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Theory of spin-orbit mediated hole spin-photon coupling in lateral Ge/SiGe quantum dots

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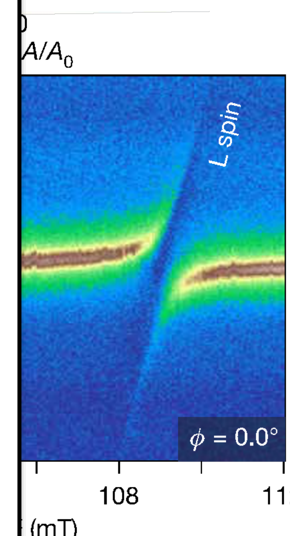
Entangling Distant Semiconductor Qubits

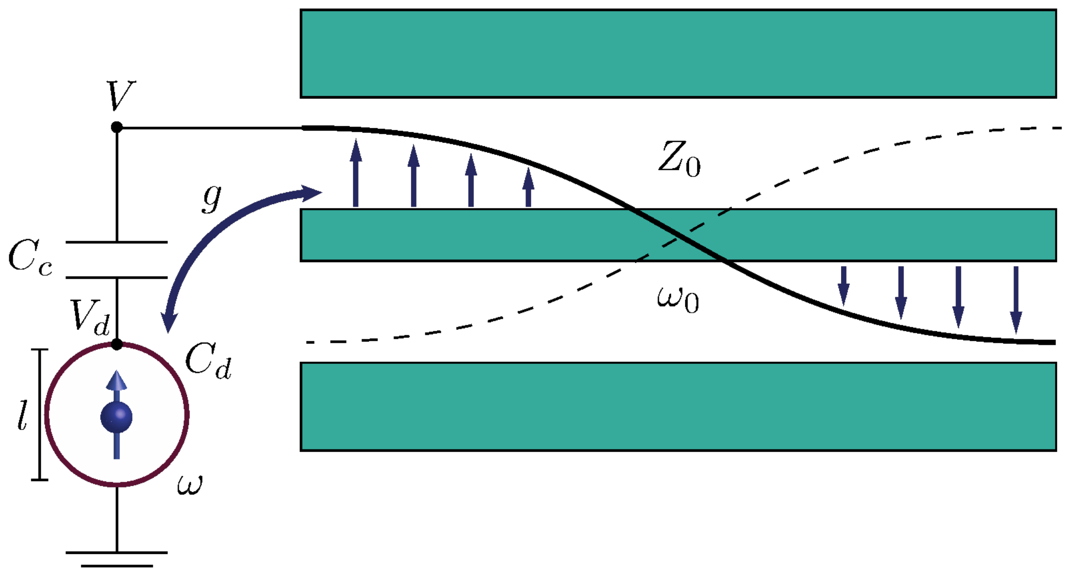
- Circuit QED: microwave photons
  - Interaction over distances ~mm-cm
  - Strong
    - M
      2
  - Micro
    -spin c
    - B
- Hole sp
  quantu
  - Valen
    prese
  - Stron
    - M
  - Large
    - H
  - Single
    gates
    - H
  - Built-
    decoherence expected
    - Wang *et al*. (arXiv 2019)

