Achieving strong spin-photon coupling with a semiconductor hole qubit

José C. Abadillo-Uriel
CEA Grenoble France

Strong photon coupling to a hole spin in silicon

Cécile Yu, Simon Zihlmann, José C. Abadillo-Uriel, Vincent P. Michal, Nils Rambel, Heimanu Niebojewski, Thomas Bedecarrats, Etienne Dumur, Michele Filippone, Benoît Bertrand, Maud Vinet, Silvano De Franceschi, Yann-Michel Niquet, and Romain Maurand

Many thanks to the experimentalists that made this possible

Cécile Yu

Simon Zihlmann

Romain Maurand

Warning!!! Theorist talking (partially) about an experiment

DE LA RECHERCHE À L'INDUSTRIE
cea

Outline

-Introduction:

QD qubits

Hole spin qubits

cQED experiments with electrons in QDs

-The experimental results

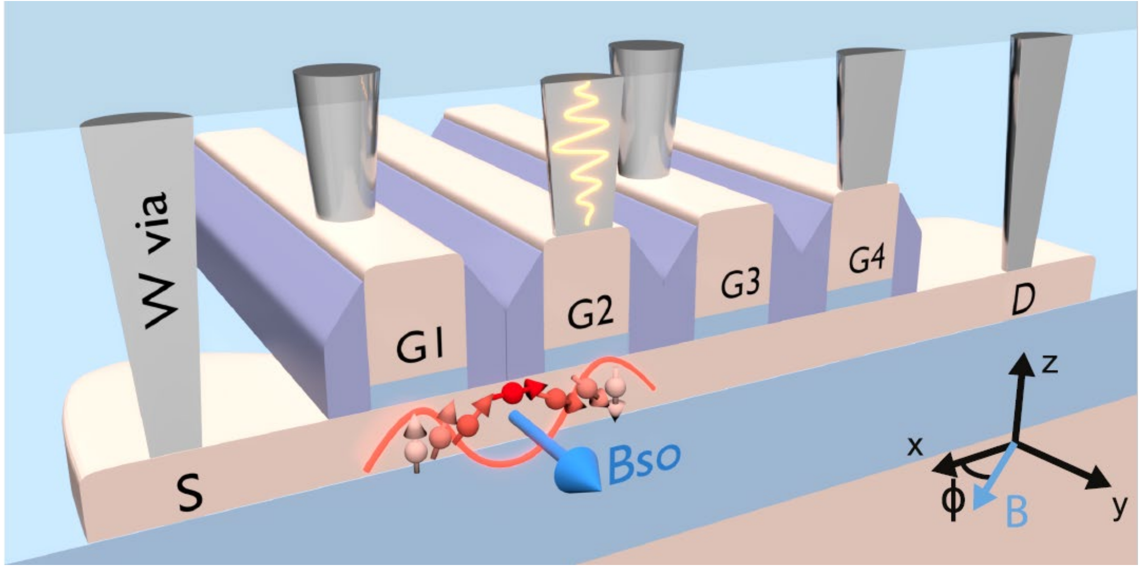
Charge-photon coupling

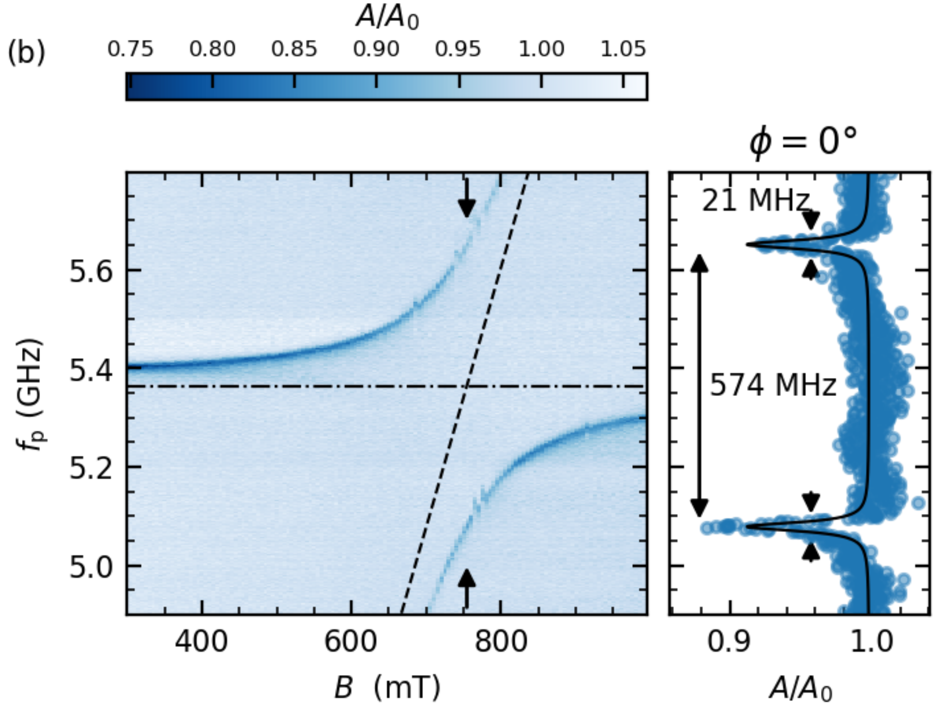
Spin-photon coupling

Angular dependence

Single-dot limit

-Perspectives and conclusions

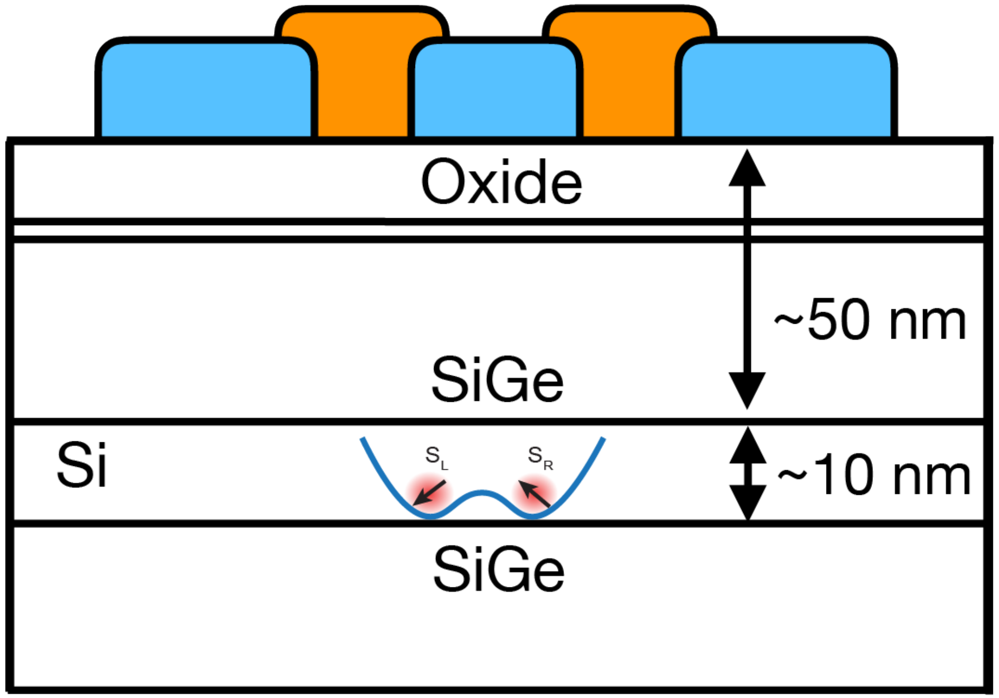




Semiconductor QD qubits: an introduction

Loss & Di Vincenzo, Phys. Rev. A **57**, 120 (1998).

- Electrons are confined in a quantum well
- The spin qubit is manipulated with oscillating magnetic fields. Electrical manipulation is viable with micromagnets.
- Exchange interactions mediate two-qubit gates
- Readout: spin-to-charge conversion
- Compatible with industrial semiconductor manufacturing

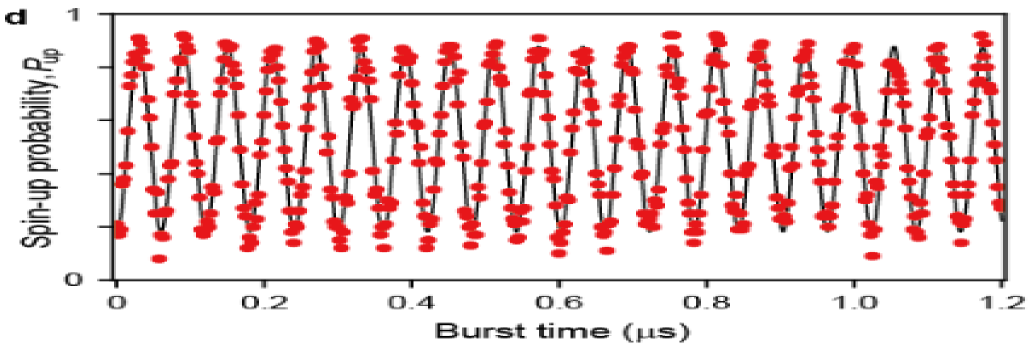


Semiconductor QD qubits with electrons: highlights

- Single-qubit gate fidelities above 99.9%

  Yoneda et al., Nature Nanotechnology 13, 102-106 (2018)

  Huang et al., Nature 569, 532-536 (2019)



- Two-qubit gates above 99%

  Noiri et al., Nature 601, 338–342 (2022)

  Xue et al., Nature 601, 343–347 (2022)

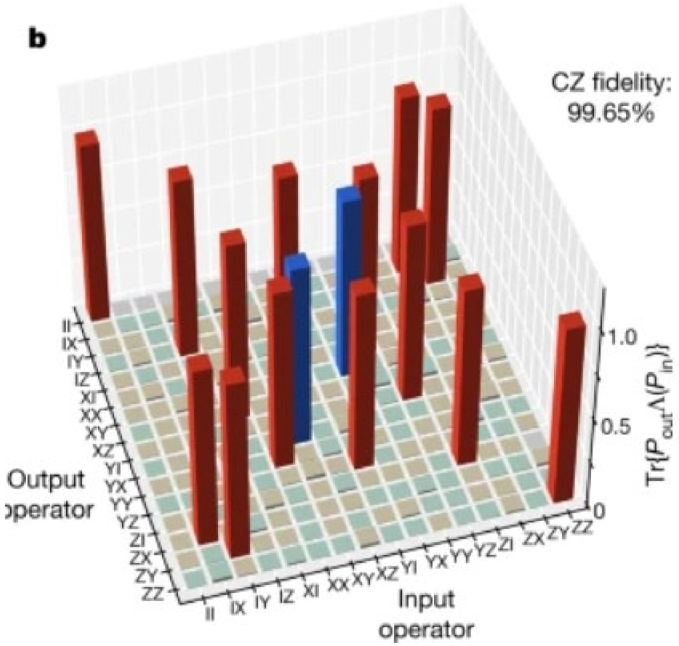
- 6-qubit processor

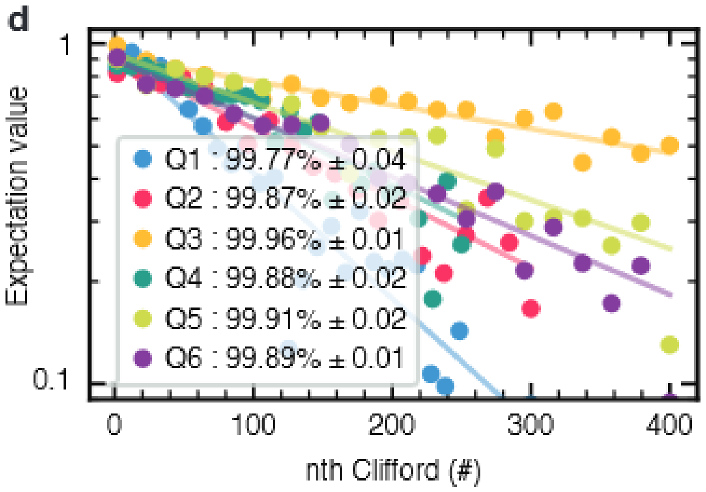
  Philips et al., arXiv:2202.09252 (2022)

- "Hot"-qubit operation ~ 4K

  Yang et al., Nature 580, 350–354 (2020)

  Petit et al., Nature 580, 355–359 (2020)





Semiconductor QD qubits with electrons: current limitations

- Magnetic manipulation is hard and too energy consuming
- Electrical manipulation requires the presence of micromagnets, adding an element of complexity
- Variability in some properties with low tunability
- Interactions are limited to nearest neighbors

Embrace the hole spin qubits!!

