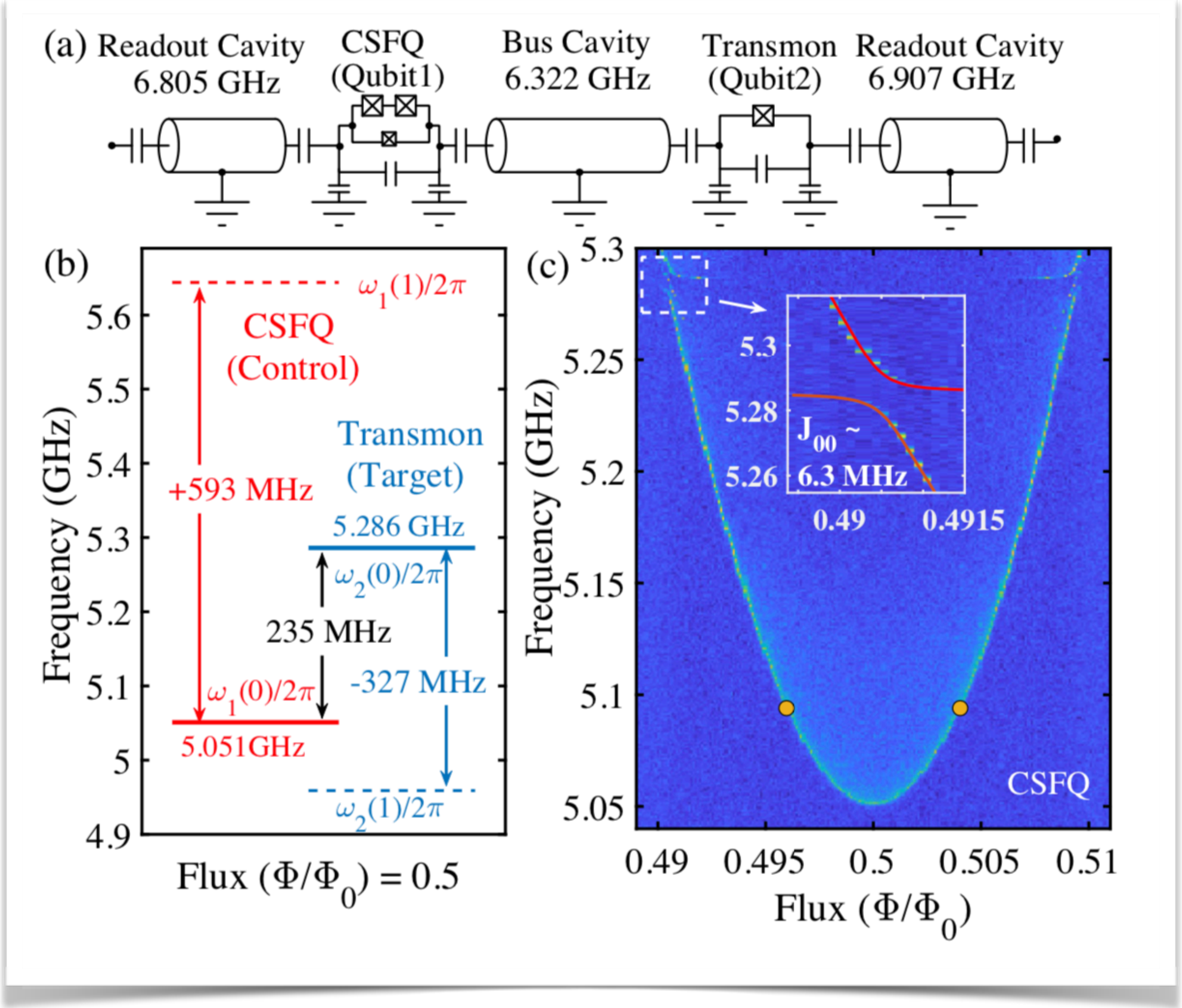
$$\tilde{\delta}_{q2} = \omega_{q2} - J^2/\Delta_{12} + \chi_{12} - \omega_{\mathrm{d}}$$

Suppression of unwanted ZZ-coupling

and again... anharmonicities :)

