SAND2017-8721C

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Adiabatically-controlled two-qubit gates using quantum dot hybrid qubits

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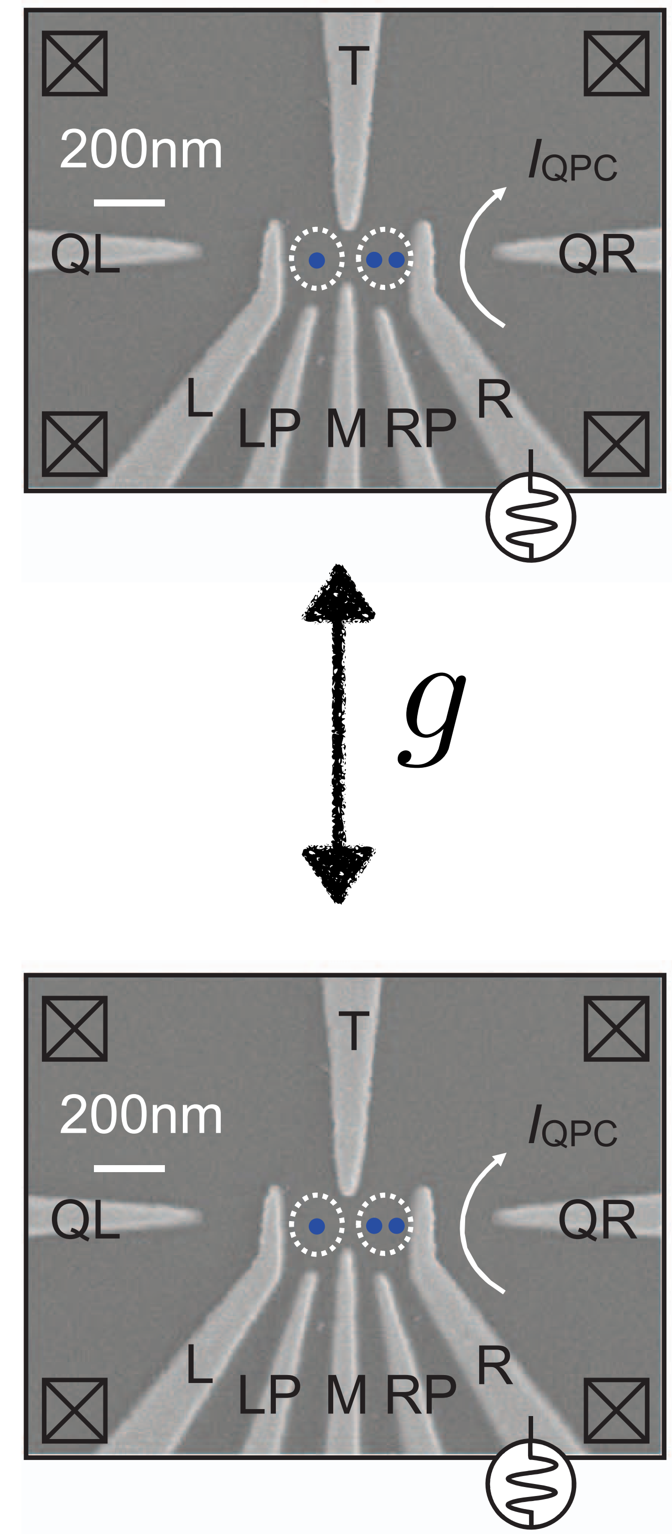
Introducing a control scheme for capacitively coupled QDHQs

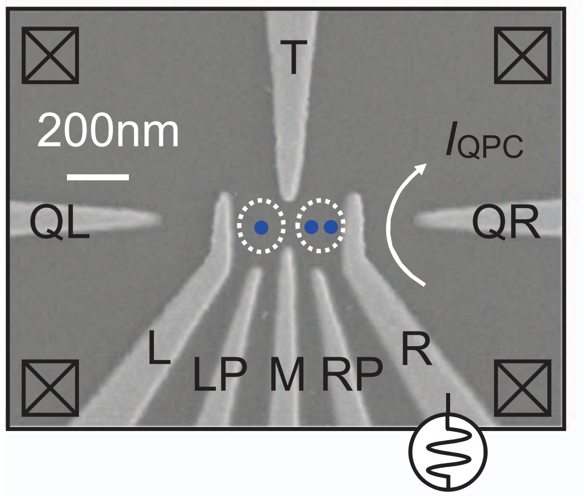
- Given two capacitively coupled quantum dot "hybrid" qubits (QDHQs), we propose an entanglement gate which only requires adiabatic control of detunings

- We show that these entanglement gates are robust under charge noise



Device by C. B. Simmons

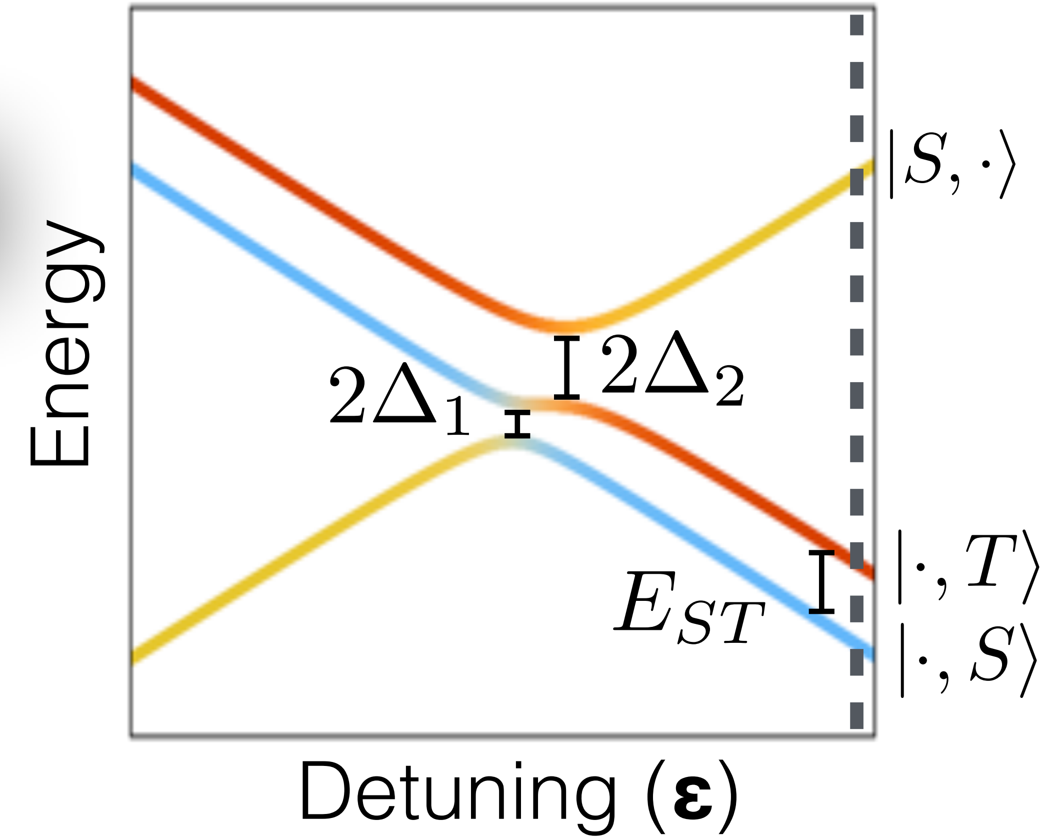
Quantum dot “hybrid” qubit has a tunable qubit dipole