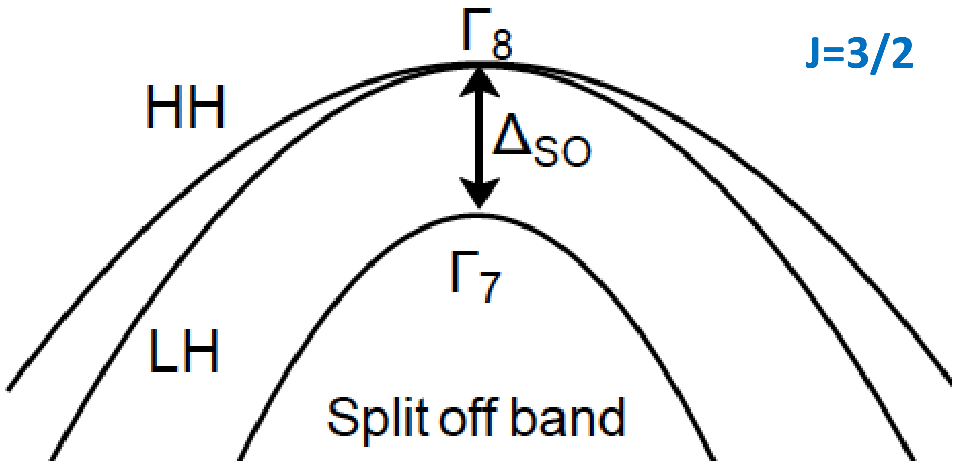
Encoding the qubit in a spin-orbit qubit

Hole spins in Si/Ge inherit the spin-orbit interaction from the valence band

Spin degree of freedom is coupled to the movement of the hole: allows all-electrical manipulation of the hole

Qubit properties are highly tunable through gate voltages

Cool physics: anisotropic g-matrices, Rashba SOC, sweet spots



Hole spin qubits: quick growth

- First demonstration of hole qubit in Si and Ge

  Maurand et al., Nat. Comms. 7, 13575 (2016)

  Hendrickx et al., Nat. Comms. 11, 3478 (2020)

- 4-qubit processor: single-qubit gates above 99.9% and two-qubit above 98%

  Hendrickx et al., Nature 577, 487–491 (2020)

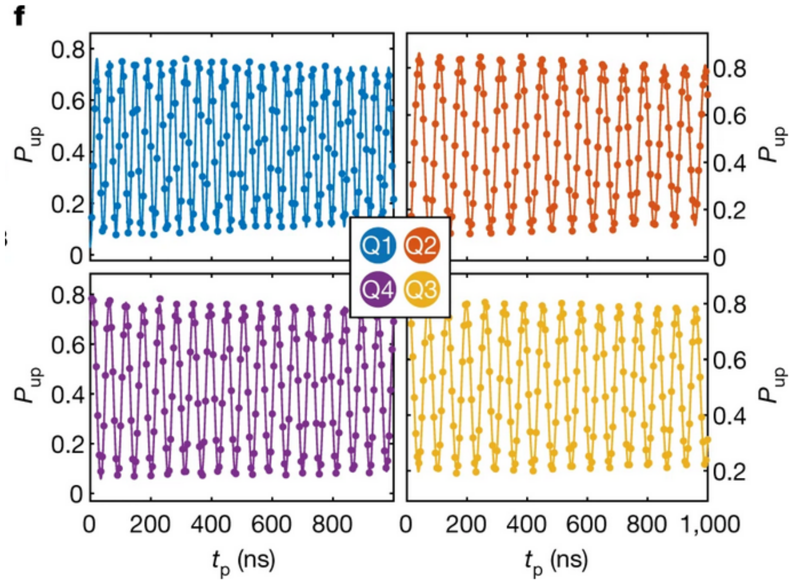
  Hendrickx et al., Nature 591, 580–585 (2021)

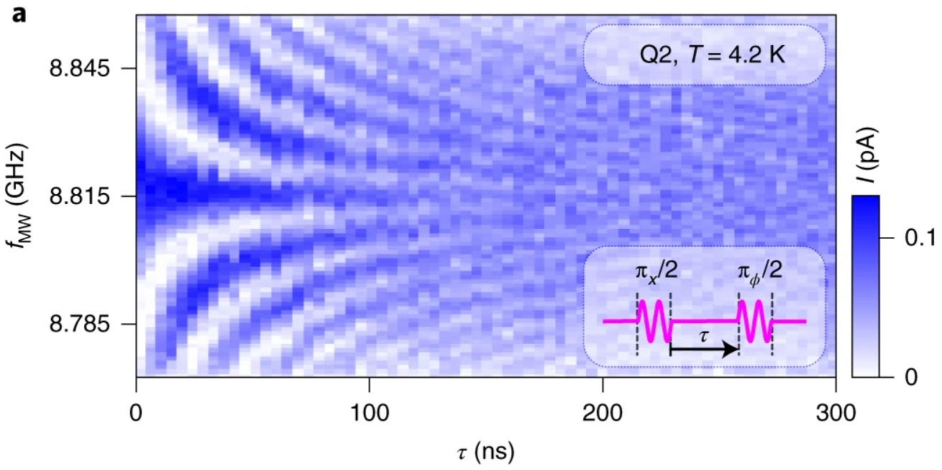
- Large coherence T_2*~90 µs

  Piot et al., to appear in Nat. Nano (2022)

- “Hot”-qubit operation ~ 4K

  Carmenzind et al., Nat. Electronics 5, 178–183 (2022)



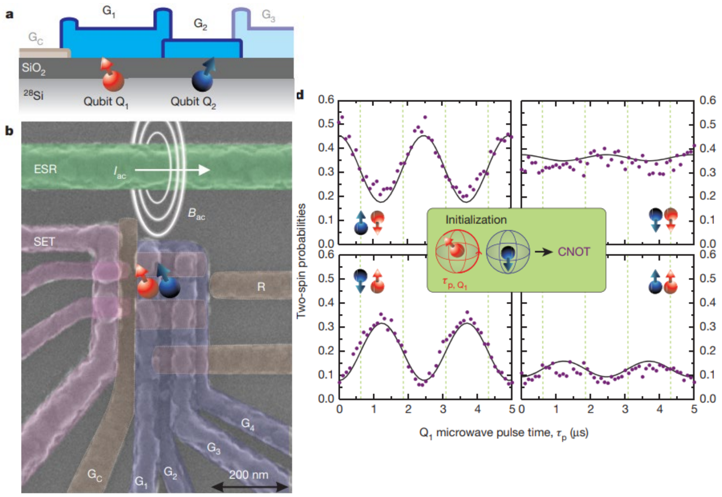


The missing link: long-range two-qubit gates

Interaction distance

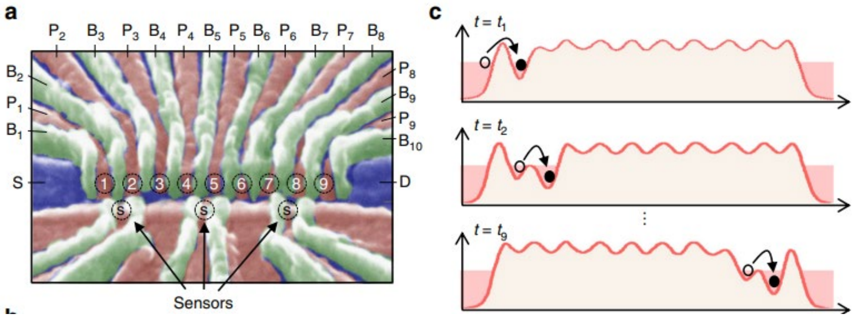
$\sim 50nm$ $\sim 50nm - 50\mu m$ $\sim 1cm$

Nearest neighbor exchange interaction

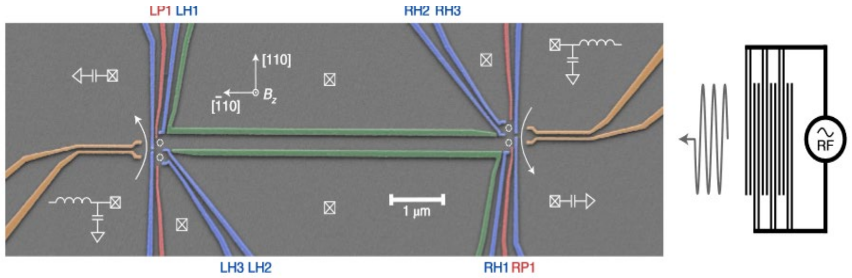


Veldhorst et al., Nature **526** (2015)

Charge shuttling in a QD array

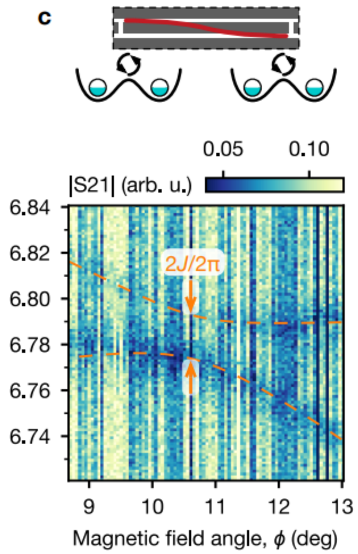


Mills et al., Nat. Comm. **10** (2019)



Jadot et al., Nat. Nano. 16, 570–575 (2021)

Photon mediated interaction



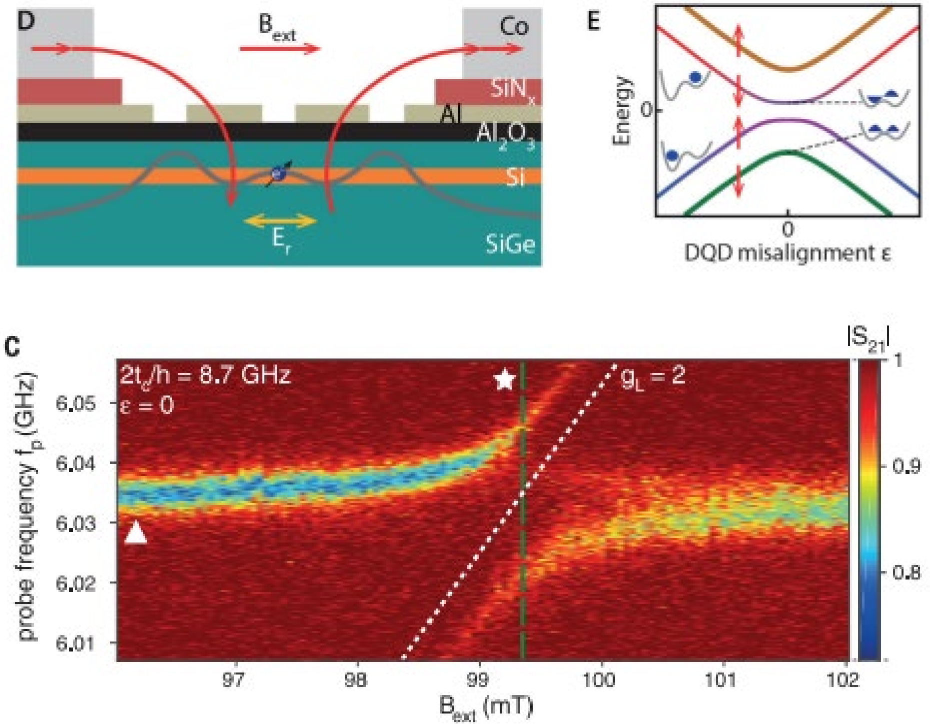
Harvey-Collard et al., PRX **12** (2022)

Electron-photon interfaces in Si

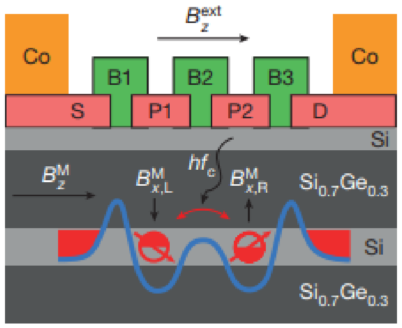
Photons couple readily to the charge of the electron