Mi Nature 2018

ns Nature 2019



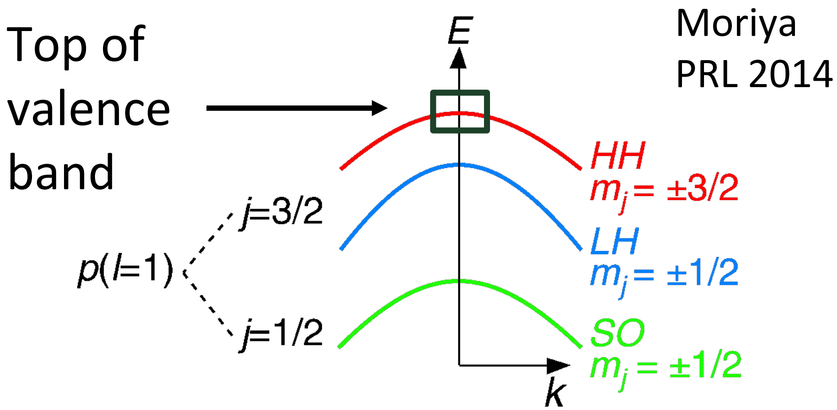
Ge hole spin-photon coupling

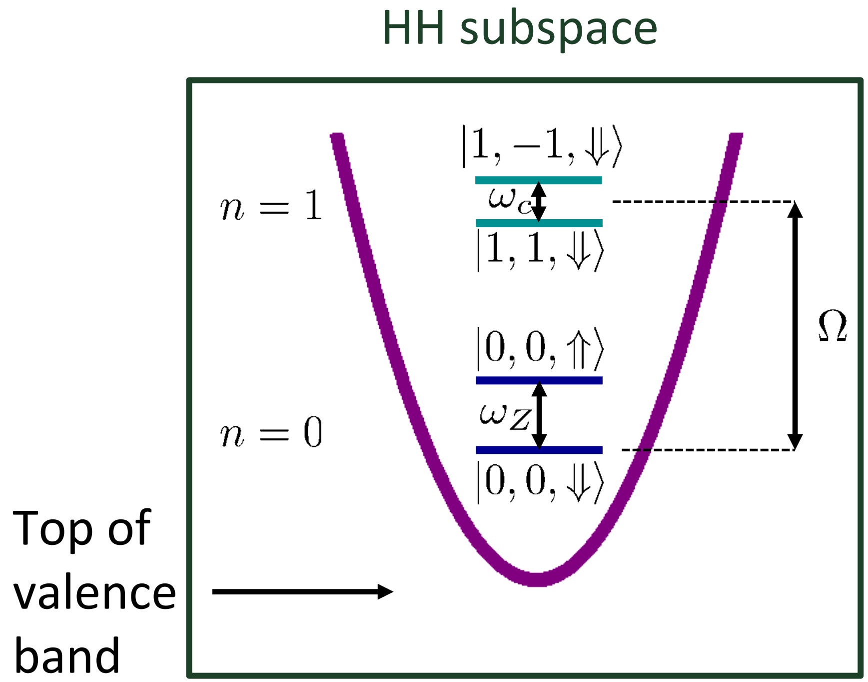


Photon

Ge Quantum Dot Heavy Hole Spin

- Heavy hole (HH) spectrum
  - Bualev *et al.* (PRL 2007)





$$H_d = H_{\rm orb} + H_Z$$

$$\boldsymbol{B} = B_\perp \hat{z} \qquad b_{g(d)} \equiv \frac{1}{\sqrt{2}}(b_x \pm i b_y)$$

$$H_d = \hbar\Omega\,(n+1) - \frac{\hbar\omega_c}{2} m + \frac{\hbar\omega_Z}{2}\sigma_z$$

$$n = n_d + n_g$$

$$m = n_d - n_g$$

$|n, m, \sigma\rangle$:

$$E_{nm\sigma} = \hbar\Omega\left(n + 1 - m\frac{\gamma}{2} + \sigma\frac{\xi}{2}\right)$$

$$\gamma \equiv \frac{\omega_c}{\Omega}$$

$$\xi \equiv \frac{\omega_Z}{\Omega}$$

Fock-Darwin states with spin ±3/2 (σ =±1)

Cubic Rashba Spin-Orbit Interaction

$$H_{HH} = H_d + V_{\mathrm{so}}$$

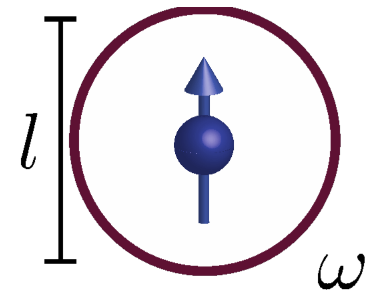
- Include dominant spin-orbit terms as perturbations
  - Bualev *et al*. (PRL 2007), Trif *et al*. (PRB 2008), Marcellina *et al*. (PRB 2017), Terrazos *et al*. (arXiv 2020)

$$V_{\mathrm{so}} = H_{\mathrm{so}} = i\hbar\omega_{\mathrm{so}} l^3 \left(k_-^3 \sigma_+ - k_+^3 \sigma_-\right)$$

$$V_{\mathrm{so}} = H'_{\mathrm{so}} = i\hbar\omega'_{\mathrm{so}} l^3 \left(k_+ k_- k_+ \sigma_+ - k_- k_+ k_- \sigma_-\right)$$

