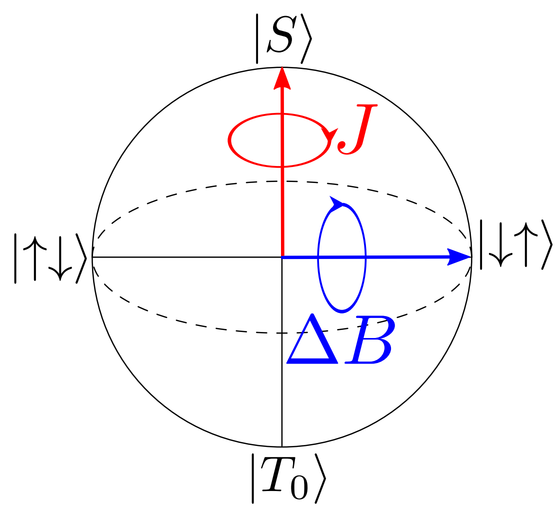
Long distance coupling of resonant exchange qubits

Maximilian Russ

Capri Spring School, 15.04.2016

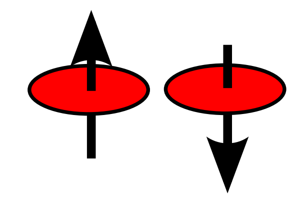
Universität Konstanz

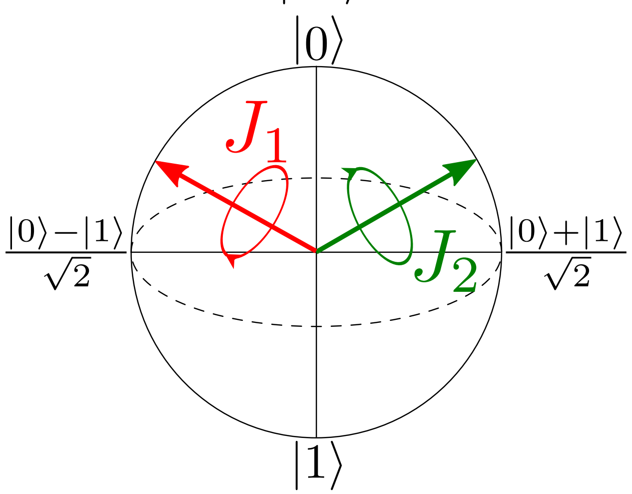
Why use multi-dot qubits?



singlet-triplet qubit

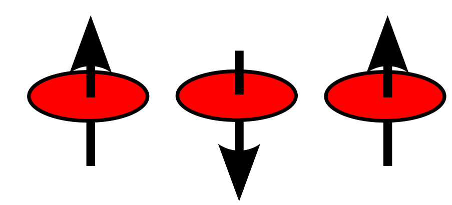
Double quantum dot
exchange + B-field gradient



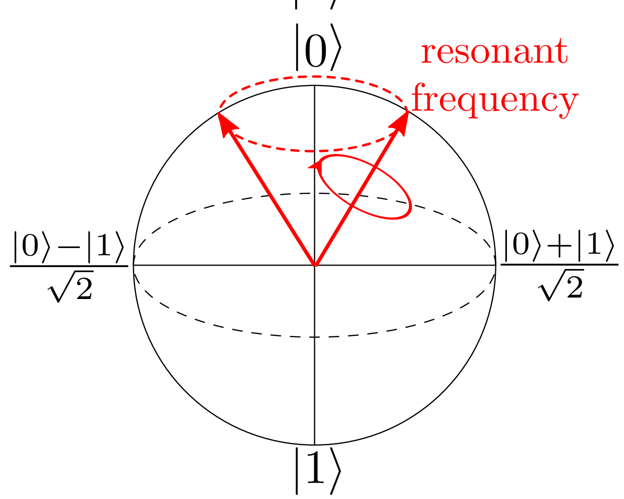


exchange-only qubit

Triple quantum dot
exchange only

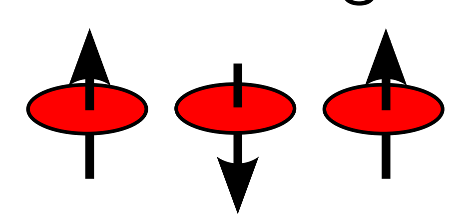


DiVincenzo et al.
Nature **408**, 339-342 (2000)



resonant exchange (RX) qubit

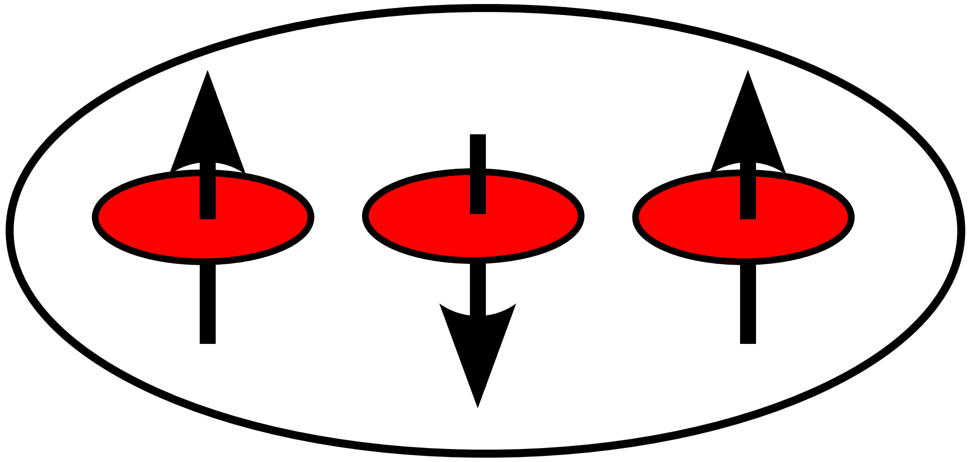
Triple quantum dot
microwave signals



Medford et al. PRL **111**, 050501 (2013)
Taylor et al. PRL **111**, 050502 (2013)

Resonant exchange (RX) qubit

three electrons in triple quantum dot



Resonant exchange (RX) qubit

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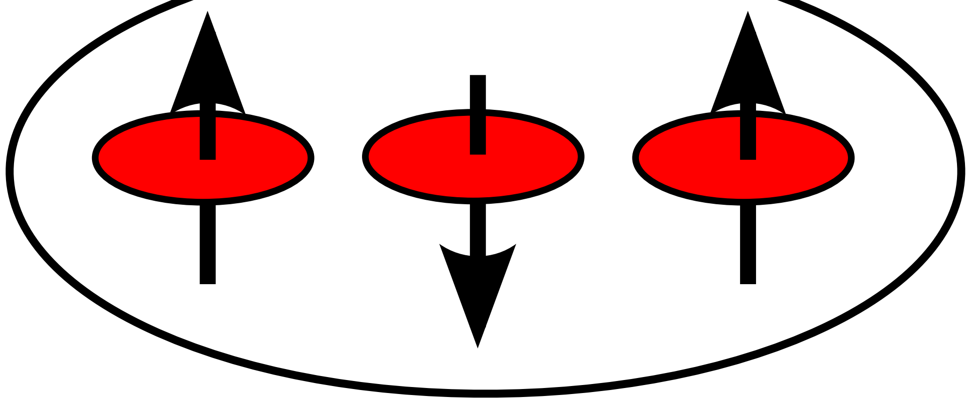

Single qubit gates by resonant driving

Medford et al., PRL 111, 050501 (2013)

Taylor et al., PRL 111, 050502 (2013)

Resonant exchange (RX) qubit

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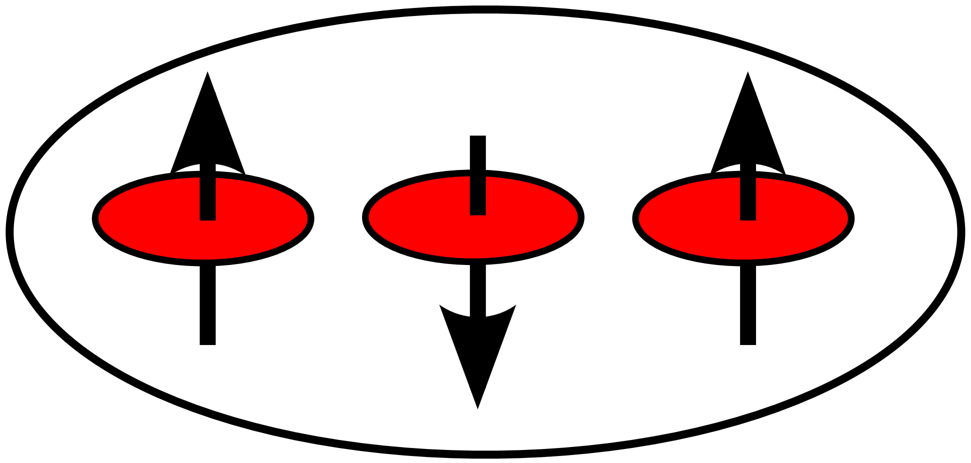

Single qubit gates by resonant driving

Medford et al., PRL 111, 050501 (2013)

Taylor et al., PRL 111, 050502 (2013)

Long coherence

Medford et al., PRL 111, 050501 (2013)

Taylor et al., PRL 111, 050502 (2013)

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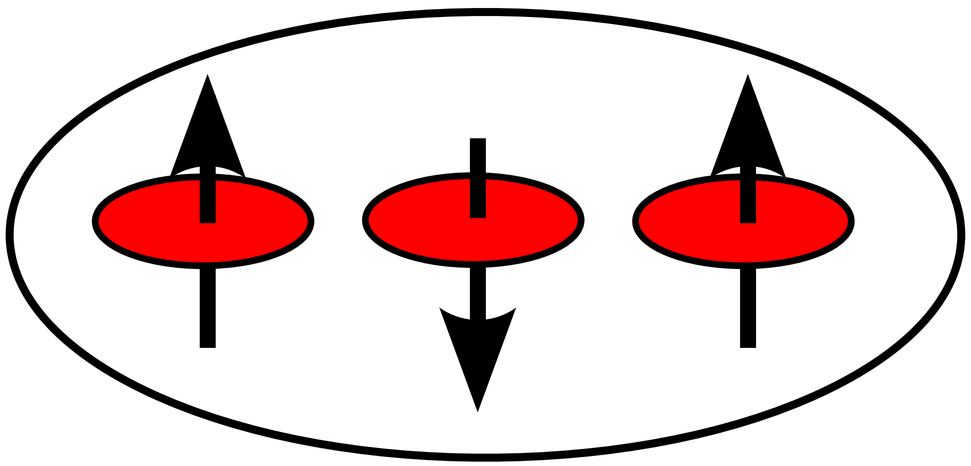
Phys. Rev. B **91**, 235411 (2015)

Resonant exchange (RX) qubit

three electrons in triple quantum dot



Single qubit gates by resonant driving

Medford et al., PRL 111, 050501 (2013)

Taylor et al., PRL 111, 050502 (2013)

Long coherence

Medford et al., PRL 111, 050501 (2013)