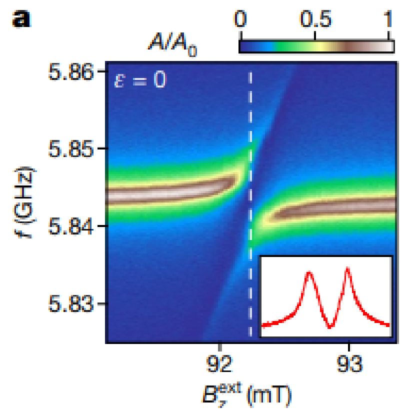
To couple the spin to the photon one needs to induce an artificial SOC: micromagnets

Coupling in the tens MHz
Decoherence rates in few MHz



Samkharadze et al.
Science 359, 1123 (2018)

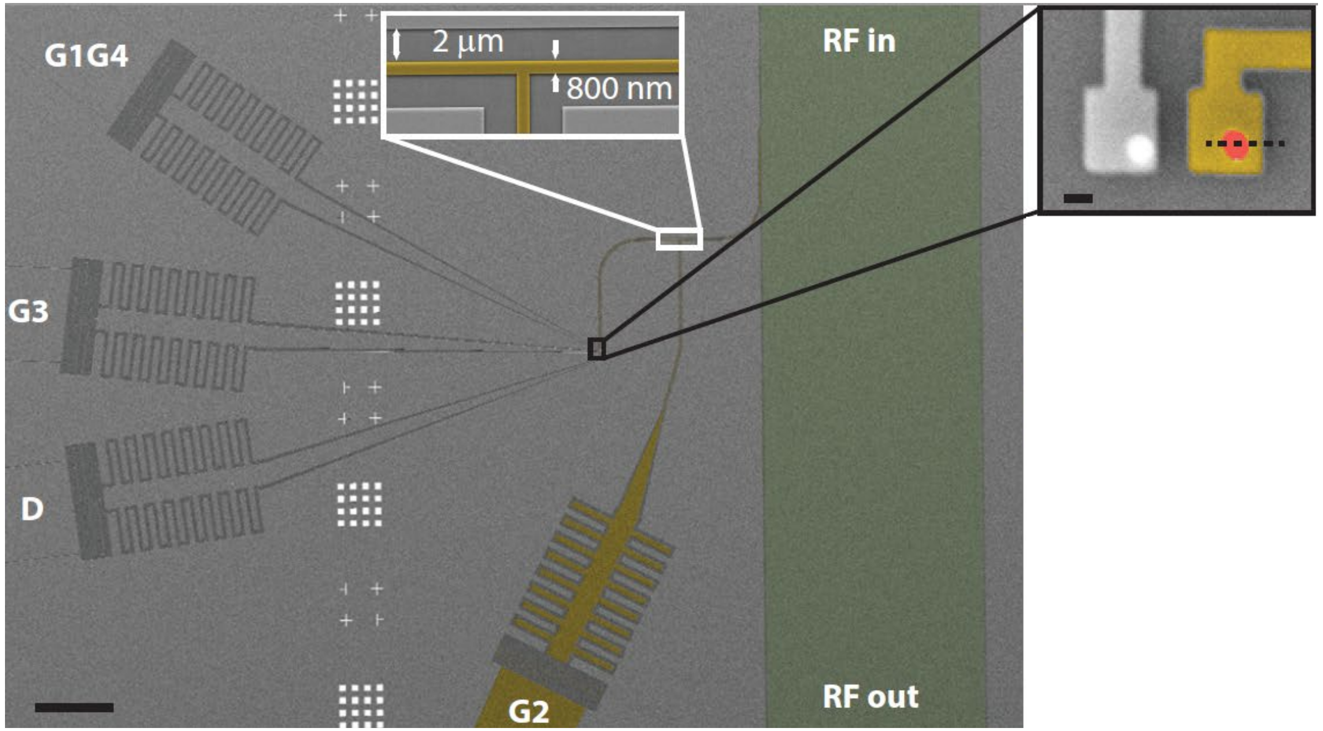


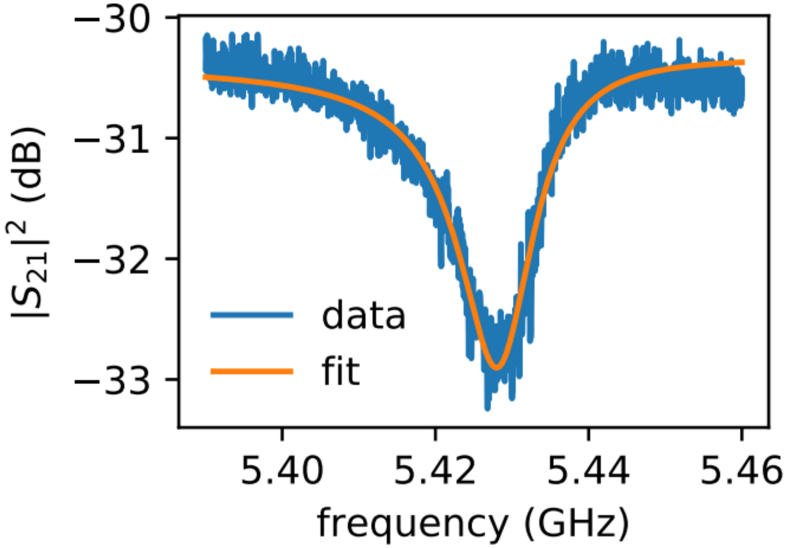


Mi et al.
Nature 555, 590 (2018)

What if we take advantage of the intrinsic SOC of holes?

Circuit QED with hole spins in Si





$\omega_r/2\pi = 5.43$ GHz

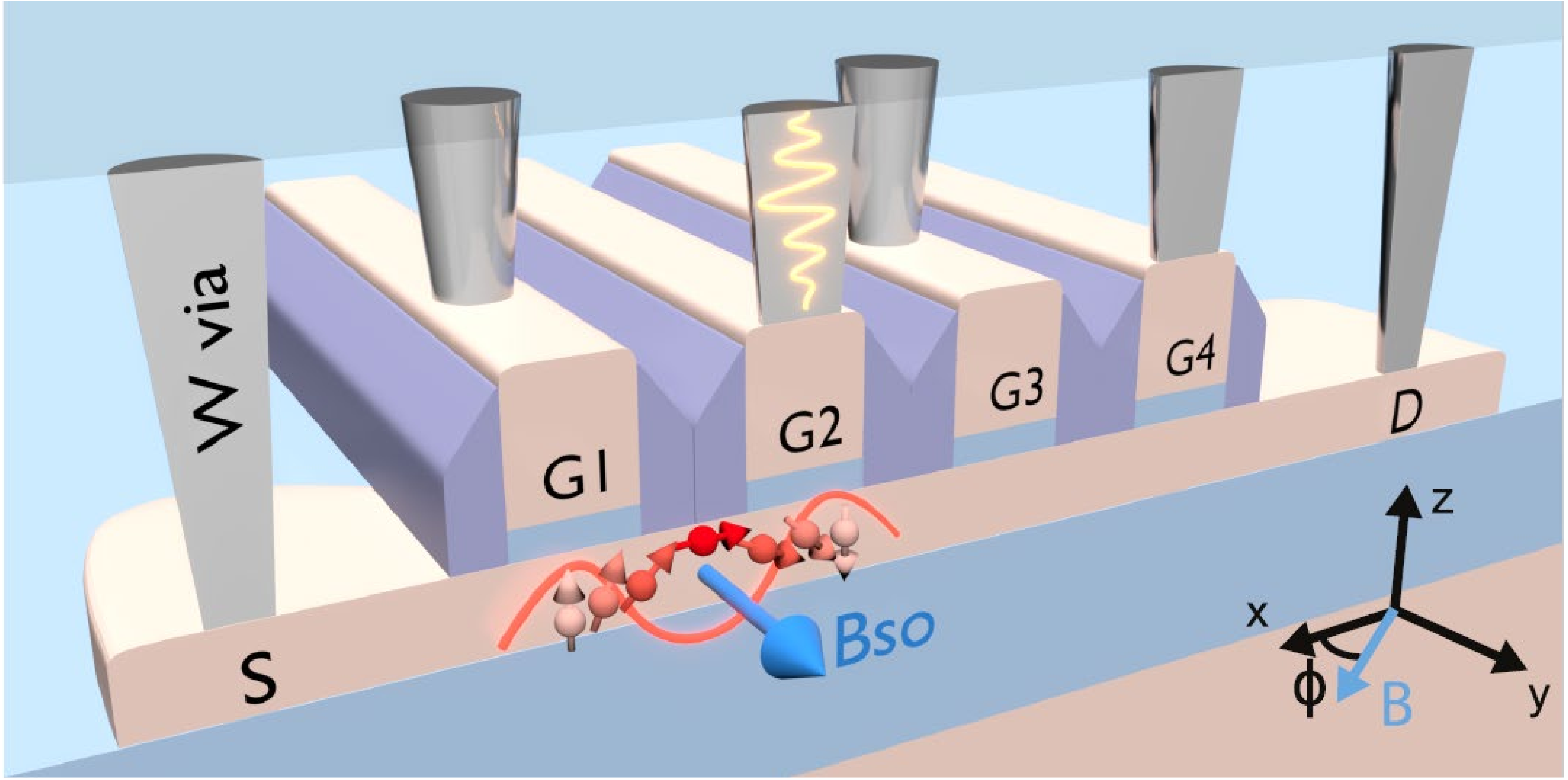
$\kappa/2\pi = 13.5$ MHz

$\kappa_{int}/2\pi = 10$ MHz

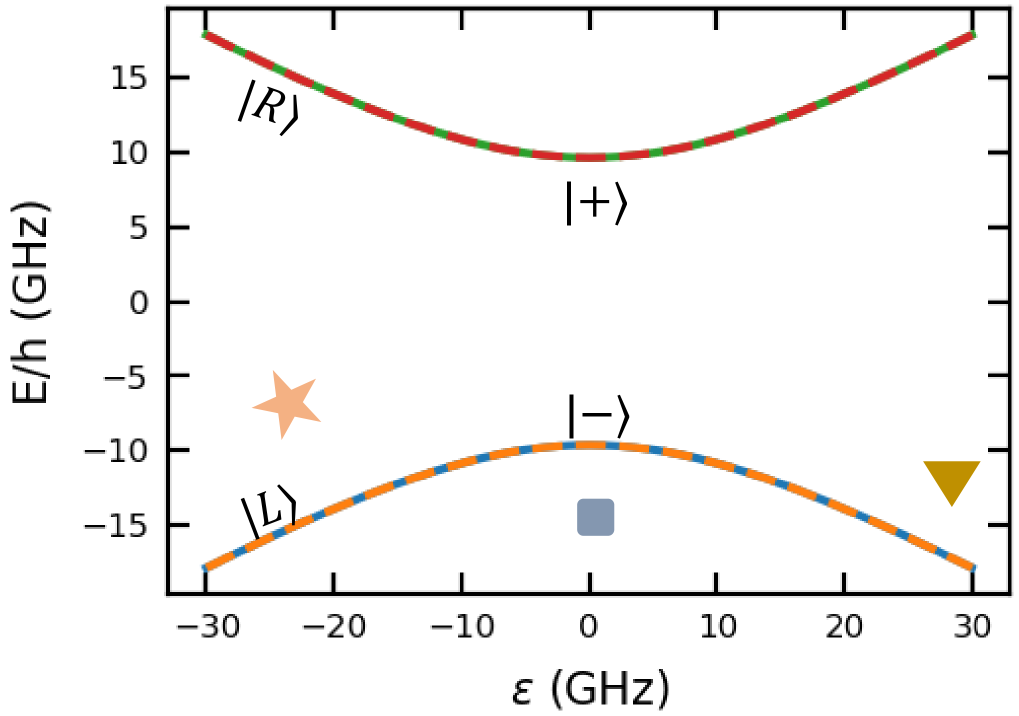
$\kappa_{ext}/2\pi = 3.5$ MHz

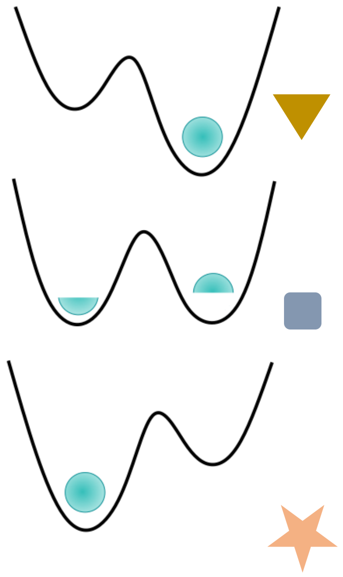
- $\lambda/2$ NbN CPW resonator $Z_c = 2\ k\Omega$, $f_r = 5.4$ GHz
- Co-fabrication with resonator at interconnect layer (M1), connected by W vias
- Si nanowire transistor on SOI with one gate connected to the resonator

