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

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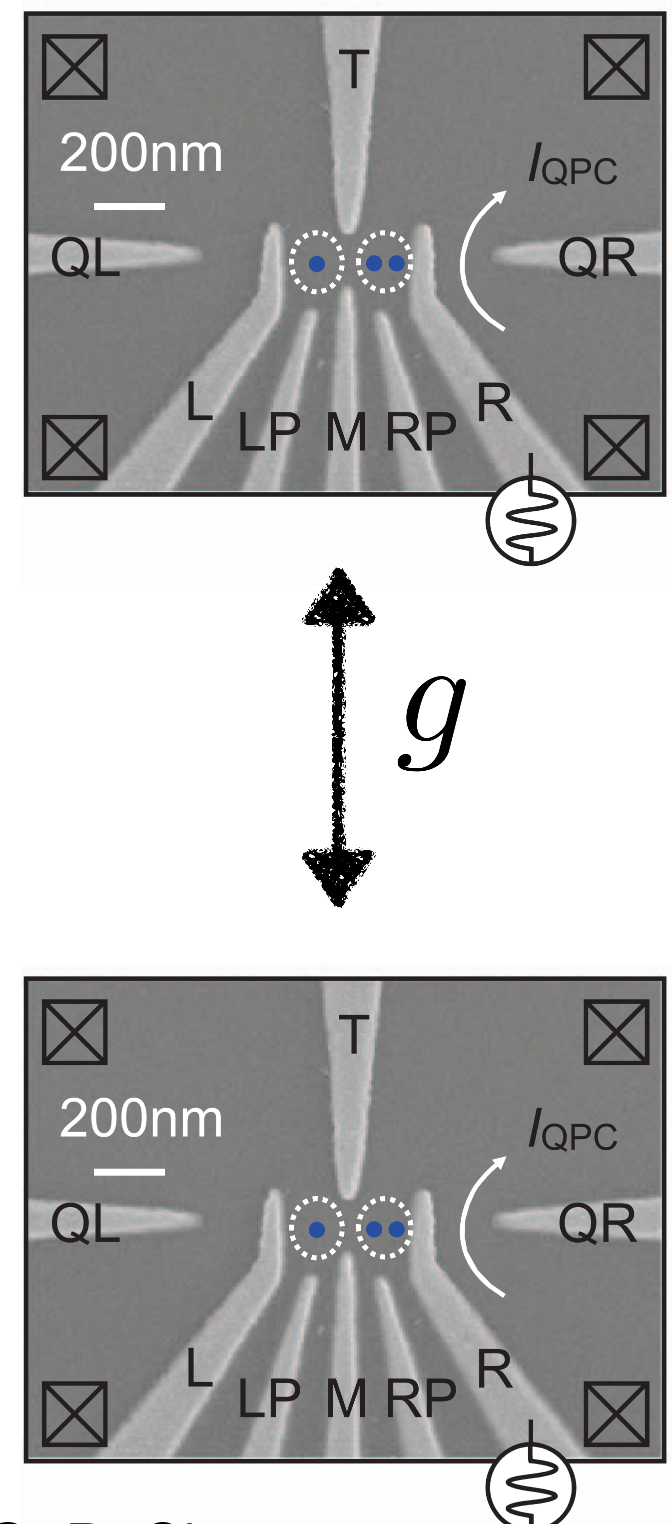
Introducing a new control scheme for capacitively coupled QDHQs

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

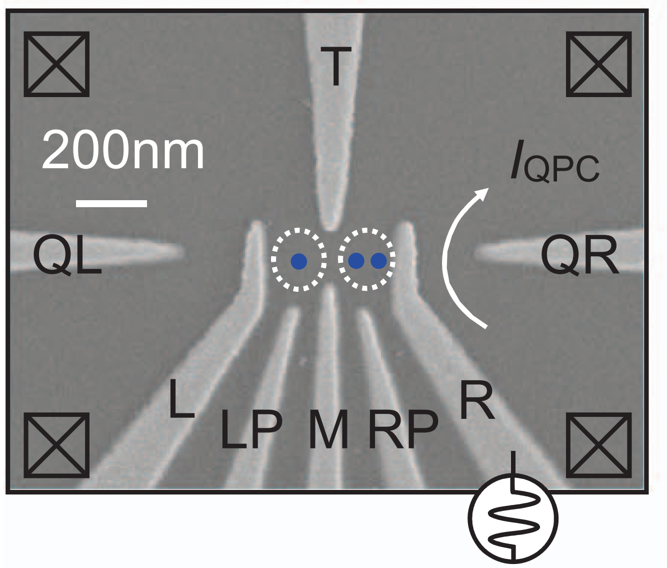
- We show that these entanglement gates are robust under charge noise



Device by C. B. Simmons

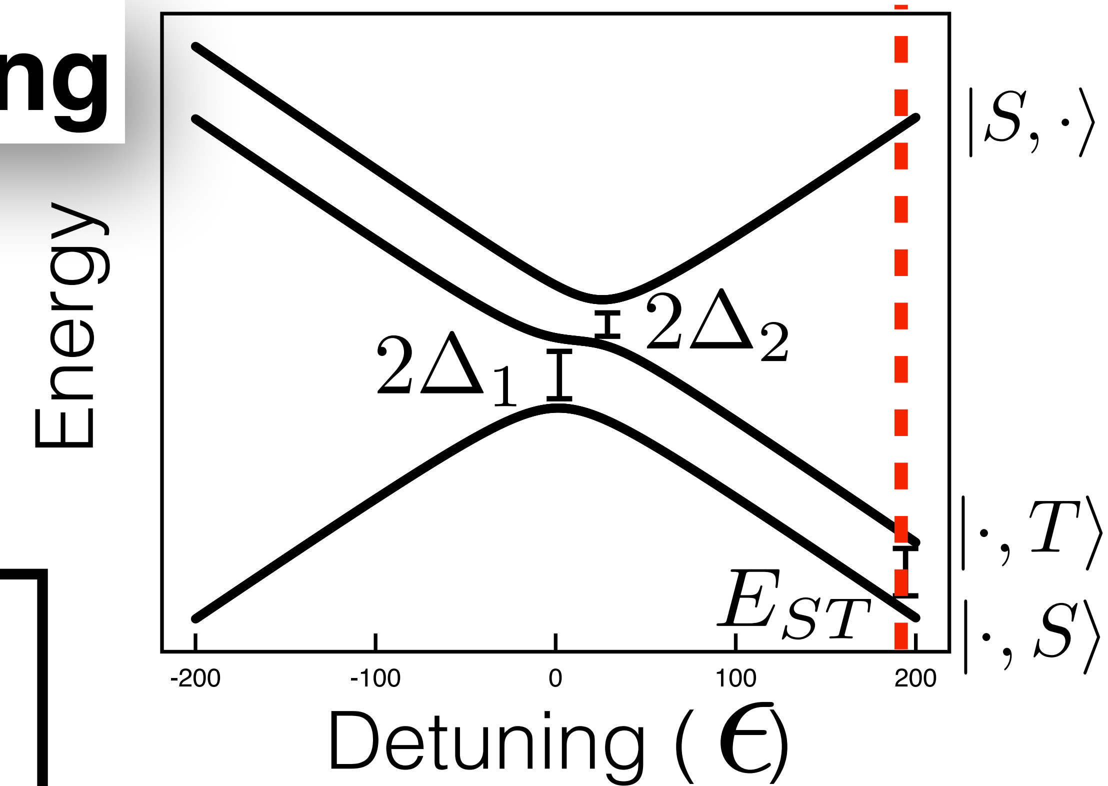
Quantum dot "hybrid" qubit has a tunable qubit dipole