Taylor et al., PRL 111, 050502 (2013)

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Strong dipole coupling

Taylor et al., PRL 111, 050502 (2013)

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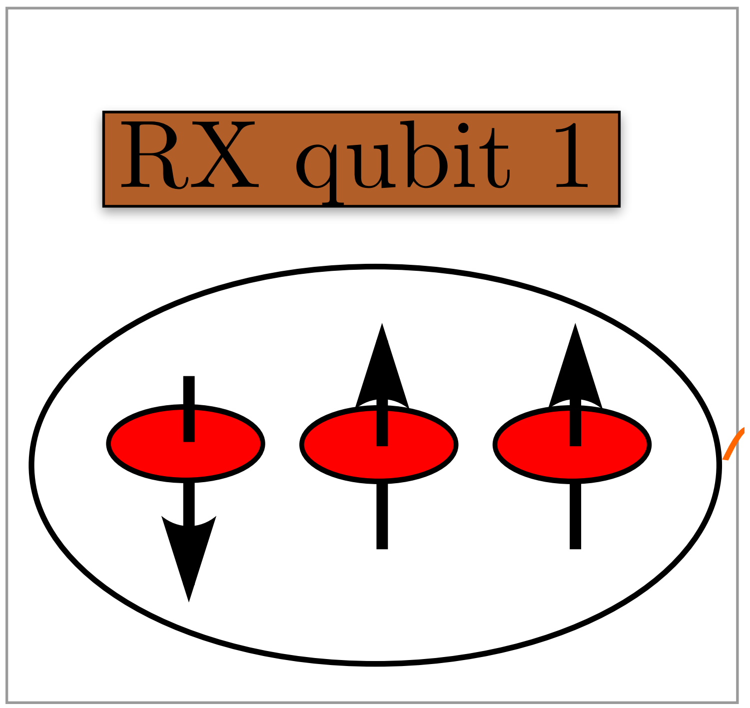
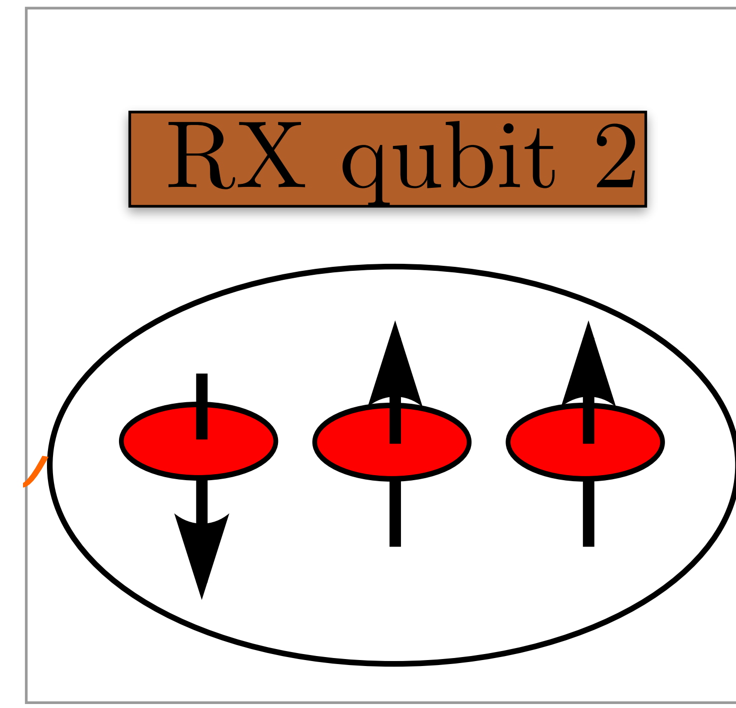
Phys. Rev. B **92**, 205412 (2015)

Long range interaction (Motivation)

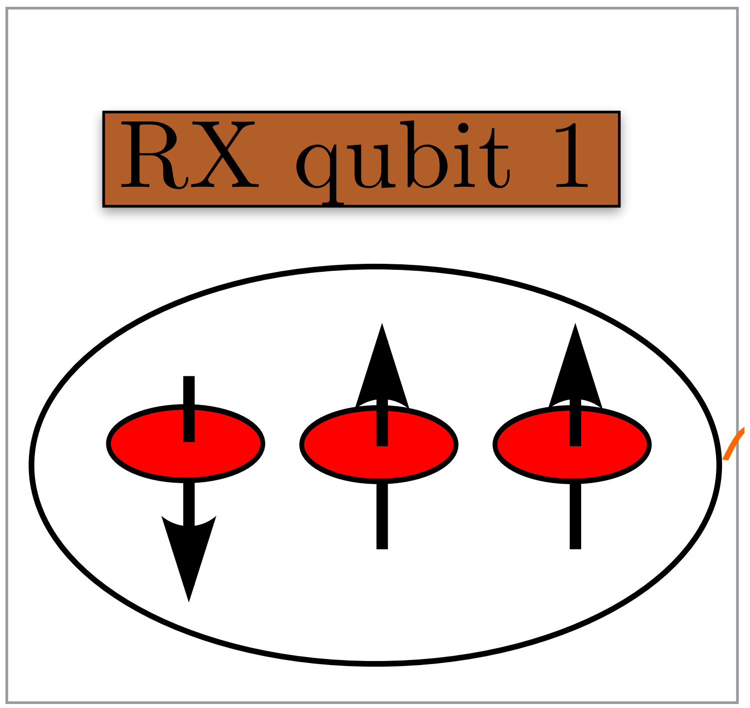


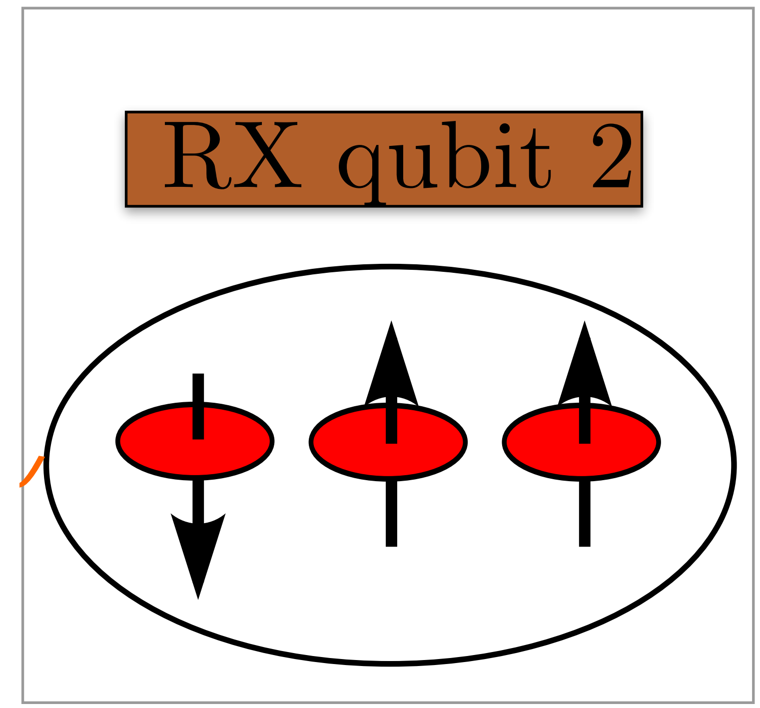


Known:
Exchange Coupling (short range)

Andrew C. Doherty and Matthew P. Wardrop
Phys. Rev. Let. **111**, 050503 (2013)

Long range interaction (Motivation)



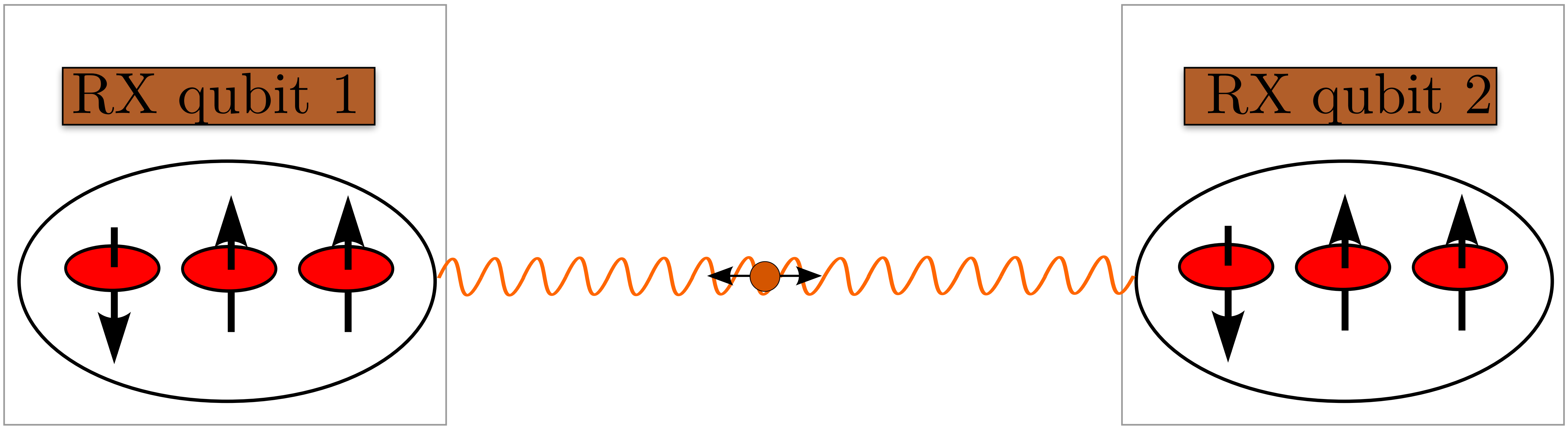


Known:
Exchange Coupling (short range)

Andrew C. Doherty and Matthew P. Wardrop
Phys. Rev. Let. **111**, 050503 (2013)

Central Goal:
Fast long-range two-qubit interaction

Long range interaction (Motivation)



New:
Photon mediated Coupling

Maximilian Russ and Guido Burkard
Phys. Rev. B **92**, 205412 (2015)

Central Goal:
Fast long-range two-qubit interaction

Model: Setup

- two TQD qubits in a shared microwave cavity:

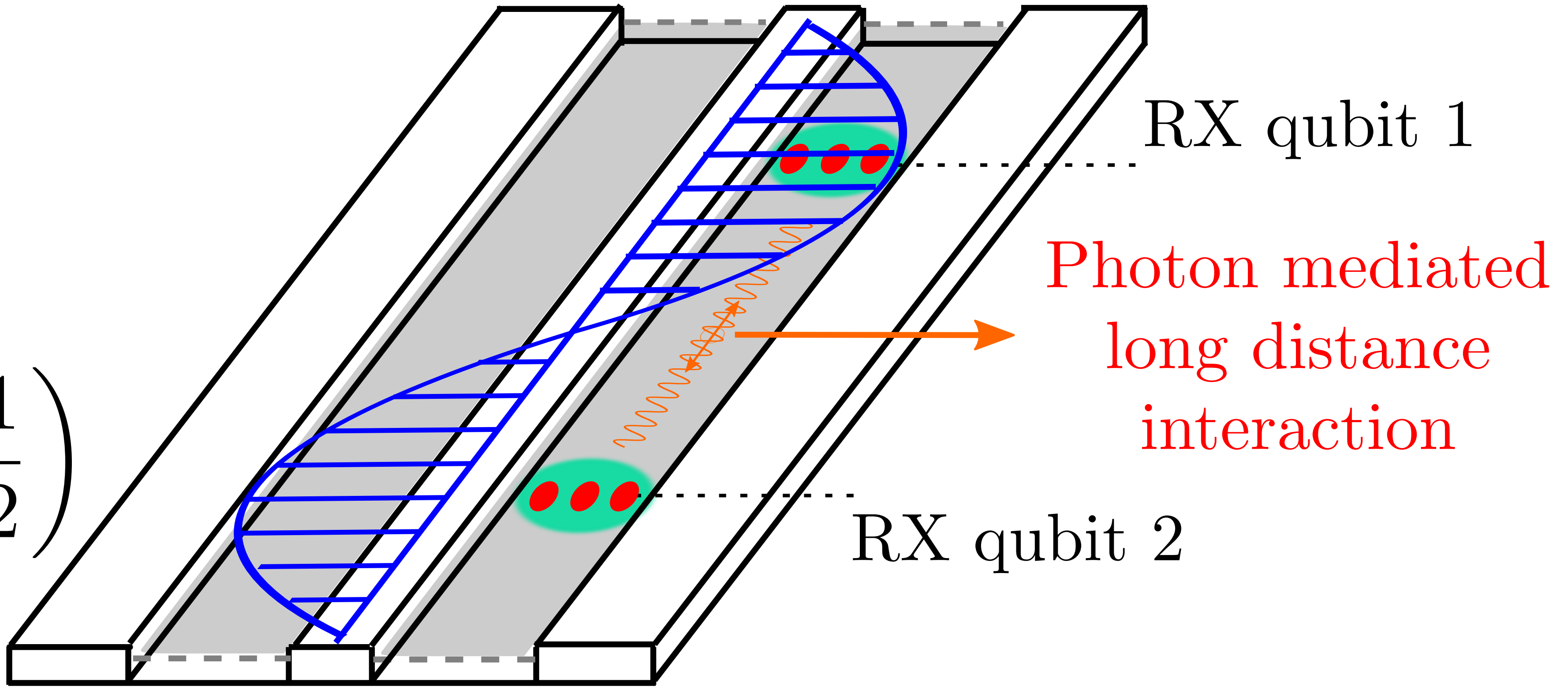
$$H = \sum_{i=1,2} (H_i + H_{\text{int},i}) + H_{\text{cav}}$$

- Qubit Hamiltonian:

$$H_i = \frac{\hbar\omega_{\text{RX},i}}{2}\sigma_z$$

- Cavity Hamiltonian

$$H_{\text{cav}} = \hbar\omega_{\text{ph}}\left(a^\dagger a + \frac{1}{2}\right)$$



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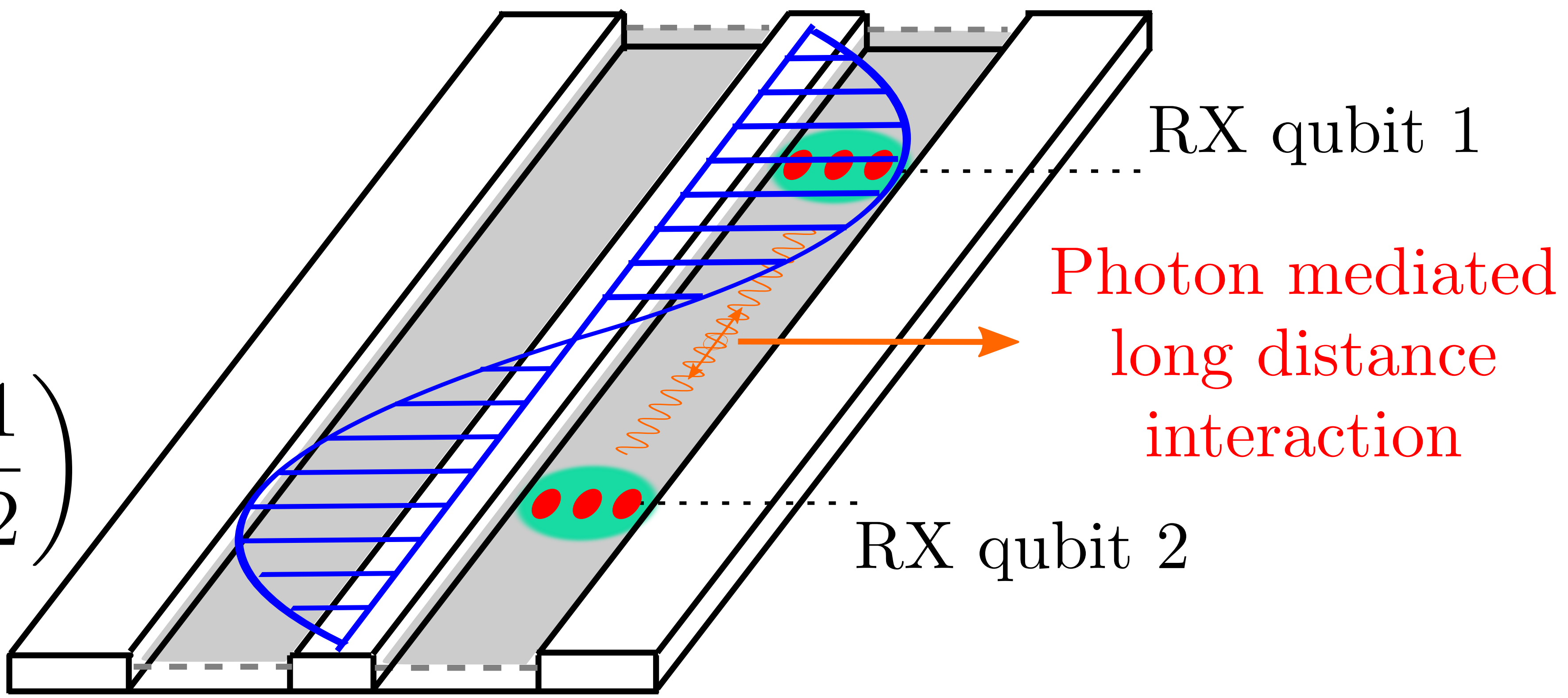
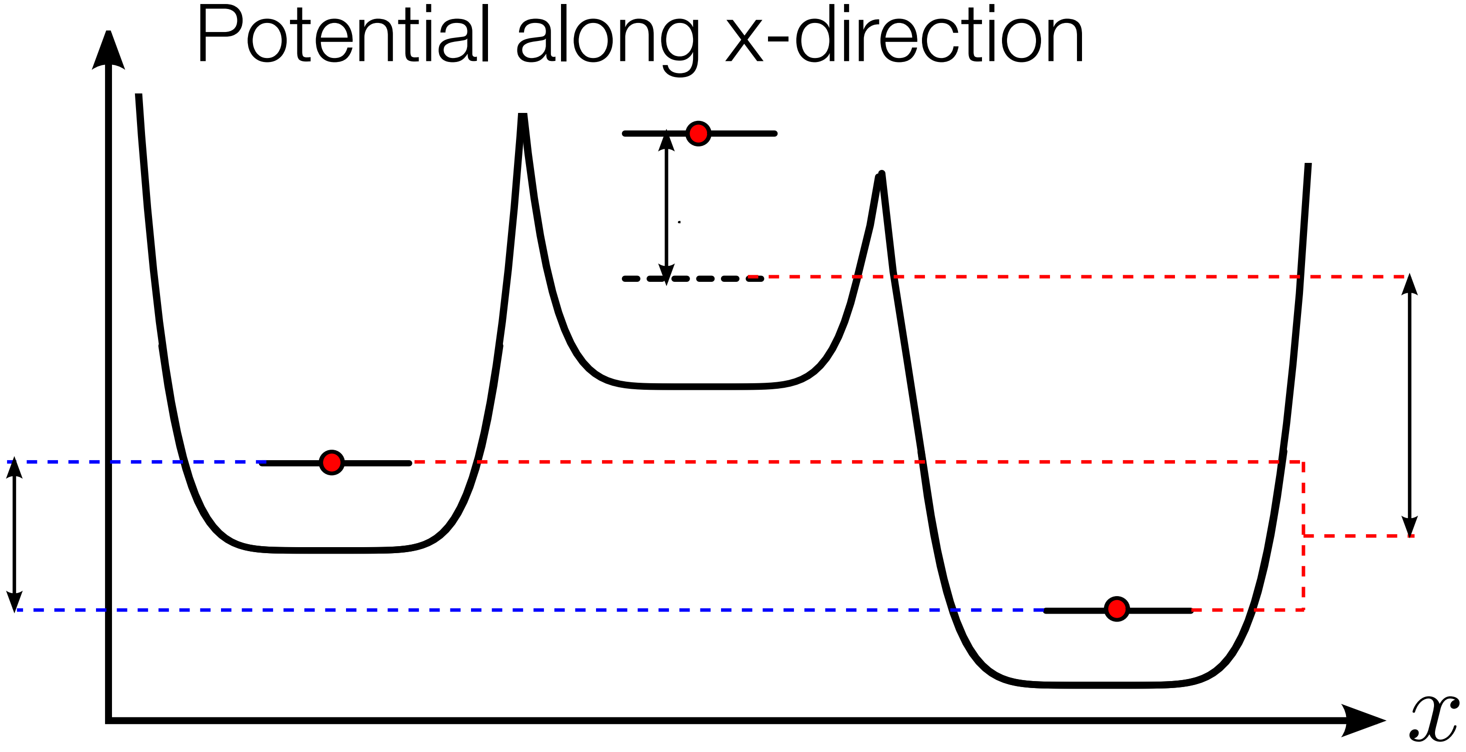


Central Task:
Find interaction Hamiltonian

Coupling between cavity and RX qubit

- coupling to detuning parameters:

Potential along x-direction

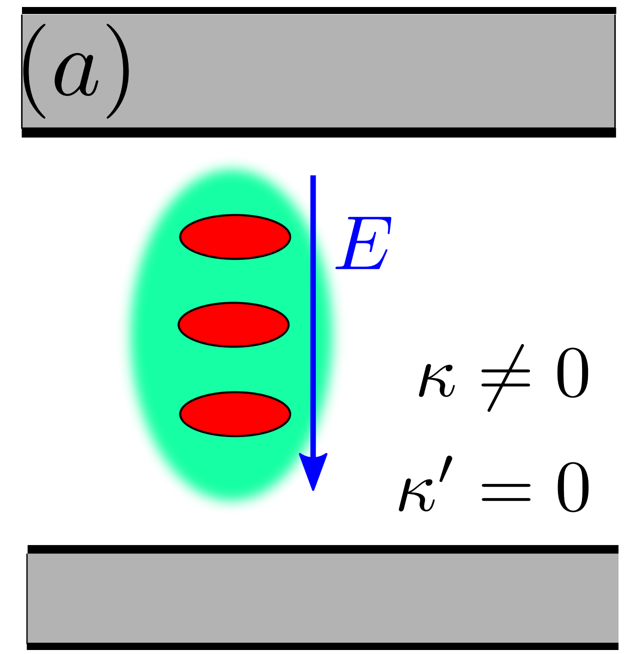


Coupling between cavity and RX qubit

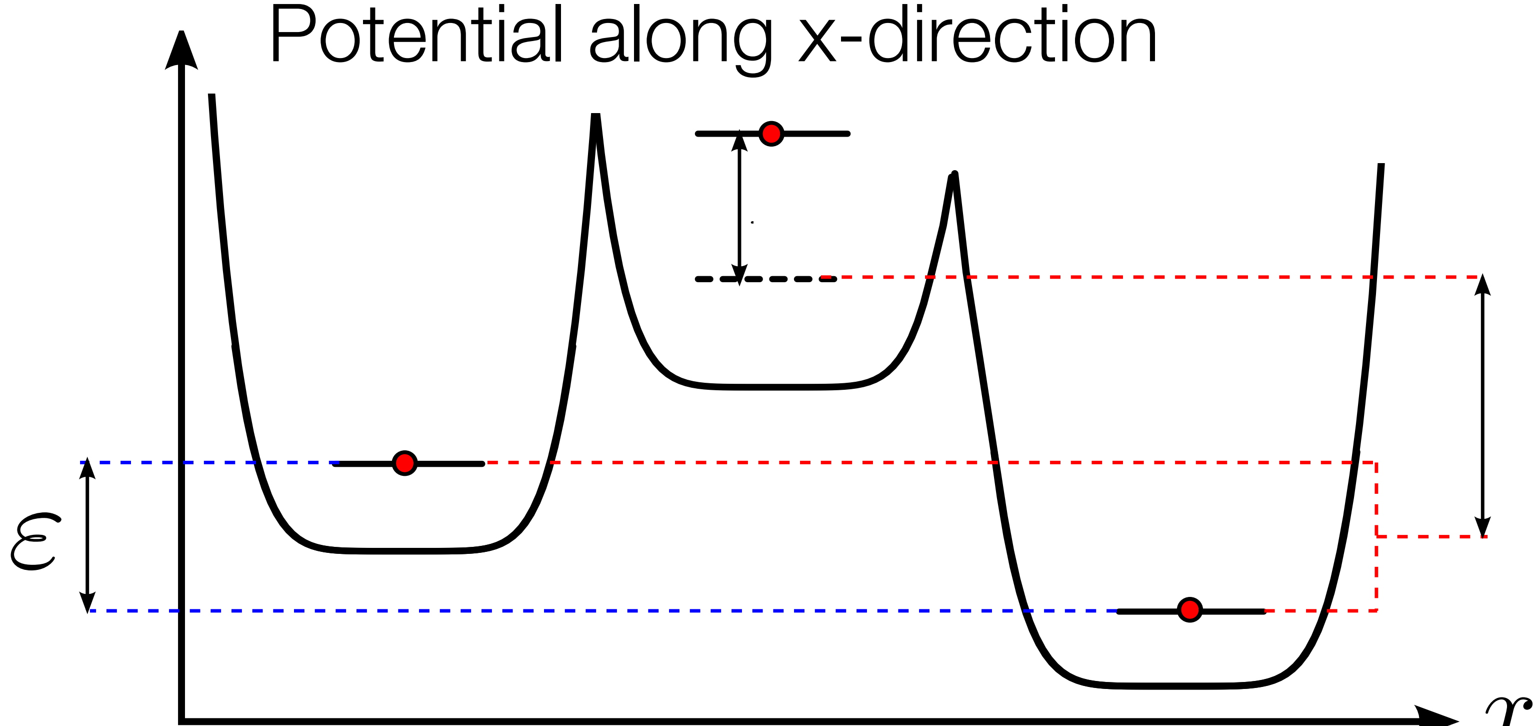
- coupling to detuning parameters:

  (a) Energy difference left right QD

$$\varepsilon \to \varepsilon + \kappa(a + a^\dagger)$$



Potential along x-direction



Coupling between cavity and RX qubit

- coupling to detuning parameters:

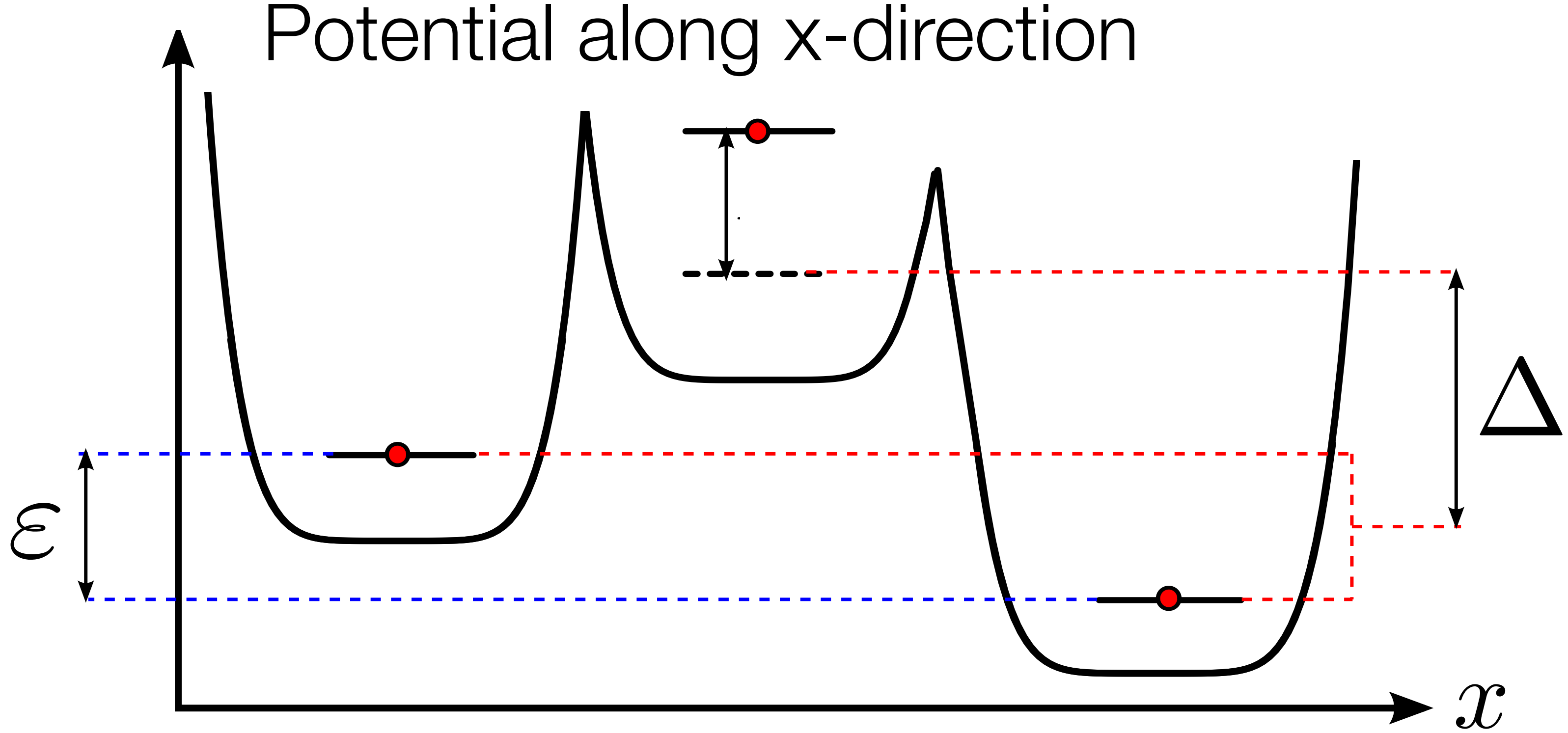
  (a) Energy difference left right QD

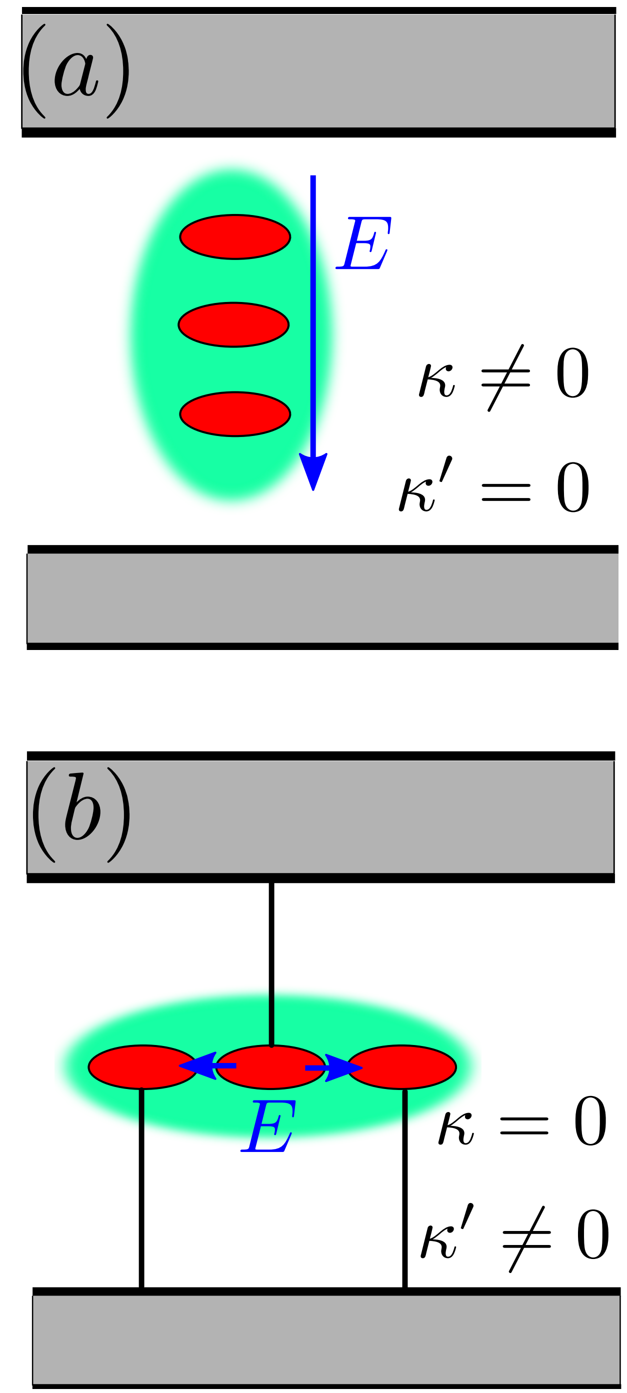
  $$\varepsilon \to \varepsilon + \kappa(a + a^\dagger)$$