Circuit QED with hole spins in Si



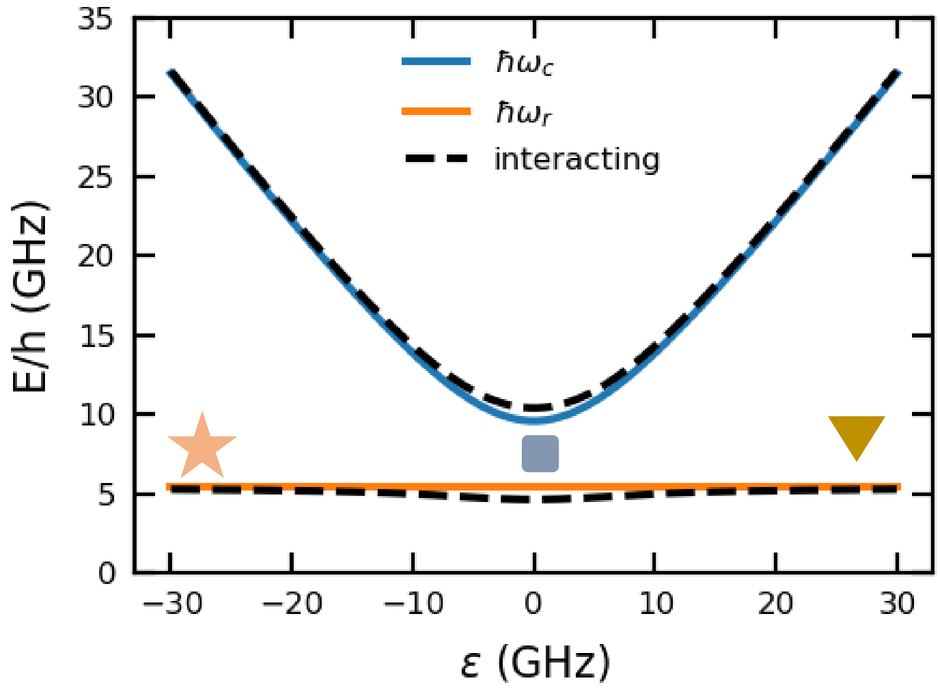
Charge-photon interaction (B=0)

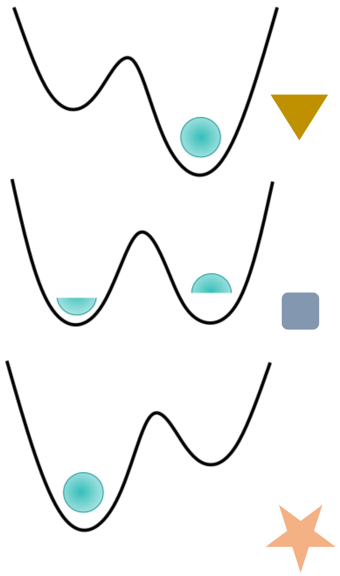




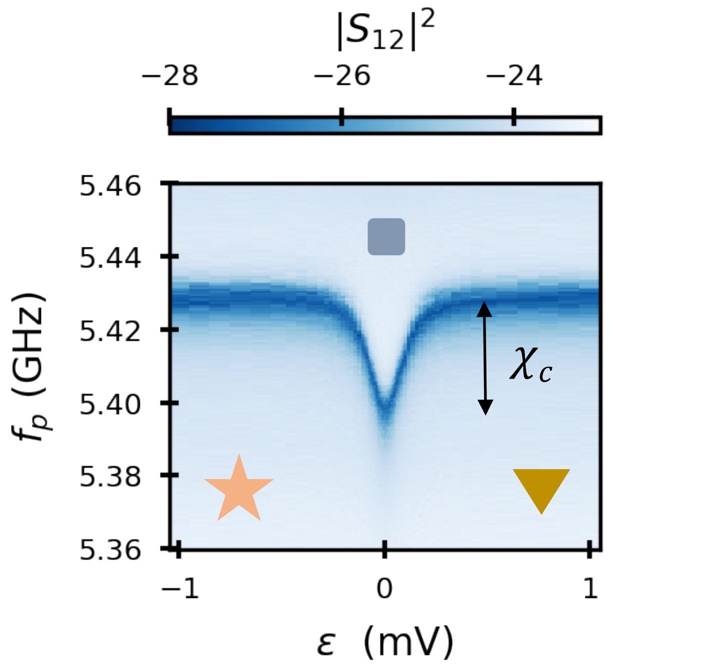
$$H_c = \begin{pmatrix} \epsilon/2 & t_c \\ t_c & -\epsilon/2 \end{pmatrix}, \begin{pmatrix} |L\rangle \\ |R\rangle \end{pmatrix}$$

Charge-photon interaction





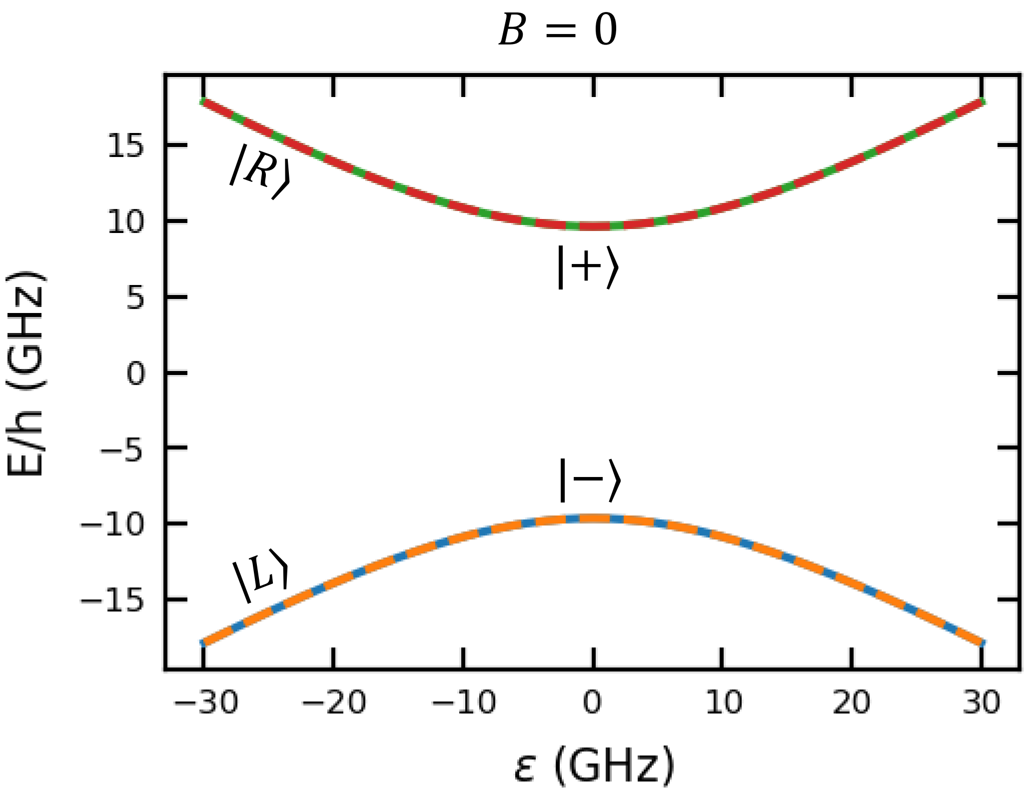
Cavity response to a probe field

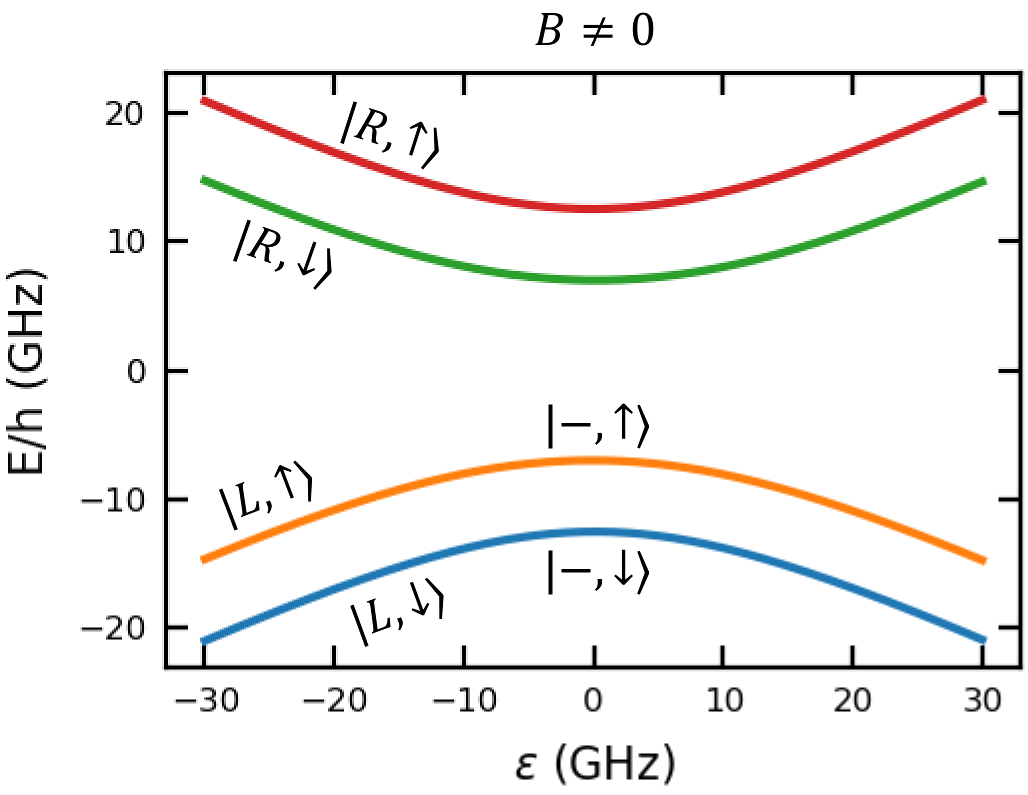


$g_c/2\pi =$ **513 MHz**

$t_c/h = 9.6$ **GHz**

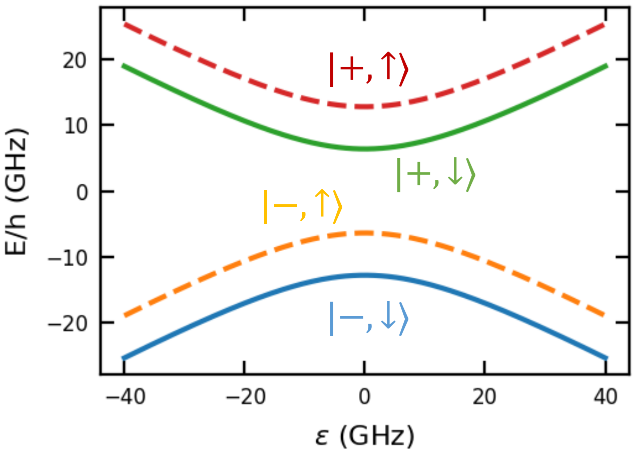
Where is the spin?