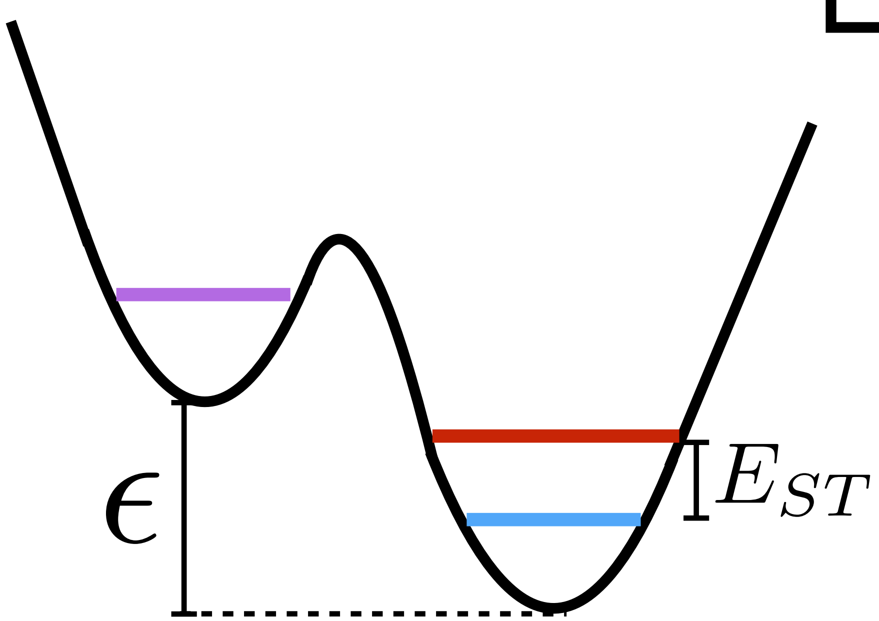
Large detuning



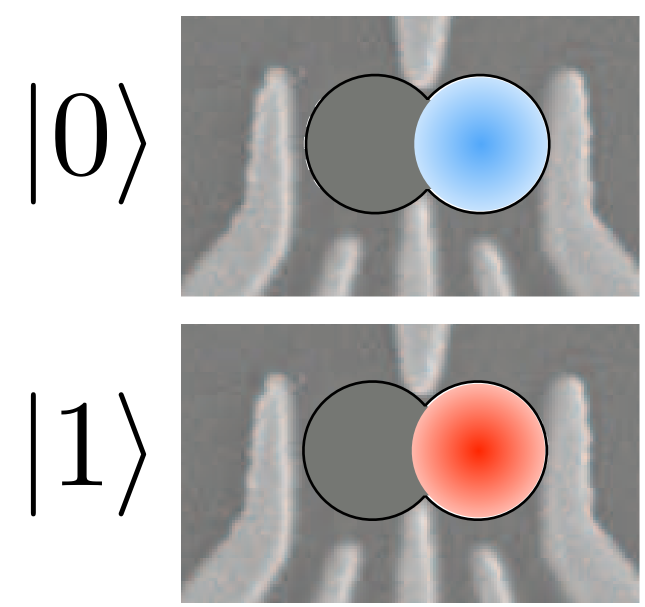
Device by C. B. Simmons

Effective dipole ~0



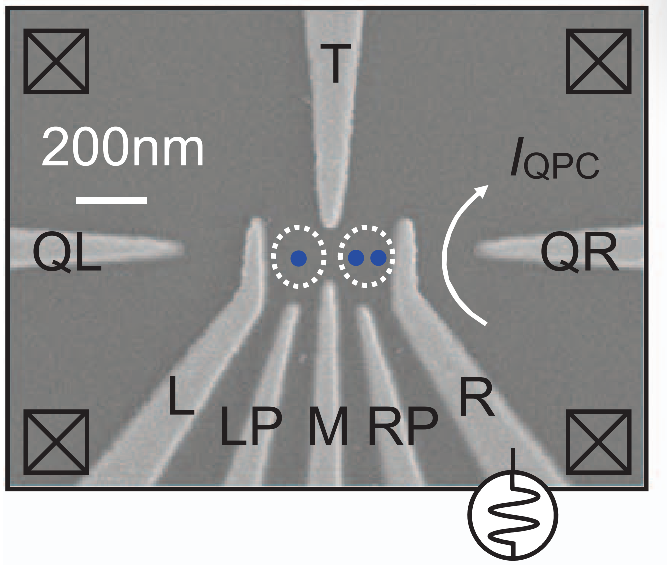


Electron position is the same for both states



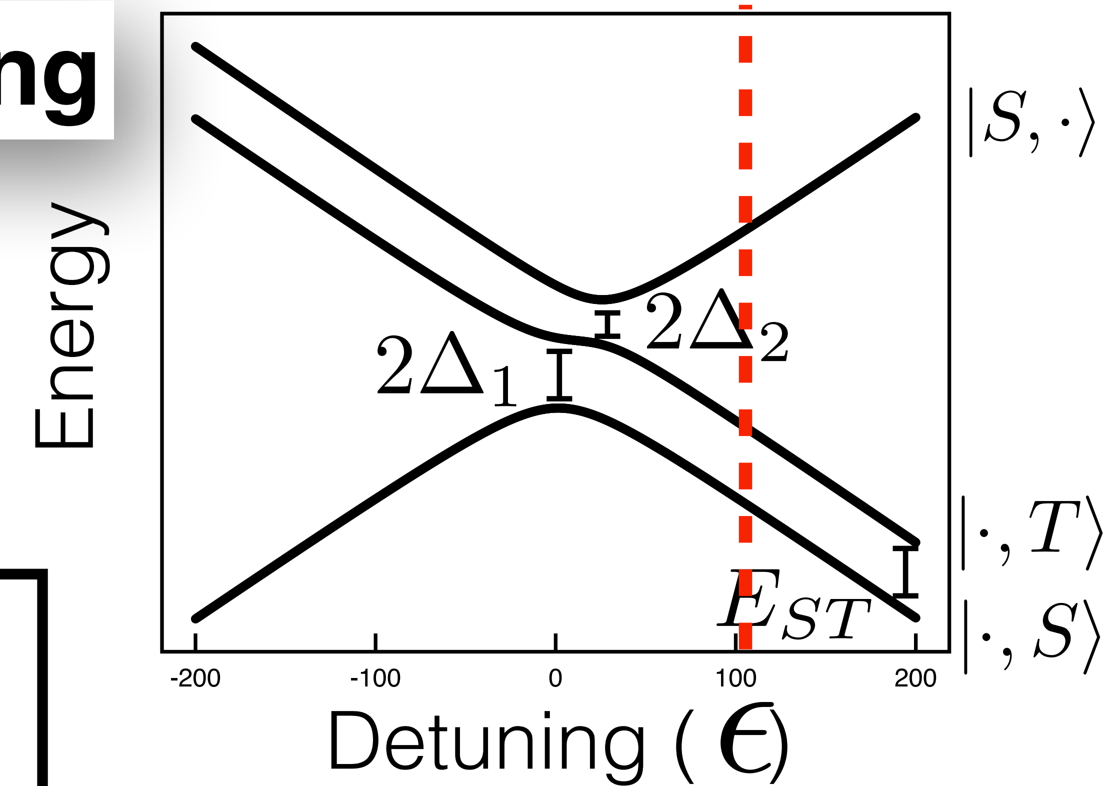
Quantum dot "hybrid" qubit has a tunable qubit dipole

