SAND2016-2008C

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Towards optimizing two-qubit operations in three-electron double quantum dots

Adam Frees
John King Gamble, Sebastian Mehl, Mark Friesen, and S.N. Coppersmith

The Laboratory for Physical Sciences

Sandia National Laboratories

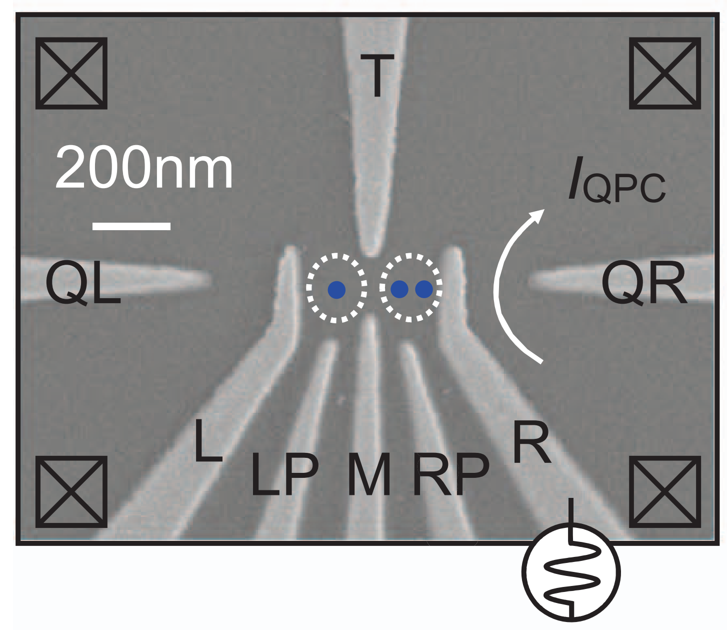
U.S. DEPARTMENT OF ENERGY

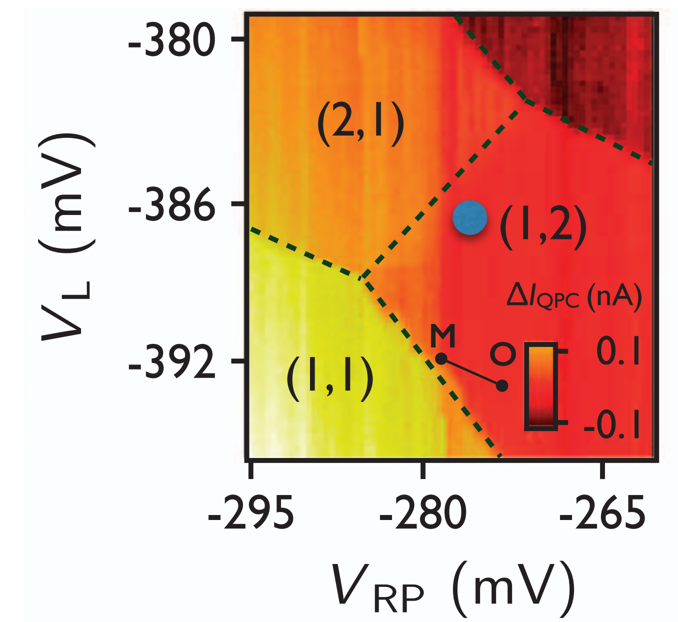
NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

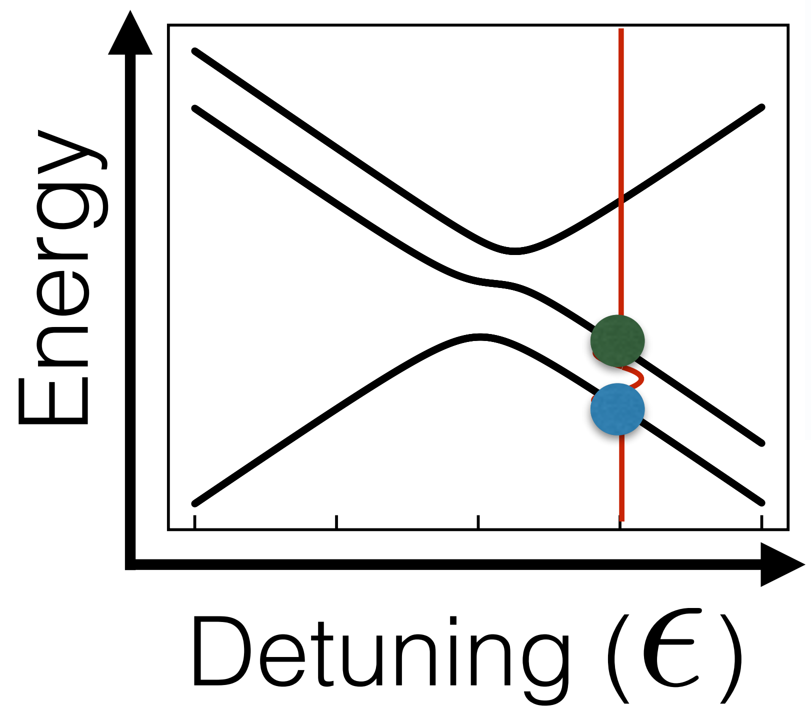
Quantum dot “hybrid” qubit has had experimental success

