Nonlinear response and crosstalk of strongly driven silicon spin qubits

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Spin Journal Club

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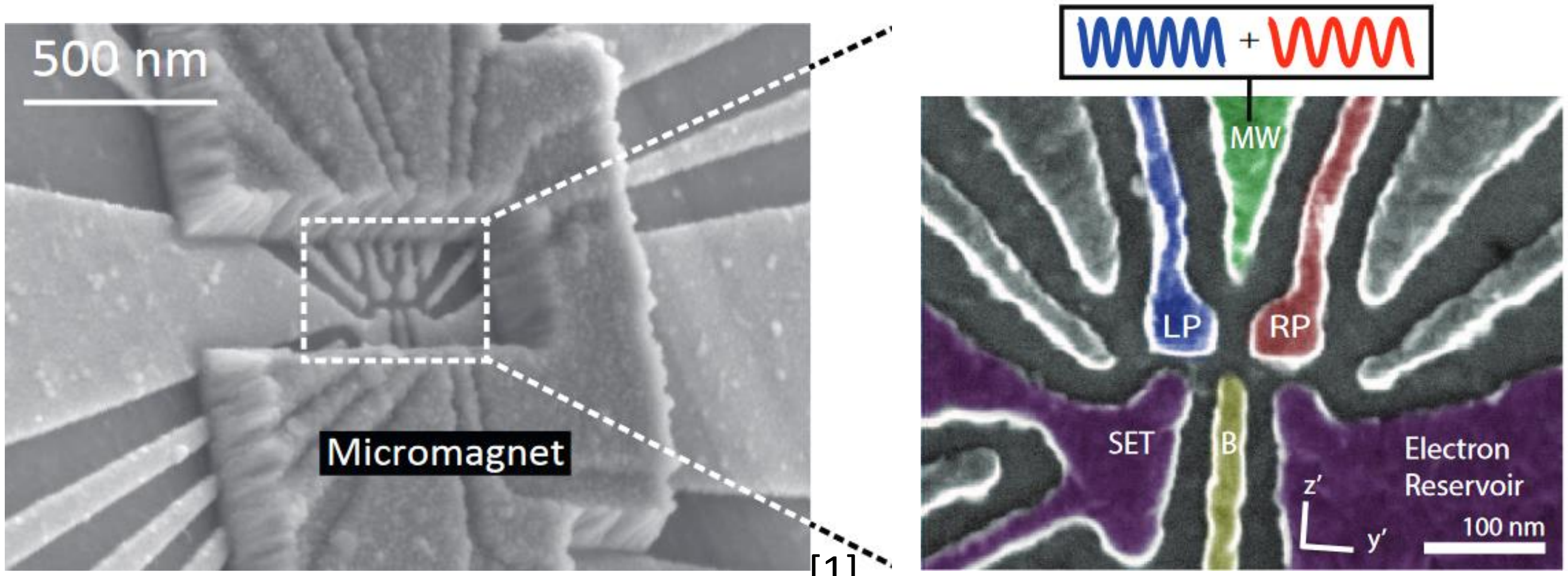
Nonlinear response and crosstalk of strongly driven silicon spin qubits