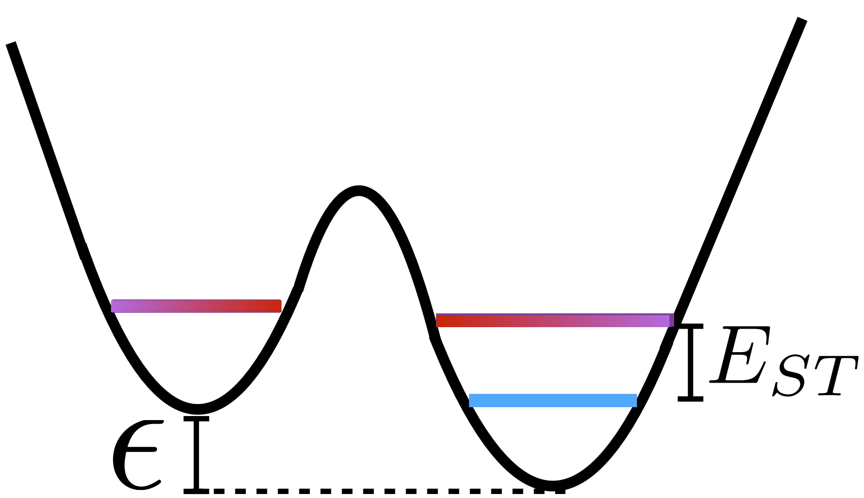
Smaller detuning



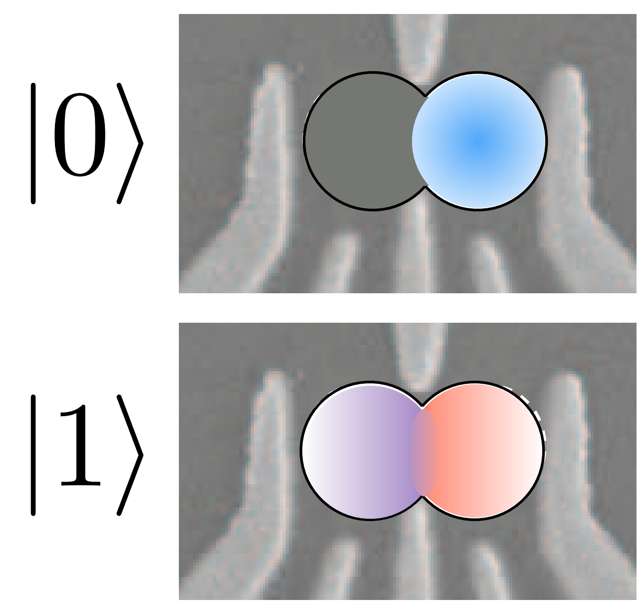
Device by C. B. Simmons

Effective dipole ≠0

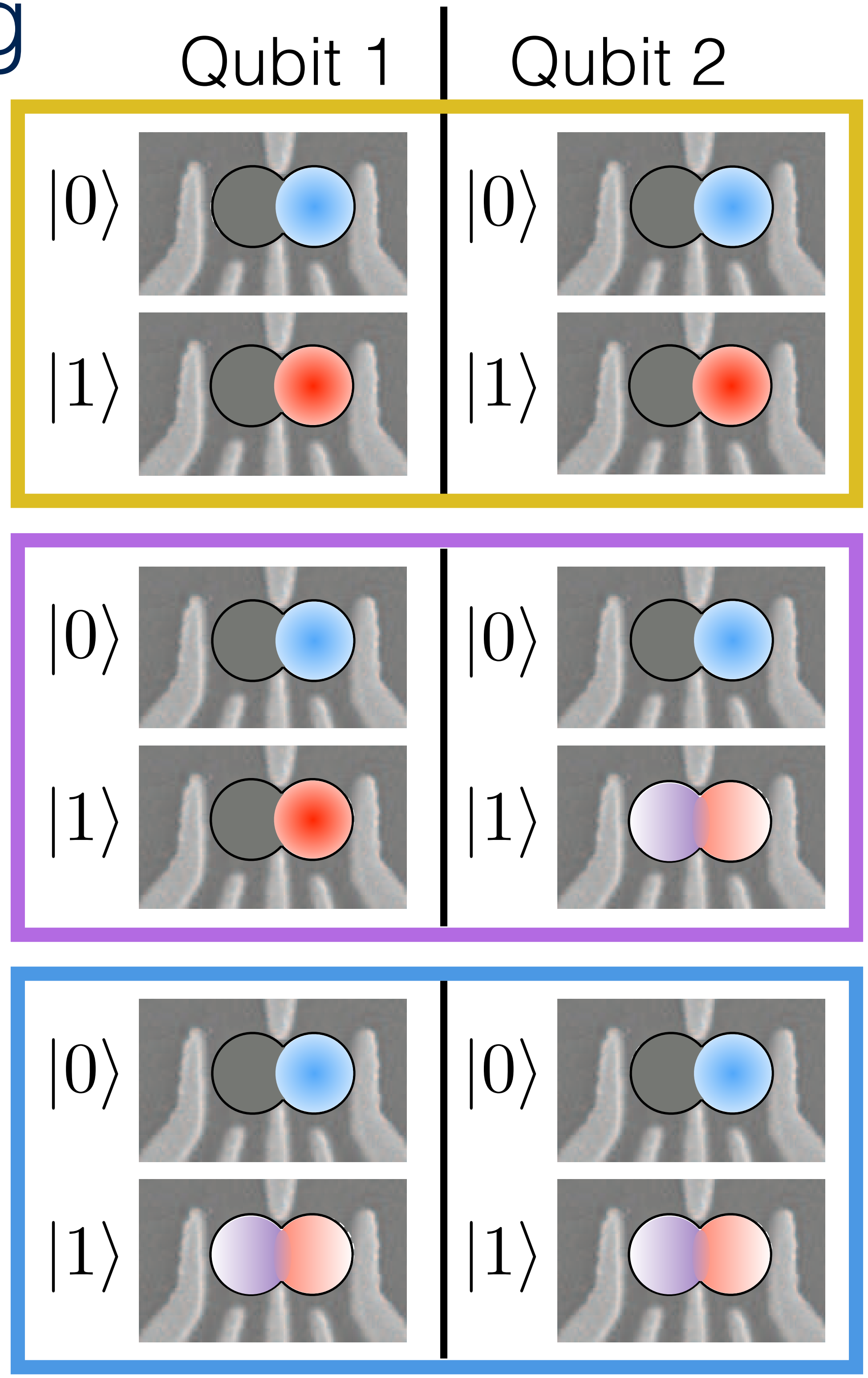




Electron position is different for each state



Changes in detuning yield a tunable effective coupling



Large ϵ_1
Large ϵ_2

$\lvert 00\rangle$	$\lvert 01\rangle$	$\lvert 10\rangle$	$\lvert 11\rangle$
→ →	→ →	→ →	→ →
$+g$	$+g$	$+g$	$+g$

$g(I \otimes I)$

Large ϵ_1
Small ϵ_2

$\lvert 00\rangle$	$\lvert 01\rangle$	$\lvert 10\rangle$	$\lvert 11\rangle$
→ →	→ ←	→ →	→ ←
$+g$	$-g$	$+g$	$-g$

$g(I \otimes \sigma_z)$

Small ϵ_1
Small ϵ_2

$\lvert 00\rangle$	$\lvert 01\rangle$	$\lvert 10\rangle$	$\lvert 11\rangle$
→ →	→ ←	← →	← ←
$+g$	$-g$	$-g$	$+g$

$g(\sigma_z \otimes \sigma_z)$

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

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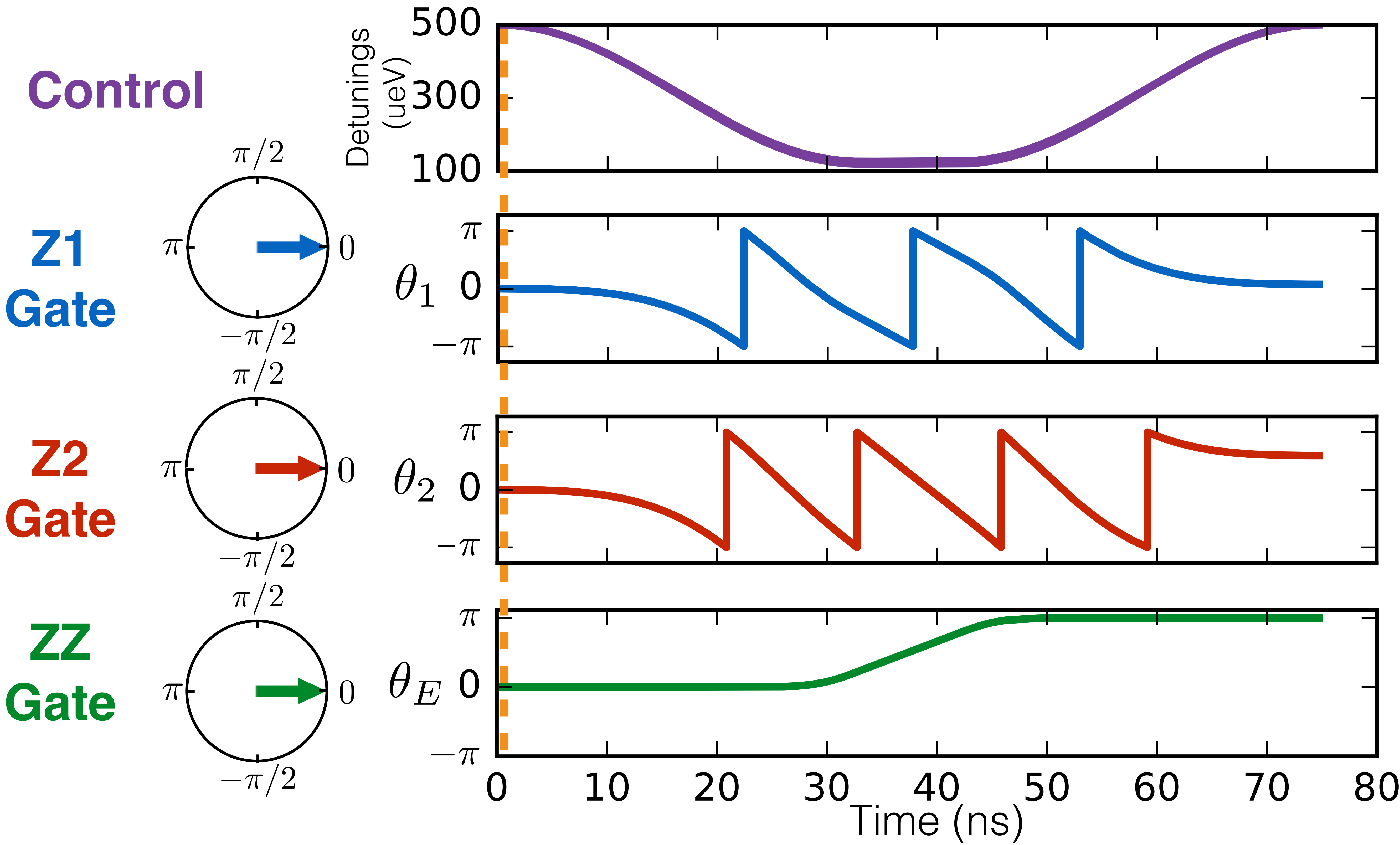
An adiabatic process will only affect the phases of a state (in the adiabatic basis):