  (b) Energy difference inner outer QD

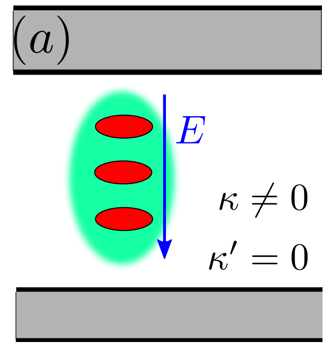
  $$\Delta \to \Delta + \kappa'(a + a^\dagger)$$

Potential along x-direction





Microscopic model



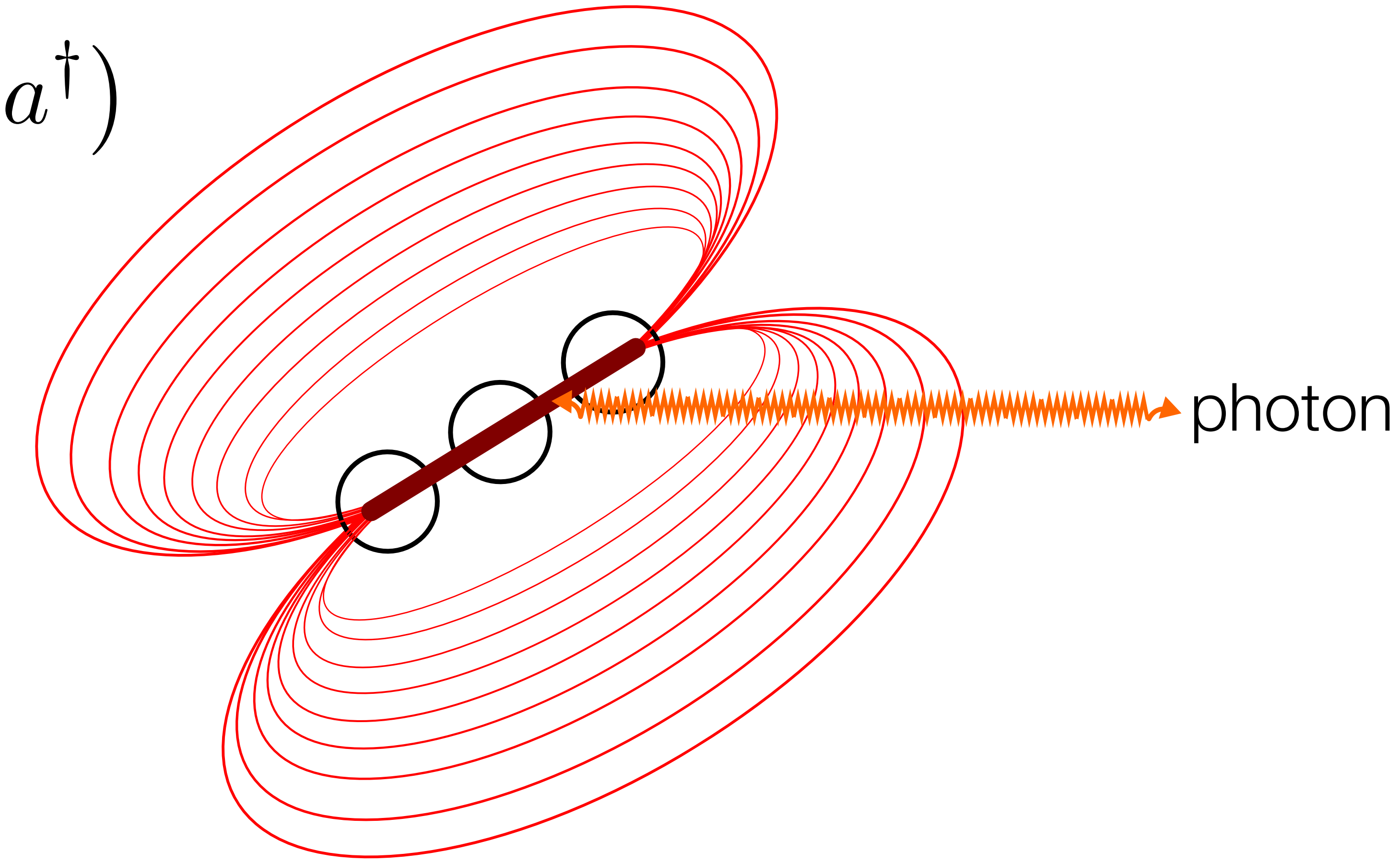
- Electric-dipole coupling Hamiltonian:

$$H_{\text{int}} = -\frac{e}{m}\mathcal{A}\boldsymbol{\epsilon}\cdot\boldsymbol{p}\left(a + a^{\dagger}\right)$$

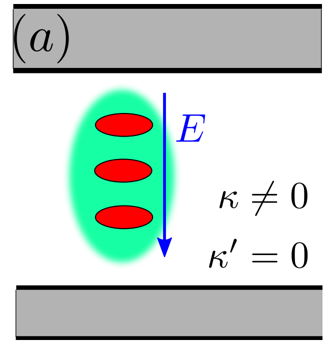
- Coupling strength:

$$g_r = -\frac{e}{m}\mathcal{A}\left\langle 0\right|\boldsymbol{\epsilon}\cdot\boldsymbol{p}\left|1\right\rangle$$

$$\mathcal{A} = \frac{E_0}{\omega_{\text{ph}}}$$



Microscopic model



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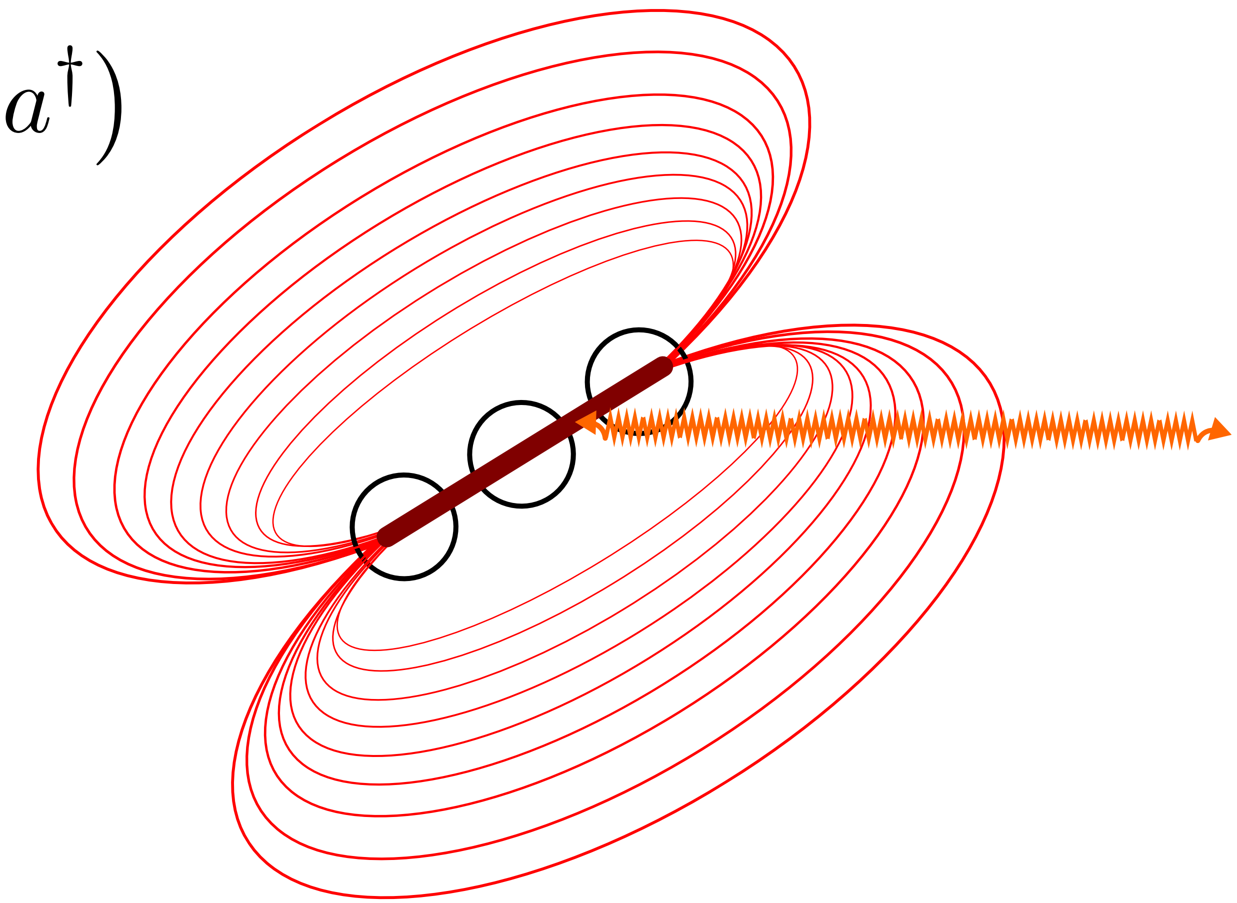
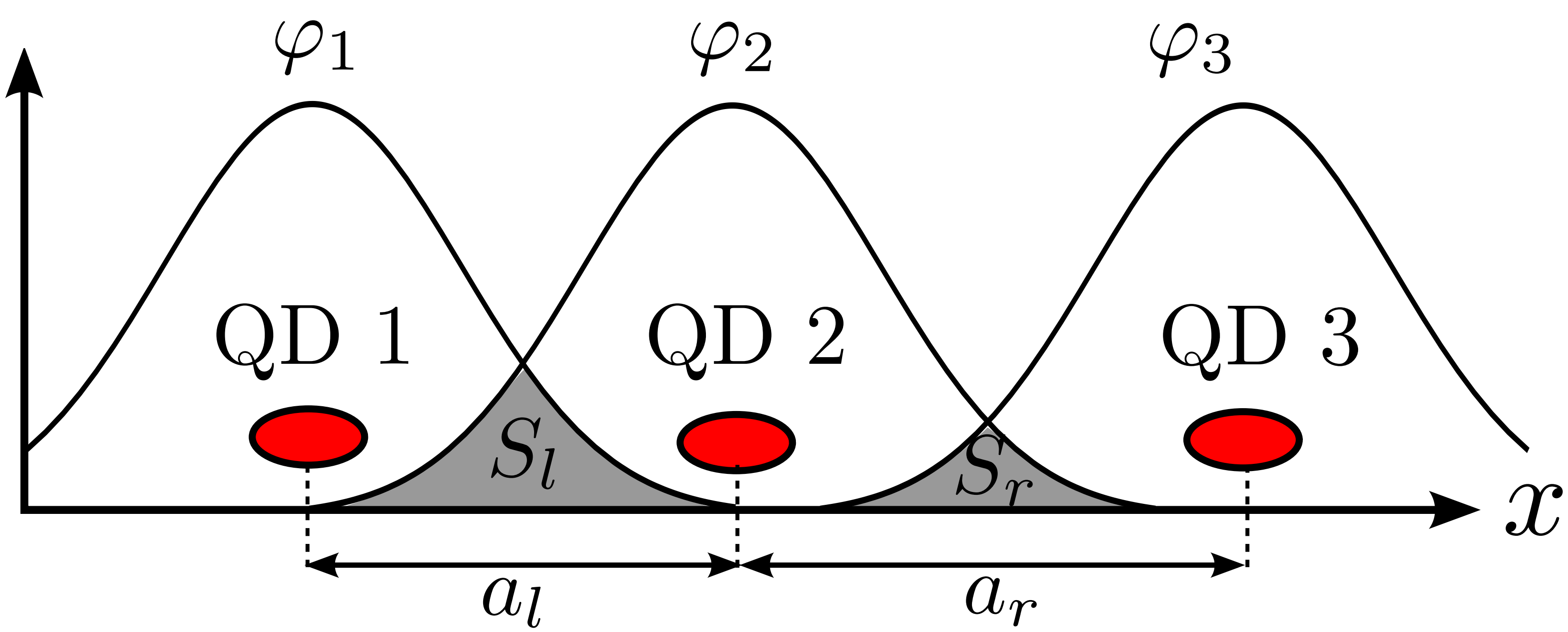


