Strong Coupling between a photon and a hole spin in silicon

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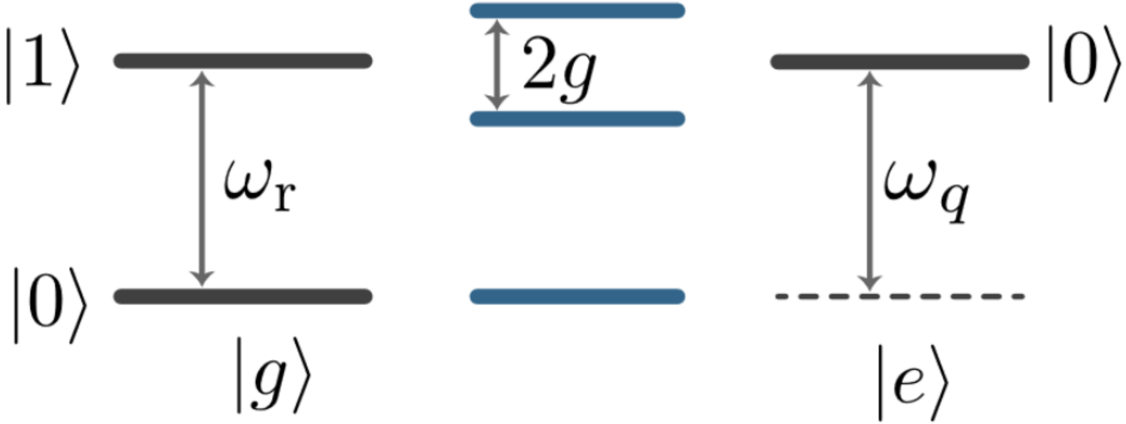
Abstract

Spins in semiconductor quantum dots constitute a promising platform for scalable quantum information processing[1]. Coupling them strongly to the photonic modes of superconducting microwave resonators would enable fast non-demolition readout and long-range, on-chip connectivity, well beyond nearest-neighbor quantum interactions[2–4]. Here we demonstrate strong coupling between a microwave photon in a superconducting resonator and a hole spin in a silicon-based double quantum dot issued from a foundry-compatible MOS fabrication process. By leveraging the strong spin-orbit interaction intrinsically present in the valence band of silicon[5,6], we achieve a spin-photon coupling rate as high as 330 MHz largely exceeding the combined spin-photon decoherence rate. This result, together with the recently demonstrated long coherence of hole spins in silicon[7], opens a new realistic pathway to the development of circuit quantum electrodynamics with spins in semiconductor quantum dots.

Background

$$\hat{H}_{\mathrm{JC}} = \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_q}{2}\hat{\sigma}_z + \hbar g(\hat{a}^\dagger \hat{\sigma}_- + \hat{a}\hat{\sigma}_+)$$

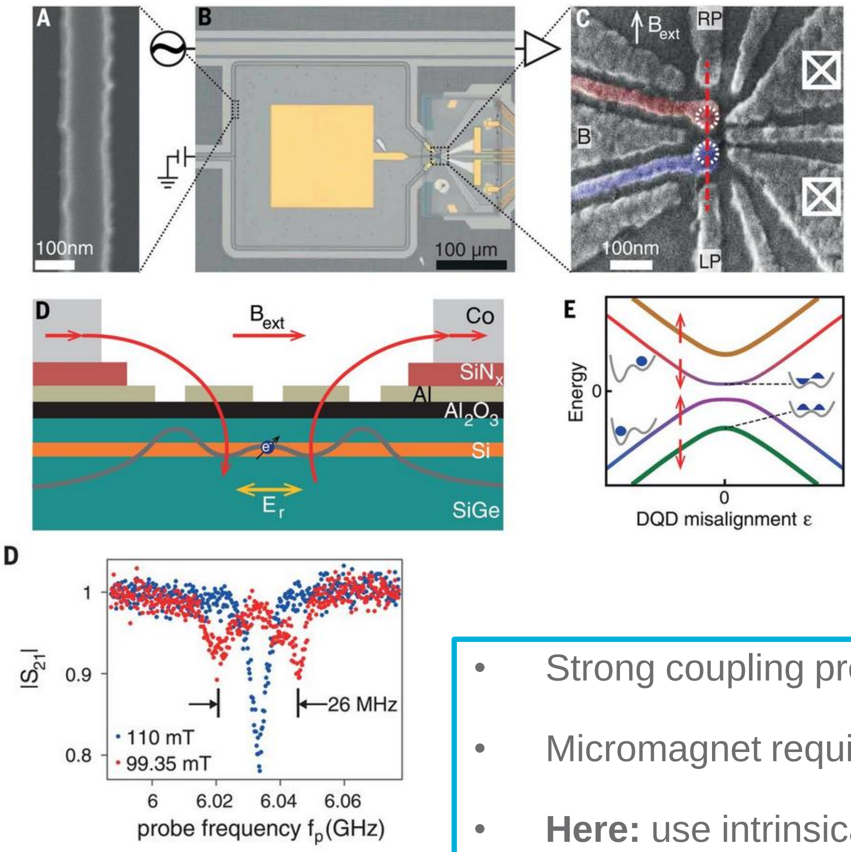
- Strong coupling between qubit and resonator when $\omega_r = \omega_q$
- Formation of hybridized states separated in energy by coupling strength g
- Signature: vacuum Rabi splitting $(g > \kappa, \gamma)$



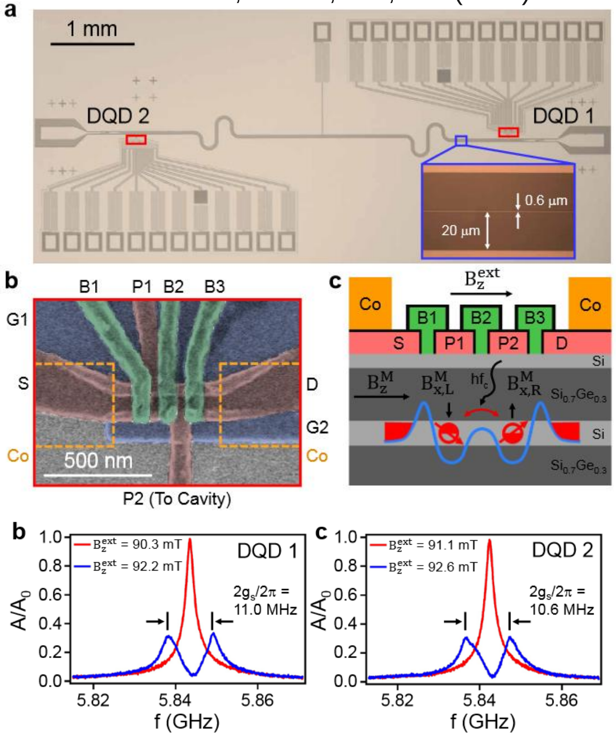
A. Blais et. al., Rev. Mod. Phys. **93,** 025005 (2021)