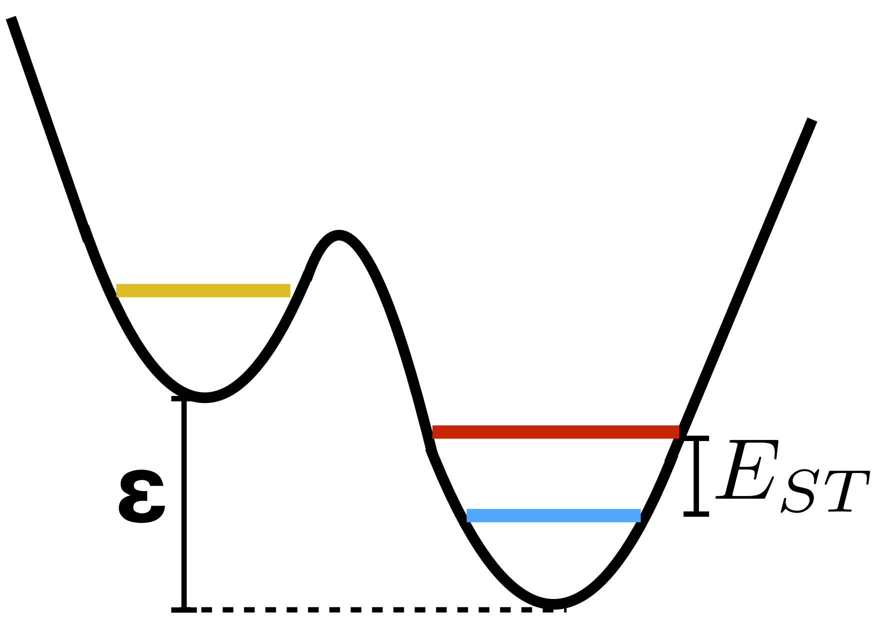


Device by C. B. Simmons

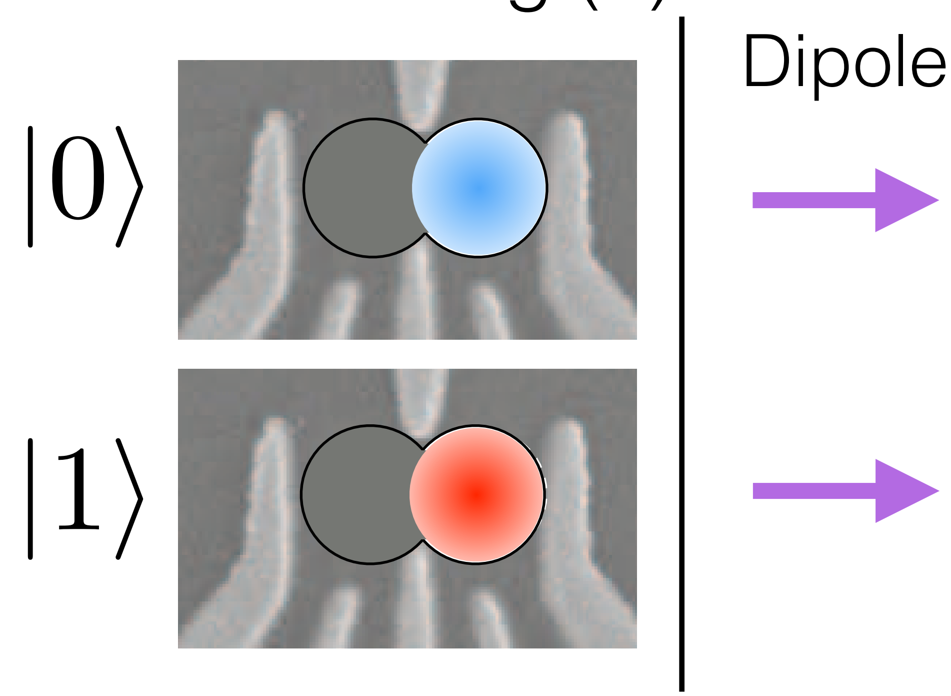
Large detuning

Effective dipole difference ~0

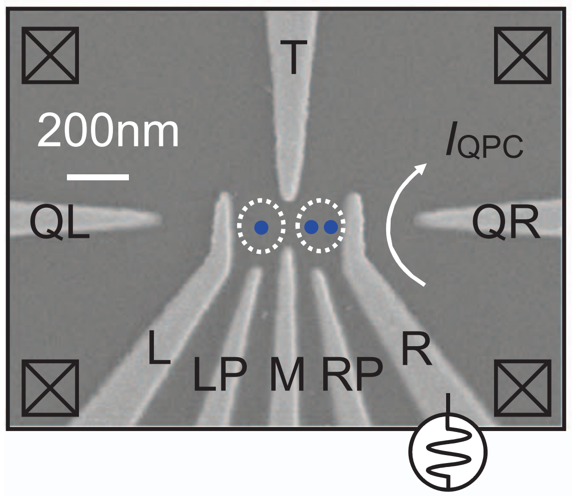




Electron position is the same for both states



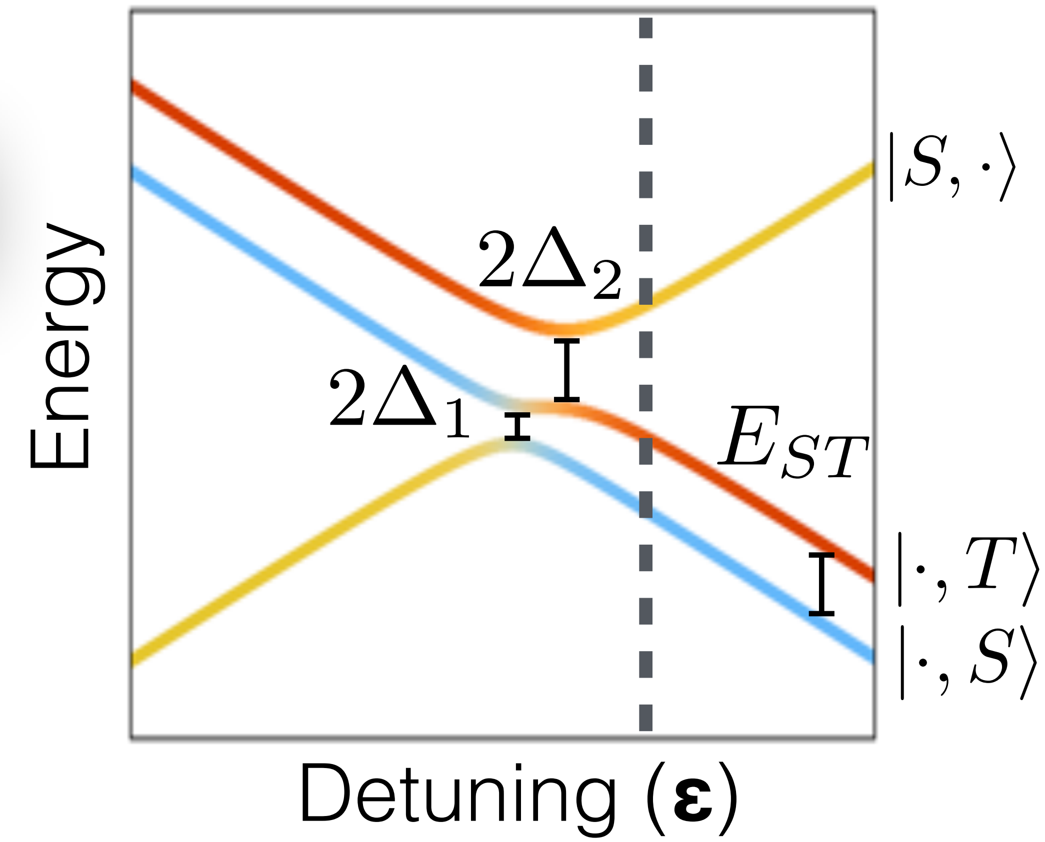
Quantum dot “hybrid” qubit has a tunable qubit dipole

