Coherent long-distance spin-qubit–transmon coupling

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Spin qubits and superconducting qubits are among the promising candidates for a solid state quantum computer. For the implementation of a hybrid architecture which can profit from the advantages of either world, a coherent long-distance link is necessary that integrates and couples both qubit types on the same chip. We realize such a link with a frequency-tunable high impedance SQUID array resonator. The spin qubit is a resonant exchange qubit hosted in a GaAs triple quantum dot. It can be operated at zero magnetic field, allowing it to coexist with superconducting qubits on the same chip. We find a working point for the spin qubit, where the ratio between its coupling strength and decoherence rate is optimized. We observe coherent interaction between the resonant exchange qubit and a transmon qubit in both resonant and dispersive regimes, where the interaction is mediated either by real or virtual resonator photons.

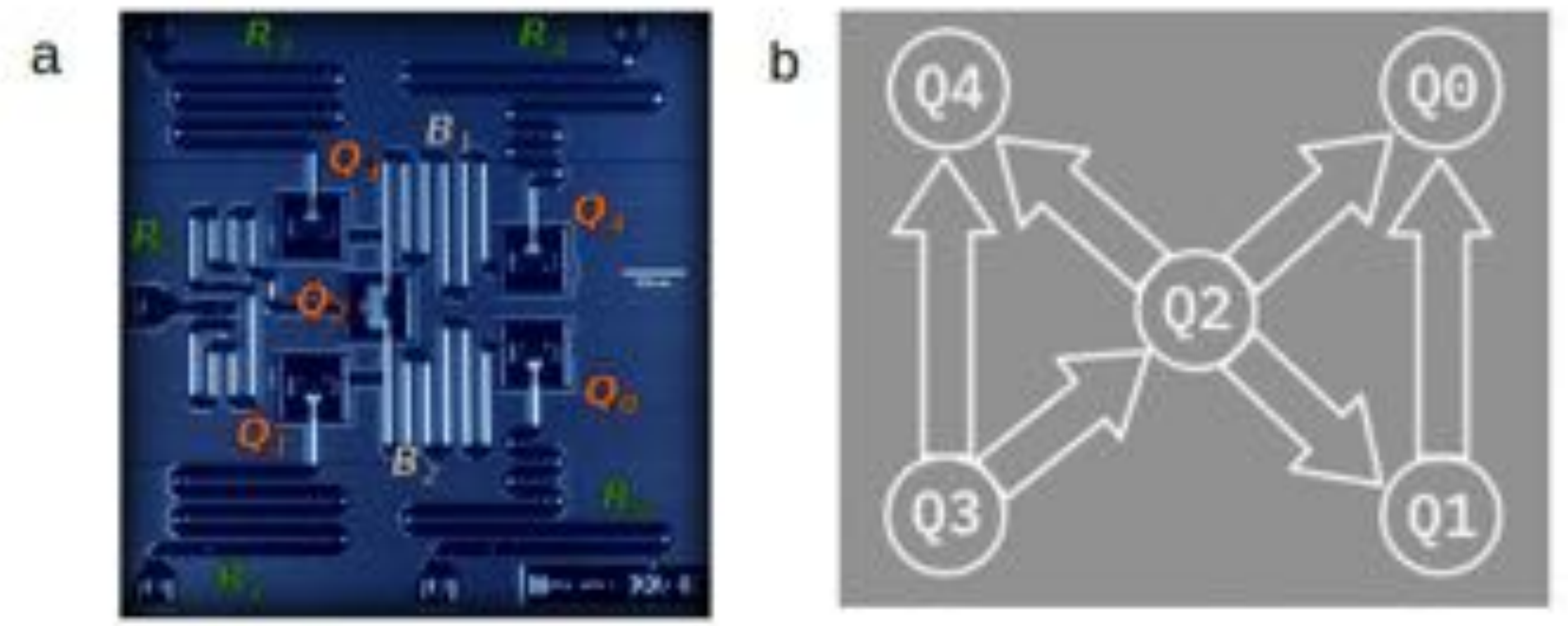
Motivation: toward 2-qubit programmable quantum computer

- there are 5-qubit quantum computer prototypes with transmons
- spin qubits might have longer lifetime
- spin qubits are smaller than transmons
- this work (#1): warm-up for: spin-based quantum computer prototype
- this work (#2): warm-up for: transmon processor, spin qubit memory

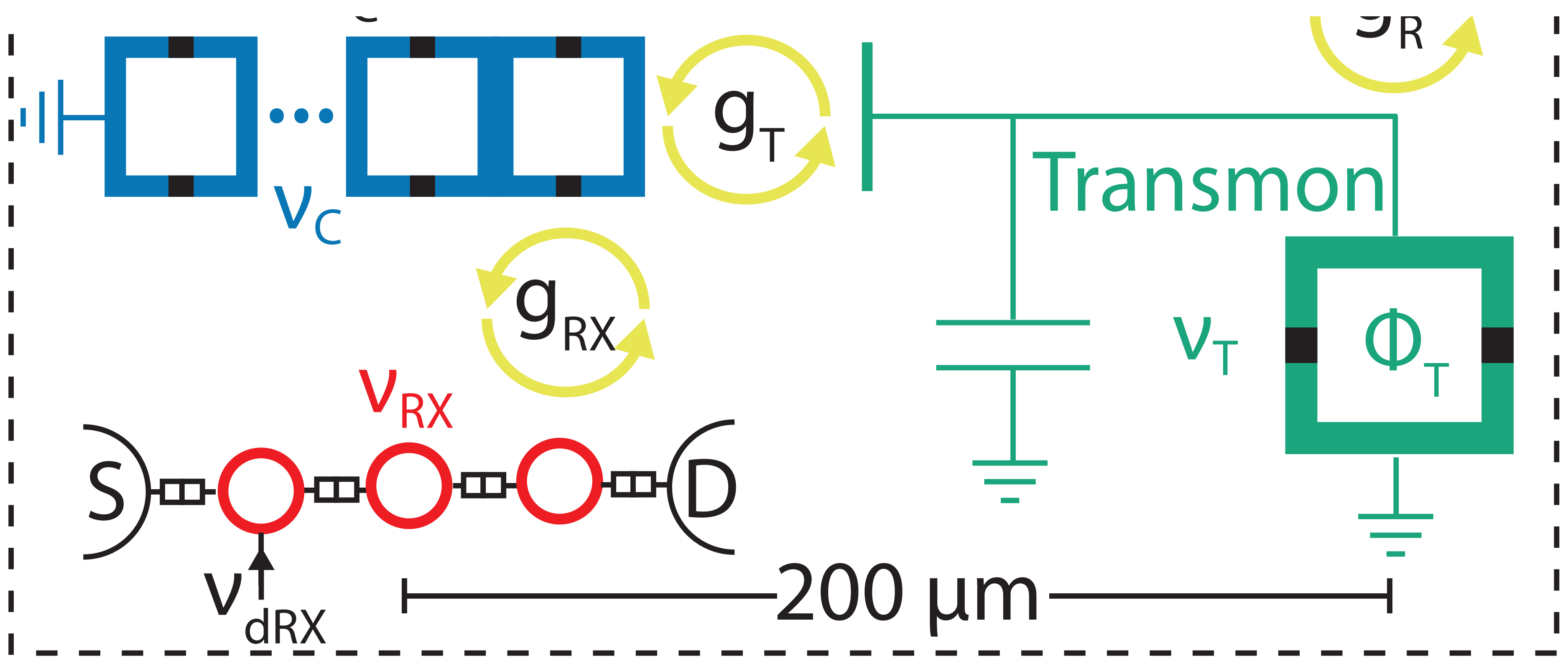
Q: in this experiment, does the spin qubit have longer lifetime than the transmon?

A: No:

IBM Quantum Experience: 5 transmons



This paper: 1 spin qubit + 1 transmon



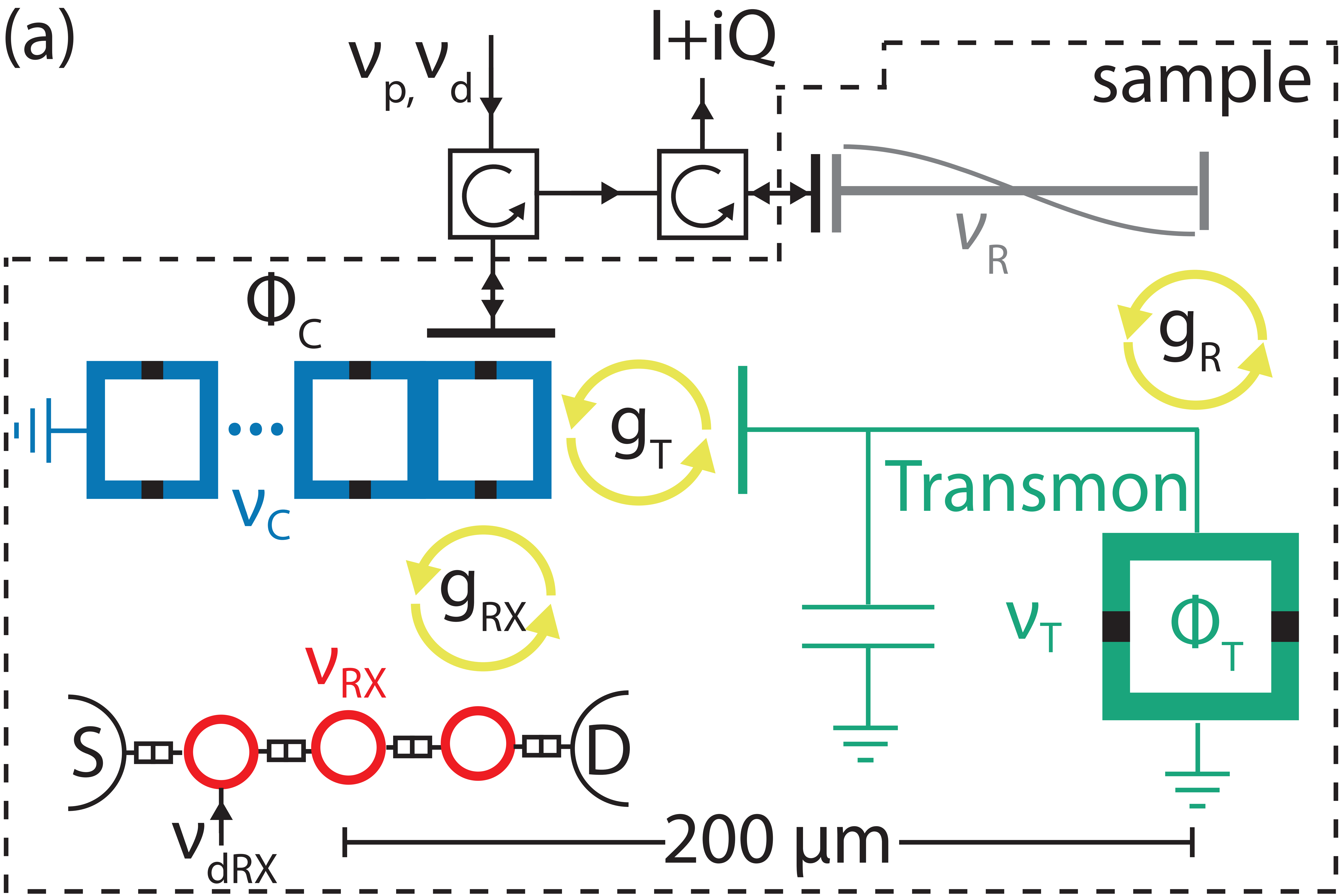
How far is this from a 2-qubit programmable quantum computer?

- **reflectometry on resonator**

- **spectroscopic evidence for qubit-resonator coupling**
- single-shot readout of qubits
- **single-qubit spectroscopy**
- single-qubit gates
- state transfer between qubit and resonator

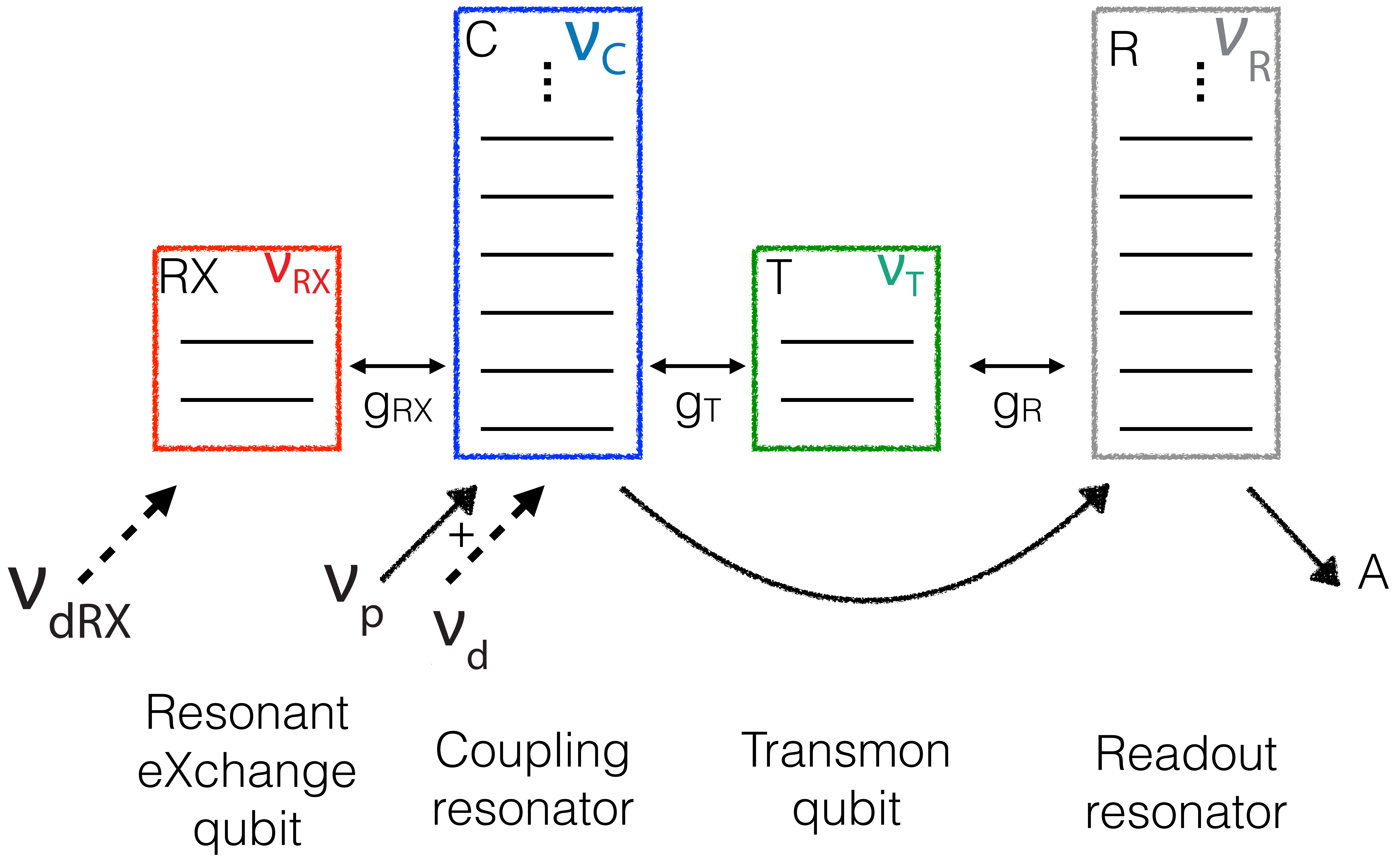
- **spectroscopic evidence for qubit-resonator-qubit coupling**
- two-qubit gate