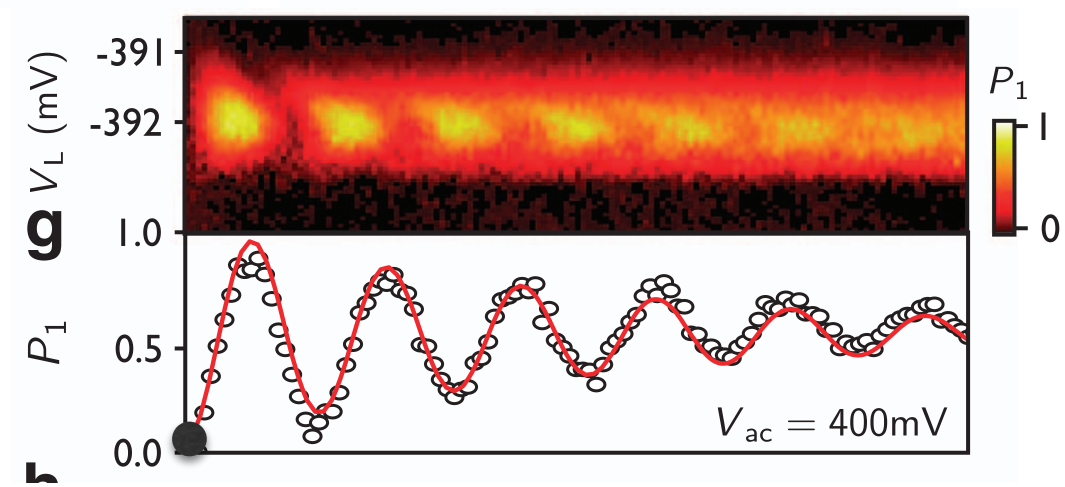
- The hybrid qubit consists of three electrons and two dots