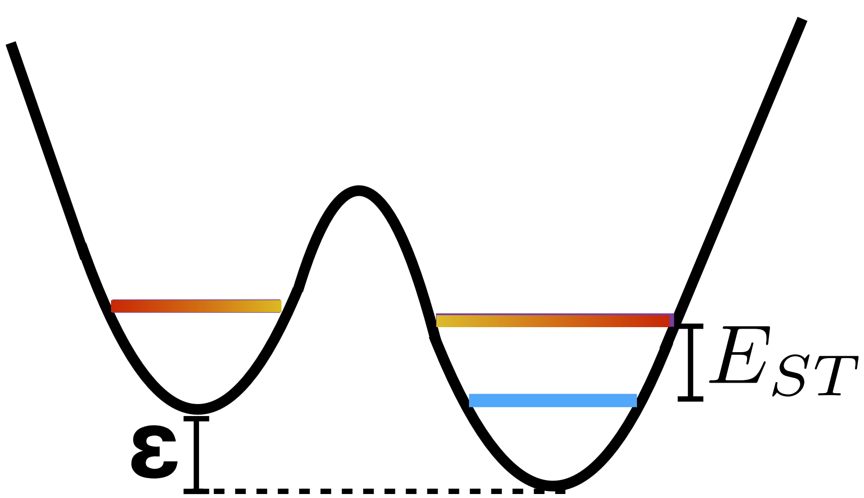


Device by C. B. Simmons

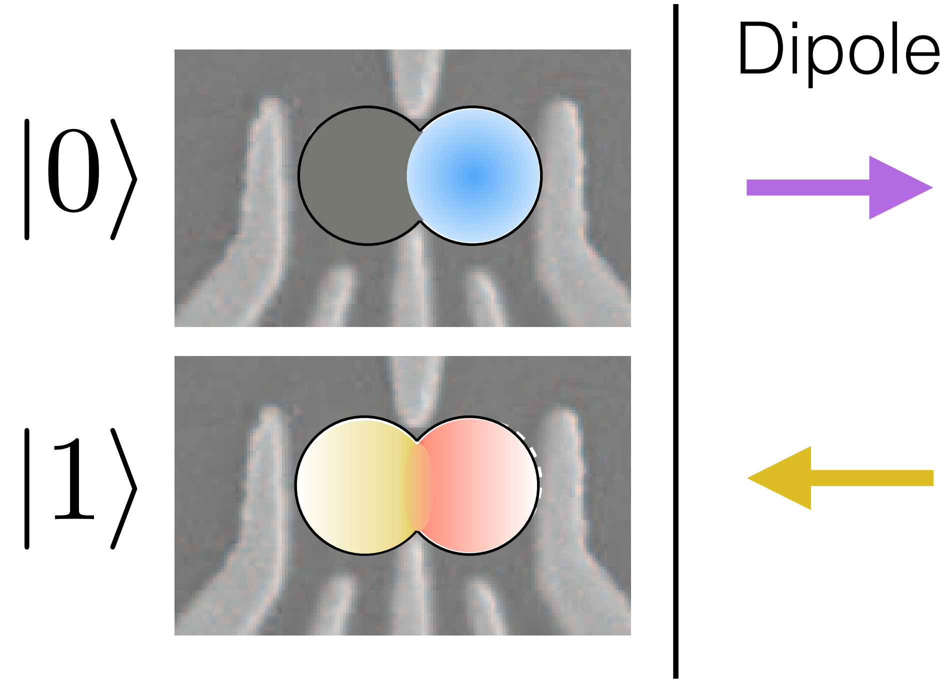
Smaller detuning

Effective dipole difference ≠0

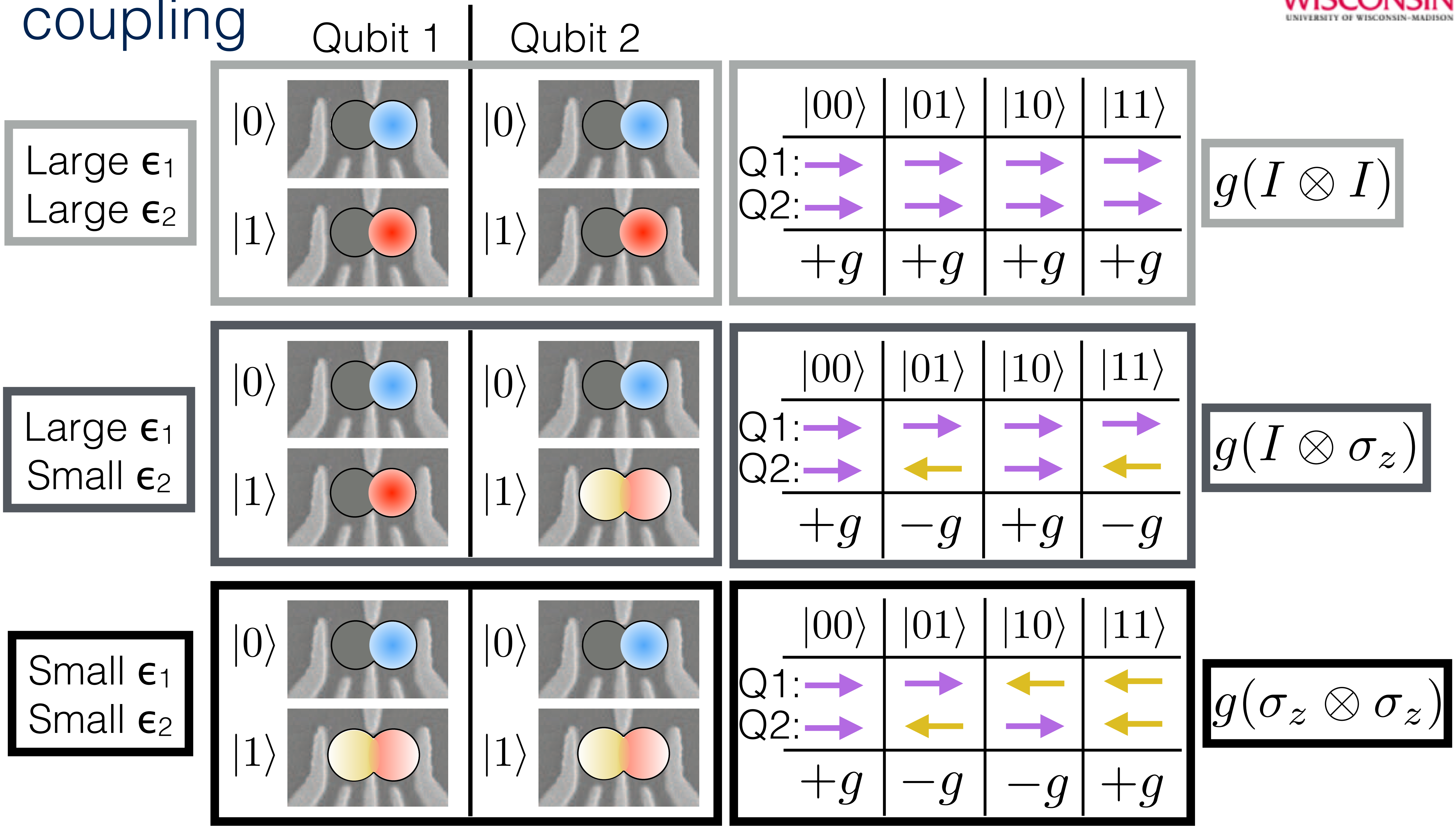




Electron position is different for each state



Changes in detuning yield a tunable effective coupling



Similar to S-T qubits: M. D. Shulman *et al.*, Science **336** (6078), 202-205 (2012).

Adiabatic changes yield only Z1, Z2, and ZZ (entangling) gates

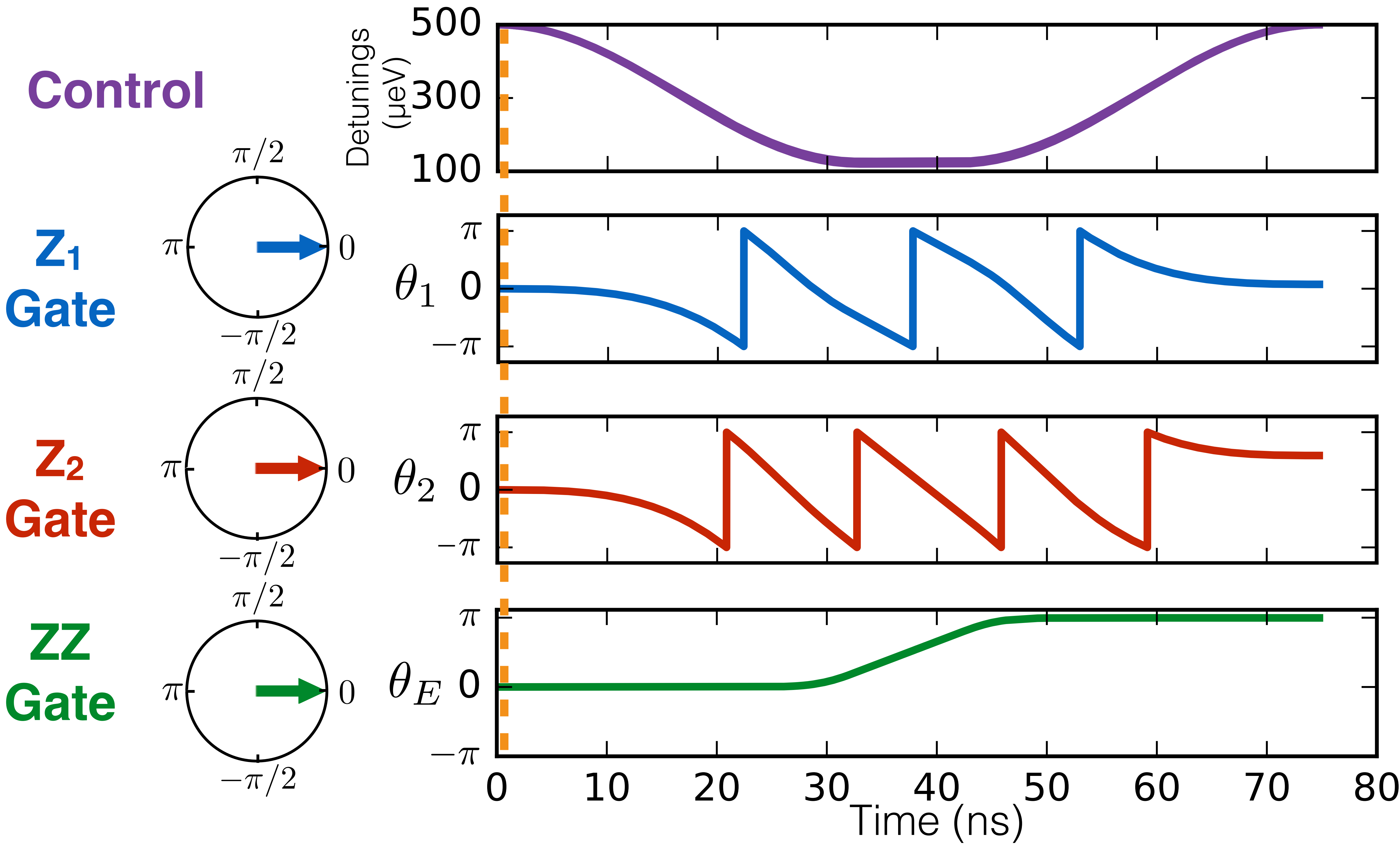
An adiabatic process will only affect the phases of a state (in the adiabatic basis):

$$\begin{matrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{matrix} \begin{pmatrix} \alpha_{00} \\ \alpha_{01} \\ \alpha_{10} \\ \alpha_{11} \end{pmatrix} \xrightarrow{\text{adiabatic process}} \begin{pmatrix} \alpha_{00}\, e^{(i(-\theta_1-\theta_2+\theta_E)/2)} \\ \alpha_{01}\, e^{(i(\theta_1-\theta_2-\theta_E)/2)} \\ \alpha_{10}\, e^{(i(-\theta_1+\theta_2-\theta_E)/2)} \\ \alpha_{11}\, e^{(i(\theta_1+\theta_2+\theta_E)/2)} \end{pmatrix}$$

θ_1	θ_2	θ_E
Z_1 Gate	Z_2 Gate	ZZ Gate

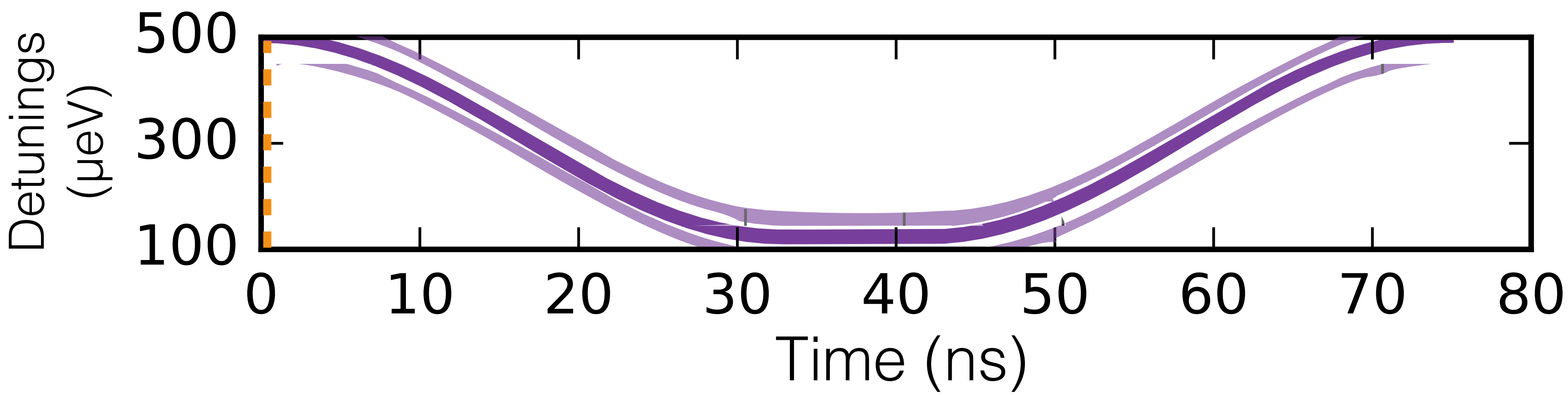
Want: $\theta_E = \pi$

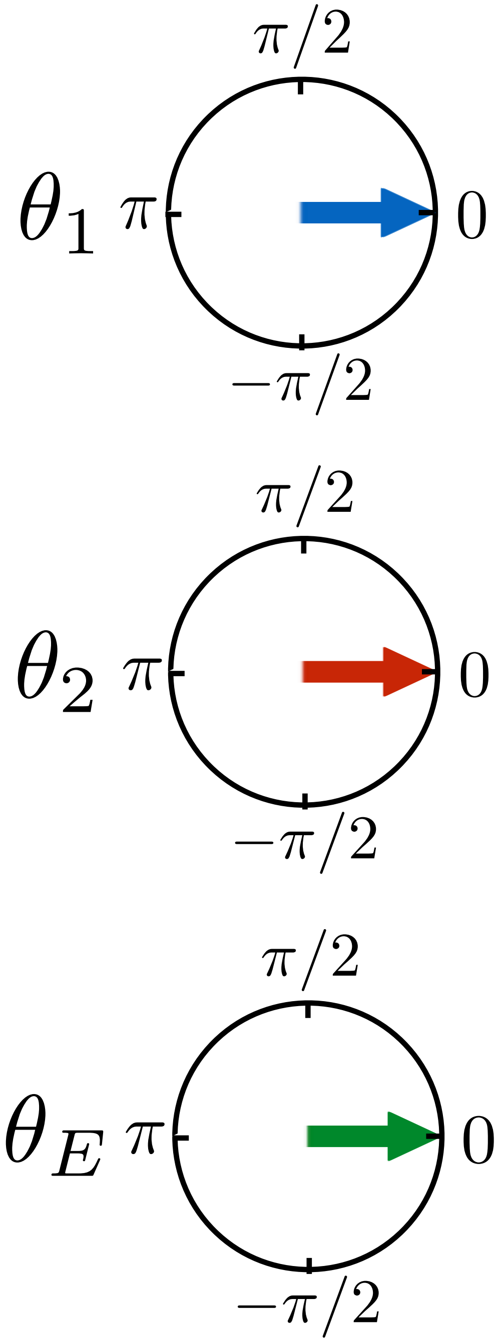
Operating a controlled-Z gate in capacitively coupled QDHQ system