J. Ku et al., *Physical Review Letters* 125.20 (2020): 200504

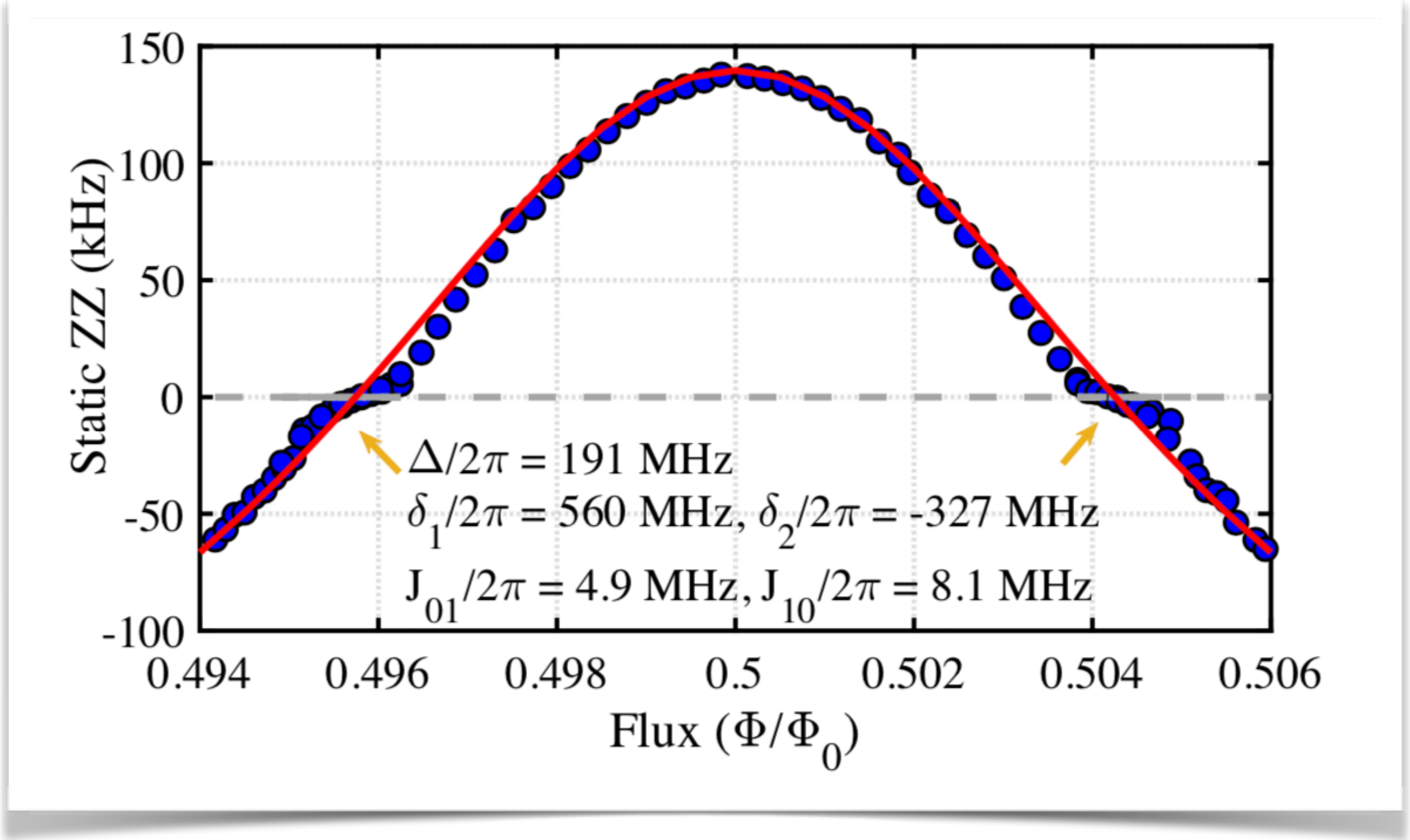
Capacitively shunted flux qubit and transmon system



system Hamiltonian:

$$H_{\text{eff}} = -\tilde{\omega}_1 \frac{ZI}{2} - \tilde{\omega}_2 \frac{IZ}{2} + \zeta \frac{ZZ}{4},$$

$$\zeta = -\frac{2J_{01}^2}{\Delta + \delta_2} + \frac{2J_{10}^2}{\Delta - \delta_1},$$