Setup

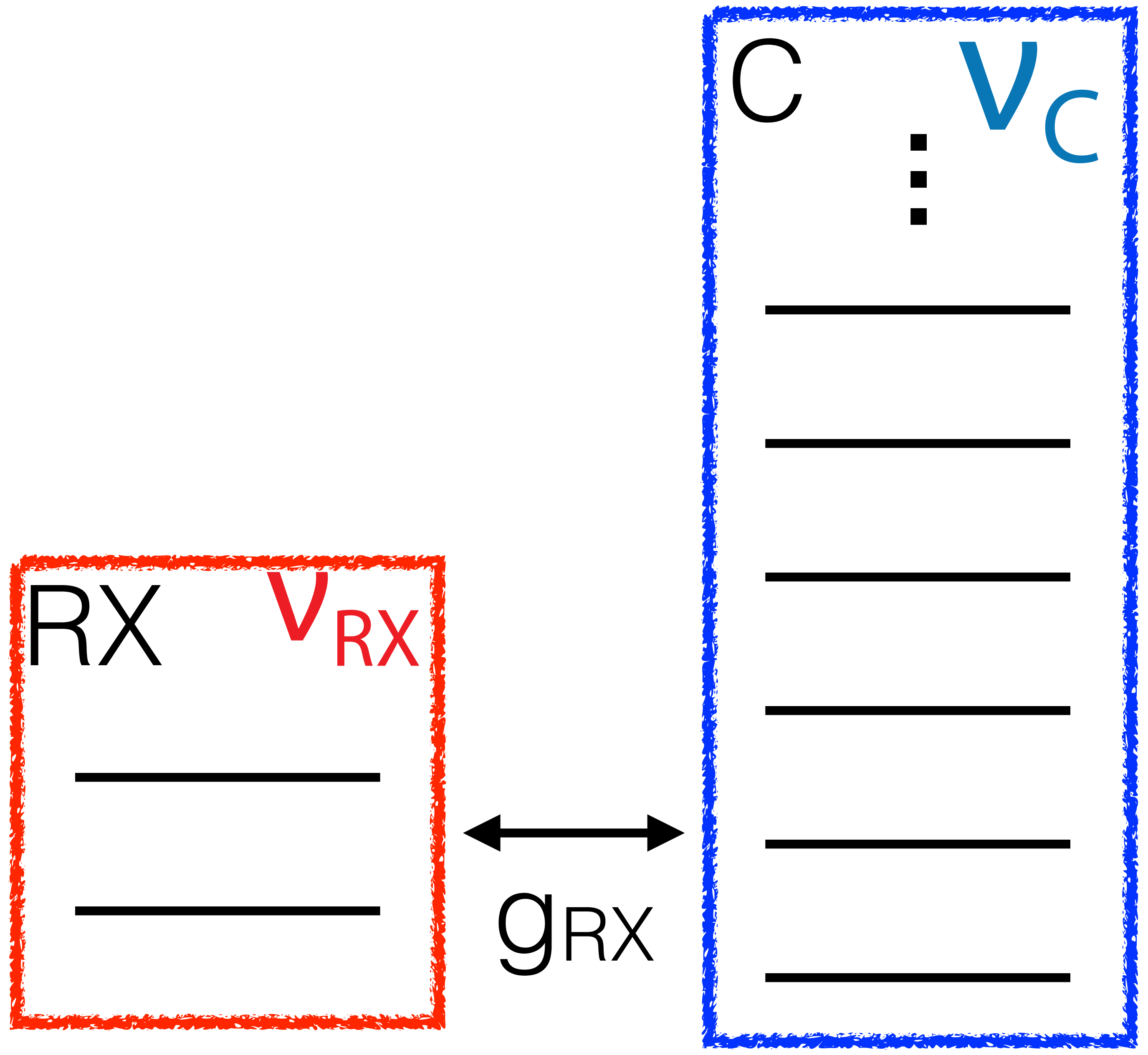


(a)
$\nu_{p,}\nu_d$
I+iQ
sample
ν_R
Φ_C
g_R
g_T
ν_C
Transmon
g_{RX}
ν_T
Φ_T
ν_{RX}
S
D
ν_{dRX}
200 µm

Setup (theorist's picture)



Jaynes-Cummings Hamiltonian



Setup: qubit interacting with a harmonic oscillator

oscillator frequency
(`resonator frequency')

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + \sigma^+ a) + H_\kappa + H_\gamma.$$

qubit-oscillator coupling strength

oscillator = resonator = cavity = one mode of a microwave resonator

qubit = e-charge, e-spin, superconducting qubit

'strong coupling' regime: $\gamma, \kappa \ll g$

many back-and-forth oscillations of an energy quantum between qubit and oscillator are possible

Blais et al., Phys. Rev. A 69, 062320 (2004)

Typical parameter values in `cavity/circuit quantum electrodynamics'

Parameter	Symbol	3D optical	3D microwave	1D circuit
Resonance or transition frequency	$\omega_r/2\pi$, $\Omega/2\pi$	350 THz	51 GHz	10 GHz
Vacuum Rabi frequency	g/π, g/ω_r	220 MHz, 3×10^{-7}	47 kHz, 1×10^{-7}	100 MHz, 5×10^{-3}
Transition dipole	d/ea_0	~1	1×10^3	2×10^4
Cavity lifetime	$1/\kappa, Q$	10 ns, 3×10^7	1 ms, 3×10^8	160 ns, 10^4
Atom lifetime	$1/\gamma$	61 ns	30 ms	2 μs
Atom transit time	t_{transit}	$\geqslant50$ μs	100 μs	∞
Critical atom number	$N_0=2\gamma\kappa/g^2$	6×10^{-3}	3×10^{-6}	$\leqslant6\times10^{-5}$
Critical photon number	$m_0=\gamma^2/2g^2$	3×10^{-4}	3×10^{-8}	$\leqslant1\times10^{-6}$
Number of vacuum Rabi flops	$n_{\text{Rabi}}=2g/(\kappa+\gamma)$	~10	~5	$\sim10^2$

strong coupling achieved in circuit QED

we assume strong coupling from now on

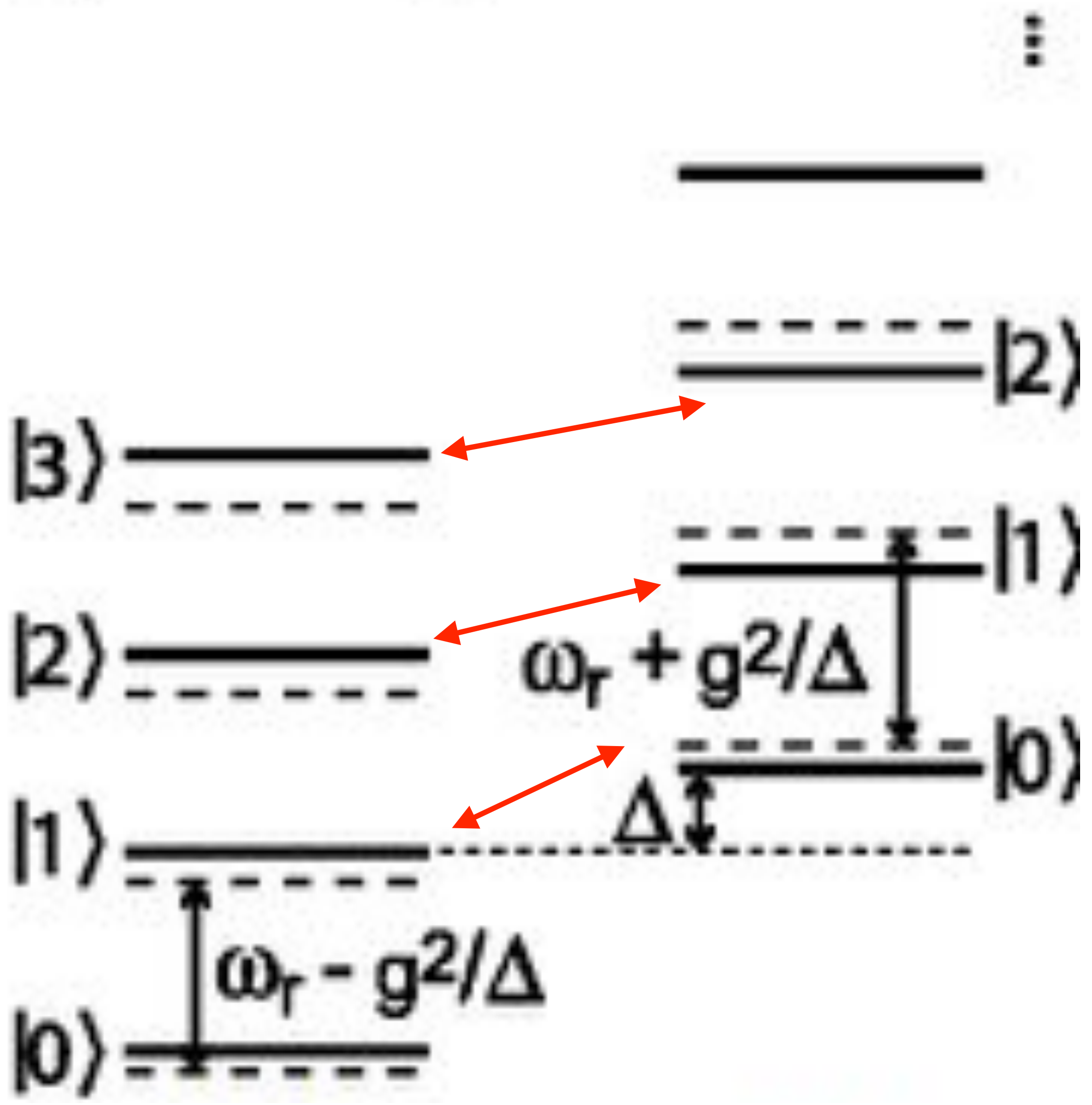
Table I. from Blais et al., Phys. Rev. A 69, 062320 (2004)

`Dispersive qubit readout' in circuit QED

$$H = \hbar\omega_r\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + \sigma^+ a) + H_\kappa + H_\gamma.$$

qubit-oscillator detuning: $\Delta \equiv \Omega - \omega_r$

`large detuning regime' or `dispersive regime': $g/\Delta \ll 1$



$|g\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ $|e\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$