We consider the effect of quasistatic charge noise on two-qubit gate fidelities

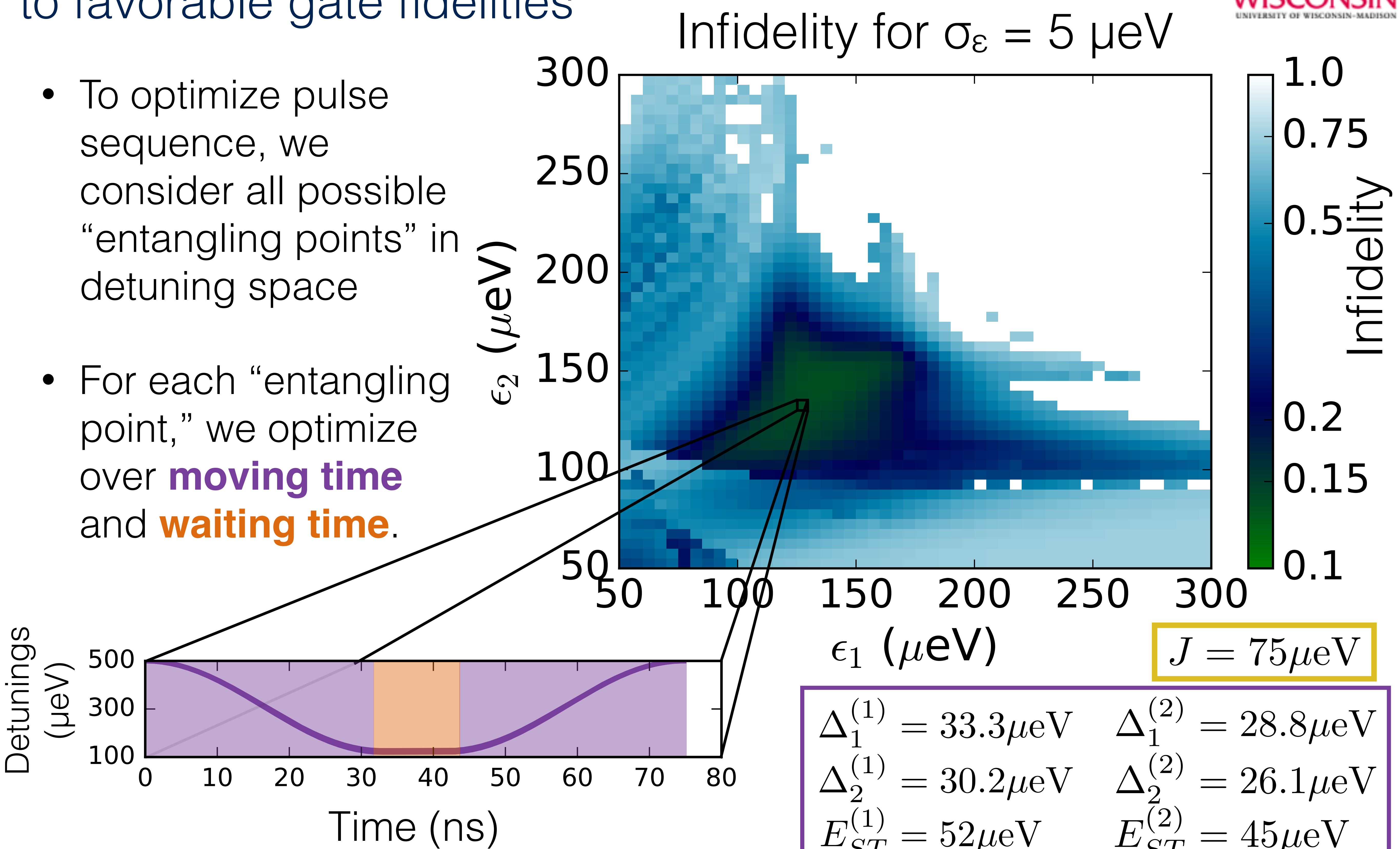
- Low-frequency charge noise will dominate the noise spectrum.
- This leads to dephasing (of Z_1, Z_2, and ZZ)





A numerical search for optimal pulse sequence leads to favorable gate fidelities

- To optimize pulse sequence, we consider all possible "entangling points" in detuning space
- For each "entangling point," we optimize over **moving time** and **waiting time**.



$J = 75\mu\text{eV}$

$\Delta_1^{(1)} = 33.3\mu\text{eV}$ $\Delta_1^{(2)} = 28.8\mu\text{eV}$

$\Delta_2^{(1)} = 30.2\mu\text{eV}$ $\Delta_2^{(2)} = 26.1\mu\text{eV}$

$E_{ST}^{(1)} = 52\mu\text{eV}$ $E_{ST}^{(2)} = 45\mu\text{eV}$

For chosen parameters gate achieves 90% fidelity at ~4 μeV charge noise, 99% at ~1 μeV

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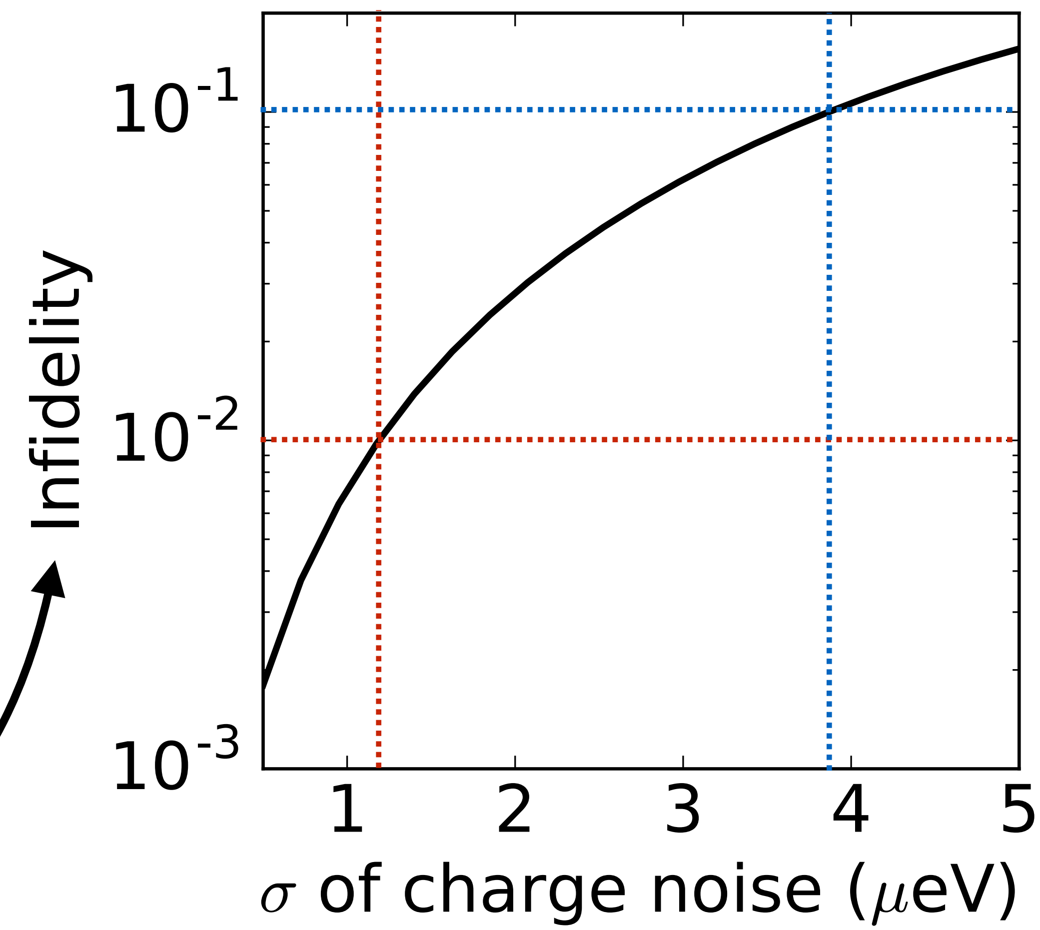
- Introduce quasistatic noise on both detunings, taken from gaussian distribution with some σ.
- Calculate resulting average process fidelity A. Gilchrist, N. K. Langford, and M. A. Nielsen, arXiv:quant-ph/0408063.

$$F \equiv \mathrm{Tr}\left(\chi_{ideal}\chi^{\dagger}_{real}\right)$$



- Achieve 90% fidelity at σ ≈ 4 μeV, 99% at σ ≈ 1 μeV

D. R. Ward *et al. npj Quant. Inf.* ***2****, 16032 (2016)*

$J = 75\mu\text{eV}$

$\Delta_1^{(1)} = 33.3\mu\text{eV}$	$\Delta_1^{(2)} = 28.8\mu\text{eV}$
$\Delta_2^{(1)} = 30.2\mu\text{eV}$	$\Delta_2^{(2)} = 26.1\mu\text{eV}$
$E_{ST}^{(1)} = 52\mu\text{eV}$	$E_{ST}^{(2)} = 45\mu\text{eV}$

Summary

The proposed coupling scheme:

- Allows for static, non-equal qubit frequencies: *in the simulations here,* $\omega_1 = (52\ \mu eV)/\hbar$, $\omega_2 = (45\ \mu eV)/\hbar$

- Compatible with pre-existing single-qubit control schemes: *lowering detuning on only one qubit does not turn on coupling*