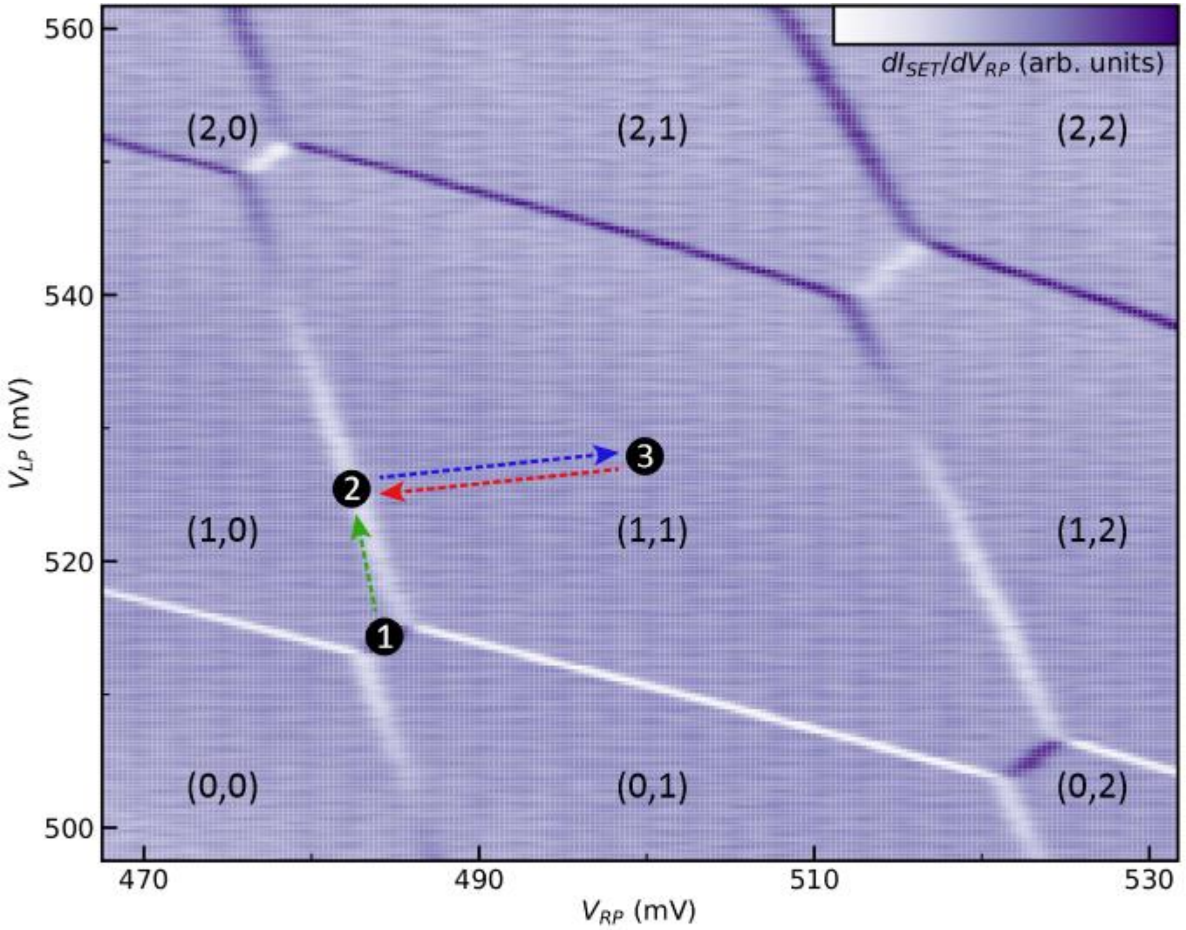
- Scaling: Multiplexed driving field to address individual, spectrally separated qubits
- Challenge: Maintaining high fidelity operations if qubit dynamics are affected by off-resonant tones
- Here: Experimental characterization of crosstalk for single-qubit rotations
- System: Electron QD in ^{28}Si/SiGe QW, with Co micromagnet placed on top for «synthetic» SOI



[1]