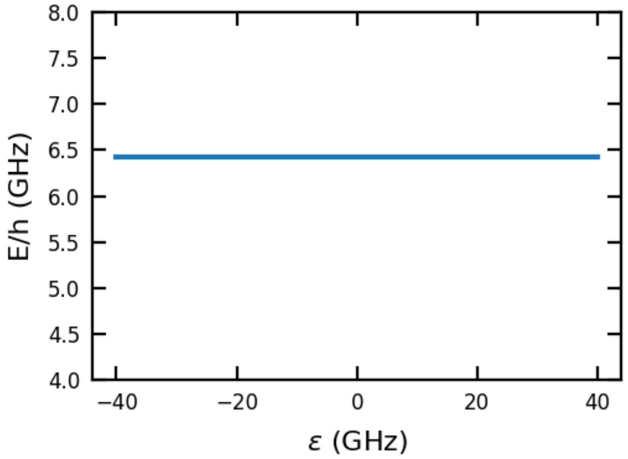




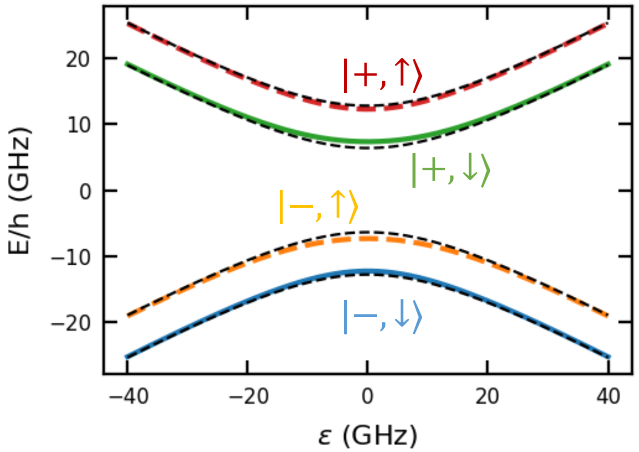
Spin transition in DQD with SOC

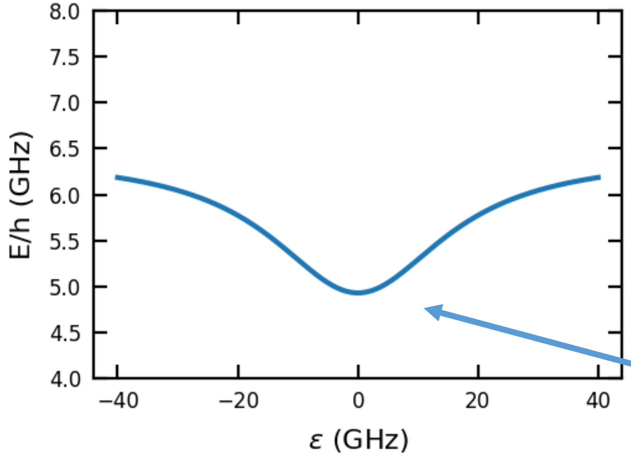
No SOC





With SOC

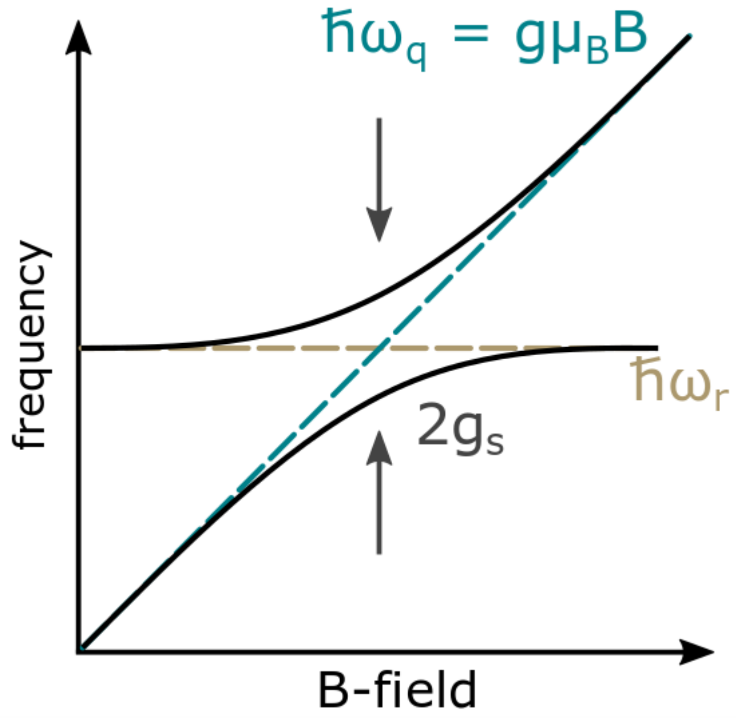




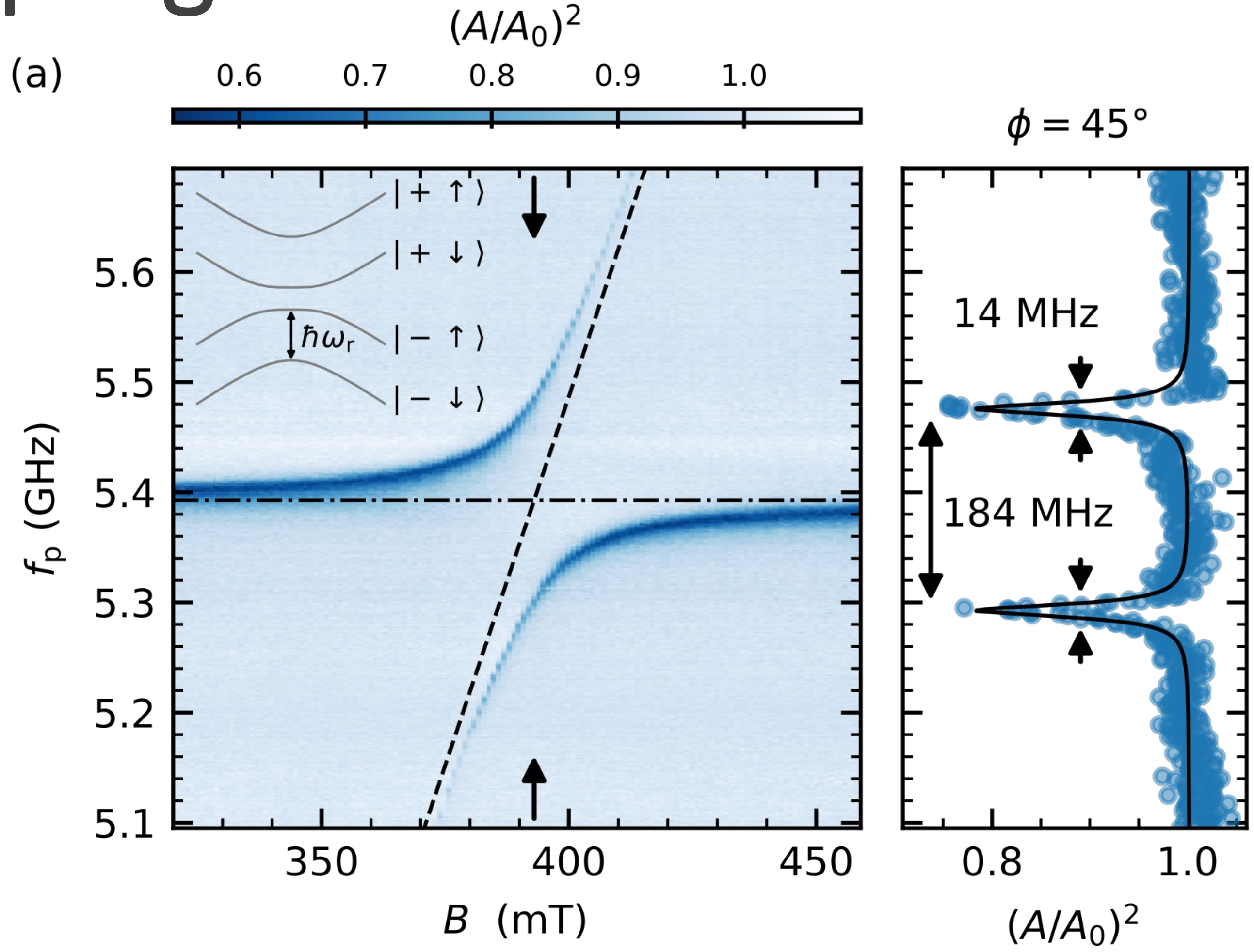
Sweet spot with respect to charge noise

$$|-,\uparrow\rangle \longrightarrow \alpha|-,\uparrow\rangle + \beta|+,\downarrow\rangle$$

Strong spin-photon coupling

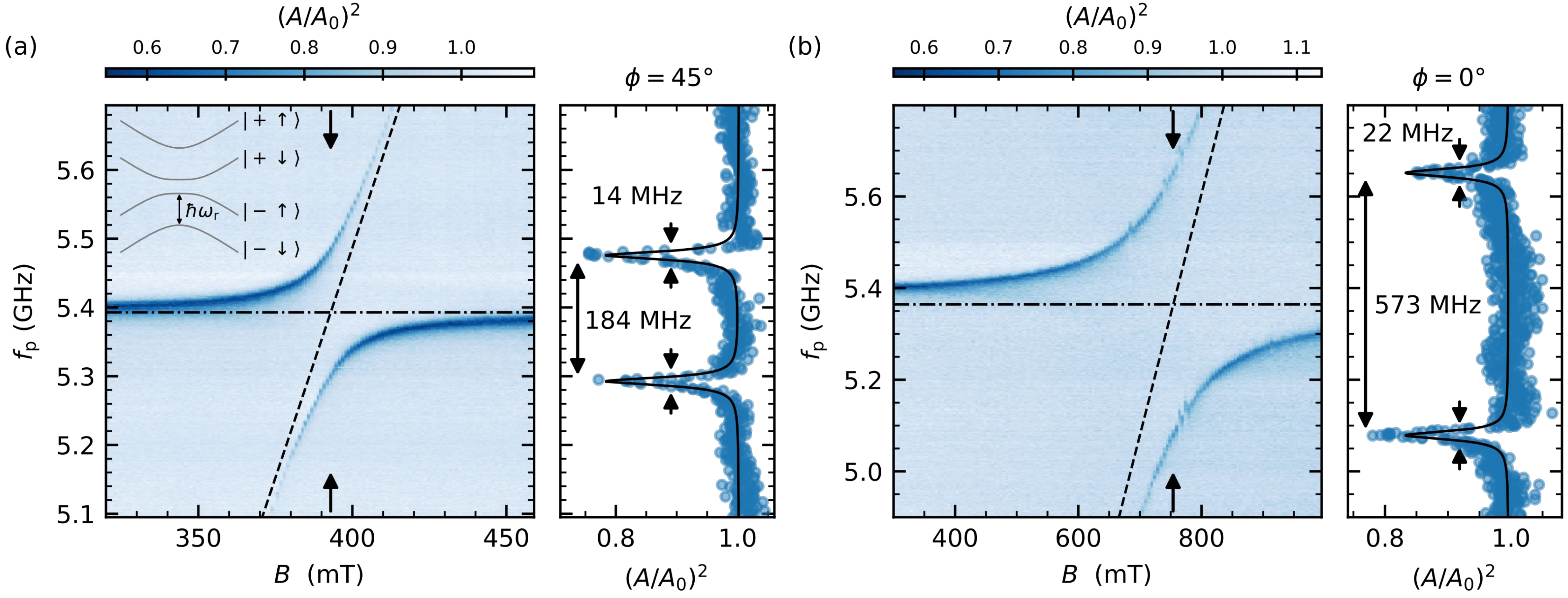


Vacuum Rabi mode splitting
→ signature of strong coupling



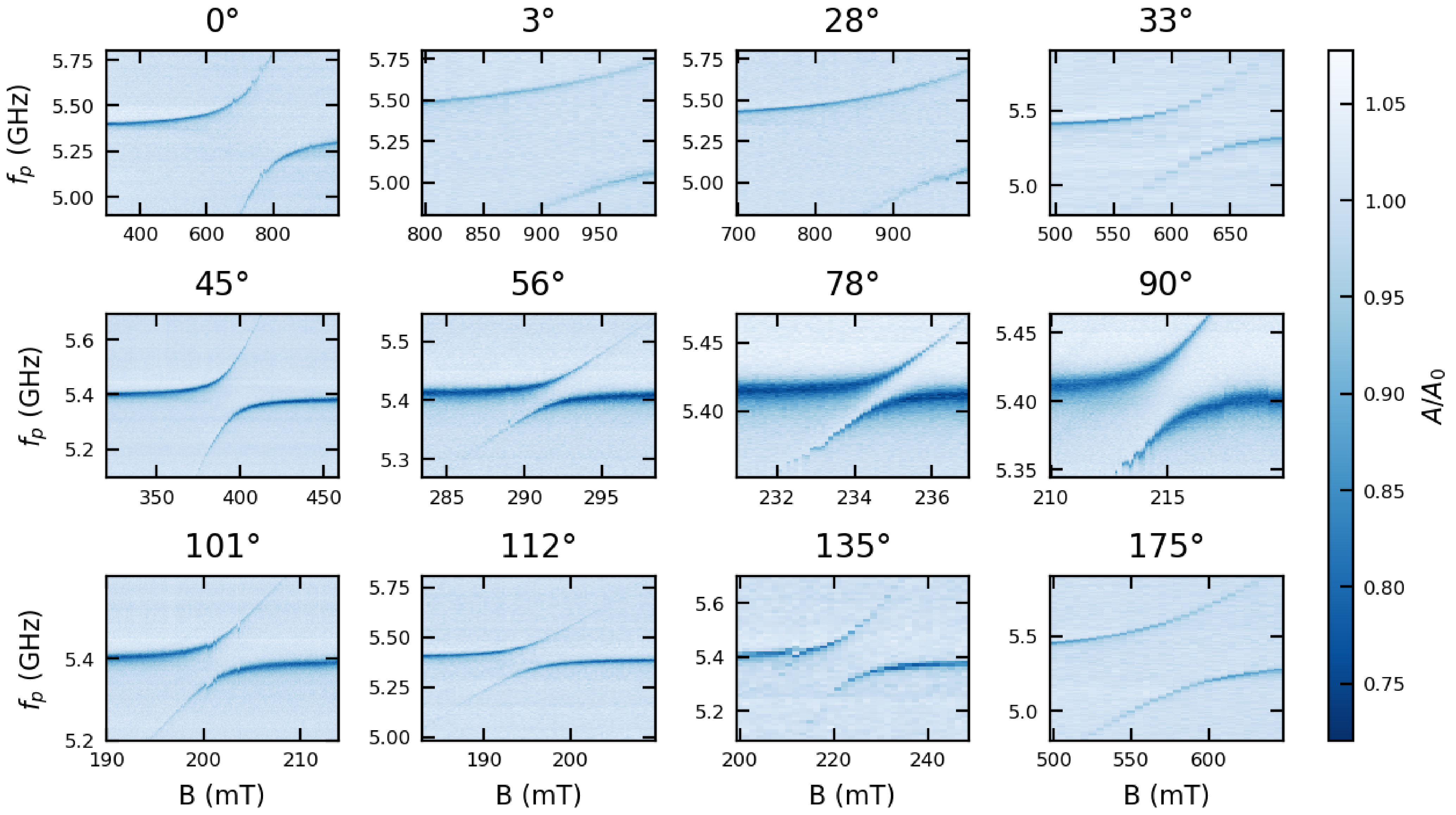
Strong spin-photon coupling with
$2g_s/2\pi = 184$ MHz $\gg 13$ MHz