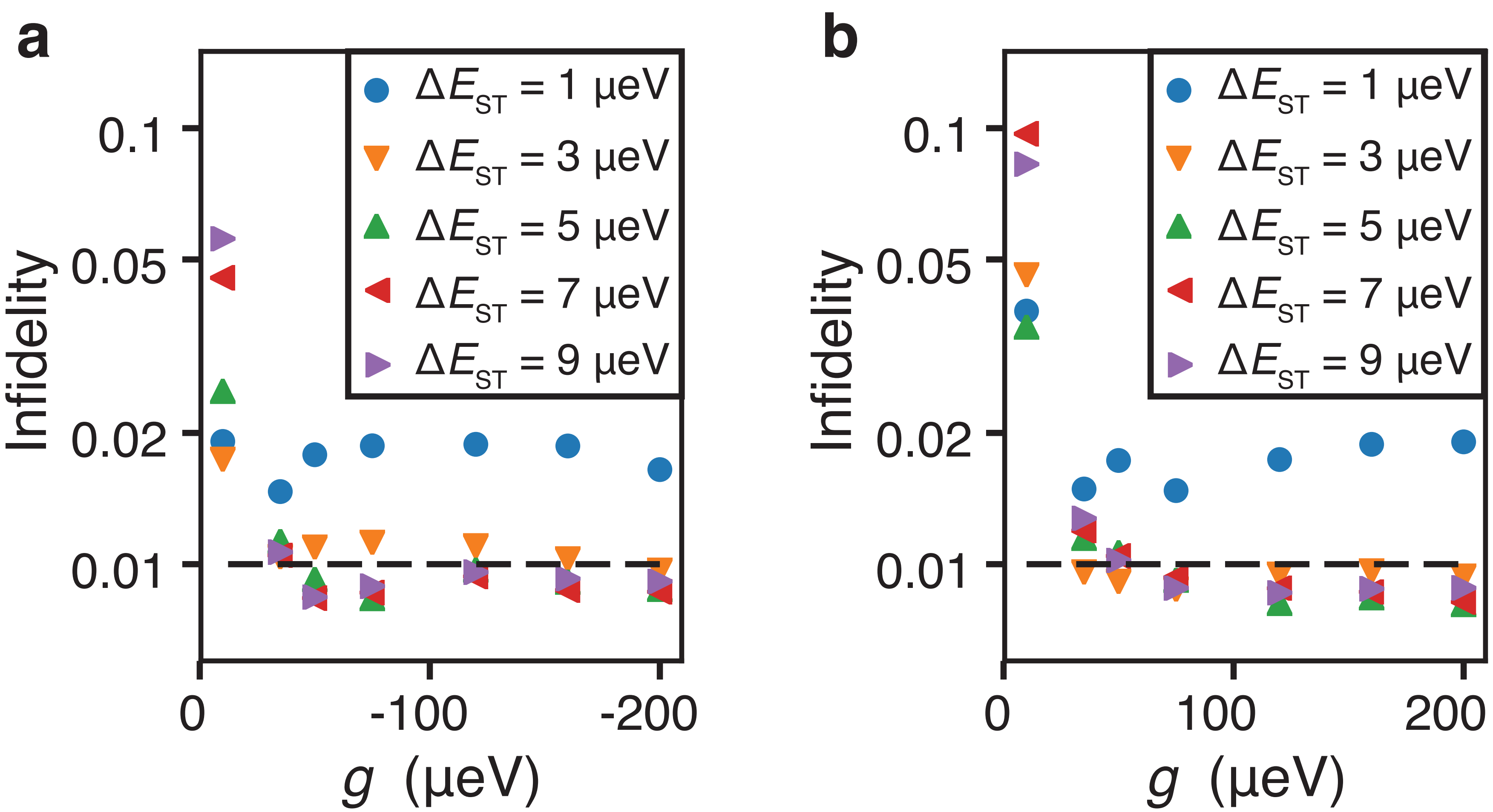
- Only requires adiabatic control of detunings: *induces* Z_1, Z_2, *and ZZ gates*

- Relatively robust under charge noise: *90% fidelity at ~4 μeV charge noise, 99% at ~1 μeV*

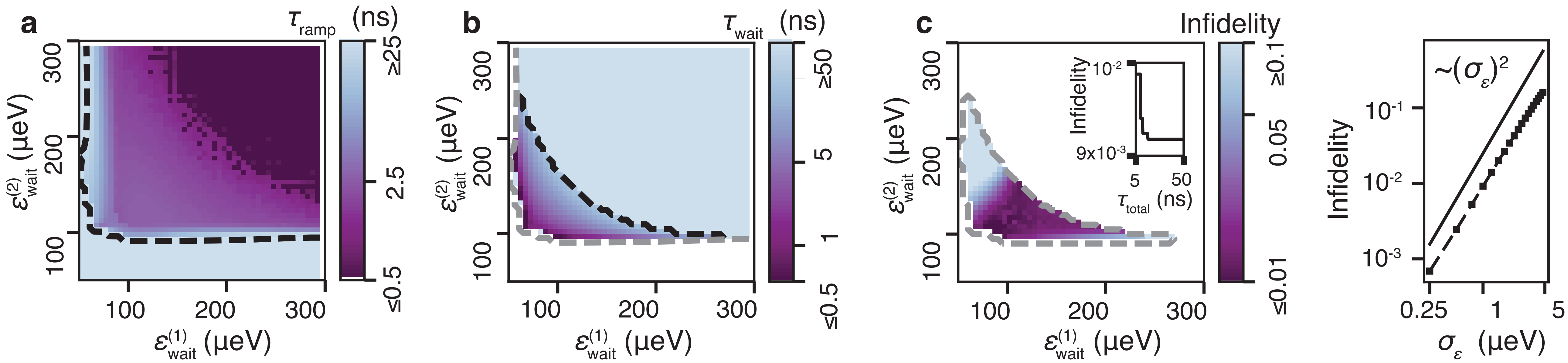
Thank you!

Additional slides

Small g and ΔE_{ST} lead to drop in fidelity



Search algorithm steps



$$\omega_g = 8g\frac{\left(g-\varepsilon^{(1)}-\varepsilon^{(2)}\right)\prod_{i=1,2}\left(\left(\Delta_1^{(i)}\right)^2-\left(\Delta_2^{(i)}\right)^2\right)}{\left(g-2\varepsilon^{(1)}\right)^2\left(g-2\varepsilon^{(2)}\right)^2\left(\varepsilon^{(1)}+\varepsilon^{(2)}\right)}$$

Optimizing single qubit dispersion

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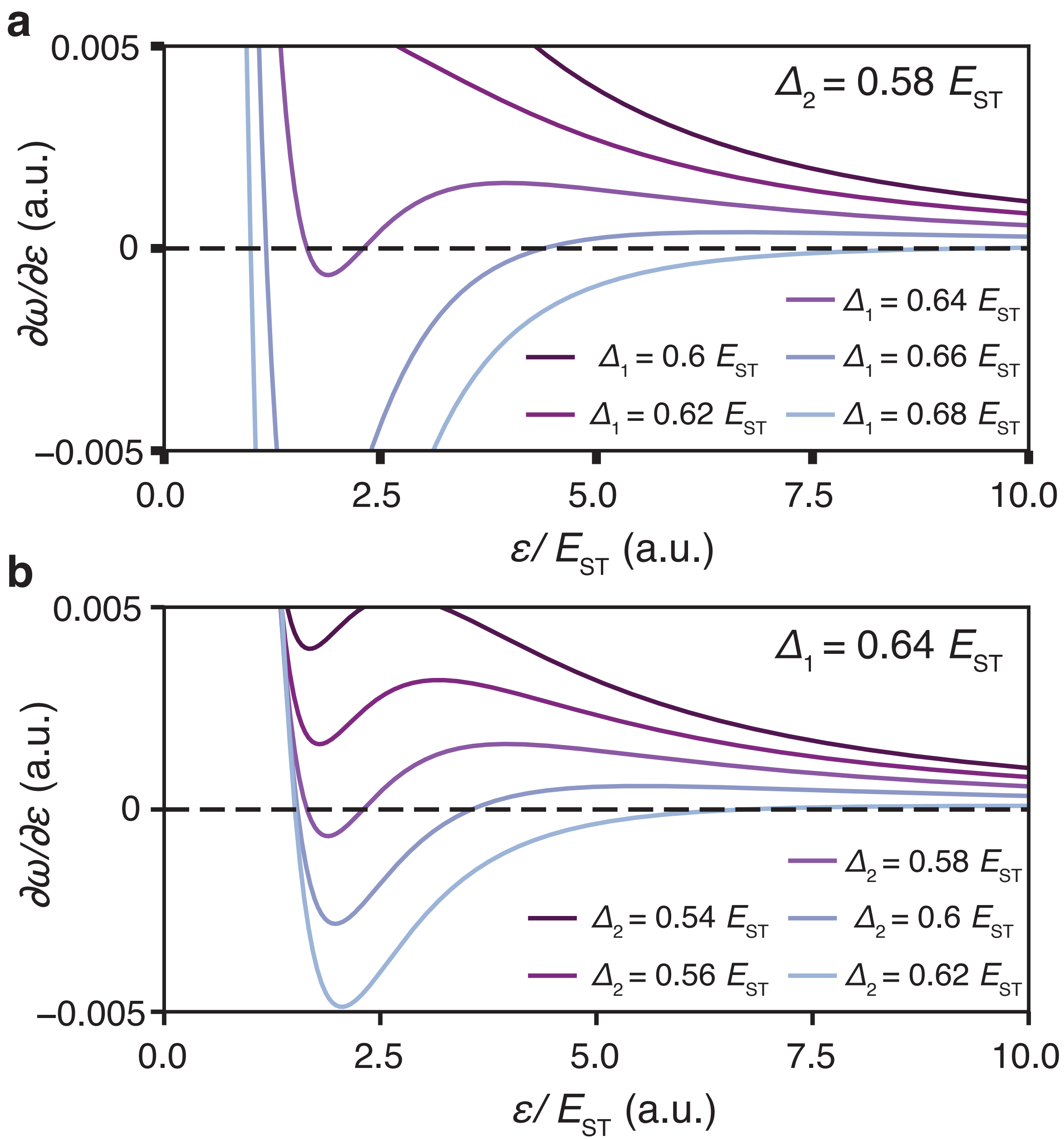
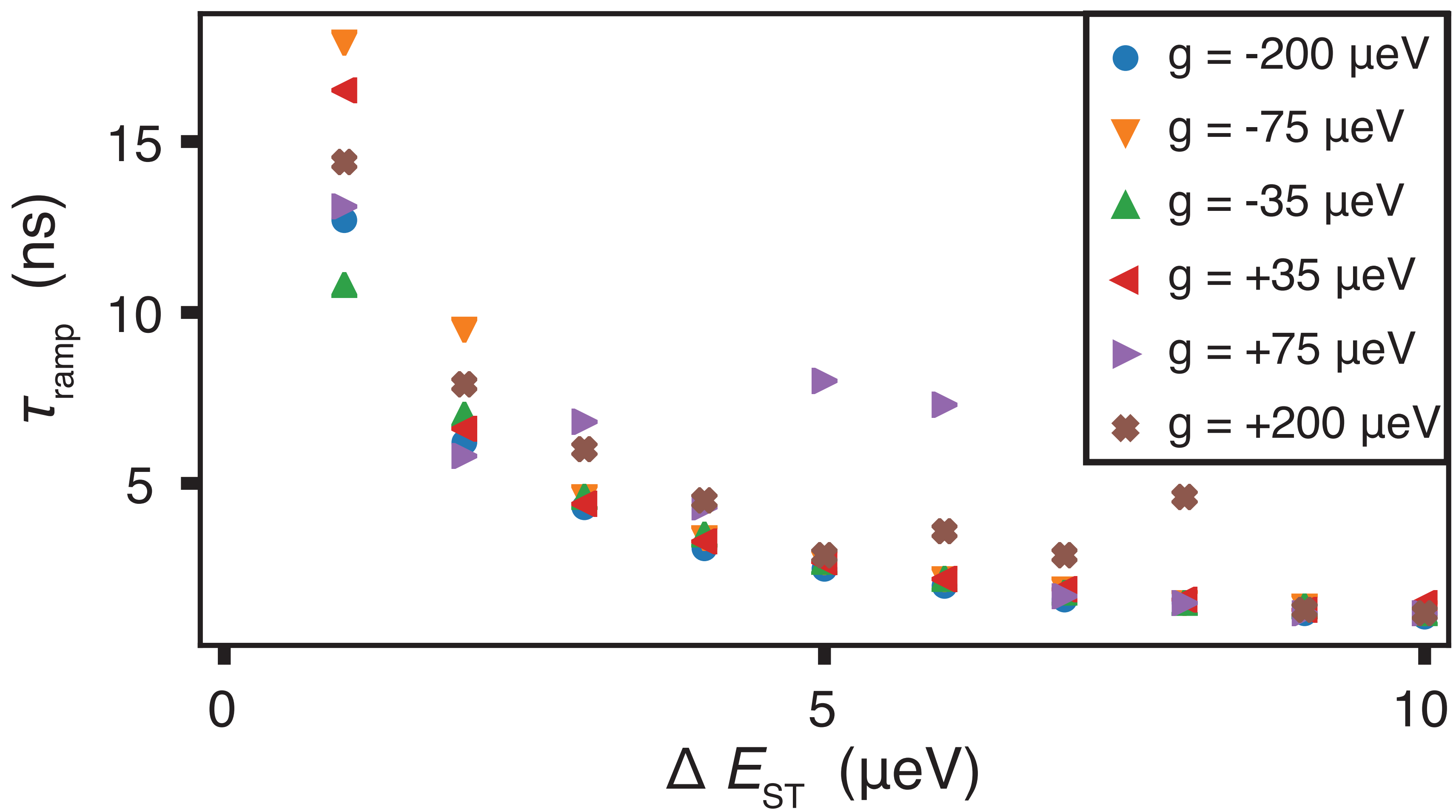