[1] X. Xue et al., Nature 2022

Initialization, readout and control



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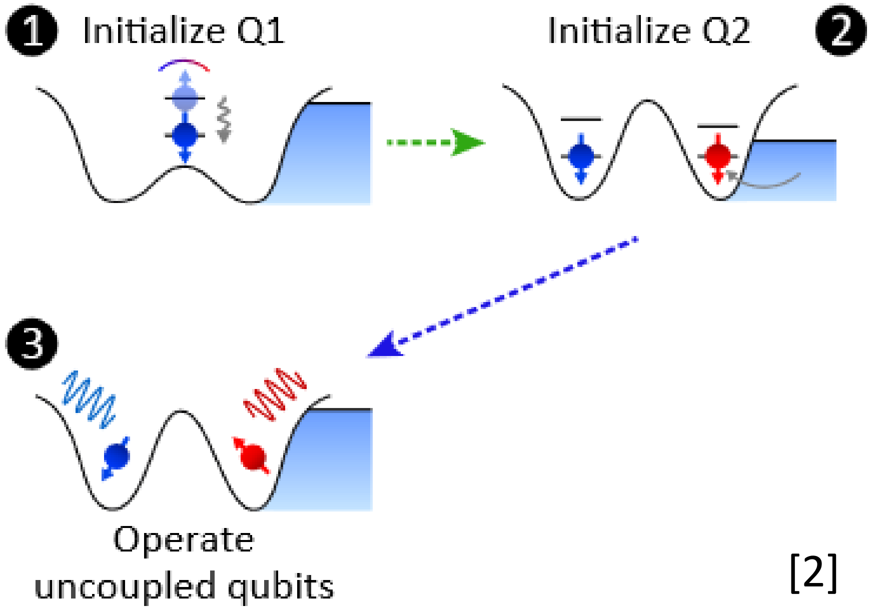

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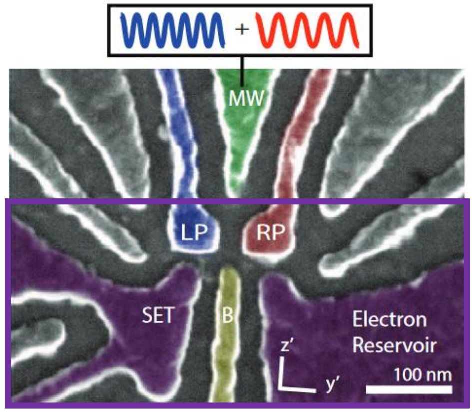
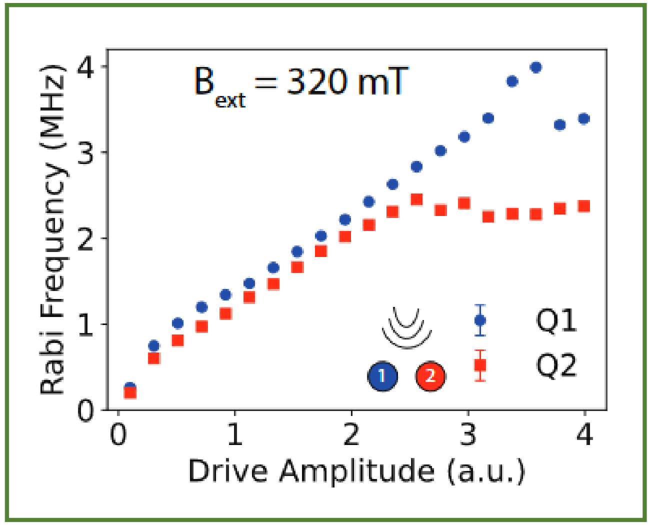


- Readout: Spin-selective tunneling to electron reservoir

[1] X. Xue et al., Nature 2021

Nonlinear Rabi frequency scaling (I)



- Gate-defined QDs in Si: EDSR mediated by orbit-like or valley-like hybridized states
- In either case, linear scaling of Rabi frequencies with drive amplitude is expected
- Driving tones for either Qubit 1 or 2 are applied (not simultaneously):