Central Task:
Calculation of dipole matrix element

Orthonormalized Wannier functions

$$|0,1\rangle \in \{|\varphi_1\rangle \otimes |\varphi_2\rangle \otimes |\varphi_3\rangle\}$$



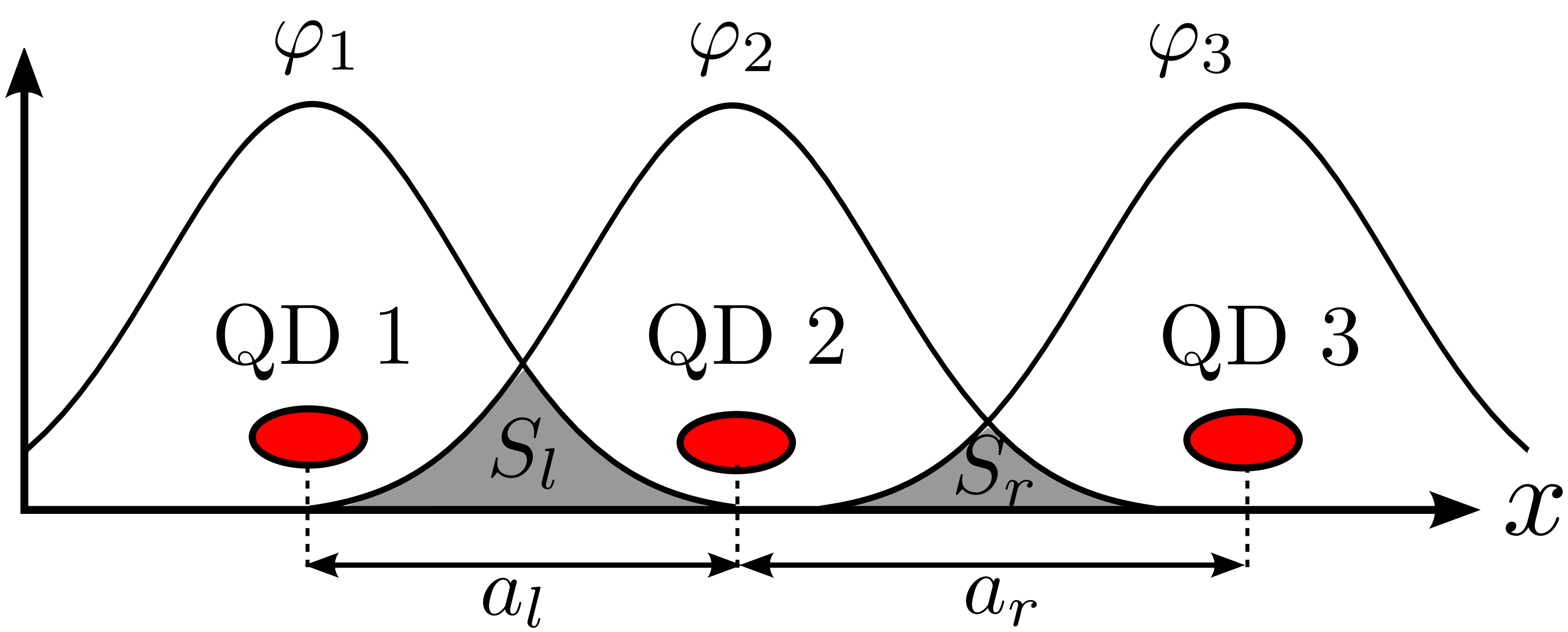
overlaps

$$S_l = \langle\varphi_1|\varphi_2\rangle$$

$$S_r = \langle\varphi_3|\varphi_2\rangle$$

Orthonormalized Wannier functions

$|0,1\rangle \in \{|\varphi_1\rangle \otimes |\varphi_2\rangle \otimes |\varphi_3\rangle\}$



overlaps

$$S_l = \langle \varphi_1 | \varphi_2 \rangle$$

$$S_r = \langle \varphi_3 | \varphi_2 \rangle$$

Problem: $S_l \neq 0$ and $S_r \neq 0$

Orthonormalized Wannier functions

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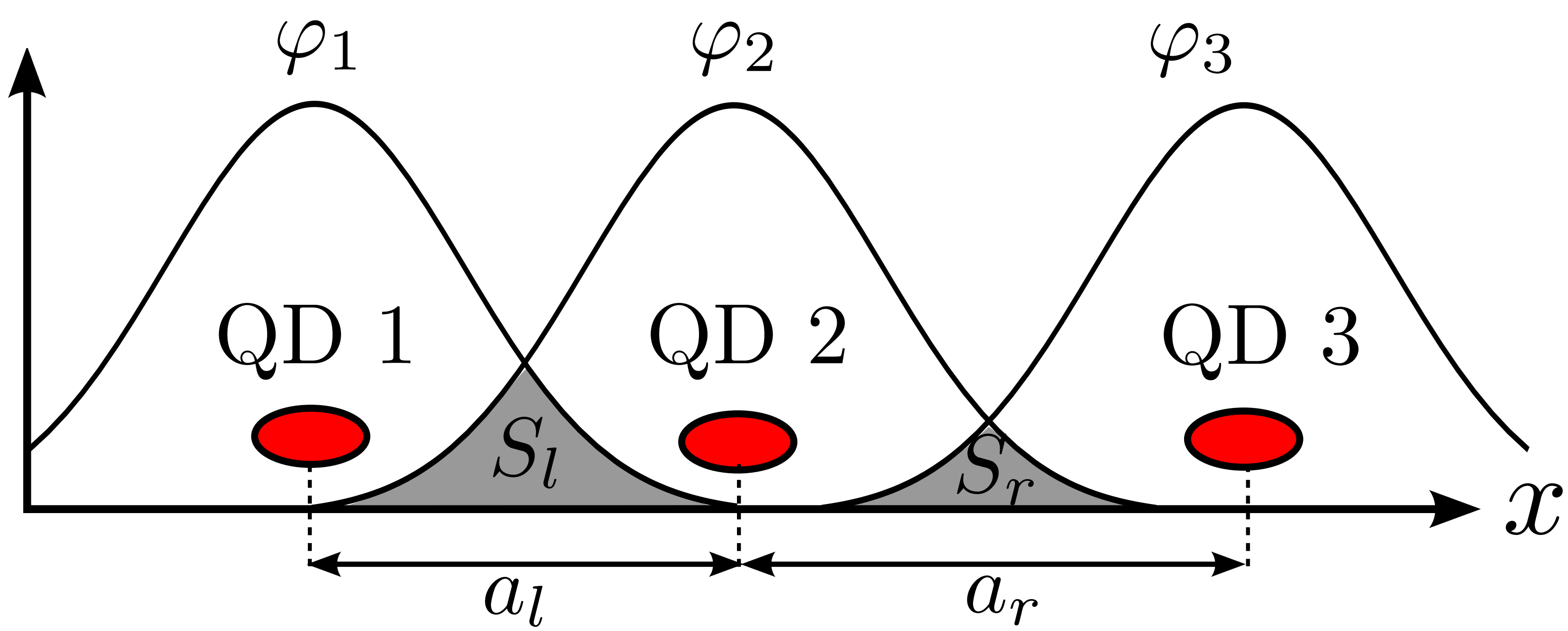

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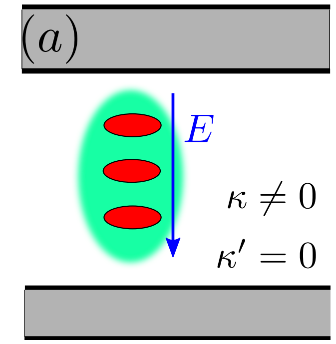
$$S_l = \langle \varphi_1 | \varphi_2 \rangle$$

$$S_r = \langle \varphi_3 | \varphi_2 \rangle$$

Problem: $S_l \neq 0$ and $S_r \neq 0$

Solution: Construct $|\Phi_i\rangle = \sum_{j=1}^{3} a_{i,j} |\varphi_j\rangle$ with $\langle \Phi_i | \Phi_j \rangle = \delta_{ij}$

Result (qubit-cavity coupling)

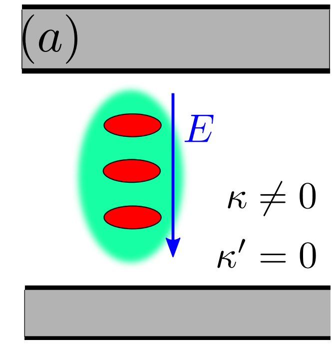


$$g_r = \frac{eE_0}{\hbar\omega_{\mathrm{ph}}}\Big\{\sqrt{3}\frac{t_l t_r \varepsilon}{\Delta^2-\varepsilon^2}\mathrm{Re}\,(x_{13})\,\sigma_y$$

$$+\Big[\frac{t_l t_r \varepsilon}{\Delta^2-\varepsilon^2}\mathrm{Im}\,(x_{13}) + \sqrt{2}t_r\mathrm{Im}(x_{23}) - \sqrt{2}t_l\mathrm{Im}(x_{12})\Big]\sigma_z$$

$$-\sqrt{6}\left[t_l\mathrm{Im}(x_{12}) + t_r\mathrm{Im}(x_{23})\right]\sigma_x\Big\}$$

Result (qubit-cavity coupling)

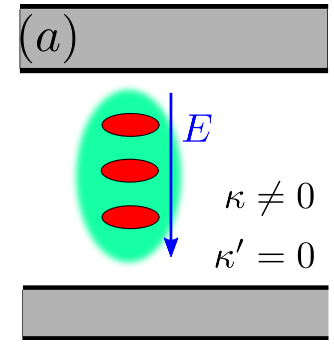


$$g_r = \frac{eE_0}{\hbar\omega_{\rm ph}}\left\{\sqrt{3}\frac{t_l t_r \varepsilon}{\Delta^2-\varepsilon^2}\mathrm{Re}\left(x_{13}\right)\sigma_y + \left[\frac{t_l t_r \varepsilon}{\Delta^2-\varepsilon^2}\mathrm{Im}\left(x_{13}\right) + \sqrt{2}t_r\mathrm{Im}(x_{23}) - \sqrt{2}t_l\mathrm{Im}(x_{12})\right]\sigma_z - \sqrt{6}\left[t_l\mathrm{Im}(x_{12}) + t_r\mathrm{Im}(x_{23})\right]\sigma_x\right\}$$

