Gate Tunable Hole Charge Qubit Formed in a Ge/Si Nanowire Double Quantum Dot Coupled to Microwave Photons

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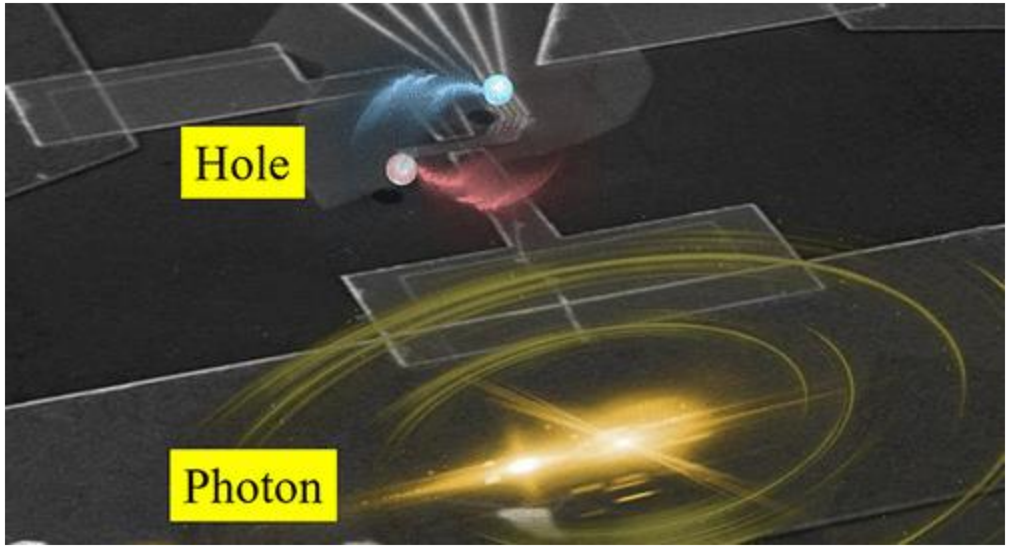


-FAM talk-

Fabian Müller
22.03.2019

Motivation

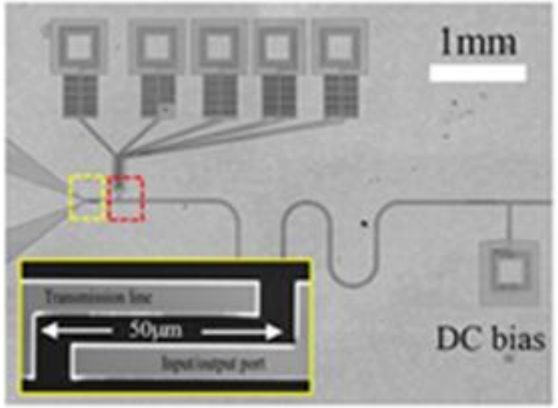
- Hole qubit:
  - P-wave nature leads to **enhanced qubit-cavity coupling** $\boldsymbol{g_c}$
  - Strong spin orbit interaction (SOI) → **Fast manipulation** of hole spin qubit

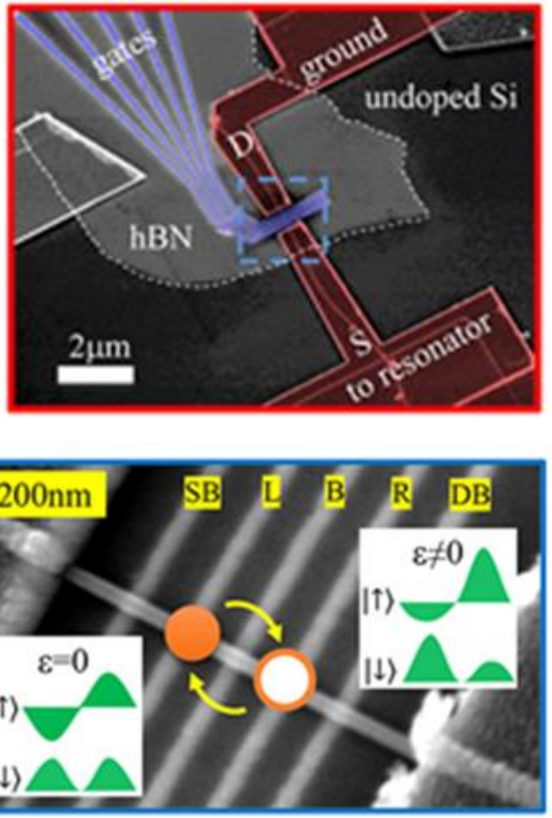
- Ge/Si NW:
  - Lack of nuclear spin scattering → no hyperfine → **lower decoherence rate** $\boldsymbol{\gamma}$