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

θ_1	θ_2	θ_E
Z1 Gate	Z2 Gate	ZZ Gate

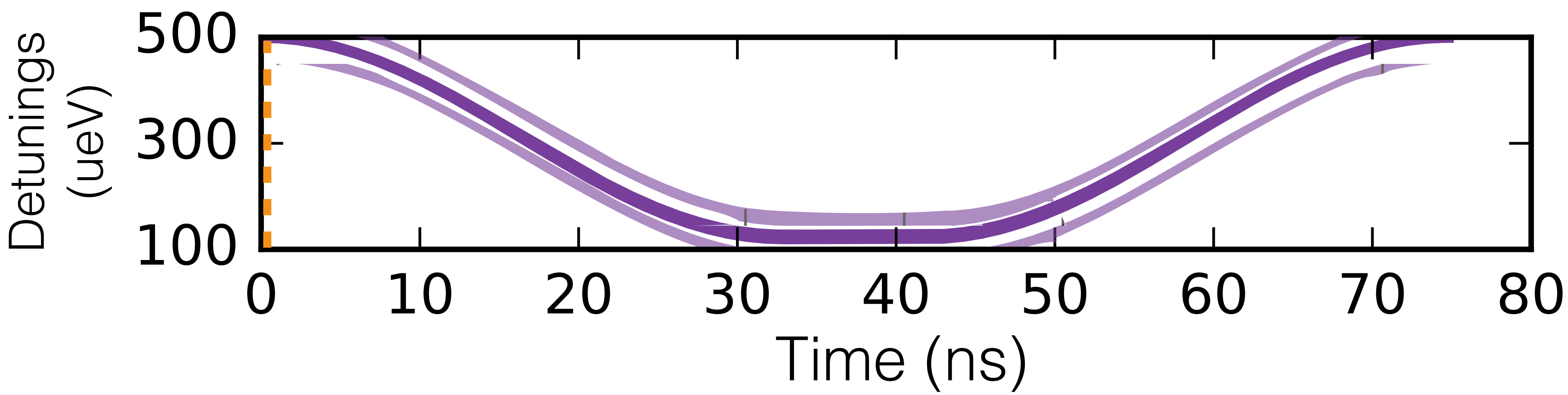
Want: $\theta_E = \pi$

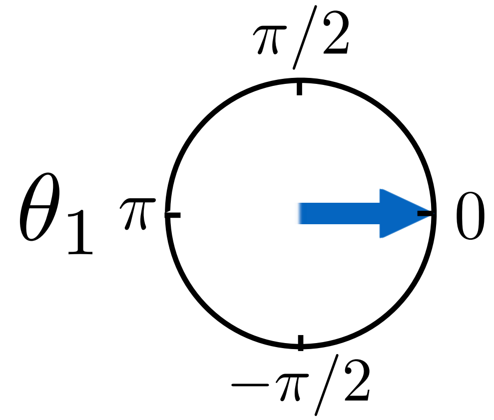
Operating a controlled-Z gate in capacitively coupled QDHQ system

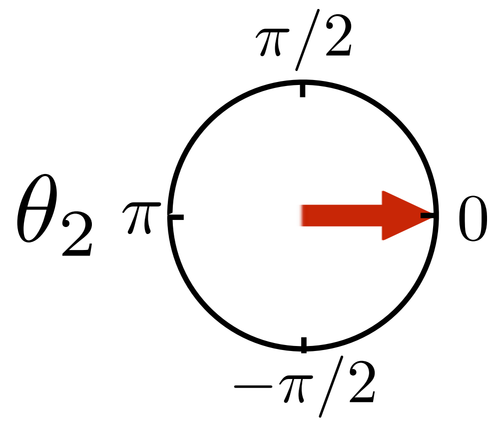


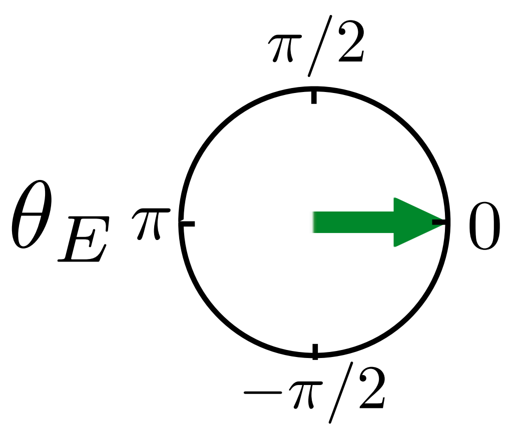
We consider the effect of quasistatic charge noise on two-qubit gate fidelities

- Low-frequency charge noise will dominate the noise spectrum.
- This leads to dephasing (of Z1, Z2, and ZZ)









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

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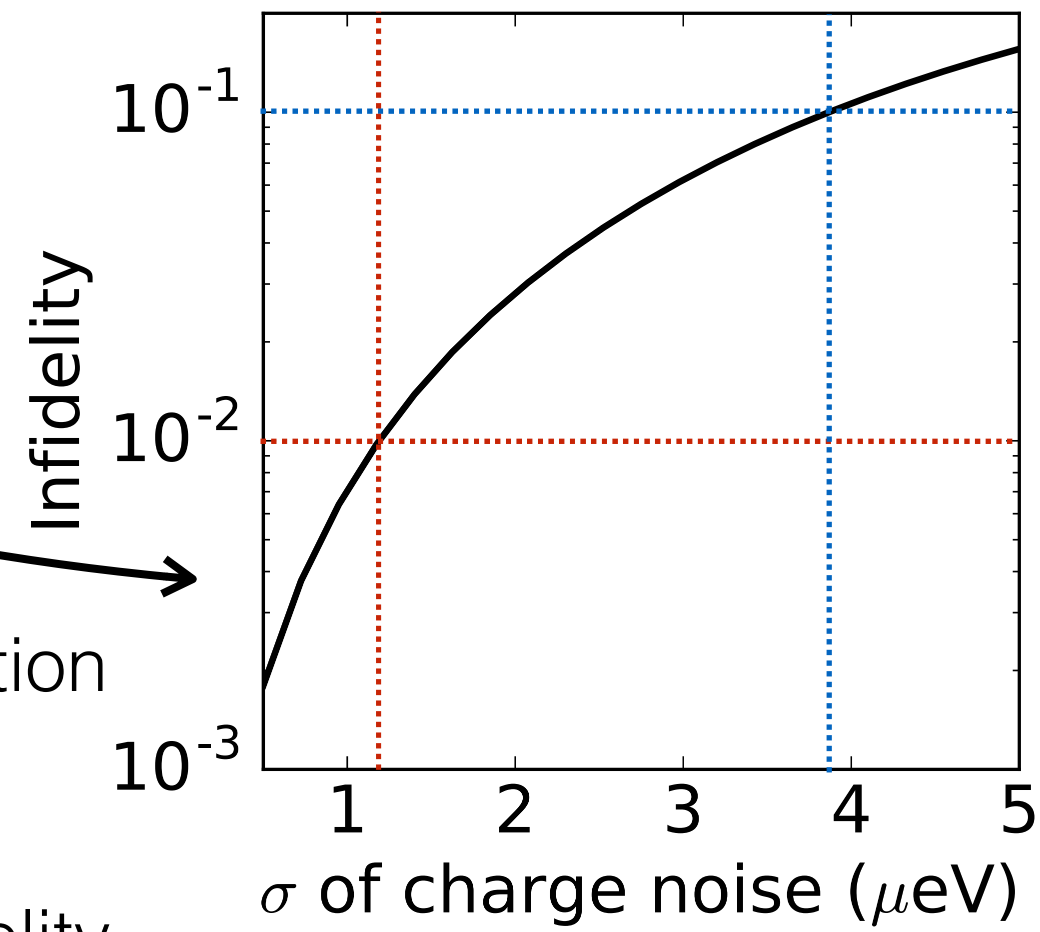
$$\mathcal{H}' = \mathcal{H} + \delta\epsilon_1 \mathcal{H}^{(1)}_{noise} + \delta\epsilon_2 \mathcal{H}^{(2)}_{noise}$$