- The sweet spot is very broad, which makes it fairly resistant to charge noise

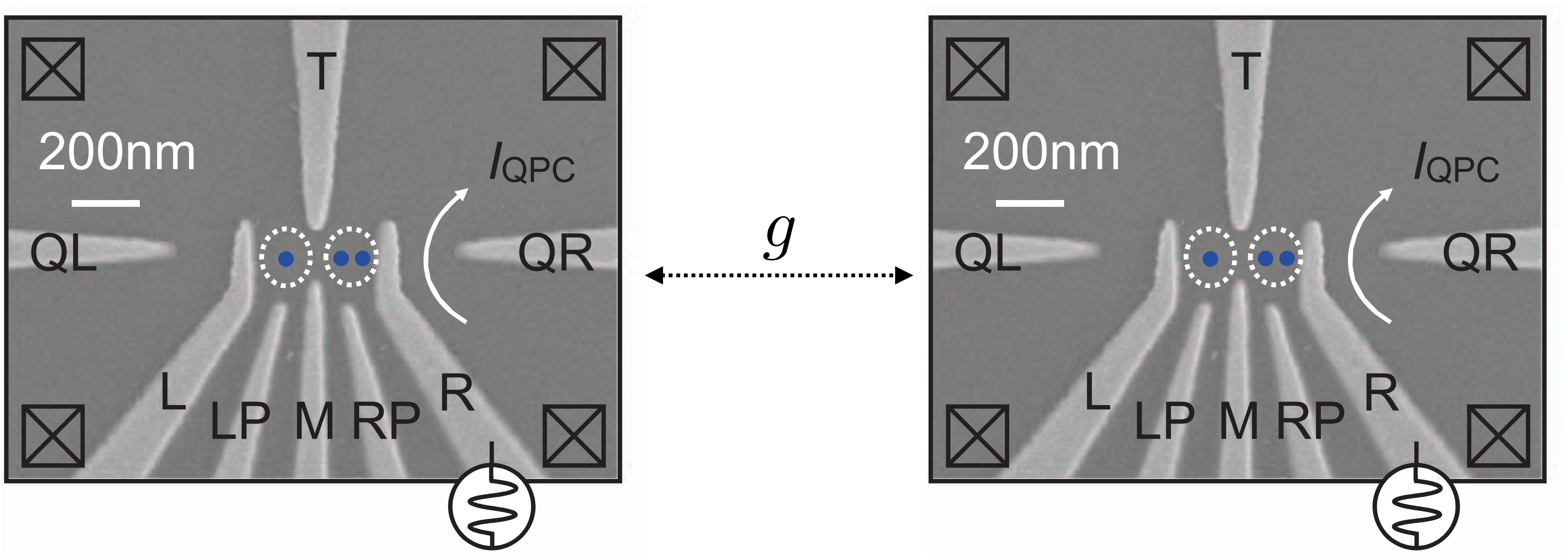




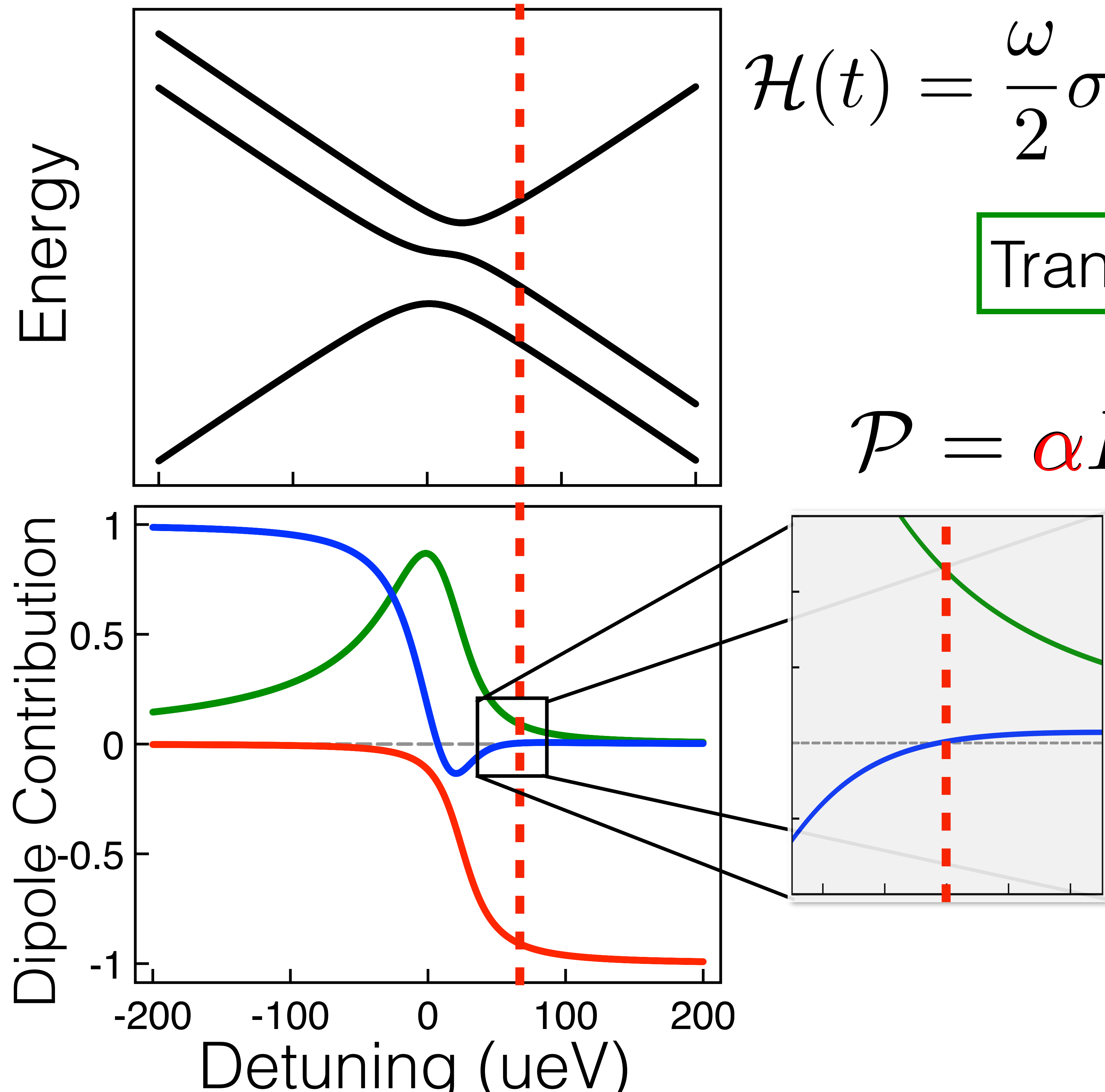
Dohun Kim, D. R. Ward, C. B. Simmons, D. E. Savage, M. G. Lagally, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson, npj Quant. Inf. 1, 15004 (2015).