$$\frac{\omega'_{\mathrm{so}}}{\omega_{\mathrm{so}}} \approx 0.15$$

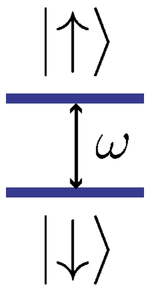
$$\eta \equiv \frac{\omega_{\mathrm{so}}}{\Omega} \ll 1 \qquad \eta' \equiv \frac{\omega'_{\mathrm{so}}}{\Omega} \ll 1$$



$$[H_{\mathrm{orb}}, \boldsymbol{r}] = -\frac{i\hbar^2}{m^*}\boldsymbol{k}$$

Momentum matrix elements related linearly to position matrix elements

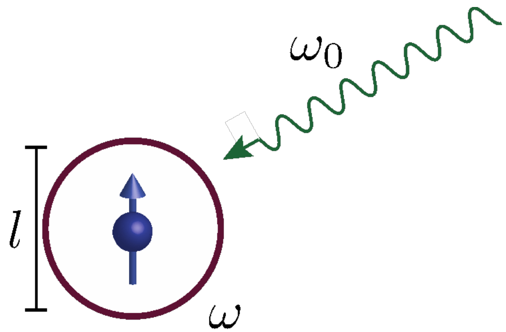
$$r_+ = r_-^\dagger \equiv x + iy = l\left(b_d^\dagger + b_g\right)$$



Qubit defined by spin-orbit corrected hole states

VS *et al*. (in preparation)

Semiclassical Case: Effective Rabi Frequencies



$$H = H_{HH} + H_{\text{int}}$$

$$H_{\text{int}} = -\boldsymbol{d}\cdot\boldsymbol{\mathcal{E}} = -e\mathcal{E}_x\left(t\right)x$$

$$\left[H_{\text{orb}}, \boldsymbol{r}\right] = -\frac{i\hbar^2}{m^*}\boldsymbol{k}$$

$$V_{\text{so}} = H_{\text{so}} = i\hbar\omega_{\text{so}}l^3\left(k_-^3\sigma_+ - k_+^3\sigma_-\right)$$

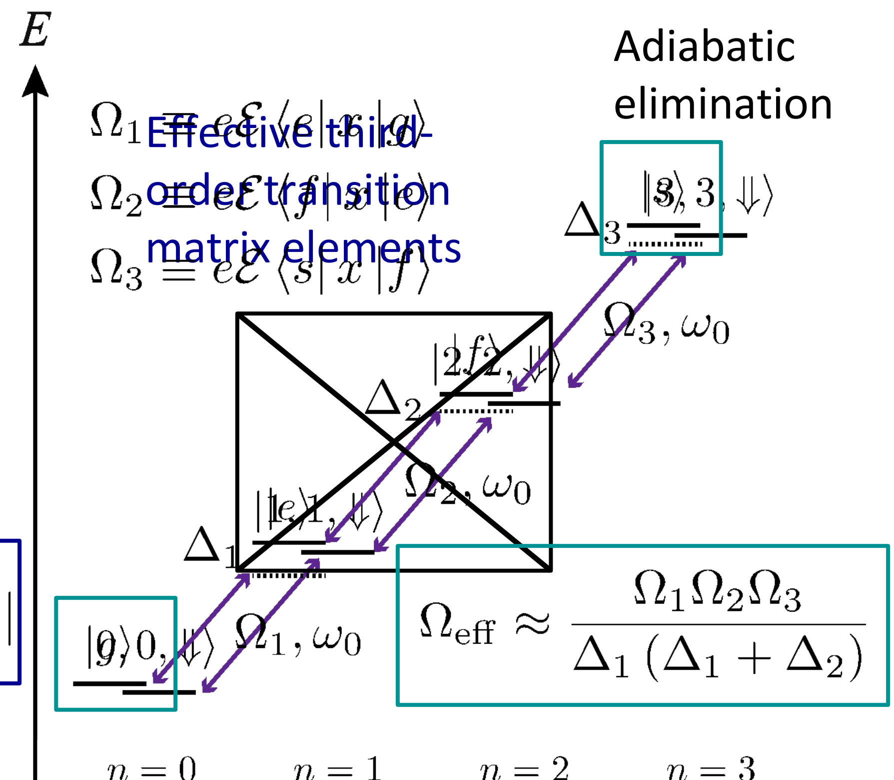
$$\langle\uparrow|\,H_{\text{int}}\,|\downarrow\rangle = 0$$