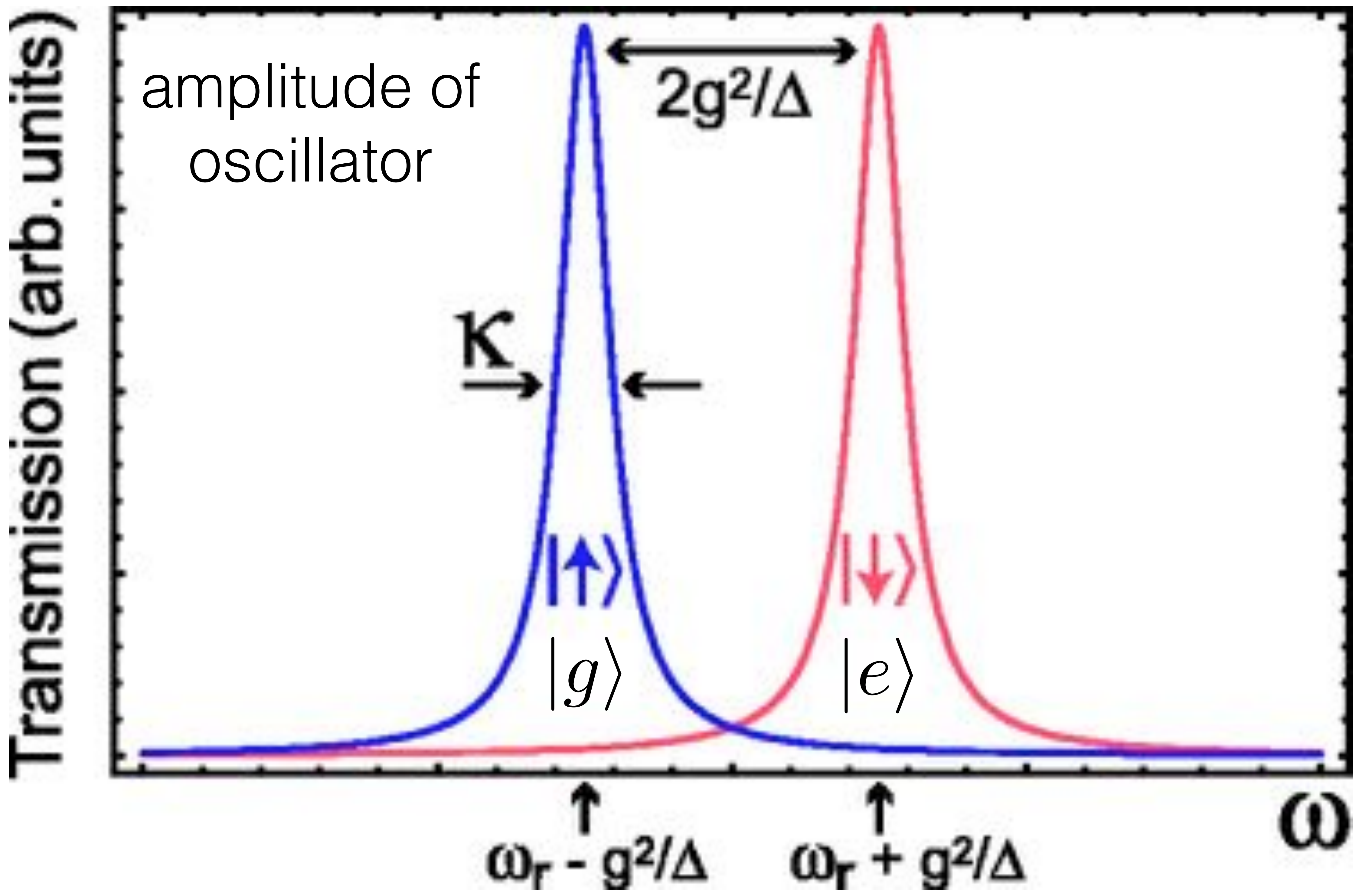
do perturbation theory:

$$E_n^{(2)} = \sum_{k\neq n} \frac{\left|\langle k^{(0)}|V|n^{(0)}\rangle\right|^2}{E_n^{(0)} - E_k^{(0)}} \Rightarrow E_{g1}^{(2)} = -\frac{g^2}{\Delta}$$

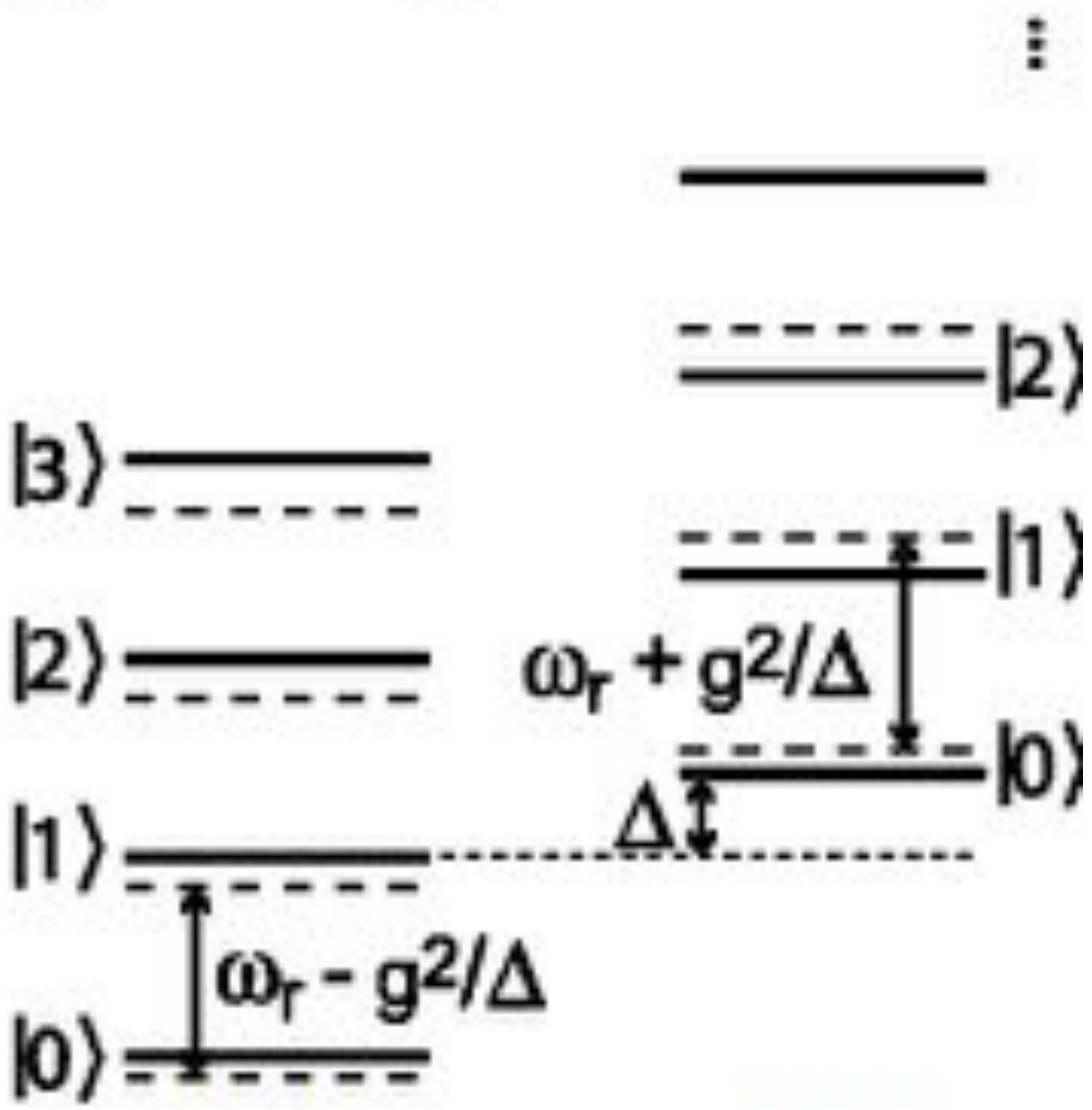
In the dispersive regime, the resonator acquires a qubit-state dependent shift of its eigenfrequency.

`Dispersive qubit readout’ in circuit QED (if tranmission is measured)

$$H = \hbar\omega_{\mathrm{r}}\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + \sigma^+ a) + H_\kappa + H_\gamma.$$



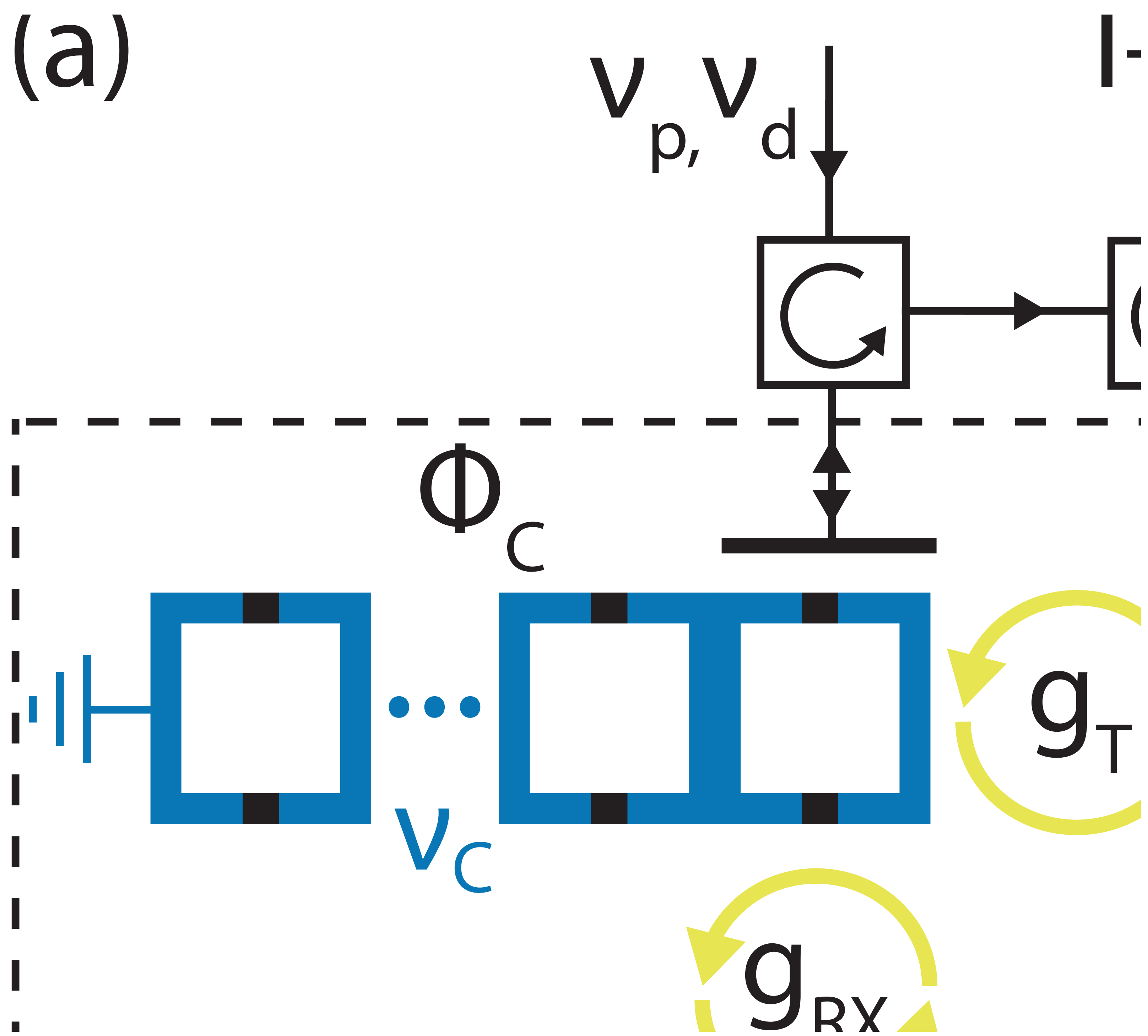
drive frequency of oscillator

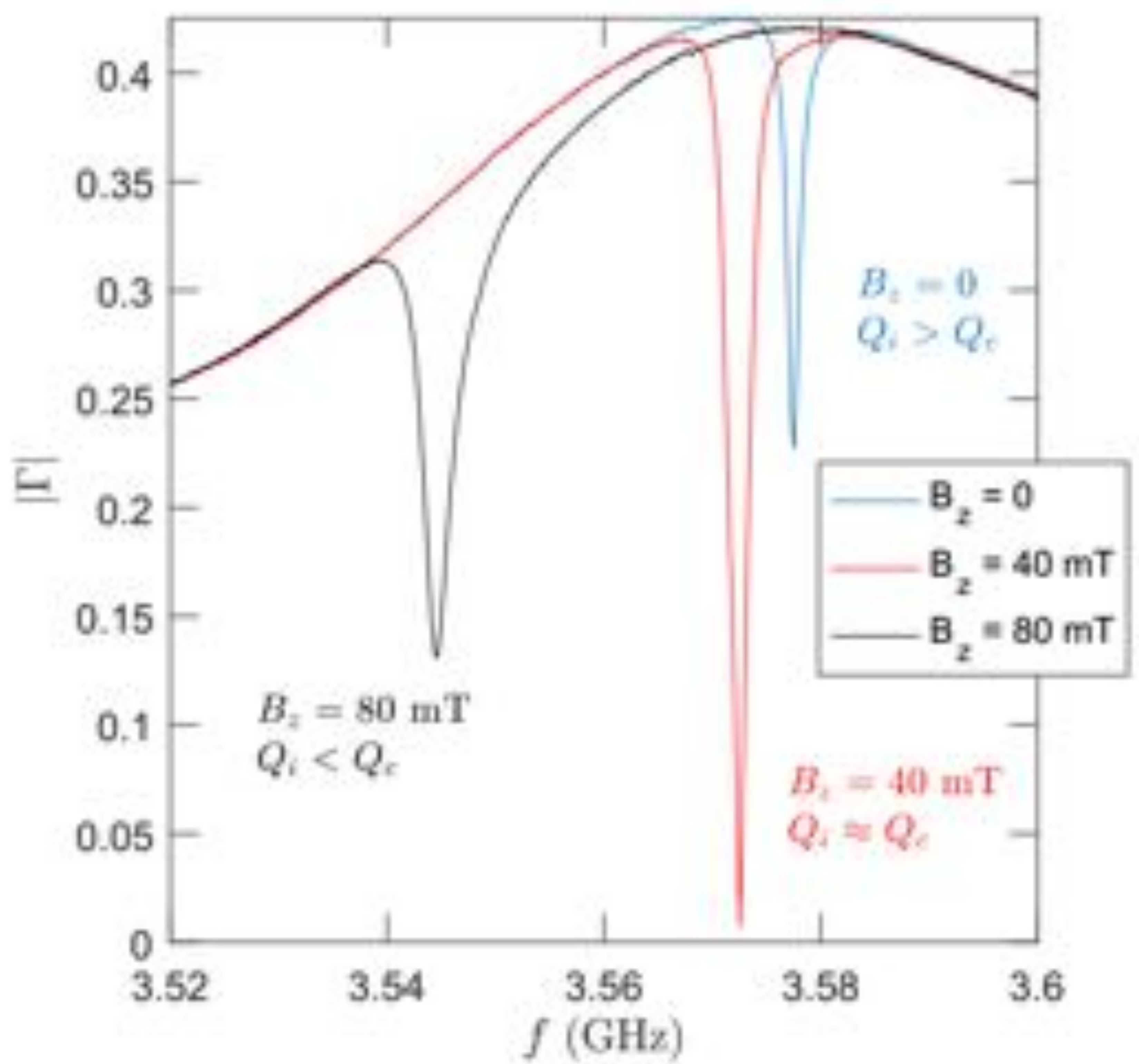


$$|g\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad |e\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