Background

N. Samkharadze et. al., Science, **359**, 6380 (2018)

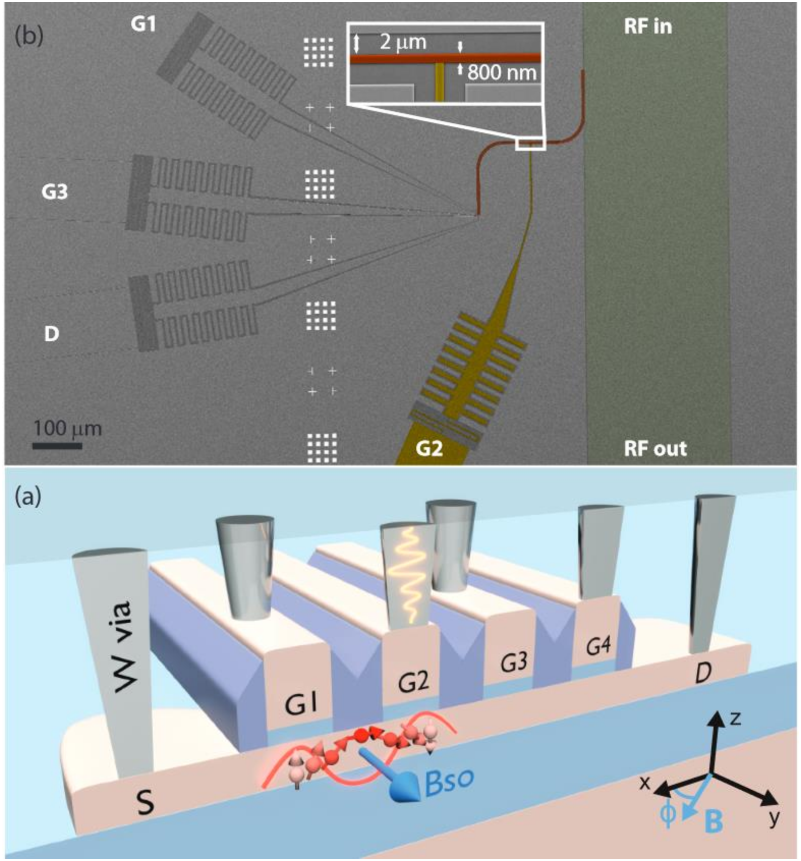


X. Mi et. al., Nature, **555**, 599 (2018)



- Strong coupling previously demonstrated for electrons in Si/SiGe
- Micromagnet required for coupling spin to E-field of resonator
- **Here:** use intrinsically present spin-orbit interaction for holes in Si

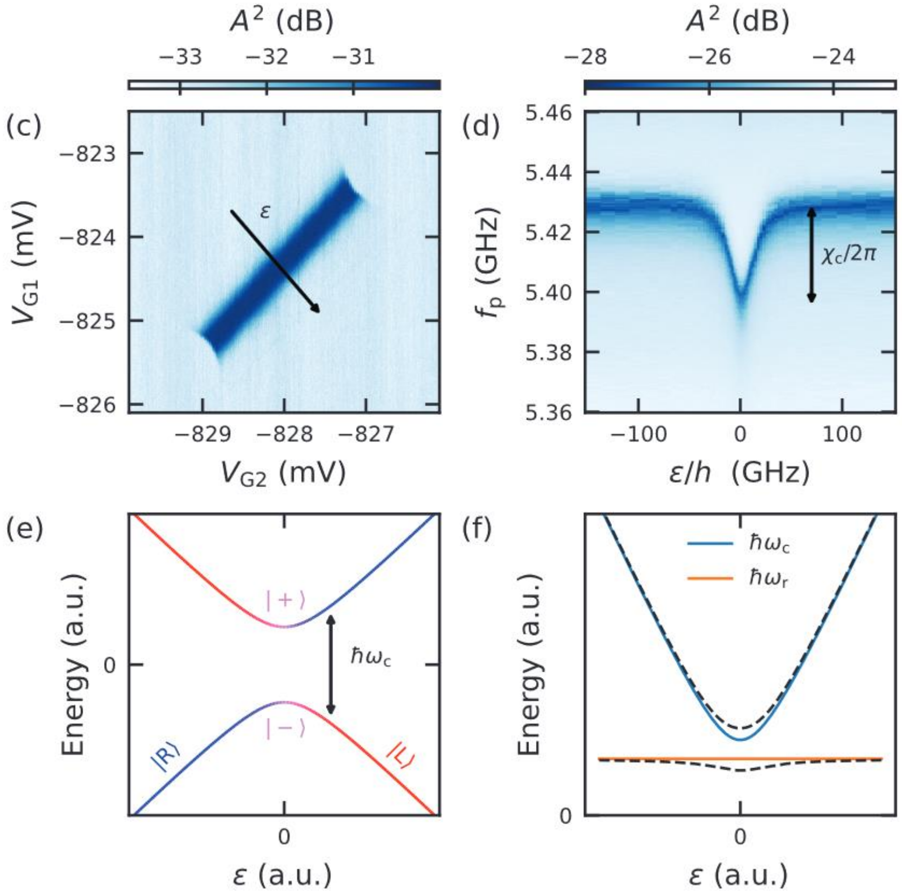
Device Architecture

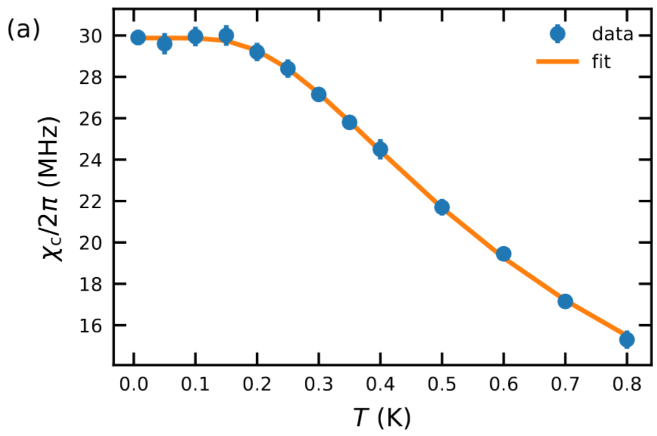


- Resonator and DC lines fabricated from NbN on packaging oxide
- λ/2 CPW hanger resonator with bias tap
- DC lines with LC lowpass filters f_c = 1.2 GHz (L = 123 nH, C = 0.134 pF)
- Connections to NbN circuitry through W interconnects
- G3, G4 shorted at device level
- Source hard grounded to NbN ground plane
- DQD defined under G1, G2