→ long-distance interaction between qubits & fast spin manipulation

Contents

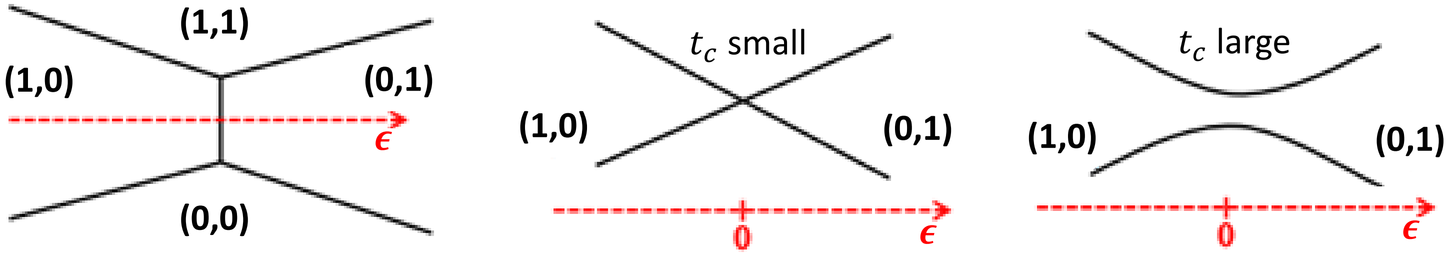
- MoRe superconducting transmission line resonator (Q ≈ 6000), $f_c = 5.9667\text{GHz}$
- Ge/Si core/shell NW
- hBN as dielectric
- Tens of holes in QD, few holes regime unstable





- Qubit energy (TLS):

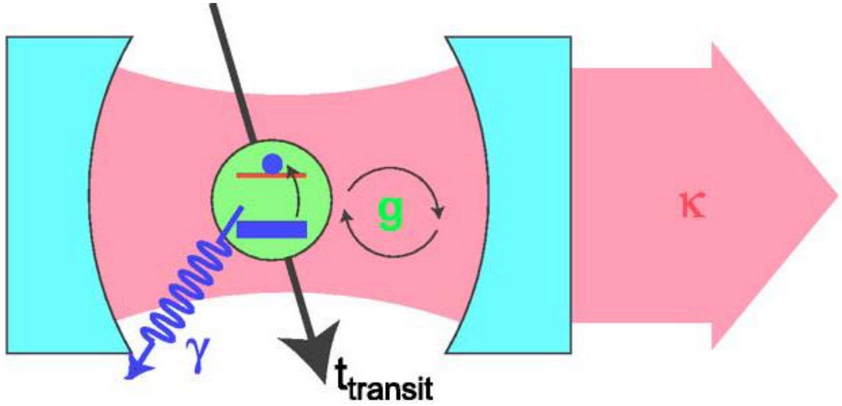
$$E_{qb} = \hbar\omega_{qb} = \sqrt{\epsilon^2 + (2t_c)^2}$$



- Jaynes-Cumming:

$$H_{JC} = \hbar\omega_c\left(a^\dagger a + \frac{1}{2}\right) + \frac{1}{2}\hbar\omega_{qb}\sigma_z + \hbar g_{eff}\left(a\sigma^+ + a^\dagger\sigma^-\right)$$

- Dressed States: $\frac{|\downarrow,1\rangle + |\uparrow,0\rangle}{\sqrt{2}}$ and $\frac{|\downarrow,1\rangle - |\uparrow,0\rangle}{\sqrt{2}}$