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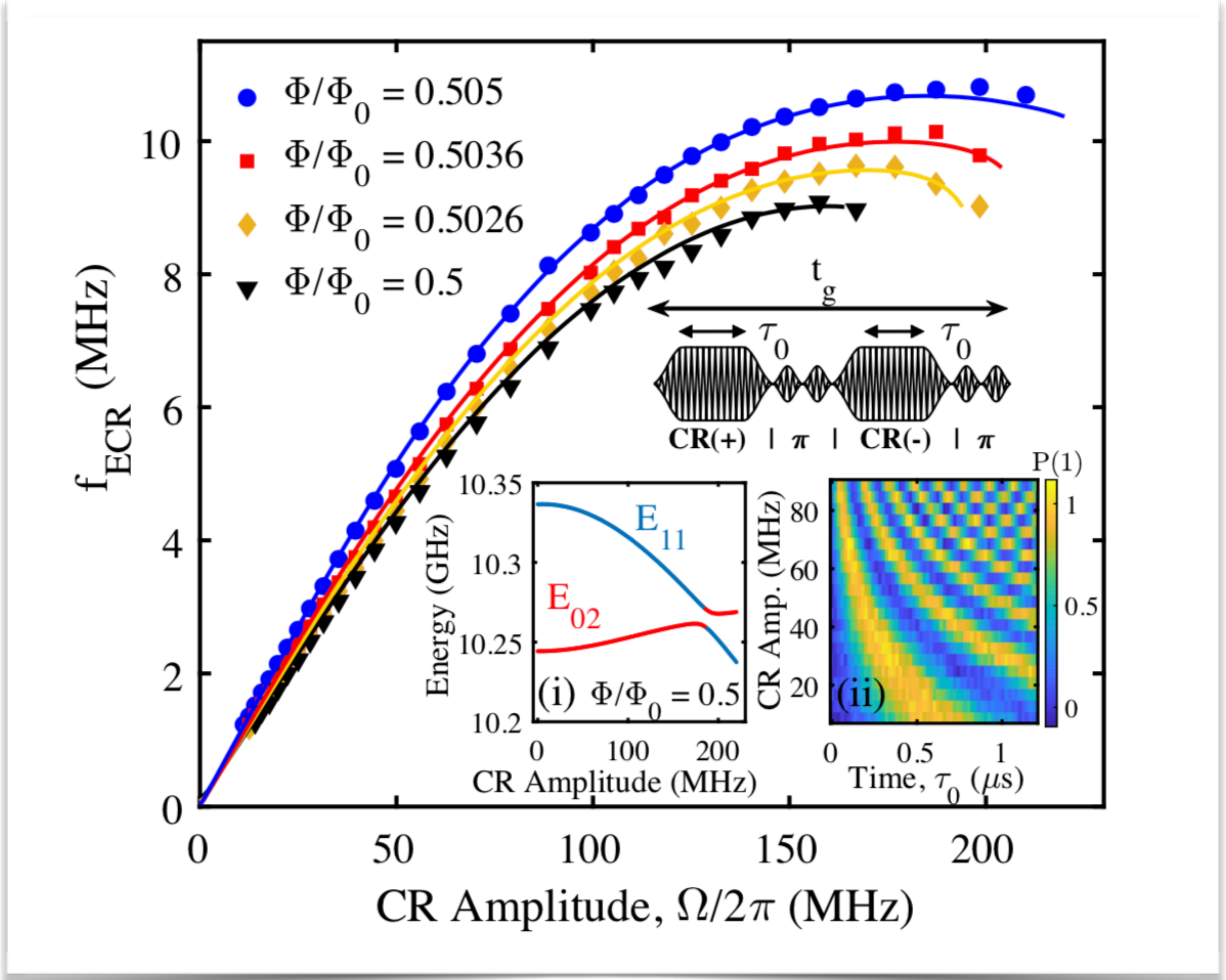
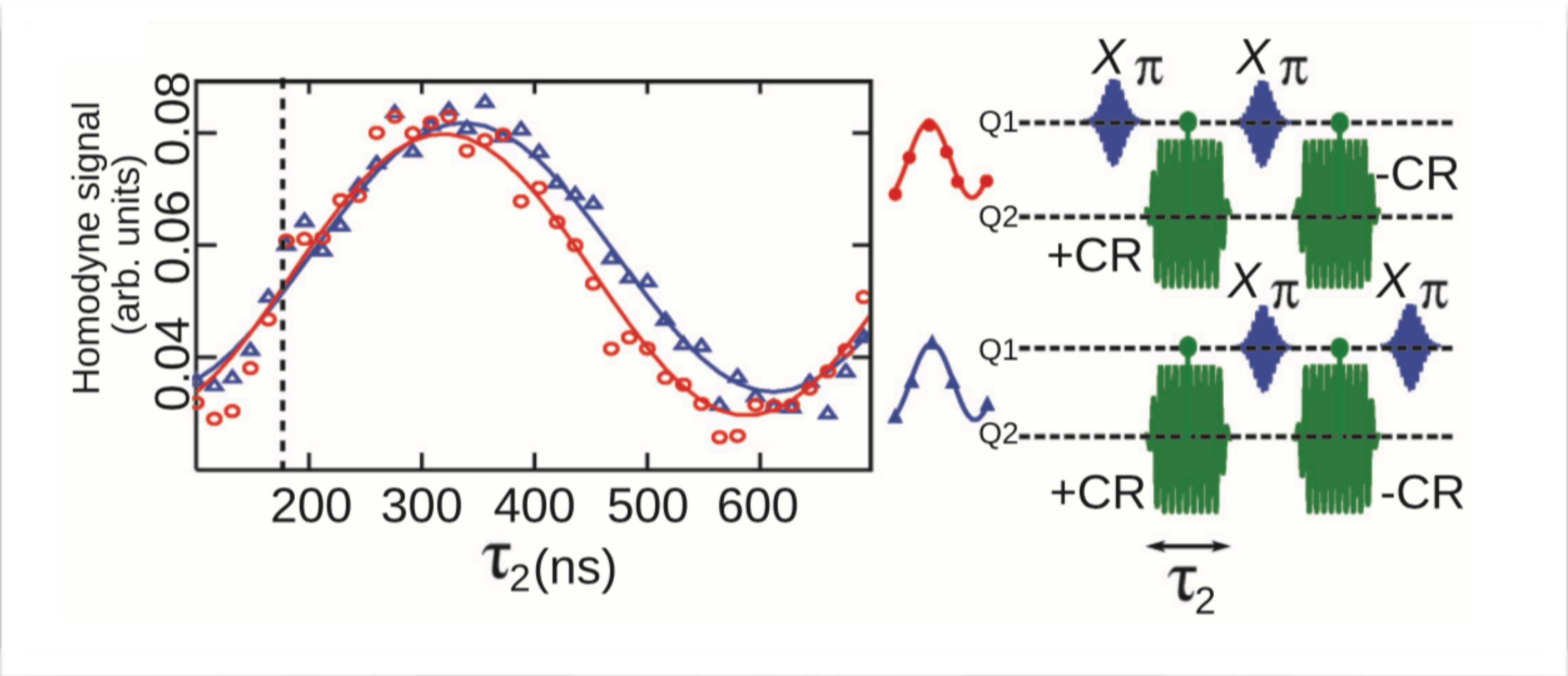
J. Ku et al., *Physical Review Letters* 125.20 (2020): 200504