$$\begin{aligned}\Omega_{\text{eff}} &= \left|\langle\uparrow|\,H_{\text{int,eff}}\,|\downarrow\rangle\right| \\ &\approx \eta\,|A_1\,\langle 3,3,\Downarrow|\,H_{\text{int,eff}}\,|0,0,\Downarrow\rangle \\ &\quad + B_1\,\langle 0,0,\Uparrow|\,H_{\text{int,eff}}\,|3,-3,\Uparrow\rangle|\end{aligned}$$

$$\Omega_{\text{eff}} \approx \frac{3\Omega_d^3}{32\Omega^2}\eta\left|\Lambda_+\left(\gamma,\xi,\omega_0\right) + \Lambda_-\left(\gamma,\xi,\omega_0\right)\right|$$

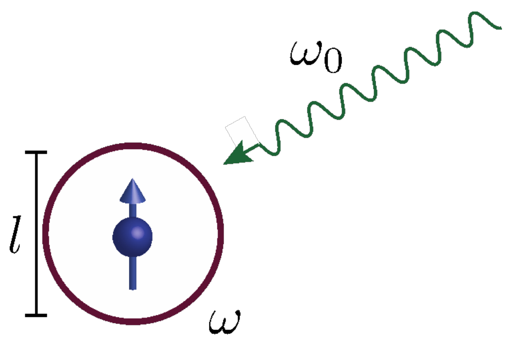
$$\Omega_d \equiv e\mathcal{E}l$$

Effective three -photon Rabi frequency



VS *et al*. (in preparation)

Semiclassical Case: Effective Rabi Frequencies



$$H = H_{HH} + H_{\text{int}}$$
$$H_{\text{int}} = -\boldsymbol{d} \cdot \boldsymbol{\mathcal{E}} = -e\mathcal{E}_x(t)\,x$$

$$[H_{\text{orb}}, \boldsymbol{r}] = -\frac{i\hbar^2}{m^*}\boldsymbol{k}$$

$$V_{\text{so}} = H'_{\text{so}} = -i\hbar\omega'_{\text{so}} l^3 \left(k_+ k_- k_+ \sigma_+ - k_- k_+ k_- \sigma_-\right)$$

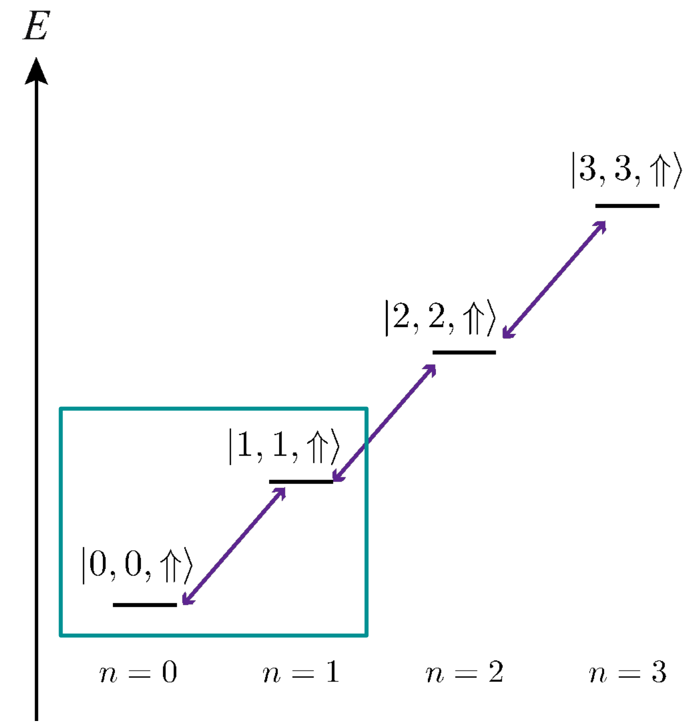
$$\langle \uparrow' | H_{\text{int}} | \downarrow' \rangle \neq 0$$

$$\begin{aligned} \Omega'_{\text{eff}} &= \left| \langle \uparrow' | H_{\text{int}} | \downarrow' \rangle \right| \\ &\approx \eta' \left| P_1 \langle 1, -1, \Downarrow | H_{\text{int}} | 0, 0, \Downarrow \rangle \right. \\ &\quad \left. + R_1 \langle 0, 0, \Uparrow | H_{\text{int}} | 1, 1, \Uparrow \rangle \right| \end{aligned}$$

$$\boxed{\Omega'_{\text{eff}} \approx 2\Omega_d \eta' \left| \Lambda'(\gamma, \xi) \right|}$$