Strong spin-photon coupling: angular dependence



→ g_s heavily depends on the magnetic field orientation

Angular dependence



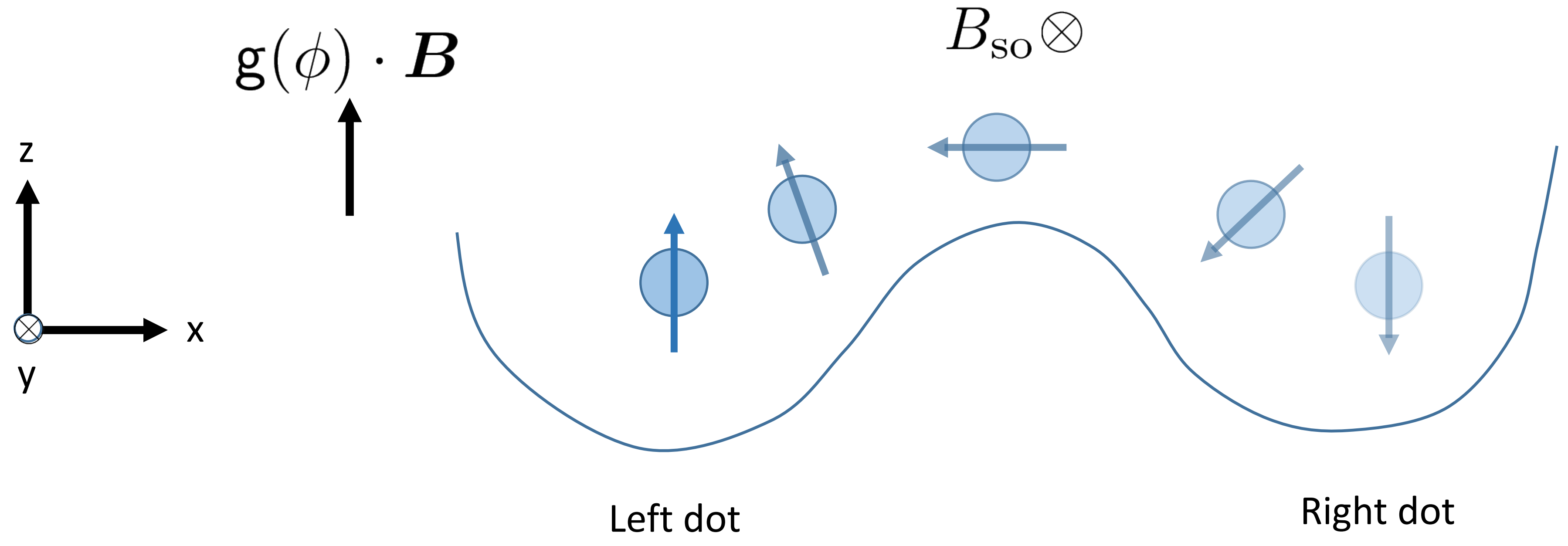
Interplay between Zeeman and SO field

$$H_{\rm so} = \frac{\hbar^2}{m_{||}\ell_{\rm so}} k_x B_{\rm so} \cdot \boldsymbol{\sigma}$$

$B_{\rm so}$ is the spin-orbit vector over which the spin precesses as it moves in x

$\ell_{\rm so}$ is the length over which there is a spin flip

$\mathrm{g}(\phi) \cdot \boldsymbol{B}$



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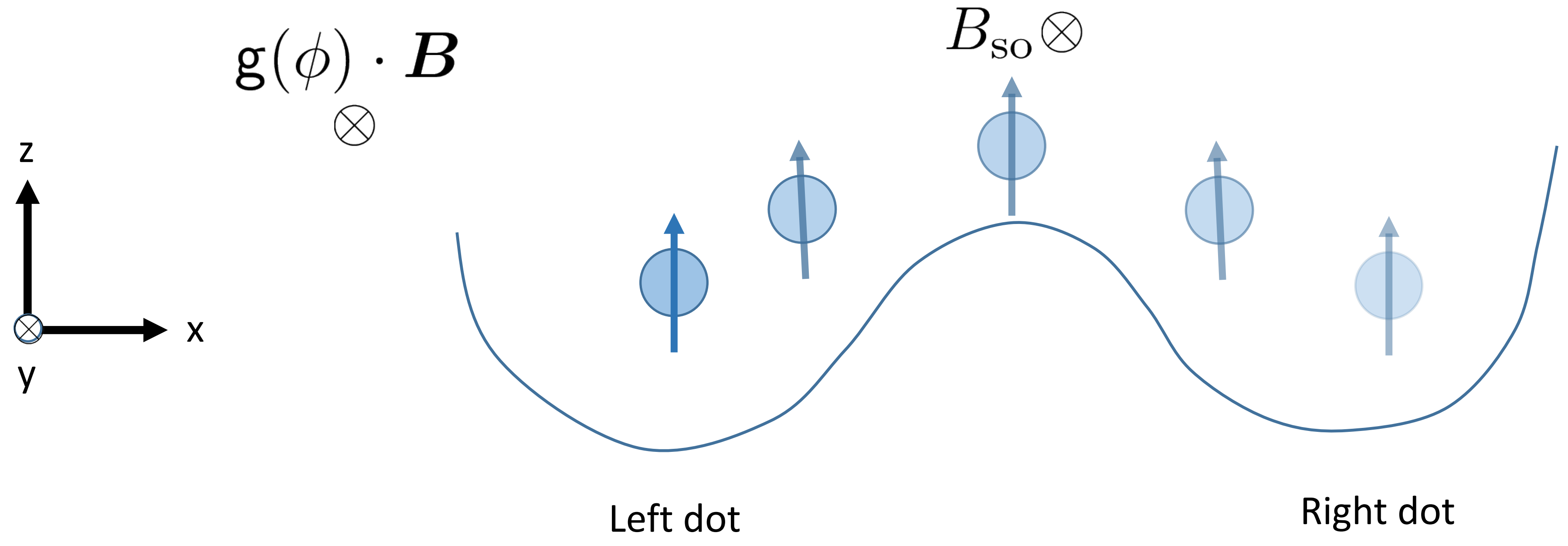
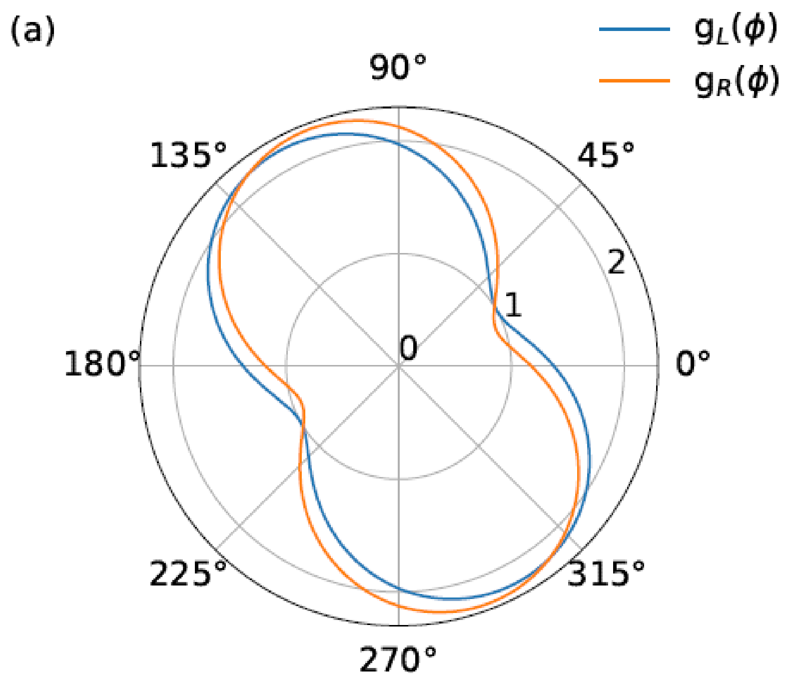


$$t_{\mathrm{sc}}(\phi) = t_c(\cos(d/\ell_{so}) + \sin(d/\ell_{so})\frac{(\mathrm{g}\cdot\mathrm{B})\cdot B_{\mathrm{so}}}{|g \cdot B|}$$

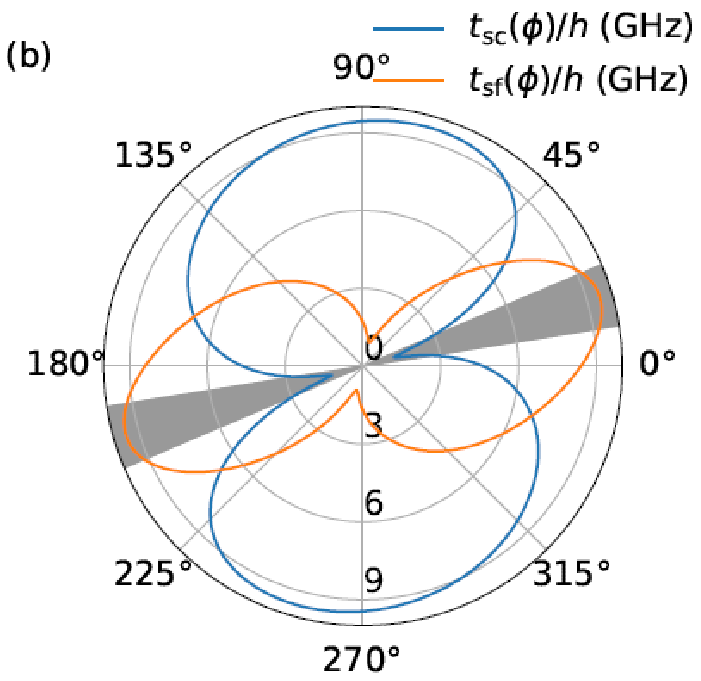
$$t_{\mathrm{sf}}(\phi) = t_c \sin(d/\ell_{so})\frac{(\mathrm{g}\cdot\mathrm{B}) \times B_{\mathrm{so}}}{|g \cdot B|}$$