- 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 ueV, 99% at σ ≈ 1 ueV

$$\begin{aligned}\Delta_1^{(1)} &= 33.3\mu\text{eV}\\ \Delta_2^{(1)} &= 30.2\mu\text{eV}\\ E_{ST}^{(1)} &= 52\mu\text{eV}\\ \Delta_1^{(2)} &= 28.8\mu\text{eV}\\ \Delta_2^{(2)} &= 26.1\mu\text{eV}\\ E_{ST}^{(2)} &= 45\mu\text{eV}\\ g &= 75\mu\text{eV}\end{aligned}$$

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

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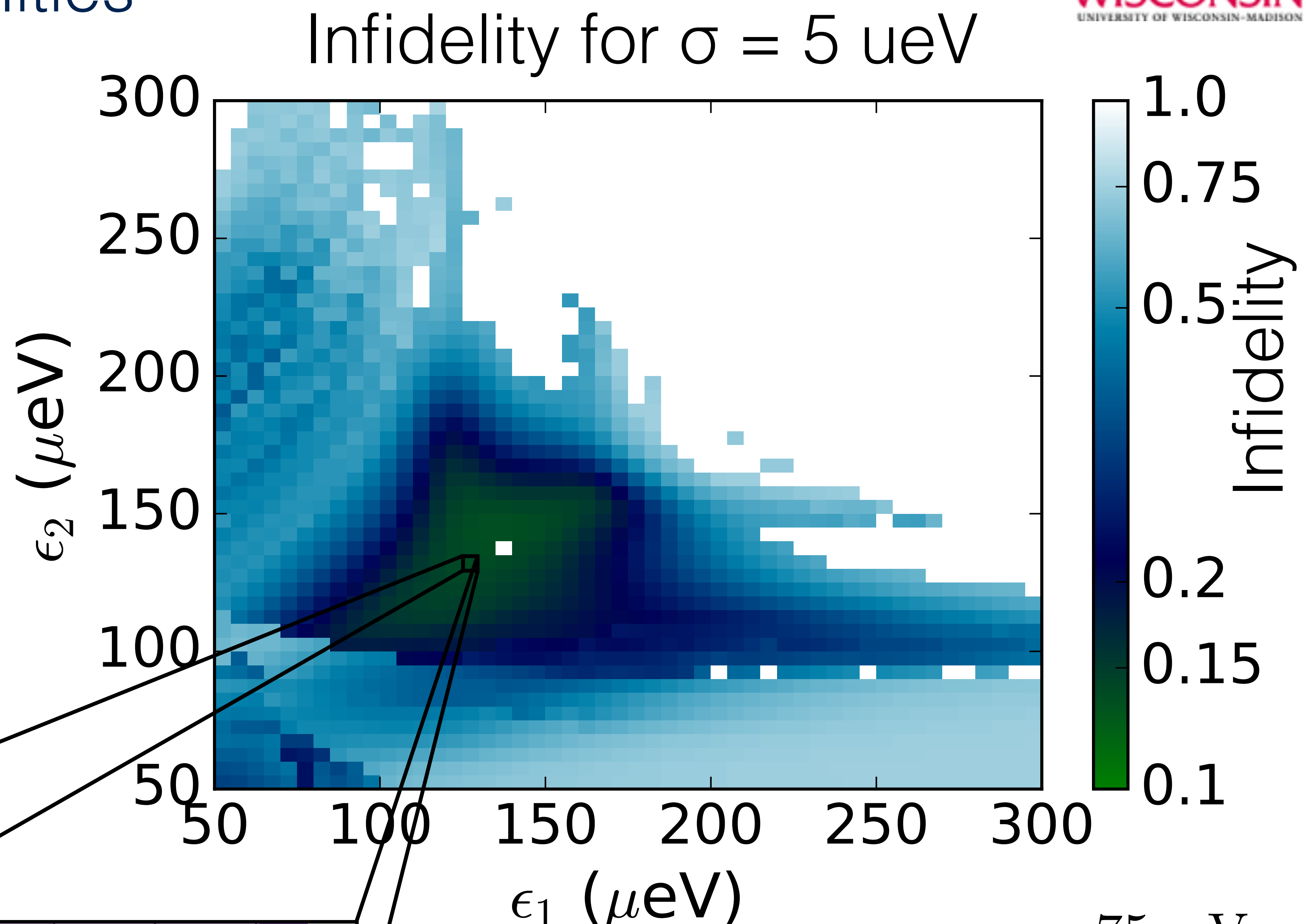
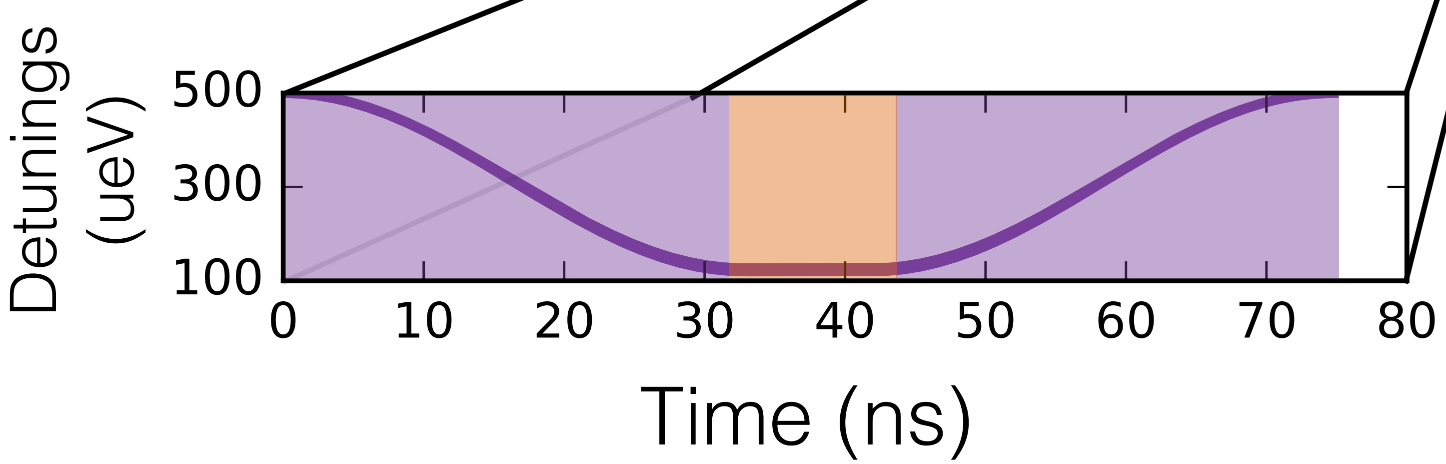
- To optimize pulse sequence, we consider all possible “entangling points” in detuning space
- For each “entangling point,” we optimize over **moving time** and **waiting time**.





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

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

Summary

The proposed coupling scheme:

- Allows for static, non-equal qubit frequencies: *in the simulations here, ω_1 = (52 ueV)/ħ, ω_2 = (45 ueV)/ħ*
- 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 Z1, Z2, and ZZ gates*
- Relatively robust under charge noise: *90% fidelity at ~4ueV charge noise, 99% at ~1 ueV*

Thank you!