- f_r = 5.428 GHz
- Q_{int} = 530
- Q_{ext} = 1550

Resonator – DQD Charge Coupling



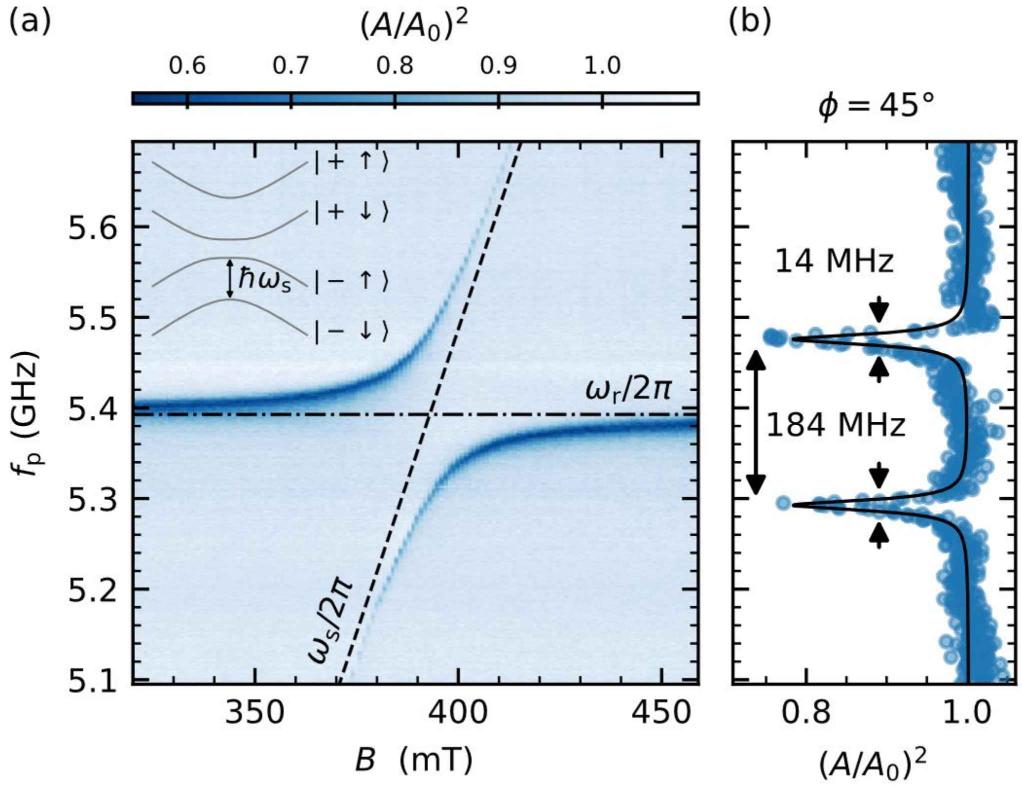


From $\chi_c(T)$:

$$\frac{g_c}{2\pi} = 513\text{ MHz}$$

$$\frac{t_c}{2\pi} = 9.57\text{ GHz}$$

Strong Hole Spin-Photon Coupling

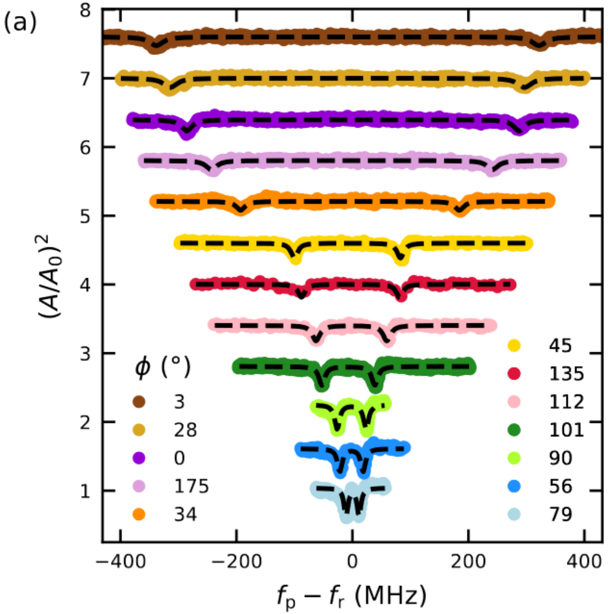


linewidth: $\frac{1}{2}\left(\gamma_s + \frac{\kappa}{2}\right)/2\pi$ = 7 MHz

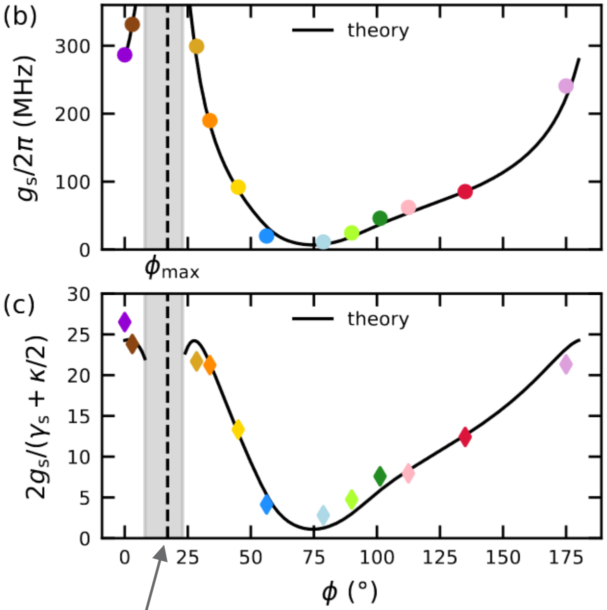
Cavity decay rate: $\kappa/2\pi$ = 14 MHz

Extracted spin decoherence: $\gamma_s/2\pi$ = 7 MHz

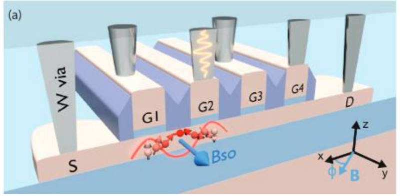
Spin-Photon Coupling vs. Magnetic Field Orientation



Angle between B and nanowire axis



B-field > 1 T required



Maximum g_s=330 MHz at 3º

Minimum g_s=10 MHz at 79º

Model:

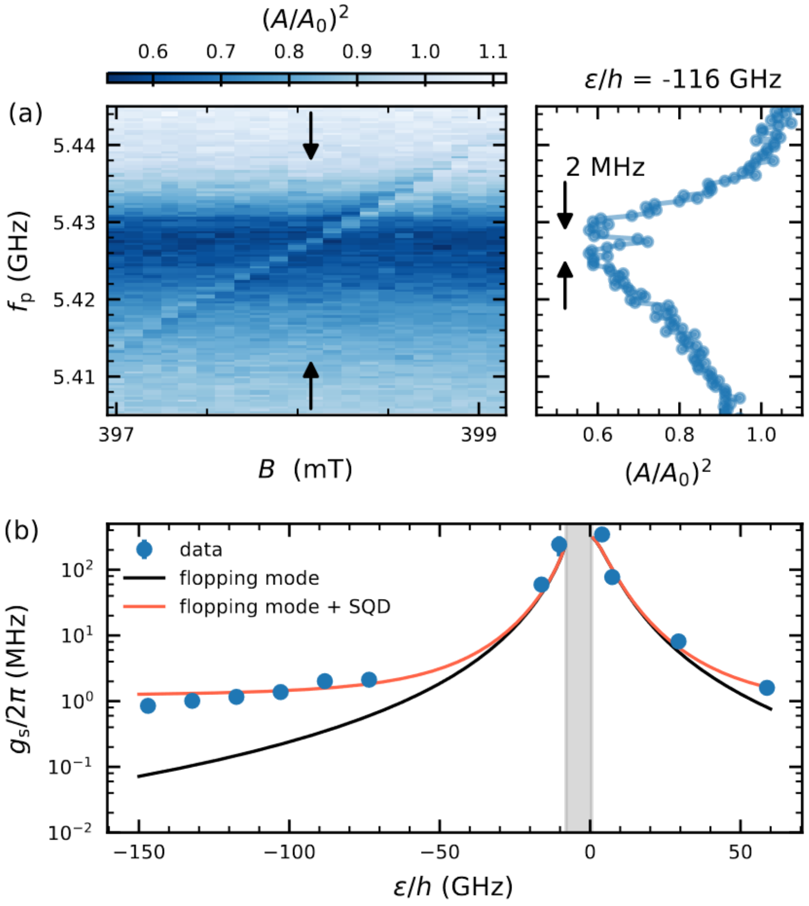
$$g_s \propto g_c |(\bar{g}\boldsymbol{B}) \times (\bar{g}\boldsymbol{B}_{so})|$$

$\bar{g}$ is average g-tensor of the two dots

g_s near maximum when $\boldsymbol{B} \perp \boldsymbol{B}_{so}$ (not exactly orthogonal due to g-matrix anisotropy)

$\boldsymbol{B}_{so}$ mostly in-plane perpendicular to nanowire

Spin-Photon Coupling in Single Dot Limit

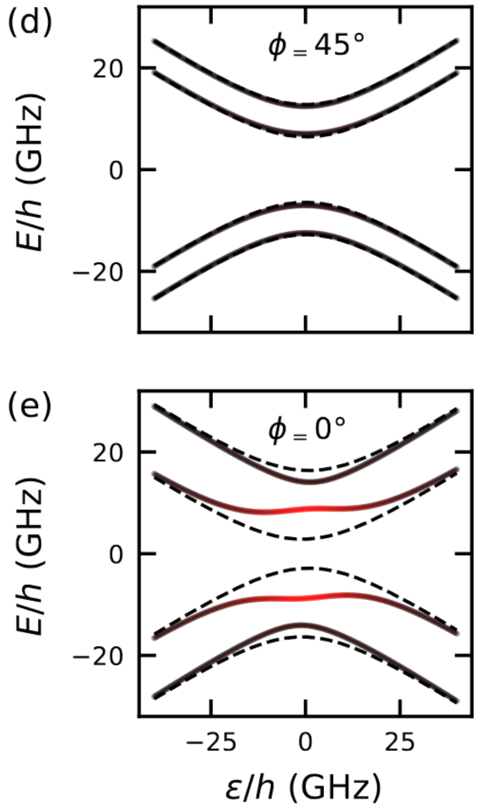


$$g_s^{(R)} = 1.16\,MHz$$
$$g_s^{(L)} = 0.66\,MHz$$

Conclusion / Future work

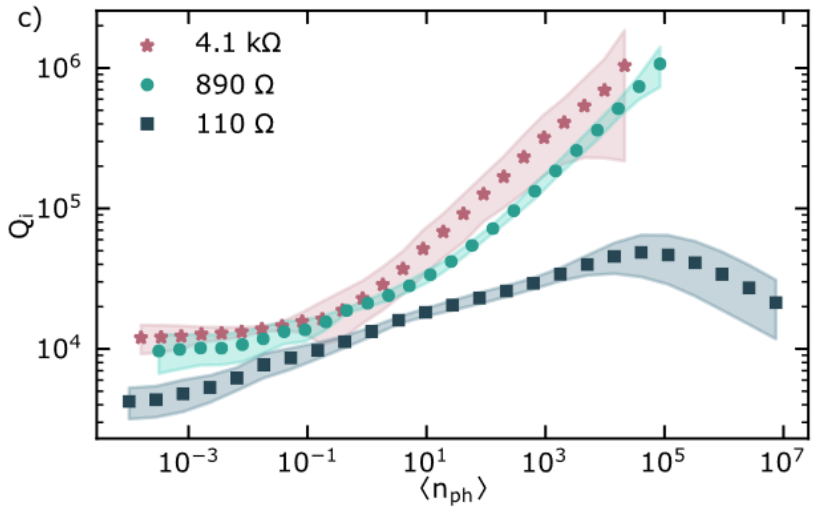
- Spin-photon coupling largely exceeds results for electrons in Si
- Modified layout and resonator optimization to increase charge photon coupling and reduce resonator losses (aim: < 1 MHz)
- Implementation of spin-photon coupling schemes relying on charge noise sweet spots