Ramp times as a function of ΔE_{ST}



Capacitive coupling in two charge qubits leads to a static coupling

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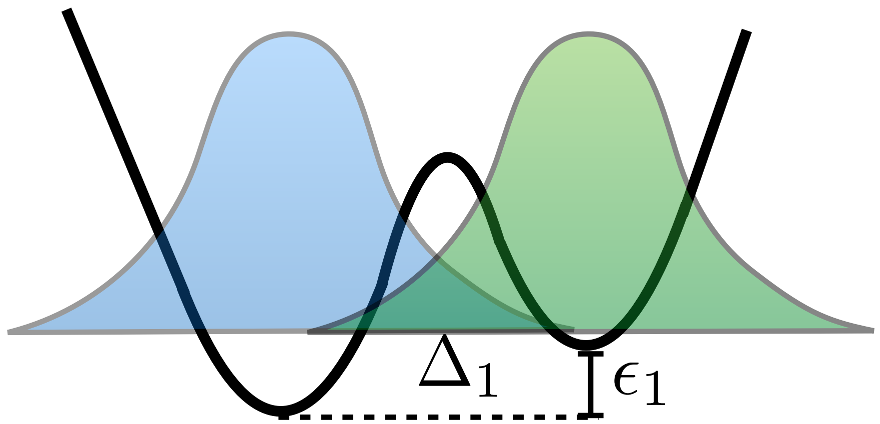
One qubit



$$\mathcal{H} = \epsilon_1 \sigma_z + \Delta_1 \sigma_x$$

Two qubits

$$\mathcal{H} =$$

$$\epsilon_1 \sigma_z \otimes I + \Delta_1 \sigma_x \otimes I +$$

$$\epsilon_2 I \otimes \sigma_z + \Delta_2 I \otimes \sigma_x +$$

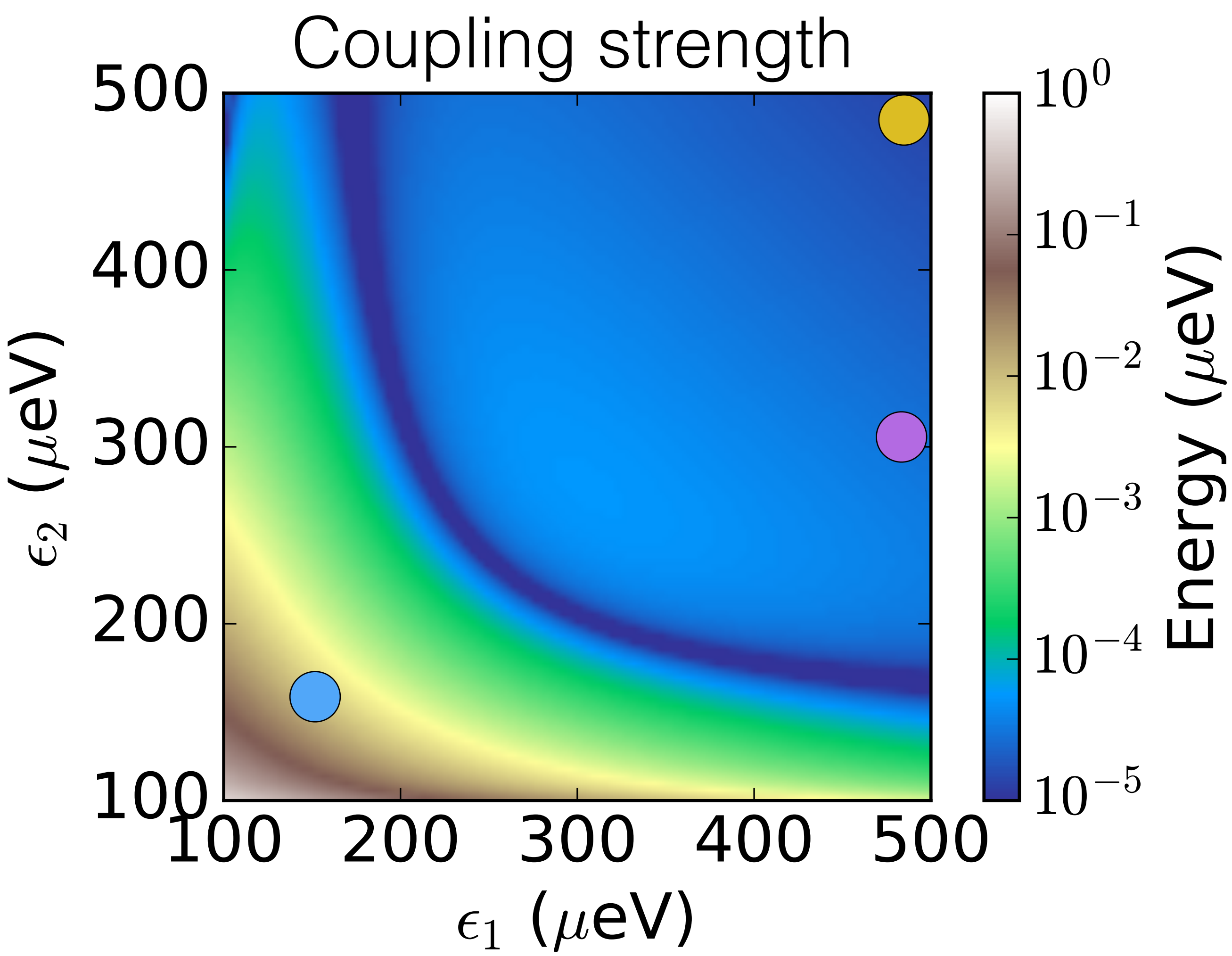
$$g\sigma_z \otimes \sigma_z$$?

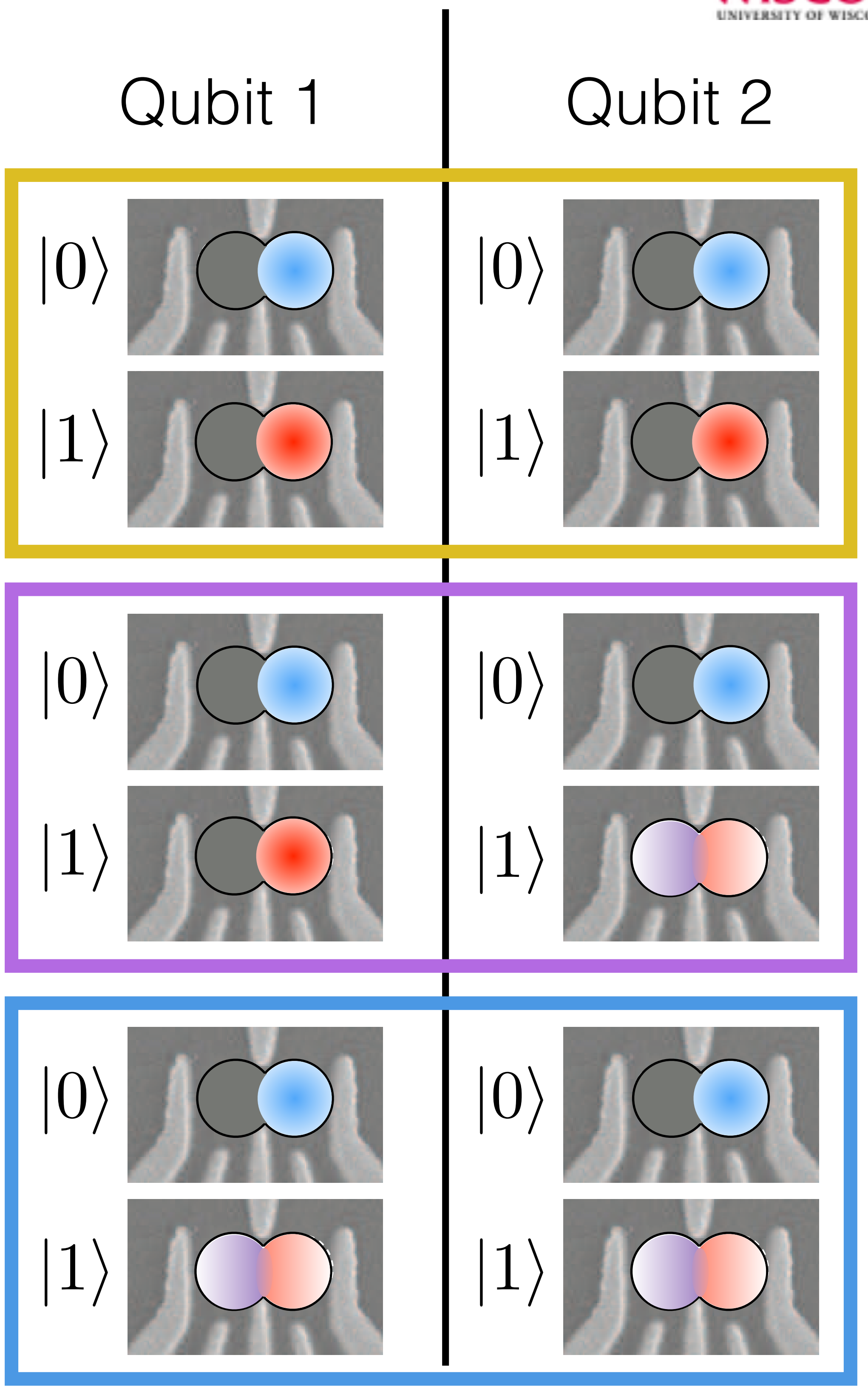
What is the coupling term between 2 capacitively-coupled charge qubits?