Dipole matrix elements

$$x_{ij} = \langle\Phi_i|\,\hat{x}\,|\Phi_j\rangle \in \mathbb{R}$$

Result (qubit-cavity coupling)



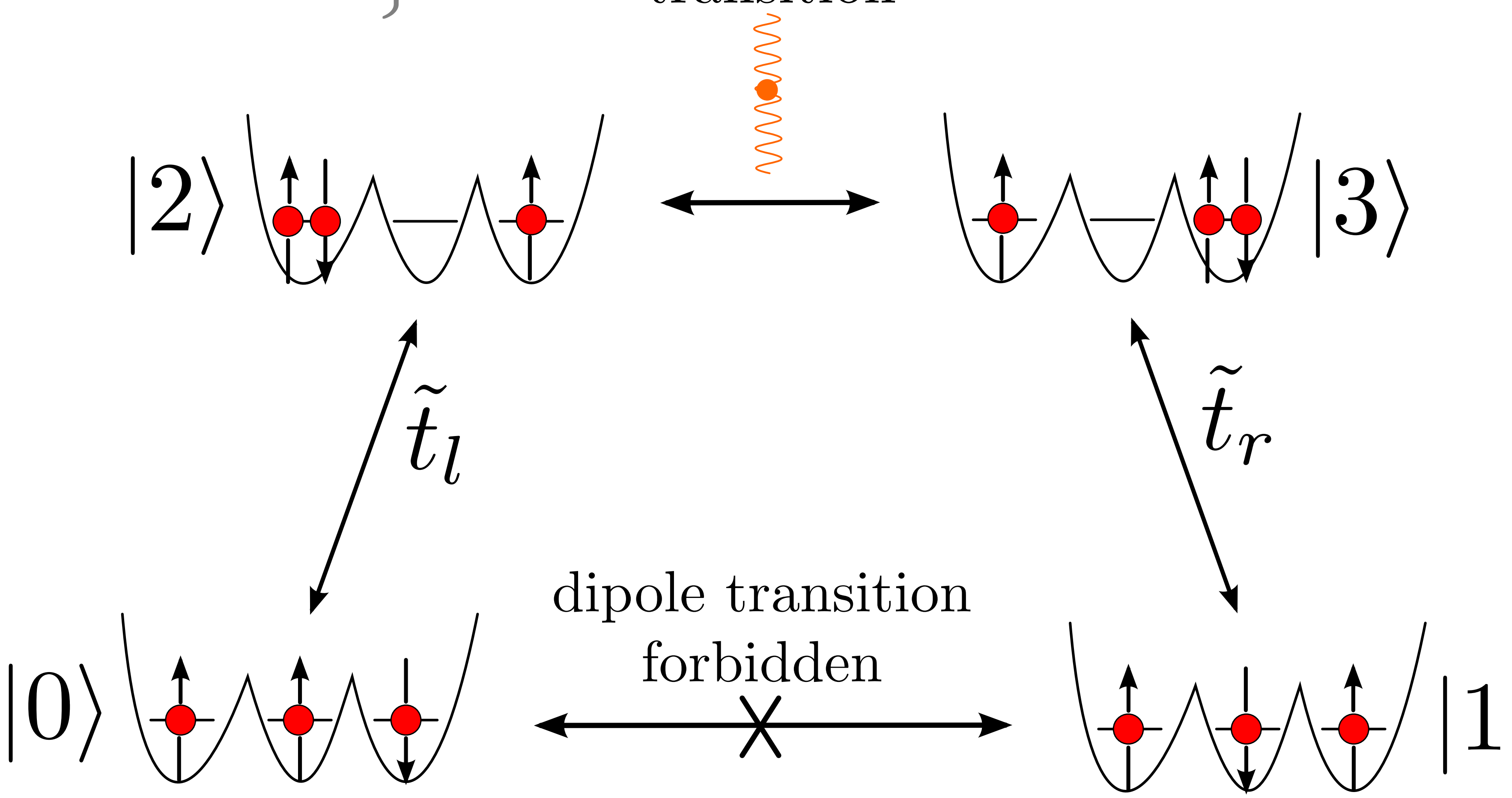
$$g_r = \frac{eE_0}{\hbar\omega_{\rm ph}} \Big\{ \sqrt{3}\frac{t_l t_r \varepsilon}{\Delta^2 - \varepsilon^2} \mathrm{Re}\left(x_{13}\right)\sigma_y$$

$$+ \left[\frac{t_l t_r \varepsilon}{\Delta^2 - \varepsilon^2} \mathrm{Im}\left(x_{13}\right) + \sqrt{2} t_r \mathrm{Im}(x_{23}) - \sqrt{2} t_l \mathrm{Im}(x_{12}) \right] \sigma_z$$

$$-\sqrt{6}\left[t_l \mathrm{Im}(x_{12}) + t_r \mathrm{Im}(x_{23})\right]\sigma_x \Big\}$$

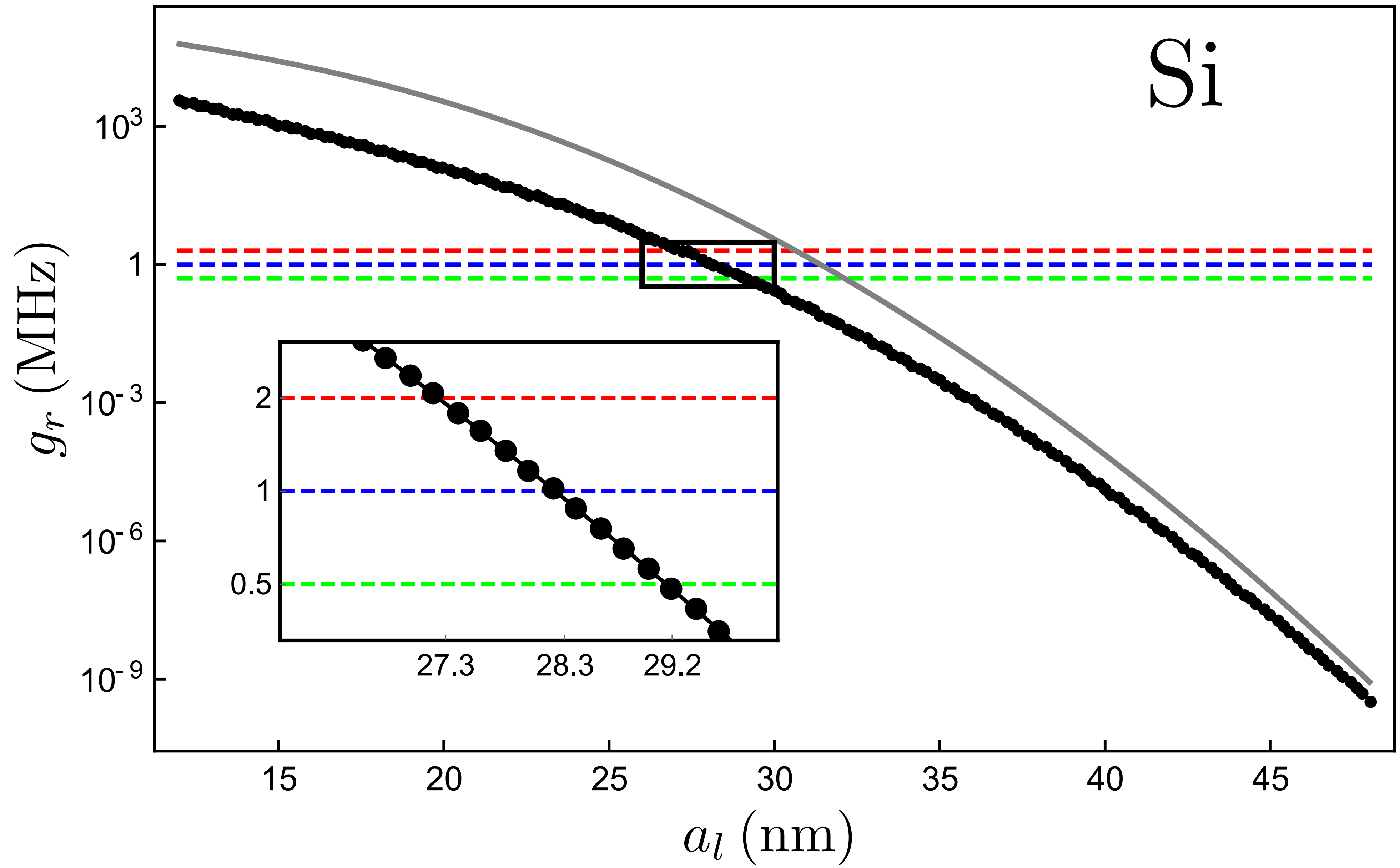
Dipole matrix elements

$$x_{ij} = \langle \Phi_i | \hat{x} | \Phi_j \rangle \in \mathbb{R}$$



Results (two-qubit gates)

$$g_{\mathrm{r}} = -\frac{\sqrt{3}\, e\, E_0}{2\hbar\omega_{\mathrm{ph}}} \frac{t_l t_r \varepsilon}{\Delta^2 - \varepsilon^2} \tilde{a}_{\mathrm{rel}} \left(a_l - a_r\right) S_l S_r$$