[1] A. Blais *et al.*, Phys. Rev. A **69**, 062320

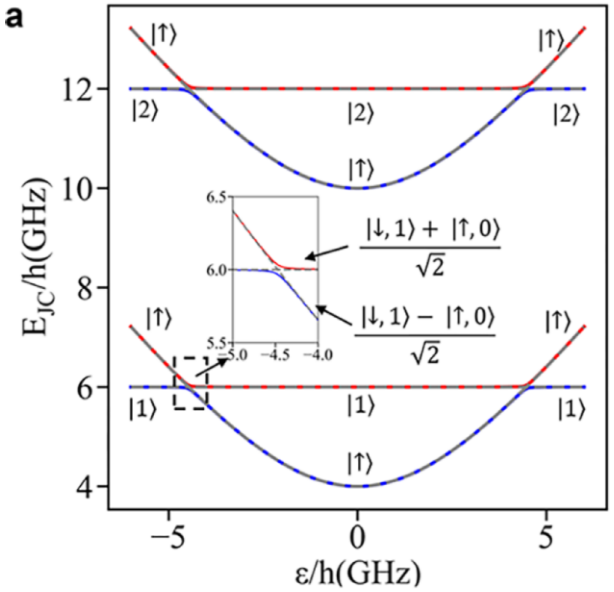
Simulation of cQED System

- Qubit-cavity coupling: $g_{eff} = g_c \times 2t_c/E_{qb}$ with $E_{qb} = \hbar\omega_{qb} = \sqrt{\epsilon^2 + (2t_c)^2}$

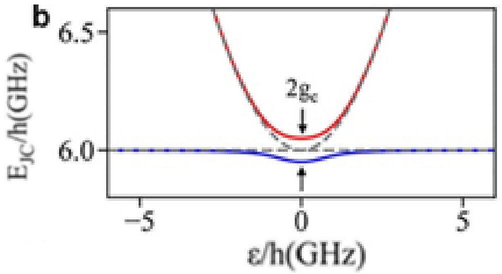
Resonant regime: $f_{qb} \leq f_{resonator}$

Dispersive regime: $f_{qb} > f_{resonator}$

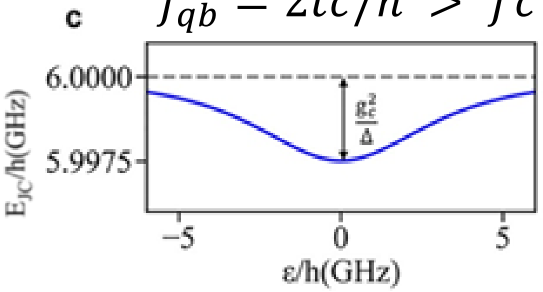
$f_{qb} = 2tc/h < fc$



$f_{qb} = 2tc/h = fc$



$f_{qb} = 2tc/h > fc$



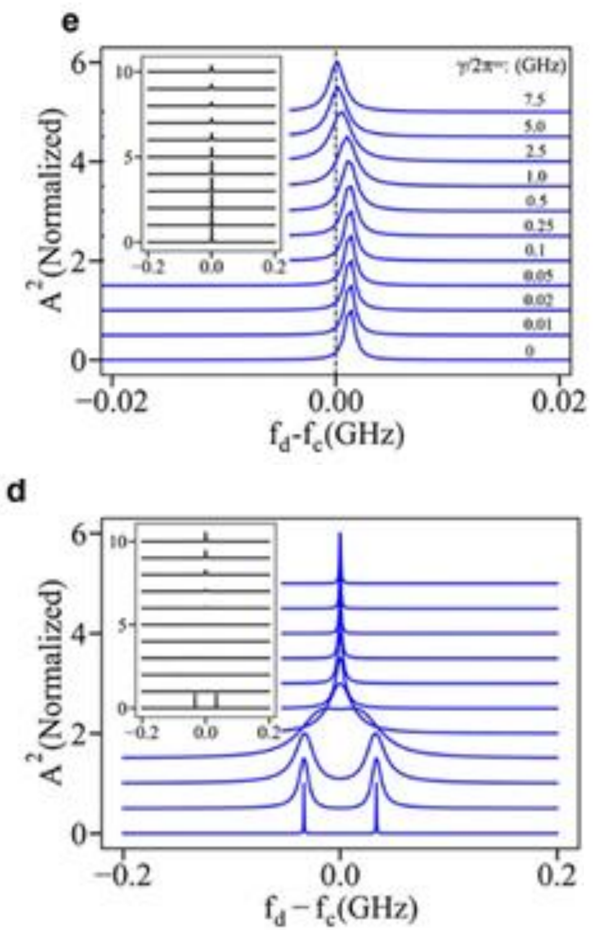
Cavity mode shift of $\Delta\theta = \frac{g_{eff}^2}{\Delta}$