Li, H.-O., *et al.* Nature Comm. **6**, 7681 (2015).

Changes in detuning yield a tunable effective coupling

- By changing detuning, we can change the rate of entanglement, as in S-T qubits M. D. Shulman *et al.*, Science **336** (6078), 202-205 (2012).

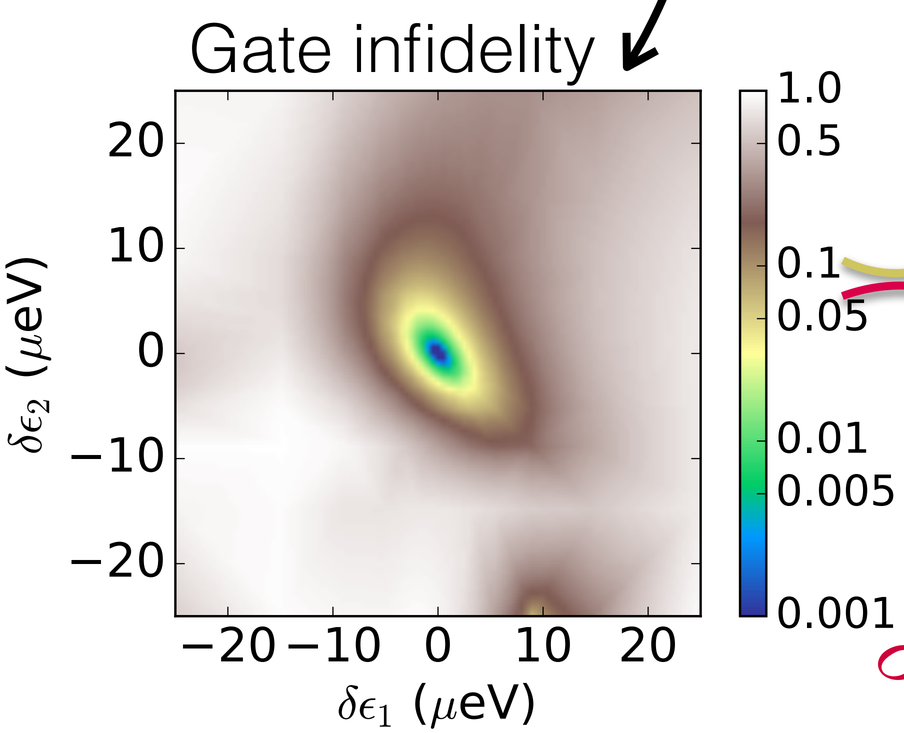




For chosen parameters gate achieves 90% fidelity at ~4ueV charge noise, 99% at ~1 ueV

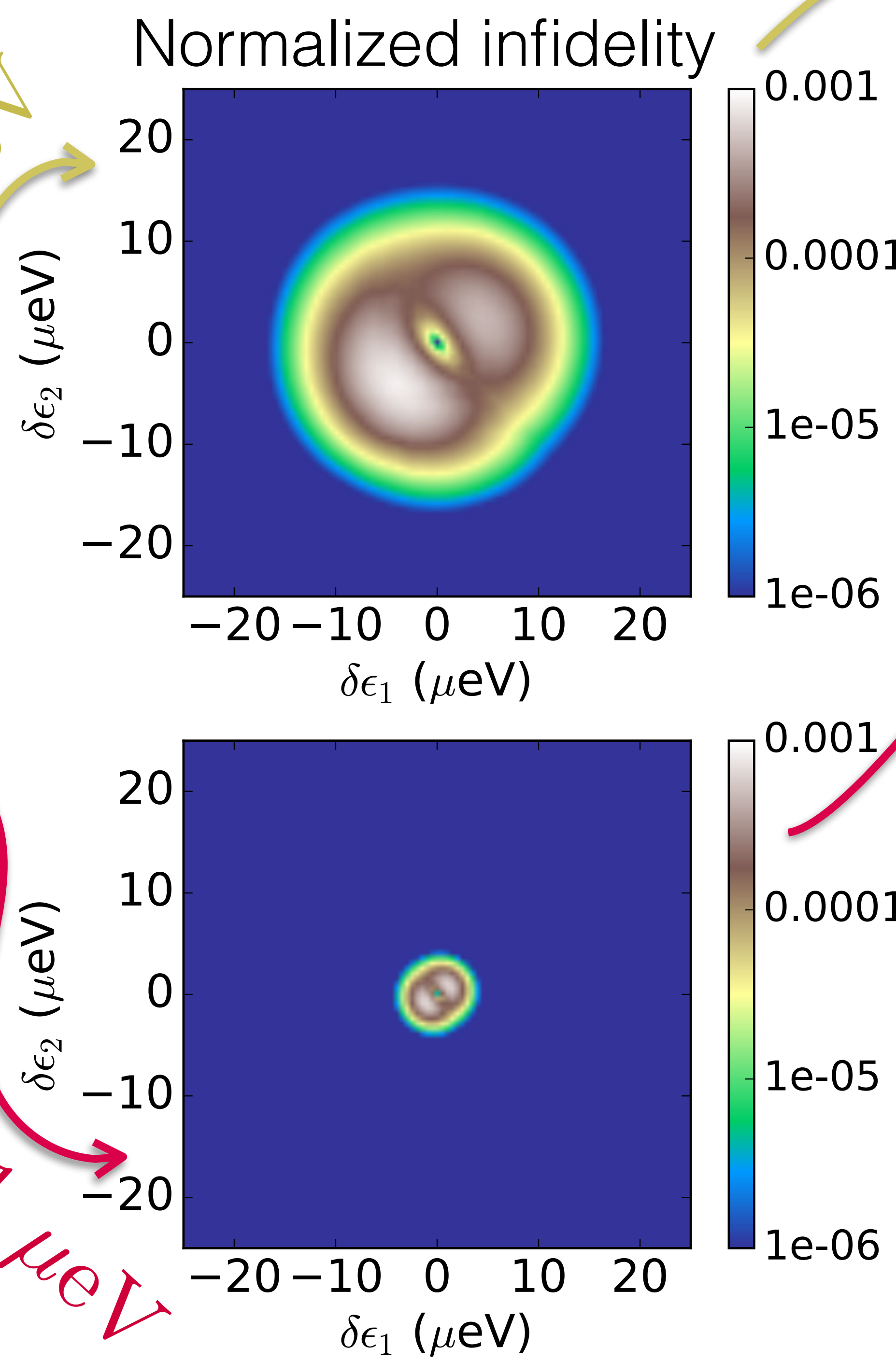
$$\mathcal{H}' = \mathcal{H} + \delta\epsilon_1 \mathcal{H}^{(1)}_{noise} + \delta\epsilon_2 \mathcal{H}^{(2)}_{noise}$$

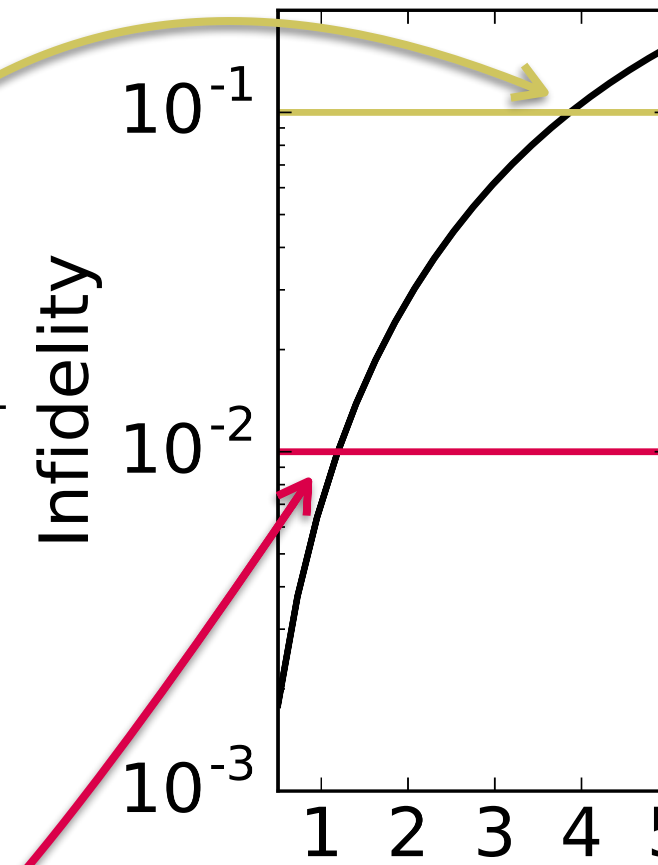
Process fidelity: A. Gilchrist, N. K. Langford, and M. A. Nielsen, arXiv:quant-ph/0408063.