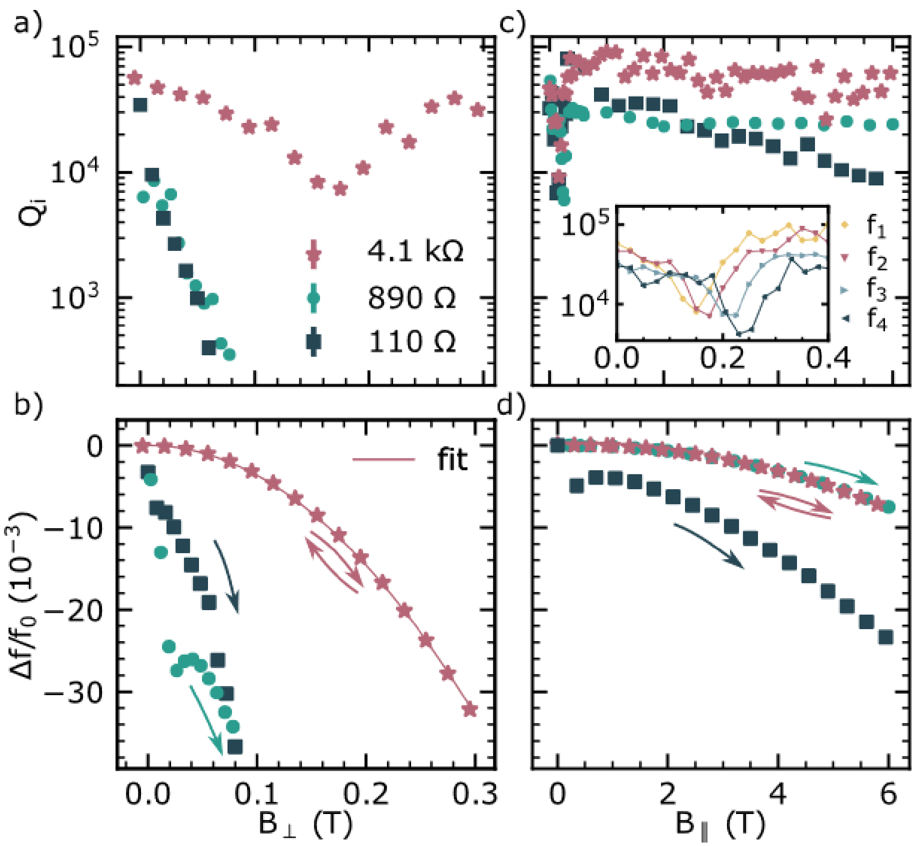
Spin-Charge Mixing



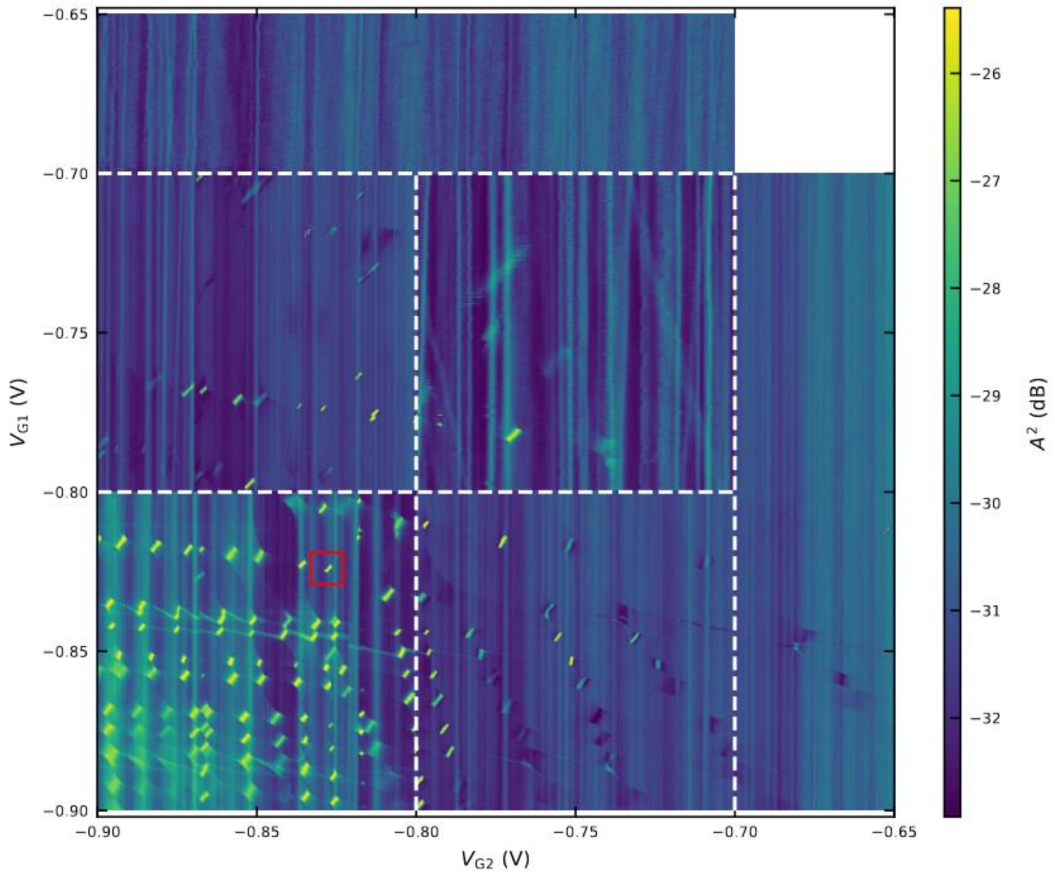
Resonator

C. Yu et. al., Appl. Phys. Lett. **118**, 054001 (2021)





Charge Stability Diagram



Charge-Photon Coupling Characterisation

$$\chi_c = g_c^2 d_{01}^2 (p_0 - p_1) \left(\frac{1}{\Delta} + \frac{1}{\omega_c + \omega_r} \right)$$