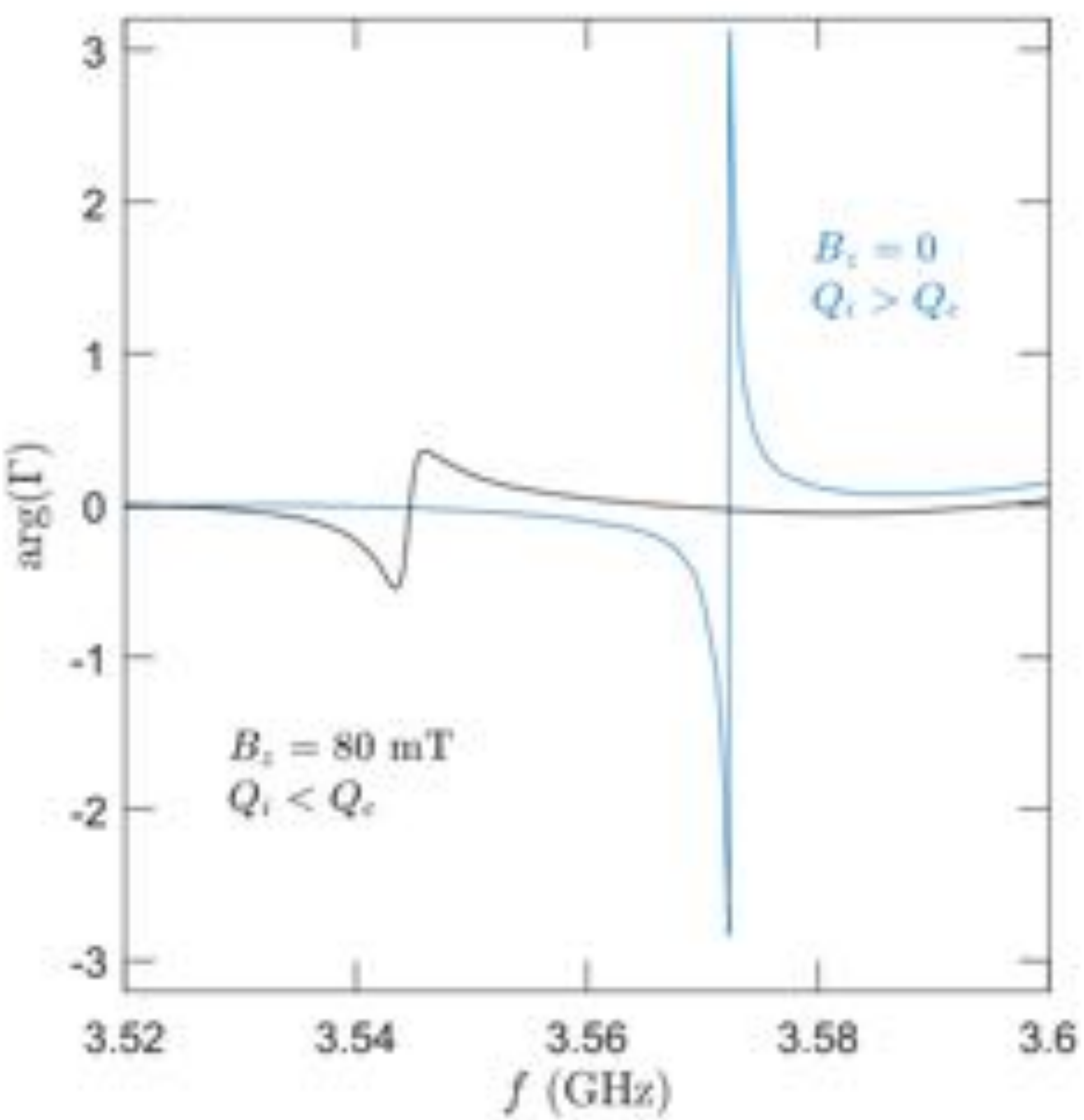
In the dispersive regime, the qubit can be read out by probing the oscillator.

If reflection is measured (data from Gergő Fülöp)