Additional slides

Capacitive coupling in two charge qubits leads to a static coupling

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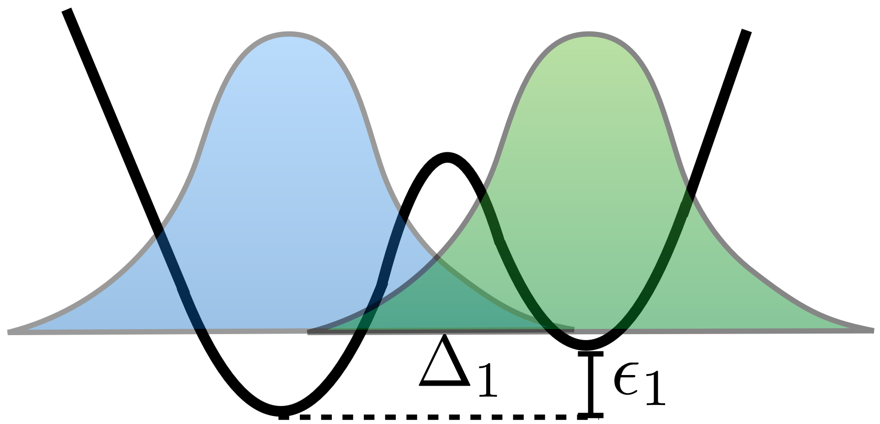
One qubit



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

Two qubits

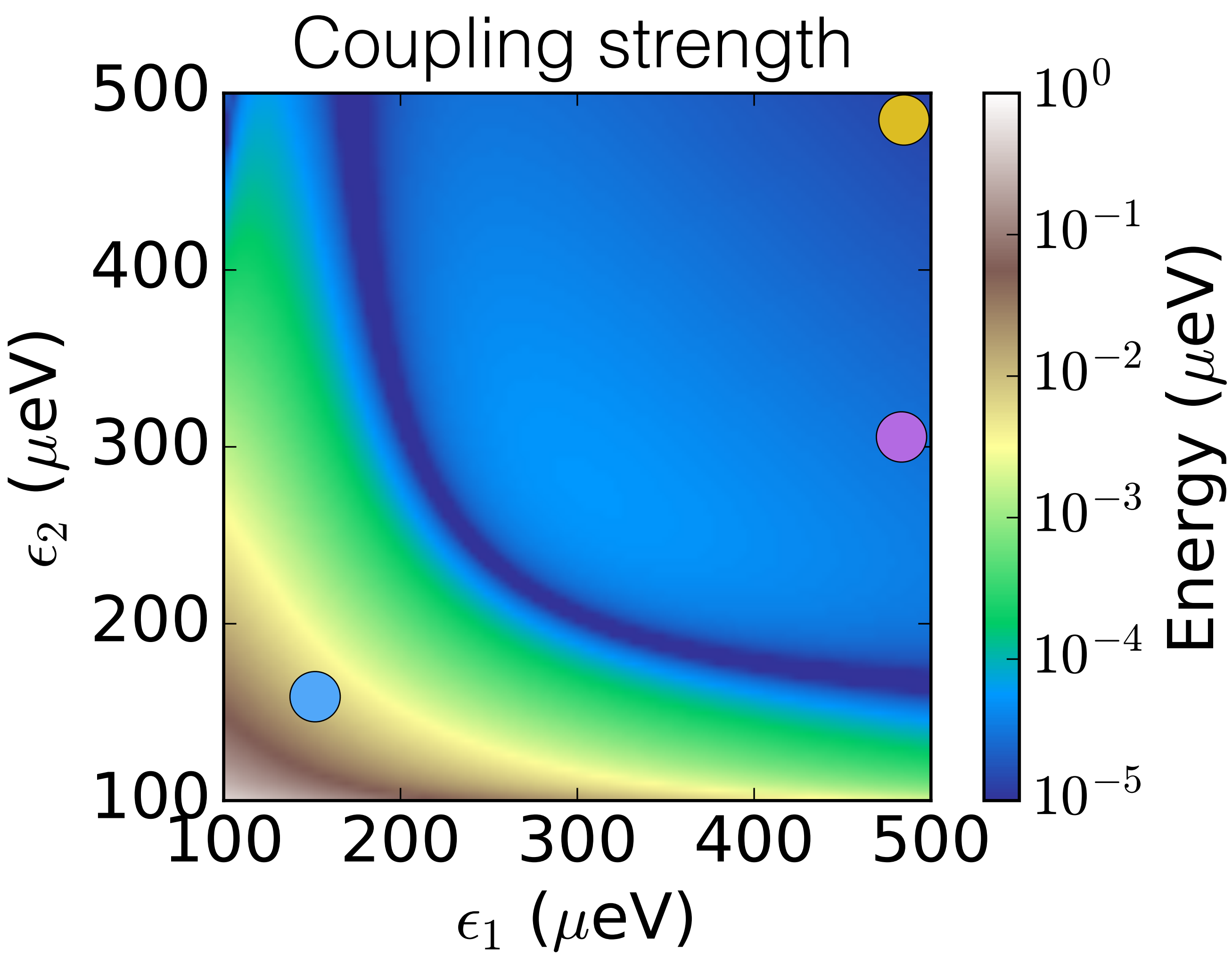
$$\mathcal{H} =$$
$$\epsilon_1 \sigma_z \otimes I + \Delta_1 \sigma_x \otimes I +$$
$$\epsilon_2 I \otimes \sigma_z + \Delta_2 I \otimes \sigma_x +$$
$$g \sigma_z \, ? \, \otimes \sigma_z$$

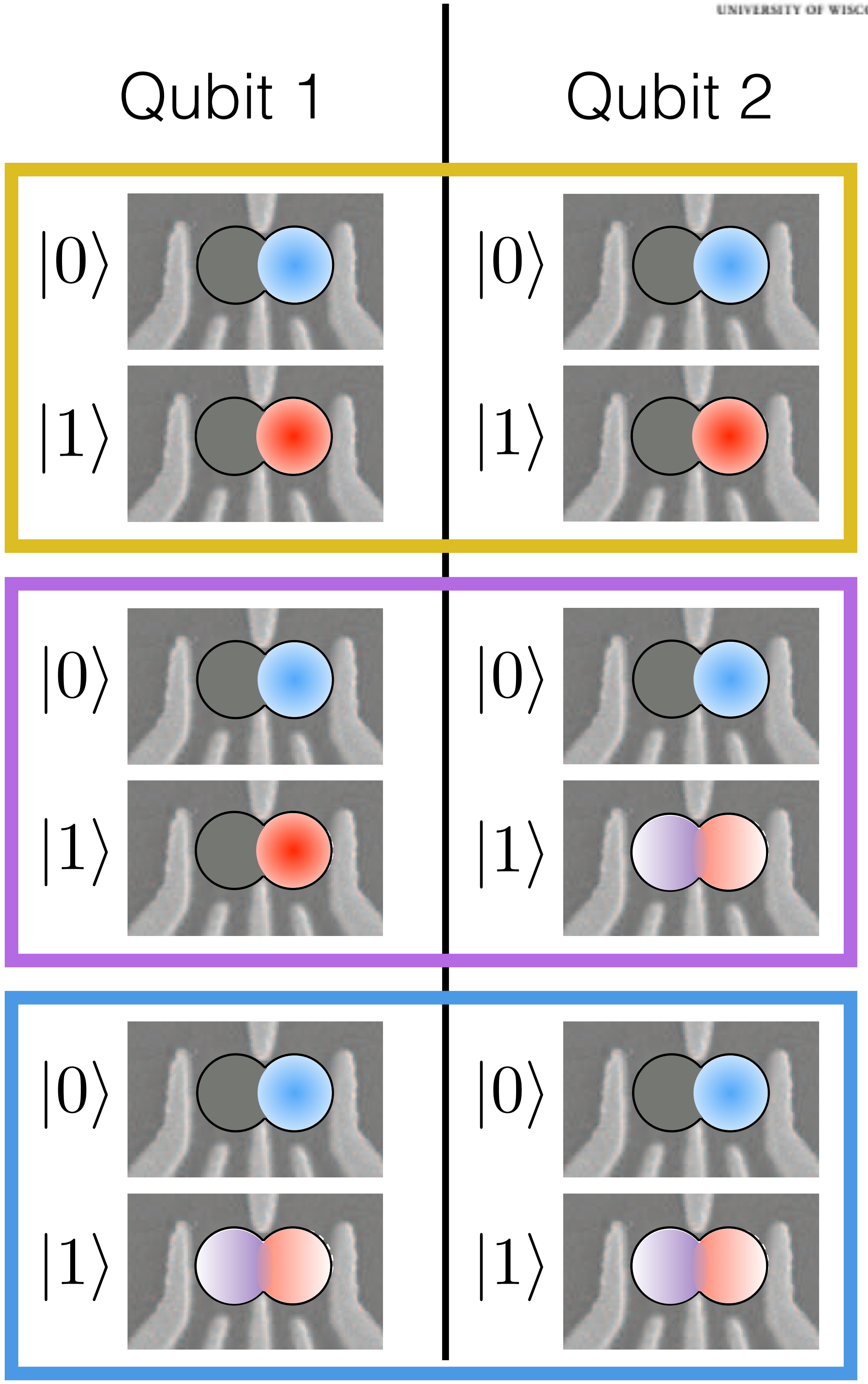
What is the coupling term between 2 capacitively-coupled charge qubits?