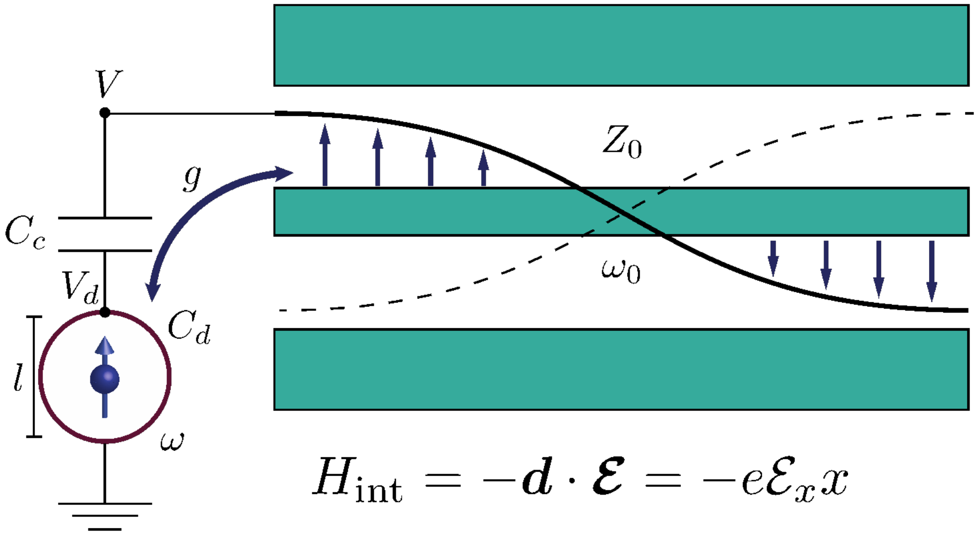
Effective one-photon Rabi frequency

$$\Omega_d \equiv e\mathcal{E}l$$



VS *et al*. (in preparation)

Quantized Case: Ge Hole Spin-Photon Coupling



$$H_{\text{int}} = -\boldsymbol{d} \cdot \boldsymbol{\mathcal{E}} = -e\mathcal{E}_x x$$

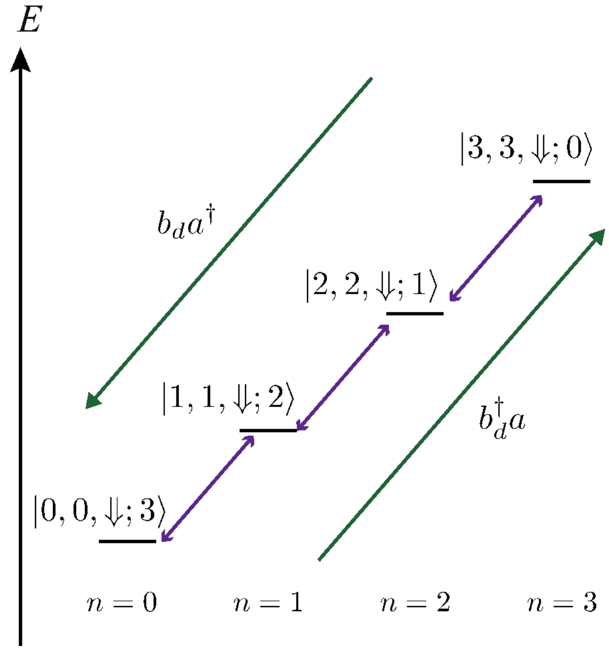
$$\hat{V} = \omega_0 \sqrt{\frac{\hbar Z_0}{\pi}} \left(a + a^\dagger\right)$$