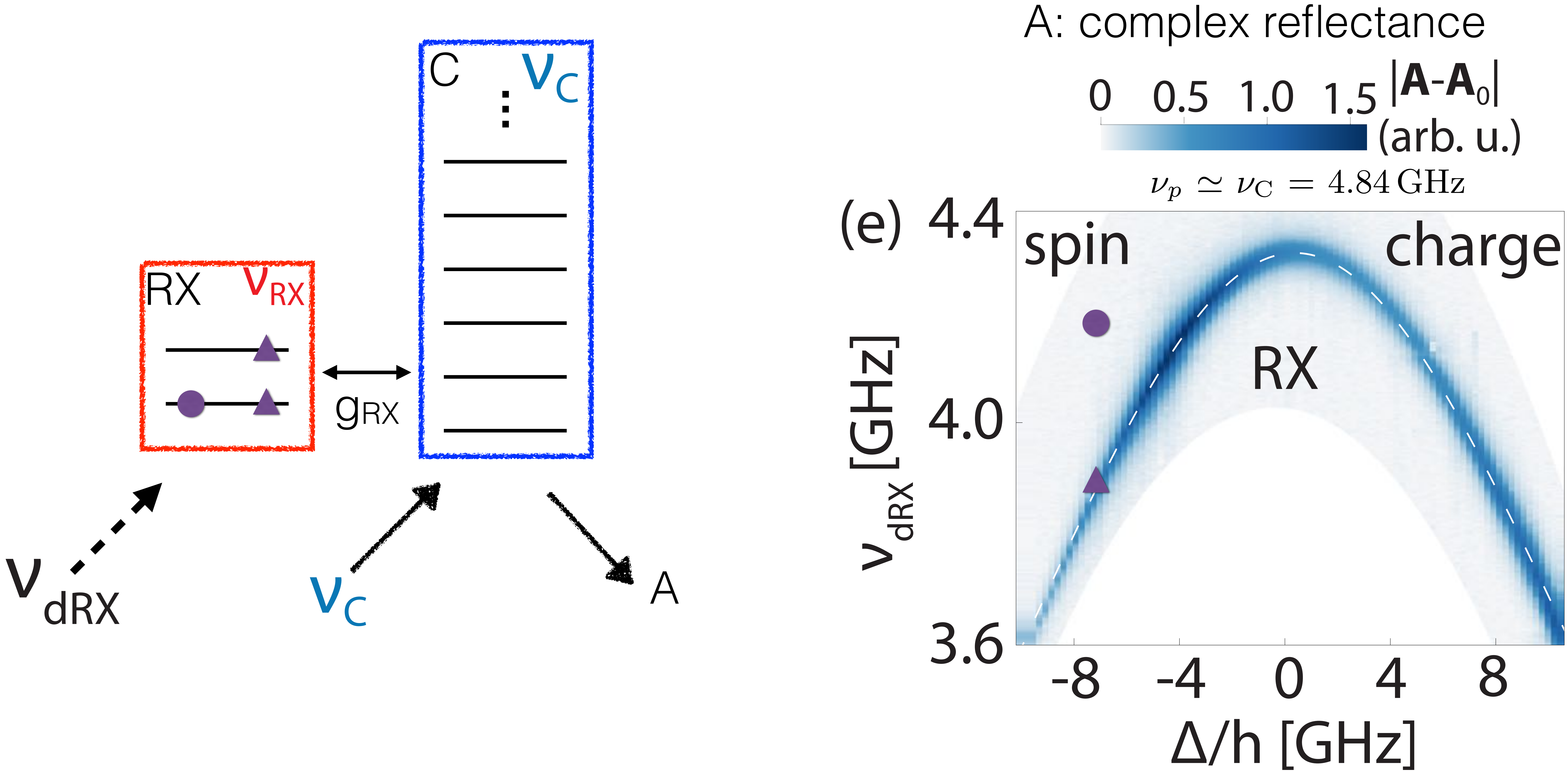


(a) B_z-dependence, magnitude traces



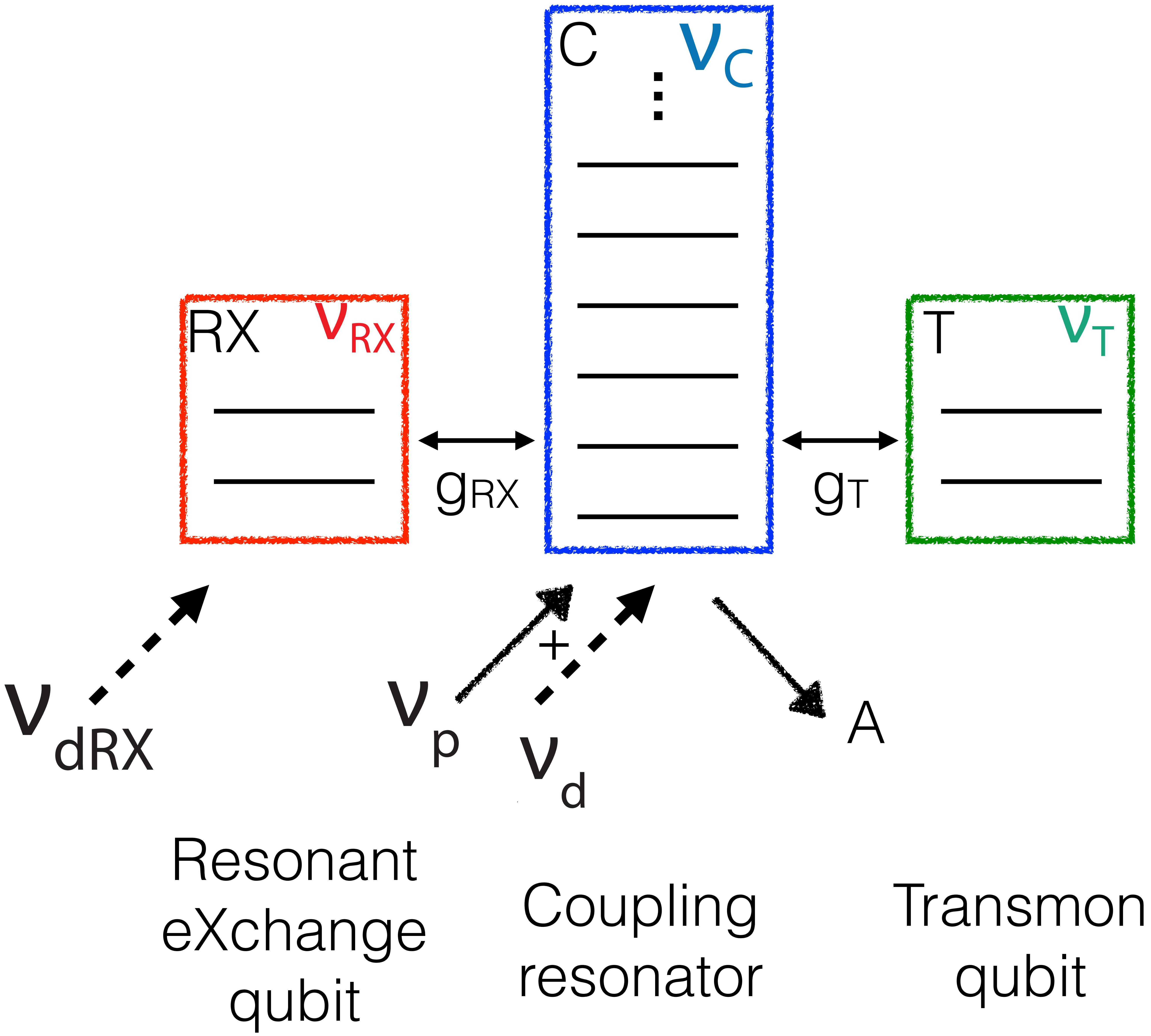
(b) B_z-dependence, phase traces

Reflectance of Coupling resonator is used to infer RX qubit splitting



Δ: tunes RX qubit splitting

Further gadgets allowed by the resonator



1. indirect driving of transmon when $\nu_p = \nu_T$
2. qubit-qubit coupling

Vacuum Rabi splitting: low (<1) photon number is important here

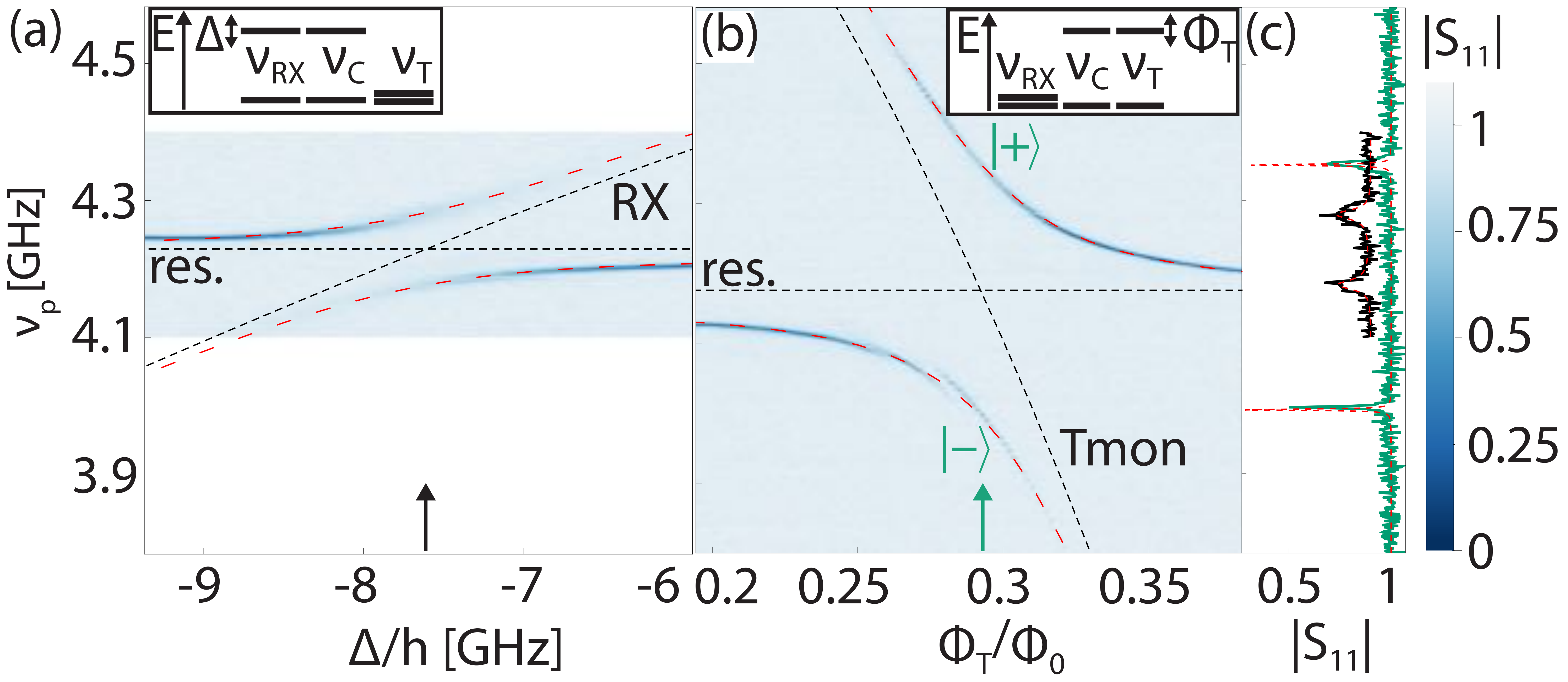
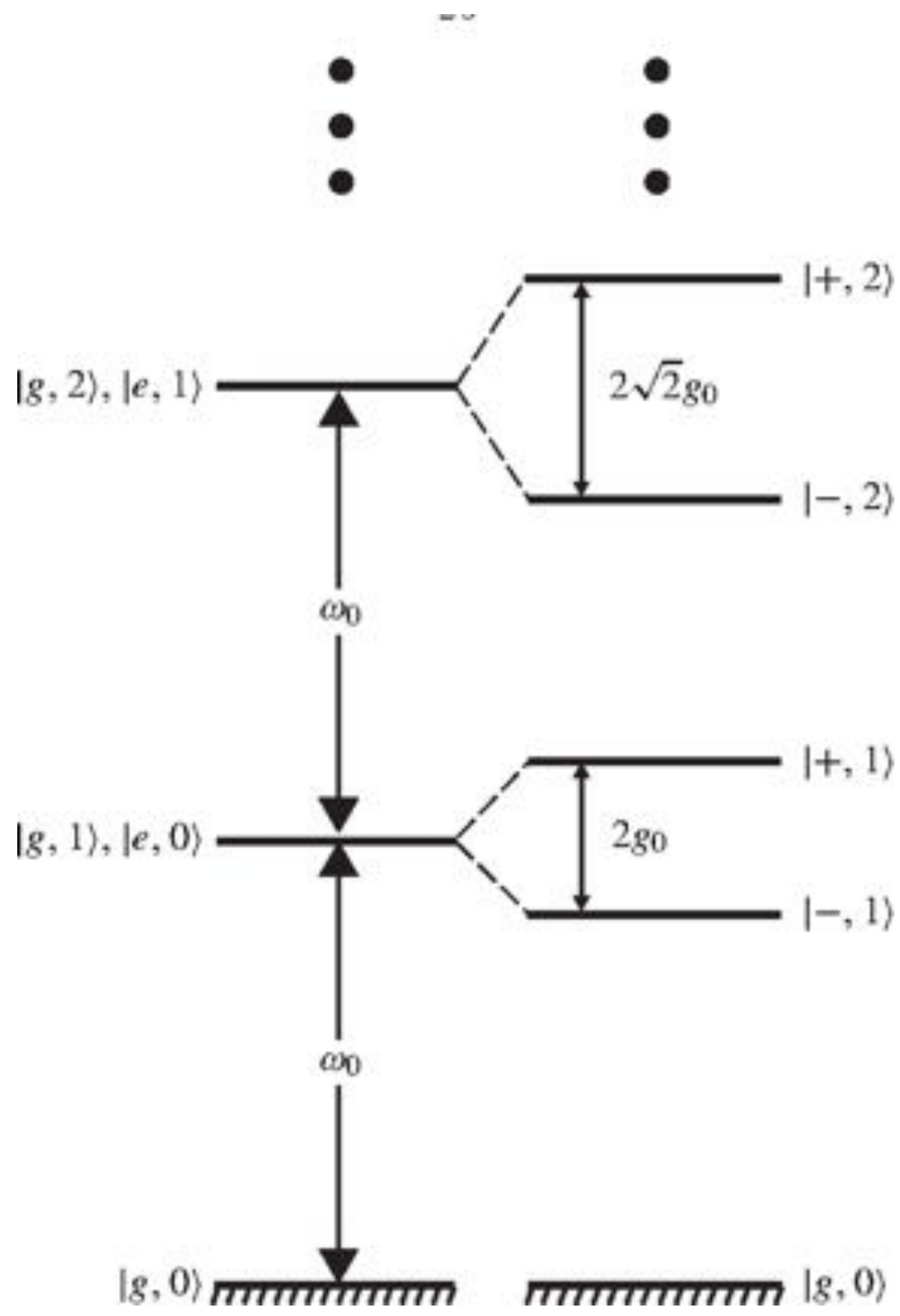
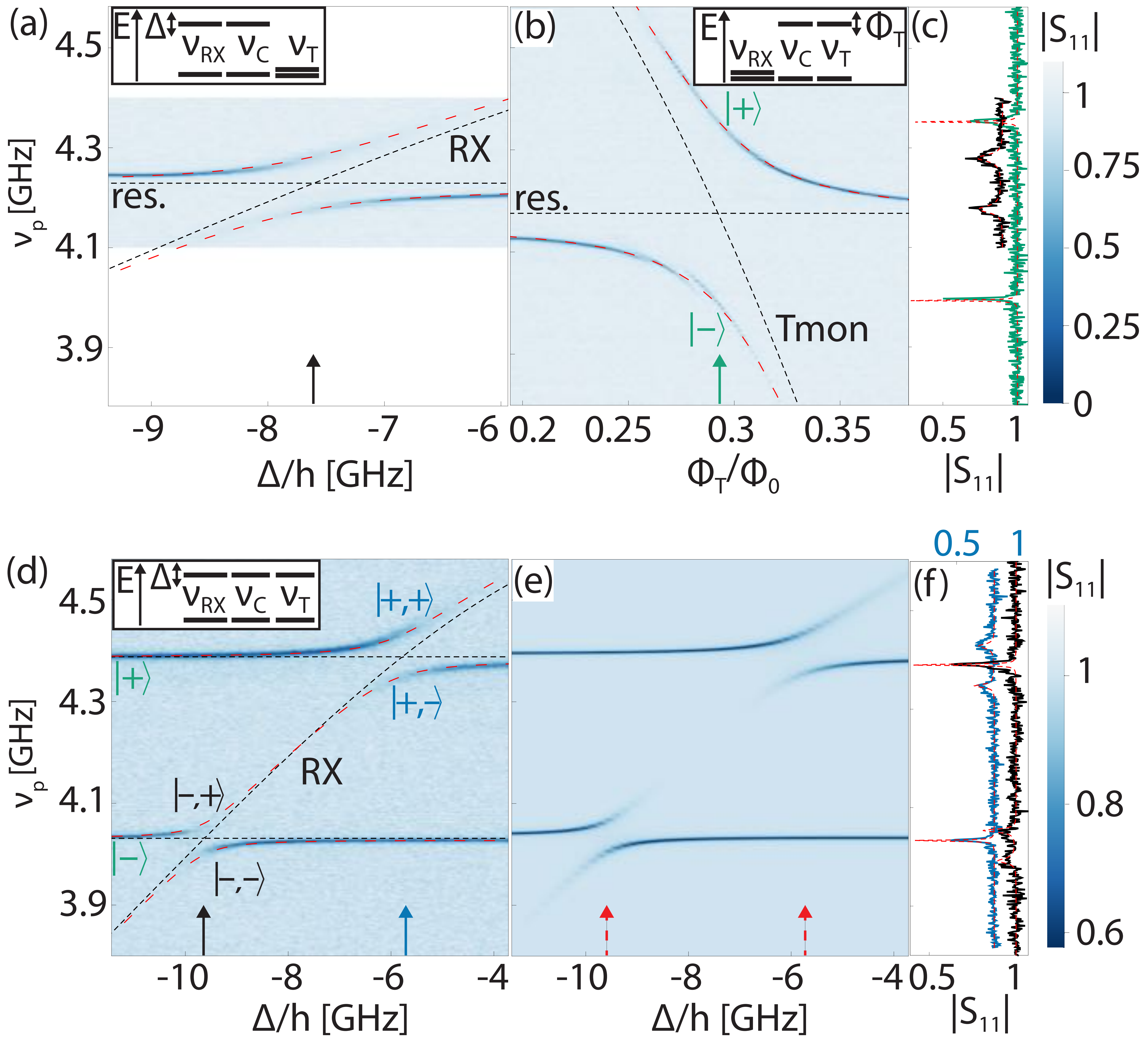
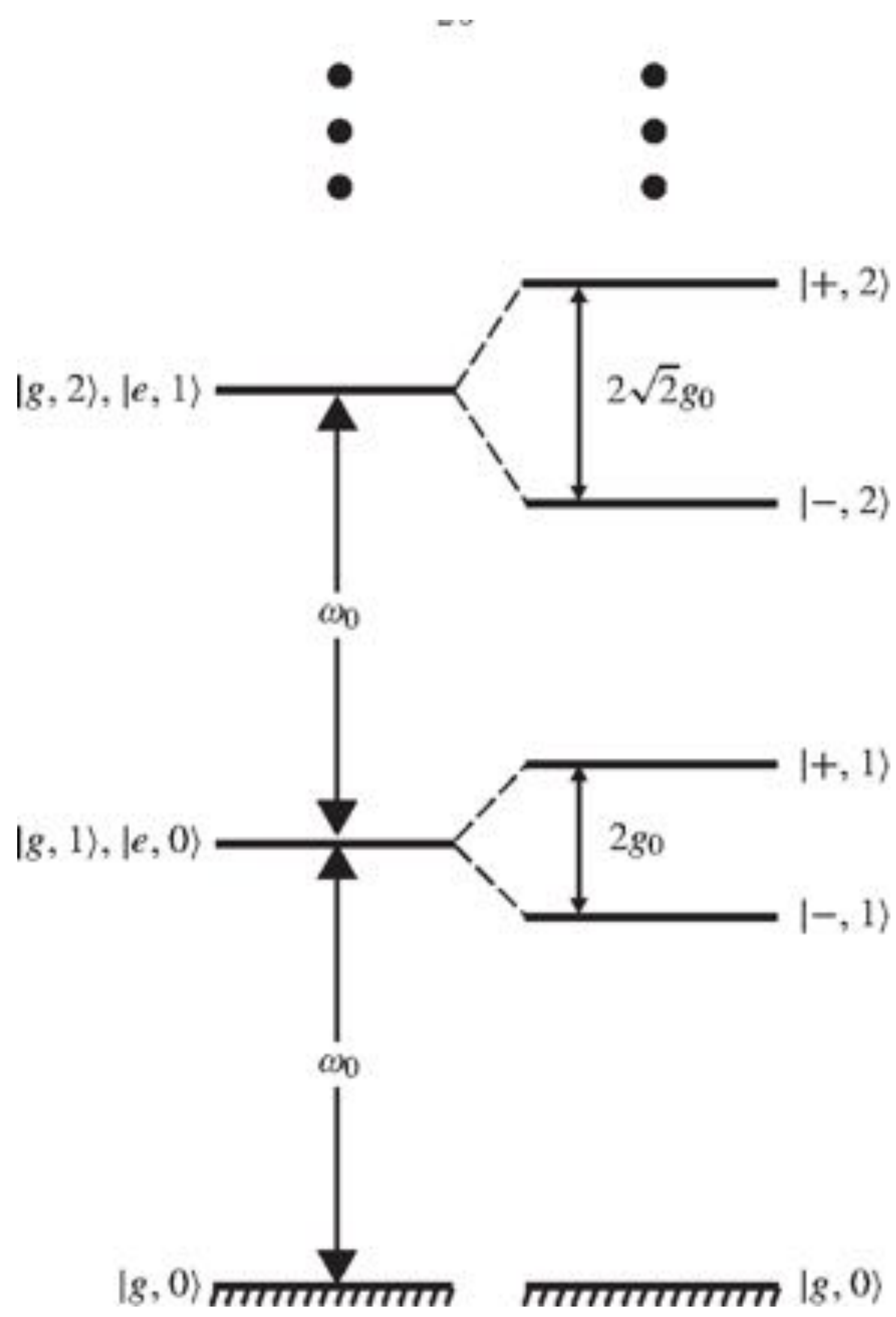