→ Nonlinearity distinct to each qubit frequency

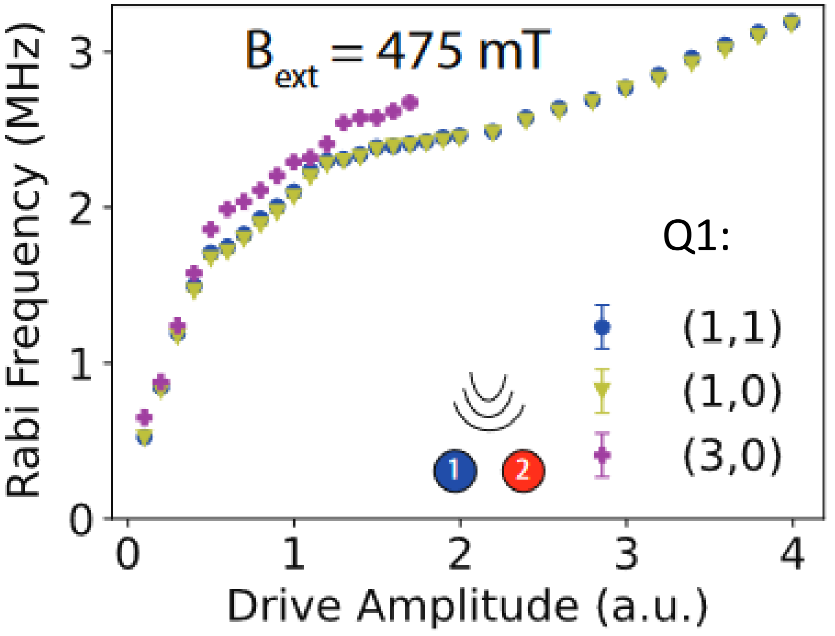
→ Rule out

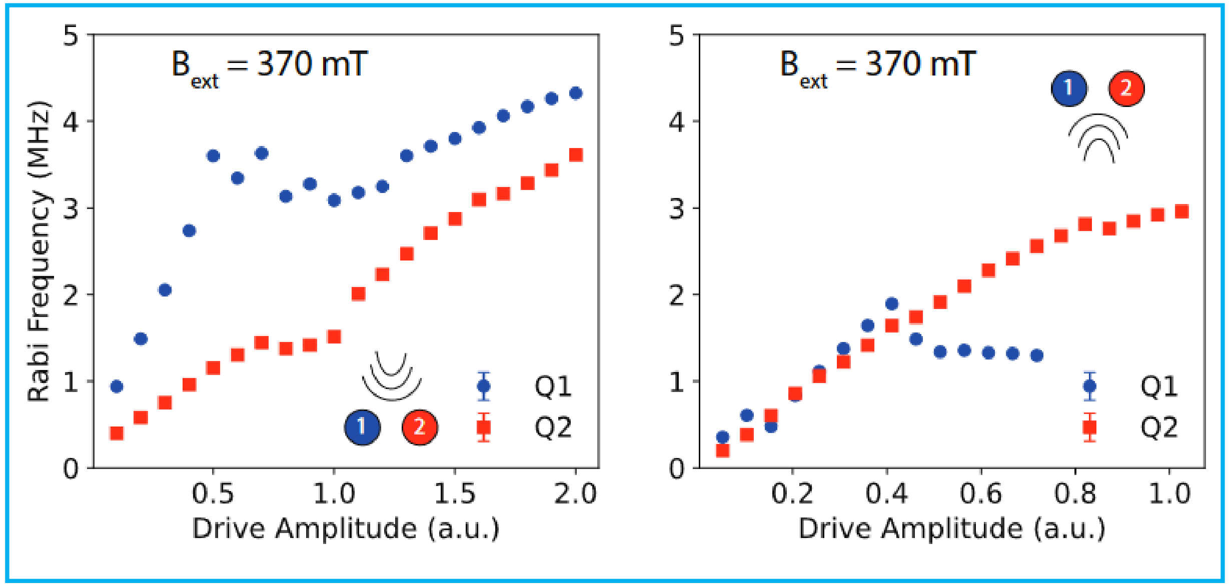
- Micromagnet gradient: nearly constant over QD length scale
- Resonance frequency shift: Would increase f_{Rabi}