$\Delta = h(f_{qb} - f_c)$

Simulation of Transmission Spectrum

- $g_c = 50\text{MHz}$

- $\Delta > 0$ **dispersive**, $f_{qb} = \frac{2t_c}{h}$
- $\forall\gamma \rightarrow g_{eff}/\,\Delta$ Shift due to dispersive pull



- $\Delta = h(f_{qb} - f_c) = 0$ **resonant**
- $\gamma < 2geff$ → two separated peaks
- $\gamma >> g_{eff}$ → narrow peak

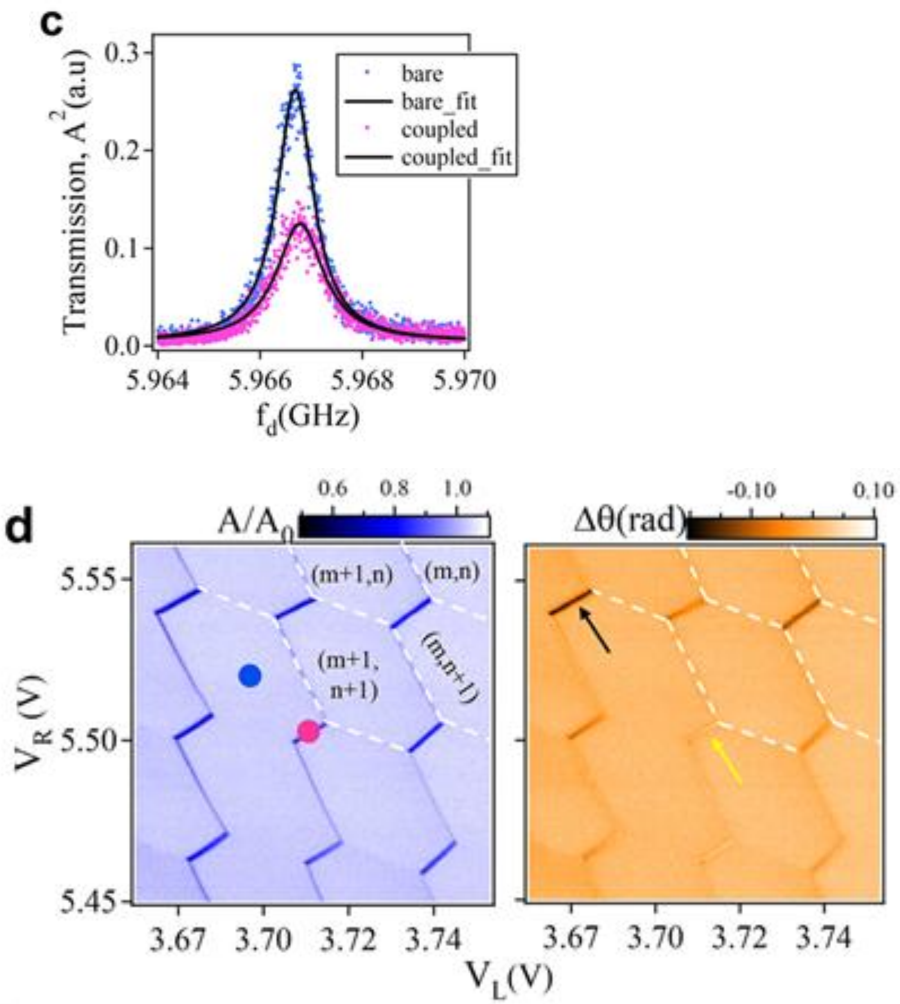
- Strong coupling regime: $g_c > \gamma, \kappa$

Transmission Spectroscopy

- $\boldsymbol{\varepsilon >> 0}$: qubit is only capacitively coupled to the resonator
- $\boldsymbol{\varepsilon = 0}$: if t_C is close to photon energy, there is qubit-resonator dipole coupling

→ altered amplitude (dissipation) and shift (dispersive pull).