Cross resonance rate vs CR amplitude



pulse sequence to measure CR effective coupling



$$H_D/\hbar \approx \epsilon(t)(mIX - \mu ZX + \eta ZI),$$

A.D. Córcoles et al., *Physical Review A* 87.3 (2013): 030301.

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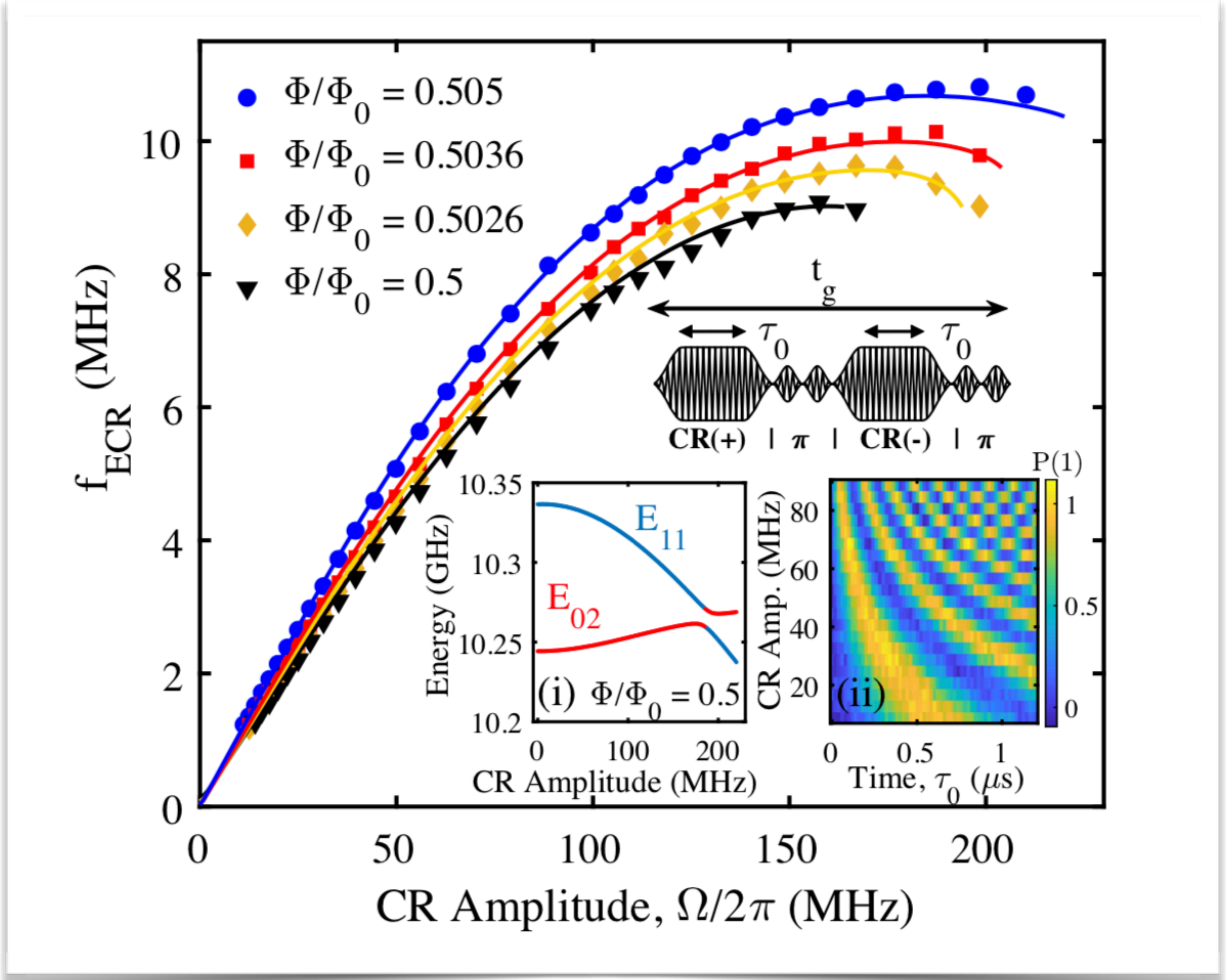
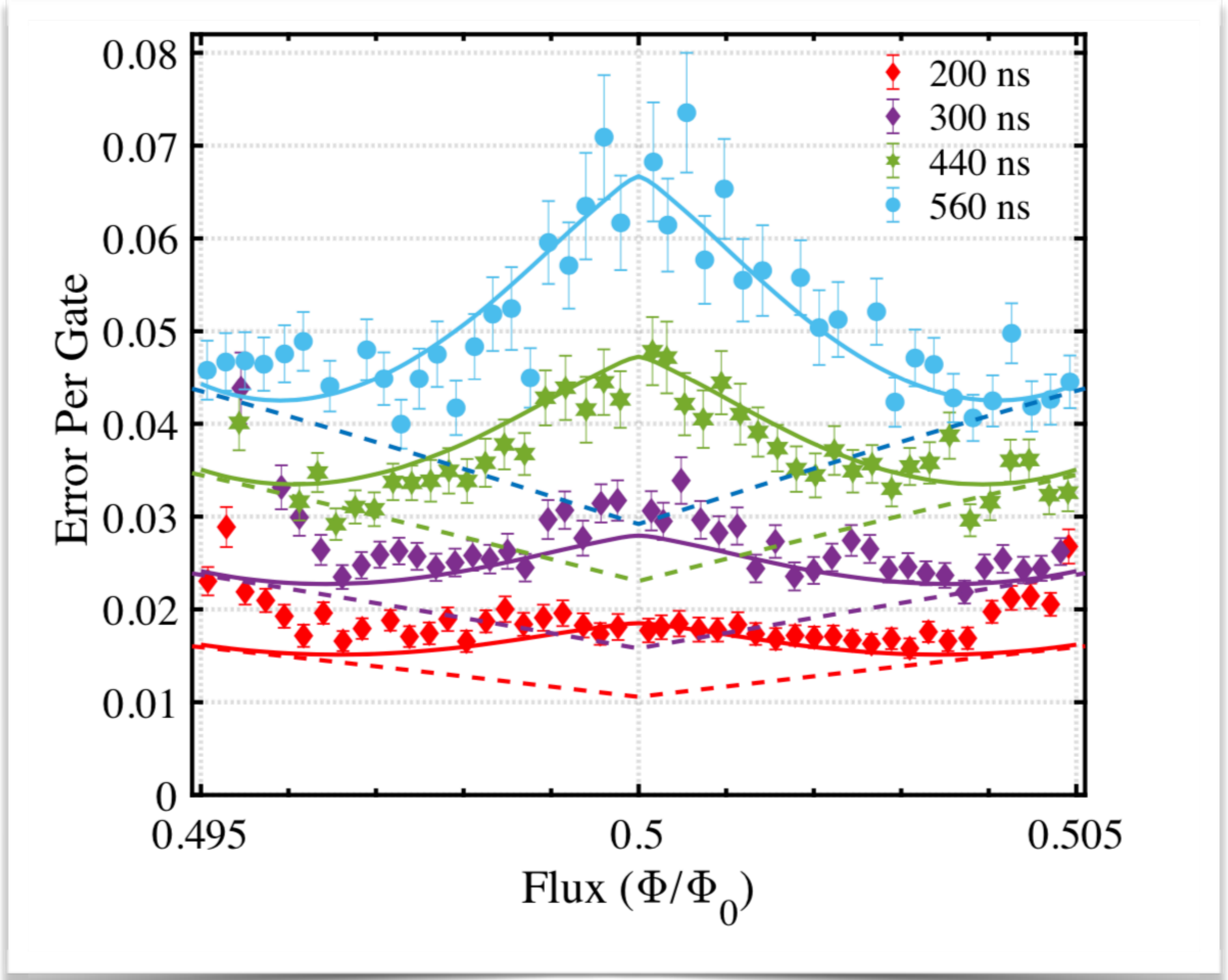