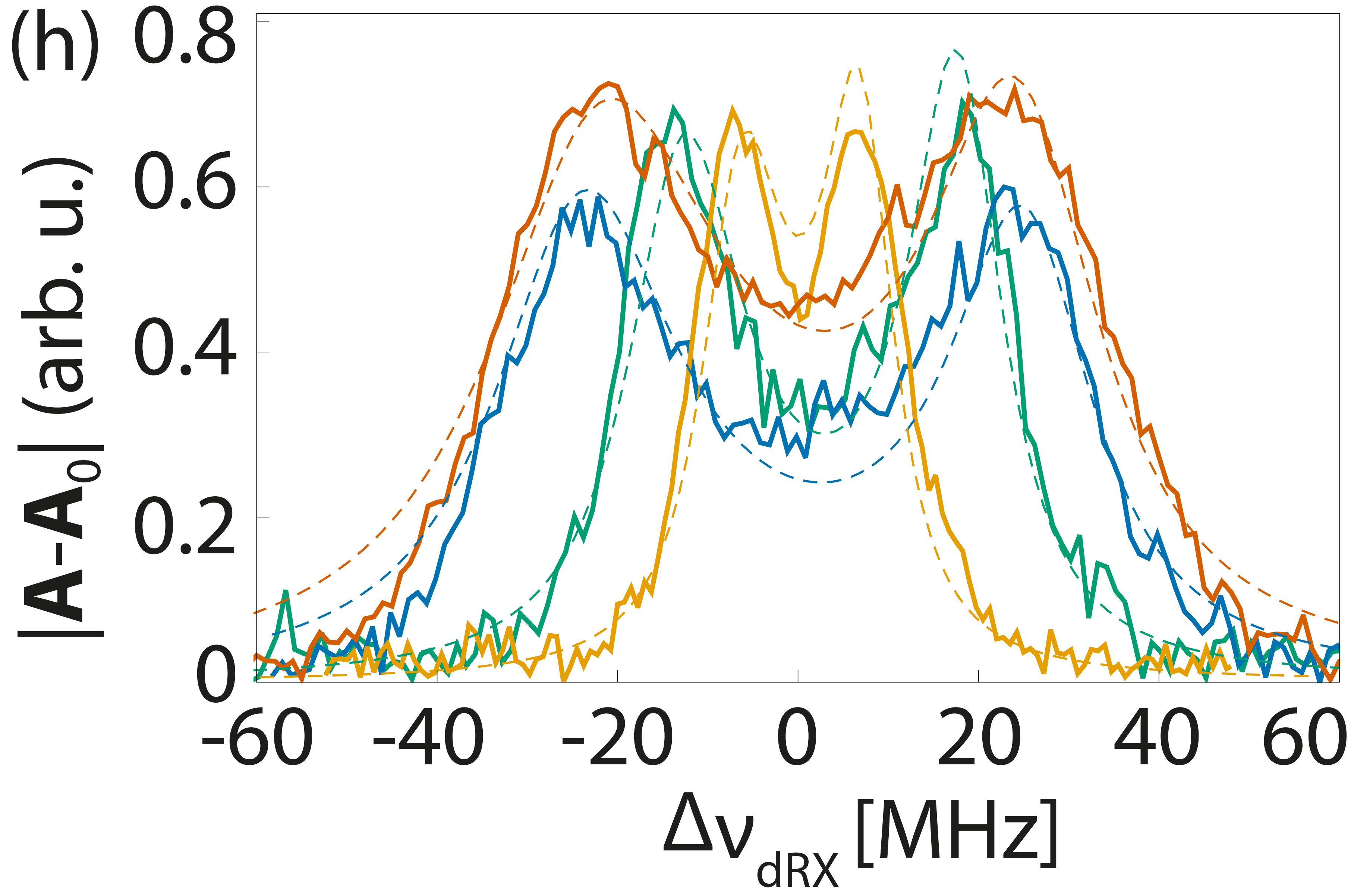
FIG. 2. Resonant interaction. The schematics at the top of the graphs indicate the energy levels of the RX qubit (ν_{RX}), coupling resonator (ν_{C}) and transmon (ν_{T}). Theory curves in the absence (presence) of coupling are shown as dashed black (red) lines. (a) Reflected amplitude $|S_{11}|$ as a function of RX detuning Δ and probe frequency ν_{p} for RX qubit configuration 2. (b) Reflected amplitude $|S_{11}|$ as a function of relative transmon flux Φ_{T}/Φ_0 and ν_{p}. The states $|\pm\rangle$ are discussed in the main text. (c) Cuts from panel (a) at $\Delta/h \simeq -7.6\,\mathrm{GHz}$ (black) and from panel (b) at $\Phi_{\mathrm{T}}/\Phi_0 \simeq 0.3$ (green) as marked with arrows in the respective panels. The black trace is offset in $|S_{11}|$ by 0.1. Theory fits are shown as red dashed lines. (d)




(a)
(b)
(c)
(d)
(e)
(f)
E
Δ
ν_{RX}
ν_C
ν_T
Φ_T
RX
res.
Tmon
|+⟩
|−⟩
|+,+⟩
|+,−⟩
|−,+⟩
|−,−⟩
ν_p [GHz]
Δ/h [GHz]
Φ_T/Φ_0
$|S_{11}|$
4.5
4.3
4.1
3.9
-9
-8
-7
-6
0.2
0.25
0.3
0.35
0.5
1
0.75
0.25
0
-10
-4
0.8
0.6


|+, 2⟩
|g, 2⟩, |e, 1⟩
$2\sqrt{2}g_0$
|−, 2⟩
ω_0
|+, 1⟩
|g, 1⟩, |e, 0⟩
$2g_0$
|−, 1⟩
ω_0
|g, 0⟩
|g, 0⟩

A sqrt-of-iSWAP gate in circuit QED



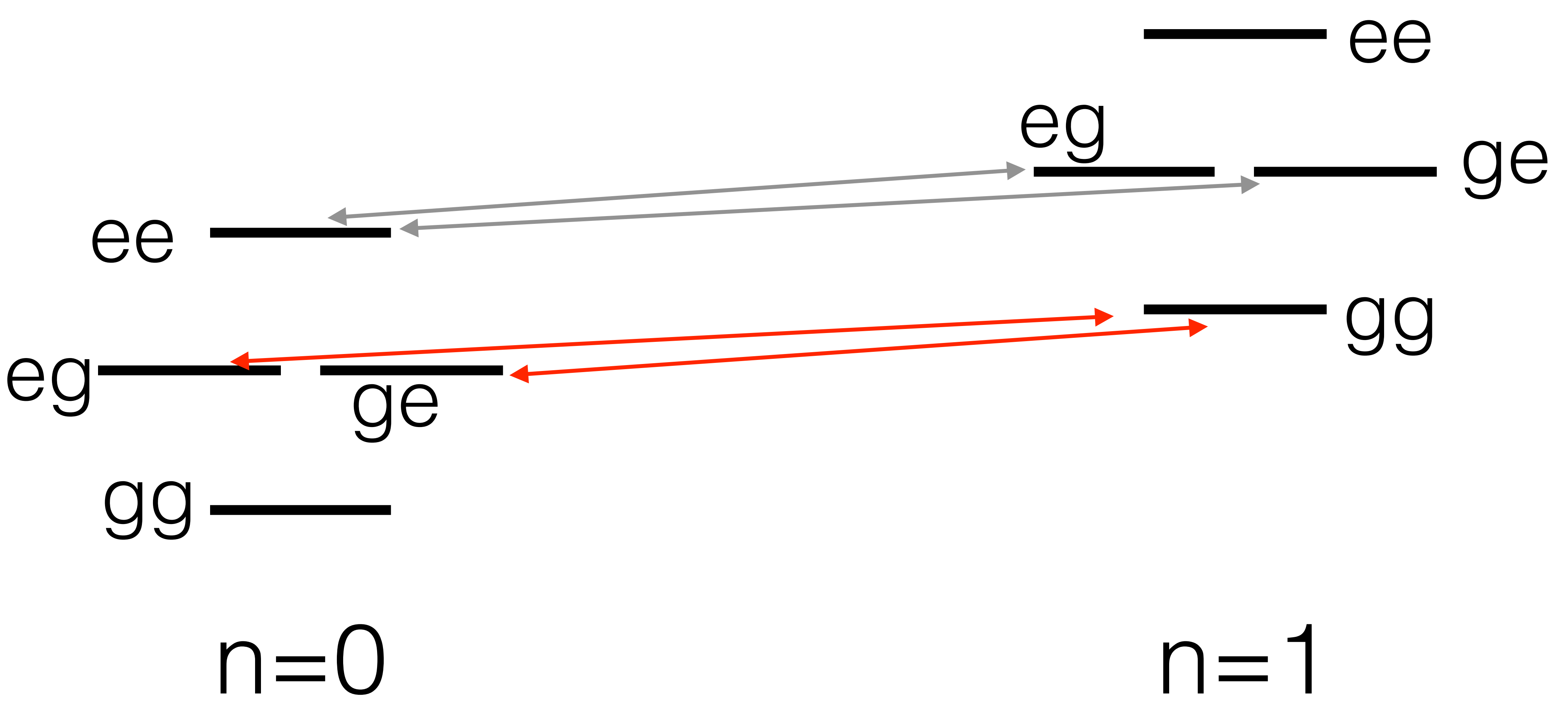
- Setup: two qubits (i and j) interacting with the same oscillator
- Do the unitary transformation + expansion from the last slide

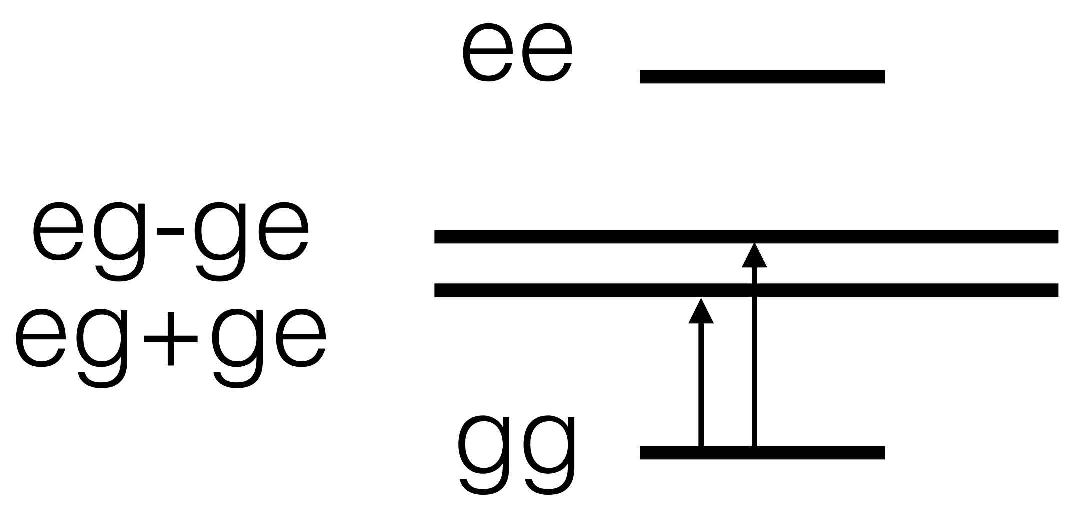
$$H_{2q} \approx \hbar\left[\omega_r + \frac{g^2}{\Delta}(\sigma_i^z + \sigma_j^z)\right]a^\dagger a + \frac{1}{2}\hbar\left[\Omega + \frac{g^2}{\Delta}\right](\sigma_i^z + \sigma_j^z)$$

$$+\hbar\frac{g^2}{\Delta}(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+). \quad (32)$$