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).





put frequency and energy on same colorbar

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

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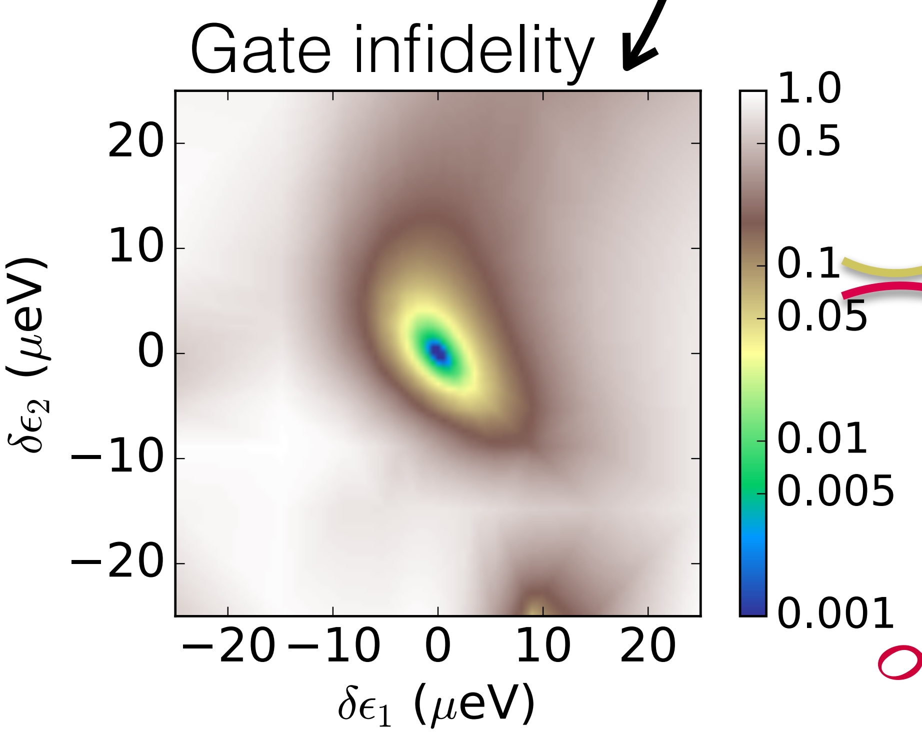
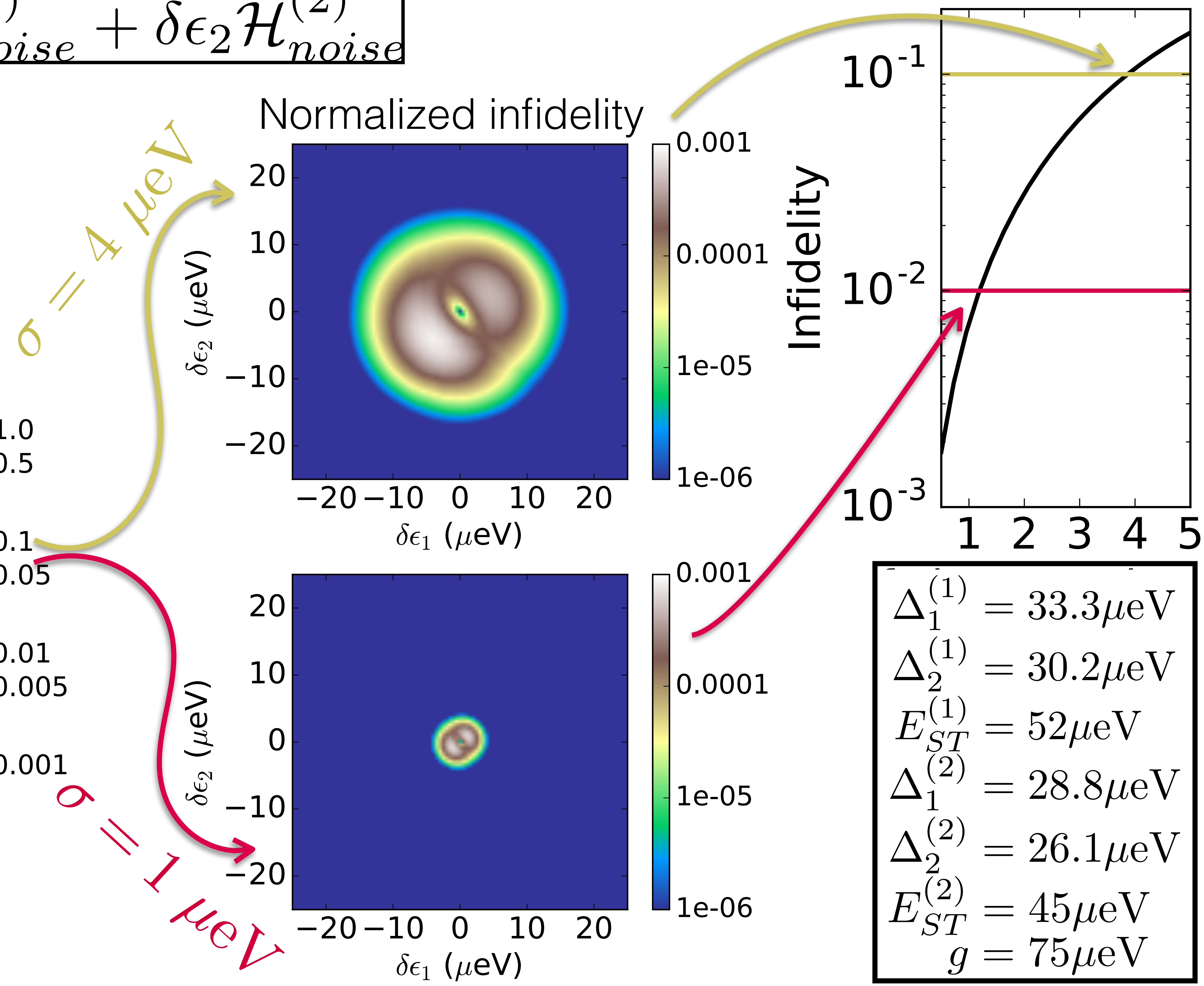
$$\mathcal{H}' = \mathcal{H} + \delta\epsilon_1 \mathcal{H}^{(1)}_{noise} + \delta\epsilon_2 \mathcal{H}^{(2)}_{noise}$$

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





$$\Delta_1^{(1)} = 33.3\mu\text{eV}$$
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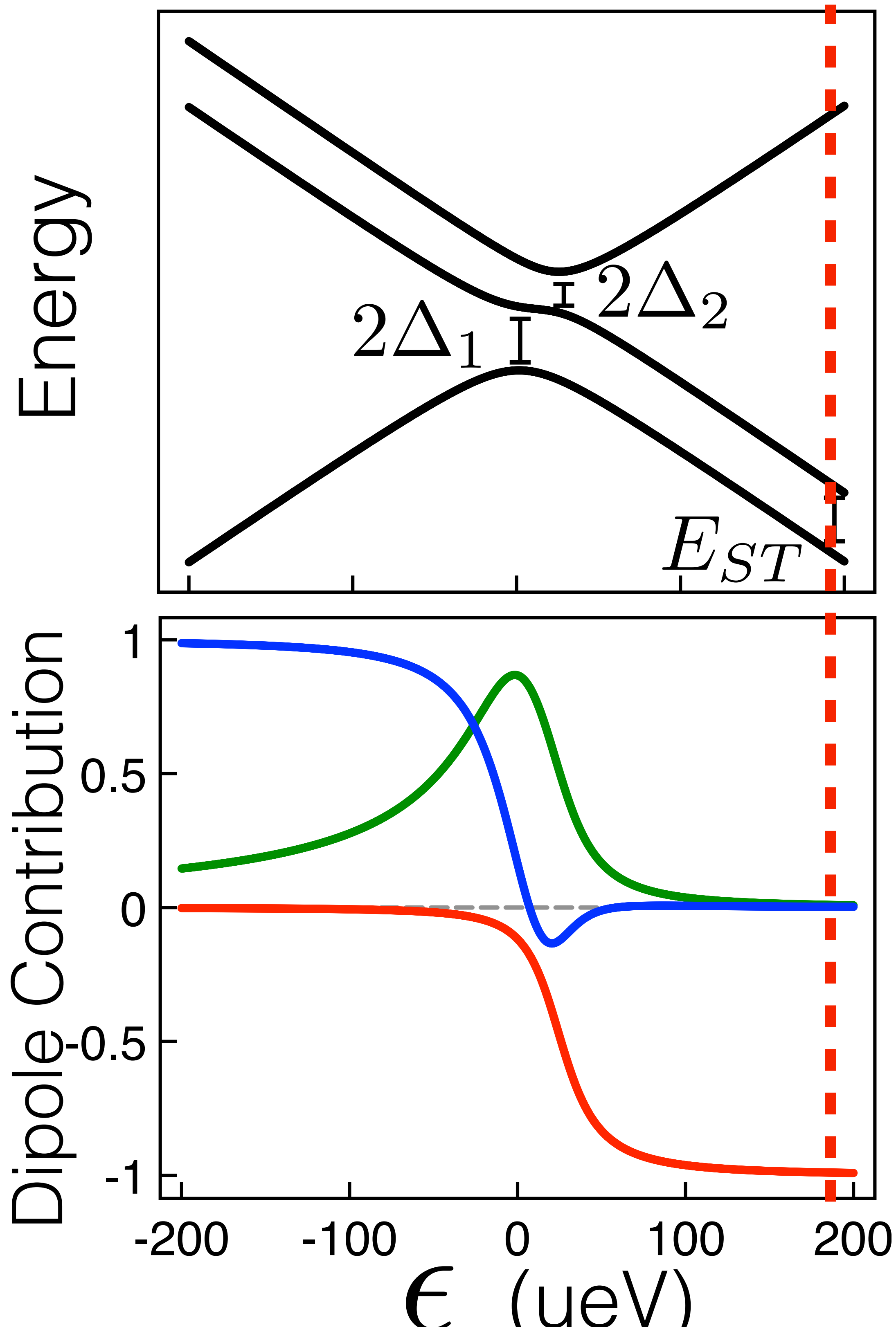
$$E_{ST}^{(1)} = 52\mu\text{eV}$$
$$\Delta_1^{(2)} = 28.8\mu\text{eV}$$
$$\Delta_2^{(2)} = 26.1\mu\text{eV}$$
$$E_{ST}^{(2)} = 45\mu\text{eV}$$
$$g = 75\mu\text{eV}$$