- Positive and negative phase shift implies that the qubit is close to resonance with the resonator frequency



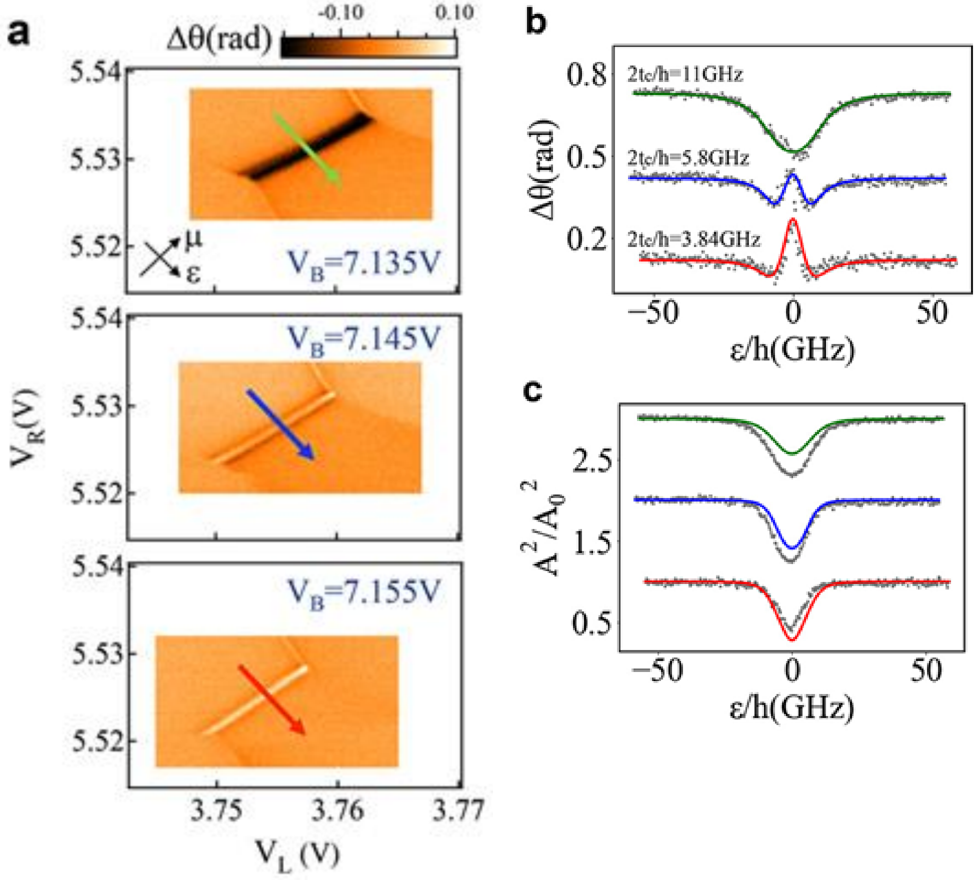
Transmission Spectroscopy

- V_B in 10mV steps

→ change of tunneling rate $2t_c/h$
→ lowers E_{qb}

- Change from $f_{qb} > f_c$ $(+\Delta)$ to $f_{qb} < f_c$ $(-\Delta)$

- $\Delta\theta = -\arctan\left(\frac{2g_c^2}{\kappa\Delta}\right)$



$\gamma = 2\pi \times 5.25\text{GHz}$
$g_c = 2\pi \times 0.038\text{GHz}$

$\gamma = 2\pi \times 4{,}5\text{GHz}$
$g_c = 2\pi \times 0.035\text{GHz}$