$\sigma = 4\ \mu$eV

$\sigma = 1\ \mu$eV





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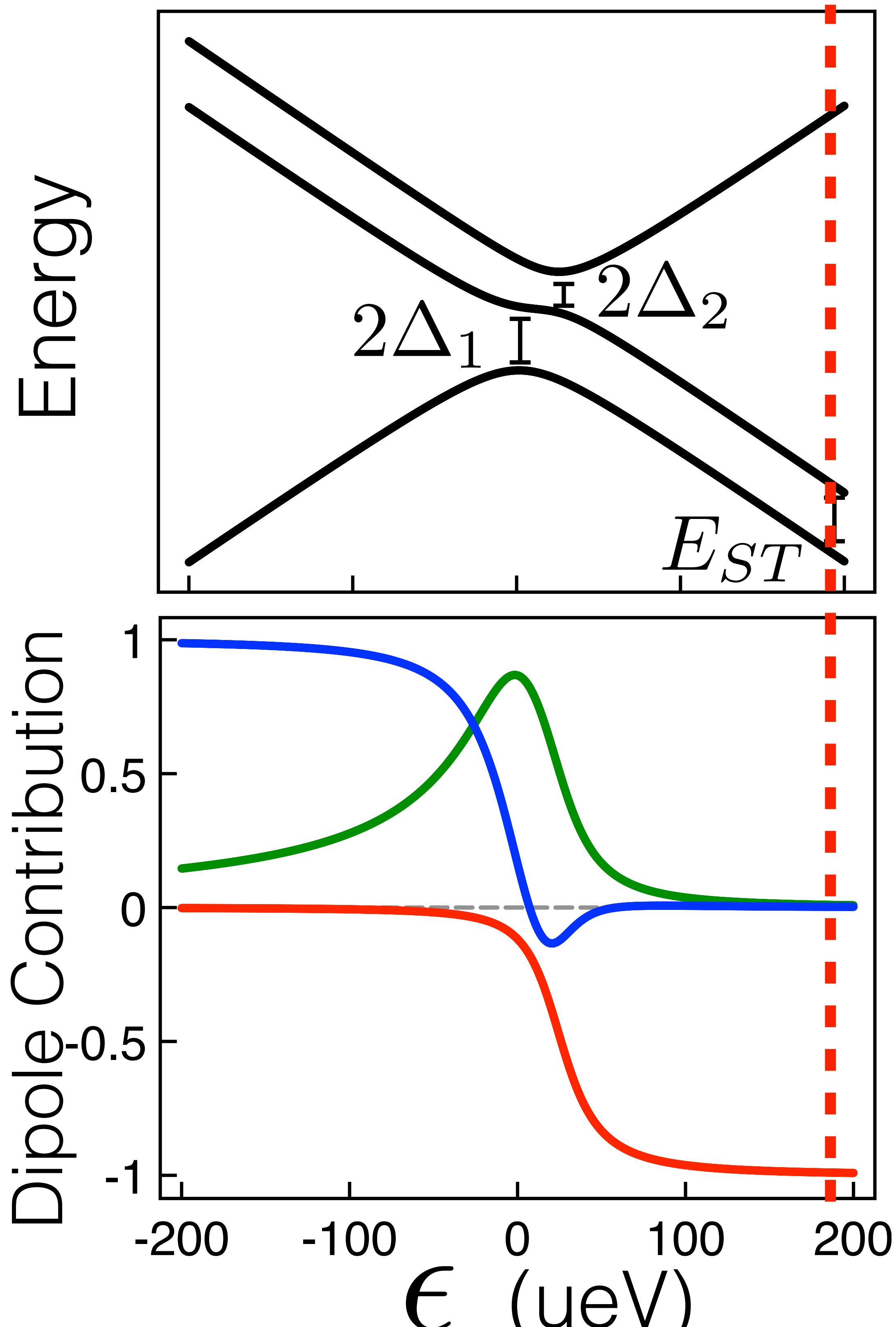
$$\Delta_2^{(2)} = 26.1\mu\text{eV}$$
$$E_{ST}^{(2)} = 45\mu\text{eV}$$
$$g = 75\mu\text{eV}$$

To minimize interaction with electric field in QDHQ, go to large detuning



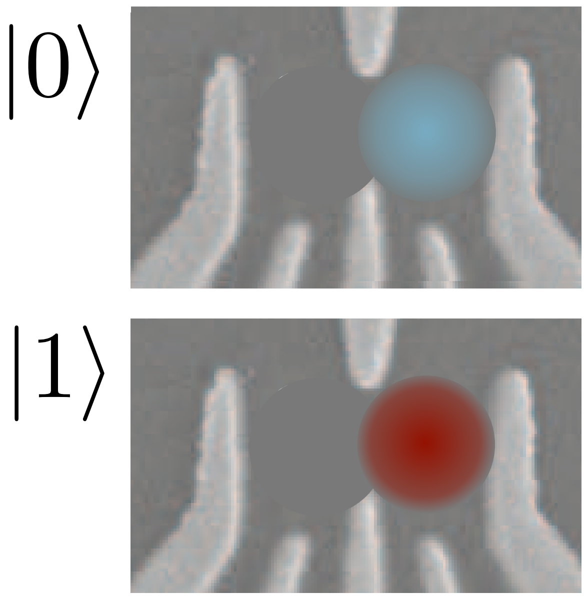
$$\mathcal{P} \equiv \frac{\partial}{\partial \epsilon}\mathcal{H}$$

Transverse field

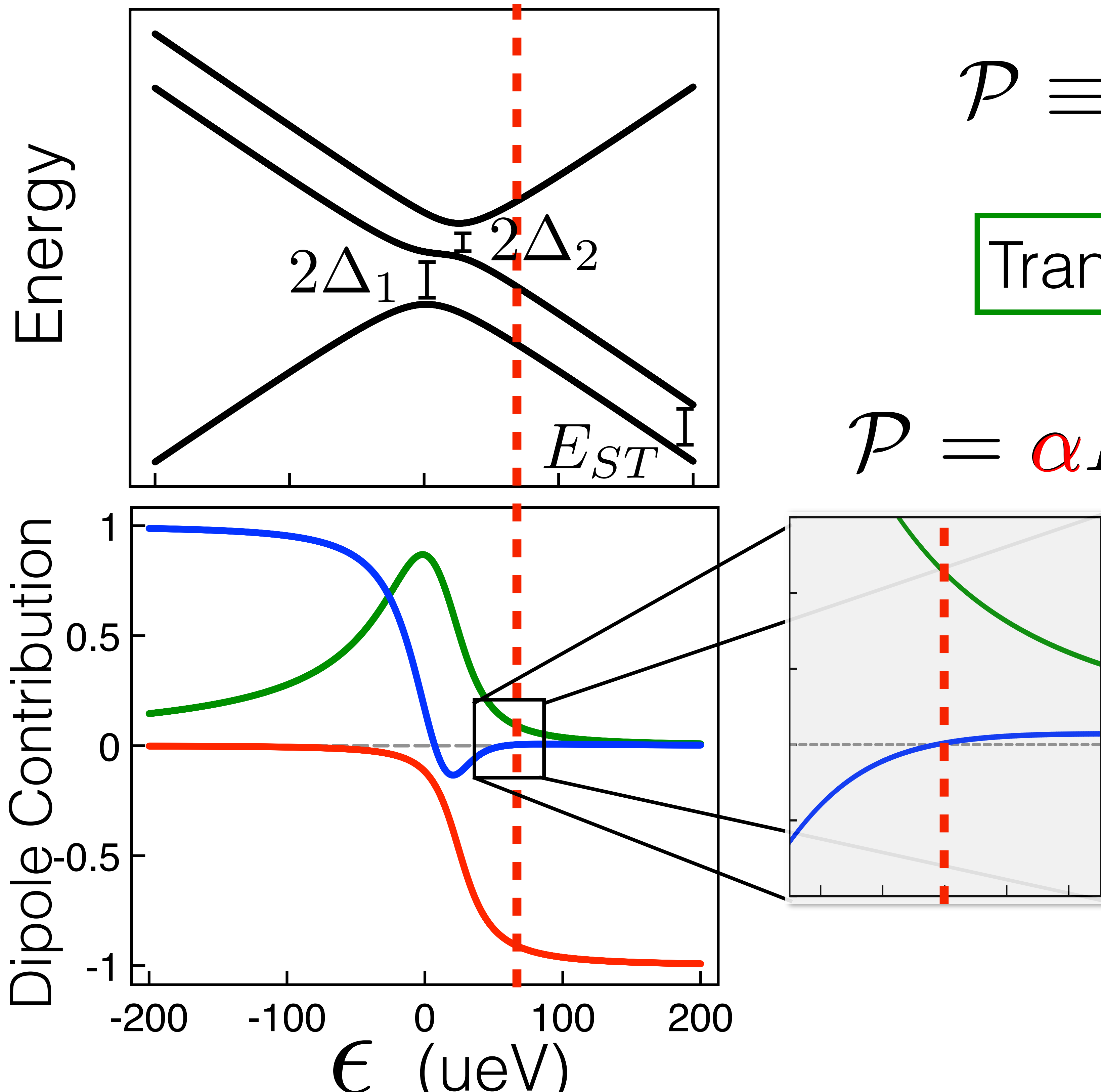
$$\mathcal{P} = \alpha I + \beta \sigma_x + \gamma \sigma_z$$

Longitudinal field

Electron position is the same for both states



To operate QDHQ, go to detuning where longitudinal field is zero



$$\mathcal{P} \equiv \frac{\partial}{\partial \epsilon}\mathcal{H}$$

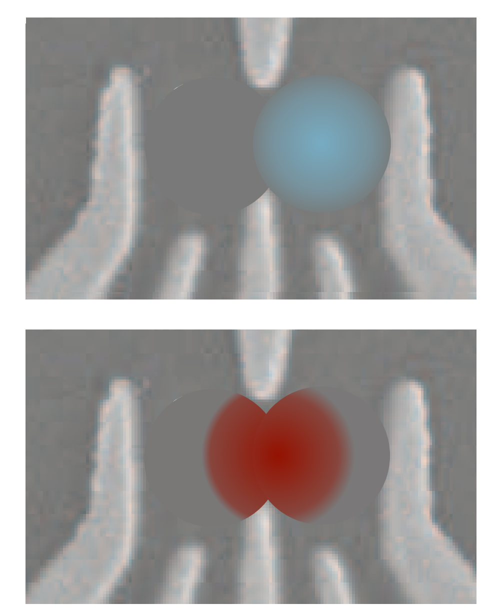
Transverse field

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

Longitudinal field

$|0\rangle$

$|1\rangle$



Goal: find order of magnitude of any potential two-qubit operation

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

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

$$g \ll E_{ST}, \Delta \ll \epsilon$$

$$\beta, \gamma \sim \left(\frac{\Delta}{\epsilon}\right)^2$$

Ignore single-qubit operations

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

$$+g\beta^{(1)}\gamma^{(2)}\sigma_x \otimes \sigma_z + g\beta^{(1)}\gamma^{(2)}\sigma_x \otimes \sigma_z$$

$$+g\gamma^{(1)}\gamma^{(2)}\sigma_z \otimes \sigma_z$$

Entangling gate strength

$$\left(\frac{g}{\Delta}\right)^2 \left(\frac{\Delta}{\epsilon}\right)^8$$