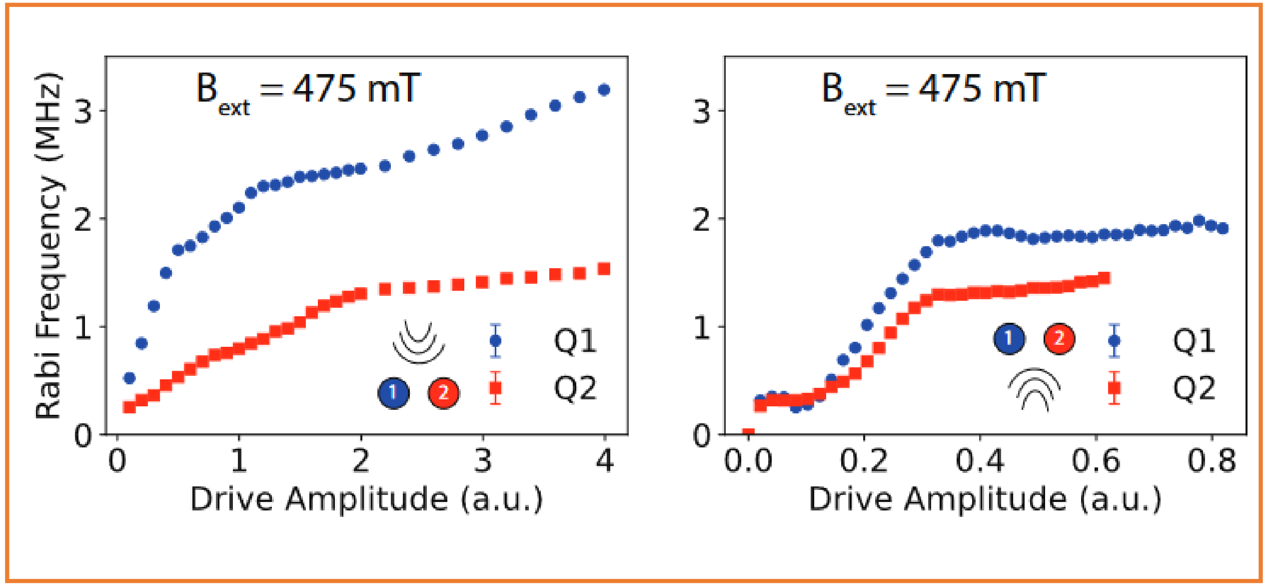
Nonlinear Rabi frequency scaling (II)

- Shape of nonlinearity changes with B_{ext} and driving gate

- Change of Q2 occupancy only weakly affects Rabi scaling of Q1:

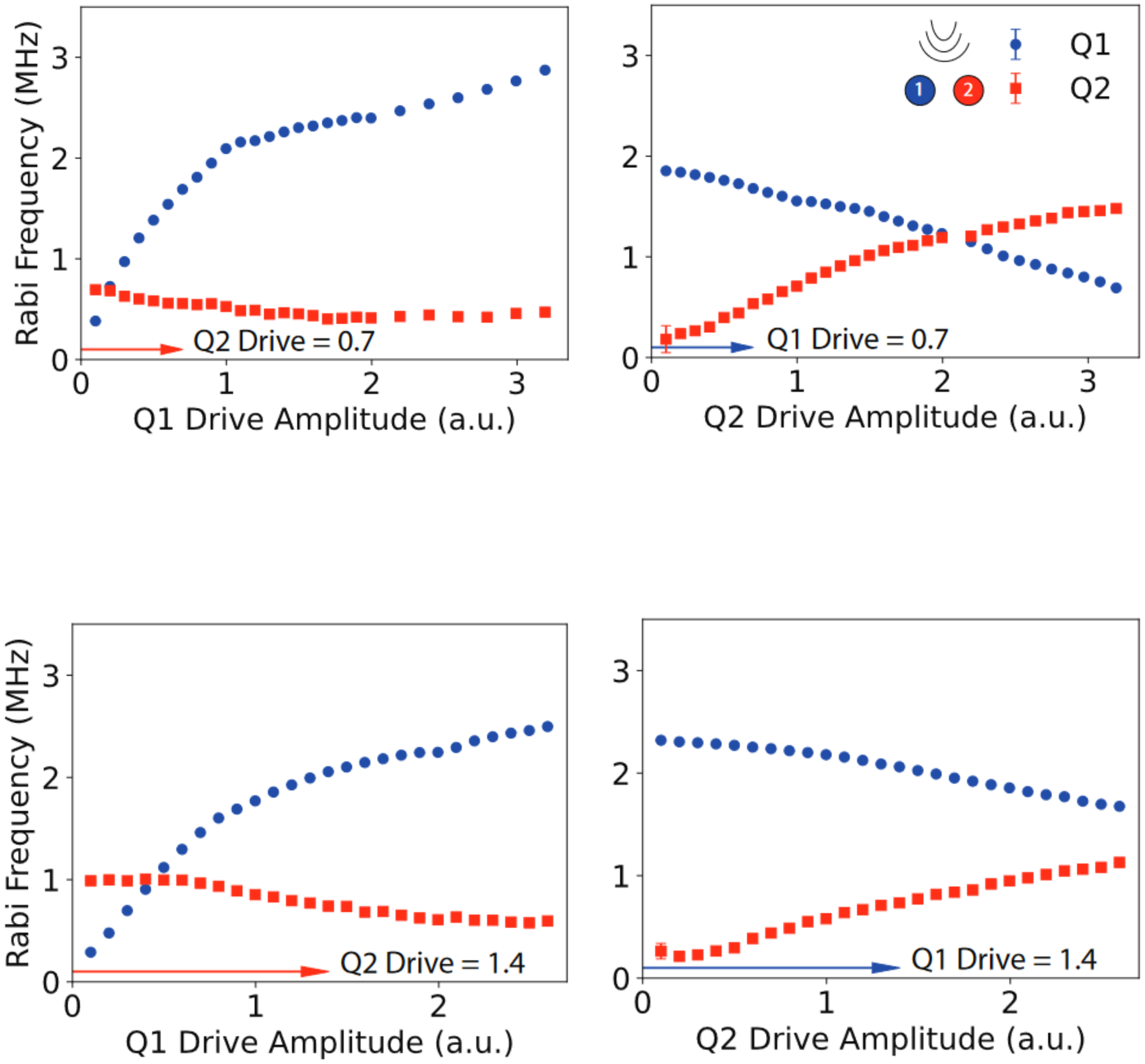






Single-qubit crosstalk

- Both qubit driving tones applied simultaneously; one of them at a fixed drive amplitude (arrow)



- Effect on f_{Rabi} is stronger when resonant tone amplitude is smaller than off-resonant tone (atleast for Q1 this seems to be the case…)

→ Crosstalk would become more severe as single-qubit operations are more densely multiplexed

Phenomenological model (I)

$$H(t) = H_0 - \frac{E_Z}{2}\sigma_z + b'_{SL}\hat{x}\vec{n}\cdot\vec{\sigma} + E'_{ac}(t)\hat{x}$$

Orbital and valley degrees of freedom of charge state

Zeeman energy $E_Z = g\mu_B B_{tot}$, with B_{tot} along σ_z spin quantization axis

$b'_{SL} = \frac{1}{2}g\mu_B|\vec{b}_{SL}|$

With $|\vec{b}_{SL}|$ the magnitude of the magnetic field along driving axis (x), and $\vec{n} = (0, \cos\theta, \sin\theta)^T$ (θ: angle of gradient relative to σ_y)

Electric drive: $E'_{ac}(t) = e\sum_k E_{ac,k}\sin(\omega_k t)$

Harmonic confinement: $H_0 = \hbar\omega_0(\hat{a}^\dagger\hat{a} + \frac{1}{2}) \rightarrow \Omega_{rabi} \propto E_{ac}$ (does not explain nonlinearity)

Anharmonic confinement: $H(t) = -\frac{\Delta_0}{2}\tau_z + E'_{ac}\sin(\omega t)\hat{x} - \frac{E_Z}{2}\sigma_z + b'_{SL}\hat{x}\sigma_x$ (Δ_0: energy splitting between ground/excited state, e.g. orbital-mediated or valley-mediated; acted on by set of Pauli operators $\{\tau_i\}$)