$\gamma = 2\pi \times 6{,}49\text{GHz}$
$g_c = 2\pi \times 0.055\text{GHz}$

$f_c = 5{,}9667\text{GHz}$
$\kappa = 6\text{MHz}$

[1] K. Petersson *et al.*, *Nature* **490**, 380–383

Transmission Spectroscopy

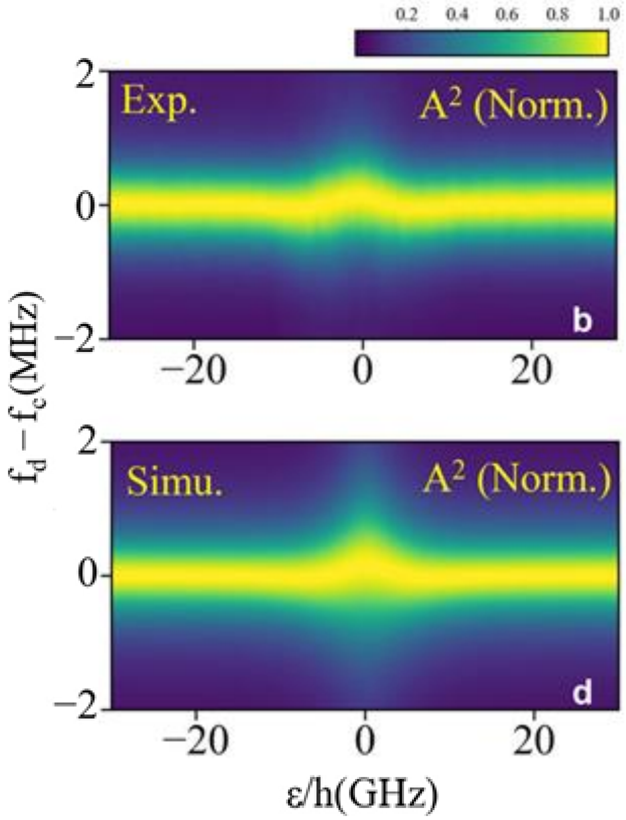
- No splitting (dressed state) resolved!

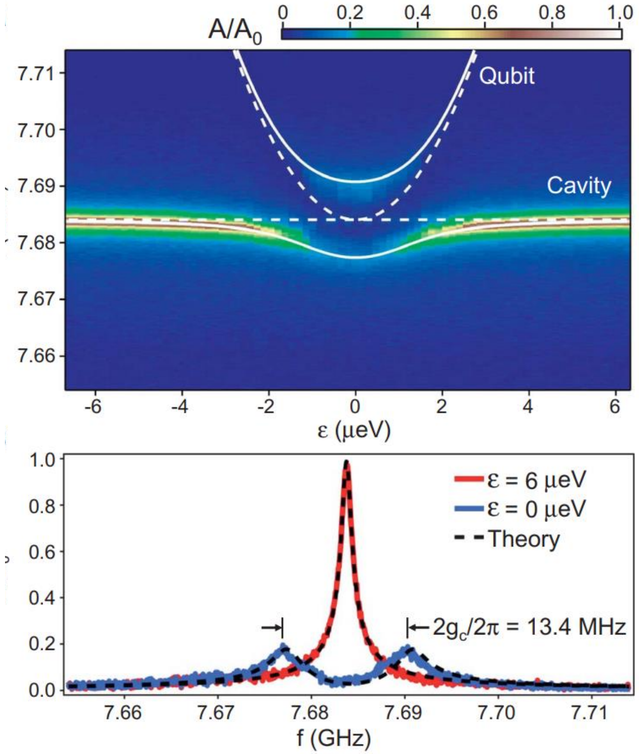
$\rightarrow \boldsymbol{\gamma \gg g_c}$

$(\gamma = 2\pi \times 4 - 6\text{GHz}, g_c = 90\text{MHz})$

- Lower charge noise sensitivity of real device

$2t_c/h = 3.84GHz < f_c$





Compared to strong coupling regime [1]