Average error per two-qubit gate:



Two-qubit gate / Summary

State-of-the-art high-fidelity, two-qubit gates in superconducting qubits / beginning 2020

Acronym[b]	Layout[c]	First demonstration [Year]	Highest fidelity [Year]	Gate time
CZ (ad.)	T–T	DiCarlo et al. (72) [2009]	99.4%[e] Barends et al. (3) [2014]	40 ns
			99.7%[e] Kjaergaard et al. (73) [2020]	60 ns
$\sqrt{\text{iSWAP}}$	T–T	Neeley et al. (81)[d] [2010]	90%[g] Dewes et al. (74) [2014]	31 ns
CR	F–F	Chow et al. (75)[h] [2011]	99.1%[e] Sheldon et al. (5) [2016]	160 ns
$\sqrt{\text{bSWAP}}$	F–F	Poletto et al. (76) [2012]	86%[g] Poletto et al. (76) [2012]	800 ns
MAP	F–F	Chow et al. (77) [2013]	87.2%[g] Chow et al. (75) [2011]	510 ns
CZ (ad.)	T–(T)–T	Chen et al. (55) [2014]	99.0%[e] Chen et al. (55) [2014]	30 ns
RIP	3D F	Paik et al. (78) [2016]	98.5%[e] Paik et al. (78) [2016]	413 ns
$\sqrt{\text{iSWAP}}$	F–(T)–F	McKay et al. (79) [2016]	98.2%[e] McKay et al. (79) [2016]	183 ns
CZ (ad.)	T–F	Caldwell et al. (80) [2018]	99.2%[e] Hong et al. (6) [2019]	176 ns
CNOT_{L}	BEQ-BEQ	Rosenblum et al. (13) [2018]	~99%[f] Rosenblum et al. (13) [2018]	190 ns
$\text{CNOT}_{\text{T-L}}$	BEQ-BEQ	Chou et al. (82) [2018]	79%[g] Chou et al. (82) [2018]	4.6 μs

M. Kjaergaard et al., "Superconducting qubits: Current state of play." *Annual Review of Condensed Matter Physics* 11 (2020): 369-395.