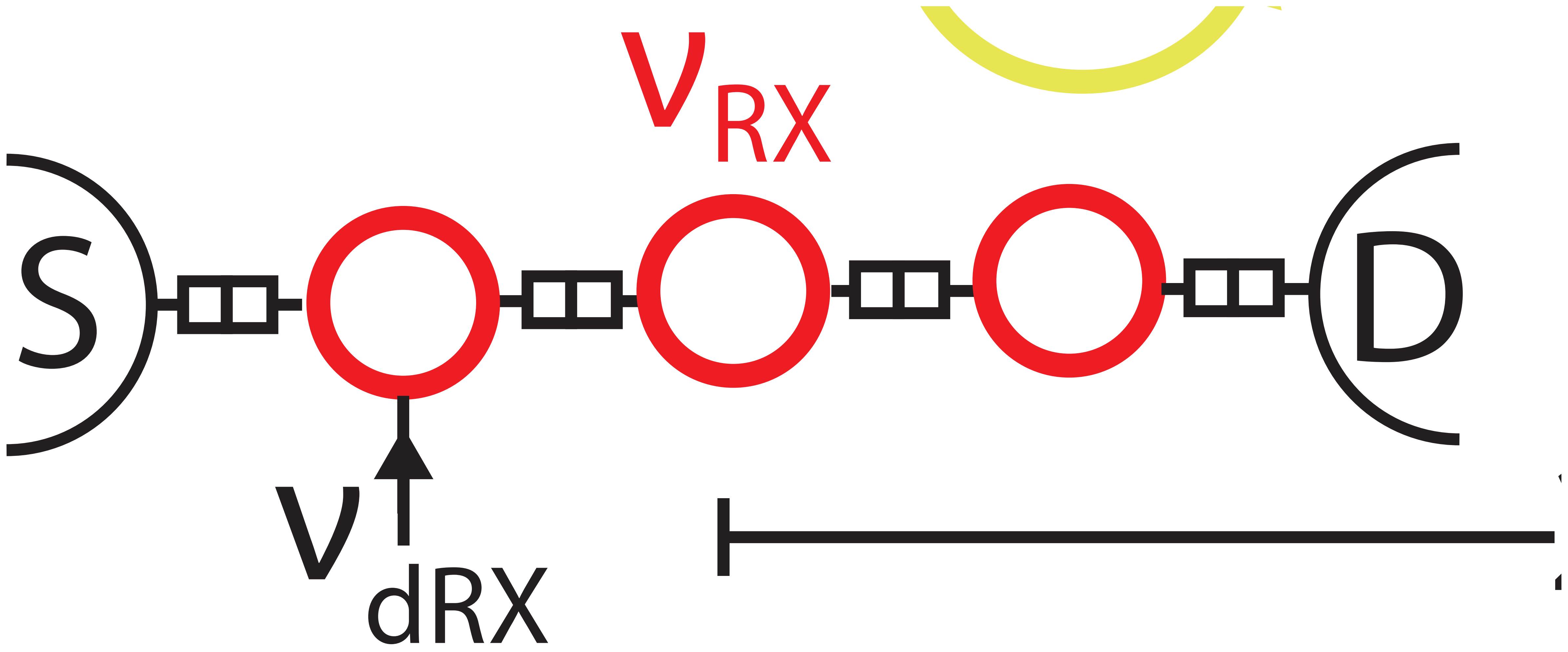
qubit-qubit interaction

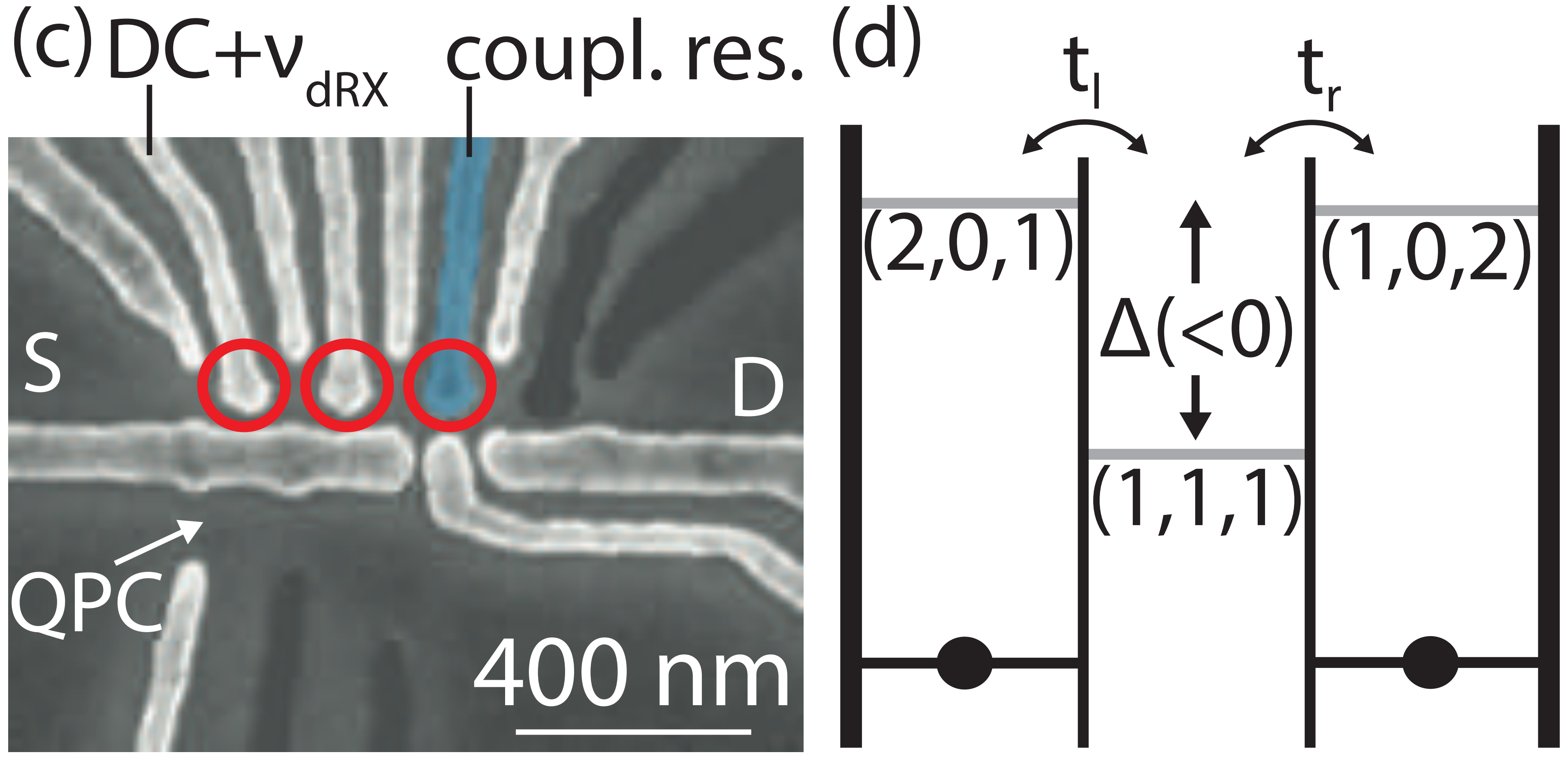
qubit-qubit interaction:
from
`virtual photon exchange'





What is the spin qubit?

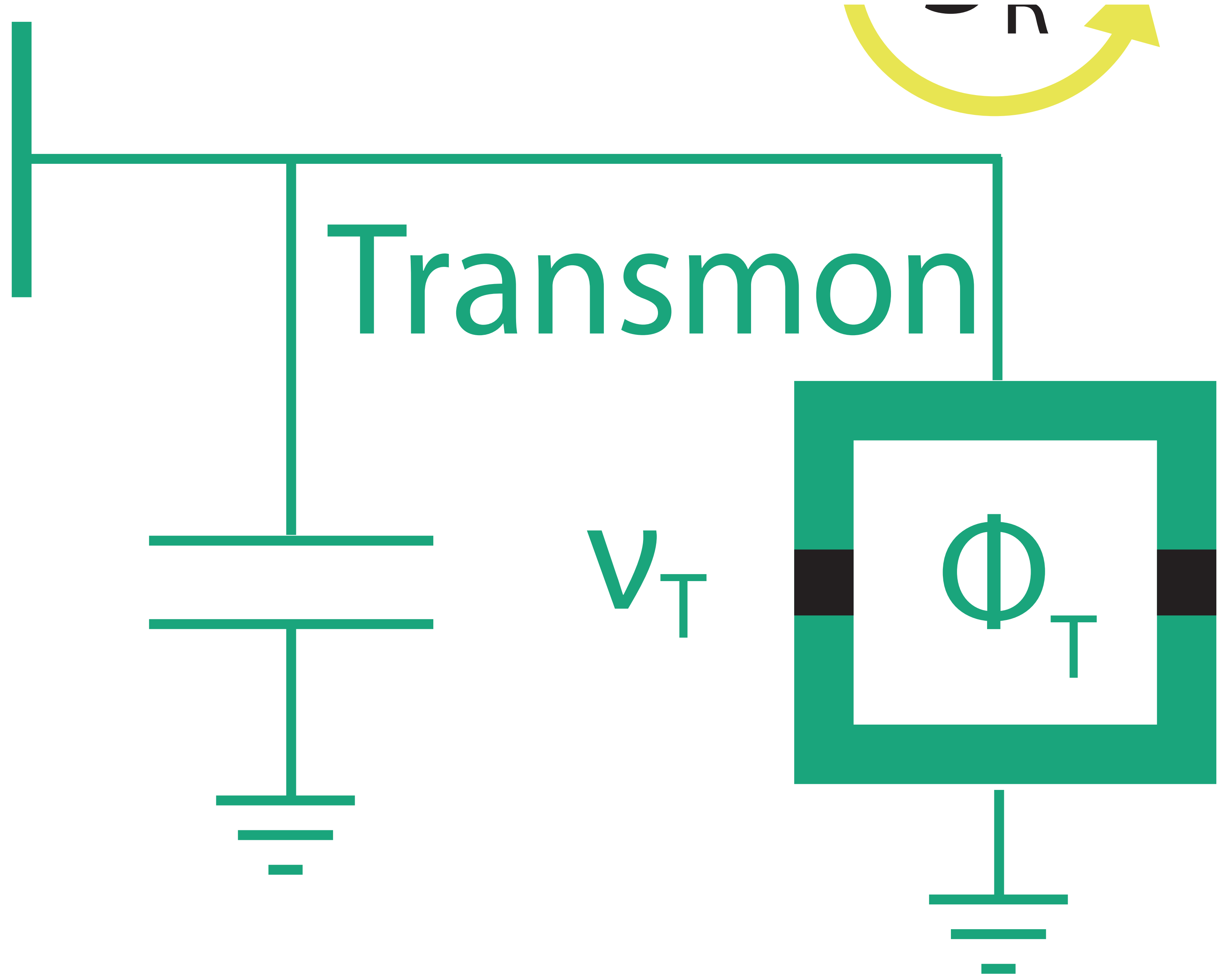




(1,1,1) charge configuration - 8 different spin states

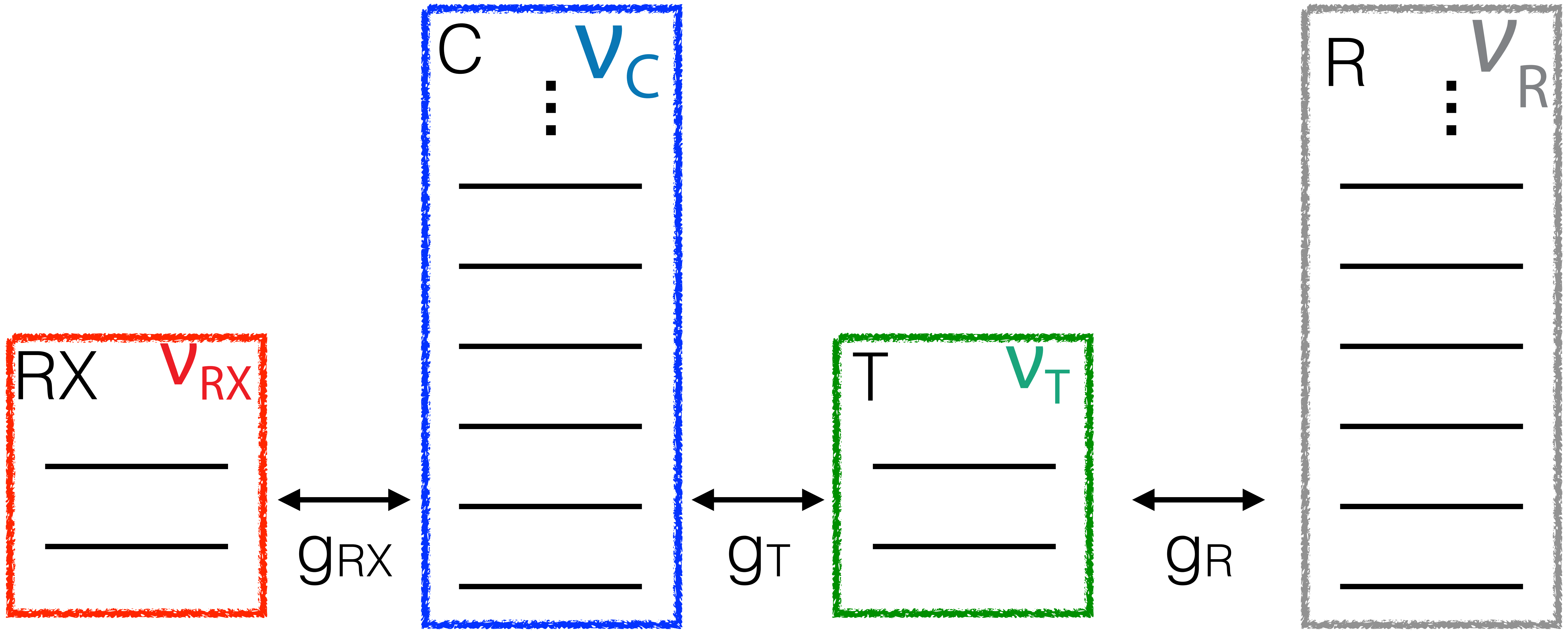
Is this spin qubit better than the state-of-the art silicon single-electron spin qubits?

What is the transmon?



How is the coupling achieved?

How coherent is the coupling?



$g_{\mathrm{RX}}/2\pi \;=\; 52\,\mathrm{MHz}$

$g_{\mathrm{R}}/2\pi \simeq 141\,\mathrm{MHz}$

$2g_{\mathrm{T}}/2\pi \;=\; 360\,\mathrm{MHz}$

$\gamma_{2,\mathrm{RX}}/2\pi \;=\; 11\,\mathrm{MHz}$

$\nu_{\mathrm{R}} = 5.62\,\mathrm{GHz}$

$\gamma_{2,\mathrm{T}}/2\pi = 0.7\,\mathrm{MHz}$

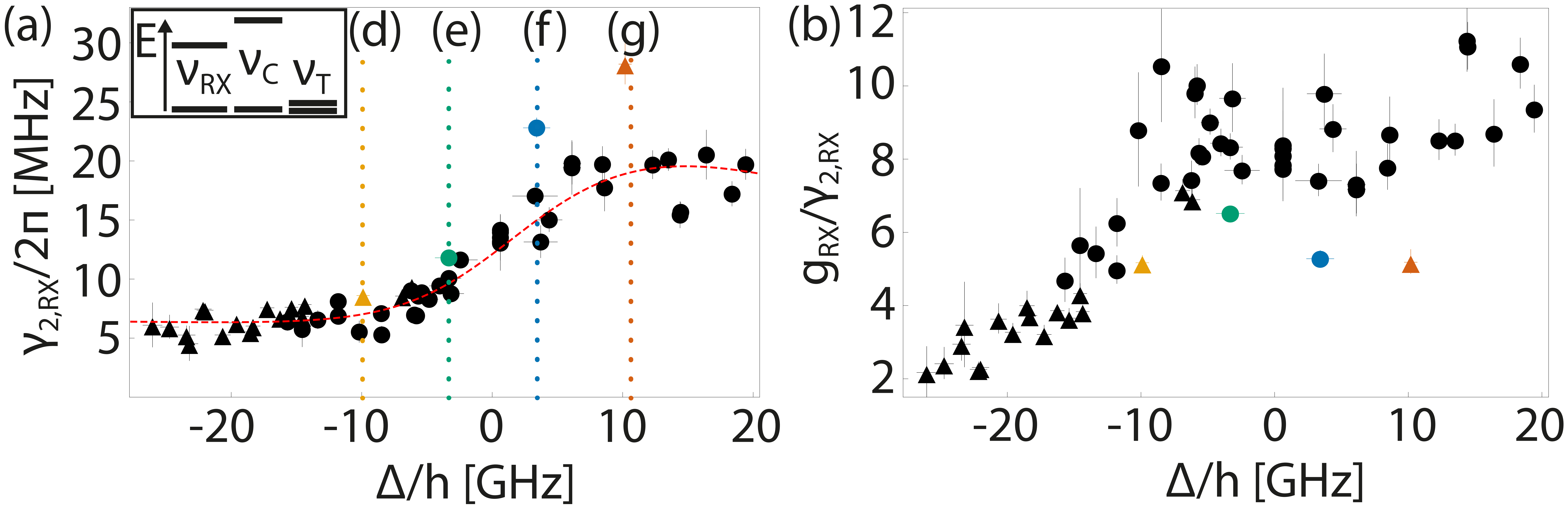
$\kappa_{\mathrm{R}}/2\pi = 5.3\,\mathrm{MHz}$