[1] X. Mi *et al.*, Science **355**, 156-158

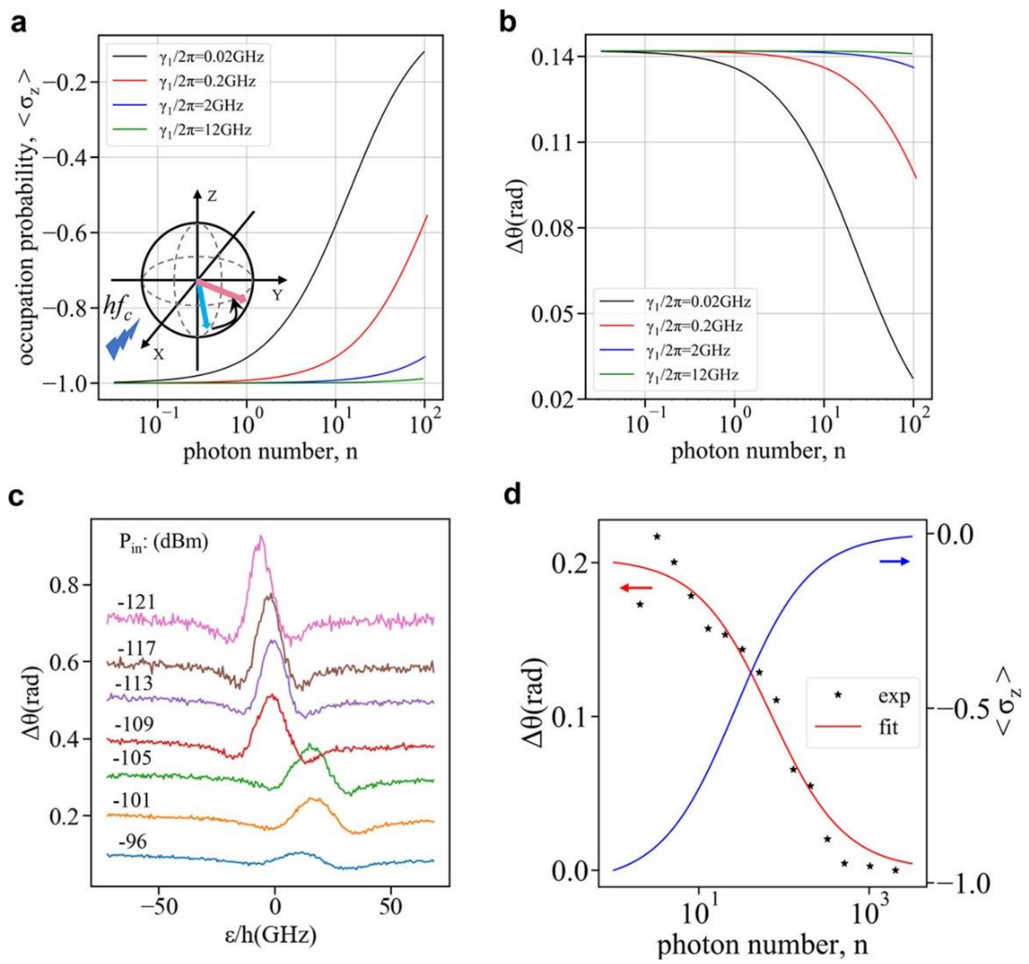
Power Dependence of Transmission

Separate influence of qubit energy relaxation γ_1 and pure dephasing γ_φ

- Phase-shift goes to zero for large Power (n)
  $\gamma = 2\pi \times 5\text{GHz}, \gamma_1 = 2\pi \times 70\text{MHz}$
  $\rightarrow \gamma_\phi = 2\pi \times 5\text{GHz}$ (charge noise)

- Large drive power induces broadening, merging, splitting of Rabi peaks when qubit and resonator resonantly coupled

→ Pure dephasing dominates the decoherence



Conclusion and Outlook

- Expect stronger coupling for hole qubit than for electron qubit, but they could not reach strong coupling regime

- Power dependence of the cavity mode dispersive shift revealed pure dephasing dominates decoherence of the qubit

→ Improve qubit coherence times for strong coupling by **increase cleanness of hBN/NW interface**
→ Zajac et al claim **accumulation type QD** will have reduced environmental noise
→ **High-impedance resonator** to elevate coupling strength (several fold)