$$\hbar\omega_c = \sqrt{\varepsilon^2 + 4t_c^2}$$

$$d_{01} = \frac{2t_c}{\sqrt{\varepsilon^2 + 4t_c^2}}$$

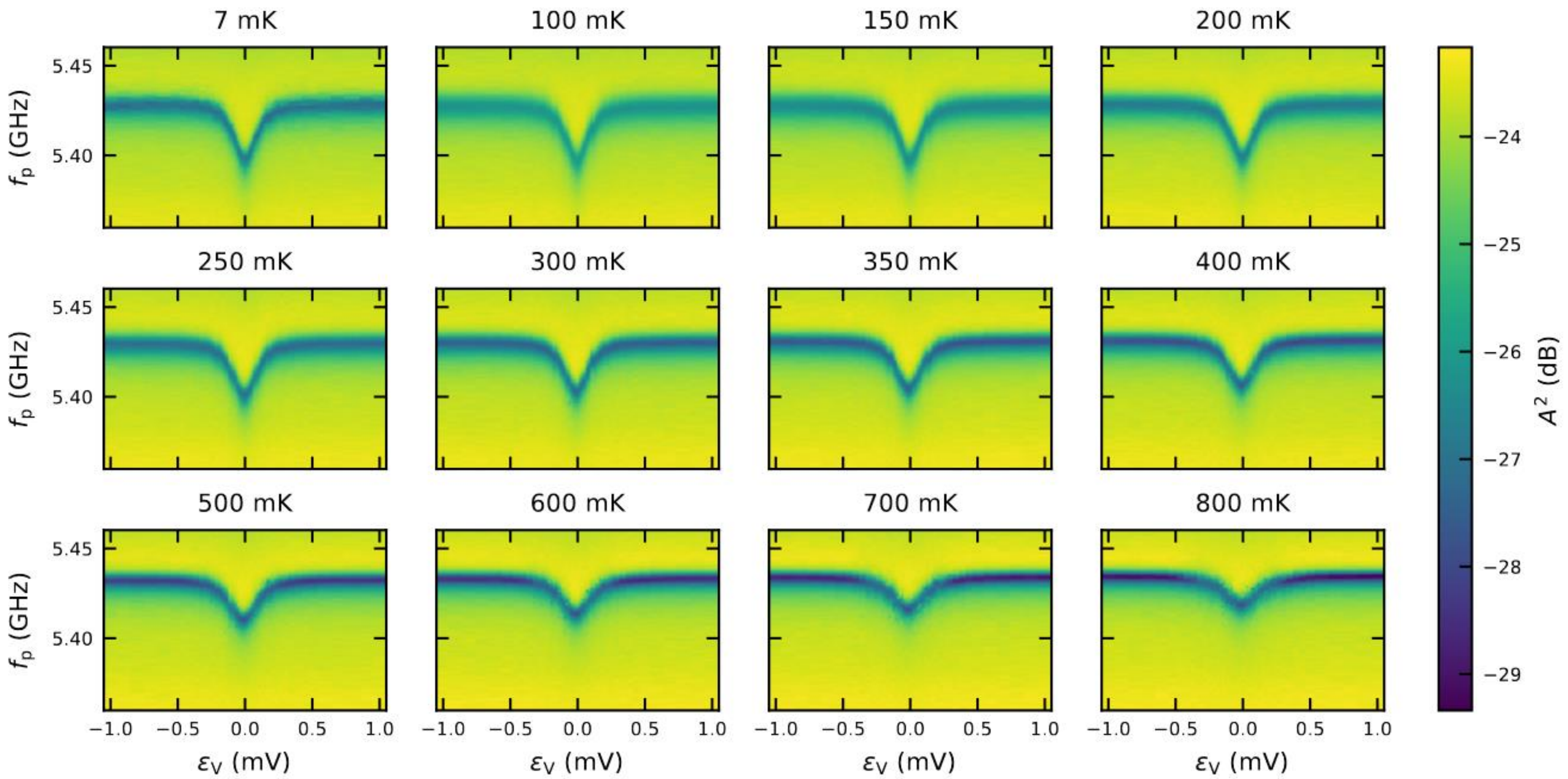
Zero detuning:

$$\chi_c = 2g_c^2 \frac{\omega_c}{\omega_c^2 - \omega_r^2} (p_0 - p_1)$$

$$p_1 = \frac{1}{1 + e^{\hbar\omega_c/(k_B T)}},$$

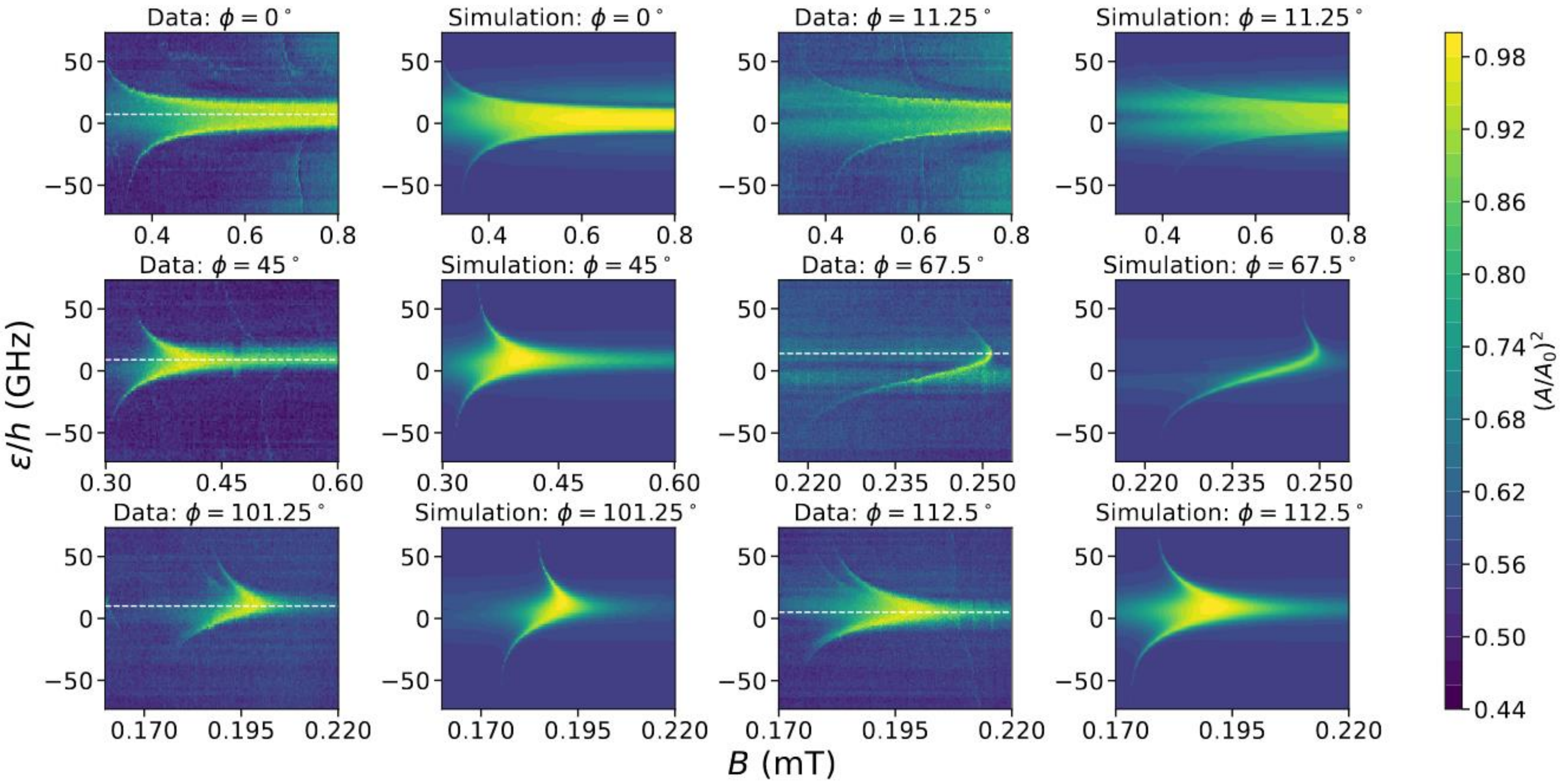
$$p_0 = 1 - p_1,$$

Detuning Field Maps



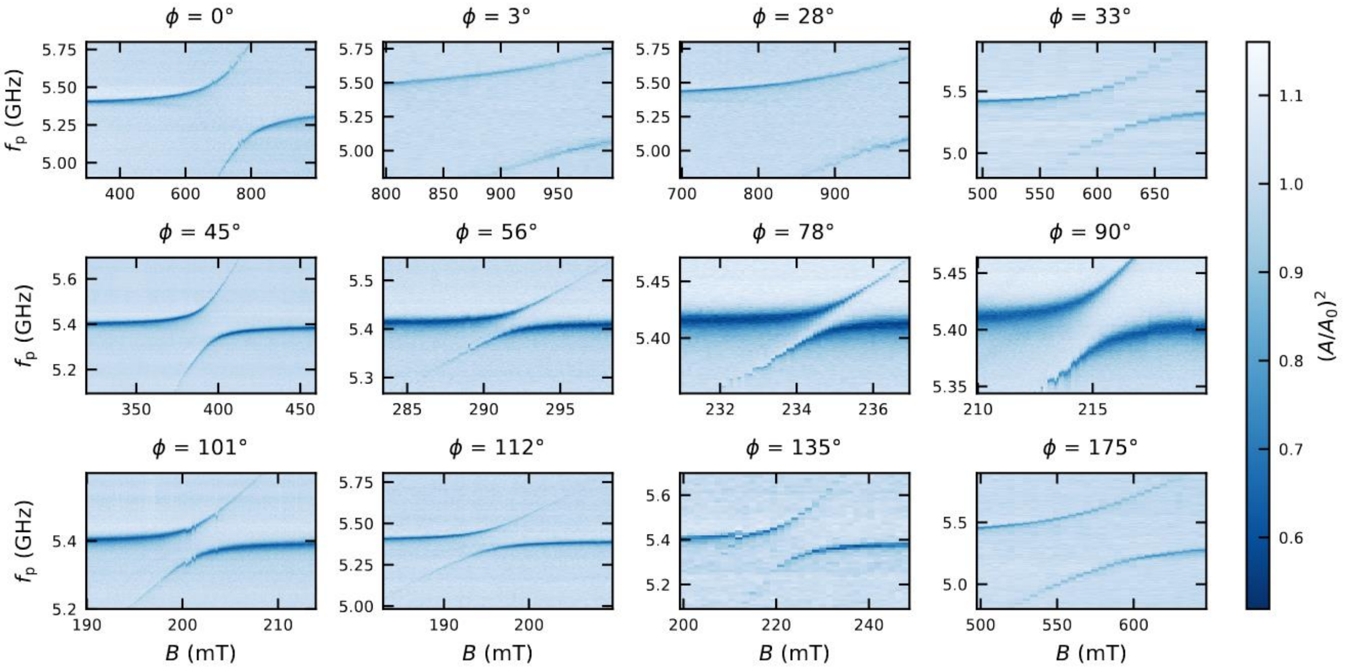
Angular Dependence Spin-Photon Coupling

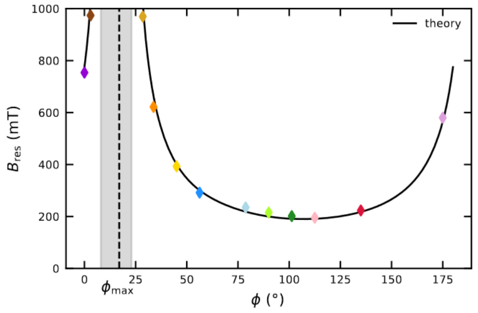
Resonance Field



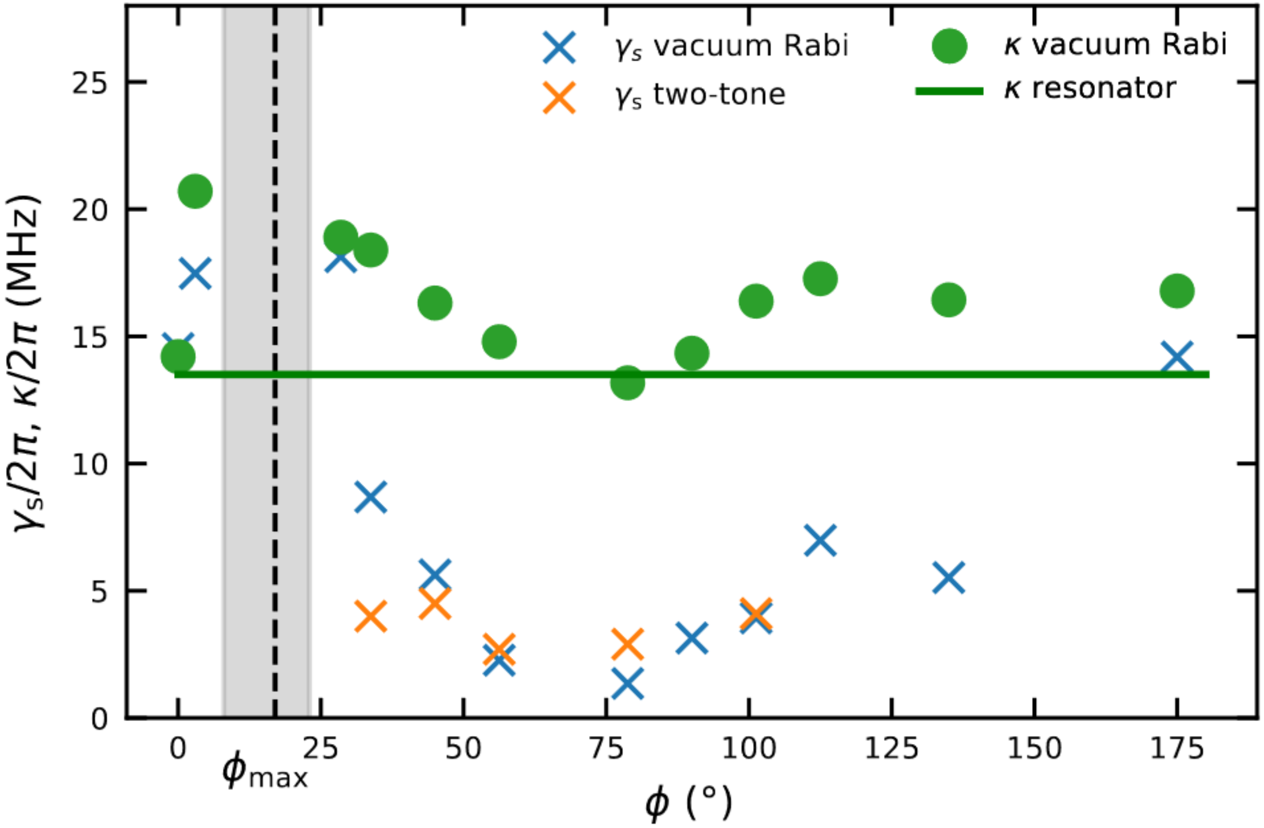
Angular Dependence Spin-Photon Coupling

Resonance Field

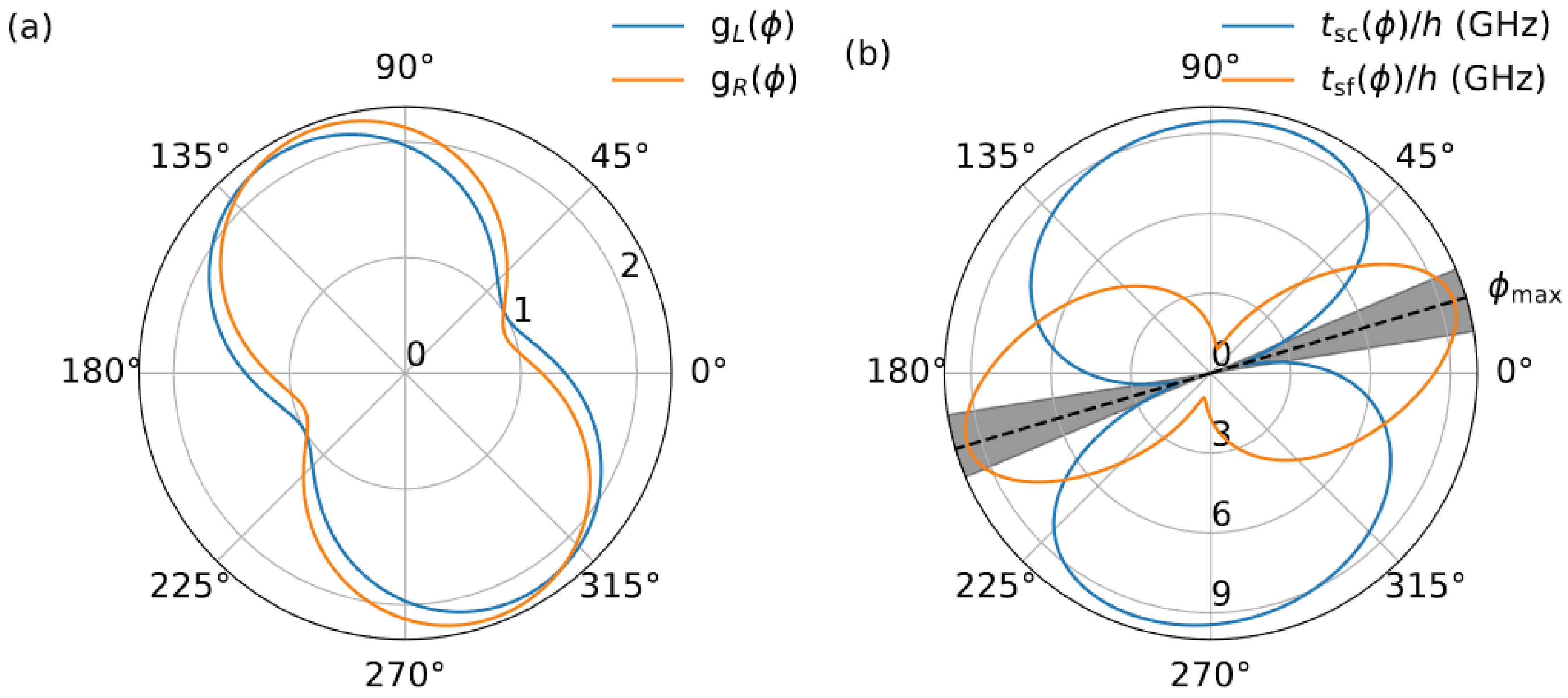




Angular Dependence of γ_s and κ



Anisotropy of g-Factors and Tunnel Couplings



Theory of Angular Dependence Spin-Photon Coupling

$$H_{\text{tunnel}} = t_0 \tau_x - (\mathbf{t} \cdot \boldsymbol{\sigma}) \tau_y$$

$$t_c = \sqrt{t_0^2 + |\mathbf{t}|^2}$$

$$t_0 = t_c \cos \eta \qquad \mathbf{t} = t_c \sin \eta \, \mathbf{n}_{\text{so}}$$

$$\begin{aligned} H_{\text{DD}} &= H_\varepsilon + H_{\text{Zeeman}} + H_{\text{tunnel}} \\ &= -\frac{\varepsilon}{2}\tau_z + \frac{1}{2}\mu_{\text{B}}\tau_L \left(\boldsymbol{\sigma} \cdot \tilde{\text{g}}_L V_L^\dagger \mathbf{B}\right) + \frac{1}{2}\mu_{\text{B}}\tau_R \left(\boldsymbol{\sigma} \cdot \tilde{\text{g}}_R V_R^\dagger \mathbf{B}\right) + t_0 \tau_x - \tau_y \left(\mathbf{t} \cdot \boldsymbol{\sigma}\right) \end{aligned}$$