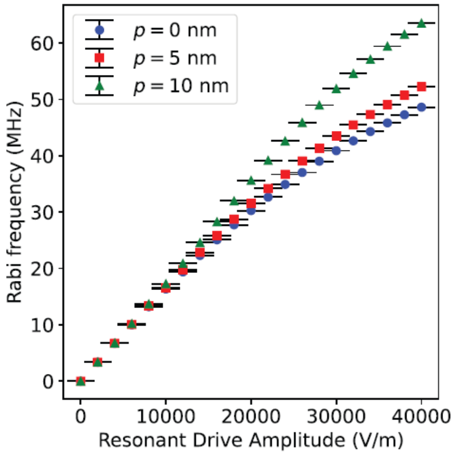
Eigenstates $|VO_0\rangle$ and $|VO_1\rangle$ may contain transverse/longitudinal terms: $\hat{x} = r\tau_x - p\tau_z$ (r: dipole transition element; p: influence of asymmetric confinement)

Phenomenological model (II)

Anharmonic confinement: $H(t) = -\frac{\Delta_0}{2}\tau_z + E'_{ac}\sin(\omega t)\hat{x} - \frac{E_Z}{2}\sigma_z + b'_{SL}\hat{x}\sigma_x$ (Δ_0: energy splitting between ground/excited state, e.g. orbital-mediated or valley-mediated; acted on by set of Pauli operators $\{\tau_i\}$)

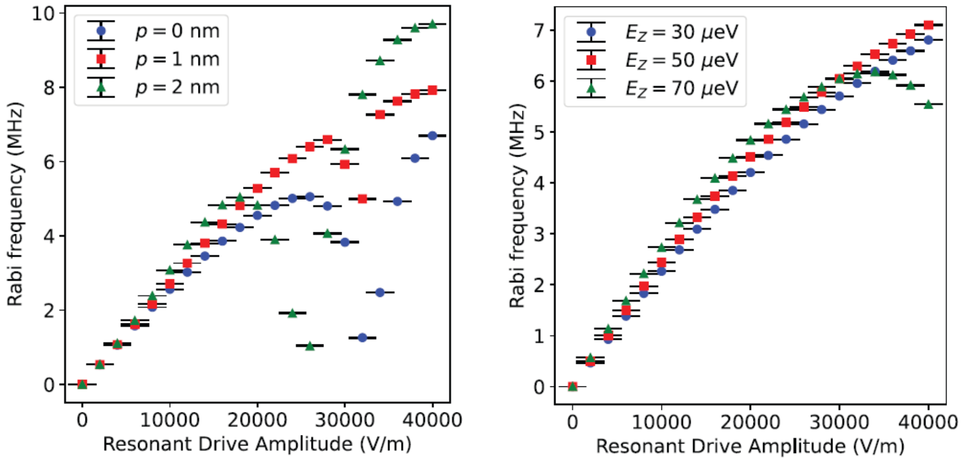
Eigenstates $|VO_0\rangle$ and $|VO_1\rangle$ may contain transverse/longitudinal terms: $\hat{x} = r\tau_x - p\tau_z$ (r: dipole transition element; p: influence of asymmetric confinement)

Orbital-mediated:



$\Delta_0 = 1\,\mathrm{meV},\ r = 20/\sqrt{2}\ \mathrm{nm},\ \mathrm{and}\ E_Z = 60\,\mu\mathrm{eV}$

Valley-mediated:

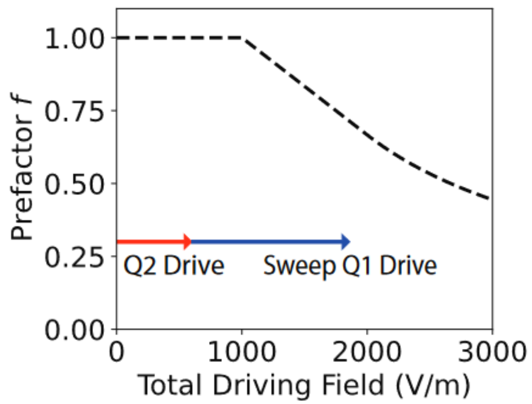


$\Delta_0 = 150\,\mu\mathrm{eV},\ r = 2\,\mathrm{nm},\ \mathrm{and}\ E_Z = 60\,\mu\mathrm{eV}.$