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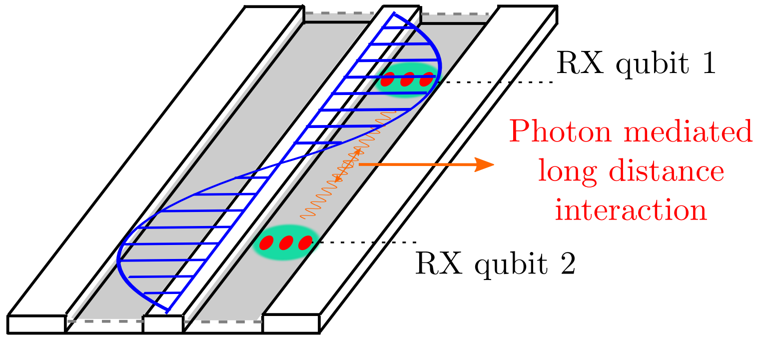
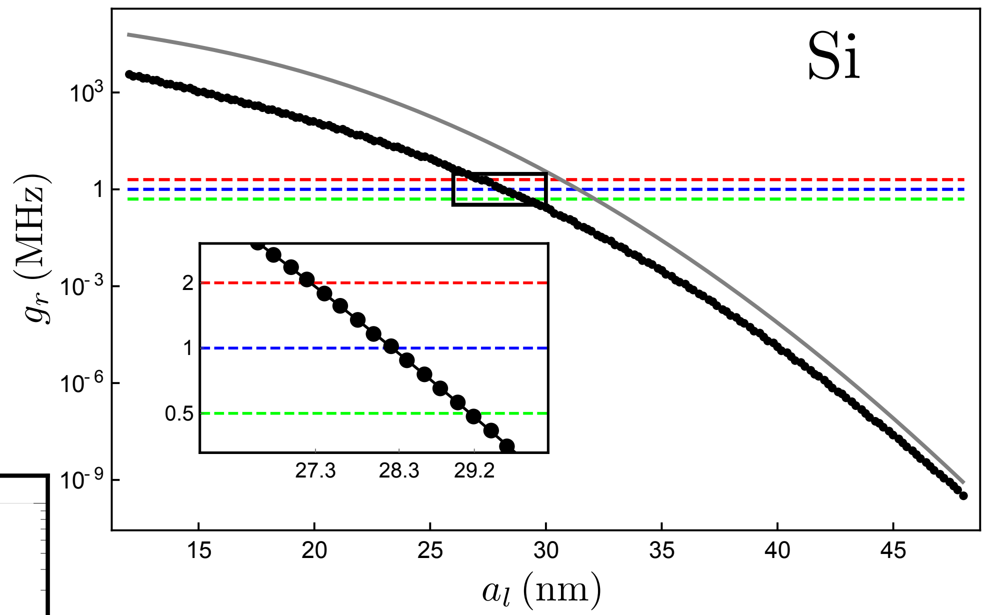
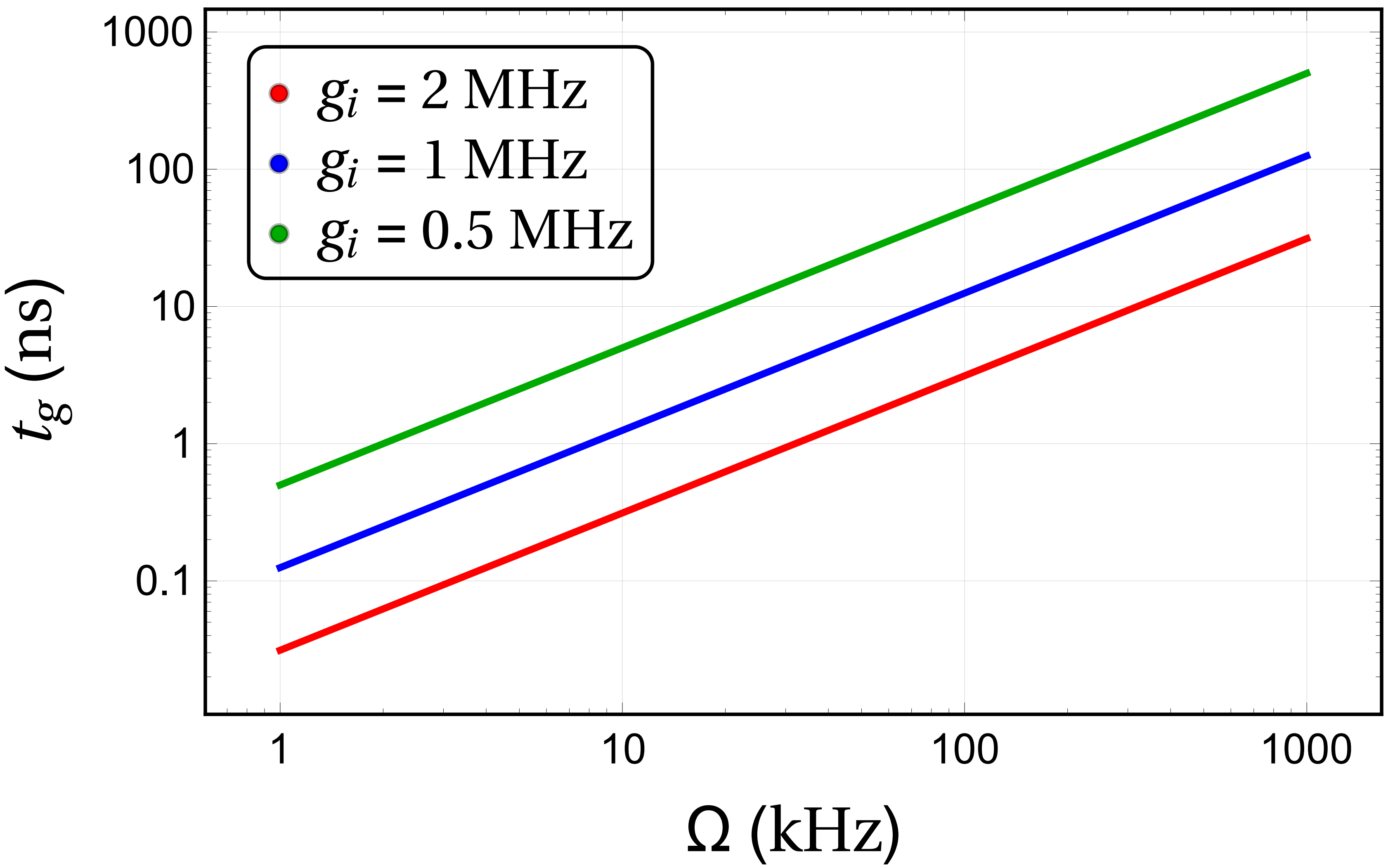


$$g_{\rm r} = -\frac{\sqrt{3}\, e\, E_0}{2\hbar\omega_{\rm ph}} \frac{t_l t_r \varepsilon}{\Delta^2 - \varepsilon^2} \tilde{a}_{\rm rel} \left(a_l - a_r\right) S_l S_r$$

$t_g = \pi^2 \hbar^2 \Omega / 2 g_r^2$ two-qubit gate time



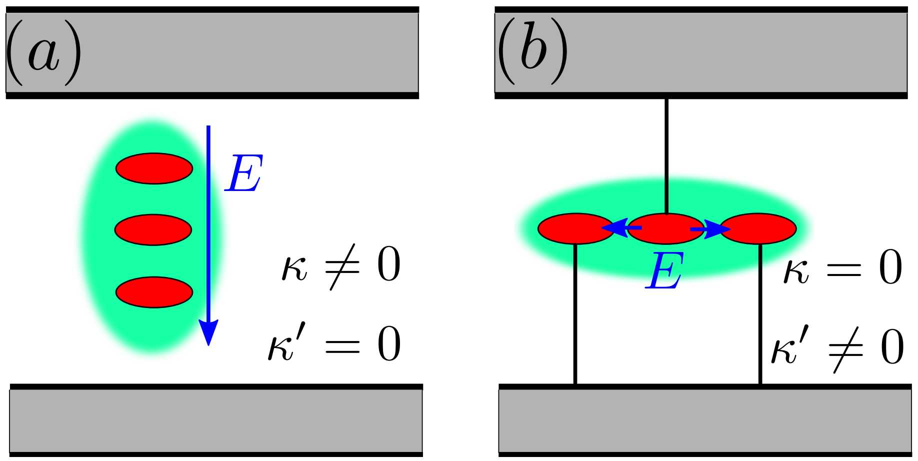


Detuning resonance frequency and cavity

$$\Omega = |\omega_{\rm RX} - \omega_{\rm ph}|$$

Summary and Conclusion

- 2 different alignments of RX qubit in cavity
  - (a) asymmetric coupling to detuning parameter
  - (b) symmetric coupling to detuning parameter
- microscopic coupling mechanism
  - strong qubit-cavity coupling in the order of MHz
  - fast two-qubit gates in the order of ns



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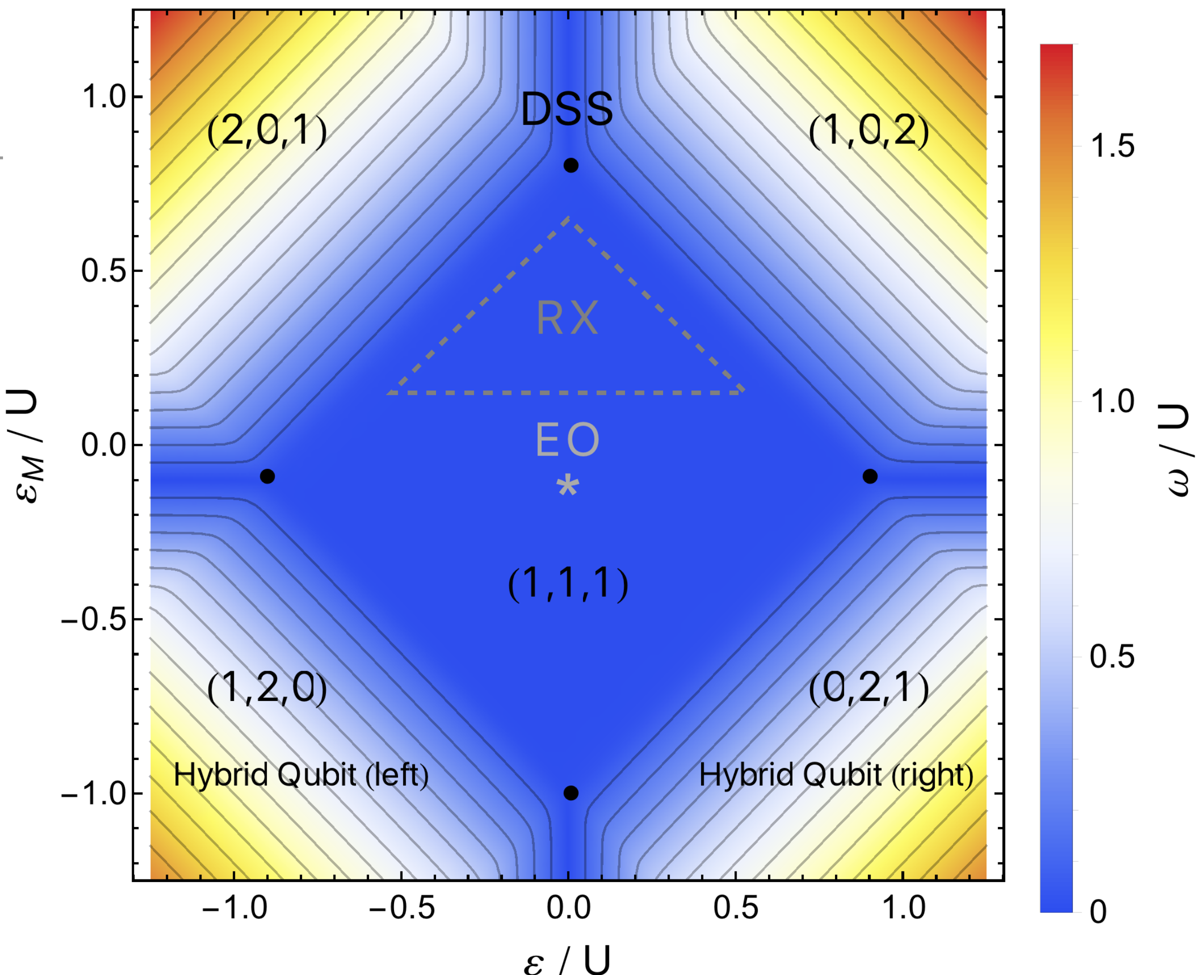
Phys. Rev. B **92**, 205412 (2015)



Related topic: charge noise in RX qubits

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