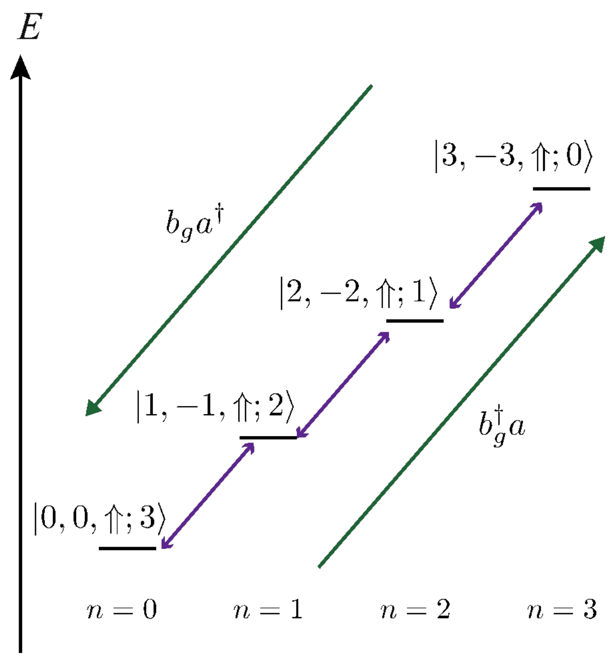
$$\hat{\mathcal{E}}_x = \frac{\hat{V}_d}{l} = \frac{C_c \hat{V}}{l\left(C_c + C_d\right)} \equiv \frac{v\hat{V}}{l}$$

$$g_0 \equiv \frac{ev}{2}\omega_0 \sqrt{\frac{Z_0}{\pi\hbar}}$$

$$H_{\text{int,RWA}} \equiv -\hbar g_0 \left(b_d a^\dagger + b_d^\dagger a\right) - \hbar g_0 \left(b_g a^\dagger + b_g^\dagger a\right)$$

$|n, m, \sigma; n_{\text{ph}}\rangle$





VS *et al*. (in preparation)

Ge Hole Spin-Photon Coupling Strengths

- Strength of coupling to resonator electric field via cubic Rashba spin-orbit interaction

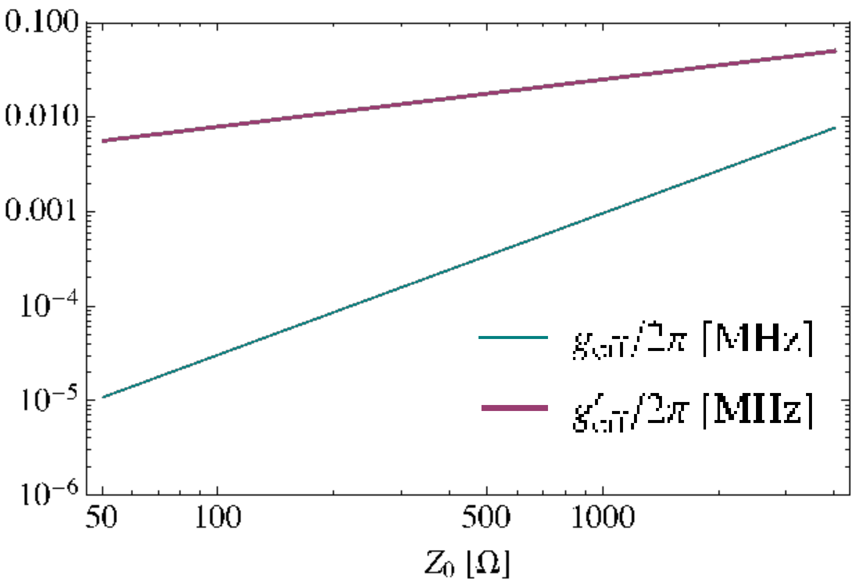
$$g_{\text{eff}} = \left|\langle\uparrow;3|\, H_{\text{int,RWA,eff}}\, |\downarrow;0\rangle\right|$$
$$g'_{\text{eff}} = \left|\langle\uparrow';1|\, H_{\text{int,RWA}}\, |\downarrow';0\rangle\right|$$