Angular dependence of g_L, g_R, t_{sc} and t_{sf}

g-factors



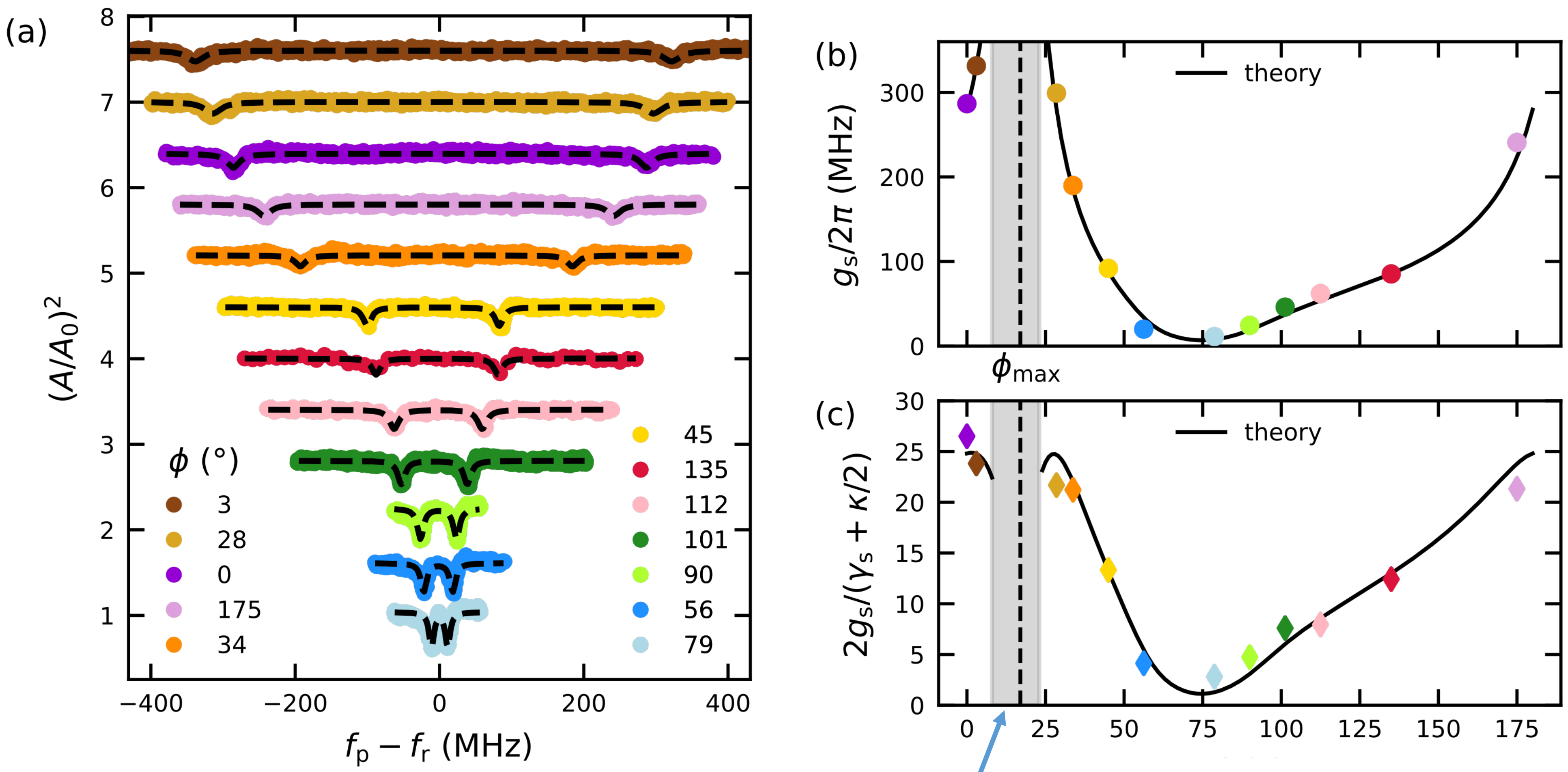
t_{sc} and t_{sf} for anisotropic g-factors



$$t_{\rm sc}(\phi) = t_c(\cos(d/\ell_{so}) + \sin(d/\ell_{so})\frac{(\mathrm{g}\cdot\mathrm{B})\cdot B_{\rm so}}{|g\cdot B|}$$

$$t_{\rm sf}(\phi) = t_c \sin(d/\ell_{so})\frac{(\mathrm{g}\cdot\mathrm{B})\times B_{\rm so}}{|g\cdot B|}$$

Strong spin-photon coupling: angular dependence



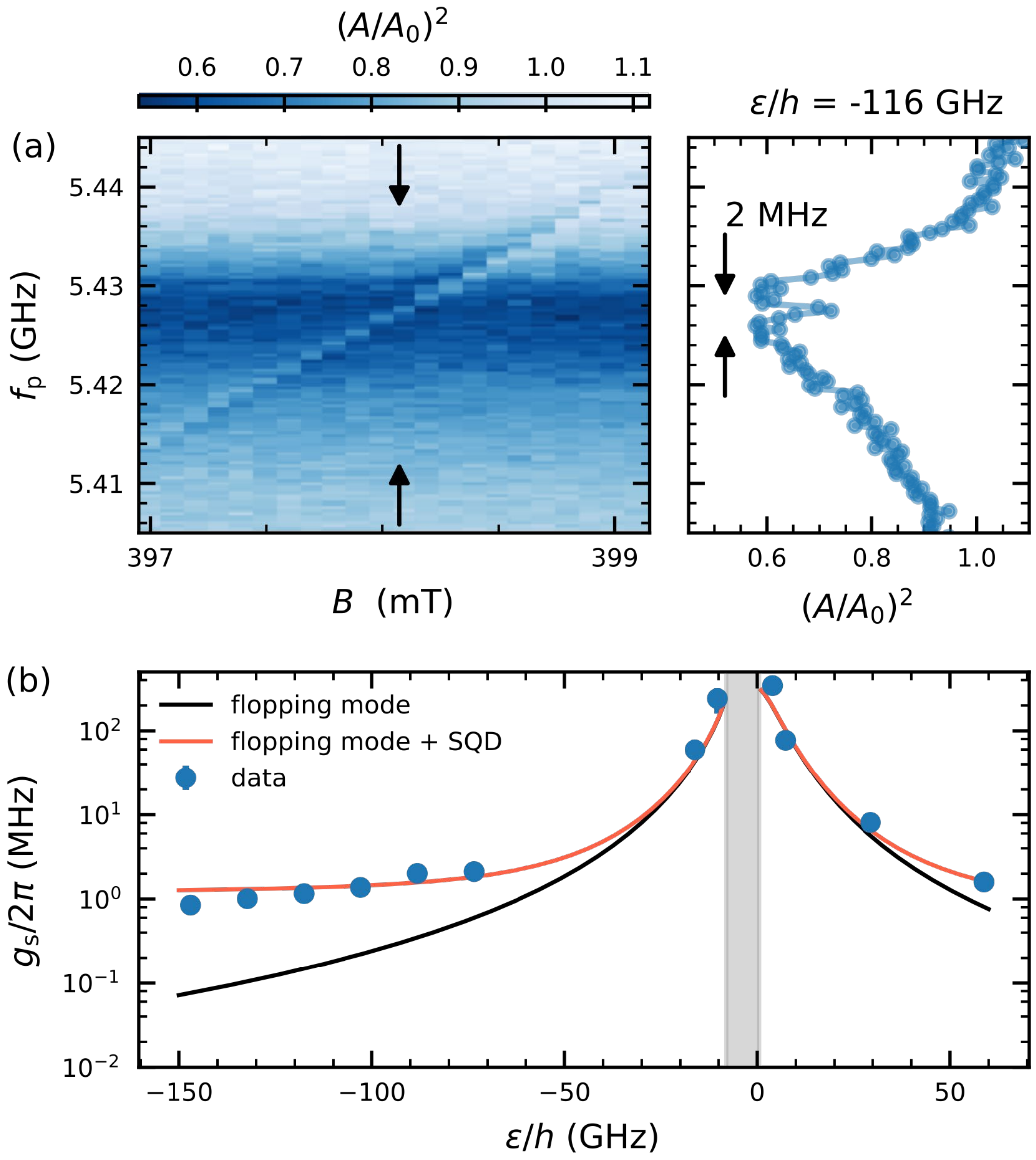
Max cooperativity

$$C = \frac{4g_s^2}{\gamma\kappa} = 1600$$

ϕ_{max} maximizes spin-photon coupling

$$g_s \propto g_c |\,(\hat{g} \cdot \vec{B}) \times \vec{B}_{so}|$$

Single dot limit



Tunable hole spin-photon interaction based on g-matrix modulation

V. P. Michal,[1] J. C. Abadillo-Uriel,[1] S. Zihlmann,[2] R. Maurand,[2] Y.-M. Niquet,[1] and M. Filippone[1,*]

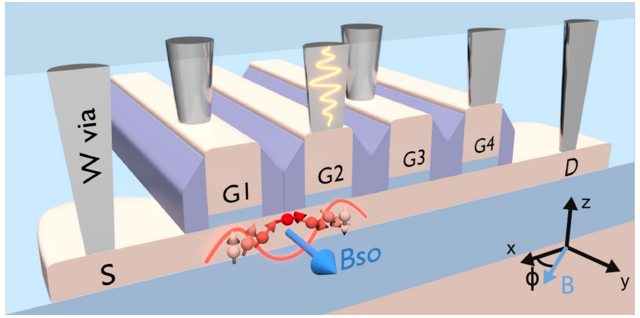
We estimate ~10 MHz when perfectly aligned for g-factor modulation and in the experimental paper a 1 MHz coupling is observed in the SD limit

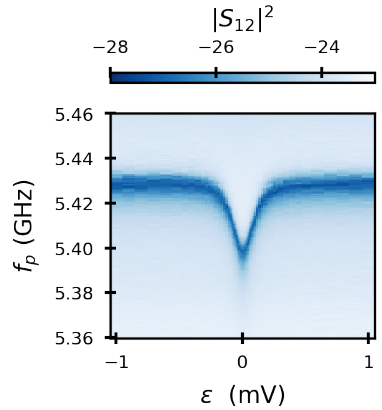
Perspectives

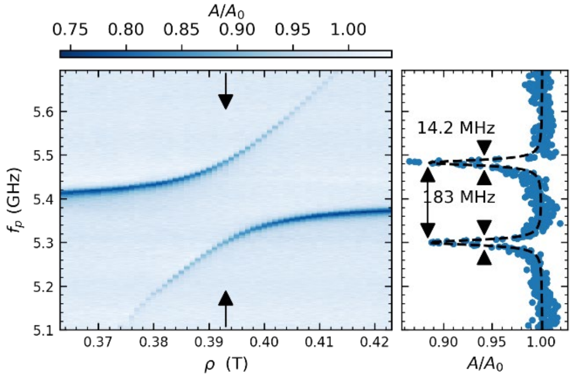
- cQED platform accessible to hole-spin qubits
- High fidelity two-qubit gates mediated by a resonator within reach
- Fast single-shot dispersive spin readout (no need for spin to charge conversion)
- Longitudinal coupling

Take home message

- Si-MOS hole spins embedded in a high-impedance cavity
- Bordering ultra-strong charge-photon coupling with $g_c = 513\ MHz$
- Unprecedented spin-photon coupling $g_s = 330$ MHz
- Extremely strong light-matter interaction, cooperativity of ~1600
- First demonstration of sizable coupling in single dot limit $g_s \simeq 1$ MHz