Transform Hamiltonian with diagonalization of Zeeman term:

$$H'_{\text{DD}}(\phi) = T(\phi)^\dagger H_{\text{DD}} T(\phi) = -\frac{\varepsilon}{2}\tau_z + \tau_L \frac{1}{2}\text{g}_L^*(\phi)\mu_{\text{B}} B \sigma_z + \tau_R \frac{1}{2}\text{g}_R^*(\phi)\mu_{\text{B}} B \sigma_z + t_{\text{sc}}(\phi)\tau_x - t_{\text{sf}}(\phi)\tau_y \sigma_y$$

Theory of Angular Dependence Spin-Photon Coupling

$$g_s = g_c \left|\langle - \uparrow| \tau_z |- \downarrow\rangle\right| \text{ with } g_c = \frac{1}{2\hbar}\alpha\beta_2 e V_{zpf}$$

When average Zeeman energy for both dots is << $2t_c$:

$$g_s = g_c \frac{\bar{E}_Z t_{sf}}{2t_c^2}$$

Transform Hamiltonian with diagonalization of Zeeman term (assuming left and right g-matrices are the same):

$$t_{sf} = t_c \sin\eta \left|\mathbf{n}_l \times \mathbf{n}_{so}\right|$$

Introduce Effective Spin-Orbit Field:

$$\mu_B \mathbf{g}\mathbf{B}_{so} = t_c \sin\eta\,\mathbf{n}_{so}$$

$$g_s = g_c \frac{\mu_B^2}{2t_c^2}\left|(\mathbf{g}\mathbf{B}) \times (\mathbf{g}\mathbf{B}_{so})\right|$$