$g_\perp = 15$ $\quad l = 140$ nm

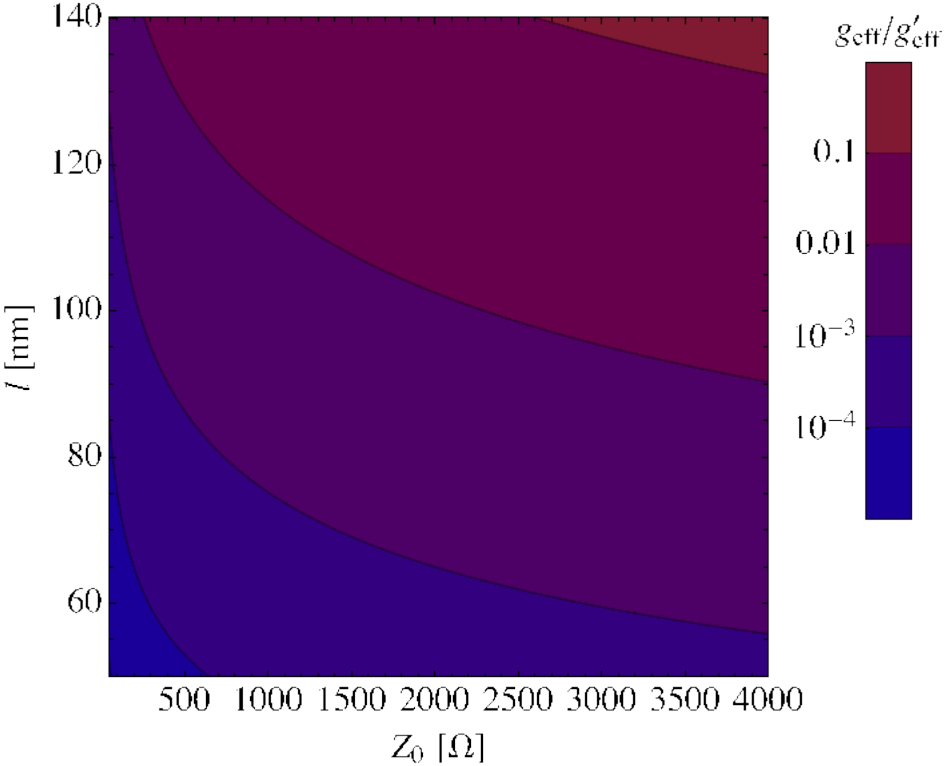
$B_\perp = 5$ mT $\quad \omega/2\pi \approx \omega'/2\pi = 3.1$ GHz

$v = 1$ $\quad \omega_{\text{so}}/2\pi = 2.7$ MHz

$\omega_0/2\pi = 4.5$ GHz $\quad \omega'_{\text{so}}/\omega_{\text{so}} \approx 0.15$



Comparison of coupling strengths



$Z_0 = 4$ kΩ $\quad \dfrac{g_{\text{eff}}}{g'_{\text{eff}}} \approx 0.15$

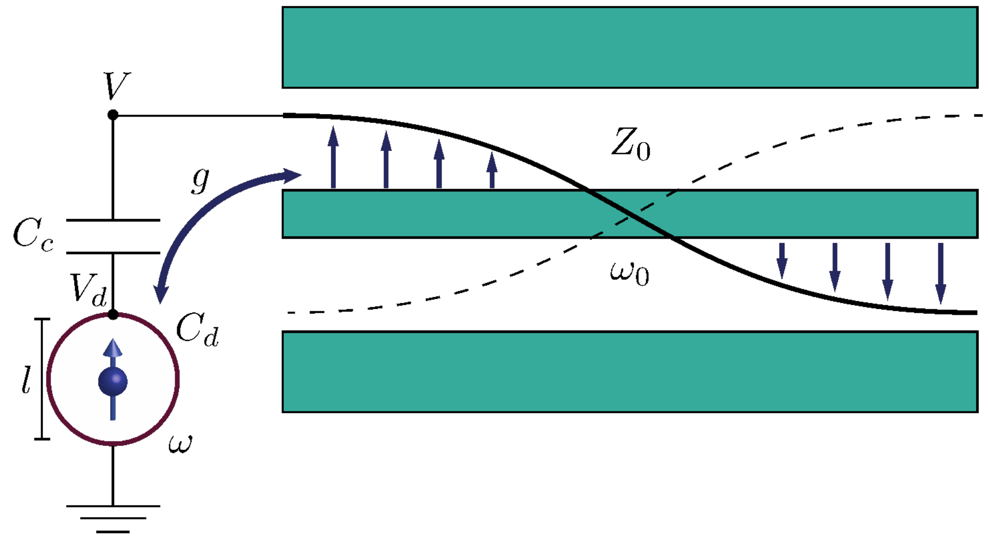
$l = 140$ nm

VS *et al*. (in preparation)

Summary

- Analytical formulation of one -photon and three-photon coupling to hole spins in Ge/SiGe quantum dots

- Three-photon coupling may contribute significantly to spin-photon coupling strength for sufficiently large dot size and resonator impedance



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