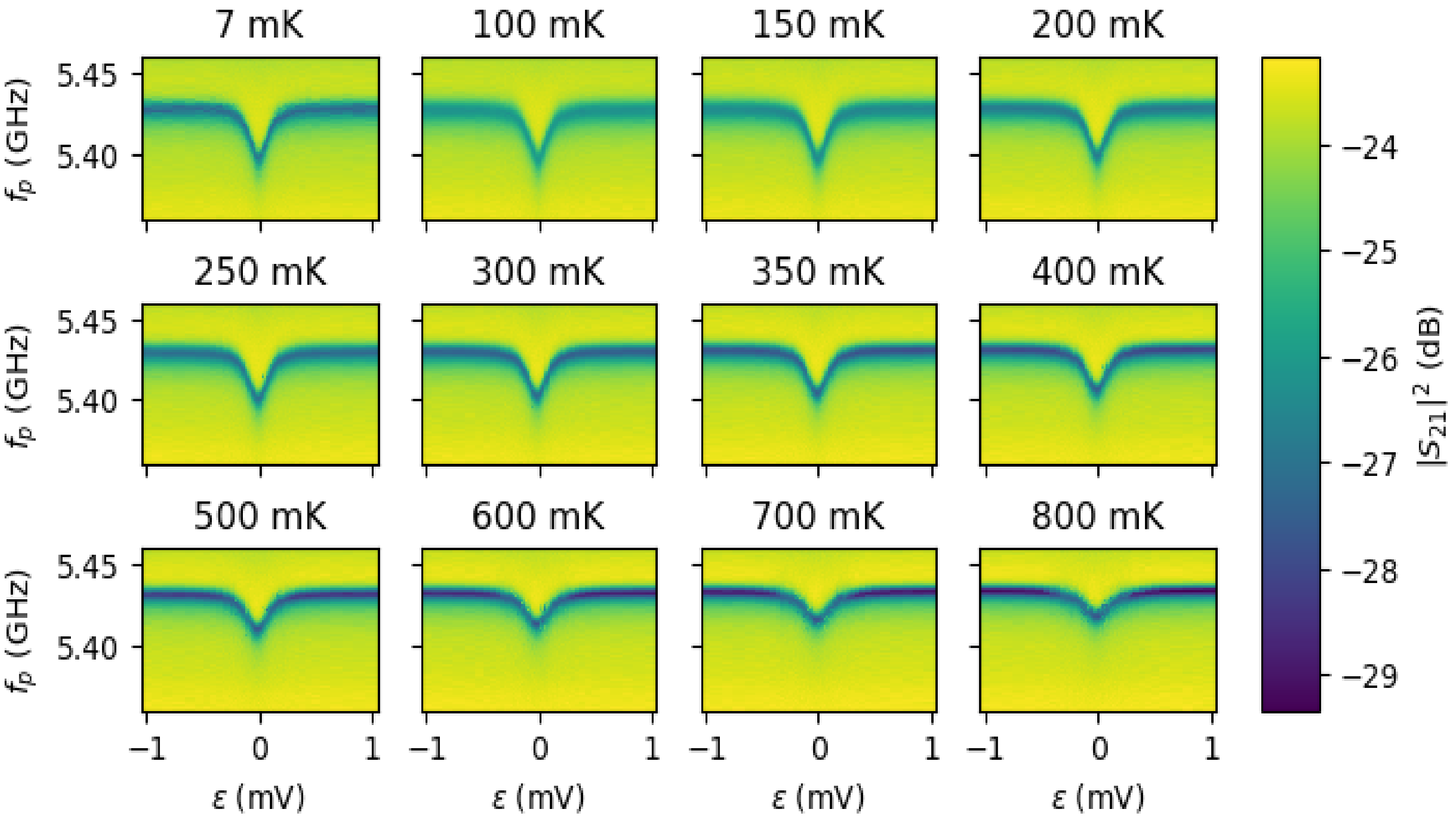






Soon on arxiv (hopefully)

Characterizing the charge-photon coupling



Dispersive shift at $\epsilon = 0$

$$\chi_c = g_c^2 \cdot (p_0 - p_1) \cdot \left(\frac{1}{\omega_q - \omega_r} + \frac{1}{\omega_q + \omega_r}\right)$$

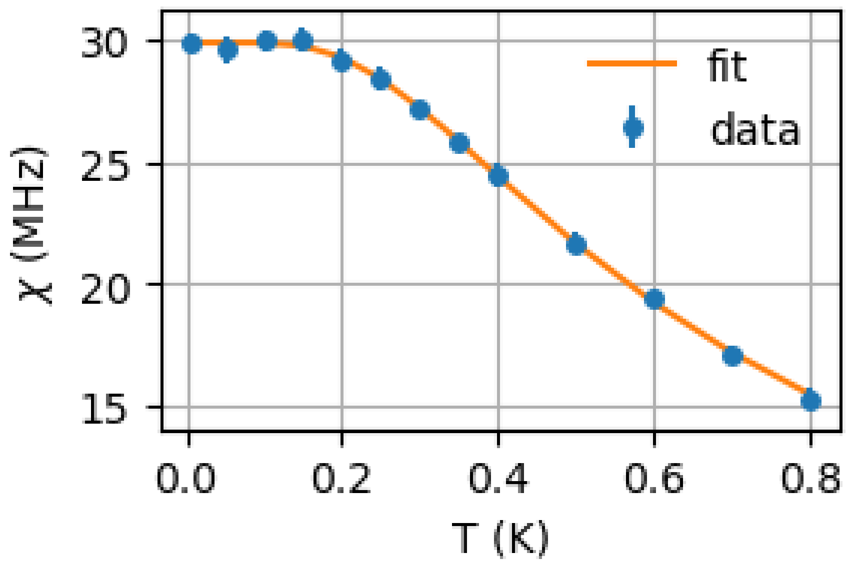
$$p_1 = \frac{1}{1+e^{\hbar\omega_q/k_B T}}$$

$$p_0 = 1 - p_1$$

$\boldsymbol{g_c/2\pi} = \mathbf{513\ MHz}$

$\boldsymbol{t_c/h} = \mathbf{9.6\ GHz}$

Charge-photon coupling



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$$p_1 = \frac{1}{1+e^{\hbar\omega_q/k_B T}}$$

$$p_0 = 1 - p_1$$

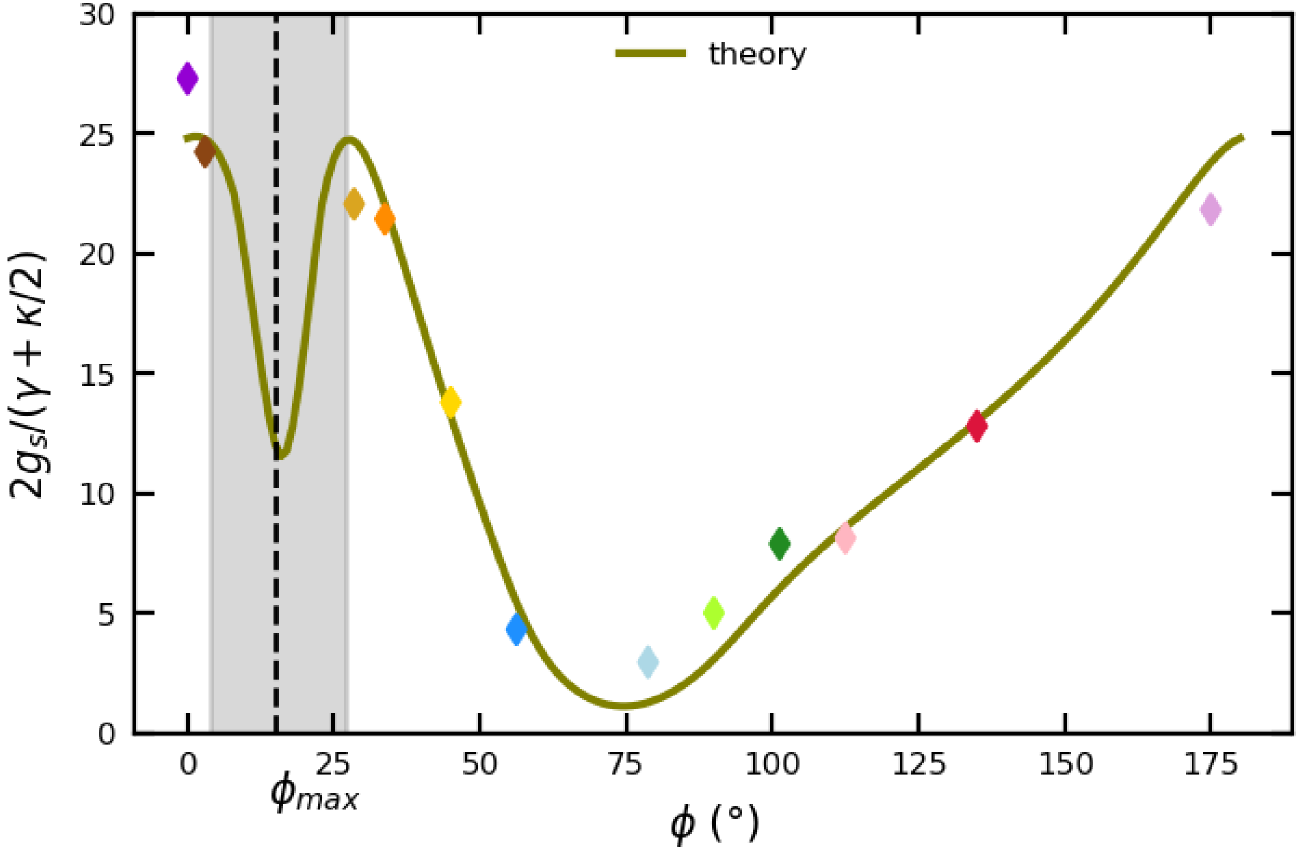
$$\boldsymbol{g_c/2\pi = 513}\ \textbf{MHz}$$

$$g_c = \frac{\alpha e V_{zpf}}{2h}$$

$$\boldsymbol{t_c/h = 9.6}\ \textbf{GHz}$$

$$\boldsymbol{\alpha = 0.6}$$

Quality of spin-photon interface

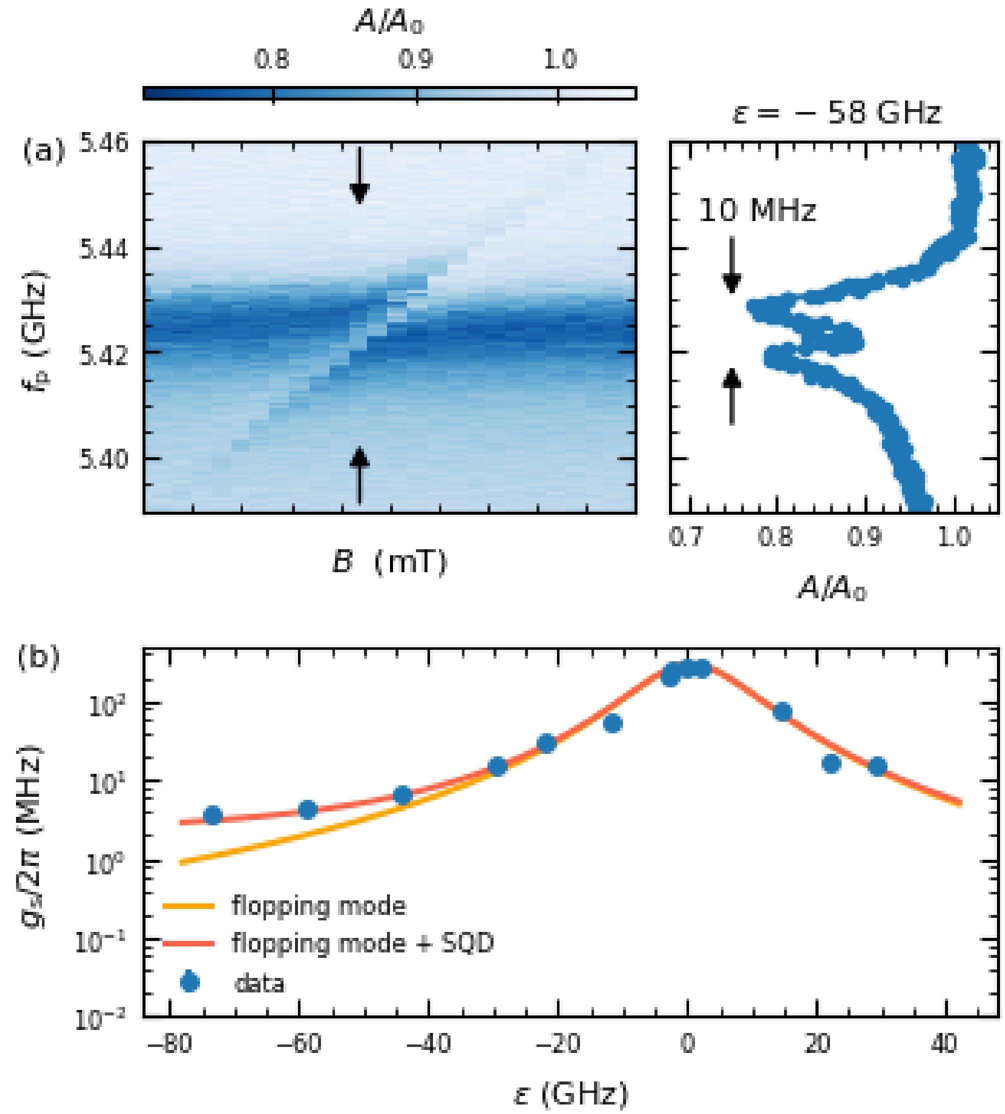


$\gamma_s = \gamma_\epsilon + \gamma_0$

$$\gamma_\epsilon/2\pi = \frac{1}{8\pi^2 h}\left|\frac{\partial^2 \omega_s}{\partial \epsilon^2}\right| \sigma_\epsilon^2$$

$\sigma_\epsilon = 5.8\ \mu\text{eV}$
$\gamma_0/2\pi = 3.3$ MHz
$\kappa/2\pi = 18$ MHz

Single dot limit at 0°



ϵ vs B –maps: Measurement of g_L, g_R and SOI