Proposed approach: AC-driven capacitively coupled hybrid qubits

- Capacitively coupled hybrid qubits show promise as high-fidelity two-qubit system.
- It may be possible to tune the system parameters to extend the beneficial properties of the single-qubit operations to two-qubit operations.
- Here we focus on the weakly coupled limit, putting a lower bound on the resulting entangling gates.



Two-level systems have dipoles with longitudinal and transverse components



$$\mathcal{H}(t) = \frac{\omega}{2}\sigma_z + \mathcal{P}\sin(\omega_d t + \phi)$$

Transverse field

$$\mathcal{P} = \alpha I + \beta\sigma_x + \gamma\sigma_z$$

Longitudinal field

Capacitively coupled hybrid qubits in the weakly coupled limit

$$\mathcal{H} = \frac{\omega_1}{2}\sigma_z \otimes I + \frac{\omega_2}{2} I \otimes \sigma_z + g\mathcal{P}^{(1)} \otimes \mathcal{P}^{(2)}$$

↓ Take coupling to first order

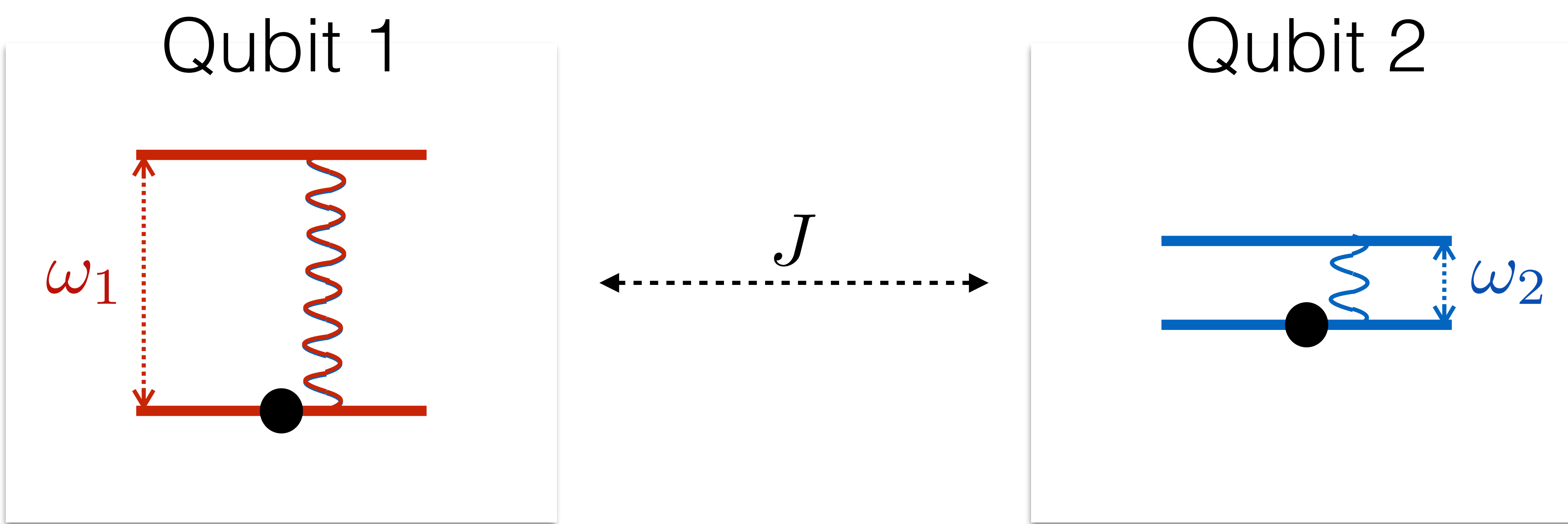
$$\mathcal{H} = \left(\frac{\omega_1}{2} + g\alpha^{(2)}\gamma^{(1)}\right)\sigma_z \otimes I + \left(\frac{\omega_2}{2} + g\alpha^{(1)}\gamma^{(2)}\right) I \otimes \sigma_z + \\ + g\left(\beta^{(1)}\sigma_x + \gamma^{(1)}\sigma_z\right) \otimes \left(\beta^{(2)}\sigma_x + \gamma^{(2)}\sigma_z\right)$$