$\kappa_{\mathrm{C}}/2\pi \;=\; 4.6\,\mathrm{MHz}$

$E_{\mathrm{c}} = 0.22\,\mathrm{GHz}$

$E_{\mathrm{J,max}} \;=\; 18.09\,\mathrm{GHz}$

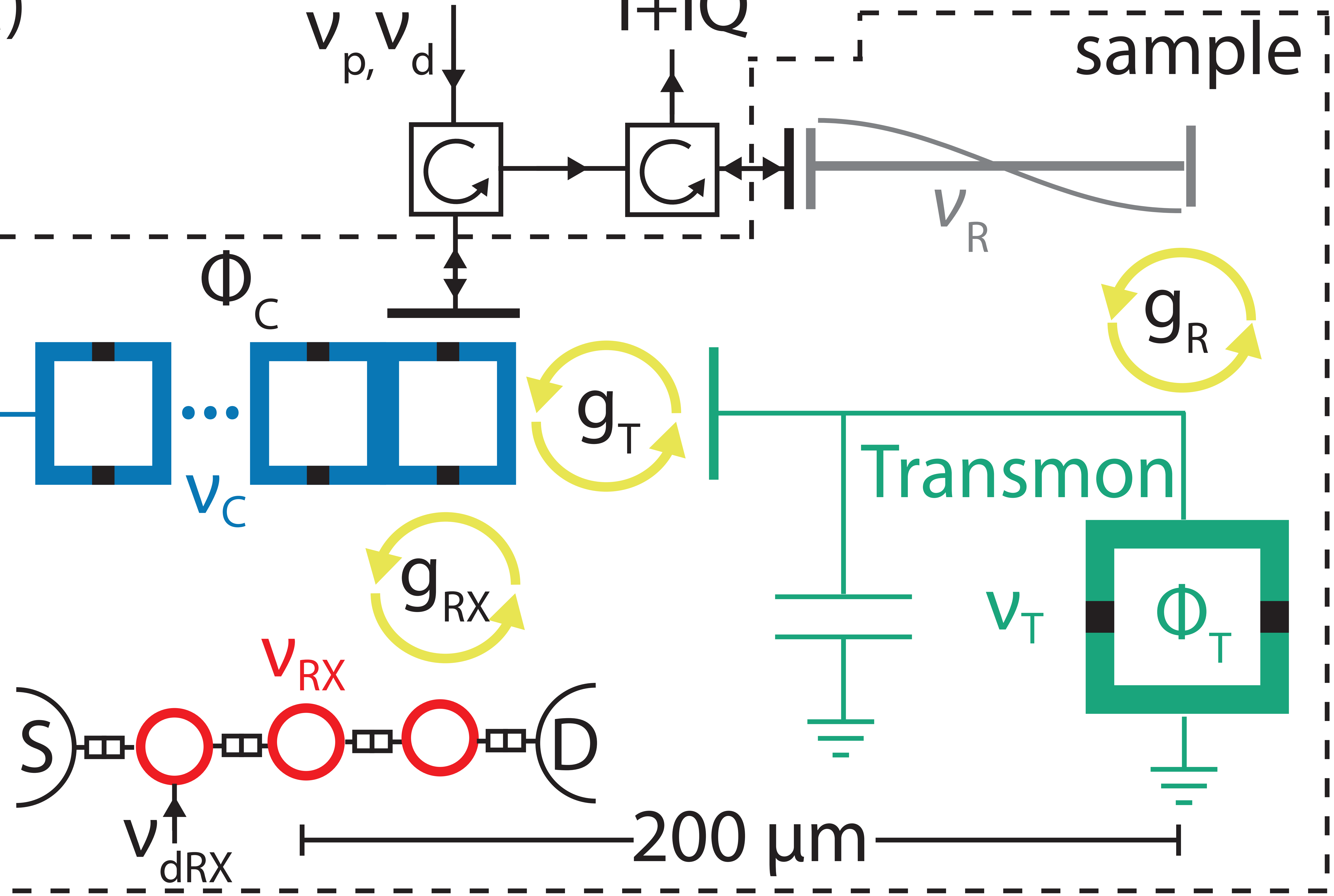
How coherent is the coupling?



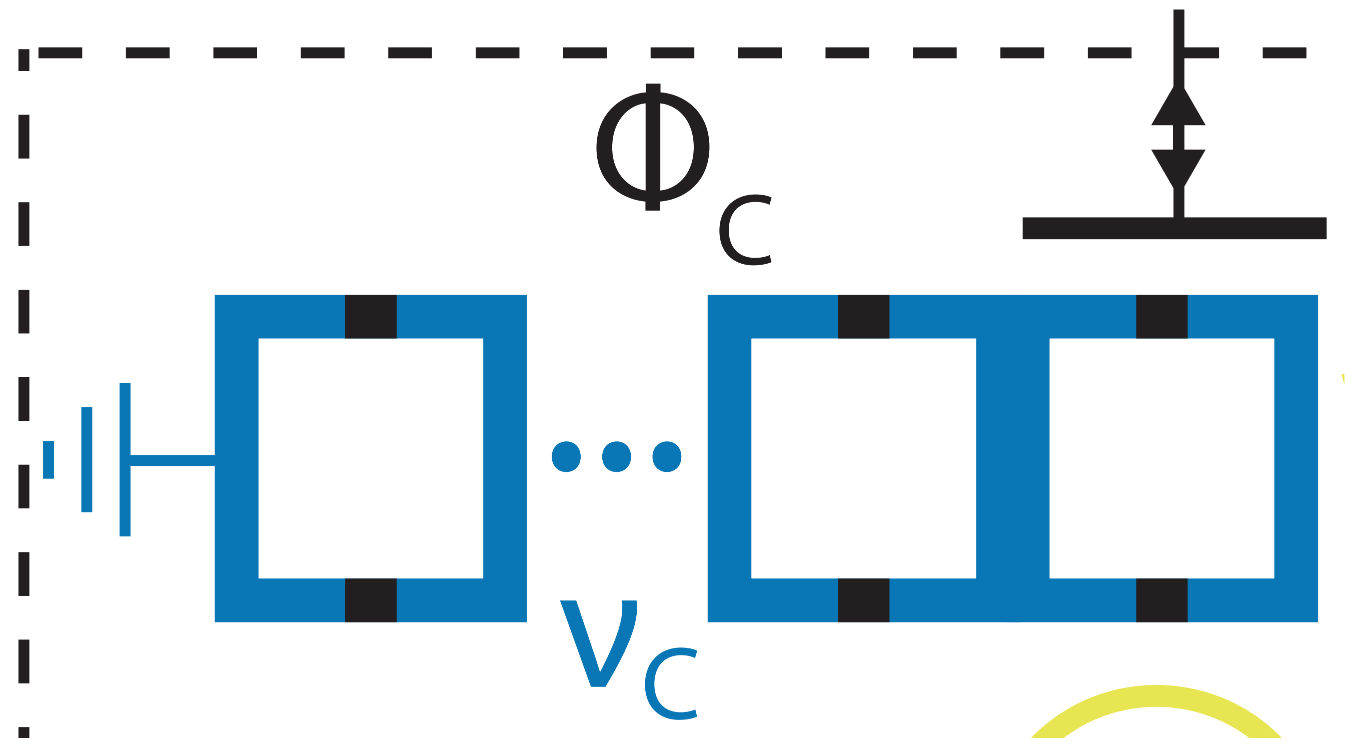
Coherent long-distance spin-qubit–transmon coupling

How long is the distance?

(a)

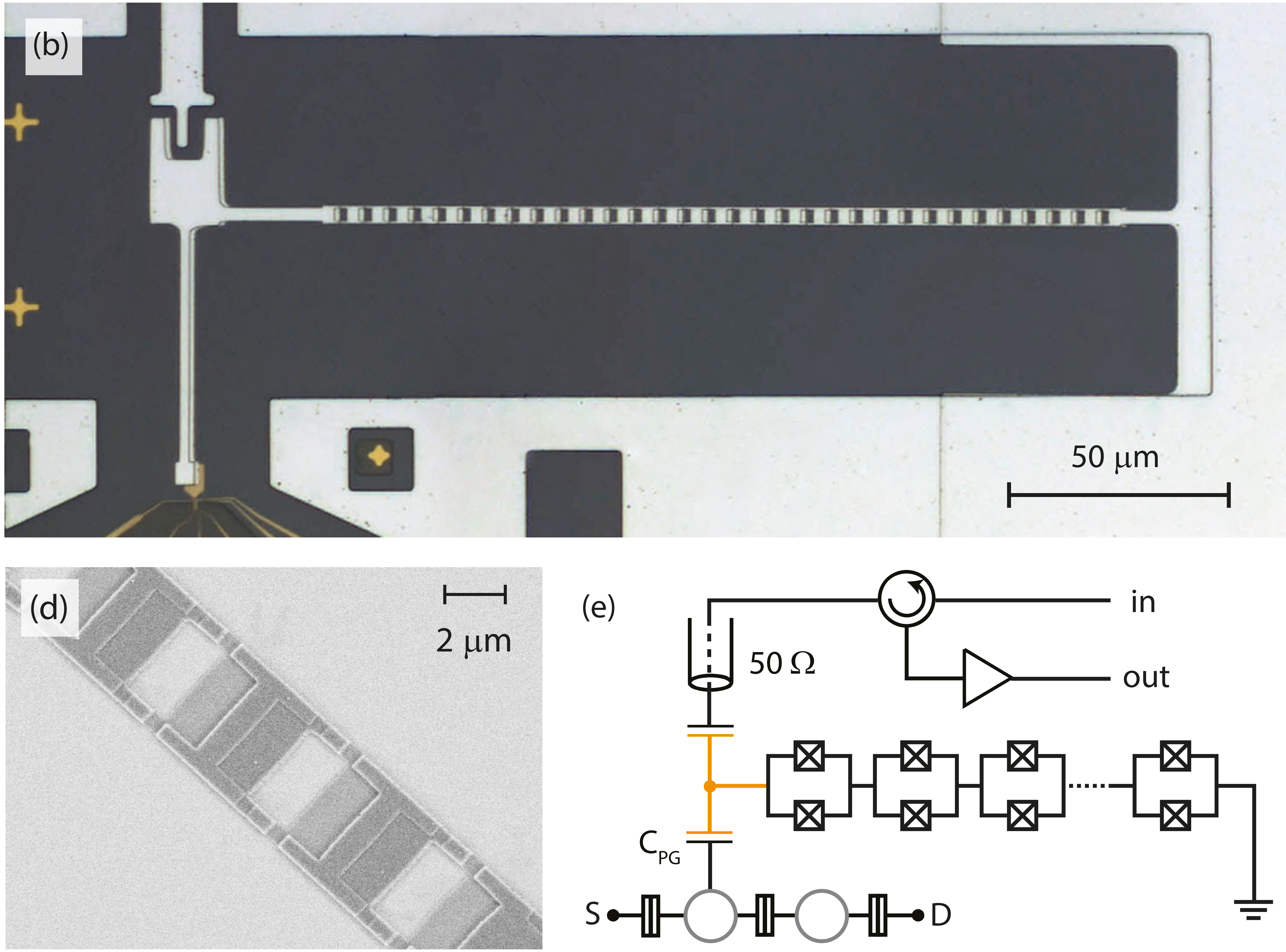


How does the SQUID array resonator work?



High impedance:
1.8 kOhm >> 50 Ohm

tunable with local magnetic flux:
4.5 - 6.0 GHz



Stockklauser et al., PRX 2017

A sqrt-of-iSWAP gate in circuit QED

$$H_{2q} \approx \hbar\left[\omega_{\mathrm{r}} + \frac{g^2}{\Delta}(\sigma_i^z + \sigma_j^z)\right]a^\dagger a + \frac{1}{2}\hbar\left[\Omega + \frac{g^2}{\Delta}\right](\sigma_i^z + \sigma_j^z) + \hbar\frac{g^2}{\Delta}(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+)\,. \qquad (32)$$

In a frame rotating at the qubit's frequency Ω, H_{2q} generates the evolution

$$U_{2q}(t) = \exp\left[-i\frac{g^2}{\Delta}t\left(a^\dagger a + \frac{1}{2}\right)(\sigma_i^z + \sigma_j^z)\right] \times \begin{pmatrix} 1 & & & \\ & \cos\frac{g^2}{\Delta}t & i\sin\frac{g^2}{\Delta}t & \\ & i\sin\frac{g^2}{\Delta}t & \cos\frac{g^2}{\Delta}t & \\ & & & 1 \end{pmatrix} \otimes \mathbb{1}_r, \qquad (33)$$

Up to phase factors, this corresponds at $t = \pi\Delta/4g^2$ to a $\sqrt{i\mathrm{SWAP}}$ operation.

Together with single-qubit gates, it forms a universal gate set.

Turning the sqrt-of-iSWAP gate On and Off

$$H_{2q} \approx \hbar\left[\omega_r + \frac{g^2}{\Delta}(\sigma_i^z + \sigma_j^z)\right]a^\dagger a + \frac{1}{2}\hbar\left[\Omega + \frac{g^2}{\Delta}\right](\sigma_i^z + \sigma_j^z)$$
$$+\hbar\frac{g^2}{\Delta}(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+). \qquad (32)$$

qubit-qubit interaction: always On

- the effect of the qubit-qubit interaction on dynamics is suppressed at `large qubit-qubit detuning', that is, if:

$$g^2/\Delta \ll |\Omega_i - \Omega_j|$$

- the sqrt-of-iSWAP gate can be turned Off by detuning the two qubits from each other