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



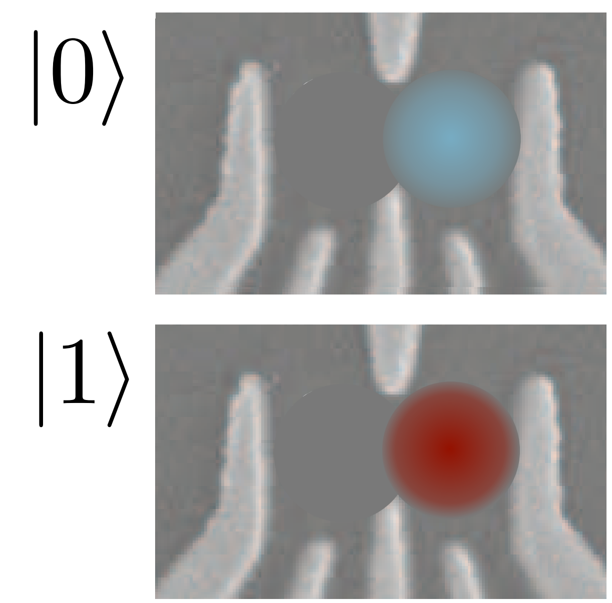
$$\mathcal{P} \equiv \frac{\partial}{\partial \epsilon}\mathcal{H}$$

Transverse field

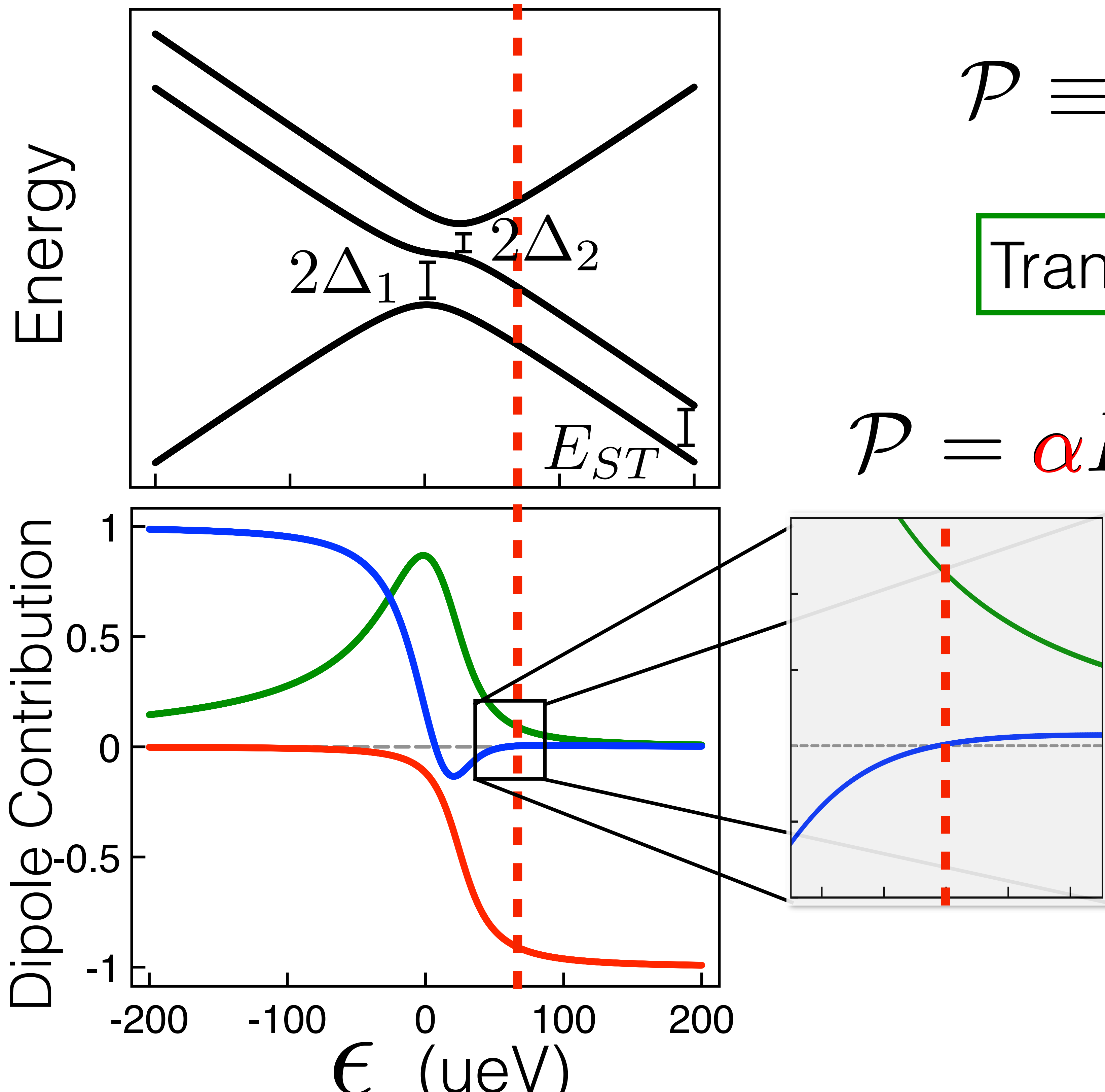
$$\mathcal{P} = \alpha I + \beta \sigma_x + \gamma \sigma_z$$

Longitudinal field

Electron position is the same for both states



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

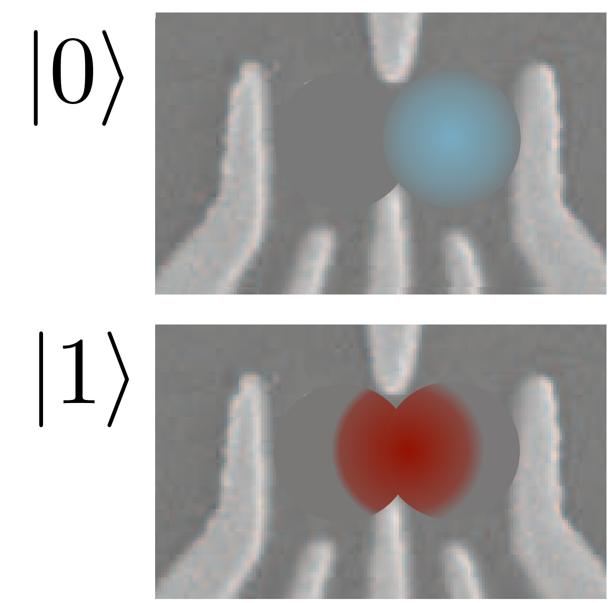


$$\mathcal{P} \equiv \frac{\partial}{\partial \epsilon}\mathcal{H}$$

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

Transverse field

Longitudinal field



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

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