↓ Remove single-qubit longitudinal field

$$\mathcal{H} = \frac{\omega_1}{2}\sigma_z \otimes I + \frac{\omega_2}{2} I \otimes \sigma_z + g\beta^{(1)}\beta^{(2)}\sigma_x \otimes \sigma_x$$

The "cross-resonant" Hamiltonian is an ideal coupled system

$$\mathcal{H} = \frac{\omega_1}{2}\sigma_z \otimes I + \frac{\omega_2}{2} I \otimes \sigma_z + J\sigma_x \otimes \sigma_x$$

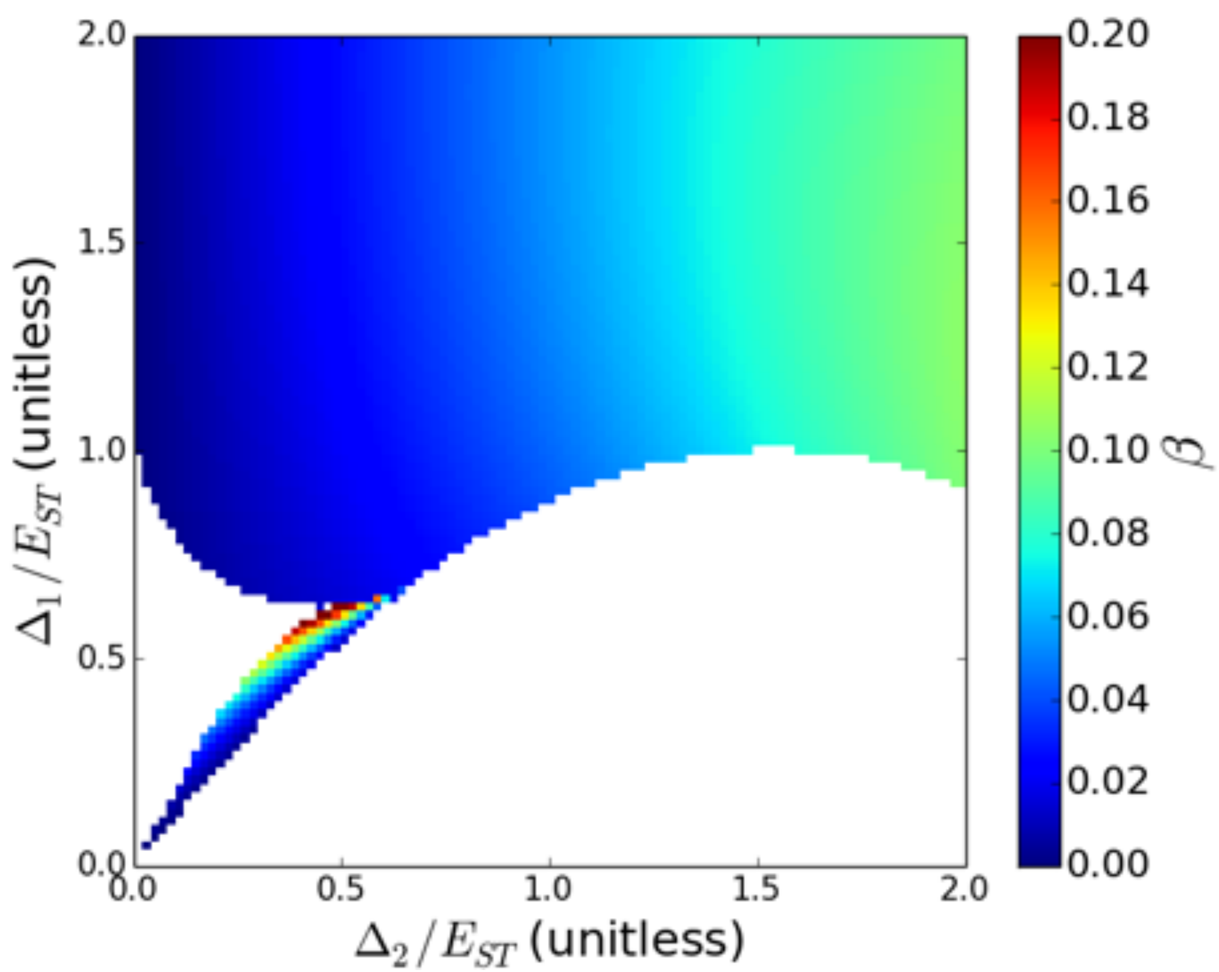


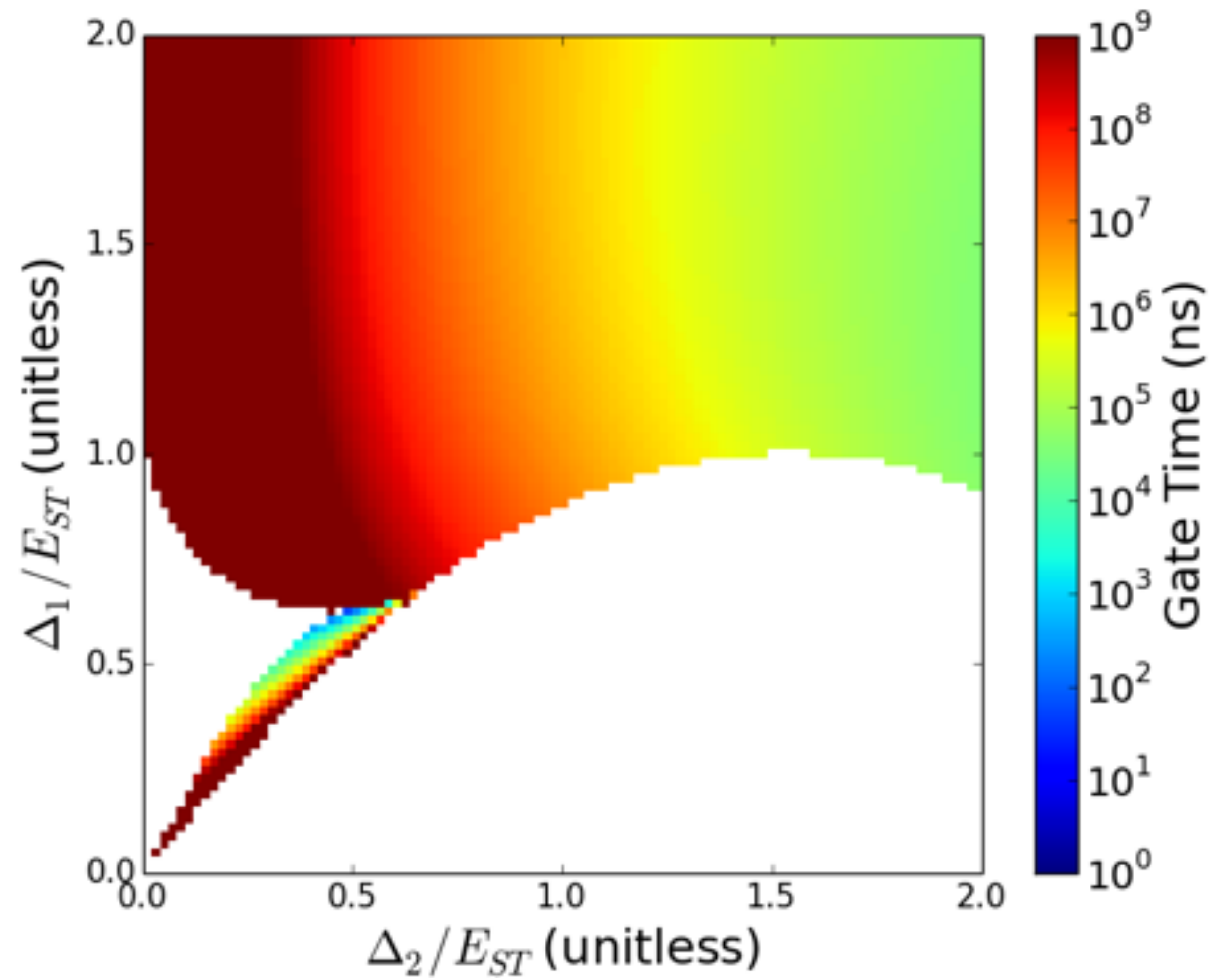
C. Rigetti, A. Blais, and M. Devoret, PRL **94**, 240502 (2005)