→ Captures saturation effect, but not full breadth of nonlinear features observed in experiment

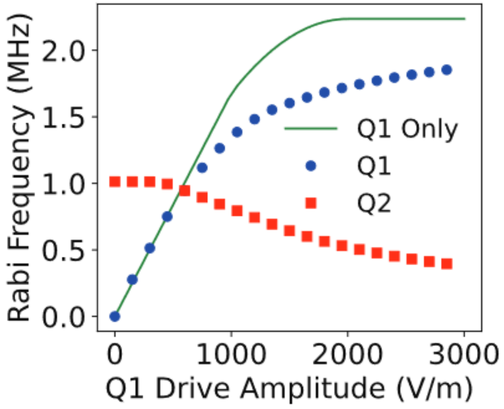
Phenomenological model (III)

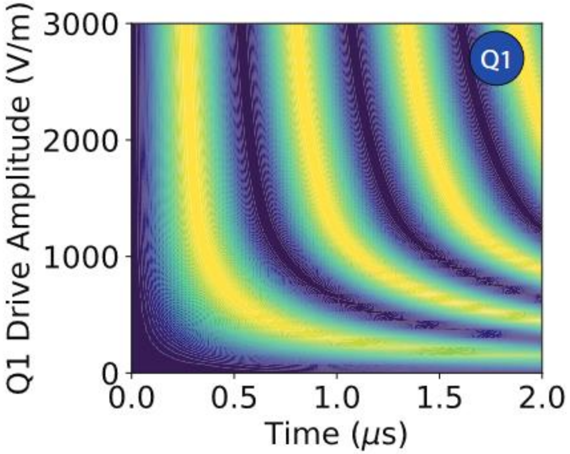
- Electric driving term in $H(t) = H_0 - \frac{E_Z}{2}\sigma_z + b'_{SL}\hat{x}\vec{n}\cdot\vec{\sigma} + E'_{ac}(t)\hat{x}$ is extended by prefactor: $\boxed{E'_{ac}(t)\hat{x} \rightarrow f(P_k,\omega_k)E'_{ac}(t)\hat{x}}$

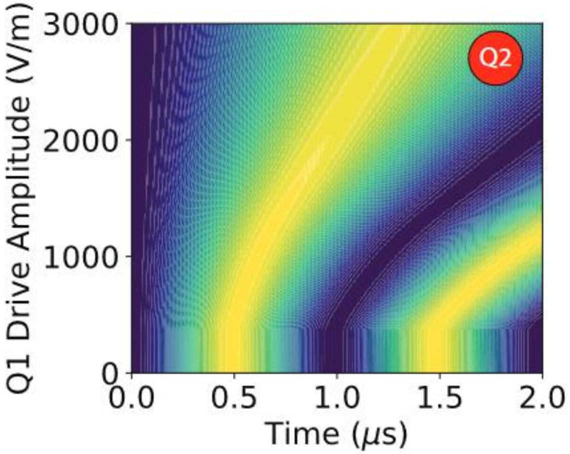


- Dependence on microwave power P_k, frequency ω_k

- Prefactor included: Rabi saturation + crosstalk as in experiment







Possible origins of nonlinearity:

- **Electric drive distortion**: Driving on same gate gives different nonlinear response depending on which qubit is addressed
  → Points to microscopic origin of nonlinearity (though, driving frequencies differ as well)

- **Device heating**: Microwave drive may induce change to QD confinement, modifying orbital structure (e.g. via device strain or filling of charge traps)

Summary

- Measurements of nonlinear Rabi frequency scaling and crosstalk effect
- EDSR Hamiltonian (harmonic&anharmonic confinement) doesn‘t capture full breadth of nonlinear effects
- Nonlinearity possibly caused by drive distortion and/or device heating
- Observed crosstalk poses a challenge for scaling via multiplexed qubit control