J.M. Chow, A.D. Córcoles, J.M. Gambetta, C. Rigetti, B.R. Johnson, J.A. Smolin, J.R. Rozen, G.A. Keefe, M.B. Rothwell, M.B. Ketchen, and M. Steffen, PRL **107**, 080502 (2011)

Small cross-resonant matrix element means slow entangling gate

- Cross-resonant matrix element is $\sim \dfrac{g}{(\omega_1 - \omega_2)}\beta^3$
- For weak coupling approximation to hold, $\beta^3 \gg \dfrac{g}{(\omega_1 - \omega_2)}$





Strong coupling regime has faster gate times, is more complicated

- We can expand in the inverse of the energy separation between the logical and leakage states

- Single qubit operations are second order interactions, entangling operations are fourth order

- β^3 is sixth order, therefore it does not dominate other two-qubit interactions

Thank You!

Additional Slides

Dipole operators are useful diagnostic tools

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Dipole operators

$$\mathcal{H} = \mathcal{H}_0 + \frac{\epsilon^{(1)}}{2}\mathcal{P}^{(1)} + \frac{\epsilon^{(2)}}{2}\mathcal{P}^{(2)}$$

depends on e.g.

$$\Delta_1^{(1)}, \Delta_2^{(1)}, \Delta_1^{(2)}, \Delta_2^{(2)}, E_{ST}^{(1)}, E_{ST}^{(2)}, g$$

Properties of Dipole:

- $\langle \Psi_i | \mathcal{P}^{(j)} | \Psi_i \rangle = \frac{\partial E_i}{\partial \epsilon^{(j)}}$ is a measure of dephasing due to charge noise
- $\langle \Psi_i | \mathcal{P}^{(j)} | \Psi_l \rangle$ is inversely proportional to the Rabi frequency

The "cross-resonant" Hamiltonian is an ideal coupled system

- In the coupled eigenbasis, the cross-resonant Hamiltonian takes the form:

$$\mathcal{H} = \frac{\omega_1}{2}\sigma_z \otimes I + \frac{\omega_2}{2} I \otimes \sigma_z + J\sigma_x \otimes \sigma_x$$

- With the dipoles:

$$\mathcal{P}_1 = \sigma_x \otimes I \qquad\qquad \mathcal{P}_2 = I \otimes \sigma_x$$

- Which means that in the eigenbasis,

$$\mathcal{P}_1 = \cos\left(\theta_+\right)\sigma_x \otimes I + \sin\left(\theta_+\right)\sigma_z \otimes \sigma_x$$

$$\mathcal{P}_2 = \cos\left(\theta_-\right) I \otimes \sigma_x + \sin\left(\theta_-\right)\sigma_x \otimes \sigma_z$$

- with:

$$\theta_+ = \frac{\theta_1 + \theta_2}{2} \quad \theta_- = \frac{\theta_2 - \theta_1}{2} \quad \tan\theta_1 = \frac{2J}{\omega_1 + \omega_2} \quad \tan\theta_2 = \frac{2J}{\omega_1 - \omega_2}$$

WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON

Small cross-resonant matrix element means slow entangling gate

$$\mathcal{H} = \frac{\omega_1}{2}\sigma_z \otimes I + \frac{\omega_2}{2} I \otimes \sigma_z + g\beta^{(1)}\beta^{(2)}\sigma_x \otimes \sigma_x$$

Diagonalize, take coupling to first order

$$\mathcal{P}^{(1)} = \alpha^{(1)} I + \beta^{(1)}\sigma_x \otimes I + g\frac{2\omega_1\left(\beta^{(1)}\right)^2\beta^{(2)}}{\left(\omega_1^2 - \omega_2^2\right)}\sigma_z \otimes \sigma_x$$

$$\mathcal{P}^{(2)} = \alpha^{(2)} I + \beta^{(2)} I \otimes \sigma_x + g\frac{2\omega_2\beta^{(1)}\left(\beta^{(2)}\right)^2}{\left(\omega_1^2 - \omega_2^2\right)}\sigma_x \otimes \sigma_z$$

Entangling gate far too slow! (~0.1 s)